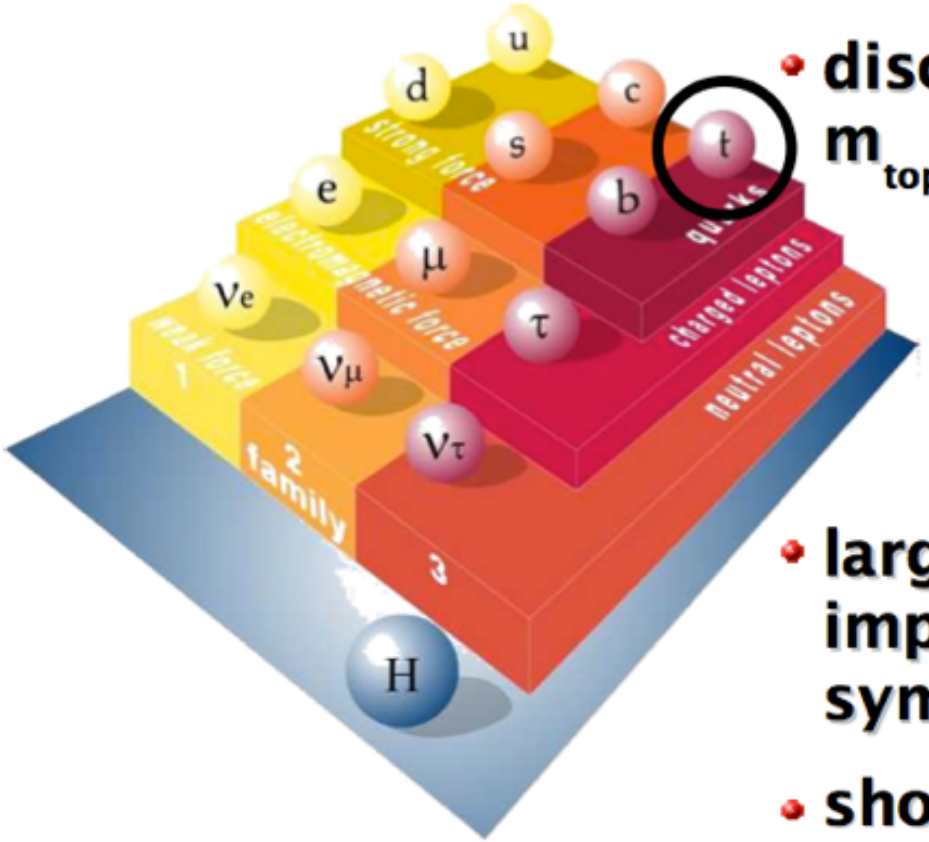
Top Precision and Searches for New Physics

Christian Schwanenberger

DESY

DESY Physics Seminar
16 February, 2016

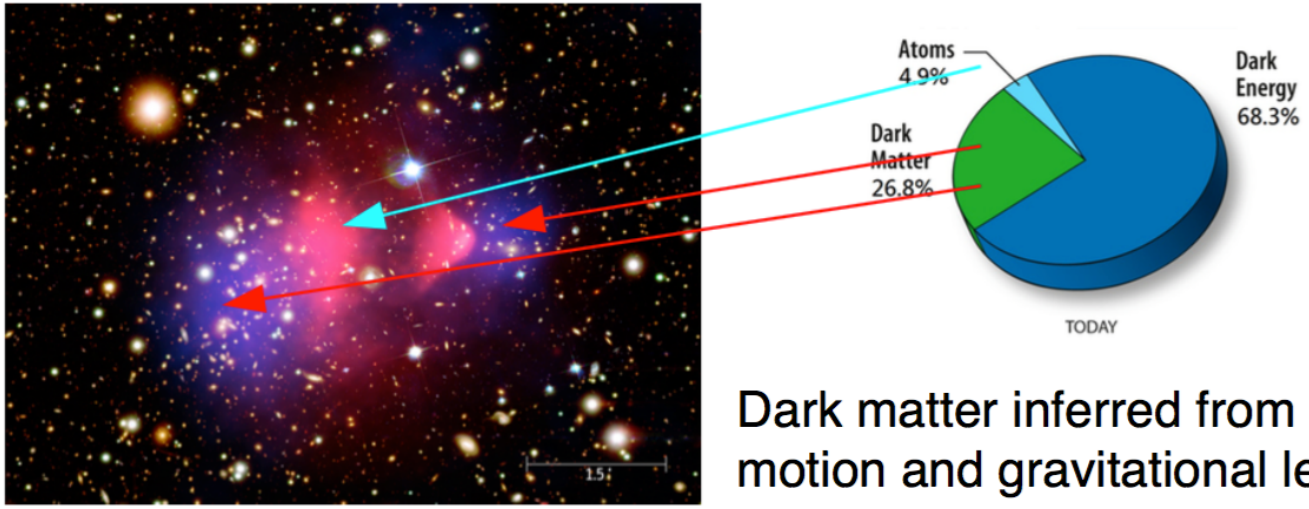
The Top Quark



- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

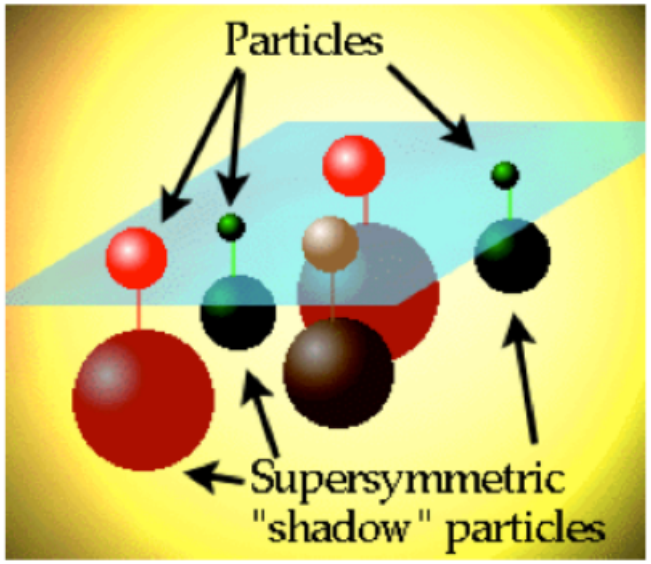
Is the top quark the particle as predicted by the SM?

Search for New Phenomena



Dark matter inferred from star motion and gravitational lensing

Supersymmetry:

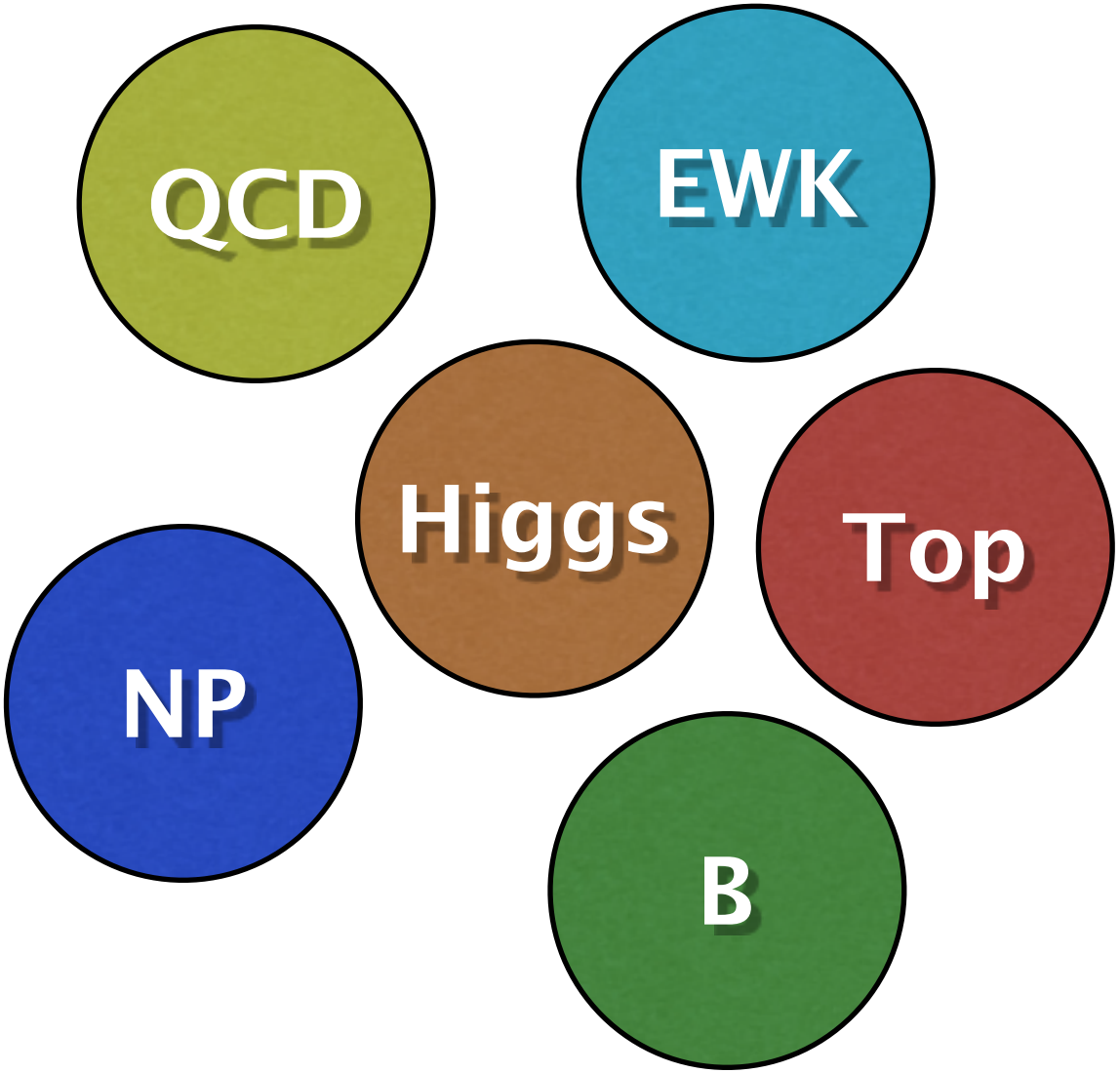


Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

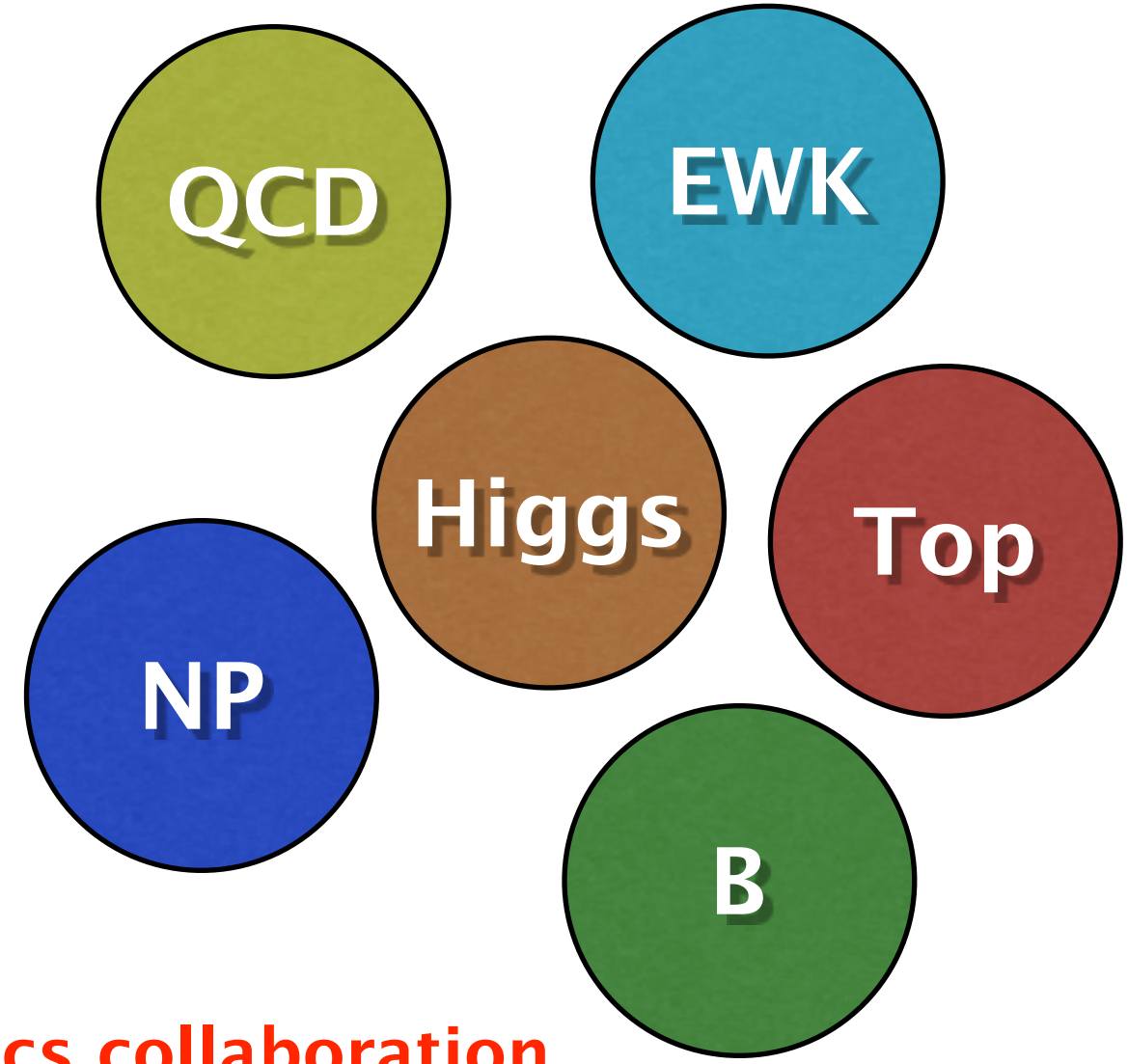
Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$Wino^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

remedies shortcomings of SM: e.g. dark matter candidate

Physics Groups: DØ Collaboration

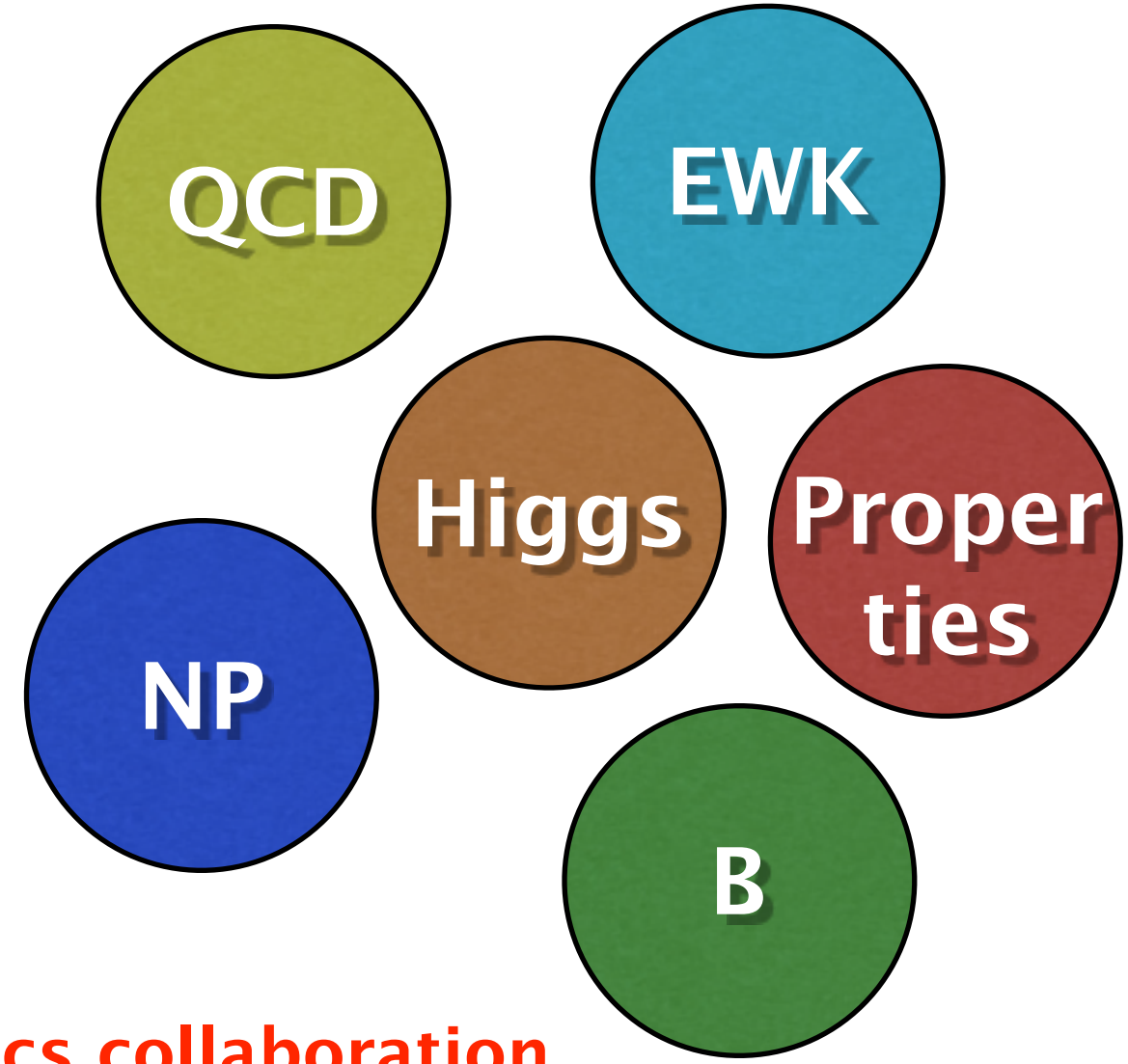


Top Quark Physics Topics



→ top physics collaboration

Top Quark Physics Topics



→ top physics collaboration

Top Quark Physics Topics

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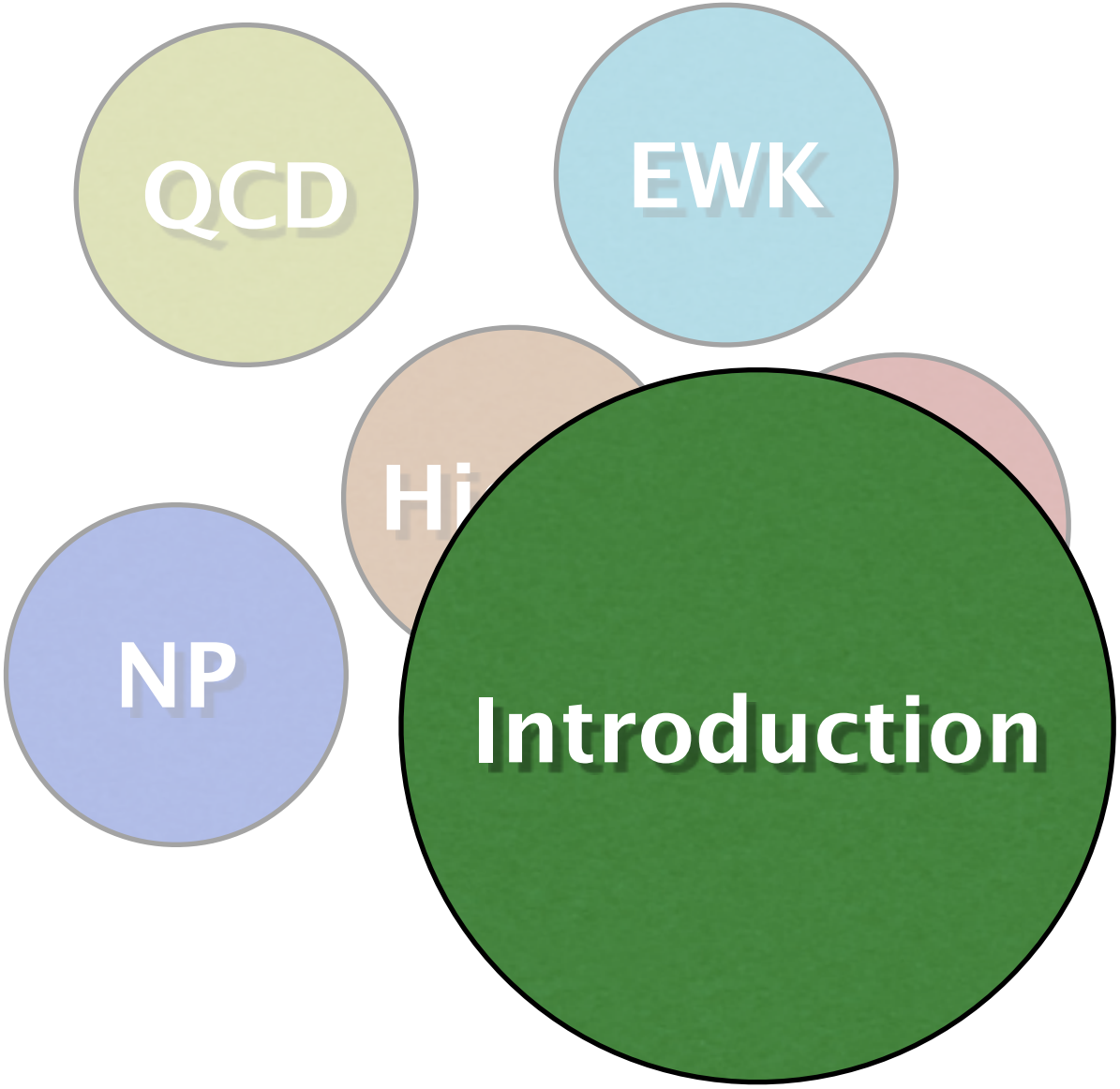
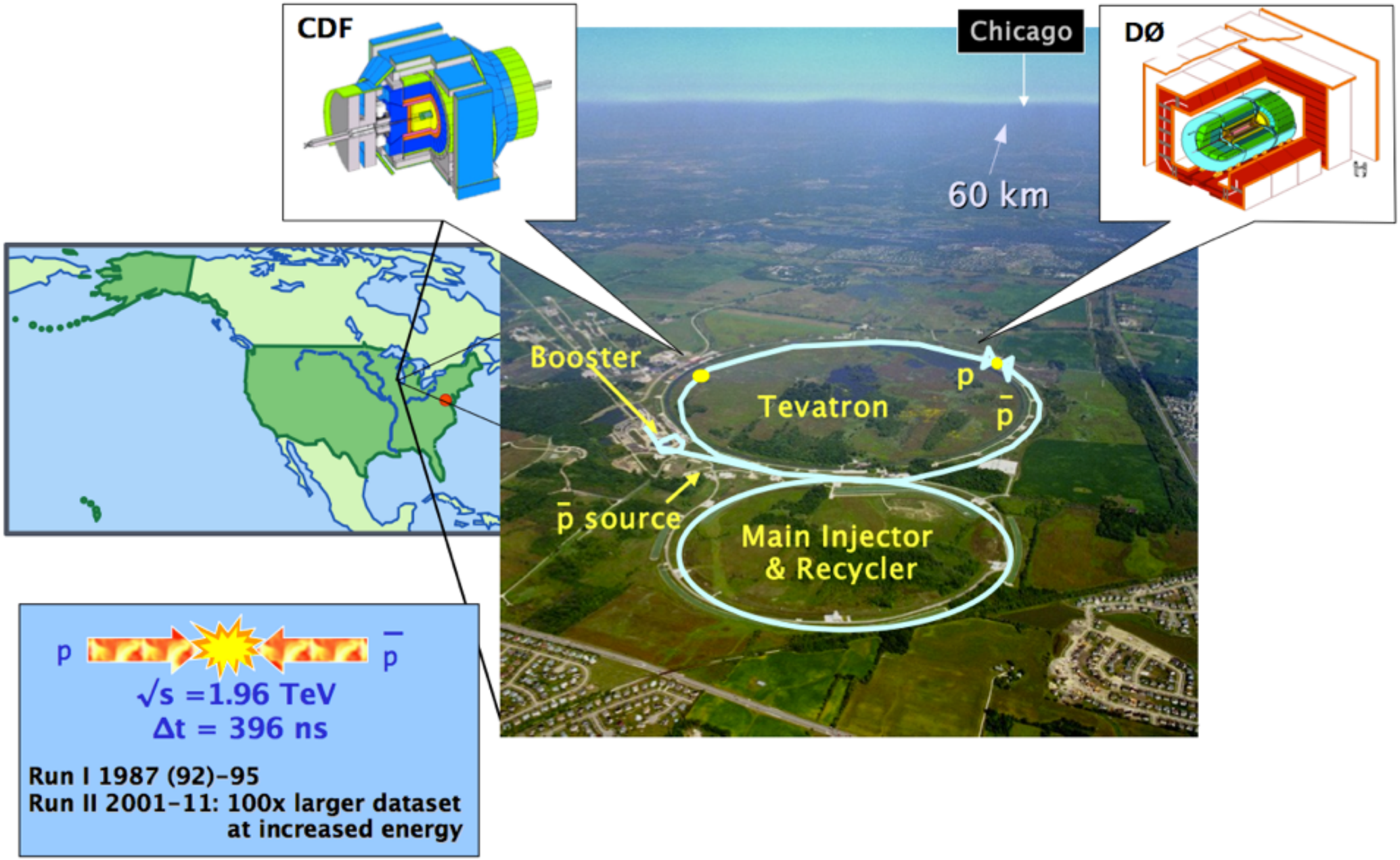
Top Quark Physics Topics



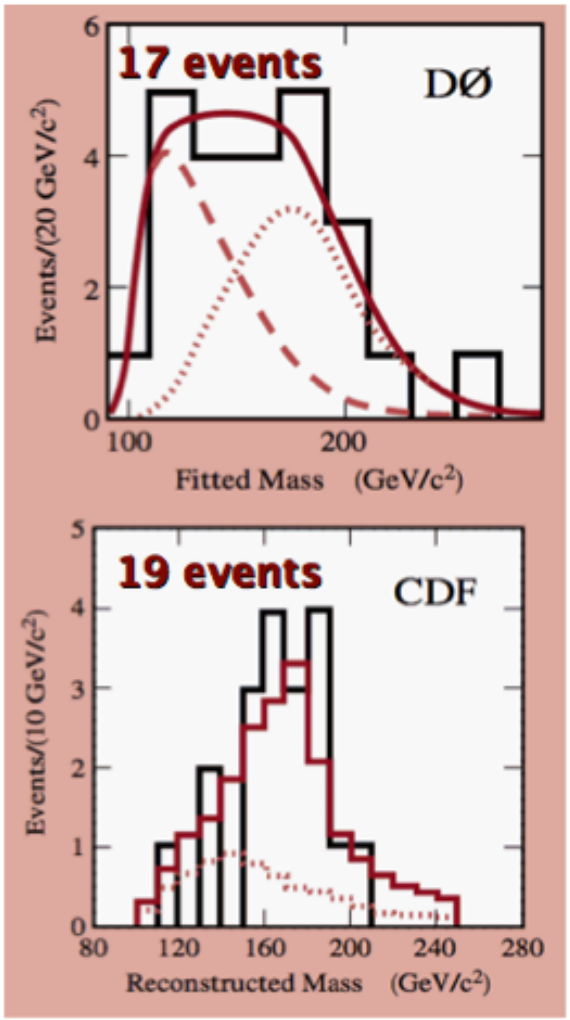
The Tevatron $p\bar{p}$ Collider at Fermilab



The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

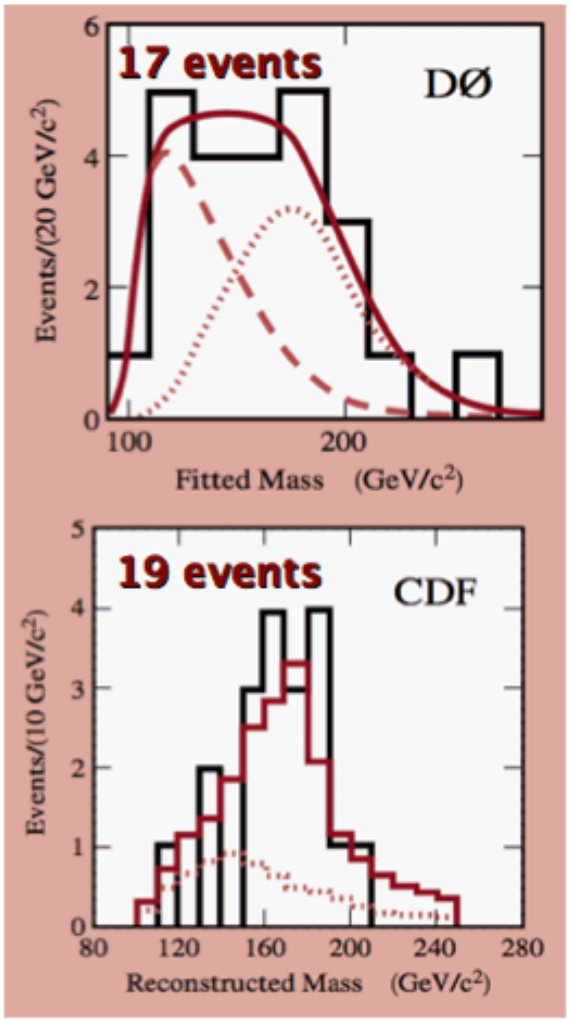
March 2nd, 1995:

First announcement of Top Discovery in public seminar at Fermilab

The Top Quark

discovery

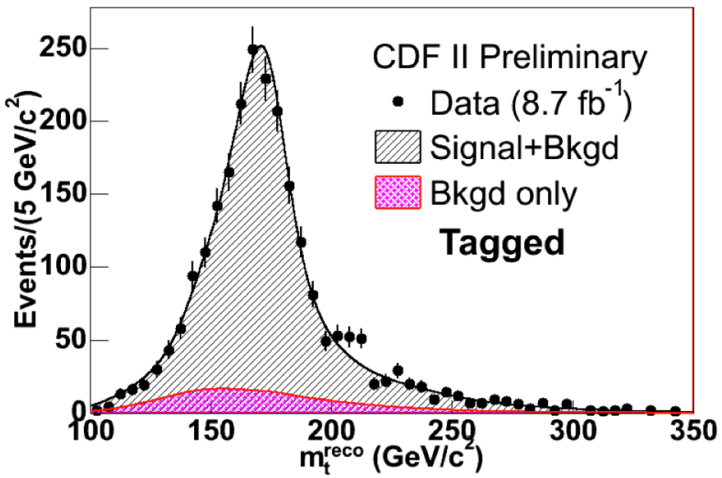
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

1000s of events



The Top Quark

discovery

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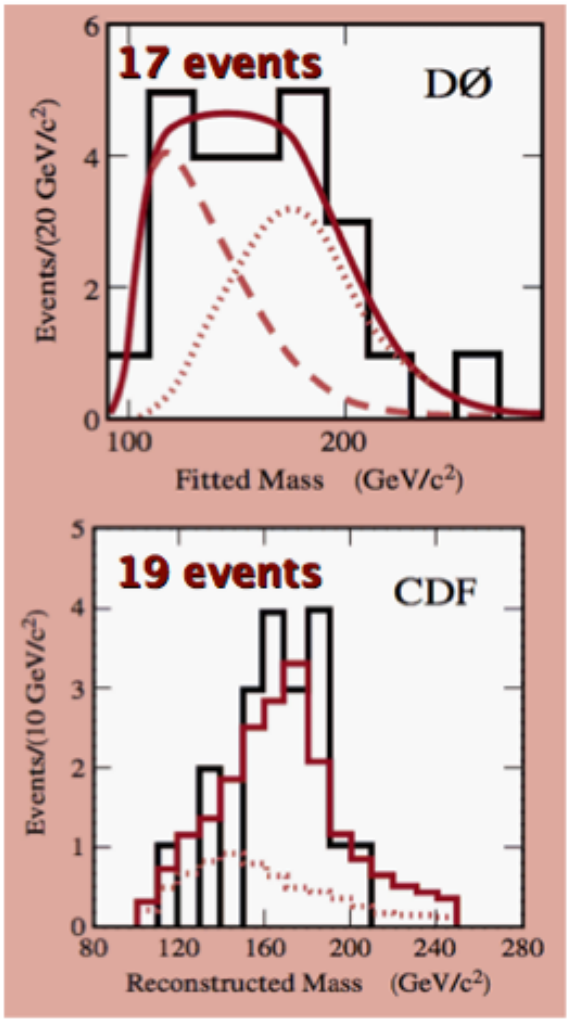

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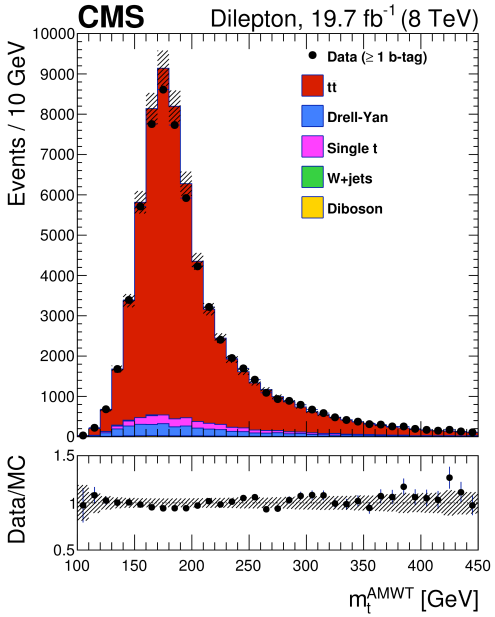
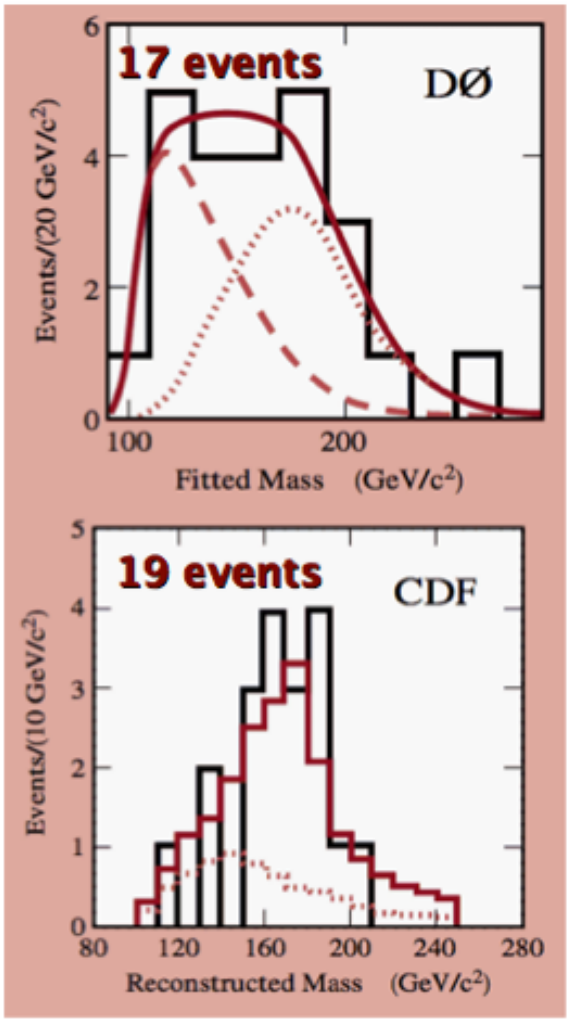


LHC: top quark factory

The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



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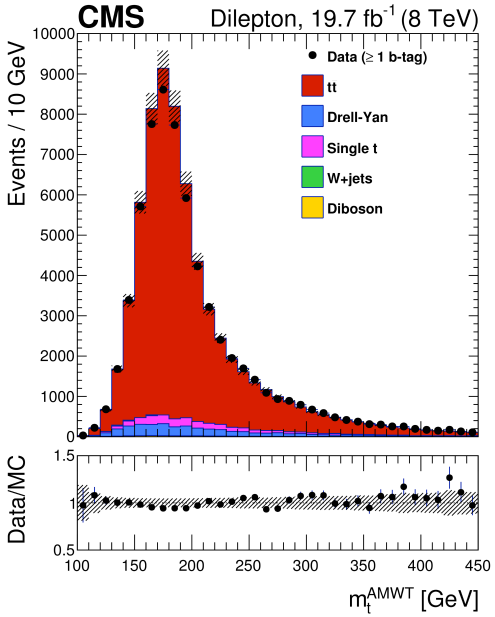
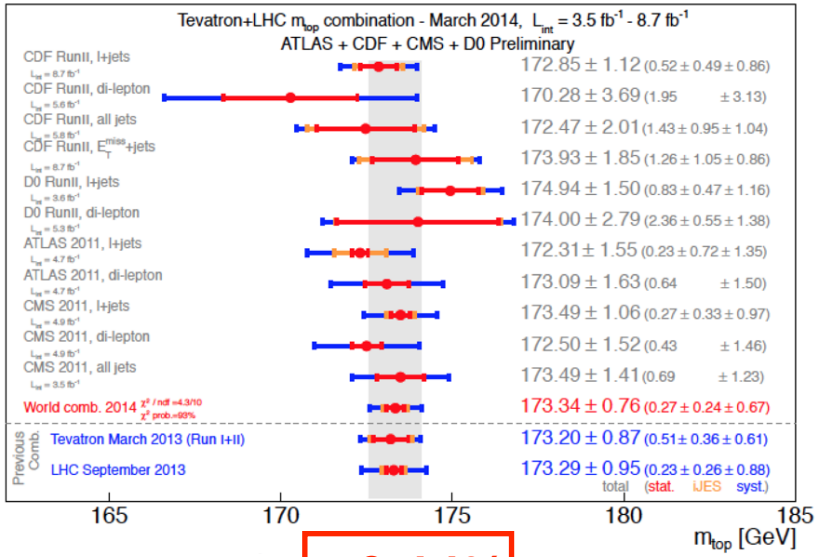


LHC: top quark factory

precision

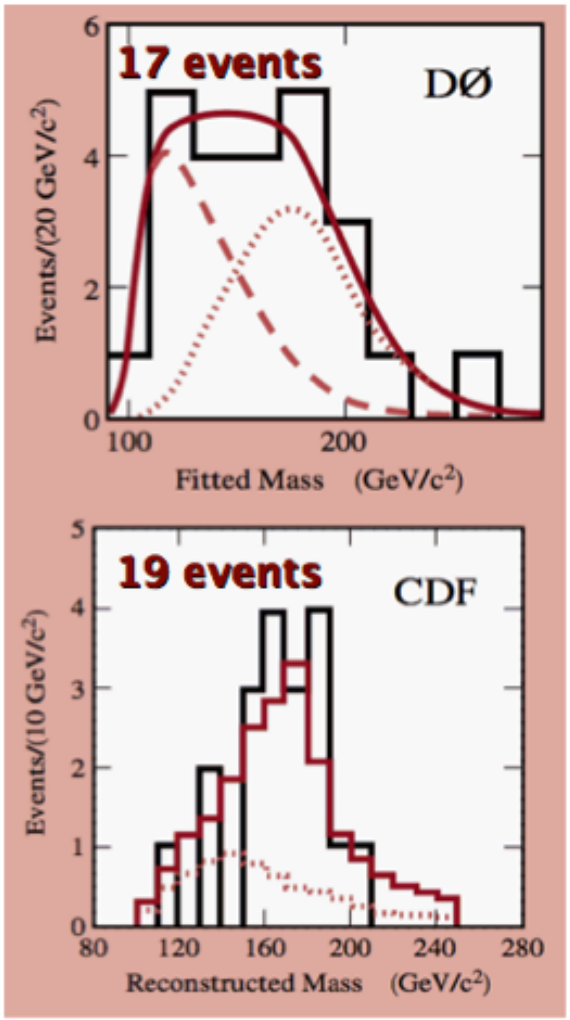


±0.44%

The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

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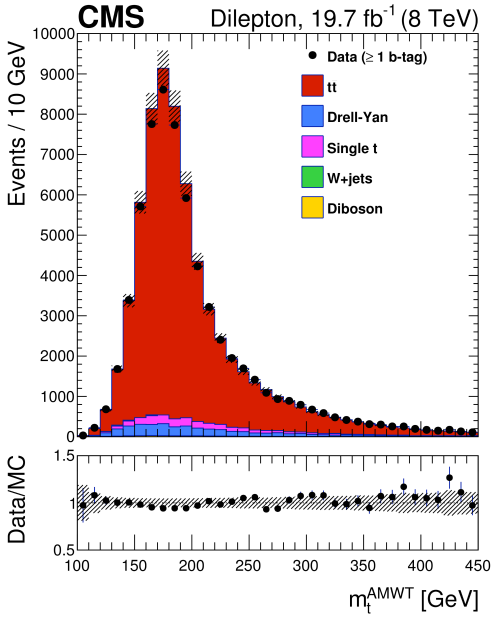
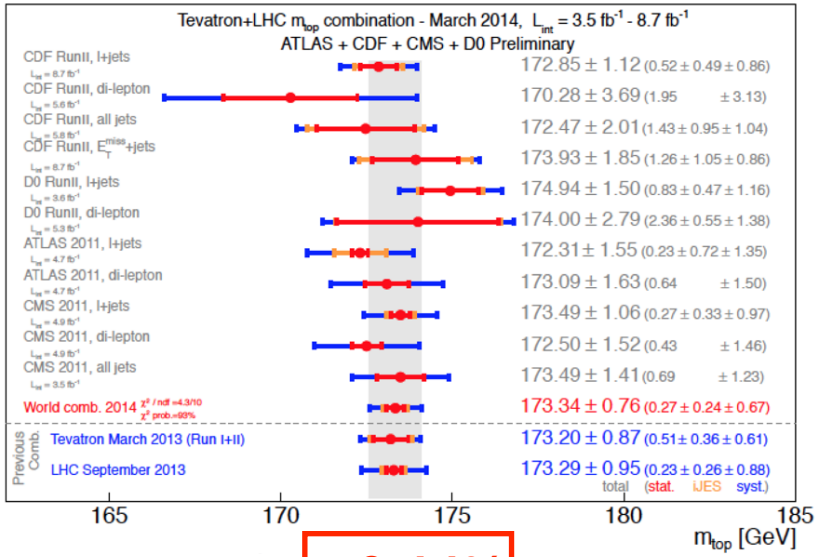


LHC: top quark factory

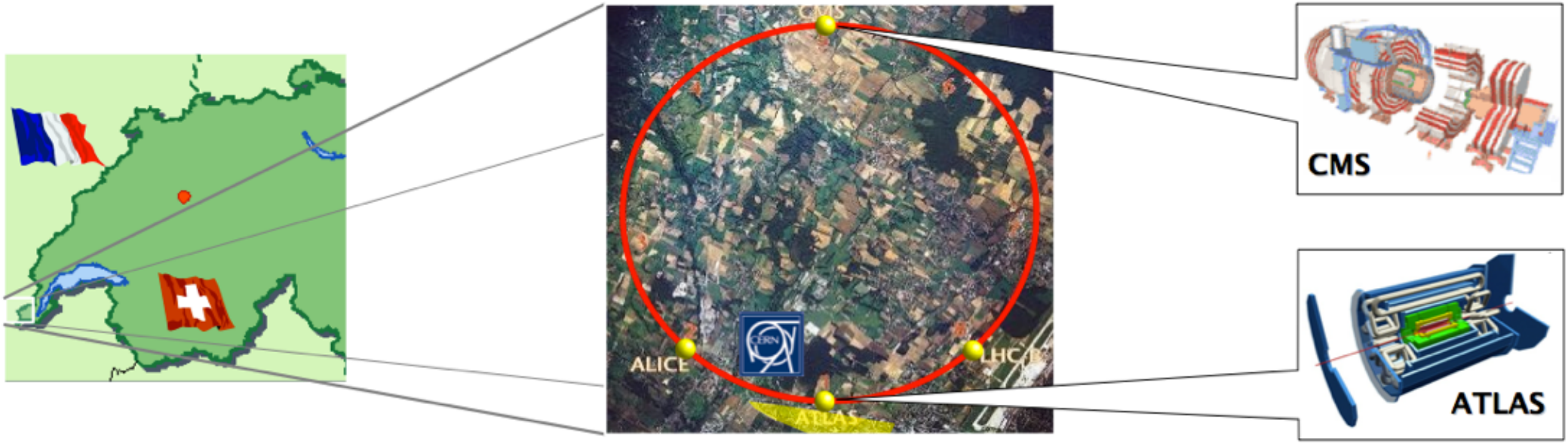
precision



±0.44%

searches

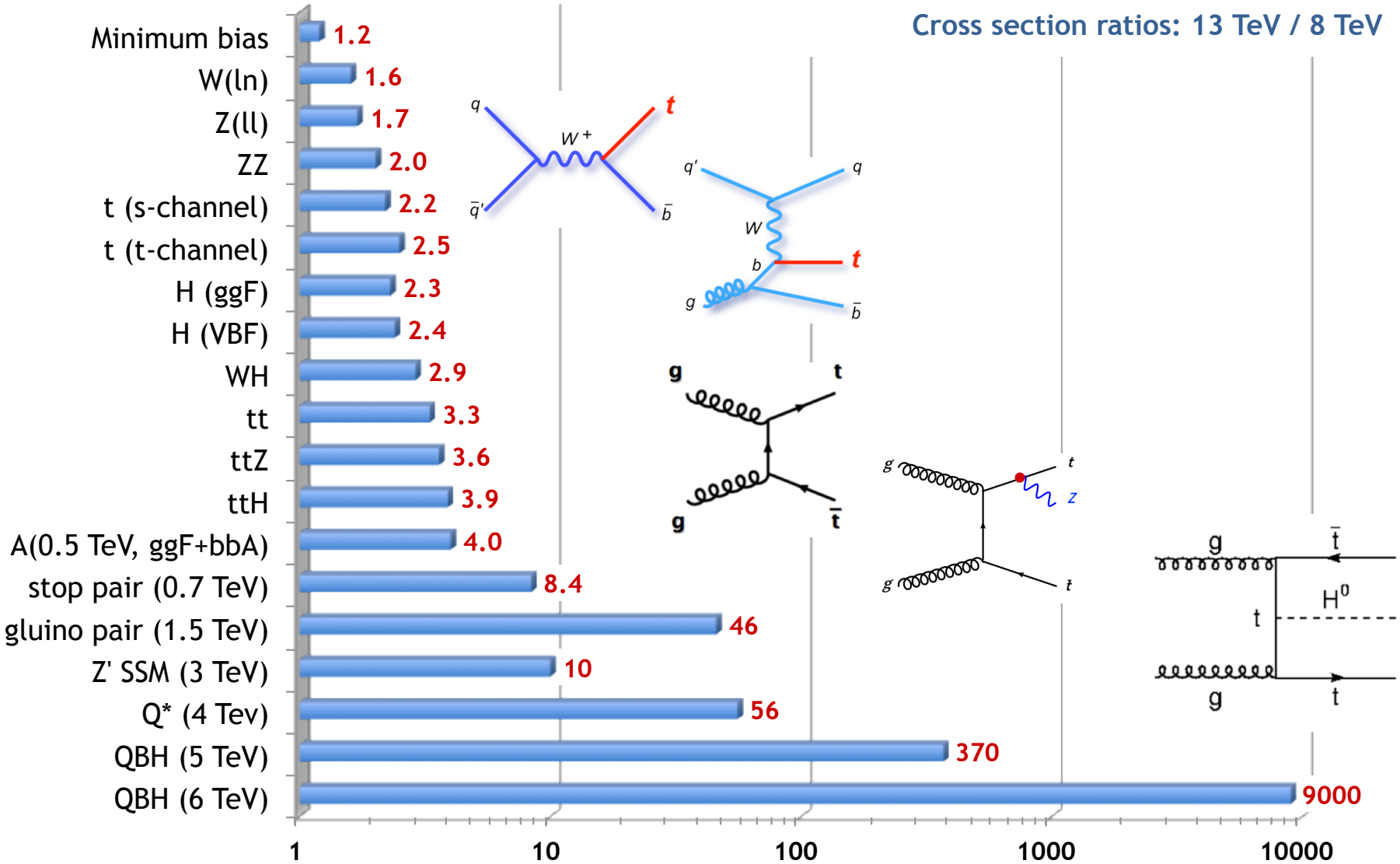
The LHC pp Collider at CERN



	√s [TeV]	years	Ldt (rec.)
pp	7	2010-11	5.1 fb-1
pp	8	2012	21.3 fb-1
Pb+Pb	2.76	2010-11	160 µb-1
Pb+p	5	2013	30 nb-1

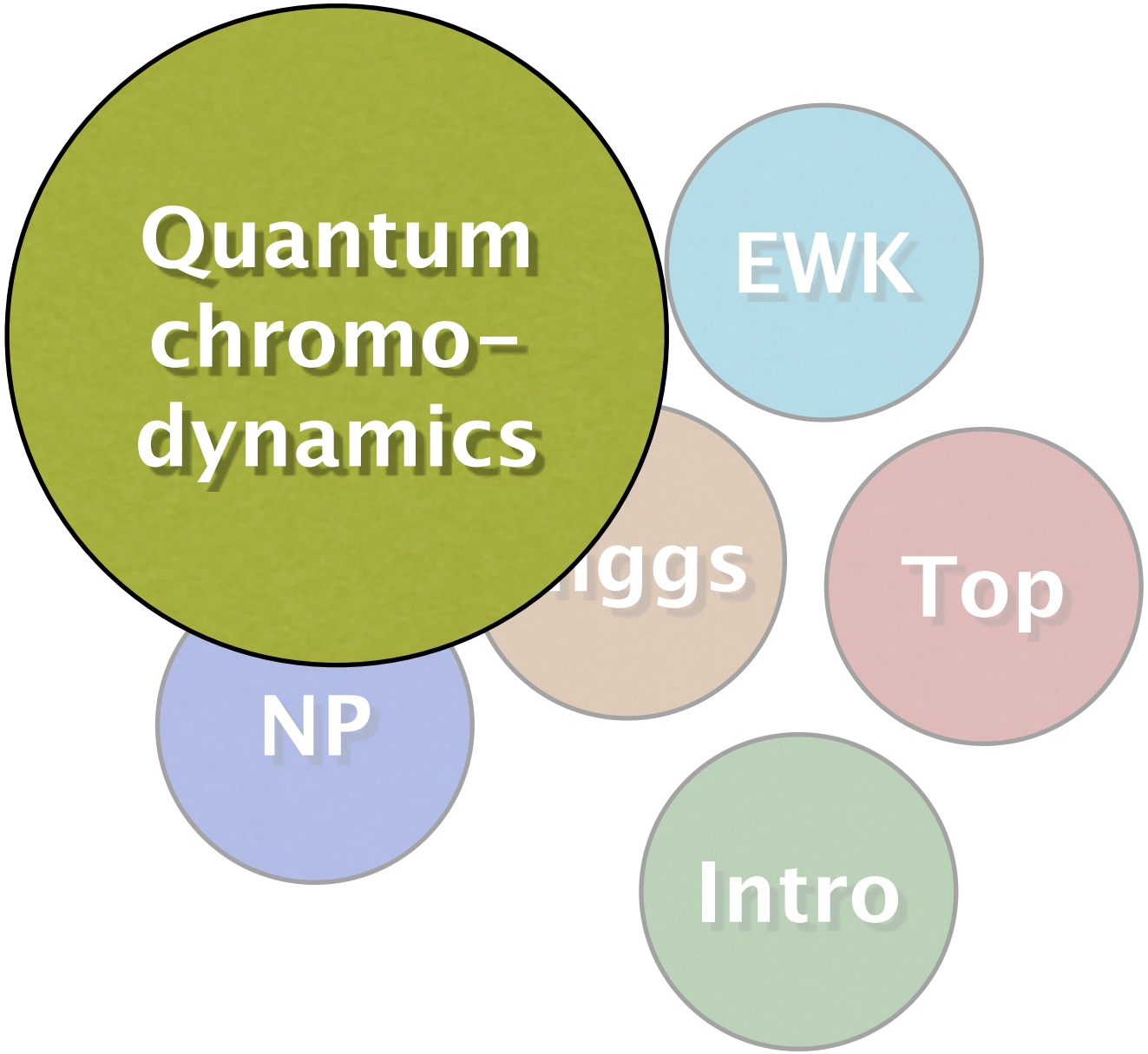
June 3rd, 2015: First Collisions @ 13 TeV

Cross Sections: 13 TeV/8 TeV

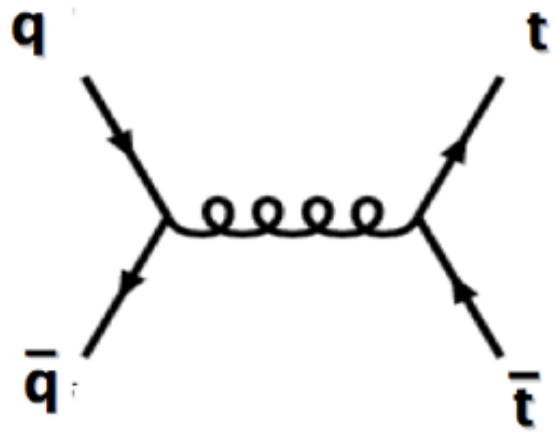


→ excellent prospects for top physics

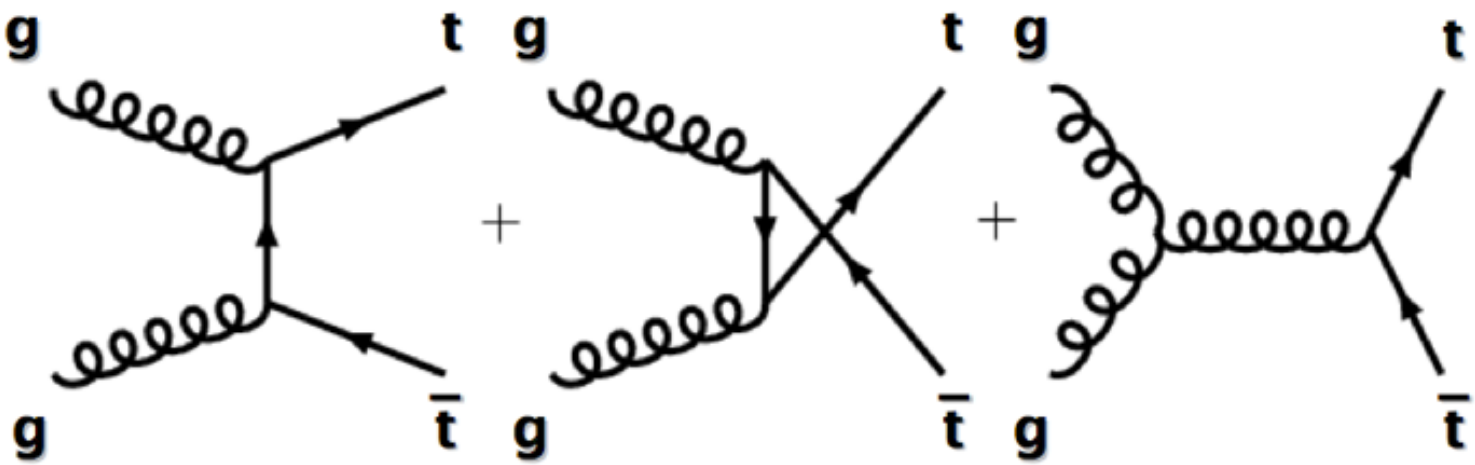
Top Quark Physics Topics



Top Quark Pair Production



Tevatron (~85%)



LHC (~87%)
(8 TeV)

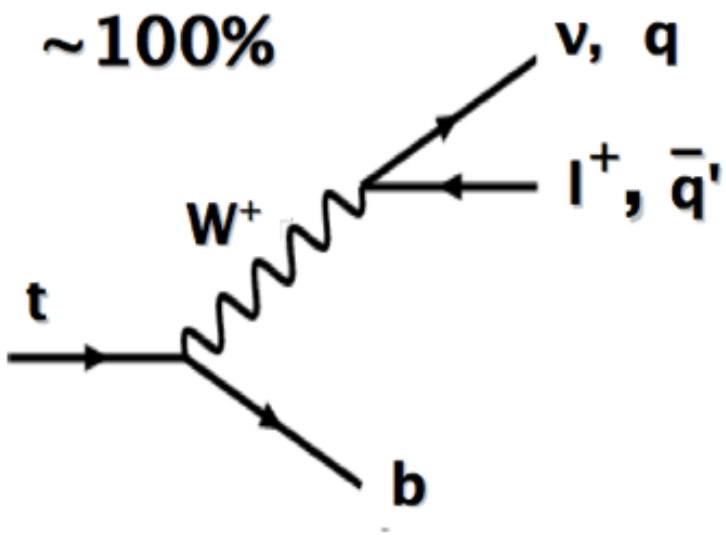
Top Quark Pair Signatures

τ's
14%

alljets
46%

top decay:

~100%



- high p_T leptons, missing E_T
- jets
- b-jets

Top Pair Decay Channels

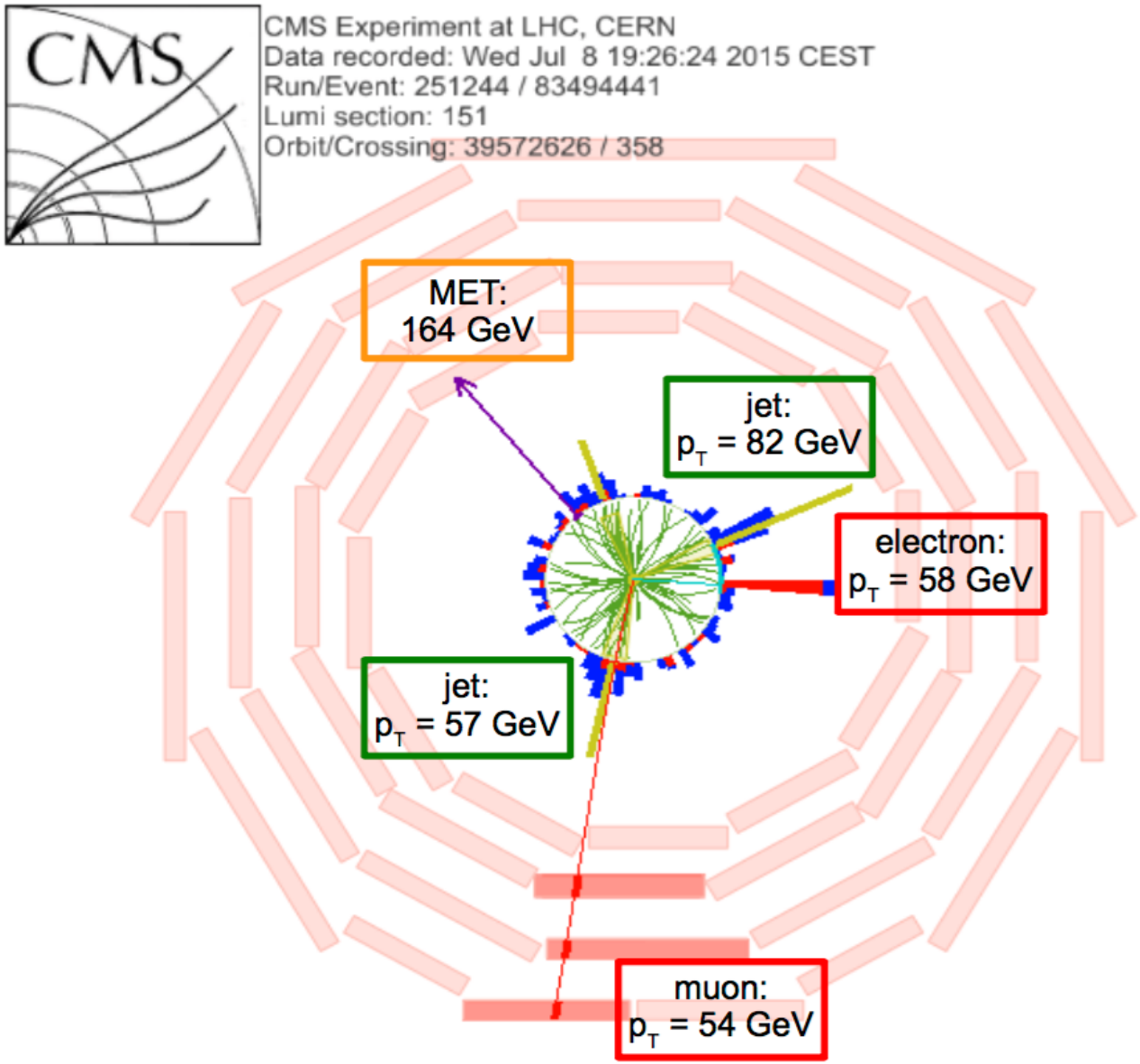
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	

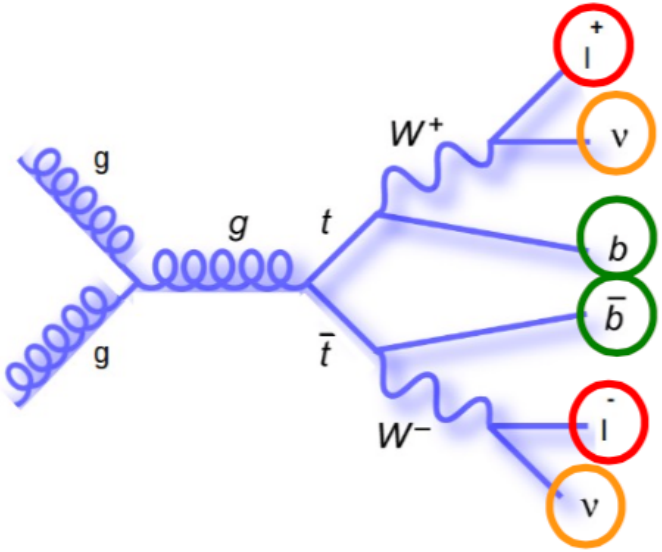
dileptons

dilepton (e/μ)
6%

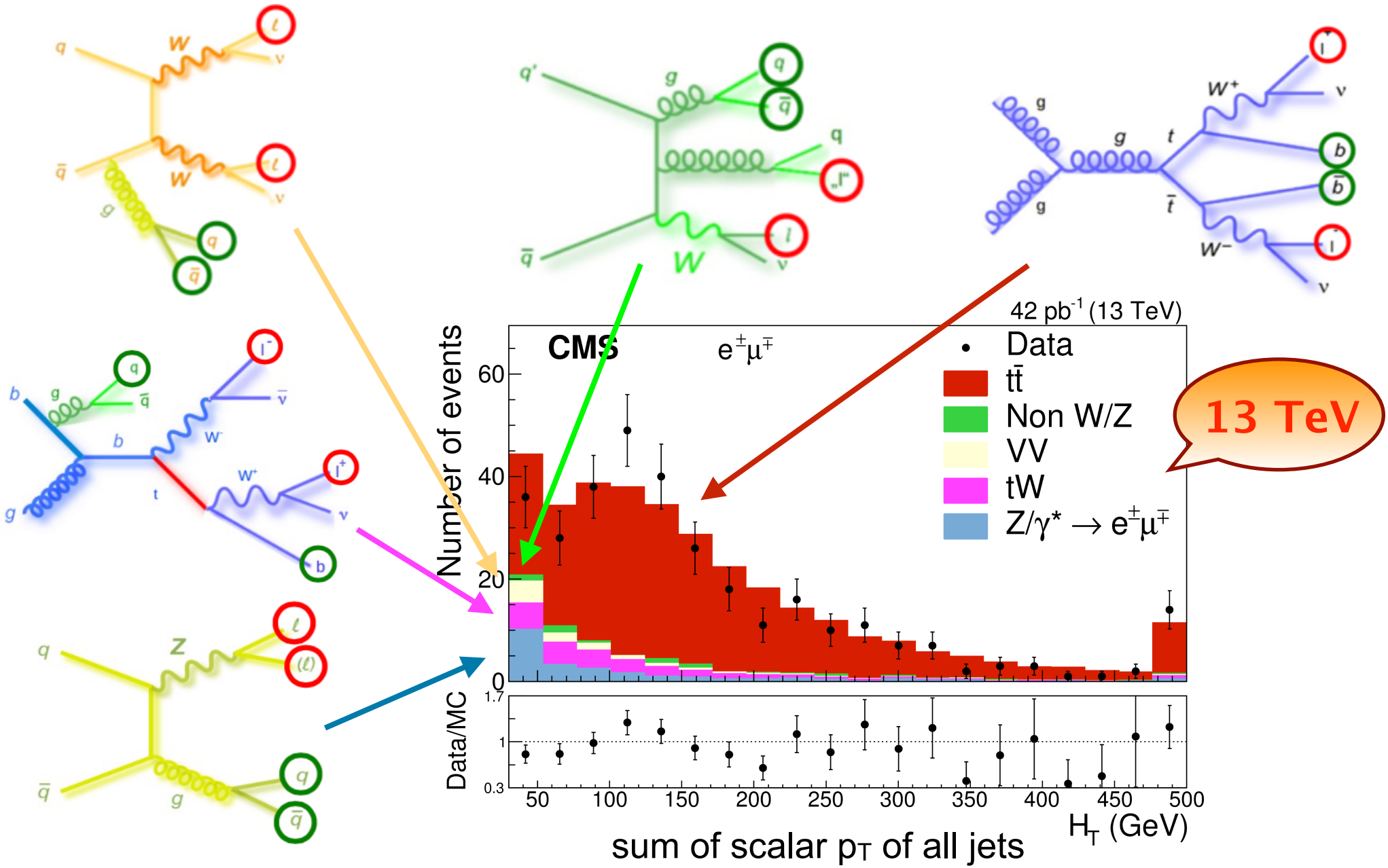
e/μ+jets
34%

Dilepton Signature

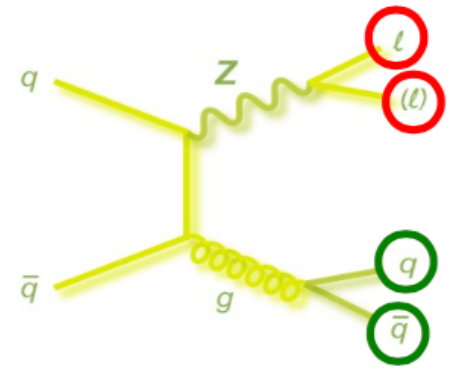


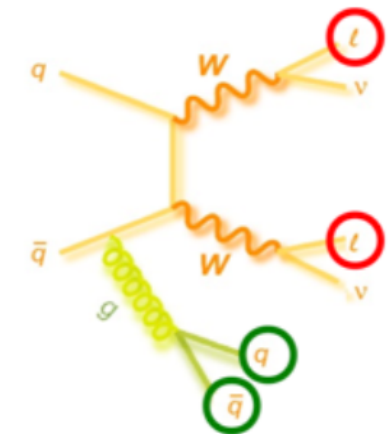


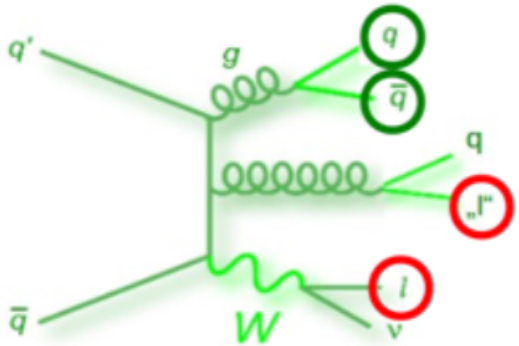
Dilepton Events at 13 TeV

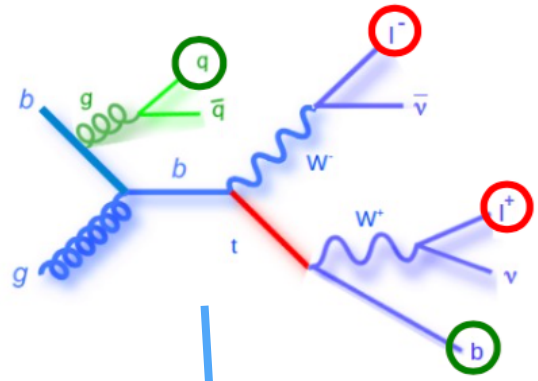


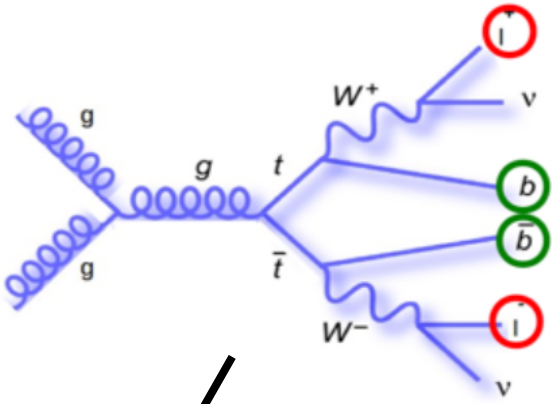
Dilepton Events at 13 TeV

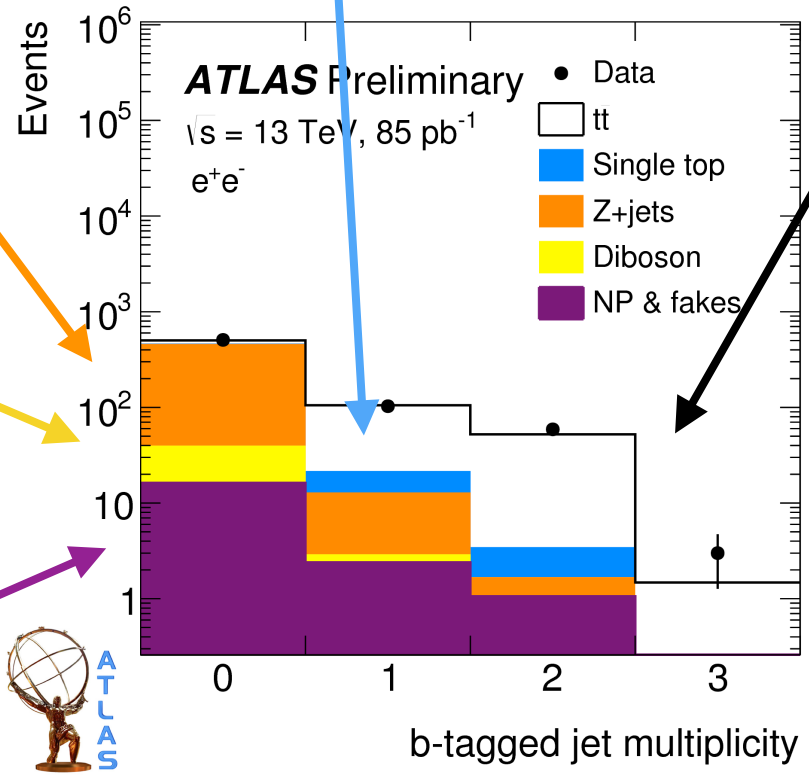


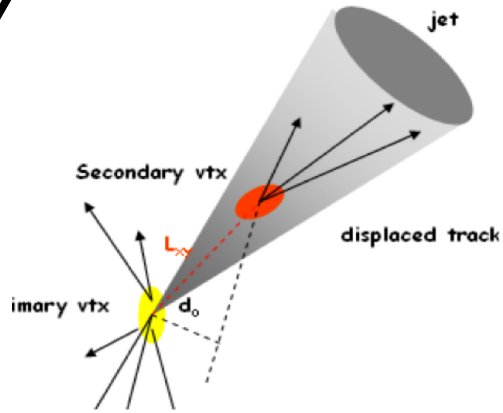






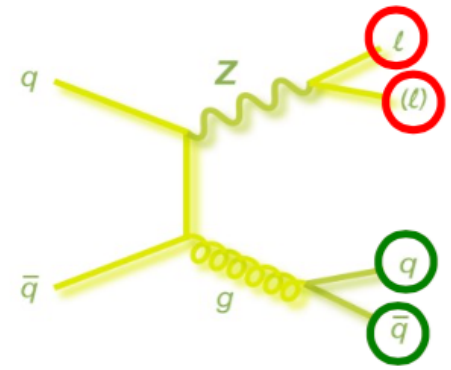


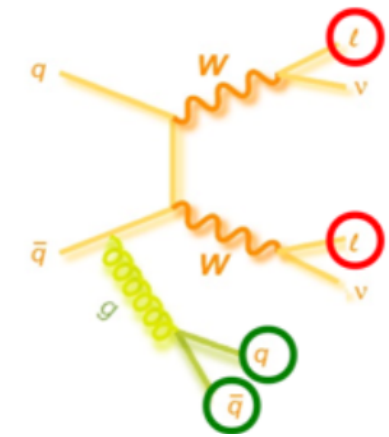


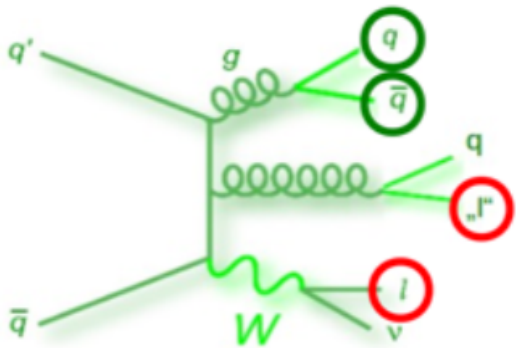


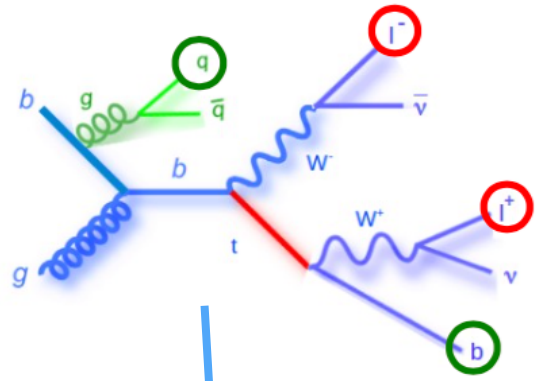
very powerful!

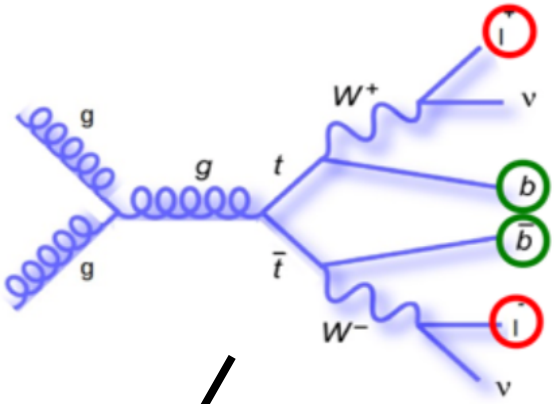
Dilepton Events at 13 TeV

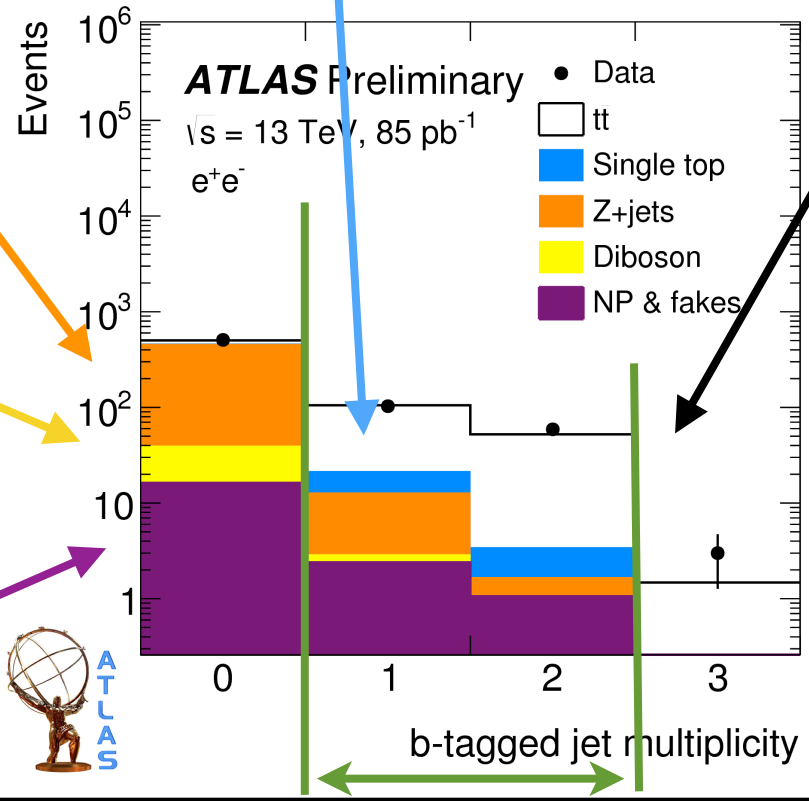


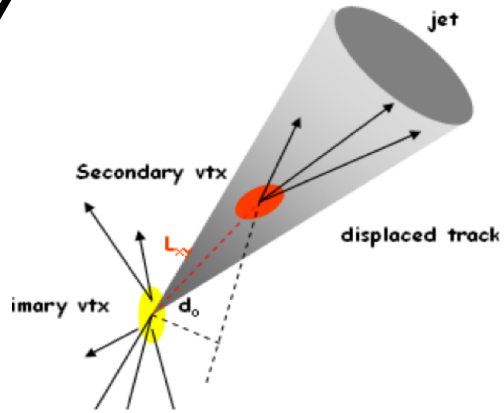






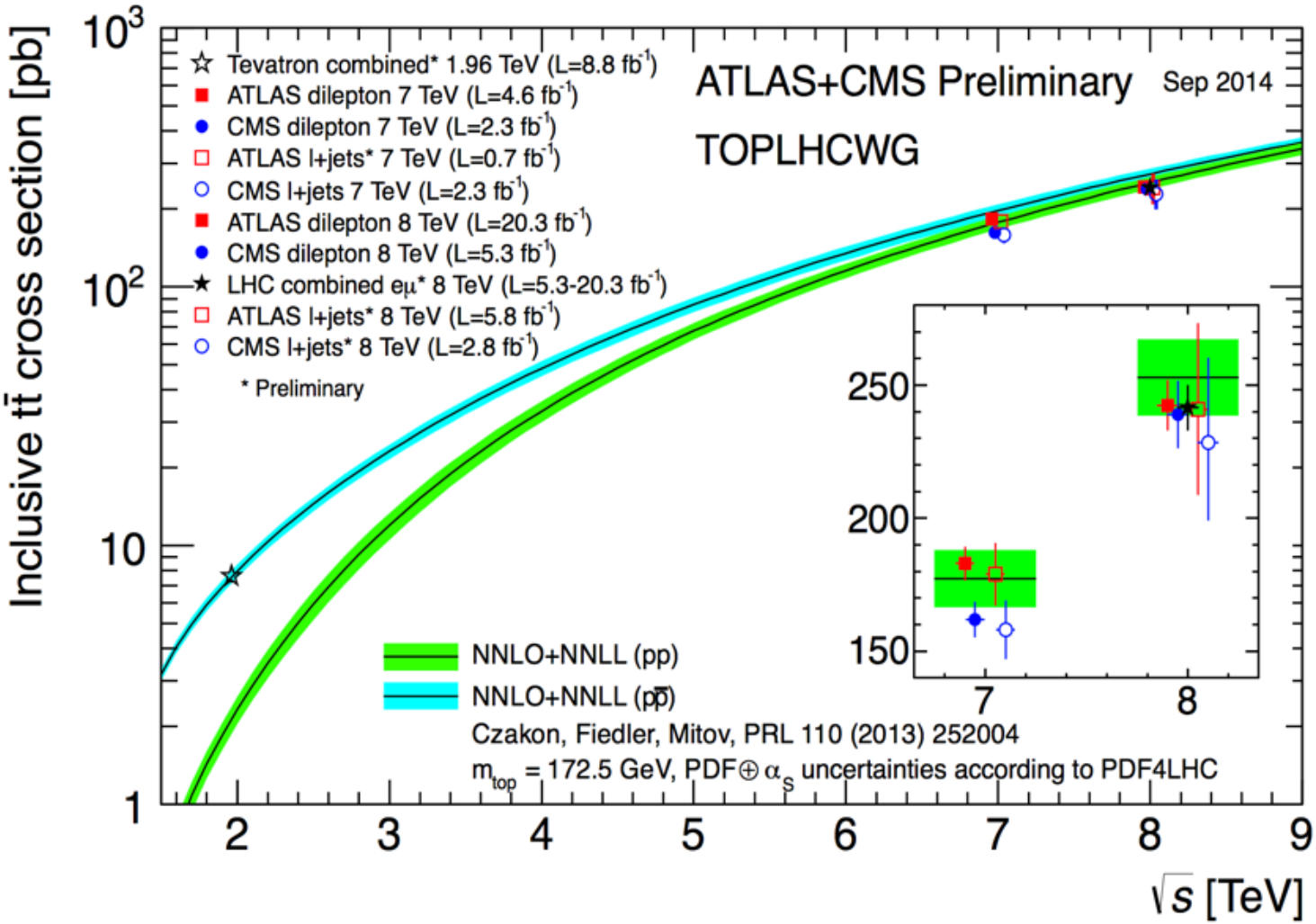






very powerful!

Top pair production at hadron colliders

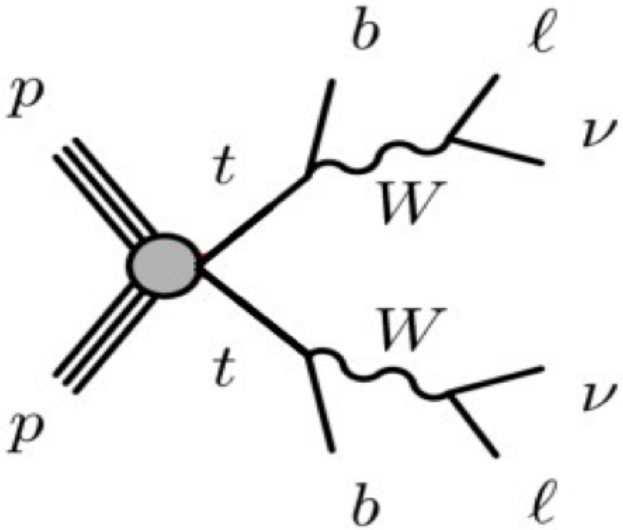


±5.7% (theo)

±3.9% (eμ)

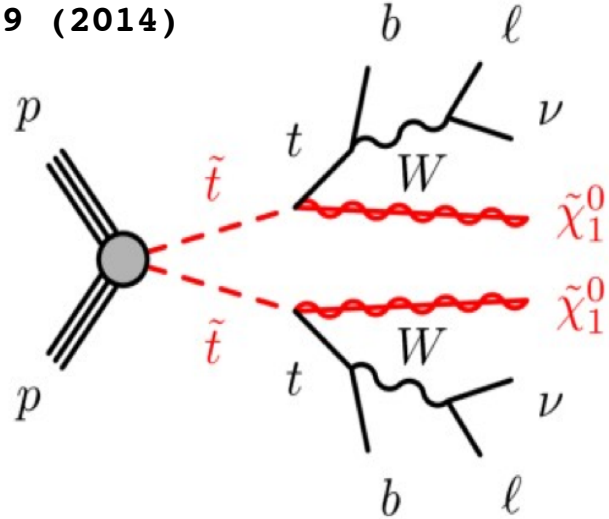
→ experiments challenge theory again

Stop Quark Pair Production

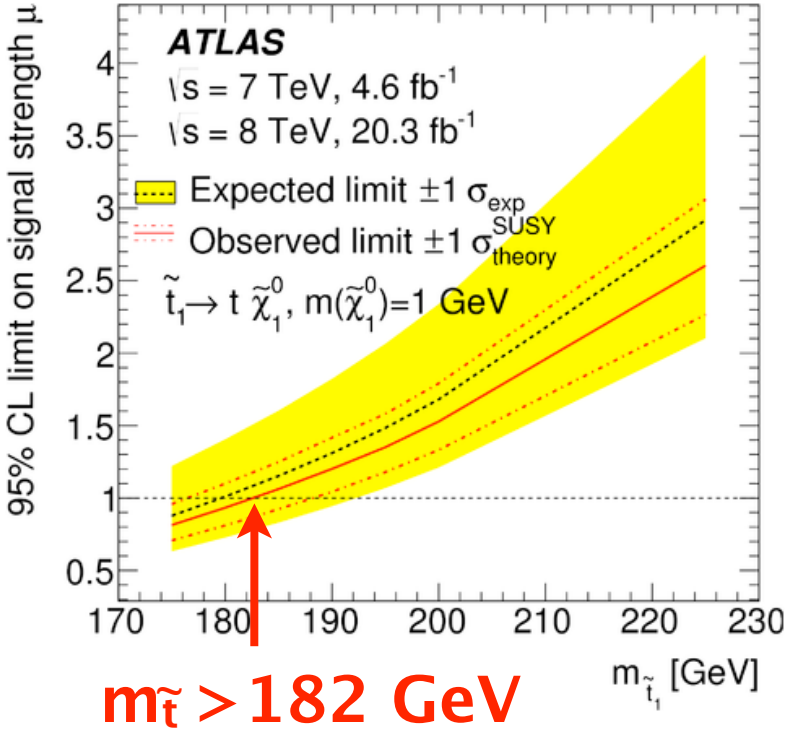


Eur. Phys. J. C74 3109 (2014)

do we see left or right?



$$\frac{\sigma_{limit}}{\sigma_{SUSY}}$$

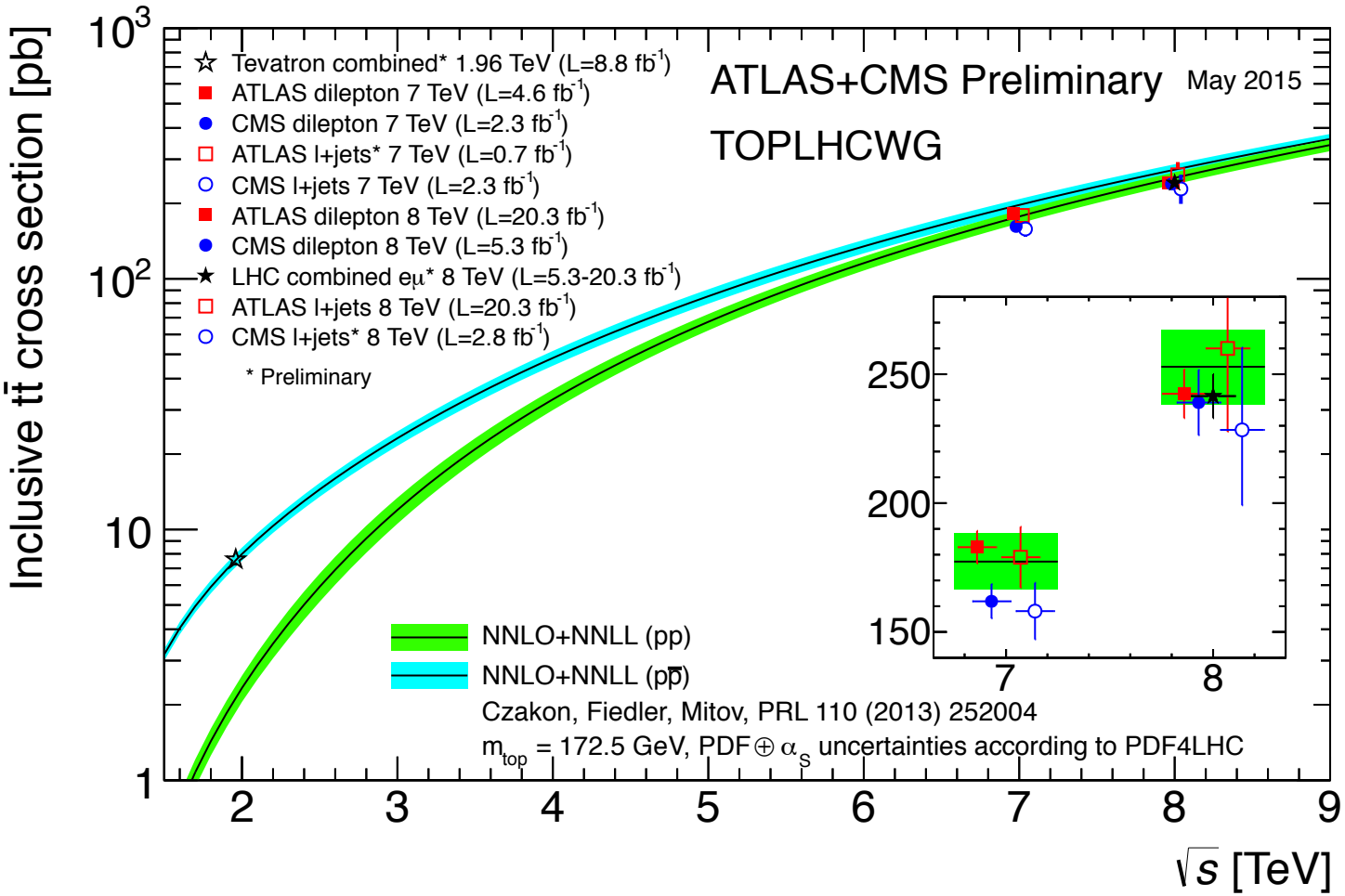


$m_{\tilde{t}} > 182$ GeV

"stealth" scenario:
– small sneutrino mass
– stop mass close to top mass

Top pair production at hadron colliders

eager to put points here

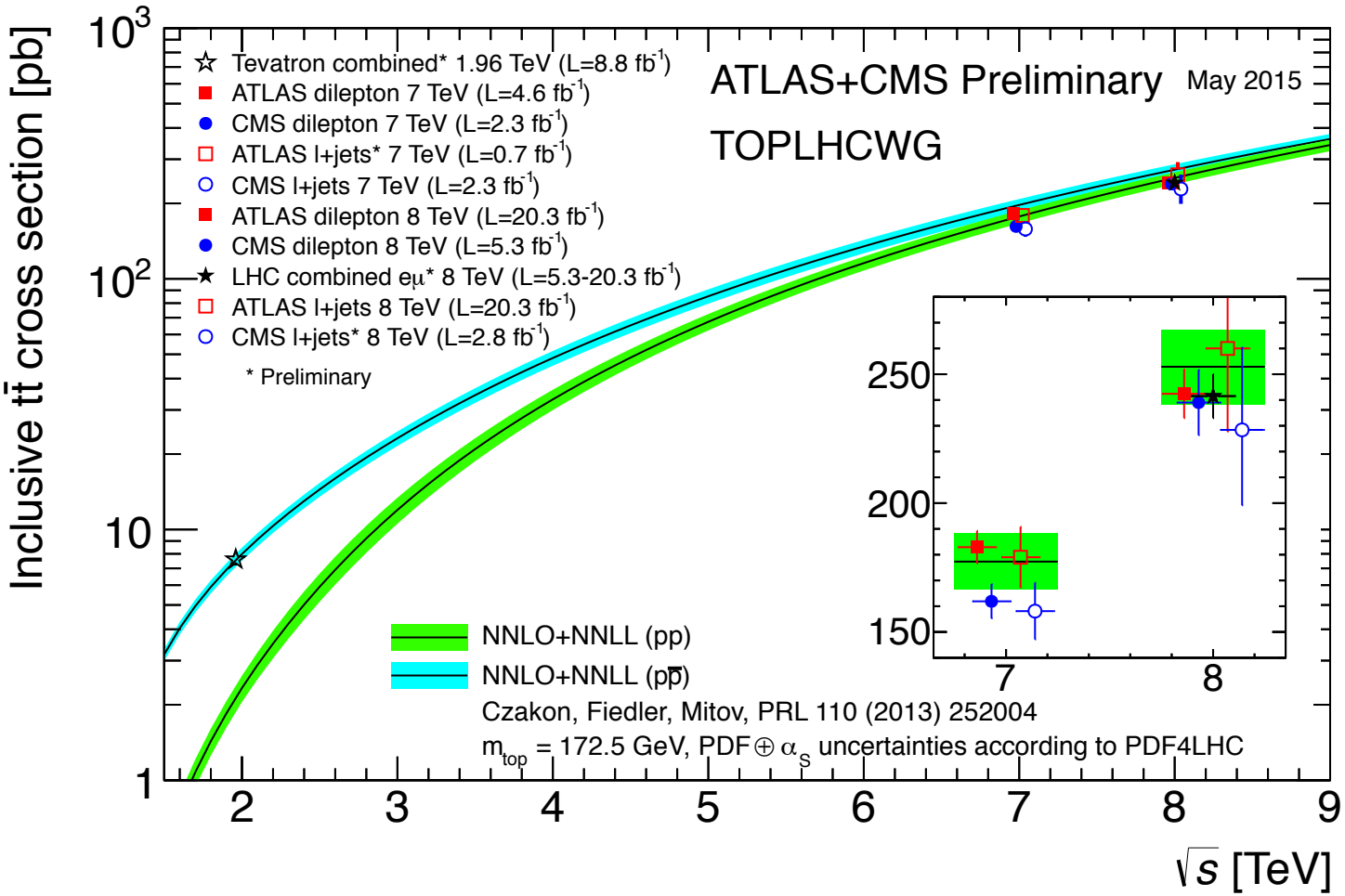


±5.7% (theo)

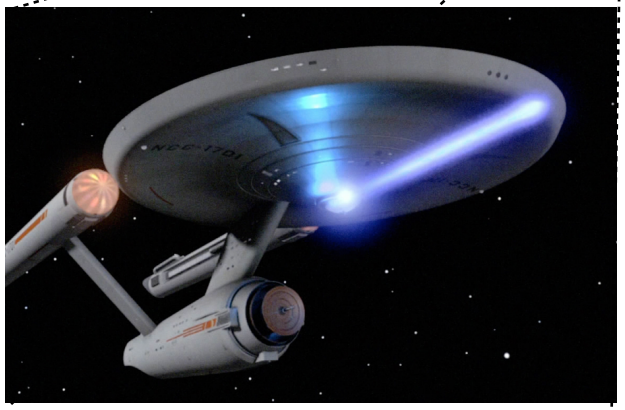
±3.9% (eμ)

→ experiments challenge theory again

Top pair production at hadron colliders

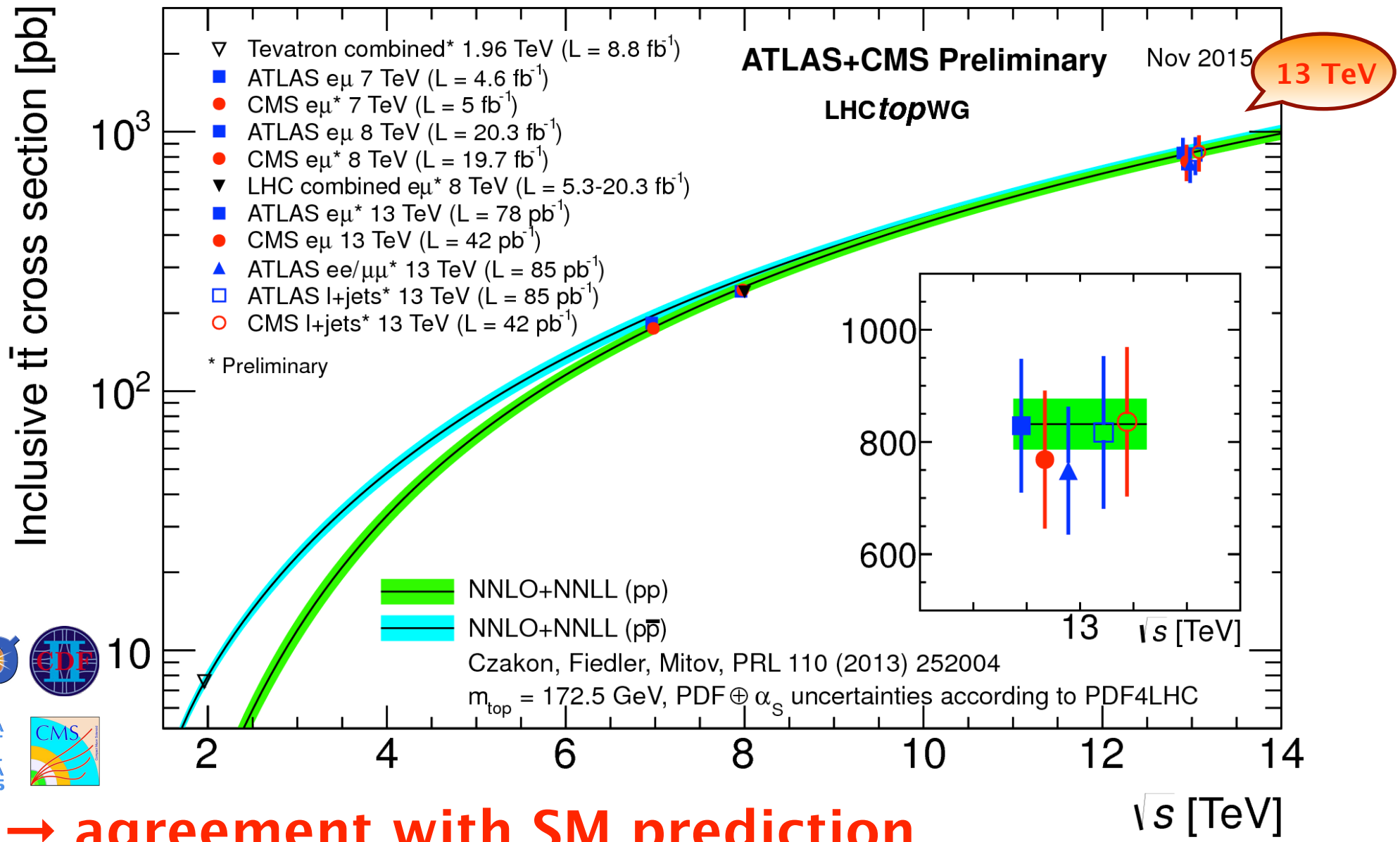


boldly go where no man has gone before



→ **experiments challenge theory again**

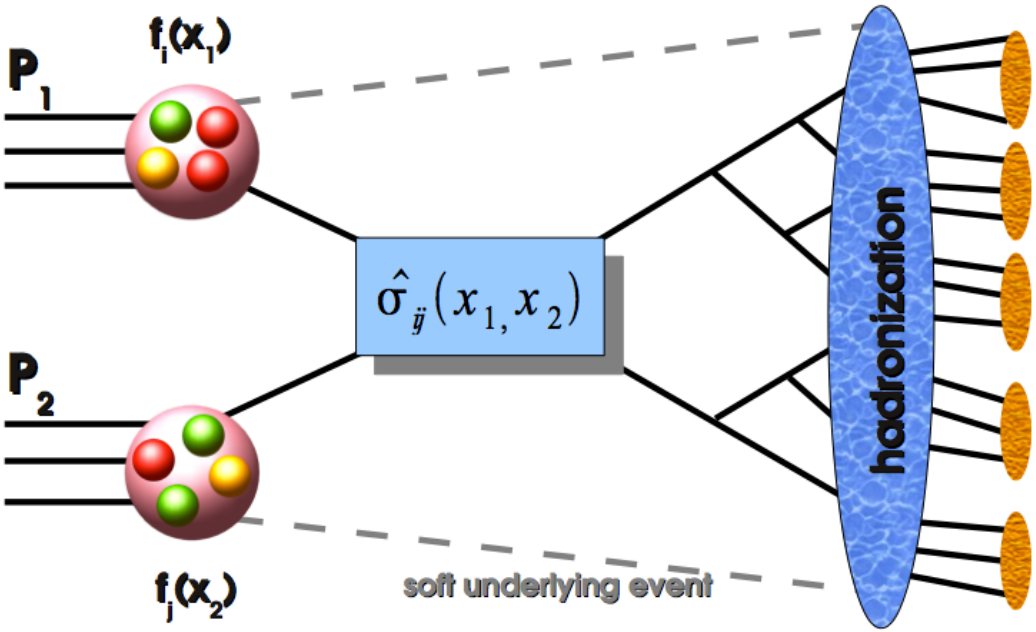
Top pair production at 13 TeV



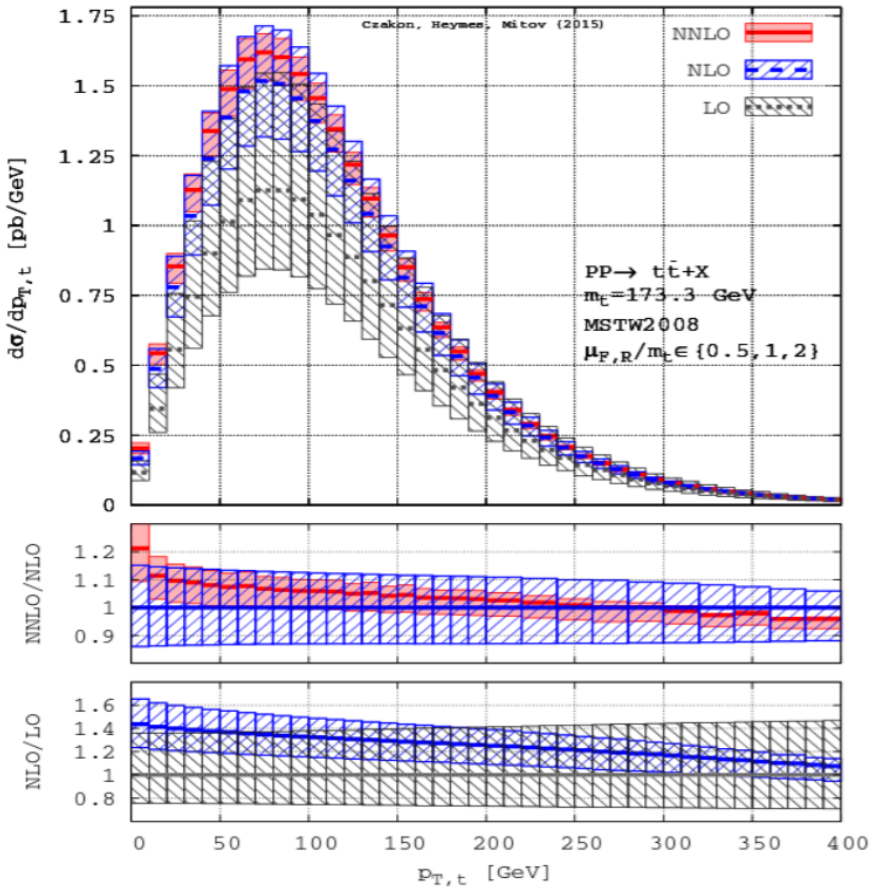
→ agreement with SM prediction

Differential Cross Sections

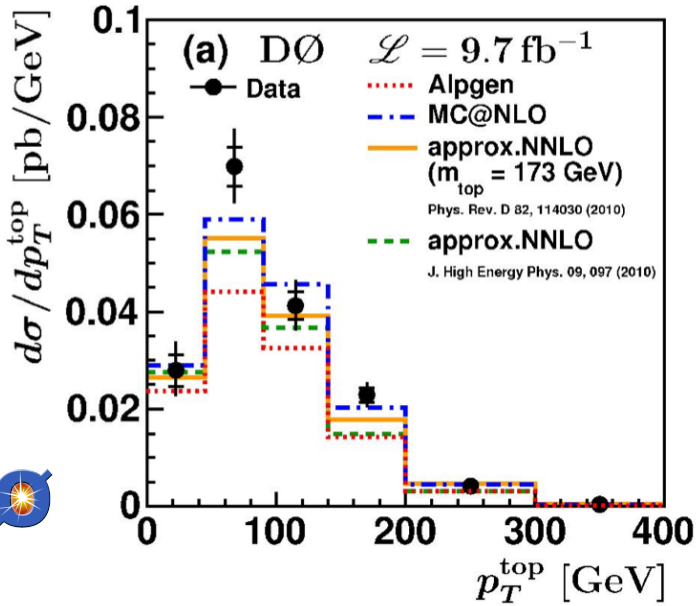
important tests of higher order QCD calculations:
requires "unfolding" to parton level



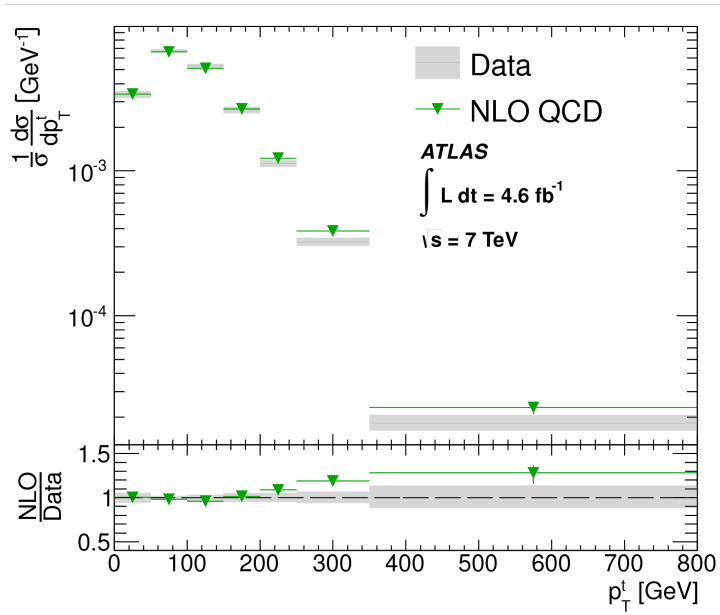
$t\bar{t}$ production in full NNLO:



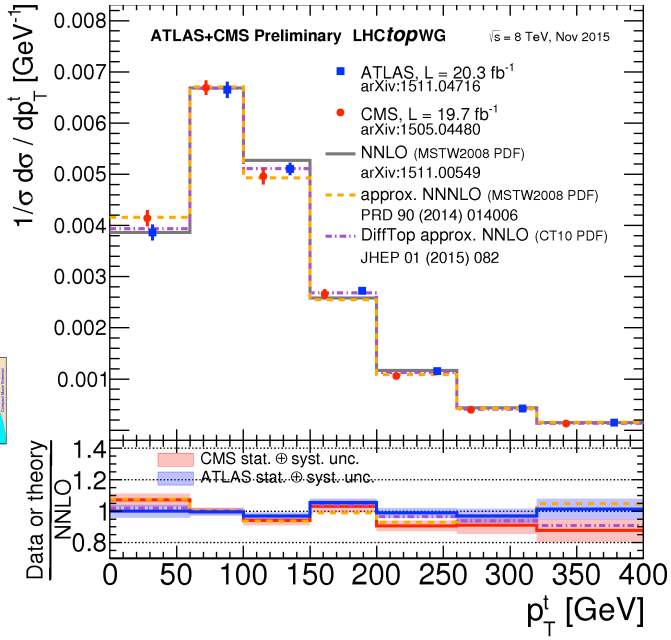
Differential, unfolded: top p_T



2 TeV

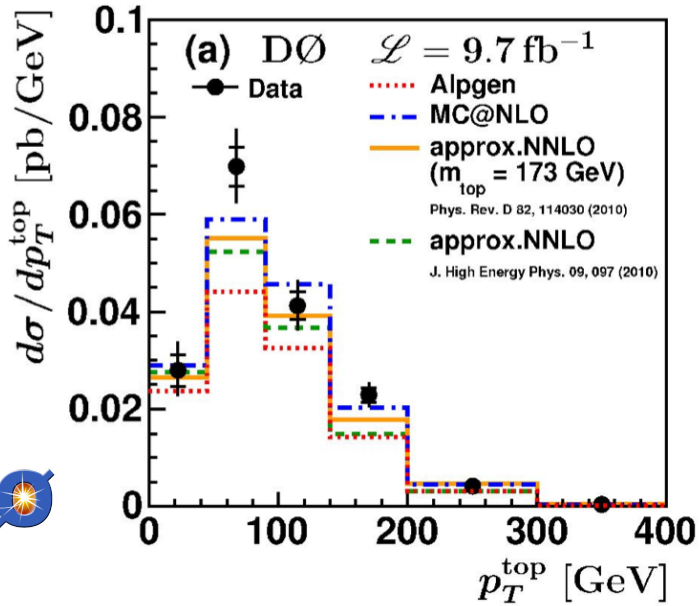


7 TeV

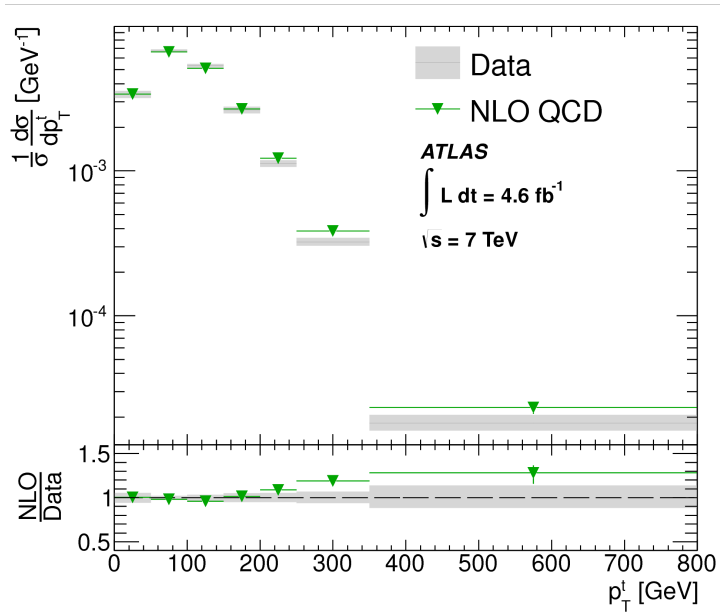


8 TeV

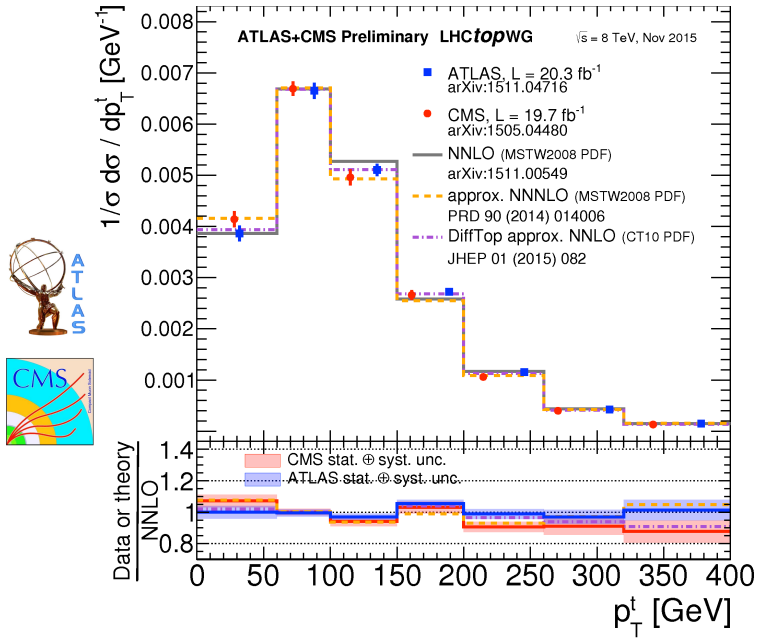
Differential, unfolded: top p_T



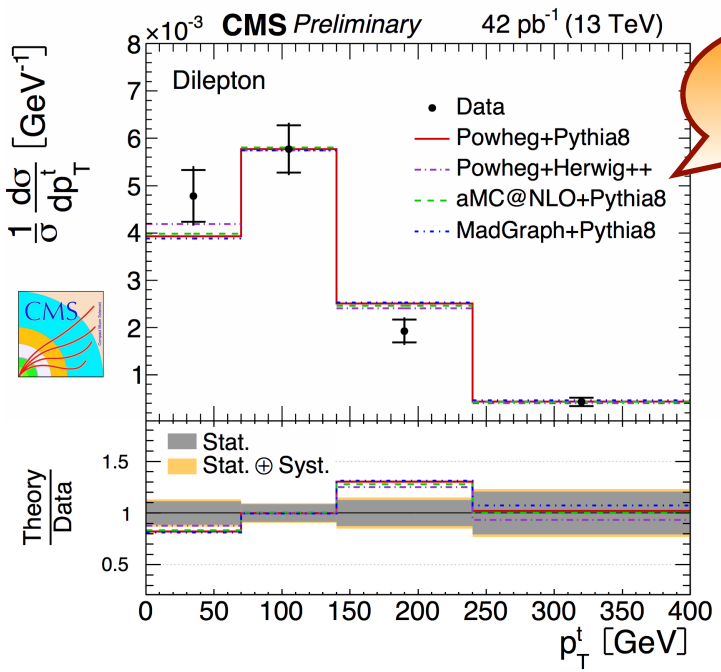
2 TeV



7 TeV

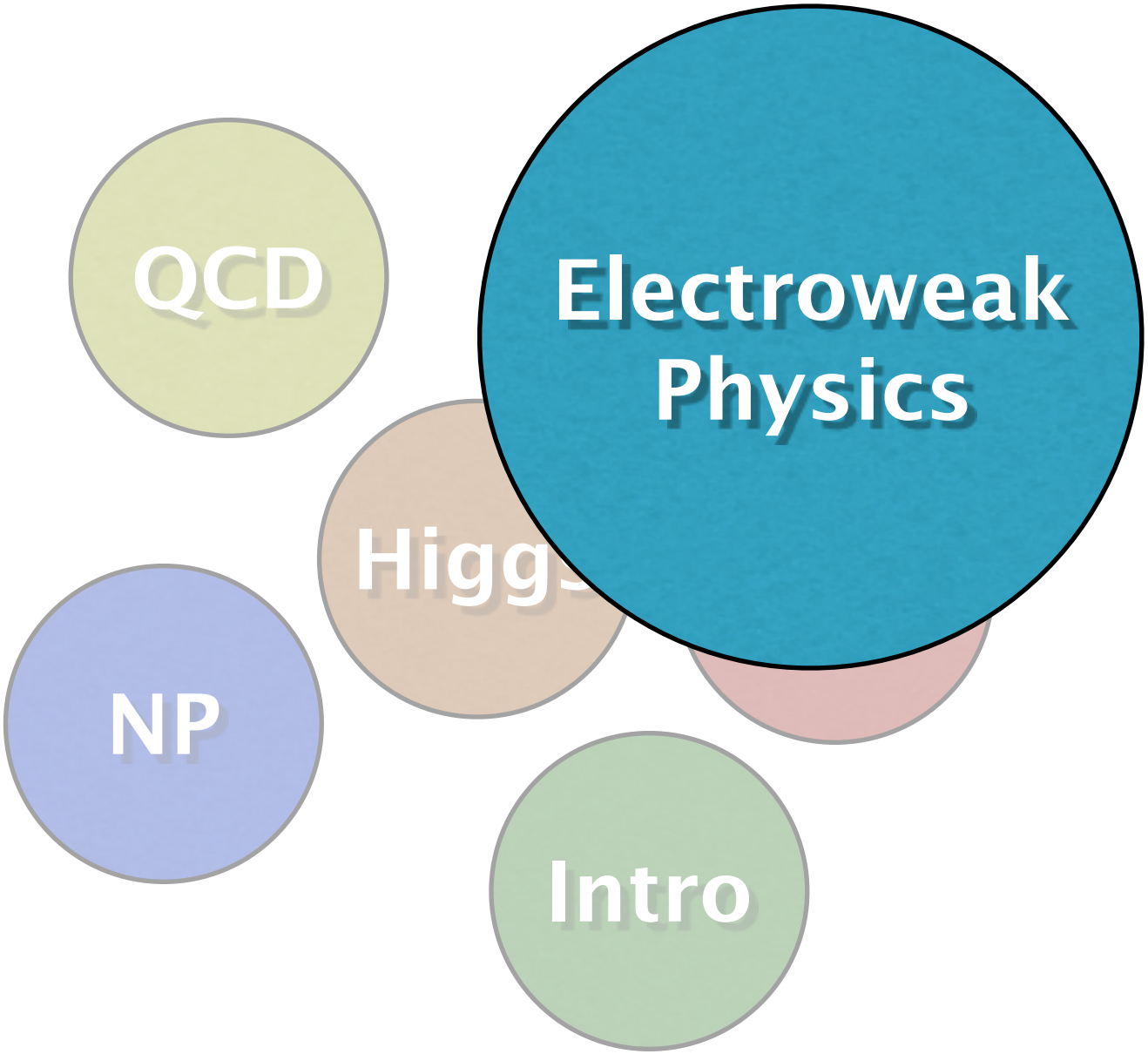


8 TeV



13 TeV

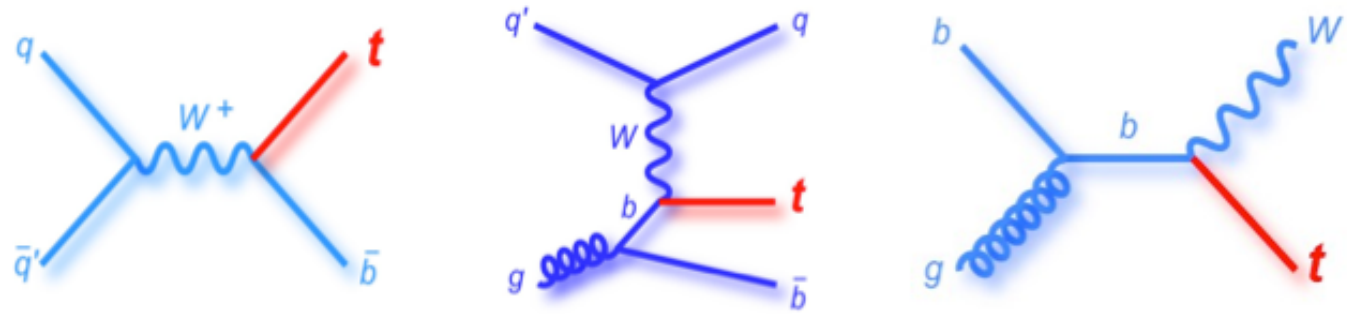
Top Quark Physics Topics

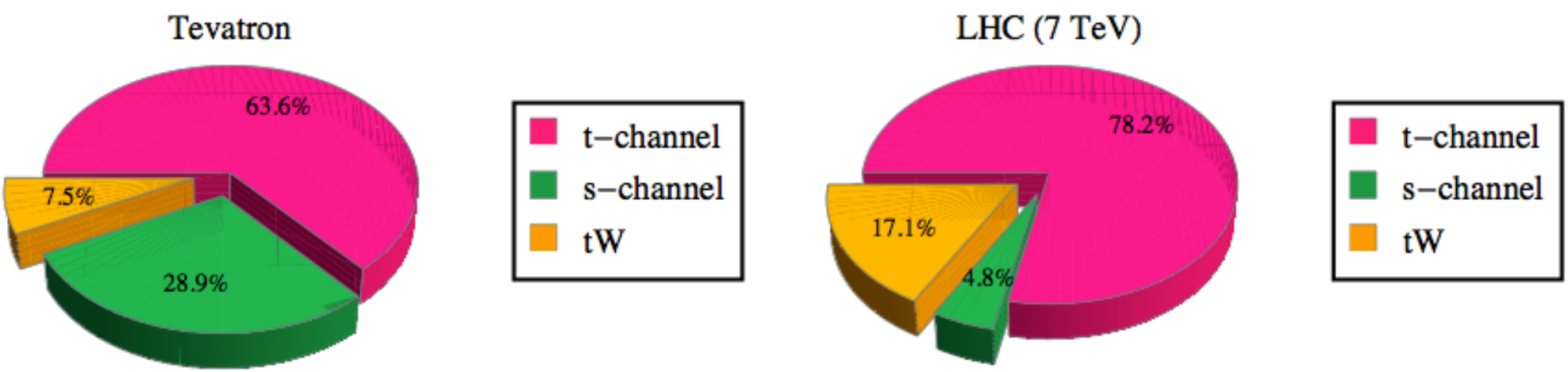


Single Top Quark Production

direct measurement of $|V_{tb}|$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



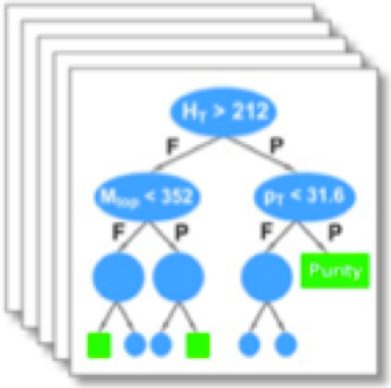


⇒ important to measure all channels separately to search for new physics

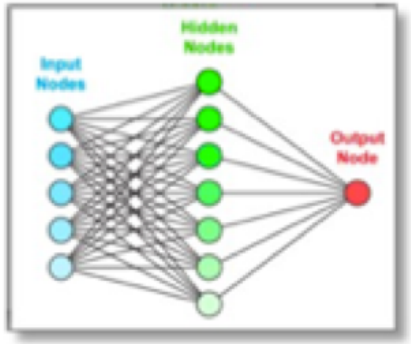
BUT: do not separate Wt in higher orders – an unphysical question!

Multivariate Analyses

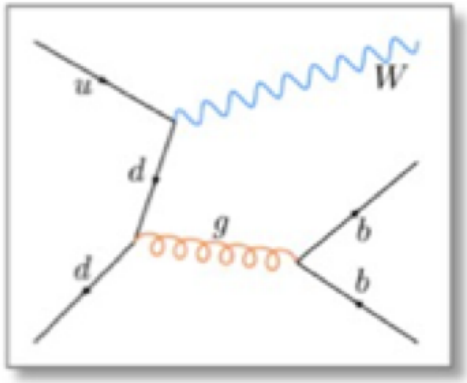
Boosted Decision Trees



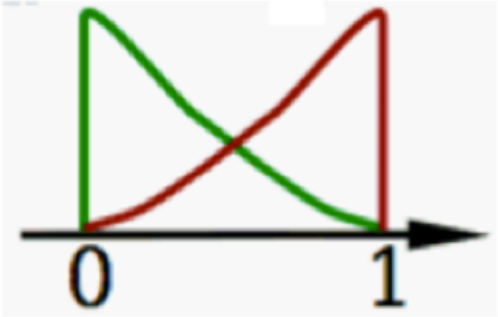
Neural Networks



Matrix Elements



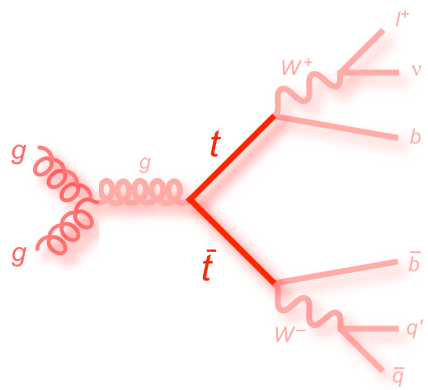
background **signal**

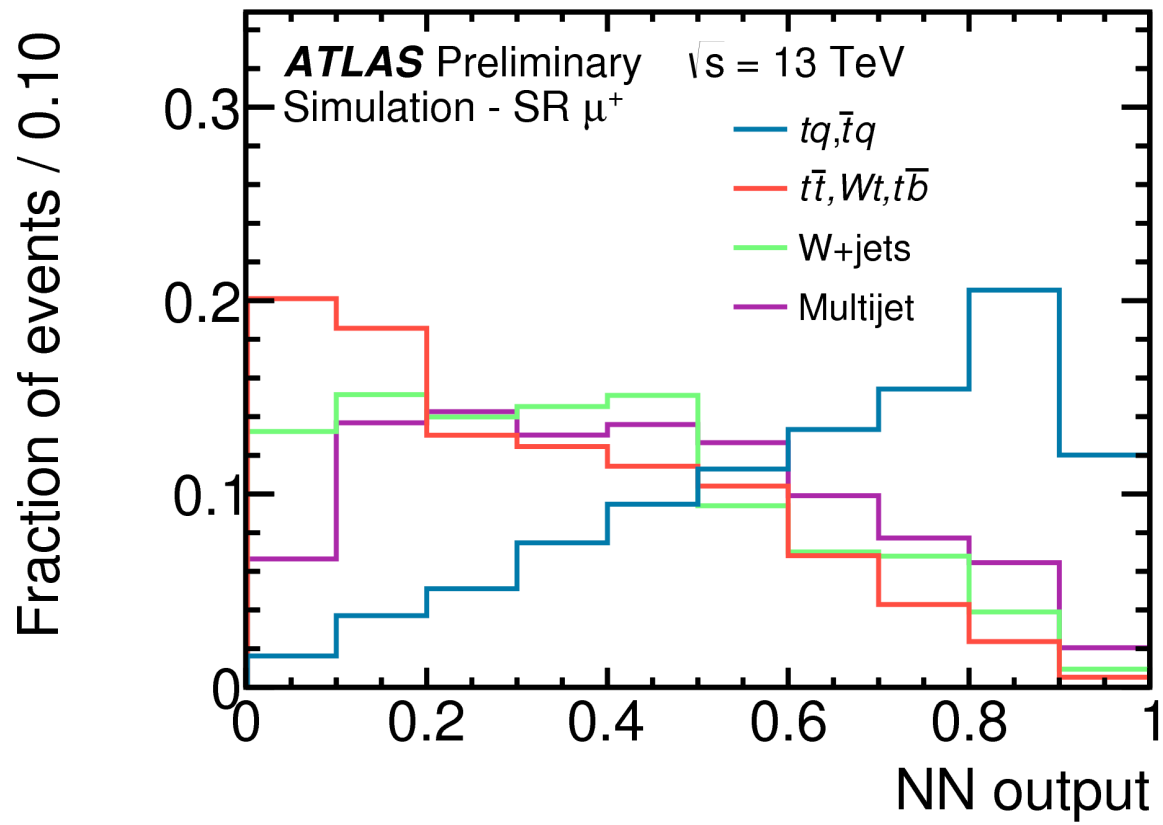


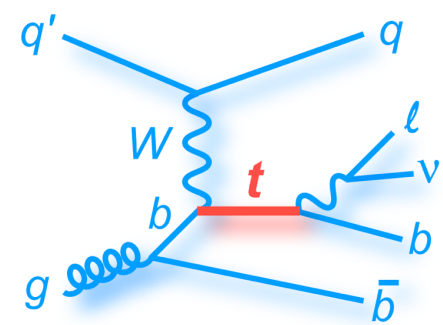
- s+t channel observed by CDF and D0 in 2009
- important step to establish MVA techniques

Output Discriminant t-channel

13 TeV



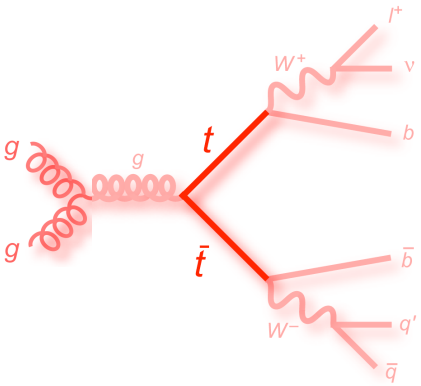


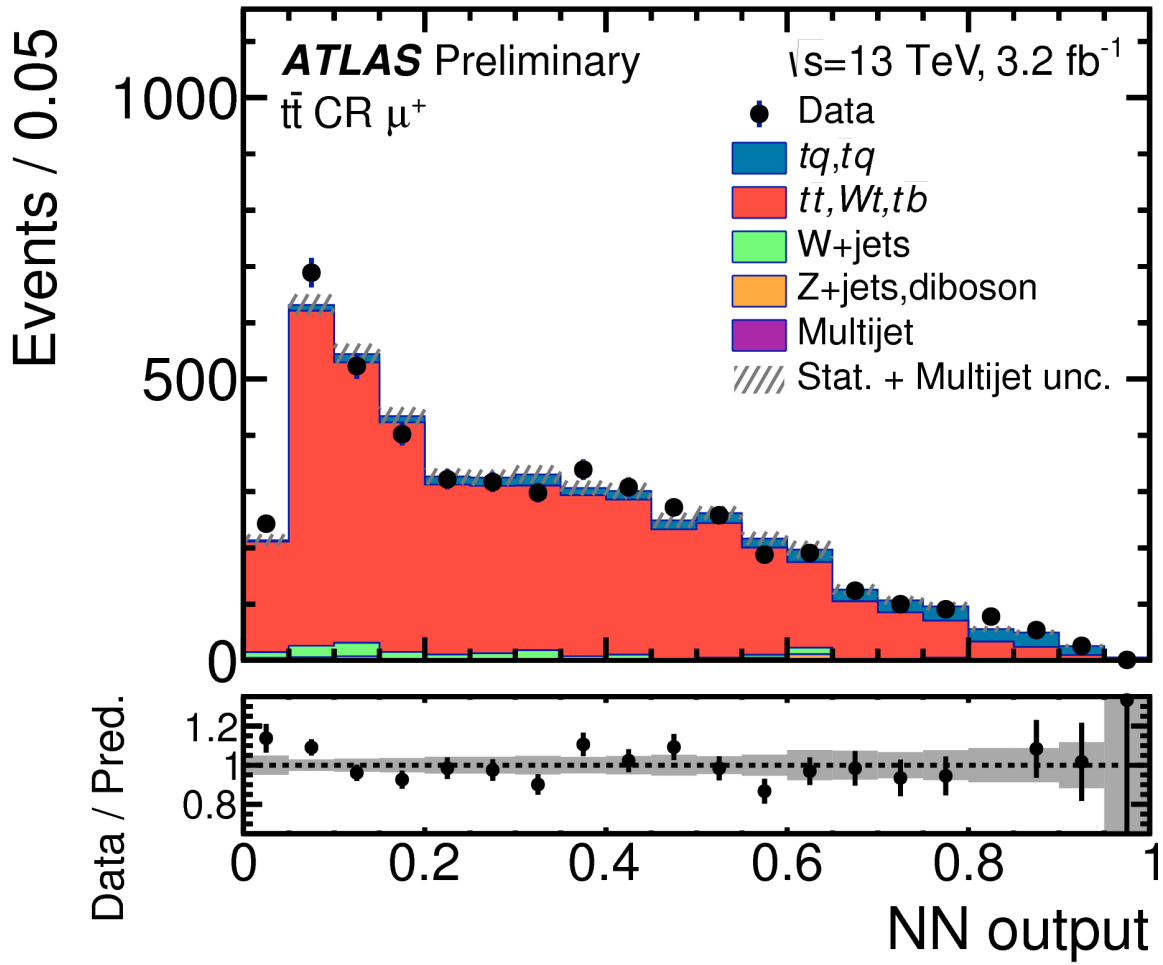


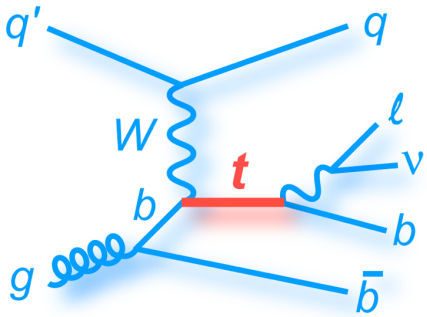
NN Discriminant

Output Discriminant t-channel

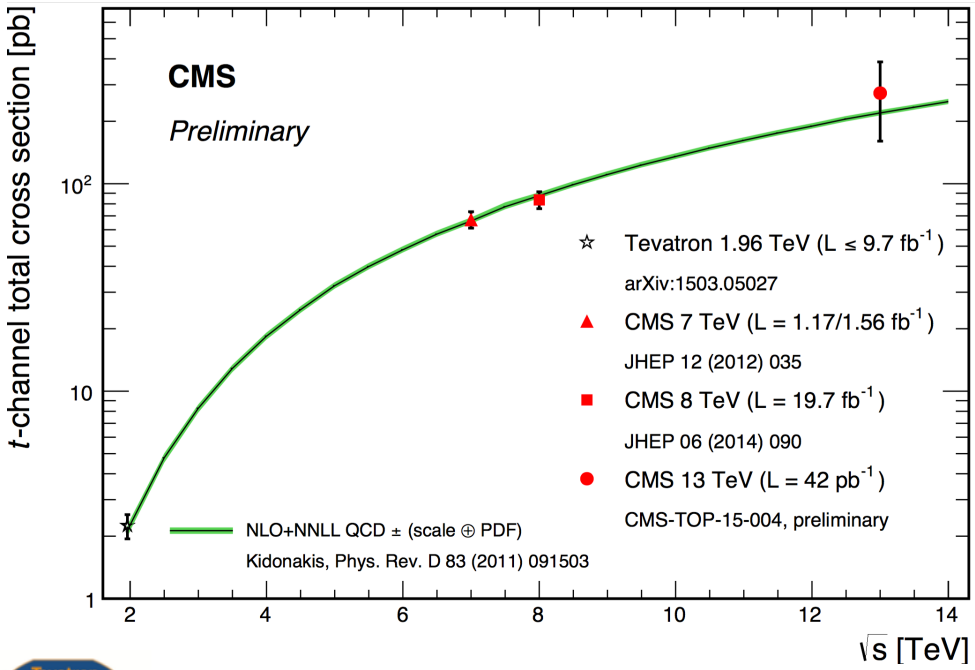
13 TeV



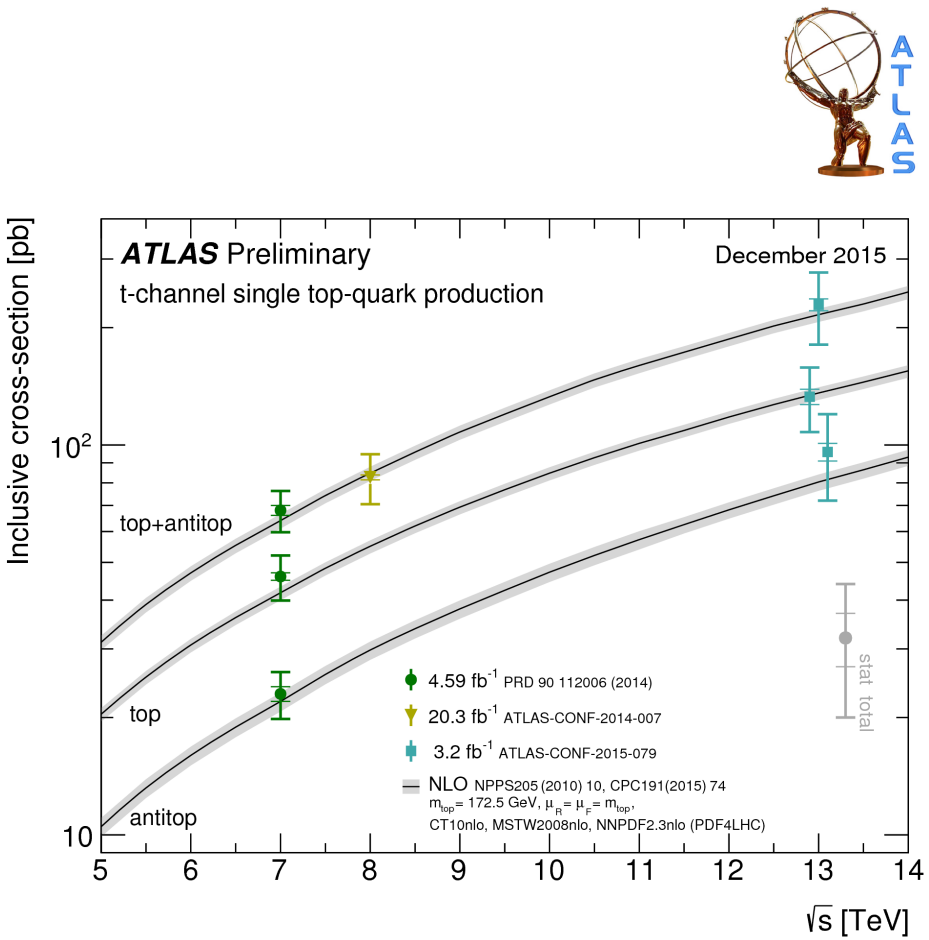




Single top t-channel cross section



13 TeV

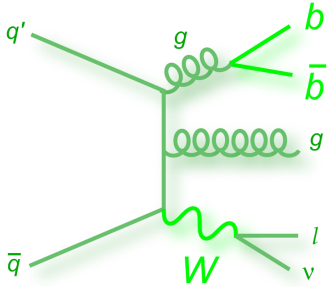


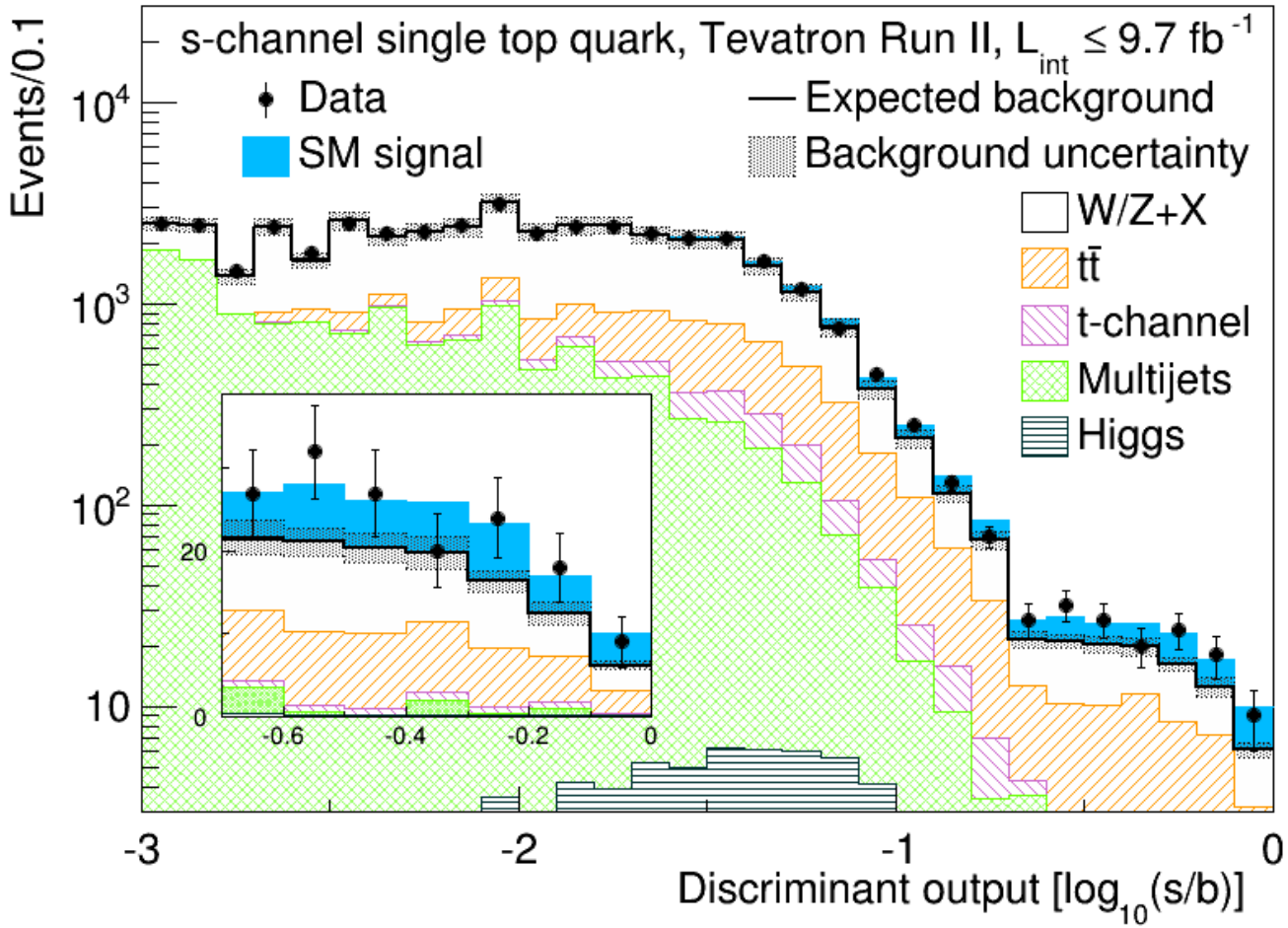
→ agreement with SM predictions!

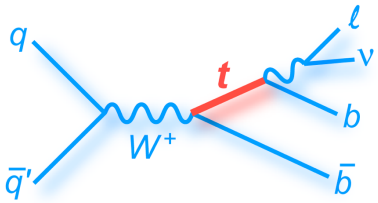
s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)

- **Tevatron: combine individual discriminants including all correlations**

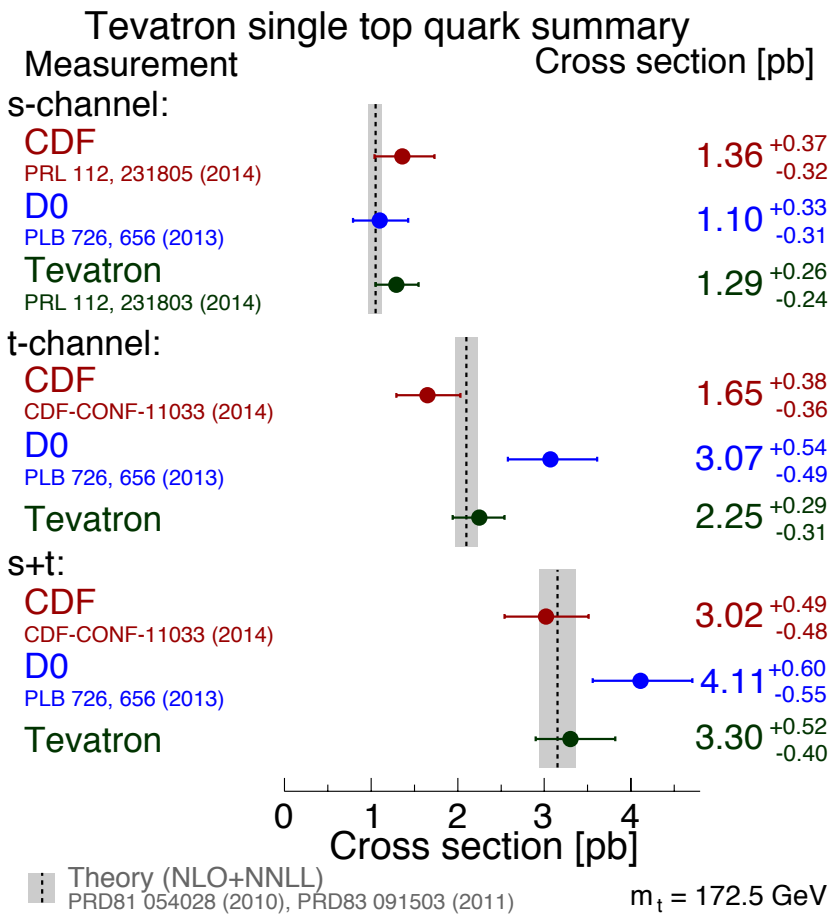


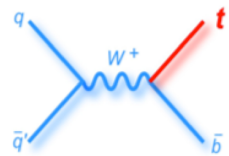




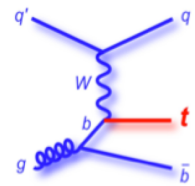
→ observation: 6.3 s.d.

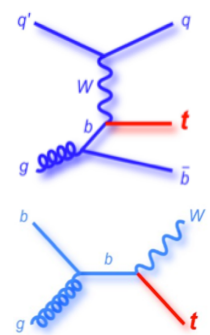
Single channel cross sections



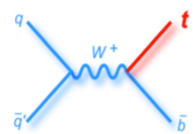


→ observation





→ observation

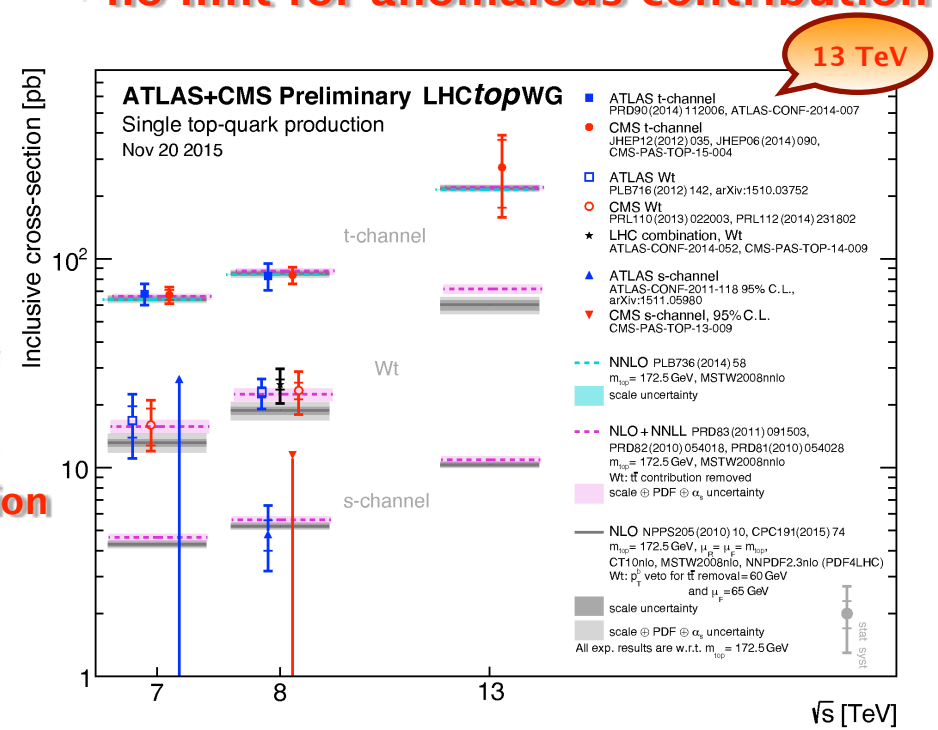


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{tb}| = 0.998 \pm 0.041$ ±4.1%

$|V_{tb}| > 0.92$ @ 95%CL

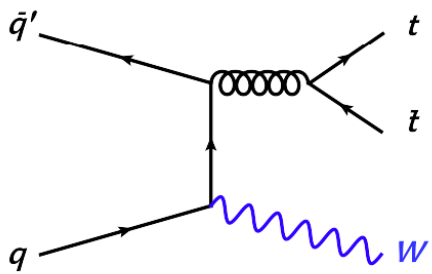
→ no hint for anomalous contribution



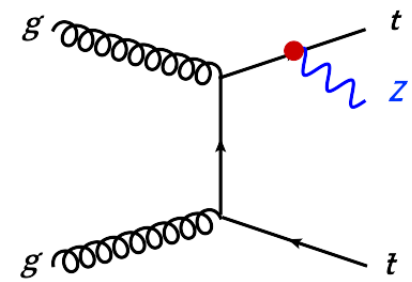
this is the final word from the Tevatron!

→ all production modes observed!

Search for ttZ and ttW

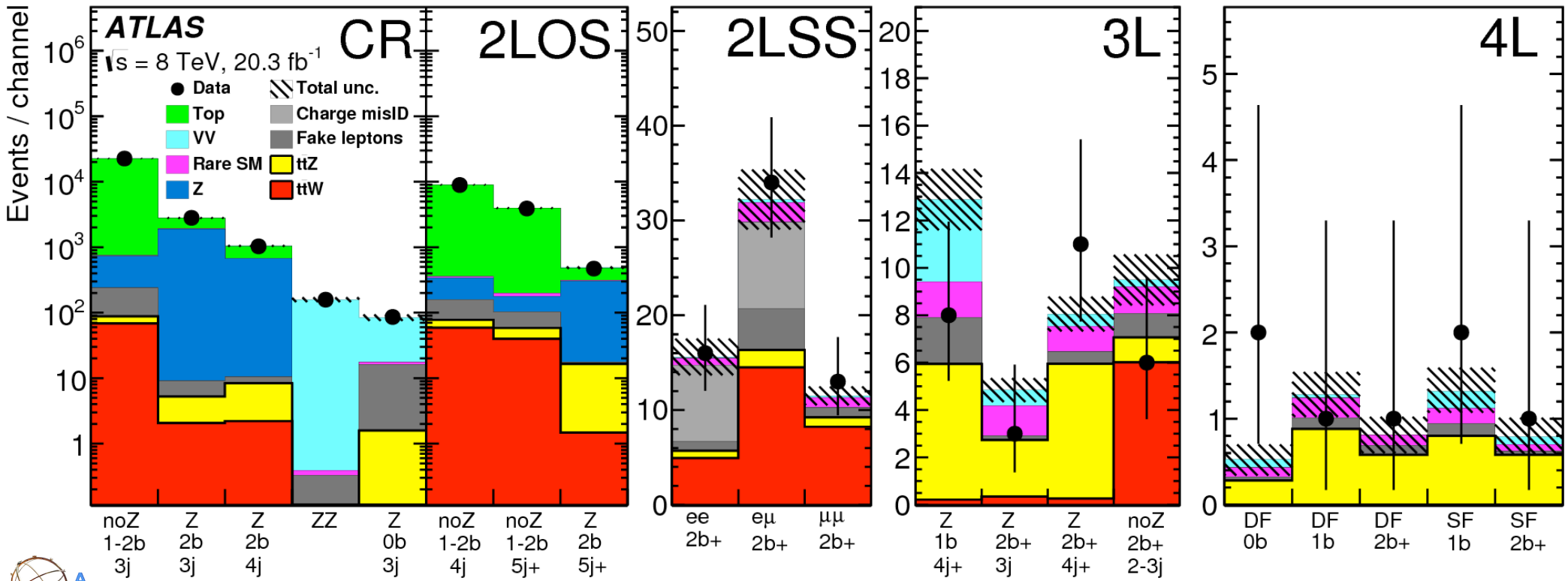


ISR



FSR

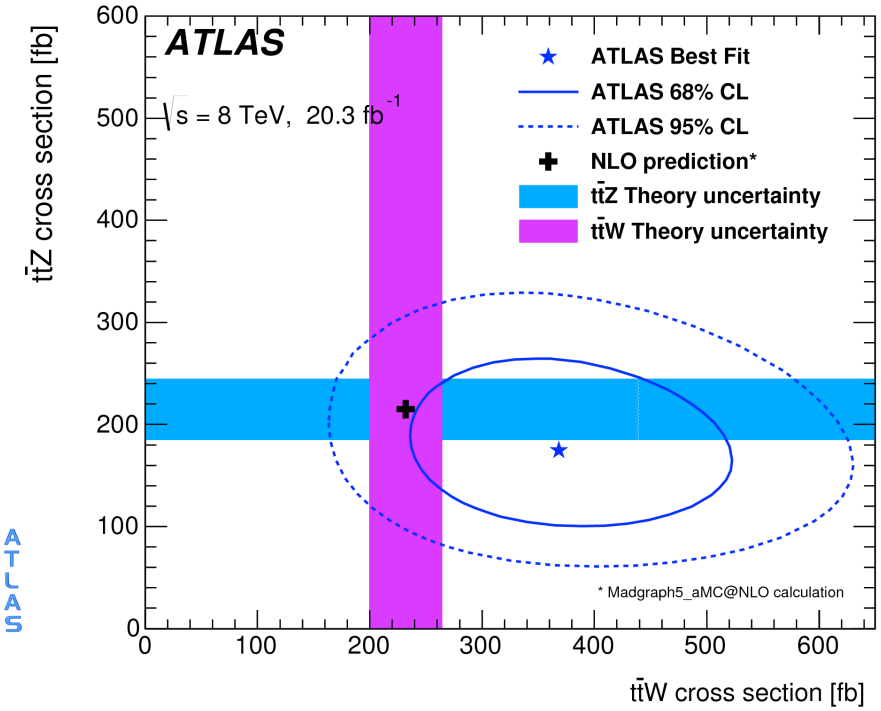
$$-i\frac{e}{\sin\vartheta_W \cos\vartheta_W}(T_3 - \sin^2\vartheta_W Q_t)\gamma^\mu$$



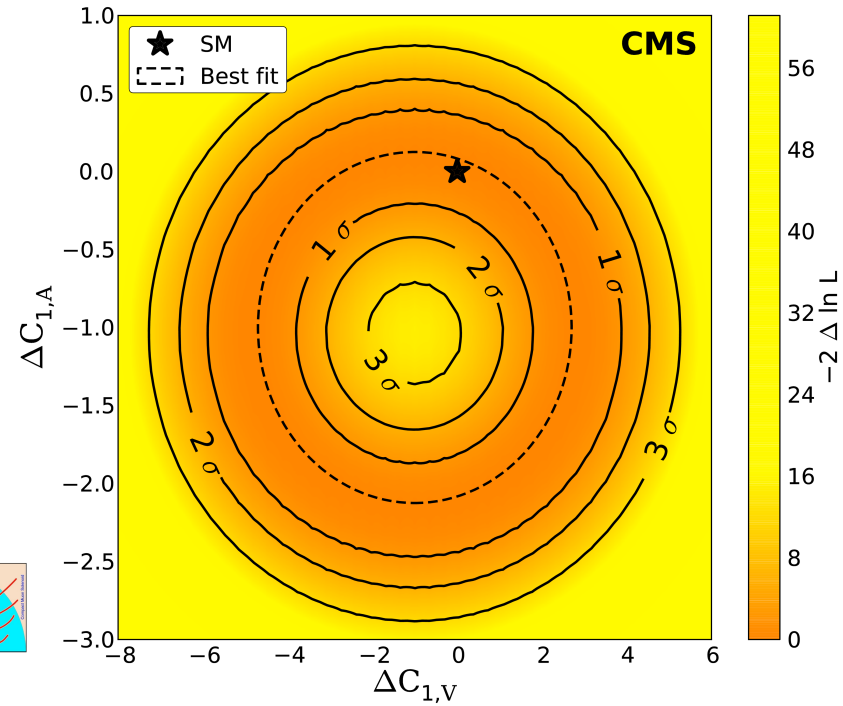
ttW ← → ttZ

Observation of ttV production

ttZ vs. ttW cross sections:



anomalous V or A ttZ couplings:

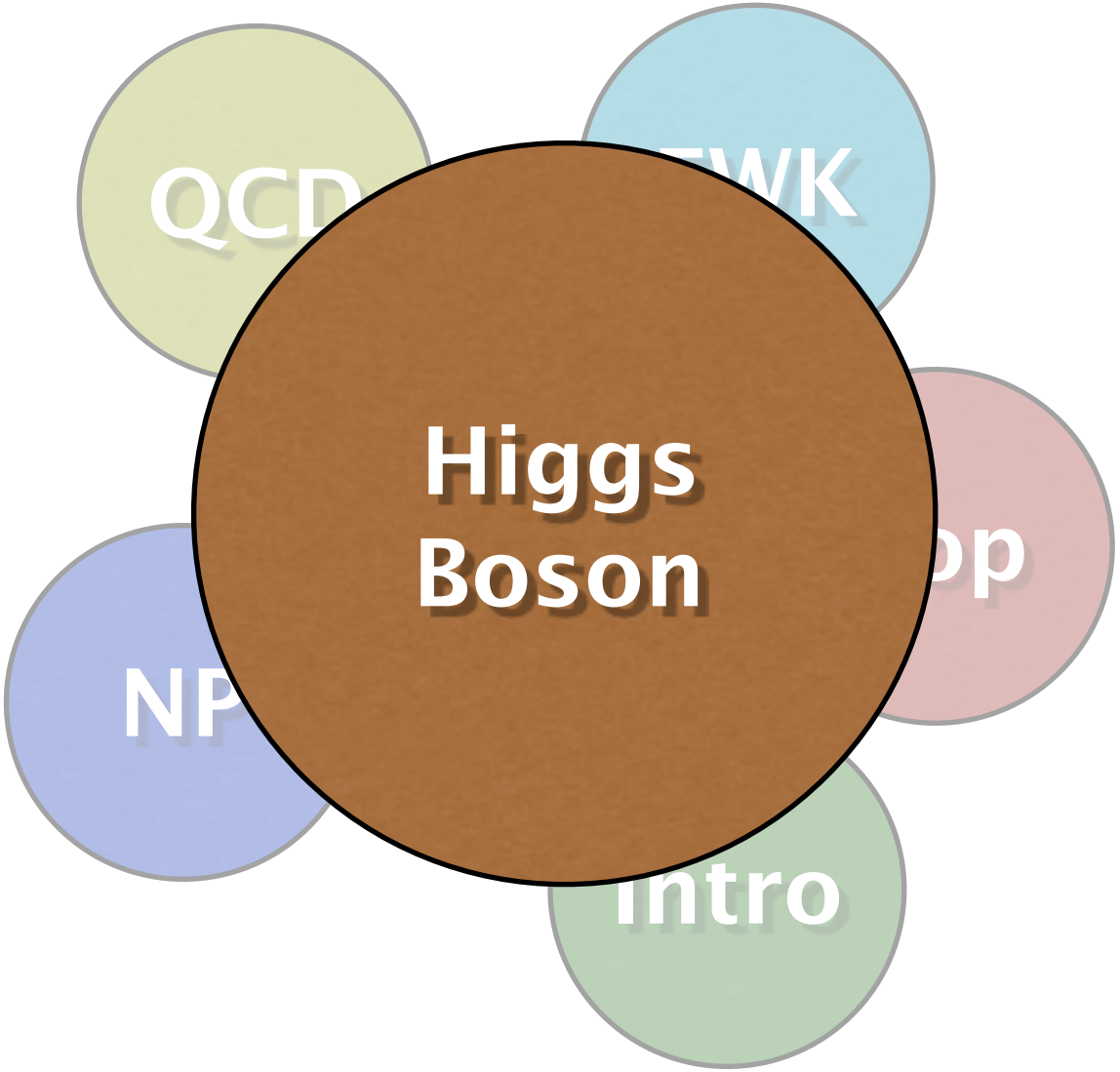


ttW:	3.2 σ (exp)	5.0 σ (obs)
ttZ:	4.5 σ (exp)	4.2 σ (obs)

ttW:	3.8 σ (exp)	4.8 σ (obs)
ttZ:	5.7 σ (exp)	6.4 σ (obs)

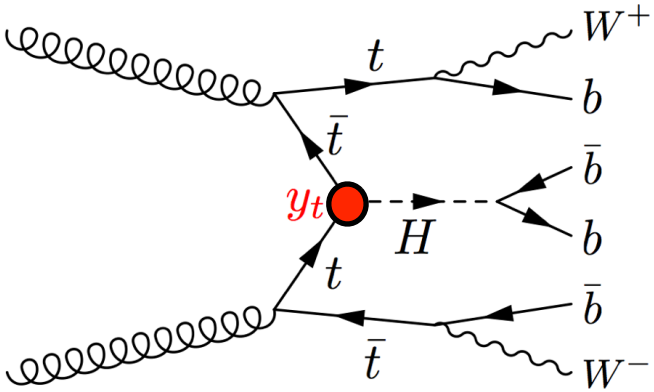
→ **in agreement with the SM prediction**
(ttγ also in agreement with SM prediction)

Top Quark Physics Topics

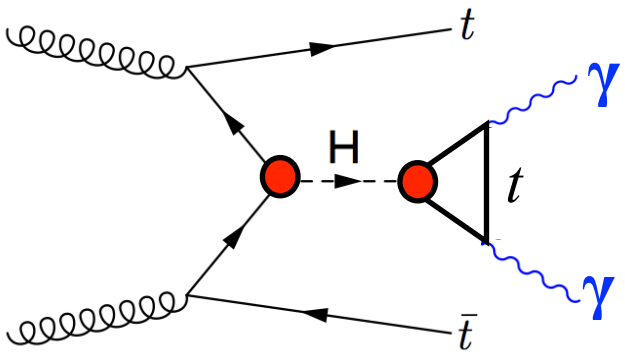


Search for ttH production

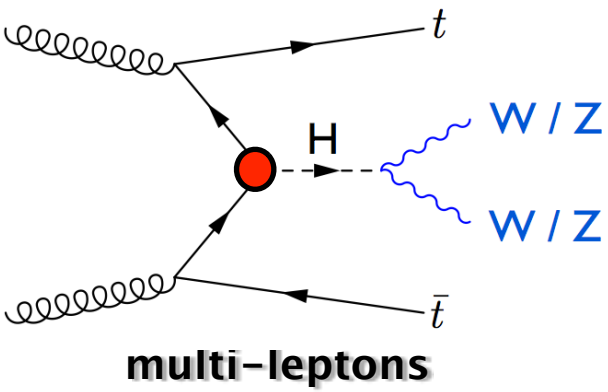
H→bb



H→γγ

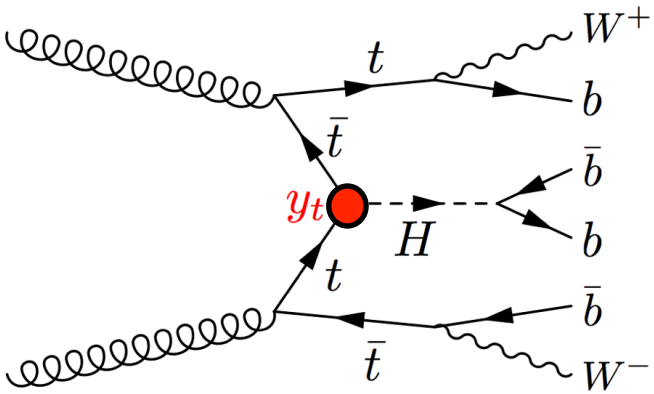


H→WW, ZZ

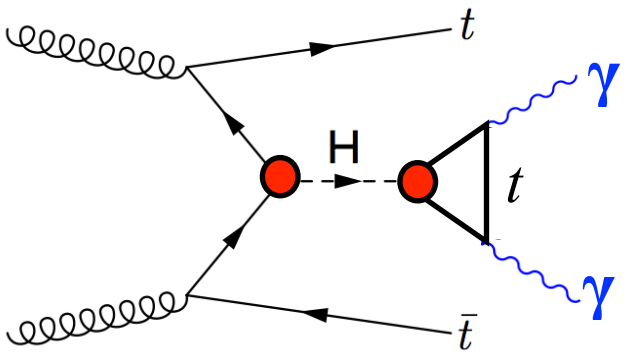


Search for ttH production

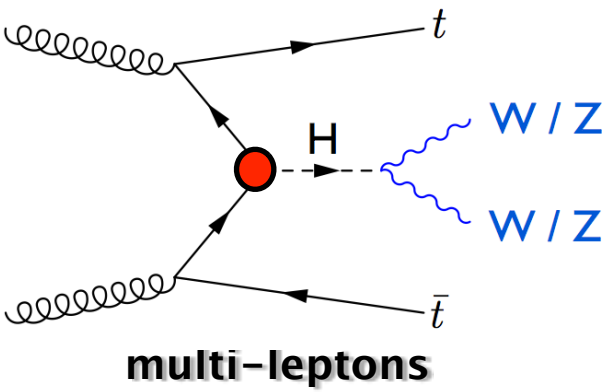
H→bb

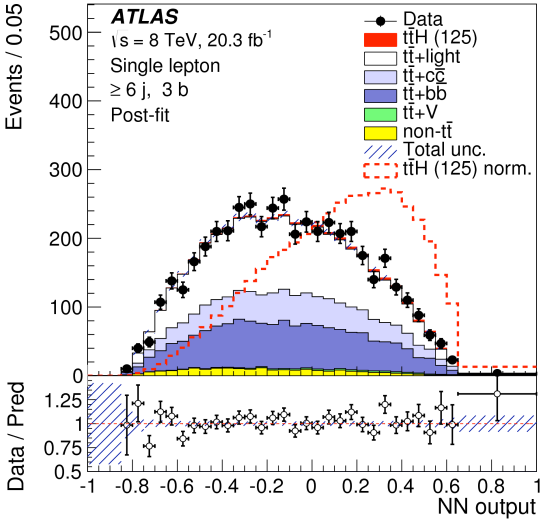


H→γγ



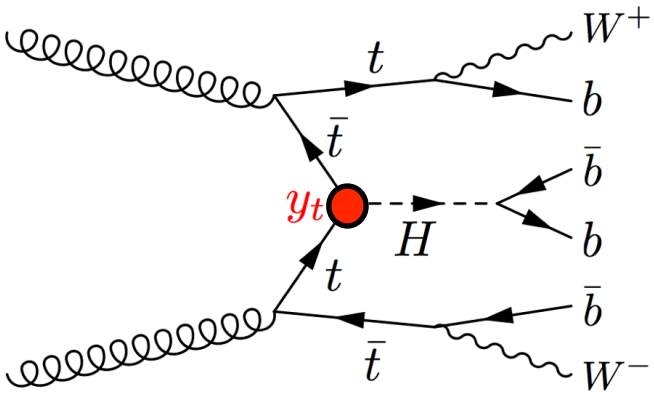
H→WW, ZZ



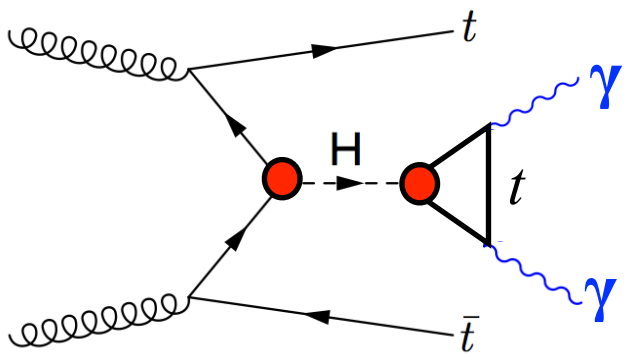


Search for ttH production

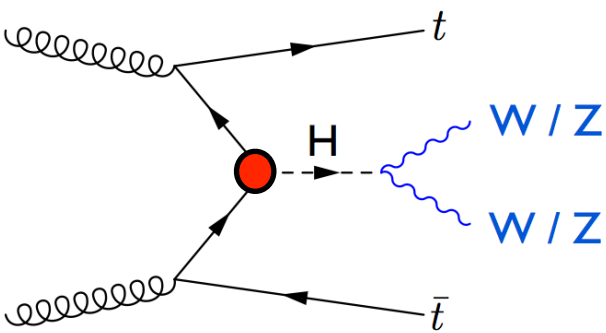
H→bb



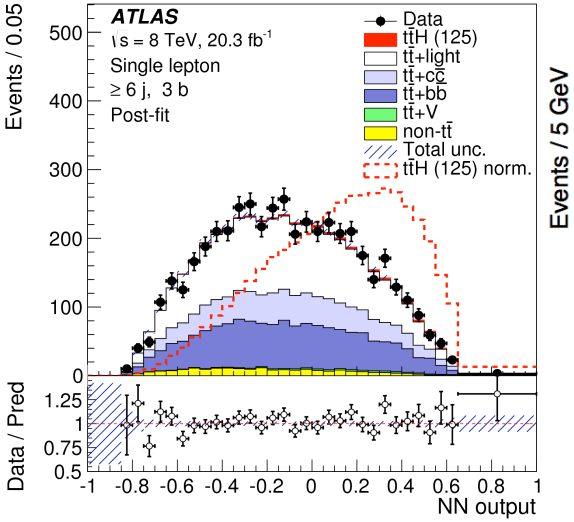
H→γγ

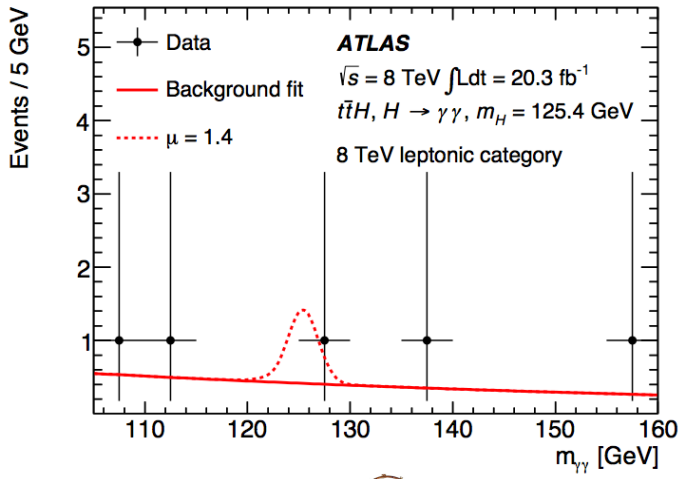


H→WW, ZZ



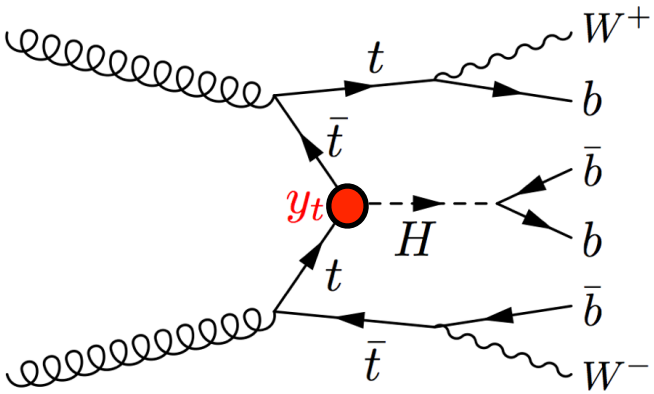
multi-leptons



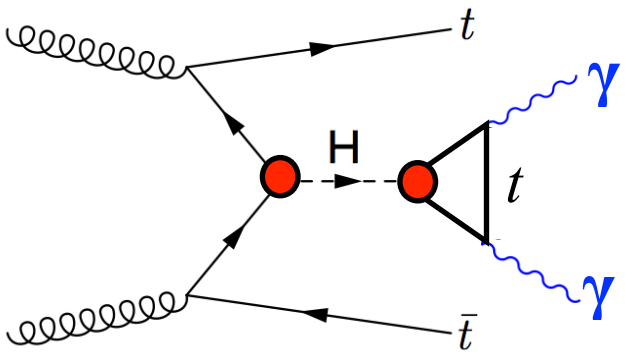


Search for ttH production

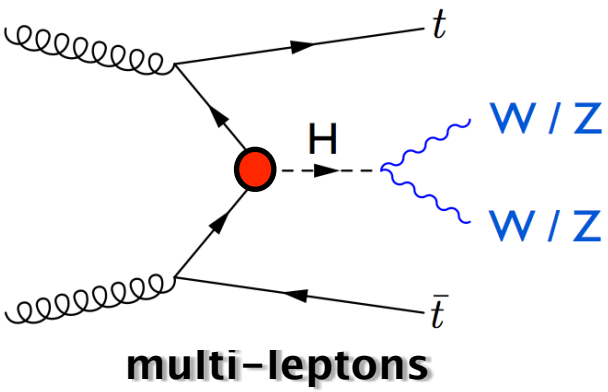
H→bb

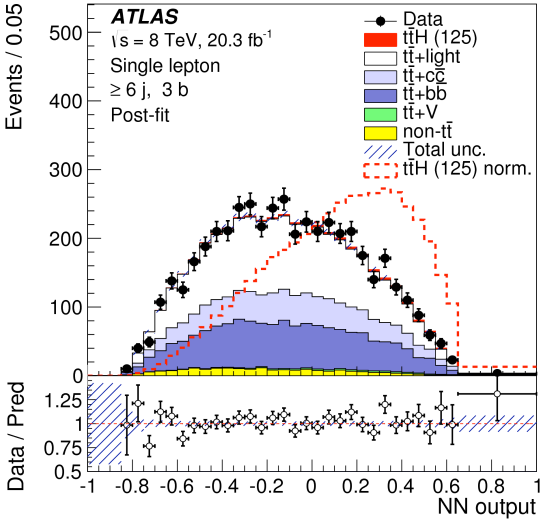


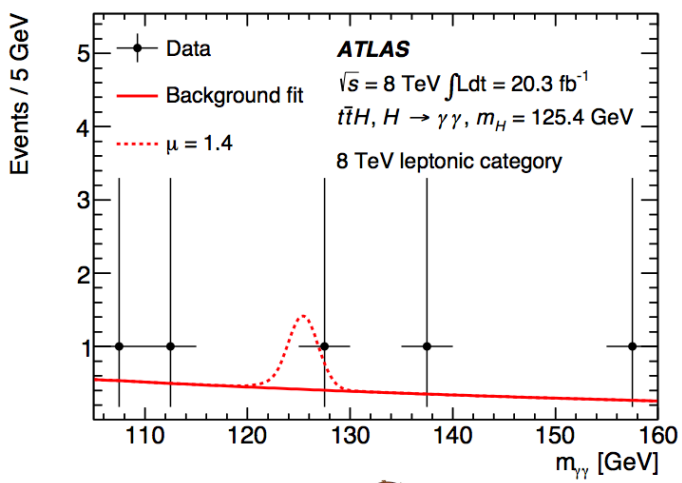
H→γγ

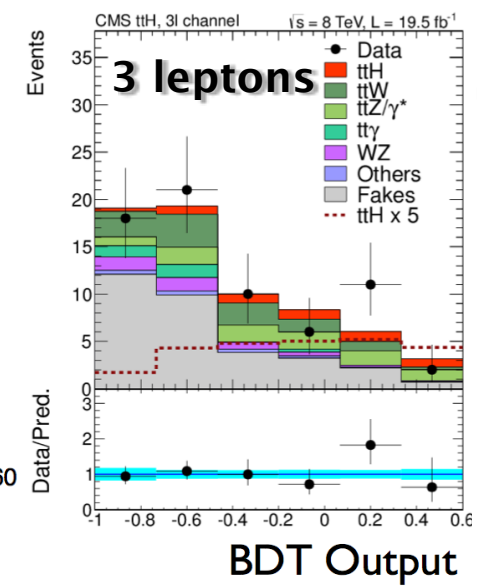


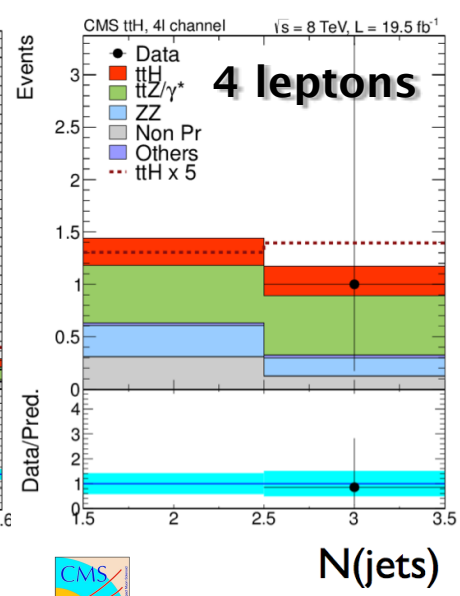
H→WW, ZZ



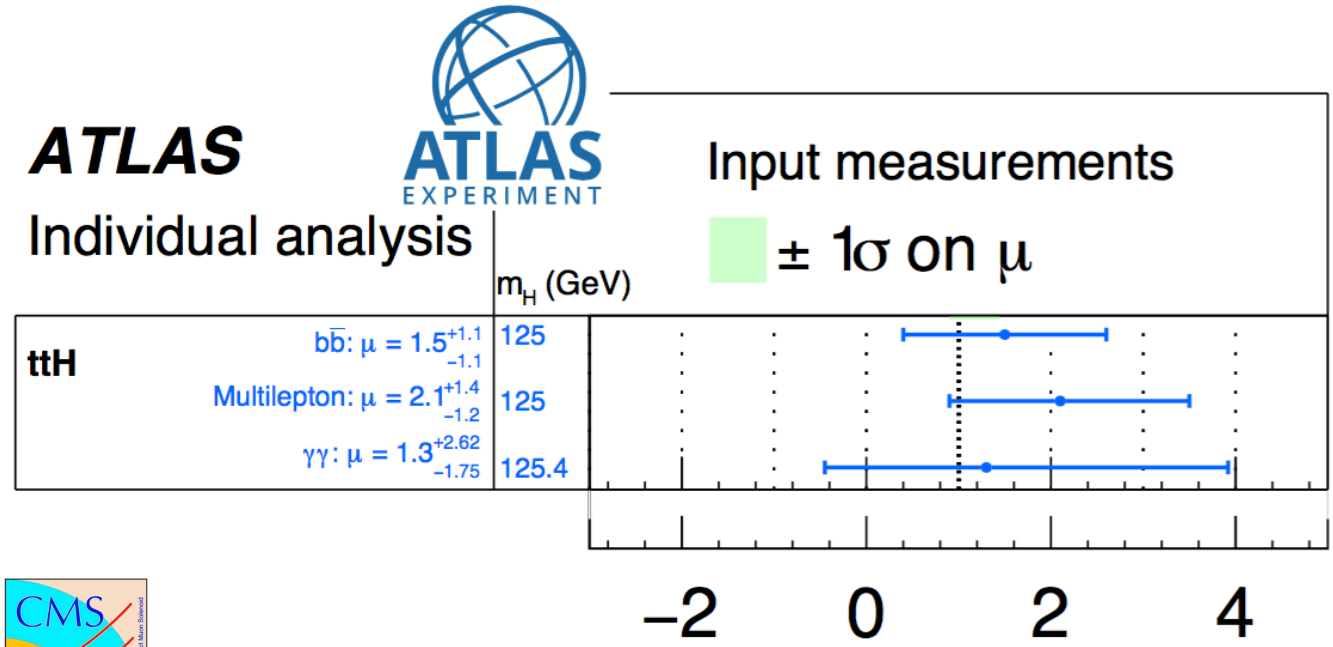






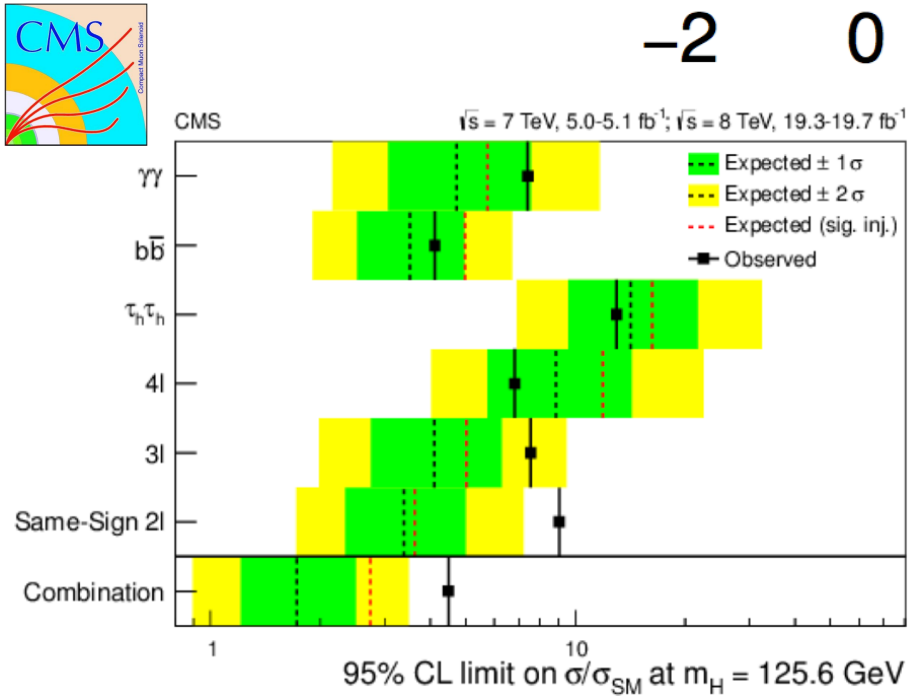


Results in ttH



3.2σ (1.4σ exp)

σ/σ_{SM}

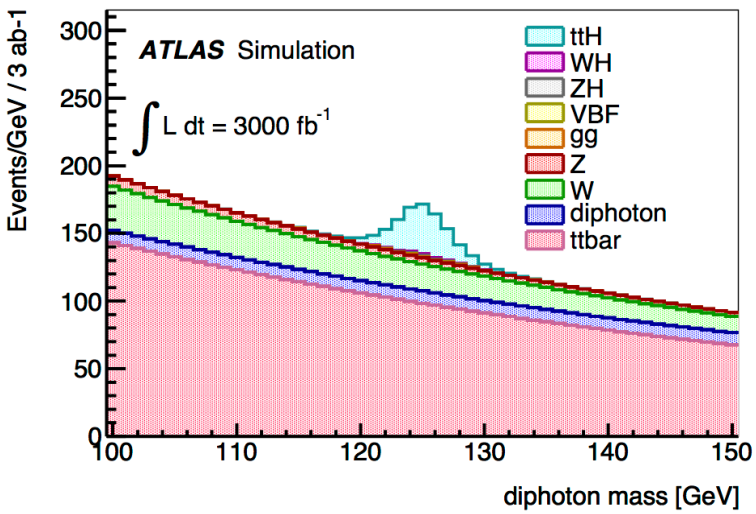


4.5σ (1.7σ exp)

limit on σ/σ_{SM}

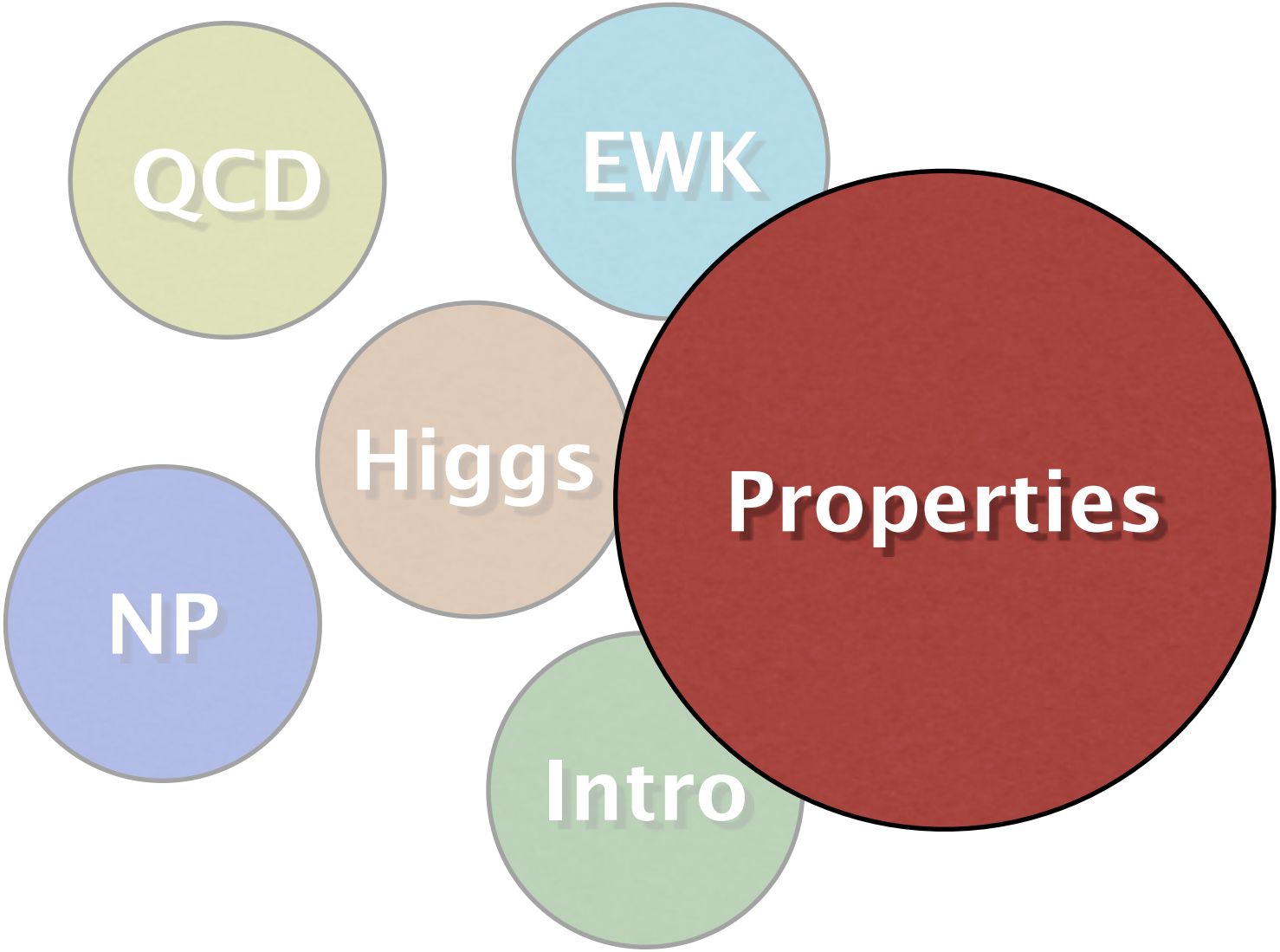
High lumi LHC:

arXiv:1307.7292

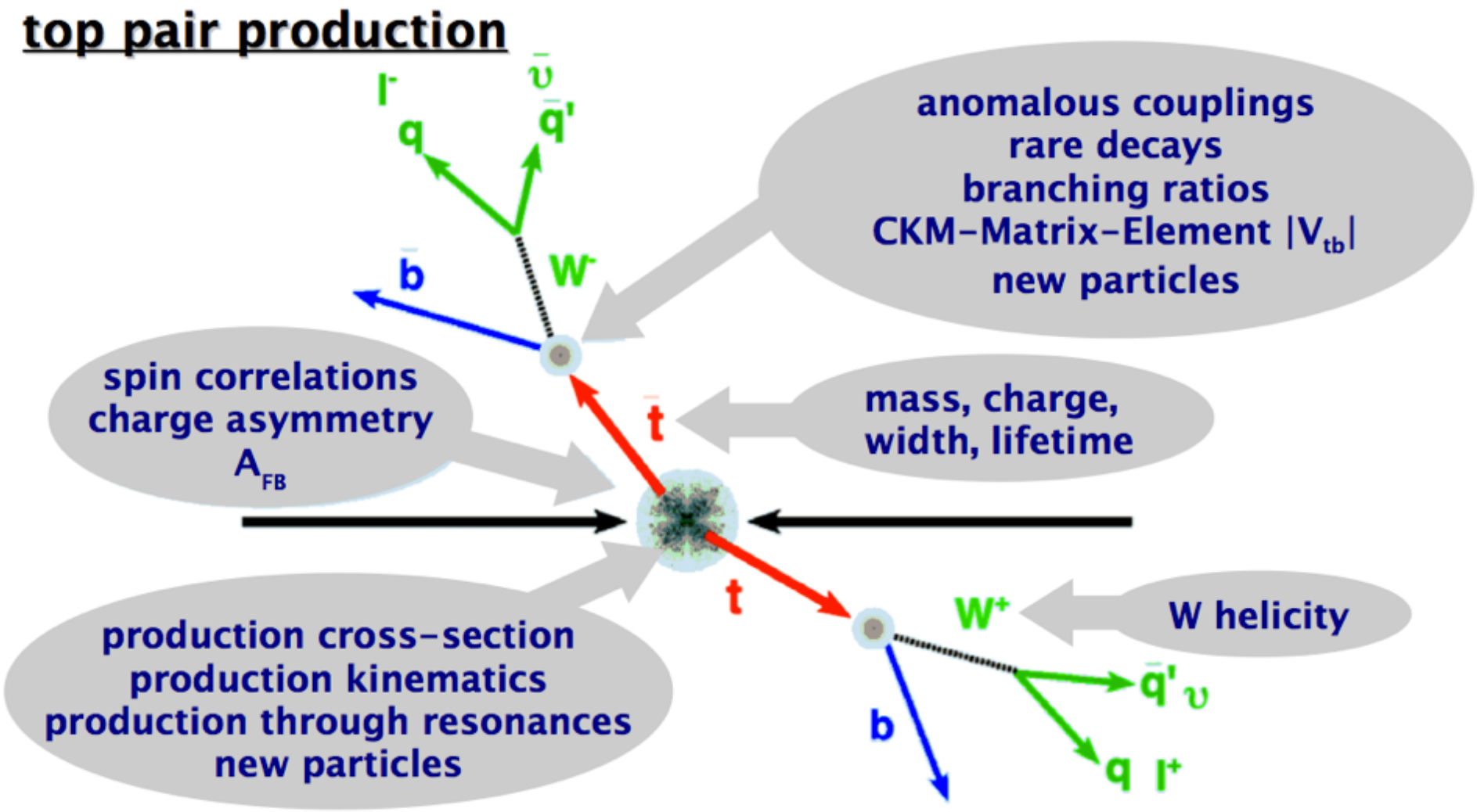


→ observation in Run-II
→ measurement of top-Yukawa coupling

Top Quark Physics Topics



Top Quark Analyses

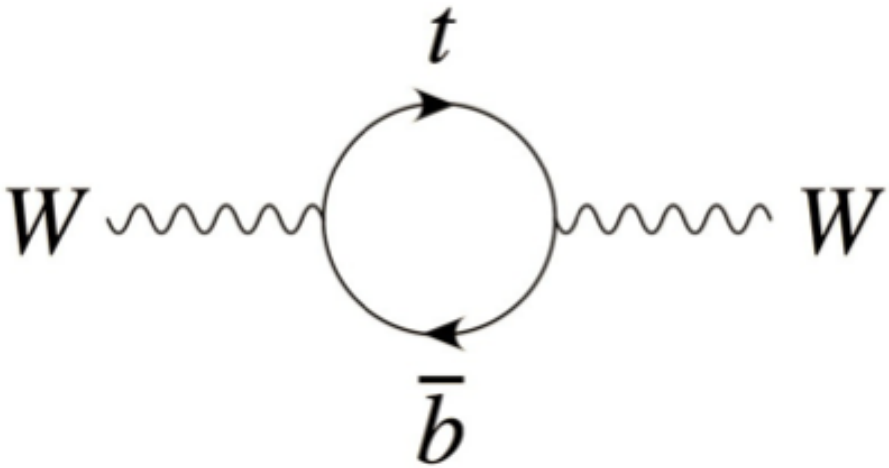


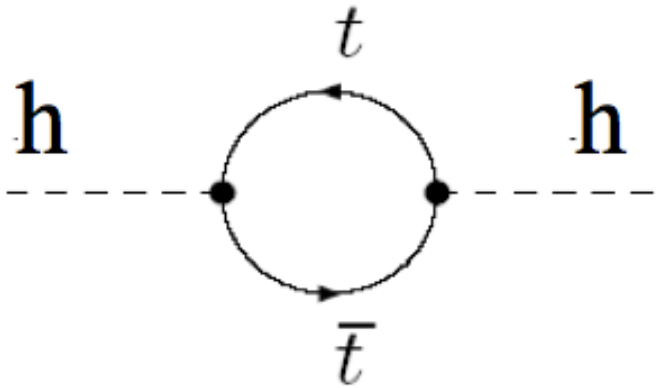
single top production cross sections, CKM matrix element $|V_{tb}|$, polarisation, SM and anomalous couplings, searches, …

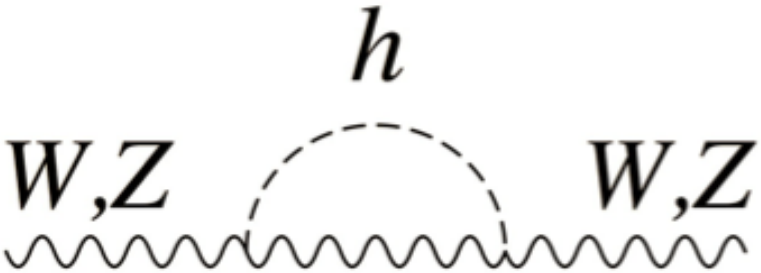
other production modes tt+jets, ttbb, ttZ, ttW, ttH and their couplings

The Top Quark Mass

- free parameter in the Standard Model
- check the **self-consistency of the Standard Model** in combination with W mass and **Higgs mass**

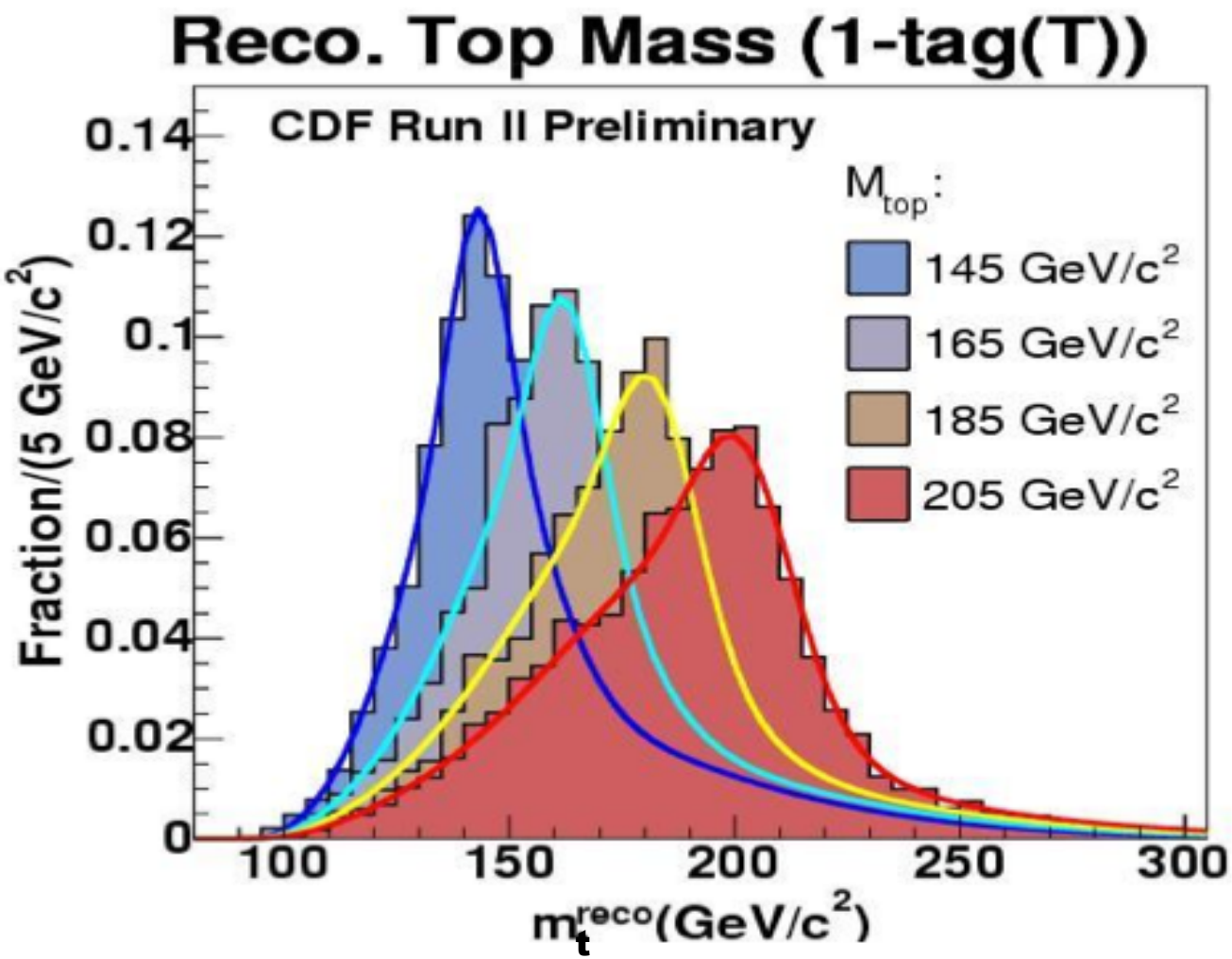






Extraction Techniques: Templates

- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses



Extraction Techniques: Templates

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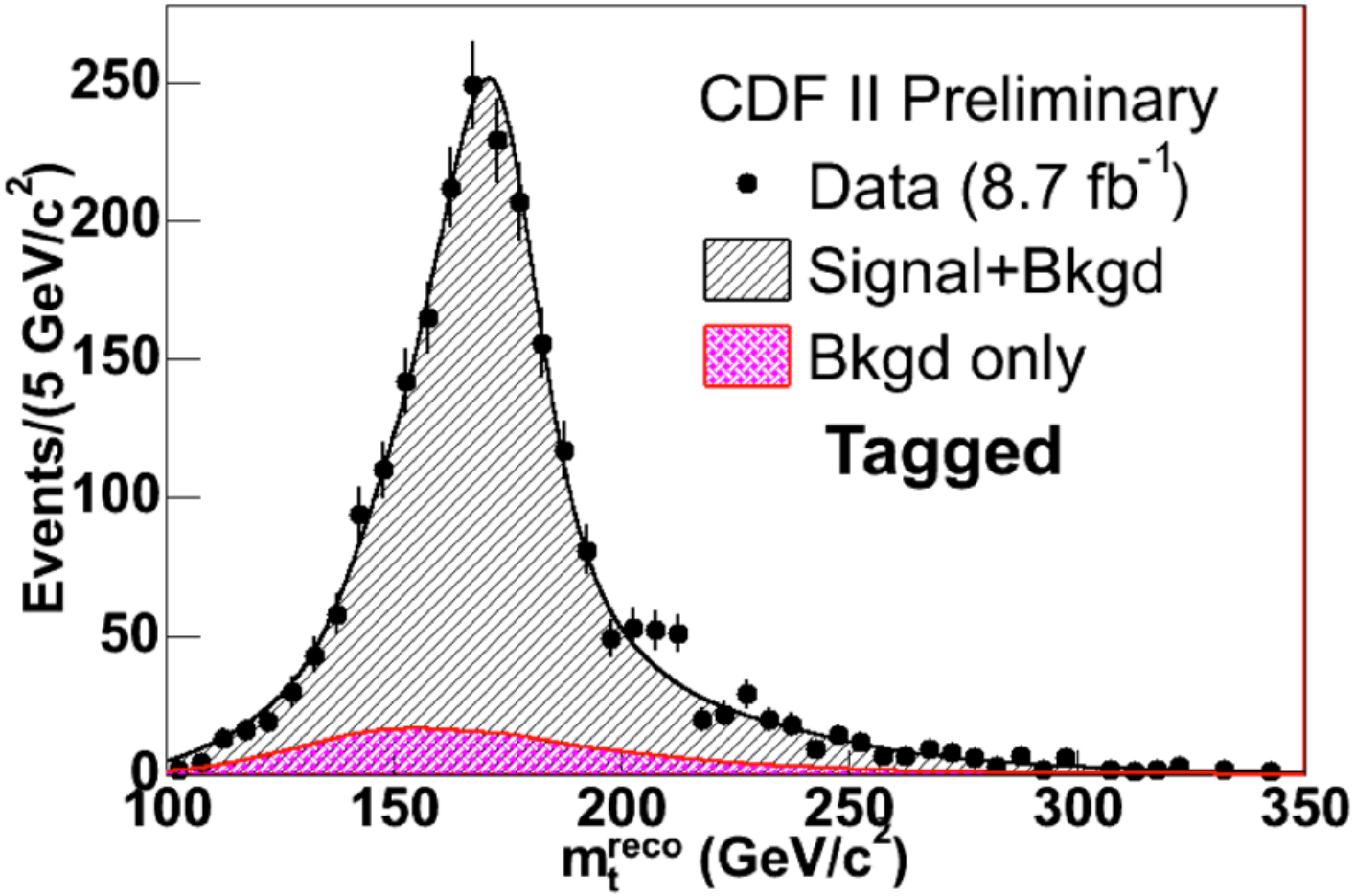

Extraction Techniques: Templates

- use variables strongly correlated with m_{top}
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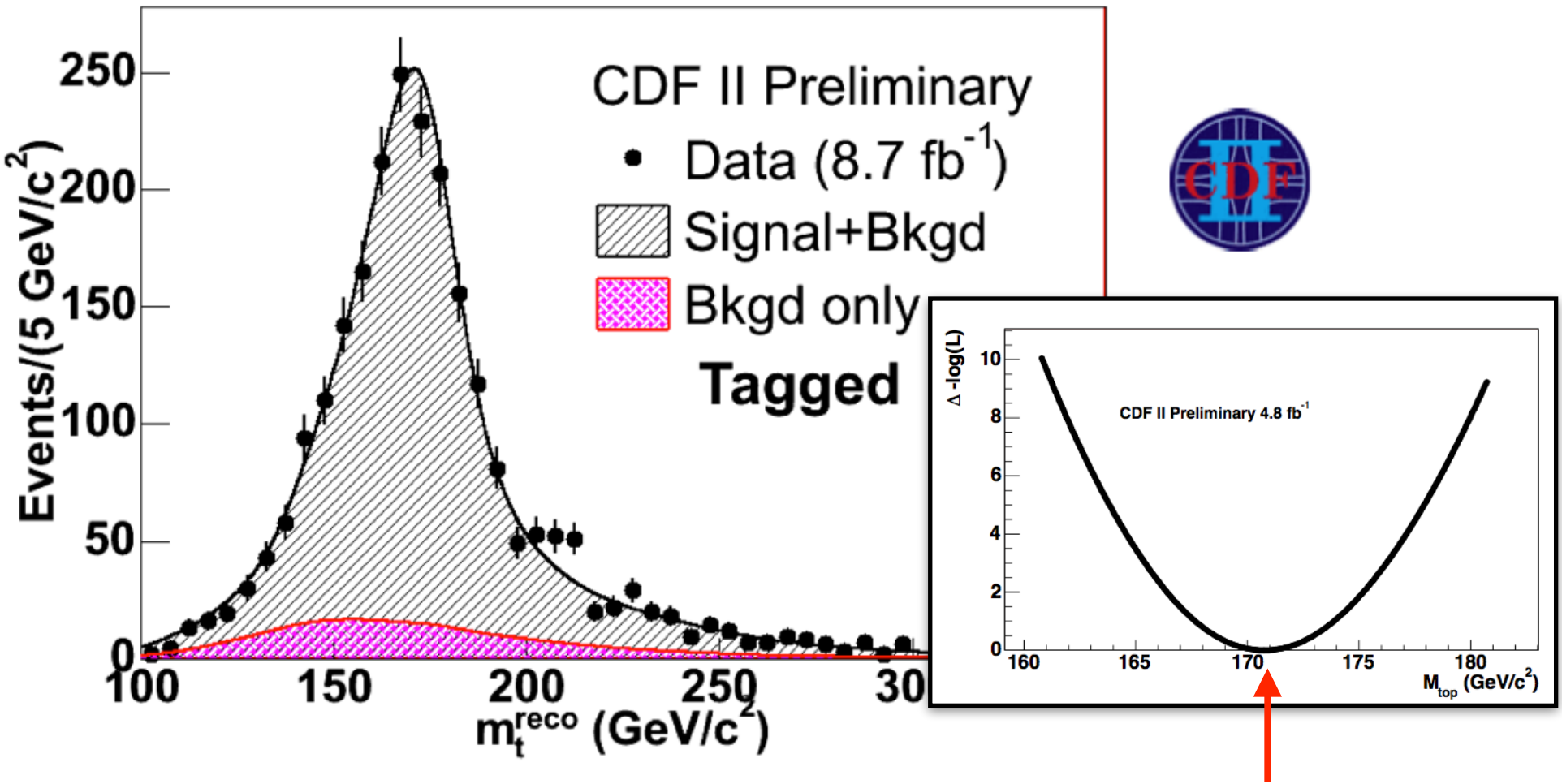
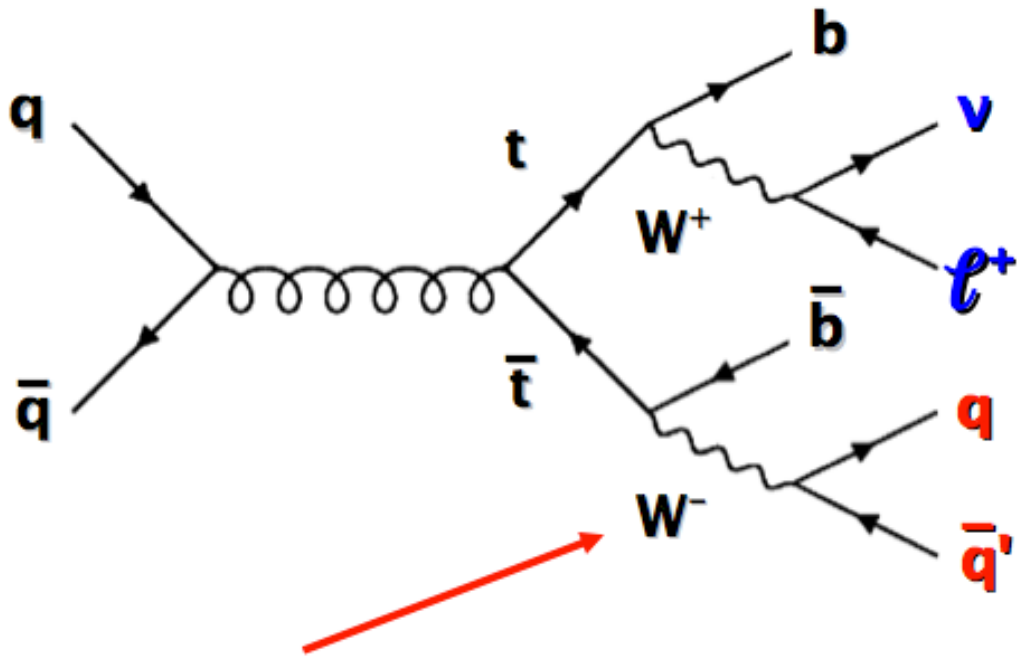


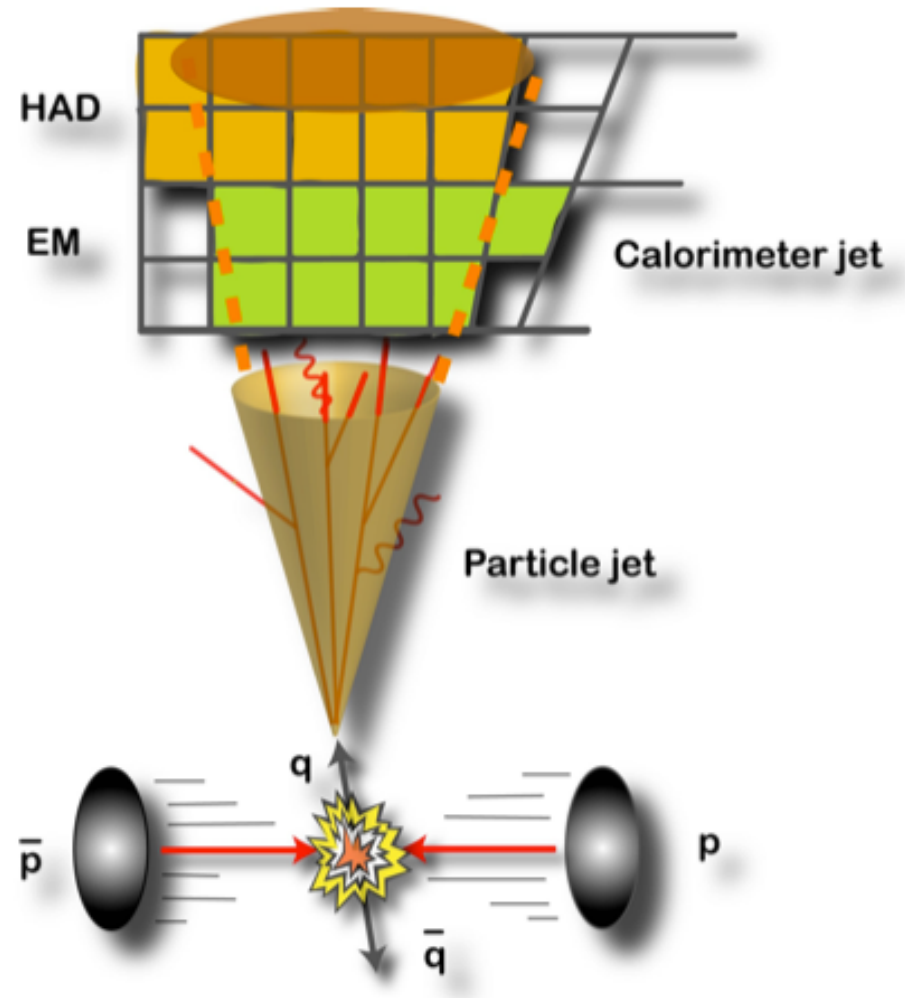
JES calibration



W mass constrains jet energy scale

jet energy scale:

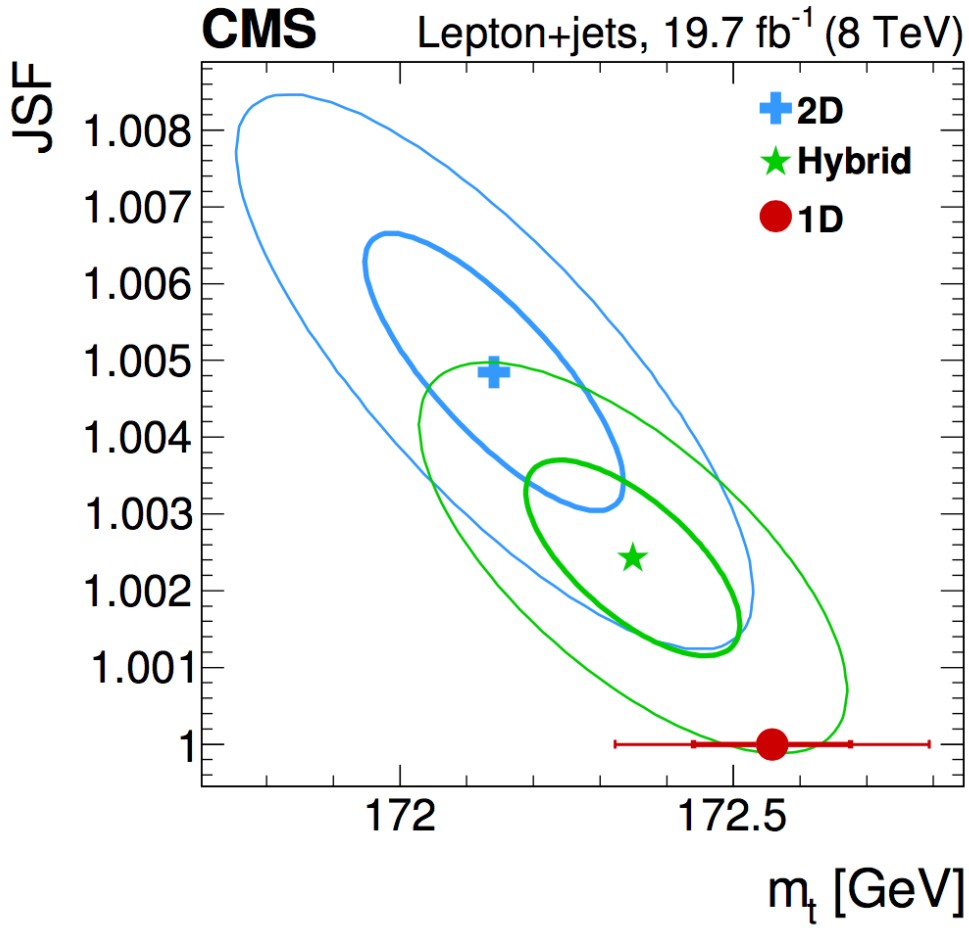
translate jet into parton energy



Result in l+jets Channel

jet energy scale:

translate jet into parton energy



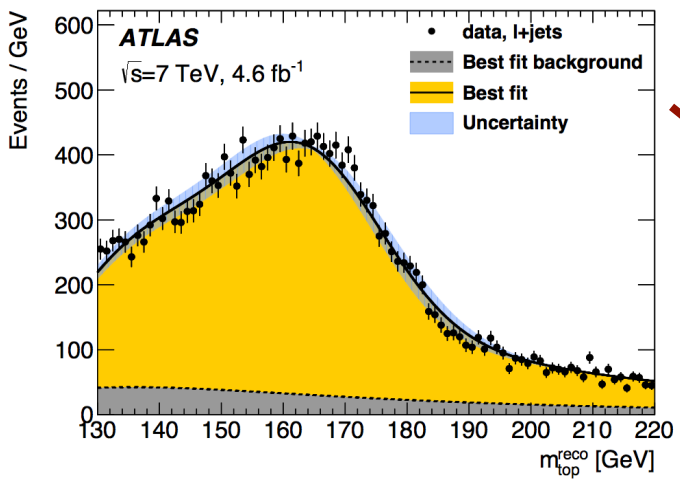
maximum likelihood fit to data

$$m_t^{hyb} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\,\text{GeV}$$

most precise single measurement

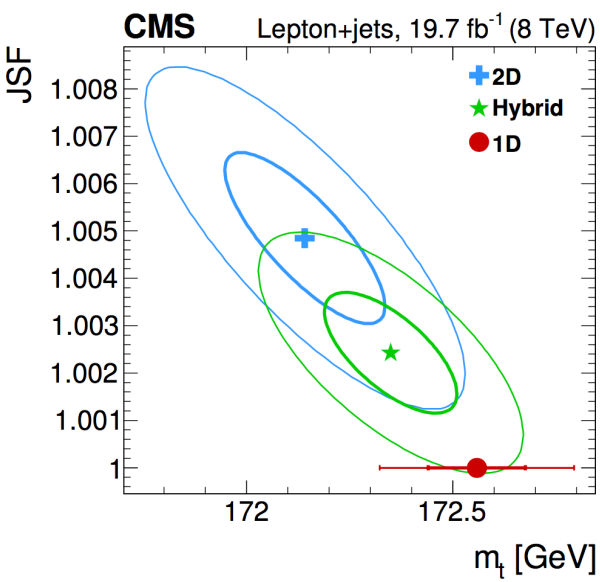
±0.29%

Top mass at the LHC



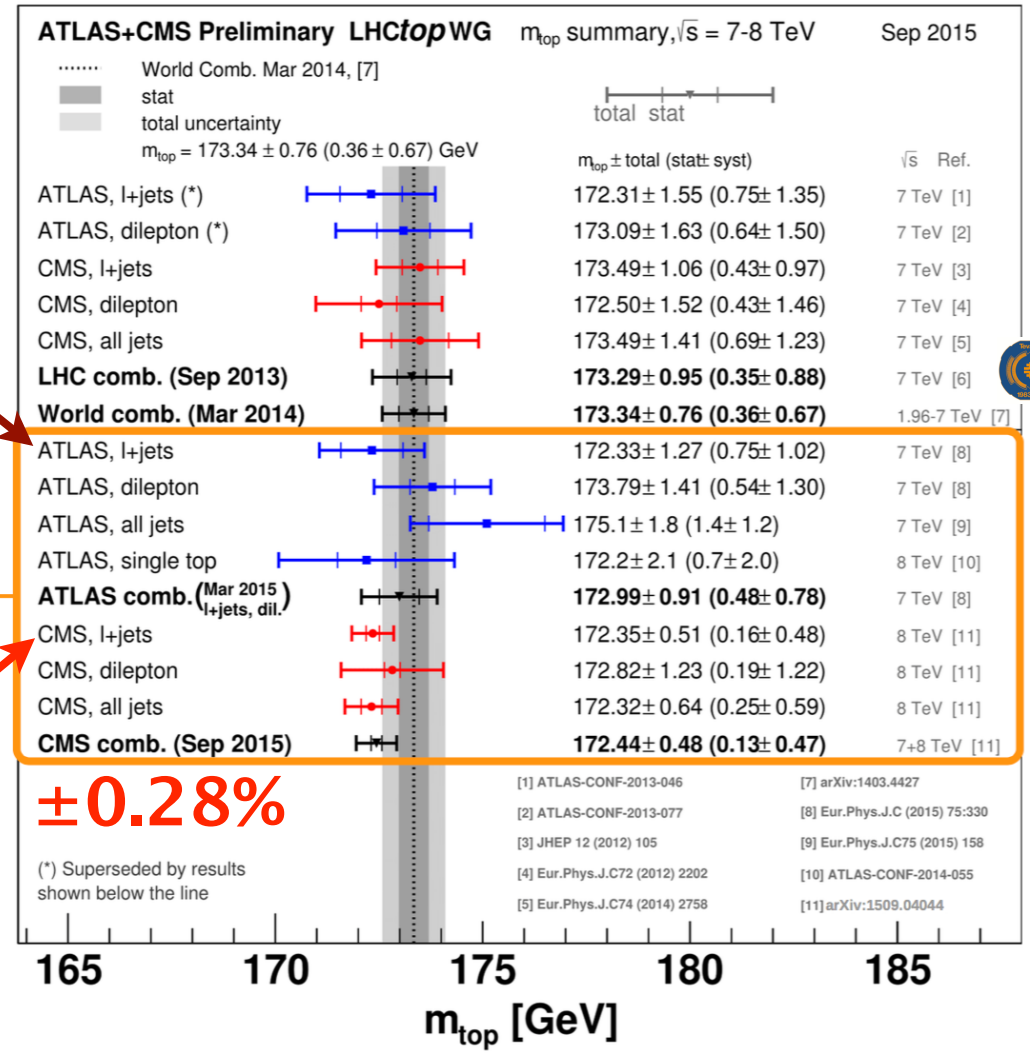
±0.73%

$$m_{\text{top}}^{\ell+\text{jets}} = 172.33 \pm 0.75\ (\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.02\ (\text{syst})\ \text{GeV}$$



±0.29%

$$m_t^{\text{hyb}} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\,\text{GeV}$$

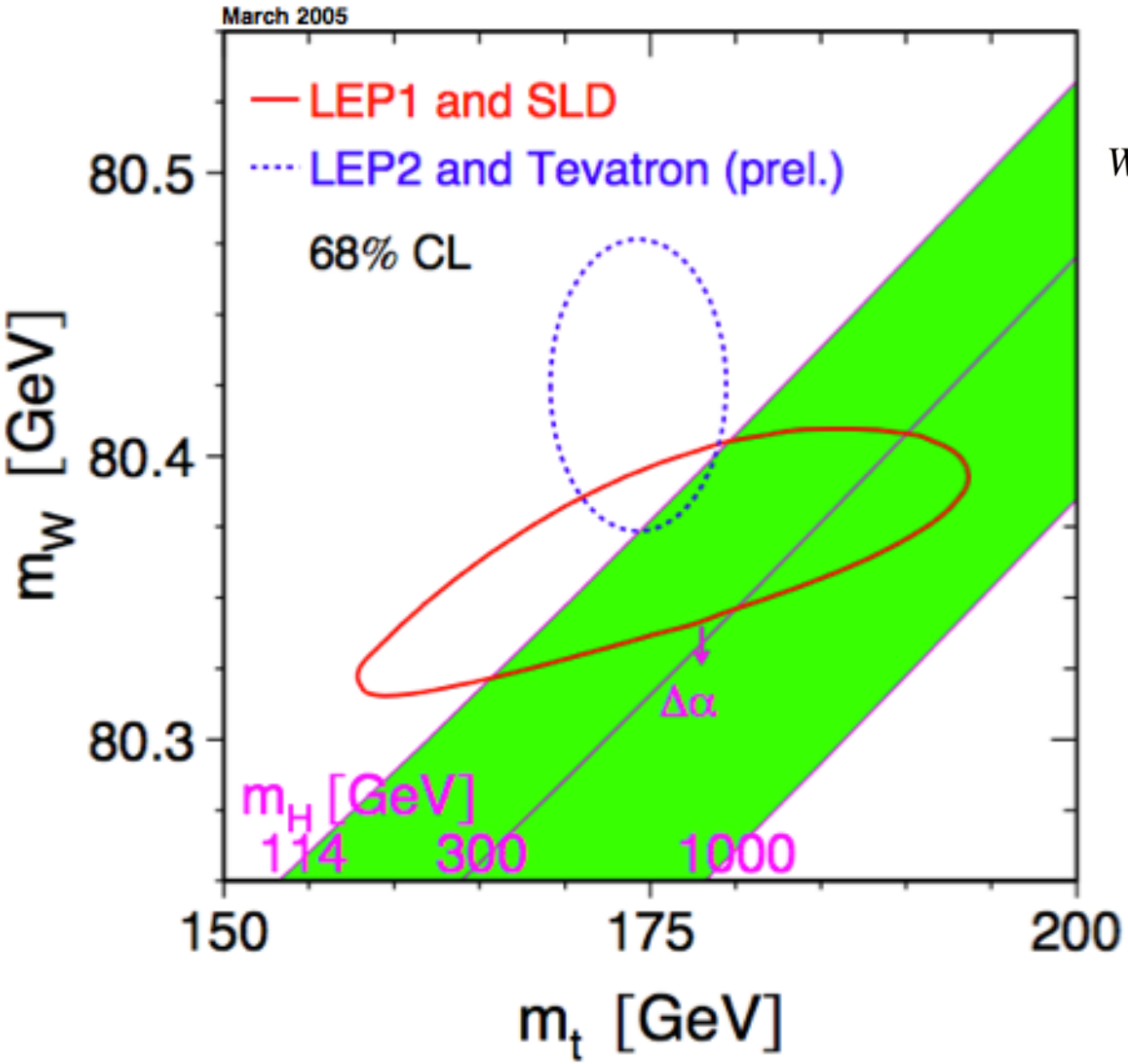


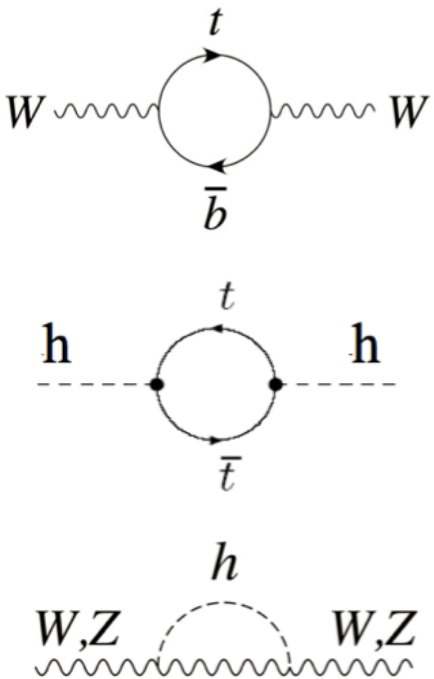
±0.28%

New results waiting for combination!
(in addition to latest results from Tevatron)

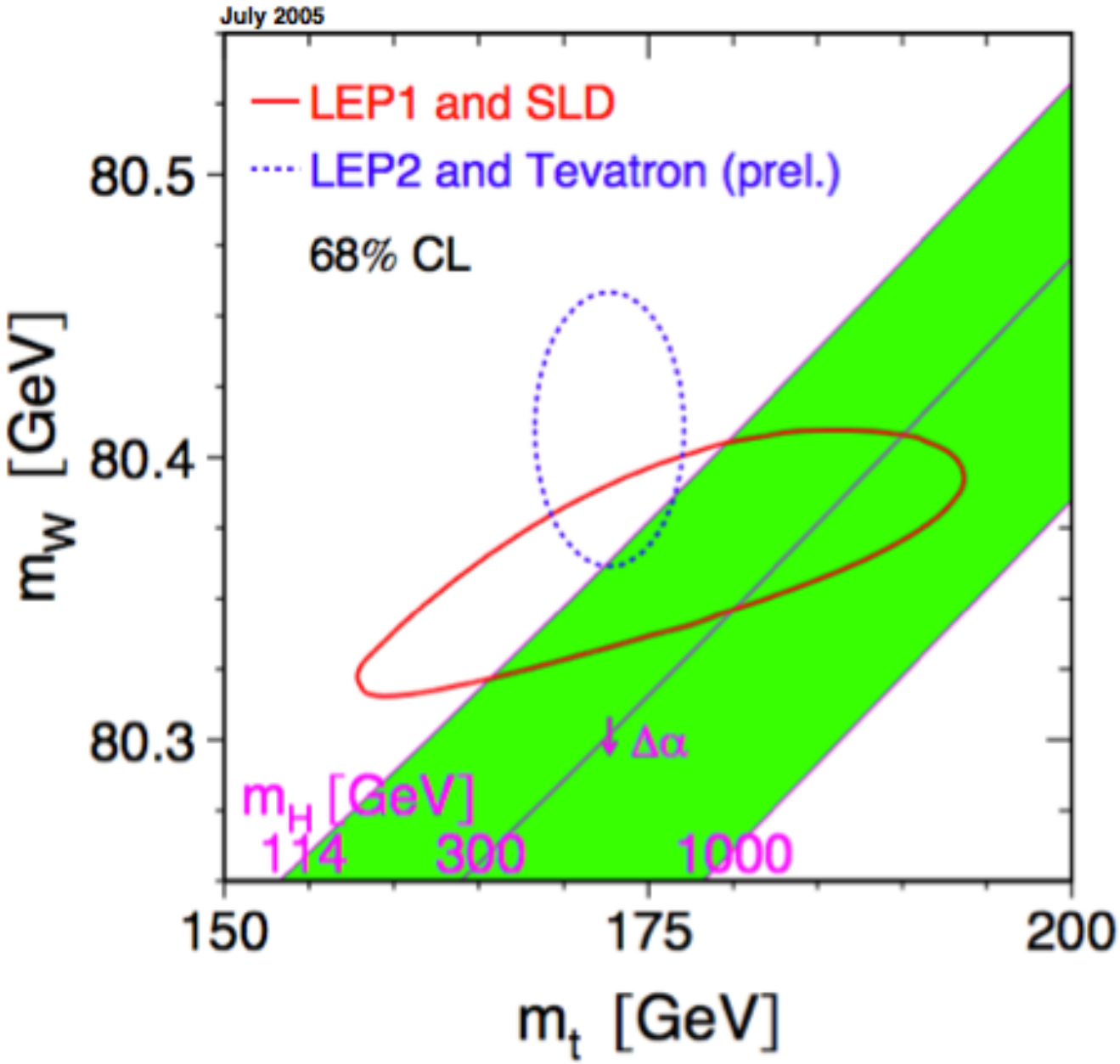
→ jet energy scale is crucial

History m_{top} vs. M_W

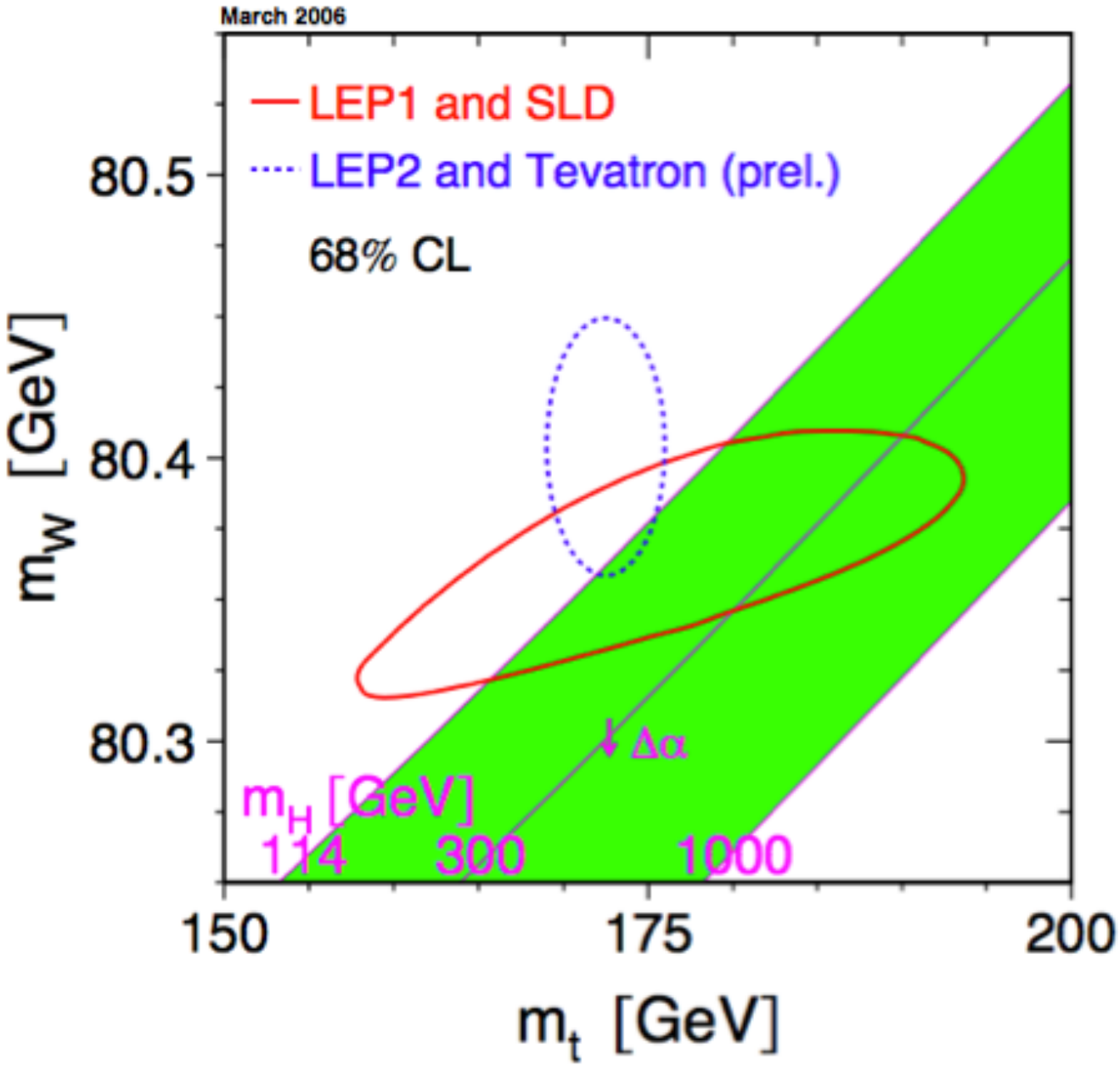




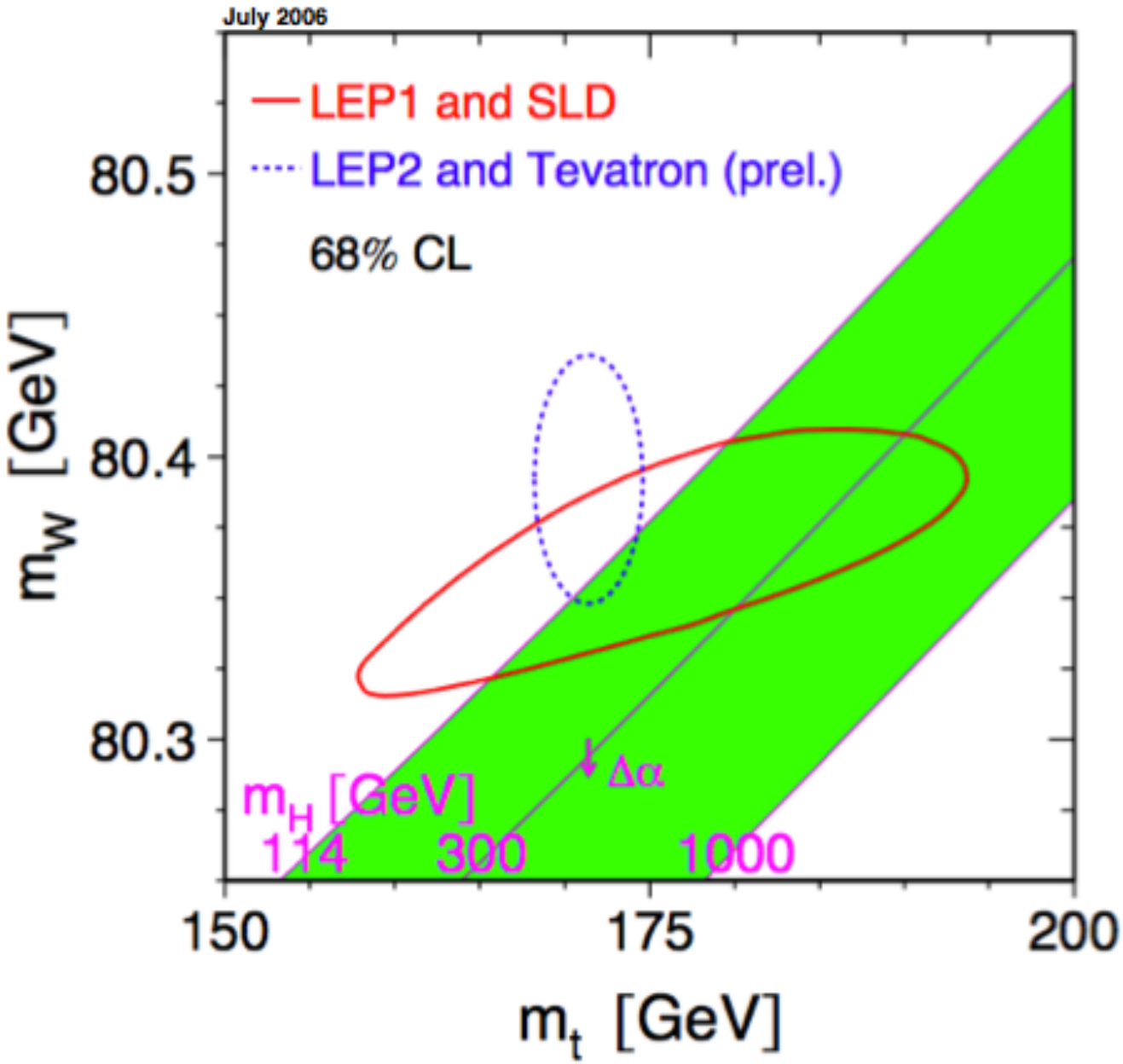
History m_{top} vs. M_W



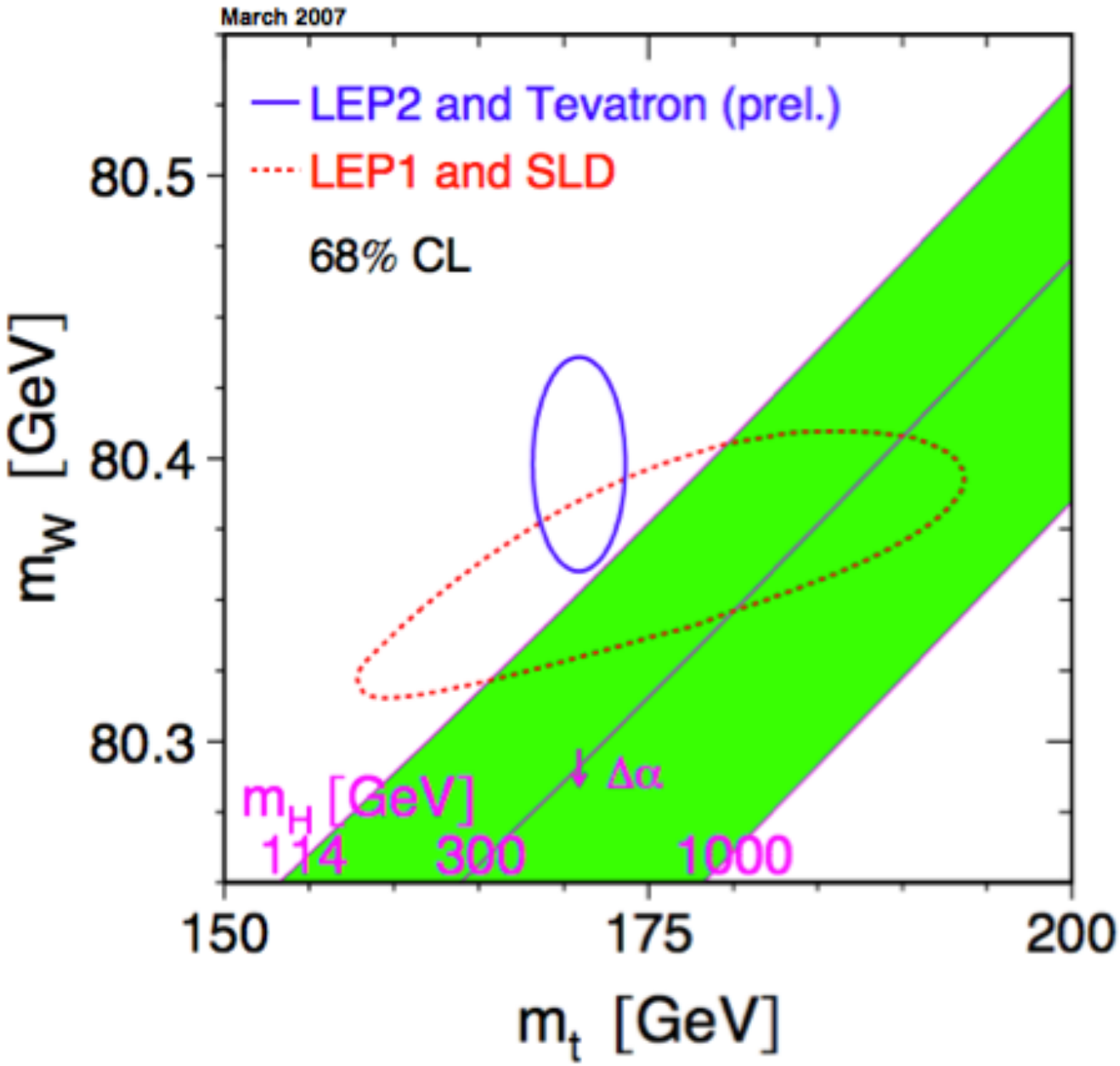
History m_{top} vs. M_W



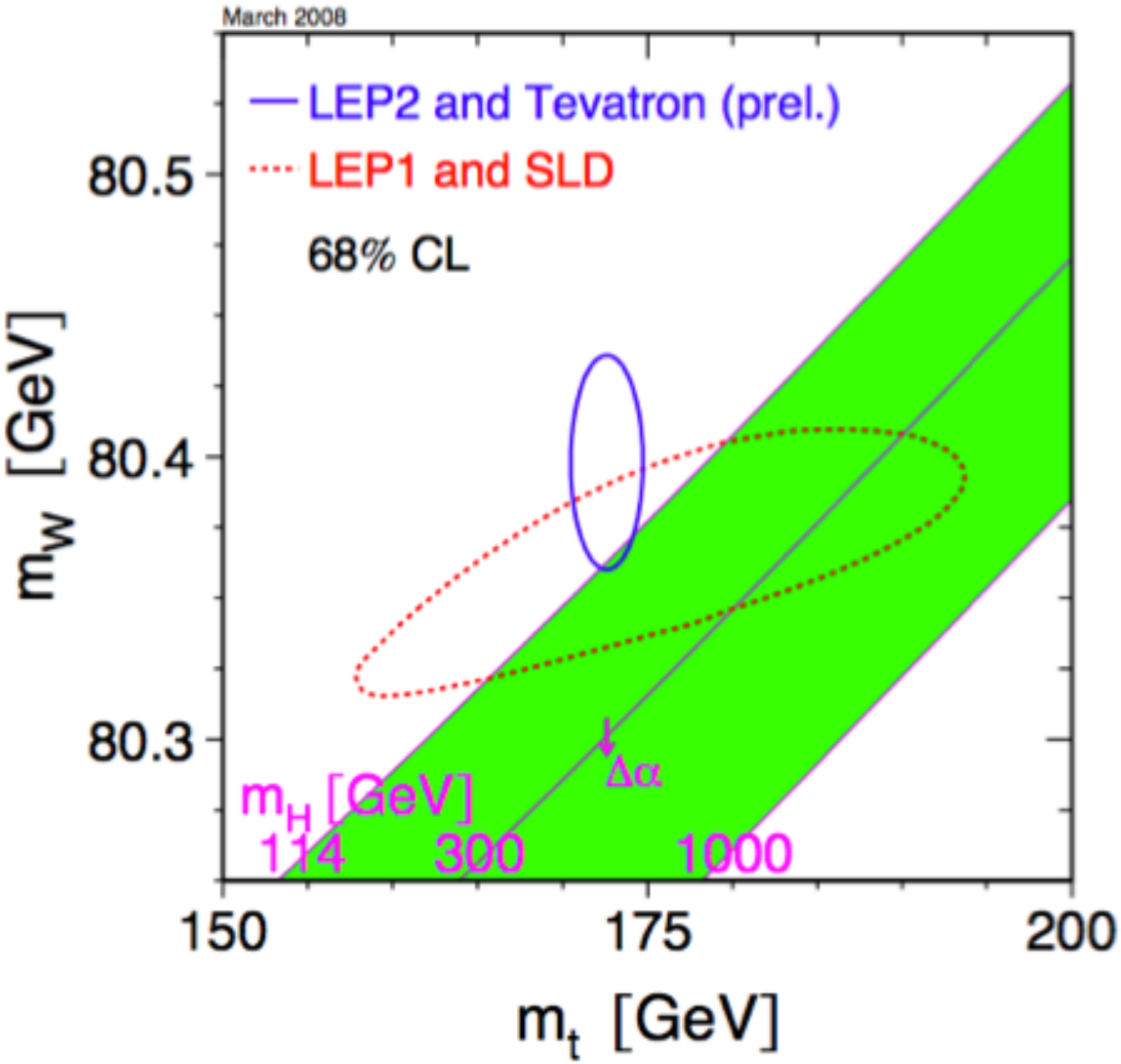
History m_{top} vs. M_W



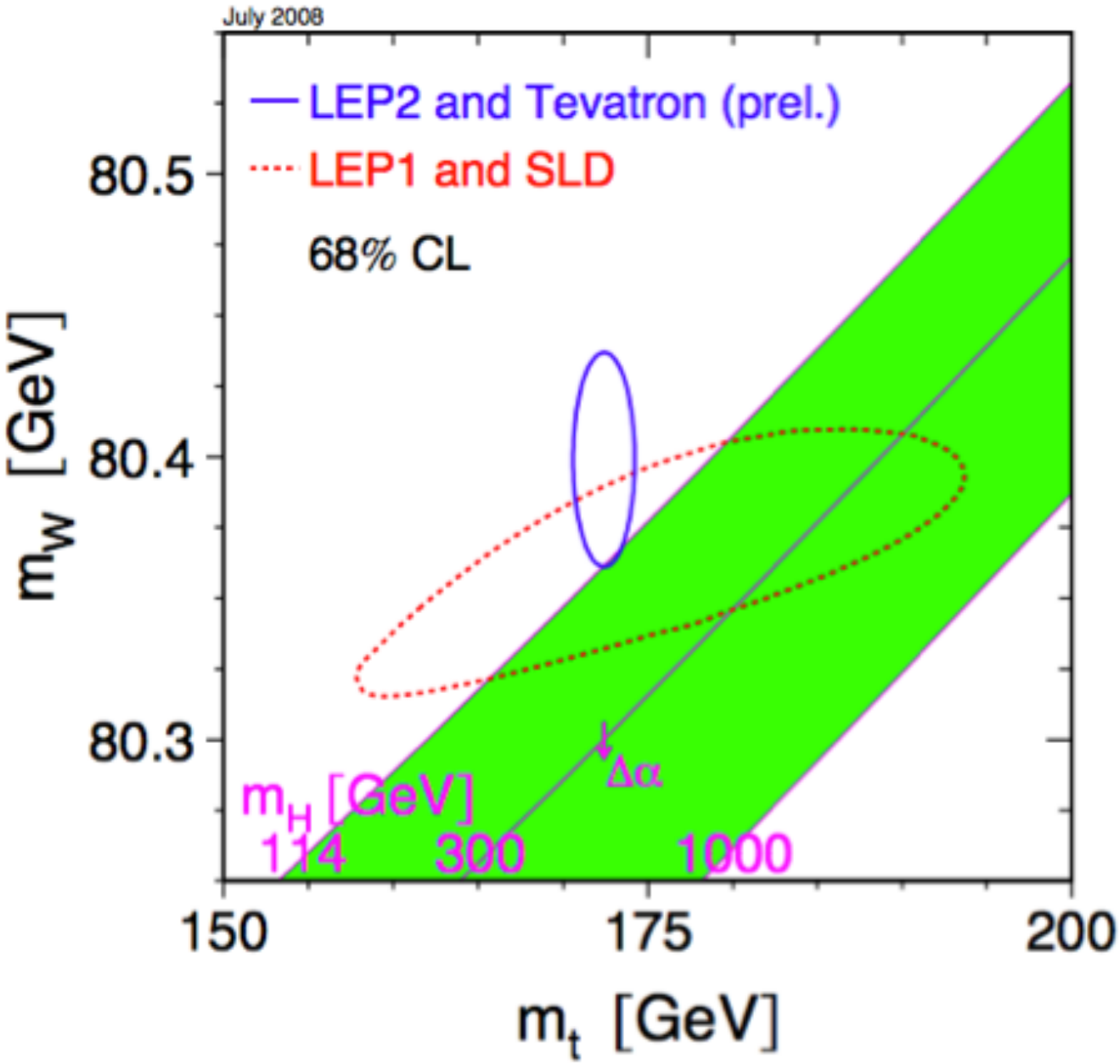
History m_{top} vs. M_W



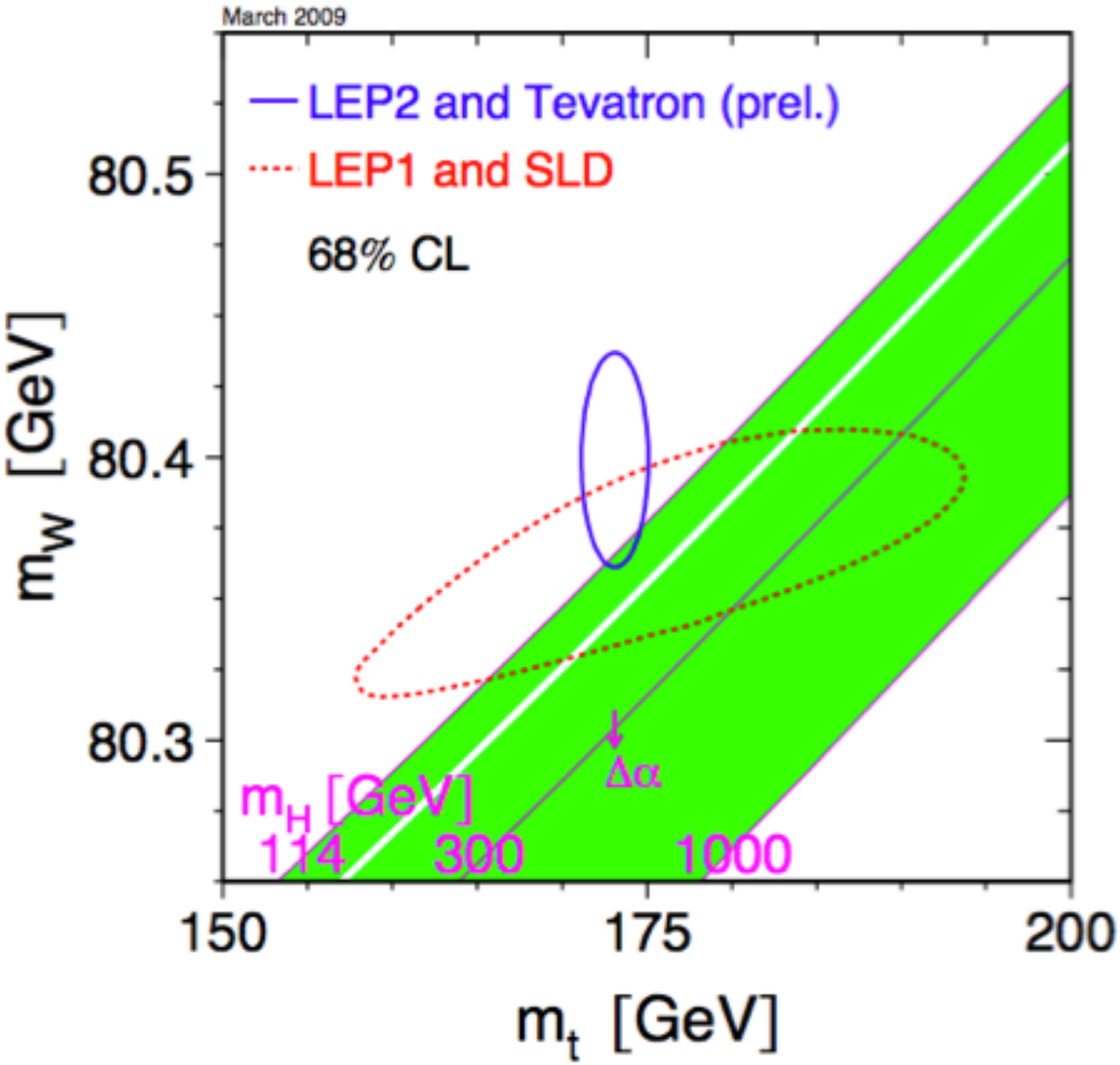
History m_{top} vs. M_W



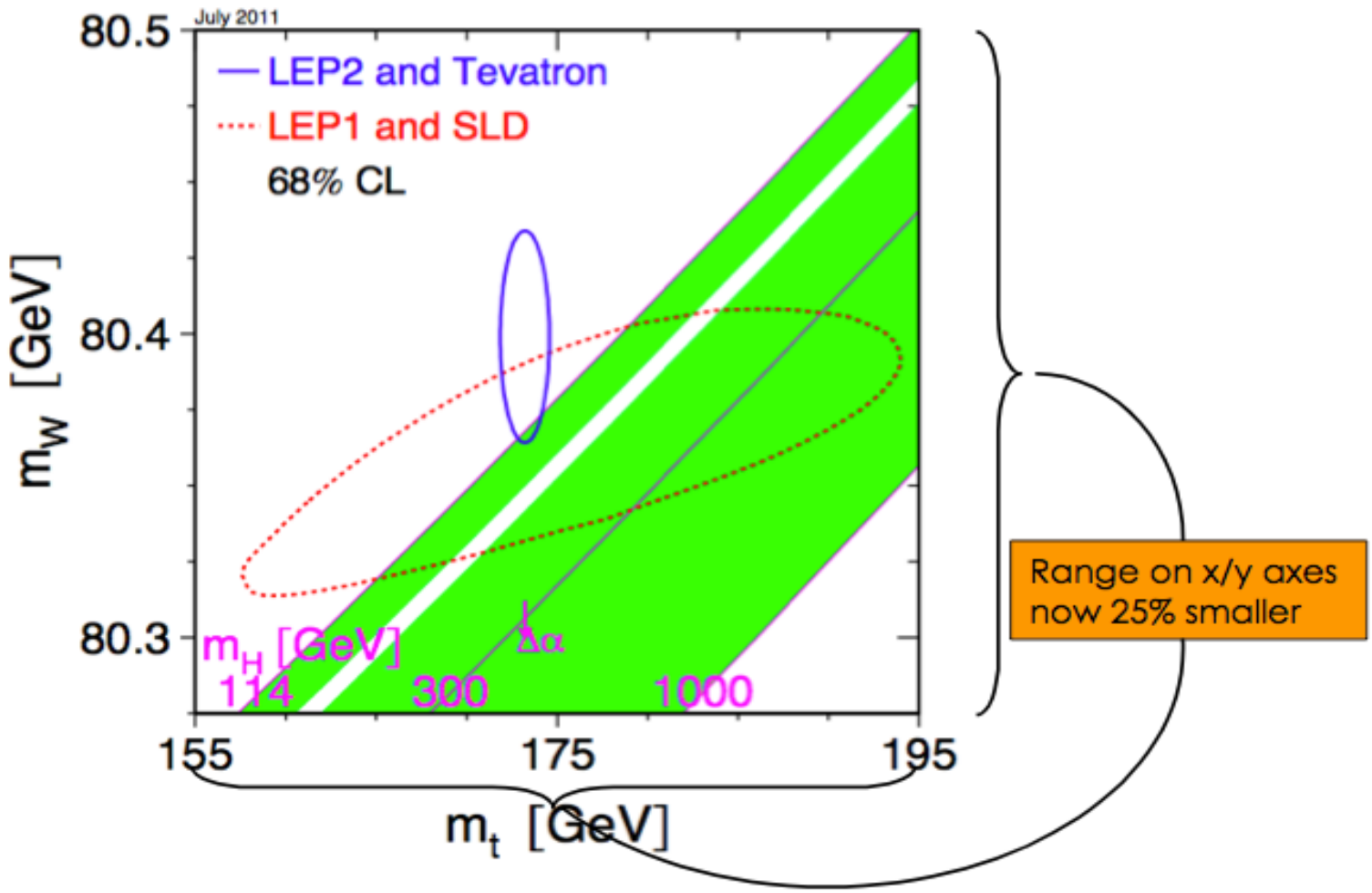
History m_{top} vs. M_W



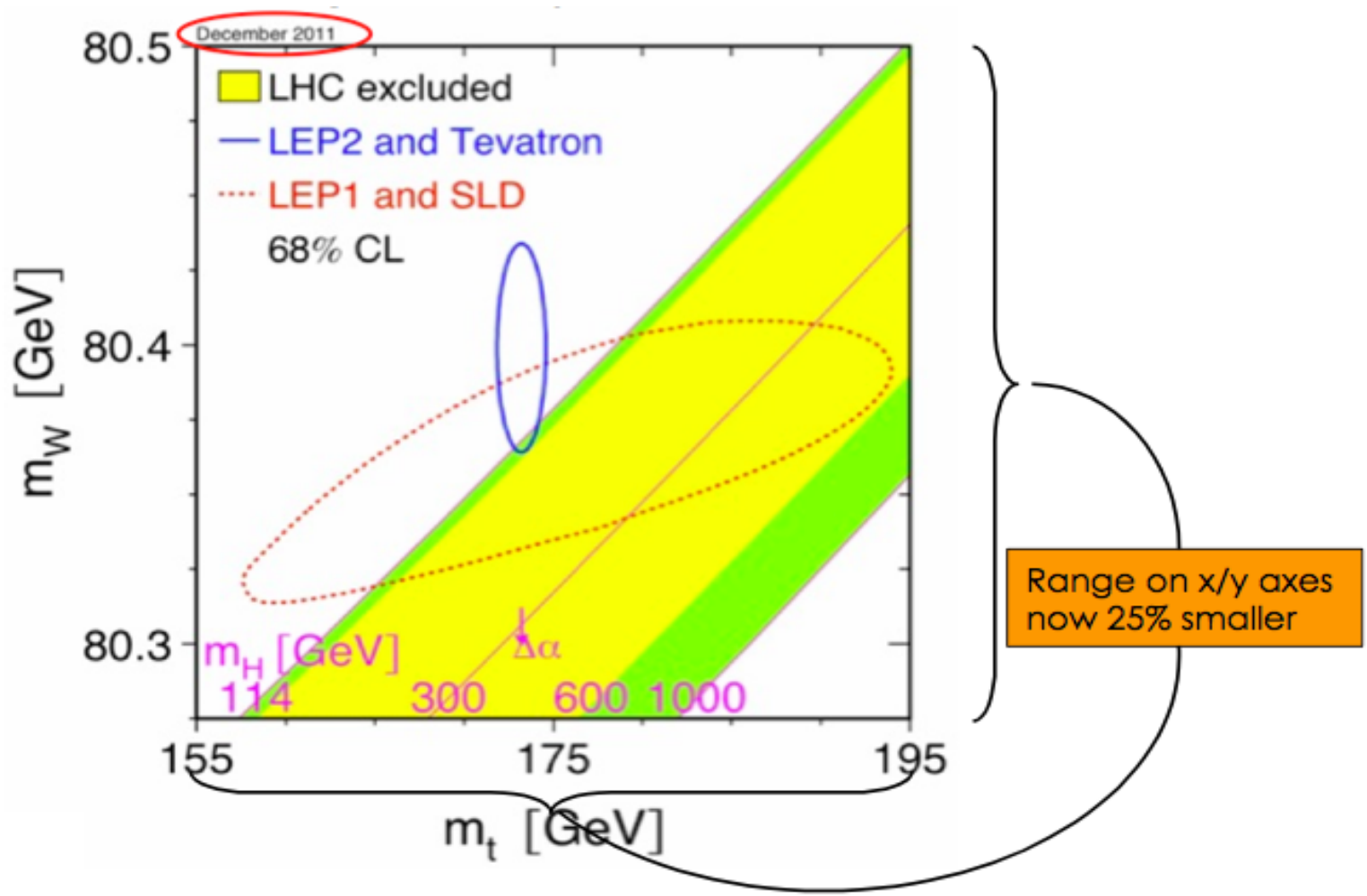
History m_{top} vs. M_W



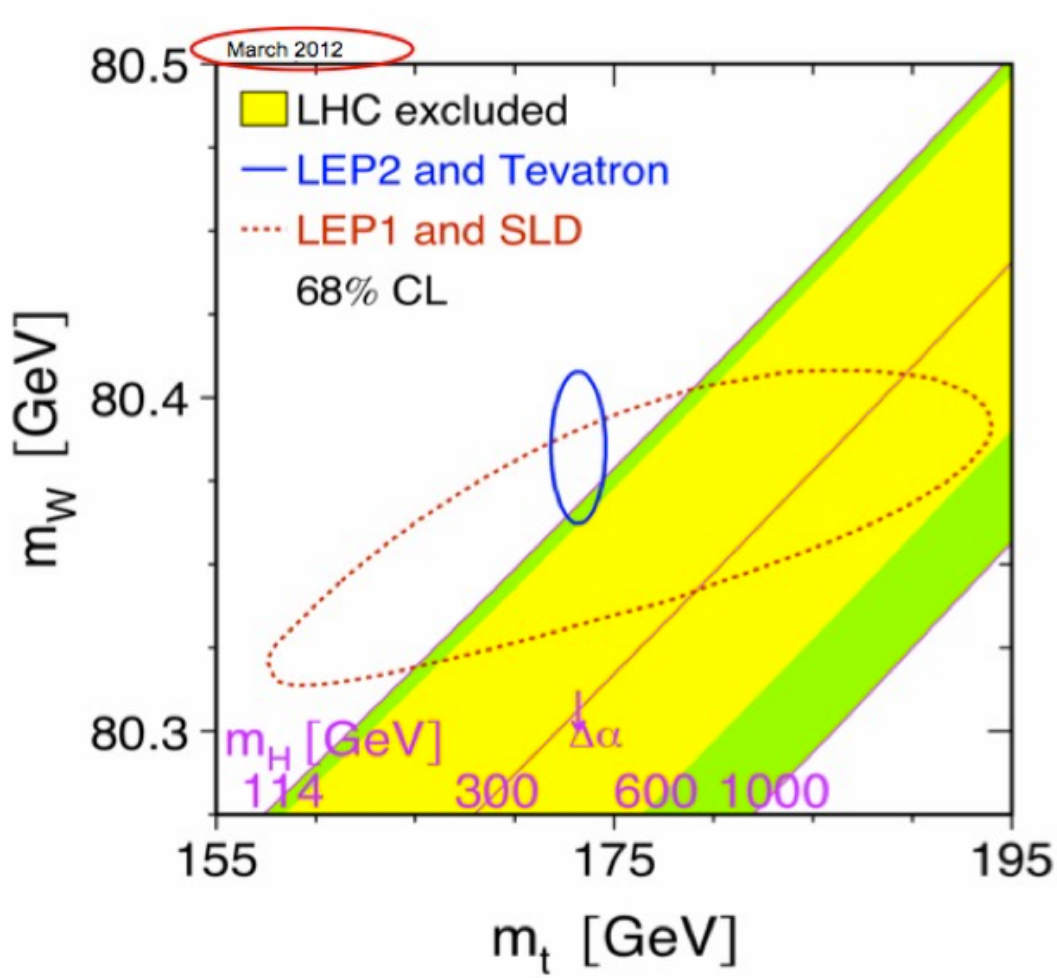
History m_{top} vs. M_W



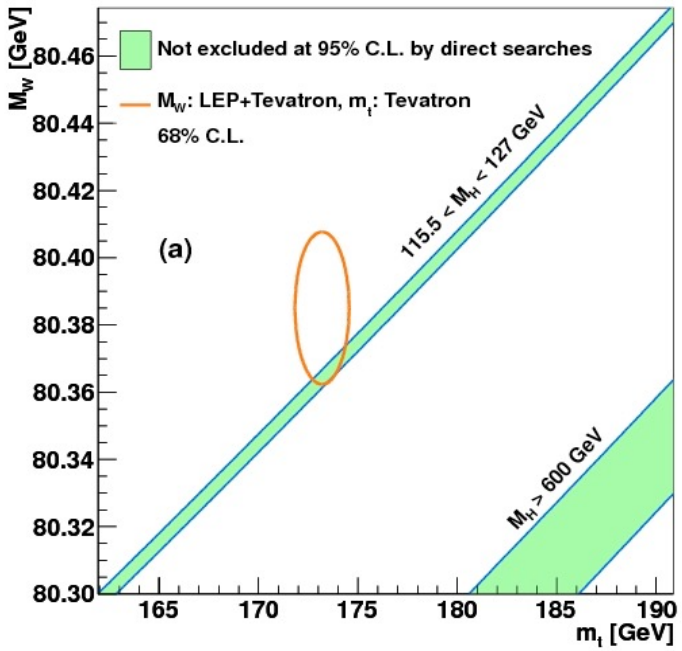
History m_{top} vs. M_W



History m_{top} vs. M_W

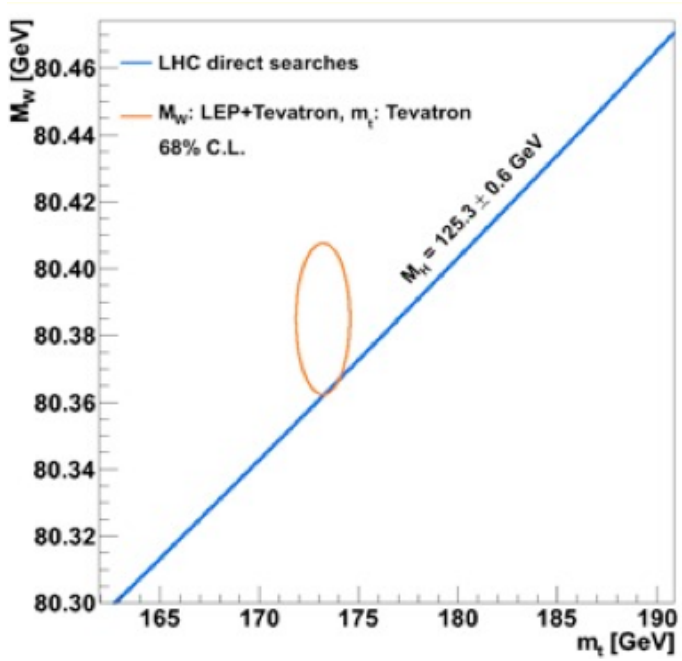


History m_{top} vs. M_W



History m_{top} vs. M_W

July 2012

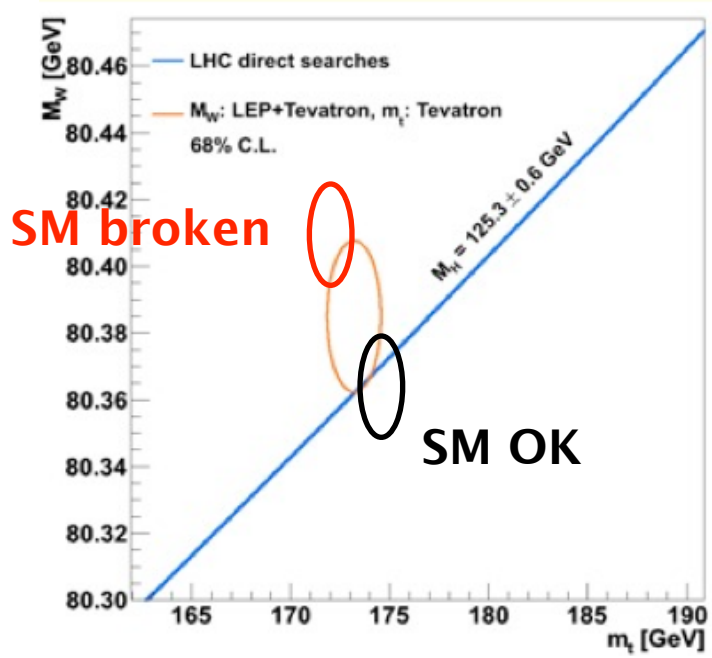


→ Standard Model is self-consistent

History m_{top} vs. M_W

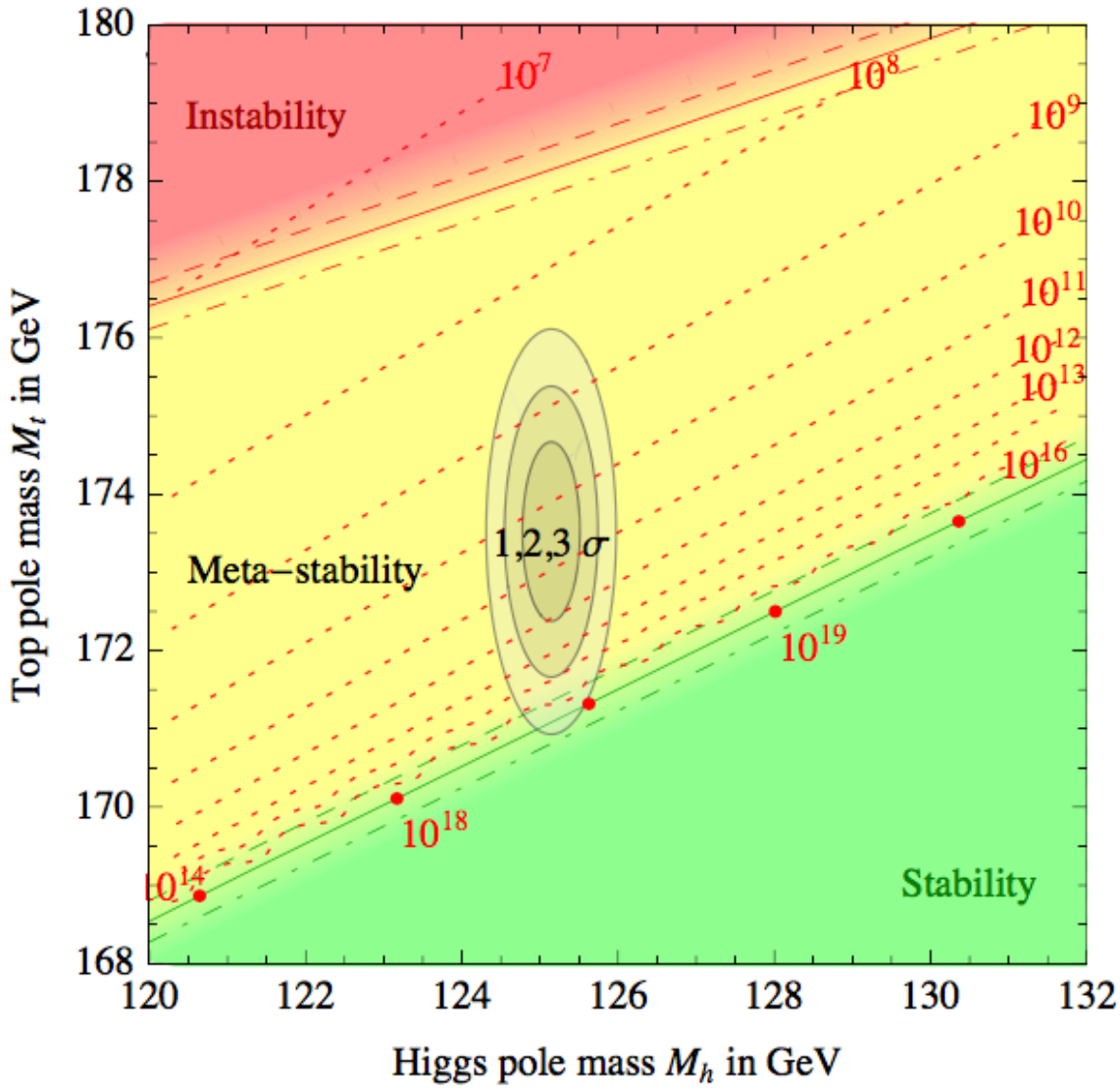
July 2012

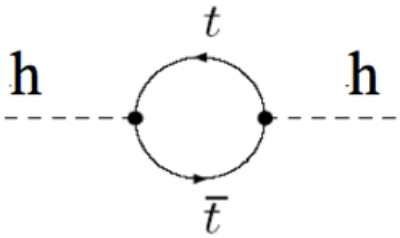
future:
$\Delta(m_W)$=6 MeV



improved W mass measurement is critical

m_{top} vs. M_H





check the "fate of the Universe"

What mass do we measure?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

m_{top}

- **LO QCD: free parameter**
- **NLO QCD: dependent on the renormalisation scale M**

"Bare" parameters of QCD:

$$g_s,\ m_u,\ m_d,\ m_s,\ m_c,\ m_b,\ m_t$$

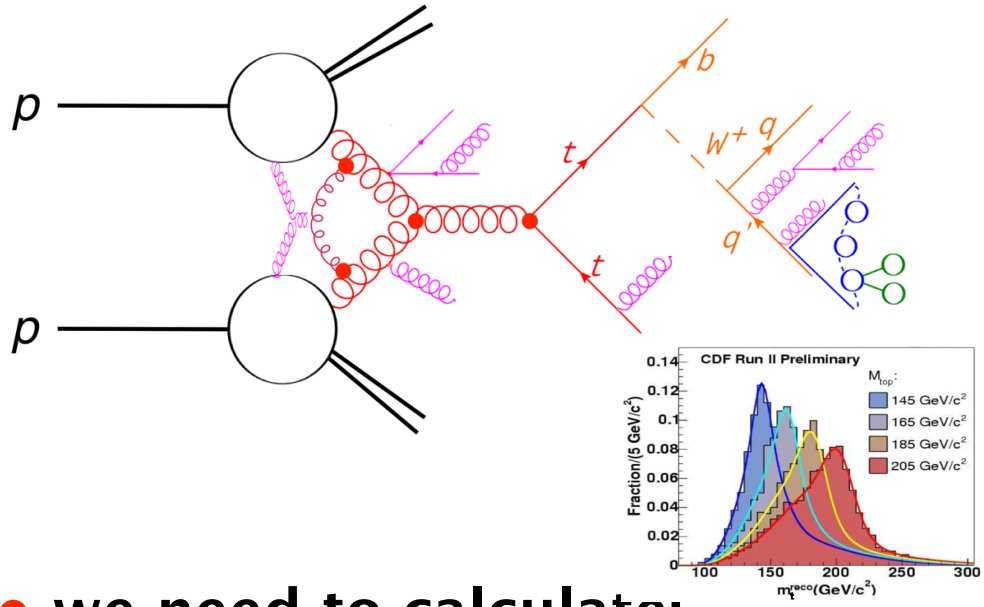
Renormalised parameters of QCD:

$$g_s(M),\ m_u(M),\ m_d(M),\ m_s(M),\ m_c(M),\ m_b(M),\ m_t(M)$$

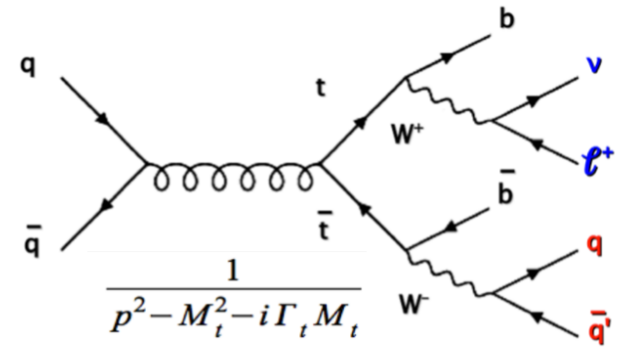
the concept of quark mass is convention-dependent!

What mass do we need?

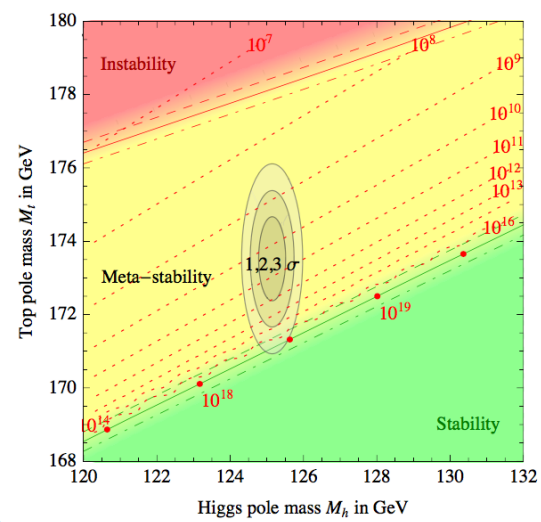
- **we measure the MC mass**



- **we need the pole mass**



$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$



- **we need to calculate:**

Scheme-dependent

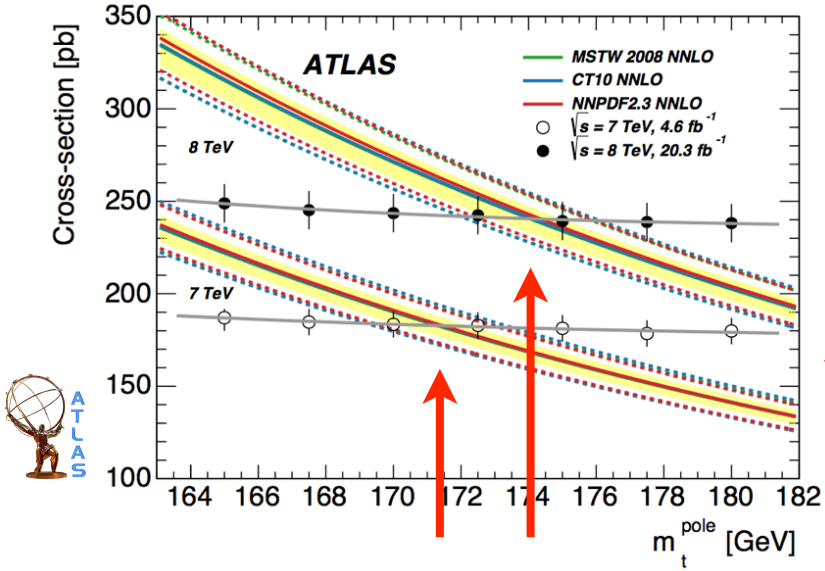
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{quark}} + \Delta$$

~ O(1 GeV)

e.g. pole mass

- **every MC generator mass can can correspond to a different pole mass**

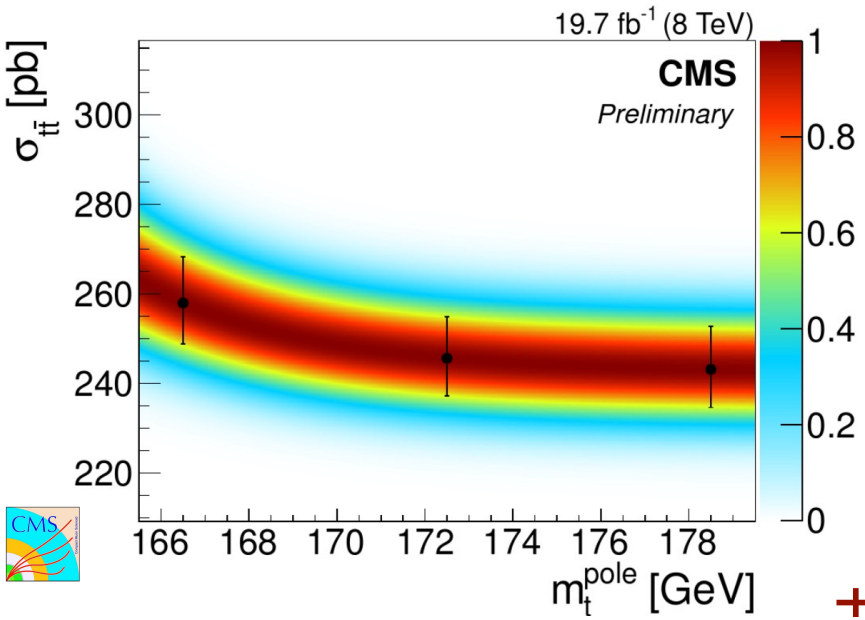
Top Quark Pole Mass



$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\,\text{GeV}\ (\sqrt{s} = 7/8\,\text{TeV})$$

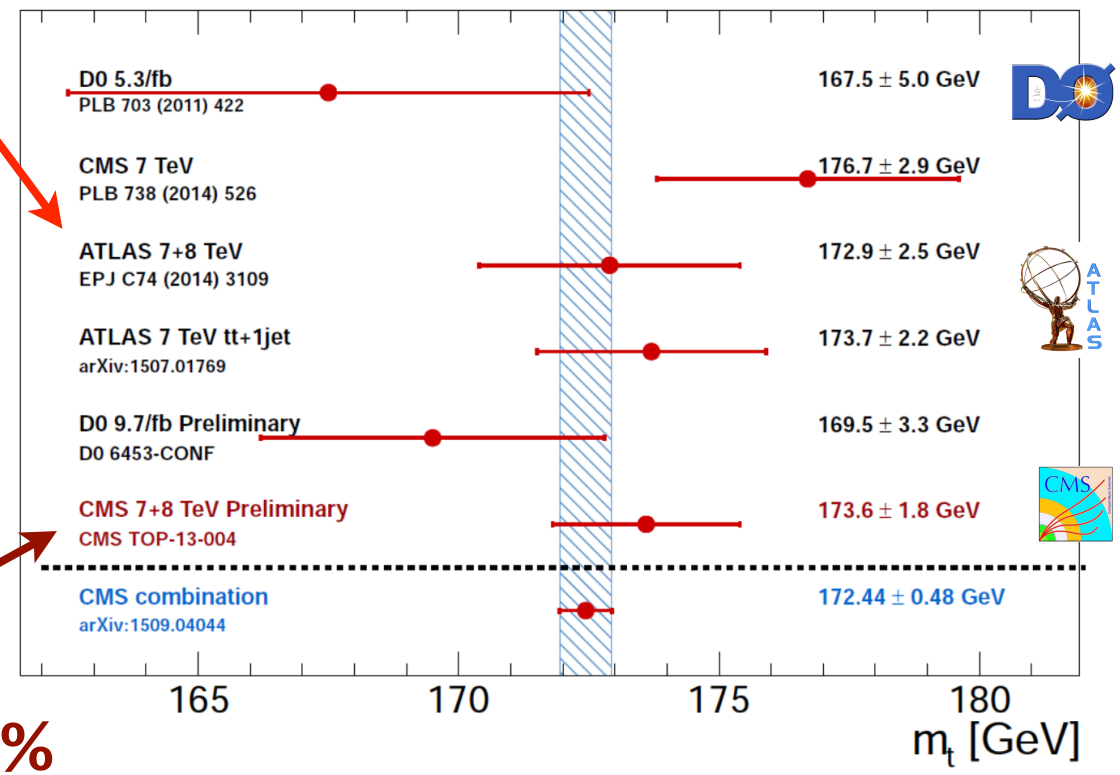
→ pole mass unambiguously!

±1.4%

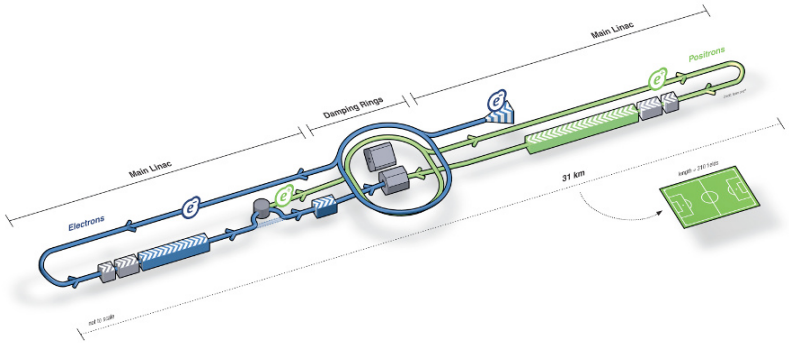


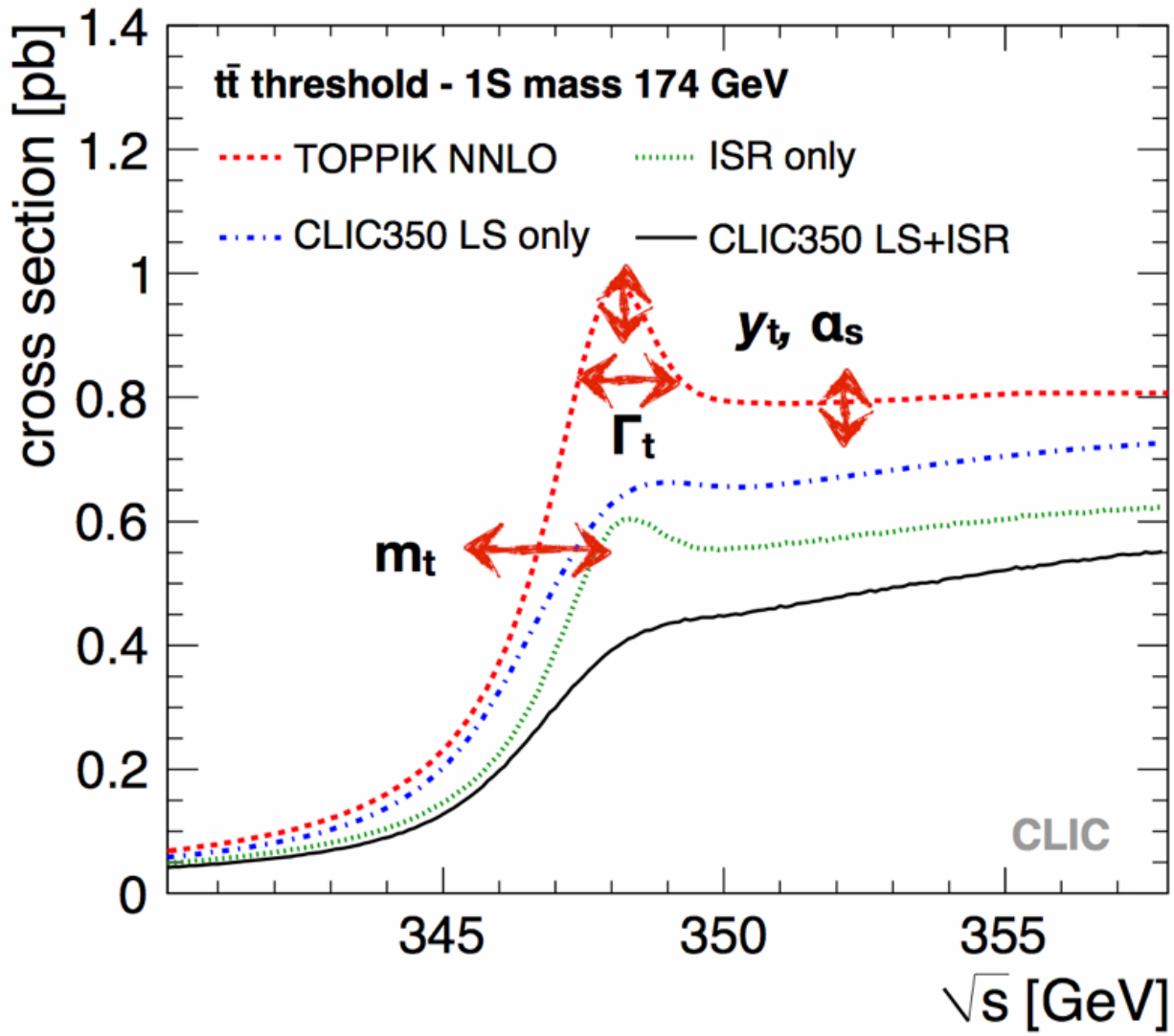
M_t^{pole}=173.6 ± 1.8 GeV

±1.0%



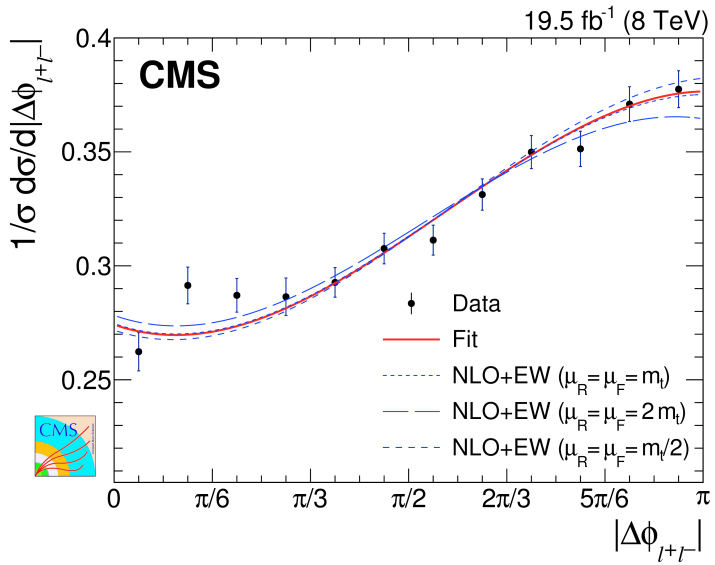
Top mass at ILC



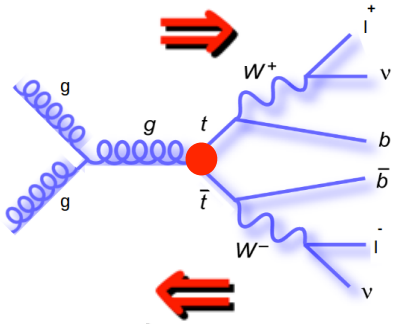


→ **well-defined top mass with ~O(100 MeV) uncertainty**

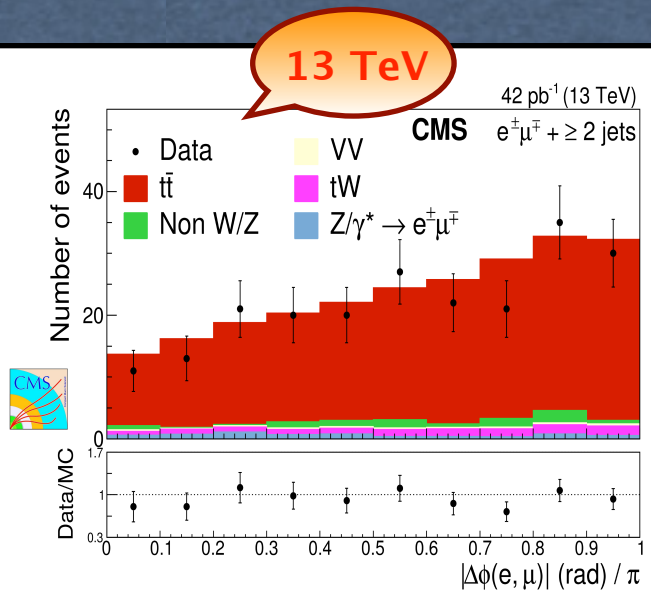
Polarisation and Spin Correlation



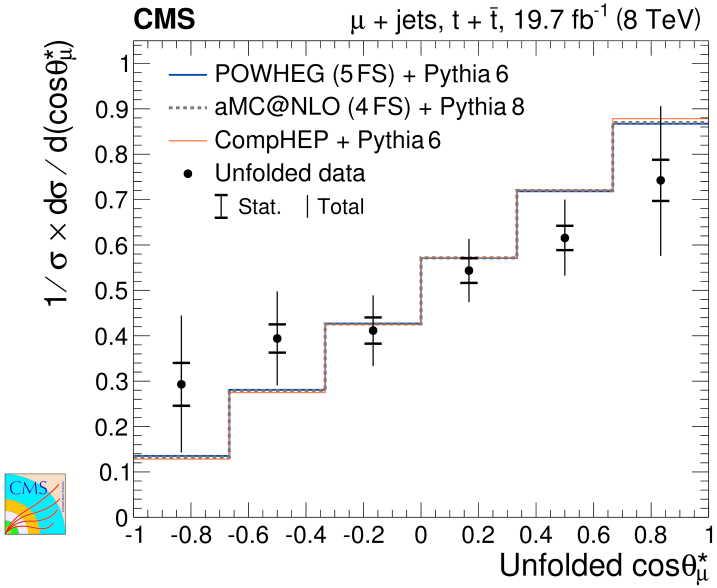
→ no chromomagnetic dipole moments



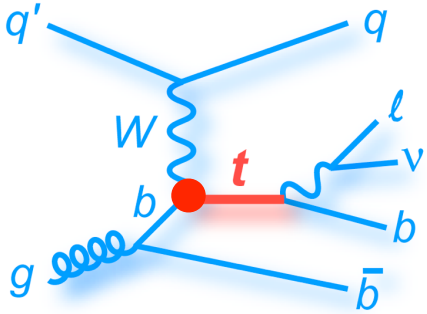
$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}G_{\mu\nu}t$$



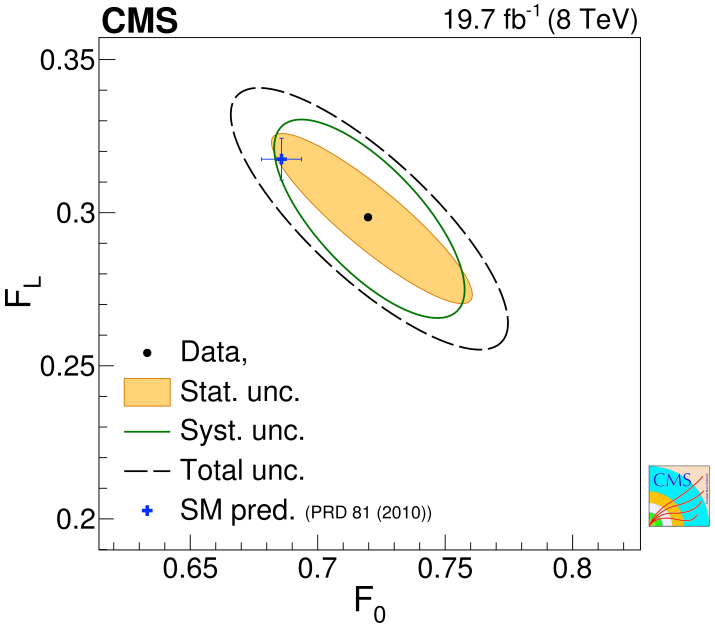
→ spins correlated as in SM



→ top quarks polarised as in SM

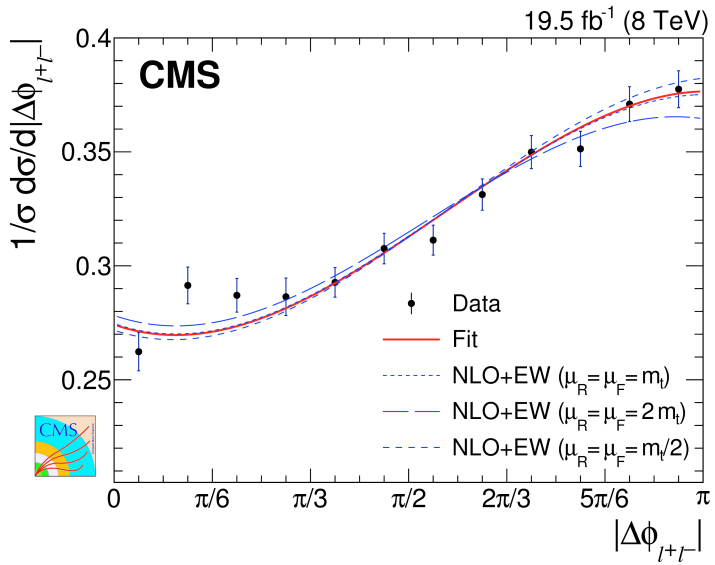


$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^5)V_{tb}bW_{\mu}$$

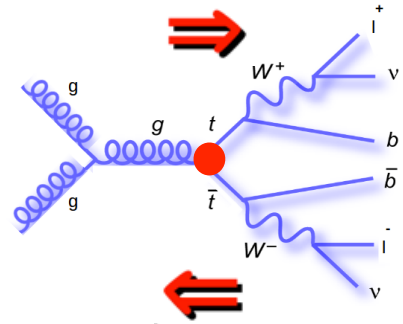


→ no anomalous couplings

Polarisation and Spin Correlation

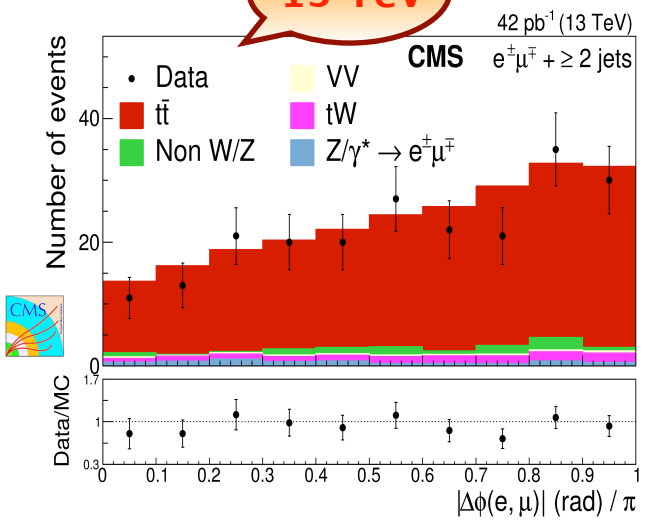


→ no chromomagnetic dipole moments



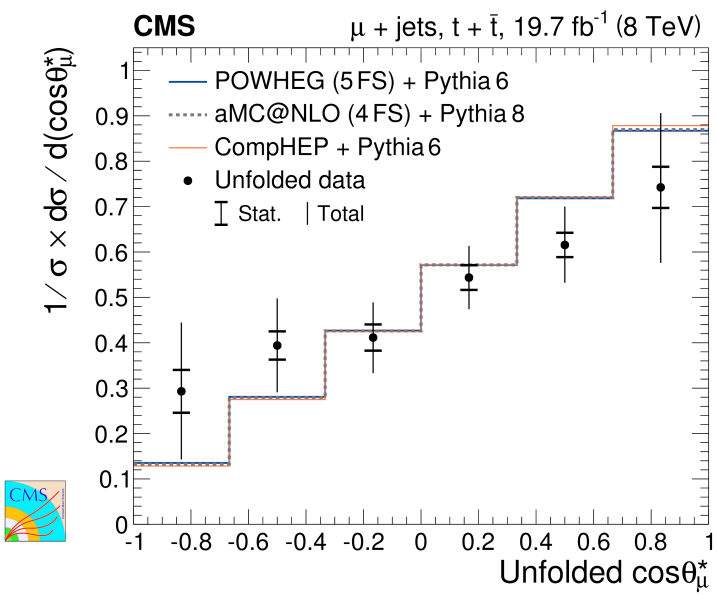
$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}G_{\mu\nu}t$$

13 TeV

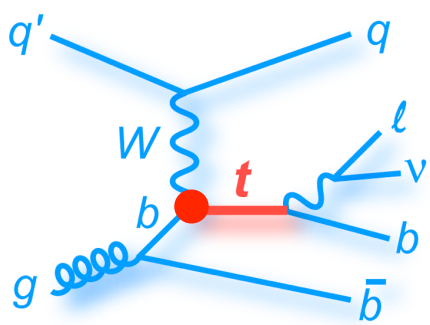


→ spins correlated as in SM

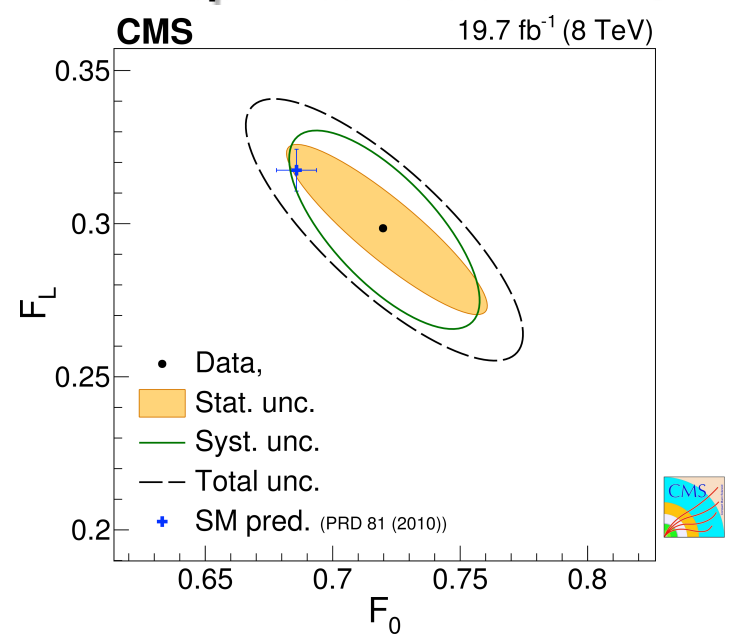
no new physics



→ top quarks polarised as in SM

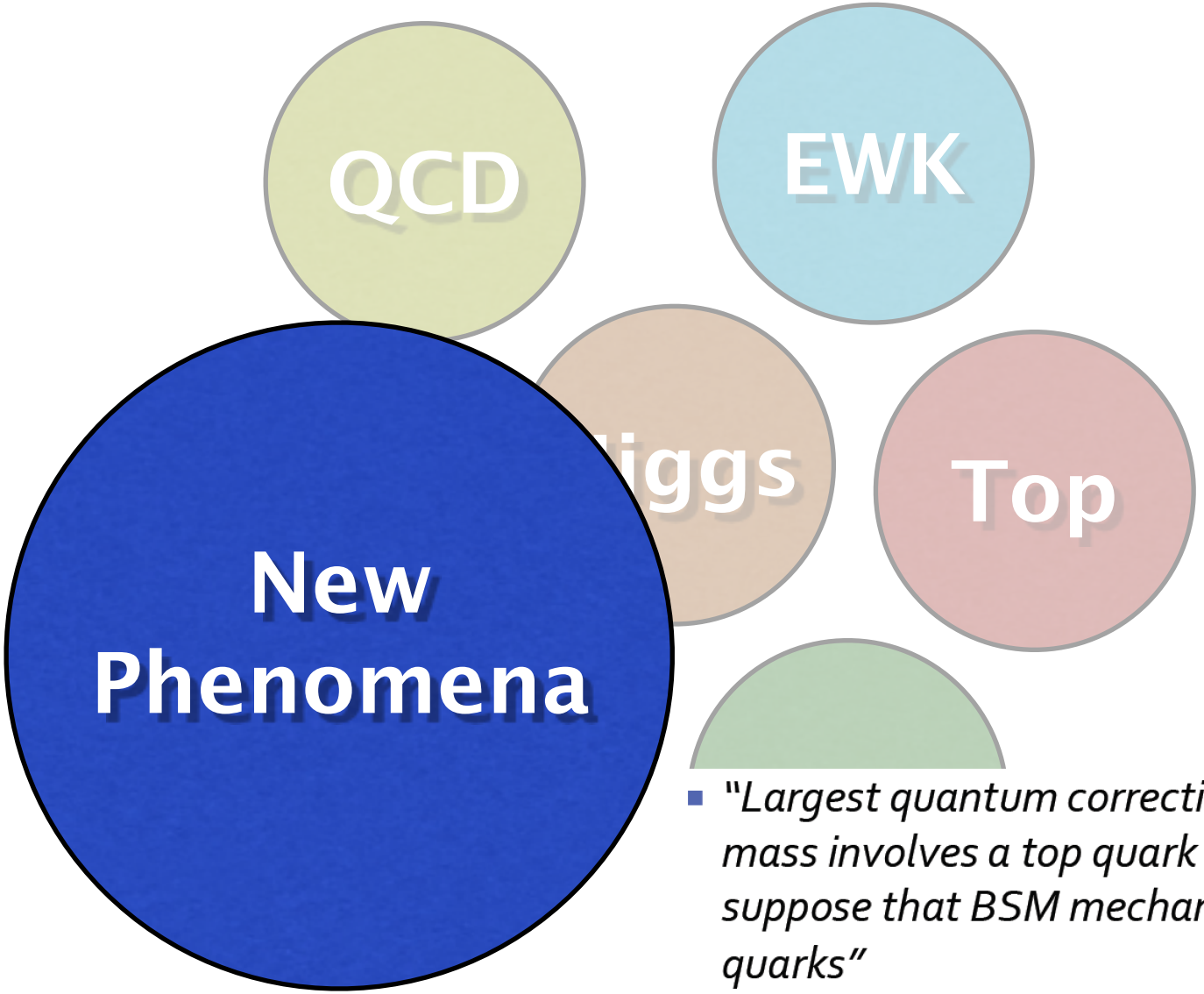


$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^5)V_{tb}bW_{\mu}$$



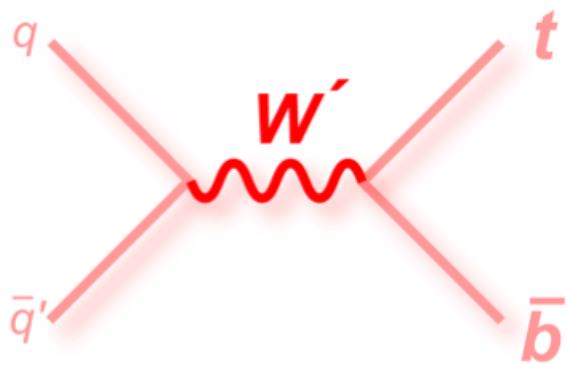
→ no anomalous couplings

Top Quark Physics Topics

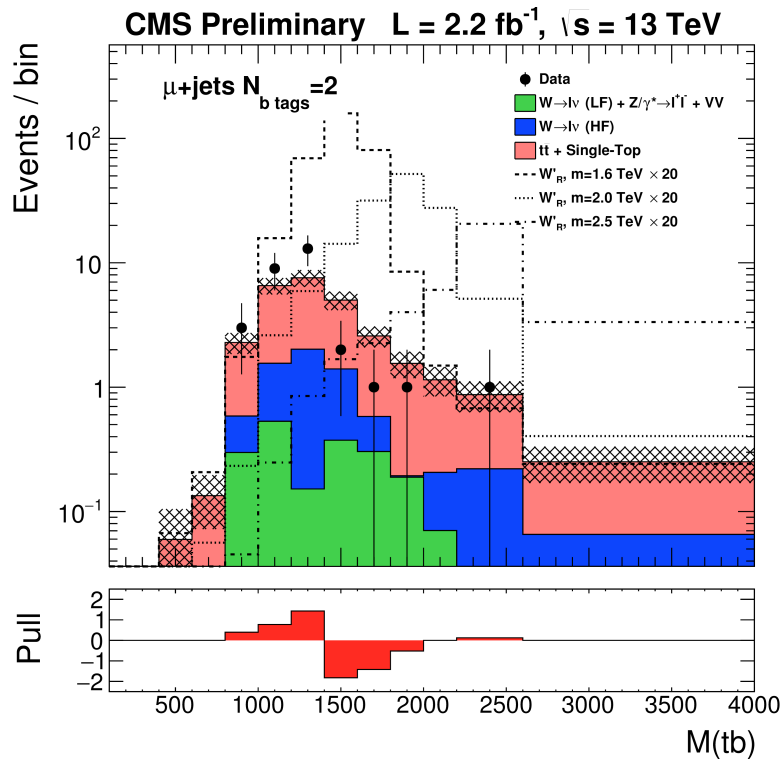


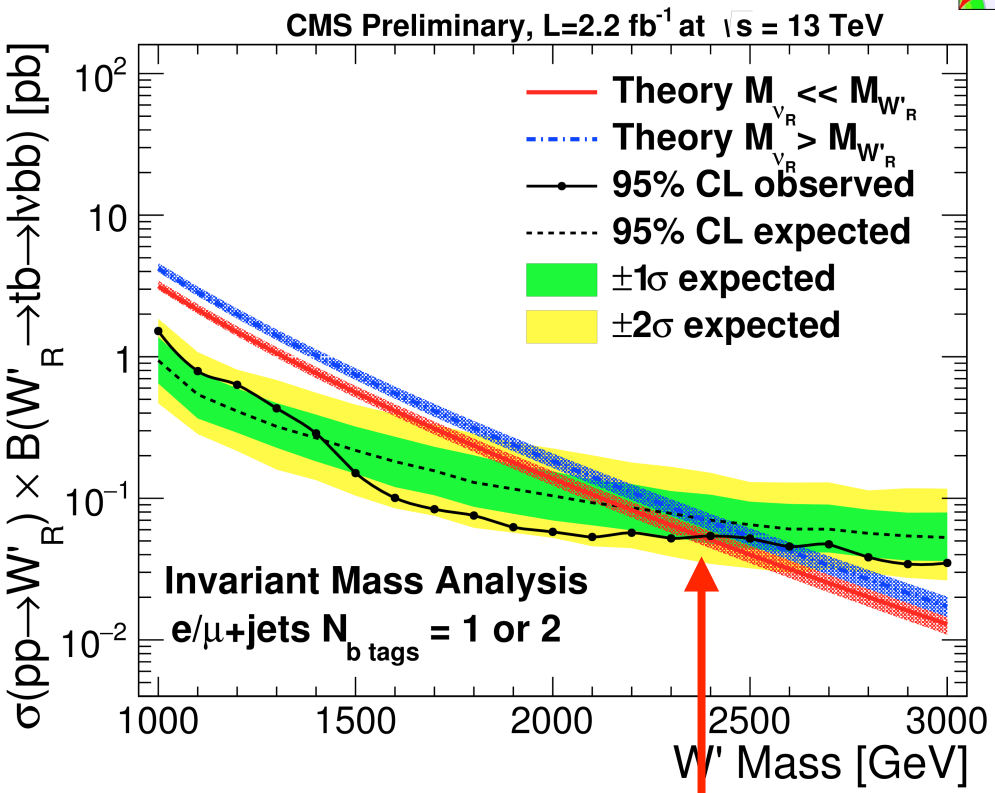
- *"Largest quantum correction to the Higgs boson mass involves a top quark loop, it is natural to suppose that BSM mechanisms involve top quarks"*

Search for W' production



13 TeV

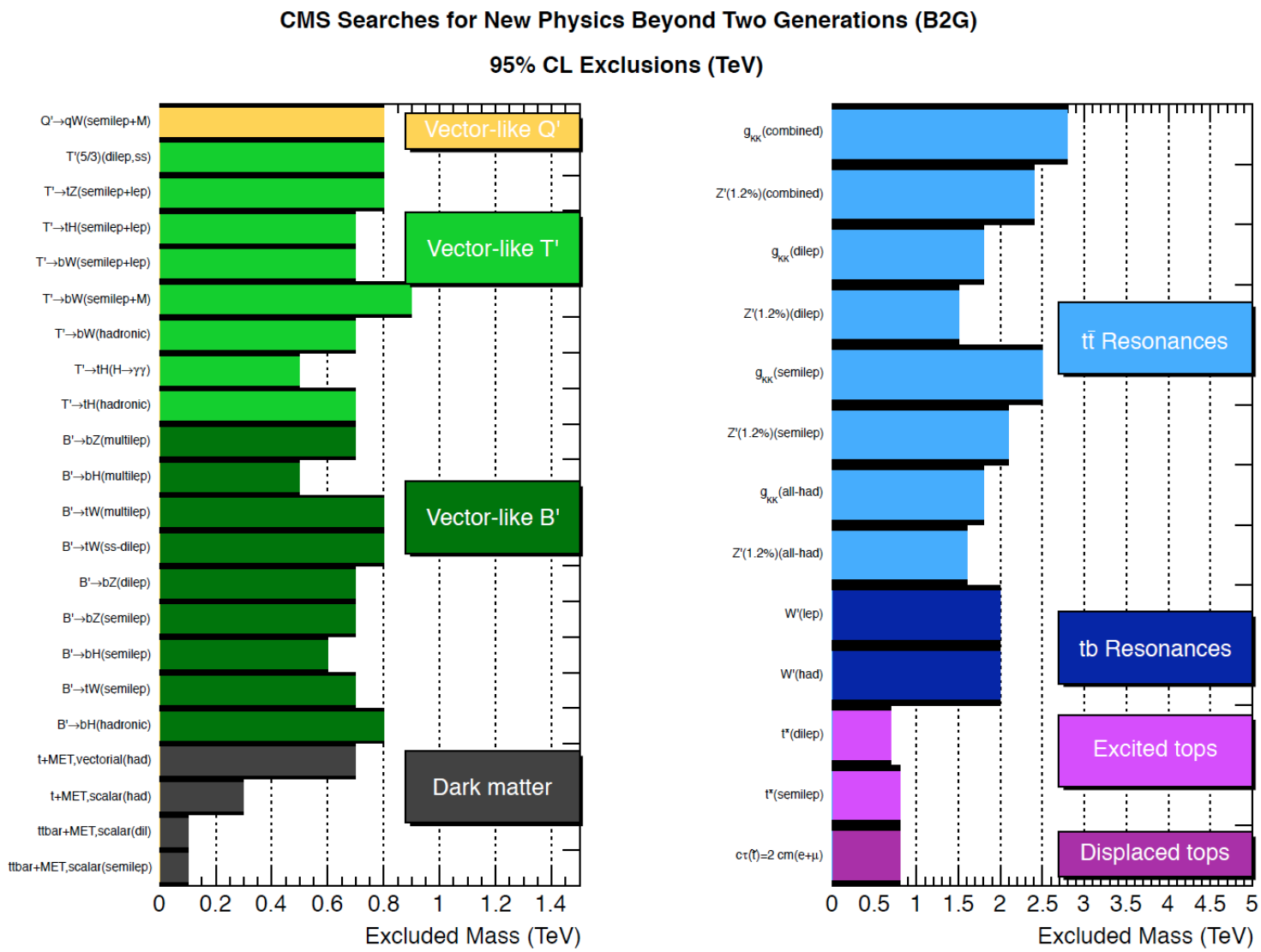




→ no new physics

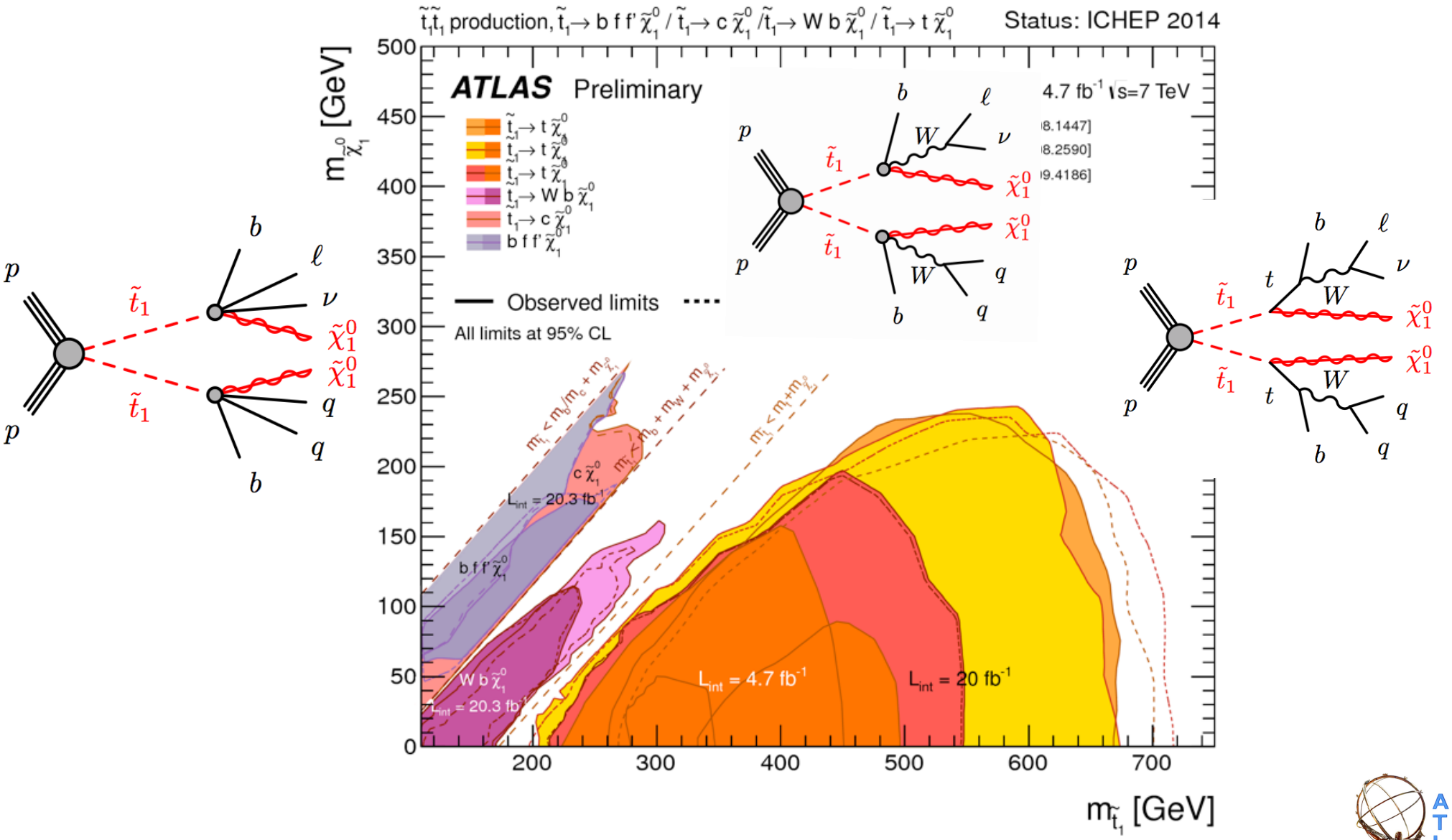
2.38 TeV

Pushing the TeV scale



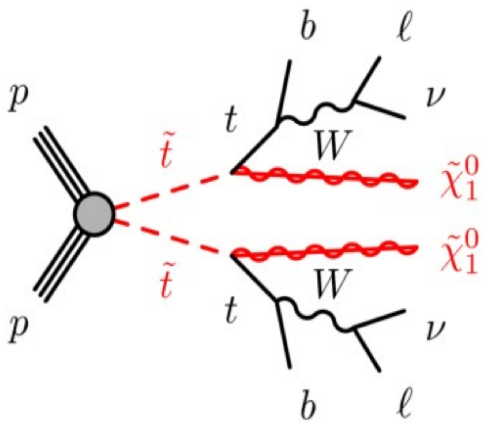
→ lots of opportunities for discovery in Run-II

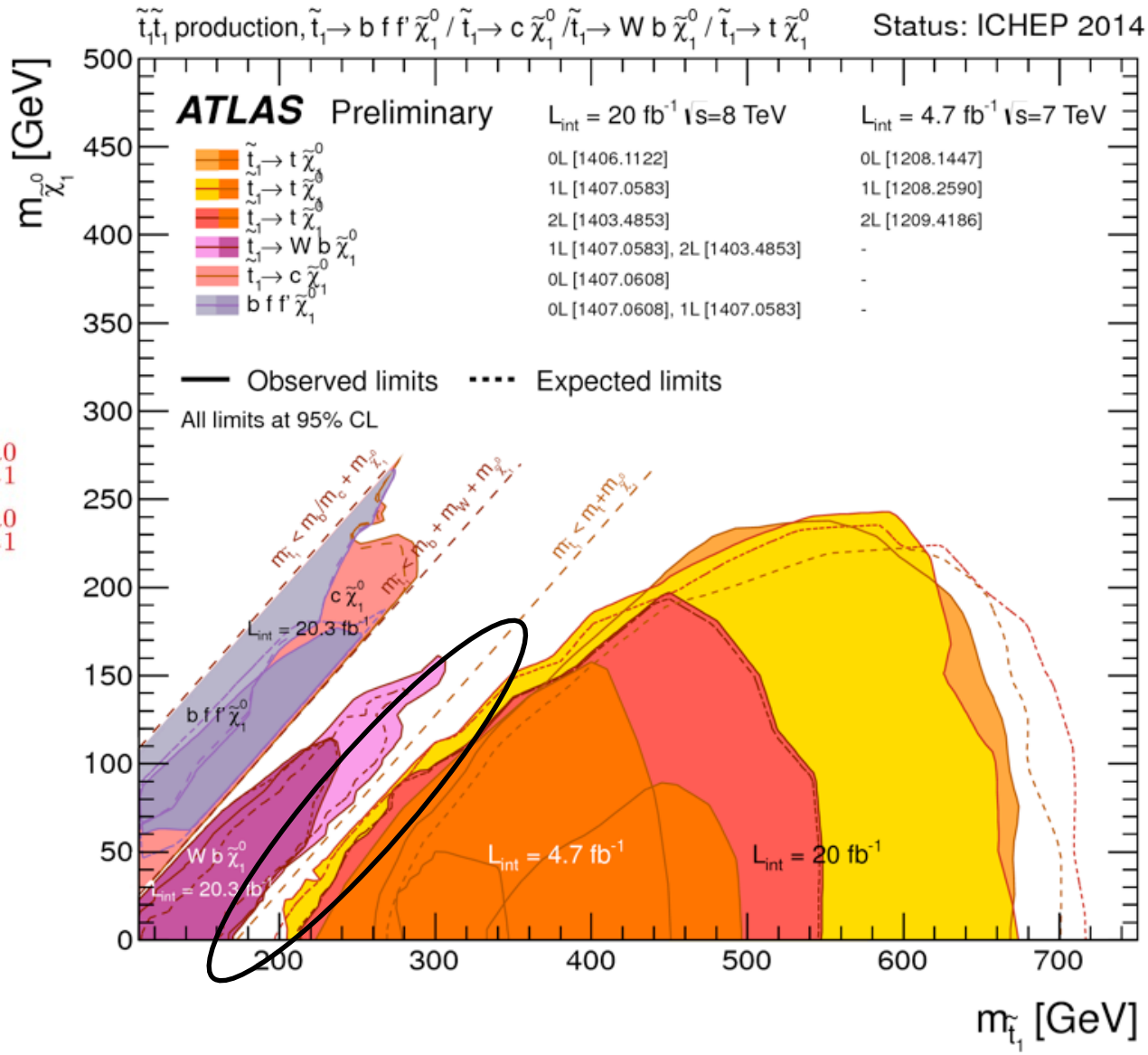
Direct stop searches



we check every little corner...

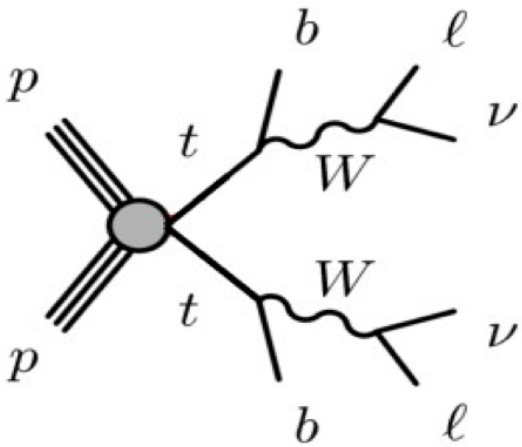
“Stealth” Stop Quarks

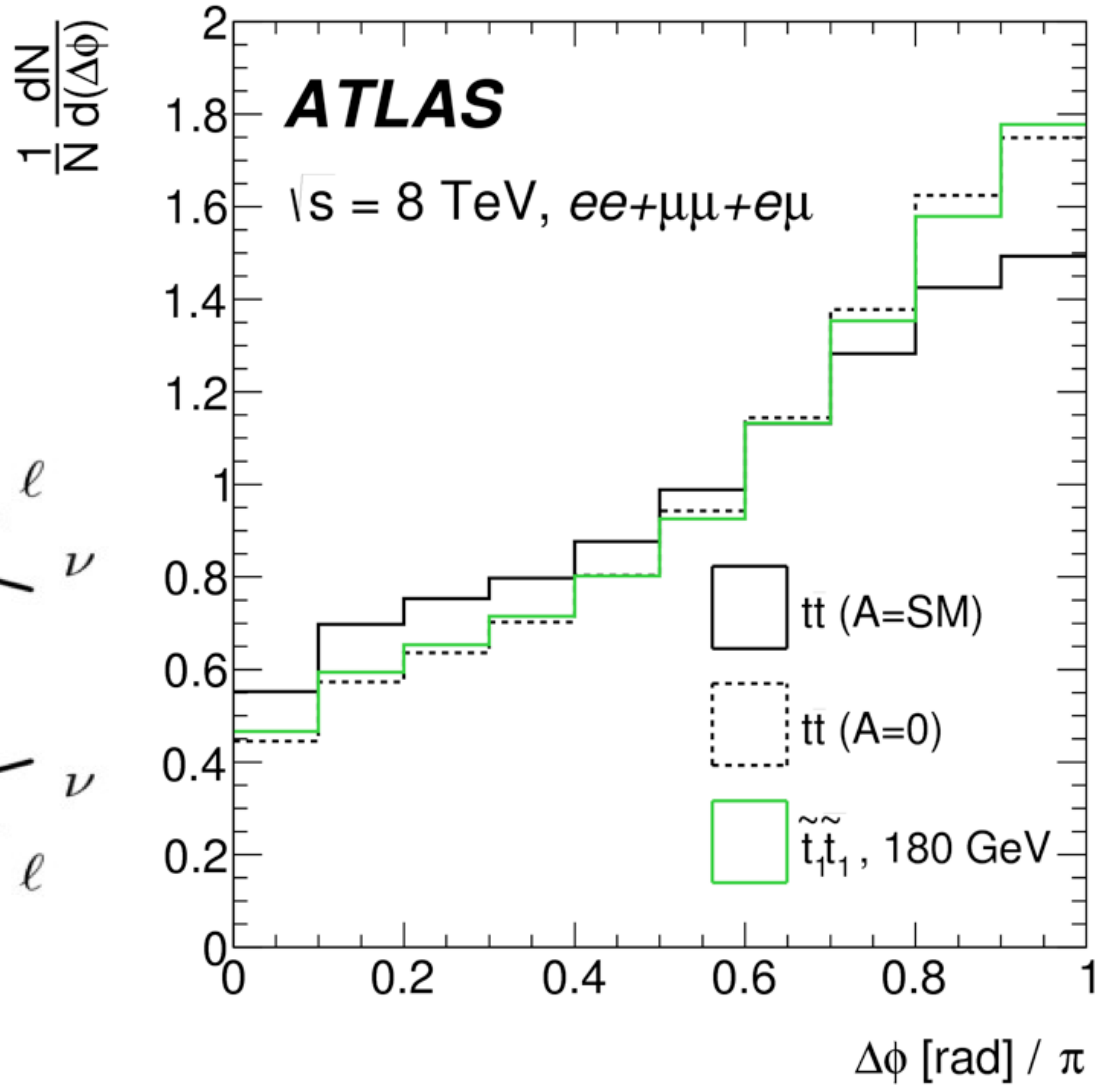


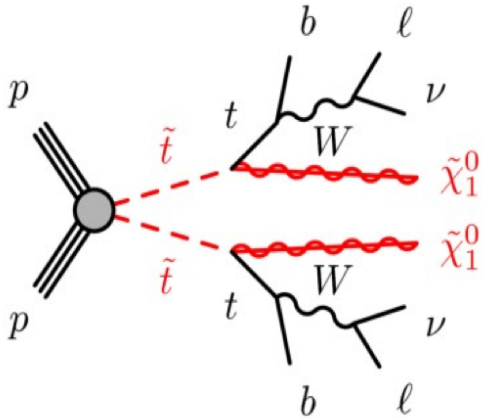


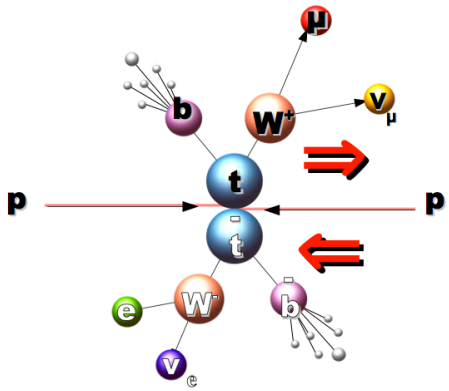
we check every little corner...

Spin correlations for "Stealth" Stop

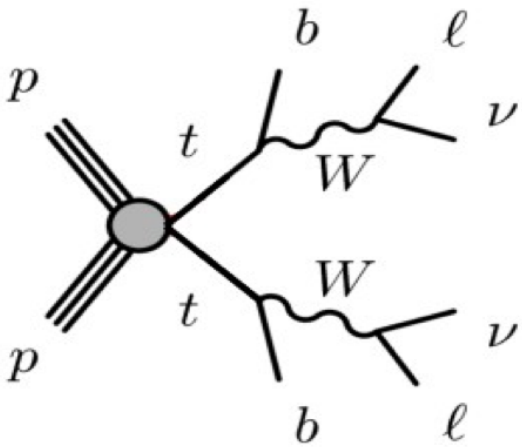


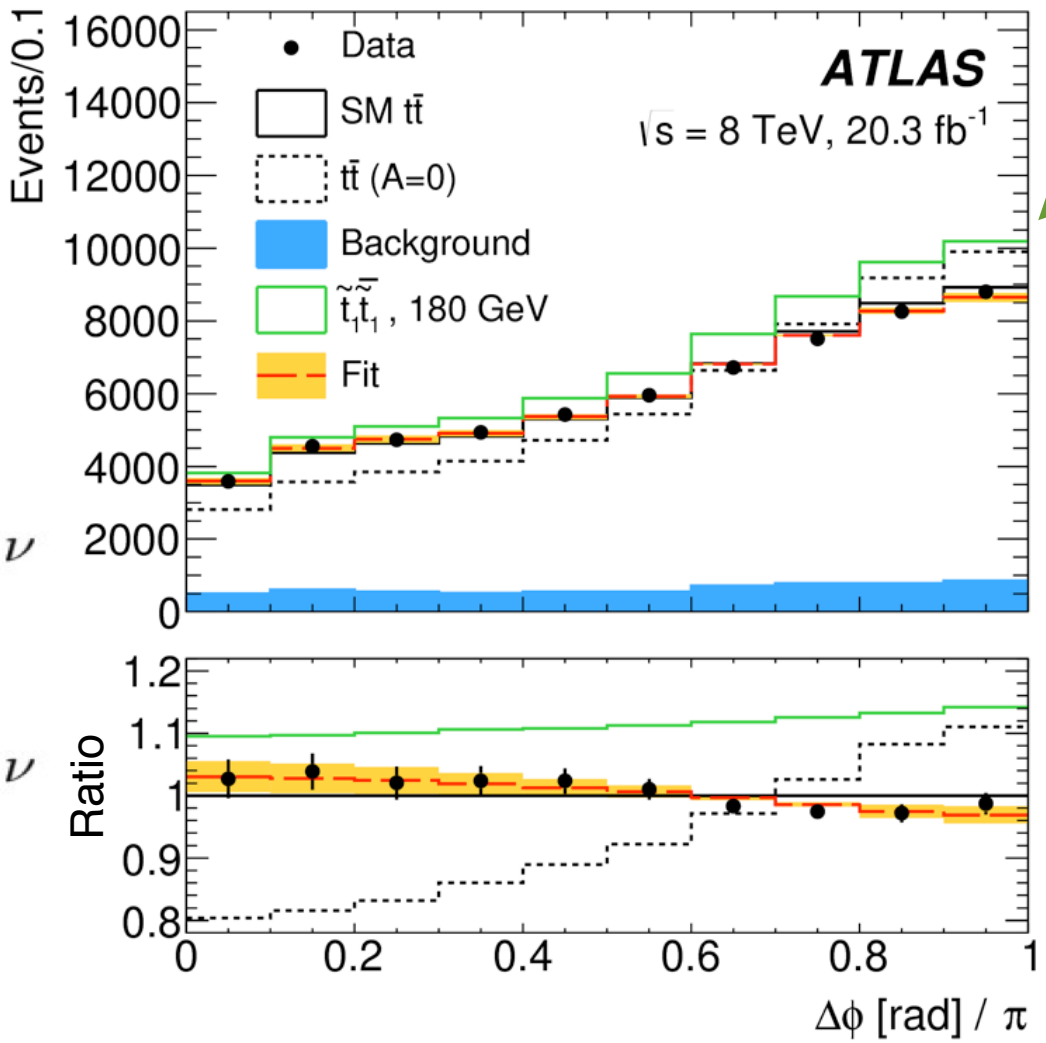


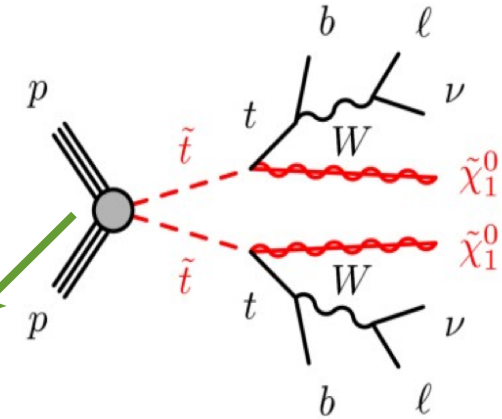


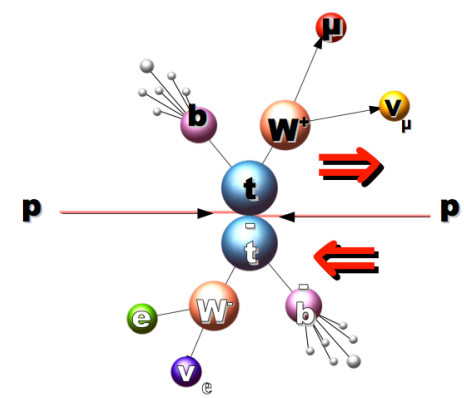


Spin correlations for "Stealth" Stop



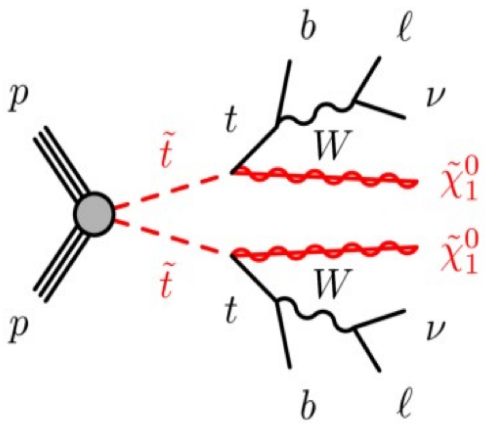


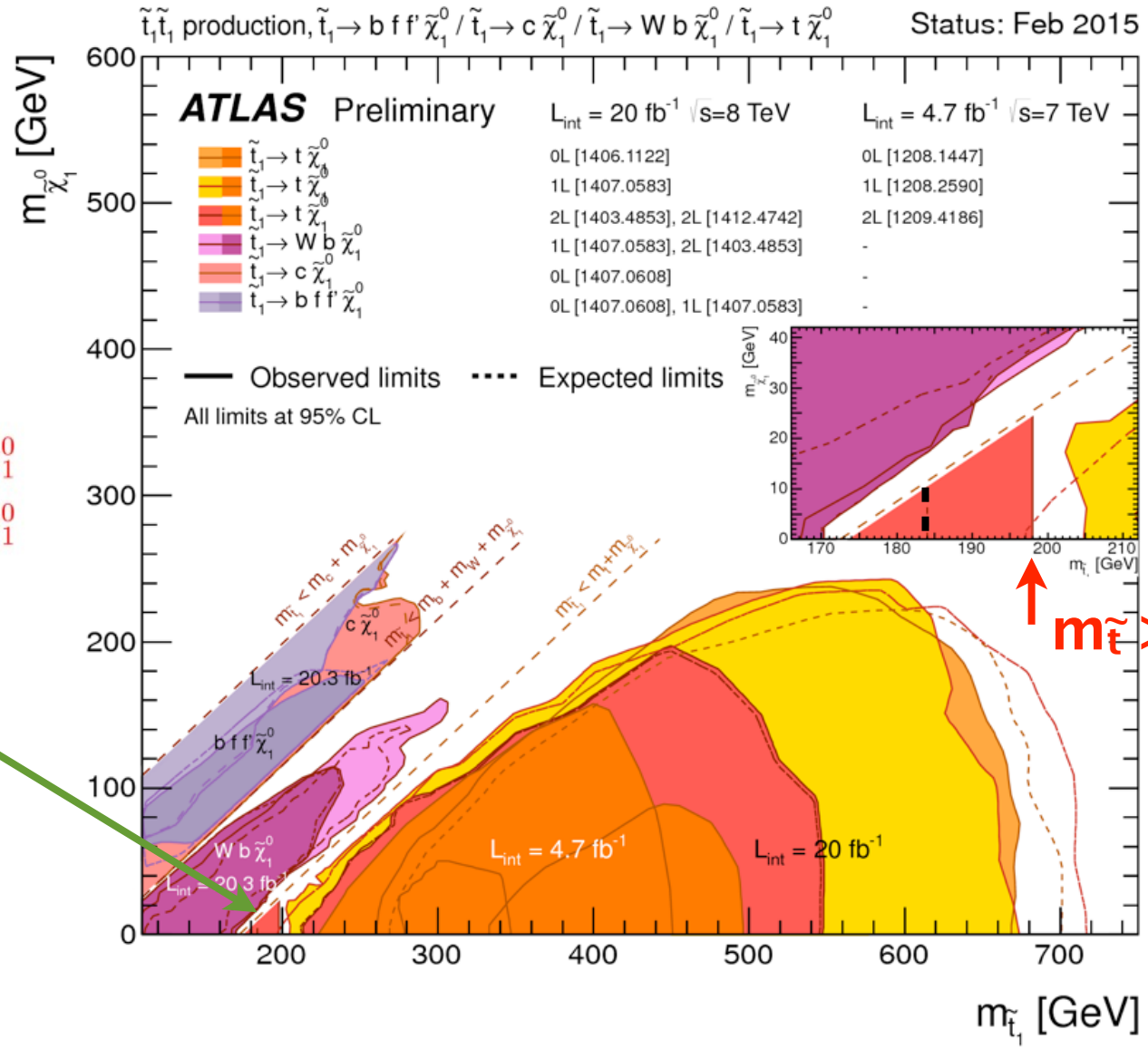




→ **no hint of stop quarks**

Direct stop searches





$m_{\tilde{t}} > 198$ GeV

→ using a "standard candle" for complementary exclusion

Summary

- very rich and diverse field of research!
- new energy frontier: first results at 13 TeV!
- many high precision measurements: cross sections, mass, couplings, …
- high precision tools: NNLO calculations…
- new SM processes: s-channel single top, Wt, ttγ, ttZ, ttW, ttH, …
- sensitive direct searches and sensitive searches through precision measurements

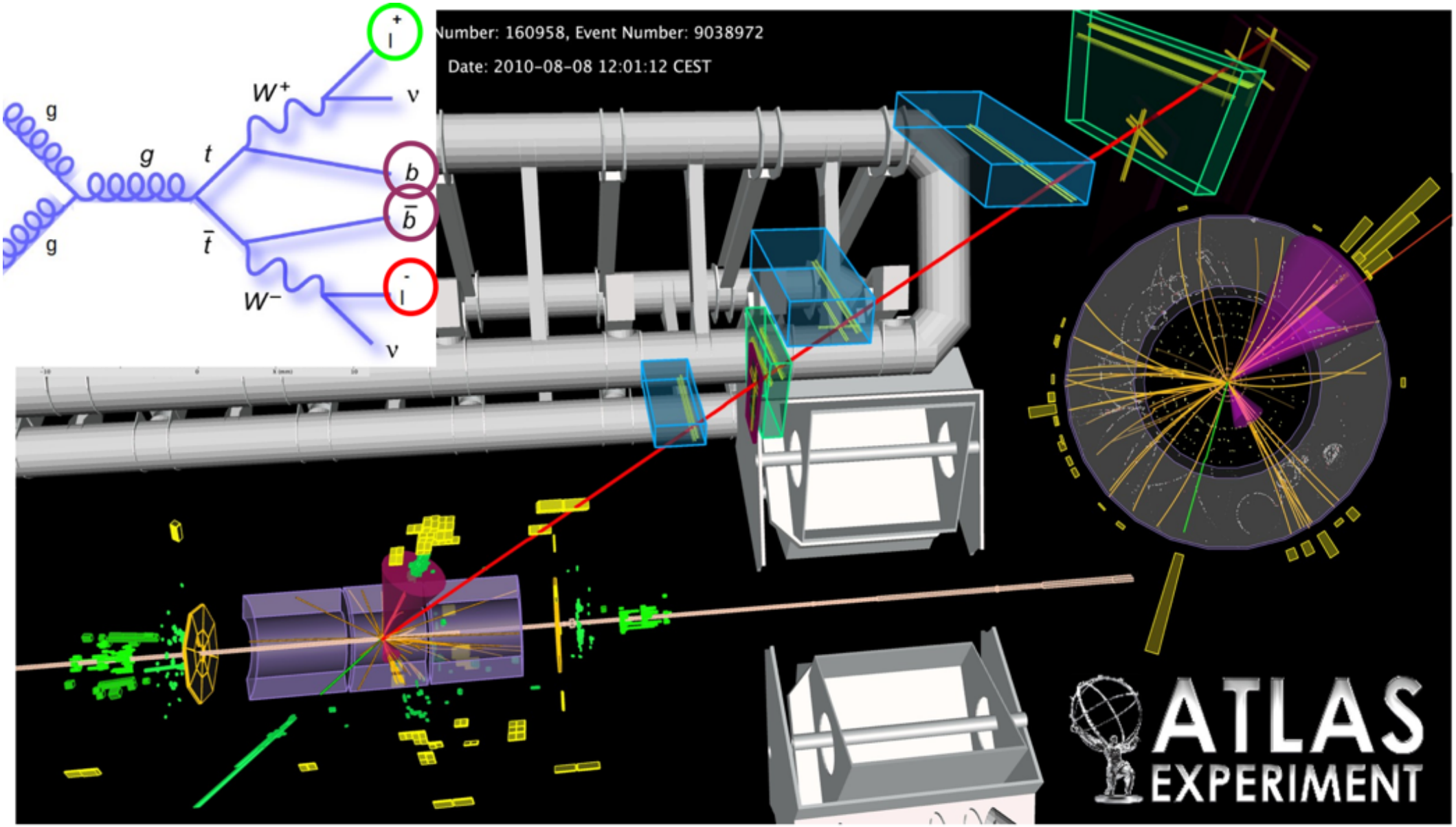
→ observe more SM processes in Run-II, many high precision property/cross section measurements to come, many mass discussions, new physics?!?

Summary

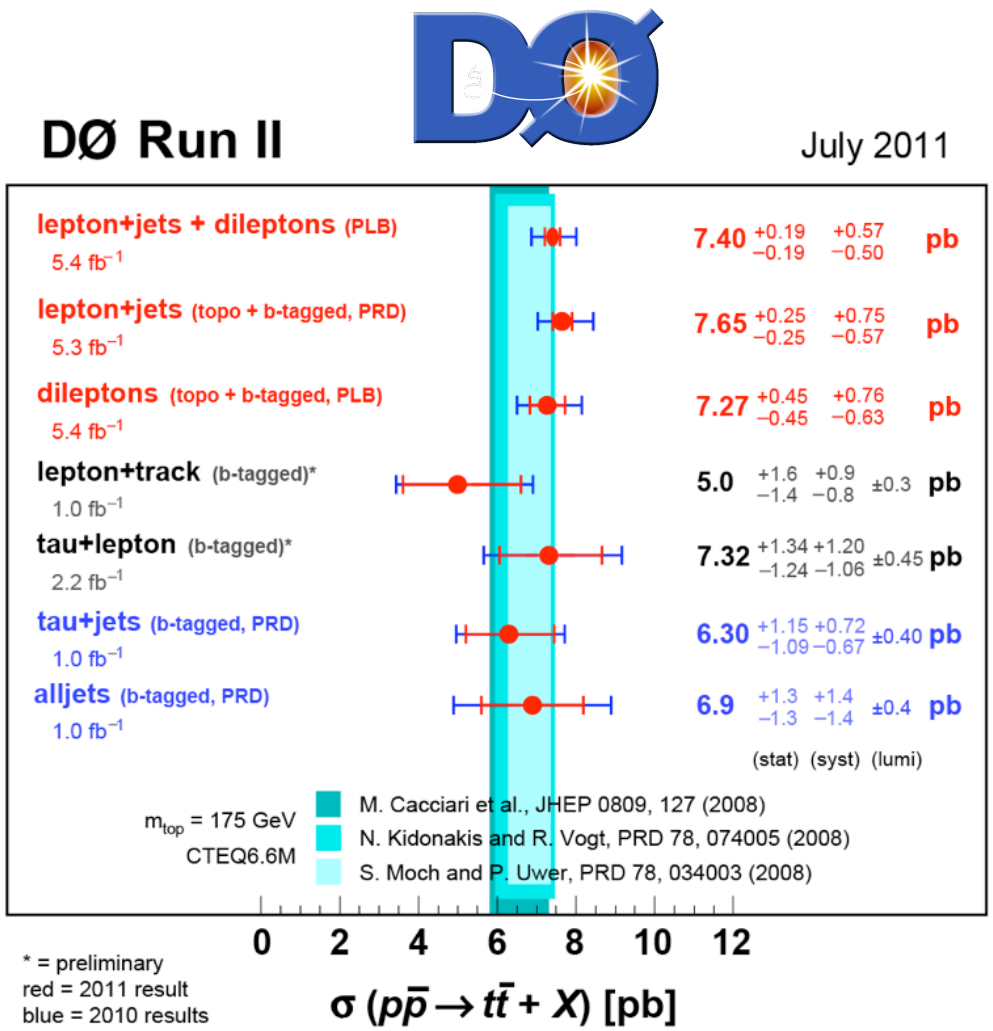
let's smash the SM in Run-2!

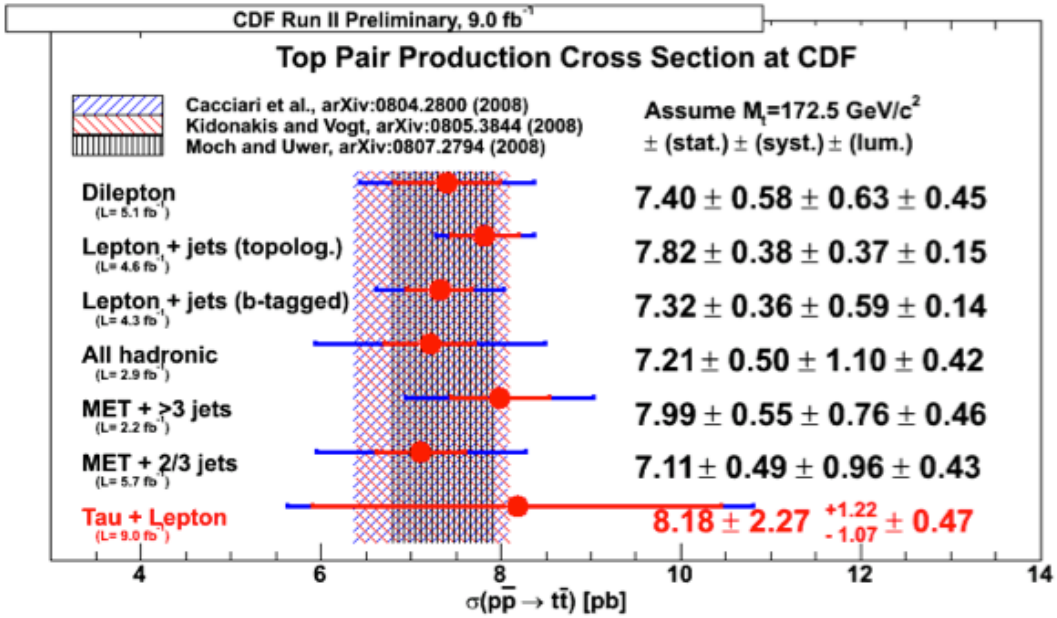
Backup

Dilepton Event



Top Pair Production Cross Section

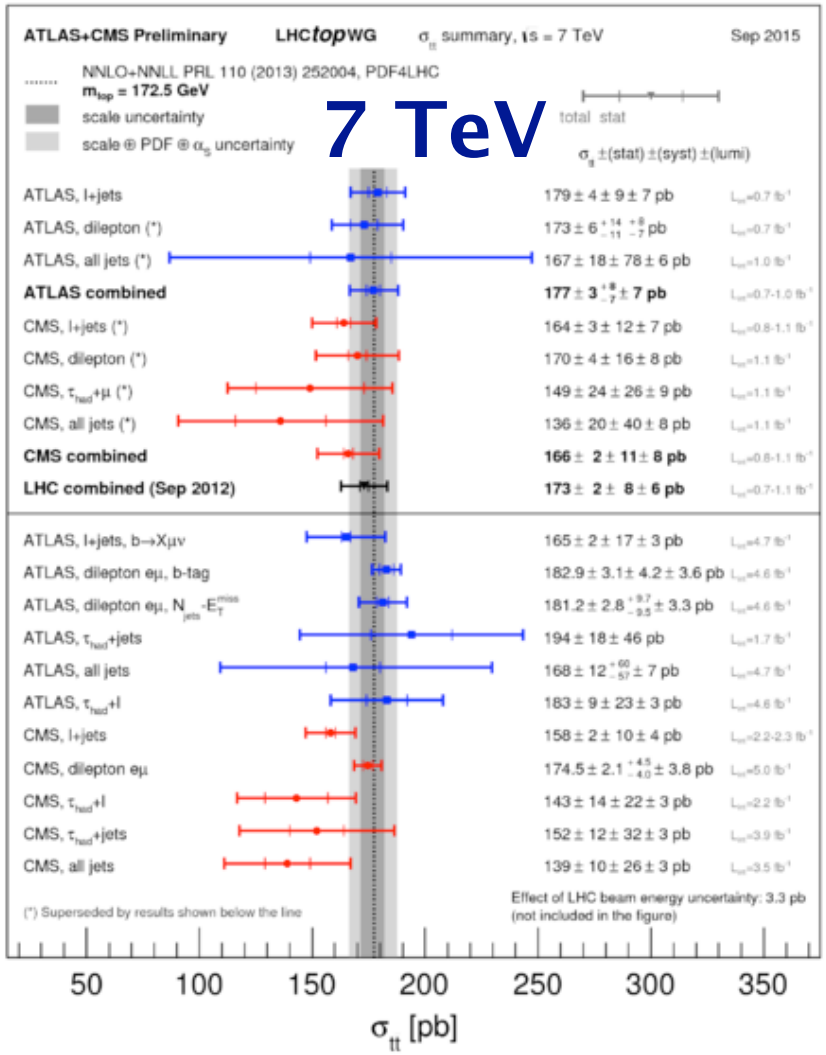


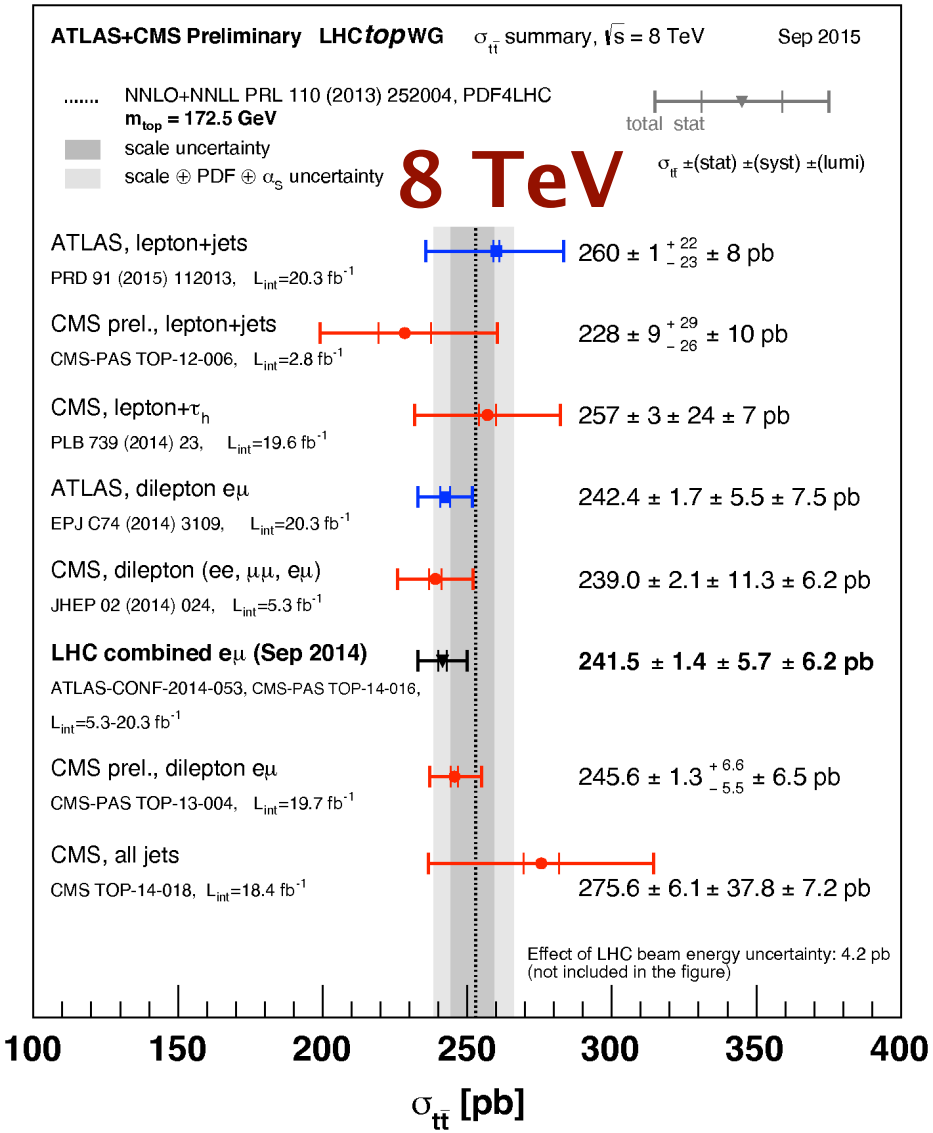


all channels measured except for $\tau_{had}\ \tau_{had}$

→ **good agreement with each other**

Top pair production cross section



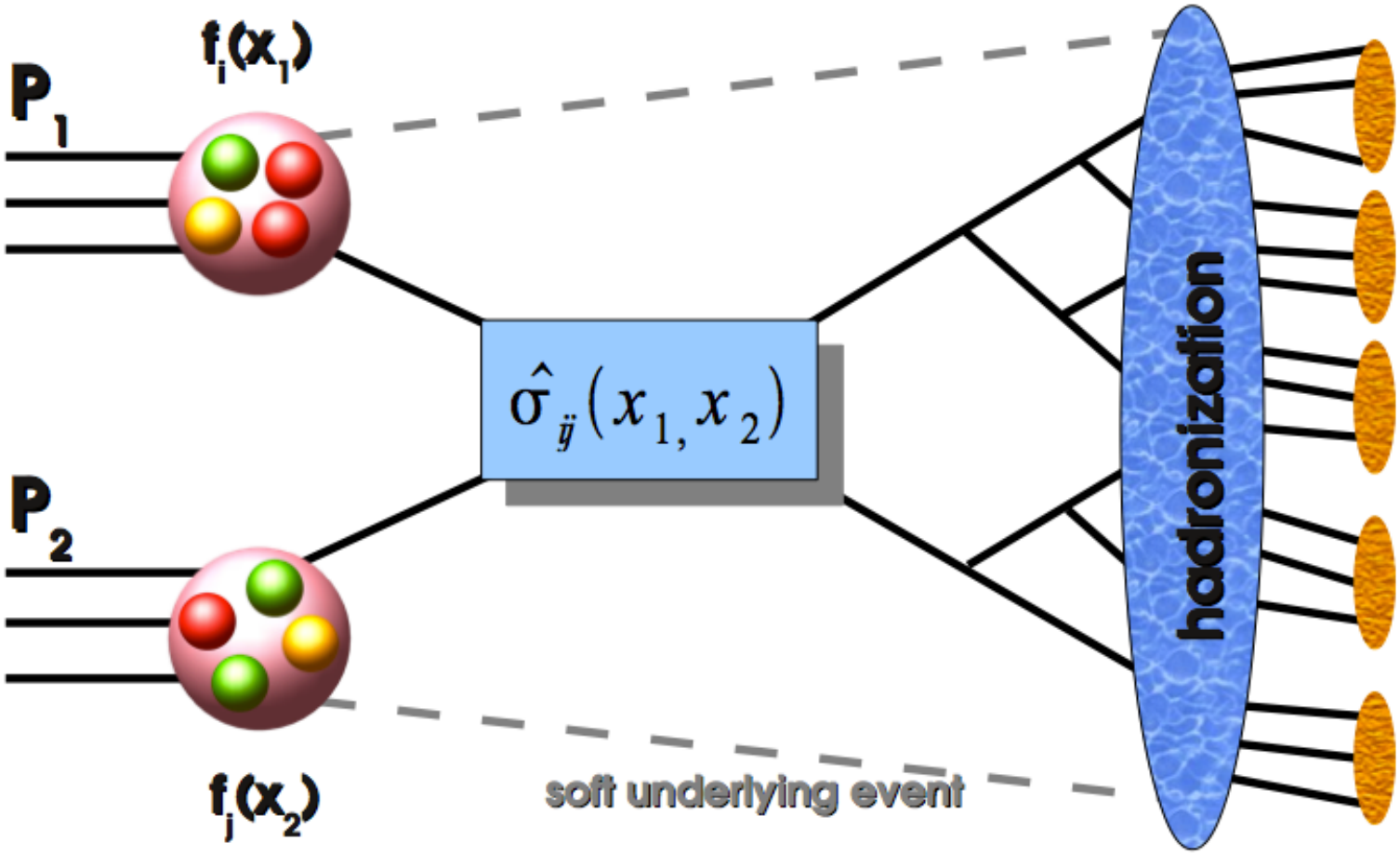


→ (all) channels measured to look for the unexpected

→ no new physics

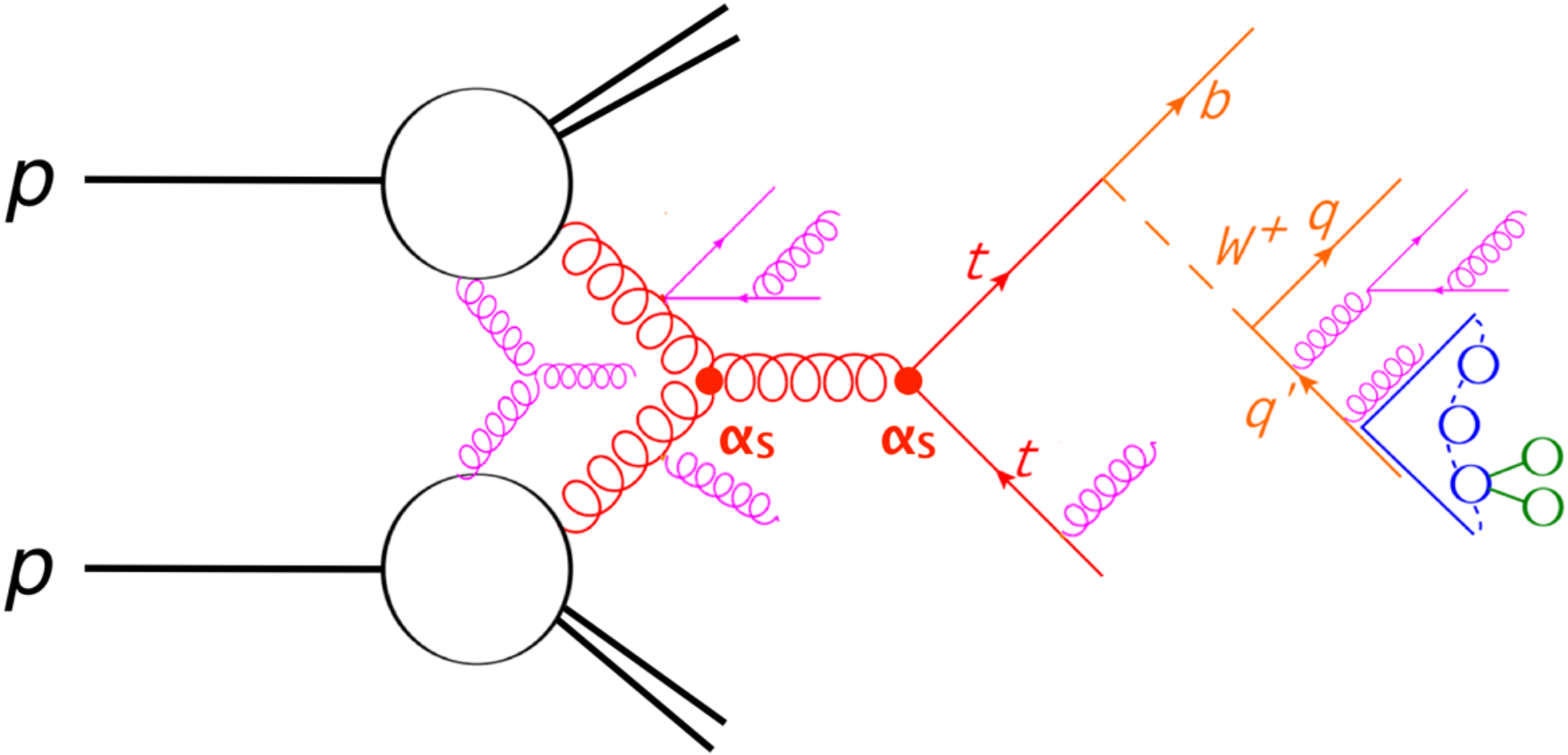
Differential Cross Sections

important tests of higher order QCD calculations:
requires "unfolding" to particle level



“Revolution” in Phenomenology

- **LO QCD+parton shower generators**
  Pythia, Herwig, ...



“Revolution” in Phenomenology

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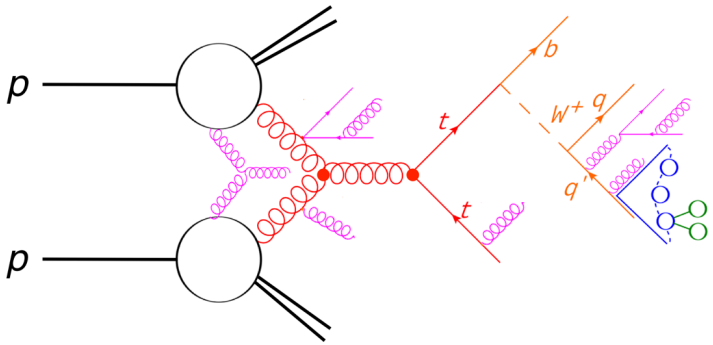
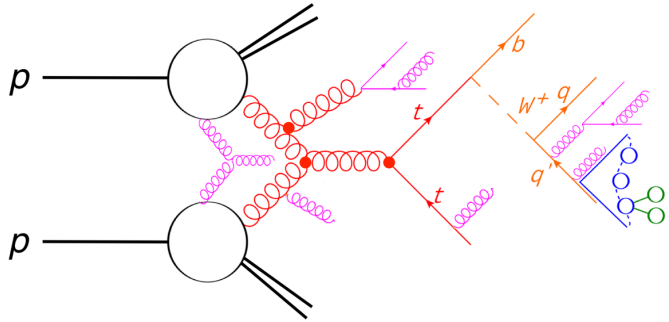
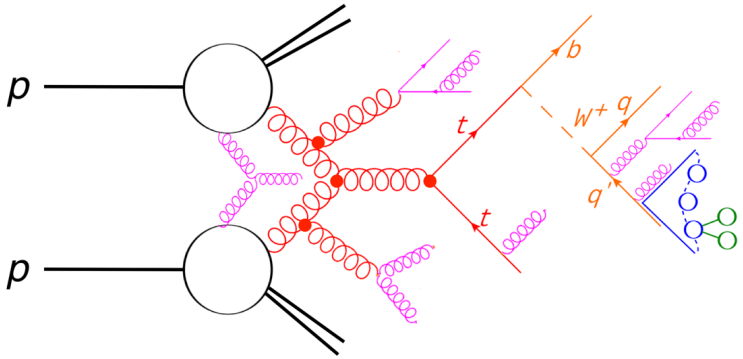
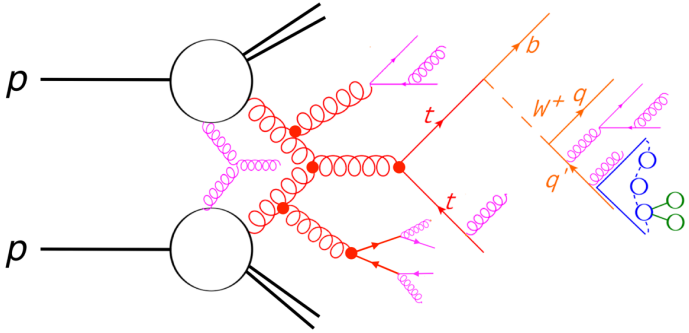


- **LO multileg generators matched with parton shower**

  Alpgen+Pythia, Alpgen+Herwig, ...







...

“Revolution” in Phenomenology

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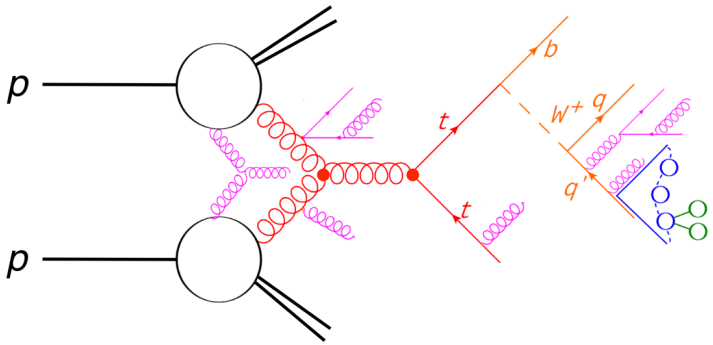

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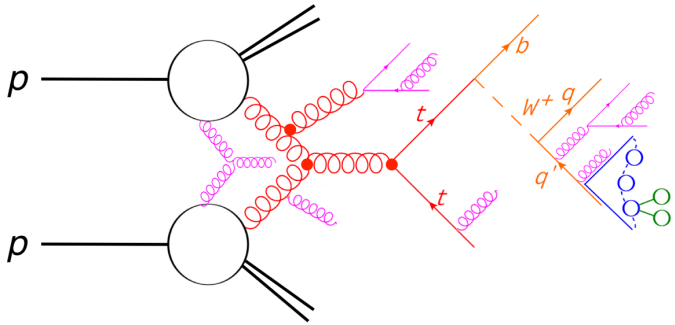
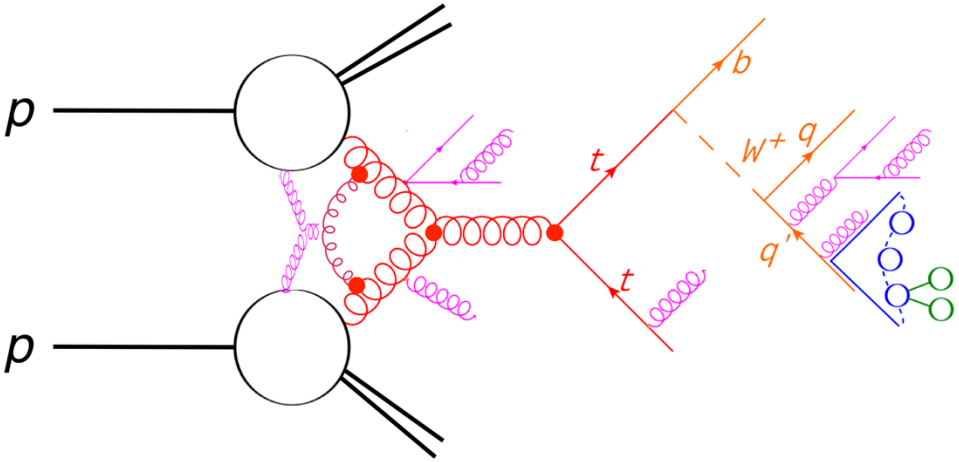


- **NLO+parton shower generators**
  Powheg+Pythia, MC@NLO+Herwig, ...



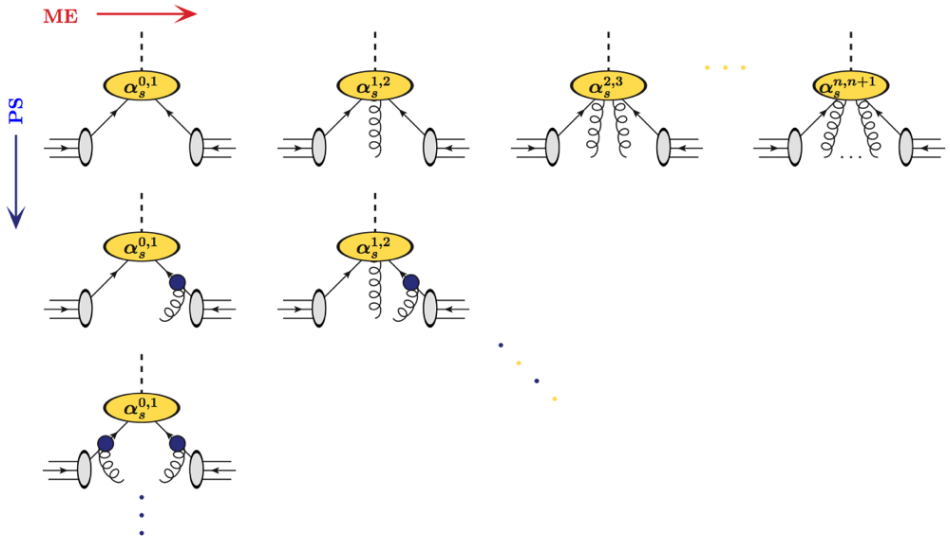
“Revolution” in Phenomenology

- **LO QCD+parton shower generators**
  Pythia, Herwig, ...

- **LO multileg generators matched with parton shower**
  Alpgen+Pythia, Alpgen+Herwig, ...

- **NLO+parton shower generators**
  Powheg+Pythia, MC@NLO+Herwig, ...

- **NLO+LO multileg generators matched with parton showers**



“Revolution” in Phenomenology

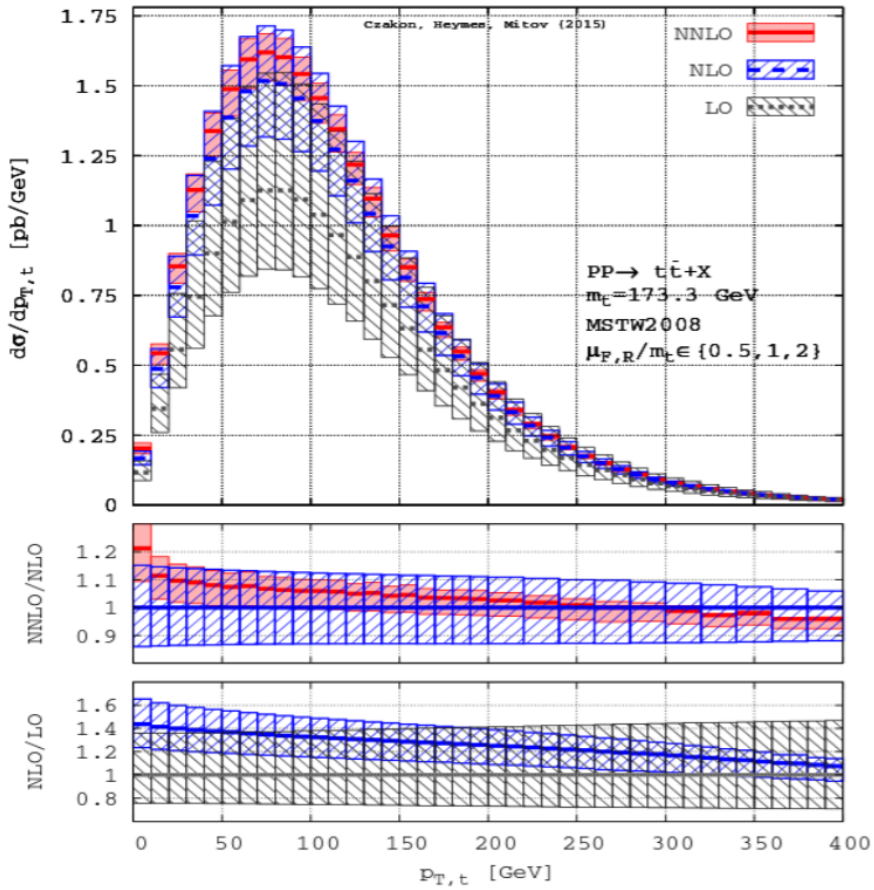
- **LO QCD+parton shower generators**
  Pythia, Herwig, ...

- **LO multileg generators matched with parton shower**
  Alpgen+Pythia, Alpgen+Herwig, ...

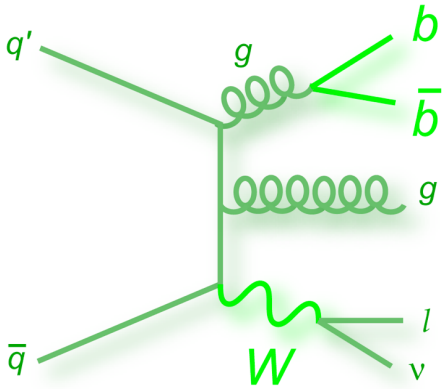
- **NLO+parton shower generators**
  Powheg+Pythia, MC@NLO+Herwig, ...

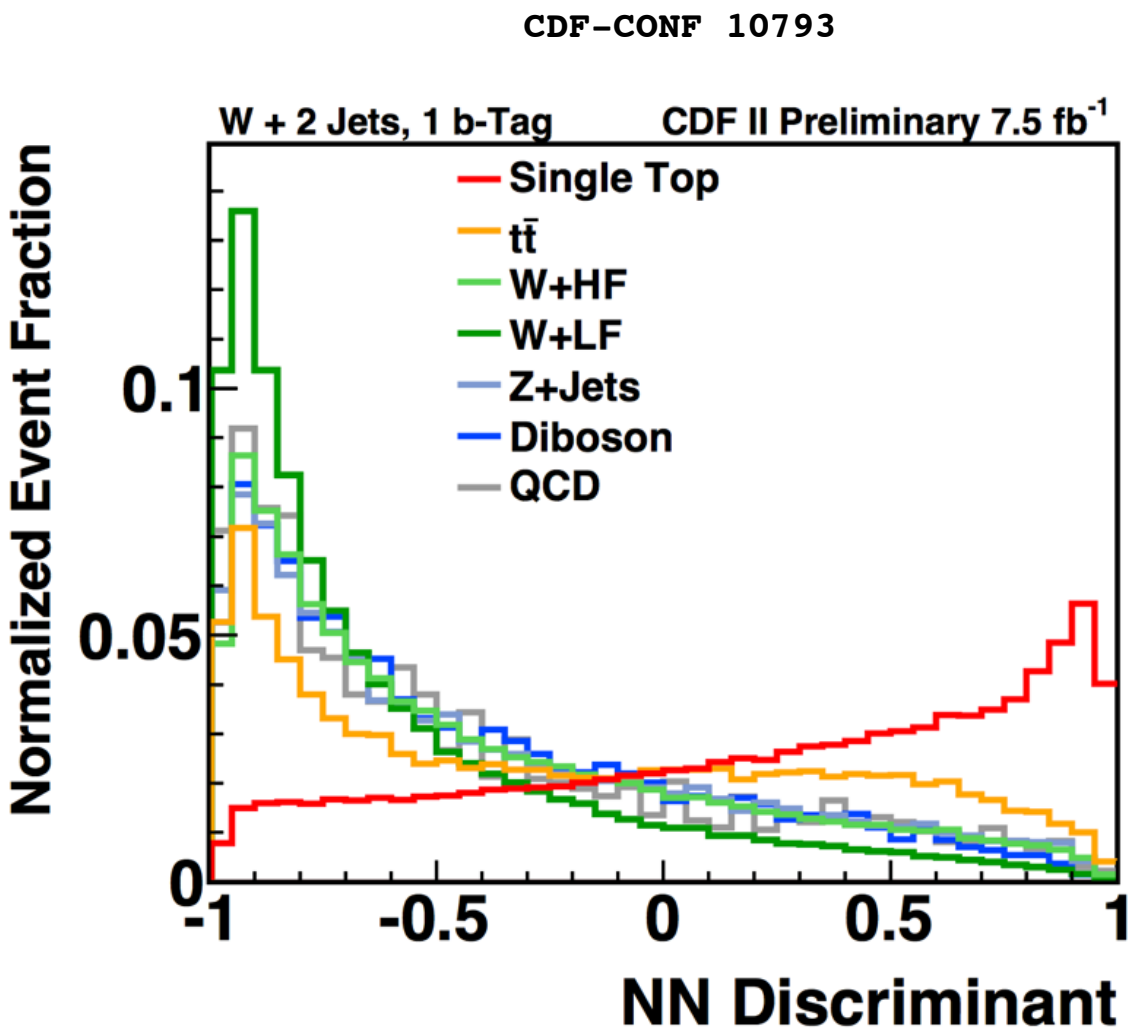
- **NLO+LO multileg generators matched with parton showers**

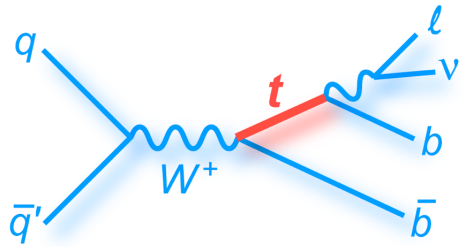
- **NNLO QCD calculations**

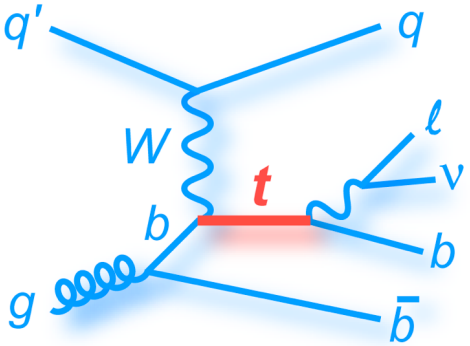


Output Discriminant for s+t

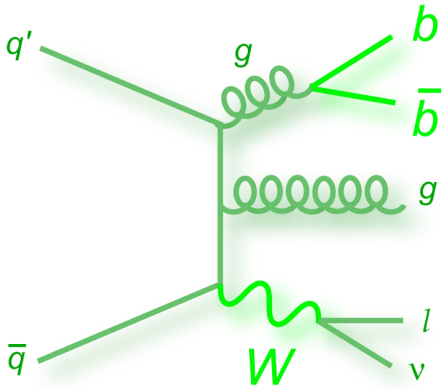




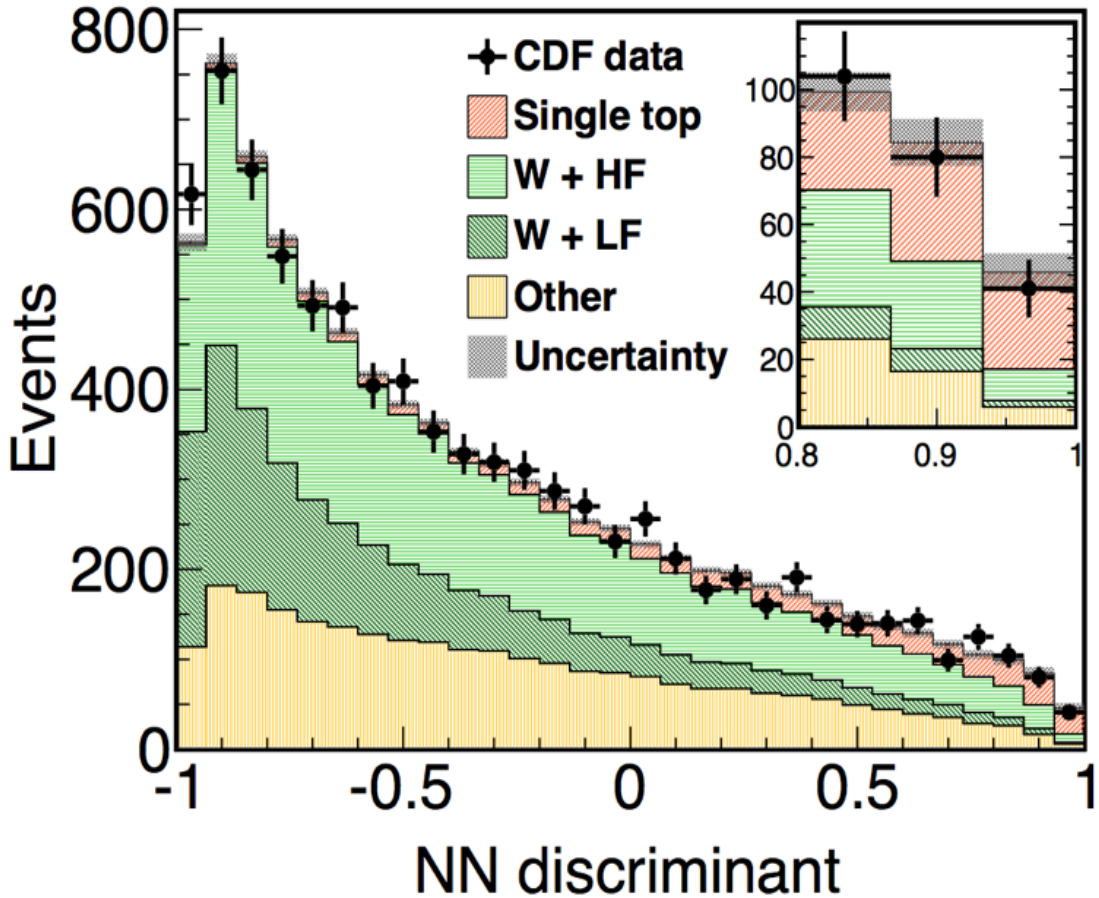


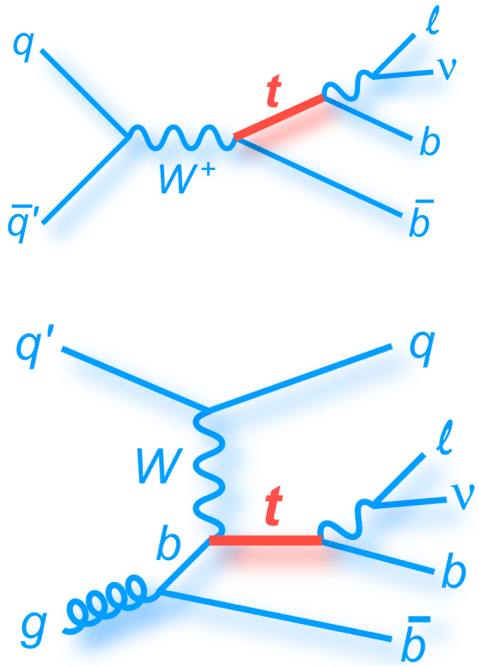


Output Discriminant for s+t channel



Phys. Rev. Lett. 113, 261804 (2014)



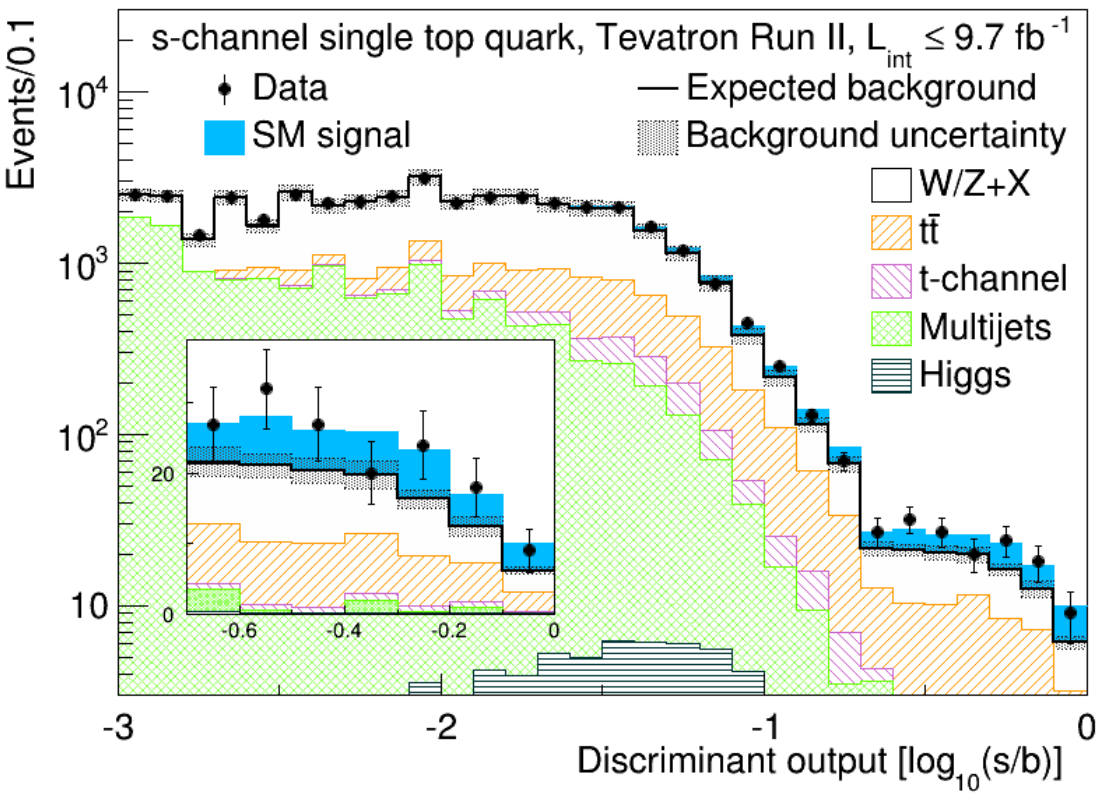


- s+t channel observed by CDF and D0 in 2009
- important step to establish MVA techniques

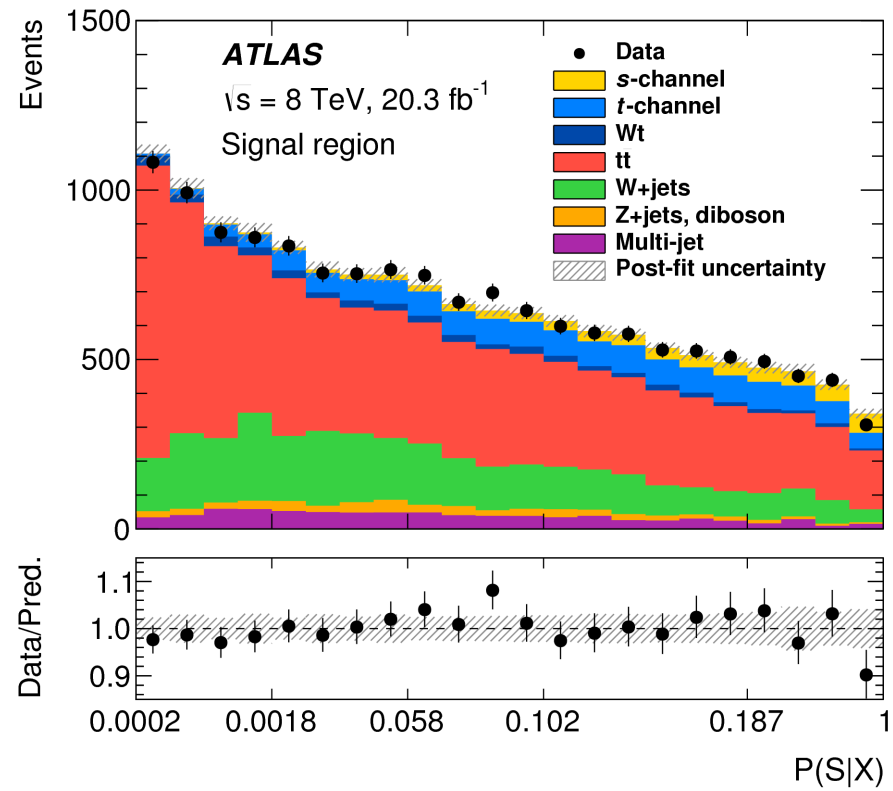
s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)

- **Tevatron: combine individual discriminants including all correlations**



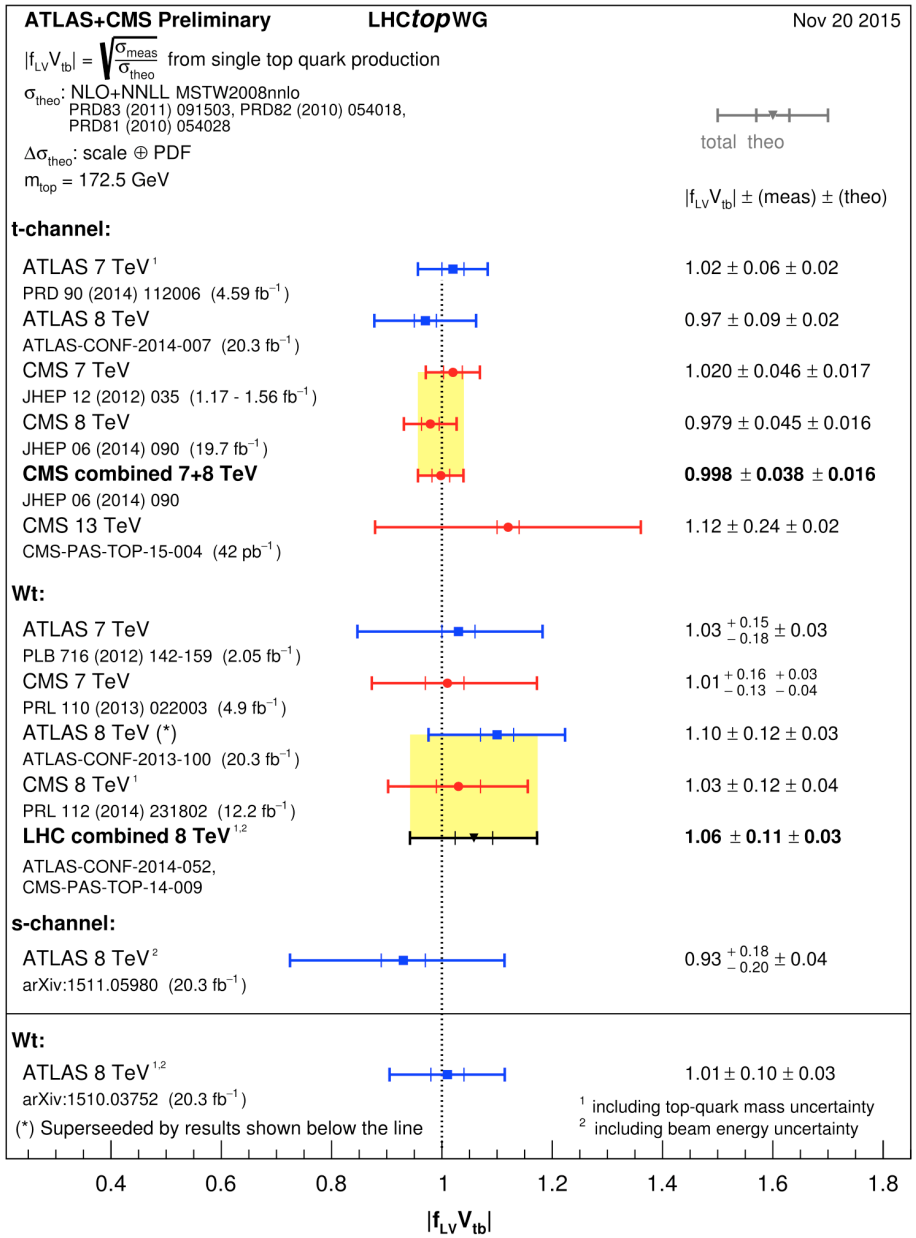
- **ATLAS: matrix element method**



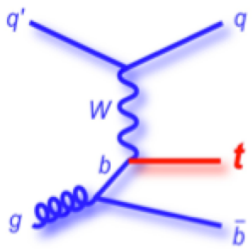
→ **observation: 6.3 s.d.**

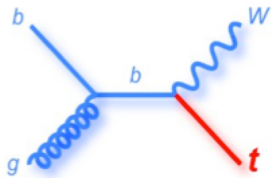
→ **evidence: 3.2 s.d.**

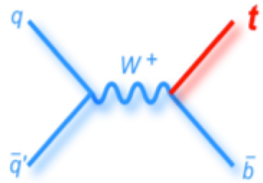
Extraction of $|V_{tb}|$



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

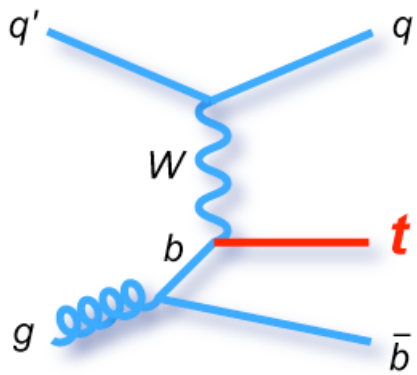




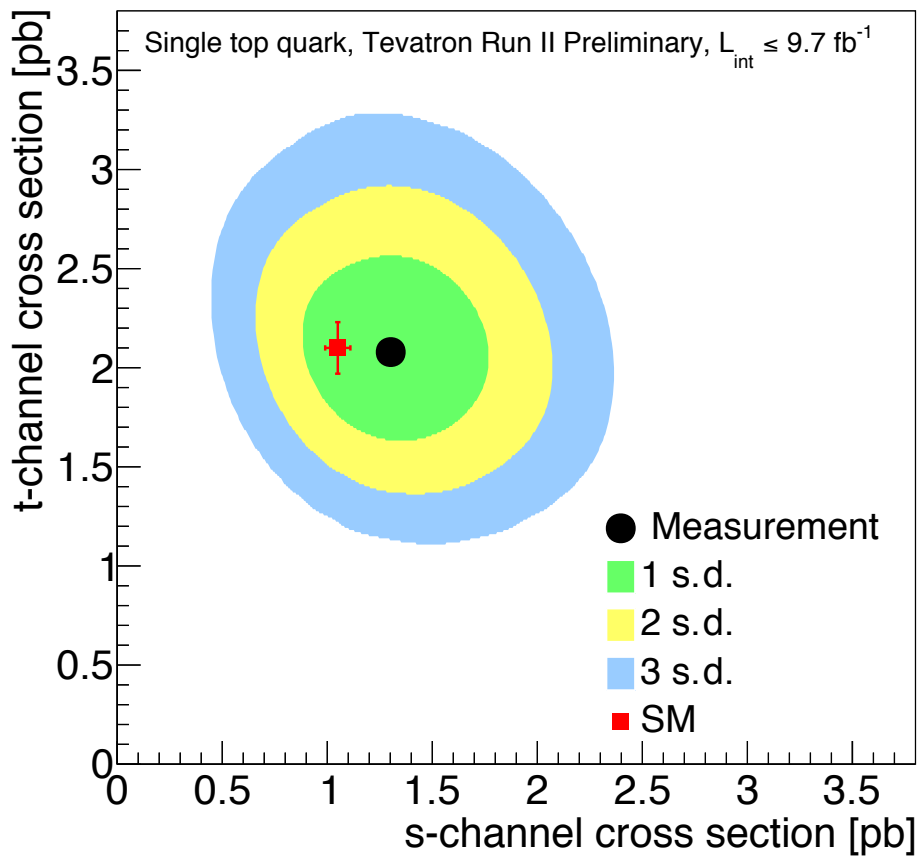


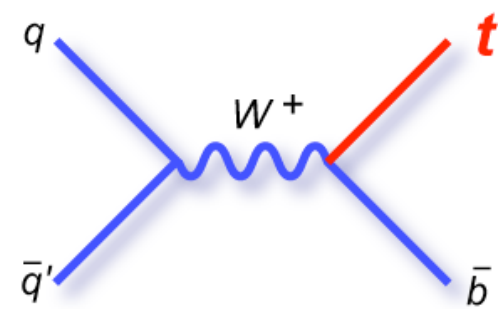
→ no hint for anomalous contributions!

Single Top s- vs. t-channel



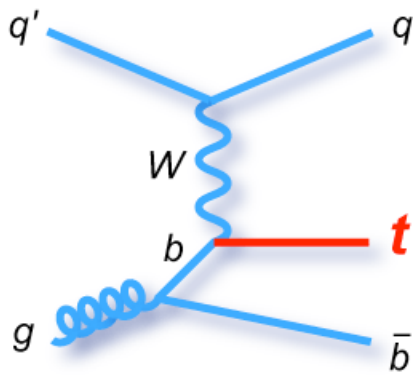
arXiv:1503.05027 [hep-ex]

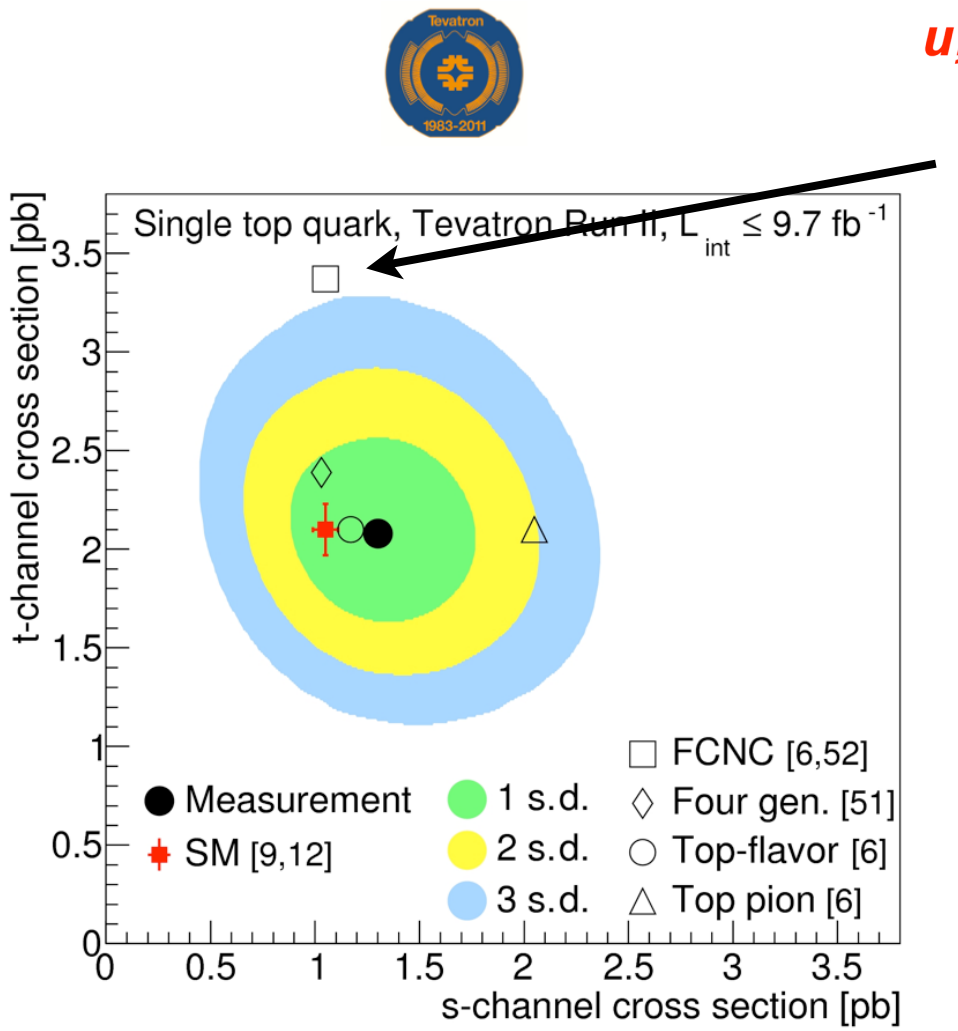


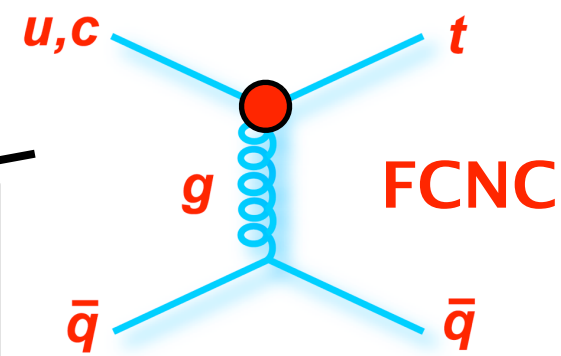


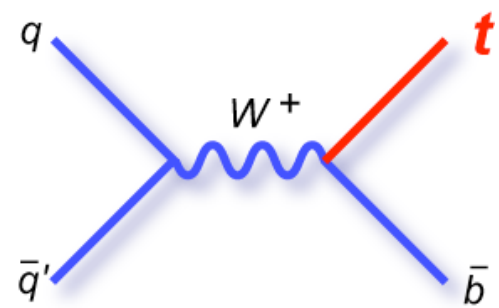
→ observed!

Single Top s- vs. t-channel



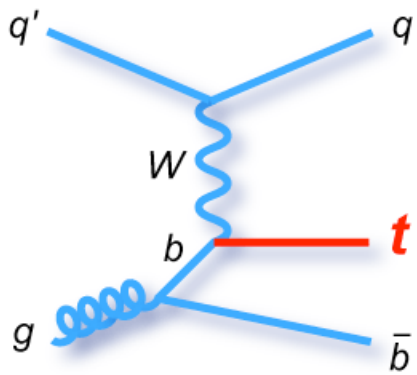


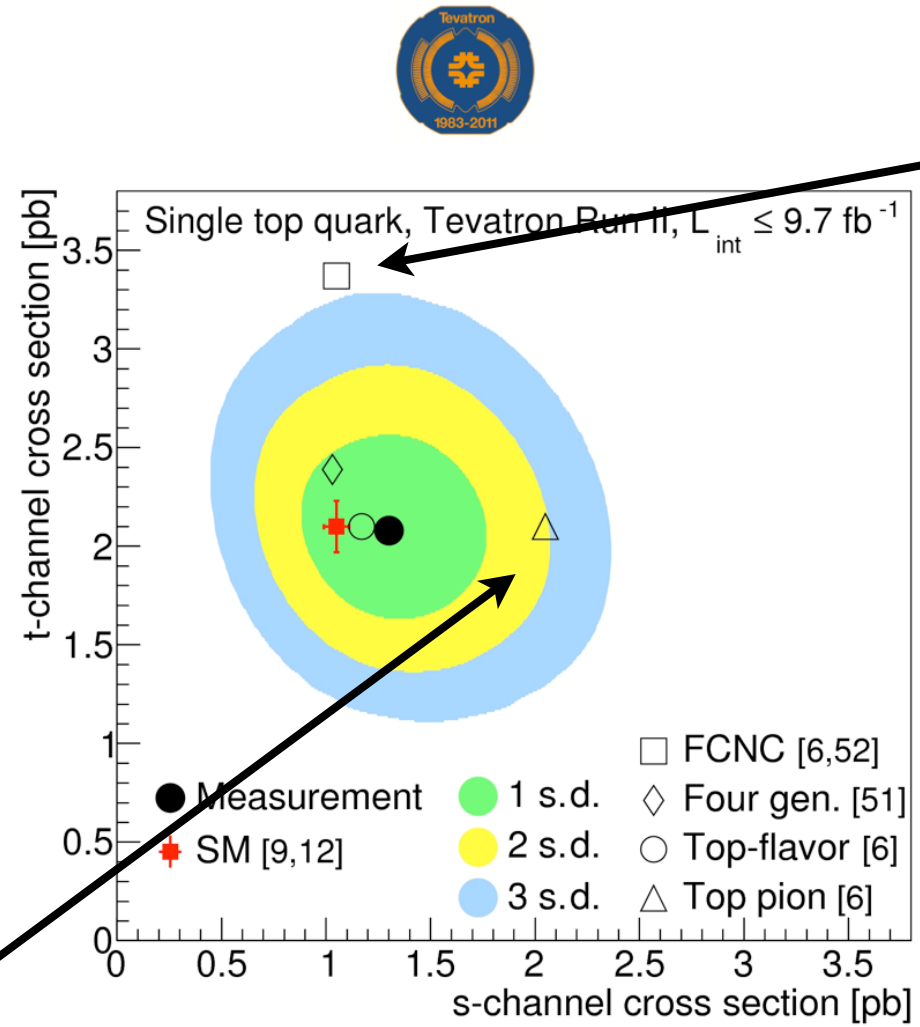


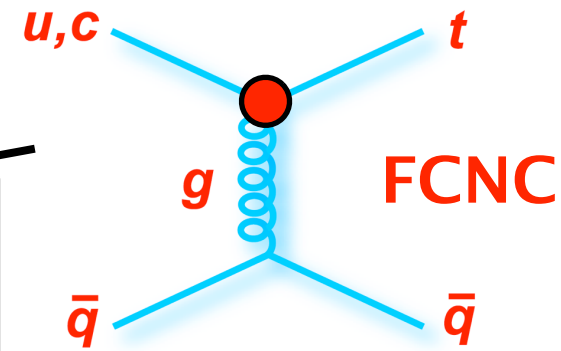


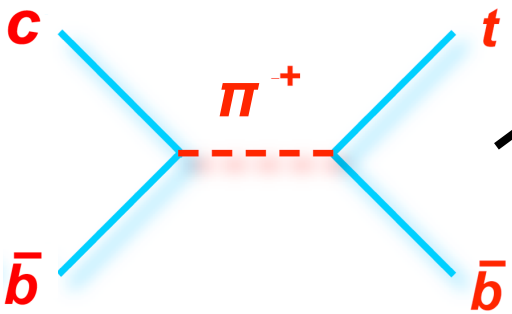
→ observed!

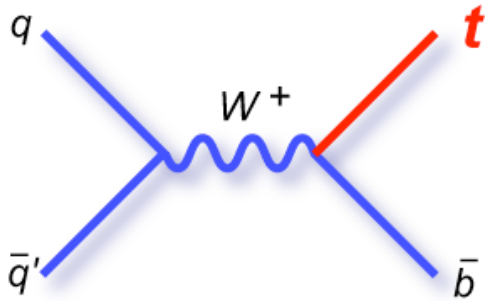
Single Top s- vs. t-channel







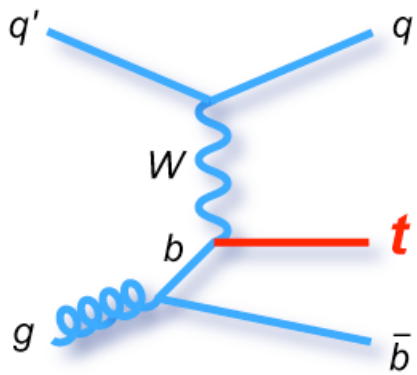


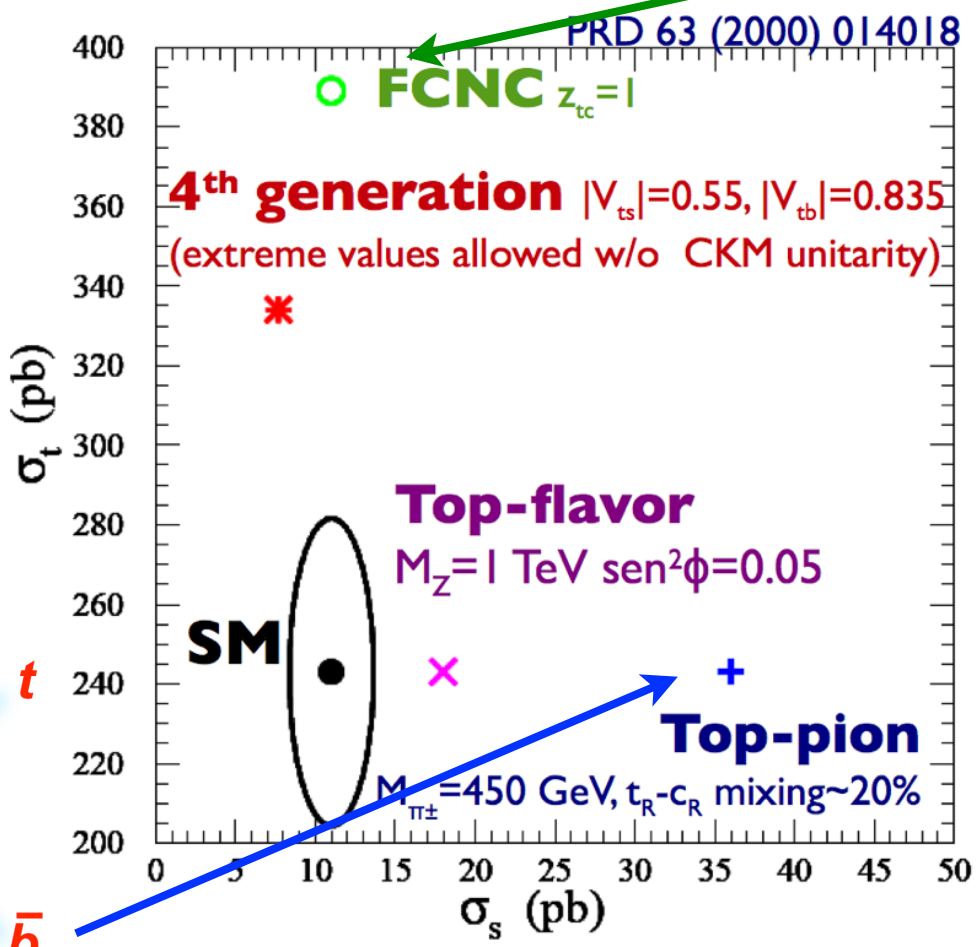


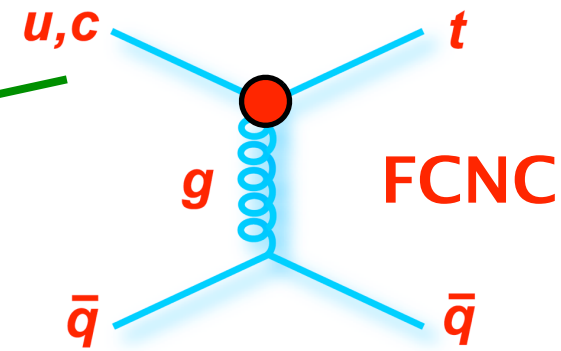
→ observed!

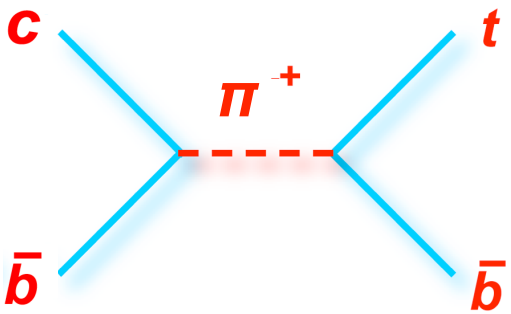
⇒ important to study production channels separately

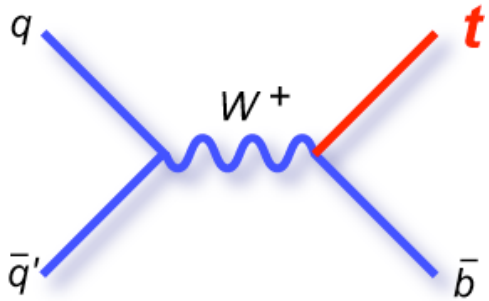
Single Top s- vs. t-channel: Run-II









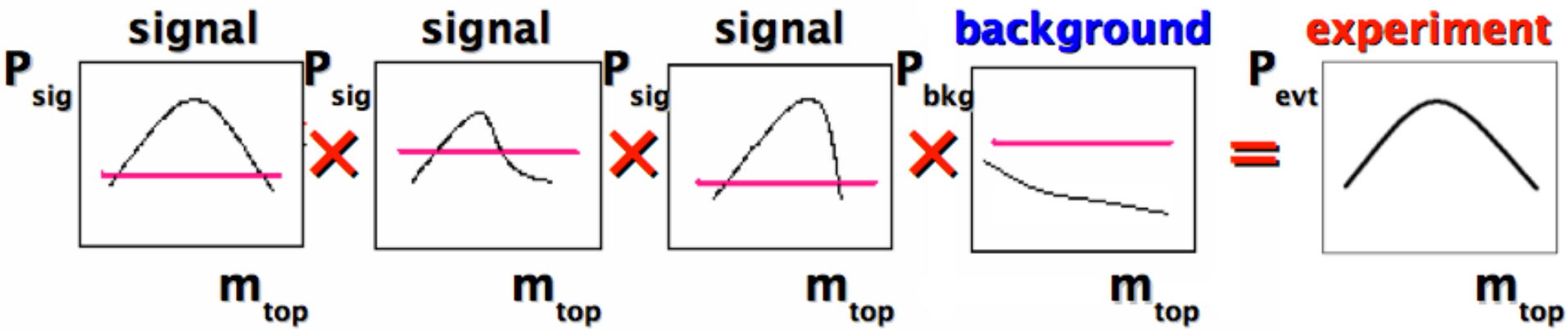


→ observed!

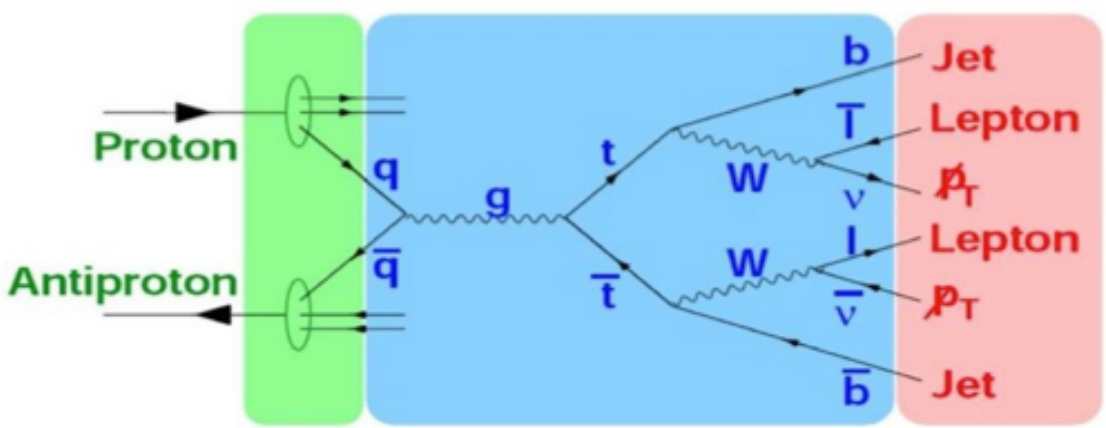
⇒ important to study production channels separately

Extraction Techniques: Matrix

- **probability densities for every event as function of m_{top}**



$$P_{sig}(x;m_{top},JES)=Acc(x)\times\frac{1}{\sigma}\int d^n\sigma(y;m_{top})\,dq_1\,dq_2\,f(q_1)\,f(q_2)\,W(x,y;JES)$$



PDF's

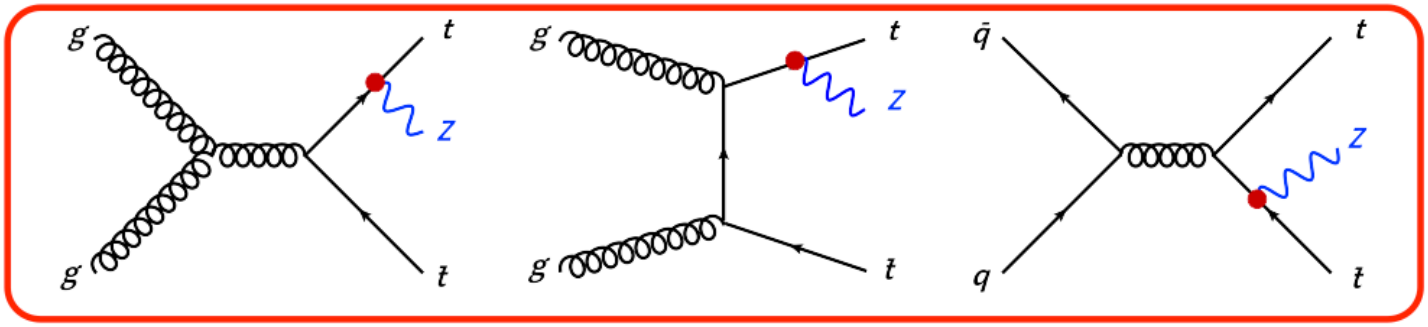
LO-Matrix element

transfer functions (probability to measure x when y was produced)

$t\bar{t}Z$ and $t\bar{t}W$ Production

ISR

FSR

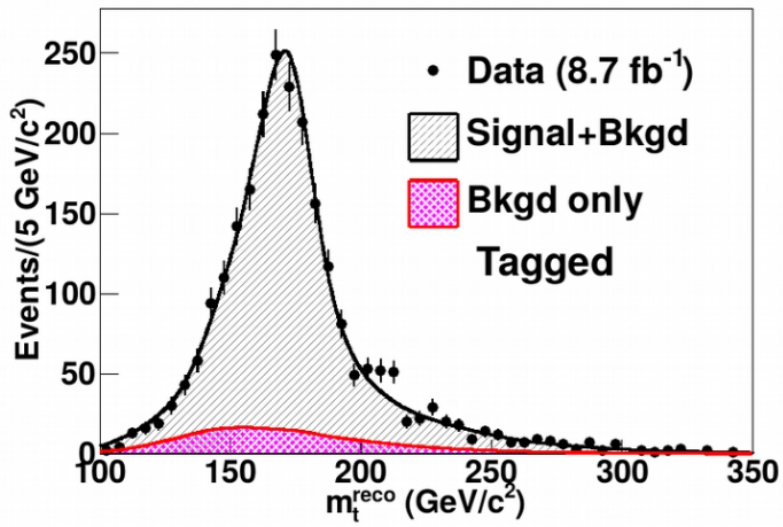


$$-i\,\frac{e}{\sin\vartheta_W \cos\vartheta_W}\left(T_3 - \sin^2\vartheta_W\, Q_t\right)\gamma^\mu$$

- measure 3rd component of weak isospin
- search for anomalous couplings in $t\bar{t}Z$ vertex (basically unexplored)

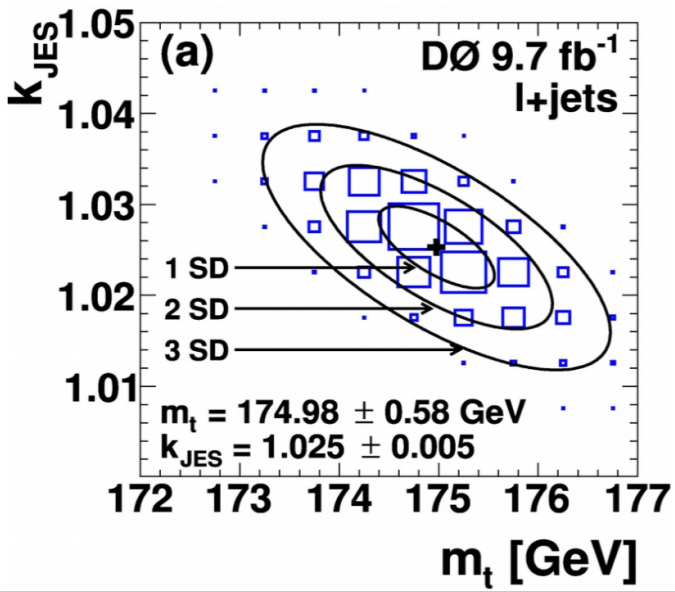
→ both processes are important backgrounds to searches (e.g. $t\bar{t}H$ in multilepton events)

Top mass at the Tevatron



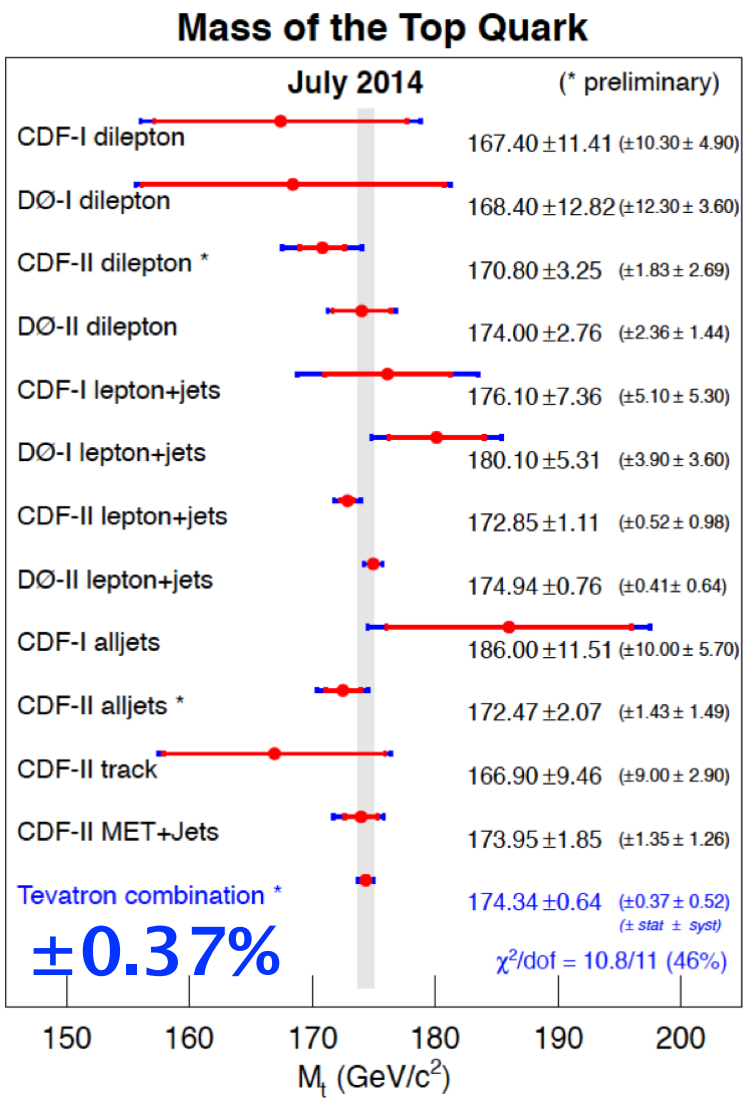
$m_t = 172.85 \pm 0.71$ (stat.) $\pm$ 0.85 (syst) GeV

±0.63%



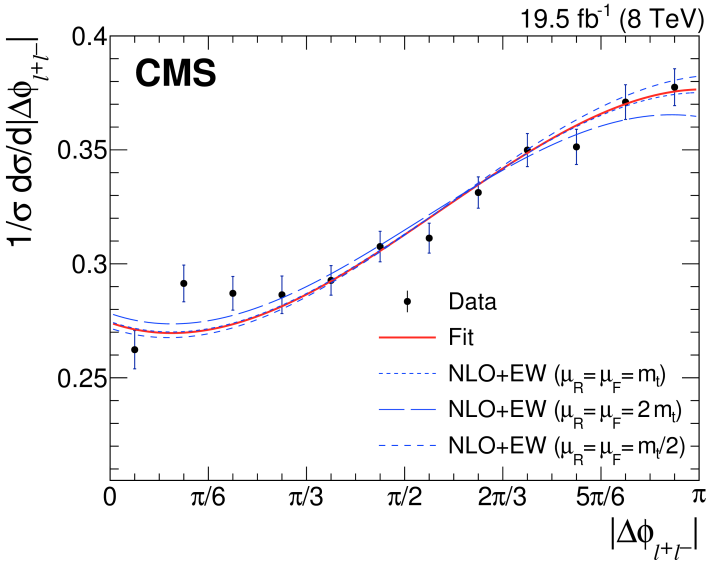
±0.43%

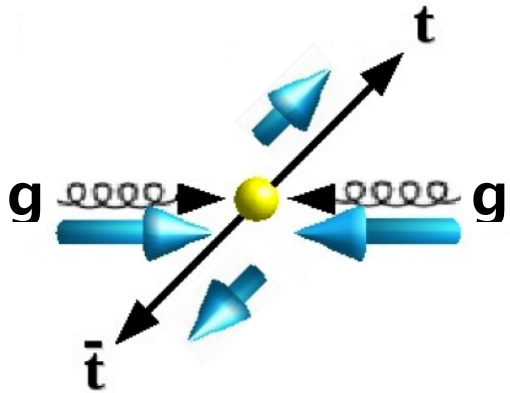
$m_t = 174.98 \pm 0.58$ (stat.) $\pm$ 0.49 (syst) GeV



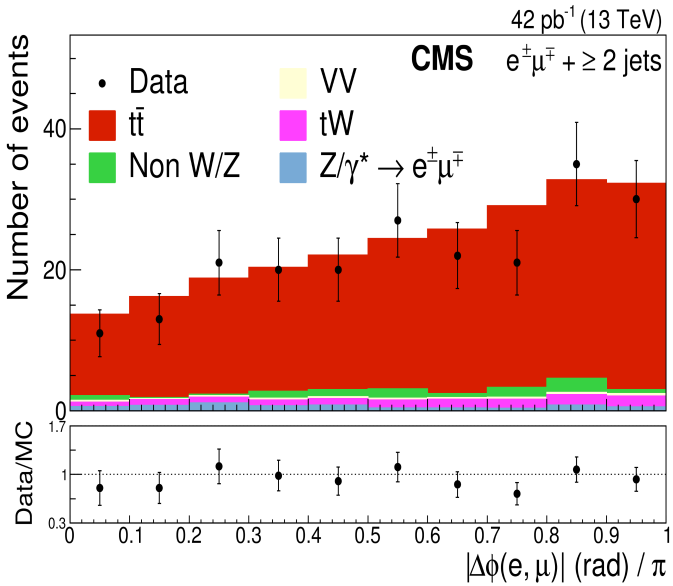
good agreement between all channels...

Polarisation and Spin Correlation

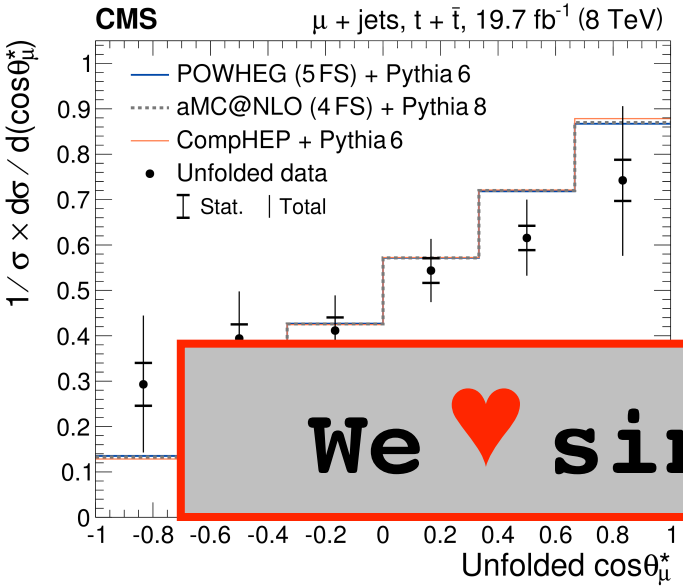




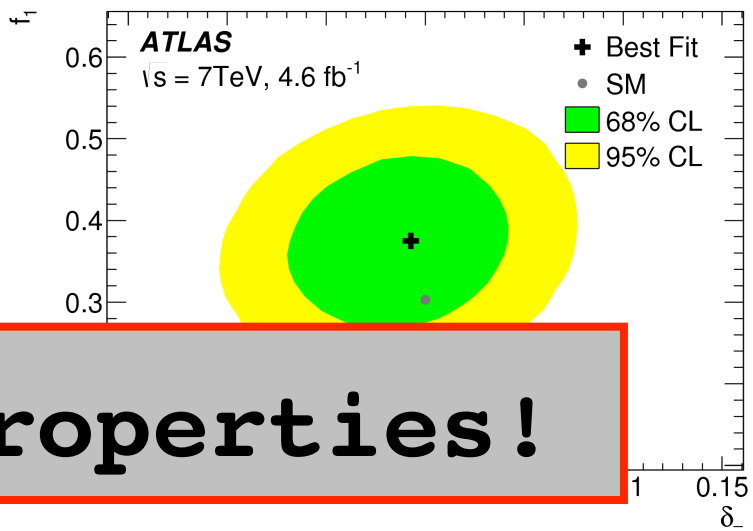
→ spins of tt pairs: correlated as in SM



→ no chromomagnetic dipole moments



no new physics

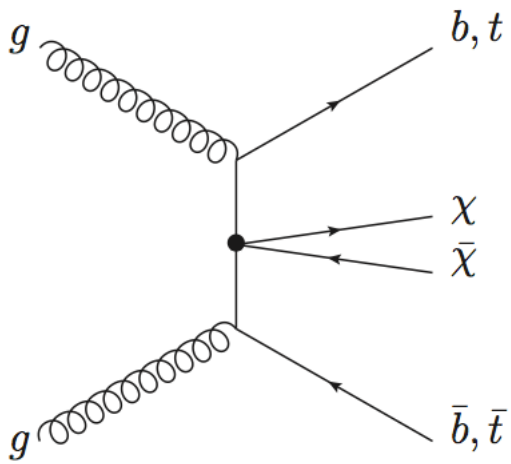


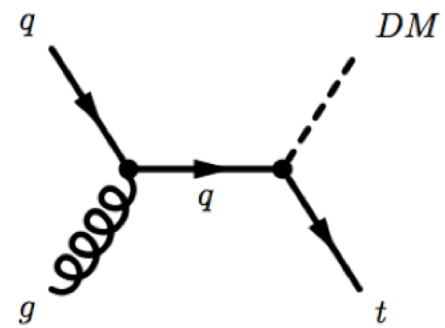
We ♥ single top properties!

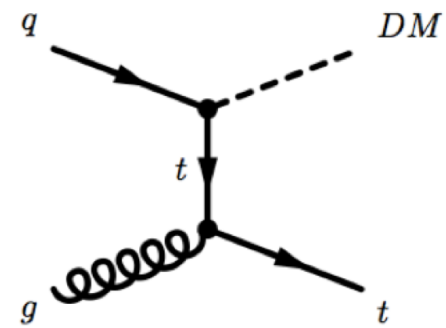
→ top quarks polarised as in SM

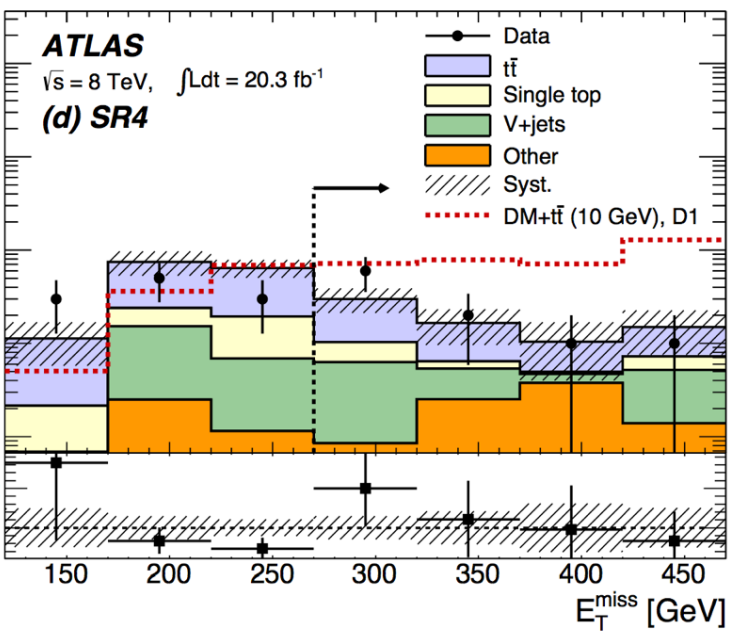
→ no anomalous couplings

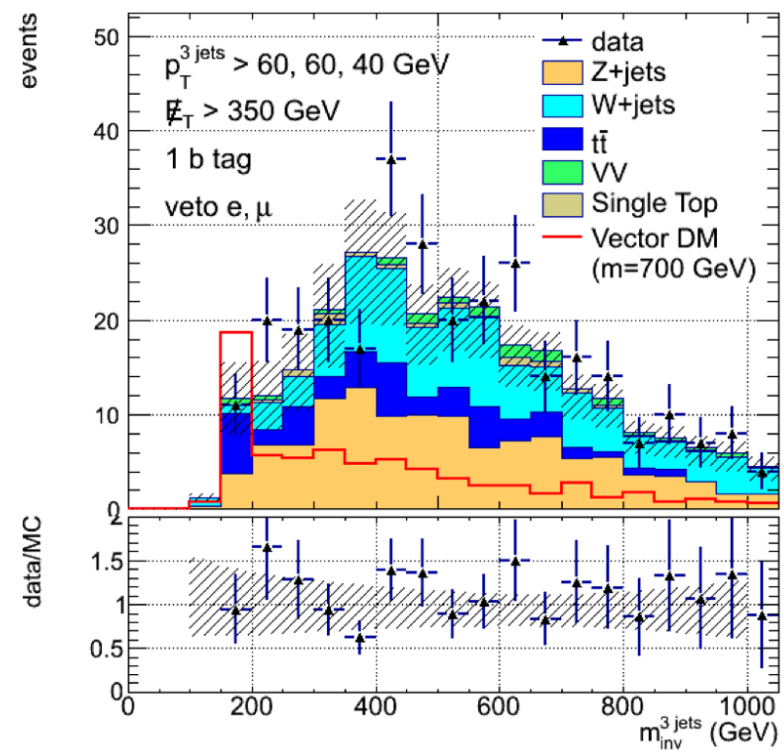
Search for dark matter











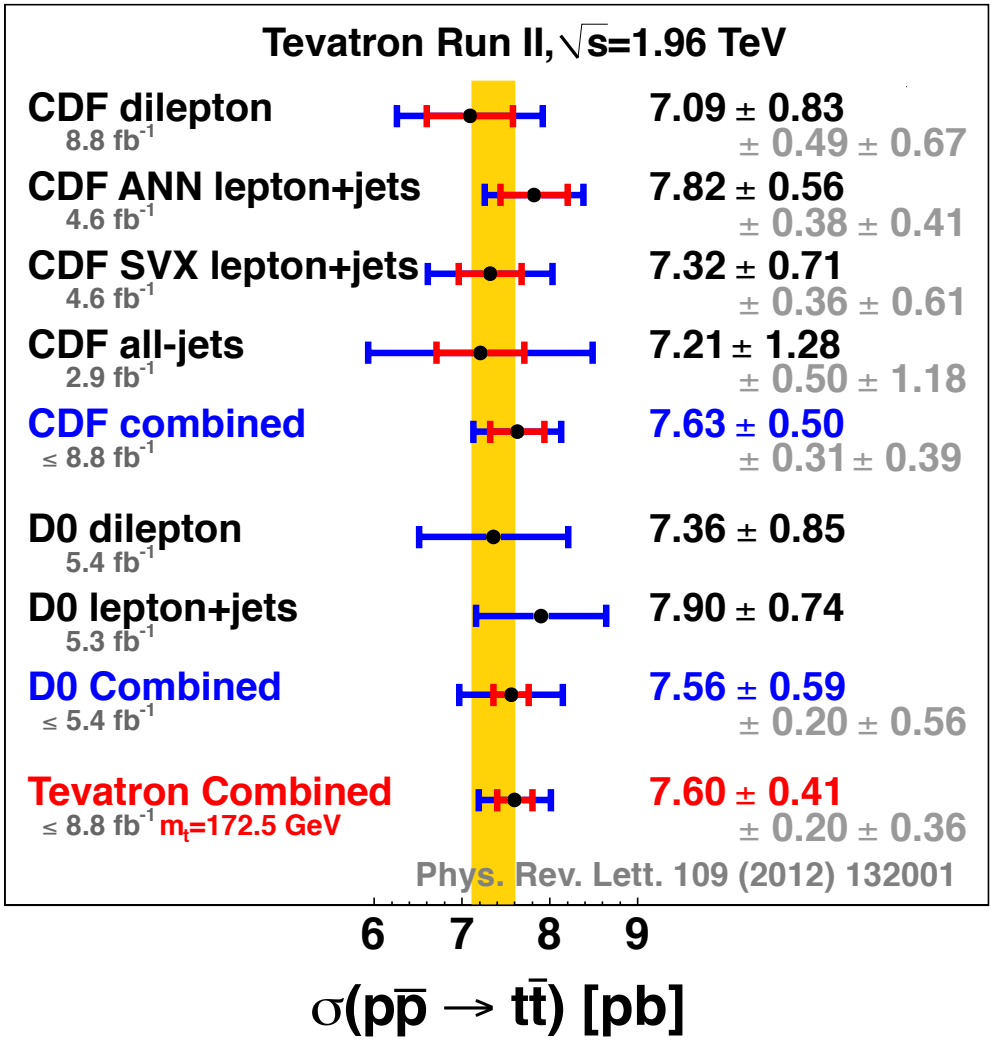
→ **no hint for dark matter**

Summary

"It is much too early to expect any discovery, we will have to be patient"
CERN DG

Top Pair Production Cross Section

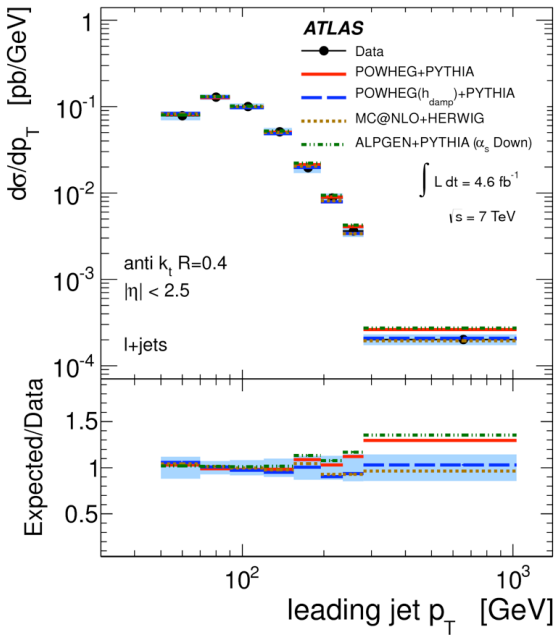
NNLO+NNLL



±5.4%

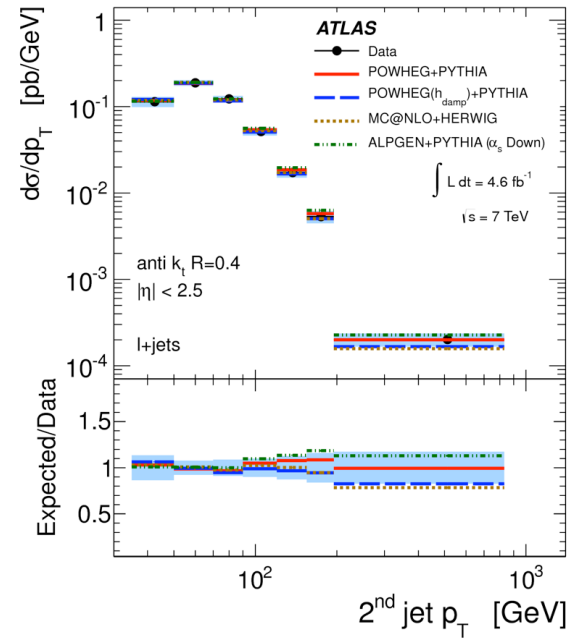
→ good agreement with NNLO+NNLL

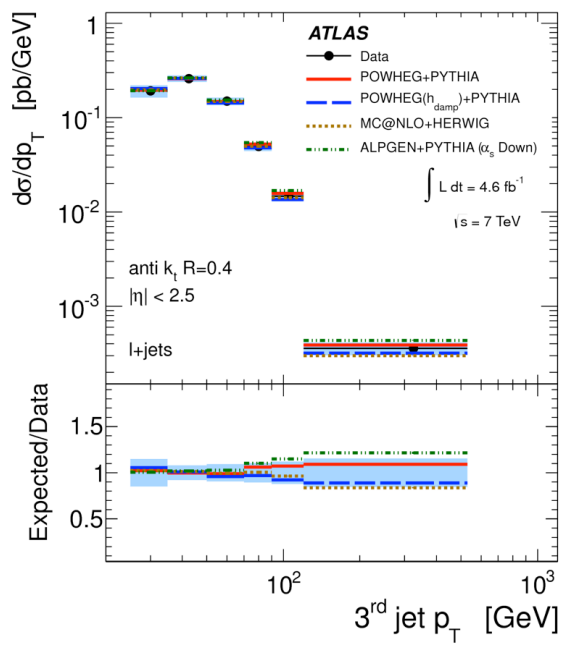
Differential (l+jets): jet p_T

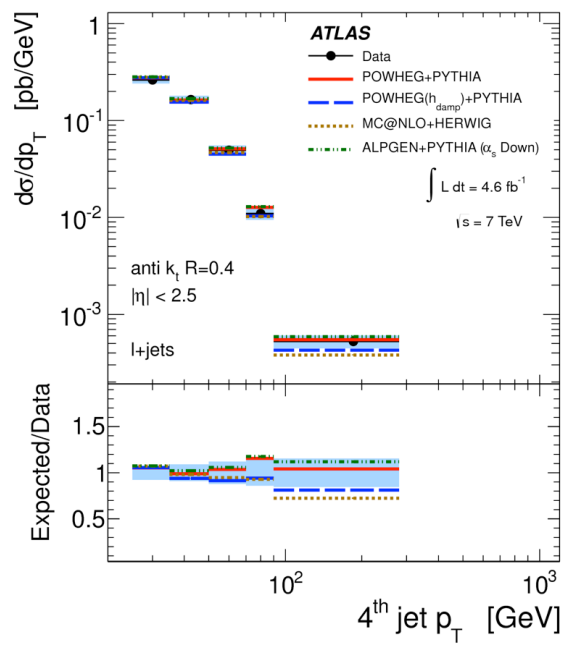


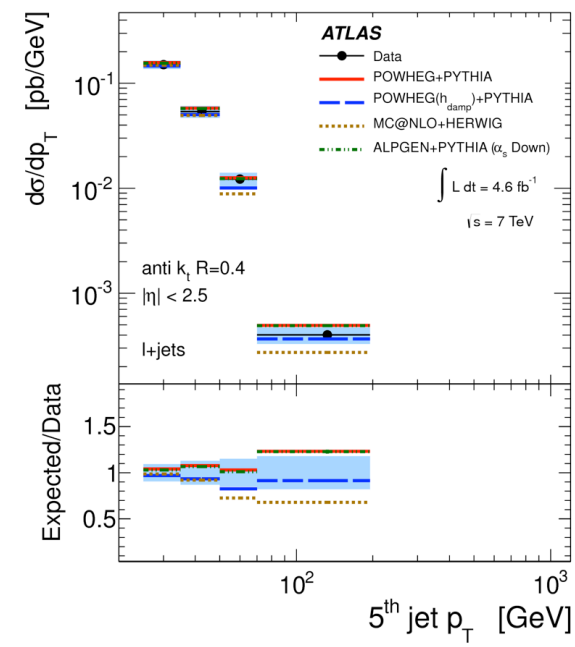
→ **NLO MCs are needed!**

Alpgen+Pythia and Powheg+Pythia disfavoured

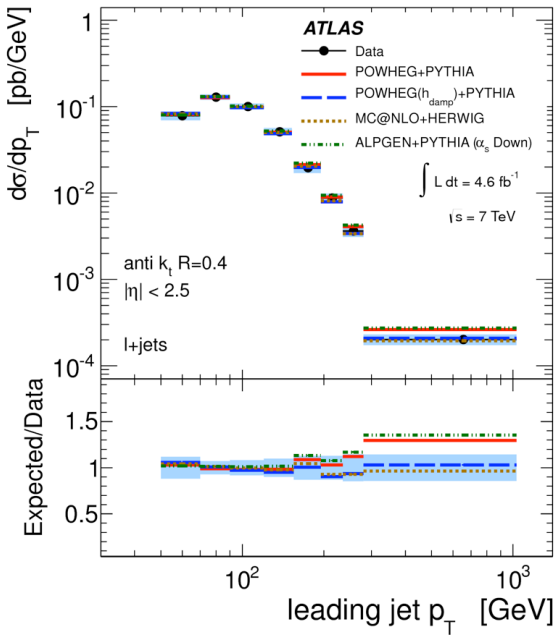




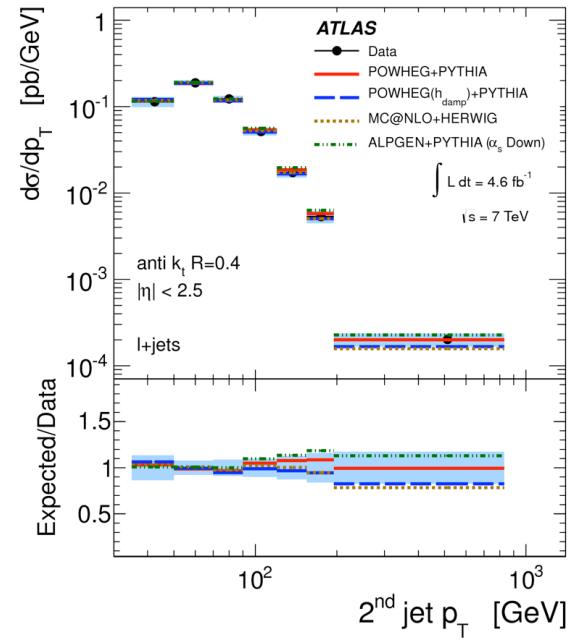




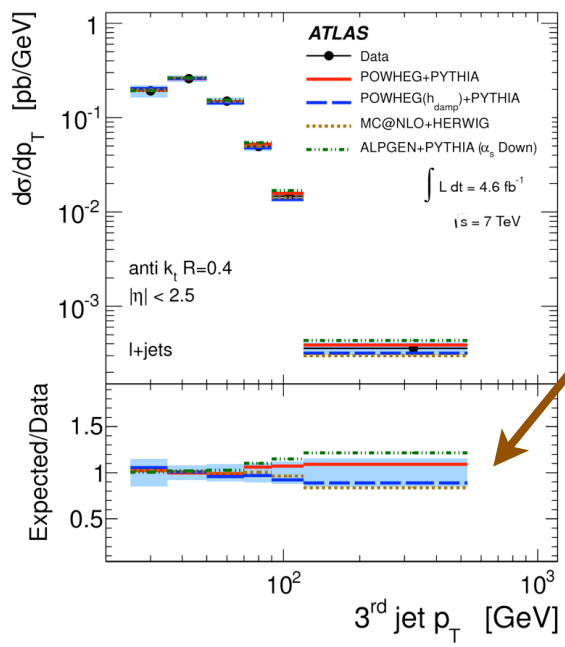
Differential (l+jets): jet p_T

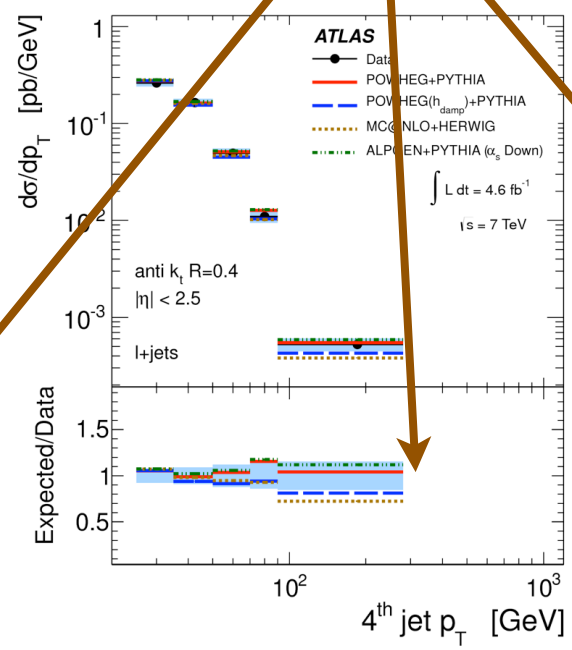


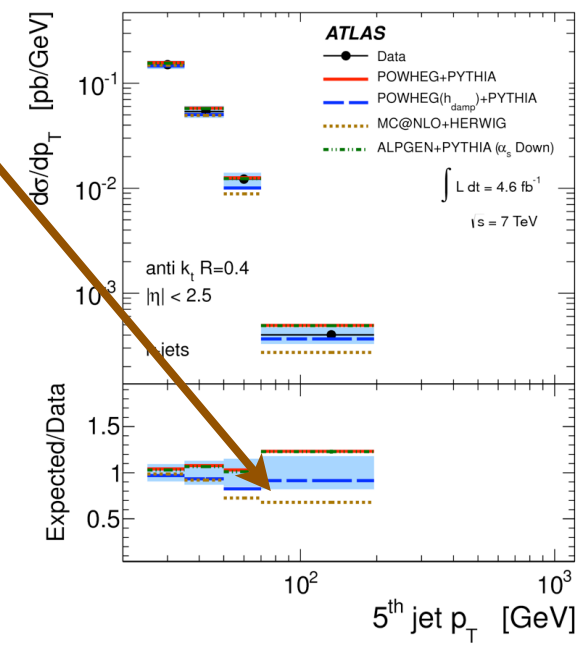
→ **multileg MEs are needed!**



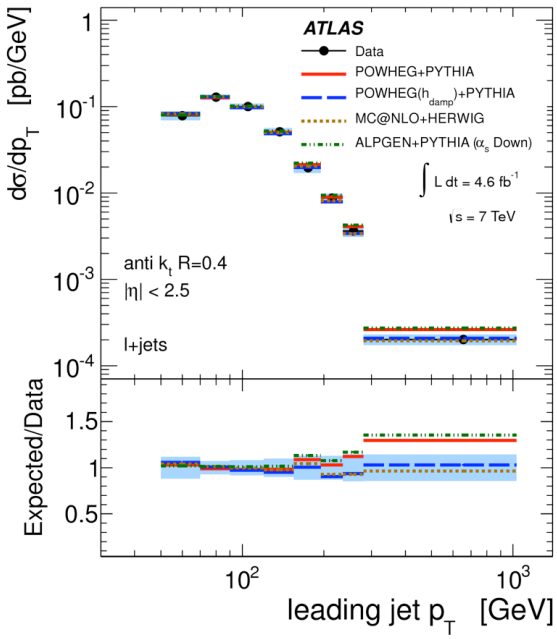
MC@NLO+Herwig too soft







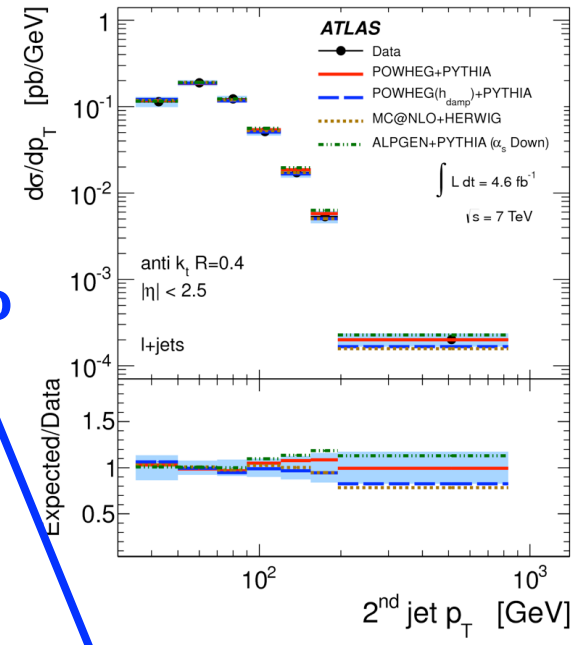
Differential (l+jets): jet p_T

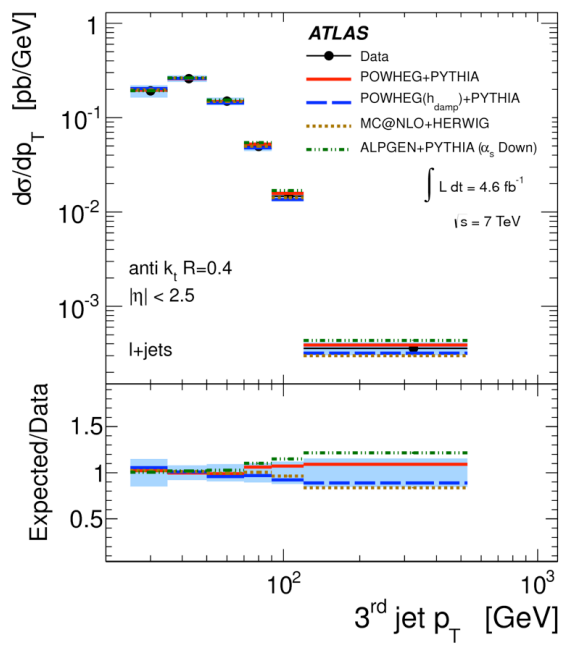


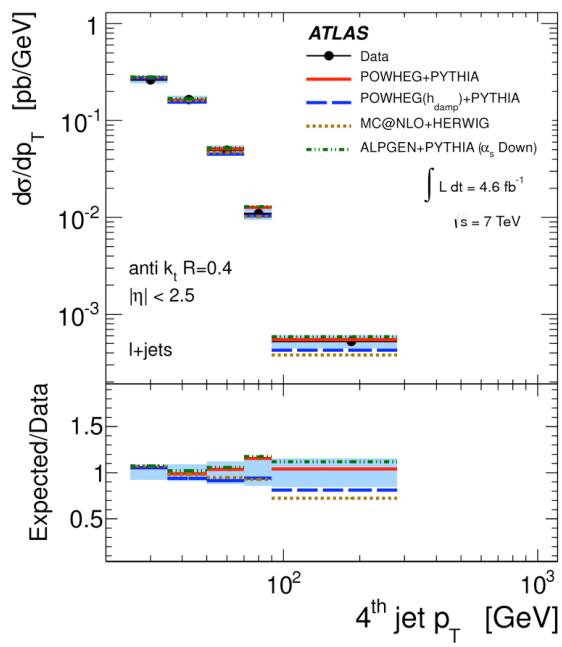
Powheg+Pythia in reasonable agreement

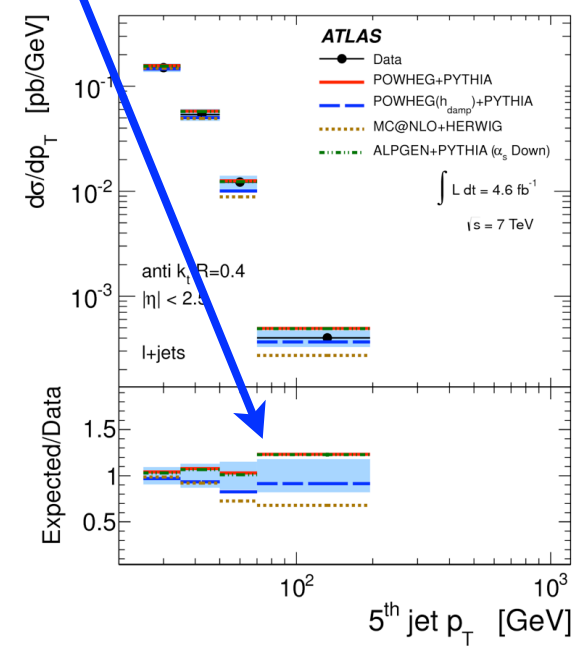
Powheg+Pythia with damping softer, due to damping of hardest emission

→ matter of tuning
($h_{damp}=m_{top}$ works best)



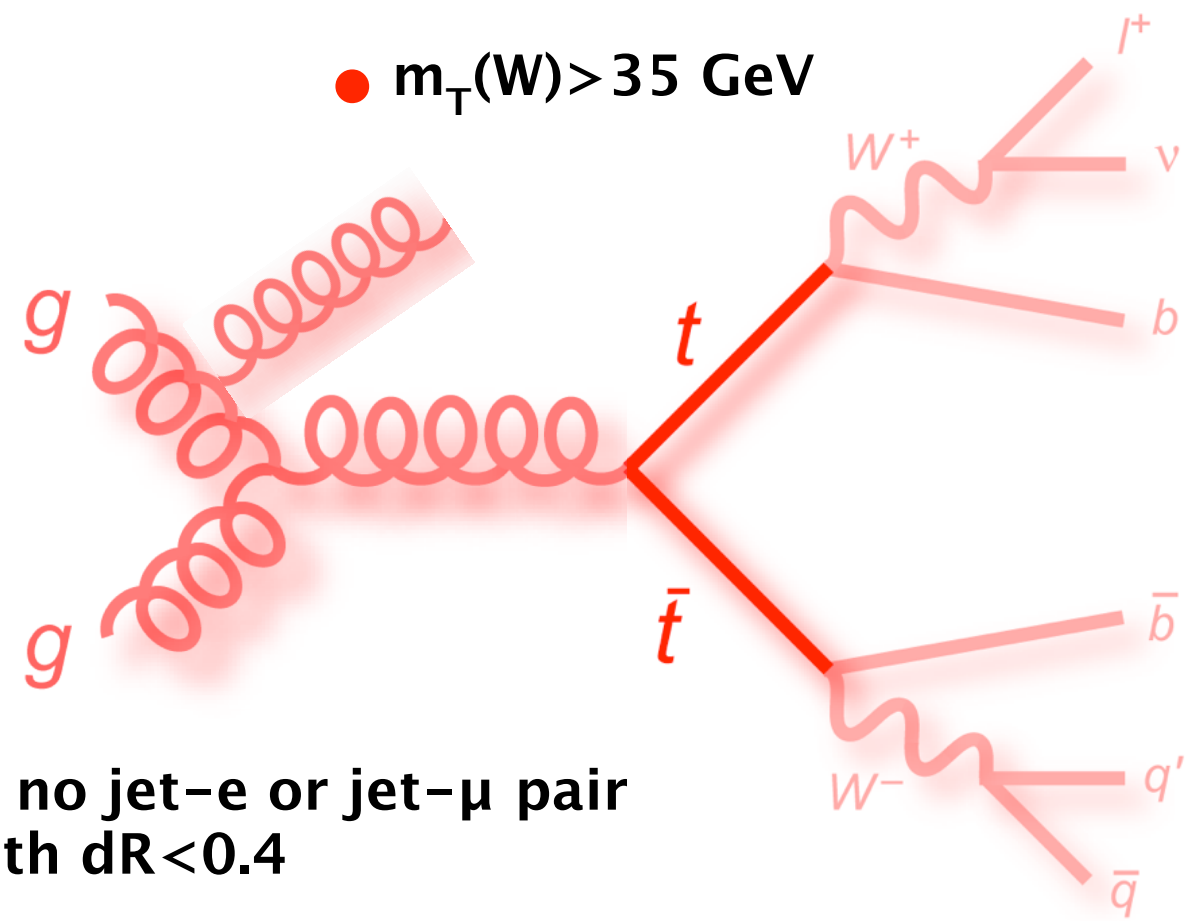






Fiducial Kinematic Phase Space

- no additional e or μ with p_t>15 GeV & |η|<2.5
- m_T(W)>35 GeV
- exactly one isolated e or μ with |η|<2.5, p_t>25 GeV (including clustering with γ in cone ΔR=0.1)
- $E_{t,miss}$ > 30GeV
- ≥ 3 Jets with p_t>25 GeV & |η|<2.5 incl. ≥1 b-tagged jet
- jets: anti-k_t R=0.4, clusters all but prompt particles (i.e. e, μ, ν from hadronic decays are inside jets)



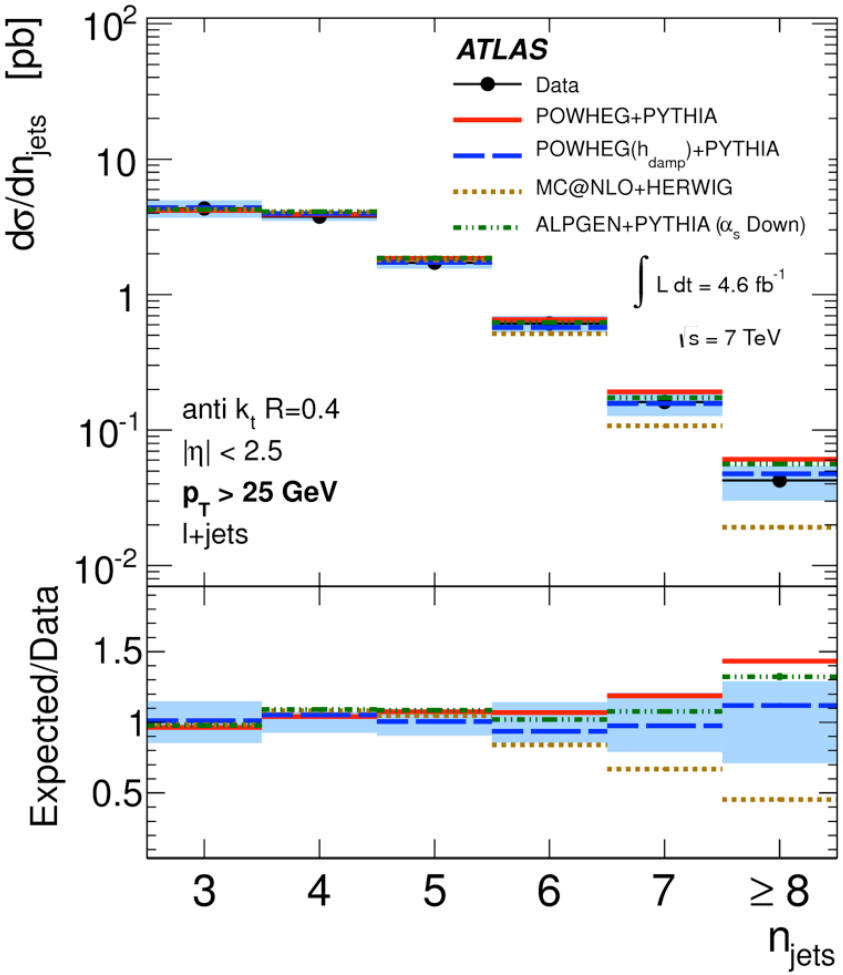
- no jet-e or jet-μ pair with dR<0.4
- no jet-jet pair with dR<0.5

- background subtraction
- corrections to particle level

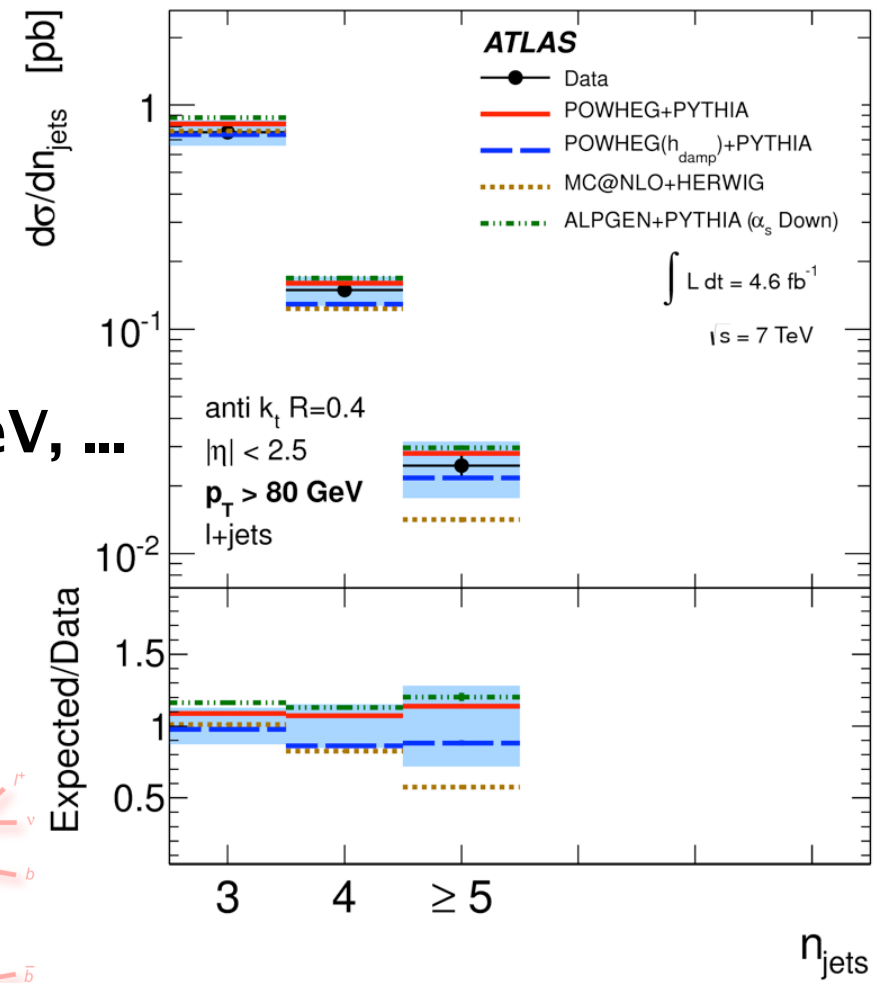
→ reduced dependence on MC model

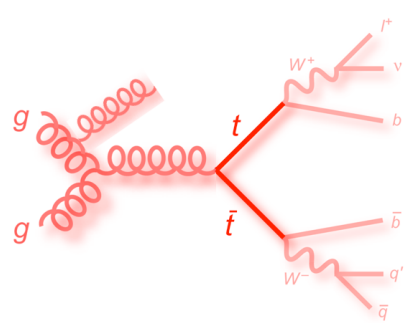
Jet Multiplicities

- uncertainties dominated by JES and MC modeling of QCD radiation



... 40, 60 GeV, ...



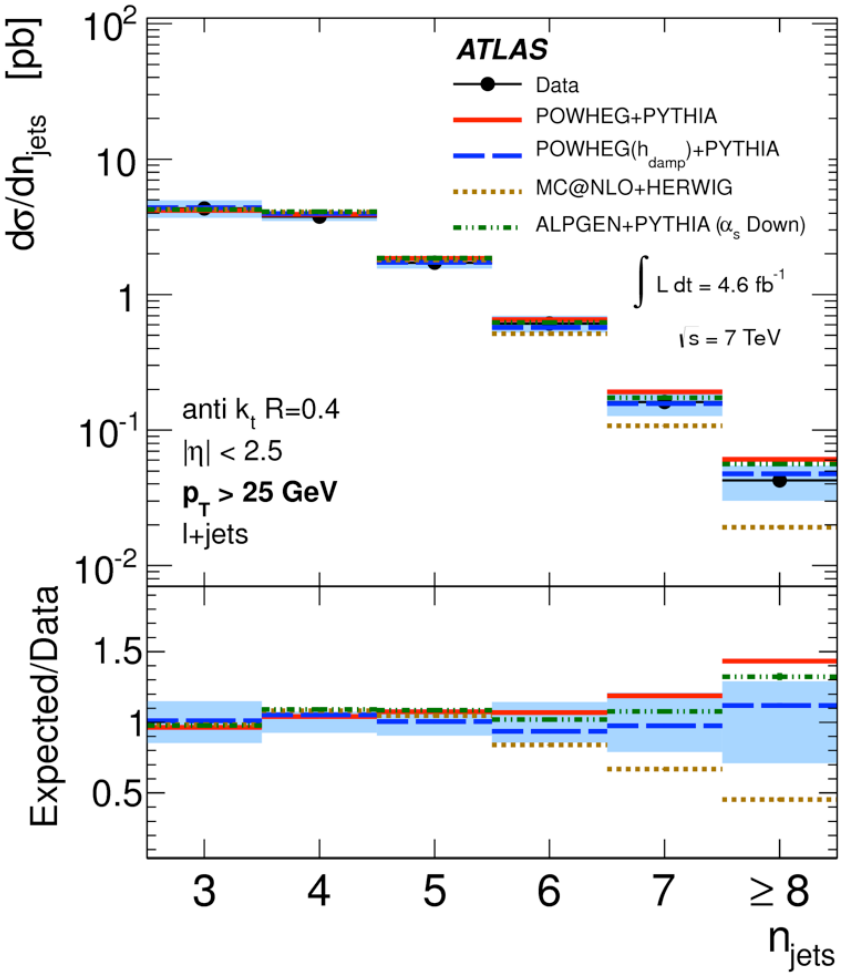


JHEP 1501, 020 (2015)

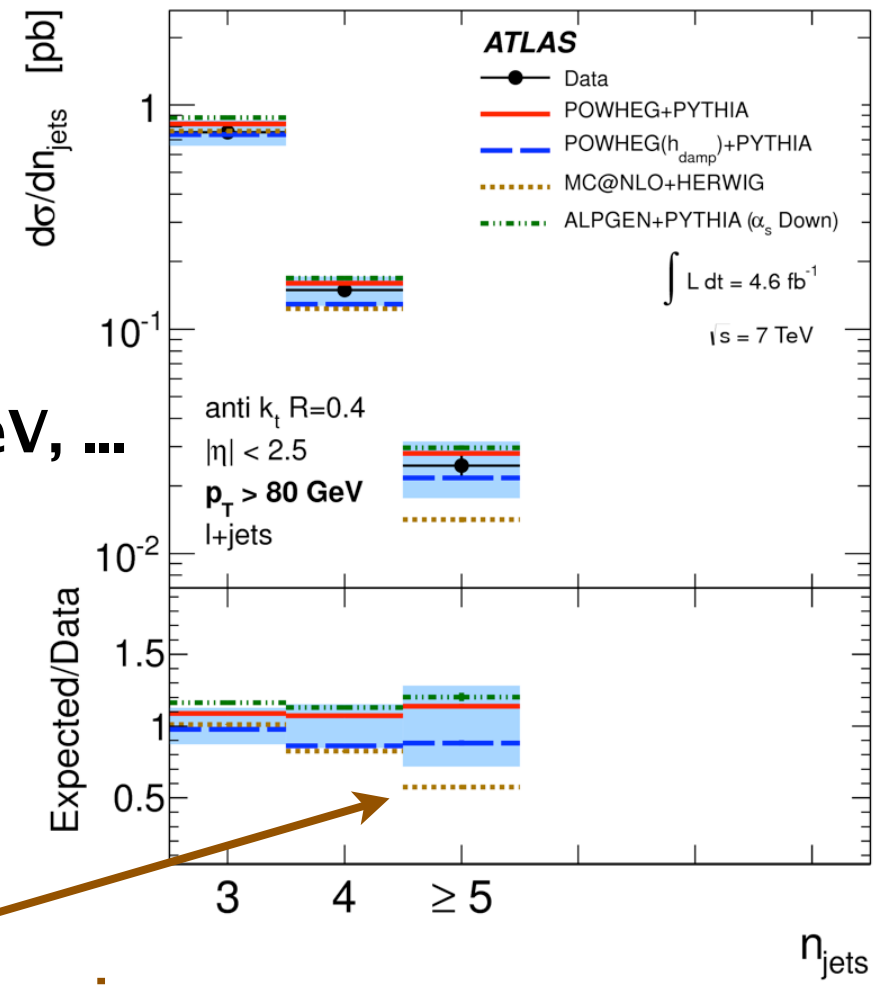
→ high sensitivity on higher order QCD modeling of MC generators

Jet Multiplicities

- **Uncertainties dominated by JES and MC modeling of QCD radiation**



... 40, 60 GeV, ...

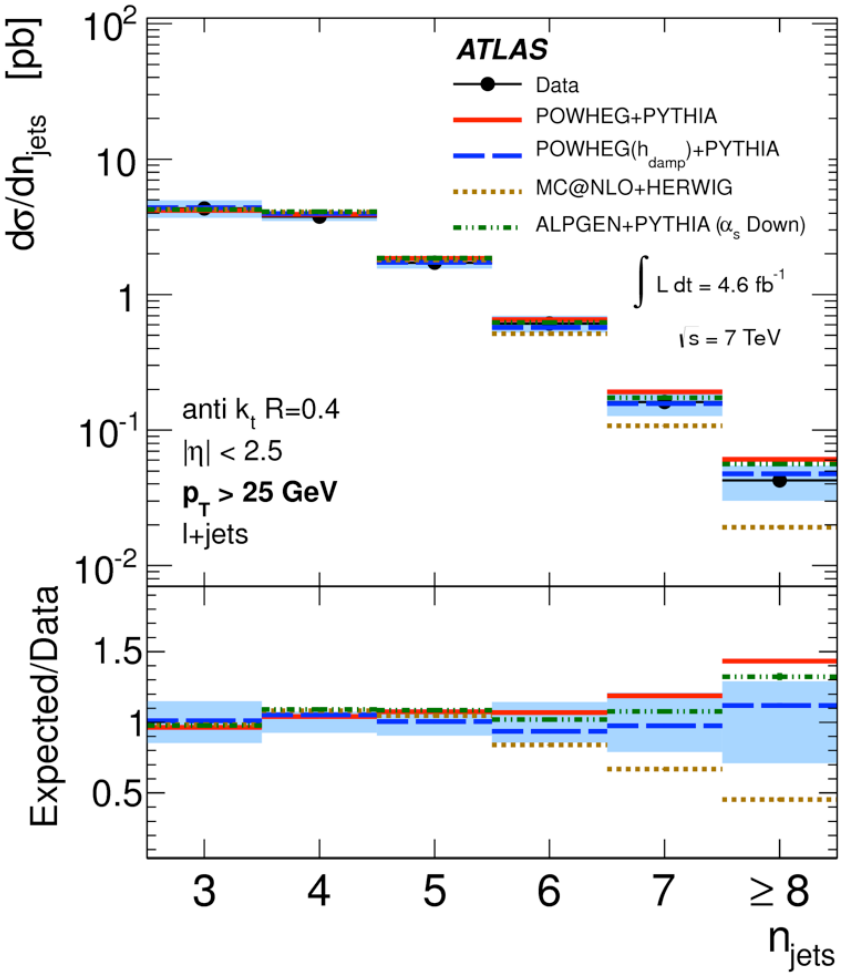


ALPGEN+Pythia ok

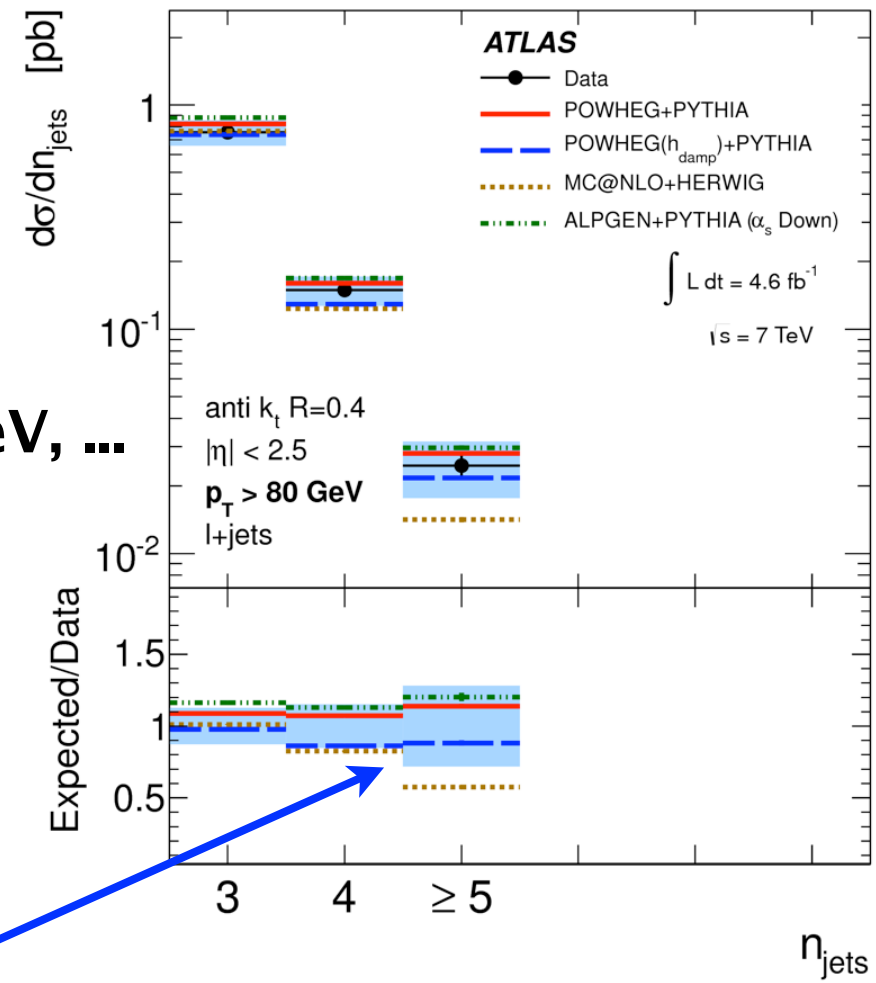
MC@NLO+Herwig disfavoured (since those come mostly from parton showers)

Jet Multiplicities

- **Uncertainties dominated by JES and MC modeling of QCD radiation**

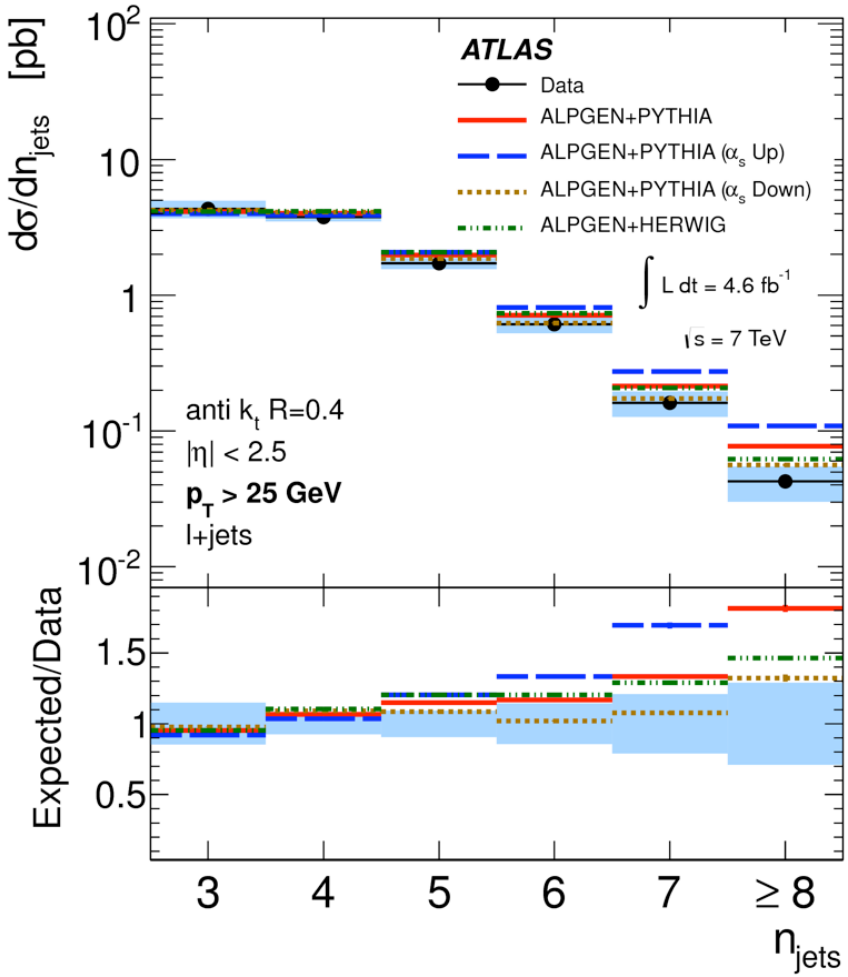


… 40, 60 GeV, …

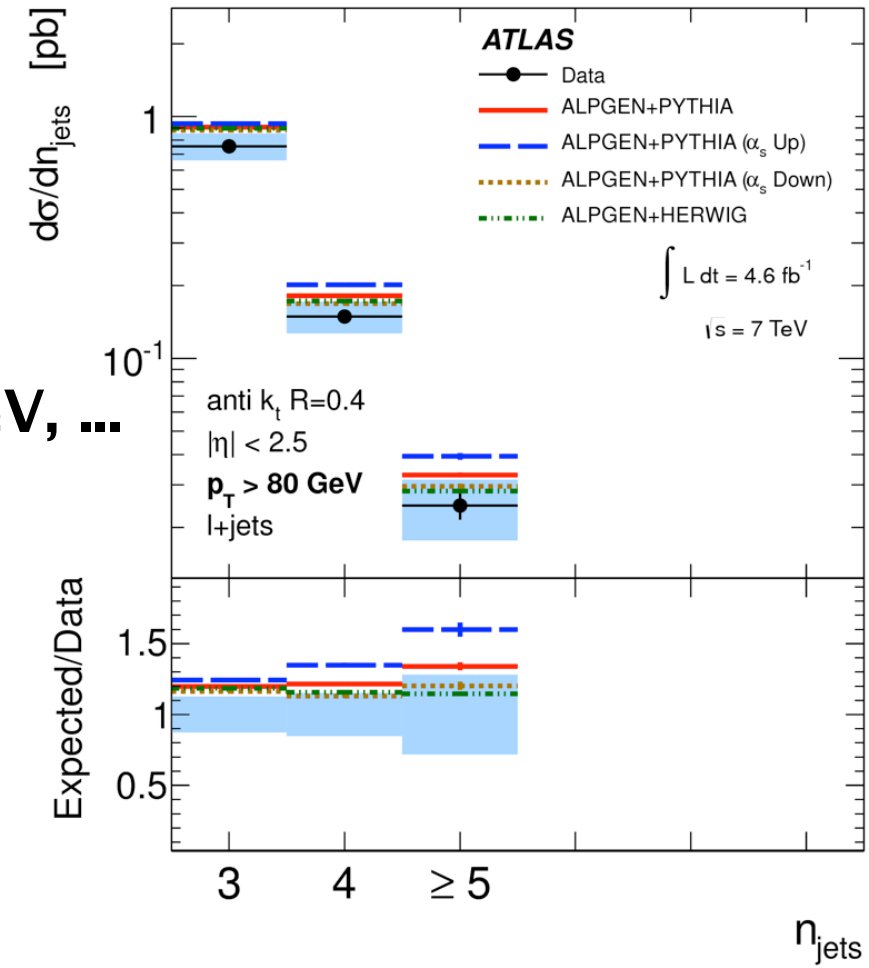


Powheg+Pythia with damping of the hardest emissions is best (high n_{jets} still get large contributions from the matrix element)

Strong Coupling and Parton Showers



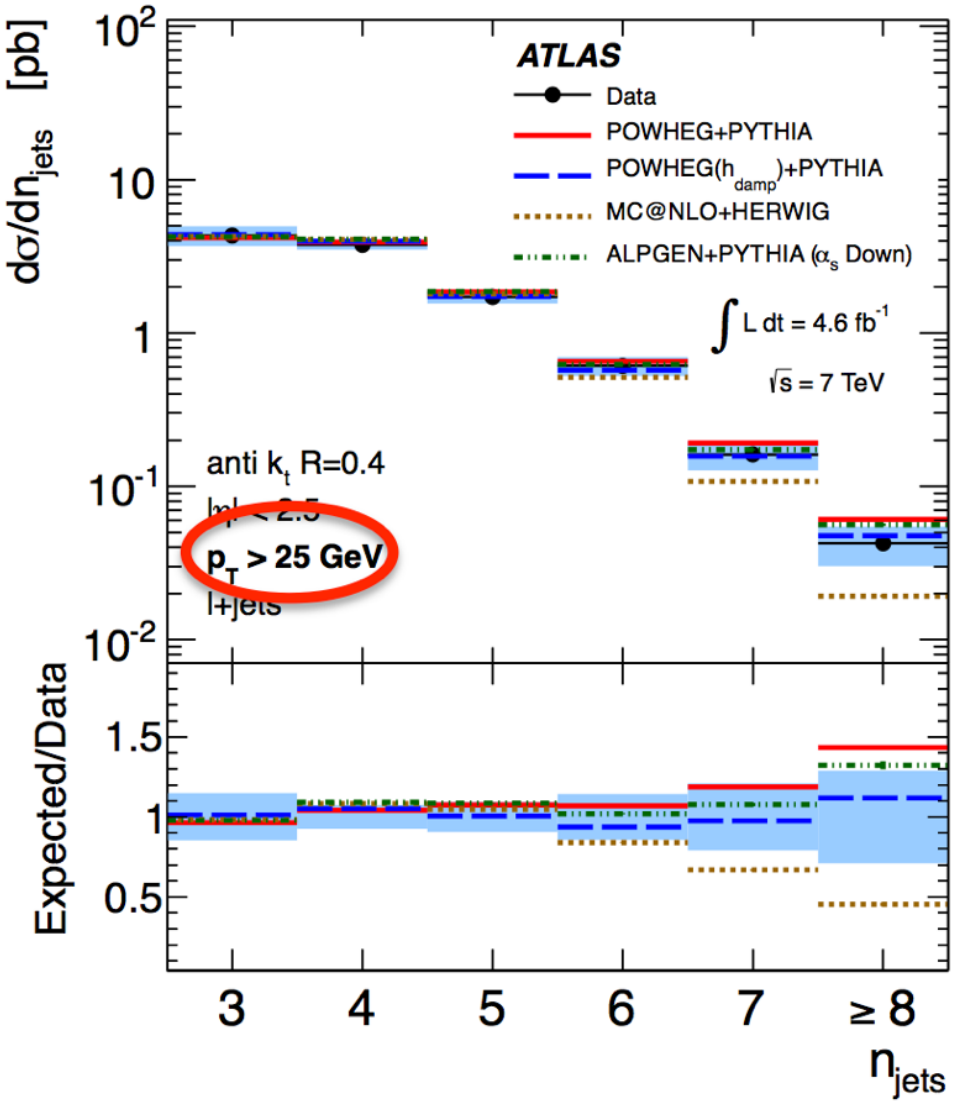
… 40, 60 GeV, …

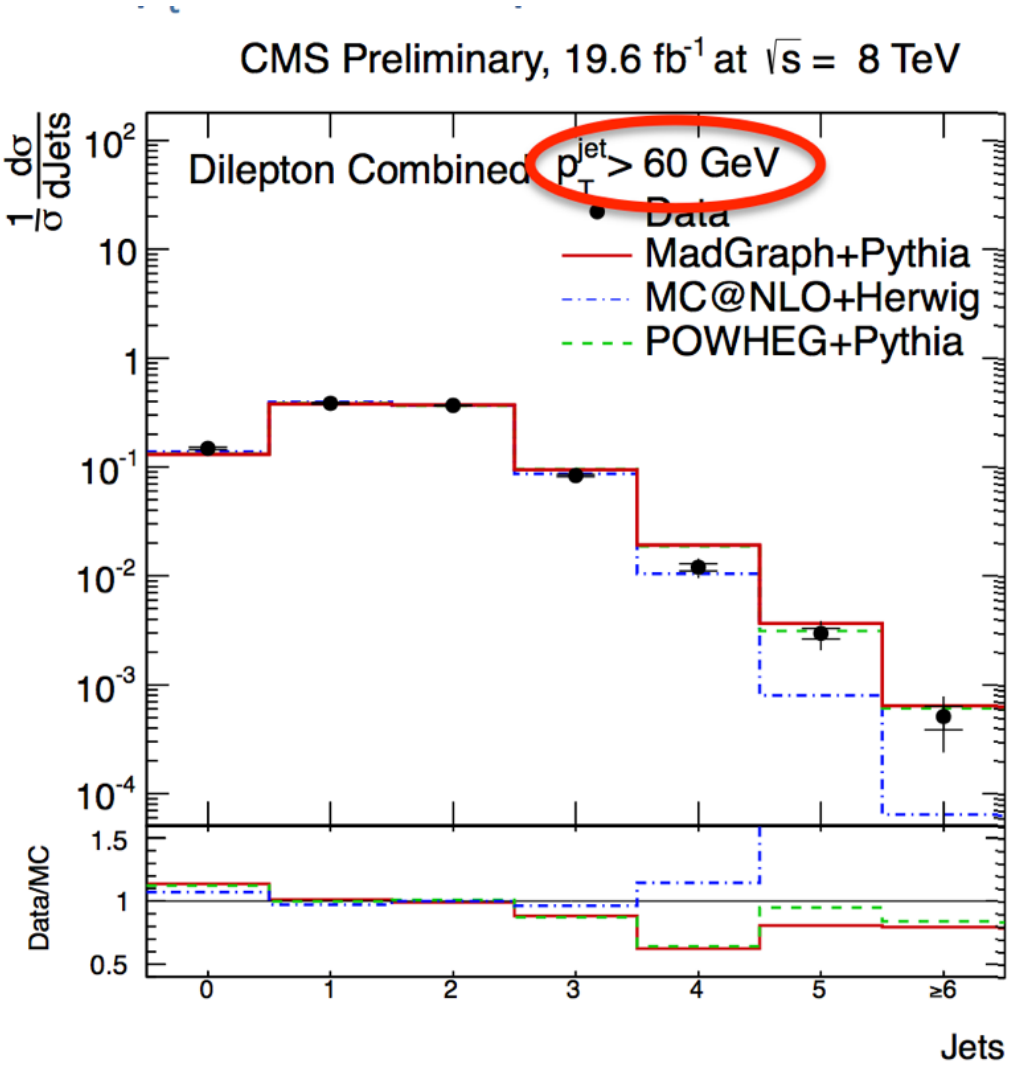


- → high sensitivity on α_S and parton showers
- → very valuable for improving models and reduce uncertainties
- → used for MC tuning: `ATL-PHYS-PUB-2015-007`
- → improves our understanding of higher order QCD calculations

Differential: jet multiplicities

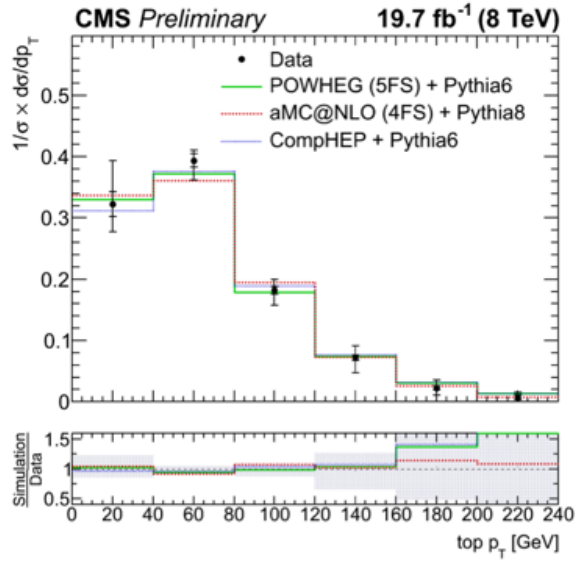
J. Katzy



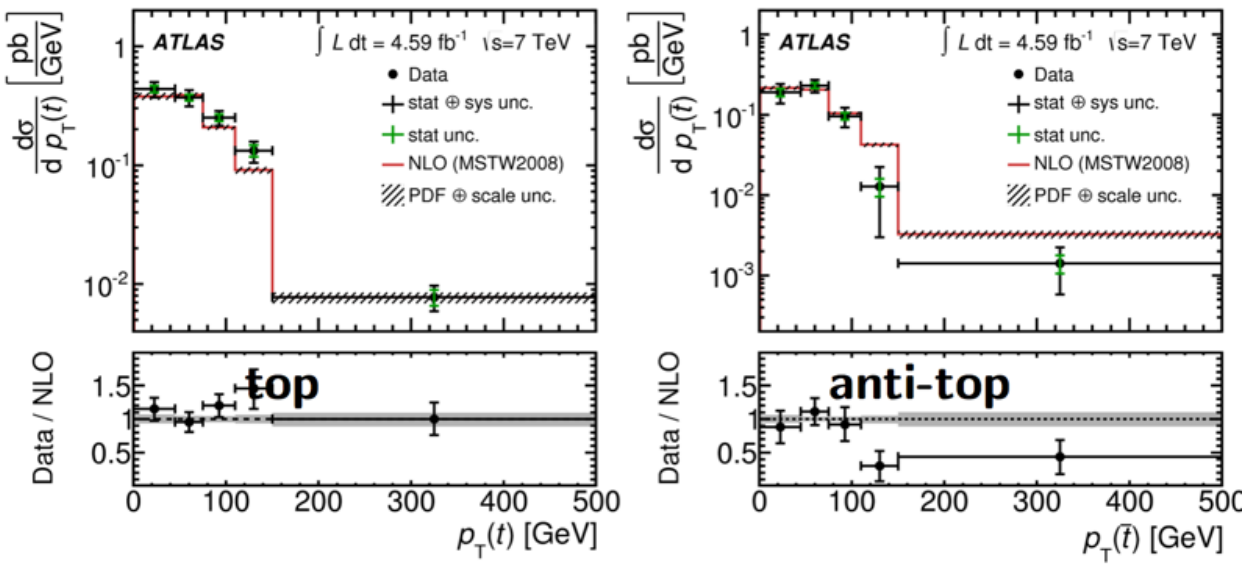


→ large differences between generators: helps to improve

Differential single top: top p_T



8 TeV

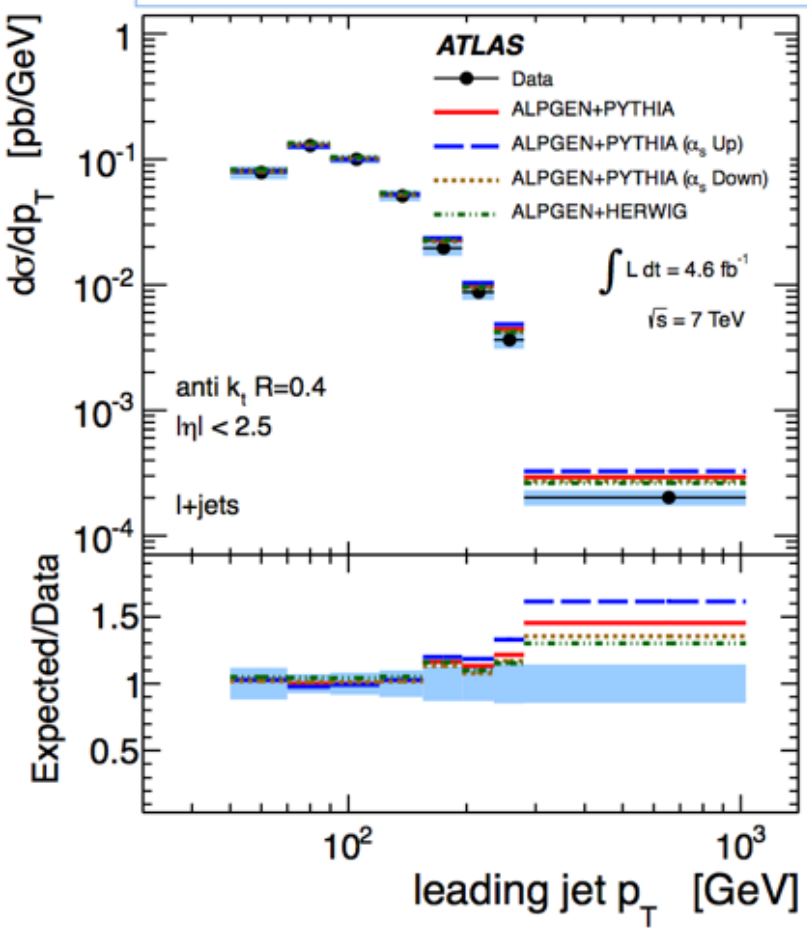


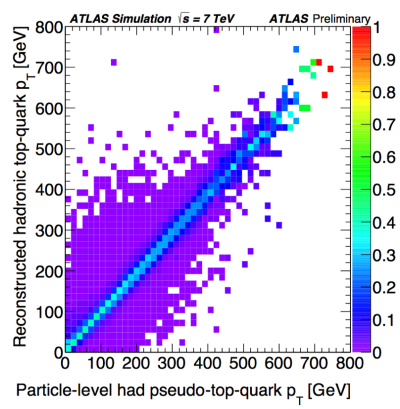
7 TeV

→ **good description**

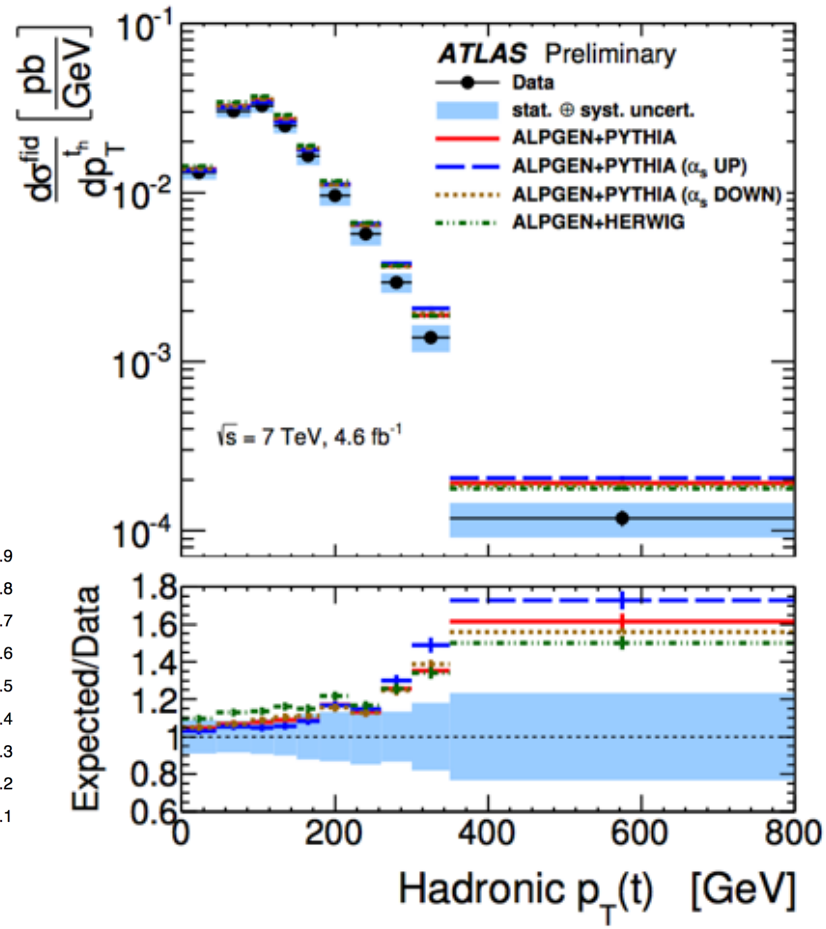
Top decay products: pseudo-top

Fiducial phase space:
>=1 b-jet, 1 lepton, >=3 jets,
1st jet p_t>50 GeV, 2nd jet p_t>35 GeV





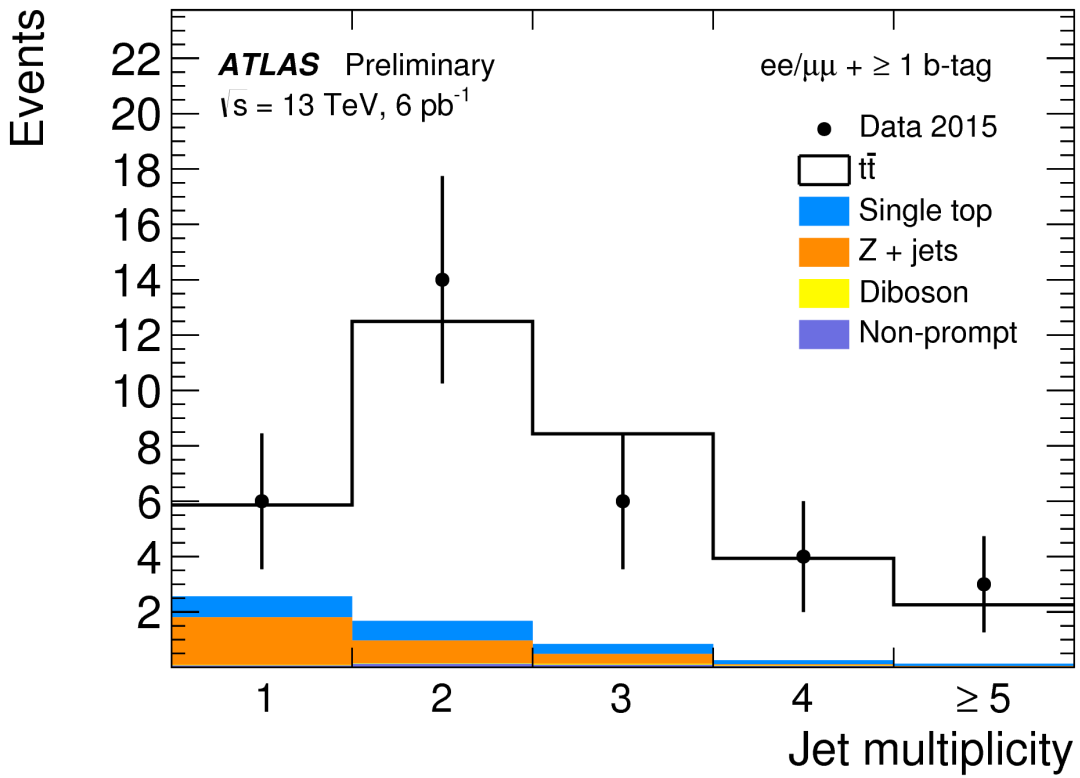
Fiducial phase space:
2 b-jets, 1 lepton, >=4 jets

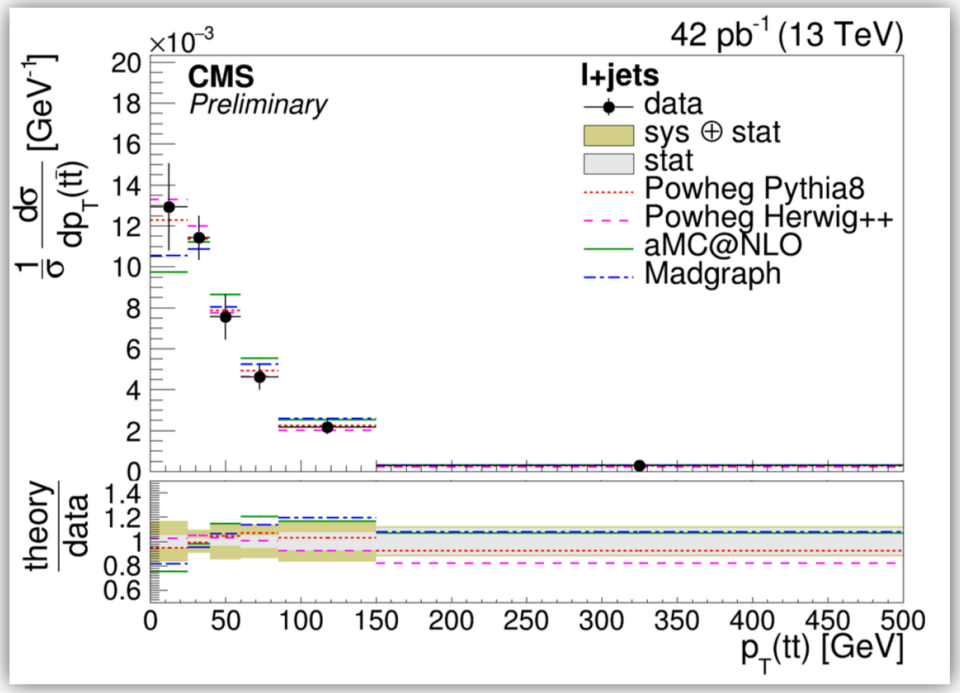


→ reconstruct tops on particle level

→ very valuable for theorists today and in future

Differential: top pair p_T

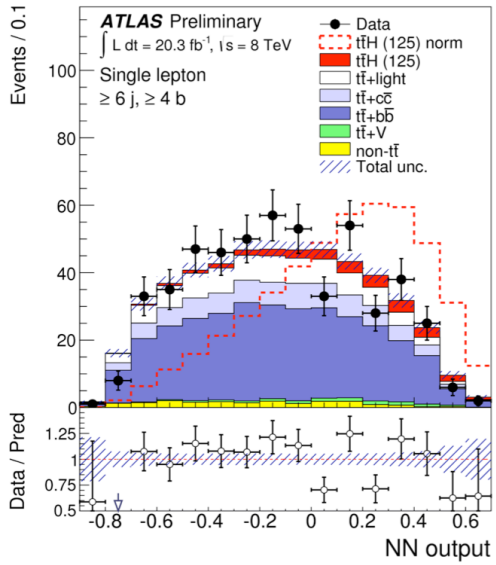


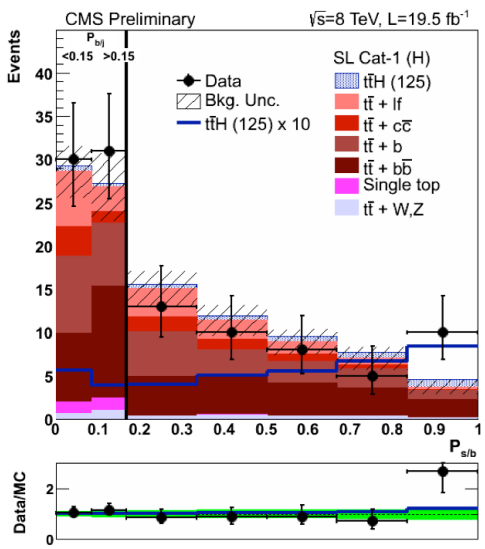


→ **good agreement with new MC tools so far, but low statistics still**

Search for ttH production

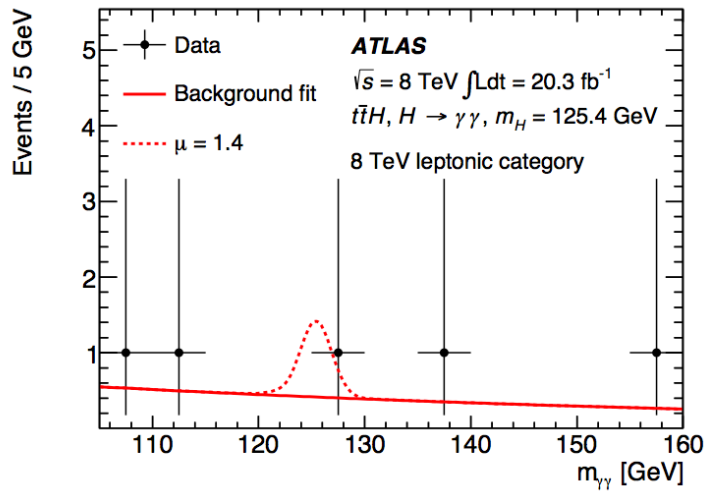
H→bb

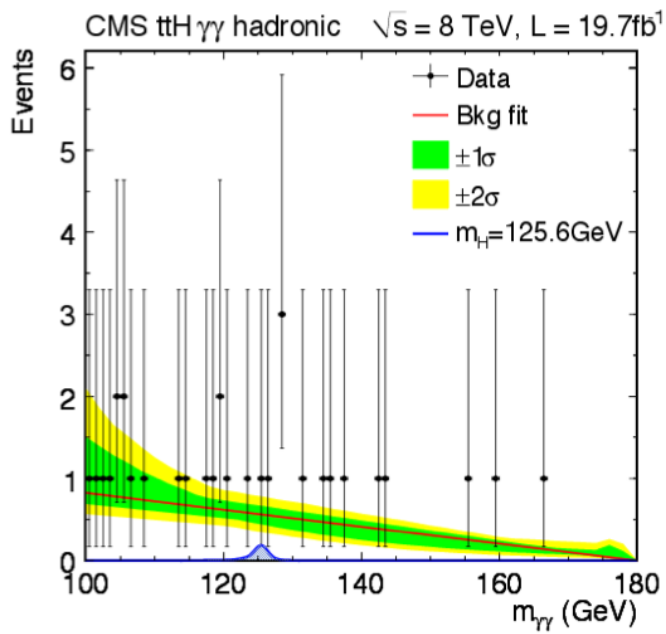




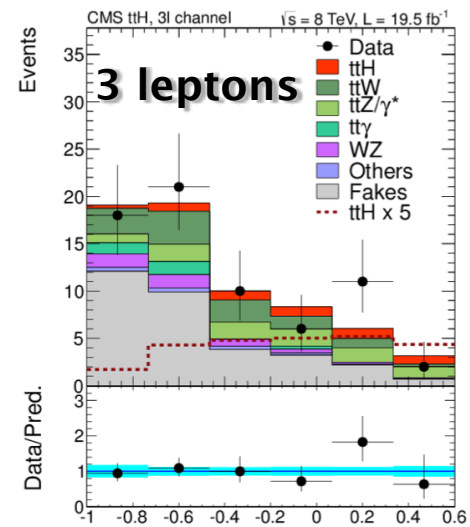
matrix element

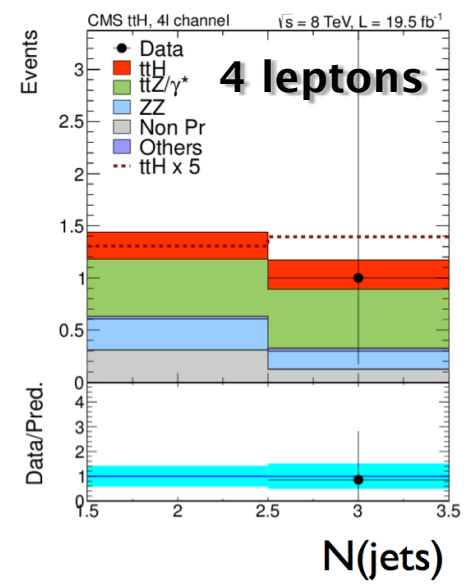
H→γγ





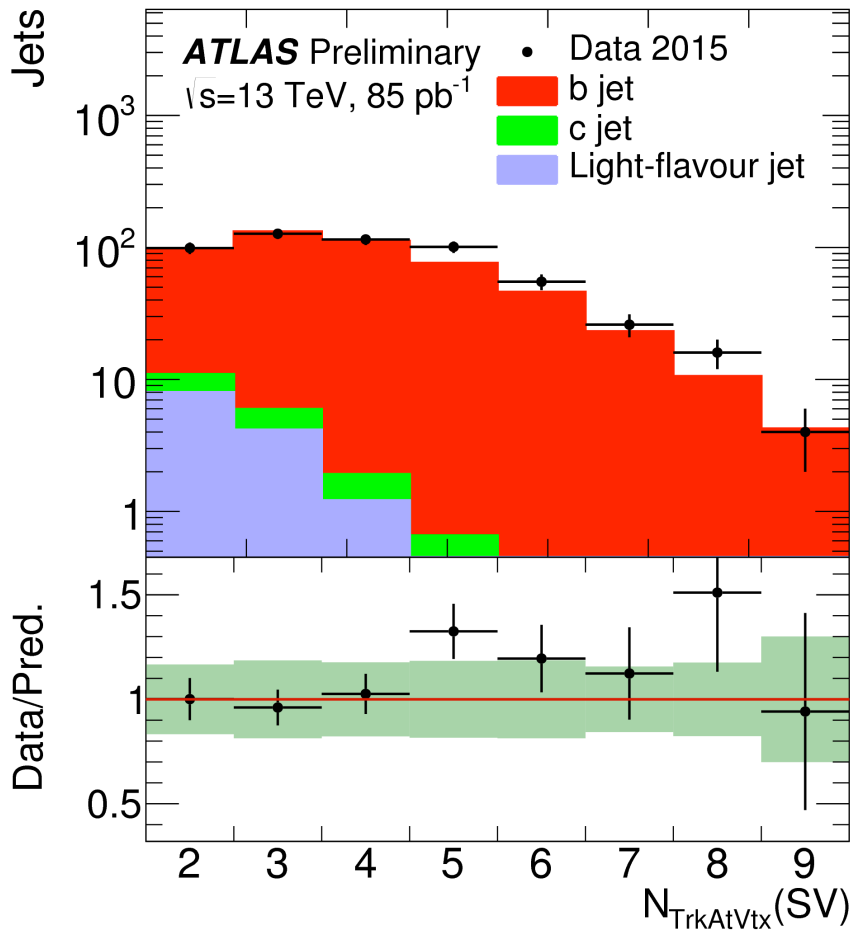
H→WW, ZZ





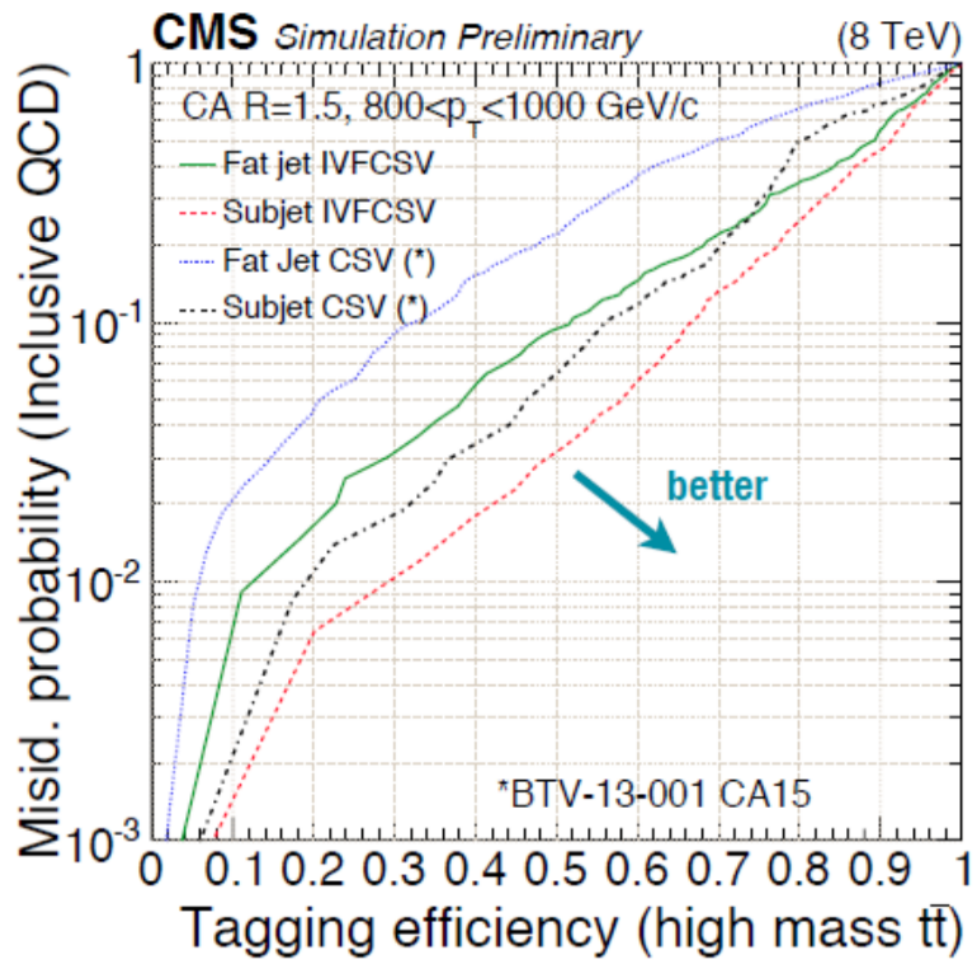
Tools from and for tops

b-tagging from top pairs (eμ)



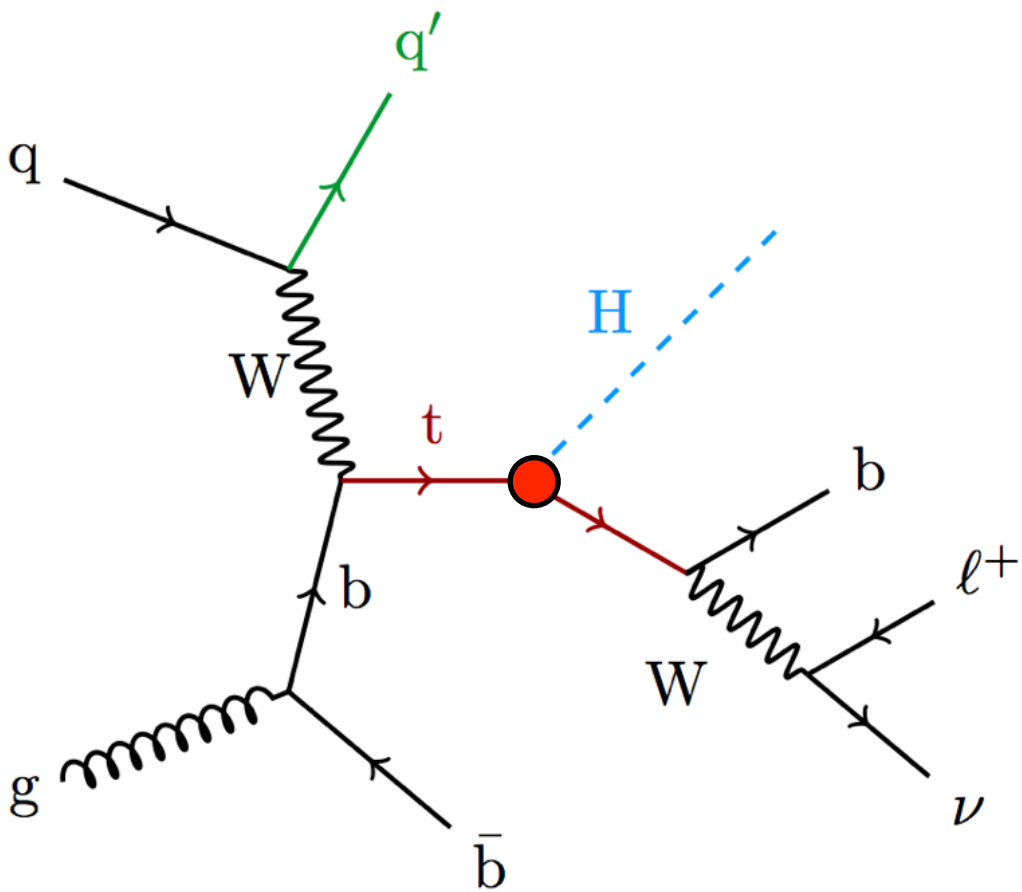
→ great importance for all types of physics

t-tagging in boosted topologies



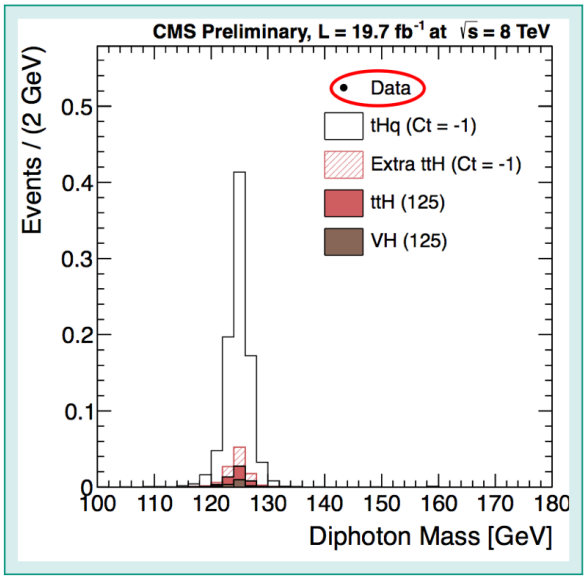
→ huge improvements

Search for tHq production



H→γγ

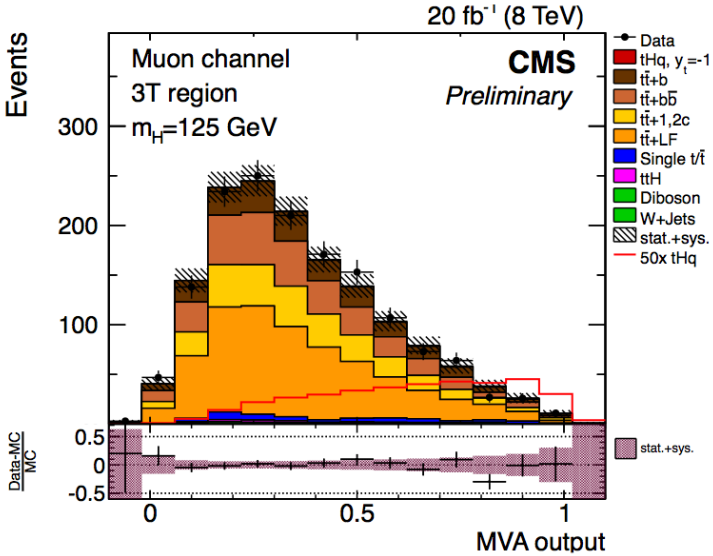
4.1×σ/σ(κt) expected



H→bb

5.1×σ/σ(κt) expected

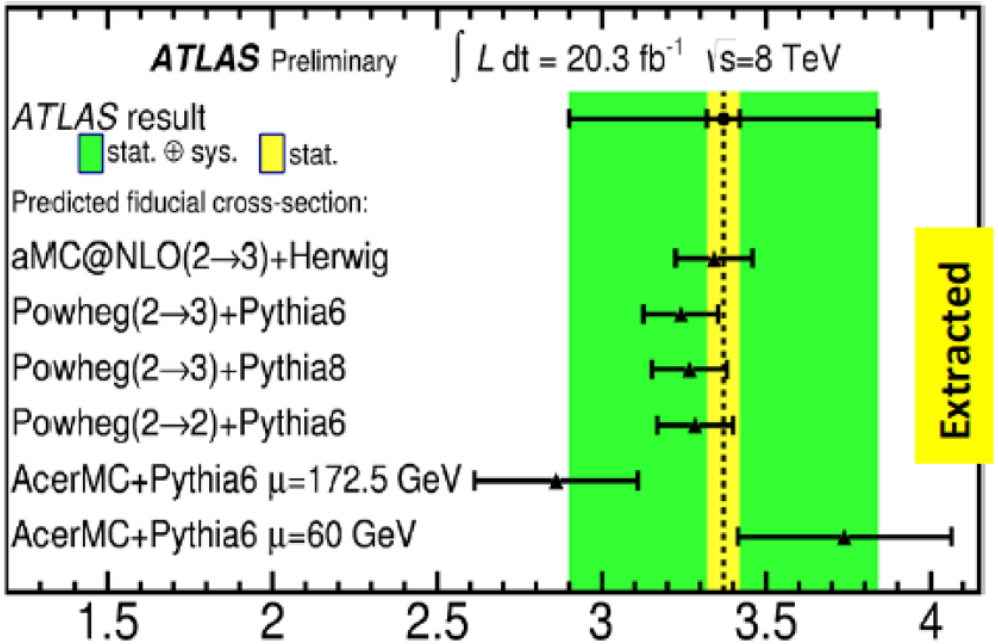
7.6×σ/σ(κt) observed

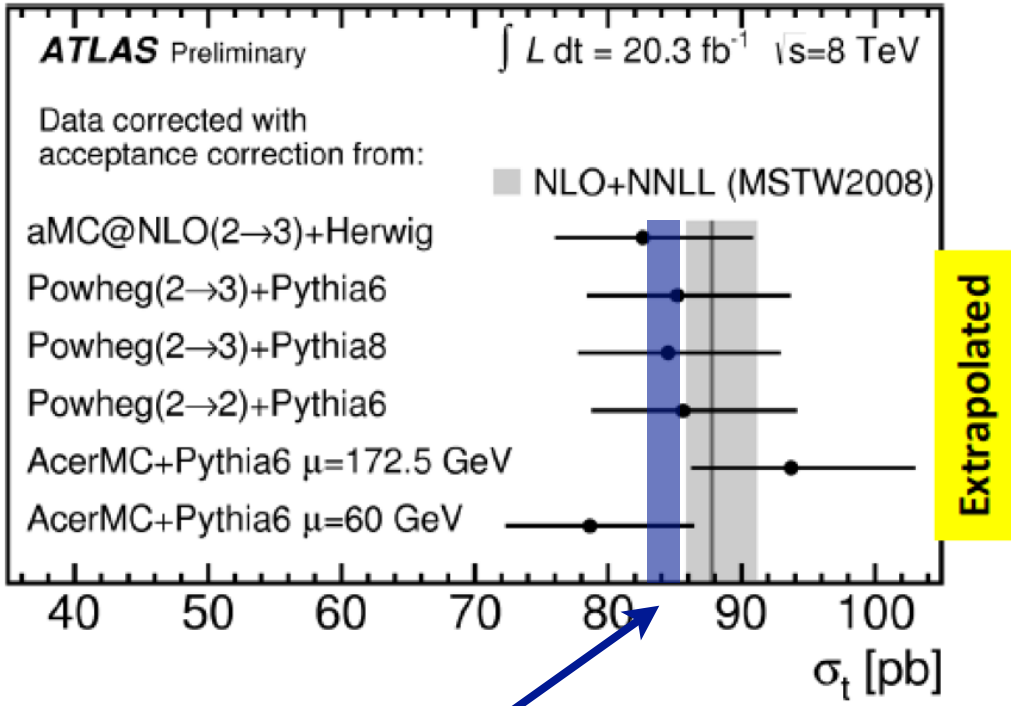


in case top Yukawa coupling $\kappa_t = y_t/y_t^{SM} = -1$ coupling: cross section can be enhanced by factor 13

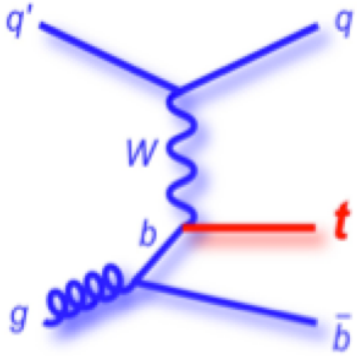
→ fun in Run-II

Fiducial t-channel cross section



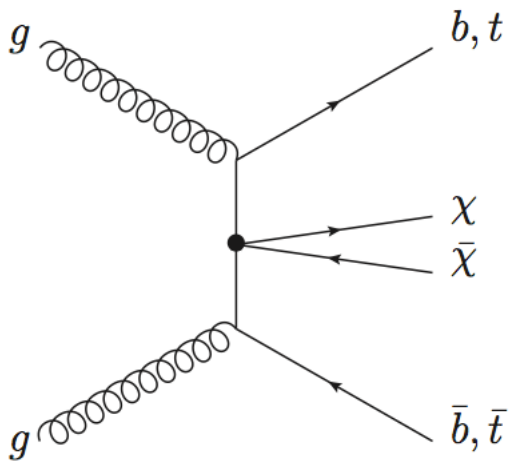


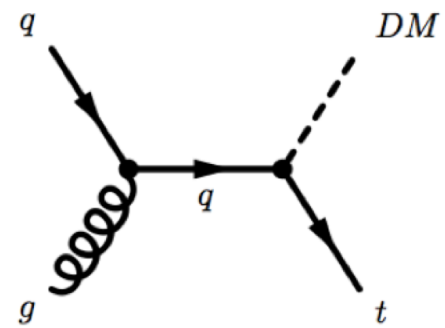
NNLO

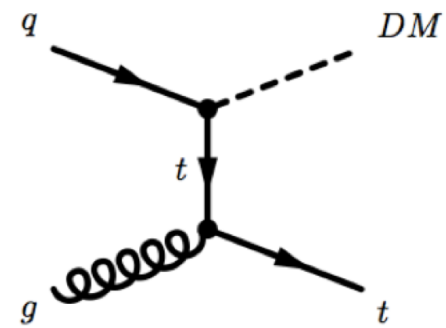


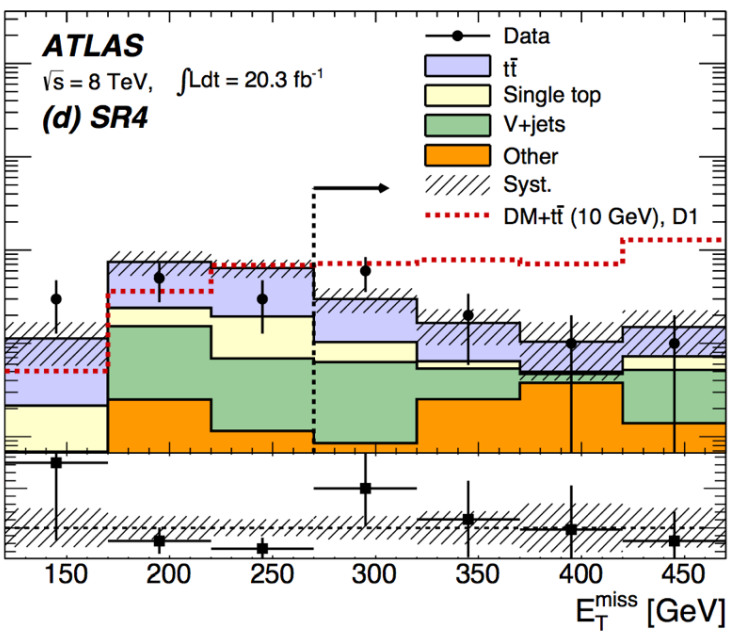
→ **good agreement with SM predictions**

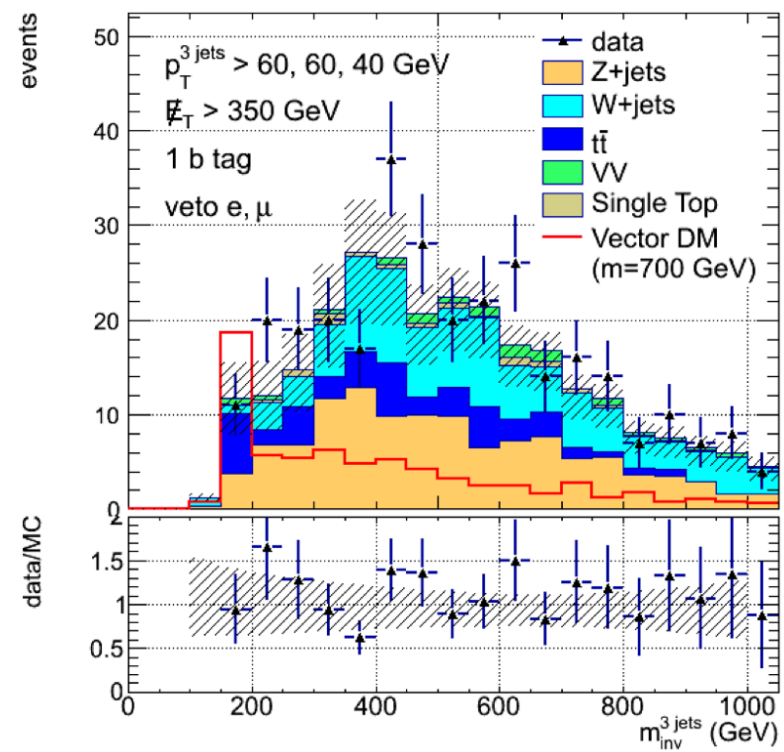
Search for dark matter







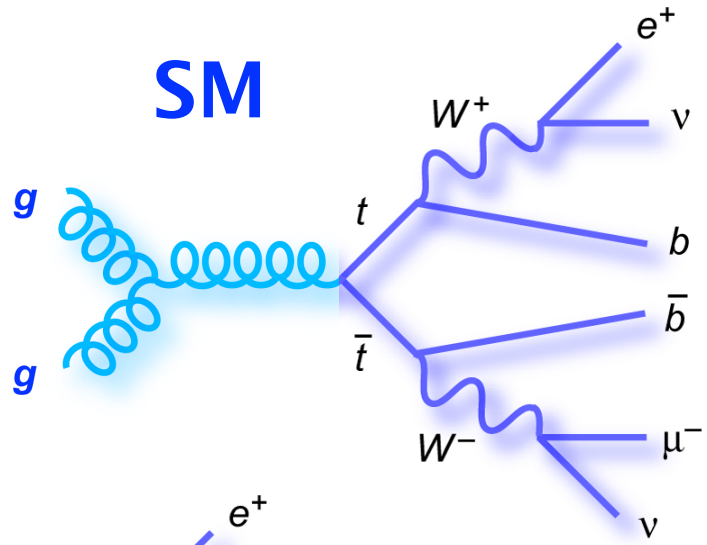


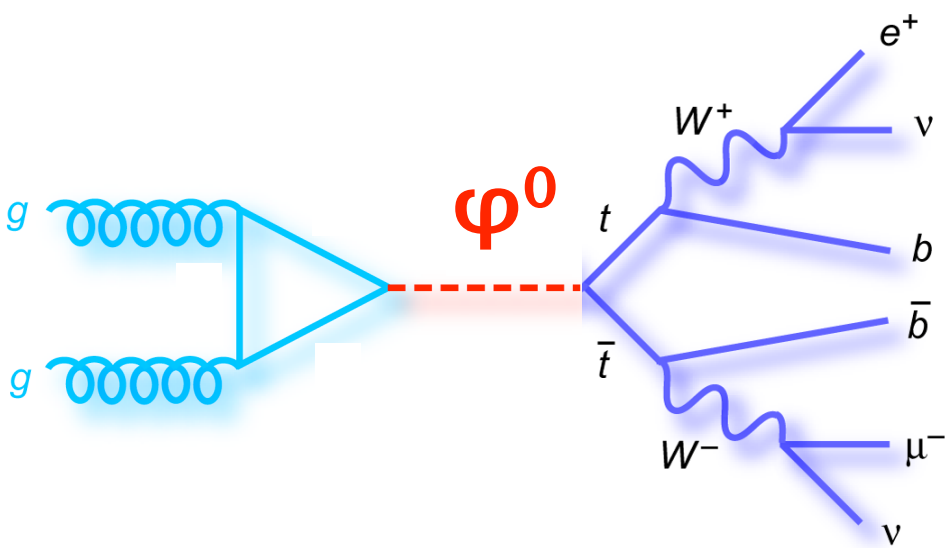


→ **no hint for dark matter**

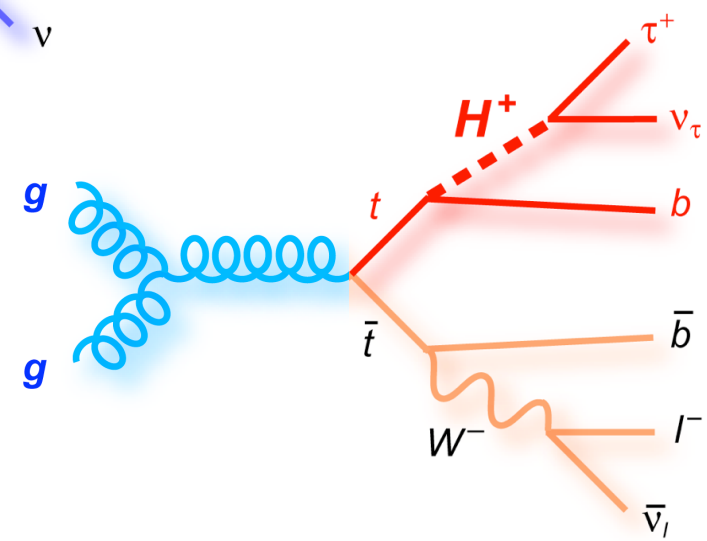
New physics impact on spin

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay





Higgs, KK gravitons, Z', stop pairs, ...



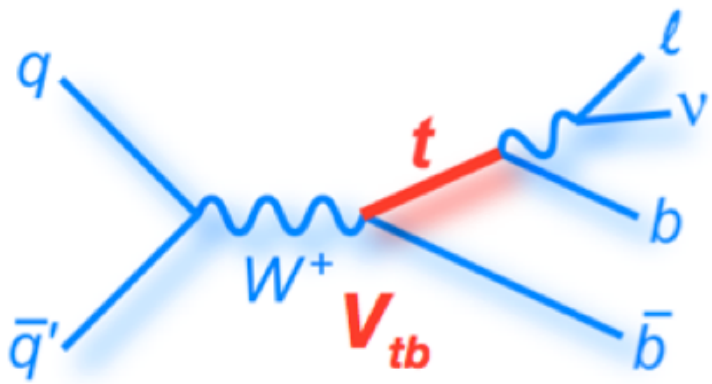
charged Higgs, b', ...

Single Top Quark Selection

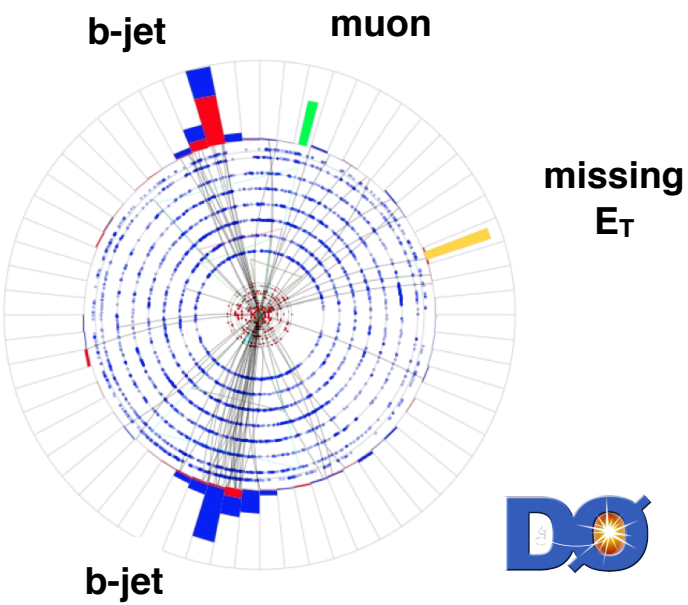
s-channel: $\sigma_s = 1.05 \pm 0.06$ pb

NLO+NNLL, $m_t = 172.5$ GeV

Kidonakis, PRD 81, 054028 (2010)



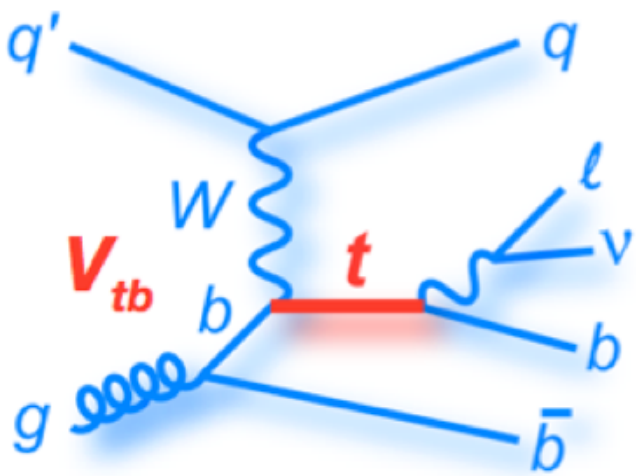
- lepton
- missing E_T
- b-jets



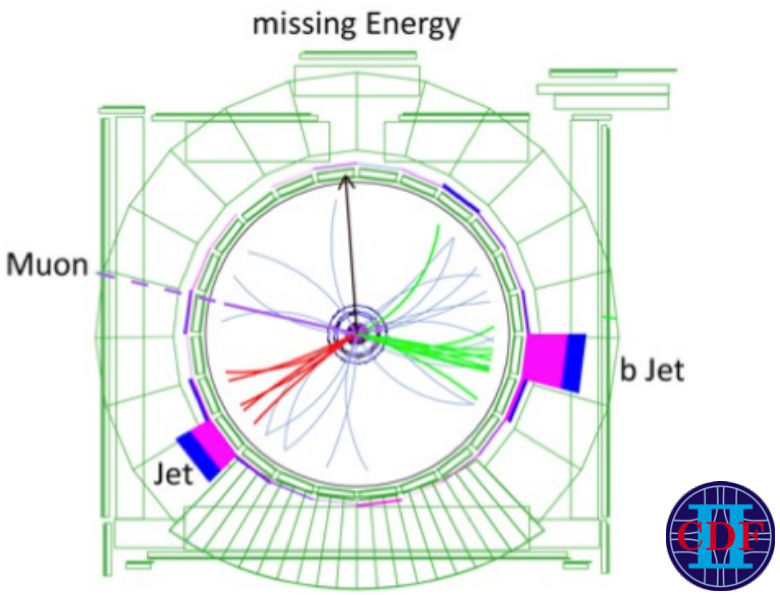
t-channel: $\sigma_t = 2.12 \pm 0.16$ pb

NLO+NNLL, $m_t = 172.5$ GeV

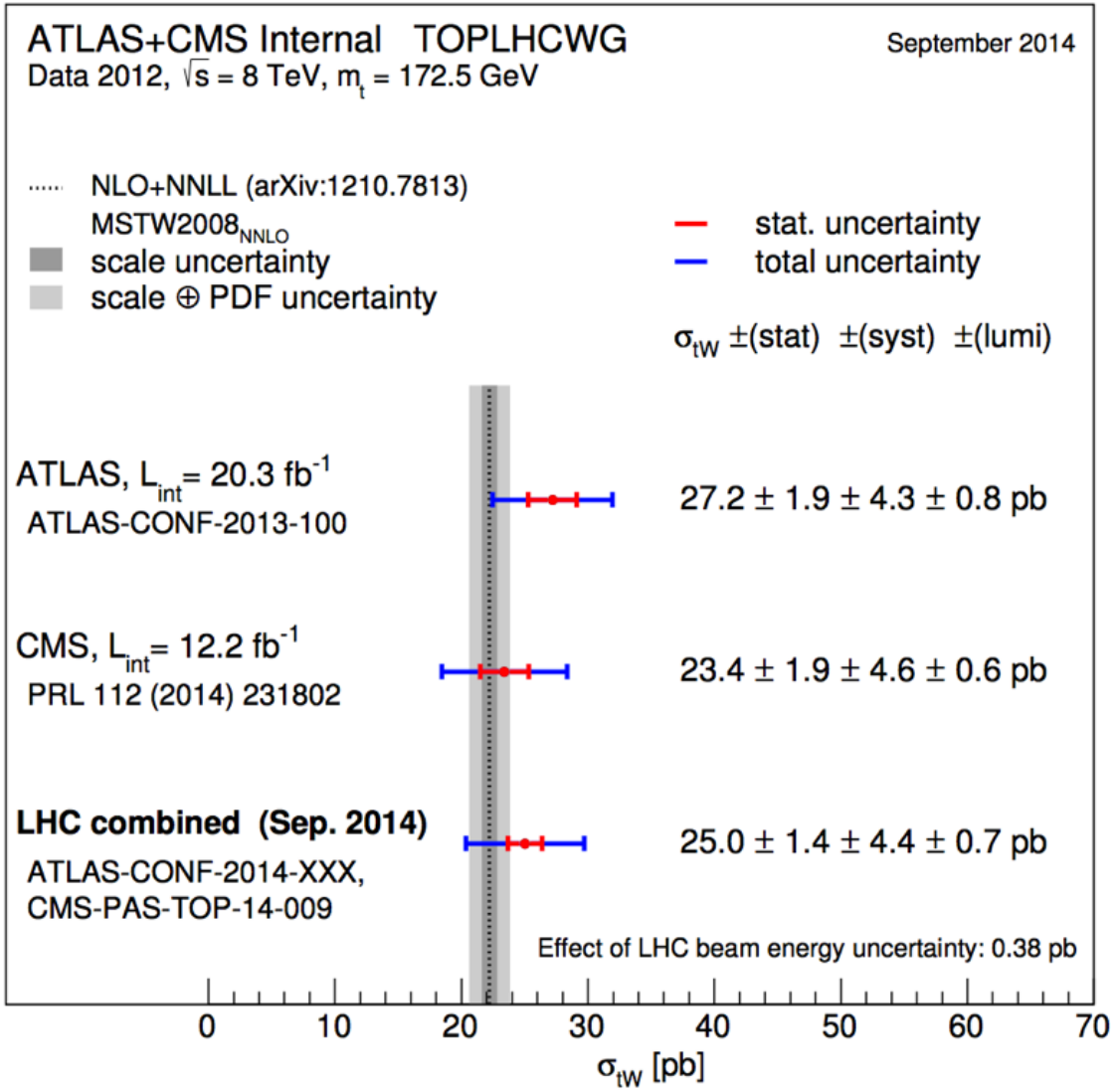
Kidonakis, PRD 83, 091503 (2011)



- jets
- lepton
- missing E_T
- b-jets



Single Top Wt Cross Section

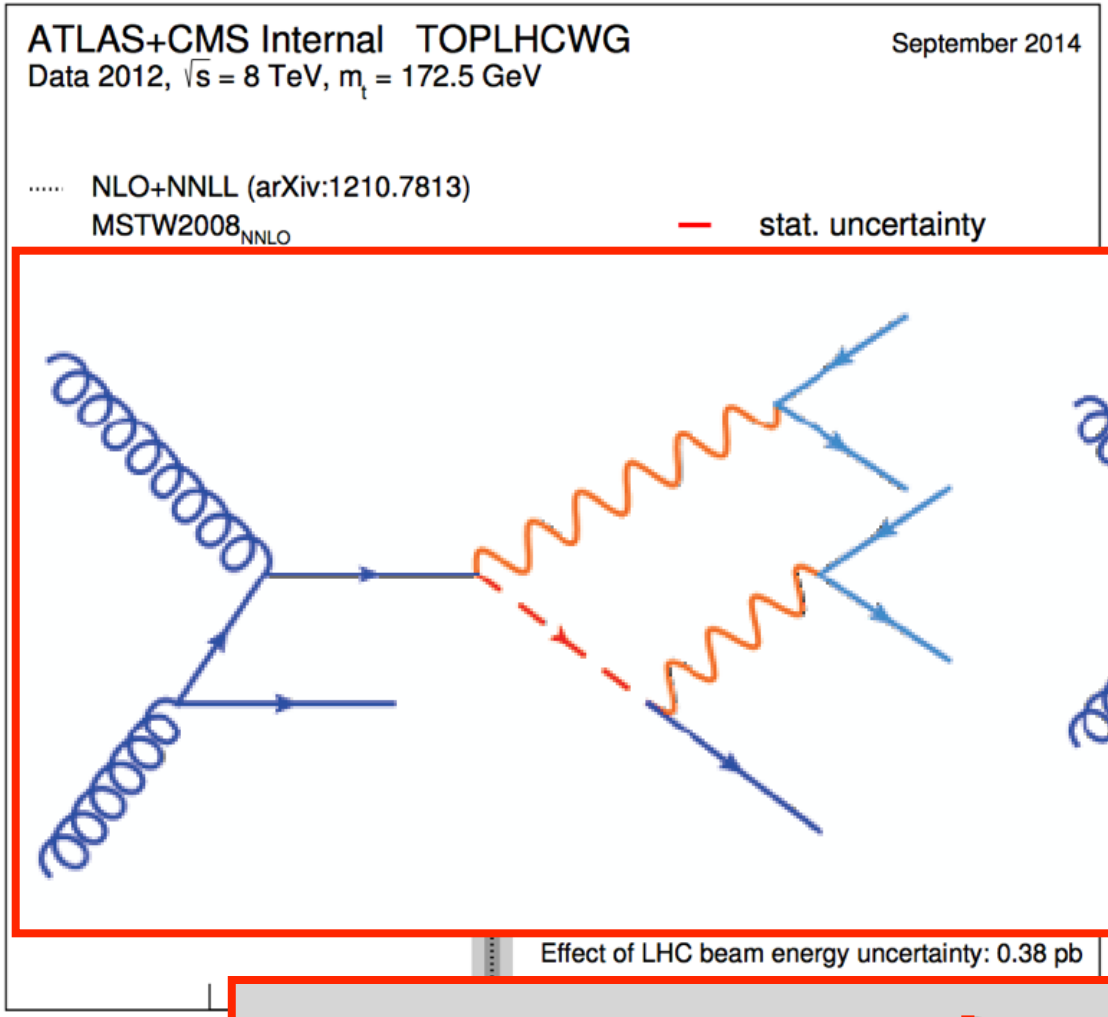


A. Jafari

Source	Uncertainty (%)	Uncertainty (pb)
Data statistics	5.5%	1.4
Simulation statistics	1.8%	0.5
Luminosity	2.7%	0.7
Theory modeling	15.8%	4.0
Background normalization	2.3%	0.6
Jets	5.3%	1.3
Detector modeling	4.9%	1.2
Total systematics (excl. lumi)	17.5%	4.4
Total systematics (incl. lumi)	17.7%	4.4
Total uncertainty	18.6%	4.7

→ observed!

Single Top Quark Cross Section



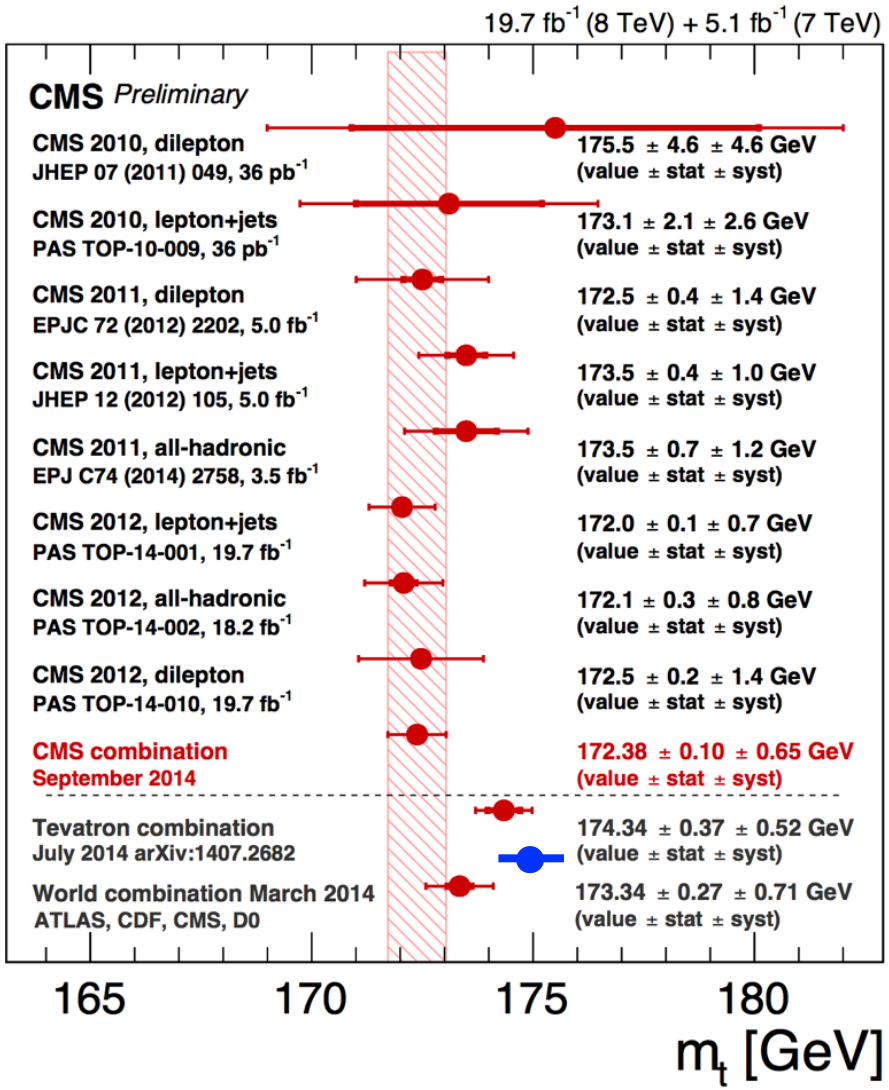
Total systematics (incl. lumi)	17.7%	4.4
	18.6%	4.7

→ **measure WWb cross section**

(single resonant enriched)

CMS top mass combination

top mass crisis?

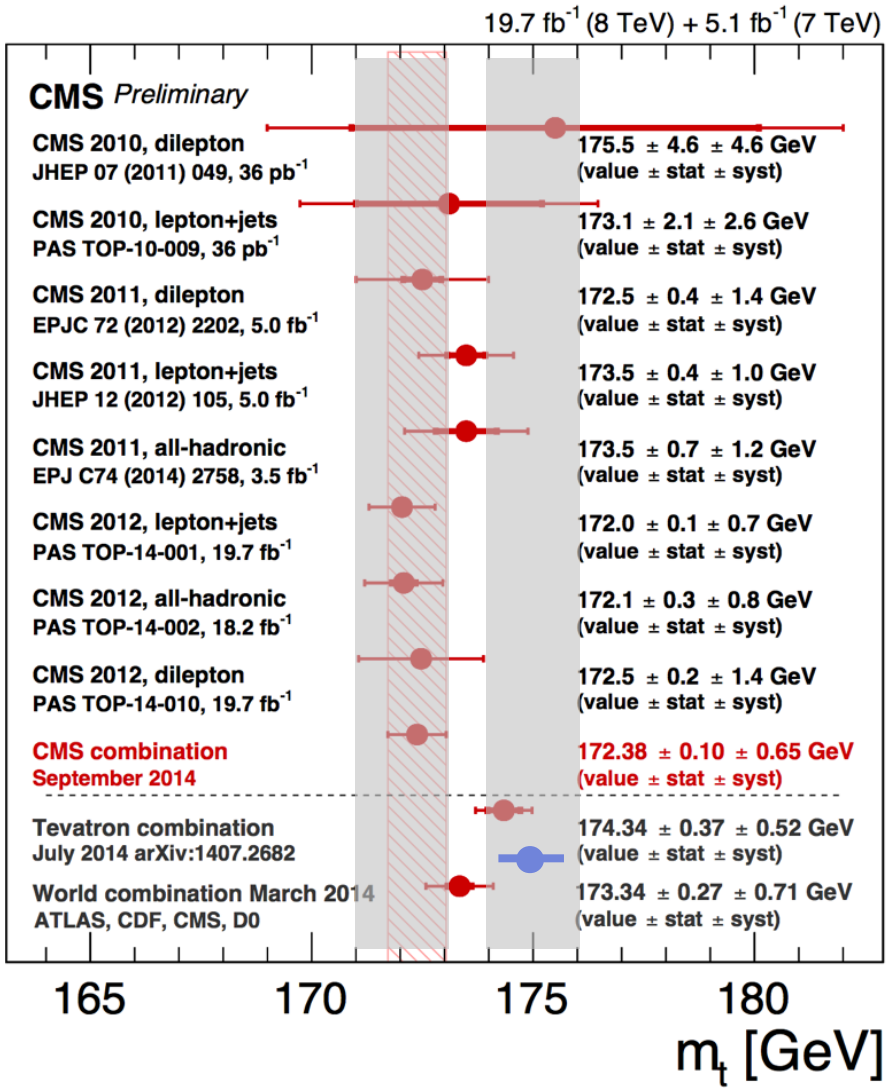


DØ l+jets, 9.7 fb^{-1}

- discussions about JES, b-JES, other systematics
- differences between CMS and D0 to be understood during combination

I am just speculating...

top mass crisis?



DØ l+jets, 9.7 fb^{-1}

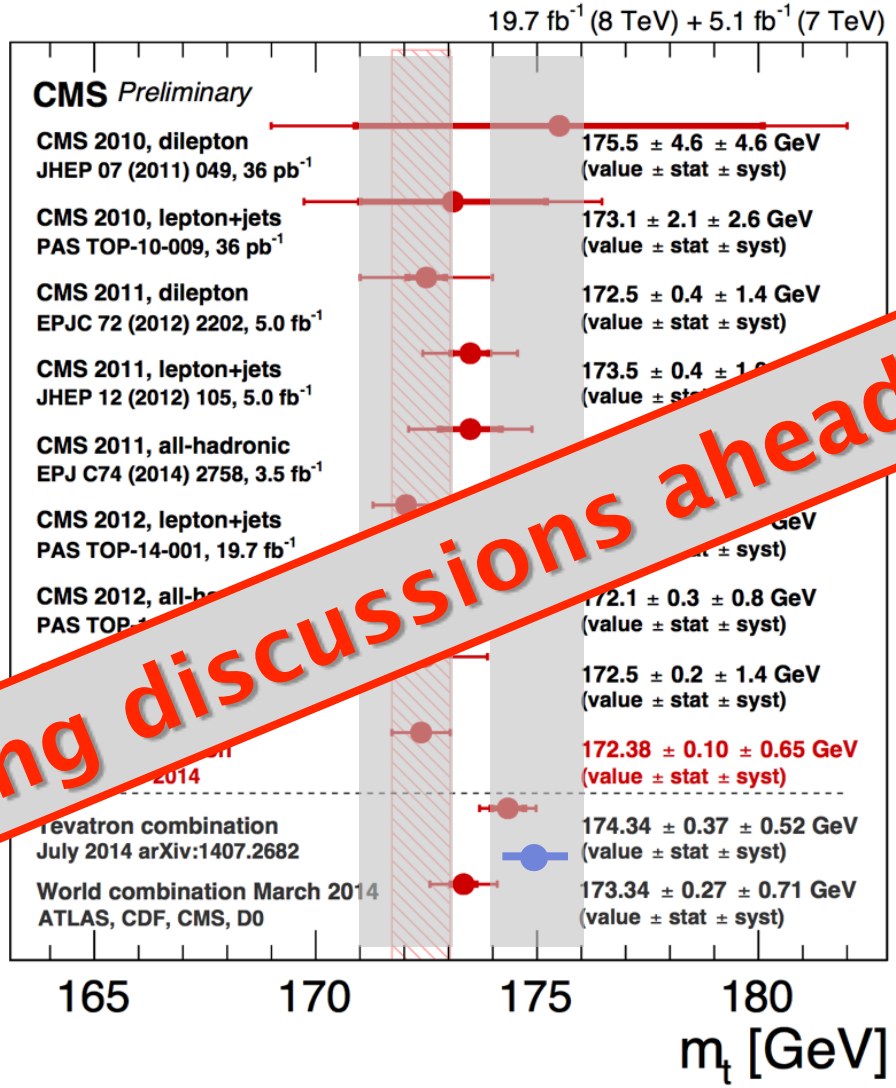
- each MC mass can shift by up to $\Delta \approx O(1\ \text{GeV})$ to QFT mass
- WbWb off-shell effects: can move $\langle m_{lb} \rangle$ by O(1 GeV)

J. Winter

I am just thinking...

top mass crisis?

E. Schlieckau



→ exciting discussions ahead of us...

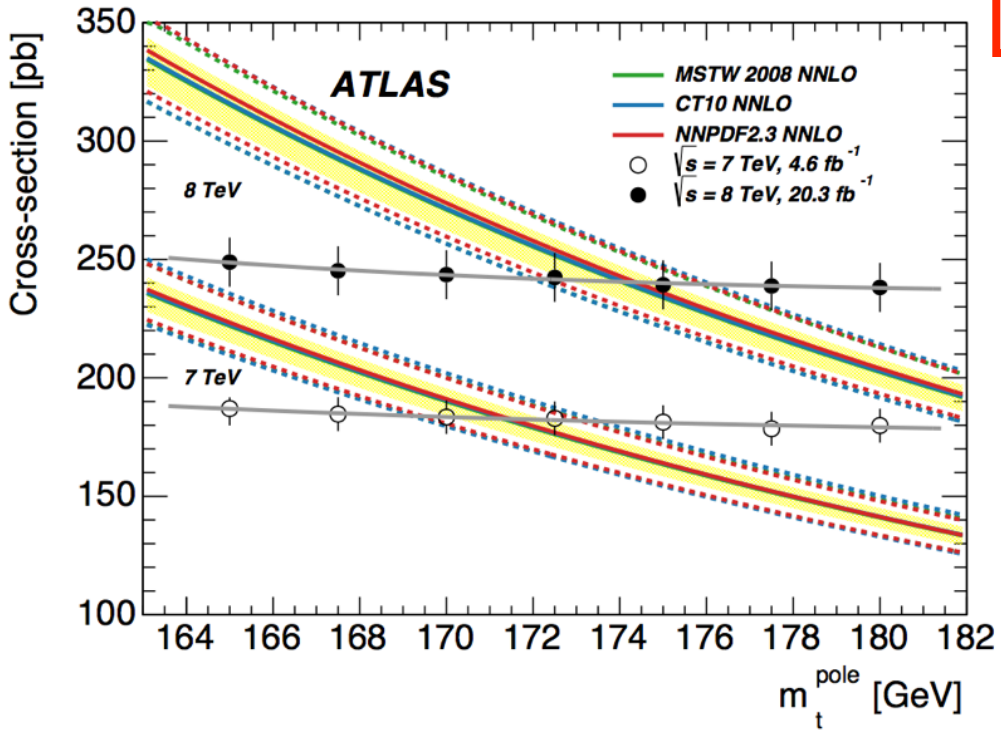
DØ l+jets, 9.7 fb^{-1}

A. Hoang

- each MC mass can shift by up to $\Delta \approx O(1\ \text{GeV})$ to QFT mass
- WbWb off-shell effects: can move $\langle m_{lb} \rangle$ by O(1 GeV)

J. Winter

Top Quark Pole Mass



$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\,\text{GeV}\ (\sqrt{s} = 7/8\,\text{TeV})$$

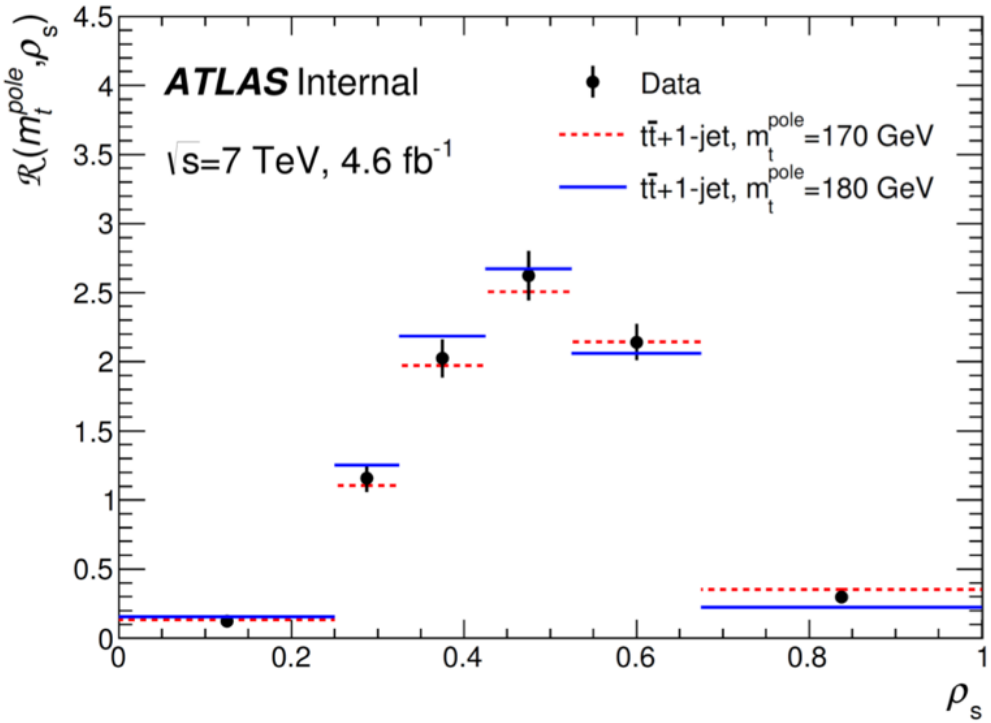
→ pole mass unambiguously!

many alternative measurements

tt+1jet: differential cross section

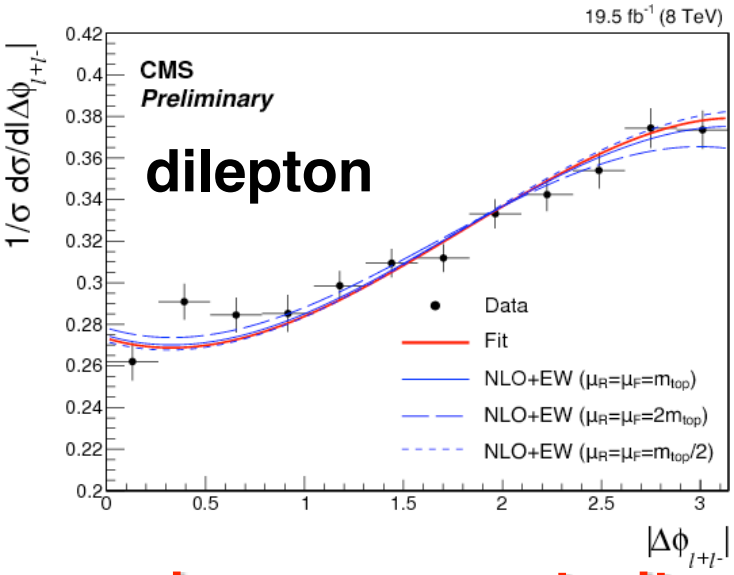
$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\text{jet}}} \frac{d\sigma_{t\bar{t}+1-\text{jet}}}{\rho_s}(m_t^{pole}, \rho_s)$$

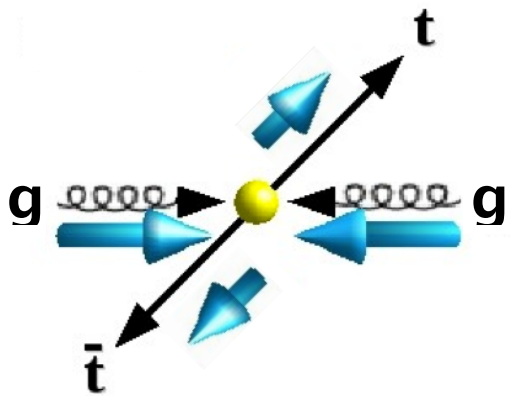
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \qquad m_0 = 170\ GeV$$



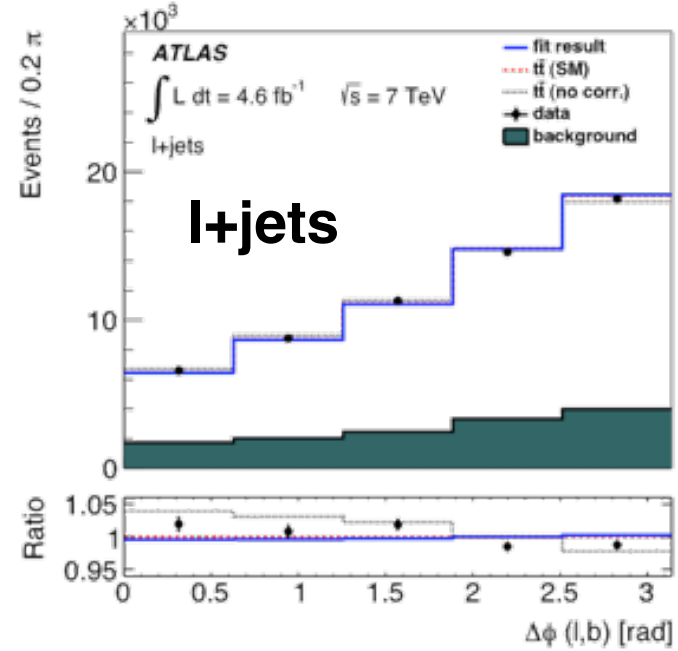
is it really the pole mass?

Polarisation and Spin Correlation

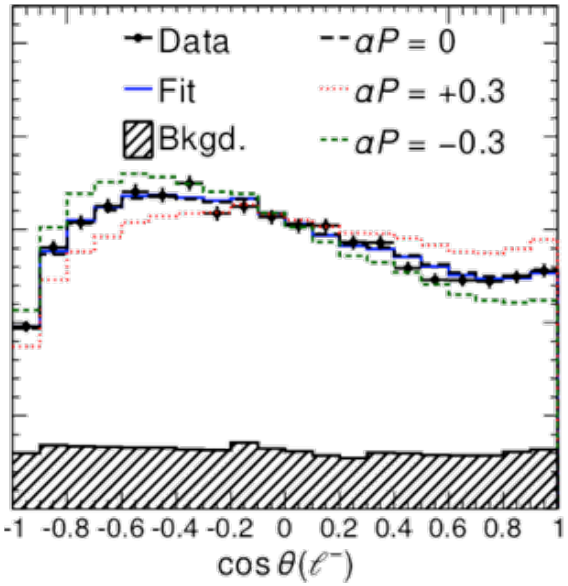


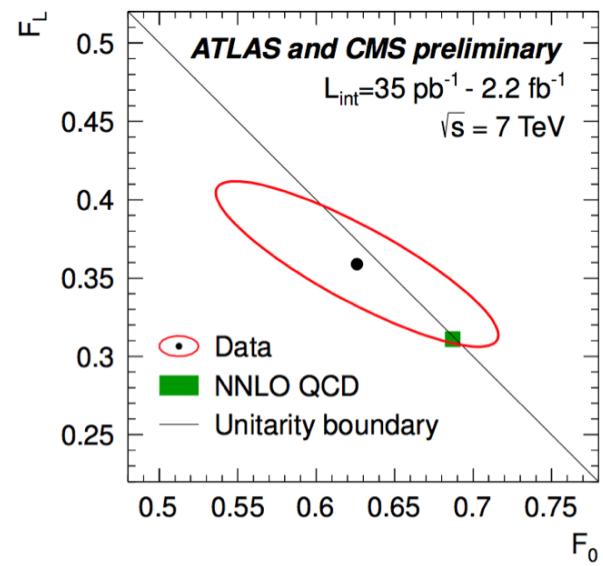


→ spins of tt pairs: correlated as in SM



→ no chromomagnetic dipole moments

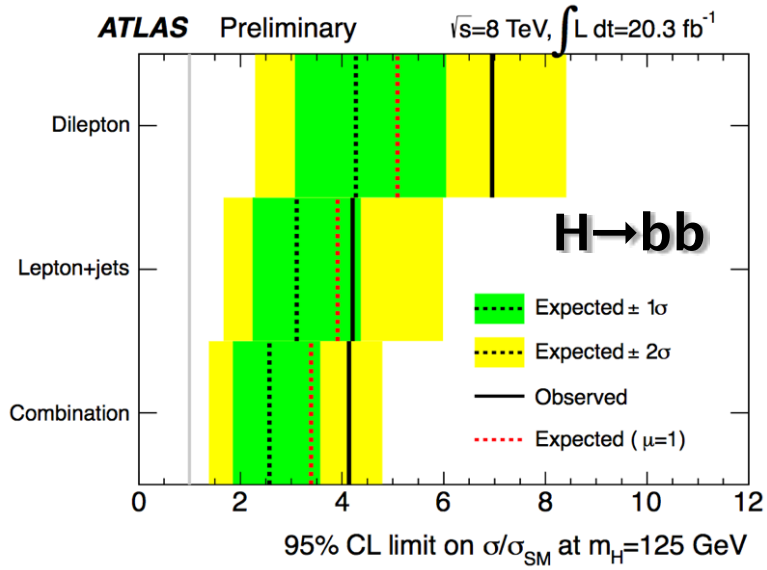




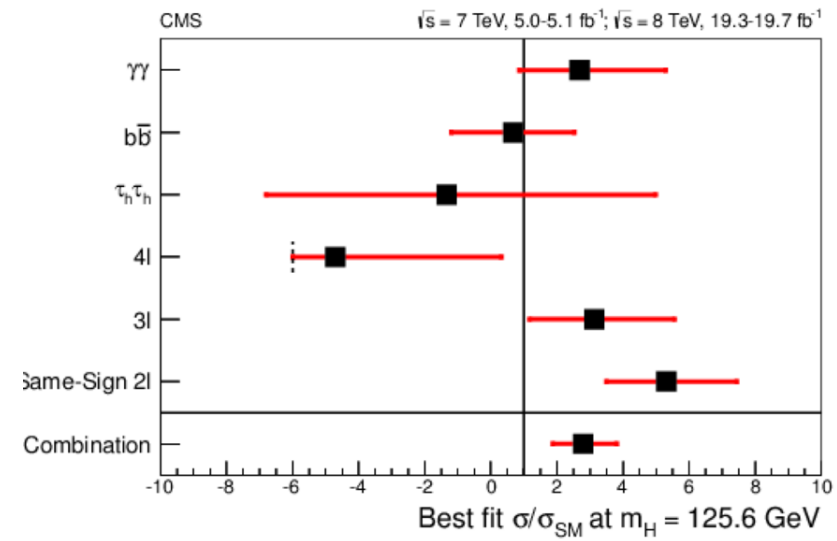
→ top quarks unpolarised

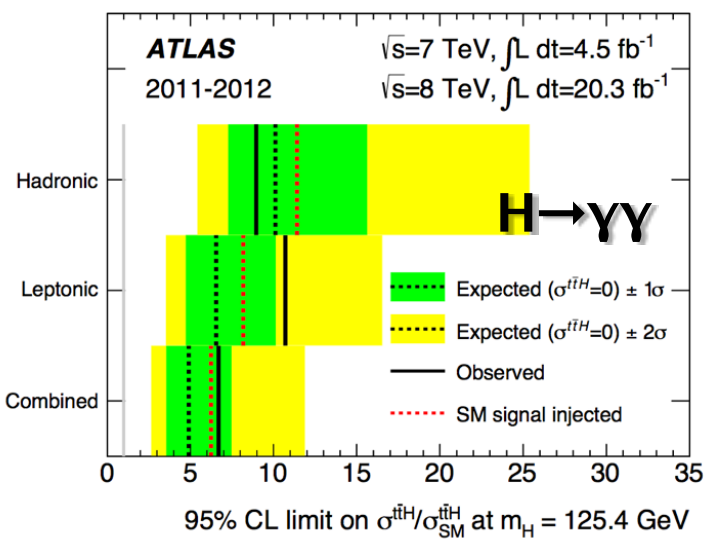
→ W polarisation as in SM

Results in ttH

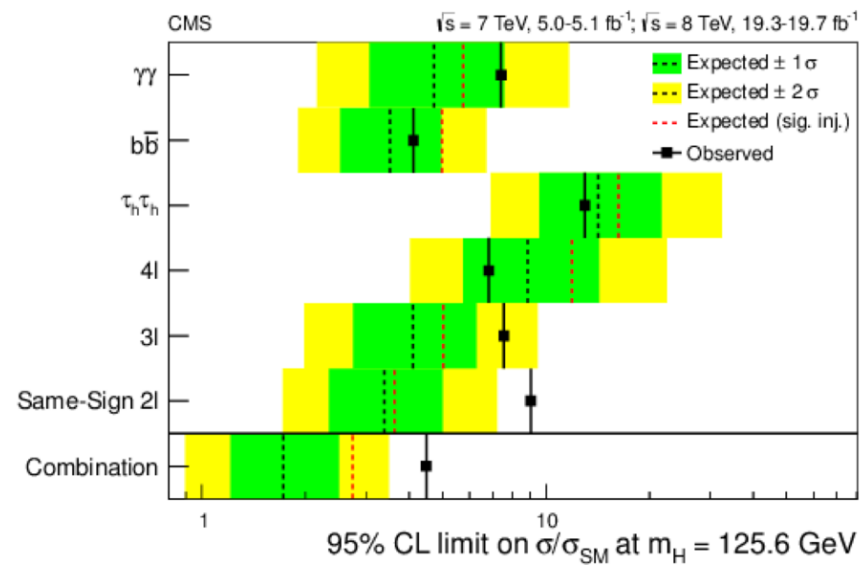


Fitted σ/σ_{SM} = 2.9±2.3



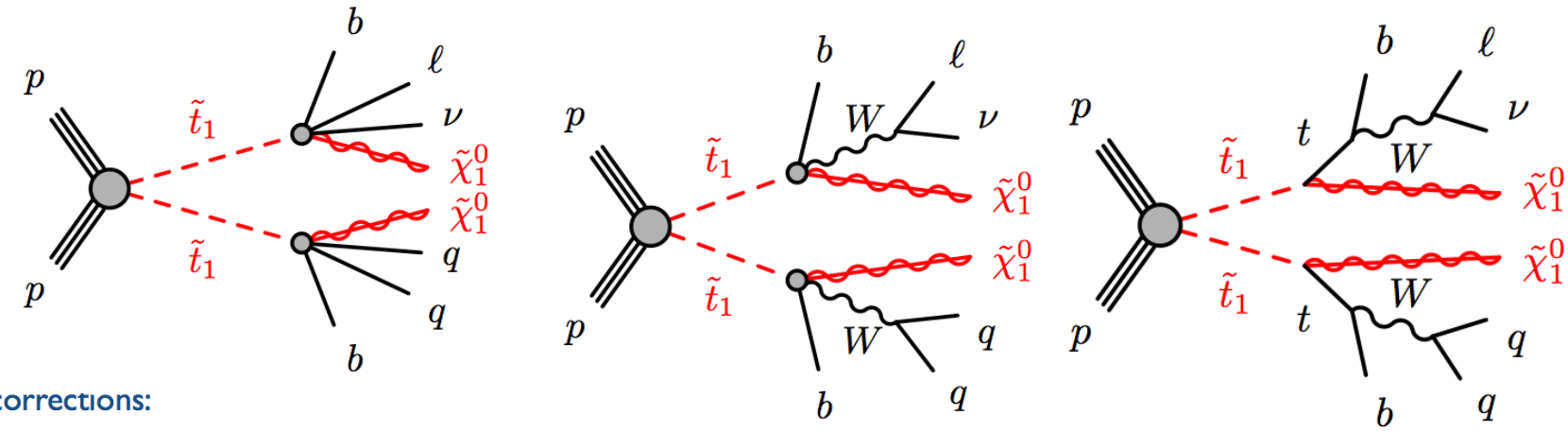


Fitted signal $\sigma/\sigma_{SM} = 1.4\ ^{+2.2}_{-1.4}$

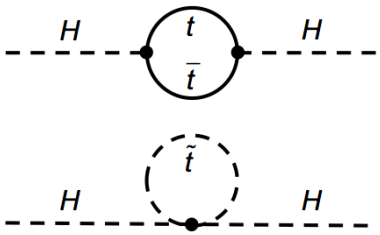


→ observation in Run-II

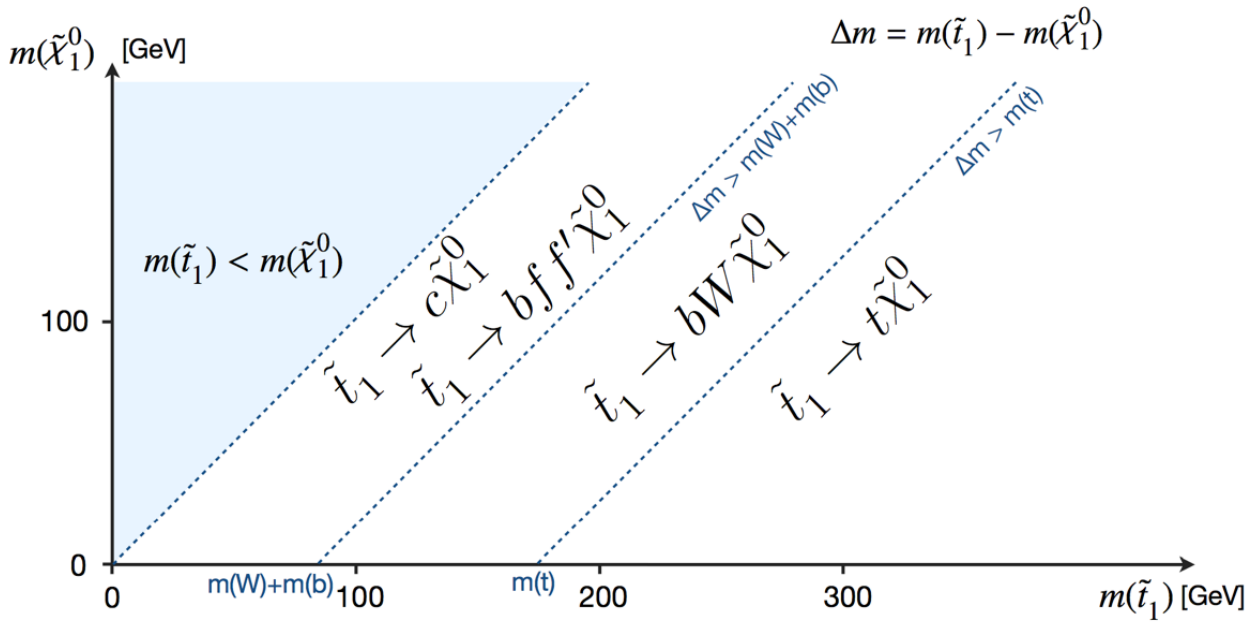
Direct searches for light stop



Recall: **Top loop** is the most i
contribution in Higgs virtual corrections:



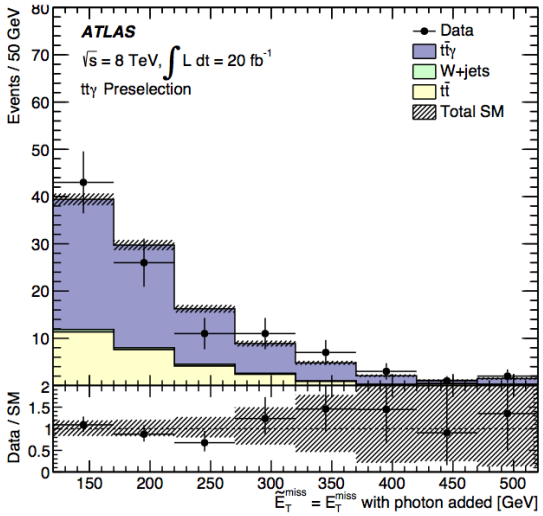
small stop mass is natural

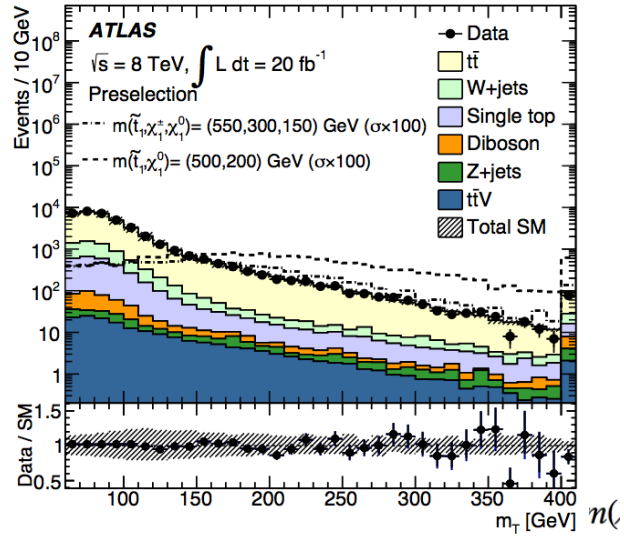


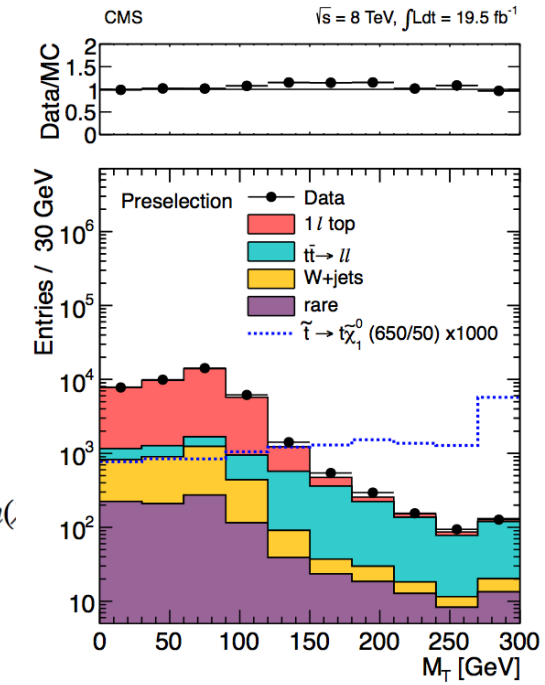
T. Eifert

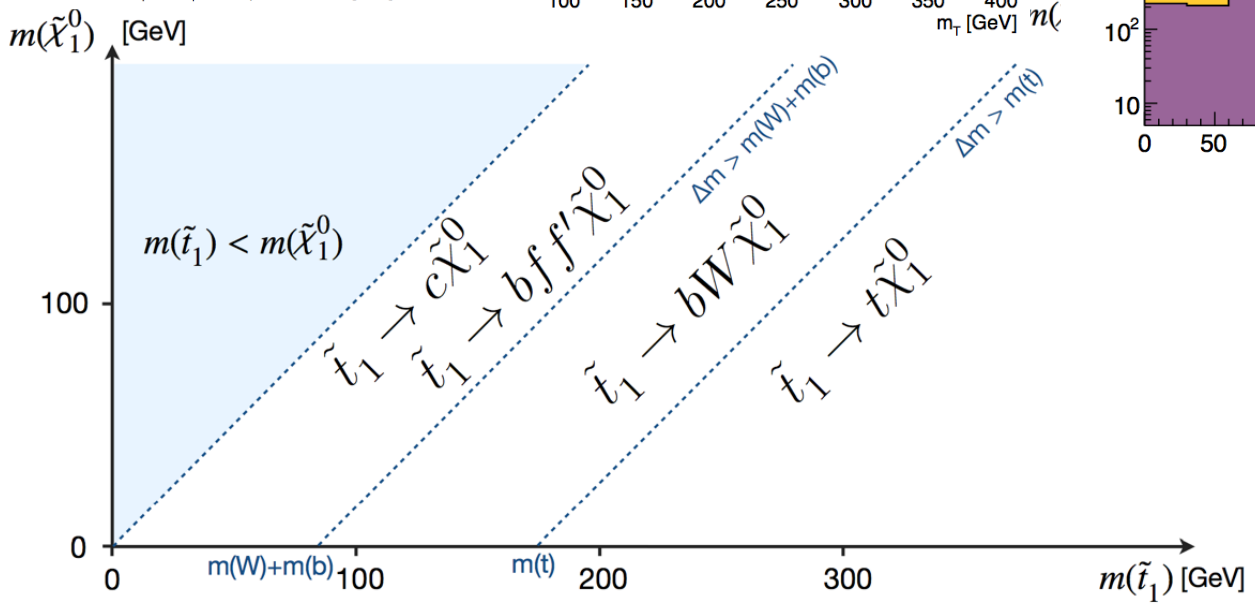
we check every little corner...

Direct stop searches







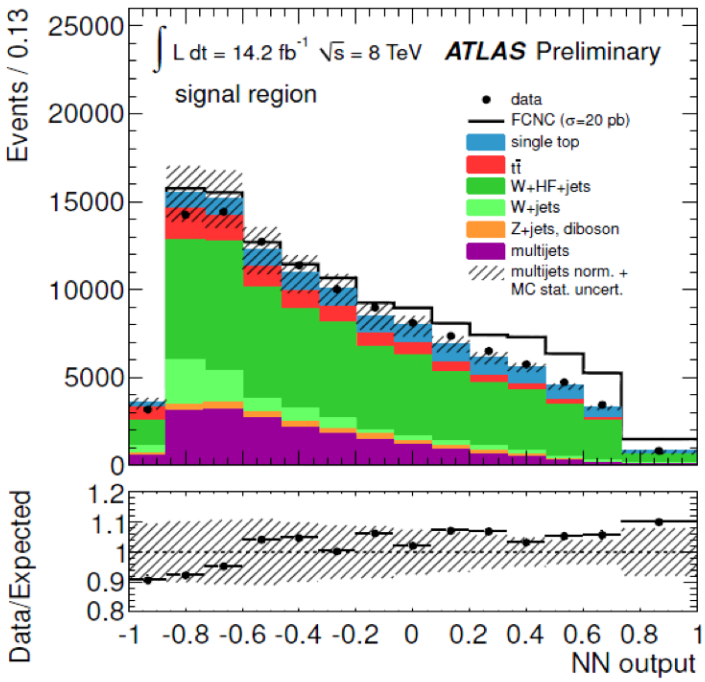


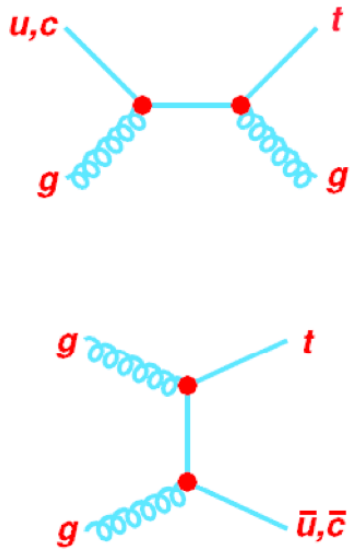
T. Eifert

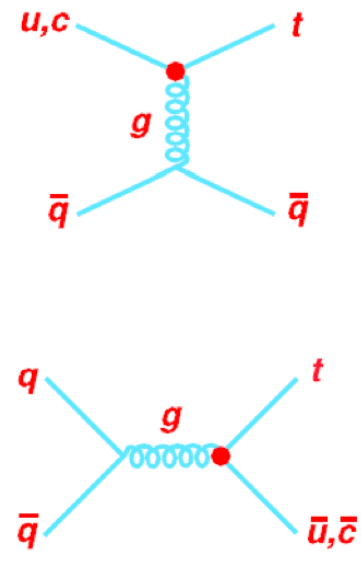
we check every little corner…

Search for FCNC

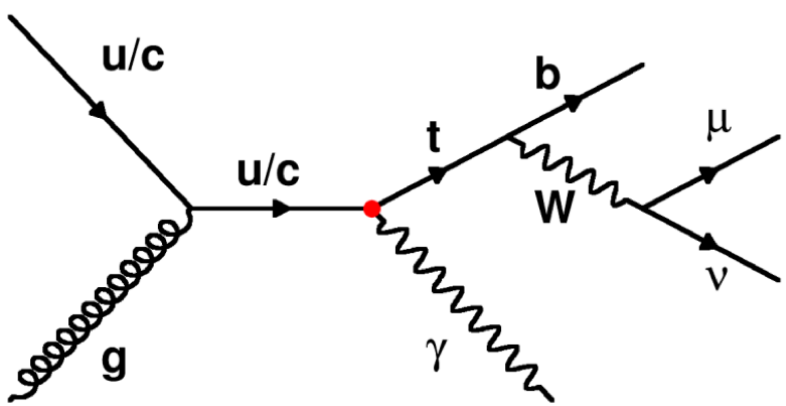
R. Goldouzian

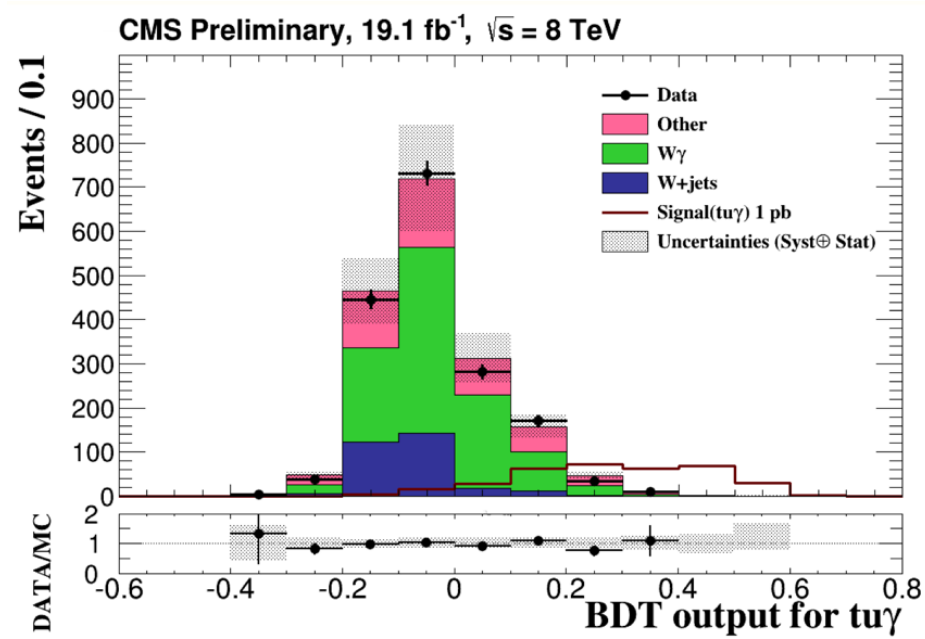






IR divergent?

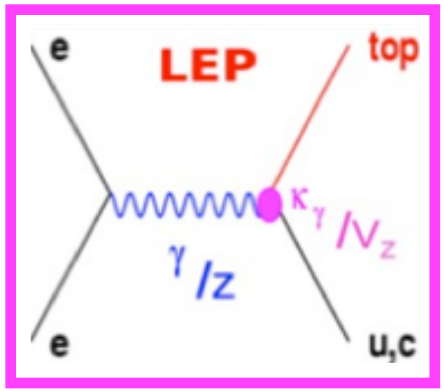


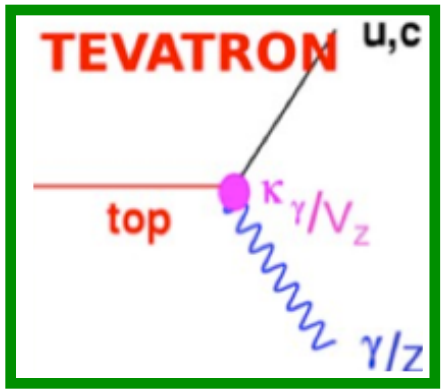


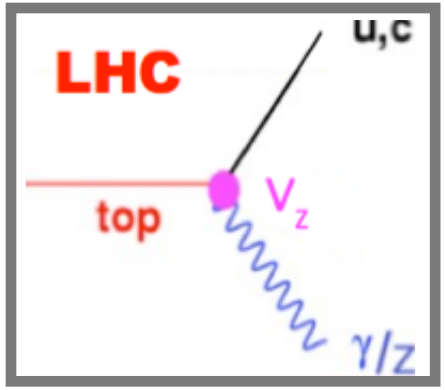
→ no hint for new physics

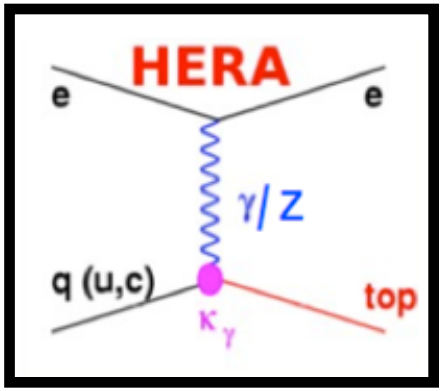
FCNC Top Couplings at

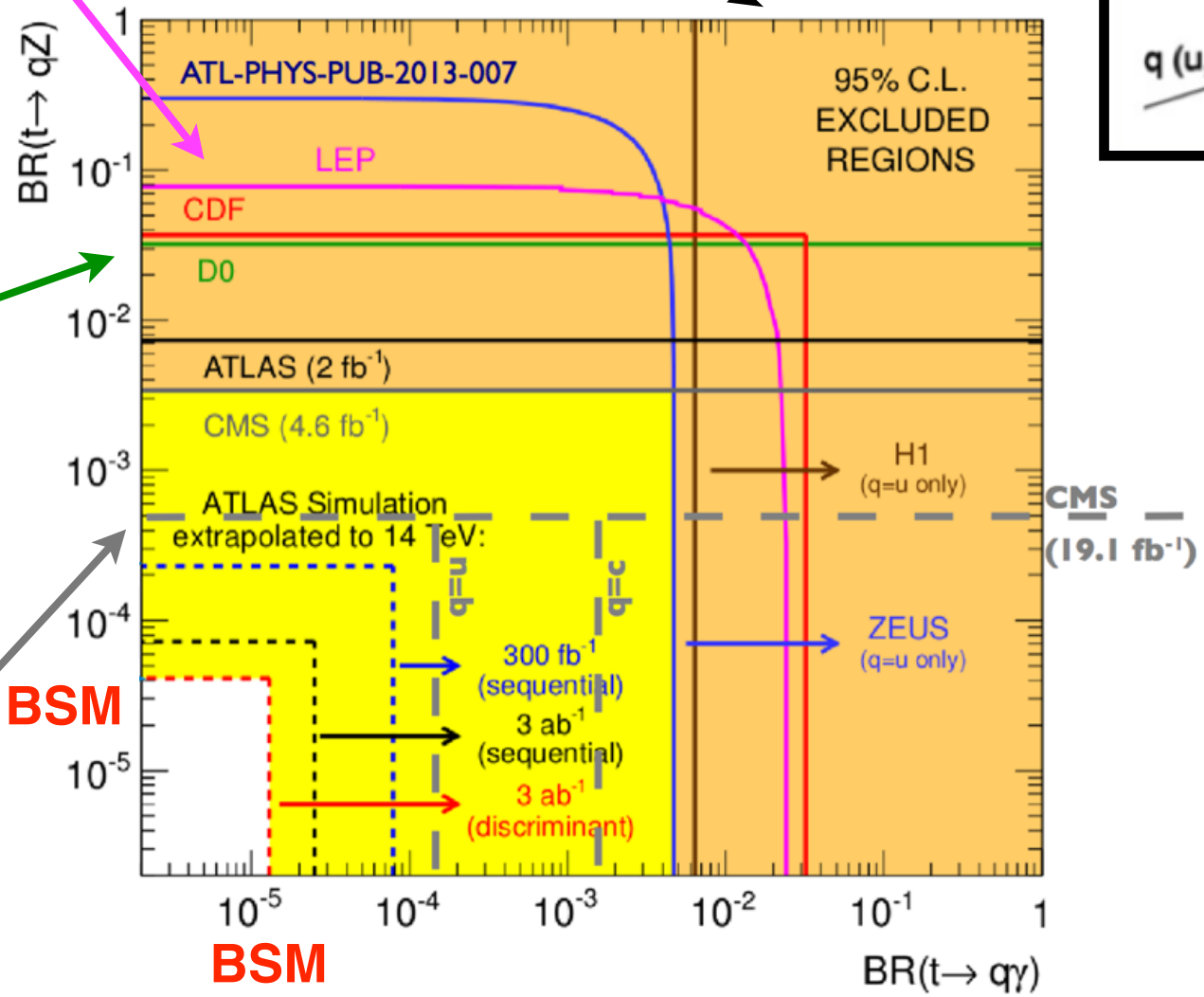
P. Silva









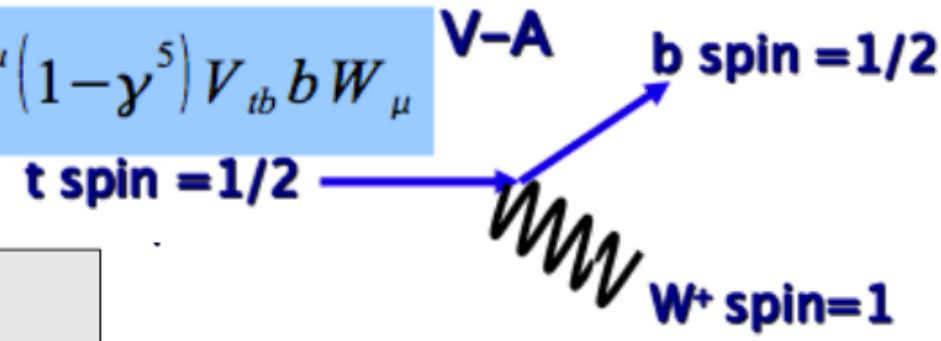


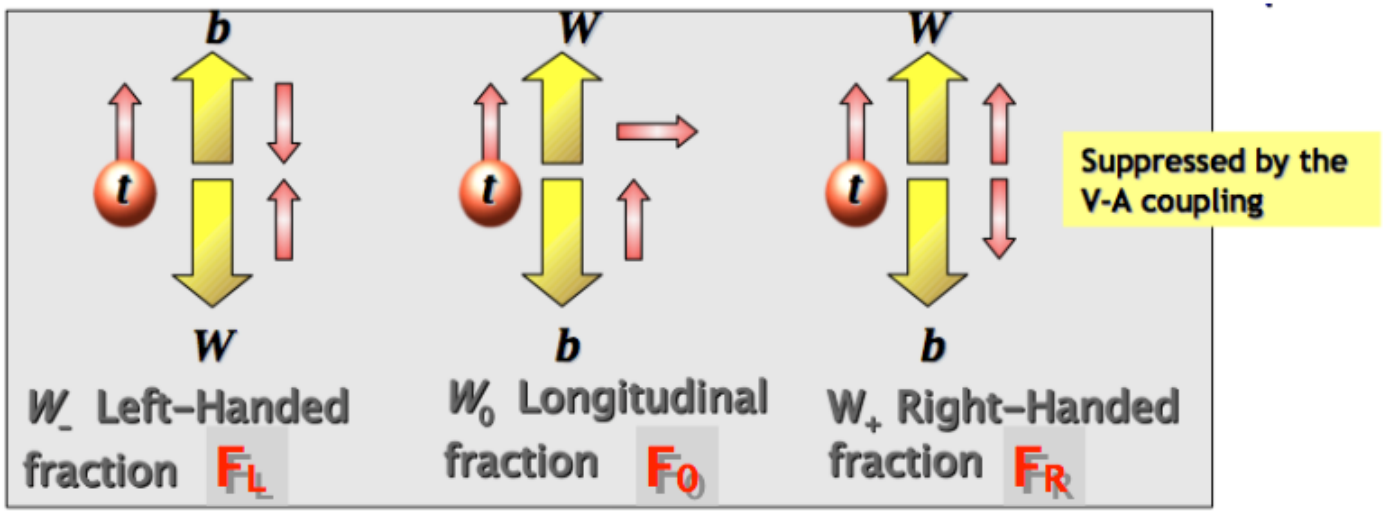
W Boson Helicity Fractions

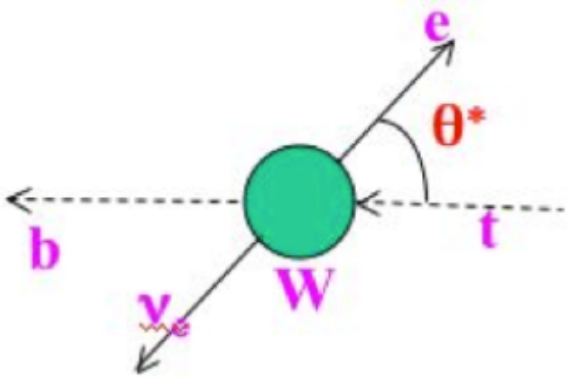
Phys. Rev. D83, 032009 (2011)

$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$

V–A

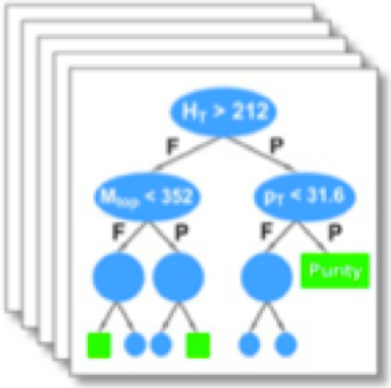




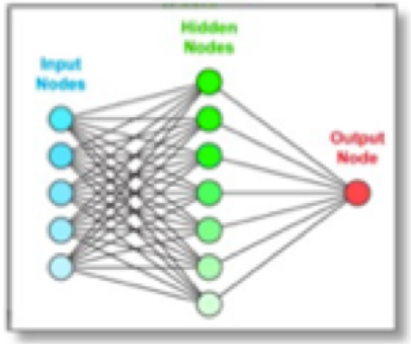


Multivariate Analyses

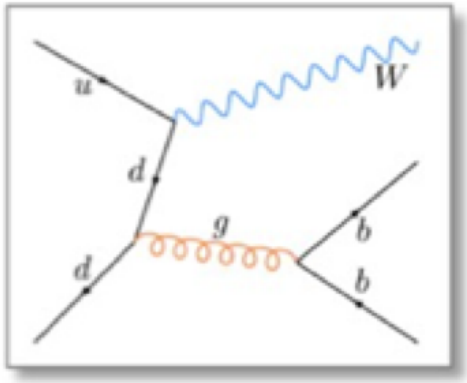
Boosted Decision Trees



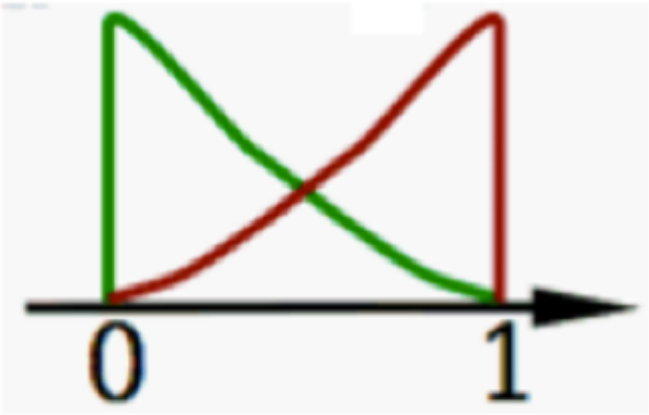
Neural Networks



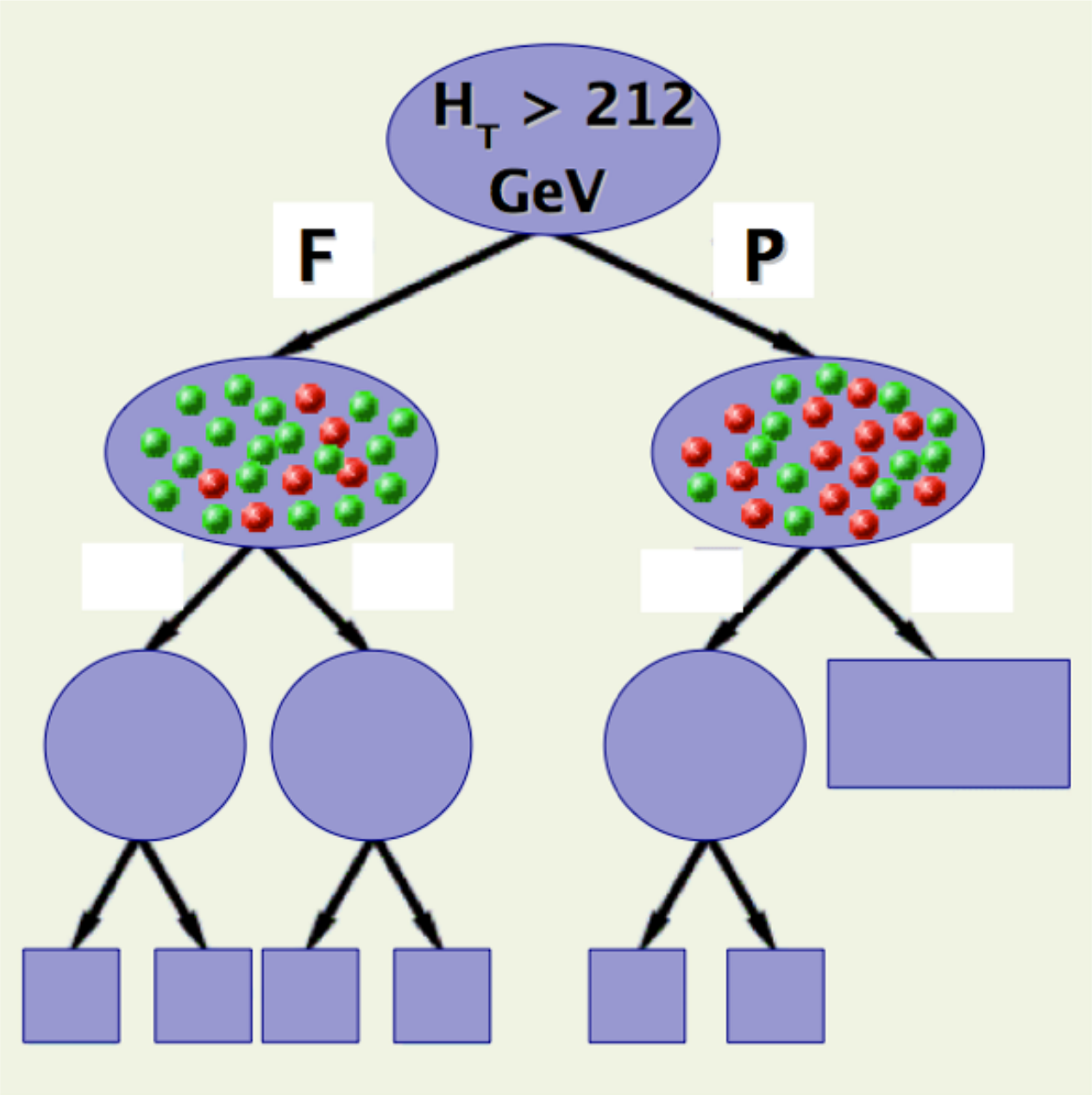
Matrix Elements



background **signal**

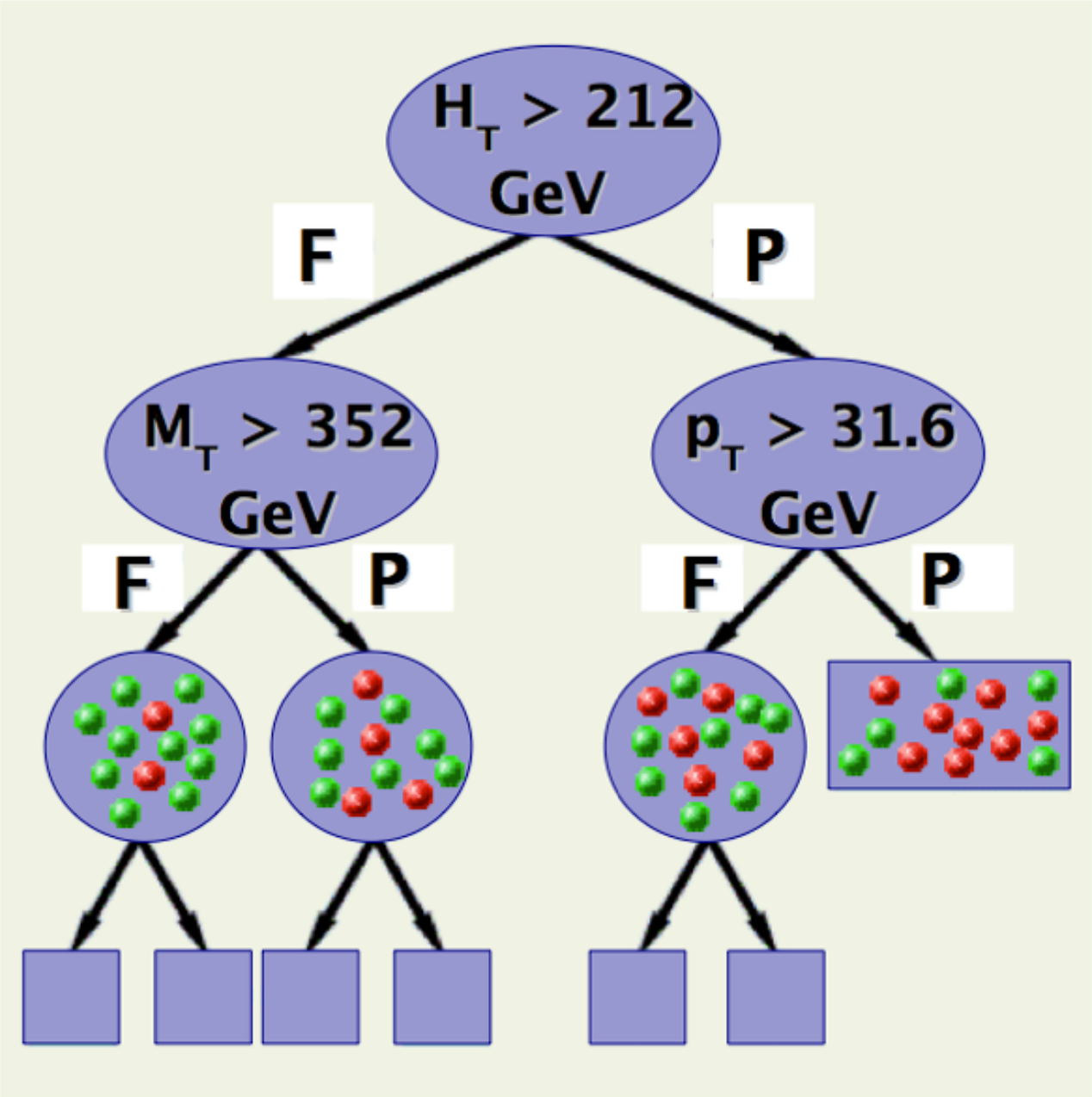


Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



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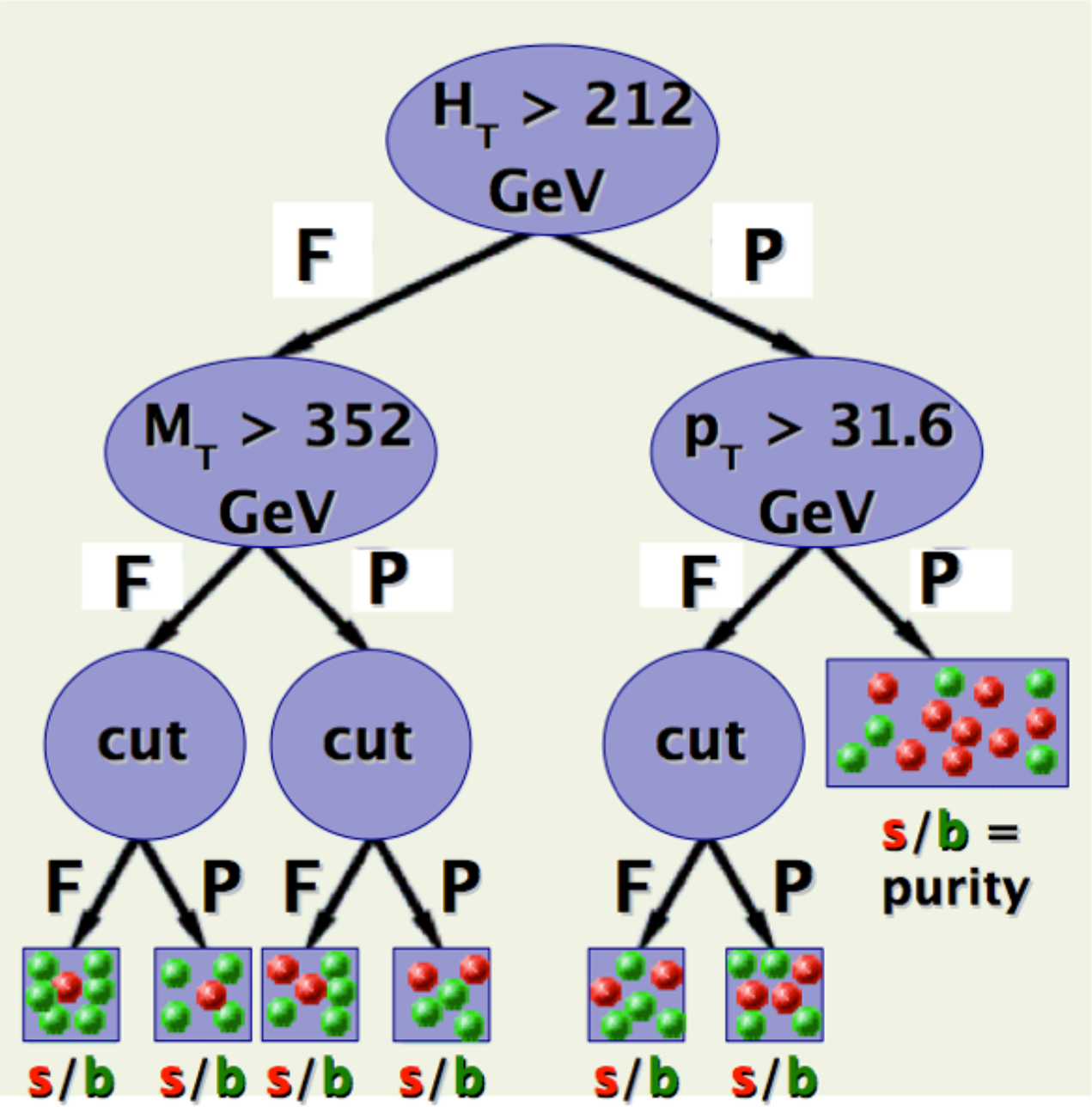
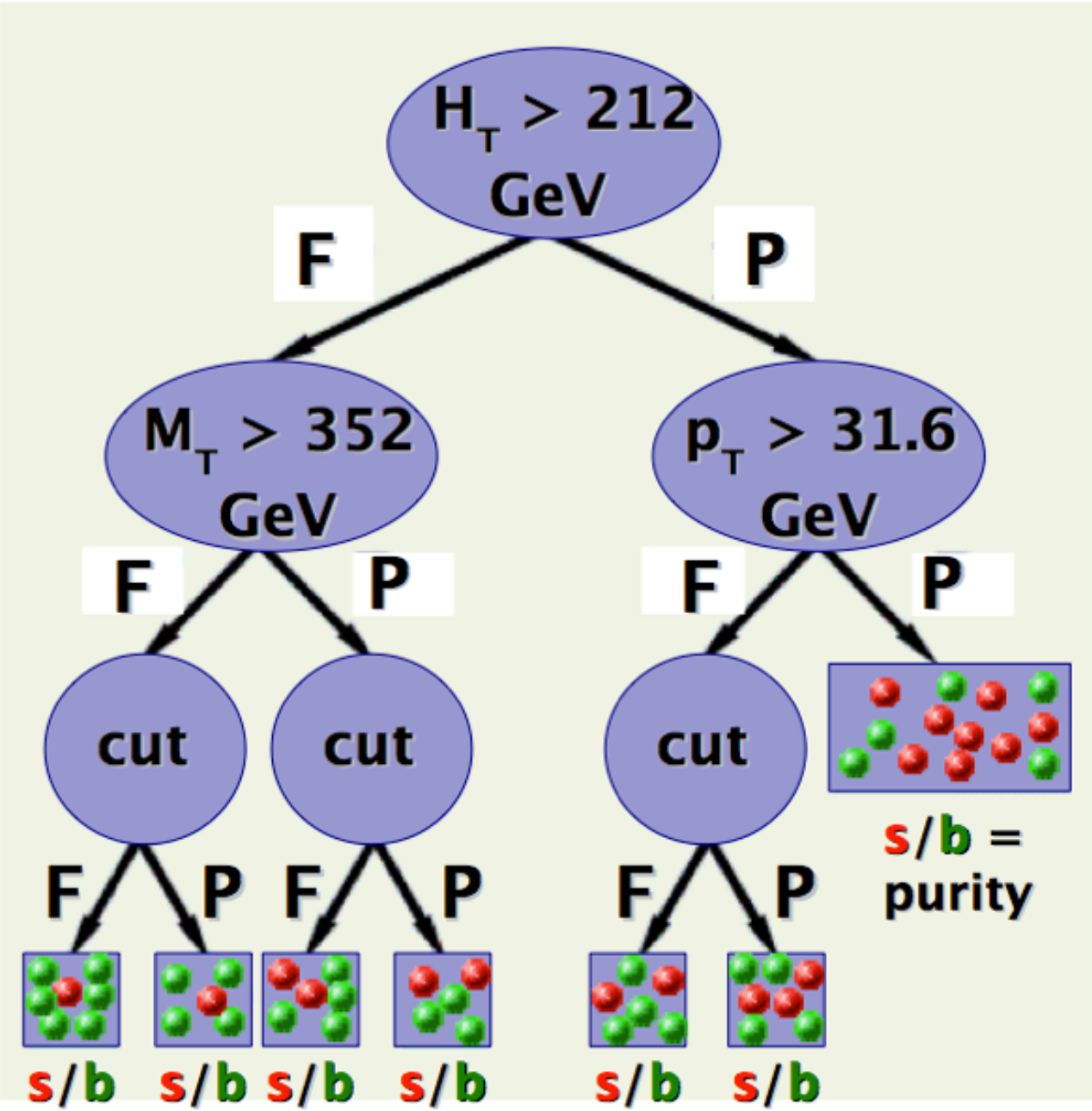


- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

Boosted Decision Trees

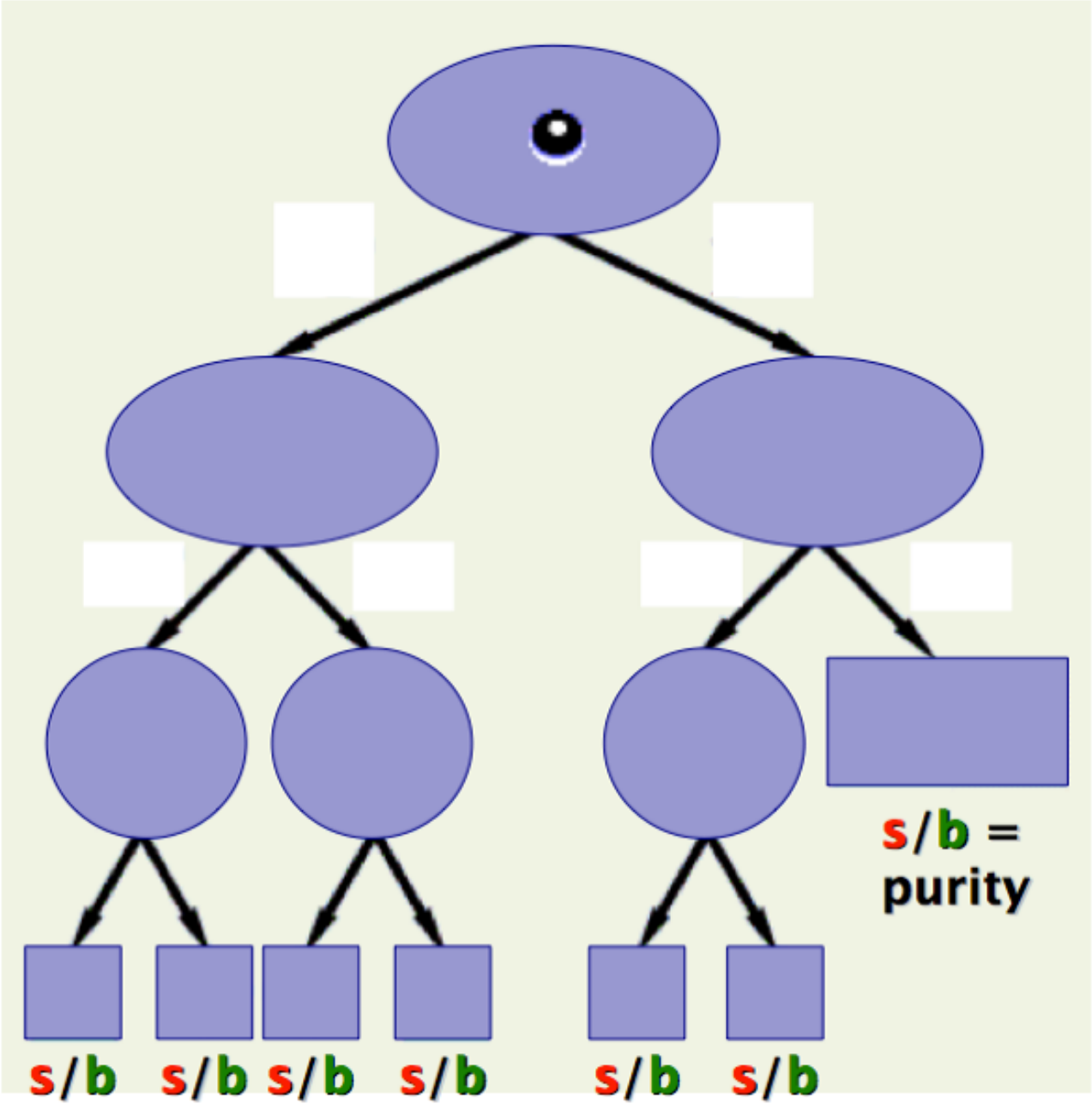


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

- train tree: T_k
- derive weight: α_k
- retrain tree: T_{k+1} to minimize error
- average: $T = \Sigma\, \alpha_i\, T_i$

Boosted Decision Trees



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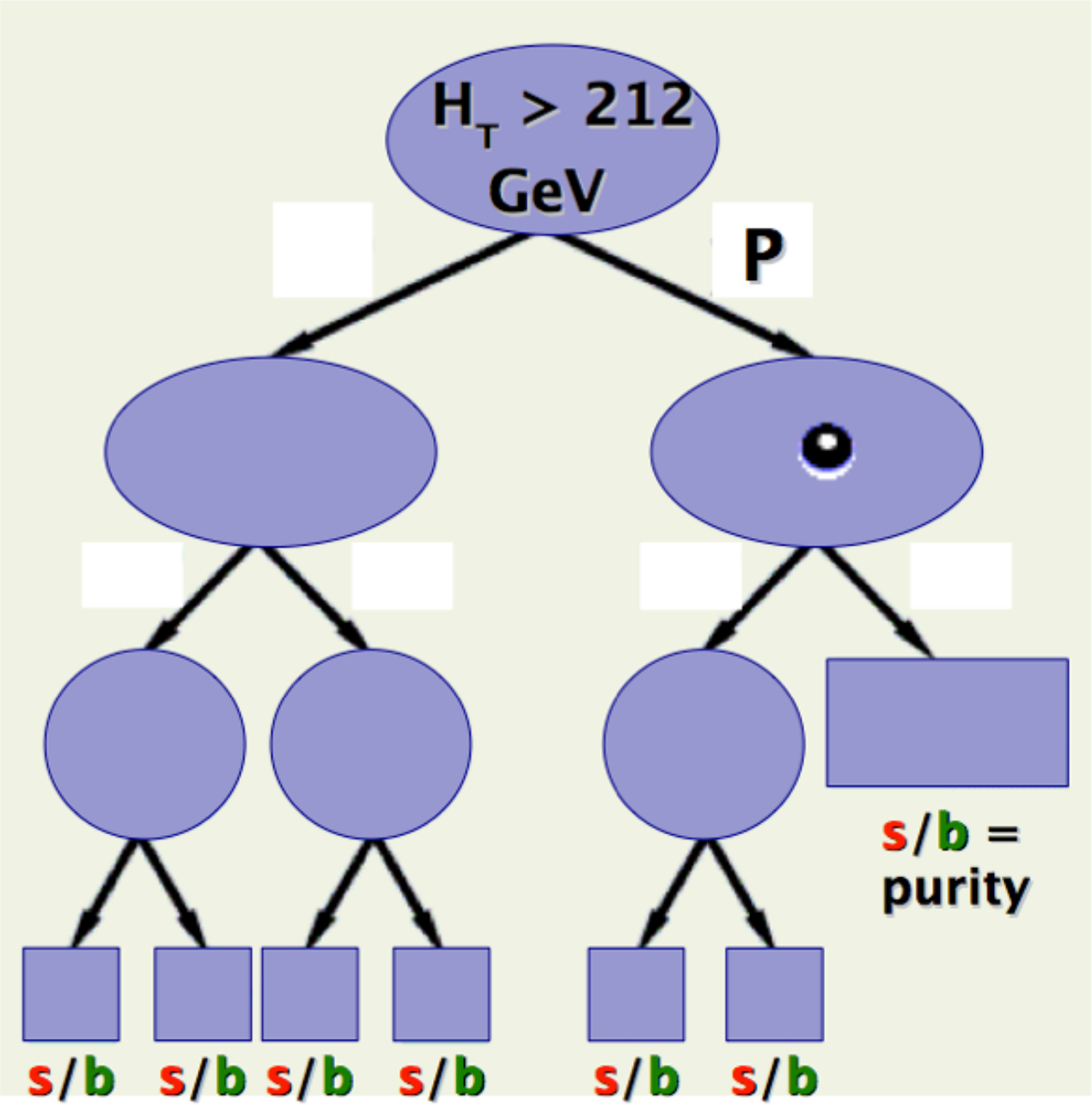
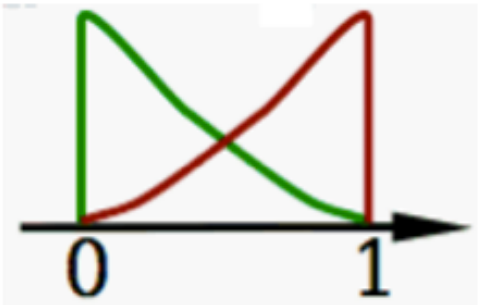
Boosted Decision Trees



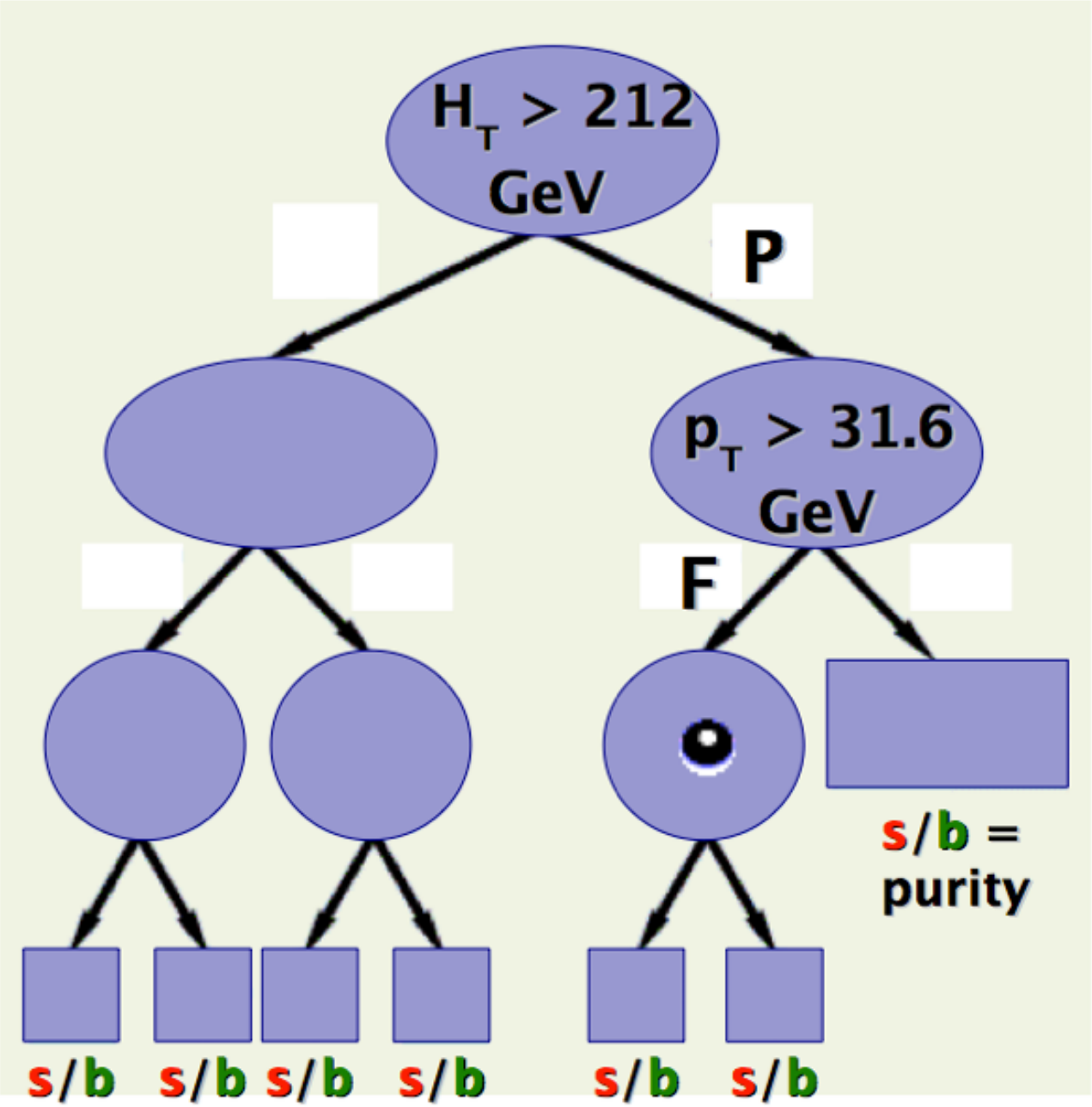
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**



Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**

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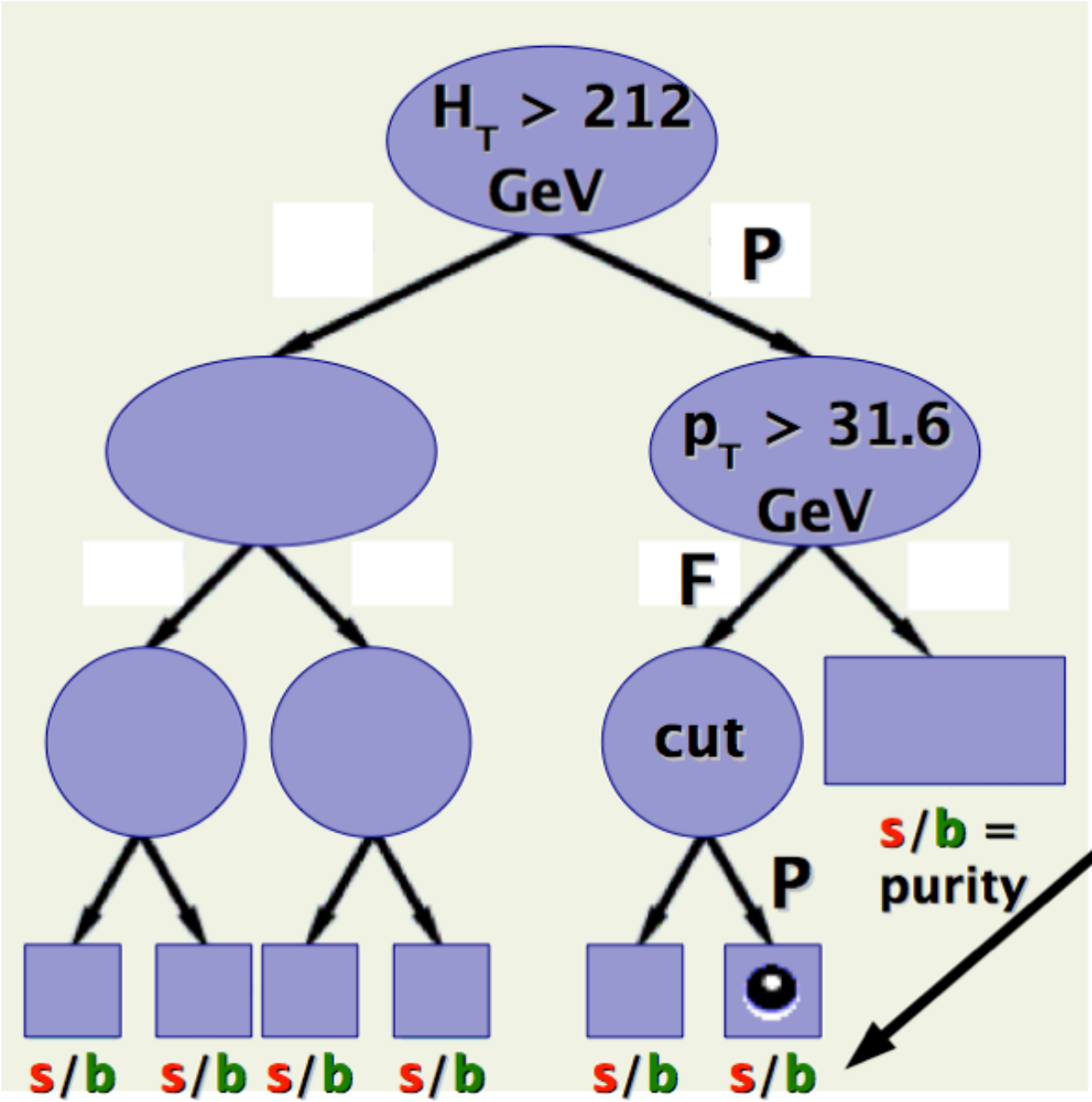
Boosted Decision Trees



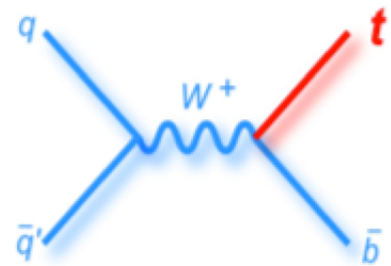
- **IDEA: recover events that fail criteria in cut-based analyses**

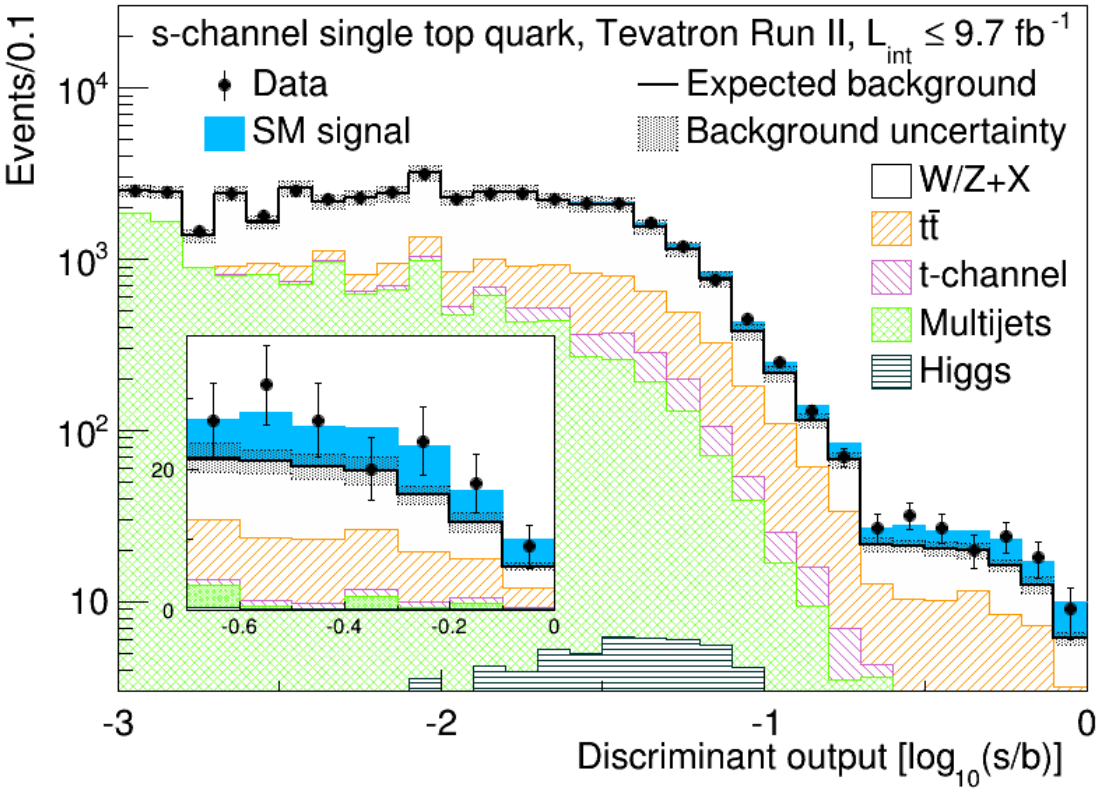
- **result: weight for every event**

s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)

- **Tevatron: combine individual discriminants including all correlations**



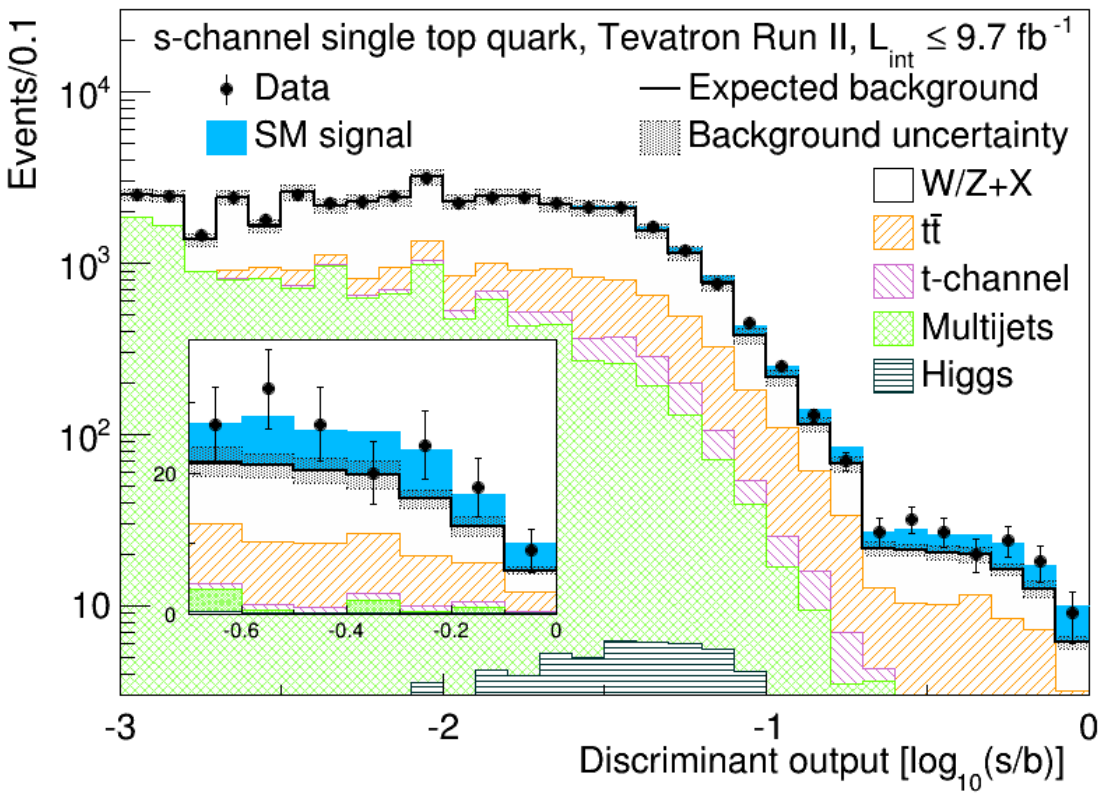


→ **observation: 6.3 s.d.**

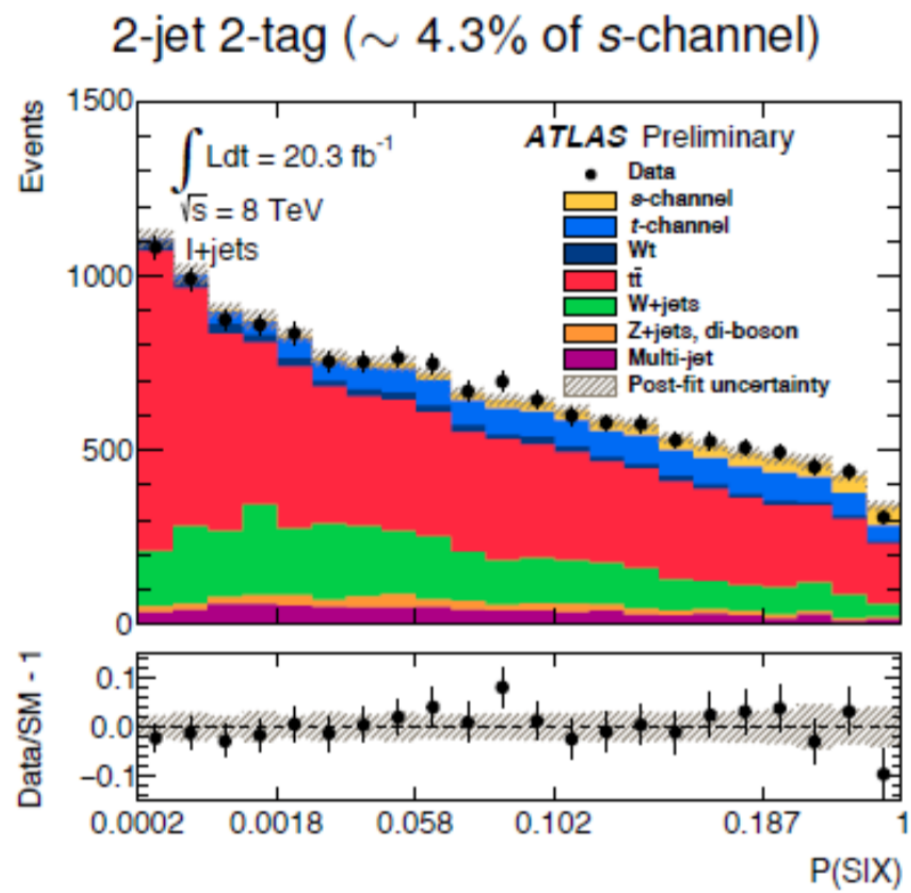
s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)

- **Tevatron: combine individual discriminants including all correlations**



- **ATLAS: matrix element method**



→ observation: 6.3 s.d.

→ evidence: 3.2 s.d.