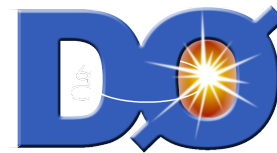


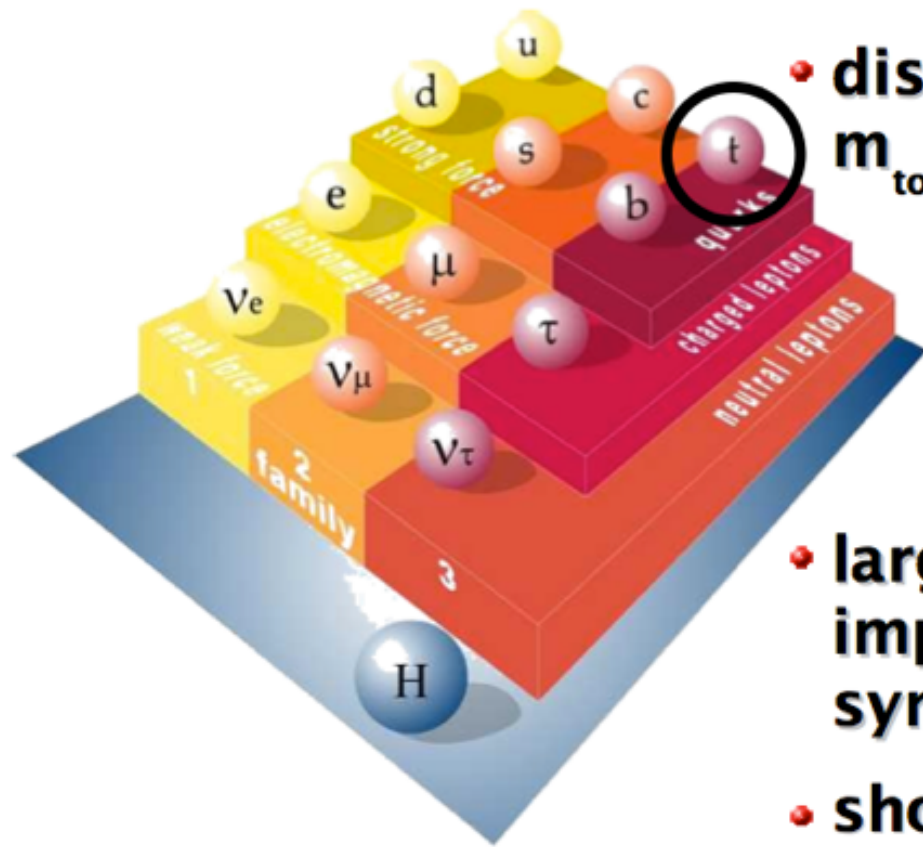
Top Precision and Searches for New Physics

Christian Schwanenberger
DESY

DESY–Zeuthen Physics Seminar
17 February, 2016



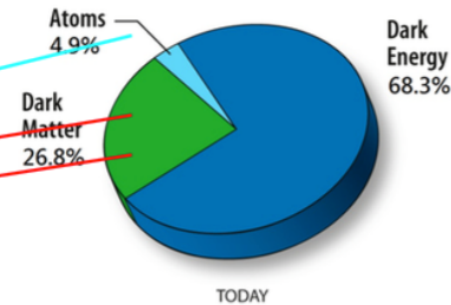
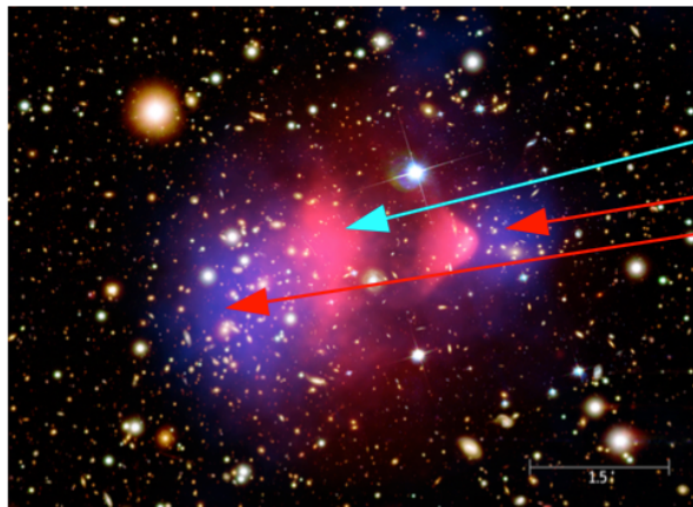
The Top Quark



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

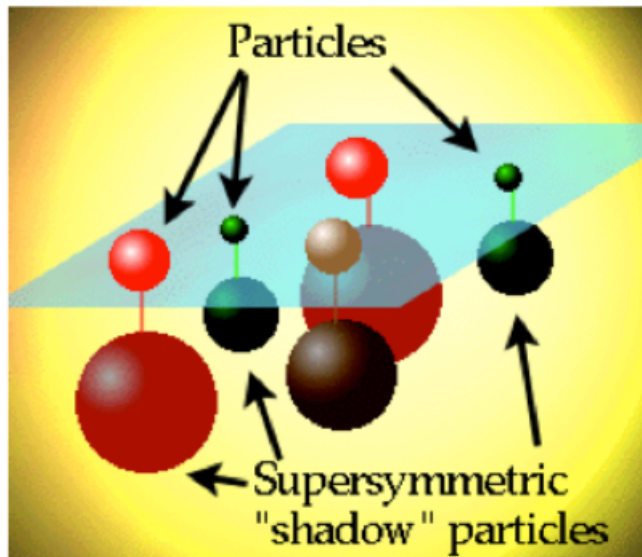
Is the top quark the particle as predicted by the SM?

Search for New Phenomena



Dark matter inferred from star motion and gravitational lensing

Supersymmetry:

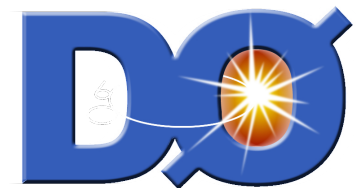
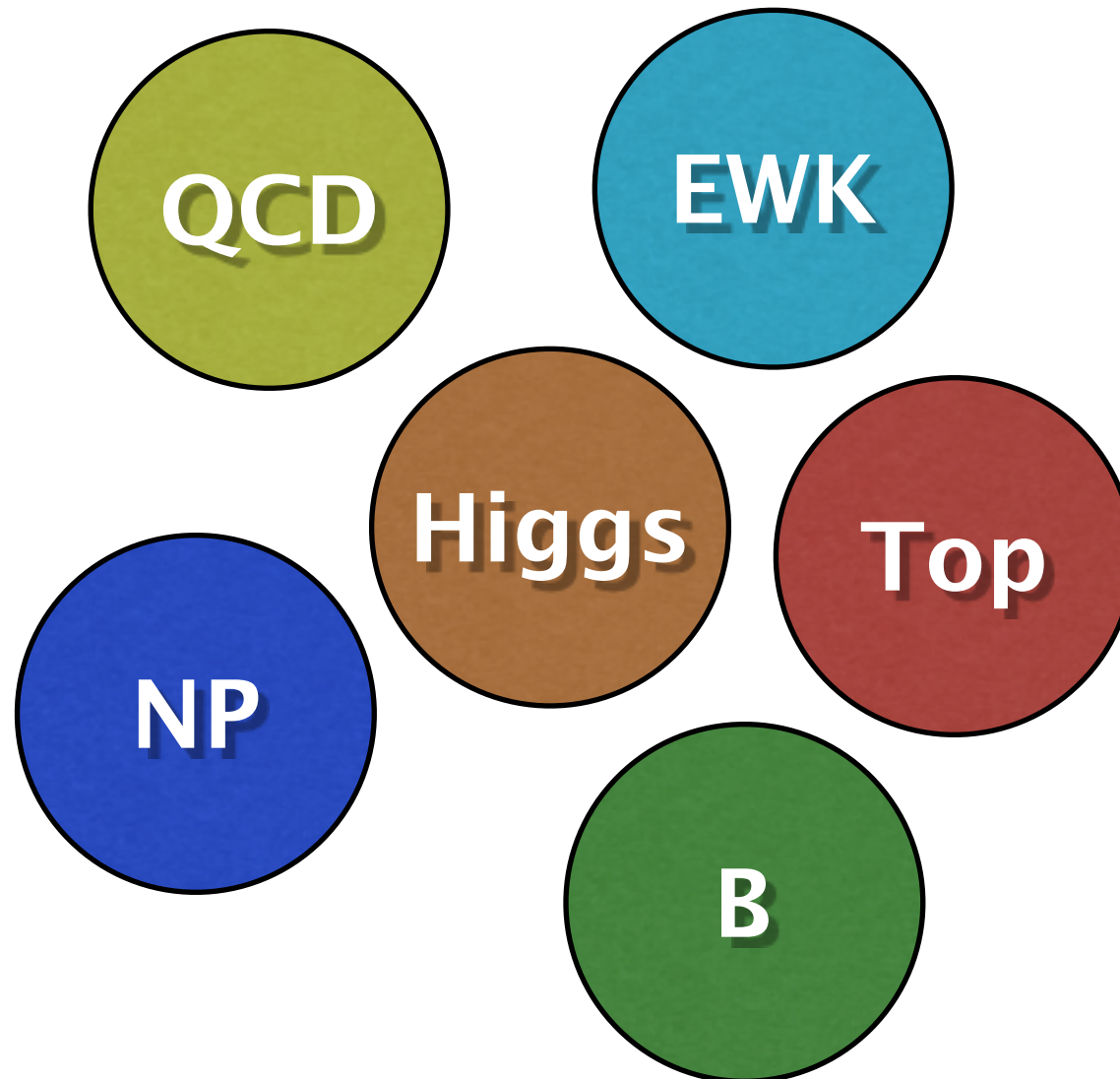


Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

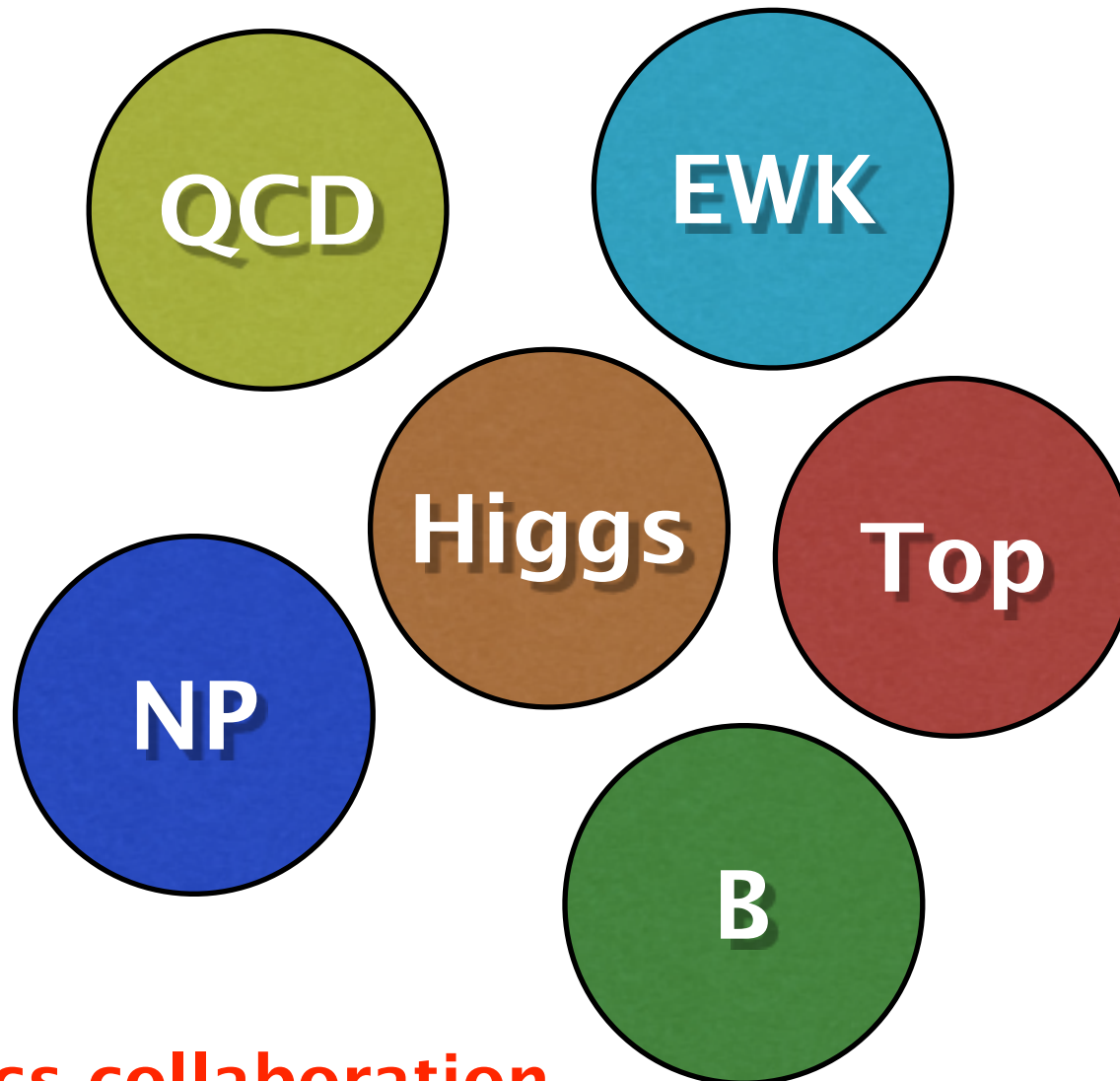
Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$Wino^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

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

Physics Groups: DØ Collaboration

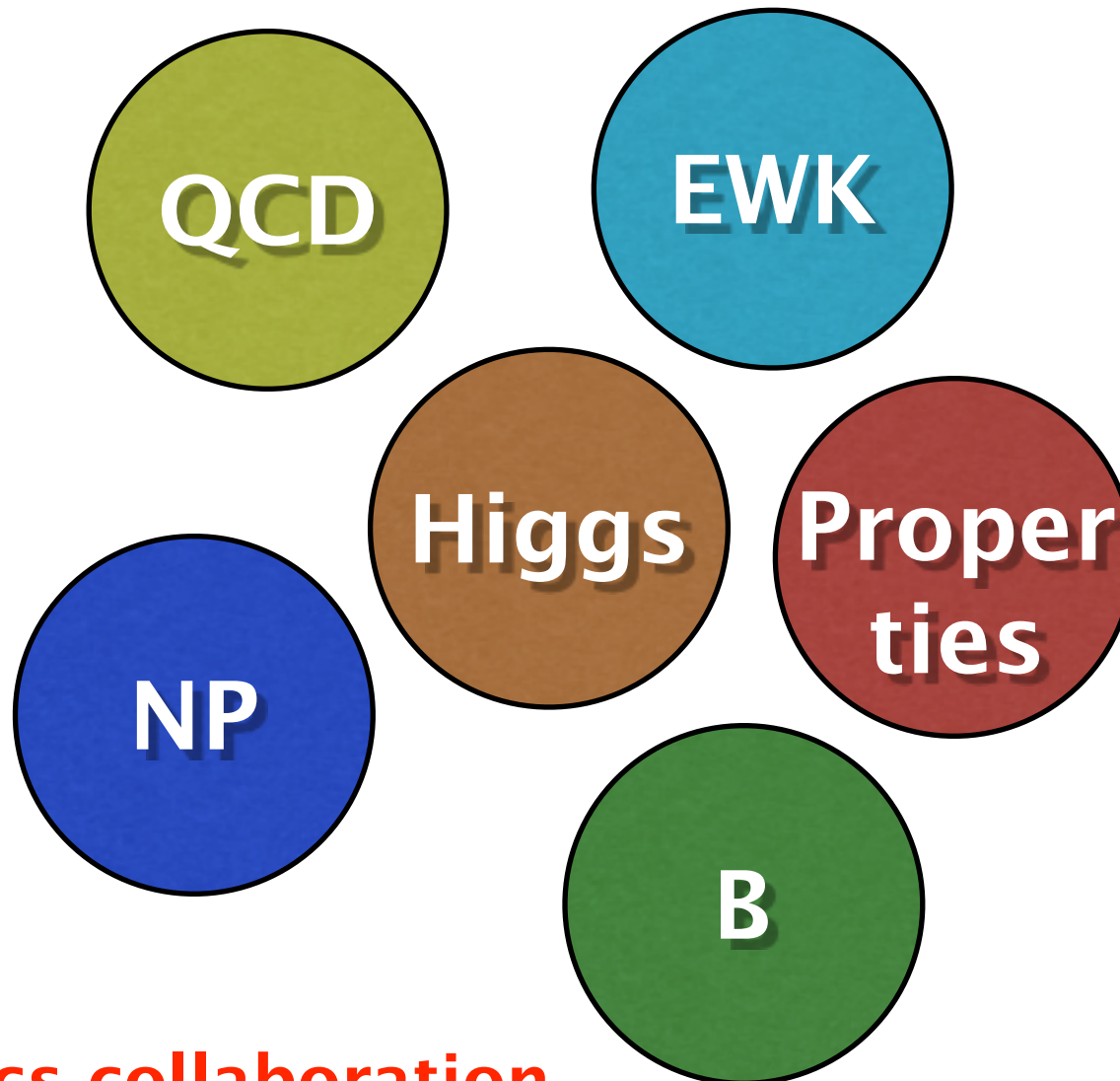


Top Quark Physics Topics



→ top physics collaboration

Top Quark Physics Topics



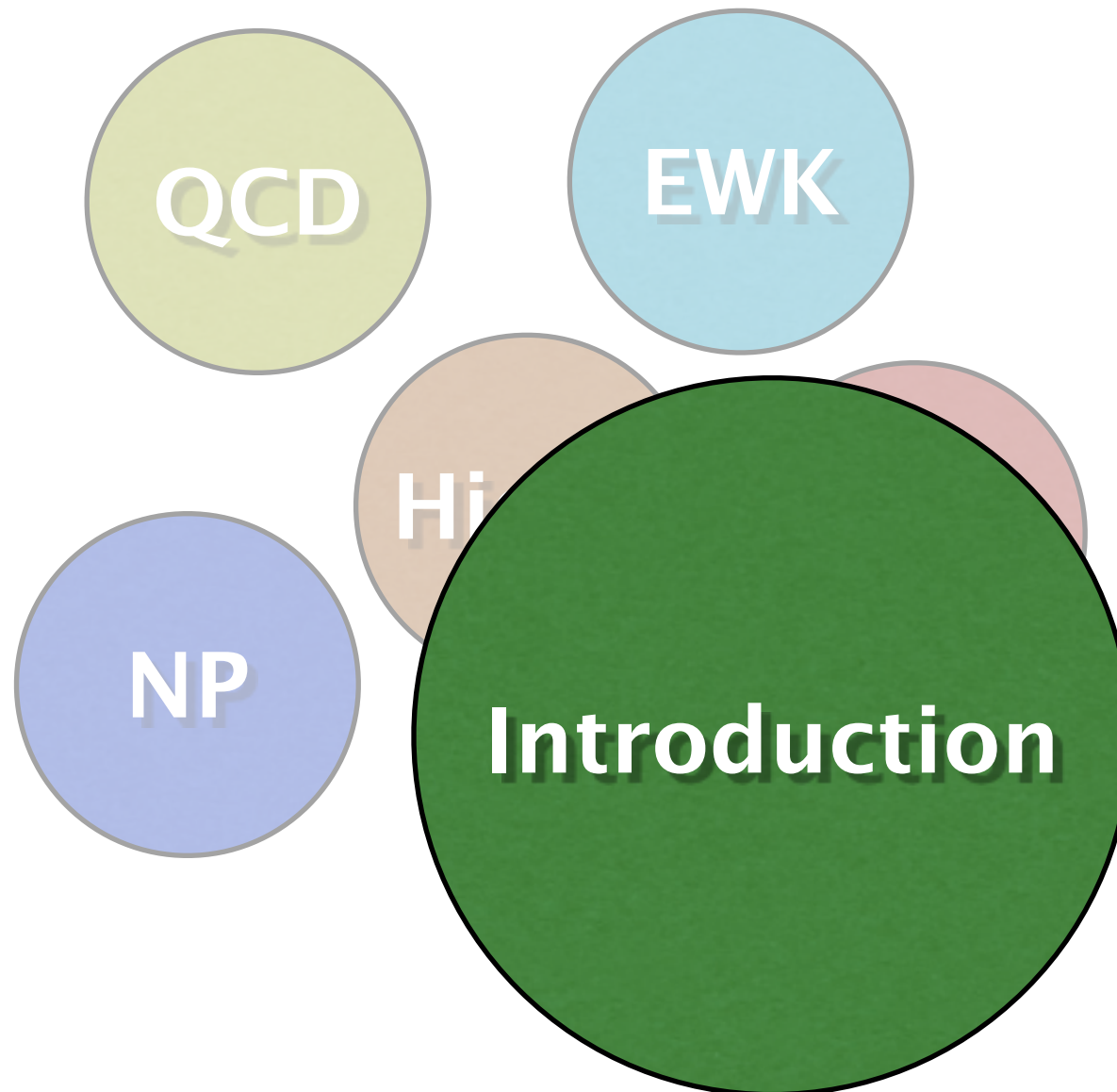
→ top physics collaboration

Top Quark Physics Topics

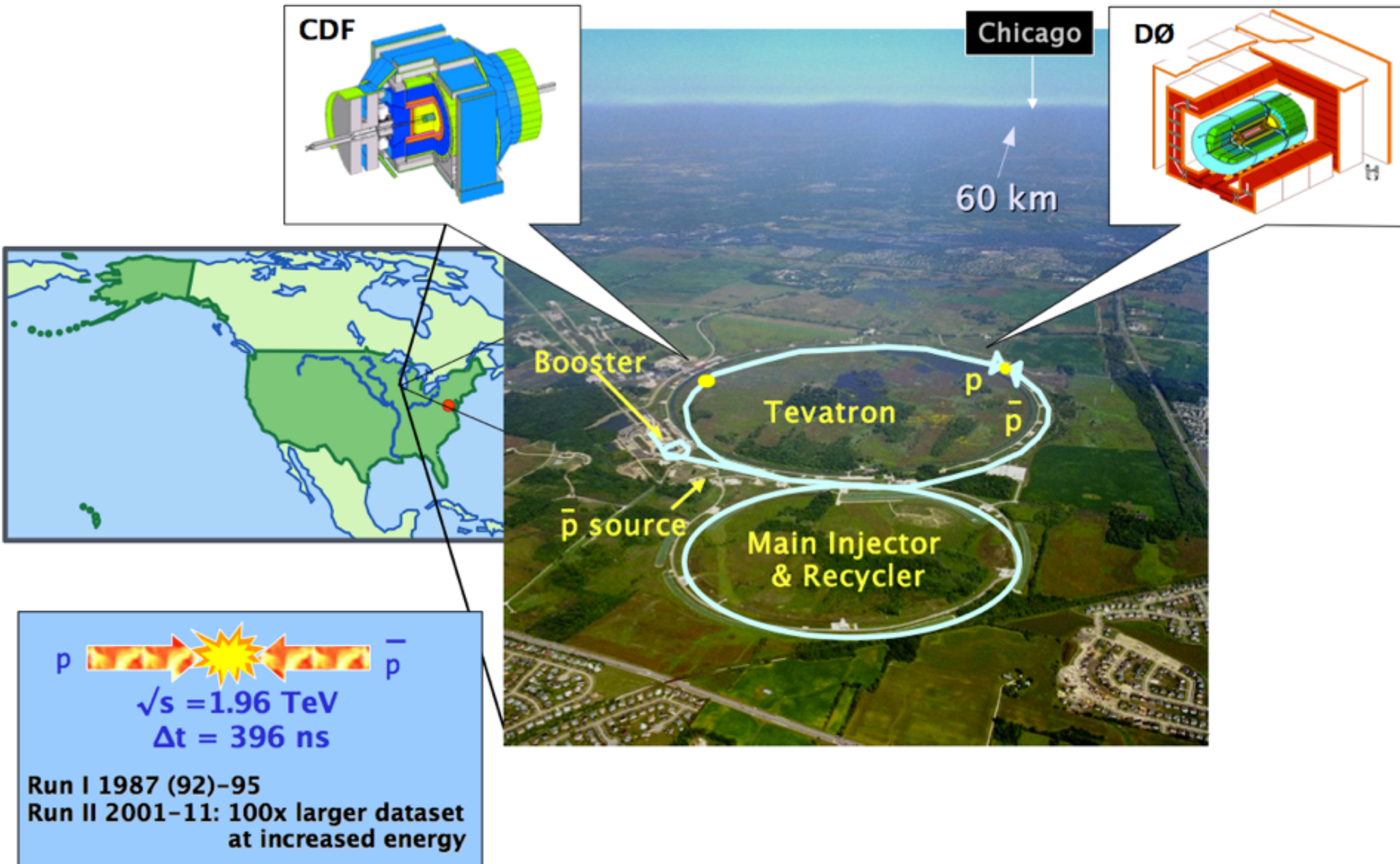


→ top physics collaboration

Top Quark Physics Topics



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



The Top Quark

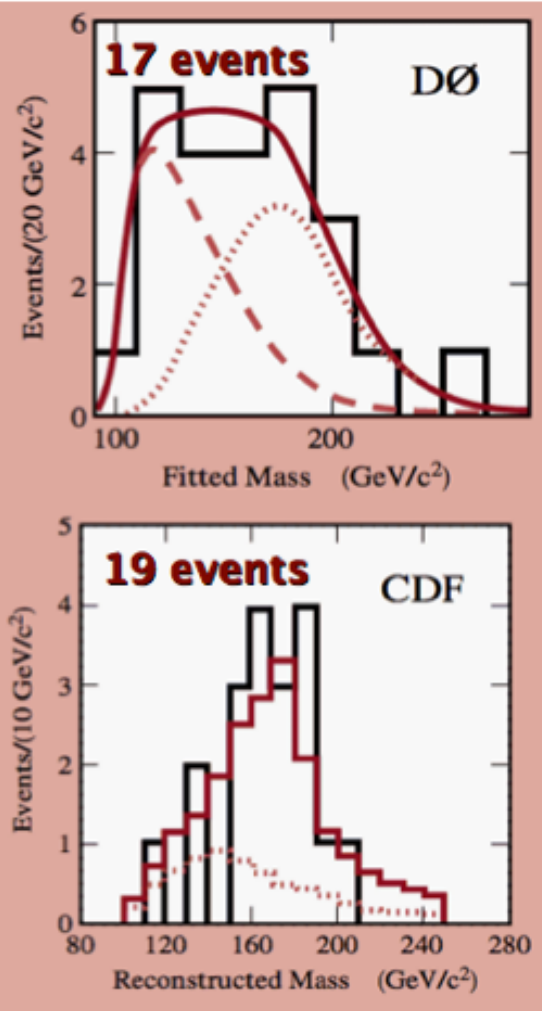


discovery

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

March 2nd, 1995:

First announcement of Top Discovery
in public seminar at Fermilab



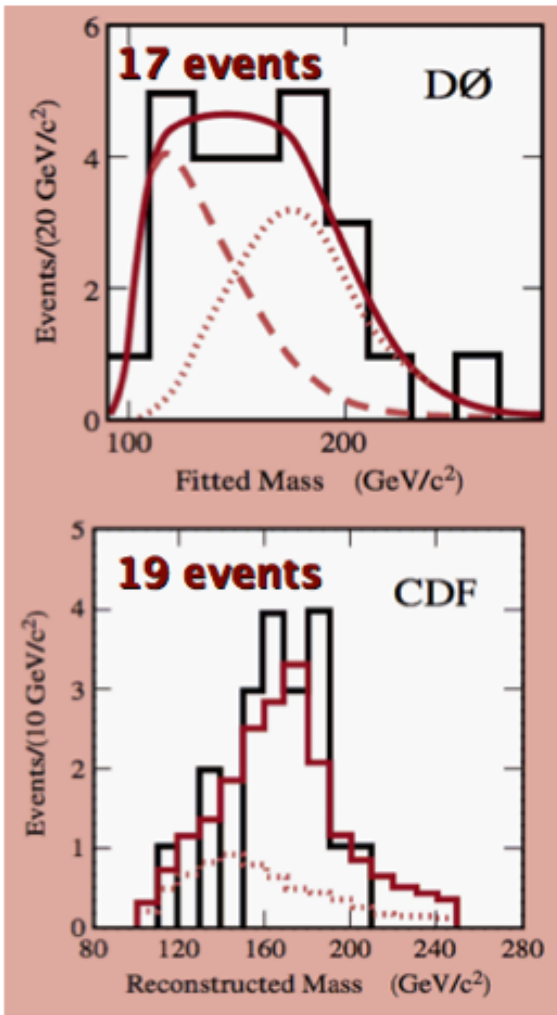
**1995, CDF and DØ
experiments, Fermilab**



The Top Quark

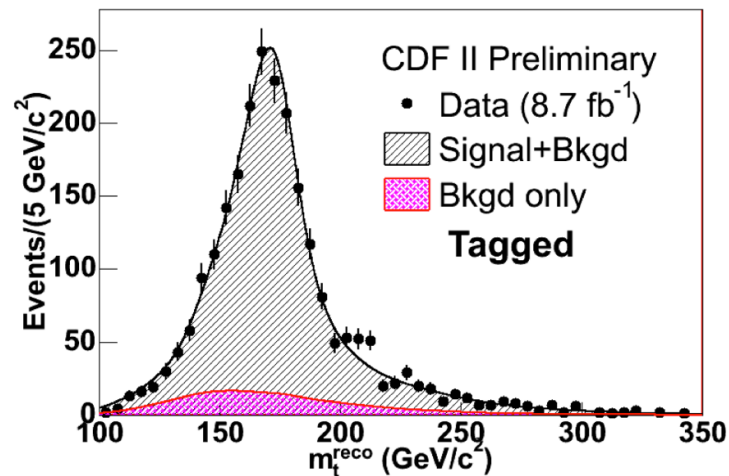
discovery

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



today

1000s of events

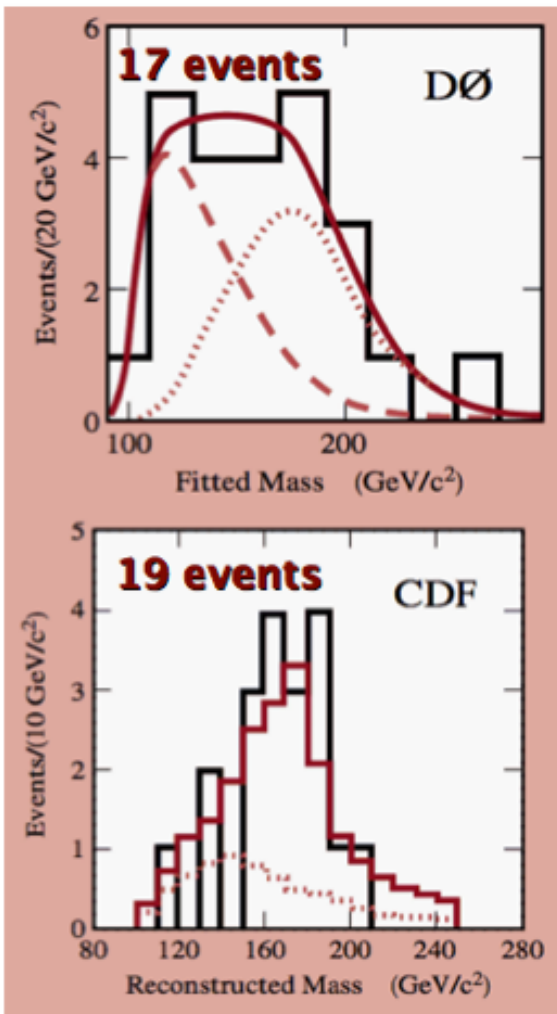


**1995, CDF and DØ
experiments, Fermilab**

The Top Quark

discovery

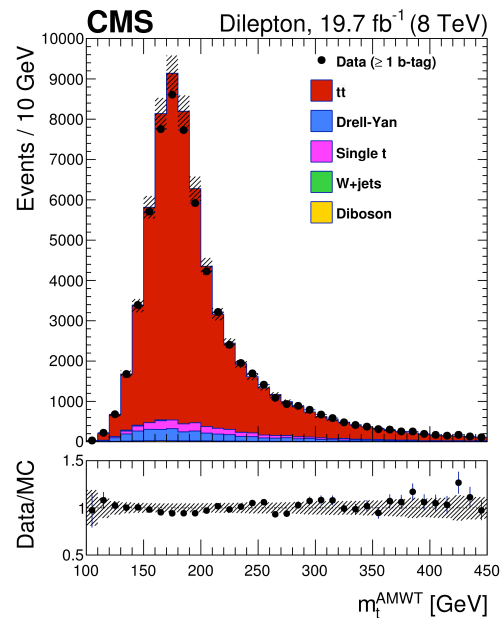
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



**1995, CDF and DØ
experiments, Fermilab**

today

100000s of events

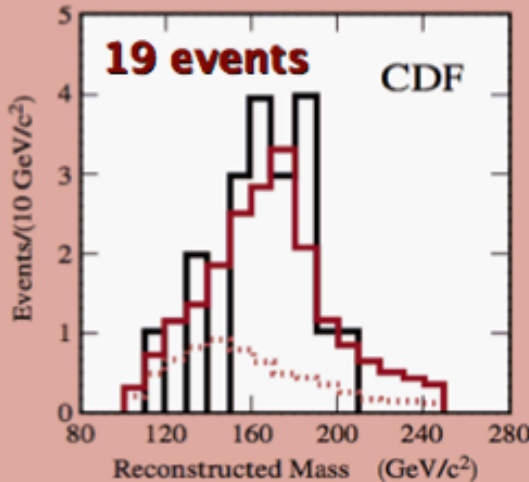
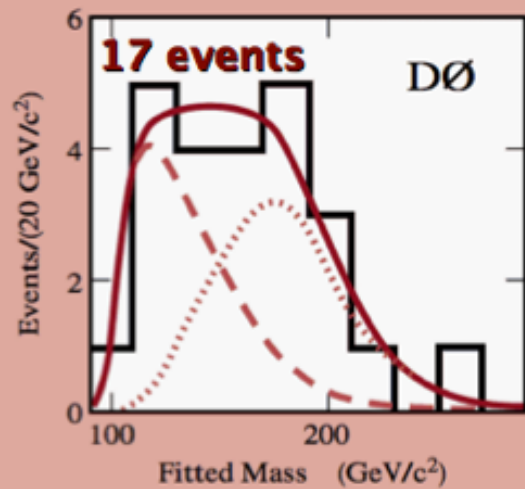


**LHC:
top quark
factory**

The Top Quark

discovery

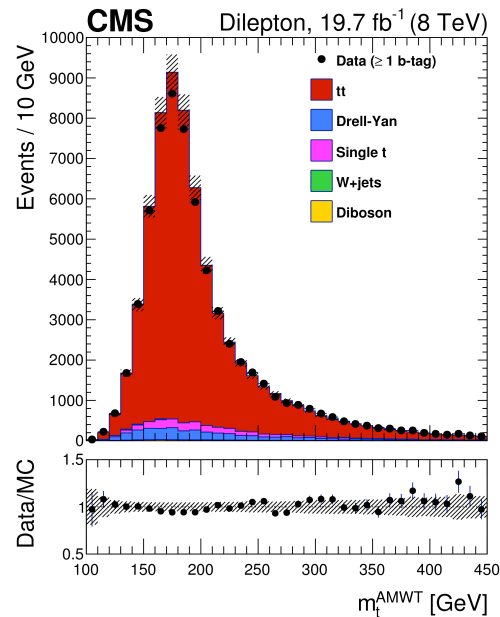
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ
experiments, Fermilab

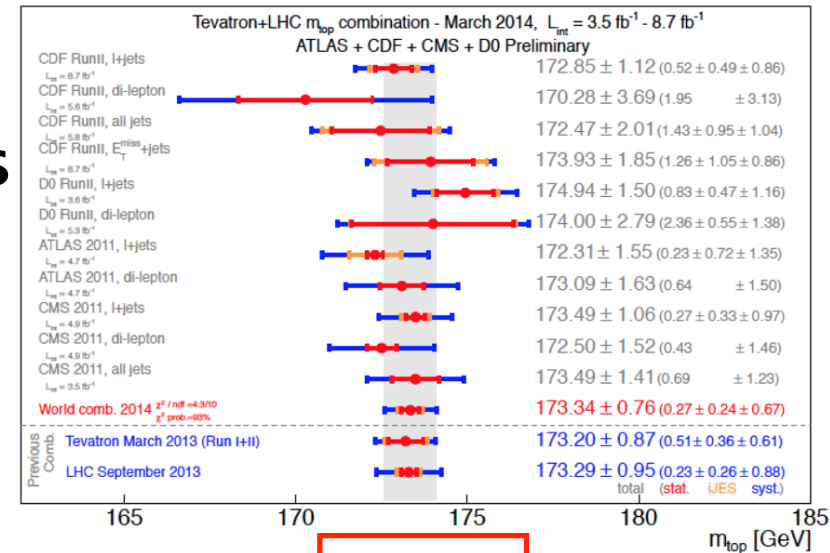
today

100000s of events



LHC:
top quark
factory

precision

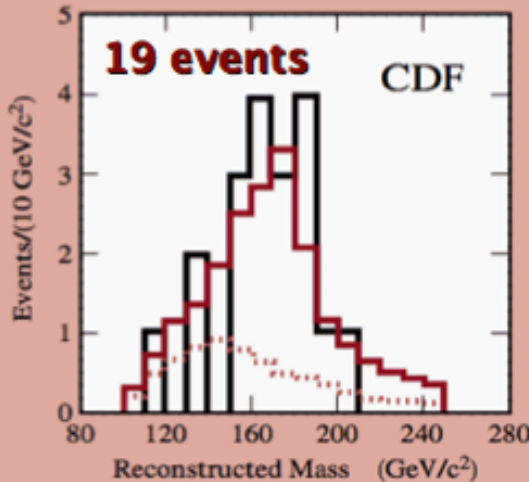
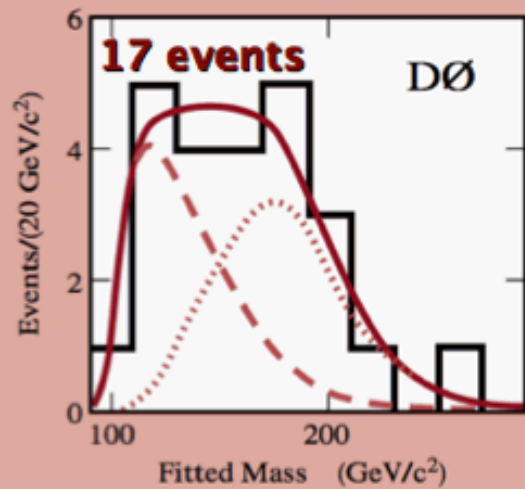


$\pm 0.44\%$

The Top Quark

discovery

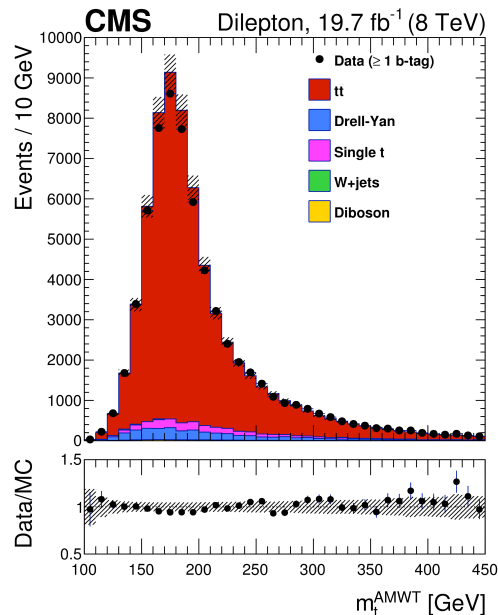
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ
experiments, Fermilab

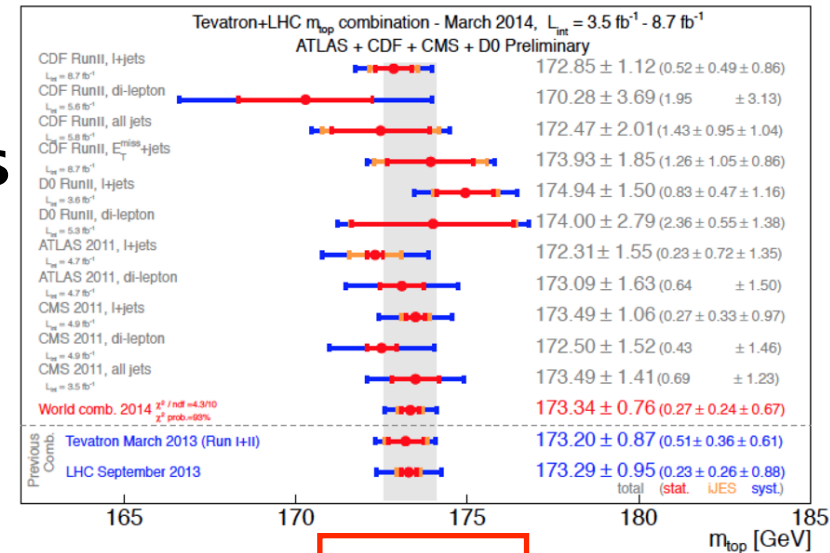
today

100000s of events



LHC:
top quark
factory

precision

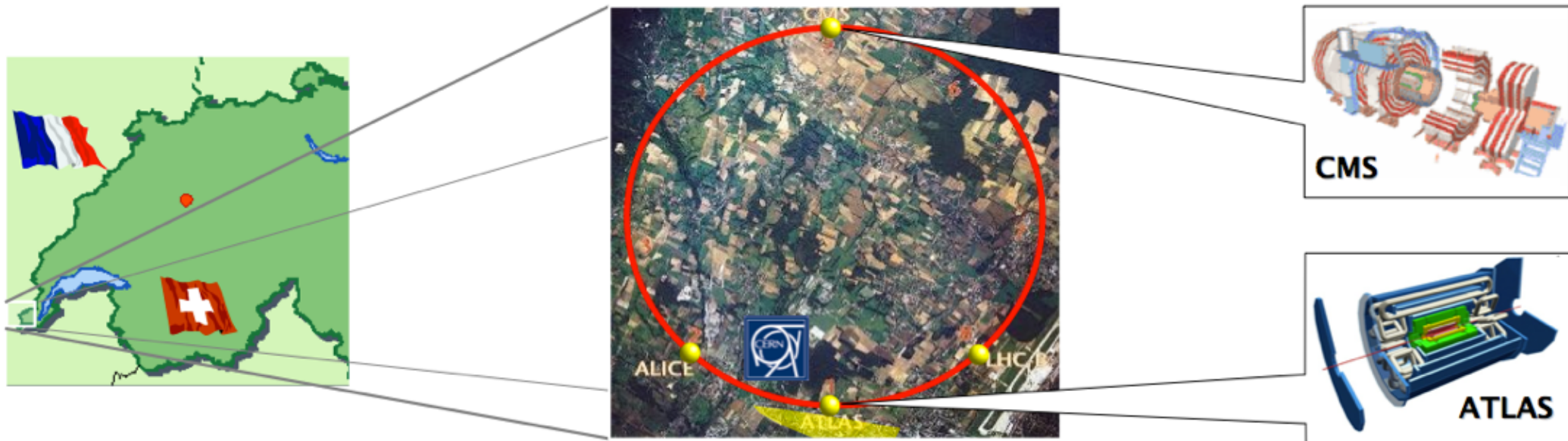


±0.44%

searches



The LHC pp Collider at CERN

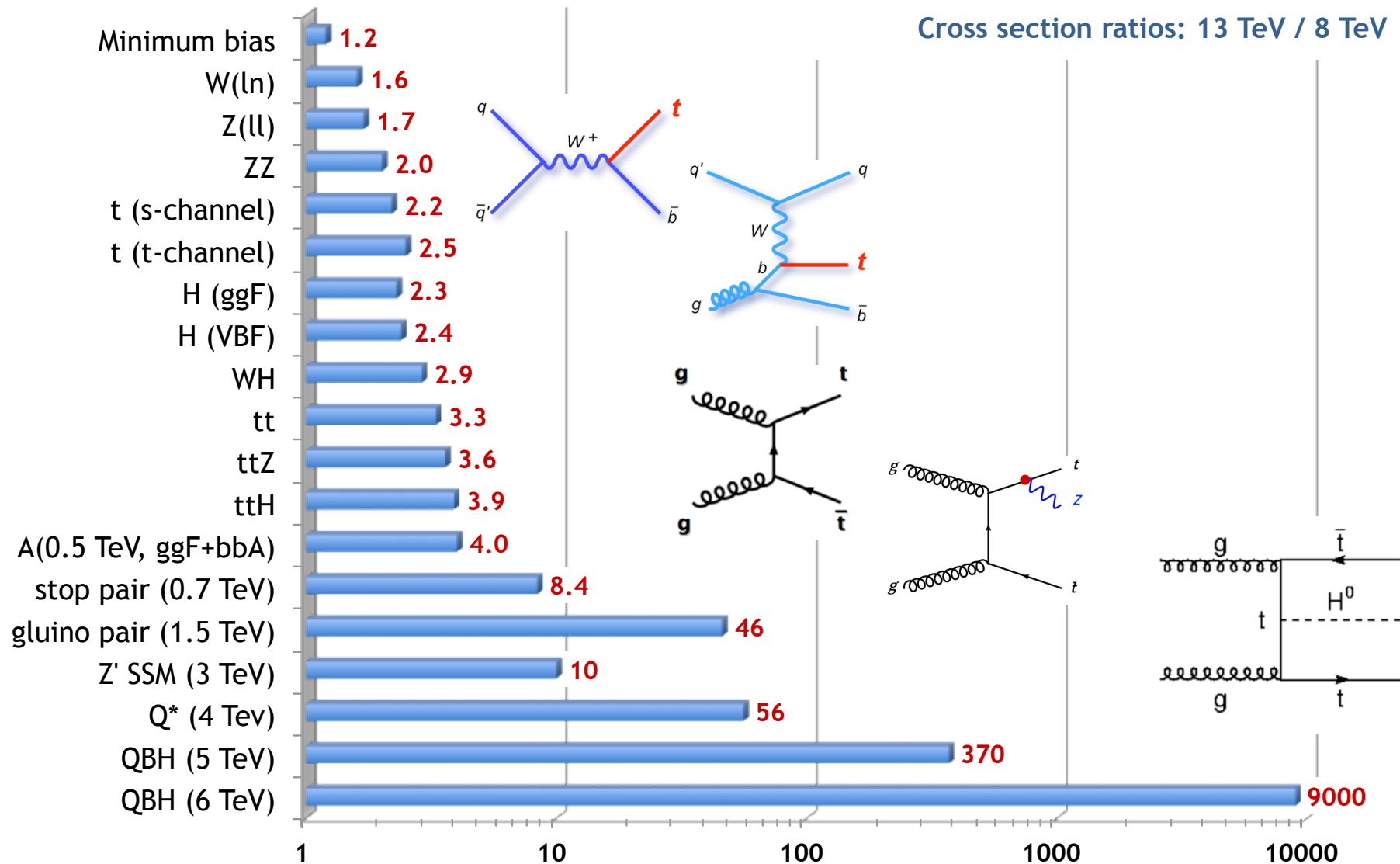


	$\sqrt{s}$ [TeV]	years	Ldt (rec.)
pp	7	2010-11	5.1 fb ⁻¹
pp	8	2012	21.3 fb ⁻¹
Pb+Pb	2.76	2010-11	160 μb ⁻¹
Pb+p	5	2013	30 nb ⁻¹

June 3rd, 2015: First Collisions @ 13 TeV

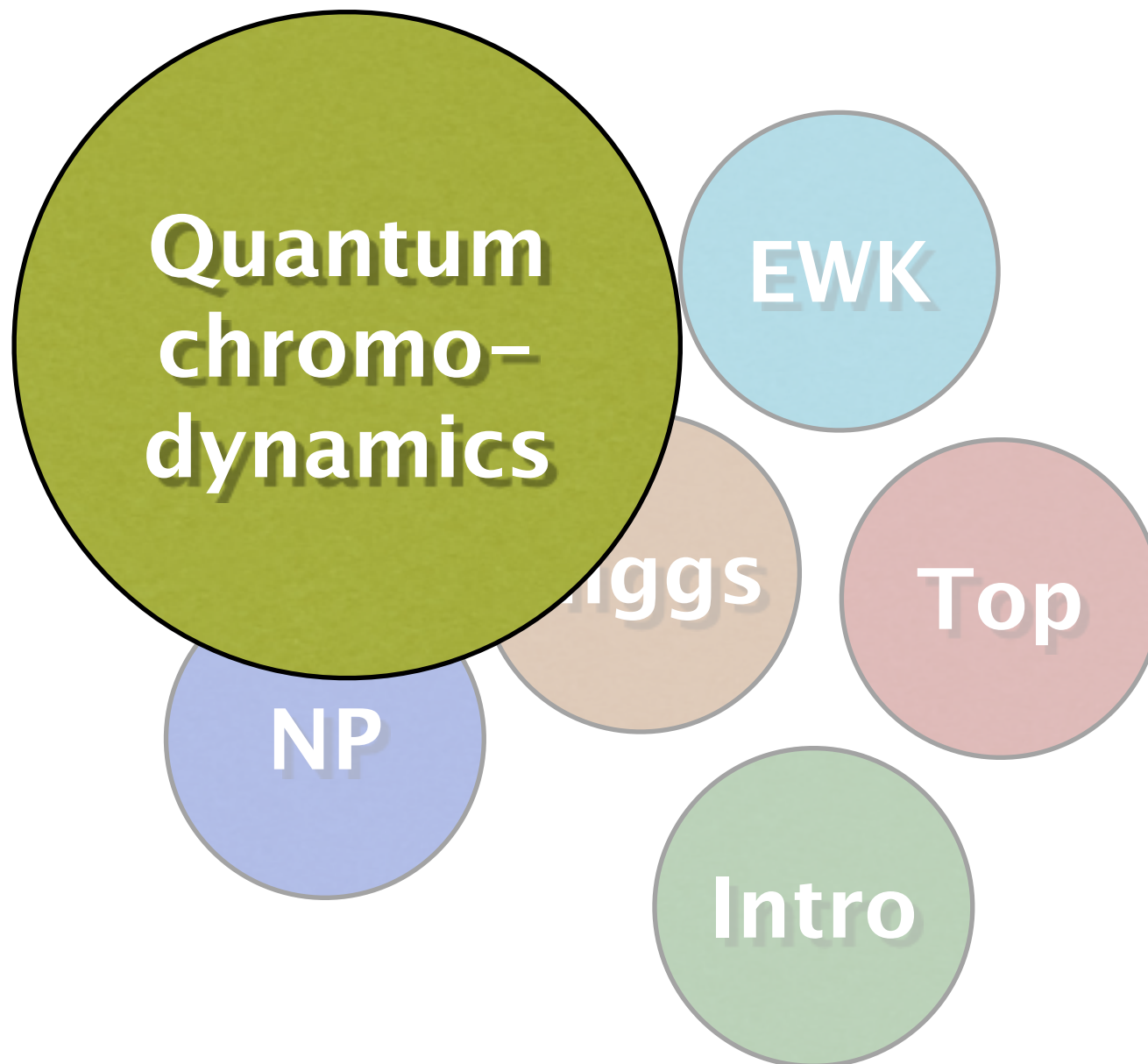


Cross Sections: 13 TeV/8 TeV

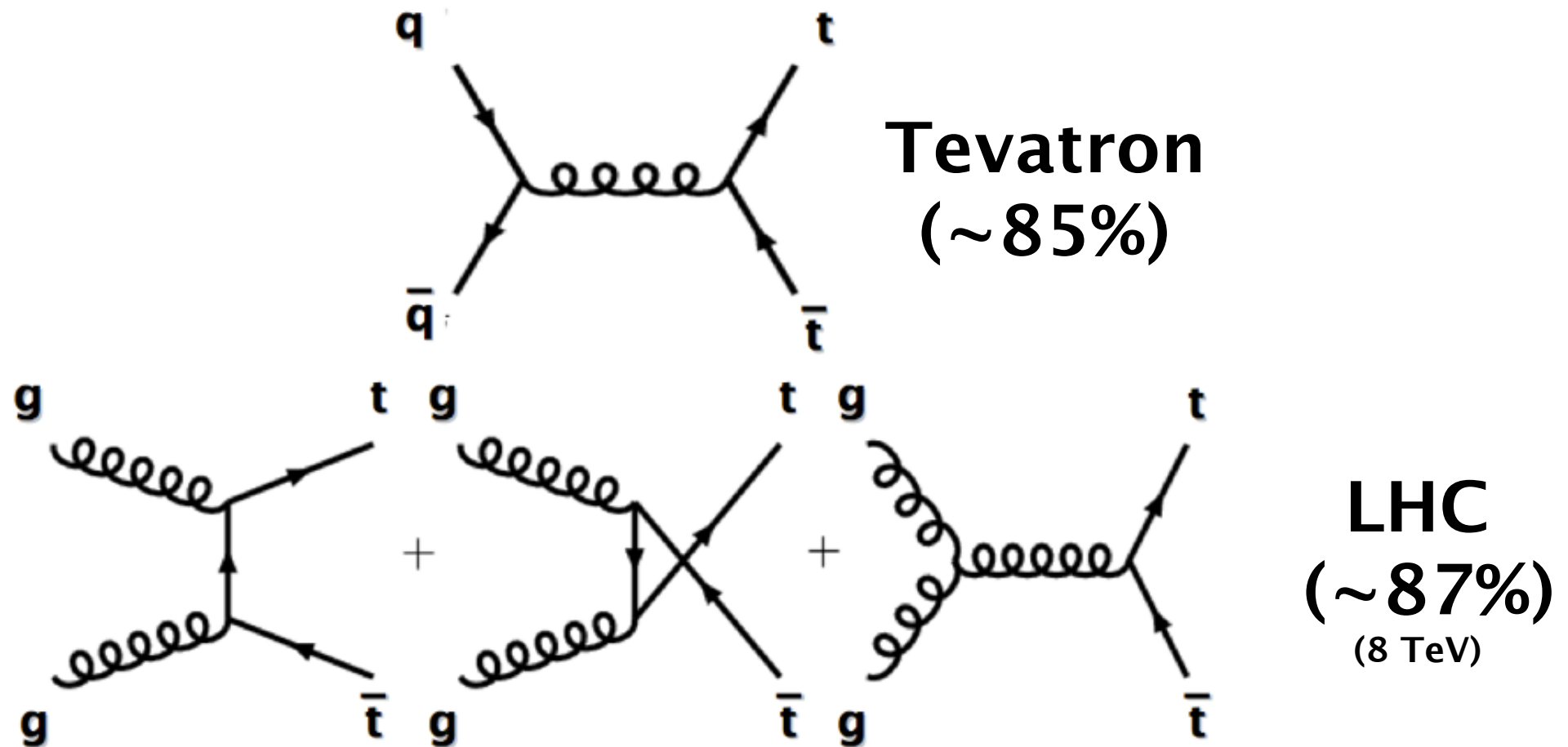


→ excellent prospects for top physics

Top Quark Physics Topics



Top Quark Pair Production



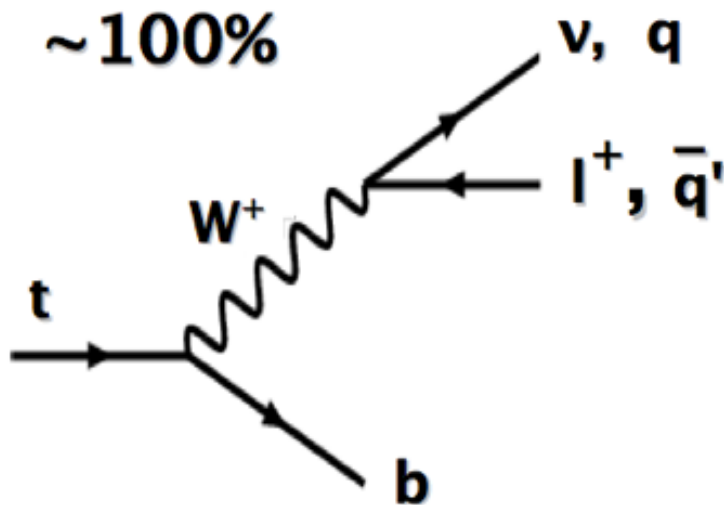
Top Quark Pair Signatures

τ 's
14%

Top Pair Decay Channels

alljets
46%

top decay:



$\bar{c}s$	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	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

dilepton (e/ μ)
6%

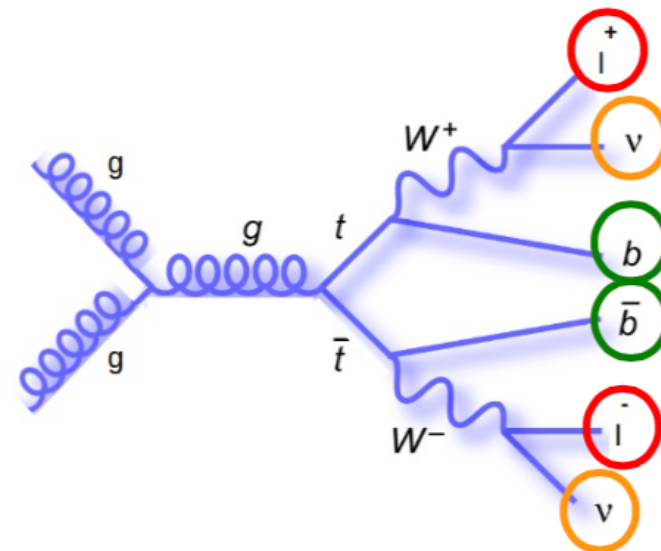
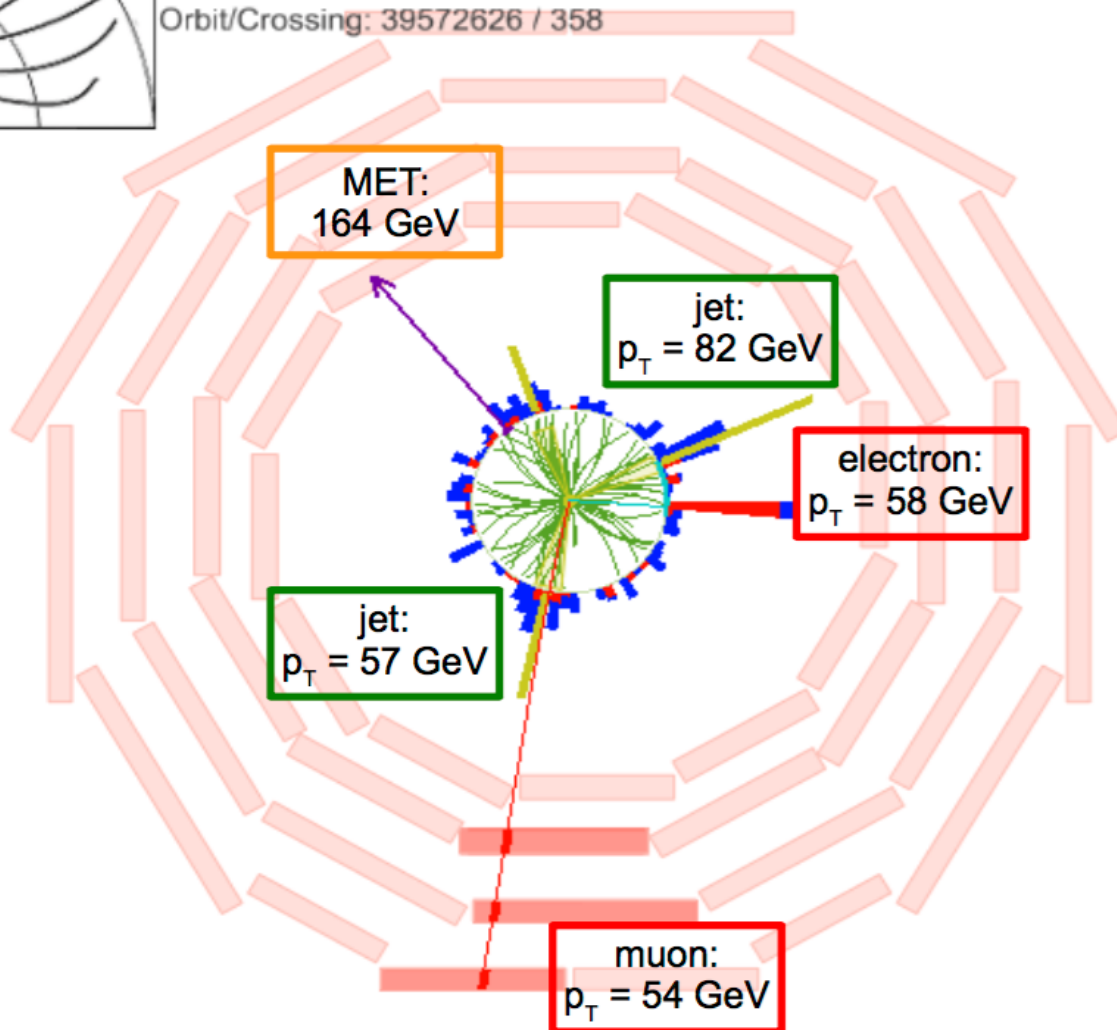
e/ μ +jets
34%

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

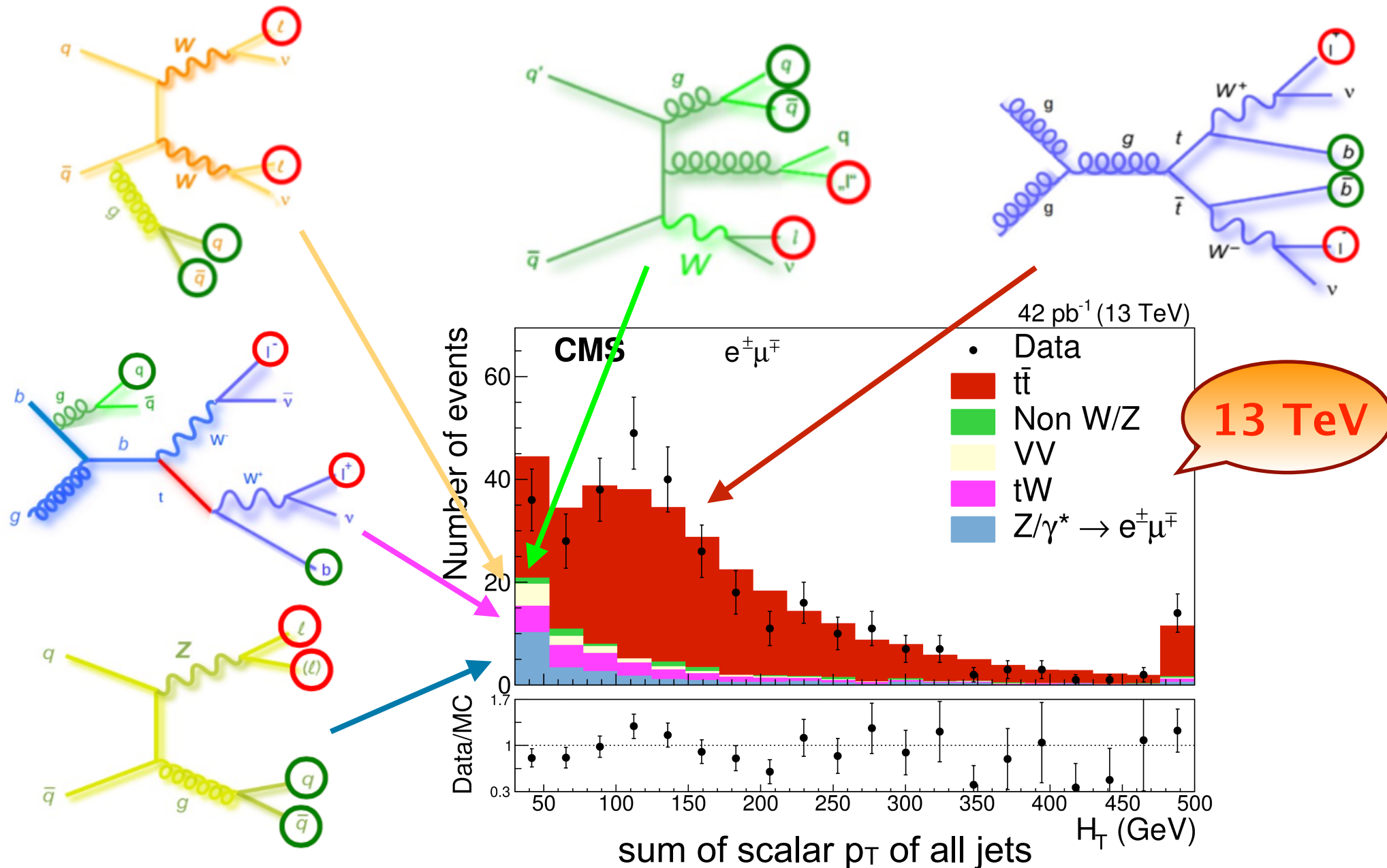
Dilepton Signature



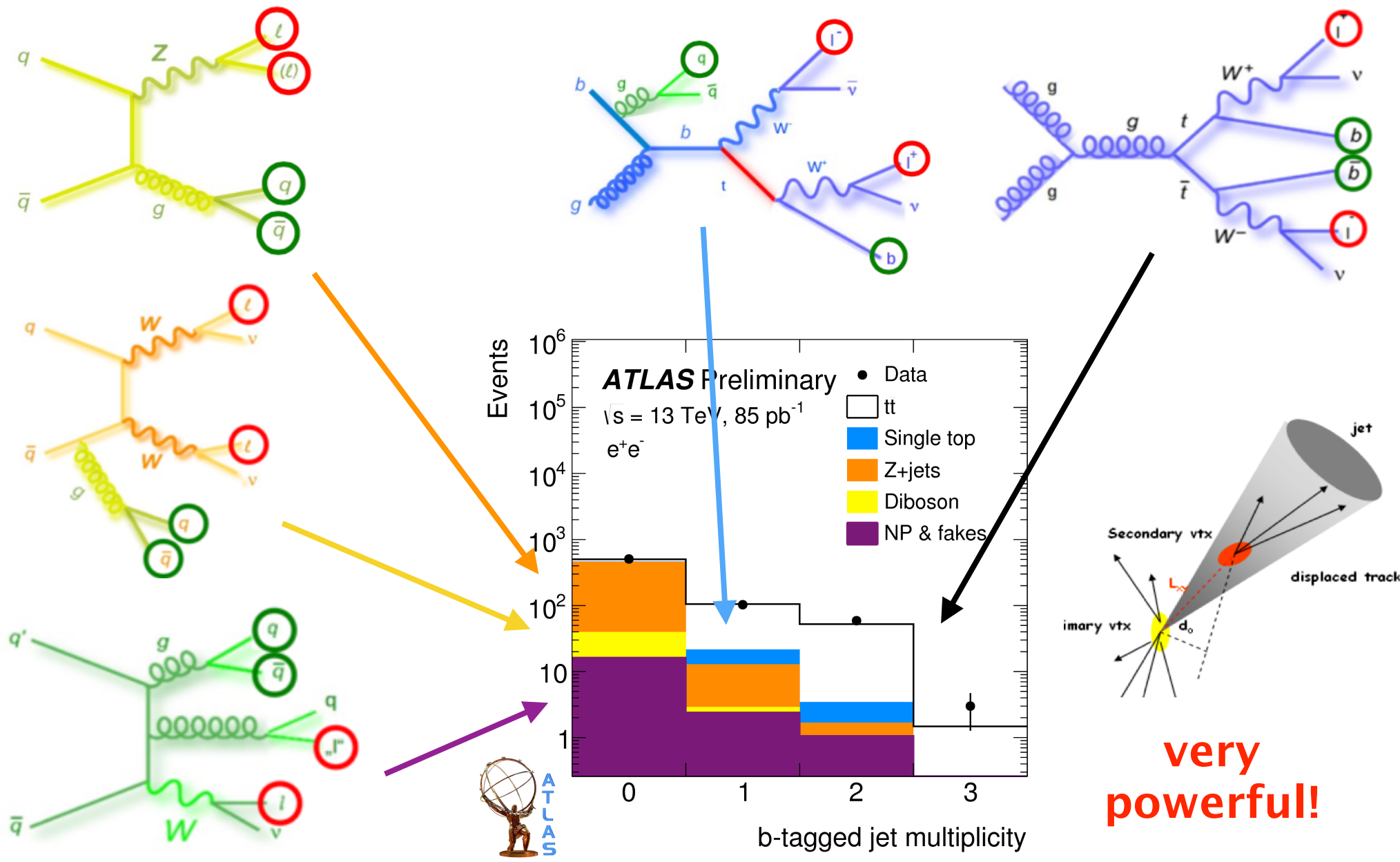
CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 19:26:24 2015 CEST
Run/Event: 251244 / 83494441
Lumi section: 151
Orbit/Crossing: 39572626 / 358



Dilepton Events at 13 TeV

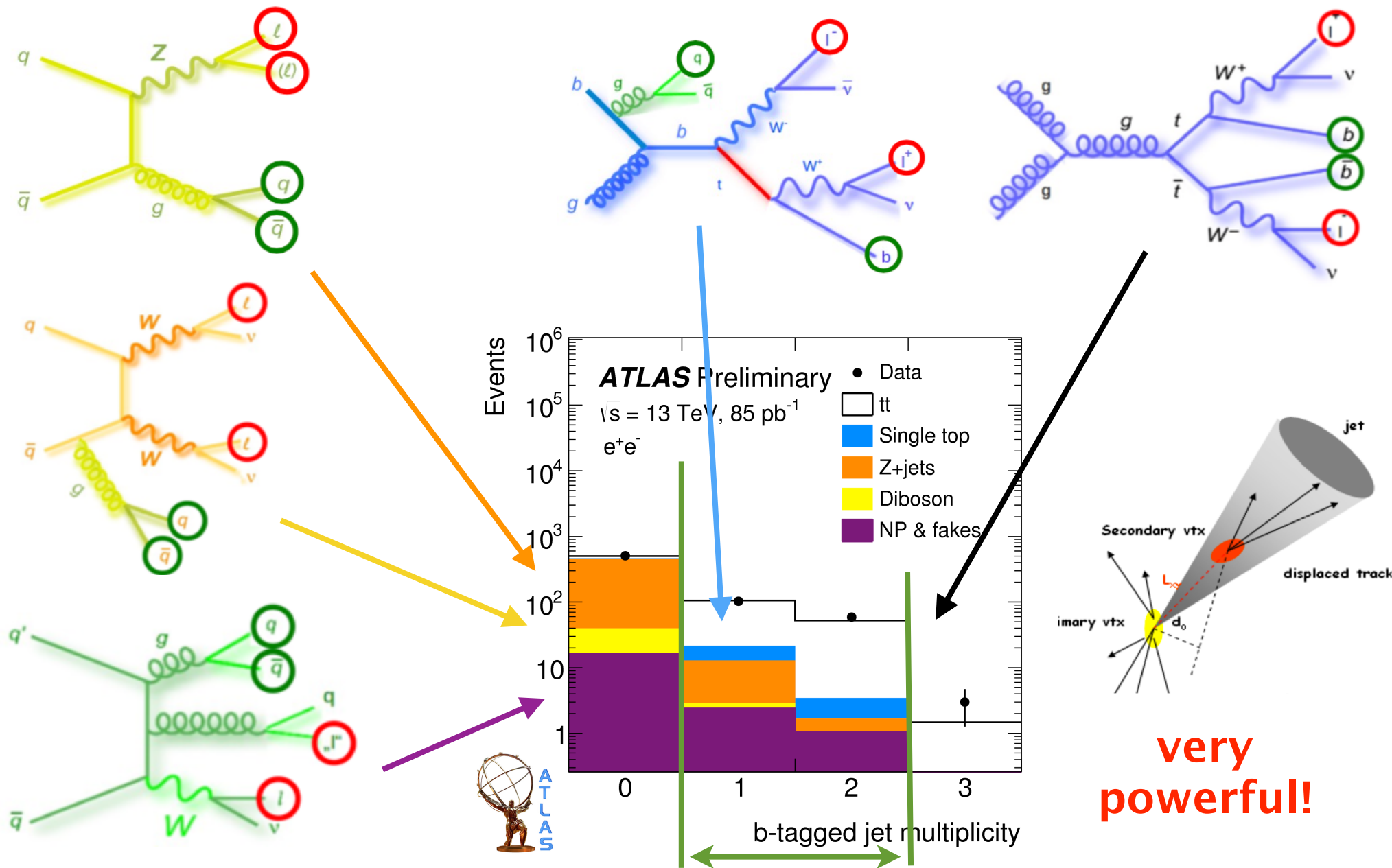


Dilepton Events at 13 TeV



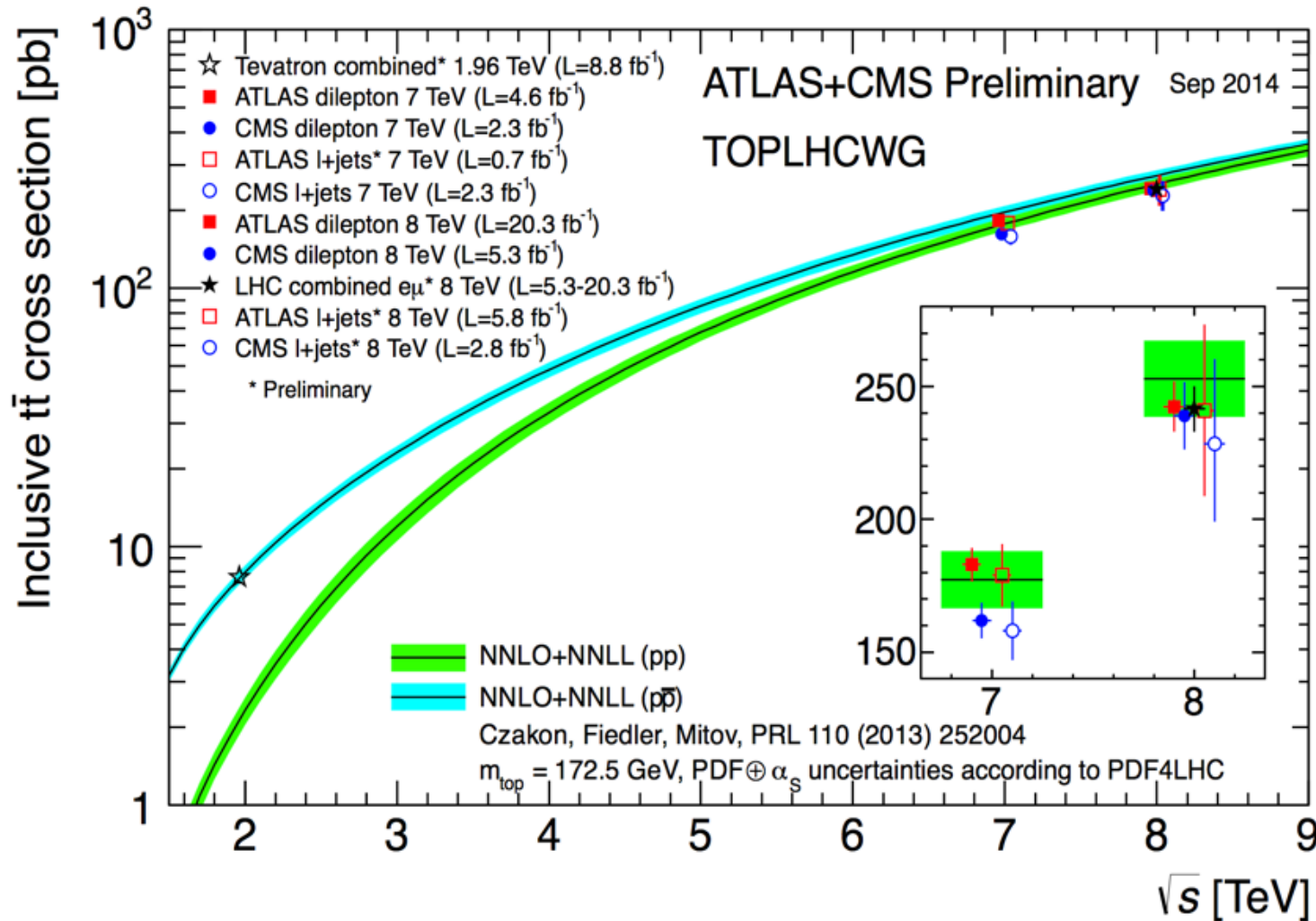
very powerful!

Dilepton Events at 13 TeV



very powerful!

Top pair production at hadron colliders



$\pm 5.7\%$
(theo)

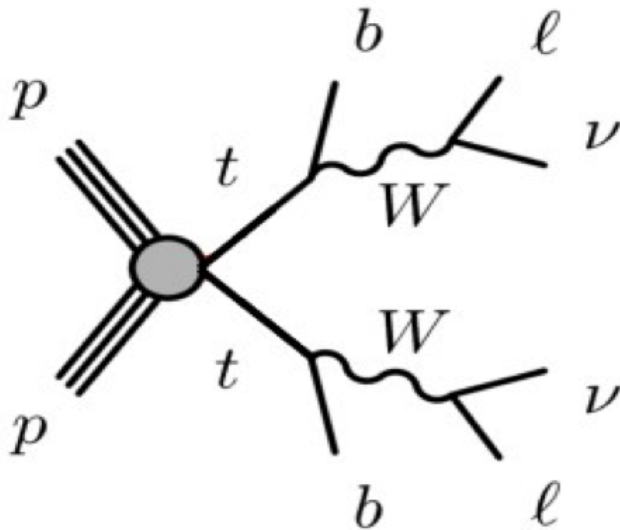
$\pm 3.9\%$
($e\mu$)



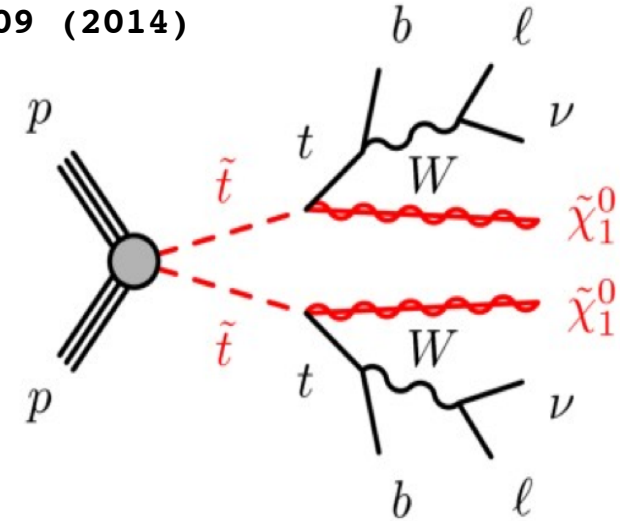
→ experiments challenge theory again

Stop Quark Pair Production

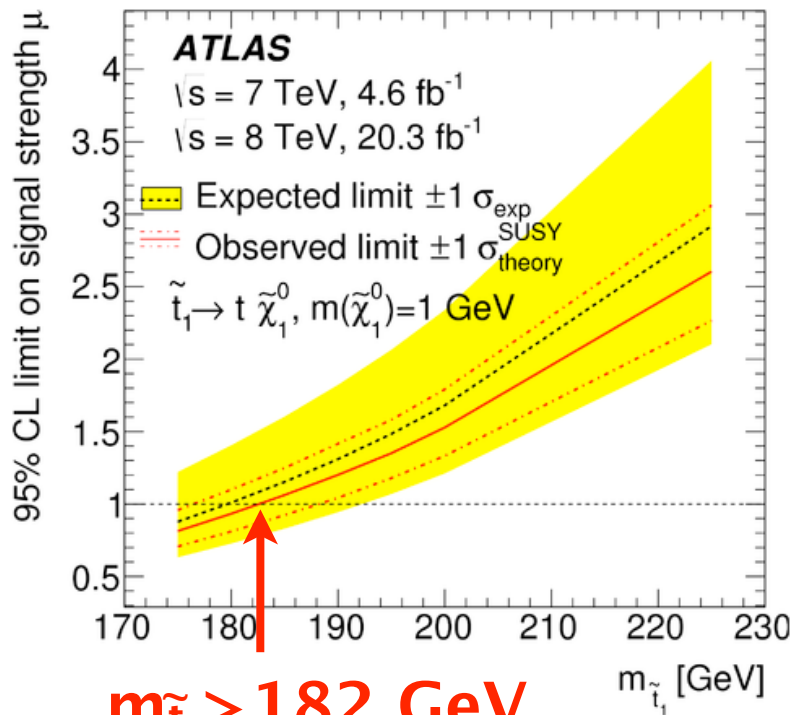
Eur. Phys. J. C74 3109 (2014)



do we see
left or
right?



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



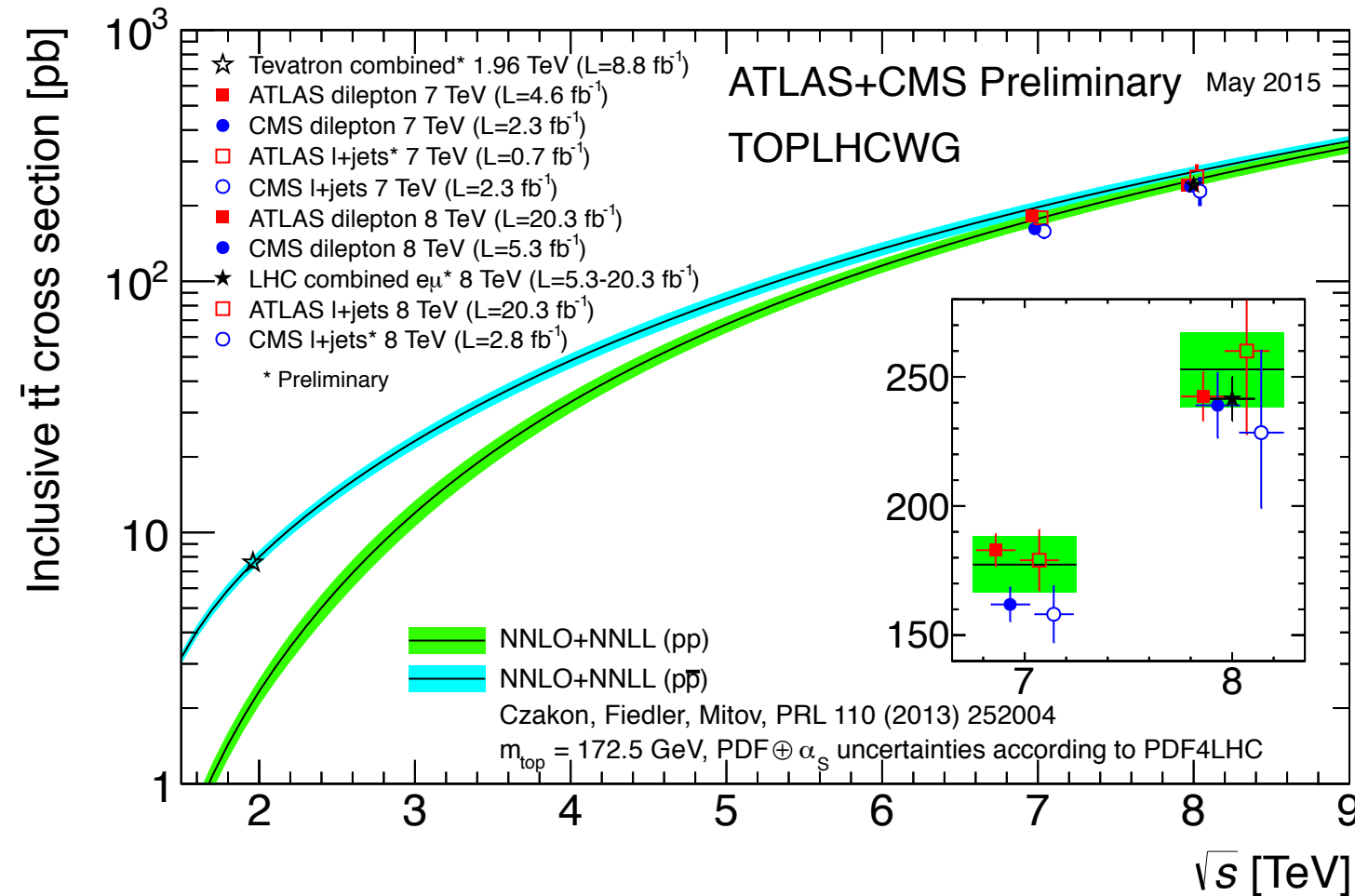
“stealth” scenario:
 - small sneutrino mass
 - stop mass close to top mass



$m_{\tilde{t}_1} > 182 \text{ GeV}$

Top pair production at hadron colliders

eager to put points here



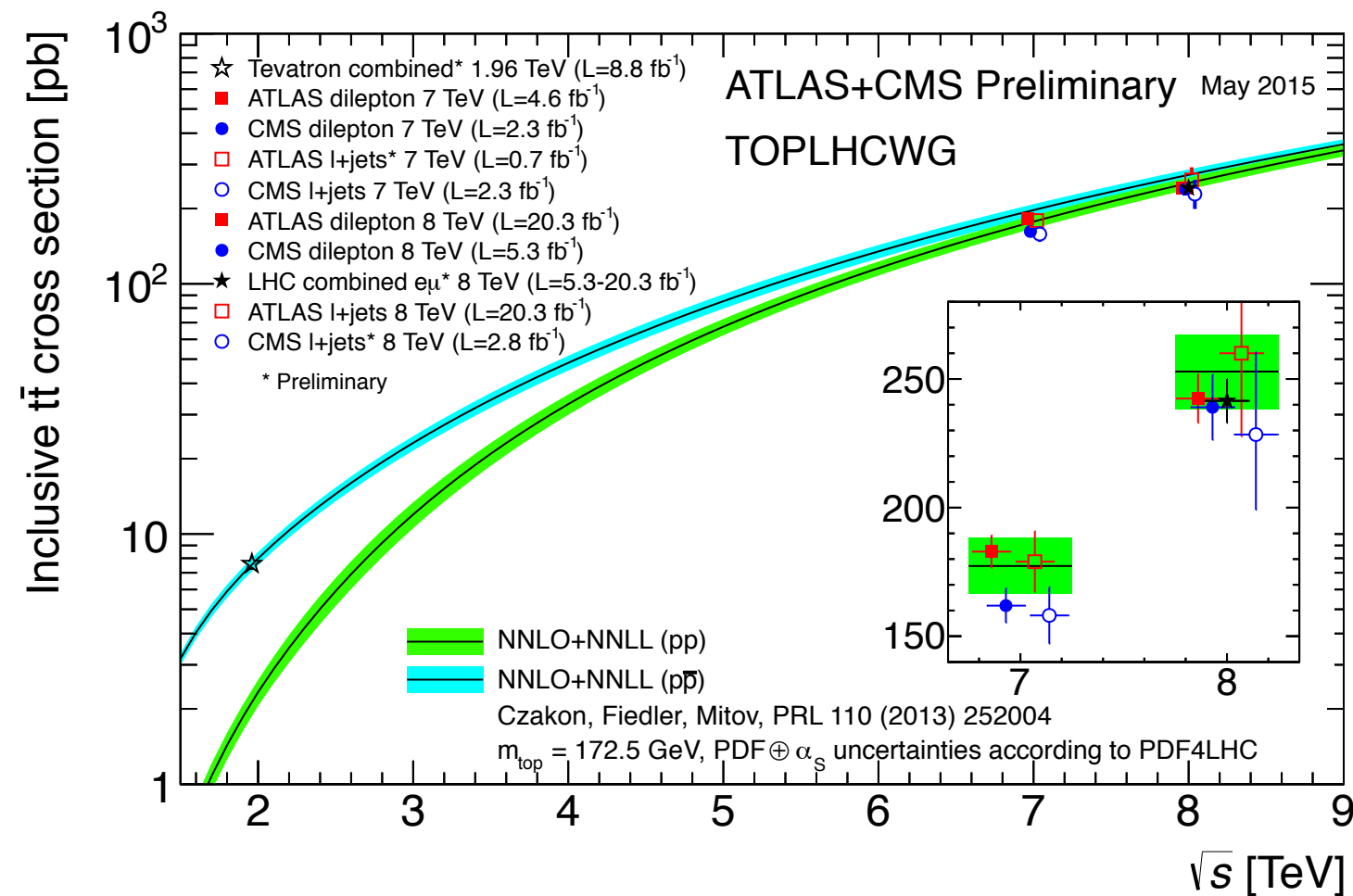
$\pm 5.7\%$
(theo)

$\pm 3.9\%$
($e\mu$)



→ experiments challenge theory again

Top pair production at hadron colliders

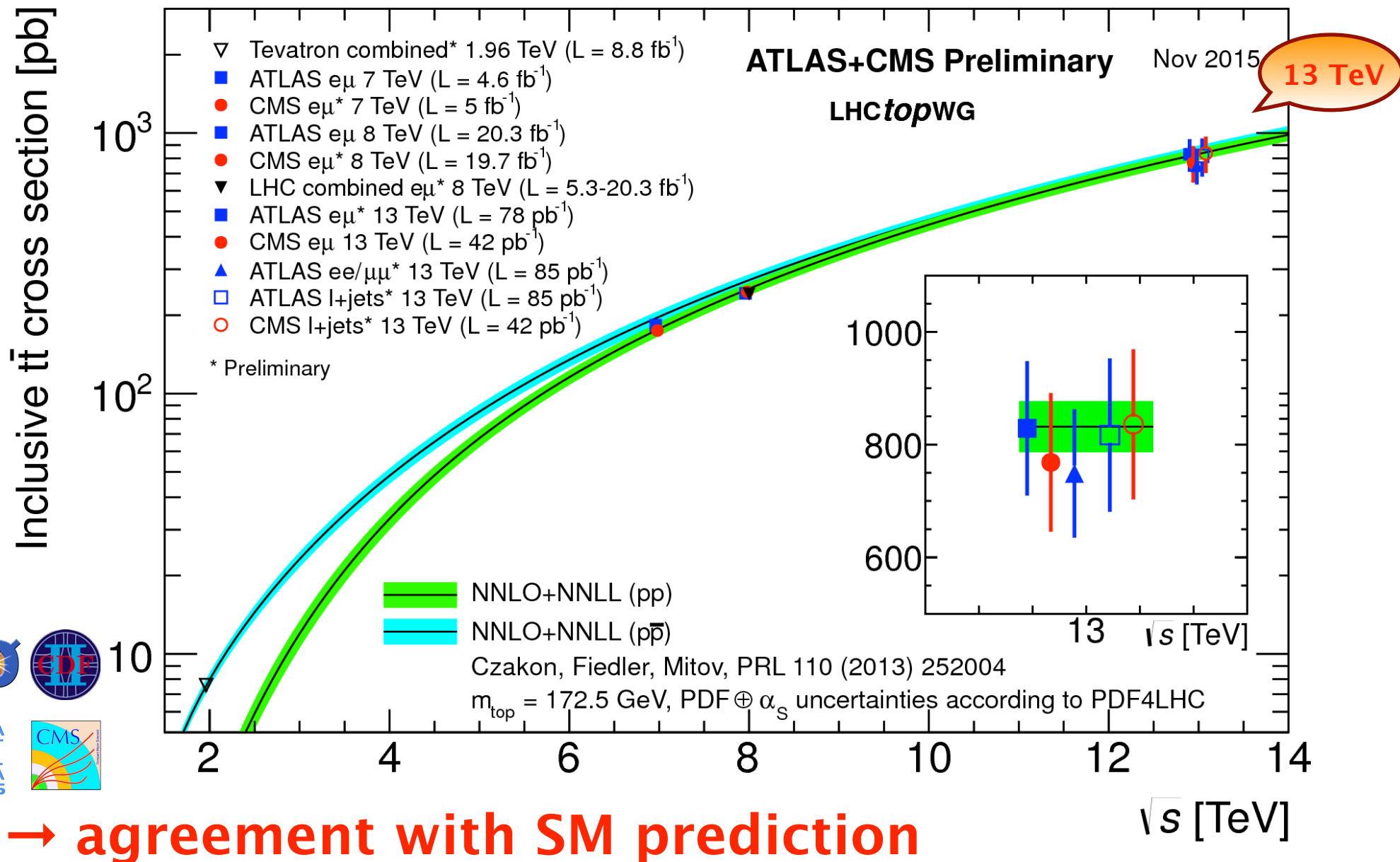


**boldly go
where no
man has
gone before**



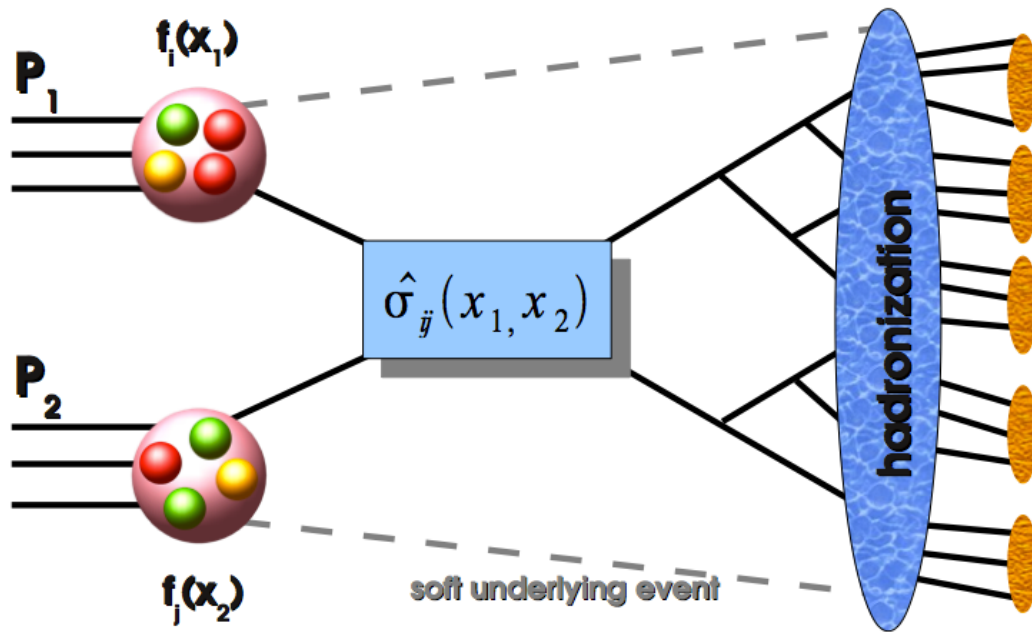
→ experiments challenge theory again

Top pair production at 13 TeV

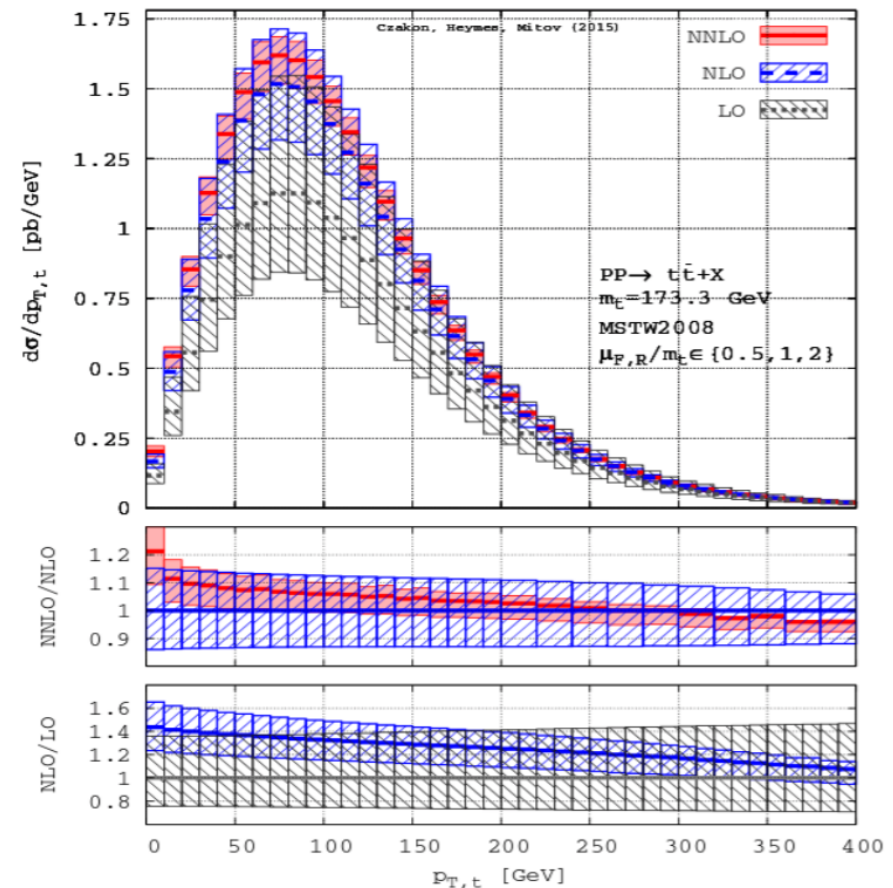


Differential Cross Sections

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

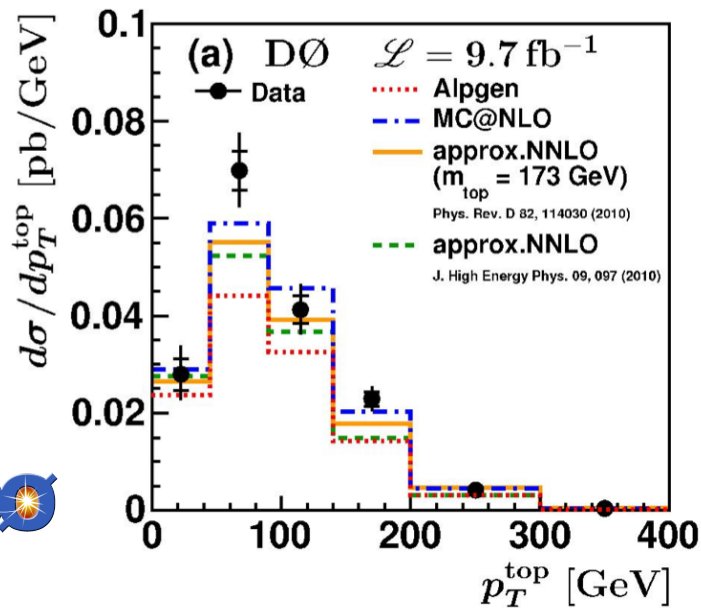


$t\bar{t}$ production in full **NNLO**:

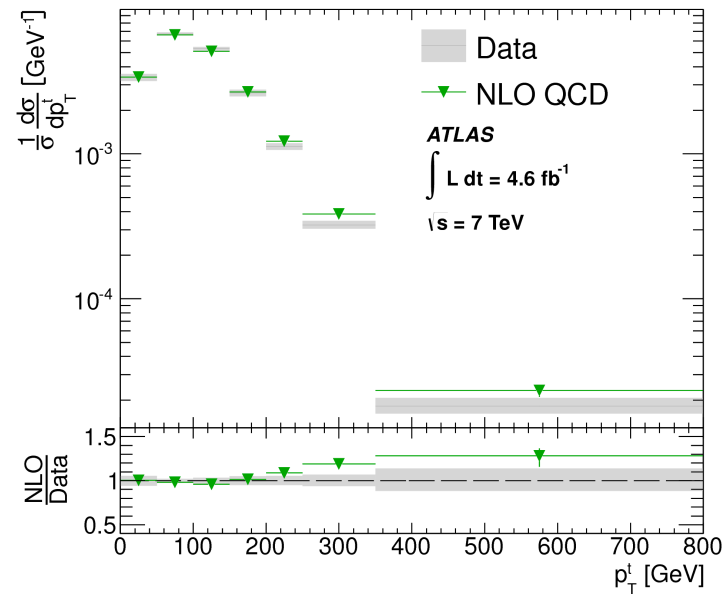


Differential, unfolded: top p_T

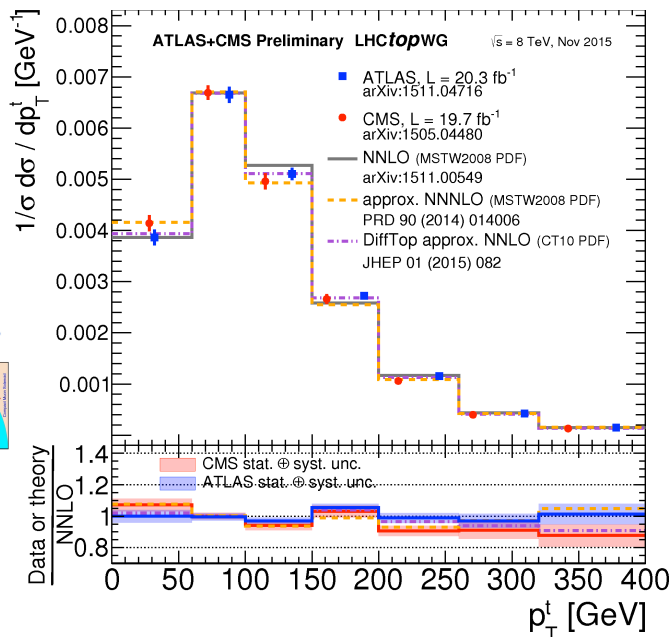
2 TeV



7 TeV

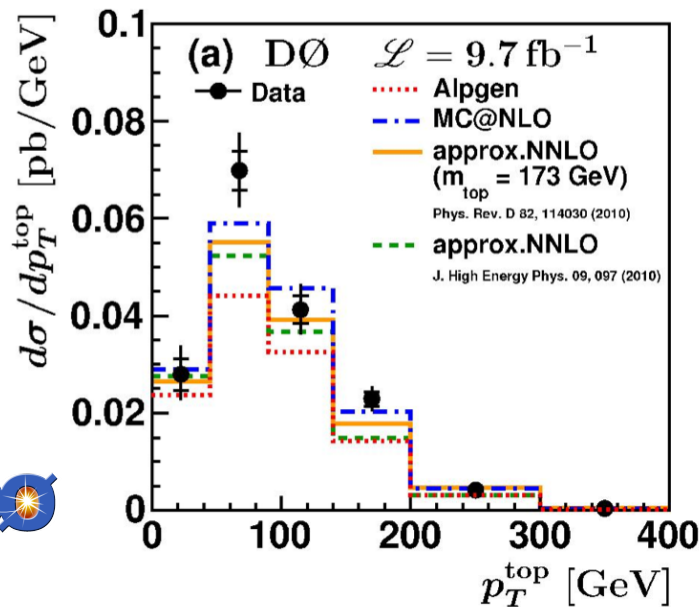


8 TeV

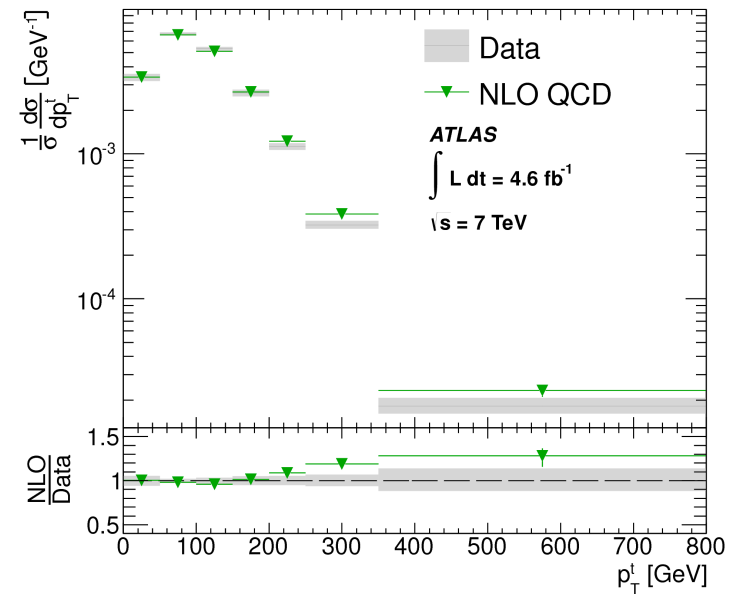


Differential, unfolded: top p_T

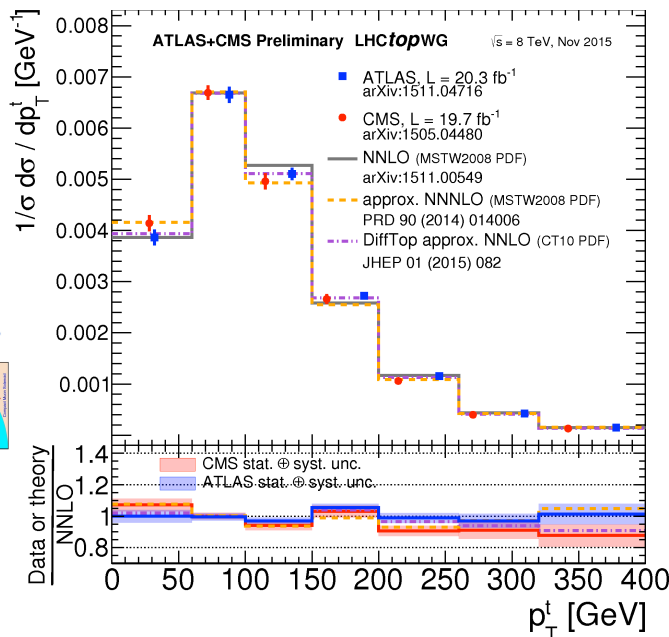
2 TeV



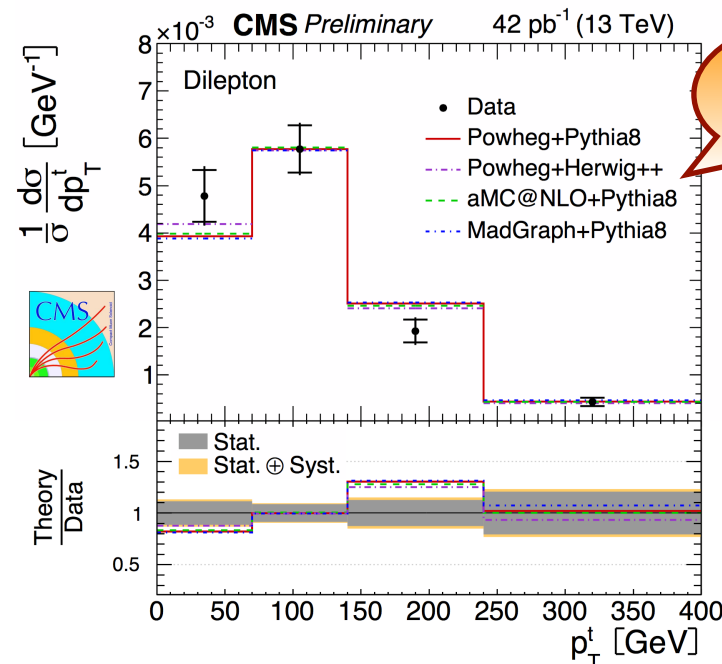
7 TeV



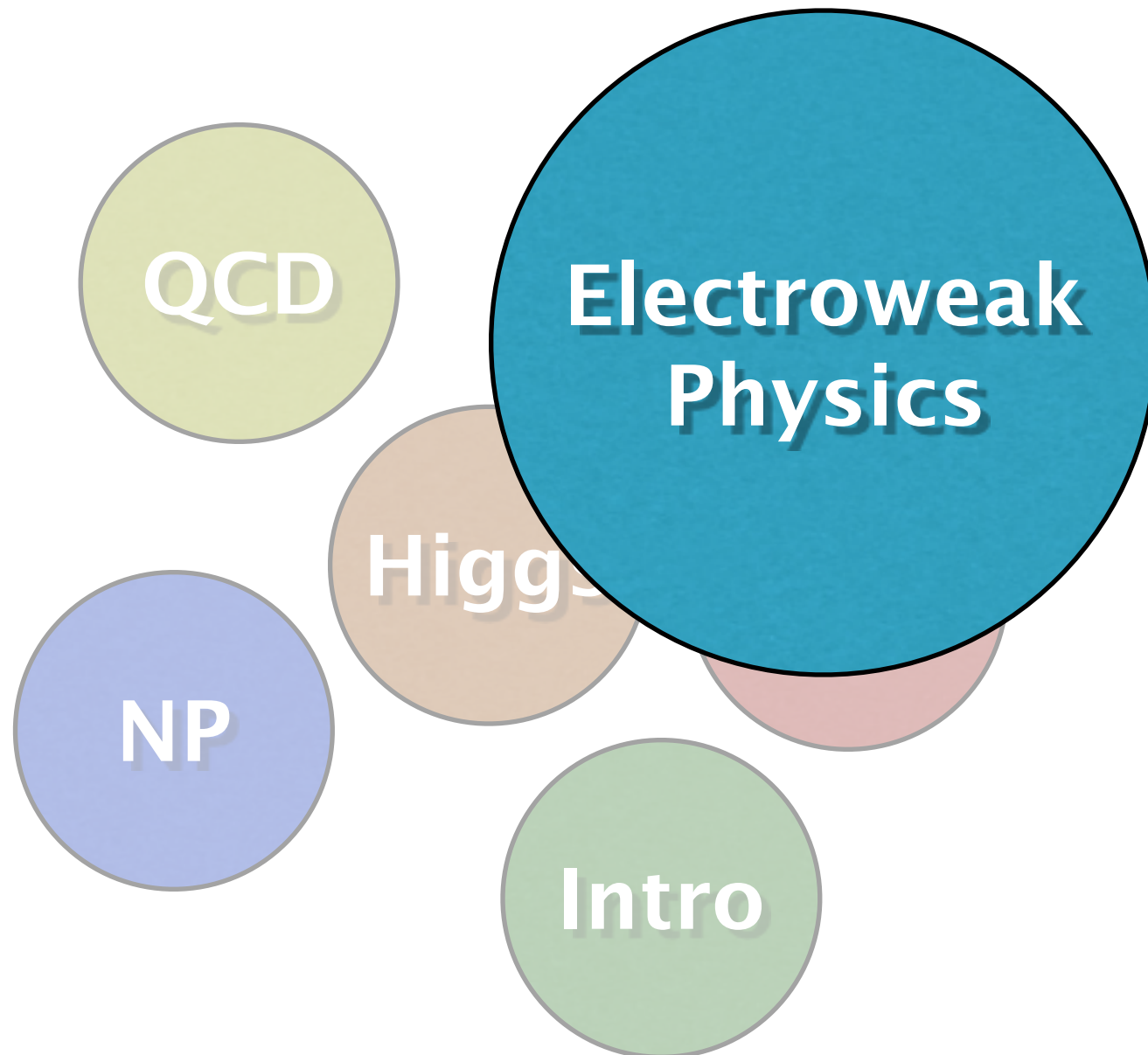
8 TeV



13 TeV



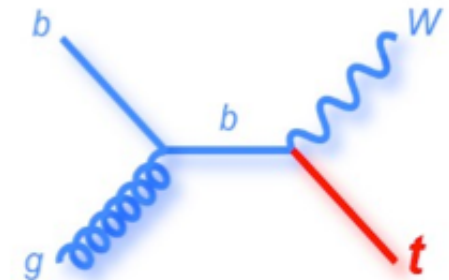
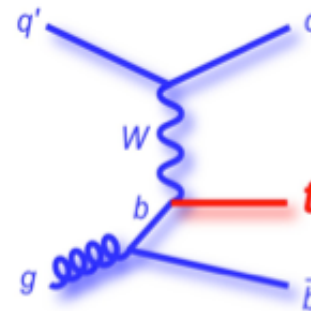
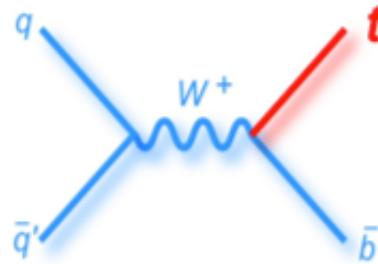
Top Quark Physics Topics



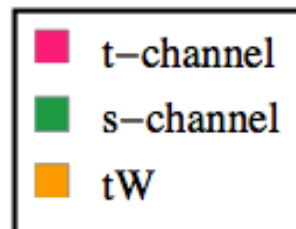
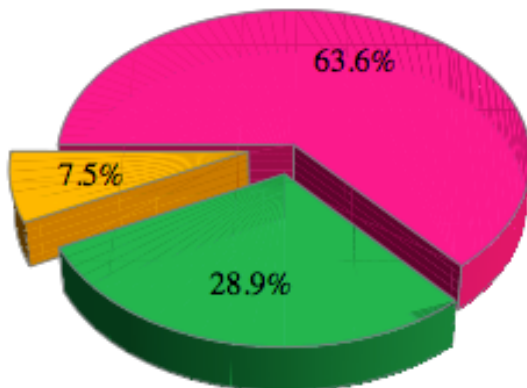
Single Top Quark Production

direct measurement of $|V_{tb}|$

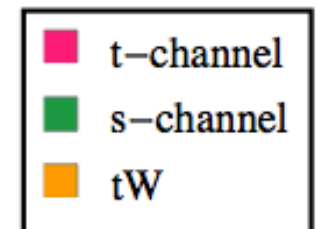
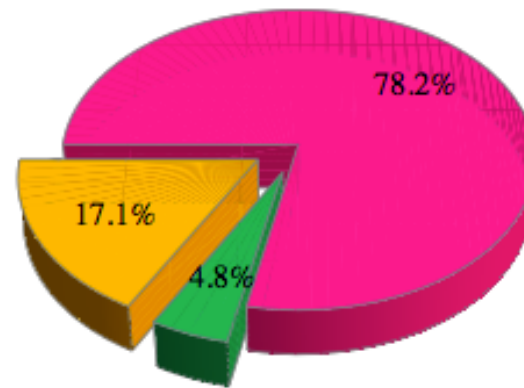
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$



Tevatron



LHC (7 TeV)

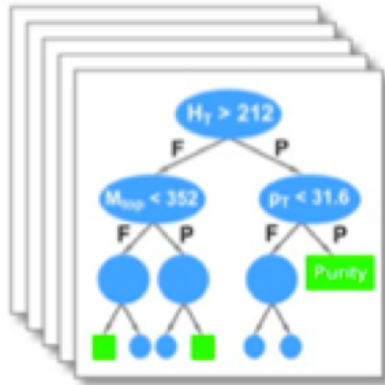


⇒ important to measure all channels separately to search for new physics

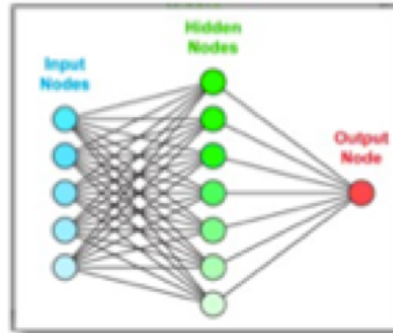
BUT: do not separate Wt in higher orders – an unphysical question!

Multivariate Analyses

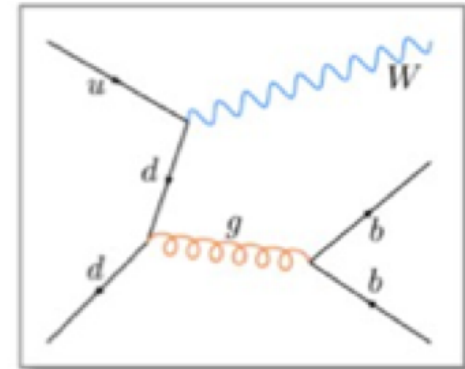
Boosted Decision Trees



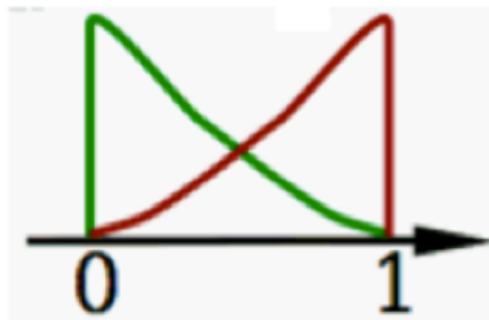
Neural Networks



Matrix Elements



background signal

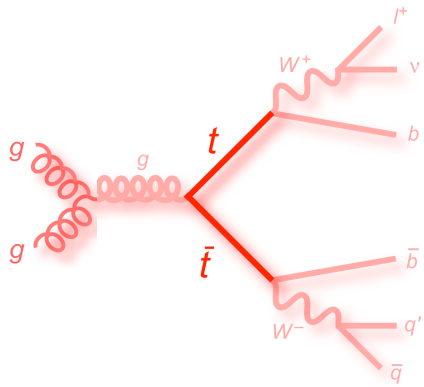


- s+t channel observed by CDF and D0 in 2009
- important step to establish MVA techniques

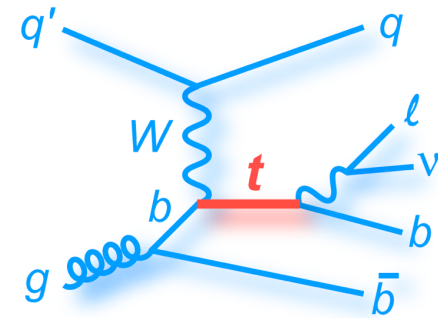
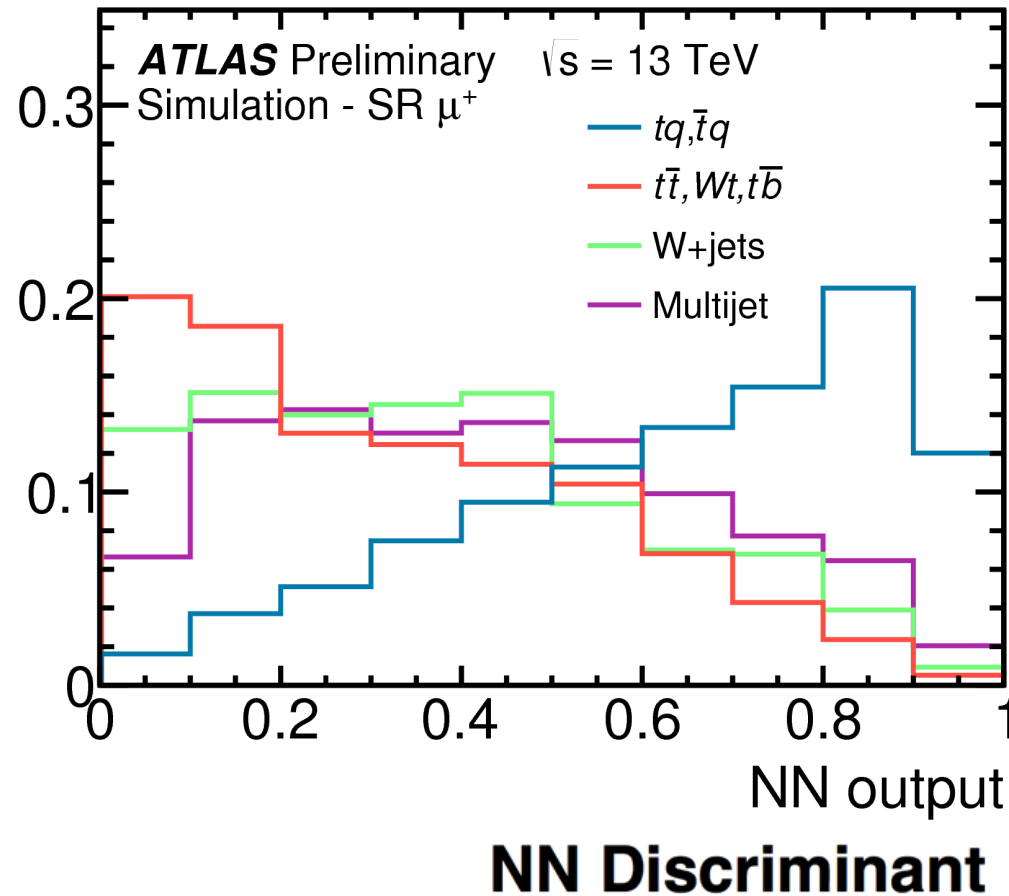


Output Discriminant t-channel

13 TeV

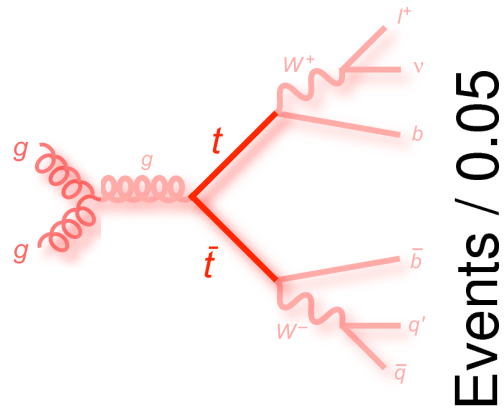


Fraction of events / 0.10

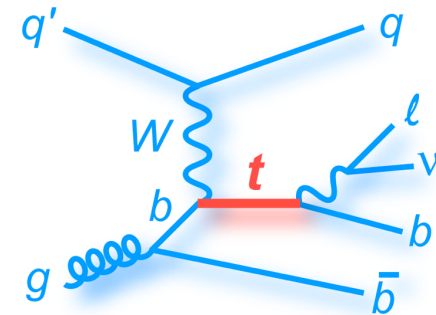
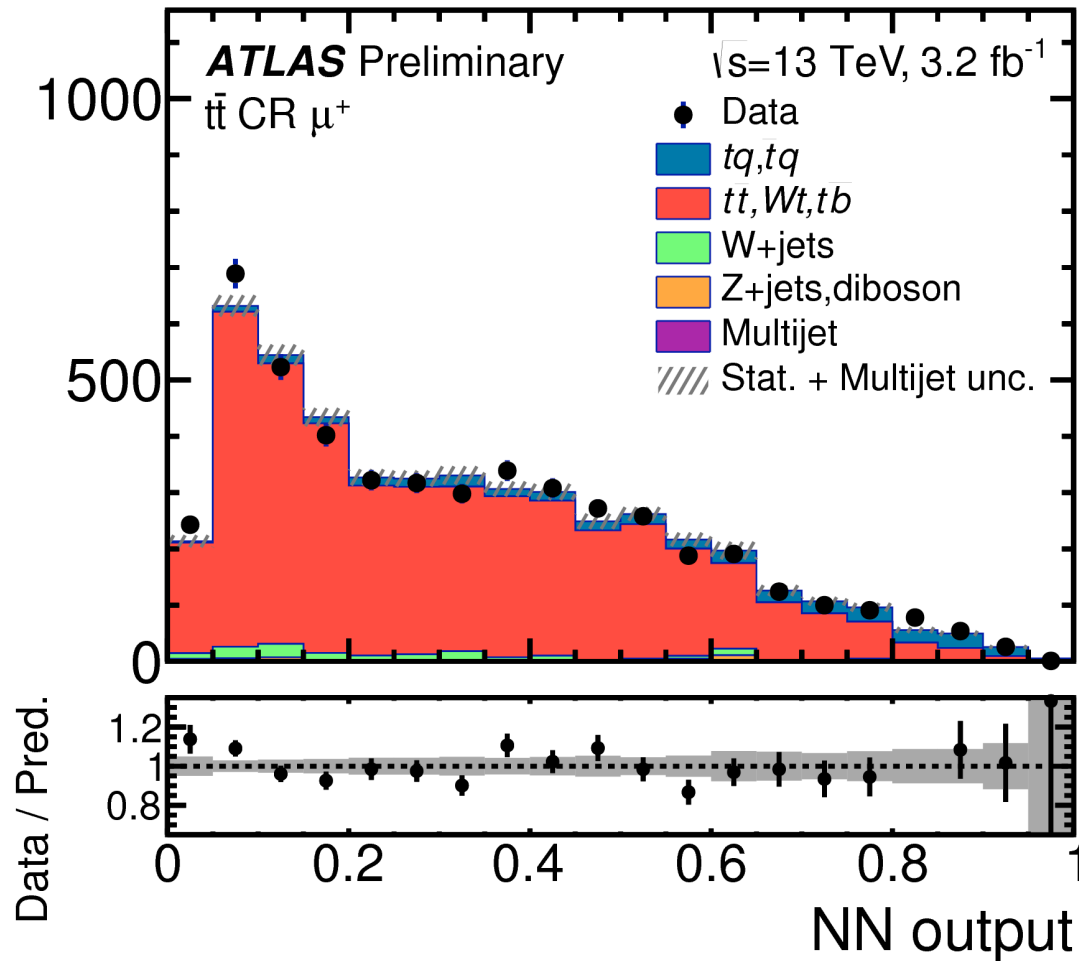


Output Discriminant t-channel

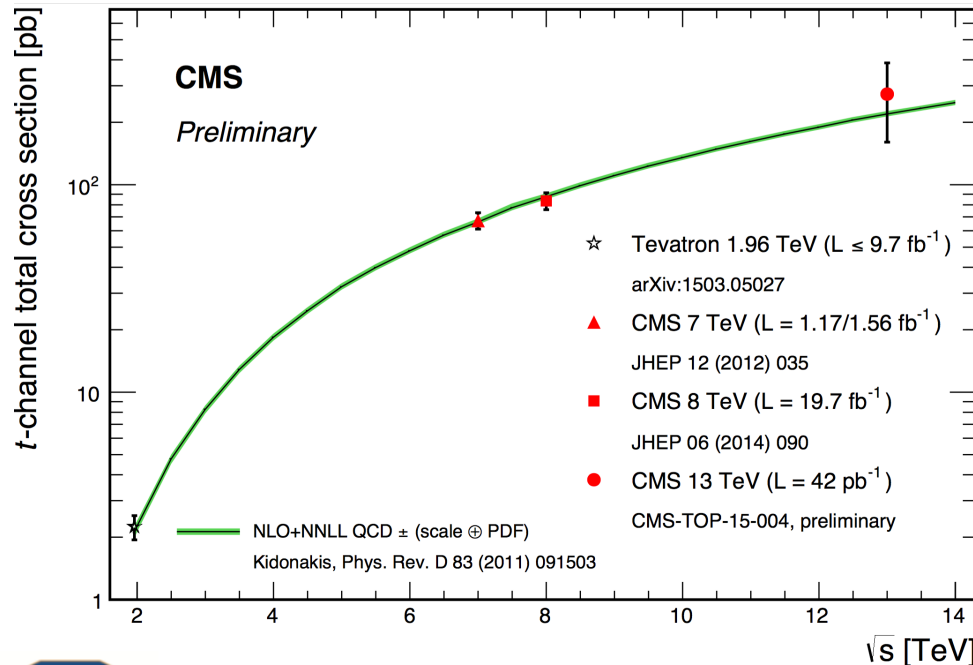
13 TeV



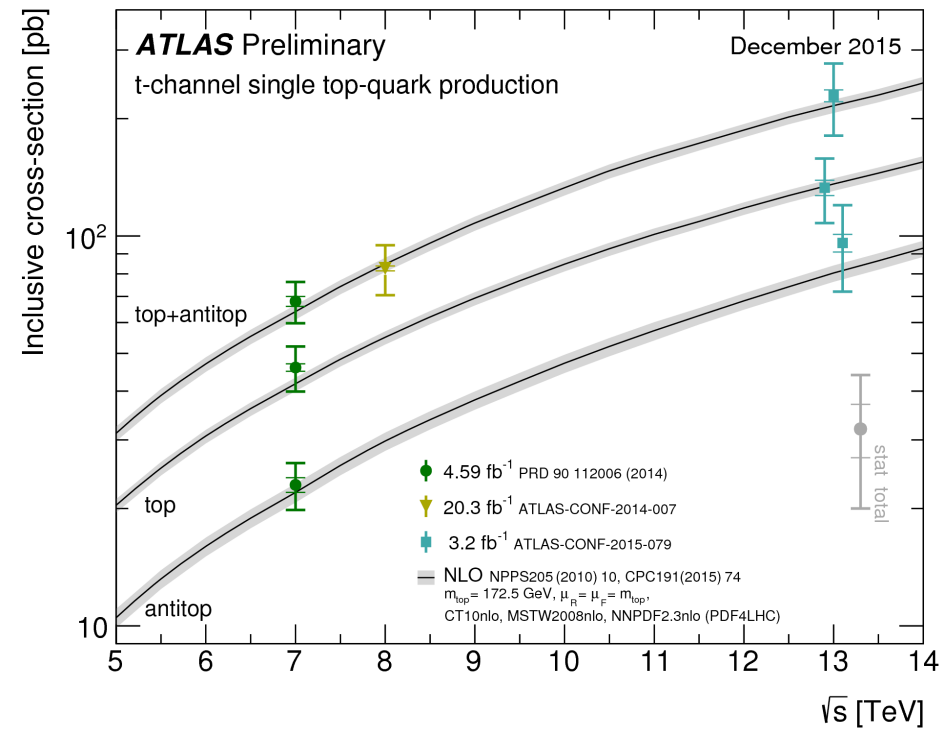
Events / 0.05



Single top t-channel cross section



13 TeV

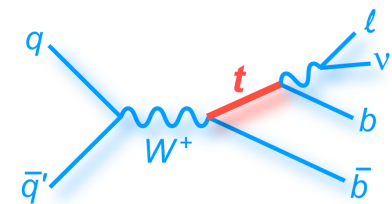
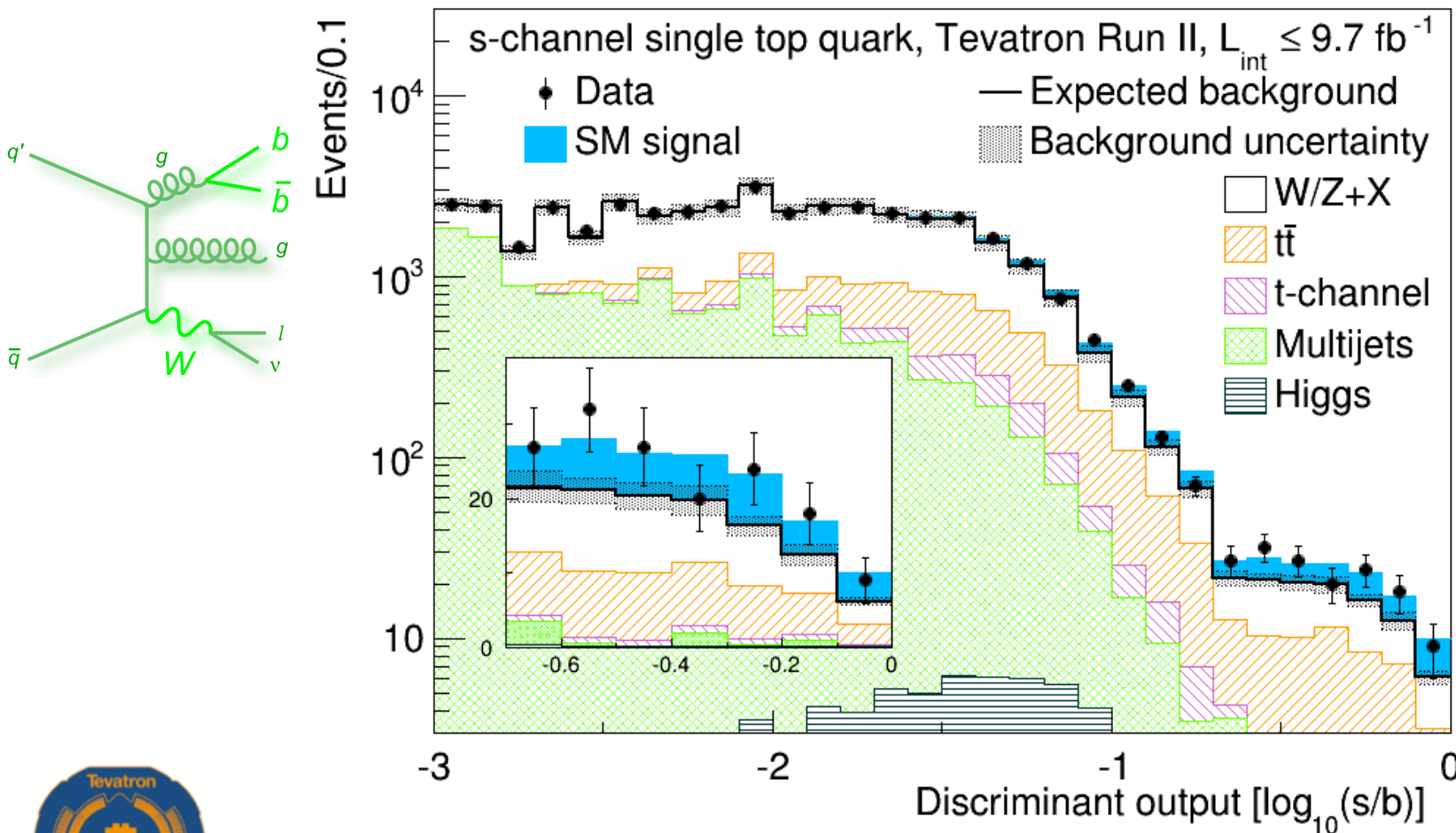


→ agreement with SM predictions!

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

Tevatron single top quark summary
Measurement Cross section [pb]

s-channel:

CDF
PRL 112, 231805 (2014)

D0
PLB 726, 656 (2013)

Tevatron
PRL 112, 231803 (2014)

t-channel:

CDF
CDF-CONF-11033 (2014)

D0
PLB 726, 656 (2013)

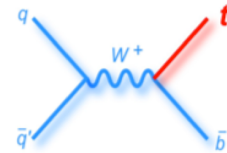
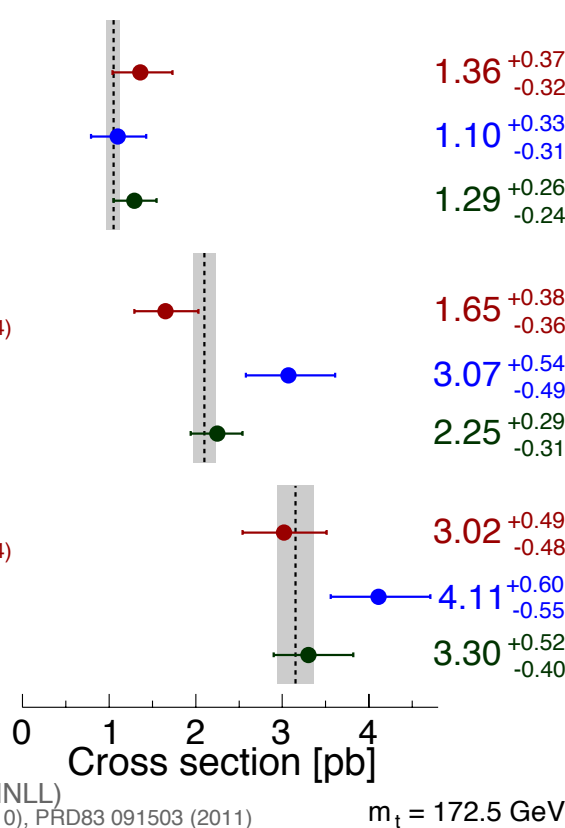
Tevatron

s+t:

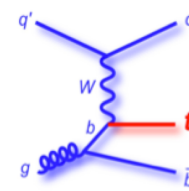
CDF
CDF-CONF-11033 (2014)

D0
PLB 726, 656 (2013)

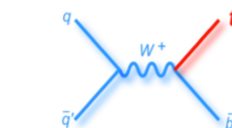
Tevatron



→ observation



→ observation



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

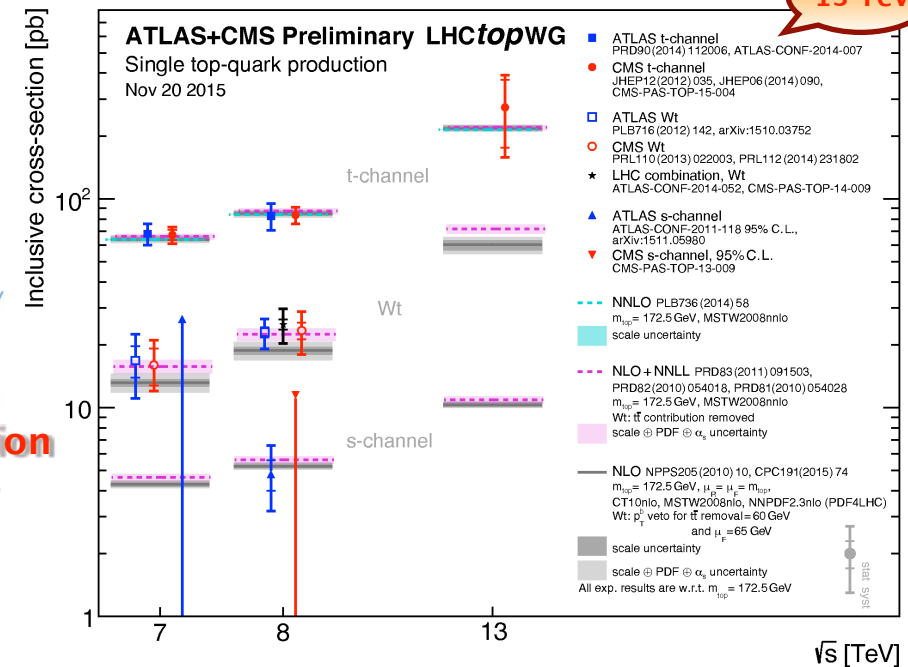


$$|V_{tb}| = 0.998 \pm 0.041 \pm 4.1\%$$

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

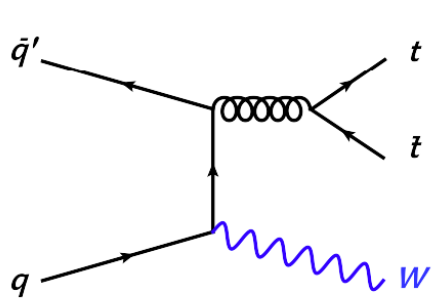
→ no hint for anomalous contribution

this is the final word
from the Tevatron!

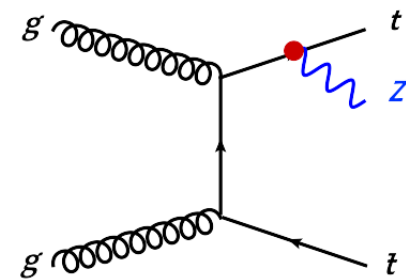


→ all production modes observed!

Search for ttZ and ttW

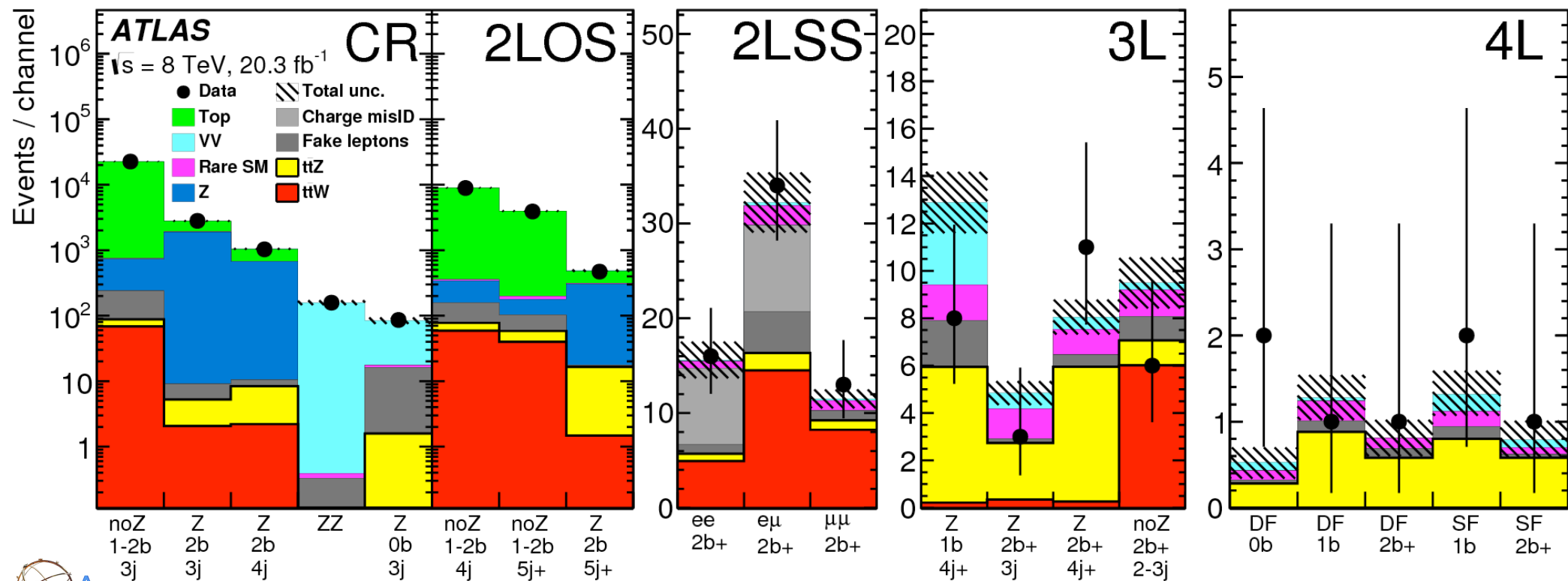


ISR



FSR

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

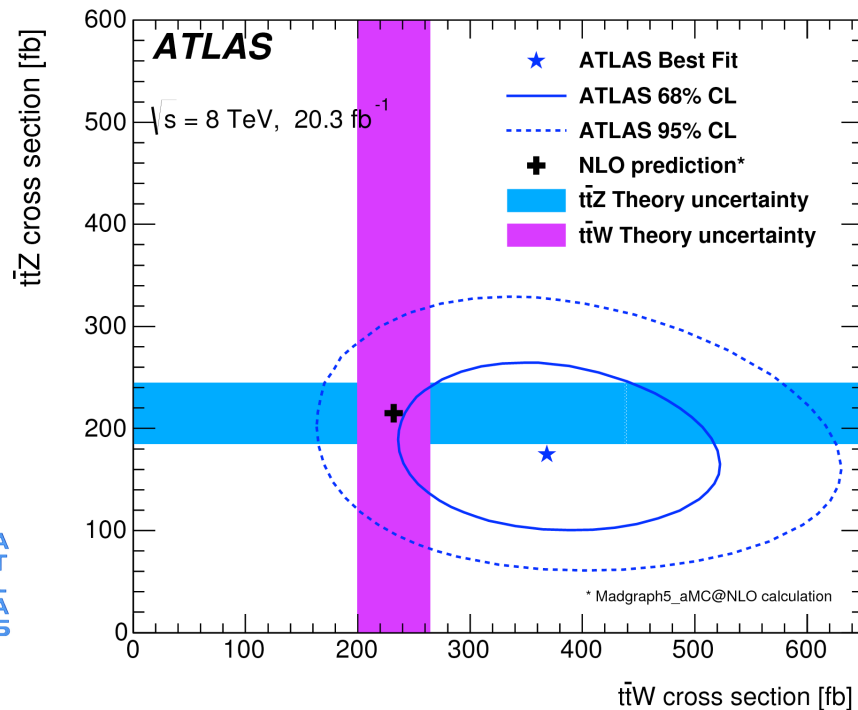


ttW

ttZ

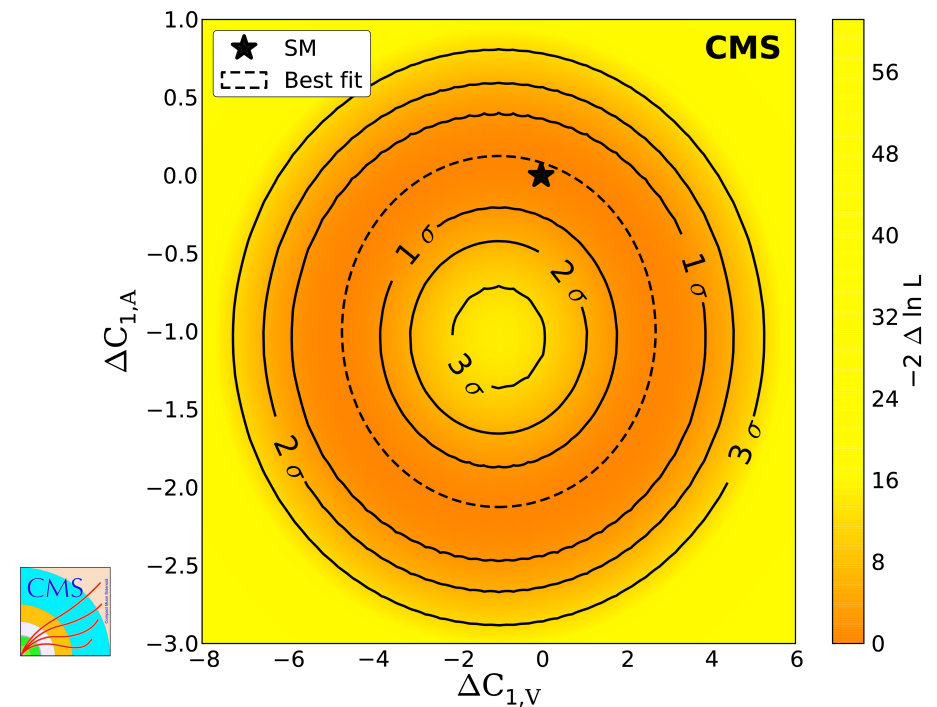
Observation of $t\bar{t}V$ production

$t\bar{t}Z$ vs. $t\bar{t}W$ cross sections:



$t\bar{t}W$: 3.2 σ (exp) 5.0 σ (obs)
 $t\bar{t}Z$: 4.5 σ (exp) 4.2 σ (obs)

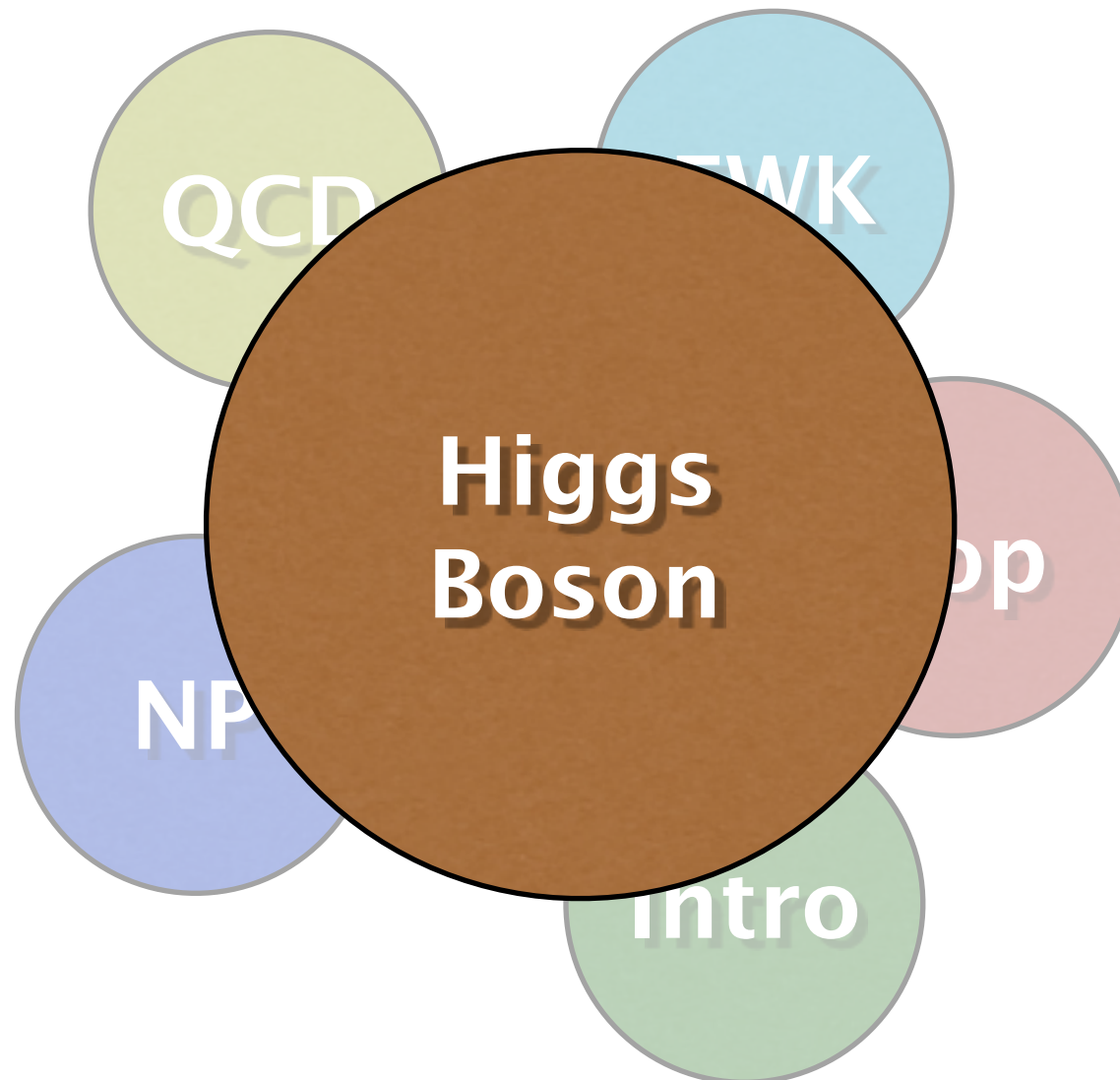
anomalous V or A $t\bar{t}Z$ couplings:



$t\bar{t}W$: 3.8 σ (exp) 4.8 σ (obs)
 $t\bar{t}Z$: 5.7 σ (exp) 6.4 σ (obs)

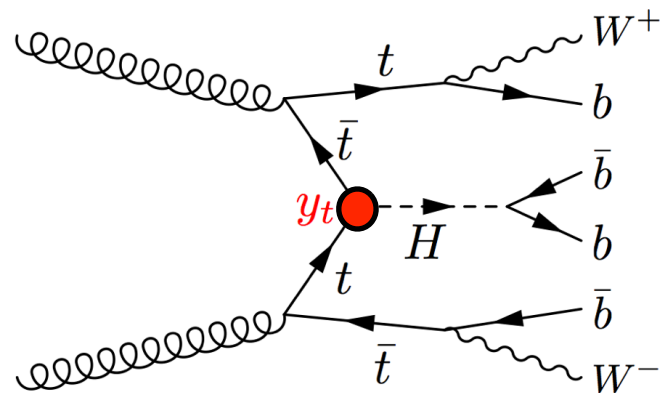
→ in agreement with the SM prediction
 (ttγ also in agreement with SM prediction)

Top Quark Physics Topics

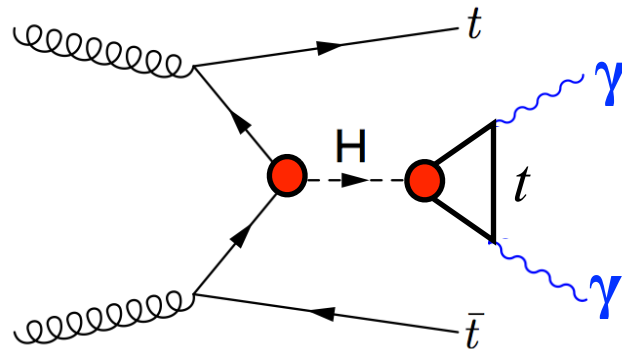


Search for $t\bar{t}H$ production

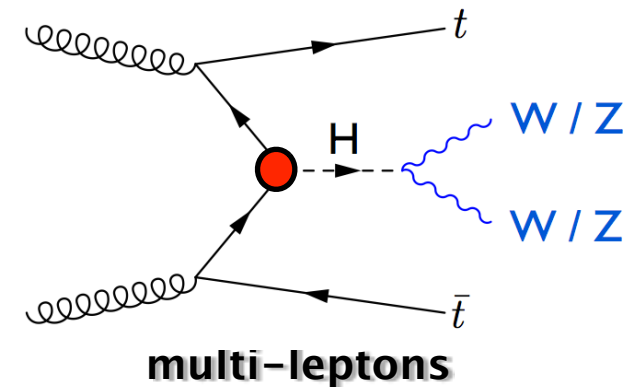
$H \rightarrow b\bar{b}$



$H \rightarrow \gamma\gamma$

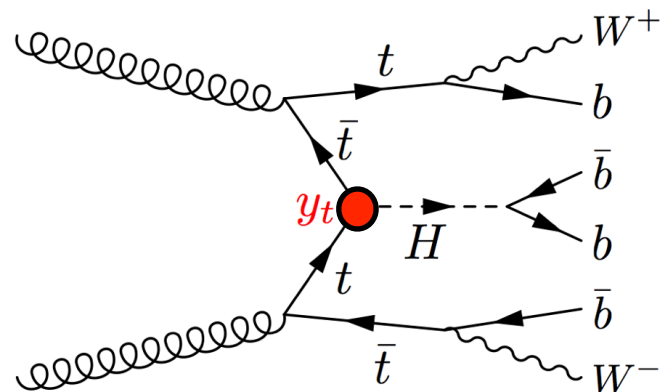


$H \rightarrow WW, ZZ$

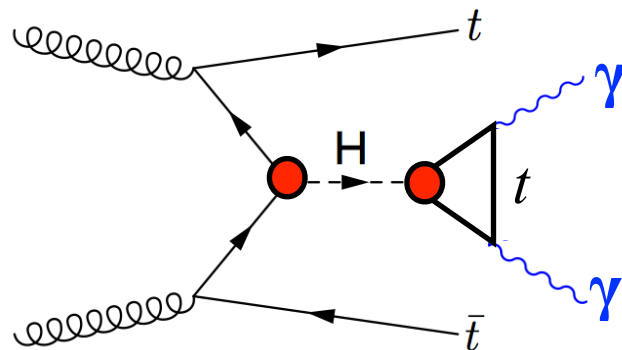


Search for $t\bar{t}H$ production

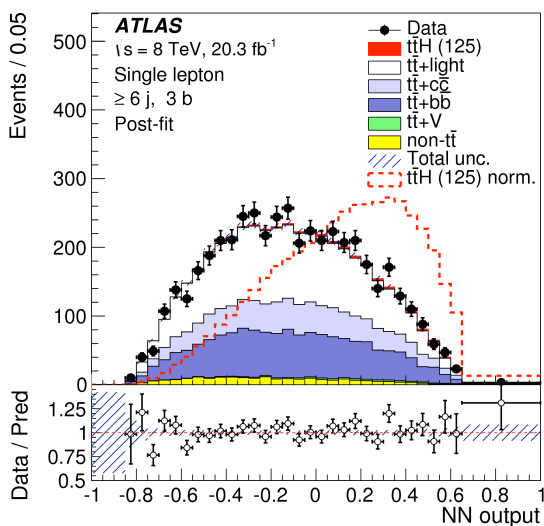
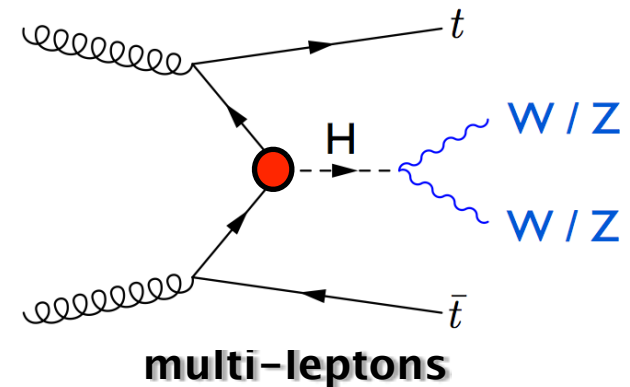
$H \rightarrow b\bar{b}$



$H \rightarrow \gamma\gamma$

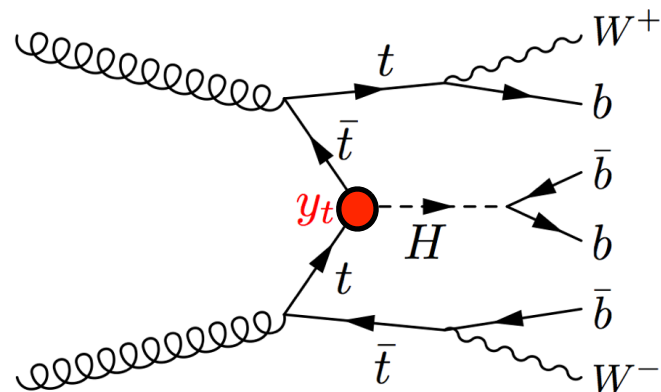


$H \rightarrow WW, ZZ$

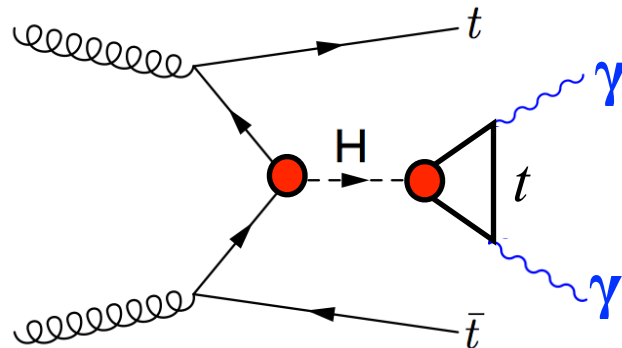


Search for $t\bar{t}H$ production

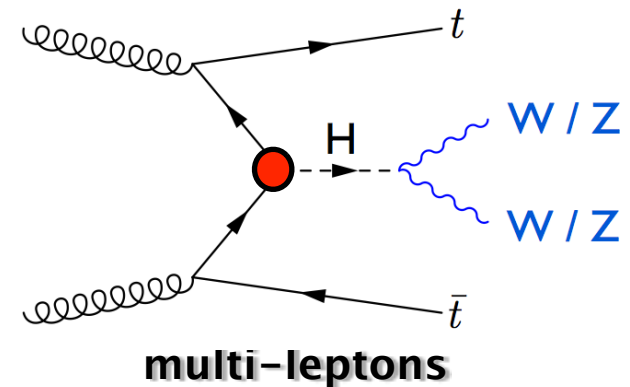
$H \rightarrow b\bar{b}$



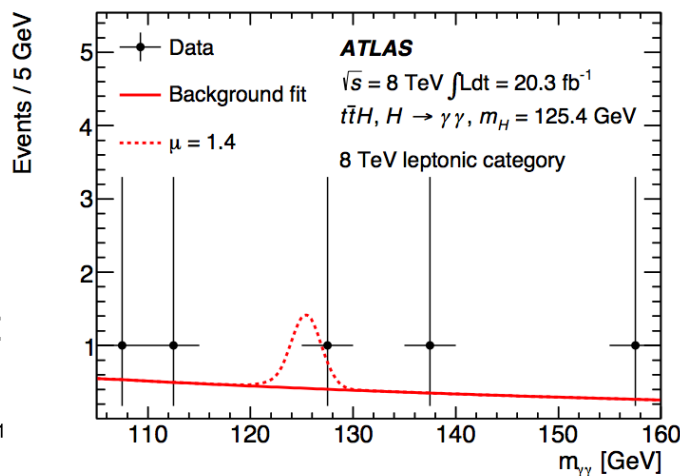
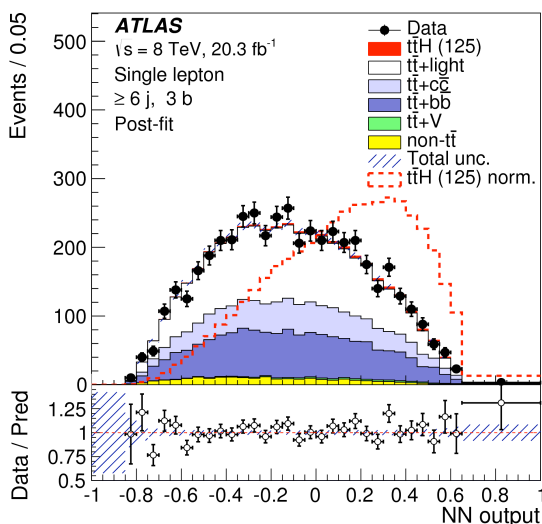
$H \rightarrow \gamma\gamma$



$H \rightarrow WW, ZZ$

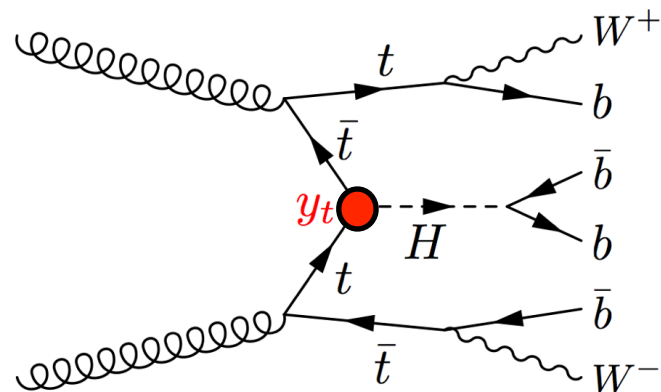


multi-leptons

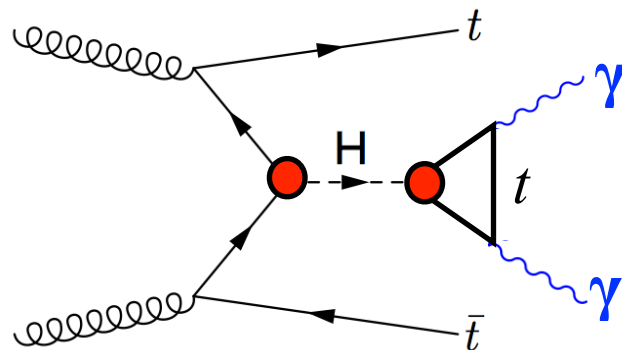


Search for $t\bar{t}H$ production

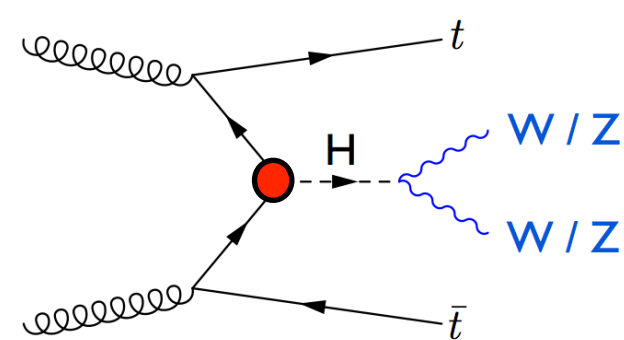
$H \rightarrow b\bar{b}$



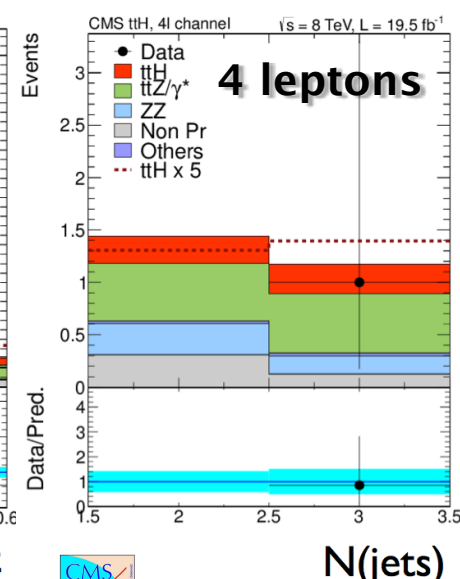
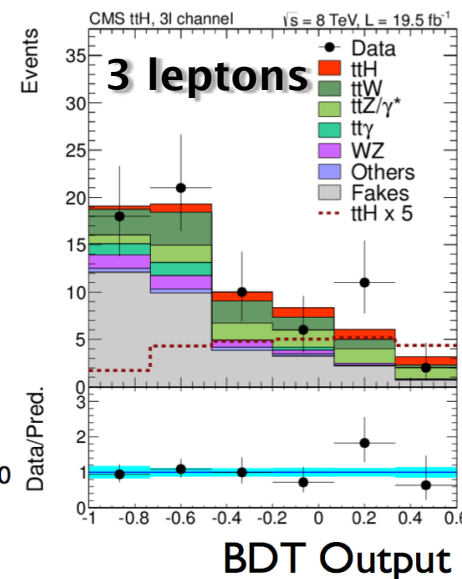
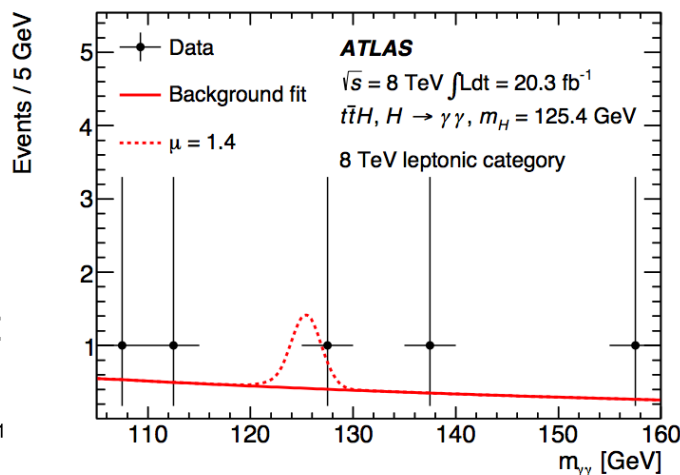
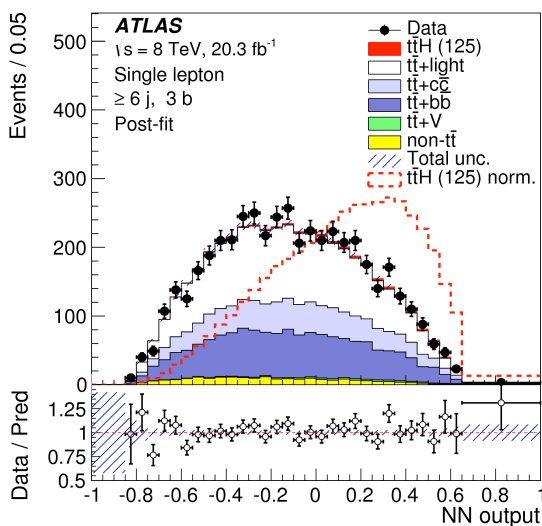
$H \rightarrow \gamma\gamma$



$H \rightarrow WW, ZZ$



multi-leptons



Results in ttH

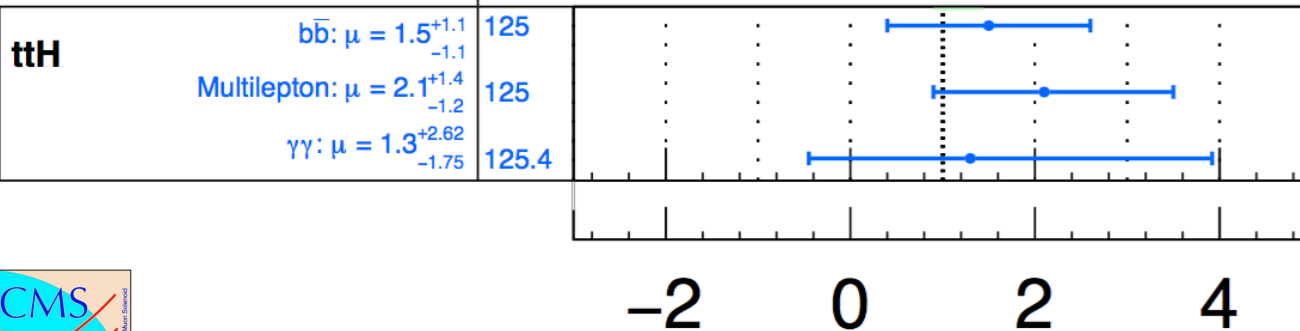
ATLAS



Individual analysis

Input measurements

$\pm 1\sigma$ on μ



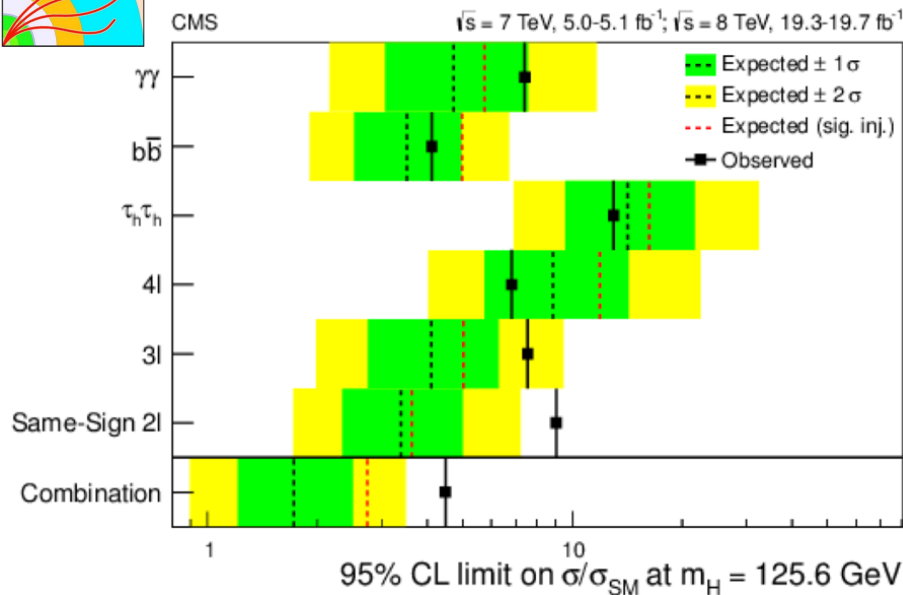
3.2 σ (1.4 σ exp)

σ/σ_{SM}

High lumi LHC:



arXiv:1307.7292

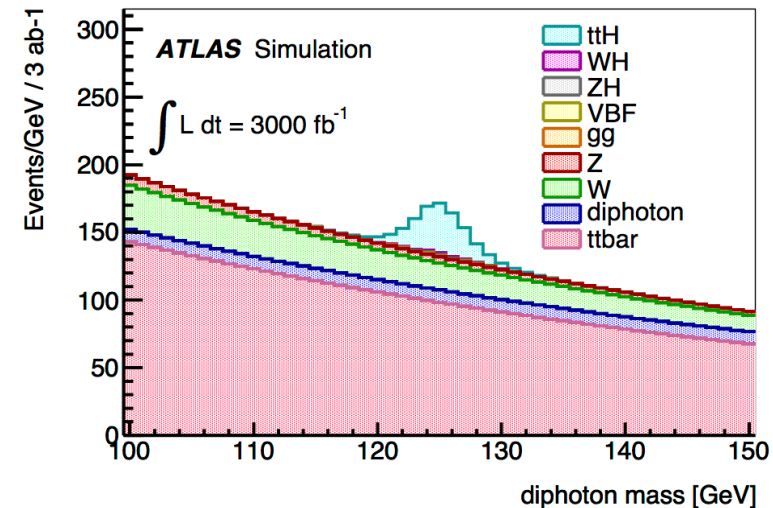


4.5 σ (1.7 σ exp)

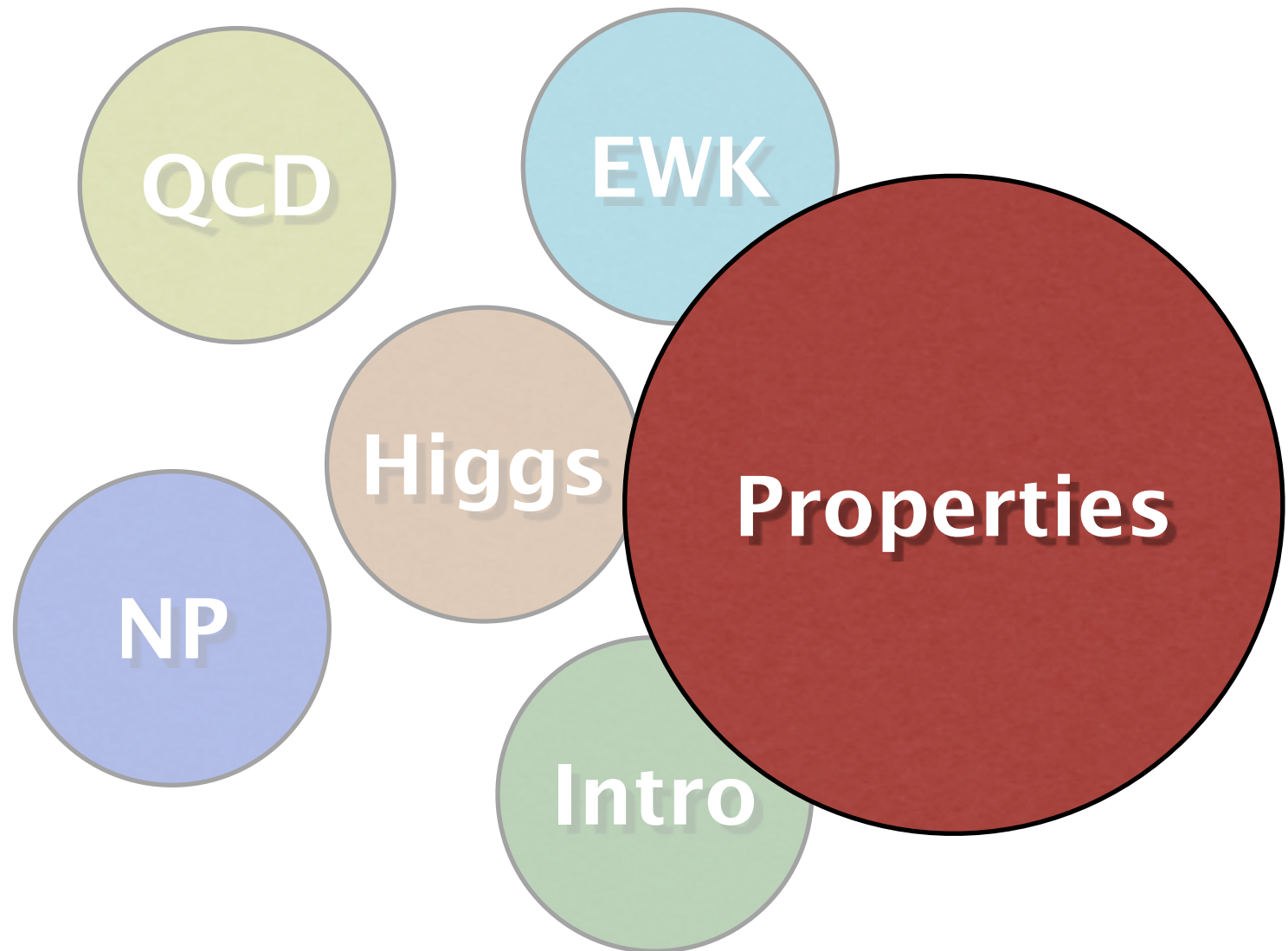
limit on σ/σ_{SM}

→ observation in Run-II

→ measurement of top-Yukawa coupling

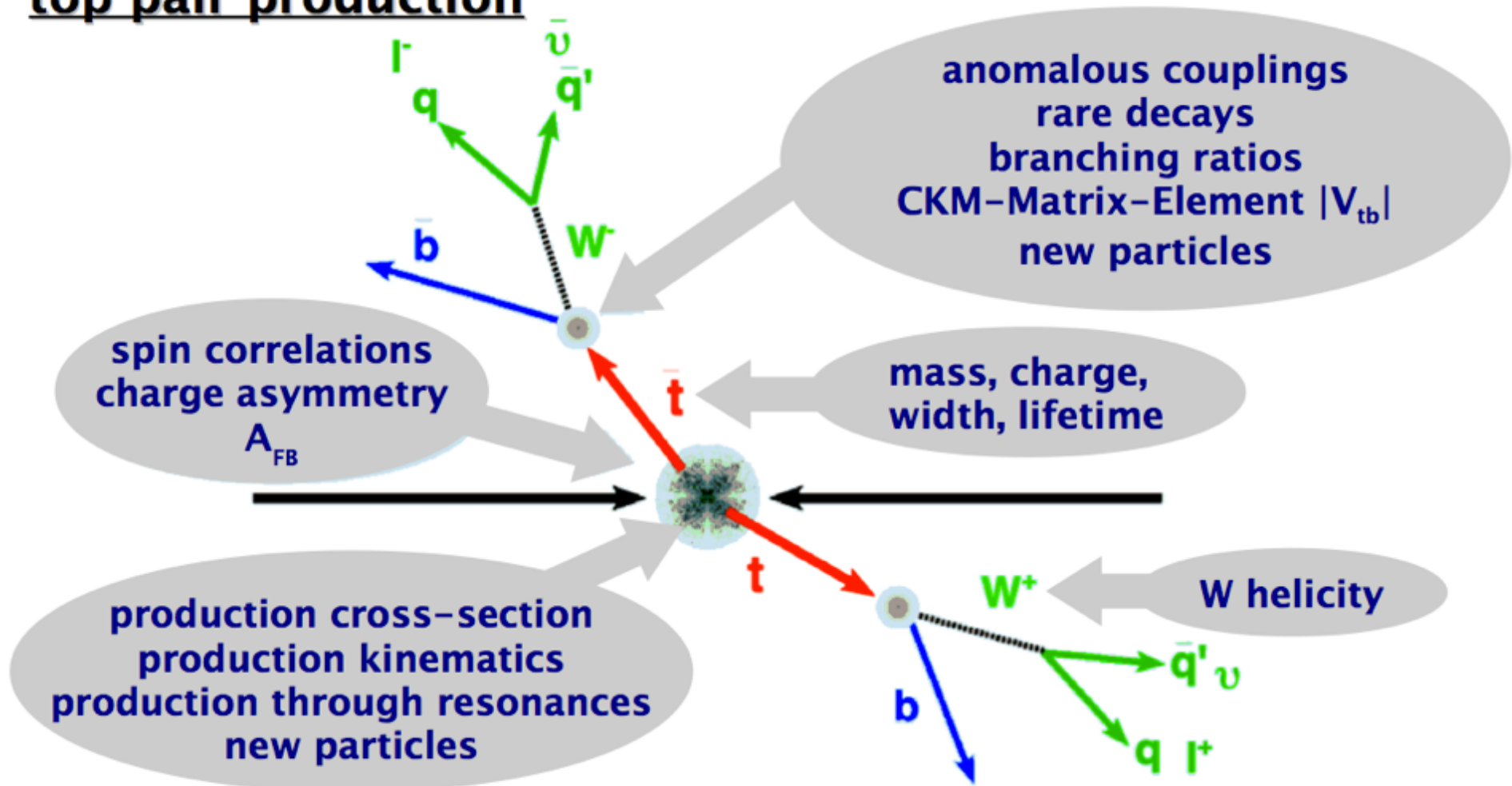


Top Quark Physics Topics



Top Quark Analyses

top pair production



single top production

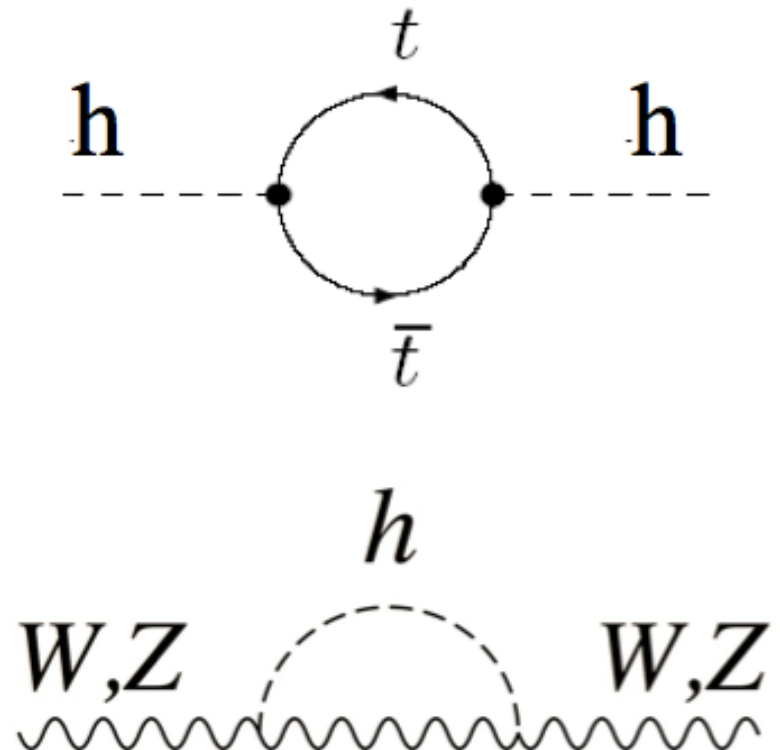
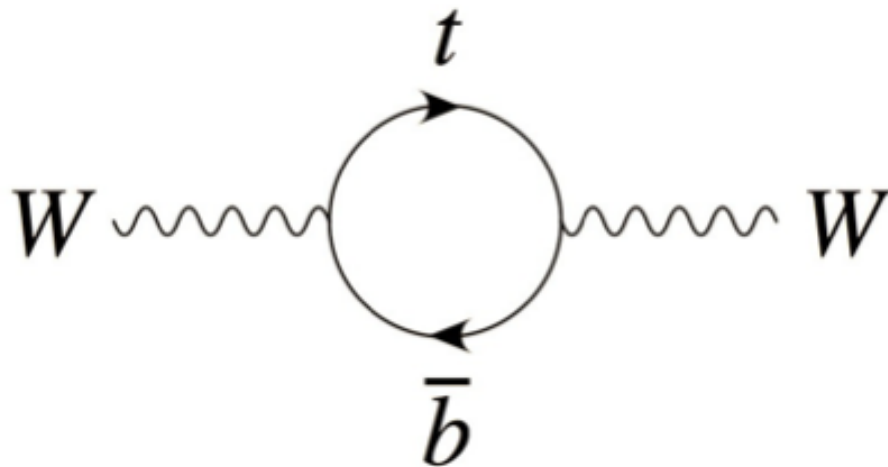
cross sections, CKM matrix element $|V_{tb}|$, polarisation, SM and anomalous couplings, searches, ...

other production modes

$t\bar{t}$ +jets, $t\bar{t}b\bar{b}$, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$ and their couplings

The Top Quark Mass

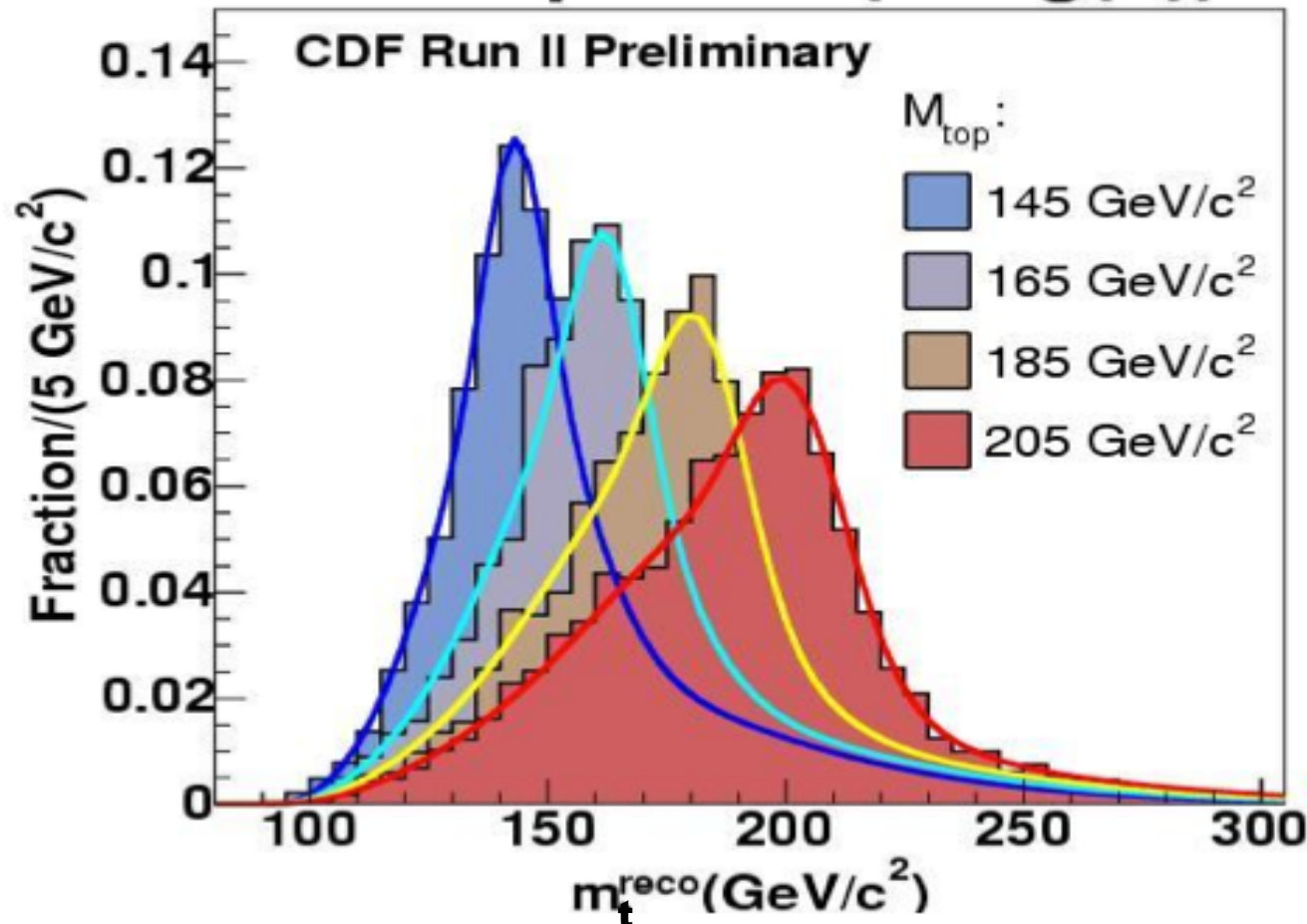
- free parameter in the Standard Model
- check the **self-consistency of the Standard Model** in combination with **W mass** and **Higgs mass**



Extraction Techniques: Templates

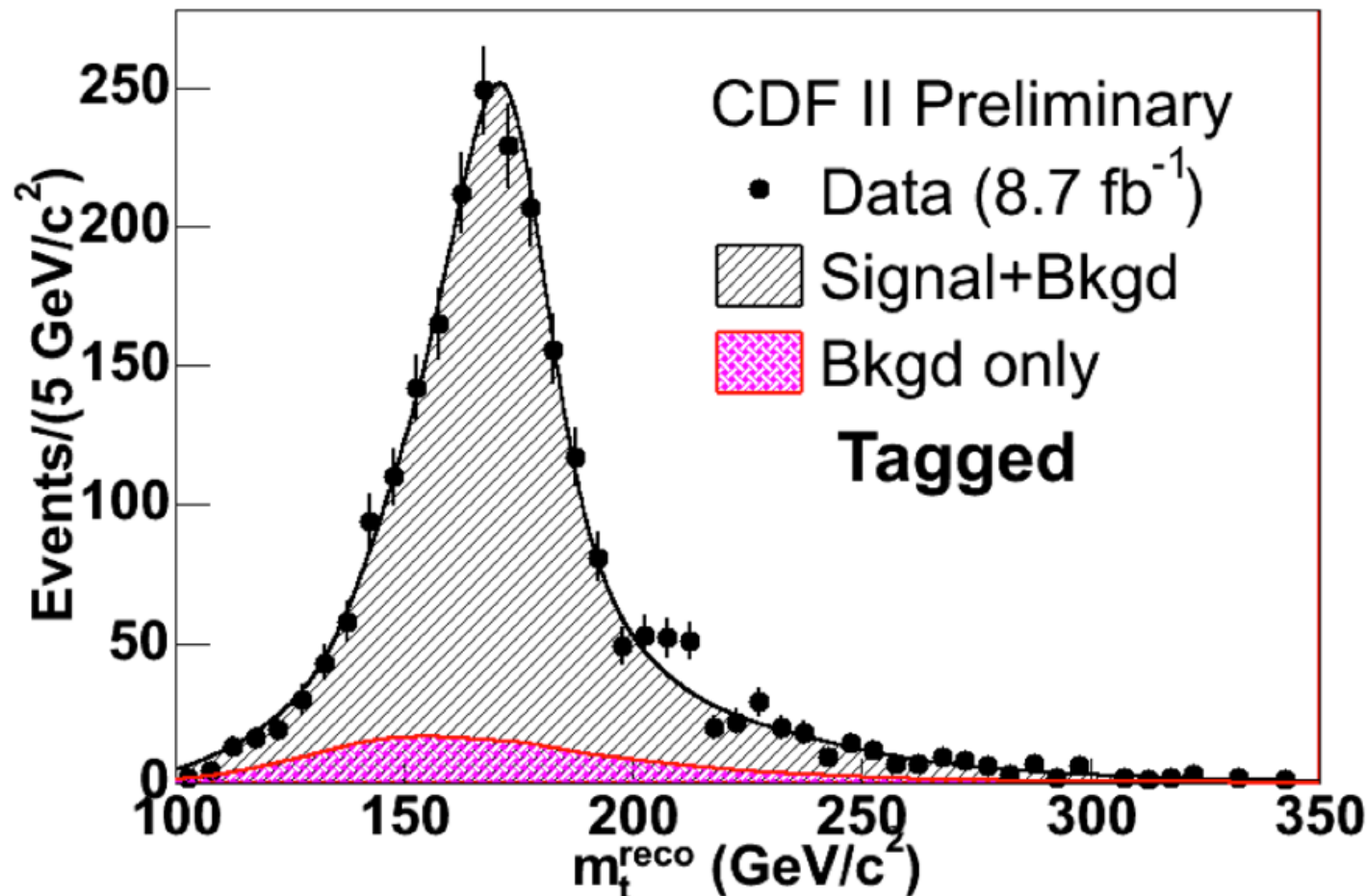
- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses

Reco. Top Mass (1-tag(T))



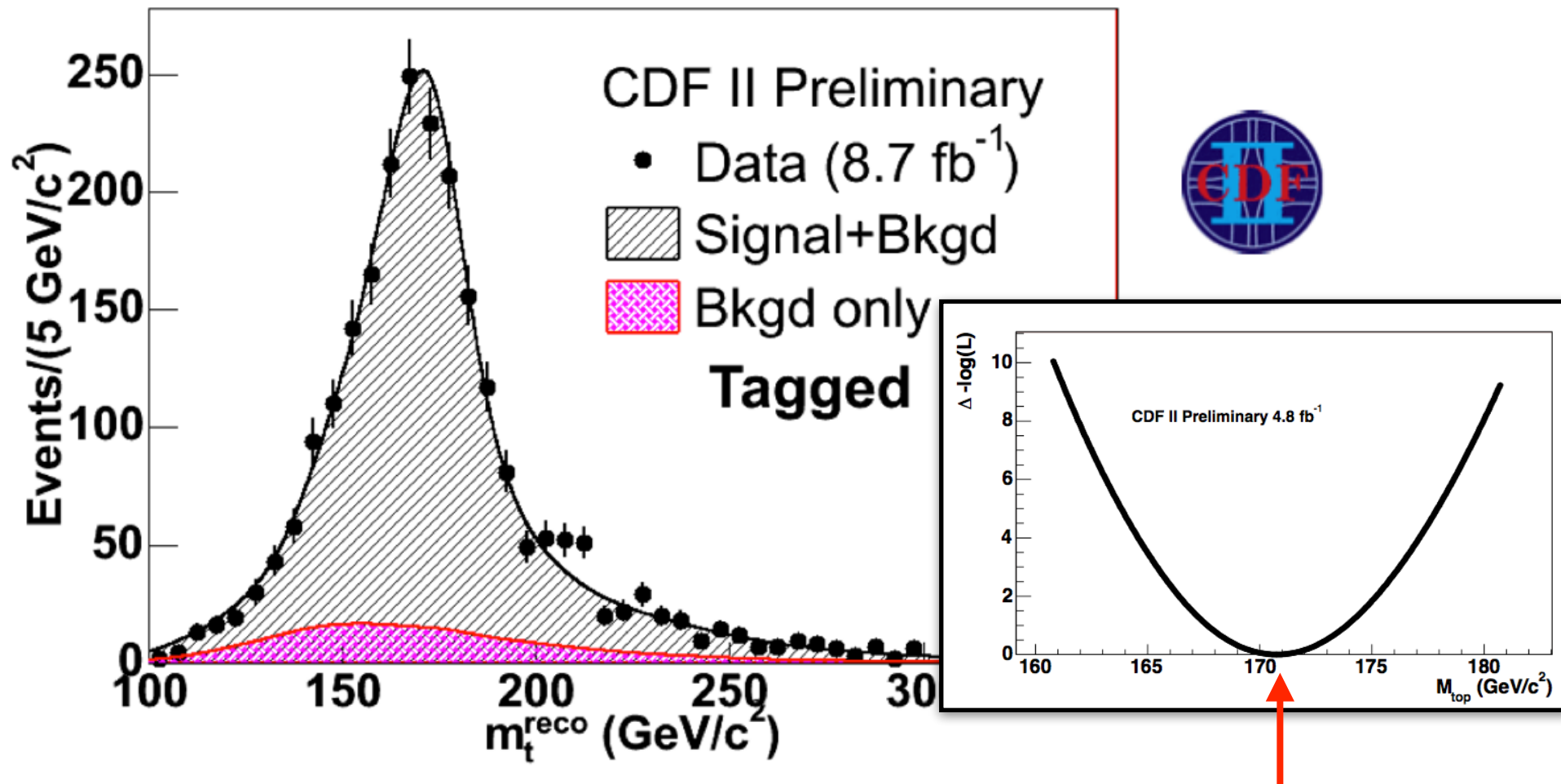
Extraction Techniques: Templates

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



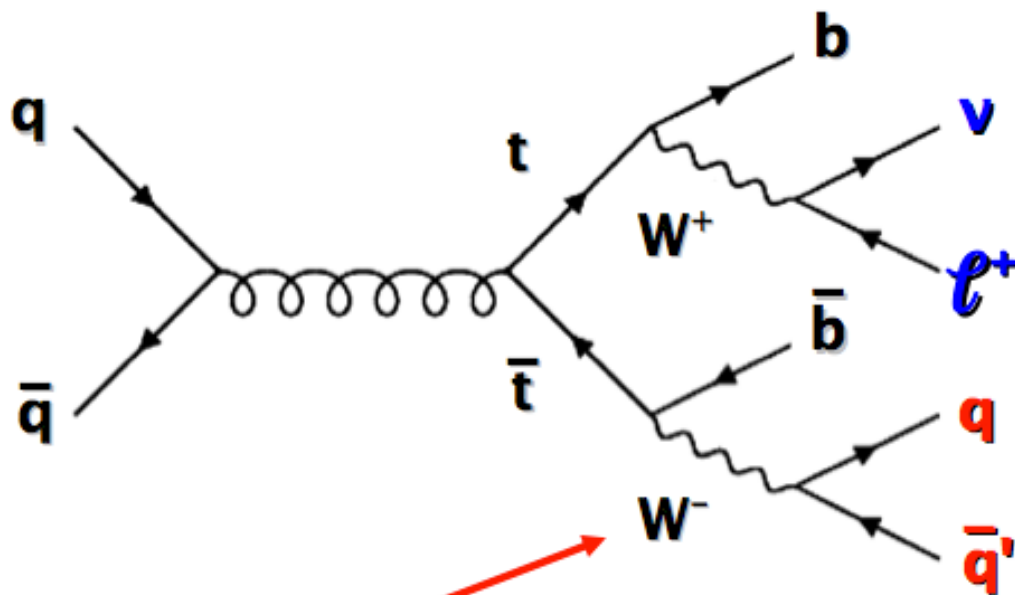
Extraction Techniques: Templates

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

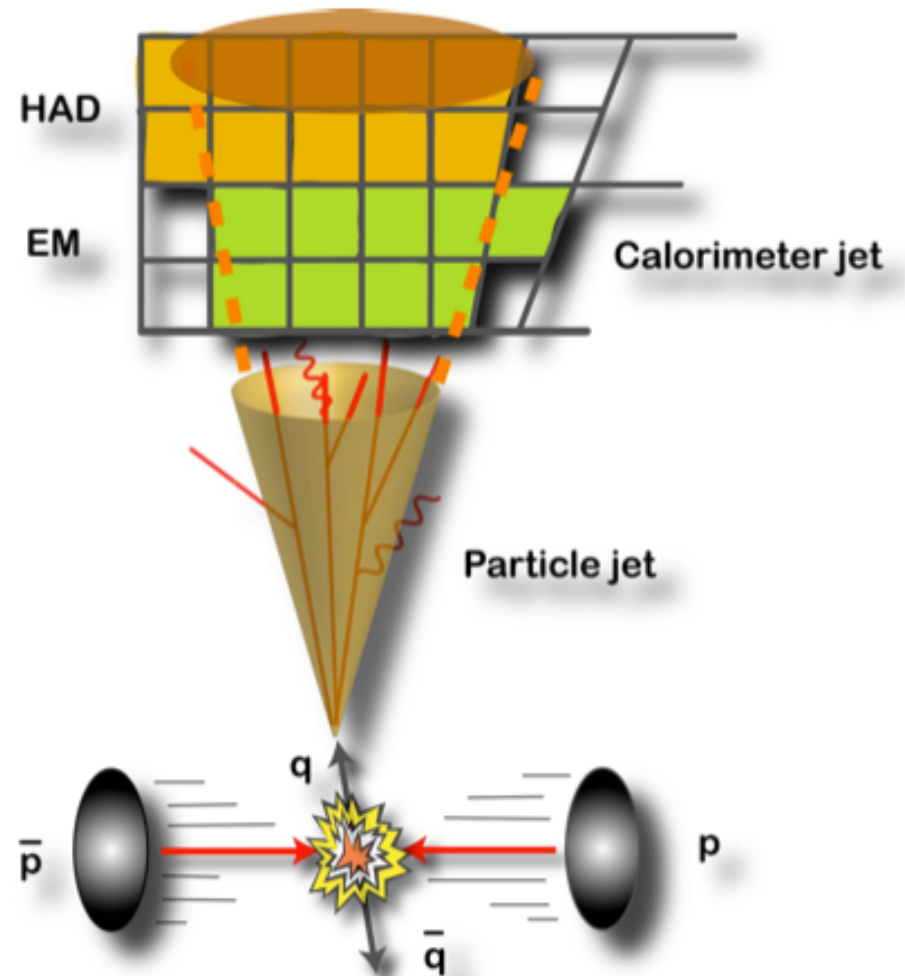


JES calibration

jet energy scale:
translate jet into parton energy



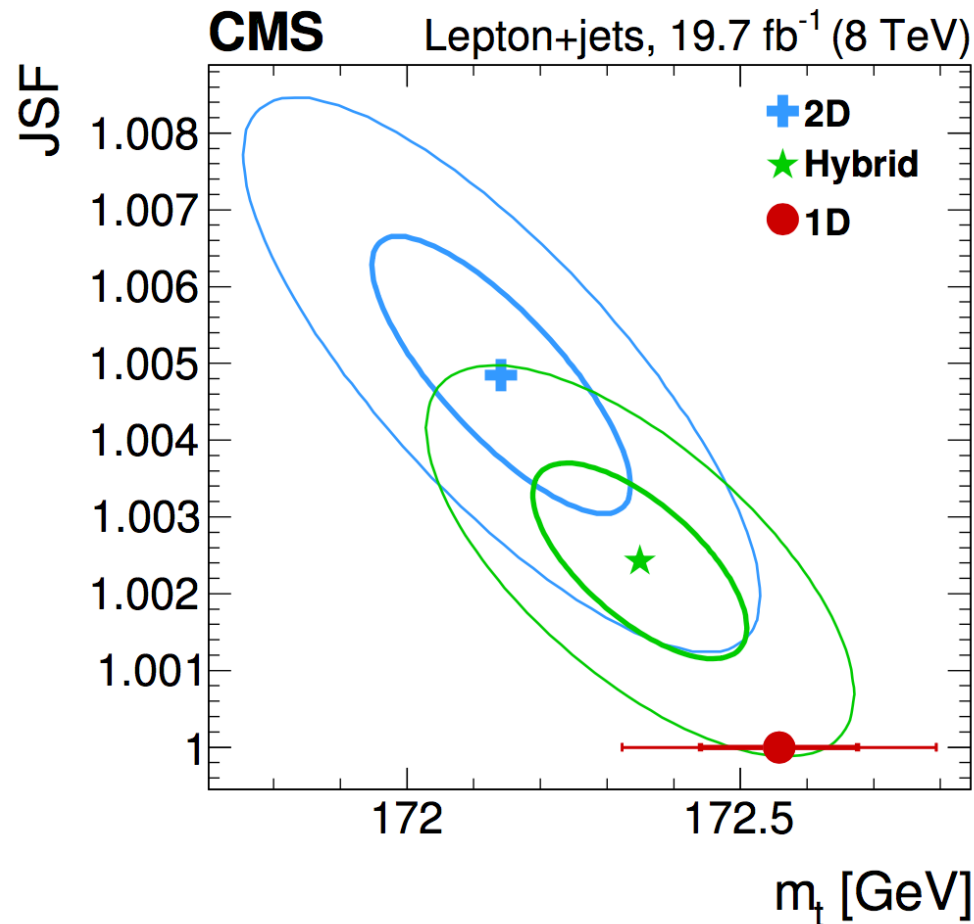
**W mass
constrains jet
energy scale**



Result in l+jets Channel



**jet energy scale:
translate jet into
parton energy**



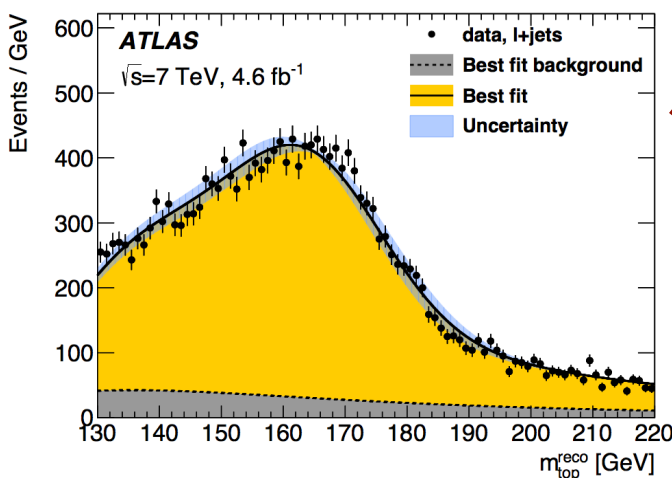
**maximum
likelihood fit
to data**

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

most precise single measurement

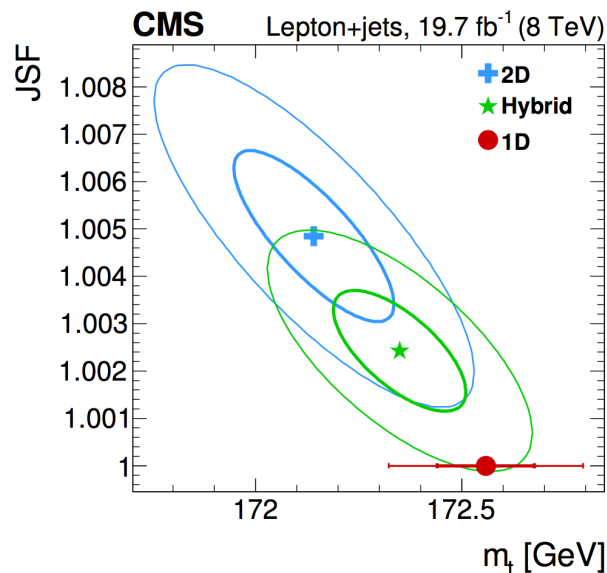
$\pm 0.29\%$

Top mass at the LHC



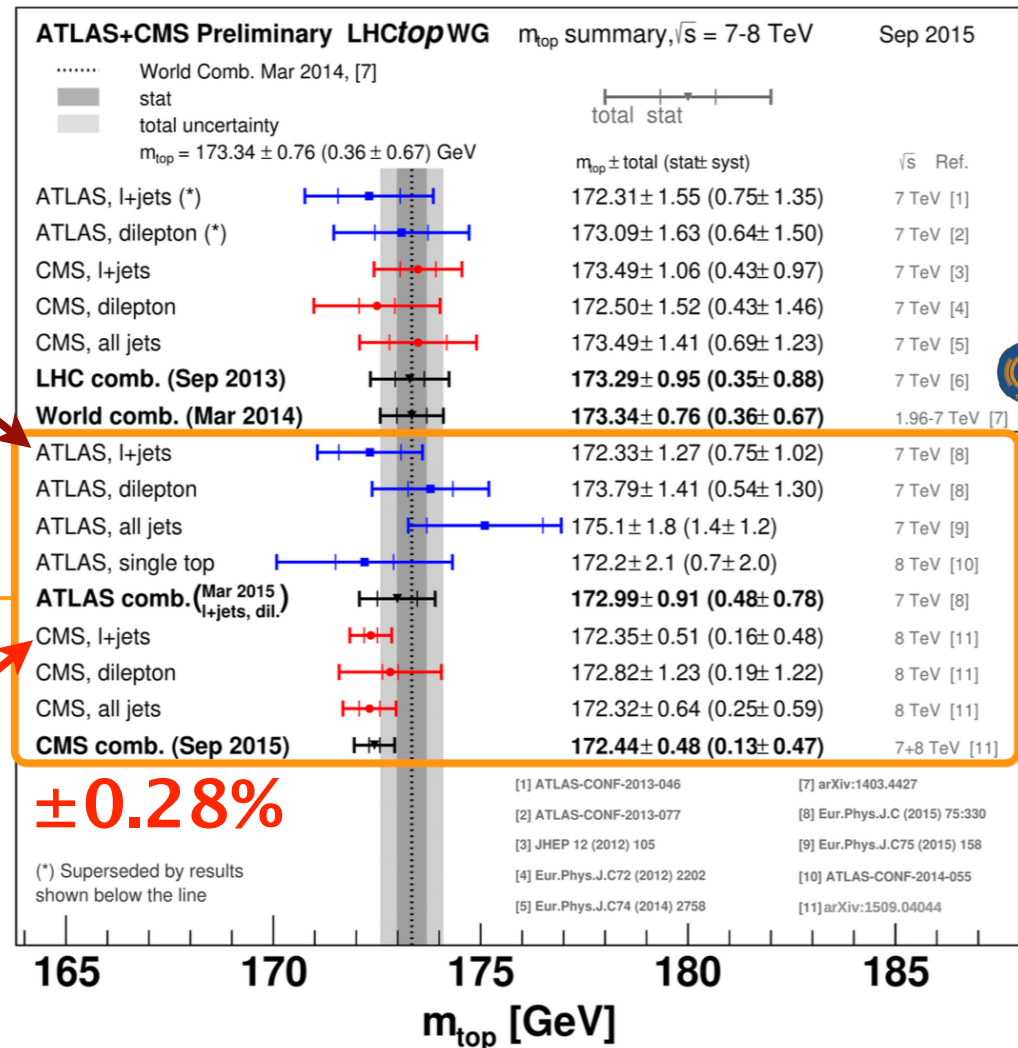
$\pm 0.73\%$

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



$\pm 0.29\%$

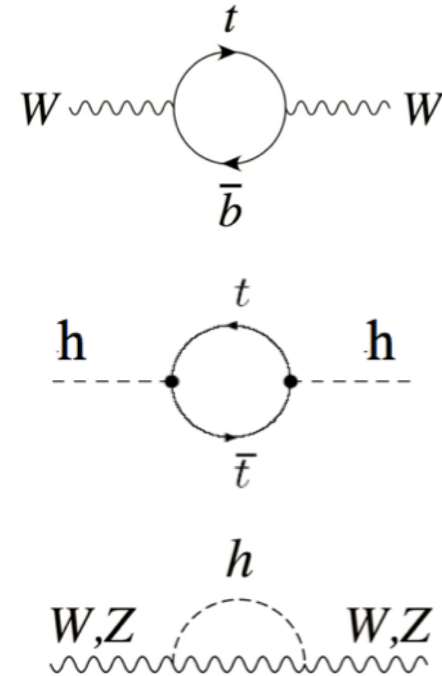
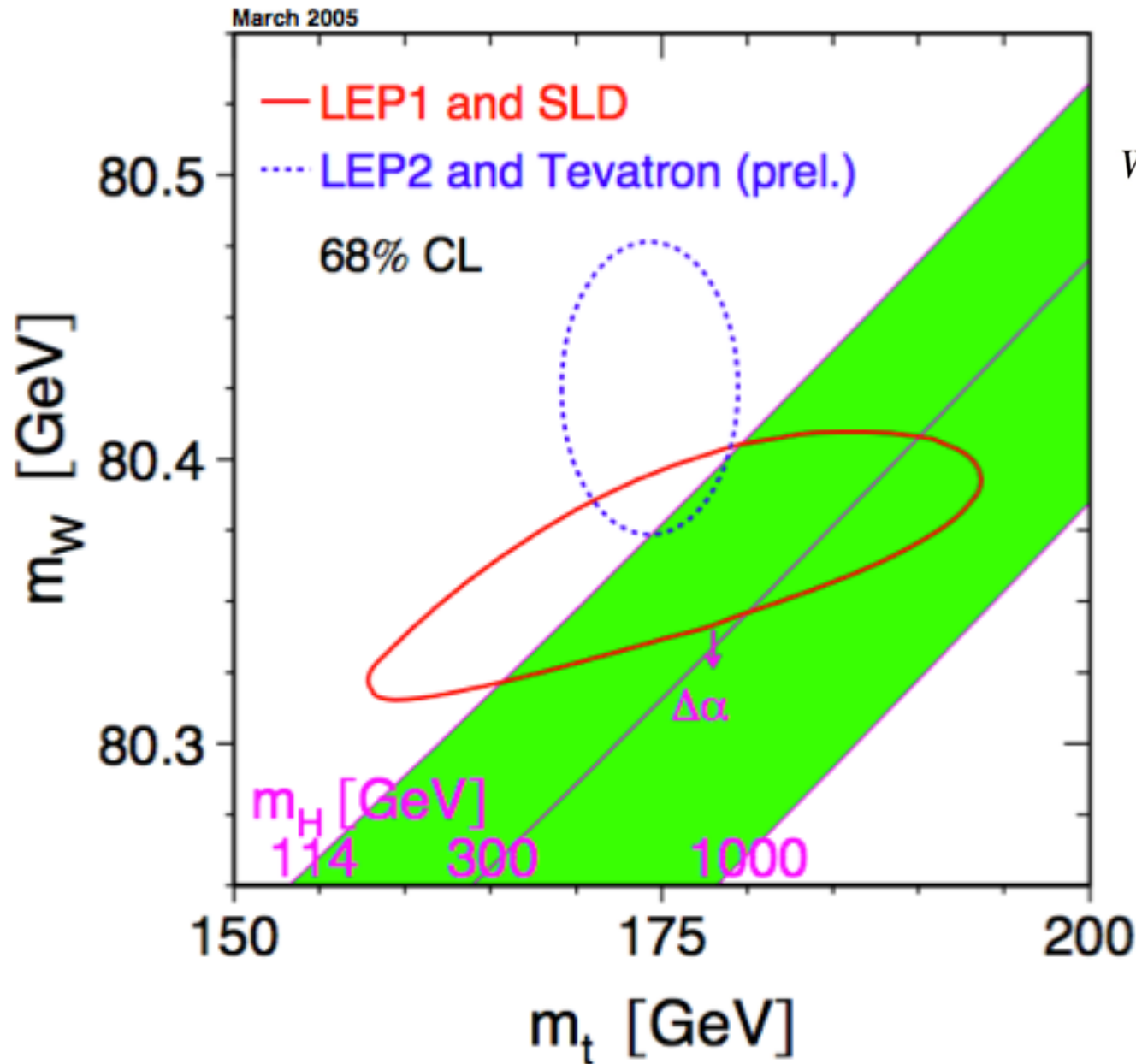
$$m_t^{\text{hyb}} = 172.35 \pm 0.16 \text{ (stat+JSF)} \pm 0.48 \text{ (syst)} \text{ GeV}$$



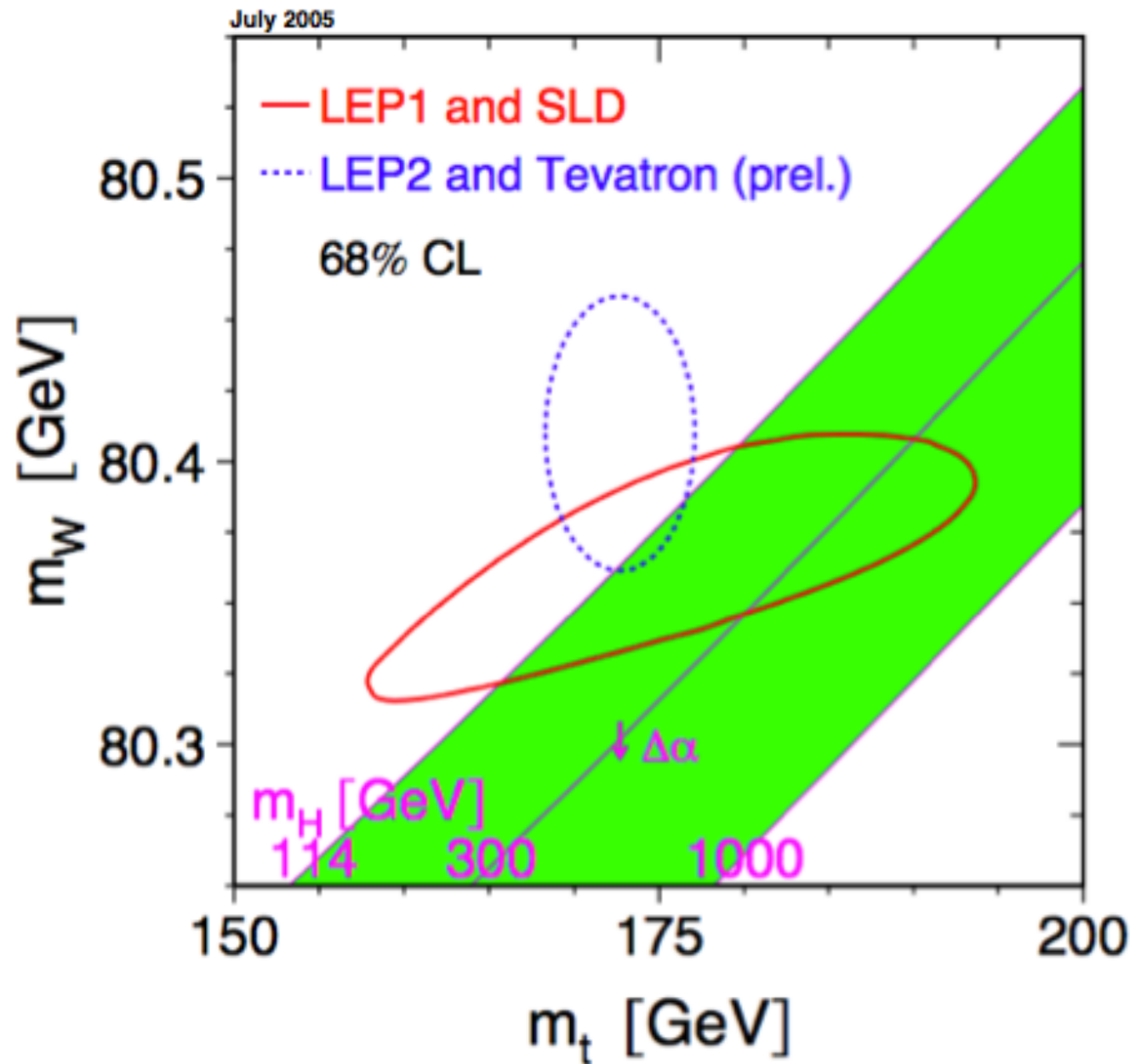
New results waiting for combination!
 (in addition to latest results from Tevatron)

→ jet energy scale is crucial

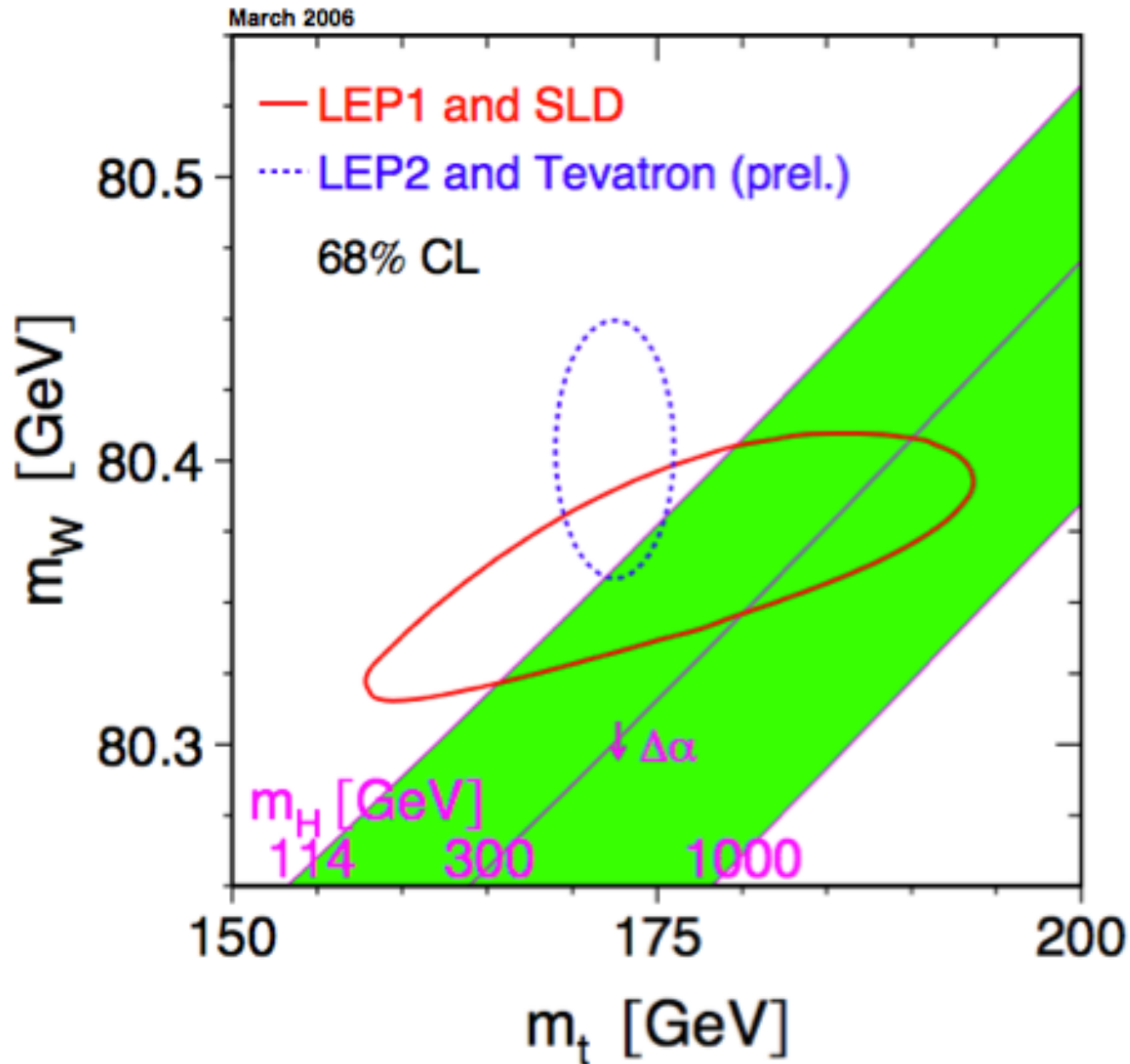
History m_{top} vs. M_W



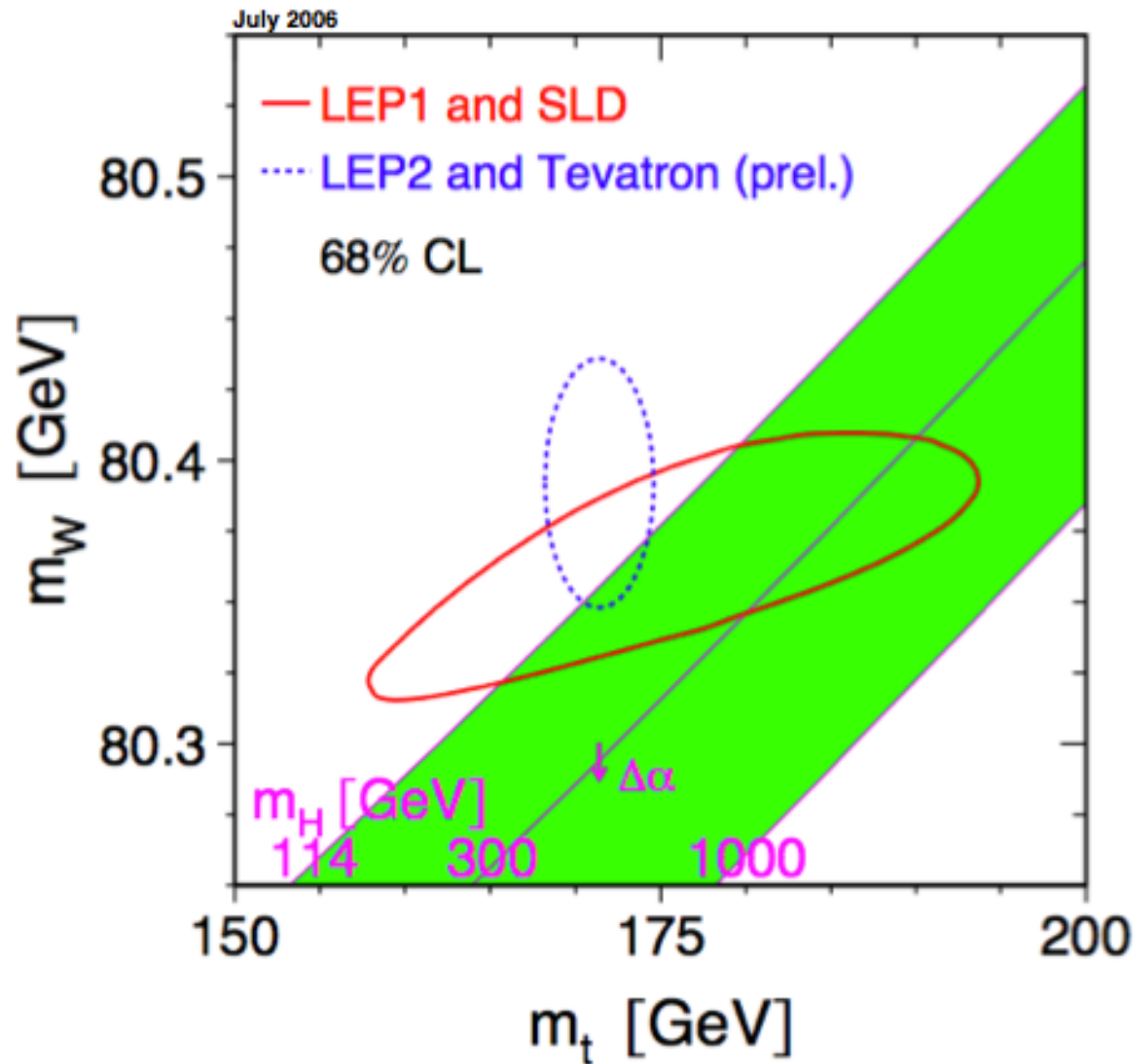
History m_{top} vs. M_W



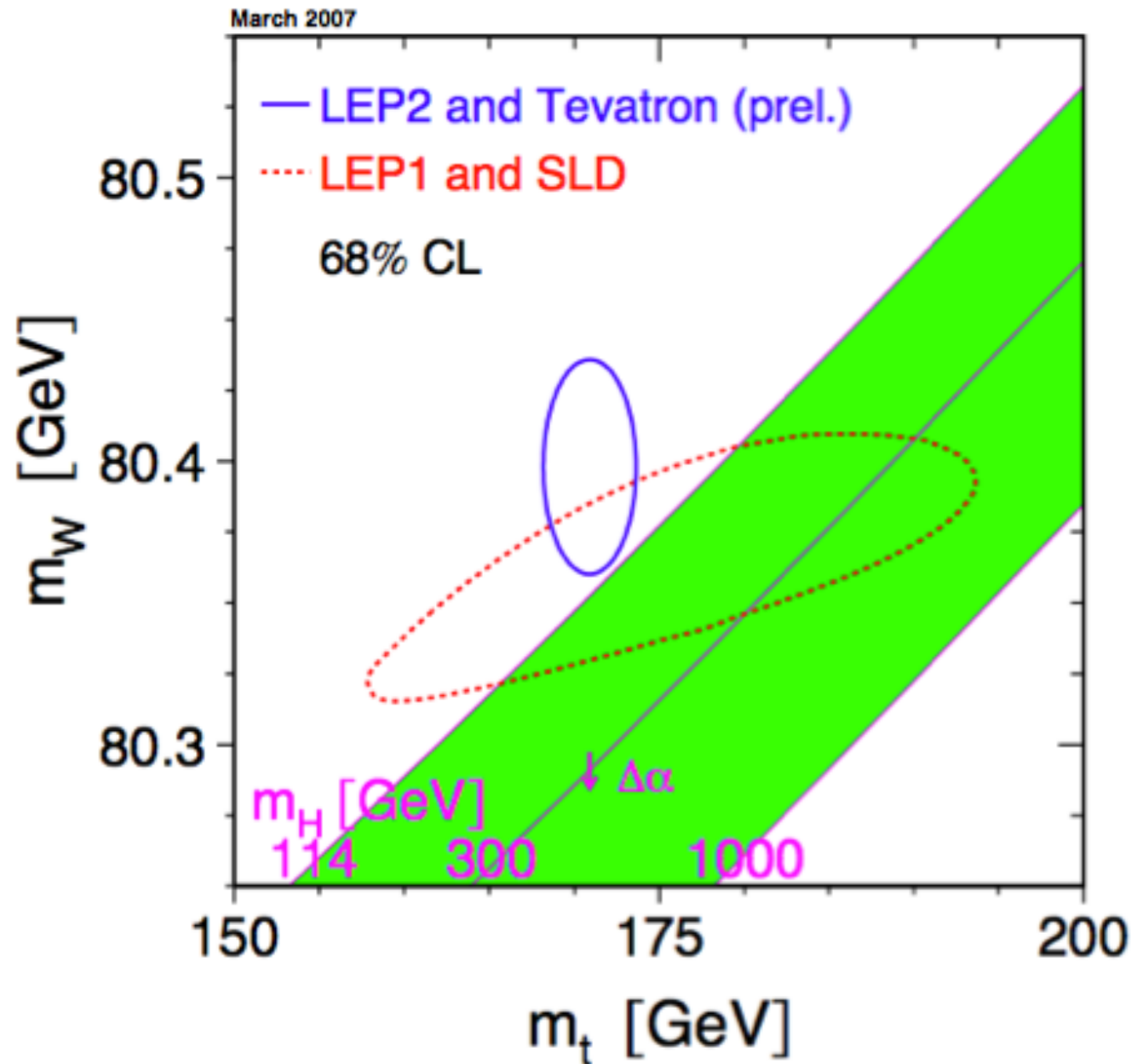
History m_{top} vs. M_W



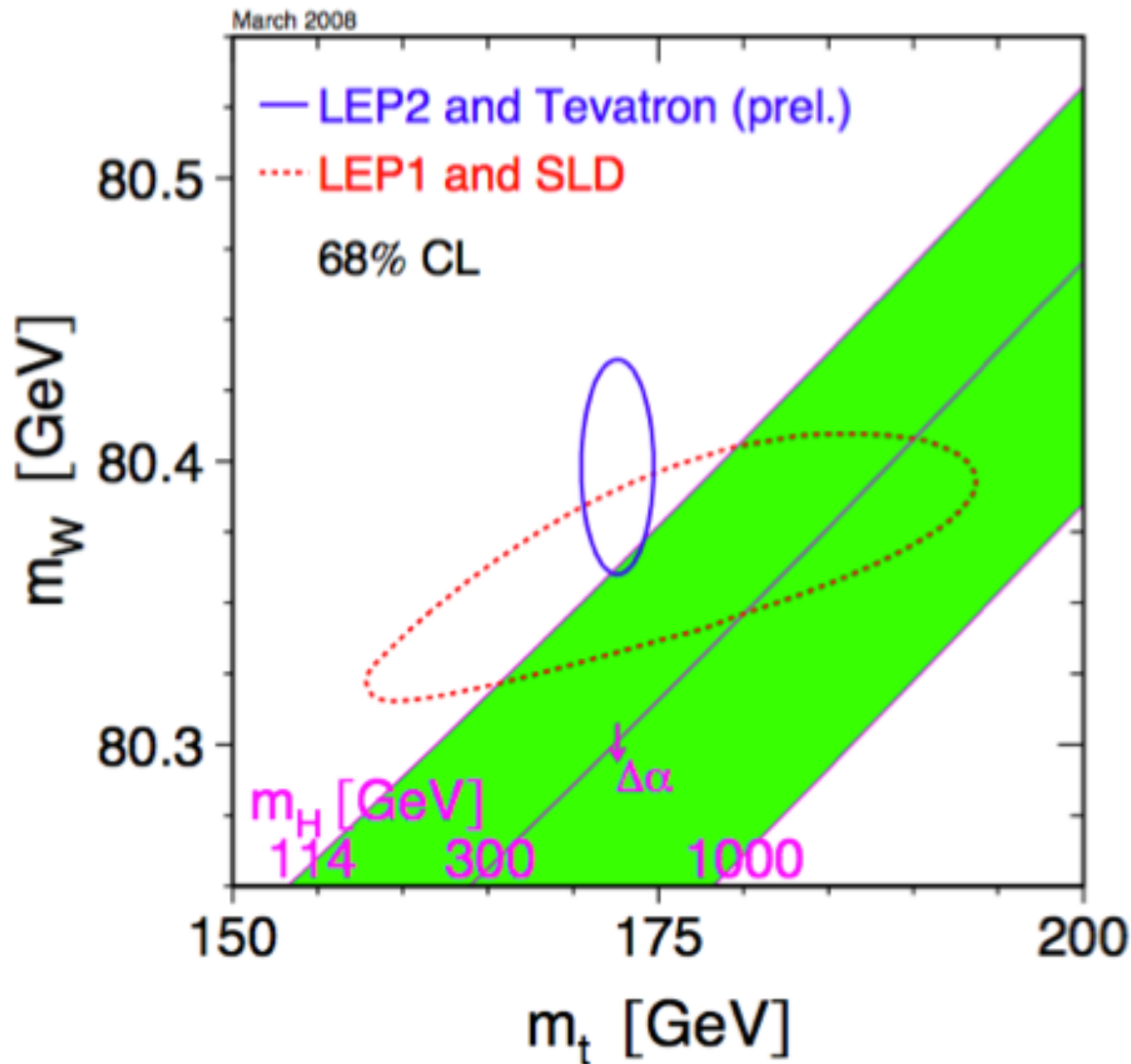
History m_{top} vs. M_W



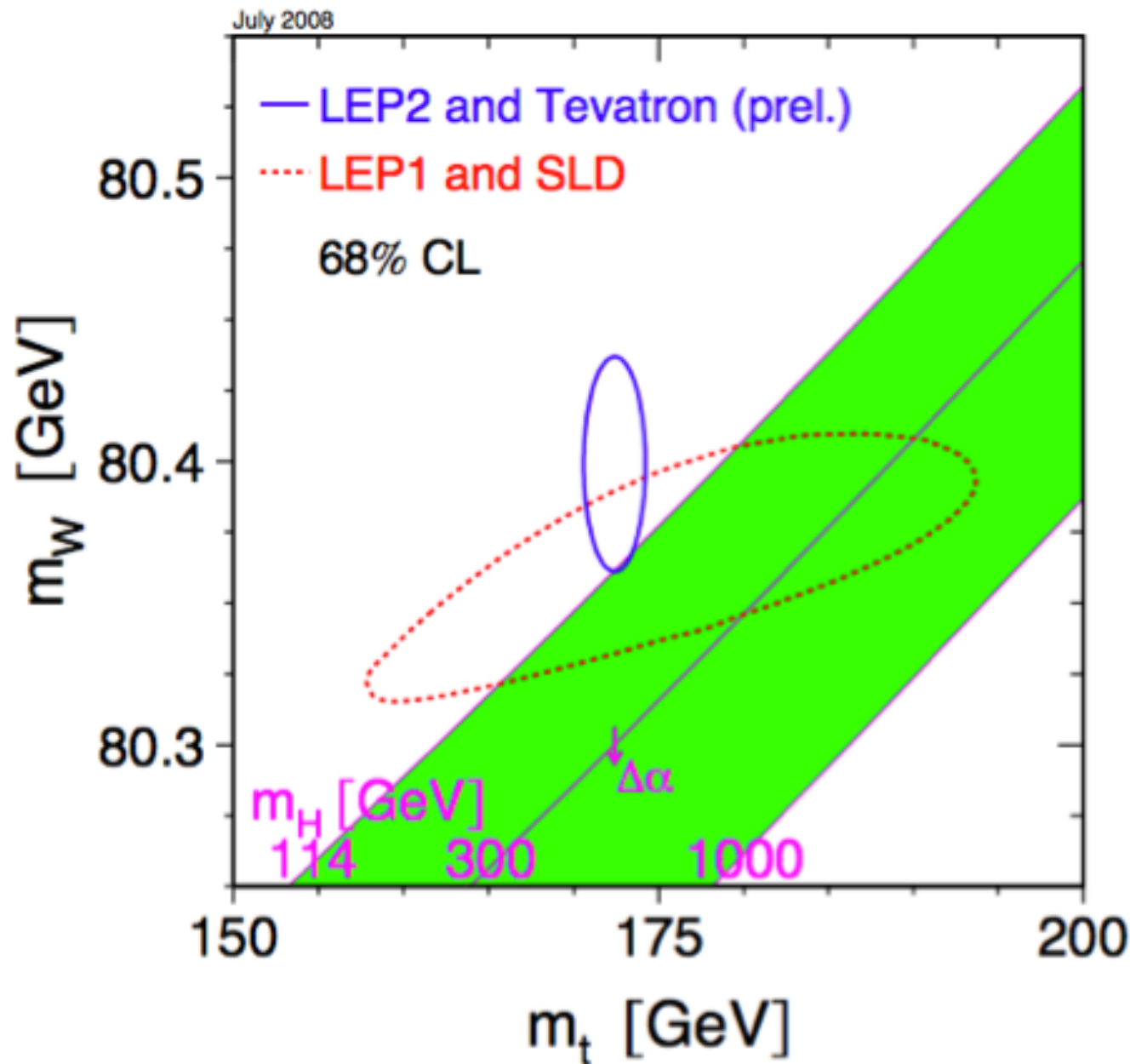
History m_{top} vs. M_W



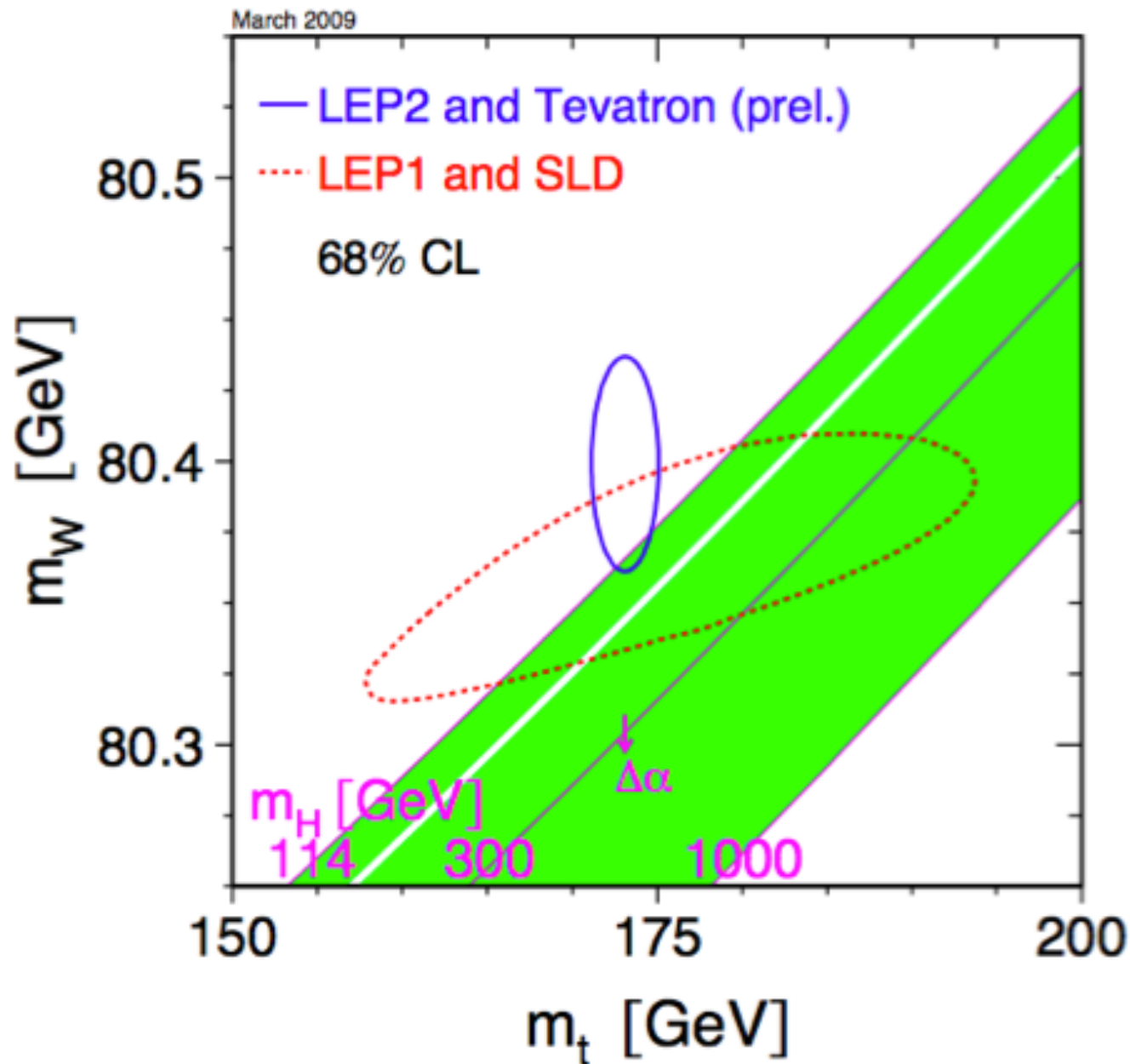
History m_{top} vs. M_W



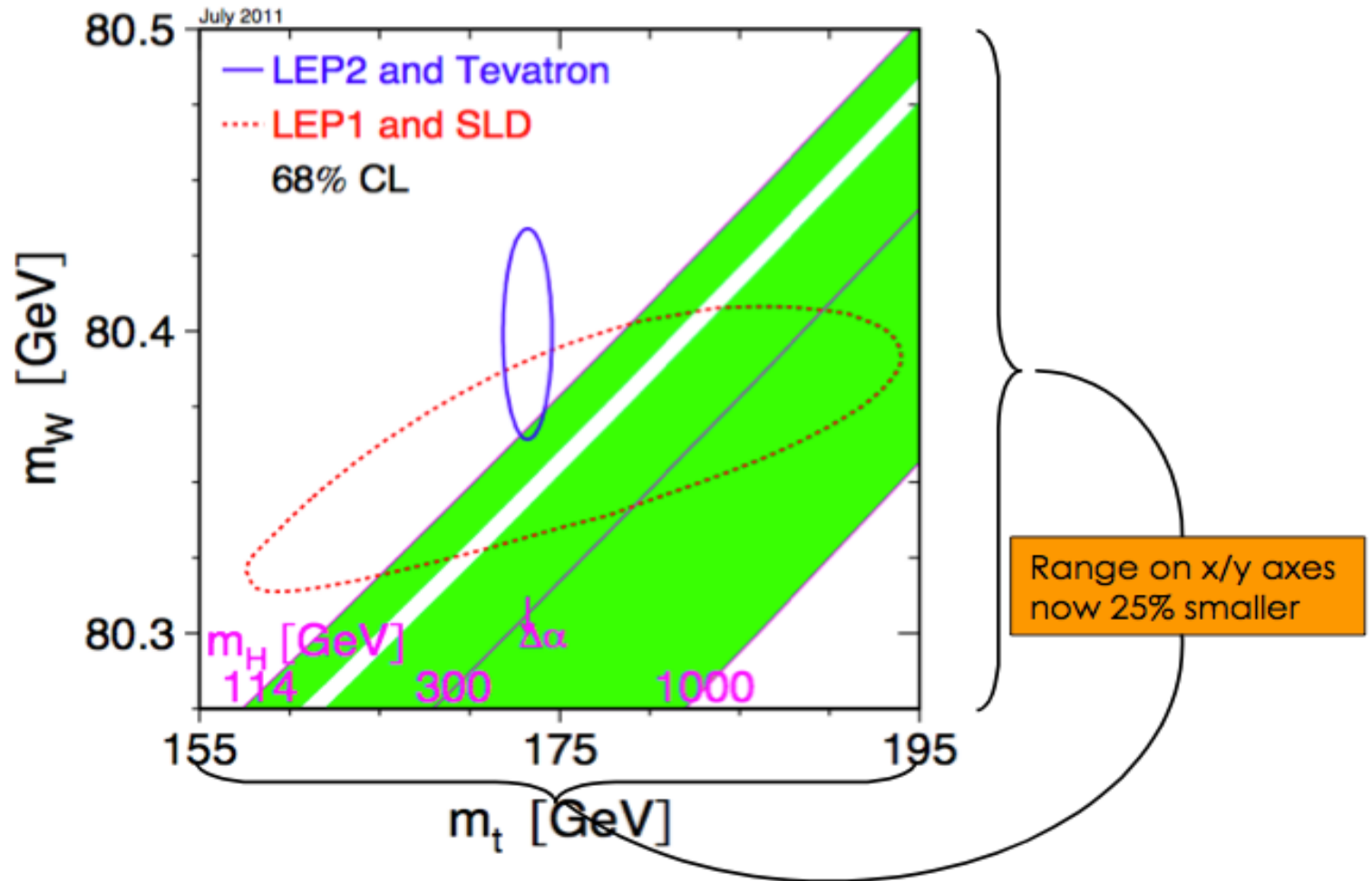
History m_{top} vs. M_W



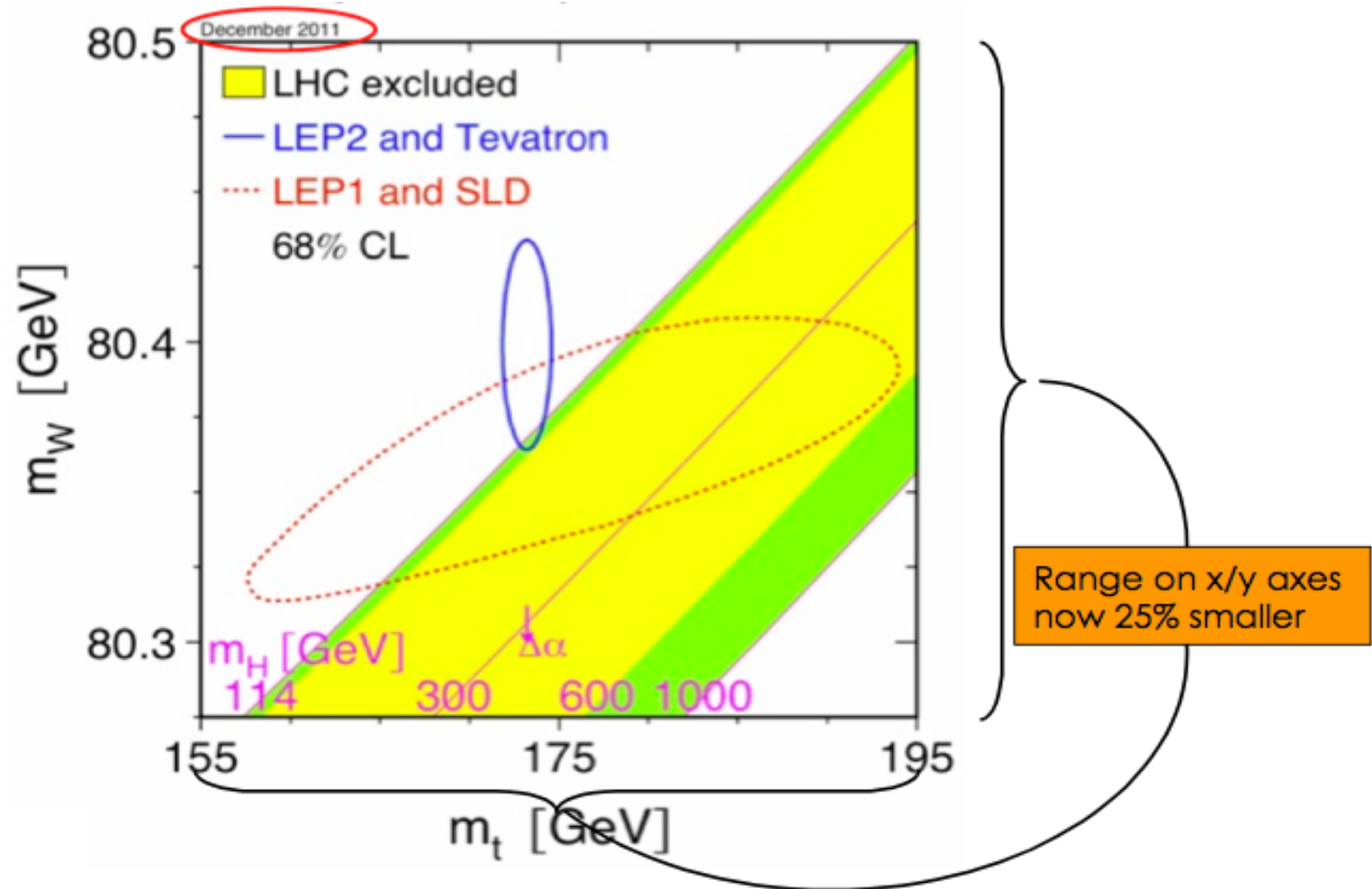
History m_{top} vs. M_W



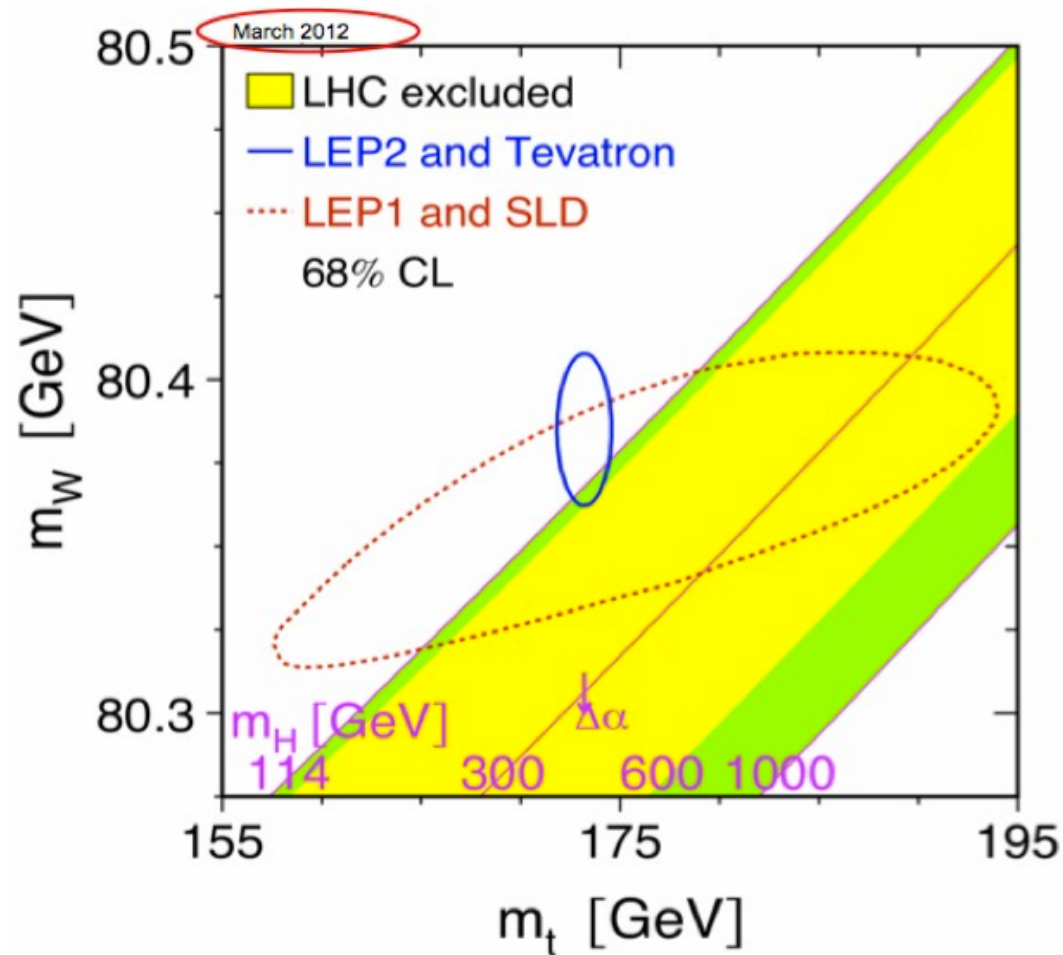
History m_{top} vs. M_W



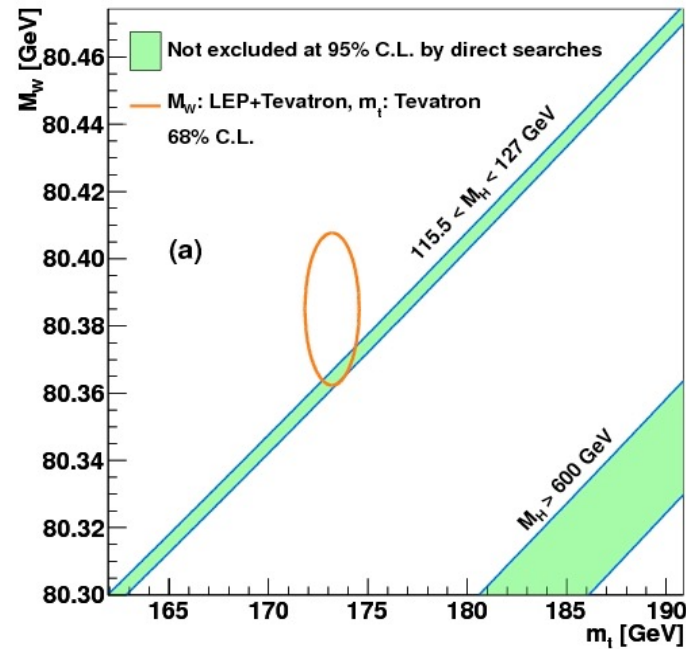
History m_{top} vs. M_W



History m_{top} vs. M_W

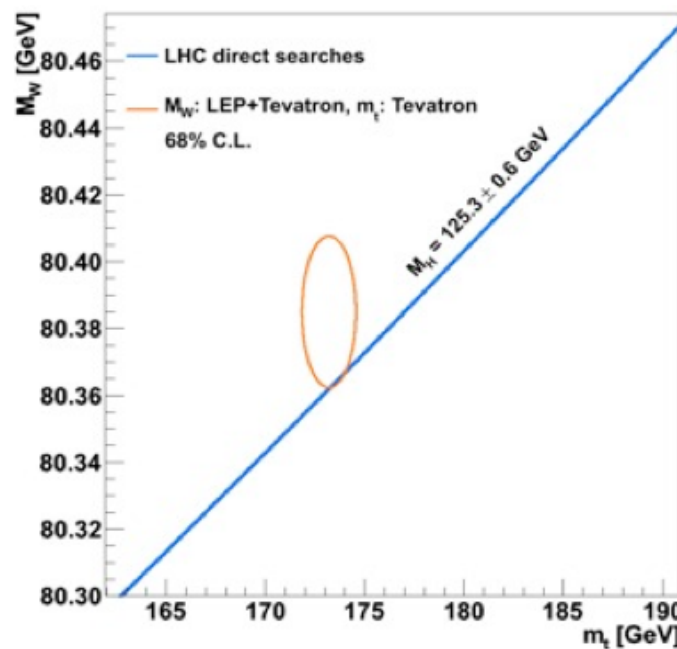


History m_{top} vs. M_W



History m_{top} vs. M_W

July 2012

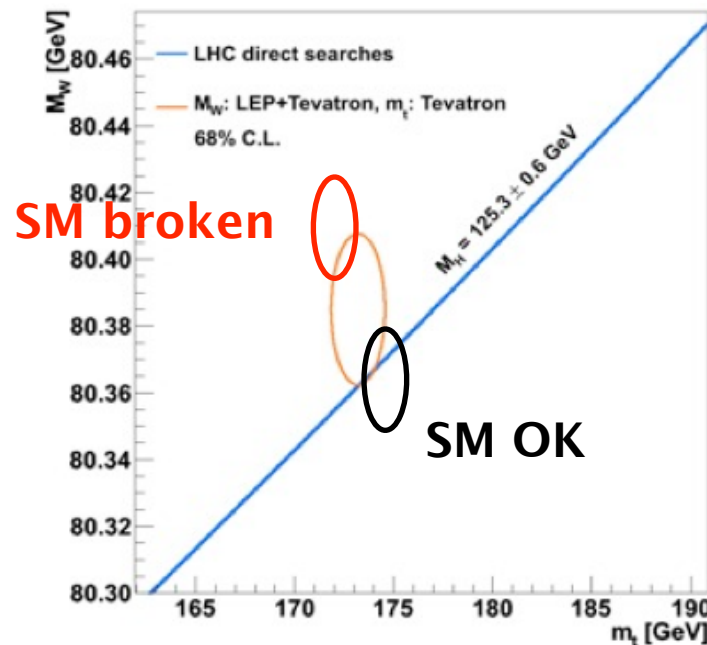


→ Standard Model is self-consistent

History m_{top} vs. M_W

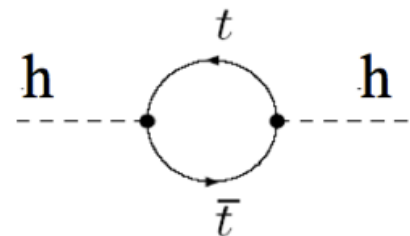
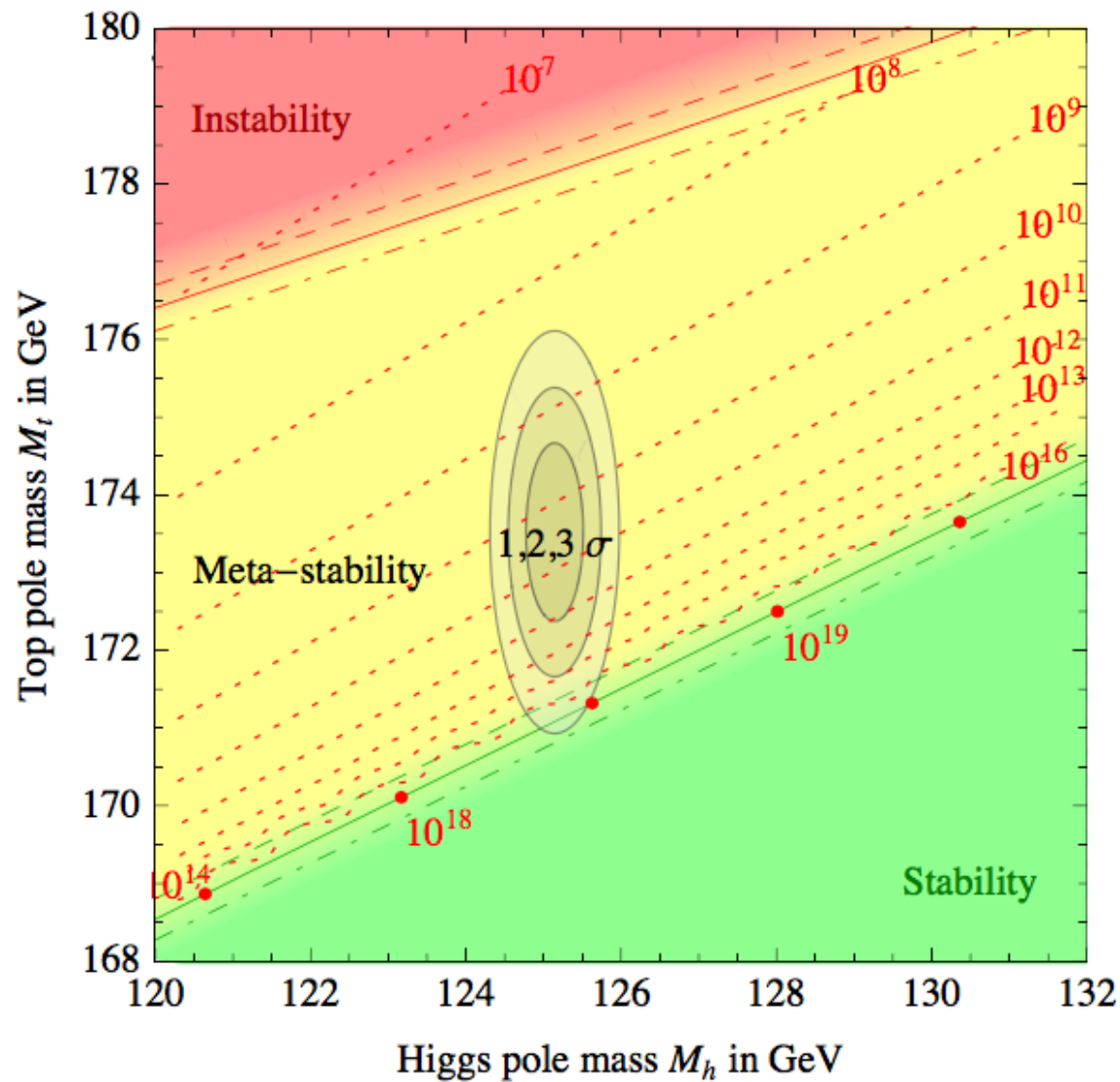
July 2012

future:
 $\Delta(m_W) = 6 \text{ MeV}$



improved W mass measurement is critical

m_{top} vs. M_H



check the “fate of the Universe”

What mass do we measure?

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

m_{top}

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

"Bare" parameters of QCD:

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

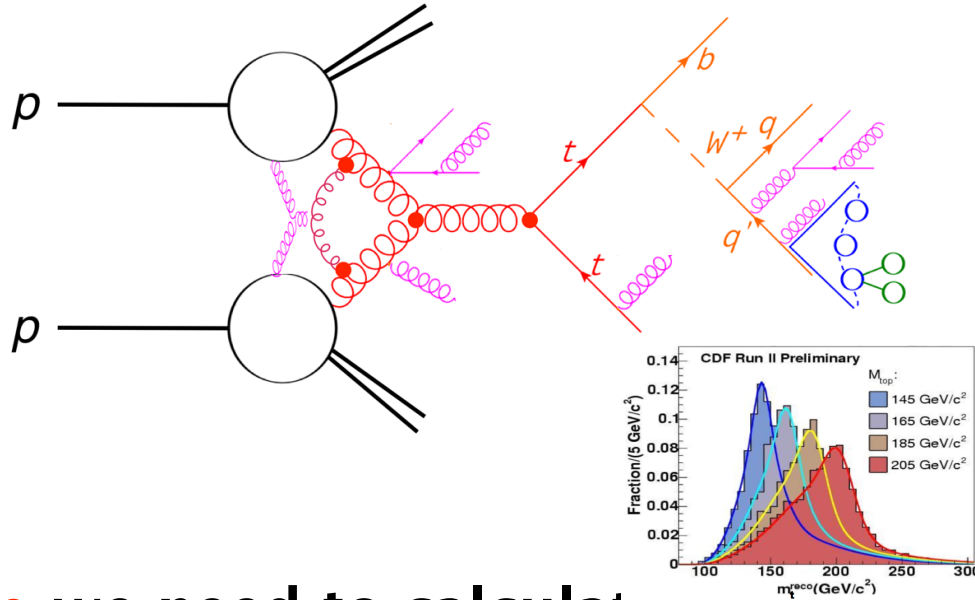
Renormalised parameters of QCD:

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

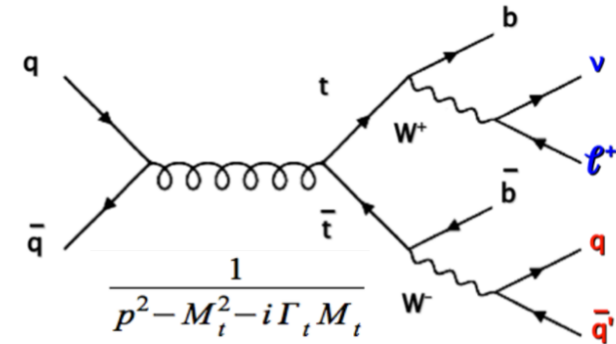
the concept of quark mass is convention-dependent!

What mass do we need?

- we measure the MC mass



- we need the pole mass

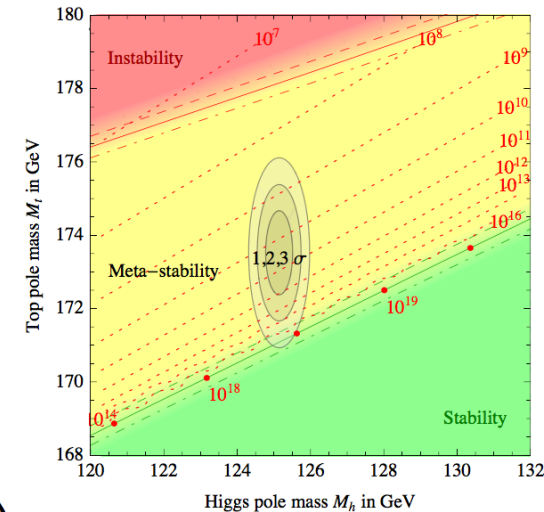


- we need to calculate:

Scheme-dependent

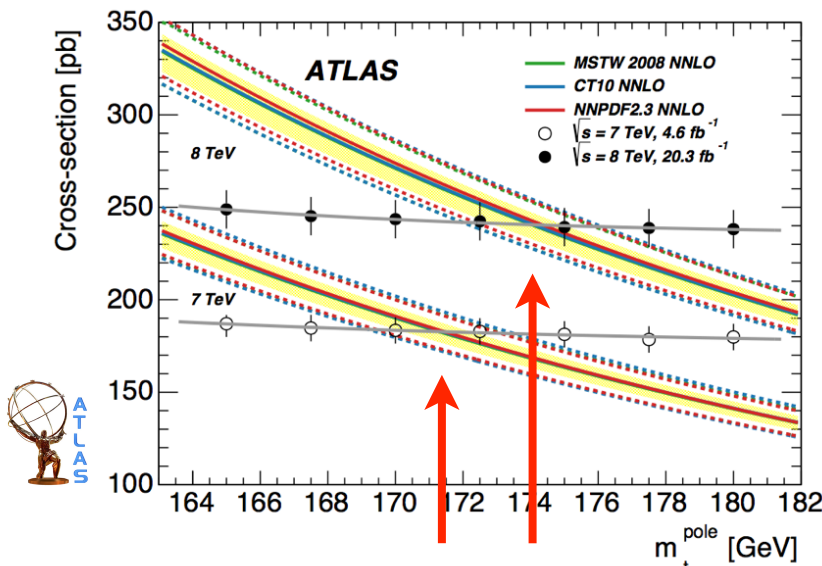
$$m_t^{\text{MC}} = m_t^{\text{quark}} + \Delta \quad \sim O(1 \text{ GeV})$$

e.g. pole mass



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

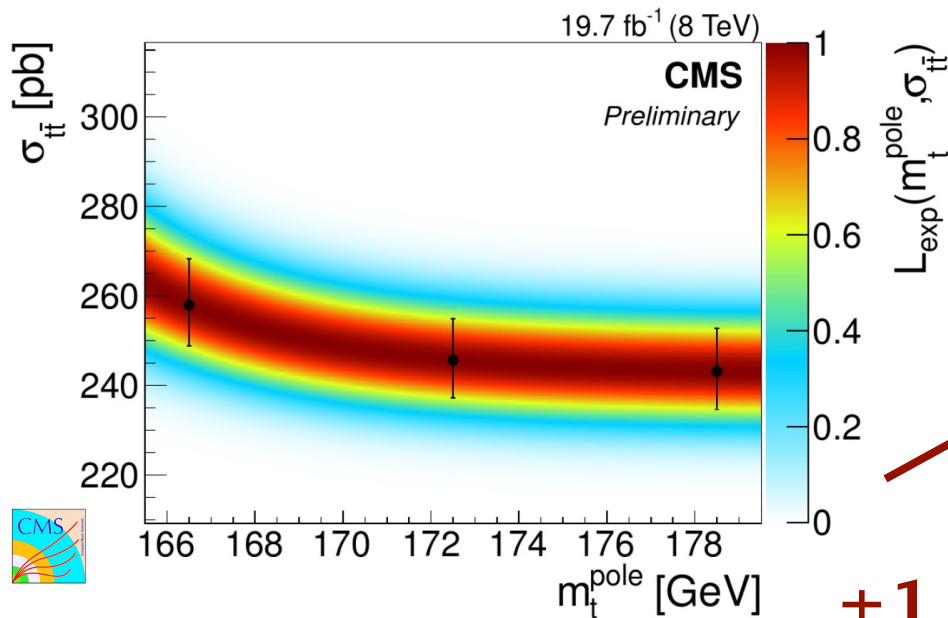
Top Quark Pole Mass



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

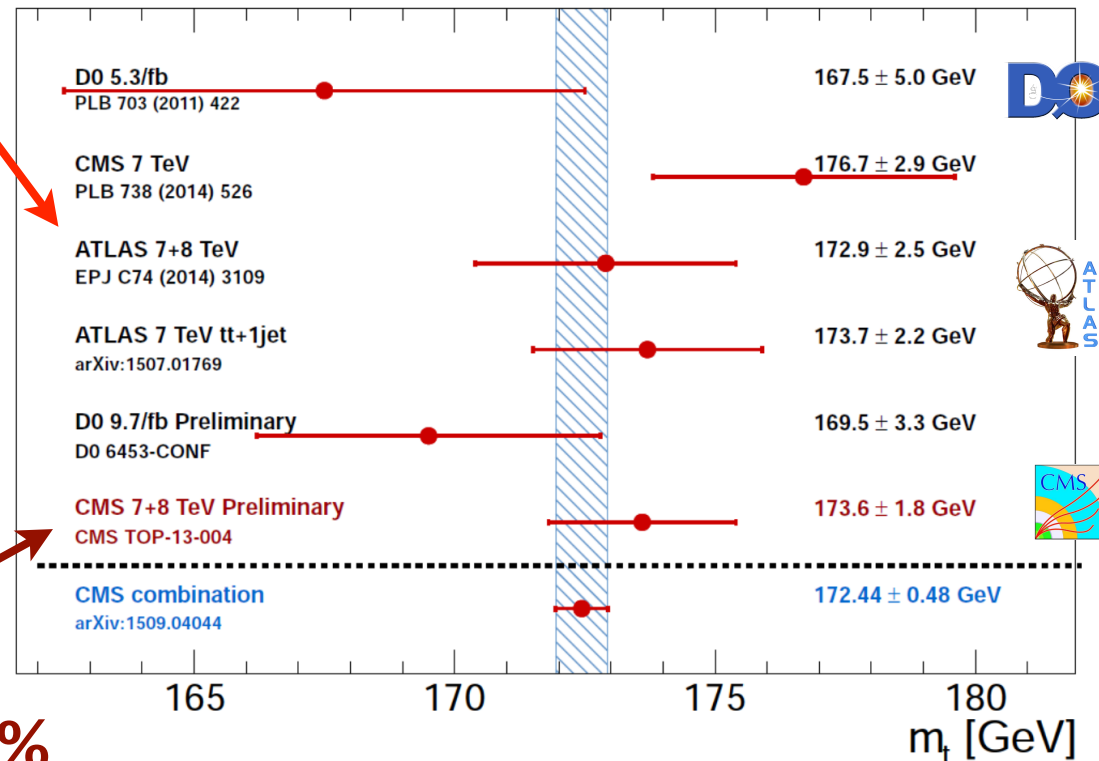
→ pole mass
unambiguously!

± 1.4%

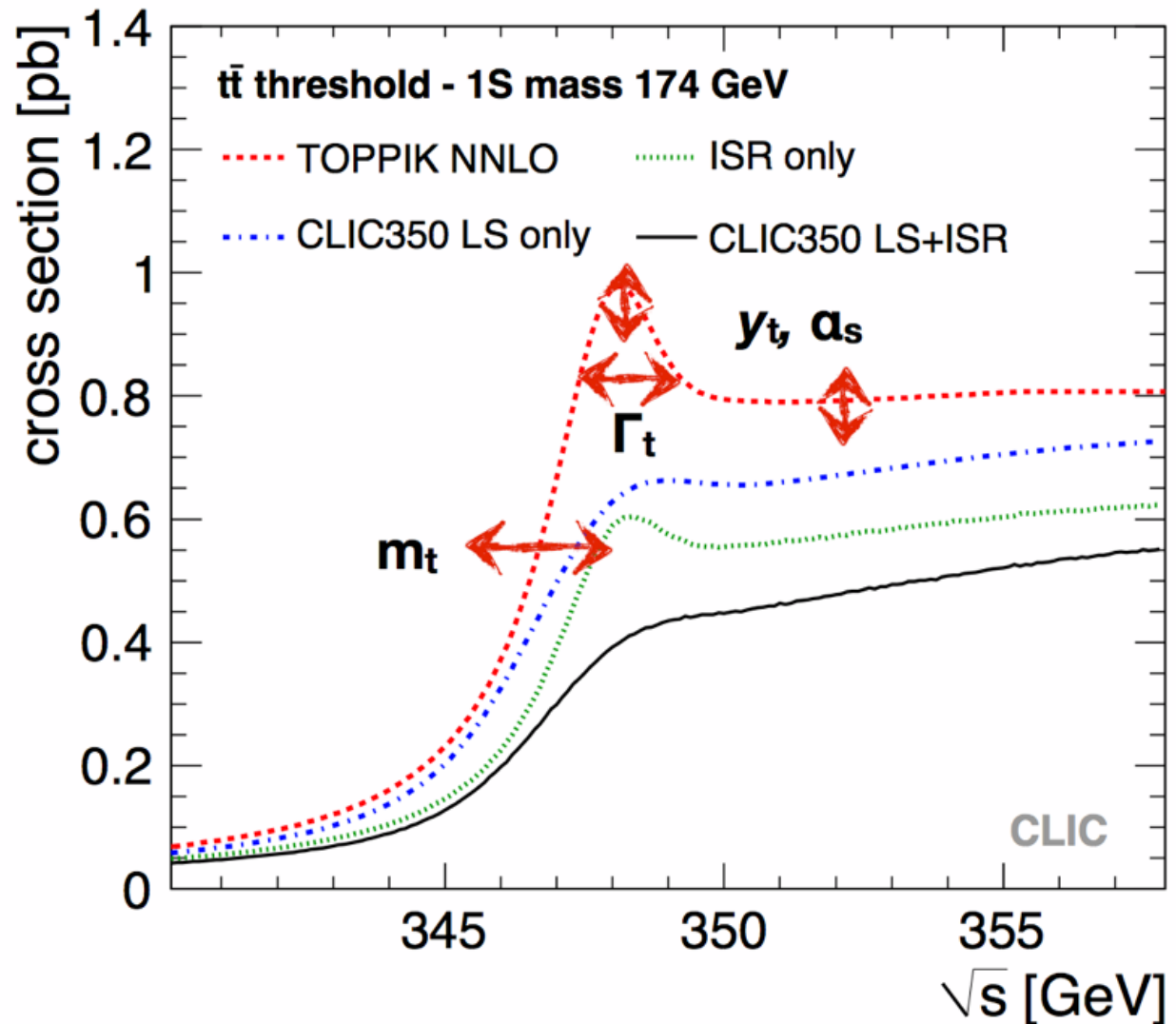
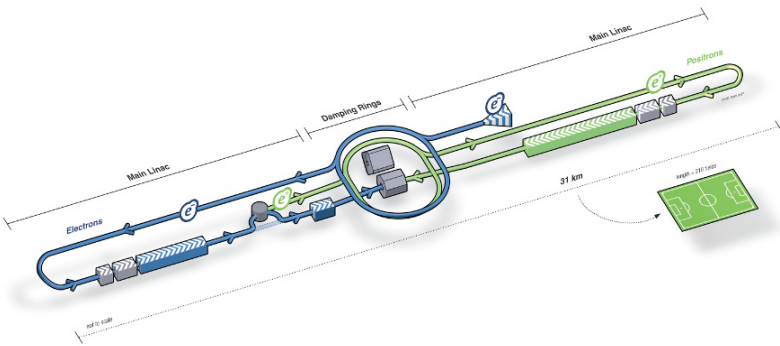


$$M_t^{\text{pole}} = 173.6 \pm 1.8 \text{ GeV}$$

± 1.0%

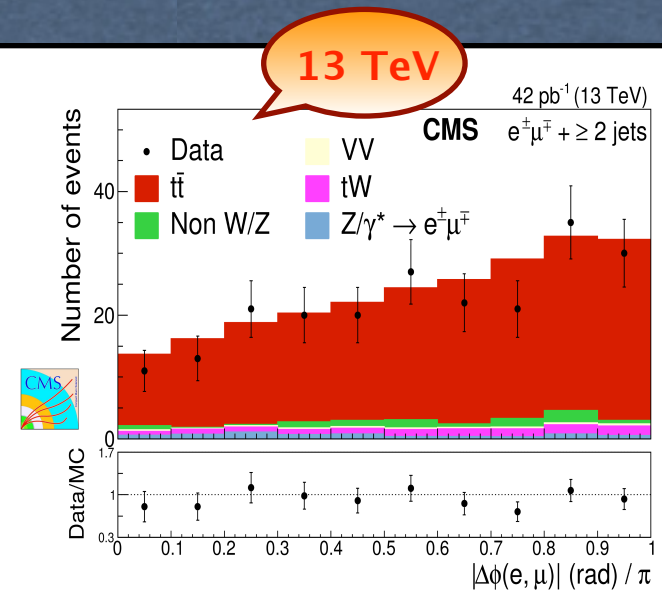
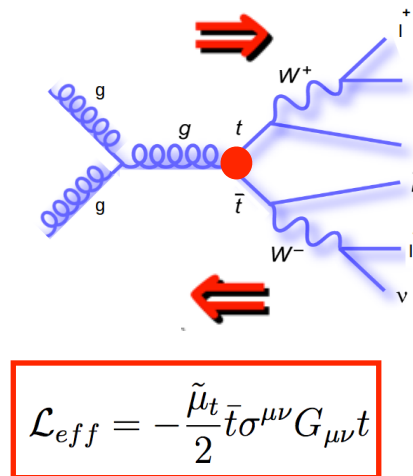
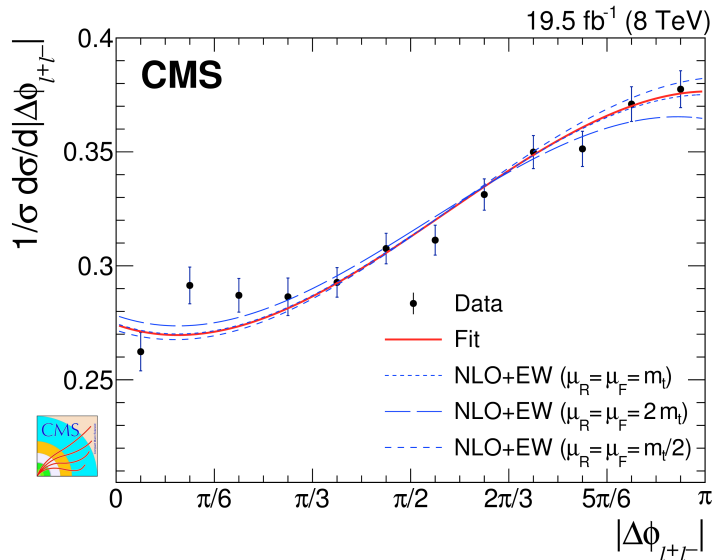


Top mass at ILC

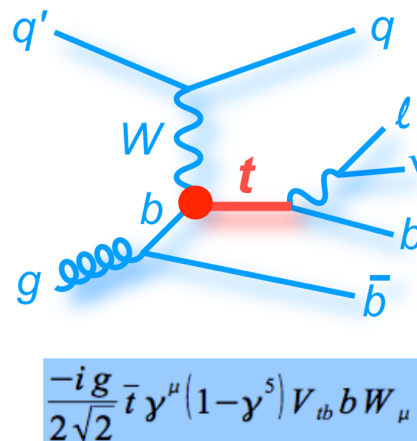
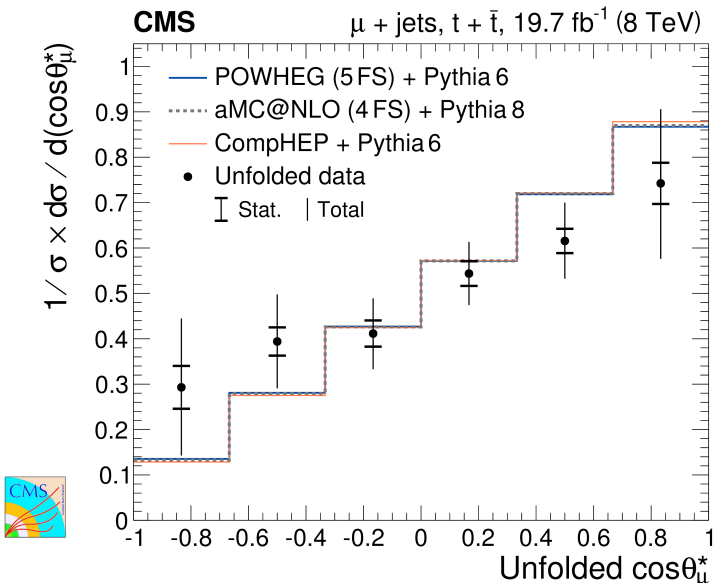


→ well-defined top mass with $\sim O(100 \text{ MeV})$ uncertainty

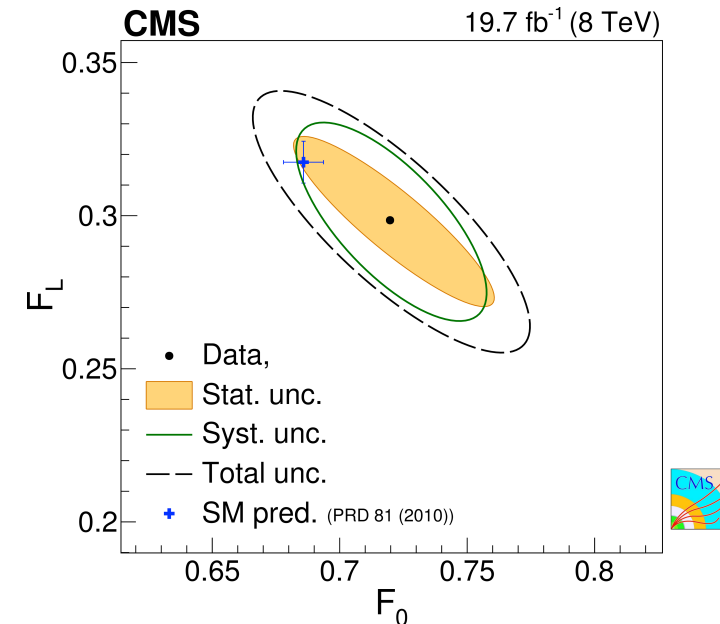
Polarisation and Spin Correlation



→ no chromomagnetic dipole moments



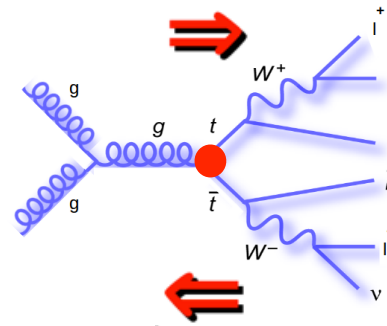
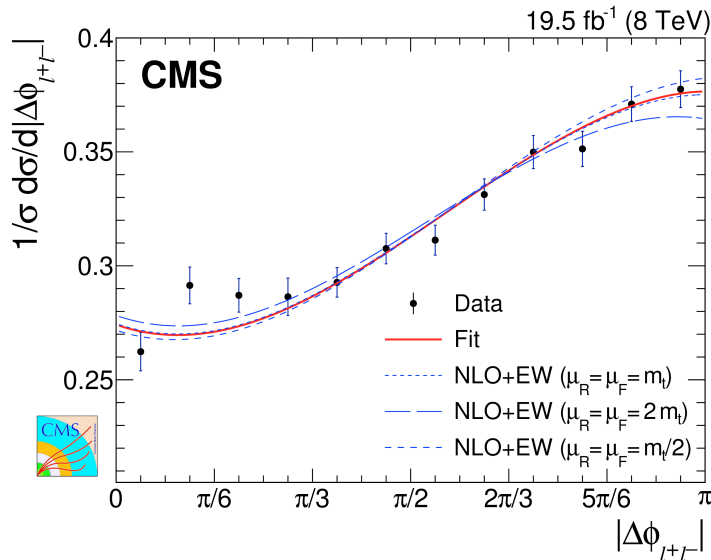
→ spins correlated as in SM



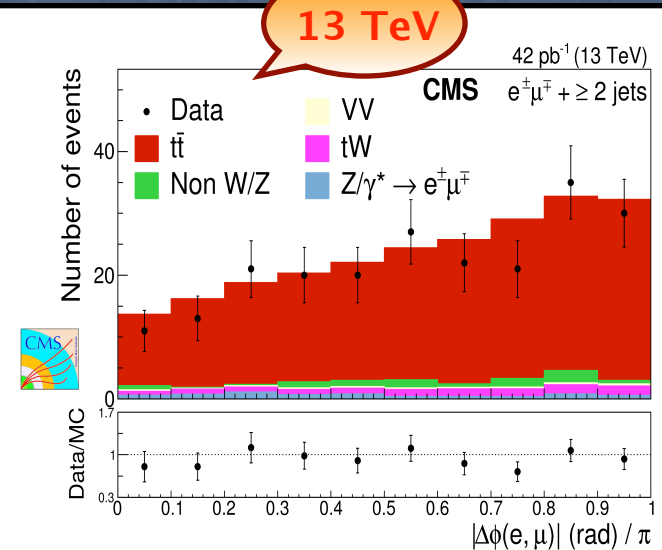
→ top quarks polarised as in SM

→ no anomalous couplings

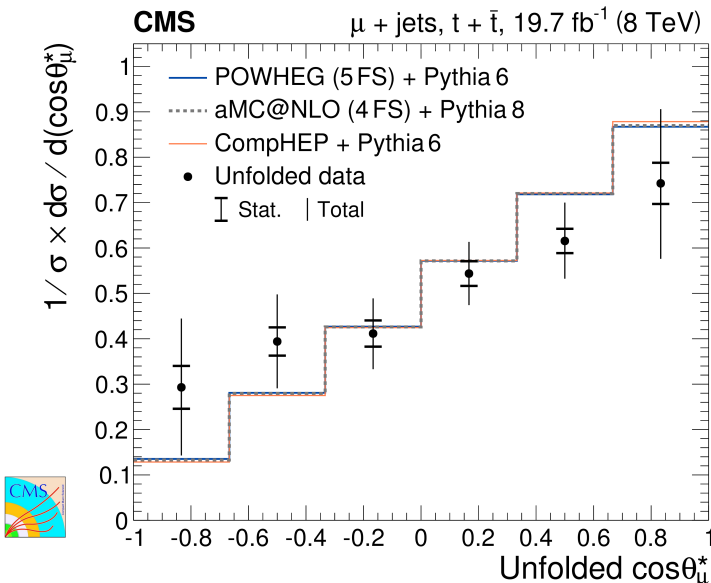
Polarisation and Spin Correlation



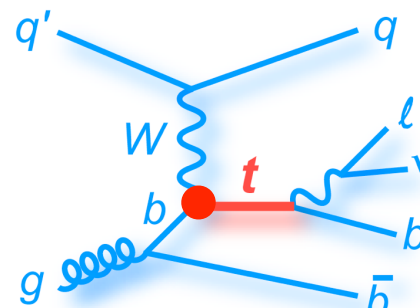
$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2} \bar{t} \sigma^{\mu\nu} G_{\mu\nu} t$$



→ no chromomagnetic dipole moments



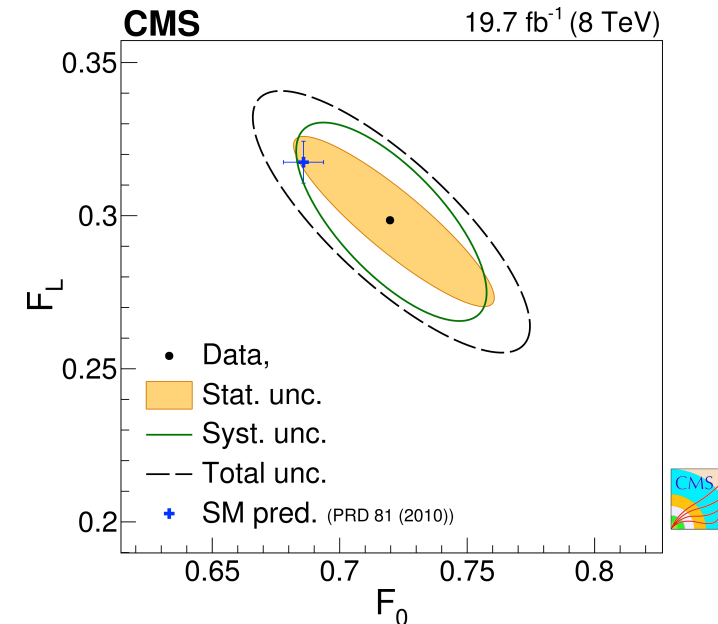
no new physics



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

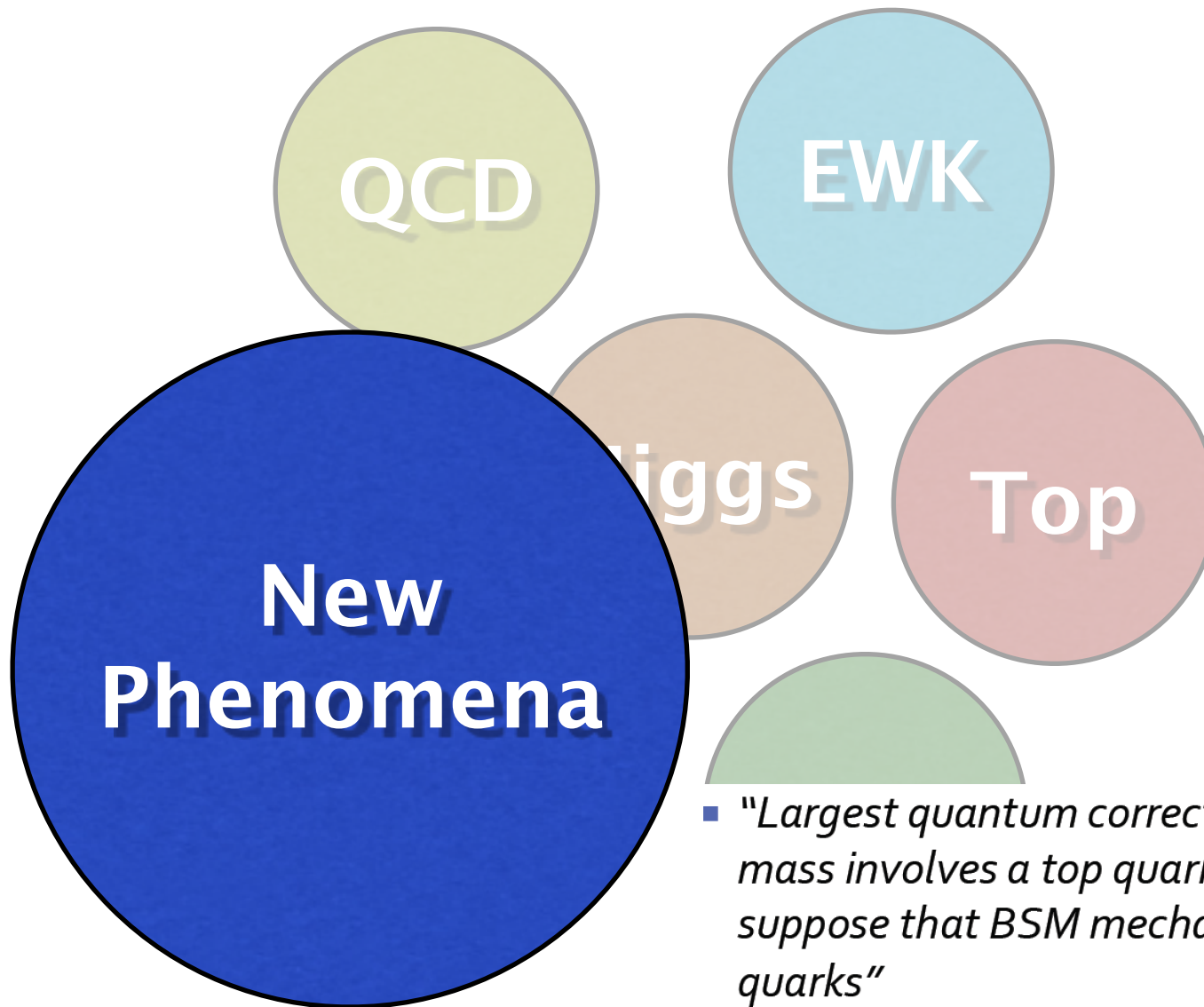
→ top quarks polarised as in SM

→ spins correlated as in SM



→ no anomalous couplings

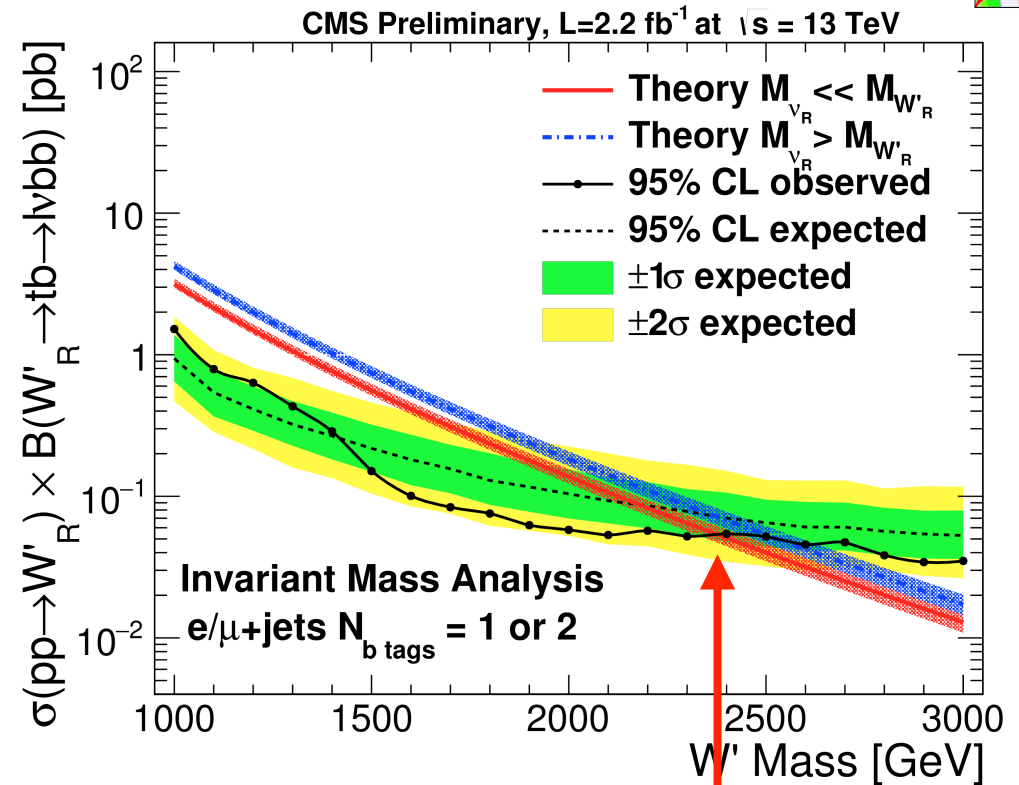
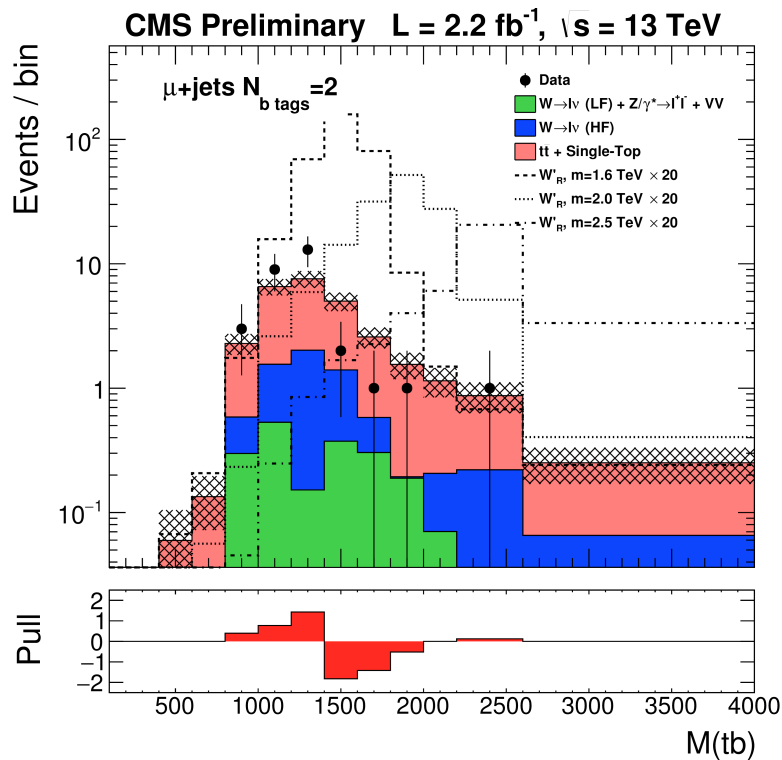
Top Quark Physics Topics



- *"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



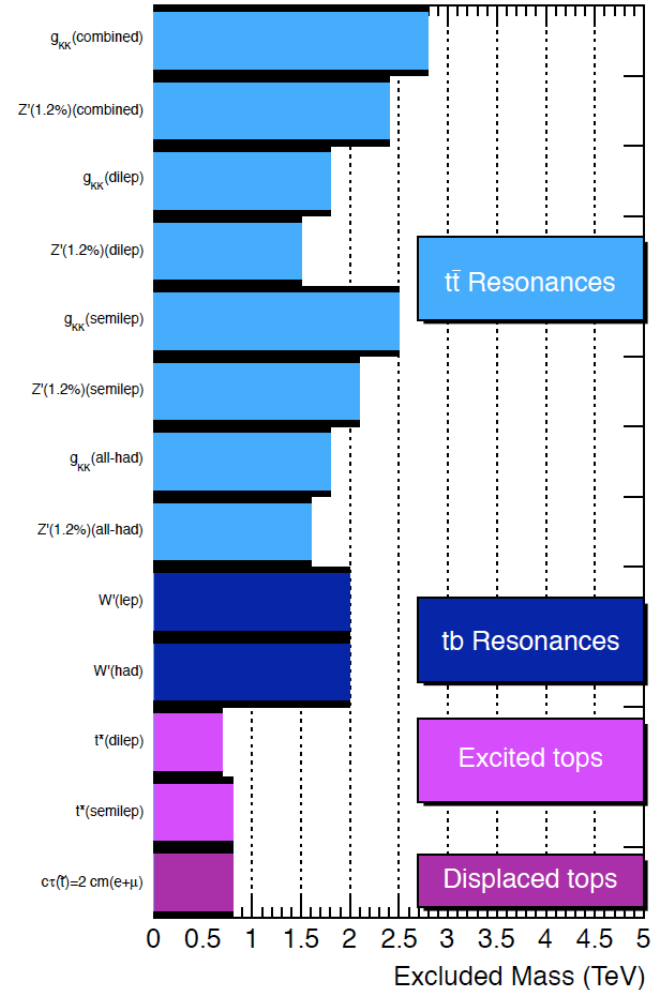
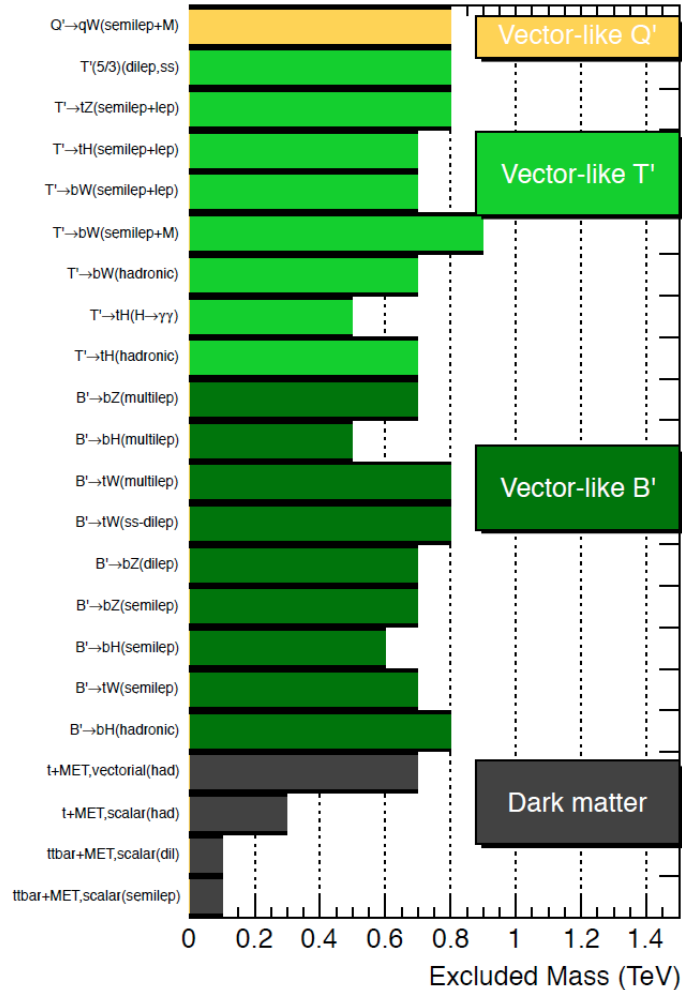
2.38 TeV

→ no new physics

Pushing the TeV scale

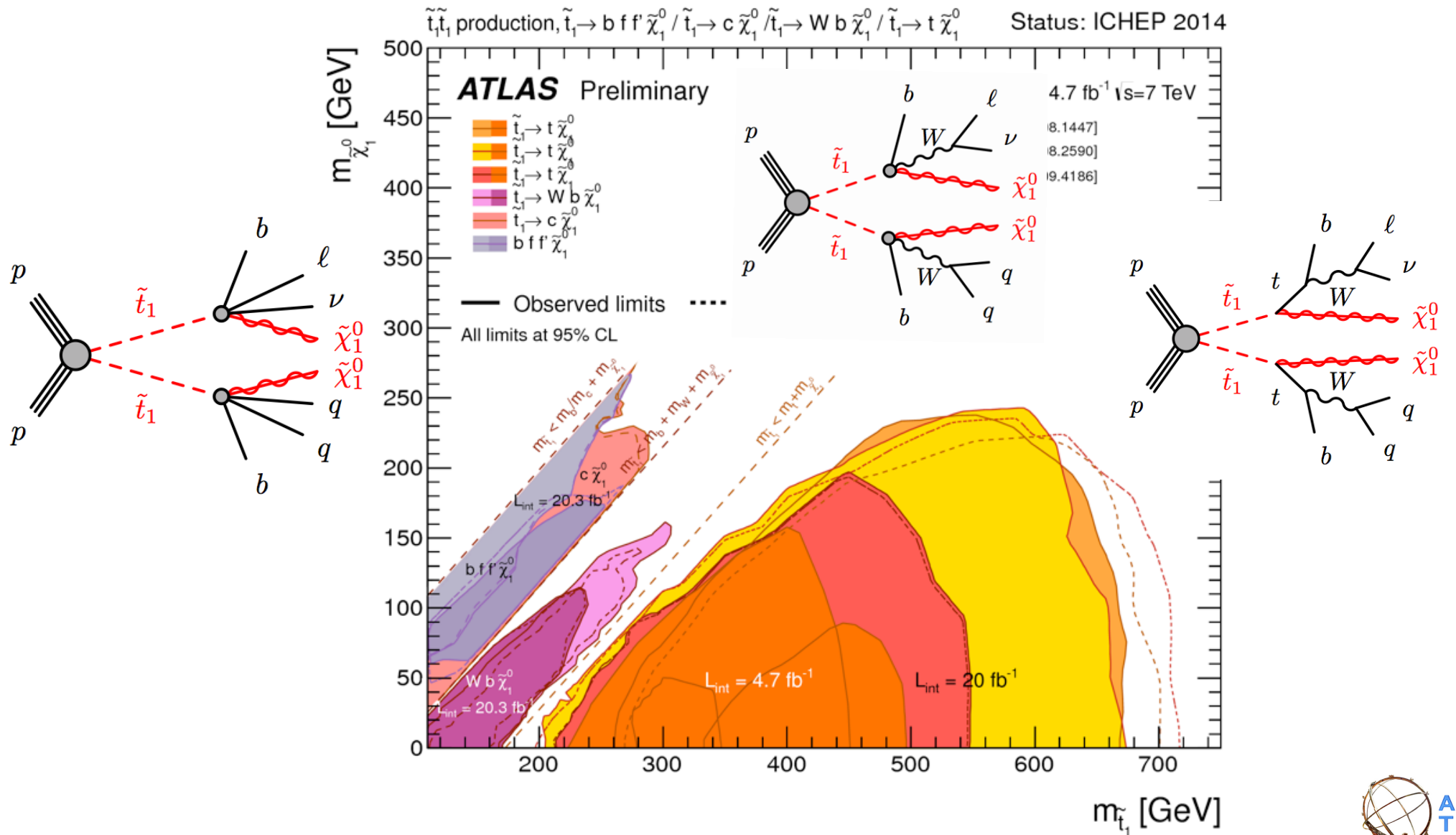
CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)



→ lots of opportunities for discovery in Run-II

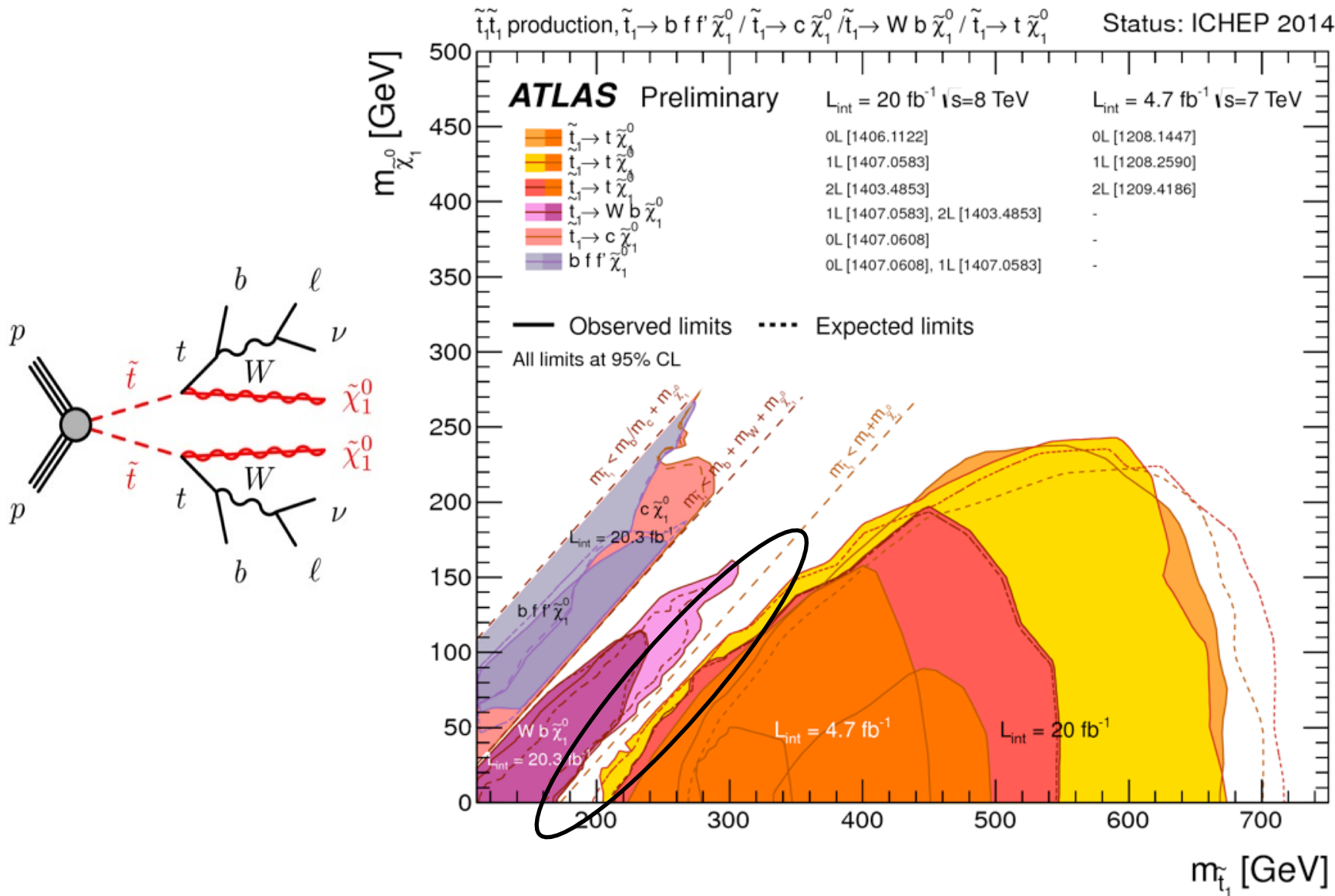
Direct stop searches



we check every little corner...



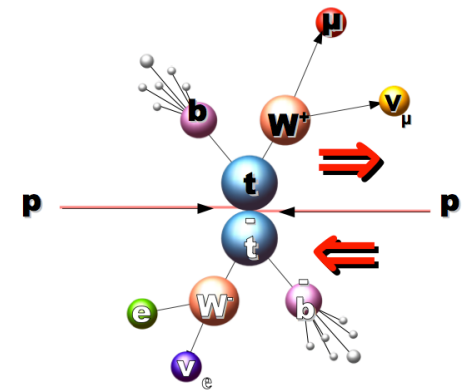
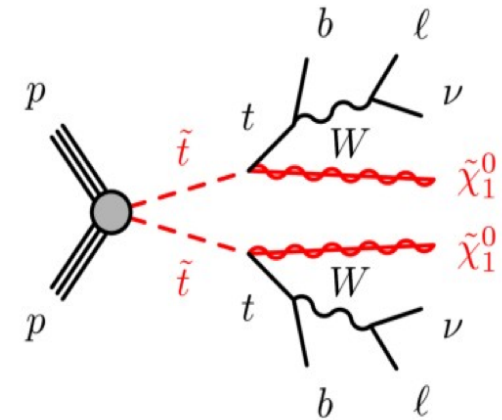
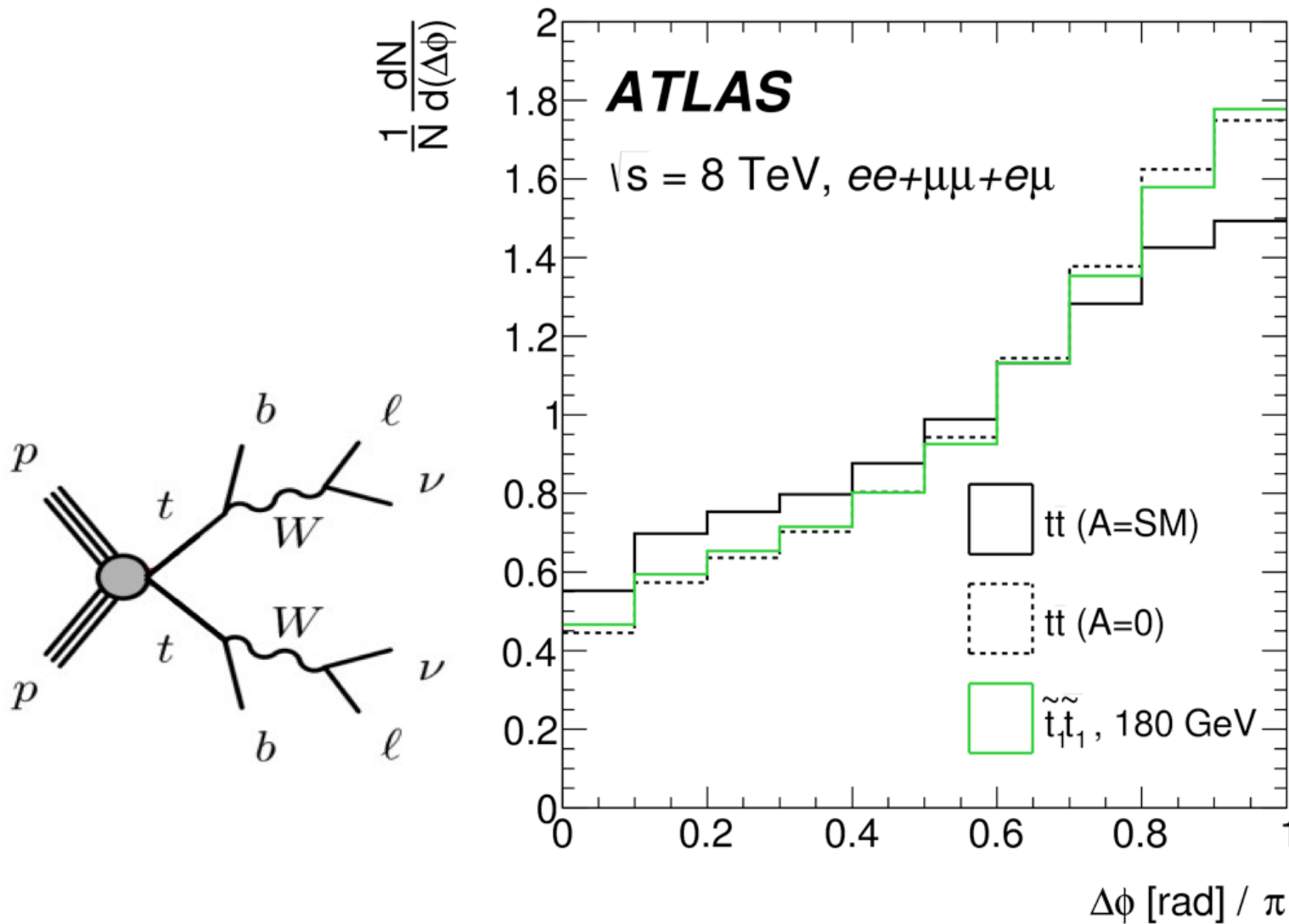
“Stealth” Stop Quarks



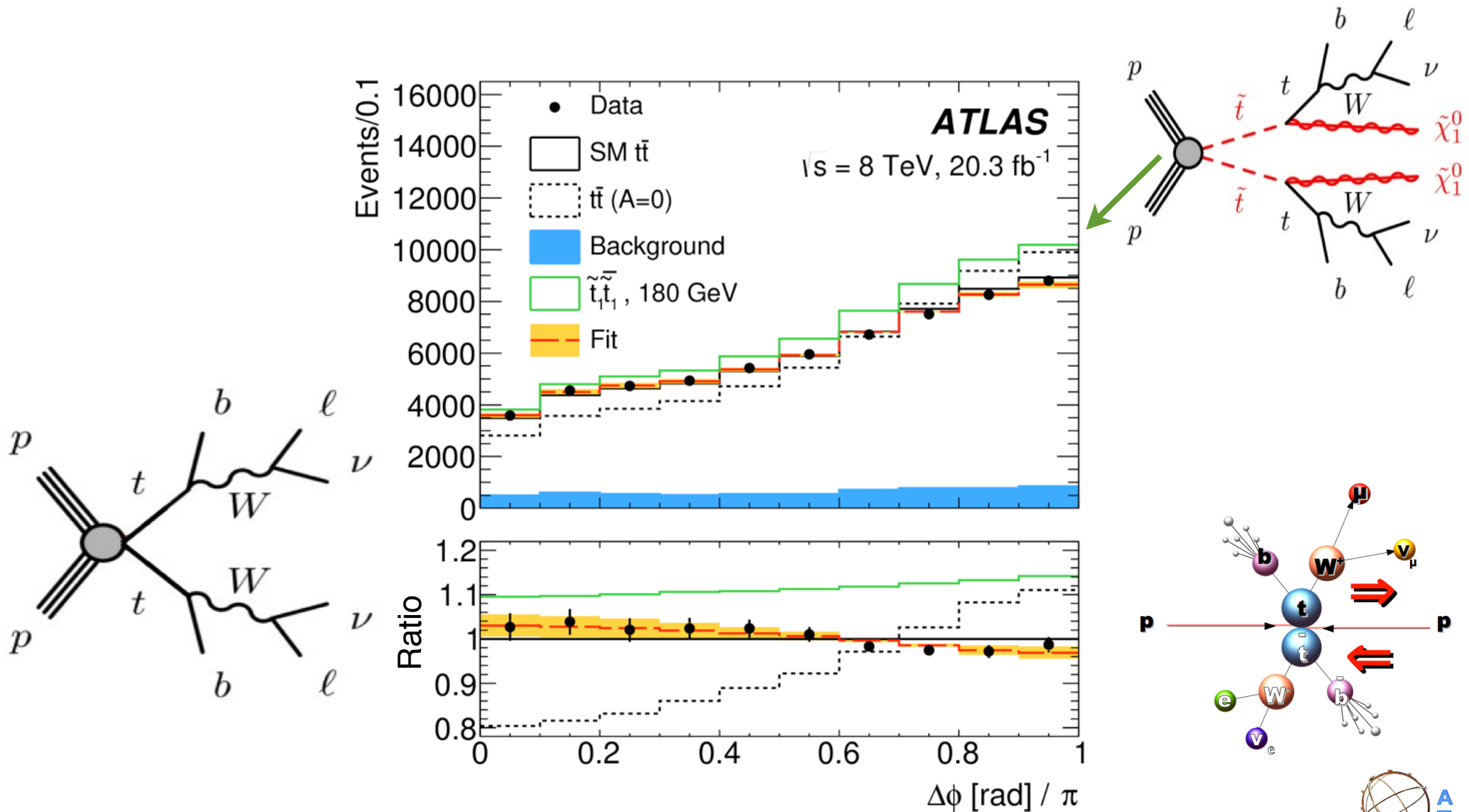
we check every little corner...



Spin correlations for “Stealth” Stop



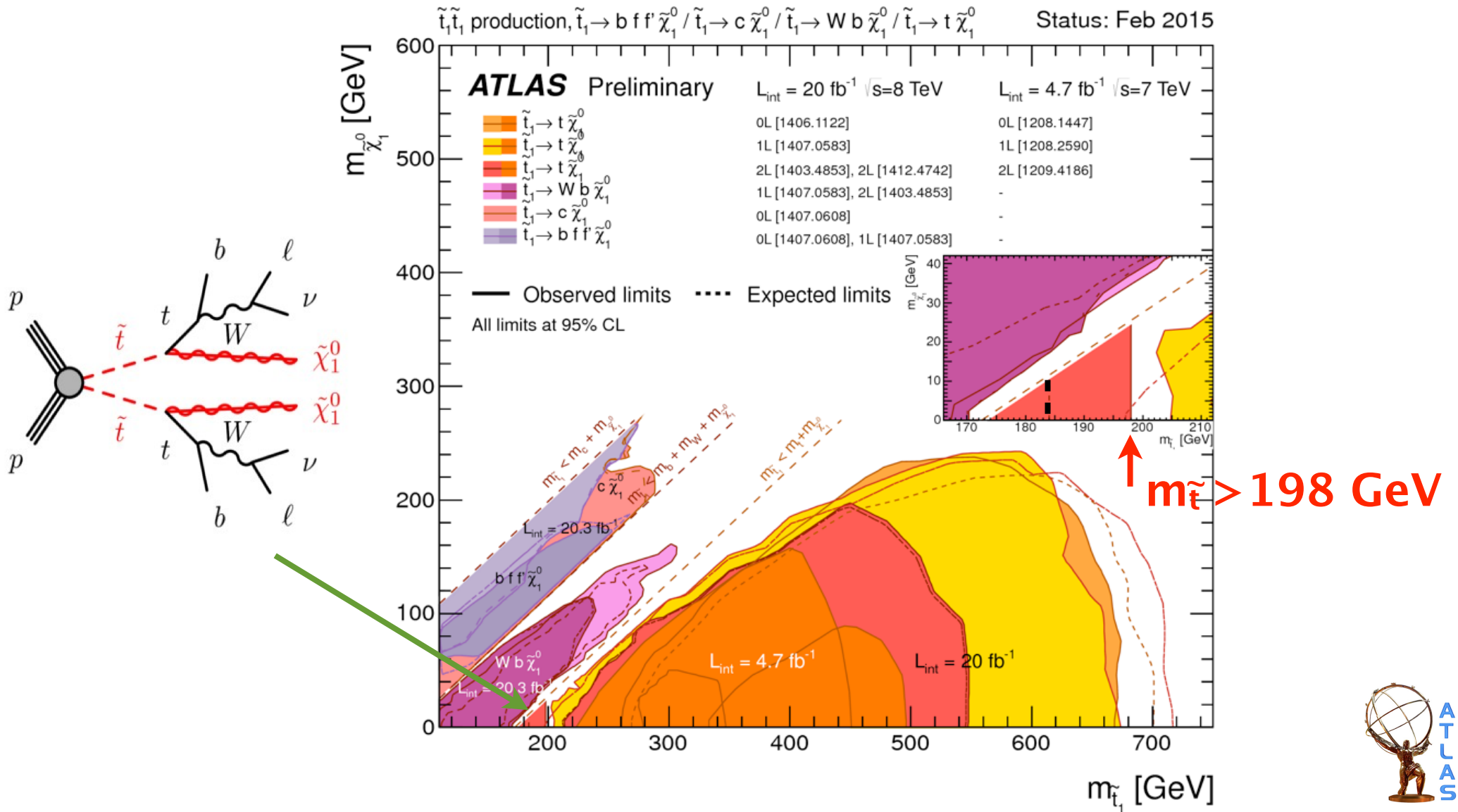
Spin correlations for “Stealth” Stop



→ no hint of stop quarks



Direct stop searches



→ 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 , $t\bar{t}Y$, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$, ...
- **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

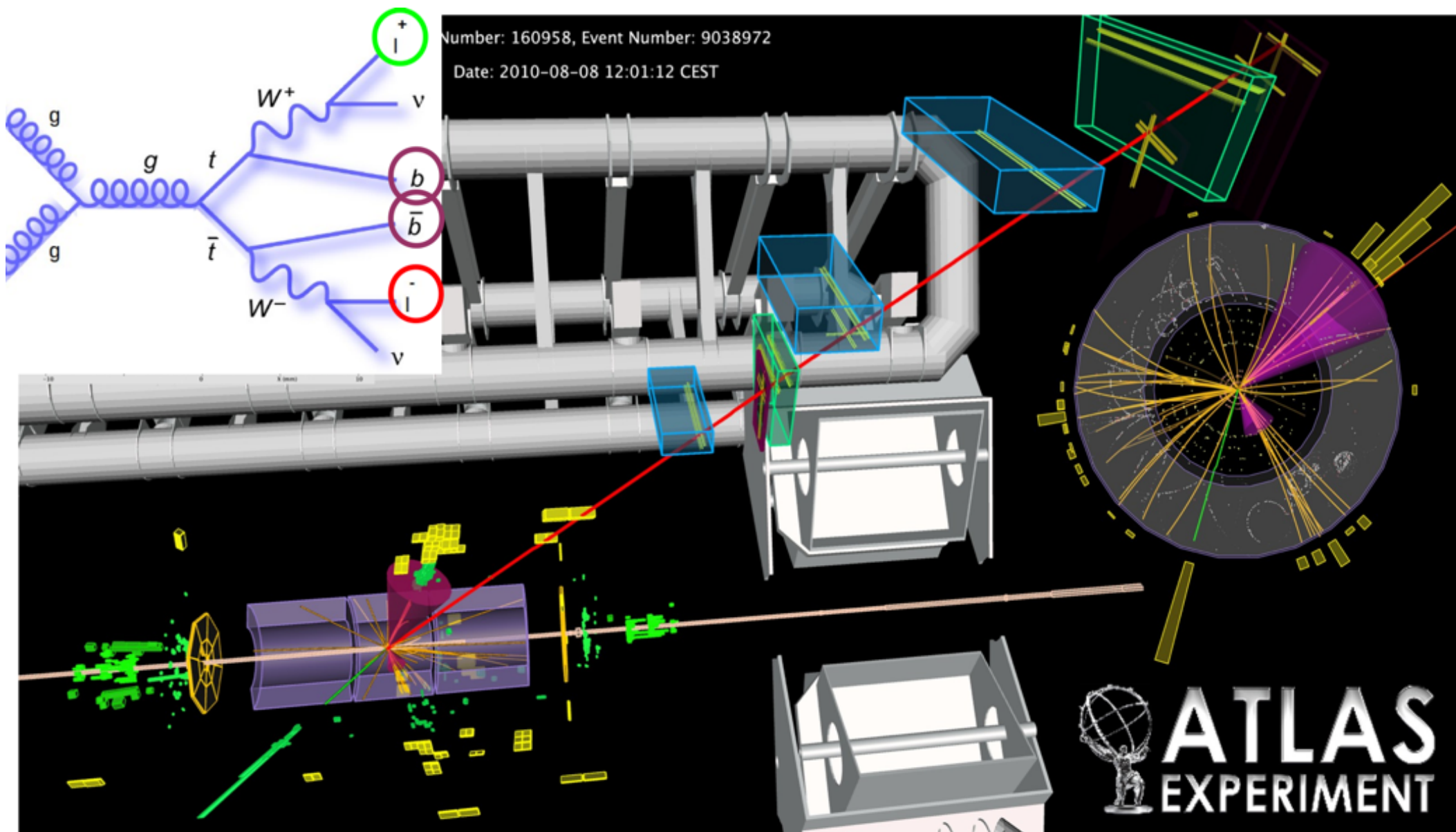


WE NEED YOU

**let's smash the SM
in Run-2!**

Backup

Dilepton Event

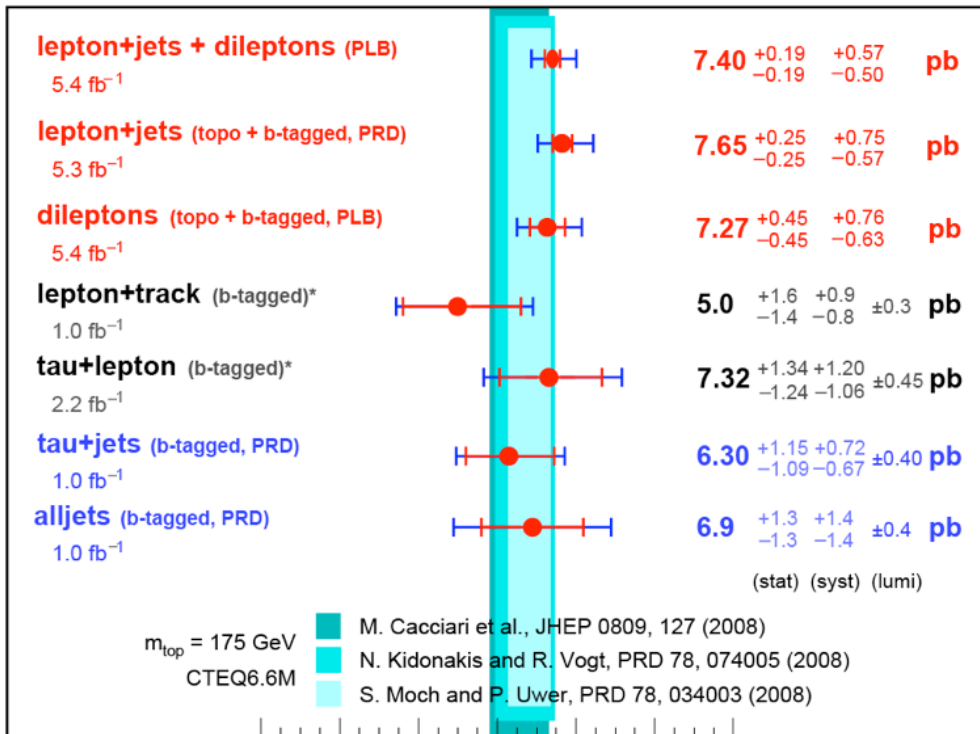


Top Pair Production Cross Section

DØ Run II



July 2011

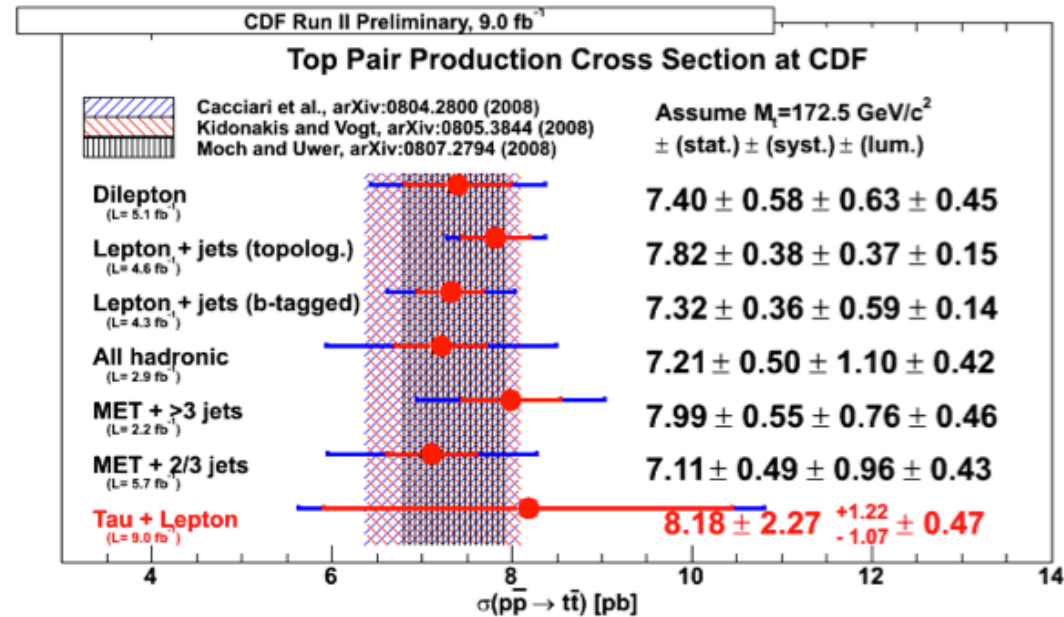


* = preliminary
red = 2011 result
blue = 2010 results

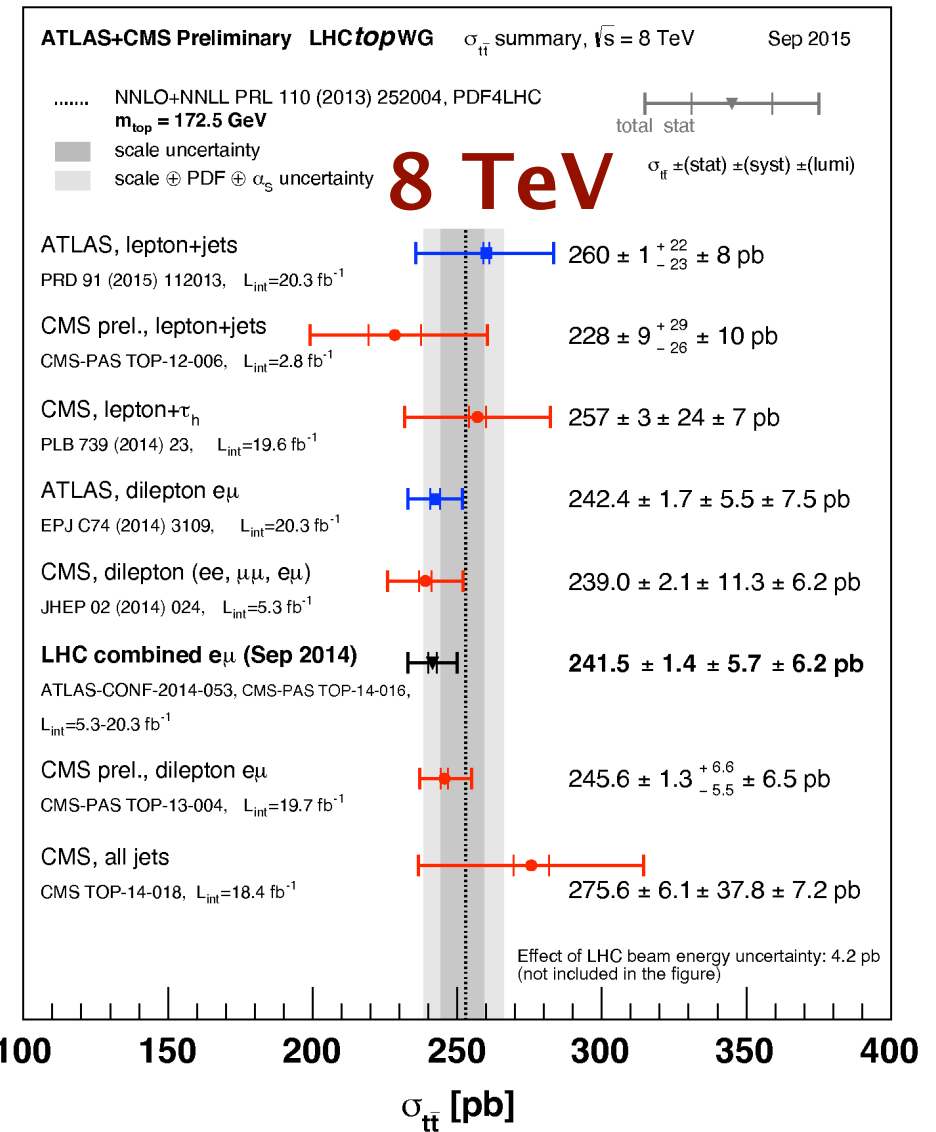
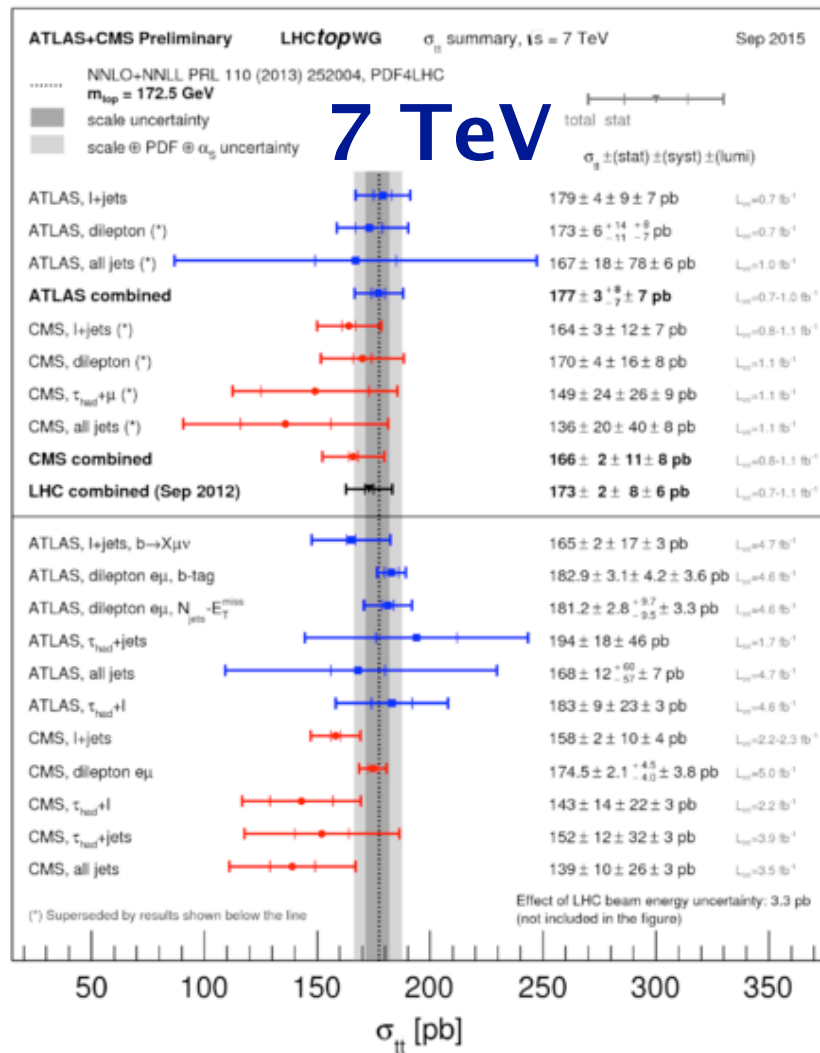
$\sigma(p\bar{p} \rightarrow t\bar{t} + X) [\text{pb}]$

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

→ good agreement with each other



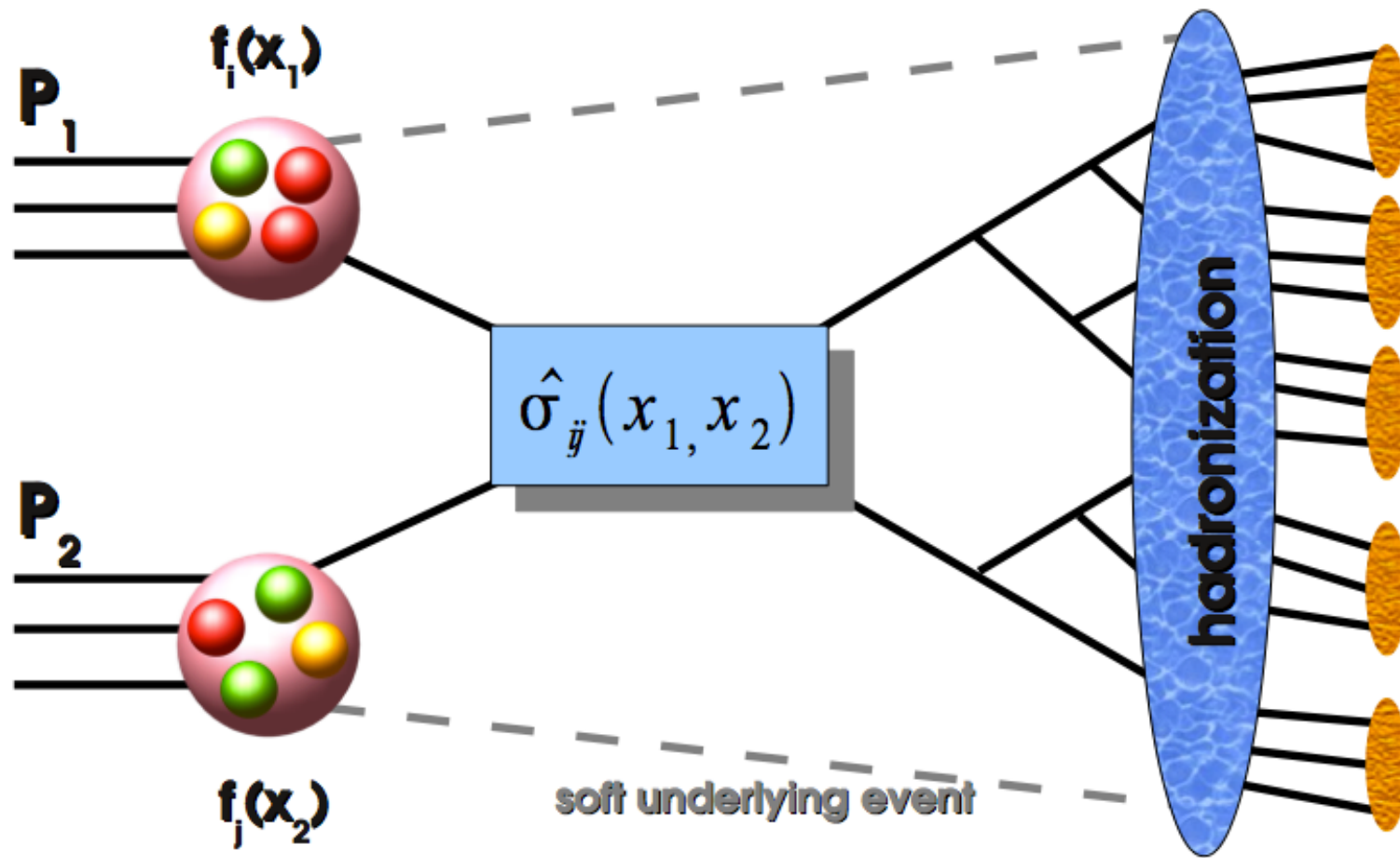
Top pair production cross section



→ (all) channels measured to look for the unexpected
 → no new physics

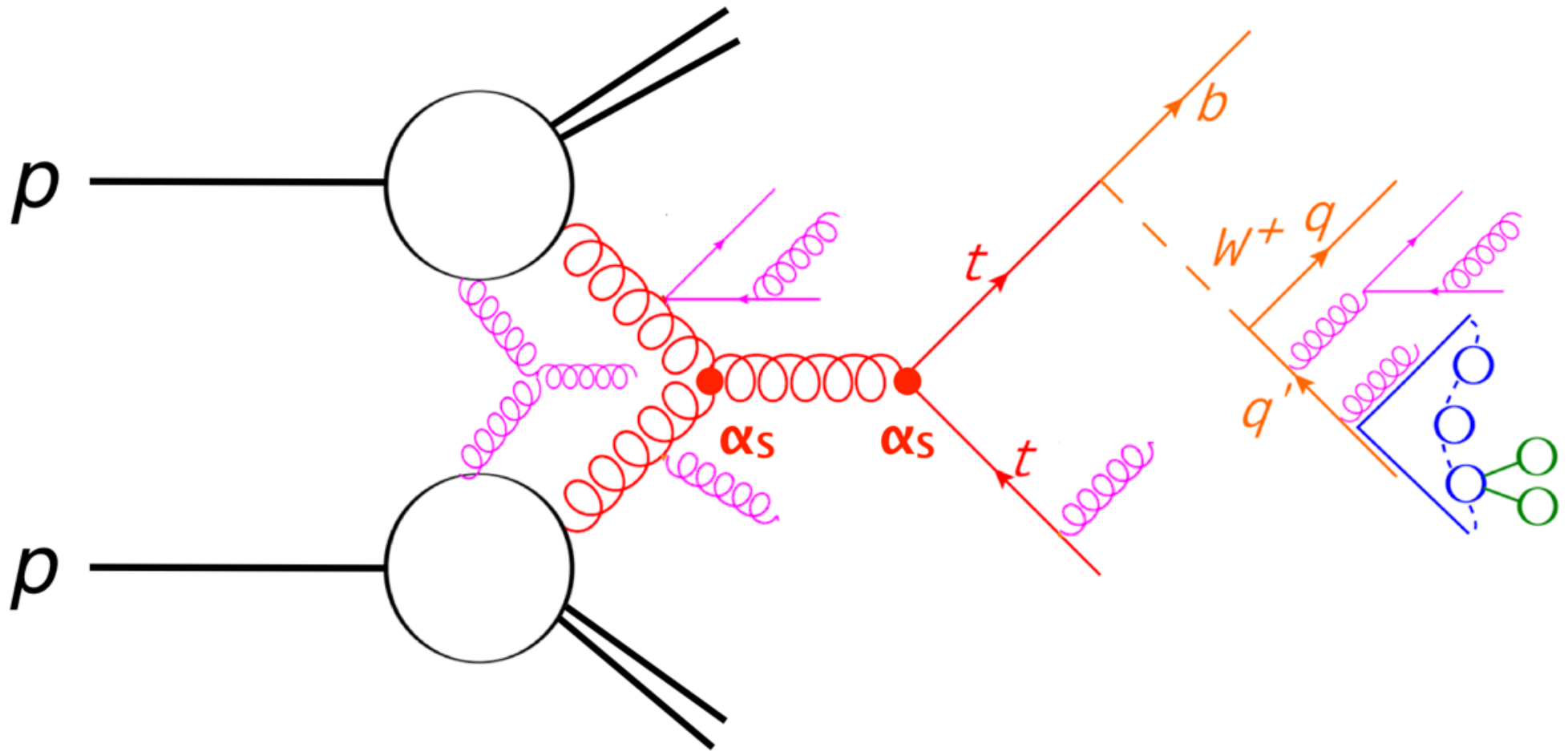
Differential Cross Sections

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



“Revolution” in Phenomenology

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



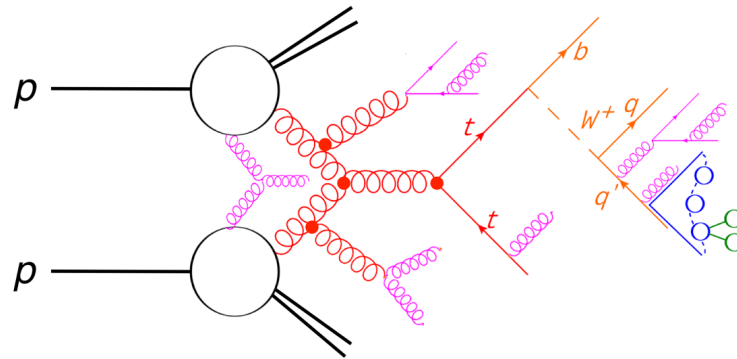
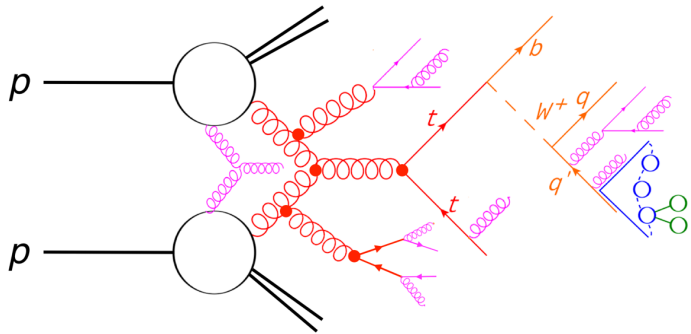
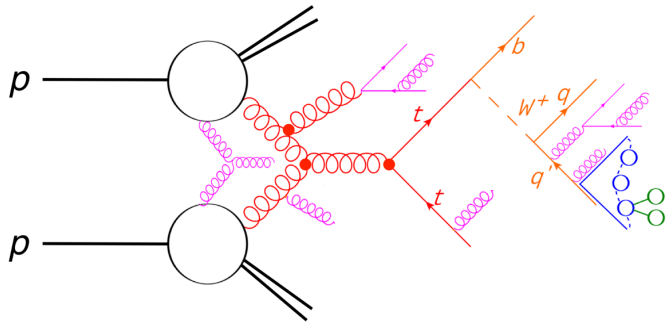
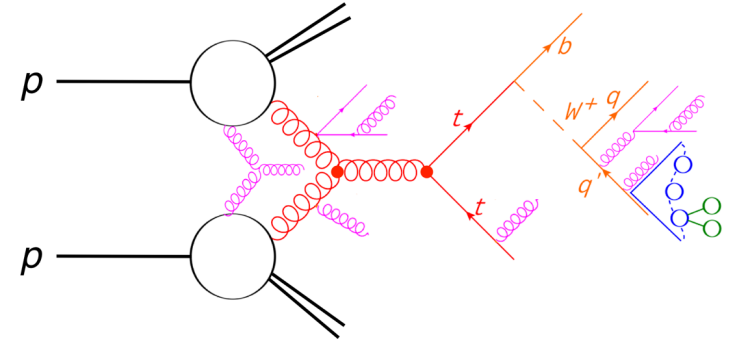
“Revolution” in Phenomenology

- LO QCD+parton shower generators

Pythia, Herwig, ...

- LO multileg generators matched with parton shower

Alpgen+Pythia, Alpgen+Herwig, ...



...

“Revolution” in Phenomenology

- LO QCD+parton shower generators

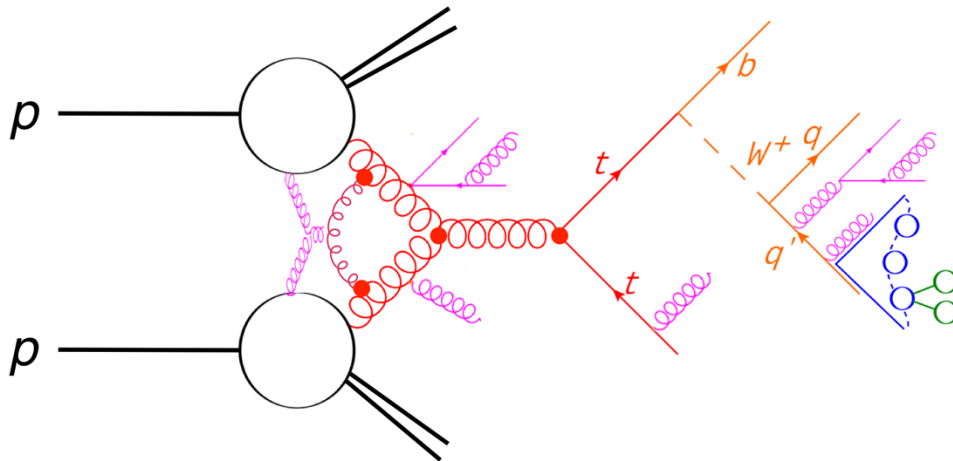
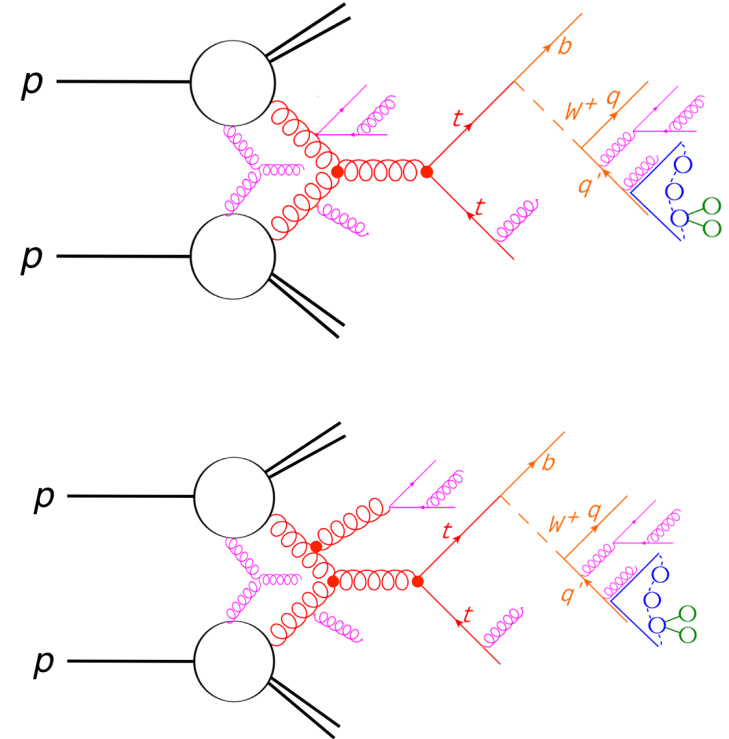
Pythia, Herwig, ...

- LO multileg generators matched with parton shower

Alpgen+Pythia, Alpgen+Herwig, ...

- NLO+parton shower generators

Powheg+Pythia, MC@NLO+Herwig, ...



“Revolution” in Phenomenology

- LO QCD+parton shower generators

Pythia, Herwig, ...

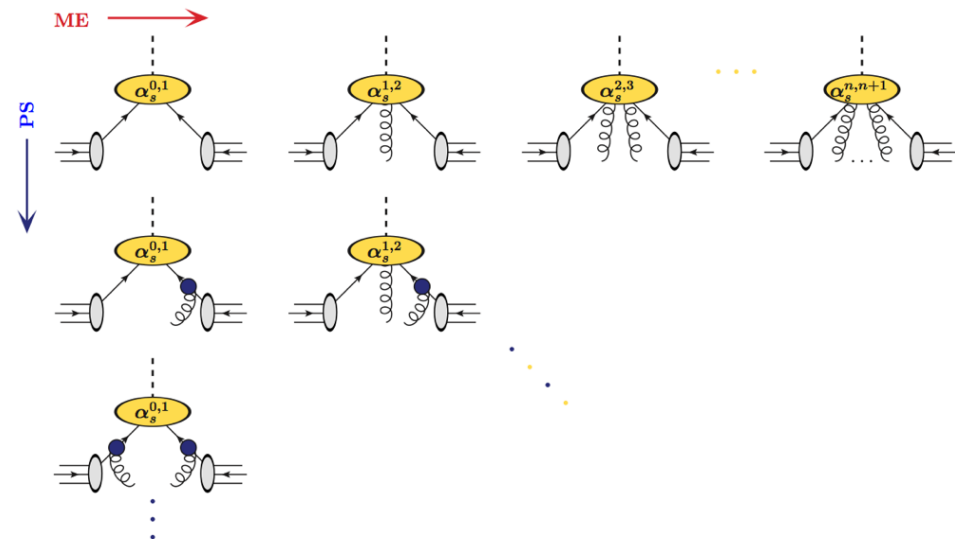
- LO multileg generators matched with parton shower

Alpgen+Pythia, Alpgen+Herwig, ...

- NLO+parton shower generators

Powheg+Pythia, MC@NLO+Herwig, ...

- NLO+LO multileg generators matched with parton showers



“Revolution” in Phenomenology

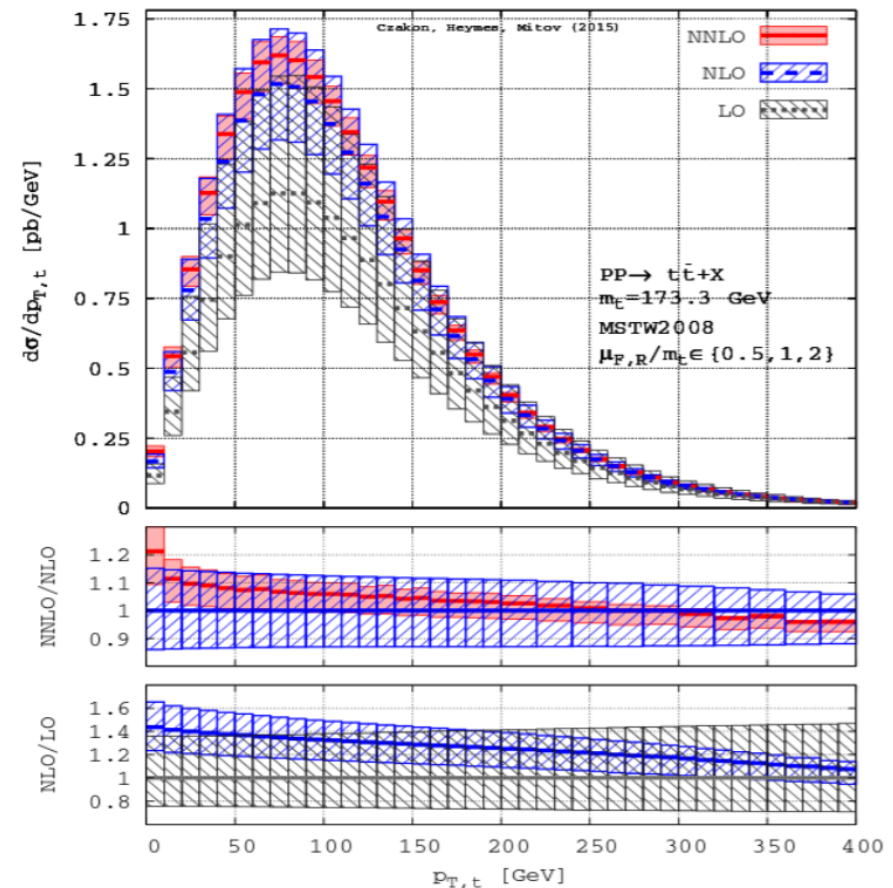
- LO QCD+parton shower generators
Pythia, Herwig, ...

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

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

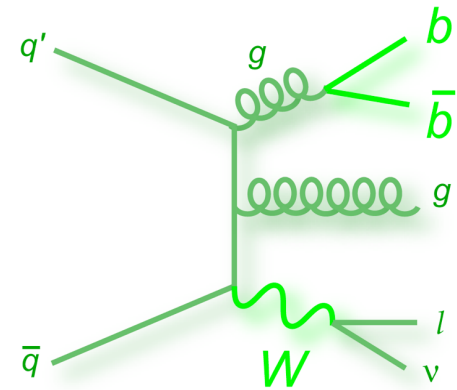
- NLO+LO multileg generators matched with parton showers

- NNLO QCD calculations

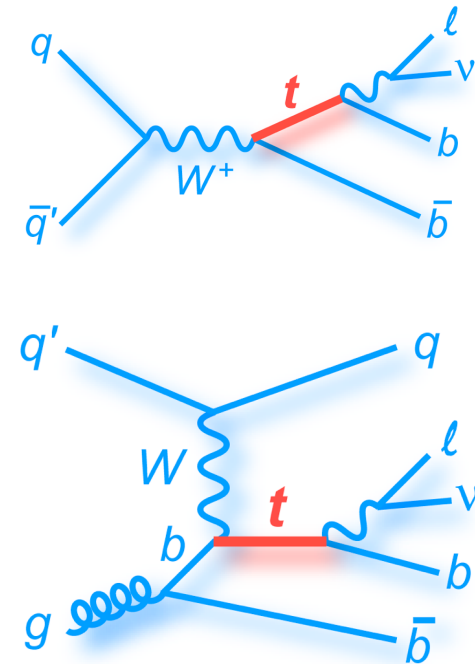
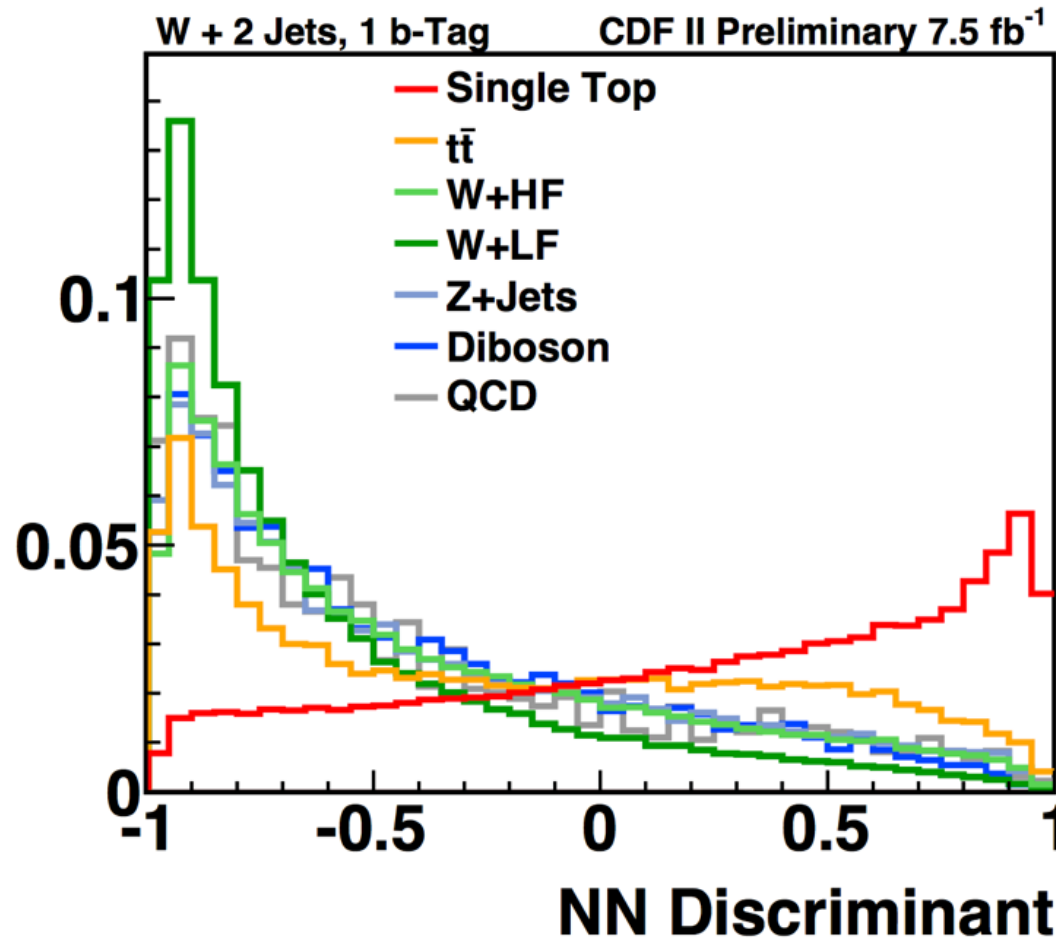


Output Discriminant for s+t

CDF-CONF 10793

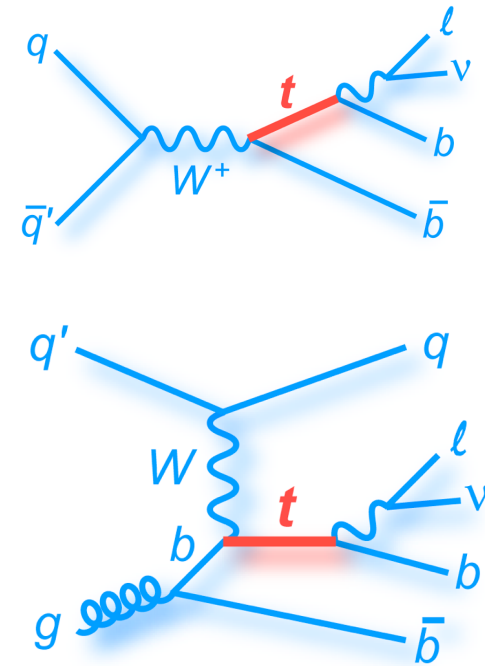
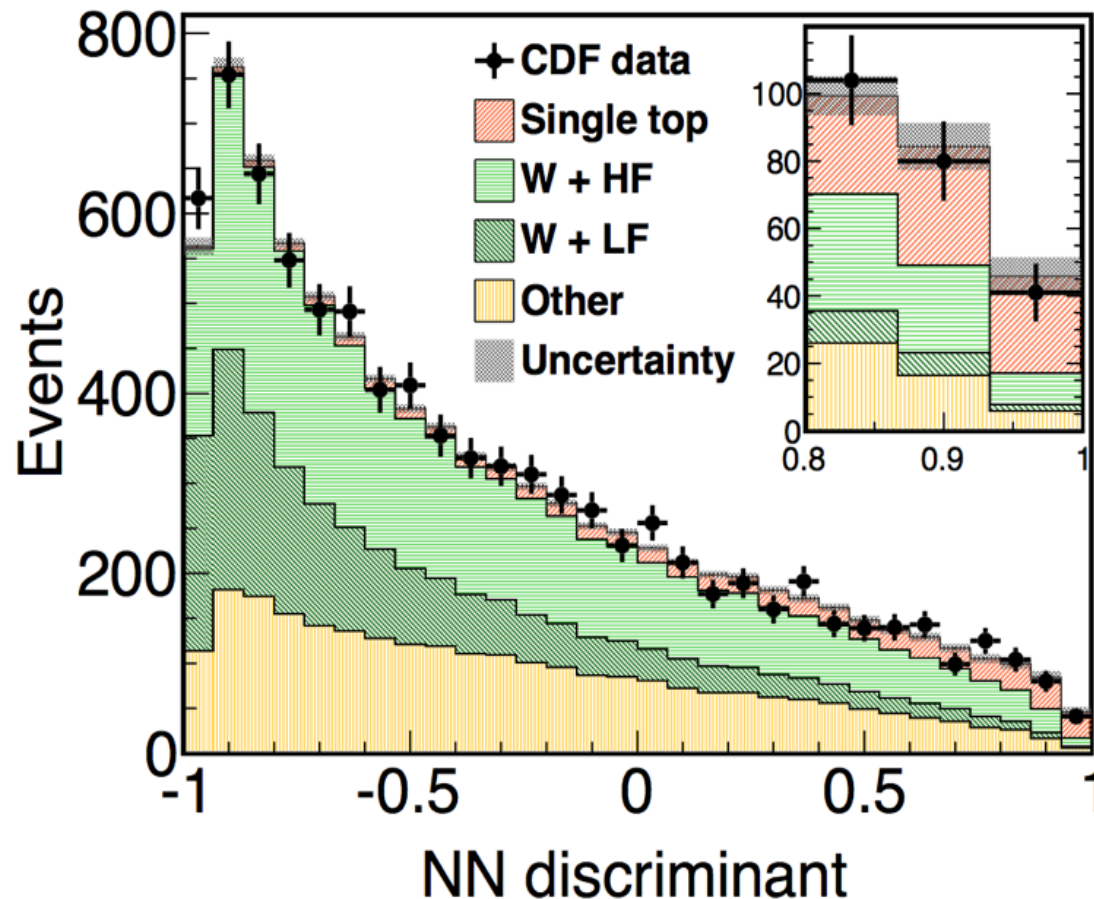
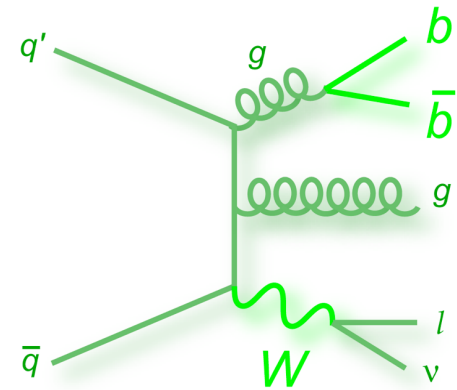


Normalized Event Fraction



Output Discriminant for s+t channel

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



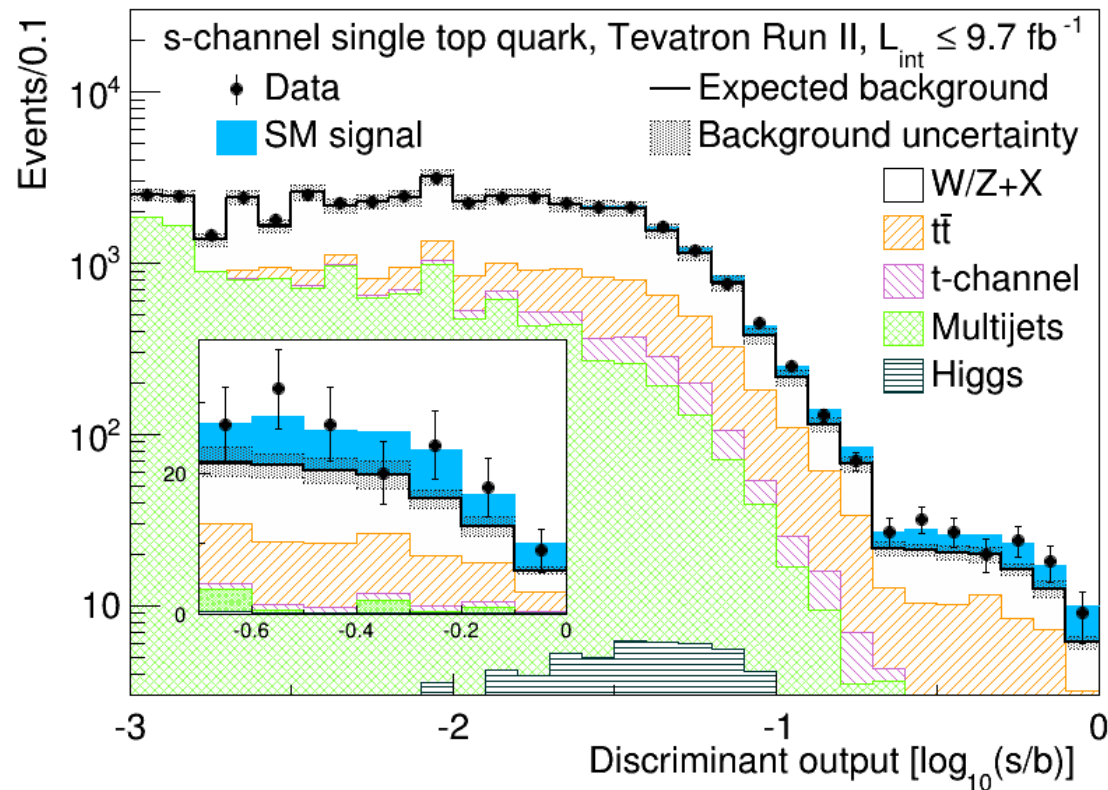
- s+t channel observed by CDF and D0 in 2009
- important step to establish MVA techniques



s-channel Production

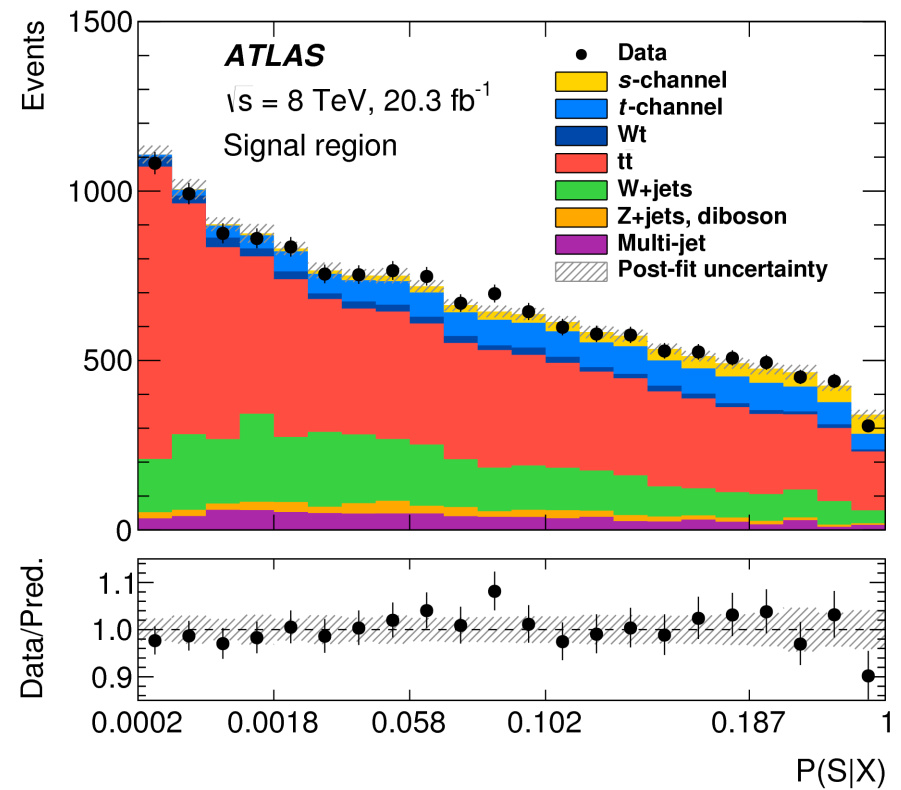
Phys. Rev. Lett. 112, 231803 (2014)

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



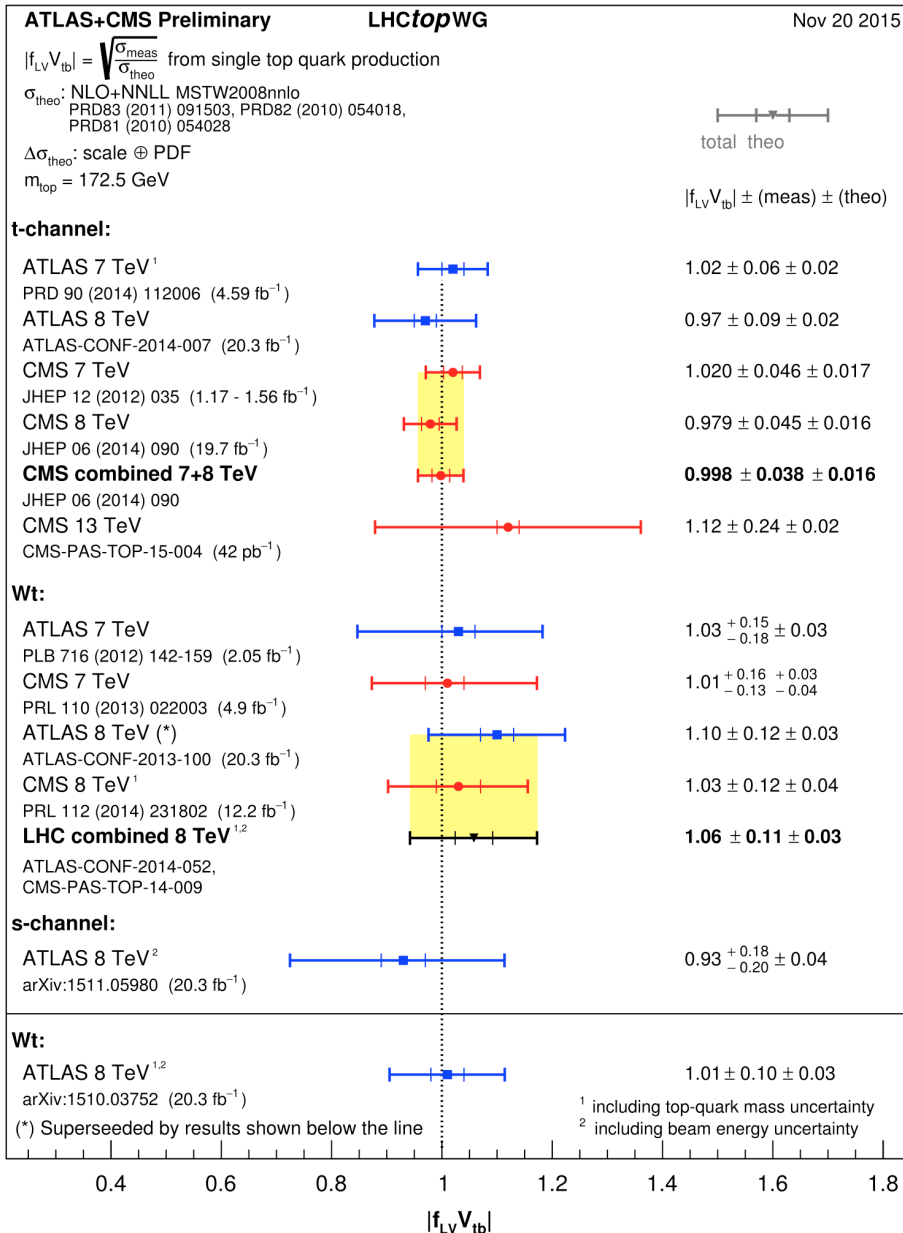
→ **observation: 6.3 s.d.**

- **ATLAS: matrix element method**

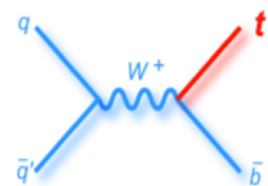
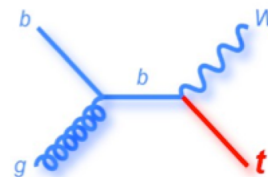
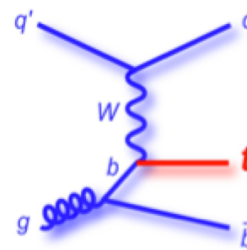


→ **evidence: 3.2 s.d.**

Extraction of $|V_{tb}|$

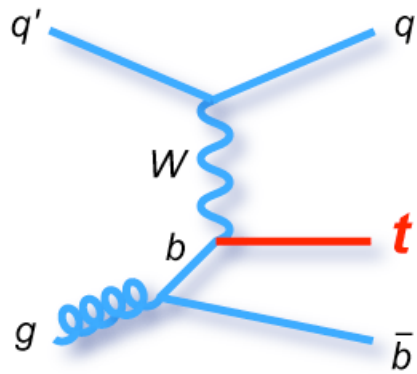


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$

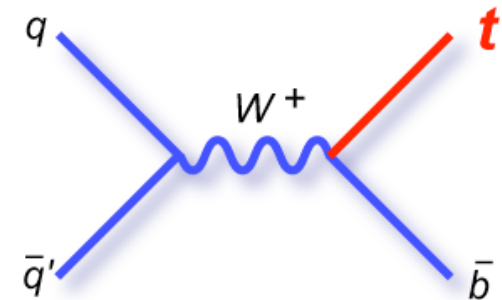
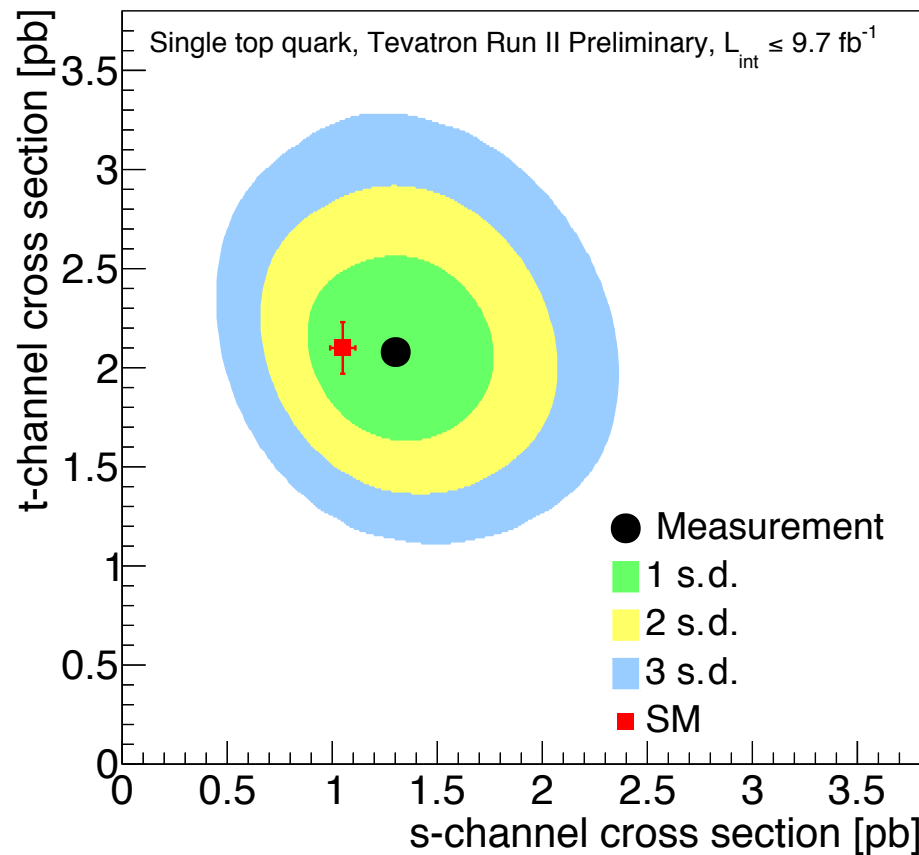


→ no hint for anomalous contributions!

Single Top s- vs. t-channel

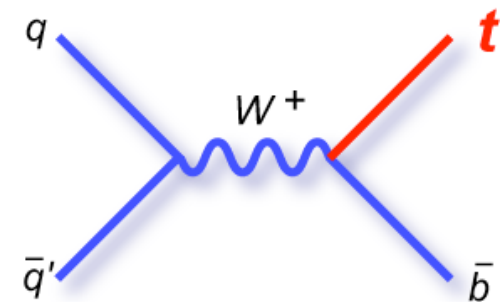
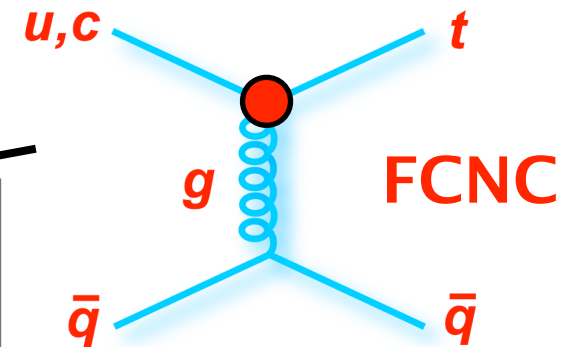
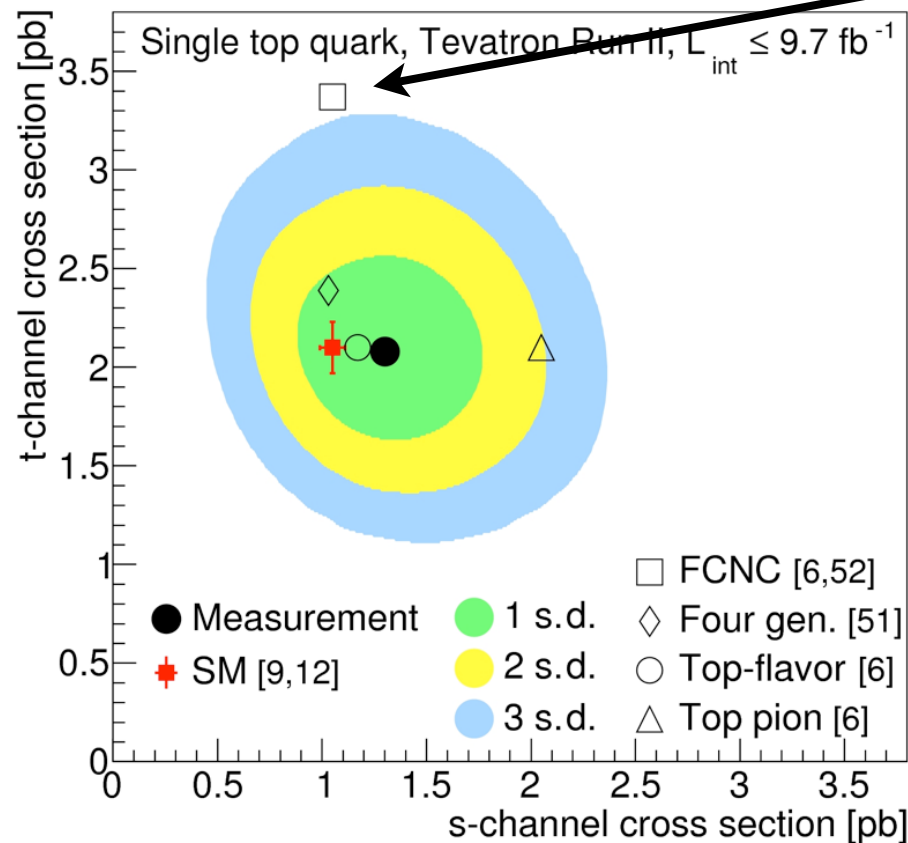
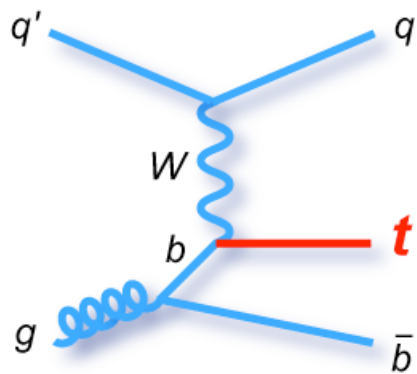


arXiv:1503.05027 [hep-ex]



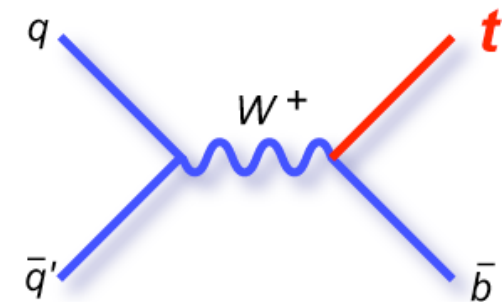
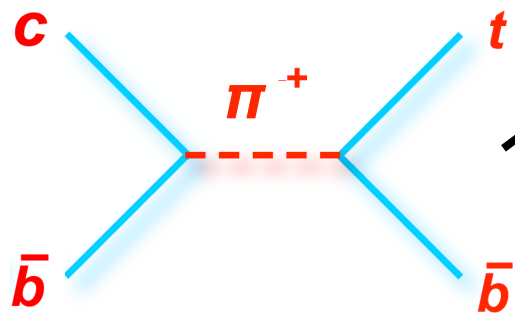
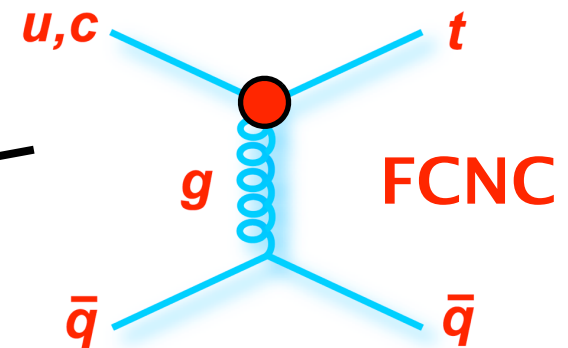
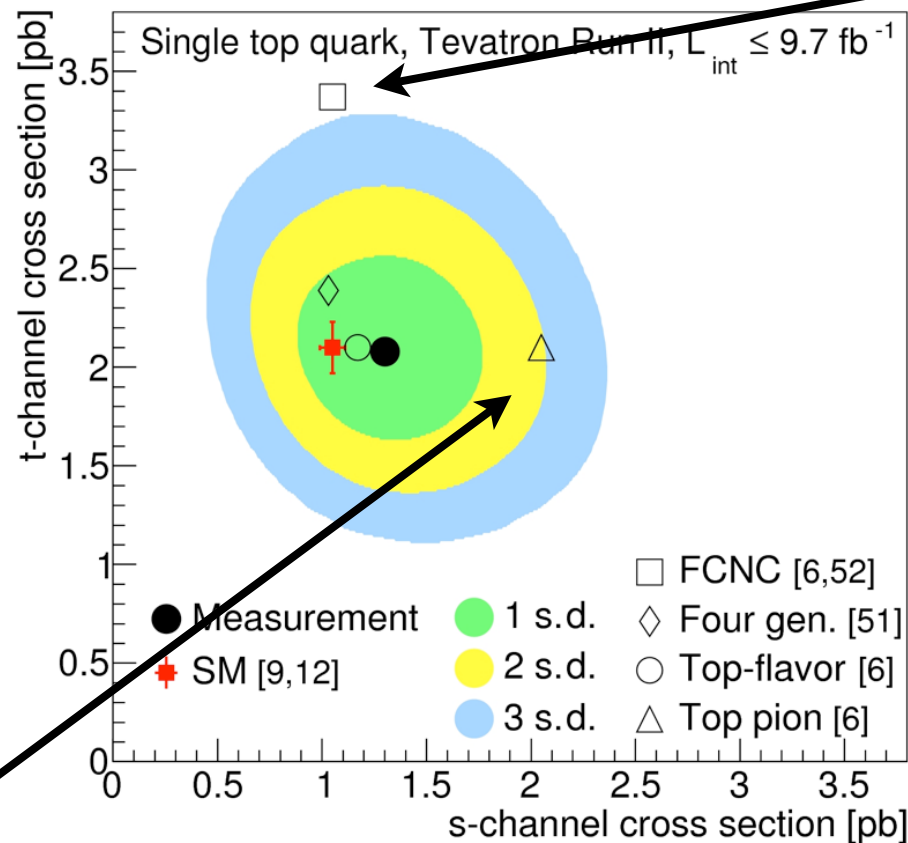
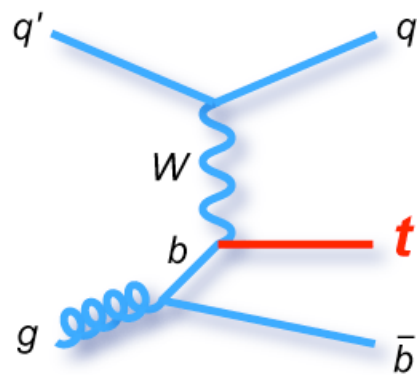
→ **observed!**

Single Top s- vs. t-channel



→ observed!

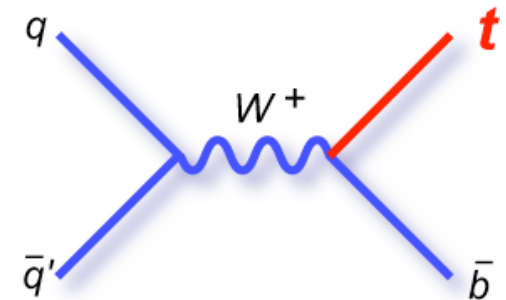
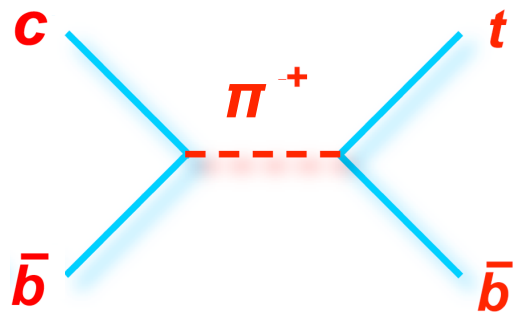
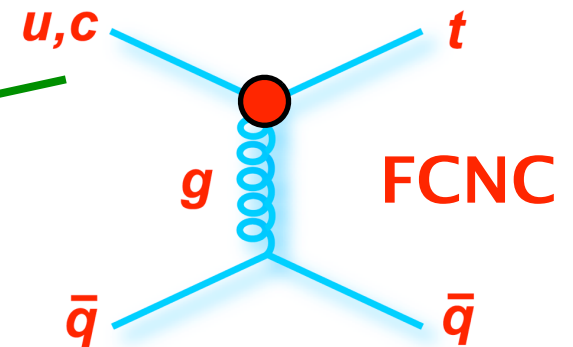
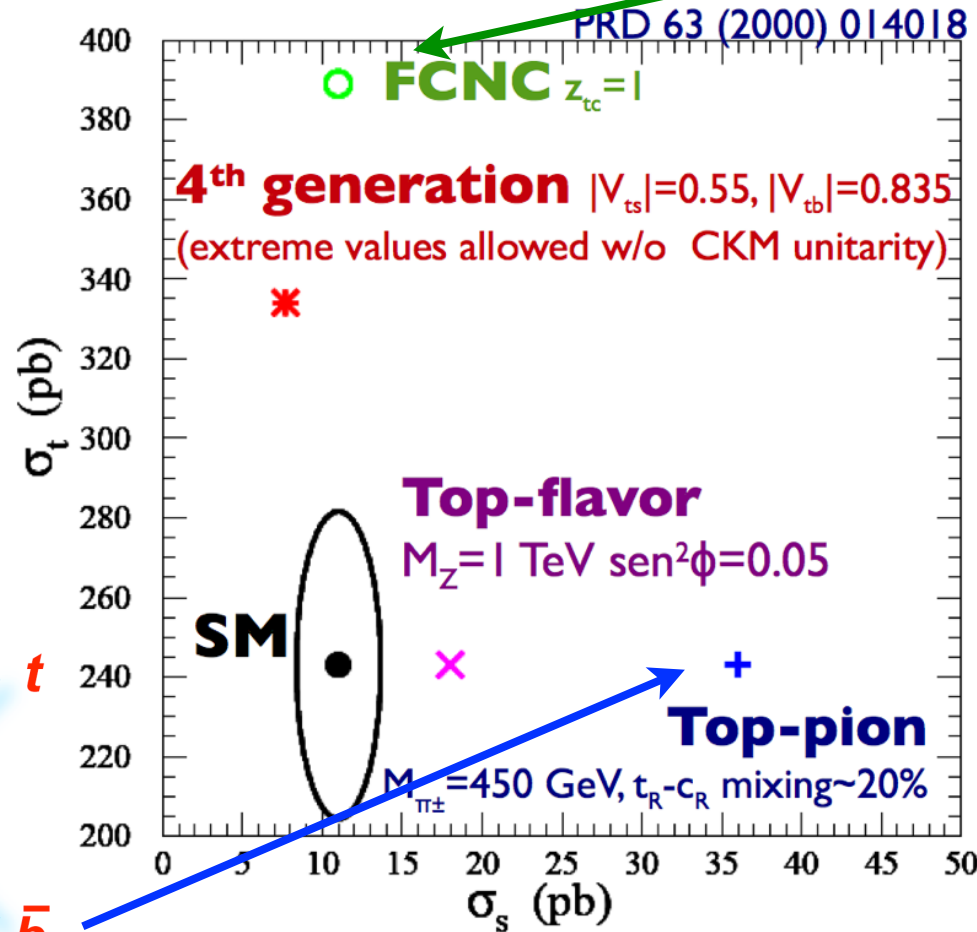
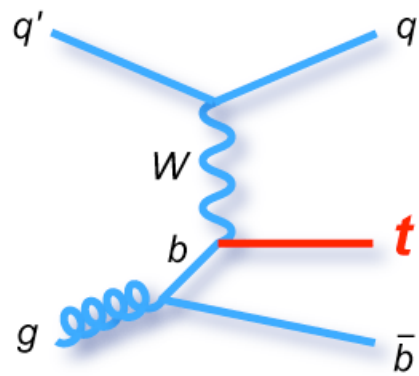
Single Top s- vs. t-channel



→ observed!

⇒ important to study production channels separately

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

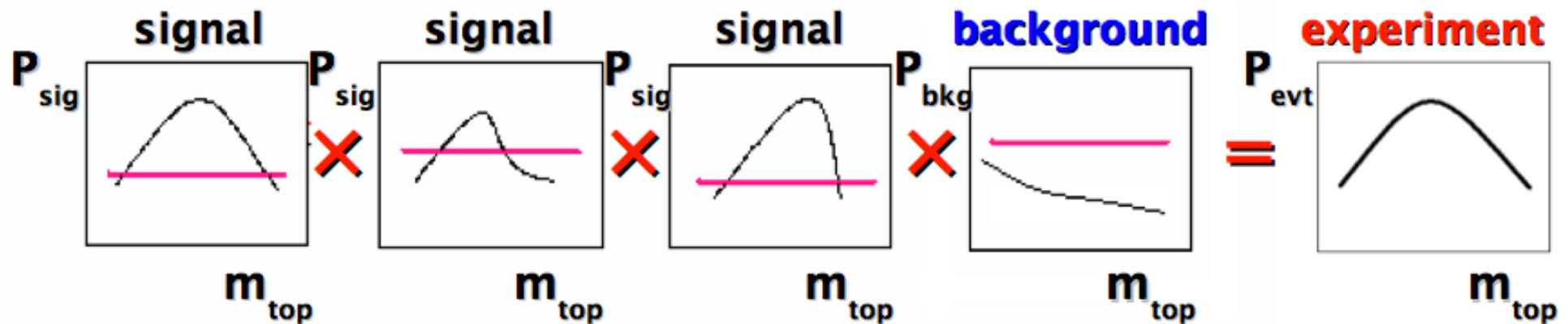


→ **observed!**

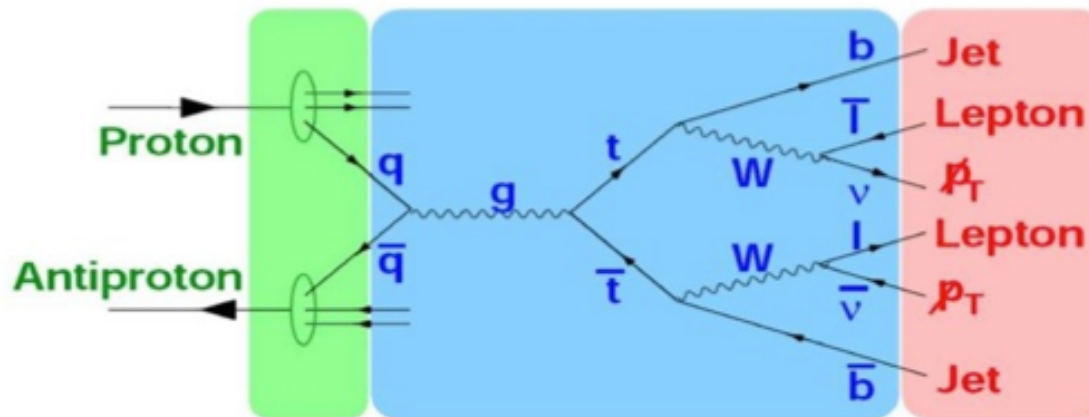
⇒ **important to study production channels separately**

Extraction Techniques: Matrix

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



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

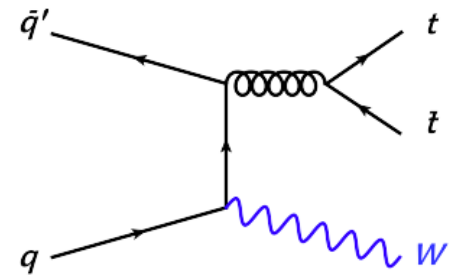
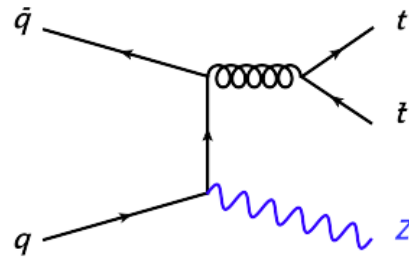


PDF's LO-Matrix element

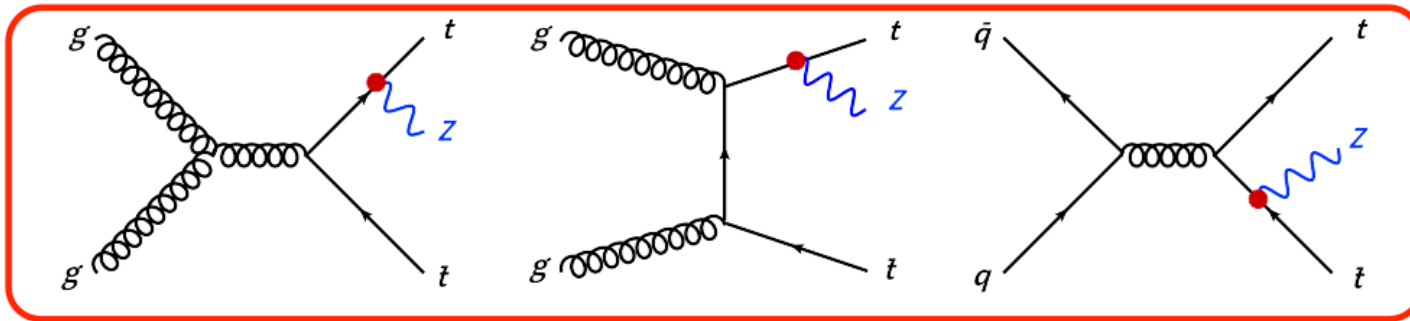
transfer functions
(probability to measure x
when y was produced)

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

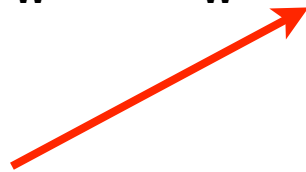
ISR



FSR

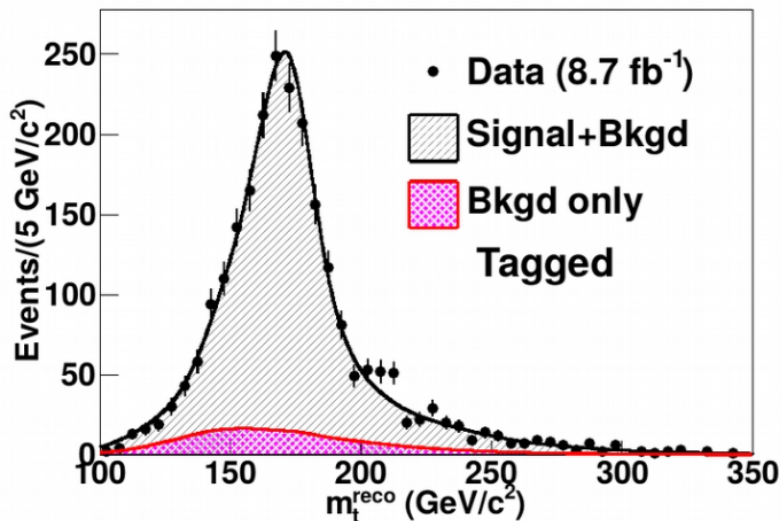


$$-i \frac{e}{\sin\theta_W \cos\theta_W} (\mathbf{T}_3 - \sin^2\theta_W \mathbf{Q}_t) \gamma^\mu$$

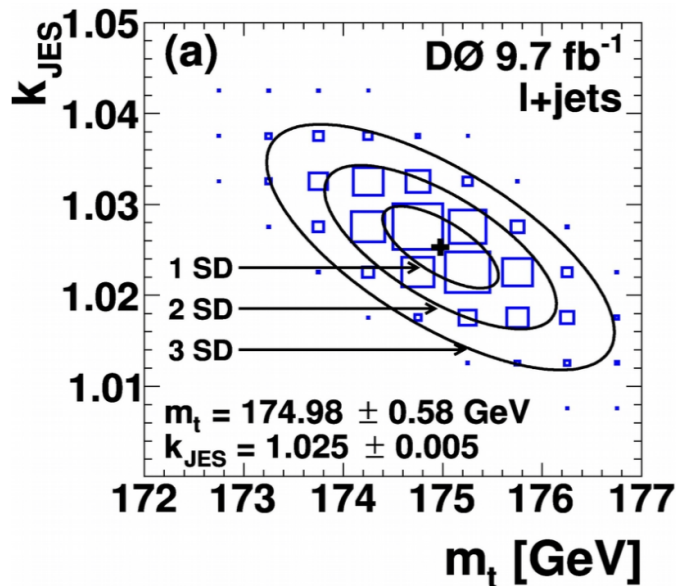


- measure 3rd component of weak isospin
 - search for anomalous couplings in $t\bar{t}Z$ vertex (basically unexplored)
- both processes are important backgrounds to searches (e.g. $t\bar{t}H$ in multilepton events)

Top mass at the Tevatron



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

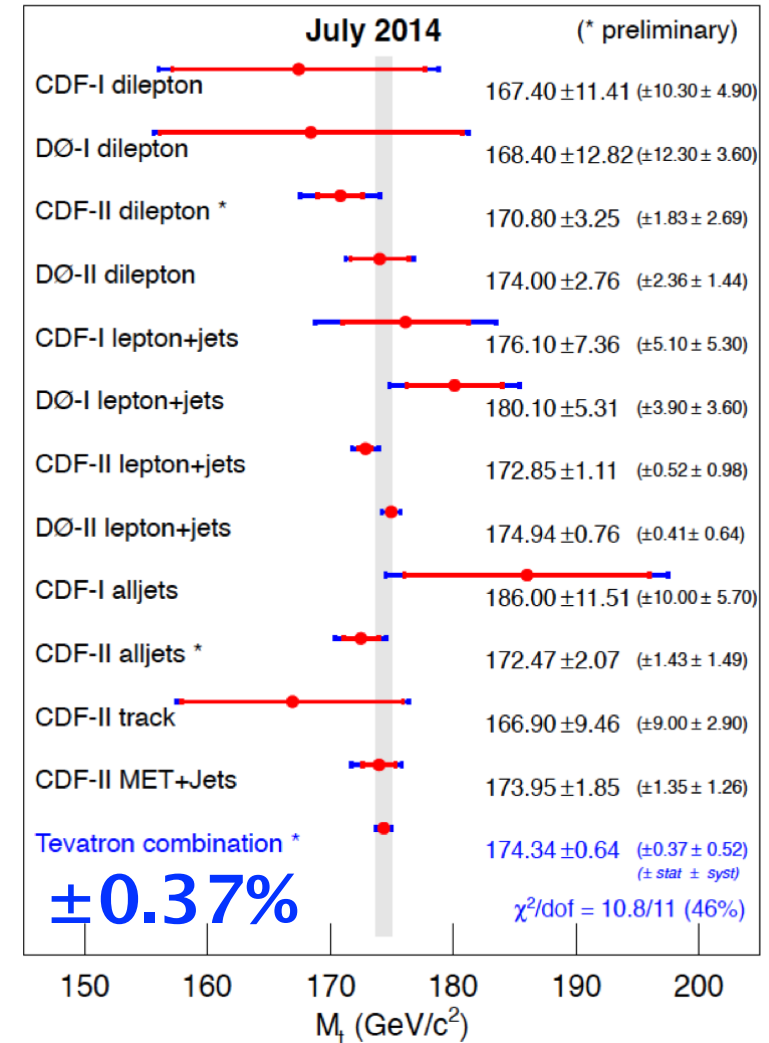


$$m_t = 174.98 \pm 0.58 \text{ (stat.)} \pm 0.49 \text{ (syst) GeV}$$

$\pm 0.63\%$

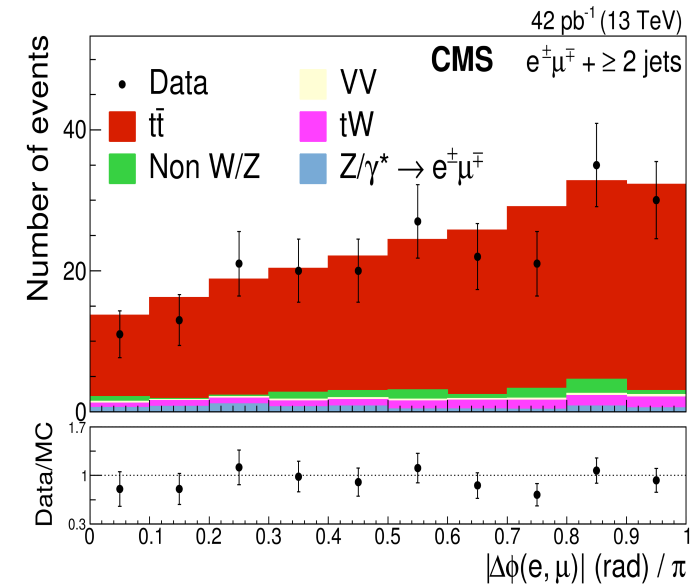
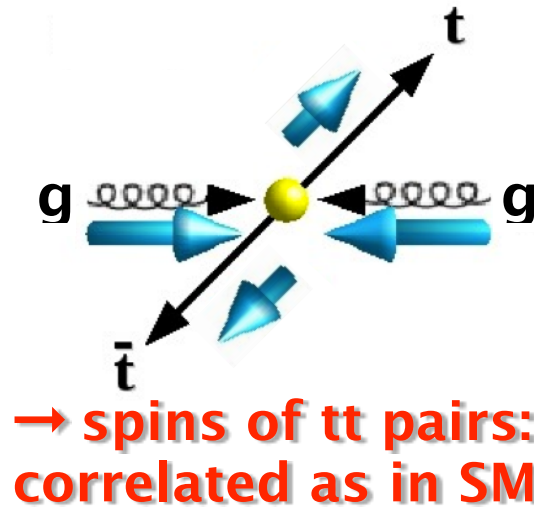
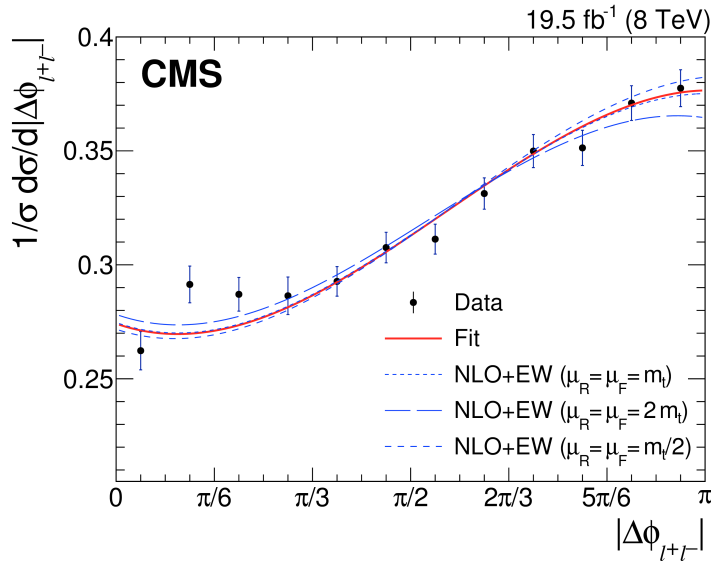
$\pm 0.43\%$

Mass of the Top Quark

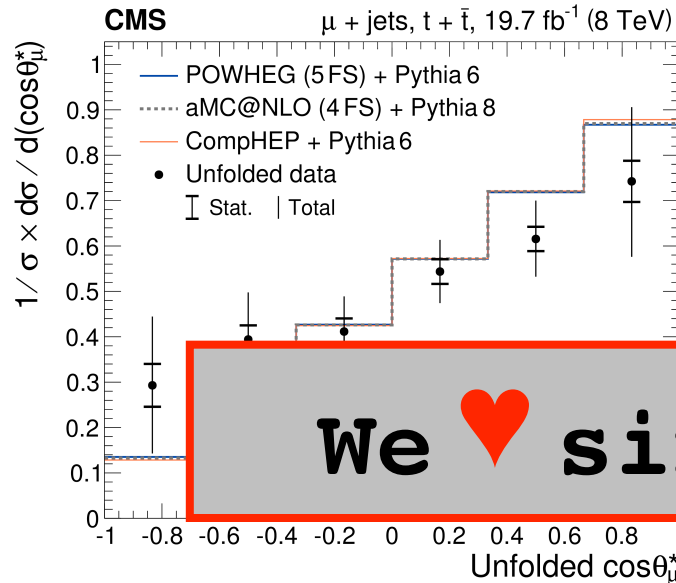


good agreement
between all channels...

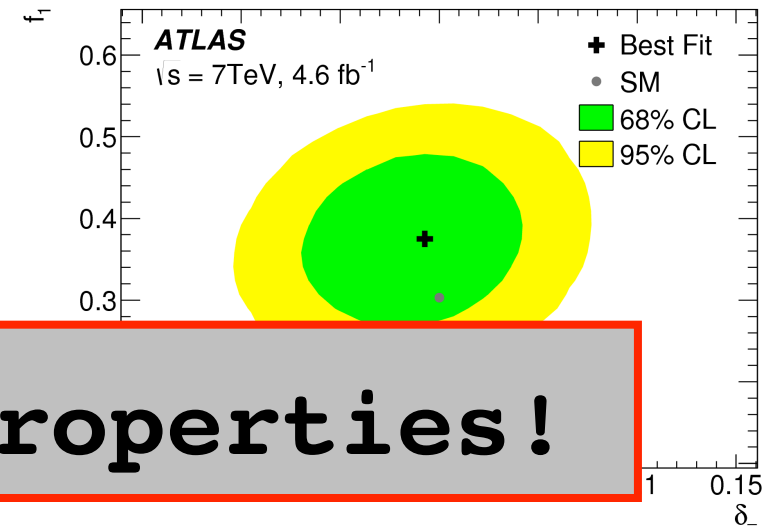
Polarisation and Spin Correlation



→ no chromomagnetic dipole moments



no new
physics

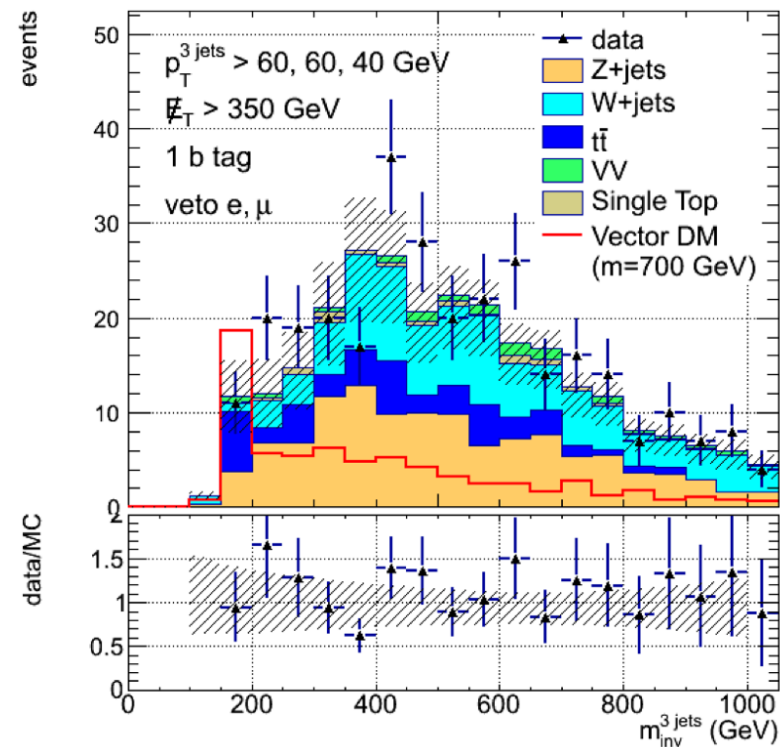
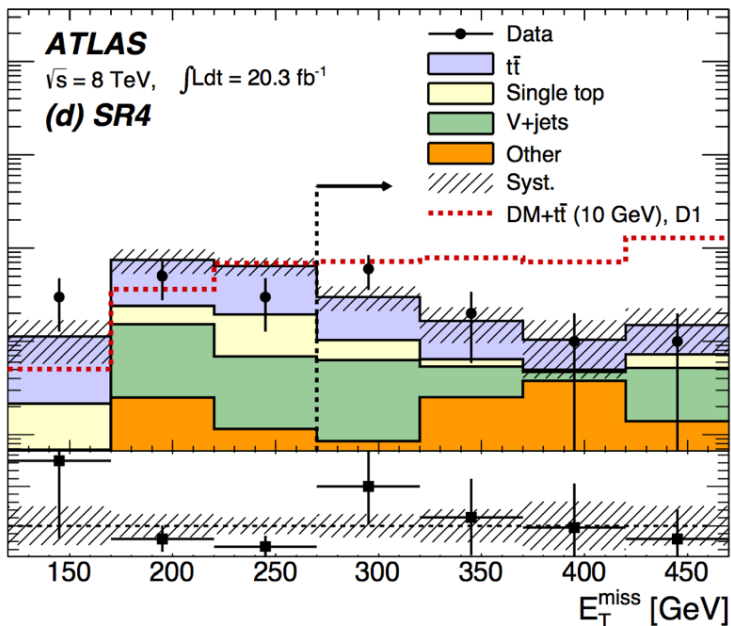
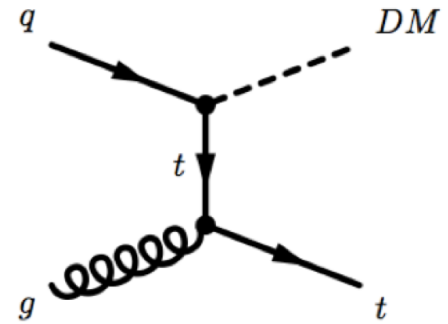
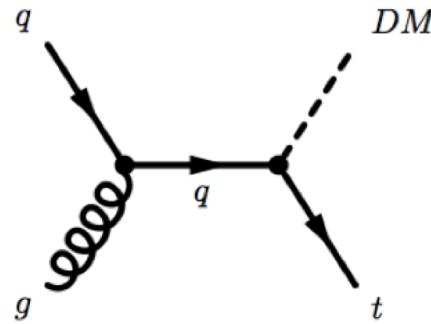
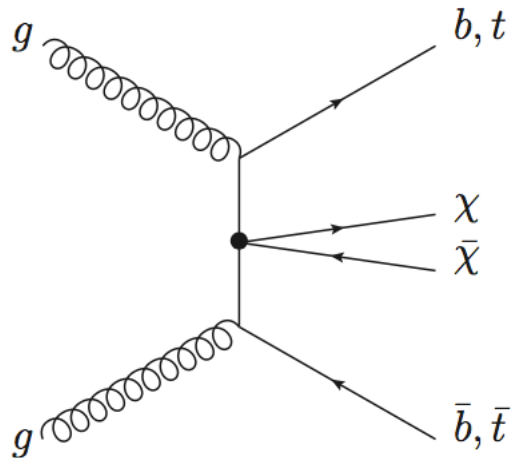


We ♥ single top properties!

→ top quarks polarised as in SM

→ no anomalous couplings

Search for dark matter



→ no hint for dark matter

Summary

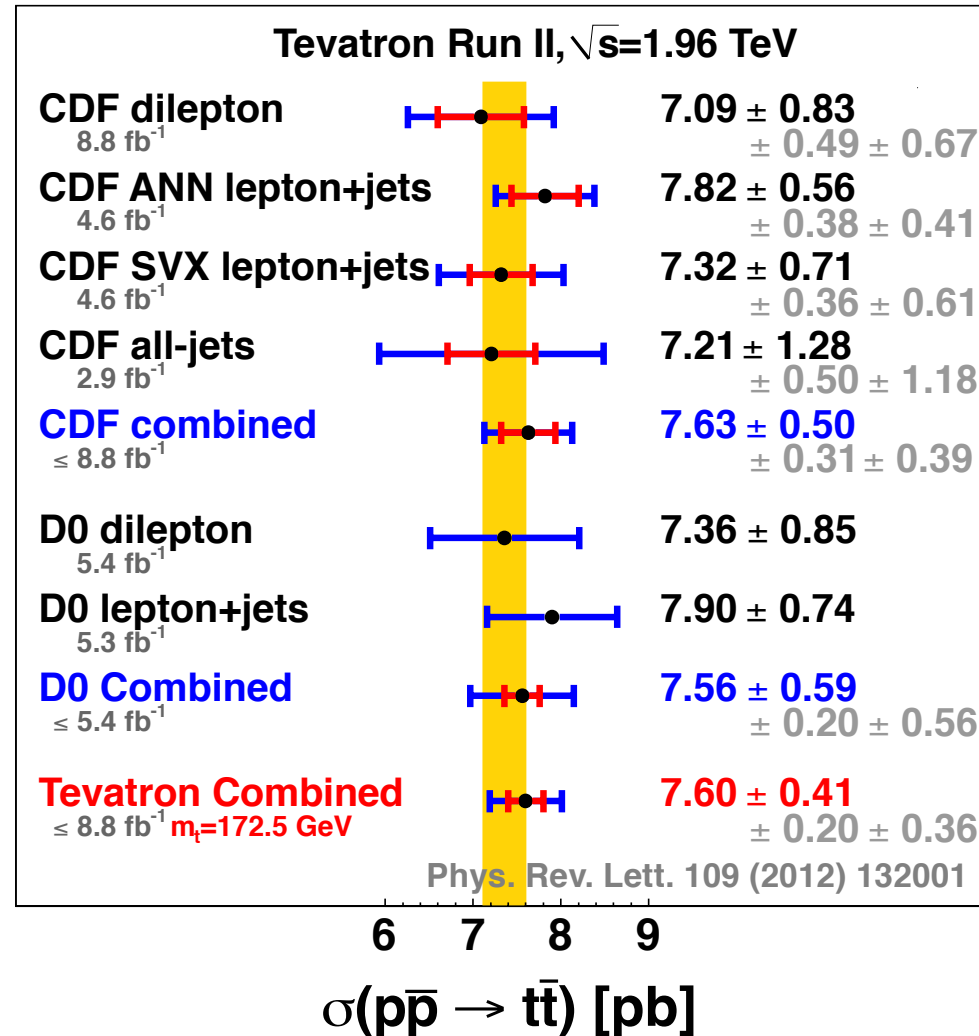


"It is much too early to expect any discovery, we will have to be patient"
CERN DG

Top Pair Production Cross Section



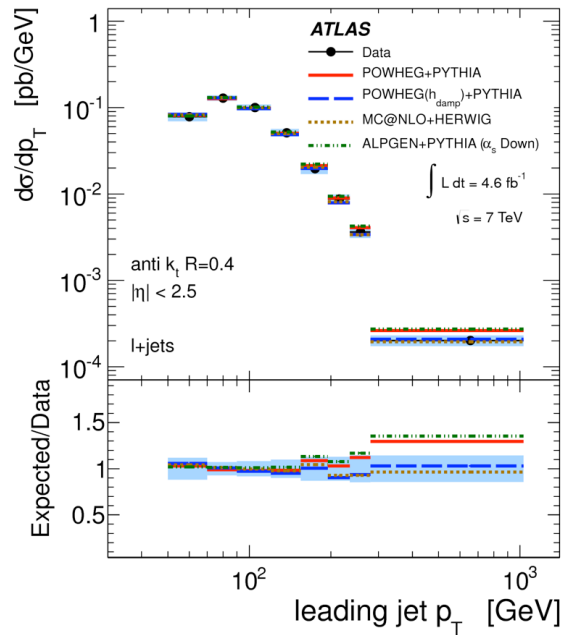
NNLO+NNLL



$\pm 5.4\%$

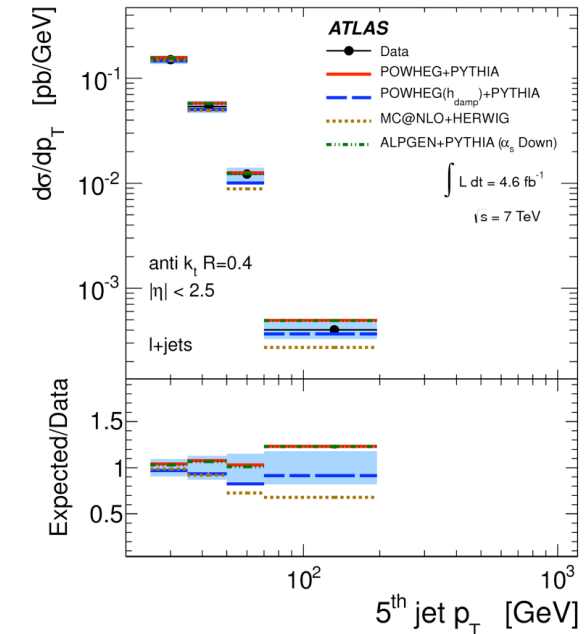
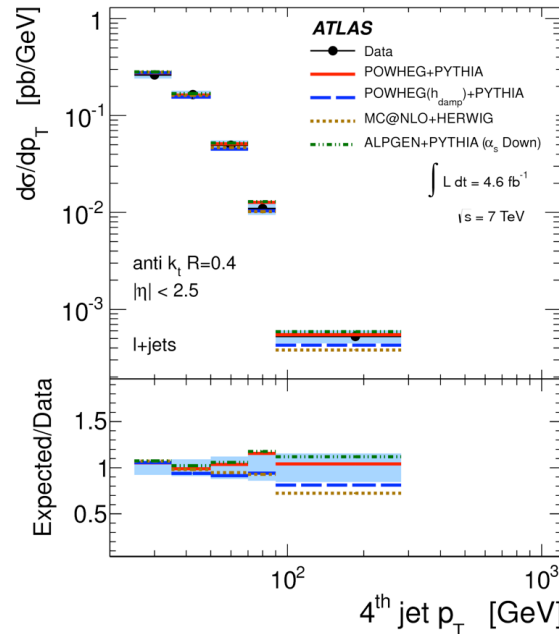
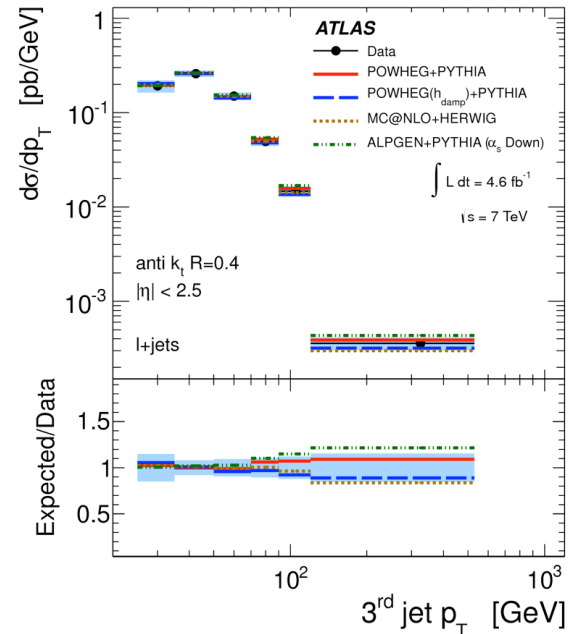
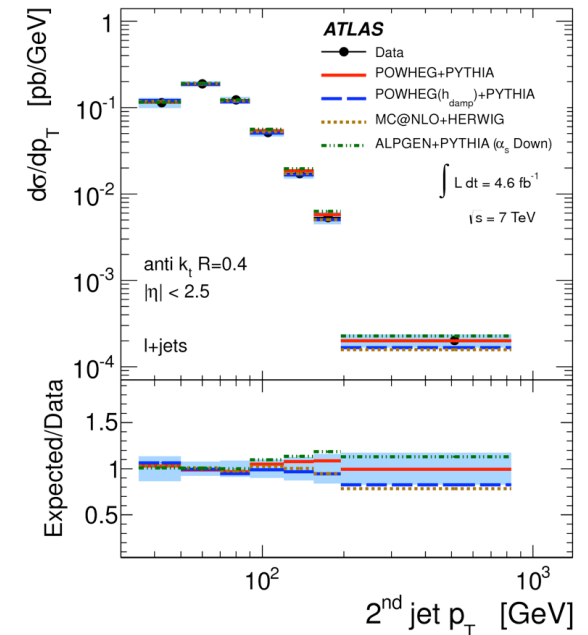
→ good agreement with NNLO+NNLL

Differential (l+jets): jet p_T

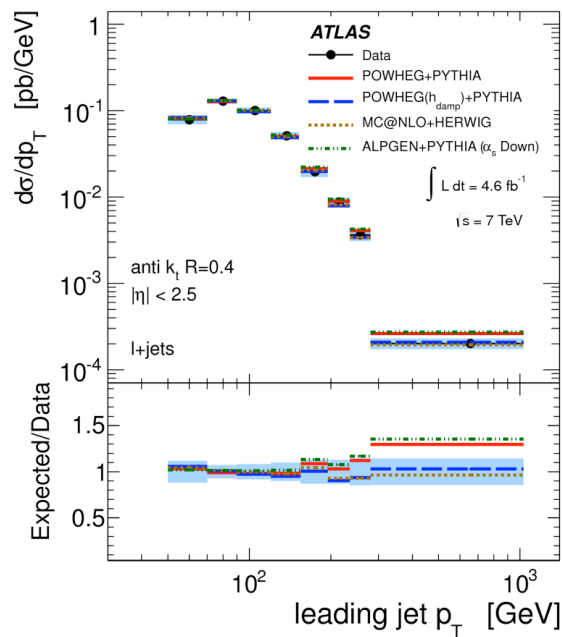


→ NLO MCs
are needed!

← AlpGen+Pythia and
Powheg+Pythia
disfavoured

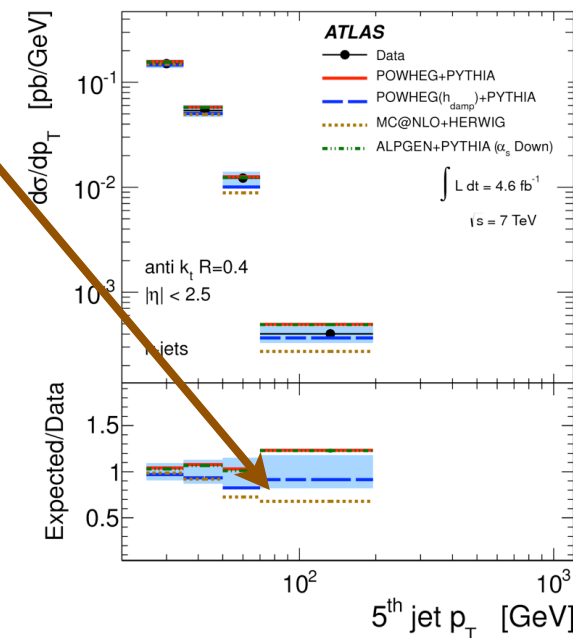
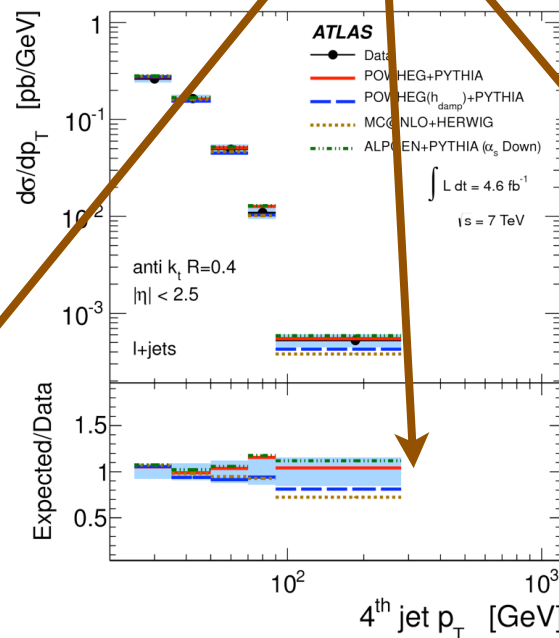
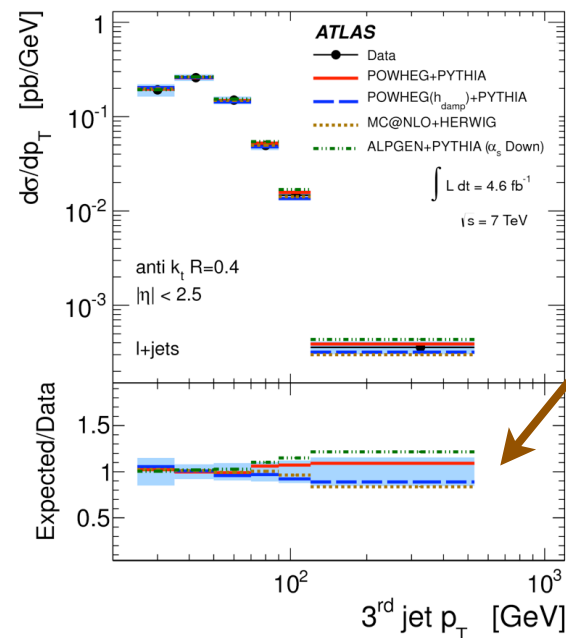
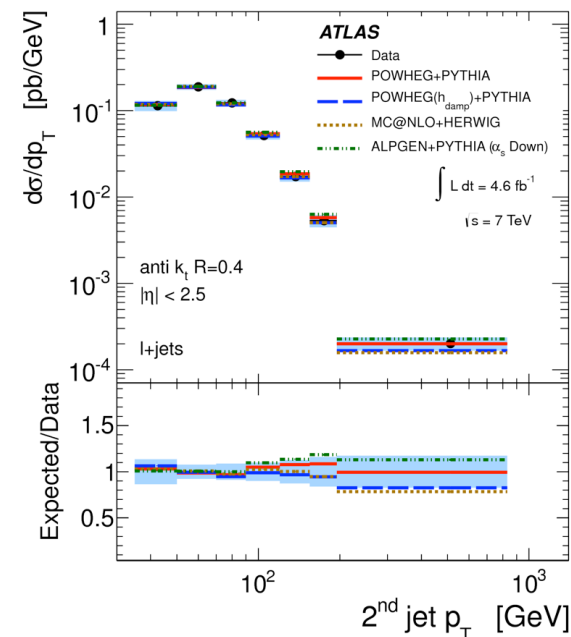


Differential (l+jets): jet p_T

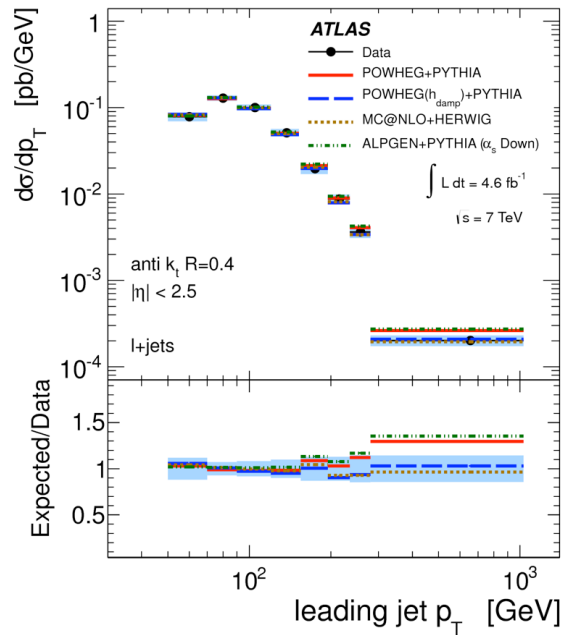


→ multileg MEs are needed!

MC@NLO+Herwig too soft



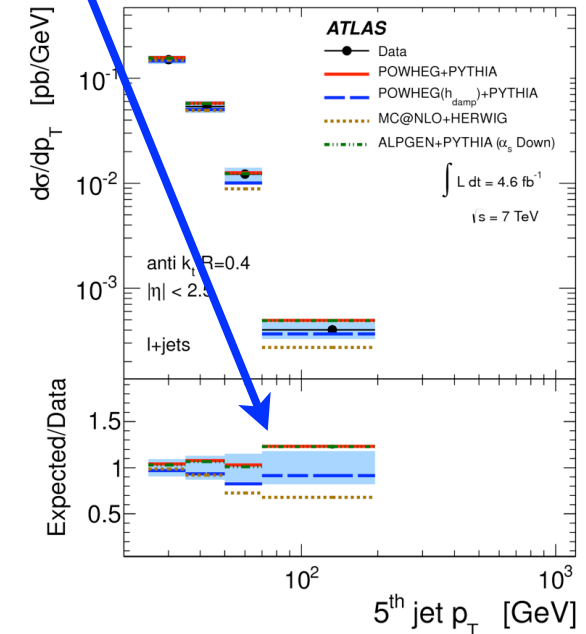
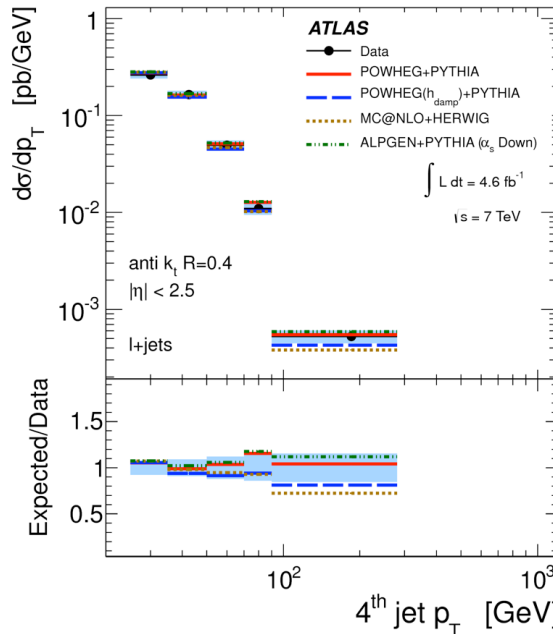
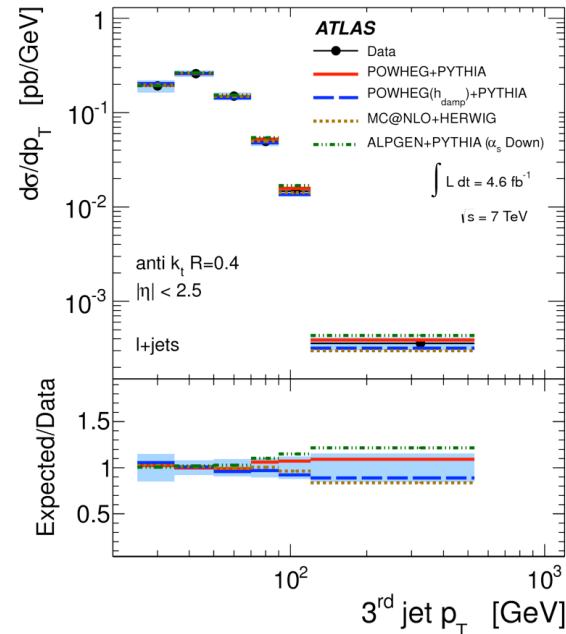
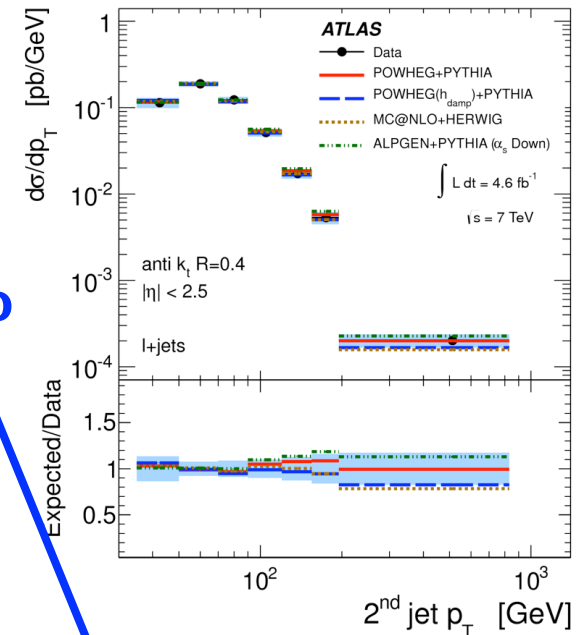
Differential (l+jets): jet p_T



Powheg+Pythia in reasonable agreement

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

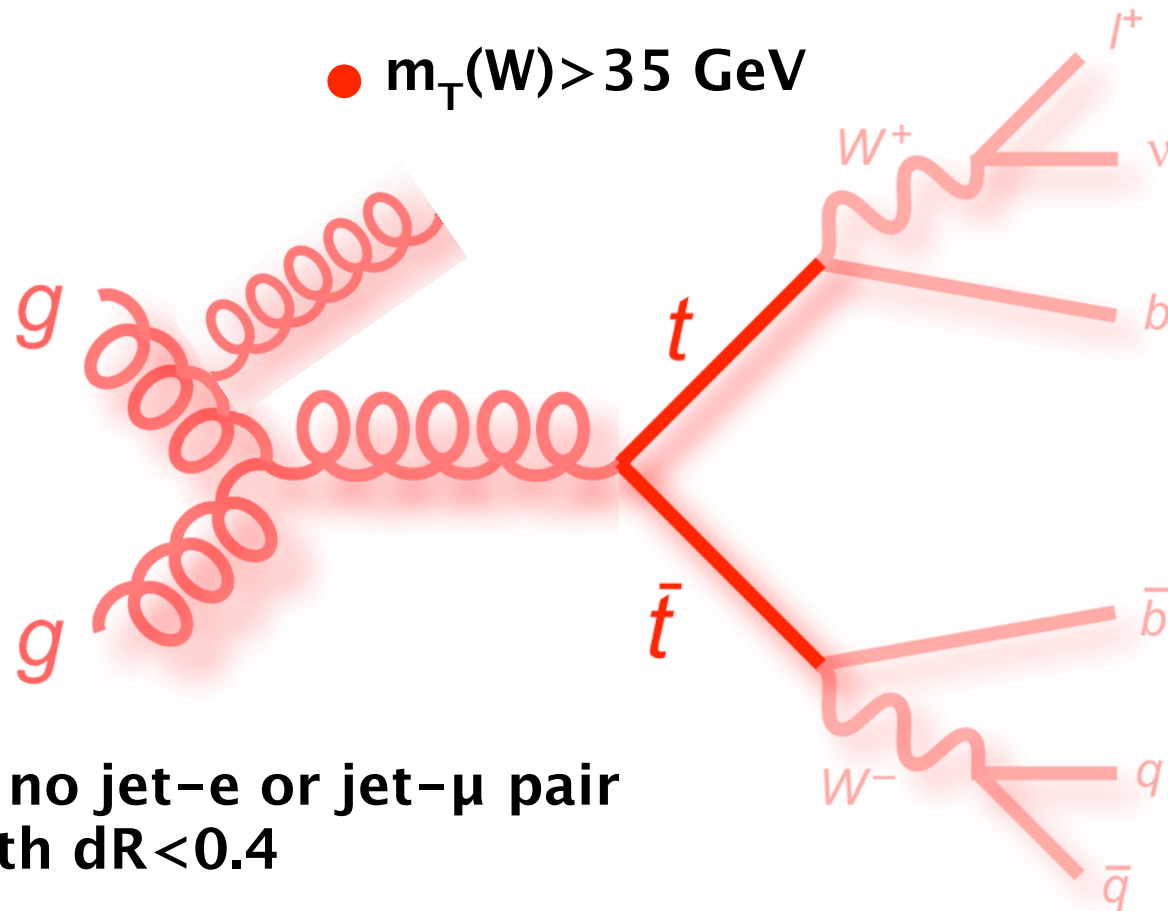
→ **matter of tuning**
($h_{\text{damp}} = m_{\text{top}}$ works best)



Fiducial Kinematic Phase Space

- no additional e or μ with $p_t > 15$ GeV & $|\eta| < 2.5$

- $m_T(W) > 35$ GeV



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

- no jet-jet pair with $dR < 0.5$

- exactly one isolated e or μ with $|\eta| < 2.5$, $p_t > 25$ GeV (including clustering with γ in cone $\Delta R = 0.1$)

- $E_{t,miss} > 30$ GeV

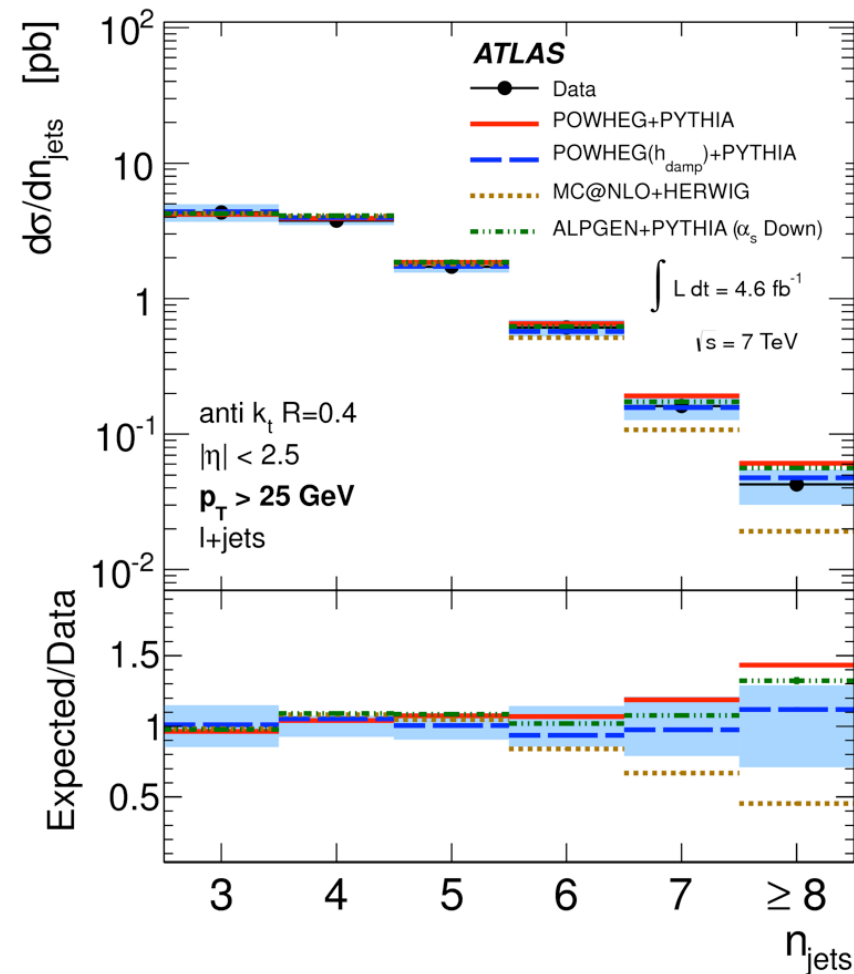
- ≥ 3 Jets with $p_t > 25$ GeV & $|\eta| < 2.5$ incl. ≥ 1 b-tagged jet

- jets: anti- k_t $R = 0.4$, clusters all but prompt particles (i.e. e, μ , ν from hadronic decays are inside jets)

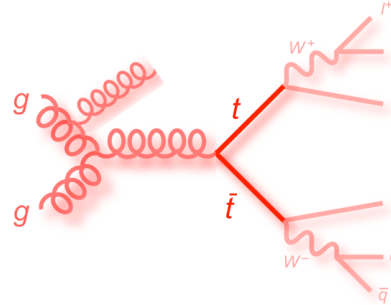
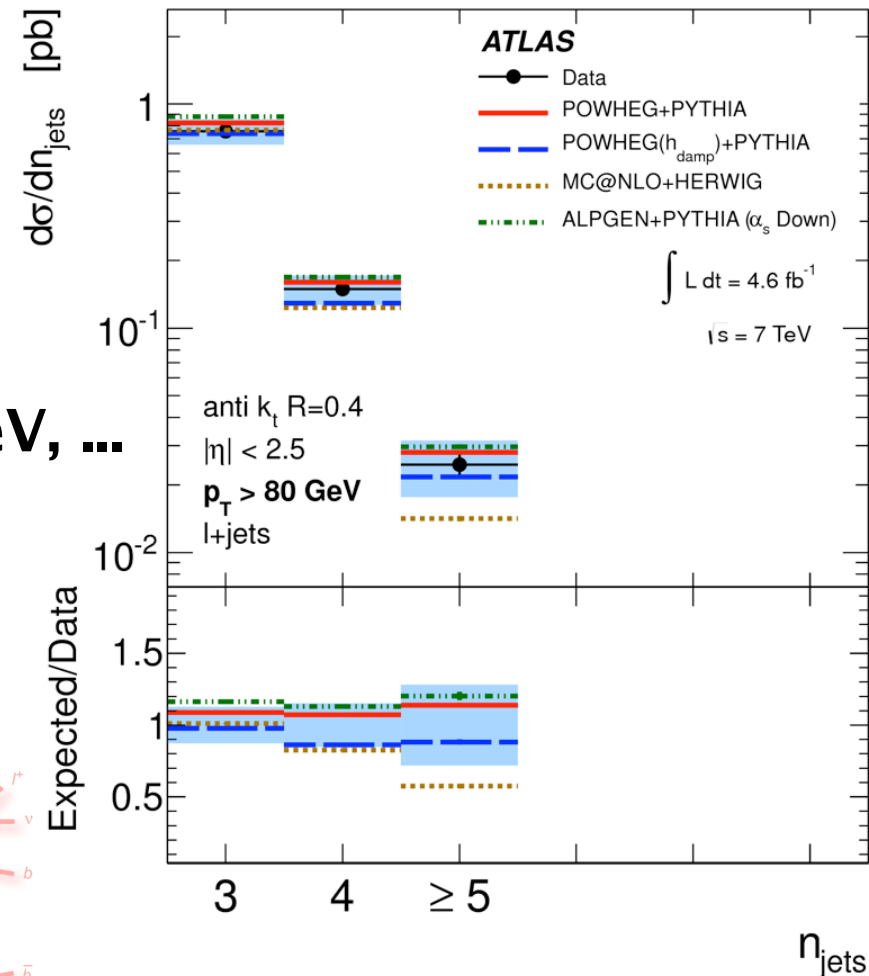
- background subtraction
- corrections to particle level
- reduced dependence on MC model

Jet Multiplicities

- uncertainties dominated by JES and MC modeling of QCD radiation



... 40, 60 GeV, ...

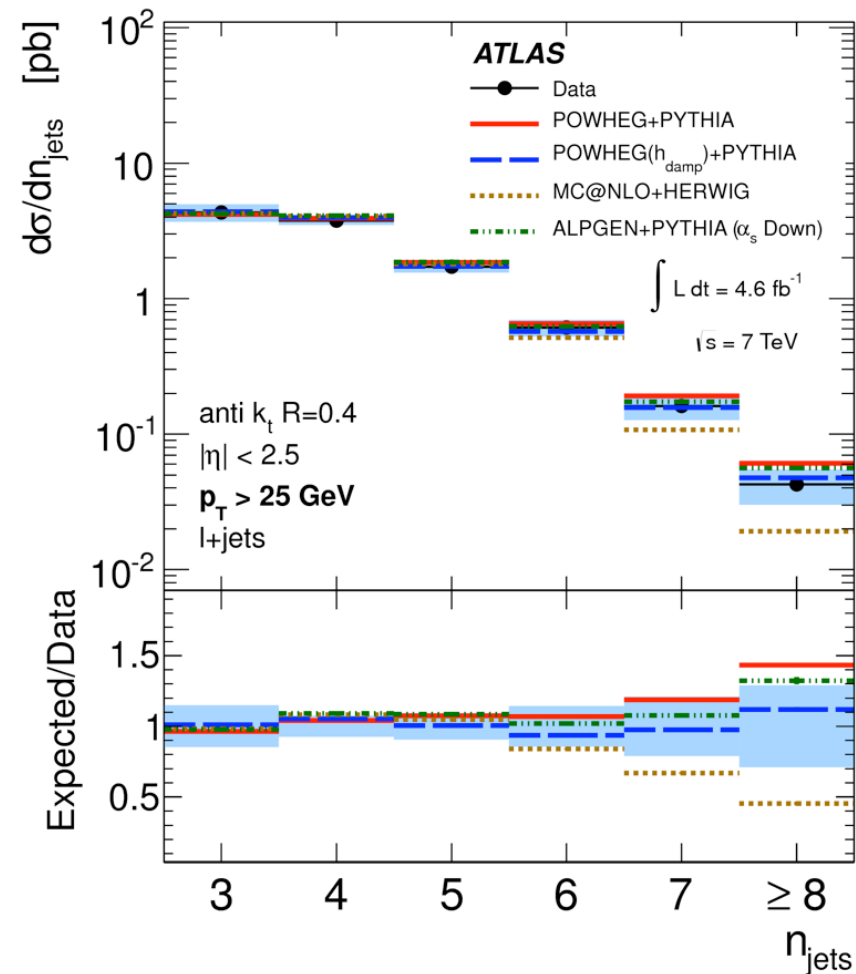


JHEP 1501, 020 (2015)

→ high sensitivity on higher order QCD modeling of MC generators

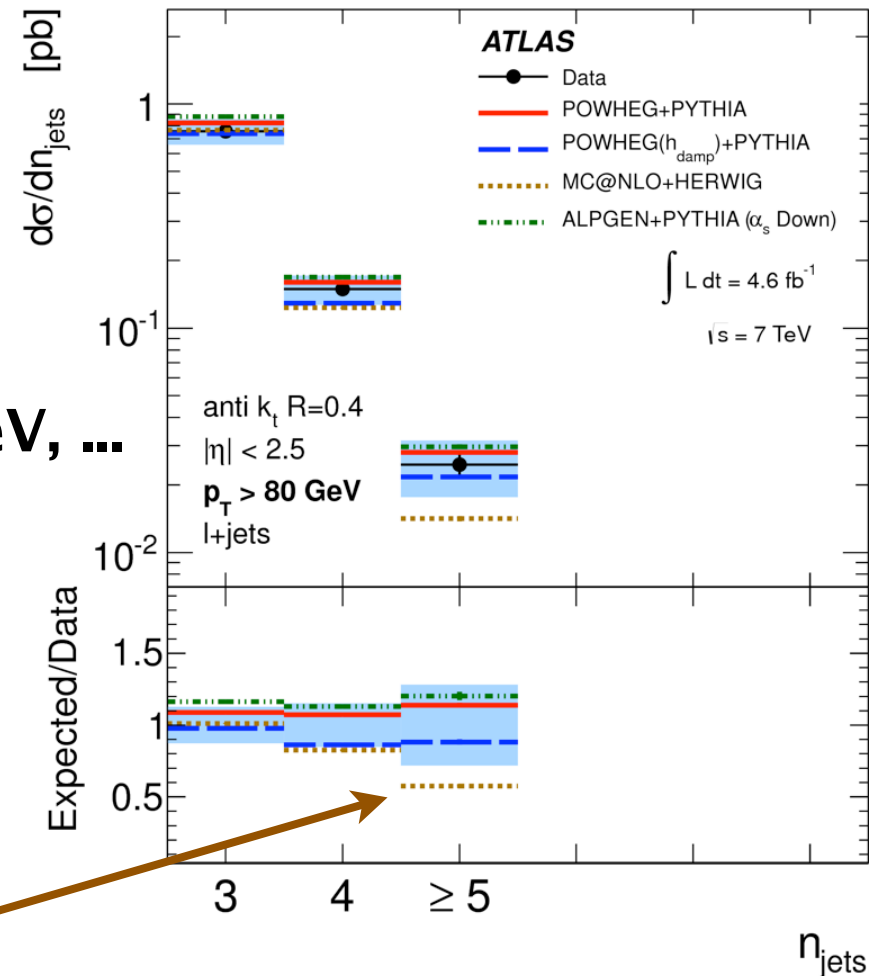
Jet Multiplicities

- Uncertainties dominated by JES and MC modeling of QCD radiation



ALPGEN+Pythia ok

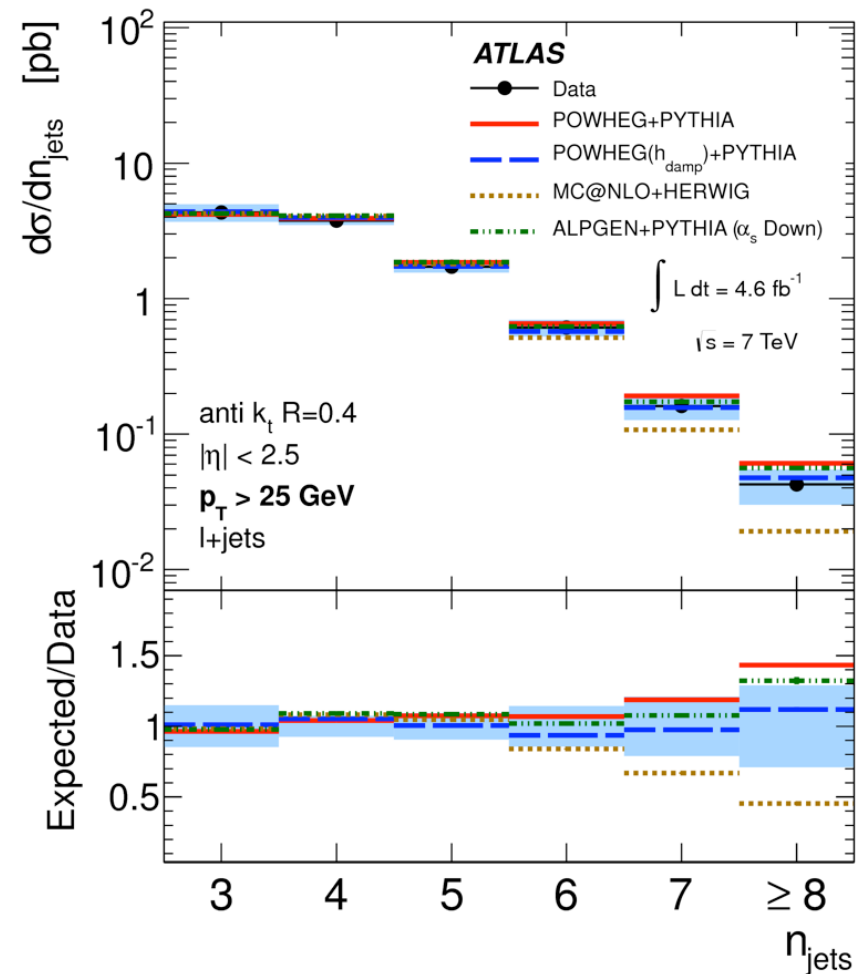
... 40, 60 GeV, ...



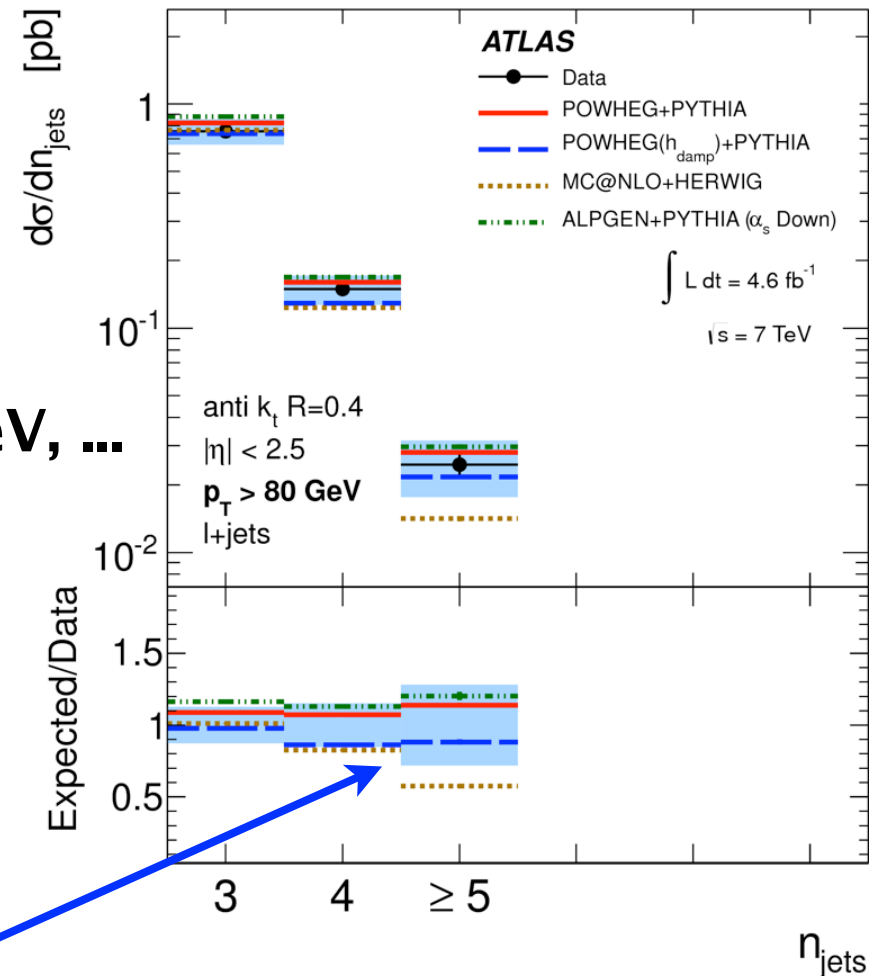
MC@NLO+Herwig
 disfavoured (since those come
 mostly from parton showers)

Jet Multiplicities

- Uncertainties dominated by JES and MC modeling of QCD radiation

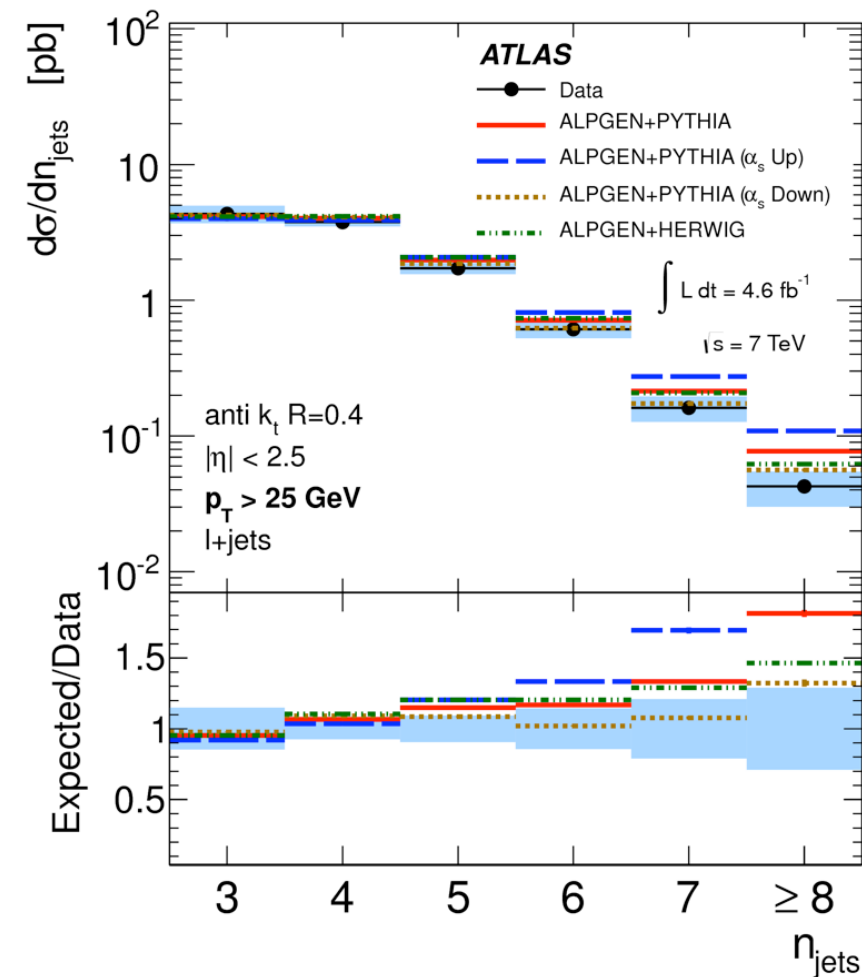


... 40, 60 GeV, ...

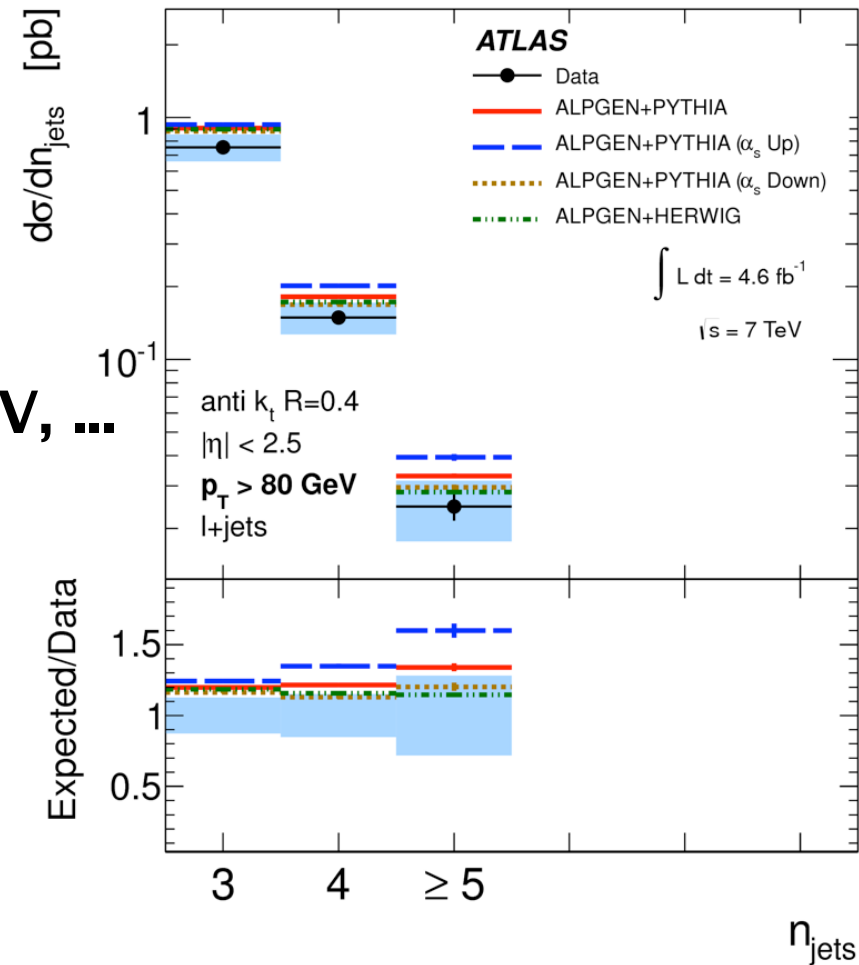


Powheg+Pythia with damping of the hardest emissions is best (high n_{jets} still get large contributions from the matrix element)

Strong Coupling and Parton Showers



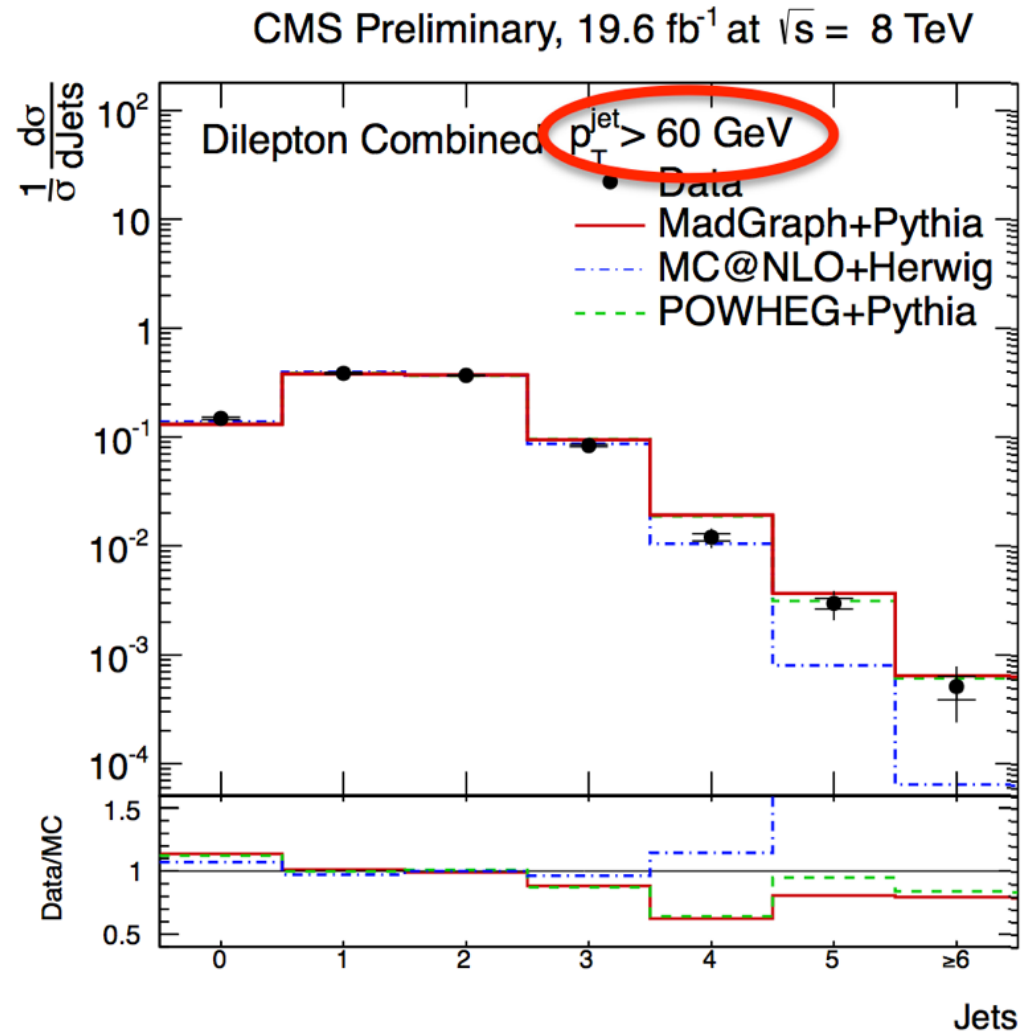
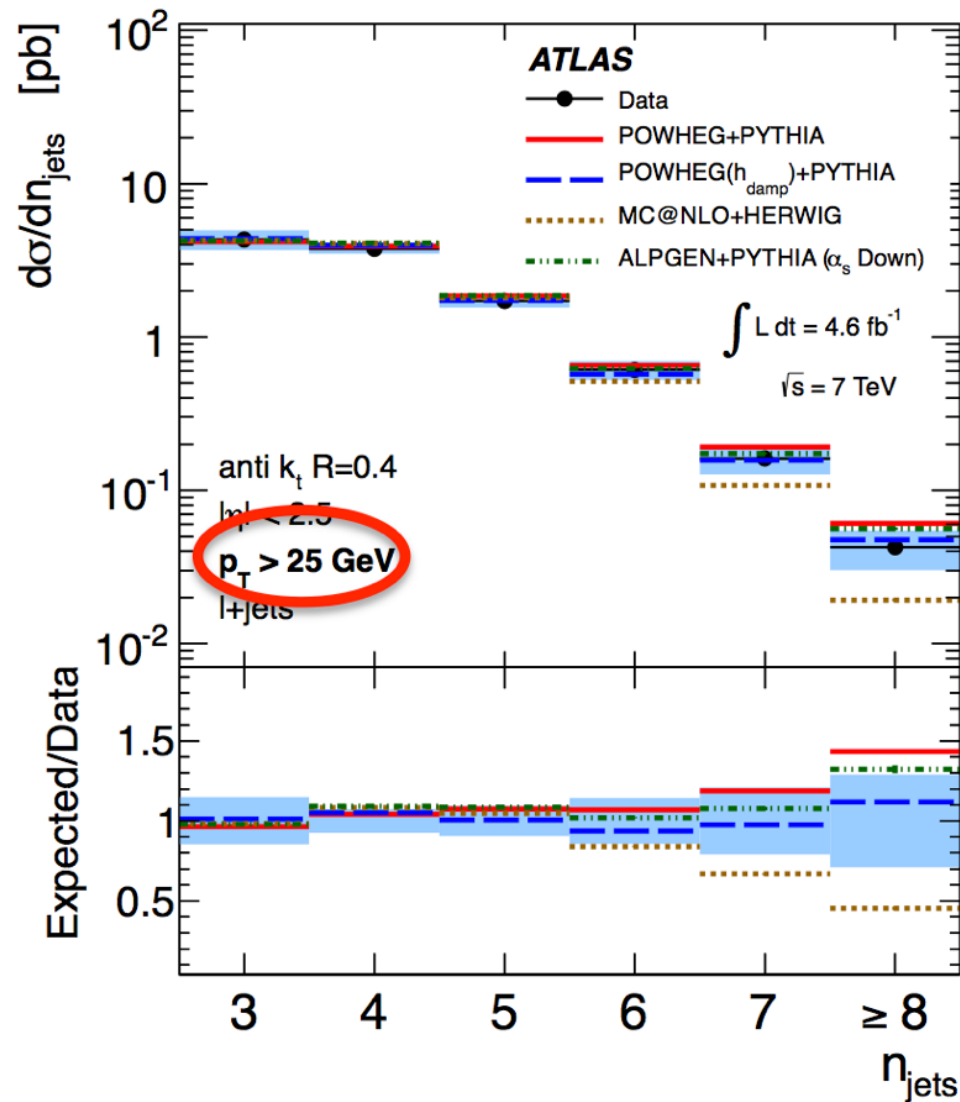
... 40, 60 GeV, ...



- 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

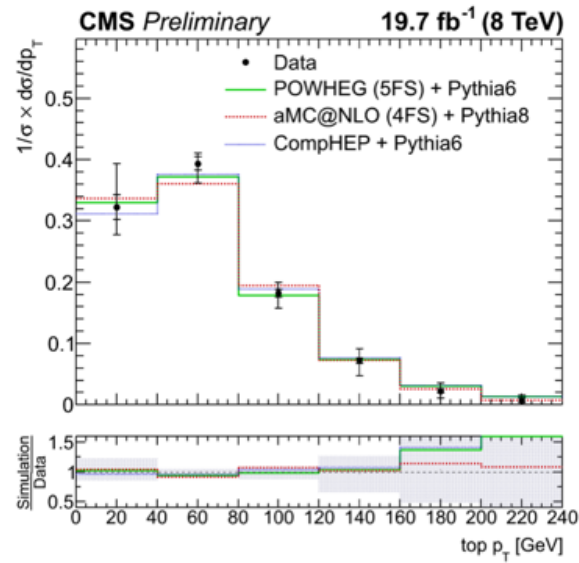
Differential: jet multiplicities

J. Katzy

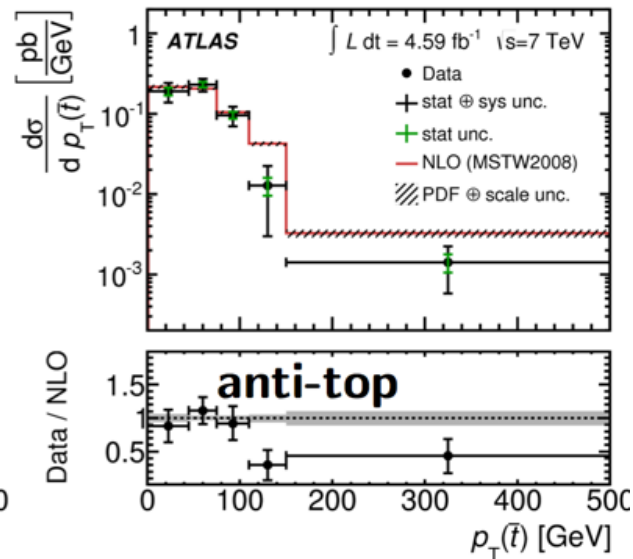
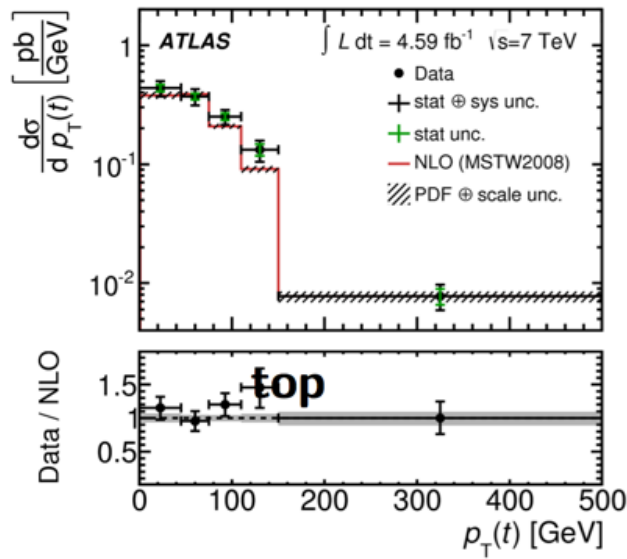


→ large differences between generators: helps to improve

Differential single top: top p_T



8 TeV



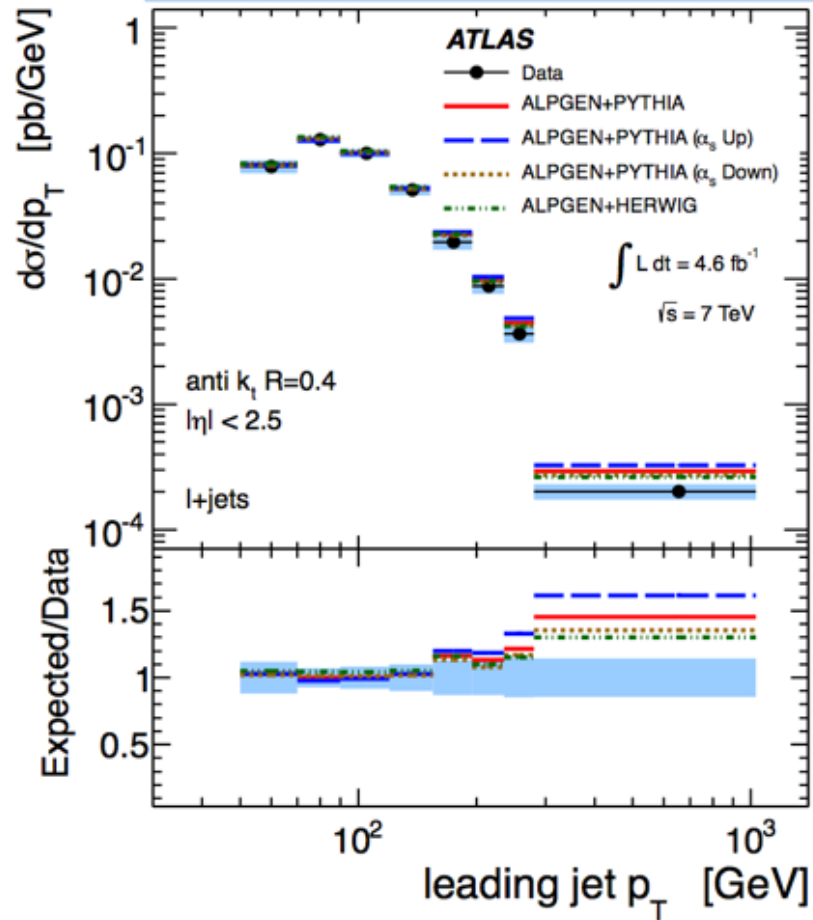
7 TeV

→ **good description**

Top decay products: pseudo-top

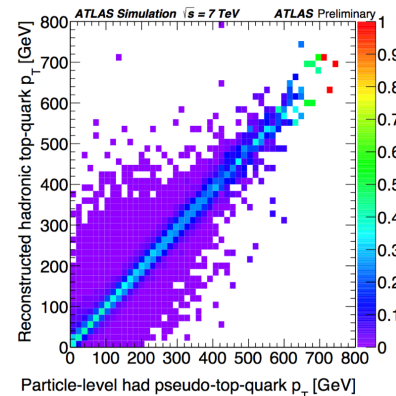
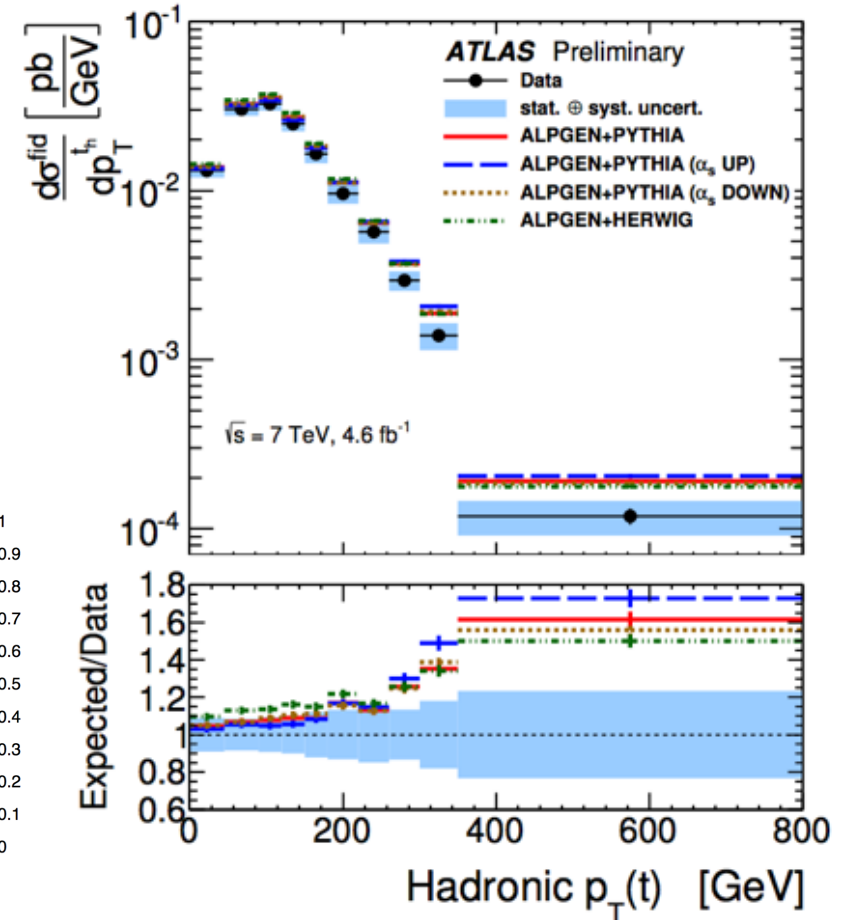
Fiducial phase space:

≥ 1 b-jet, 1 lepton, ≥ 3 jets,
1st jet $p_T > 50$ GeV, 2nd jet $p_T > 35$ GeV



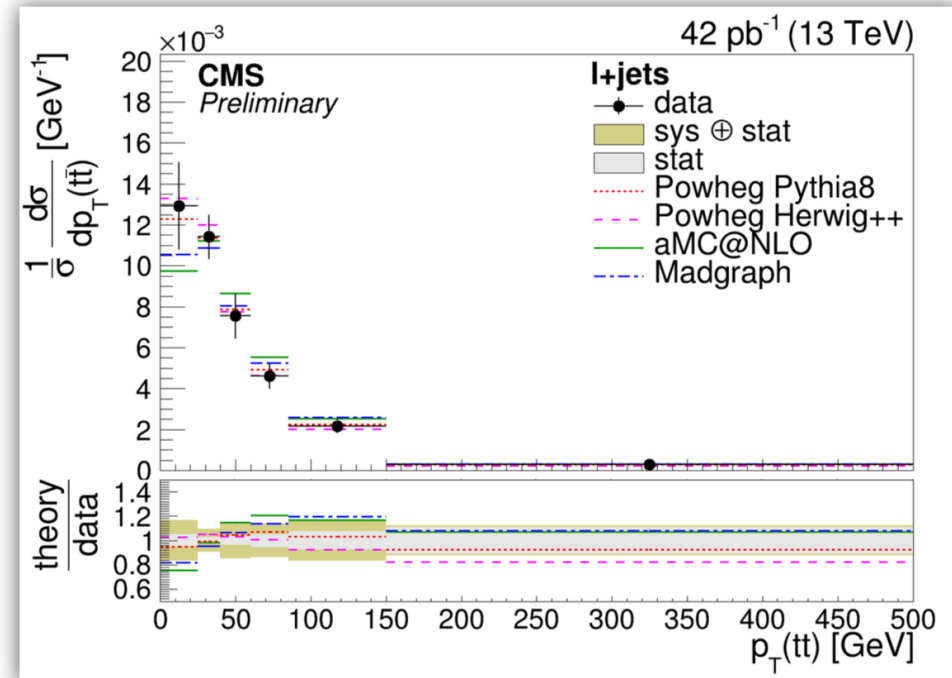
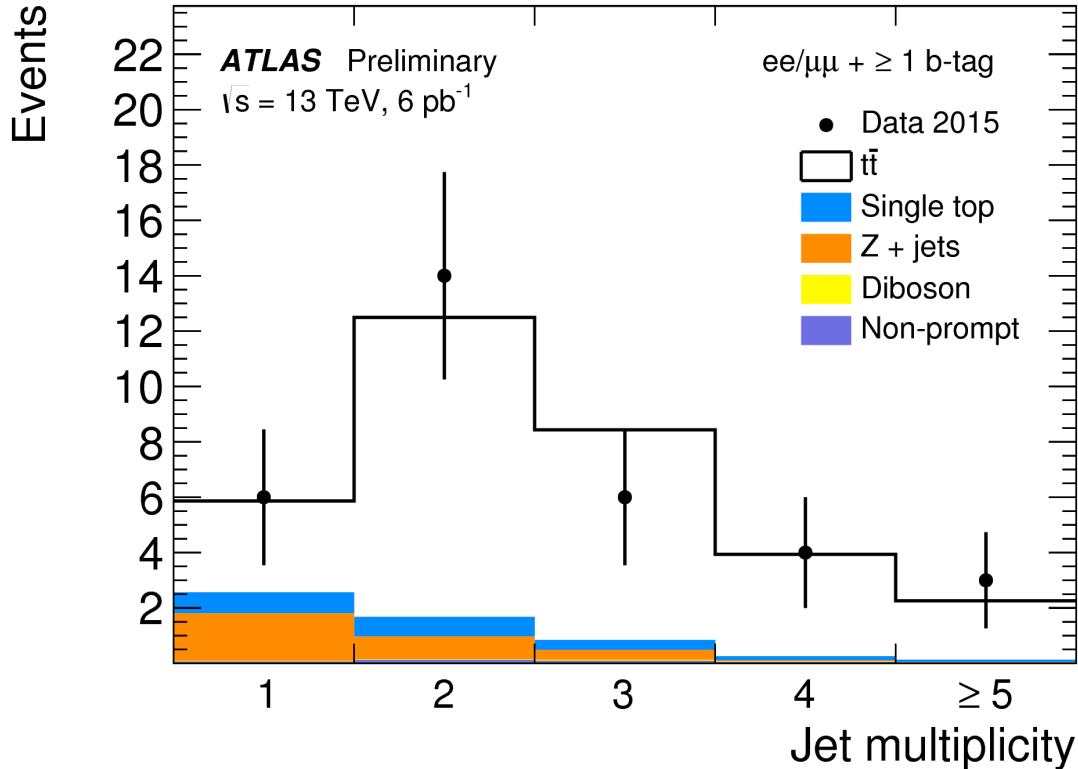
Fiducial phase space:

2 b-jets, 1 lepton, ≥ 4 jets



→ reconstruct tops on particle level
→ very valuable for theorists today and in future

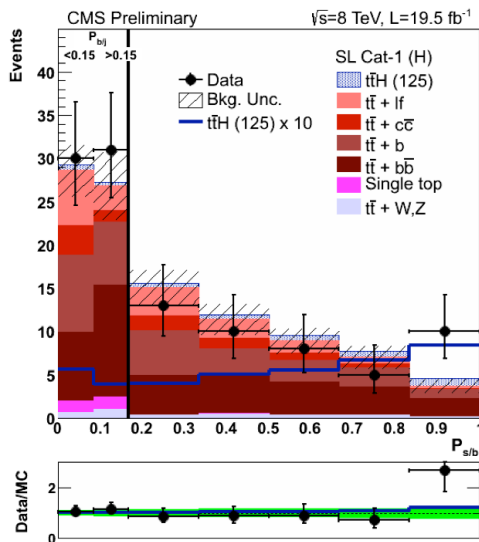
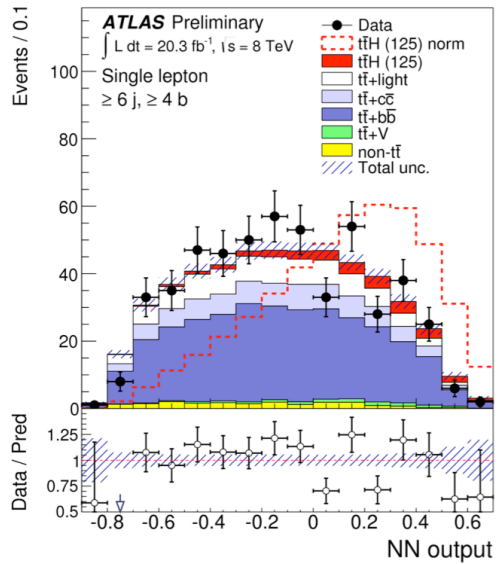
Differential: top pair p_T



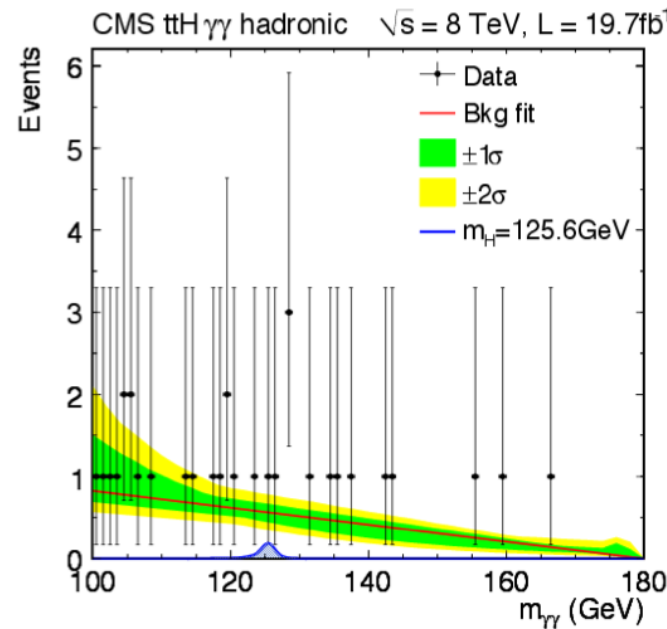
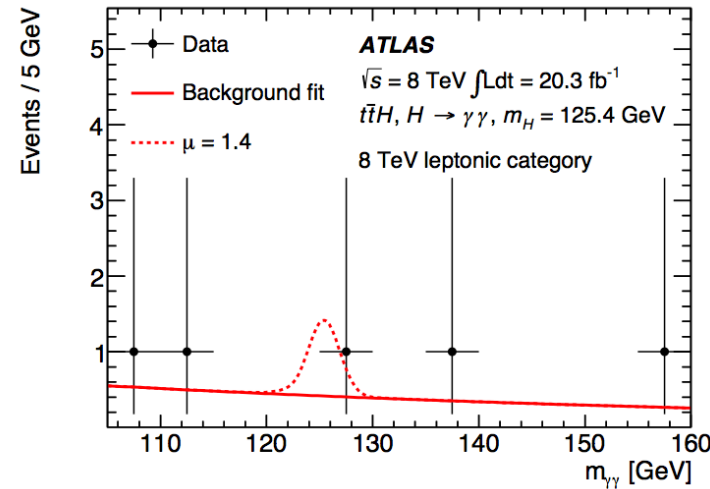
→ good agreement with new MC tools so far, but low statistics still

Search for ttH production

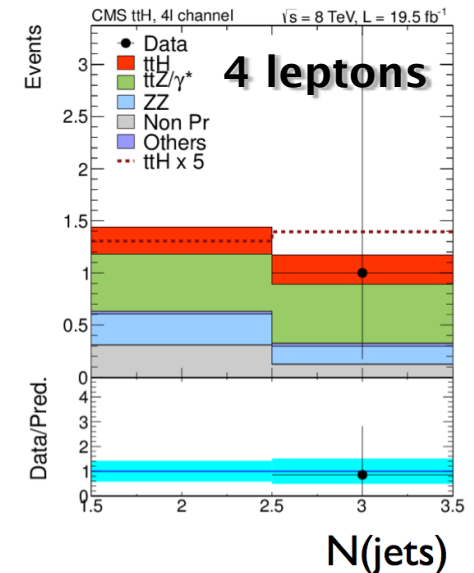
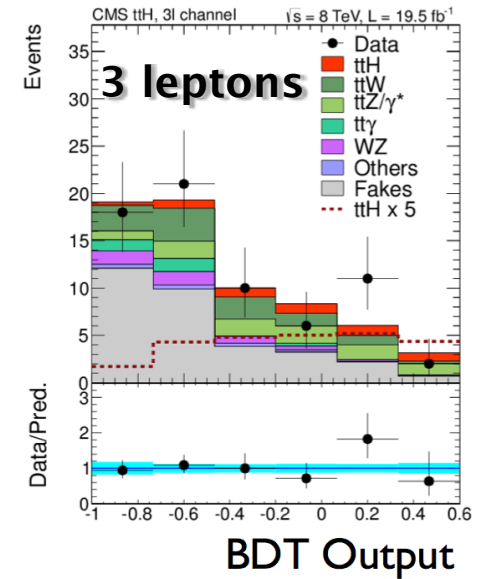
H → bb



H → γγ

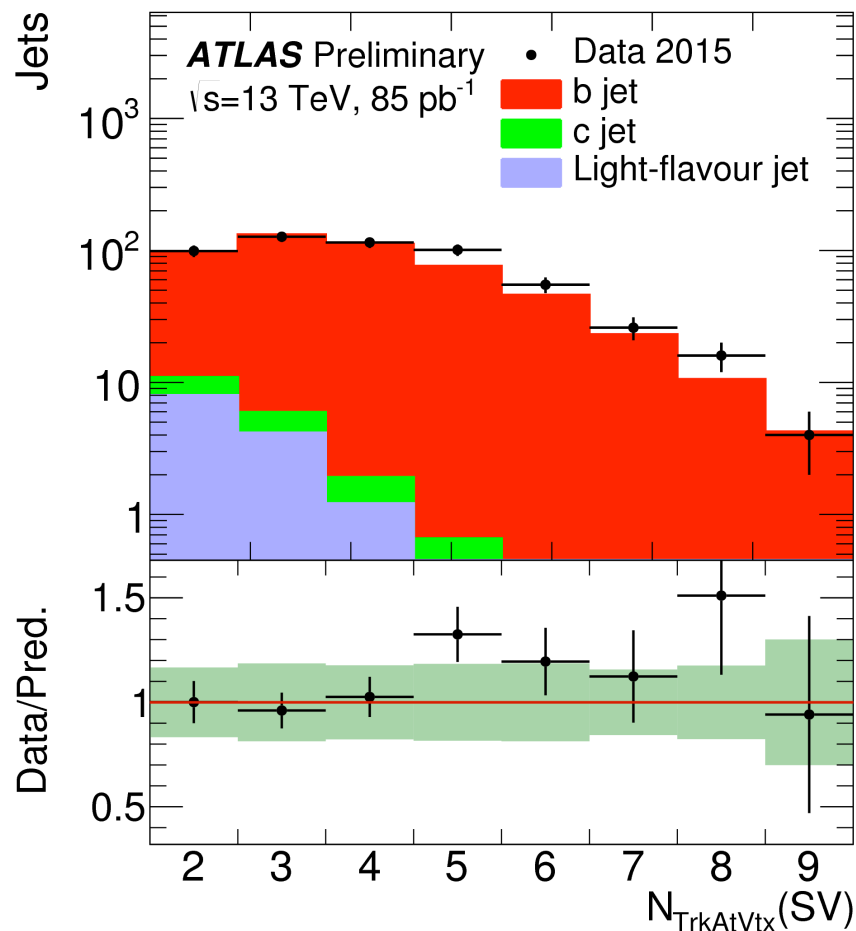


H → WW, ZZ



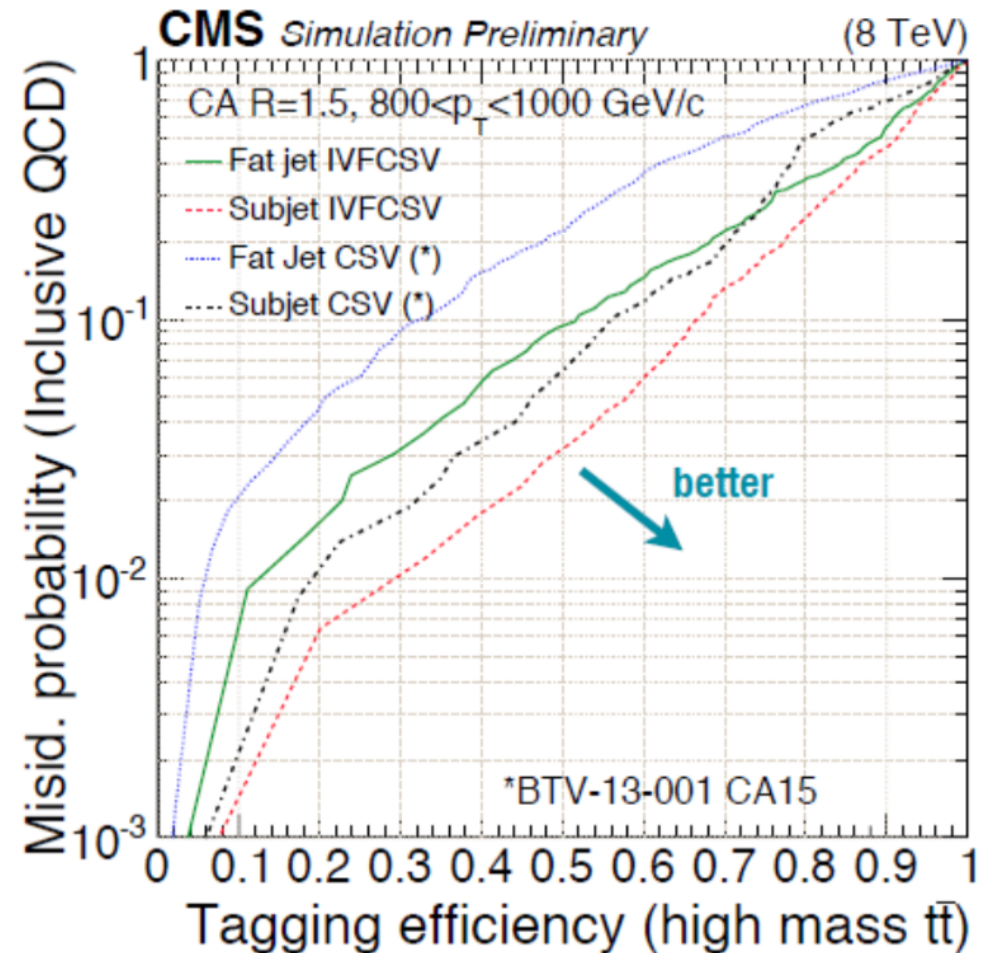
Tools from and for tops

b-tagging from top pairs ($e\mu$)



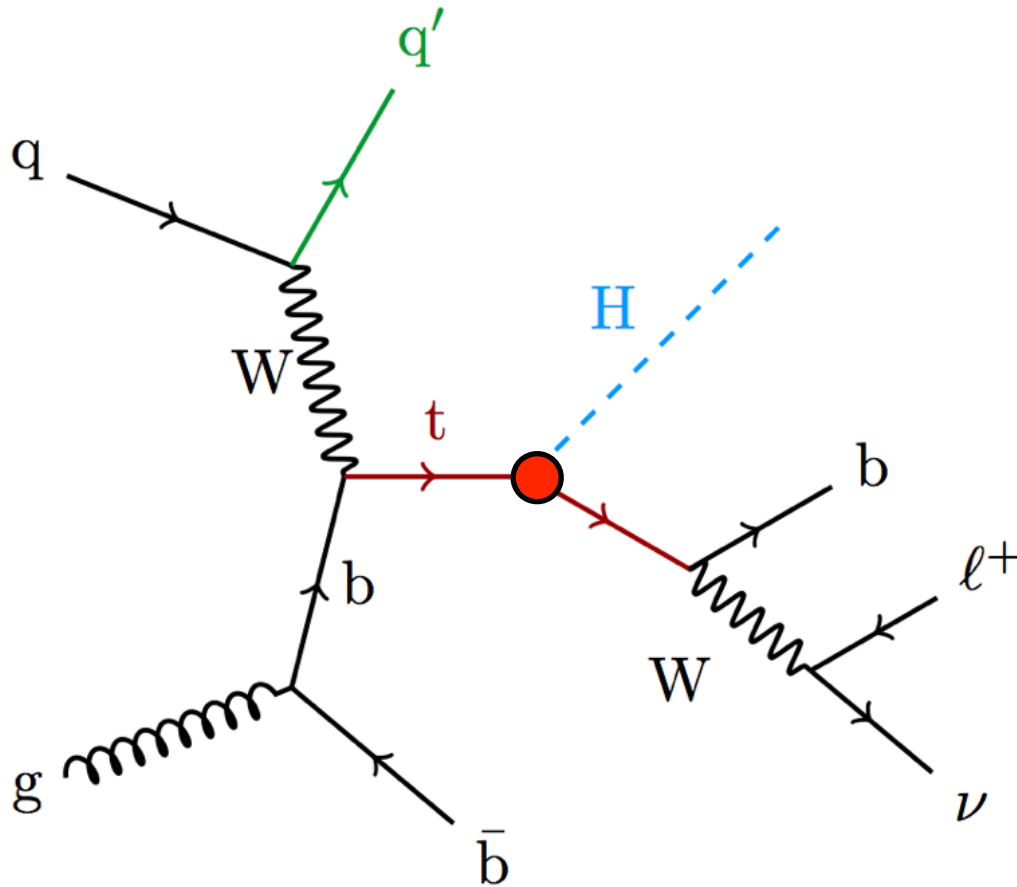
→ great importance for all types of physics

t-tagging in boosted topologies



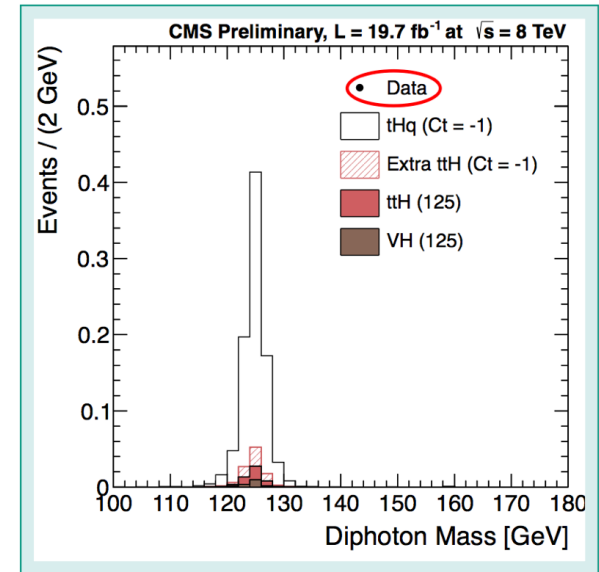
→ huge improvements

Search for tHq production

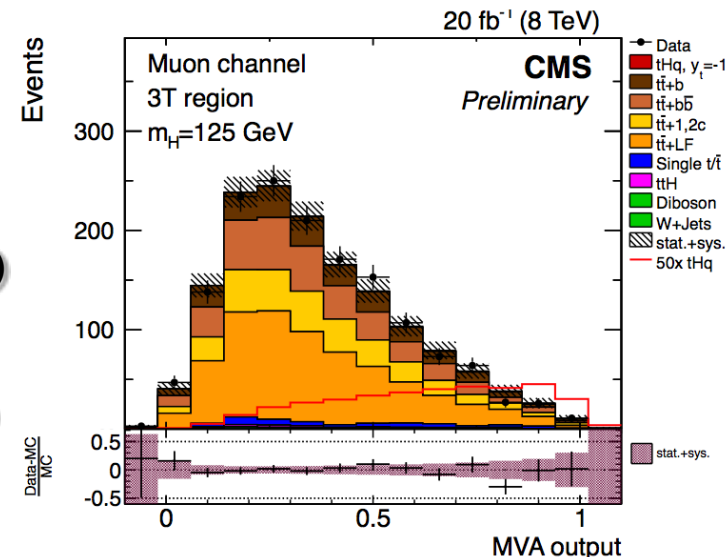


in case top Yukawa coupling
 $\kappa_t = y_t / y_t^{\text{SM}} = -1$ coupling: cross
 section can be enhanced by
factor 13

$H \rightarrow \gamma\gamma$
 $4.1 \times \sigma / \sigma(\kappa_t)$
expected

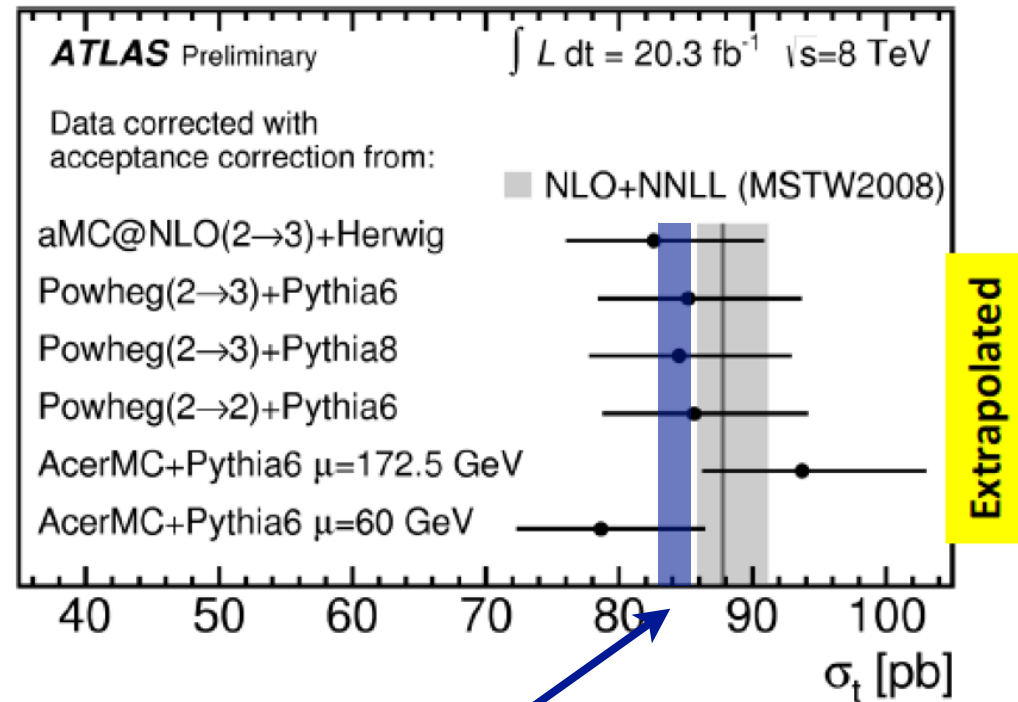
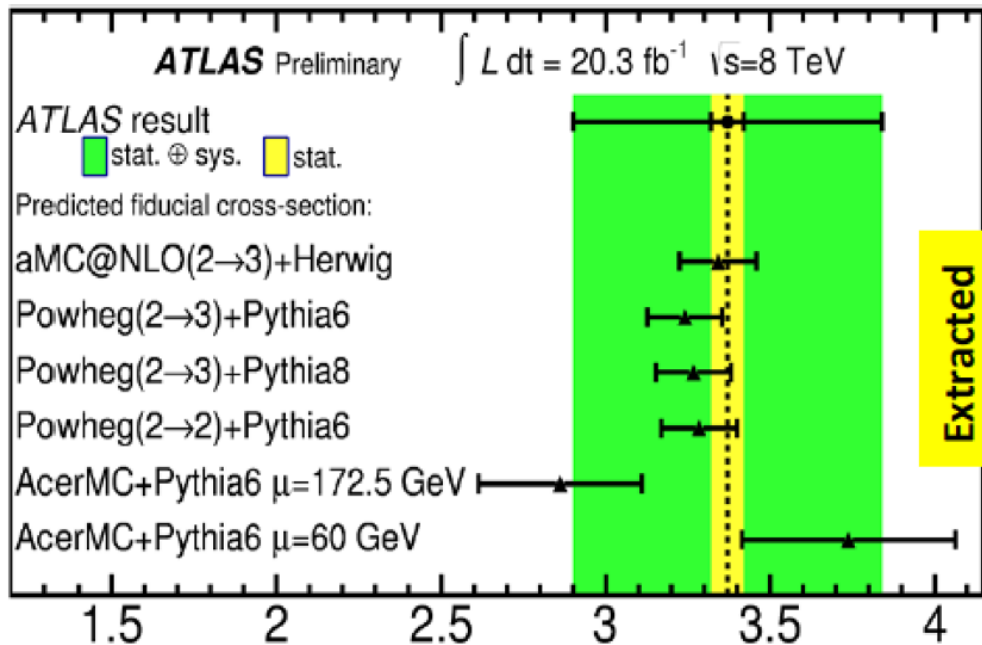


$H \rightarrow b\bar{b}$
 $5.1 \times \sigma / \sigma(\kappa_t)$
 $7.6 \times \sigma / \sigma(\kappa_t)$
observed

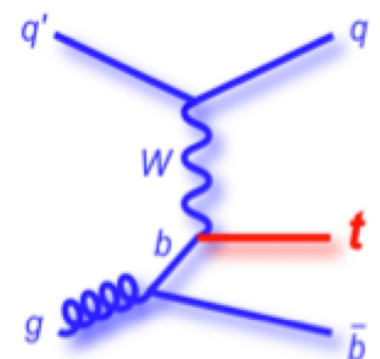


→ fun in Run-II

Fiducial t-channel cross section

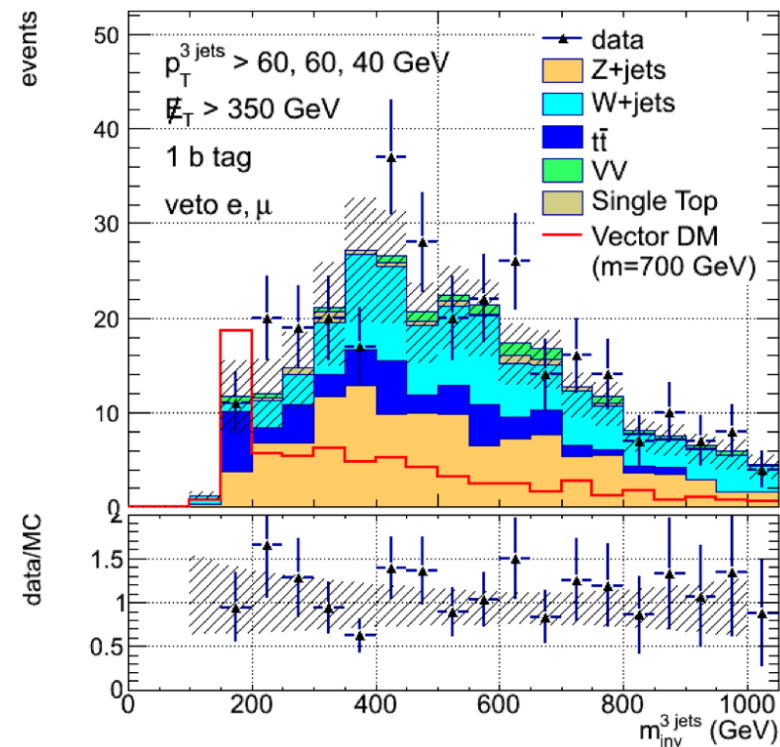
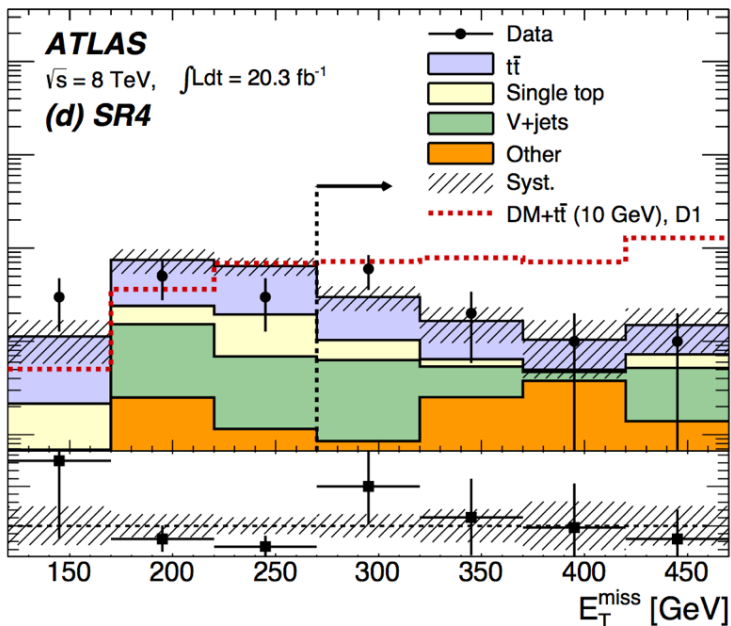
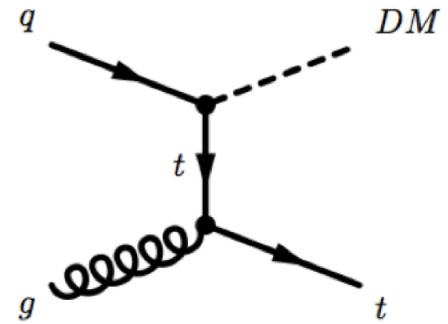
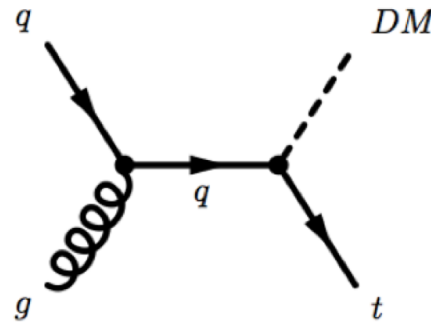
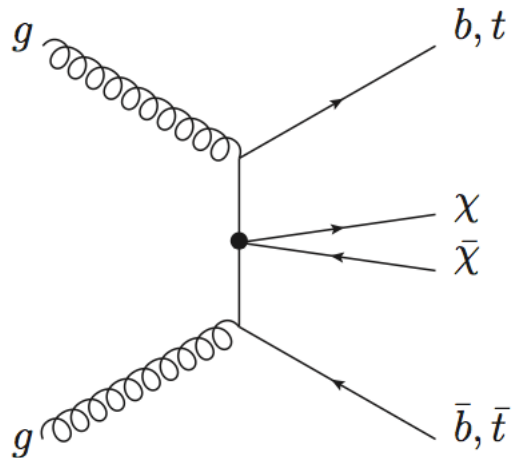


NNLO



→ good agreement with SM predictions

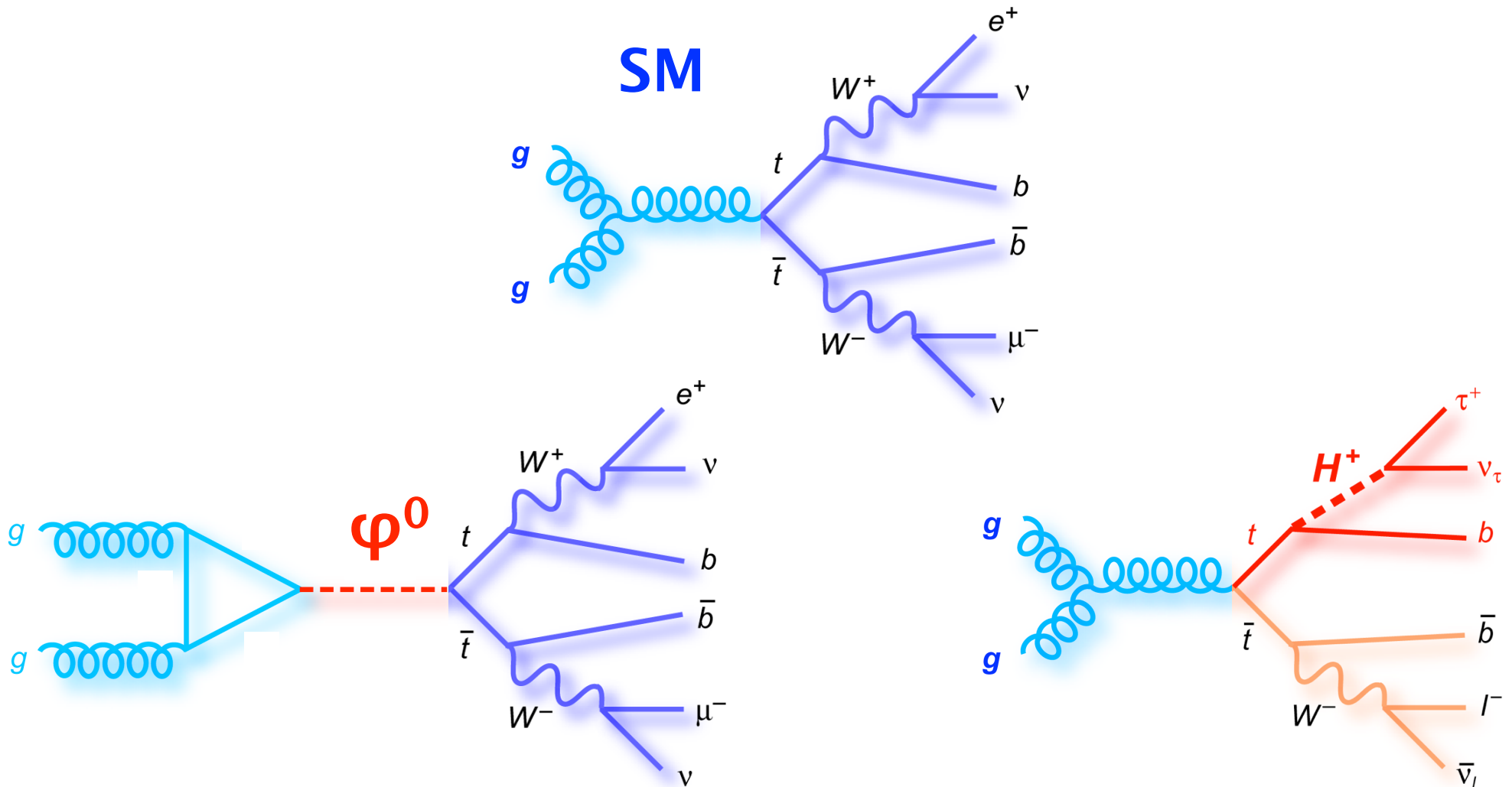
Search for dark matter



→ 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



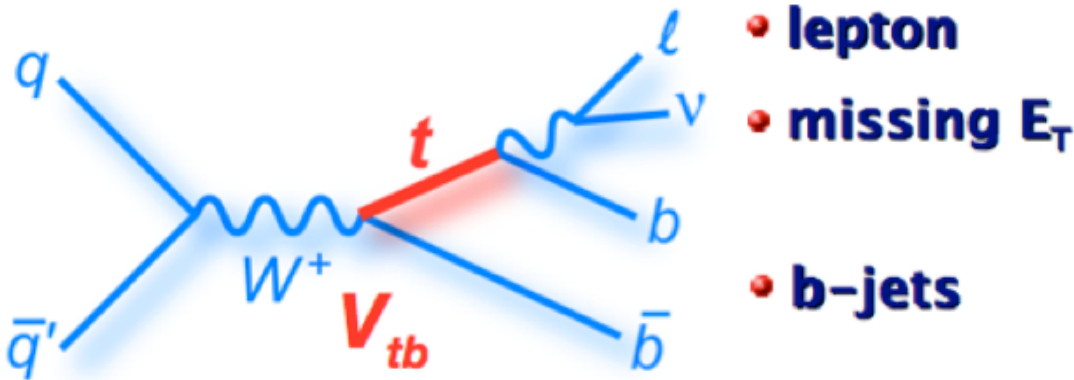
Higgs, KK gravitons, Z' , stop pairs, ...

charged Higgs, b' , ...

Single Top Quark Selection

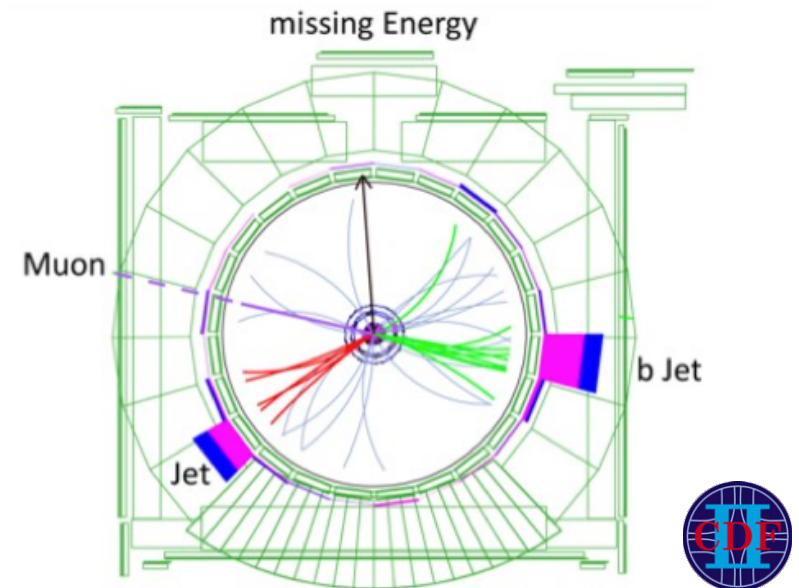
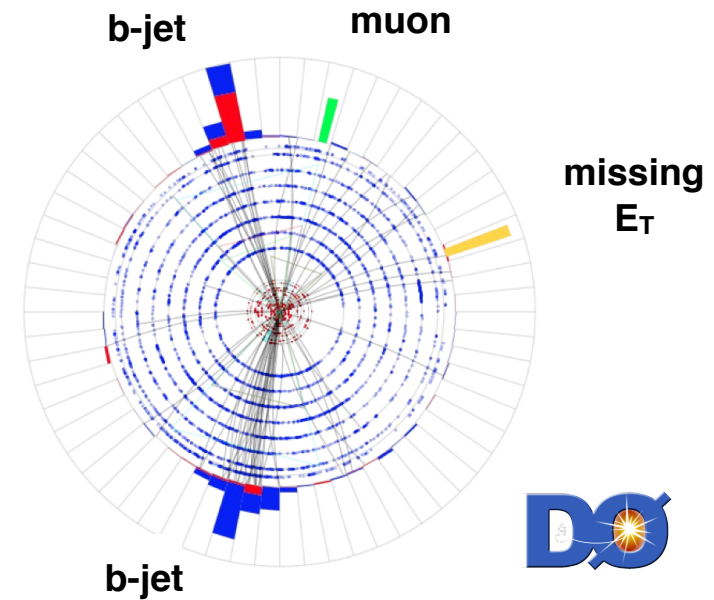
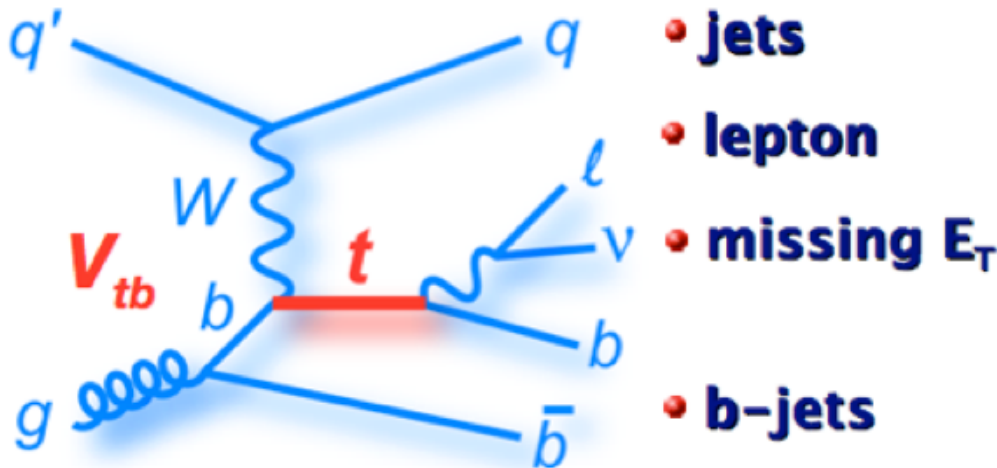
s-channel:

$\sigma_s = 1.05 \pm 0.06 \text{ pb}$
 NLO+NNLL, $m_t = 172.5 \text{ GeV}$
 Kidonakis, PRD 81, 054028 (2010)



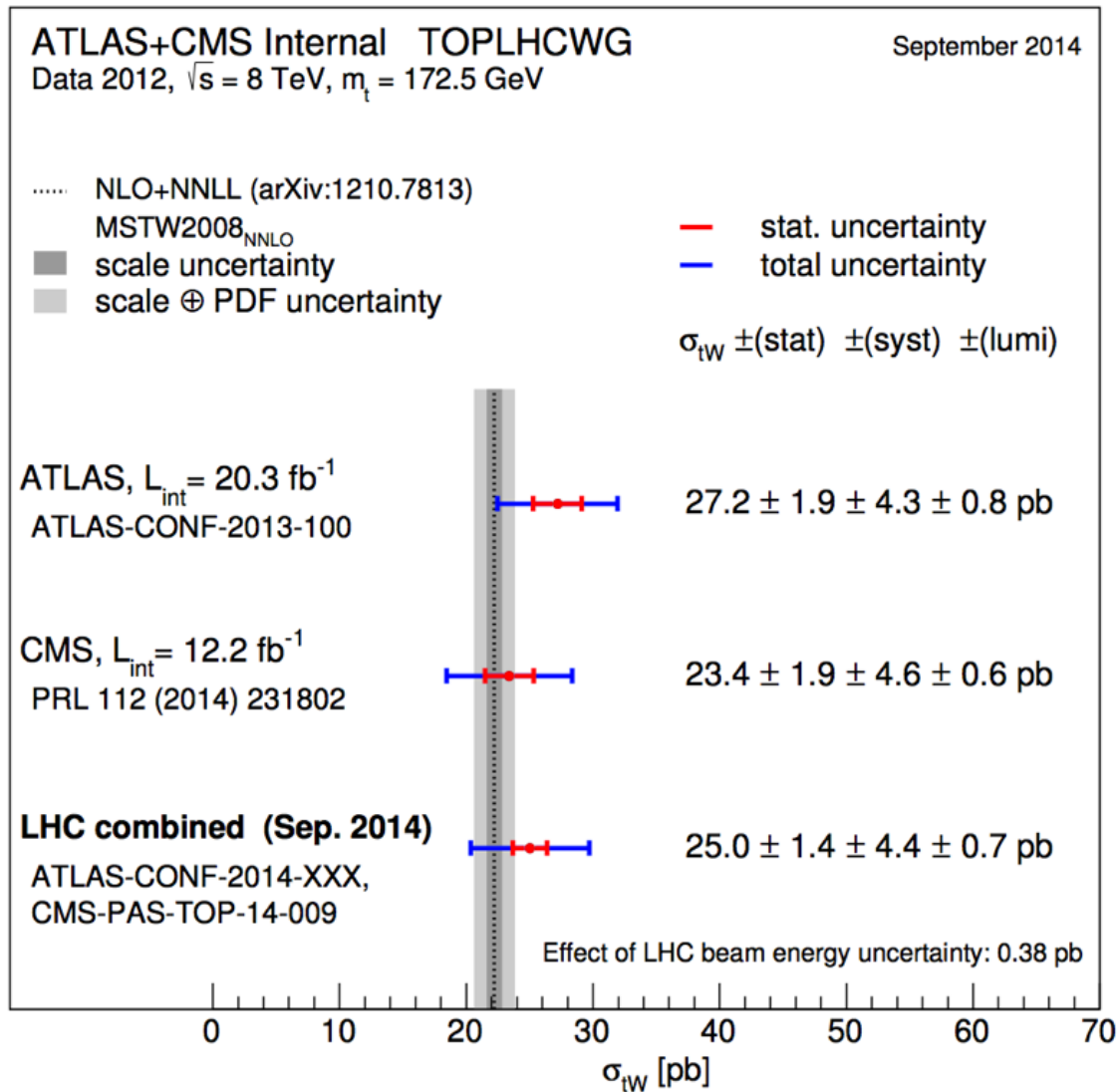
t-channel:

$\sigma_t = 2.12 \pm 0.16 \text{ pb}$
 NLO+NNLL, $m_t = 172.5 \text{ GeV}$
 Kidonakis, PRD 83, 091503 (2011)



Single Top Wt Cross Section

A. Jafari



Source	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

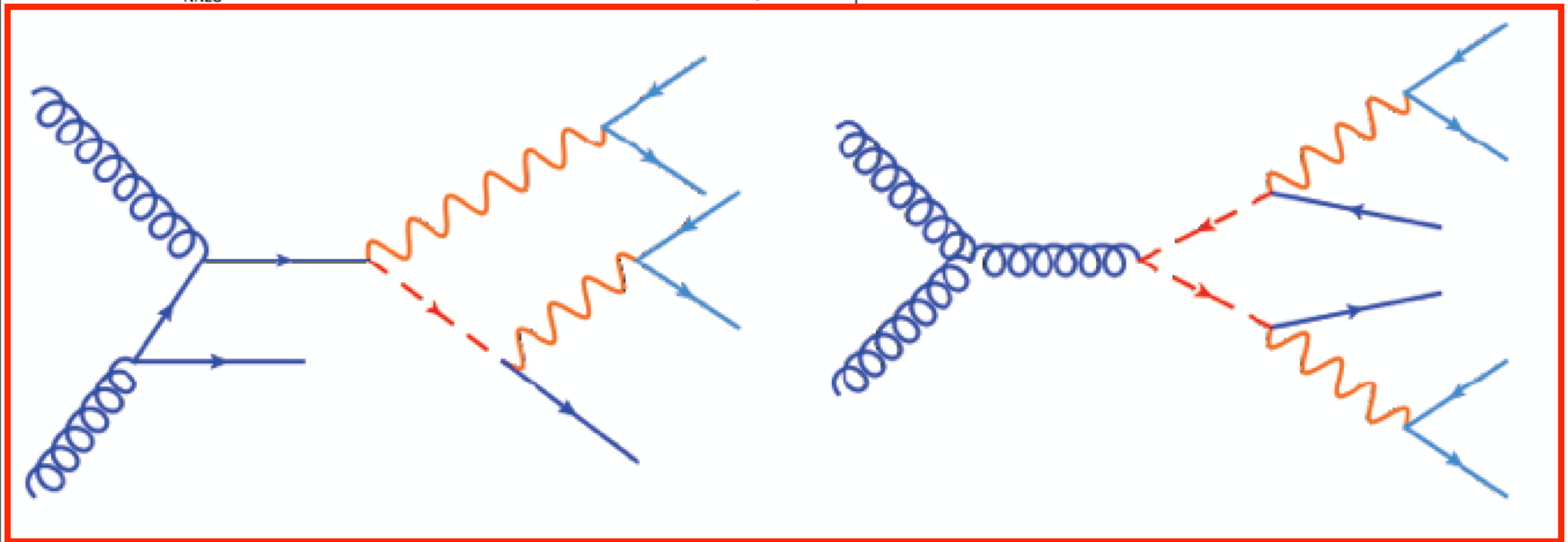
ATLAS+CMS Internal TOPLHCWG
Data 2012, $\sqrt{s} = 8$ TeV, $m_t = 172.5$ GeV

September 2014

..... NLO+NNLL (arXiv:1210.7813)

MSTW2008_{NNLO}

— stat. uncertainty



Effect of LHC beam energy uncertainty: 0.38 pb

Total systematics (incl. lumi)

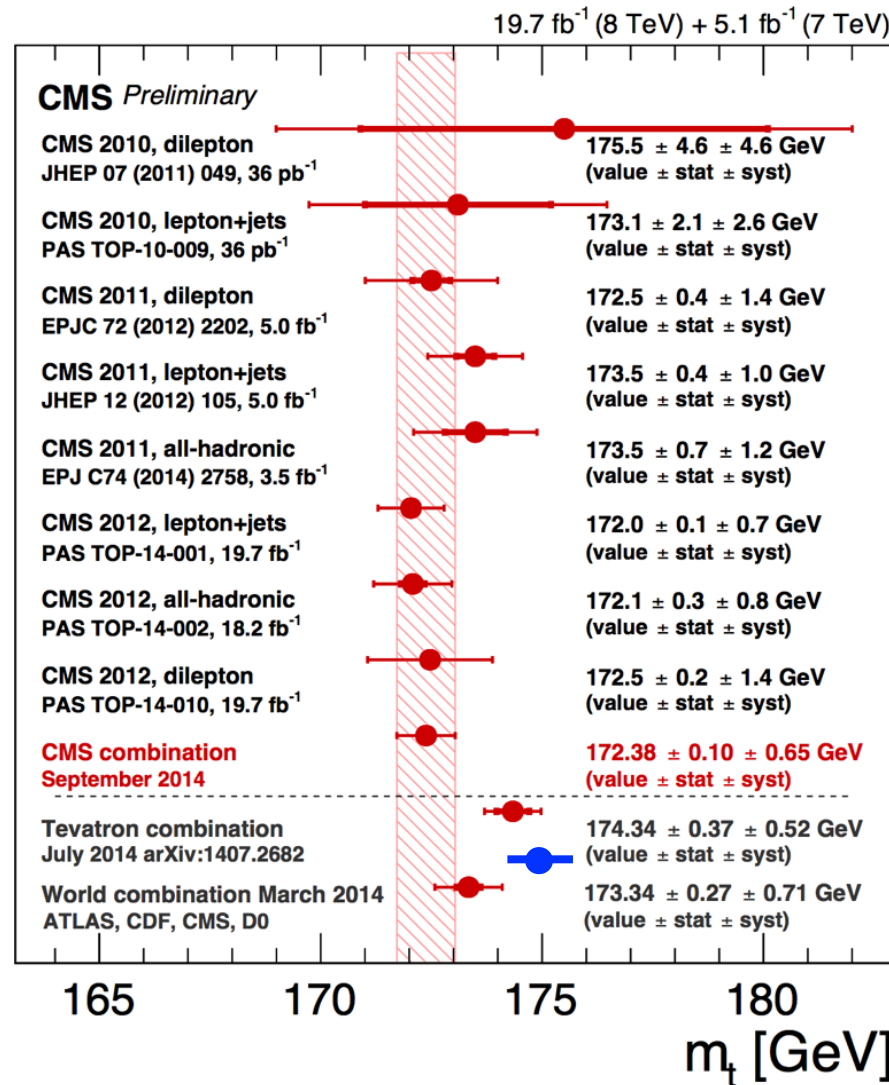
17.7% 4.4

18.6% 4.7

→ **measure WWb cross section**
(single resonant enriched)

CMS top mass combination

top mass crisis?

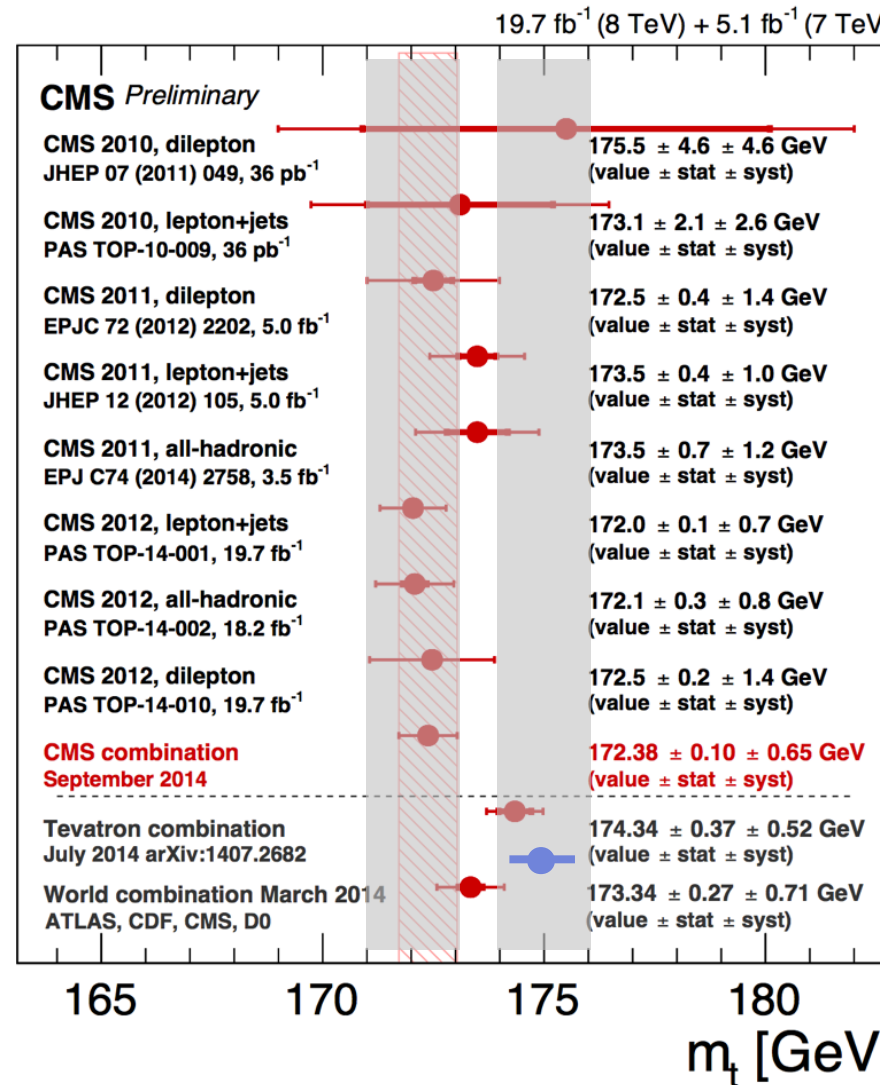


DØ l+jets, 9.7 fb⁻¹

- 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

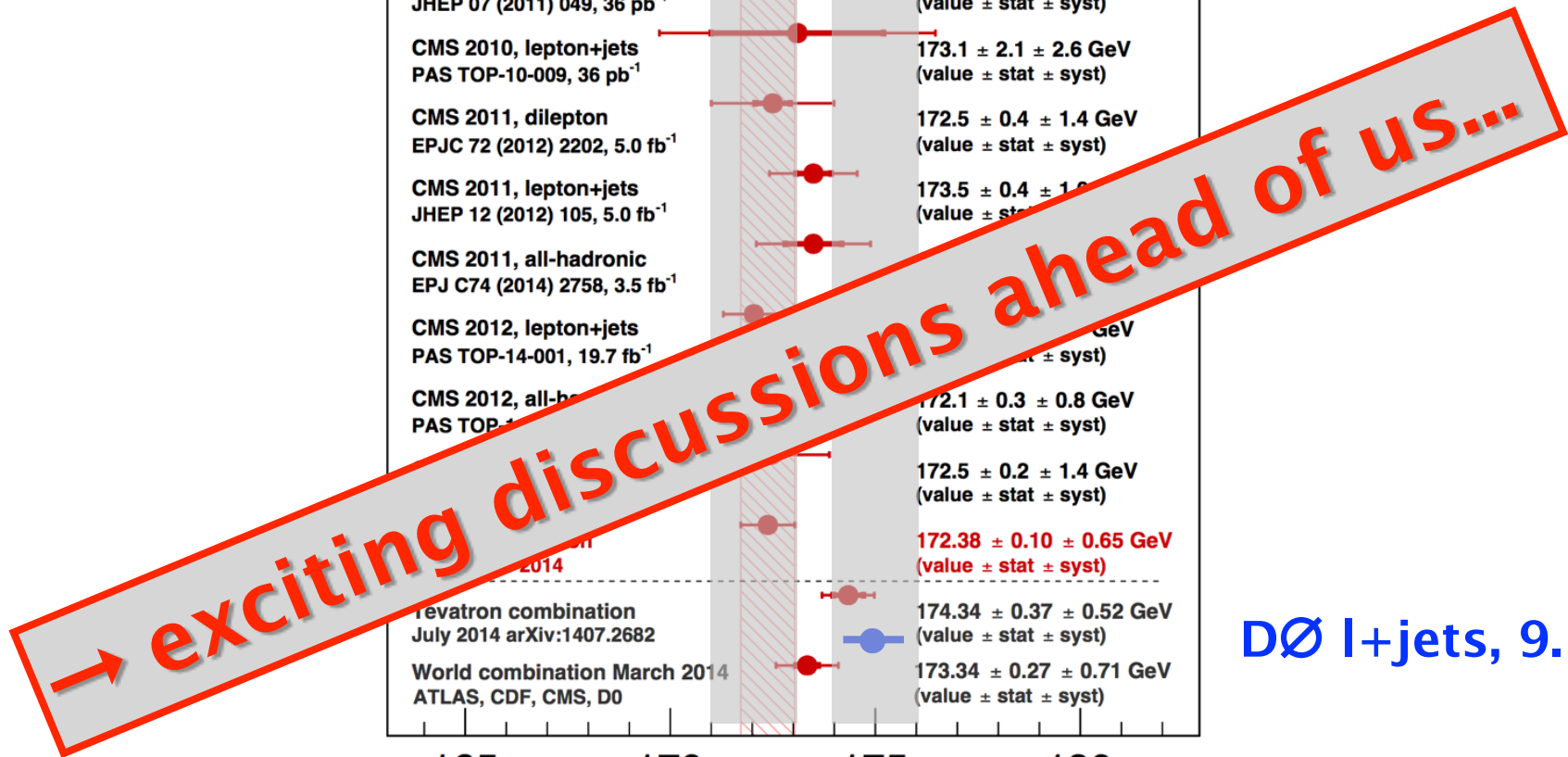
- each MC mass can shift by up to $\Delta \approx O(1 \text{ GeV})$ to QFT mass
- WbWb off-shell effects: can move $\langle m_{lb} \rangle$ by $O(1 \text{ GeV})$

J. Winter

I am just thinking...

top mass crisis?

E. Schlieckau



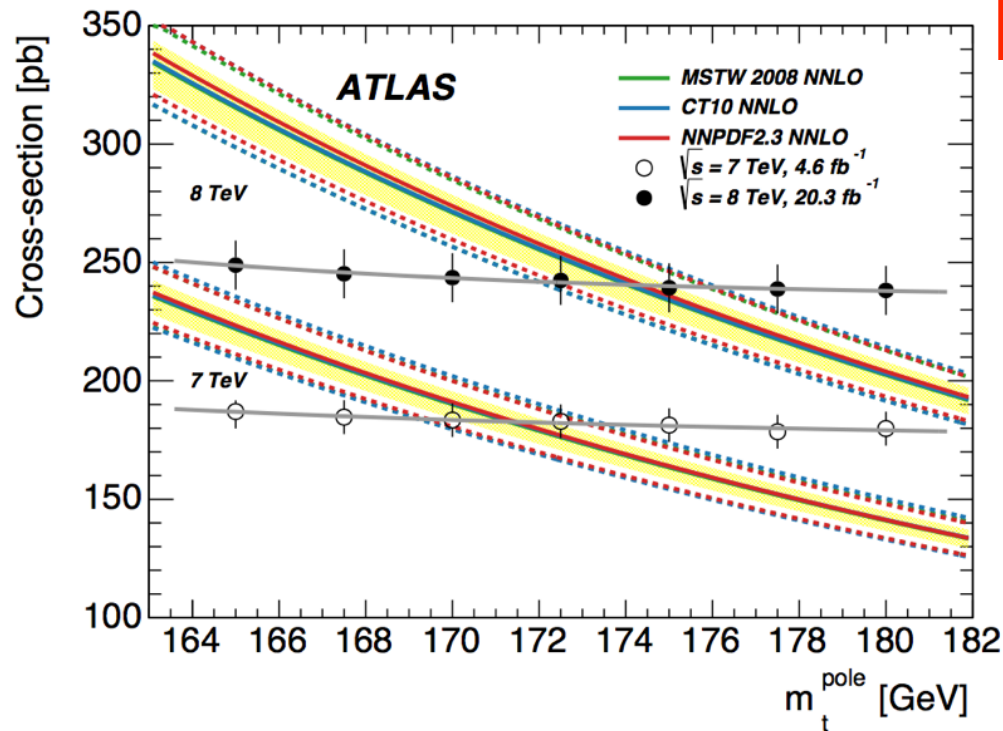
DØ l+jets, 9.7 fb⁻¹

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 $O(1 \text{ GeV})$

J. Winter

Top Quark Pole Mass



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

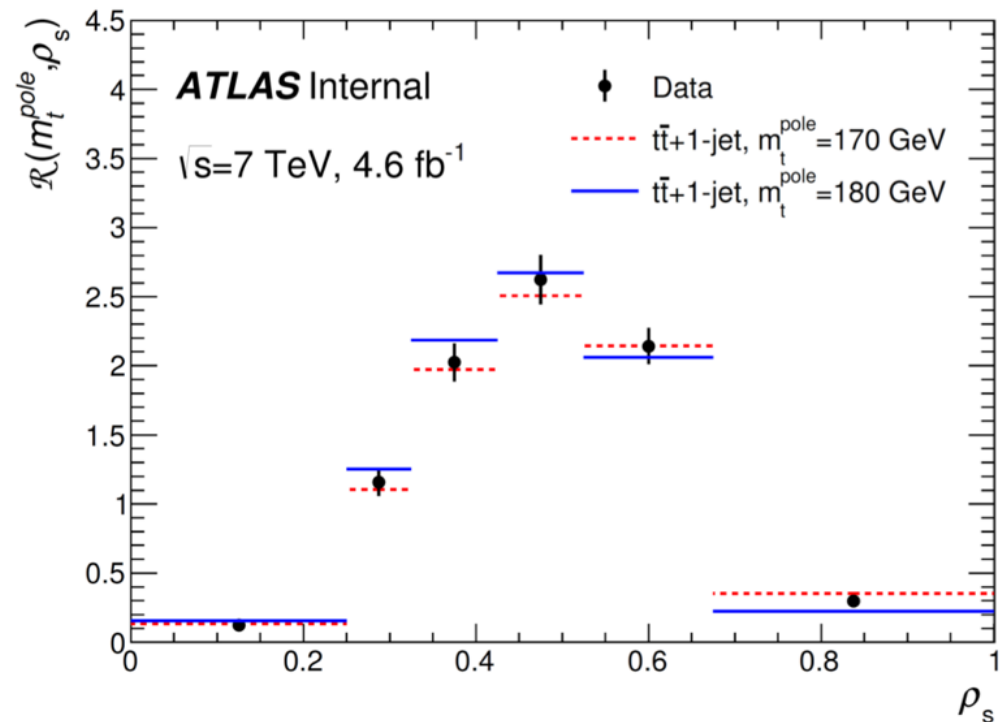
→ pole mass
unambiguously!

many alternative measurements

tt+1jet: differential cross section

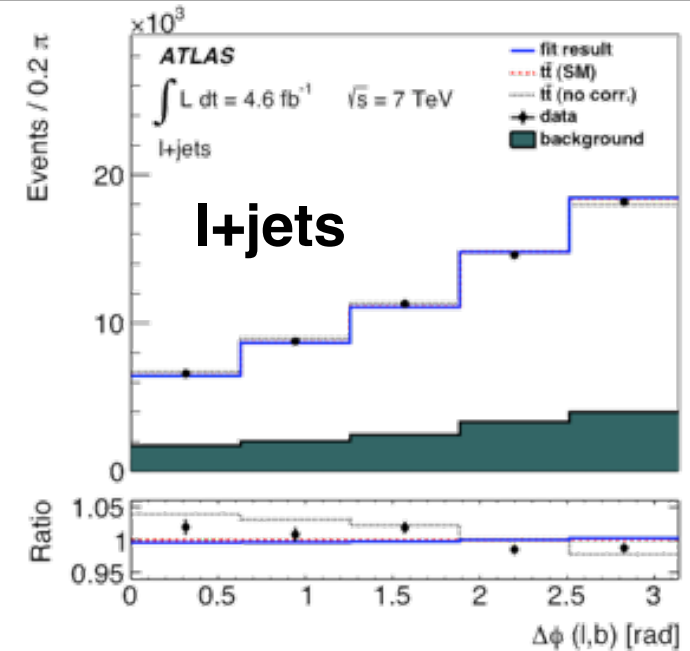
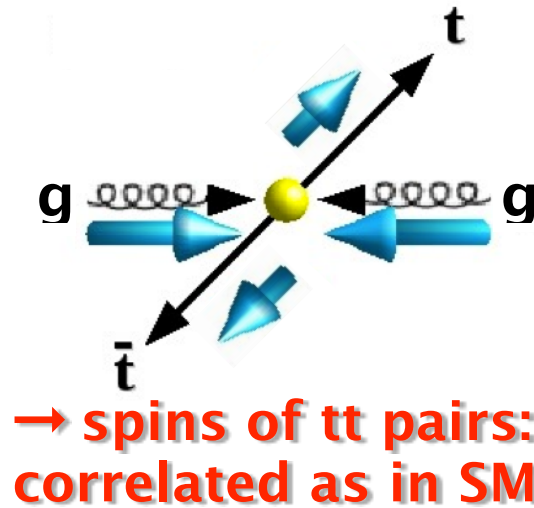
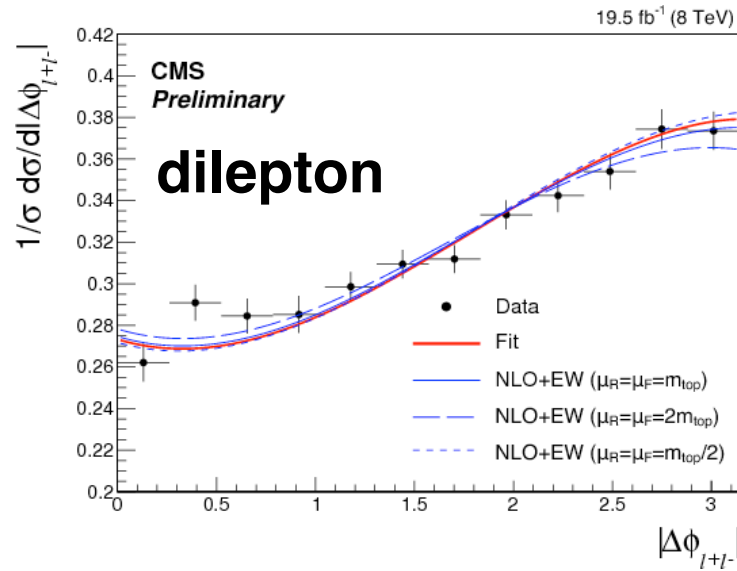
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s)$$

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

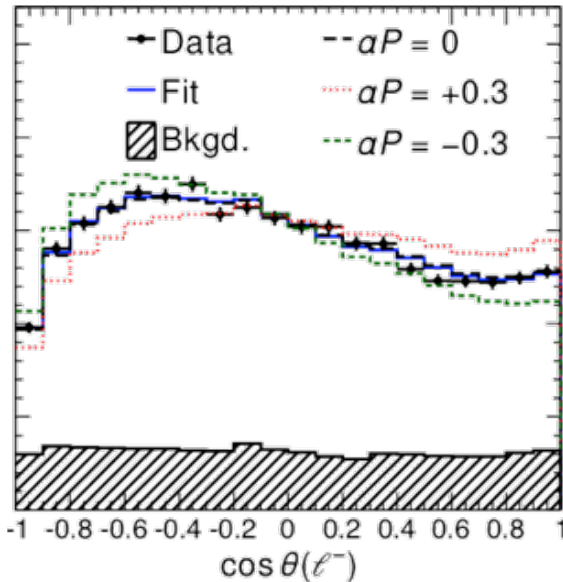


is it really the pole mass?

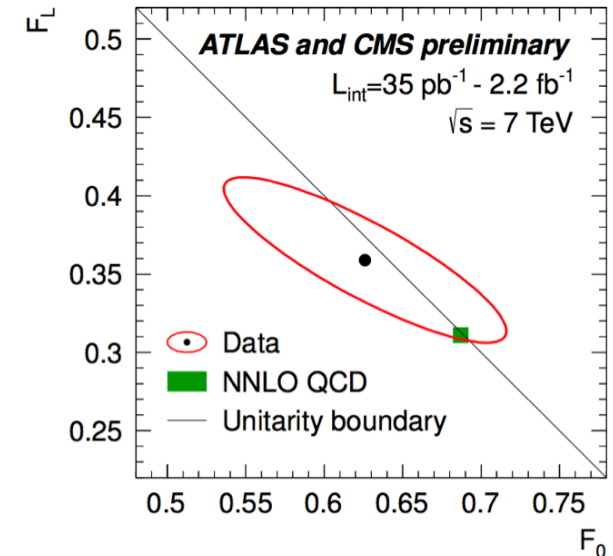
Polarisation and Spin Correlation



→ no chromomagnetic dipole moments

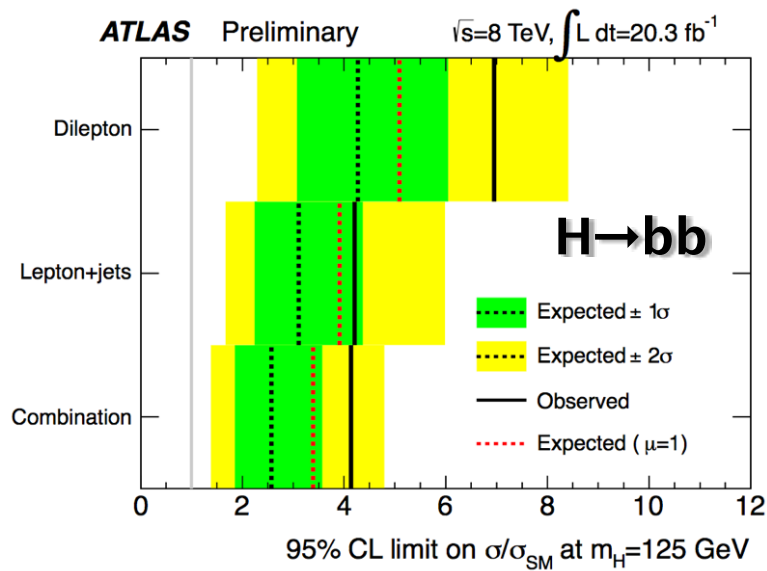


→ top quarks unpolarised

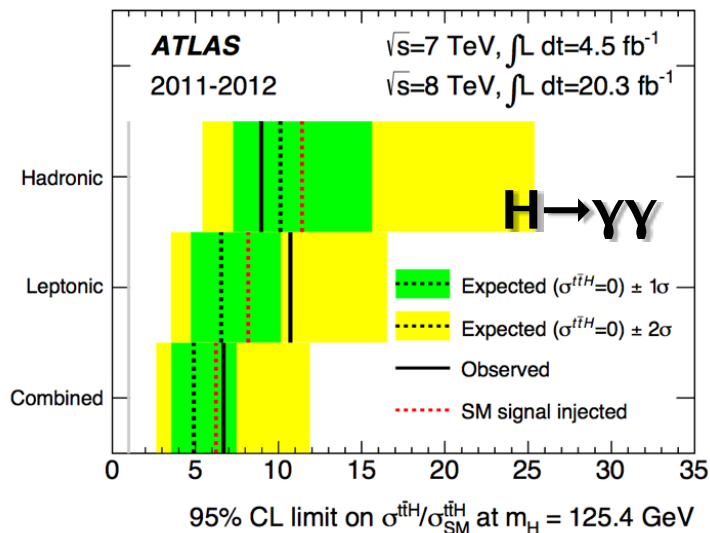


→ W polarisation as in SM

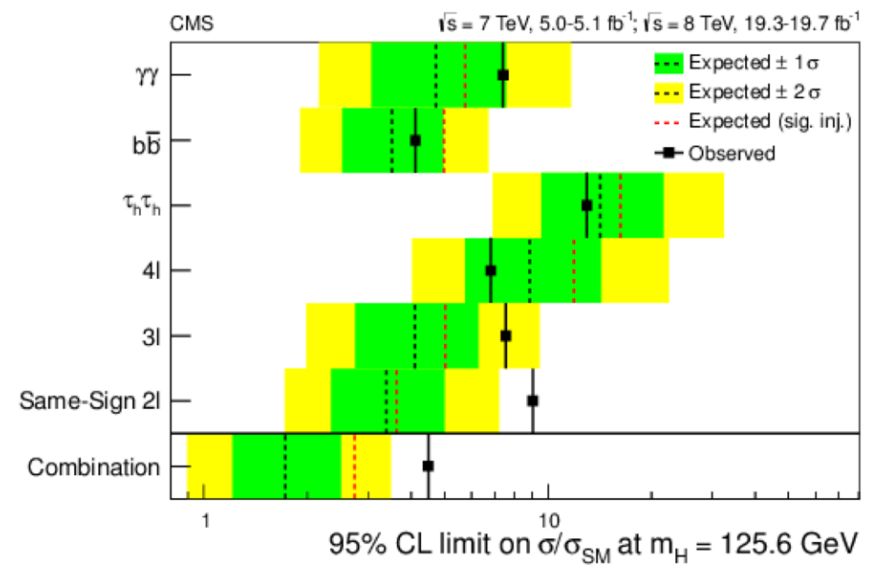
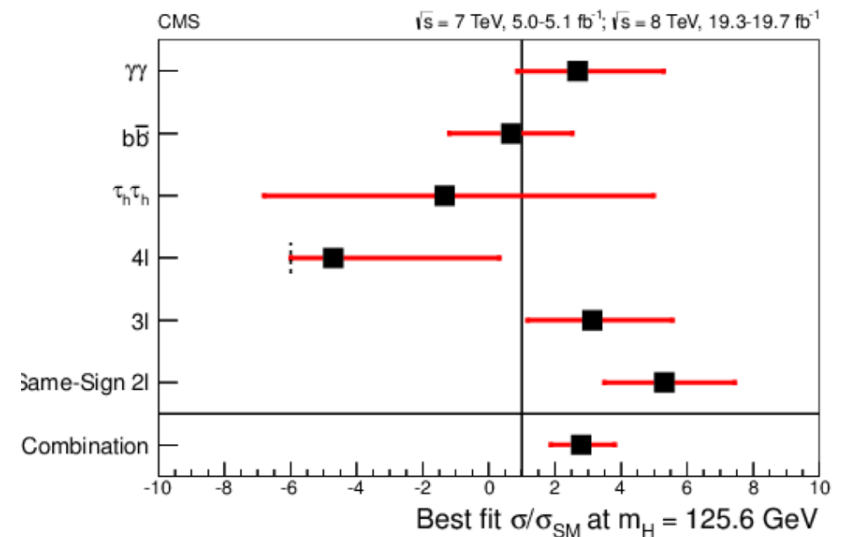
Results in ttH



Fitted $\sigma/\sigma_{\text{SM}} = 2.9 \pm 2.3$

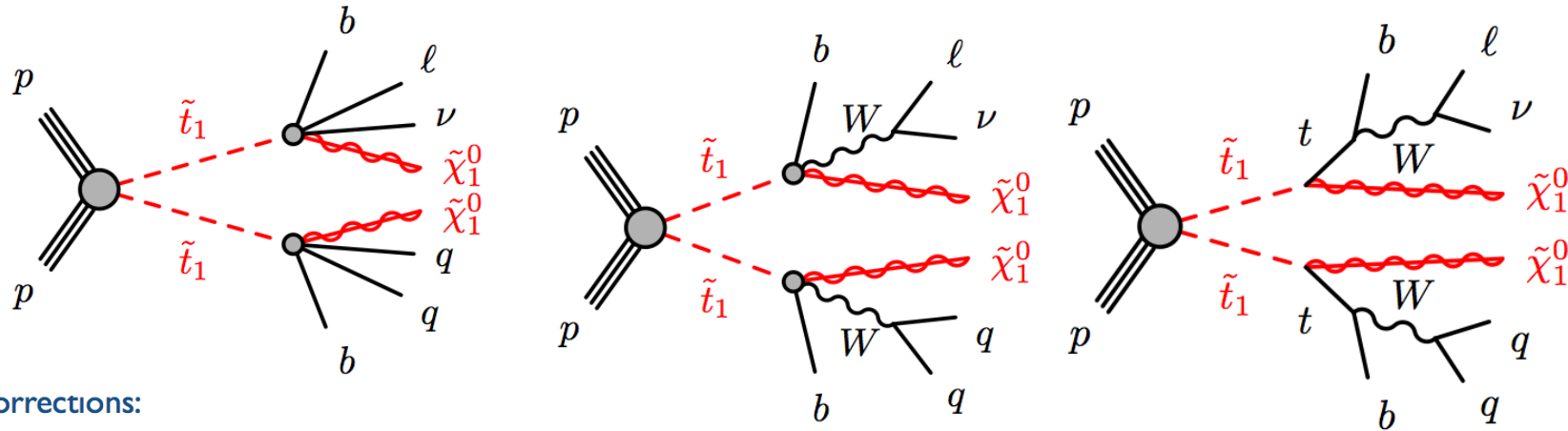


Fitted signal $\sigma/\sigma_{\text{SM}} = 1.4^{+2.2}_{-1.4}$

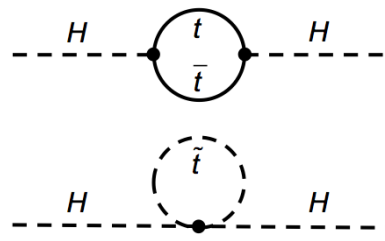


→ observation in Run-II

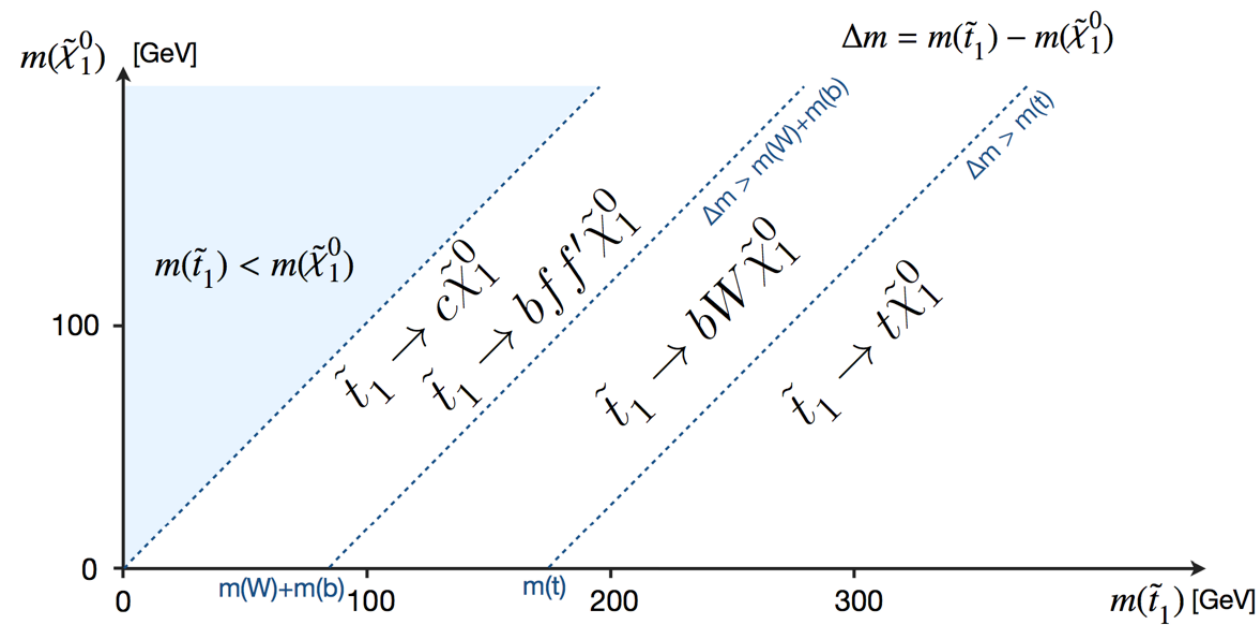
Direct searches for light stop



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



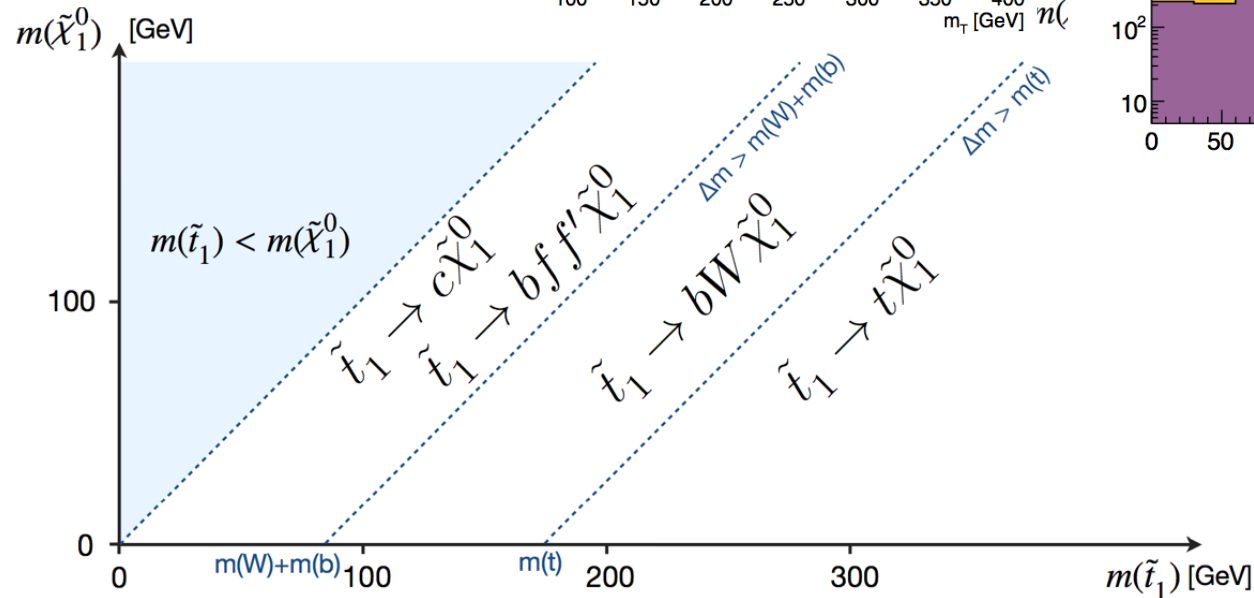
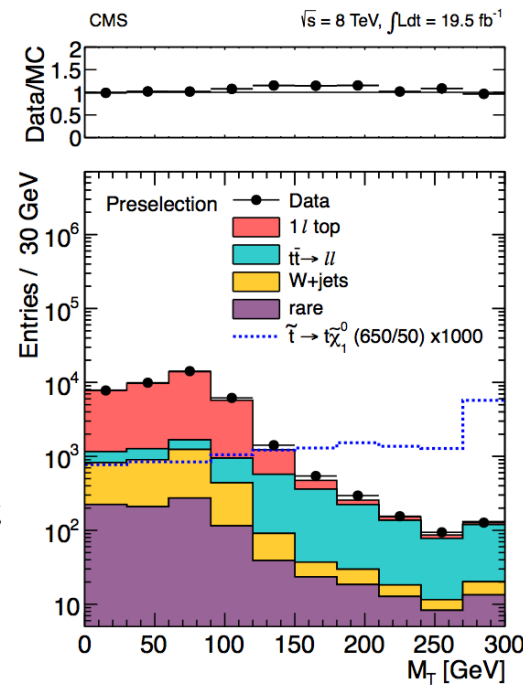
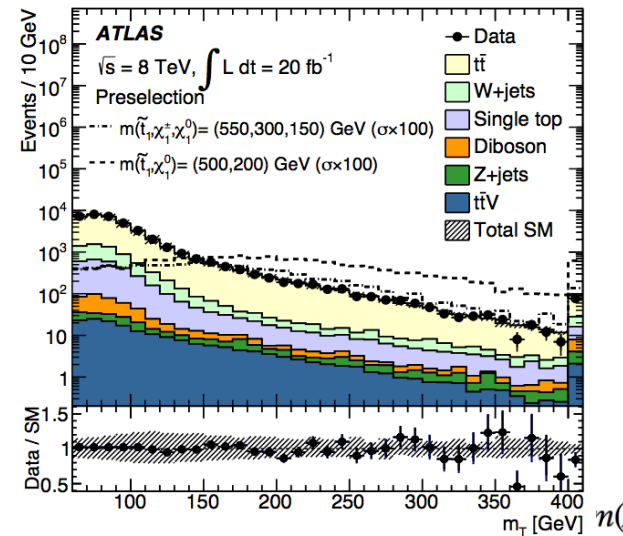
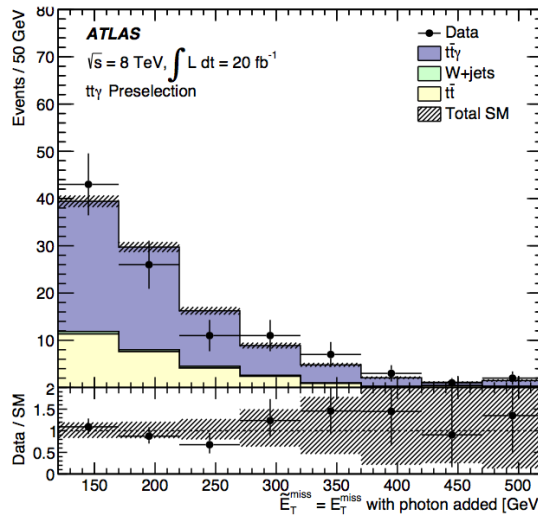
small stop mass is natural



T. Eifert

we check every little corner...

Direct stop searches

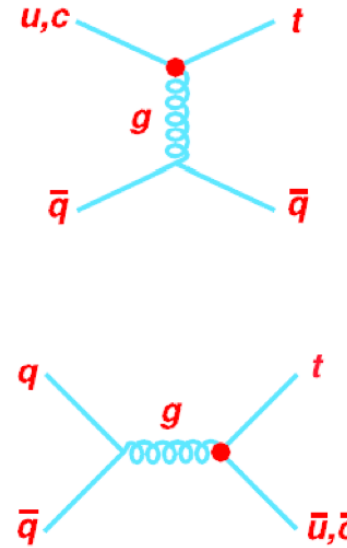
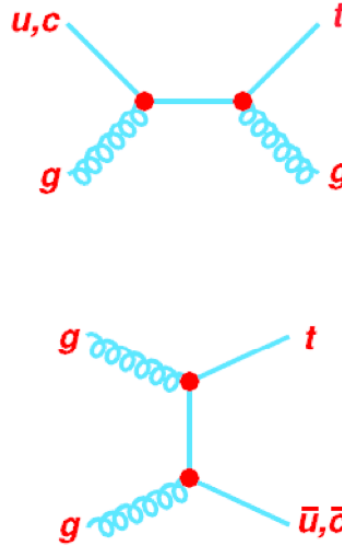
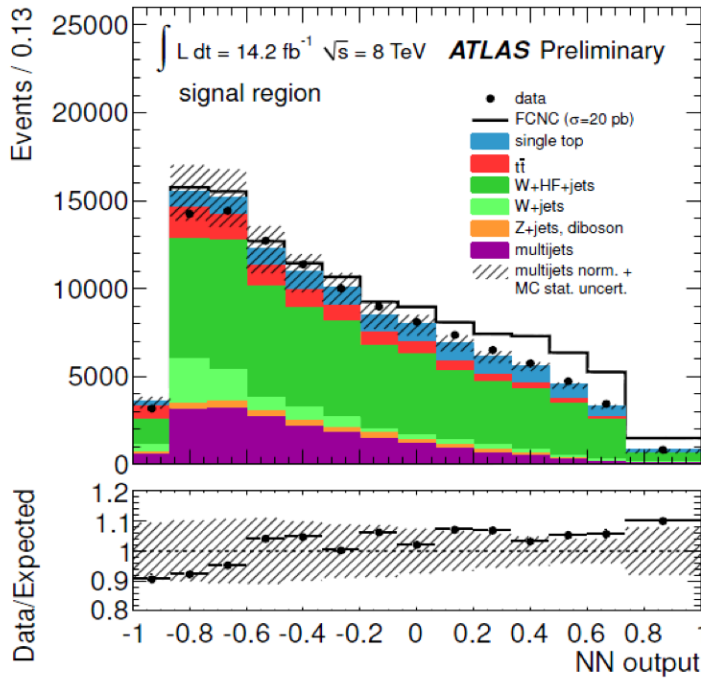


T. Eifert

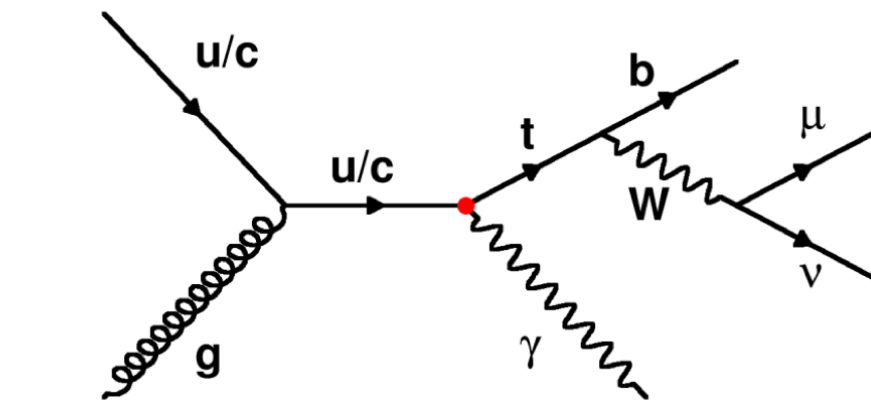
we check every little corner...

Search for FCNC

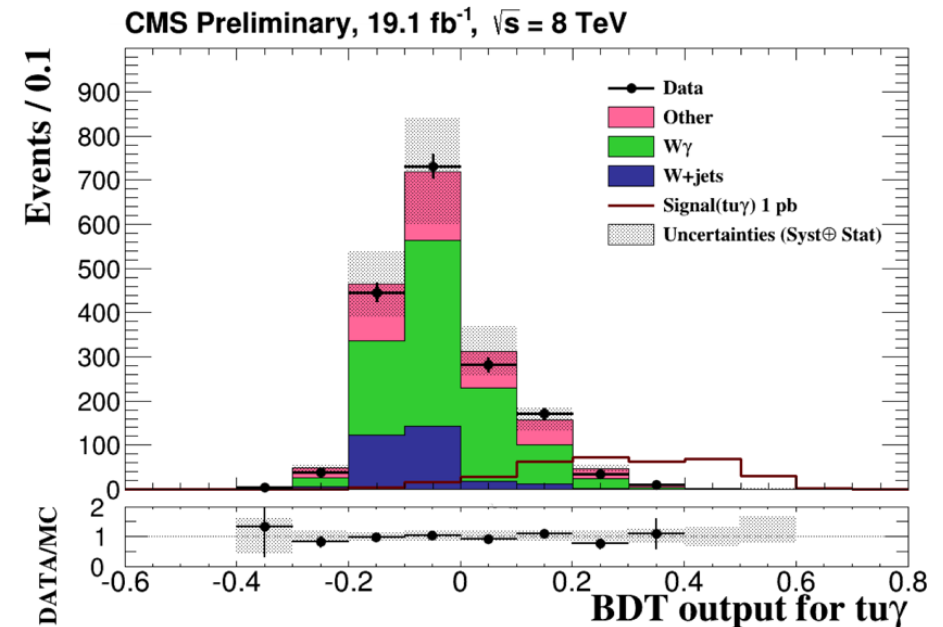
R. Goldouzian



IR divergent?

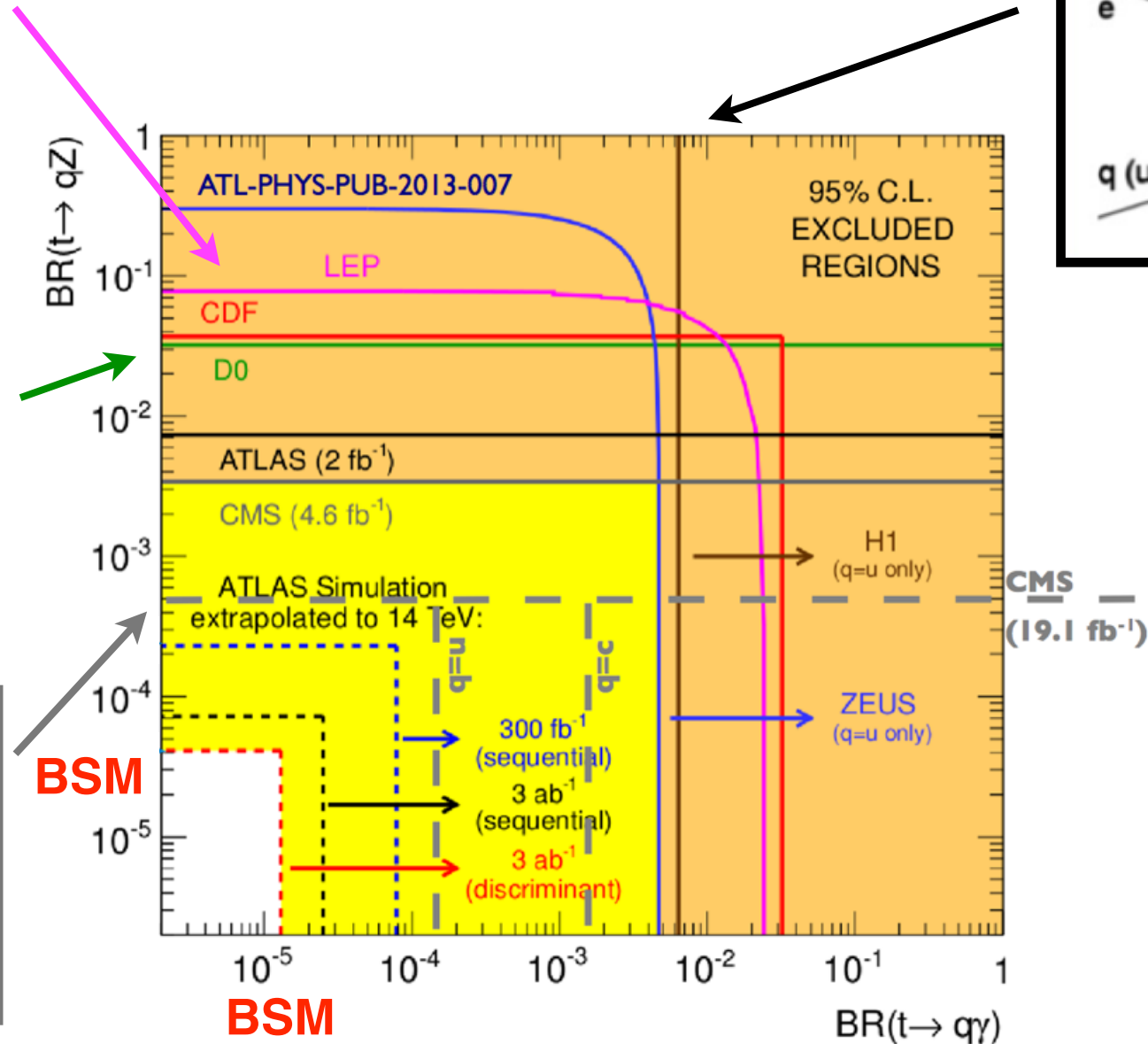
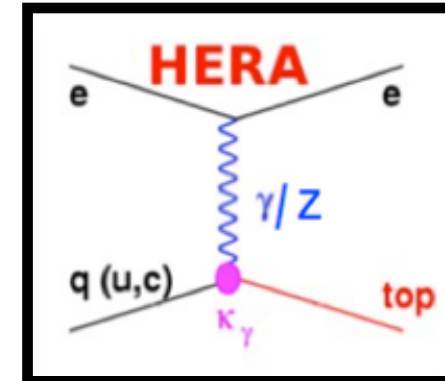
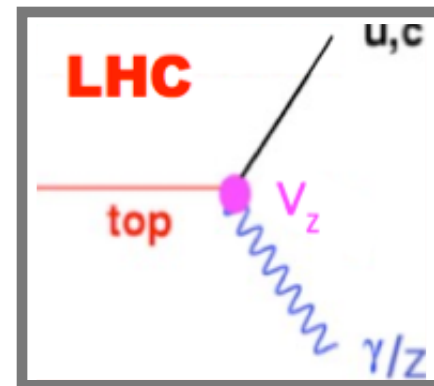
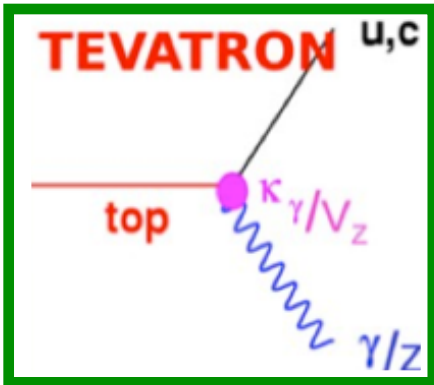
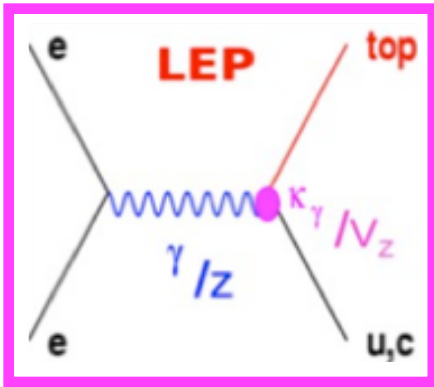


→ no hint for new physics



FCNC Top Couplings at

P. Silva

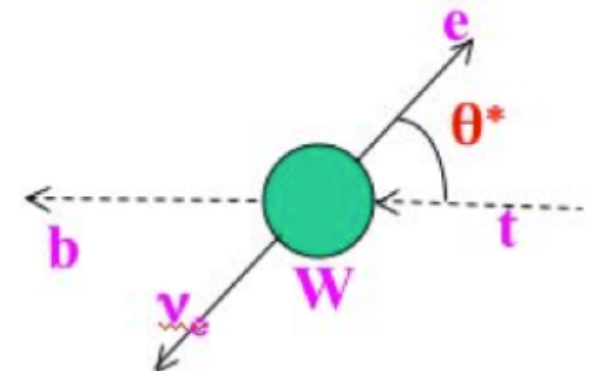
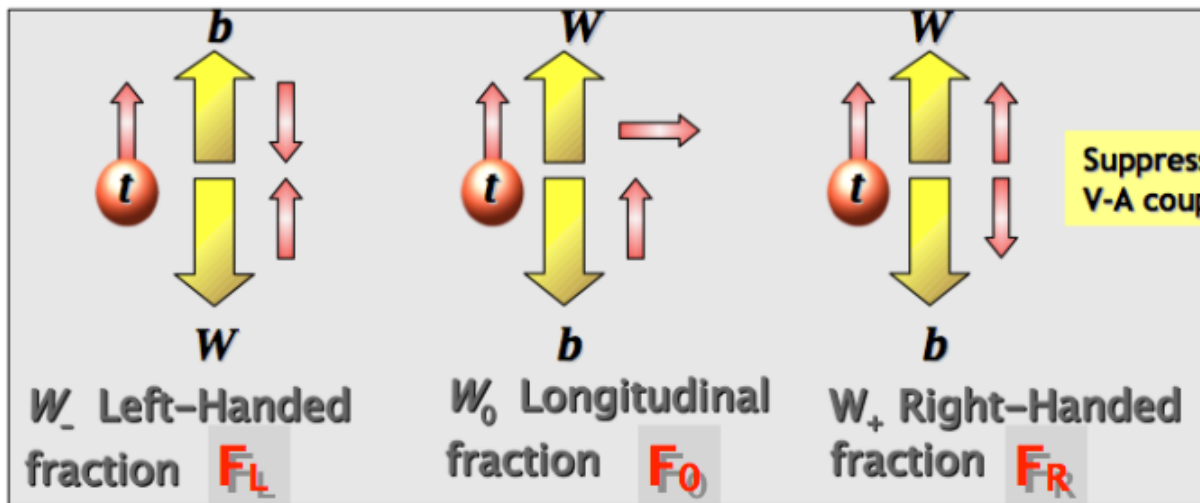


W Boson Helicity Fractions

Phys. Rev. D83, 032009 (2011)

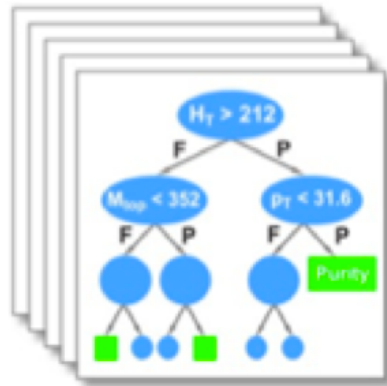
$$\frac{-ig}{2\sqrt{2}} \bar{t} \gamma^\mu (1 - \gamma^5) V_{tb} b W_\mu$$

V-A
t spin = 1/2 → b spin = 1/2
W⁺ spin = 1

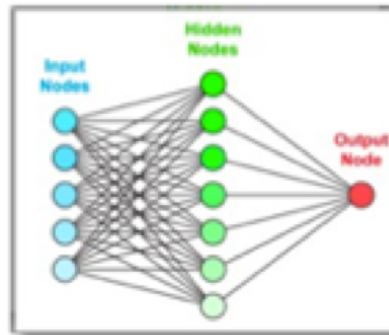


Multivariate Analyses

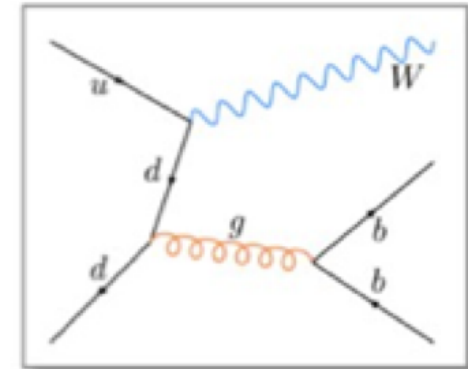
Boosted Decision Trees



Neural Networks

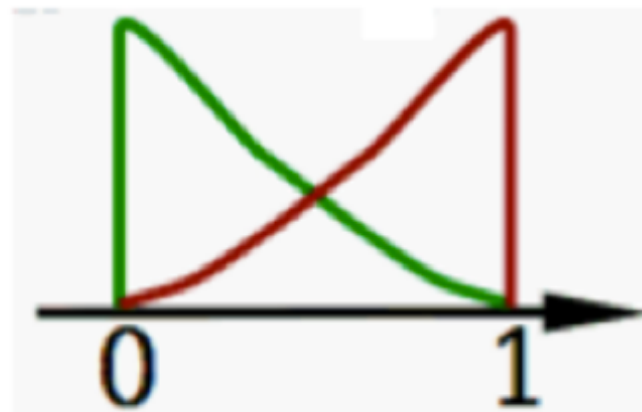


Matrix Elements

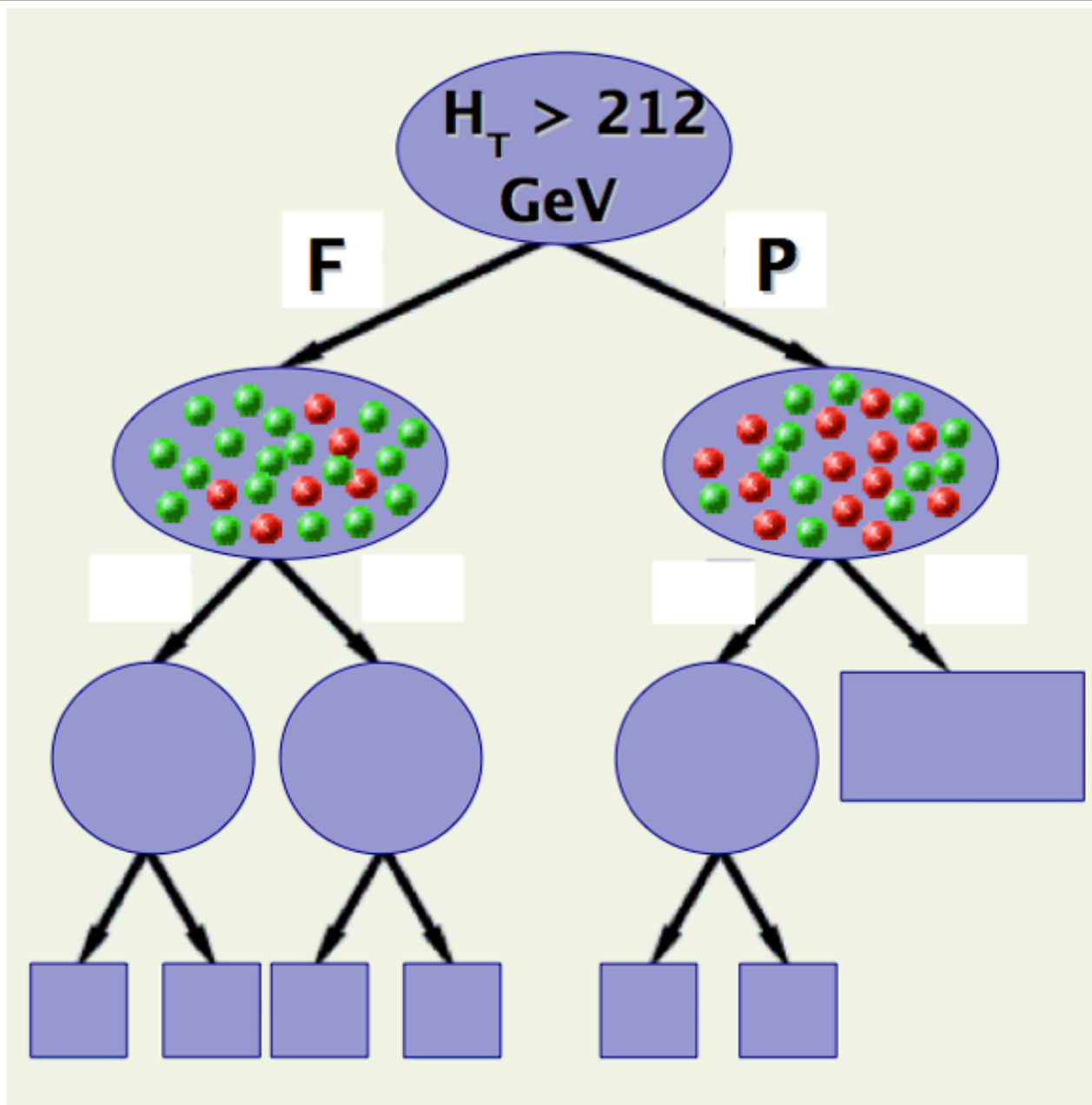


background

signal



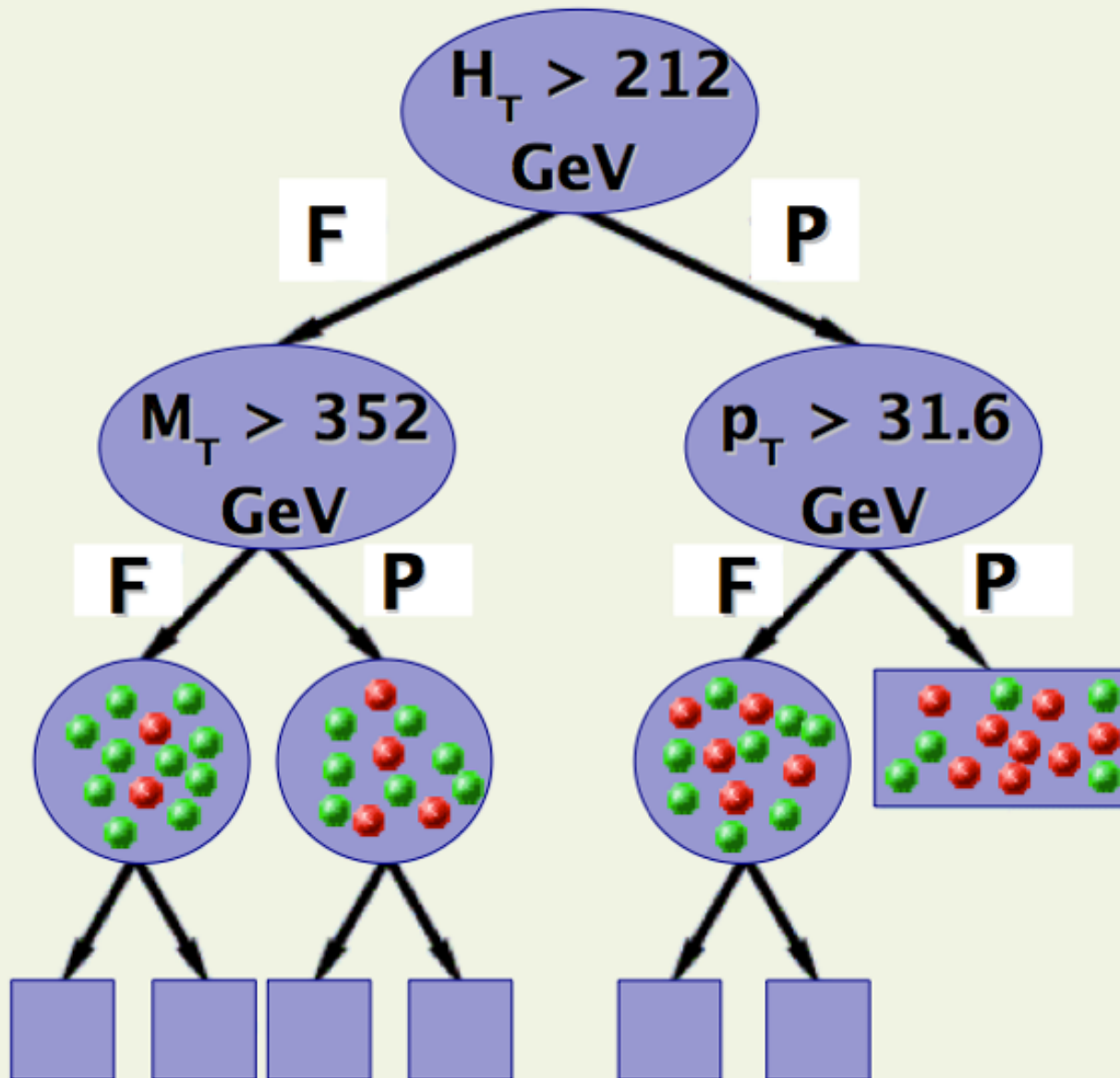
Boosted Decision Trees



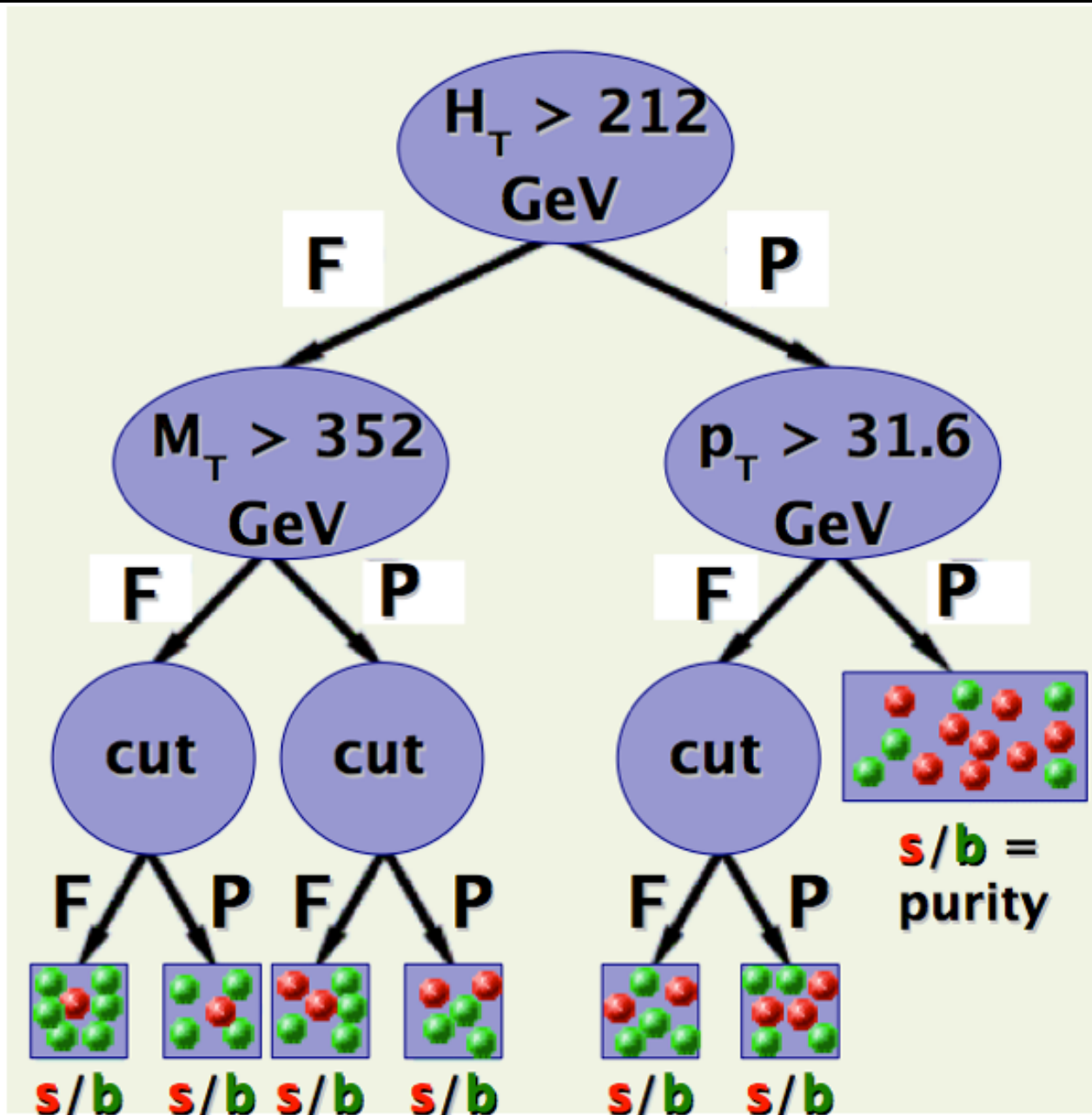
- **IDEA:** recover events that fail criteria in cut-based analyses

Boosted Decision Trees

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

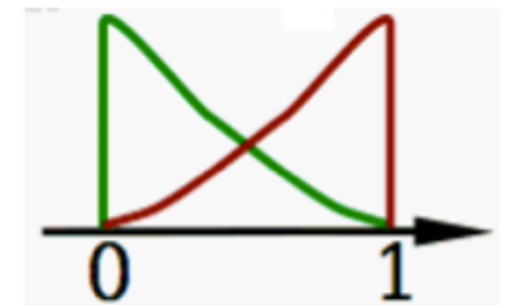


Boosted Decision Trees

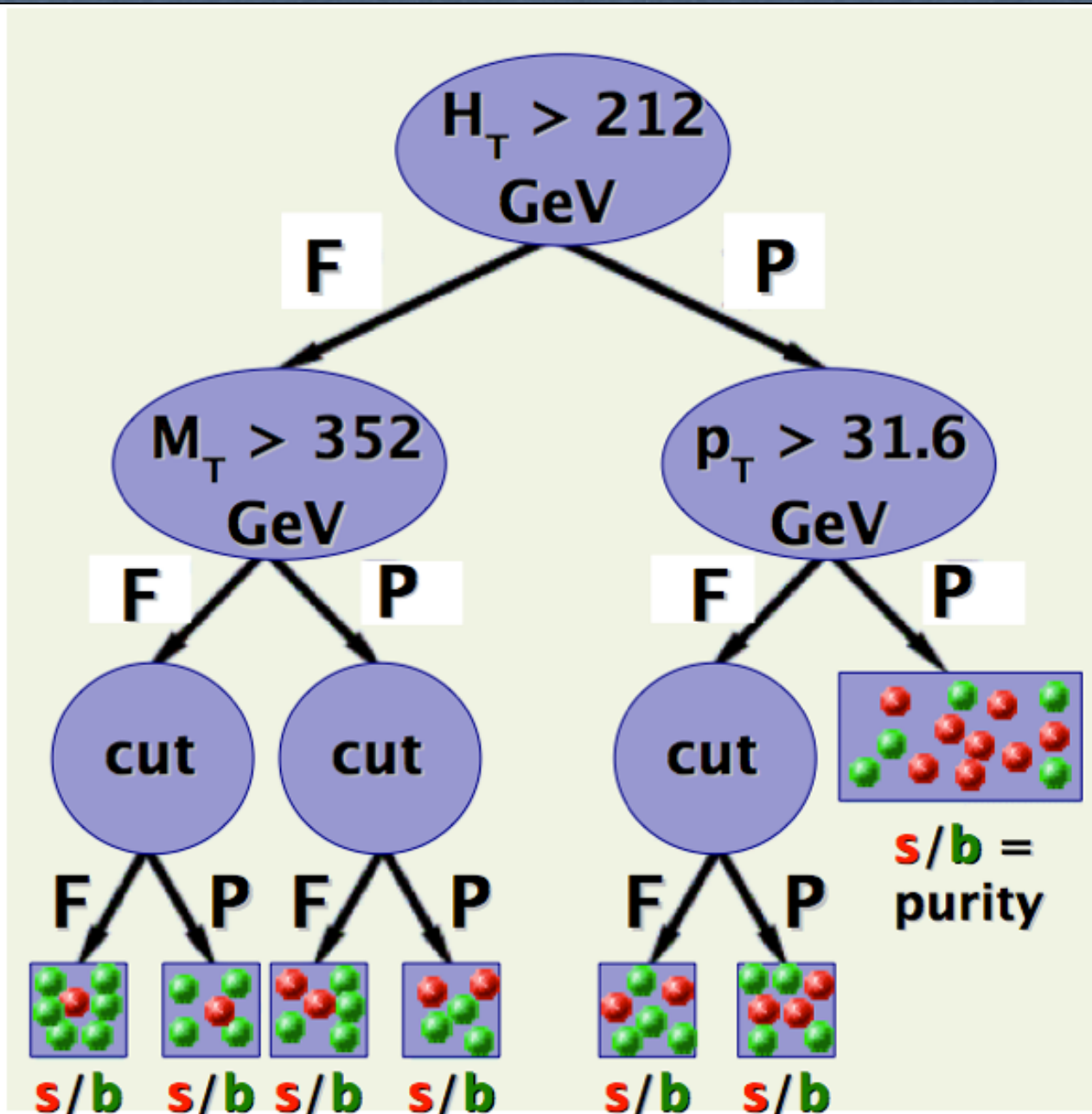


- **IDEA:** recover events that fail criteria in cut-based analyses

- **result:** weight for every event
background signal



Boosted Decision Trees

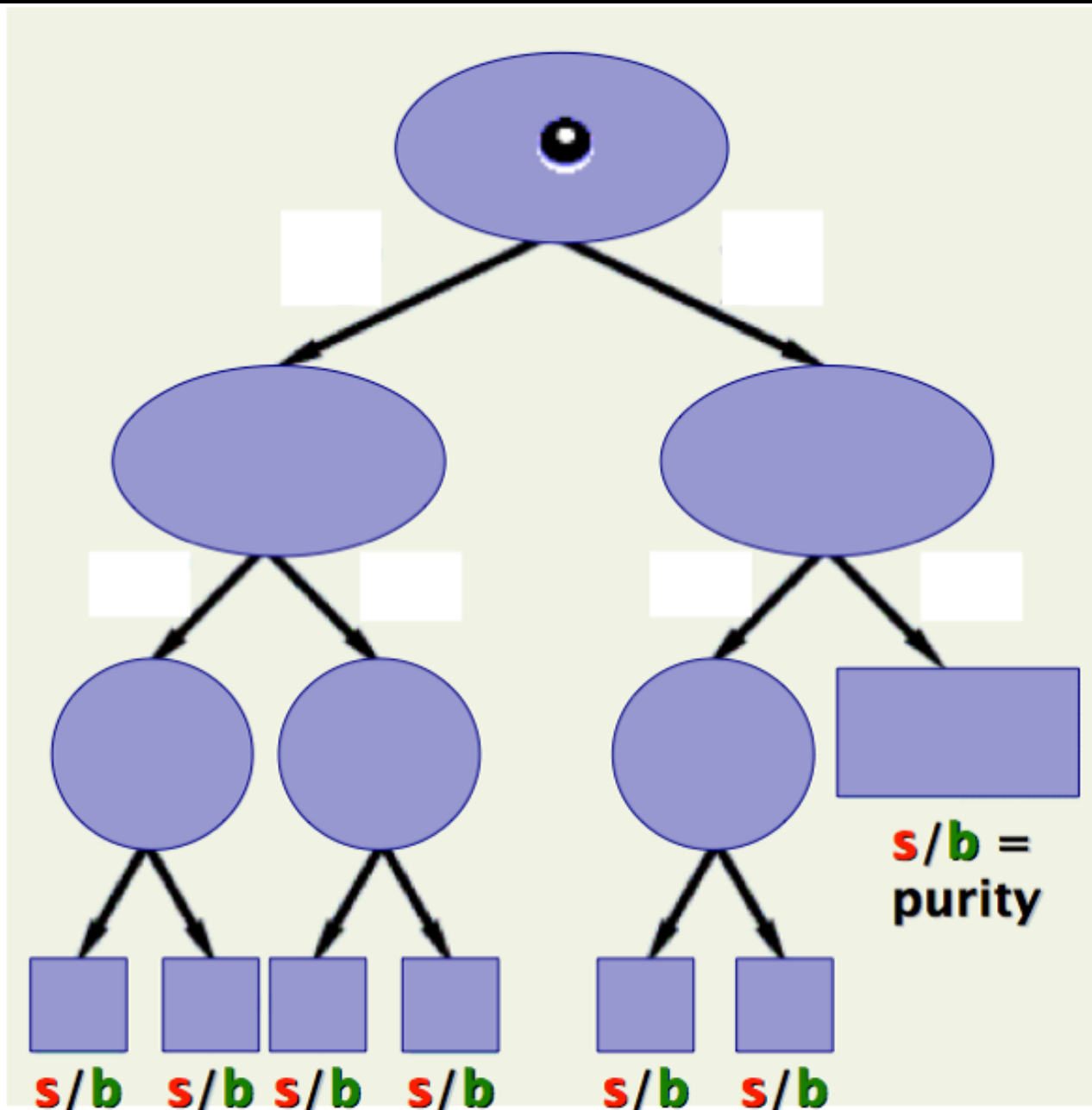


- **IDEA:** recover events that fail criteria in cut-based analyses

boosting:

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

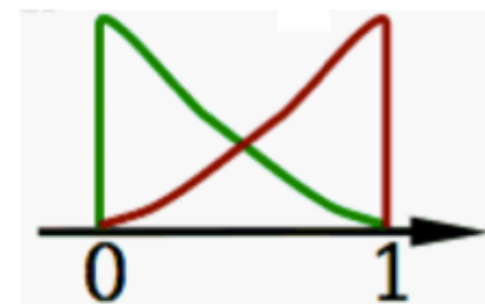
Boosted Decision Trees



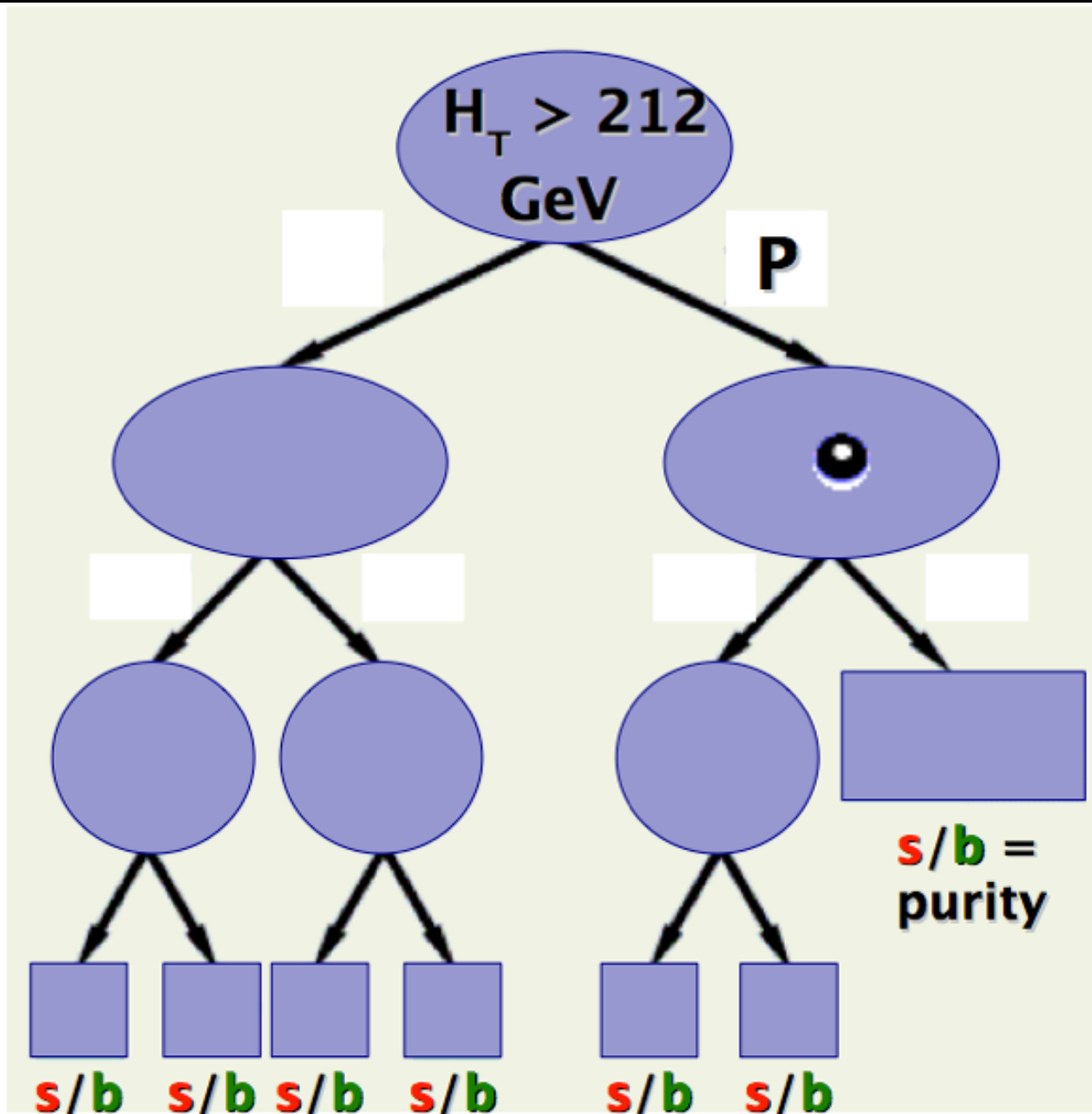
- **IDEA:** recover events that fail criteria in cut-based analyses

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background signal



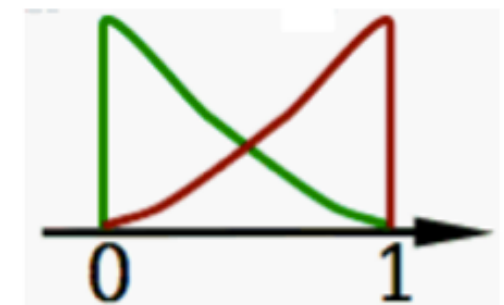
Boosted Decision Trees



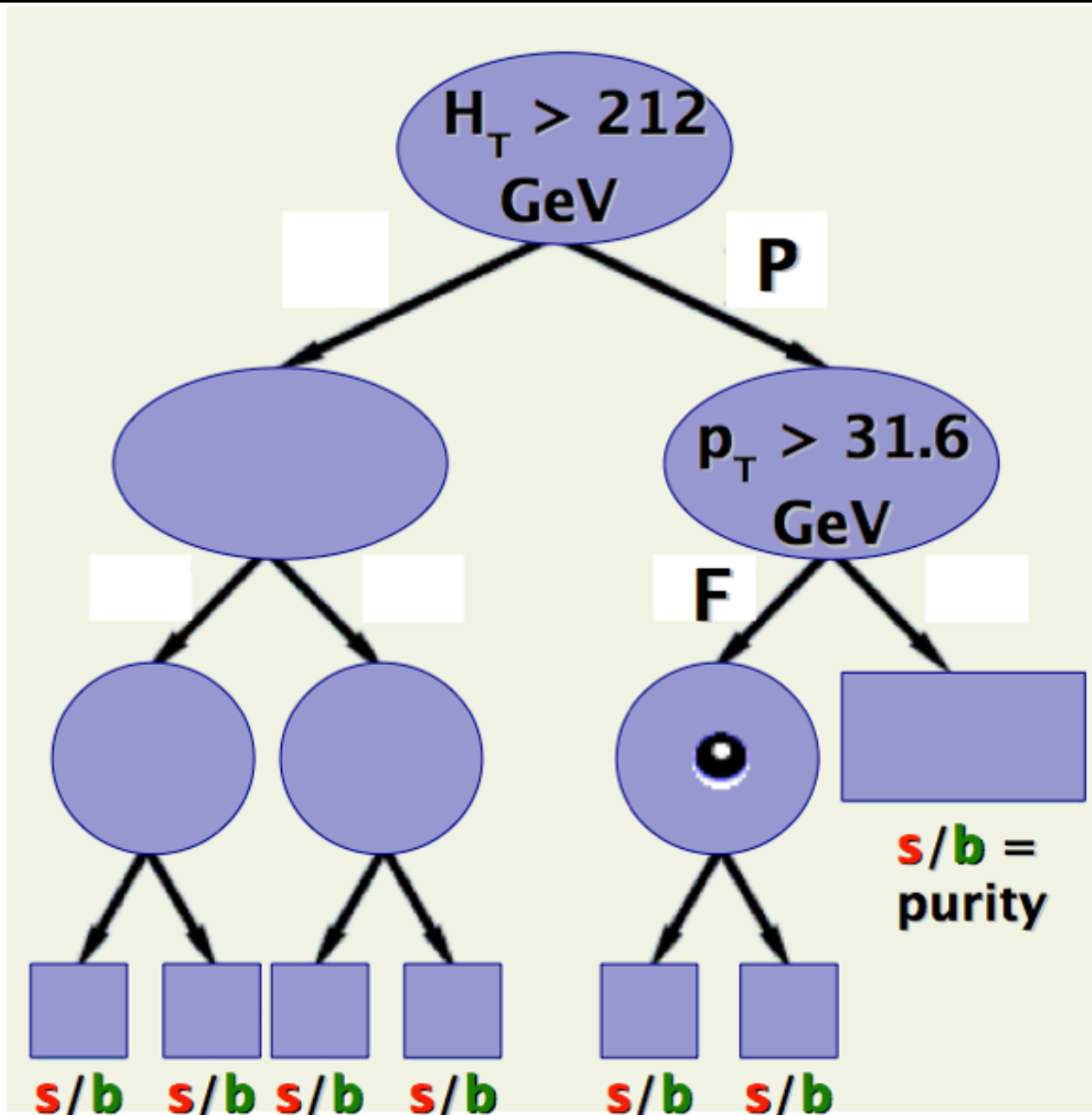
- **IDEA:** recover events that fail criteria in cut-based analyses

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background signal



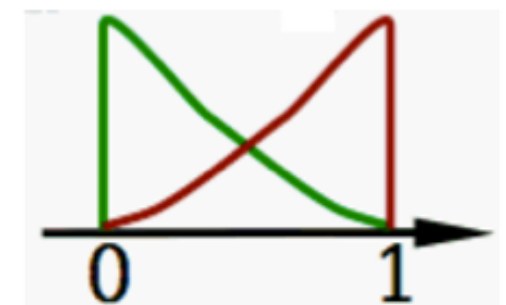
Boosted Decision Trees



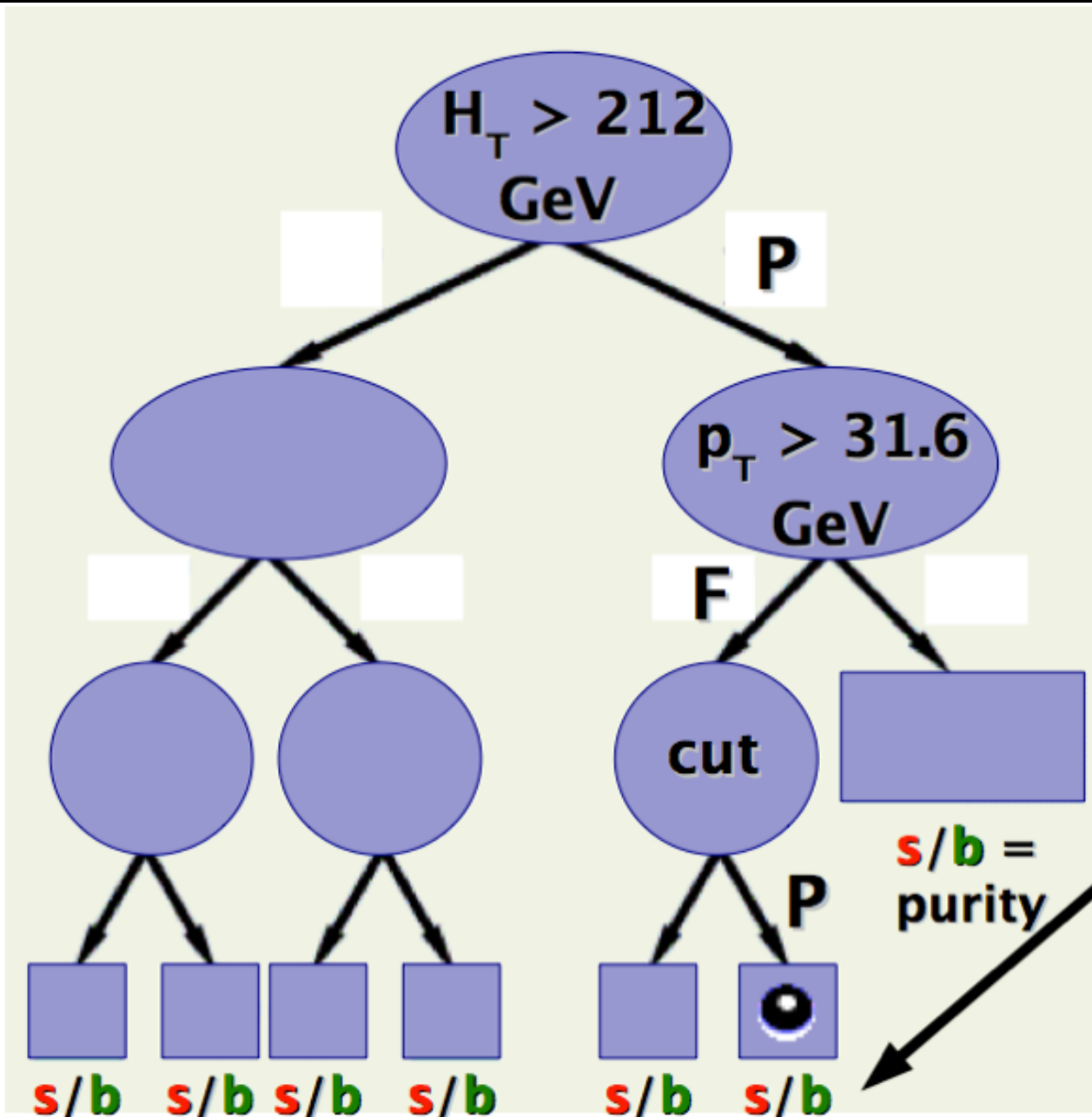
- **IDEA:** recover events that fail criteria in cut-based analyses

- **result:** weight for every event

background signal



Boosted Decision Trees

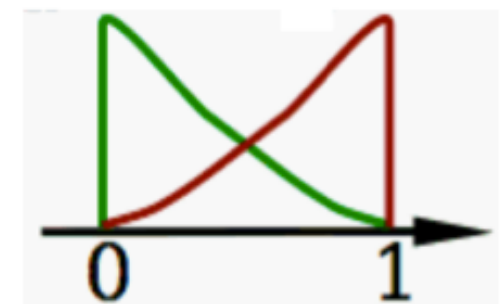


- **IDEA:** recover events that fail criteria in cut-based analyses

- **result:** weight for every event

background

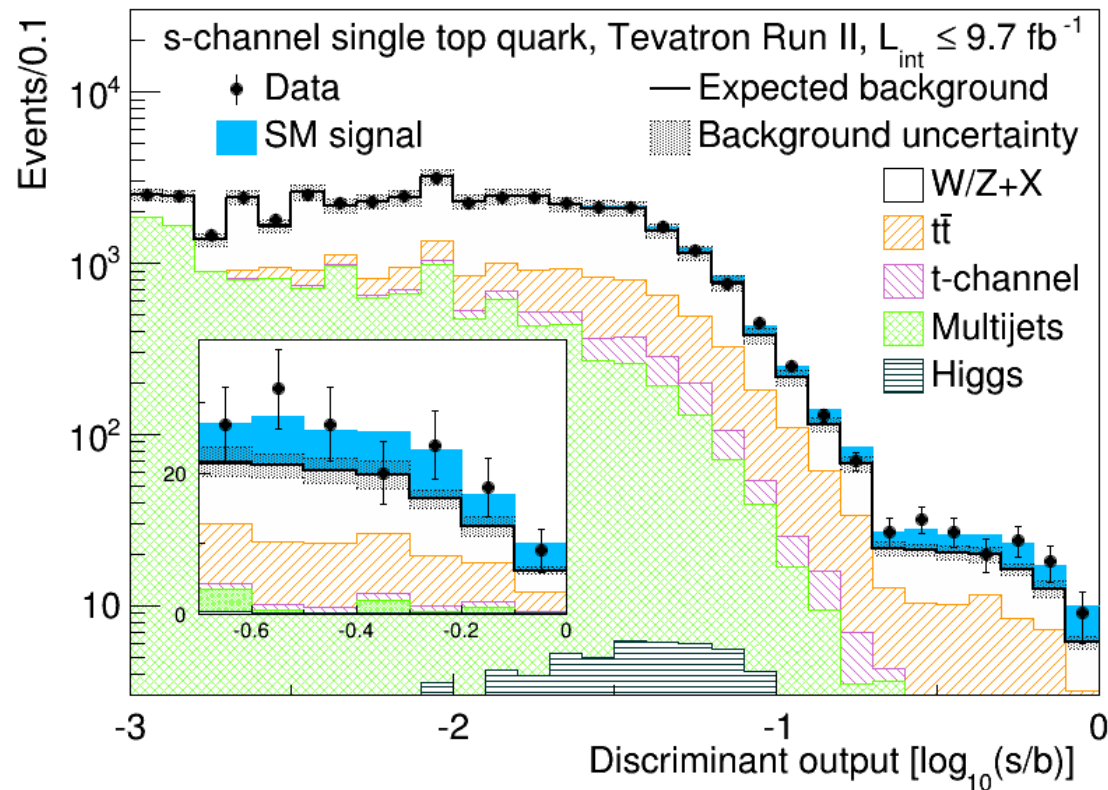
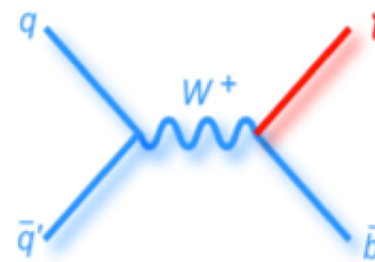
signal



s-channel Production

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

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

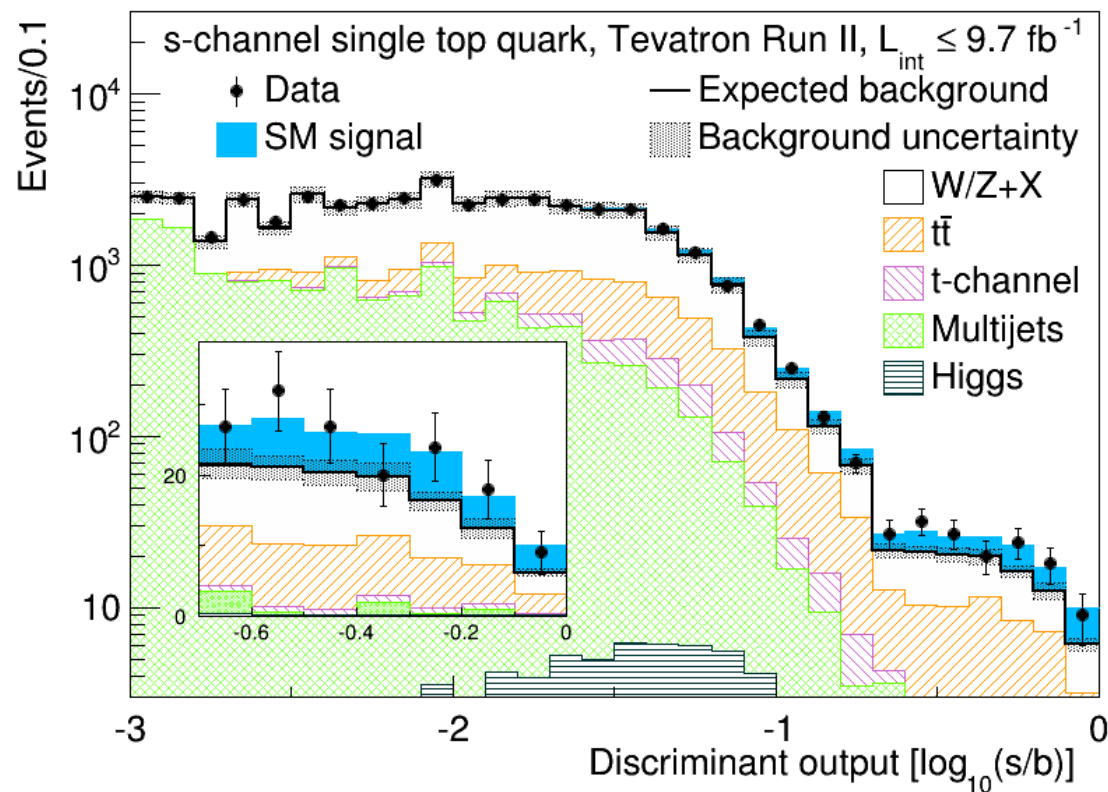


→ **observation: 6.3 s.d.**

s-channel Production

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

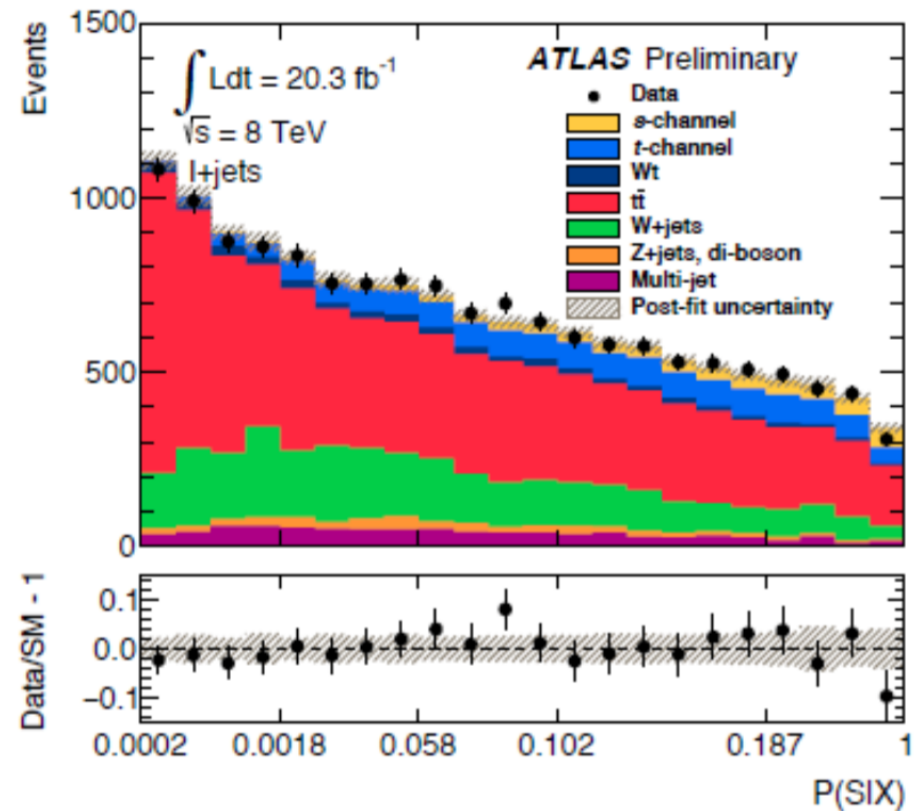
- **Tevatron: combine individual discriminants including all correlations**



→ **observation: 6.3 s.d.**

- **ATLAS: matrix element method**

2-jet 2-tag ($\sim 4.3\%$ of s-channel)



→ **evidence: 3.2 s.d.**