Top quarks at the new energy frontier

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DESY Seminar, 23 – 24 May 2017

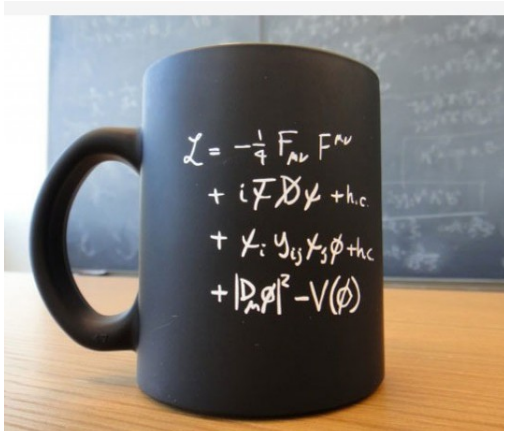
HELMHOLTZ GEMEINSCHAFT

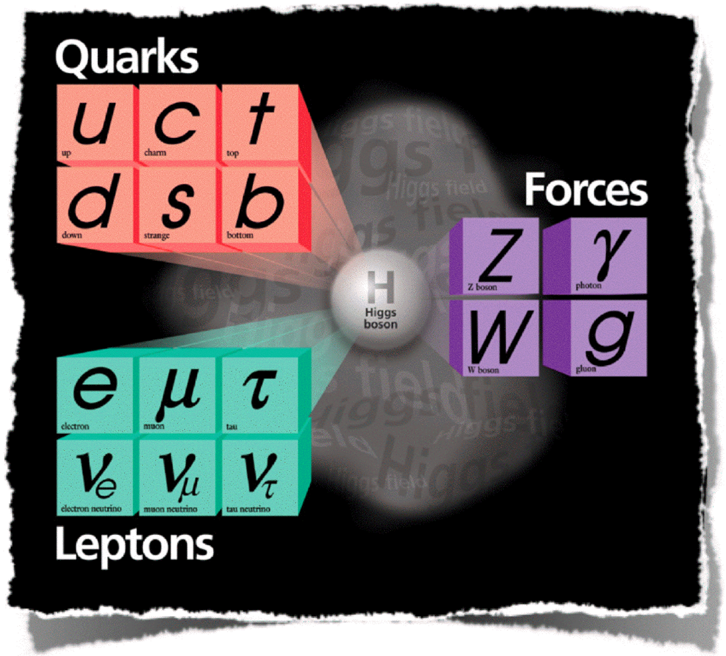
DESY

The Standard Model (SM) of particle physics

One of the greatest achievements of 20th Century Fundamental Science

… and fits in a mug





- Successful description of matter structure
  - 12 matter and 12 antimatter particles (fermions)
  - 3 fundamental interactions (carriers: bosons)

- Experimentally confirmed over the last 50 years with incredible precision (< 1%) !

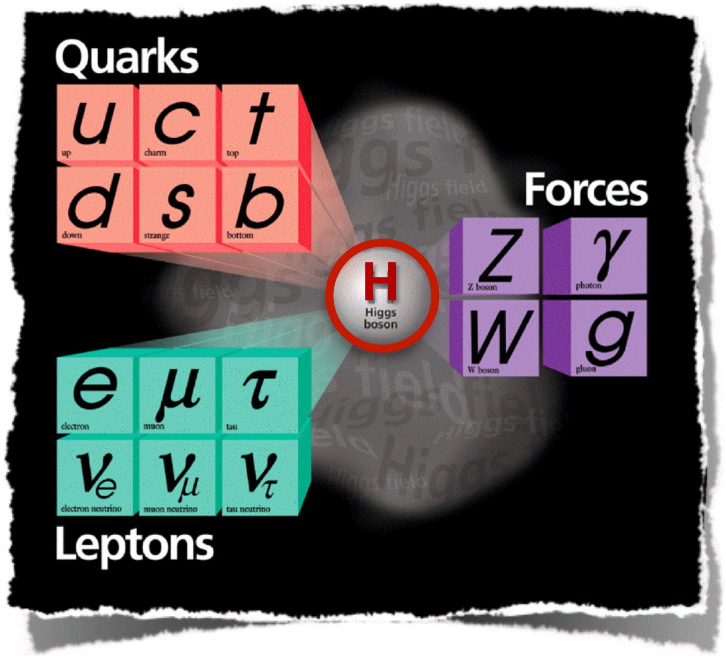
- **Last missing piece:** the Higgs boson

The Standard Model (SM) of particle physics

One of the greatest achievements of 20th Century Fundamental Science

- 2012: LHC experiments discovered a new Higgs-like boson
  - Huge deal: candidate to close the long-standing puzzle of how elementary particles acquire mass in the SM
  - Since then, focus set to measure its properties as precisely as possible

But does it behave like the SM Higgs?

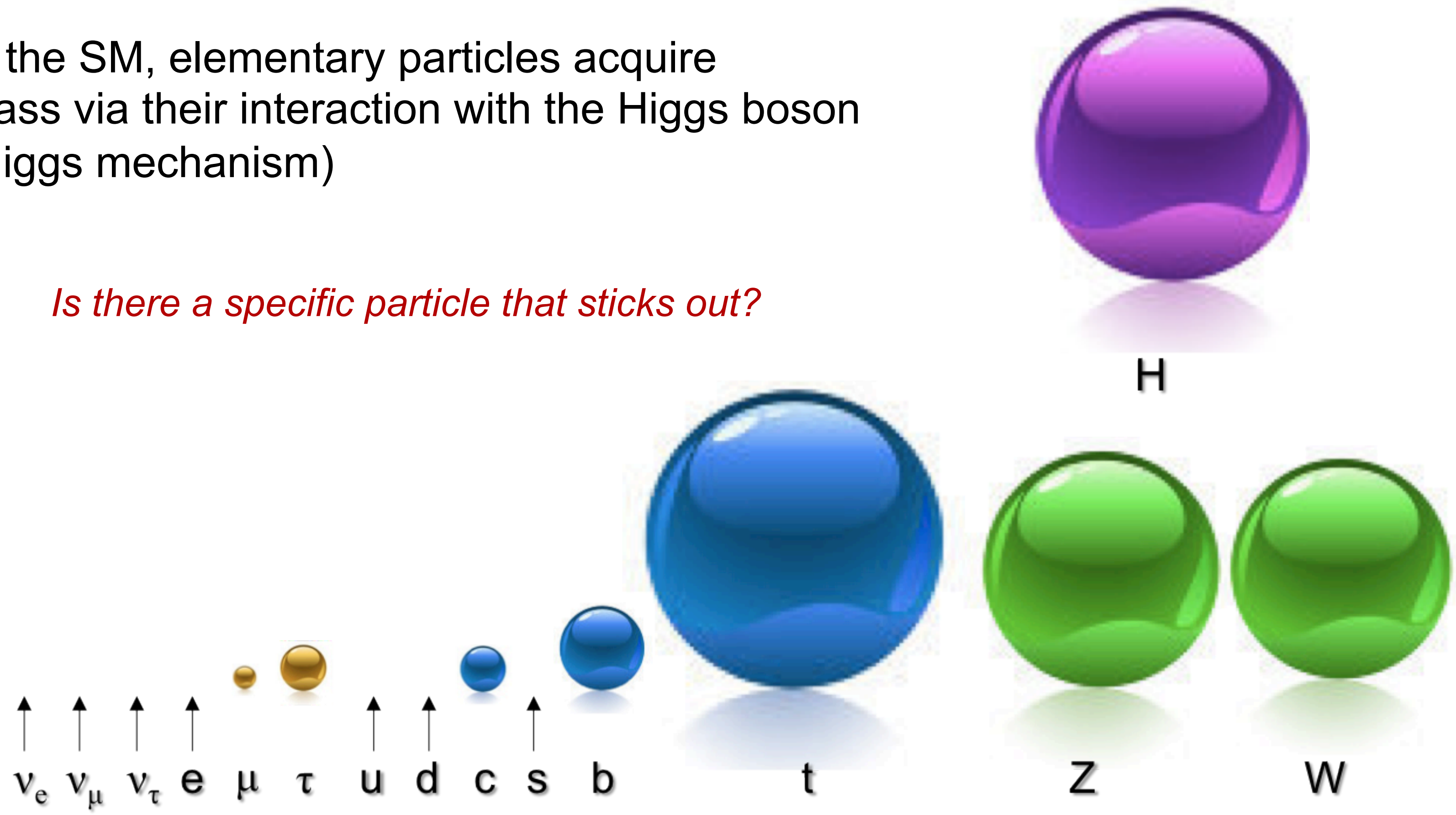


Announcement in a seminar at CERN on July 4th, 2012

What is the origin of particle mass?

In the SM, elementary particles acquire mass via their interaction with the Higgs boson (Higgs mechanism)

Is there a specific particle that sticks out?



Volume of sphere proportional to particle mass

Top quarks at the LHC are crucial to pin down the SM nature of the Higgs

The (in)complete Standard Model picture

- There are several open questions that the SM cannot answer

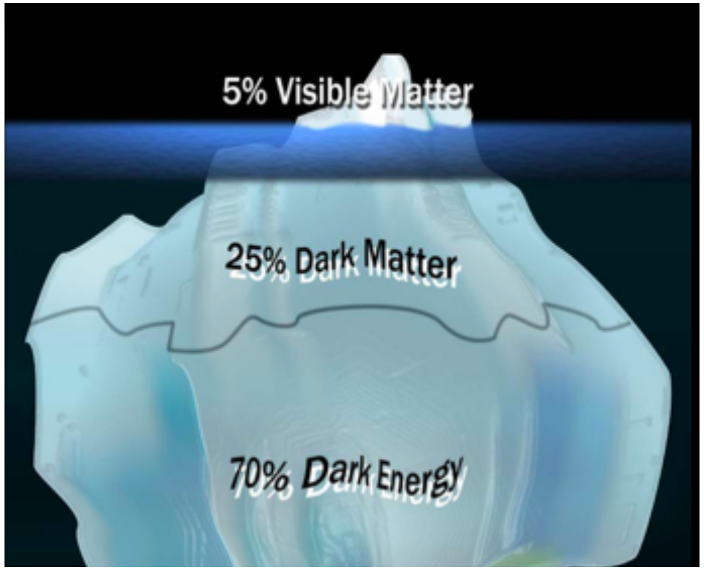
  Neutrino masses, why only three families of elementary particles, the matter/antimatter imbalance in the Universe, the nature of dark-matter and dark energy, gravitation is missing, […]

- Extensive search for possible SM extensions, but no signs of New Physics yet

Searches for New Physics

→ Direct test of specific models

→ Precision SM measurements



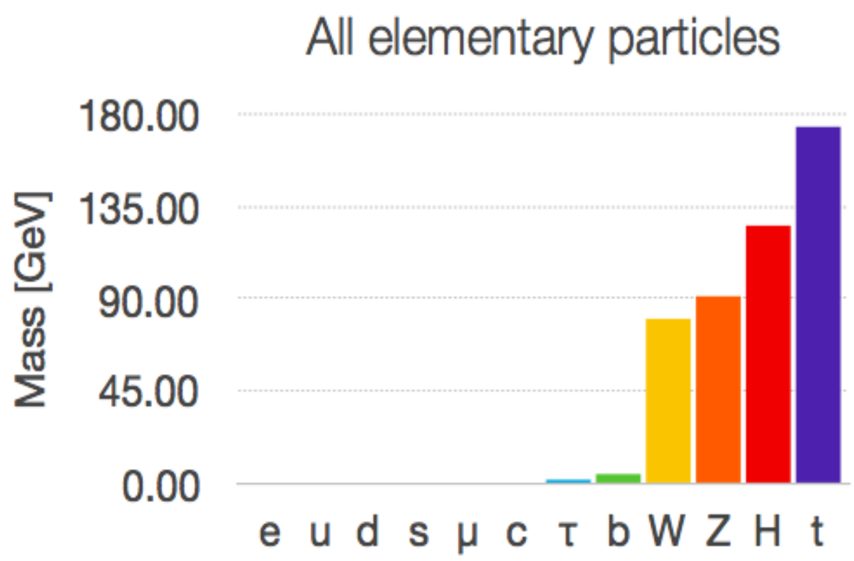
… we just know the tip of the iceberg

Top quarks at the LHC are an excellent tool for stringent tests of the SM and direct search for BSM physics

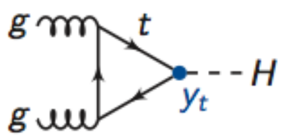
The top quark is special

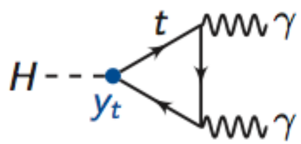
Heaviest elementary particle known to date

- **Short lived**
  - Decays before hadronizing
  - Does not form bound states
  - Spin transferred to decay products



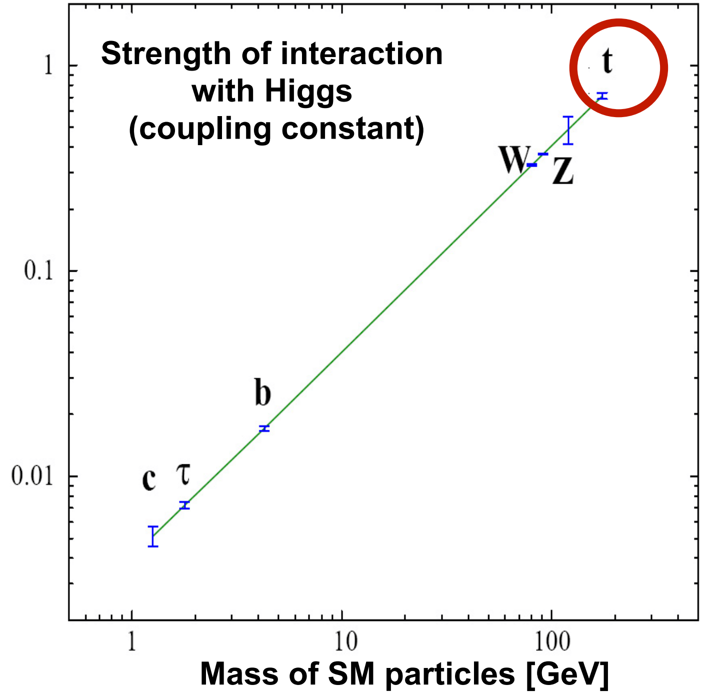
- **Couples strongly to Higgs**
  - $y_t \sim 1$





Several open questions:

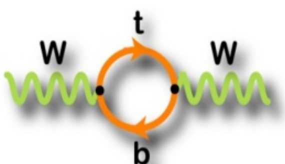
- Is the top mass generated by the Higgs mechanism?
- Role in EW symmetry breaking?
- Role in beyond BSM physics?



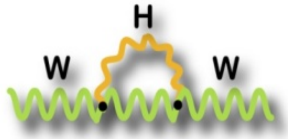
Constraining the Standard Model

- The top quark mass is a fundamental parameter of the SM

- Top, W and Higgs masses are related at loop level



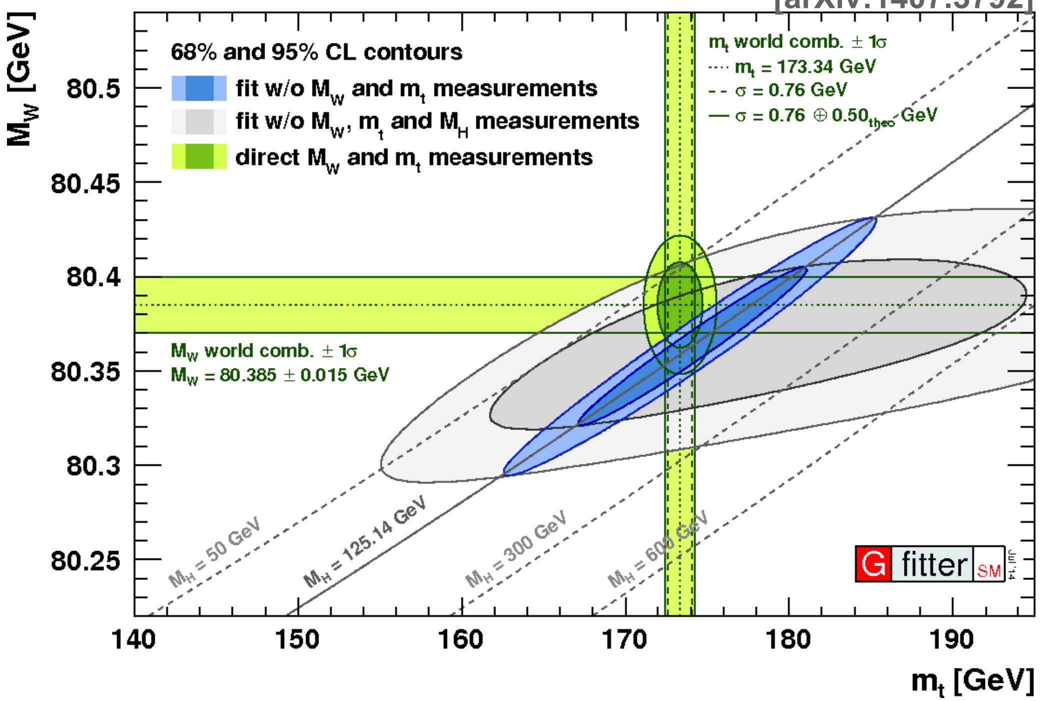
$\delta m_W \propto m_t^2$



$\delta m_W \propto \ln(m_H)$

  - Precise m_{top} measurement: assessment of self-consistency within the SM

[arXiv:1407.3792]



- Other properties of the top quark (electroweak couplings, production asymmetries, etc) are predicted by the SM

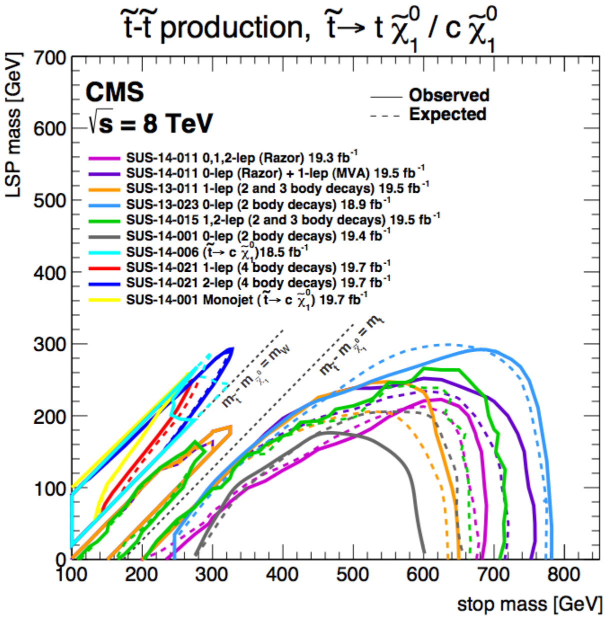
→ Precision measurements could reveal the SM breaking down

Every top quark precision measurement is a search

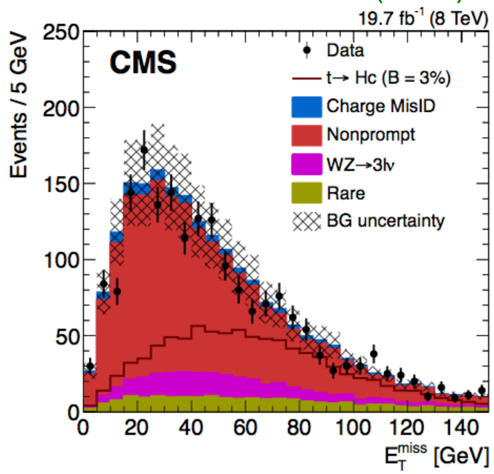
Direct probe for New Physics

- Top is a main ingredient of many BSM scenarios

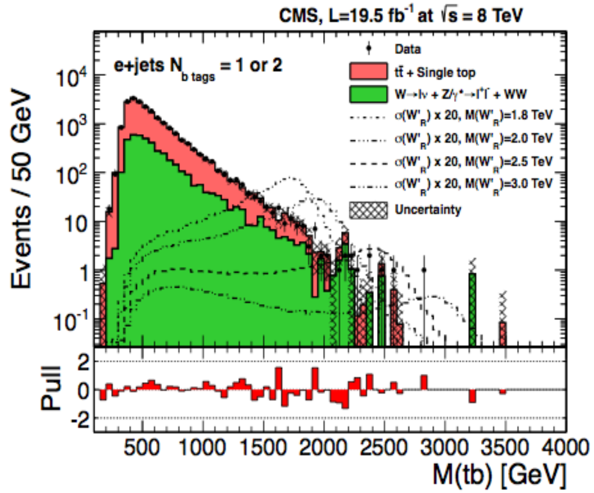
Exotic partners, rare decays,
heavy resonances decaying to top,
new particles produced with top …



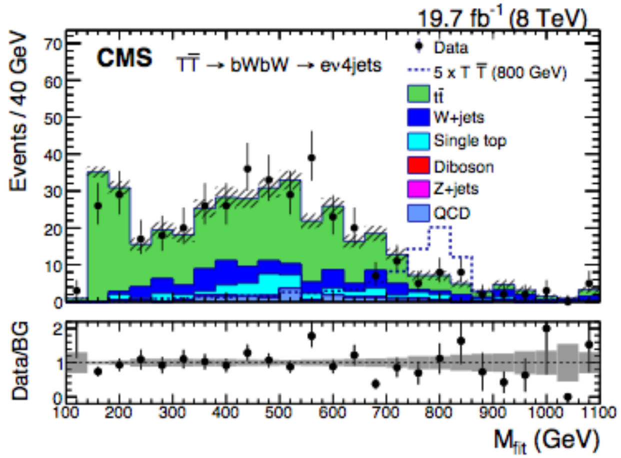
FCNC t→Hc JHEP 02 (2017) 079



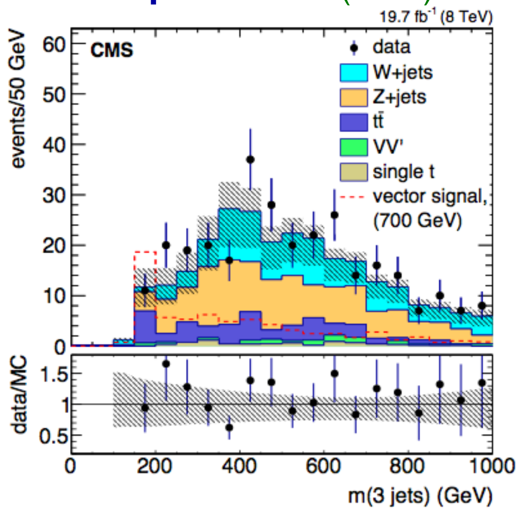
W'→tb JHEP 05 (2014) 108



Vector-like T (2/3) PRD 93 (2016) 012003



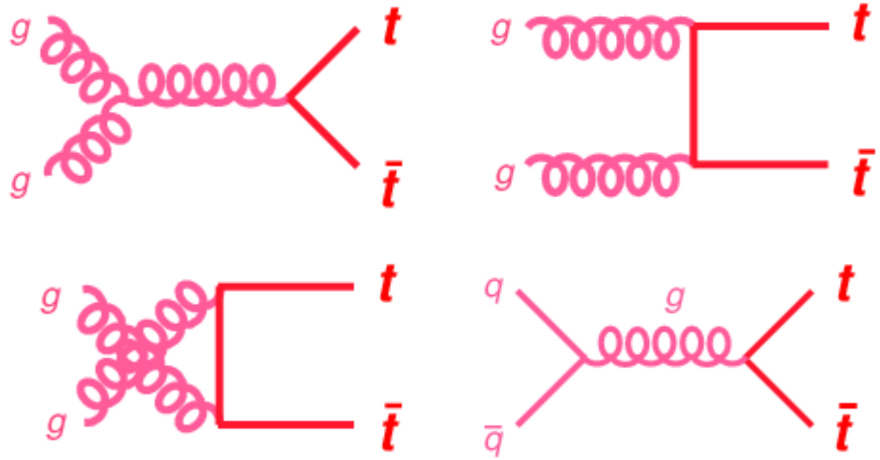
Monotop PRL 114 (2015) 101801



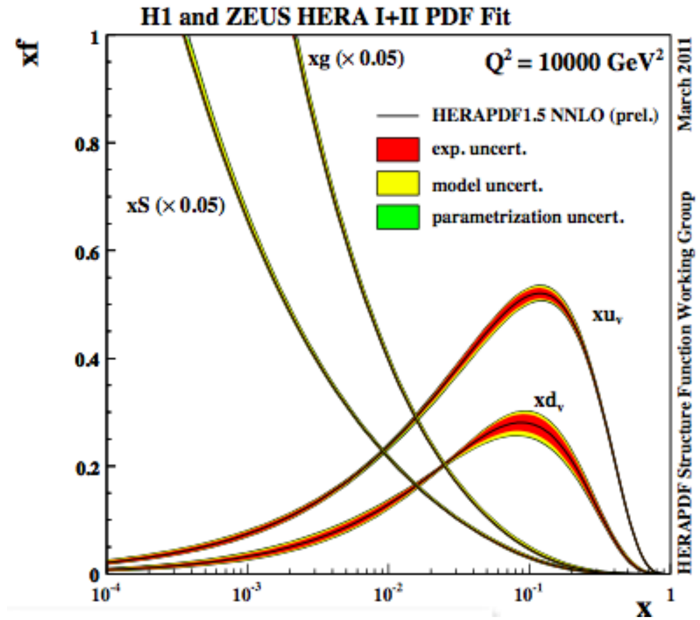
The top quark is a sensitive probe for New Physics

How are top quarks produced?

- Strong top pair ($t\bar{t}$) production: sensitive to α_s, top mass, PDFs



	LHC(13)	LHC(7)	Tev(1.9)
gg	~90%	~85%	~10%
qq	~10%	~15%	~90%



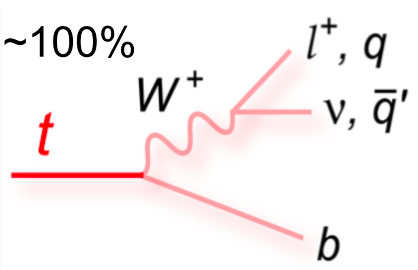
NNLO+NNLL predictions available since 2013:

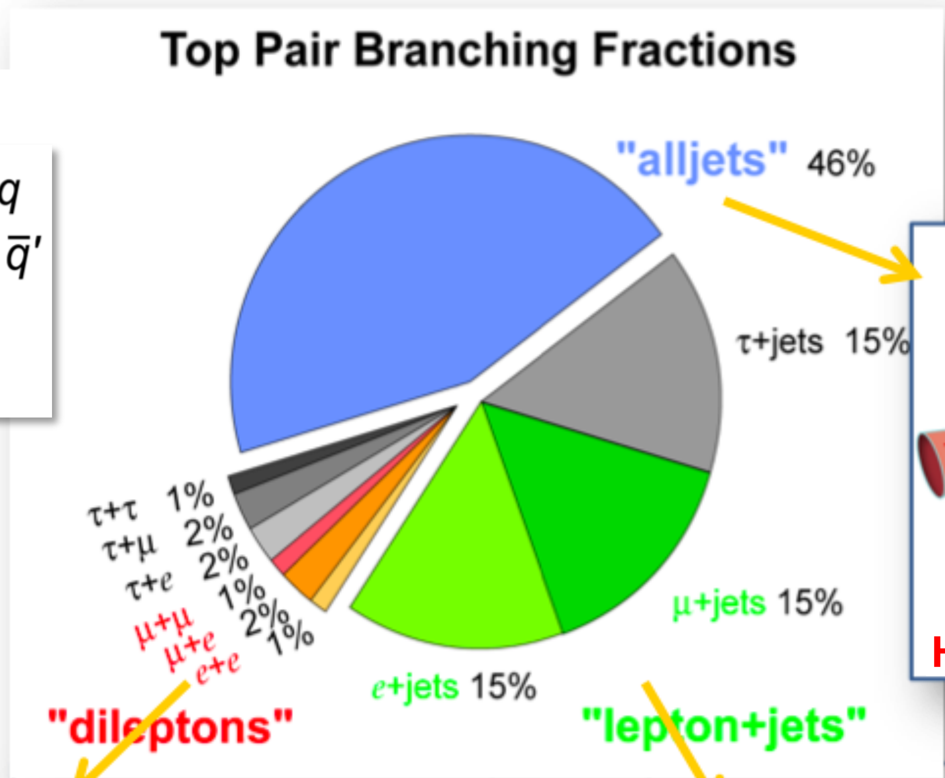
$$\sigma(7\ \mathrm{TeV}) = 177\ \mathrm{pb} \pm 7\%$$
$$\sigma(8\ \mathrm{TeV}) = 253\ \mathrm{pb} \pm 6\%$$
$$\sigma(13\ \mathrm{TeV}) = 832\ \mathrm{pb} \pm 5\%$$
$$R_{13/8} = 3.28$$

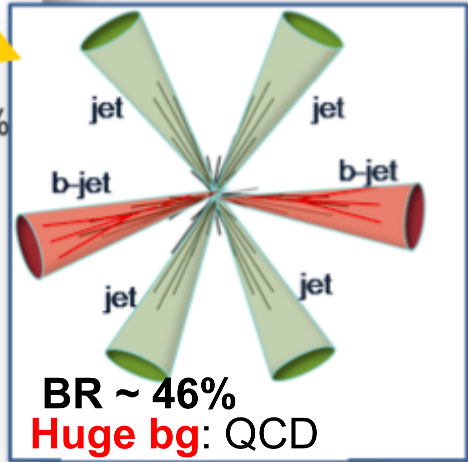
[PRL 110 (2013) 252004]

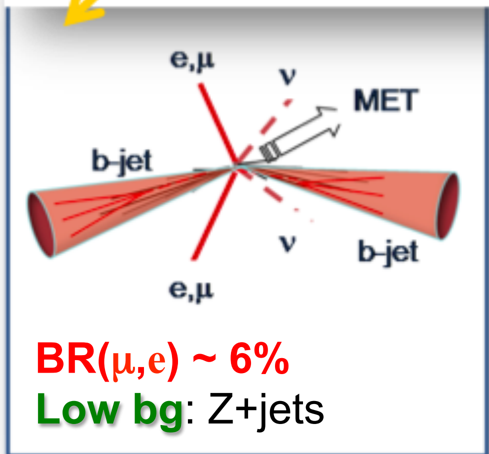
… and how do they decay?

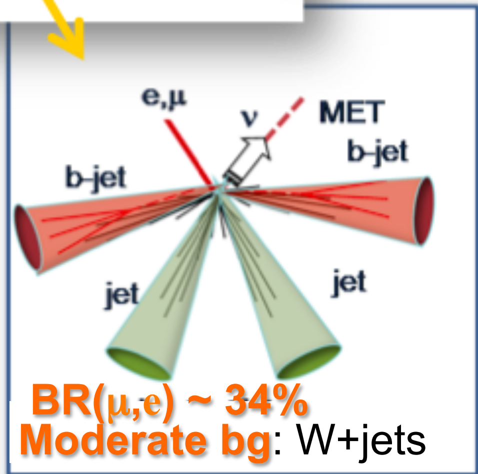
In the SM:





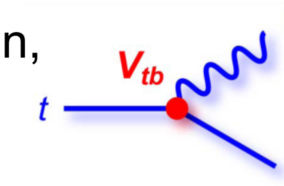




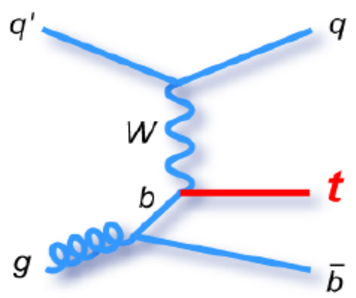


Single top quark

- Electroweak single top quark production: tWb vertex in production, sensitive to Vtb, sensitive to PDFs

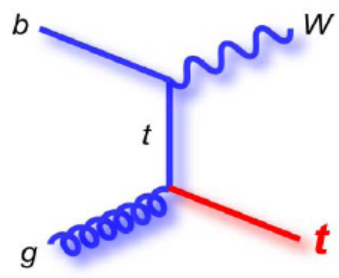


V_{tb}~1



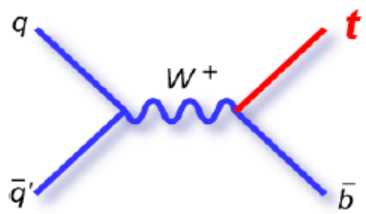
t-channel

$$\sigma(7\ \text{TeV}) = 64\ \text{pb} \pm 4.5\%$$
$$\sigma(8\ \text{TeV}) = 85\ \text{pb} \pm 4.4\%$$
$$\sigma(13\ \text{TeV}) = 217\ \text{pb} \pm 4.1\%$$
$$R_{13/8} = 2.6$$



tW-channel

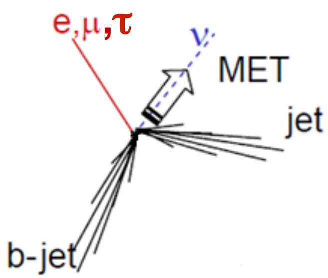
$$\sigma(7\ \text{TeV}) = 15.7\ \text{pb} \pm 7.6\%$$
$$\sigma(8\ \text{TeV}) = 22.4\ \text{pb} \pm 6.8\%$$
$$\sigma(13\ \text{TeV}) = 71.7\ \text{pb} \pm 5.3\%$$
$$R_{13/8} = 3.2$$

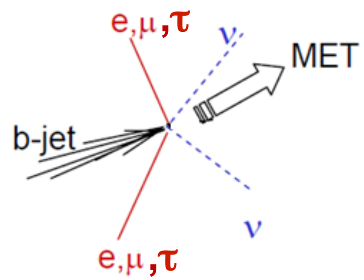


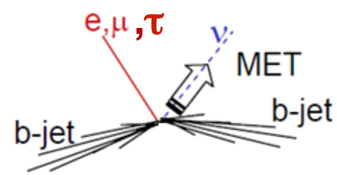
s-channel

$$\sigma(7\ \text{TeV}) = 4.3\ \text{pb} \pm 4.4\%$$
$$\sigma(8\ \text{TeV}) = 5.2\ \text{pb} \pm 4.2\%$$
$$\sigma(13\ \text{TeV}) = 10.3\ \text{pb} \pm 3.9\%$$
$$R_{13/8} = 1.9$$

- Final states:



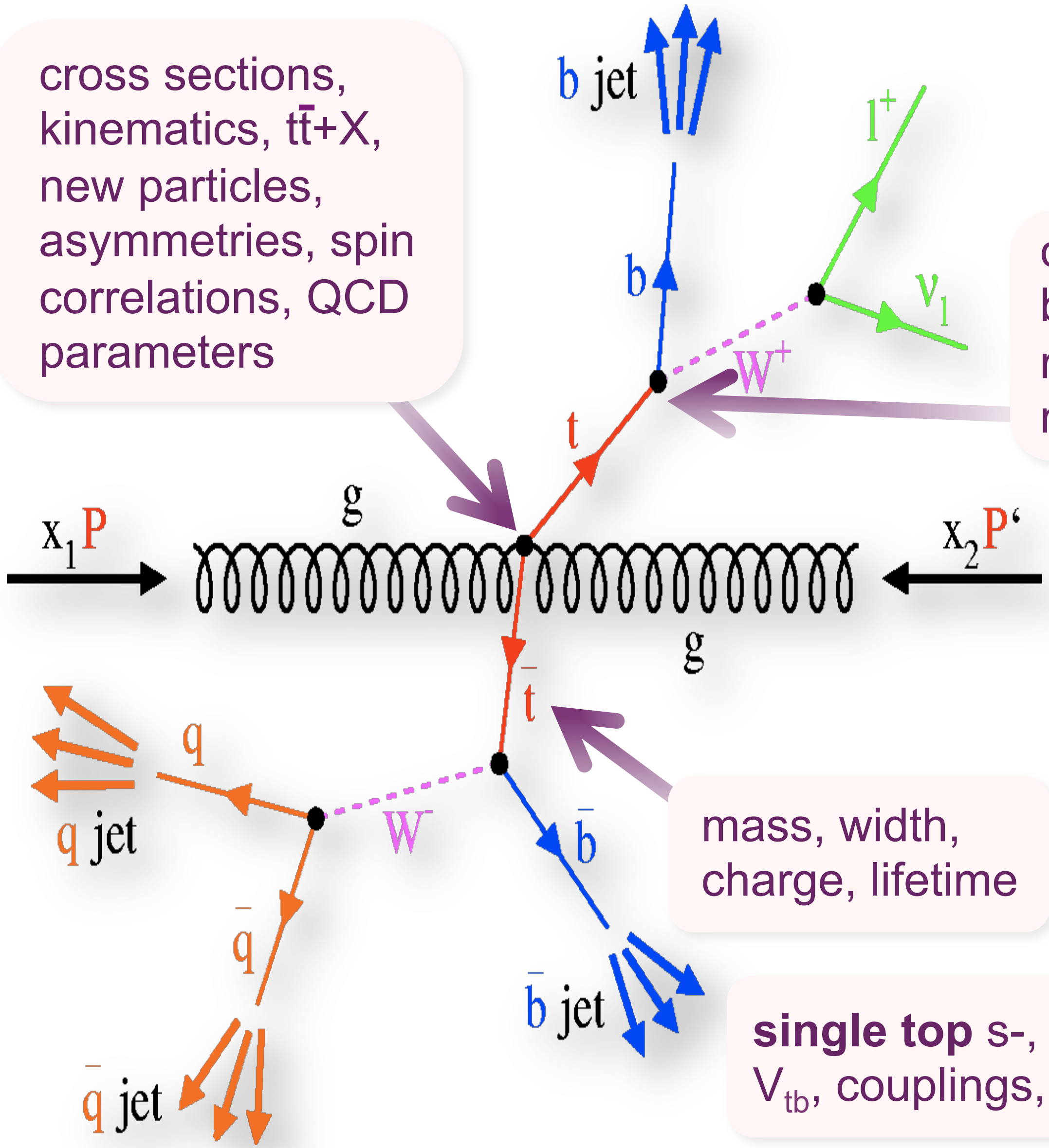




- Large backgrounds: W/Z+jets, $t\bar{t}$, QCD

Top quark properties in production and decay

cross sections, kinematics, $t\bar{t}$+X, new particles, asymmetries, spin correlations, QCD parameters



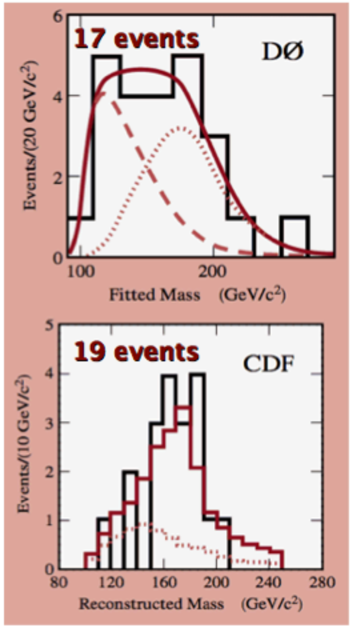
couplings, FCNC, branching ratios, V_{tb}, rare decays, W-helicity, new particles

mass, width, charge, lifetime

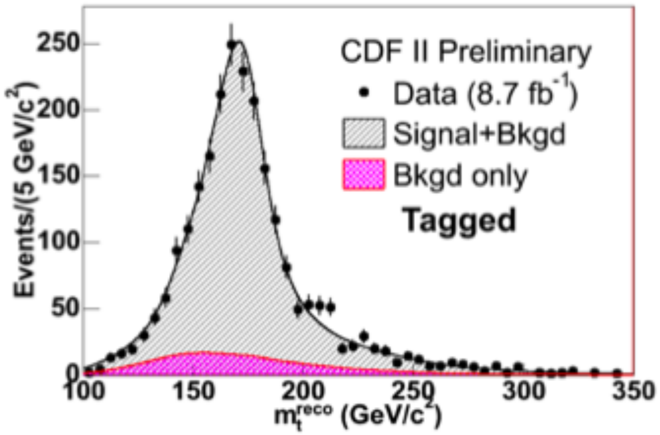
single top s-, t-, tW-channel production, V_{tb}, couplings, FCNC, polarization, mass

Trip down memory lane

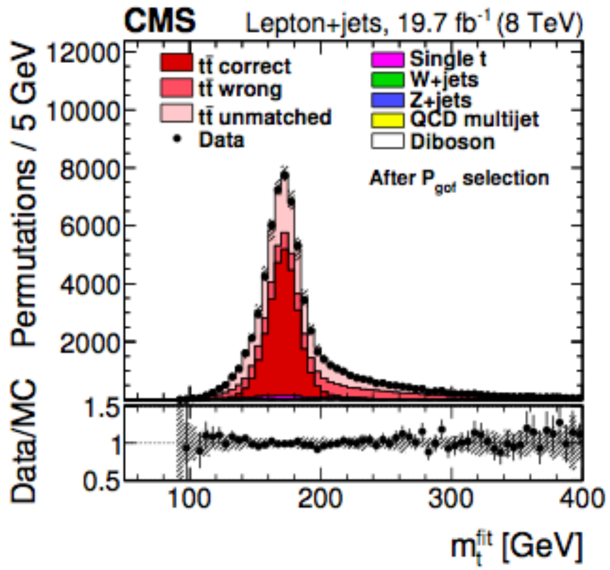
36 events



1000s events



100000s events



Tevatron $p\bar{p}$ 1.96 TeV

- "Birthplace" of the top
- Scrutinize and measure
- Establish top as SM quark

First observation of single top production

LHC Run-I pp (7 and 8 TeV)

- pp: complementary initial state
- Larger statistics: **top factory**:

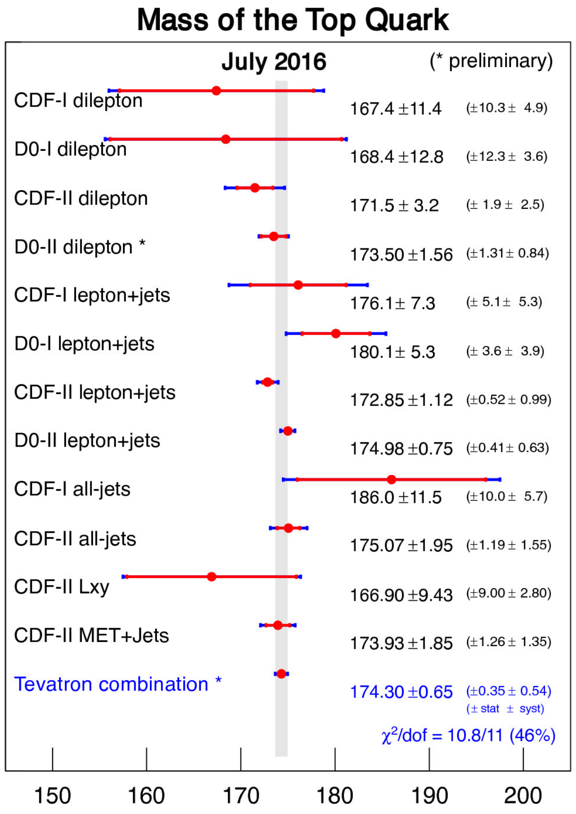
More than 5M tt pairs

→ 20x more than Tevatron in its lifespan!

1995 2009 2010 2012

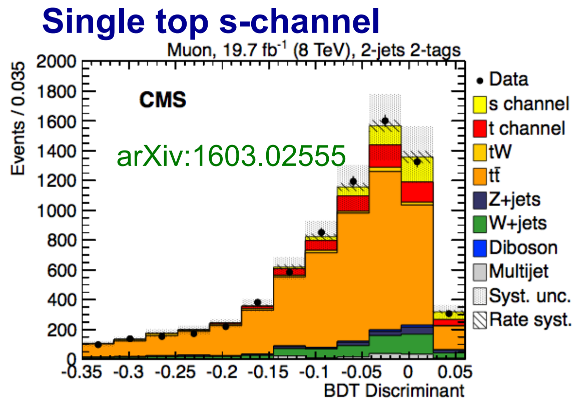
The present

Some examples

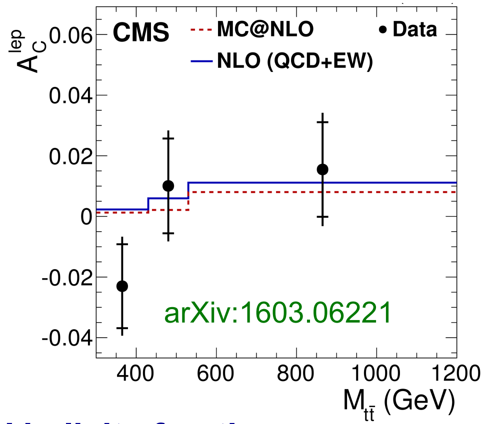


m_{top} **Tevatron = 174.30 ± 0.65 GeV**

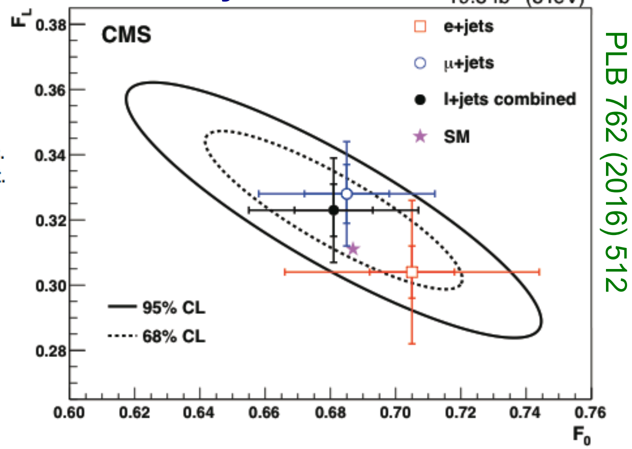
Single top s-channel



Leptonic charge asymmetry



W-helicity fractions



Tevatron and LHC Run-I Legacies:
Measurements of top cross sections, mass and properties at highest possible precision

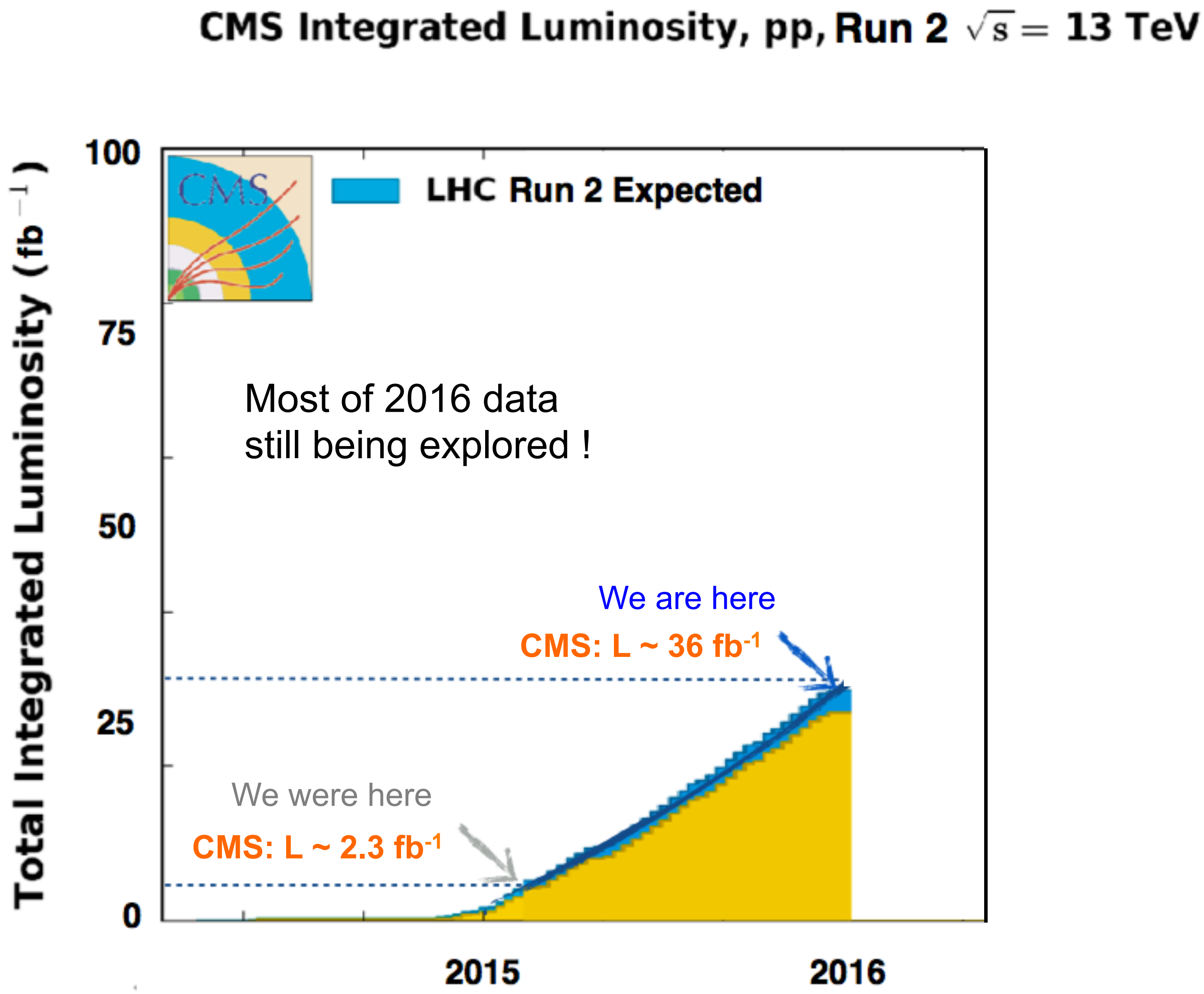
LHC Run-II 13 TeV (2015 – 2016)
- Rediscover
- Measure

30M tt pairs!

LHC Run-II 13 TeV restarts ~**now**!

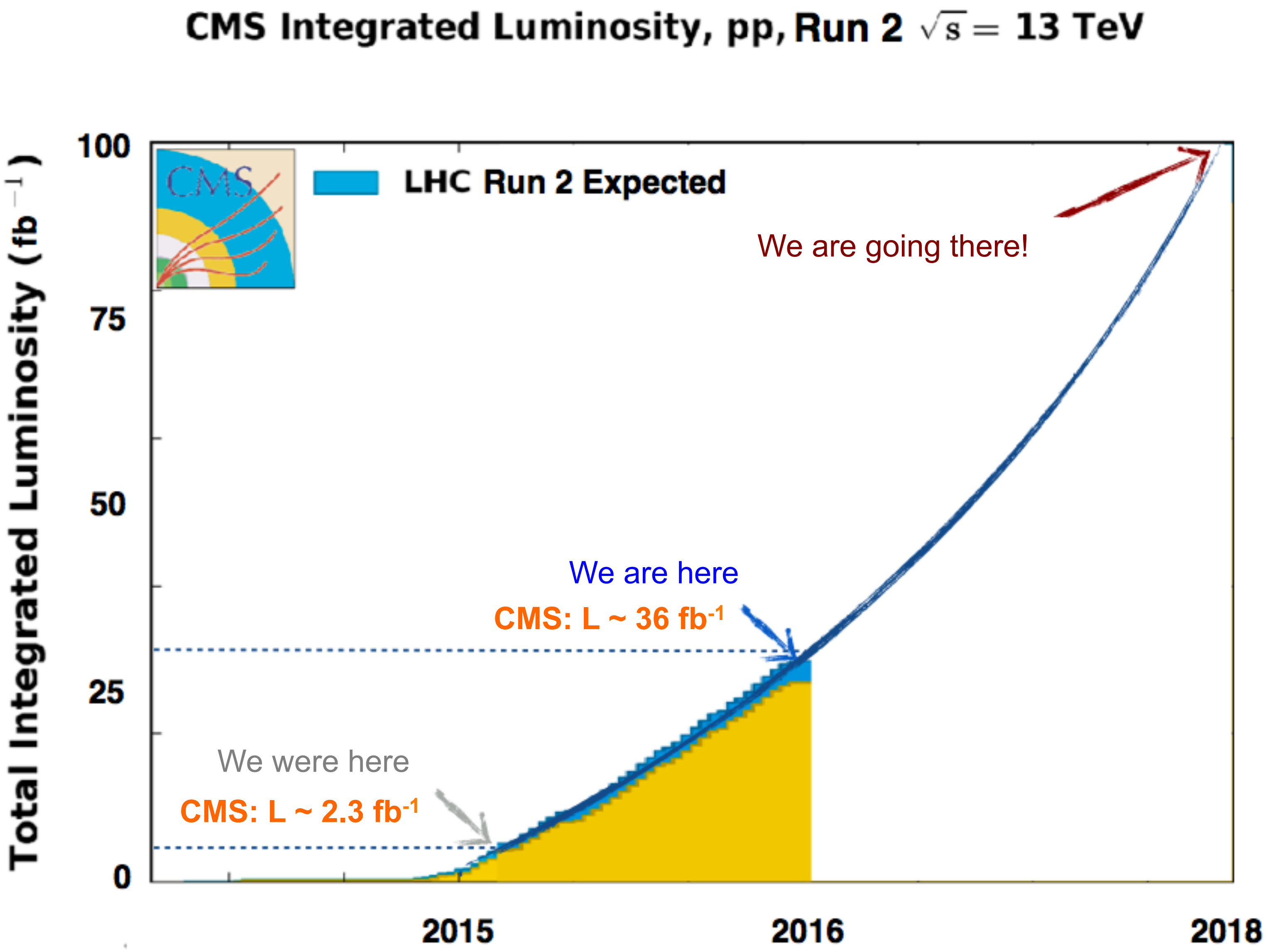
2012 2015 2016 2017

The present…

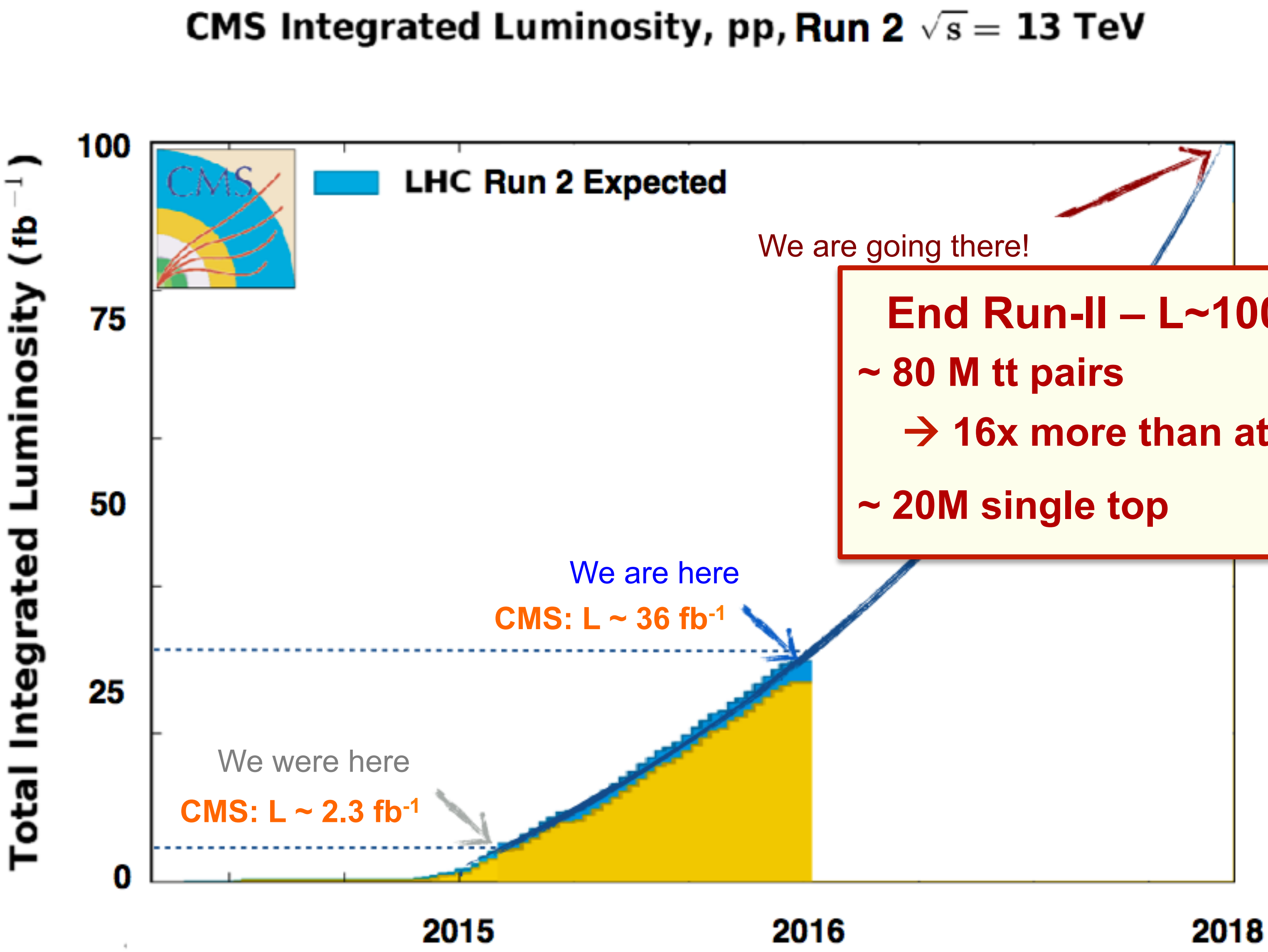


CMS Integrated Luminosity, pp, Run 2 $\sqrt{s} = 13$ TeV
Total Integrated Luminosity (fb^{-1})
100
75
50
25
0
CMS
LHC Run 2 Expected
Most of 2016 data
still being explored !
We are here
CMS: L ~ 36 fb^{-1}
We were here
CMS: L ~ 2.3 fb^{-1}
2015
2016

The present… and the future!



The present… and the future!



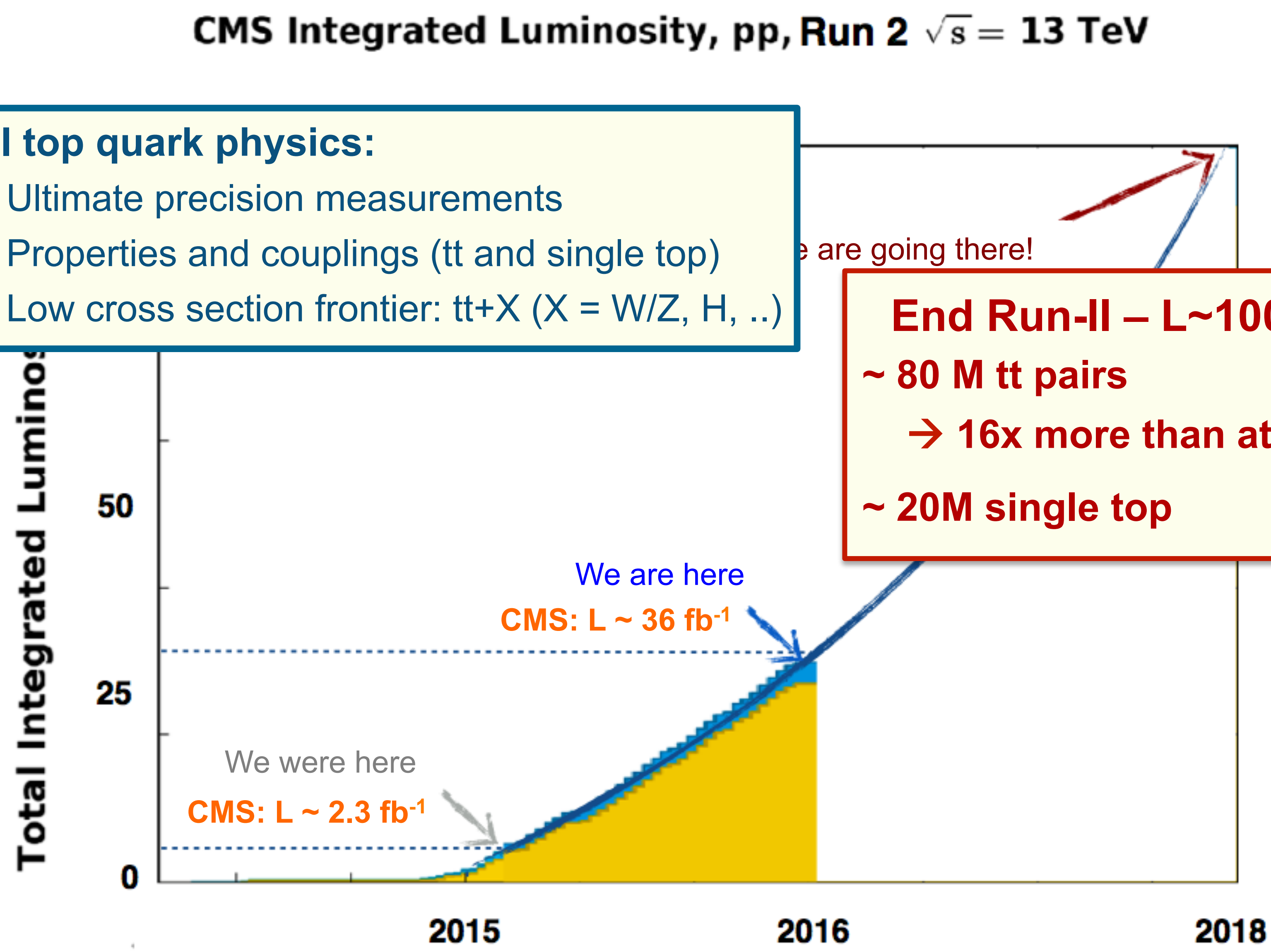
End Run-II – L~100 fb^{-1}:

~ 80 M tt pairs

→ 16x more than at 8 TeV

~ 20M single top

The present… and the future!



Run-II top quark physics:

- Ultimate precision measurements
- Properties and couplings (tt and single top)
- Low cross section frontier: tt+X (X = W/Z, H, ..)

End Run-II – L~100 fb^{-1}:

~ 80 M tt pairs

→ 16x more than at 8 TeV

~ 20M single top

The present… and the future!

CMS Integrated Luminosity, pp, Run 2 $\sqrt{s}$ = 13 TeV

Run-II top quark physics:

Today's talk:

Personal selection of CMS results mostly from Run-II

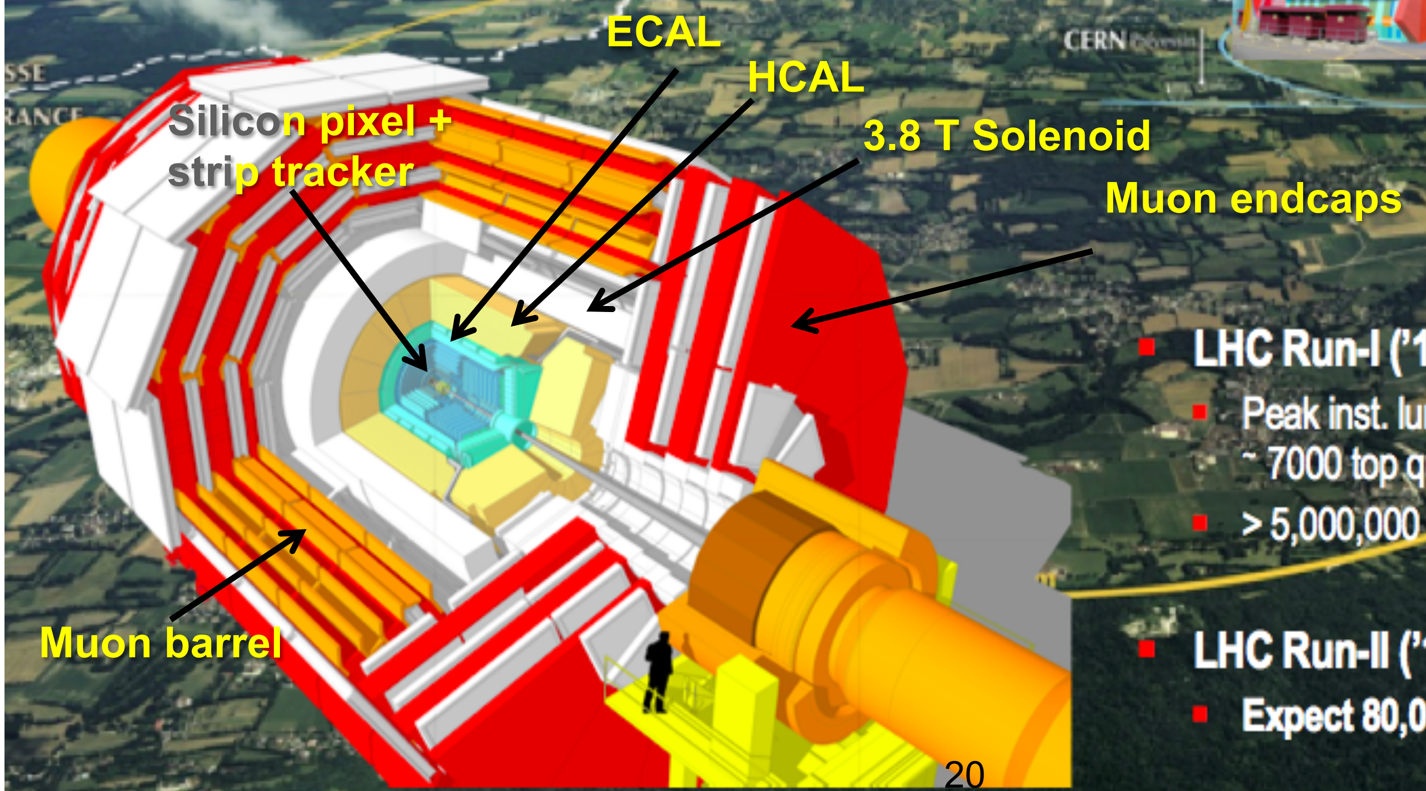
- $t\bar{t}$ production rate and dynamics
- $t\bar{t}$+Z/W, $t\bar{t}$+H
- Single top quark
- (A glympse of) top quark properties

All CMS top quark results can be found here:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

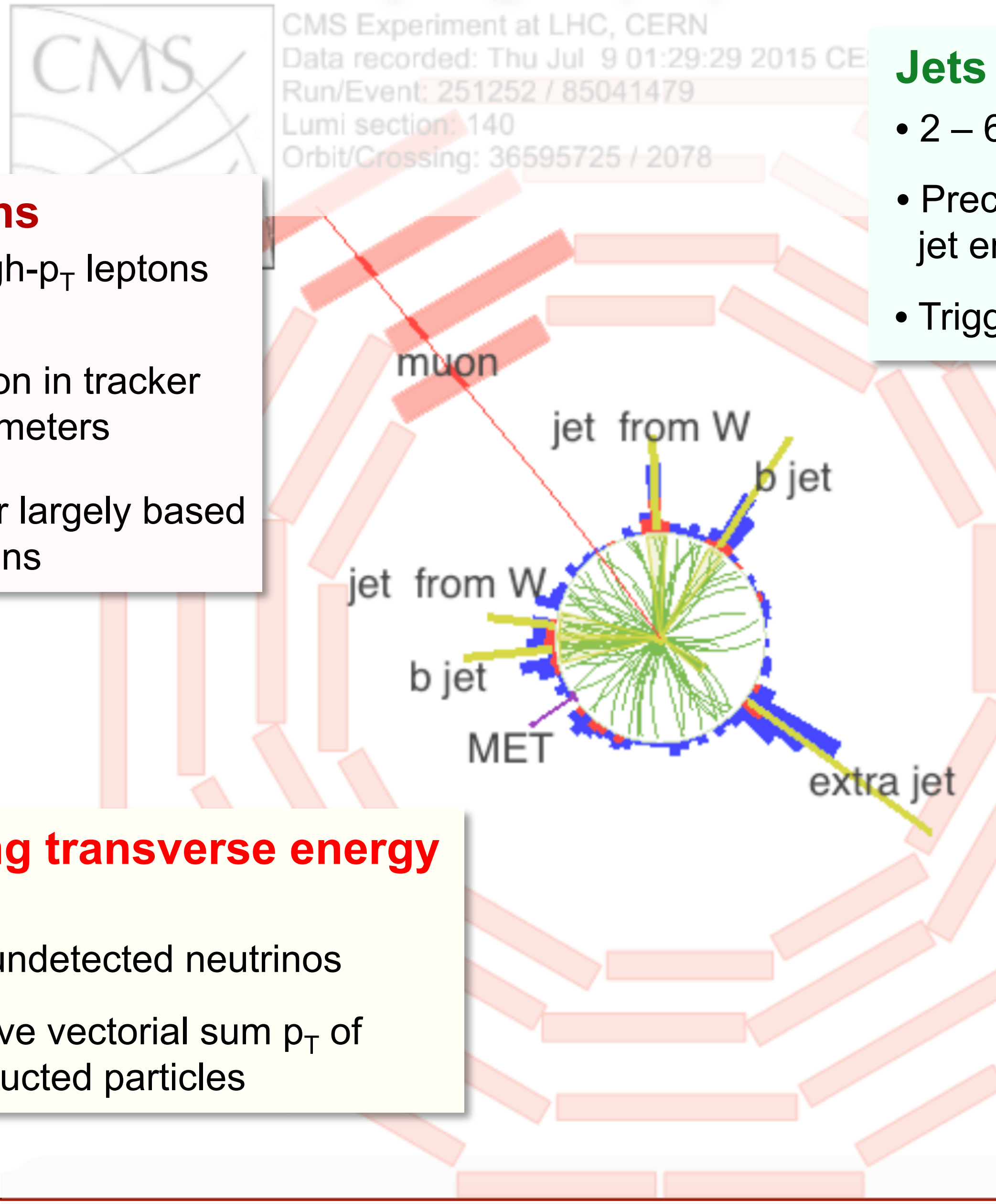
CMS Experiment at the LHC

- Total Weight 14000 t
- Diameter 15 m
- Magnetic Field 3.8 T
- Silicon Pixel and Strip Trackers
- Crystal ECal, Brass HCal
- Muon Chambers, DT, RPC, CSC
- Trigger L1: 100kHz, ~500 Hz to tape



- LHC Run-I ('10-'12): 25 fb^{-1}
  - Peak inst. luminosity: 8 x 10^{33} $cm^{-2}s^{-1}$
  - ~ 7000 top quark pairs per hour (8 TeV)
  - > 5,000,000 top each CMS and ATLAS
- LHC Run-II ('15-'18): 100 fb^{-1} (13 TeV)
  - Expect 80,000,000 $t\bar{t}$ and 80,000 $t\bar{t}Z$

Identifying top quarks in CMS



Leptons

- < 2 high-p_T leptons from W
- Isolation in tracker & calorimeters
- Trigger largely based on leptons

Missing transverse energy (MET)

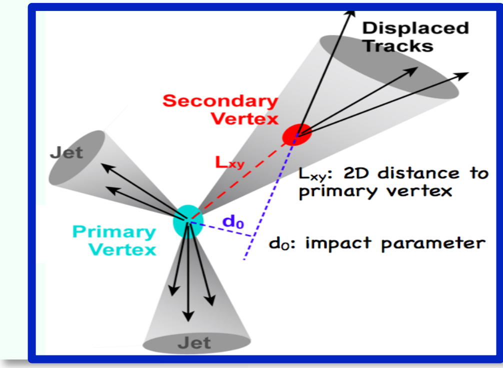
- From undetected neutrinos
- Negative vectorial sum p_T of reconstructed particles

Jets

- 2 – 6 high-p_T jets
- Precise measurement with small jet energy scale uncertainty
- Trigger on lepton+jets signatures

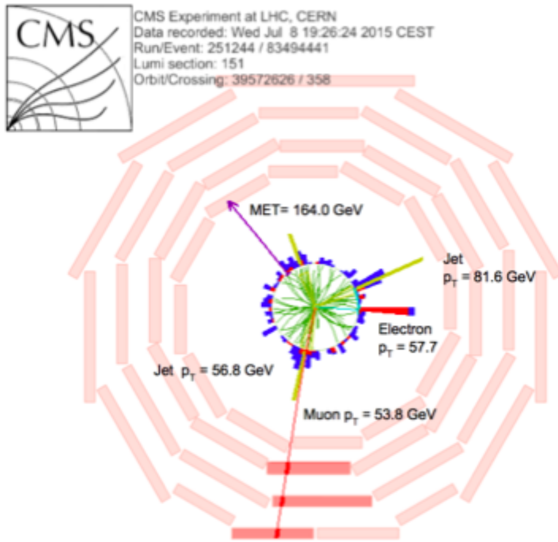
b-jet ID (b-tagging)

- B-hadron properties: large lifetime ~ 1.5 ps
  → large decay length
- Use secondary vertices, displaced tracks, non-iso leptons inside b-decays



13 TeV candidate:

eμ + 2 *b*-tags



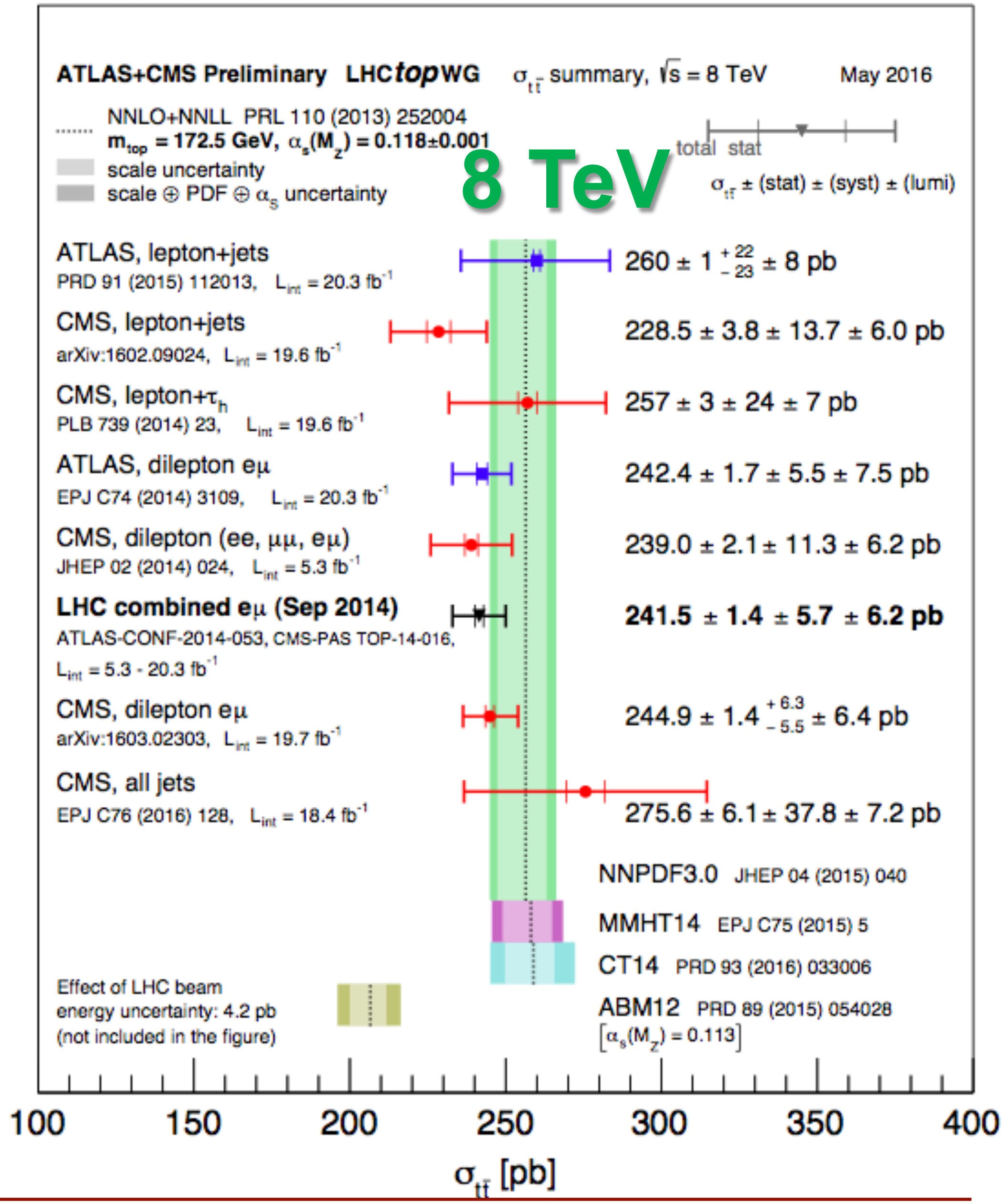
Rates and dynamics of top quark pair production

- First step in understanding top physics
- Test of QCD calculations and search for new physics

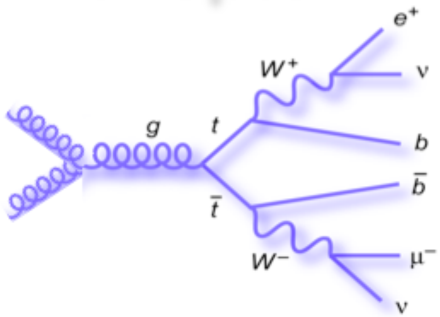
Run-I inclusive $t\bar{t}$ cross section

All channels measured at 7 & 8 TeV
to look for the unexpected

- Good agreement with NNLO+NNLL
- Highest precision: dilepton eμ channel ~4%, similar to theory prediction
  - High purity (~90%)
- LHCtopWG Run-I combinations underway



Run-II $t\bar{t}$ cross section: dilepton



- Simple and robust approach

Selection: opposite-sign isolated eμ, ≥ 2 jets, 1 b-tag

- Focus on counting high-purity **eμ** events

$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon_{t\bar{t}} \int Ldt}$$

σ(tt) = 815 ± 9 (stat) ± 38 (syst) ± 19 (lumi) pb

(precision~ 5.3%)

$\sigma^{theory}(tt) = 832\ ^{+40}_{-46}$ pb

Main uncertainties: luminosity (2.3%), lepton efficiencies (2.3%) jet energy scale (2.1%), signal modelling (2.1%)

Systematics can be further reduced with more data and more sophisticated analysis techniques → learn from Run-I

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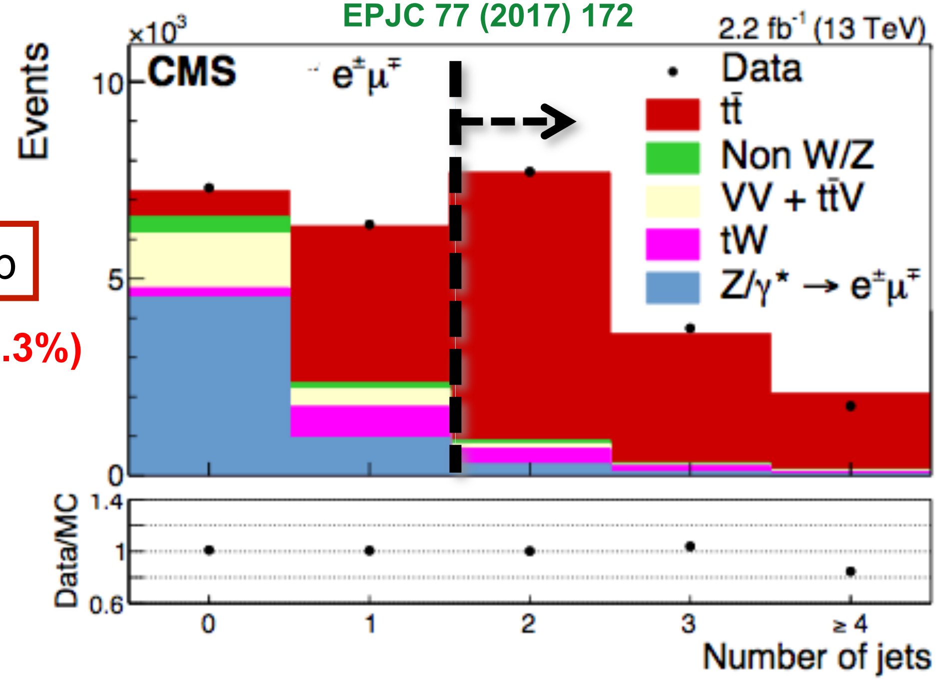


First measurement with only 43 pb^{-1} of data: **precision ~ 11%**, statistically limited

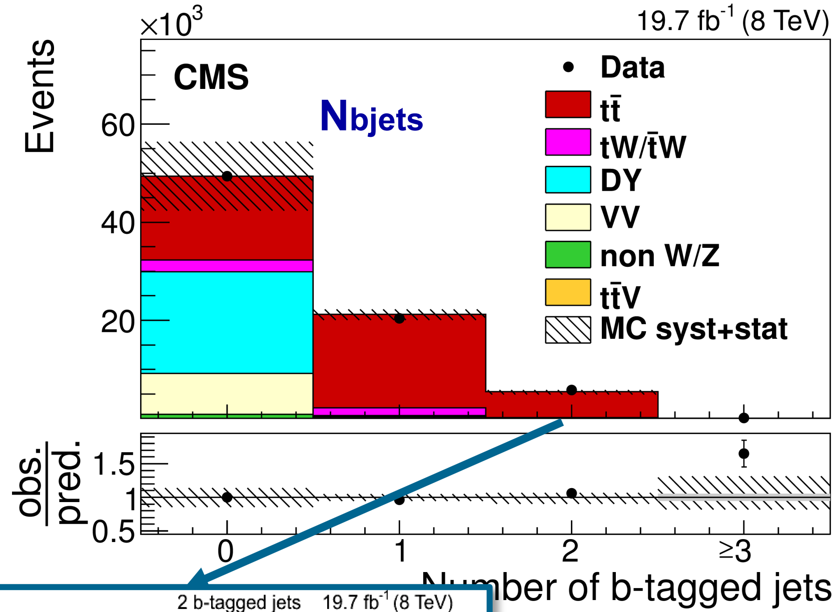
PRL 116 (2016) 052002

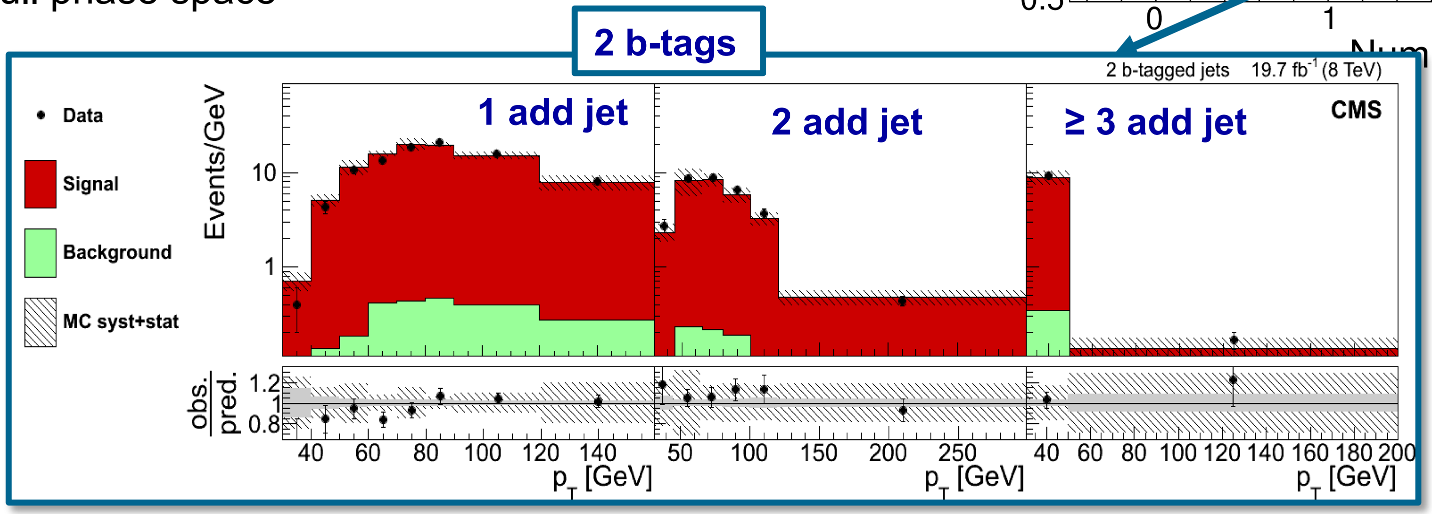
Run-I Legacy $t\bar{t}$ cross sections

Eroding the systematics wall

Selection: opp.-sign isolated eμ pair, jets, b-tags

- Study differentially event categories for signal/background discrimination, modelling sensitivity
  - Constrain backgrounds and main systematic uncertainties in fiducial region, extrapolate to full phase space





7 TeV: $\sigma_{t\bar{t}} = 173.6 \pm 2.1\,(\text{stat})^{+4.5}_{-4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb}$

8 TeV: $\sigma_{t\bar{t}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})\,\text{pb}$

(precision ~ 3.7%)

JHEP 08 (2016) 029

Run-II $t\bar{t}$ cross sections: challenges

Systematic uncertainties:

	Source	Δσ/σ (%)
Experimental	Trigger	1.2
	Lepton ID	1.5
	Jet Energy Scale	0.8
	Drell-Yan Bg.	1.4
	b-tag	0.5
	Luminosity	2.6
	Total visible	3.6
Theory	Scale (extrap.)	0.2
	ME/PS (extrap.)	0.2
	Top pt (extrap.)	0.5
	PDF (extrap.)	0.1

Possible improvements for Run-II:

- Experimental
  - Trigger → maximize trigger efficiency
  - Lepton ID → reduce syst with statistics
  - Backgrounds→ additional categories
  - Luminosity
  - Measure tt/Z ratio
- Theory
  - NLO+parton shower (PS) Monte Carlos
  - Improved MC tuning

7 TeV: $\sigma_{t\bar{t}} = 173.6 \pm 2.1\,(\text{stat})^{+4.5}_{-4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb}$

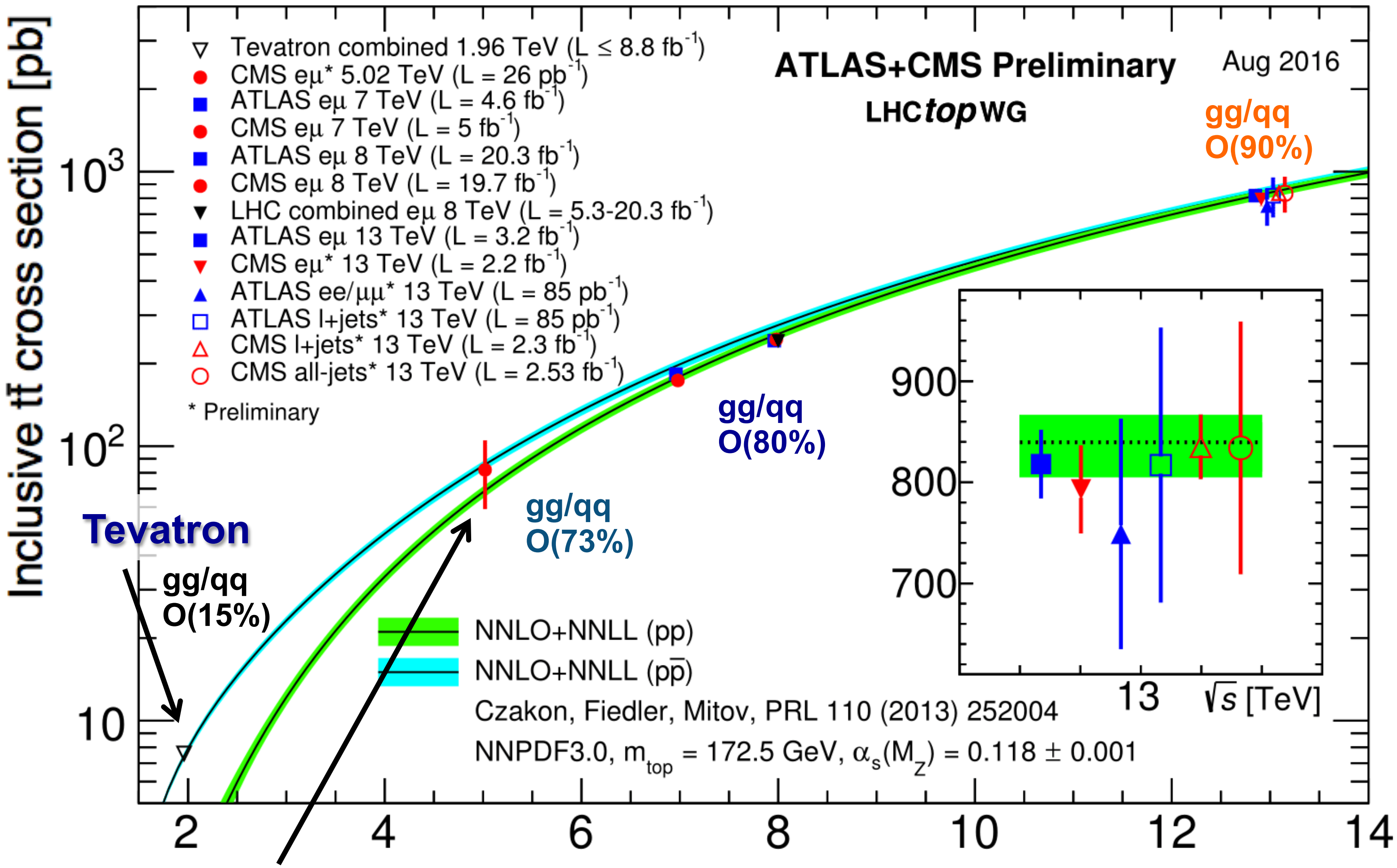
8 TeV: $\sigma_{t\bar{t}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})\,\text{pb}$

(precision ~ 3.7%)

JHEP 08 (2016) 029

$t\bar{t}$ cross section measured at all energies

Dependence as a function of √s well understood



5.02 TeV: First measurement ever at this energy !

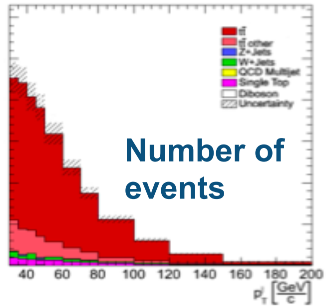
σ(tt) = 69.5 ± 8.4 pb (limited by statistical uncertainty) **CMS-PAS TOP-16-023**

$t\bar{t}$ differential cross sections

Scrutinize $t\bar{t}$ production in all channels as a function of many kinematic observables

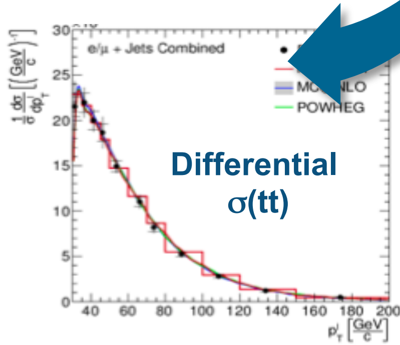
→ Precision tests of pQCD in different regions of phase space, window to BSM physics

- Use final-state products to reconstruct top quark candidates
- Compare to theory calculations and MC simulations
- Correct for detector, parton shower, acceptance effects (unfolding):

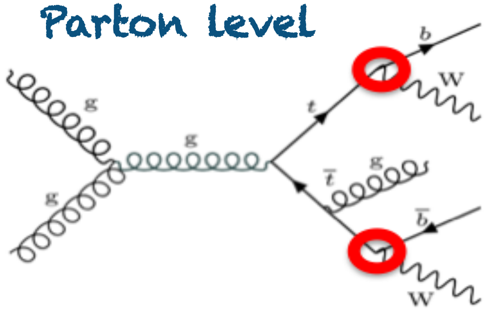


Δ^X_i = bin width for variable X

$$\frac{d\sigma_i}{dX} = \frac{\text{unfold}(s_i^X - b_i^X)}{\Delta_i^X \cdot \int \mathcal{L}dt}$$



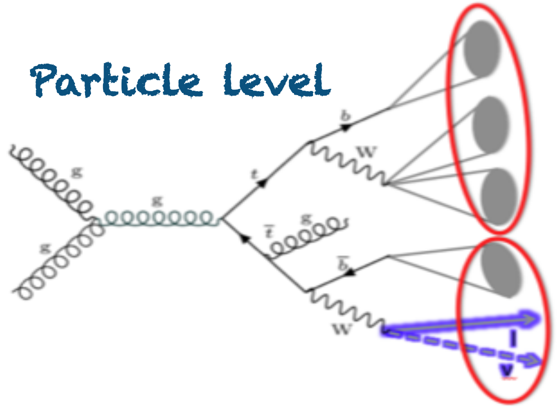
Parton level



Top quarks after radiation before decay

Allows comparison with fixed-order calculations

Particle level

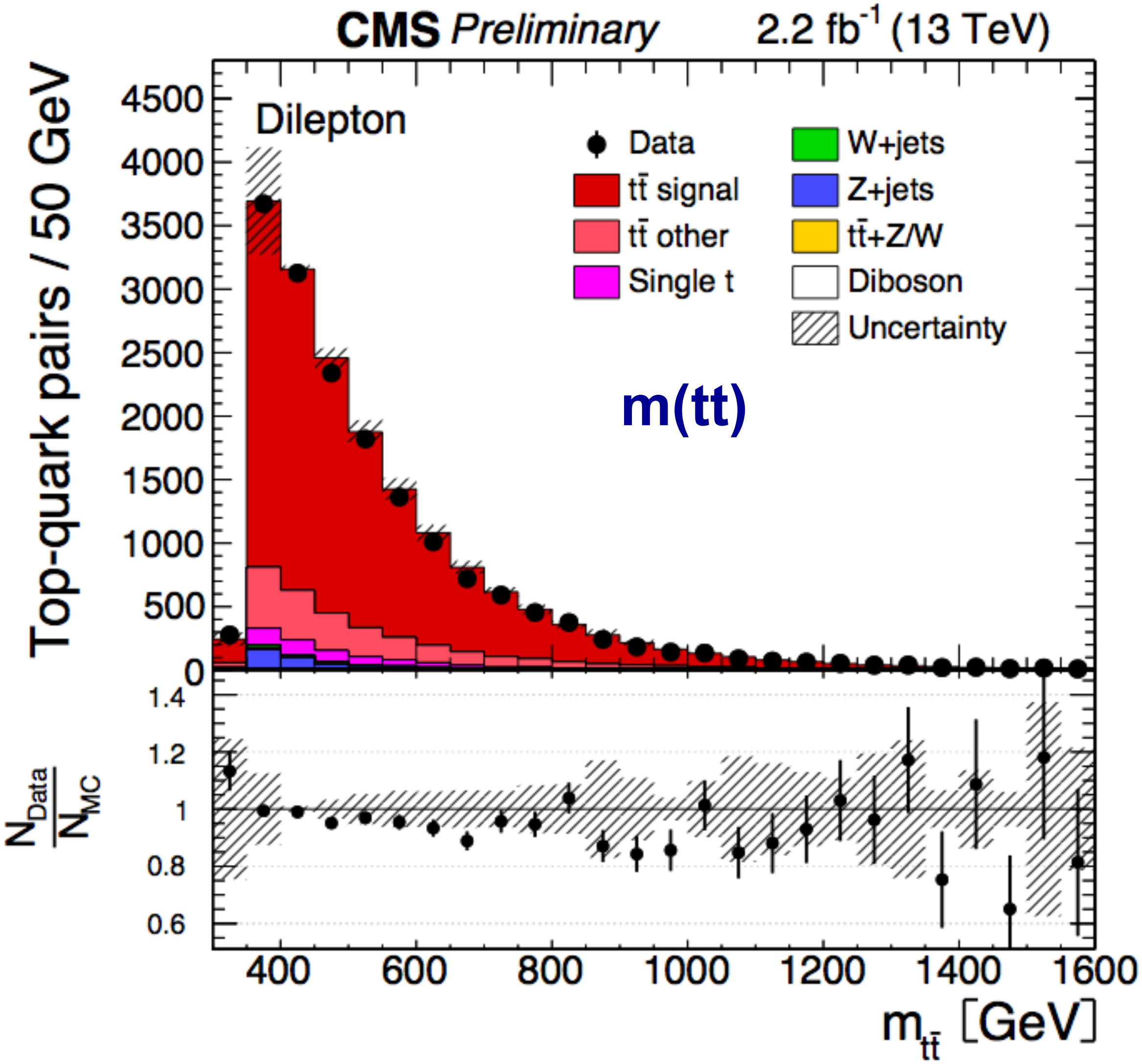


Top quark proxy reconstructed from decay products after hadronization

Useful for MC tuning

Measured $t\bar{t}$ invariant mass

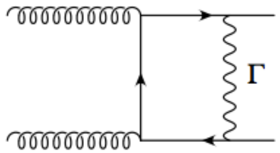
- Rate and shape reproduced within uncertainties



CMS-PAS TOP-16-011

Run-II: towards probing precisely $t\bar{t}$ invariant mass

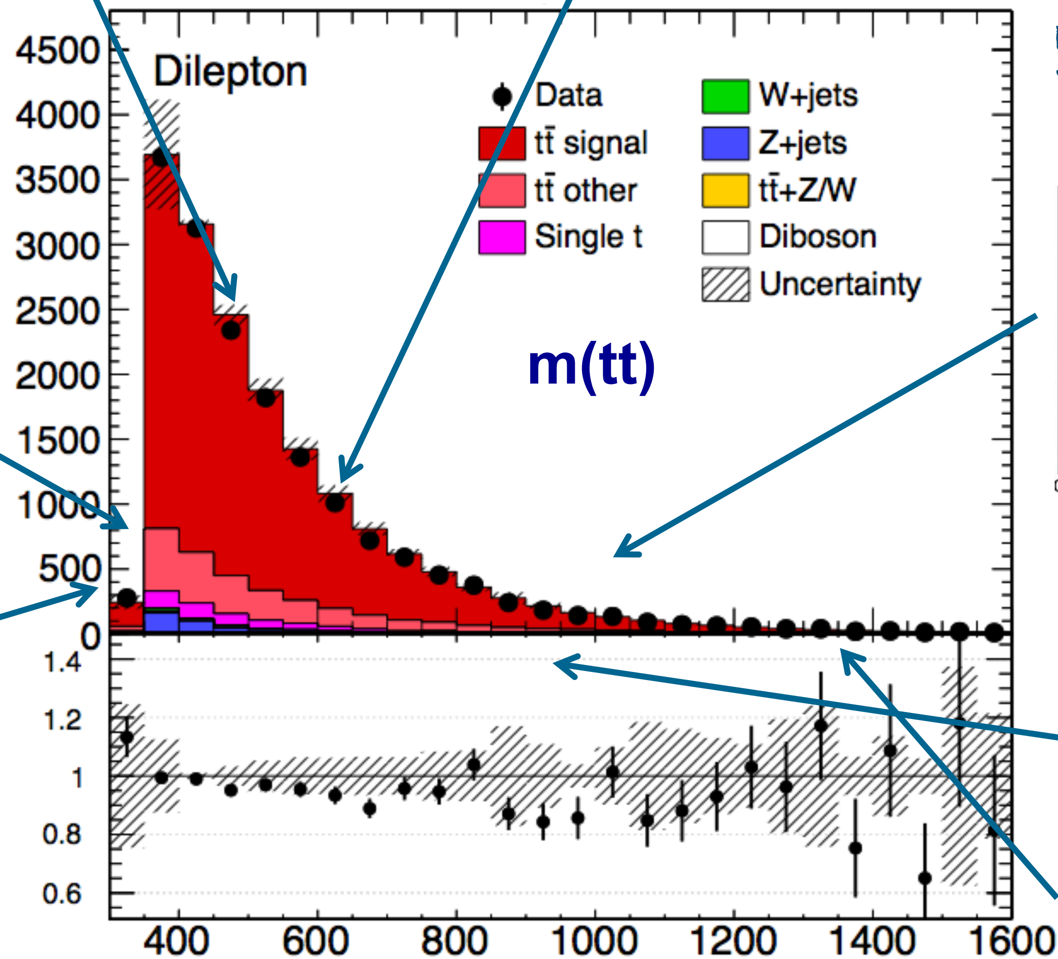
Test EW corrections (Z,γ,H)



[PRD 91 (2015) 01420]

Elusive signs of new physics

[PRD 90 (2014) 014008] [JHEP 01 (2015) 092]



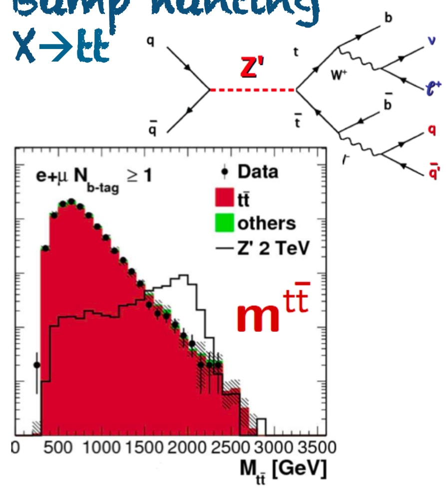
Test QCD production modes near threshold

[JHEP 034 (2010) 1009]

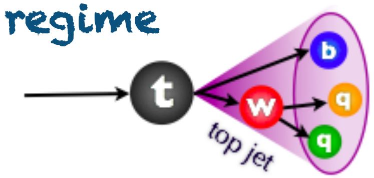
Top pole mass

Running mass (m(μ))

Bump hunting X→tt



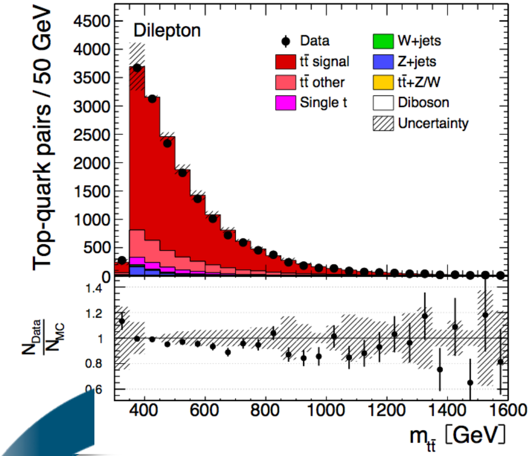
Entering boosted regime



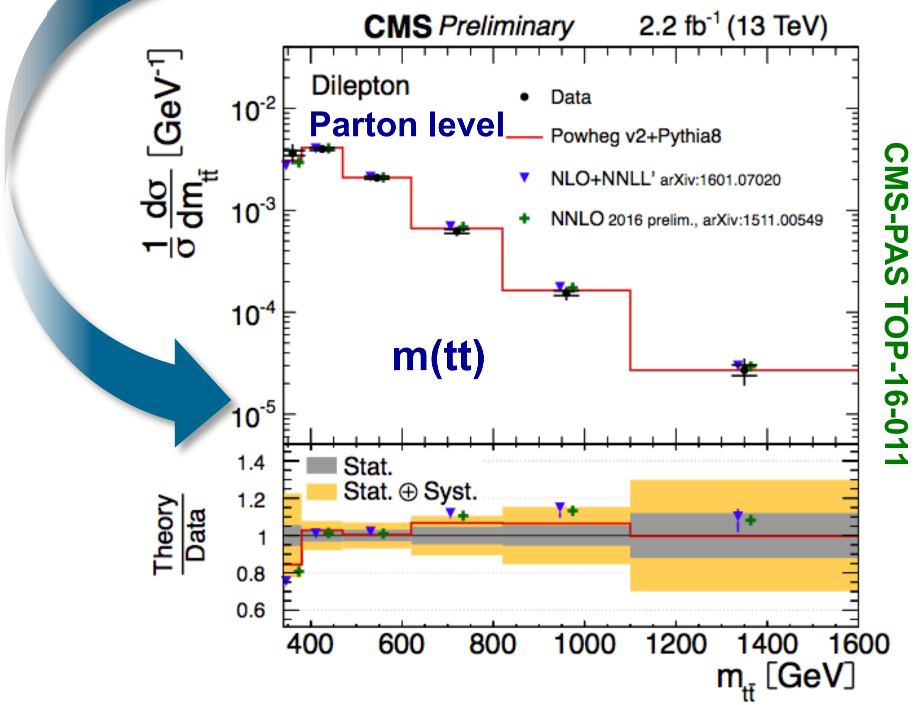
PDF, αs at high x

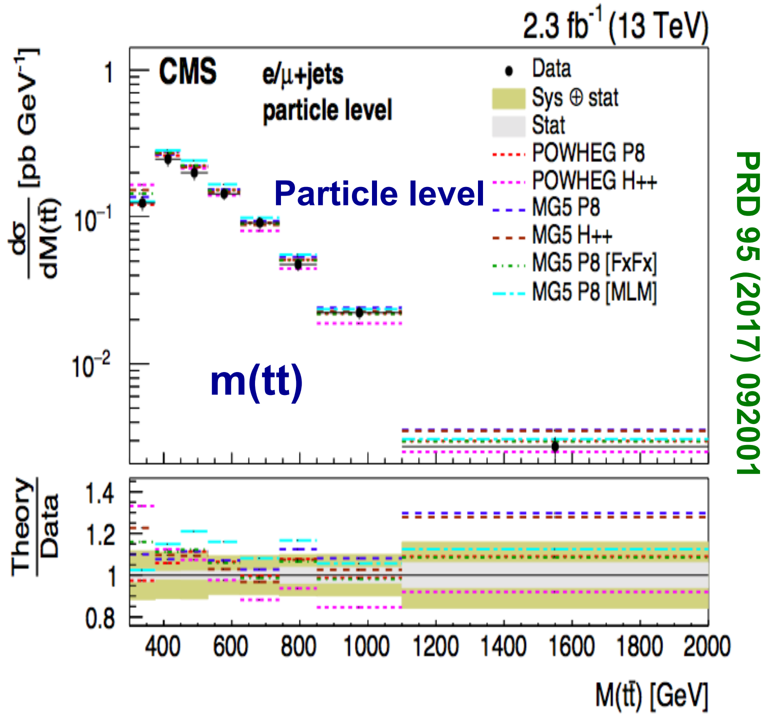
Run-II will push ahead the differential meaurements program of Run-I

$t\bar{t}$ differential cross sections



- Many Run-II results already, more to come
  - Parton/particle, resolved/boosted
  - Many observables, probing different regions of phase space
- Comparison with state-of-the-art predictions





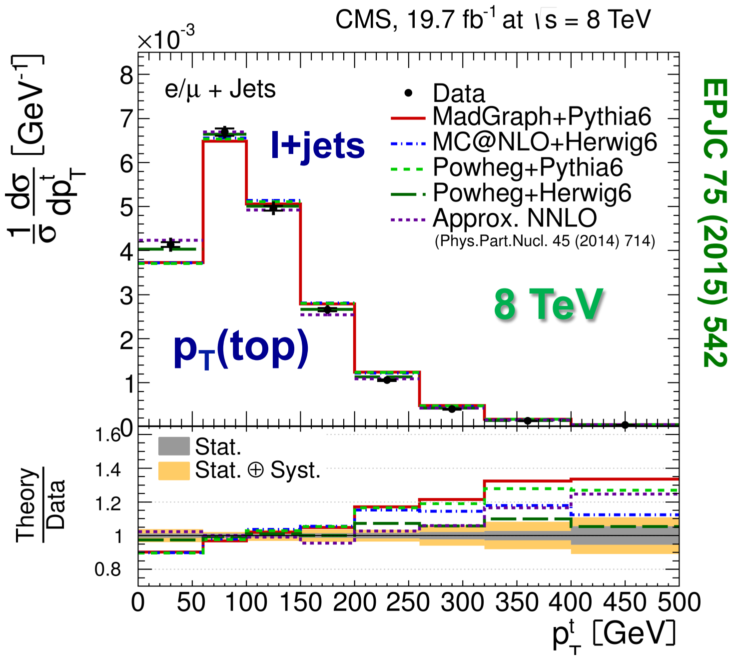
In general: agreement with SM predictions for all measured distributions

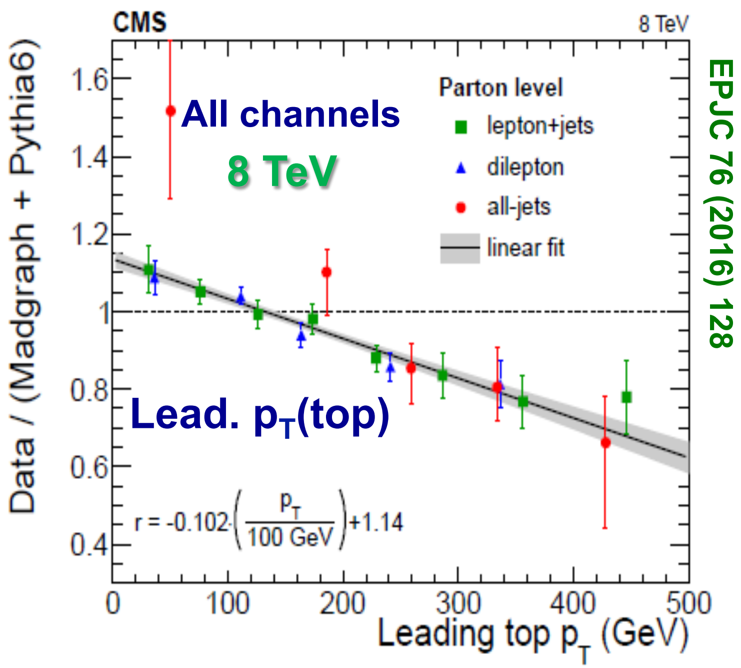
The p_T(top) distribution

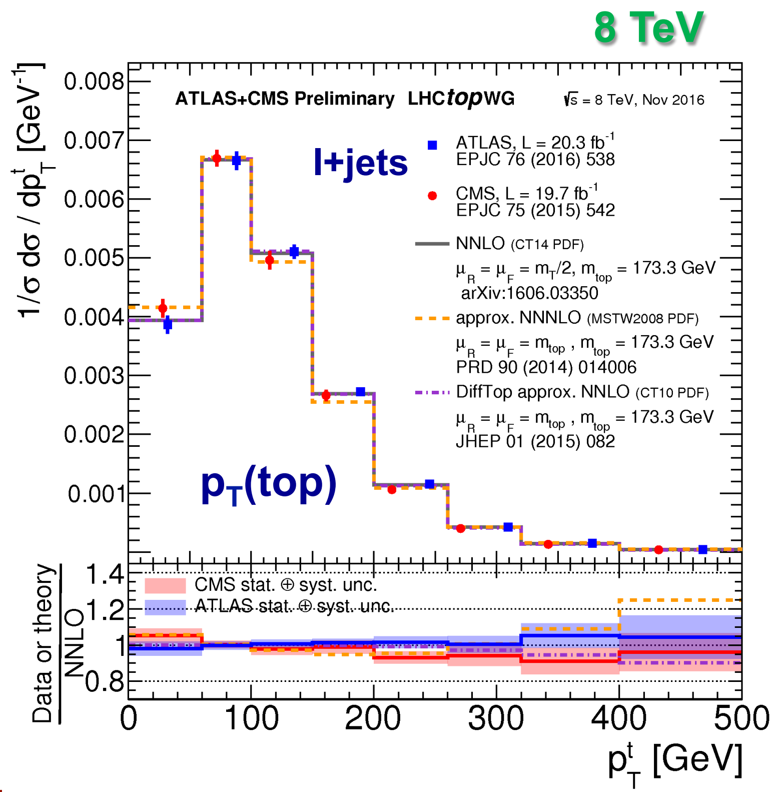
Run-I 'discovery': top-p_T spectrum is softer in data than in (most) MC simulations

Better described by beyond NLO QCD calculations (exact NNLO only available since 2015)

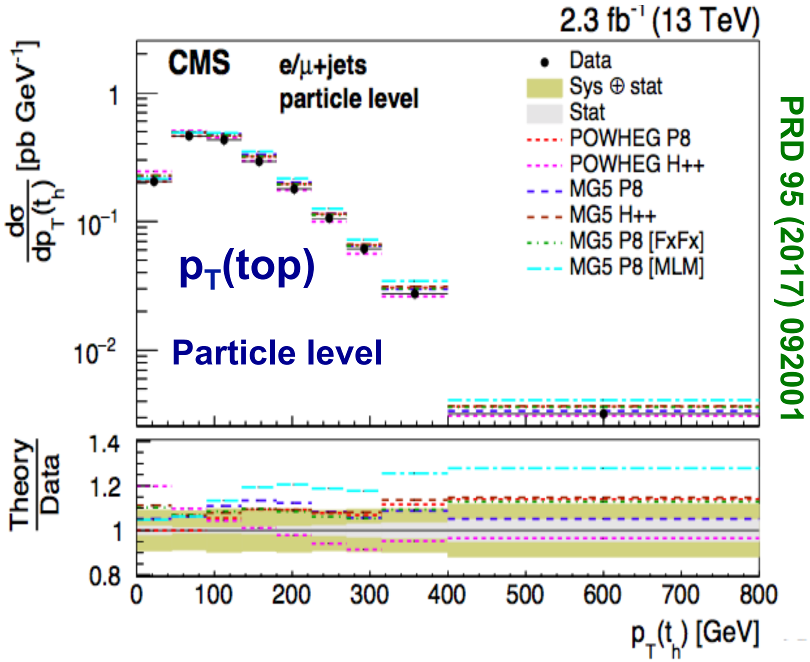
Fair agreement between ATLAS and CMS
(working on quantifying consistency between experiments)







The p_T(top) distribution

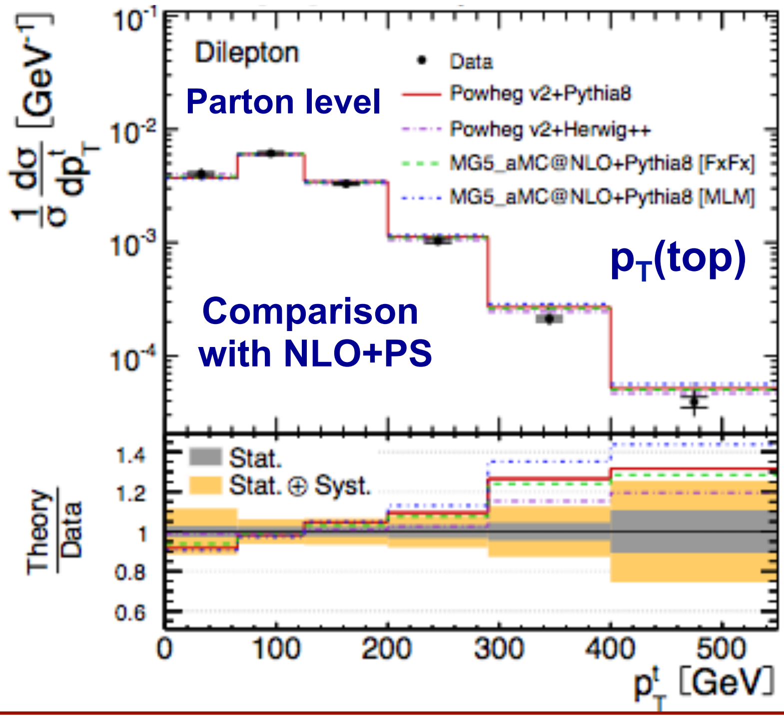


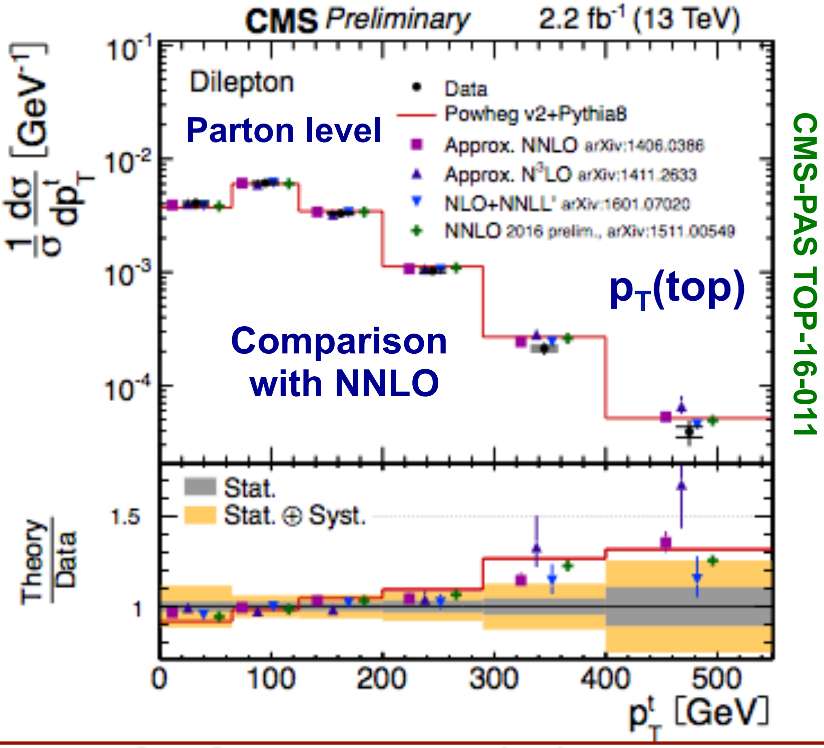
Run-I 'discovery': top-p_T spectrum is softer in data than in (most) MC simulations

Better described by beyond NLO QCD calculations (exact NNLO only available since 2015)

Fair agreement between ATLAS and CMS
(working on quantifying consistency between experiments)

Also observed at 13 TeV



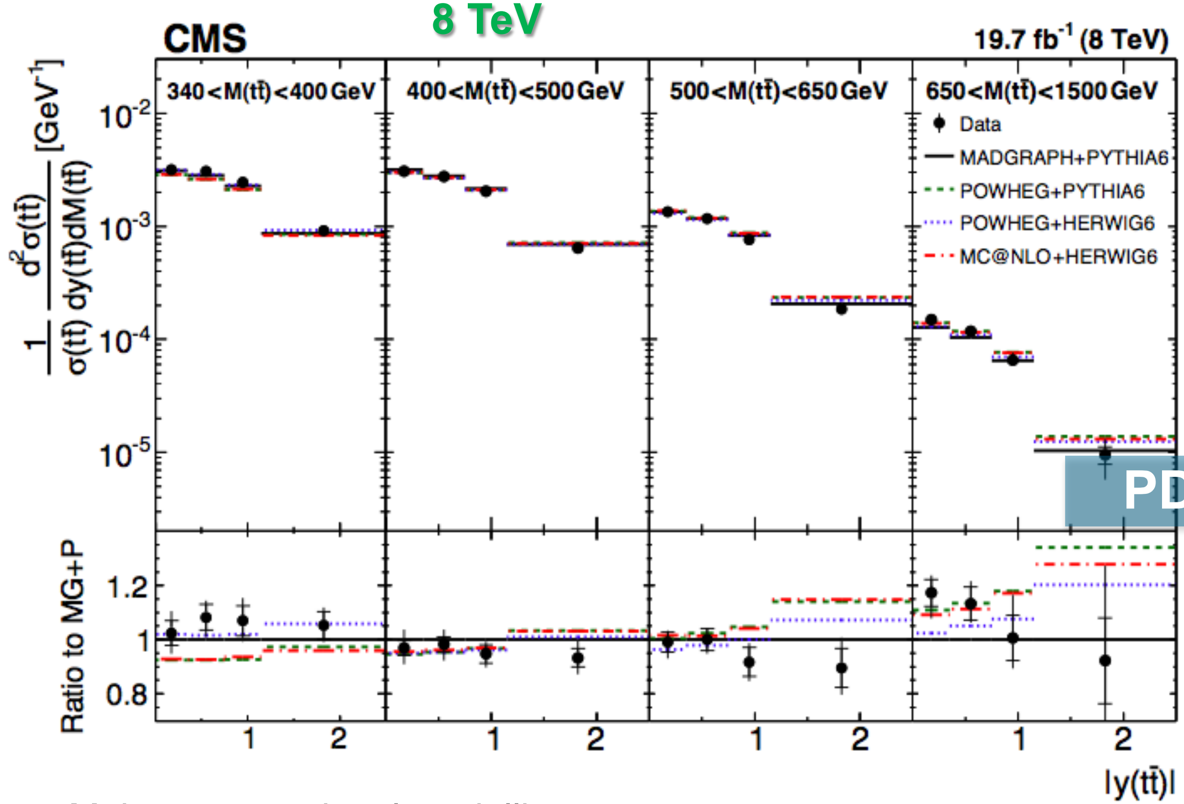


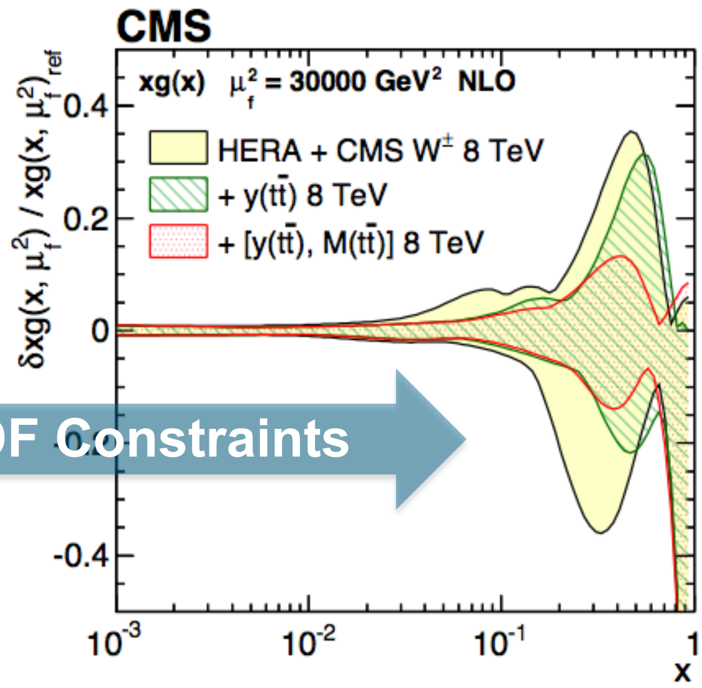
Zooming in: double differential $t\bar{t}$ cross sections

arXiv:1703.01630

- First measurement of its kind at the LHC !
- Bin tt events in two variables of p_T(top), y(top), m(tt), y(tt)
- 2D distributions provide stronger PDF constraints than 1D

8 TeV



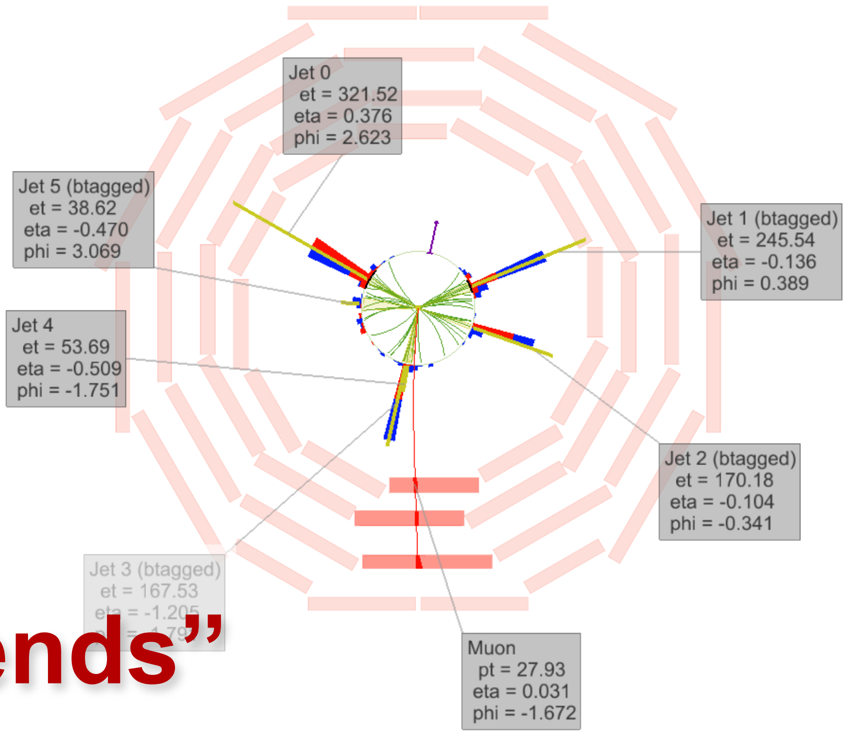


Main uncerts: signal modelling

Run-II: improve precision, extend phase space, go 3D differential, constrain m_{top}, α_S, PDF

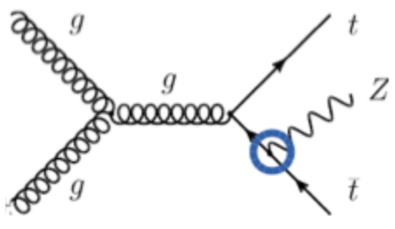
13 TeV

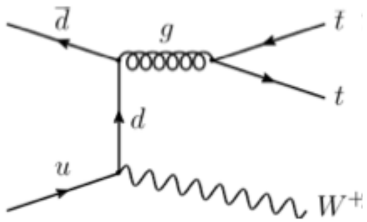
ttH(bb) candidate:
1μ, 6 jets, 4 b-tags

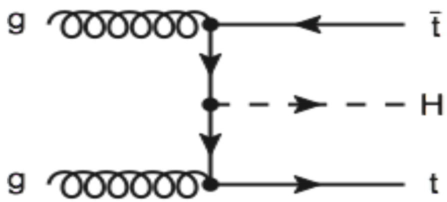


$t\bar{t}$ production + "friends"

- Very low production cross sections O(fb)
- Typically need multivariate analysis techniques to maximize sensitivity



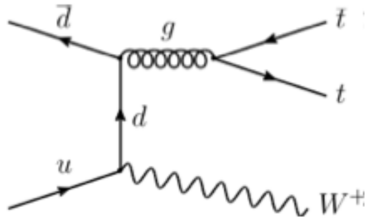




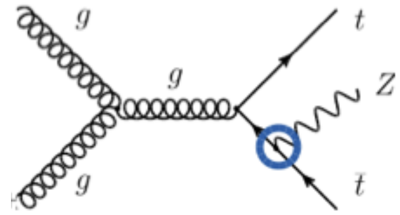
$t\bar{t}$+Z and $t\bar{t}$+W

Very rare processes in SM

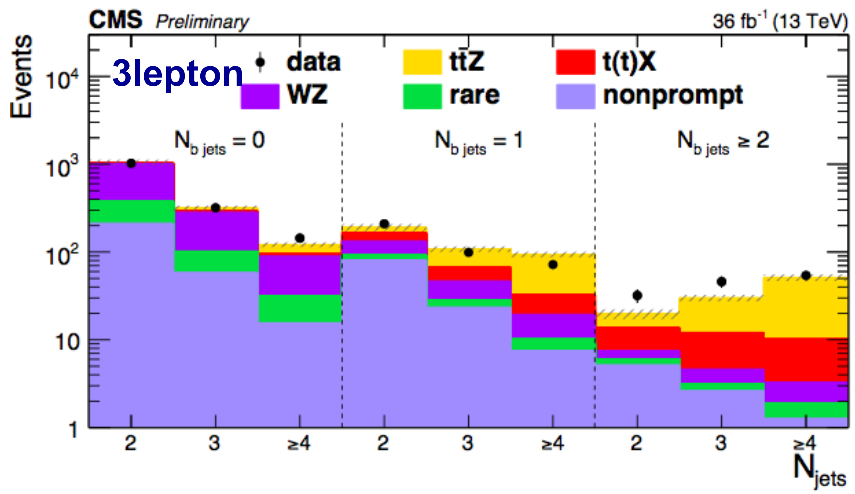
- Direct probe of top-Z coupling (new physics?), important backgrounds for BSM and $t\bar{t}$+H
  - Selection based on leptons, further split in jets & b-tags to increase sensitivity
  - Simultaneous fit across several signal and control regions

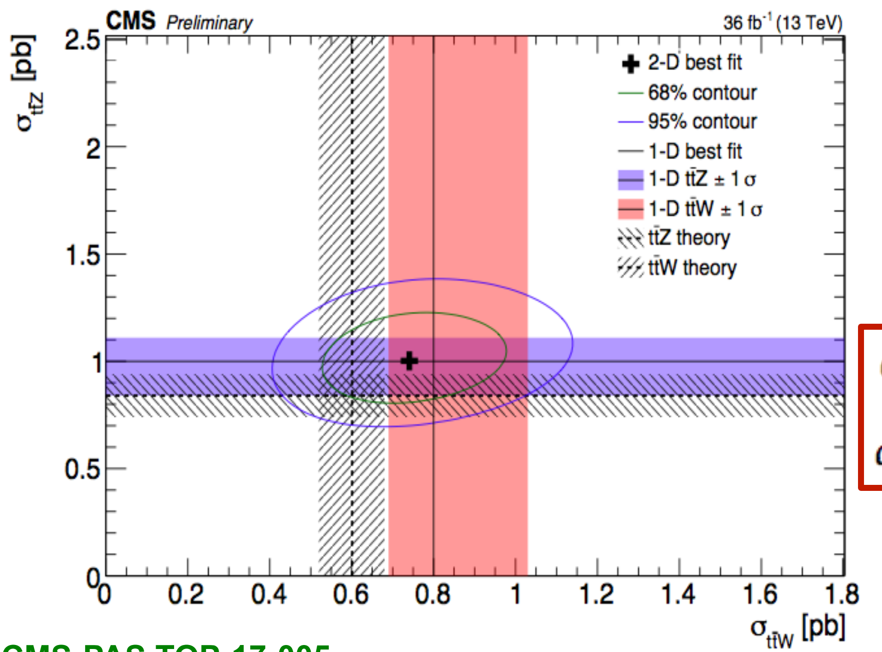


ttW: Same-sign 2lepton



ttZ: 3lepton, 4lepton





$$\sigma(pp \to t\bar{t}Z) = 1.00^{+0.09}_{-0.08}(\text{stat.})\ ^{+0.12}_{-0.10}(\text{sys.})\ \text{pb} \quad (9.9\ \text{std})$$

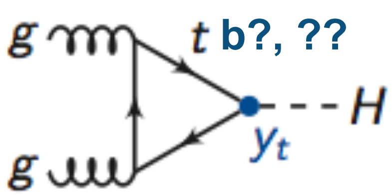
$$\sigma(pp \to t\bar{t}W) = 0.80\ ^{+0.12}_{-0.11}(\text{stat.})\ ^{+0.13}_{-0.12}(\text{sys.})\ \text{pb} \quad (5.5\ \text{std})$$

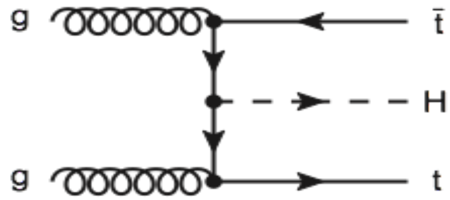
CMS-PAS TOP-17-005

Top-Higgs coupling: the hunt for $t\bar{t}$+H

Vital step towards verifying the SM nature of the Higgs boson

- Top quark: most strongly-coupled SM particle ($y_t \sim 1$)
- $t\bar{t}$H (also tH): only direct access to y_t
- Experimentally very challenging
  - Tiny signal and overwhelming background from $t\bar{t}$+jets, $t\bar{t}$+W/Z





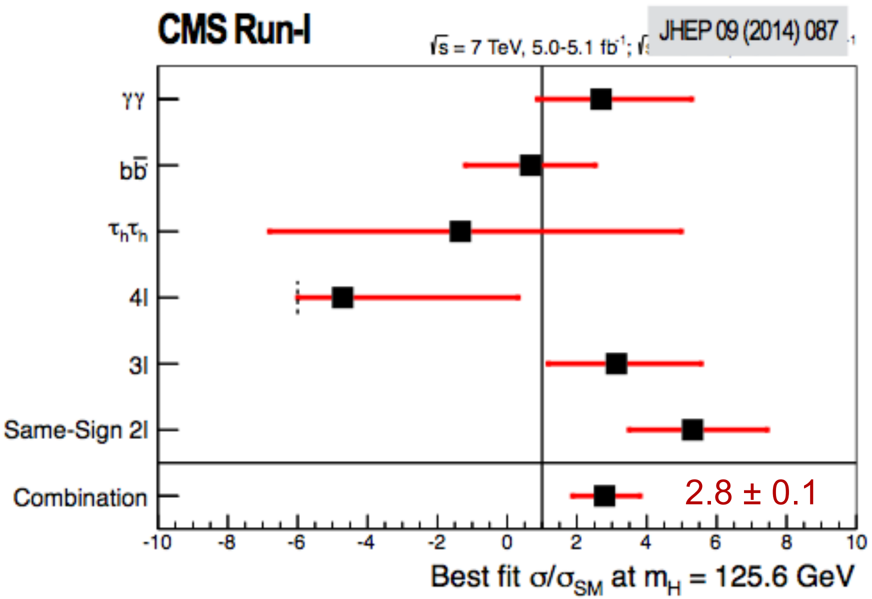
From theory:

σ(ttH) at 7 TeV	= 90 fb
σ(ttH) at 8 TeV	= 130 fb
σ(ttH) at 13 TeV	= 510 fb

x 3.8

σ(tt+jets) at 7 TeV	= 177000 fb
σ(tt+jets) at 8 TeV	= 253000 fb
σ(tt+jets) at 13 TeV	= 830000 fb

x 3.3

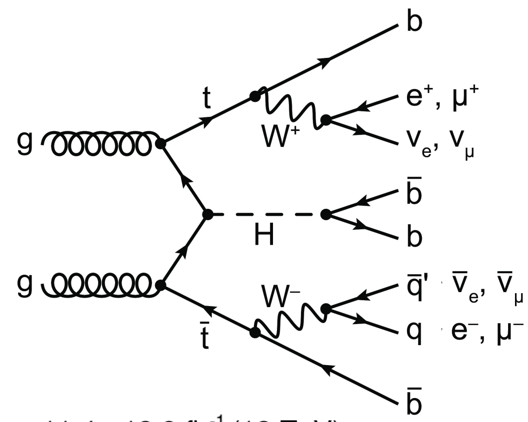


LHC Run-I combination: μ = 2.3 +0.7 -0.6

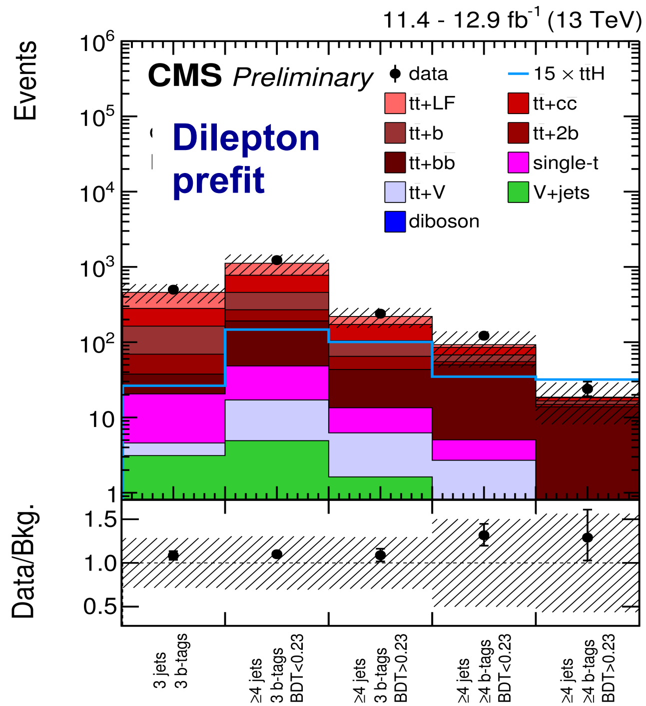
Not observed so far, high priority for Run-II

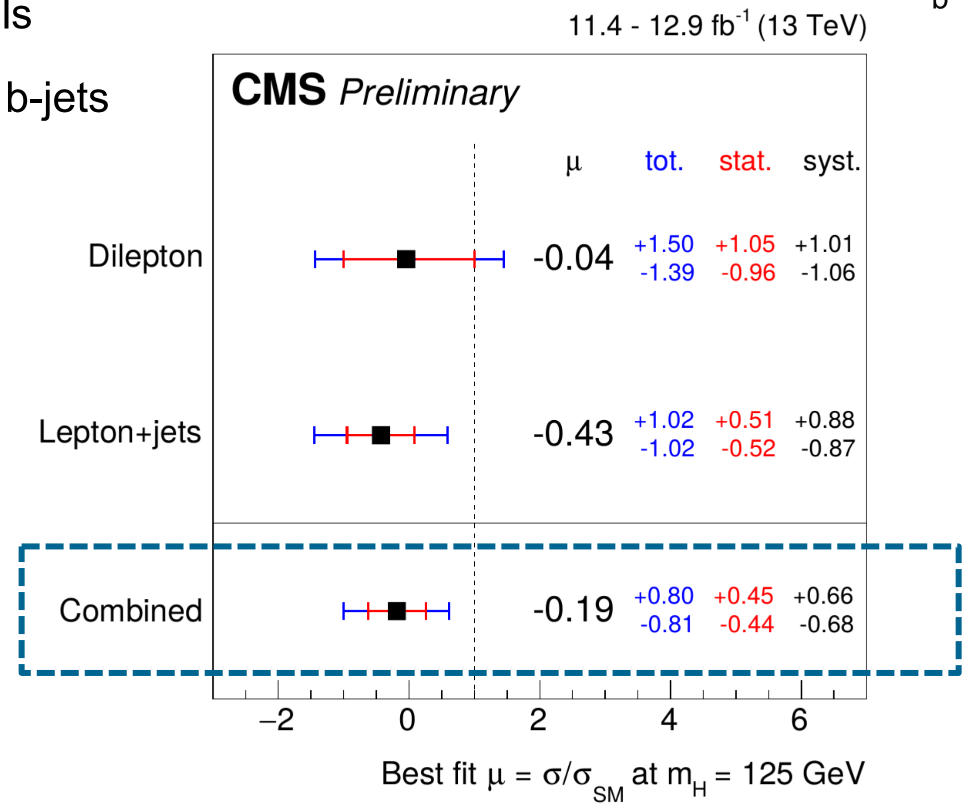
$t\bar{t}$+H, H→$b\bar{b}$

Allows investigating coupling of the Higgs boson to 3rd generation fermions



- H→$b\bar{b}$ has largest BR, but huge background ($t\bar{t}$+$b\bar{b}$) and associated large theory uncertainties on its modelling
- Categorize via $t\bar{t}$ l+jets, dilepton channels
- Classify according to number of jet and b-jets
- Use MVA techniques to further improve sensitivity (BDT, Matrix Element Method)





CMS-PAS HIG-16-038

Upper limit on σ_{ttH} of 1.5 (obs.) and 1.7 (exp.) x SM expectation

Compatible with SM expectation at the level of 1.5 std

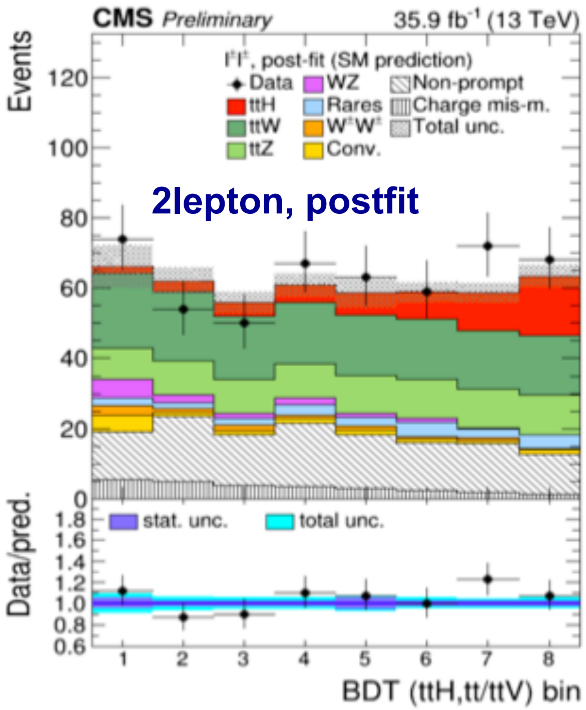
$t\bar{t}$+H, all searches

Many channels: bosonic (H→ZZ→4l, H→γγ), leptonic (H→WW, H→$\tau_l\tau_{any}$), hadronic (H→bb, H→$\tau_h\tau_h$)

$t\bar{t}$+H, H→multileptons

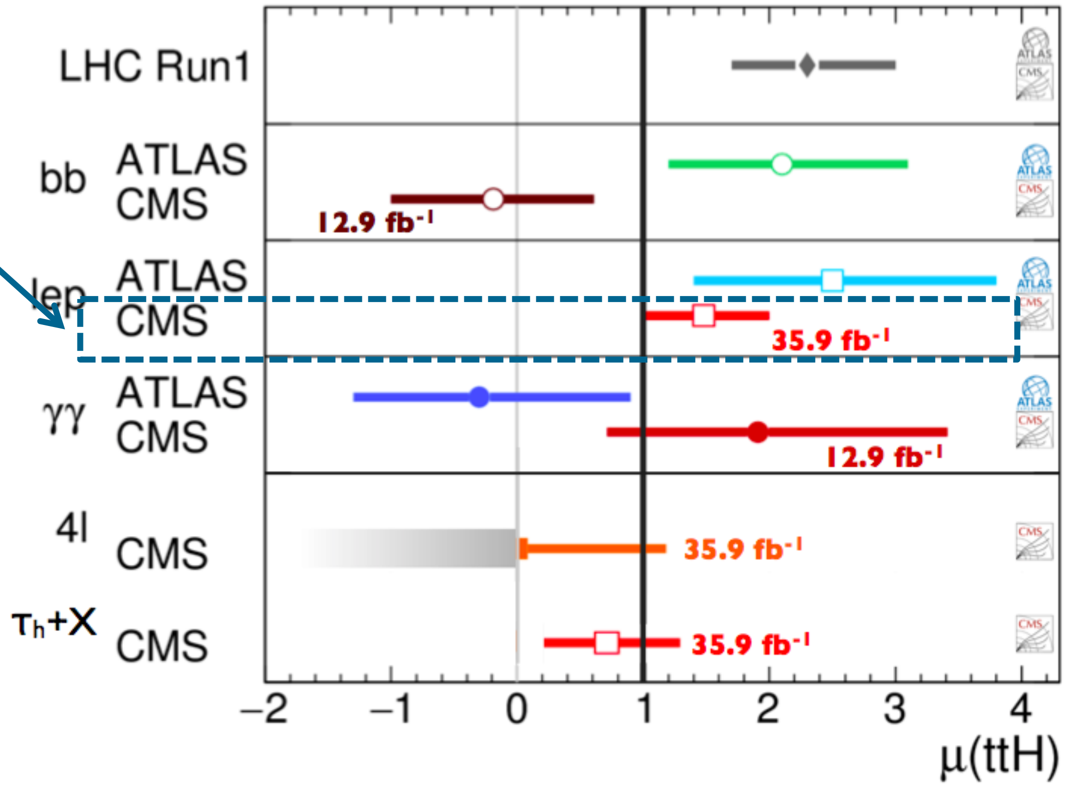
- 2lepton SS, 3lepton: 2 kinematic BDTs against tt and tt+W/Z
- 3lepton: use also MEM for additional tt+W, tt+Z separation
- 4lepton: counting experiment

CMS-PAS HIG-17-004



Best fit μ = 1.5 ± 0.5 → significance: 3.3σ obs. (2.5σ exp.)

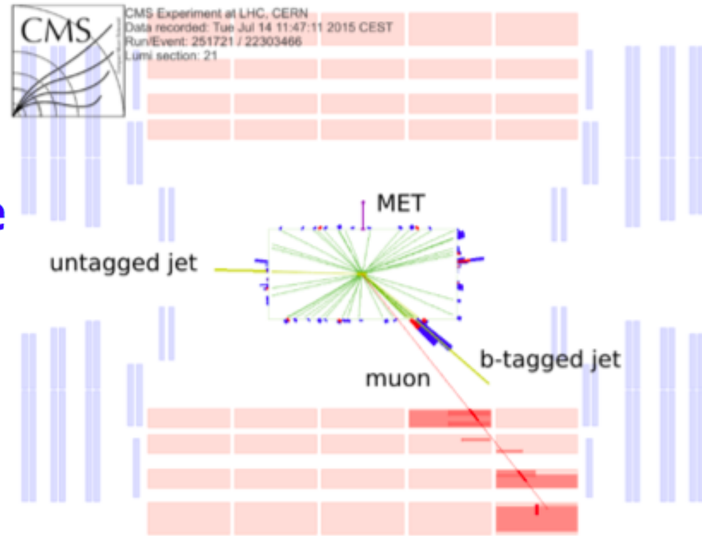
All channels, ATLAS+CMS



G. Petrucciani, Moriond EWK 2017

"There's not yet a single analysis with a strong & unambiguous ttH signal, and it will take time and effort to get there"

→ Run-II and beyond !



13 TeV

single top candidate

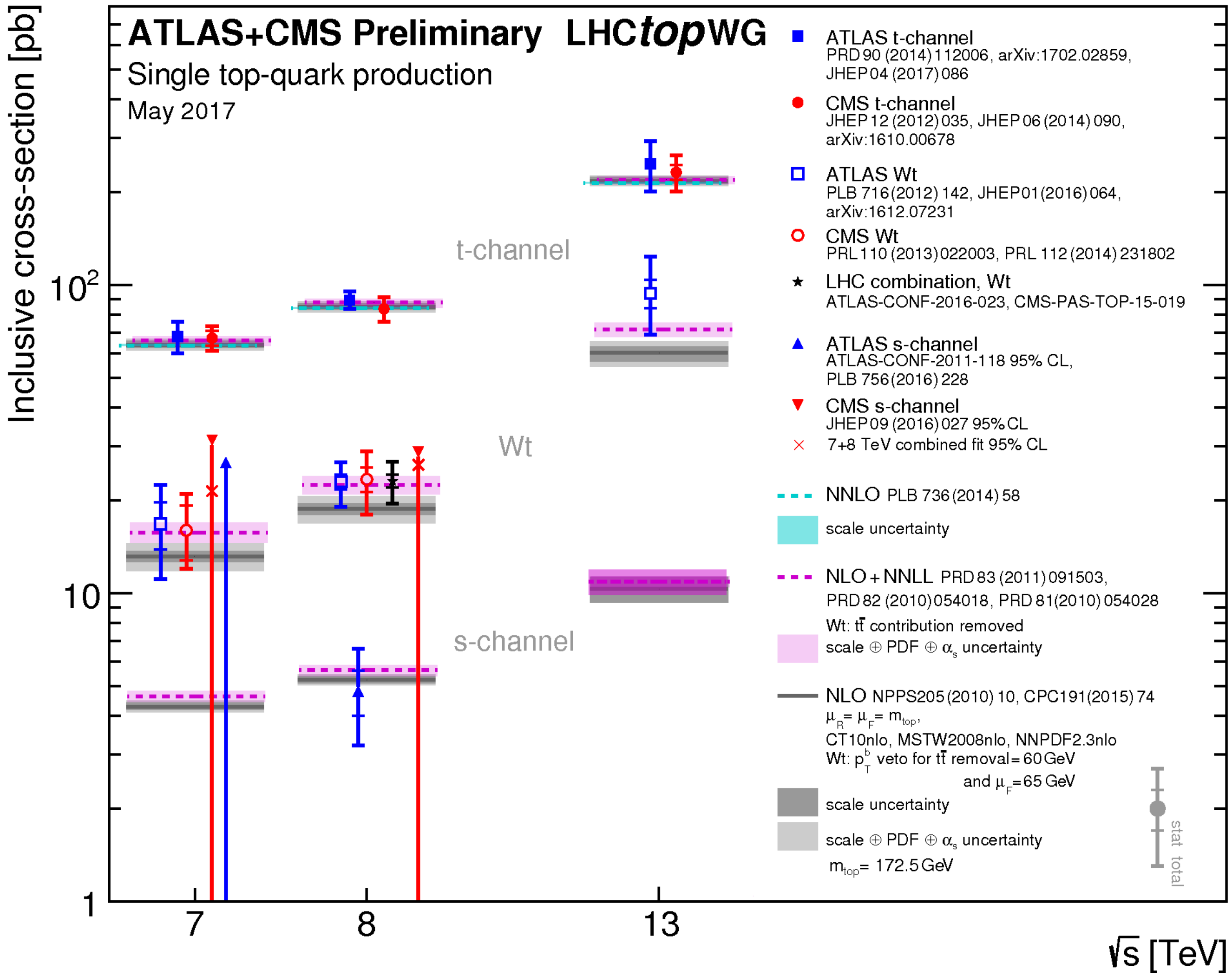
Single top quark

- Probe CKM matrix element $|V_{tb}|$, EWK coupling structure
- Probe alternative production mechanisms (e.g heavy bosons, FCNC)

Single top production: the big picture

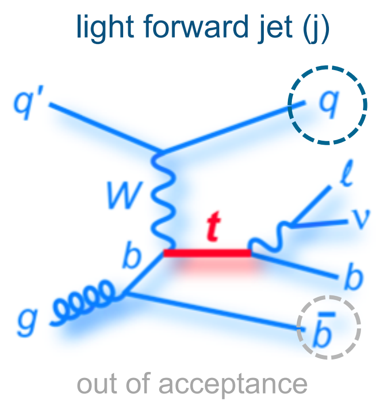
Run-I:

- Main production mode: t-channel, measured to high precision
  - Properties, differential distrbutions
- First observation of tW process
- Study of s-channel
- Rare single top modes explored
  - tZq, tγ



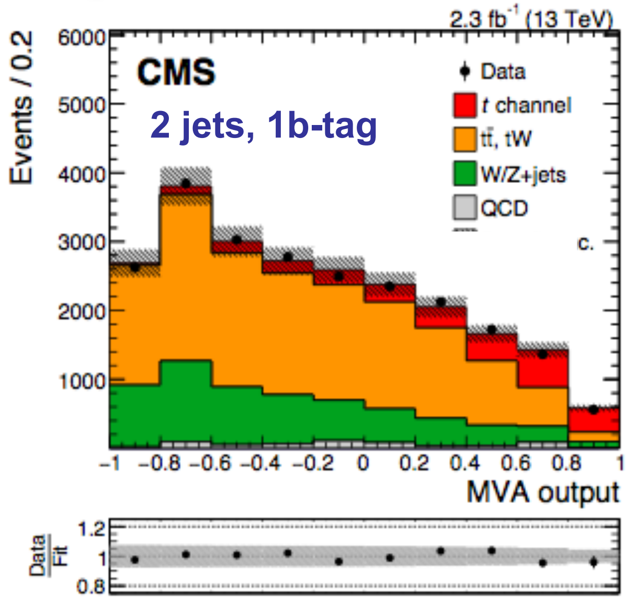
Run-II: ramping up towards new era of high-precision in single top

Run-II: single top t-channel



Selection:
1 μ, 2 jets, 1 b-tag

Control regions for main backgrounds (3j1b, 3j0b)

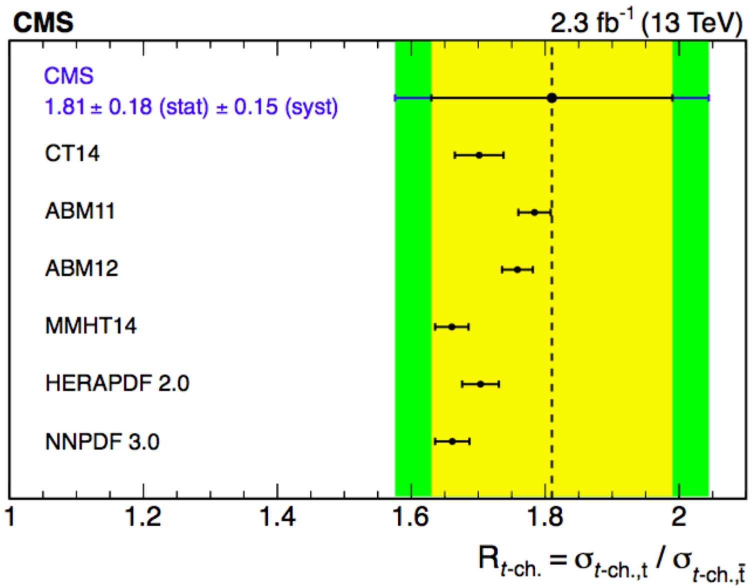


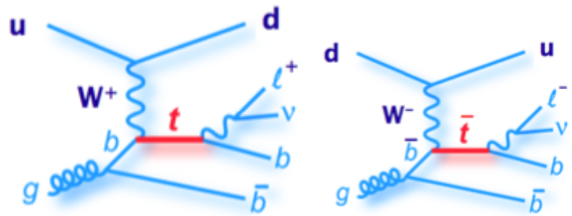
arXiv:1610.00678

- Fit to MVA discriminant using different regions enriched in signal and background

$\sigma(t+\bar{t}) = 232 \pm 31$ pb **(14%)** Main syst: signal model, JES

- Potential constraints on u- , d-quark ratio:





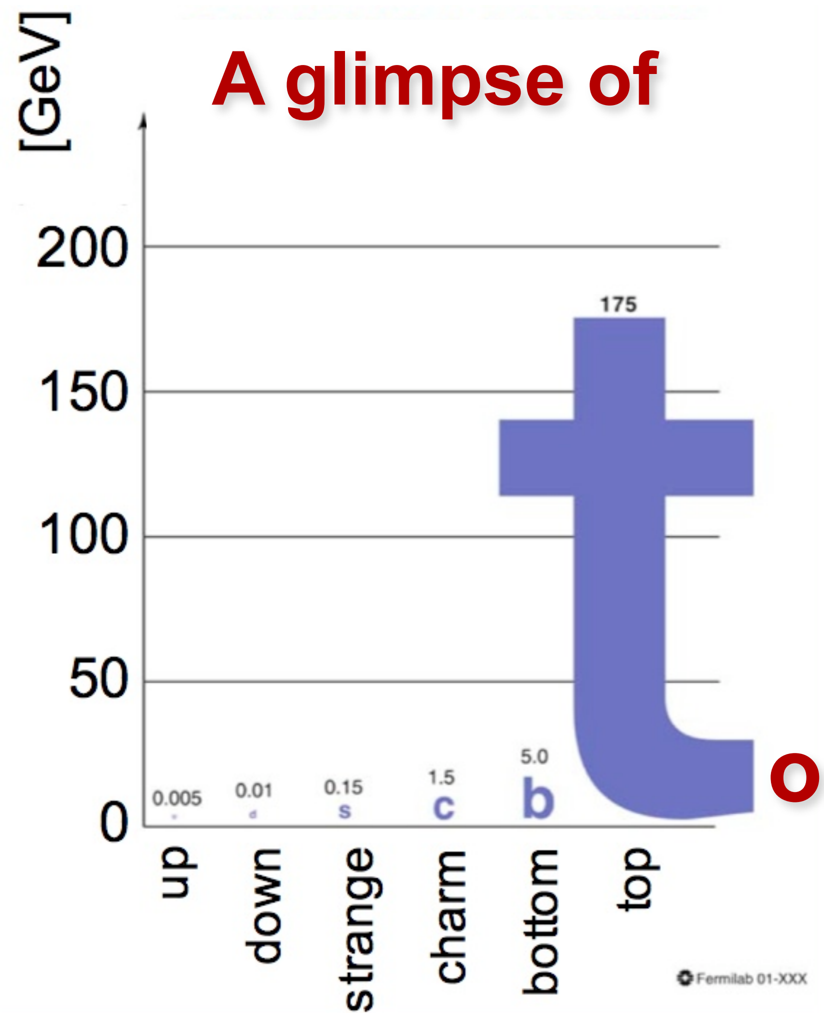
- CKM matrix element $|V_{tb}| = \sqrt{(\sigma^{obs.}_{t\text{-}ch.} / \sigma^{theo.}_{t\text{-}ch})}$:

$|V_{tb}| = 1.03 \pm 0.07\,(\text{exp}) \pm 0.02\,(\text{theo})$ **(7%)**

(for $|V_{ts}|$, $|V_{td}|$ << $|V_{tb}|$)

Full program of detailed measurements (differential distributions, properties, couplings) lies ahead

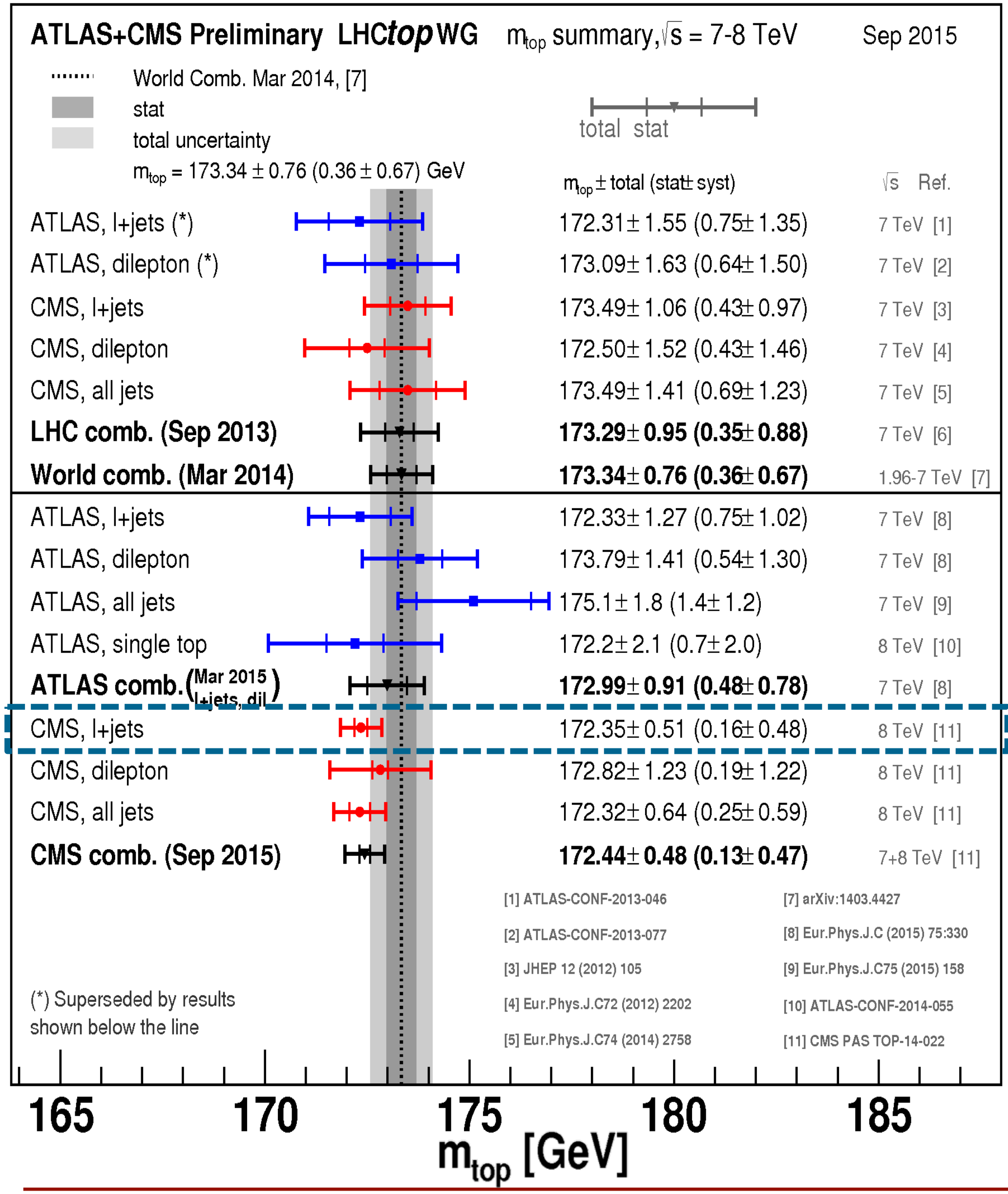
A glimpse of



op quark properties

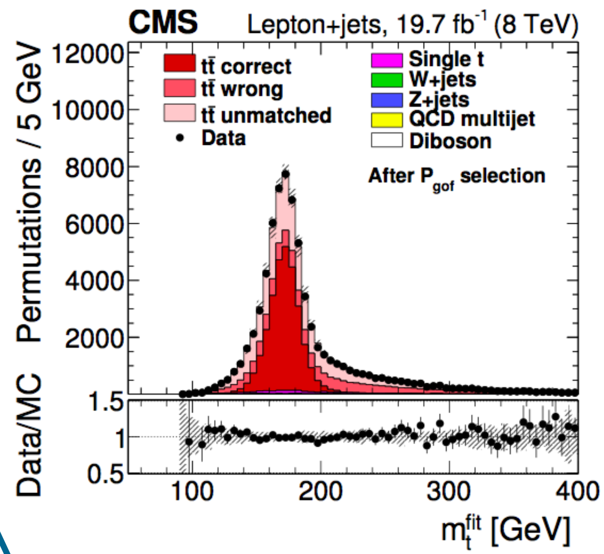
mass

"Direct" top quark mass



- Direct m_{top} measurements: from kinematic reconstruction of top quark decay products → highest sensitivity

- Most precise result from CMS (l+jets):
  - 2D likelihood fit to extract m_{top} and light-quark jet energy scale factor (JSF) from W-mass constraint



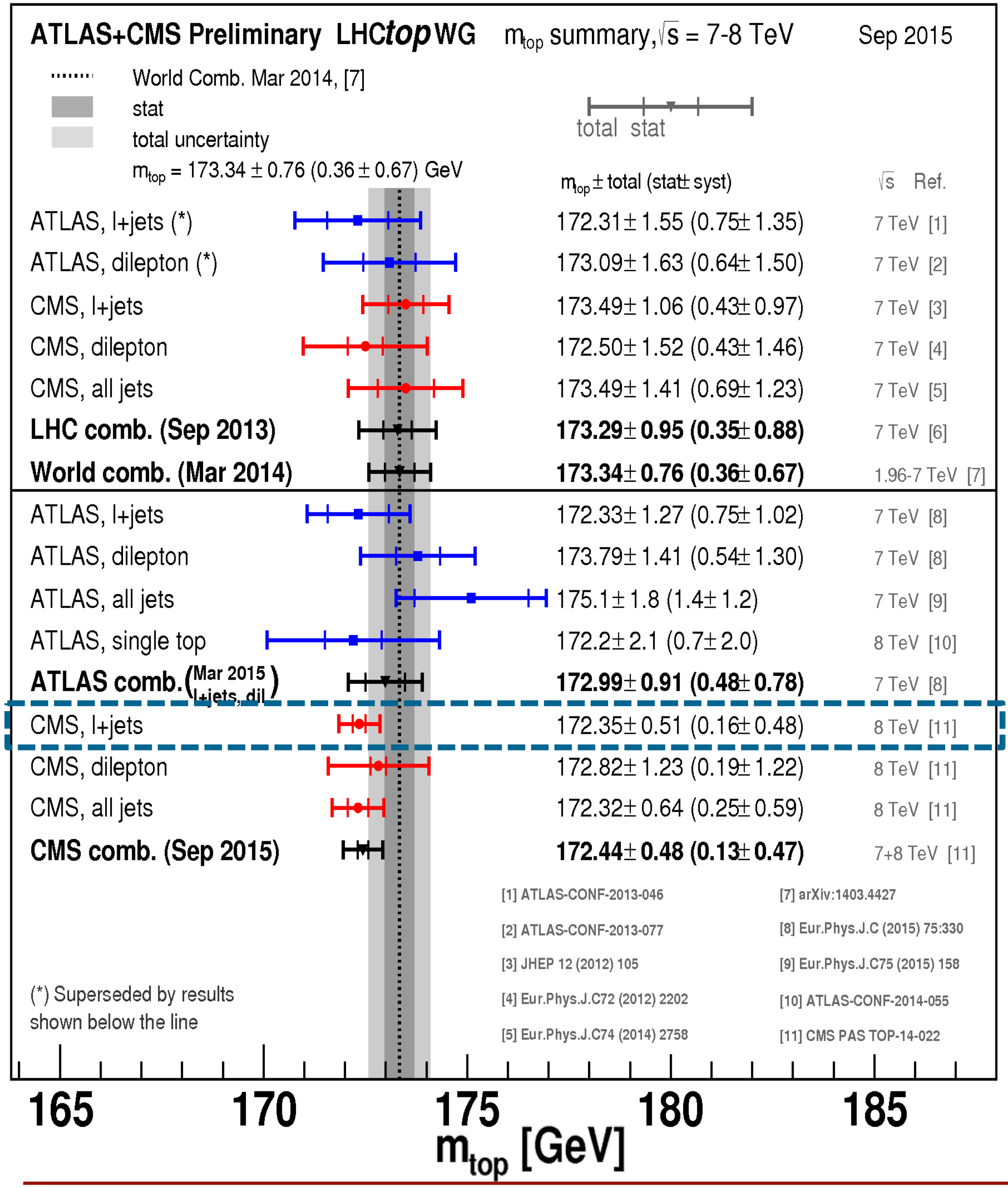
PRD 93 (2016) 072004

(prec.: 0.29%)

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

Main syst: flavour dependence of JES, signal model

"Direct" top quark mass



- Direct m_{top} measurements: from kinematic reconstruction of top quark decay products → highest sensitivity

- First measurement at 13 TeV:
  - Following the 8 TeV measurement in μ+jets

$$m_t = 172.62 \pm 0.38\,(\text{stat+JSF}) \pm 0.70\,(\text{syst})\ \text{GeV}$$

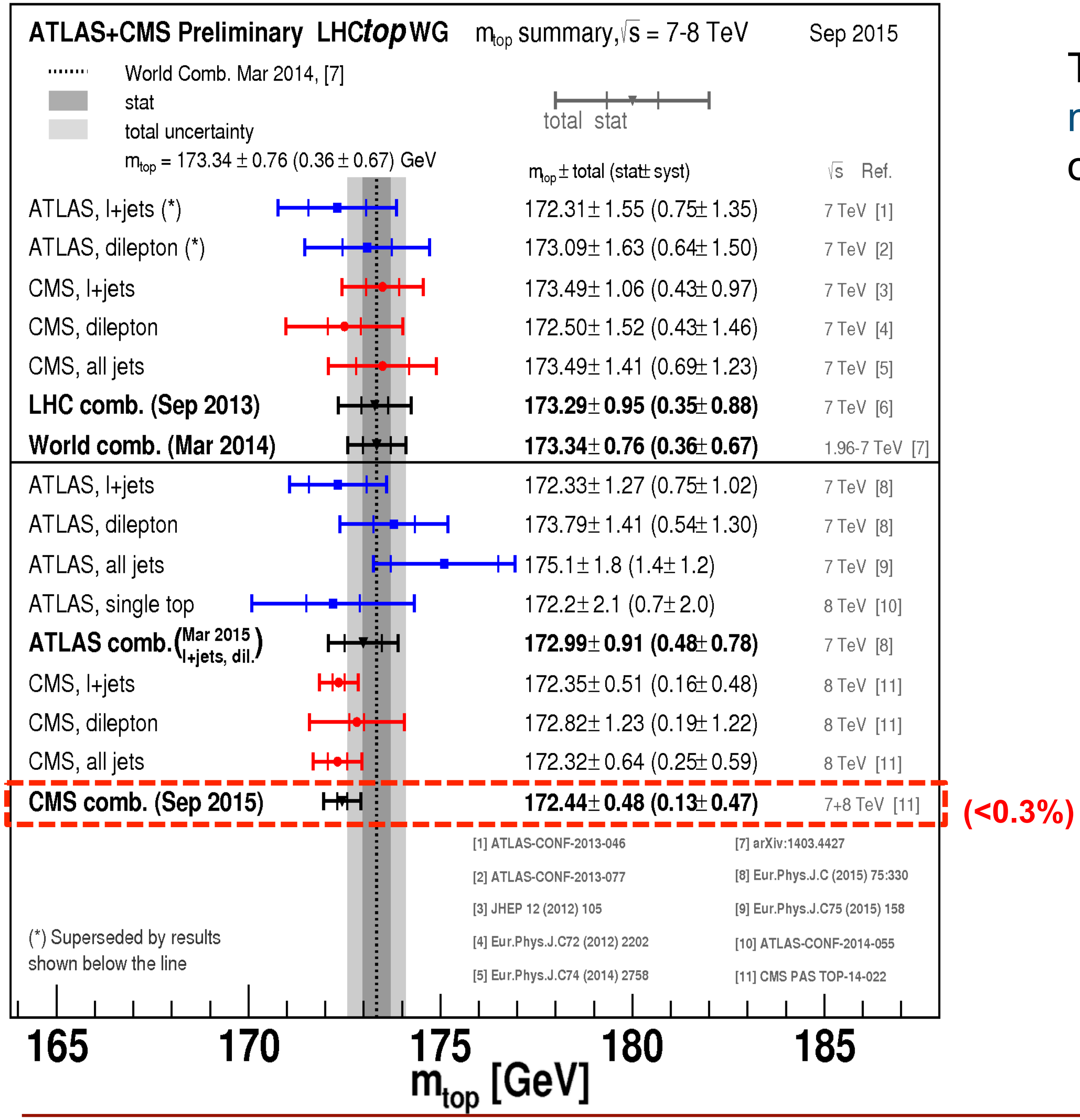
(prec.: 0.46%)

Main syst: JES, signal model

CMS-PAS TOP-16-022

- In good agreement with the 8 TeV result

"Direct" top quark mass



Top mass results using direct methods are reaching a precision of **order 500 MeV** (< 0.3%)

- Dominant uncertainties:
  - Jet energy response calibration
  - Hadronization modelling
- Continuous efforts to:
  - Improve current techniques
  - Develop new methods
  - Combine results

Top pole mass from σ($t\bar{t}$)

Mass dependence of predicted cross section allows determining m_{top} from measured σ(tt)

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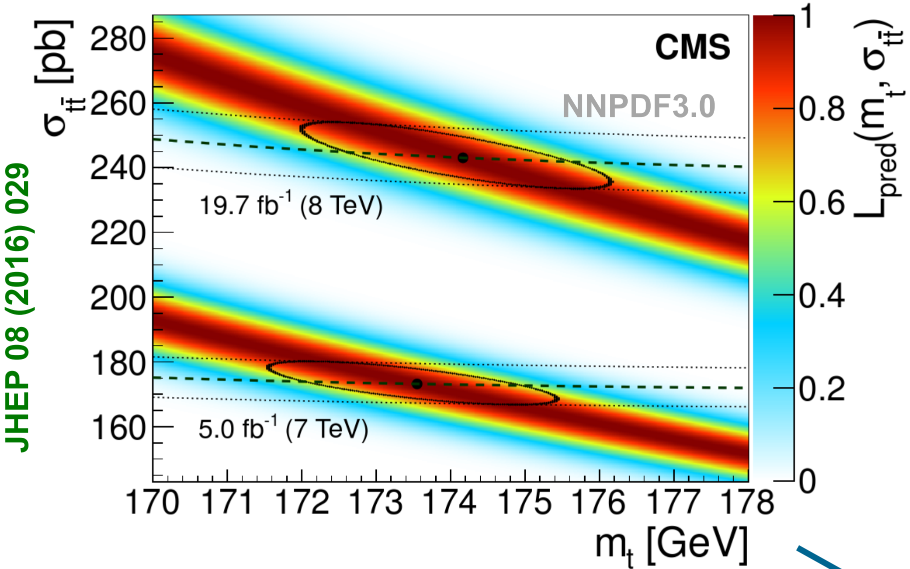
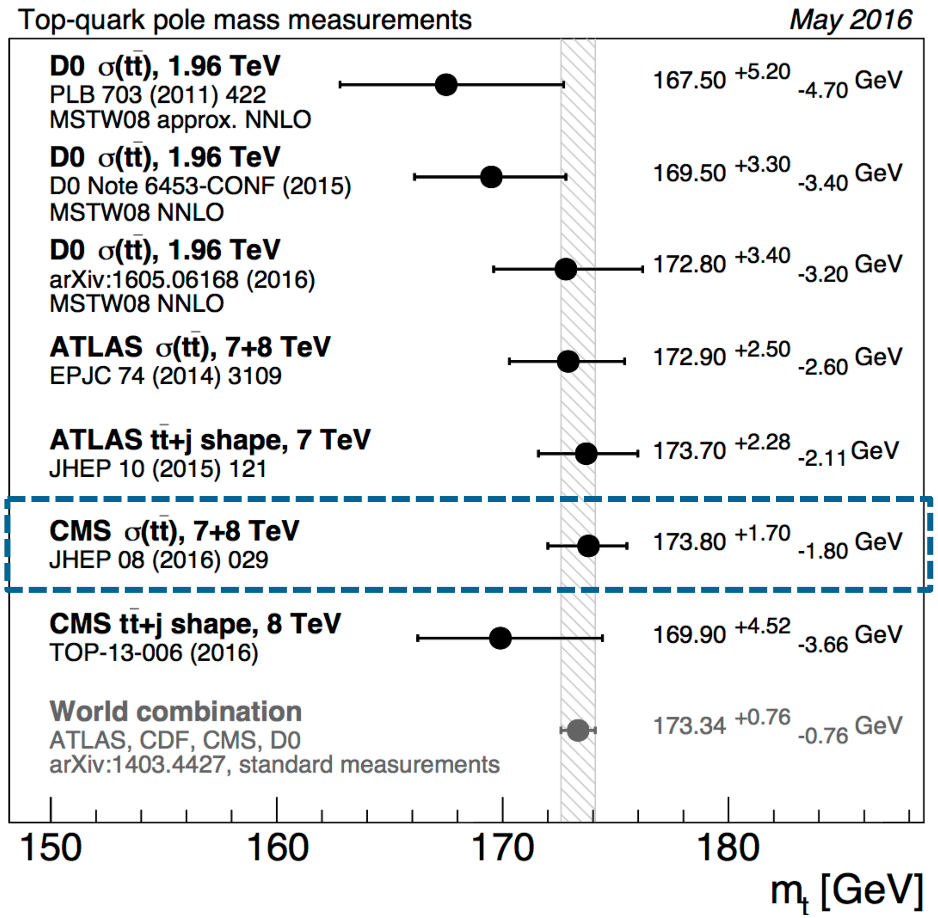


$$m_t^{pole} = 173.8^{+1.7}_{-1.8}\ \text{(GeV)}$$

(prec.: ~ 1%)

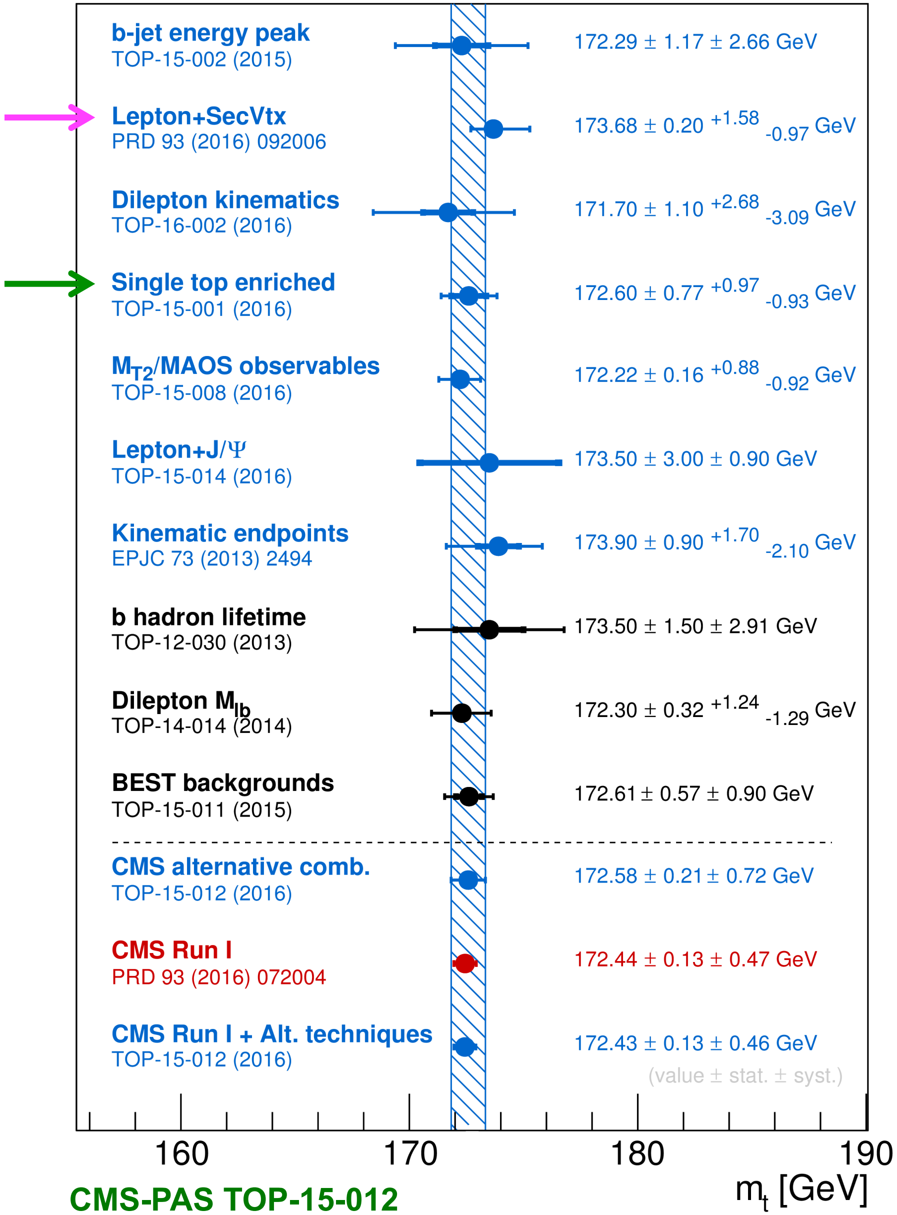
Use most precise theory (NNLO) and measurements to extract m_{top} (for fixed α_S and PDF)



Run-II:

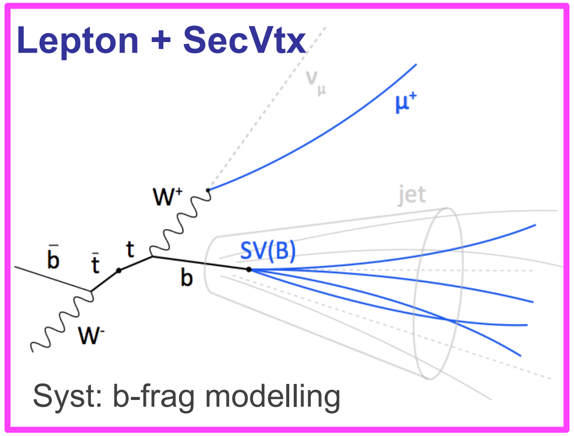
- With current 5.5% theory uncertainty and ~2% experimental:
  → could reach ~ 0.5% on pole mass
- Exploit differential measurements and calculations at NNLO

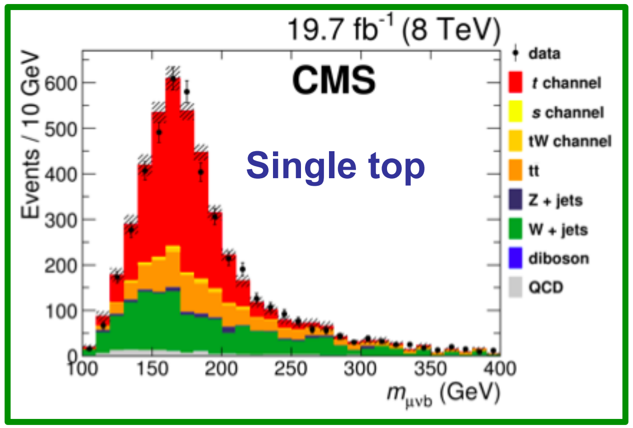
Top quark mass: other "alternative" methods



CMS-PAS TOP-15-012

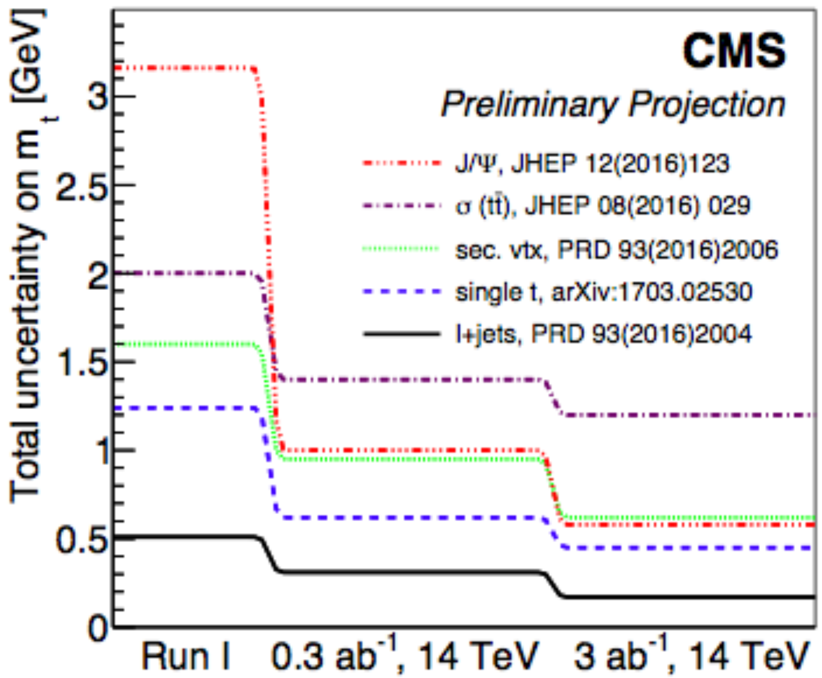
- Exploit experimentally clean(er) observables
  - Do not use jets → avoid hadronization issues
- Alternative systematic sensitivities
- Non-conventional different channels





This is just the beginning…

- Run-II will end with 2018 leaving ~ 100 fb^{-1} at 13 TeV
- Run-III will follow (2021), targeting ~ 300 fb^{-1} at 14 TeV (new centre-of-mass energy)
- After: HL-LHC (Run-IV, 2015) and then future colliders (such as CLIC or FCC possible)
- Opportunities at future facilities start by almost unlimited precision in measurements
  - Directly translates into sensitivity to BSM in deviations
- Extreme regions of the phase space
- Very rare final states



CMS-PAS FTR-16-006

Summary

- **Top physics: key to QCD, electroweak and New Physics**
- **In Run-I, the LHC became a real "top factory"**
  - **Top quark production & properties measurements entered precision regime**
  - **Started to challenge theory predictions in many respects**
- **First 13 TeV results !**
  - **Inclusive cross section measurements, differential distributions**
  - **First results for low cross section processes $t\bar{t}$+X**
  - **First properties measurements start to appear**
- **Run-II: expect 100 fb^{-1} by end of 2018:**
  ~80M $t\bar{t}$, ~20M single top, ~80000 $t\bar{t}$Z and tZ events
  - **Trade off statistics for systematics**
  - **Improvements in MC models and theory calculations**
  - **Access to new physics in the top environment**

The ultimate potential for top physics at the LHC is ahead of us

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Additional information