Highlights of Top Physics Results from CMS at LHC Run I

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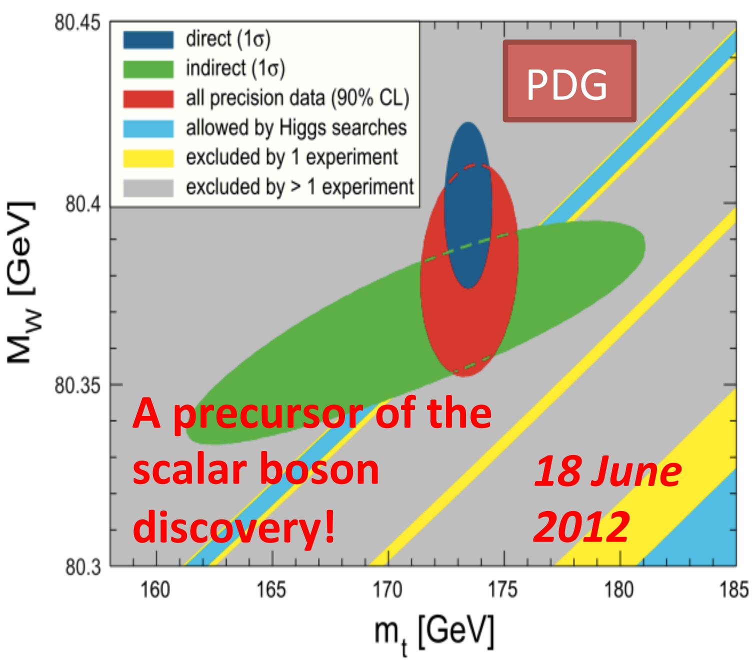
Fundamental Interactions – be and IAP Meeting
19 June 2015 Université Libre de Bruxelles, Brussels, Belgium

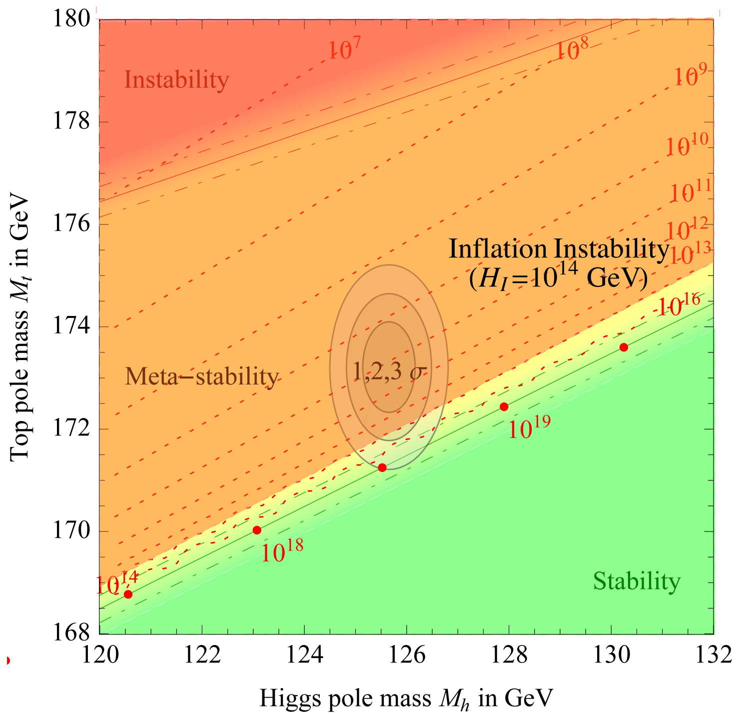
The Top Quark

- The most massive particle known to date
- Lifetime < hadronization timescale
  - "Bare" quark properties
- The only elementary high mass particle that has color → EWK, QCD and flavor physics.
- The largest Yukawa coupling among the fermions
  - Special role in EWSB?
- Top quark and the scalar boson modify tree level SM processes through radiative corrections.



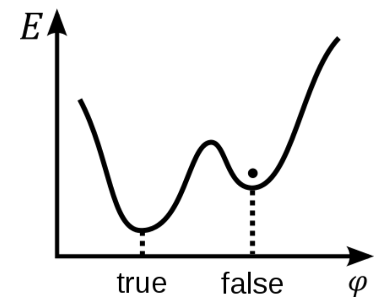
→ Electroweak fit before the scalar boson discovery consistent with measured mass within 1.3σ.
→ One of the most critical tests of the standard model!

Top Quark Mass and Existence

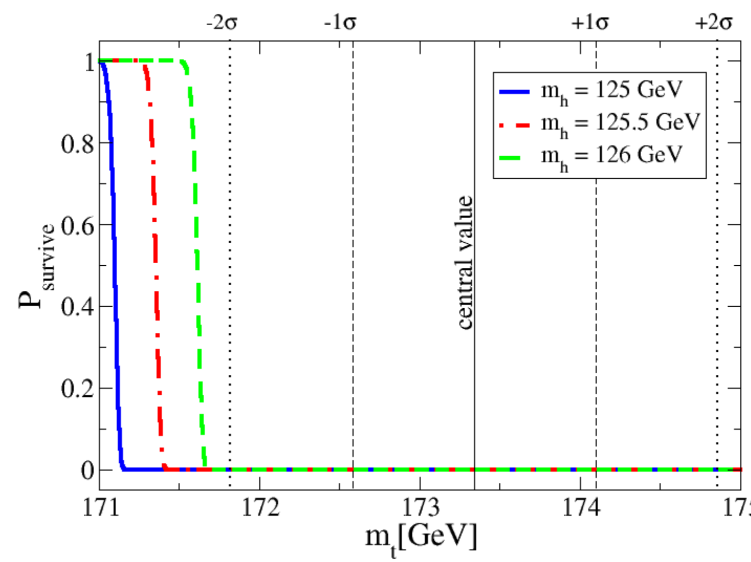


S. Moch et al. arXiv:1405.4781

- Initial BICEP2 results suggests Large Hubble rate (H_I~$10^{14\text{-}16}$ GeV ~ GUT scale) during inflation → large amplitude fluctuations of the scalar field → vacuum decay.



Survival probability of the universe



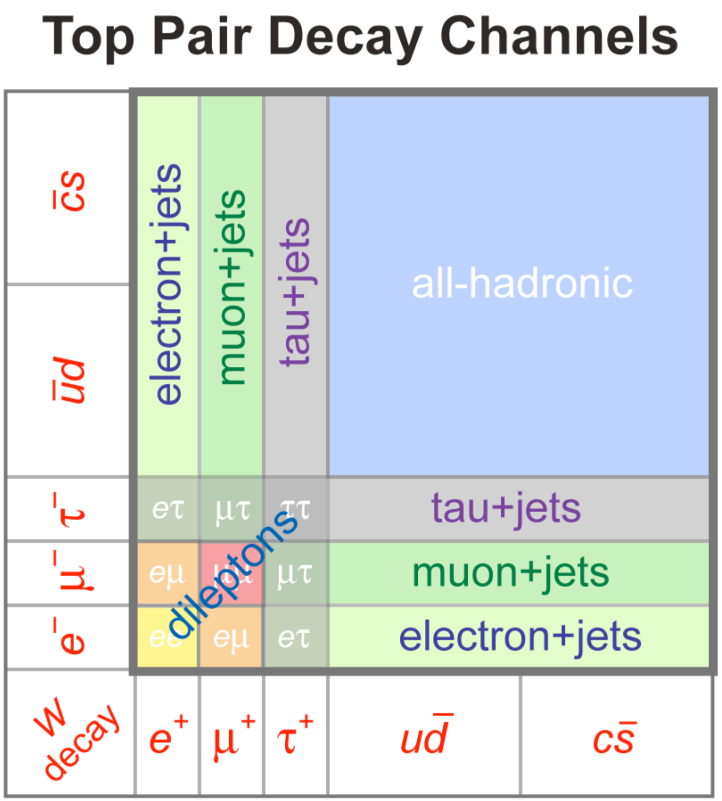
Top Quark and QCD

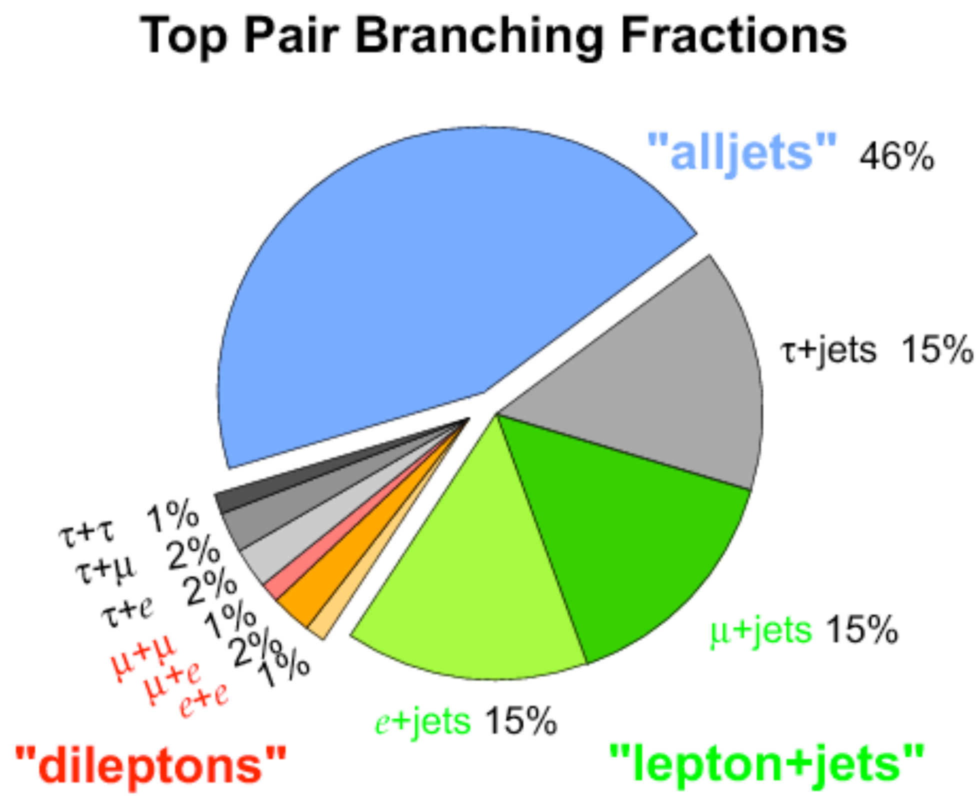
- Top quark measurements
  - *Test perturbative QCD*
  - *Understanding perturbative and non-perturbative QCD effects → ultimate precision in top quark mass and its interpretation.*
- A selection of measurements from CMS

All public CMS results at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Top Quark Decays

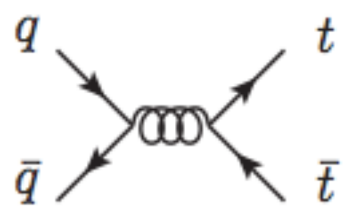
- Top quarks decay into a W boson and a b-quark ~100% of the time.
- $t\bar{t}$ decay channels are categorized by the W boson decay modes.



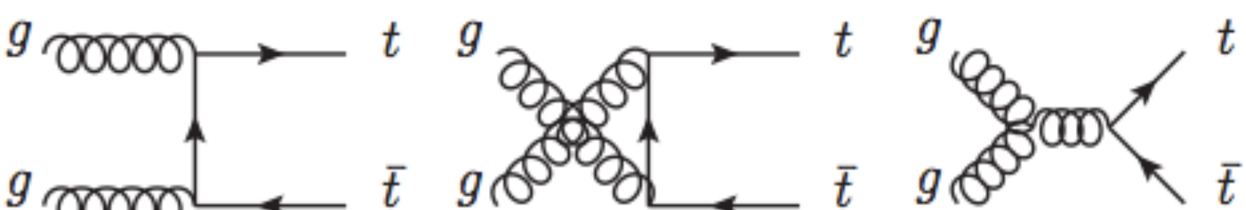


Top Quark Production

- $t\bar{t}$ pair production through QCD interactions: Dominant mechanism at hadron colliders.



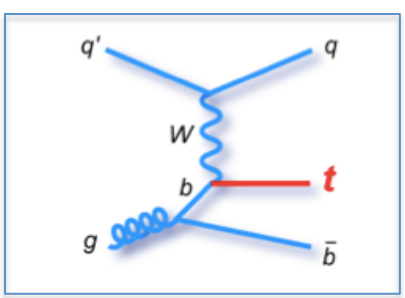
$q\bar{q}$ annihilation
~15% (LHC)
~85% (Tevatron)



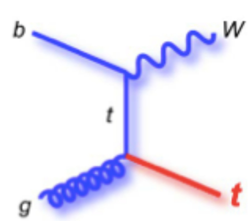
Gluon fusion
~ 85% (LHC)
~15% (Tevatron)

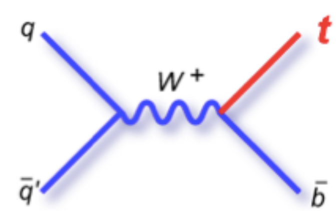
At LO QCD → $O(\alpha_s^2)$

- single top production through EWK interactions:

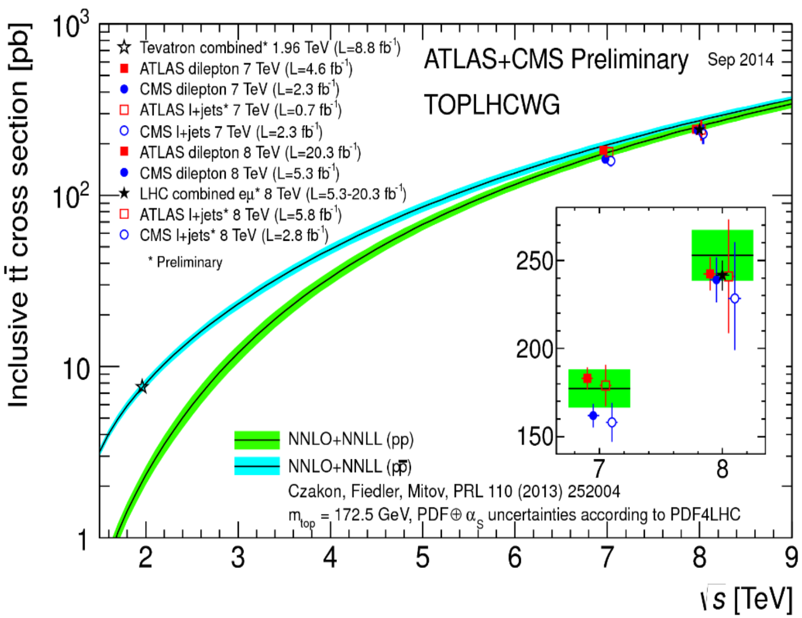


sensitive to u/d-PDFs



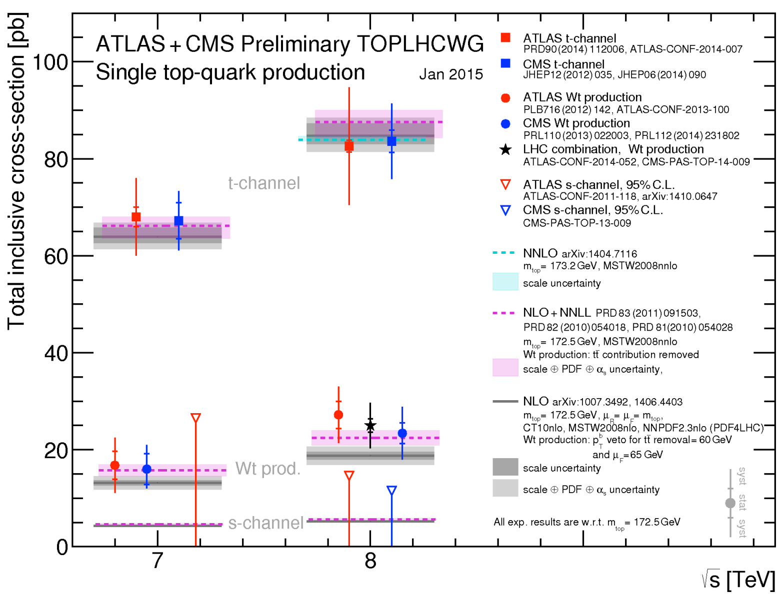


Top Quark Production



- Top pair cross sections at NNLO precision

$$\delta_{NNLO-theory} = 5.7\% \;>\; \delta_{e\mu} = 3.5\%$$



- Single top t-channel cross section at NNLO precision
  - theory uncertainty ~1%
  - Measurement uncertainty ~10%

Top quark Pair Production and QCD Factorization

$$\sigma_{pp\to t\bar{t}}\left(s,m_t\right)=\sum_{i,j=partons}\int dx_1\,dx_2 f_i^{pdf}\left(x_1,\mu_f^2\right)f_j^{pdf}\left(x_2,\mu_f^2\right)\hat{\sigma}_{ij\to t\bar{t}}\left(\hat{s},m_t,\mu_f,\mu_r,\alpha_s\left(\mu_r\right)\right)$$

Non-perturbative *Perturbative*

factorization ➔ $PDFs\left(x,\mu_f^2\right)\otimes\hat{\sigma}\left(\hat{s},m_t,\mu_f,\mu_r,\alpha_s\left(\mu_r\right)\right)$

PDFs (parton distribution functions)
→ determined from data
(α_s in QCD evolution of PDFs)

Partonic cross-section → short-distance interactions:
Coupling small at high energy → hard scattering; calculated perturbatively *(series in α_s).*

$p_T^{parton} < \mu_F$ → absorbed in PDFs
$p_T^{parton} > \mu_F$ → part of the short distance cross section

$$\mu_f\sim Q\sim\sqrt{\hat{s}}\sim\sqrt{x_1x_2s}$$ *(Q: energy scale of the hard process)*

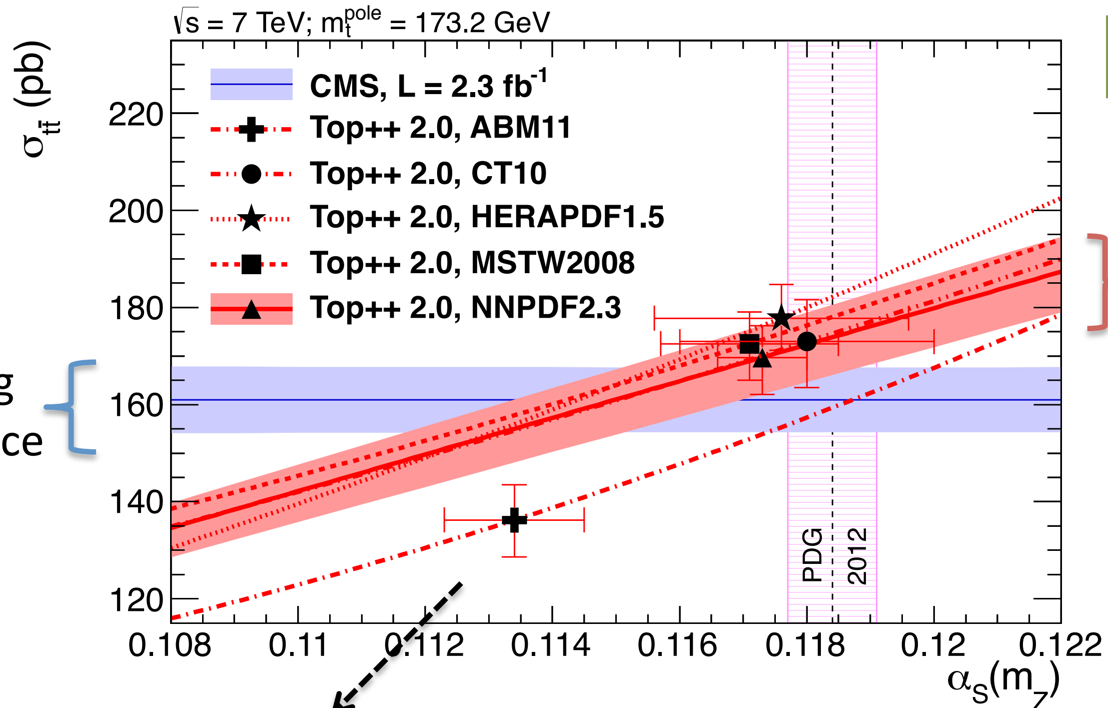
→ *inputs: m_t, α_s, and PDFs*

Fix m_t and PDF → Determine α_s

- $\sigma_{t\bar{t}}$ (CMS; 7 TeV; dilepton) [JHEP, 11 (2012) 067]
- TOP++ 2.0 calculation (@ NNLO+NNLL) with $\alpha_s(M_Z)$ scan.

PLB 728, 496 (2014)

4.1% (including acceptance effects)



scale & PDF uncertainties

($\mu_r=\mu_f=m_t^{pole}$ → 0.5 – 2 x μ)

$$m_t^{pole} = m_t^{Tevatron} =$$

$$173.18 \pm 0.94\ GeV \oplus 1\ GeV$$

ABM: smaller gluon density.

assumed difference between m_t^{pole} & m_t^{MC}

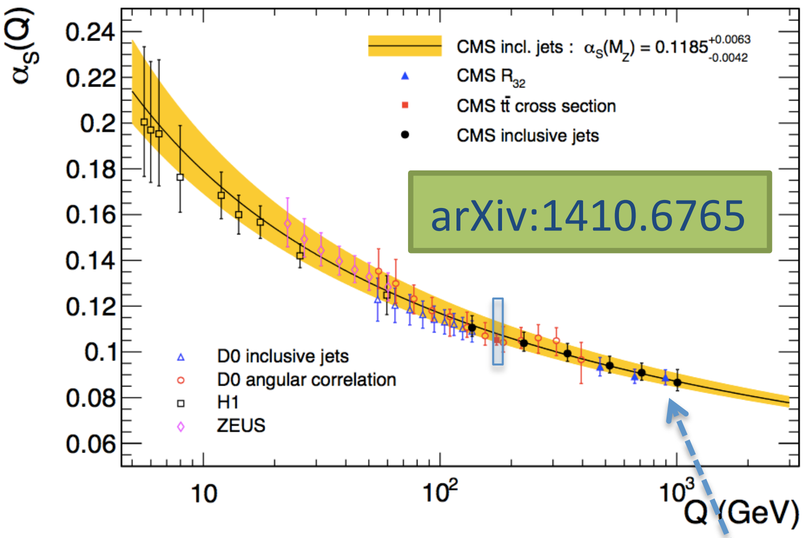
using NNPDF2.3:

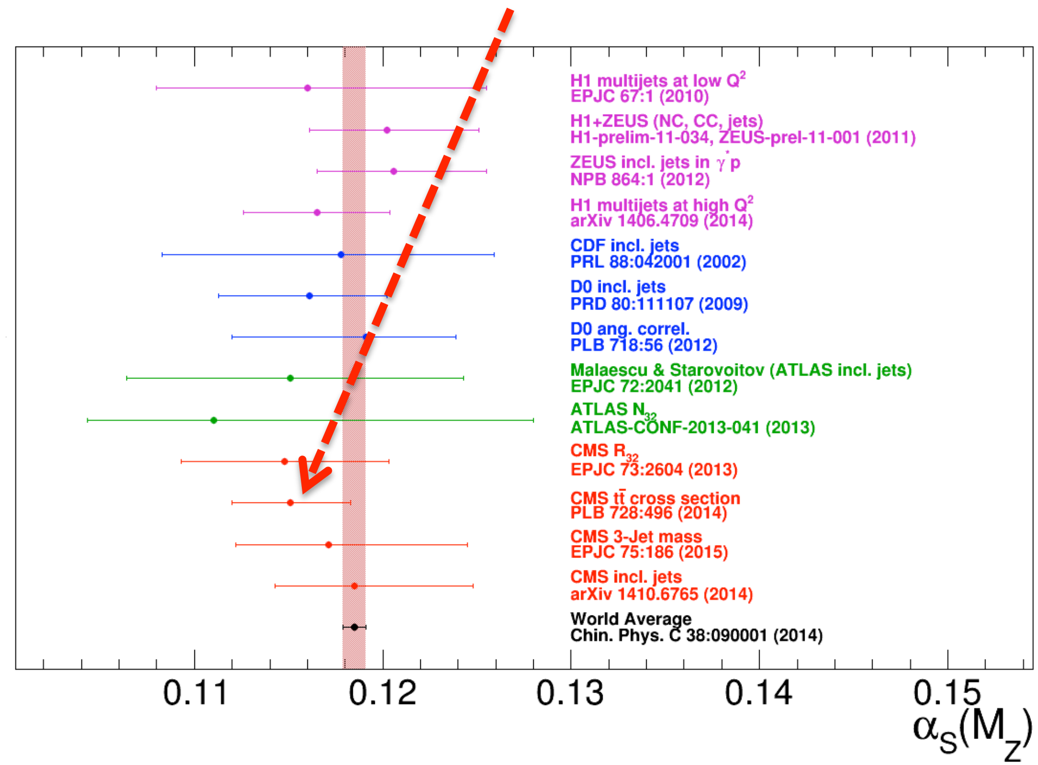
$$\alpha_s(m_Z) = 0.1151^{+0.0028}_{-0.0027}$$

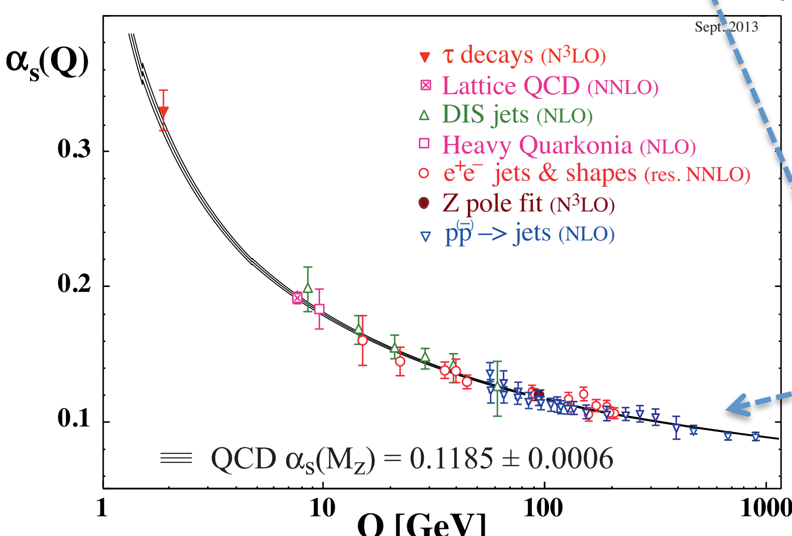
$\delta(\alpha_s)$=2.4%
→ δ(scale): 0.8%
→ $\delta(m_t)$: 1.1%
→ LHC beam energy: $\delta(\sqrt{s})$=46 GeV → 0.7%

Determination of α_s

- The first determination of $\alpha_s(m_Z)$ from top quark production.
- The first $\alpha_s(m_Z)$ result at a hadron collider at full NNLO QCD.

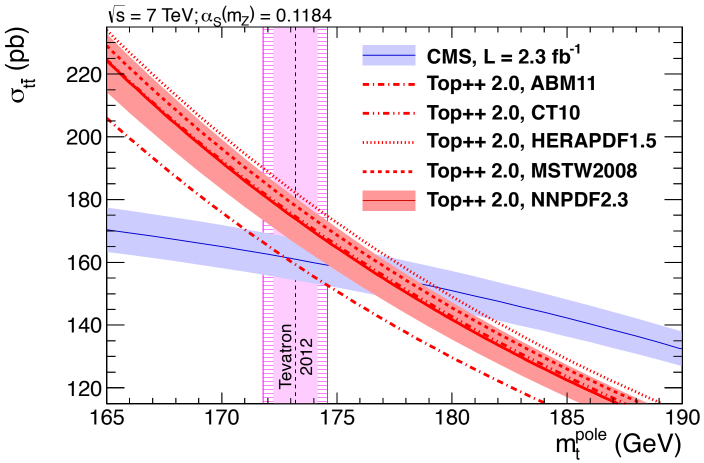


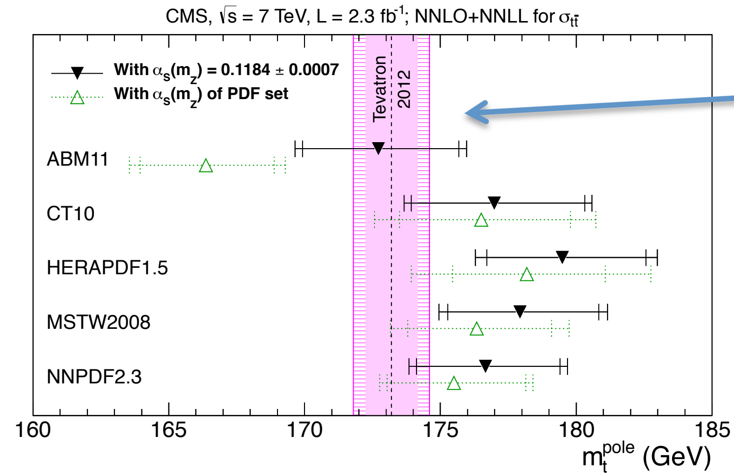




(aprox.)NLO
with large scale uncertainties and
non-perturbative corrections.

Fix $\alpha_s(m_Z)$ and PDF → Determine m_t^{pole}





outer band: MC-pole mass.

PLB 728, 496 (2014) (arXiv:1307.1907v3)

Inner error bar: cross-section, beam energy, PDF, scale.
Outer error bar: + $\delta(\alpha_s)$.

Compare measured inclusive $t\bar{t}$ production cross-section to fully inclusive calculations at NNLO QCD that involve an unambiguous m_t.

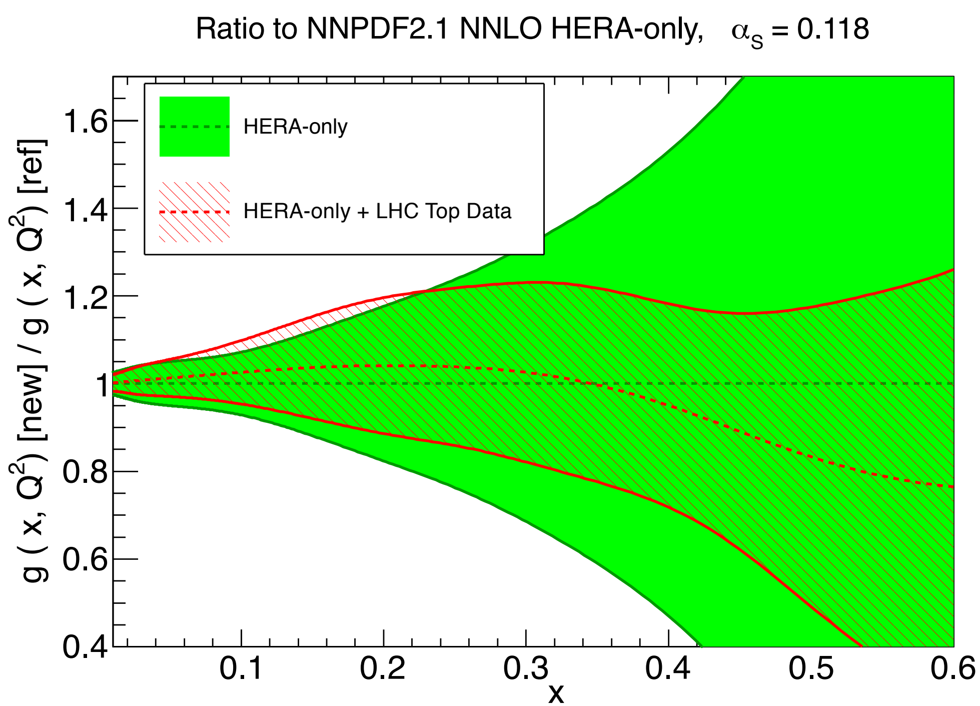
$$m_t^{pole} = 176.7^{+3.0}_{-2.8}\, GeV$$

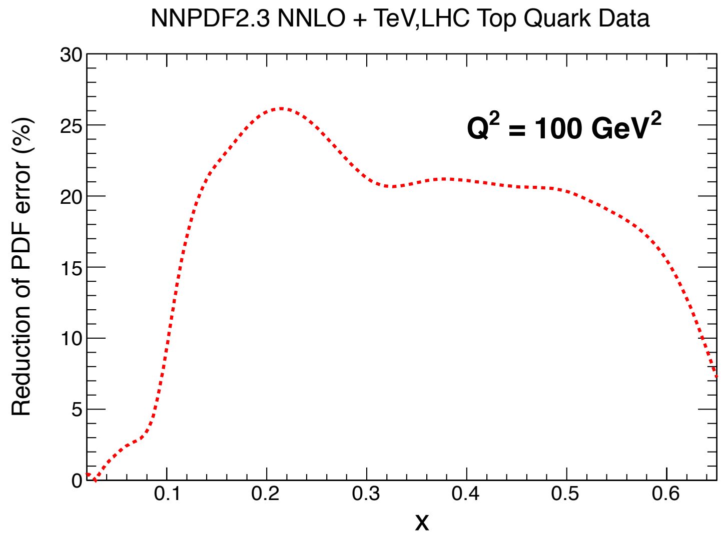
→First NNLO top mass.

Dominant systematic uncertainties: measured $t\bar{t}$ cross-section and PDF.

Constraints on the gluon PDF from Top Pair Production

Czakon et al.
arXiv:1303.7215





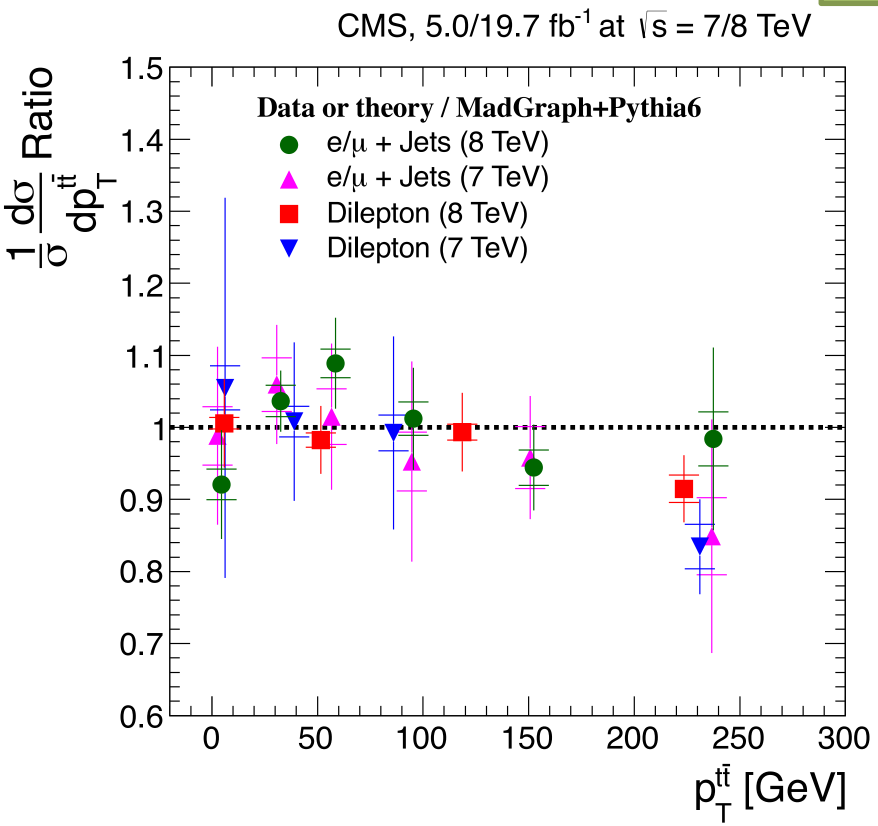
Relative reduction of error due to the inclusion of top data in the PDF fit.

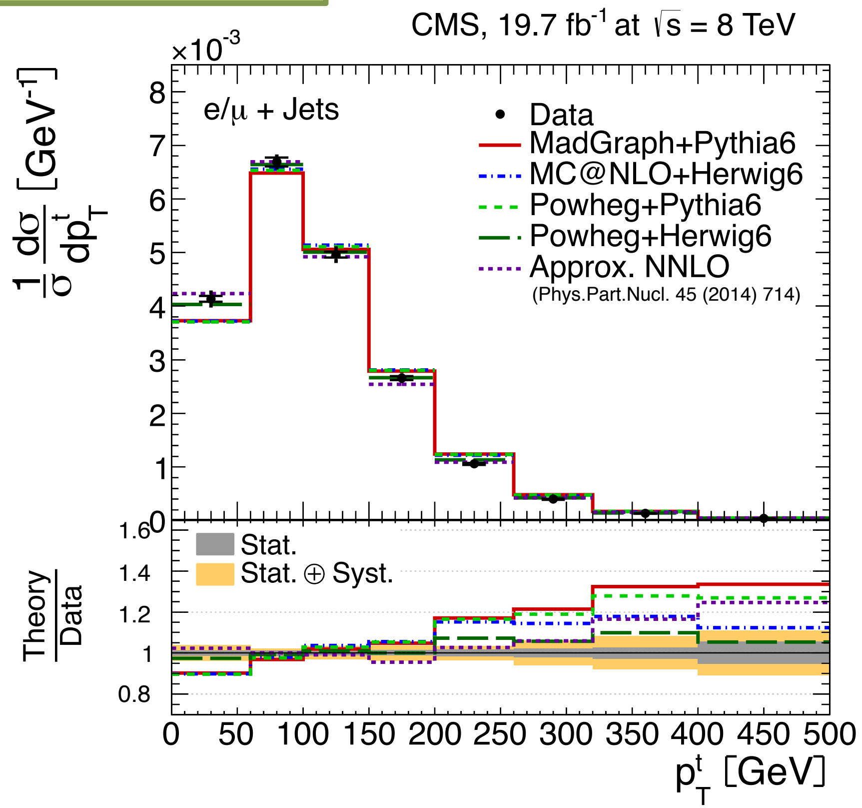
- LHC top quark production cross section data already providing significant constraints on gluon PDF at large x.
- Significant impact on predictions for the scalar boson, and BSM predictions (dominated by gg processes).

Top Pair Differential Cross Sections

- Test various levels of pQCD approximations for top quark production
- Test and tune MC models
- Differential distributions from data are described reasonably well except top p_T.
- For all distributions trend is the same for 7 & 8 TeV and in lepton+jets and dilepton measurements.

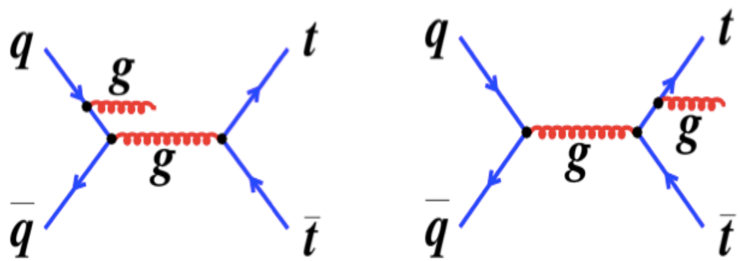
arXiv:1505.04480





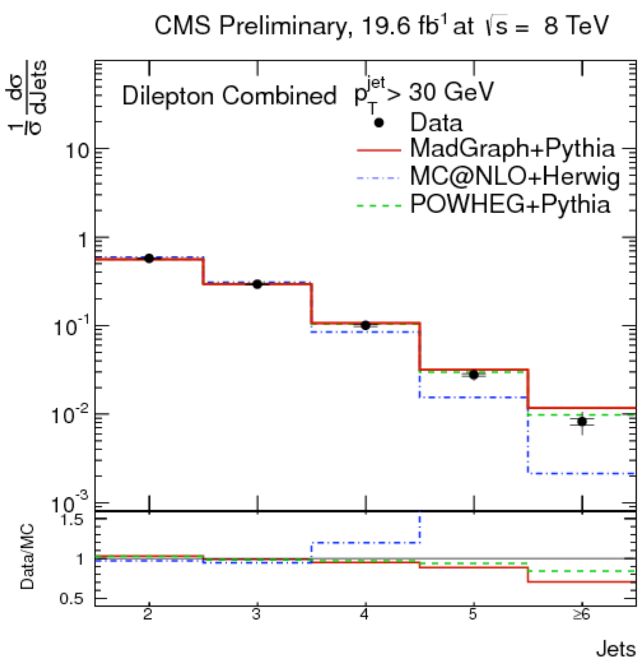
$t\bar{t}$ + jets

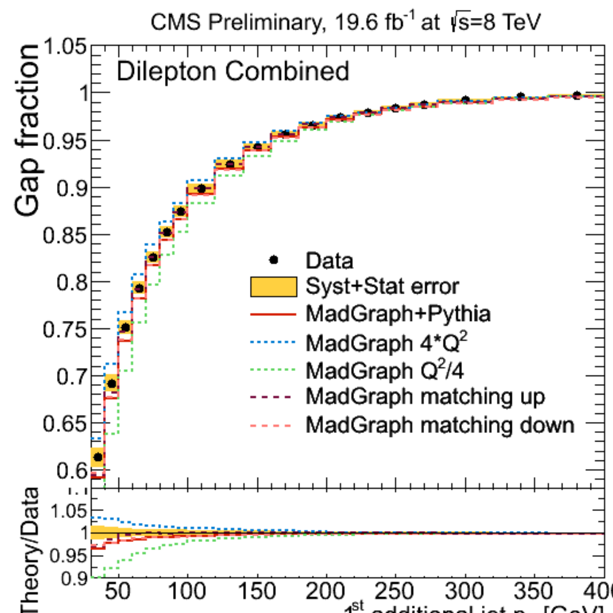
- At the LHC, $t\bar{t}$ events are usually accompanied by additional hard jets from initial or final state QCD radiation (ISR/FSR).
  - Test higher-order QCD calculations (ISR parameters, QCD scales, ..)
  - Improve model choices and uncertainties for coming measurements.



- $t\bar{t}$ + 1 and 2 jet calculations are available at NLO.
- $t\bar{t}$ + jets: background to H→$b\bar{b}$, ...

arXiv:1404.3171, CMS-PAS-TOP-12-041





- "Gap fraction": fraction of events w/o additional jets above a threshold.
  - Alternative way to investigate jet activity from QCD radiation.

Top Properties: Mass

- m_t: free parameter of QCD Lagrangian, i.e. not an observable → no unique interpretation.
  - Pole mass
  - "running mass" (m_t^{MSbar})

$$m_t^{pole} - m_t^{MSbar} \approx 10\ GeV$$

but can be related to each other:

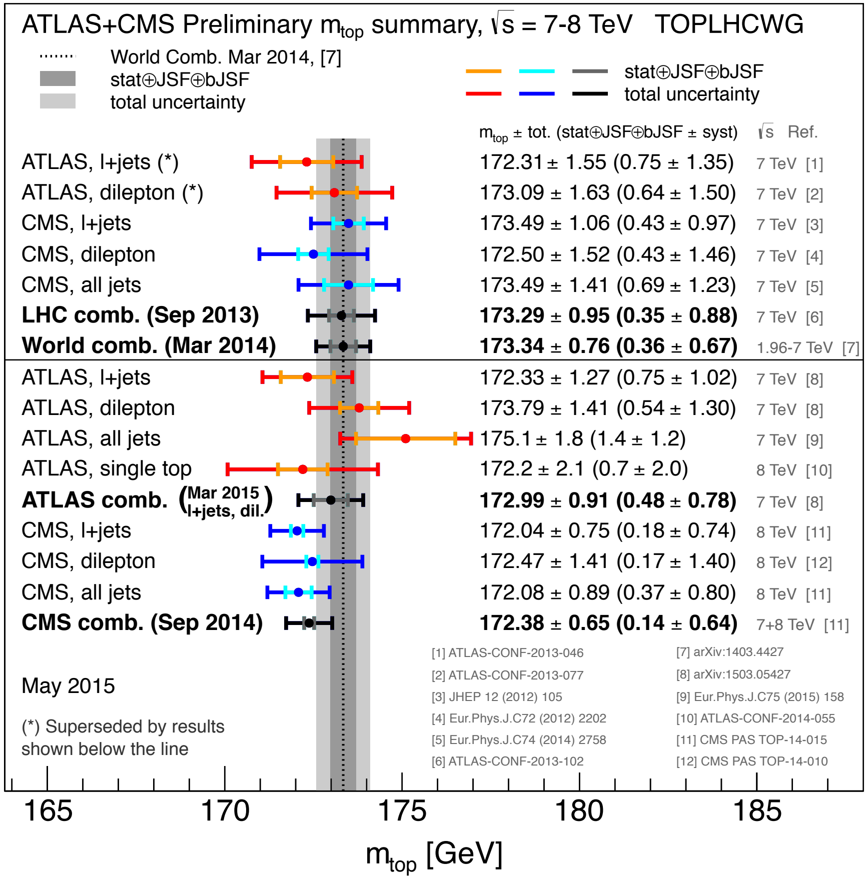
$$m_t^{\overline{MS}}(\mu) = m_t^{pole} / \left(1 + \frac{4}{3}\frac{\alpha_s(m_t^{\overline{MS}}(\mu))}{\pi} + 8.2364\left(\frac{\alpha_s(m_t^{\overline{MS}}(\mu))}{\pi}\right)^2 + 73.638\left(\frac{\alpha_s(m_t^{\overline{MS}}(\mu))}{\pi}\right)^3\right)$$

PLB482 (2000),99

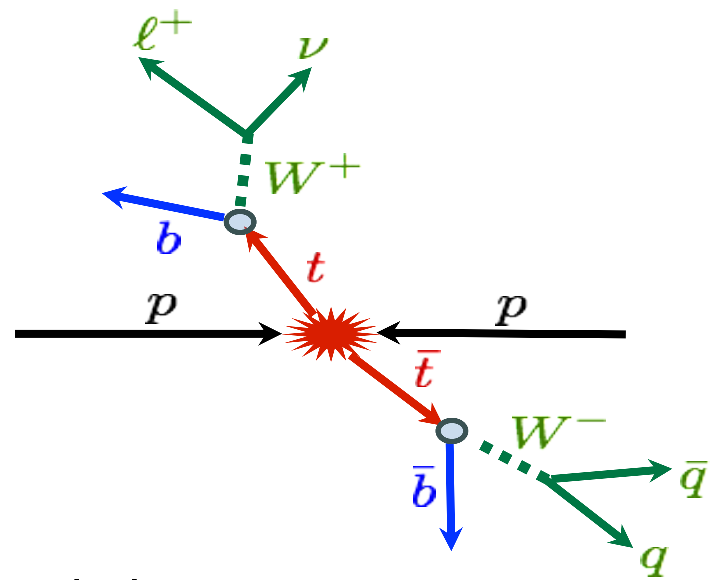
  - Monte Carlo Mass
    - No straightforward definition in ***direct top mass measurements***
    - MEs at fixed order (LO or NLO) QCD + higher orders by parton showers

$$m_t^{MC} \neq m_t^{pole} \neq m_t^{MSbar} \neq m_t^{XX}$$

Top Quark Mass – Direct Measurements



- General features:
  - Assign each jet to a top decay product (constrained kinematic fits)
  - Calibration of the method
  - Determination of m_t^{MC} (and JES simultaneously) from data.



Main Challenges:

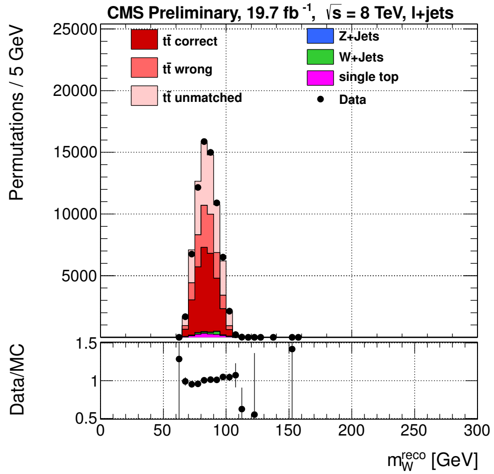
→ Hadronization and other modeling uncertainties.

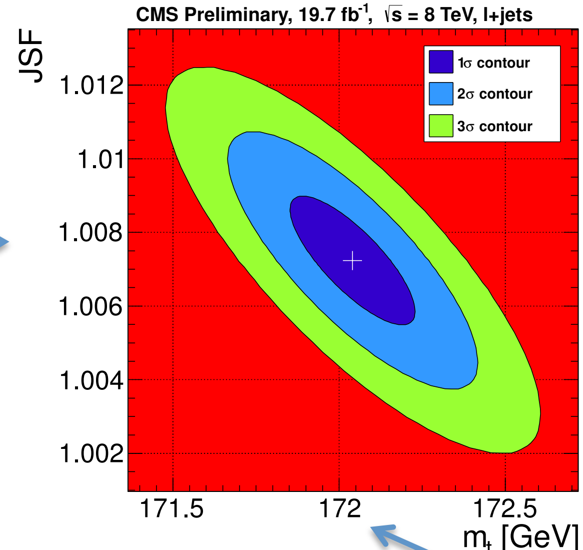
→ Precision only a few times Λ_{QCD} (*i.e. where the measurements and interpretations starts to become more difficult*).

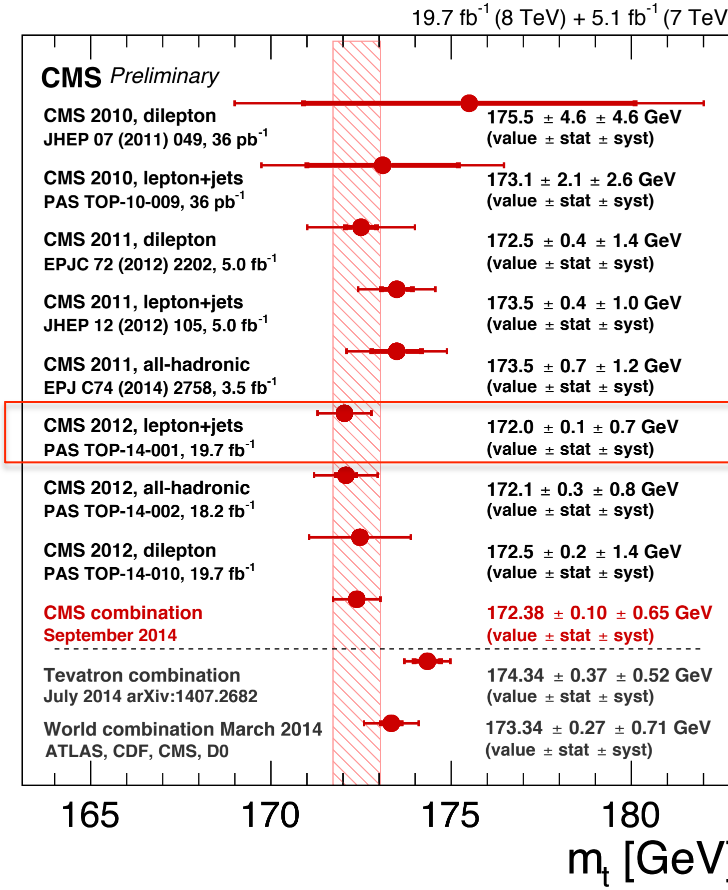
Top Mass in the lepton+jets Final State at 8 TeV

Determine m_t simultaneously with jet energy scale factor in a joint likelihood fit.

CMS-PAS-TOP-14-001

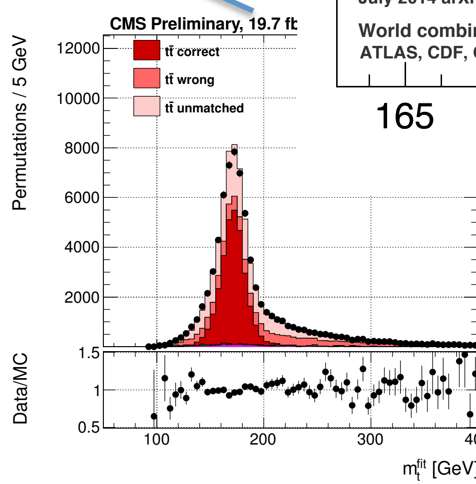






$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

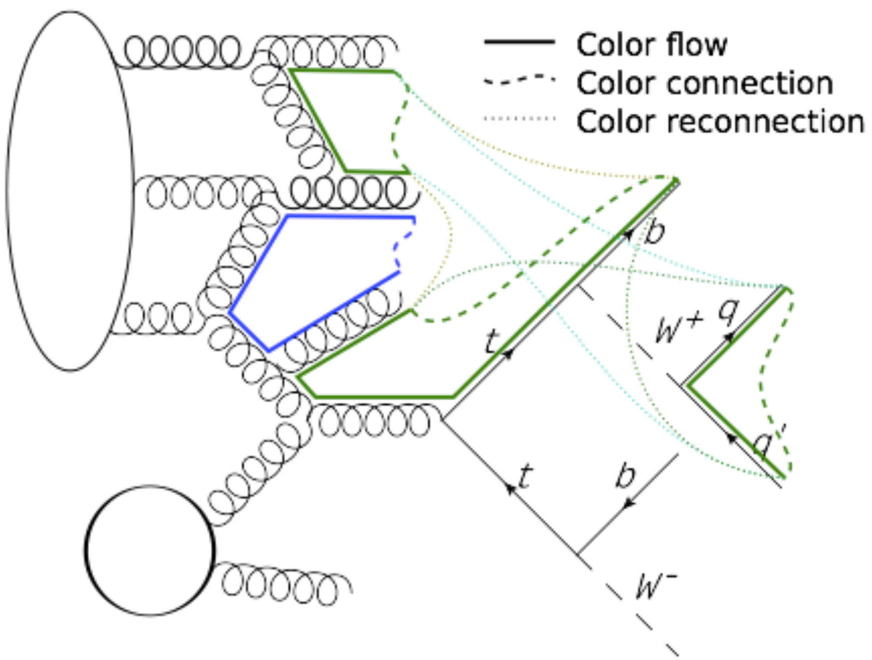
→ First single measurement with < 1 GeV precision.



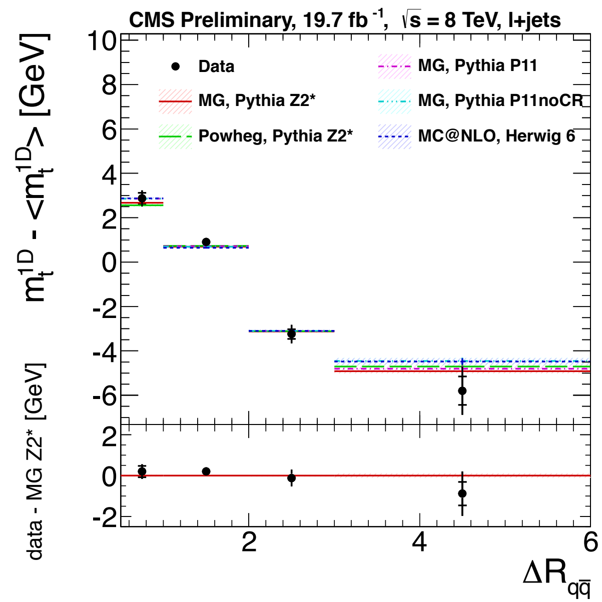
Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-14-001

- Interpretation of the top mass measurements is not straightforward for δ ~< 1 GeV ~Γ_t.
- Study model uncertainties.
  - some (non-)perturbative effects have different kinematic dependences.
  - Difficult to define a pole mass for an unstable and colored particle.



- Study variables sensitive to
  - color connection,
  - ISR/FSR,
  - b-quark kinematics.



No mis-modeling of data.

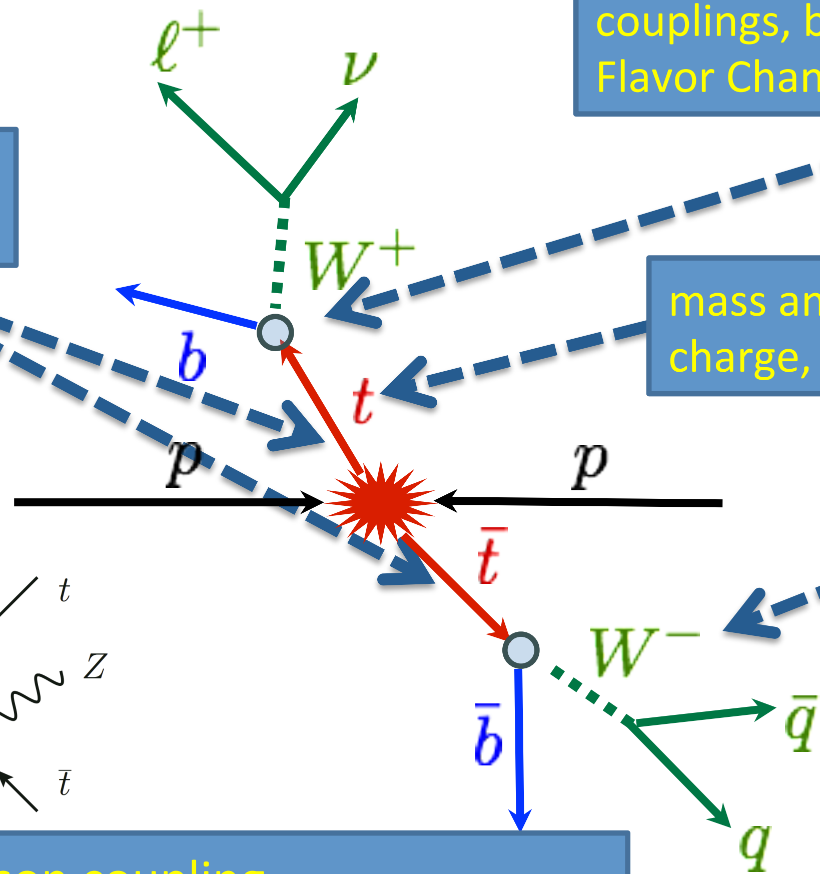
Top Properties from Production and Decay

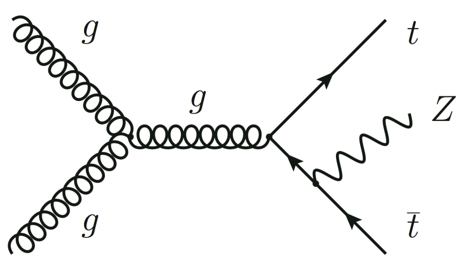
couplings, branching ratios,
Flavor Changing Neutral Currents (FCNC)

asymmetries,
spin correlation

mass and top-antitop mass difference,
charge, width, lifetime

W helicity

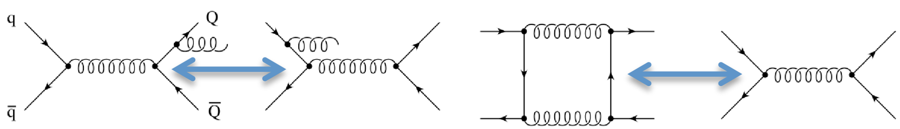


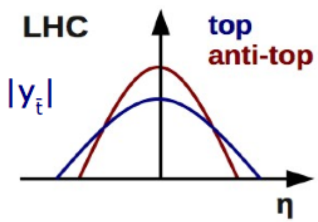


Top quark – Z boson coupling
Top quark – Scalar boson coupling

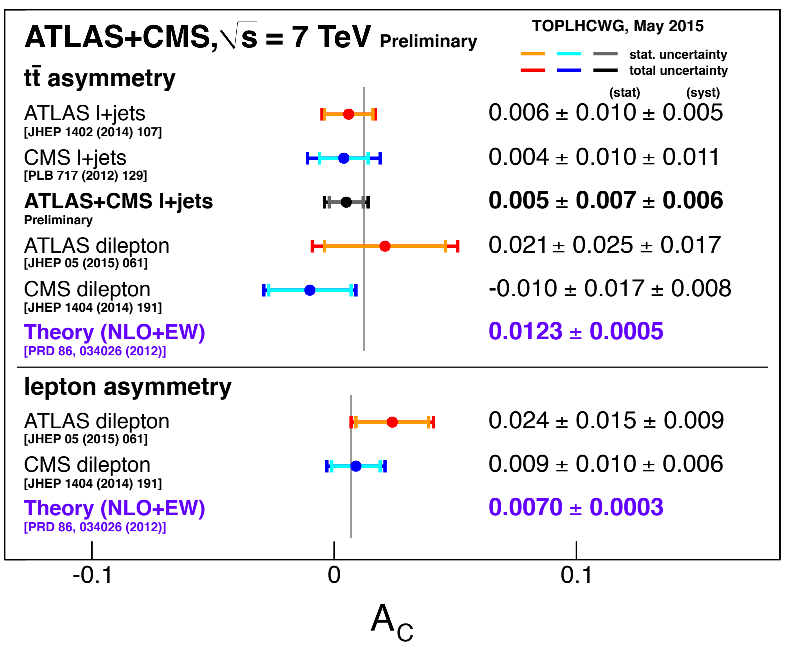
And properties from electroweak single top production (mostly from t-channel)

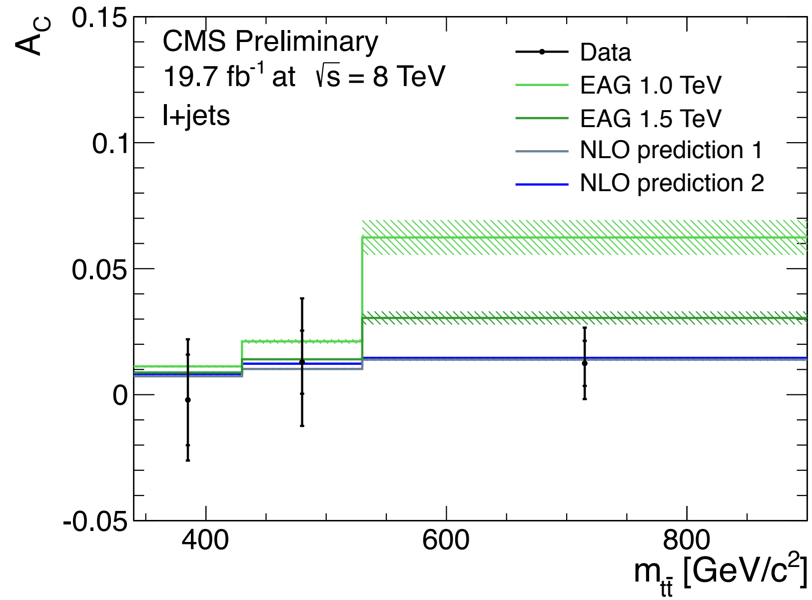
Top Properties: $t\bar{t}$ Asymmetry



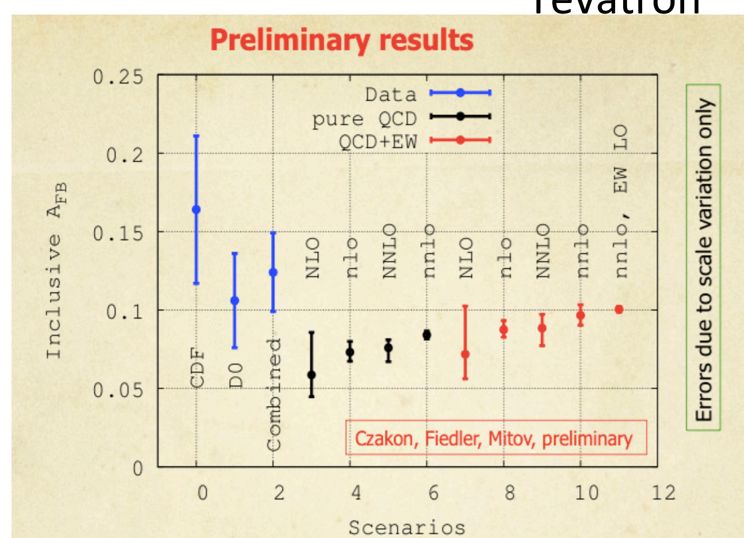


No asymmetry
at the leading order.





Tevatron



- Measurements consistent with NLO+EW calculations.
- $b\bar{b}$ asymmetry measurements consistent with LO predictions (LHCb arXiv:1406.4789).
- No new physics up to ~1 TeV.

Czakon et al. 2014, CKM2014, Vienna, 9 Sep. 2014

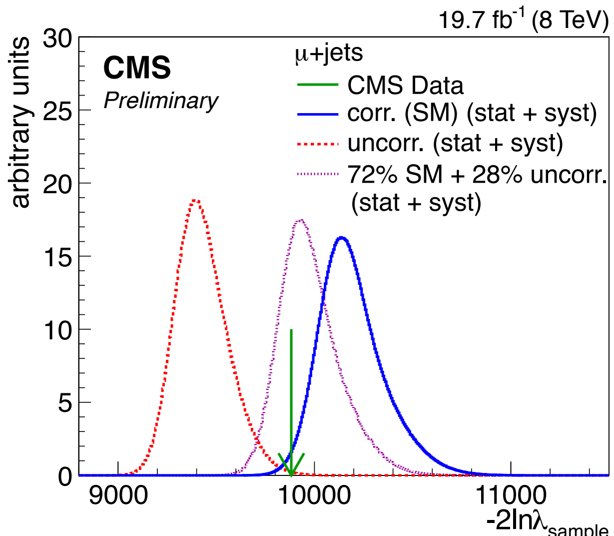
Top Properties: $t\bar{t}$ Spin Correlation (l+jets) using the matrix Element Method

$$P(x_i|H) = \frac{1}{\sigma_{obs}} \int f_{PDF}(q_1) f_{PDF}(q_2) dq_1 dq_2 \frac{(2\pi)^4 |M(y,H)|^2}{q_1 q_2 s} W(x,y) d\Phi_6$$

CMS-TOP-13-015

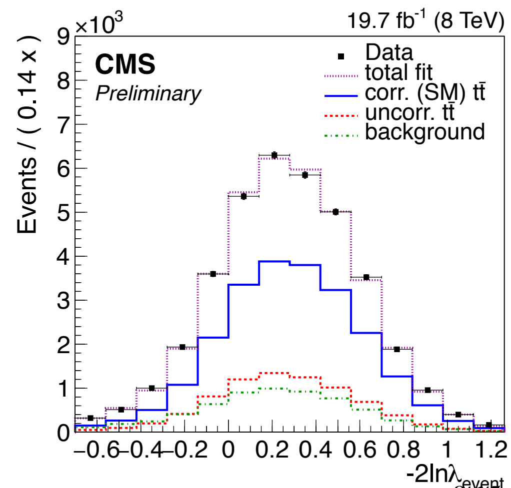
Calculate the likelihoods using ***MadWeight***: P. Artoisenet, V. Lemaitre, F. Maltoni, and O. Mattelaer, "Automation of the matrix element reweighting method", *JHEP* **1012** (2010) 068

Hypothesis testing using sample likelihood ratios: SM vs uncorrelated top - anti-top quark.



Data agree with
SM within 2.2σ and uncorrelated $t\bar{t}$ within 2.9σ

Template fit to event likelihood ratios: SM vs uncorrelated top - anti-top quark.



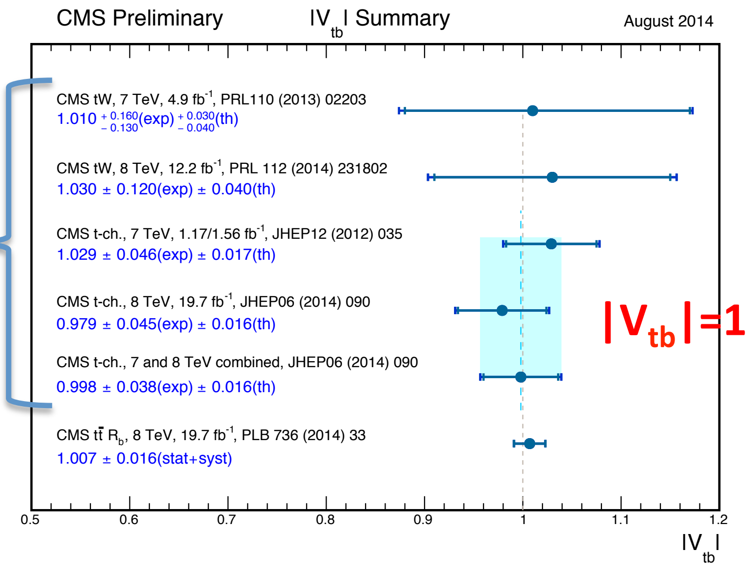
$$f = 0.72 \pm 0.09(stat.)^{+0.15}_{-0.13}(syst.)$$

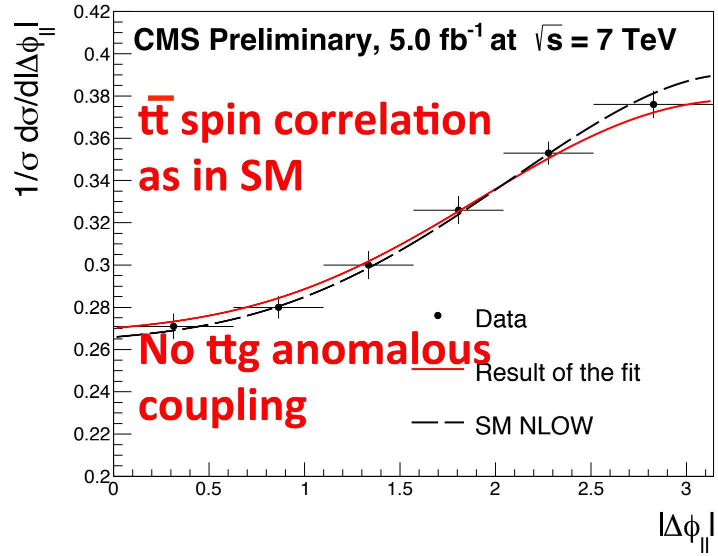
$$A_{hel}^{measured} = 0.22 \pm 0.03(stat.)^{+0.05}_{-0.04}(syst.)$$

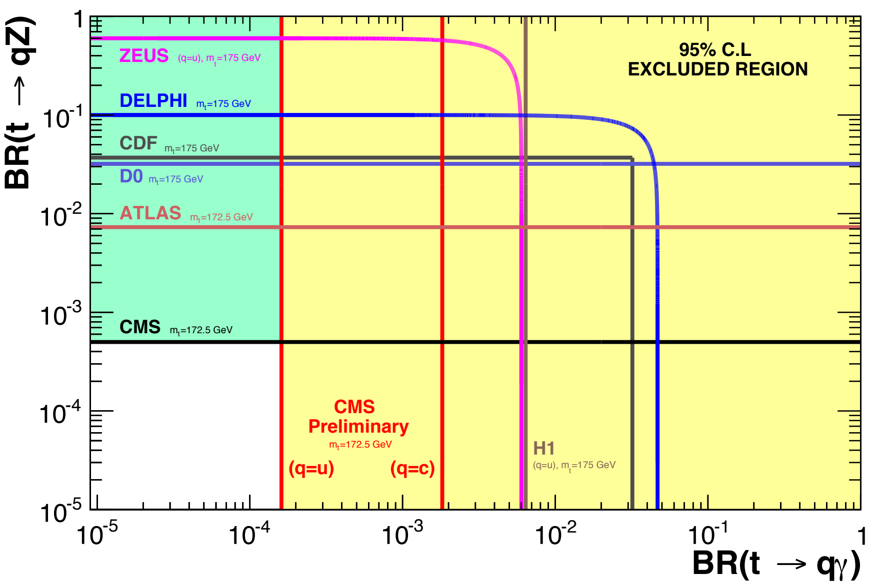
Most precise measurement of f in lepton+jets channel.
Precision similar to dilepton channel.

Other Top Properties → No New Physics

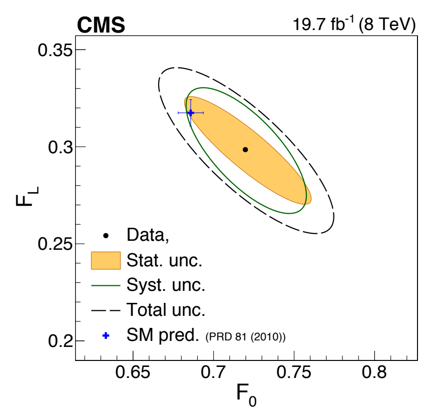
Single top

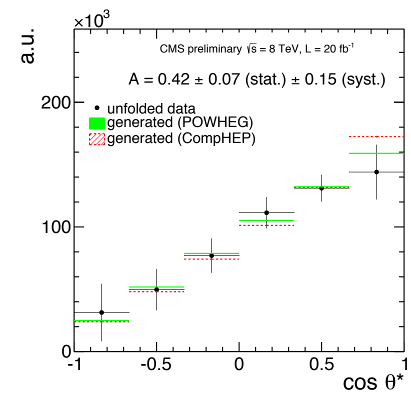






No FCNC: tqZ, tqg, tqγ, tqH





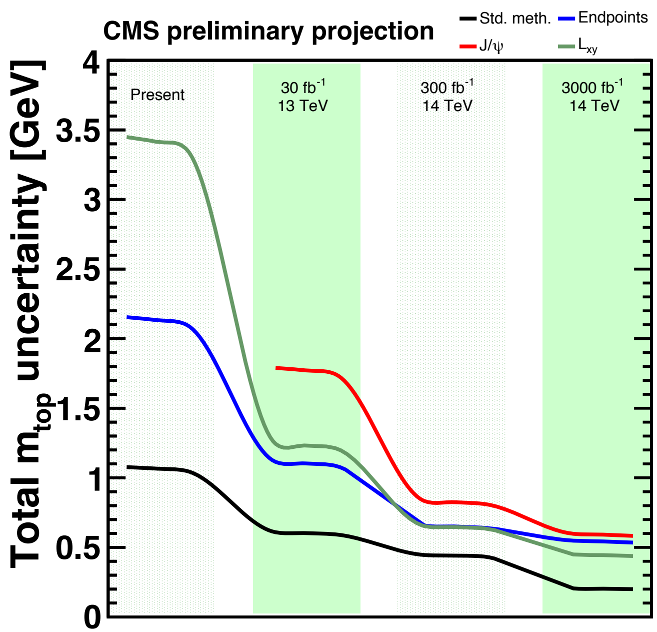
W and top polarizations as expected by SM.
No anomalous couplings in the Wtb vertex.

Conclusions

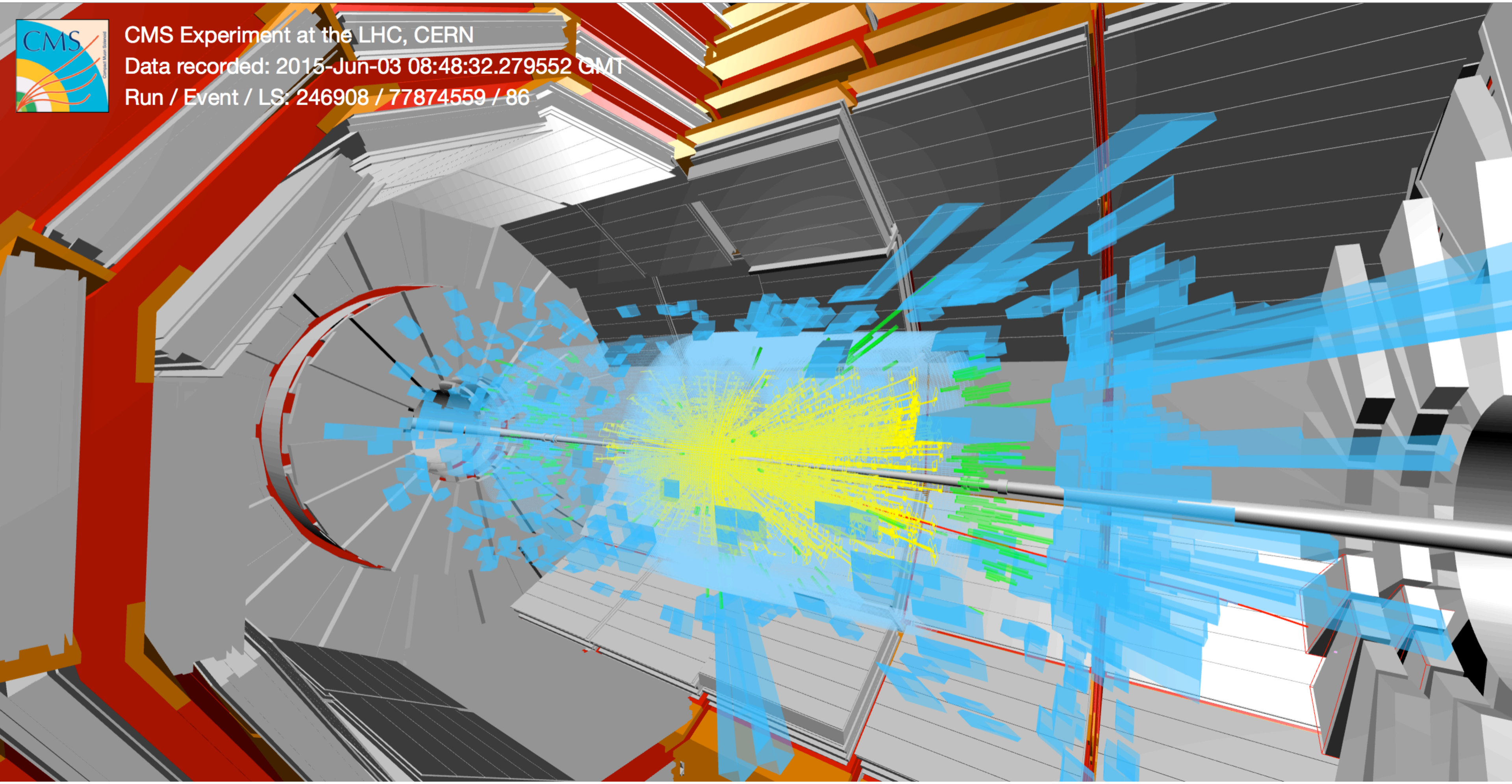
- Top quark plays an important role in testing and understanding QCD, electro-weak, flavor and searches for new physics.
- $t\bar{t}$ cross section
  - SM predictions at NNLO. → Experimental precision <5%.
- Top pair differential cross sections
  - NLO (+PS) MC predictions.
  - SM predictions at NNLO.
  - Simultaneous precise determination of top quark mass, strong coupling, and constraints on PDFs (esp. gluon PDFs at high x).
- Run-II measurements at ultimate precision require dedicated effort in top quark event modeling.

Conclusions

- Top quark mass
  - <1 GeV precision in a single measurement ~ world combination
  - Top mass related variables vs event kinematics to improve understanding of its interpretation.
  - Alternative top mass measurements to defeat systematic obstructions.



- Pin down top properties (both from $t\bar{t}$ and single-top) with increased precision and better methods.
  - Couplings, branching ratios, $t\bar{t}$ spin-correlation, asymmetries, polarizations, FCNC, …
- LHC Run I set the stage for new physics searches and other precision measurements.



- Lumi delivered to CMS by Sunday: ~ $6pb^{-1}$.
  - Already have thousands of top quark events from $\sqrt{s}$ = 13 TeV collisions.

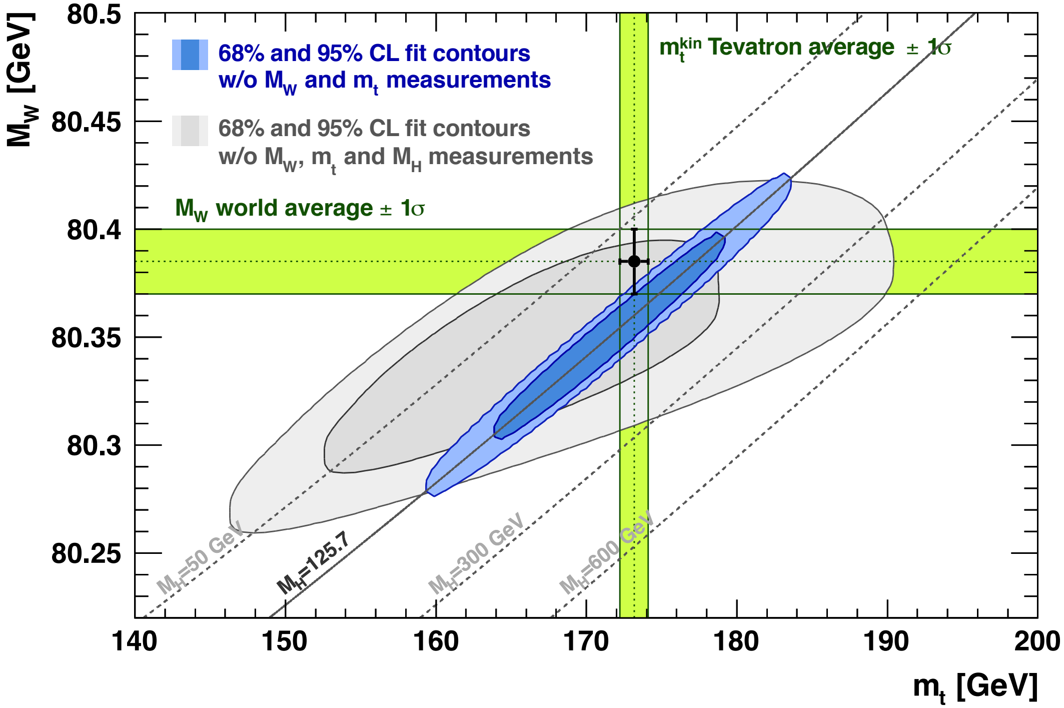
Backup

Electroweak fit before H boson discovery: $m_H = 94^{+25}_{-22}\,GeV$ consistent with measured m_H within 1.3σ.

$$m_H^{CMS-Run\ I} = 125.02^{+0.26}_{-0.27}(stat)^{+0.14}_{-0.15}(sys.)\ GeV$$

arXiv:1412.8662

The Gfitter Group, M. Baak et al., EPJC 72, 2205 (2012)

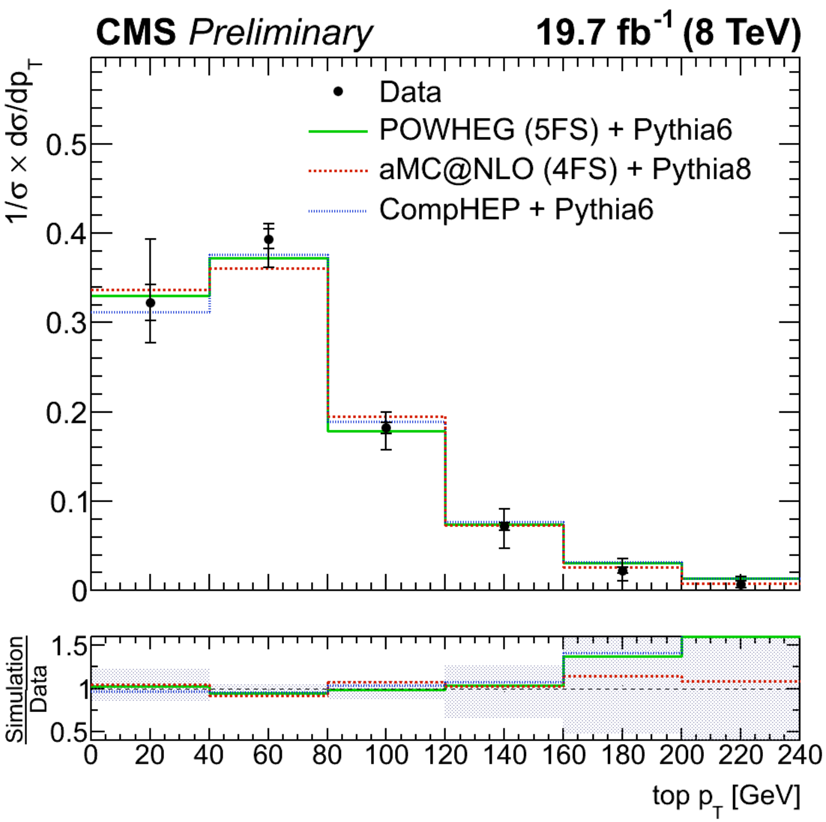


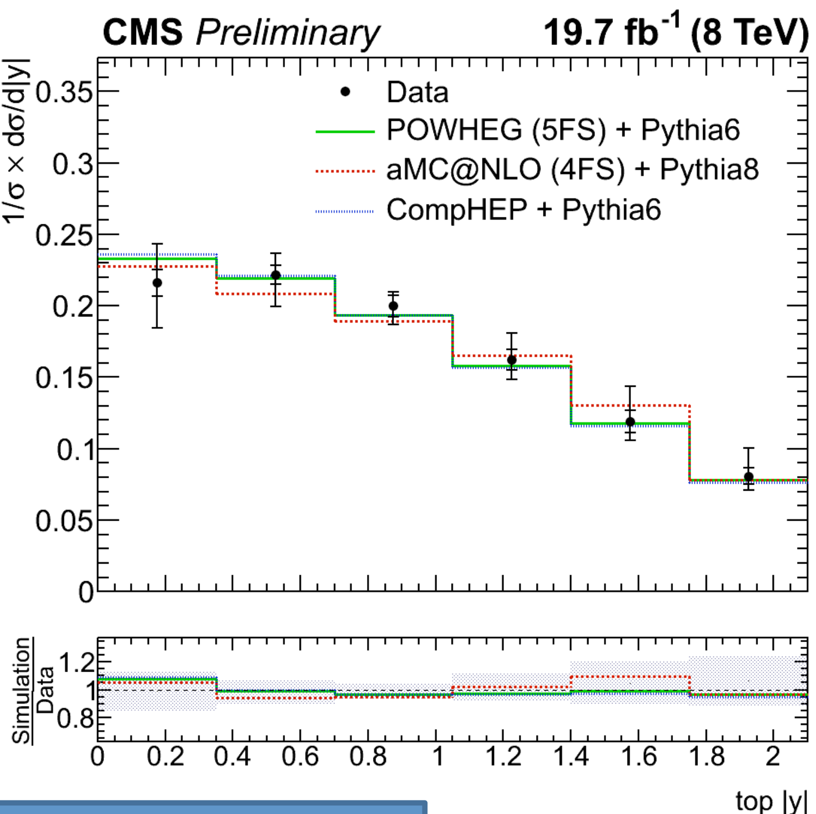
Analysis assumes that the SM is the fundamental theory with nothing beyond.

→ One of the most critical tests of the standard model!

Differential Measurements in the single top t-channel

- Different implementations for b-quark modeling in the initial state for NLO generators.
- CompHep: combination of 2→2 and 2→3 processes based on the p_T spectrum of the second b quark (as an NLO approximation).
- Data distributions (corrected to parton level) are described well by both NLO and LO MCs + Pythia6.



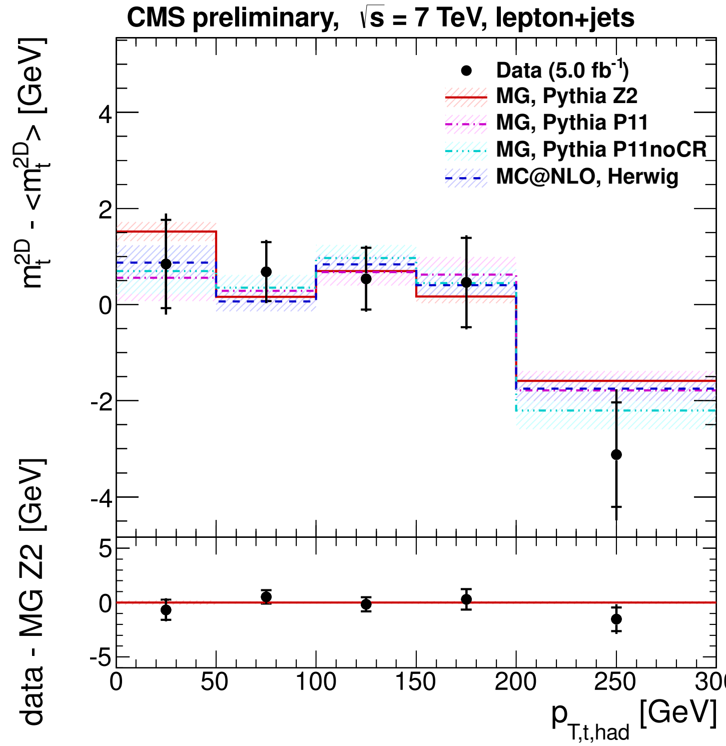


CMS-PAS-TOP-14-004

Dependence of Top Mass on Event Kinematics

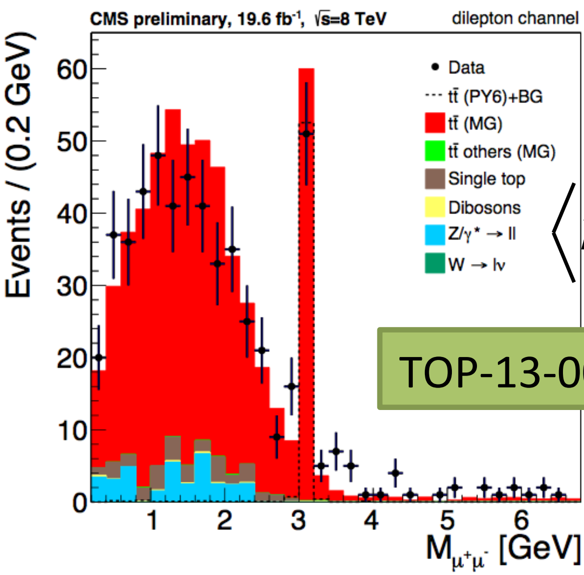
CMS-PAS-TOP-12-029

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$

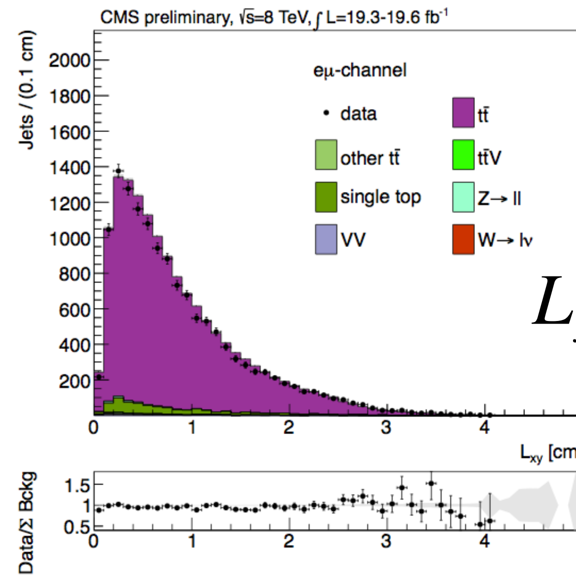


Alternative Top Quark Mass Measurements

- Measurements with different/independent systematic uncertainties or with different m_t definitions.



$$\langle m_{J/\psi+\ell} \rangle \propto m_t$$



$$L_{xy} \propto m_t$$

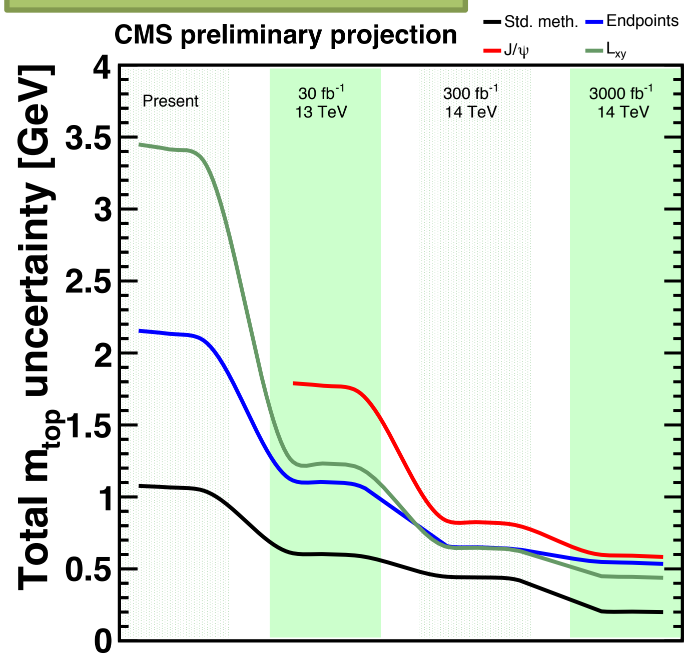
b-quark kinematics from J/ψ.
→ precise fragmentation functions.

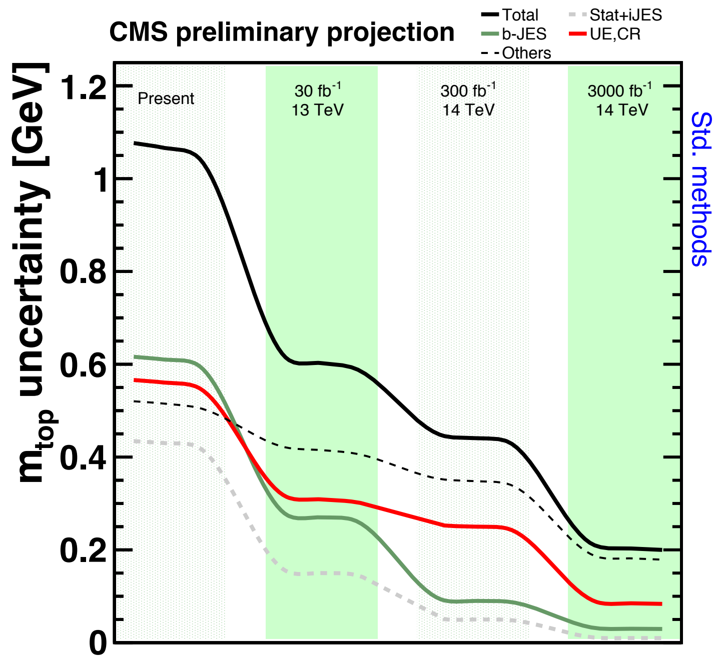
Top mass from B-hadron lifetime.
→ L_{xy} from tracks.
→ No jet reconstruction.
→ ttbar and top kinematics.

- + Mass from kinematic end-points (m_{lb}).
- Alternative measurements compatible with standard measurements but not as precise yet.

Projections for Upgraded LHC

CMS-PAS-FTR-13-017



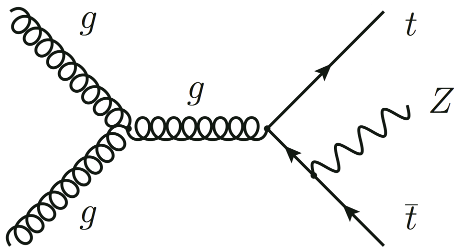


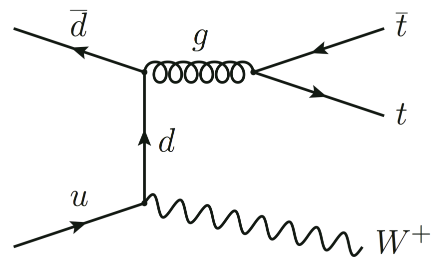
- Basic assumptions
  - improvements in experimental and theoretical systematic uncertainties believed to be possible with the large datasets of the future.
  - No limiting irreducible uncertainties (none known currently).

Top Properties: tt+W/Z

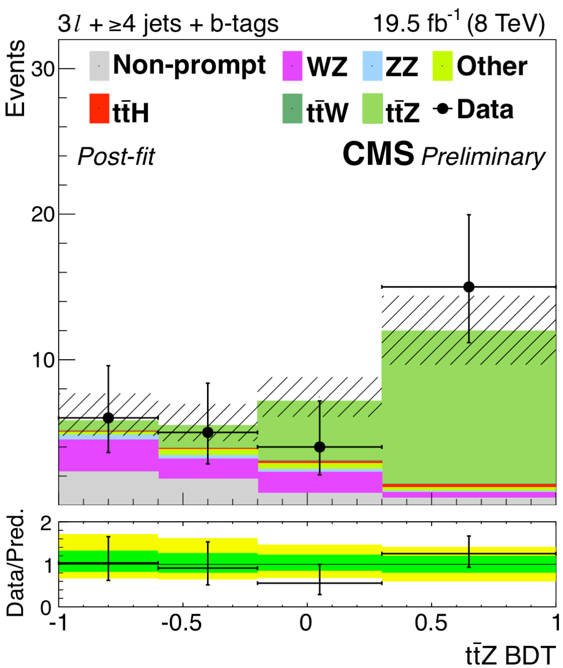
- ttZ → Direct measurement of top-Z coupling.
- tt+Z/W important backgrounds to ttH.

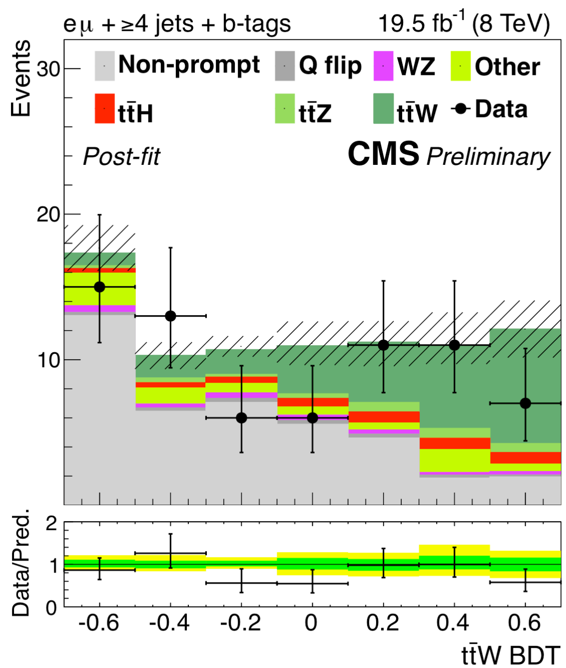
$$\sigma_{8\ TeV}\left(t\bar{t}Z\right) = \sigma_{8\ TeV}\left(t\bar{t}W\right) \approx 200\ fb$$



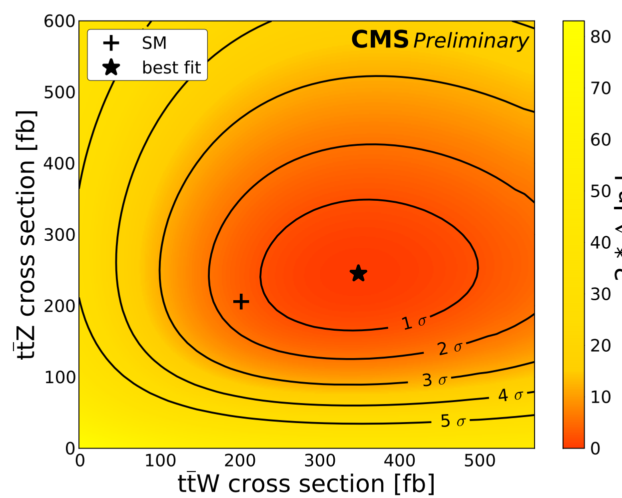


Significance	Expected	Observed
ttZ	5.73	6.44
ttW	3.54	4.81

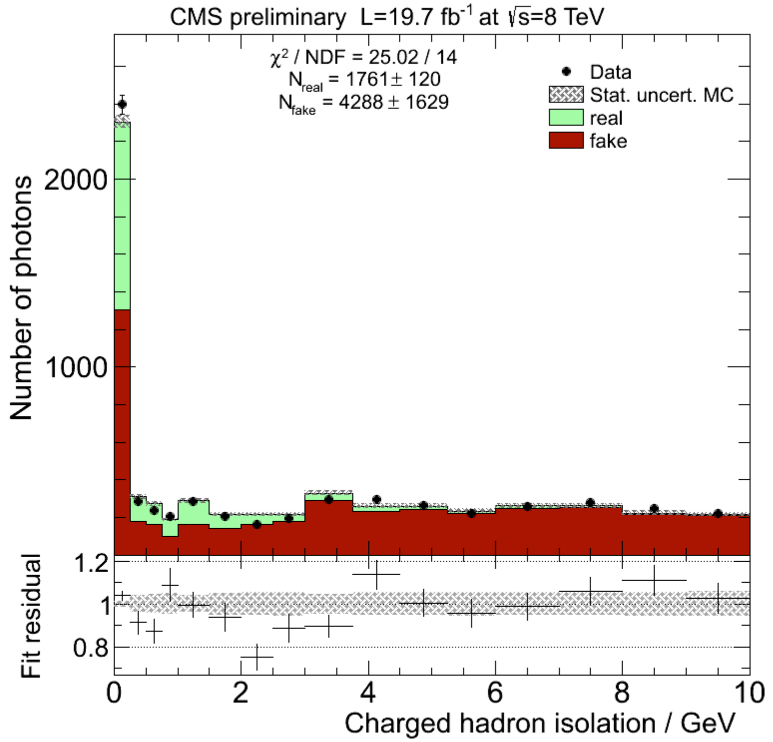


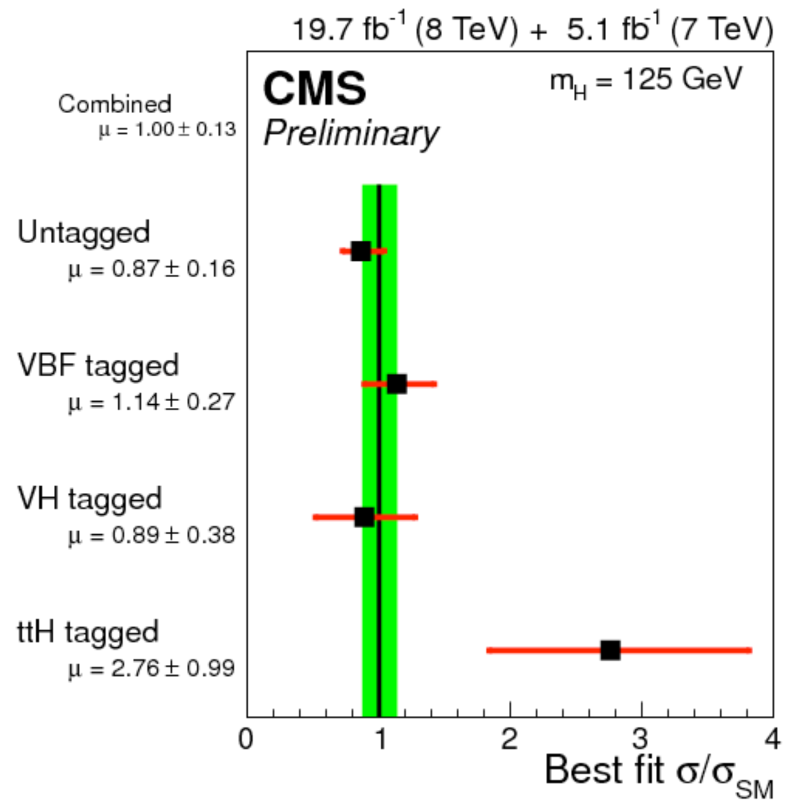


+ Constraints on the axial and vector components of the top-Z coupling using EFT.



Top Properties: tt+γ/H





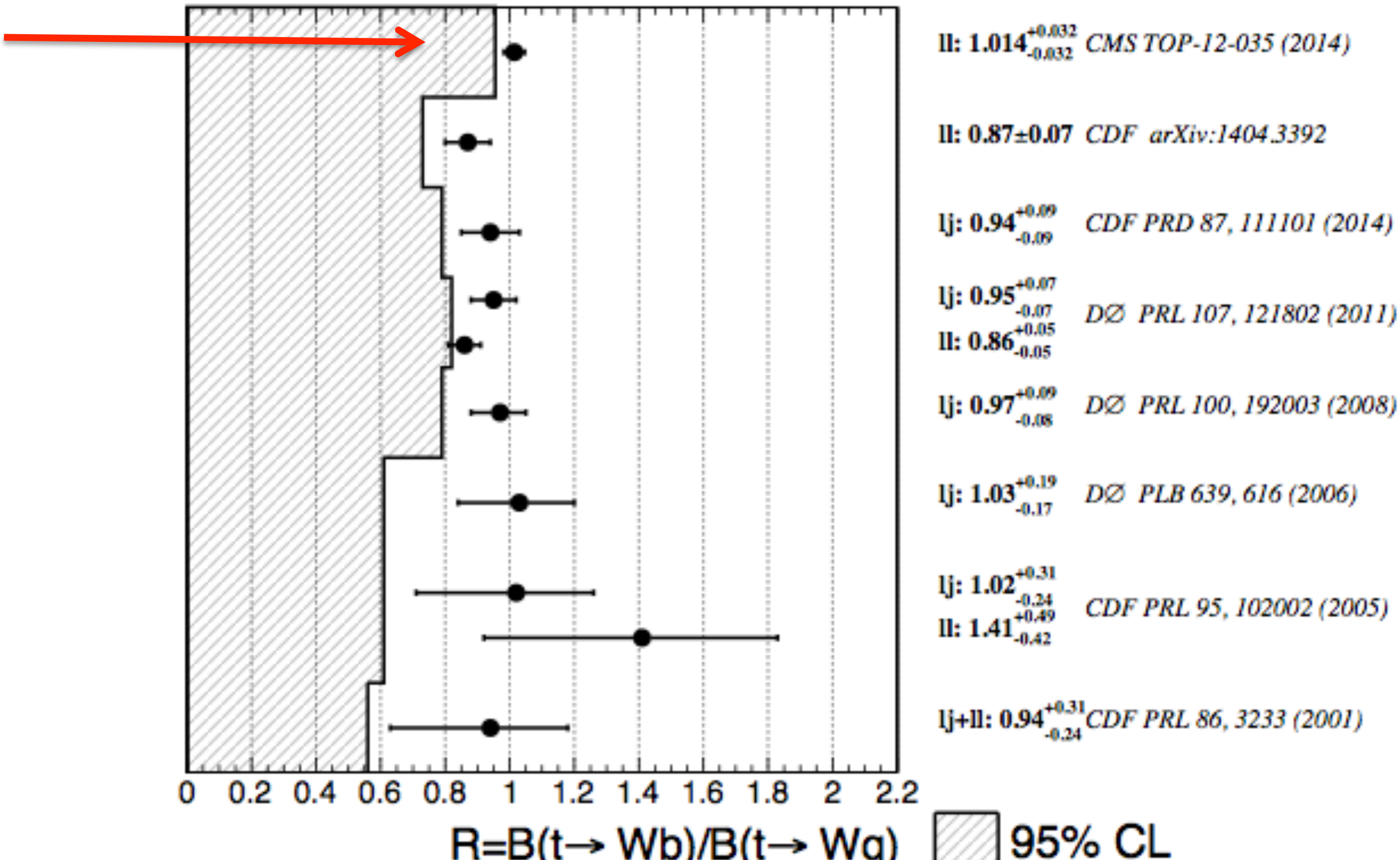
ttγ observed at 7 TeV (ATLAS)
Cross section measured at 8 TeV (CMS):

$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t}$$
$$= (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \cdot 10^{-2}$$

$$\sigma_{t\bar{t}+\gamma} = R \cdot \sigma_{\bar{t}t}^{\text{CMS}}$$
$$= 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\ \text{pb}$$

Measuring top-Yukawa coupling:
One of the most important
Goals of LHC Run II.

Top Properties: Branching Ratios



arXiv:1404.2292