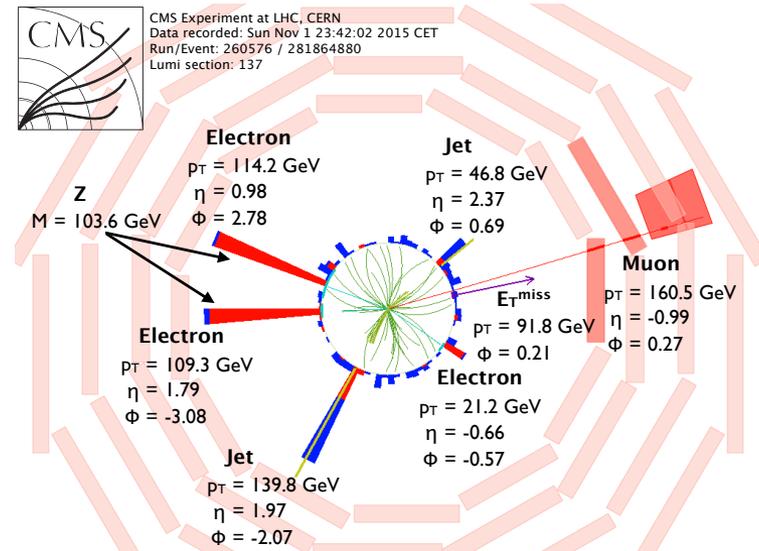


Recent Results on Top Quark Physics with the CMS Detector

Efe Yazgan



CERN LPCC EP-LHC Seminar Series, May 31st 2016

The Top Quark

- The most massive particle known to date
 - ◆ very short lifetime

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5 \times 10^{-24} \text{ s} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3 \times 10^{-21} \text{ s} \ll \tau_b \sim 10^{-12} \text{ s}$$

$$\tau_t < \tau(\text{hadronization}) < \tau(\text{spin-decorrelation}) \ll \tau_b$$



No hadronic bound states

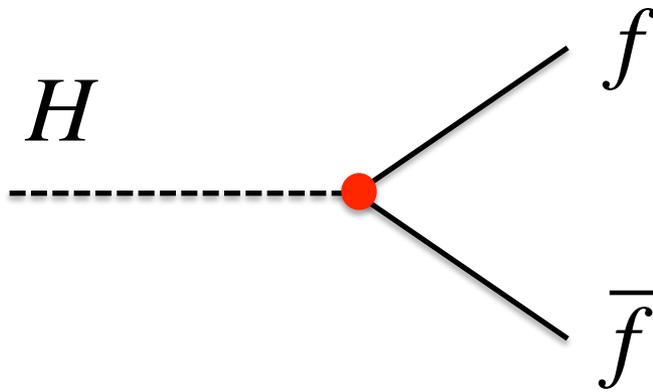


Spin effects propagate to decay products.

→ Behaves like a bare quark
→ Top quark properties “directly”
accessible (mass, V_{tb} , spin, charge, ..)

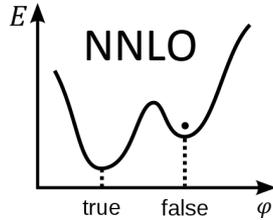
The Top Quark

The largest Yukawa coupling among the fermions – special role in electroweak symmetry breaking?

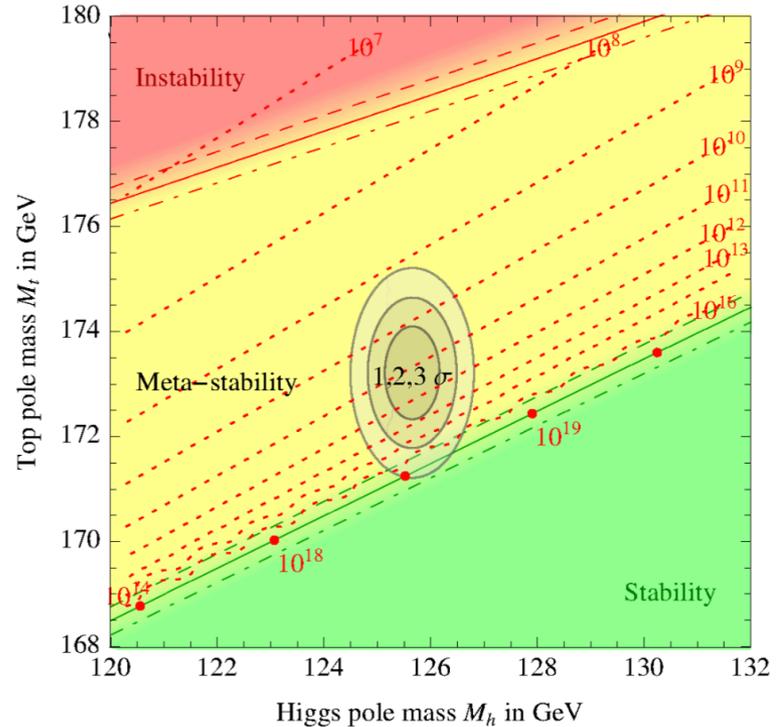
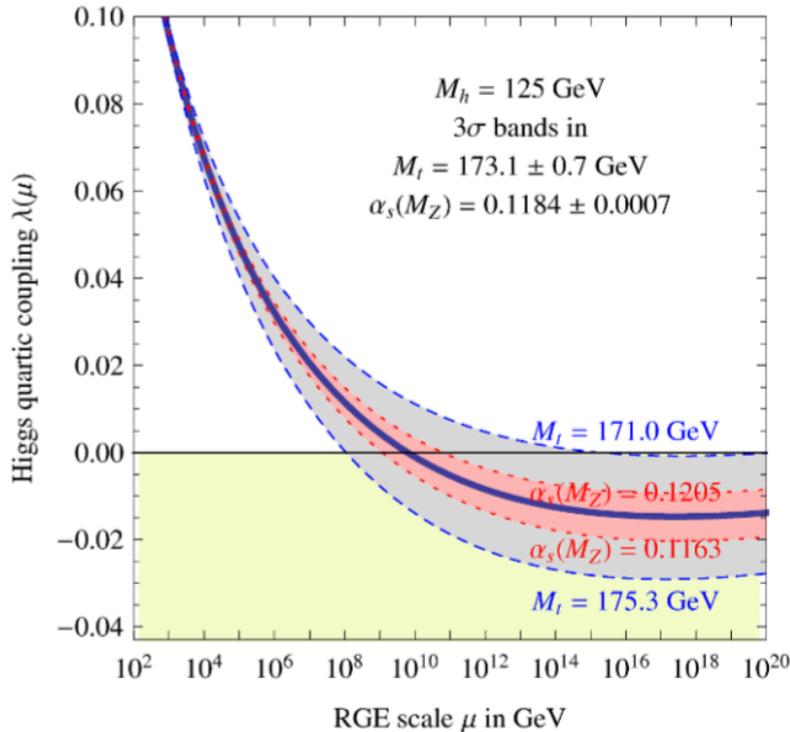


$$y_t = \frac{\sqrt{2}m_t}{v} \cong 1$$

The Top Quark



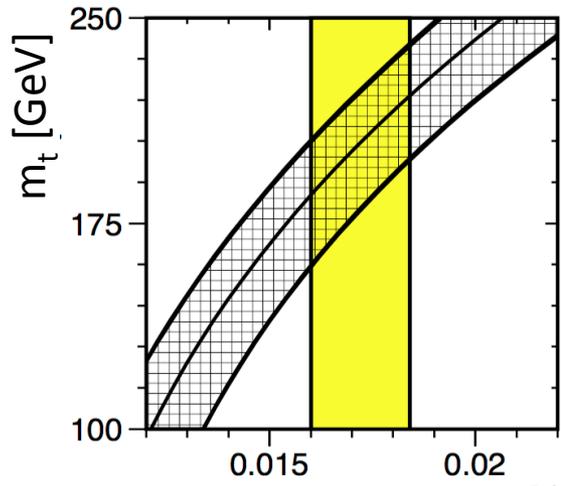
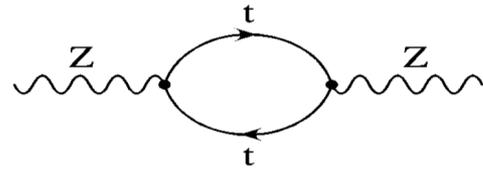
Degrassi et al. JHEP 08 (2012) 098, arXiv:1405.6852



- The measured values of the top quark and the higgs boson mass
 - ◆ SM is consistent and could be valid up to Planck scale.
 - ◆ Vacuum may be Meta-stable.

SM predictions, Top Quark and Higgs Boson

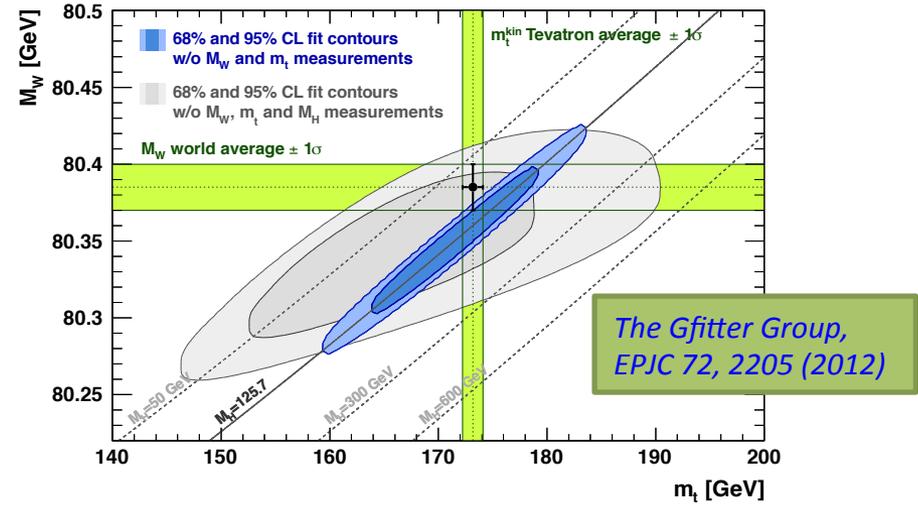
$$\sqrt{s} \approx 100 \text{ GeV} < m_t$$



LEP 1 prediction:

$$m_t = 173^{+13}_{-10} \text{ GeV}$$

LEP Collaborations CERN-PPE/95-172



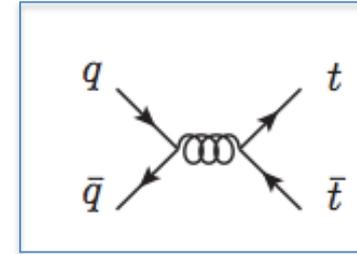
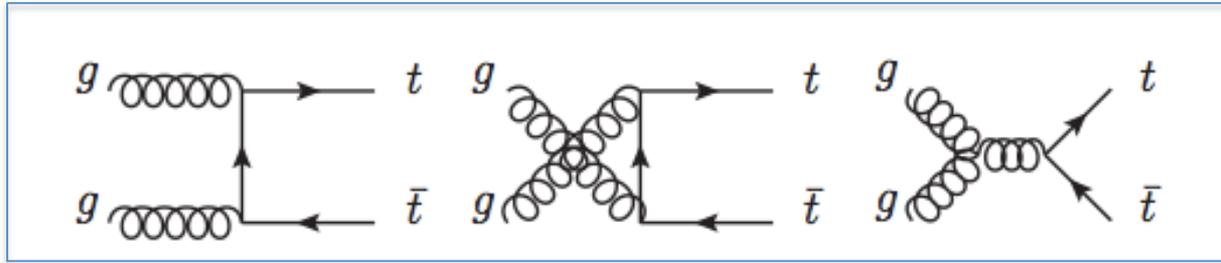
Electroweak fit before Higgs discovery:

$$m_H = 94^{+25}_{-22} \text{ GeV}$$

consistent with directly measured m_H within 1.3 SD.

Most critical tests of the standard model!

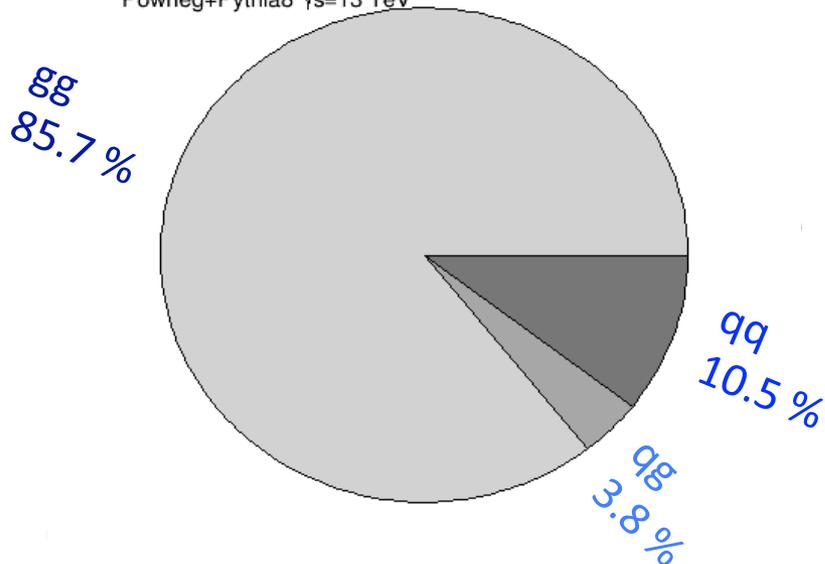
Top pair production through QCD interactions.



$$\sigma(t\bar{t}) \sim 830 \text{ pb @ } 13 \text{ TeV}$$

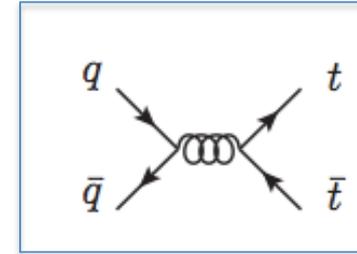
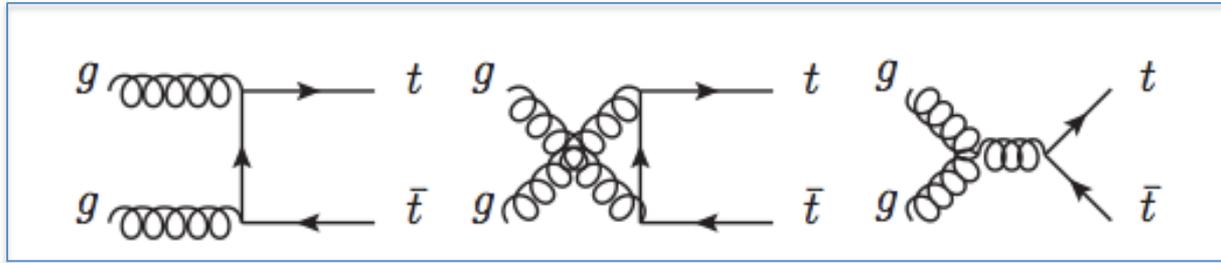
$$\sigma_{t\bar{t}}^{13\text{TeV}} \sim 3 \times \sigma_{t\bar{t}}^{8\text{TeV}}$$

Powheg+Pythia8 $\sqrt{s}=13 \text{ TeV}$



- Sensitive to PDFs, α_s , m_t
- Backgrounds to Higgs and many new physics searches

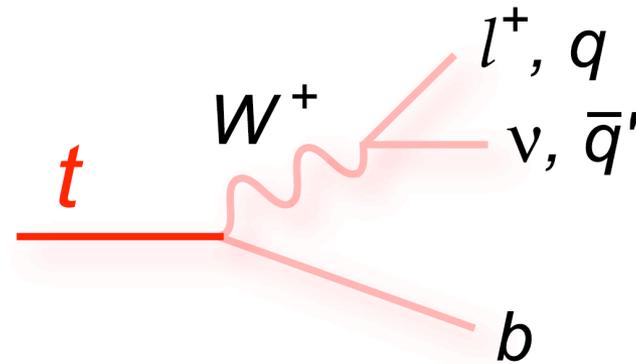
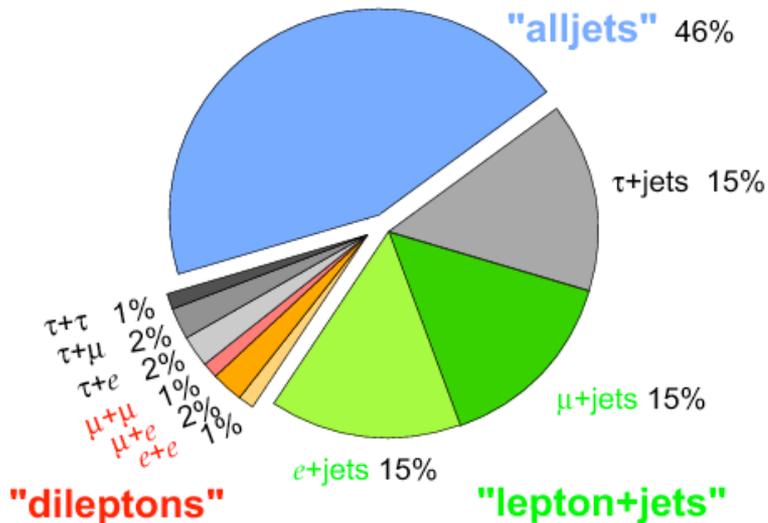
Top pair production through QCD interactions.



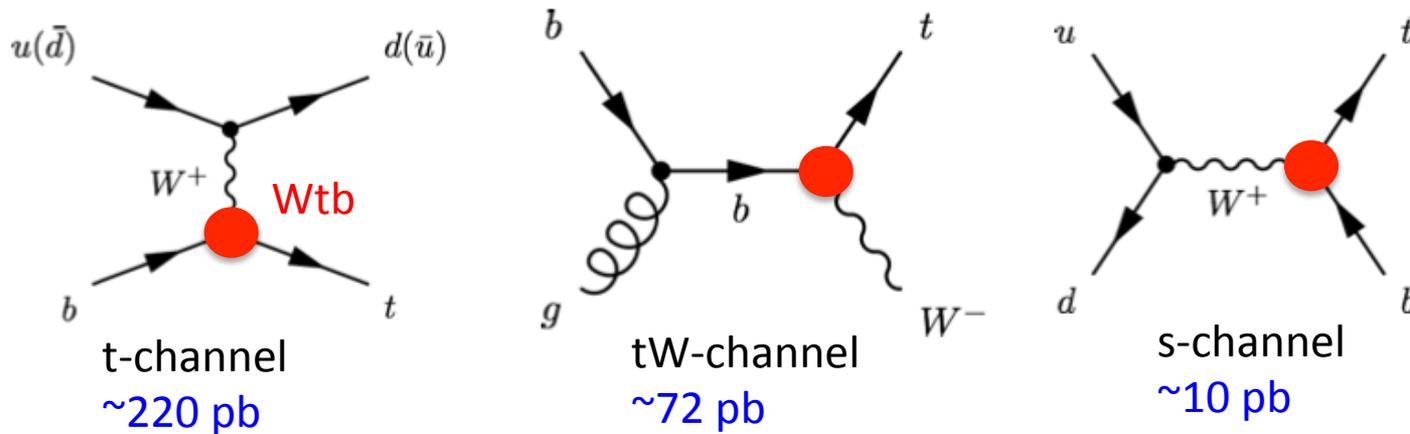
$$\sigma(t\bar{t}) \sim 830 \text{ pb @ } 13 \text{ TeV}$$

$$\sigma_{t\bar{t}}^{13\text{TeV}} \sim 3 \times \sigma_{t\bar{t}}^{8\text{TeV}}$$

Top Pair Branching Fractions



Electroweak single top production

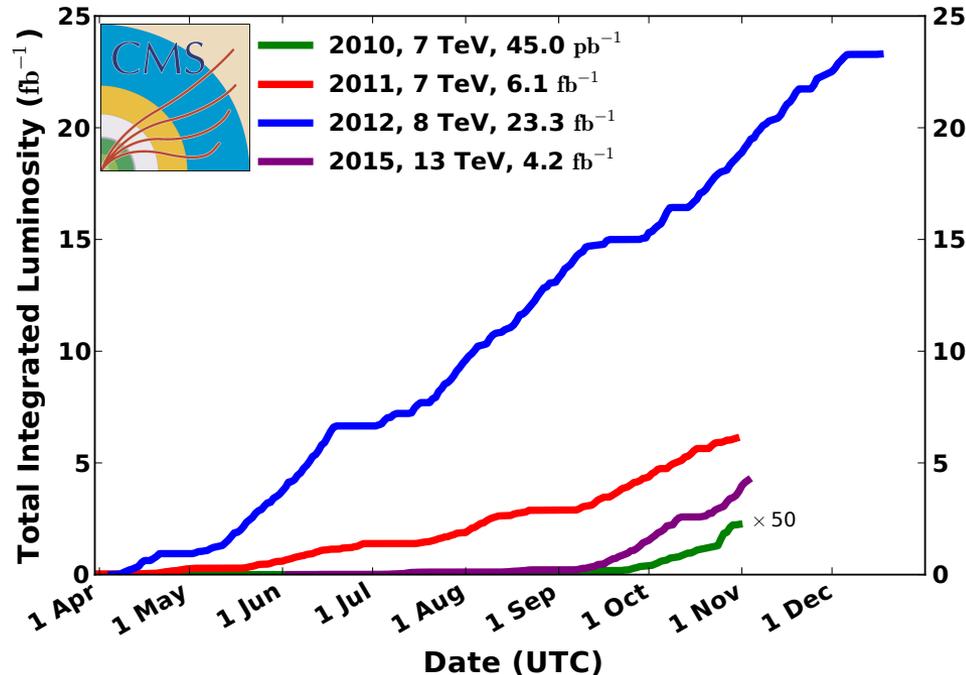


$$\sigma_{t\text{-chan}}^{13\text{TeV}} \sim 2.5 \times \sigma_{t\text{-chan}}^{8\text{TeV}}$$

- Sensitive to Wtb vertex (V-A coupling), b- and u/d-PDFs.
 - ◆ V-A coupling: cross sections, W boson and top quark polarizations.
- Backgrounds to Higgs and many searches

Outline

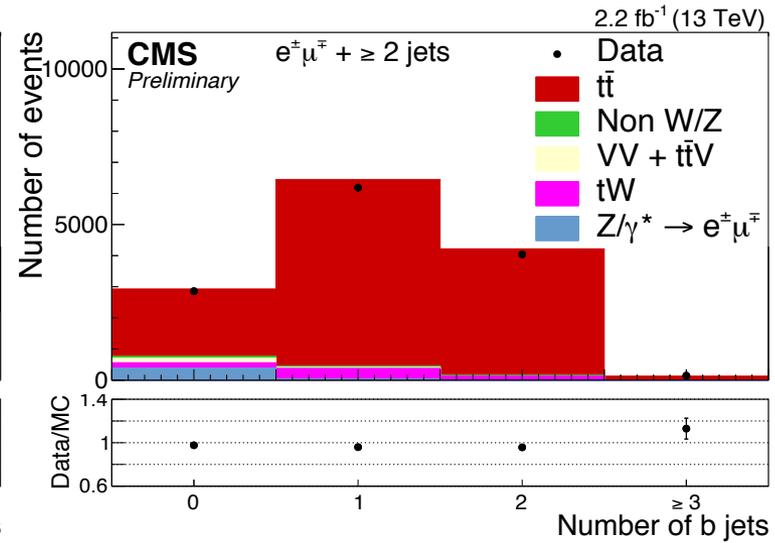
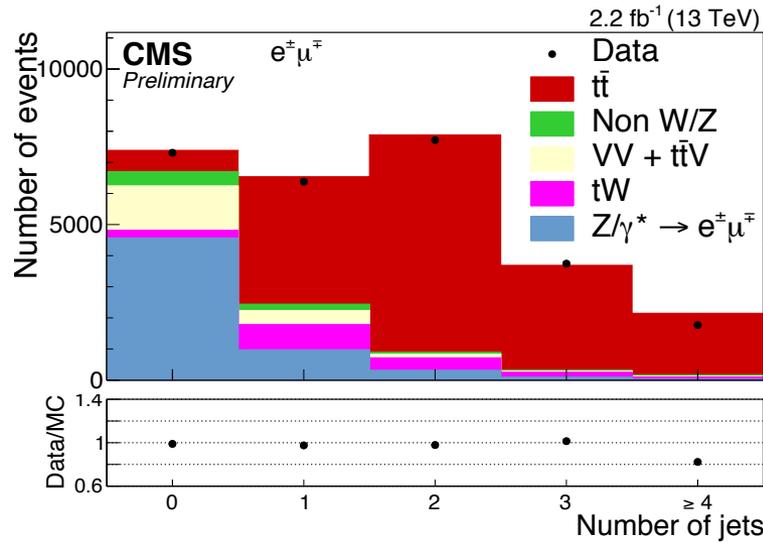
CMS Integrated Luminosity, pp



- This talk: recent results on top physics using 13 and 8 TeV CMS data
 - ◆ Production and modelling,
 - ◆ Spin correlation and polarization
 - ◆ Couplings
 - ◆ Mass

Top Quark Production Cross Sections

Top Pair Cross Section at $\sqrt{s} = 13$ TeV in the $e\mu$ Channel



■ Cut and count

- ◆ Select $e\mu$ pair with ≥ 2 jets and ≥ 1 b-tag

TOP-16-005

$$\sigma_{t\bar{t}}(m_t = 172.5 \text{ GeV}) = 793 \pm 8(\text{stat}) \pm 38(\text{syst}) \pm 21(\text{lumi}) \text{ pb}$$

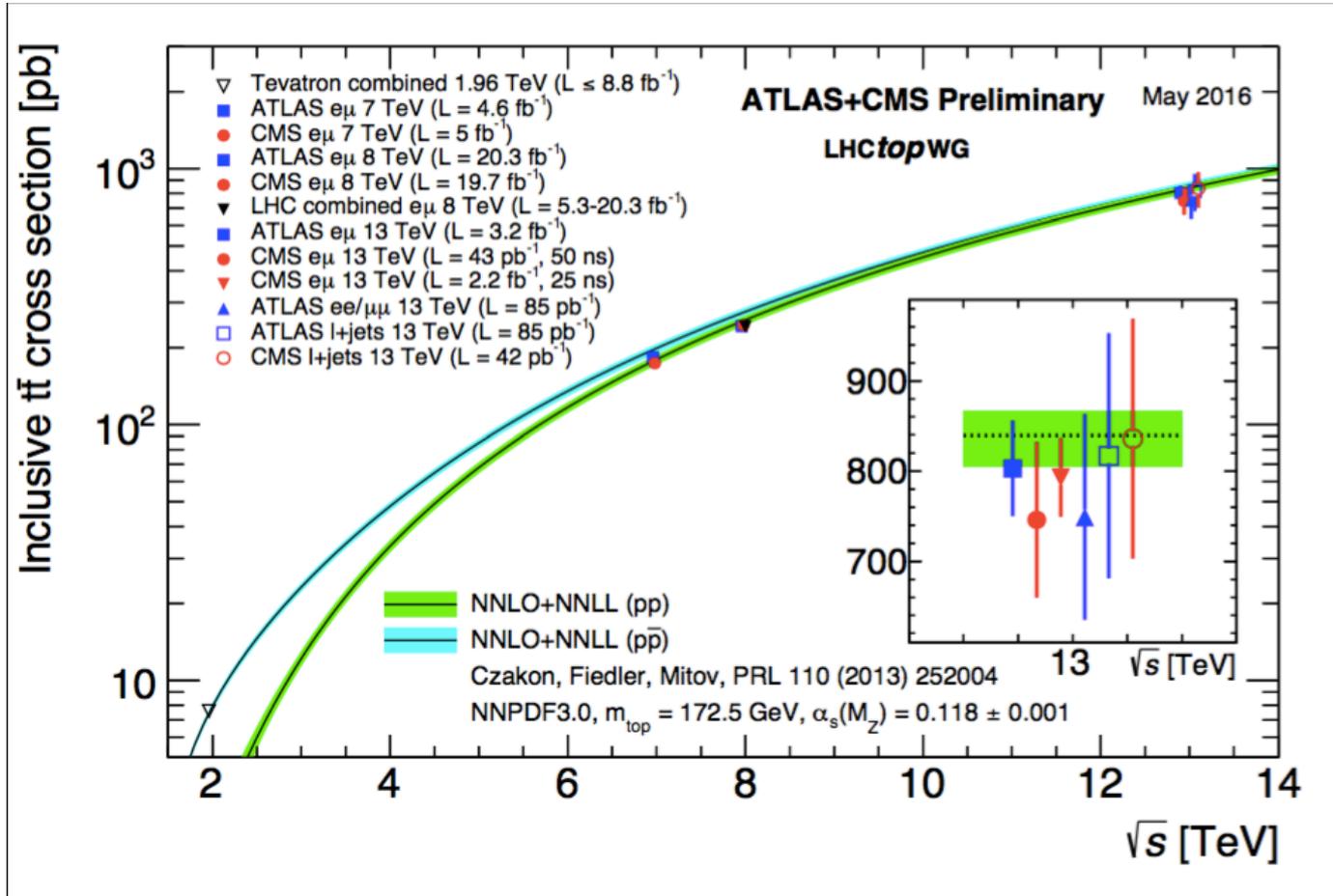
→ Consistent with NNLO+NNLL prediction and other measurements from ATLAS and CMS.

→ Already dominated by systematic uncertainties:

→ Luminosity, efficiencies, jet energy scale

→ Effect of generator choice on acceptance (POWHEG vs MG5_aMC@NLO)

Cross Sections from $\sqrt{s} = 2$ to 13 TeV

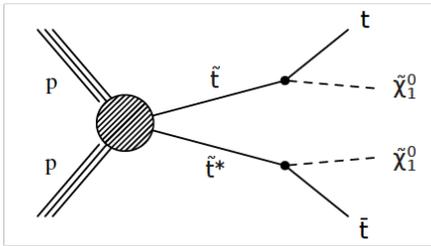


- $e\mu$ channel

- ◆ 13 TeV top pair cross section measurements: already at NNLO + NNLL precision: $\sim 5.5\%$.
- ◆ Run I legacy measurement precision: $\sim 3.5\%$. [arXiv:1603.02303](https://arxiv.org/abs/1603.02303)

Top Squark Pair Production

arXiv:1603.02303



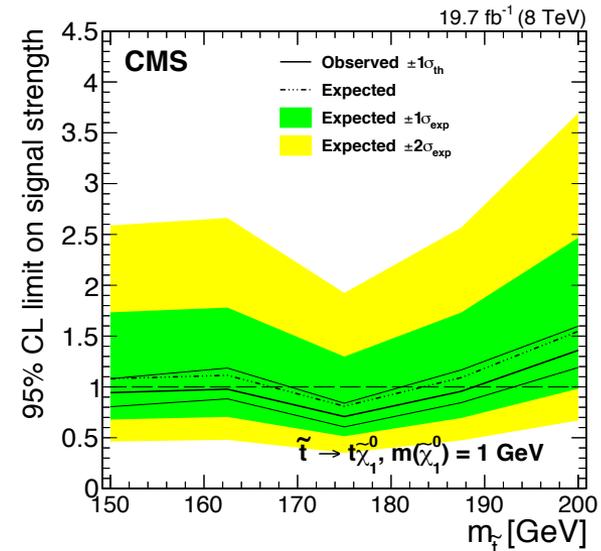
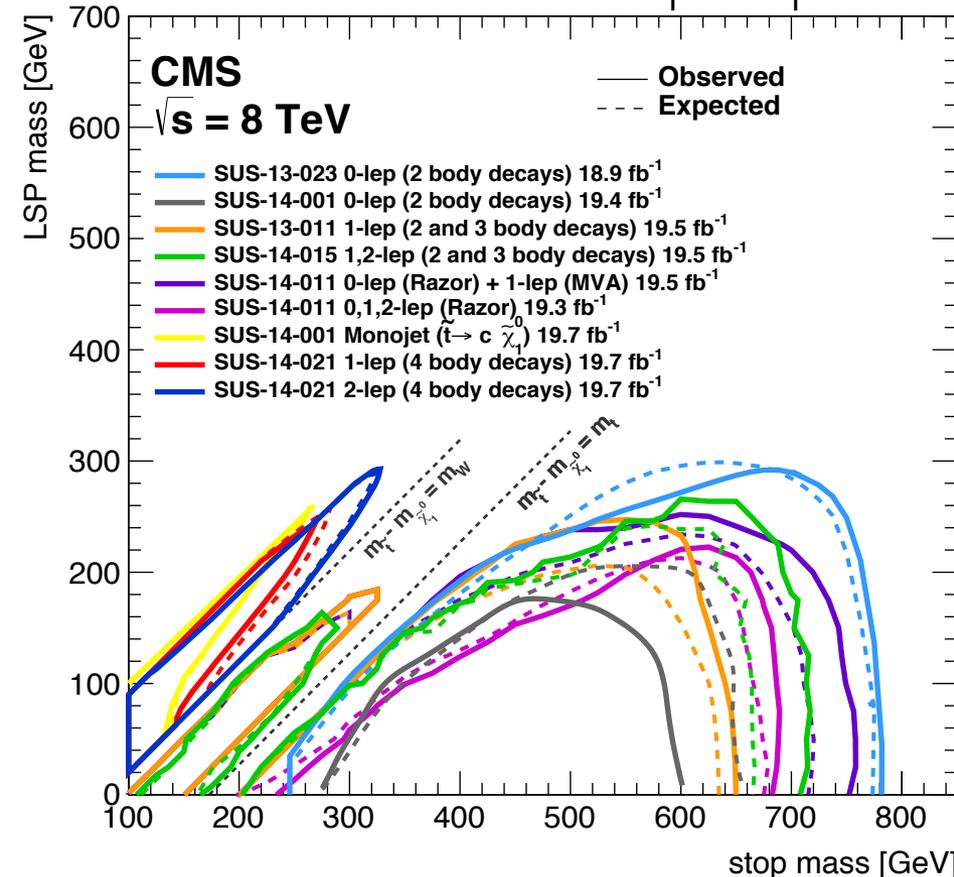
$$m(\tilde{t}) \approx m(\tilde{\chi}_1^0) + m_t \longrightarrow \sigma_{t\bar{t}} \text{ (and } t\bar{t} \text{ spin correlations)}$$

more sensitive than standard SUSY searches for low $m(\tilde{\chi}_1^0)$ and $m(\tilde{t}) \approx m_t$

$\tilde{t}\text{-}\tilde{t}^*$ production, $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$

Simplified model with two parameters:

$$m(\tilde{t}), m(\tilde{\chi}_1^0)$$



$$m(\tilde{t}; \tilde{\chi}_1^0 = 1 \text{ GeV}) > 189 \text{ GeV}$$

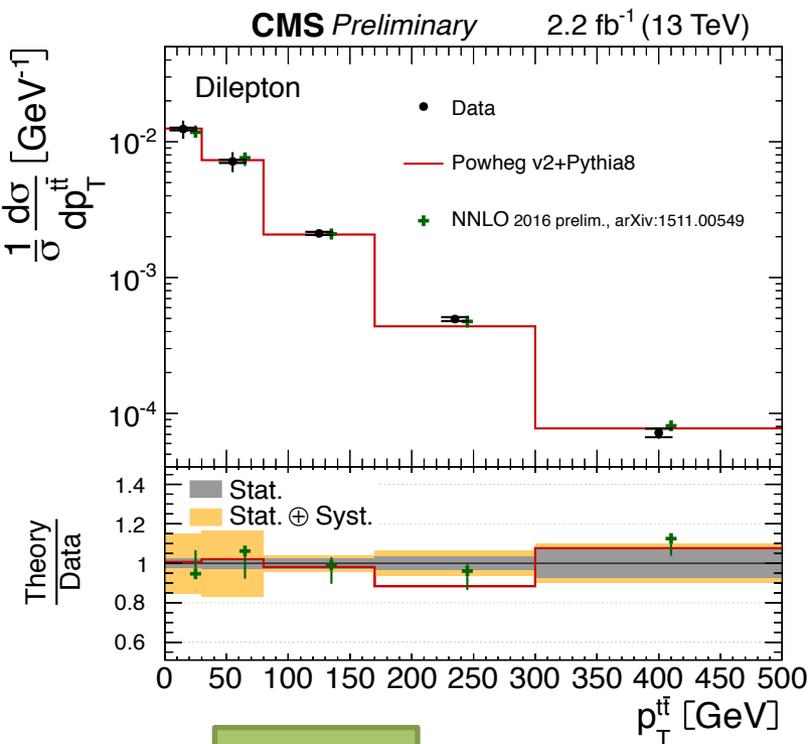
$$m(\tilde{t}; \tilde{\chi}_1^0) \notin 185 - 189 \text{ GeV}$$

Improving Uncertainties

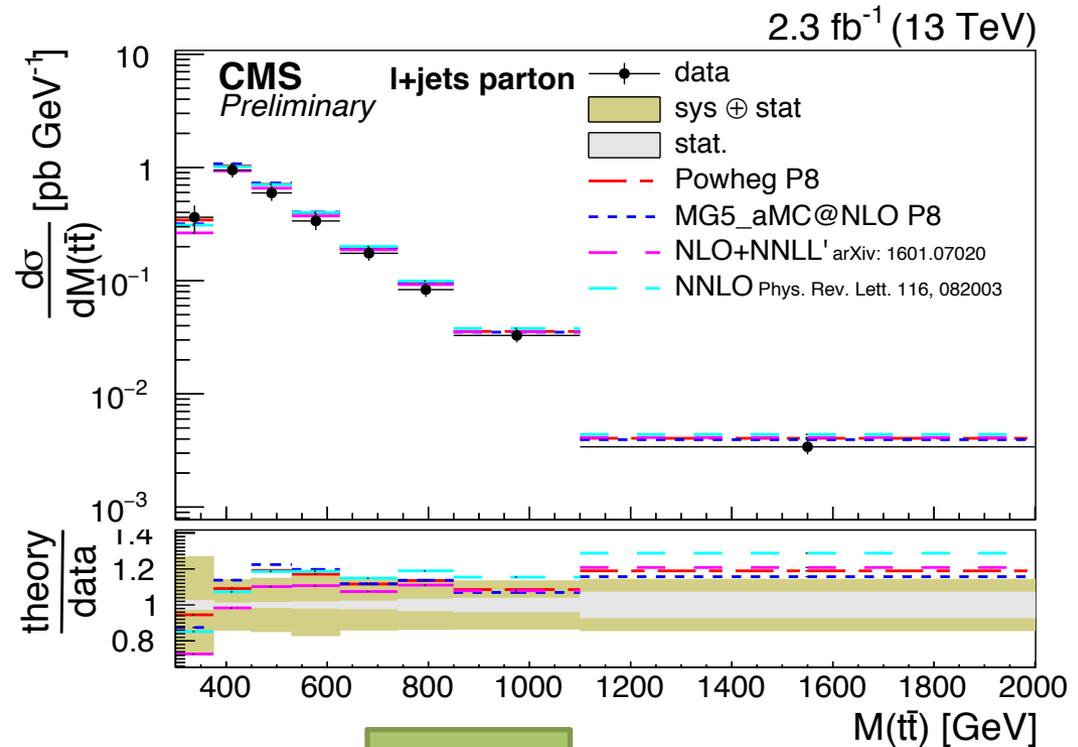
- Contributions to total uncertainty spread over many different sources
- Some experimental uncertainties will improve with time
 - ◆ Lepton id and isolation
 - ◆ Jet energy scale
 - ◆ ...
- Theory uncertainties can partially be tested and improved with measurements
 - ◆ Hadronization
 - ◆ Top quark p_T modelling
 - ◆ ...

Top Pair Differential Cross Sections

- Test QCD description of the top quark (both as signal and background)
- Test and tune **new MCs (NLO ME + LO PS MC)**



TOP-16-011

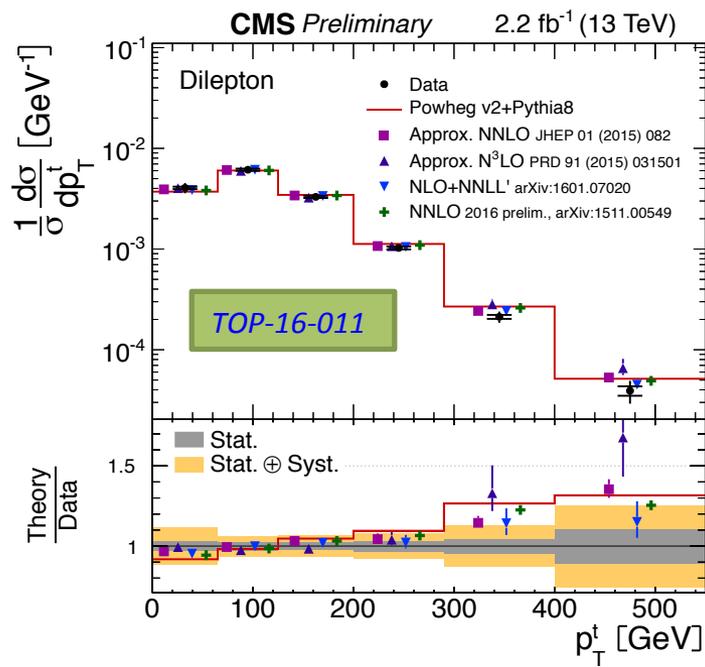
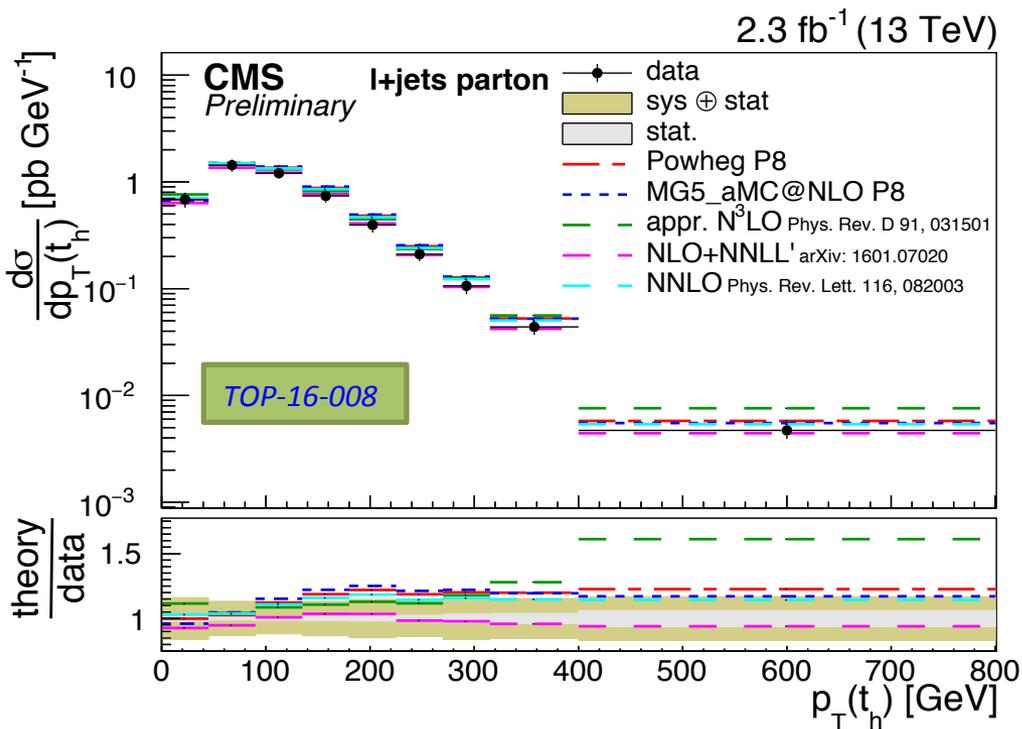
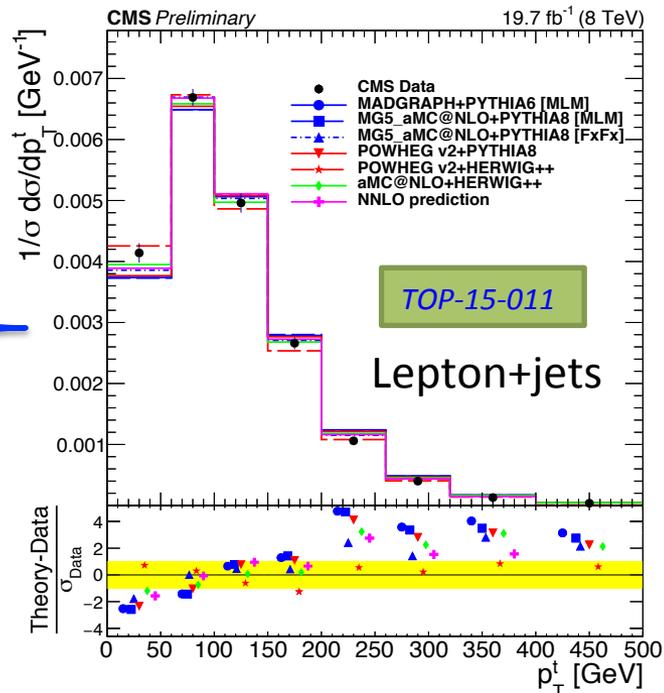


TOP-16-008

- Differential distributions described reasonably well.

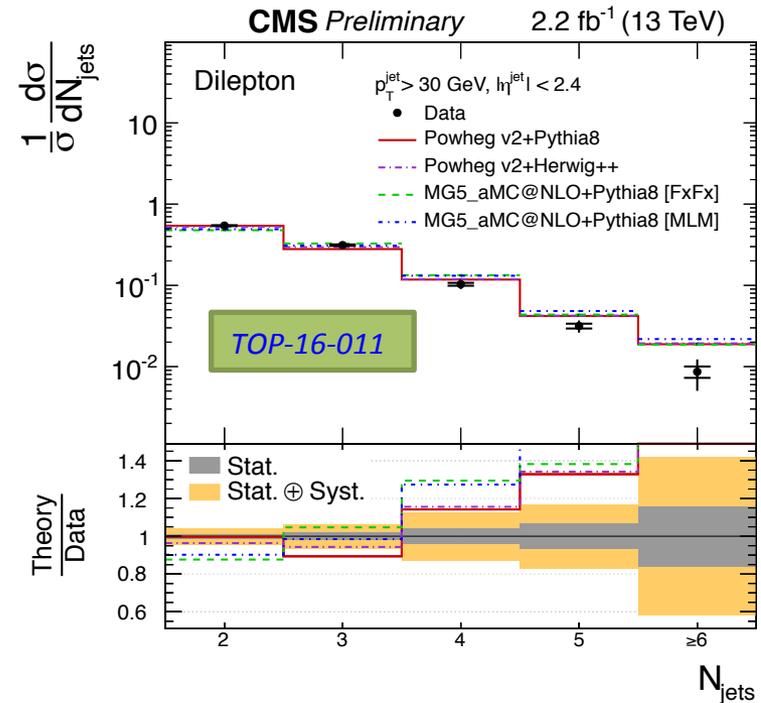
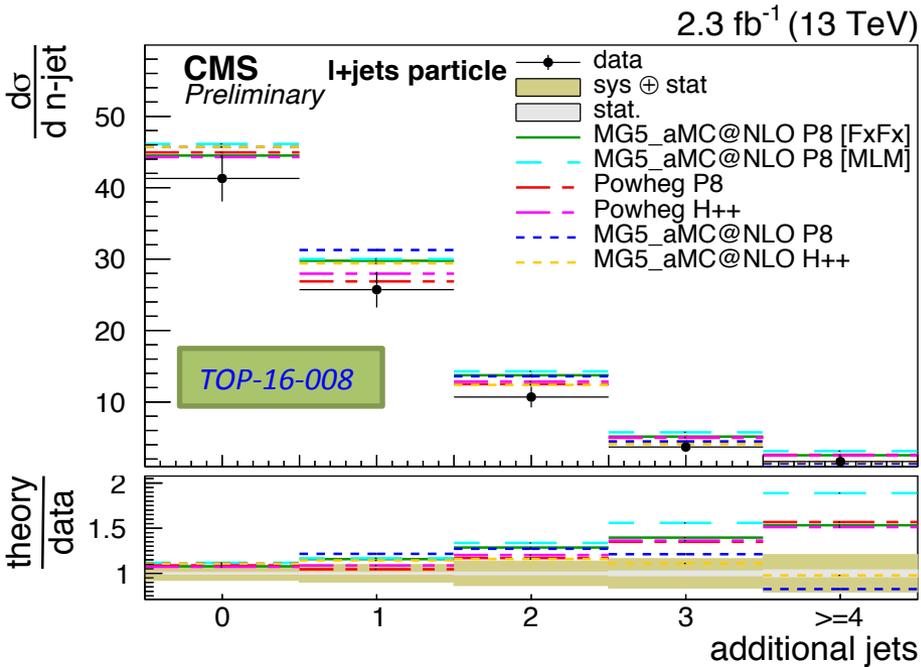
The Top Quark p_T

- LHC Run 1 “discovery”: harder spectrum in LO/NLO+PS predictions than in data.
 - NNLO+NNLL \rightarrow significantly better description of top p_T .
- First results at 13 TeV: similar behavior.



Jet Multiplicity at $\sqrt{s} = 13$ TeV

- Low jet multiplicities \rightarrow Sensitive to Matrix element and matching to parton shower.
- High jet multiplicities \rightarrow parton shower
- $t\bar{t}$ +jets important background to $t\bar{t}H$.

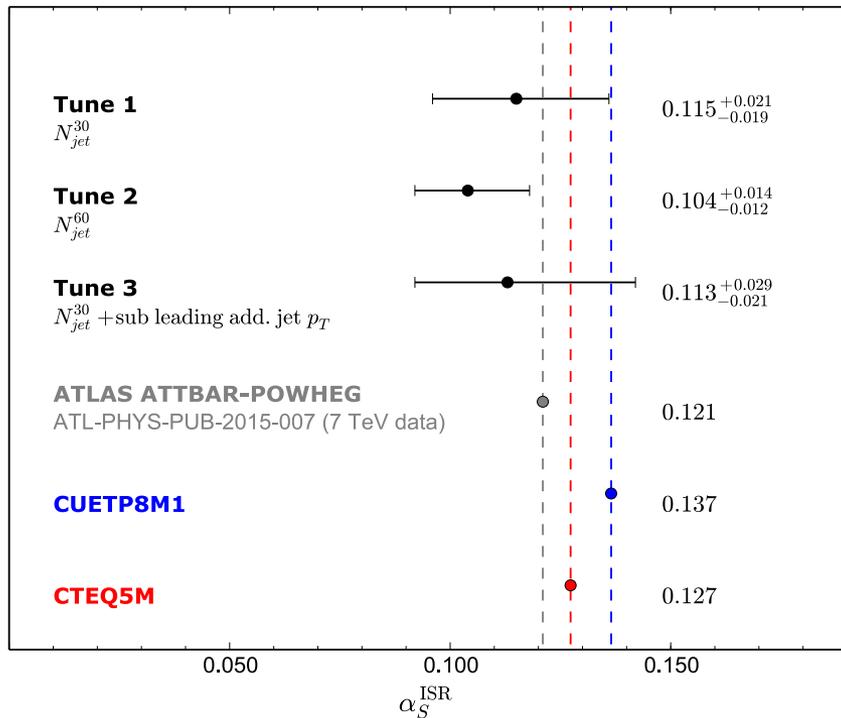


- New ME generator + PS codes in Run II
- Predictions overshoot the data for jet large multiplicities when out of the box parameters are used (in Monash-based tunes).

Shower α_s Tuning

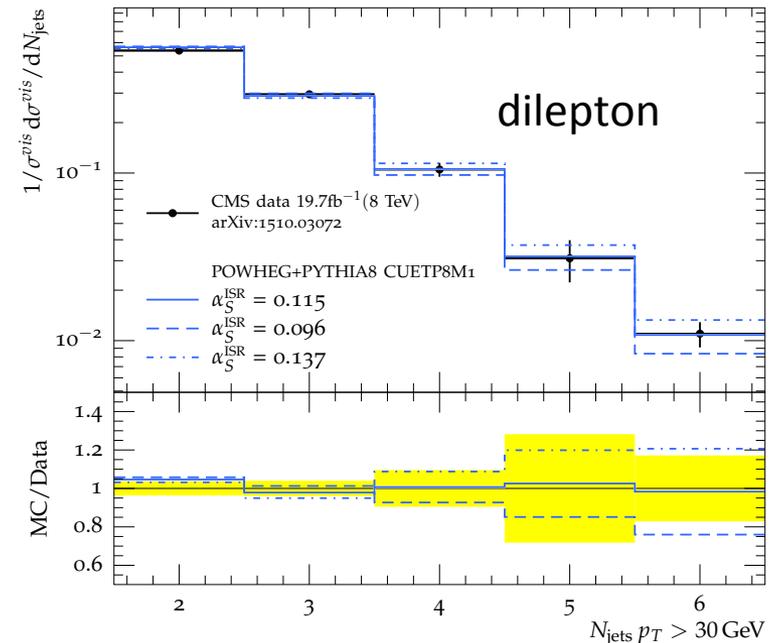
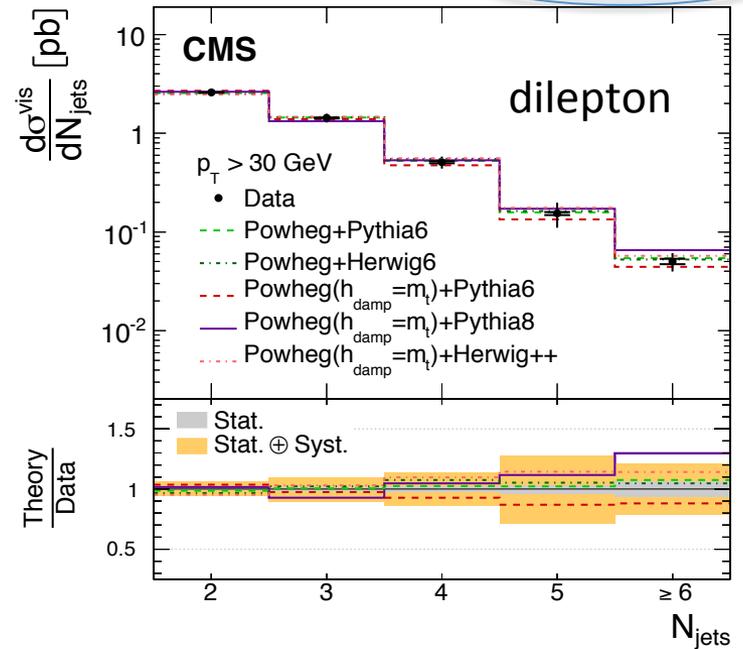
- Discrepancies at high N_{jets} \rightarrow
e.g. non-optimal parton shower α_s .
- Use $N_{\text{jets}} > 3$ where jets predominantly originate from the parton shower.

Rivet routine:
CMS_2015_I1397174



arXiv:1510.03072

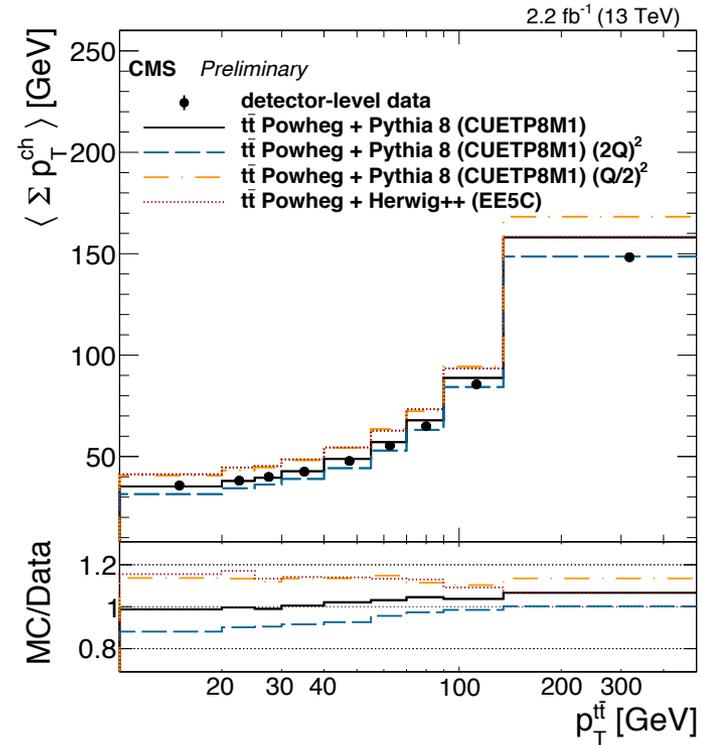
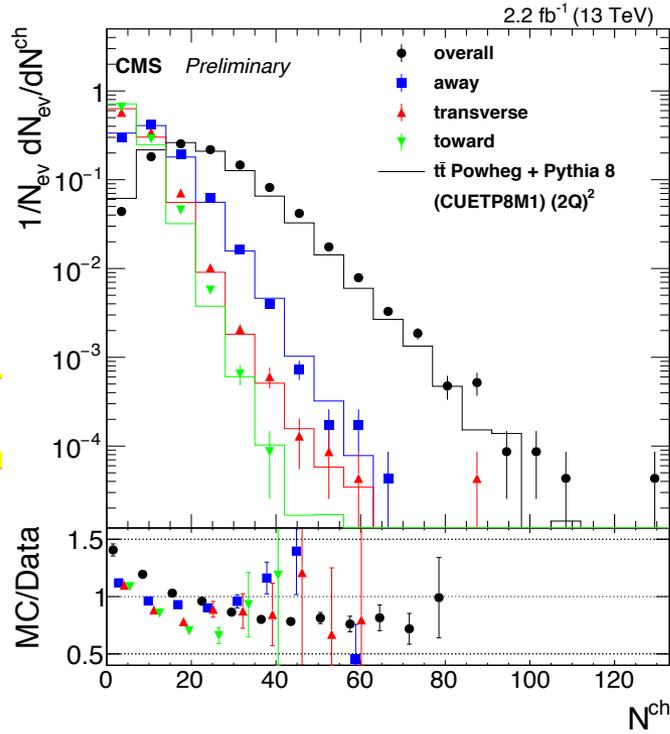
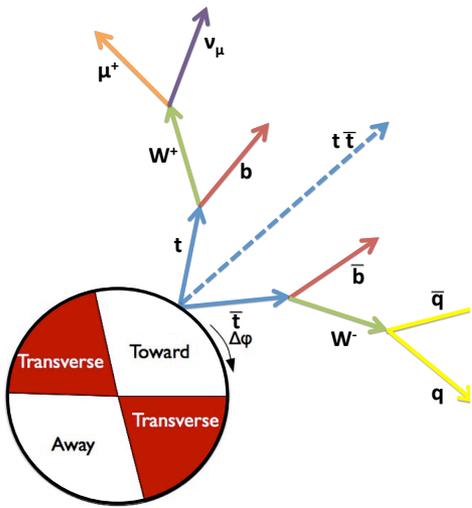
19.7 fb⁻¹ (8 TeV)



Underlying Event in ttbar Events at $\sqrt{s} = 13$ TeV

TOP-15-017

- Investigate and improve ttbar event modeling.
- Charged particle activity through N^{ch} , Σp_T^{ch} , $\langle p_T^{\text{ch}} \rangle$ vs $p_T(\text{ttbar})$ and N_{jets} .

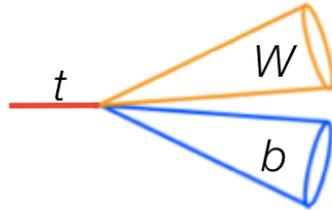


→ Not necessary to have separate heavy-quark UE tunes.
 → UE is sensitive QCD scales.

Boosted Top Pair Production

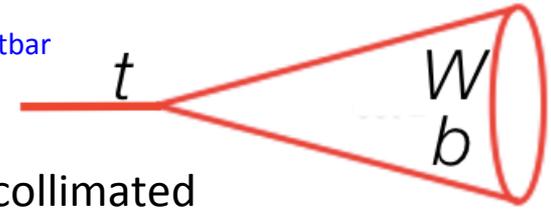
arXiv:1605.00116

Resolved topology:
Each parton matched
to a single jet.



High top p_T or high $m_{t\bar{t}}$

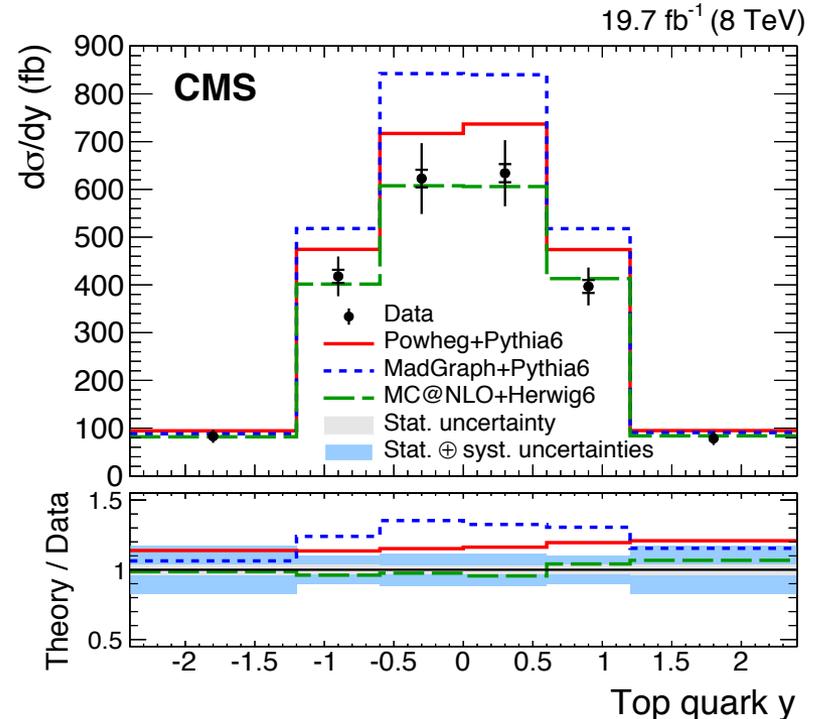
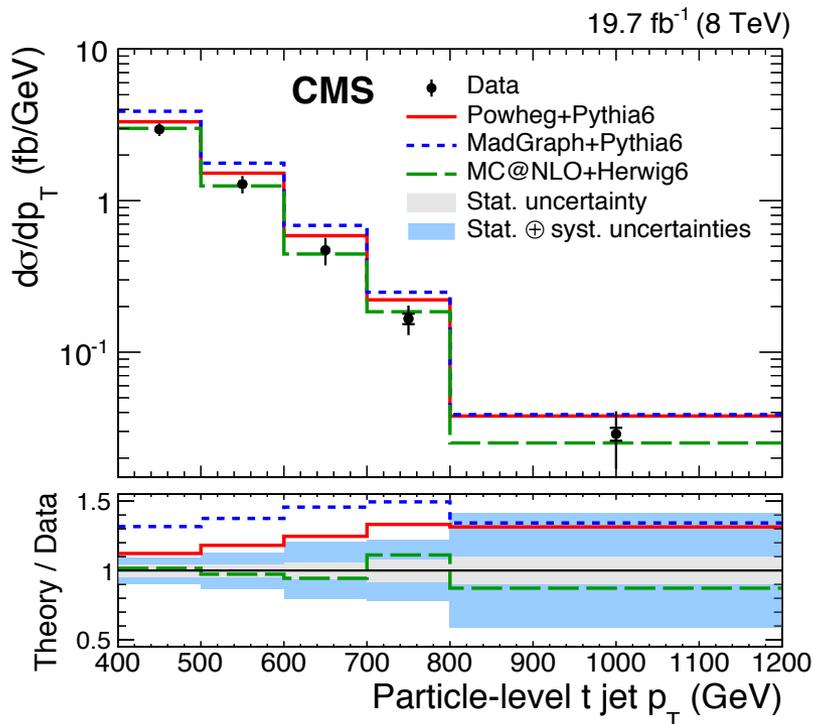
Boosted topology:
→ Decay products collimated



"fat jet", $R=0.8$

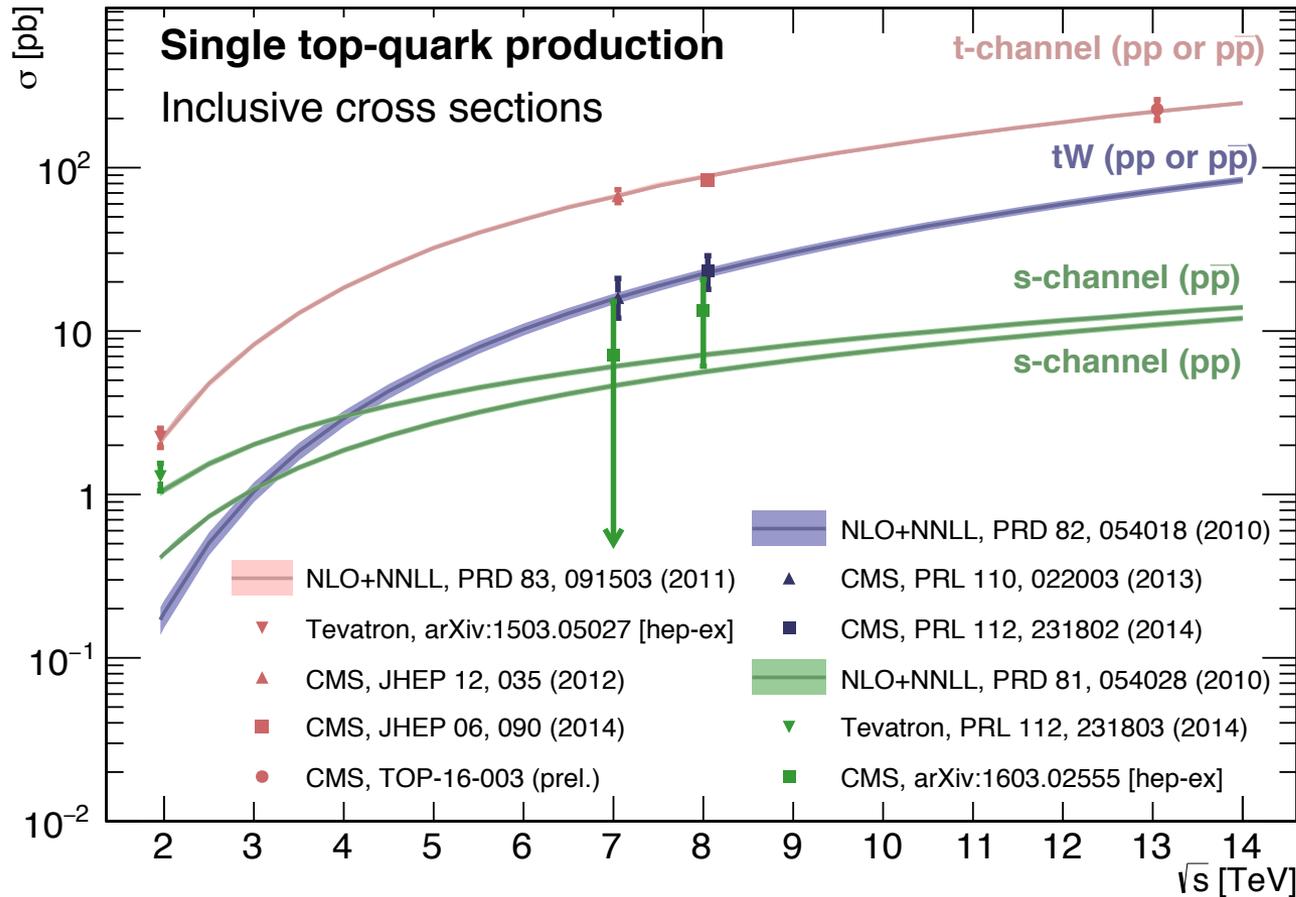
- Measurements at parton and particle levels.
- Best description with MC@NLO+Herwig6.

Available in
RIVET



Single Top Production

Single Top Cross Sections



- All single top quark production modes measured at Run I
- Latest ATLAS+CMS tW combination at 8 TeV.

TOP-15-019

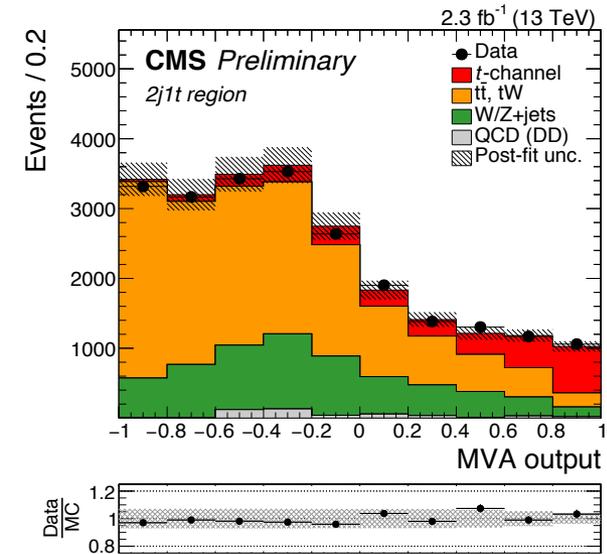
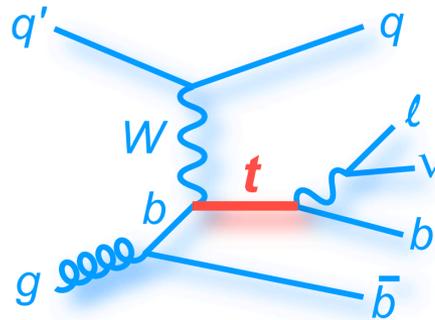
$$\sigma_{tW} = 23.1 \pm 1.1(\text{stat}) \pm 3.3(\text{syst}) \pm 0.8(\text{lumi}) \text{ pb}$$

- Single top t-channel cross section at NNLO precision
 - ◆ Theory uncertainty $\sim 1\%$
 - ◆ Measurement uncertainty
 - $\sim 10\%$ at 8 TeV (with 20 fb^{-1})
 - $\sim 15\%$ at 13 TeV (with 2.3 fb^{-1})

Single Top Cross Section at $\sqrt{s} = 13$ TeV

TOP-16-003

- Event selection: 1 μ , 2 or 3 jets, 1 or 2 b-jets.
- Signal from binned likelihood fits to MVA discriminators with n_j , m_{lvb} , m_{jb} , $m_T(W)$, ... in different categories.



$$\sigma_{t\text{-ch.}}(t + \bar{t}) = 227.8 \pm 9.1(\text{stat}) \pm 14.0(\text{exp})_{-27.7}^{+28.7}(\text{theo}) \pm 6.2(\text{lumi}) \text{ pb} = 227.8_{-33.0}^{+33.7} \text{ pb}$$

$$|V_{td}|, |V_{ts}| \ll |V_{tb}|, \text{Br} \cong 1$$

$$\rightarrow |f_V^L V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma_{t\text{-ch.}}^{\text{theo.}}}} = 1.02 \pm 0.07(\text{exp}) \pm 0.02(\text{theo})$$

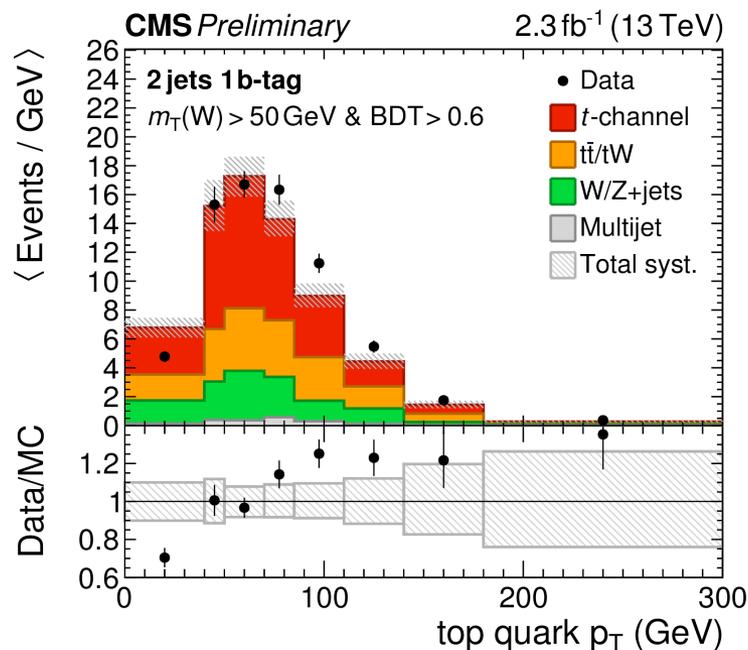
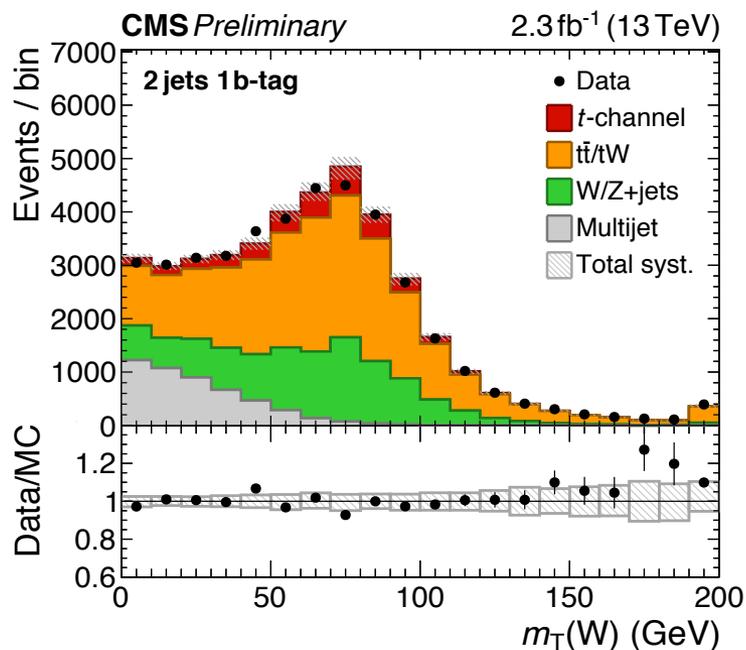
Result dominated by signal modelling and QCD scale uncertainties.

$$7+8 \text{ TeV} \rightarrow \delta_{|V_{tb}|} = 4\%$$

Differential Single-Top t-Channel at $\sqrt{s} = 13$ TeV

TOP-16-004

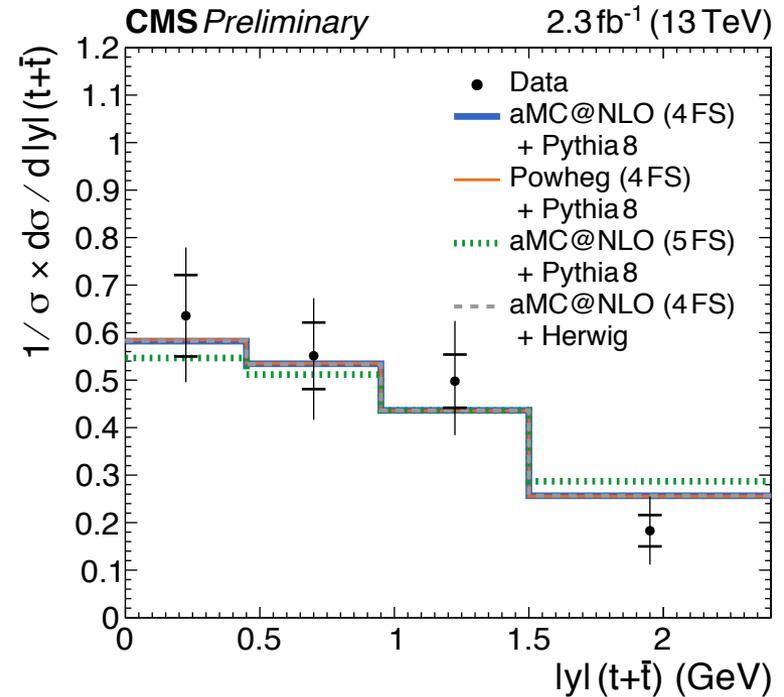
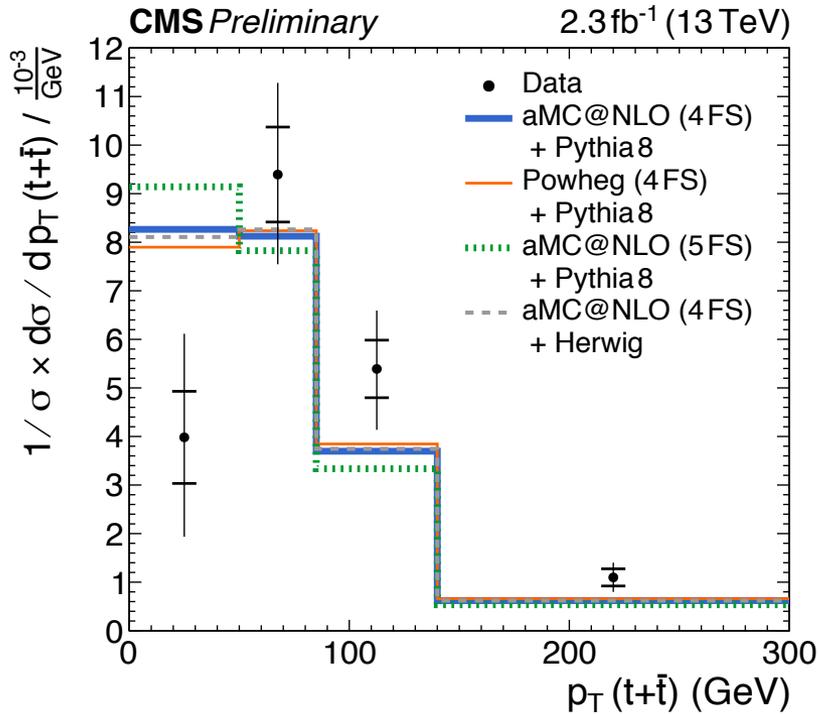
- Already enough statistics to make differential measurements.
- 1 e/ μ , 1 b-jet, 1 relatively forward jet, E_T^{miss} .
- Maximum likelihood fit to $m_T(W)$ for $m_T(W) < 50$ GeV and multivariate discriminant for $m_T(W) > 50$ GeV.
 - ◆ Observables in the discriminant selected to have minimum correlation with top p_T and Y.



Dominant uncertainties: Data statistics, QCD scales,
top quark mass, jet energy scale corrections

Differential Single-Top t-Channel at $\sqrt{s} = 13$ TeV

TOP-16-004

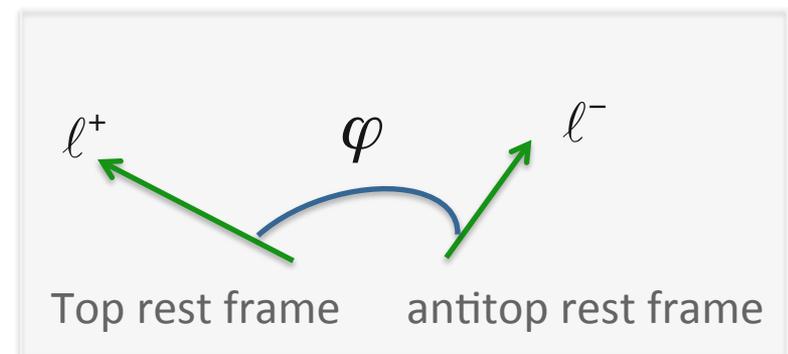
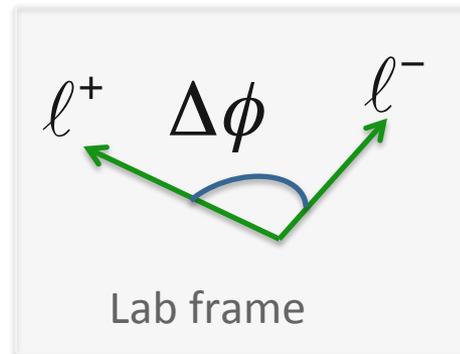
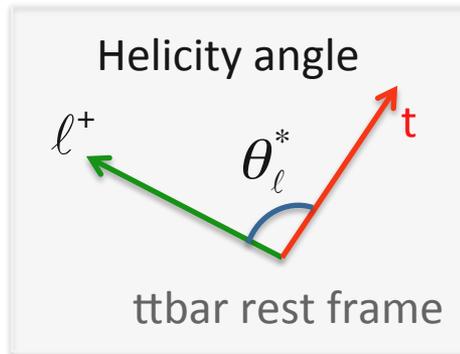


- First Run II measurement of differential single-top cross sections.
- Many more and precise measurements to come.

Top Quark Properties

ttbar production: Tops are unpolarized but heavy quark spins are correlated

Angles with or without top quark reconstruction:

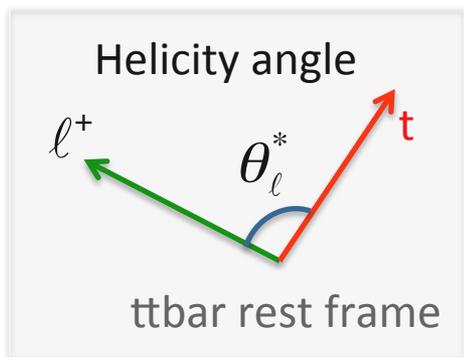


Or a multivariate method using more information from the events; e.g. Matrix Element Method:

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

Top Quark Polarization in $t\bar{t}$ Dilepton Channel

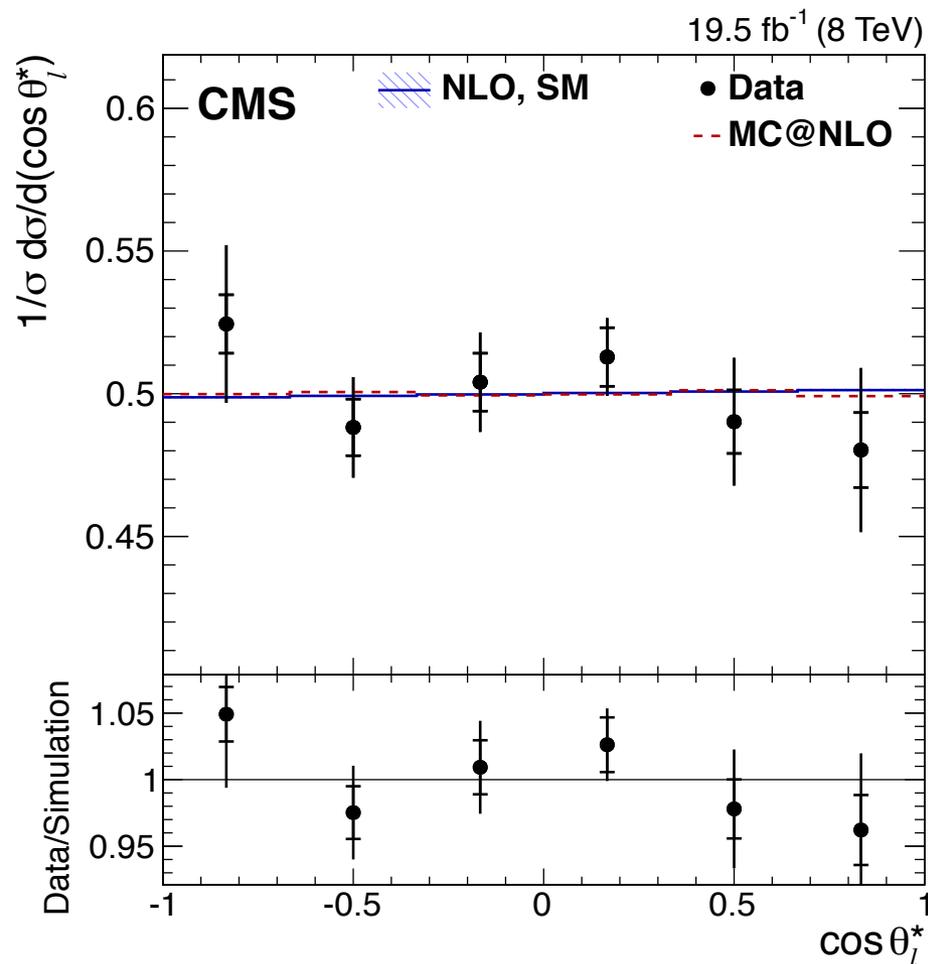
PRD 93 (2016) 052007



$$\frac{1}{2} P^\pm = A_{P^\pm} = \frac{N(\cos\theta_{\ell^\pm}^* > 0) - N(\cos\theta_{\ell^\pm}^* < 0)}{N(\cos\theta_{\ell^\pm}^* > 0) + N(\cos\theta_{\ell^\pm}^* < 0)}$$

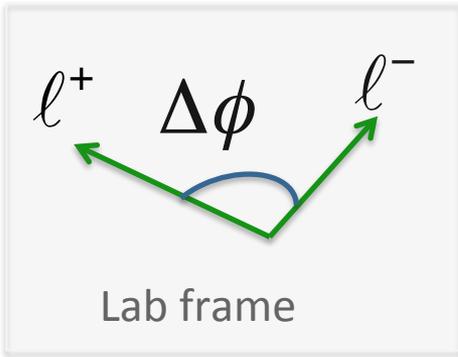
$$P^{SM(CP\text{-conserving})} = (A_{P_+} + A_{P_-}) = -0.022 \pm 0.058$$

$$P^{CP\text{-violating}} = (A_{P_+} - A_{P_-}) = 0.000 \pm 0.016$$



Top Quark Spin Correlation in Dilepton Channel

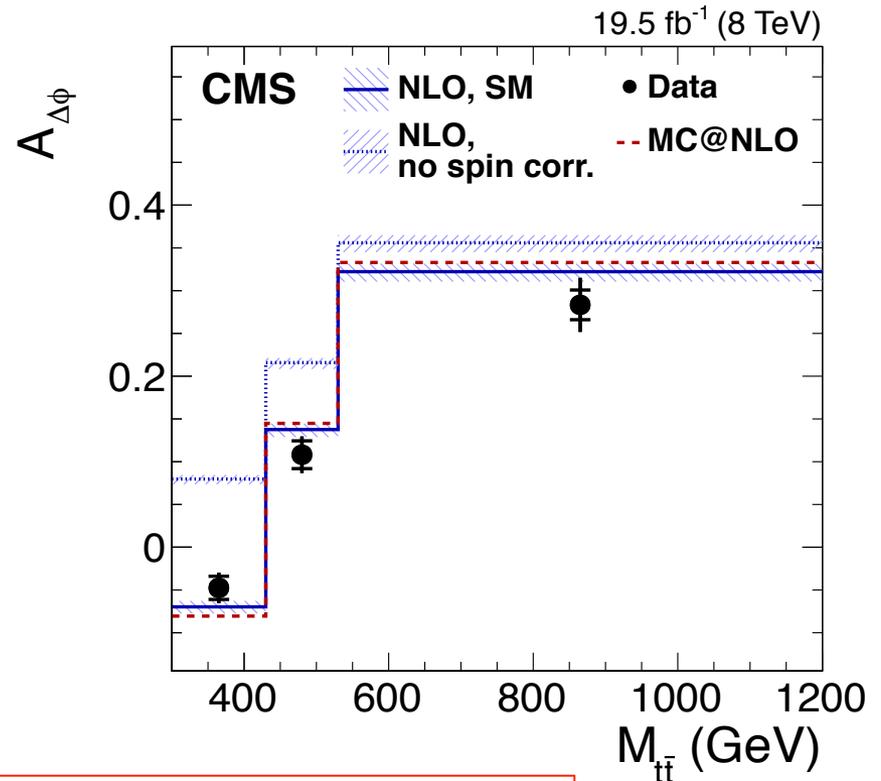
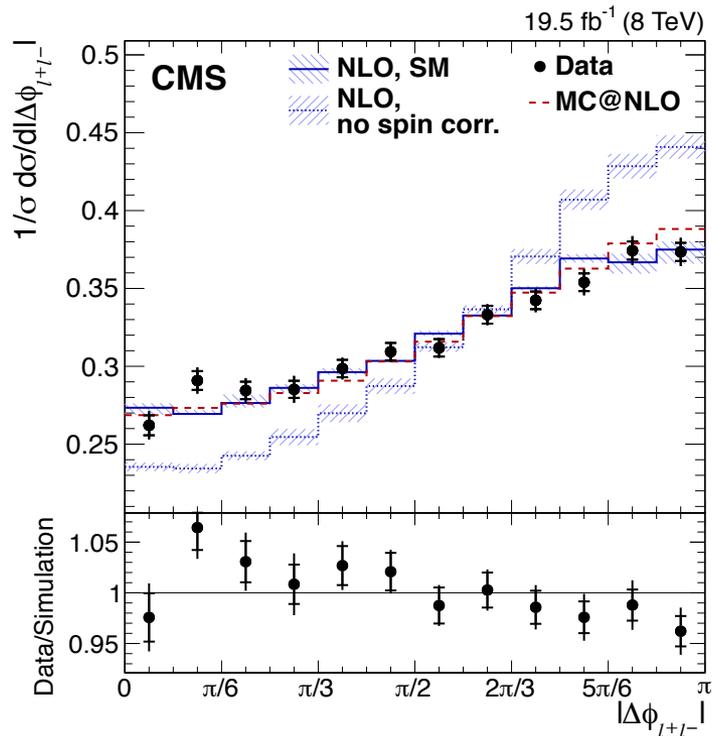
PRD 93 (2016) 052007



$\Delta\phi$ distribution becomes flatter when tops are correlated.

$$A_{\Delta\phi} = \frac{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) - N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) + N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}$$

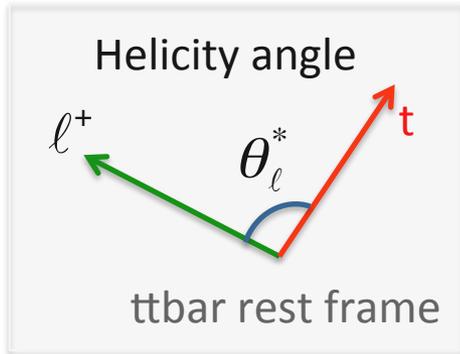
$$f \equiv \frac{N_{SM}}{N_{SM} + N_{non-SM}}, \quad f_{SM} = 1$$



$$f_{SM} \left(\text{from } A_{\Delta\phi} \text{ vs } M_{t\bar{t}} \right) = 1.12 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})_{-0.11}^{+0.08}(\text{theor})$$

Top Quark Spin Correlation in Dilepton Channel

PRD 93 (2016) 052007



$$\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{\sigma}{4} (1 + \alpha_+ P_+ \cos\theta_+ + \alpha_- P_- \cos\theta_- + A\alpha_+\alpha_- \cos\theta_+ \cos\theta_-)$$

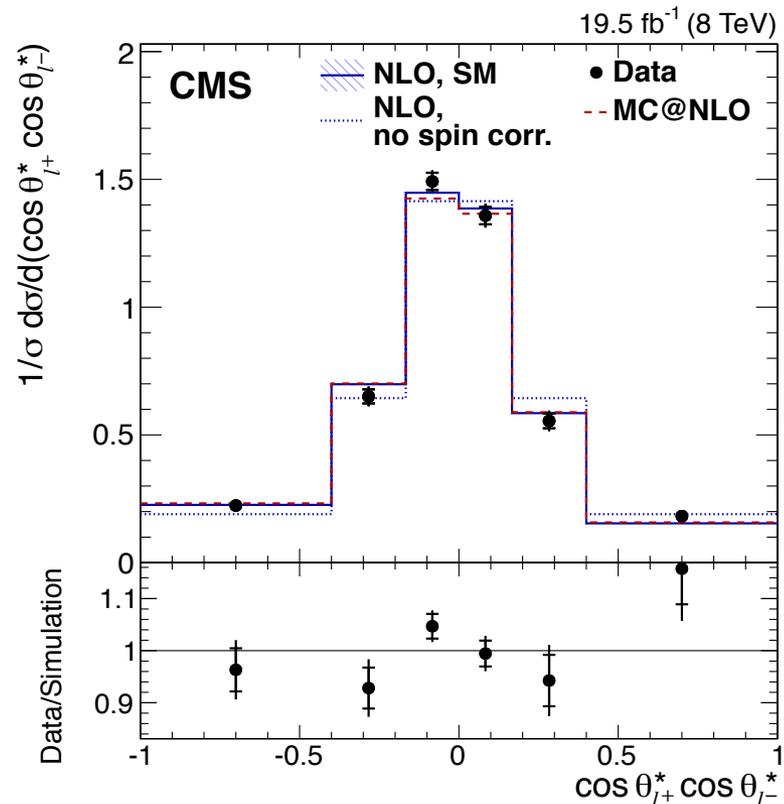
$$A_{c_1 c_2} = \frac{N(c_1 c_2 > 0) - N(c_1 c_2 < 0)}{N(c_1 c_2 > 0) + N(c_1 c_2 < 0)}$$

$$c_1 = \cos\theta_{\ell^+}^* \quad C_{hel} = -4A_{c_1 c_2}$$

$$c_2 = \cos\theta_{\ell^-}^* \quad (\text{spin correlation coefficient})$$

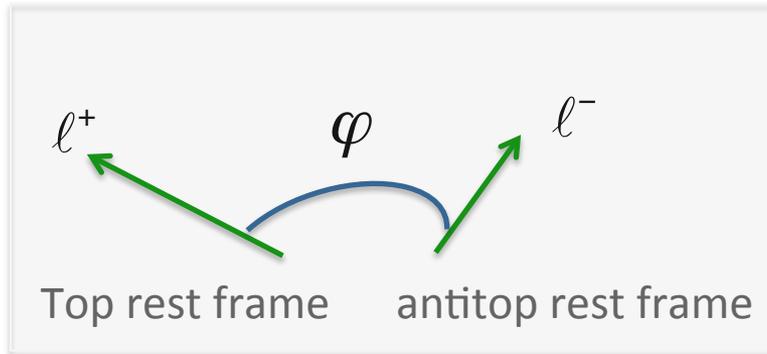
$$f_{c_1 c_2}^{SM} = 0.87 \pm 0.27$$

$$f \equiv \frac{N_{SM}}{N_{SM} + N_{non-SM}}, \quad f_{SM} = 1$$



Top Quark Spin Correlation in Dilepton Channel

PRD 93 (2016) 052007

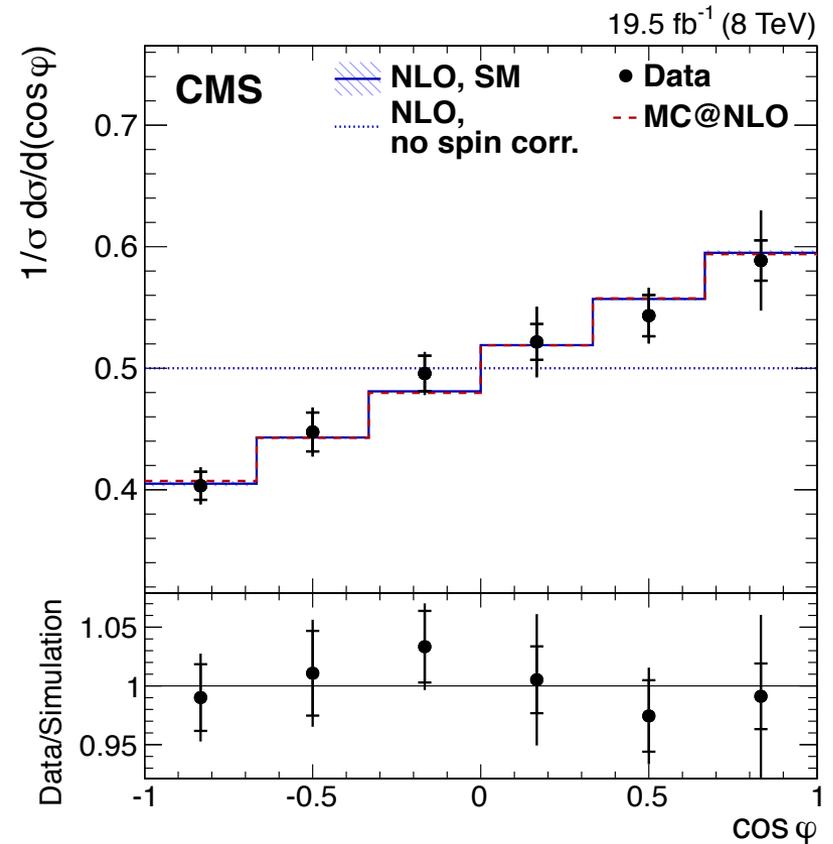


$$A_{\cos\varphi} = \frac{N(\cos\varphi > 0) - N(\cos\varphi < 0)}{N(\cos\varphi > 0) + N(\cos\varphi < 0)}$$

$$D = -2A_{\cos\varphi} \text{ (spin correlation coefficient)}$$

$$f_{\cos\varphi}^{SM} = 0.90 \pm 0.15$$

$$f \equiv \frac{N_{SM}}{N_{SM} + N_{non-SM}}, \quad f_{SM} = 1$$



Anomalous Top-Gluon Interaction

PRD 93 (2016) 052007

- SM: dipole moments generated radiatively and are very small.
- BSM: dipole moment couplings can occur at tree level.

Anomalous interaction from a heavy-particle exchange ($M > m_t$) :

$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2} \bar{t} \sigma^{\mu\nu} T^a t G_{\mu\nu}^a - \frac{\tilde{d}_t}{2} i \bar{t} \sigma^{\mu\nu} \gamma_5 T^a t G_{\mu\nu}^a$$

Chromo magnetic dipole moment
CP conserving

$$D = D_{SM} + \text{Re}(\hat{\mu}_t) D_{NP}$$

$$-0.053 < \text{Re}(\hat{\mu}_t) < 0.026 \quad @95\% \text{ C.L.}$$

Chromo electric dipole moment
CP violating

$$P^{CP\text{-violating}} = \text{Im}(\hat{d}_t) P_{NP}^{CP\text{-violating}}$$

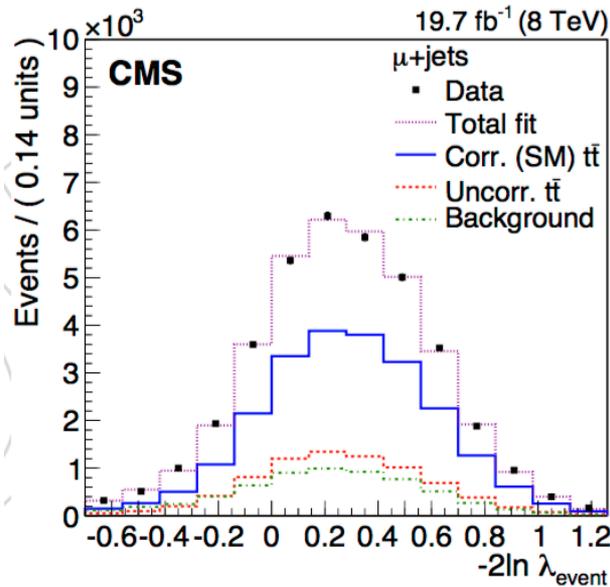
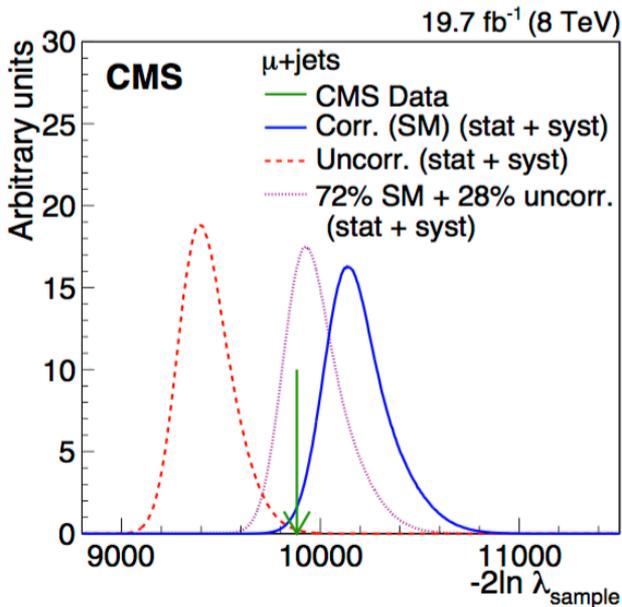
$$-0.068 < \text{Im}(\hat{d}_t) < 0.067 \quad @95\% \text{ C.L.}$$

Bernreuther & Si,
PLB 725 (2013) 115
PLB 744 (2015) 413

$t\bar{t}$ Spin Correlations – Lepton+Jets Channel

Leading order ME method to calculate event likelihoods for SM and uncorrelated hypotheses (H) using MadWeight [JHEP 12 \(2010\) 068](#)

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



$$f = 0.72 \pm 0.08 (stat)^{+0.15} (syst)^{-0.13}$$

Most precise result in
l+jets to-date

[PLB 758 \(2016\) 321](#)

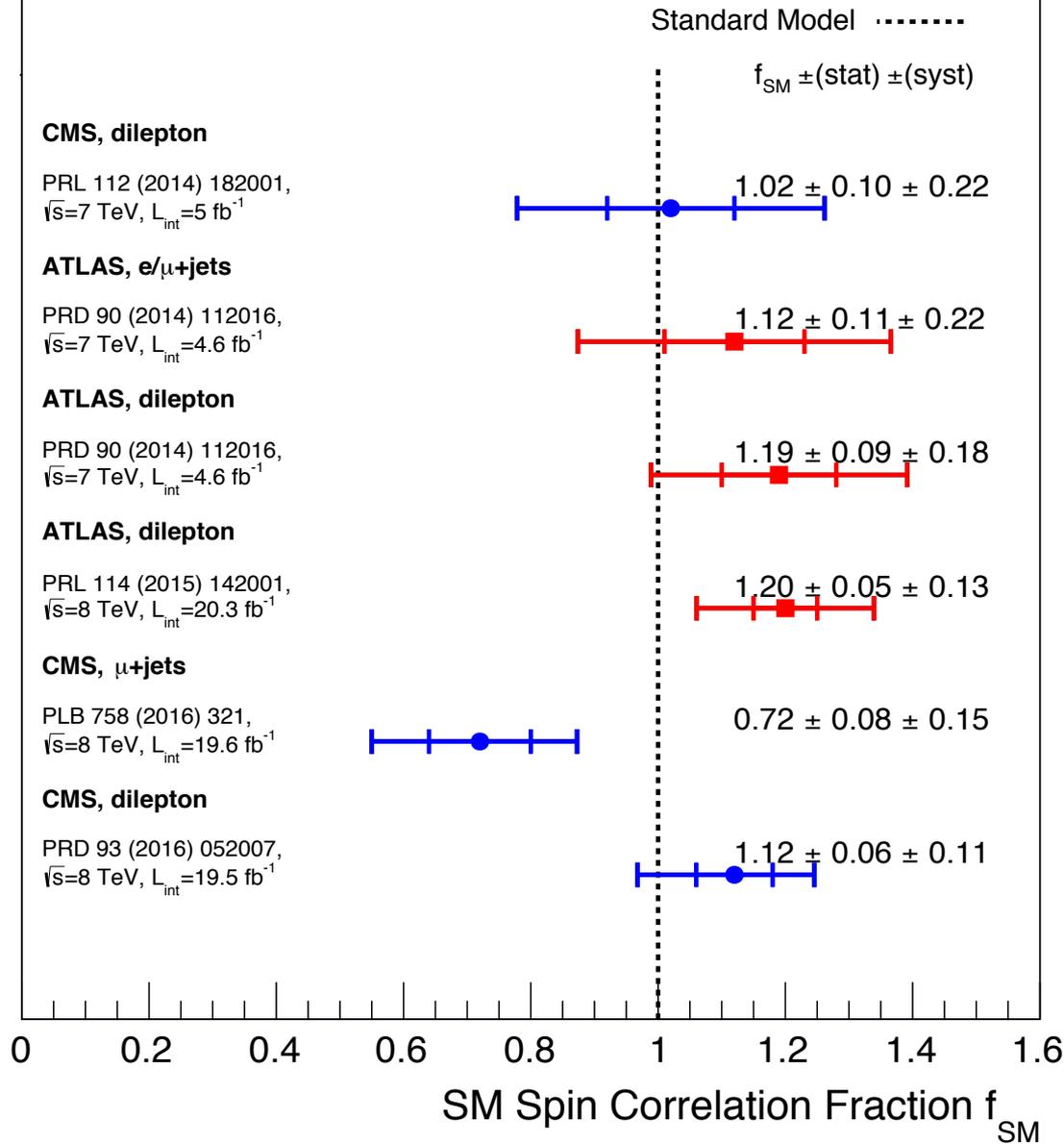
2.2 SD agreement w/ SM hypothesis.
2.9 SD agreement w/ uncorrelated hypothesis.

Dominated by:
JES, QCD scale, top quark mass

Hypothesis testing and template fit results consistent.

tt Spin Correlation Measurements Summary

May 2016



$$f \equiv \frac{N_{SM}}{N_{SM} + N_{non-SM}}, \quad f_{SM} = 1$$

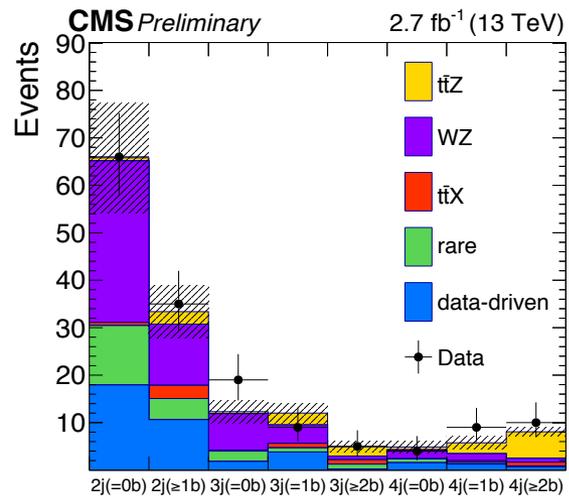
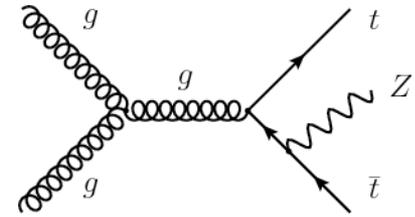
Top Quark Couplings

TOP-16-009

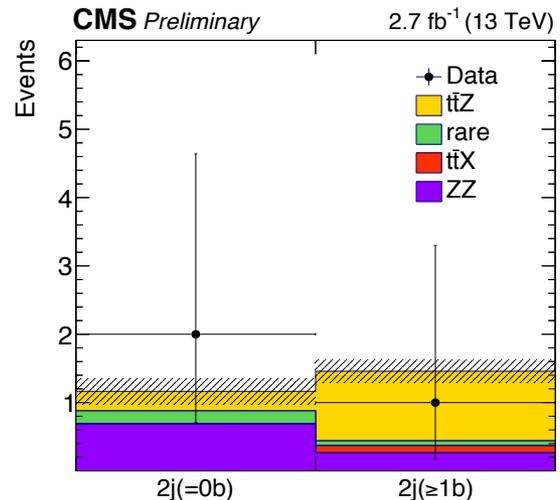
- ttZ and tty → Direct access to top-electroweak couplings.
- ttW and ttZ : important backgrounds for top-Higgs coupling measurements.
- ttZ/W and tty measured and limits on anomalous couplings, four-top production and ttH have been placed at 8 TeV.

Run II:

- ◆ $\sigma(ttZ)@13\text{ TeV} \rightarrow \sim 4 \times \sigma(ttZ)@8\text{ TeV}$
- ◆ ttZ cross section from 3-lepton and 4-lepton final states.
- ◆ Exploit jet and b-jet multiplicities to enhance the signal.



3-lepton



4-lepton

Expected significance: 3.1 SD
Observed significance: 3.6 SD

$$\sigma_{t\bar{t}Z} = 1065_{-313}^{+352} (stat)_{-142}^{+168} (syst) fb$$

$$\sigma_{t\bar{t}Z}^{NLO} = 839.3_{-92}^{+80} (scale) \pm 25(pdf) \pm 25(\alpha_s) fb$$

W Boson Polarization

- Wtb vertex \rightarrow electroweak V-A structure.
- W helicity fractions (F_x) sensitive to the Wtb vertex structure.

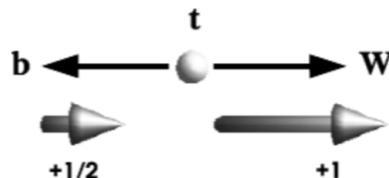
$$\frac{d\sigma}{d\cos\theta^*} \approx \frac{3}{8}(1 - \cos\theta^*)^2 F_L + \frac{3}{4}(\sin\theta^*)^2 F_0 + \frac{3}{8}(1 + \cos\theta^*)^2 F_R$$

$F_L \sim 0.3$

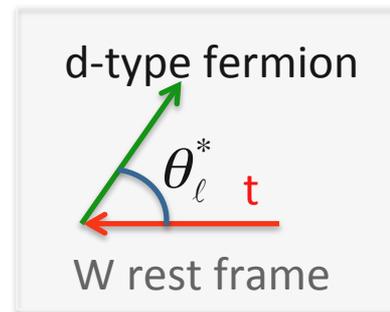
$F_0 \sim 0.7$

$F_R \sim 0$

Top quark prefers to couple more to longitudinally polarized W bosons.



Top quark decay to a right-handed W boson is forbidden \leftarrow angular momentum conservation (when $m_b=0$).

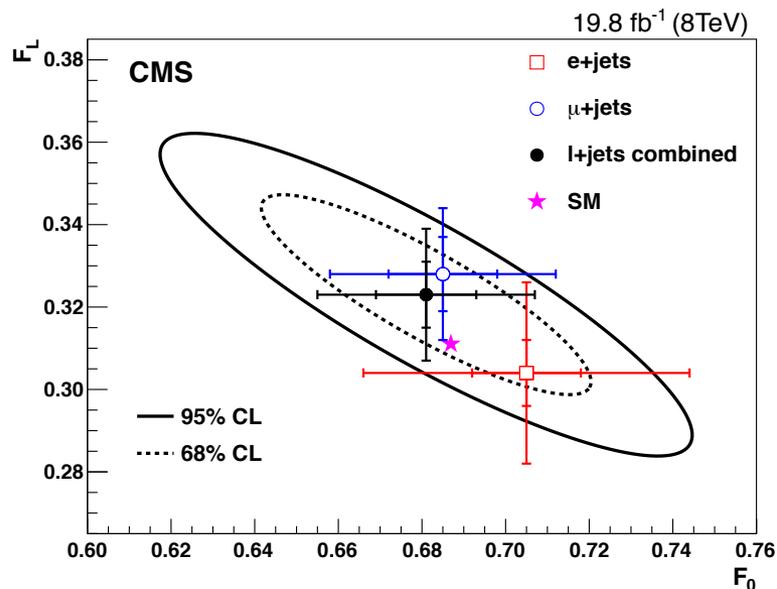
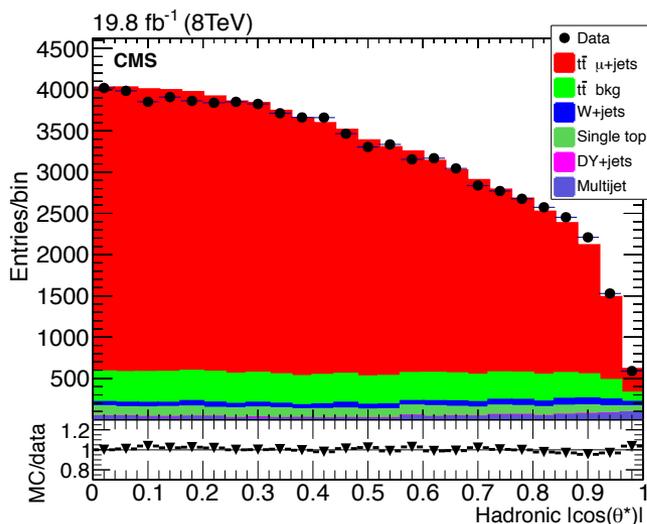
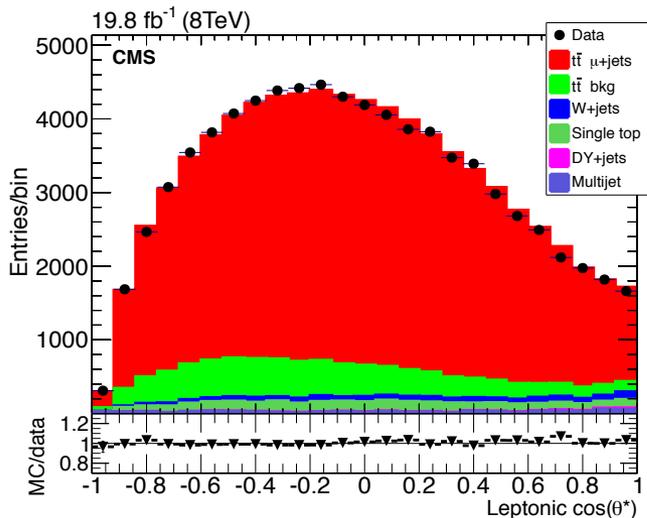


Higher orders and $m_b \neq 0$ modify the helicity fractions by $\sim 2\%$.
(at NNLO QCD)

W Boson Polarization



$e/\mu + 4$ jets (2 b-tagged)



$$F_0 = 0.681 \pm 0.012(stat) \pm 0.023(syst)$$

$$F_L = 0.323 \pm 0.008(stat) \pm 0.014(syst)$$

$$F_R = -0.004 \pm 0.005(stat) \pm 0.014(syst)$$

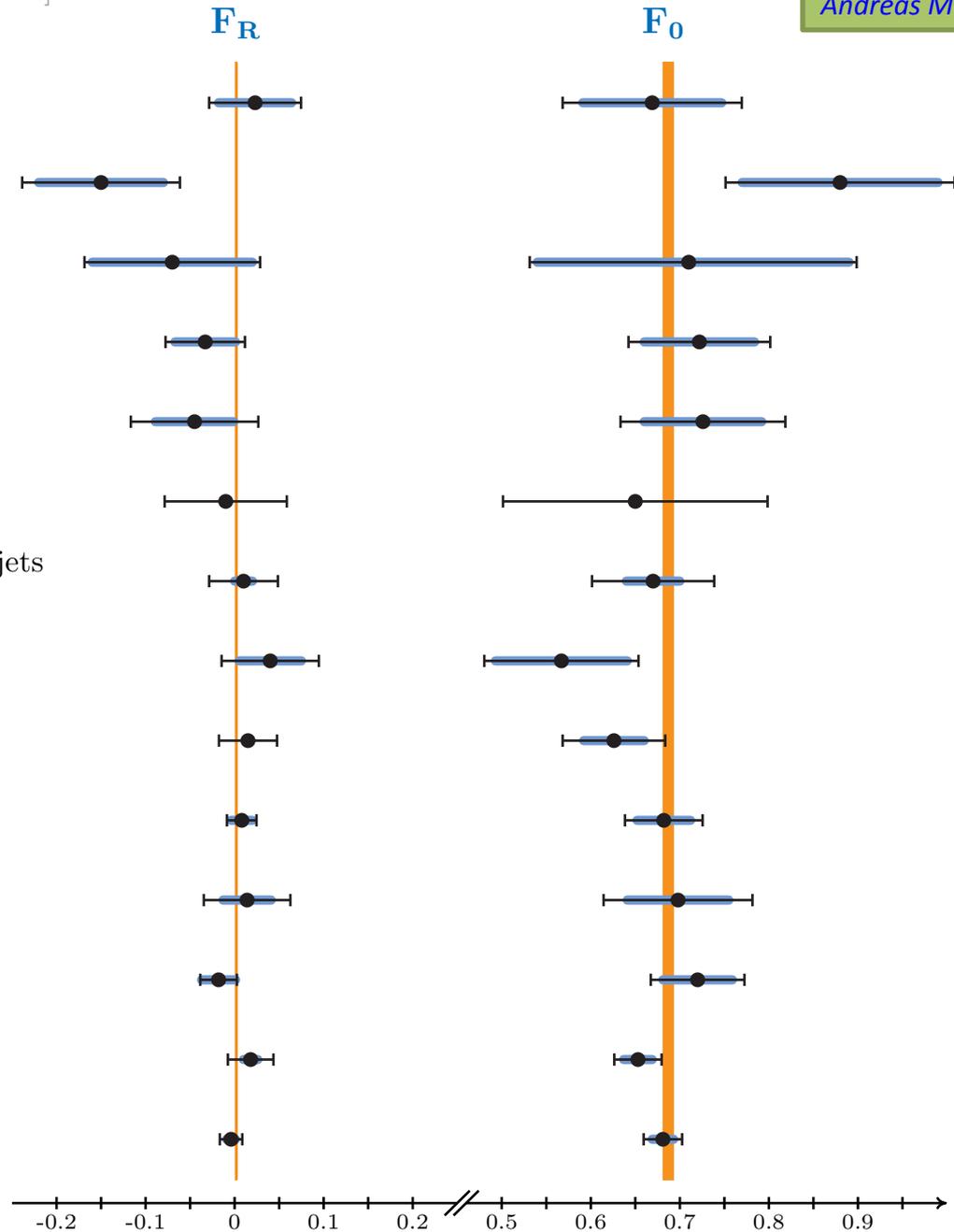
Dominant uncertainties: Top quark mass and QCD scales.

Most precise measurement of helicity fractions to date.

— SM expectations [PRD 81 (2010) 111503]

Uncertainty: —|— total, —|—|— stat. only

- $D\bar{O}$, 5.4 fb^{-1} , $t\bar{t} \rightarrow \ell(\ell) + \text{jets}$
[PRD 83 (2011) 032009]
- CDF , 2.7 fb^{-1} , $t\bar{t} \rightarrow \ell + \text{jets}$
[PRL 105 (2010) 042002]
- CDF , 5.1 fb^{-1} , $t\bar{t} \rightarrow \ell\ell + \text{jets}$
[PRB 722 (2013) 48–54]
- \rightarrow **Tevatron combination**
[PRD 85 (2012) 071106]
- CDF , 8.7 fb^{-1} , $t\bar{t} \rightarrow \ell + \text{jets}$
[PRD 87 (2013) 031104]
- \rightarrow **ATLAS**, 35 pb^{-1} (7 TeV), $t\bar{t} \rightarrow \ell + \text{jets}$
[ATLAS CONF-2011-037]
- \rightarrow **ATLAS**, 1.04 fb^{-1} (7 TeV), $t\bar{t} \rightarrow \ell(\ell) + \text{jets}$
[JHEP 06 (2012) 088]
- \rightarrow **CMS**, 2.2 fb^{-1} (7 TeV), $t\bar{t} \rightarrow \mu + \text{jets}$
[CMS PAS TOP-11-020]
- \rightarrow **LHC combination**, 7 TeV
[ATLAS CONF-2013-033]
- CMS**, 5.0 fb^{-1} (7 TeV), $t\bar{t} \rightarrow \ell + \text{jets}$
[JHEP 10 (2013) 167]
- CMS**, 4.6 fb^{-1} (7 TeV), $t\bar{t} \rightarrow \ell\ell + \text{jets}$
[CMS PAS TOP-12-015]
- CMS**, 19.7 fb^{-1} (8 TeV), single top
[JHEP 01 (2015) 053]
- CMS**, 19.7 fb^{-1} (8 TeV), $t\bar{t} \rightarrow \ell\ell + \text{jets}$
[CMS PAS TOP-14-017]
- CMS**, 19.6 fb^{-1} (8 TeV), $t\bar{t} \rightarrow \ell + \text{jets}$
[submitted to PLB]



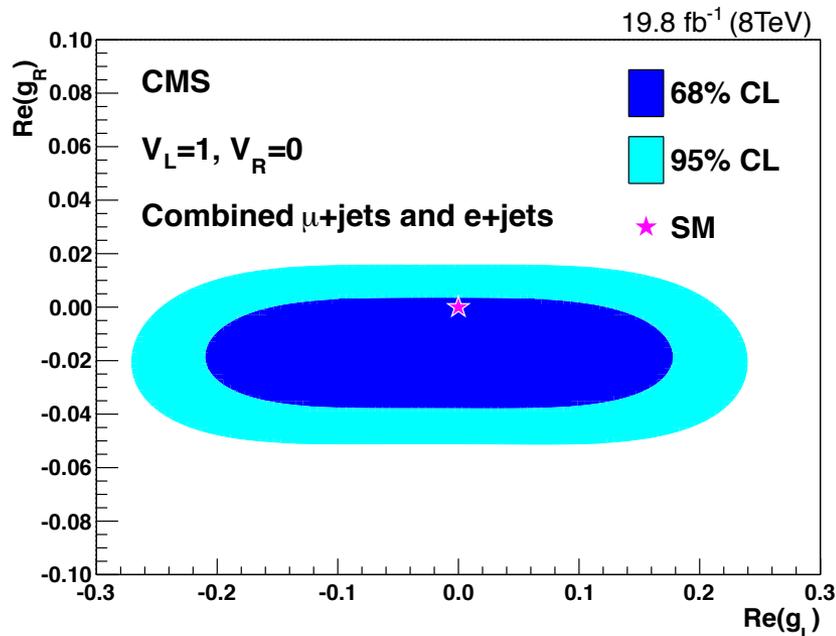
W Boson Polarization

- Wtb : magnitude determined by $|V_{tb}|$.
- BSM contributions to Wtb vertex modify helicity fractions.
- In the effective operative framework:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}$$

$$SM : V_L = V_{tb} \approx 1$$

$$V_R = g_L = g_R = 0$$

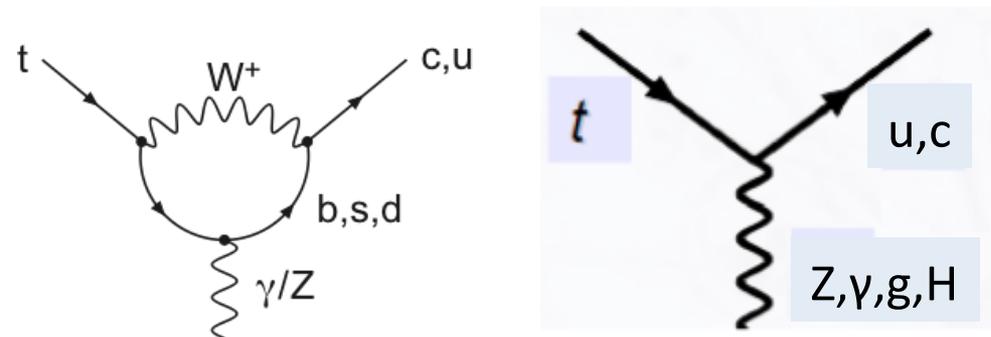


*CMS-PAPER-TOP-13-008,
 submitted to PLB*



Flavor Changing Neutral Currents

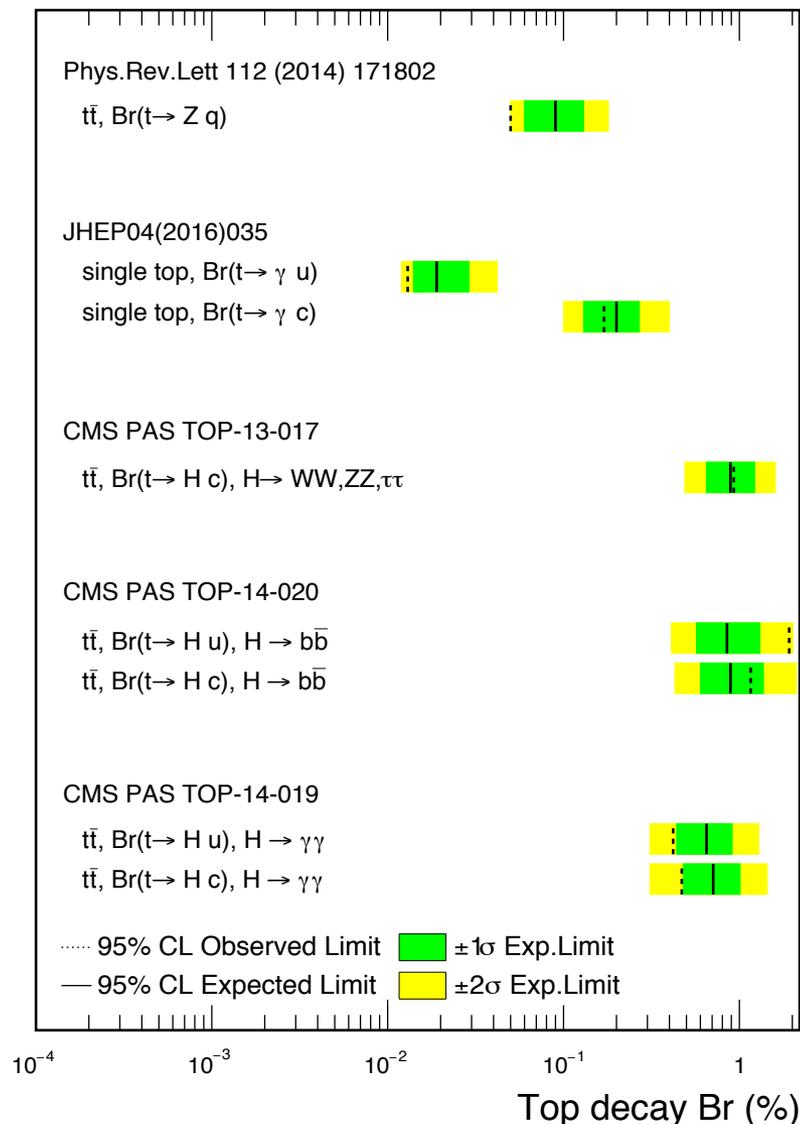
- SM: Forbidden at tree level
- Suppressed at higher orders due to GIM mechanism.
- Occurs only at the level of loop corrections with $\mathcal{B}(t \rightarrow Xq) \sim 10^{-15} - 10^{-10}\%$
- BSM $\mathcal{B}(t \rightarrow Xq) \sim 10^{-7} - 10^{-1}\%$
- Measurements $\sim 10^{-2} - 1\%$



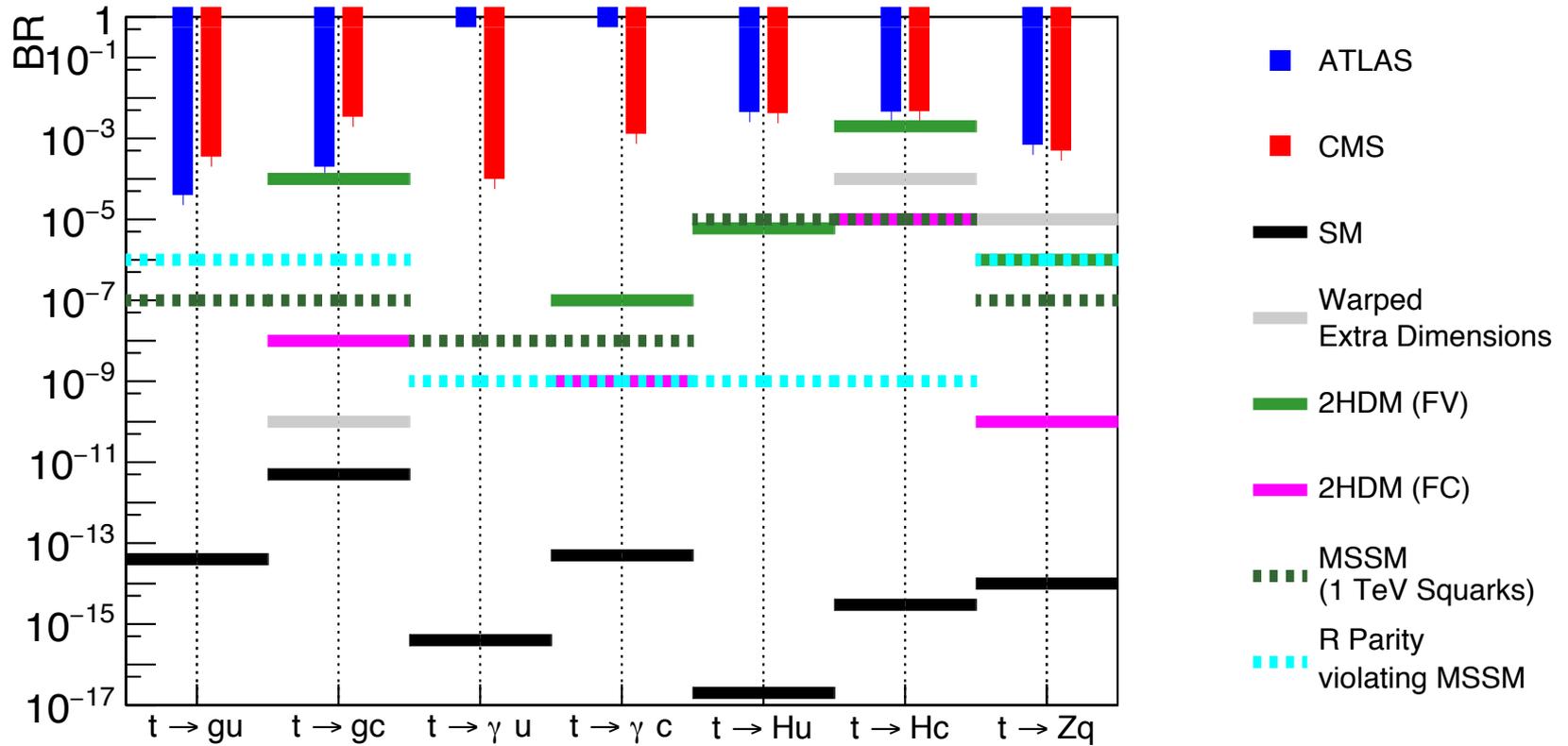
- No sign of FCNC in $t\bar{t}$ and single top
- Measurements statistics dominated.

CMS Preliminary, 8 TeV

March 2016



FCNC vs Data in Some Particular Models



Andreas Meyer

CP Violation in $t\bar{t}b\bar{b}$ Production

- Search for an anomalous top-gluon coupling using T-odd observables $\rightarrow CP(O_i) = -O_i$.

e.g.

$$O_4 = Q_\ell \epsilon (P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

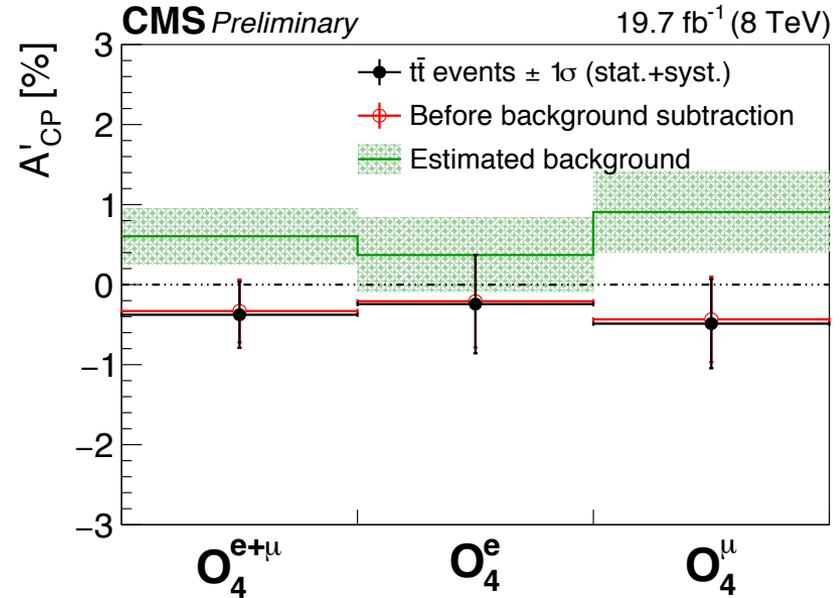
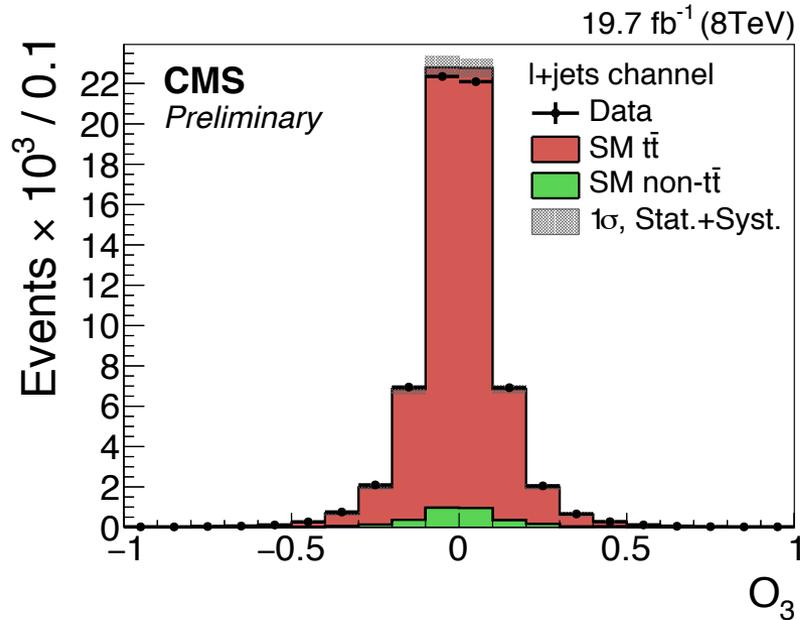
CP violation $\rightarrow \neq 0$ asymmetry in $A_{CP}(O_i) = \frac{N(O_i > 0) - N(O_i < 0)}{N(O_i > 0) + N(O_i < 0)}$

Anomalous couplings can give rise to asymmetries up to $\sim 7-8\%$.

Hayreter & Valencia
PRD 93 (2016) 014020

CP Violation in $t\bar{t}b\bar{r}$ Production

TOP-16-001



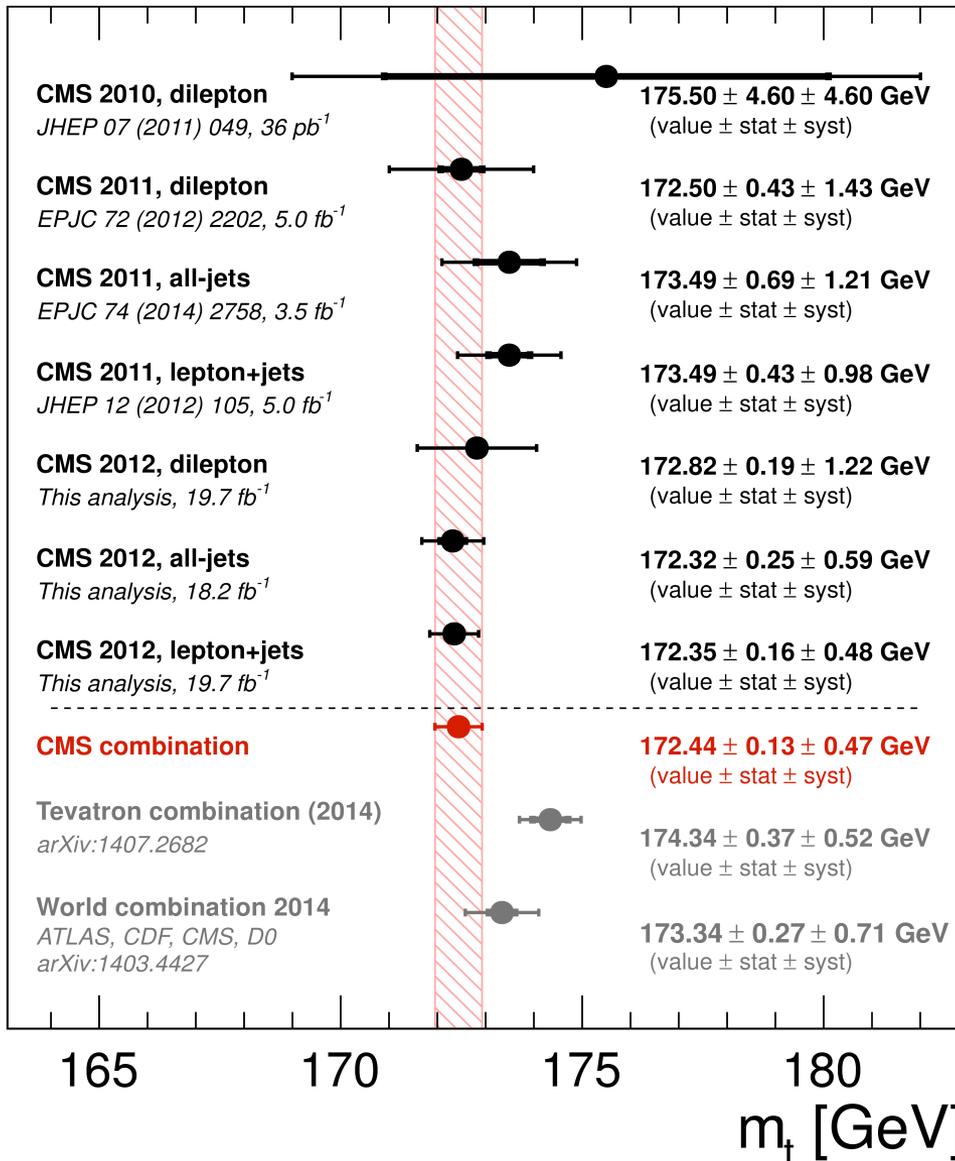
$A'_{CP}(O_i)$	e+jets	μ +jets	ℓ +jets
O_2	$-0.01 \pm 0.61 \pm 0.01$	$+0.50 \pm 0.56 \pm 0.02$	$+0.27 \pm 0.41 \pm 0.01$
O_3	$-0.34 \pm 0.61 \pm 0.02$	$-1.03 \pm 0.56 \pm 0.04$	$-0.71 \pm 0.41 \pm 0.03$
O_4	$-0.24 \pm 0.61 \pm 0.02$	$-0.49 \pm 0.56 \pm 0.04$	$-0.38 \pm 0.41 \pm 0.03$
O_7	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$

- No evidence for CP violation in $t\bar{t}b\bar{r}$.
- Measurement dominated by statistical uncertainties.

Top Quark Mass

Direct Top Quark Mass Measurements

arXiv:1509.04044



- Run I combination: 7+8 TeV in lepton +jets, dilepton, and all-hadronic channels
- Precision 0.3%
- Dominant systematic uncertainties: flavor-dependent JEC and b jet modeling.

Improving Top Mass Measurements

- Major uncertainties

- ◆ b hadronization modelling (and effect on jet energy scale)
- ◆ Modelling of hard scattering
- ◆ Jet energy calibration and pile-up.

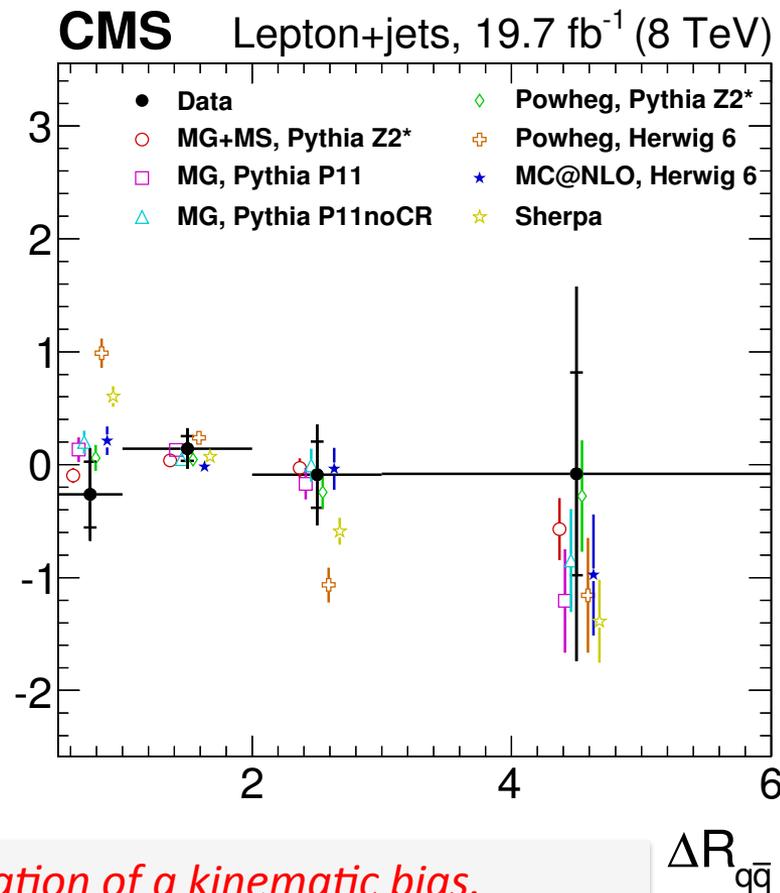
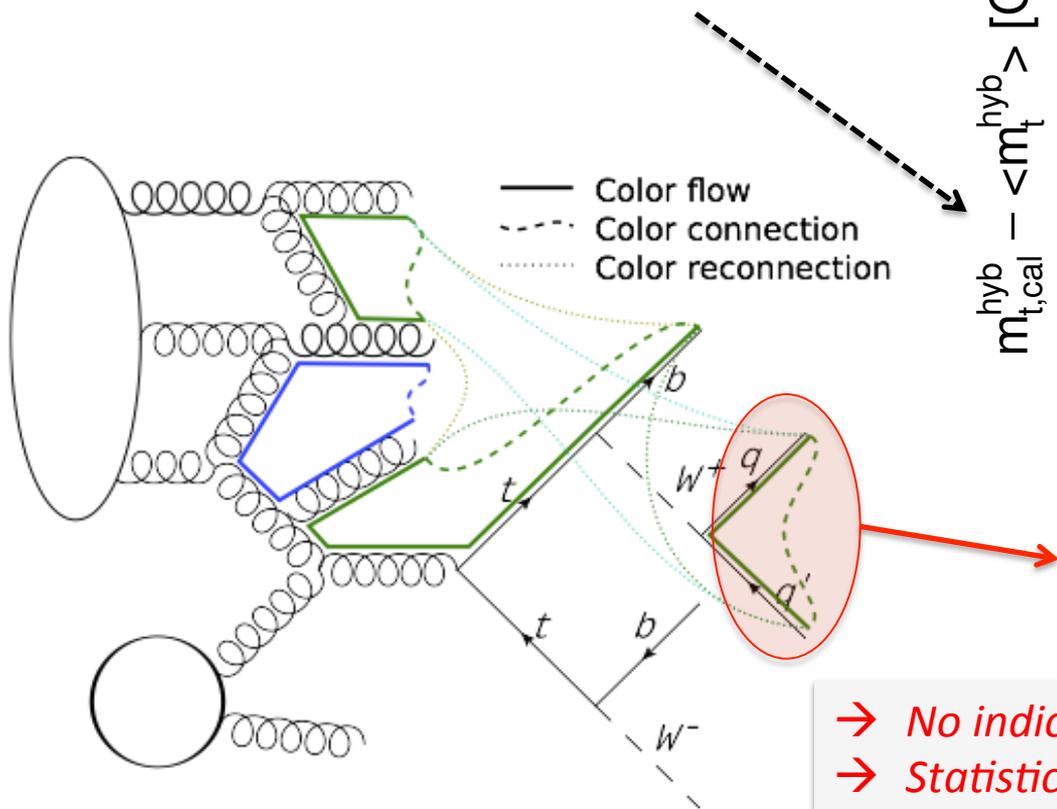
- Dedicated measurements and theory studies to improve modelling.
- Alternative measurements displaying different aspects of systematics
- Use observables with a well-defined mass definition in pQCD:
 $\sigma(t\bar{t}b)$, $m(lb)$, $m(t\bar{t},\text{jet})$, ...
- And alternative topologies.

(non-)perturbative effects that have different kinematic dependences?

arXiv:1509.04044

- Study 8 variables sensitive to color reconnections, ISR/FSR, b-quark kinematics.

Measurement calibrated in each bin –
Average from the inclusive measurement.

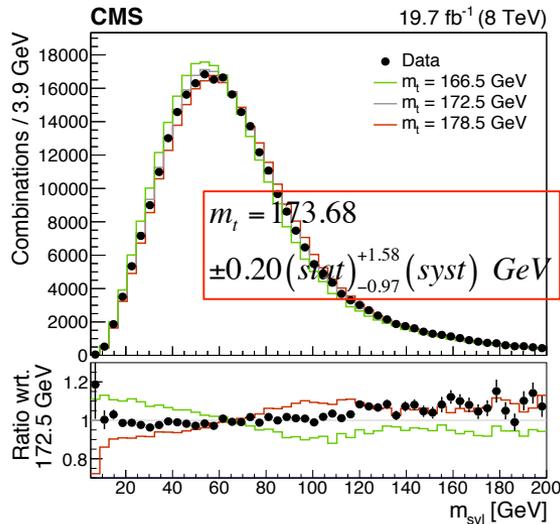
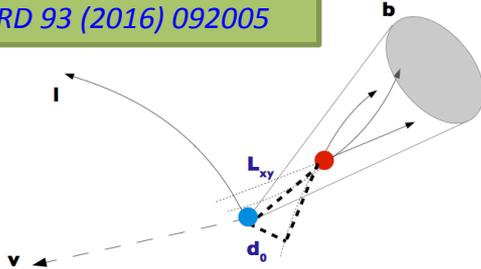


→ No indication of a kinematic bias.
 → Statistics not yet enough to constrain further some of the alternate $t\bar{t}$ models.

Recent Alternative Top Quark Mass Measurements

Invariant mass of the secondary vertex w/ ≥ 3 tracks + lepton.

PRD 93 (2016) 092005



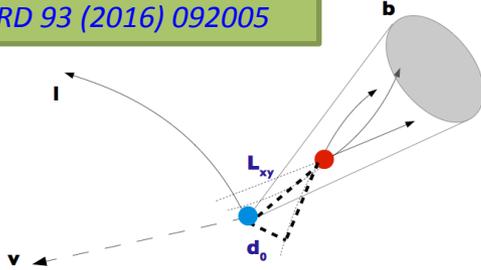
Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

M_{svtx} mass:
b fragmentation

Recent Alternative Top Quark Mass Measurements

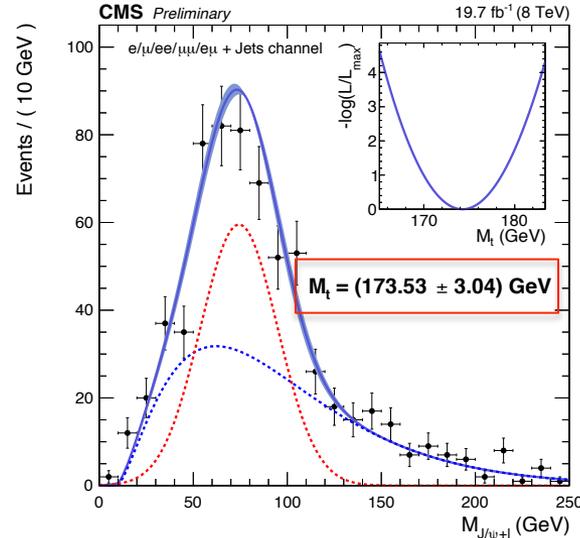
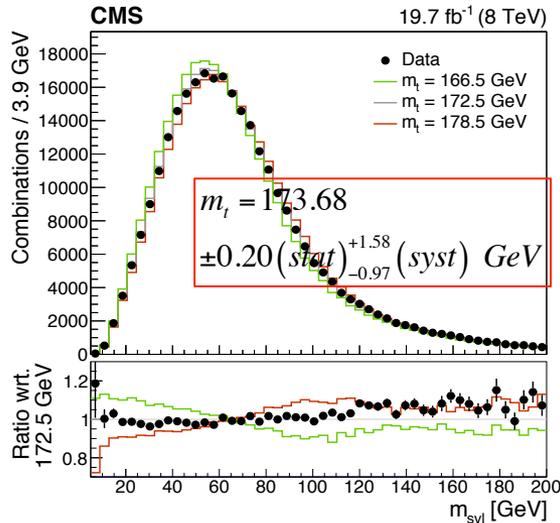
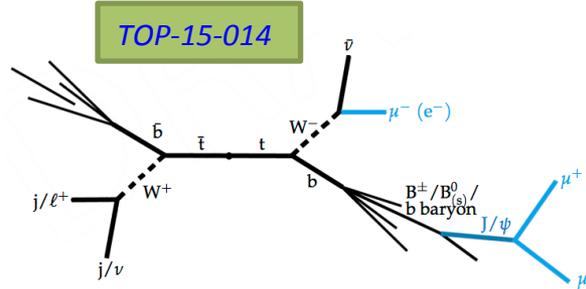
Invariant mass of the secondary vertex w/ ≥ 3 tracks + lepton.

PRD 93 (2016) 092005



J/ψ +lepton mass

TOP-15-014



Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

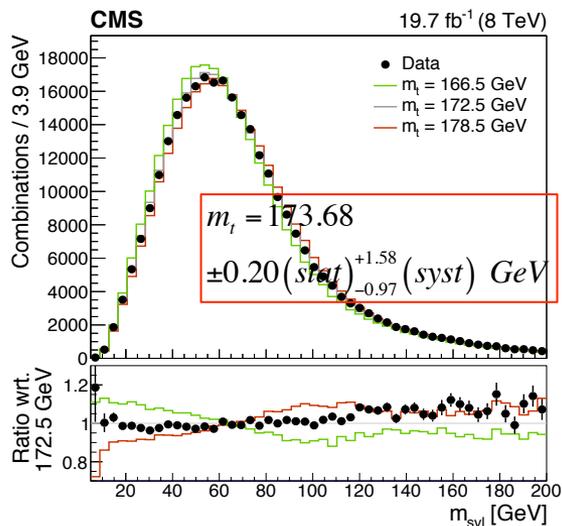
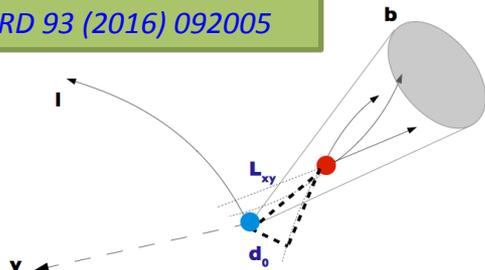
M_{svtx} mass:
b fragmentation

J/ψ +lepton mass:
Result statistically limited

Recent Alternative Top Quark Mass Measurements

Invariant mass of the secondary vertex w/ ≥ 3 tracks + lepton.

PRD 93 (2016) 092005

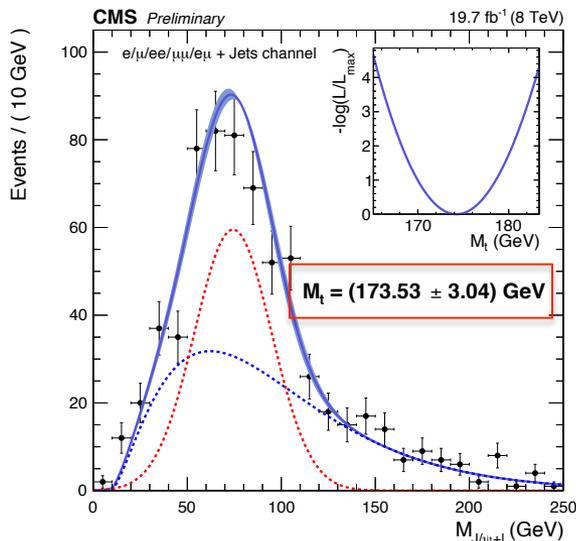
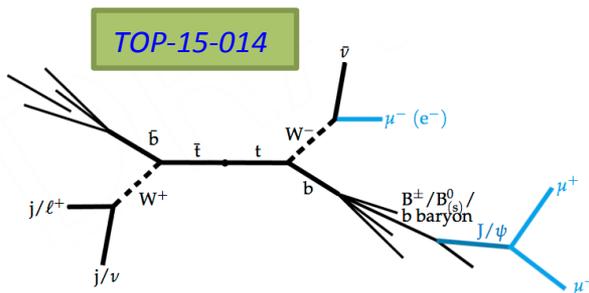


Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

M_{svtx} mass:
b fragmentation

J/ψ +lepton mass

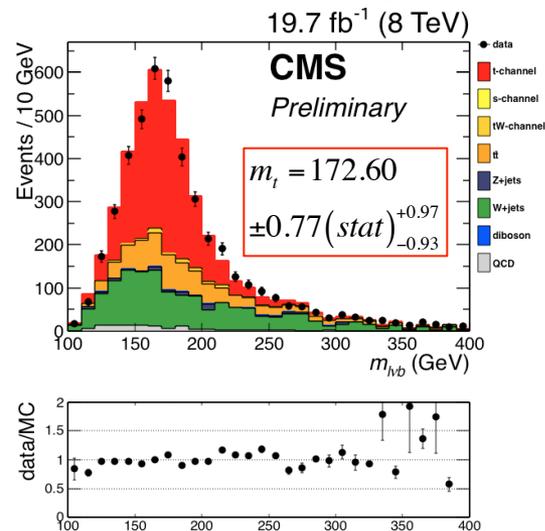
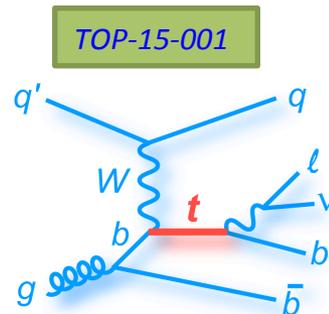
TOP-15-014



J/ψ +lepton mass:
Result statistically limited

M_{lvb} in single top topology

TOP-15-001

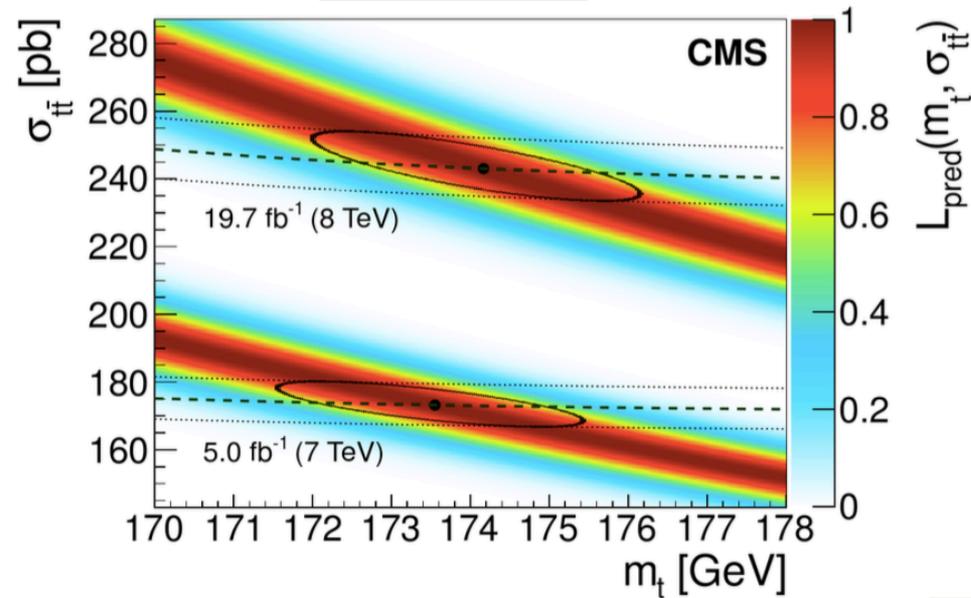


Alternative event topology
Partially uncorrelated systematics
Different color flow \rightarrow check for "unknown" syst.

Top Quark Pole Mass Measurements

$\sigma_{t\bar{t}}$ vs m_t^{pole} from NNLO+NNLL prediction with different PDF sets with a fixed α_s

arXiv:1603.02303



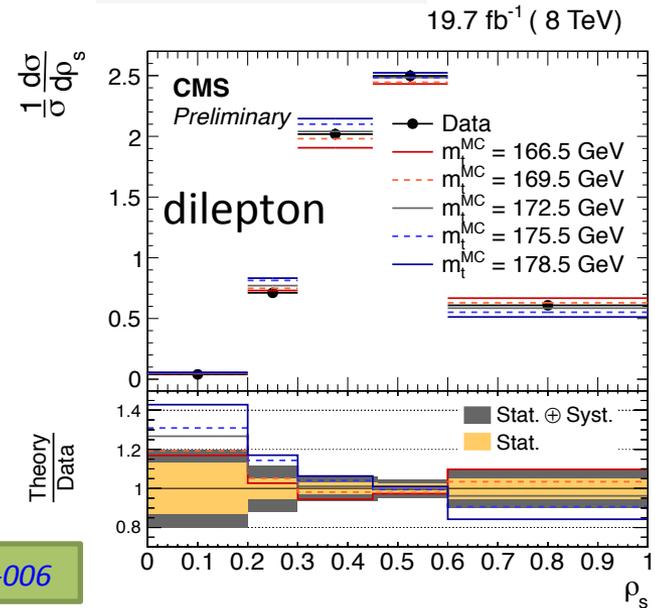
$$m_t = 173.8_{-1.8}^{+1.7} \text{ GeV}$$

- No MC calibration →
- Top quark pole mass @ NNLO
- Dominant uncertainties:
Luminosity, beam energy

Invariant mass of $t\bar{t}$ +jet system

$$\rho_s = \frac{340 \text{ GeV}}{\sqrt{m(t\bar{t}, \text{jet})}}$$

Alioli et al.
EPJ C73 (2013) 2438



TOP-13-006

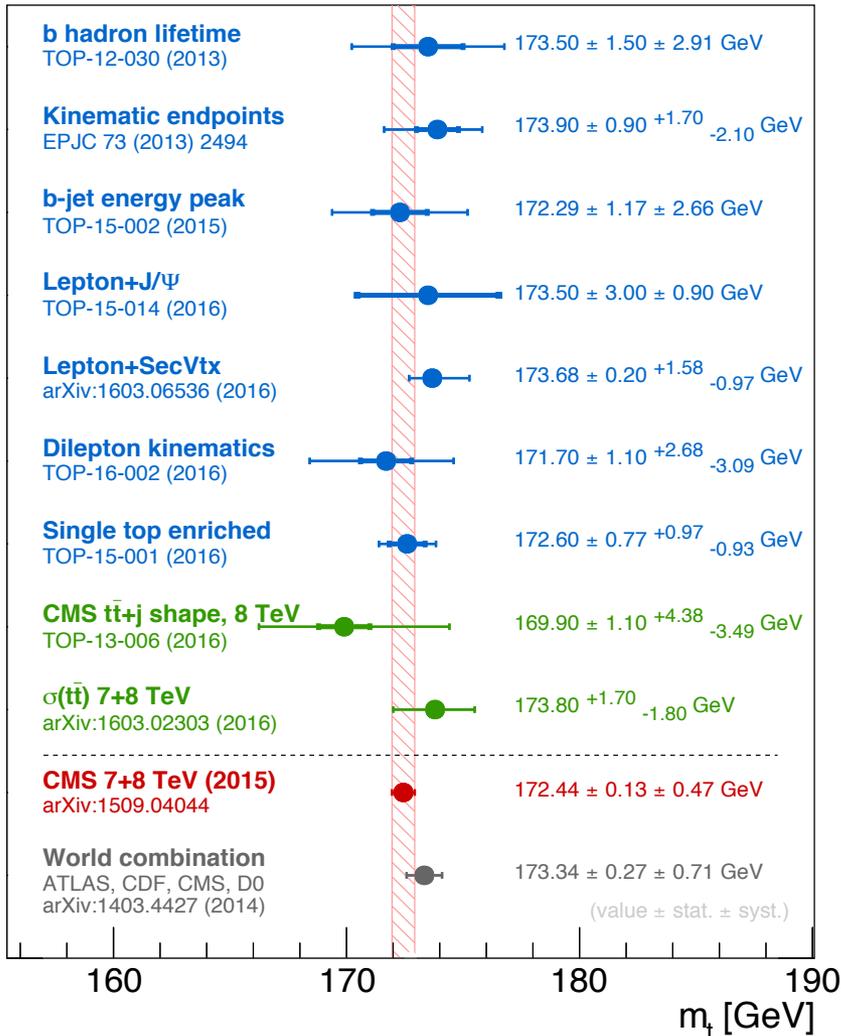
$$m_t = 169.9 \pm 1.1(\text{stat})_{-3.1}^{+2.5} (\text{syst})_{-1.6}^{+3.6} \text{ GeV}$$

- Compare unfolded distribution to NLO predictions (POWHEG+PYTHIA8).
- Dominated by scale uncertainties.

Summary of Alternative (Indirect) Top Mass Measurements

CMS Preliminary

May 2016



- So far, all the top mass definitions tested with CMS data look consistent within uncertainties
 - ◆ Many different techniques and observables have been explored at 8 TeV in all channels.
- Looking forward to further understand this parameter with LHC Run II data.

Summary

- Top quark plays an important role in precision measurements and new particles searches.
- Most CMS Run I measurements dominated by systematic uncertainties.
 - ◆ $\sigma_{tt} < 4\%$ better than NNLO accuracy
 - ◆ m_t with ~ 500 MeV precision.
 - ◆ Precise properties measurements and constraints on anomalous couplings.
- So far, all results in agreement with SM predictions.

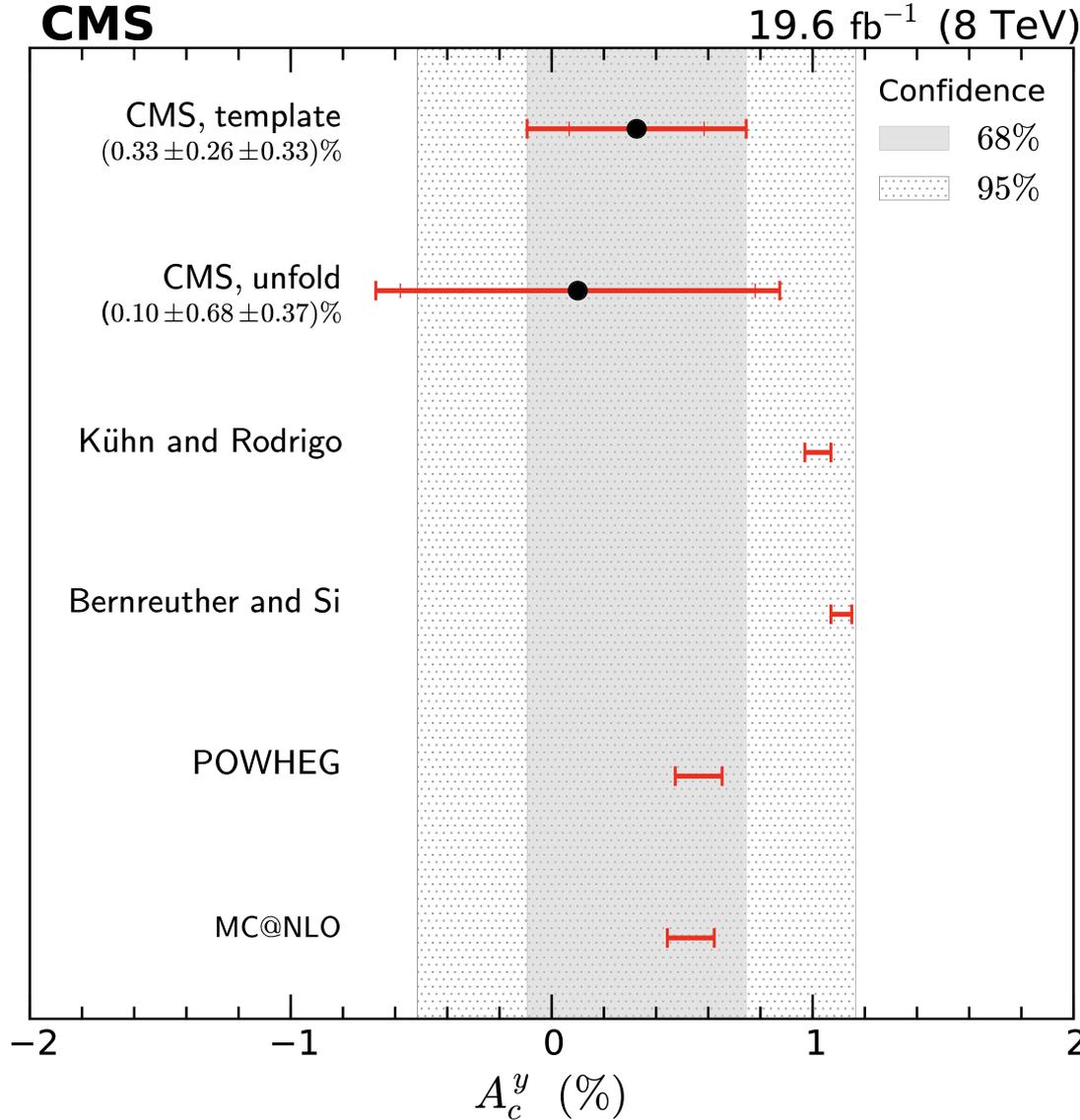
CMS Run II

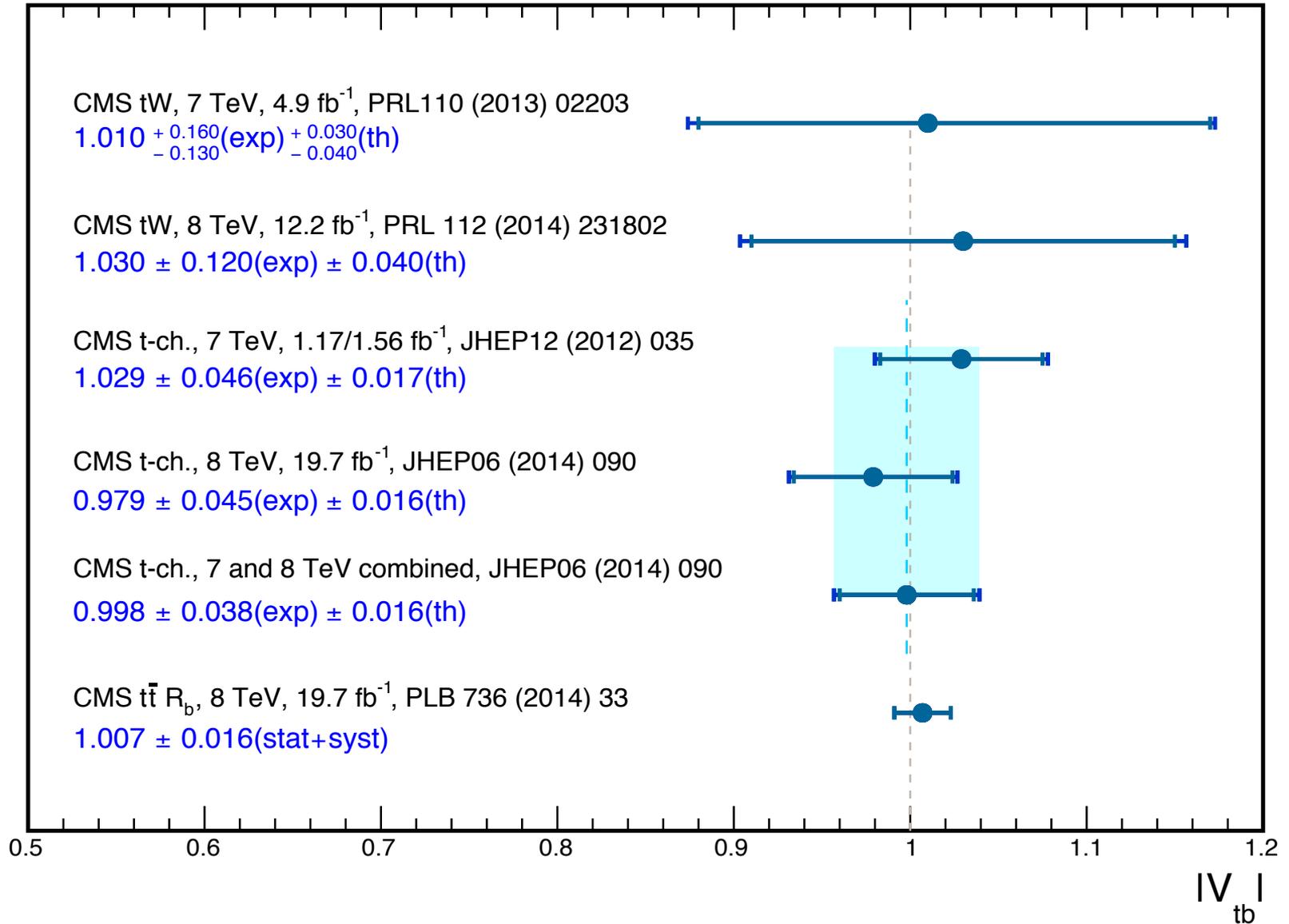
- Top rediscovered with 13 TeV data.
- Inclusive $t\bar{t}$ cross section already at NNLO precision.
- Single top t-channel precisely established.
- In both cases starting to probe differential spectra to understand new MCs
- Evidence for $t\bar{t}Z$ at 13 TeV.
- Looking forward to establishing couplings to all bosons in Run II.
- Direct or indirect indications of new physics?

<http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html>

Bonus

ttbar Charge Asymmetry





Top Polarization in Single Top Production

- Single tops are produced left-handed polarized in SM (V-A coupling)
 - BSM particles or interactions can modify the top polarization to be < 100%.
- Signal and background are extracted by a boosted decision tree (BDT) fit to the data.
- Unfolding to parton-level.

$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2} (1 + P_t \alpha_X \cos\theta_X) \equiv \Gamma \left(\frac{1}{2} + A_X \cos\theta_X \right)$$

$$A_\ell \equiv \frac{1}{2} \cdot P_t \cdot \alpha_\ell = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

$$A_\mu(t + \bar{t}) = 0.26 \pm 0.03(\text{stat}) \pm 0.10(\text{syst})$$

$$A_{SM} = 0.44 \quad 2\sigma \text{ away from SM prediction.}$$

Dominant uncertainties: W+jets modelling, QCD scales

[arXiv:1511.02138](https://arxiv.org/abs/1511.02138)

$\theta_x \rightarrow$ between l+ and untagged jet in the top frame.

