Top Quark Properties Measurements in CMS

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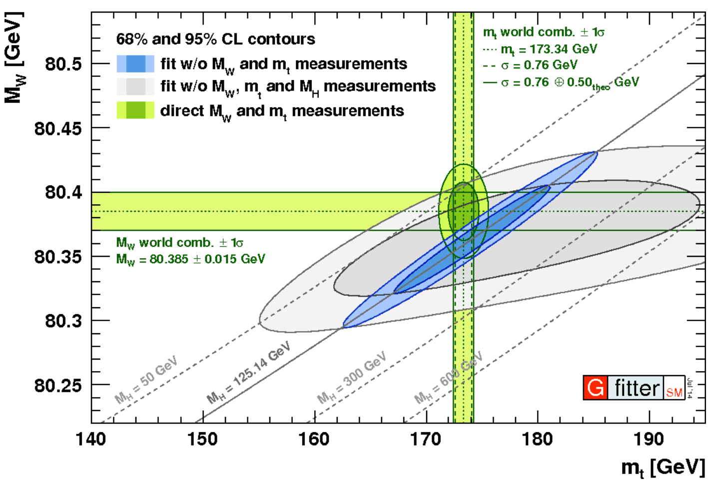
on behalf of the CMS Collaboration

La Thuile 2016: Les Rencontres de Physique de la Vallée d’Aoste, 6-12 March Italy

The Top Quark

- The most massive particle known to date
- Very short lifetime shorter than the 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 and Higgs modify tree level SM processes through radiative corrections.

The Gfitter Group, M. Baak et al., EPJC 74, 3046 (2014)



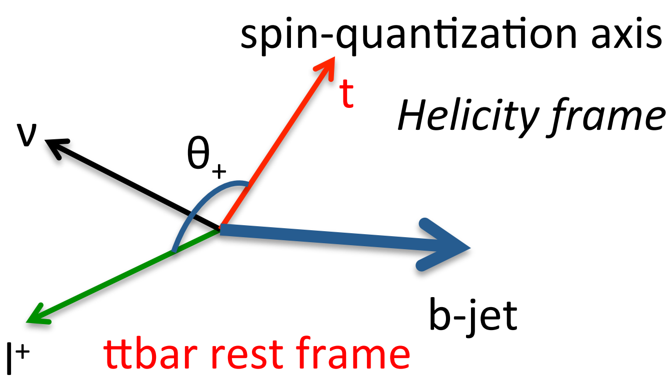
Electroweak fit before Higgs discovery consistent with measured m_H within 1.3σ.

EPJC 72, 2205 (2012)

- A selection of measurements from CMS
  - ttbar spin correlation
  - ttbar asymmetries
  - Top quark mass
  - Underlying event in ttbar events
- All public CMS results at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Spin Correlations

- Heavy quark spins are correlated in QCD.
- Top quarks decay before their spins de-correlate.
- Can be measured with or without ttbar system reconstruction.



$$\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{\sigma}{4}\left(1 + \overbrace{\alpha_+ P_+ \cos\theta_+}^{\sim 0} + \overbrace{\alpha_- P_- \cos\theta_-}^{\sim 0} + A\alpha_+\alpha_- \cos\theta_+ \cos\theta_-\right)$$

$$C = A\alpha_+\alpha_-$$

spin analyzing power of the decay particle

$$\alpha_i(NLO) = \begin{cases} 0.998(l^+) \\ 0.966(\bar{d}, \bar{s}) \\ -0.31(u, c, \bar{\nu}) \\ -0.393(b) \\ 0.393(W^+) \end{cases}$$

$0.998(l^+)$ → easiest in the dilepton channel.

$0.966(\bar{d}, \bar{s})$, $-0.31(u, c, \bar{\nu})$: difficult to distinguish u- and d-type quarks

Spin correlation strength

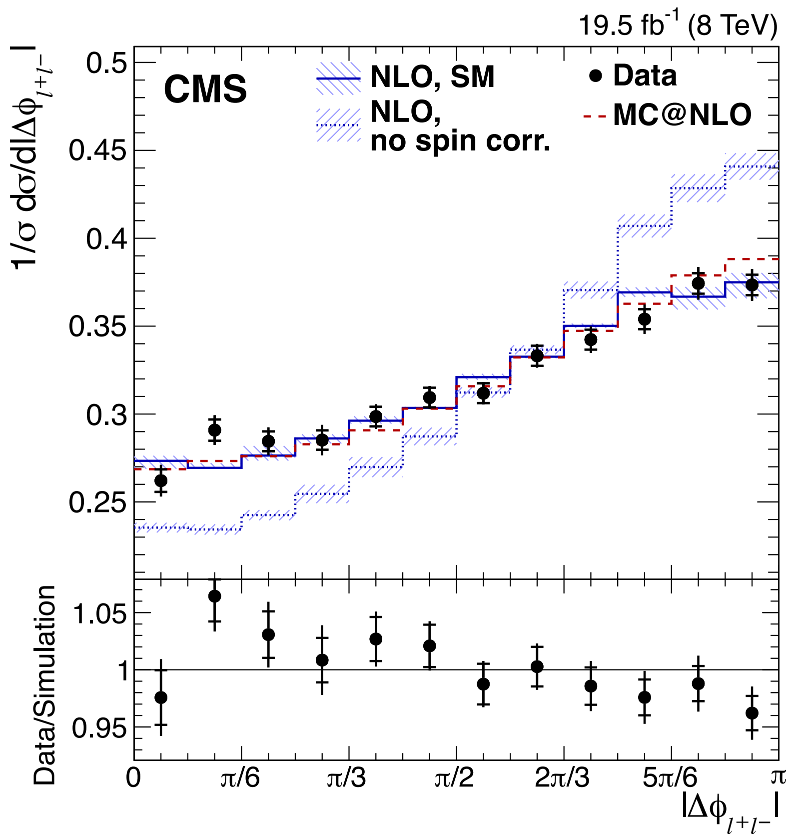
$$A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$$

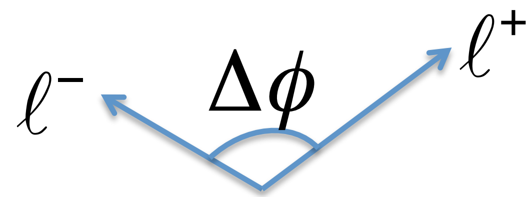
$$A_{basis}^{meas} = A_{basis}^{SM} f$$

$$f = \frac{N_{SM}}{N_{SM} + N_{non-SM}}$$

Brandenburg et al. PLB539, 235 (2002),
Bernreuther et al Nucl.Phys.B690, 81 (2004), ...

Spin Correlations – Dilepton Channel





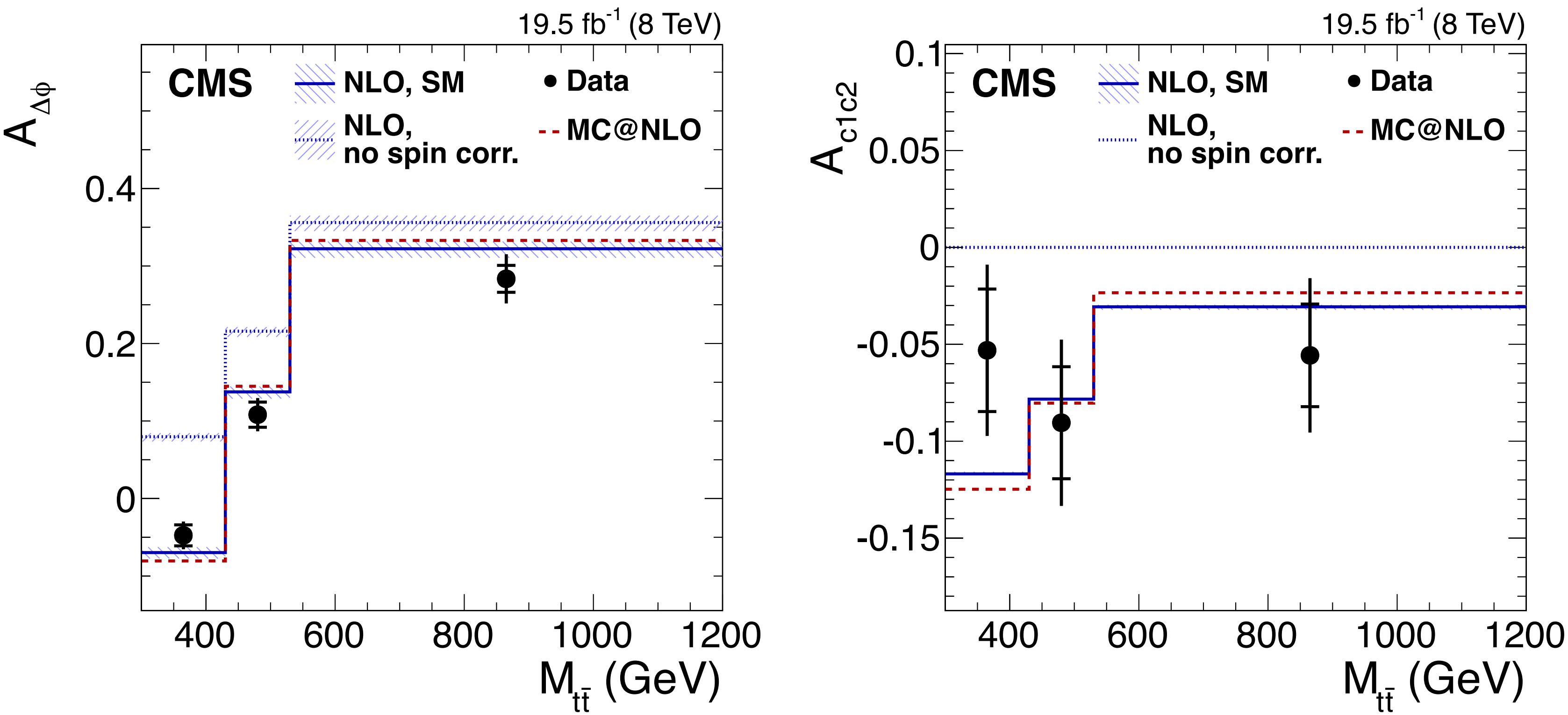
CMS-PAS-TOP-14-023
arXiv:1601.01107

- Lepton angles → very high resolution.
- Δϕ (defined from lab-frame leptons) most sensitive, single variable
- Data corrected to *parton level*.
- Data agree well with the SM prediction.
- Dominant systematic uncertainty: top p_T modelling
- Asymmetries translated to f using NLO (QCD+EW) predictions.

Variable	$f_{SM} \pm$ (stat) $\pm$ (syst) $\pm$ (theor)	Total uncertainty
$A_{\Delta\phi}$	$1.14 \pm 0.06 \pm 0.13 ^{+0.08}_{-0.11}$	$^{+0.16}_{-0.18}$
$A_{\cos\varphi}$	$0.90 \pm 0.09 \pm 0.10 \pm 0.05$	± 0.15
$A_{c_1c_2}$	$0.87 \pm 0.17 \pm 0.21 \pm 0.04$	± 0.27
$A_{\Delta\phi}$ (vs. $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08 ^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

Spin Correlations – Dilepton Channel

- Differential measurement of asymmetry variables in bins of $M_{t\bar{t}}, |y_{t\bar{t}}|, p_T^{t\bar{t}}$



CMS-PAS-TOP-14-023, arXiv:1601.01107

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

→ Spin correlation sensitive variables have the largest variability w.r.t M_{tt}.
→ Unfolding M_{tt} significantly reduces the top p_T uncertainty.

Spin Correlations – Dilepton Channel Limits on Chromo-Moments

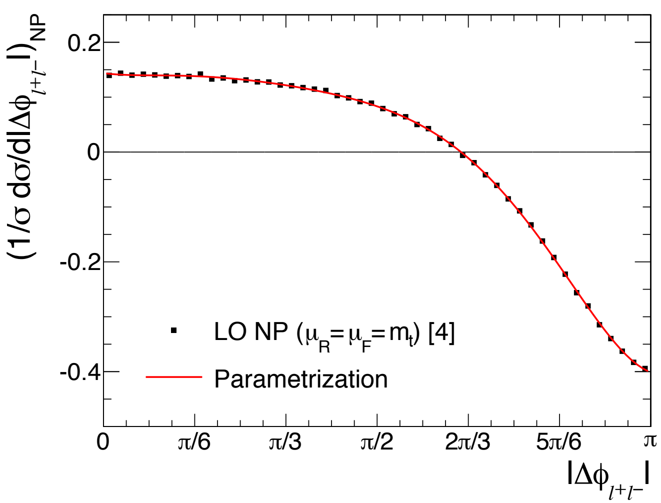
- Anomalous, flavor-conserving, strong interaction between top quark and gluon?
  - *Model independent* search using an effective model.
  - Assume a particle exchange with a mass scale $M > m_t$

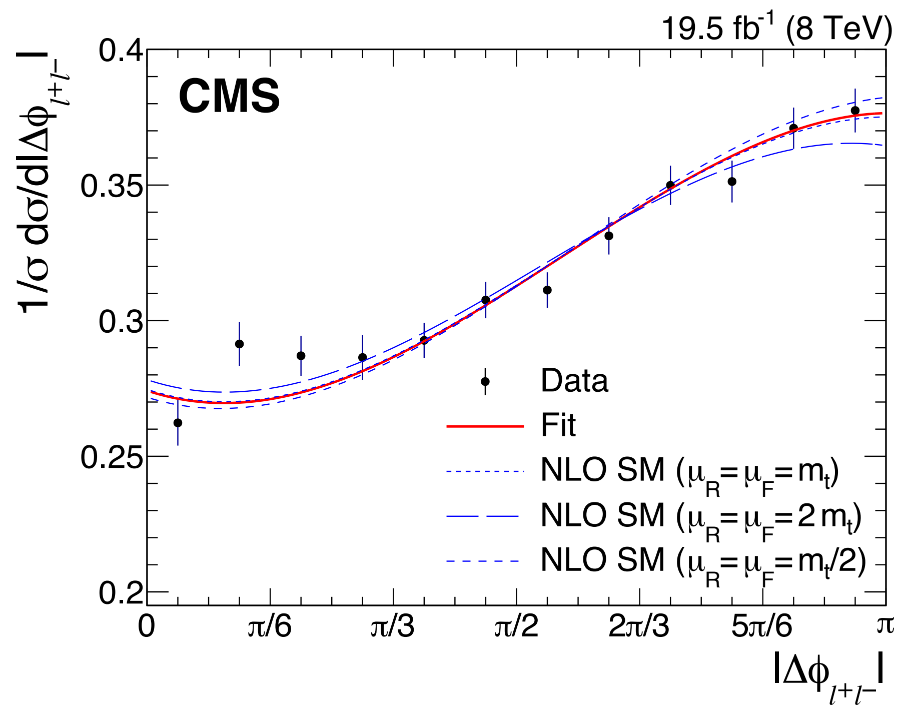
CMS-PAS-TOP-14-023
arXiv:1601.01107

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

If $\mathrm{Re}(\mu_t) \ll 1 \rightarrow$

$$\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{ll}|} = \left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{ll}|}\right)_{SM} + \mathrm{Re}(\hat{\mu}_t)\left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{ll}|}\right)_{NP}$$





$$-0.053 < \mathrm{Re}\left(\hat{\mu}_t\right) < 0.026$$

$$-0.068 < \mathrm{Im}\left(\hat{d}_t\right) < 0.067$$

Spin Correlations – Lepton+Jets Channel -- Matrix Element Method

- Spin correlation more difficult to measure in the lepton+jets channel.
  - Use a multivariate method.
    - leading order matrix element method to calculate event likelihoods.

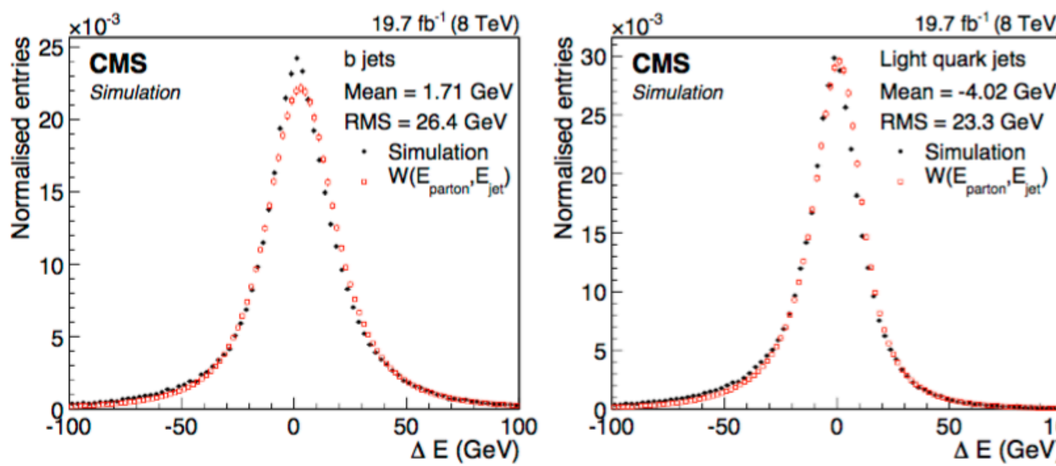
q_1, q_2 : initial parton kinematics

H = correlated ttbar (H_{cor}) or
H = un-correlated ttbar (H_{uncor})

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

reconstructed kinematics x → parton level y
(in three different detector regions)

CMS-PAS-TOP-13-015
arXiv:1511.06170



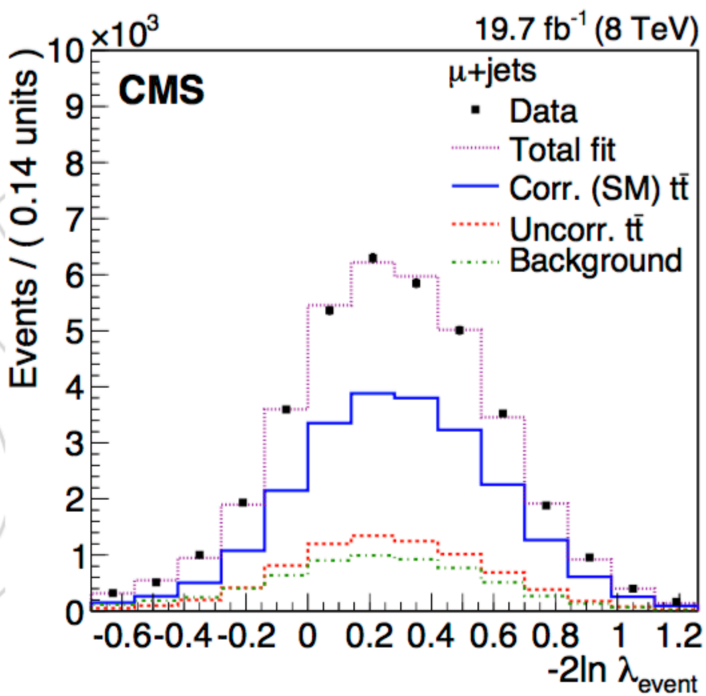
Spin Correlations – Lepton+Jets Channel -- Matrix Element Method

- *MadWeight* [JHEP 12 (2010) 068] to calculate per-event probabilities for the two hypotheses
- *MadWeight* partially corrects for ISR effect using the overall partonic p_T(ttbar)
- Kinematic fitter to select the 4 jets from LO ttbar as input to the LO ME.

$$-2\ln\lambda = -2\ln\frac{P\left(H_{non-SM}\right)}{P\left(H_{SM}\right)}$$

→ Fit to event likelihood ratios of f and bkg fraction using spin-correlated and –uncorrelated templates (constructed from NLO MC events)

→ Method calibration



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

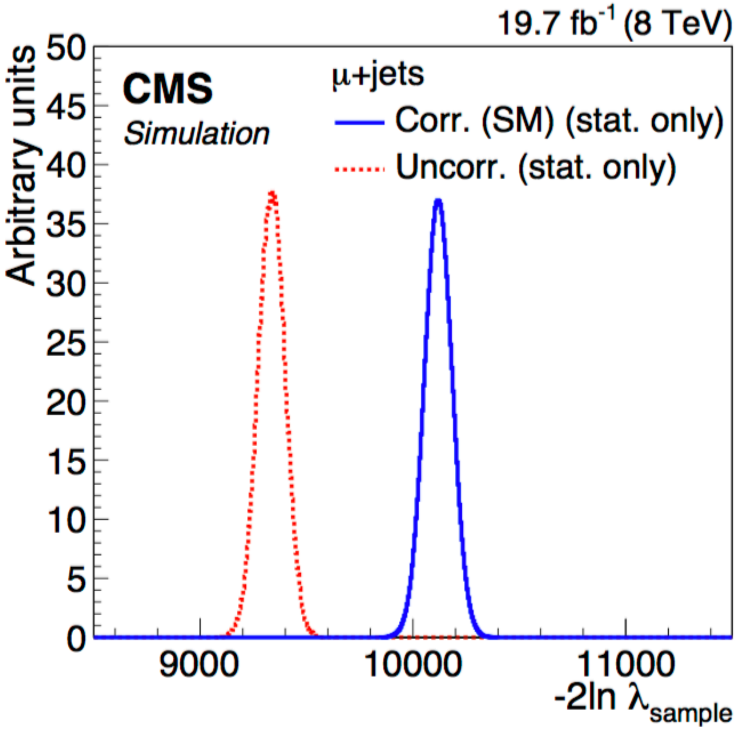
Dominant systematic uncertainties:
JES, QCD scale, top quark mass

Most precise result in l+jets to-date

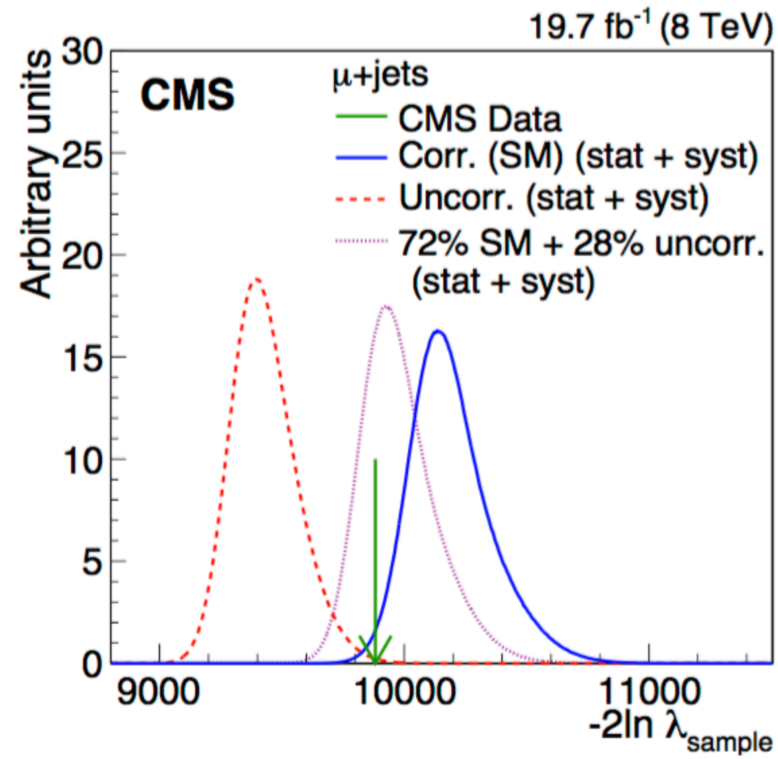
CMS-PAS-TOP-13-015, arXiv:1511.06170

Spin Correlations – Lepton+Jets Channel -- Matrix Element Method

- Hypotheses testing using sample likelihoods: $L(x_1,\ldots,x_n|H) = \Pi_{i=1}^{n} P(x_i|H)$



+ syst.



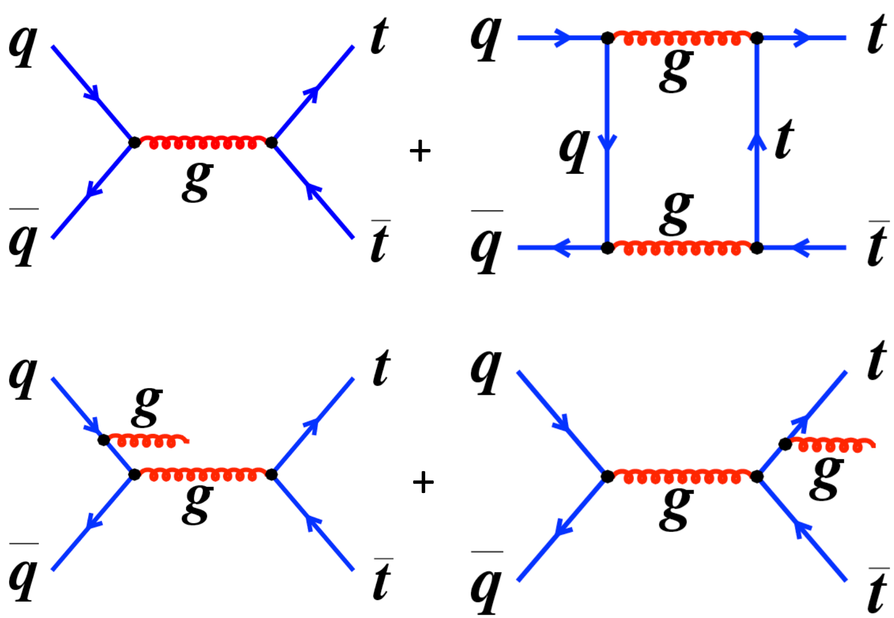
CMS-PAS-TOP-13-015
arXiv:1511.06170

2.2σ agreement with SM hypothesis
2.9σ agreement with the uncorrelated hypothesis

Hypothesis testing and template fit results consistent.

ttbar Asymmetries

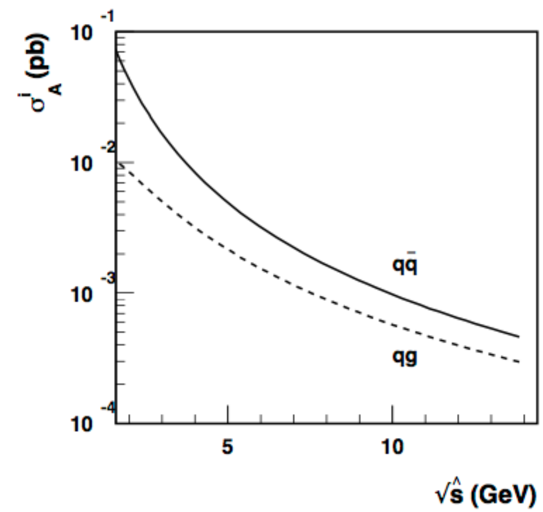
tree-level + box diagrams
(positive asymmetry)



ISR+FSR
(negative asymmetry)

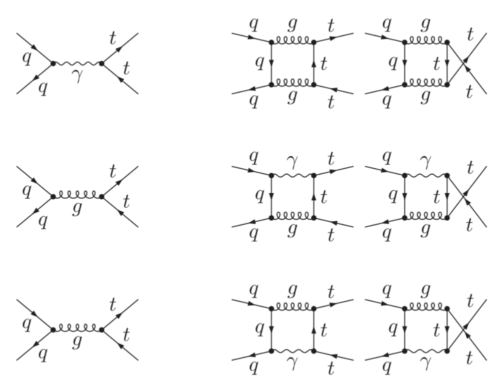
- At LO → No asymmetry
- At NLO: Interferences between qqbar diagrams
- No asymmetry from gluon fusion

only small contributions from
quark-gluon scattering



Kuhn & Rodrigo,
PRD 59 (1999) 054017

significant contributions from
QCD-electroweak interference terms.



Hollik & Pagani
PRD 84 (2011) 093003

Charge Asymmetry at 8 TeV

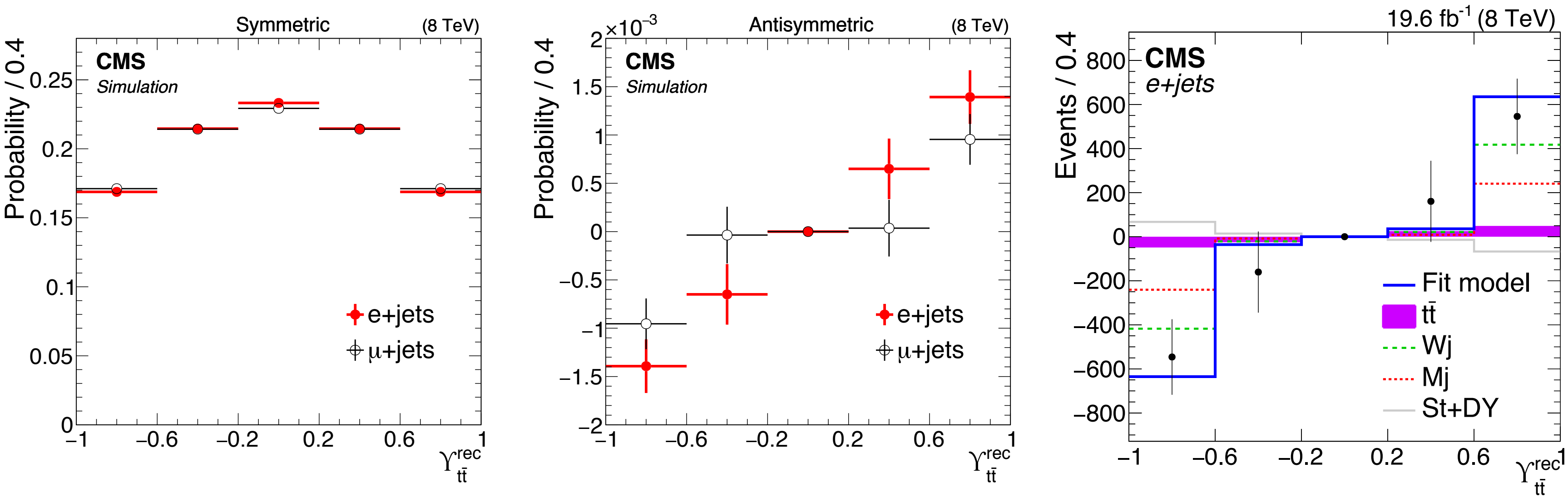
$$\Delta|y|_{t\bar{t}} = |y_t| - |y_{\bar{t}}| \rightarrow \Upsilon_{t\bar{t}} = \tanh \Delta|y|_{t\bar{t}}$$ → Changes sign under the exchange $t \leftrightarrow \bar{t}$

$$\rho(\Upsilon) = \frac{1}{\sigma}\frac{d\sigma}{d\Upsilon}$$ expressed in symmetric (ρ^+) and anti-symmetric (ρ^-) parts:

$$\rho^{\pm}(\Upsilon) = [\rho(\Upsilon) \pm \rho(-\Upsilon)]/2 \rightarrow \hat{A}_C^{\Upsilon} = 2\int_0^{\tilde{\Upsilon}} \rho^-(\Upsilon) d\Upsilon$$

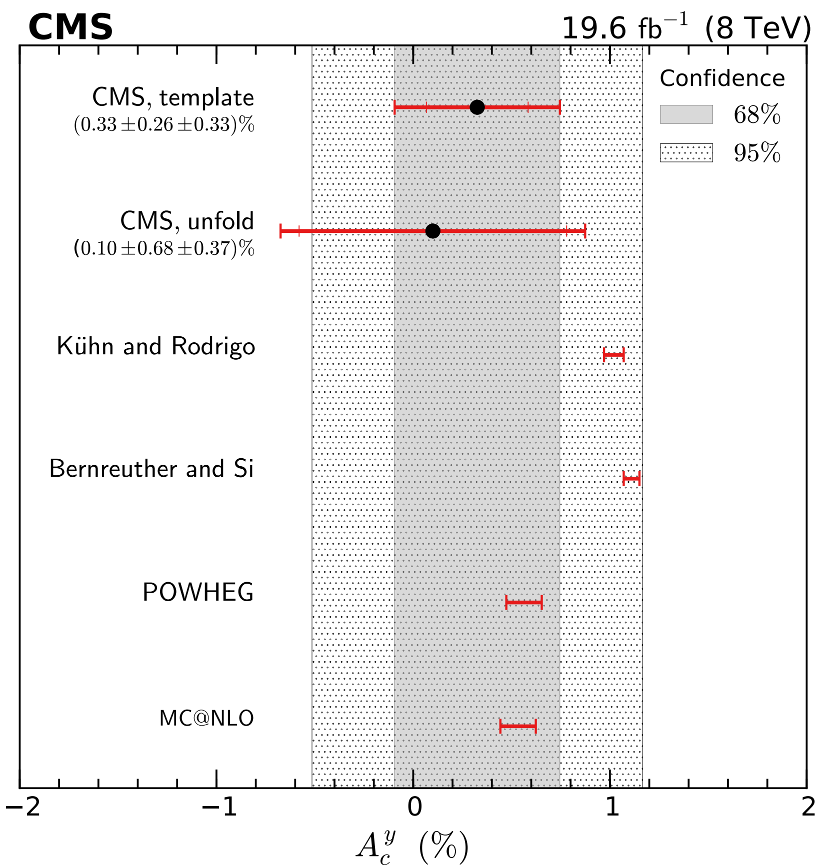
CMS-PAS-TOP-13-013
arXiv:1508.03862

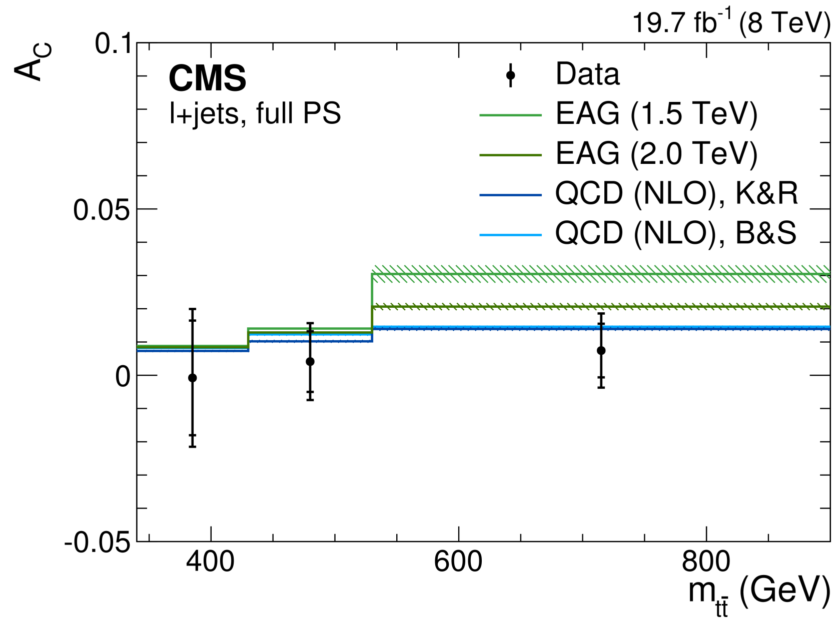
$$\rho(\alpha) = \rho^+ + \alpha\rho^- \rightarrow A_C^{\Upsilon} = \alpha \hat{A}_C^{\Upsilon}$$ Template fit to extract the only free parameter α



$$A_C^{\Upsilon} = [0.33 \pm 0.26(stat) \pm 0.33(syst)]\%$$

Charge Asymmetry at 8 TeV





- Most precise A_C.
- Result consistent with NLO QCD but does not rule out the alternative models considered (i.e. 200 GeV and 2 TeV axigluons, Z') .

CMS-PAS-TOP-13-013, arXiv:1508.03862

- M >~450 GeV, A_c ~2σ below predictions from EFT with new physics scale of 1.5 TeV.

CMS-PAS-TOP-12-033
arXiv:1507.03119

Top Mass – Run I Legacy - The Ideogram Method

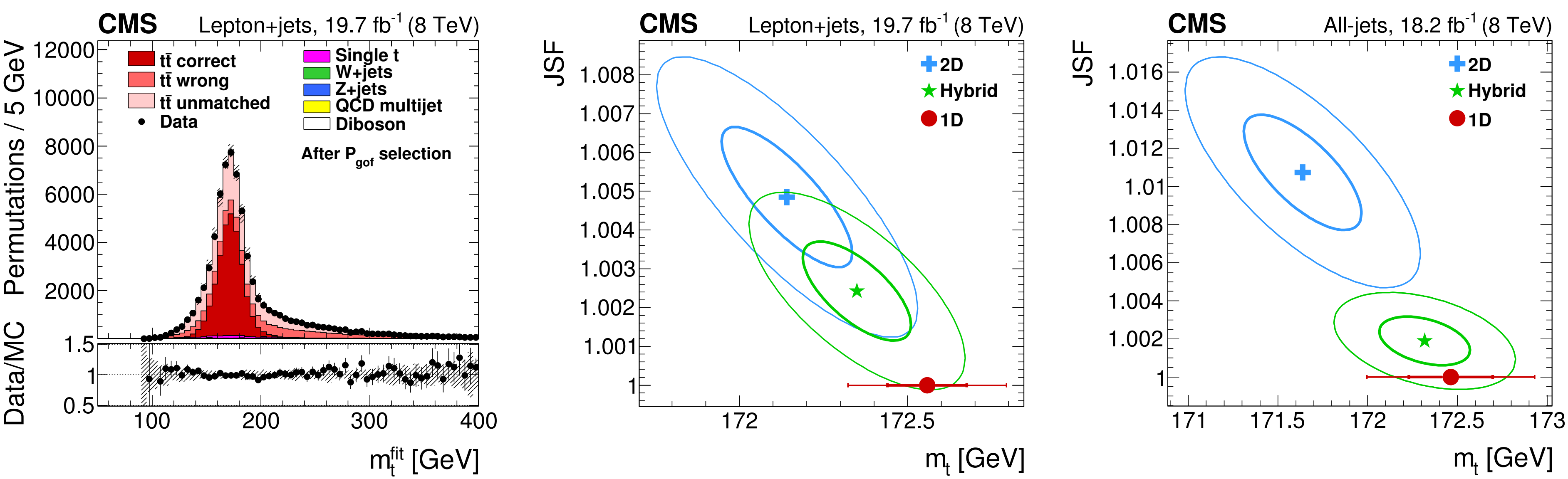
- Template method with multiple permutations (correct, wrong, unmatched) per event.
- All different permutations taken into account with weights + include b-quark tagging.
- Kinematic fit → improve mass reconstruction.

2D fit: Determine m_t simultaneously with jet energy scale factor (JSF) in a joint likelihood fit.

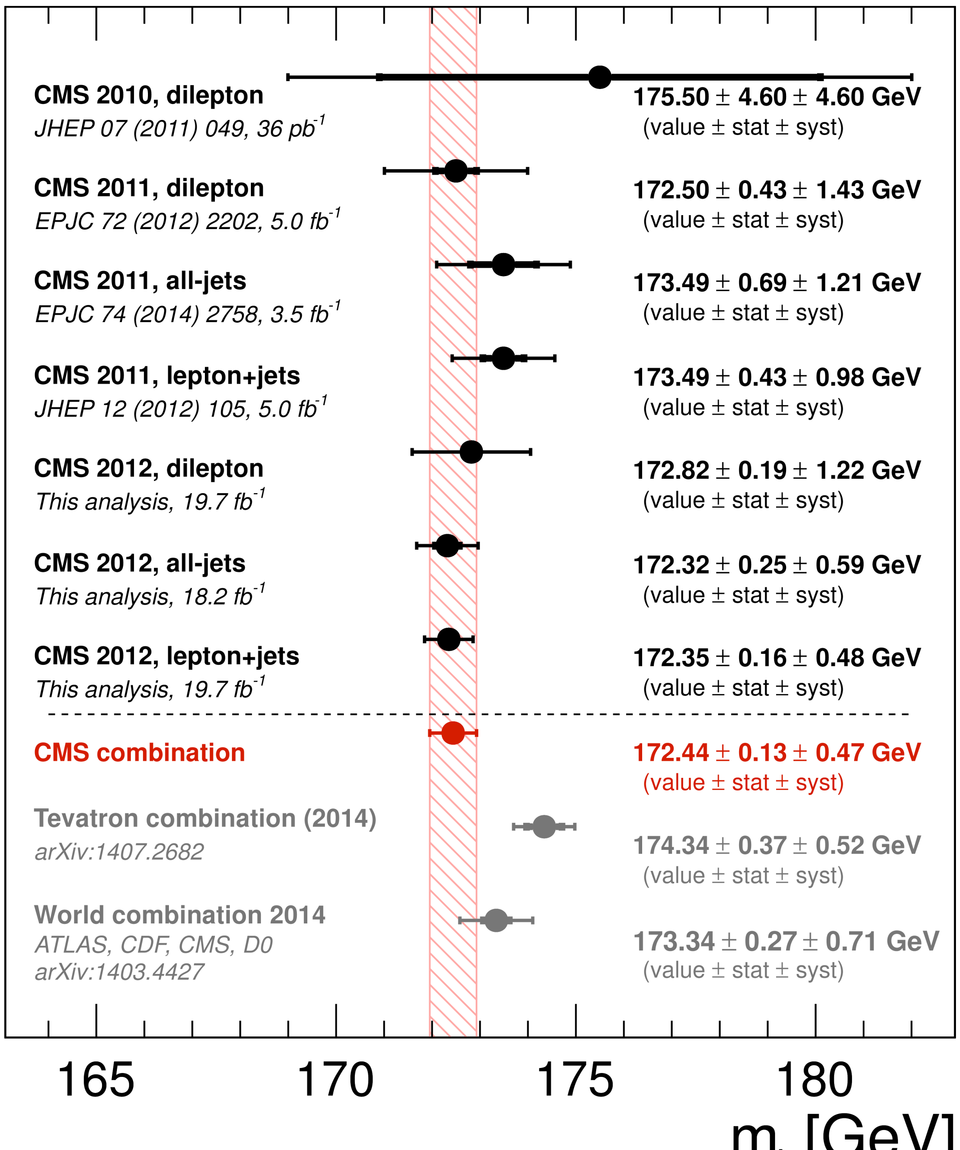
Hybrid fit: use a prior for JES → Gaussian constraint with μ=1 and variance = total JEC uncertainty.

1D fit: JSF = 1.

CMS-PAS-TOP-14-022
arXiv:1509.04044



Top Quark Mass Measurements



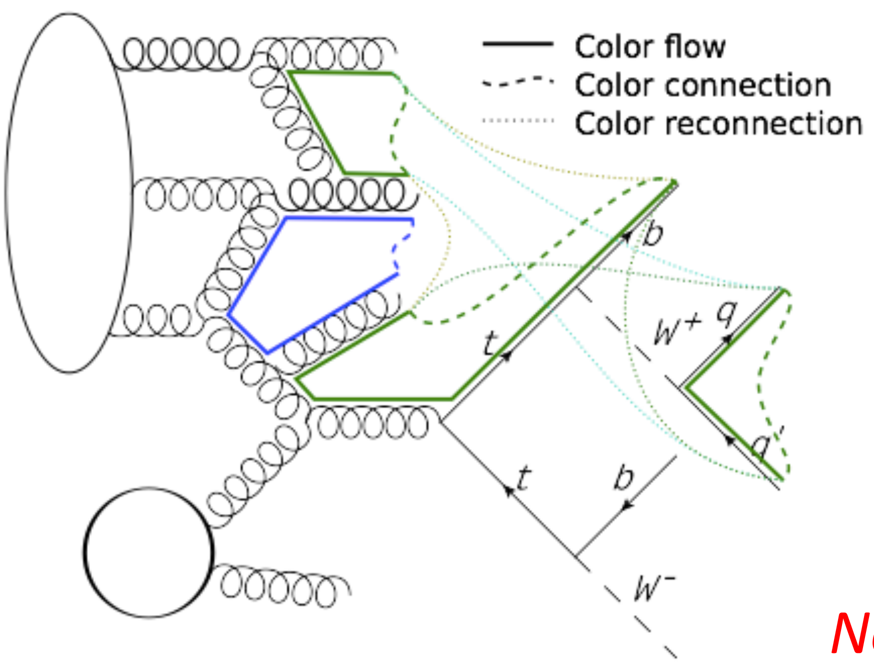
- Run I combination: 7+8 TeV in lepton+jets, dilepton, and all-hadronic channels
- Precision 0.3%
- Dominant systematic uncertainties: flavor-dependent JEC and b jet modeling.

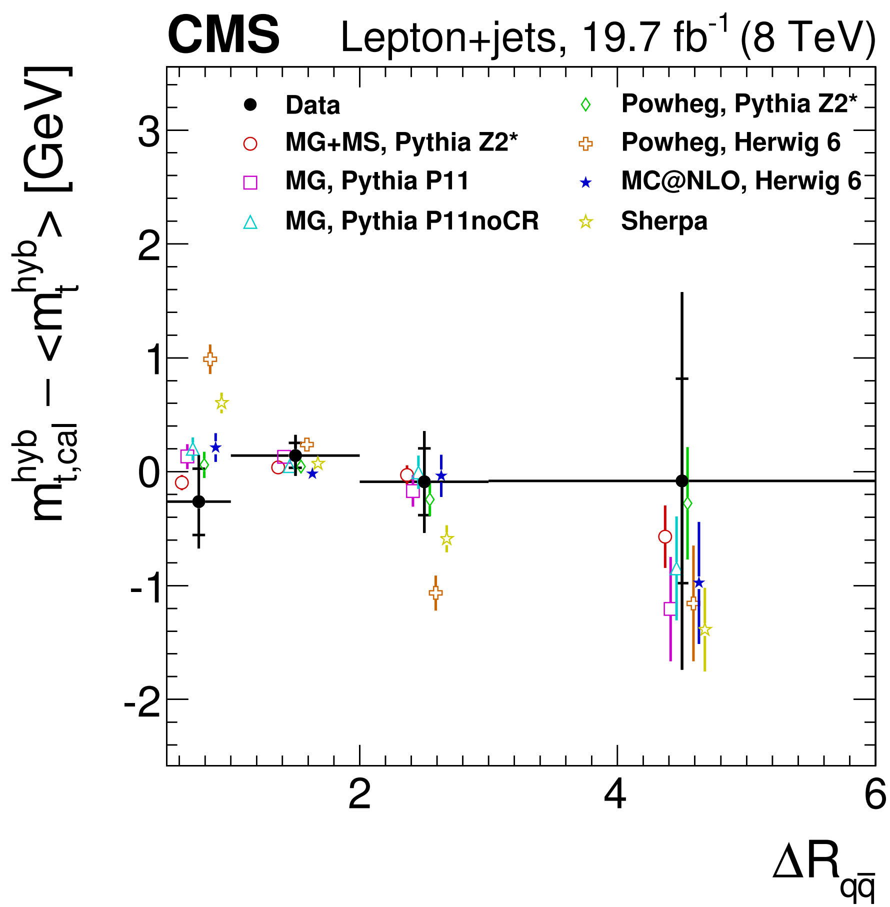
CMS-PAS-TOP-14-022
arXiv:1509.04044

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-14-022
arXiv:1509.04044

- Find out (non-)perturbative effects that have different kinematic dependences.
- Study variables sensitive to
  - color connection,
  - ISR/FSR,
  - b-quark kinematics.



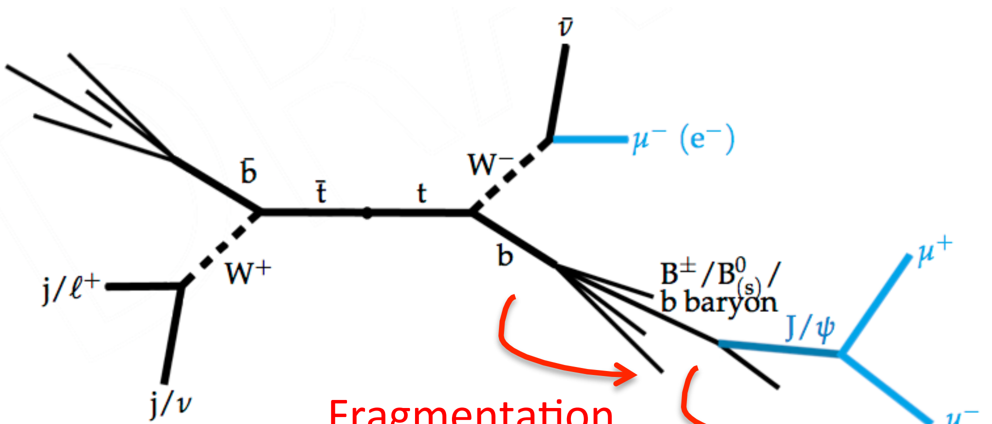


No indication of a kinematic bias.

Top Quark Mass in ttbar Events with a J/ψ

- Mass from direct reconstruction → dominated by uncertainties in (b) jet energy scale and soft QCD modeling (e.g. b quark hadronization).
- Alternative: Use the correlation between the 3-prong leptonic mass and the top quark mass [CMS Coll., CERN-LHCC 92-003, 1992].

NEW



Fragmentation function

Precisely known from B factories

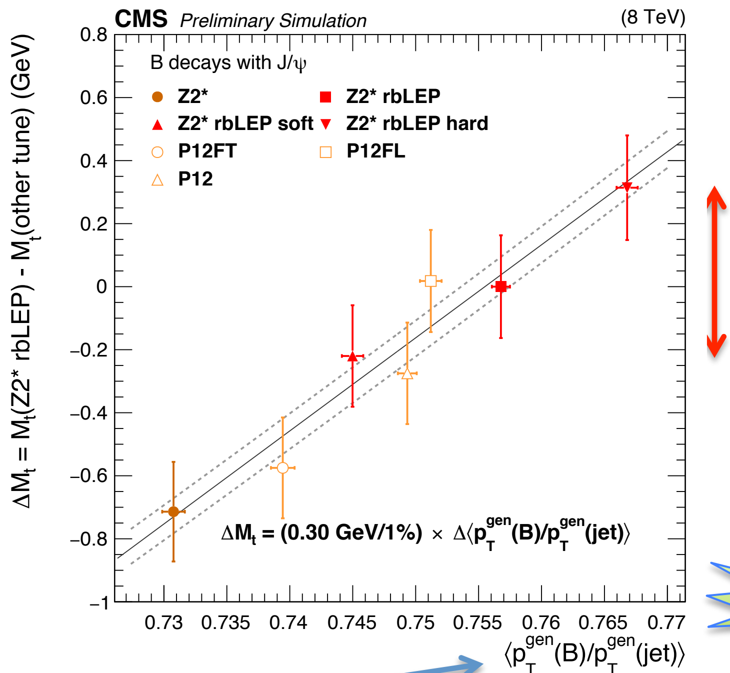
- Signal: ttbar and single top
- J/Ψ candidate mass: 3.0-3.2 GeV from 2 non-isolated muons (from the same jet) with p_T>4 GeV
- Wrong lepton-pairing: 51%.
- Wrong pairings still have some correlation to top mass
  - Use good & wrong pairings
- Fit to $M_{J/\Psi + l}$ with an analytic function

- Minimal experimental uncertainties.
- Large reliability on fragmentation modeling.
- Small number of events due to the small BR (=3.2×10^{-4}).

CMS-PAS-TOP-15-014

Top Quark Mass in ttbar Events with a J/ψ

CMS-PAS-TOP-15-014



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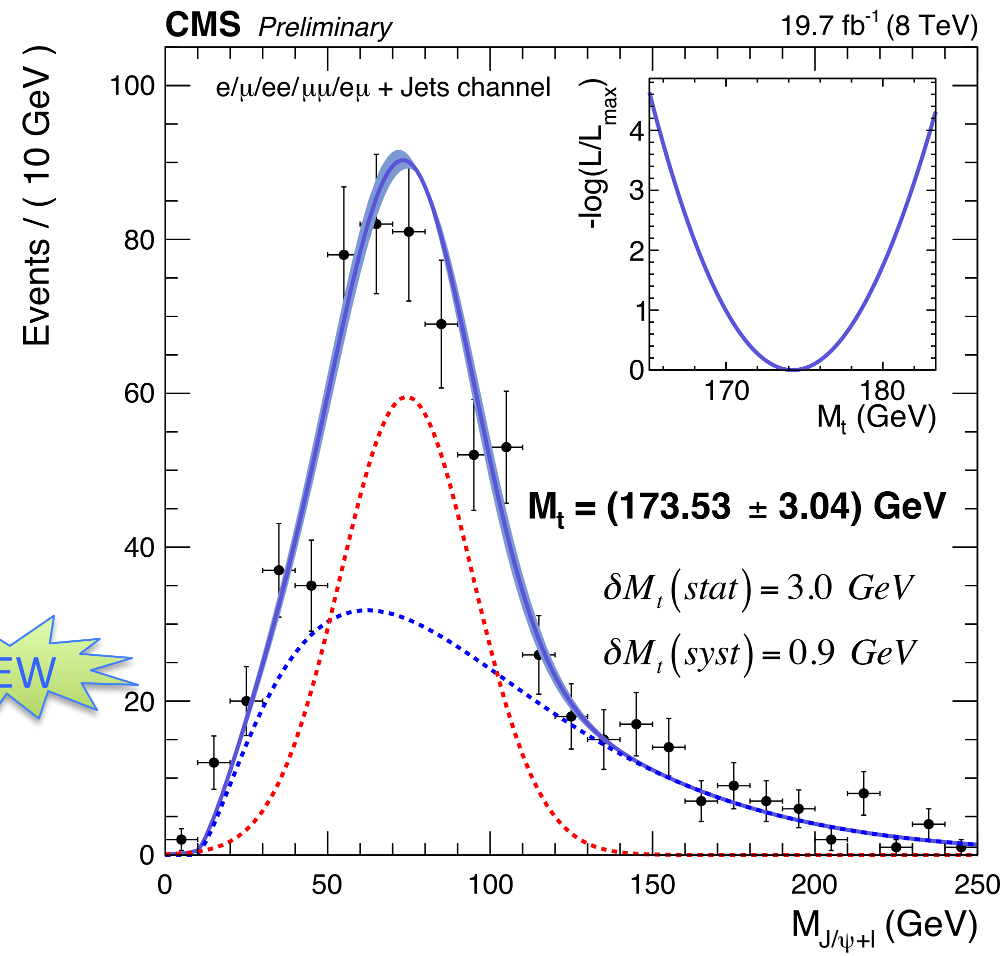


Average fragmentation

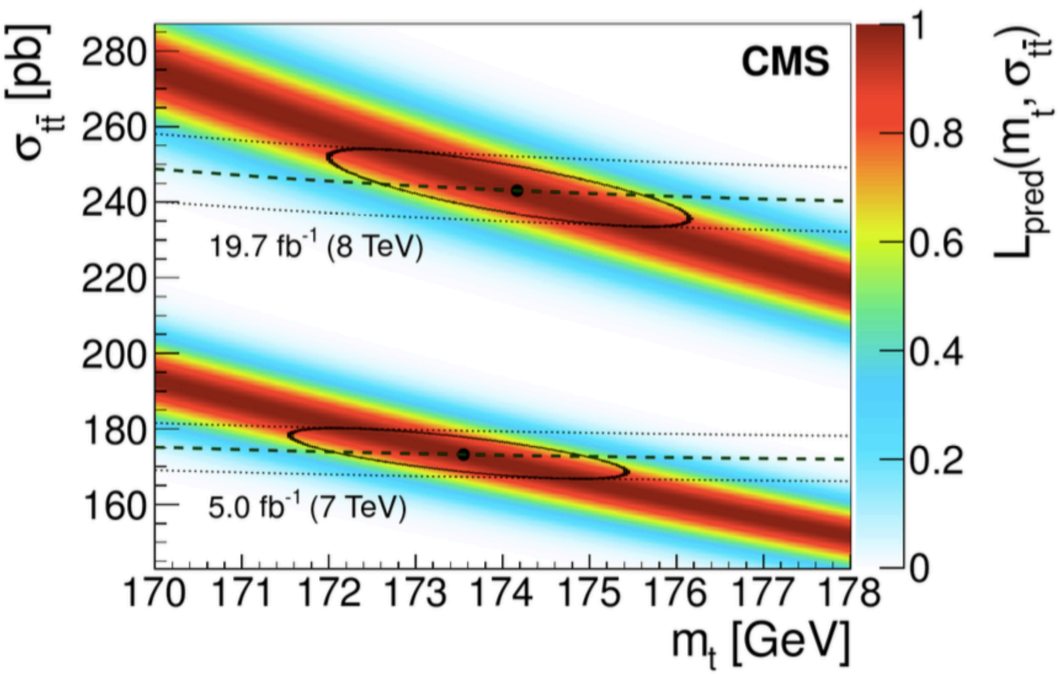
$$M_t(Z2^*rbLEP) - M_t(Z2^*) = -0.71$$

- First experimental result using this method.
- Result statistically limited: With next runs of LHC → as good as direct mass measurements.
- Most dominant systematic uncertainties: Top p_T, b-fragmentation, and MadGraph5 Born-level vs Powheg. →Might be improved with the upcoming versions of generators.

Top Quark Pole Mass from ttbar Production Cross Section

NEW

- σ_{tt} vs m_t^{pole} from NNLO+NNLL prediction with different PDF sets with a fixed α_s.
- Full phase space cross sections at parton level with full Run-I data at 7 and 8 TeV in the most precise channel (eμ). → See Abideh Jafari's presentation in the morning session.
- The cross section fit repeated for three mass assumptions.
  - Uncertainties from detector effects evaluated separately for each mass point.
- Minimize theory x experimental likelihoods.

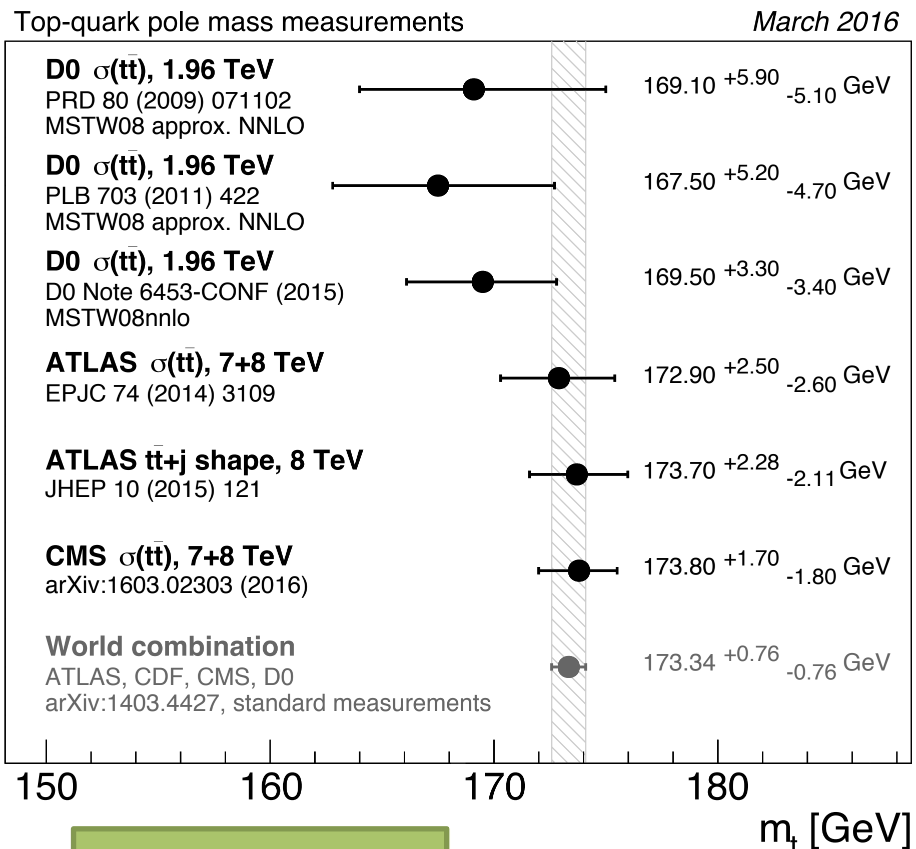


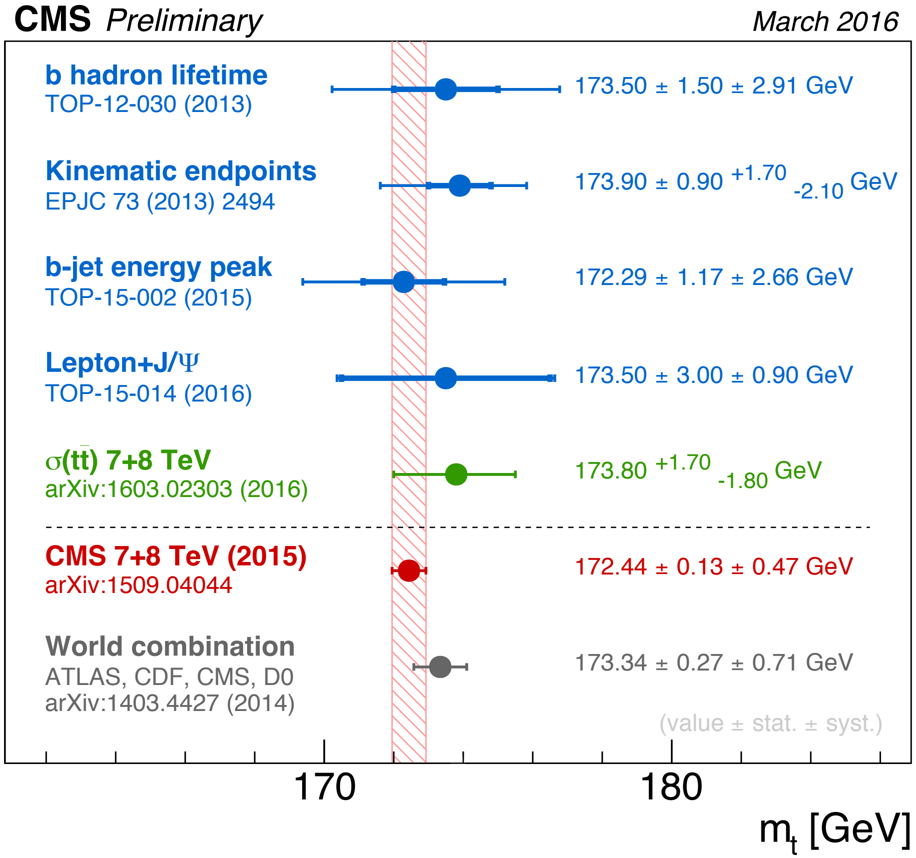
	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

Dominant uncertainties: Luminosity, beam energy

arXiv:1603.02303

Summaries of Top Quark Mass Measurements

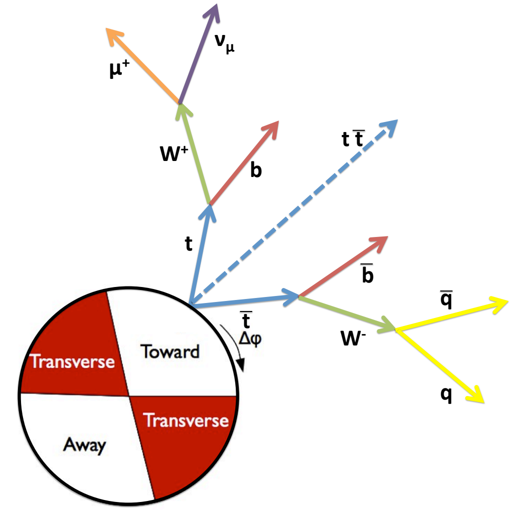




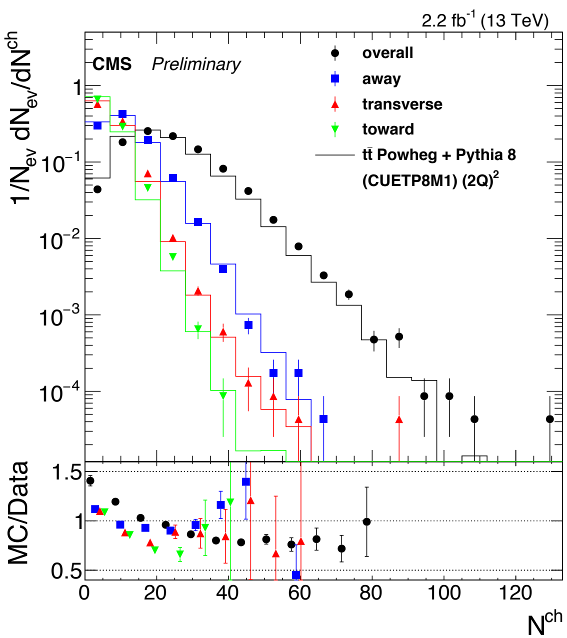
Benjamin Stieger

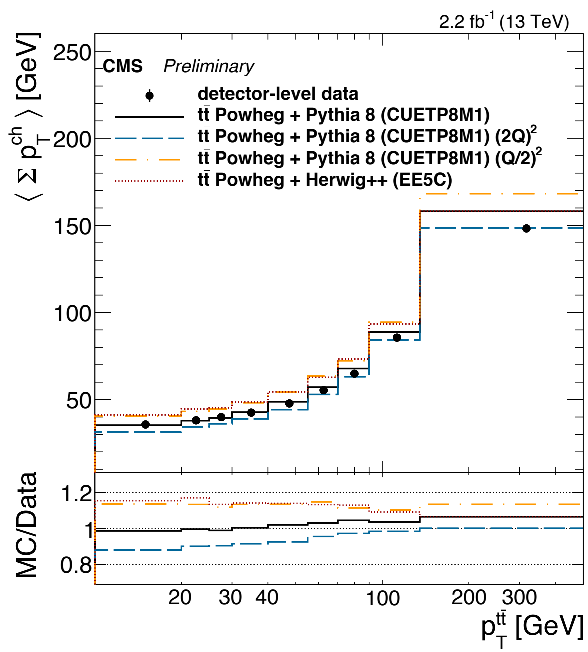
Underlying Event in tt Events at 13 TeV

- Investigate and improve ttbar event modeling.
- Charged particle activity through N^{ch}, Σp_T^{ch}, $\langle p_T^{ch} \rangle$ in different regions defined relative to the ttbar system direction, vs p_T(ttbar) and Njets.



CMS-PAS-TOP-15-017





It doesn't appear necessary to have separate heavy-quark UE tunes.

Summary

- Measurements of top quark properties at CMS are providing thorough tests of the standard model.
- Precise top quark properties measurements from run I
  - ttbar spin correlation
  - asymmetry and polarization measurements
  - Top quark mass (precision 0.3%)
  - Alternative top quark mass measurements
    - First measurement of ttbar → J/Ψ
    - …
  - Underlying event modeling
  - New physics searches: ttg coupling, EAG, FCNC, …
  - …
- LHC Run II:
  - Systematic uncertainty limited differential measurements
  - Top quark – Z, γ, H couplings
  - Ultimate precision in top quark mass
  - New physics through top quark properties?