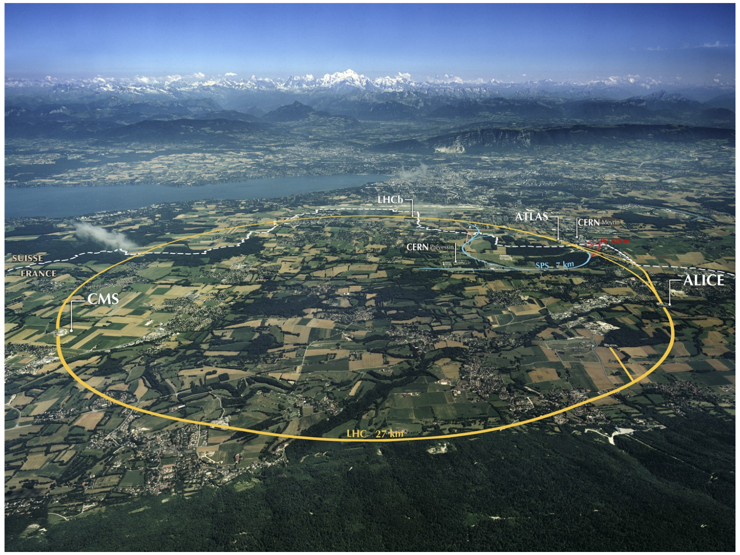
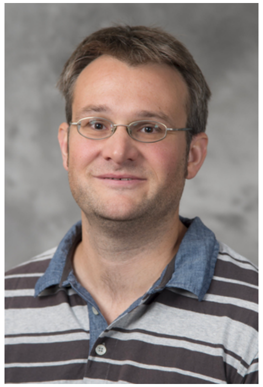
# Top quark properties: Mass, spin correlation, polarization




(Introduction)
→ Mass
→ Spin correlations & Polarization
→ Conclusions & Outlook

Francisco Yumiceva (Andreas Jung) for the ATLAS & CMS collaboration

Large Hadron Collider Physics – 7th edition May 23rd, 2019



May 15, 2019
Top Quark Physics at the
Precision Frontier
Fermilab

Slides prepared by Andy Jung (Prof. at Purdue)
Presented by Francisco Yumiceva (Prof. at Florida Tech)

# The Special Properties of the Top Quark

**Taken from the PDG:**

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

**t**

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\,e$ Top $= +1$

The only particle with 3 different masses!

- Mass (direct measurements) $m = 173.1 \pm 0.6$ GeV [a,b] (S = 1.6)
- Mass from cross-section measurements) $m = 160^{+5}_{-4}$ GeV [a]
- Mass (Pole from cross-section measurements) $m = 173.5 \pm 1.1$ GeV

$m_t - m_{\overline{t}} = -0.2 \pm 0.5$ GeV (S = 1.1)

Full width $\Gamma = 1.41^{+0.19}_{-0.15}$ GeV (S = 1.4)

$\Gamma(Wb)/\Gamma(Wq(q = b, s, d)) = 0.957 \pm 0.034$ (S = 1.5)

***t*-quark EW Couplings**

$F_0 = 0.685 \pm 0.020$

$F_- = 0.320 \pm 0.013$

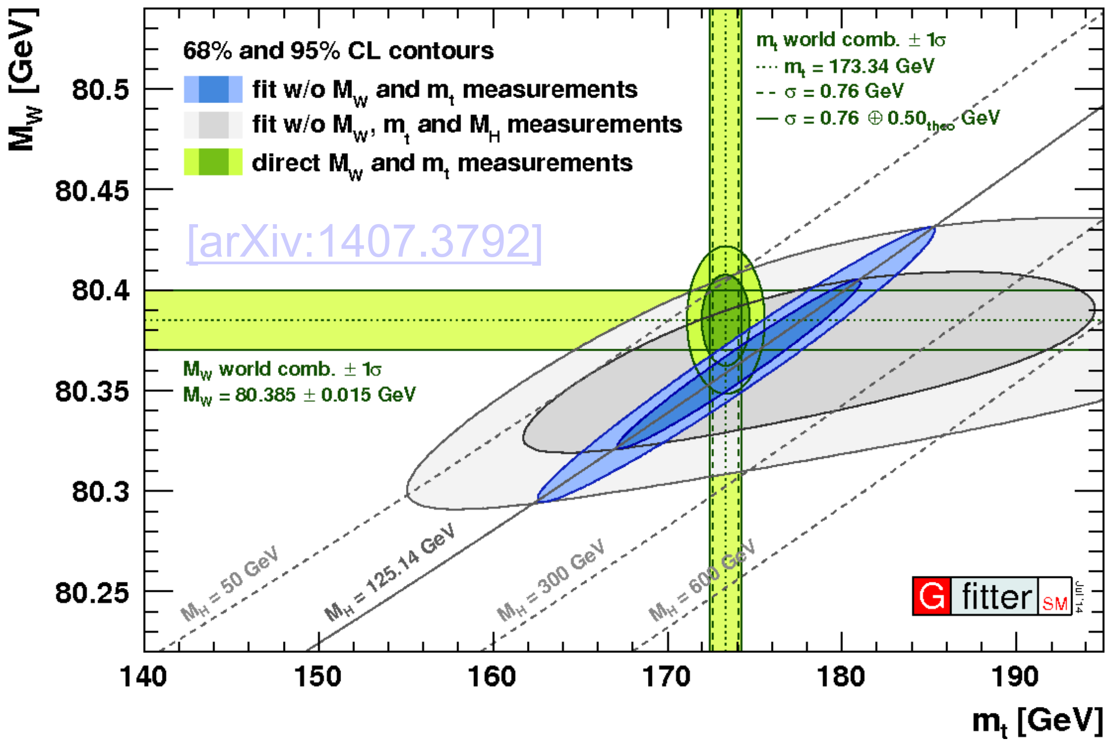
$F_+ = 0.002 \pm 0.011$

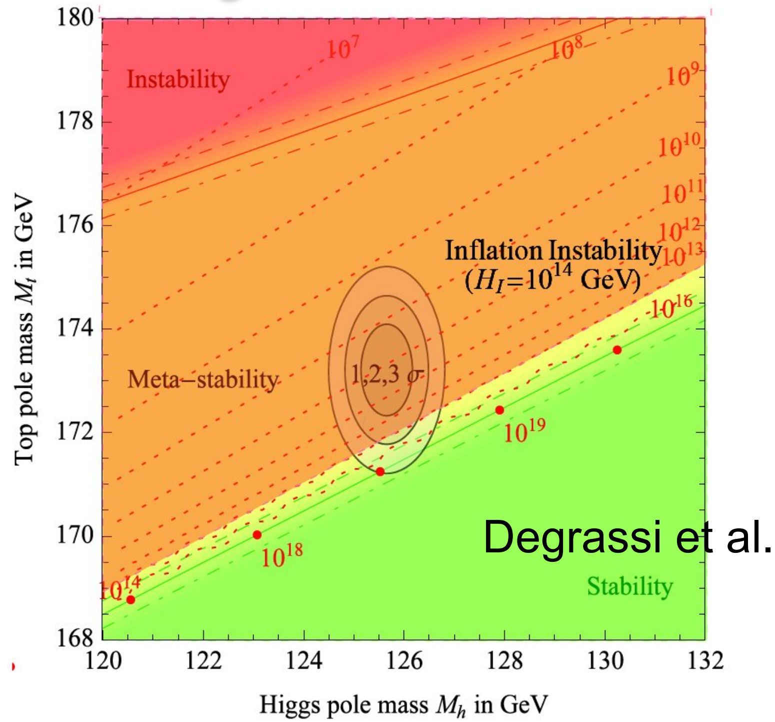
$F_{V+A} < 0.29$, CL = 95%

El Santo (Lucha Libre)

**A unique character …**

# Top Quark Mass, why?



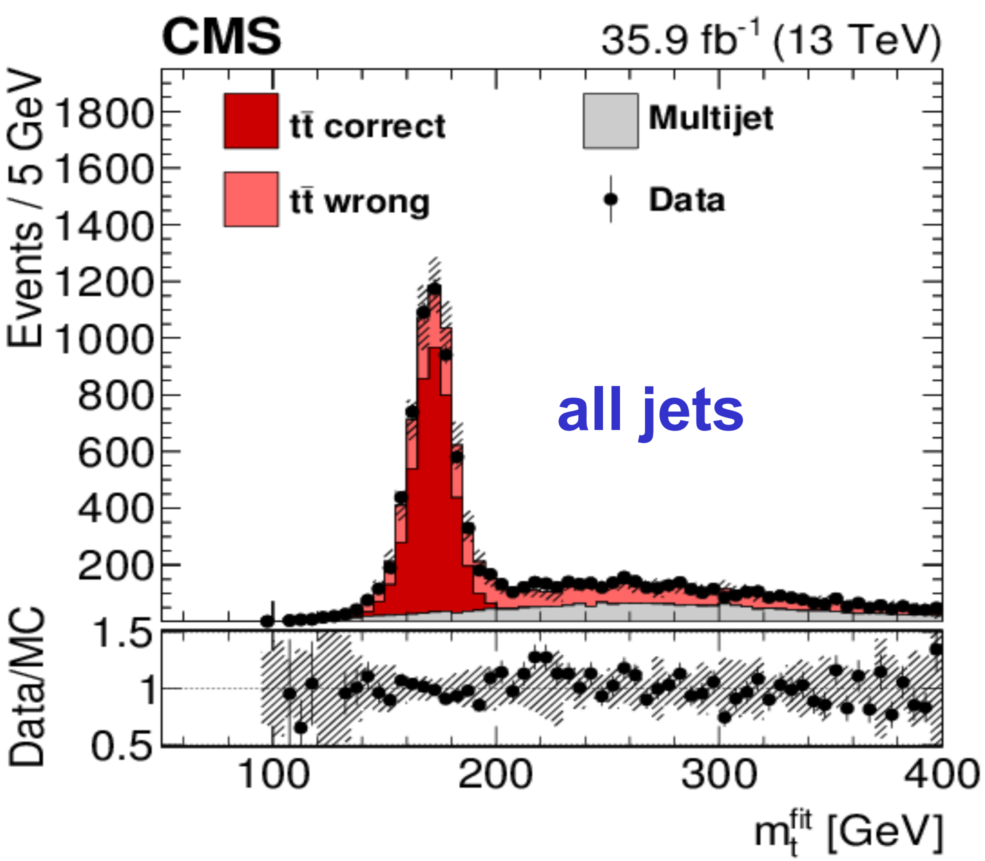



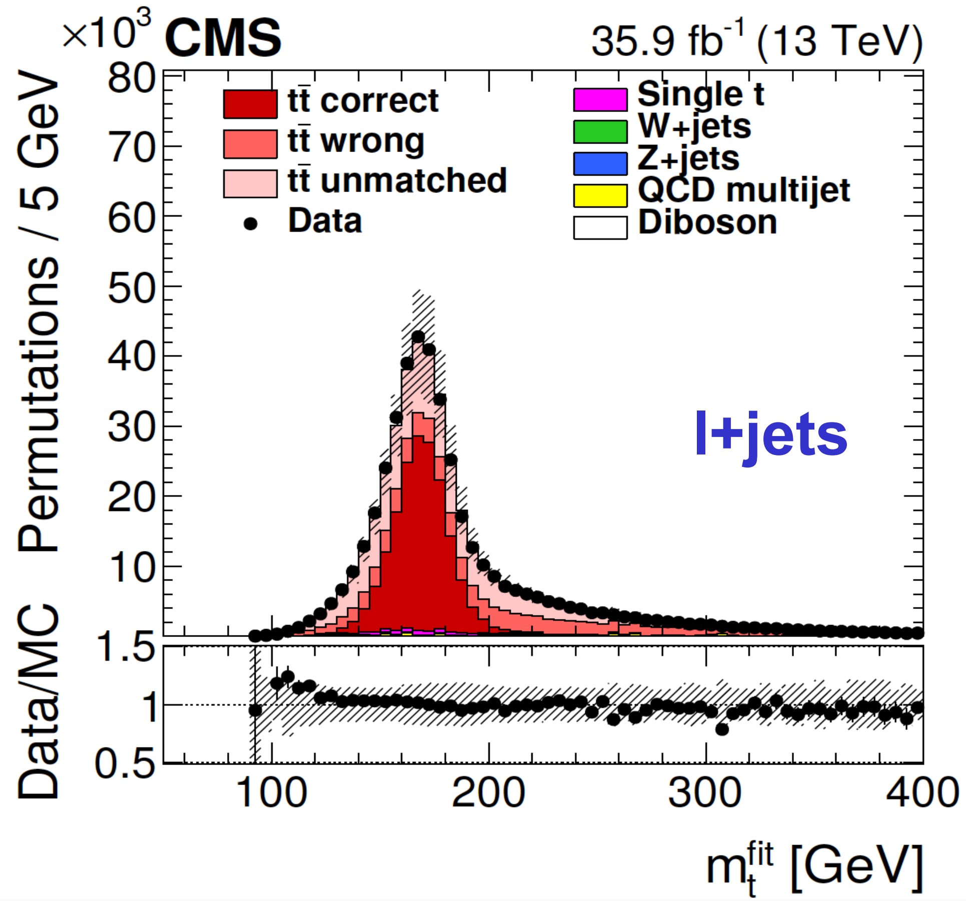

- Self-consistency of the SM (global fit) and important for the stability of the EW vacuum.
  - Direct measurements:
    - Based on reconstruction of decay products.
    - Rely on simulation to extract the mass “MC mass”.
    - Interpreted as the “pole mass” (uncertainty ~0.5-1 GeV)
  - Indirect measurements:
    - From cross section or differential distributions.
    - Mass can be extracted in the pole mass scheme or MS scheme (running mass)

# Direct method: (all jets) + (l+jets)

Eur. Phys. J. C (2019) 79:313

- Top quarks reconstructed using a kinematic fit with a W mass constraint.
- 2D fit of m(top) vs. Jet Energy Scale Factor (JSF)
- Extracted via single likelihood function simultaneously fit for l+jets and all-jets

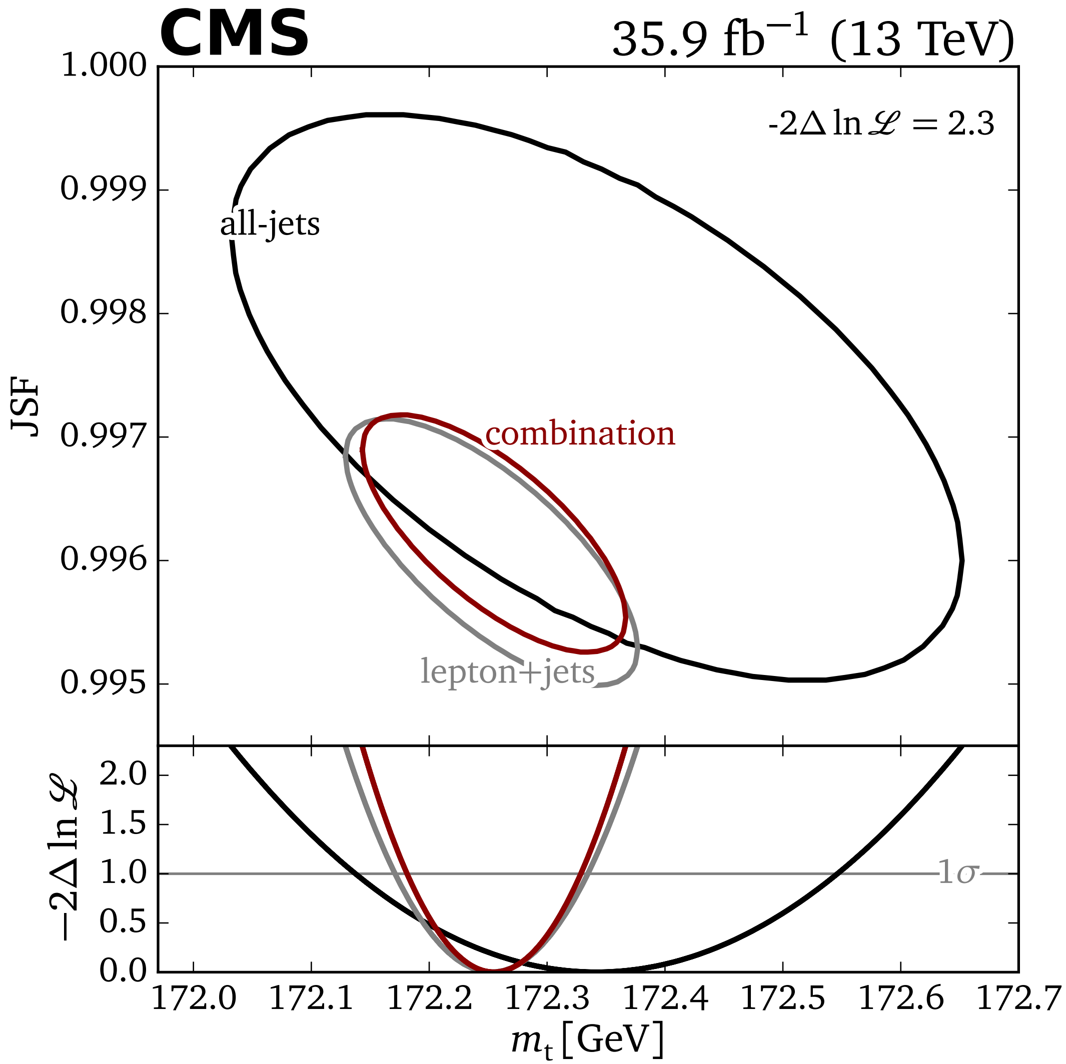


# Direct method: (all jets) + (l+jets)

Eur. Phys. J. C (2019) 79:313

- Dominant systematics:
  - Jet energy flavor: 0.34 GeV
    - Dominated by b jets
  - Color Reconnection: 0.36 GeV
  - ME/PS matching: 0.24 GeV




$M_{top}$ = 172.26 ± 0.07 (stat+JSF) ± 0.61 (syst.) GeV

$\delta m_t/m_t$ = 0.36%

# Direct method: tt+1 jet

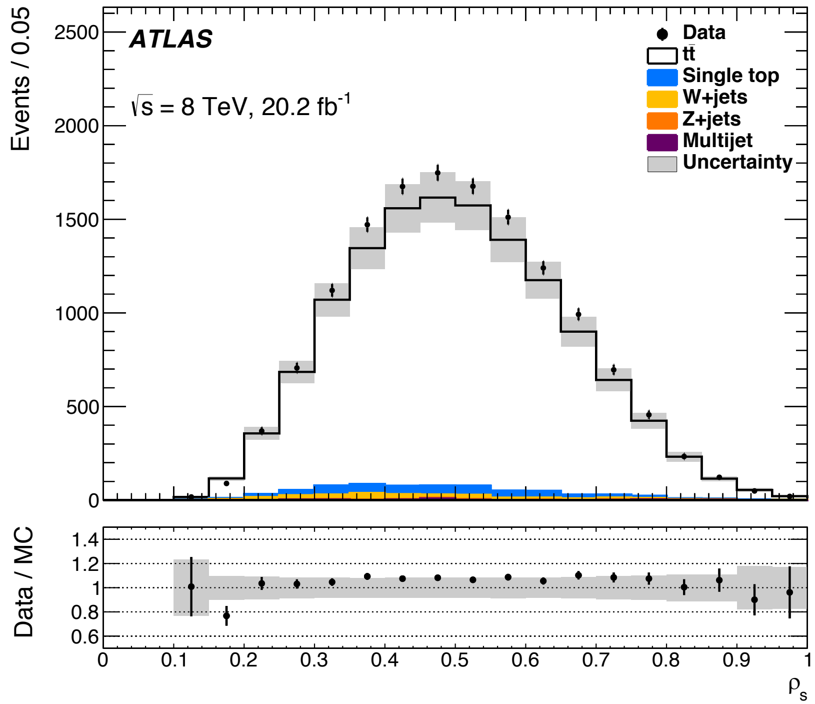
arXiv:1905.02302

**Take advantage of observable sensitive to the top mass in tt + one jet**

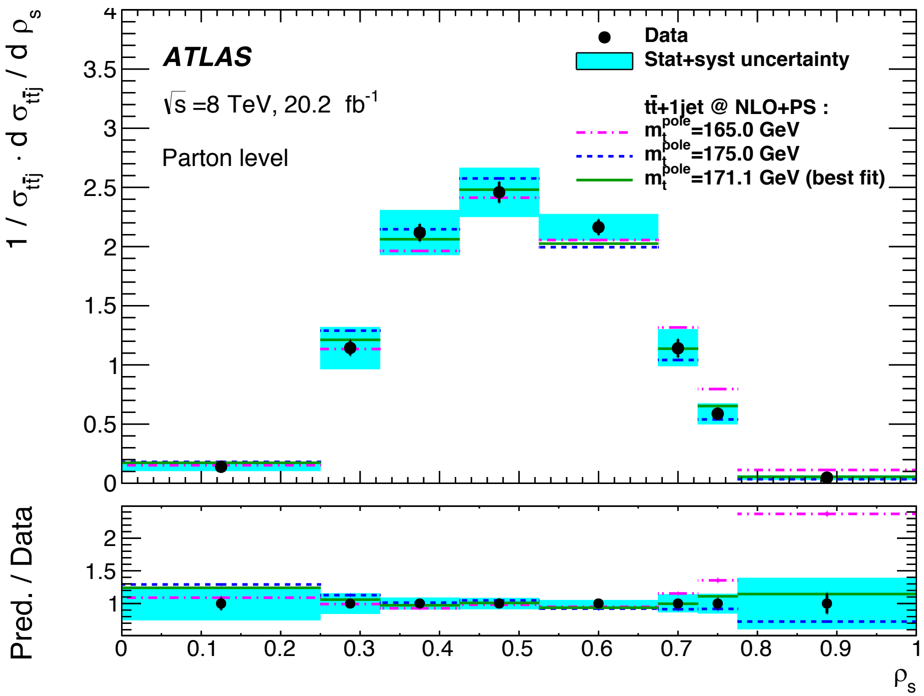
**Observable considered is:** $\rho_s = 2m_0/m_{t\bar{t}+1\text{-jet}}$

- **$m_0$ = 170 GeV constant**
- **$m_{t\bar{t}+1\,\text{jet}}$ invariant mass**
- **presence of one extra jet increases sensitivity to top-quark mass**

(from M. Cristinziani)




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




- Leading uncertainties: shower & hadronization, color reconnection, JES, scale variations.

$$m_t^{\text{pole}} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})\,^{+0.7}_{-0.3}\,(\text{theo})\ \text{GeV}$$

$$m_t(m_t) = 162.9 \pm 0.5\,(\text{stat}) \pm 1.0\,(\text{syst})\,^{+2.1}_{-1.2}\,(\text{theo})\ \text{GeV}$$

$\delta m_t/m_t = 0.65\%$

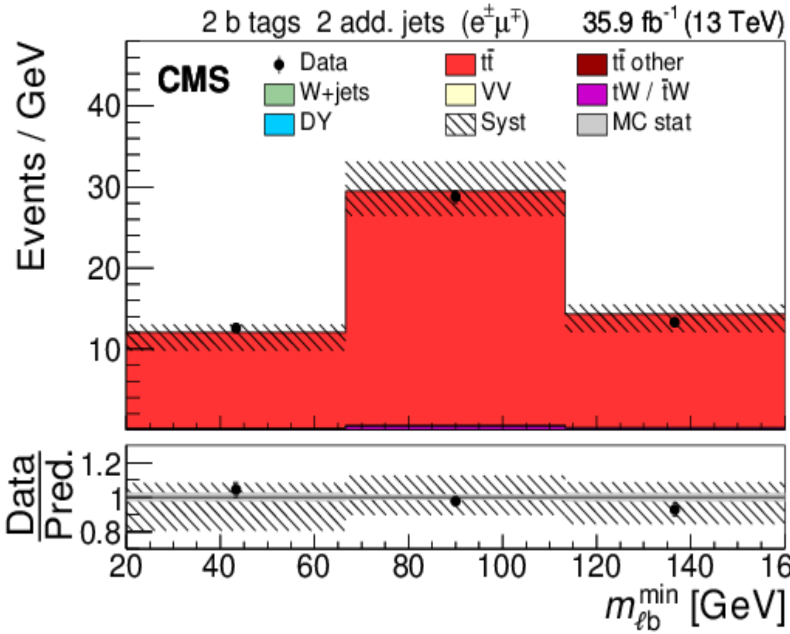
# Indirect: Inclusive cross-section

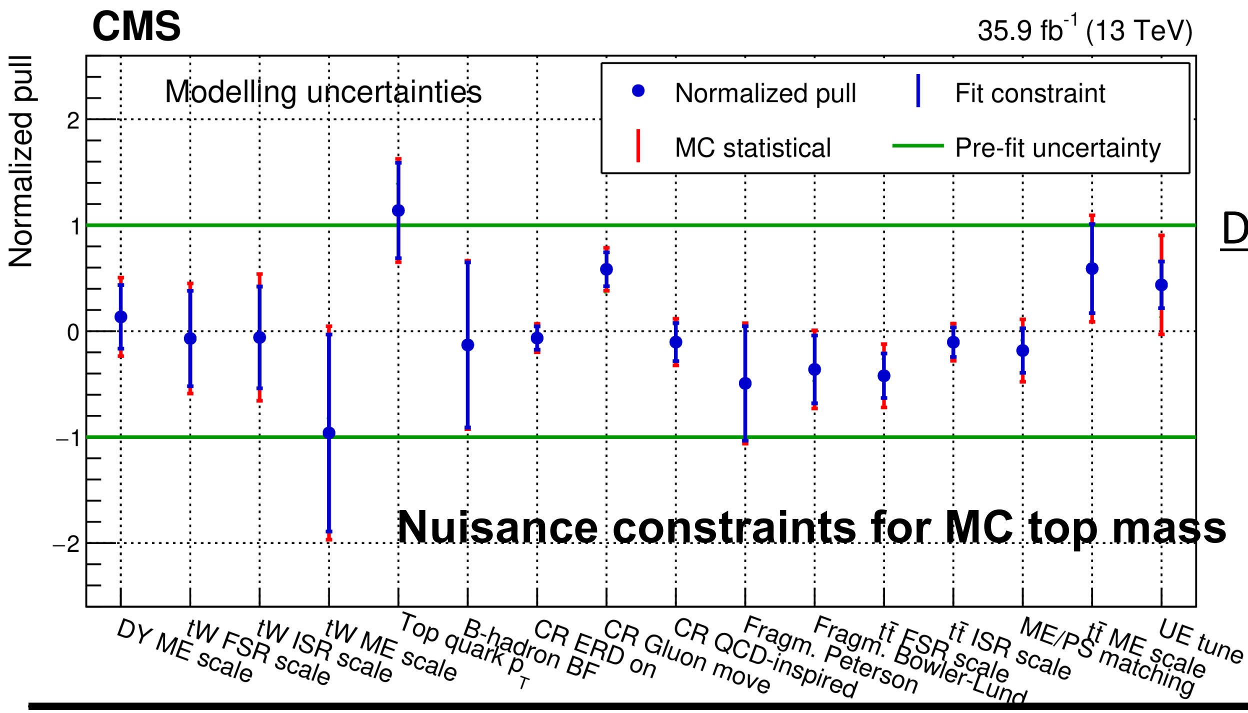
Eur. Phys. J. C (2019) 79:368

- Simultaneous fit of cross-section and MC top mass
- 12 categories based on b and light jet multiplicities
- Distributions used: $m_{lb}^{min}$, $p_T$ softest jet, total event yield

$$\sigma_{t\bar{t}} = 815 \pm 2(\text{stat}) \pm 29(\text{syst}) \pm 20(\text{lumi})\ \text{pb}$$
$$m_t^{MC} = 172.33 \pm 0.14(\text{stat})^{+0.66}_{-0.72}(\text{syst})\ \text{GeV}$$

Total $m_t^{MC}$ uncertainty: 0.73 GeV (Δ = 0.42%)




**Nuisance constraints for MC top mass**

Dominant systematics:

| | |
|---|---|
| → Jet energy | (0.57 GeV) |
| → MC statistics | (0.36 GeV) |
| → Background | (0.28 GeV) |

# Indirect: Inclusive cross-section

Eur. Phys. J. C (2019) 79:368

**Most precise MS $m_t(m_t)$ result to date**

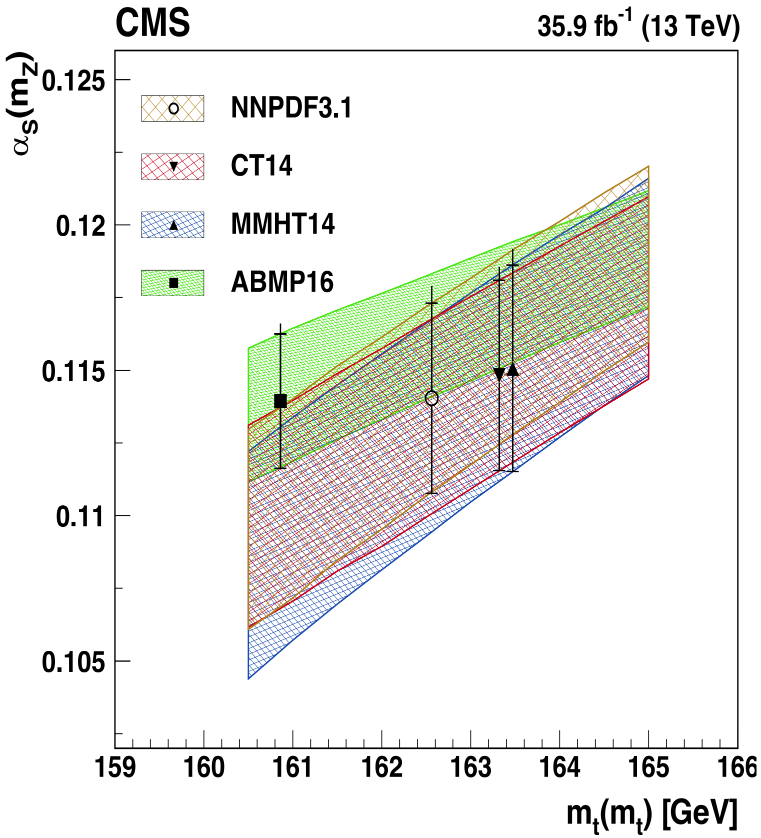
Total $m_t(m_t)$ uncertainty: 1.9 GeV (Δ = 1.2%)

| PDF set | Nominal $m_t(m_t)$ [GeV] | Extracted $m_t(m_t)$ [GeV] |
|---|---|---|
| ABMP16 | 160.86 | $161.6 \pm 1.6\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.1}_{-1.0}(\text{scale})$ |
| NNPDF3.1 | 162.56 | $164.5 \pm 1.6\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.1}_{-1.0}(\text{scale})$ |
| CT14 | 163.30 | $165.0 \pm 1.8\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.1}_{-1.0}(\text{scale})$ |
| MMHT14 | 163.47 | $164.9 \pm 1.8\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.1}_{-1.1}(\text{scale})$ |

Total $m_t^{\text{pole}}$ uncertainty: 2.2 GeV (Δ = 1.3%)

| PDF set | Nominal $m_t^{\text{pole}}$ [GeV] | Extracted $m_t^{\text{pole}}$ [GeV] |
|---|---|---|
| ABMP16 | 170.37 | $169.9 \pm 1.8\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.8}_{-1.2}(\text{scale})$ |
| NNPDF3.1 | 172.5 | $173.2 \pm 1.9\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.3}(\text{scale})$ |
| CT14 | 173.3 | $173.7 \pm 2.0\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.4}(\text{scale})$ |
| MMHT14 | 174.2 | $173.6 \pm 1.9\ (\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.4}(\text{scale})$ |

**Linear dependence observed between $\alpha_s$ and $m_t(m_t)$**



# Indirect method: diff. cross-section

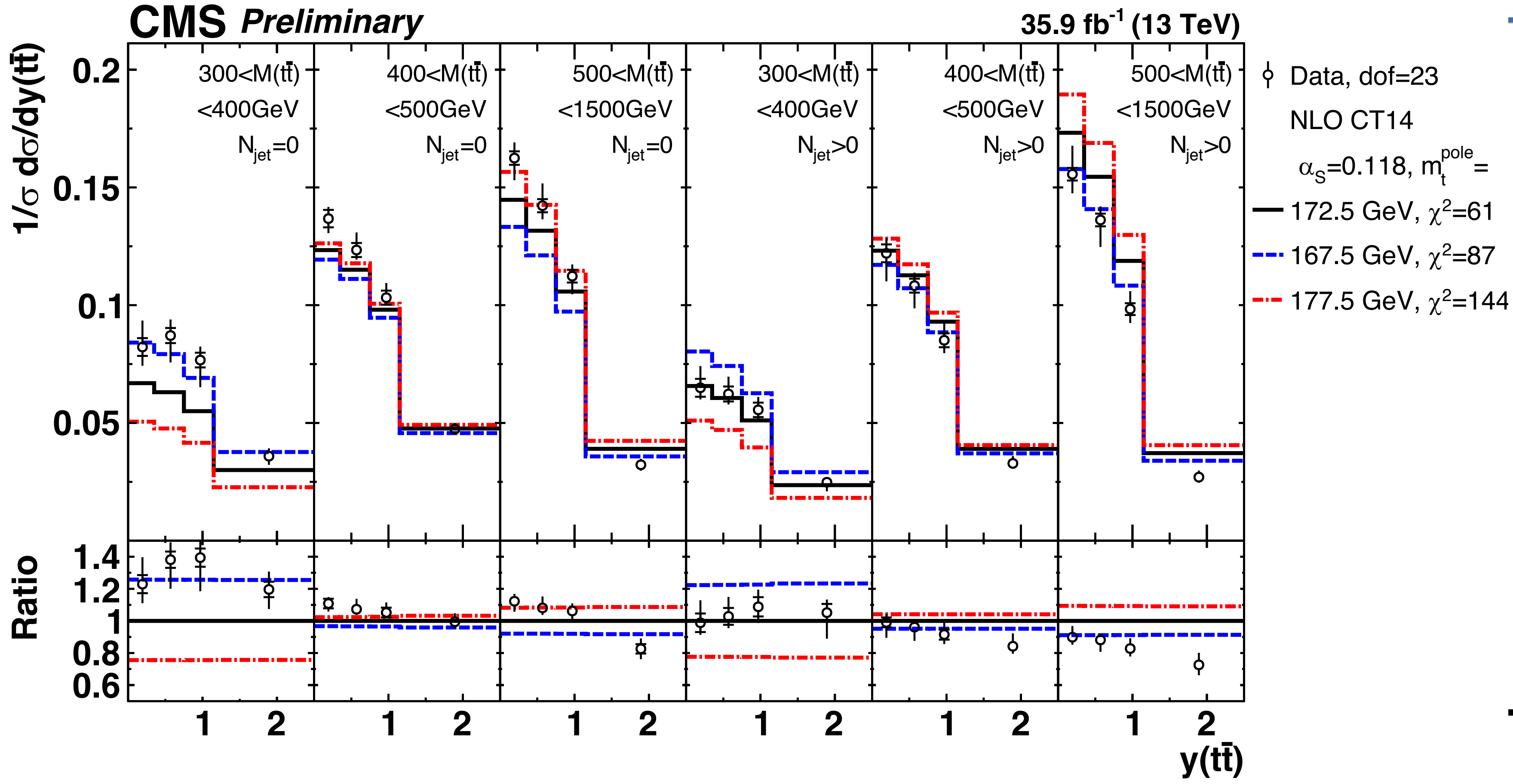
arXiv:1904.05237, sub. To EPJC

- Use y(tt), M(tt), N(add. jet) in dilepton events.
- Unfolded to parton level compared with NLO fixed order and 7 PDF sets in a simultaneous fit of PDF, $\alpha_s$ , $m_t^{pole}$
- Weak correlation of 0.3 between $\alpha_s$ and $m_t^{pole}$

$\delta m_t/m_t = 0.47\%$

$$\alpha_S = 0.1135 \pm ^{+0.0021}_{-0.0017}(\text{total})$$

$$m_t^{pole} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\ \text{GeV} = 170.5 \pm 0.8(\text{total})\ \text{GeV}$$



# Combinations / All results

Using BLUE:

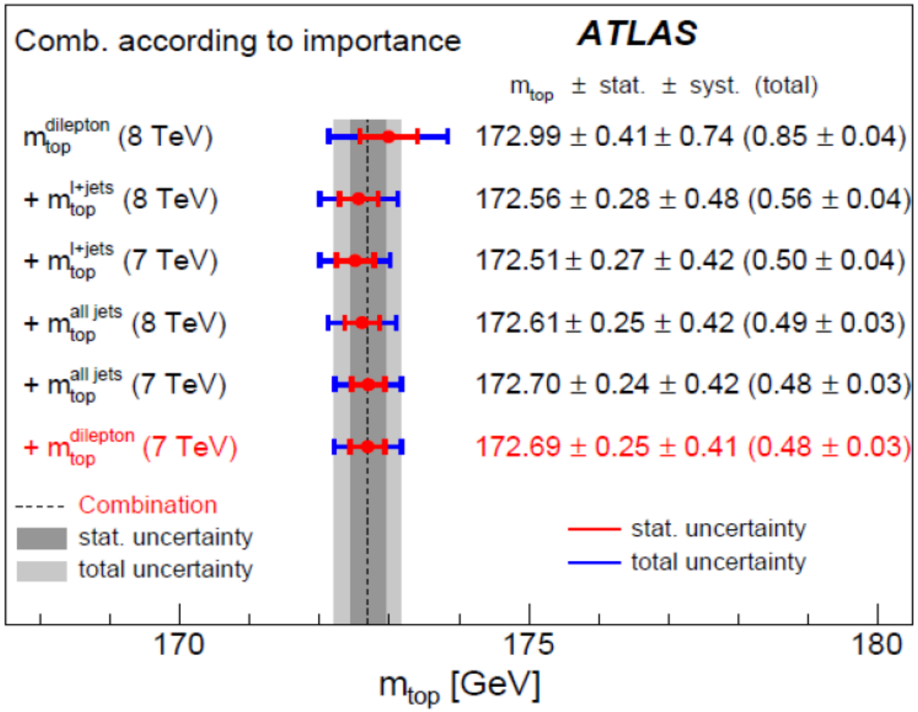
- Latest CMS combination

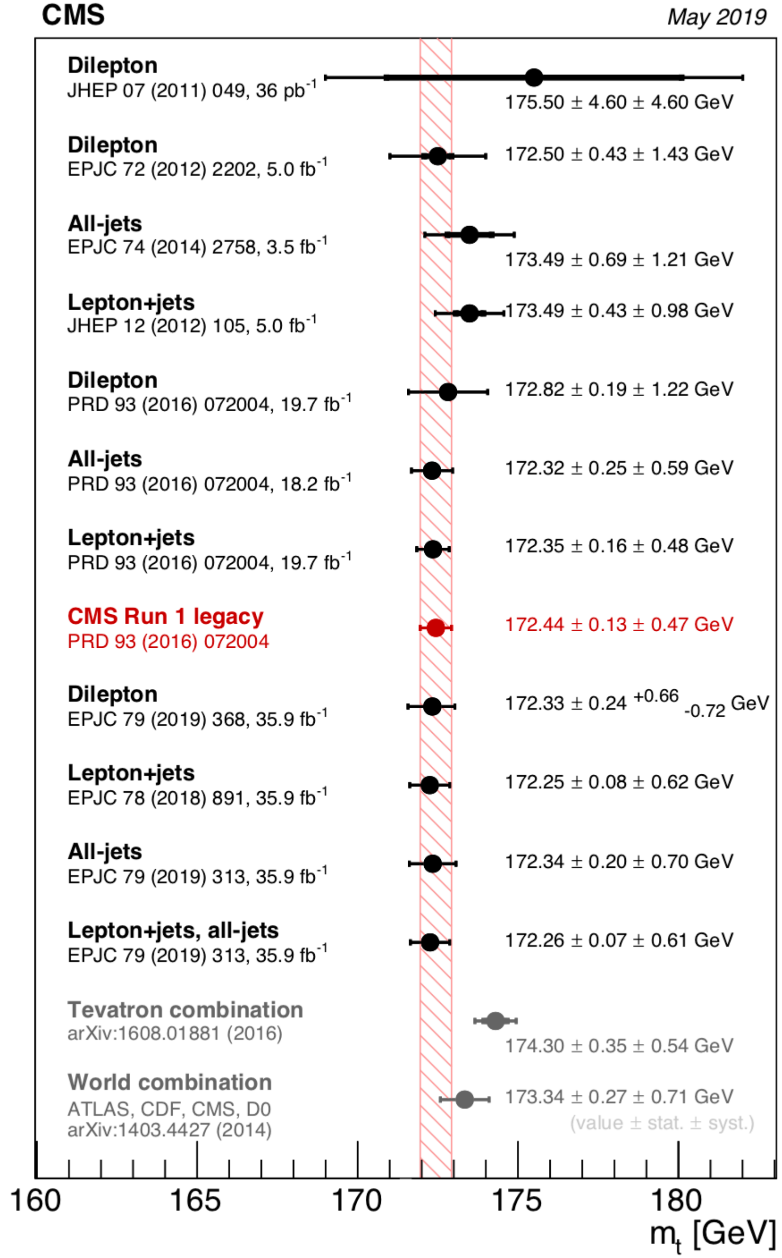
  $m_{top}$ = 172.44 ± 0.48 GeV    $\delta m_t/m_t$ = 0.28%

- Latest ATLAS combination

  $m_{top}$ = 172.69 ± 0.48 GeV    $\delta m_t/m_t$ = 0.28%

→ Anti-correlations of systematic uncertainties used, provides a non-trivial improvement

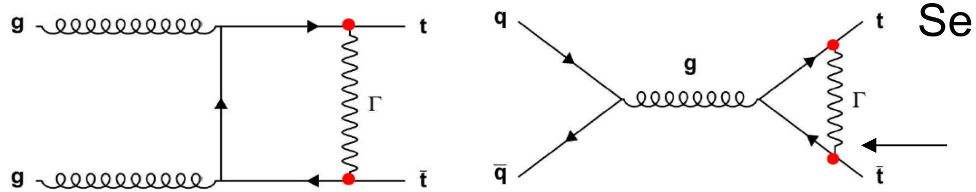


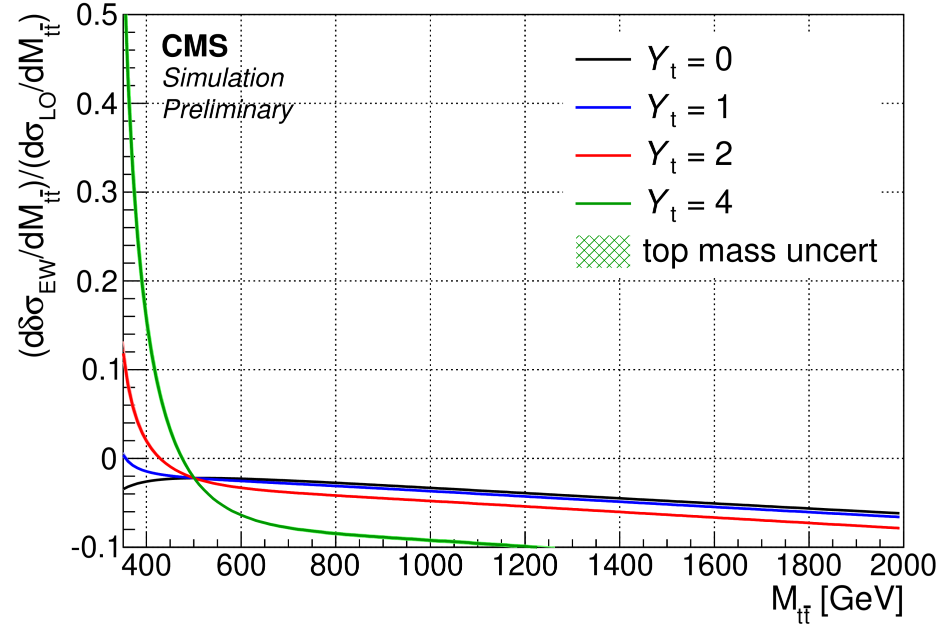
# Extraction of Yukawa

CMS-TOP-17-004

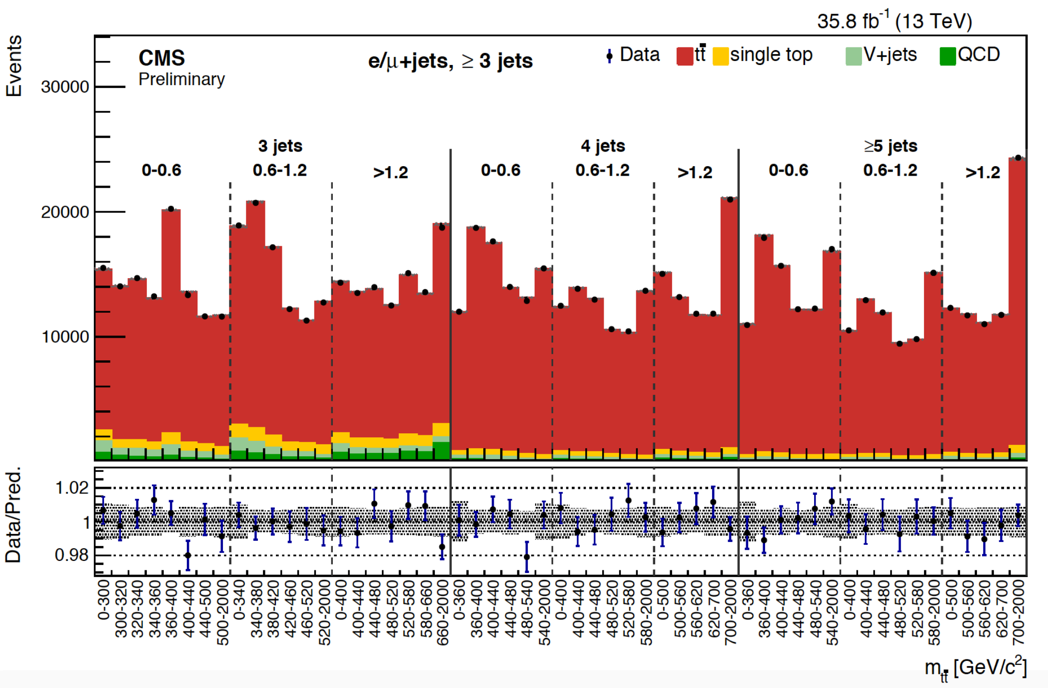
- Extract $y_t$ by using l+jets differential cross sections in 3, 4, and 5 jet bins




Weak corrections
Sensitive to $y_t$




- Relies on Hathor to extract scale factors for Powheg, templates in $y_t$
- Likelihood fit in 55 bins to extract $y_t$:




Extract top quark Yukawa coupling:

| Channel | Expected 95% CL | Observed 95% CL |
|---|---|---|
| 3 jets | $Y_t < 2.17$ | $Y_t < 2.59$ |
| 4 jets | $Y_t < 1.88$ | $Y_t < 1.77$ |
| 5 jets | $Y_t < 2.03$ | $Y_t < 2.23$ |
| Combined | $Y_t < 1.62$ | $Y_t < 1.67$ |

Jet energy corrections dominant uncertainty

# Spin correlations

# Spin correlations

- Unique quark:

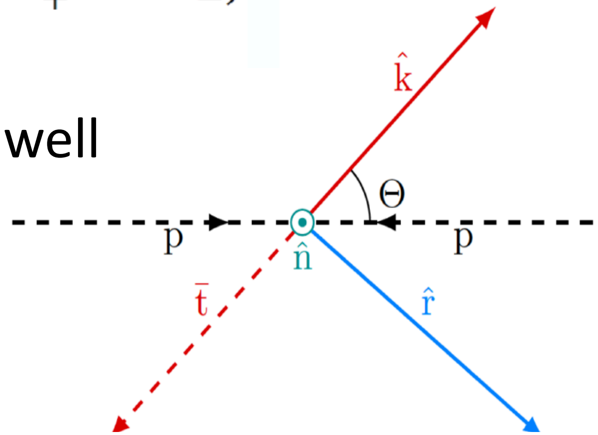
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \text{s}}}$$

- Double-differential cross section allows to access spin correlation and polarization information in top quark events

**Double diff. xsec** **Polarisation (0 in SM)** **Spin Correlation**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b)\cos\theta_+^a \cos\theta_-^b)$$

- Charged lepton is perfect spin analyzer, well reconstructed as well
- Can probe top quark spin in 3 dimensions
  - Using the {k, r, n} basis

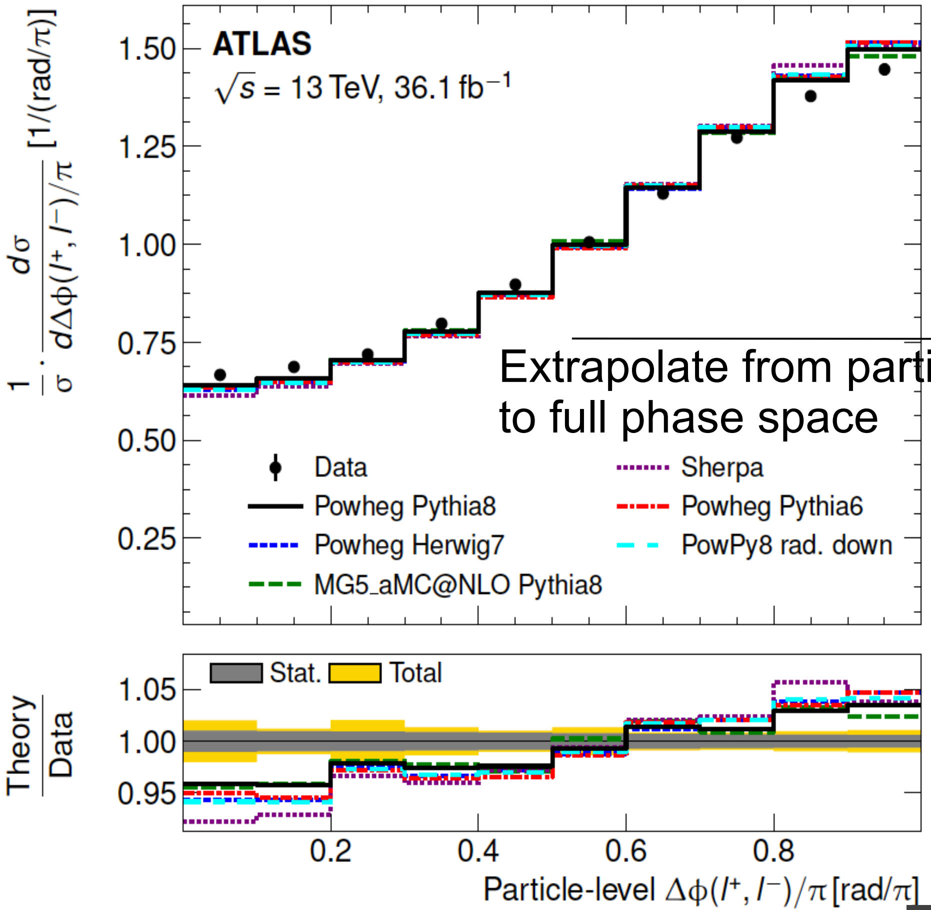



- Sensitive to BSM physics:
  - more spin corr's = s-channel dark matter; less spin corr's = new scalars)

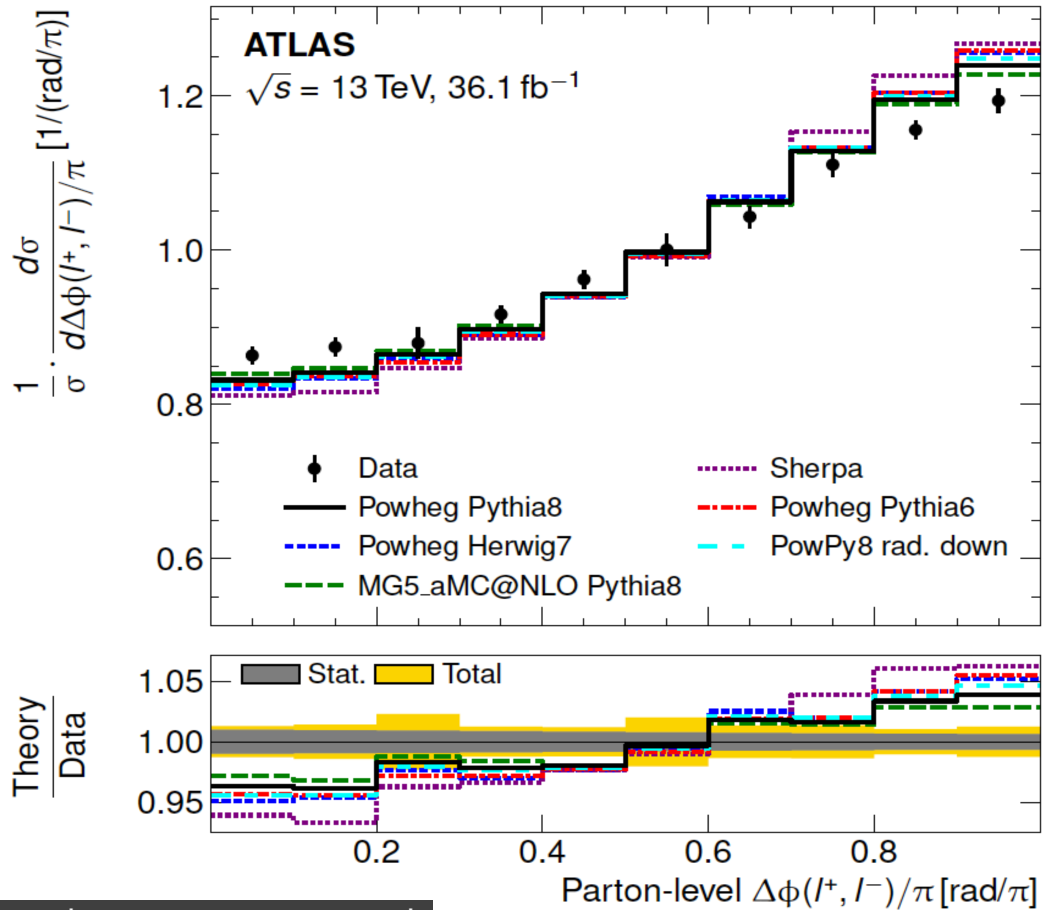
# *Spin correlations*

- ATLAS measures Δϕ in 1D and as a function of $m_{tt}$
- Discrepancy between NLO simulations and data at the 3σ level in Δϕ at particle **and** parton level, also seen in differential in $m_{tt}$ bins:
  - Fraction of SM-like spin corr. $f_{SM}$ of 1 agrees with NLO SM, **observe: (stat + syst + theory)**

**$f_{SM} = 1.25 \pm 0.02 \pm 0.06 \pm 0.04$**



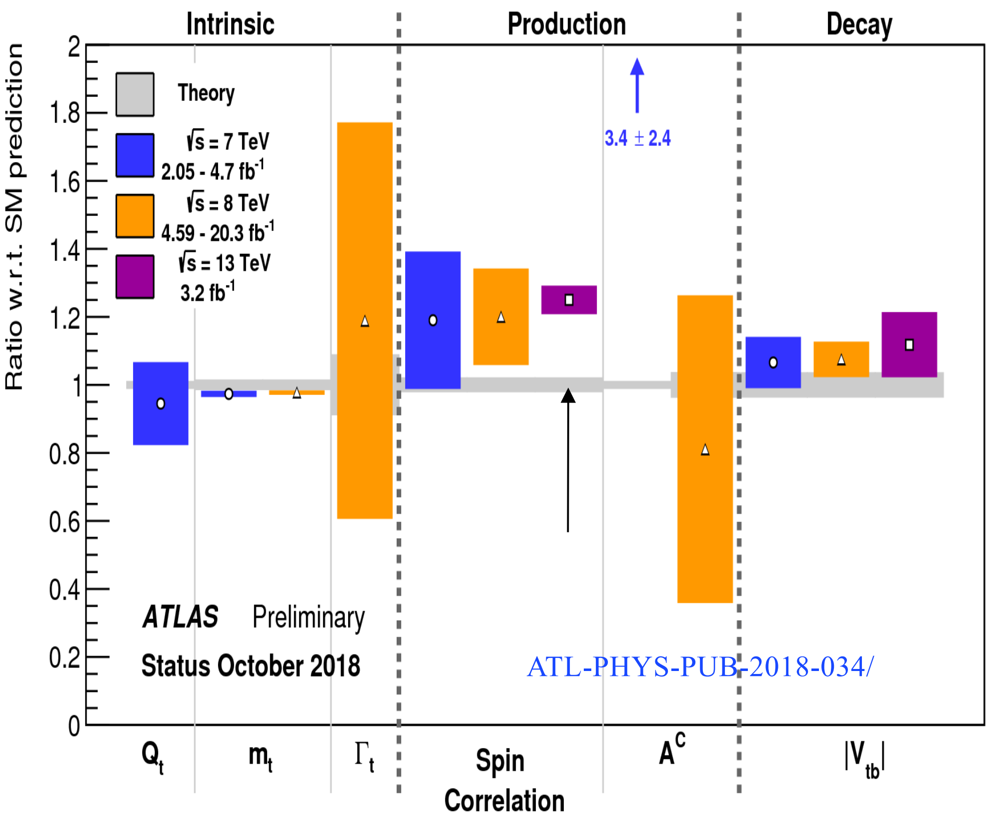

Extrapolate from particle to full phase space

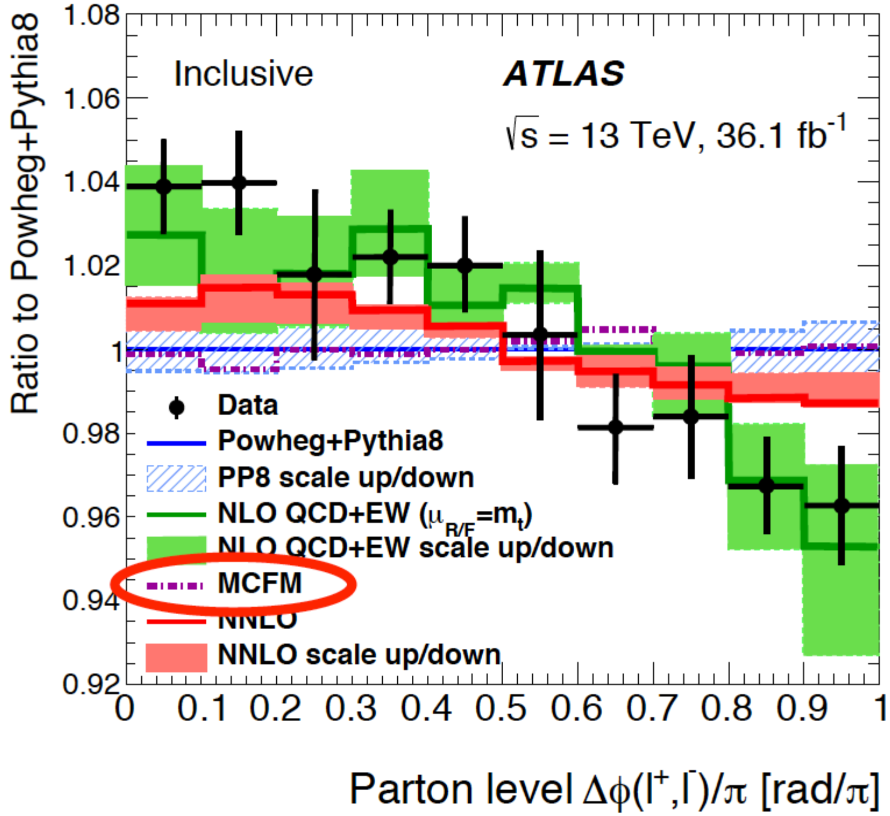



$$|\Delta\phi_{ll}| = \left|\left|\phi_{l_1} - \phi_{l_2}\right| - \pi\right| - \pi$$

# Spin correlations

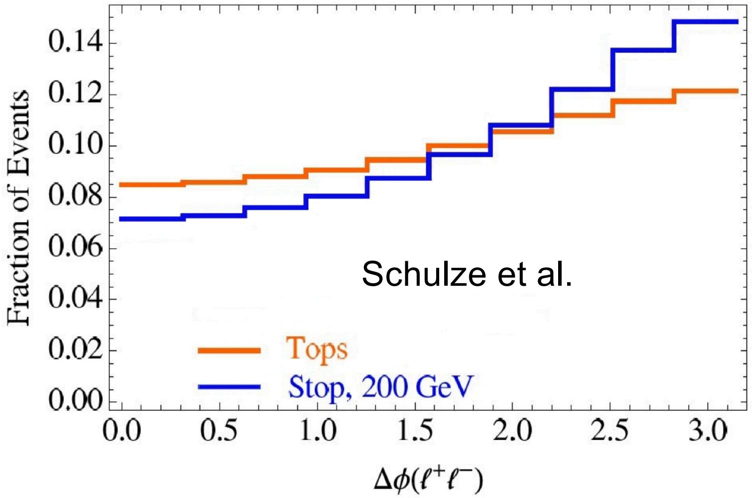
- Further insights to spin correlations:
  - NLO effects in decay (modeled by MCFM) similar to Powheg+Pythia8 (no NLO effects in decay)
- Discrepancy **likely explained by missing higher order correction** to top quark kinematics relevant to fiducial phase space



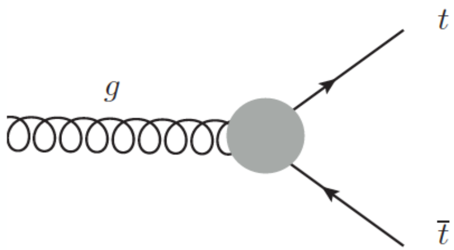
# EFT and SUSY constraints

- ATLAS employs spin correlation to constrain SUSY top quark partner, low mass preferred by naturalness arguments
  - Signature: Top quark spins more uncorrelated since stop is scalar



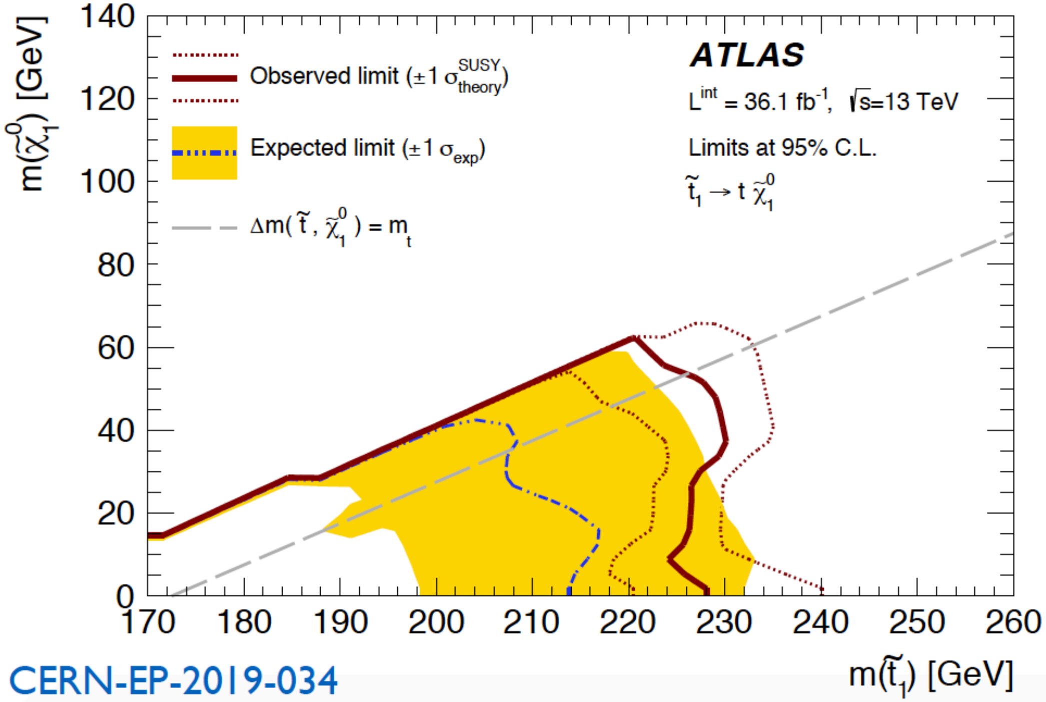

- CMS uses EFT approach for $O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{\phi}G^a_{\mu\nu}$ density matrix measurement

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}\mathcal{O}_i^{(6)}}{\Lambda^2}$$

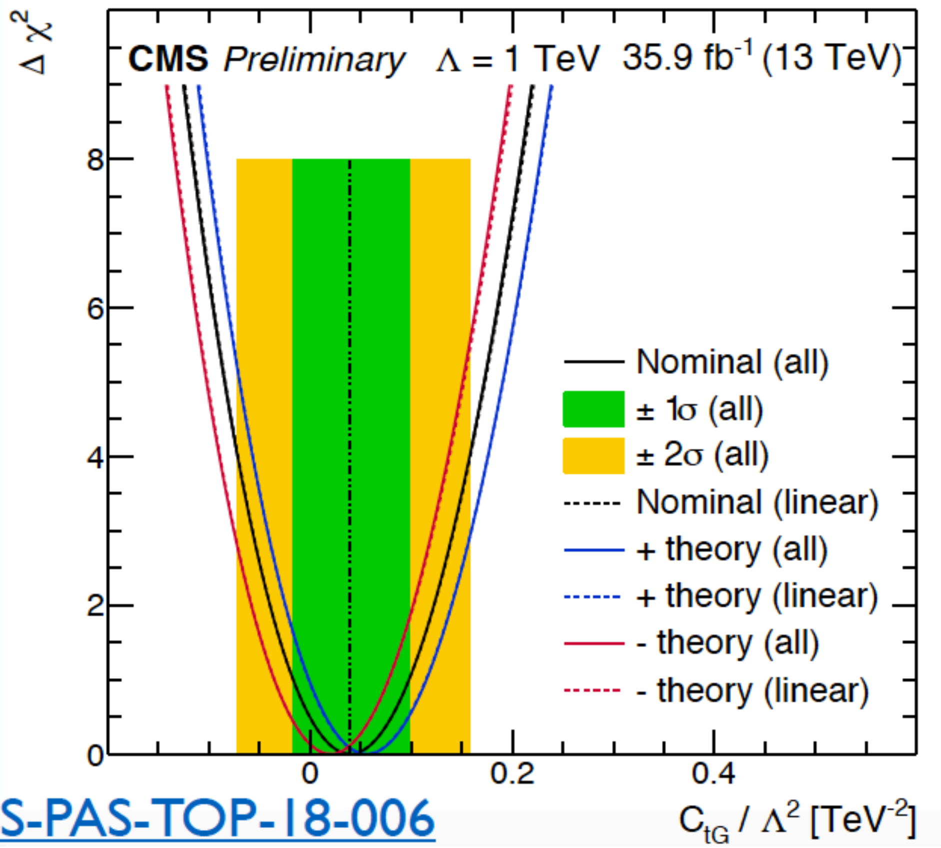



- Stringent constrain on chromomagnetic dipole moment: -0.07 < CtG/L2 < 0.16 TeV-2

# EFT and SUSY constraints




CERN-EP-2019-034



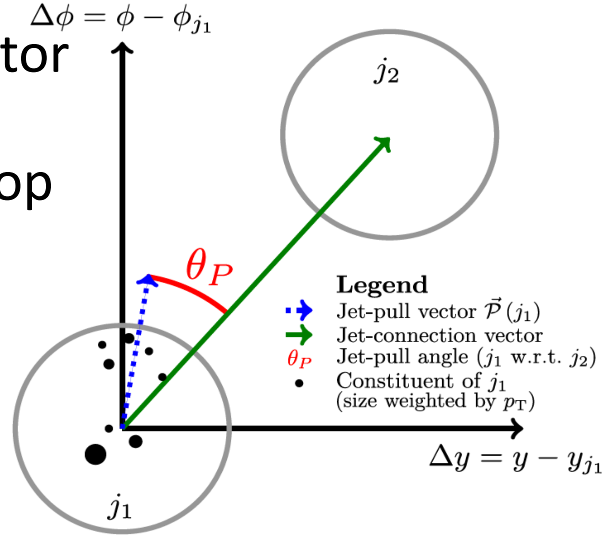

CMS-PAS-TOP-18-006

- Stringent constrain on chromomagnetic dipole moment: -0.07 < CtG/L2 < 0.16 TeV-2

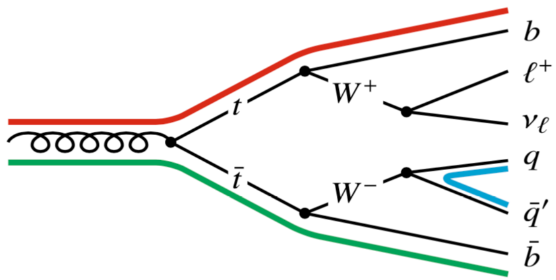
# Color Flow

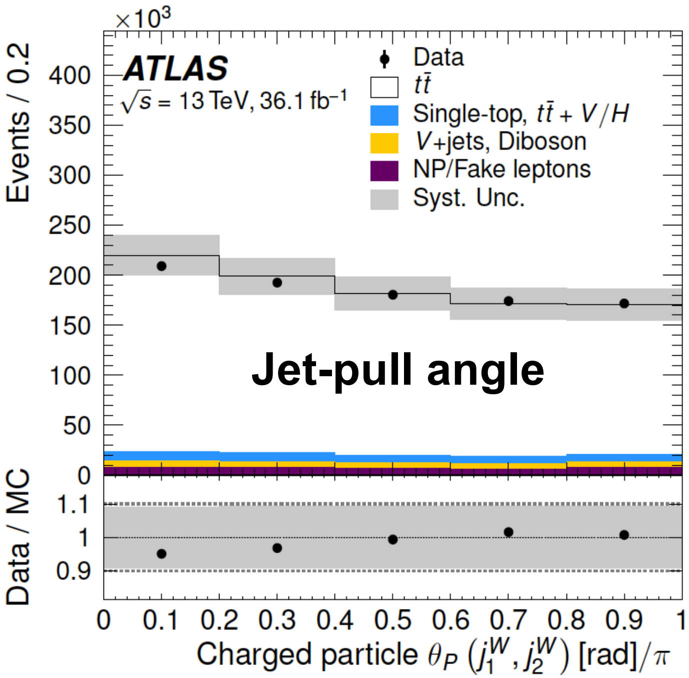
Eur. Phys. J. C 78 (2018) 847
(sketch by Y.Peters)

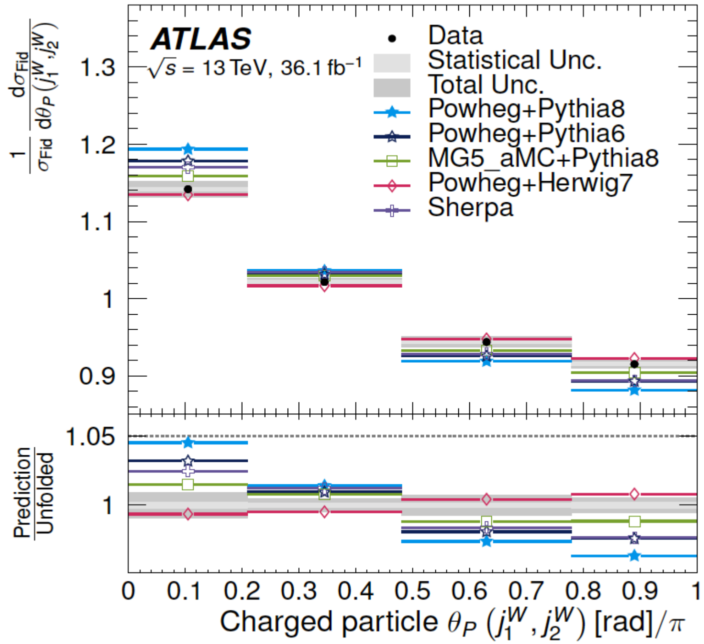
- ATLAS uses 13 TeV l+jets data to measure color flow at detector level and unfolded level
- Two dijet systems: $j_1 j_2$ from W (color singlet) and $b_1 b_2$ from top quarks (color disconnected)



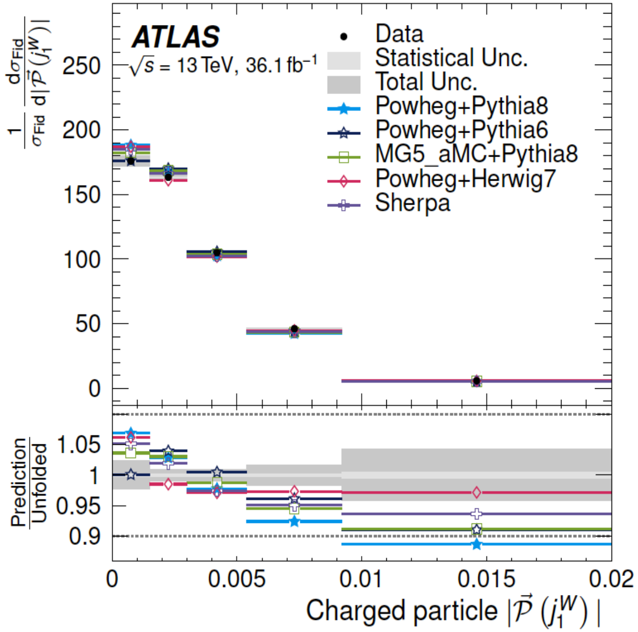

- Allows for MC tuning
- Color-flipped model dis-favored by c2/ndf = 45.3/3




Jet-pull magnitude



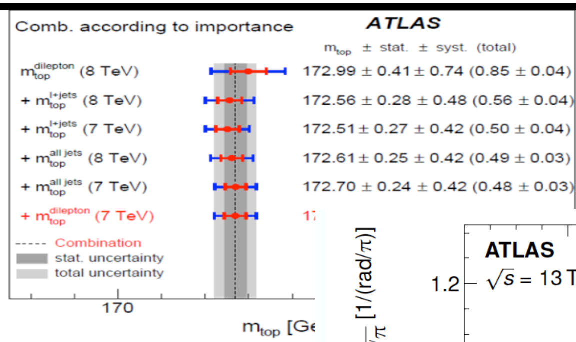

A. Jung & F. Yumiceva

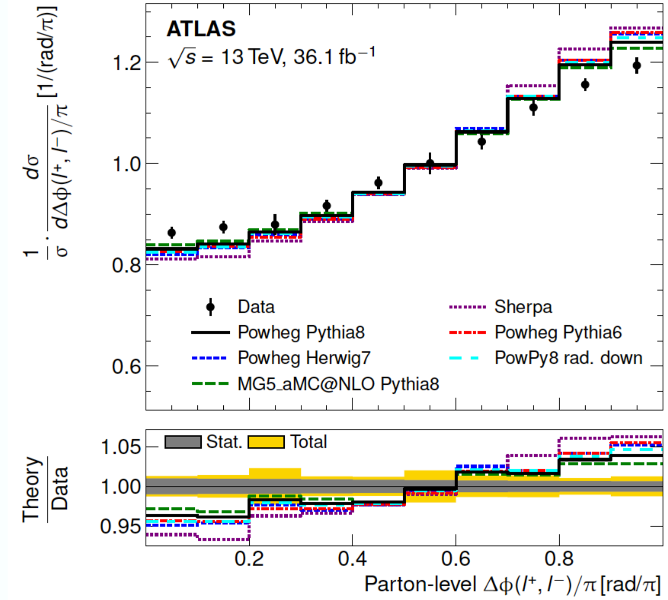
# Conclusions

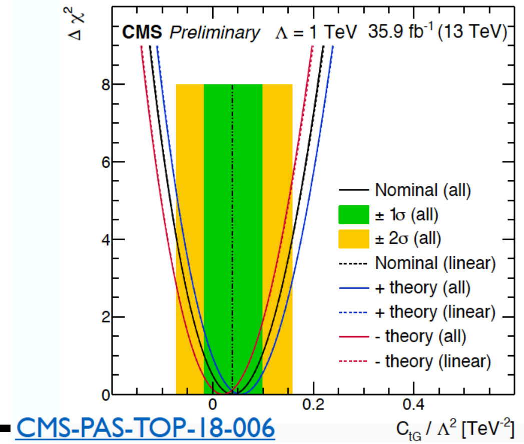
- Direct methods provide high precision
  $\delta m_t/m_t$ = 0.28%
- Indirect methods are improving in precision and providing pole mass
- Spin correlations results are higher than NLO predictions.
  - Measurements deviate by 1-3σ from NLO simulations
  - Likely explained by higher order corrections to top quark kinematics
- Provide stringent EFT and BSM constraints by using top properties

Only small limited selection of results shown, more information:

CMS Top Physics Results    ATLAS Top Physics Results




CMS-PAS-TOP-18-006

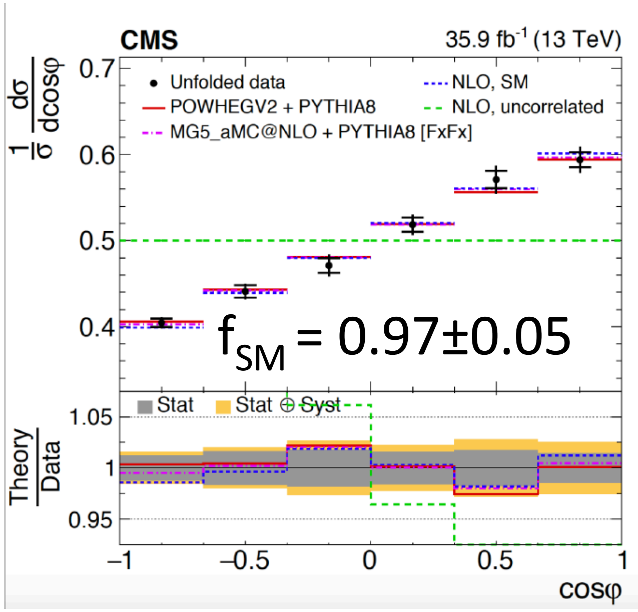
Thank you!

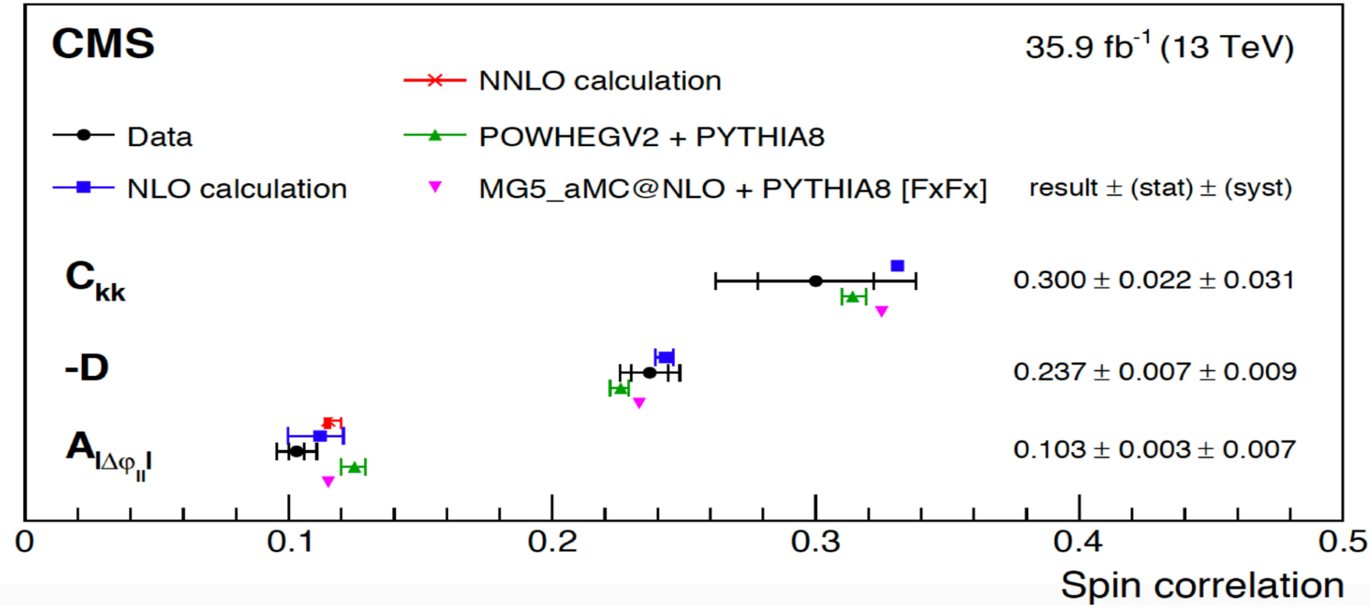
# Backup

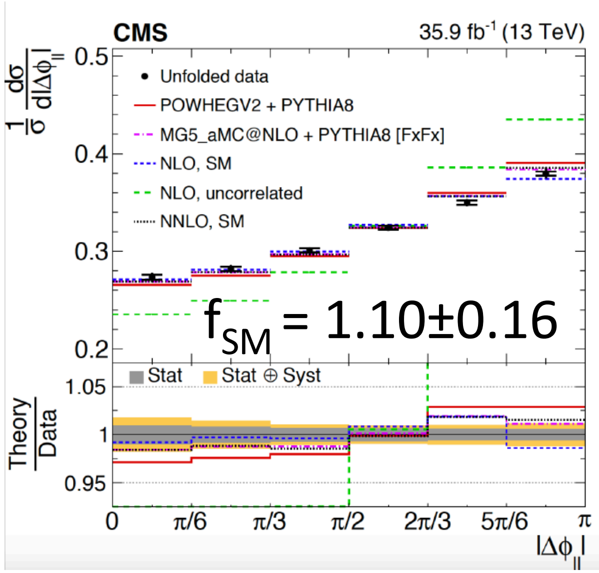
# Spin correlations

- CMS employs 13 TeV dilepton data
- Opening angle maximally sensitive to alignment of top quark spins
- Most precise direct measurement via cos $\varphi$
  - Systematic: $p_T$ and BG modeling
- Indirect measurement via $\Delta\phi$ shows about 1σ discrepancy to NLO simulations

**cosφ = opening angle between the leptons, $D=-(C_{kk}+C_{rr}+C_{nn})/3$**



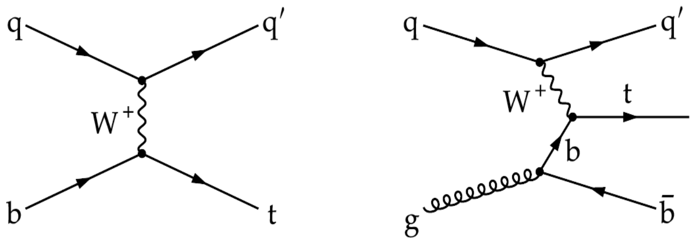



# Asymmetries

CMS-PAS-TOP-17-023

- Single top cross sections measured and employed to extract spin asymmetry

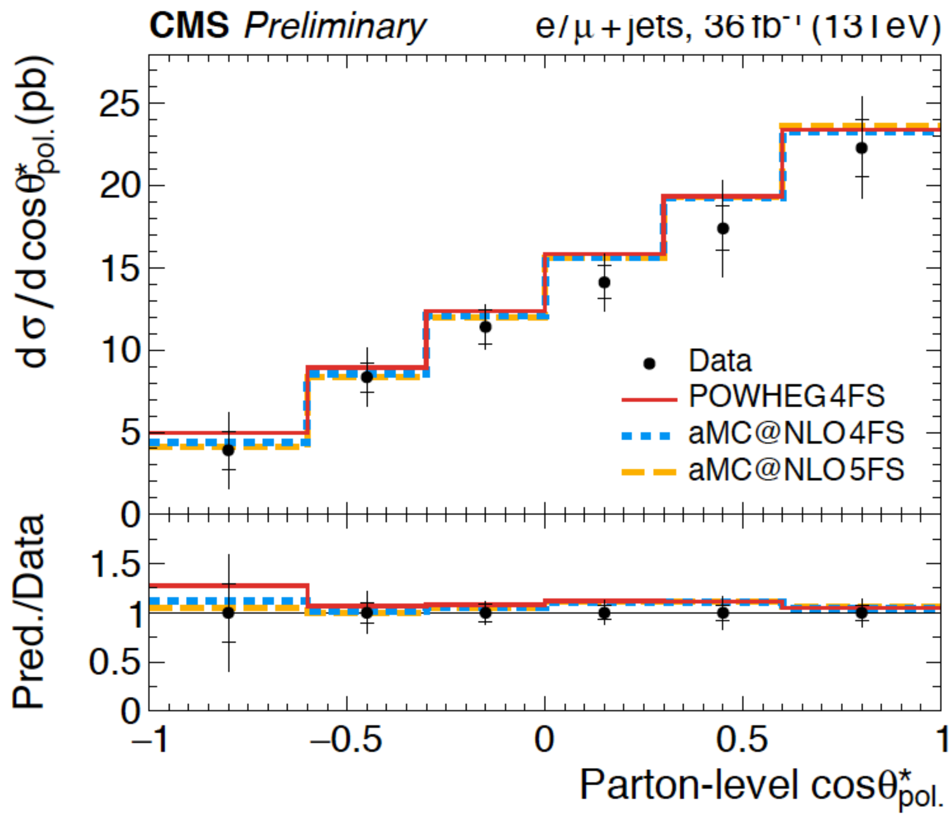



- Distributions are in agreement with predictions at NLO
- SM prediction for spin asymmetries is:
  0.436
  - Earlier seen deviation at 2 SD is not strengthened

$$A_c^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}$$

$$A_c^{\ell\bar{\ell}} = \frac{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) - \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) + \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}$$

- CMS also extracted asymmetries based on dEta, dY particle+parton level cross sections

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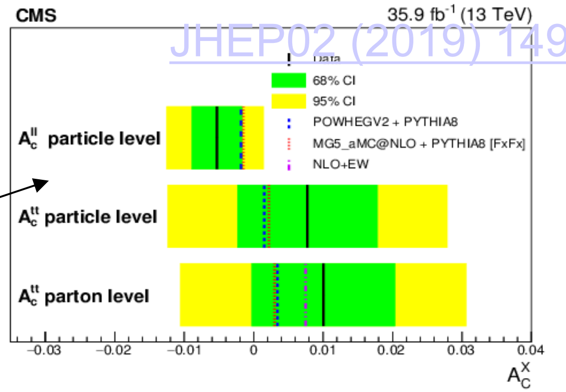
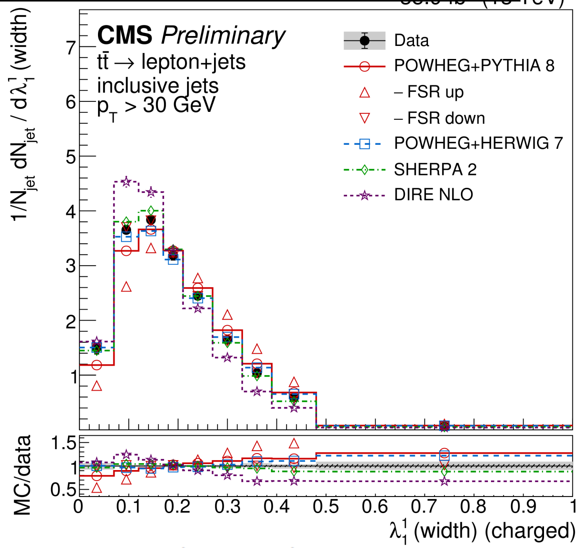
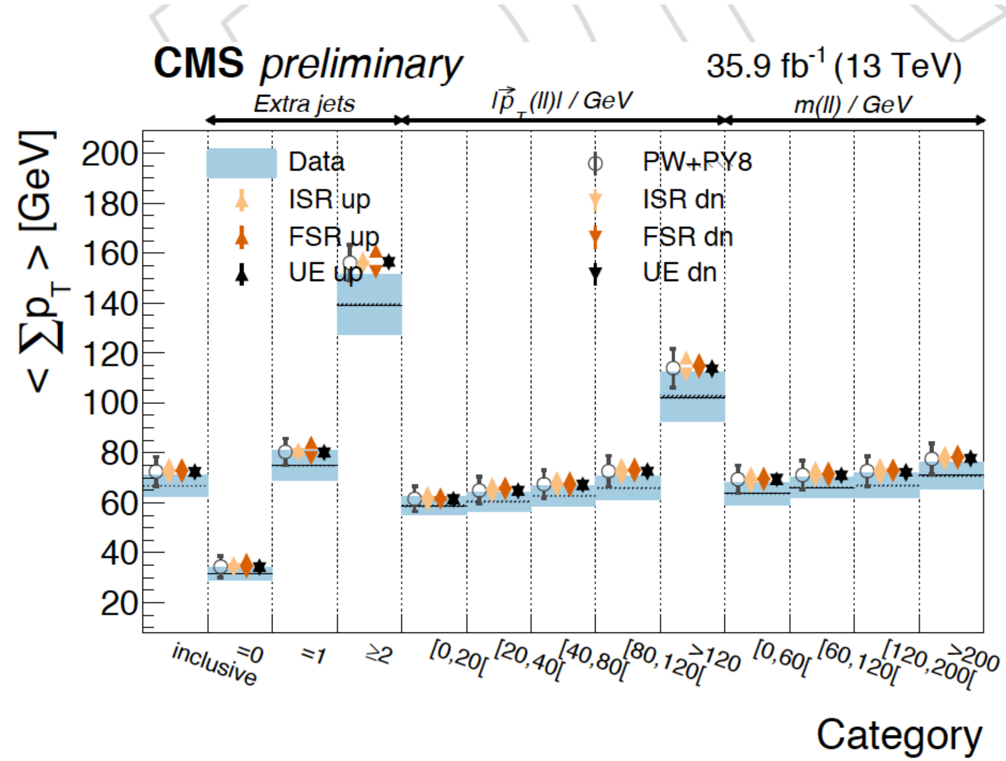


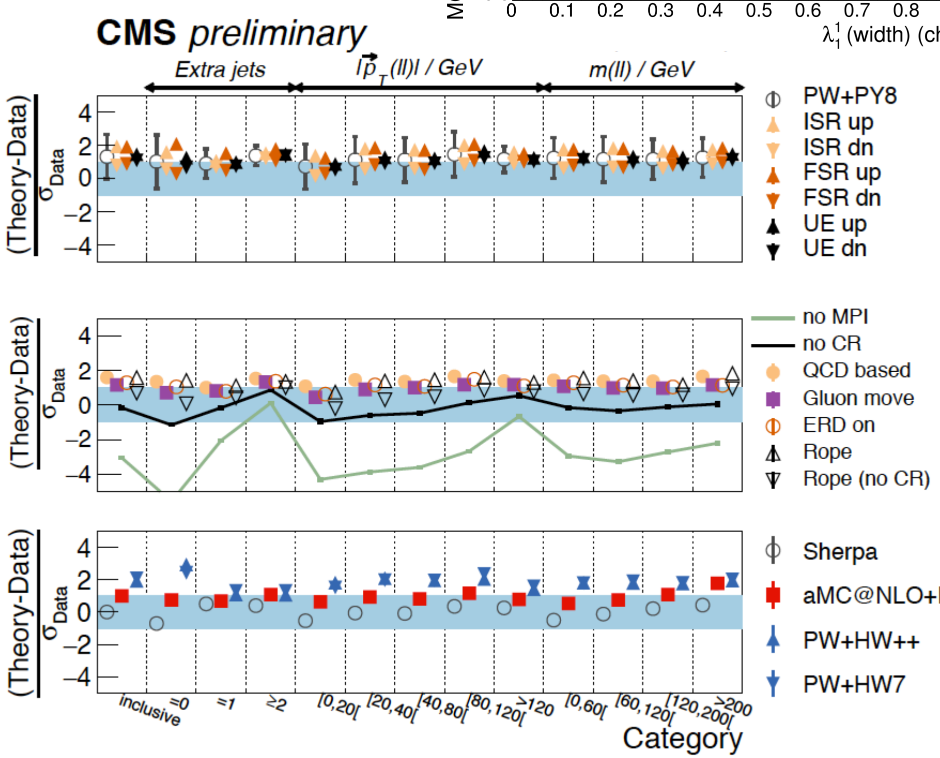
# *Underlying event*

CMS-PAS-TOP-17-013
CMS-PAS-TOP-17-015




- CMS used 13 TeV data to measure multiple jet structure variables: particle multiplicity, width, $p_T$, E correlations
- Unfolded to stable particle level, used for **MC tuning** to further constrain systematics due to:
  - Sensitivity to **Color Reconnection model**
  - Sensitivity to **α(Final State Radiation)**



# The top quark

- Top is the heaviest fundamental particle discovered so far
  → $m_t$ = **173.34 ± 0.76 GeV** [arxiv:1403.4427]
- Unique quark:

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

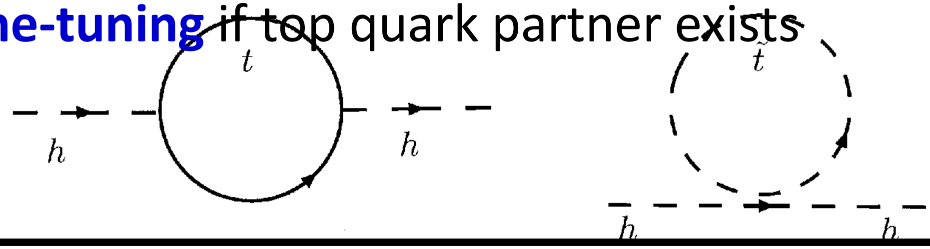
  → **Observe bare quark properties**

- Large Yukawa coupling to Higgs boson

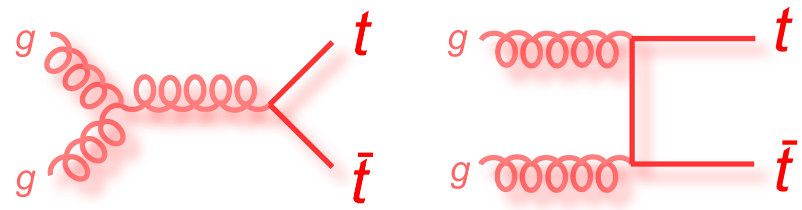
  **only $m_t$ is natural mass**

  Special role in EW symmetry breaking ?

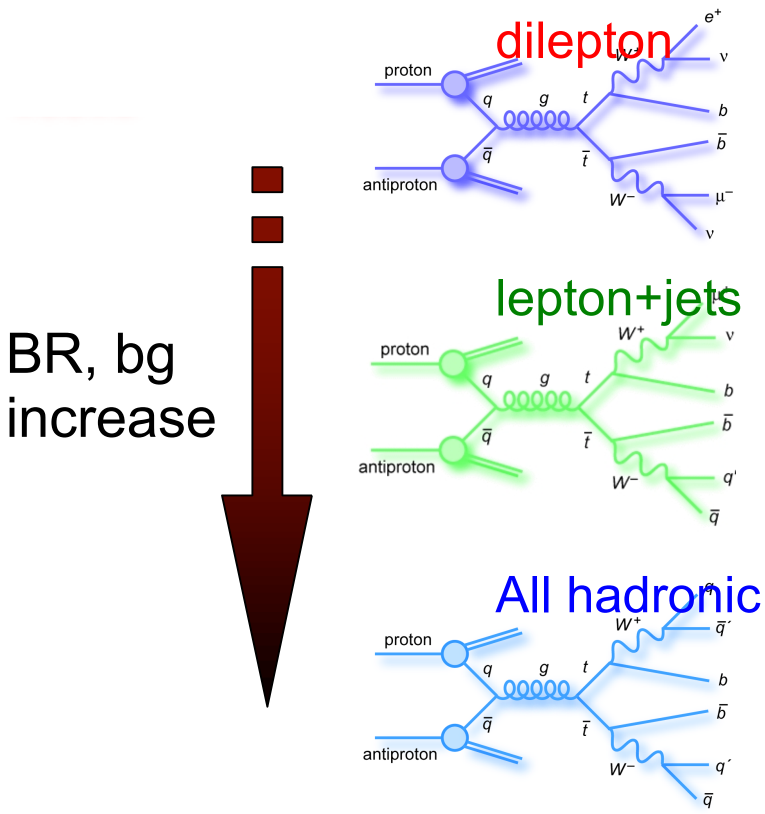
- **No fine-tuning** if top quark partner exists



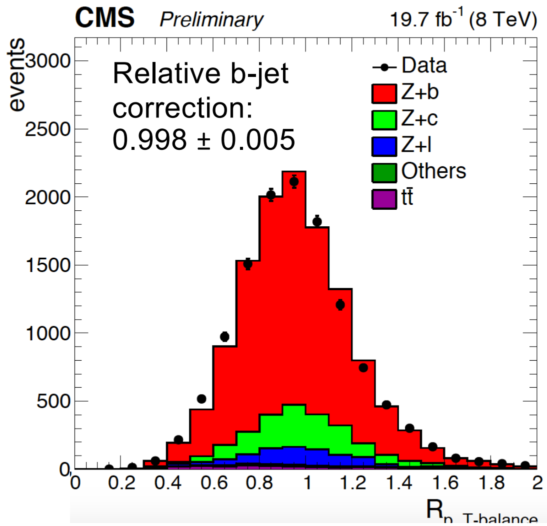

- Production dominated by gg fusion:



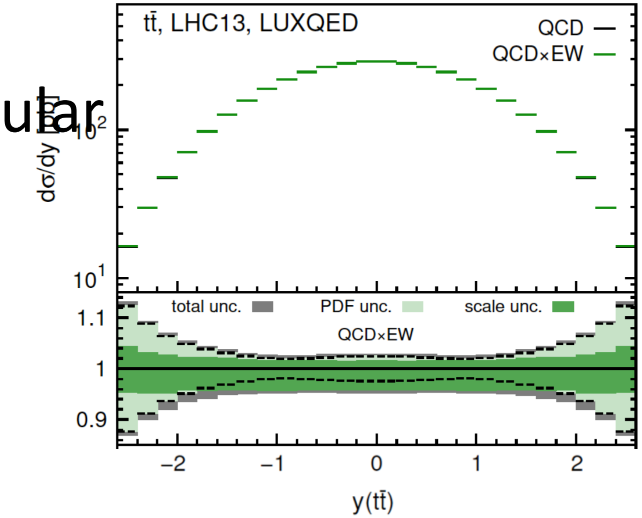

- Decay channels:



# Challenges/Perspectives




**Direct methods**:
- Reconstruct top candidates (kinematic fits)
- Determine m(t) or m(t) & Jet energy SF, *b*-jet energy SF, bg fraction parameters
- Likelihood based on templates (ATLAS+CMS) or Ideogram (CMS)
- Most precise results, no single large uncertainty left
  - **Alternative methods**: larger uncertainties but perpendicular




**Indirect methods**:
- Relies on theoretical predictions (various choices)
- Fully corrected data, more complex
- Larger uncertainties, pole mass interpretation

- Employ different decay channels (different systematics, in-situ jet energy scale)
- Use direct (classical), direct (alternative), and indirect (based on σ, dX/dσ)

# Direct methods: l+jets

- CMS measurement at 13 TeV, e/μ+jets decay channel:
- At least 4 jets, exactly 2 jets b-tagged
- Kinematic fit to constrain the W mass and using decay of 2 same mass heavy particles
  - Keep all permutations
- Follow <u>same strategy as 8 TeV result</u>:
  - 2D fit of m(top) vs. Jet energy scale factor

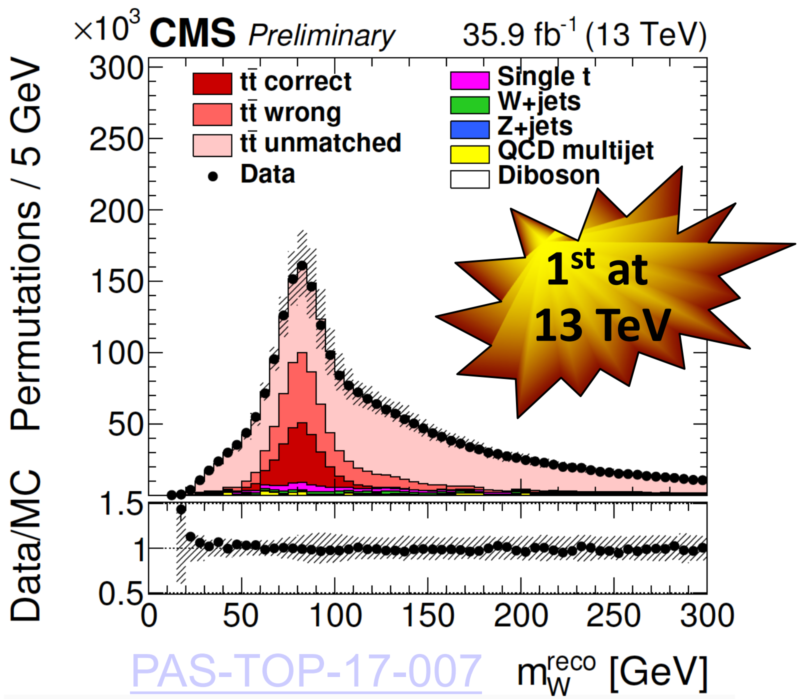
→ $M_{top}$ = 172.25 ± 0.08 (stat+JSF) ± 0.62 (syst.) GeV

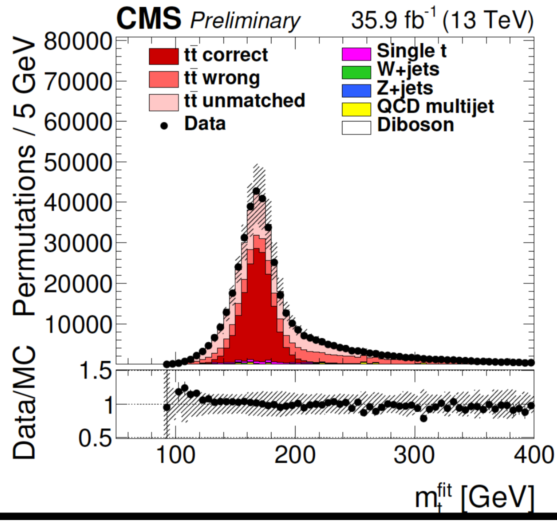
$\delta m_t/m_t$ = 0.36%

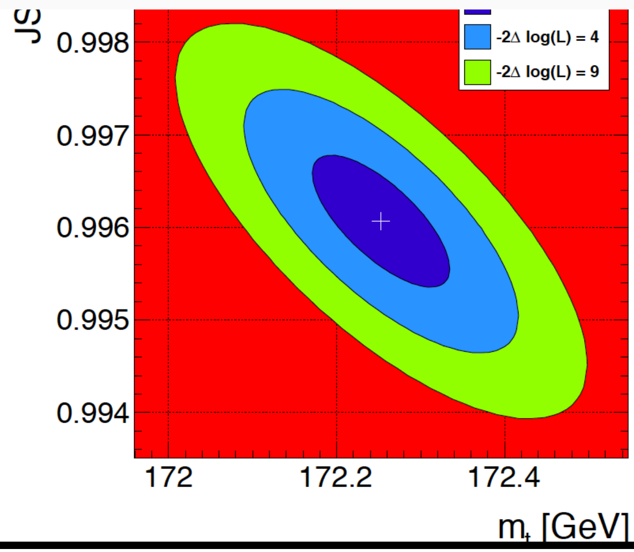
<u>Dominant systematics:</u>

→ Flavor (0.41 GeV)
→ Model (0.41 GeV)
→ JSF (0.19 GeV)

**<u>Note:</u> CR treatment changed from 8 to 13 TeV**

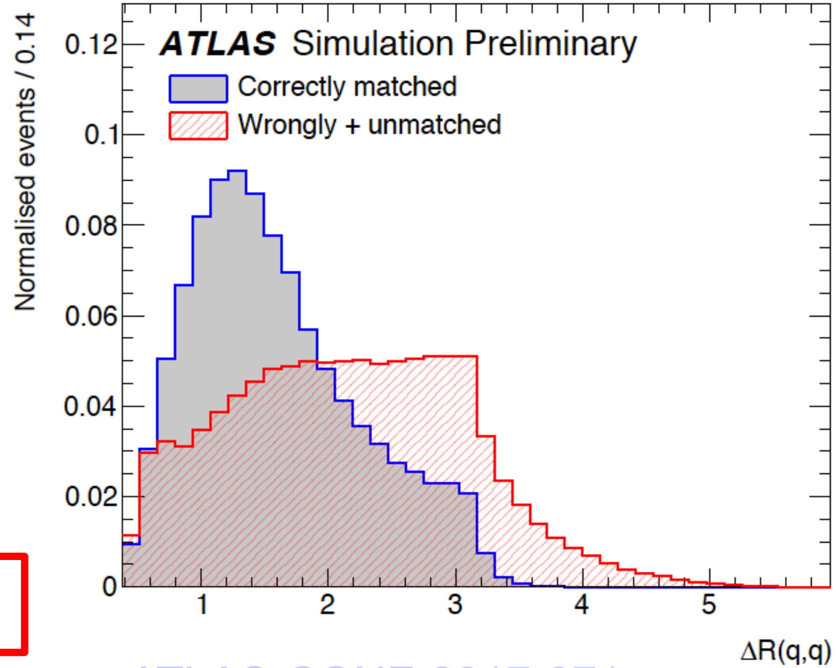


# Direct methods: l+jets

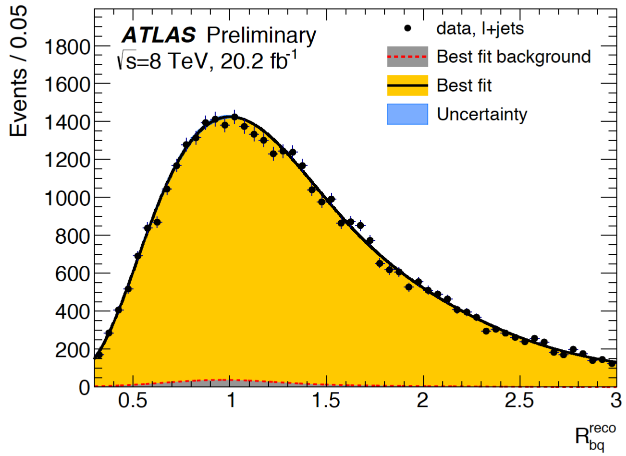
- ATLAS measurement at 8 TeV, e/μ+jets decay channel:
- At least 4 jets, exactly 2 jets b-tagged
- Kinematic fit to constrain the W mass and using decay of 2 same mass heavy particles
  - BDT rejects events w worse resolution
- Template fit to three distributions to determine: m(t), b-JSF, and JSF

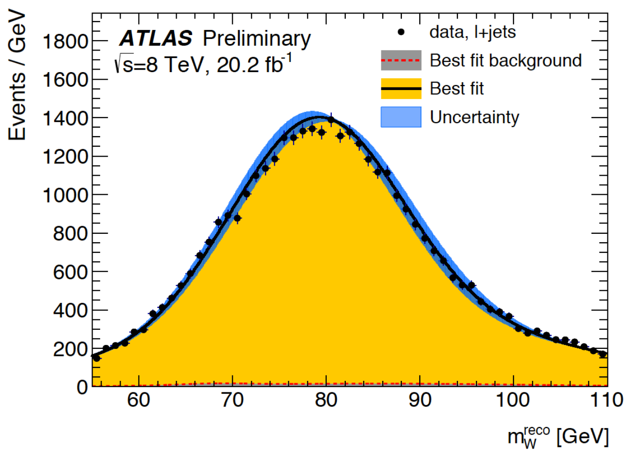


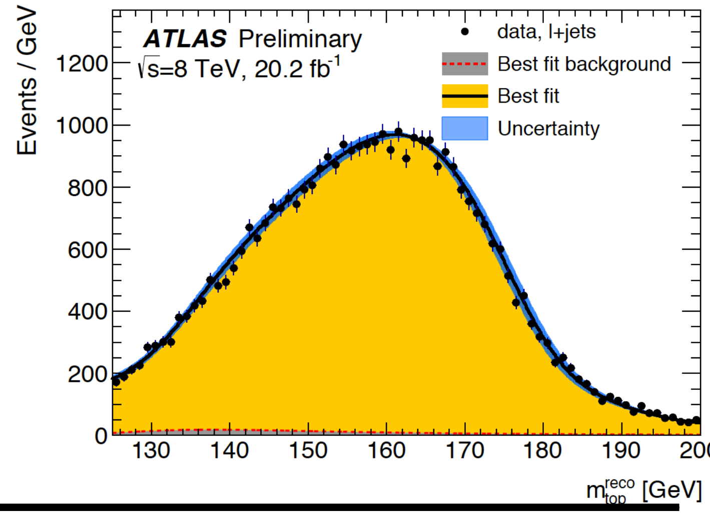

ATLAS-CONF-2017-071

$M_{top}$ = 172.08 ± 0.39 (stat+JSF) ± 0.82 (syst.) GeV

$\delta m_t/m_t$ = 0.53%



# Direct methods: alljets + l+jets

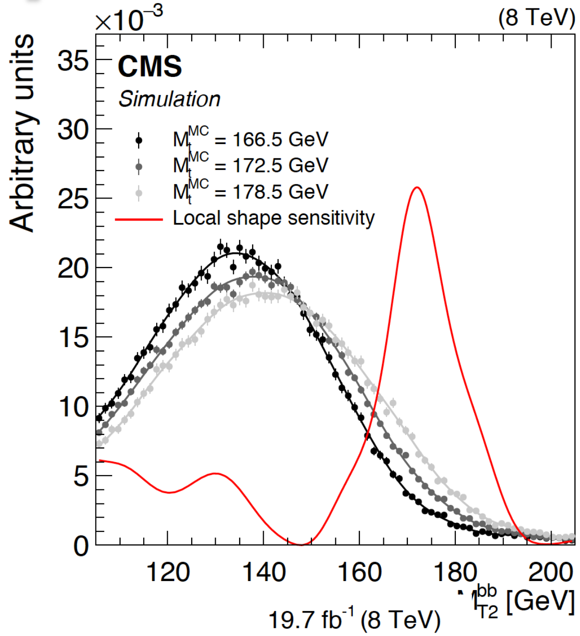
Eur. Phys. J. C79 (2019)

| | $\delta m_t^{hyb}$ [GeV] | | |
|---|---|---|---|
| | All-jets | $\ell$+jets | Combination |
| *Experimental uncertainties* | | | |
| Method calibration | 0.06 | 0.05 | 0.03 |
| JEC (quad. sum) | 0.15 | 0.18 | 0.17 |
| Intercalibration | −0.04 | +0.04 | +0.04 |
| MPFInSitu | +0.08 | +0.07 | +0.07 |
| Uncorrelated | +0.12 | +0.16 | +0.15 |
| Jet energy resolution | −0.04 | −0.12 | −0.10 |
| b tagging | 0.02 | 0.03 | 0.02 |
| Pileup | −0.04 | −0.05 | −0.05 |
| All-jets background | 0.07 | – | 0.01 |
| All-jets trigger | +0.02 | – | +0.01 |
| $\ell$+jets background | – | +0.02 | −0.01 |
| *Modeling uncertainties* | | | |
| JEC flavor (linear sum) | −0.34 | −0.39 | −0.37 |
| light quarks (uds) | +0.07 | +0.06 | +0.07 |
| charm | +0.02 | +0.01 | +0.02 |
| bottom | −0.29 | −0.32 | −0.31 |
| gluon | −0.13 | −0.15 | −0.15 |
| b jet modeling (quad. sum) | 0.09 | 0.12 | 0.06 |
| b frag. Bowler–Lund | −0.07 | −0.05 | −0.05 |
| b frag. Peterson | −0.05 | +0.04 | −0.02 |
| semileptonic b hadron decays | −0.03 | +0.10 | −0.04 |
| PDF | 0.01 | 0.02 | 0.01 |
| Ren. and fact. scales | 0.04 | 0.01 | 0.01 |
| ME/PS matching | +0.24 | −0.07 | +0.07 |
| ME generator | – | +0.20 | +0.21 |
| ISR PS scale | +0.14 | +0.07 | +0.07 |
| FSR PS scale | +0.18 | +0.13 | +0.12 |
| Top quark $p_T$ | +0.03 | −0.01 | −0.01 |
| Underlying event | +0.17 | −0.07 | −0.06 |
| Early resonance decays | +0.24 | −0.07 | −0.07 |
| CR modeling (max. shift) | −0.36 | +0.31 | +0.33 |
| "gluon move" (ERD on) | +0.32 | +0.31 | +0.33 |
| "QCD inspired" (ERD on) | −0.36 | −0.13 | −0.14 |
| Total systematic | 0.70 | 0.62 | 0.61 |
| Statistical (expected) | 0.20 | 0.08 | 0.07 |
| Total (expected) | 0.72 | 0.63 | 0.61 |

| | 2D | | 1D | Hybrid | |
|---|---|---|---|---|---|
| | $\delta m_t^{2D}$ [GeV] | $\delta JSF^{2D}$ [%] | $\delta m_t^{1D}$ [GeV] | $\delta m_t^{hyb}$ [GeV] | $\delta JSF^{hyb}$ [%] |
| *Experimental uncertainties* | | | | | |
| Method calibration | 0.03 | 0.0 | 0.03 | 0.03 | 0.0 |
| JEC (quad. sum) | 0.12 | 0.2 | 0.82 | 0.17 | 0.3 |
| Intercalibration | −0.01 | 0.0 | +0.16 | +0.04 | +0.1 |
| MPFInSitu | −0.01 | 0.0 | +0.23 | +0.07 | +0.1 |
| Uncorrelated | −0.12 | −0.2 | +0.77 | +0.15 | +0.3 |
| Jet energy resolution | −0.18 | +0.3 | +0.09 | −0.10 | +0.2 |
| b tagging | 0.03 | 0.0 | 0.01 | 0.02 | 0.0 |
| Pileup | −0.07 | +0.1 | +0.02 | −0.05 | +0.1 |
| All-jets background | 0.01 | 0.0 | 0.00 | 0.01 | 0.0 |
| All-jets trigger | +0.01 | 0.0 | 0.00 | +0.01 | 0.0 |
| $\ell$+jets Background | −0.02 | 0.0 | +0.01 | −0.01 | 0.0 |
| $\ell$+jets Trigger | 0.00 | 0.0 | 0.00 | 0.00 | 0.0 |
| Lepton isolation | 0.00 | 0.0 | 0.00 | 0.00 | 0.0 |
| Lepton identification | 0.00 | 0.0 | 0.00 | 0.00 | 0.0 |
| *Modeling uncertainties* | | | | | |
| JEC flavor (linear sum) | −0.39 | +0.1 | −0.31 | −0.37 | +0.1 |
| Light quarks (uds) | +0.11 | −0.1 | −0.01 | +0.07 | −0.1 |
| Charm | +0.03 | 0.0 | −0.01 | +0.02 | 0.0 |
| Bottom | −0.31 | 0.0 | −0.31 | −0.31 | 0.0 |
| Gluon | −0.22 | +0.3 | +0.02 | −0.15 | +0.2 |
| b jet modeling (quad. sum) | 0.08 | 0.1 | 0.04 | 0.06 | 0.1 |
| b frag. Bowler–Lund | −0.06 | +0.1 | −0.01 | −0.05 | 0.0 |
| b frag. Peterson | −0.03 | 0.0 | 0.00 | −0.02 | 0.0 |
| semileptonic b hadron decays | −0.04 | 0.0 | −0.04 | −0.04 | 0.0 |
| PDF | 0.01 | 0.0 | 0.01 | 0.01 | 0.0 |
| Ren. and fact. scales | 0.01 | 0.0 | 0.02 | 0.01 | 0.0 |
| ME/PS matching | −0.10 ± 0.08 | +0.1 | +0.02 ± 0.05 | +0.07 ± 0.07 | +0.1 |
| ME generator | +0.16 ± 0.21 | +0.2 | +0.32 ± 0.13 | +0.21 ± 0.18 | +0.1 |
| ISR PS scale | +0.07 ± 0.08 | +0.1 | +0.10 ± 0.05 | +0.07 ± 0.07 | 0.1 |
| FSR PS scale | +0.23 ± 0.07 | −0.4 | −0.19 ± 0.04 | +0.12 ± 0.06 | −0.3 |
| Top quark $p_T$ | +0.01 | −0.1 | −0.06 | −0.01 | −0.1 |
| Underlying event | −0.06 ± 0.07 | +0.1 | +0.00 ± 0.05 | −0.04 ± 0.06 | +0.1 |
| Early resonance decays | −0.20 ± 0.08 | +0.7 | +0.42 ± 0.05 | −0.01 ± 0.07 | +0.5 |
| CR modeling (max. shift) | +0.37 ± 0.09 | −0.2 | +0.22 ± 0.06 | +0.33 ± 0.07 | −0.1 |
| "gluon move" (ERD on) | +0.37 ± 0.09 | −0.2 | +0.22 ± 0.06 | +0.33 ± 0.07 | −0.1 |
| "QCD inspired" (ERD on) | −0.11 ± 0.09 | −0.1 | −0.21 ± 0.06 | −0.14 ± 0.07 | −0.1 |
| Total systematic | 0.71 | 1.0 | 1.07 | 0.61 | 0.7 |
| Statistical (expected) | 0.08 | 0.1 | 0.05 | 0.07 | 0.1 |
| Total (expected) | 0.72 | 1.0 | 1.08 | 0.61 | 0.7 |

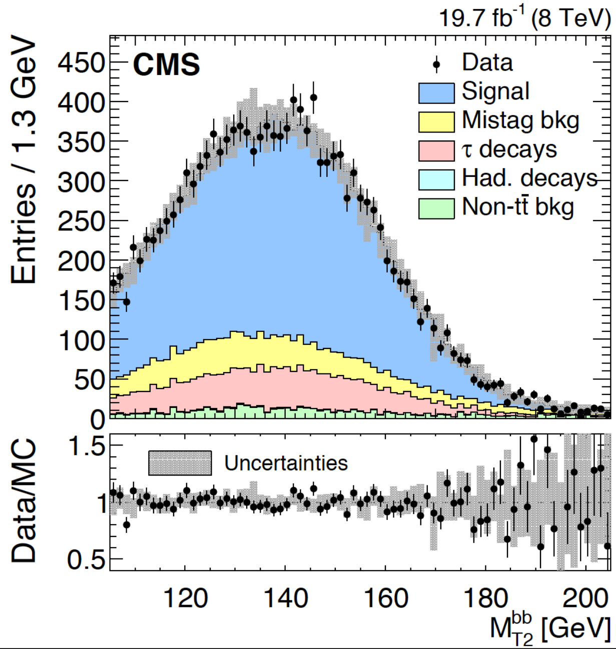
# Direct methods: dilepton

- CMS measurement at 8 TeV, dilepton
  decay channel: Cleanest sample
- At least 2 jets b-tagged
- Reconstruct invariant mass of b-tagged jet and lepton (templates)
  - $m_{lb}$, $m_{T2}^{bb}$, $m_{lb}^{b\nu}$ in 7x5 m(t) vs. JSF
- 1D, 2D, or hybrid fit
  - 80% (1D) and 20% (2D) lowest uncertainty




**$M_{top}$ = 172.22 ± 0.18 (stat) ± 0.91 (syst.) GeV**

$\delta m_t/m_t$ = 0.54%    PRD 96(2017)032002

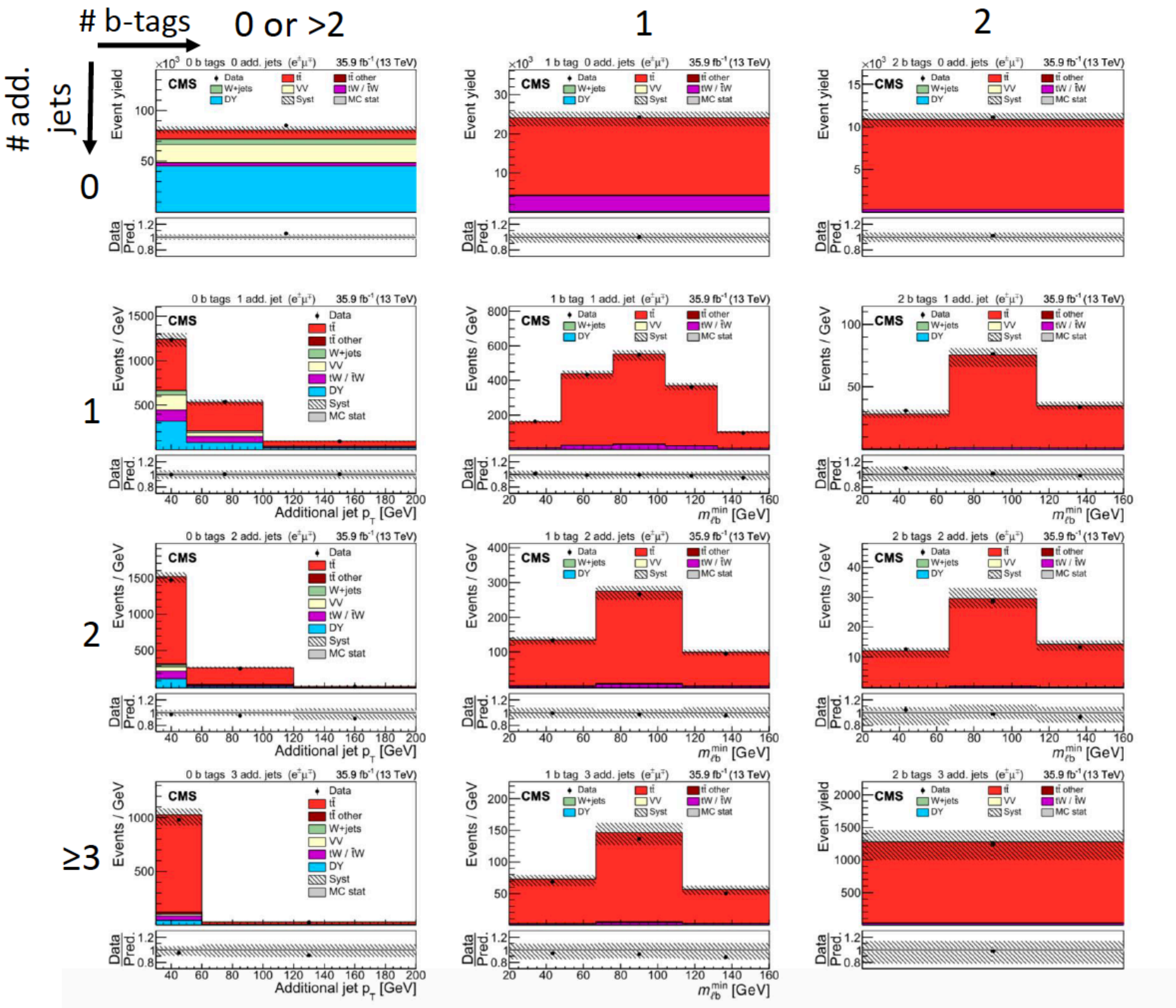



Dominant systematics:

→ Model (0.64 GeV)
→ JES (0.45 GeV)
→ b-frag (0.40 GeV)

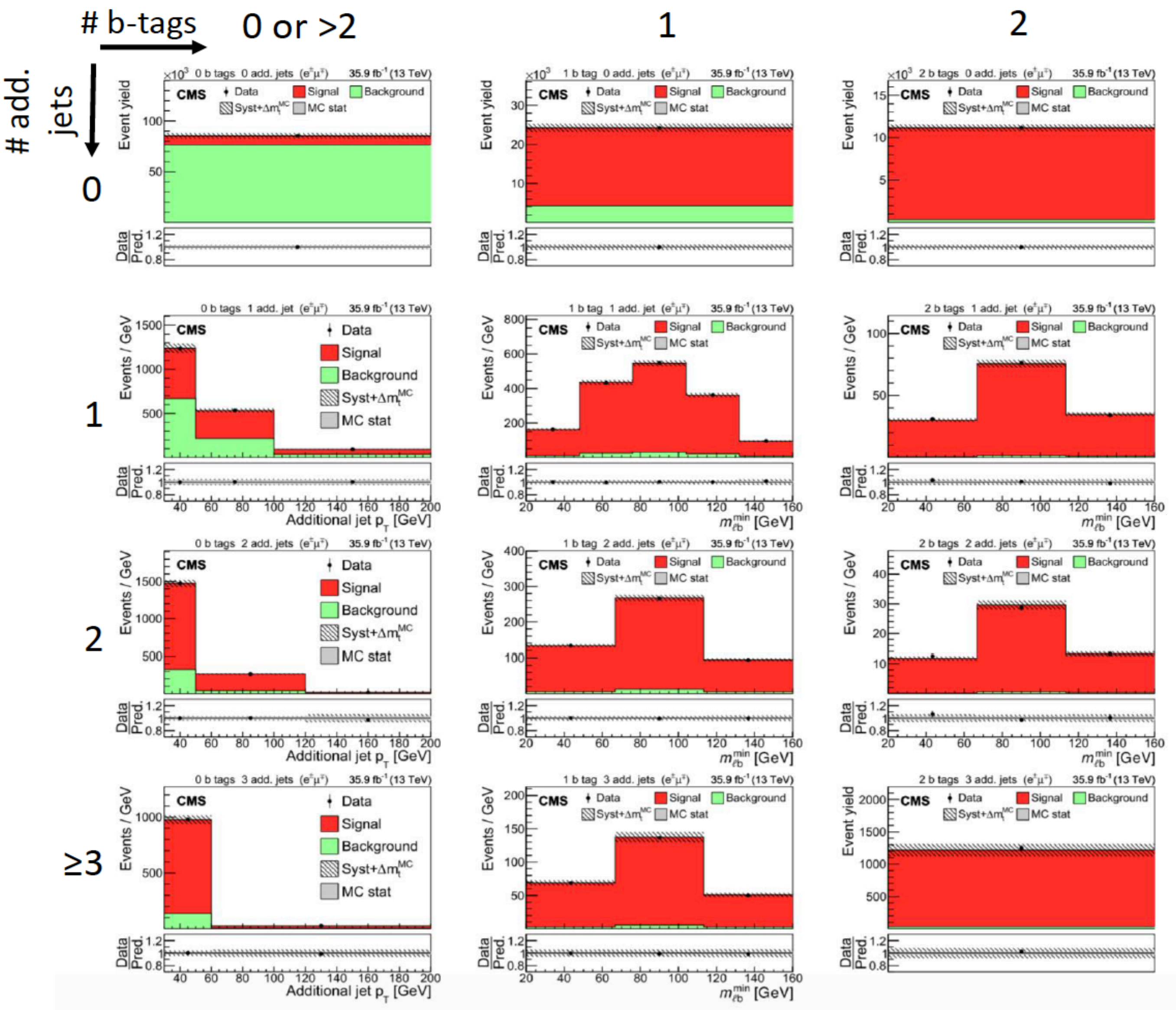
# Indirect methods: inc. s

pre-fit



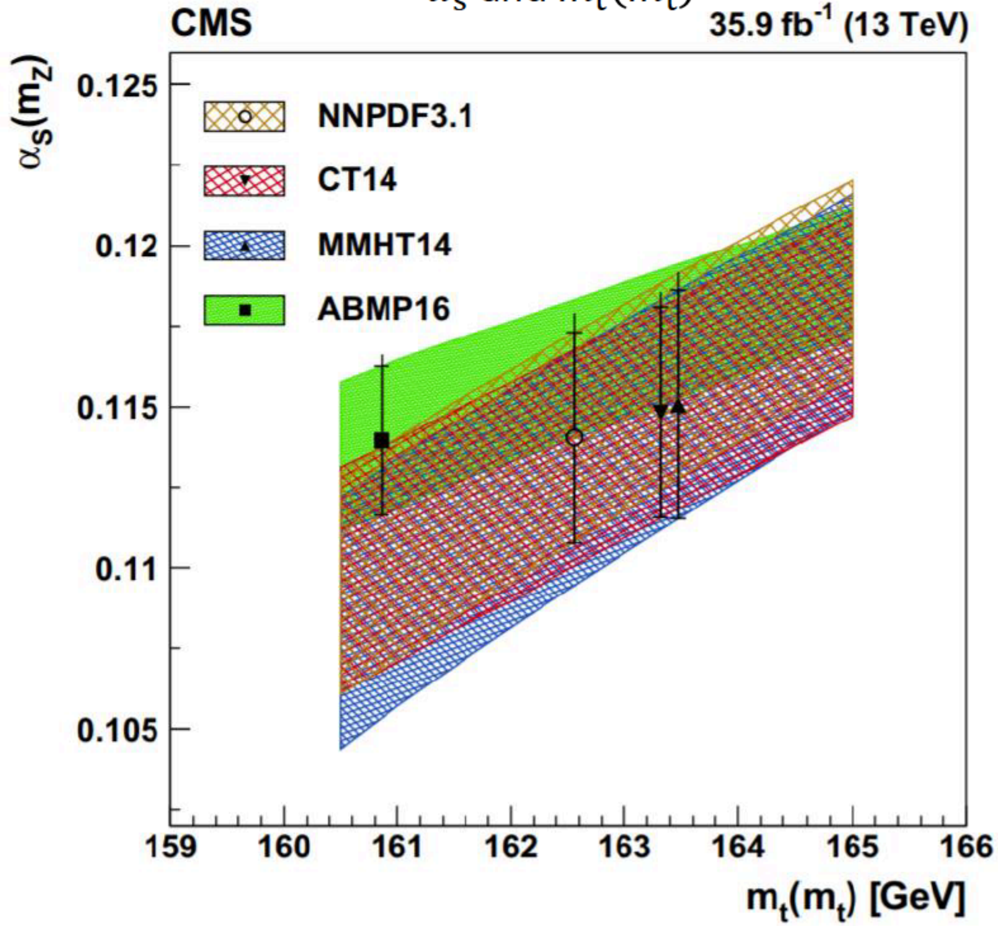
# Indirect methods: inc. s

post-fit

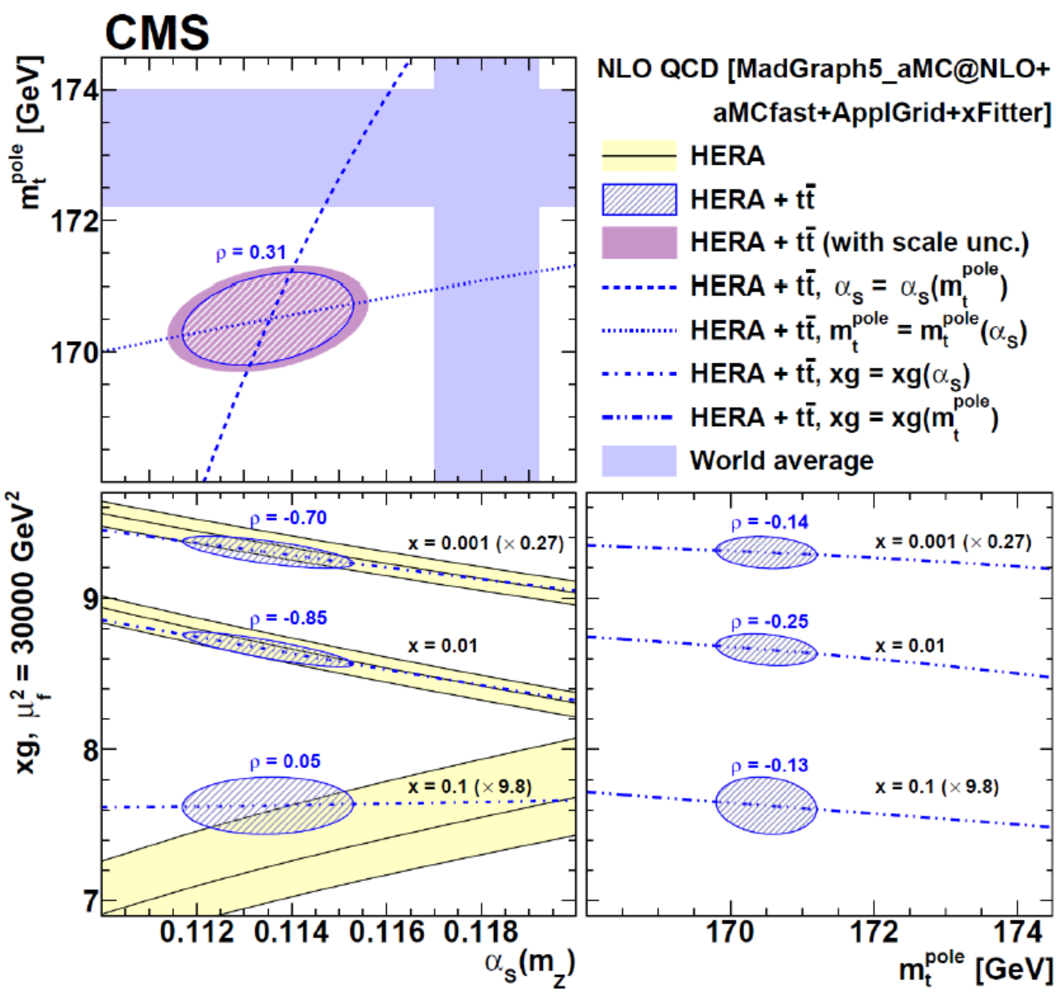


# Indirect methods: inc. s

Linear dependence observed between $\alpha_s$ and $m_t(m_t)$



# Indirect methods: diff. s




| Parameter | Variation | $\alpha_S(m_Z)$ | $m_t^{\text{pole}}$ [GeV] |
|---|---|---|---|
| | Fit uncertainty | | |
| Total | $\Delta\chi^2 = 1$ | $\pm 0.0016$ | $\pm 0.7$ |
| | Model uncertainty | | |
| $f_s$ | $f_s = 0.5$ | $+0.0001$ | 0.0 |
| $f_s$ | $f_s = 0.3$ | 0.0000 | 0.0 |
| $Q^2_{\text{min}}$ | $Q^2_{\text{min}} = 5.0\,\text{GeV}^2$ | $+0.0002$ | $+0.1$ |
| $Q^2_{\text{min}}$ | $Q^2_{\text{min}} = 2.5\,\text{GeV}^2$ | $-0.0004$ | $-0.1$ |
| $M_c$ | $M_c = 1.49\,\text{GeV}$ | $+0.0001$ | 0.0 |
| $M_c$ | $M_c = 1.37\,\text{GeV}$ | 0.0000 | 0.0 |
| Total | | $^{+0.0002}_{-0.0004}$ | $^{+0.1}_{-0.1}$ |
| | PDF parametrisation uncertainty | | |
| $\mu^2_{f,0}$ | $\mu^2_{f,0} = 2.2\,\text{GeV}^2$ | $-0.0001$ | 0.0 |
| $\mu^2_{f,0}$ | $\mu^2_{f,0} = 1.6\,\text{GeV}^2$ | $+0.0002$ | 0.0 |
| $A'_g$ | set to 0 | $+0.0002$ | $-0.1$ |
| $E_g$ | set to 0 | $+0.0008$ | 0.0 |
| Total | | $^{+0.0008}_{-0.0001}$ | $-0.1$ |
| | Scale uncertainty | | |
| $\mu_r$ variation | $\mu_r = H$ | $+0.0004$ | $-0.2$ |
| $\mu_r$ variation | $\mu_r = H/4$ | $+0.0007$ | $+0.1$ |
| $\mu_f$ variation | $\mu_f = H$ | $-0.0002$ | $+0.3$ |
| $\mu_f$ variation | $\mu_f = H/4$ | $+0.0001$ | $-0.3$ |
| $\mu_{r,f}$ variation | $\mu_{r,f} = H$ | $+0.0004$ | $+0.1$ |
| $\mu_{r,f}$ variation | $\mu_{r,f} = H/4$ | $+0.0011$ | $-0.2$ |
| alternative $\mu_{r,f}$ | $\mu_{r,f} = H/2$ | $-0.0005$ | $+0.1$ |
| Total | | $^{+0.0011}_{-0.0005}$ | $^{+0.3}_{-0.3}$ |

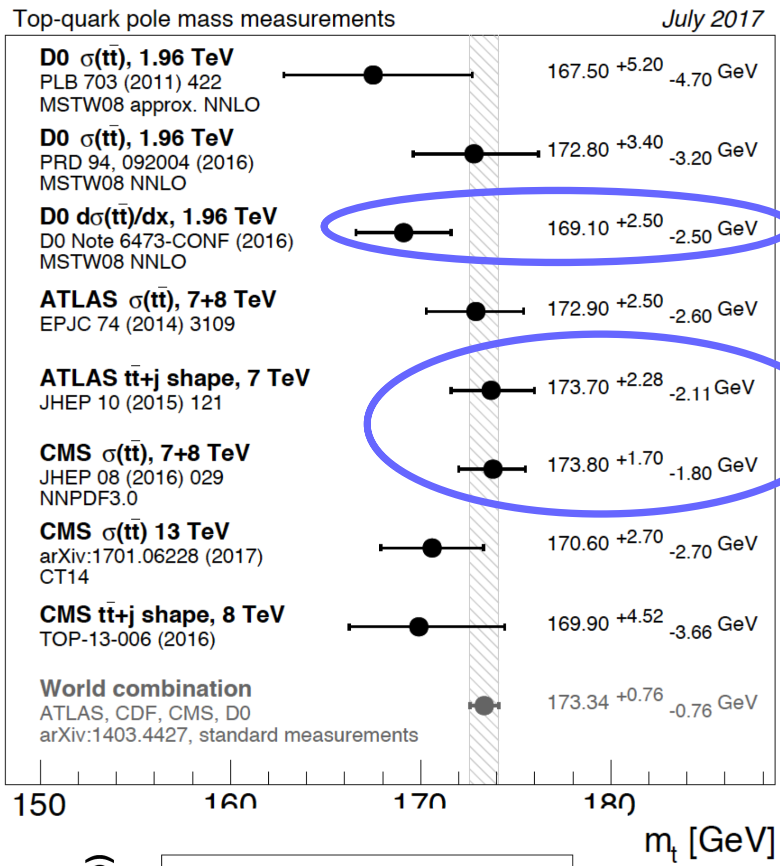
# Indirect methods

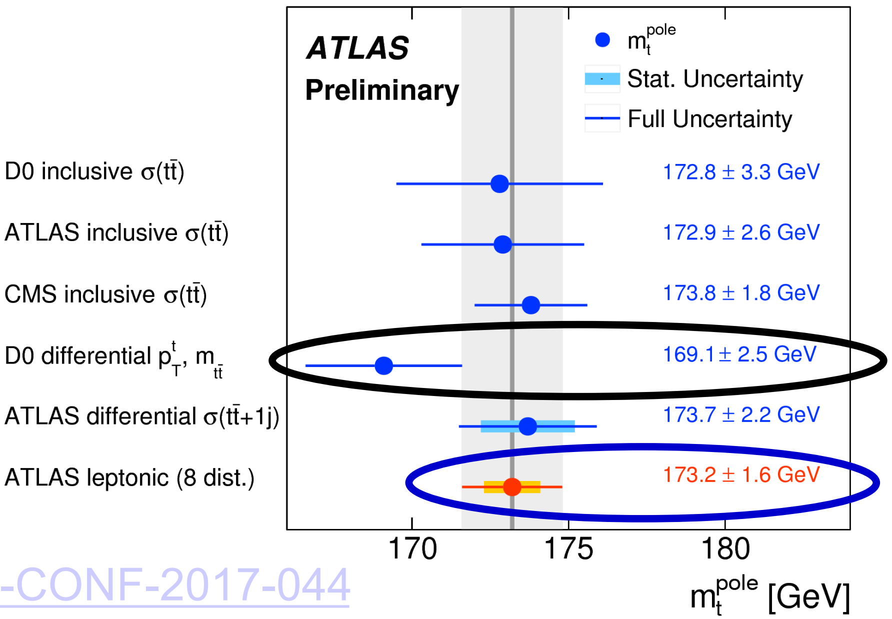
CMS [arXiv:1603.02303]
CMS-TOP-16-006

- Extraction from production cross section not (yet) competitive with direct measurements – but getting closer
- ATLAS: 0.9%; CMS precision at 1%
  - **D0** precision (best at Tevatron): ~ 1.5%

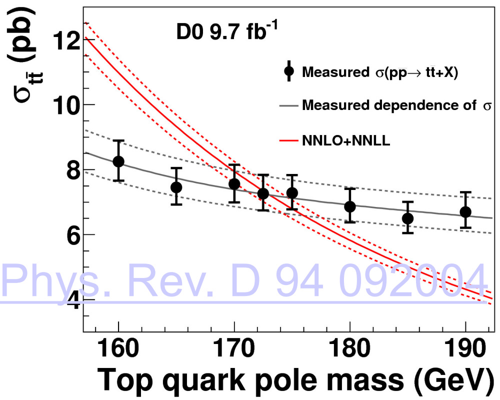
D0 6473

- With ~5% theory uncertainty and ~2% exp → can reach 0.5% on pole mass




ATLAS-CONF-2017-044




Phys. Rev. D 94 092004 (2016)

# Combinations / All results

Using BLUE:

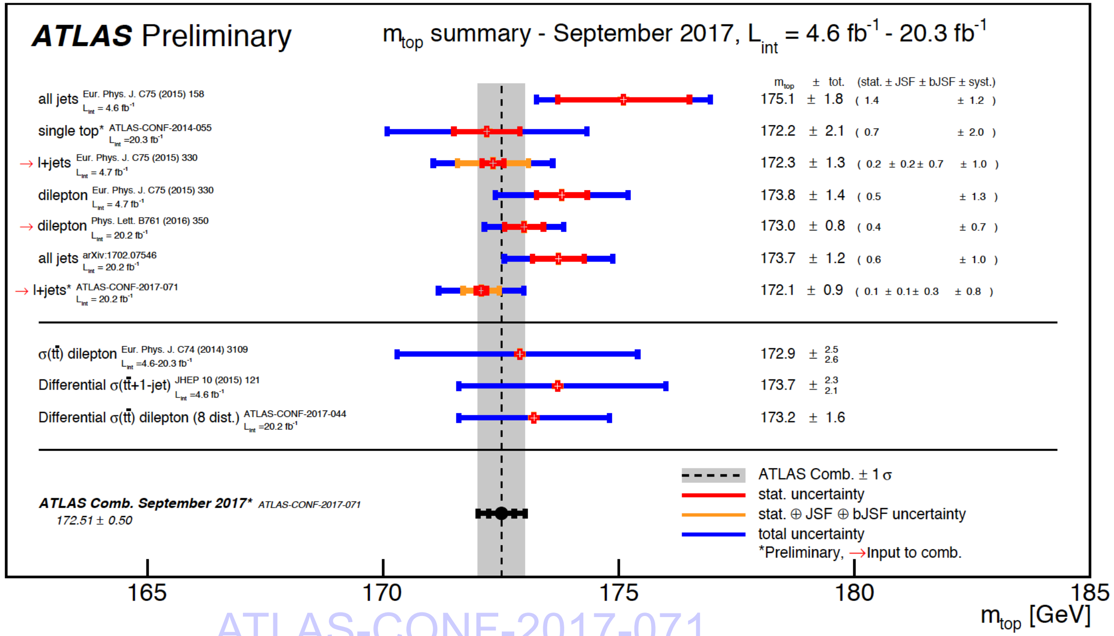
- Latest CMS combination

  $m_{top}$ = 172.44 ± 0.48 GeV $\delta m_t/m_t = 0.28\%$

- Alternative methods: CMS combination

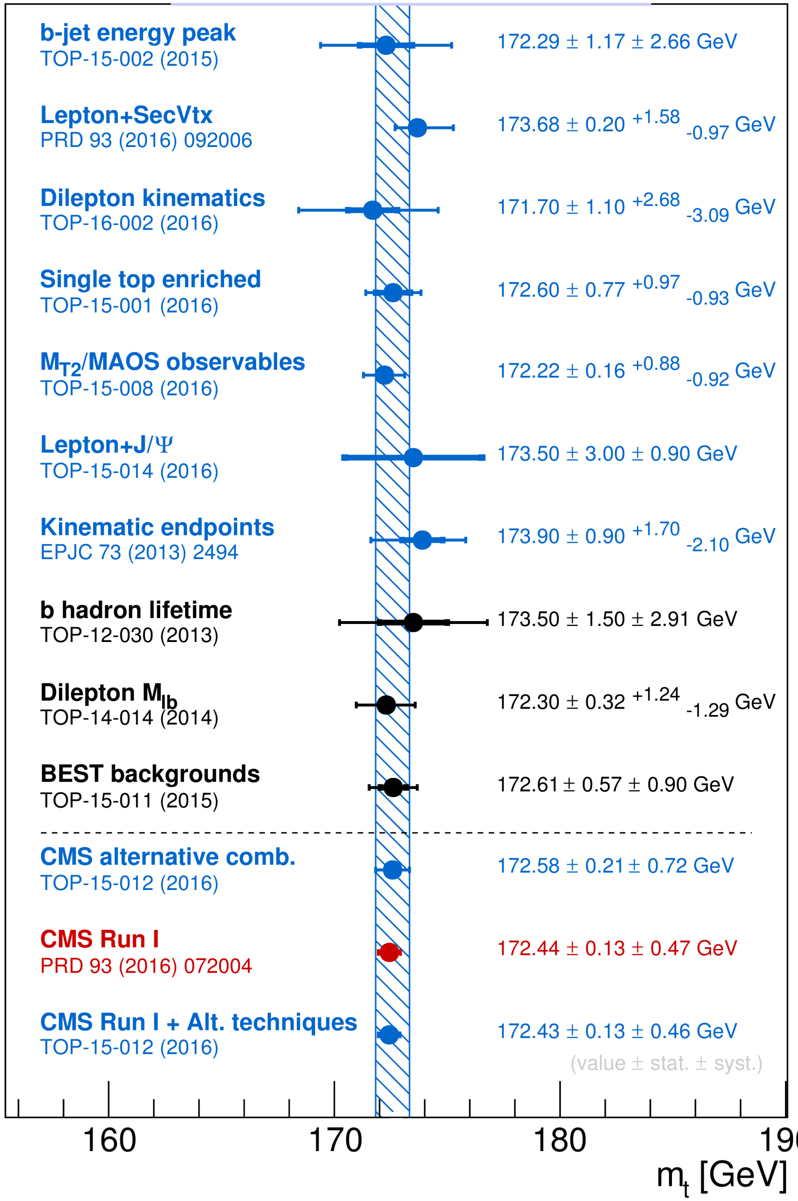
  $m_{top}$ = 172.58 ± 0.75 GeV $\delta m_t/m_t = 0.43\%$

→ Orthogonal systematic uncertainties, limited (for now) by statistical uncertainties

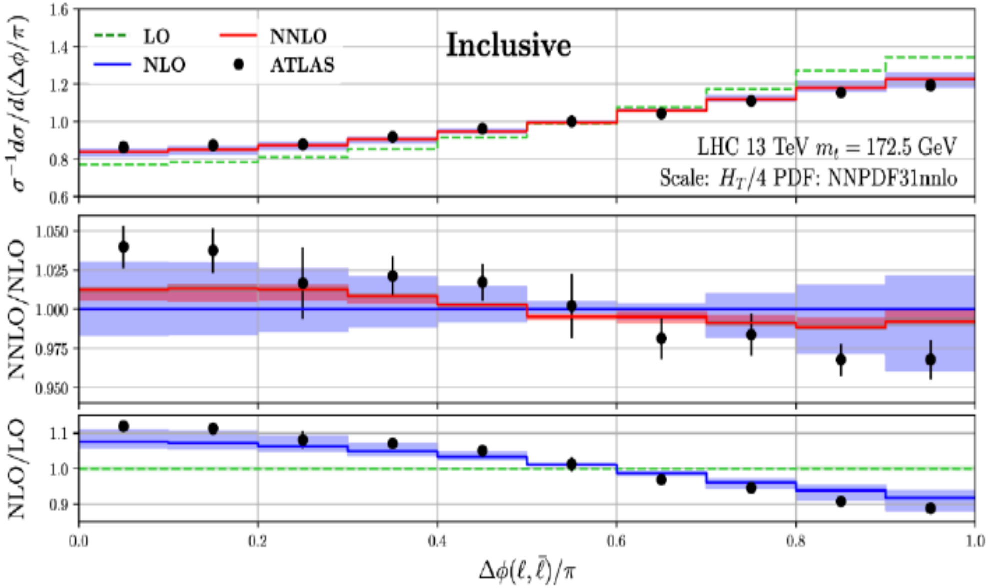


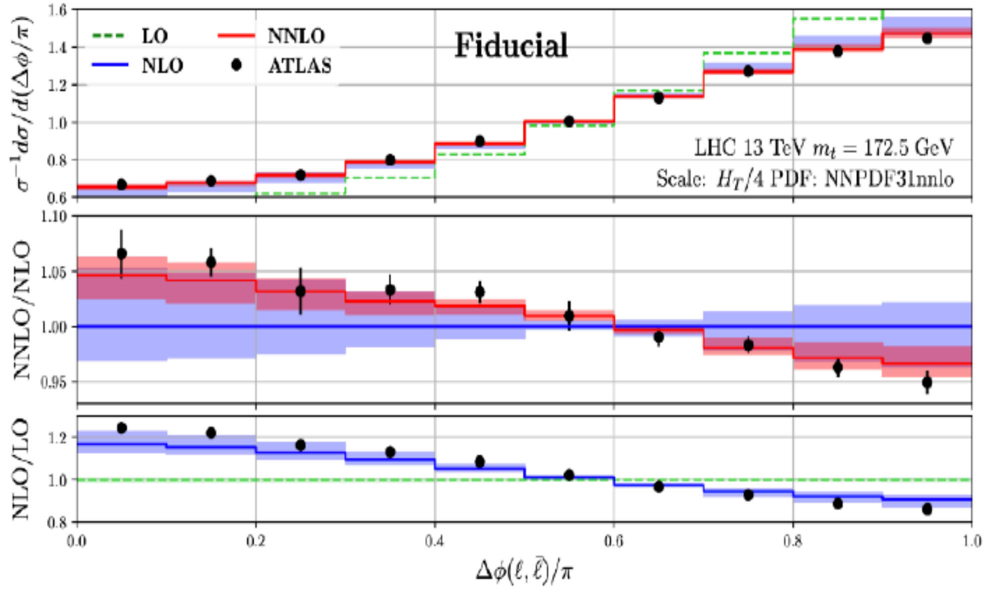

ATLAS-CONF-2017-071

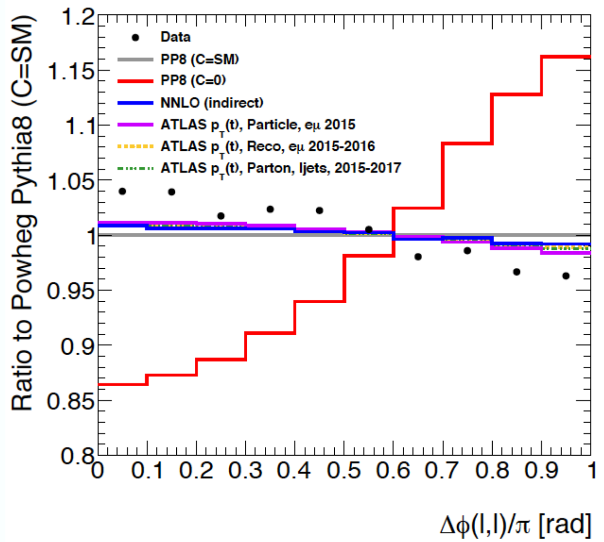
CMS-PAS-TOP-15-012



# Spin correlations



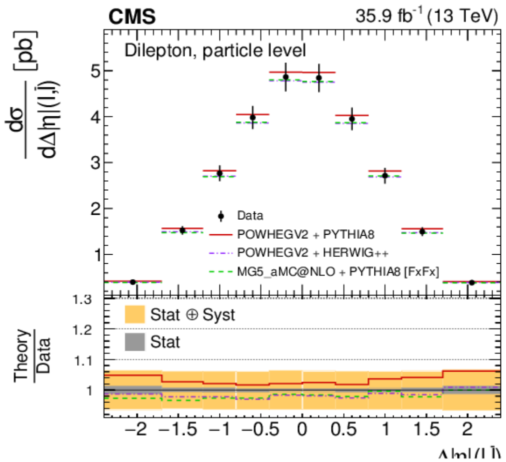
# Asymmetries

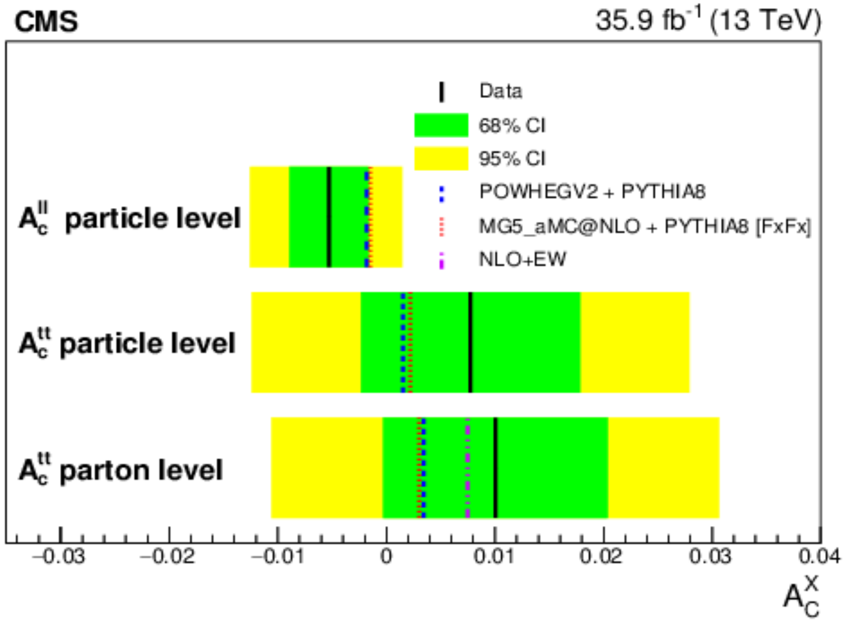
JHEP02 (2019) 149

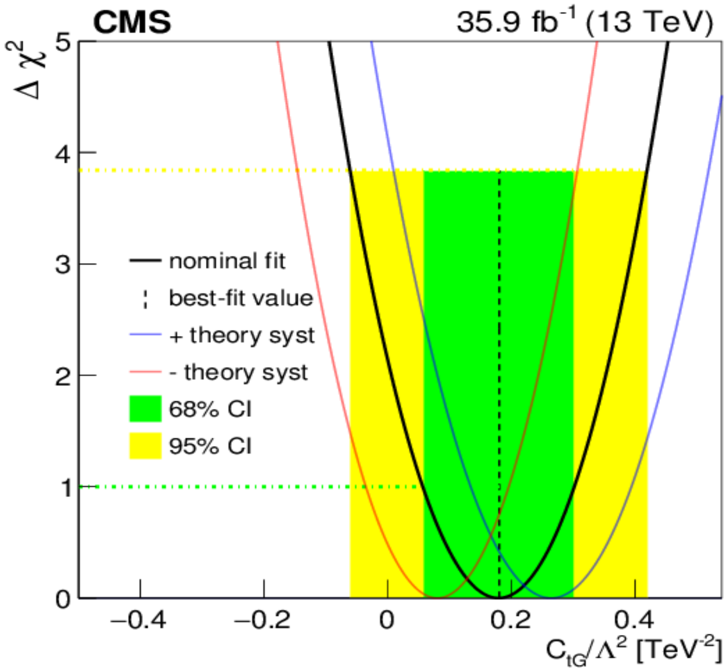
- Dilepton cross section measurement used to extract asymmetries based on unfolded particle and parton level distributions
- Employed asymmetries in dEta, dY

$$A_{c}^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}$$

$$A_{c}^{\ell\bar{\ell}} = \frac{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) - \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) + \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}$$



# tt+1jets, mtpole, MSbar

| Mass scheme | $m_t^{\text{pole}}$ [GeV] | $m_t(m_t)$ [GeV] |
|---|---|---|
| **Value** | **171.1** | **162.9** |
| **Statistical uncertainty** | **0.4** | **0.5** |
| *Simulation uncertainties* | | |
| Shower and hadronisation | 0.4 | 0.3 |
| Colour reconnection | 0.4 | 0.4 |
| Underlying event | 0.3 | 0.2 |
| Signal Monte Carlo generator | 0.2 | 0.2 |
| Proton PDF | 0.2 | 0.2 |
| Initial- and final-state radiation | 0.2 | 0.2 |
| Monte Carlo statistics | 0.2 | 0.2 |
| Background | <0.1 | <0.1 |
| *Detector response uncertainties* | | |
| Jet energy scale (including $b$-jets) | 0.4 | 0.4 |
| Jet energy resolution | 0.2 | 0.2 |
| Missing transverse momentum | 0.1 | 0.1 |
| $b$-tagging efficiency and mistag | 0.1 | 0.1 |
| Jet reconstruction efficiency | <0.1 | <0.1 |
| Lepton | <0.1 | <0.1 |
| *Method uncertainties* | | |
| Unfolding modelling | 0.2 | 0.2 |
| Fit parameterisation | 0.2 | 0.2 |
| **Total experimental systematic** | **0.9** | **1.0** |
| Scale variations | (+0.6, −0.2) | (+2.1, −1.2) |
| Theory PDF$\oplus\alpha_s$ | 0.2 | 0.4 |
| **Total theory uncertainty** | **(+0.7, −0.3)** | **(+2.1, −1.2)** |
| **Total uncertainty** | **(+1.2, −1.1)** | **(+2.3, −1.6)** |

# Even More Backup...

## Particle flow

- Combines detector information to ID particles

Jets and missing $E_T$

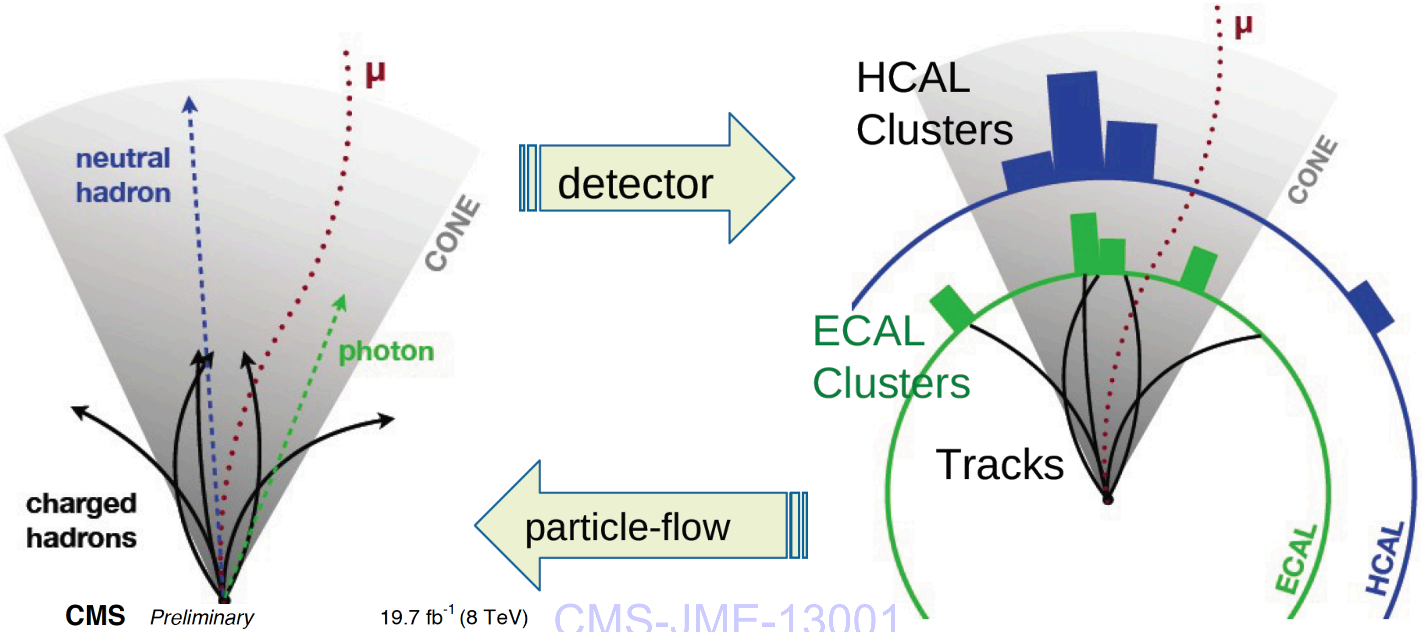
- Gamma & Z-jet balance
- Pile-up subtraction

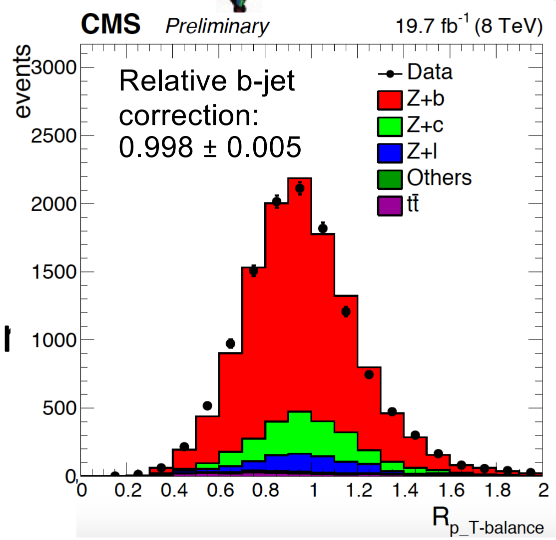
Isolated Leptons

- Dilepton resonances (Z, upsilon, J/psi)

"b-tagging" of jets

- Several techniques, dominated by silicon tracker information

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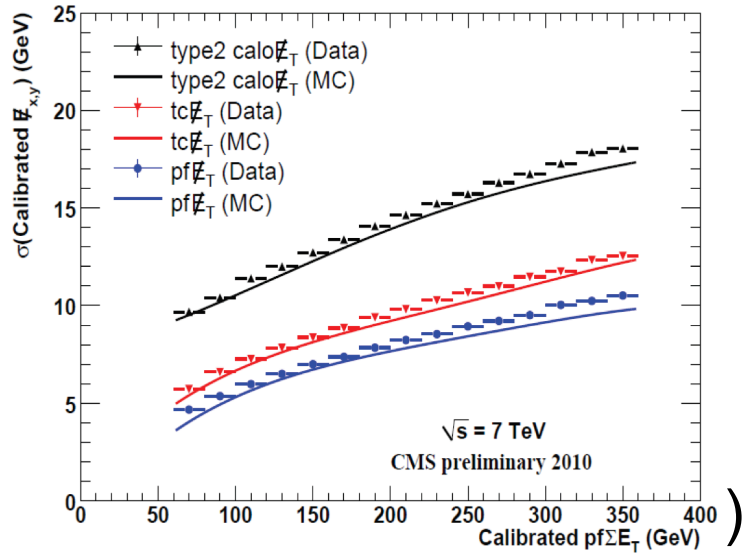
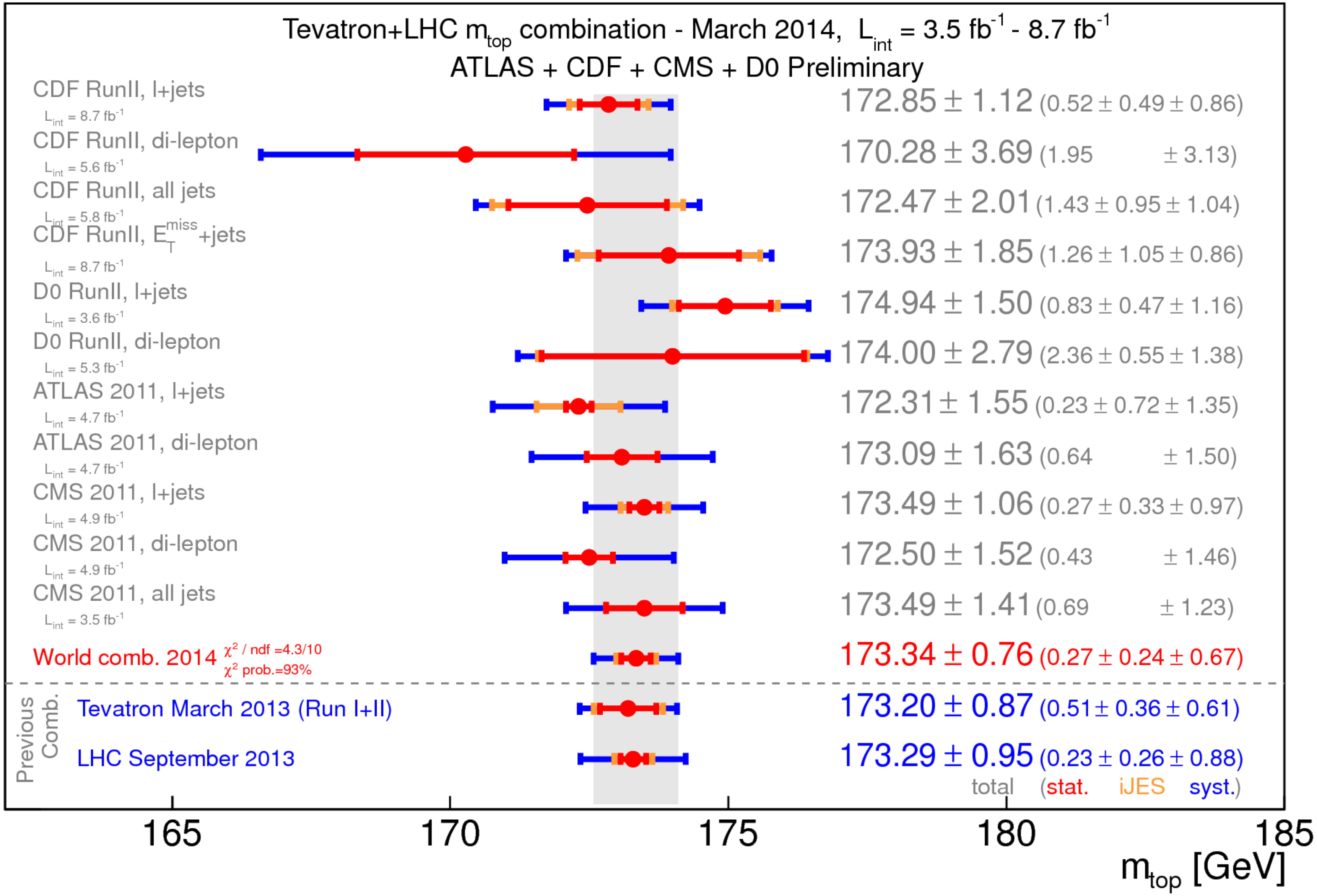



- Top quark physics requires precise b- and c-phy )

# World combination

[arxiv:1403.4427]



# LHC operations