Recent results on top quark mass and properties and rare/anomalous top quarks interactions in CMS

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

Sebastian Wuchterl (DESY)

for the CMS collaboration

13 April 2021

Link to all CMS TOP results

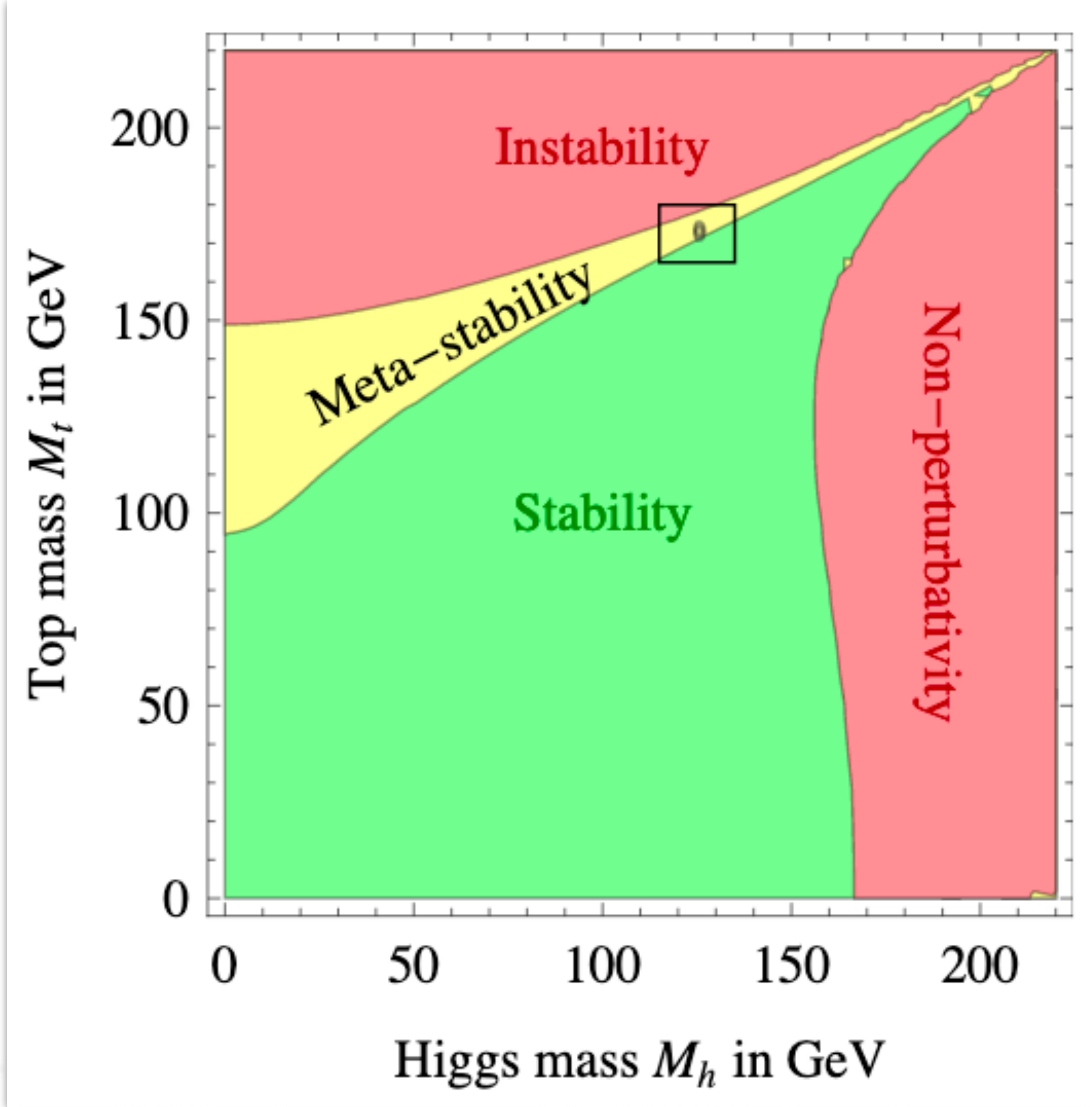
HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

Introduction

Top quark as a probe for the SM

- most massive elementary particle known
- Yukawa coupling ~1 to Higgs boson
  - high relevance for the EWK symmetry breaking
- only quark that decays before forming bound states
  - → unique way to study 'bare' quark properties



- high production rate at LHC
  - → high precision SM measurements
  - +
  - → indirect search for BSM physics

- multitude of interesting top properties measurements

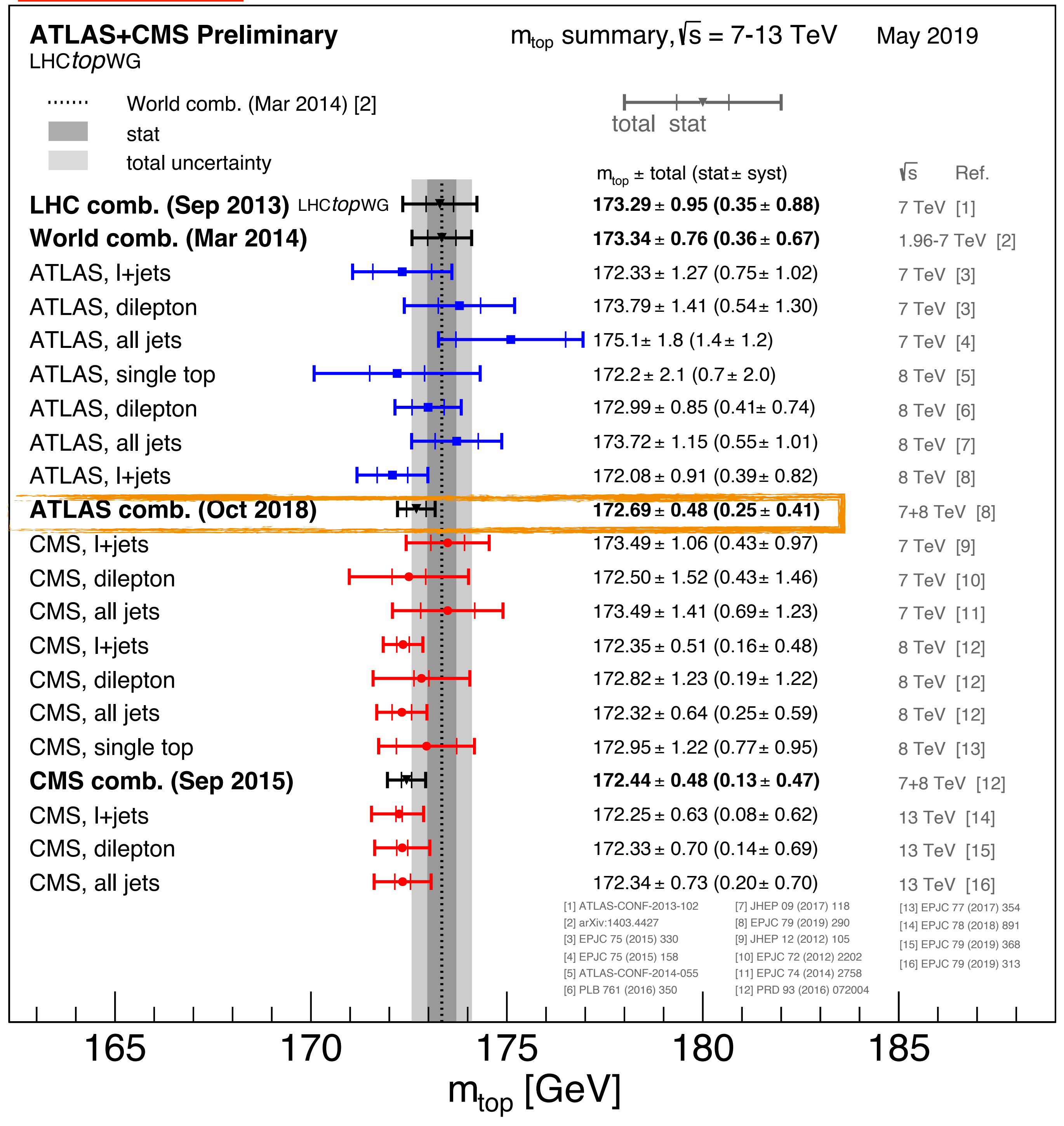
(overview about differential part of analyses in R. Verma's talk)

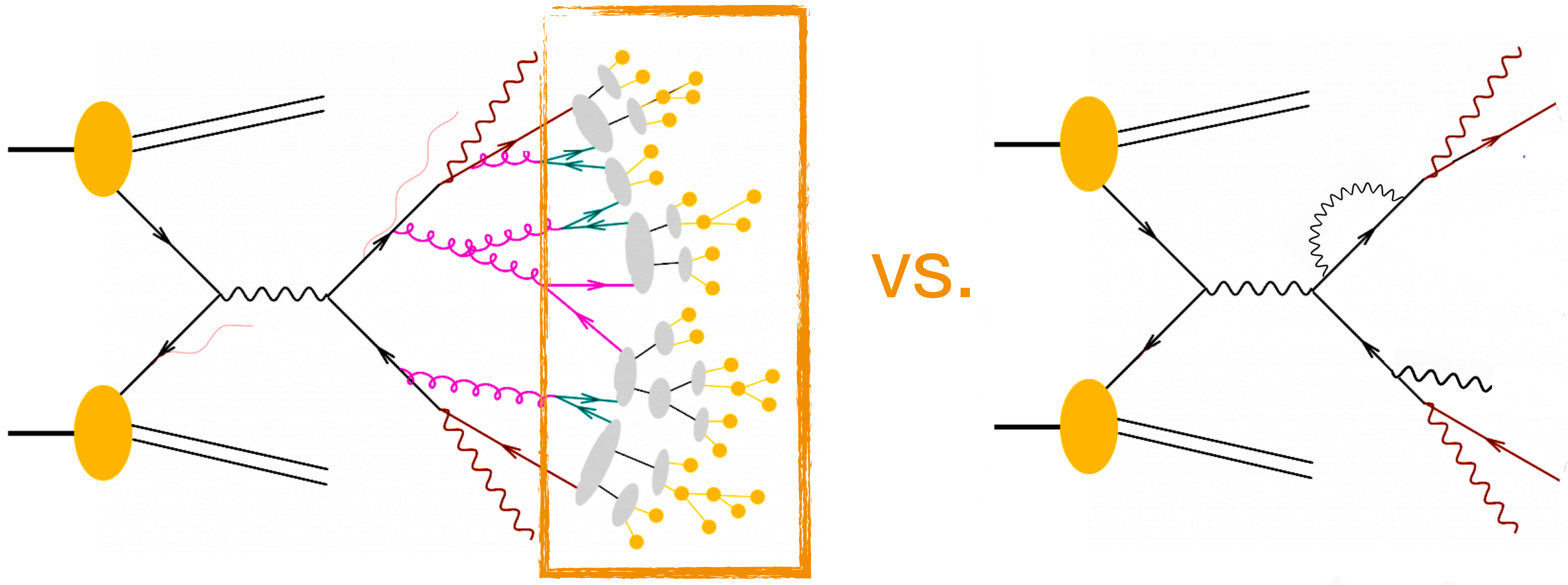
Top quark mass

Direct measurements m_t^{MC} ⟷ m_t indirect measurements

- measuring m_t^{MC} using reconstructed decay products
  - very high experimental precision
    - ~0.5 GeV
  - relies on details of MC simulation

Reference

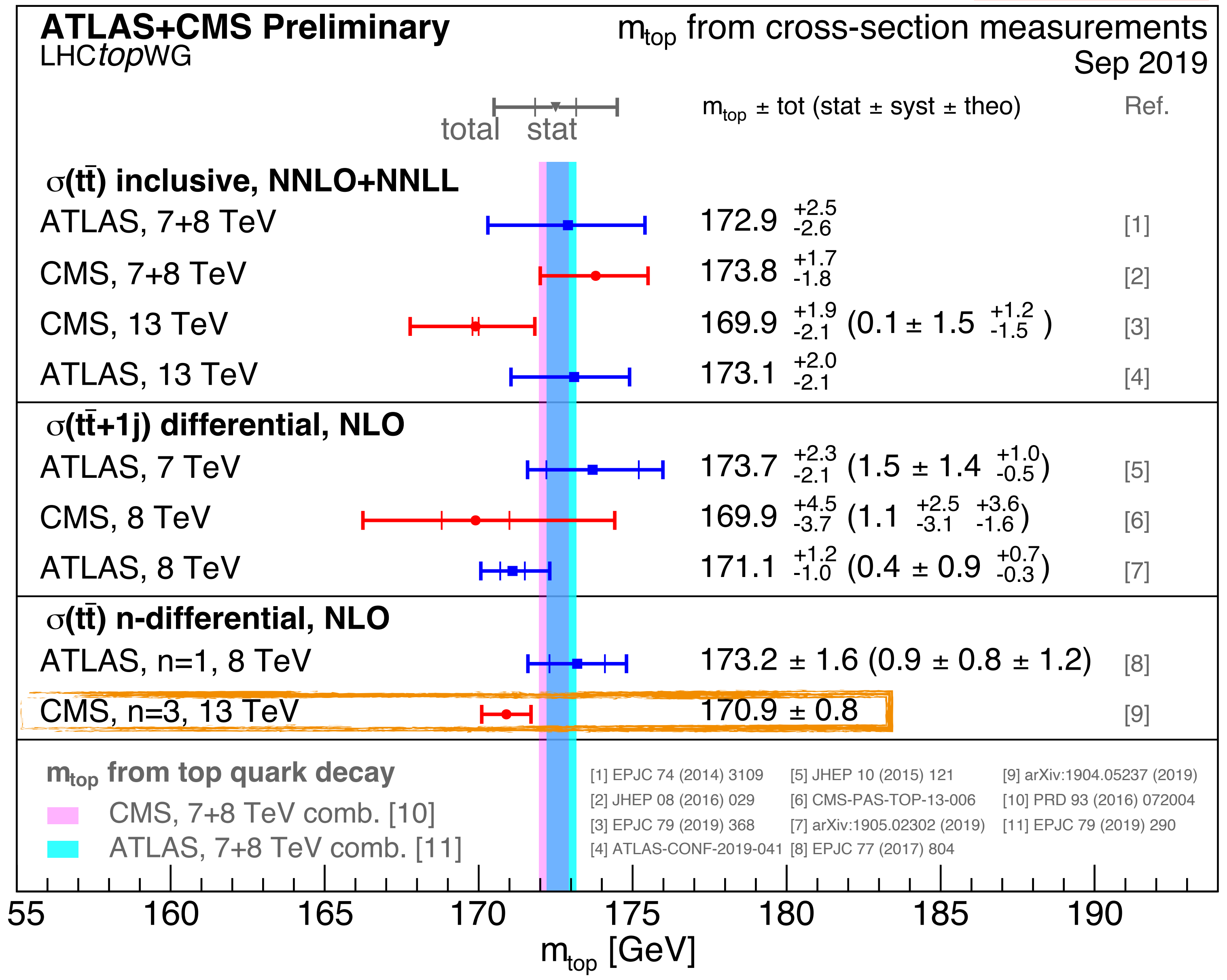




vs.

- extract m_t in well defined renormalisation scheme (pole, MS)
- measuring observables with direct sensitivity to m_t

Reference



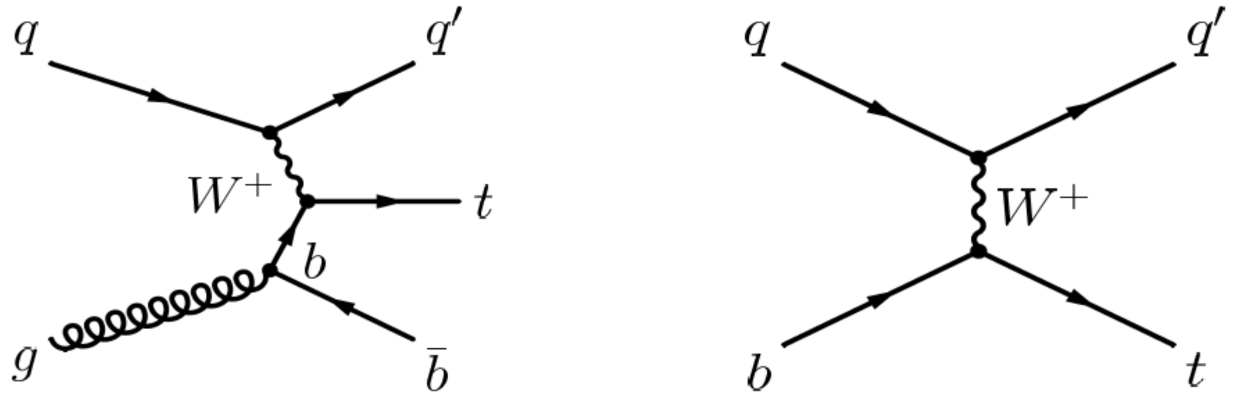
$$m_t^{MC} = m_t^{pole} \pm \Delta_{MC}\, O(1GeV)$$

Top quark mass

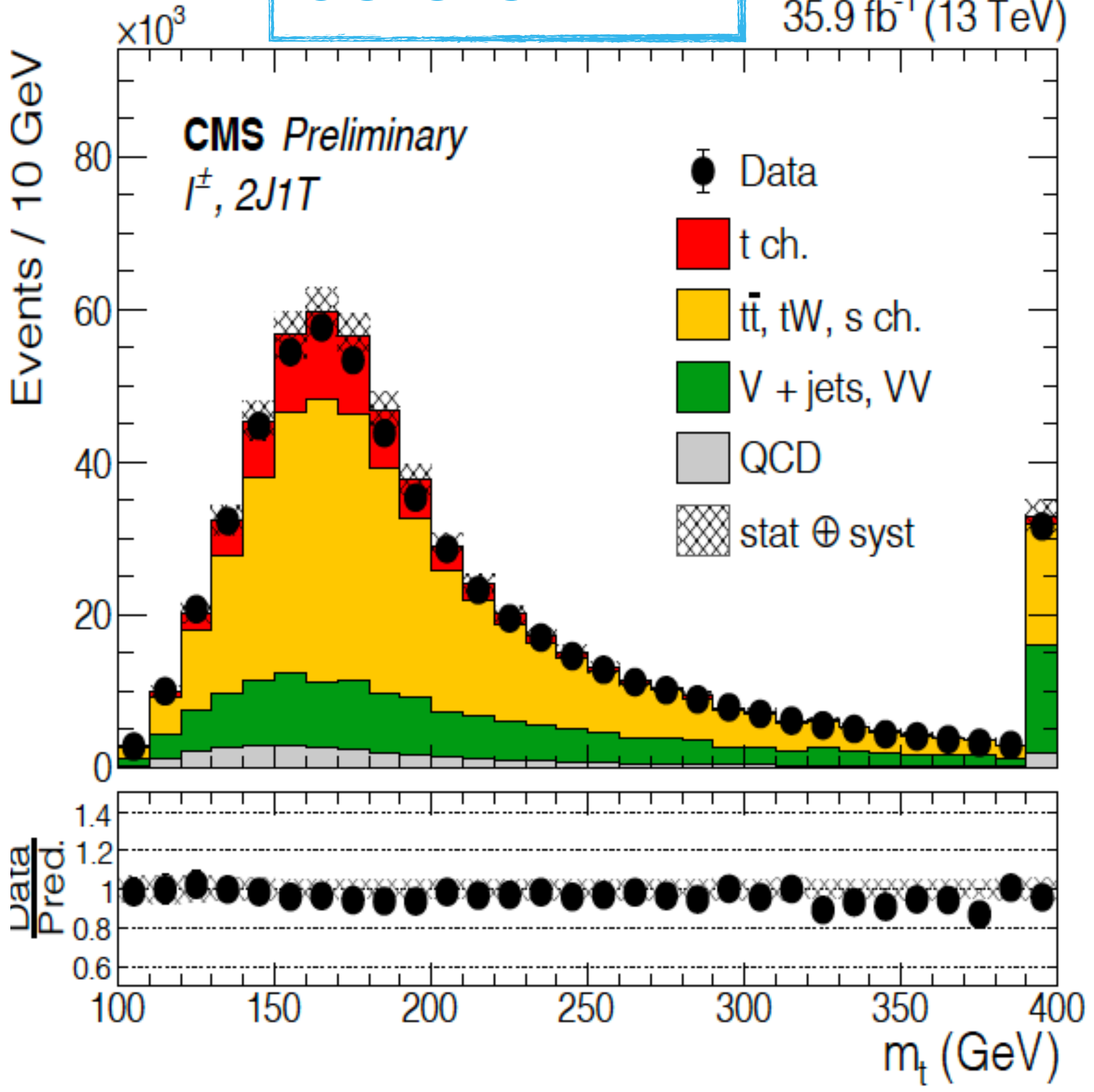
Single top t-channel | 2016 data

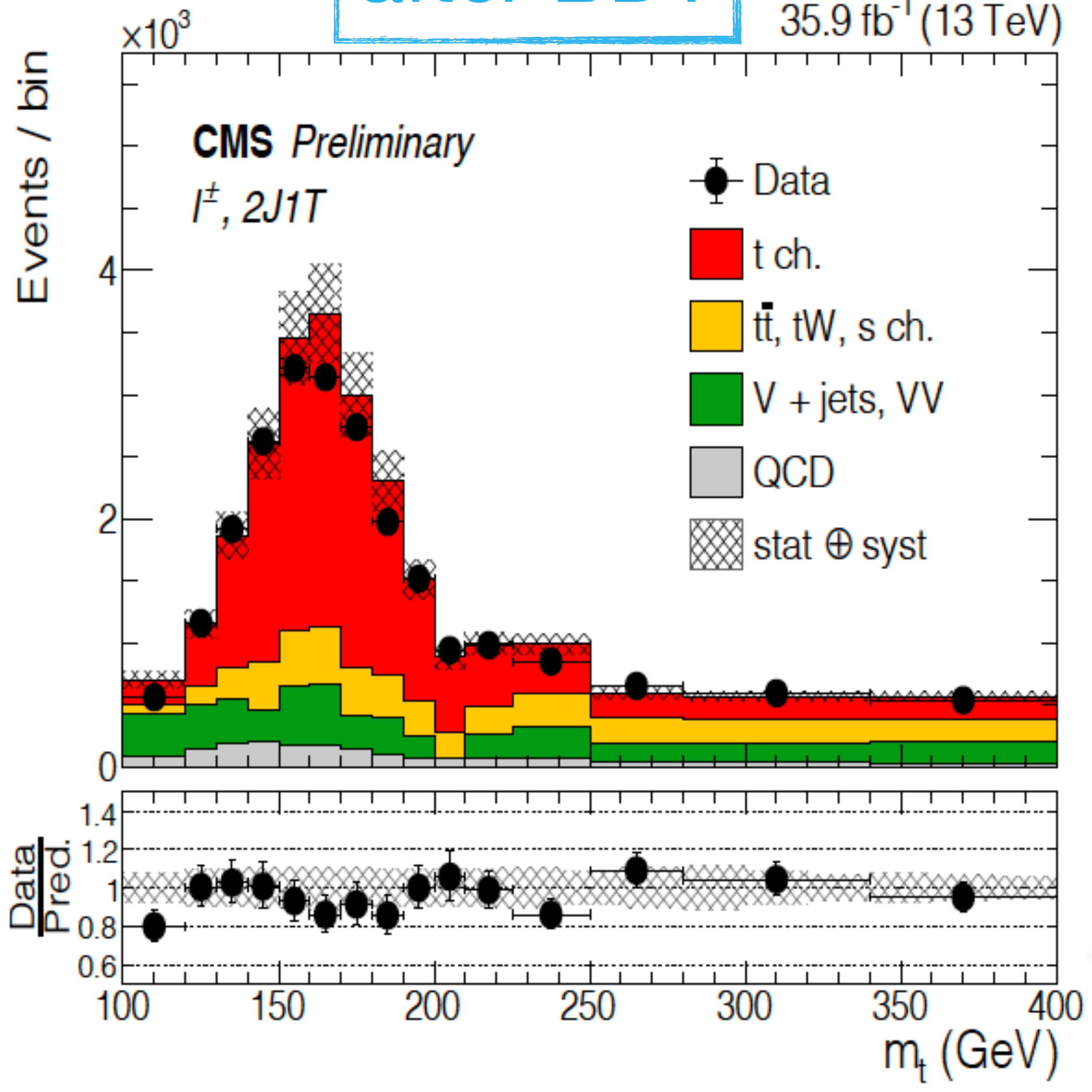
NEW!

- measurement of m_t in a data sample enriched with single top events in lepton+jets channel

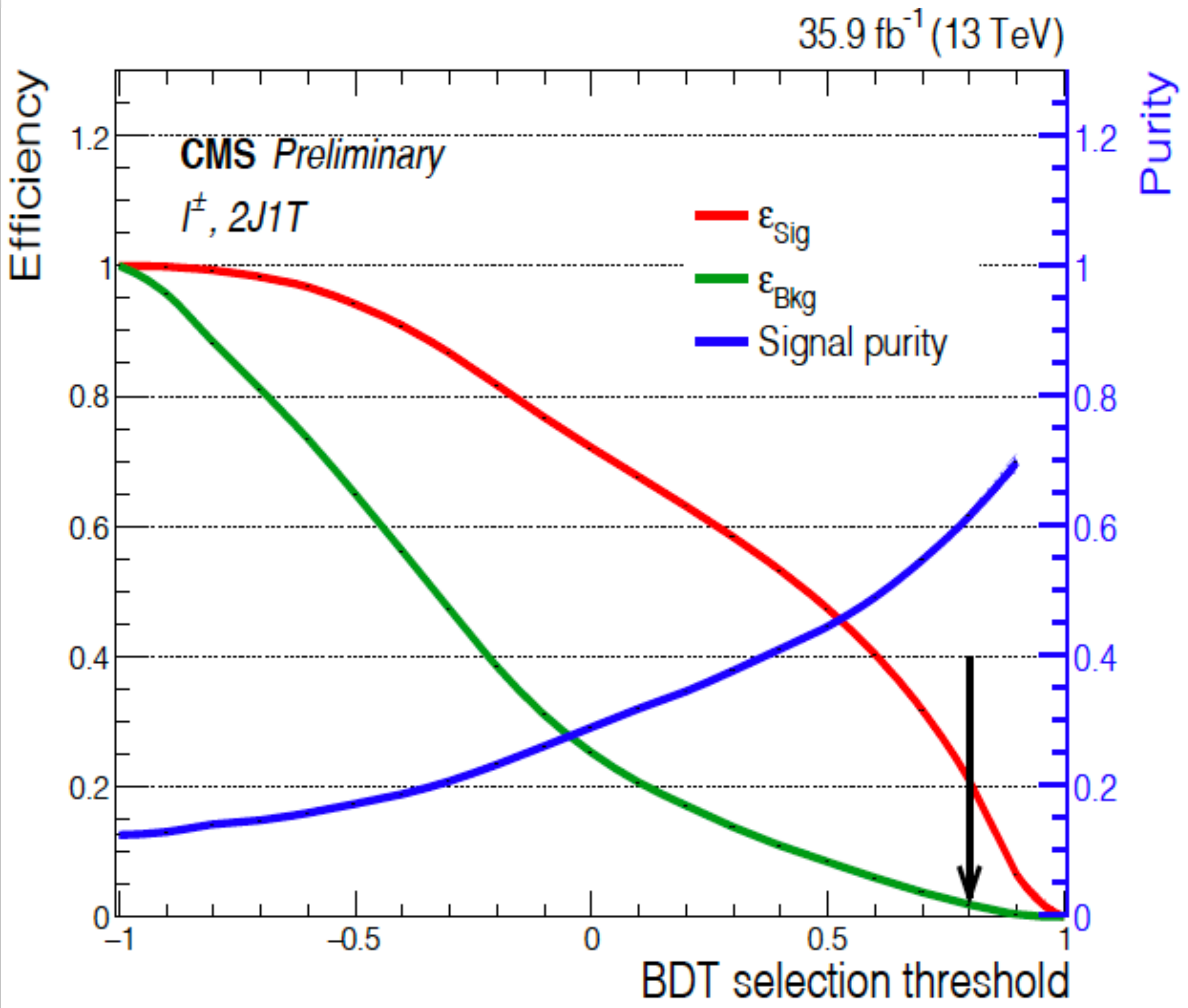


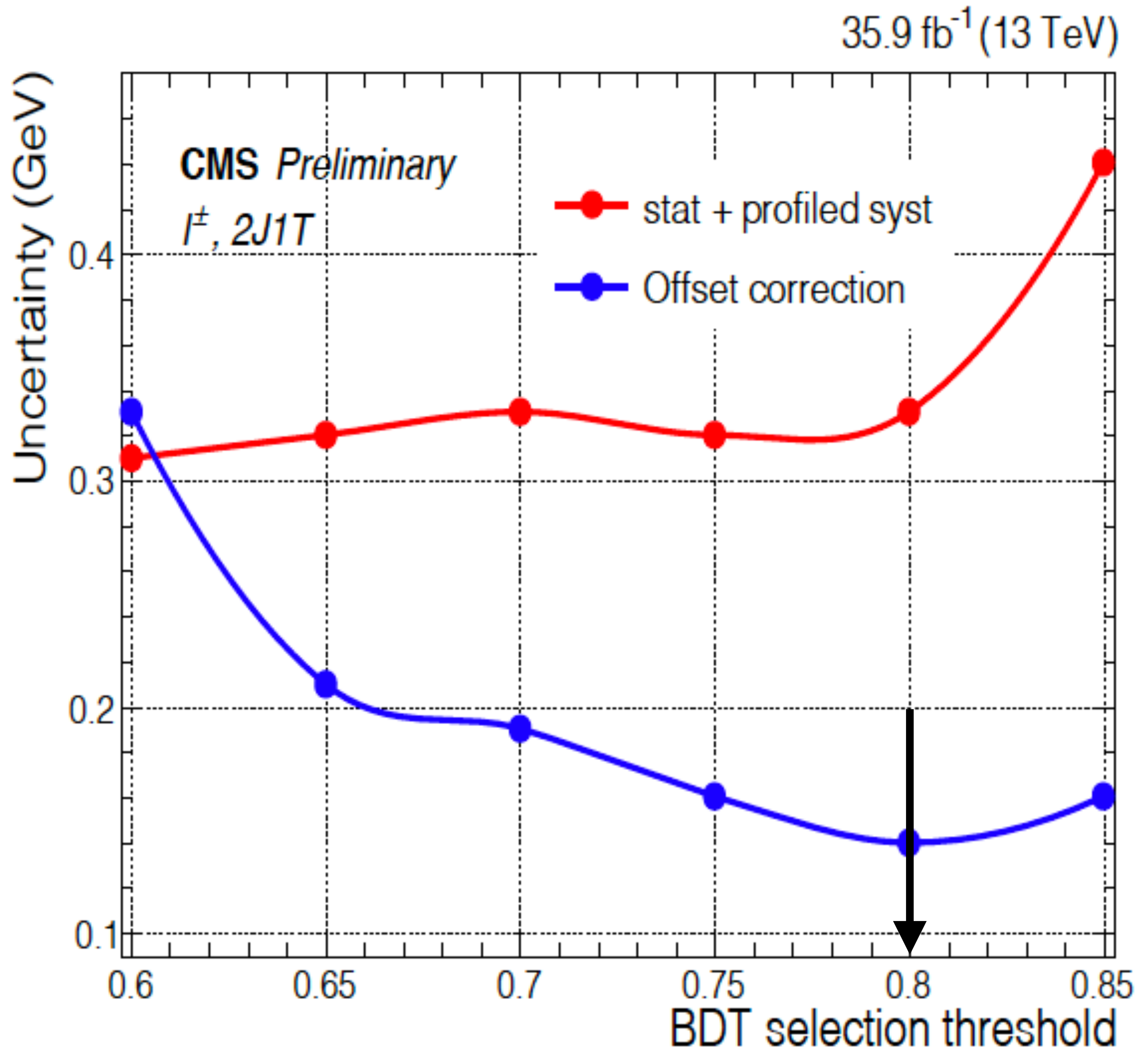
  - separated wrt. lepton flavour & charge
    → measure quark/antiquark masses individually





CMS-PAS-TOP-19-009





- intensive optimisations of **multivariate** (BDT) discriminators to enrich sample with t-ch. single top
  - reduced correlation to m_t
  - studied bias on m_t
  - calibrations based on final results

Top quark mass

Single top t-channel | 2016 data

NEW!

- extract m_t with parametric fit

$$F(y;\boxed{y_0}, f_{t-ch}, f_{Top}, f_{EWK}) = f_{t-ch}\cdot \boxed{F_{t-ch}(y;y_0)} + f_{Top}\cdot \boxed{F_{Top}(y;y_0)} + f_{EWK}\cdot \boxed{F_{EWK}(y)}$$

$y_0 = \ln(m_t)$

  - m_t also varied in $t\bar{t}$ background

$$\rightarrow \quad m_t = 172.13 \pm 0.32\,(\text{stat}+\text{prof})\,^{+0.69}_{-0.70}\,(\text{syst})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

- use of lepton charge to measure quark/antiquark masses

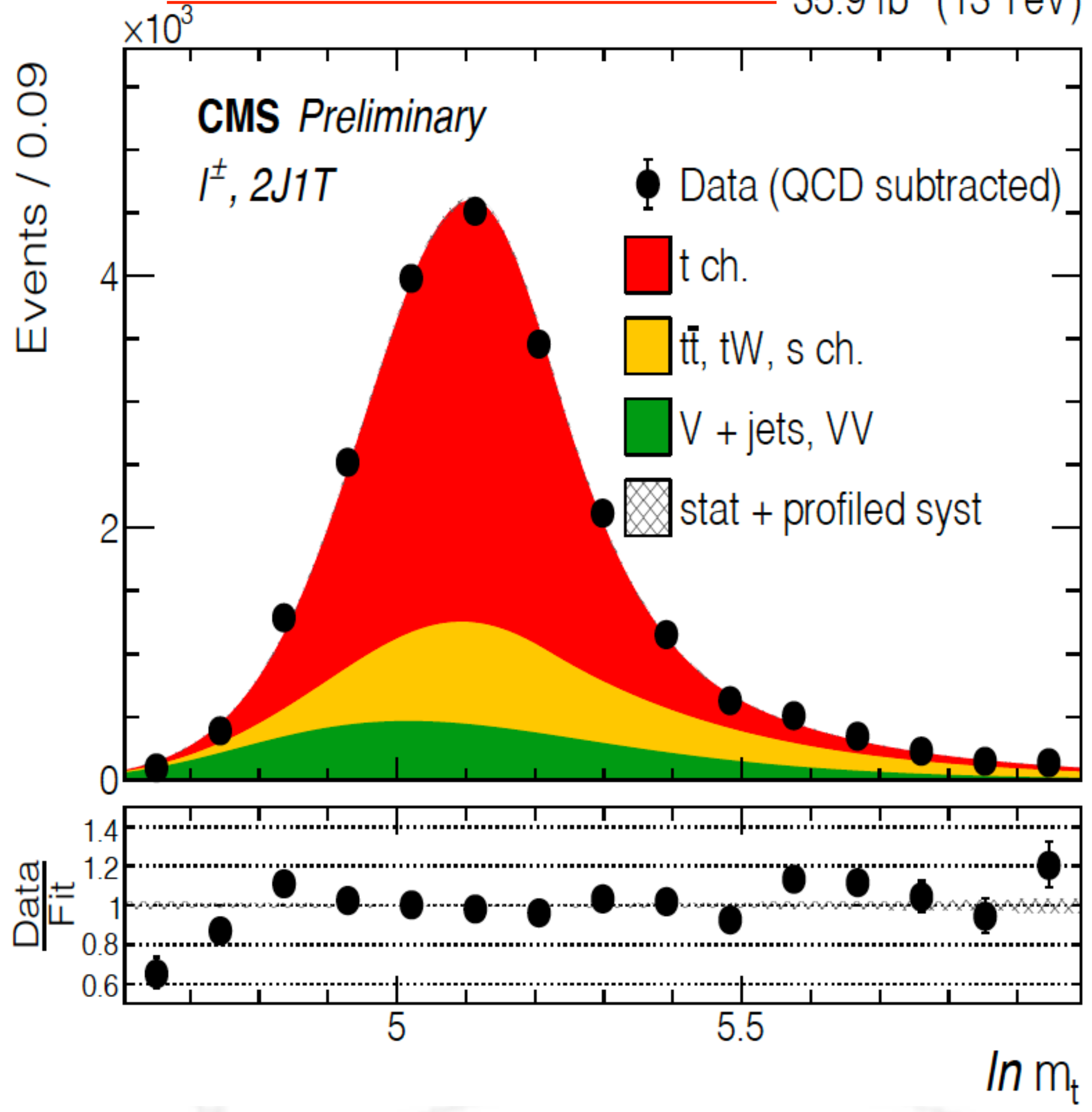
$$m_t = 172.62 \pm 0.37\,(\text{stat}+\text{prof})\,^{+0.97}_{-0.65}\,(\text{syst})\ \text{GeV}$$
$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat}+\text{prof})\,^{+1.32}_{-1.39}\,(\text{syst})\ \text{GeV}$$

  - difference + ratio in agreement with SM

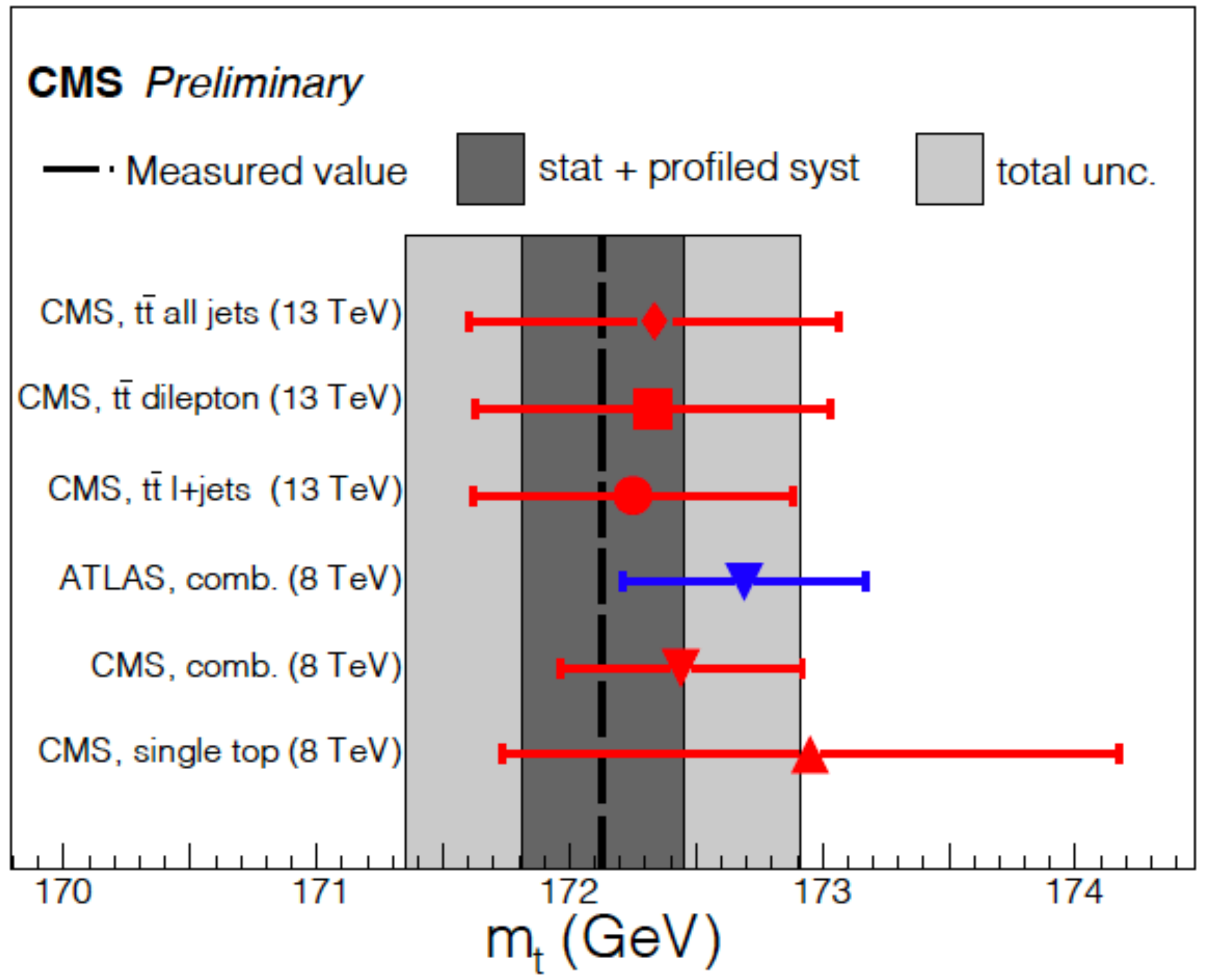
$$\Delta m_t = m_t - m_{\bar{t}} = 0.83^{+0.77}_{-1.01}\ \text{GeV} \qquad R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995^{+0.005}_{-0.006}$$

- limited by jet energy scale (JES) and modelling (FSR & CR)

CMS-PAS-TOP-19-009



first time sub-GeV precision in single top phase space

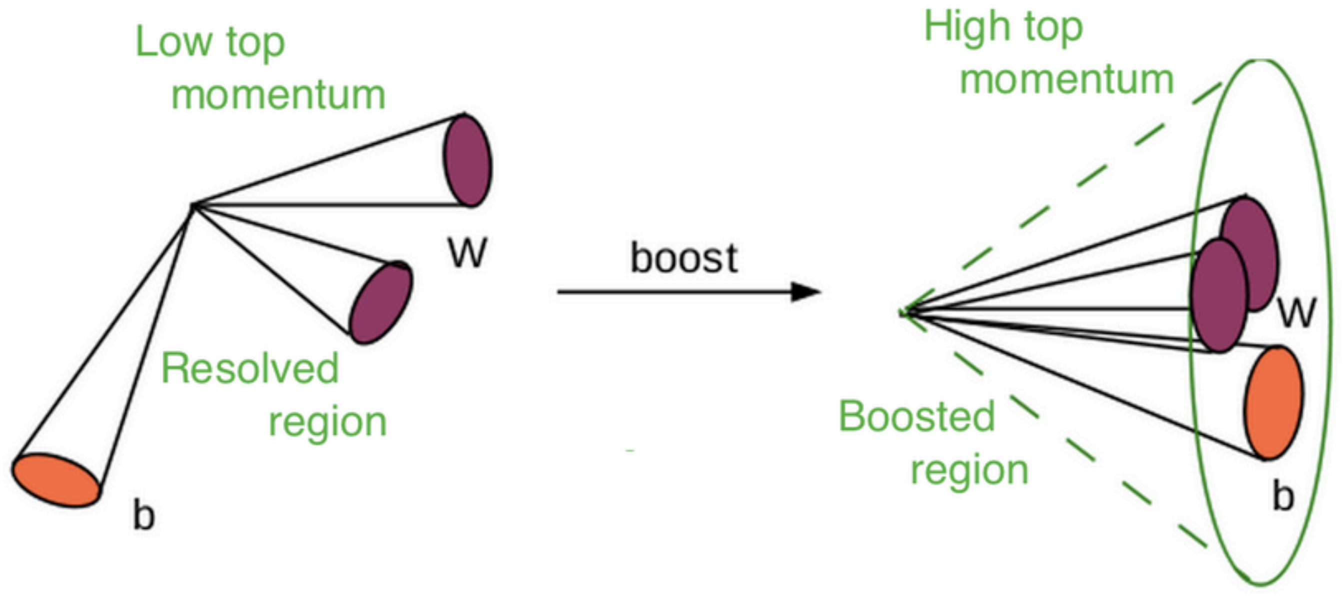


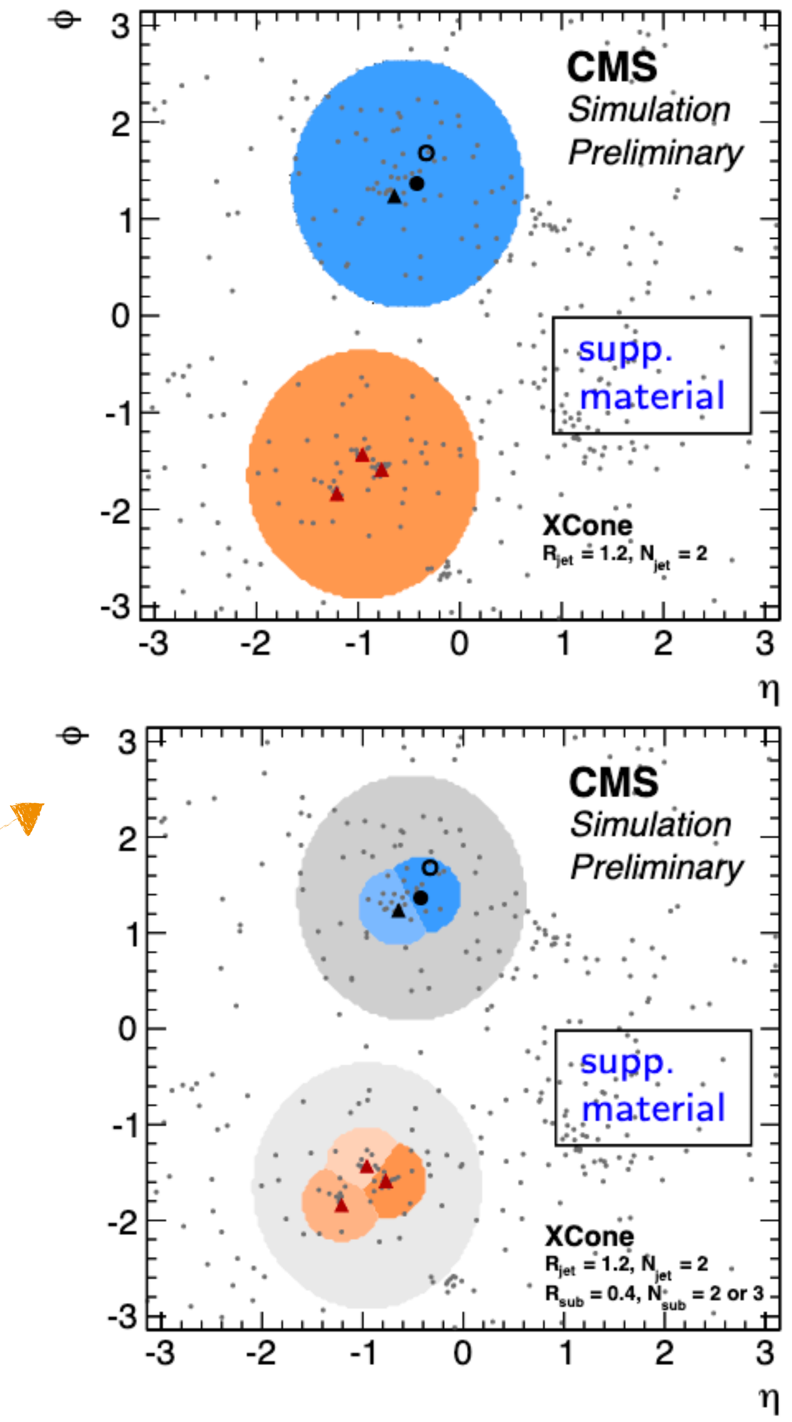
Top quark mass

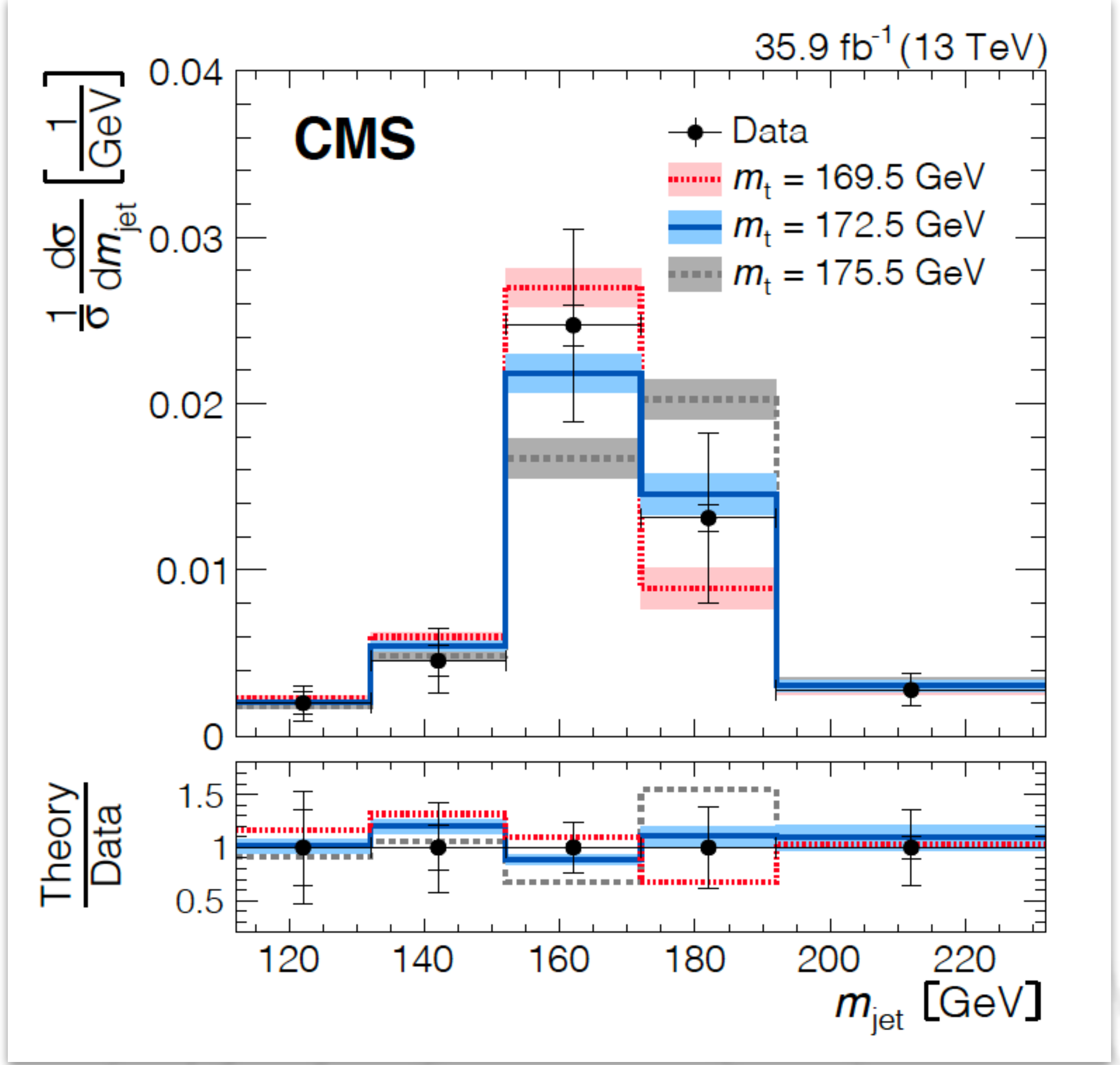
Boosted jets ($t\bar{t}$ l+jets) | 2016 data

[Phys. Rev. Lett. 124, 202001 (2020)](#)

- m_t from jet mass in boosted top decays
  - decay products merged in one single jet







  - using **Xcone algorithm** (first time at LHC)
    - two step procedure (two tops, then decay products)
    - → factor 2 improvement in jet width (particle level & exp. resolution)
    - → factor 4 improvement wrt. previous iteration using Run I data

  - m_t from comparing to Powheg+Pythia

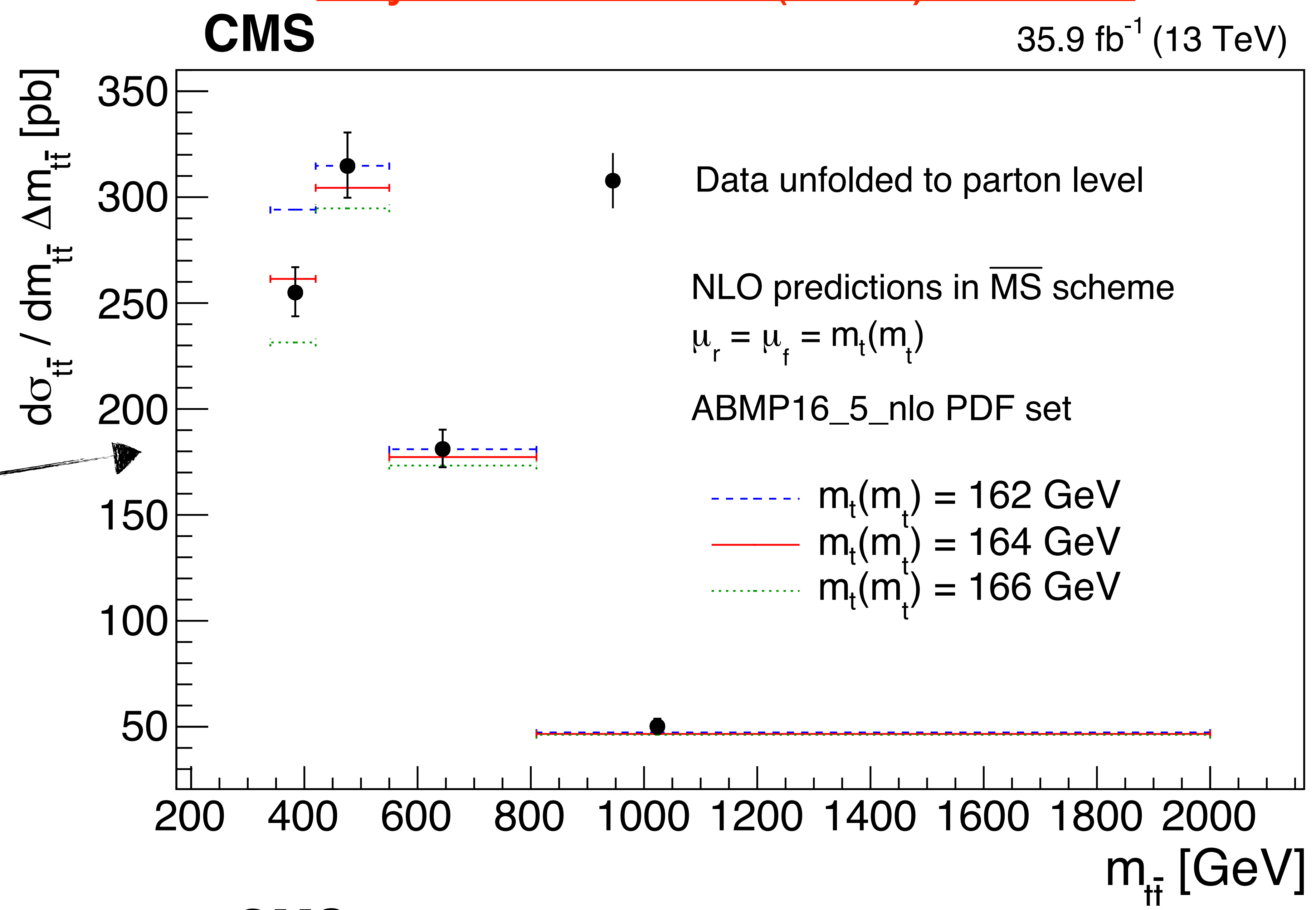
$$m_t = 172.6 \pm 0.4\,(\text{stat}) \pm 1.6\,(\text{exp}) \pm 1.5\,(\text{model}) \pm 1.0\,(\text{theo})\,\text{GeV}$$

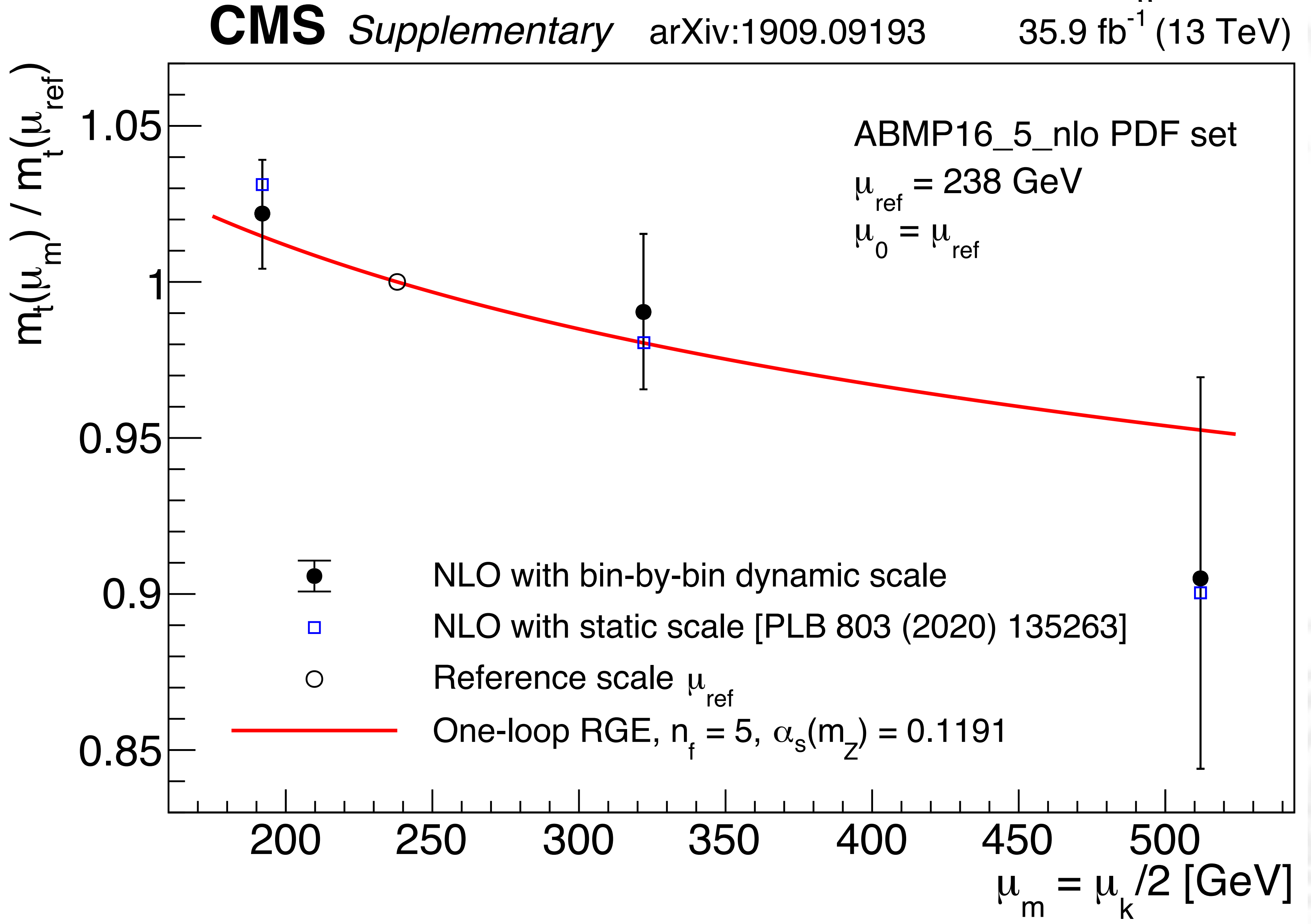
Mass running

$t\bar{t}$ dileptonic final states | 2016 data

Phys. Lett. B 803 (2020) 135263

- first experimental investigation of the top quark mass running
  - in MS scheme, m_t depends on energy scale $m_t(\mu_k)$
  - solution of RGE, like running of α_s
  - shape of invariant mass of $t\bar{t}$ pair
  - all $\sigma_{t\bar{t}}^{i}$ fitted simultaneously with m_t^{MC}
  - extract $m_t(m_t)$ in each bin of $m_{t\bar{t}}$ by comparison to NLO theory and evolve to $m_t(\mu_k)$
  - probe running by comparing to NLO predictions
    - up to a scale of 1 TeV



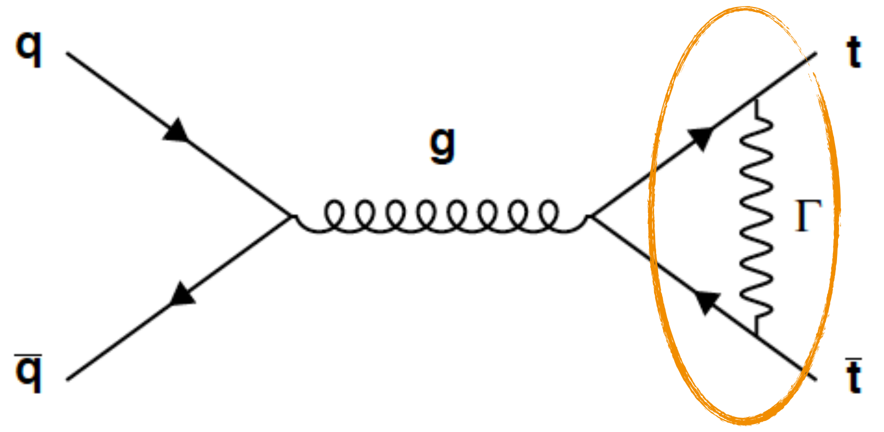


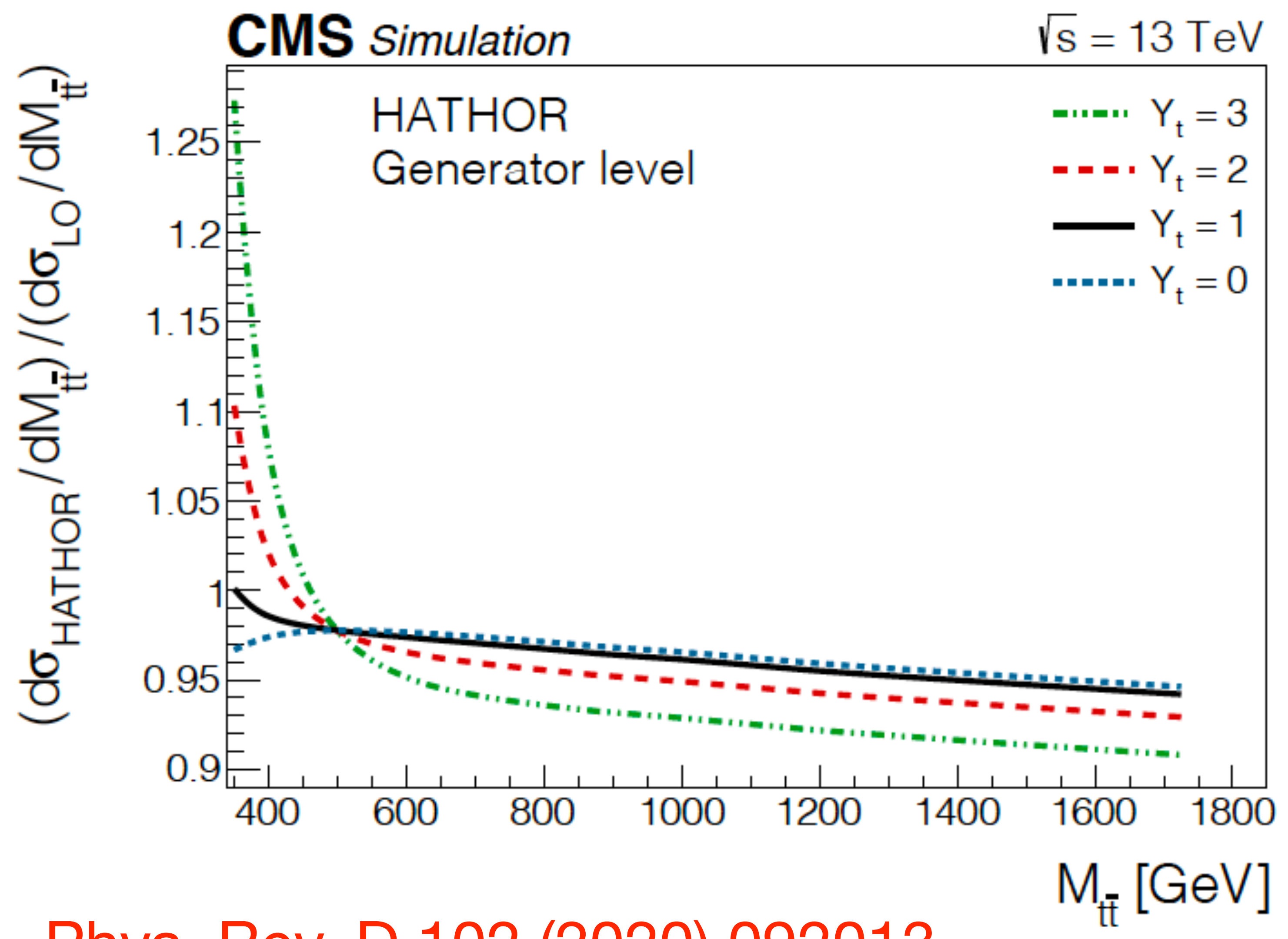
- results in agreement with SM RGE within 1.1σ
- no-running hypothesis excluded at 95% CL

Yukawa coupling

$t\bar{t}$ dileptonic final states | 2016-2018 data

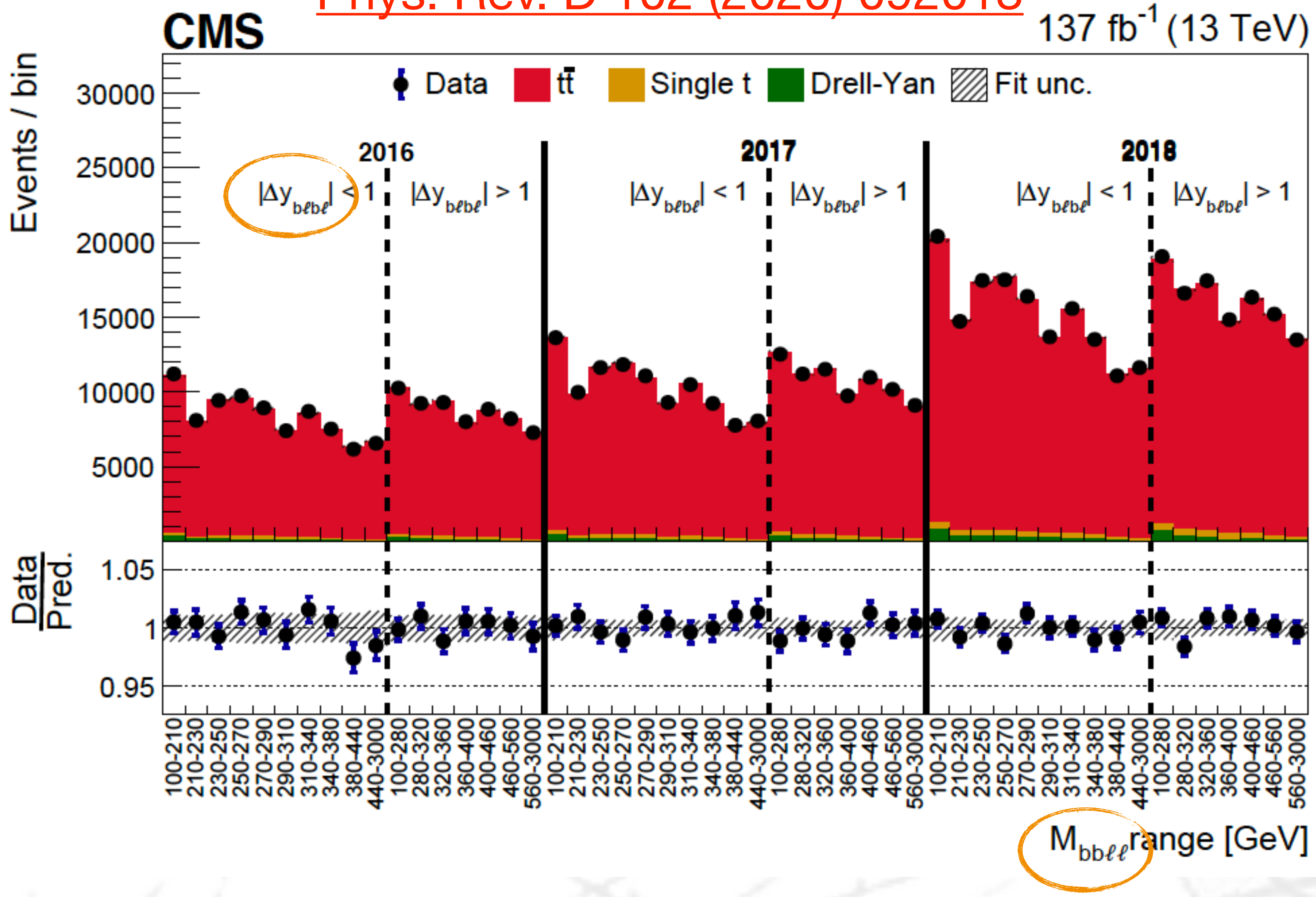
- **EW corrections** affect $t\bar{t}$ production
  - shape of $M_{t\bar{t}}$ and rapidity difference





- new analysis in $t\bar{t}$ dileptonic final states
- comparison at detector level by **reweighting NLO Powheg+Pythia** (weights obtained using HATHOR2 in 2D)

Phys. Rev. D 102 (2020) 092013



- mitigate p_T^{miss} dependence in dilepton channel by exploiting **lepton+b system as proxy**
  - multi differential fit to $M_{bb\ell\ell}\ x\ |\Delta y_{b\ell b\ell}|$

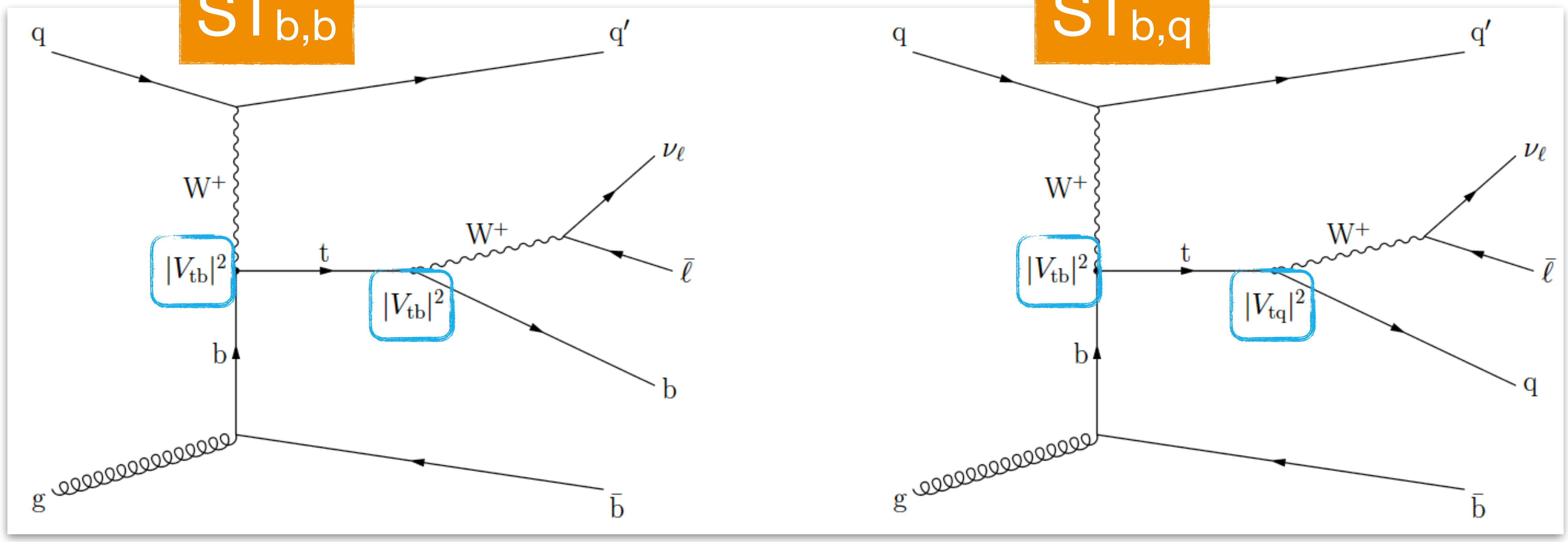
- limit at 95% CL: $Y_t < 1.54$
- best fit: $Y_t = 1.16^{+0.07}_{-0.08}\,(\mathrm{stat})^{+0.23}_{-0.34}\,(\mathrm{syst})$

- from combined Higgs measurements: $Y_t = 0.98 \pm 0.14$ (larger model dependence)
- from four tops search: $Y_t < 1.7$

$|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$

Single top t-channel | 2016 data

$ST_{b,b}$ $ST_{b,q}$



- first **simultaneous model-independent** measurement of CKM elements

- **three-fold interpretation** of signal strength parameters:
  - assuming SM CKM unitarity:

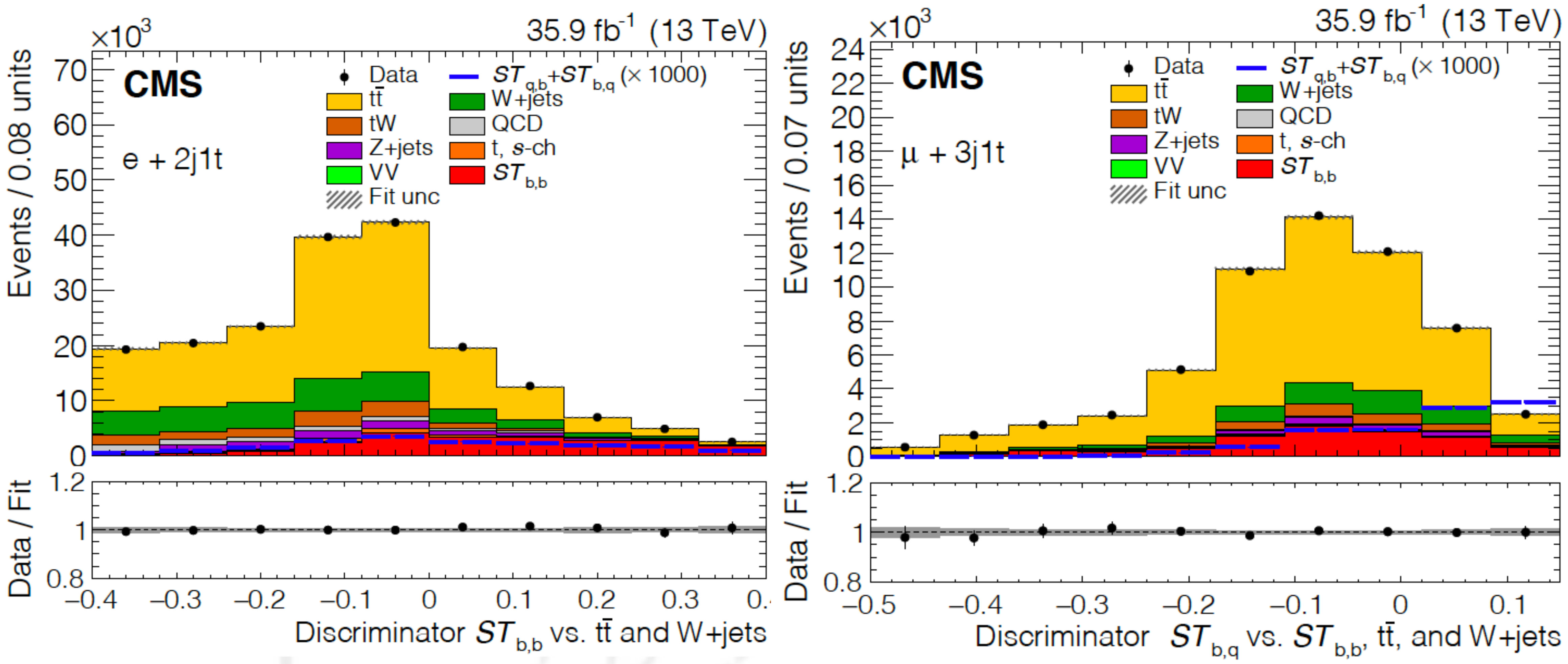
    $|V_{tb}| > 0.970$ $\quad |V_{td}|^2 + |V_{ts}|^2 < 0.057$
  - no unitary constraint (add. quark families)

    $|V_{tb}| = 0.988 \pm 0.051$ $\quad |V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$
  - top quark **total width** unconstrained

    $|V_{tb}| = 0.988 \pm 0.024$ $\quad |V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$ $\quad \frac{\Gamma_t^{obs}}{\Gamma_t} = 0.99 \pm 0.42$

- fitting multiple signals at the same time in different event categories

Phys. Lett. B 808 (2020) 135609



most precise single top measurement of $|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$ limited by modelling

W polarisation

ATLAS+CMS 8 TeV combination

JHEP 08 (2020) 051

- polarisation fractions measured at tWb vertex using top quark decay properties

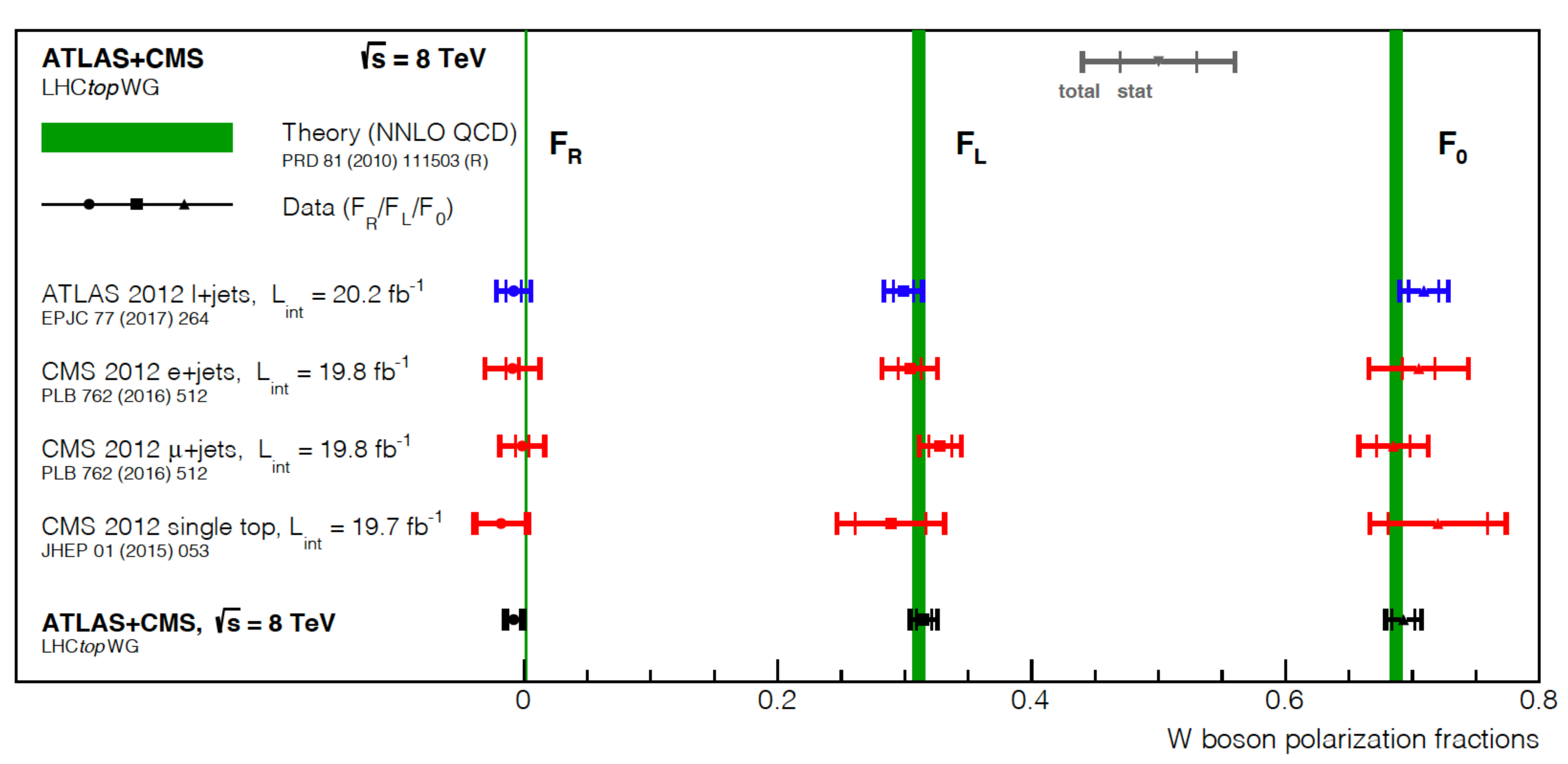
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

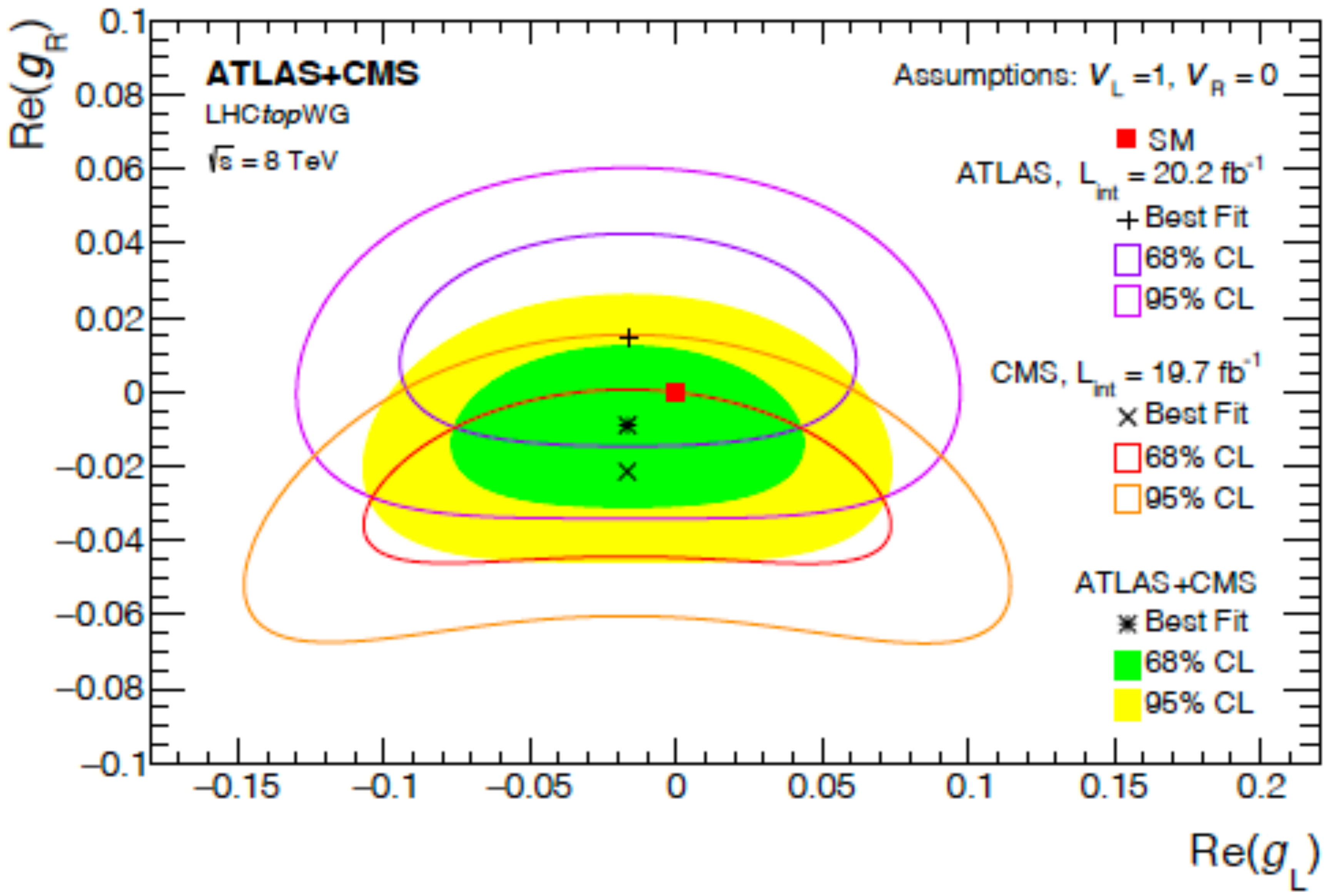
θ^* = angle of lepton wrt. b quark in W CM frame

- combining measurements of F_0 and F_L polarisation fractions (F_R via unitary constraint)
  - ATLAS:
    - $t\bar{t}$ l+jets (Eur. Phys. J. C 77 (2017) 264)
  - CMS:
    - t-channel single top (JHEP 01 (2015) 053)
    - $t\bar{t}$ mu+jets
    - $t\bar{t}$ e+jets (Phys. Lett. B 762 (2016) 512)

- **25-30-% improvement** wrt. individual measurements

- **limits on anomalous couplings** at tWb decay vertex and Wilson coefficients in EFT framework



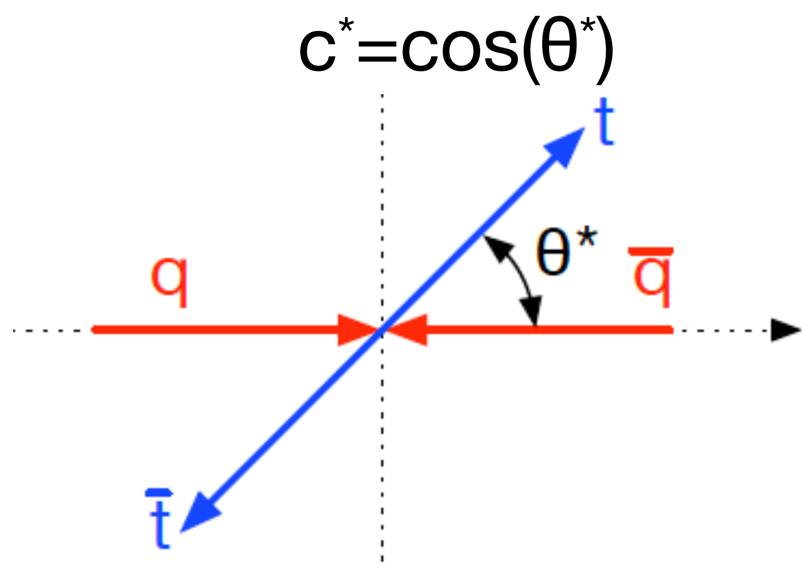


Forward backward asymmetry

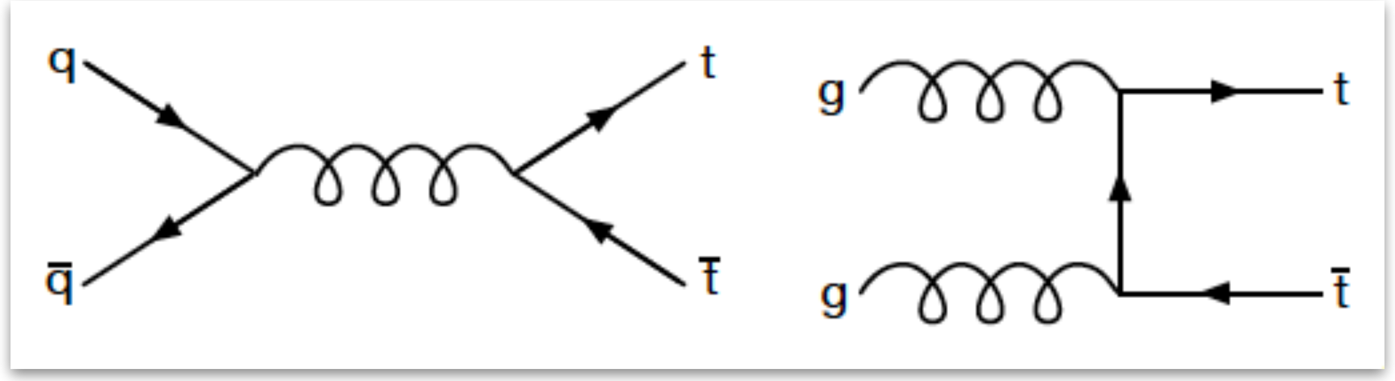
$t\bar{t}$ lepton+jets | 2016 data

- forward-backward asymmetry (A_{FB}) in $q\bar{q} \rightarrow t\bar{t}$ events

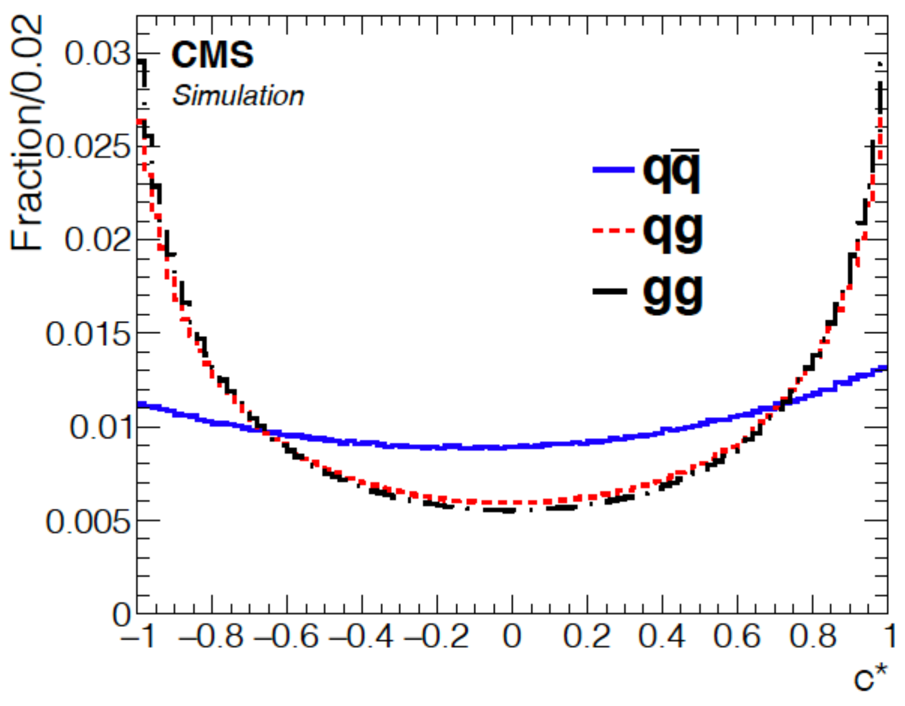
$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

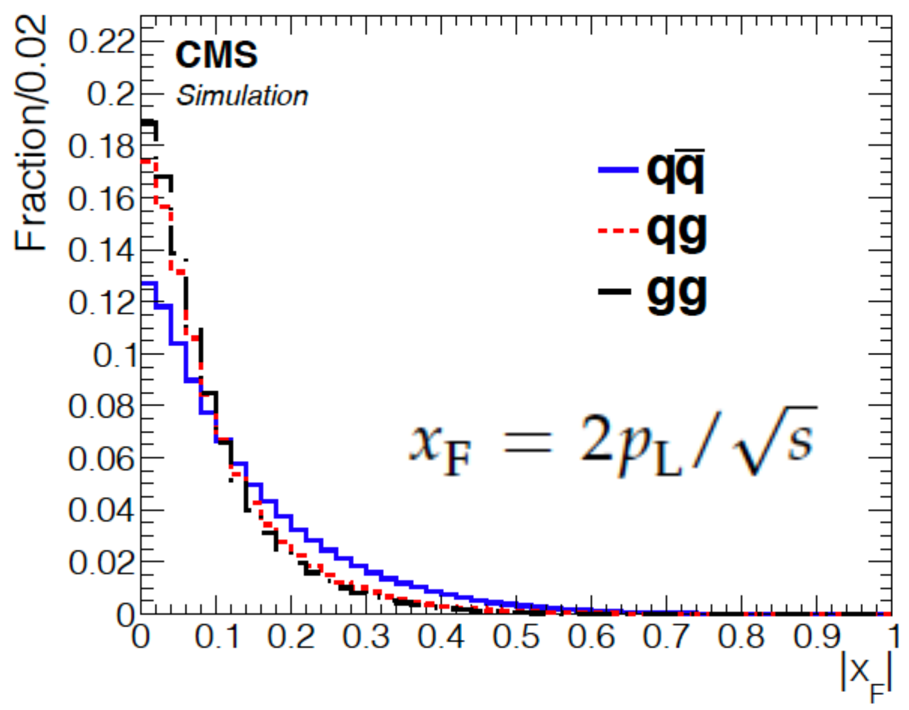


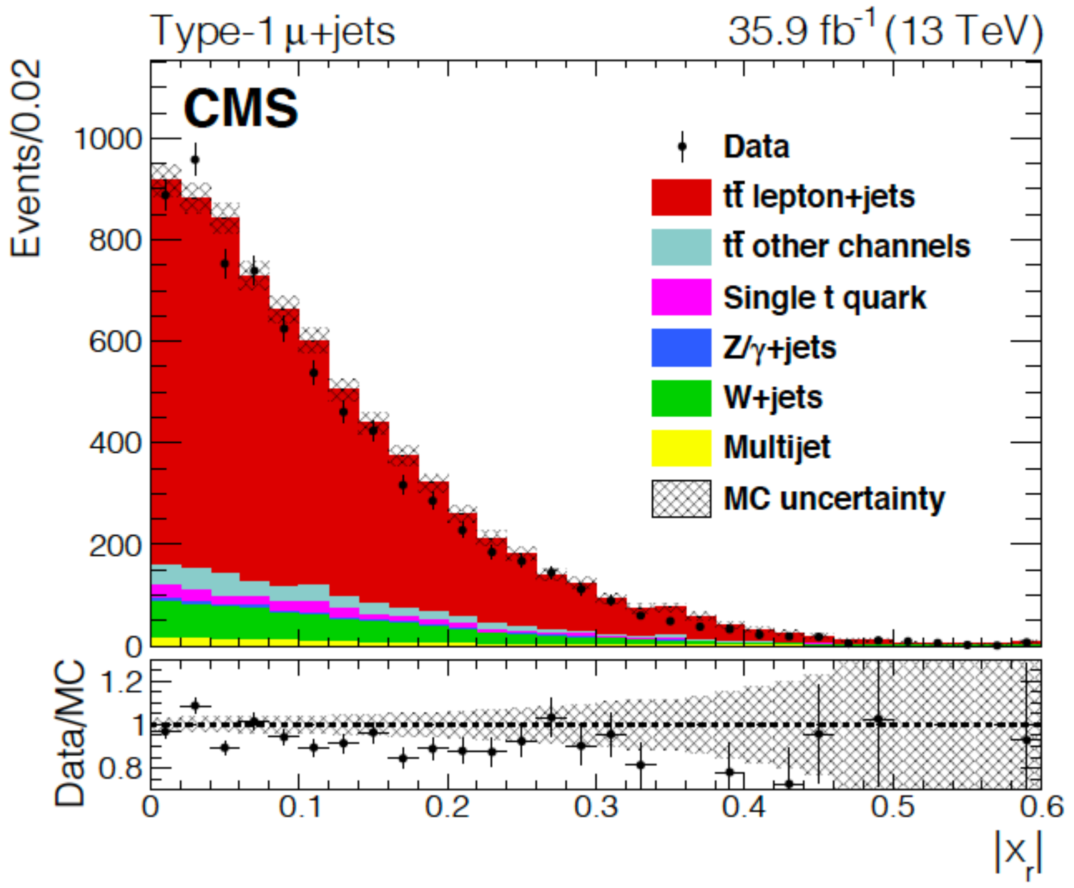
- challenge at LHC because of dominating $gg \rightarrow t\bar{t}$

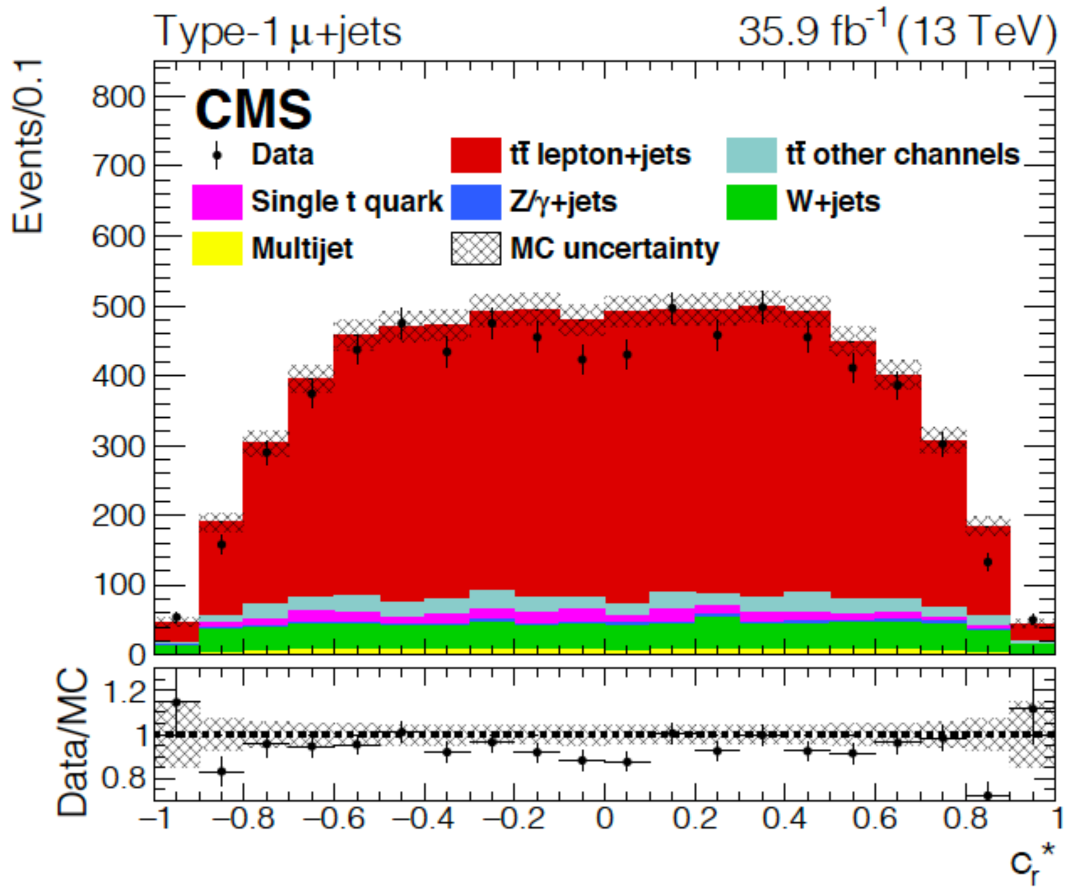


- new measurement using **c^*, x_F, and $M_{t\bar{t}}$ as sensitive observables**
- $q\bar{q} \rightarrow t\bar{t}$ fractions increases with high p_T^t
  - boosted and resolved decay topologies



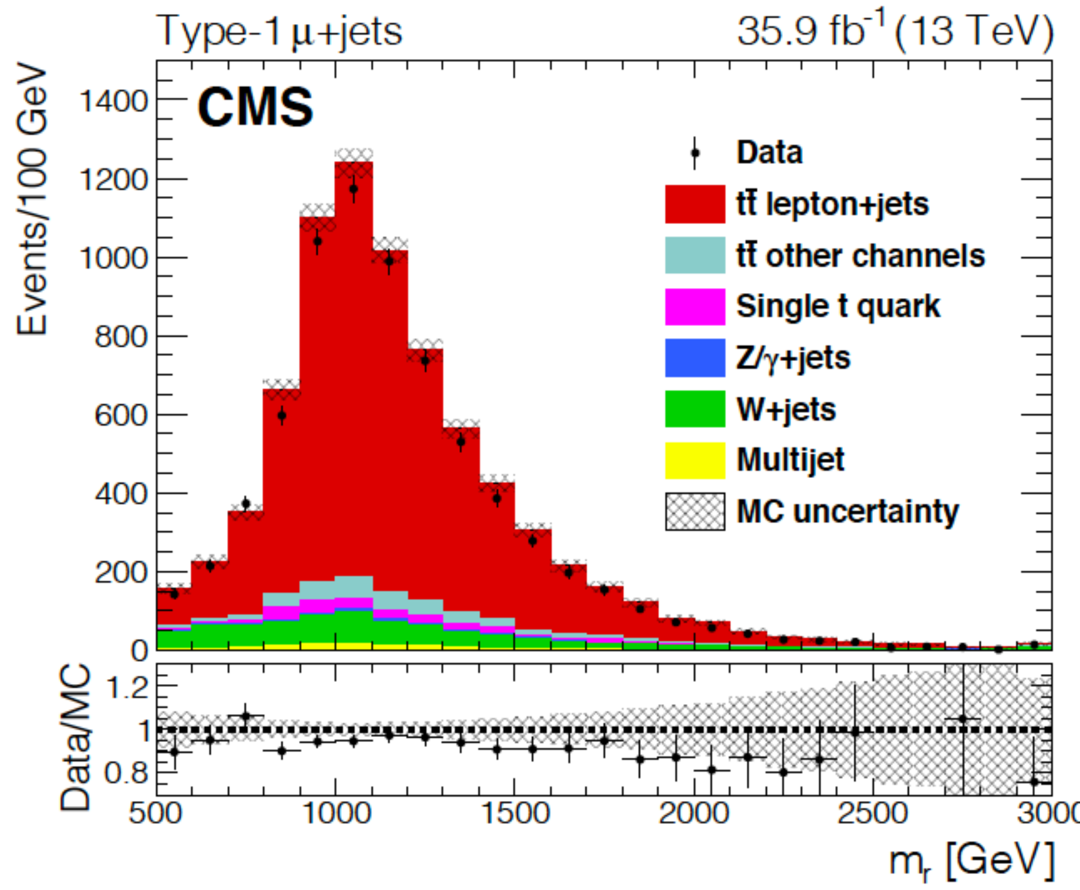






JHEP 06 (2020) 146

boosted decay topology



- measure from fit $A_{FB}^{(1)} = 0.048^{+0.095}_{-0.087}\,(\text{stat})^{+0.020}_{-0.029}\,(\text{syst})$

  also **chromomagnetic ($\hat{\mu}_t$) and chromoeletric dipole moment ($\hat{d}_t$)**

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}\,(\text{stat})^{+0.016}_{-0.011}\,(\text{syst}) \qquad |\hat{d}_t| < 0.03$$

CP violation in top decays

$t\bar{t}$ dileptonic final states | 2016 data

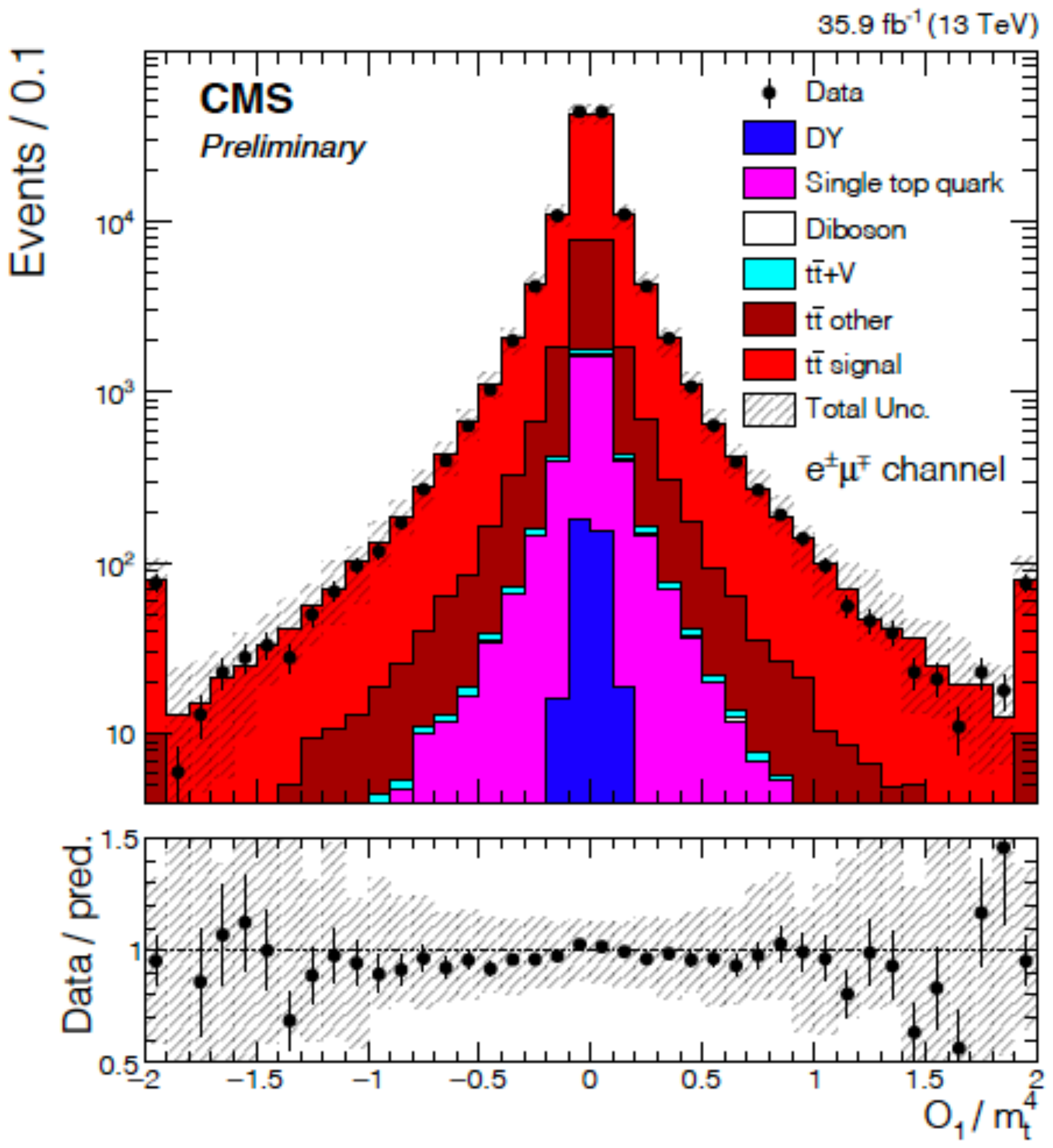
- CP symmetry known to be violated in SM
  - small amount predicted for $t\bar{t}$ process in decays
  - large CP violation expected from chromoeletric dipole moment CEDM (10-15% effect)
  - **asymmetry A_i most sensitive** to this effect

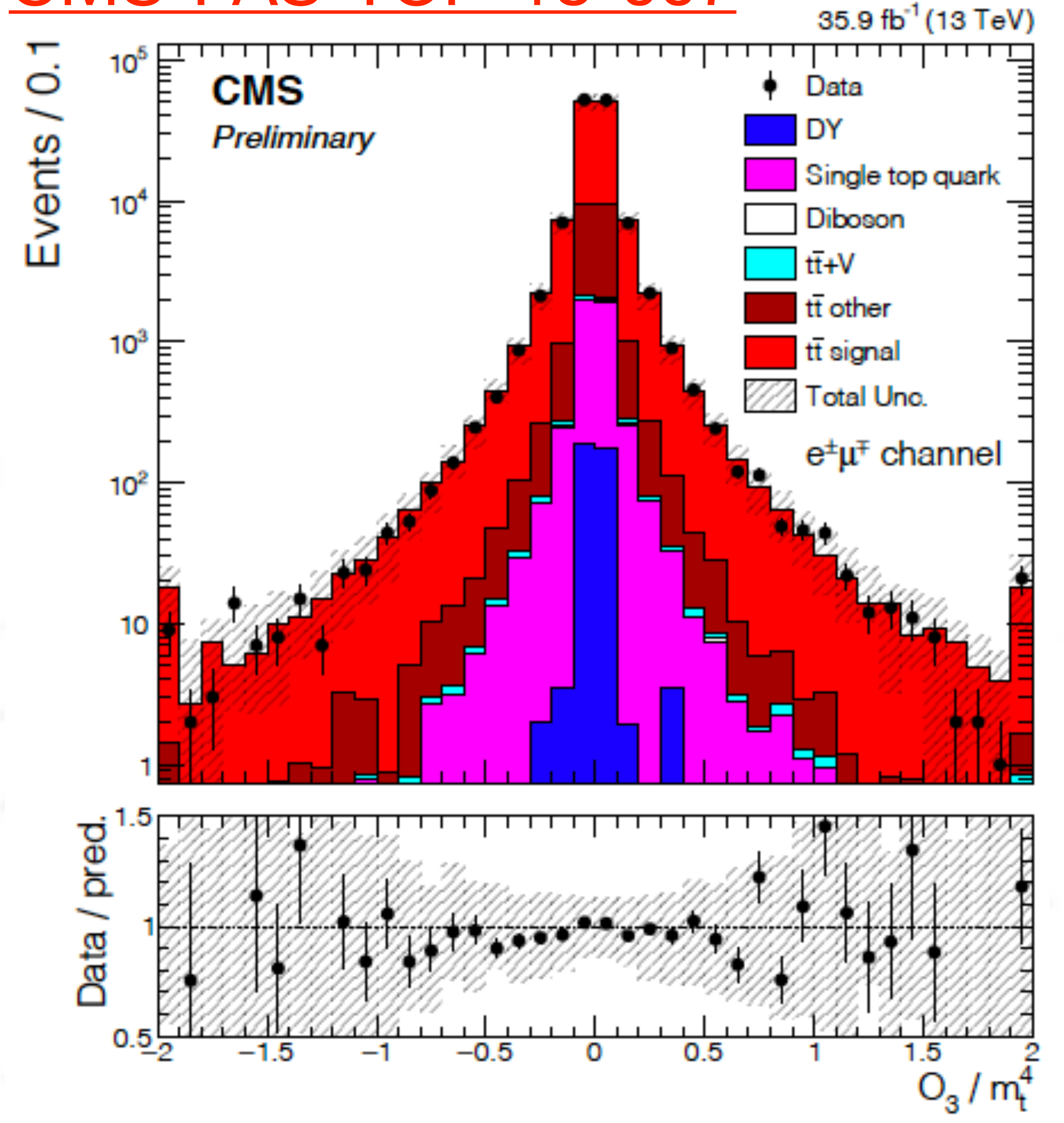
$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}$$

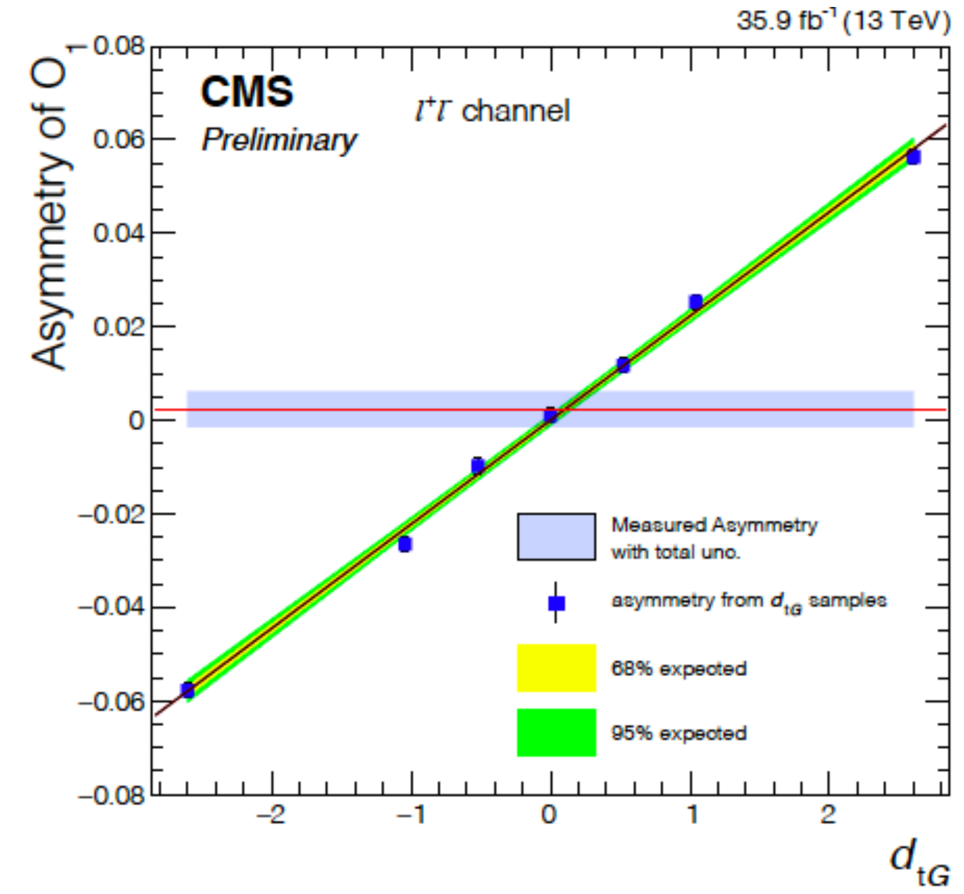
Physics observable	Asymmetry and uncertainty ($\times 10^{-3}$) $e^{\pm}\mu^{\mp}$	e^+e^-	$\mu^+\mu^-$	Combined
$\mathcal{O}_1$	6.9 ± 5.3	8.8 ± 7.5	0.6 ± 3.4	2.4 ± 2.8
$\mathcal{O}_3$	6.1 ± 5.3	4.1 ± 7.5	-1.7 ± 3.4	0.4 ± 2.8

$$\mathcal{O}_1 = \begin{vmatrix} E_t & p_{t_x} & p_{t_y} & p_{t_z} \\ E_{\bar{t}} & p_{\bar{t}_x} & p_{\bar{t}_y} & p_{\bar{t}_z} \\ E_{\ell+} & p_{\ell^+_x} & p_{\ell^+_y} & p_{\ell^+_z} \\ E_{\ell-} & p_{\ell^-_x} & p_{\ell^-_y} & p_{\ell^-_z} \end{vmatrix} \qquad \mathcal{O}_3 = \begin{vmatrix} E_b & p_{b_x} & p_{b_y} & p_{b_z} \\ E_{\bar{b}} & p_{\bar{b}_x} & p_{\bar{b}_y} & p_{\bar{b}_z} \\ E_{\ell+} & p_{\ell^+_x} & p_{\ell^+_y} & p_{\ell^+_z} \\ E_{\ell-} & p_{\ell^-_x} & p_{\ell^-_y} & p_{\ell^-_z} \end{vmatrix}$$

CMS-PAS-TOP-18-007







- linear dependence between CEDM and A_i

Physics observable	d_{tG}
$\mathcal{O}_1$	$0.10 \pm 0.12(\text{stat}) \pm 0.12(\text{syst})$
$\mathcal{O}_3$	$0.00 \pm 0.13(\text{stat}) \pm 0.10(\text{syst})$

$-0.0019 < \hat{d}_t$ (for $\mathcal{O}_3$) < 0.019

$-0.014 < \hat{d}_t$ (for $\mathcal{O}_1$) < 0.027

- in **good agreement** with measurement from spin correlations $-0.020 < \hat{d}_t < 0.012$

EFT in top quark production

Overview

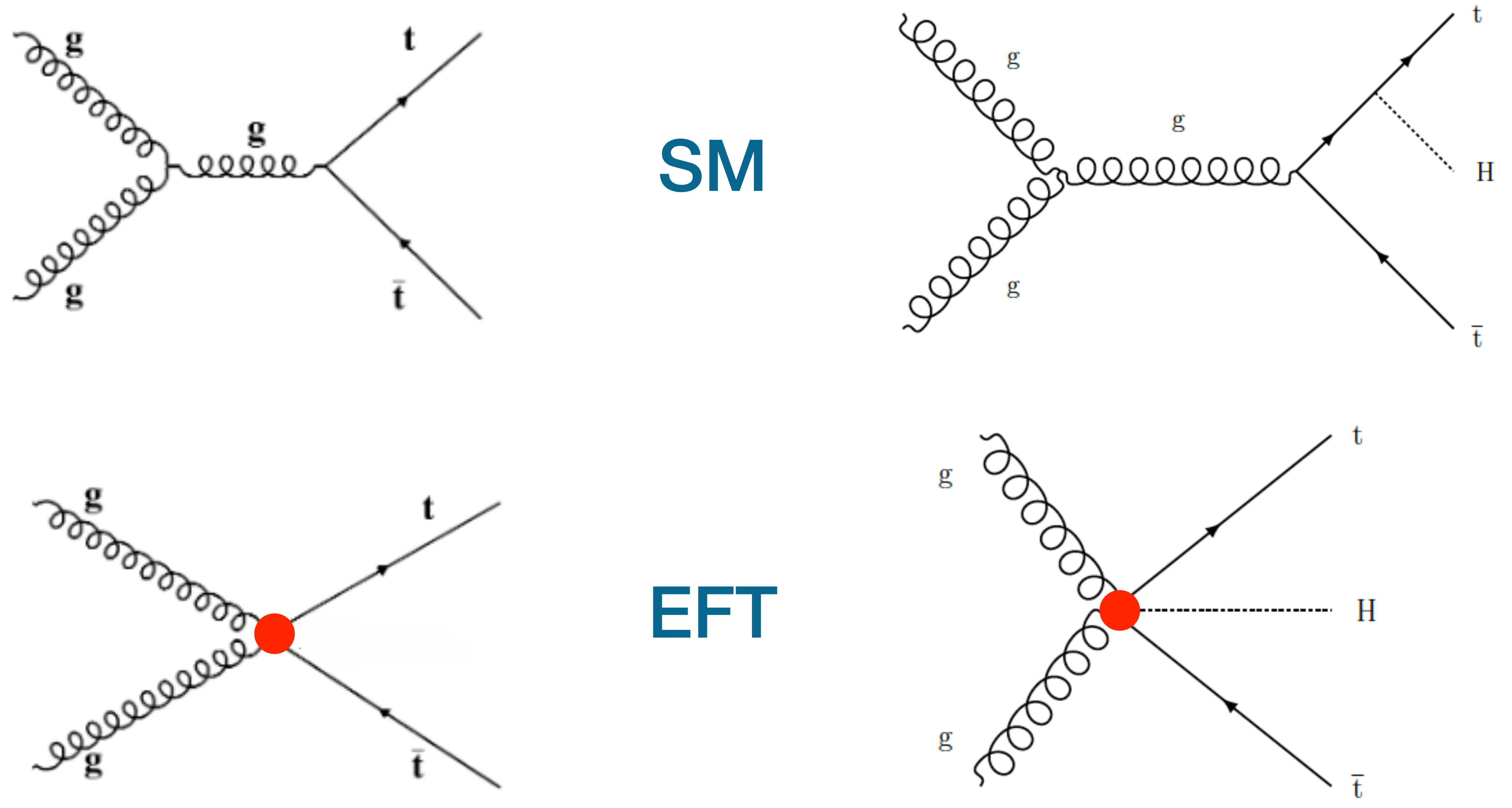
EFT $$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)}$$

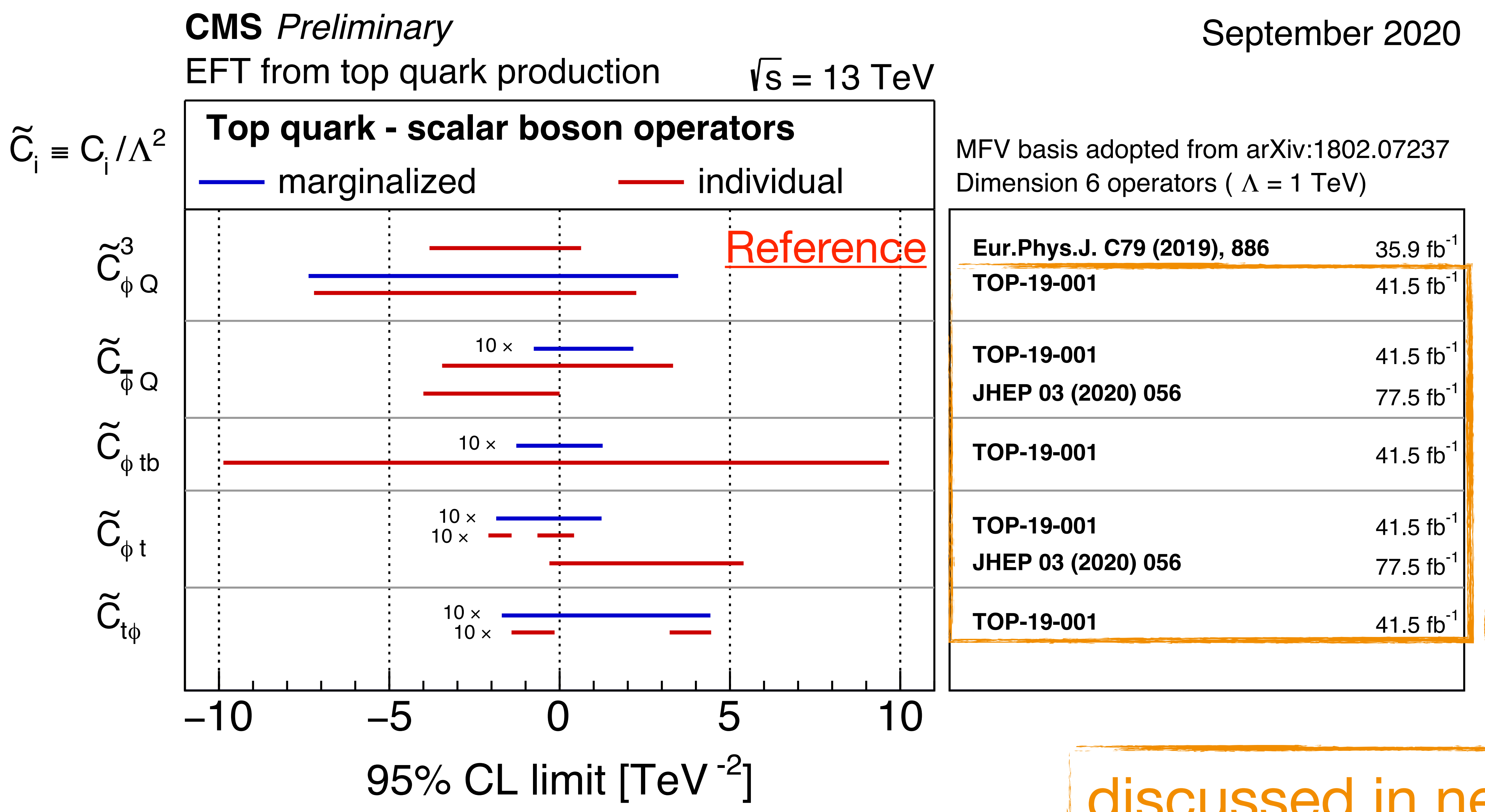
consider SM extension up to dimension 6

C_i = dimensionless Wilson coefficients

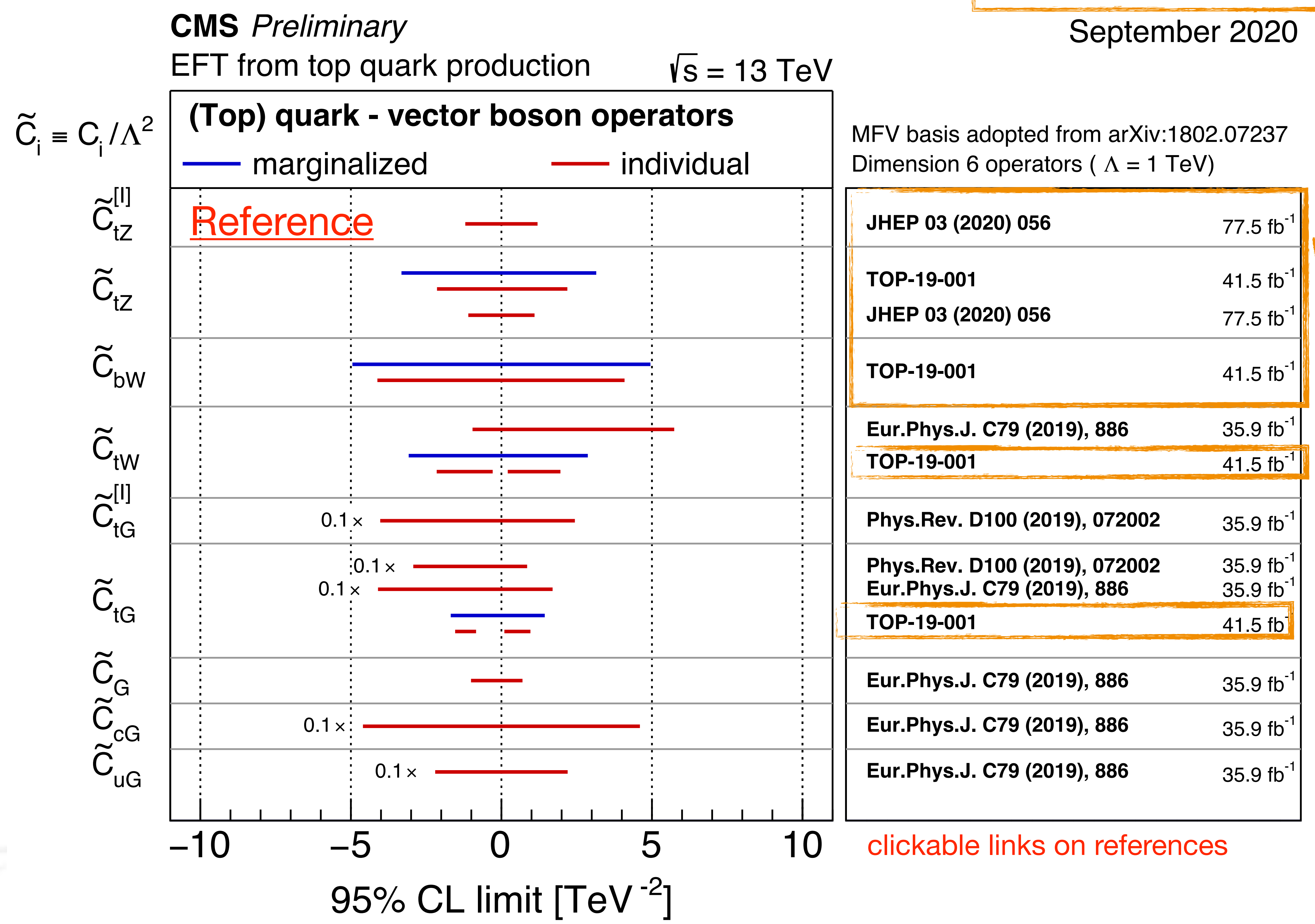
O_i = higher order EFT operators

- 59 up to 2499 independent operators





discussed in next slides



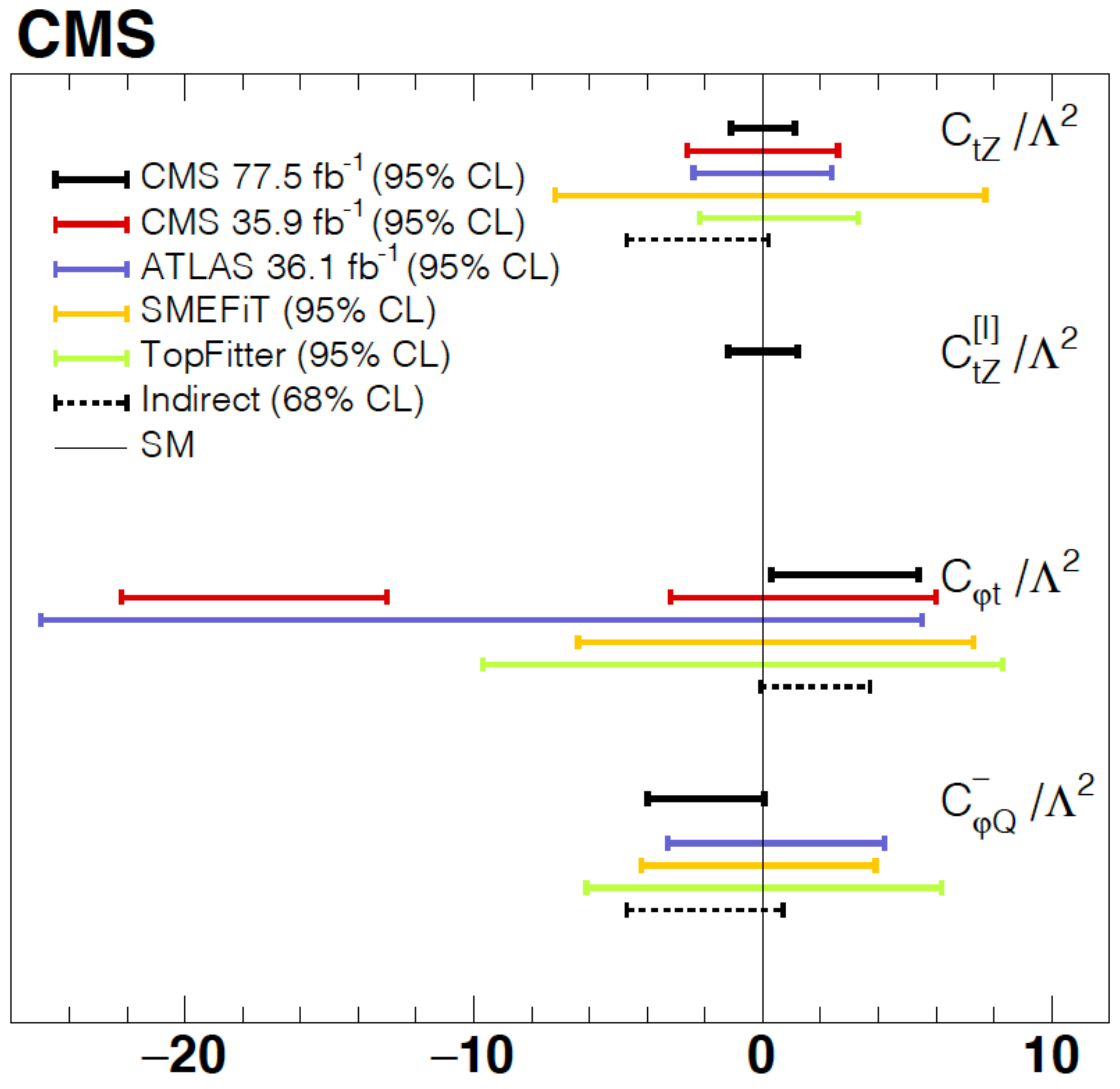
clickable links on references

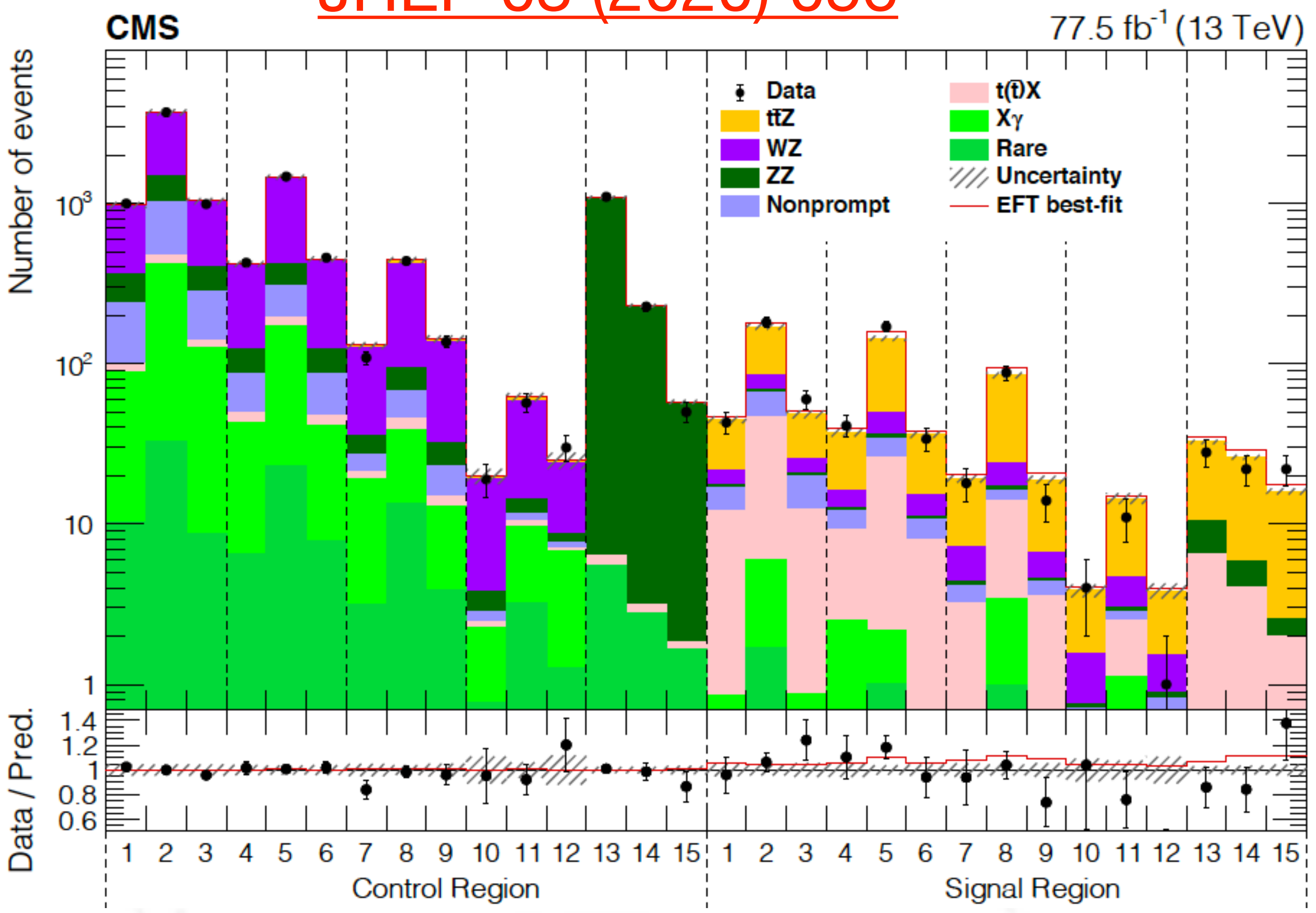
EFT in $t\bar{t}$ + vector bosons: non-global

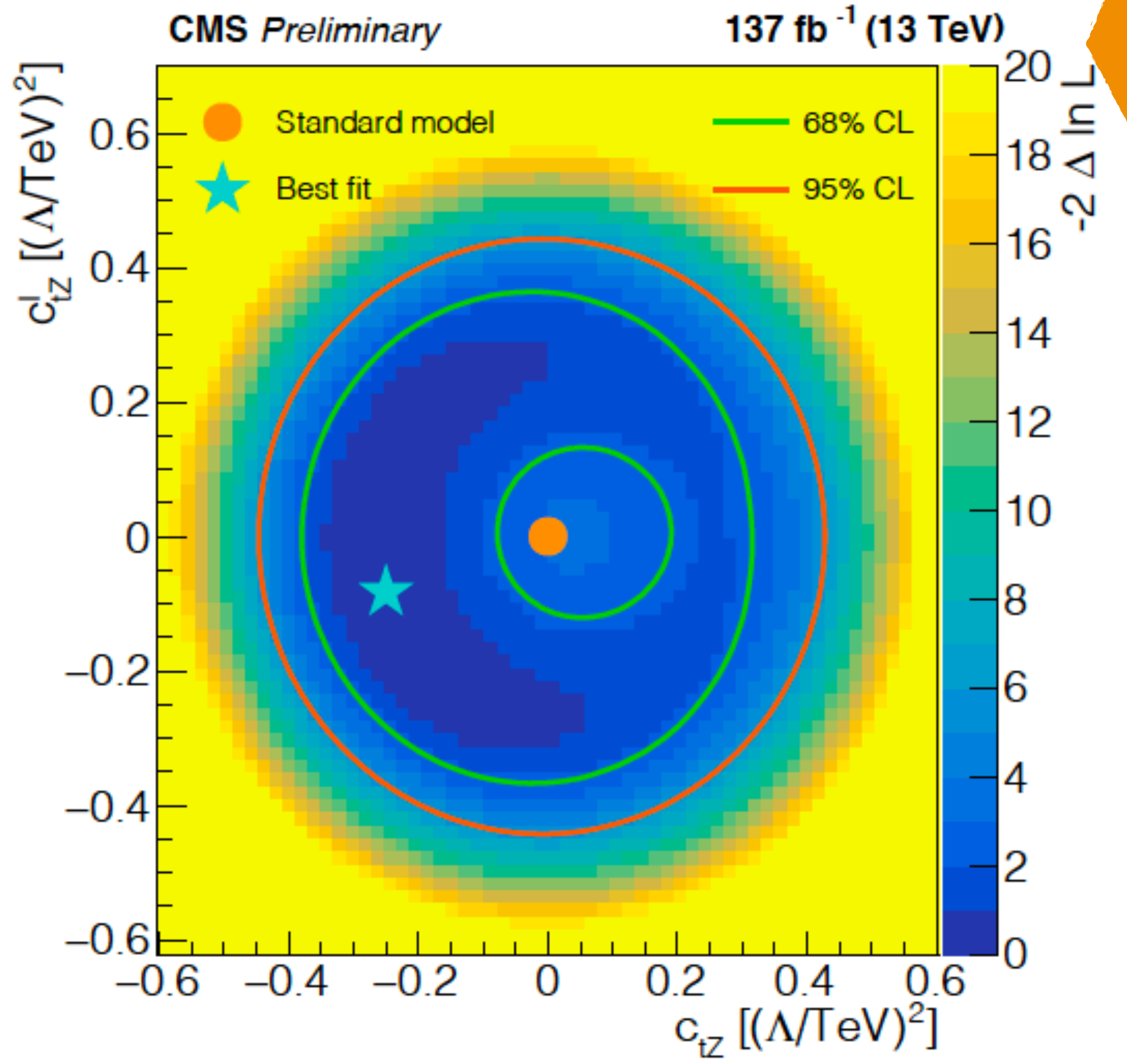
$t\bar{t}$+Z & $t\bar{t}+\gamma$

[JHEP 03 (2020) 056]

- measurement of $t\bar{t}$+Z associated production
  - p_T(Z) and cos(θ^*) most sensitive to EFT
    θ^* = angle of neg. ch. lepton in Z CM frame wrt. Z in lab frame
  - 1D and 2D limits on Wilson coefficients







NEW!

[CMS-PAS-TOP-18-010]

- measurement of $t\bar{t}+\gamma$ associated production
  - $p_T(\gamma)$ most sensitive to EFT
  - 1D and 2D limits on Wilson coefficients

Data set	Wilson coefficient	68% CL interval	95% CL interval
expected	c_{tZ}	[-0.19, 0.21]	[-0.29, 0.32]
	c^I_{tZ}	[-0.20, 0.20]	[-0.30, 0.31]
observed	c_{tZ}	[-0.35, -0.16]	[-0.42, 0.38]
	c^I_{tZ}	[-0.35, -0.16], [0.17, 0.35]	[-0.42, 0.42]

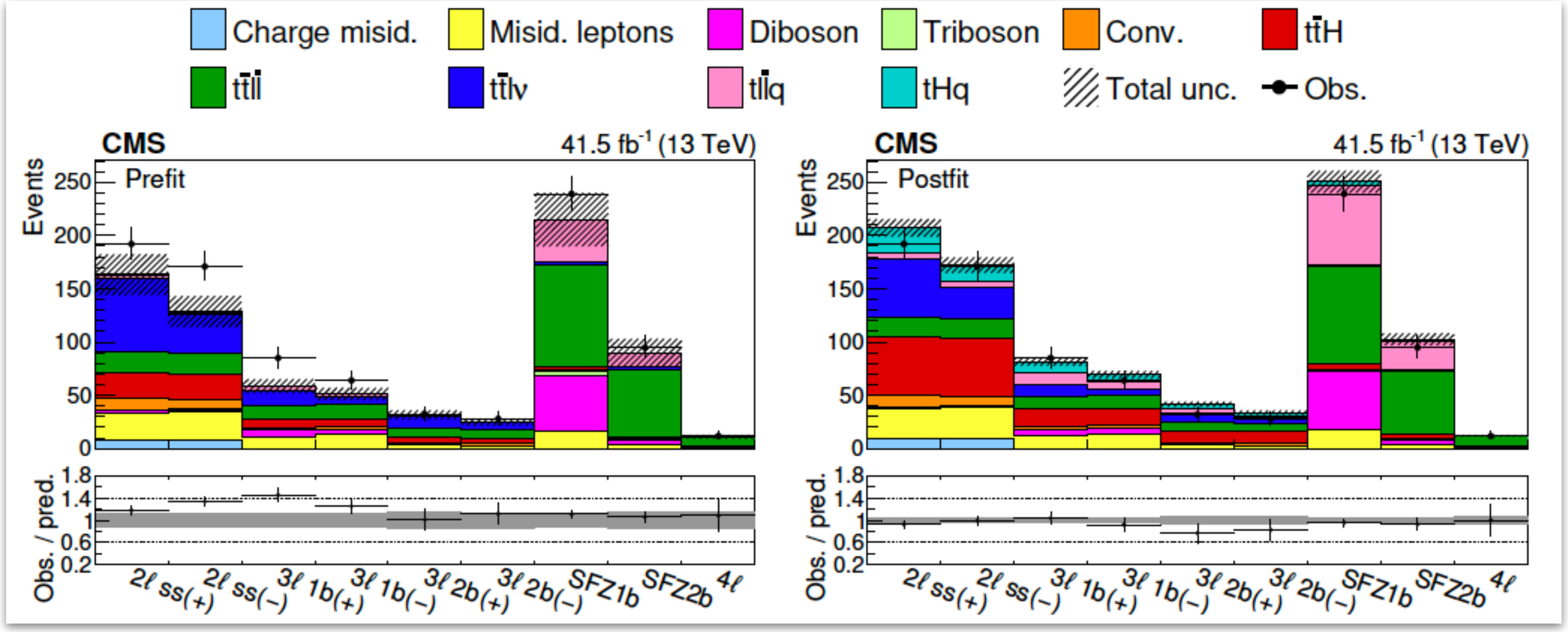
➔ 68% and 95% CL 1D limits most stringent to date

Towards a global EFT fit in top

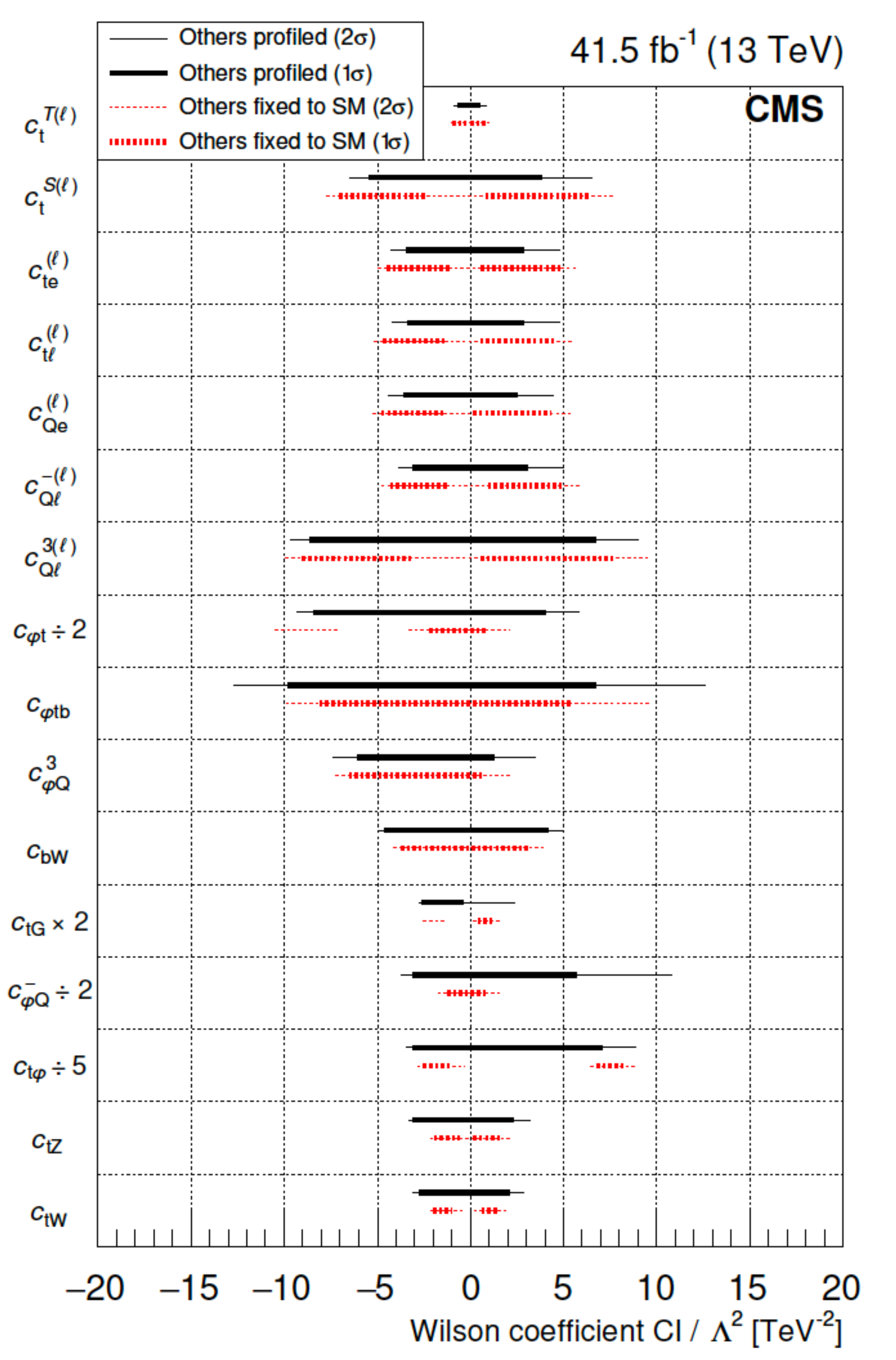
Multilepton final states | 2017 data

[JHEP 03 (2021) 095]

- search for anomalous couplings in t($\bar{t}$)+Z/H/W
  - $t\bar{t}H$, $t\bar{t}ll$, $t\bar{t}l\nu$, tllq, tHq
  - challenge to disentangle individual contributions
    - perform **global analysis**!
    - 9 event categories with different dominating contributions based on lepton charges and multiplicity



  - one-by-one and simultaneous fit of 16 Wilson coefficients
  - **first such attempt!**
    - in the future also diff. distributions considerable



agreement with SM prediction

Conclusion

- CMS has performed plenty of precision analyses measuring top quark properties
  - top quark mass measurements in different phase spaces
    - sub-GeV precision for the first time in the single top enriched sample
    - factor of 4 improvement in boosted regime wrt. Run I
  - Yukawa: indirect studies of the top Yukawa coupling
  - first direct measurement of Vtx elements in the CKM matrix
  - combination of measurements between ATLAS and CMS

    → more to come!
  - new approaches for direct and global constraints on top EFT couplings

Stay tuned for more results!

Backup

Top polarisation and $t\bar{t}$ spin correlations

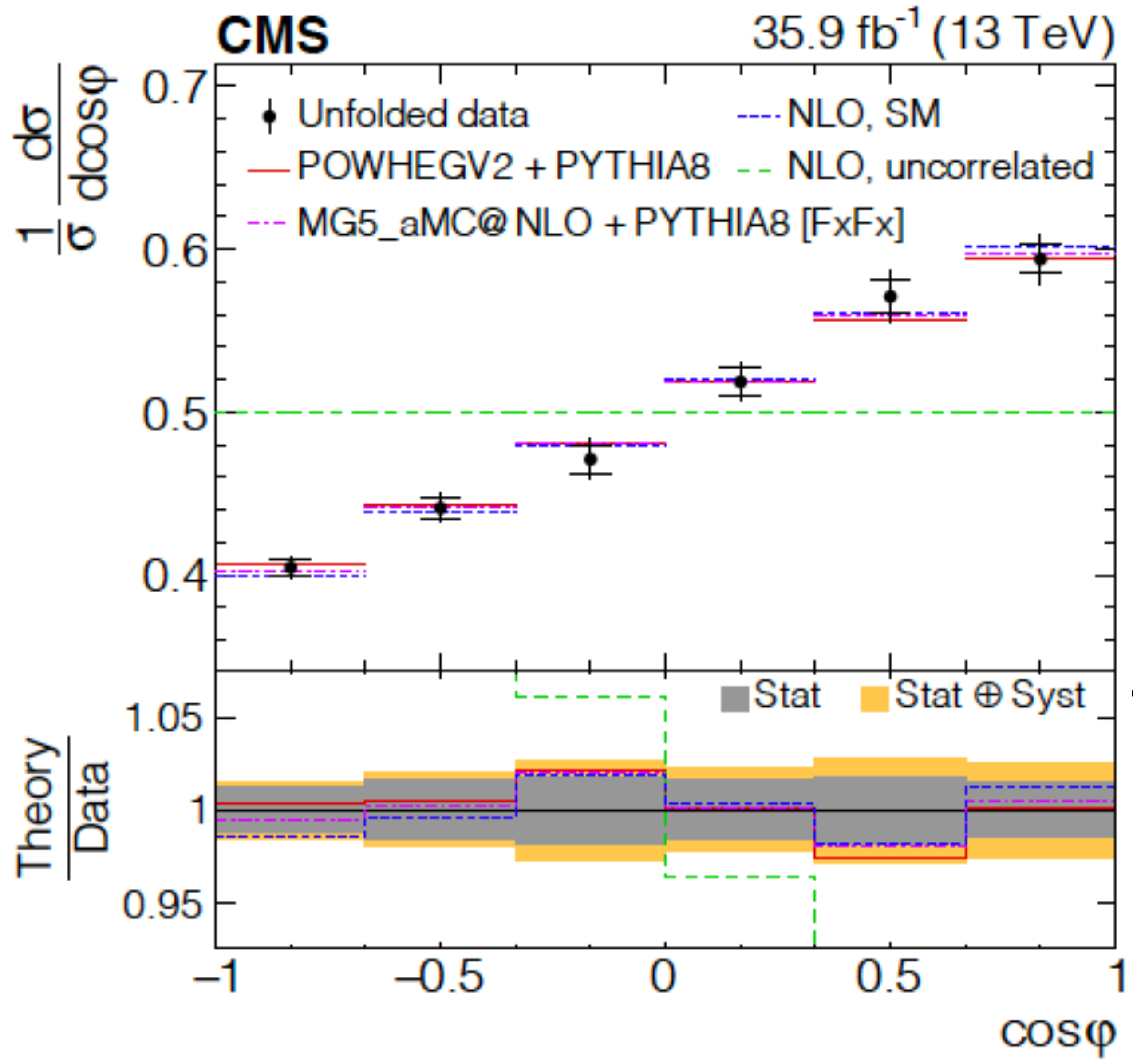
Dileptonic final states | 2016 data

Phys. Rev. D 100, 072002 (2019)

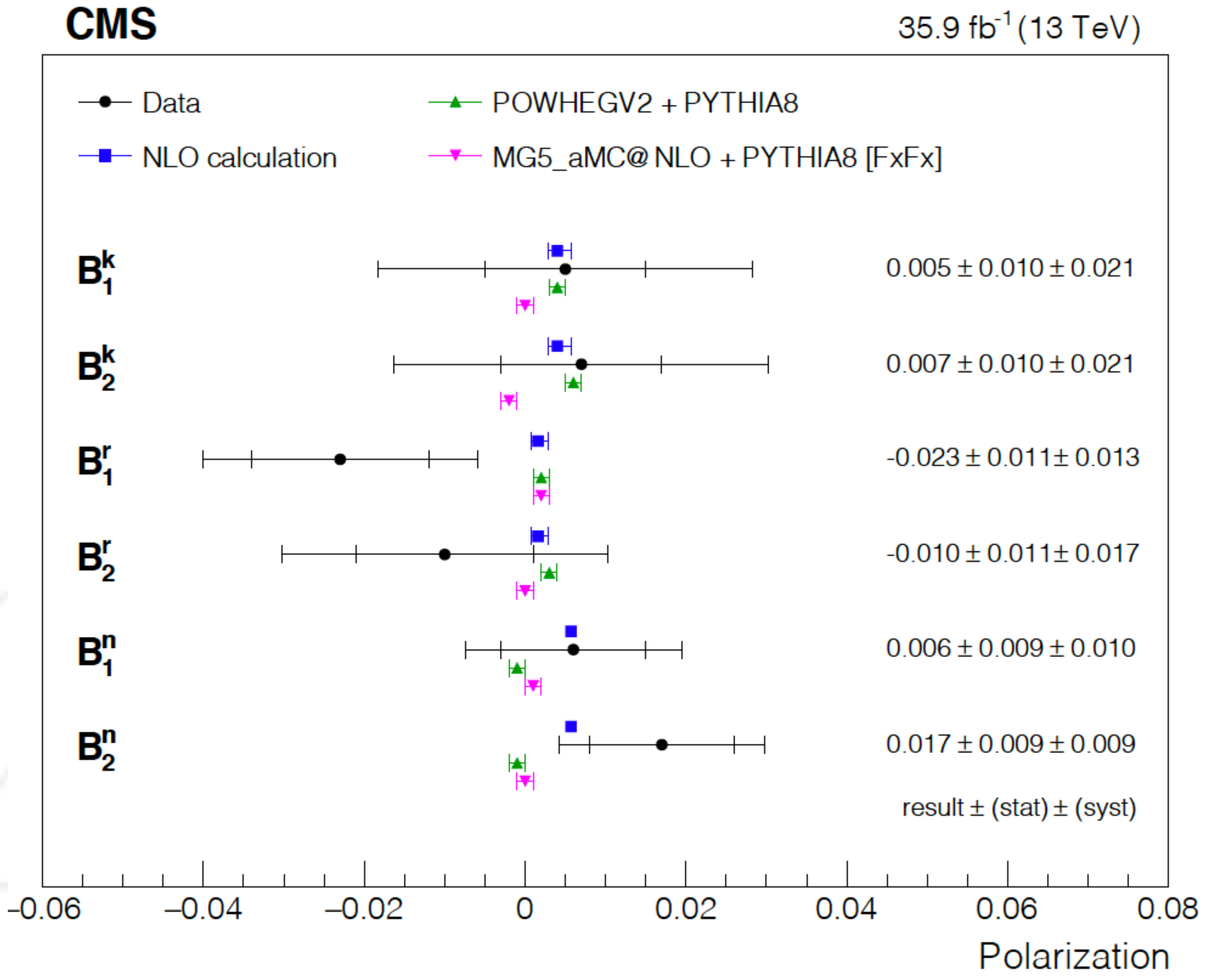
- short lifetime → spin information conserved in decay products

  $$|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to \ell^+\nu b\ \ell^-\bar{\nu}\bar{b})|^2 \propto \rho R \bar{\rho}.$$

- decompose spin density matrix R into 15 independent coefficients solely dependent on one observable at parton level
  - measurement of various norm. diff. cross sections to extract coefficients
- up to 5% precision on most sensitive observables
  - data clearly favor case of correlations
- extract limits on top chromomagnetic and chromoeletric dipole moment $-0.014 < \hat{\mu}_t < 0.004$ $\quad -0.020 < \hat{d}_t < 0.012$
- also limits on 10 Wilson coefficients in EFT framework sensitive to $t\bar{t}$ production
  - simultaneous fitted and one-by-one



angle between leptons in mother quark rest frames



Top quark mass (and α_s + PDF)
3D cross section ($t\bar{t}$ dileptonic) | 2016 data

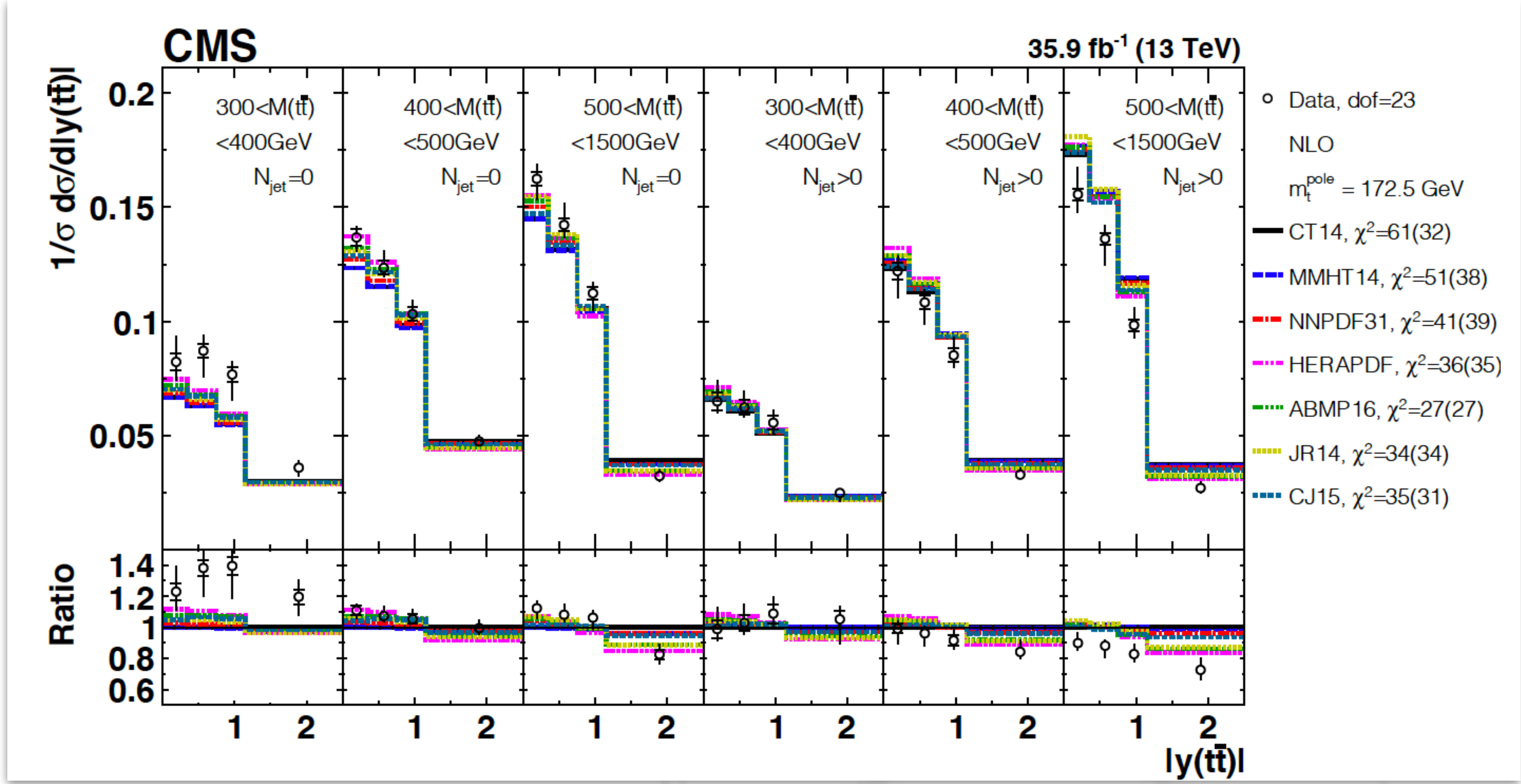
Eur. Phys. J. C 80 (2020) 658

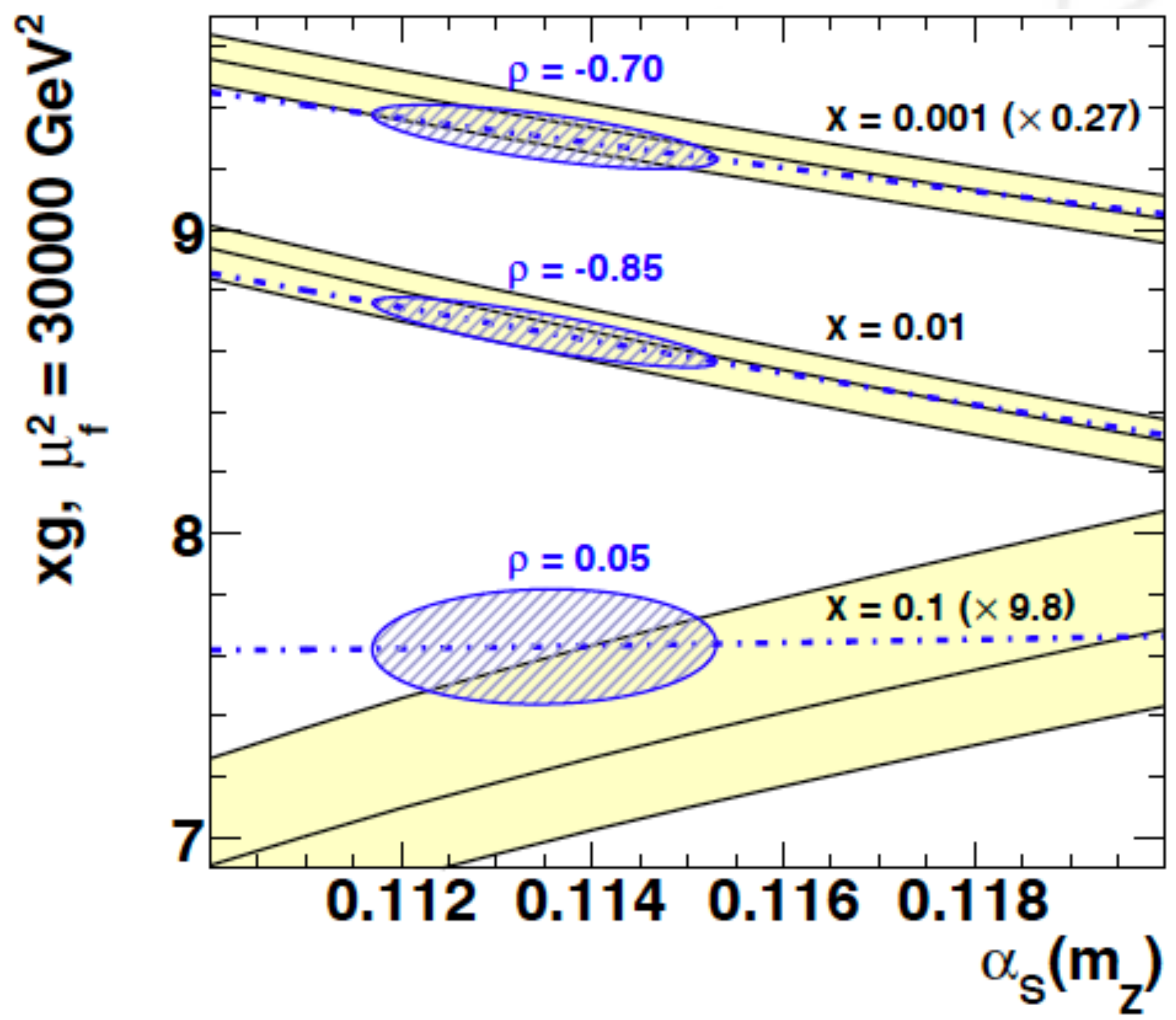
- simultaneous extraction of m_t, α_s, PDF from 3D $t\bar{t}$ cross section

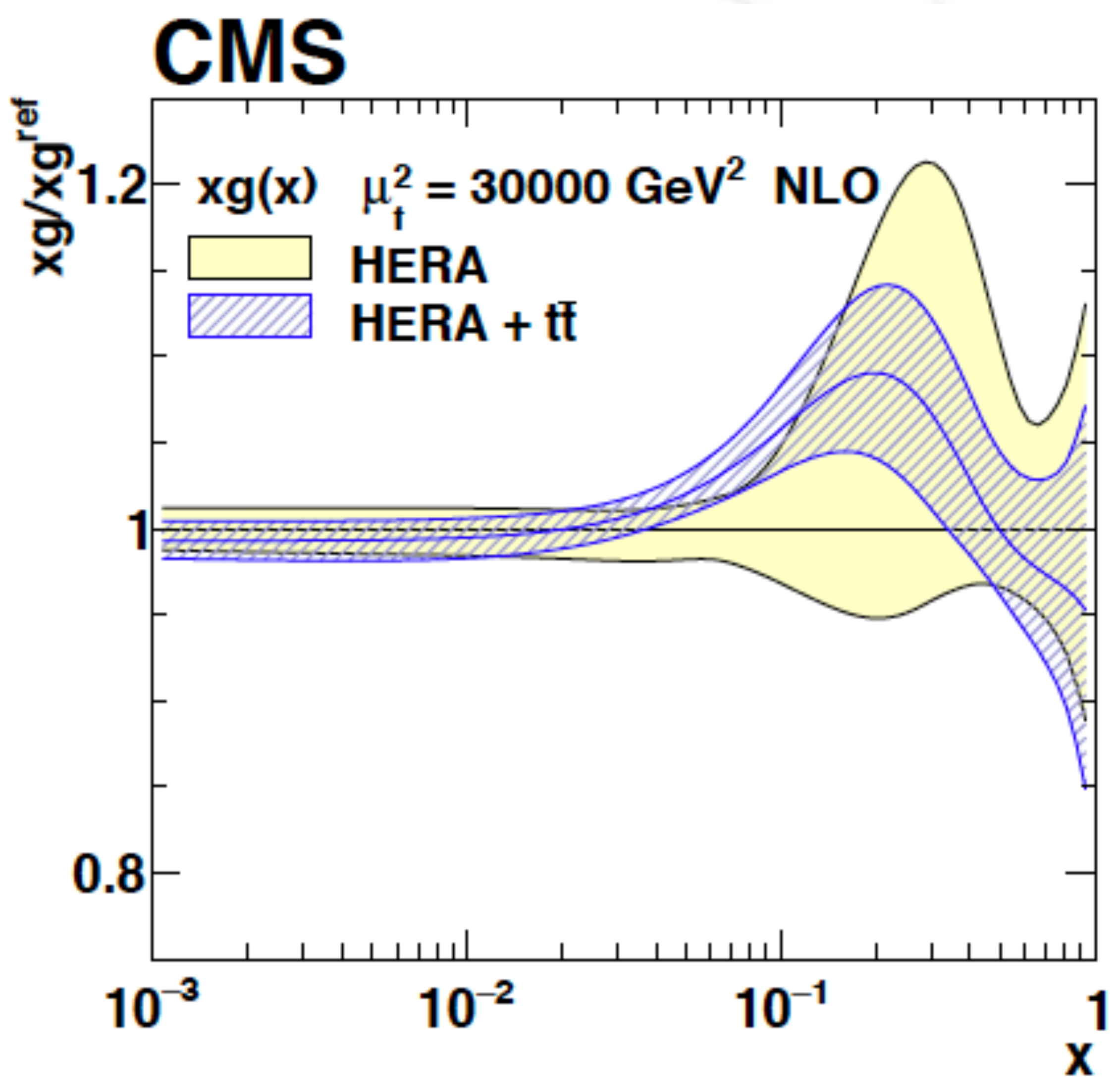
  $N_{jet} \rightarrow \alpha_s$
  $m_{t\bar{t}} \rightarrow m_t^{pole}$
  $|y_{t\bar{t}}| \rightarrow$ PDF (gluon)

- fit to HERA DIS and $t\bar{t}$ cross section sections
  - **decorrelation of parameters**
    - between gluon PDF and α_s
  - **most precise m_t^{pole} result**

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



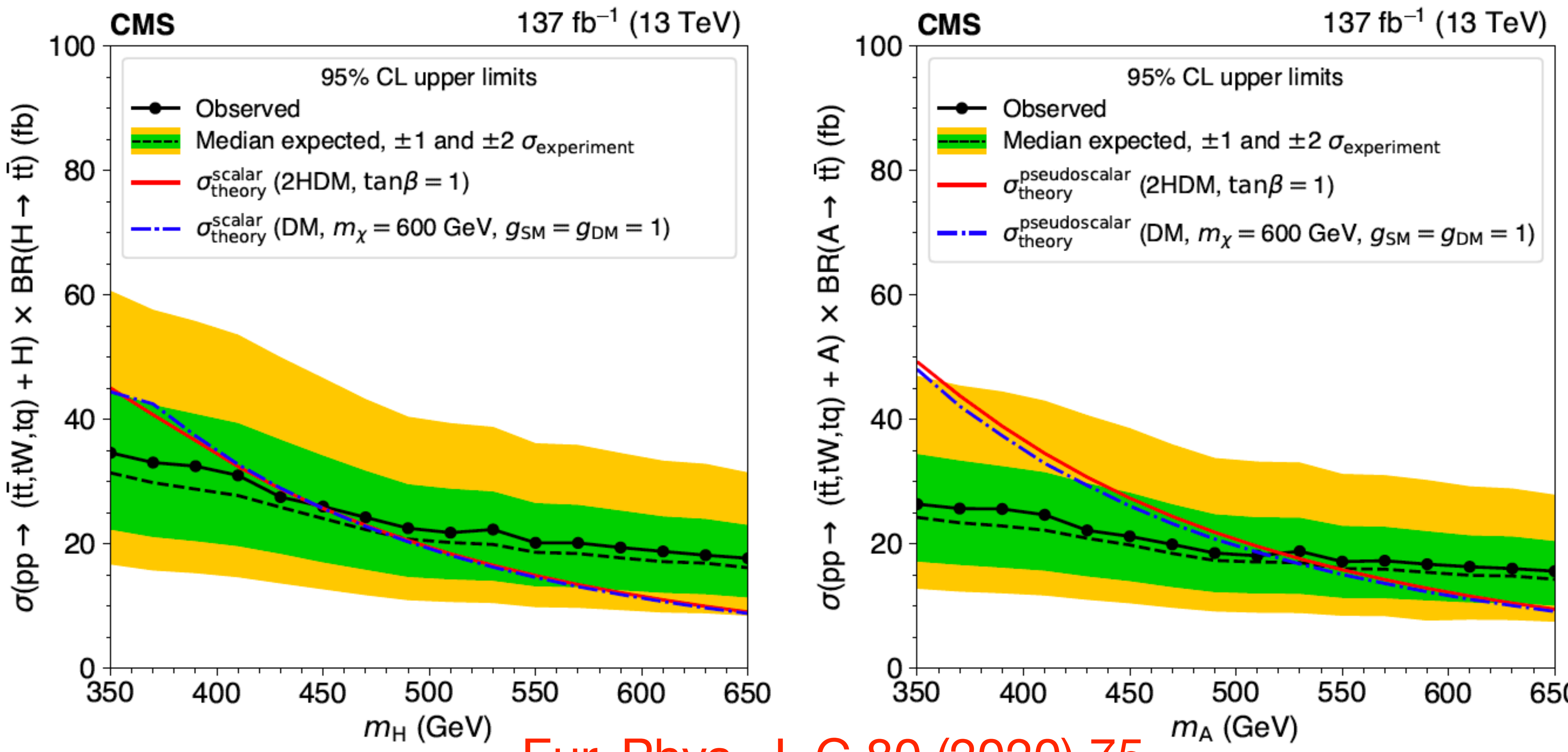




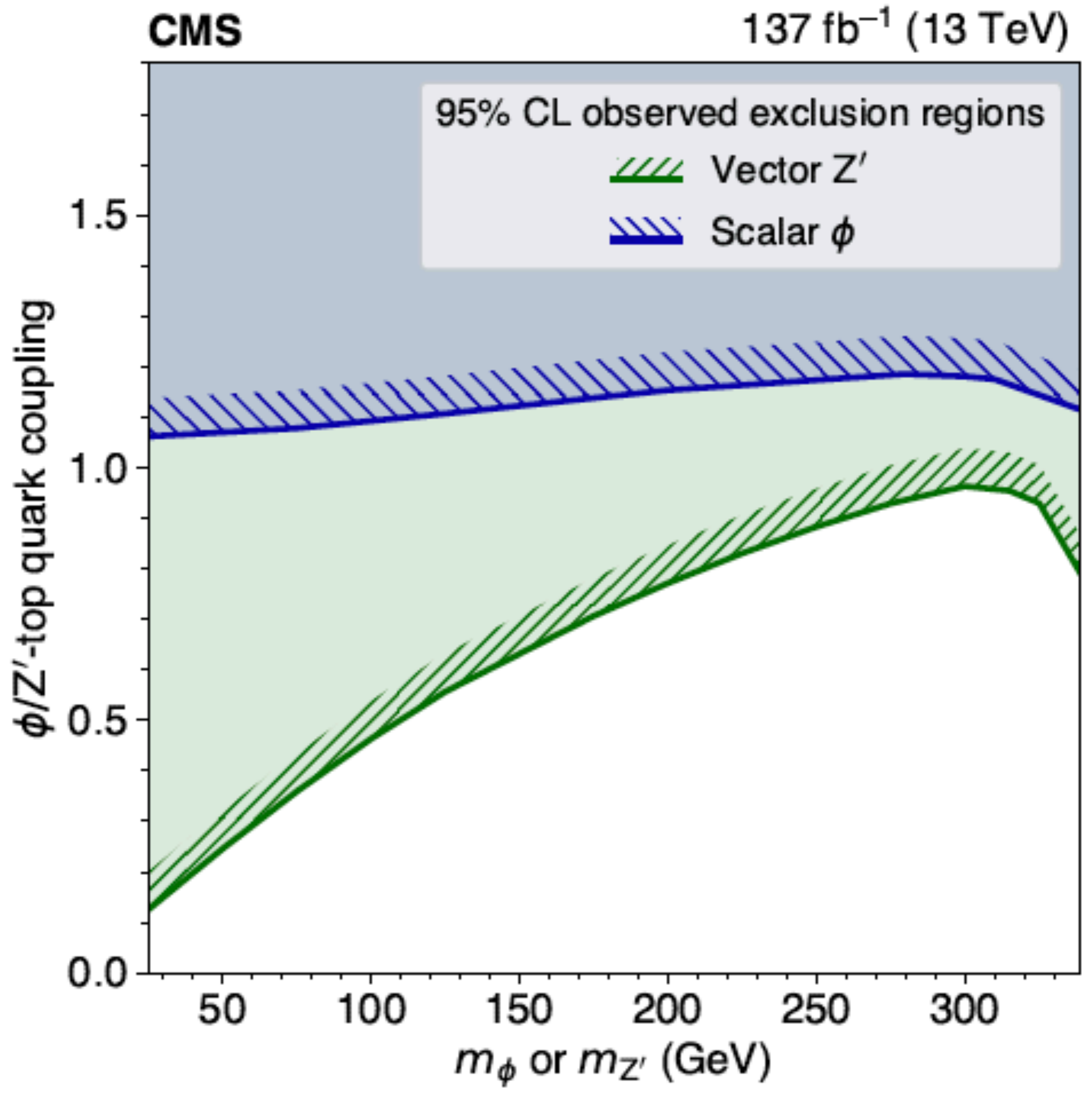
Four top production - $t\bar{t}t\bar{t}$

2016-2018 data

- same sign dilepton & multilepton final states:
  - **extensive BSM interpretation**
    - – Yukawa coupling $|y_t/y_t^{SM}| < 1.4$
    - – $\hat{H}$, Wilson coefficient modifying Higgs propagator
      $\hat{H} < 0.12$
      from Higgs combinations: $\hat{H} < 0.16$
    - – Type-II two-Higgs doublet models
      - m > 2 m_t
      - limits ~100 GeV higher wrt. previous CMS results
    - – BSM scalar ϕ or Z'
      - m < 2 m_t



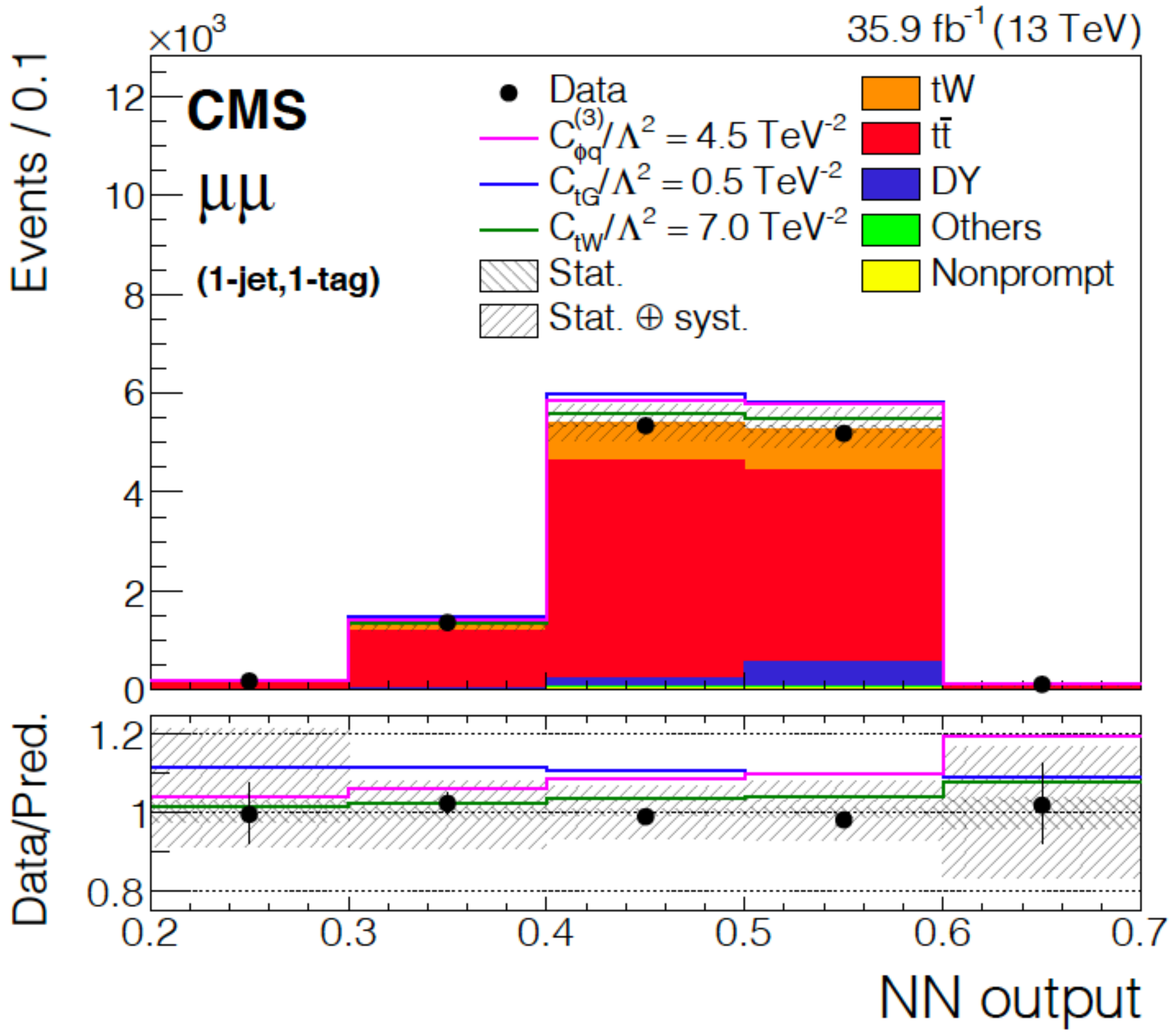
Eur. Phys. J. C 80 (2020) 75



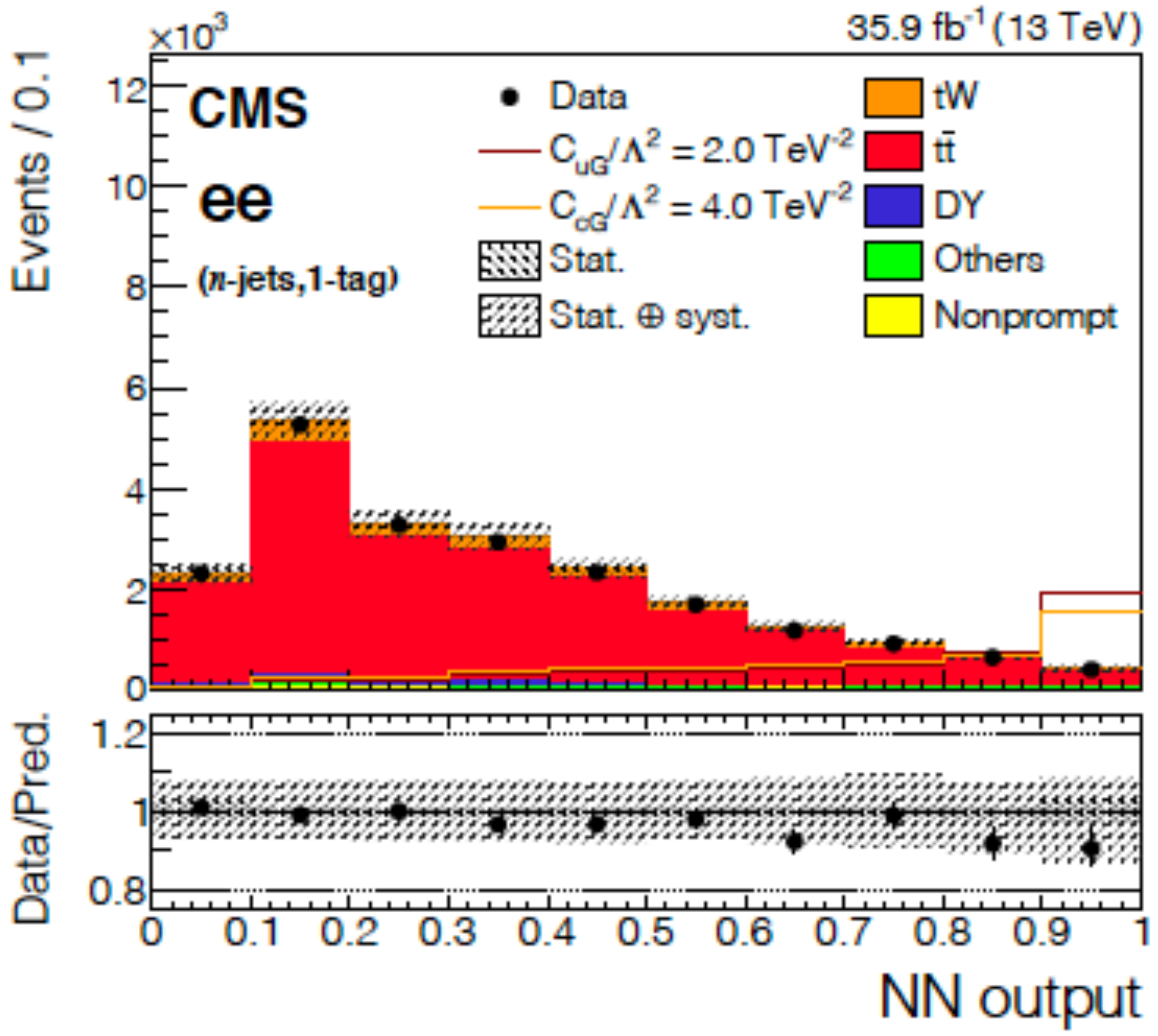
Search for new physics

$t\bar{t}$ dileptonic final states | 2016 data

- directly targeting EFT operators affecting tW and $t\bar{t}$ processes
  - **first time analyzed simultaneously**
  - rate + shape effects
- multivariate analysis based on Neural Networks in various event categories to

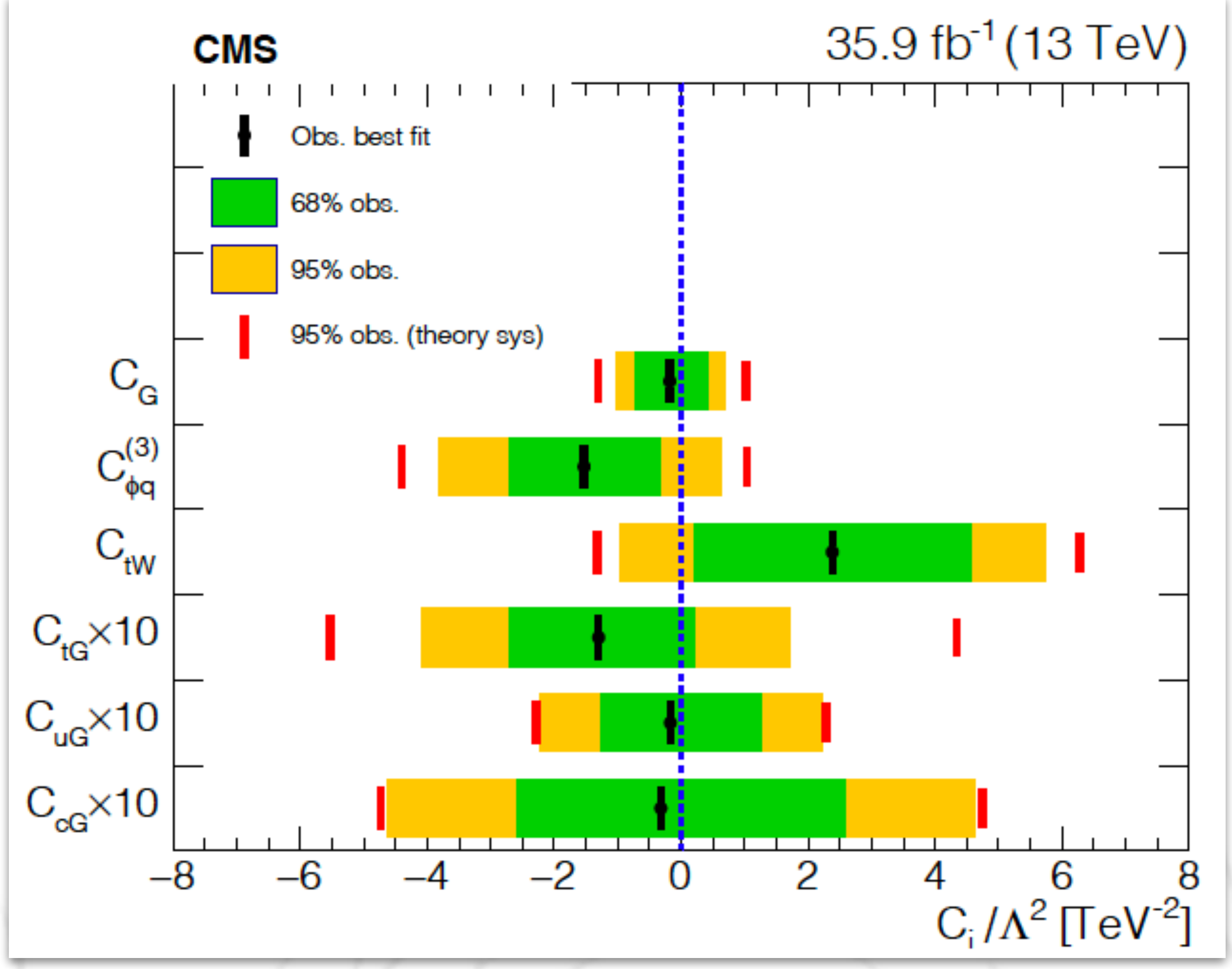


separate tW vs. $t\bar{t}$



separate SM tW and $t\bar{t}$ vs. new physics

Eur. Phys. J. C 79 (2019) 886



- considering EFT operators one-by one
- first step to more global EFT approaches

Four top production - $t\bar{t}t\bar{t}$

2016 data

JHEP 11 (2019) 082

- l+jets & opposite sign dilepton final states:
  - EFT interpretation
    - Wilson coefficients fitted
      - one-by-one
      - others marginalised

one-by-one

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	$[-2.0, 1.8]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{\mathrm{QQ}}$	$[-2.0, 1.8]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{\mathrm{Qt}}$	$[-3.3, 3.2]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{\mathrm{Qt}}$	$[-7.3, 6.1]$	$[-7.9, 6.6]$

others marginalised

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	$[-2.0, 1.9]$	$[-2.2, 2.1]$
$\mathcal{O}^1_{\mathrm{QQ}}$	$[-2.0, 1.9]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{\mathrm{Qt}}$	$[-3.4, 3.3]$	$[-3.7, 3.5]$
$\mathcal{O}^8_{\mathrm{Qt}}$	$[-7.4, 6.3]$	$[-8.0, 6.8]$

W polarisation

ATLAS+CMS 8 TeV combination

JHEP 08 (2020) 051

- polarisation fractions measured at tWb vertex using top quark decay properties

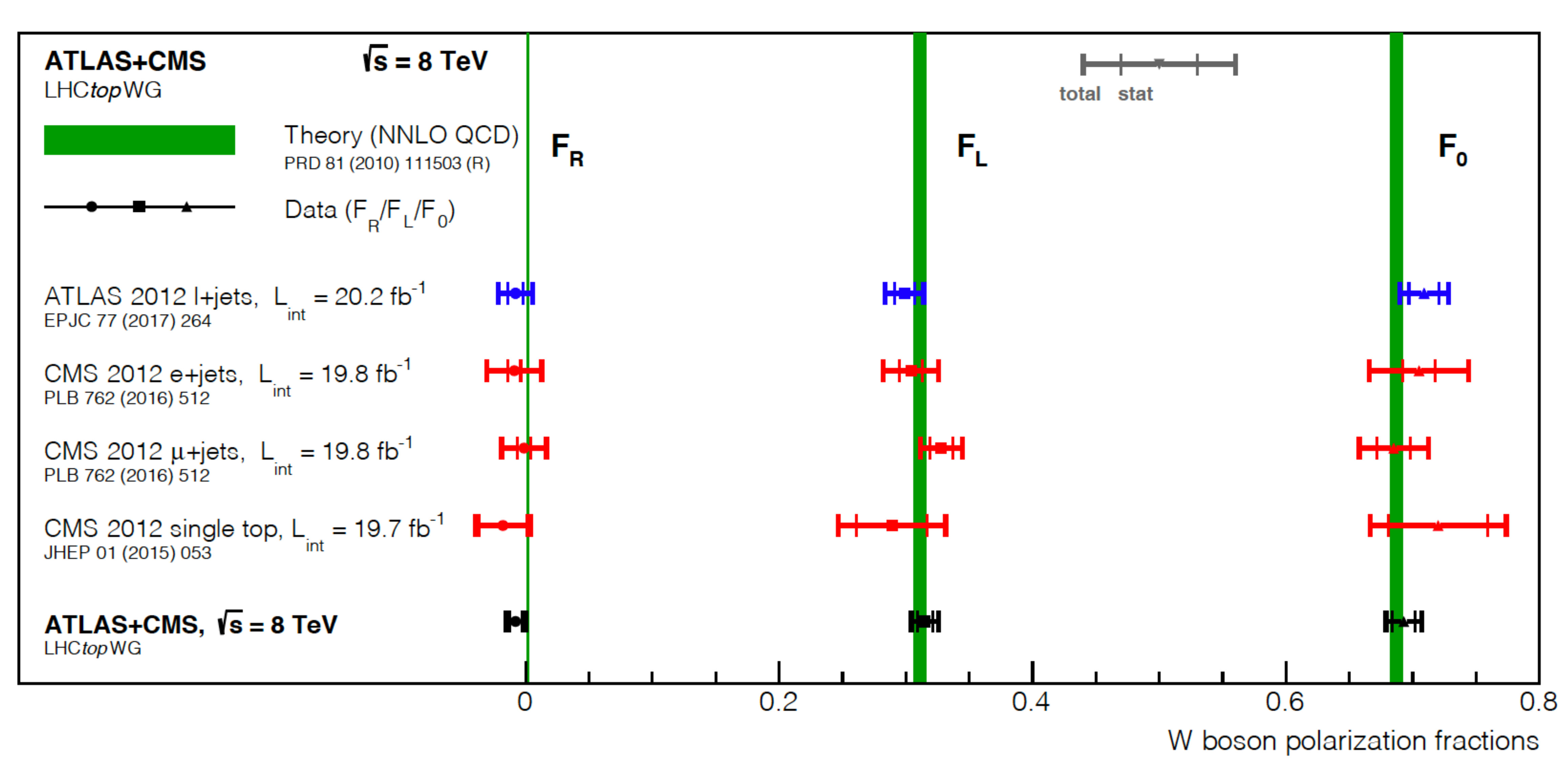
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_{\mathrm{L}} + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_{\mathrm{R}}$$

θ^* = angle of lepton wrt. b quark in W CM frame

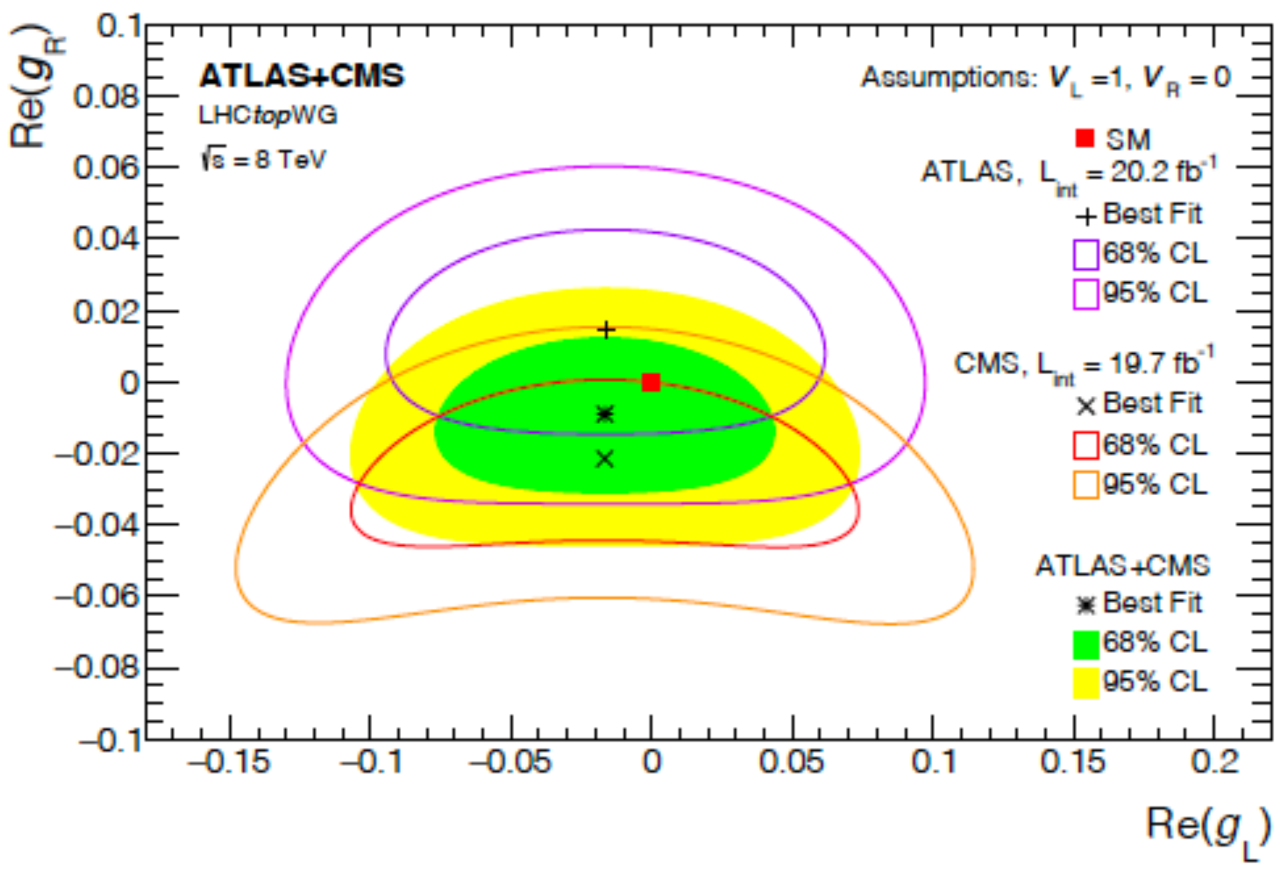
- combining measurements of F_0 and F_L polarisation fractions (F_R via unitary constraint)
  - ATLAS:
    - $t\bar{t}$ l+jets (Eur. Phys. J. C 77 (2017) 264)
  - CMS:
    - t-channel single top (JHEP 01 (2015) 053)
    - $t\bar{t}$ mu+jets
    - $t\bar{t}$ e+jets (Phys. Lett. B 762 (2016) 512)

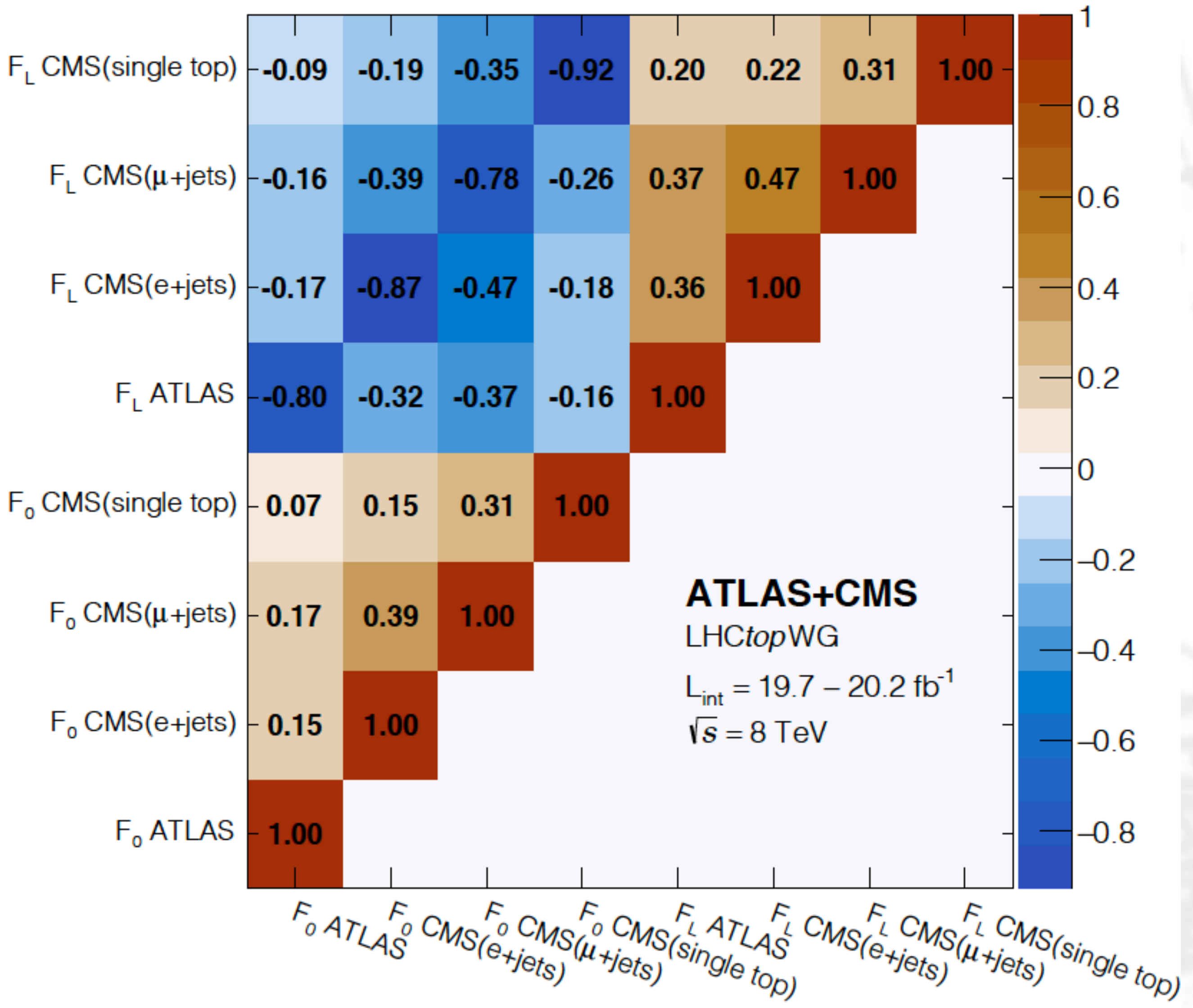
- **25-30-% improvement** wrt. individual measurements

- **limits on anomalous couplings** at tWb decay vertex and Wilson coefficients in EFT framework



correlations

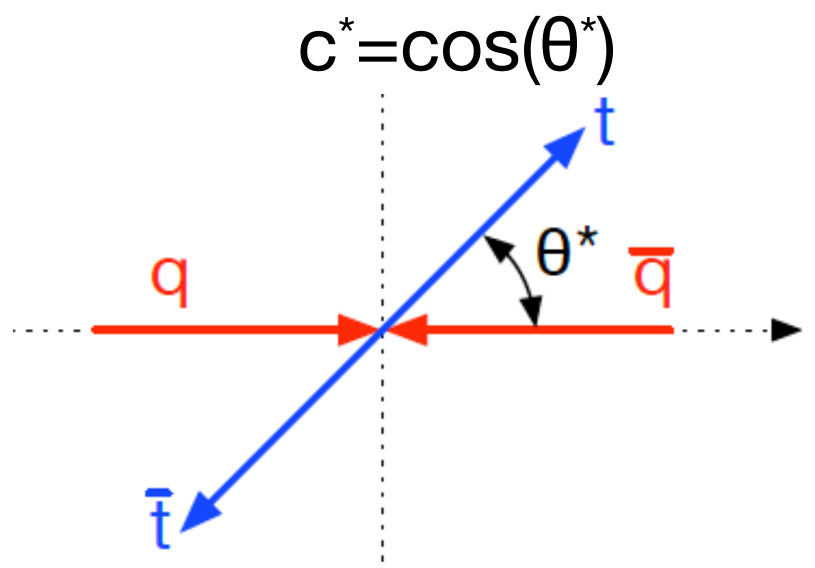


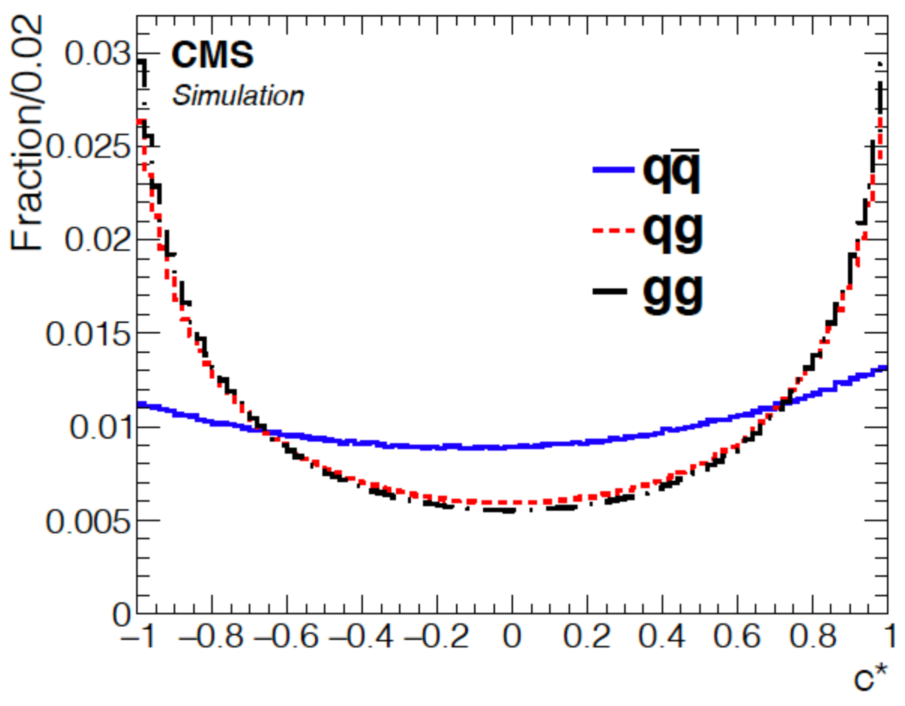


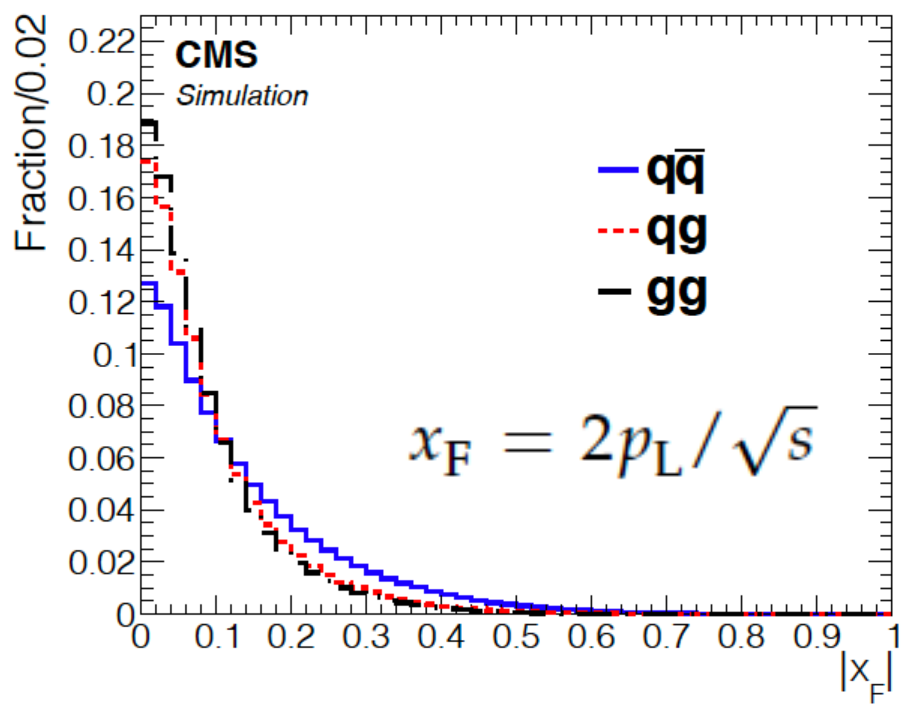
Forward backward asymmetry

$t\bar{t}$ lepton+jets | 2016 data

JHEP 06 (2020) 146



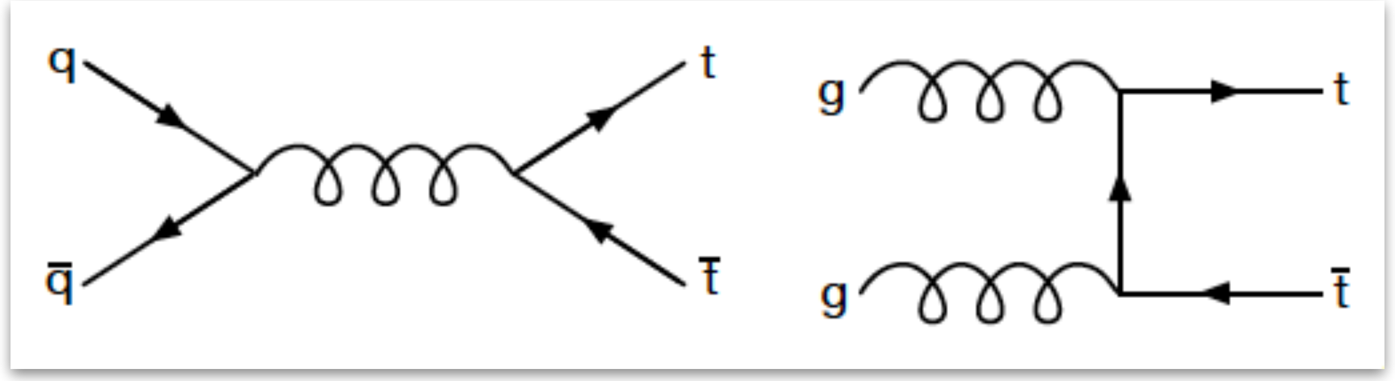




- forward-backward asymmetry (A_{FB}) in $qq \rightarrow t\bar{t}$ events

$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

  - challenge at LHC because of dominating $gg \rightarrow t\bar{t}$



  - new measurement using **c^*, x_F, and $M_{t\bar{t}}$ as sensitive observables**
  - $qq \rightarrow t\bar{t}$ fractions increases with high p_T^t
    - boosted and resolved decay topologies

- measure from fit $A_{FB}^{(1)} = 0.048^{+0.095}_{-0.087}\,(\text{stat})^{+0.020}_{-0.029}\,(\text{syst})$

  also **chromomagnetic ($\hat{\mu}_t$) and chromoeletric dipole moment ($\hat{d}_t$)**

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}\,(\text{stat})^{+0.016}_{-0.011}\,(\text{syst}) \qquad |\hat{d}_t| < 0.03$$

sensitivity comparison

Reference