Recent TOP results from CMS

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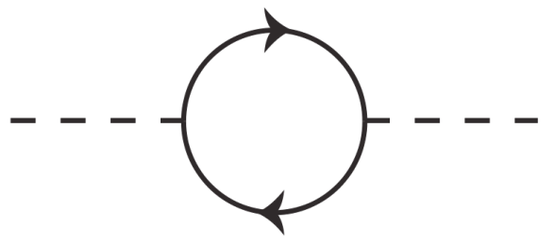
Outline

- top pair production
  - inclusive & differential cross section measurements
  - constraints of fundamental QCD parameters
  - top properties (mass, Yukawa coupling, spin polarization)
  - top pair spin correlations & charge asymmetry
  - associated production with a Z boson
- single top production
  - inclusive cross section (legacy Run I ATLAS/CMS combination)
  - differential cross section
  - associated production with a photon
- four top production
  - same sign dilepton & multi-lepton final states

Why do we care about top?

- top quark is the most massive known particle
  - significant contribution of top loops

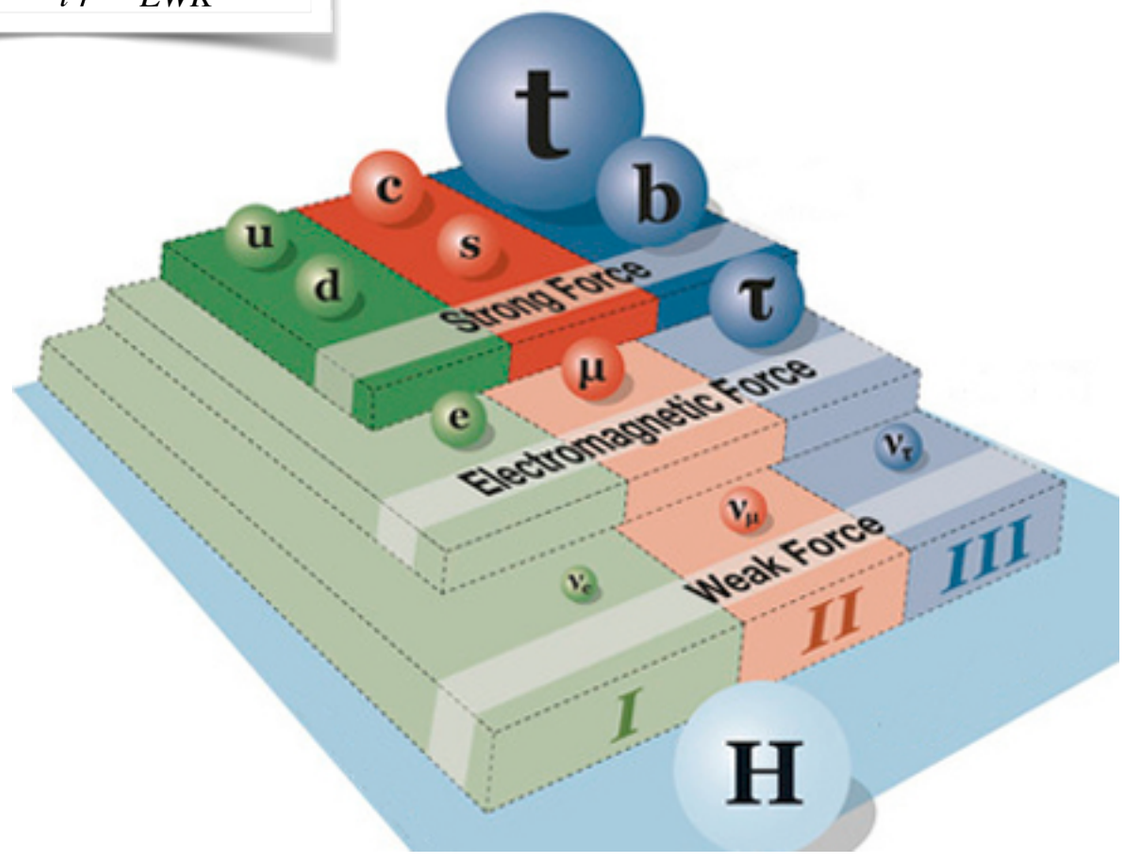


- the top Yukawa coupling is close to unity
  - coincidence or special dynamics?

$$\upsilon_{EWK} = 246\,GeV$$
$$m_t \approx 172\,GeV$$
$$y_t = \sqrt{2}\, m_t / \upsilon_{EWK} \approx 1$$

- top quark is unique because it decays before it can hadronize
  - no bound states with top can be formed
  - its decay products (W, b) largely preserve the top quark spin polarization and therefore it can be measured (unlike other quarks)

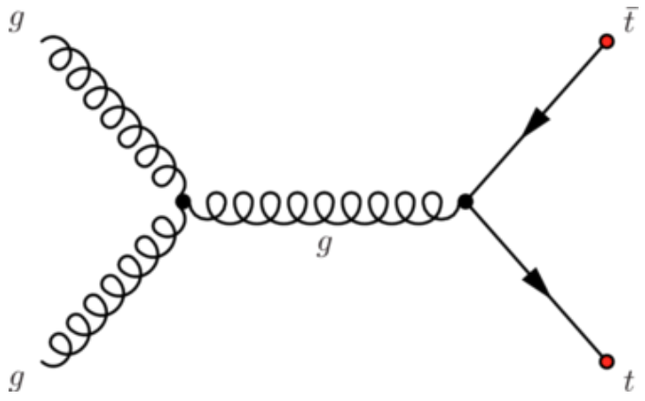
- top properties provide critical tests for the SM predictions
  - very sensitive to BSM effects



Top production and decay

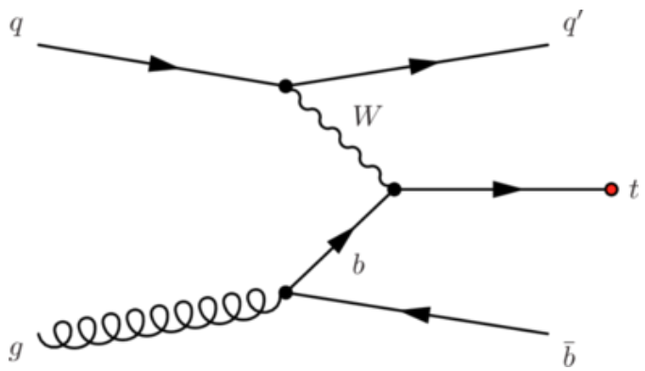
top quark pair production

σ_{tt}(pp @ 13 TeV) = 832 pb

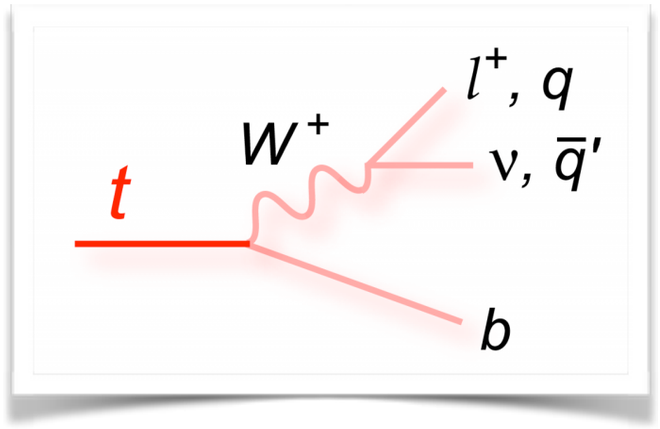


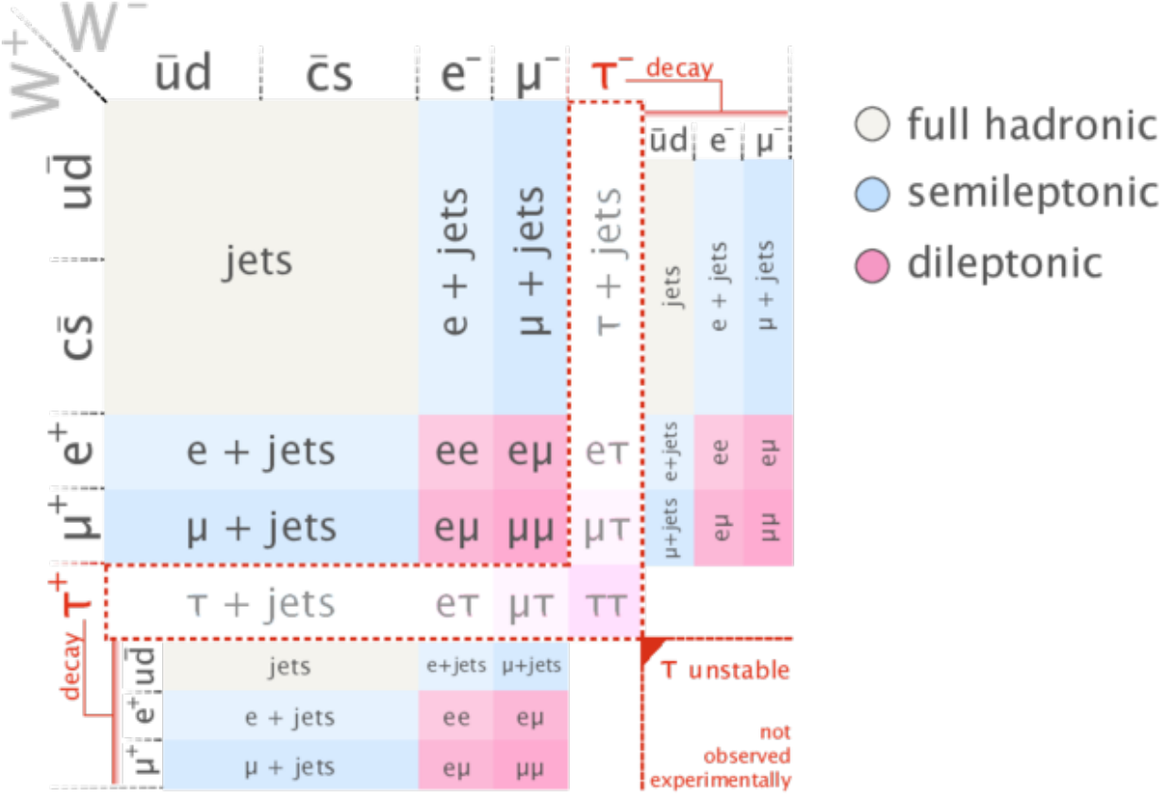
single top quark production

σ_t(pp @ 13 TeV) = 299 pb

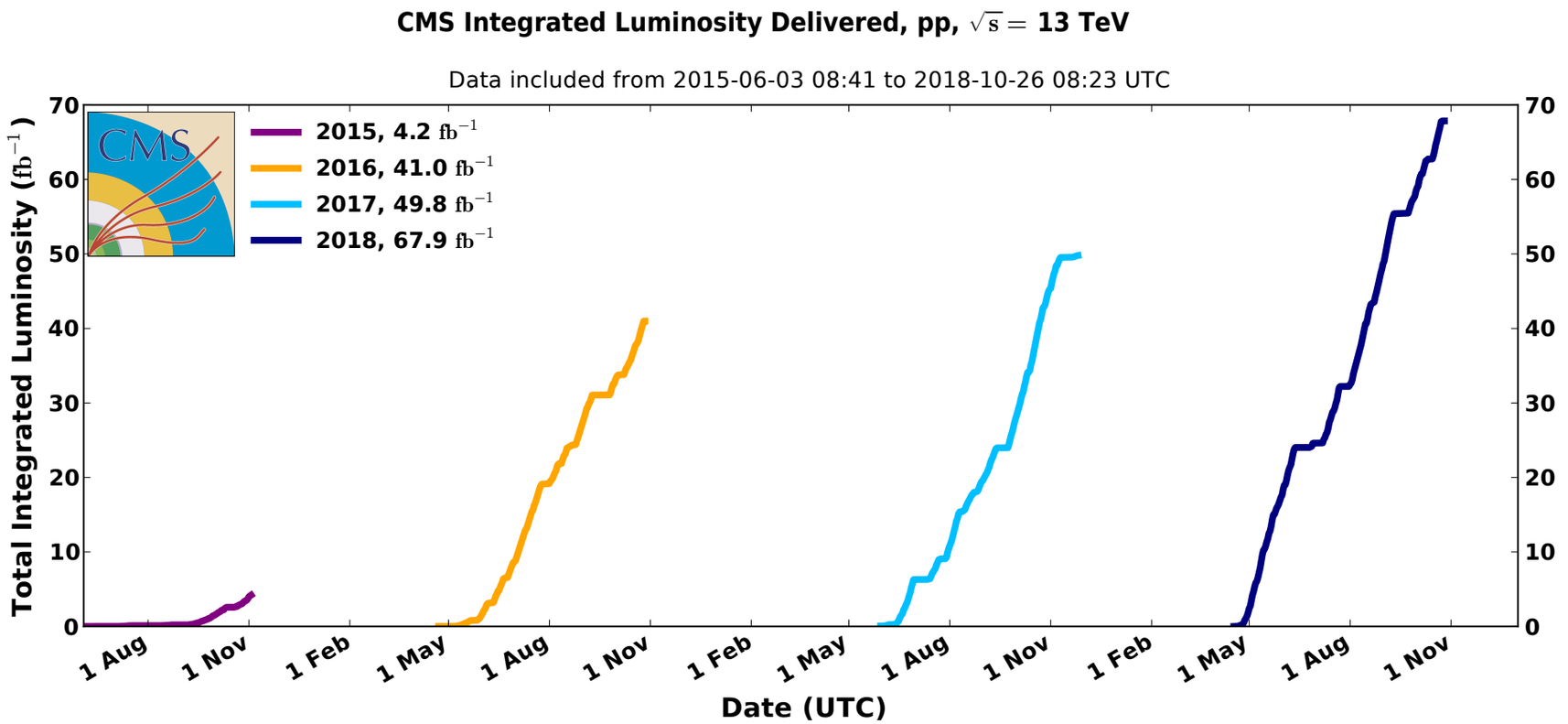


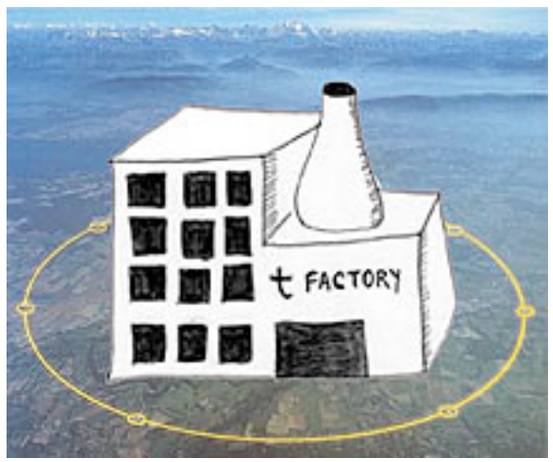
BR(t→Wb) = 0.957

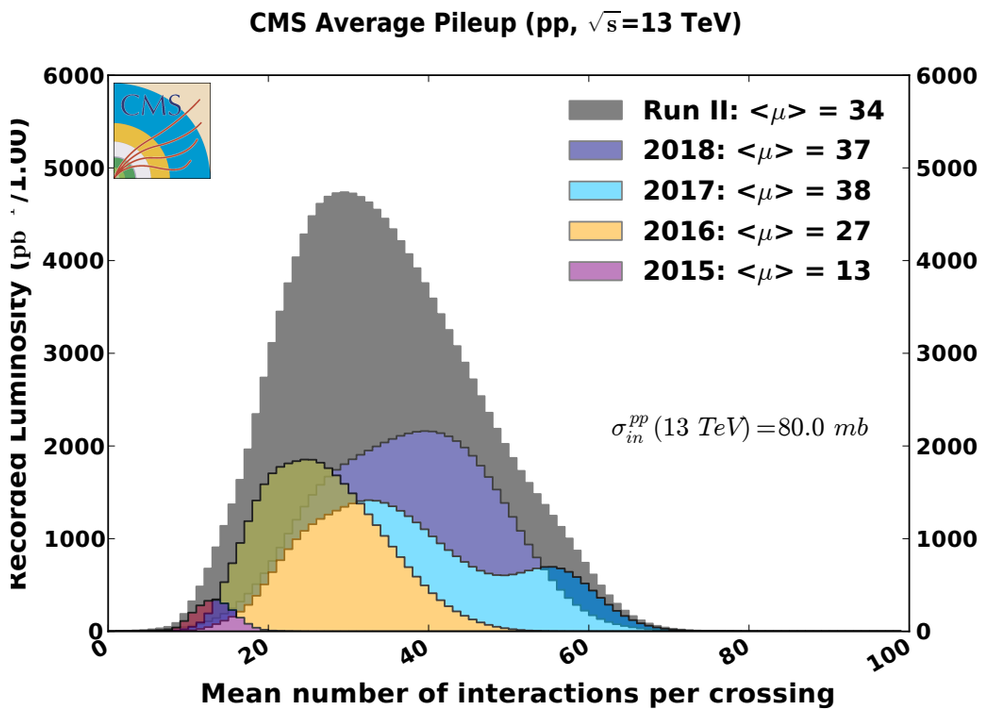




CMS @ LHC Run2 (2015 - 2018)

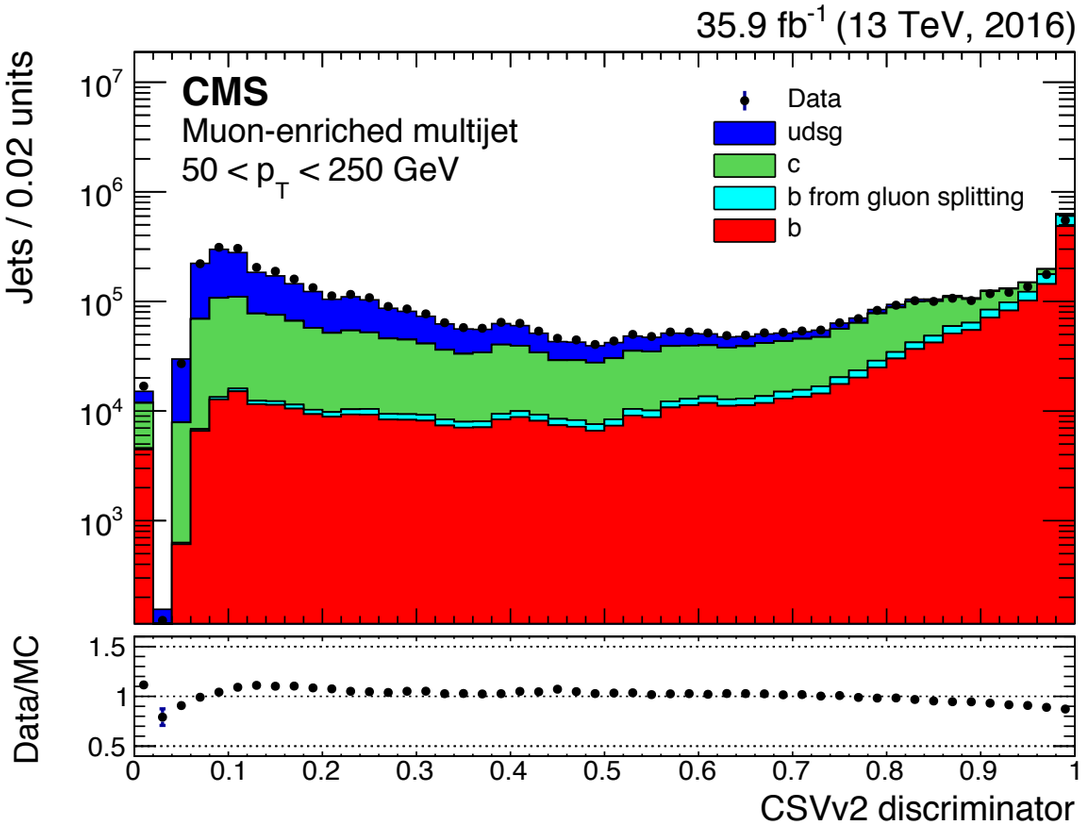


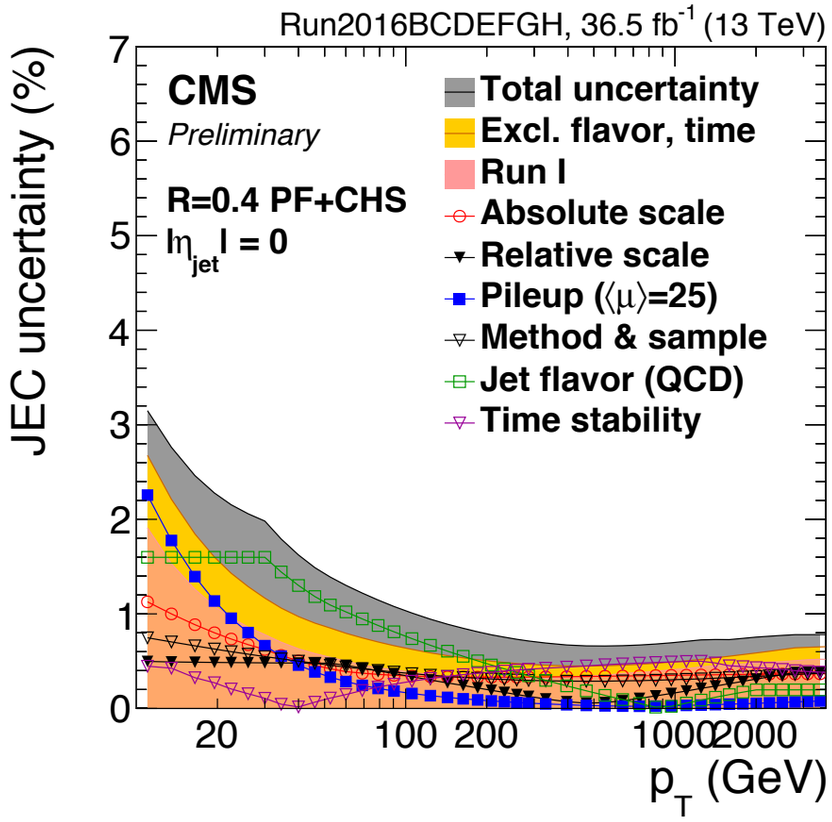




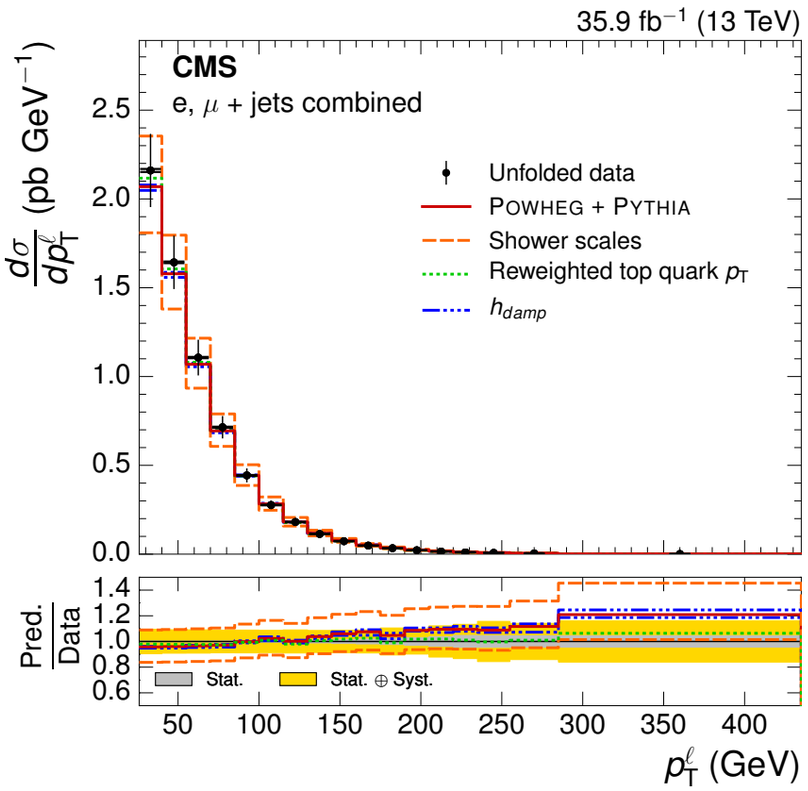
- proton-proton collisions @ **13 TeV**
- **2015 - 2018** runs
  - total luminosity ≈ **163 fb^{-1}**
  - 10^8 top quark pairs produced: LHC is a top quark factory !!
- on average **34** interactions per bunch crossing

Challenges in top measurements



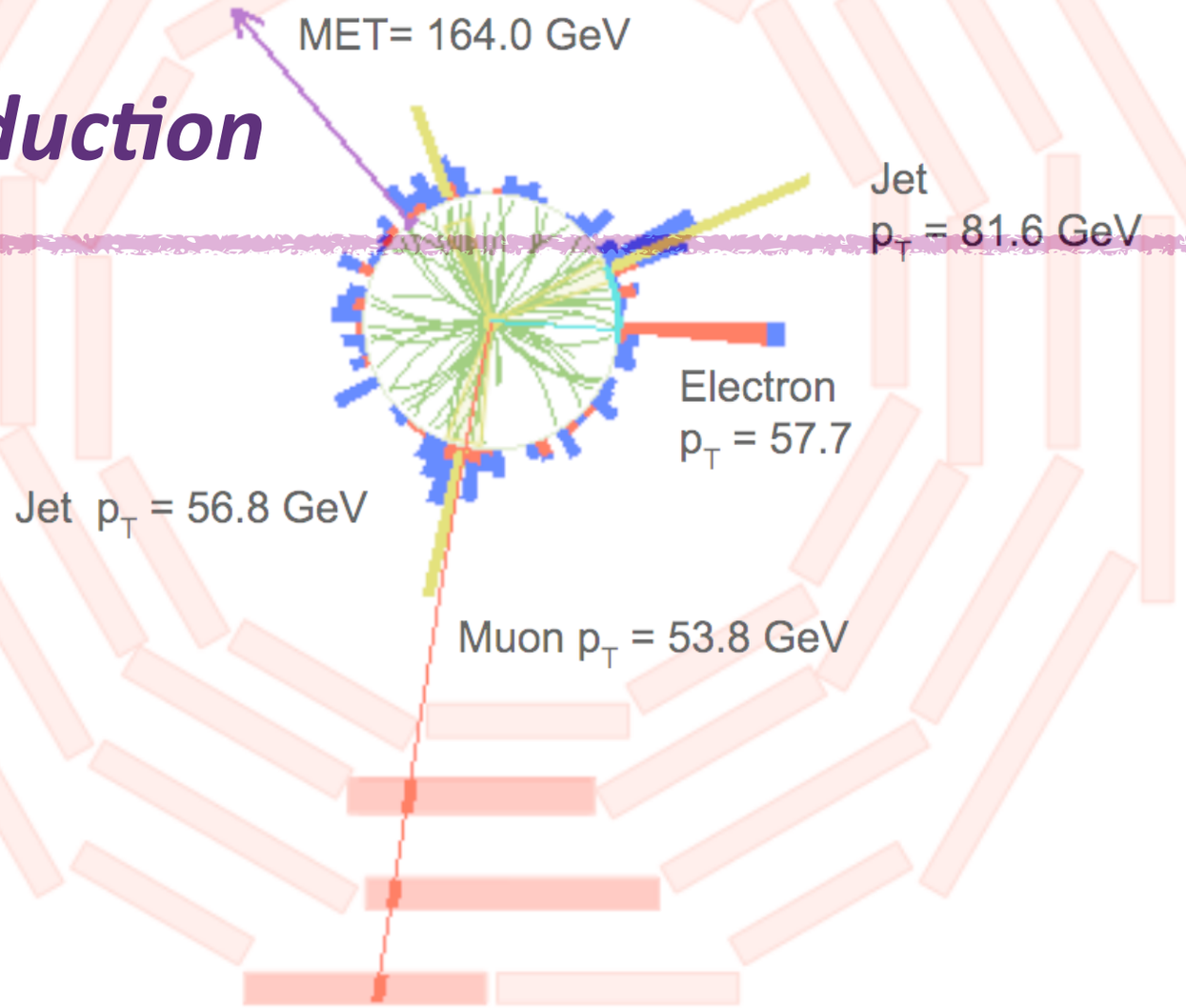


- **Top final states are complicated**
  - all types of objects involved (jets, b-jets, missing transverse momentum, leptons)
- **Experimental challenges**
  - jet energy scale (< 2%)
  - b-tagging efficiency (< 3%) & fake rate
  - lepton triggering & identification (< 2%)
- **Theoretical challenges**
  - enter through unfolding to parton & particle level
  - parton shower & underlying event modelling

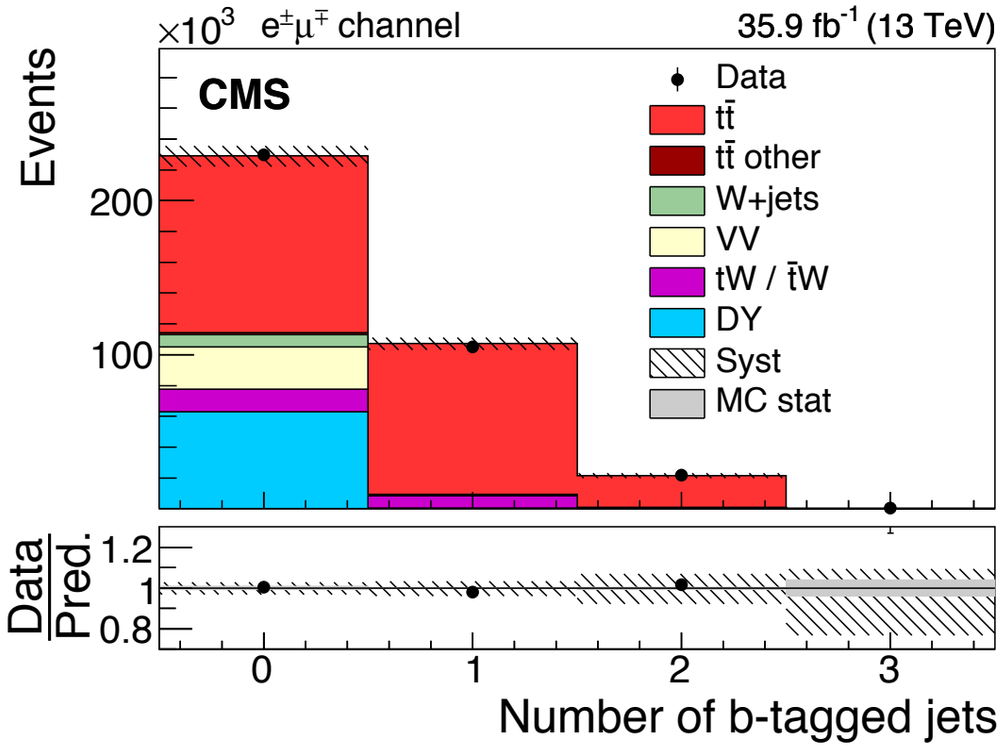


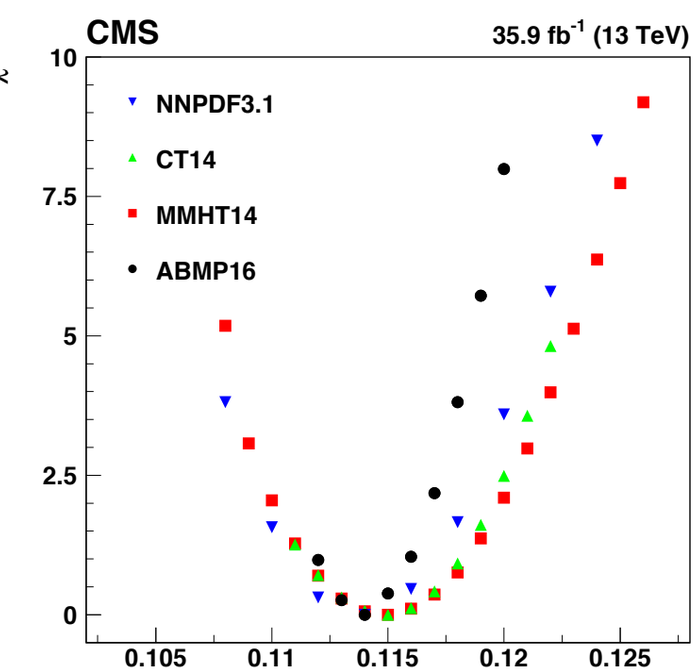
CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 19:26:24 2015 CEST
Run/Event: 251244 / 83494441
Lumi section: 151
Orbit/Crossing: 39572626 / 358

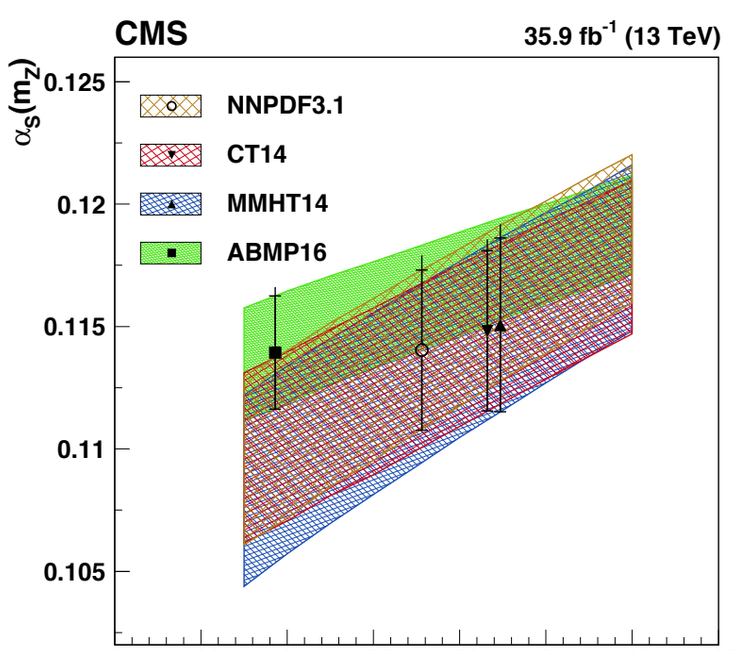
Top quark pair production



Inclusive cross section $\sigma_{t\bar{t}}$







- **dilepton events (ee, eμ, μμ)**
  - very clean final states
  - categories based on N_{bjets}
  - multi-differential template fit → in situ constraint of experimental uncertainties
- **extraction of QCD parameters**
  - Monte Carlo mass (simultaneous fit for m_t^{MC} & σ_{tt})
  - m_t in MS scheme and $\alpha_S(m_Z)$ for different PDF sets

NNLO + NNLL

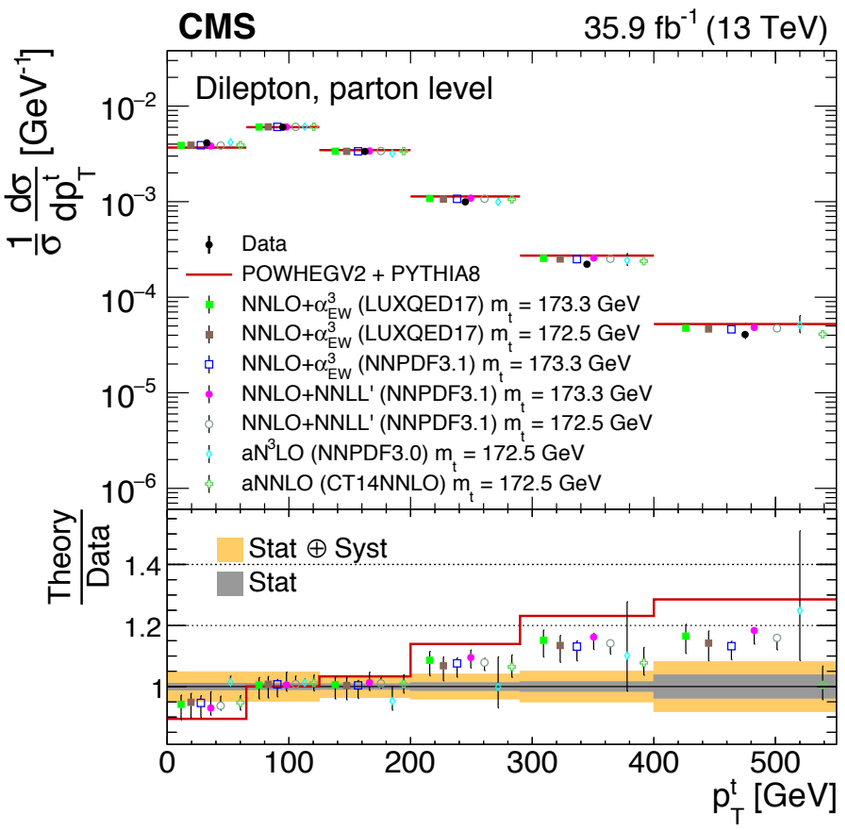
$$\sigma_{t\bar{t}}^{theo} = 832\,^{+20}_{-29}\,(scale) \pm 35\,(PDF + \alpha_S)\,pb$$

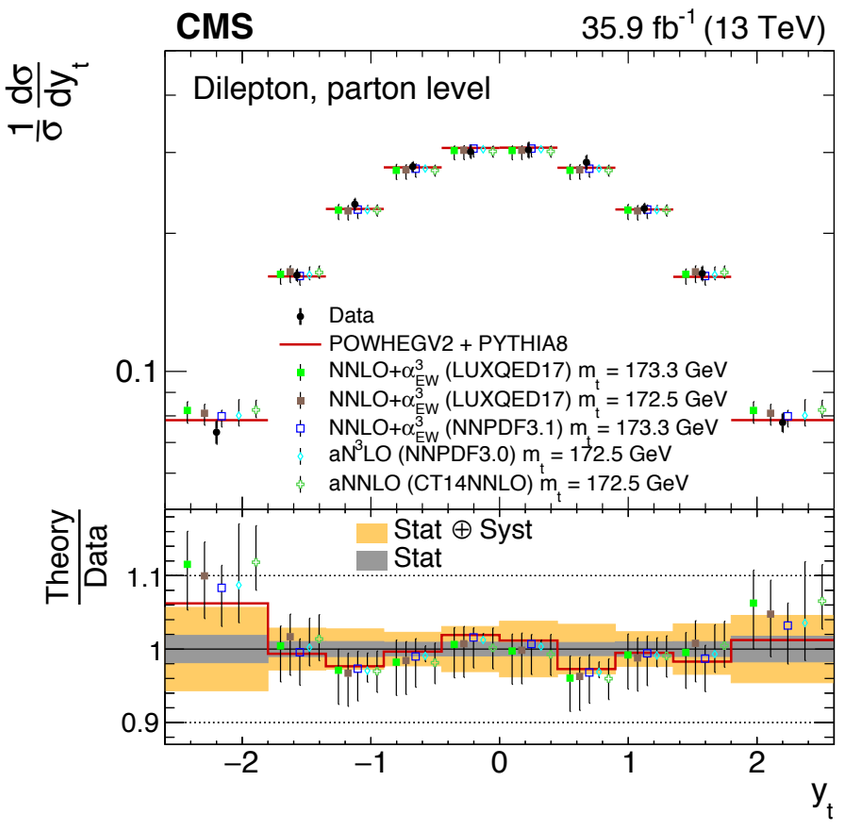
result

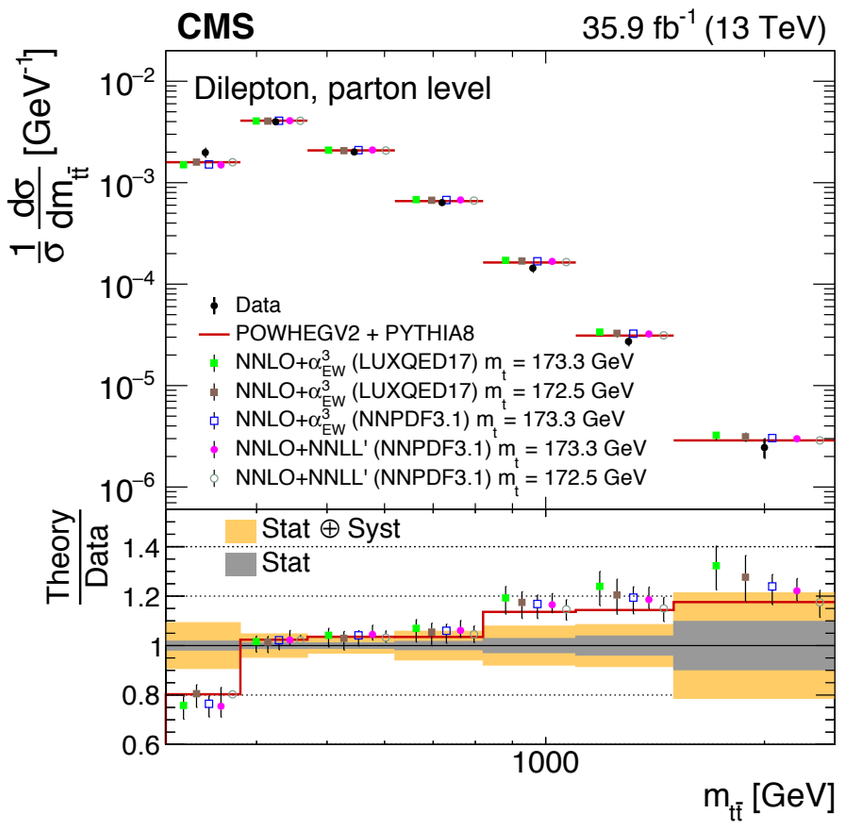
$$\sigma_{t\bar{t}} = 815 \pm 2\,(stat) \pm 29\,(syst) \pm 20\,(lumi)\,pb$$

$$m_t^{MC} = 172.33 \pm 0.14\,(stat)\,^{+0.66}_{-0.72}\,(syst)\,GeV.$$

Differential cross sections $d\sigma_{t\bar{t}}/dX$

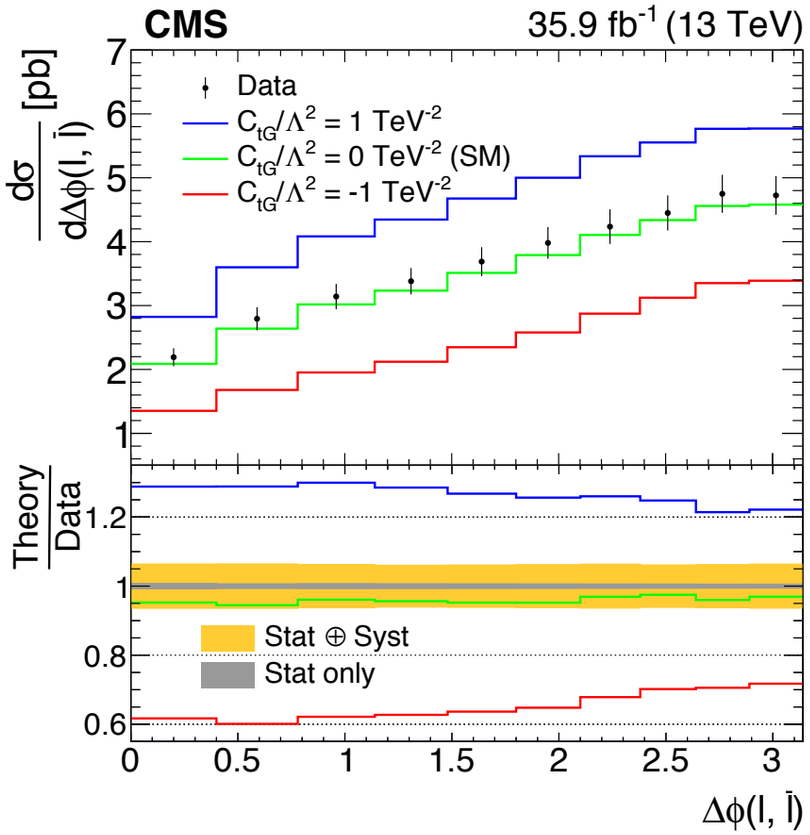


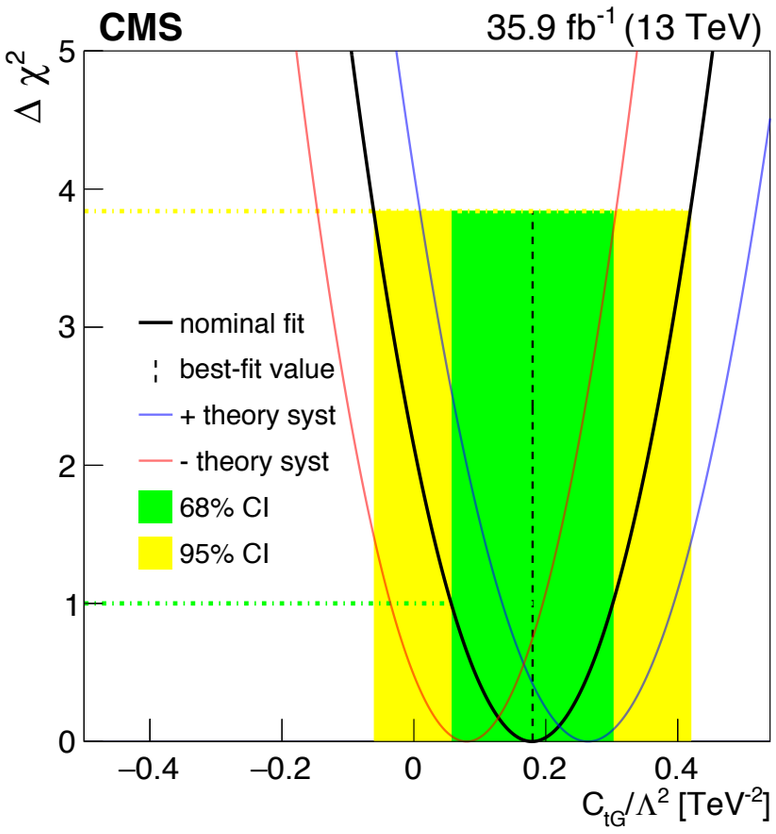


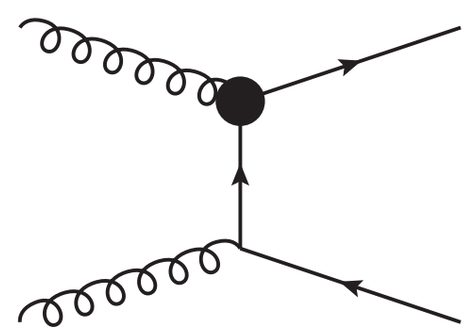


- **dilepton events (ee, eμ, μμ)**
  - novel kinematic reconstruction algorithm with W and top mass constraints
  - top pair system reconstruction efficiency of ~90%
- **measurements**
  - absolute and normalized differential cross sections @ parton & particle level
  - top & top-pair kinematic observables
  - comparison with state of the art of theory calculations at various orders
  - significant discrepancies observed that reduce with increasing perturbation order

Differential cross sections: chromomagnetic dipole moment







LO effective vertex

- **chromomagnetic dipole moment**
  - zero in SM
  - non-zero ("anomalous") in BSM models
  - affects the top pair production cross section
  - inclusive cross section & differential shapes
- **effective field theory framework**
  - expansion of additional terms in the Lagrangian
  - Λ is the scale where the new physics manifests itself
  - result compatible with the SM

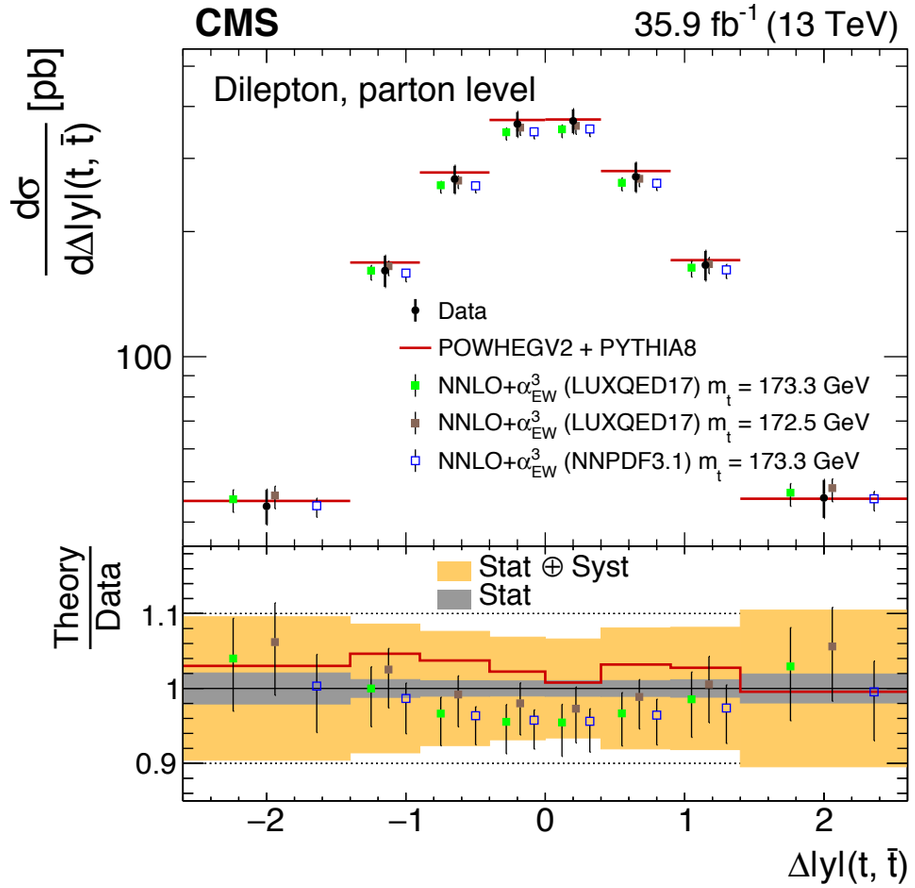
$$\mathcal{L}_{ttg} = g_s \bar{t}\gamma^\mu T^A t G^A_\mu + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}\left(d_V + i d_A \gamma_5\right) T^A t G^A_{\mu\nu}$$

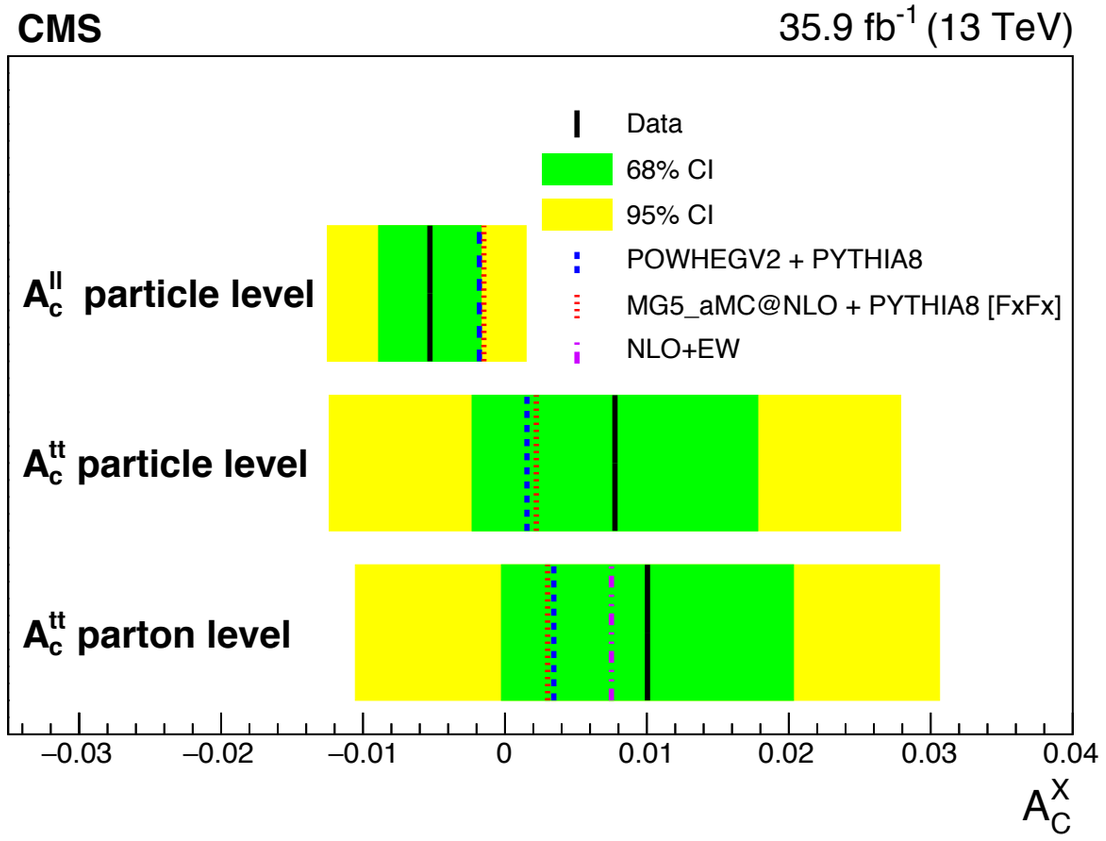
CMDM

$$\sigma = \sigma_{\mathrm{SM}} + \frac{C_{tG}}{\Lambda^2}\beta_1$$

$$\beta_1^{NLO}\,@13\,\mathrm{TeV} = 239.5^{+29.0}_{-31.8}\ \mathrm{pb\,TeV^2}$$

Differential cross sections: charge asymmetry



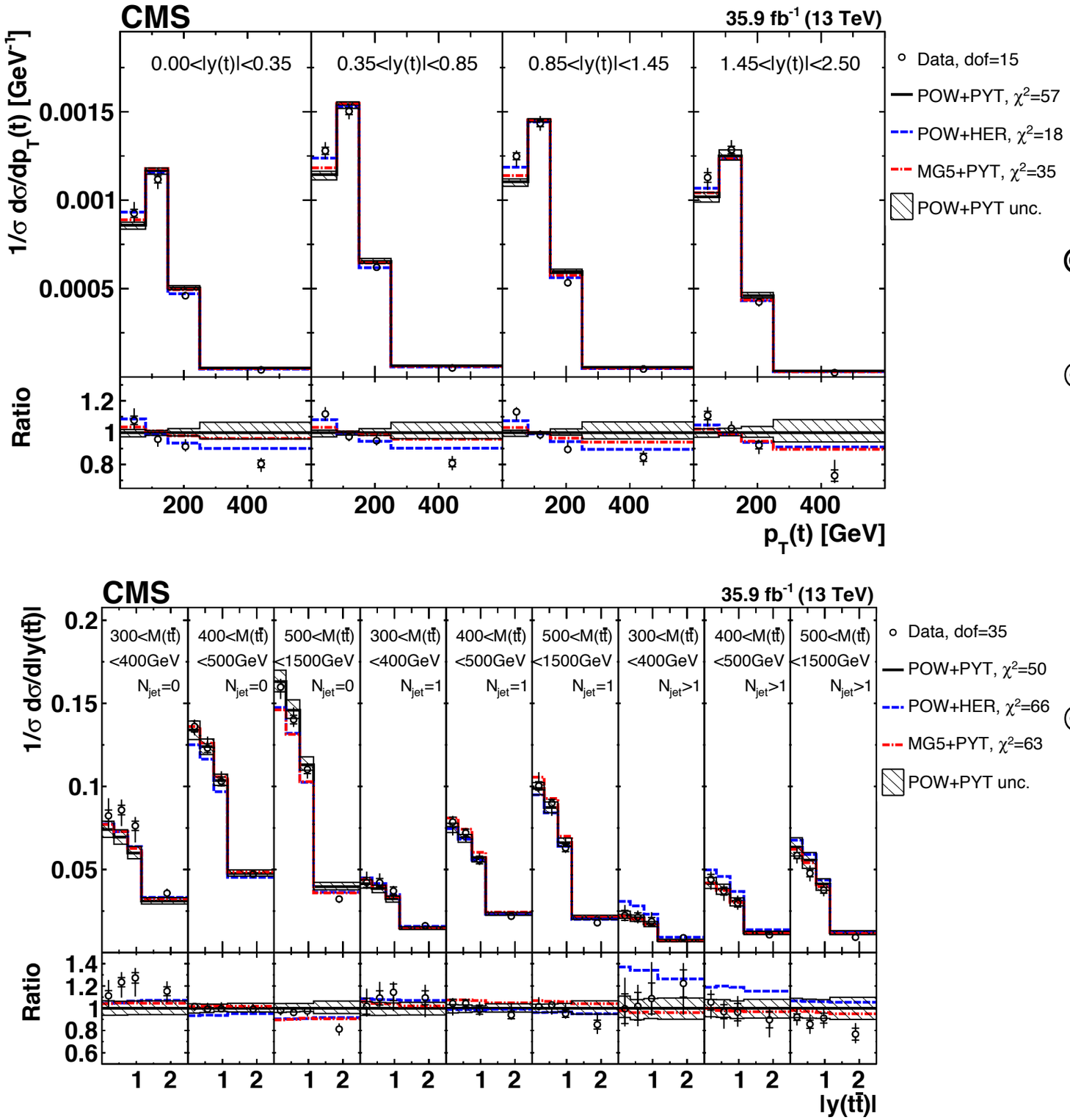


- **charge asymmetry**
  - asymmetry in top, anti-top rapidities
  - very small at LHC (gluon initiated production)
  - sensitive to BSM effects
- **experimental measurement**
  - direct (from reconstructed top quarks)
  - indirect (from decay leptons)
  - compatible with SM but uncertainty is still large

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

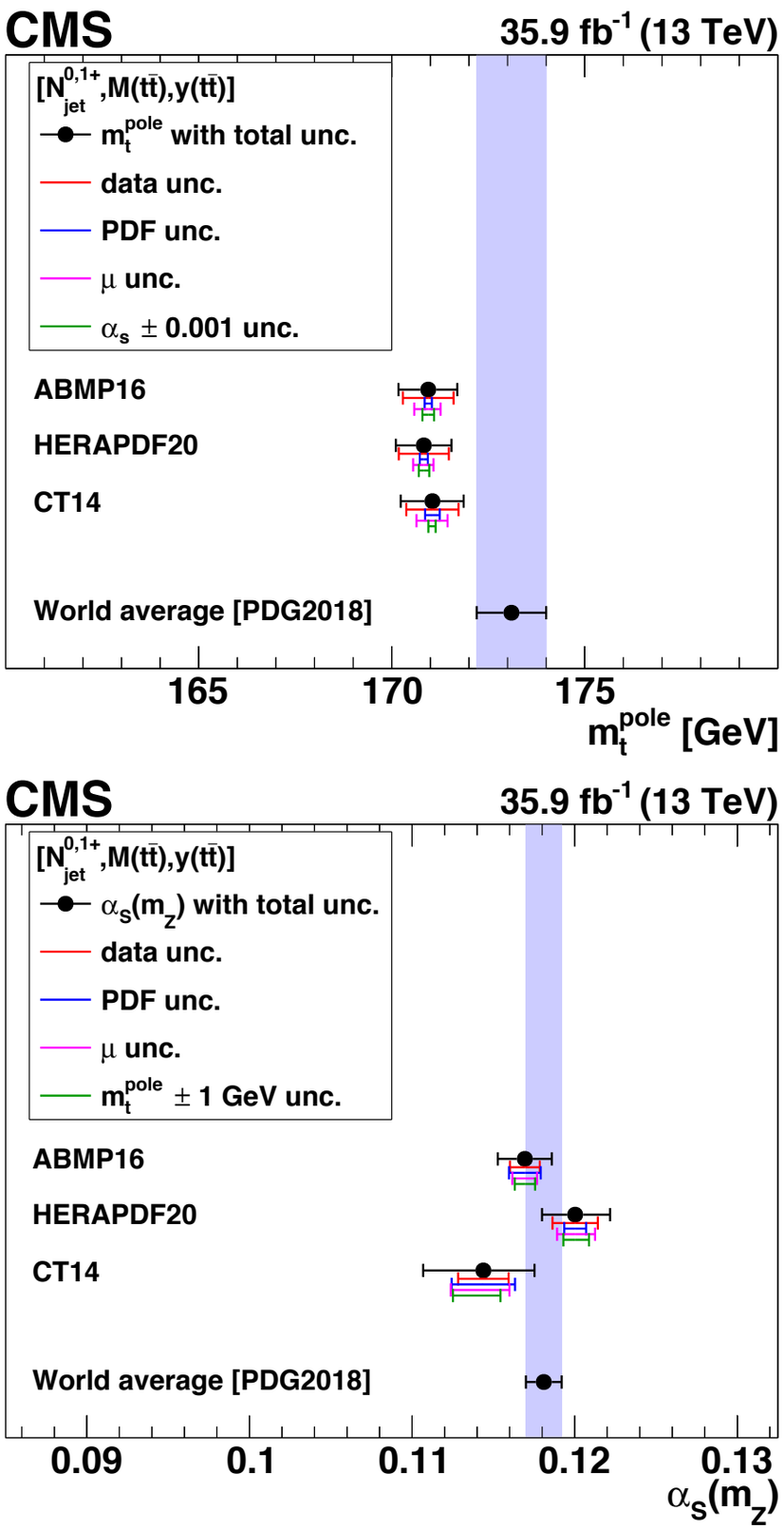
$$A_c^{\ell\bar{\ell}} = \frac{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) - \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) + \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}$$

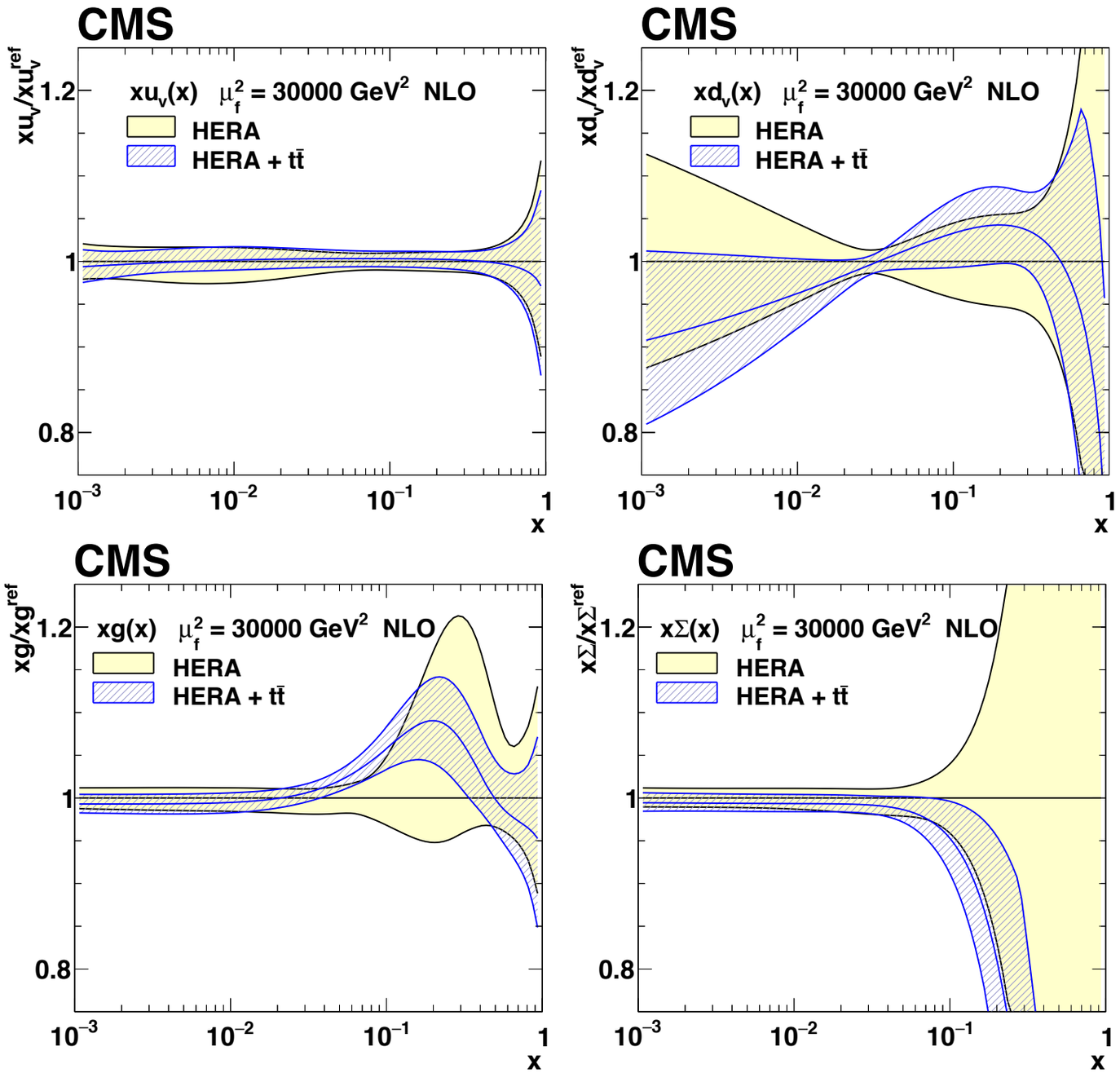
Multi-differential cross sections



- **dilepton events (ee, eμ, μμ)**
  - high purity & statistics sample
- **measurements**
  - normalized differential cross sections
  - double differential (top p_T in |y| bins, |y(tt)| in m_{tt} bins, etc)
  - triple differential (|y(tt)| in m_{tt} and jet multiplicity bins)
- **QCD analysis**
  - multi-differential measurements are very sensitive to the QCD predictions
  - extraction of α_S
  - measurement of m_t
  - simultaneous fit of PDFs, α_S and m_t
  - significant impact on gluon PDF

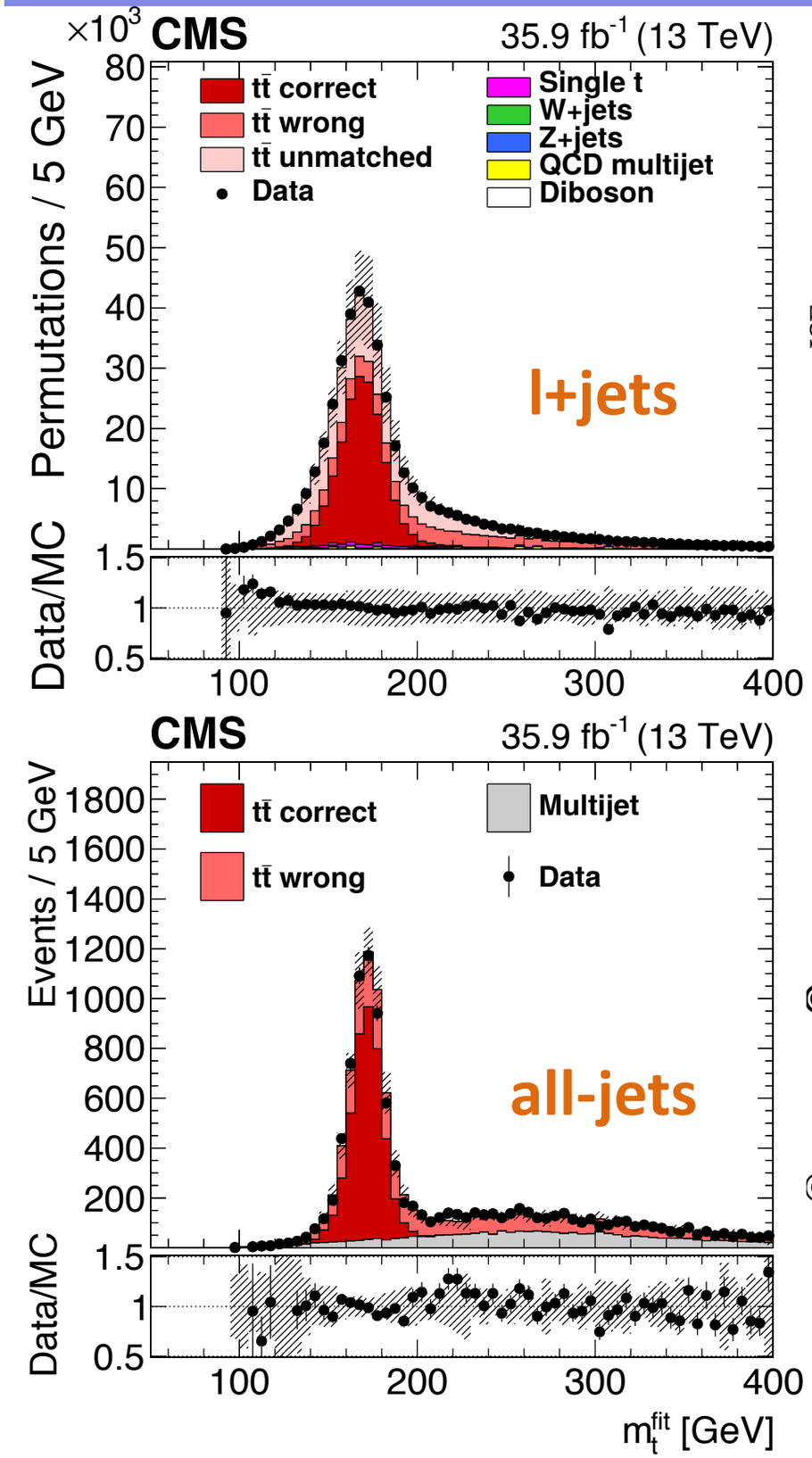
Multi-differential cross sections: QCD analysis

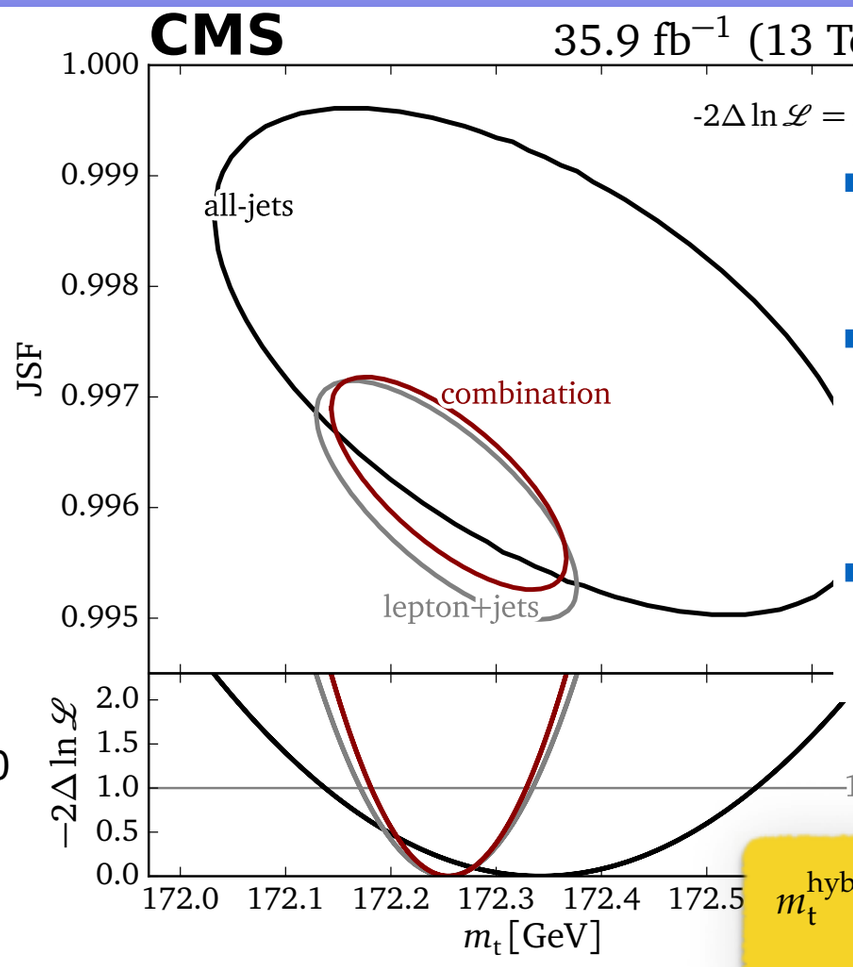




significant reduction of gluon PDF uncertainty at high-x

Top mass measurements with top quark pairs





- ➡simultaneous fit for jet energy scale & mt
- ➡"ideogram" method (each perturbation is taken into account with proper weight)
- ➡combination performed with joint likelihood

all-jets

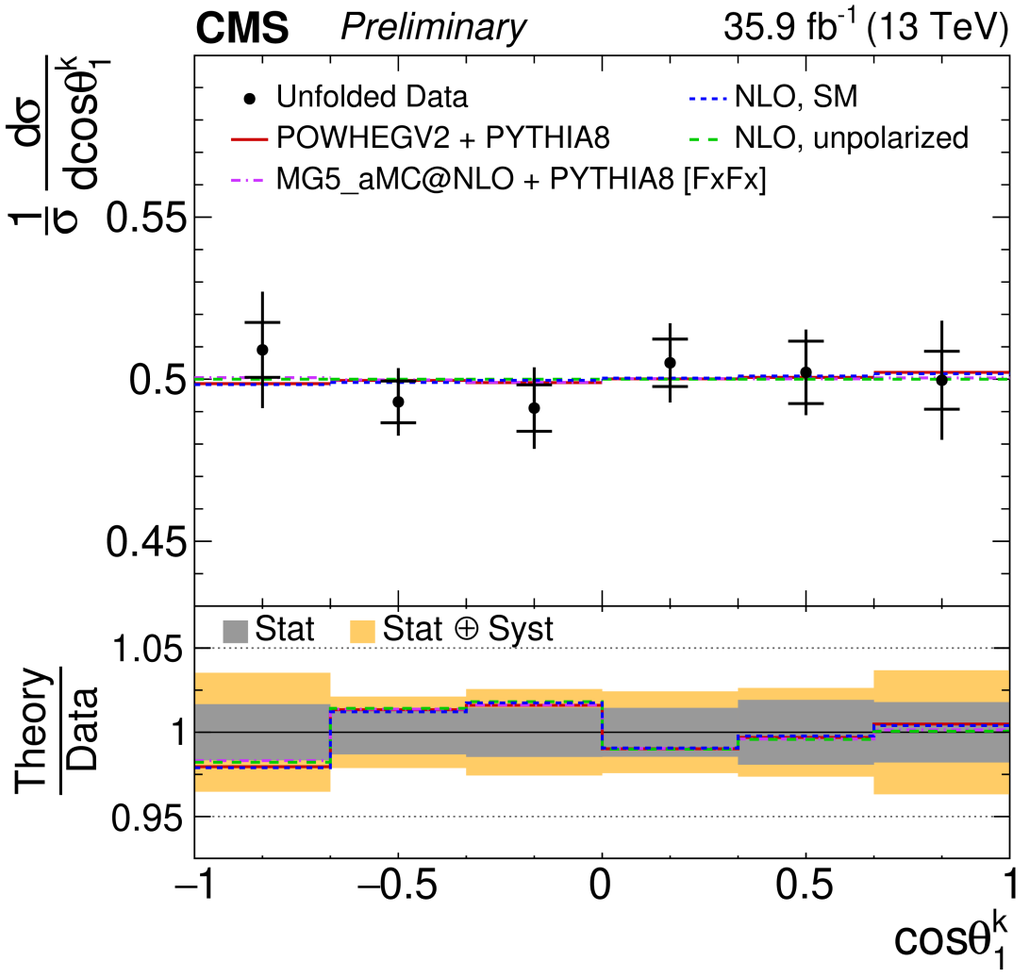
$m_t^{hyb} = 172.34 \pm 0.20\,(stat+JSF) \pm 0.70\,(syst)\,GeV$

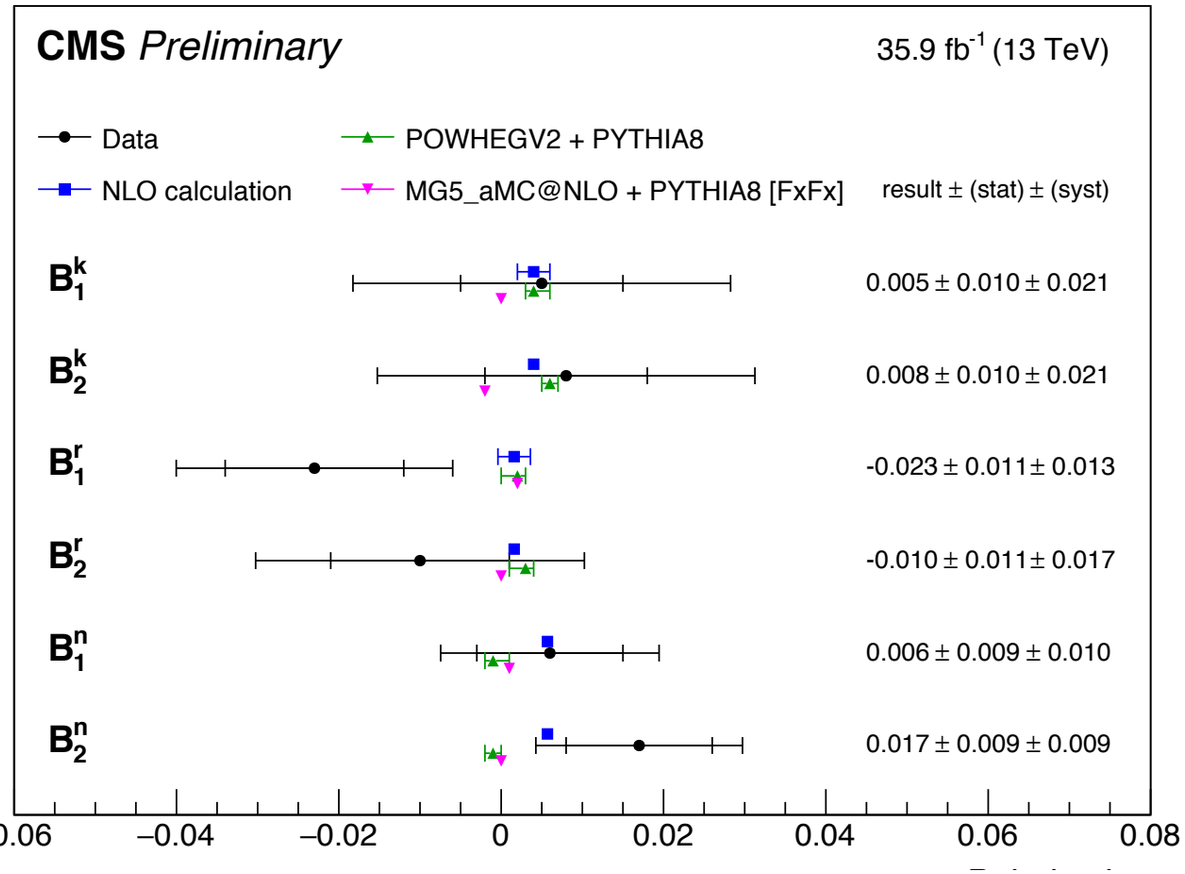
$m_t^{hyb} = 172.26 \pm 0.07\,(stat+JSF) \pm 0.61\,(syst)\,GeV$

combined

- **l+jets channel**
  - ample statistics, practically background free
  - ambiguity in top reconstruction due to the neutrino
- **all-jets channel**
  - much less statistics (higher trigger thresholds, QCD background)
  - less ambiguous top reconstruction
  - similar systematic uncertainties

Top polarization in top pair production



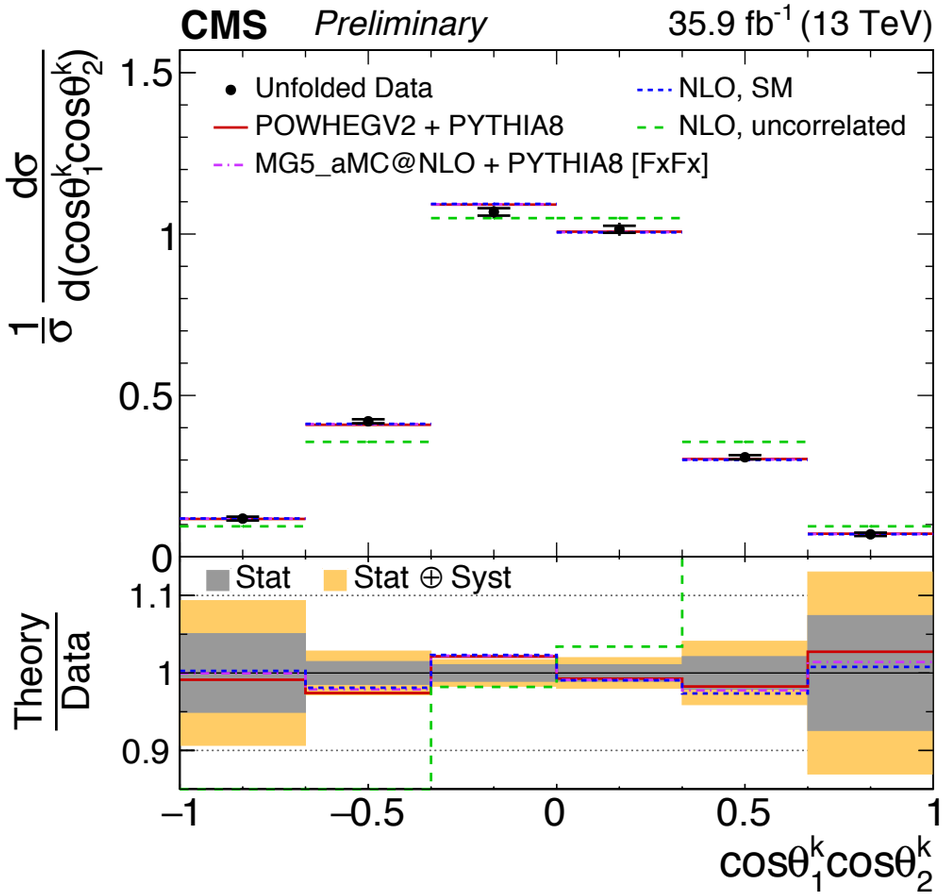


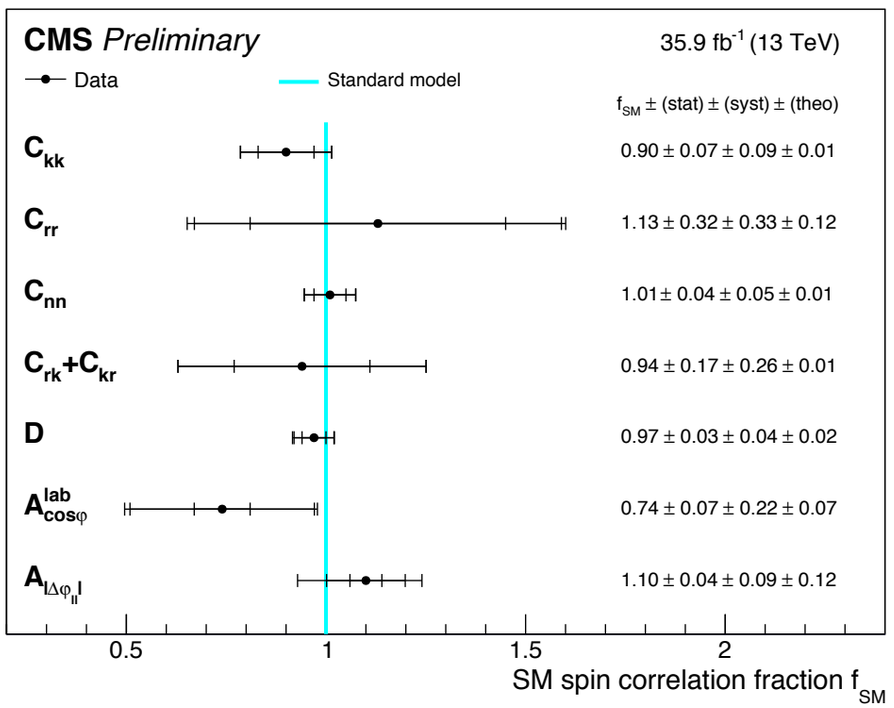
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1^i \cos\theta_1^i\right)$$

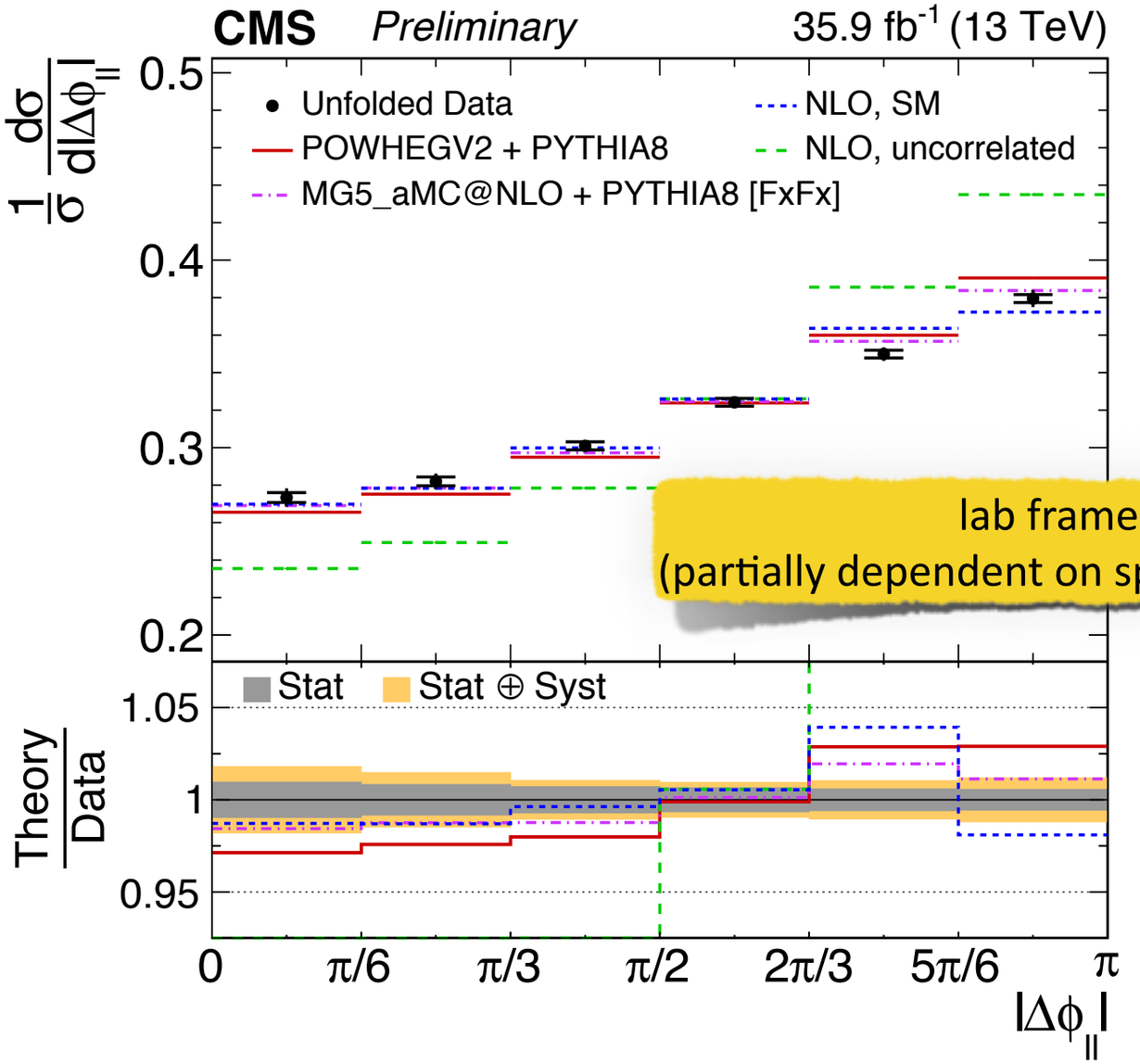
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_2^i} = \frac{1}{2}\left(1 + B_2^i \cos\theta_2^i\right)$$

- **dilepton channel**
  - leptons carry maximal information related to the top spin polarization
- **spin polarization**
  - stringent test of SM
  - measured through lepton angular distributions around reference axes in the tt CM frame
  - results compatible with SM but large uncertainties

Top pair spin correlation



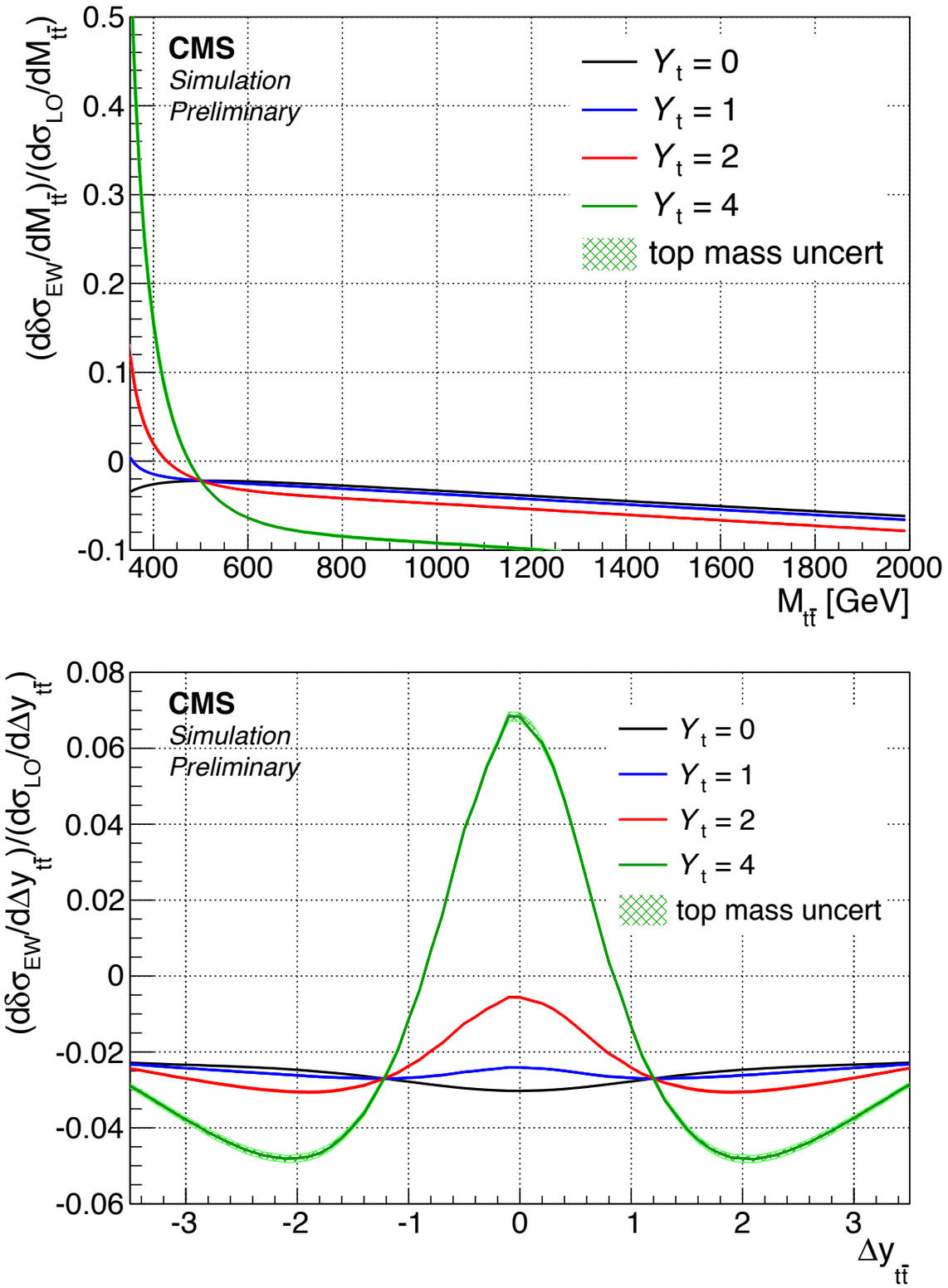




lab frame
(partially dependent on spin correlations)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i\cos\theta_2^j} = \frac{1}{2}\left(1 - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)\ln\left(\frac{1}{\left|\cos\theta_1^i\cos\theta_2^j\right|}\right)$$

Top Yukawa coupling in top pair production

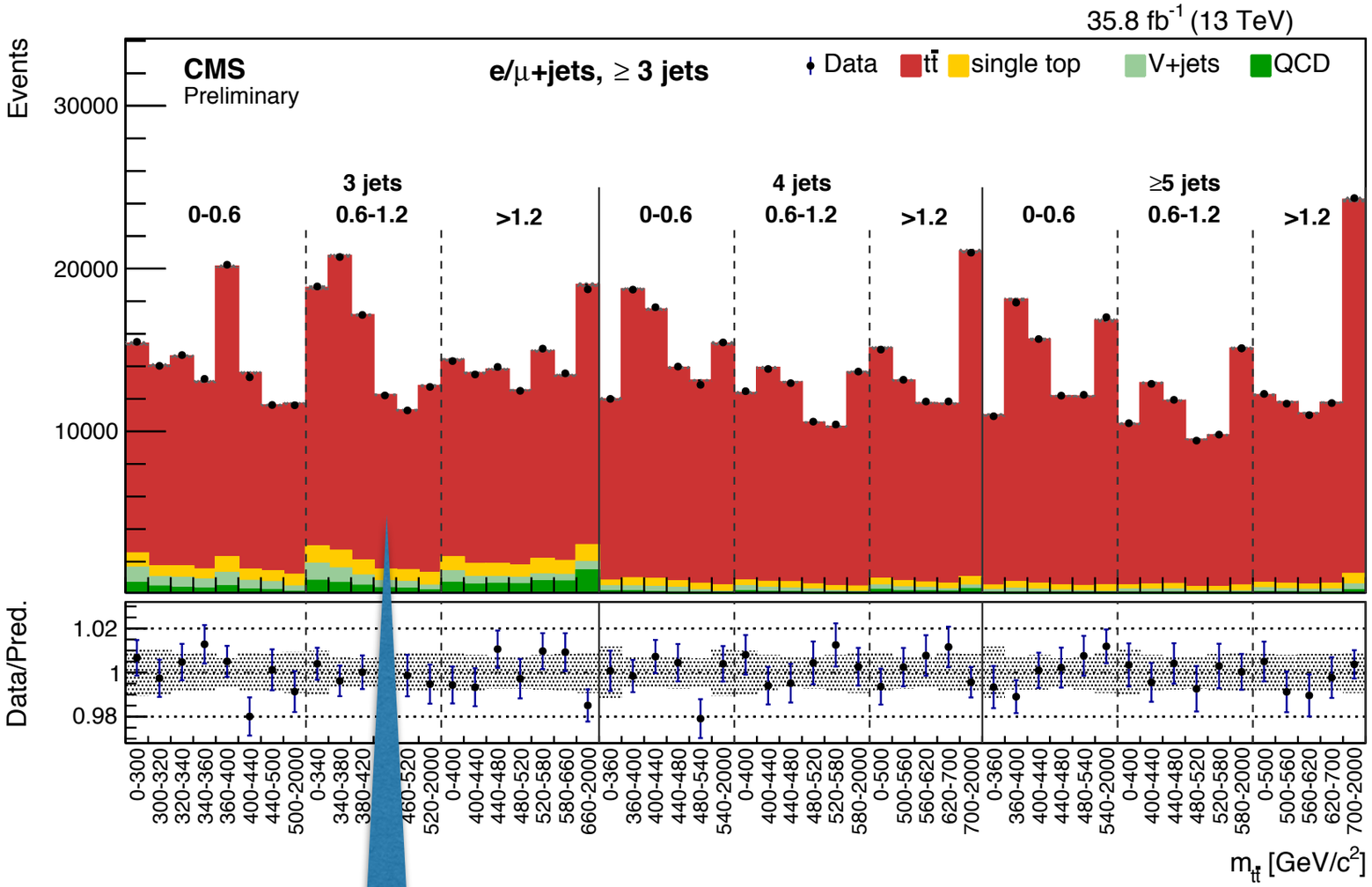


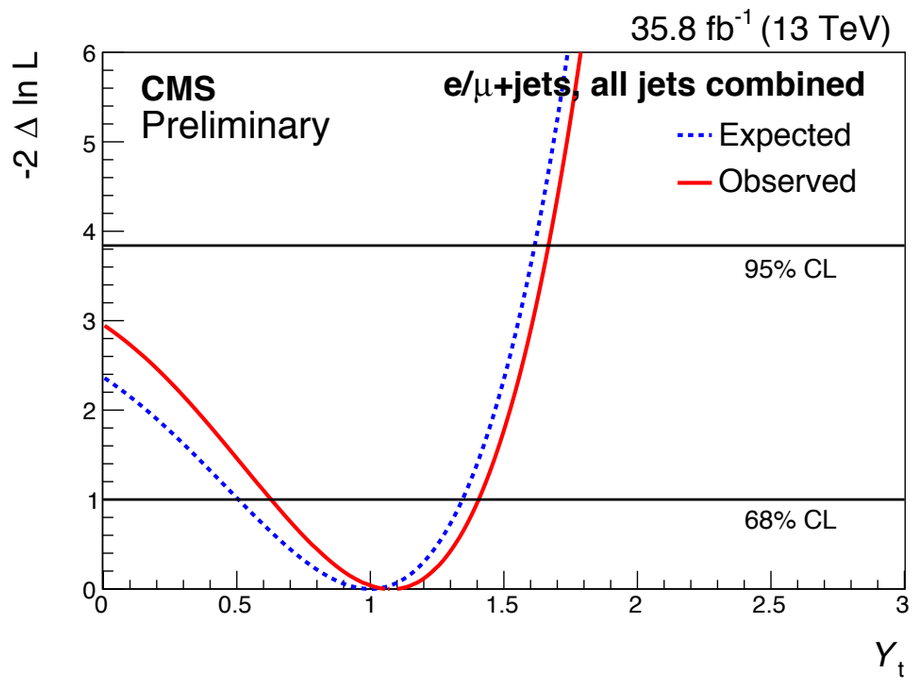
$$y_t = \sqrt{2}\, m_t / v_{EWK}$$

$$\sim \alpha_S^2 \alpha_{weak}$$

- **top pair production cross section**
  - dominated by QCD
- **EWK contributions**
  - overall negligible and not included in MC
  - become significant at large momentum transfers and near the top pair production threshold
  - sensitive to the top Yukawa coupling y_t
- **experimental measurement**
  - l+jets channel
  - novel top pair reconstruction to improve the m_{tt} resolution
  - combined fit on m_{tt} distributions in bins of $|\Delta y_{tt}|$ and jet multiplicity

Top Yukawa coupling in top pair production





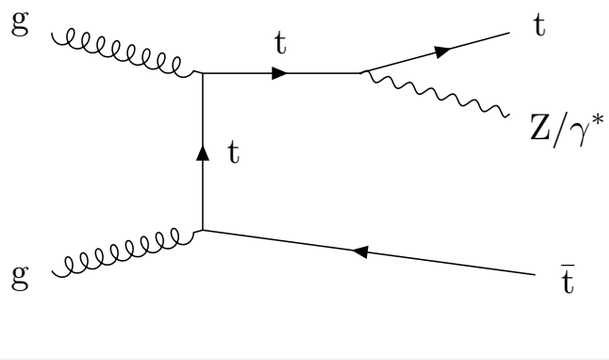
low jet multiplicity: worse m_{tt} resolution but contains more low m_{tt} events and enhances the sensitivity to the top Yukawa coupling

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	$Y_t < 1.62$	$Y_t < 1.67$

Associated production of a top pair with a Z boson

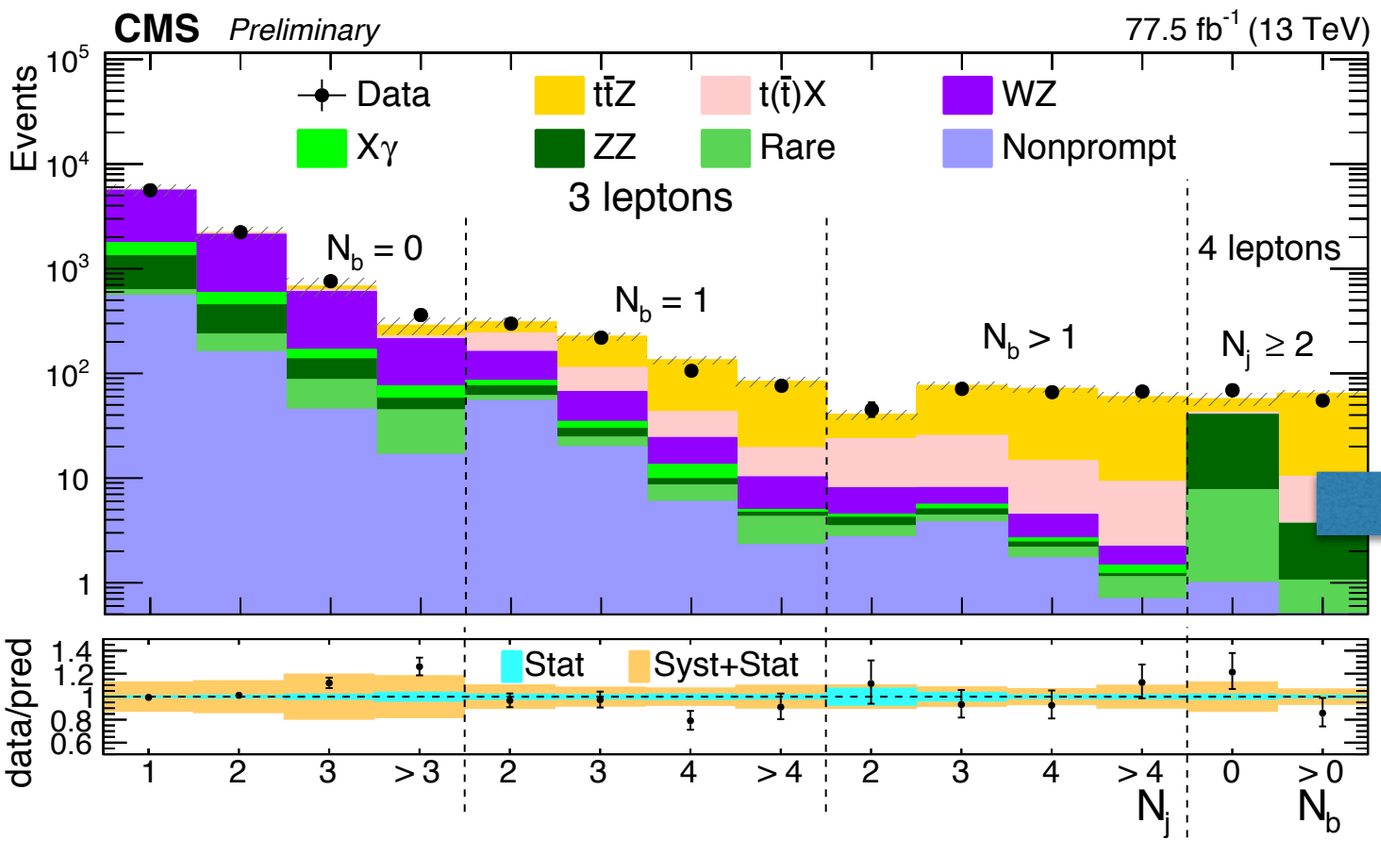
- **ttZ process**
  - sensitive to BSM effects
  - direct probe of the top coupling with Z
  - important background to searches
- **experimental measurement**
  - multi-lepton channel (3 or 4 leptons, two of which satisfy the Z mass hypothesis)
  - measurement using the jet multiplicity in bins of b tagged jets
  - uncertainties reduced by multi-category fit

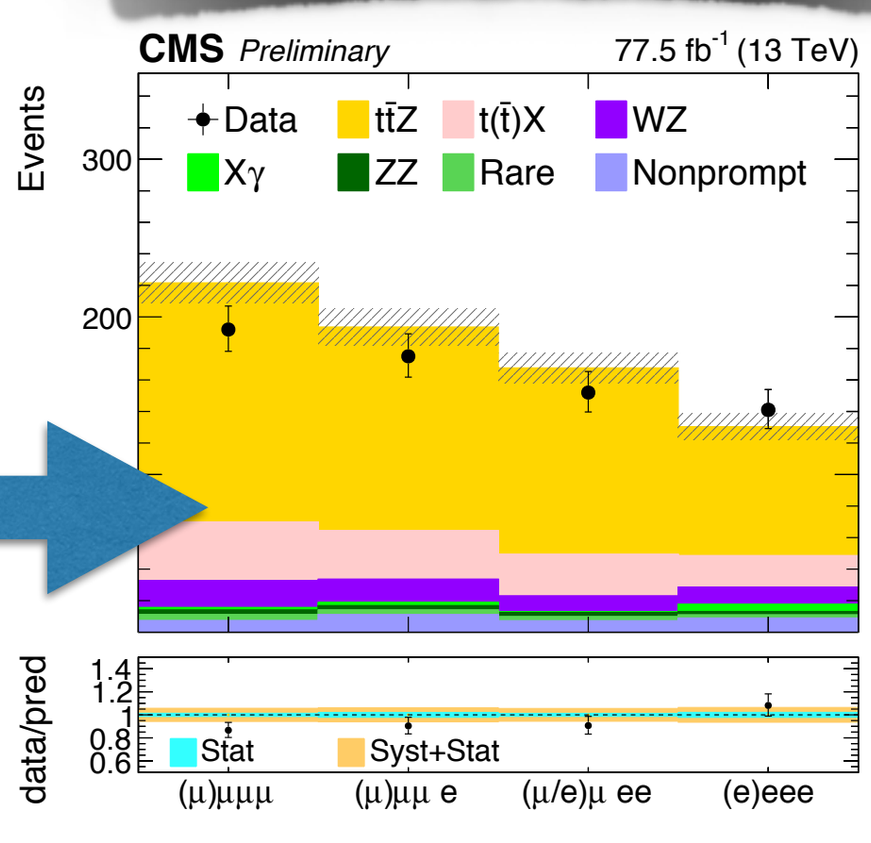
$$\sigma_{th} = 0.839 \pm 0.101\ pb$$



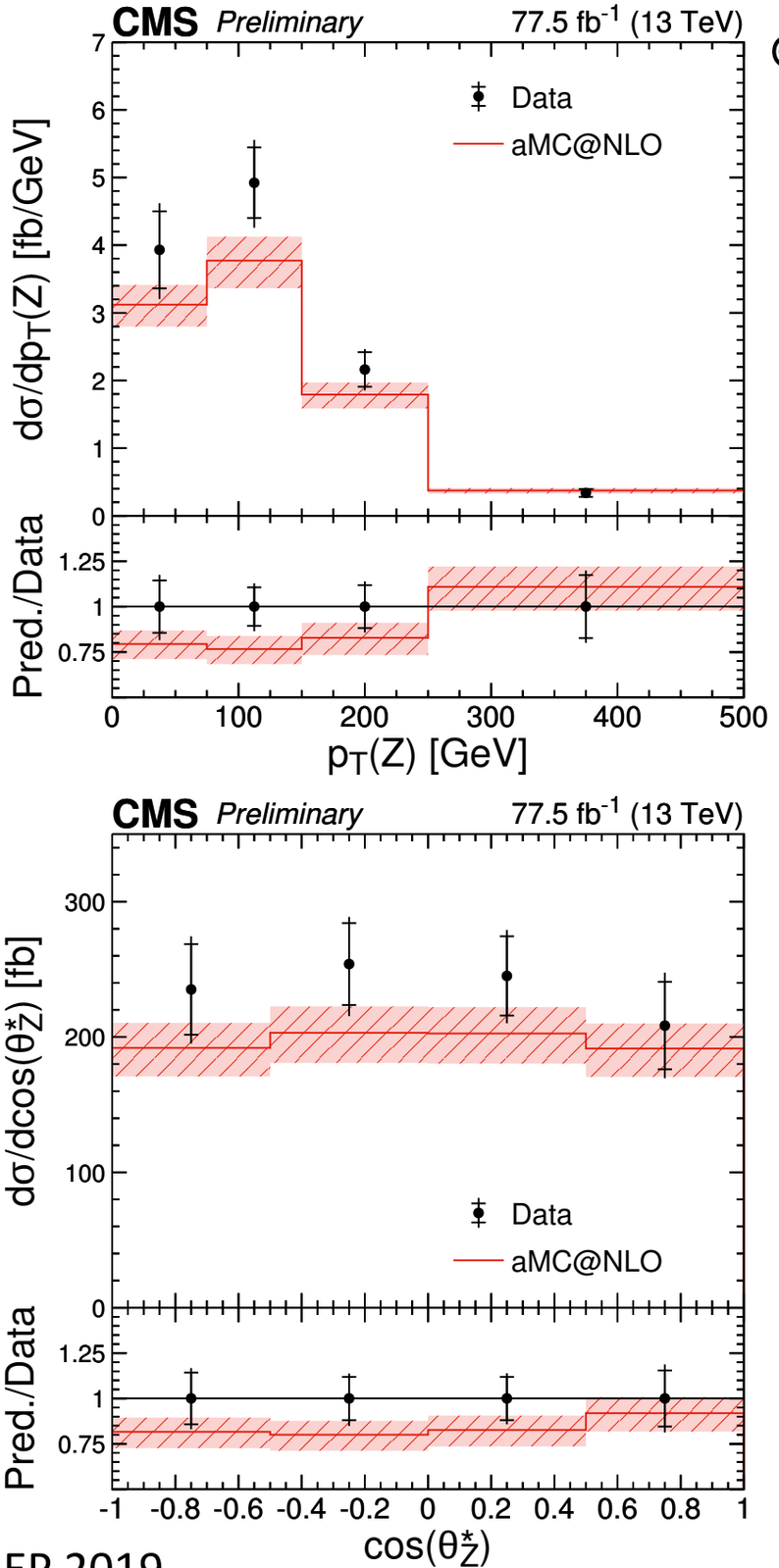
measurement

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 1.00\ ^{+0.06}_{-0.05}\,(\mathrm{stat})\ ^{+0.07}_{-0.06}\,(\mathrm{syst})\,\mathrm{pb}$$



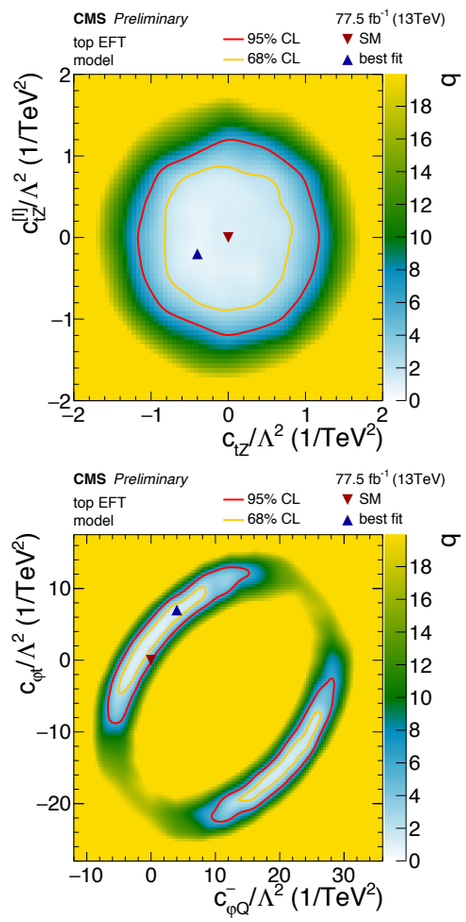


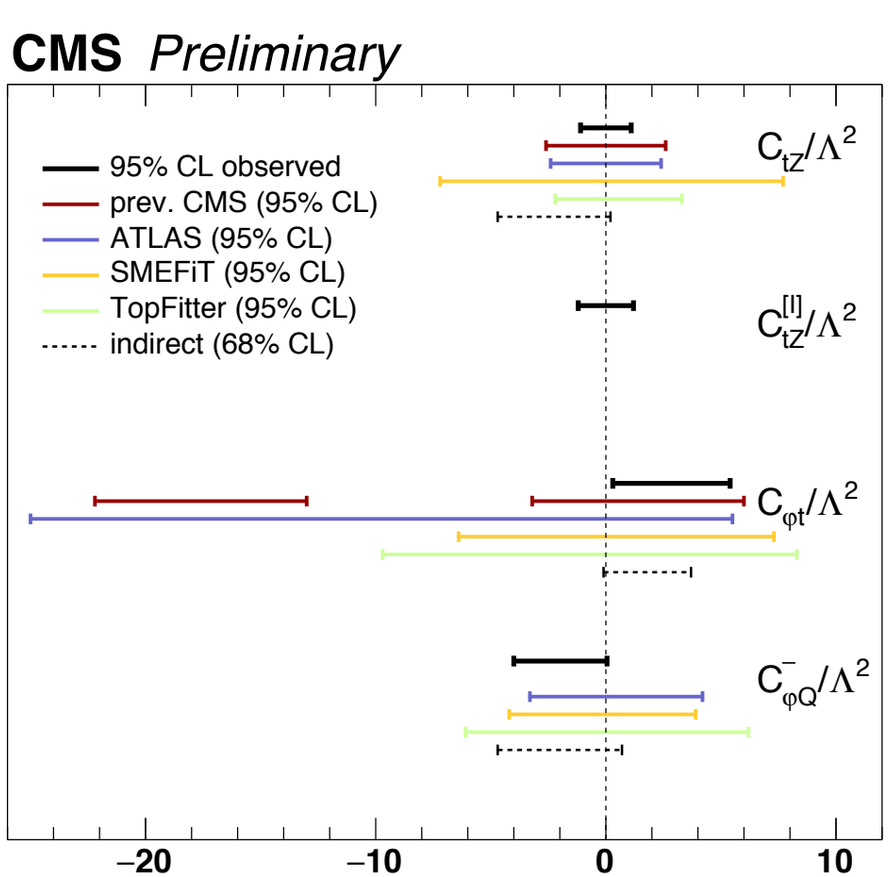
Associated production of a top pair with a Z boson



- **search for anomalous couplings and EFT interpretation**
  - exploit differential distributions of $p_{T,Z}$ and $\cos\theta_Z$
  - sensitive to anomalous vector, axial vector and dipole moment interactions that involve neutral gauge bosons (Z, γ)
  - constraint of Wilson coefficients in the top EFT

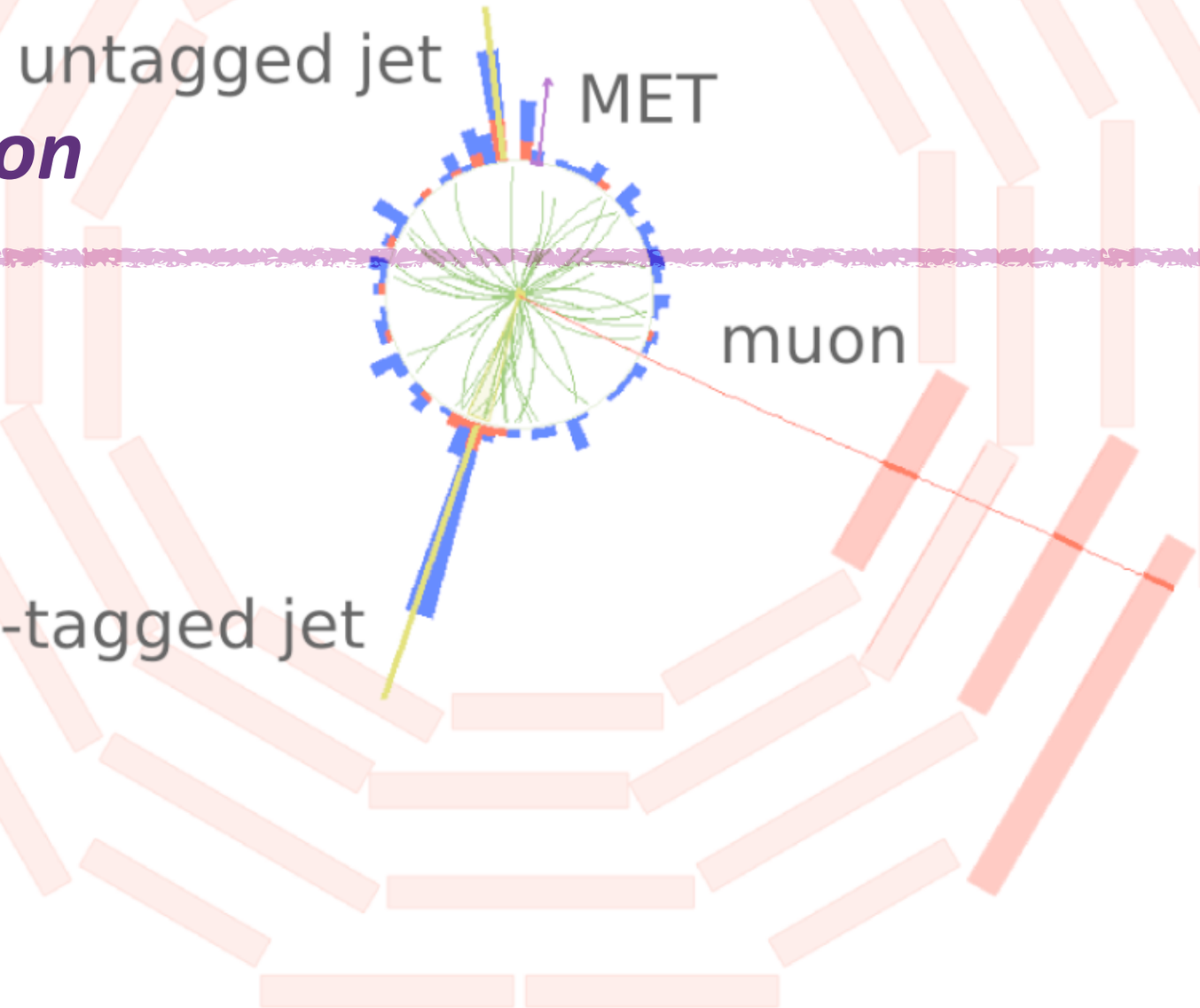
$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V} + \gamma_5 C_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V} + i\gamma_5 C_{2,A}\right)\right]v(p_{\bar{t}})\,Z_\mu$$



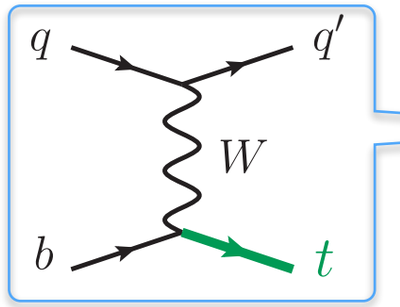


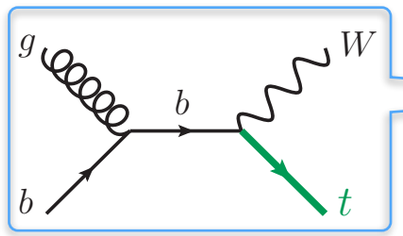
CMS Experiment at LHC, CERN
Data recorded: Tue Jul 14 11:47:11 2015 CEST
Run/Event: 251721 / 22303466
Lumi section: 21

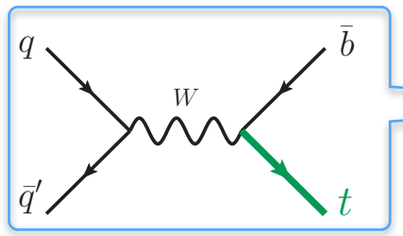
Single top production

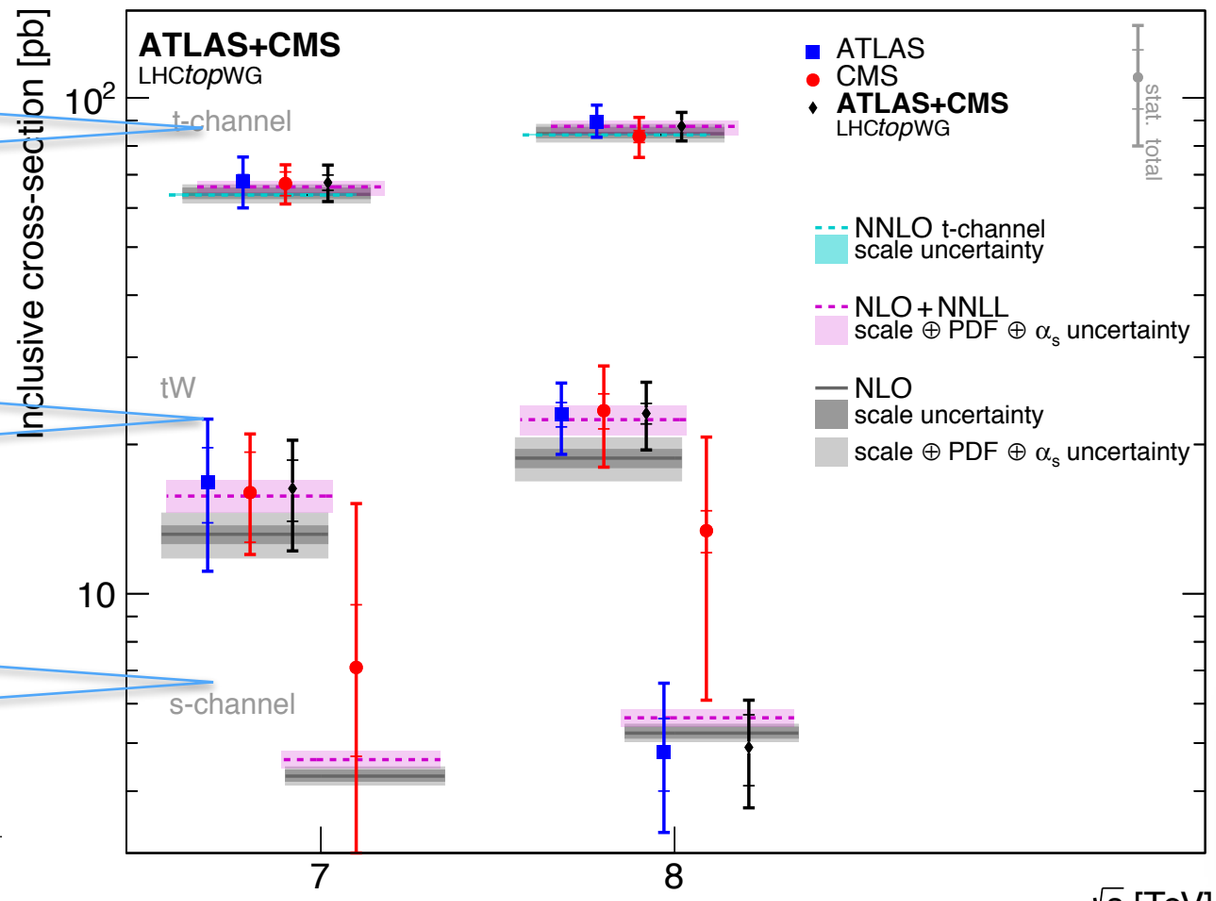


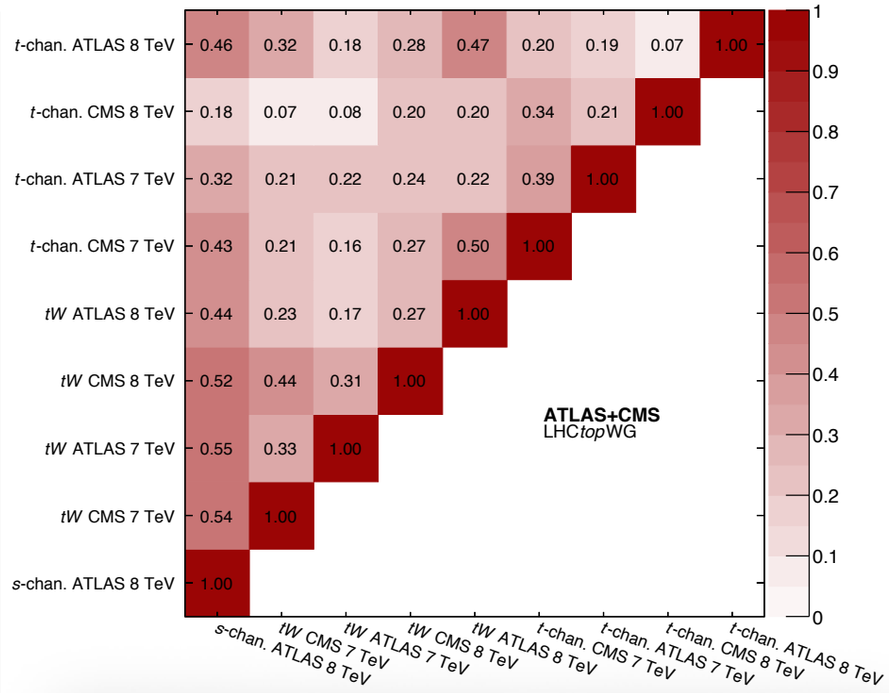
Run I (7, 8 TeV) ATLAS/CMS Combination



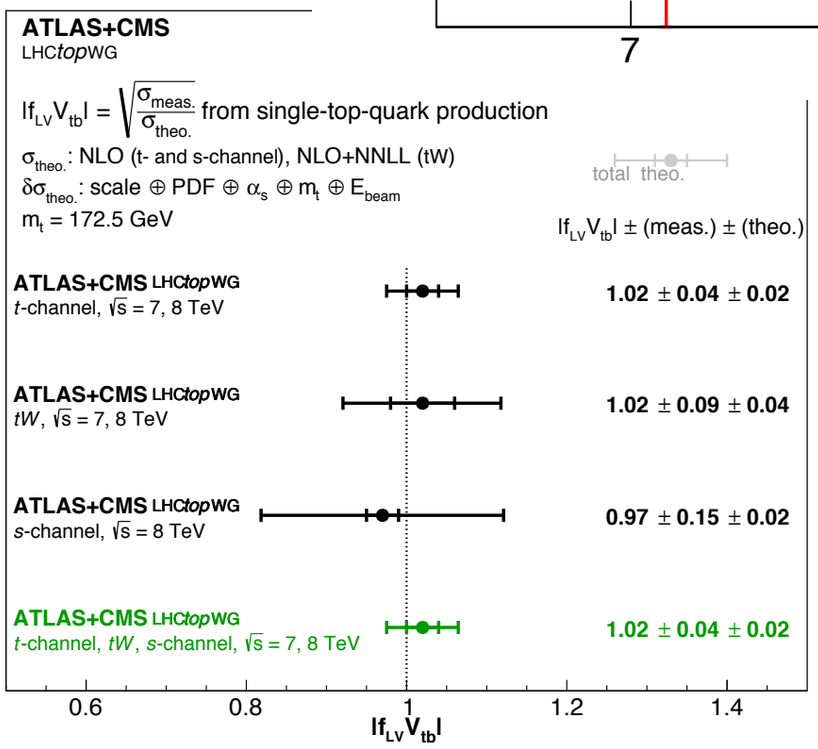








correlation matrix between measurements

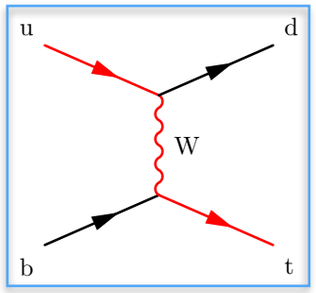


Joint effort between the ATLAS and CMS Collaborations under the LHCtopWG

Inclusive single top cross section (t-channel)

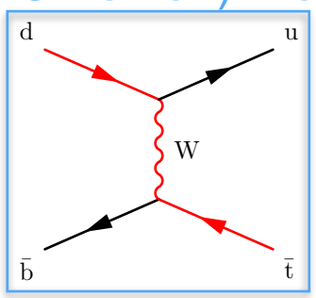
top quark production

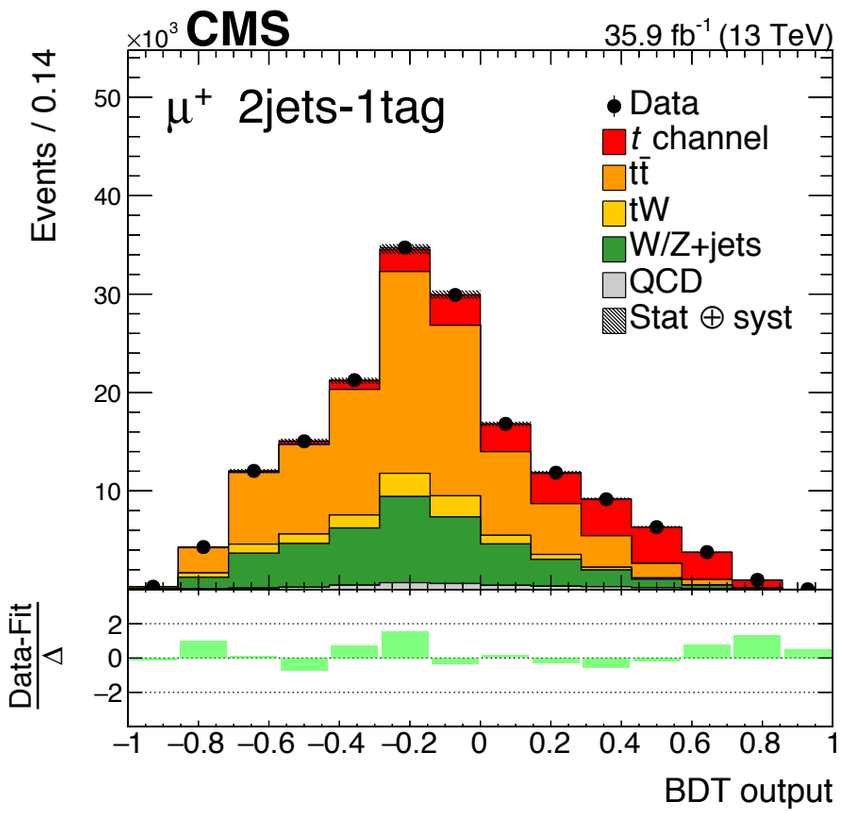
σ(pp @ 13 TeV) = 136 pb

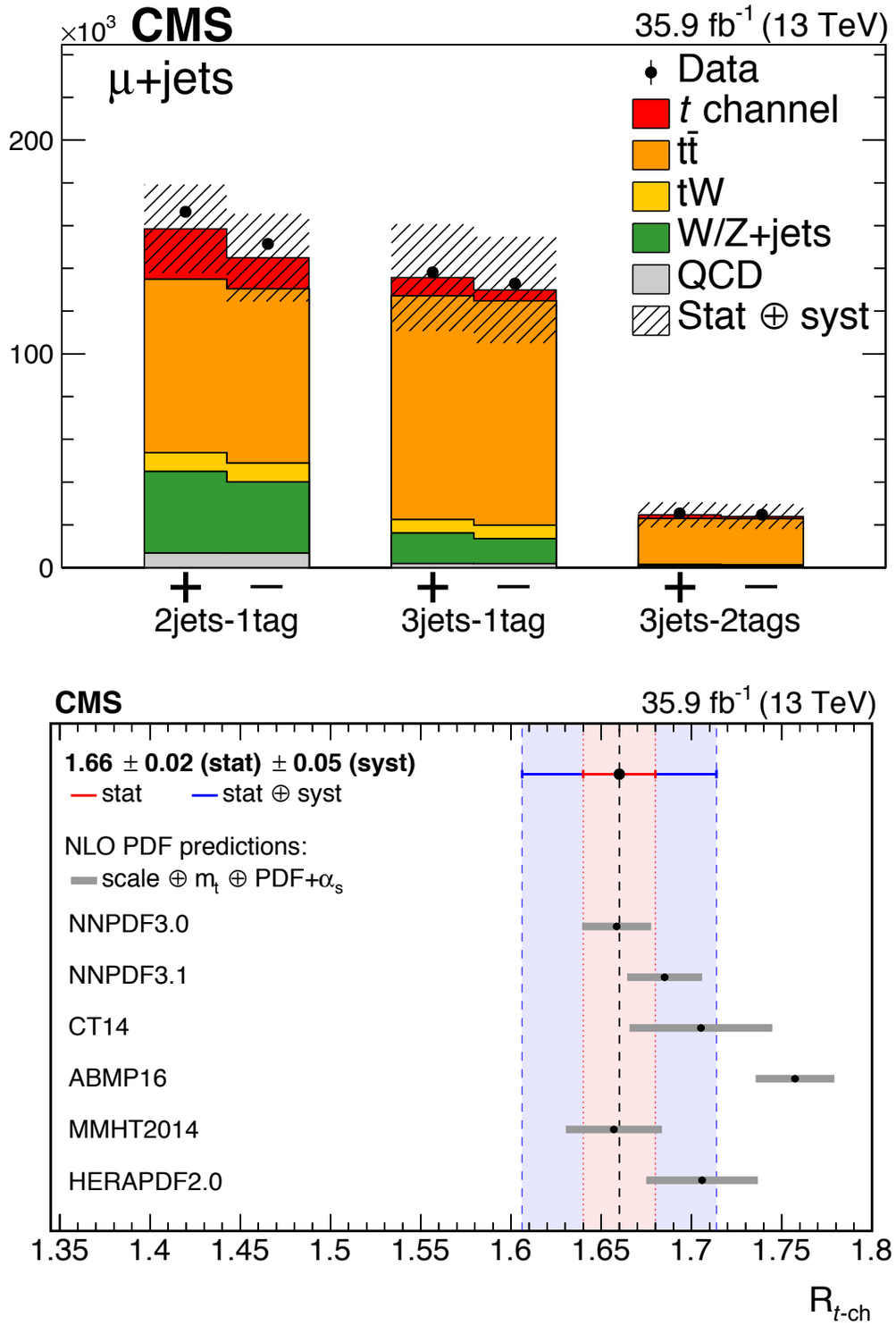


antitop quark production

σ(pp @ 13 TeV) = 81 pb

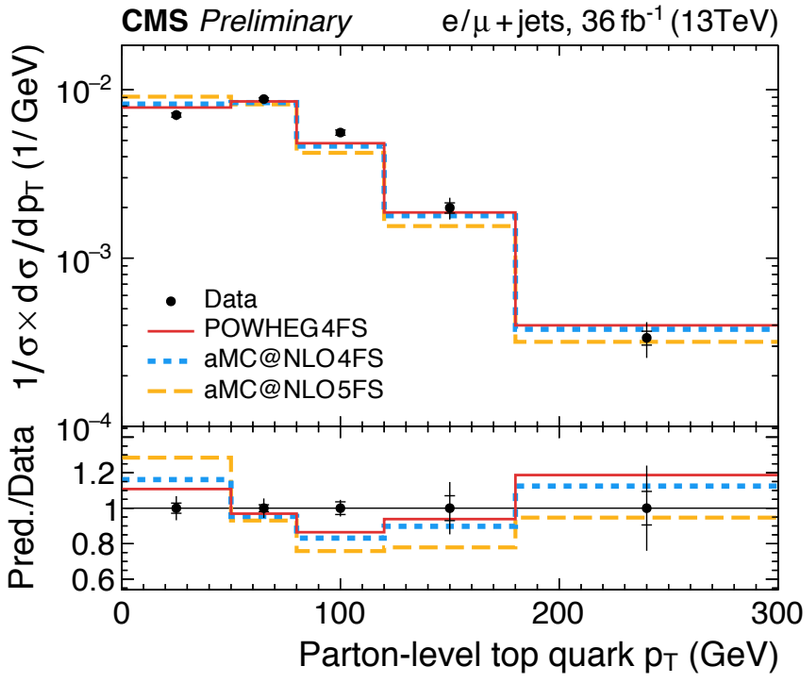


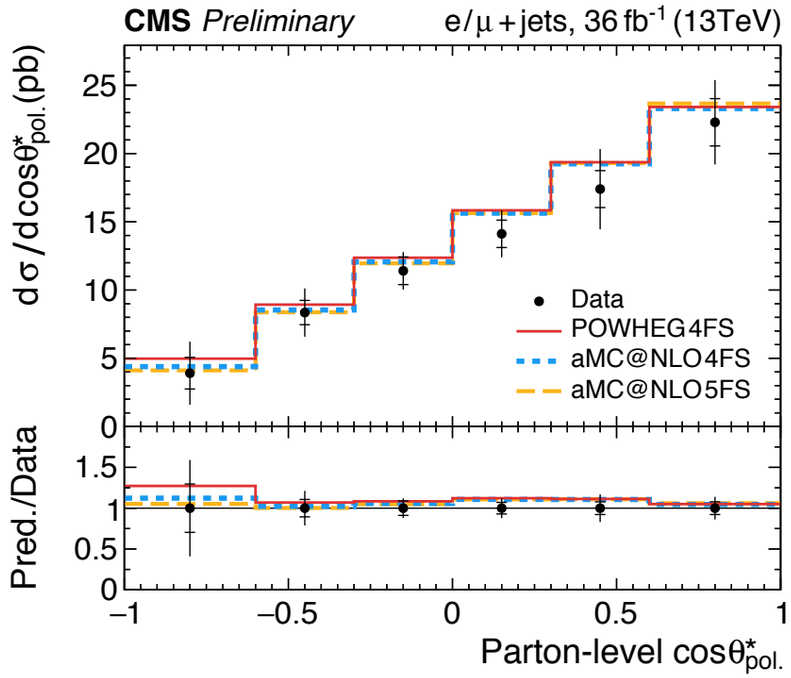


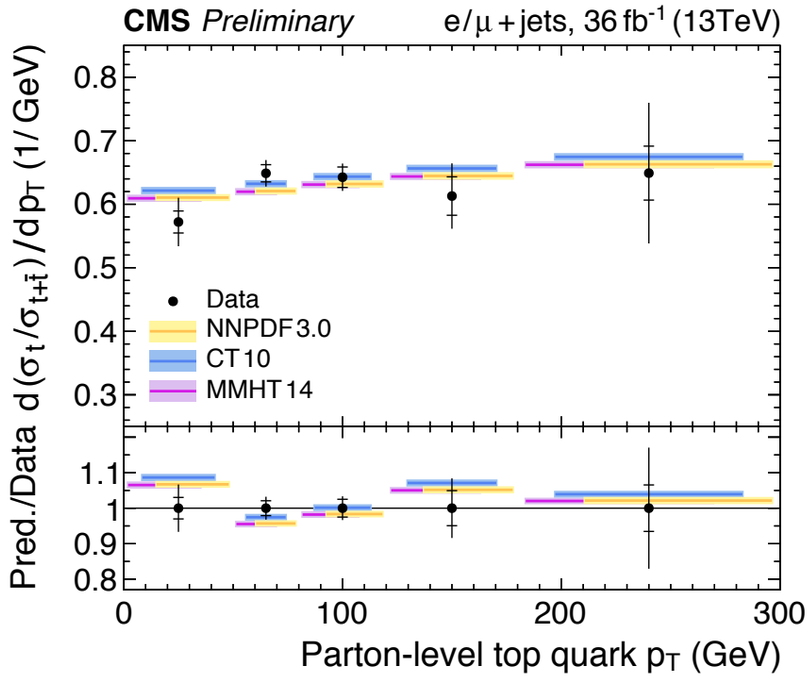


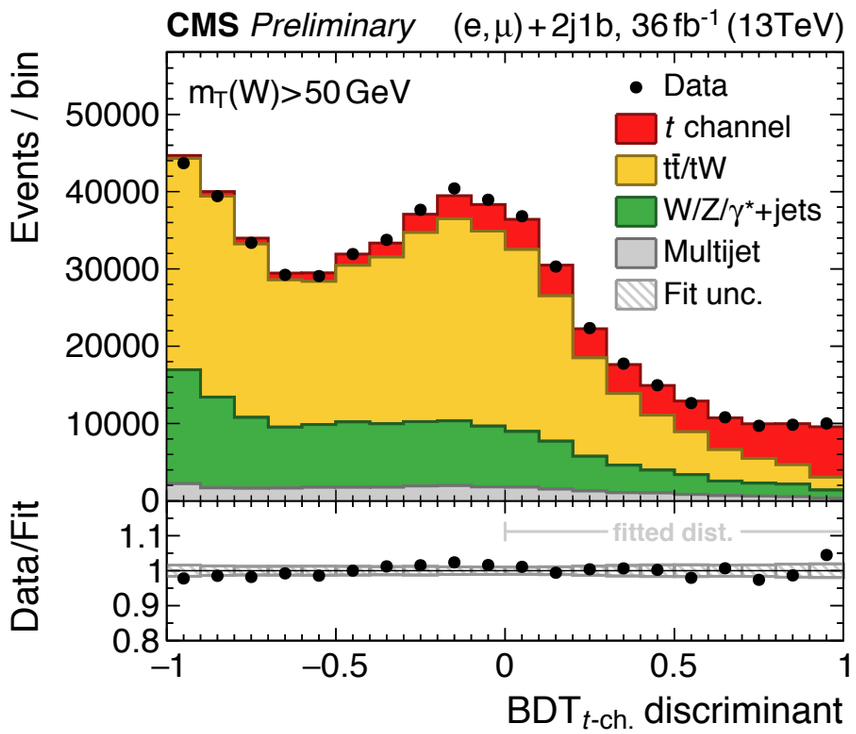
- **single top in t-channel**
  - most abundant process
  - asymmetric between top & antitop
- **experimental measurement**
  - signature: one lepton, MET and jets
  - multivariate discriminants with kinematic variables
  - combined fit in categories of number of jets and b jets
  - inclusive cross section and ratio top/antitop

Single top differential cross section (t-channel)



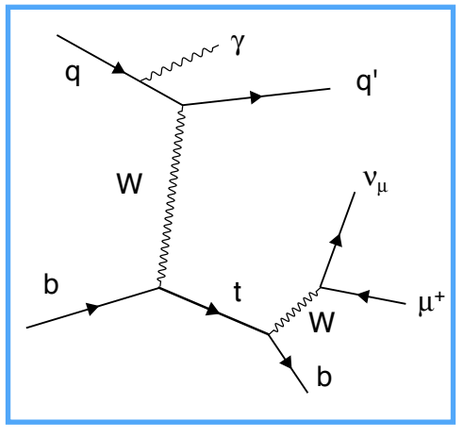


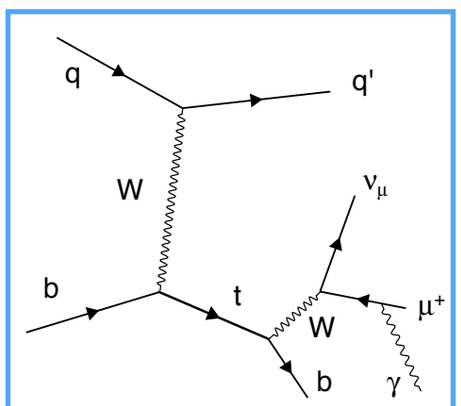


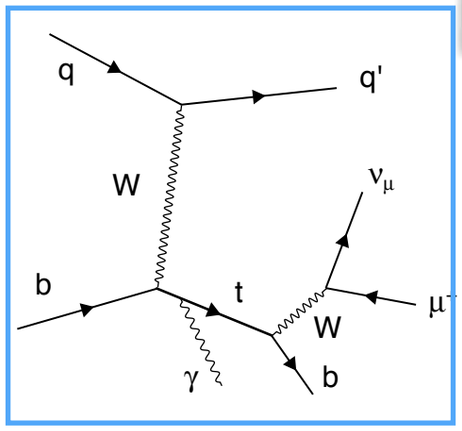


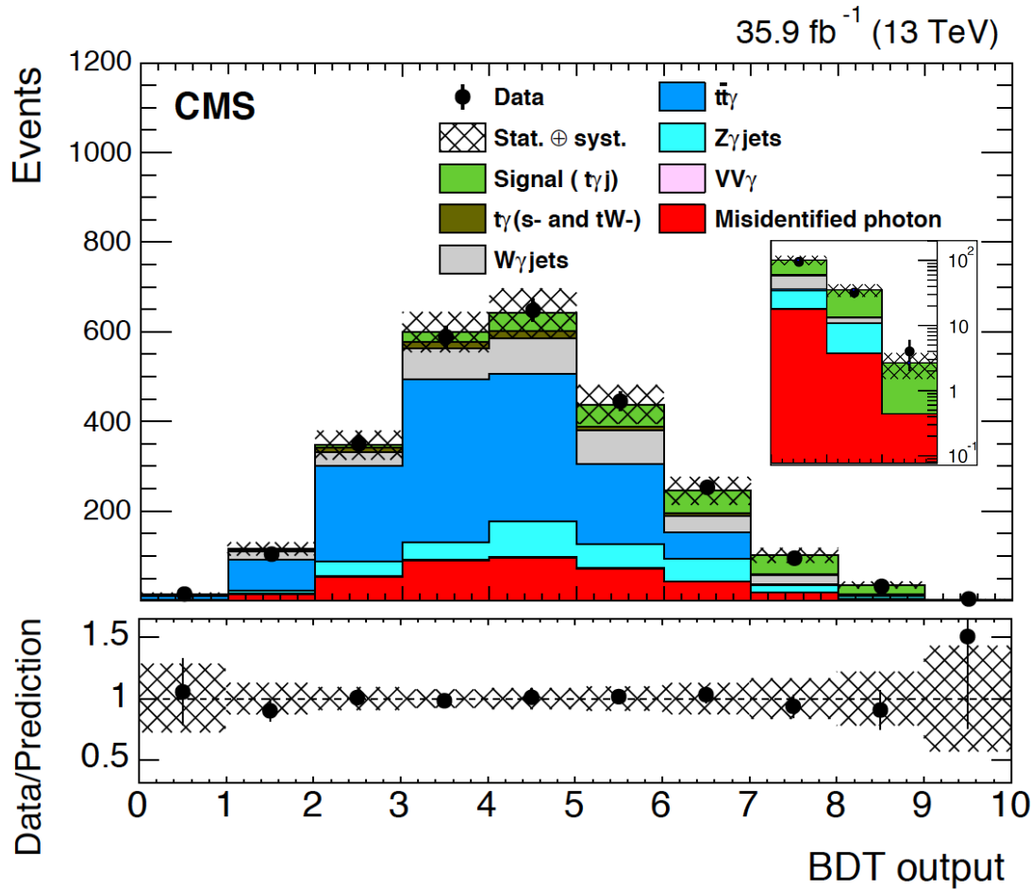
- **differential cross sections**
  - confront the QCD predictions
- **experimental measurement**
  - signature of one lepton, significant MET and jets
  - multivariate discriminants with several kinematic variables as inputs
- **results**
  - absolute & normalized cross sections vs various observables
  - unfolded to parton & particle levels
  - differential charge ratio
  - better agreement observed with 4FS predictions
  - measurement of polarization angle

Associated production of top with a photon









$$\sigma(\mathrm{pp} \to \mathrm{t}\gamma\mathrm{j})\mathcal{B}(\mathrm{t} \to \mu\nu\mathrm{b}) = 115 \pm 17\,(\mathrm{stat}) \pm 30\,(\mathrm{syst})\,\mathrm{fb}$$

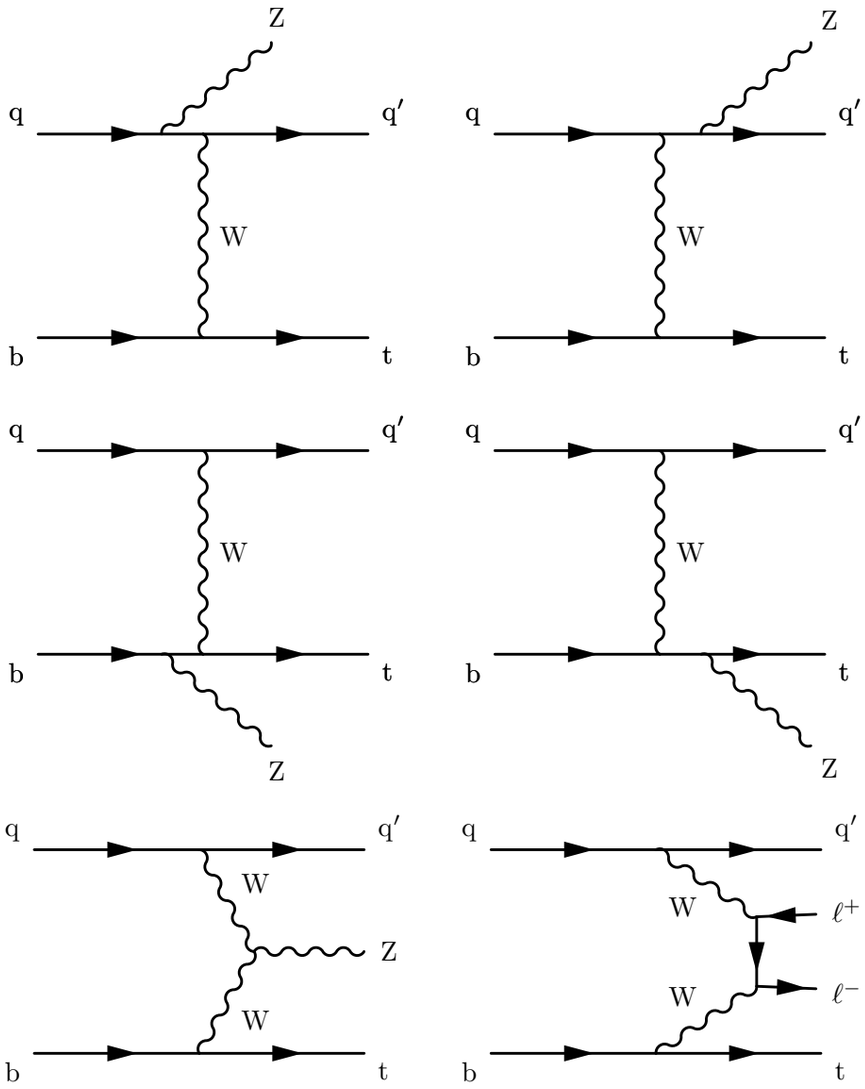
theory: 81 ± 4 fb

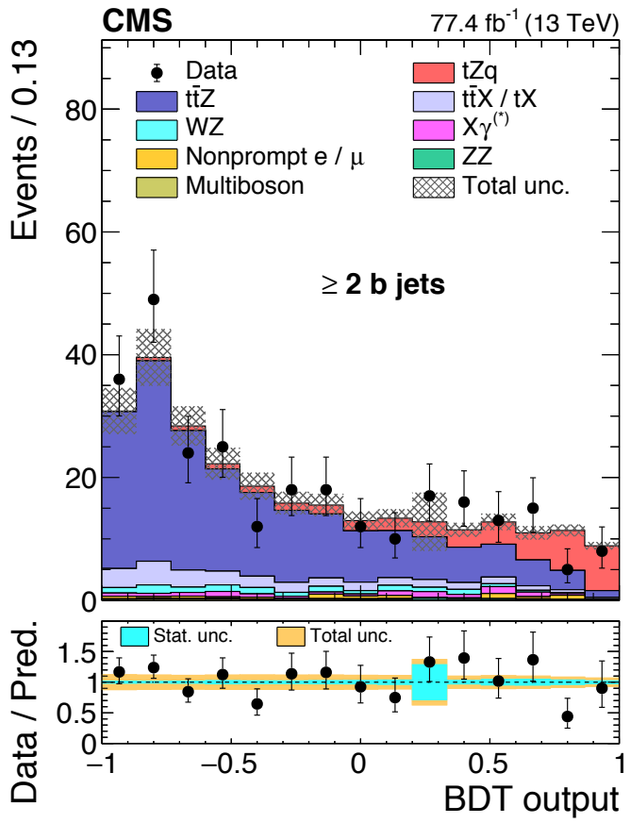
p-value: 4.27×10^{-6} (4.4 σ)

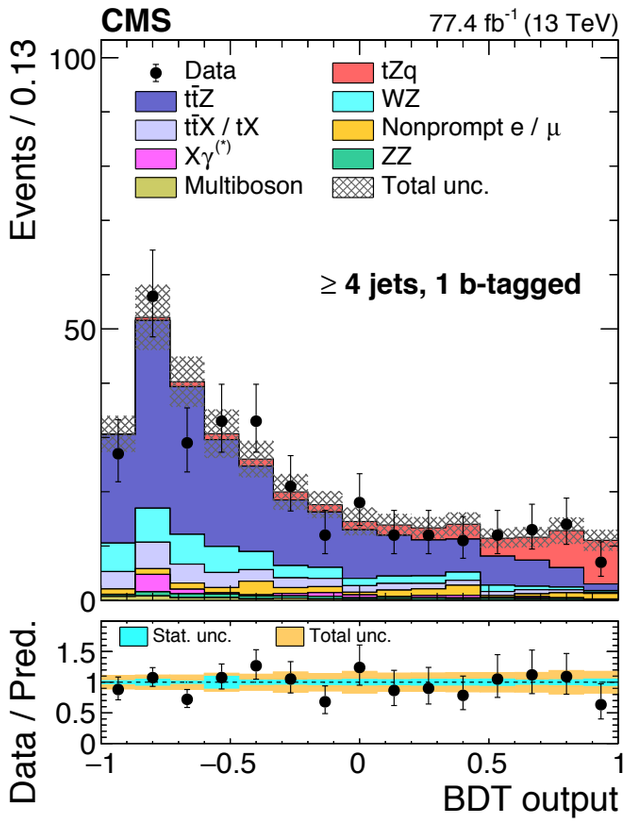
Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
$W\gamma$+jets	329 ± 78
$Z\gamma$+jets	232 ± 55
Misidentified photon	374 ± 74
$t\gamma$ (s- and tW-channel)	57 ± 8
$VV\gamma$	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535

- **motivation**
  - important test of SM
  - sensitive to the top charge and electric and magnetic dipole moments
  - background for BSM searches
- **experimental measurement**
  - muon channel
  - complicated final state with all types of objects
  - multivariate classification (BDT)
  - template fit on the BDT output

Associated production tZq

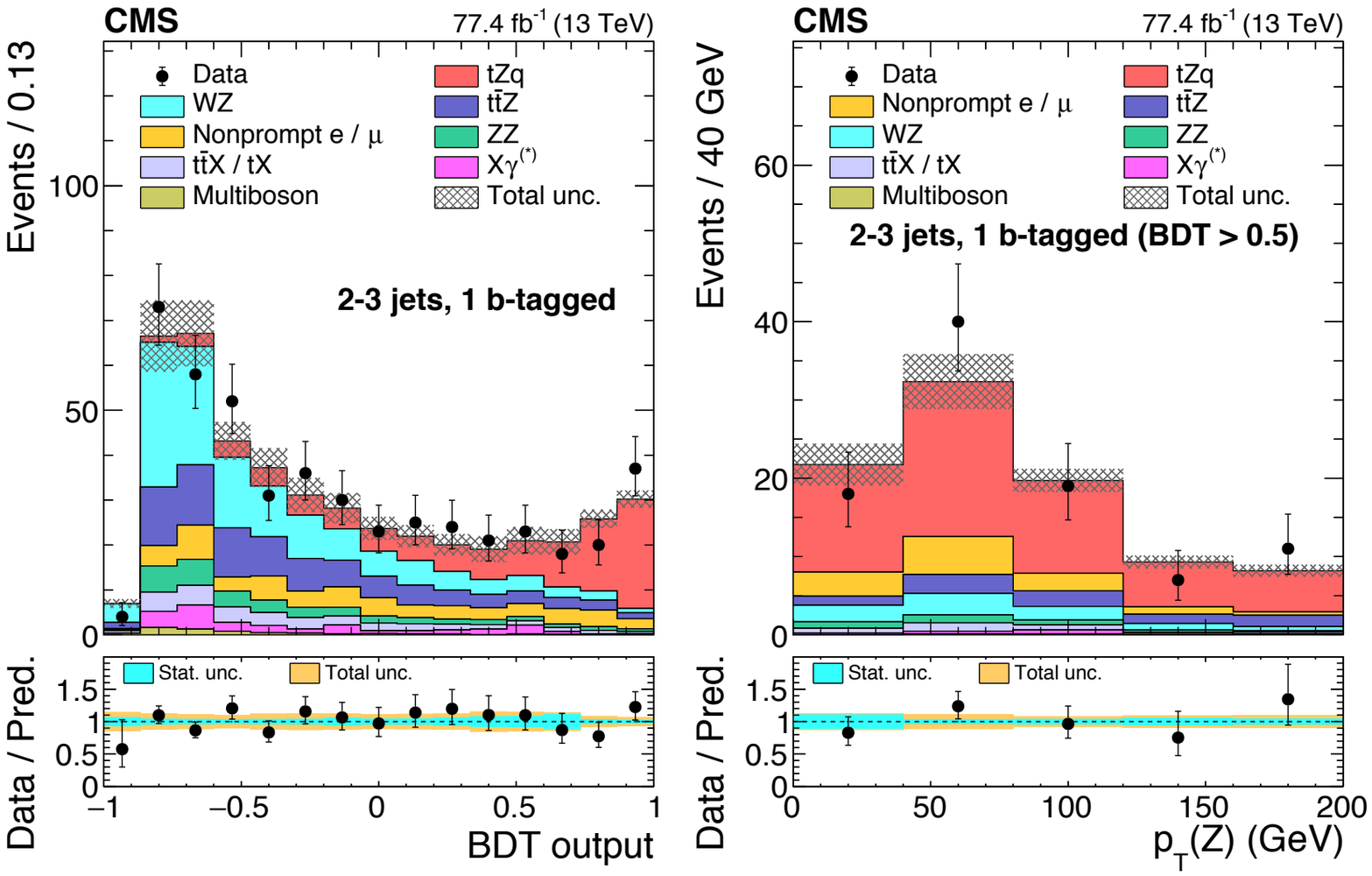






- **motivation**
  - sensitive to multiple SM effects (WWZ triple gauge coupling, ttZ, tbW couplings, etc)
  - modified tZq production can be due to flavor changing neutral currents
- **experimental measurement**
  - leptonic decays with exactly 3 leptons and at least 2 additional jets
  - complicated final state with all types of objects ==> multivariate classification (BDT)
  - template fit on the BDT output in several categories

Associated production tZq



theory: 94.2 ± 3.1 fb

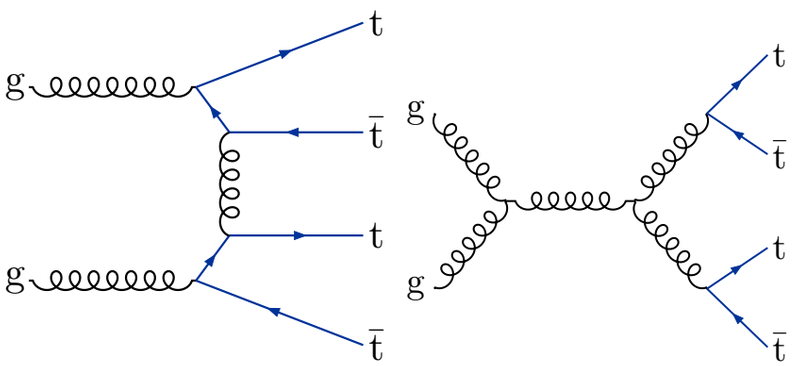
$$\sigma(\mathrm{pp} \to \mathrm{tZq} \to \mathrm{t}\ell^{+}\ell^{-}\mathrm{q}) = 111 \pm 13\,(\mathrm{stat})\,^{+11}_{-9}\,(\mathrm{syst})\,\mathrm{fb}$$

Observation
8.2 (7.7) σ observed
(expected) significance

Source	2–3 jets, 1 b-tagged SR-2/3j-1b	≥ 4 jets, 1 b-tagged SR-4j-1b	≥ 2 b jets SR-2b
Exp. background	357 ± 34	278 ± 32	228 ± 25
Exp. tZq	103 ± 5.1	38 ± 5.3	37 ± 1.8
Total exp.	460 ± 37	316 ± 35	265 ± 25
Observed	475	310	278

Four top production

tttt production

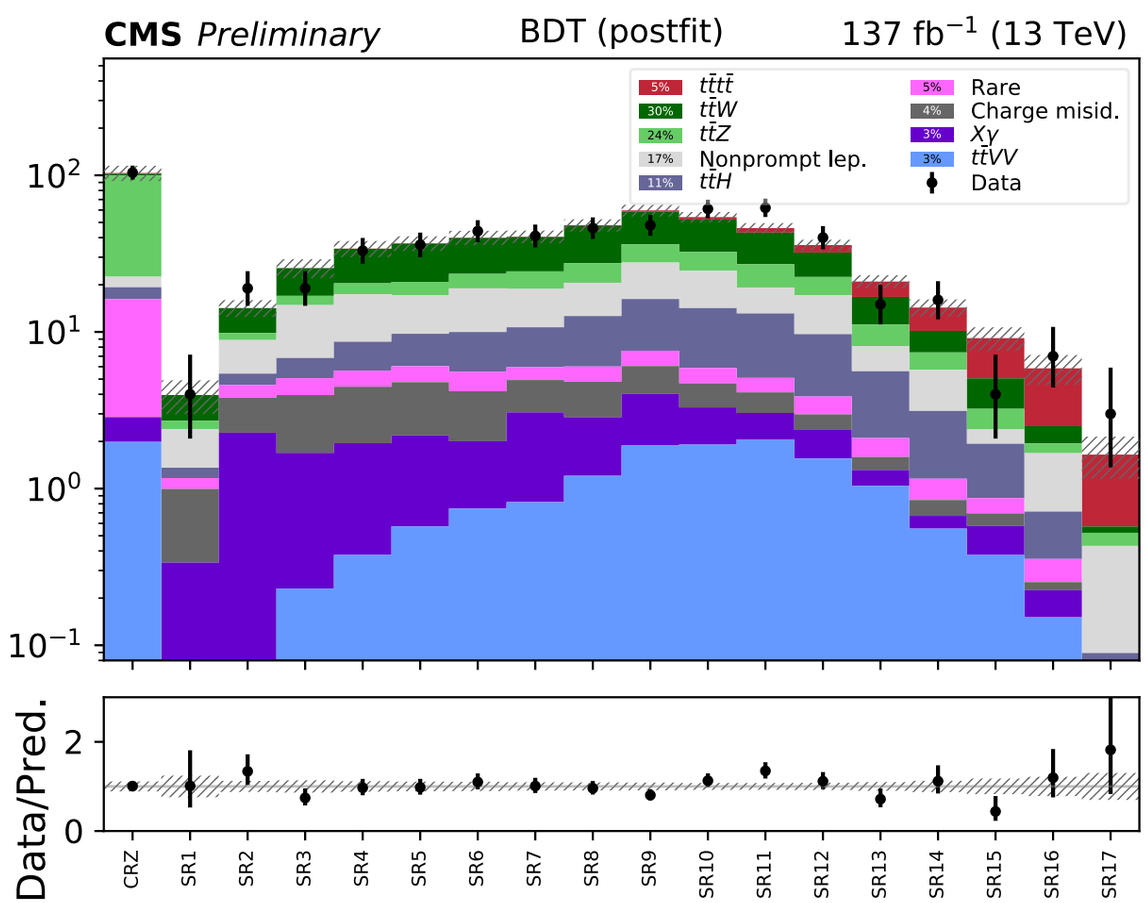


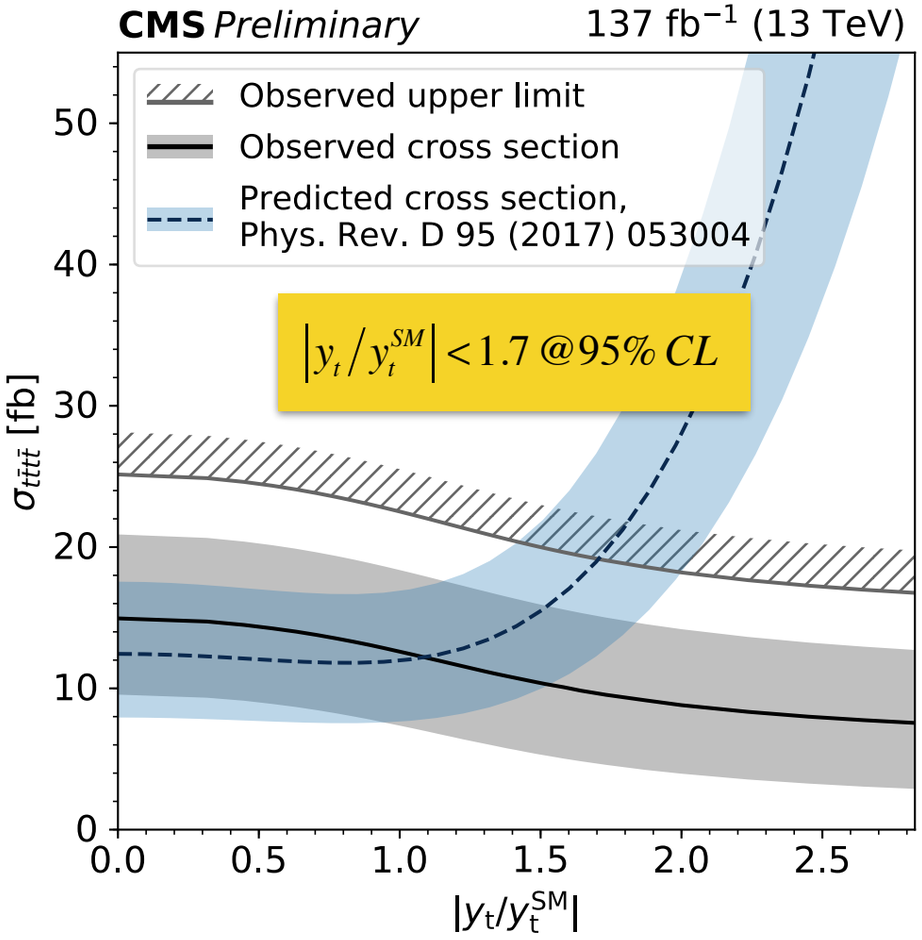
- sensitive to SM parameters
- complicated search with either 2 same sign leptons or at least 3 leptons in the final state
- multivariate classification & cut based cross check analysis
- constrain of the top Yukawa coupling

$$\sigma_{meas} = 12.6^{+5.8}_{-5.2}\ fb$$

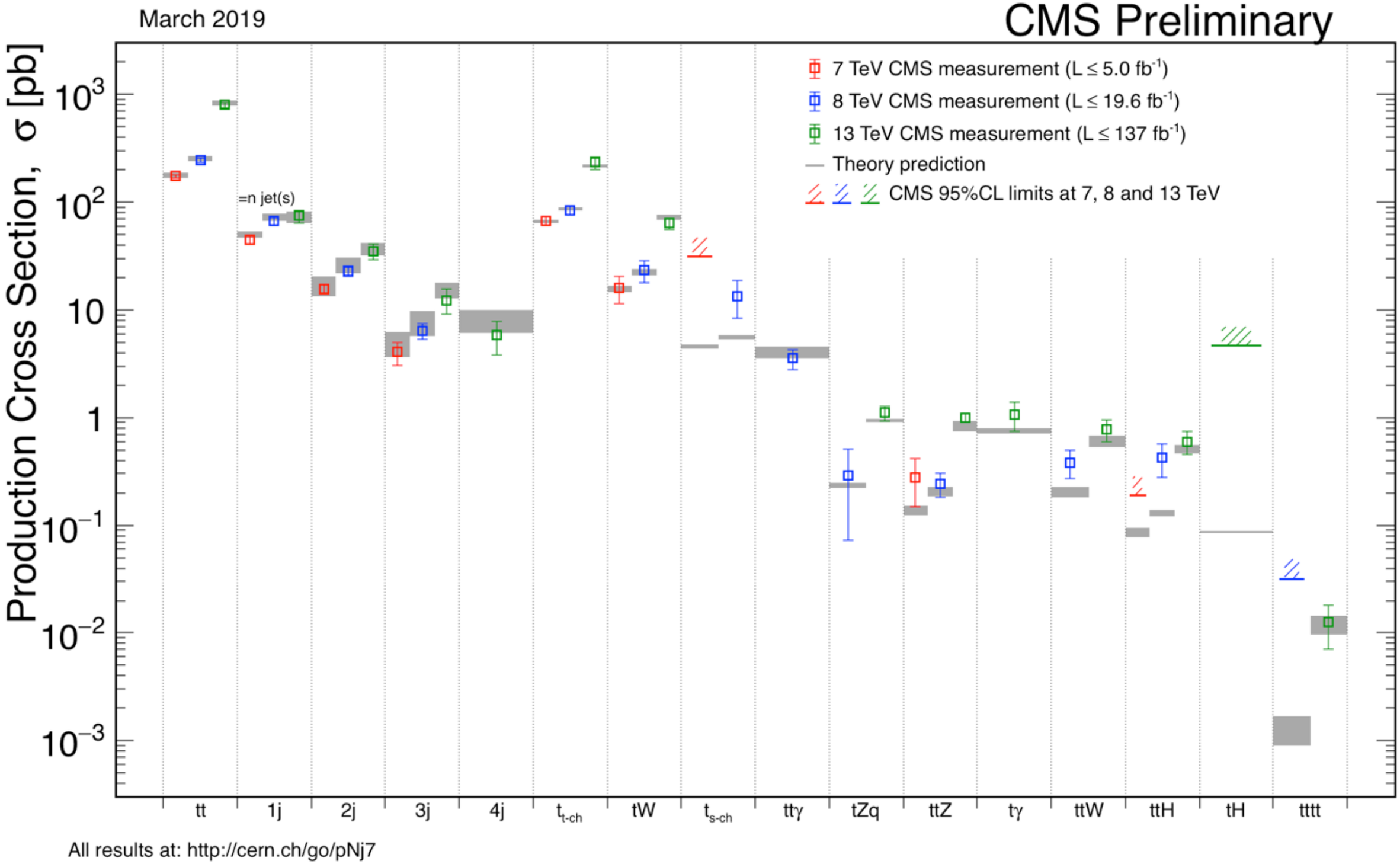
$$\sigma_{th} = 12.0^{+2.2}_{-2.5}\ fb$$

2.6σ significance





Overview of the cross sections



Summary & Outlook

- **LHC is a top factory!**
  - now possible to explore the full phase space of top production
- **CMS pursues a rich and thorough research program on top physics**
  - measurements of cross sections (inclusive, differential, multi-differential) spanning 5 orders of magnitude
  - measurements of top properties (mass, spin polarization, Yukawa coupling, etc)
  - observations or evidence of rare processes are being reported
- **interpretation of the results**
  - constraints of fundamental QCD parameters
  - indirect searches for BSM signals through top EFT framework
- **stay tuned for more CMS results!**
  - only few analyses have incorporated the 2017/2018 data (more than 70% of Run II)
  - large dataset available: will keep us busy in the next years!!

References (Publications & preliminary results)

(1) “Measurement of the ttbar production cross section, the top quark mass, and the strong coupling constant using dilepton events in pp collisions at sqrt(s) = 13 TeV”, **arXiv:1812.10505**

(2) “Measurement of ttbar normalised multi-differential cross sections in pp collisions at s√= 13 TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions”, **arXiv:1904.05237**

(3) “Measurement of the top quark mass in the all-jets final state at sqrt(s) = 13 TeV and combination with the lepton+jets channel”, **EPJC 79 (2019) 313**

(4) “Measurement of the top quark polarization and ttbar spin correlations in dilepton final states at sqrt(s) = 13 TeV”, **CMS-PAS-TOP-18-006**

(5) “Measurements of ttbar differential cross sections in proton-proton collisions at sqrt(s) = 13 TeV using events containing two leptons”, **JHEP 02 (2019) 149**

(6) “Constraining the top quark Yukawa coupling from ttbar differential cross sections in the lepton+jets final state in proton-proton collisions at sqrt(s) = 13 TeV”, **CMS-PAS-TOP-17-004**

(7) “Measurement of top quark pair production in association with a Z boson in proton-proton collisions at sqrt(s) = 13 TeV”, **CMS-PAS-TOP-18-009**

(8) “Combinations of single-top-quark production cross-section measurements and $|f_{LV}V_{tb}|$ determinations at sqrt(s) = 7 and 8 TeV with the ATLAS and CMS experiments”, **arXiv:1902.07158**

(9) “Measurement of the single top quark and antiquark production cross sections in the t channel and their ratio in proton-proton collisions at sqrt(s) = 13 TeV”, **arXiv:1812.10514**

(10) “Measurement of differential cross sections and charge ratios for t-channel single top quark production at 13 TeV”, **CMS-PAS-TOP-17-023**

(11) “Evidence for the associated production of a single top quark and a photon in proton-proton collisions at sqrt(s) = 13 TeV”, **PRL 121 (2018) 221802**

(12) “Observation of single top quark production in association with a Z boson in proton-proton collisions at sqrt(s) = 13 TeV”, **PRL 122 (2019) 132003**

(13) “Search for standard model production of four top quarks in final states with same-sign and multiple leptons in proton-proton collisions at sqrt(s) = 13 TeV”, **CMS-PAS-TOP-18-003**