Top Quark Pair Cross Section Measurement at CMS

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on behalf of the CMS collaboration

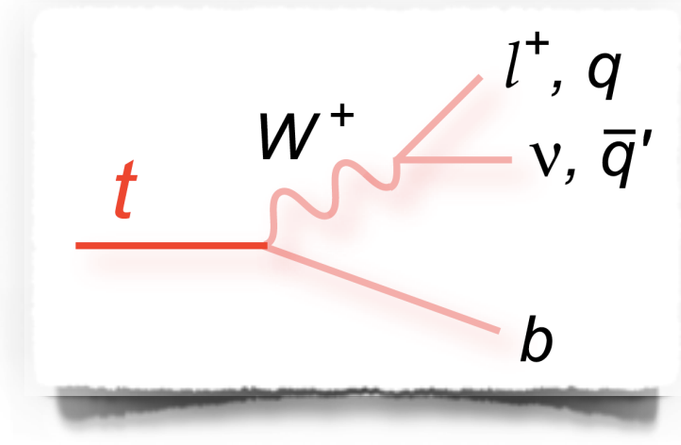
Outlines:

- Inclusive cross section
- 1D/2D differential cross section
- Parton & particle levels

LHCP 2017
May 18, 2017

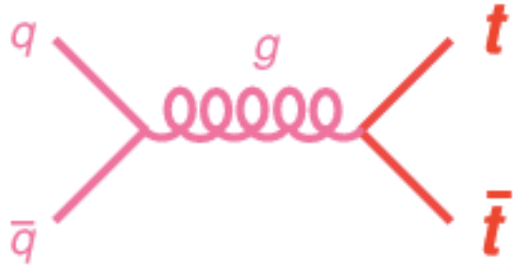
The top quark

- The most massive known particle
- It decays before hadronization; study the properties of the bare quark
- Top decays almost 100% to W+b in the SM; W decays define the final states



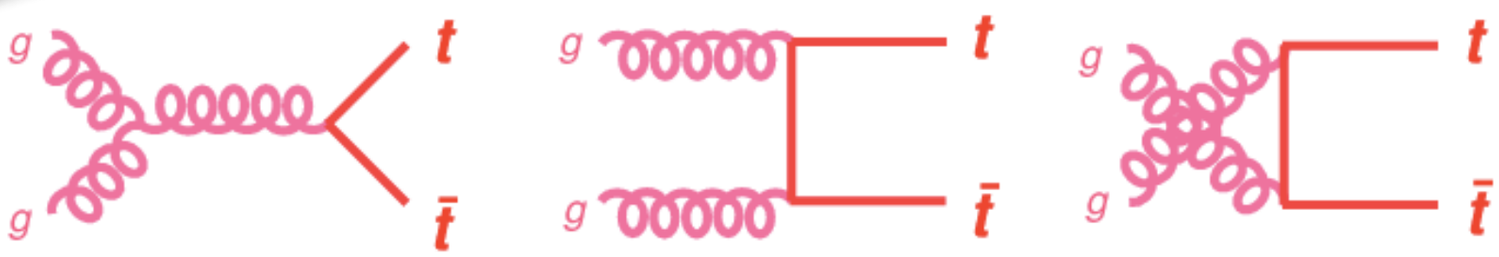
- All jets decays
  - The highest *Br.*
  - Multijets background
- ℓ + jets decays
  - Moderately high *Br.* and relatively good S/B
  - W+jets background
- Dilepton decays
  - Lower *Br.* but very good S/B

✓ qq annihilation ~ 10% at 13 TeV

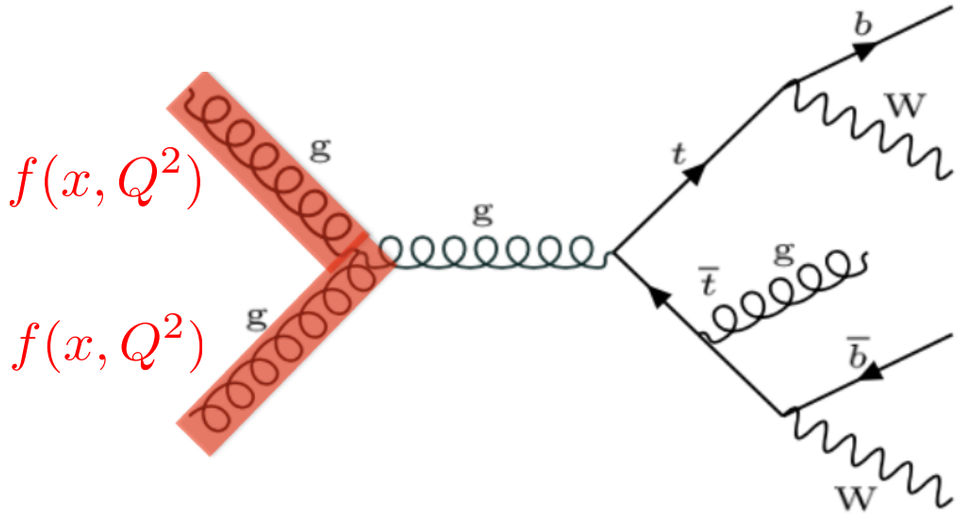


Dominant at LHC

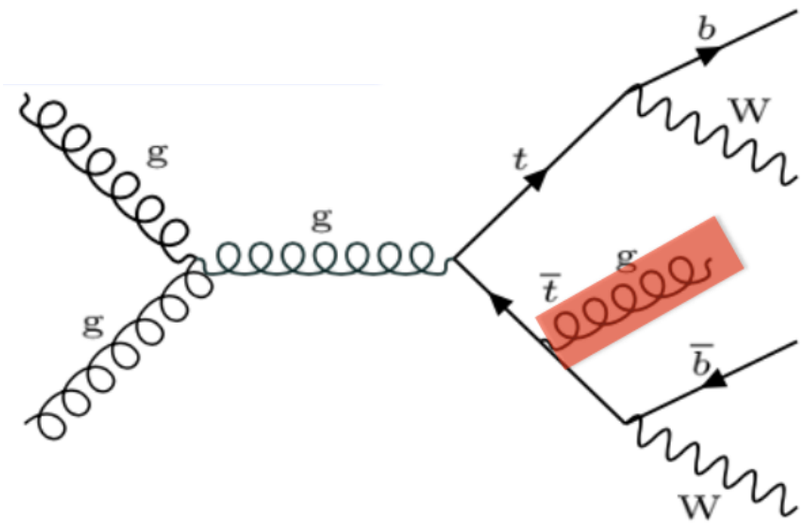
✓ gg fusion ~ 90% at 13 TeV



Why measure σ_{tt} ?

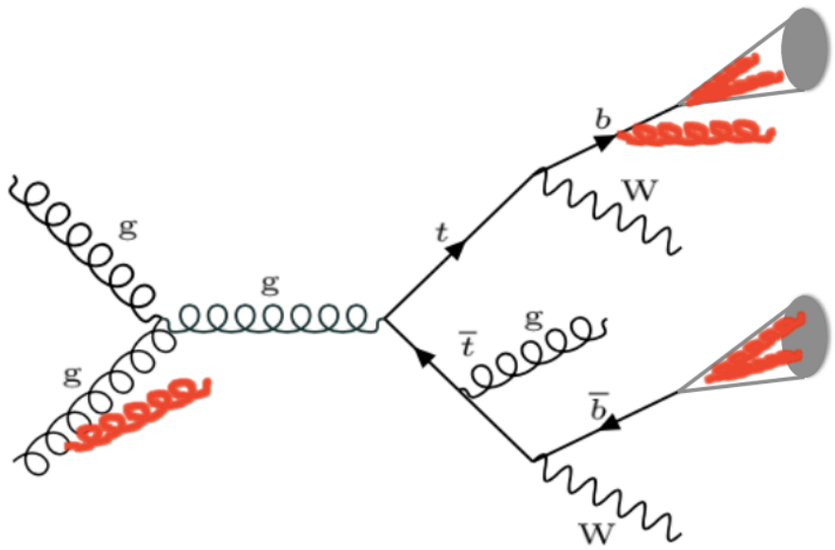


✓ **constrain gluon PDF**



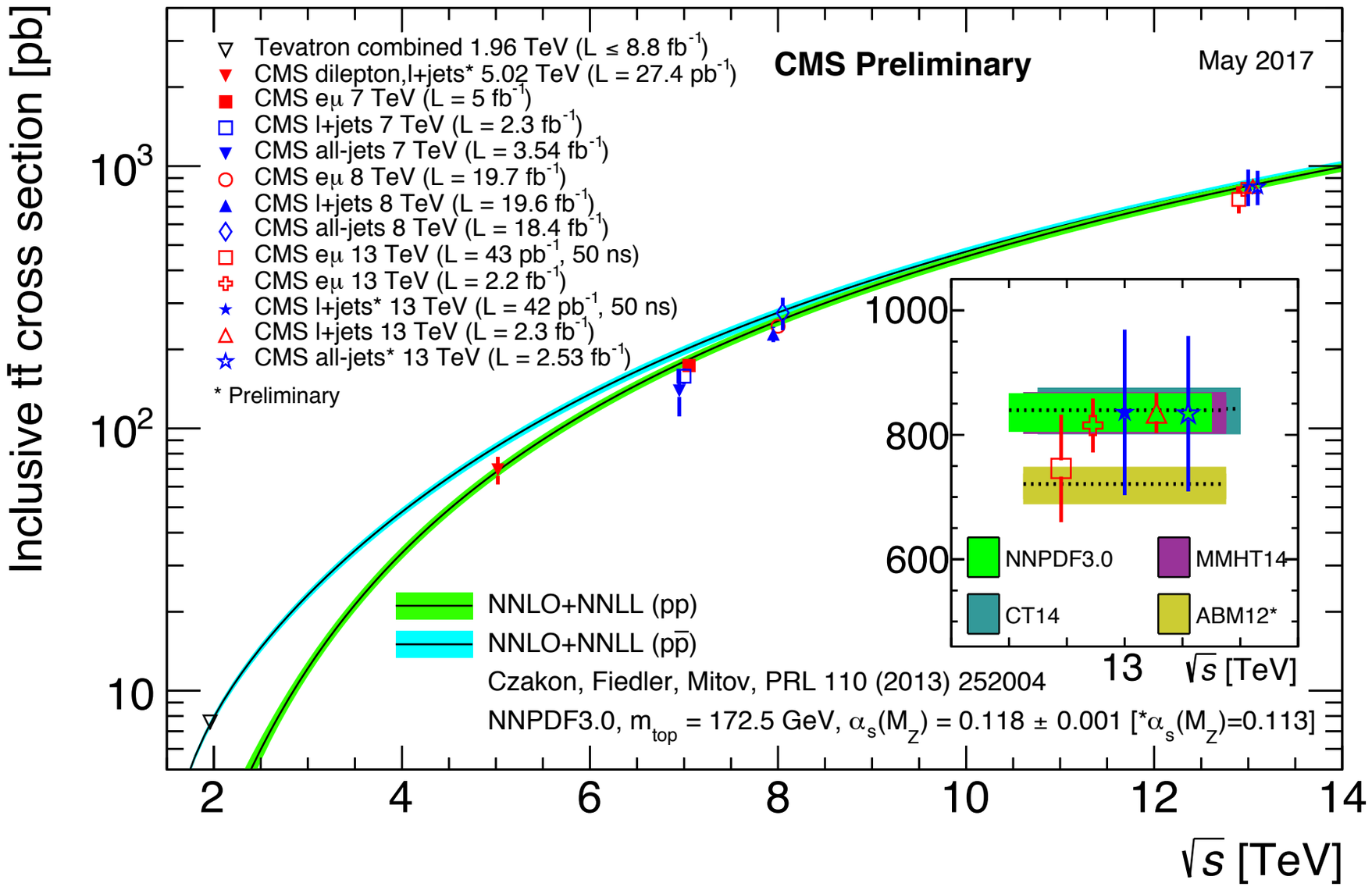
✓ **probe pQCD at higher order**

✓ **extract α_s and M_t**



✓ **modelling of parton shower and hadronization**

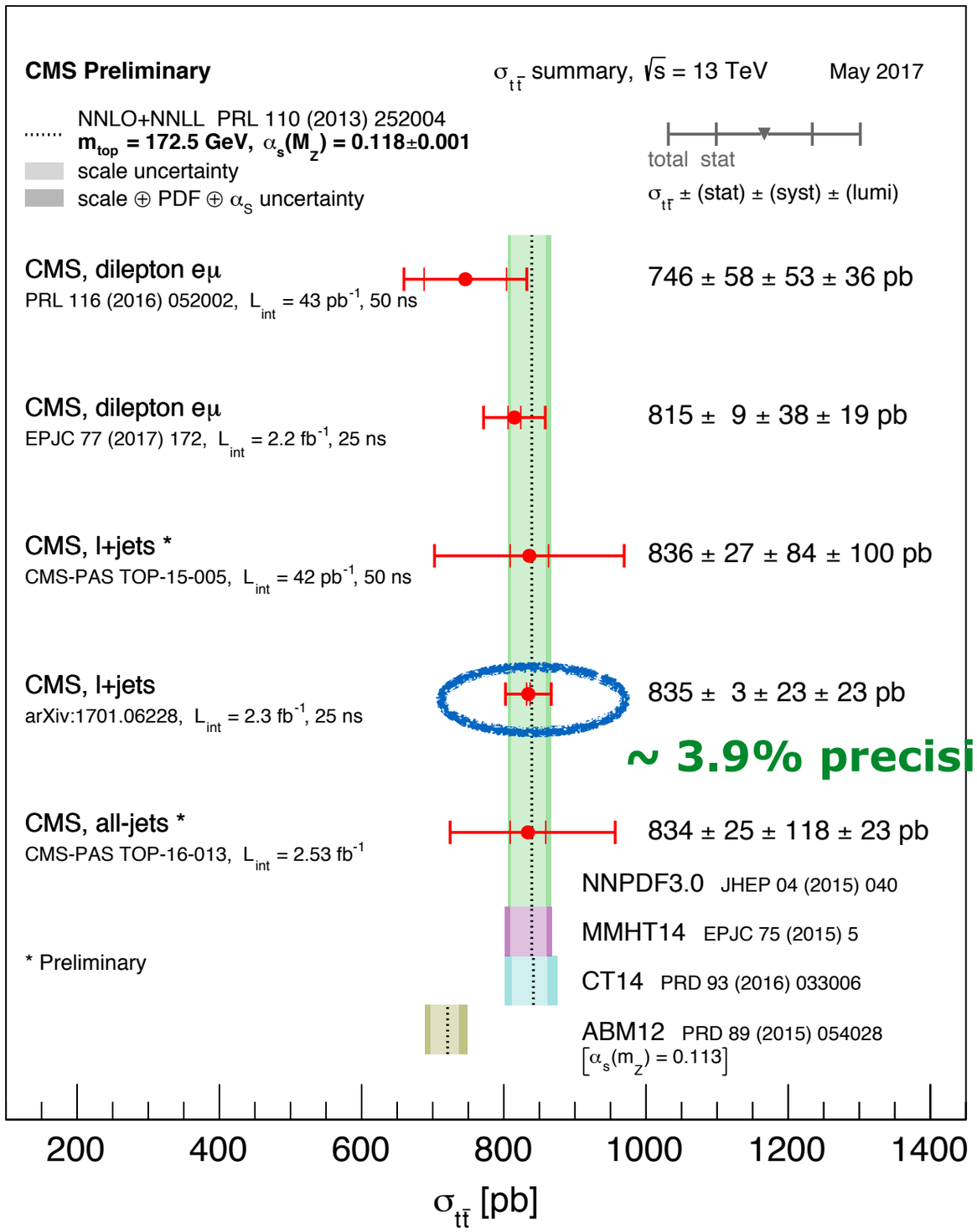
Inclusive σ_{tt} measurements



- Evolution versus √s is well understood

Link CMS TOP results, publications and twiki
Today: mainly focus on recent results

Inclusive σ_{tt} measurements at 13 TeV

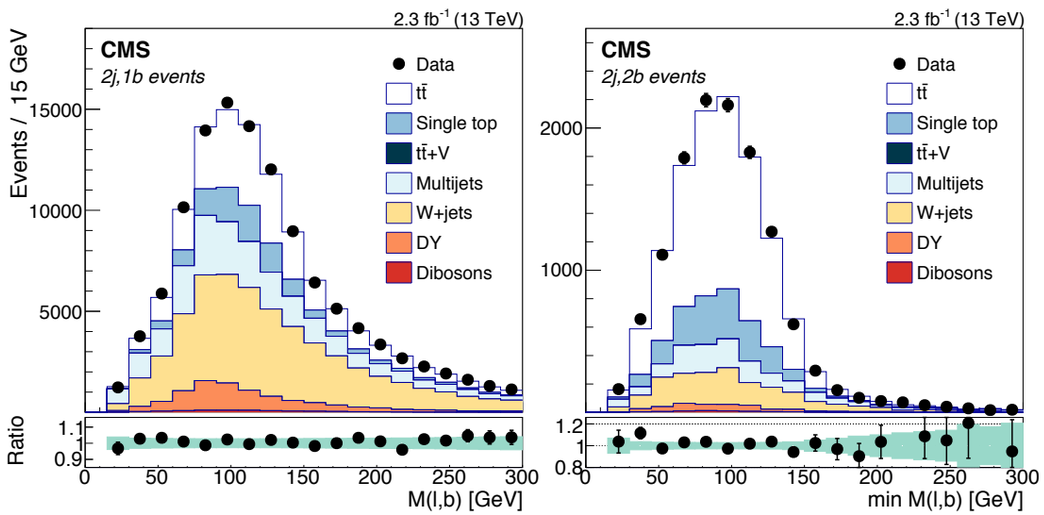


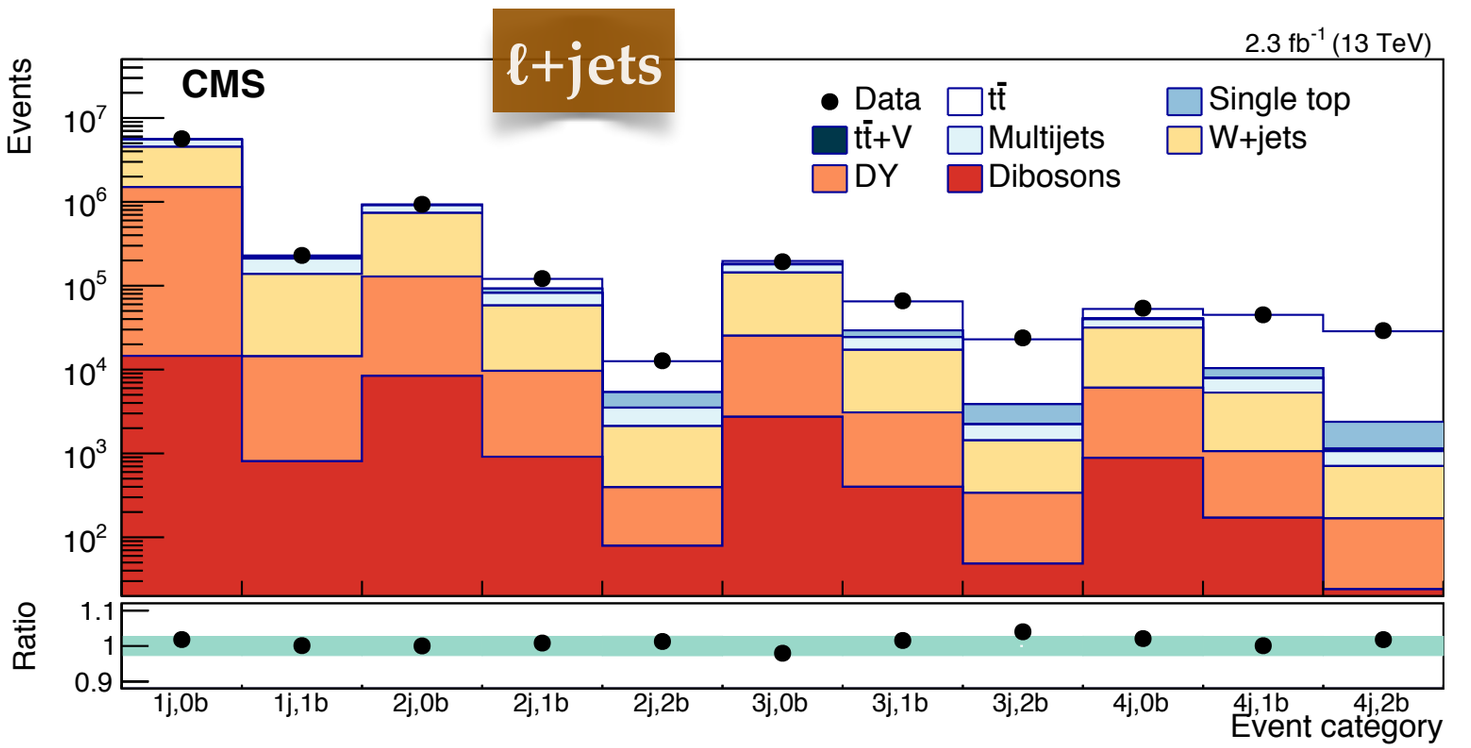
- All channels are revisited, theoretical predictions with NNLO+NNLL precision agree well with the measurements
- Uncertainty contributions from many different sources:
  - Experimental uncertainties:
    - ✓systematics from lepton reconstruction & identification, jet energy calibration, etc
  - Theoretical uncertainties can be tested and partially be constraint with measurements:
    - ✓hadronization, parton shower modelling, etc

Inclusive σ_{tt} measurement at 13 TeV

Ref. arXiv:1701.06228

(Submitted to J. High Energy Phys.)





* Mass(l,b): for events with only 1 b-tagged jet
* min Mass(l,b): for events with ≧ 2 b-tagged jets

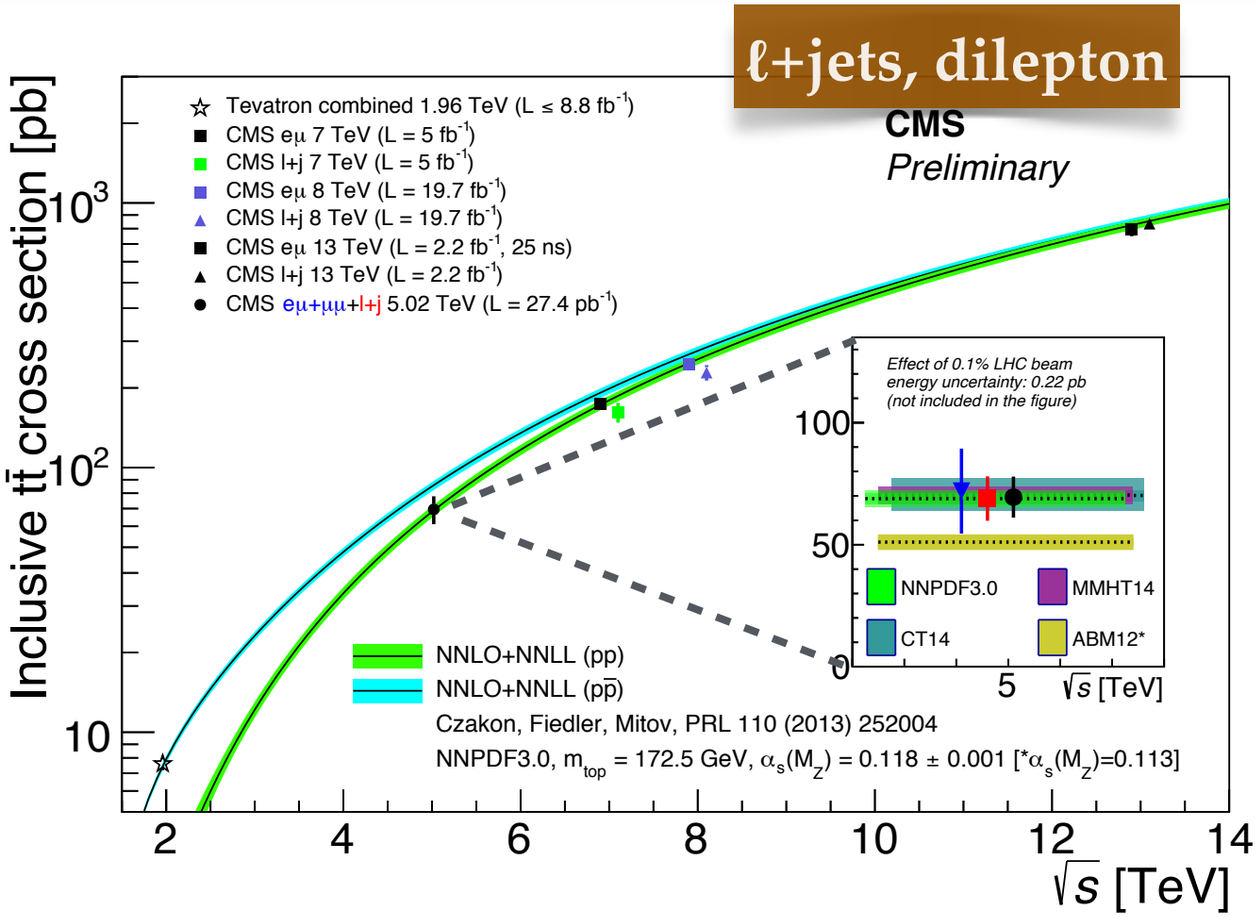
- Shape analysis on Mass(l,b) or min Mass(l,b) in 44 categories (lepton flavours and charges, number of b-tagged jet and n_{jets} multiplicity)
  - Low (b)jets categories constrain backgrounds while high (b)jets fit on the signal
  - In-situ constraints on systematic uncertainties
- Dominant uncertainties: parton shower modelling, W+jets & QCD backgrounds, luminosity
- Pole mass extracted simultaneously in the fit

σ_{tt} = 834.6 ±2.5(stat) ±22.8(syst) ±22.5(lumi) pb^{-1}

$$M_t = 172.3^{+2.7}_{-2.3}\ GeV$$

Inclusive σ_{tt} measurement at 5.02 TeV

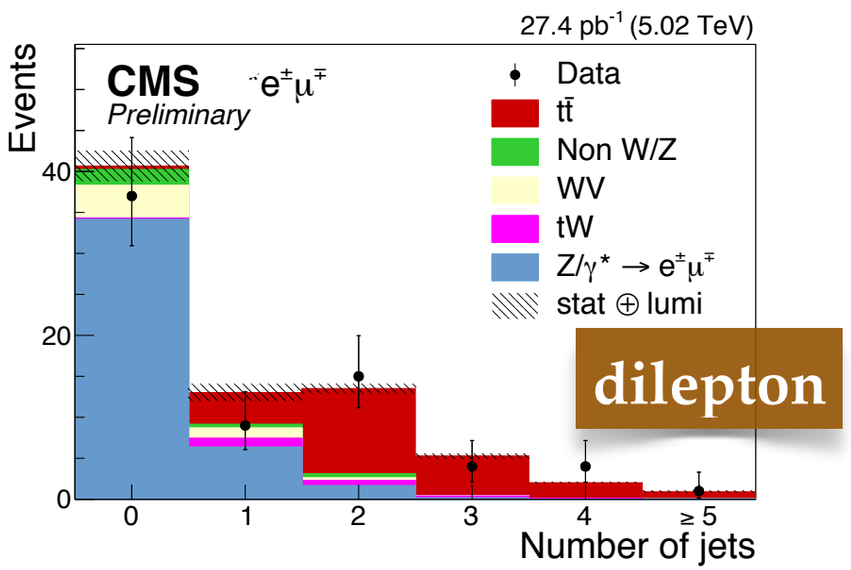
Ref. PAS TOP-16-023



- First top pair cross section measurement at this energy with integrated luminosity of 27.4 pb^{-1}
- Similar approach as measurements at 13 TeV
- Help to constrain gluon PDFs

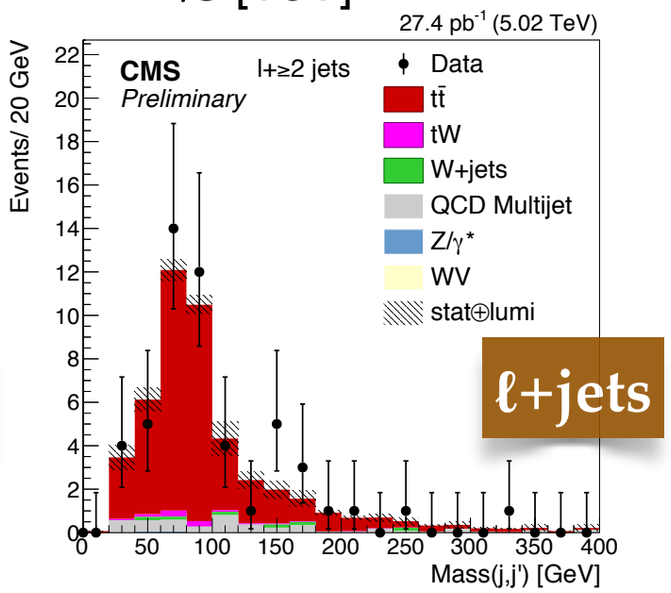
σ_{tt} = 69.5 ±6.1(stat) ±5.6(syst) ±1.6(lumi) pb^{-1} (combined channels)

✓ statistics (8.8%), systematics (8.4%) uncertainties



dilepton

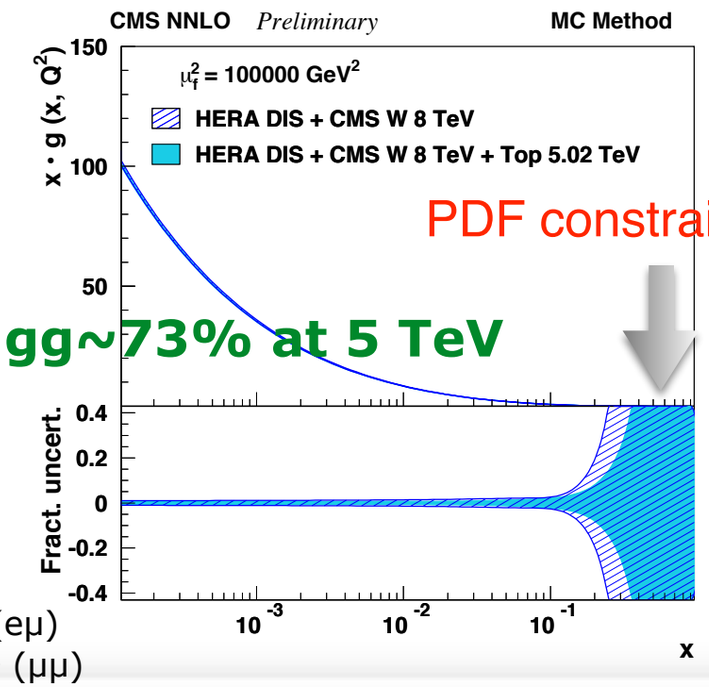
σ_{tt} = 68.9 ±6.5(stat) ±6.1(syst) ±1.6(lumi) pb^{-1}



ℓ+jets

σ_{tt} = 76.5 ±18.7(stat) ±4.4(syst) ±1.8(lumi) pb^{-1} (eμ)

σ_{tt} = 59.2 ±28.7(stat) ±10.6(syst) ±1.4(lumi) pb^{-1} (μμ)



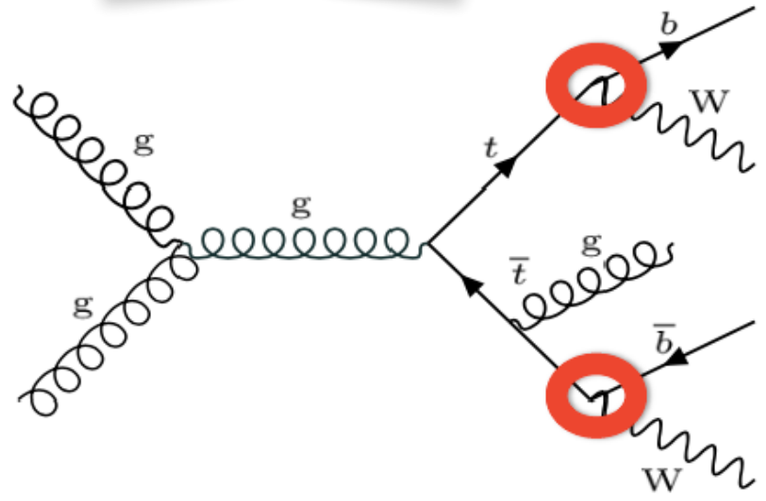
PDF constraints

✓ gg~73% at 5 TeV

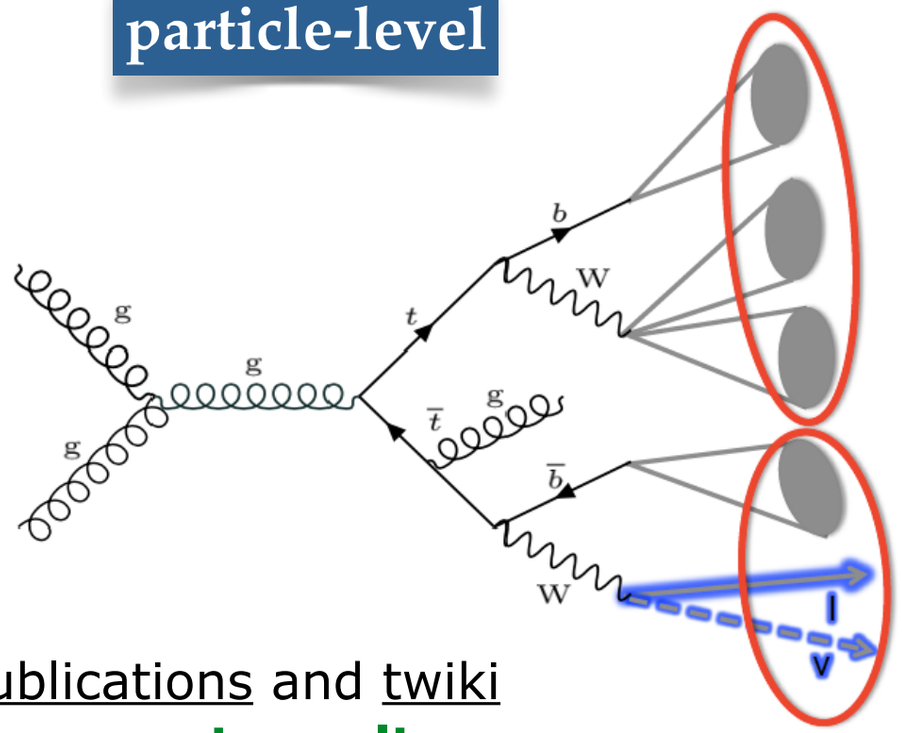
Measuring σ_{tt} differentially

- Bin-wise cross section measurements as a function of variables
  - Unfolding procedures to correct for detector effects, acceptance, and selection efficiency
- Studies are preformed in
  - Parton-level: top quark after radiation but before decays
    - ✓ Can be compared directly to QCD matrix element calculations
  - Particle-level: top quark proxy reconstructed from decay products after hadronization
    - ✓ Avoiding theory-based extrapolations from fiducial phase space to the full range, and from jets to partons
    - ✓ Reduce theoretical uncertainties in the experimental results

parton-level



particle-level



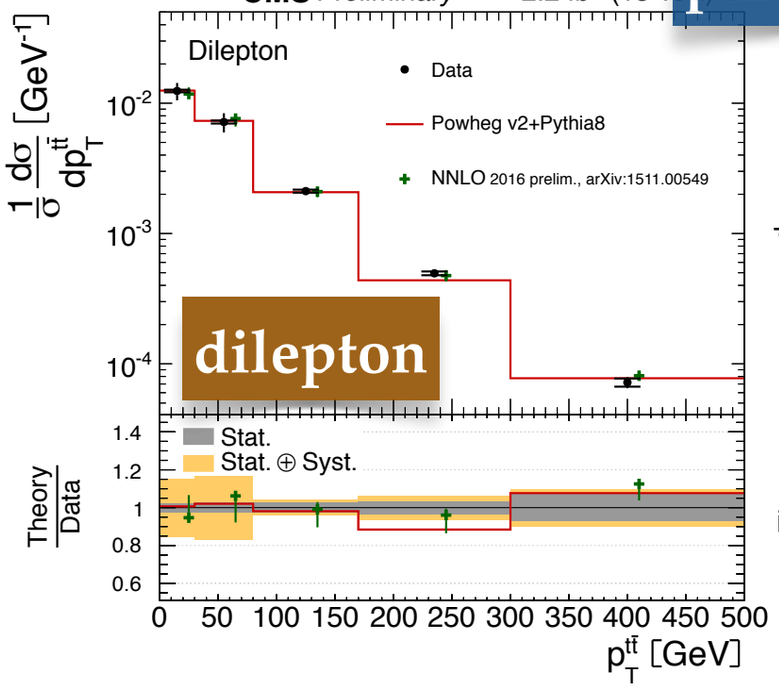
Link CMS TOP results, publications and twiki

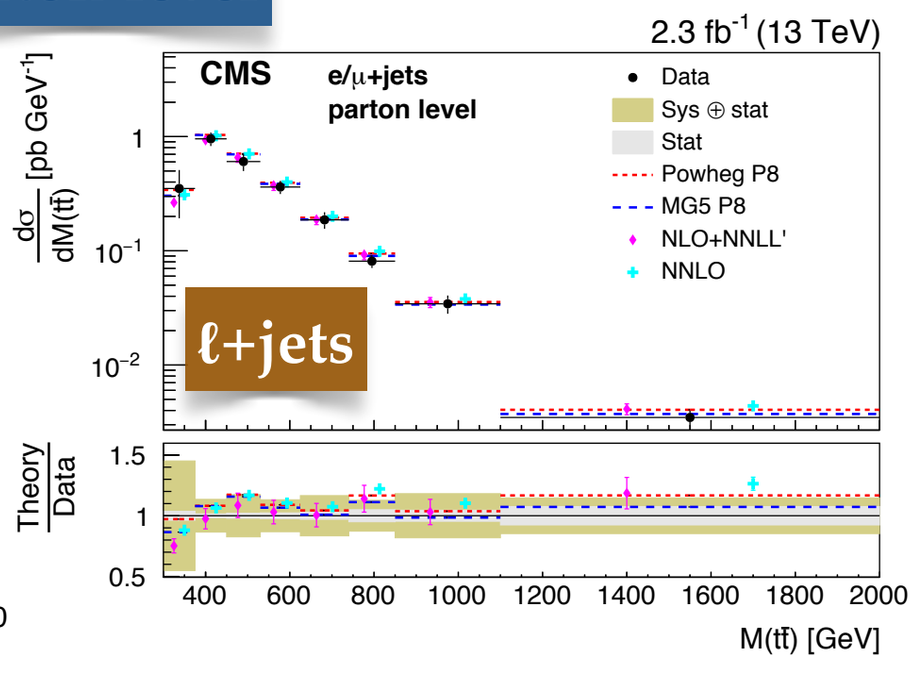
Today: mainly focus on recent results

Measuring σ_{tt} differentially

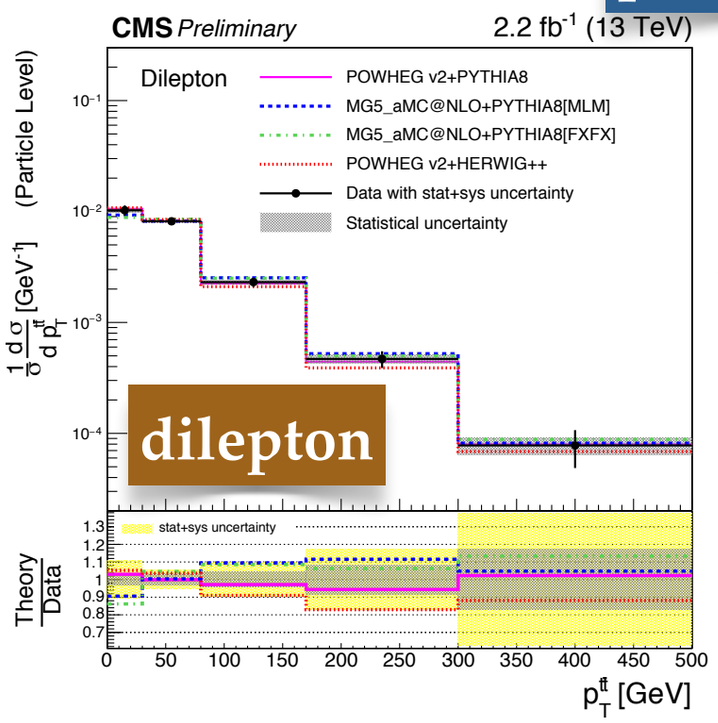
Ref. PAS TOP-16-011,
Phys. Rev. D 95, 092001,
PAS TOP-16-007

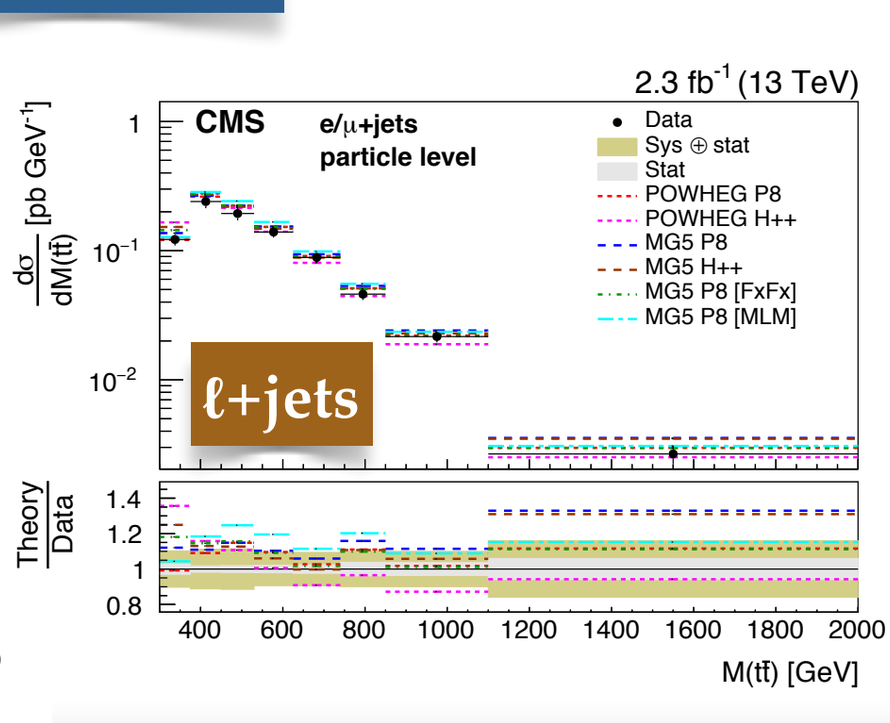
parton-level





particle-level

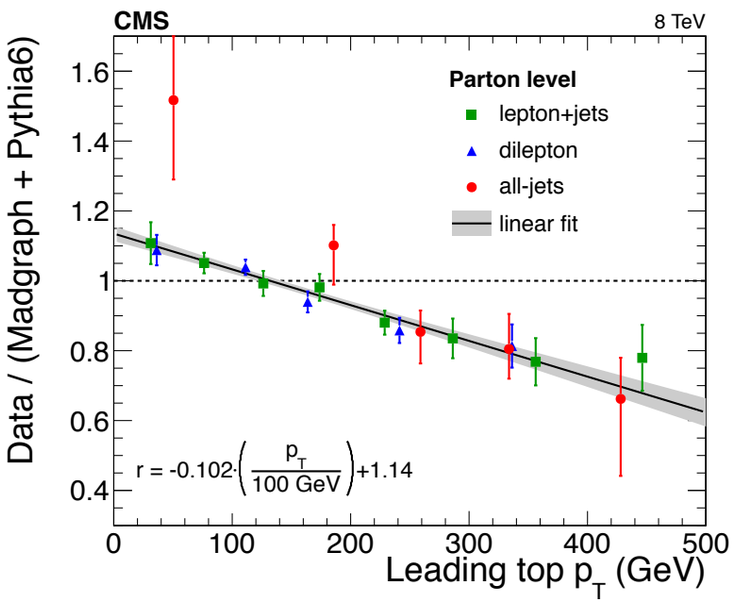


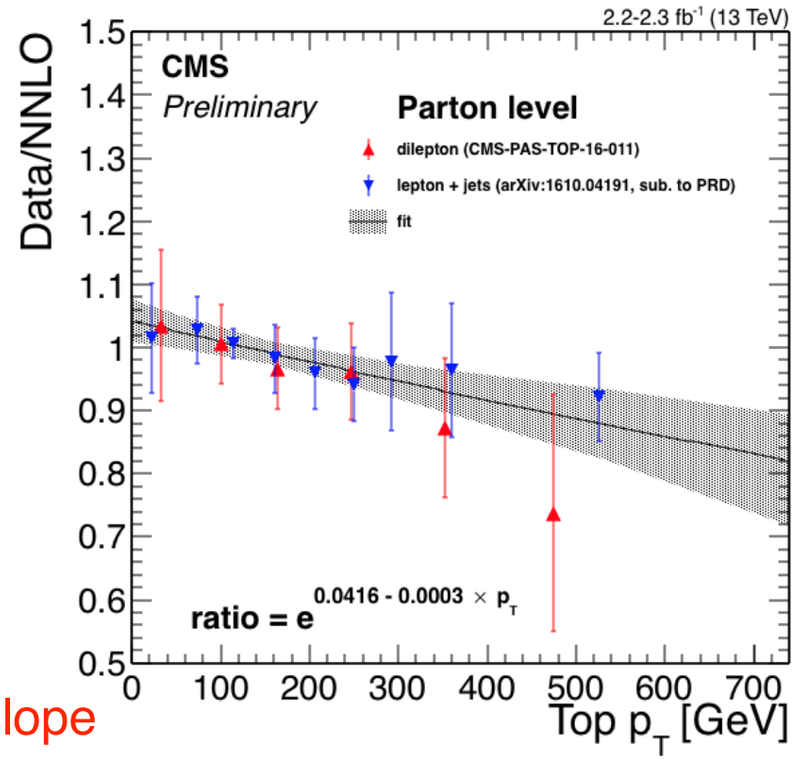


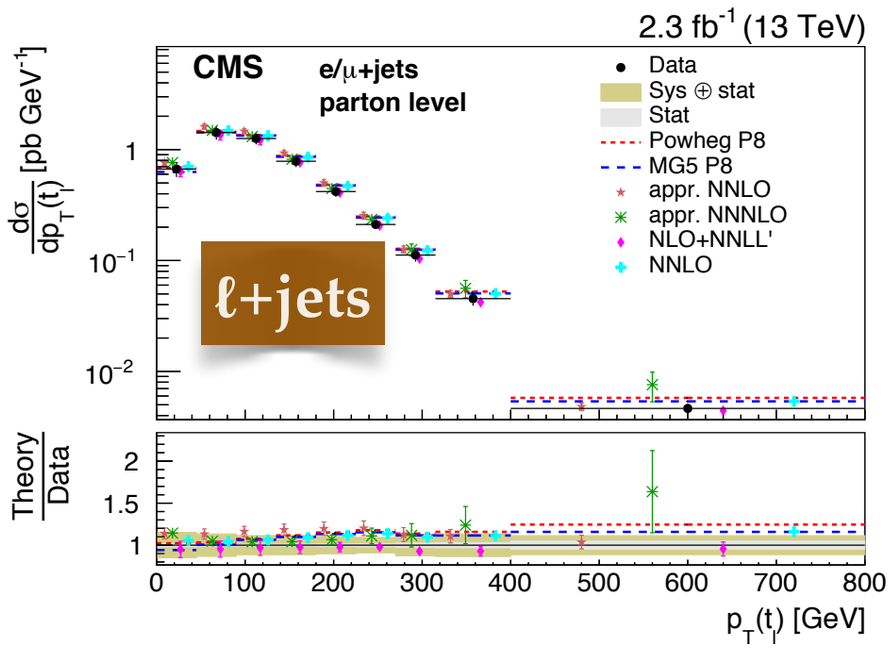
- Studies in parton-level and particle-level
- Test of nominal MC: POWHEGv2 + PYTHIA8, and compare to different predictions and generators
- Systematic uncertainties dominant
- Differential distributions described reasonably well in many different variables (apart from p_T)

top p_T differential distribution

Ref. PAS TOP-16-011,
Phys. Rev. D 95, 092001

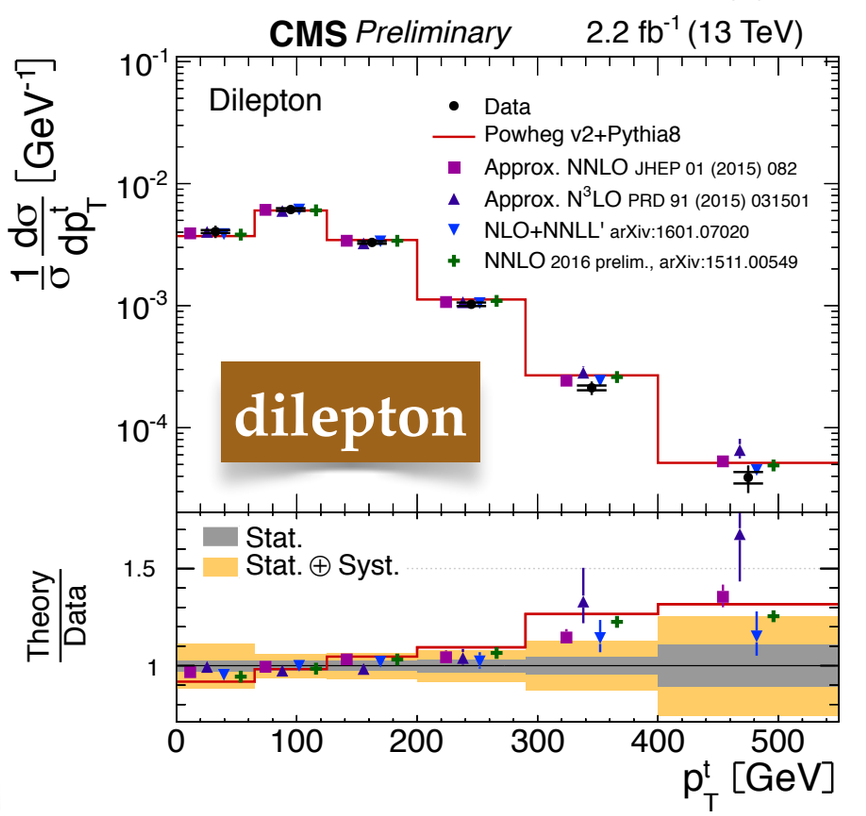






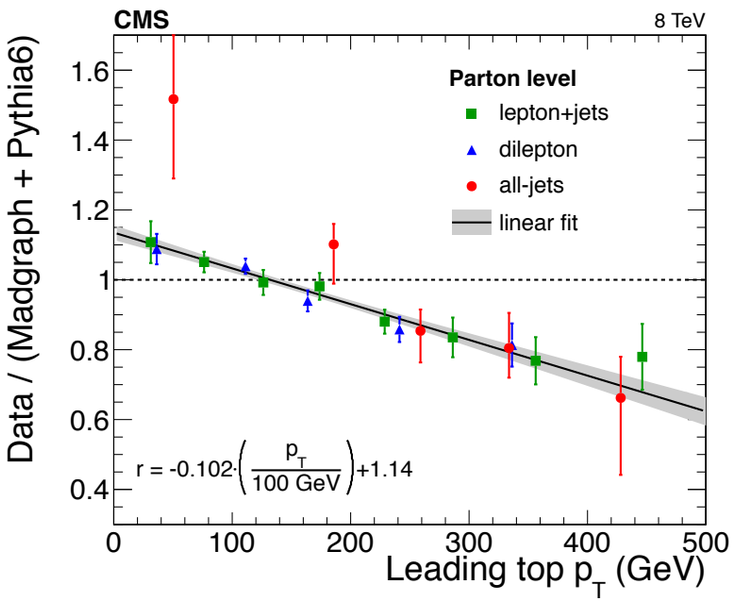
Significant slope

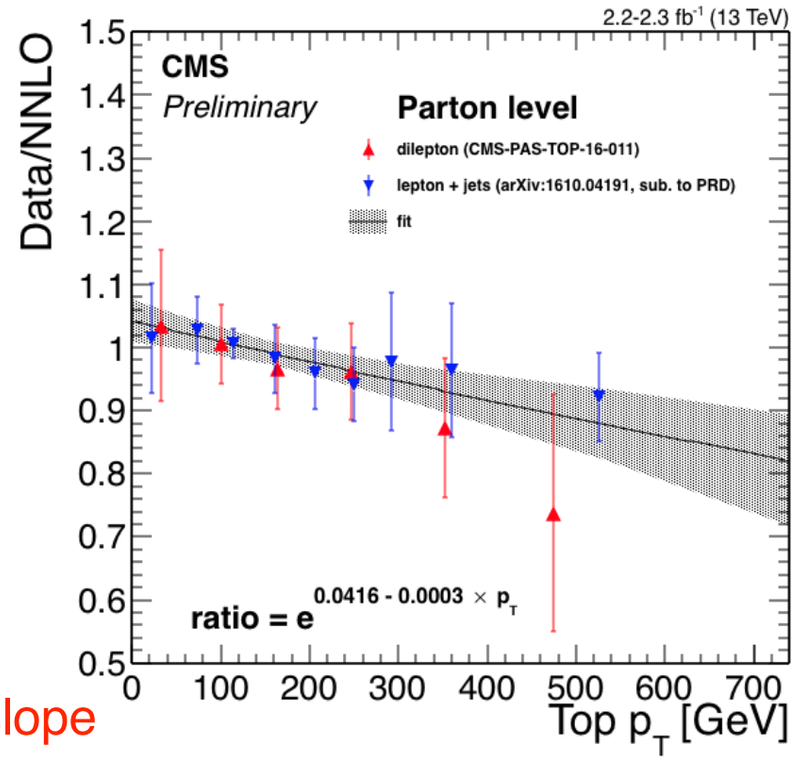
- Differential distributions show top p_T is softer
  - Comparison to different predictions
  - Discrepancy is observed in all decay channels
  - Results shows similar behaviour at all energies
- Better description with NNLO QCD predictions, but not satisfactory



top p_T differential distribution

Ref. PAS TOP-16-011,
Phys. Rev. D 95, 092001,
PAS TOP-16-013

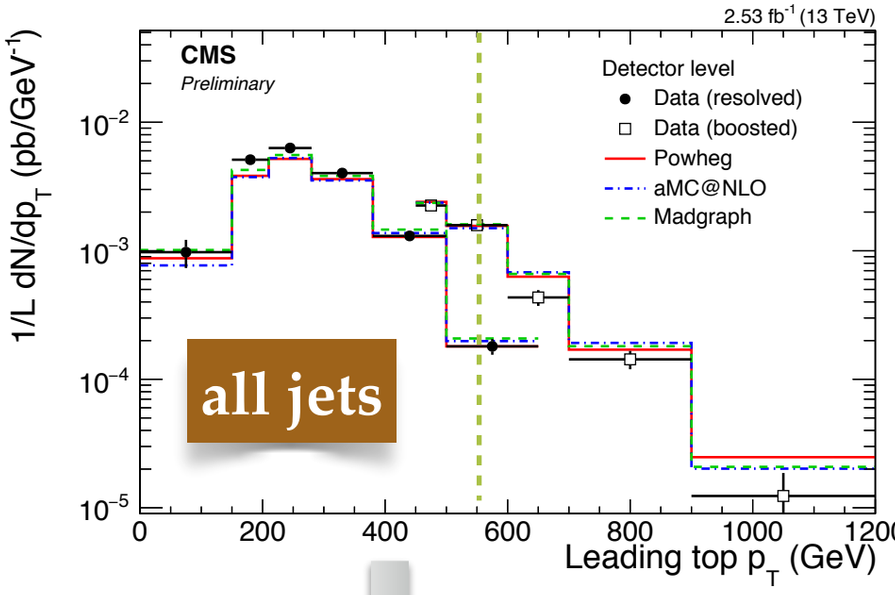




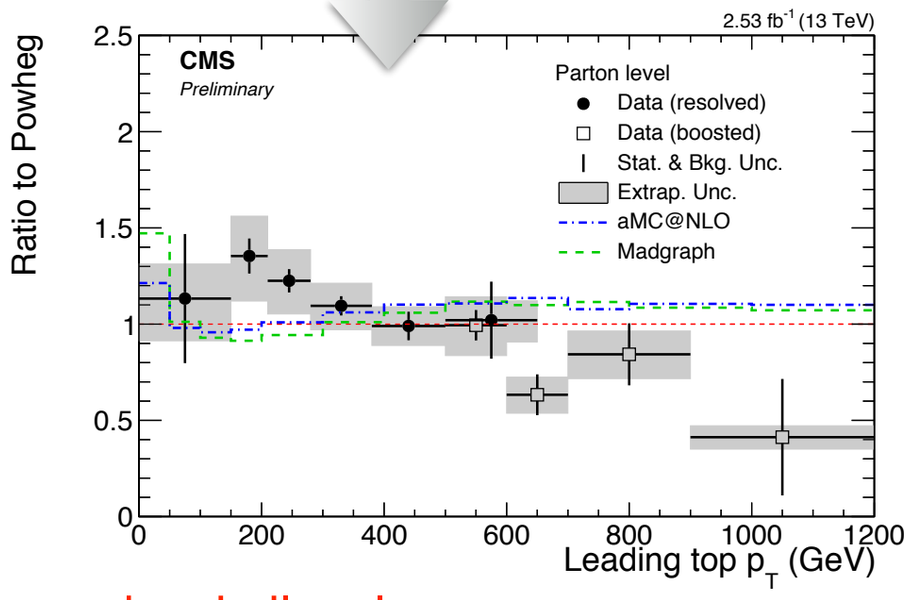
Significant slope

- In all jet channel, top p_T measured spectrum is also softer than the predictions
- Agreement is observed in the resolved and boosted overlapping regions

✓reconstruction in resolved and boosted regimes



extrapolate to full phase space

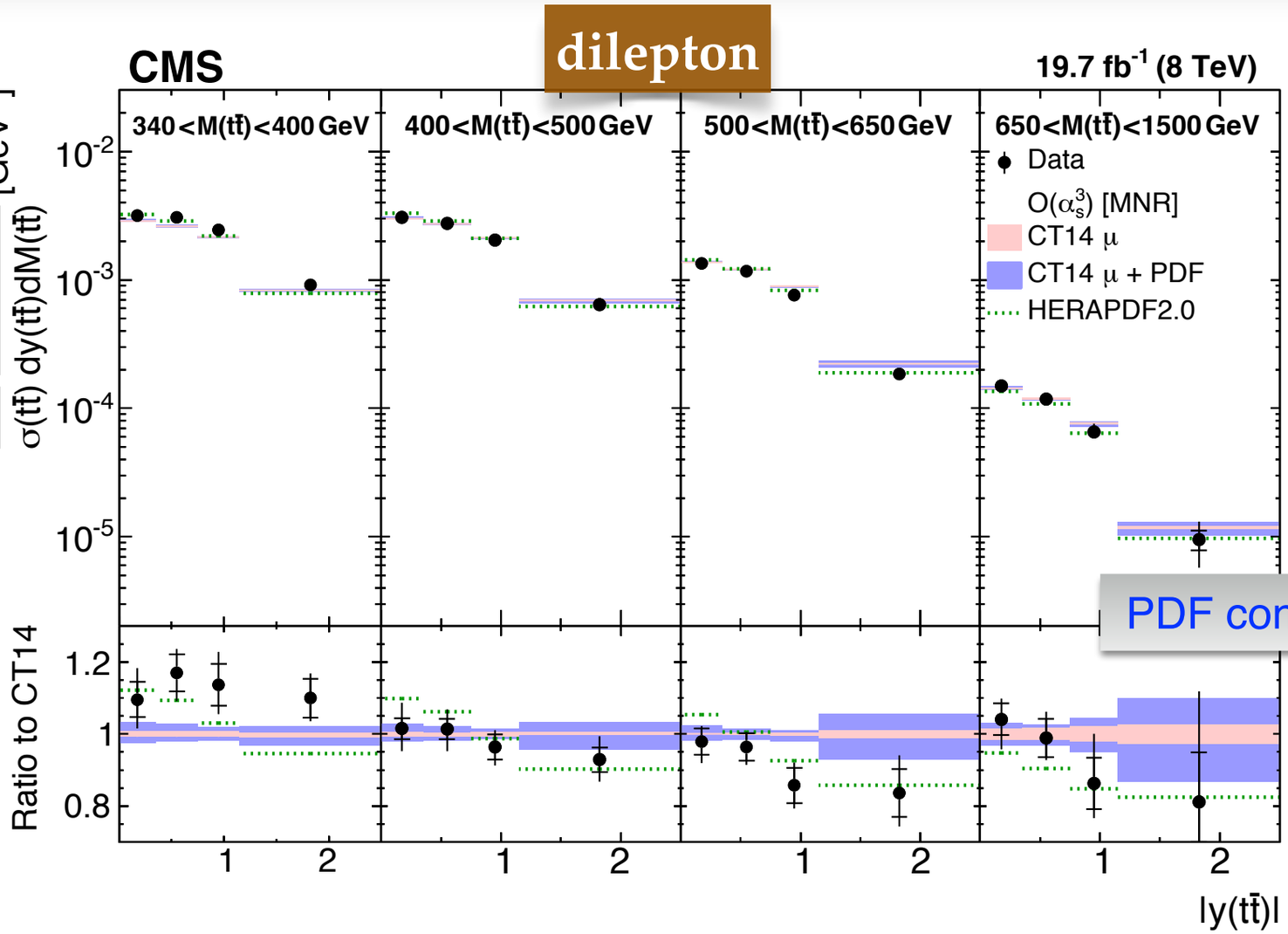


observed a similar slope

Double differential cross section at 8 TeV

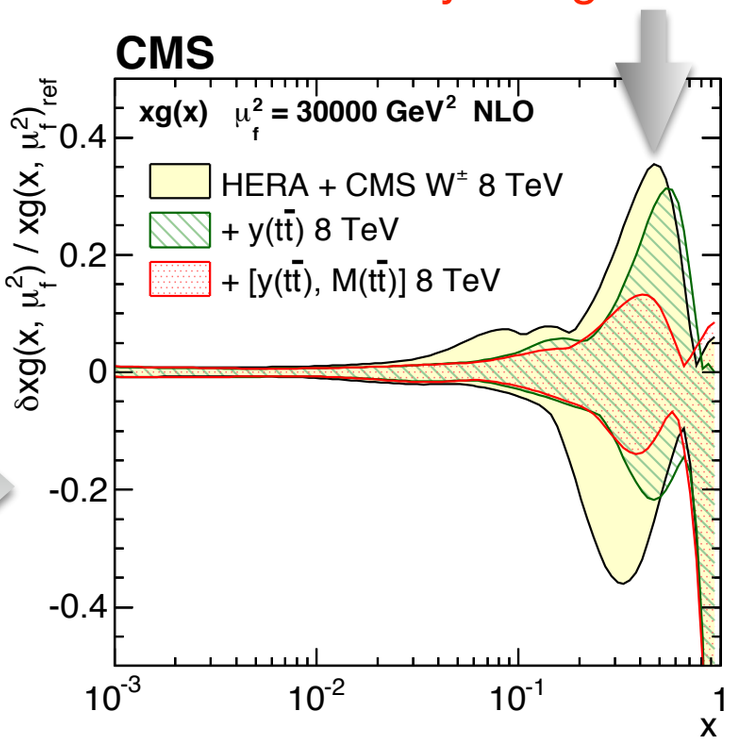
Ref. arXiv:1703.01630
(Submitted to Eur. Phys. J. C)

dilepton



PDF constraints

significantly reduce PDF uncertainty in high-x



✓ PDF uncertainty is reduced by factor of 2 at x~0.3 (the largest impact)

- First measurement of this type at the LHC
- Provide good PDFs constraint using the sensitive and correlative M_{tt}-$|y_{tt}|$ variables

2D distributions on:

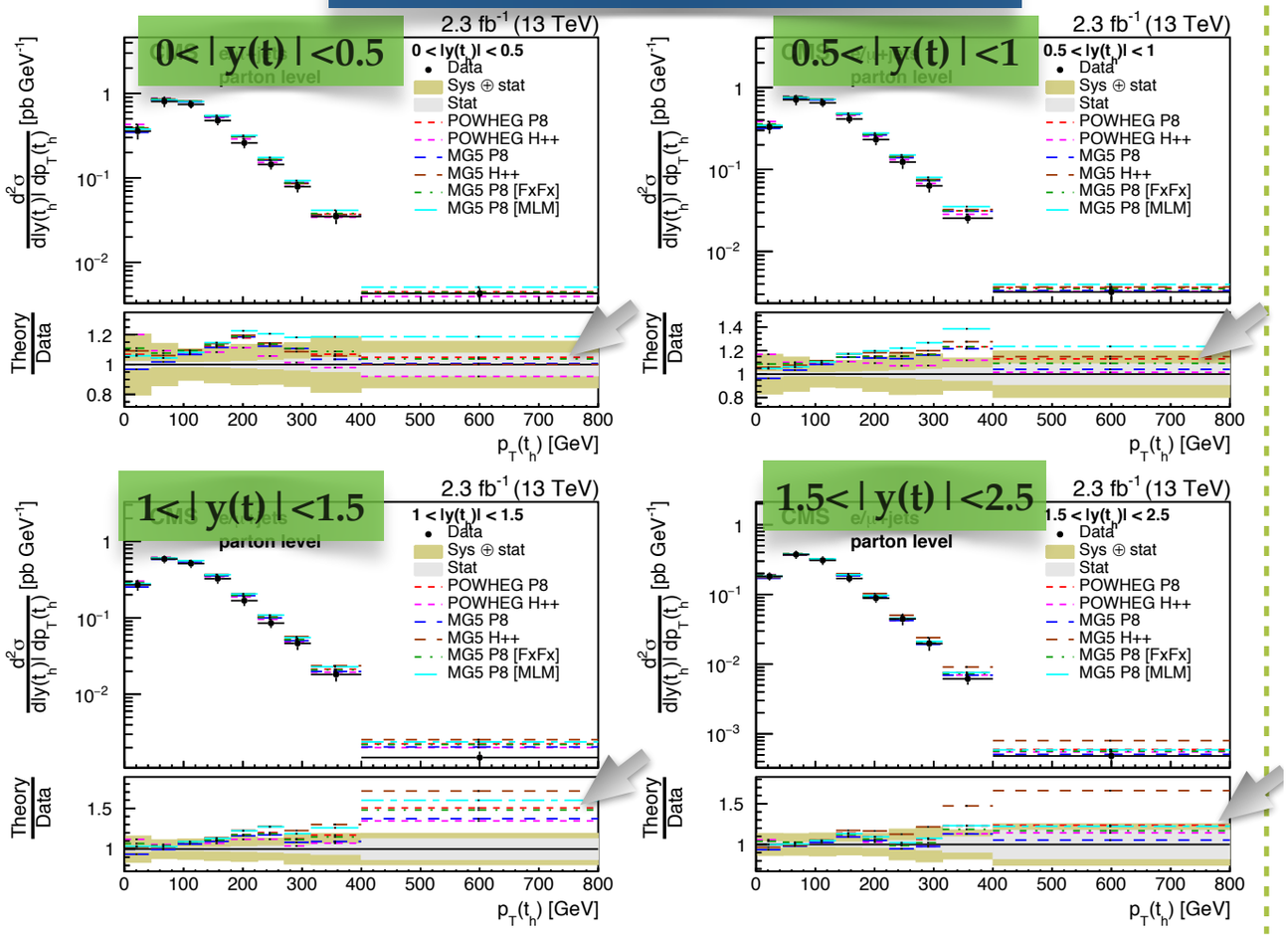
$p_T(t)$	$\|y(t)\|$
M(tt)	$\|y(t)\|$
M(tt)	$\|y(tt)\|$
M(tt)	$p_t(tt)$
M(tt)	$\Delta\eta(tt)$
M(tt)	$\Delta\phi(tt)$

Double differential cross section at 13 TeV

Ref. Phys. Rev. D 95, 092001

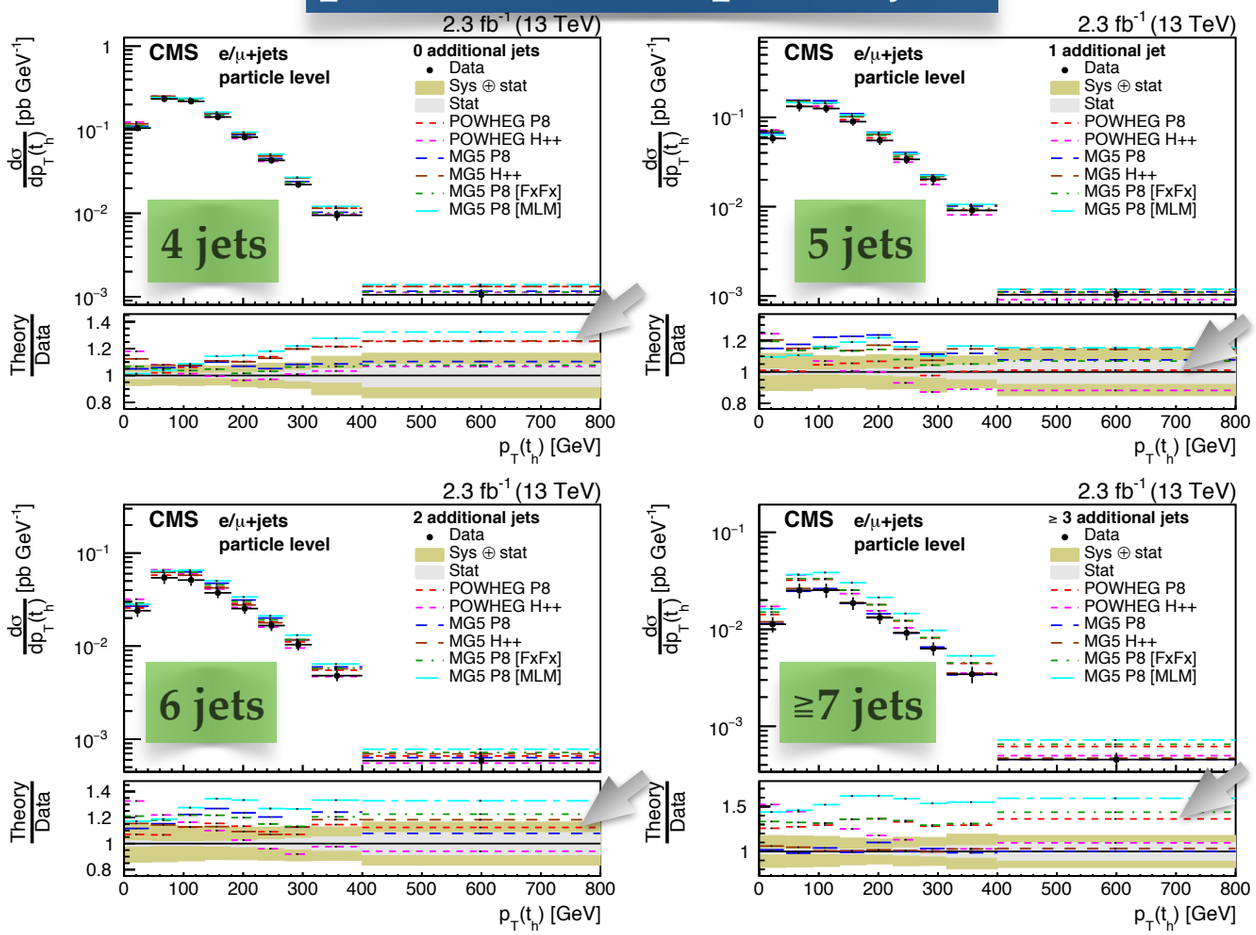
ℓ+jets

parton-level: $p_T(t)$-$|y(t)|$



✓ Observe softer $p_T(t)$ discrepancy

particle-level: $p_T(t)$-njets



✓ Observe high n_{jets} discrepancy; Theory/Data is observed being more flat as n_{jets} increases

- Distributions: $p_T(t_h)$-$|y(t_h)|$, M(tt)-$|y(tt)|$, M(tt)-$p_t(tt)$
- Also measure top pair variables and top kinematic variables as function of number of jets

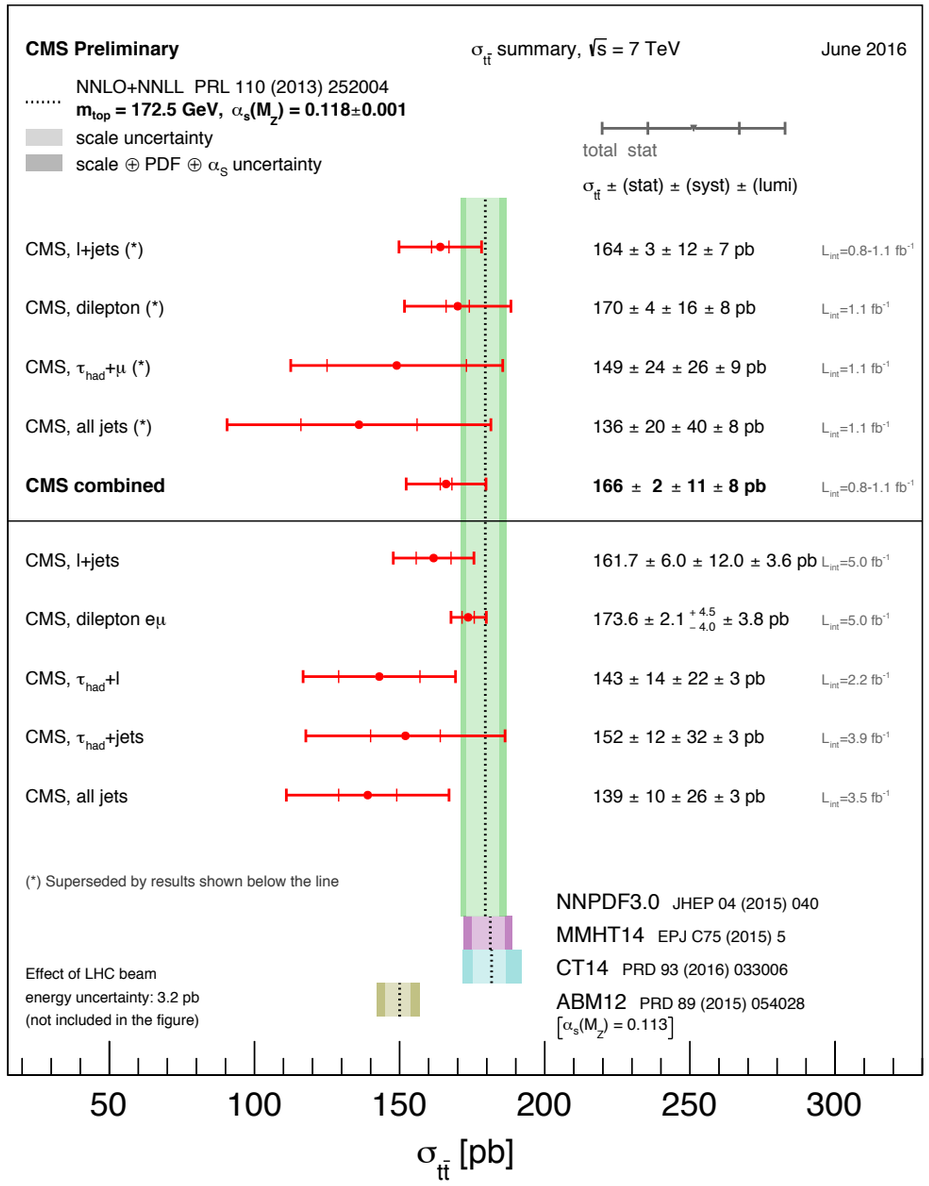
Summary and outlook

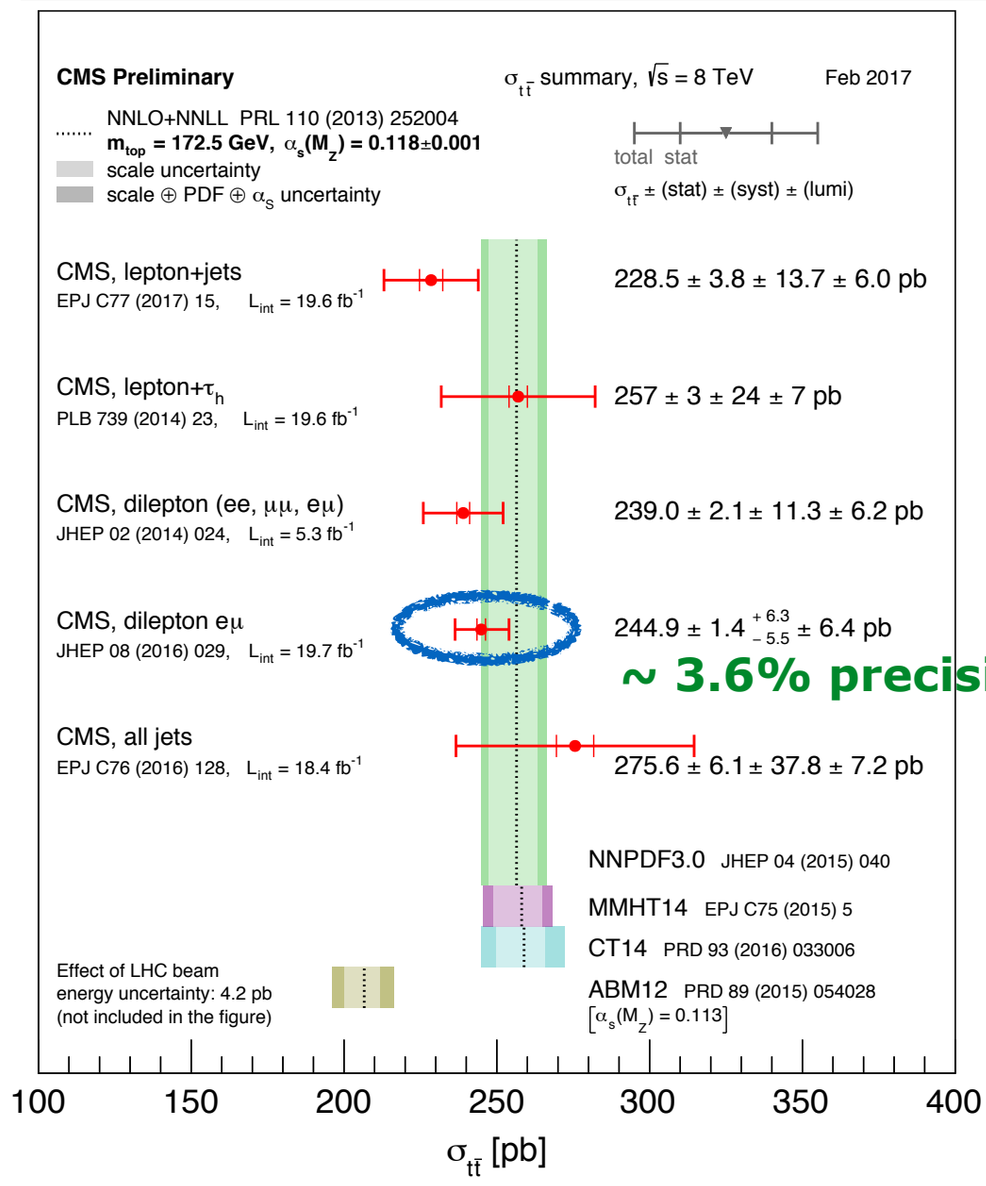
- CMS study a broad range of tt cross sections, including studies of
  - Inclusive: at four energies in different decay channels
  - 1D differential: overall agreed but top p_T spectrum is mis-modelled
  - 2D differential: deeper test and probe of modelling, PDFs constraint
  - Parton-level and particle-level

- Some differential discrepancies are observed, however, the overall top measurements are consistent with SM NNLO+NNLL predictions
- Limited by systematic uncertainties
- Currently with 2.3 fb^{-1} for Run II measurements, a better precision is expected with ~36 fb^{-1} 2016 dataset

Backup

Inclusive σ_{tt} measurements at 7, 8 TeV





- Measurements are consistent with theoretical predictions; the measured ratio of 8 to 7 TeV cross section also agrees with QCD predictions **Ref. EPJC 77 (2017) 15**

- Highest precision is reached, dileption channel gives the best sensitivity

$R^{8/7} = 1.43 \pm 0.04(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(\text{lumi})$

$R^{8/7} = 1.429 \pm 0.001(\text{scale}) \pm 0.004(\text{PDF}+\text{ff}_s+\text{mt})$ (expected value)

Top mass

Ref. arXiv:1701.06228
(Submitted to J. High Energy Phys.)

$$\sigma(m_t) = \sigma(m_{ref}) \left(\frac{m_{ref}}{m_t}\right)^4 \cdot \left[1 + a_1\left(\frac{m_t}{m_{ref}} - 1\right) + a_2\left(\frac{m_t}{m_{ref}} - 1\right)^2\right] \quad (4)$$

where $m_{ref} = 172.5\,\text{GeV}$ is the mass used as reference, a_1 and a_2 are coefficients fit after running the theory computation for different top quark mass hypotheses. The effect of the QCD scale

To measure the pole mass, the likelihood (Eq. 2) is then re-parametrised transforming μ into a functional form which depends on the parameter to extract

$$\boldsymbol{\mu}(m_t) = \frac{\sigma(m_t)}{\sigma_{th}} \cdot \frac{A}{A(m_t)} \ , \quad (5)$$

where the last term ($\frac{A}{A(m_t)}$), is a mass-dependent correction to the acceptance of this analysis.

Jet multiplicity differential distribution

Ref. PAS TOP-16-011

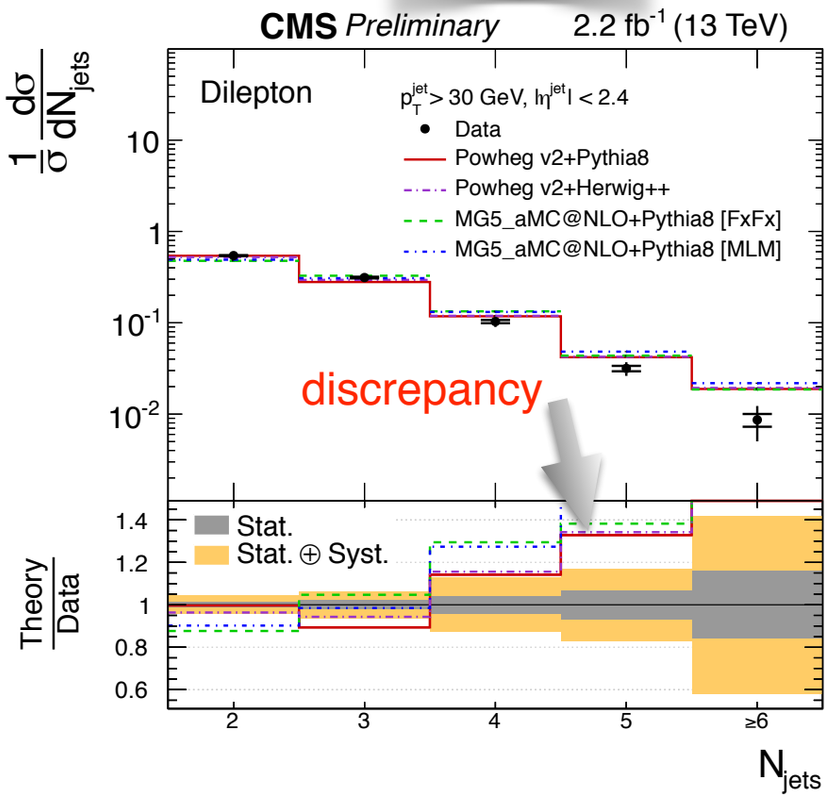
arXiv:1610.04191

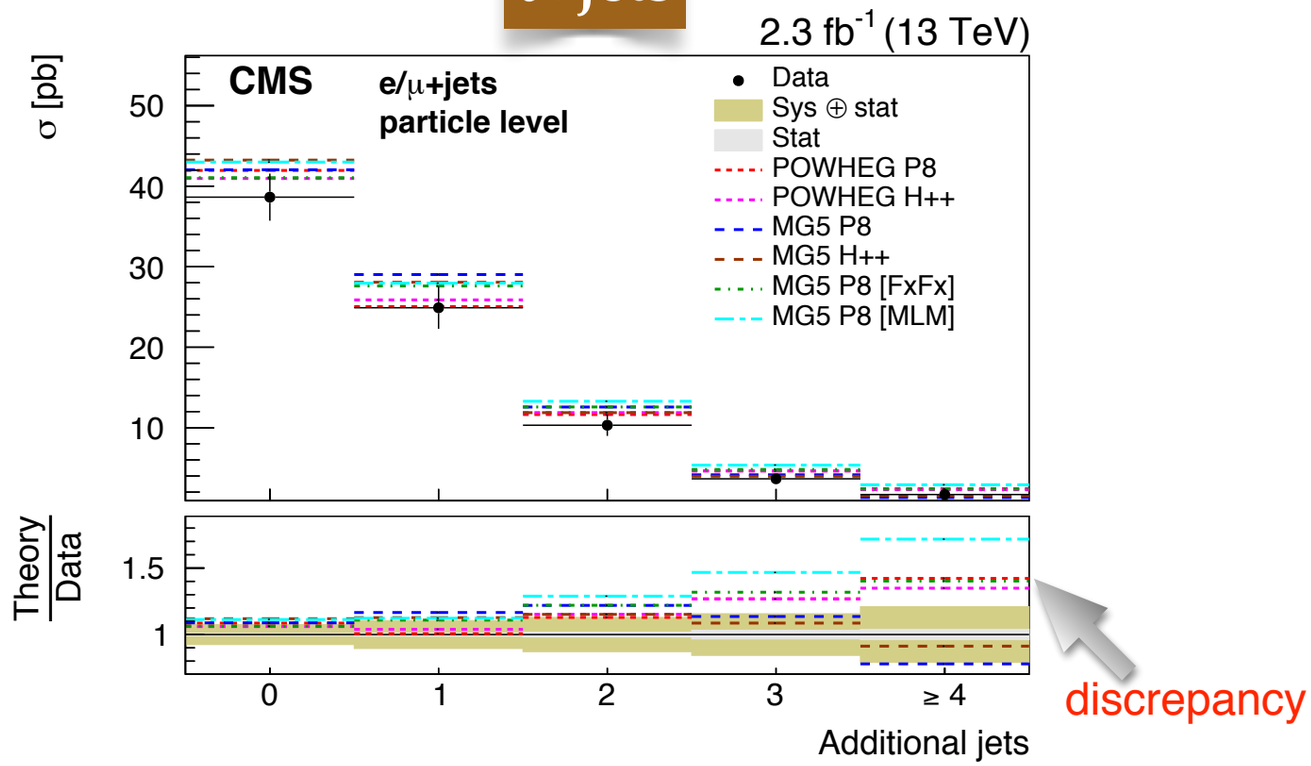
(Accepted in Phys. Rev. D)

dilepton

✓ tt+jets is also an important background to ttH

ℓ+jets





- Observe discrepancy in high jet multiplicity compare to MC with standard tune of CMS
  - Low jet multiplicities: described by matrix element
  - High jet multiplicities: strongly affect by parton shower modelling, cannot expect precise theoretical predictions
- The value of the initial-state shower scale was corrected: α_s is set from 0.1365(2.2 fb^{-1}) to 0.1108 (2016 dataset)

PDFs constraint

CMS Collaboration, "Measurement of the differential cross section and charge asymmetry for inclusive pp $\to W^{\pm} + X$ production at $\sqrt{s} = 8$ TeV", *Eur. Phys. J.* **C76** (2016), no. 8, 469, doi:10.1140/epjc/s10052-016-4293-4, arXiv:1603.01803.

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+E_g x^2+F_g x^3) - A'_g x^{B'_g}(1-x)^{C'_g},$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x+E_{u_v} x^2),$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}(1+D_{\overline{U}} x+F_{\overline{U}} x^3),$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}},$$

Data sets	χ^2/dof			
	Nominal fit	+[$p_T(t), y(t)$]	+[$y(t), M(t\bar{t})$]	+[$y(t\bar{t}), M(t\bar{t})$]
CMS double-differential $t\bar{t}$		10/15	7.4/15	7.6/15
HERA CC e^-p, $E_p = 920$ GeV	57/42	56/42	56/42	57/42
HERA CC e^+p, $E_p = 920$ GeV	44/39	44/39	44/39	43/39
HERA NC e^-p, $E_p = 920$ GeV	219/159	219/159	219/159	218/159
HERA NC e^+p, $E_p = 920$ GeV	440/377	437/377	439/377	441/377
HERA NC e^+p, $E_p = 820$ GeV	69/70	68/70	68/70	69/70
HERA NC e^+p, $E_p = 575$ GeV	221/254	220/254	221/254	221/254
HERA NC e^+p, $E_p = 460$ GeV	219/204	219/204	219/204	219/204
CMS $W^{\pm}$ asymmetry	4.7/11	4.6/11	4.8/11	4.9/11
Correlated χ^2	82	87	91	89
Log-penalty χ^2	−2.5	+2.6	−2.2	−3.3
Total χ^2/dof	1352/1138	1368/1153	1368/1153	1366/1153

- The pdf is parametrized as the following equations. A, B, C are free parameters characterising different PDFs. They are estimated simultaneously with other datasets using HERA fitter with chi2 minimisation.

PDFs constraint

Ref. PAS TOP-16-023

A. experimental uncertainties are estimated by Monte-Carlo Method

- generate pseudo-dataset with randomisation with statistical and systematic uncertainties
- perform PDF fit for each of them
- take RMS of this ensemble as uncertainties

B. model uncertainties and parametrization uncertainties are estimated according to general approach of HERAPDF package.