New CMS obtained using xFitter

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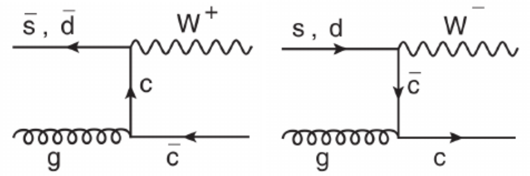
Overview of new results since March 2018

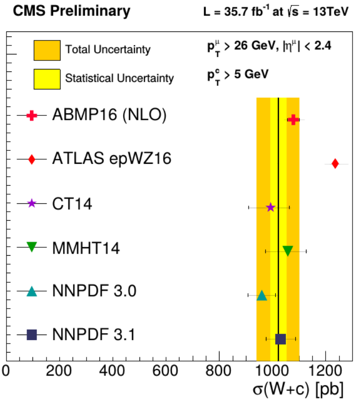
- "Measurement of associated production of a W boson and a charm quark in proton-proton collisions at $\sqrt{s} = 13$ TeV"
  [SMP-17-014, arXiv:1811.10021, submitted to Eur. Phys. J.]
- "Measurements of normalised multi-differential cross sections for top quark pair production in pp collisions at $\sqrt{s} = 13$ TeV and simultaneous determination of the strong coupling strength, top quark pole mass and parton distribution functions"
  [CMS-PAS-TOP-18-004, paper in a few days]
- "Measurement of the $t\bar{t}$ production cross section, the top quark mass, and the strong coupling constant using dilepton events in pp collisions at $\sqrt{s} = 13$ TeV"
  [TOP-17-001, arXiv:1812.10505, submitted to Eur. Phys. J.]
- "Standard Model Physics at the HL-LHC and HE-LHC"
  [CERN-LPCC-2018-03, arXiv:1902.04070]

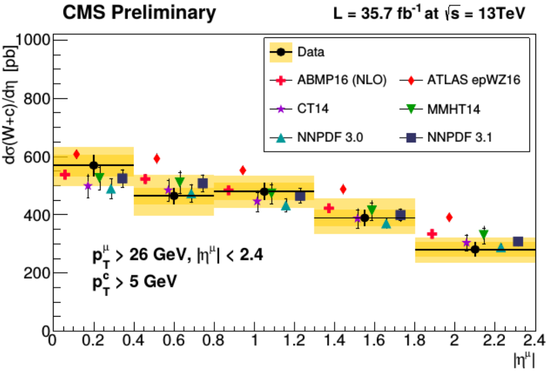
Measurement of associated production of W and c [arXiv:1811.10021]



- $W \to \mu$, $c \to D^* \to D^0 + \pi_{slow} \to K + \pi + \pi_{slow}$
- $|\eta(\mu)| < 2.4$, $p_T(c) > 5$ GeV
- Measured total cross section and differential cross section as function of $|\eta(\mu)|$
- Results are used to probe strange density in the proton at NLO (xFitter)

Measurement of associated production of W and c [arXiv:1811.10021]





- Calculations done with MCFM at NLO ($O(\alpha_s^2)$)
- $\mu_r = \mu_f = M_W$, $m_c = 1.5$ GeV
- Scales varied simultaneosuly by factor 2 (3%)
- Good agreement with theoretical predictions, except using ATLASepWZ16nnlo

Measurement of associated production of W and c [arXiv:1811.10021]

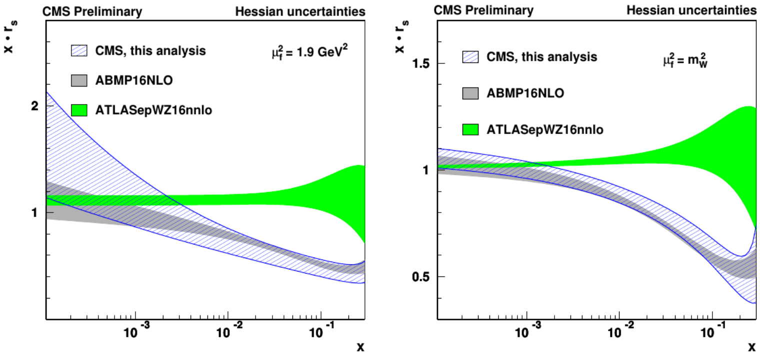
- Study performed using xFitter-2.0.0
- Fitted data:
  - HERA DIS
  - CMS W asymmetry at 7 TeV
  - CMS W asymmetry at 8 TeV
  - CMS W+c at 7 TeV
  - CMS W+c at 13 TeV
- PDF uncertainties estimated using standard HERAPDF approach
- Fit uncertainties estimated using HESSE and MC replica methods

$$x\mathrm{u_v}(x) = A_{\mathrm{u_v}}\, x^{B_{\mathrm{u_v}}}\, (1-x)^{C_{\mathrm{u_v}}}\, (1 + E_{\mathrm{u_v}} x^2),$$
$$x\mathrm{d_v}(x) = A_{\mathrm{d_v}}\, x^{B_{\mathrm{d_v}}}\, (1-x)^{C_{\mathrm{d_v}}},$$
$$x\overline{\mathrm{U}}(x) = A_{\overline{\mathrm{U}}}\, x^{B_{\overline{\mathrm{U}}}}\, (1-x)^{C_{\overline{\mathrm{U}}}}\, (1 + E_{\overline{\mathrm{U}}} x^2),$$
$$x\overline{\mathrm{d}}(x) = A_{\overline{\mathrm{d}}}\, x^{B_{\overline{\mathrm{d}}}}\, (1-x)^{C_{\overline{\mathrm{d}}}}$$
$$x\overline{\mathrm{s}}(x) = A_{\overline{\mathrm{s}}}\, x^{B_{\overline{\mathrm{s}}}}\, (1-x)^{C_{\overline{\mathrm{s}}}}$$
$$x\mathrm{g}(x) = A_{\mathrm{g}}\, x^{B_{\mathrm{g}}}\, (1-x)^{C_{\mathrm{g}}}$$

$$s(x) = \bar{s}(x)$$
$$B_{\bar{U}} \neq B_{\bar{d}} \neq B_{\bar{s}}$$

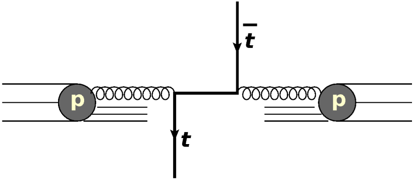
Dataset		χ^2/n_{dp}
HERA I+II charged current	e^+p	43 / 39
HERA I+II charged current	e^-p	57 / 42
HERA I+II neutral current	e^-p	218 / 159
HERA I+II neutral current	e^+p, $E_p = 820$ GeV	69 / 70
HERA I+II neutral current	e^+p, $E_p = 920$ GeV	448 / 377
HERA I+II neutral current	e^+p, $E_p = 460$ GeV	216 / 204
HERA I+II neutral current	e^+p, $E_p = 575$ GeV	220 / 254
CMS W muon charge asymmetry 7 TeV		13 / 11
CMS W muon charge asymmetry 8 TeV		4.2 / 11
W + c 7 TeV		2.2 / 5
W + c 13 TeV		2.1 / 5
Correlated χ^2		87
Total χ^2 / dof		1385 / 1160

Measurement of associated production of W and c [arXiv:1811.10021]

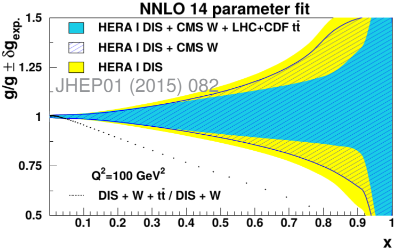


→ Determined r_s agree with earlier results obtained in neutrino scattering experiments, but do not support the hypothesis of an enhanced strange quark contribution in the proton quark sea

Why measure $t\bar{t}$ production?



- m_t provides a hard scale ($\alpha_s \approx 0.1$)
  $\Rightarrow$ ultimate probe of perturbative QCD
  (NLO, aNNLO, NNLO, ...)
- Produced mainly via *gg*
  $\Rightarrow$ constrain gluon PDF at high x
- Production sensitive to α_s and m_t^{pole}
- May provide insight into possible new physics



Why measure multidifferentially?

- differential (1D) $t\bar{t}$ data provide constraints on gluon PDF [JHEP01 (2015) 082]
- 2D $t\bar{t}$ data: stronger PDF constraints [EPJ C77 (2017) 459]
- **3D [$N_{\text{jet}}^{0,1+}$, $M(t\bar{t})$, $y(t\bar{t})$] cross sections constrain α_s, m_t^{pole}, PDFs:**
  - $y(t\bar{t})$ constrains PDFs (boost)
  - N_{jet} constrains α_s (extra radiation)
  - $M(t\bar{t})$ constrains m_t^{pole} (threshold)

Measurement of multidifferential $t\bar{t}$ cross sections [CMS-PAS-TOP-18-004]

First time measured 3D cross sections as function of $M(t\bar{t})$, $y(t\bar{t})$, $N_{\rm jet}$:

- $[N_{\rm jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$
- $[N_{\rm jet}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$

Exploited data for α_s +m_t +PDF extraction at NLO (highest available order for $t\bar{t}$ +jets):

- sensitivity to PDFs from $M(t\bar{t})$, $y(t\bar{t})$ ($x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp\left[\pm y(t\bar{t})\right]$)
- sensitivity to α_s from $N_{\rm jet}$ and $M(t\bar{t})$, $y(t\bar{t})$ (PDFs)
- sensitivity to m_t from $M(t\bar{t})$ via threshold and cone effects

Data interpretation consists of two parts:

(1) comparison theory vs data using external PDF sets:

- extracting α_s keeping $m_t^{\rm pole}$ fixed
- extracting $m_t^{\rm pole}$ keeping α_s fixed

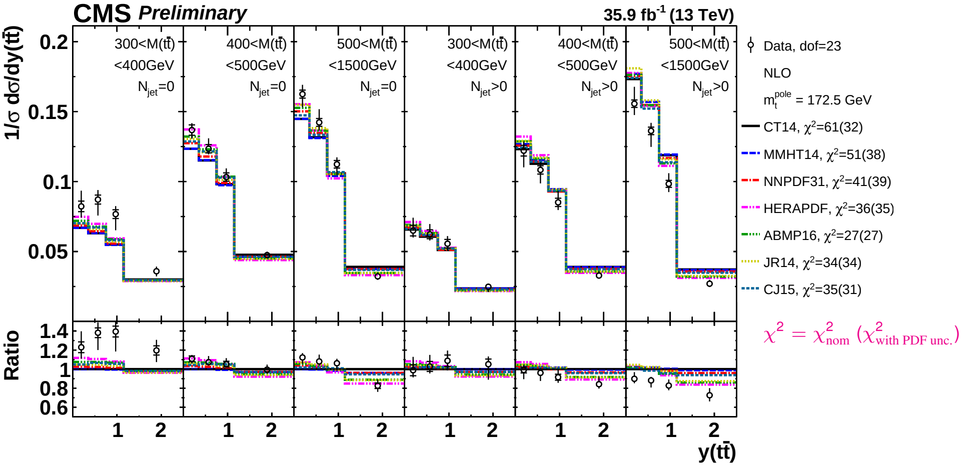
$\rightarrow$ this presents α_s, $m_t^{\rm pole}$ extraction from $t\bar{t}$ data only

(2) simultaneous fit of PDFs, α_s and $m_t^{\rm pole}$ using $t\bar{t}$ and HERA DIS:

$\rightarrow$ this presents fully consistent extraction of α_s, $m_t^{\rm pole}$ and PDFs, but using also HERA data

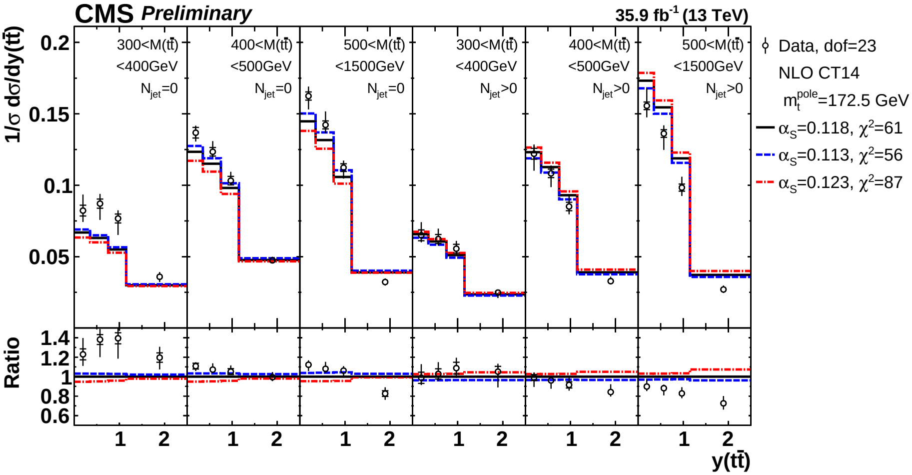
$\rightarrow$ important as exercise to understand new $t\bar{t}$ data, providing baseline for future global fits

$[N_{\mathbf{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ compared to NLO predictions with different PDFs



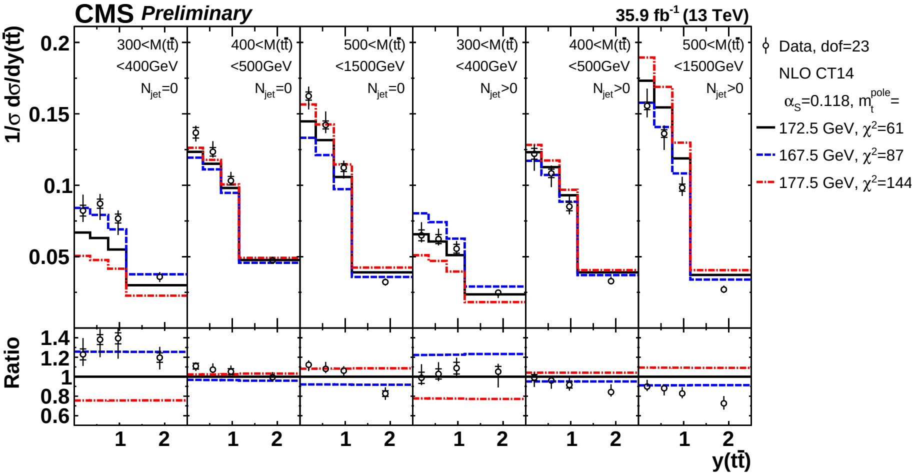
- description depends on PDFs $\rightarrow$ data are sensitive to PDFs
- all modern PDF sets considered
  - best description given by ABMP16

$[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ compared to NLO predictions with different α_s

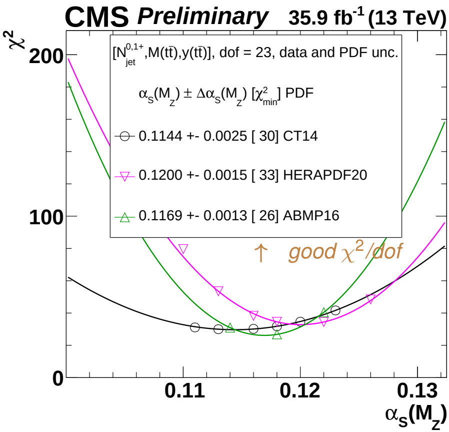


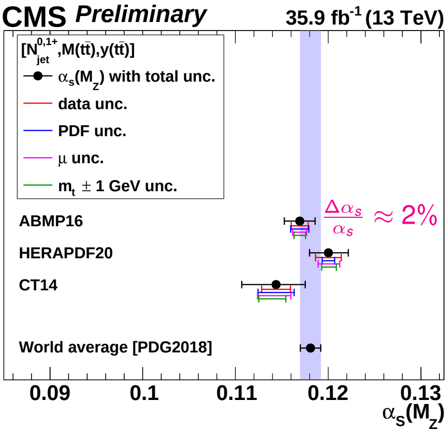
- α_s sensitivity comes from different N_{jet} bins
- further (indirect) sensitivity comes from $[M(t\bar{t}), y(t\bar{t})]$ via sensitivity to PDFs

$[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ compared to NLO predictions with different m_t^{pole}



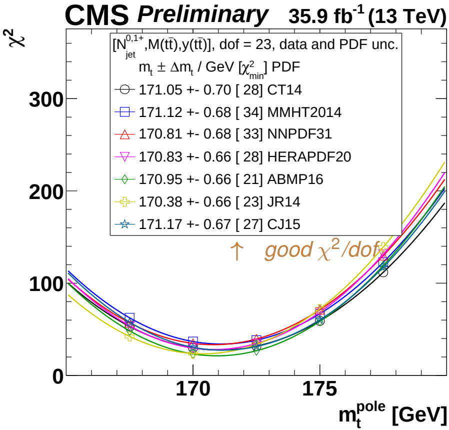
- m_t^{pole} sensitivity comes from $M(t\bar{t})$, mainly 1st bin
- this method differs from extracting m_t^{pole} from total $t\bar{t}$ x-section, and is similar to extracting m_t^{pole} from $t\bar{t}j$ diff. x-section [EPJ C73 (2013) 2438, CMS-PAS-TOP-13-006, JHEP 1510 (2015) 121]
- previous determination using this method: prelim. D0 results [FERMILAB-CONF-16-383-PPD]

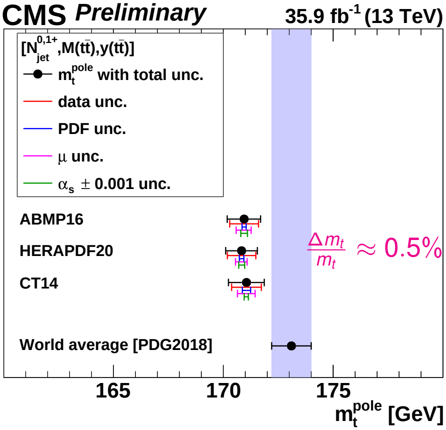




- used $m_t^{\text{pole}} = 172.5$ GeV in ME for all PDF sets (ABMP16 fitted $m_t^{\text{pole}} = 171.44$ GeV)
- precise determination of α_s is possible using these data
- significant dependence on PDF set observed (correlation between g and α_s)

Results: extraction of m_t^{pole} from $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$



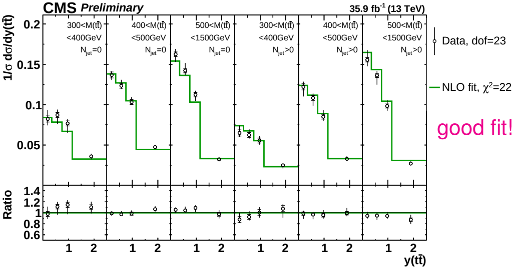


- used α_s from each PDF set ($\alpha_s = 0.118$ in CT and HERAPDF, $\alpha_s = 0.119$ in ABMP)
- precise determination of m_t^{pole} is possible using these data
  $\rightarrow$ uncertainty smaller than world average
- no significant dependence on PDF set

Simultaneous PDF + α_s + m_t^{pole} fit: results

- followed standard approach: using HERA DIS data only, or HERA + $t\bar{t}$ data to demonstrate added value from $t\bar{t}$ on PDF and α_s determination
- settings follow HERAPDF2.0 fit (very similar to TOP-14-013), use xFitter-2.0.0
- input data: combined HERA DIS [1506.06042] + $t\bar{t}$ (further details in BACKUP)

Data sets	χ^2/dof	
	Nominal fit	$+[N_{\text{jet}}, y(t\bar{t}), M(t\bar{t})]$
CMS $t\bar{t}$		10/23
HERA CC e^-p, $E_p = 920$ GeV	55/42	55/42
HERA CC e^+p, $E_p = 920$ GeV	38/39	39/39
HERA NC e^-p, $E_p = 920$ GeV	218/159	217/159
HERA NC e^+p, $E_p = 920$ GeV	438/377	448/377
HERA NC e^+p, $E_p = 820$ GeV	70/70	71/70
HERA NC e^+p, $E_p = 575$ GeV	220/254	222/254
HERA NC e^+p, $E_p = 460$ GeV	219/204	220/204
Correlated χ^2	82	90
Log-penalty χ^2	+2	−7
Total χ^2/dof	1341/1130	1364/1151

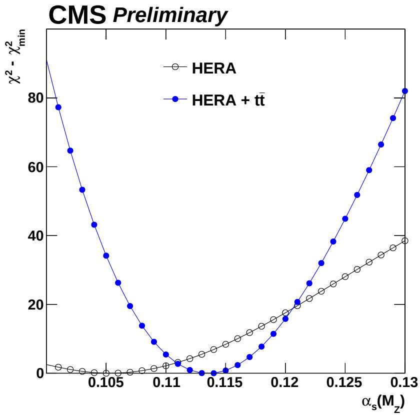


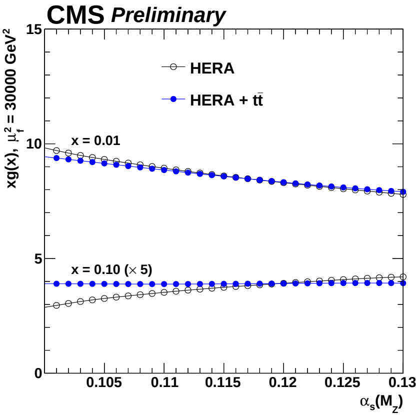
$$\alpha_s(M_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{mod})^{+0.0008}_{-0.0001}(\text{par})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

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

$\rightarrow$ two SM parameters are simultaneously determined from these data to high precision with only weak correlation between them ($\rho = 0.3$) + constraints on PDFs (next slides)

Simultaneous PDF + α_s + m_t^{pole} fit: correlation between α_s and gluon

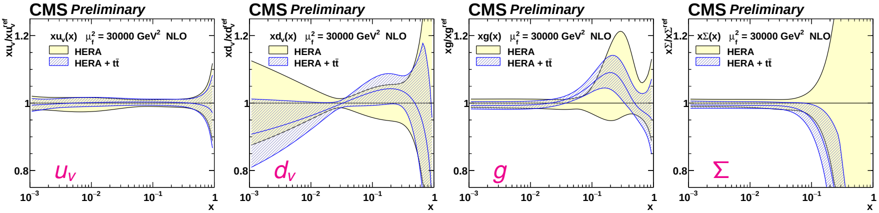




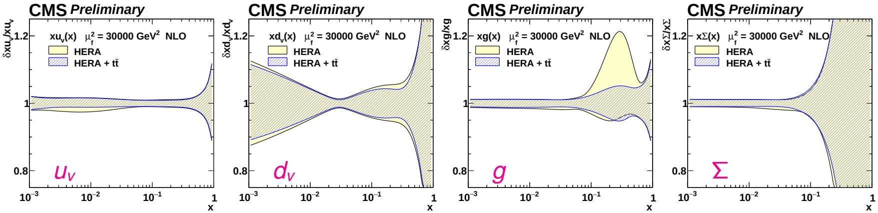
Adding $t\bar{t}$ data:

- constrain α_s (left)
- reduce correlation between α_s and gluon (g) (right)
  - weak correlation (α_s,m_t) $\rightarrow$ weak correlation (g,m_t)

PDFs (α_s in HERA-only fit set to $\alpha_s = 0.1135 \pm 0.0016$)



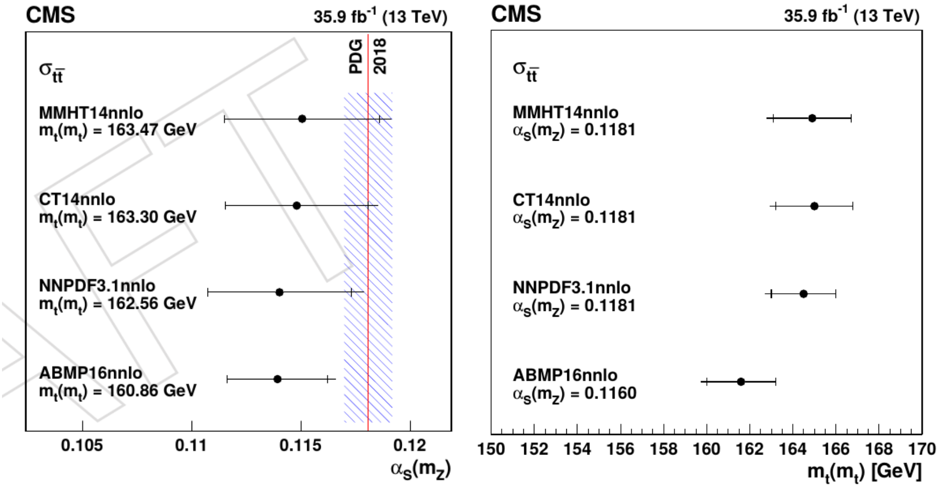
Relative PDF uncertainties



→ reduced g uncertainty at high x

→ smaller impact on other distributions via correlations in the fit

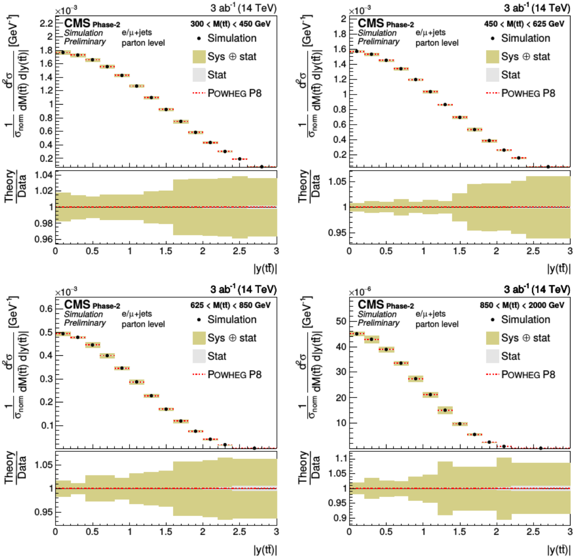
Extraction of α_s and m_t from total $t\bar{t}$ cross section [arXiv:1812.10505]



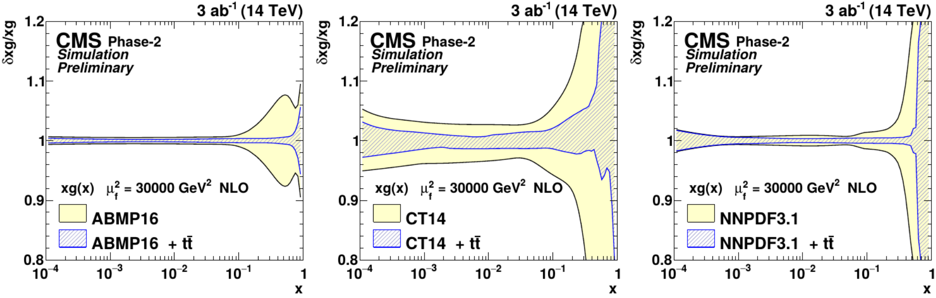
- α_s and $m_t(m_t)$ extracted from the total $t\bar{t}$ cross section at NNLO using different PDF sets
- Theoretical predictions obtained using Hathor interfaced in xFitter
- Furthermore, m_t^{pole} extracted at NNLO+NNLL using Top++

PDF constraints from double-differential $t\bar{t}$ cross sections [1902.04070]

- Presented projection of CMS differential $t\bar{t}$ cross section measurements in e/μ+jets channel with 3 ab^{-1} at 14 TeV



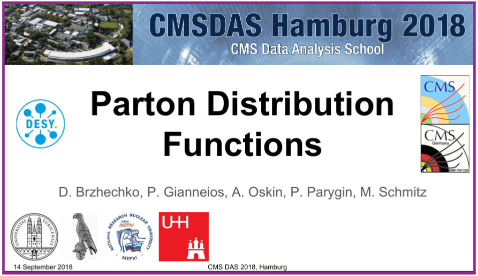
PDF constraints from double-differential $t\bar{t}$ cross sections [1902.04070]

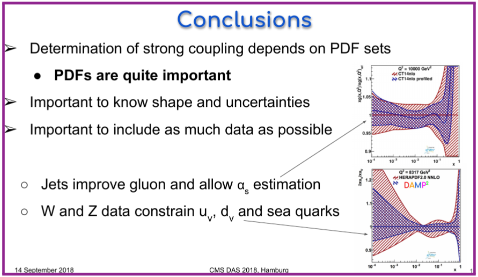


- PDF constraints from differential $t\bar{t}$ cross sections as functions of $M(t\bar{t})$ and $y(t\bar{t})$ are estimated using profiling technique implemented in xFitter

  $\rightarrow$ strong impact on gluon PDF at high x in any modern PDF set

- xFitter was presented at CMS Data Analysis School at DESY in September 2018
- The exercises were about getting familiar with PDF fitting using xFitter and studying impact of CMS measurements on PDFs
- The team of young people (new to xFitter) created a “new PDF set“ in two days





Summary

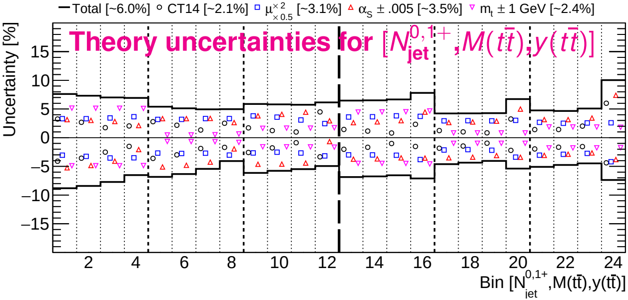
- New CMS measurements of $t\bar{t}$ and W+c production facilitate improved determination of proton PDFs
- xFitter as unique open source platform for PDF fitting plays crucial role in data interpretation
- New CMS analyses provide and exploit new developments in xFitter:
  - 3D $t\bar{t}$ measurement used recent developments in xFitter theory interface
  - new reaction (KMatrix) was implemented in the context of this analysis
- Future synergy between xFitter team and experimental collaborations is important to fully reveal potential of LHC data

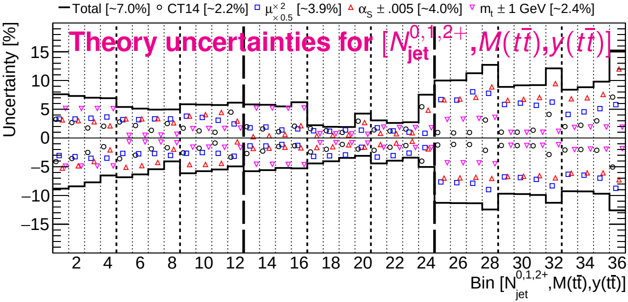
BACKUP

NLO calculations

- NLO predictions for inclusive $t\bar{t}$, $t\bar{t}$ + 1 jet and $t\bar{t}$ + 2 jets are computed and compared to data using MadGraph5_aMC@NLO + aMCfast + ApplGrid + xFitter:
  - $[N_{\rm jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ with 2 $N_{\rm jet}$ bins:
    - ⋆ $\sigma^{\rm NLO}(N_{\rm jet} = 0) = \sigma^{\rm NLO}(t\bar{t}) - \sigma^{\rm NLO}(t\bar{t} + 1\text{jet})$
    - ⋆ $\sigma^{\rm NLO}(N_{\rm jet} > 0) = \sigma^{\rm NLO}(t\bar{t} + 1\text{jet})$
  - $[N_{\rm jet}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$ with 3 $N_{\rm jet}$ bins:
    - ⋆ $\sigma^{\rm NLO}(N_{\rm jet} = 0) = \sigma^{\rm NLO}(t\bar{t}) - \sigma^{\rm NLO}(t\bar{t} + 1\text{jet})$
    - ⋆ $\sigma^{\rm NLO}(N_{\rm jet} = 1) = \sigma^{\rm NLO}(t\bar{t} + 1\text{jet}) - \sigma^{\rm NLO}(t\bar{t} + 2\text{jets})$
    - ⋆ $\sigma^{\rm NLO}(N_{\rm jet} > 1) = \sigma^{\rm NLO}(t\bar{t} + 2\text{jets})$
- $\mu_{\rm r} = \mu_{\rm f} = H'/2$, $H' = \sum_i m_{T,i}$ where the sum runs over all final-state partons (t, $\bar{t}$ and up to three light partons in the $t\bar{t} + 2$ jets calculations) and $m_T = \sqrt{m^2 + p_T^2}$. Uncertainties:
  - $\mu_{\rm r}, \mu_{\rm f}$ are varied by factor 2 (6 variations in total)
  - alternative functional form $\mu_{\rm r} = \mu_{\rm f} = H/2$, $H = \sum_i m_{T,i}$ with the sum runs over t and $\bar{t}$
- $m_t^{\rm pole} = 172.5 \pm 1$ GeV (sometimes ± 5 GeV for presentation purposes)
- PDFs and α_s from several groups via LHAPDF, $\alpha_s \pm 0.001$ for uncertainties (sometimes ± 0.005 for presentation purposes)
- multiplied with non-perturbative corrections ($< 5\%$) from parton to particle jet level (BACKUP)

Data and theory uncertainties $[N_{\mathbf{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$





- Bins are grouped for $y(t\bar{t})$, $M(t\bar{t})$ and N_{jet} (separated by different vertical lines)
- NLO scale uncertainties are comparable to PDF, α_s and m_t uncertainties

  → data can constrain PDF, α_s and m_t
- Scale uncertainties are considerably smaller for $[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$

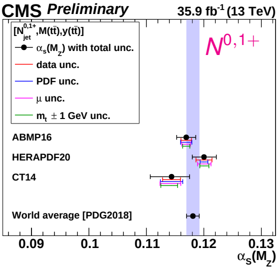
  → $[N_{\text{jet}}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$ is used for cross check only

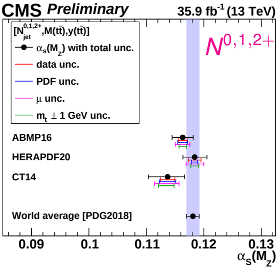
Cross checks of α_s and m_t^{pole} extraction (all results in backup):

- using $[N_{\text{jet}}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$
- using single-differential N_{jet}, $M(t\bar{t})$ or $y(t\bar{t})$ cross sections
- using $[p_T(t\bar{t}), M(t\bar{t}), y(t\bar{t})]$ cross sections with 2 $p_T(t\bar{t})$ bins
- using unnormalised cross sections

→ consistent results obtained in all cross checks

→ in this analysis, observables ($\frac{1}{\sigma}\frac{d\sigma}{d\ldots}$) have been chosen to have **maximum sensitivity to QCD paramaters and minimum experimental and scale uncertainties**

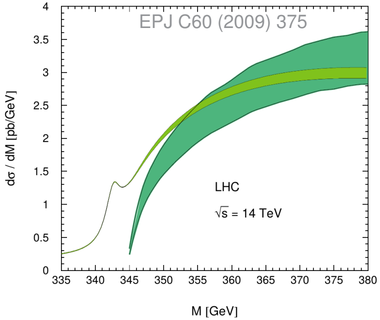


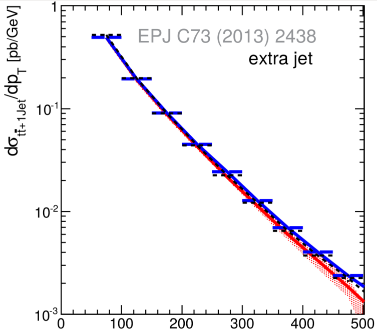


Remarks on limitations in theory calculations

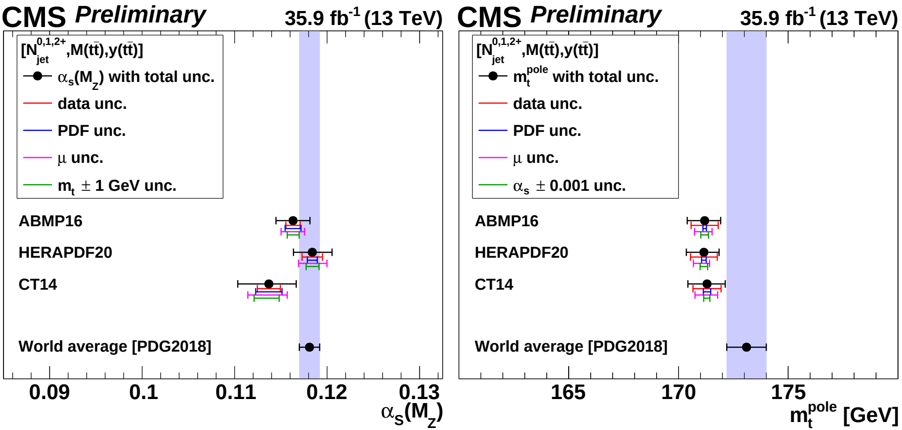
NLO is the only available theory publicly available today, but there are limitations:

- impact of missing threshold resummation is $\Delta m_t \sim 0.7$ GeV [Eur.Phys.J. C60 (2009) 375]
- impact of missing FSR resummation is $\Delta m_t \sim 0.5$ GeV [Eur. Phys. J. C73 (2013) 2438]
  - in general, good agreement between NLO and NLO+PS [Fig. 1 in Eur. Phys. J. C73 (2013) 2438]
- EW corrections could be a few % near threshold [Phys. Rev. D91 (2015) 014020] [JHEP10 (2017) 186]
- **most wanted is NNLO QCD**

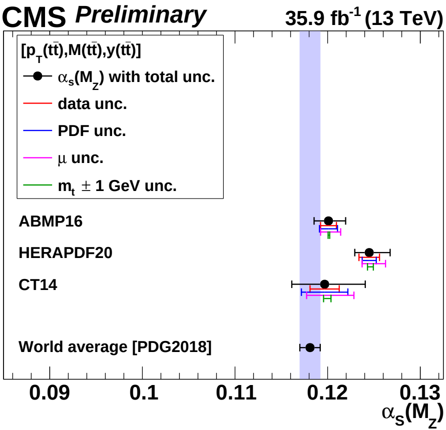


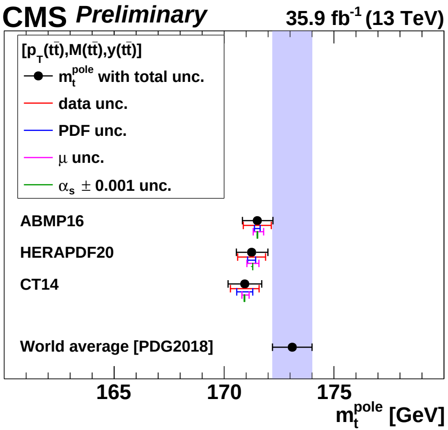


α_s and m_t^{pole} from $[N_{jet}, mtt, y(t\bar{t})]$ with 3 N_{jet} bins

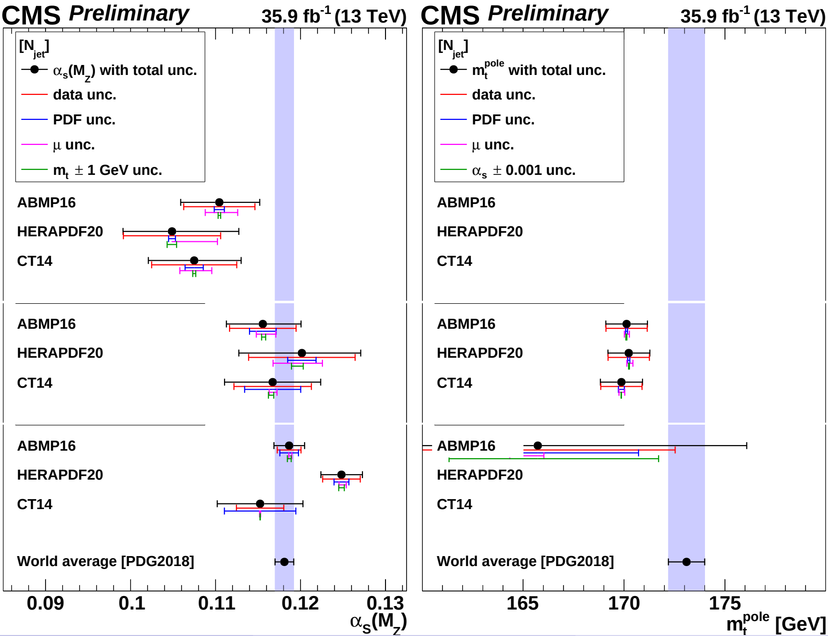


α_s and m_t^{pole} from $[p_T(t\bar{t}), mtt, y(t\bar{t})]$ with 2 $p_T(t\bar{t})$ bins





α_s and m_t^{pole} from single-differential cross sections



Simultaneous PDF+$\alpha_s + m_t^{\text{pole}}$ fit: settings

- followed standard approach: using HERA DIS data only, or HERA + $t\bar{t}$ data to demonstrate added value from $t\bar{t}$ on PDF and α_s determination
- settings follow HERAPDF2.0 fit (very similar to TOP-14-013), use xFitter-2.0.0
- input data: combined HERA DIS [1506.06042] + $t\bar{t}$
- RTOPT, $M_c = 1.47$ GeV, $M_b = 4.5$ GeV, $Q^2_{\text{min}} = 3.5^{+1.5}_{-1.0}$ GeV^2
- predictions fot $t\bar{t}$ data via MadGraph5_aMC@NLO + aMCfast + ApplGrid, $\mu_r = \mu_f = H_t/4, H_t = \sqrt{m_t^2 + (p_T(t))^2} + \sqrt{m_t^2 + (p_T(\bar{t}))^2}$ varied by factor 2
  - dependence on α_s and scales written in ApplGrid tables
  - dependence on m_t^{pole}derived by linear interpolation between tables generated with different values of m_t^{pole}(new feature for xFitter)
  - kinematic range probed by $t\bar{t}$: $x = (M(t\bar{t})/\sqrt{s}) \exp\left[\pm y(t\bar{t})\right] \Rightarrow 0.01 \lesssim x \lesssim 0.1$
- 15-parameter form (backup) determined using parametrisation scan (one extra g parameter required by $t\bar{t}$ data) at $Q_0^2 = 1.9$ GeV^2, $f_s = 0.4 \pm 0.1$
- DGLAP NLO PDF evolution via QCDNUM-17.01.14
- PDF uncertainties: fit ($\Delta\chi^2 = 1$ via HESSE, cross checked with MC replica method), model and parametrisation; in addition for α_s and m_t^{pole}scale uncertainties for $t\bar{t}$ are considered

Simultaneous PDF, α_s and m_t^{pole} fit: PDF parametrisation

Determined using parametrisation scan:

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

- additional gluon parameyter (E_g) required by new $t\bar{t}$ data
- PDF parametrisation uncertainties given by $A'_g = 0$ (13p) and $E_g = 0$ (14p), and $Q_0^2 = 1.9 \pm 0.3$ GeV^2 variation