Multi-Differential top quark pair ($t\bar{t}$) cross sections and parameter extractions

ZPW2020 workshop, Zurich, 14 Jan 2020

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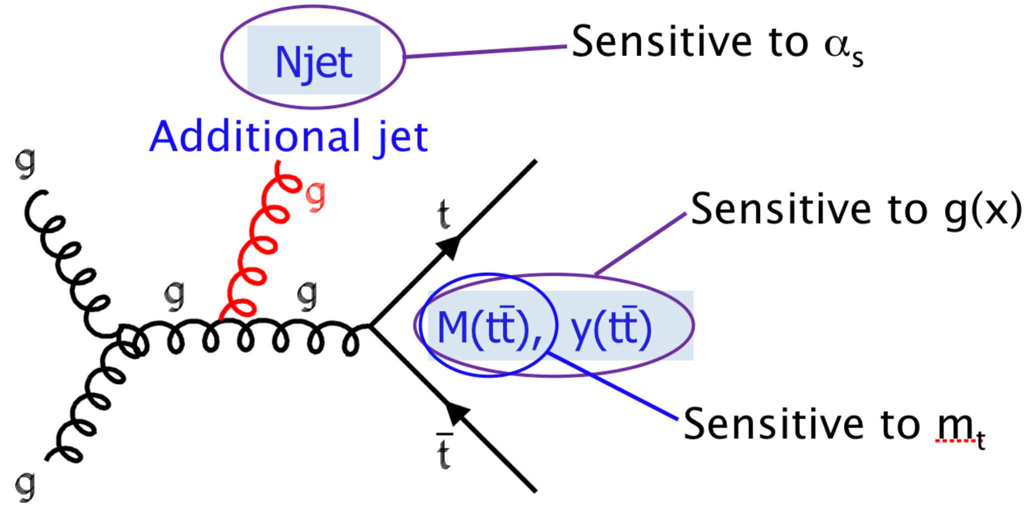
Multi-Differential $t\bar{t}$ cross sections $d^m\sigma_{t\bar{t}}$ with $m \geq 2$

$d^m\sigma_{t\bar{t}}$ vs kinematical & event topological observables:

✓ QCD+EW Test

✓ Sensitive to theory pars



Today's menu:

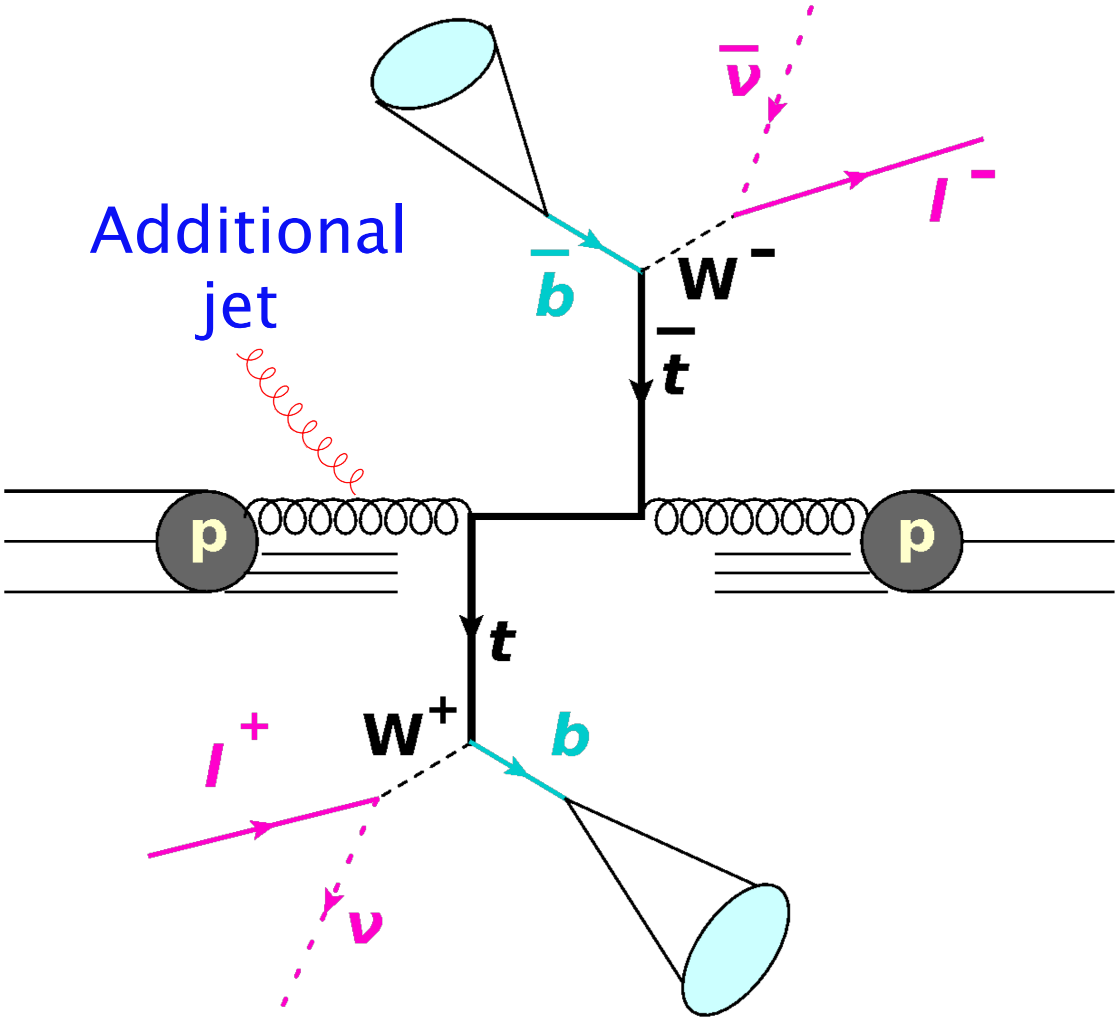
Selected 2016 data analyses in Dilepton ($t\bar{t} \to bl^+\nu\ \bar{b}l^-\bar{\nu}$) and Lepton+Jets ($t\bar{t} \to bl^+\nu\ \bar{b}jj$) channels:

1. CMS Dilepton TOP-18-004 (arXiv:1904.05237)
   - 2D and *3D* $t\bar{t}$ xsecs and *NLO extraction of α_s, m_t^{pole} & PDFs*
2. ATLAS Lepton+Jets EPJC 79 (2019) 2018:
   - 2D $t\bar{t}$ xsecs versus *up to NNLO QCD predictions*
3. ATLAS Dilepton ATLAS-CONF-2019-041 (arXiv:1910.08819)
   - Inclusive $\sigma_{t\bar{t}}$ and *lepton differential distributions*

1. CMS Dilepton $t\bar{t}$ analysis

TOP-18-004 (arXiv:1904.05237)

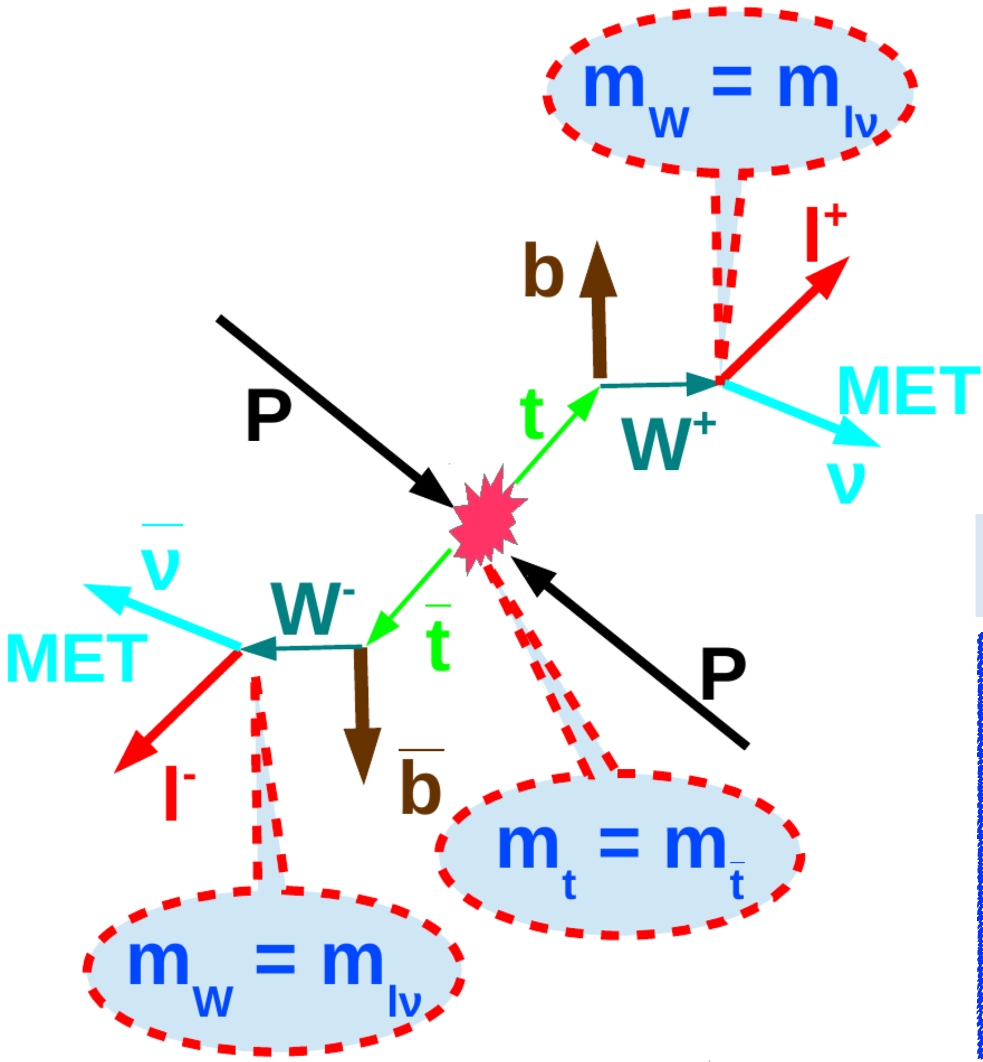
Event selection



Follows 1D measurement:
CMS-TOP-17-014 (arXiv:1811.06625)

- Leptons:
  - 2 Isolated $l^{\pm}l^{\mp}$ (e or μ)
  - p_T>25(20) GeV
  - |η|<2.4
- Jets:
  - at least 2 jets
  - p_T>30 GeV
  - |η|<2.4
  - at least 1 b-tagged

Kinematic reconstruction



- Input: leptons, jets, **MET**
- Unknowns: $\mathbf{p}_\nu$, $\mathbf{p}_{\bar{\nu}}$ (6)
- Constraints:
  - m_t, $m_{\bar{t}}$ (2)
  - m_{W^+}, m_{W^-} (2)
  - $(\mathbf{p}_\nu + \mathbf{p}_{\bar{\nu}})_T$ = **MET** (2)

Two reconstruction variants:

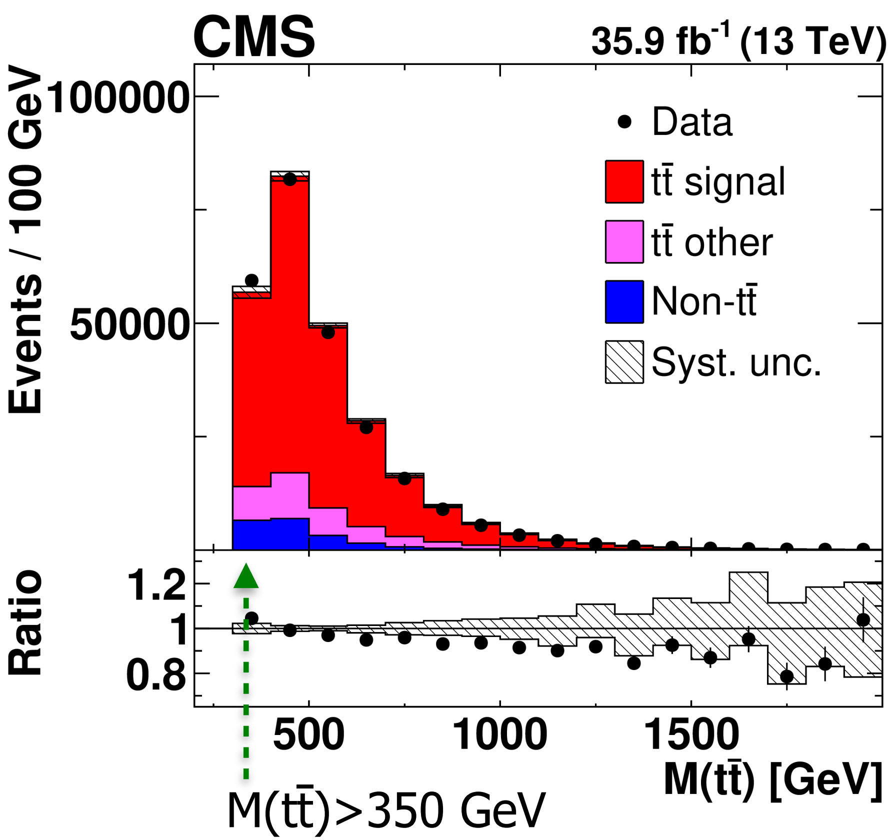
(1) Full:
- Use all constraints → $\mathbf{p}_t$, $\mathbf{p}_{\bar{t}}$

(2) Loose:
- Omit m_t constraints → $\mathbf{p}_{t\bar{t}}$
  → reliable for m_t^{pole} extraction

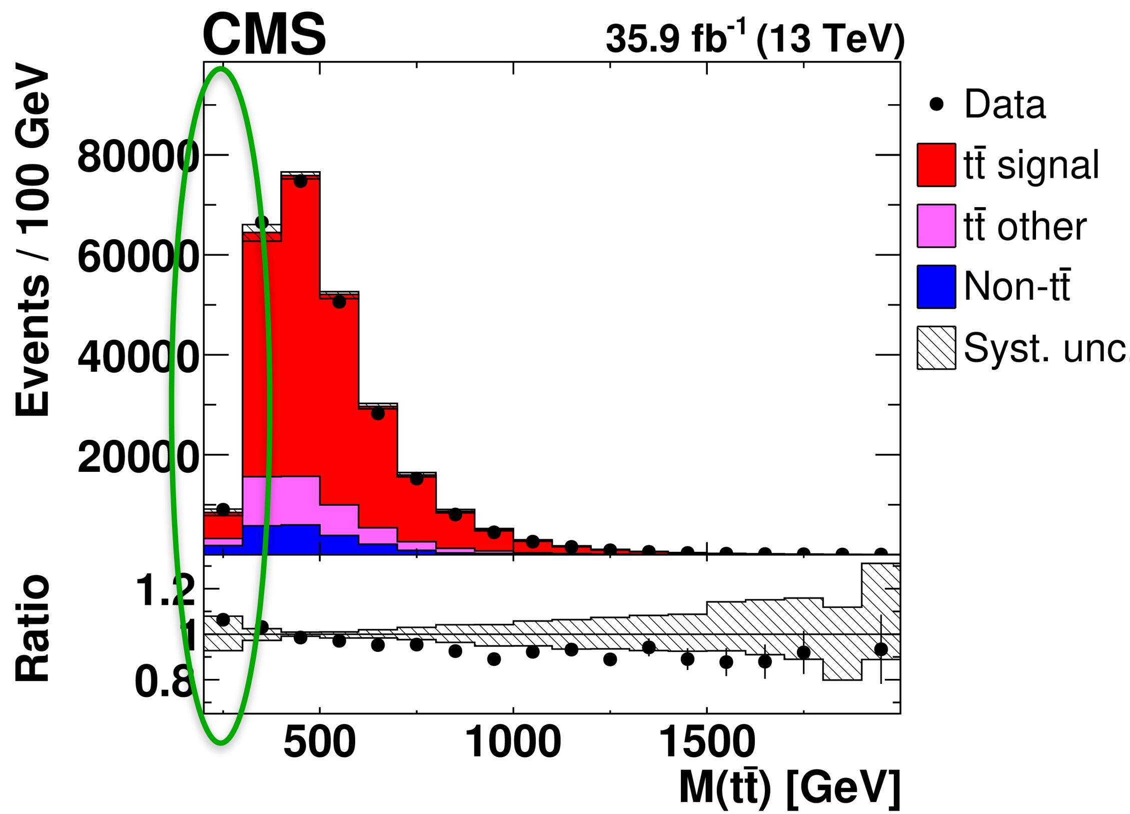
Kinematic distributions

$t\bar{t}$ signal MC: POWHEGV2 + PYTHIA8

Full Reco



Loose Reco



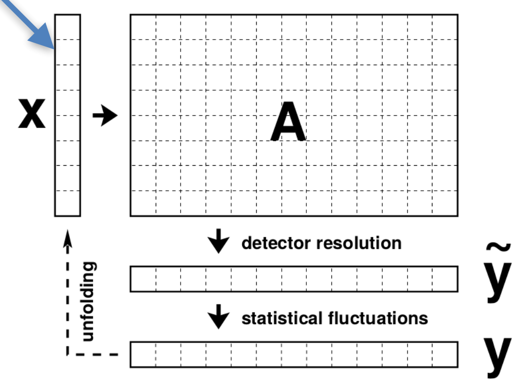
- ⇨ with loose reco "see" onset of $t\bar{t}$ production
- ⇨ Nominal MC predicts harder M($t\bar{t}$) spectrum, ~ok within uncert.

Overview of measured cross sections $1/\sigma_{t\bar{t}} \cdot d^m\sigma_{t\bar{t}}$

Xsecs

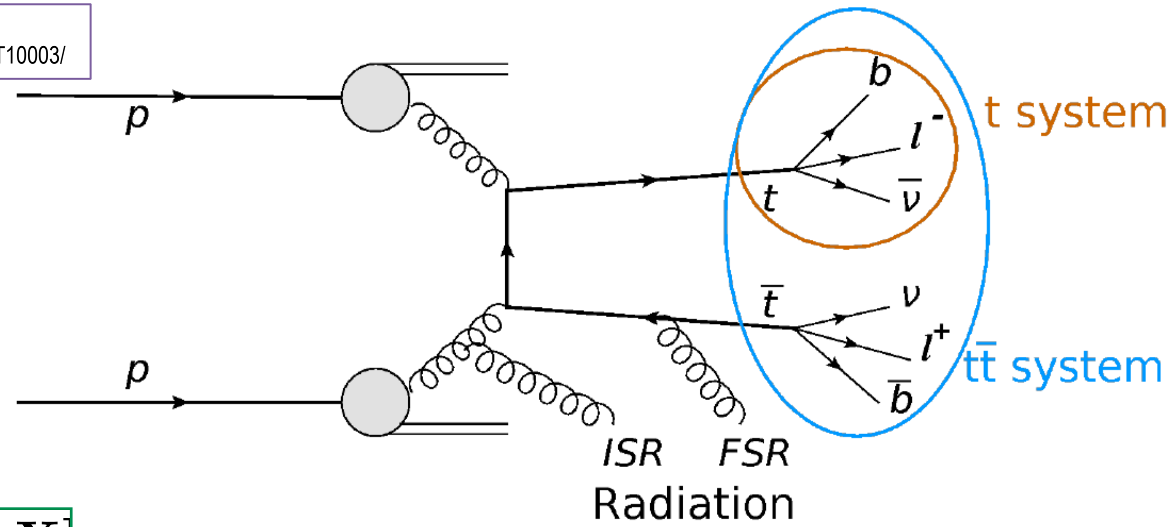
TUnfold

http://www.desy.de/~sschmitt/tunfold.html
http://iopscience.iop.org/1748-0221/7/10/T10003/



Detector level signal distribution

⇒



Min. $\chi^2 = [\mathbf{y} - \mathbf{AX}]^t \, \mathbf{V_y}^{-1} \, [\mathbf{y} - \mathbf{AX}]$

ATLAS uses in **EPJC 79 (2019) 2018** 'iterative Bayesian unfolding', see slides of my talk comparing ATLAS & CMS analysis statistical procedures
https://indico.cern.ch/event/843509/contributions/3625979/attachments/1945277/3227403/obehnke191115.pdf

2D

- t production:
  - [y(t),p_T(t)]: most simple
- tt̄ production:
  - [M(tt̄),y(tt̄)]: sensitive to PDFs
  - [M(tt̄),p_T(tt̄)]: sensitive to radiation
- t, tt̄ mixed:
  - [M(tt̄),y(t)]: sensitive to PDFs
  - [M(tt̄),Δϕ(t,t̄)]: sensitive to radiation
  - ☆ [M(tt̄),p_T(t)]:
  - ☆ [M(tt̄),Δη(t,t̄)]:

  } p_T(t) problem

3D

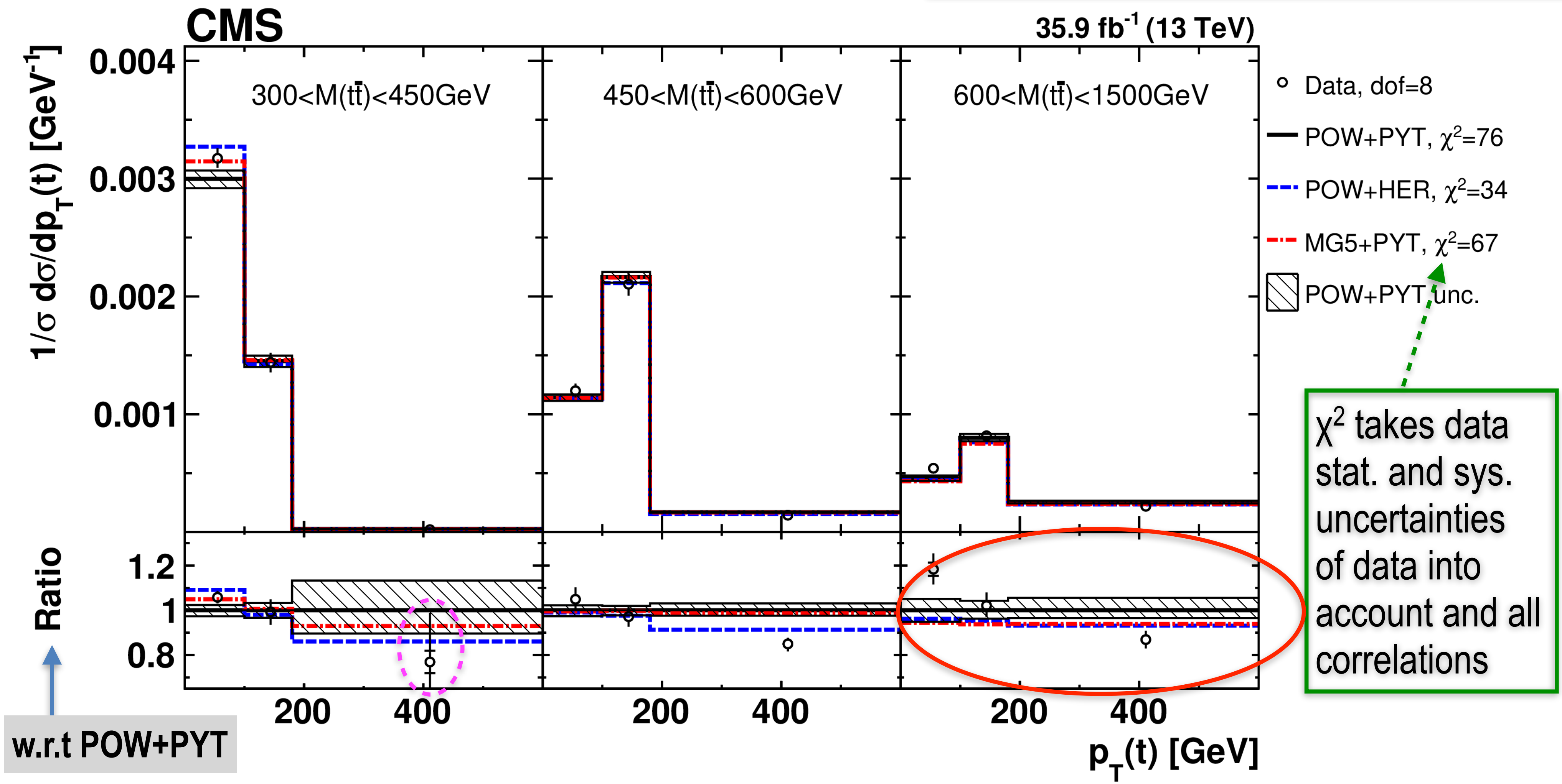
- NEW: tt̄ production with extra jets:
  - ☆ [$N_{jet}^{0,1+}$,M(tt̄),y(tt̄)]:
  - ☆ [$N_{jet}^{0,1,2+}$,M(tt̄),y(tt̄)]:

  } sensitive to α_S, m_t^{pole} and PDFs

Cross sections defined at parton level for tt̄ (before t decay) but particle level for extra jets

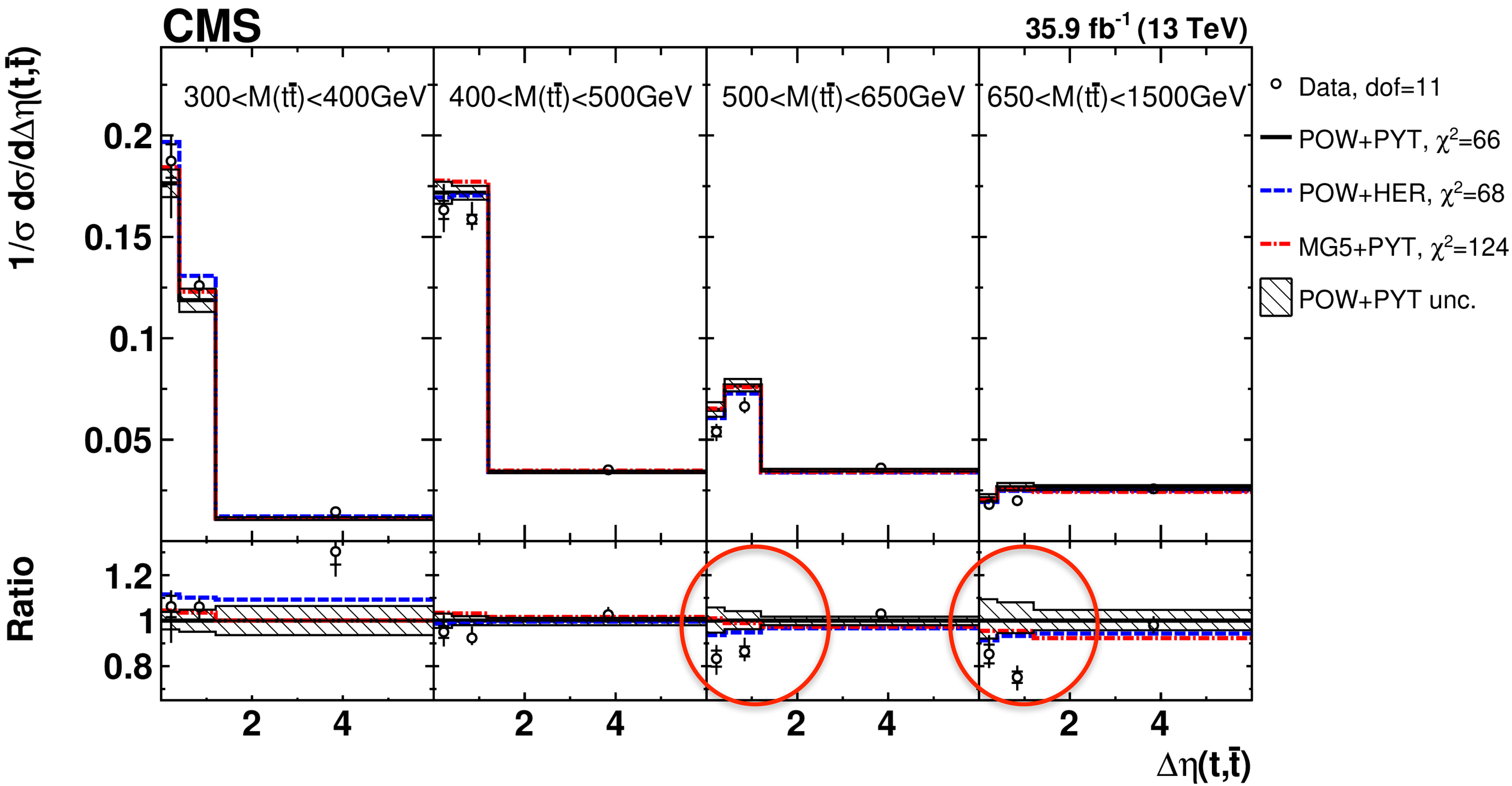
Results: 2D x-sections [$M(t\bar{t}), p_T(t)$]

- 'POW+PYT' = POWHEGV2+PYTHIA8, CUETP8M2T4
- 'POW+HER' = POWHEGV2+HERWIG++, EE5C
- 'MG5+PYT' = MG5_aMC@NLO+PYTHIA8 [FxFx], CUETP8M2T4



⇨ All MCs predict too hard $p_T(t)$ for larger $M(t\bar{t})$

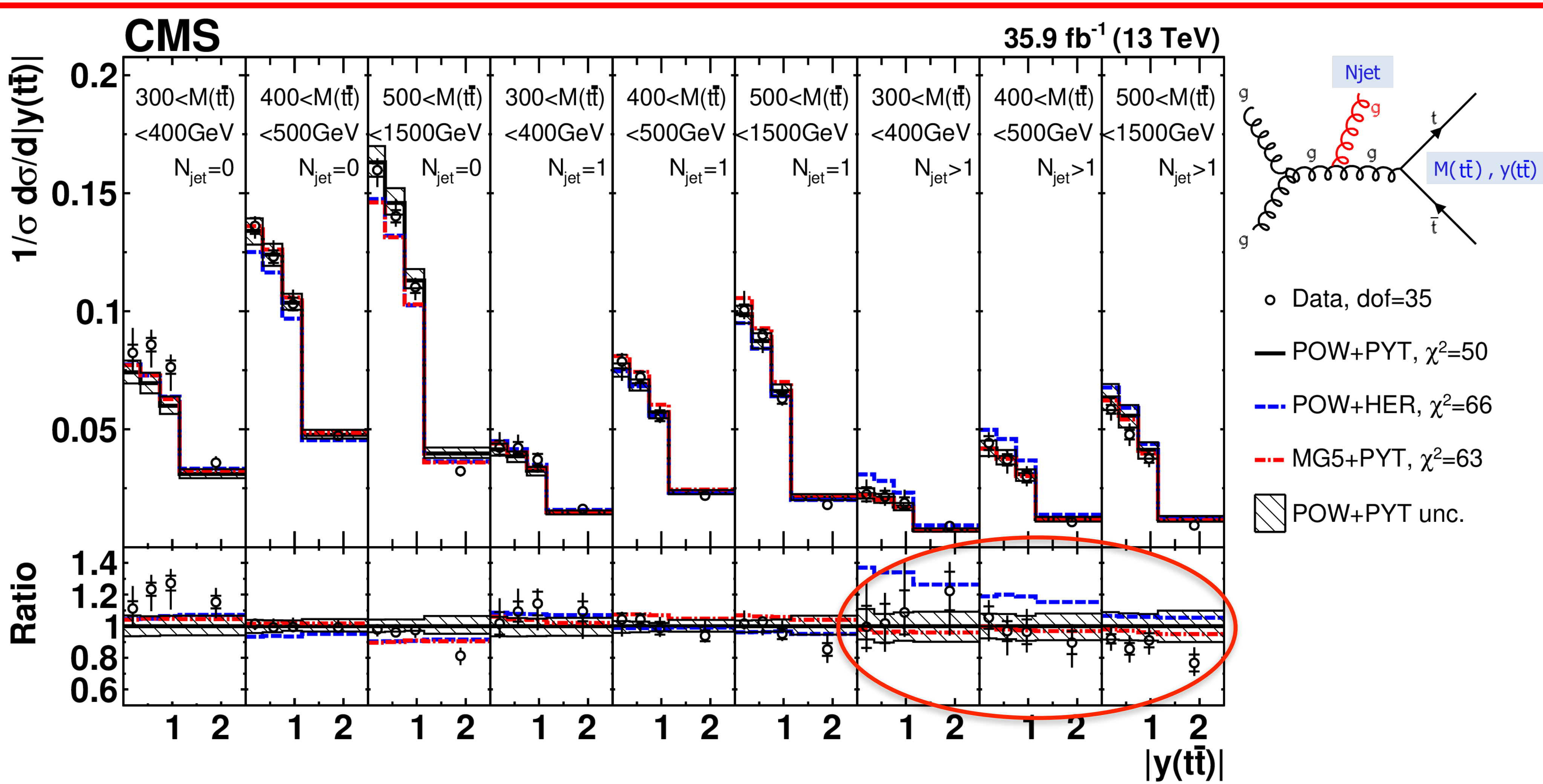
Results: 2D x-sections [$M(t\bar{t}),\Delta\eta(t,\bar{t})$]



⇨ All MCs predict smaller $\Delta\eta(t,\bar{t})$ for larger $M(t\bar{t})$

Note: small $\Delta\eta(t,\bar{t})$ ⟺ harder $p_T(t)$

Results: 3D x-sections [$N_{jet}^{0,1,2+}$, $M(t\bar{t})$, $y(t\bar{t})$]



⇨ 'POW+PYT' provides best description

⇨ 'POW+HER' predicts too many events with $N_{jet}>1$

Extraction of theory parameters consists of two parts

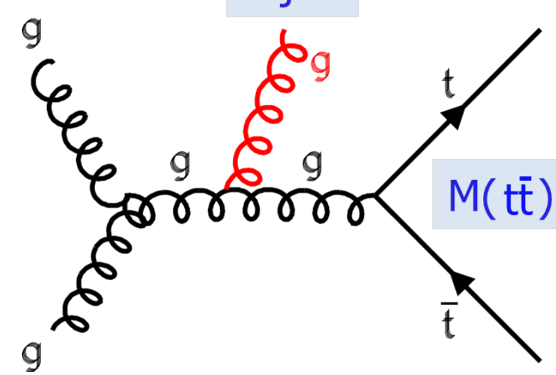
(1) Compare theory vs $t\bar{t}$ data using external PDF sets:

- Extracting α_s keeping m_t^{pole} fixed
- Extracting m_t^{pole} keeping α_s fixed

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

- Fully consistent extraction — Could be exemplary for future global fits

NLO calculation for $d^3\sigma_{t\bar{t}}$



Fixed order NLO predictions using
MadGraph5_aMC@NLO+aMCfast+ApplGrid+xFitter

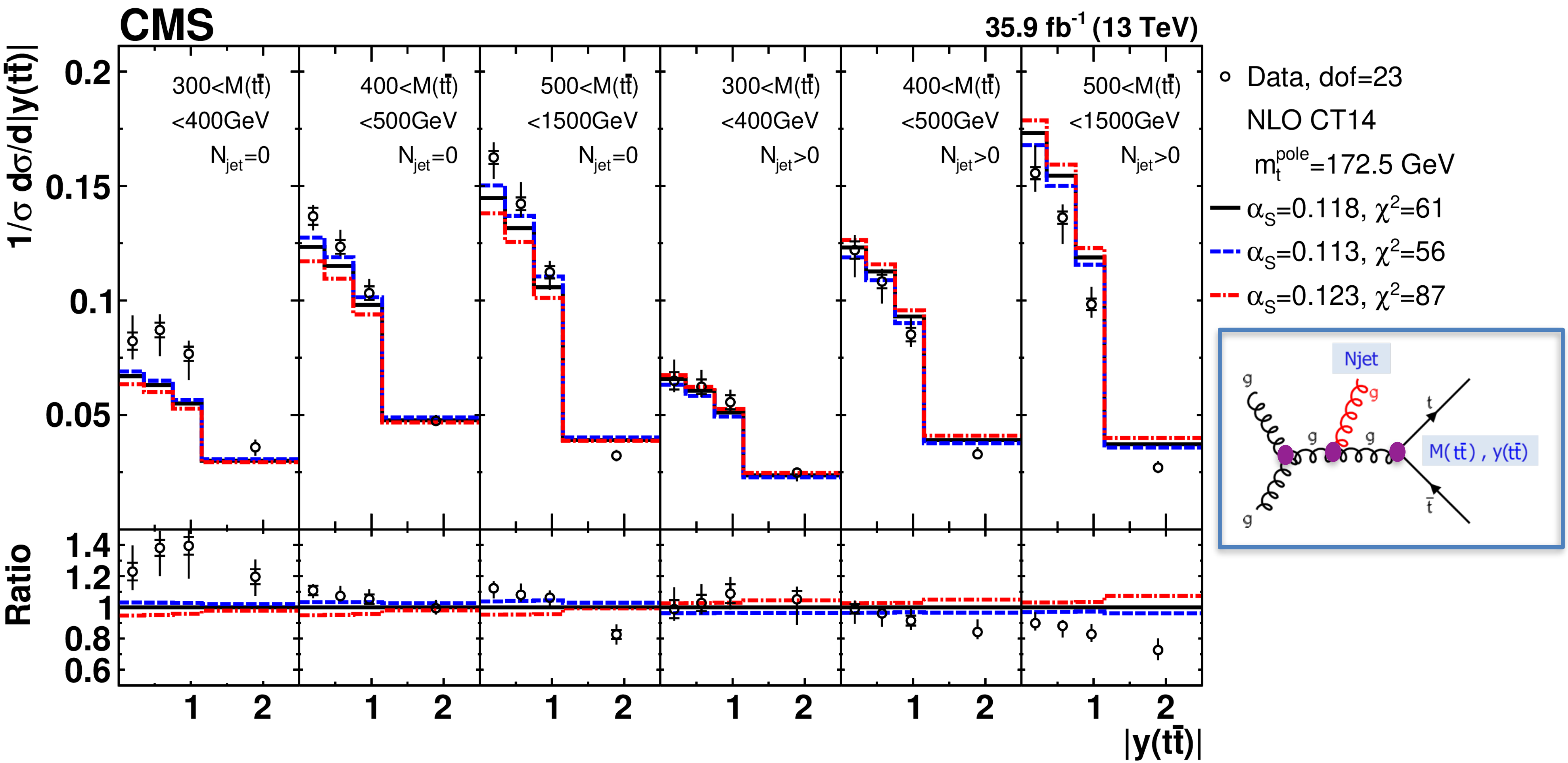
$\sigma_{t\bar{t}}$ vs [Njets, M(tt), y(tt)] calculations:

σ^{NLO}(Njets ≥0)	Mangano, Nason, Ridolfi, NPB 373 (1992) 295	$O(\alpha_s^3)$
σ^{NLO}(Njets ≥1)	Dittmaier, Uwer, Weinzierl, PRL 98 (2007) 262002	$O(\alpha_s^4)$
σ^{NLO}(Njets ≥2)	Bevilacqua, Czakon, Papadopoulos and Worek, PRL 104 (2010) 162002, PR D 84 (2011) 114017	$O(\alpha_s^5)$

Details

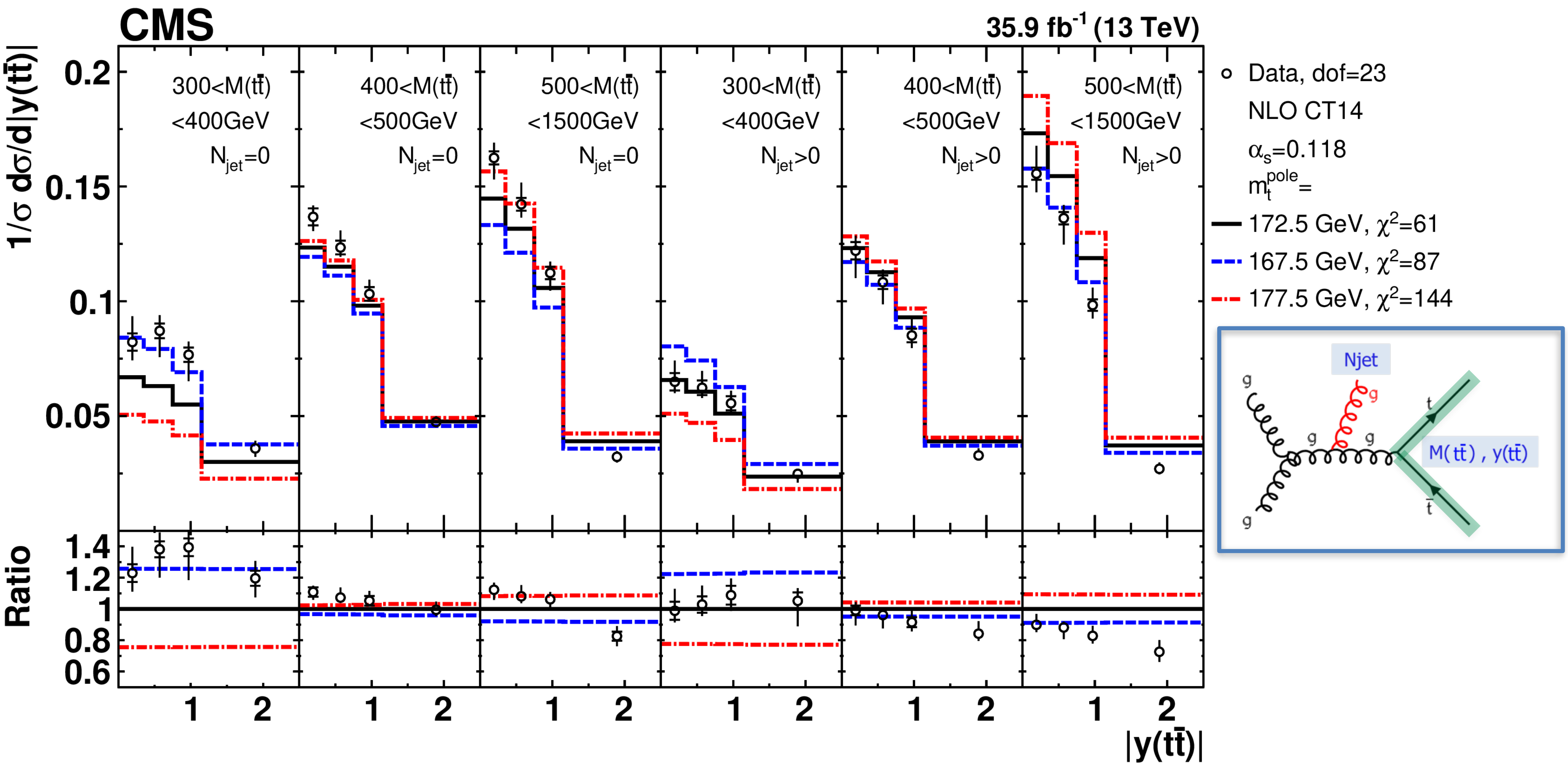
- **$\mu_r = \mu_f = H'/2$, $H' = \Sigma_i\, m_{T,i}$, sum is over all final state partons**
- **μ_r, μ_f varied by factor 2 (6 variations in total)**
- m_t^{pole} = 172.5 ± 1 GeV
- PDFs and α_s from several groups via LHAPDF, vary α_s ±0.001 for uncertainties
- Multiplied with non-perturbative corrections (<5%) from parton to particle level

Results: [$N_{jet}^{0,1+}$, $M(t\bar{t})$, $y(t\bar{t})$] vs NLO with different α_s



→ α_s sensitivity comes mainly from different N_{jet} bins

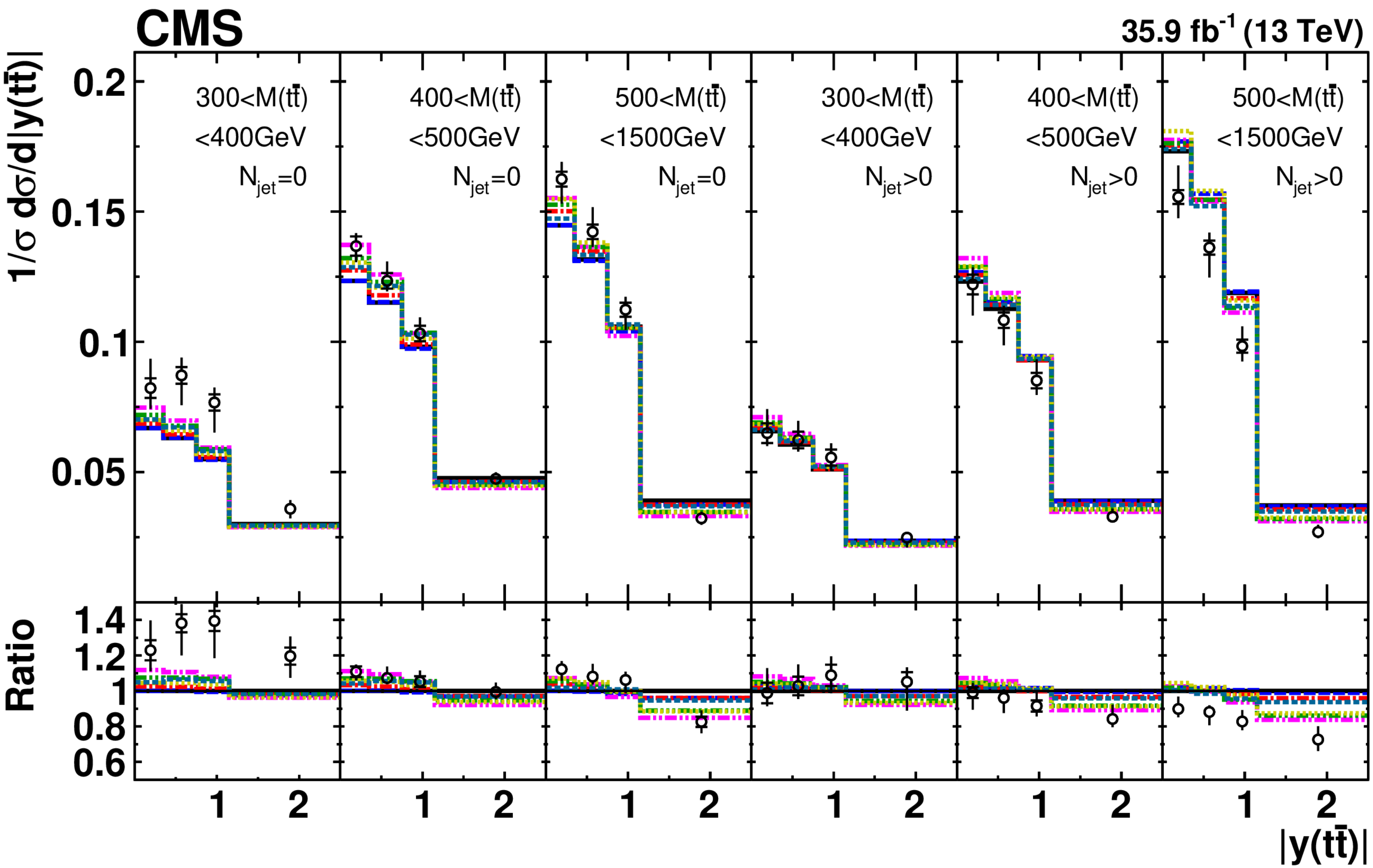
Results: $[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ vs NLO with diff. m_t^{pole}

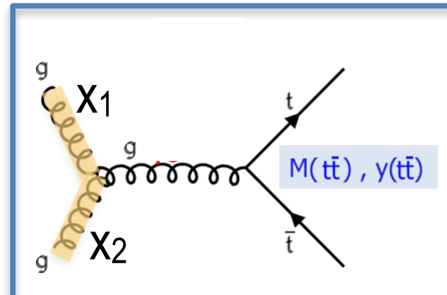


→ m_t^{pole} sensitivity mainly from first $m(t\bar{t})$ bin

- *m_t^{pole} extraction technique follows: D0 results* **[FERMILAB-CONF-16-383-PPD]**

Results: [$N_{jet}^{0,1+}$, $M(t\bar{t})$, $y(t\bar{t})$] vs NLO with diff. PDFs





$x_{1,2} = (M(t\bar{t})/\sqrt{s}) \exp\left[\pm y(t\bar{t})\right]$

$\chi^2 = \chi^2_{nom}$ ($\chi^2_{\text{with PDF unc.}}$)

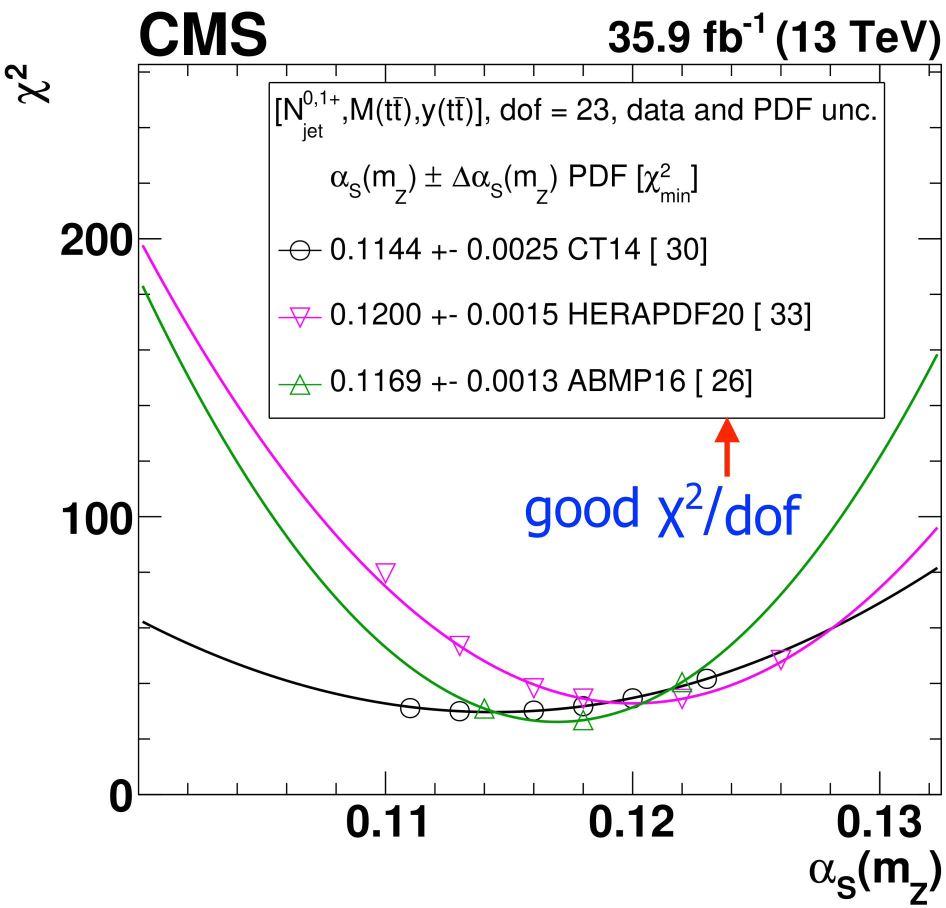
→ Sensitivity to PDFs

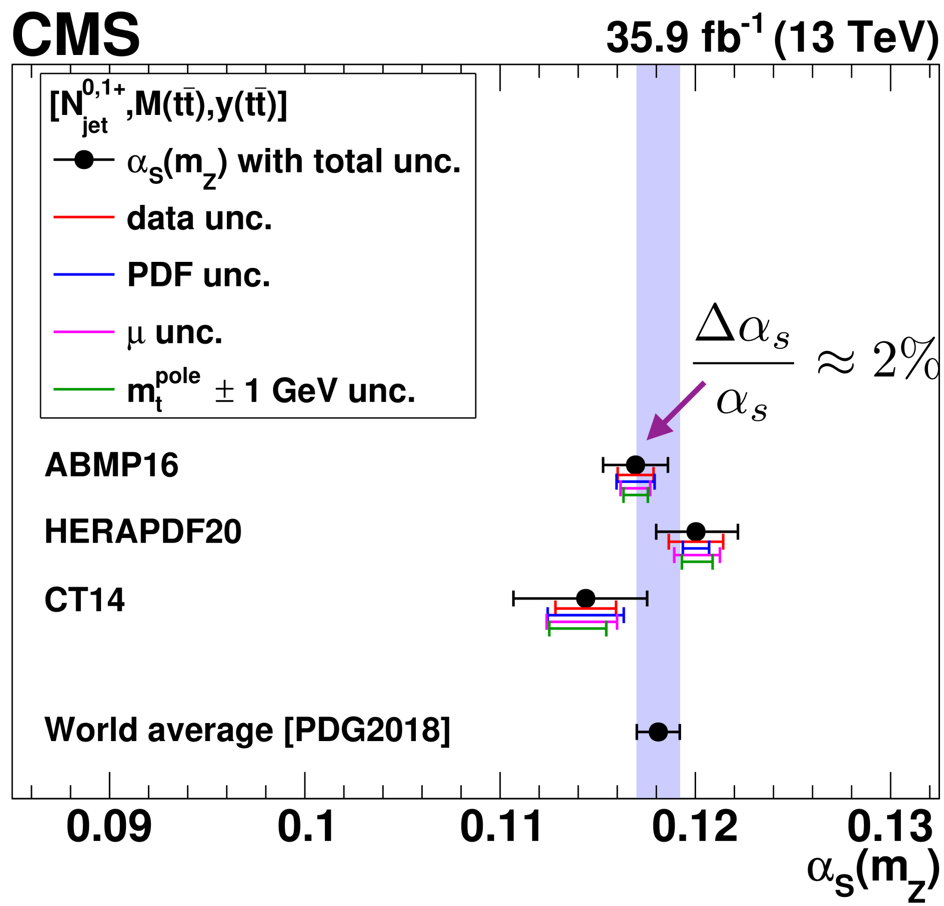
→ PDFs already using other more inclusive $t\bar{t}$ data:

MMHT2014, NNPDF3.1, ABMP16

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

Use m_t^{pole} = 172.5 GeV in ME for all PDF sets



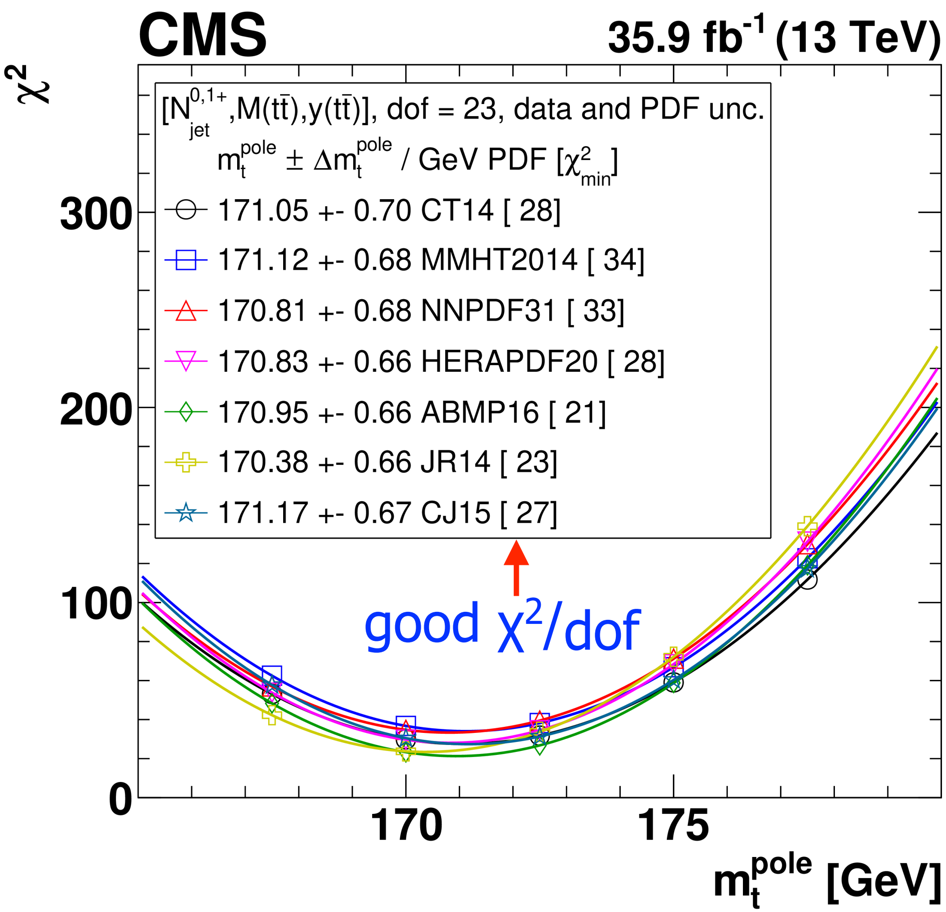


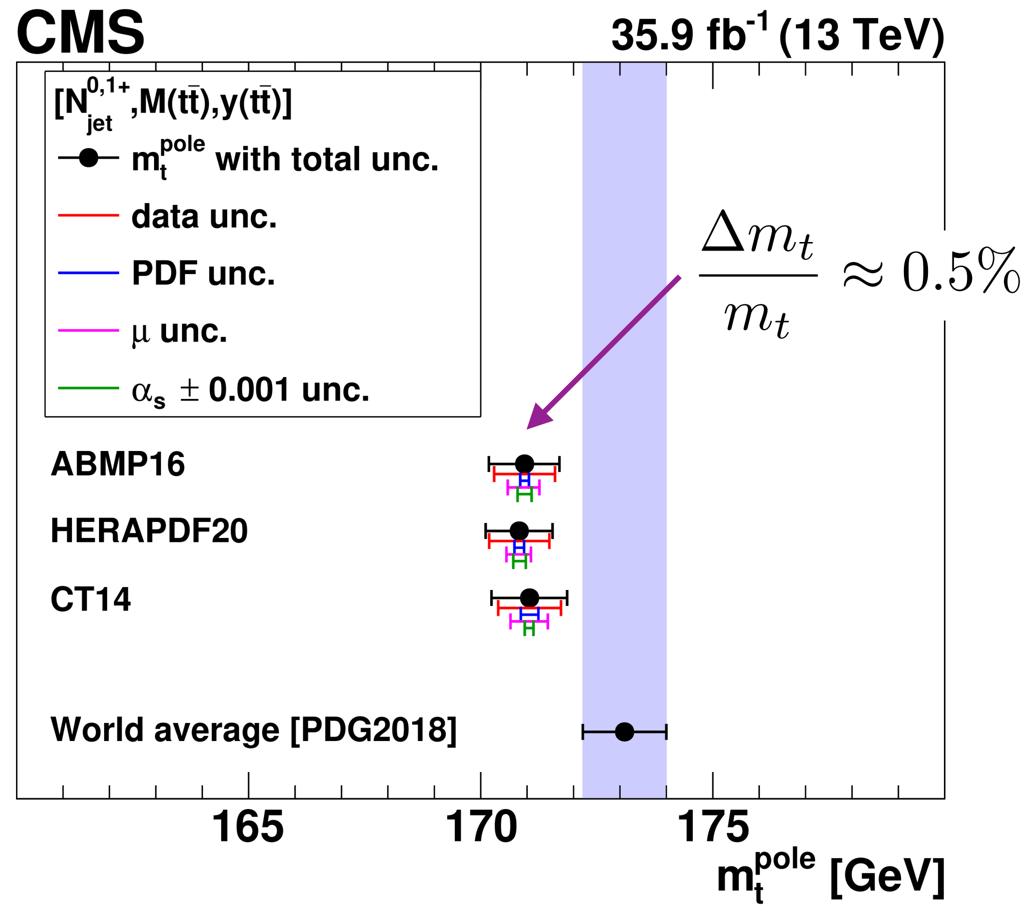
→ Precise determination of α_s using these data

→ Dependence on PDF set (correlation between g and α_s)

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

Use α_s from each PDF set (α_s = 0.118 in CT and HERAPDF, α_s = 0.119 in ABPM)



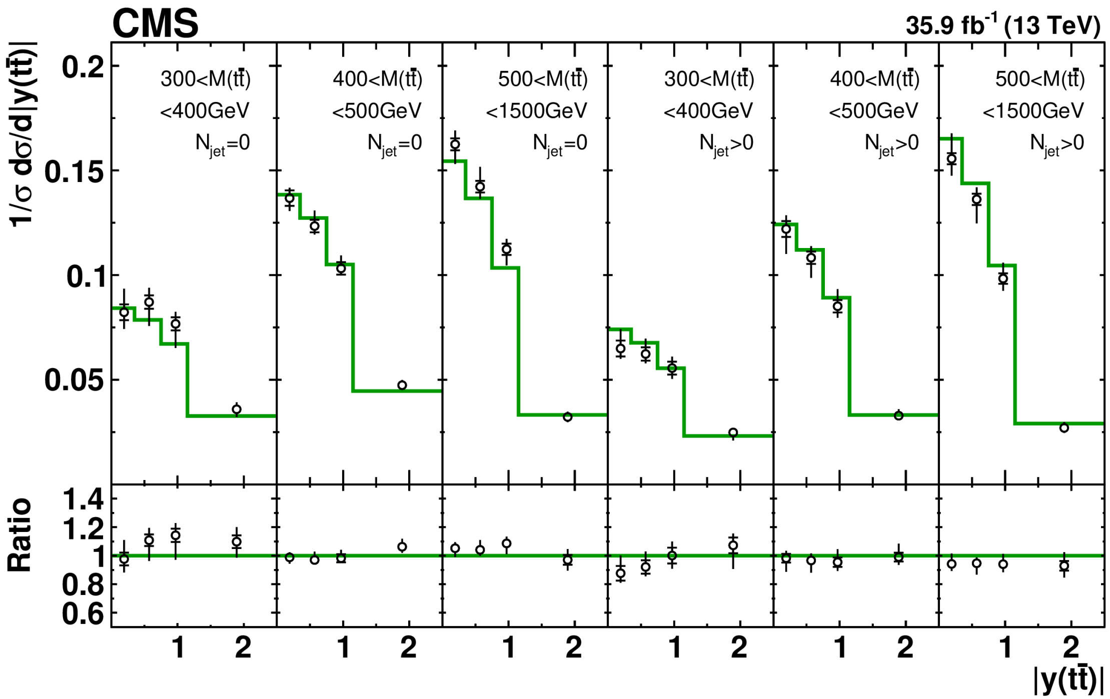


→ Precise determination of m_t^{pole}

→ Small dependence on PDF set

Simultaneous α_s, m_t^{pole} and PDF fit

- Using HERA DIS data [1506.06042] + our new $d^3\sigma_{t\bar{t}}$ data
- Use xFitter-2.0.0, HERAPDF2.0 settings



∘ Data, dof=23

— NLO fit, χ^2=20

Good fit!

$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

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

→ Two SM parameters determined precisely, weak correlation (ρ=0.3)

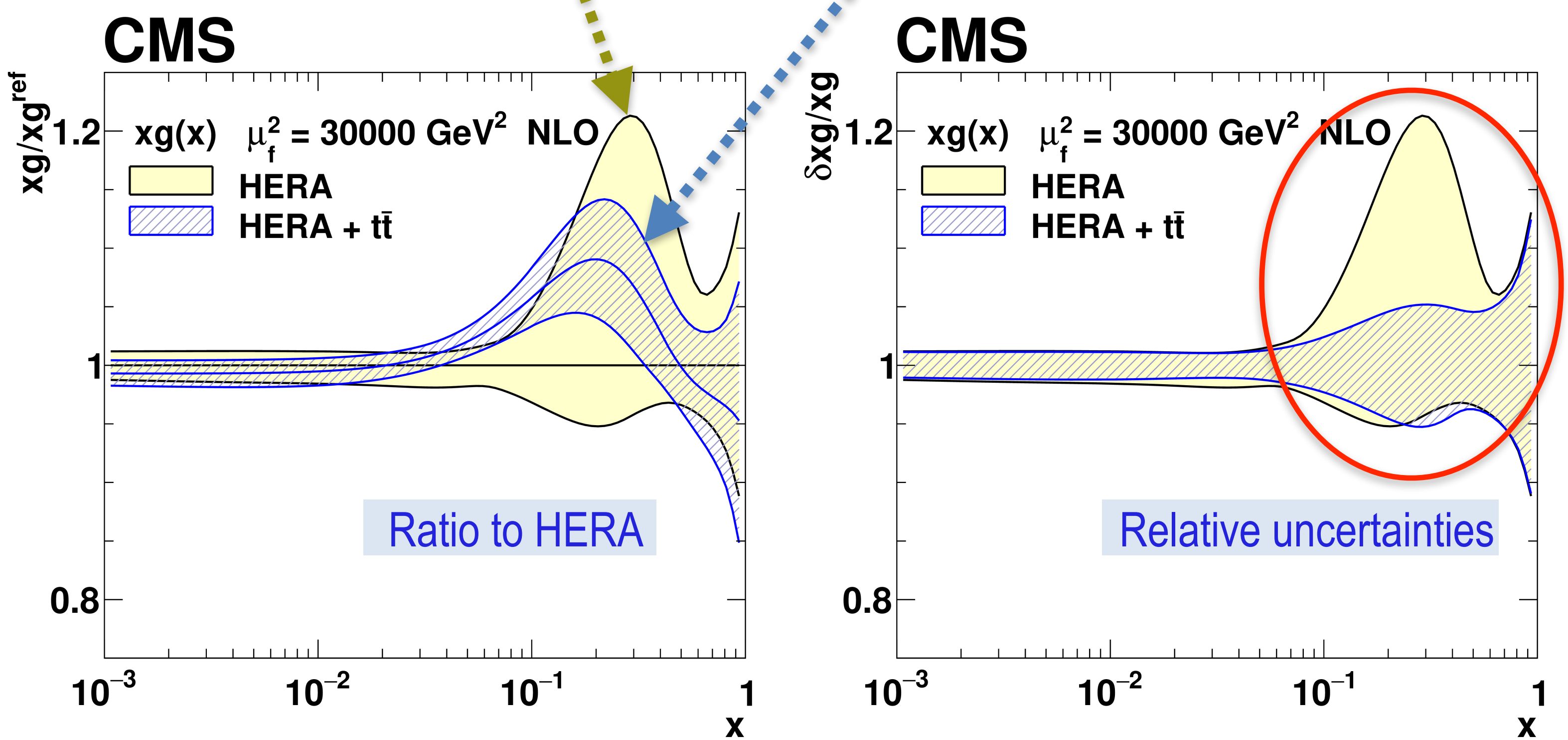
Simultaneous α_s, m_t^{pole} & PDF fit

PDF Parametrisation at Q_0^2=1.9 GeV^2

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

Gluon density results:

- Fit to HERA DIS only and including 3D $t\bar{t}$ data

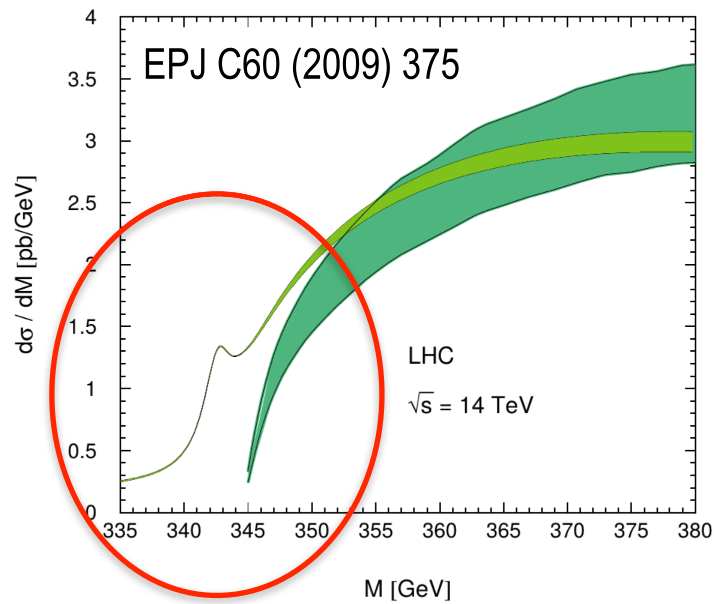


→ Reduced gluon density uncertainty at large x~0.1-0.4

Limitations in the used NLO theory calculations

NLO is only publicly available theory tool, but it has it limitations:

- Near threshold calculation with soft gluon resummation **[EPJ C60 (2009) 375]**
  → $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~+1%, attributing this to our first $M(t\bar{t})$ bin would lead to Δm_t ~0.7 GeV



- Impact of missing FSR resummation is Δm_t ~0.5 GeV **[EPJ C73 (2013) 2438]**
- EW corrections could be few% near threshold **[PR D91 (2015) 014020] [JHEP10 (2017) 186]**
- Most wanted is NNLO QCD

Dilepton vs. Lepton+Jets $d^m\sigma_{t\bar{t}}$ analyses ($m\geq2$)

ATLAS and CMS analyses using 2016 data ($L\sim36\ fb^{-1}$)

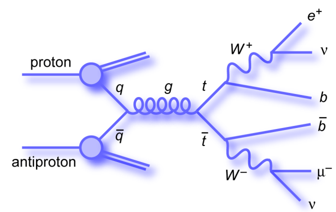
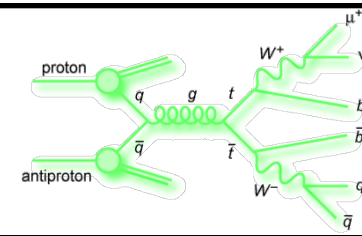
	Dilepton	Lepton+Jets
Diagram		
Analyses	• **CMS: arXiv:1908.07305**	• **ATLAS: EPJC 79 (2019) 2018** • **CMS: Phys. Rev. D97, 112003 (2018)**
$t\bar{t}$ signal events	~200.000	500.000 -1.200.000
Background fraction	~5-10%	~5-10%
Dominant backgrounds	tW	single t, Multijets, W+jets
$t\bar{t}$ reconstruction main challenge	determine $\mathbf{p}_\nu$ and $\mathbf{p}_{\bar{\nu}}$	~40% events with particle- to detector-level unmatched jets
Kinematic reach	$p_T(t)$<600 GeV	$p_T(t)$ <~1 (2) TeV resolved (boosted)
Normal. x-secs total uncert.	~3-15%	~3-15%
Dominating uncert.	syst.	syst.
Largest syst. uncert.	$t\bar{t}$ MC physics modelling	$t\bar{t}$ MC physics modelling
Largest exp. syst. uncert.	JES/JER	JES/JER, background

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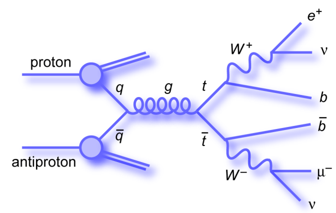
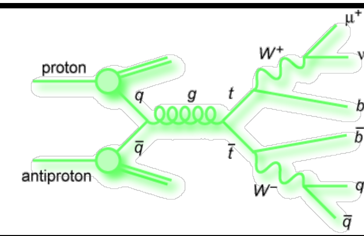
Diagram		
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Dominating uncert.	syst.	syst
Largest syst. uncert.	$t\bar{t}$ MC phy	modelling
Largest exp. syst. uncert.	JES/JER	kground

Overall ~comparable performance

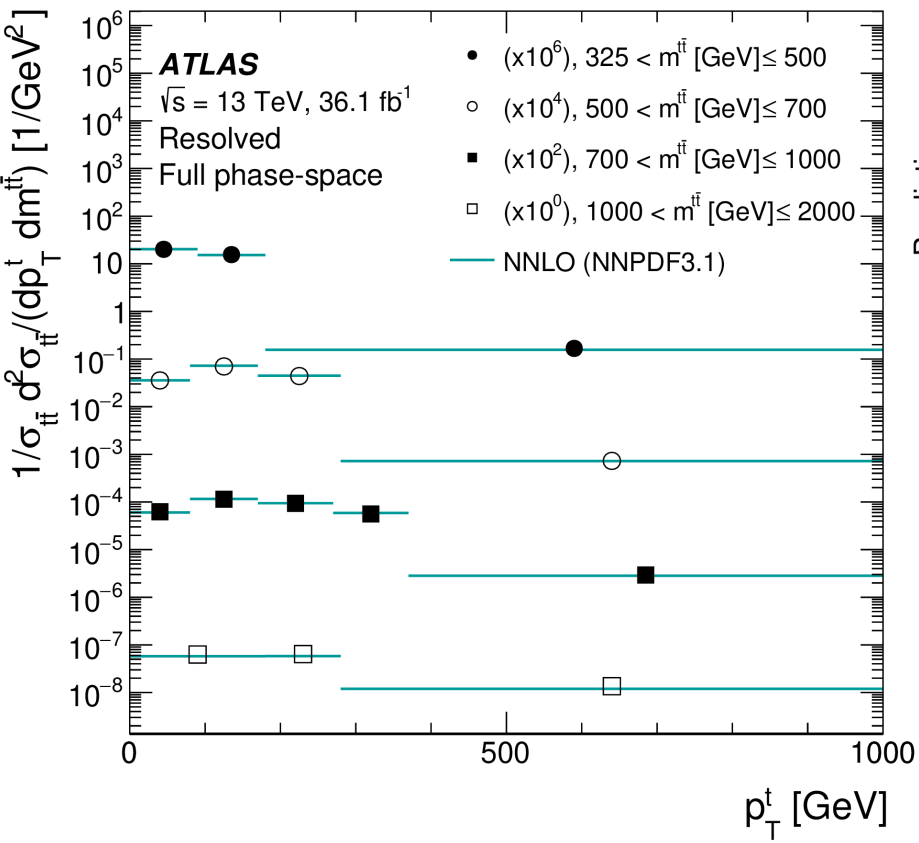
2. ATLAS Lepton+Jets $t\bar{t}$ analysis

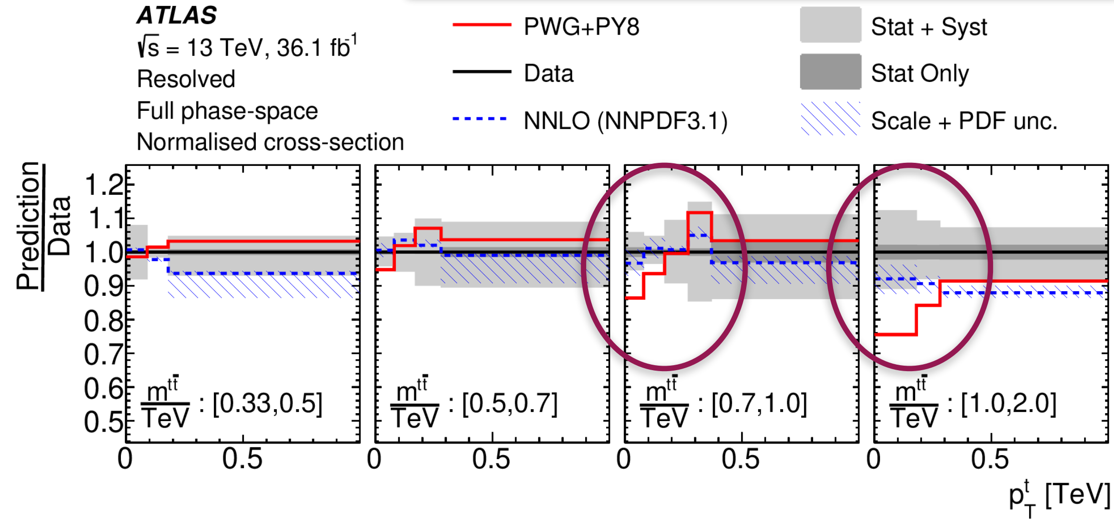
EPJC 79 (2019) 2018

Show only few selected x-section results at Parton level, many more in the paper, also particle level measurements

Results: 2D x-sections vs [$M(t\bar{t}), p_T(t)$]

- PWG+PY8': POWHEGv2+PYTHIA8, A14 tune
- NNLO: Czakon, Heymes, Mitov: PRL 116 082003 (2016), arXiv:1511.0054, JHEP 04, 071 (2017), arXiv:1606.03350





studied 2d x-sections at parton level

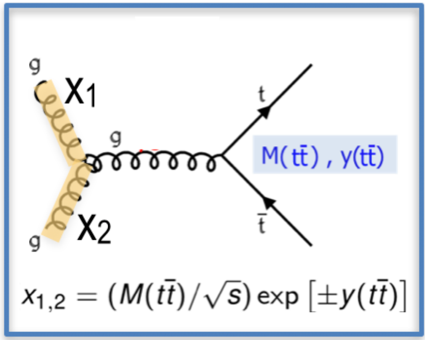
χ^2 with taking only data uncert. into account:

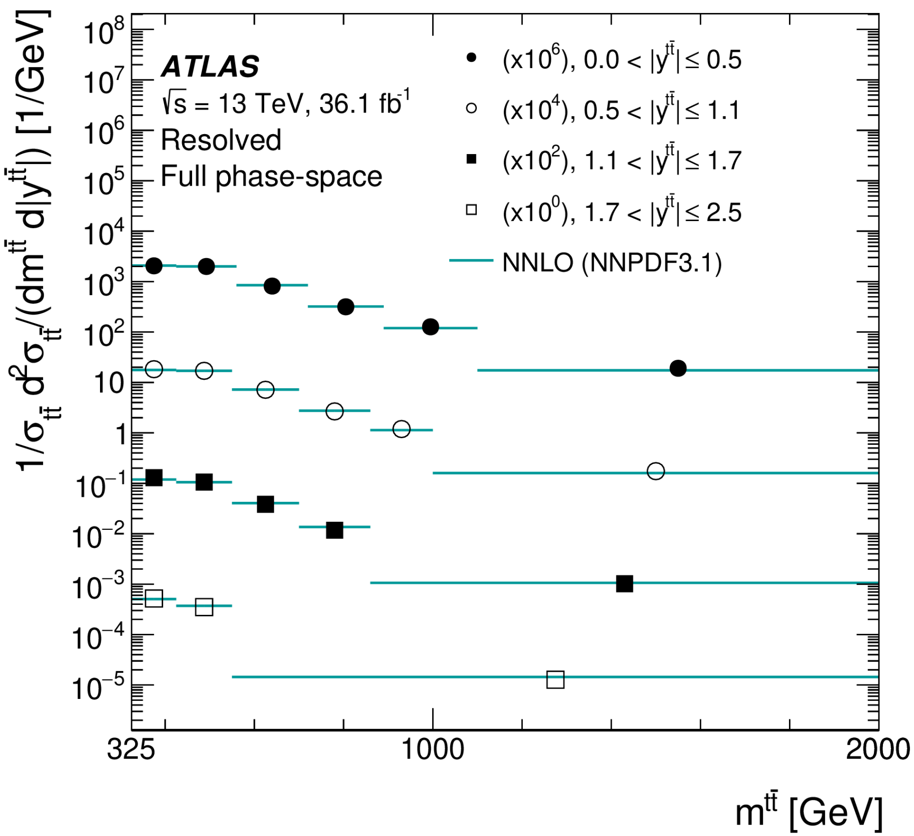
Observable	NNPDF31 NNLO χ^2/NDF	NNPDF31 NNLO p-value	PWG+PY8 χ^2/NDF	PWG+PY8 p-value
$\lvert y^t\rvert$ vs p_T^t	25.4/12	0.01	30.9/12	<0.01
$\lvert y^{t\bar{t}}\rvert$ vs $m^{t\bar{t}}$	39.9/19	<0.01	51.8/19	<0.01
$\lvert y^{t\bar{t}}\rvert$ vs $p_T^{t\bar{t}}$	15.9/13	0.26	17.6/13	0.17
$m^{t\bar{t}}$ vs p_T^t	55.7/14	<0.01	64.4/14	<0.01
$m^{t\bar{t}}$ vs $p_T^{t\bar{t}}$	40.6/16	<0.01	62.6/16	<0.01
$p_T^{t\bar{t}}$ vs $p_T^{t,\mathrm{had}}$	22.2/16	0.14	37.4/16	<0.01

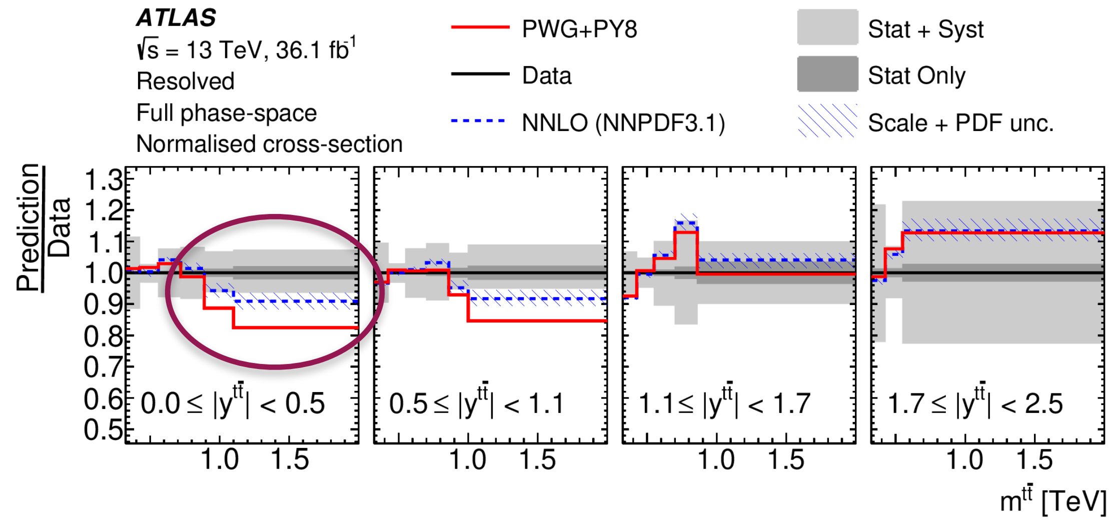
→ POWEG+PYTHIA8 predict too hard $p_T(t)$ for larger $M(t\bar{t})$

→ NNLO improves descriptions (though not perfect)

Results: 2D cross sections vs [M($t\bar{t}$),y($t\bar{t}$)]







χ^2 with taking only data uncert. into account:

Observable	NNPDF31 NNLO χ^2/NDF	NNPDF31 NNLO p-value	PWG+PY8 χ^2/NDF	PWG+PY8 p-value
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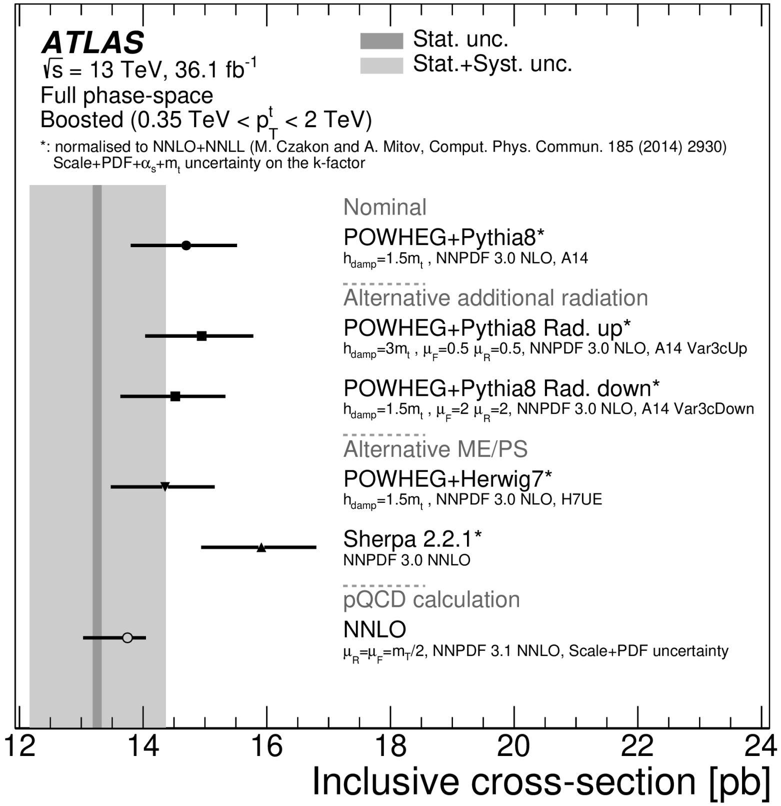
$\lvert y^{t\bar{t}}\rvert$ vs $m^{t\bar{t}}$	39.9/19	<0.01	51.8/19	<0.01
$\lvert y^{t\bar{t}}\rvert$ vs $p_{\mathrm{T}}^{t\bar{t}}$	15.9/13	0.26	17.6/13	0.17
$m^{t\bar{t}}$ vs p_{T}^{t}	55.7/14	<0.01	64.4/14	<0.01
$m^{t\bar{t}}$ vs $p_{\mathrm{T}}^{t\bar{t}}$	40.6/16	<0.01	62.6/16	<0.01
$p_{\mathrm{T}}^{t\bar{t}}$ vs $p_{\mathrm{T}}^{t,\mathrm{had}}$	22.2/16	0.14	37.4/16	<0.01

→ Models predict softer M($t\bar{t}$) for central y($t\bar{t}$)
→ Data have potential for constraining PDFs

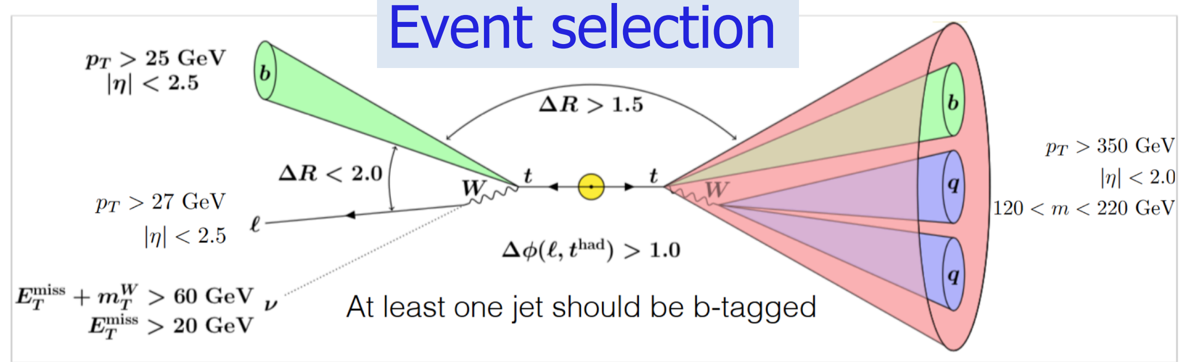
Results *Boosted tops* $p_T(t)>350$ GeV

$\sigma_{t\bar{t}}$

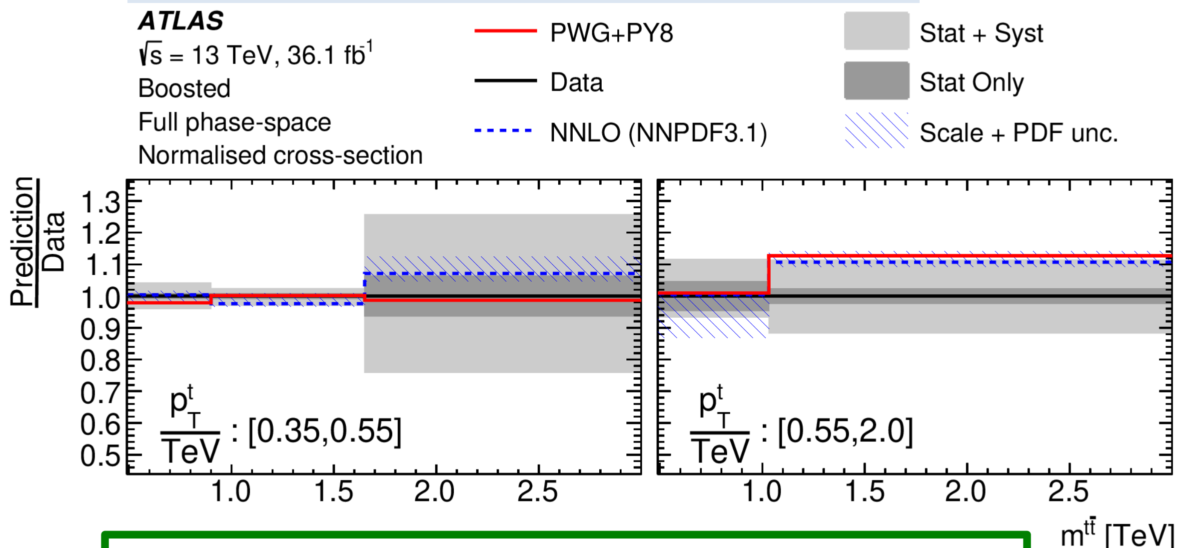


→ NLO+PS MCs a bit too high, NNLO better

Event selection

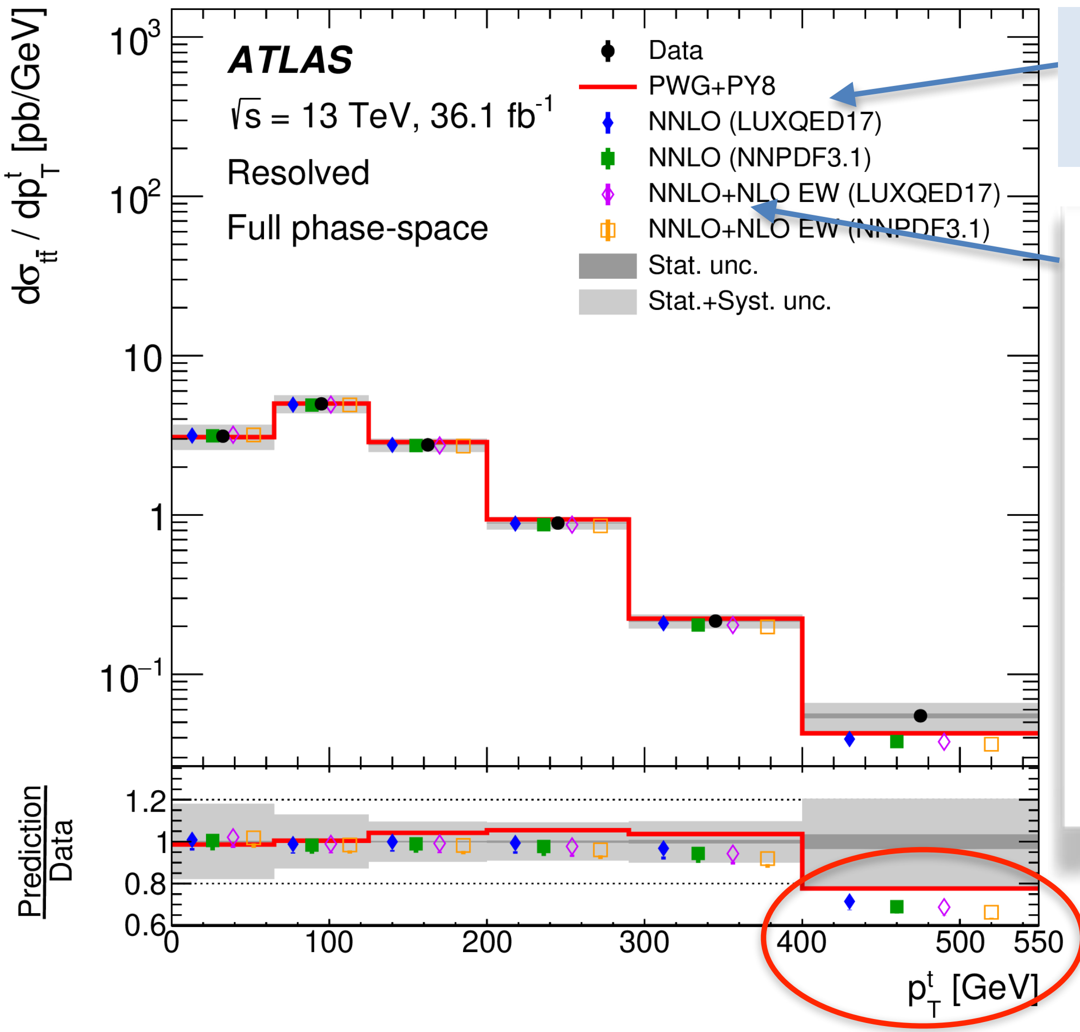


2D x-sections vs [$p_T(t)$,$M(t\bar{t})$]



→ Both POWHEG+PYTHIA8 and NNLO describe data well

Results: 1D x-sections vs $p_T(t)$, test of EW corrections



including photon component in proton structure

NNLO+NLO EW:

Czakon et al. JHEP 10 (2017) 186, arXiv:1705.04195

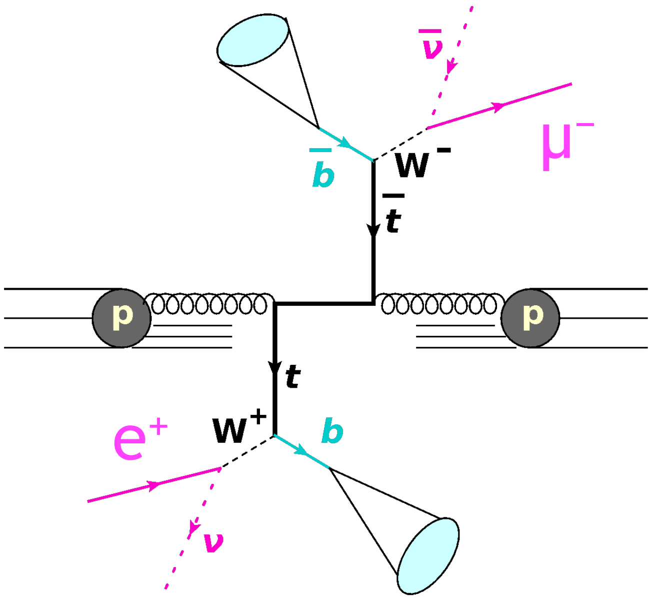
Include the NLO EW effects of $O(\alpha_s^2\,\alpha)$, all subleading NLO $O(\alpha_s\,\alpha)$ and $O(\alpha^3)$ plus higher orders in couplings

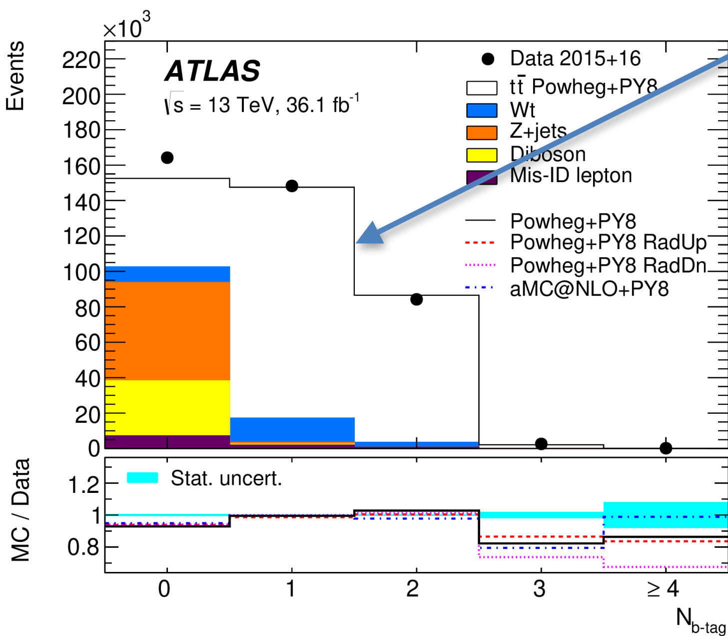
→ In probed limited $p_T(t)$ range ~small sensitivity to EW corrections

3. ATLAS Dilepton $t\bar{t}$ analysis

ATLAS-CONF-2019-041 (arXiv:1910.08819)

Measurement technique





- $e^{\pm}\mu^{\mp}$ Dilepton channel
- Study $t\bar{t}$ x-sections vs lepton kinematics
- for each x-section bin:
  - signal acceptance corrections
  - Use $N_{b\text{-tag}}$ distribution for simultaneous extraction of $\sigma_{t\bar{t}}$ and b-tag efficiency

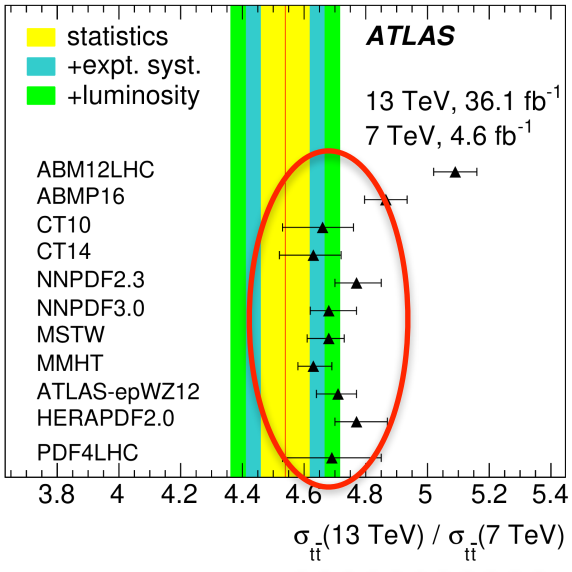
→ inclusive and differential $\sigma_{t\bar{t}}$

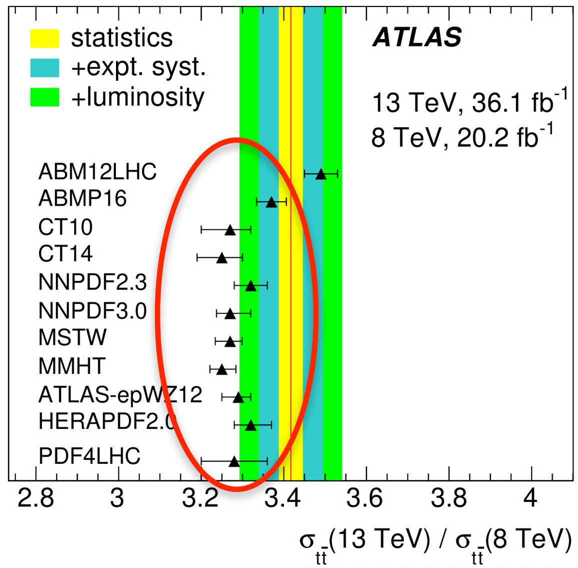
→ reaching $\mathcal{O}(1\%)$ precision for $1/\sigma_{t\bar{t}} \cdot d^m\sigma_{t\bar{t}}$,m=1,2

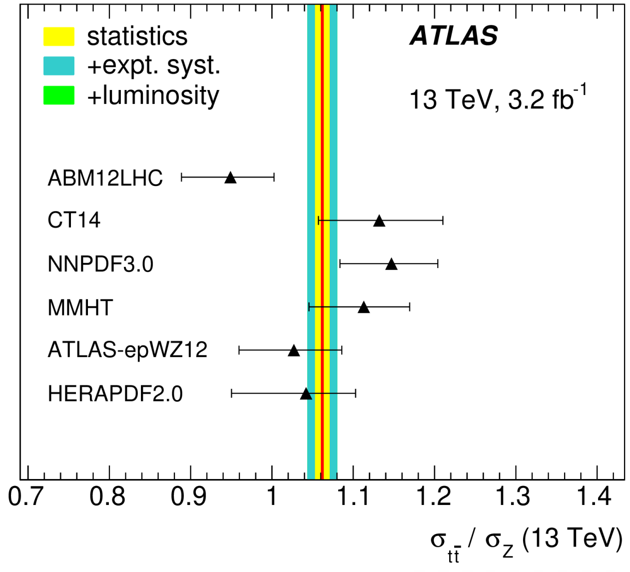
Results: Ratios of inclusive $\sigma_{t\bar{t}}$ vs sqrt(s) and $\sigma_{t\bar{t}}/\sigma_Z$

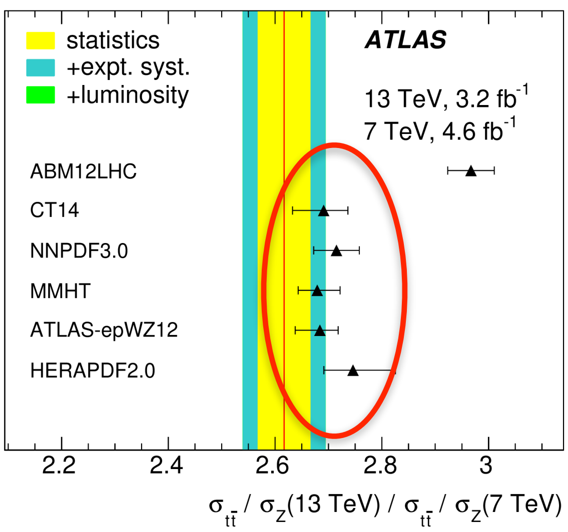
Compare to predictions based on NNLO+NNLL for $\sigma_{t\bar{t}}$

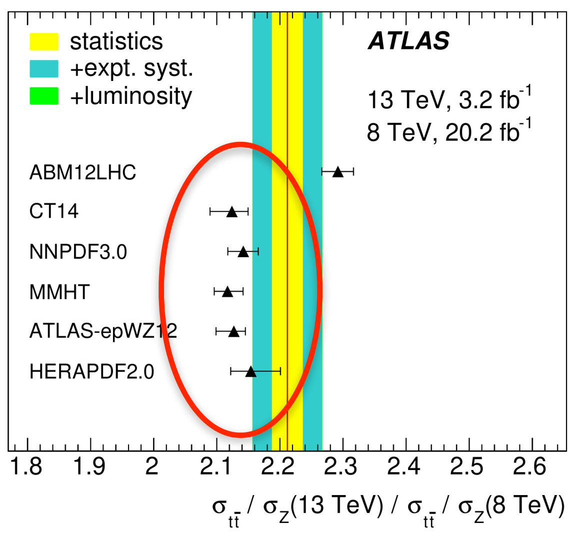
σ_Z measured in fiducial range of Z→ll









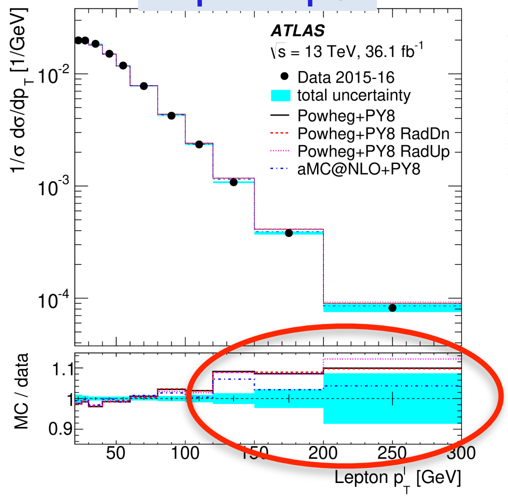


→ Increased sensitivity to PDFs for double ratios $\sigma_{t\bar{t}}/\sigma_Z$ vs sqrt(s)

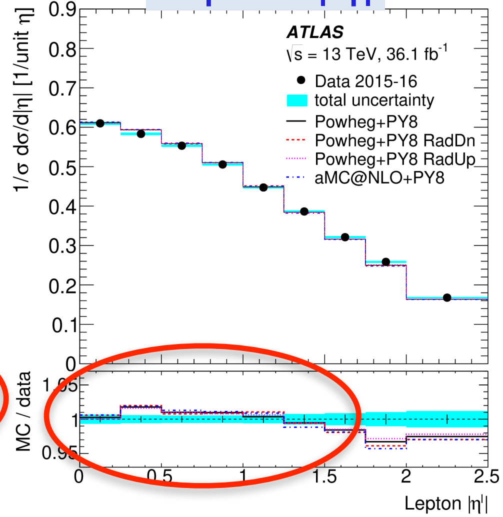
$\sigma_{t\bar{t}}$ Results: 1D cross sections

- POWHEG+PY8 RadDn (RadUp): settings with decreased (increased) initial- and final-state parton shower radiation

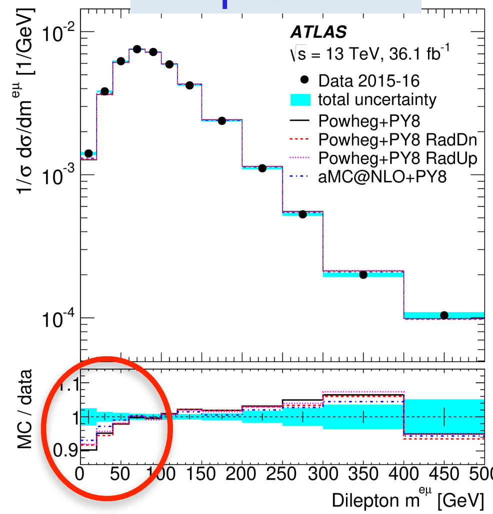
Lepton p_T



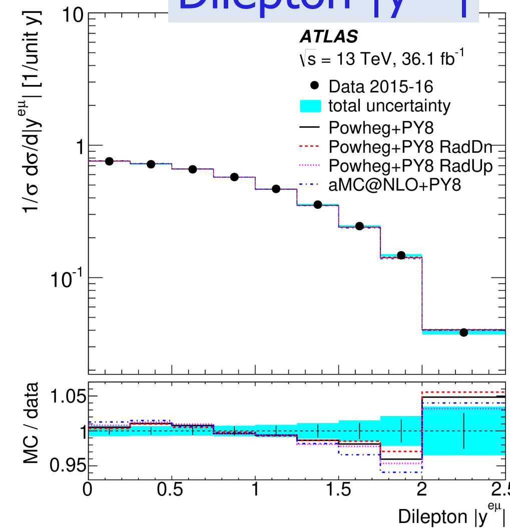
Lepton |η|



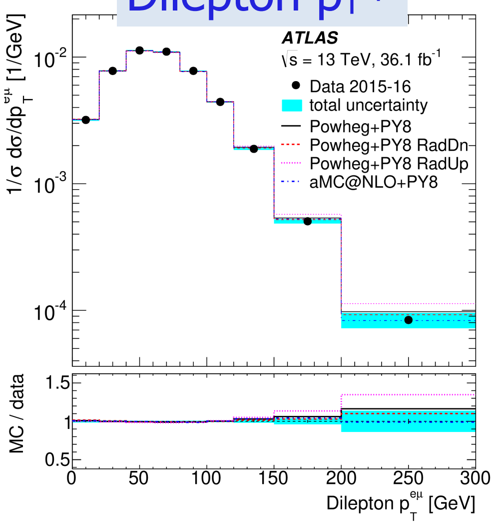
Dilepton $m^{e\mu}$



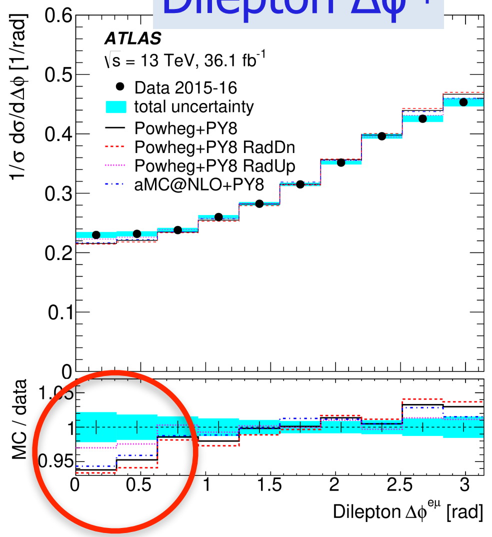
Dilepton $|y^{e\mu}|$



Dilepton $p_T^{e\mu}$



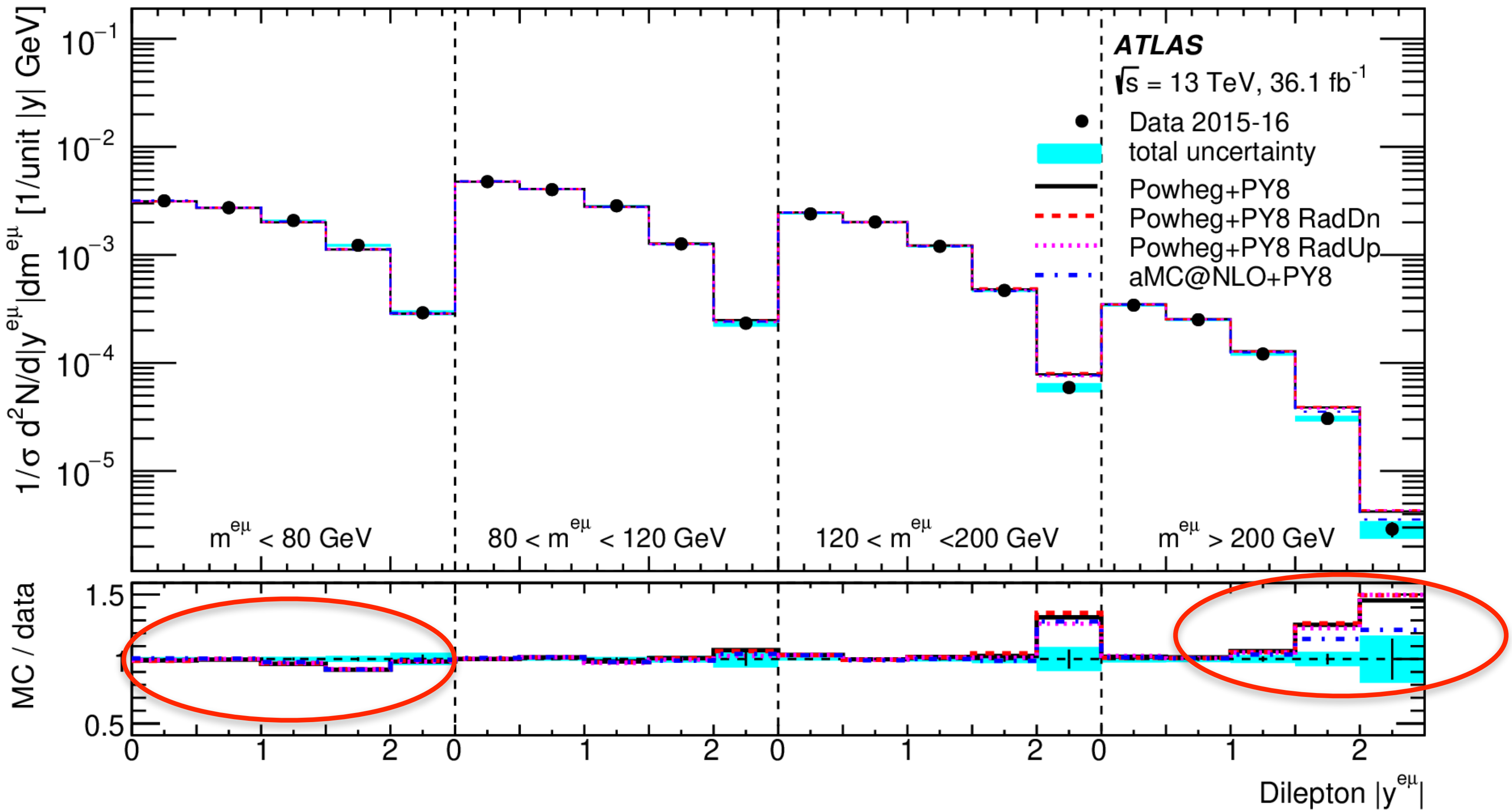
Dilepton $\Delta\phi^{e\mu}$



→ NLO+PS models deficiencies:
- too hard p^l_T
- too central $|\eta^l|$
- too few events at low $m^{e\mu}$
- too fow events at low $\Delta\phi^{e\mu}$

→ Similar trends seen in 2D Xsecs

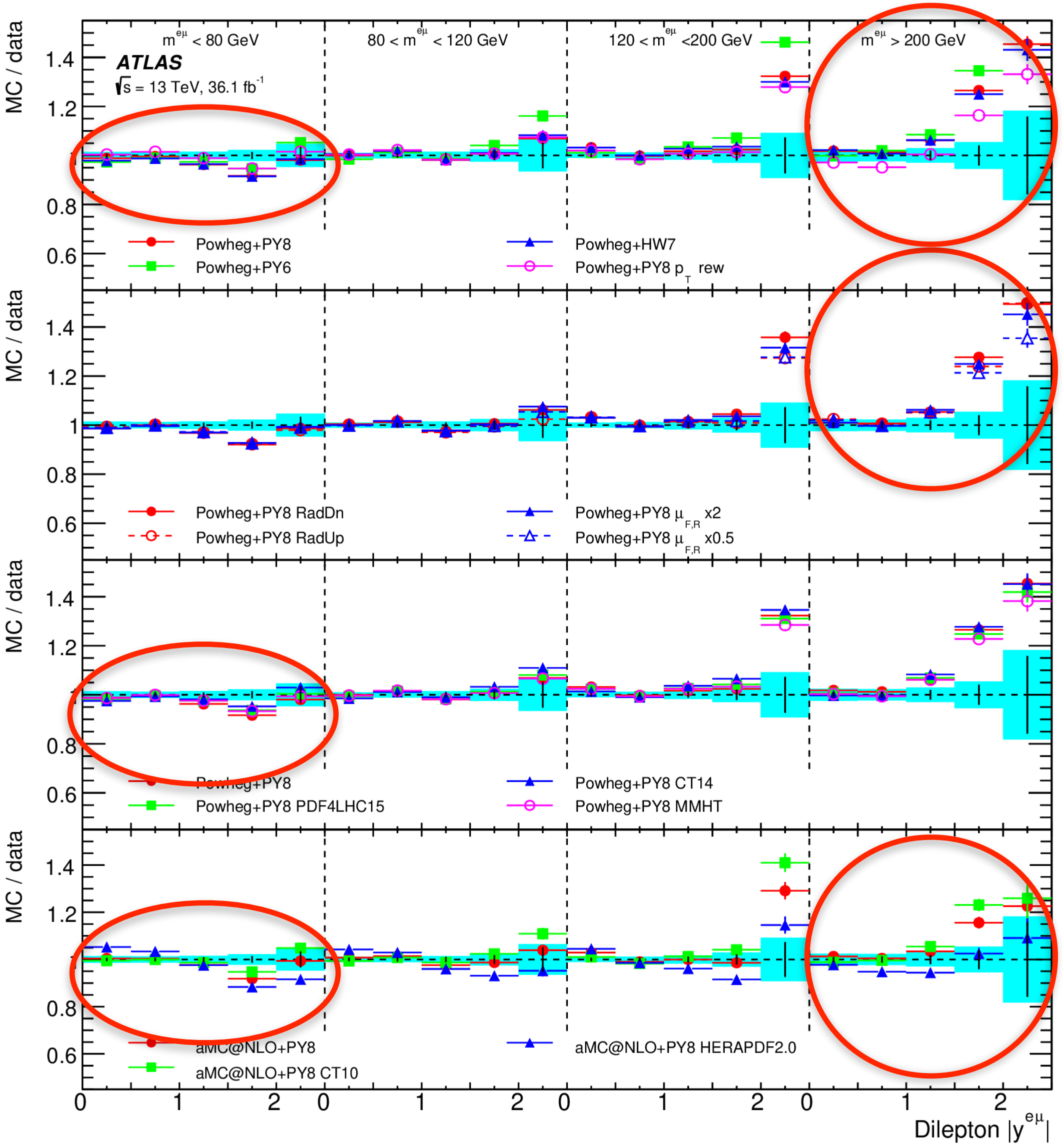
Results: 2D cross sections vs $[y^{e\mu}, m^{e\mu}]$



→ NLO+PS models predict too few events at low $m^{e\mu}$ and too many at forward $y^{e\mu}$

Results: 2D x-sections vs [$y^{e\mu}$,$m^{e\mu}$]: ratio MC/data

NLO+PS Model variations:



PS+hadr. model

ISR/FSR radiation

PDFs

Generator and PDFs

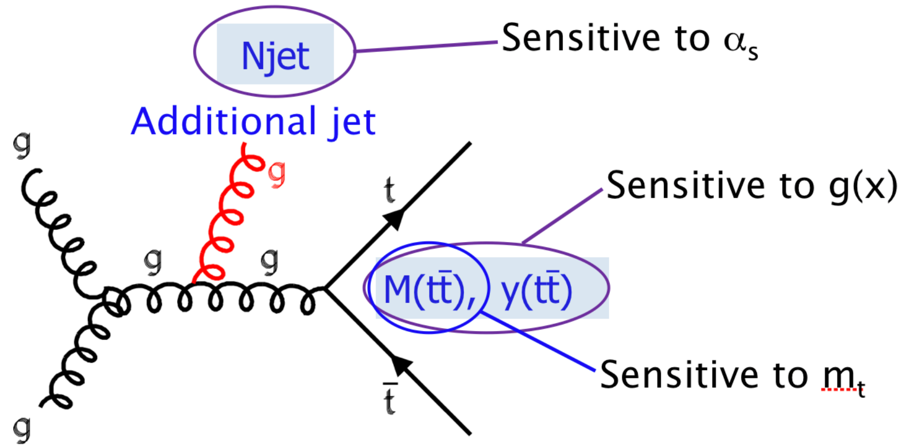
χ^2 data vs. models

Generator	$\lvert\eta^{\ell}\rvert \times m^{e\mu}$	$\lvert y^{e\mu}\rvert \times m^{e\mu}$	$\lvert\Delta\phi^{\ell}\rvert \times m^{e\mu}$
N_{dof}	35	19	39
POWHEG + PY8	53.1	72.3	65.4
POWHEG + PY6 CT10	45.9	92.9	79.5
POWHEG + HW7	49.3	67.4	63.7
POWHEG + PY8 p_{T} rew.	47.1	56.1	51.4
POWHEG + PY8 RadDn	57.1	74.2	69.9
POWHEG + PY8 RadUp	50.6	62.5	51.7
POWHEG + PY8 $\mu_{\text{F,R}} \times 2$	60.7	68.4	71.1
POWHEG + PY8 $\mu_{\text{F,R}} \times 0.5$	50.3	60.0	52.0
POWHEG + PY8 PDF4LHC15	51.5	61.5	59.7
POWHEG + PY8 CT14	50.6	67.3	60.0
POWHEG + PY8 MMHT	53.7	57.9	58.7
AMC@NLO + PY8	55.0	45.9	58.2
AMC@NLO + PY8 CT10	43.7	50.6	59.5
AMC@NLO + PY8 HERA2	130.3	97.6	58.0

→ Room for improvement!

→ ideally fit to data MC tuning pars & m_t and PDFs

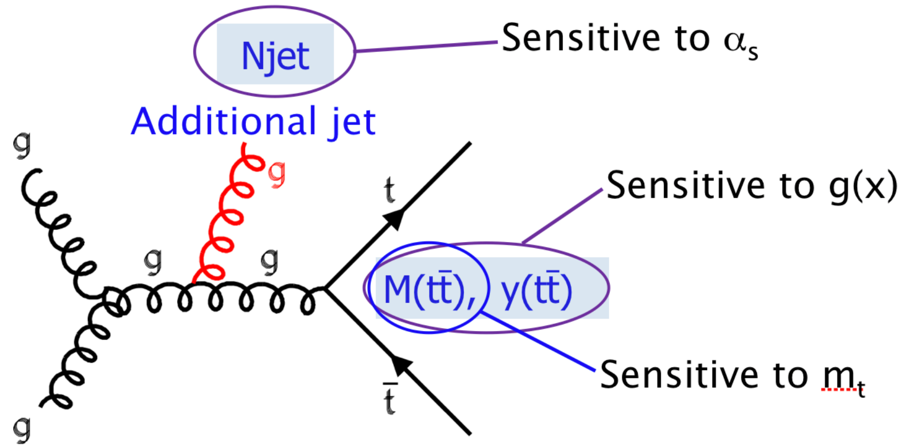
Summary



- ATLAS and CMS multi-differential $t\bar{t}$ cross section measurements with 2016 data provide high precision tests of QCD and EW sectors
  - CMS-TOP-18-004: use 3D $t\bar{t}$ cross sections to simultaneously extract at NLO α_s (~2% precision), m_t^{pole} (~0.5% precision) and improving g(x)
  - ATLAS EPJC 79 (2019) 2018: exhaustive set of 1D & 2D cross sections, including boosted tops, NNLO QCD improves description
  - ATLAS-CONF-2019-041: lepton differential distributions reach o(1%) precision and reveal specific NLO+PS MC problems, e.g. POWHEG too hard lepton p_T

Seen in all 3 above analyses: POWHEG too hard top p_T, enhanced at high $m_{t\bar{t}}$

Summary



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Seen in all 3 above analyses: POWHEG too hard top p_T, enhanced at high $m_{t\bar{t}}$

Outlook

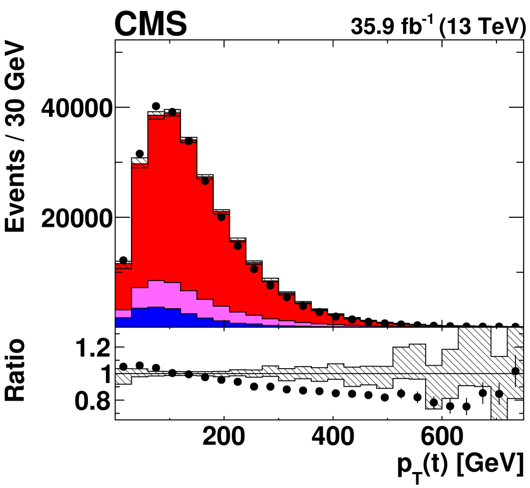
- full RUN II (2016-2018) analyses: ~4 times increased statistics
- whenever NNLO is available → compare to/use it to extract pars

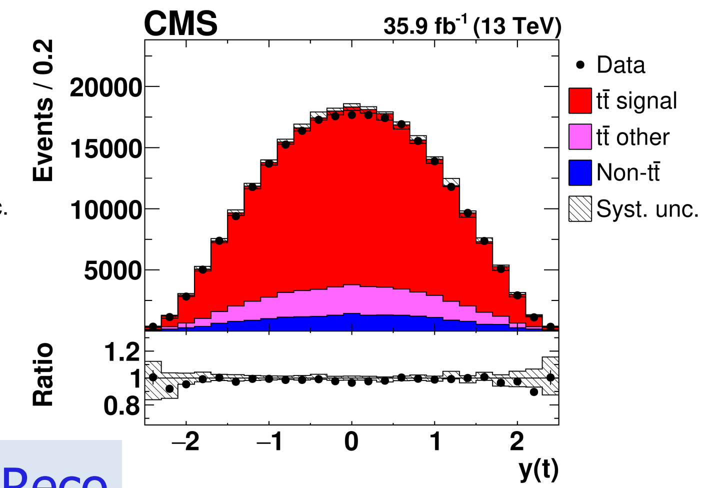
Backup slides

Kinematic distributions

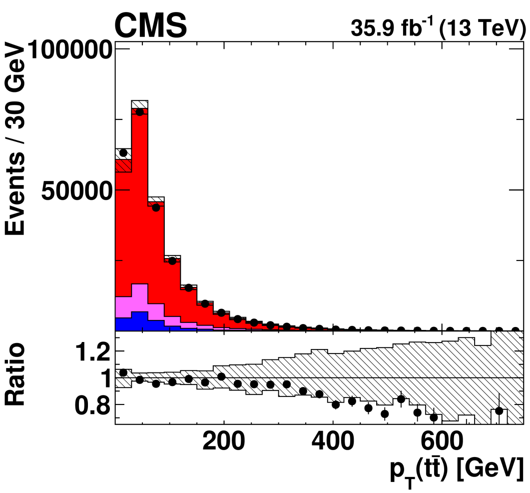
$t\bar{t}$ signal MC: POWHEGV2 + PYTHIA8

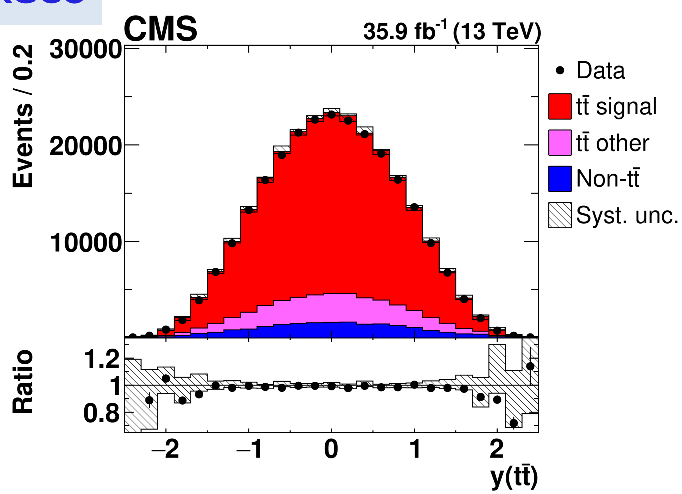
DILEPTON CMS-TOP-18-004:

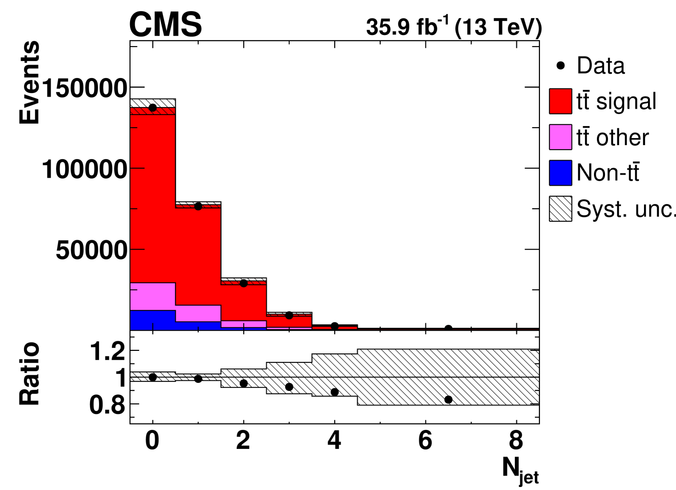




Full Reco







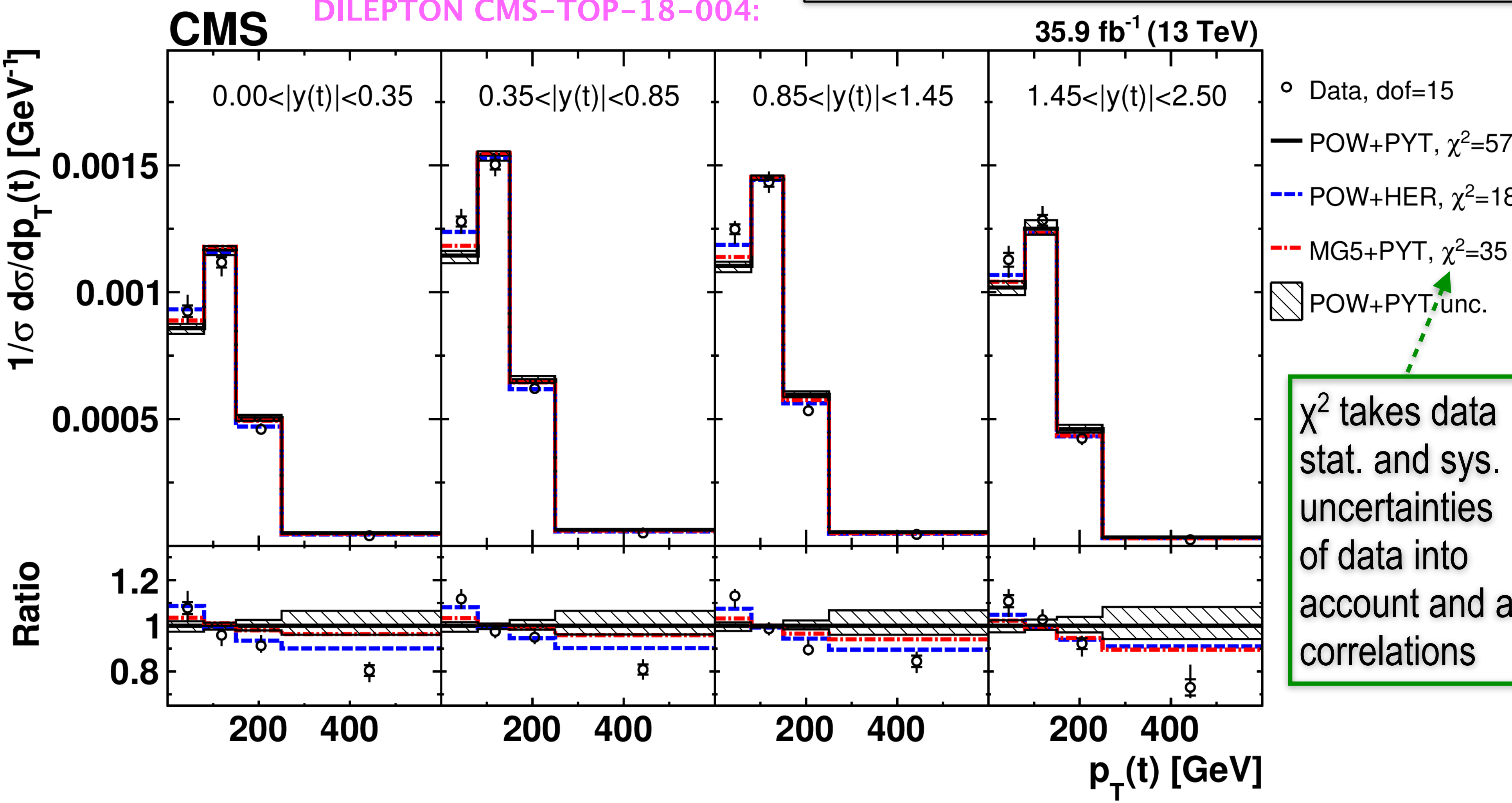
⇨ Overall reasonable description of data

⇨ Nominal MC predicts harder spectra for $p_T(t)$, $p_T(t\bar{t})$ and N_{jet}

Results: 2D x-sections [y(t),p_T(t)]

- 'POW+PYT' = POWHEGV2+PYTHIA8, CUETP8M2T4
- 'POW+HER' = POWHEGV2+HERWIG++, EE5C
- 'MG5+PYT' = MG5_aMC@NLO+PYTHIA8 [FxFx], CUETP8M2T4

DILEPTON CMS-TOP-18-004:



χ^2 takes data stat. and sys. uncertainties of data into account and all correlations

⇨ 'POW+PYT' and 'MG5+PYT' predict harder p_T(t) for all y(t) ranges

⇨ 'POW+HER' gives better description

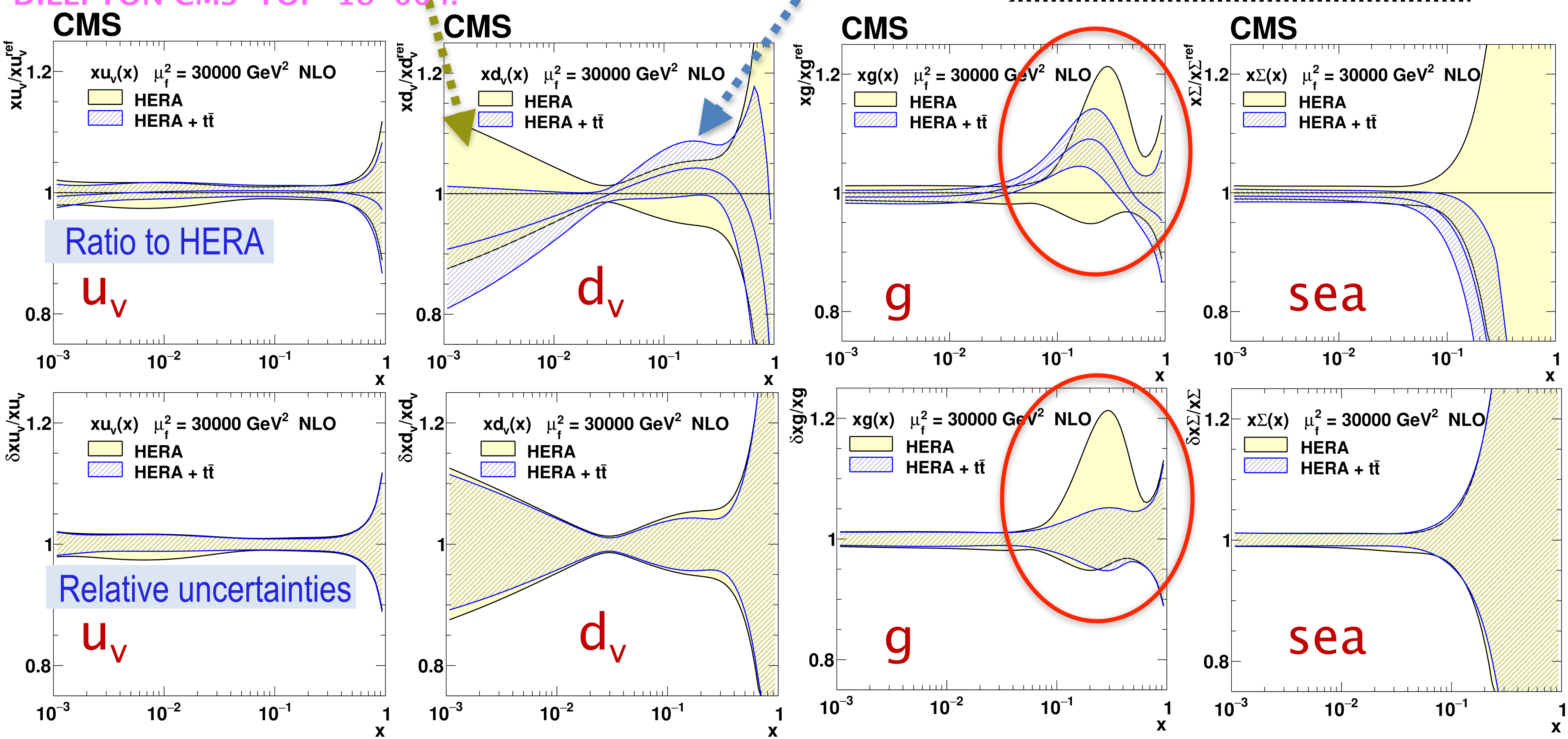
Simultaneous α_s, m_t^{pole} & PDF fit

PDF Parametrisation at Q_0^2=1.9 GeV^2

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

- Fit to HERA DIS only and including 3D $t\bar{t}$ data

DILEPTON CMS-TOP-18-004:



→ Reduced gluon density uncertainty at large x~0.1-0.4

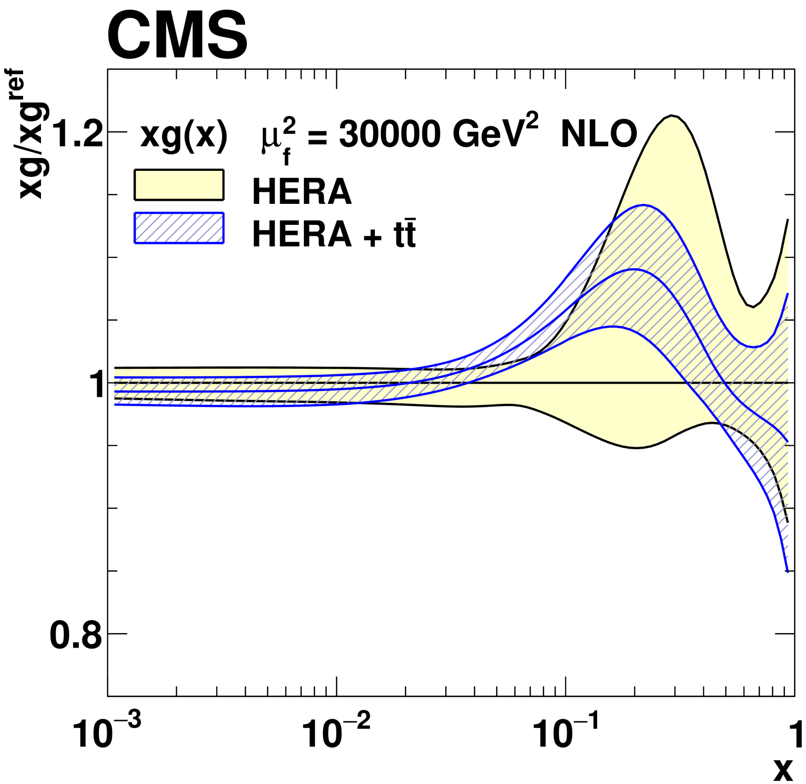
xg(x) with using different CMS data sets

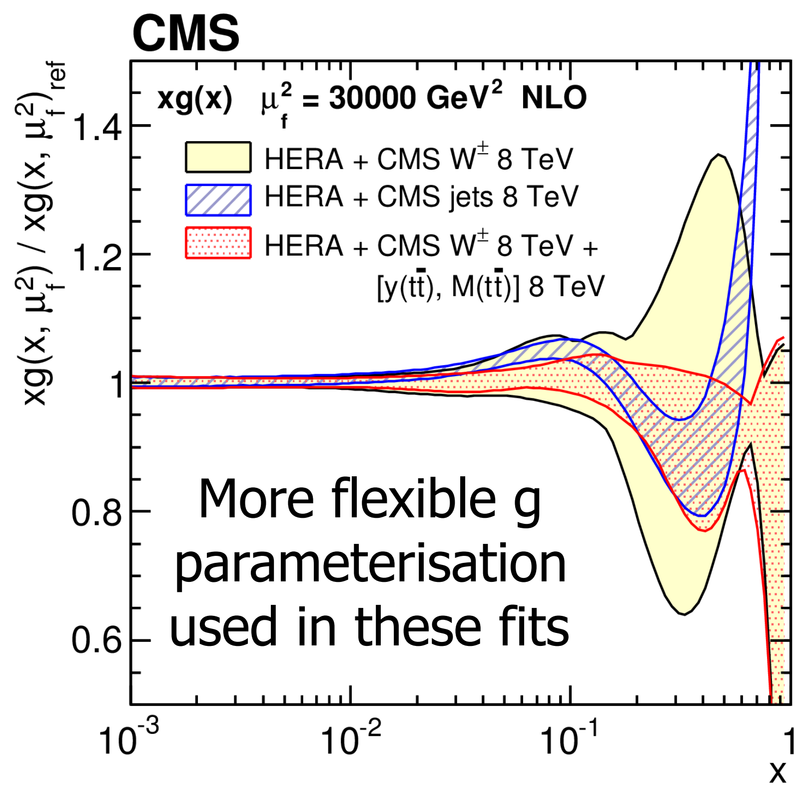
DILEPTON CMS-TOP-18-004:

- HERA
- HERA + $d^3\sigma_{t\bar{t}}$

TOP-14-013 EPJ C77 (2017) 459:

- HERA + CMS W EPJ C76 (2016) 469
- HERA + CMS jets JHEP 03 (2017) 156
- HERA + CMS W + $d^2\sigma_{t\bar{t}}$



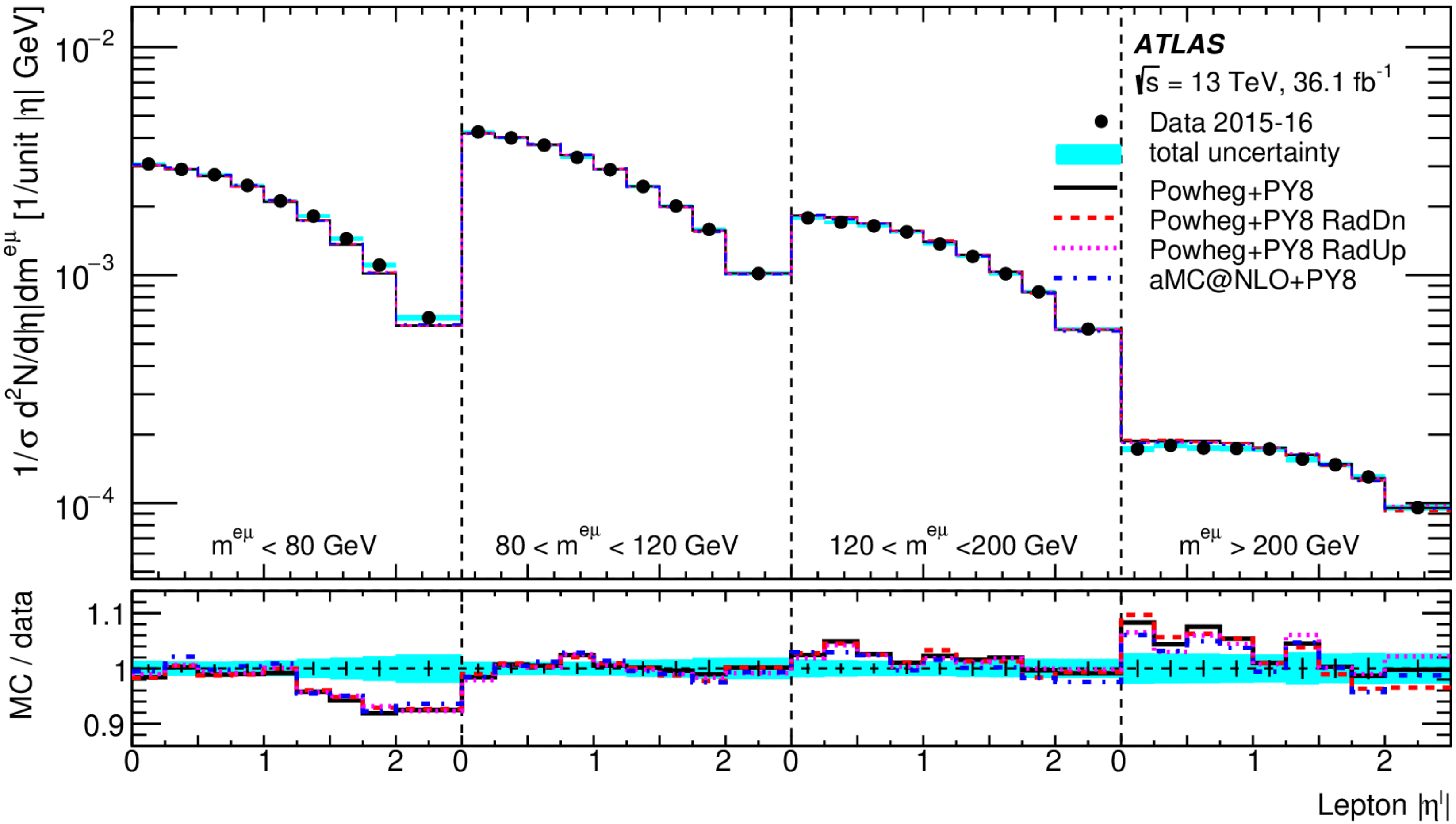


→ ~ similar improvements adding $d^3\sigma_{tt}$(RUN II) or $d^2\sigma_{tt}$ (RUN I)

→ should fit to all data simultaneously!

Results: 2D cross sections vs [$|\eta^l|$,$m^{e\mu}$]

DILEPTON ATLAS-CONF-2019-041 **arXiv:1910.08819**



→ NLO+PS models predict more central $|\eta^l|$ for all $m^{e\mu}$ ranges