Top quark pair and single top differential cross sections in CMS

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on behalf of the CMS collaboration

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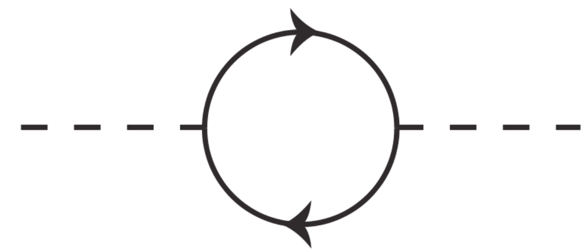
Outline

- **Top pair production**
  - Differential Cross Section measurements (high-pT)
  - Normalised multi-differential Cross Section measurements
  - Strong coupling strength a_s
  - Top quark pole mass m_t^{pole}
  - Parton distribution functions (PDF)
- **Single top production**
  - Differential cross section measurements (t-channel, tW)
  - Associated production with a W boson
  - Charge Ratios (t-channel)

Why Top?



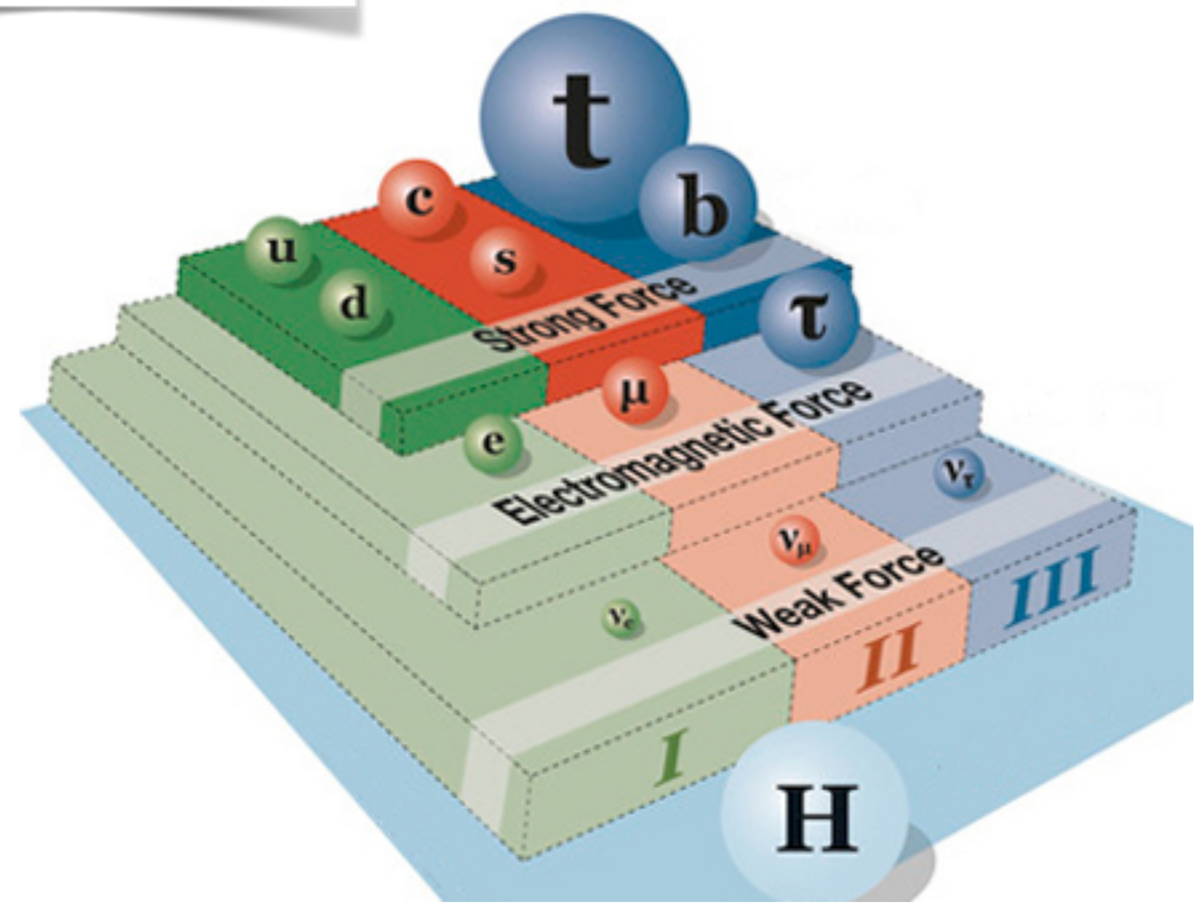
- top quark is the most massive known particle
  - significant contribution of top loops

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

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

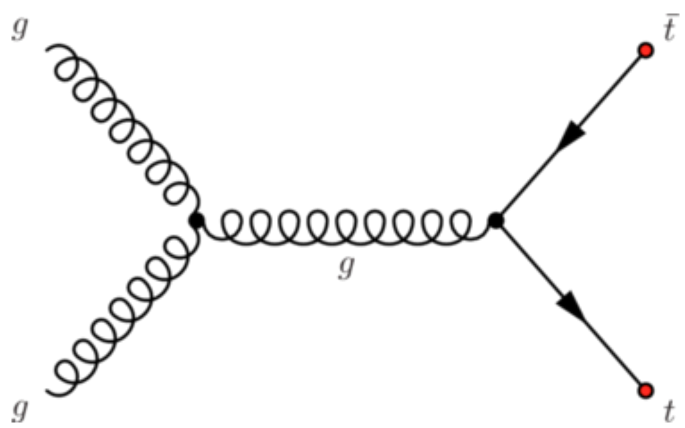
- top quark is unique because it decays before it can hadronize
  - no bound states with top can be formed

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

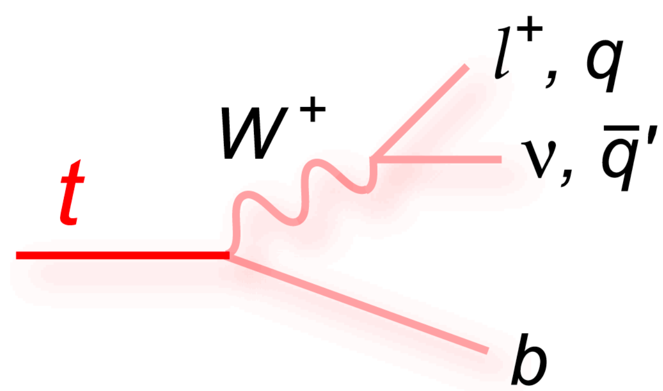


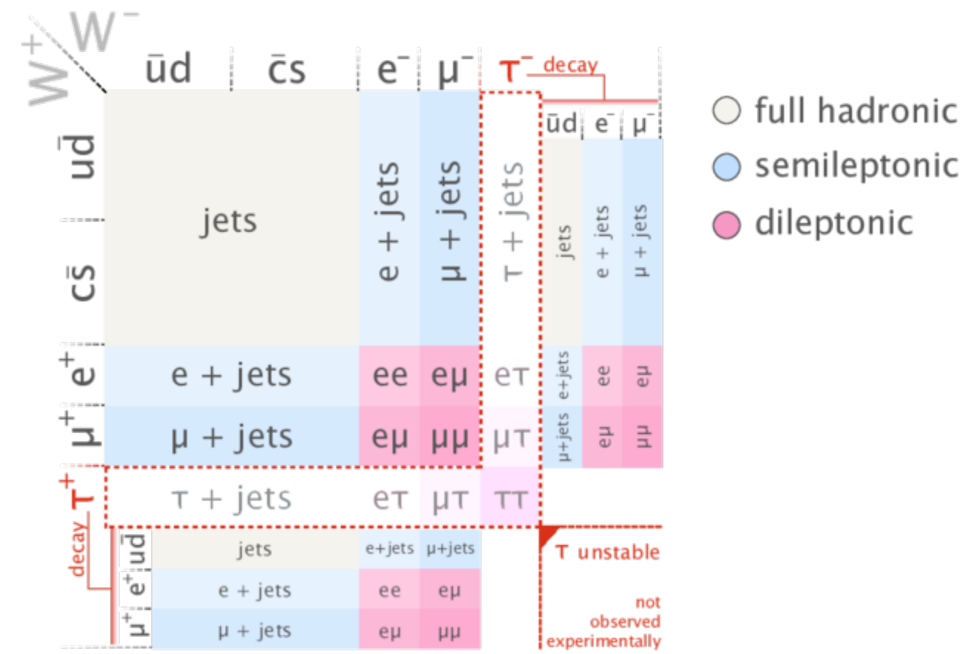
Top Production and Decay

top quark pair production

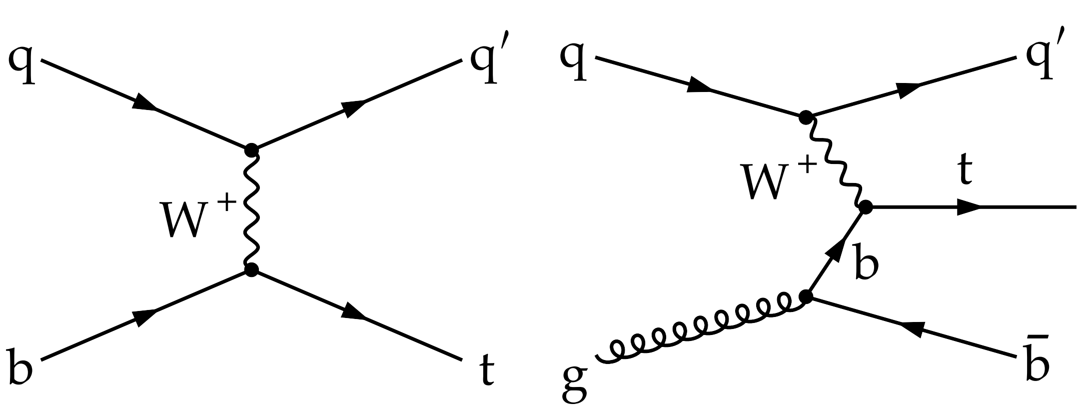


BR(t→Wb) = 0.957

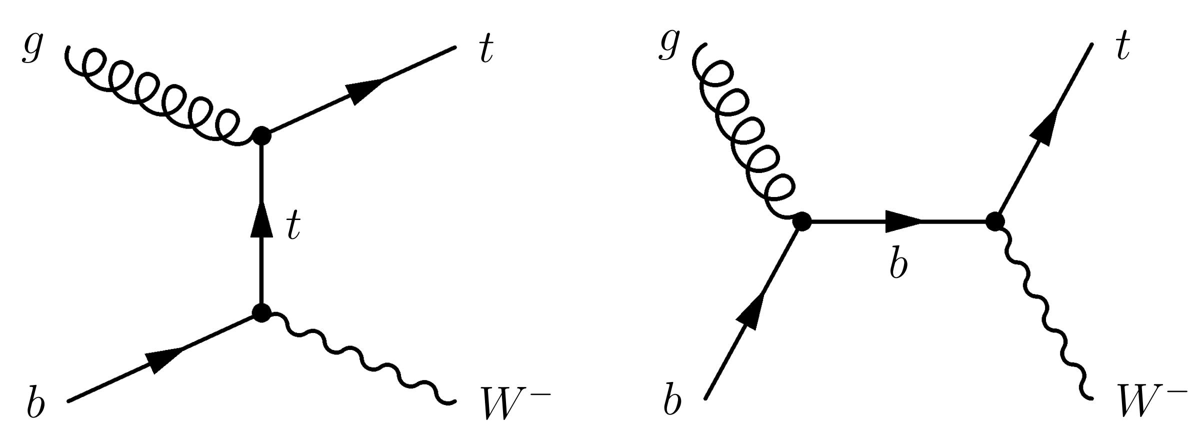




single top quark production (t channel)

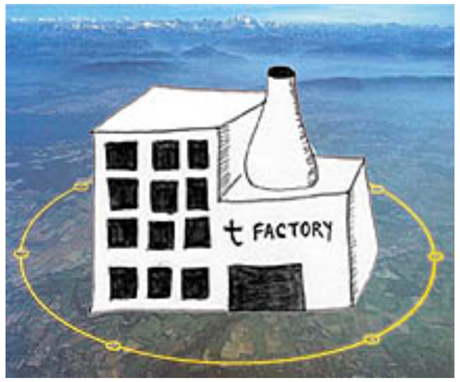


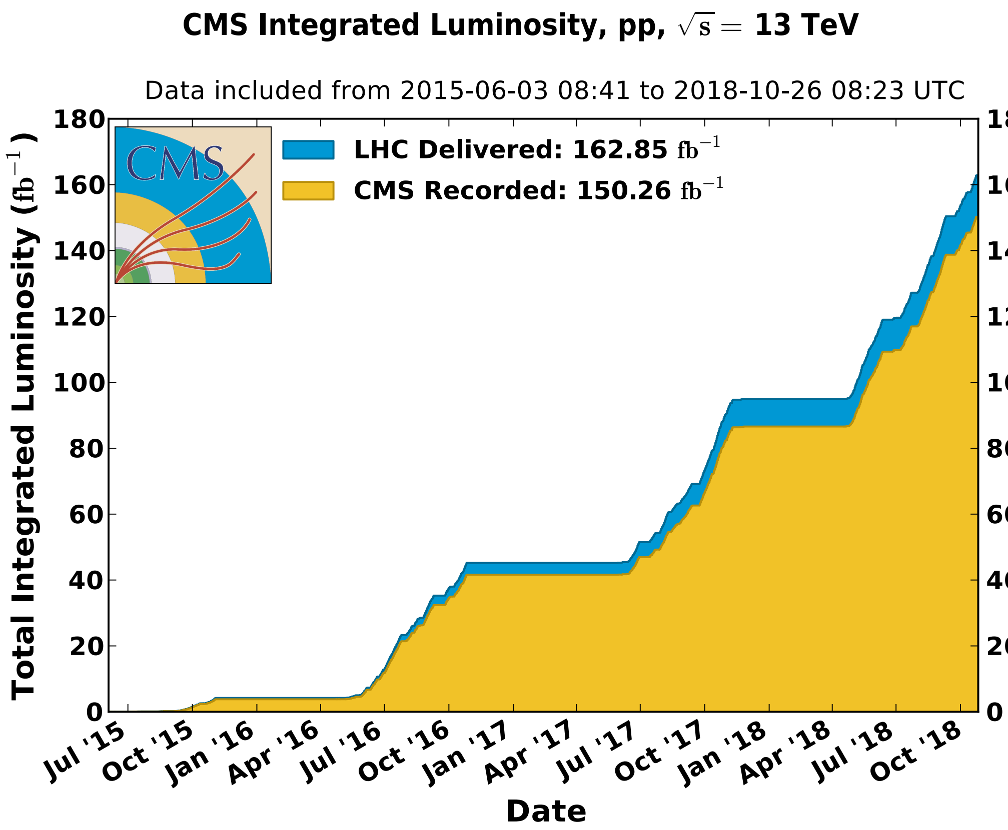
single top quark production (tW mode)



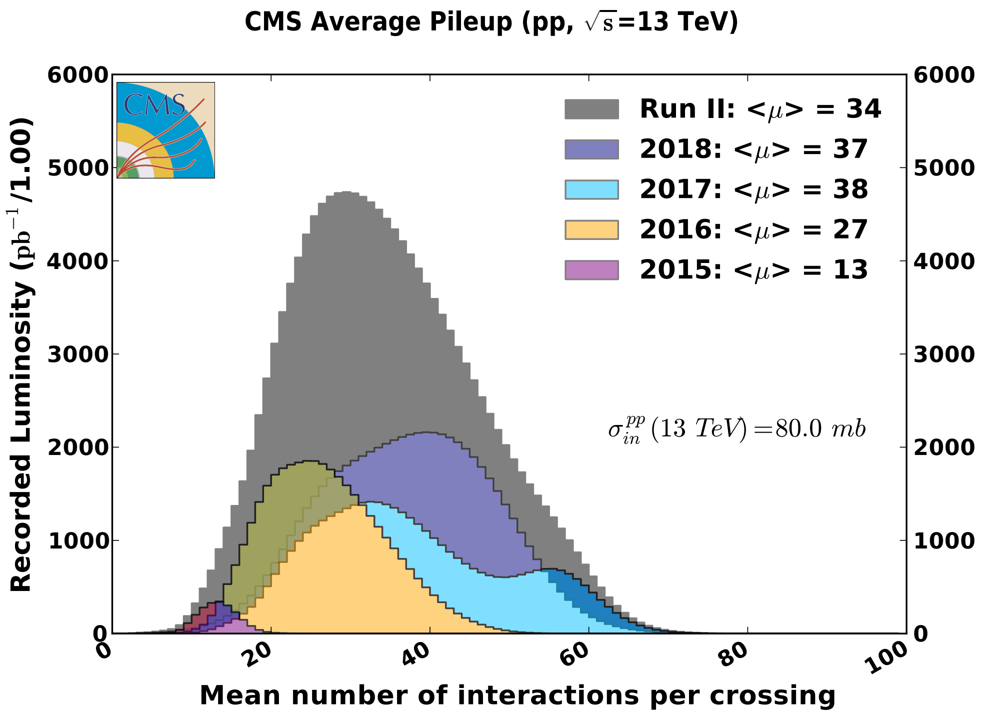
CMS @ LHC Run2 (2015-2018)

- During Run 2 the LHC produced unprecedented event samples
  - 10^{16} pp collisions @ 13TeV
  - 2015-2018 runs:
    - Total Luminosity ~ 163 fb-1
    - Top quarks: 300 million
    - On average 34 interactions per bunch crossing

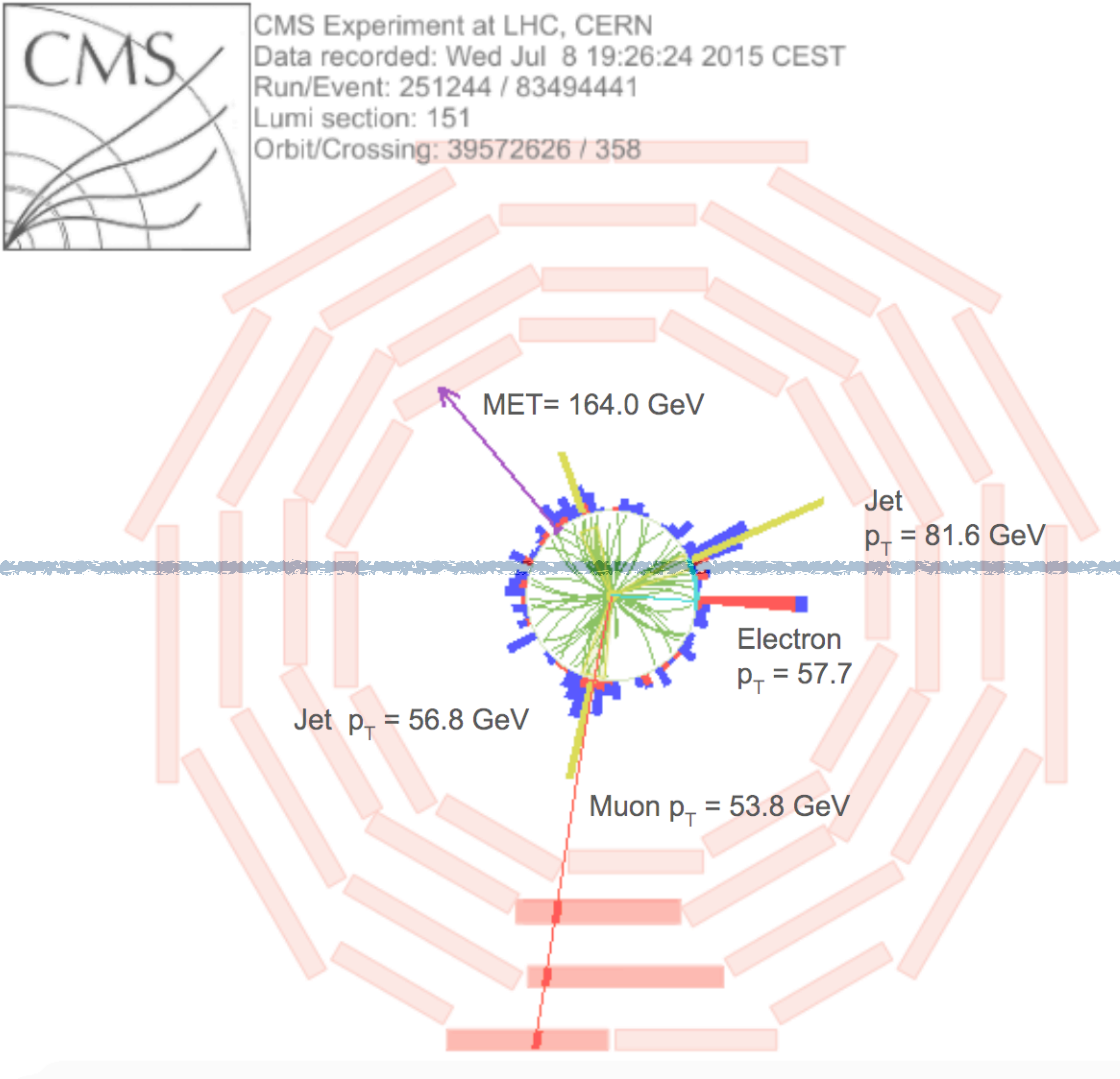




- Event sample enable broad physics that can
  - Probe SM processes/calculations with high precision
  - Detect very rare processes
  - Explore vast kinematic phase space



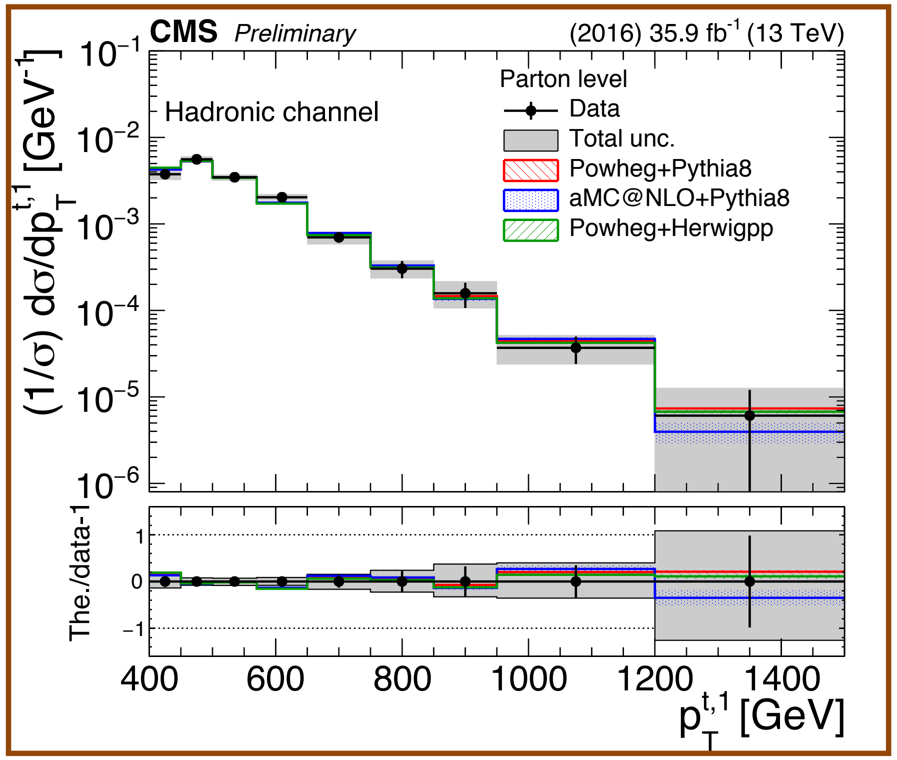
Top Pair

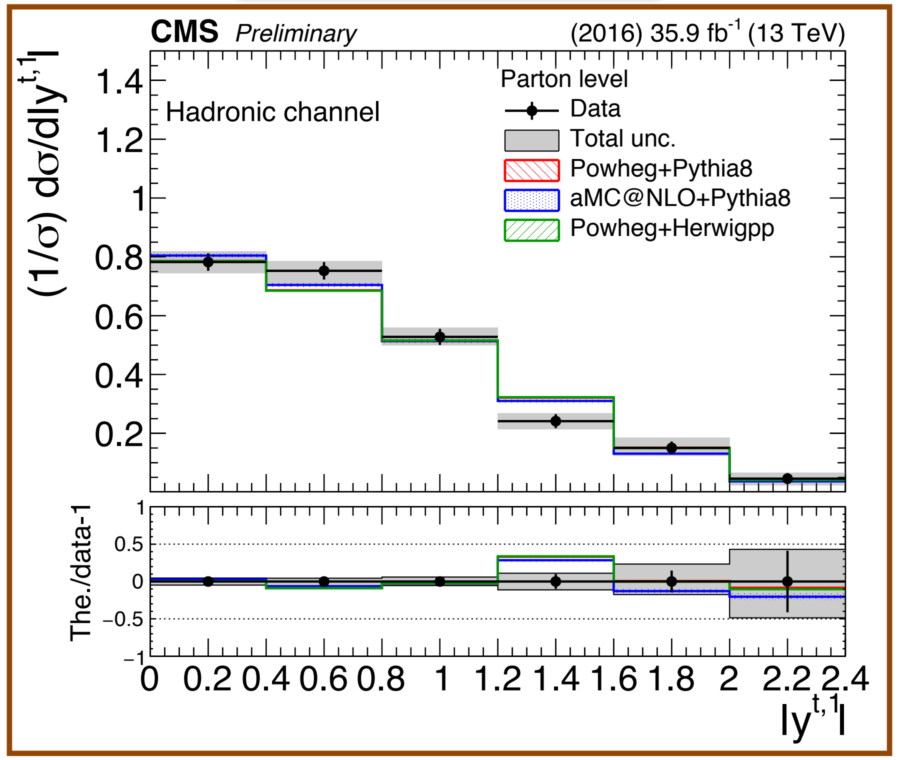


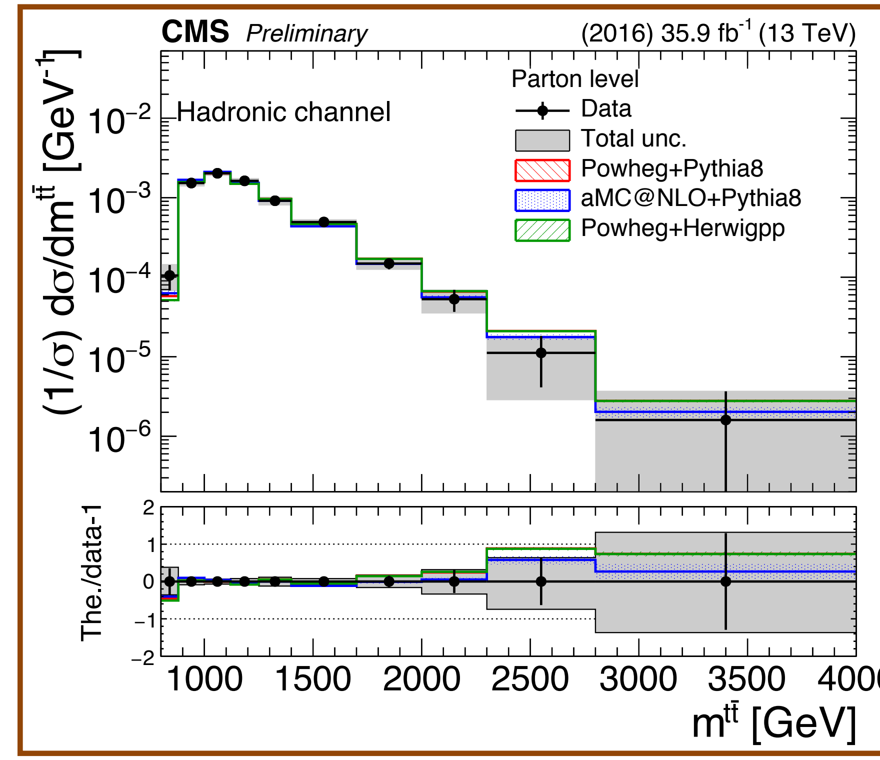
CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 19:26:24 2015 CEST
Run/Event: 251244 / 83494441
Lumi section: 151
Orbit/Crossing: 39572626 / 358
MET= 164.0 GeV
Jet
p_T = 81.6 GeV
Electron
p_T = 57.7
Jet p_T = 56.8 GeV
Muon p_T = 53.8 GeV

Differential Cross Sections $d\sigma_{t\bar{t}}/dX$

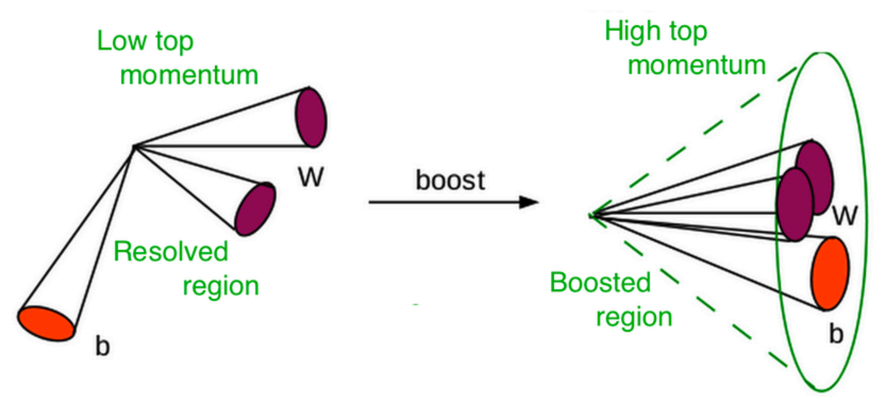
Parton







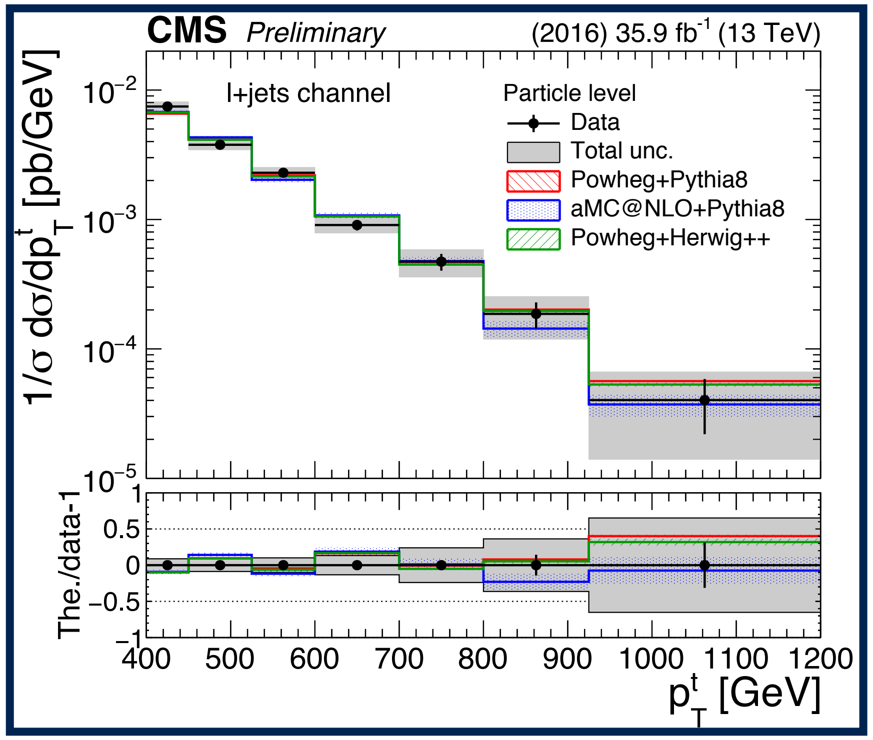
Hadronic



- Full hadronic for high-pT jets
  - Selection and ttbar reconstruction with NN
- Measurements
  - Absolute and normalised differential cross section @ Parton and particle levels
  - Top & top pair kinematic observables
- Results
  - Shapes overall compatible with theory: no top pT slope
  - Overall Shift of the order of 35% in the total cross section

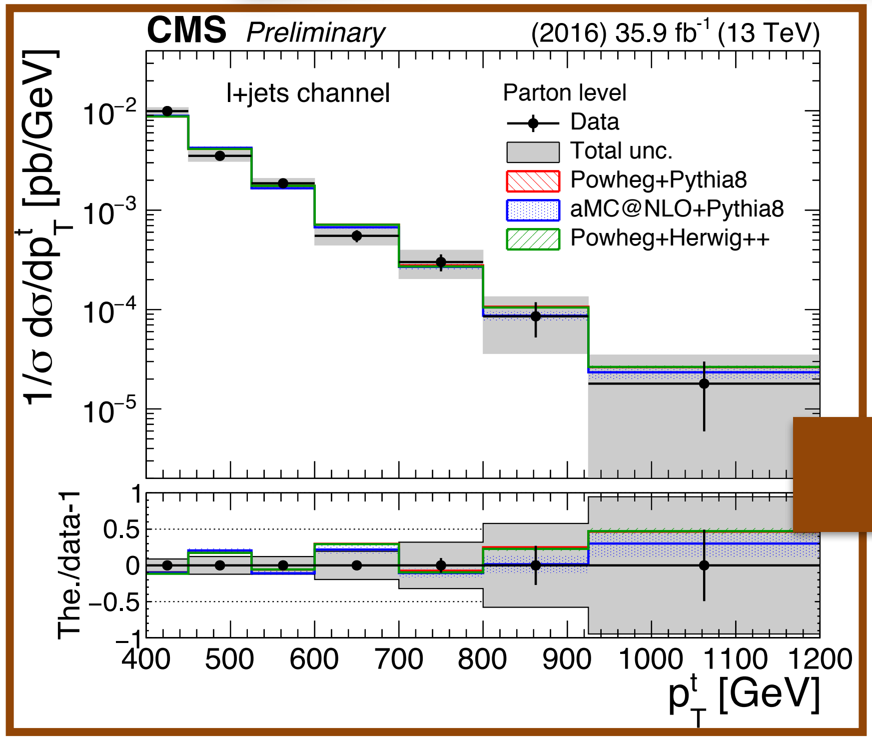
Differential Cross Sections $d\sigma_{t\bar{t}}/dX$

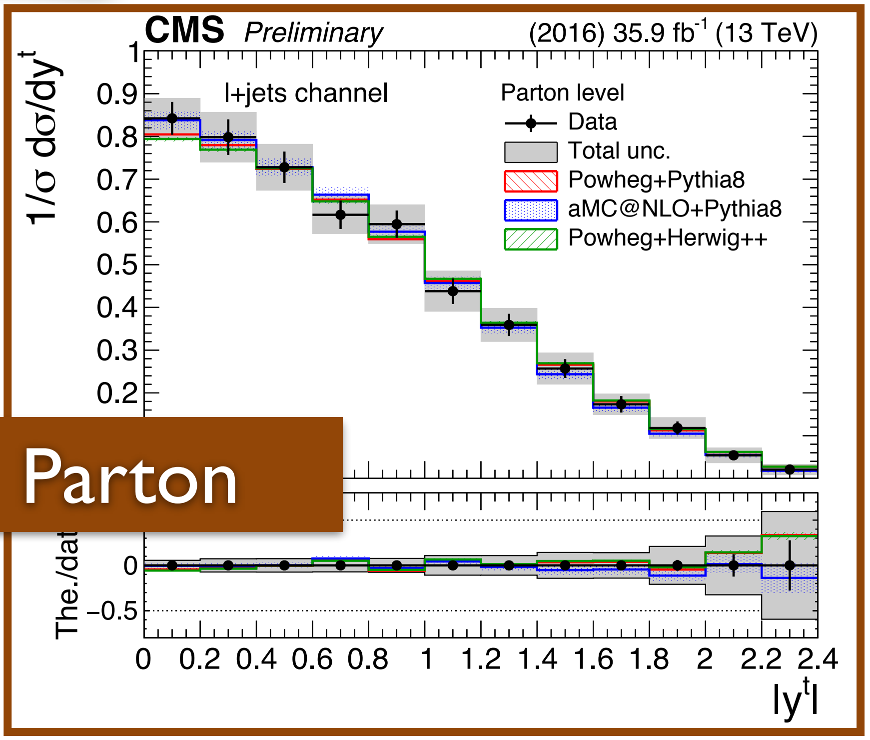
- L + jets for high-pT jets
  - Selection based on t- and b-jet categories
- Measurements
  - Absolute and normalised differential cross section @ Parton and particle levels
  - Hadronically decaying top pT and |y|
- Results
  - Differential distributions are generally well described
  - All models overpredict the absolute cross section (~20%)



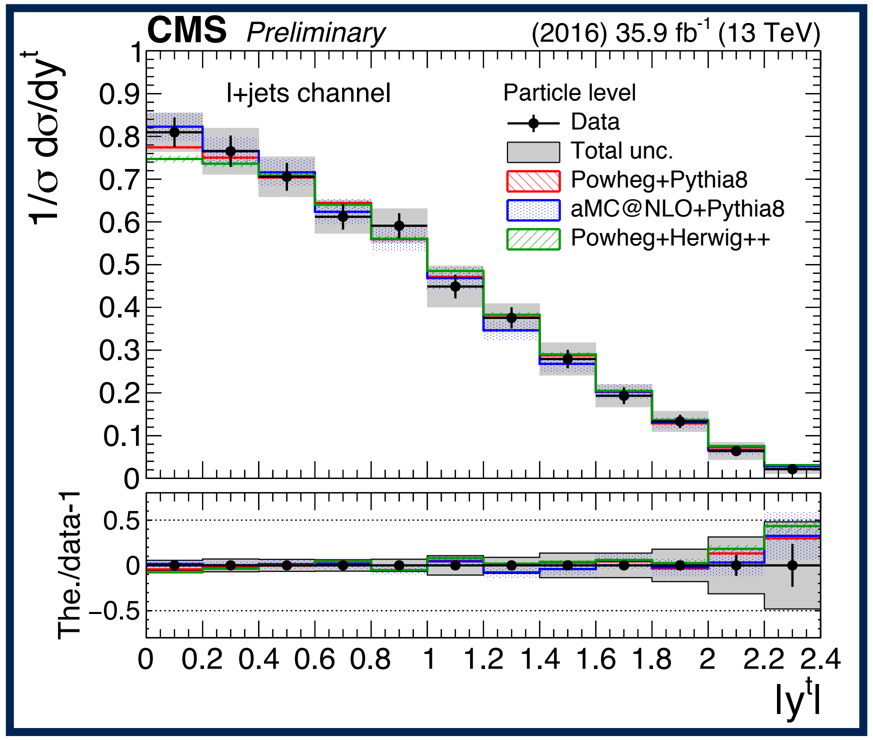
L + jets

Particle

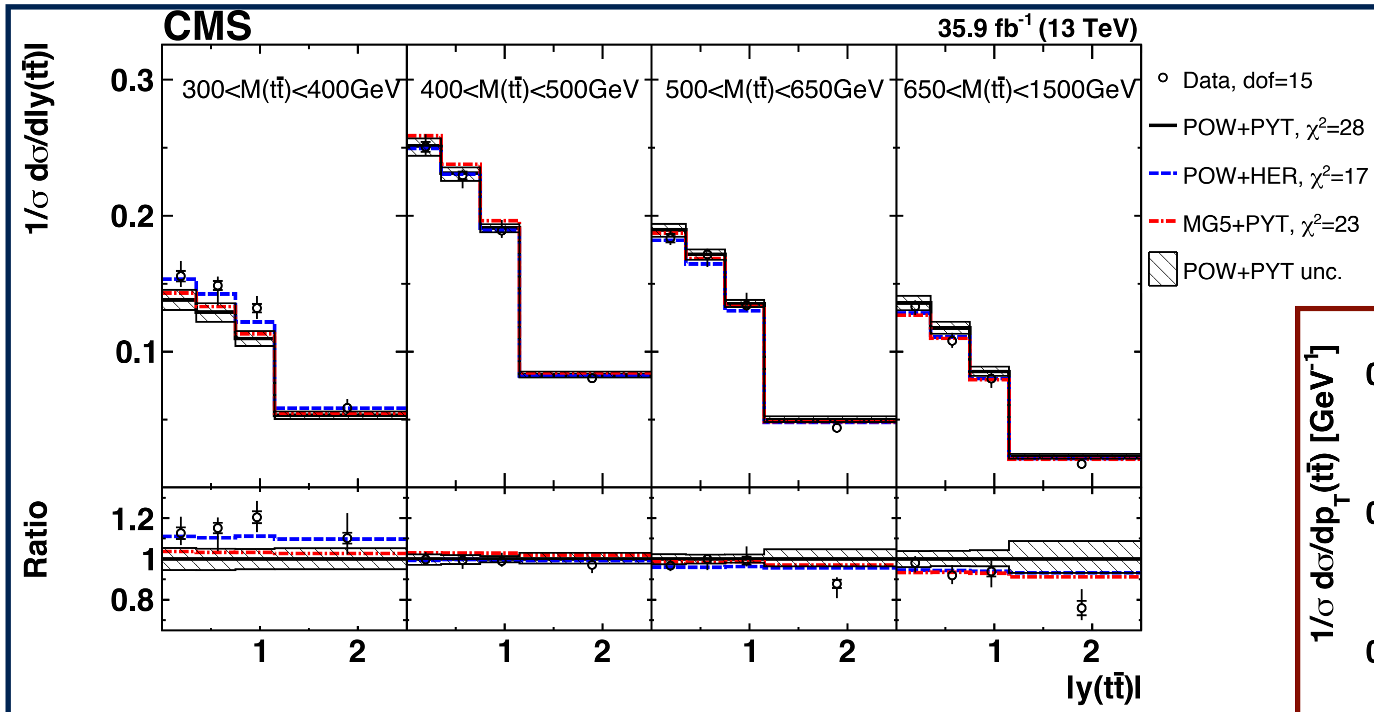




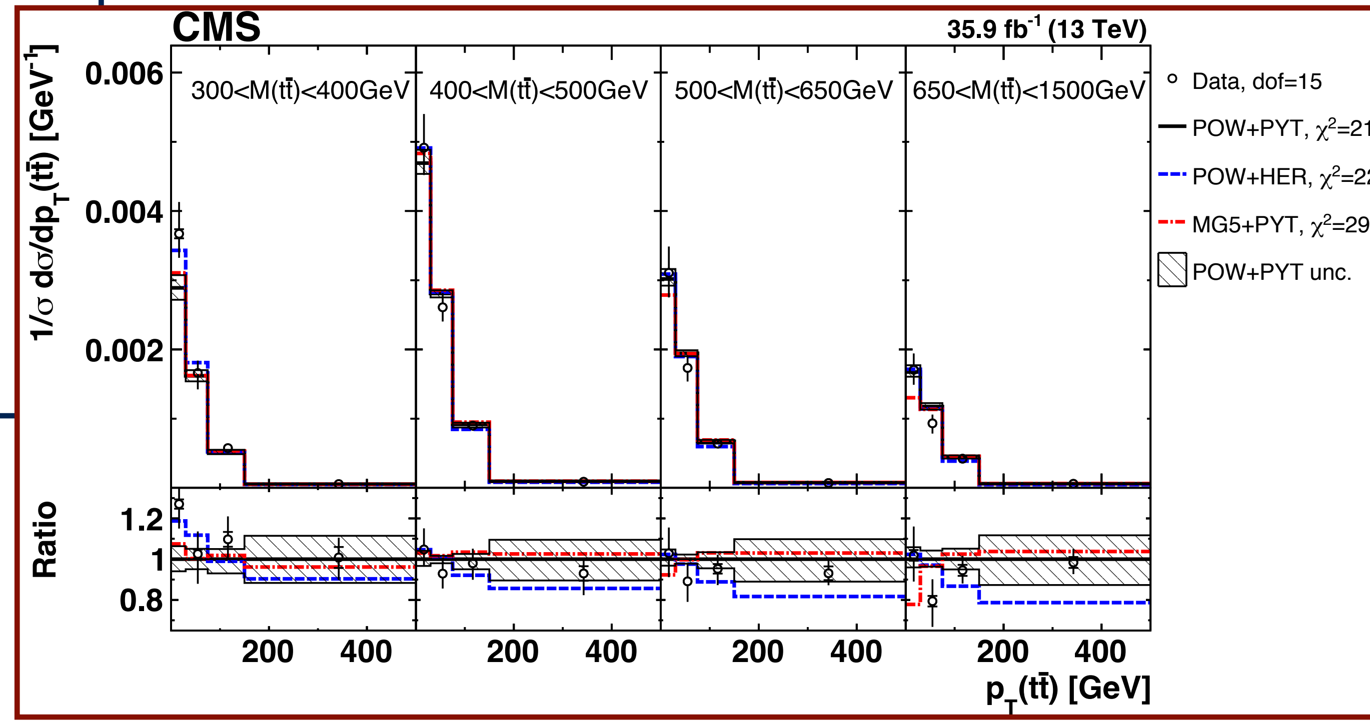
Parton



2D Differential Cross Sections



- All MC describe data well
- MG5+PYT predicts too hard pT($t\bar{t}$) at highest M($t\bar{t}$) range



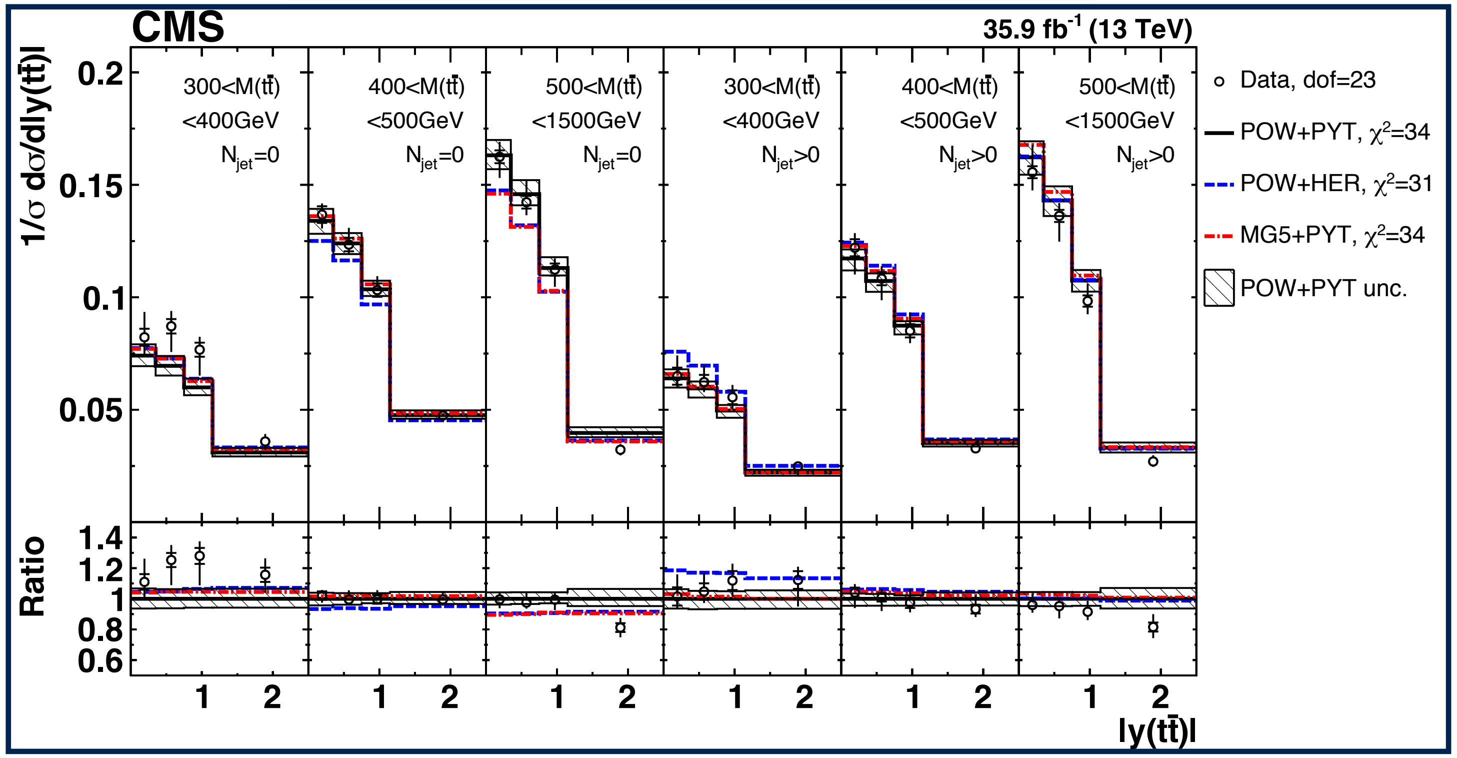
- In general shapes are well described
- MC is less central than data in largest M($t\bar{t}$) range
- Best description by 'POW+HER'

- Measured Normalised 2D and 3D $t\bar{t}$ cross section in dilepton channel using 2016 data
  - Require 2 $l^{\pm}$, 2jets (at least 1 b-tagged)
- Quantitative comparison to several MC prediction
  - Data can reveal trends and can distinguish between predictions
- 3D cross sections to constrain a_s m_t^{pole} and PDF's
  - Most precise result for m_t^{pole} up to this date
  - a_s and m_t^{pole} are extracted simultaneously

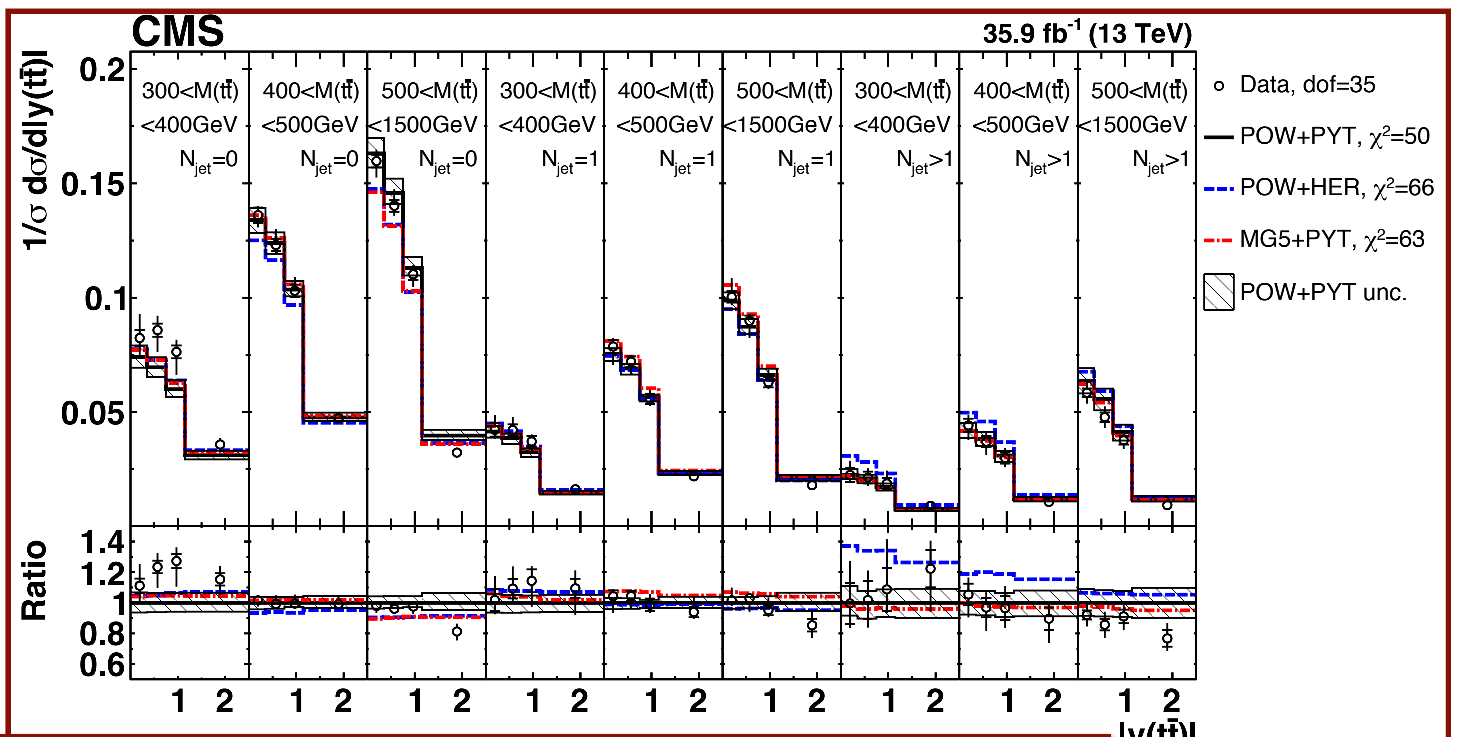
3D Differential Cross Sections

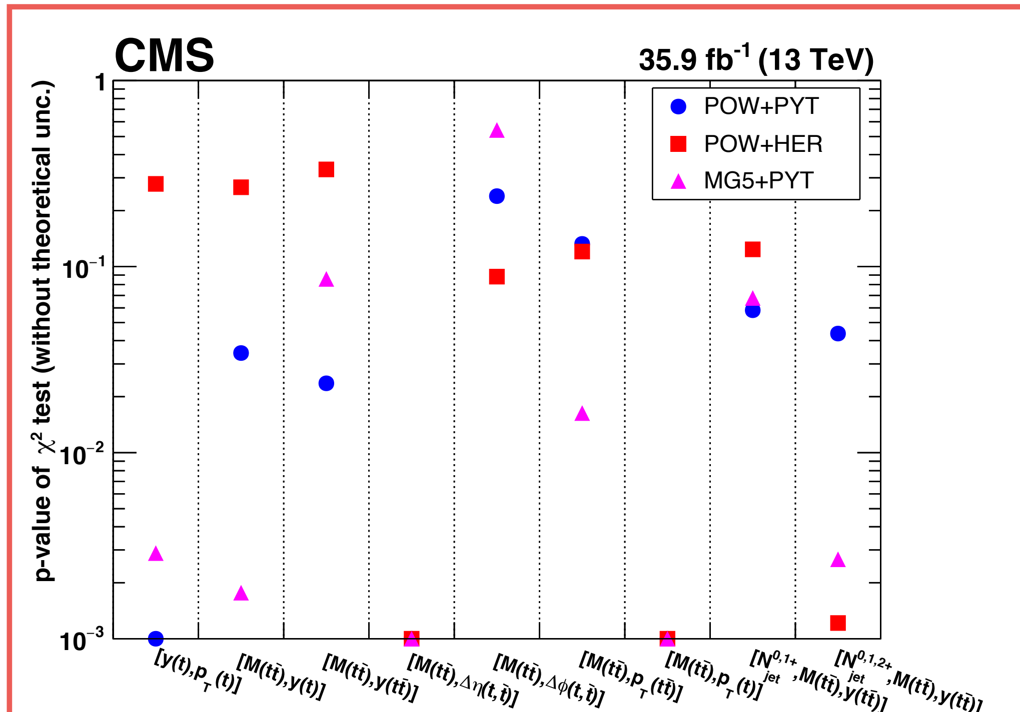
arXiv:1904.05237

All MC describe data well



Cross section variables	dof	χ^2 'POW+PYT'	'POW+HER'	'MG5+PYT'
$[y(t), p_T(t)]$	15	57	18	35
$[M(t\bar{t}), y(t)]$	15	26	18	36
$[M(t\bar{t}), y(t\bar{t})]$	15	28	17	23
$[M(t\bar{t}), \Delta\eta(t,\bar{t})]$	11	66	68	124
$[M(t\bar{t}), \Delta\phi(t,\bar{t})]$	15	14	18	10
$[M(t\bar{t}), p_T(t\bar{t})]$	15	21	22	29
$[M(t\bar{t}), p_T(t)]$	15	77	34	68
$[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$	23	34	31	34
$[N_{jet}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$	35	50	66	63





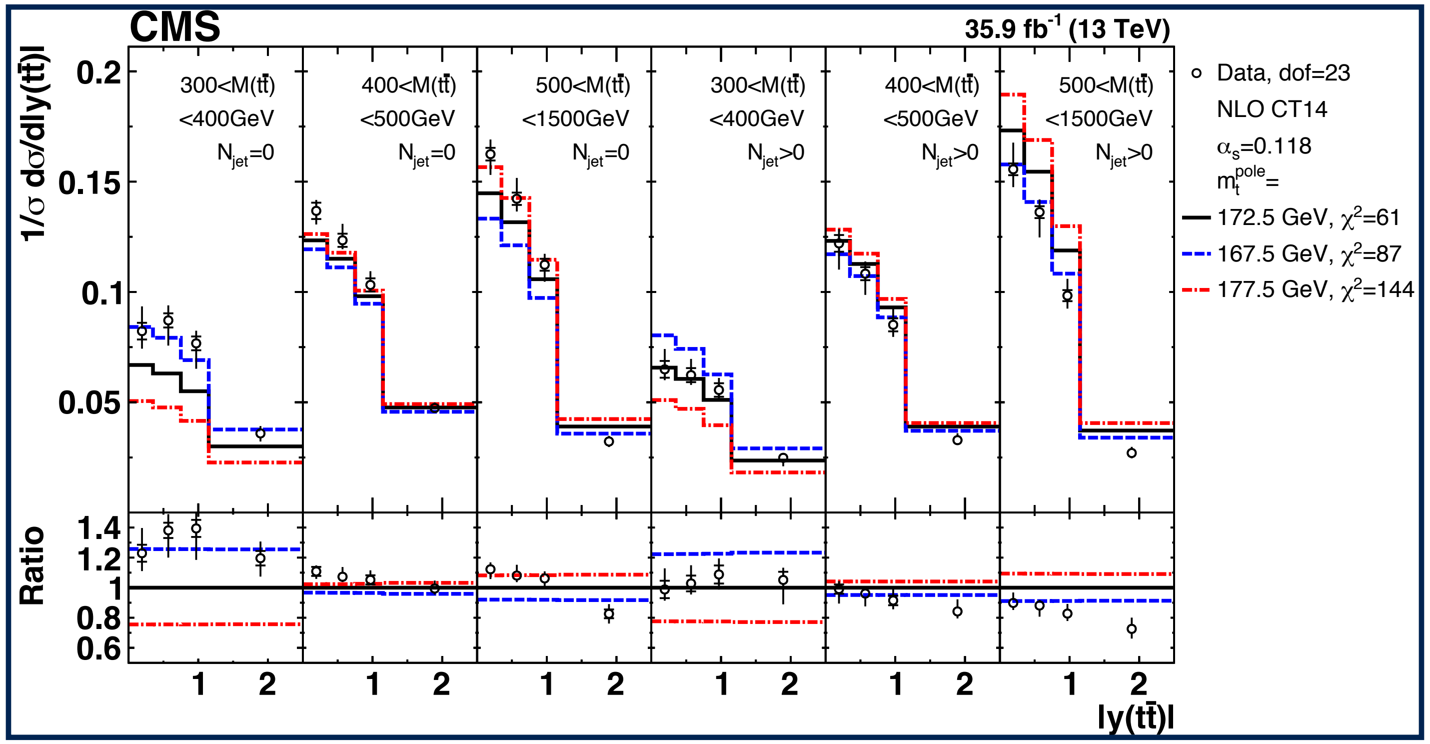
- Only 'POW+PYT' is in an agreement with data
- 'POW+HER' predicts too high XSEC for N_{jet} > 1
- 'MG5+PYT' worse $M(t\bar{t})$ at N_{jet} = 1

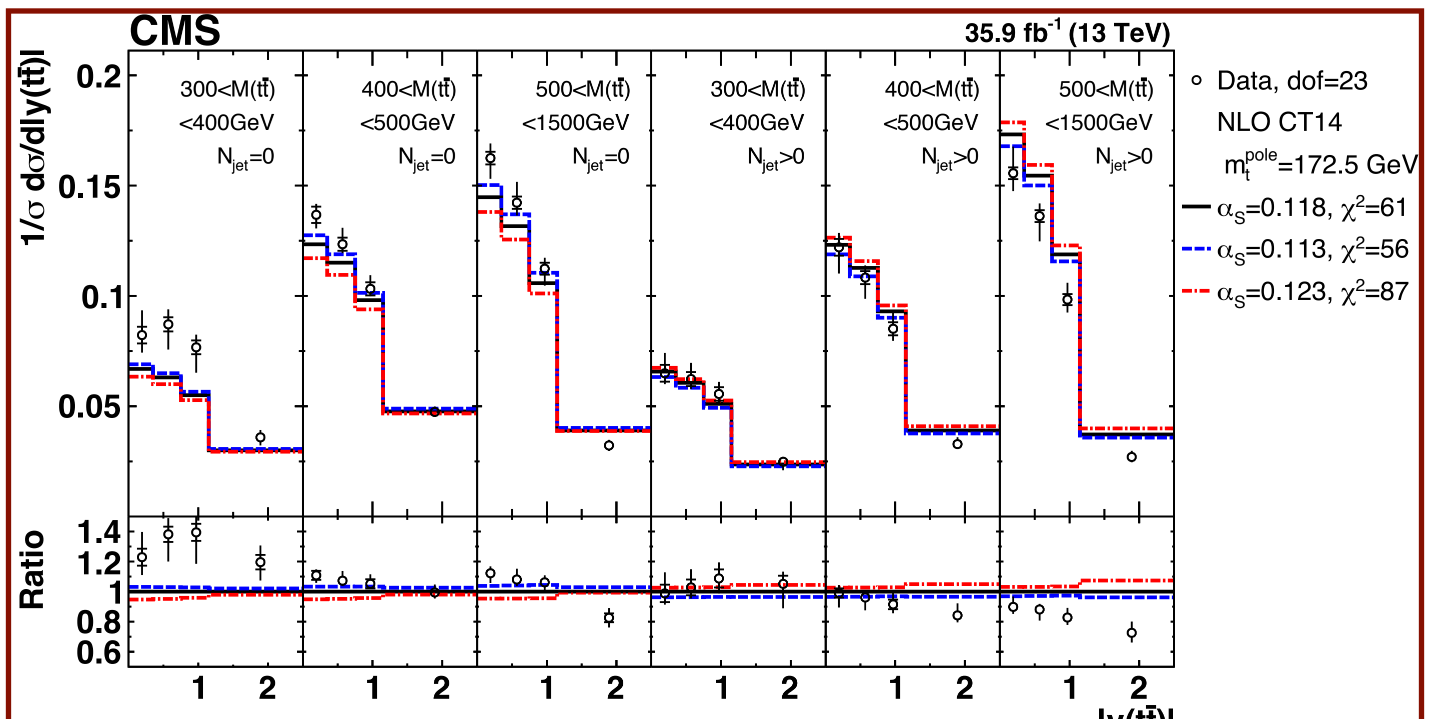
- Summary of Comparison to MC models
- None of the Central MC predictions is able to describe all distributions
- Best description by 'POW+PYT' and 'POW+HER'

Extraction of a_s, m_t^{pole} using external PDF's from 3D cross sections

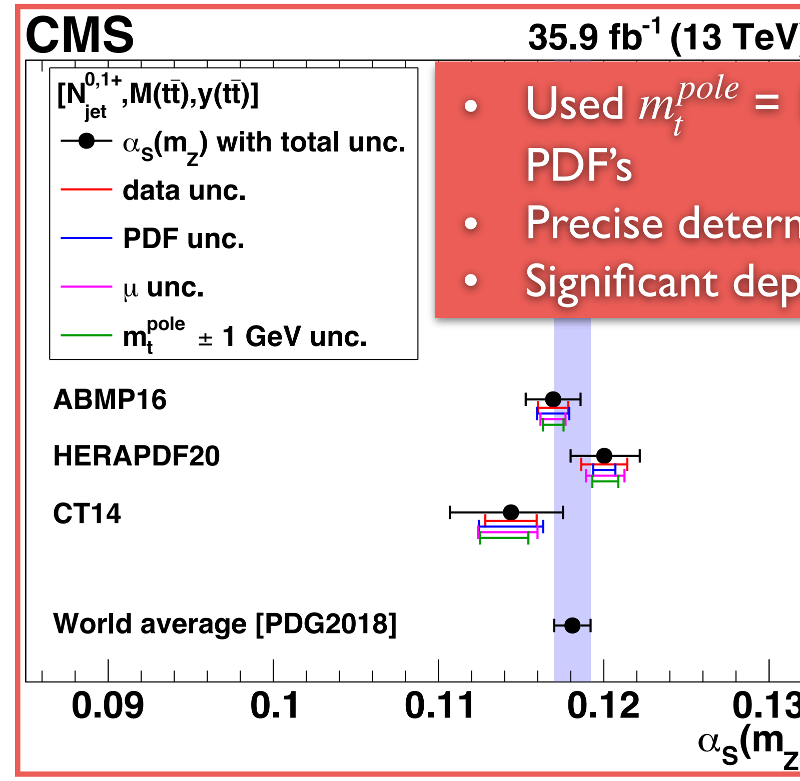
arXiv:1904.05237

m_t^{pole} sensitivity comes from $M(t\bar{t})$, mainly 1st bin

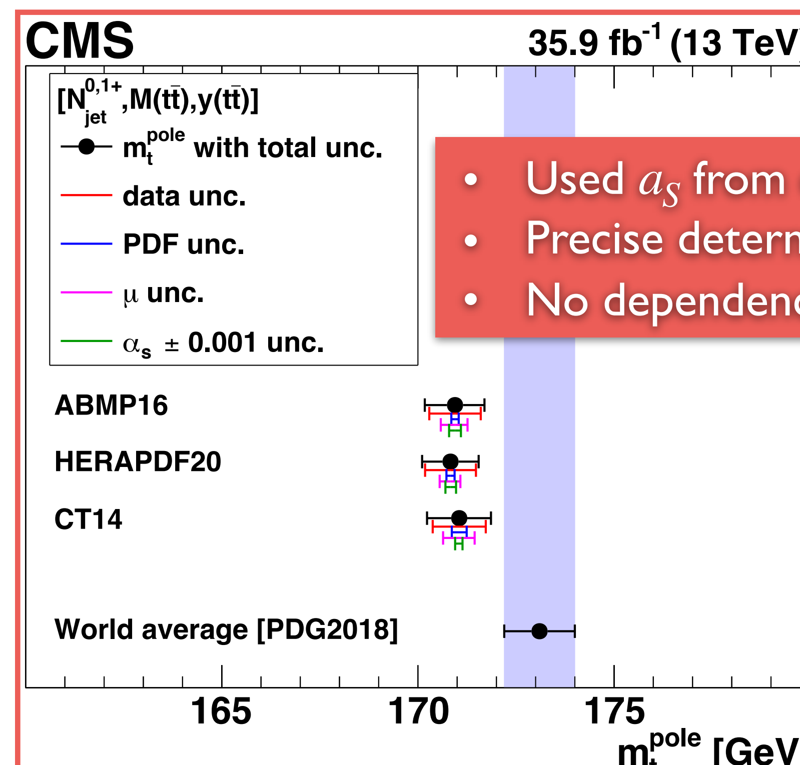




- α_S sensitivity comes from different N_{jet} bins
- Sensitivity comes from [$M(t\bar{t})$,$y(t\bar{t})$] via sensitivity to PDFs



- Used m_t^{pole} = 172.5GeV for all PDF's
- Precise determination of a_S
- Significant dependence on PDF

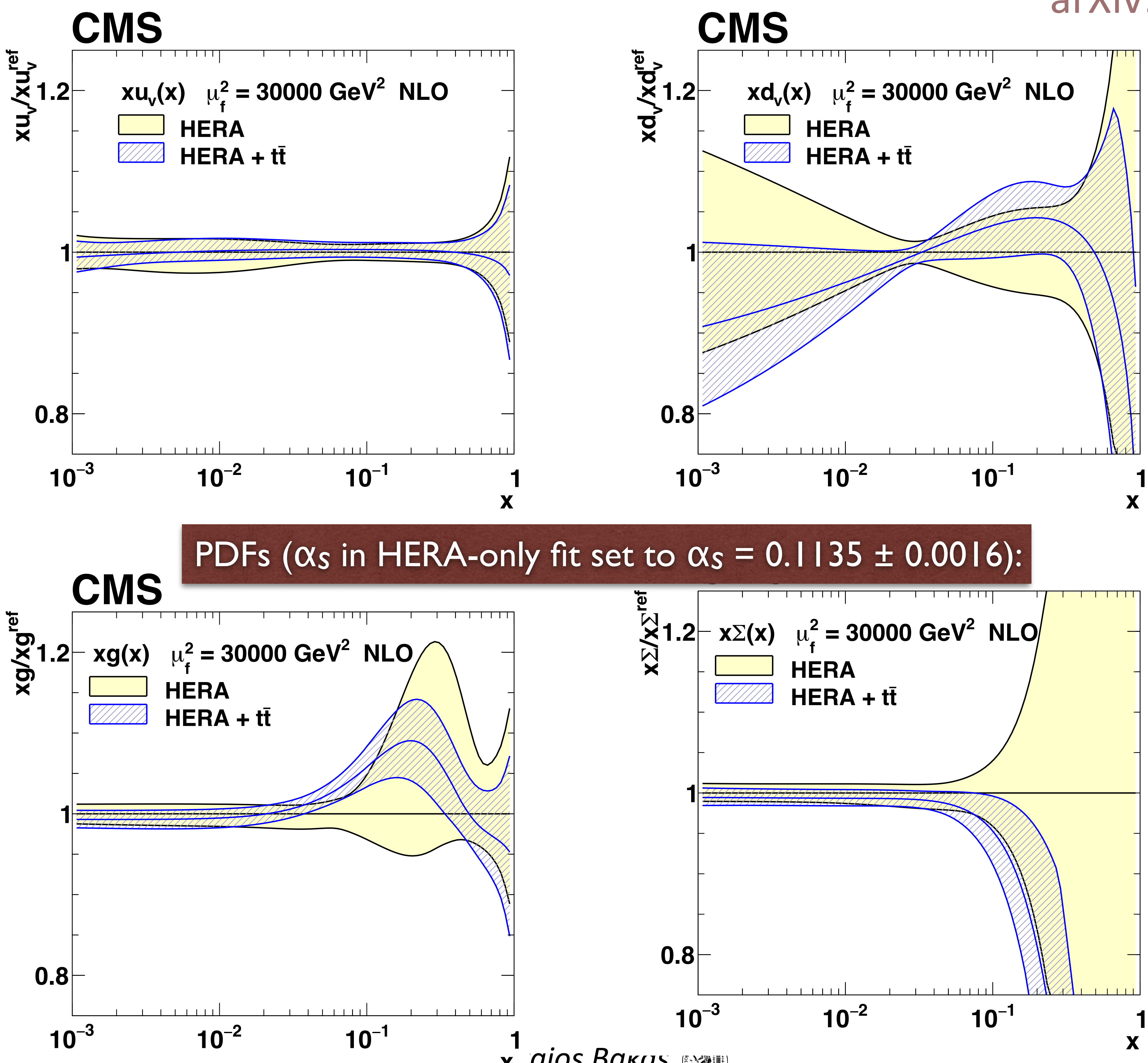


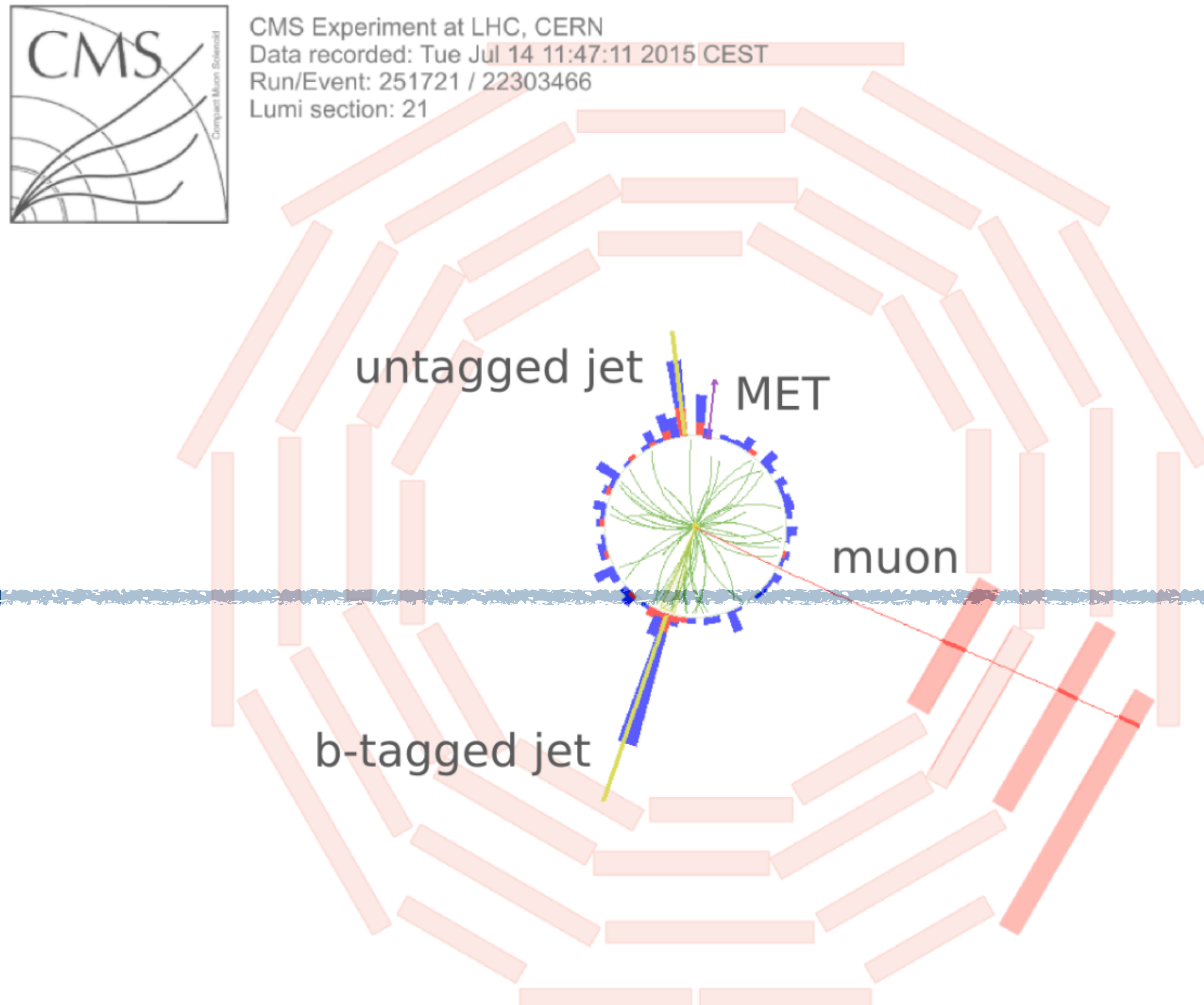
- Used a_S from each PDF set
- Precise determination of m_t^{pole}
- No dependence on PDF set

Extraction of α_s, m_t^{pole} and PDF's from 3D cross sections

arXiv:1904.05237

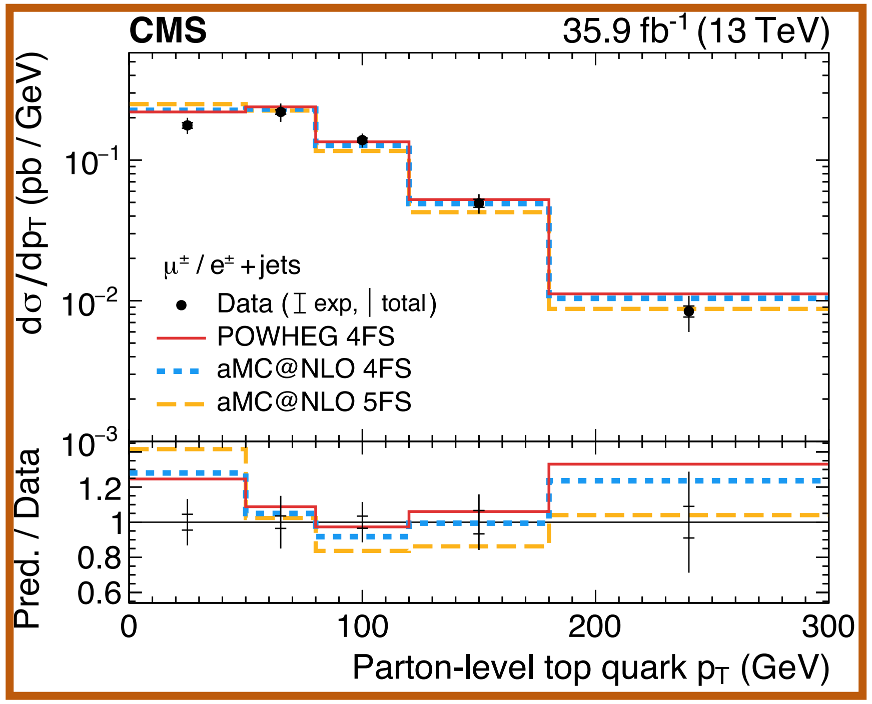
PDFs (α_S in HERA-only fit set to α_S = 0.1135 ± 0.0016):

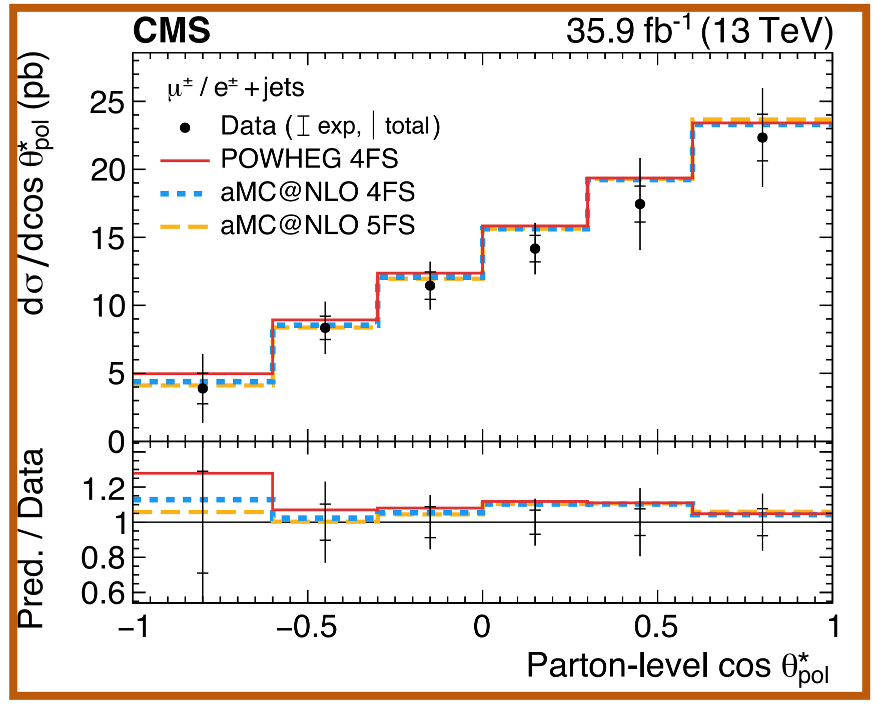


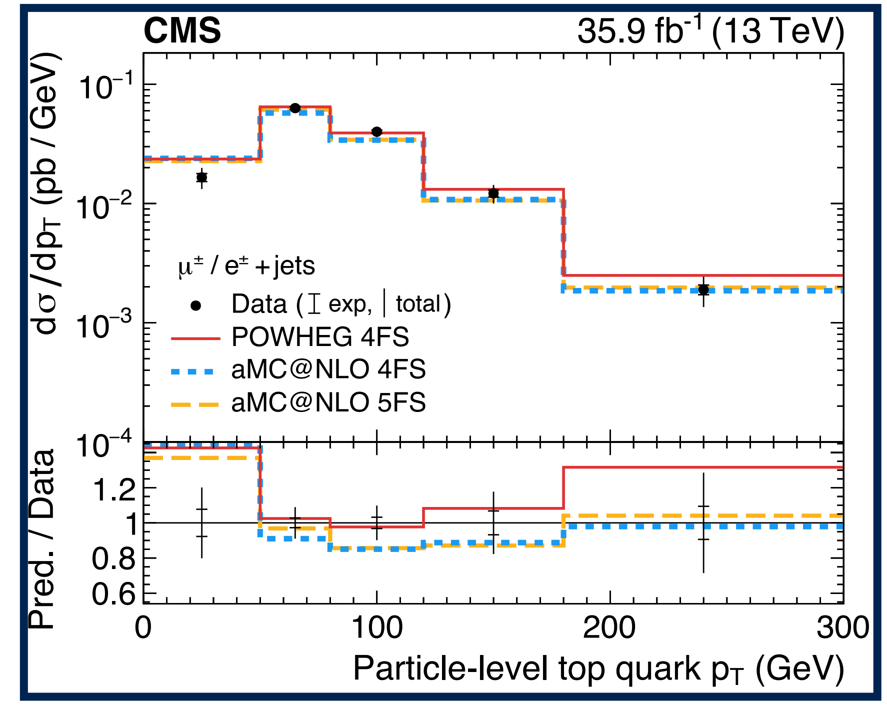

CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Jul 14 11:47:11 2015 CEST
Run/Event: 251721 / 22303466
Lumi section: 21
untagged jet
MET
muon
b-tagged jet

Single Top

Differential Cross Sections $d\sigma_{t(\bar{t})}/dX$ in t-channel



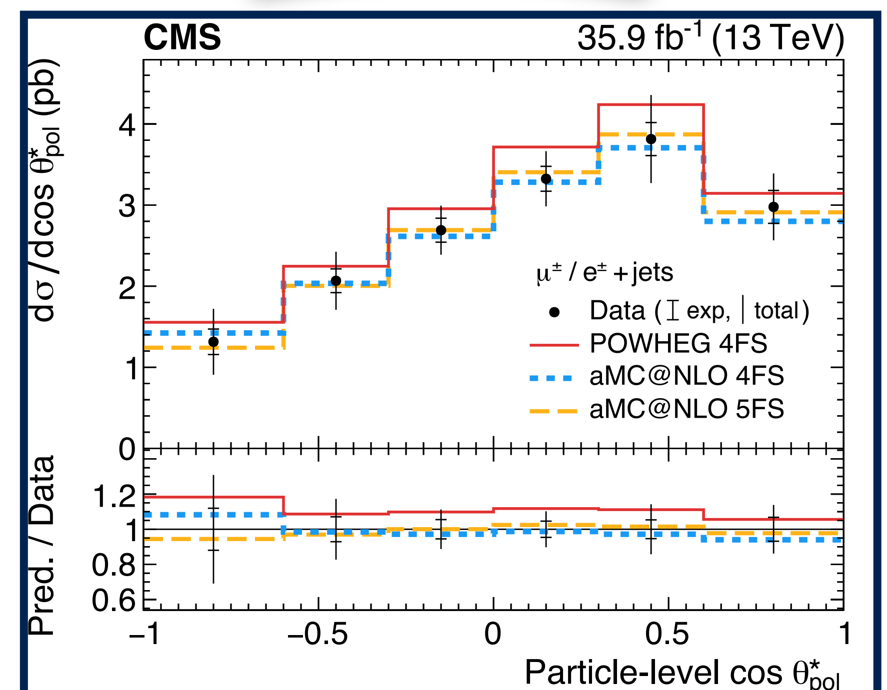




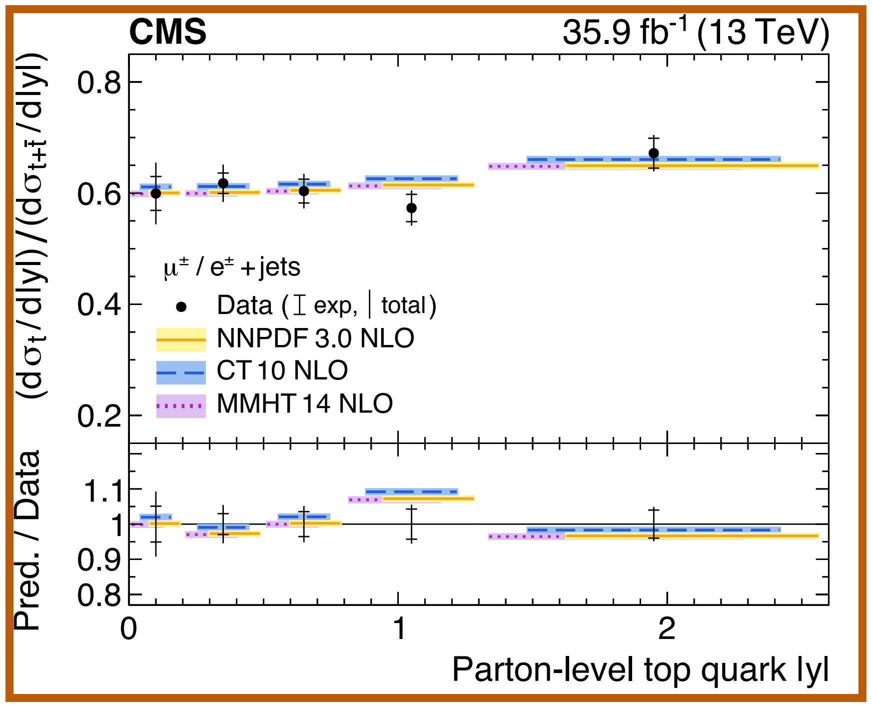
Parton

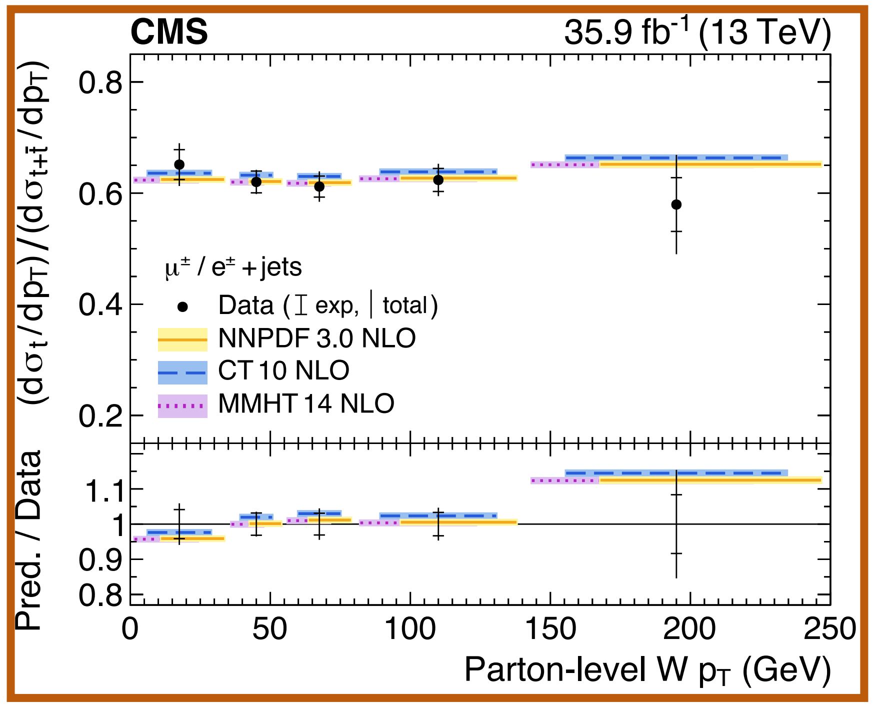
Particle

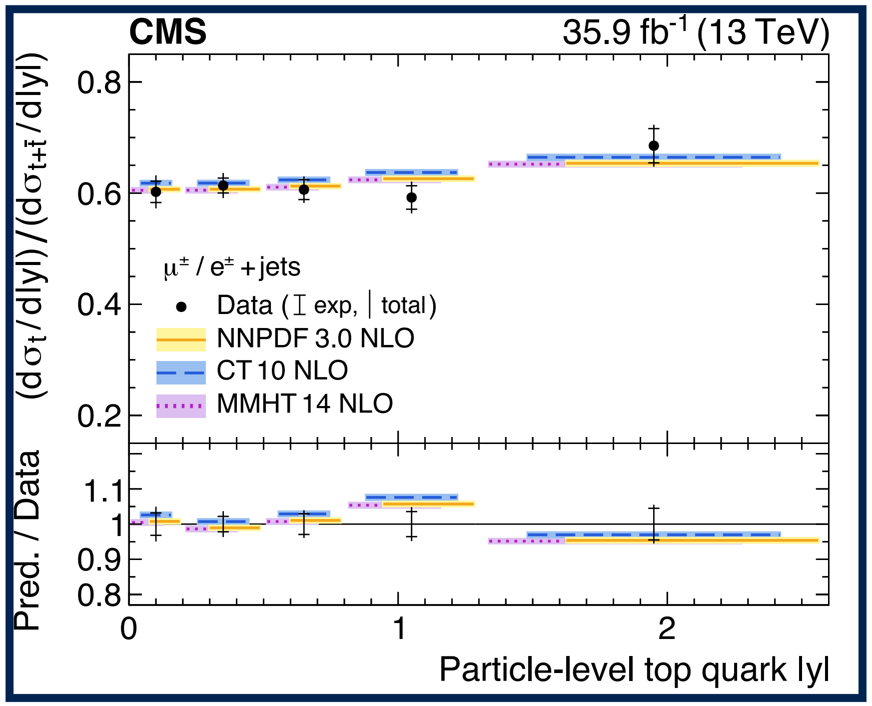
- Single top in t-channel
  - Events containing single muons or electrons and two or three jets are analysed (2j0b W+jet region, 2j1b signal region, 3j2b $t\bar{t}$ region)
- Measurements
  - Absolute and normalised differential cross section @ Parton and particle levels
  - Top quark pT, rapidity and polarisation angle $cos\theta_{pol.}^{*} = \frac{\vec{p}_{q'}^{(top)}\vec{p}_{l}^{(top)}}{|\vec{p}_{q'}^{(top)}| \cdot |\vec{p}_{l}^{(top)}|}$
  - Unlike $t\bar{t}$ productions, tops in t-channel are highly polarised due to the V-A coupling structure
  - Charged lepton pT, rapidity, W boson pT from the top quark decay
- Results
  - In agreement with predictions using various next-to-leading order event generators and various sets of parton distribution functions



Charge Ratios for single top quark in t-channel

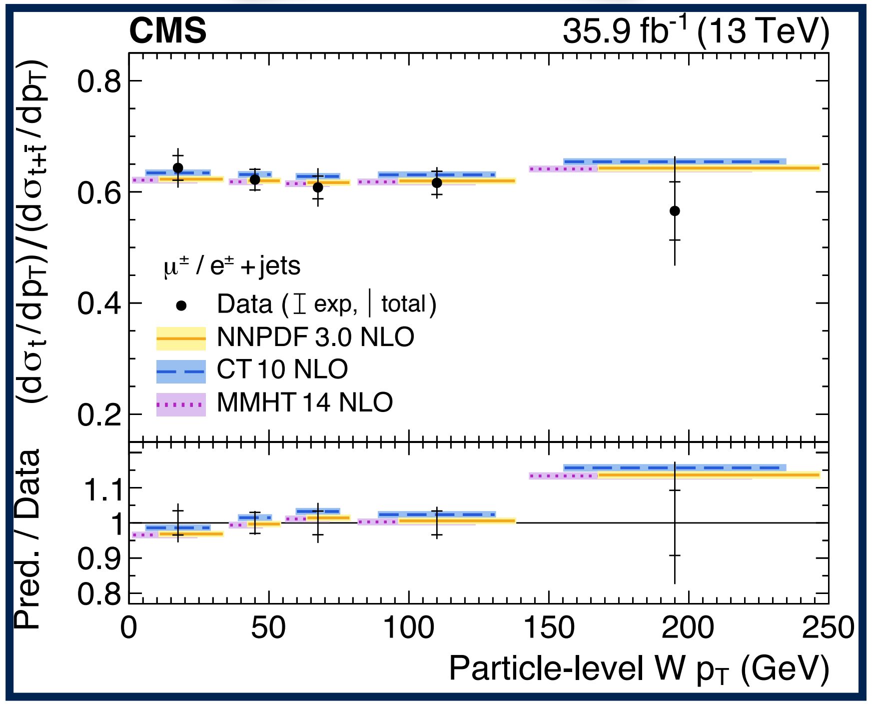






Parton

Particle



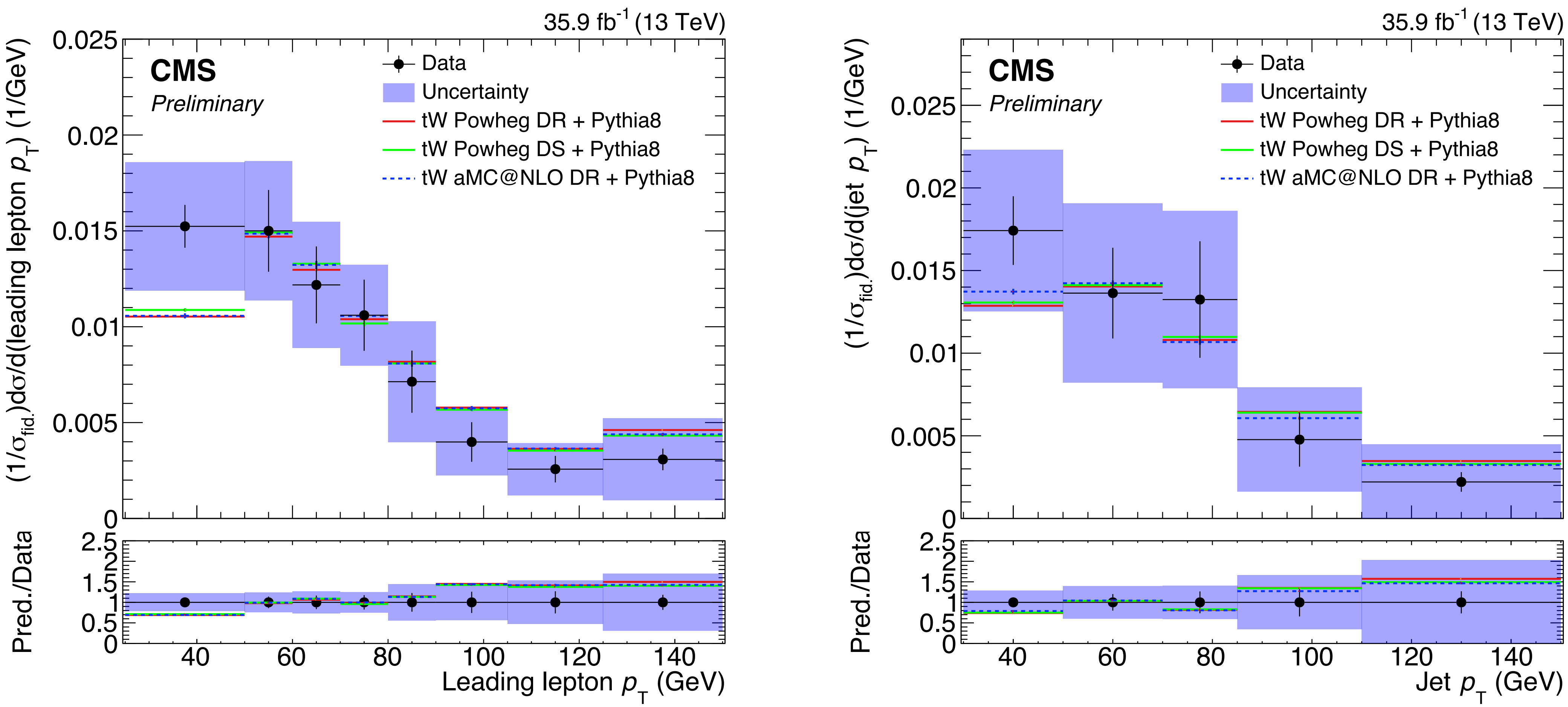
- **Charge Ratio**
  - Ratio of the single top cross section to the sum of the single top quark and antiquark cross sections
- **Measurement**
  - Differentially as a function of the top quark, charged lepton, and W boson kinematic observables
- **Results**
  - Shapes overall compatible with theory: no top pT

Spin Asymmetry in the single top t-channel

- Sensitive to top quark polarisation
- Determined from the differential distribution of the polarisation angle @ Parton Level
- In agreement with the SM predictions (POWHEG @ NLO): *0.436 (negligible uncertainty)*

		A_{μ}	A_{e}	$A_{\mu+e}$
	Central values	0.403	0.446	0.440
Profiled uncertainties	Statistical	±0.029	±0.038	±0.024
	$t\bar{t}$/tW normalisation	±0.010	±0.007	±0.007
	W/Z/γ^*+jets normalisation	±0.012	±0.011	±0.012
	Multijet normalisation	<0.001	<0.001	±0.003
	Multijet shape	<0.001	±0.006	<0.001
	Jet energy scale/resolution	±0.008	<0.001	<0.001
	b tagging efficiencies/misidentification	<0.001	±0.009	±0.004
	Others	<0.001	±0.003	±0.005
Theoretical uncertainties	Top quark mass	±0.033	±0.063	±0.044
	PDF+α_S	±0.011	±0.009	±0.011
	t channel renorm./fact. scales	±0.013	±0.018	±0.020
	t channel parton shower	±0.030	±0.008	±0.014
	$t\bar{t}$ renorm./fact. scales	±0.008	±0.019	±0.017
	$t\bar{t}$ parton shower	±0.031	±0.037	±0.033
	$t\bar{t}$ underlying event tune	<0.001	±0.014	±0.014
	$t\bar{t}$ p_T reweighting	<0.001	±0.010	±0.009
	W+jets renorm./fact. scales	<0.001	±0.019	±0.014
	Color reconnection	±0.036	±0.056	±0.031
	Fragmentation model	±0.011	±0.011	±0.011
Profiled uncertainties only (statistical+experimental)		±0.041	±0.047	±0.031
Total uncertainties		$\pm$ 0.071	±0.099	±0.070

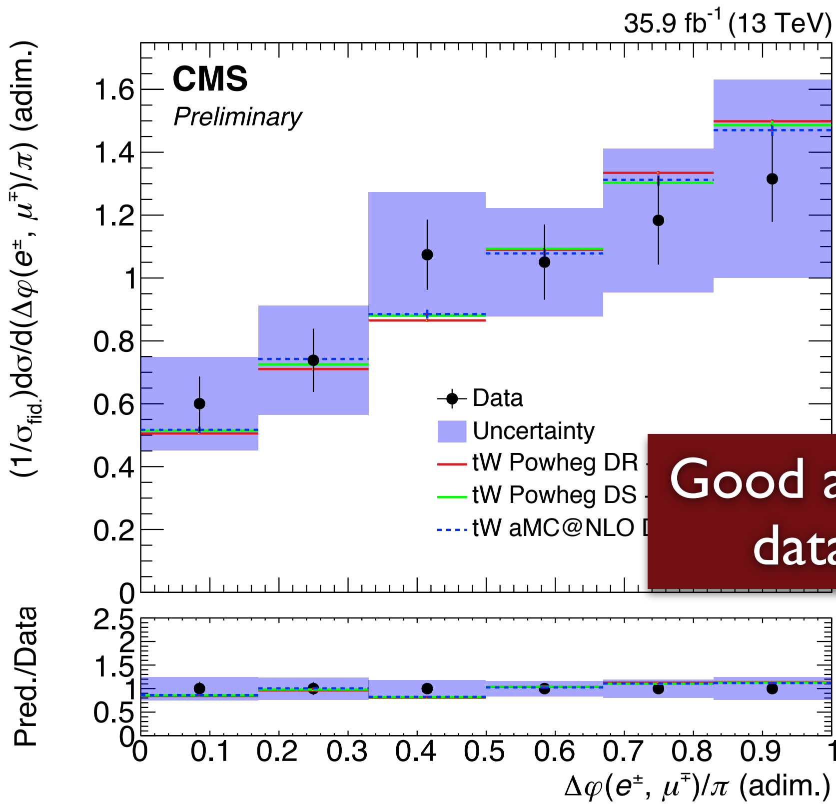
Single top - tW $d\sigma_{t(\bar{t})}/dX$

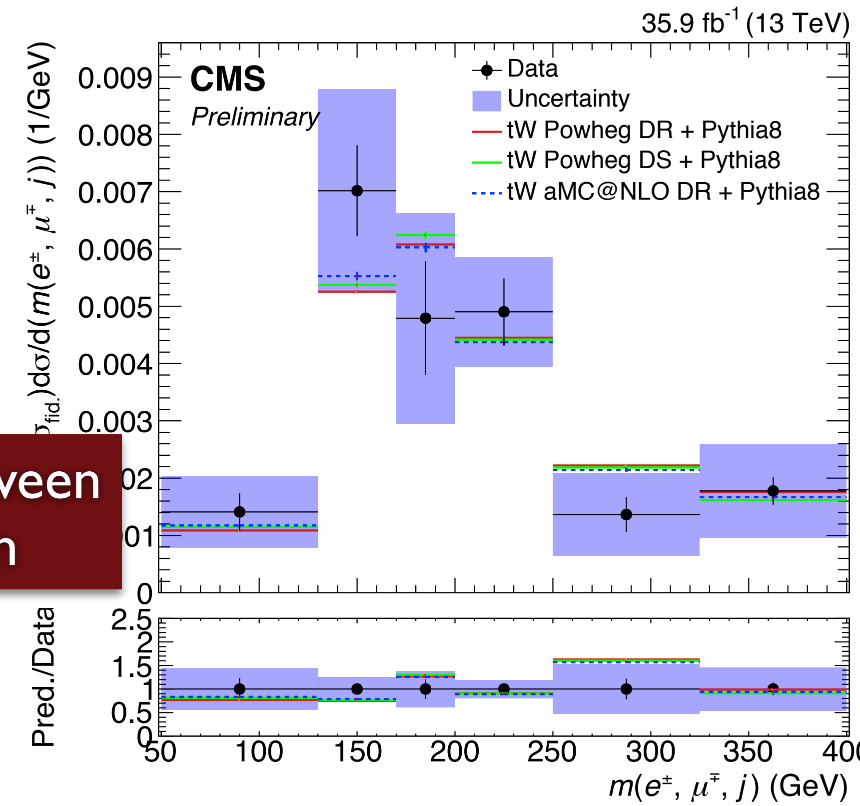


- Measurement of tW differential Cross Section
  - Main challenge is that background dominates signal—>$t\bar{t}$ being the largest
  - Signal extraction performed by subtracting bkg, estimated through MC simulations
- Measurements
  - Absolute and normalised differential cross section @ Particle level
  - pT for both the lepton and the jet, $\Delta\varphi(l_1, l_2)$, $m(l_1, l_2, j)$,$m_T(l_1, l_2, j, E_T^{miss})$ and $p_Z(l_1, l_2, j)$
- Results
  - Fair agreement, within the uncertainties with POWHEG DR, POWHEG DS and MADGRAPH5 aMC@NLO

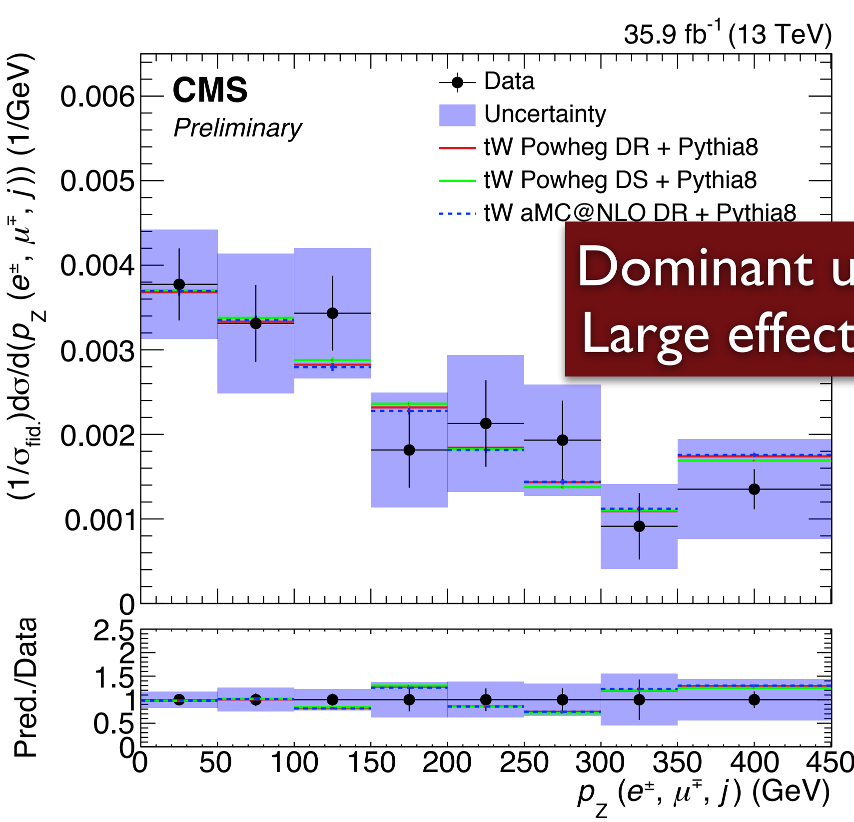
Single top - tW $d\sigma_{t(\bar{t})}/dX$

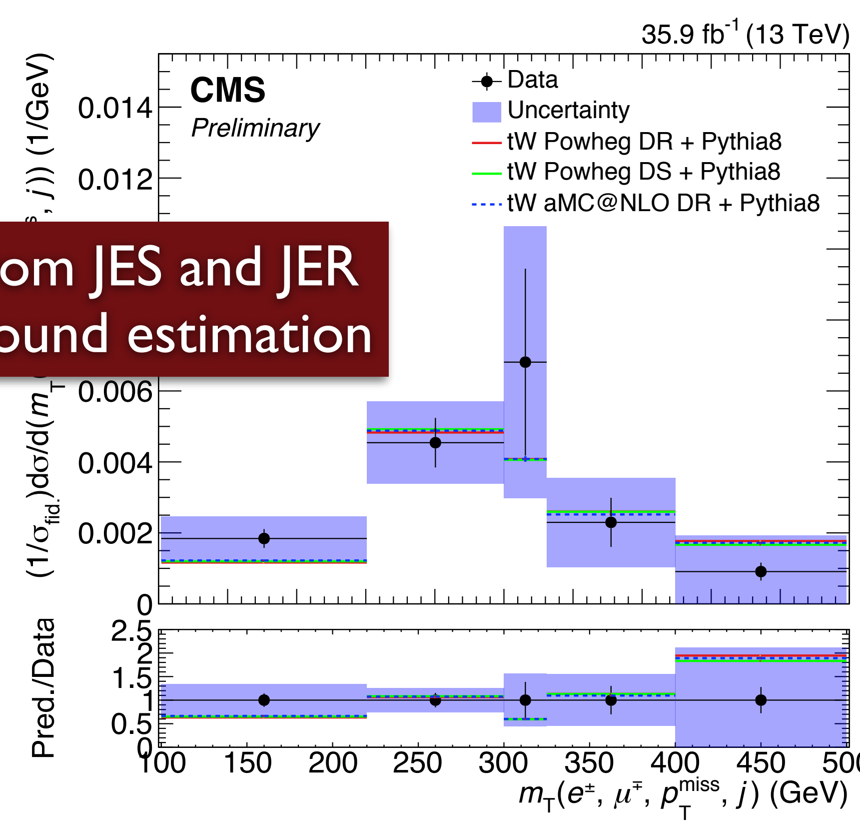
CMS-PAS-TOP-19-003





Good agreement between data and simulation





Dominant uncertainties from JES and JER
Large effect in the background estimation

Summary & Outlook

- **Single differential $t\bar{t}$ cross sections:**
  - Hadronic and $l + jets$ channel using 2016 CMS data (high pT jets)
  - All measurements are consistent with Standard Model expectations with an overall shift of the order of ~35% in the hadronic channel and ~20% in the $l + jets$ channel
- **Multi-differential $t\bar{t}$ cross sections:**
  - Dilepton channel using 2016 CMS data
  - 3D cross sections:
    - First extraction of such kind using $t\bar{t}$ differential cross sections
    - Most precise result on m_t^{pole} up to this date
    - a_S and m_t^{pole} are extracted simultaneously
- **Differential single top quark cross sections:**
  - tW process using 2016 CMS data, both absolute and normalised results
  - t-channel process using 2016 CMS data:
    - Normalised and absolute diff cross sections @ Parton and Particle levels
    - Top quark spin asymmetry estimated from $d(\sigma)/d(cos\theta_{pol})$
- **Interpretation of the results**
  - constraints of fundamental QCD parameters
  - indirect searches for BSM signals through top EFT framework
- **Stay tuned for more CMS results!**
  - large dataset available: will keep us busy in the next years!!

BACKUP

References (Publications + Preliminary Results)

(1)"Measurement of differential $t\bar{t}$ cross sections for high-p_T top quarks in proton-proton collisions at sqrt(s) = 13 TeV", **CMS-PAS-TOP-18-013**

(2)"Measurement of $t\bar{t}$ normalised multi-differential cross sections in pp collisions at sqrt(s) = 13 TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions", **arXiv:1904.05237**

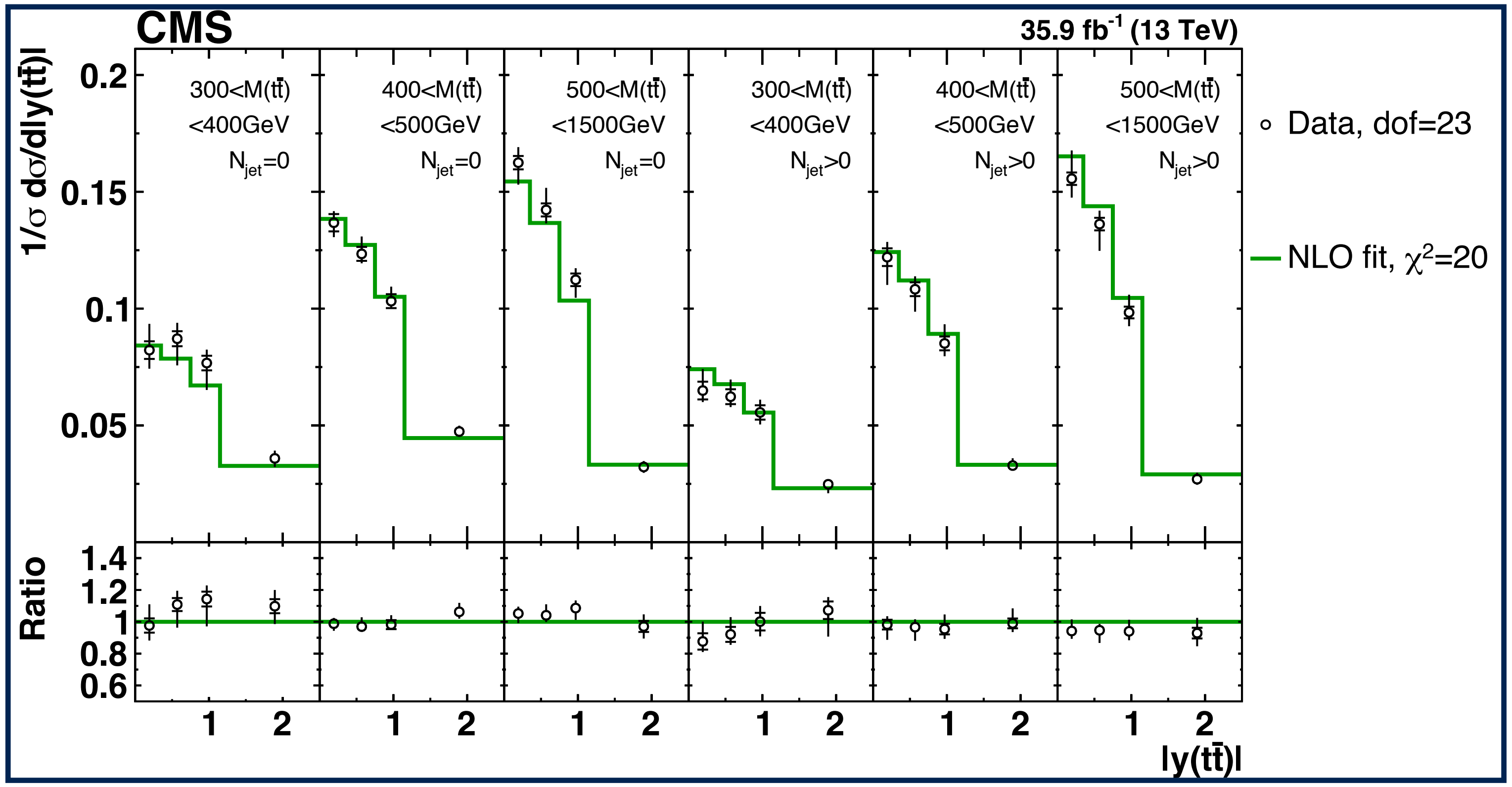
(3)"Measurement of differential cross sections for single top quark production in association with a W boson at sqrt(s) = 13 TeV", **CMS-PAS-TOP-19-003**

(4)"Measurement of differential cross sections and charge ratios for *t*-channel single top quark production in proton-proton collisions at sqrt(s) = 13 TeV", **Eur. Phys. J. C 80, 370 (2020), arXiv:1907.08330**

Simultaneous PDF, a_s and m_t^{pole} fit

- Simultaneous fit of PDF's, a_S and m_t^{pole} using HERA DIS:
  - This presents fully unbiased extraction of PDF's, a_S and m_t^{pole}, but using also HERA data
  - Important as exercise to understand $t\bar{t}$ data, providing baseline for future global fits

Data sets	χ^2/dof	
	Nominal fit	$+[N_{\text{jet}}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$
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



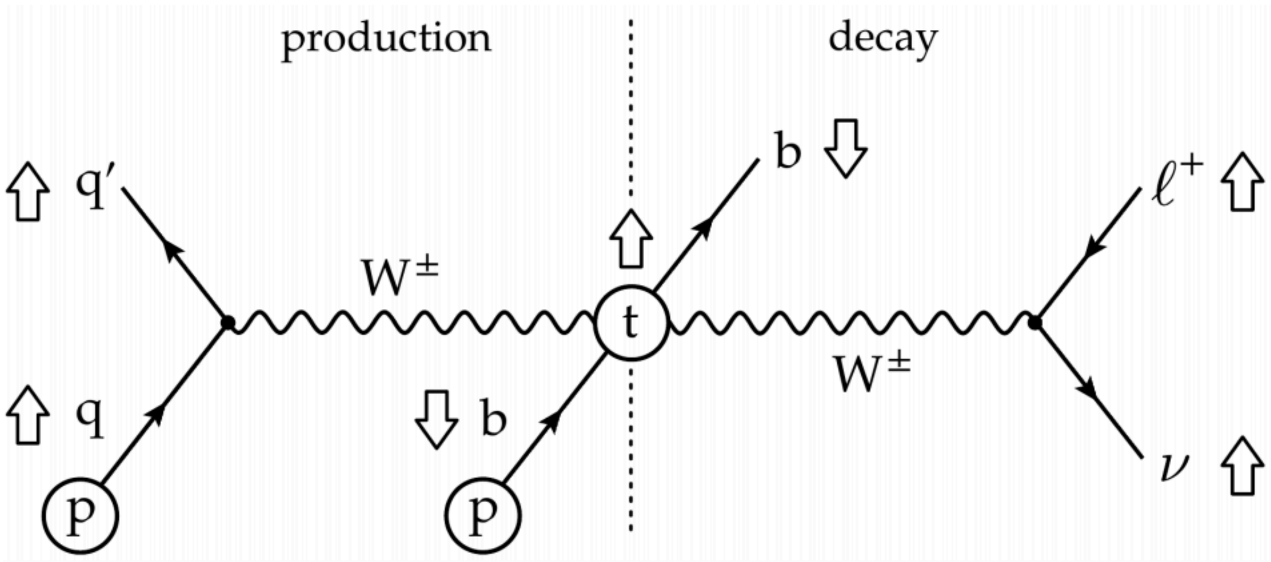
- The resulting values of a_S and m_t^{pole} extracted using NLO calculations:

a_S	$0.1135^{+0.0021}_{-0.0017}$
m_t^{pole}	170.5 ± 0.8 GeV

Comparison of the measured $[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ cross sections to the NLO predictions using the parameter values from the simultaneous PDF, a_S and m_t^{pole} fit

Spin Asymmetry in the single top t-channel

◉ Differential Cross section @ Paton Level



$$\frac{d\sigma}{\sigma dcos\theta^*_{pol.}} = \frac{1}{2}(1 + 2A_l cos\theta^*_{pol.})$$

$$cos\theta_{pol.}{}^* = \frac{\vec{p}^{\,(top)}_{q'}\vec{p}^{\,(top)}_{l}}{|\vec{p}^{\,(top)}_{q'}| \cdot |\vec{p}^{\,(top)}_{l}|}$$

$$A_l = \frac{1}{2}P \cdot a_l$$

- Spin - analyzing power a_l —> degree of alignment of charged lepton with top spin
- Polarisation P_t —> degree of alignment of spectator quark momentum with top spin

- Estimate asymmetry through linear χ^2 from $d\sigma/dcos\theta_{pol.}$