Top quark pair and single top differential cross sections in CMS

Georgios Bakas

on behalf of the CMS collaboration

ICHEP 2020

40th International Conference on High Energy Physics

28 Jul 2020

Outline

Top pair production

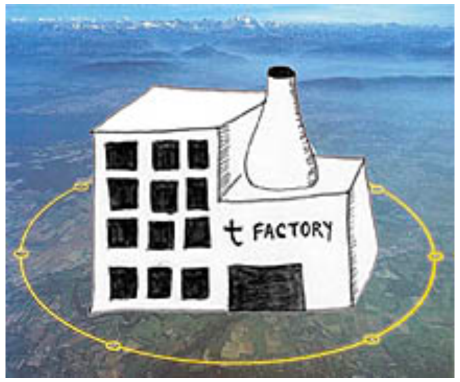
- Differential Cross Section measurements (high-pT)
- Normalised multi-differential Cross Section measurements
- Strong coupling strength a_s
- Top quark pole mass m_t^{pole}
- Parton distribution functions (PDF)

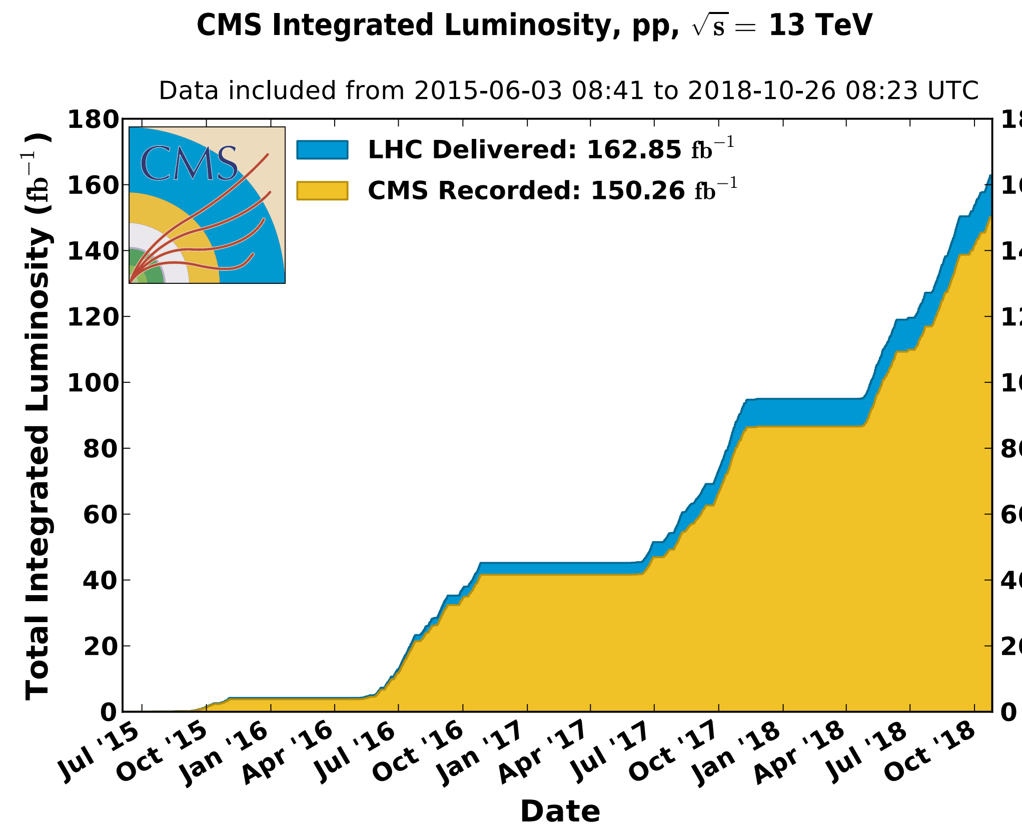
Single top production

- Differential cross section measurements (t-channel, tW)
- Associated production with a W boson
- Charge Ratios (t-channel)

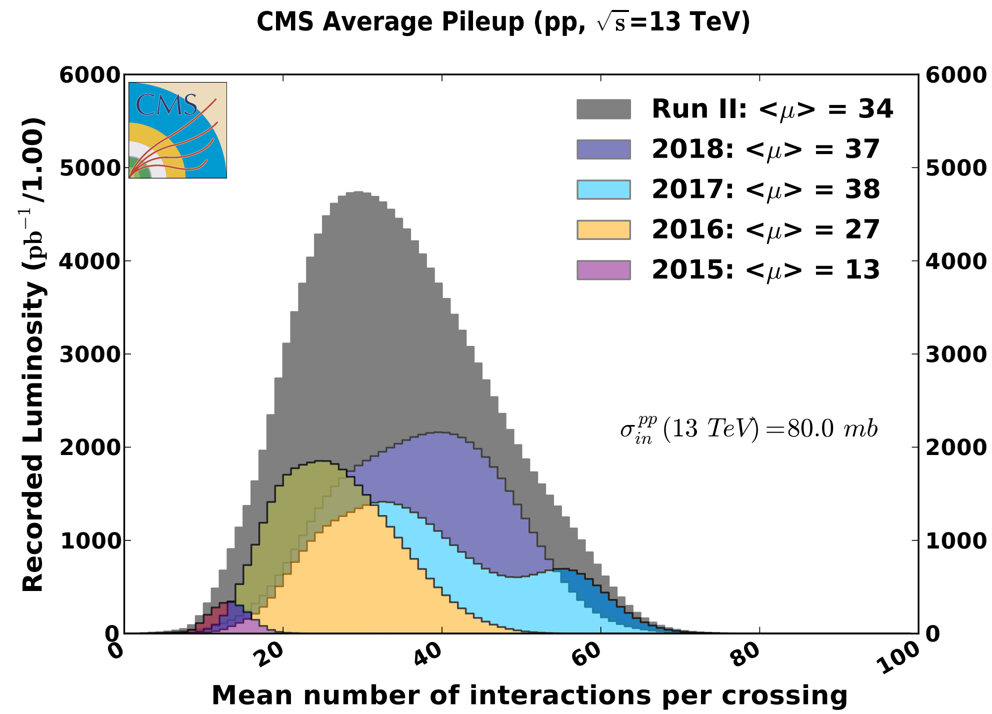
CMS @ LHC Run2 (2015-2018)

- 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



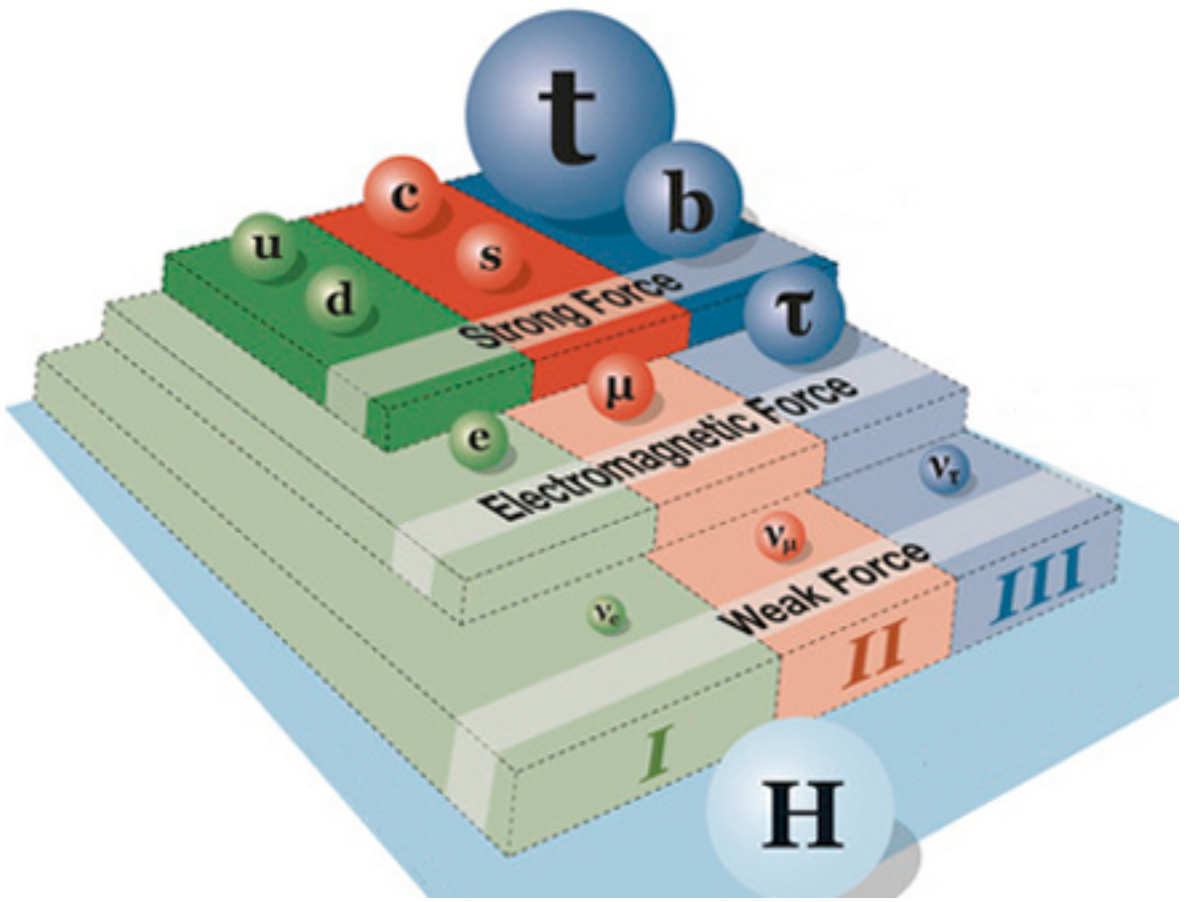


- Event sample enable broad physics that can
  - Probe SM processes/calculations with high precision
  - Detect very rare processes
  - Explore vast kinematic phase space

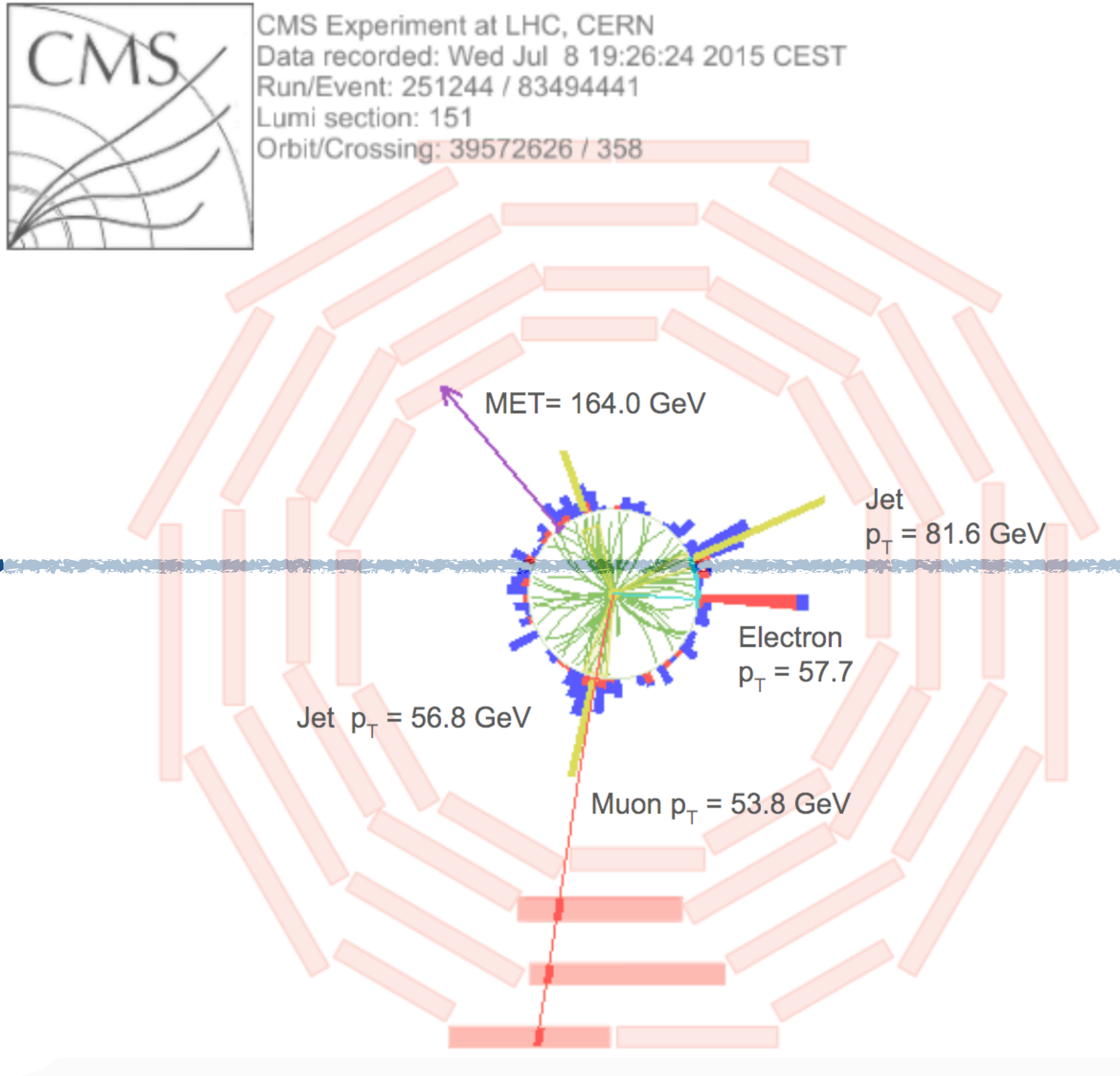


Why differential measurements?

- $t\bar{t}$ as a function of different kinematic variables:
  - Opportunity to test the SM at TeV scale
- Extensions to the SM may modify the $t\bar{t}$ differential cross sections in ways that an inclusive cross sections measurement is not sensitive to:
  - Such effects can distort top quark pT (especially at high pT's)
- Enhance sensitivity to possible BSM effects
- Challenge theoretical predictions that reach the NNLO accuracy in perturbative QCD
- Sensitive to the differences between MC generators:
  - Valuable input to the tuning of the MC parameters

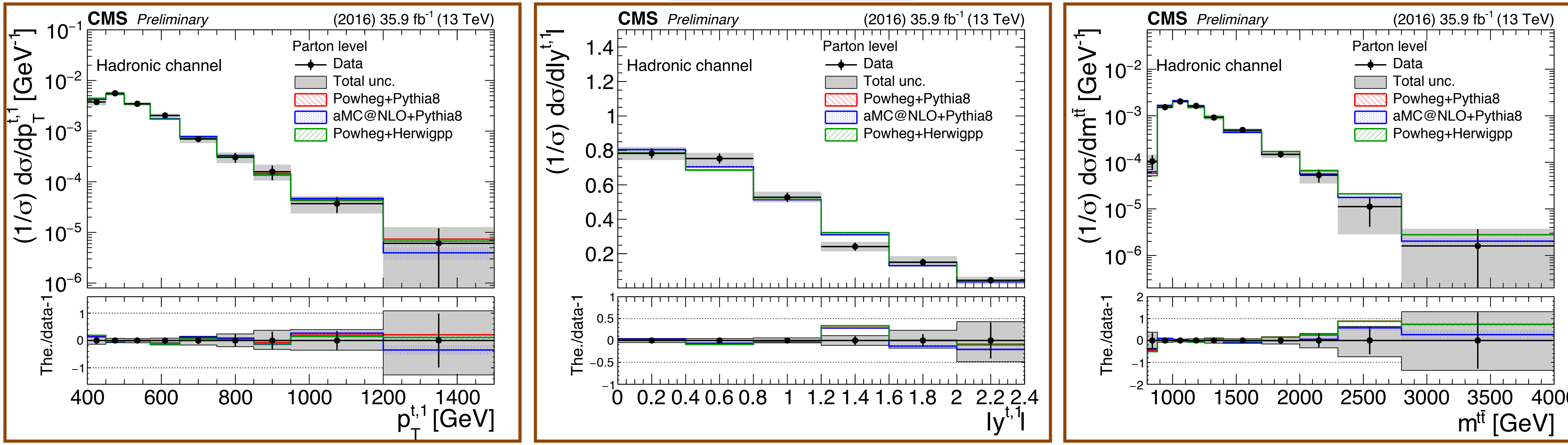


Top Pair

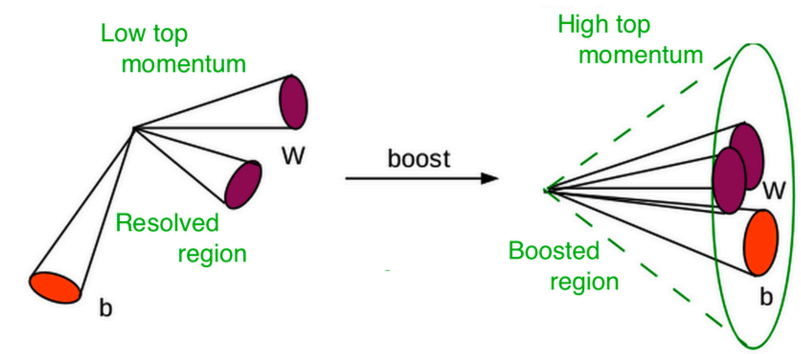

CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 19:26:24 2015 CEST
Run/Event: 251244 / 83494441
Lumi section: 151
Orbit/Crossing: 39572626 / 358
MET= 164.0 GeV
Jet
p_T = 81.6 GeV
Electron
p_T = 57.7
Jet p_T = 56.8 GeV
Muon p_T = 53.8 GeV

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

Parton



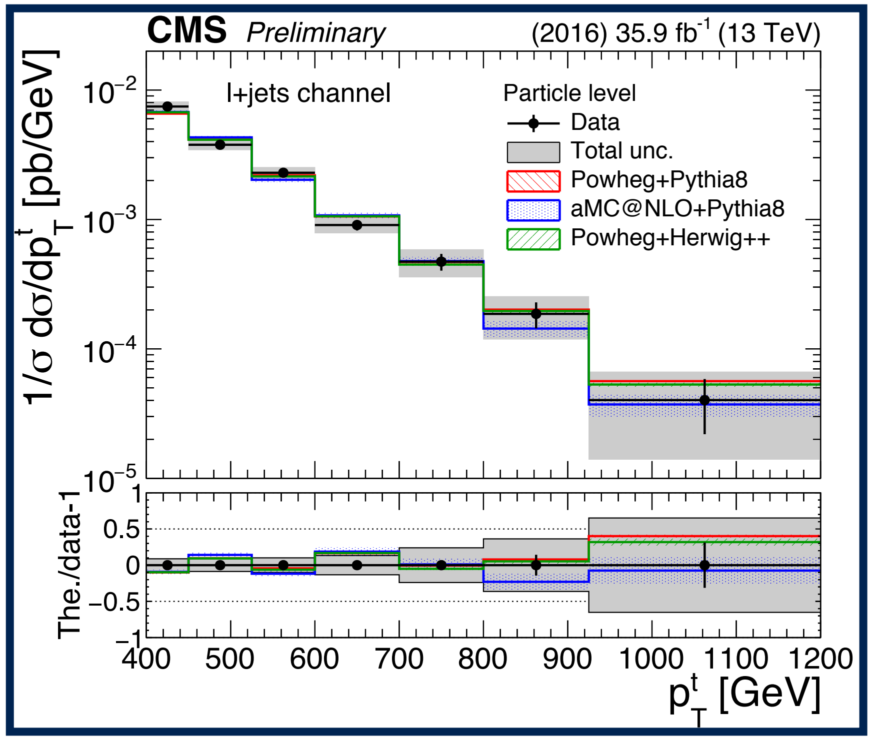
Hadronic



- Full hadronic for high-pT jets
  - Selection and $t\bar{t}$ reconstruction with NN
  - Explore the kinematic region beyond the reach of the resolved analyses
- 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 in the order of 35% in the total cross section

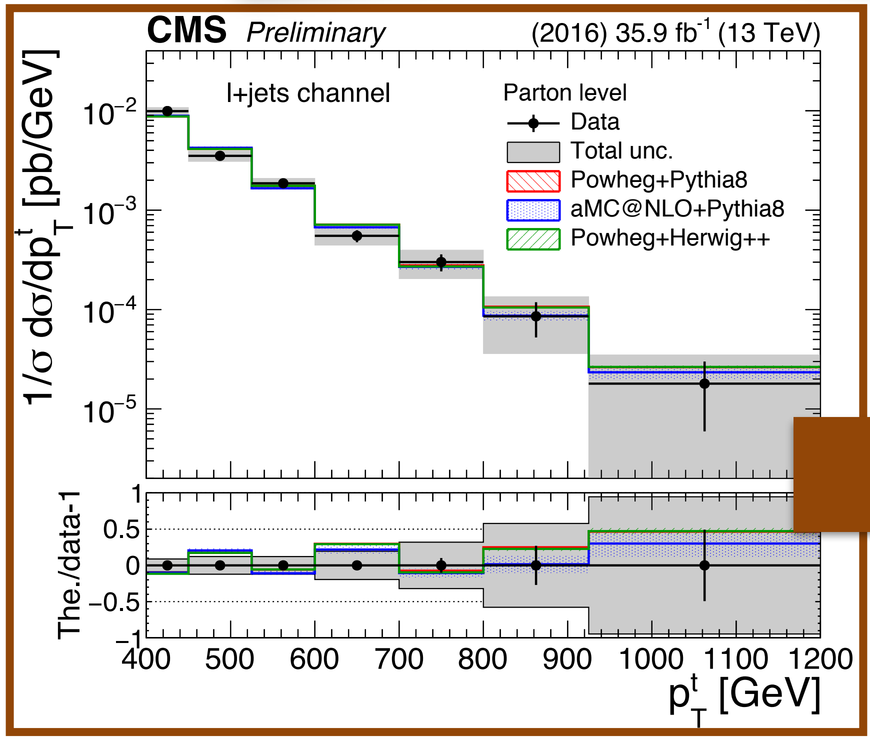
Differential Cross Sections $d\sigma_{t\bar{t}}/dX$

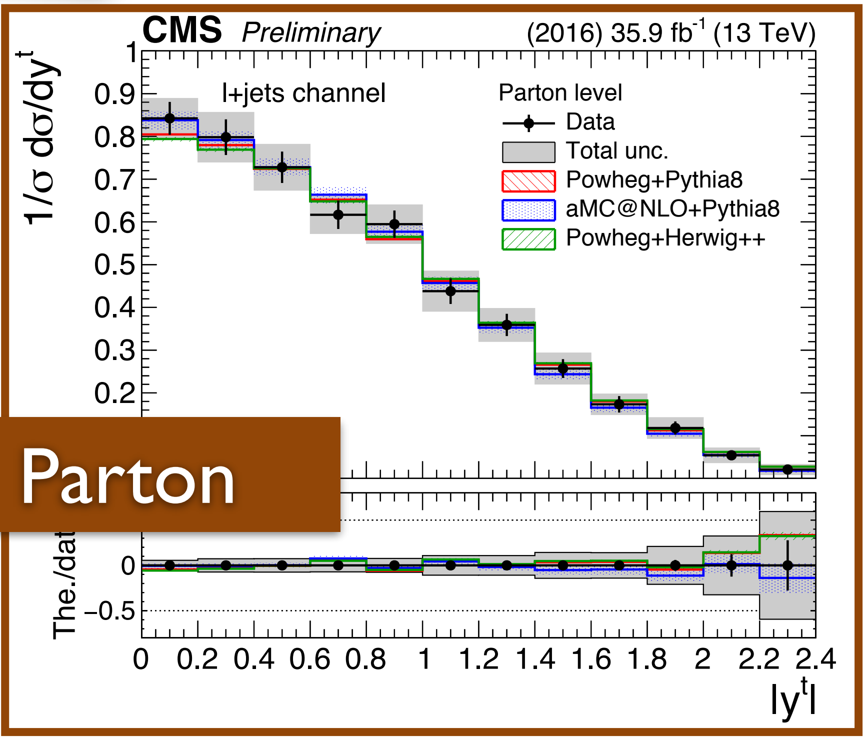
- L + jets for high-pT jets
  - Selection based on t- and b-jet categories
- Measurements
  - Absolute and normalised differential cross section @ Parton and particle levels
  - Hadronically decaying top pT and |y|
- Results
  - Differential distributions are generally well described
  - All models overpredict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



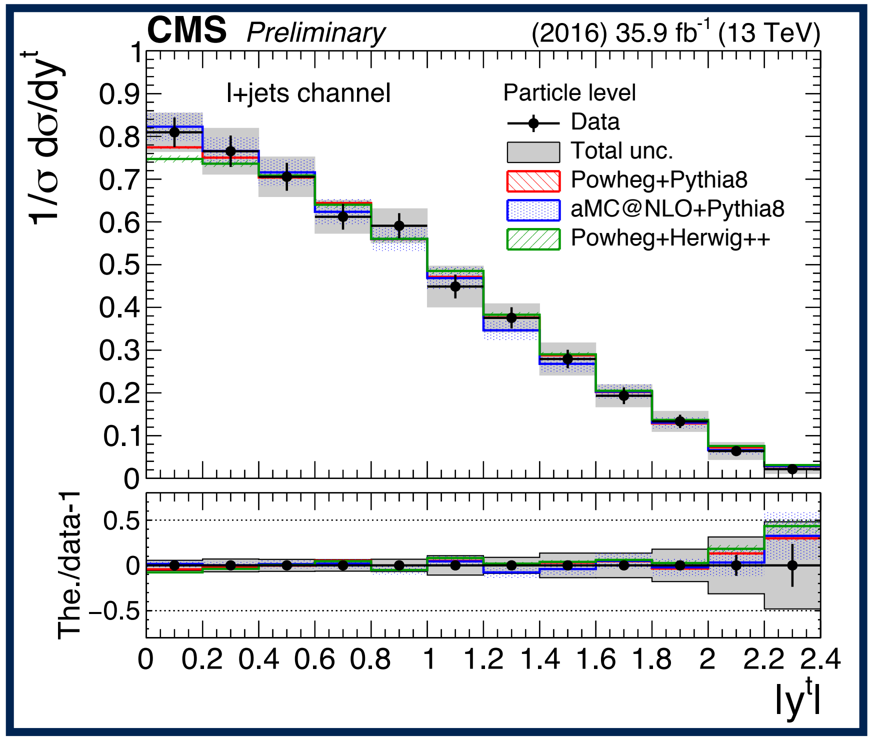
L + jets

Particle

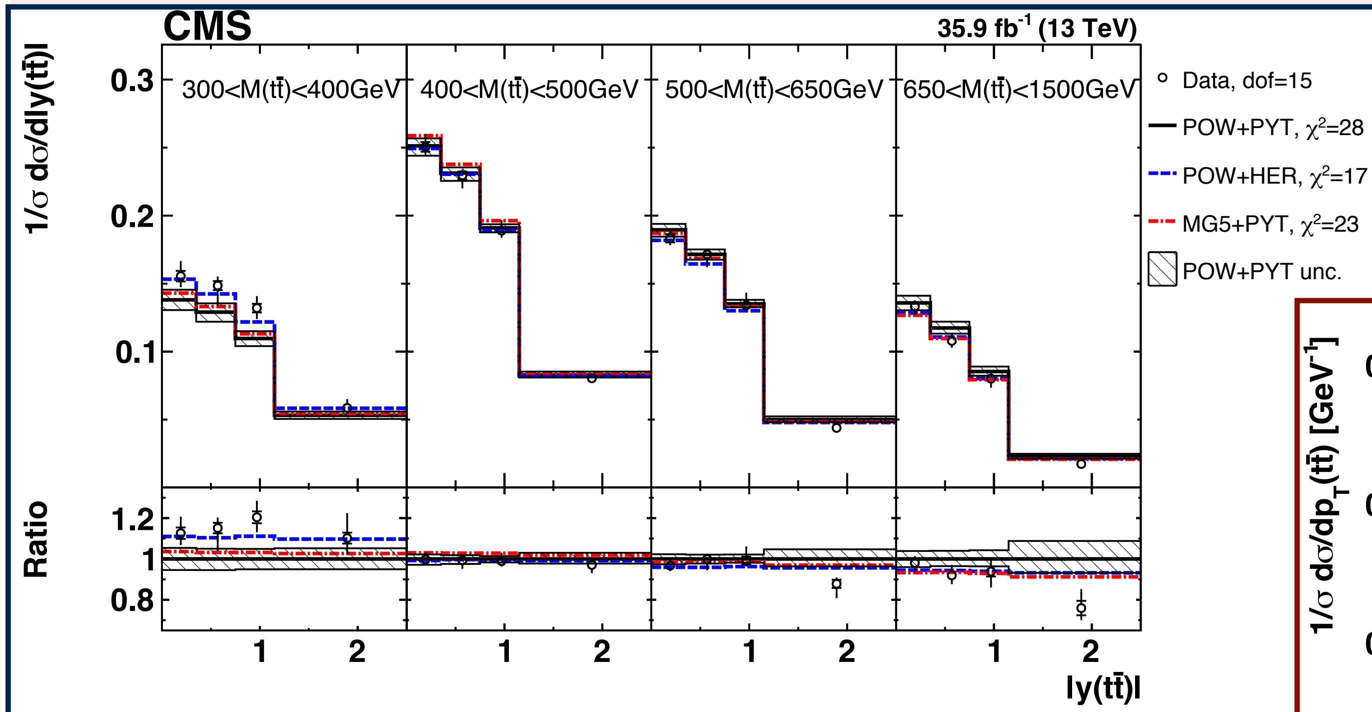




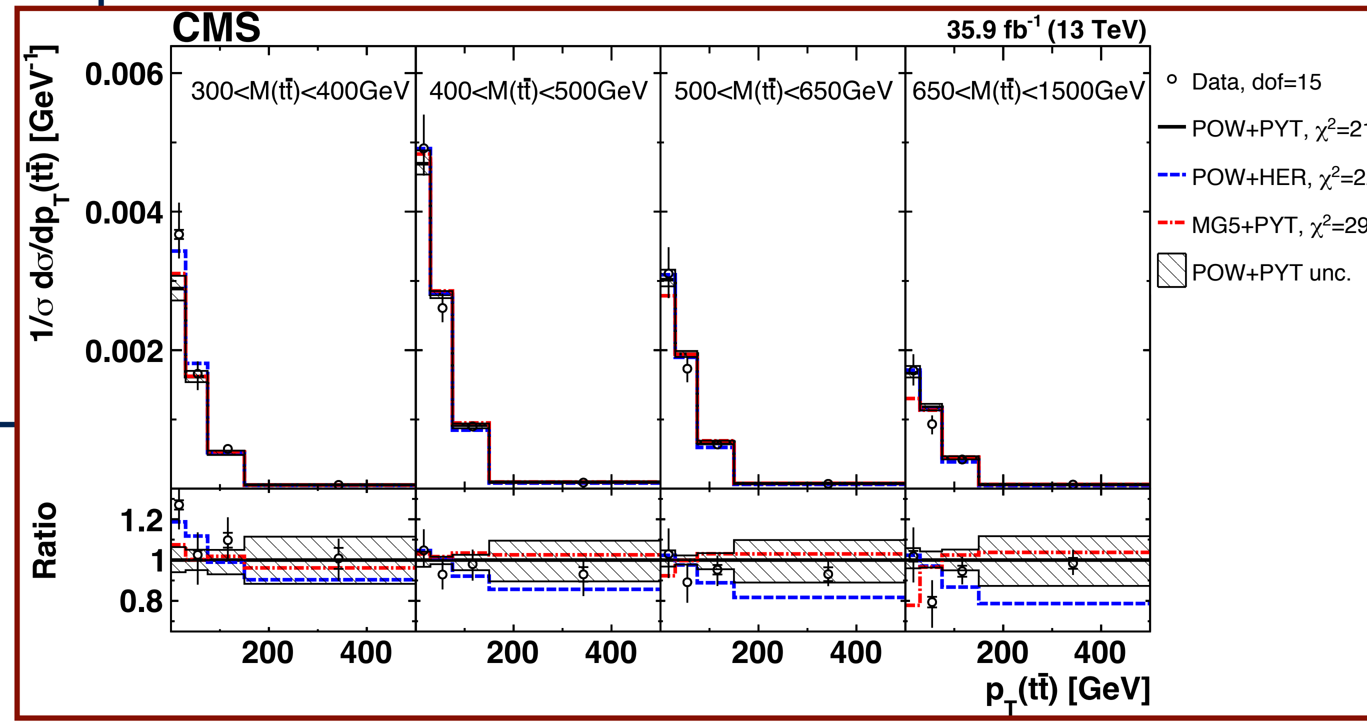
Parton



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'

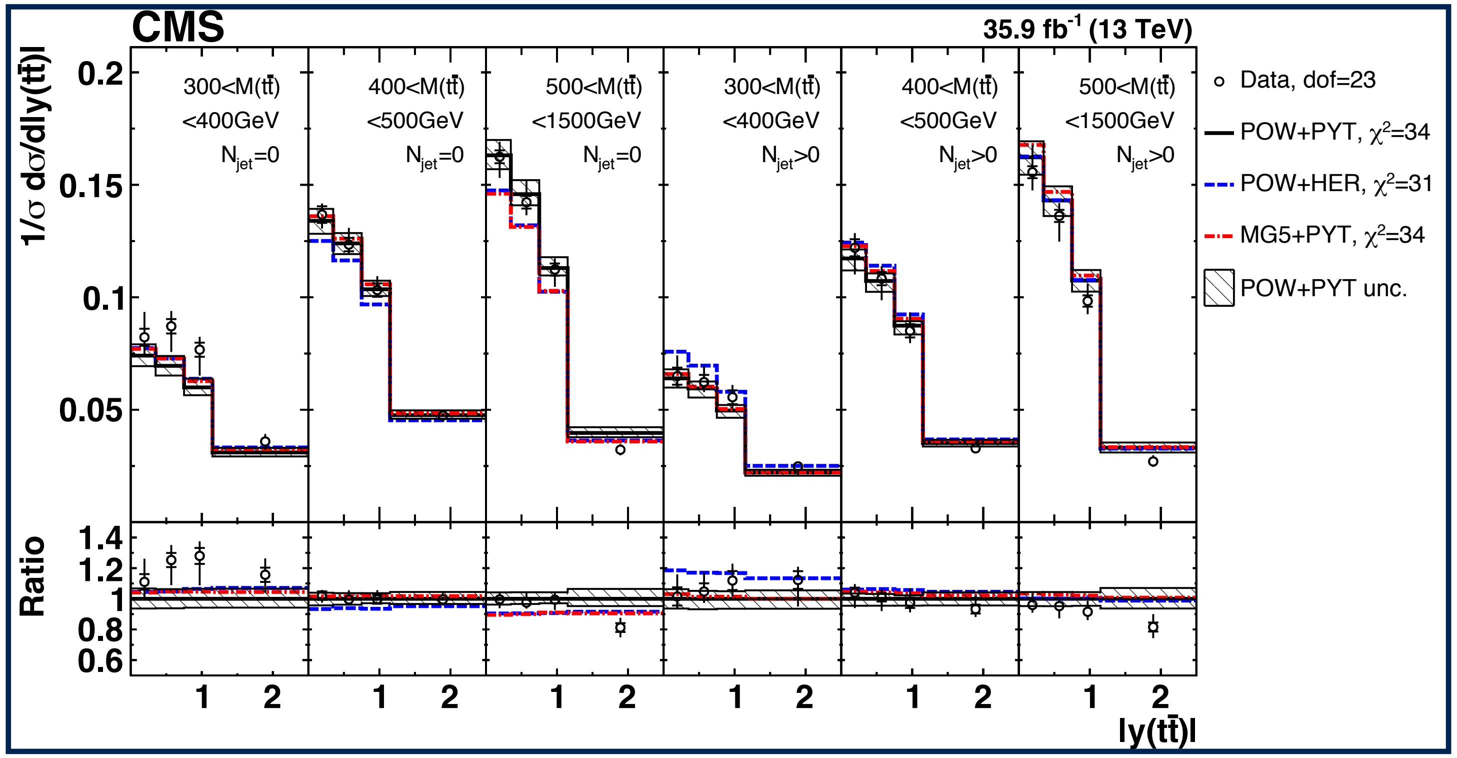
- Measured Normalised 2D and 3D $t\bar{t}$ cross section in dilepton channel
  - Require 2 $l^{\pm}$, 2jets (at least 1 b-tagged)
  - $t\bar{t}$ cross sections can be used to extract PDF's: constrain high-x gluon
  - Constrain fundamental SM parameters: a_S, m_t^{pole}
- Quantitative comparison to several 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

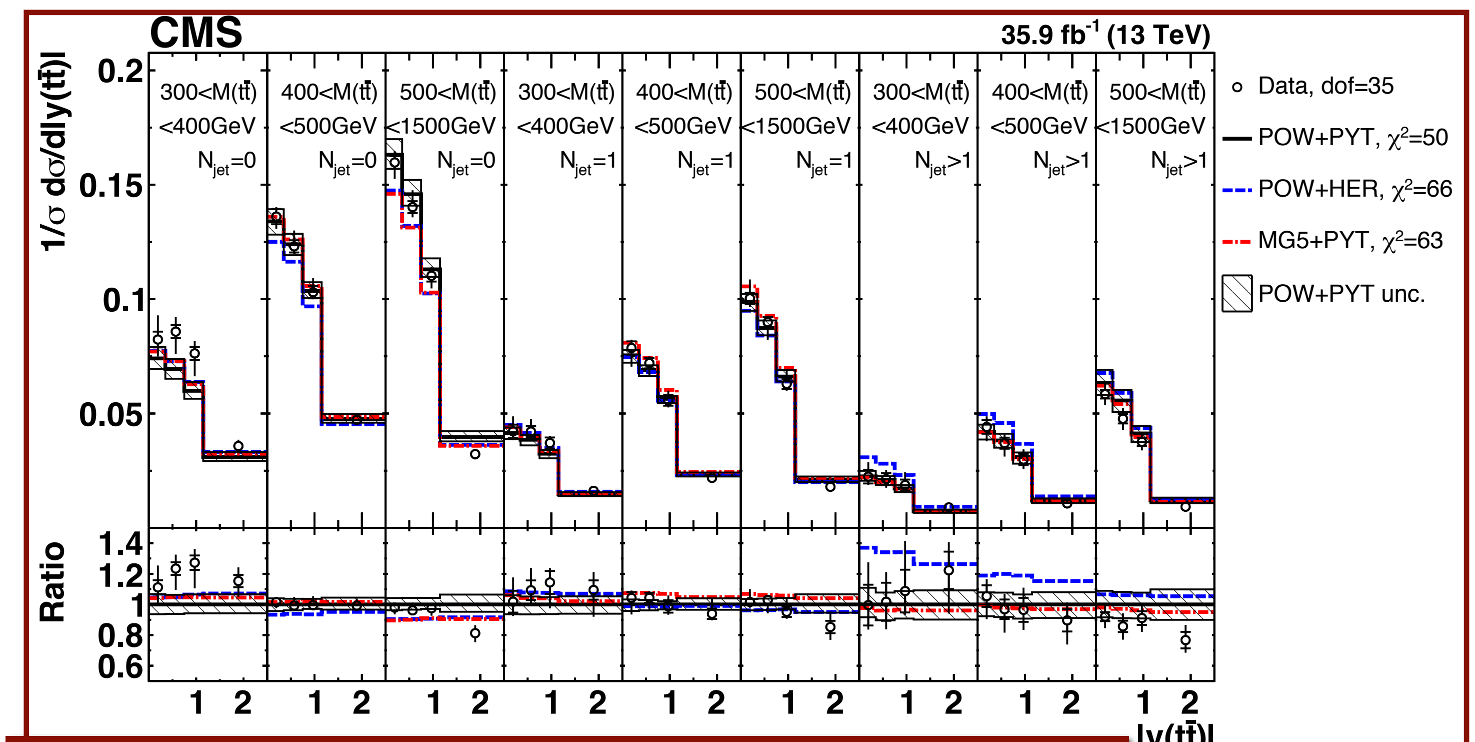
POW+PYT: POWHEG + Pythia8
POW+HER: POWHEG + Herwig++
MG5+PYT: MG5_aMC@NLO

3D Differential Cross Sections

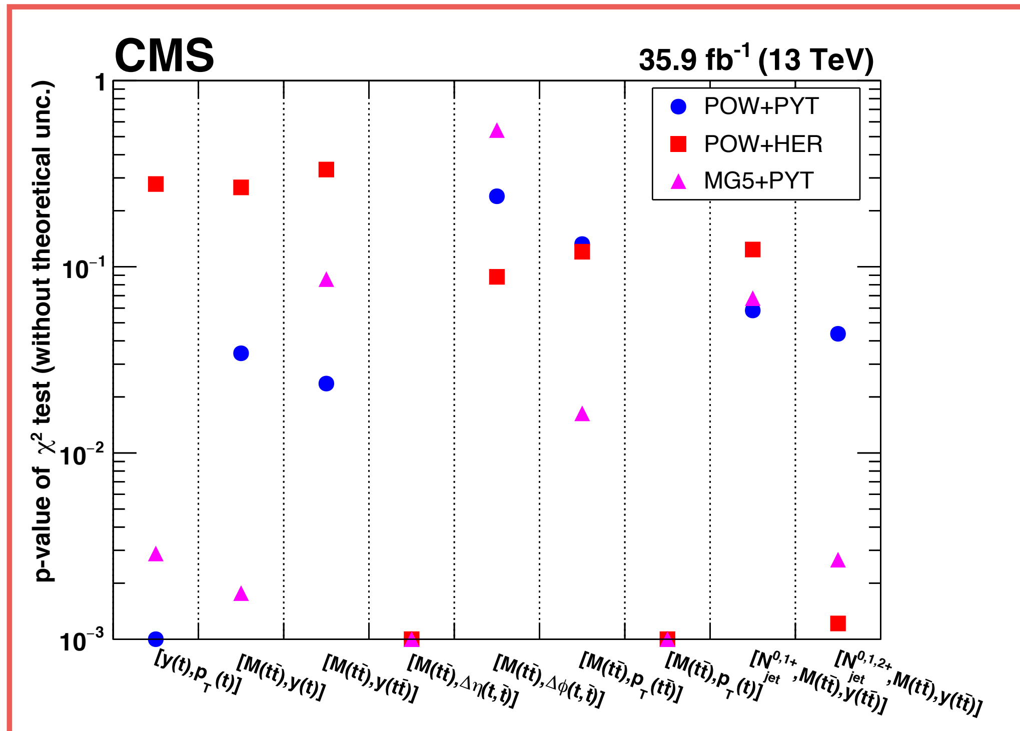
arXiv:1904.05237

All MC describe data well





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



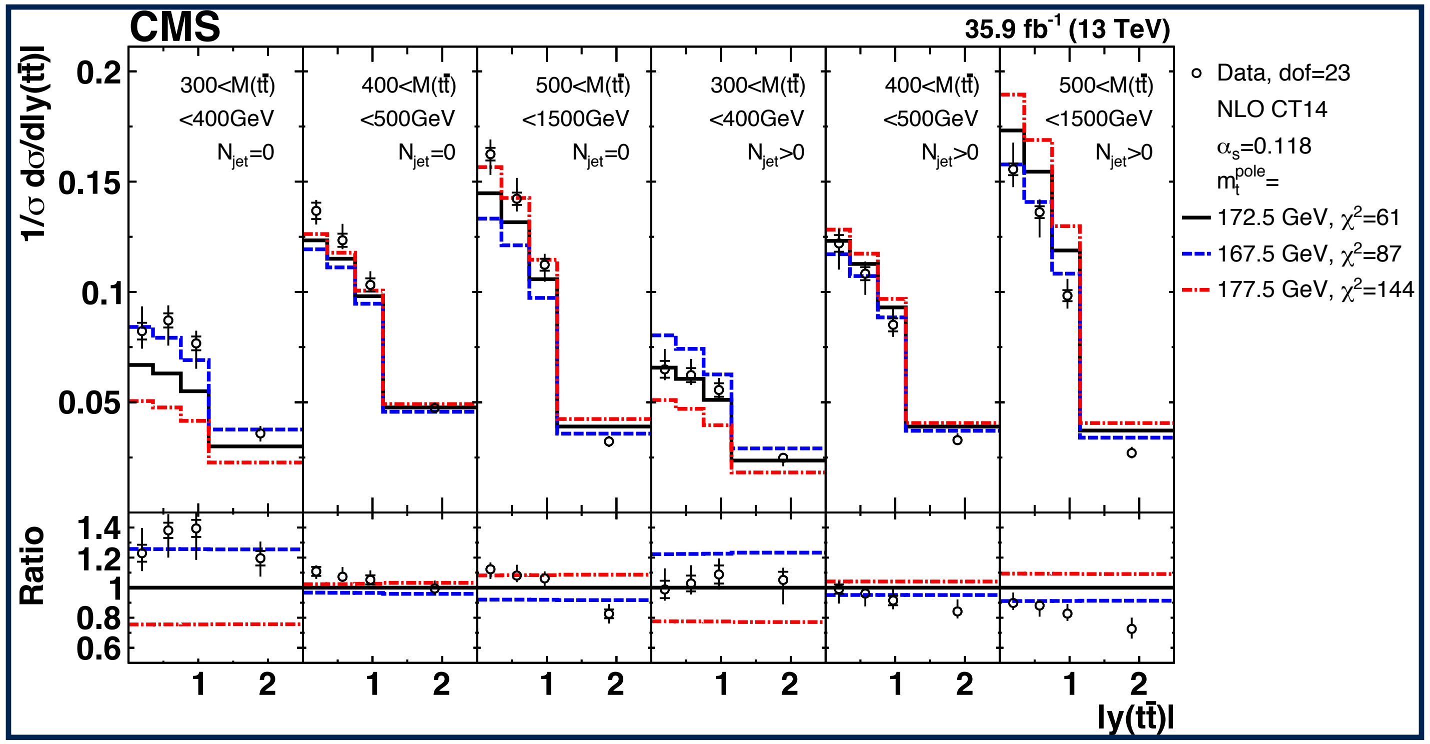
- Only ‘POW+PYT’ is in an agreement with data
- ‘POW+HER’ predicts too high XSEC for $N_{jet} > 1$
- ‘MG5+PYT’ worse $M(t\bar{t})$ at $N_{jet} = 1$

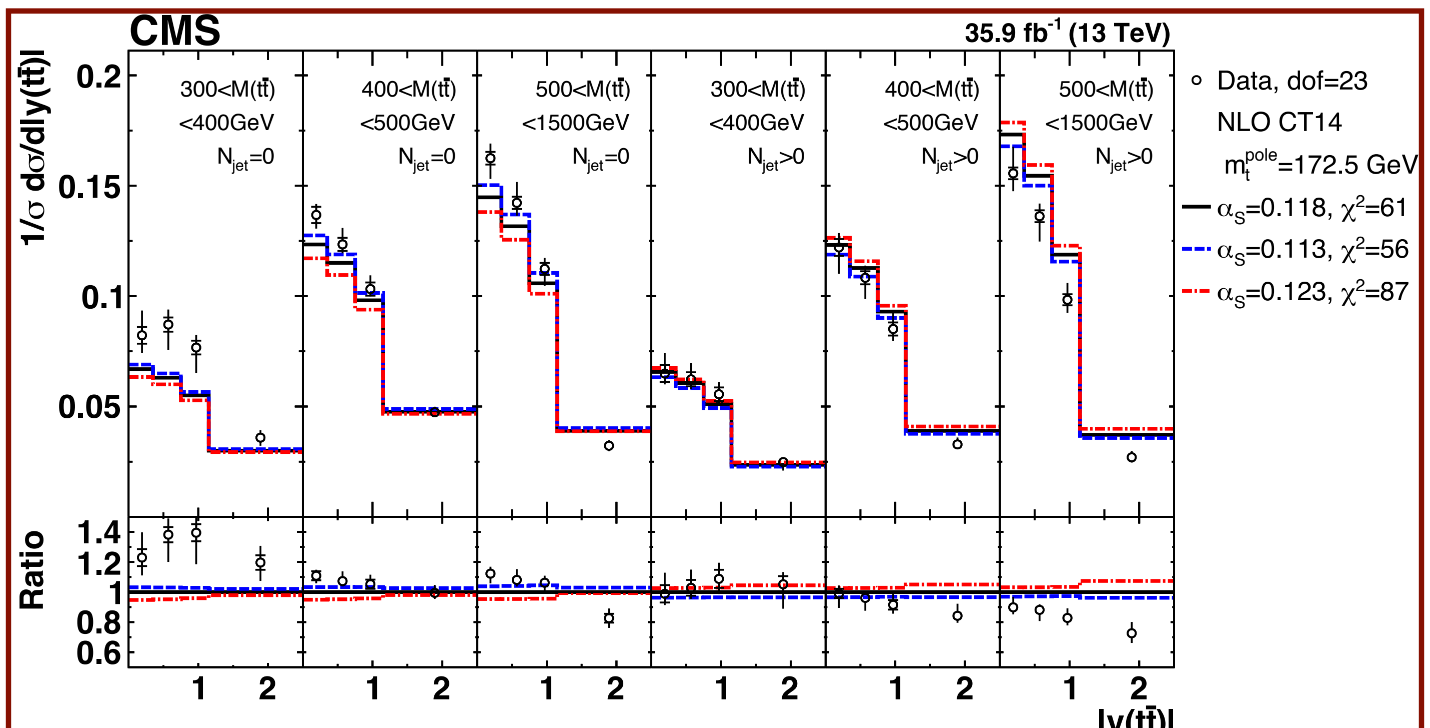
- Summary of Comparison to MC models
- None of the Central MC predictions is able to describe all distributions
- Best description by ‘POW+PYT’ and ‘POW+HER’

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

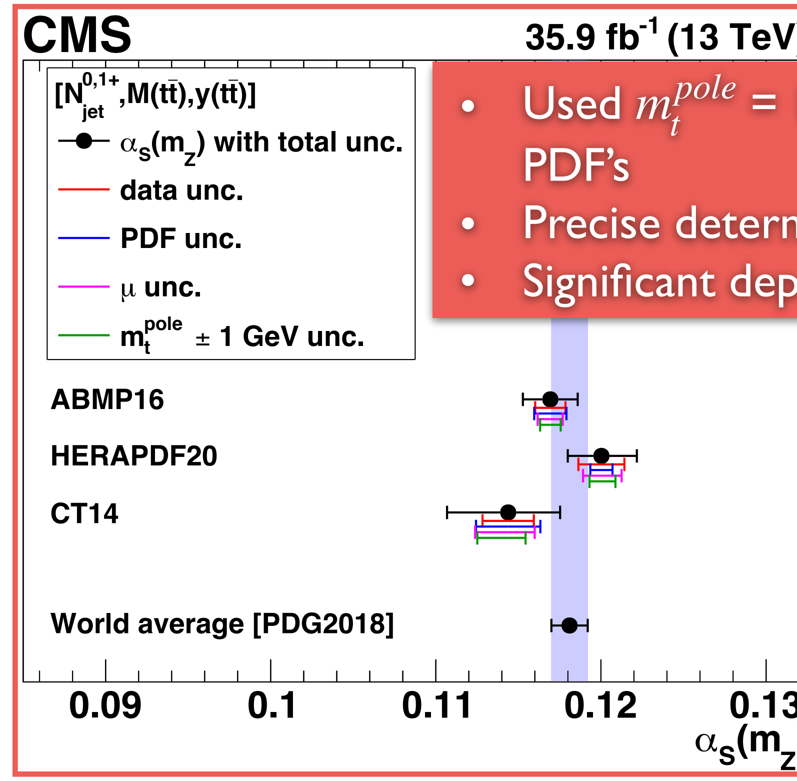
arXiv:1904.05237

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

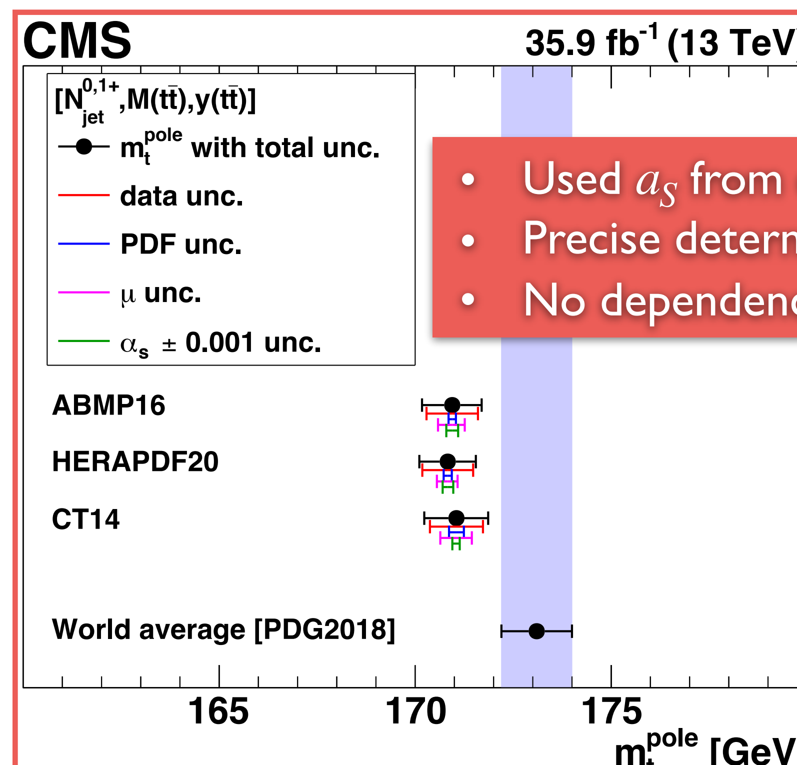




α_S sensitivity comes from different N_{jet} bins



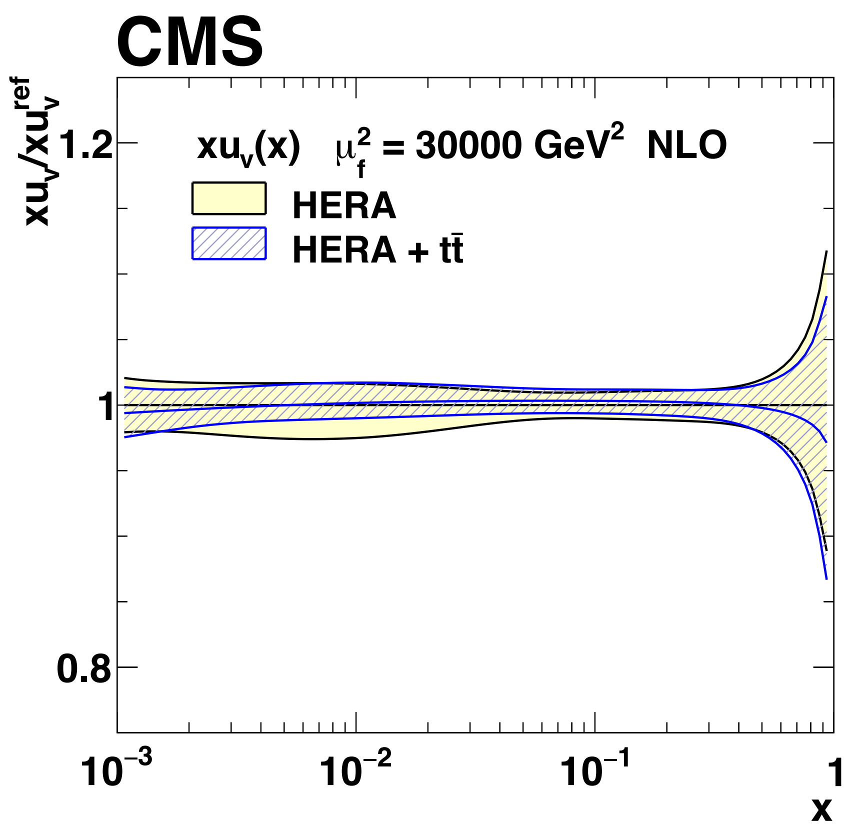
- Used m_t^{pole} = 172.5GeV for all PDF's
- Precise determination of a_S
- Significant dependence on PDF

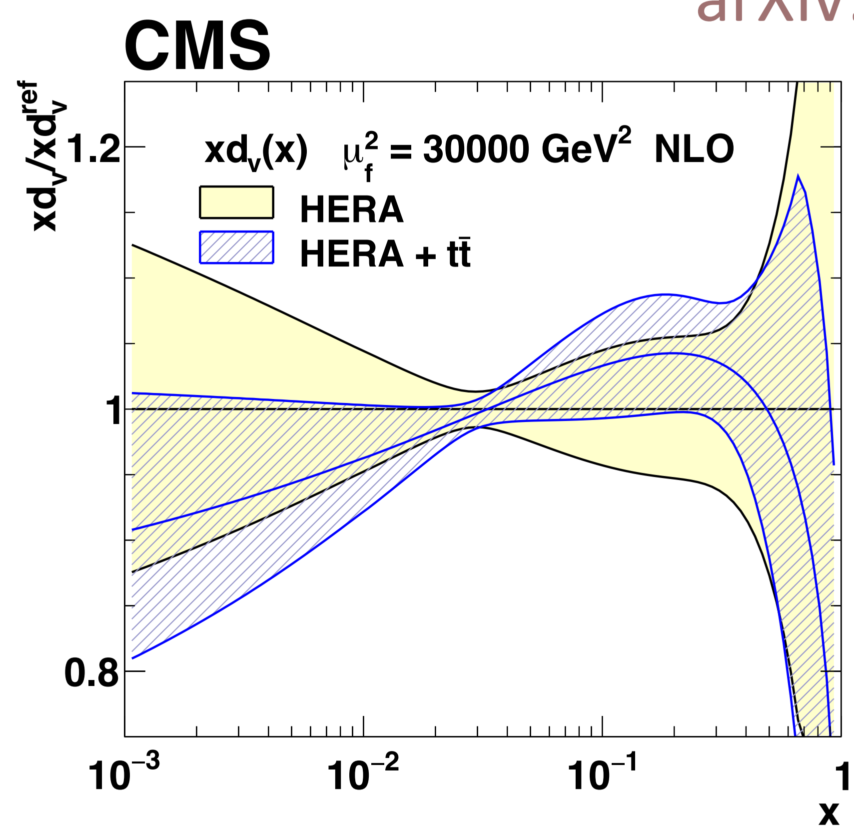


- Used a_S from each PDF set
- Precise determination of m_t^{pole}
- No dependence on PDF set

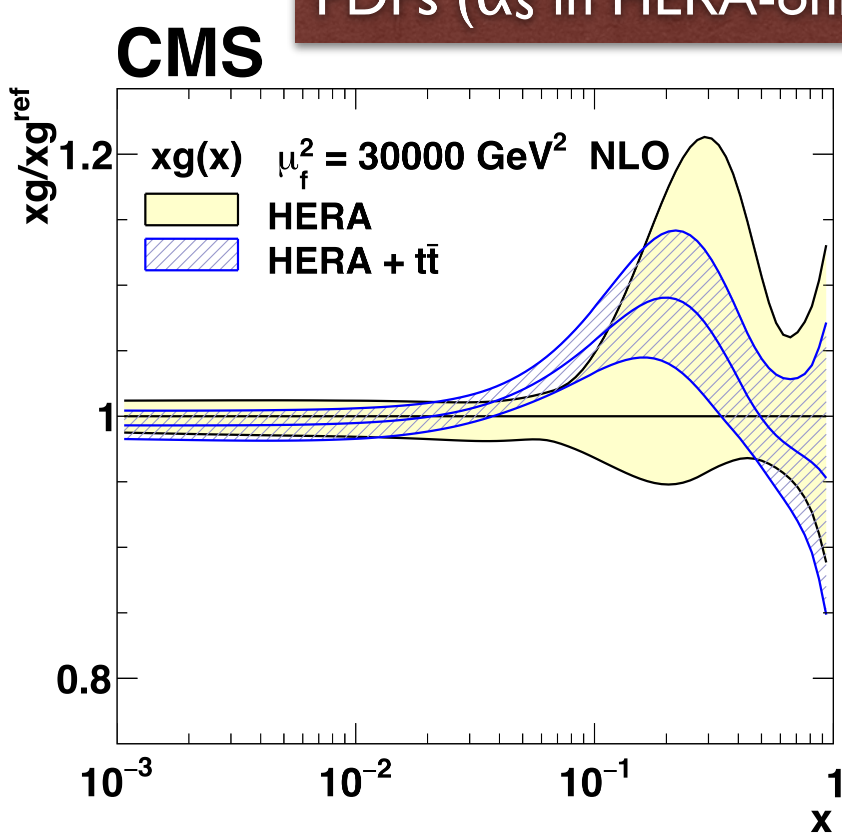
Extraction of a_s, m_t^{pole} and PDF's from 3D cross sections

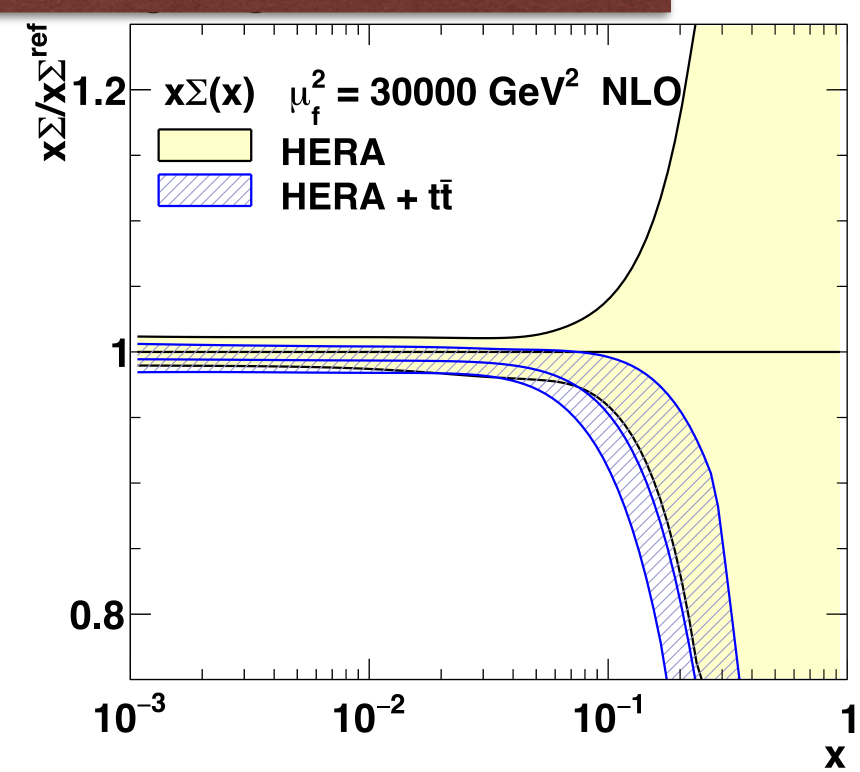
arXiv:1904.05237



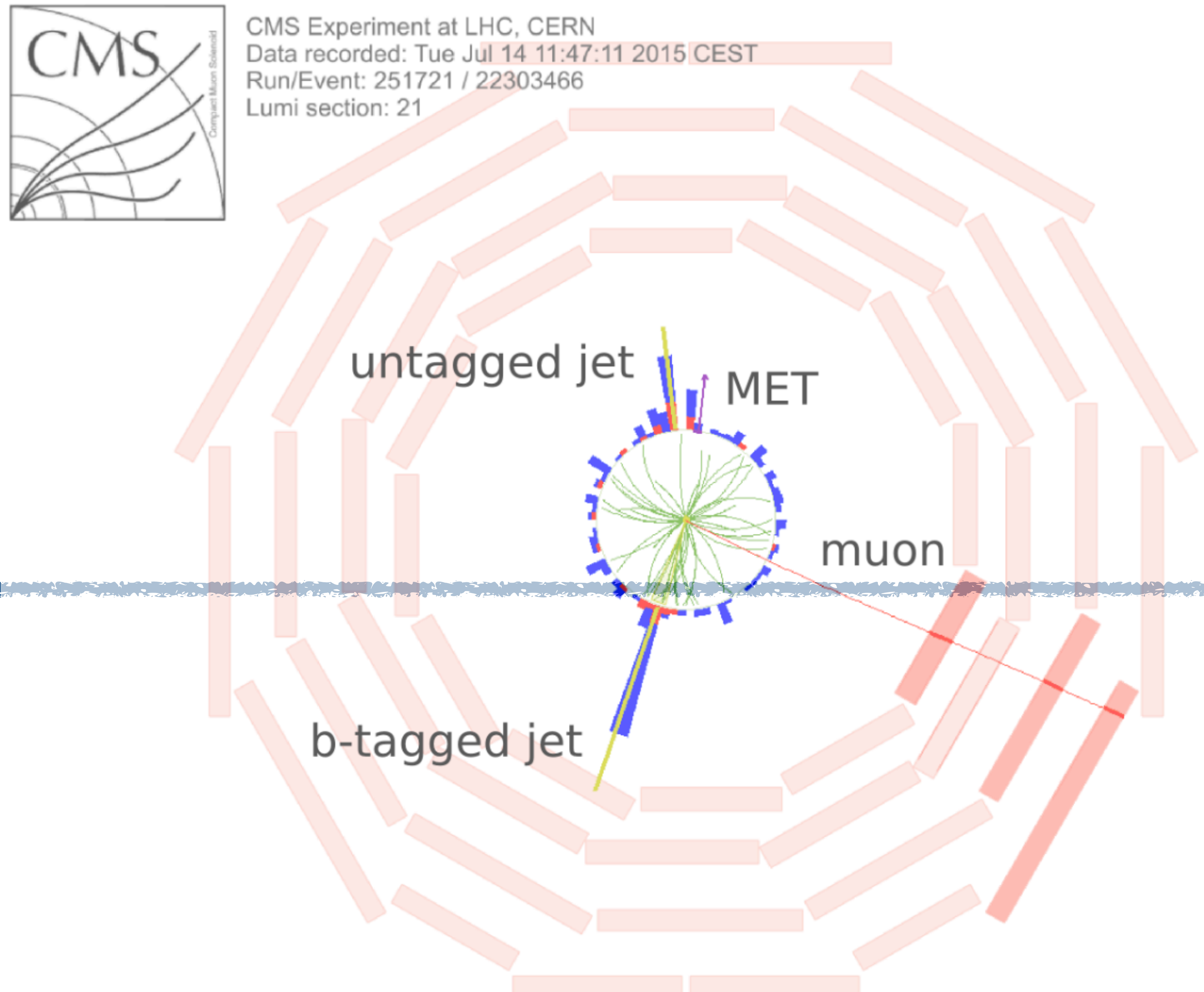


PDFs (α_S in HERA-only fit set to $\alpha_S = 0.1135 \pm 0.0016$):

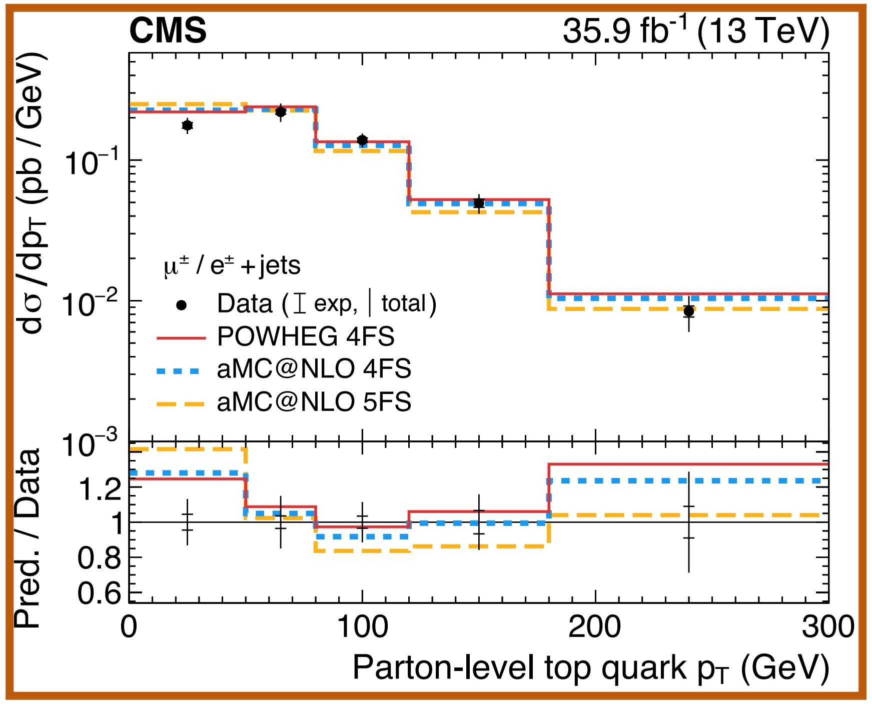


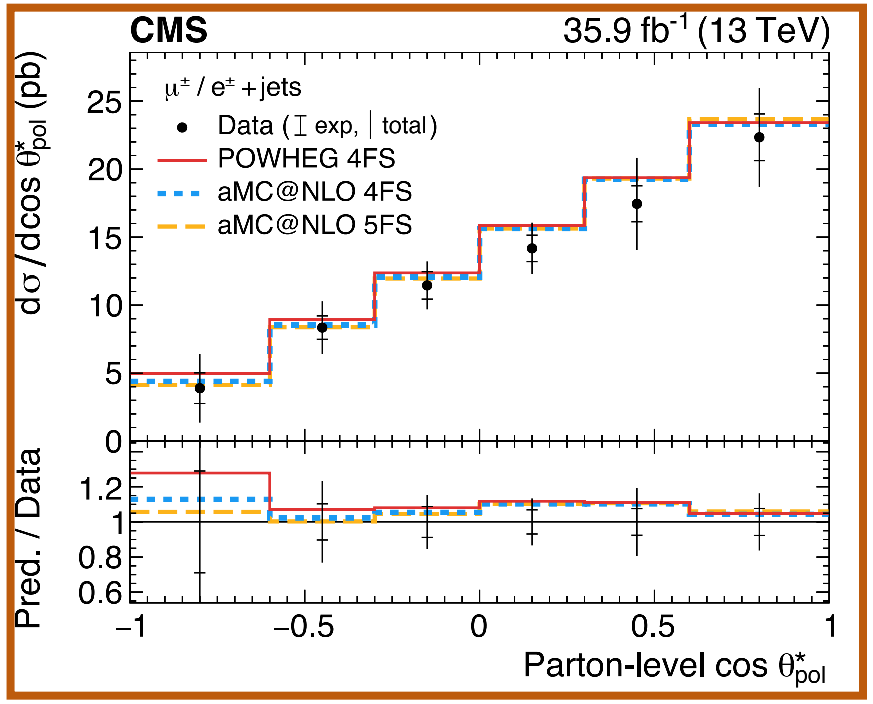


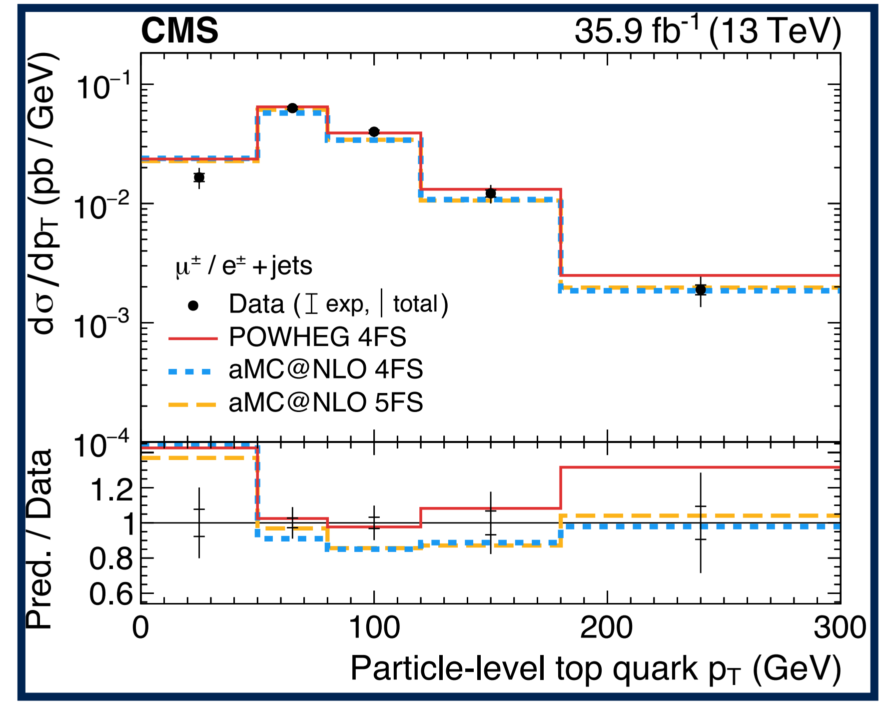
Single Top


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

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



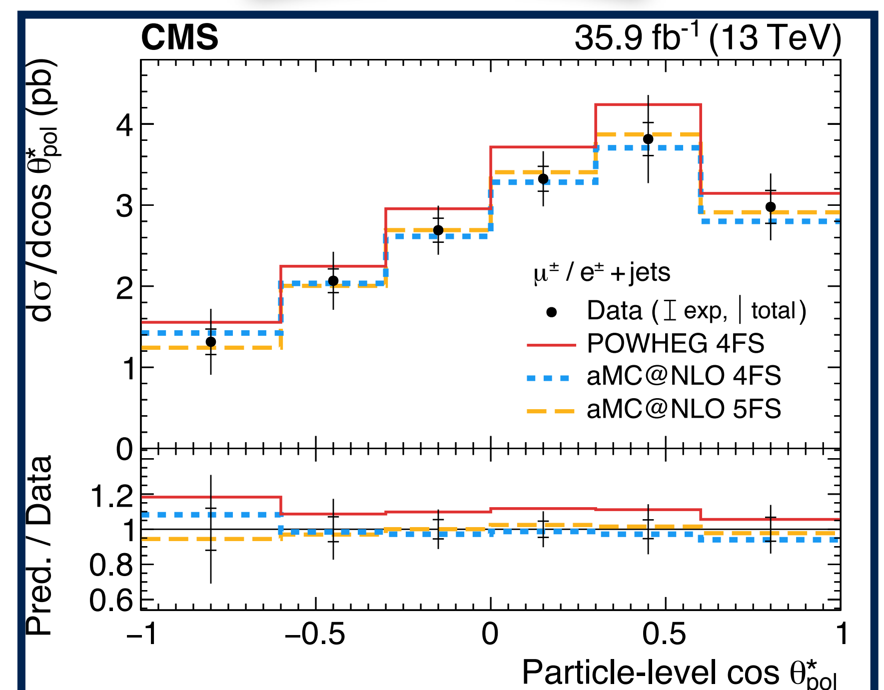




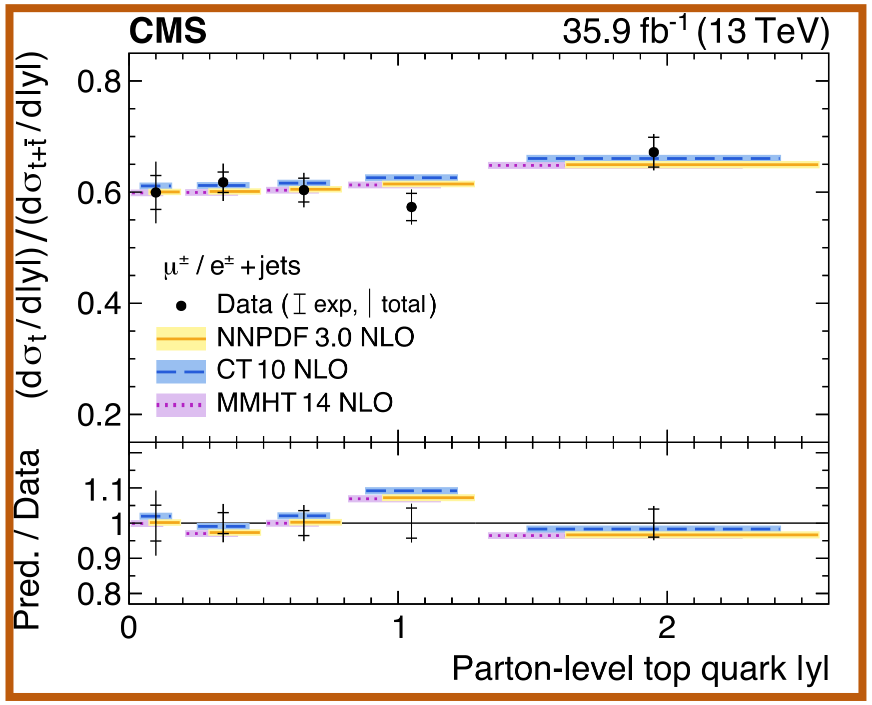
Parton

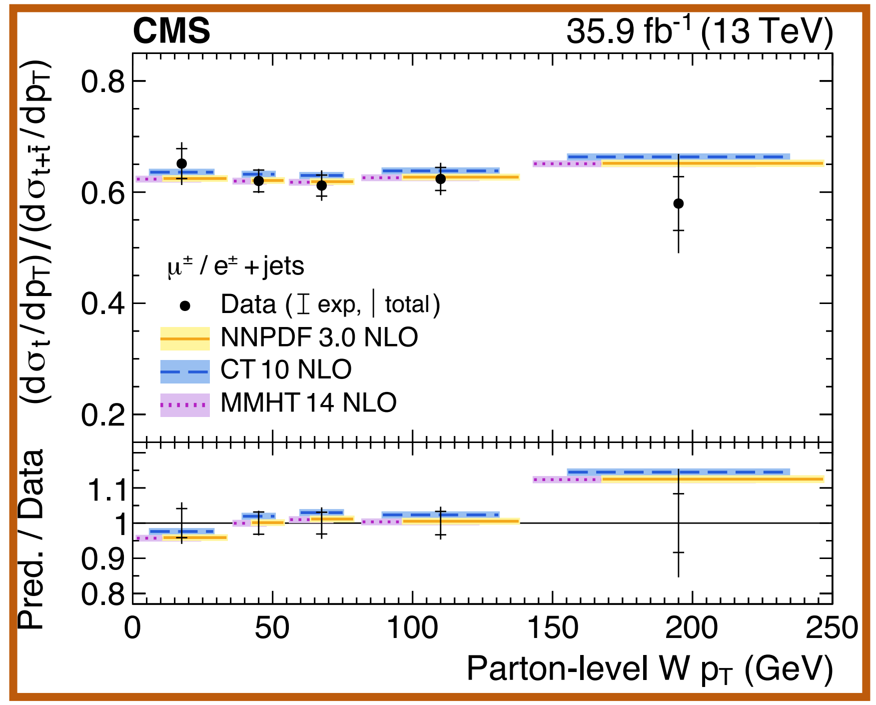
Particle

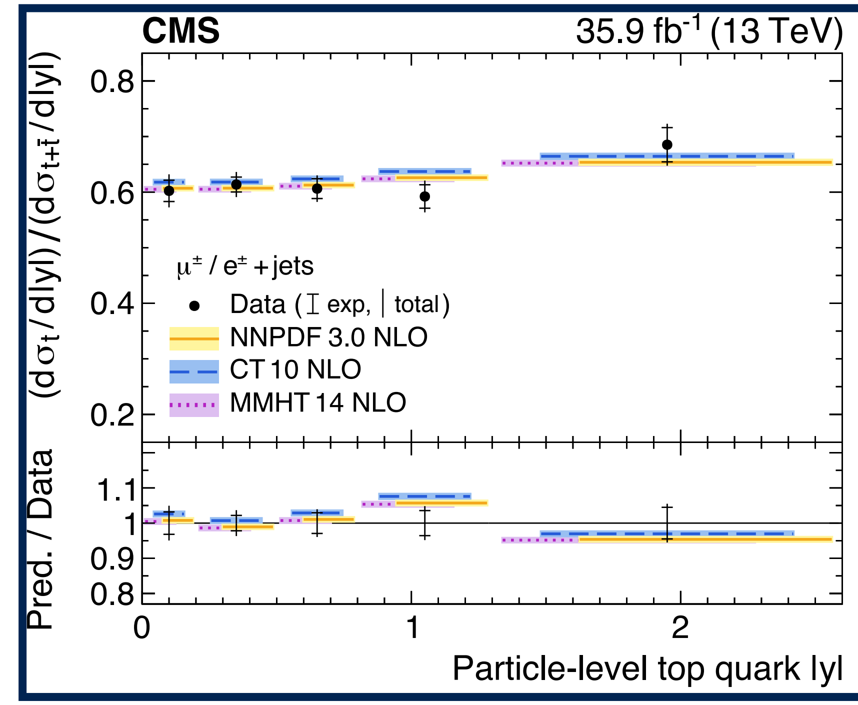
- Single top in t-channel
  - Events containing single muons or electrons and two or three jets are analysed (2j0b W+jet region, 2j1b signal region, 3j2b $t\bar{t}$ region)
- Measurements
  - Absolute and normalised differential cross section @ Parton and particle levels
  - Top quark pT, rapidity and polarisation angle $cos\theta_{pol.}{}^* = \dfrac{\vec{p}_{q'}^{(top)}\vec{p}_{l}^{(top)}}{|\vec{p}_{q'}^{(top)}|\cdot|\vec{p}_{l}^{(top)}|}$
  - 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

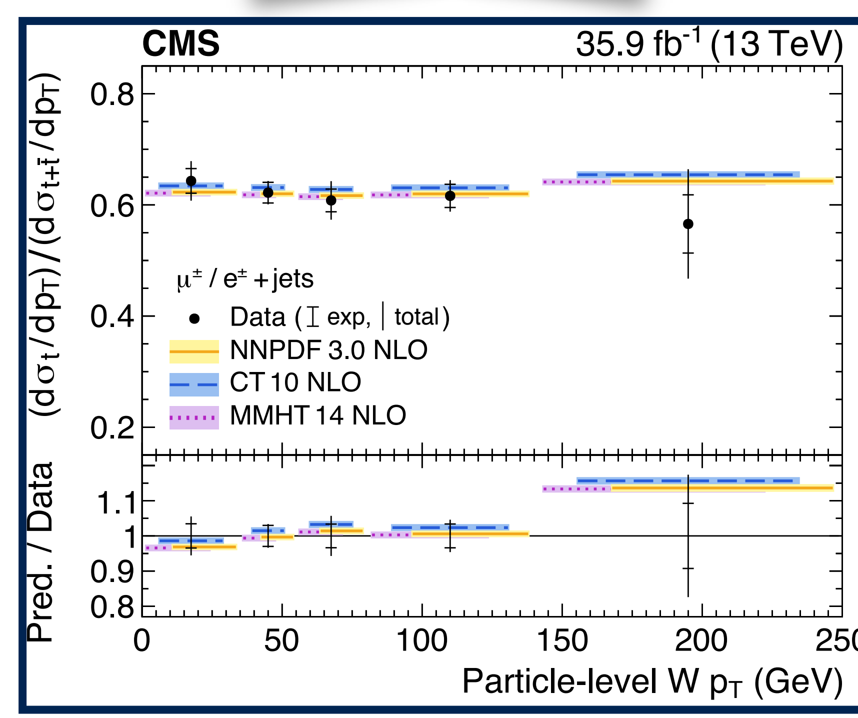






Parton

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

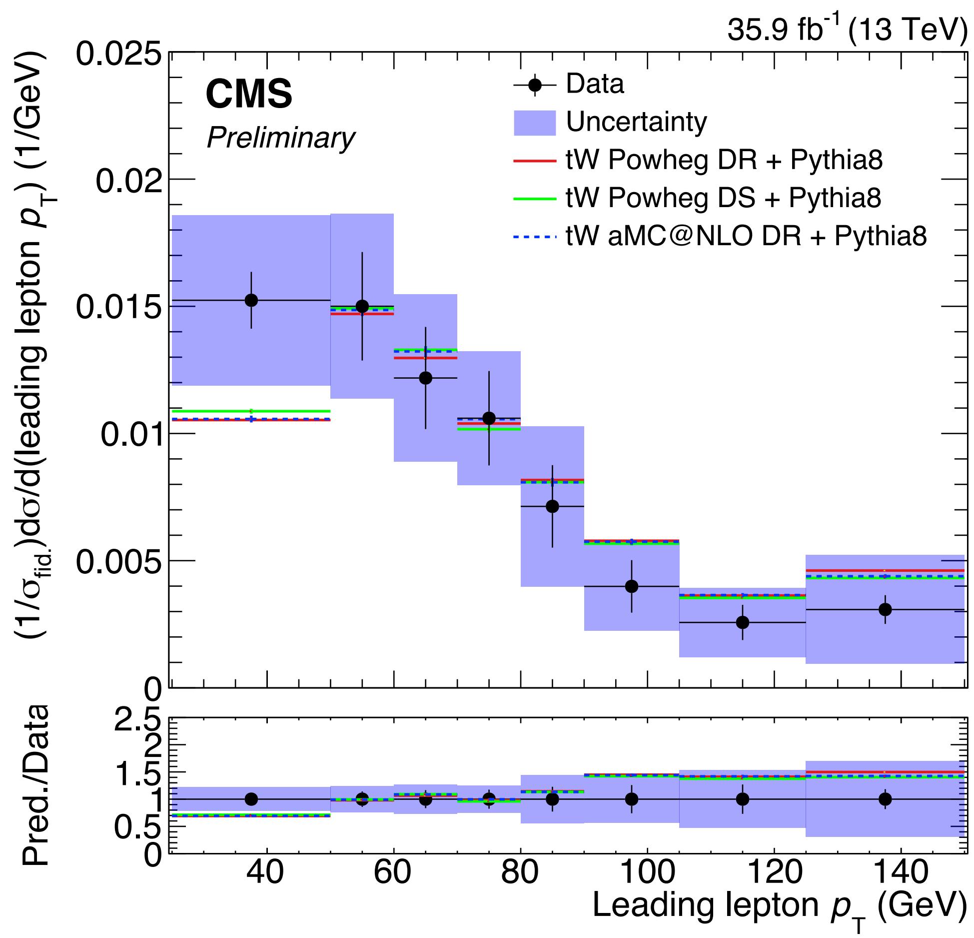
Spin Asymmetry in the single top t-channel

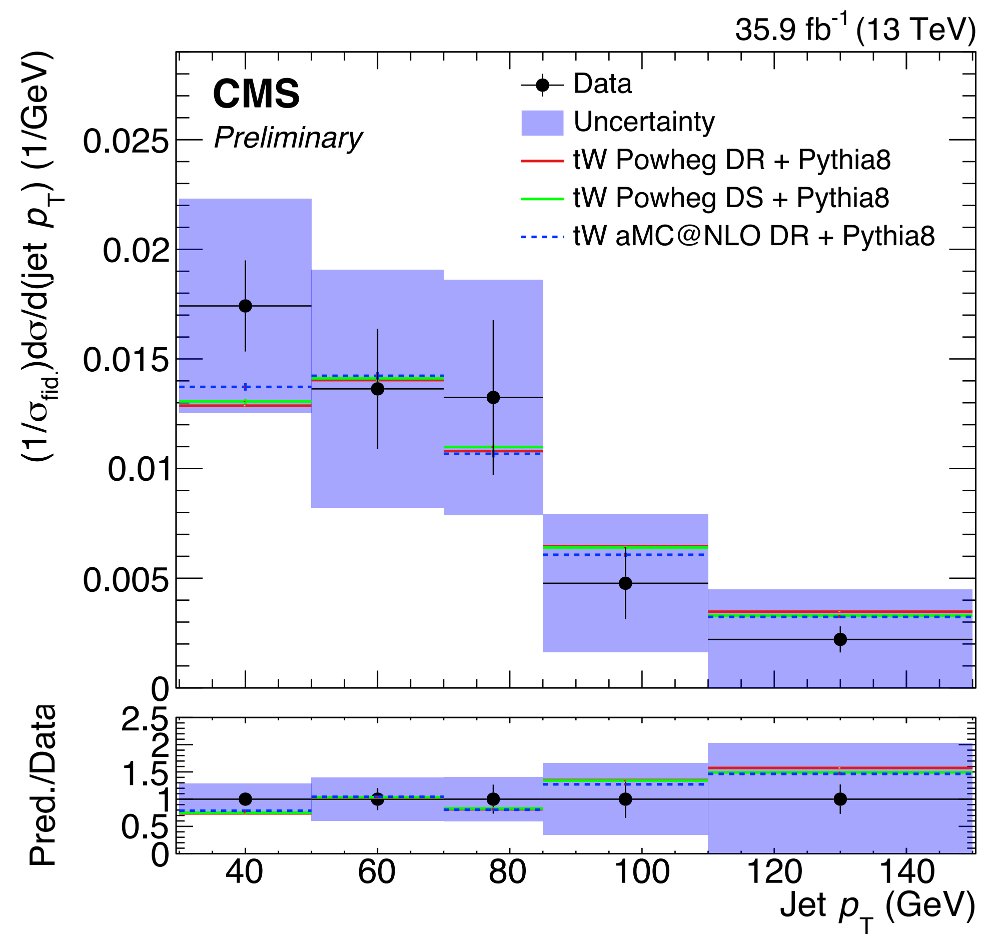
- Sensitive to top quark polarisation
- Determined from the differential distribution of the polarisation angle @ Parton Level
- In agreement with the SM predictions (POWHEG @ NLO): *0.436 (negligible uncertainty)*

		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 $d\sigma_{t(\bar{t})}/dX$

CMS-PAS-TOP-19-003

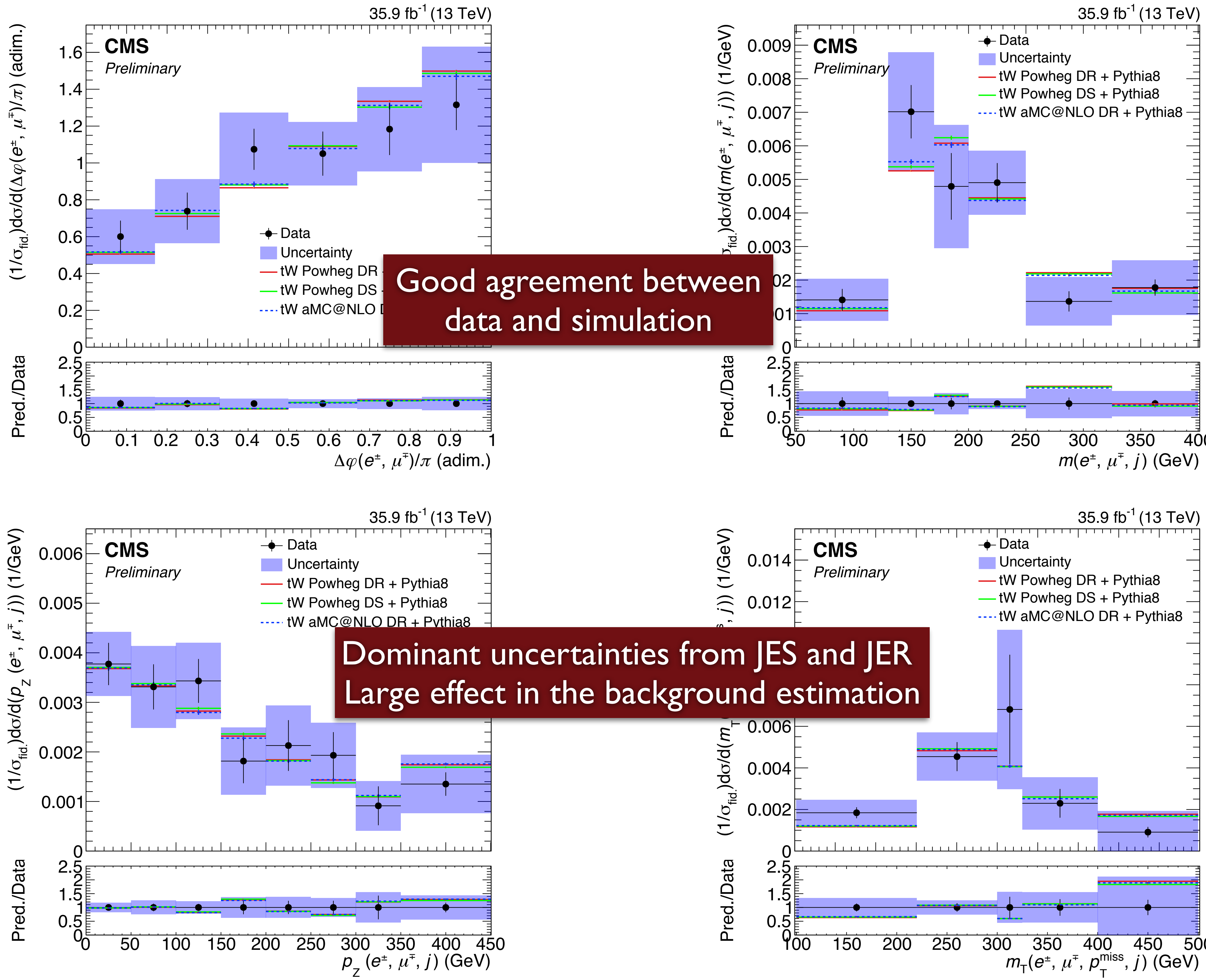




- Measurement of tW differential Cross Section
  - Main challenge is that background dominates signal—>$t\bar{t}$ being the largest
  - Signal extraction performed by subtracting bkg, estimated through MC simulations
- Measurements
  - Absolute and normalised differential cross section @ Particle level
  - 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

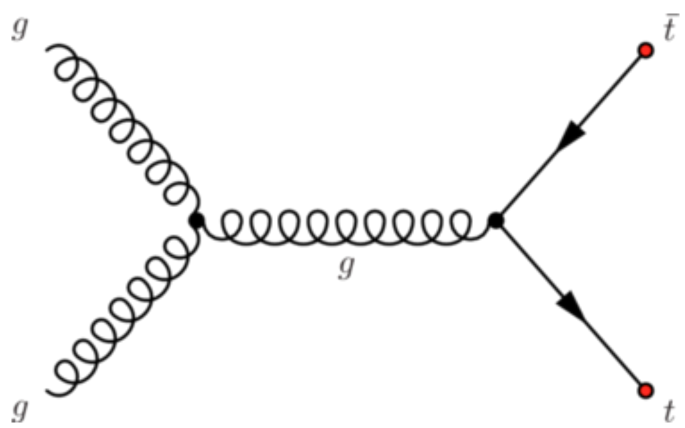
Summary & Outlook

- **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 @ Particle level
  - t-channel process using 2016 CMS data:
    - Normalised and absolute diff cross sections @ Parton and Particle levels
    - Top quark spin asymmetry estimated from $d(\sigma)/d(cos\theta_{pol})$
- **Stay tuned for more CMS results!**
  - large dataset available: will keep us busy in the next years!!

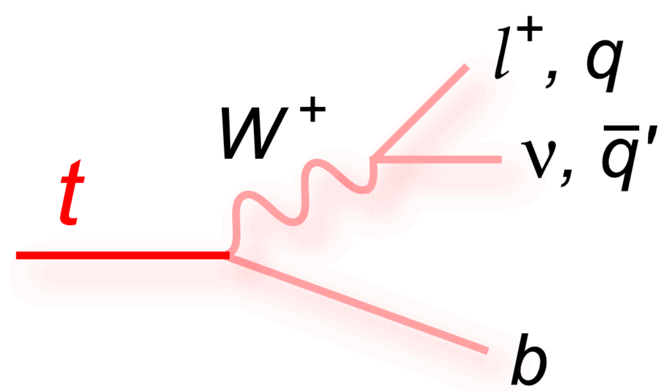
BACKUP

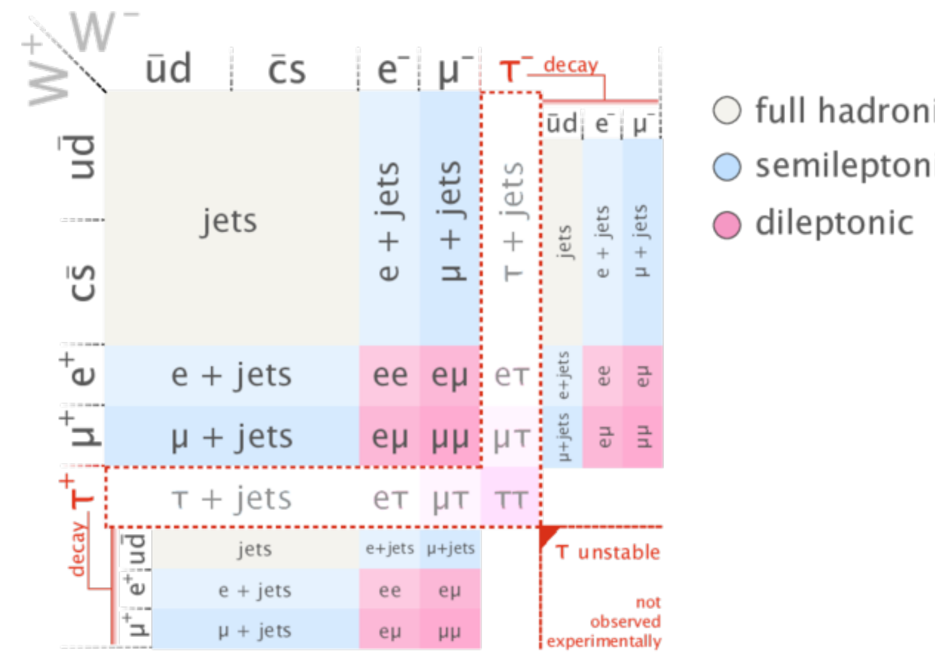
Top Production and Decay

top quark pair production

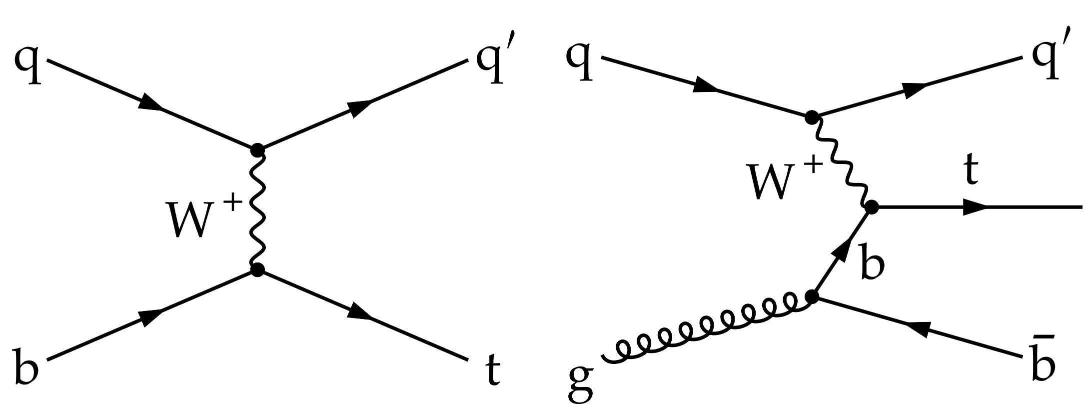


BR(t→Wb) = 0.957

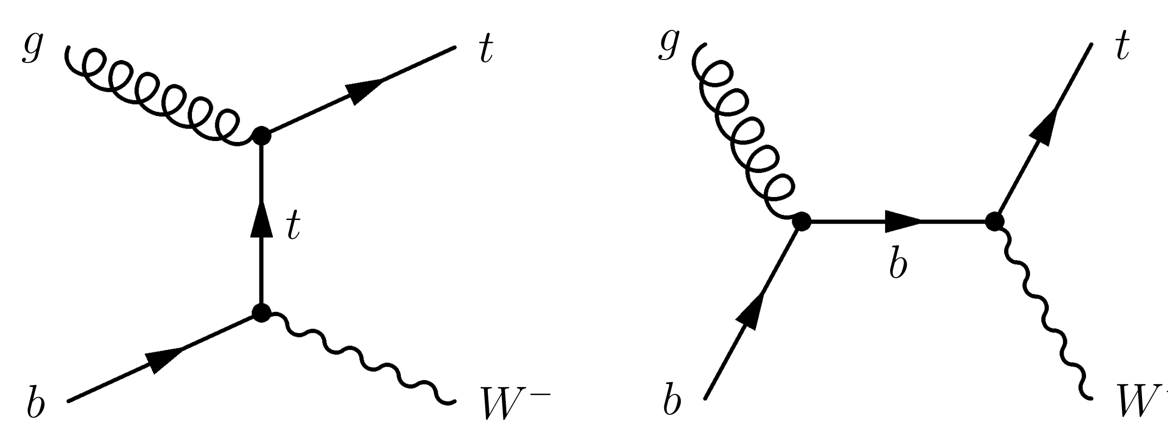




single top quark production (t channel)



single top quark production (tW mode)



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**

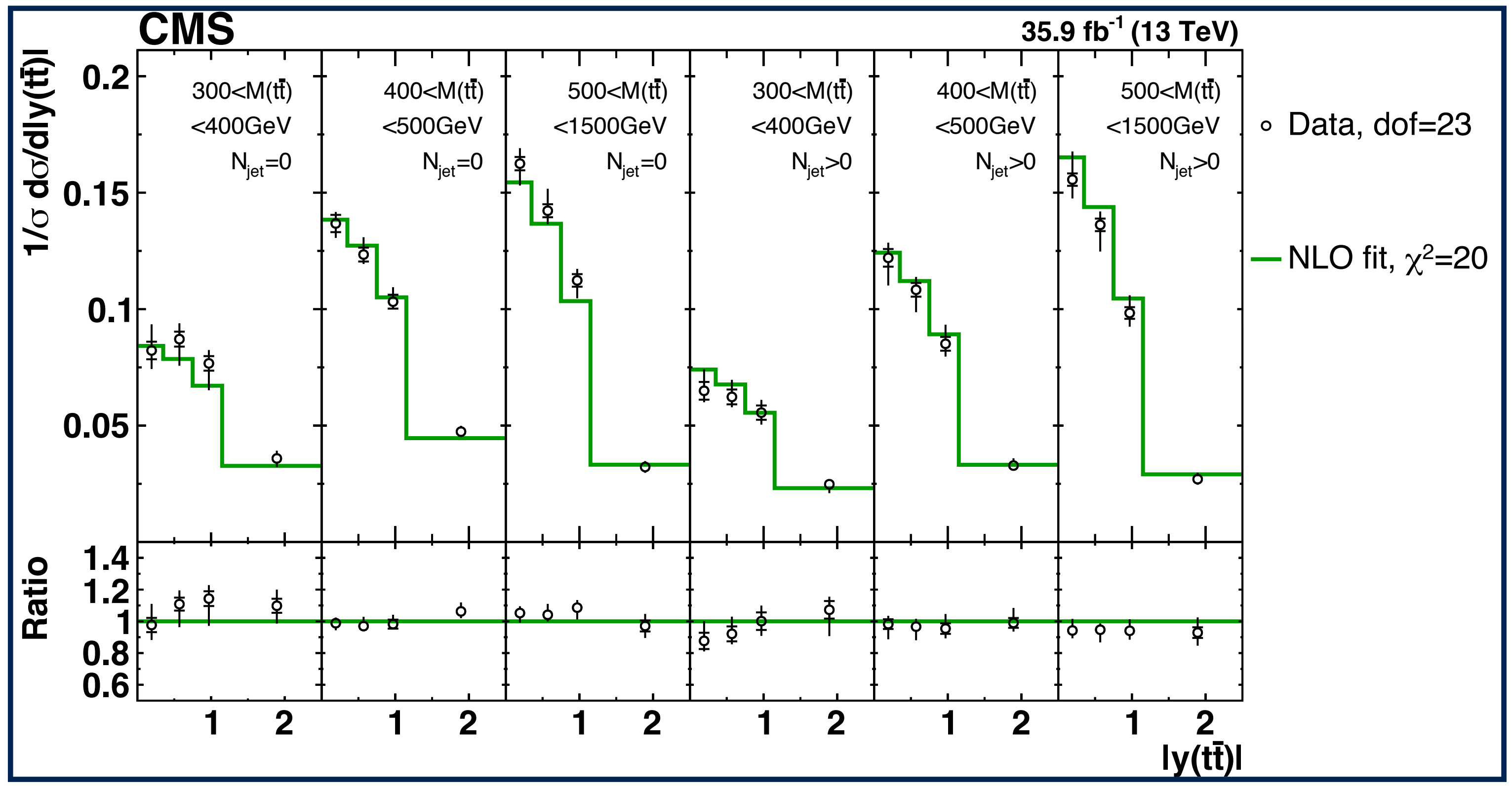
(3)"Measurement of differential cross sections for single top quark production in association with a W boson at sqrt(s) = 13 TeV", **CMS-PAS-TOP-19-003**

(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



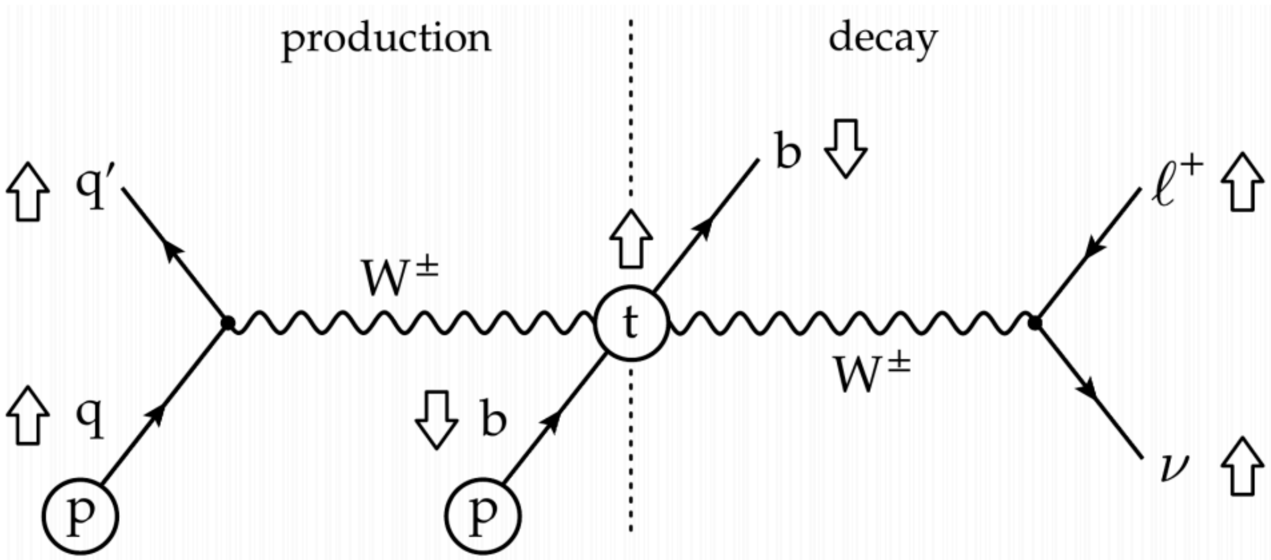
- The resulting values of a_S and m_t^{pole} extracted using NLO calculations:

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



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

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

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

- 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 $d\sigma/dcos\theta_{pol.}$