

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

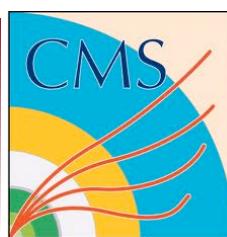
- ▶ Differential Cross Section measurements (high-pT)
- ▶ Normalised multi-differential Cross Section measurements
- ▶ Strong coupling strength a_s
- ▶ Top quark pole mass m_t^{pole}
- ▶ Parton distribution functions (PDF)

◆ Single top production



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

CMS @ LHC Run2 (2015-2018)



- ◆ During Run 2 the LHC produced unprecedented event samples

- ▶ 10^{16} pp collisions @ 13TeV

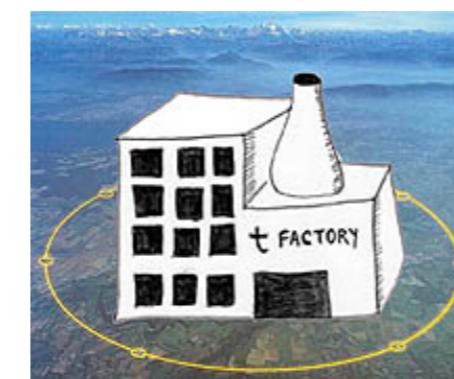
- ▶ 2015-2018 runs:

- Total Luminosity $\sim 163 \text{ fb}^{-1}$

- Top quarks: 300 million



- On average 34 interactions per bunch crossing

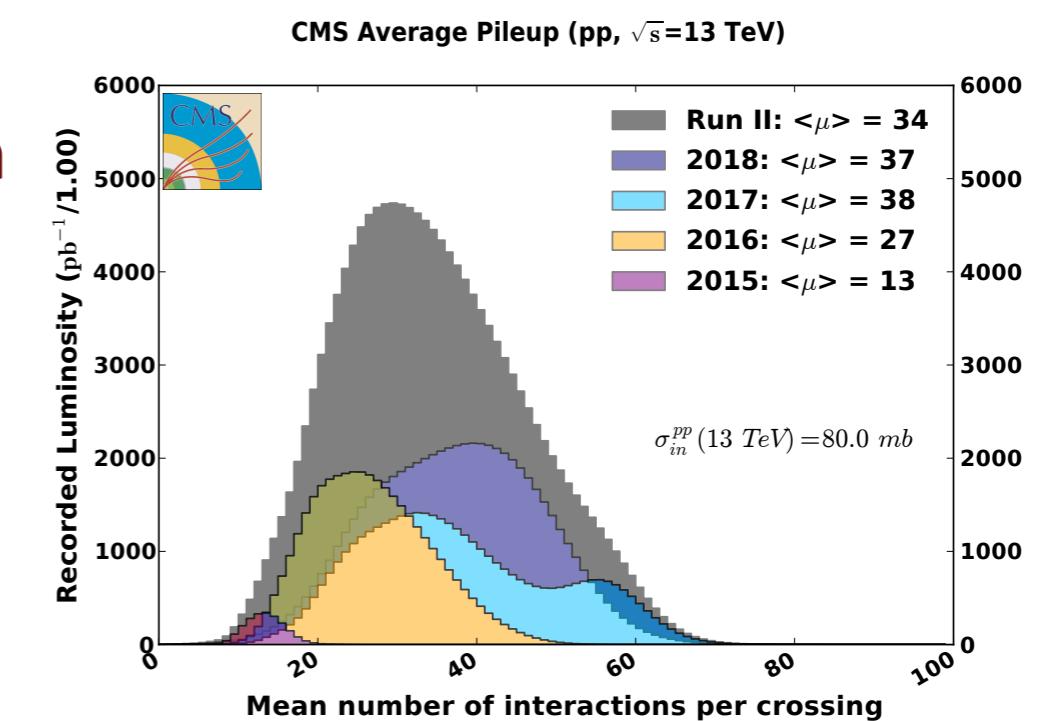
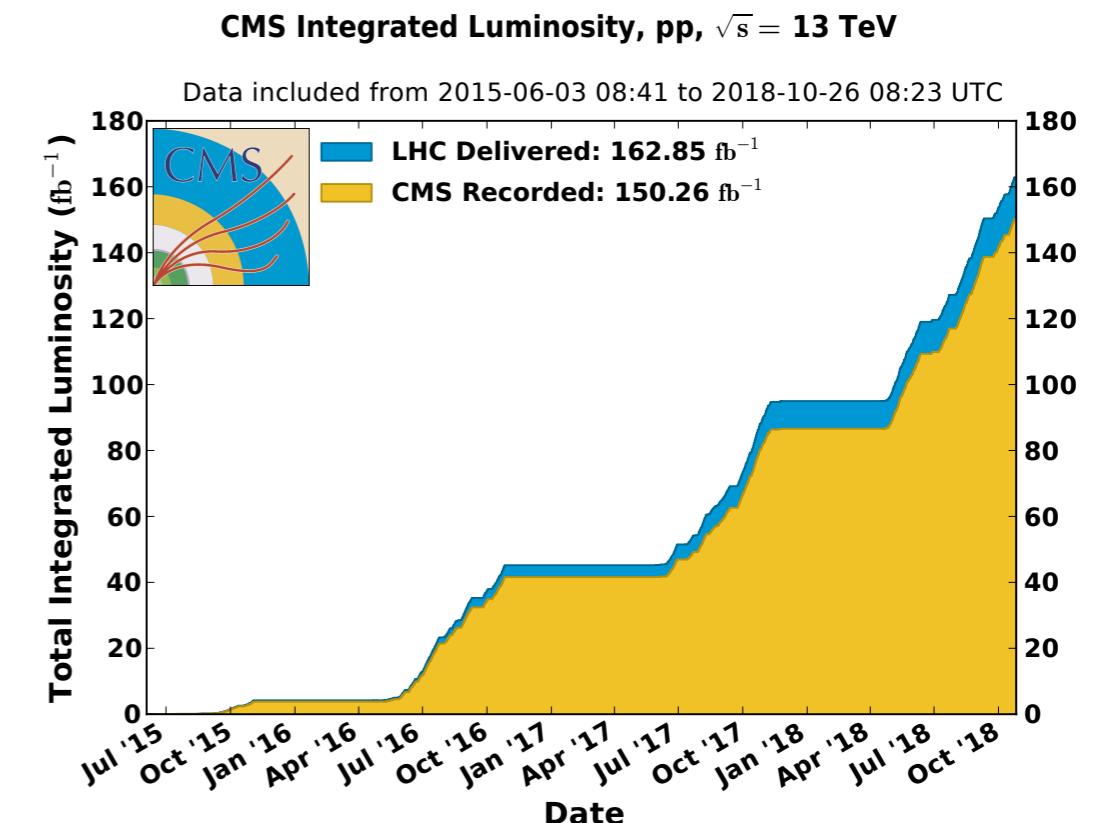


- ◆ Event sample enable broad physics that can

- ▶ 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

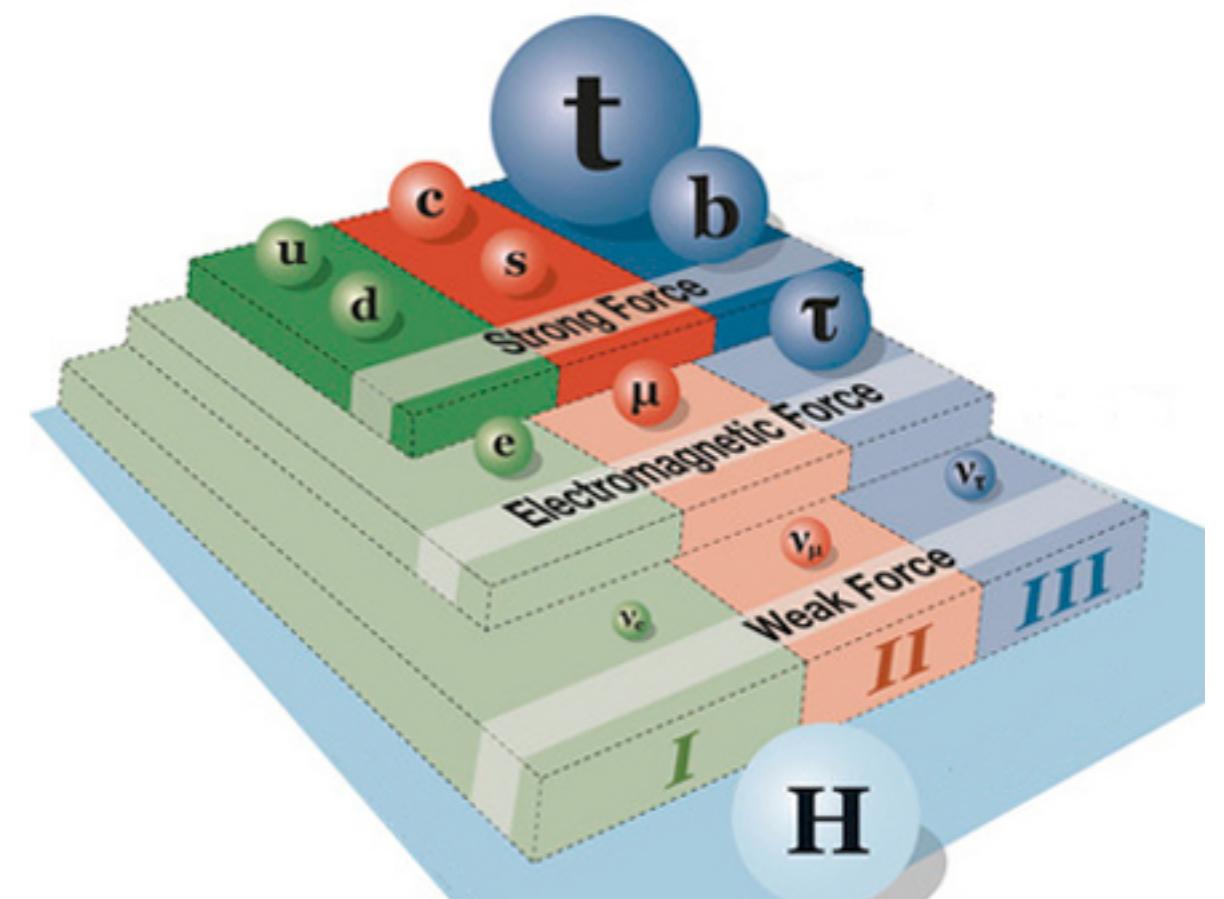
- Extensions to the SM may modify the $t\bar{t}$ differential cross sections in ways that an inclusive cross sections measurement is not sensitive to:

- Such effects can distort top quark pT (especially at high pT's)

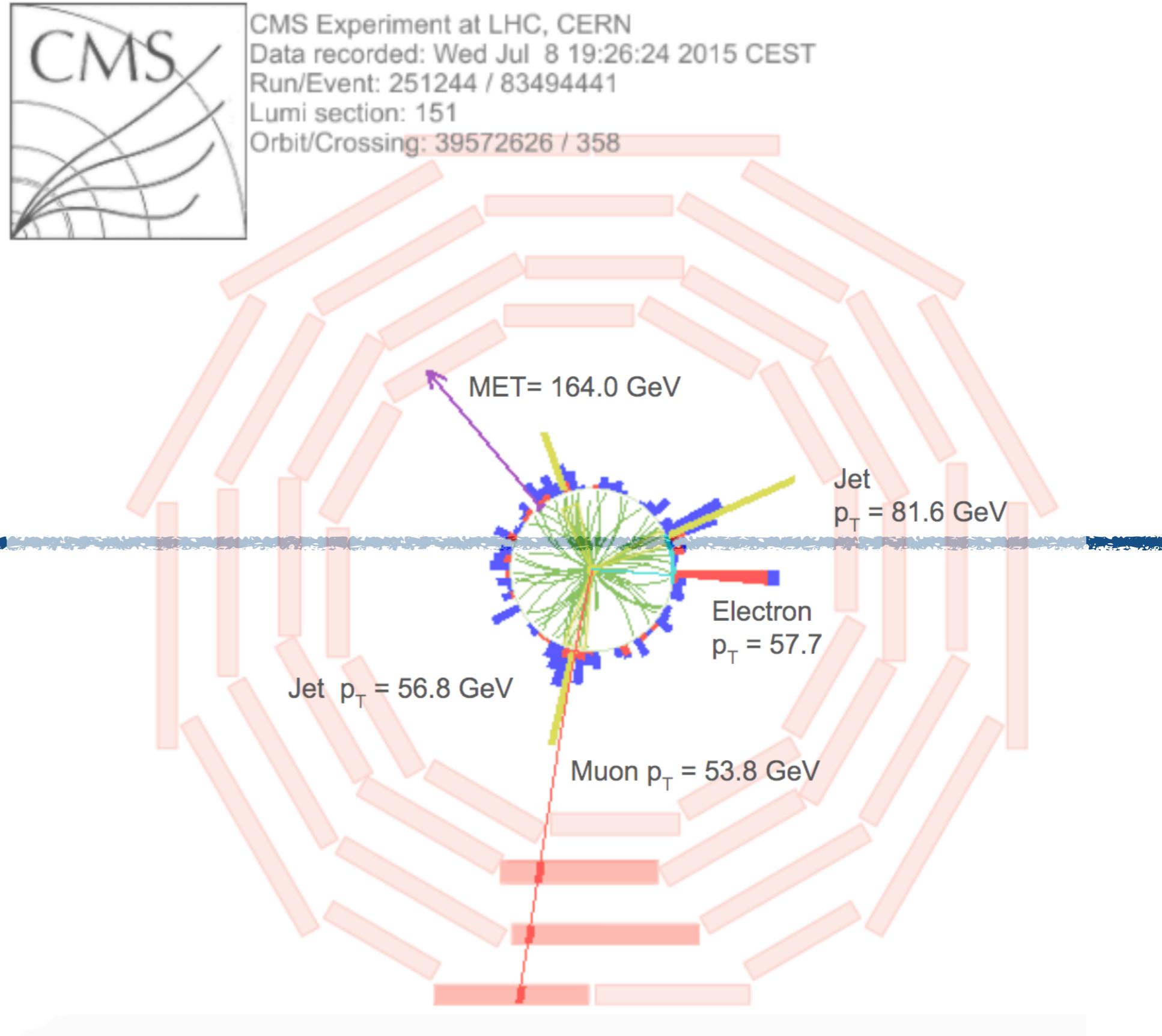
- Enhance sensitivity to possible BSM effects

- 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

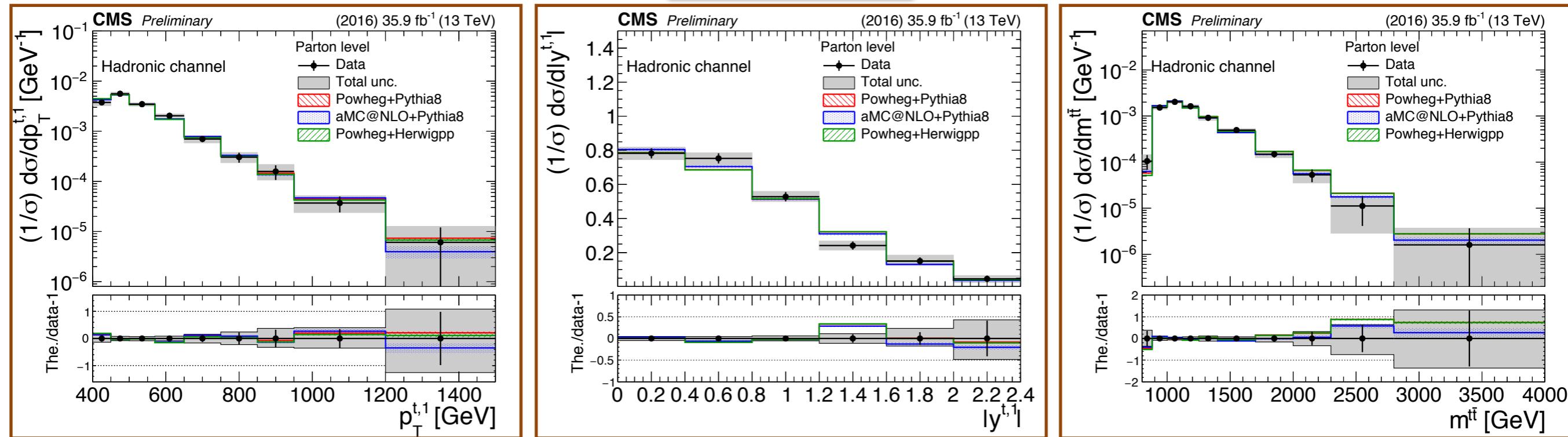


Top Pair



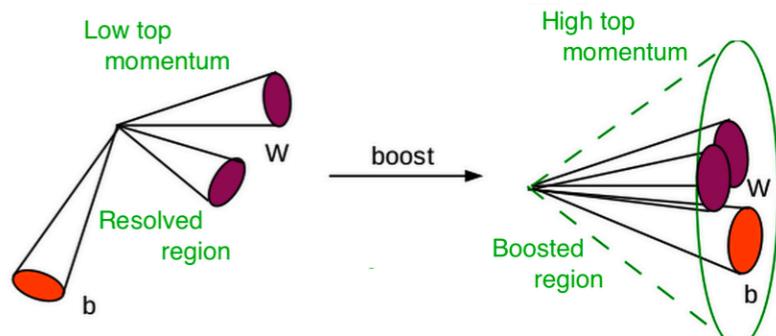
Differential Cross Sections $d\sigma_{t\bar{t}}/dX$

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



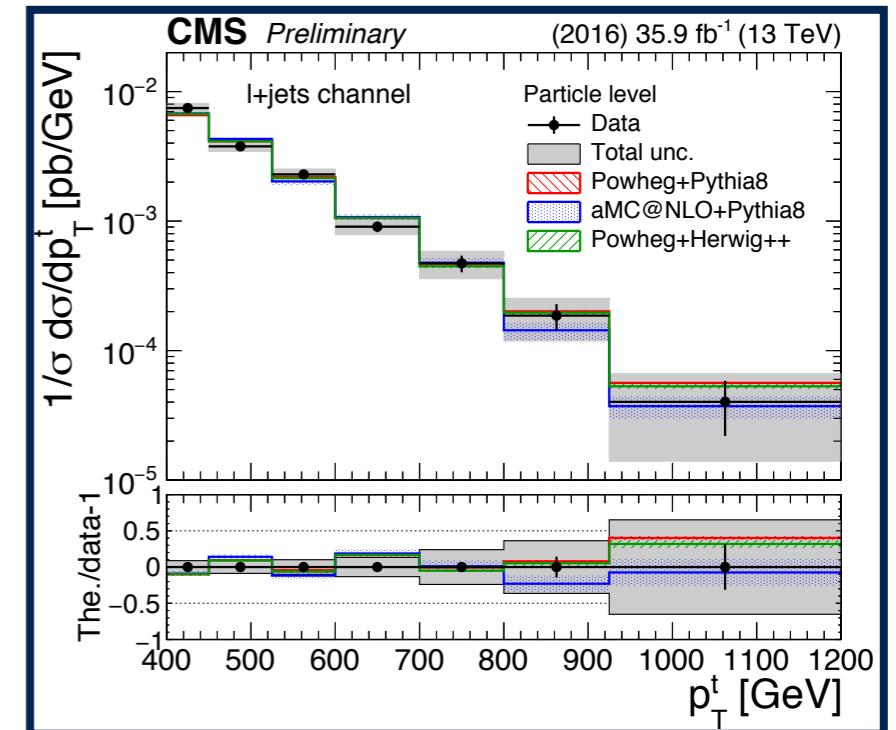
Differential Cross Sections $d\sigma_{t\bar{t}}/dX$

- L + jets for high-pT jets
 - Selection based on t- and b-jet categories

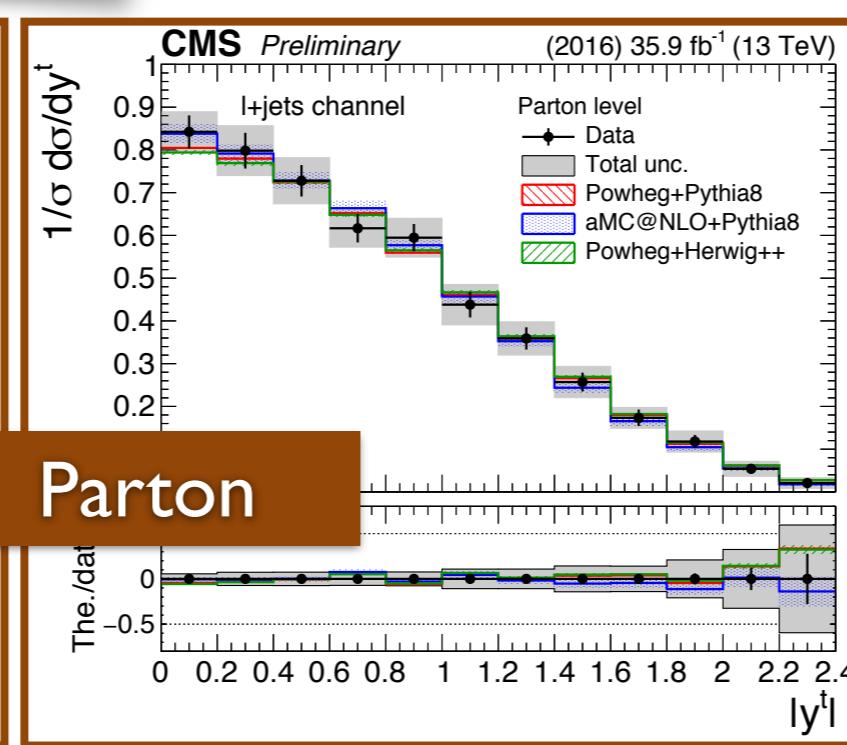
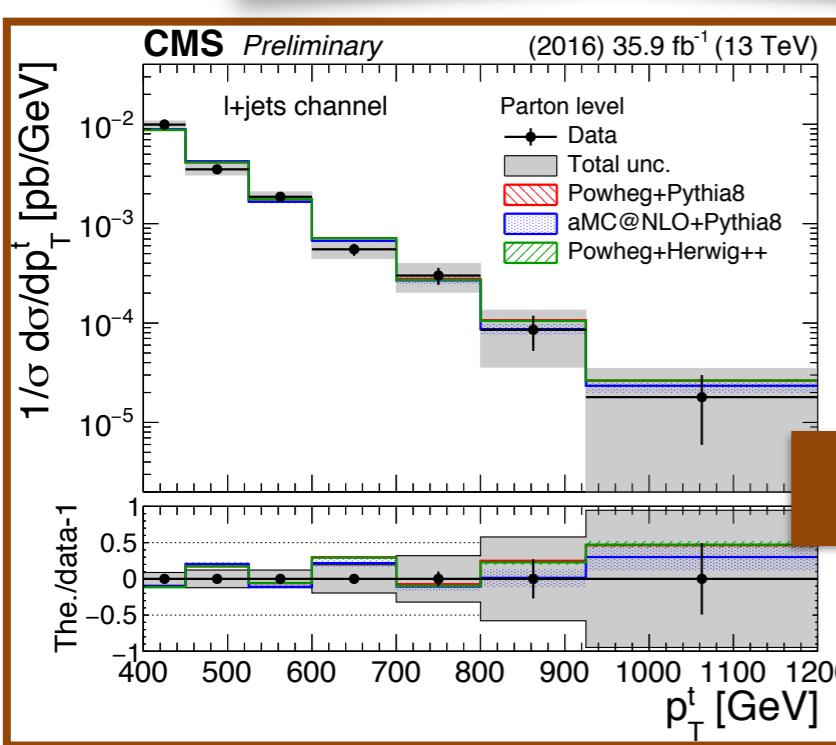
- Measurements
 - Absolute and normalised differential cross section @ Parton and particle levels
 - Hadronically decaying top pT and $|y|$

- Results
 - Differential distributions are generally well described
 - All models overpredict the absolute cross section (~20%)

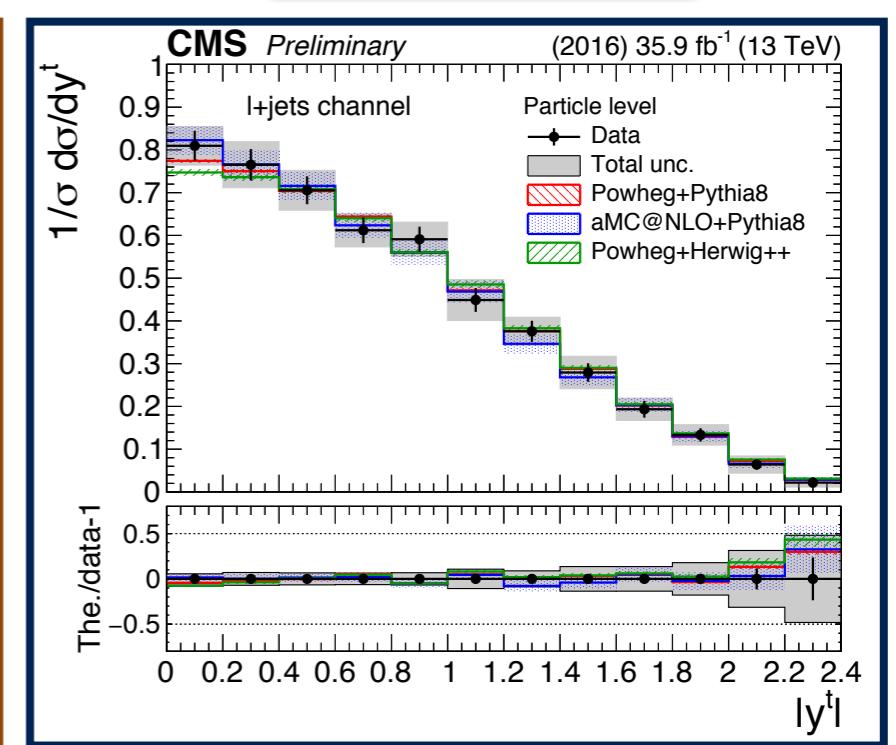
L + jets



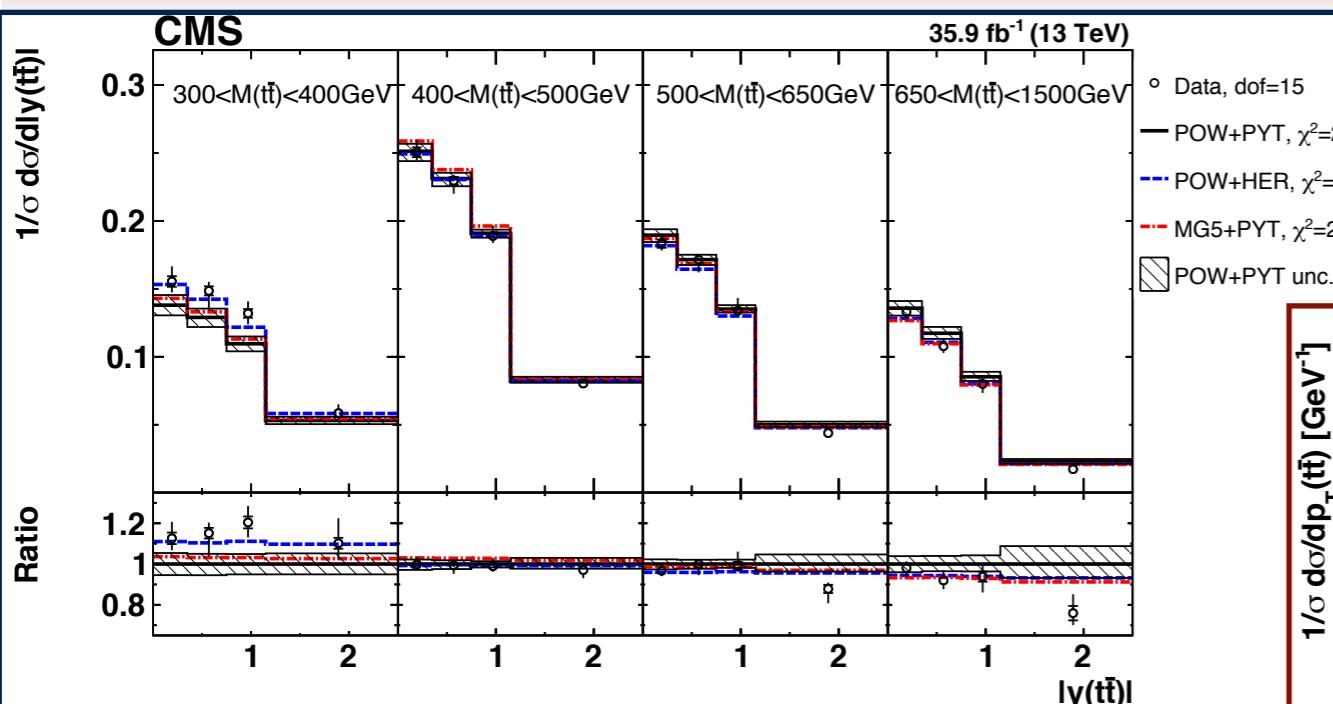
Particle



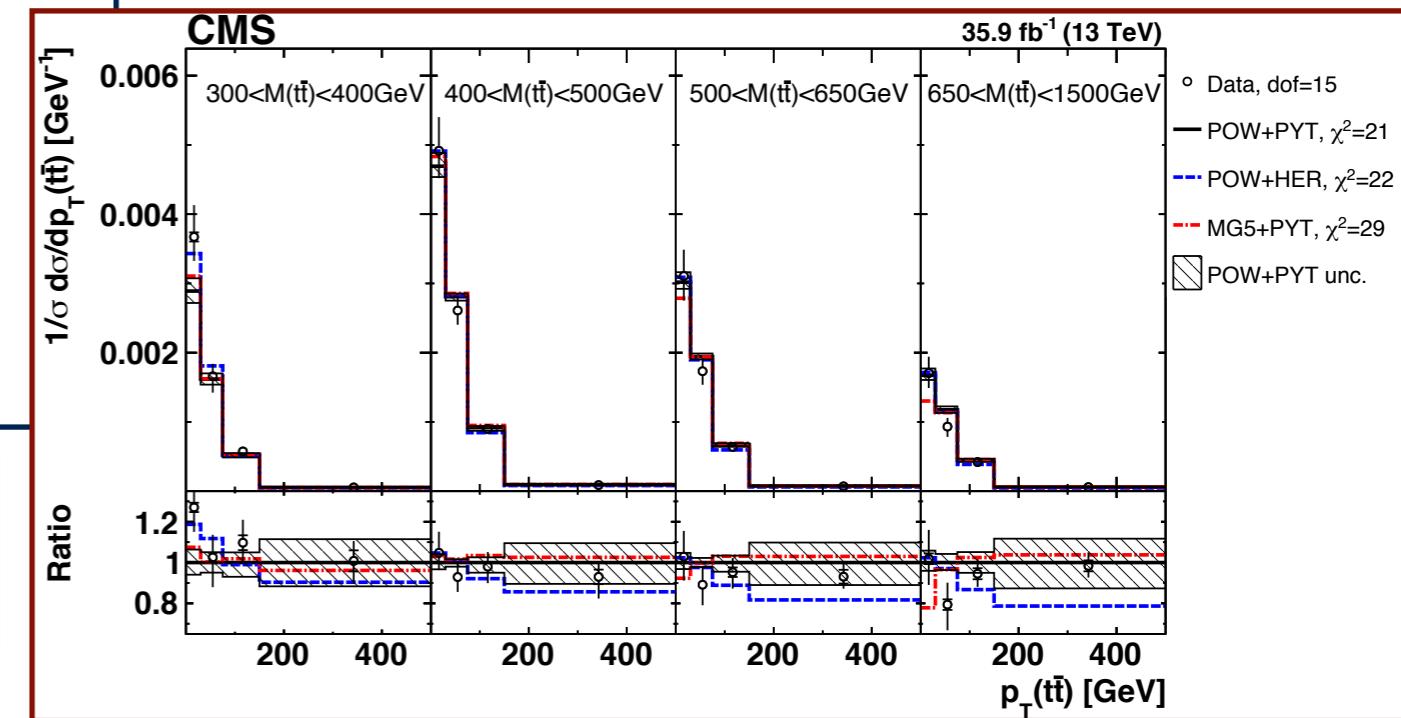
Parton



2D Differential Cross Sections



- All MC describe data well
- MG5+PYT predicts too hard $p_T(t\bar{t})$ 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 , 2 jets (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

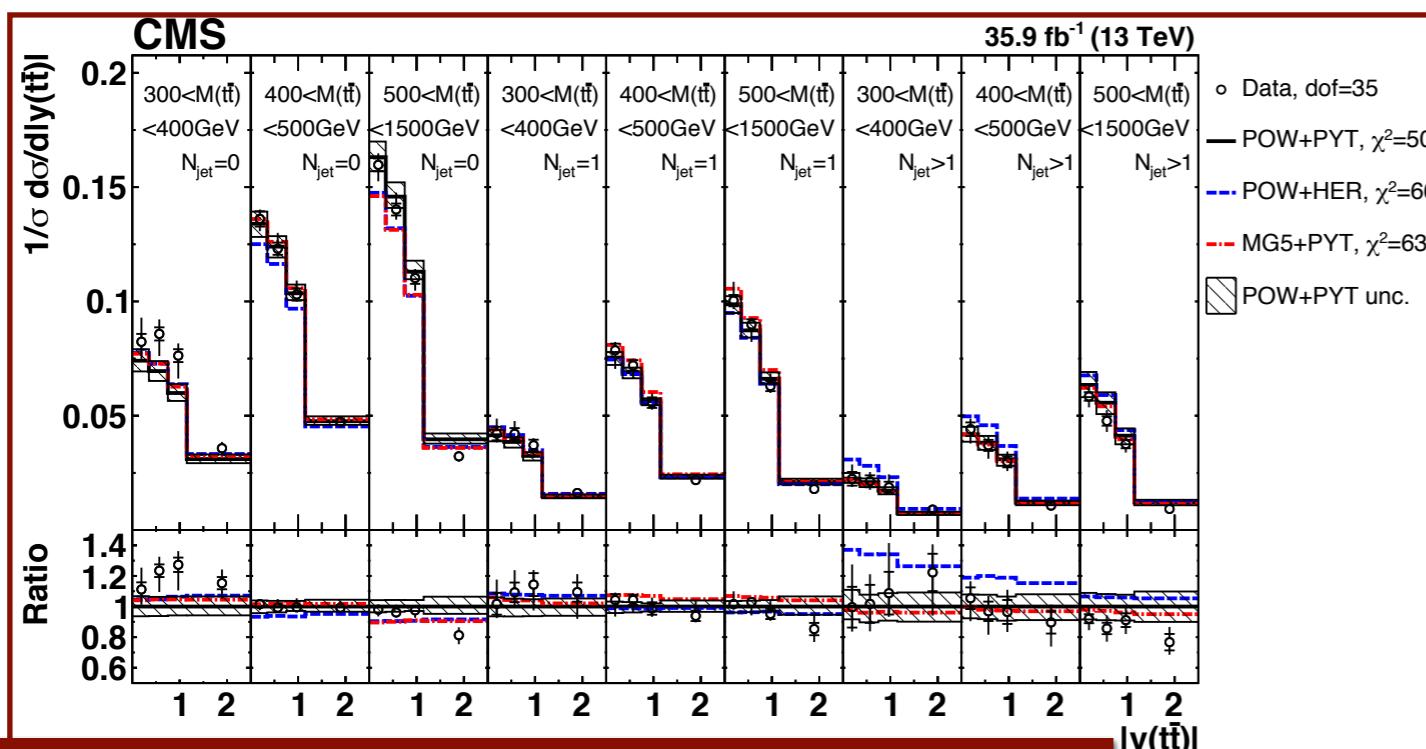
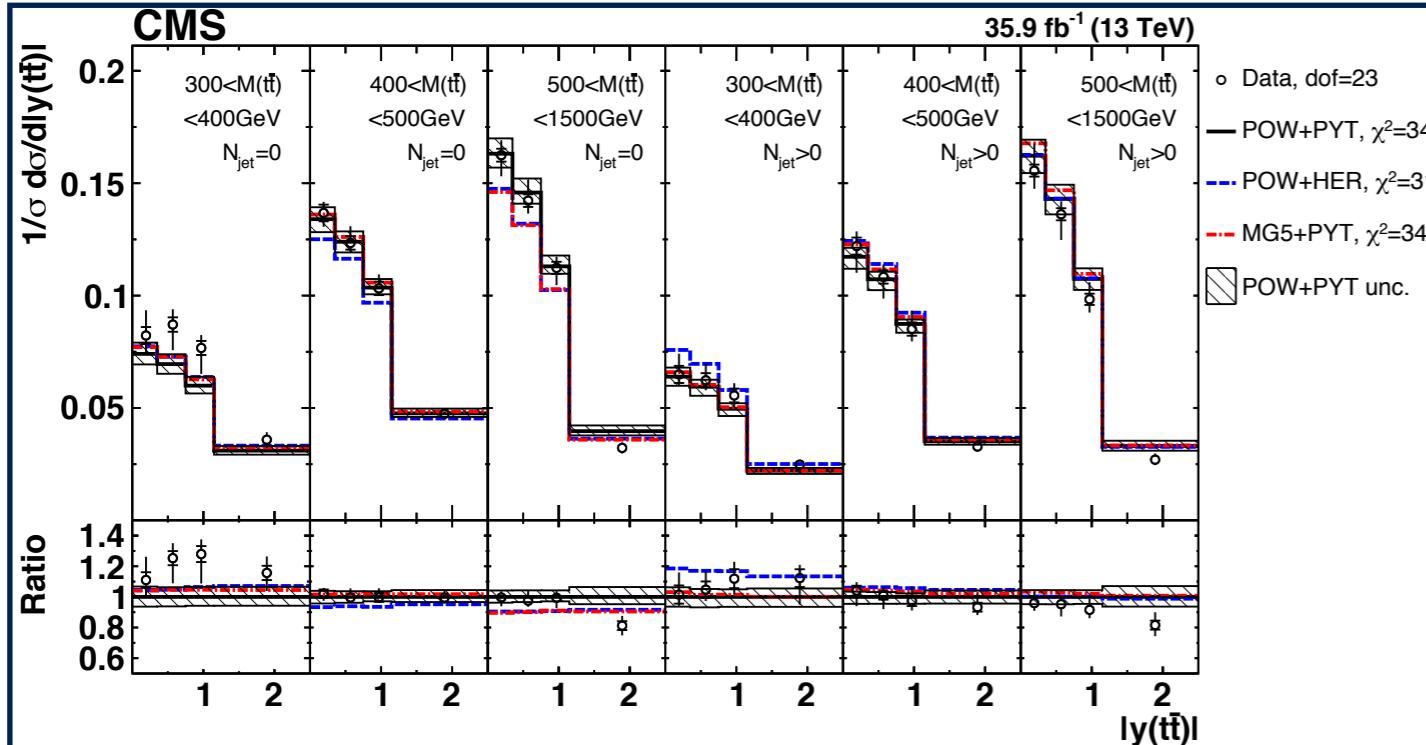
POW+PYT: POWHEG + Pythia8
 POW+HER: POWHEG + Herwig++
 MG5+PYT: MG5_aMC@NLO

3D Differential Cross Sections

arXiv:1904.05237

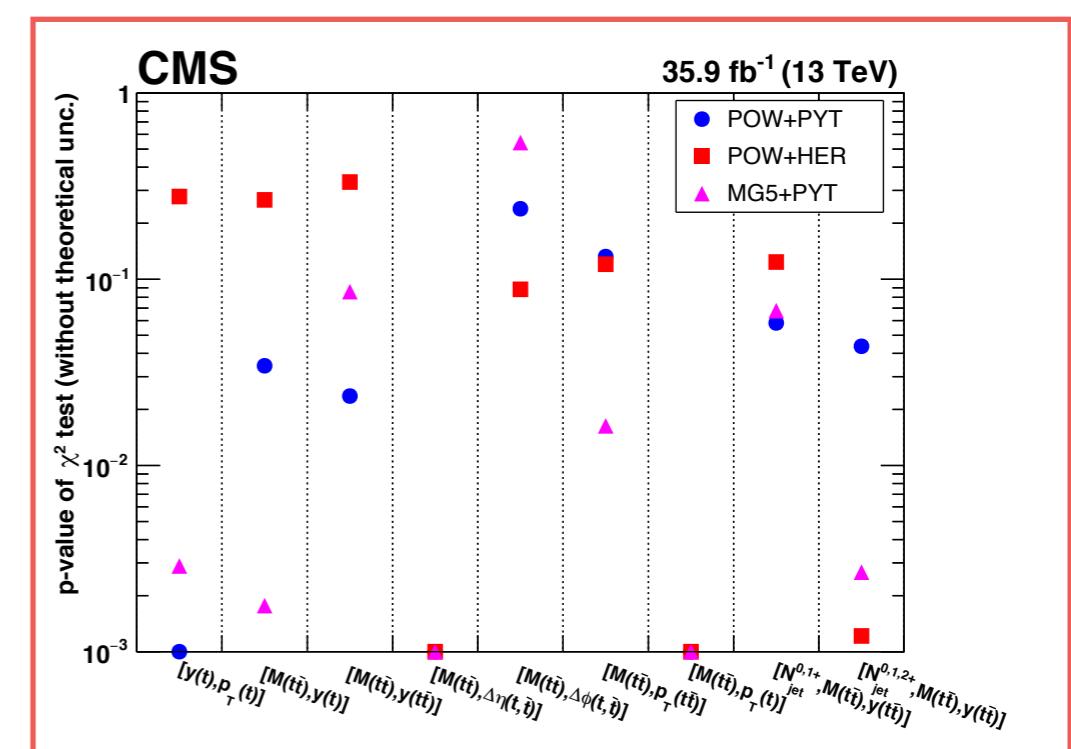


All MC describe data well



- 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 $N_{jet} = 1$

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
$[M(t\bar{t}), y(\bar{t})]$	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

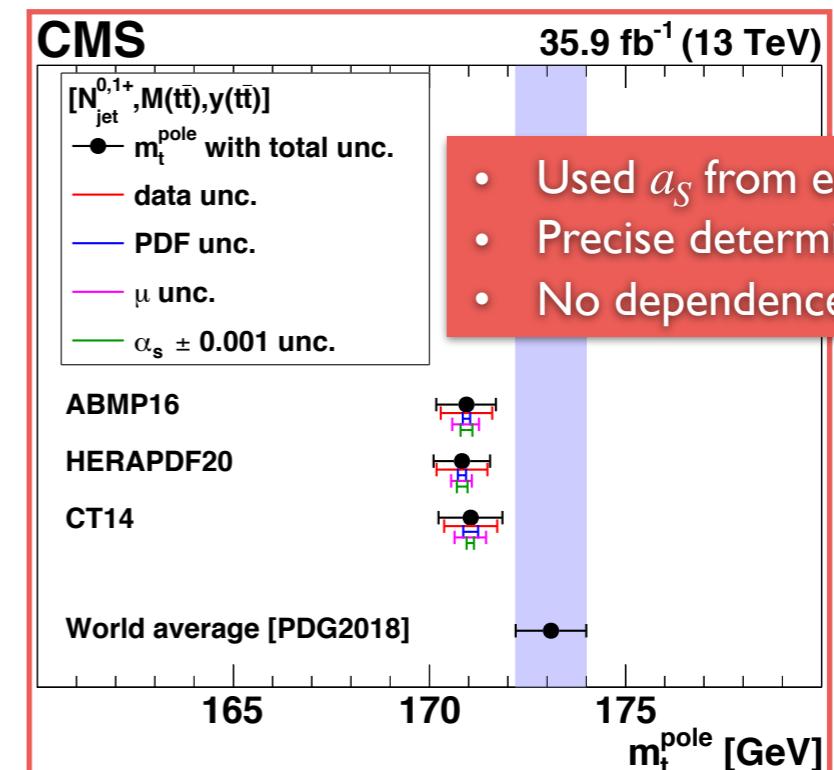
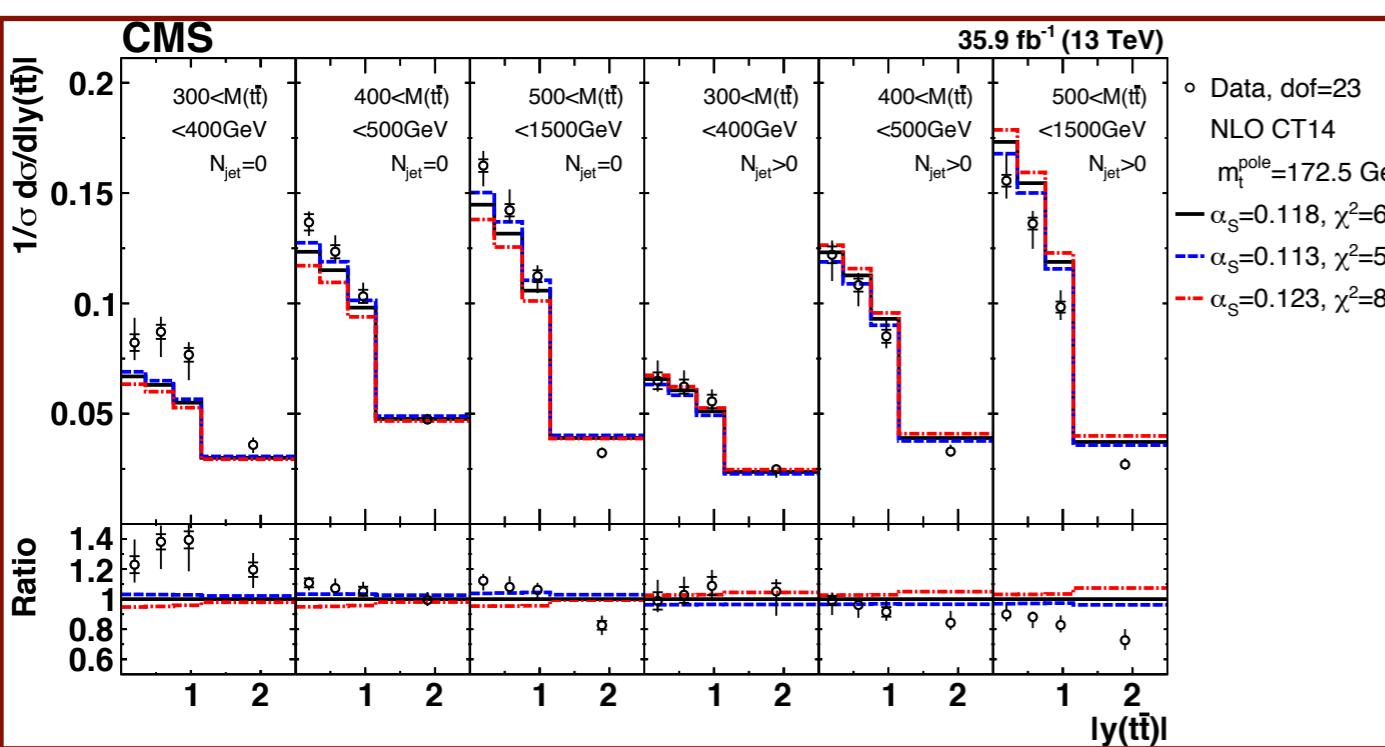
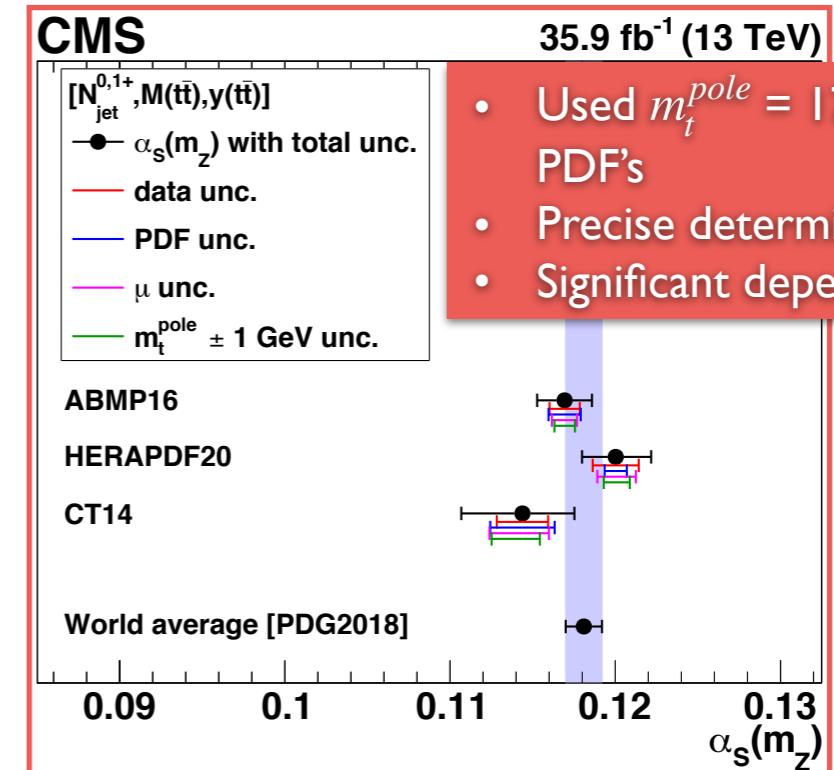
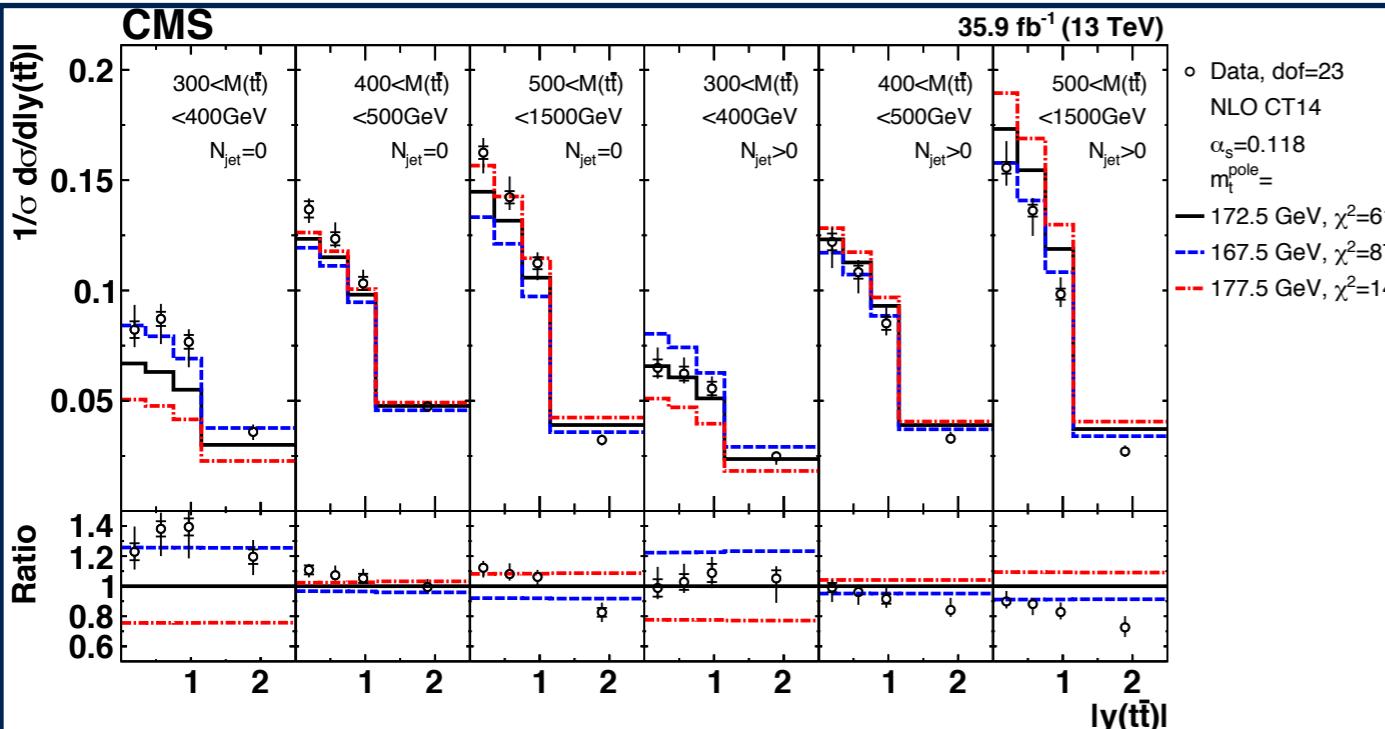


- Summary of Comparison to MC models
- None of the Central MC predictions is able to describe all distributions
- Best description by 'POW+PYT' and 'POW+HER'

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

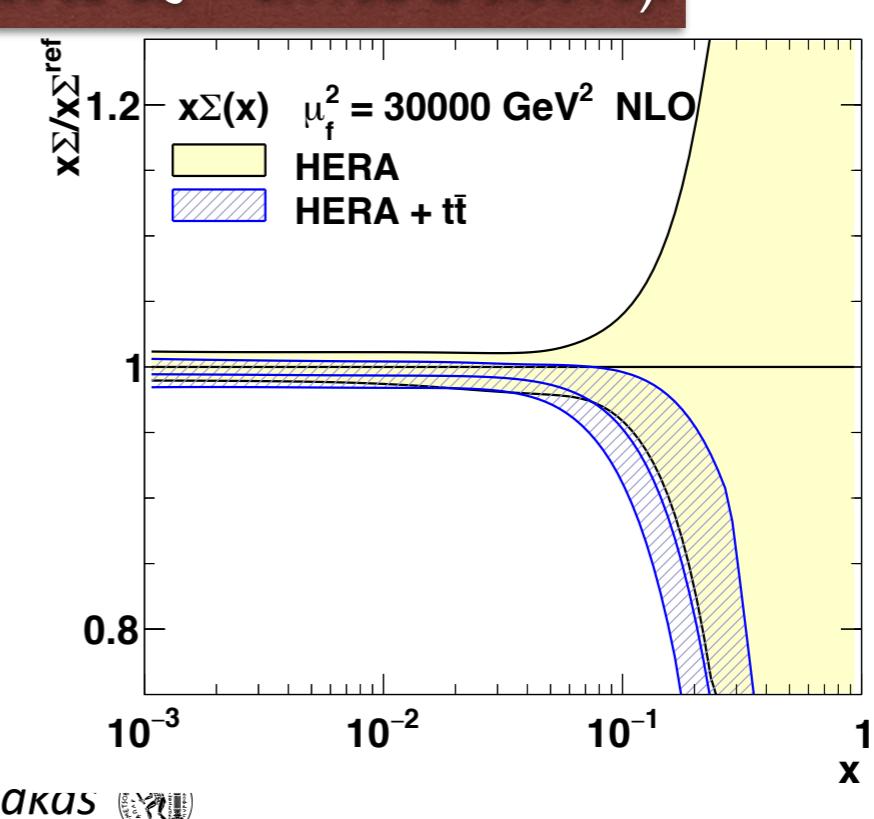
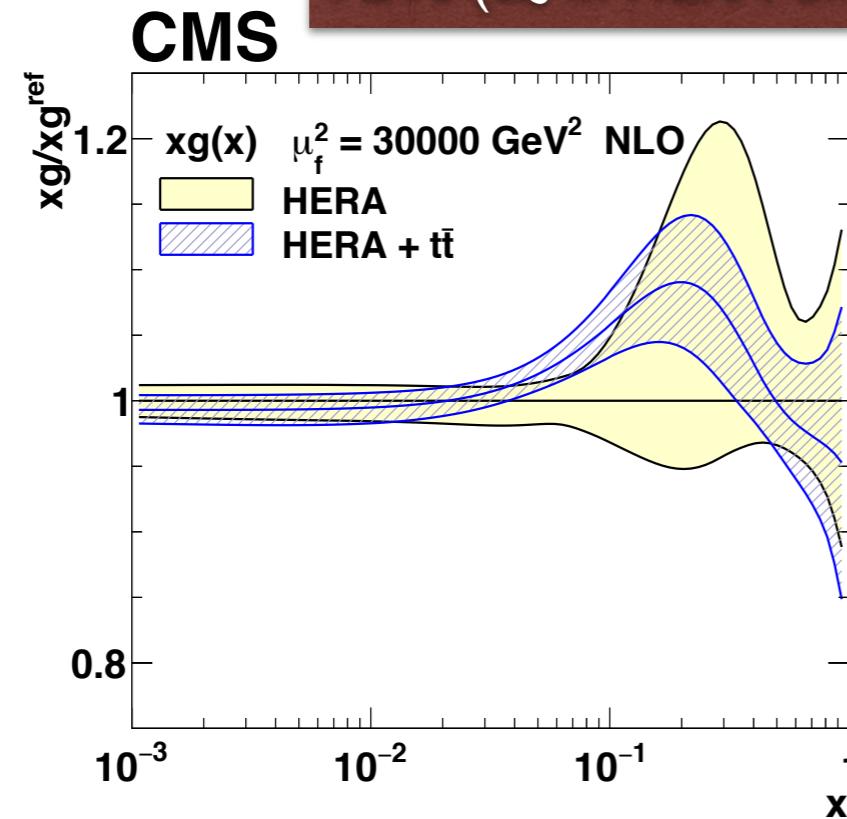
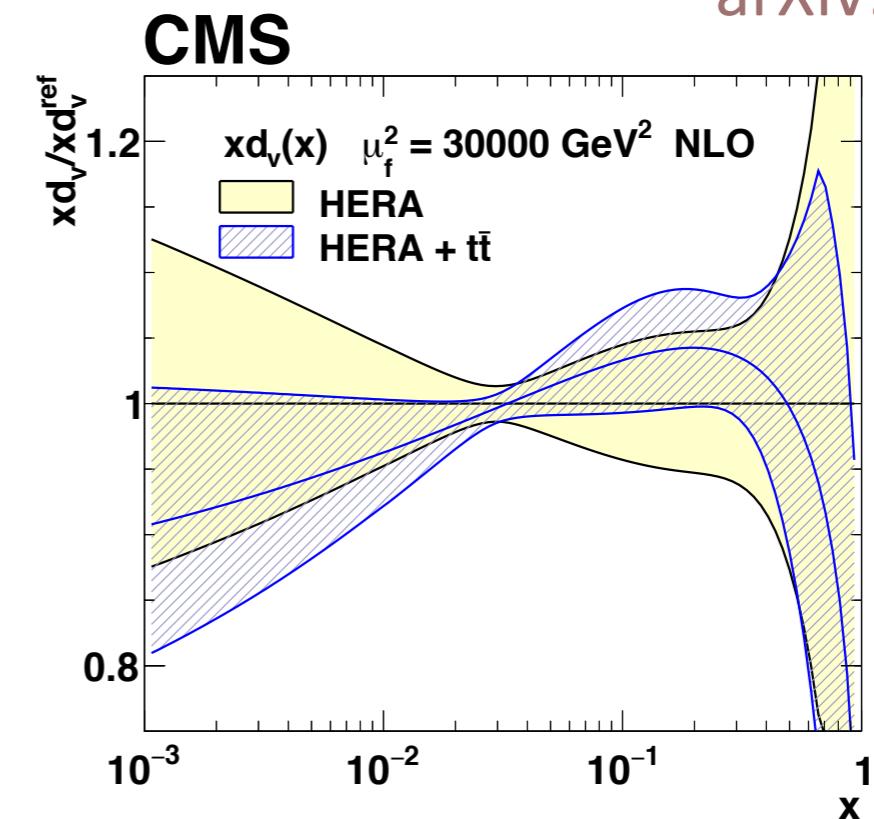
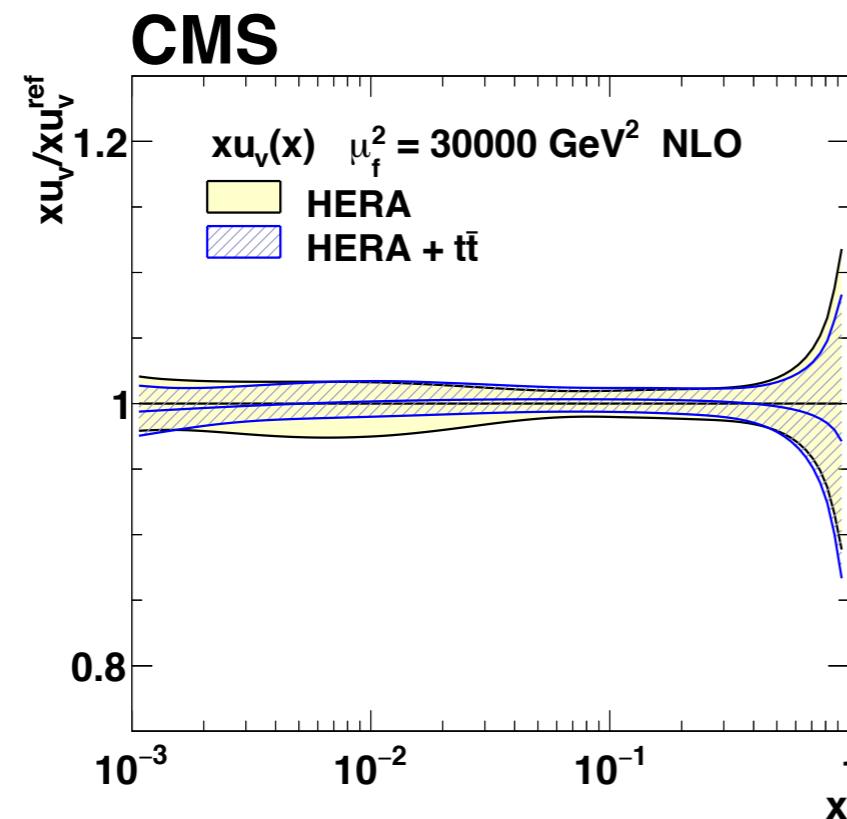


α_s sensitivity comes from different N_{jet} bins

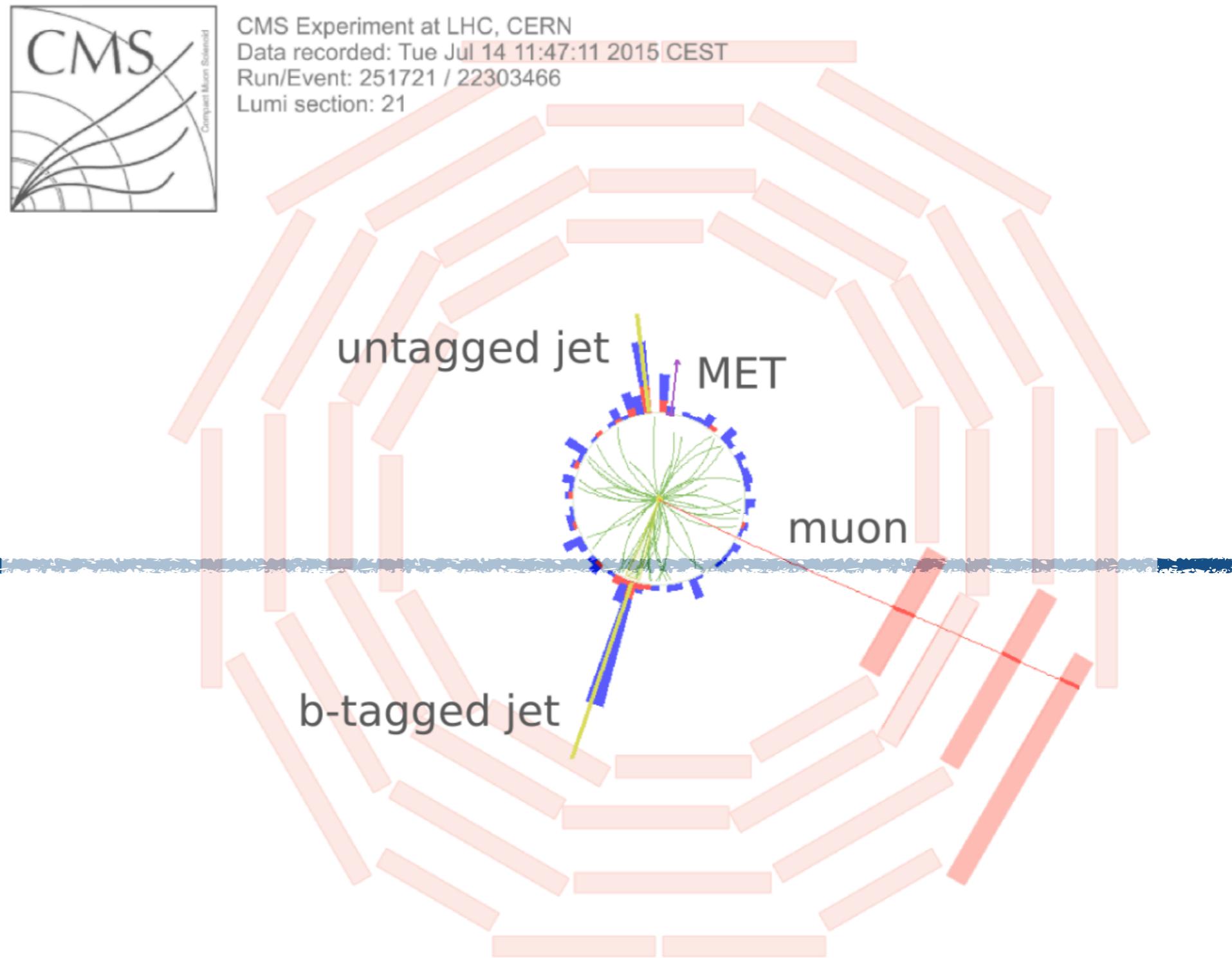
Extraction of a_s , m_t^{pole} and PDF's from 3D cross sections



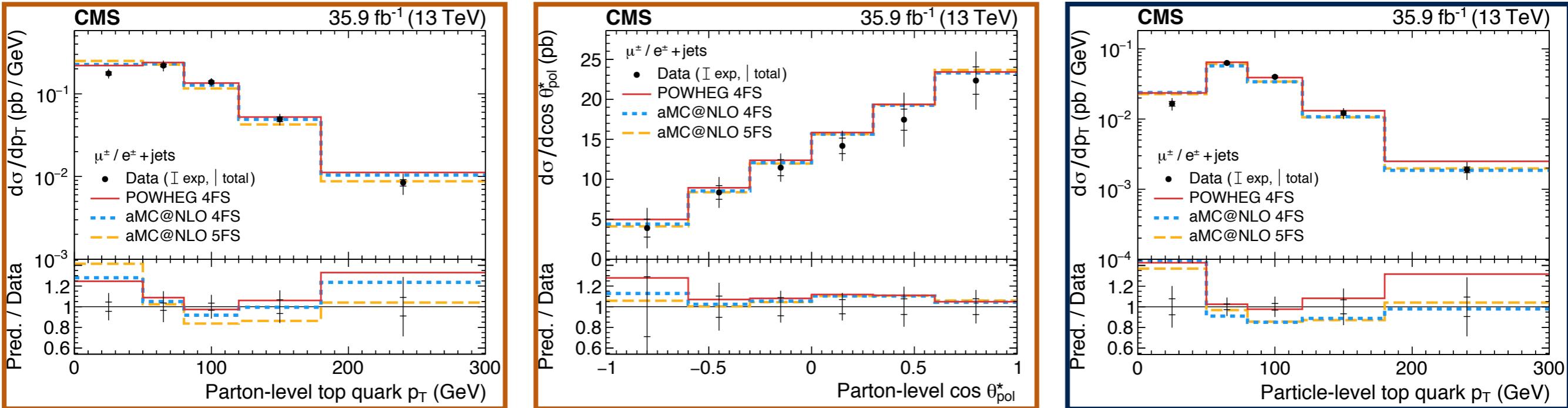
arXiv:1904.05237



Single Top



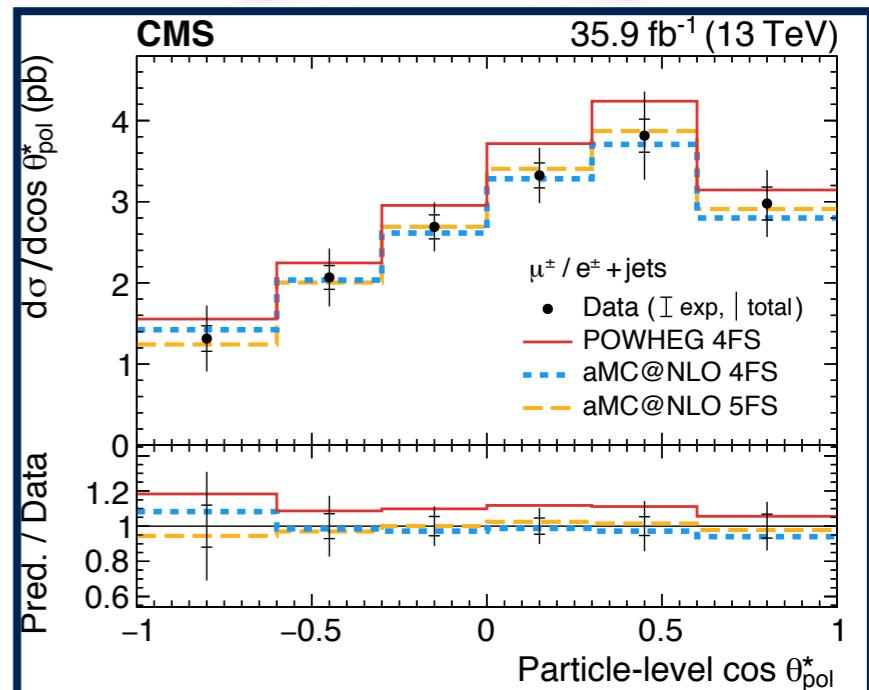
Differential Cross Sections $d\sigma_{t(\bar{t})}/dX$ in t-channel



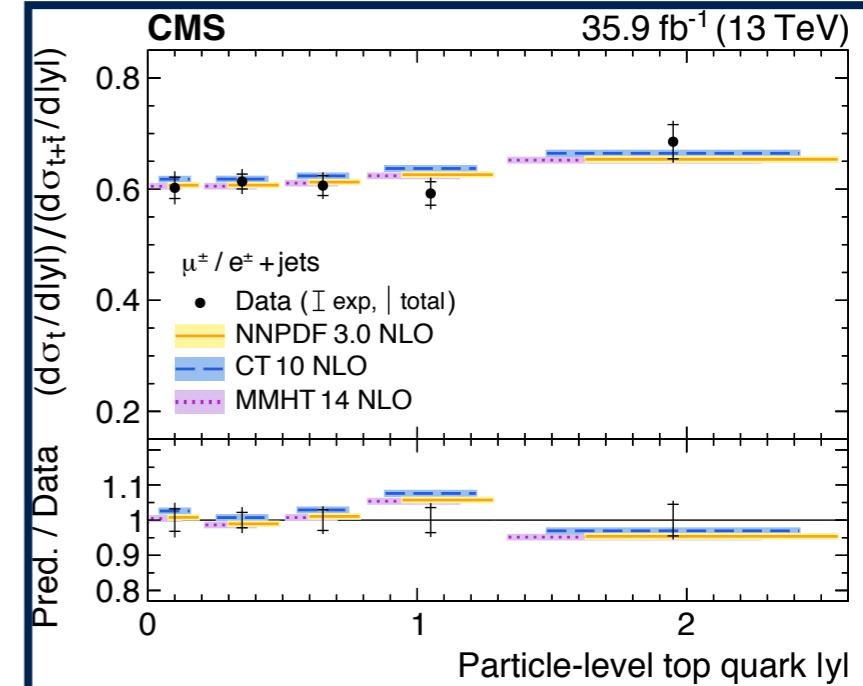
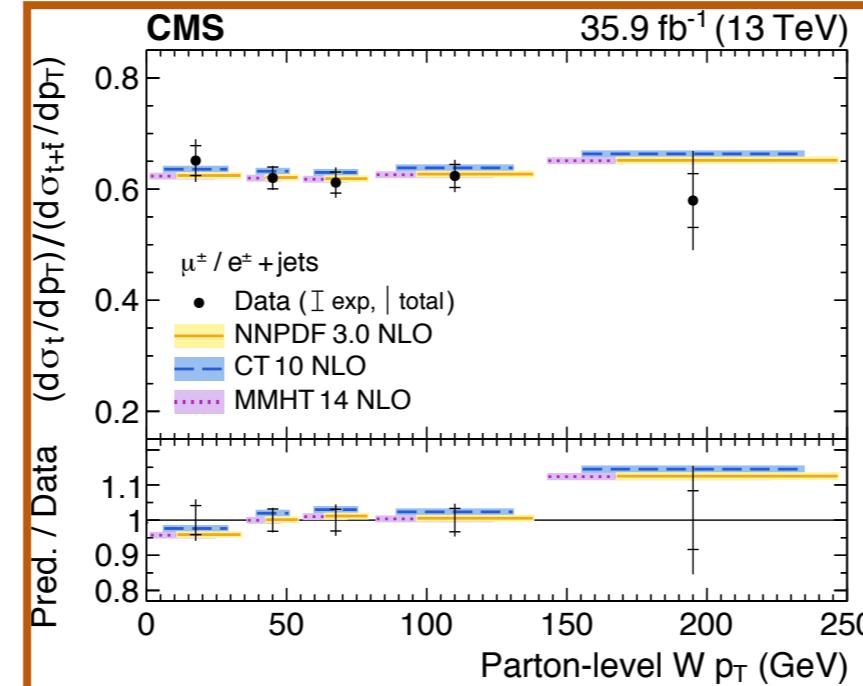
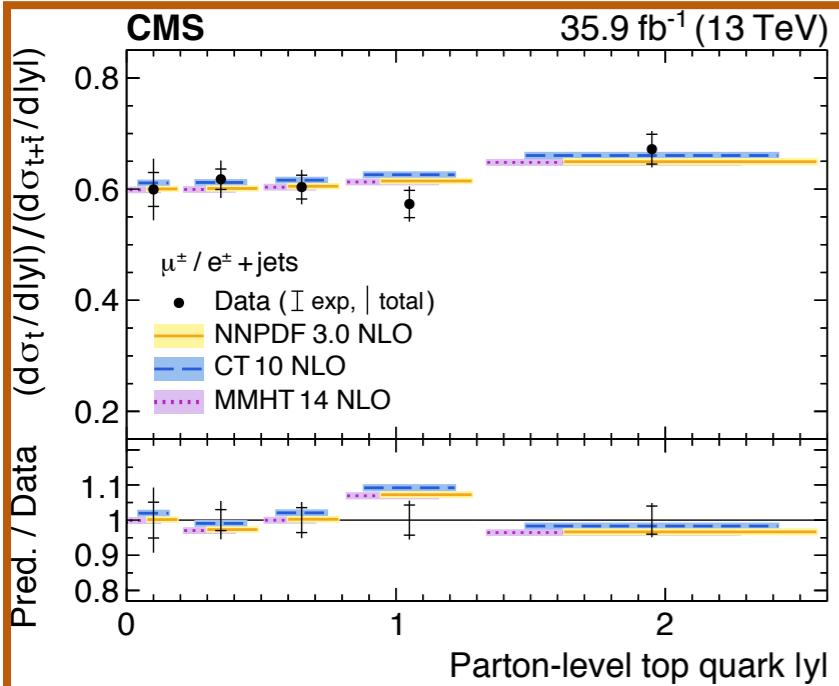
Parton

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 p_T , rapidity and polarisation angle $\cos\theta_{pol.}^* = \frac{\vec{p}_{q'}^{(top)} \cdot \vec{p}_l^{(top)}}{|\vec{p}_{q'}^{(top)}| \cdot |\vec{p}_l^{(top)}|}$
 - Unlike $t\bar{t}$ productions, tops in t-channel are highly polarised due to the V-A coupling structure
 - Charged lepton p_T , rapidity, W boson p_T 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

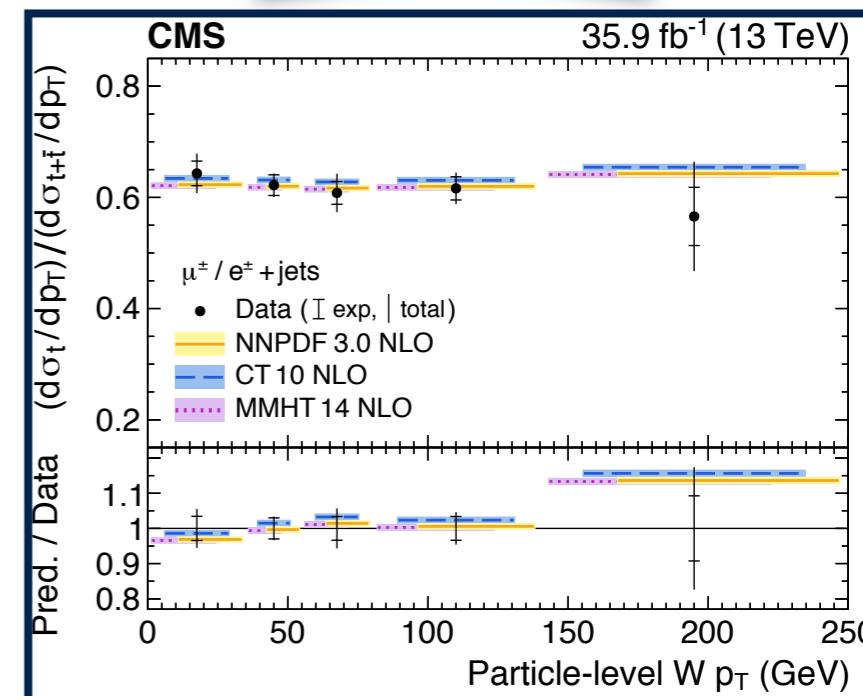
- Ratio of the single top cross section to the sum of the single top quark and antiquark cross sections

● Measurement

- Differentially as a function of the top quark, charged lepton, and W boson kinematic observables

● Results

- Shapes overall compatible with theory



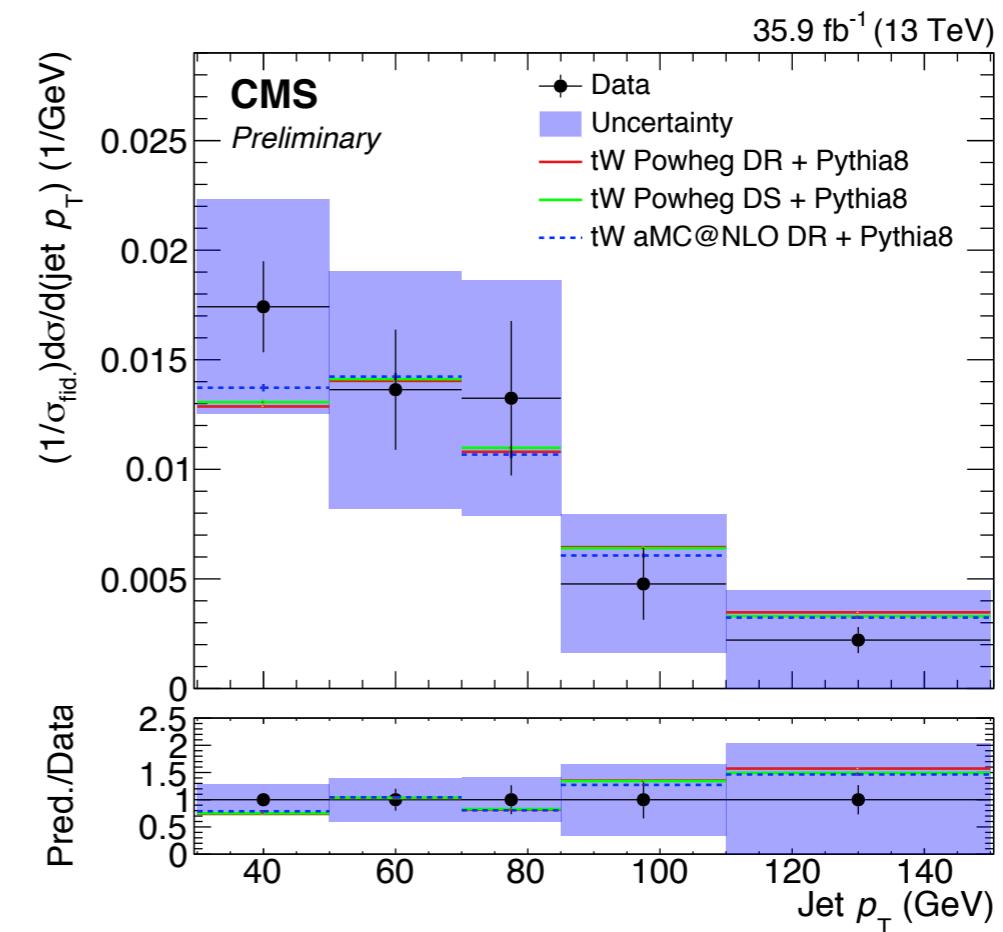
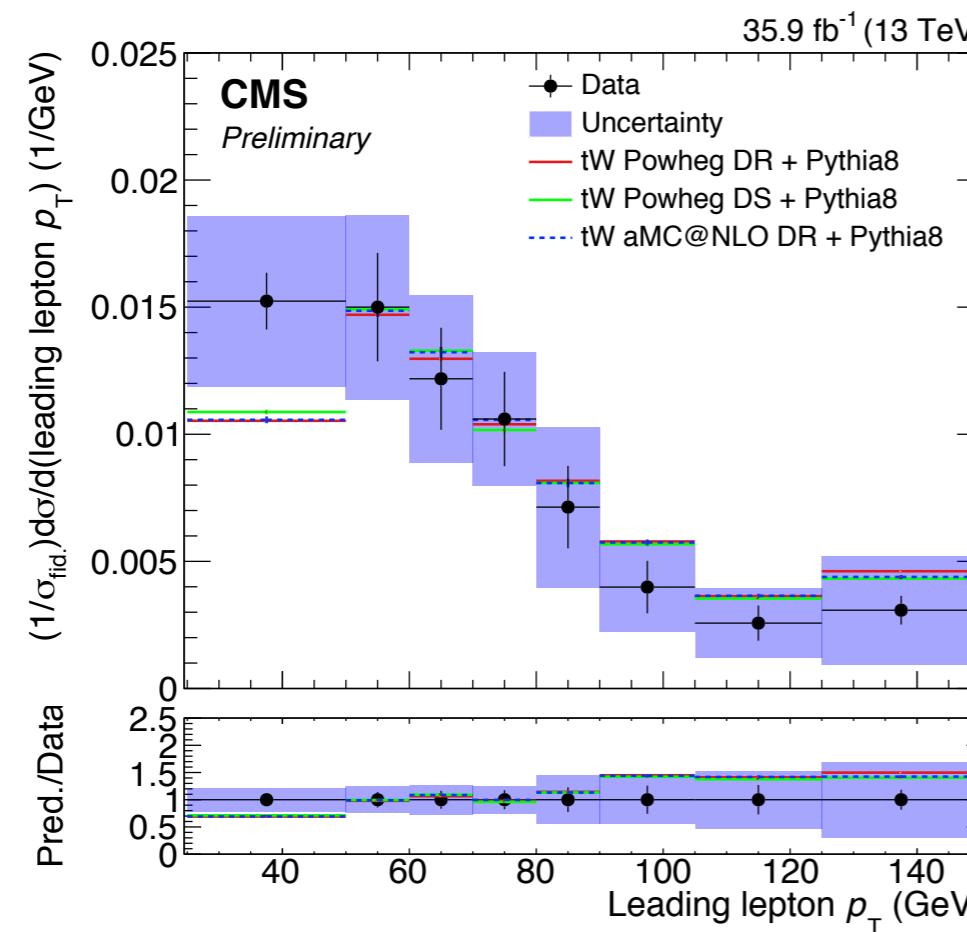
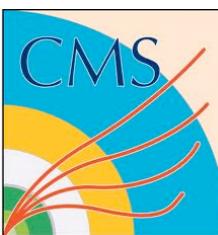
Spin Asymmetry in the single top t-channel

- 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
	$W/Z/\gamma^*+$ 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
	$PDF+\alpha_S$	± 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	± 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 $\rightarrow t\bar{t}$ being the largest
- Signal extraction performed by subtracting bkg, estimated through MC simulations

● Measurements

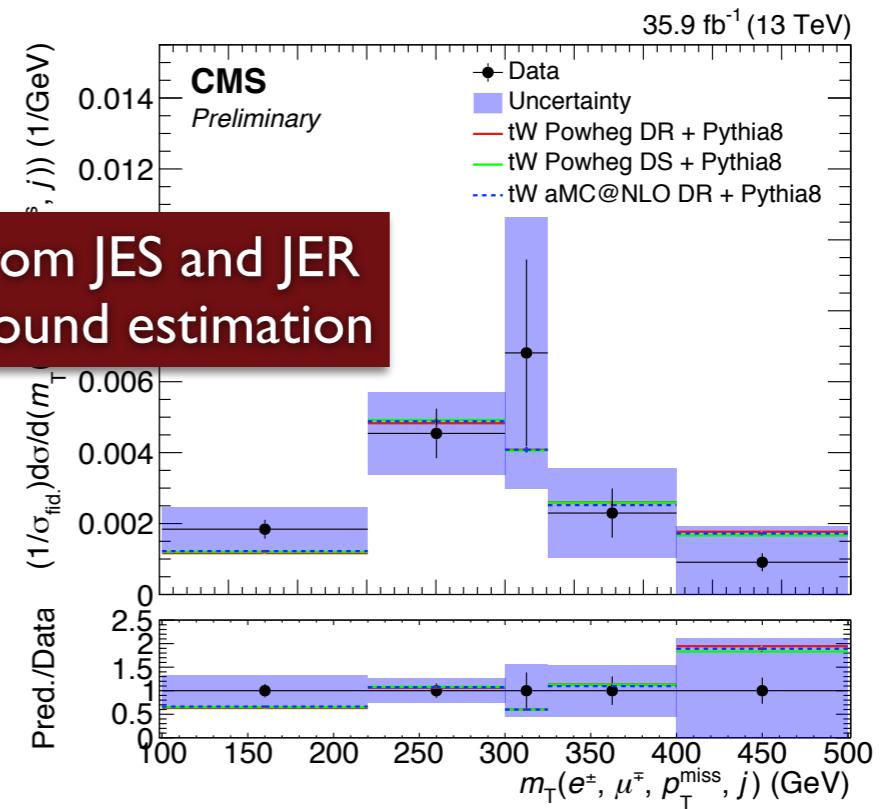
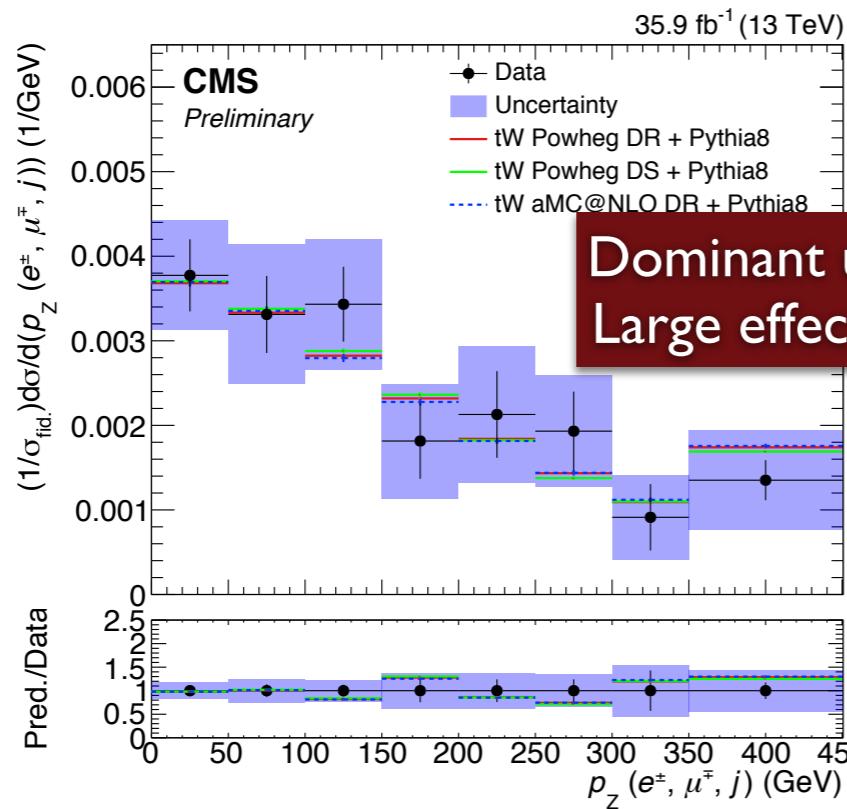
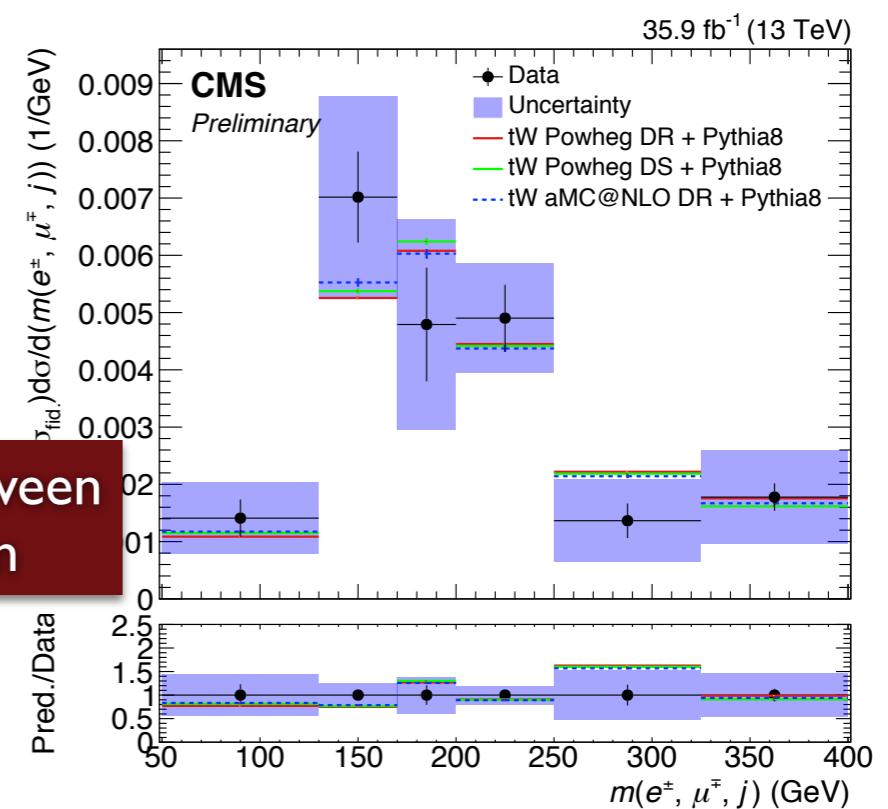
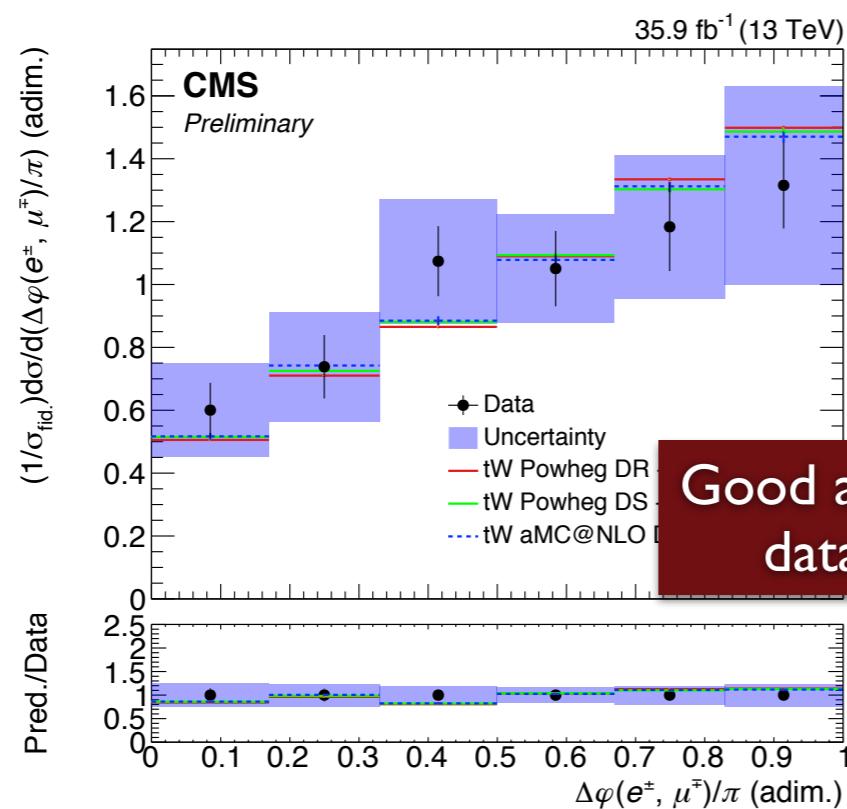
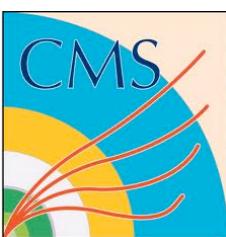
- Absolute and normalised differential cross section @ Particle level
- p_T for both the lepton and the jet, $\Delta\varphi(l_1, l_2)$, $m(l_1, l_2, j)$, $m_T(l_1, l_2, j, E_T^{\text{miss}})$ and $p_Z(l_1, l_2, j)$

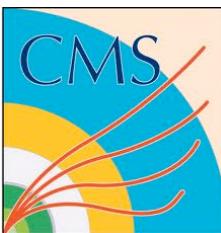
● Results

- 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





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 $\sim 35\%$ in the hadronic channel and $\sim 20\%$ 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!!

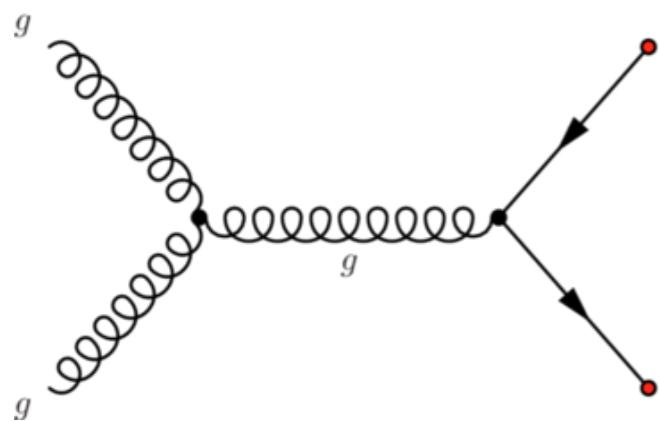


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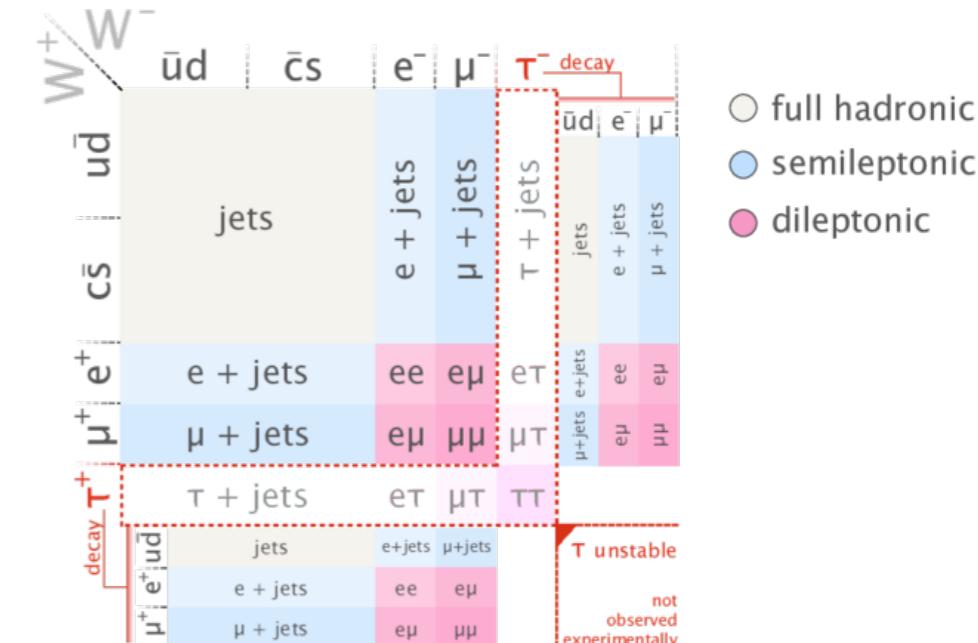
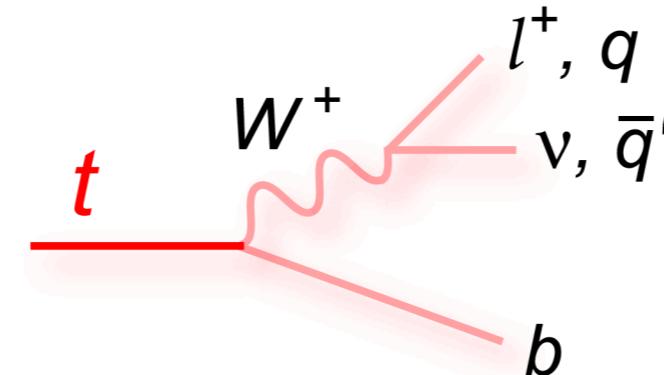


Top Production and Decay

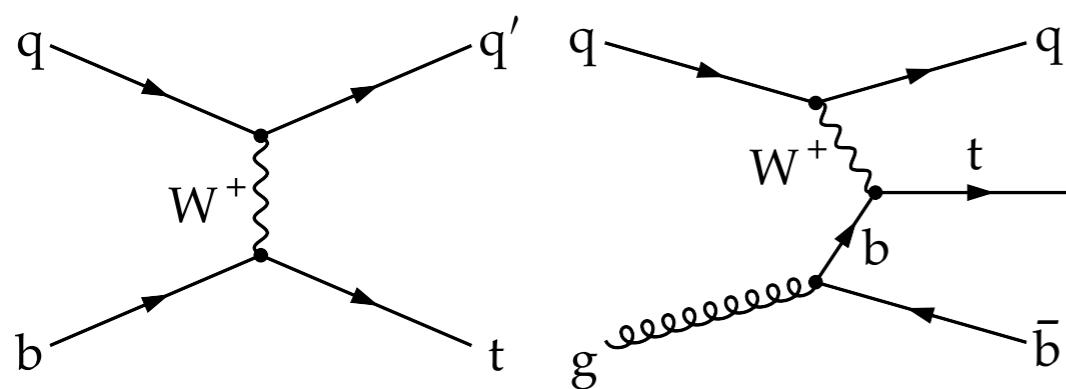
top quark pair production



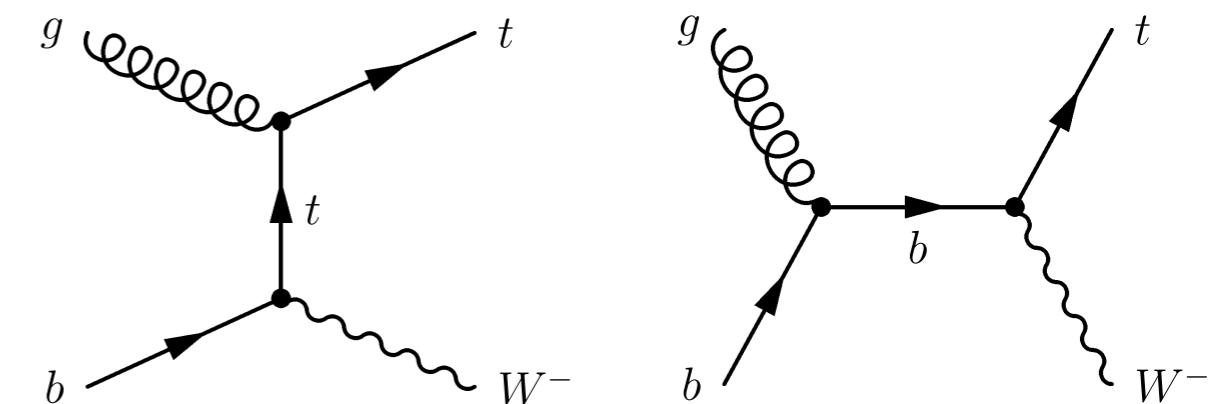
$$\text{BR}(t \rightarrow Wb) = 0.957$$



single top quark production (t channel)



single top quark production (tW mode)



References (Publications + Preliminary Results)



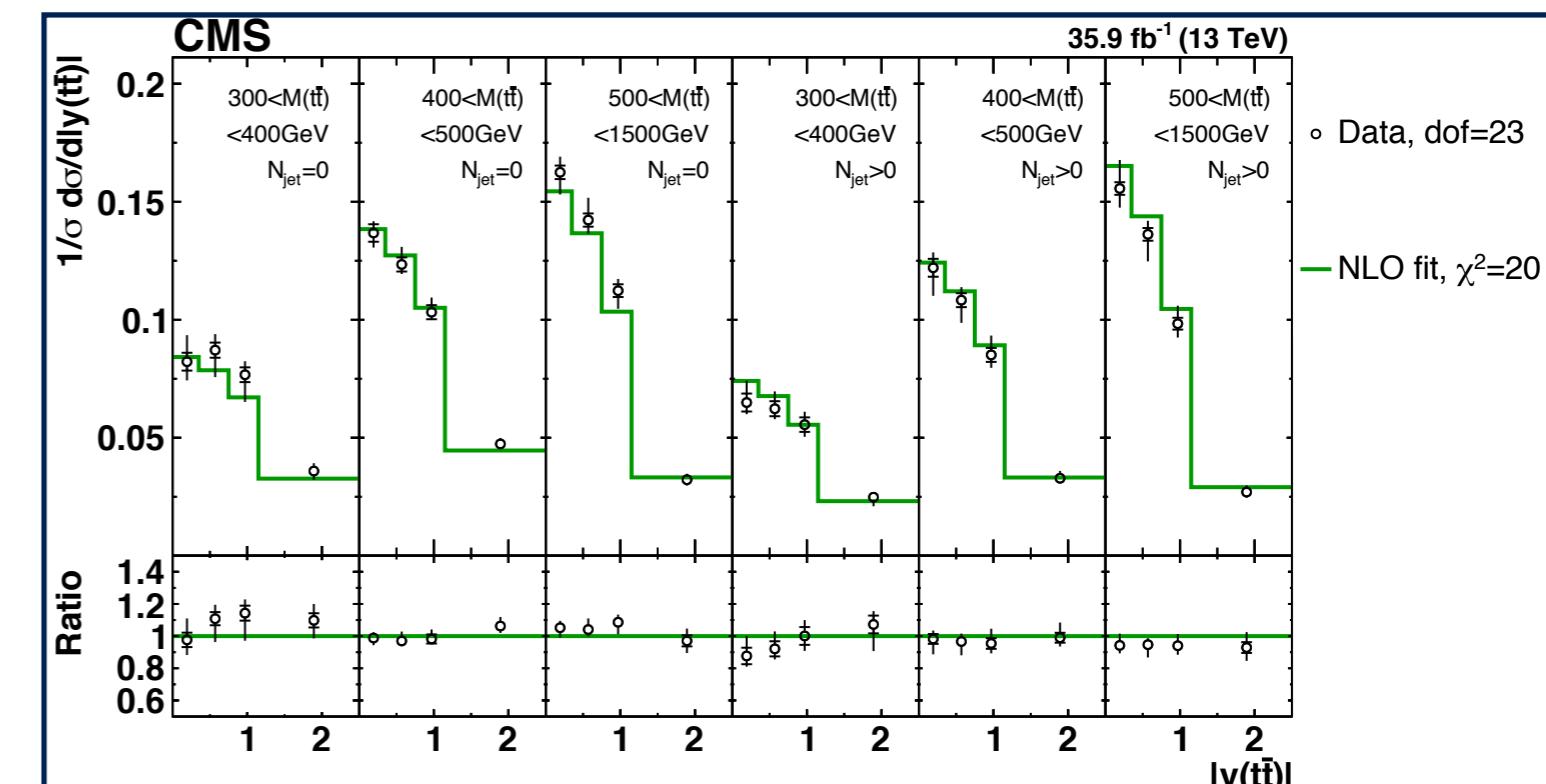
- (1) "Measurement of differential $t\bar{t}$ cross sections for high- p_T top quarks in proton-proton collisions at $\text{sqrt}(s) = 13 \text{ TeV}$ ", **CMS-PAS-TOP-18-013**
- (2) "Measurement of $t\bar{t}$ normalised multi-differential cross sections in pp collisions at $\text{sqrt}(s) = 13 \text{ TeV}$, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions", [arXiv:1904.05237](https://arxiv.org/abs/1904.05237)
- (3) "Measurement of differential cross sections for single top quark production in association with a W boson at $\text{sqrt}(s) = 13 \text{ TeV}$ ", **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 $\text{sqrt}(s) = 13 \text{ TeV}$ ", **Eur. Phys. J. C 80, 370 (2020)**, [arXiv:1907.08330](https://arxiv.org/abs/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	$+[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$
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



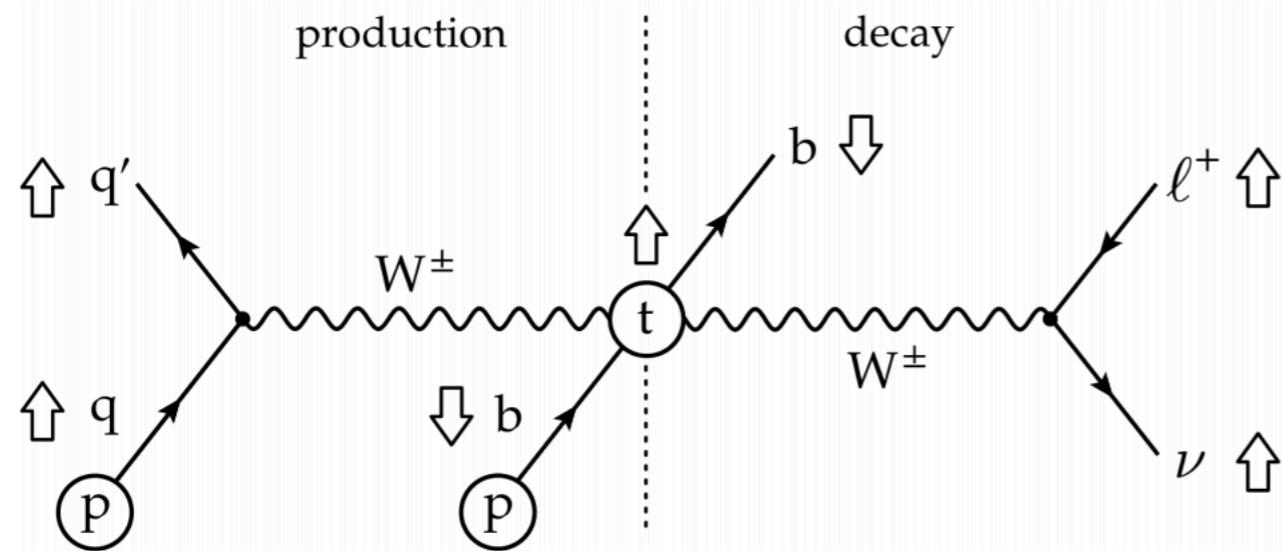
- The resulting values of a_S and m_t^{pole} extracted using NLO calculations:

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



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

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

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

- Spin - analyzing power $a_l \rightarrow$ degree of alignment of charged lepton with top spin
- Polarisation $P_t \rightarrow$ degree of alignment of spectator quark momentum with top spin
- Estimate asymmetry through linear χ^2 from $d\sigma/d\cos\theta_{pol}$.