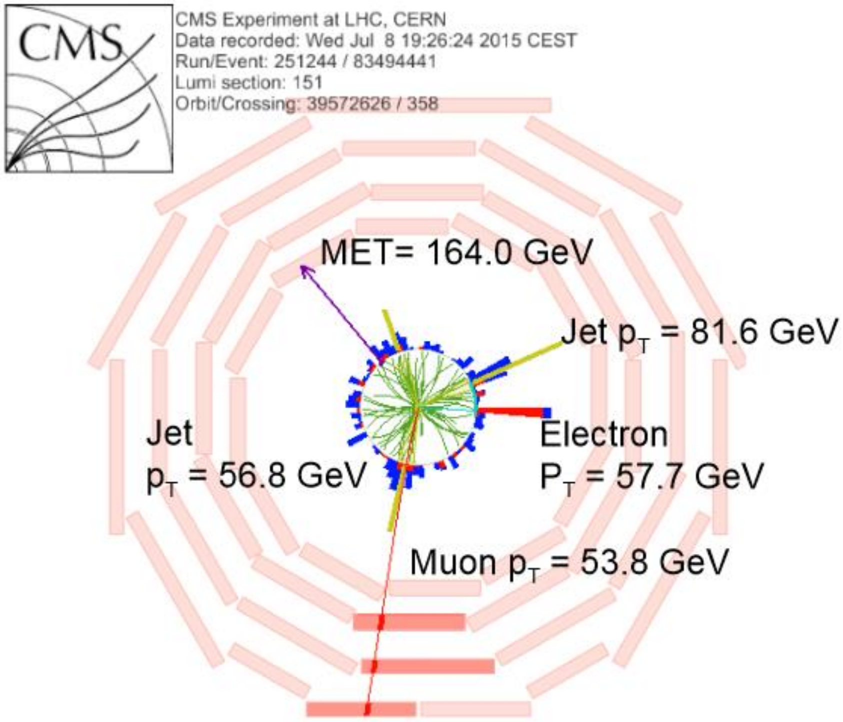
Top quark measurements in CMS



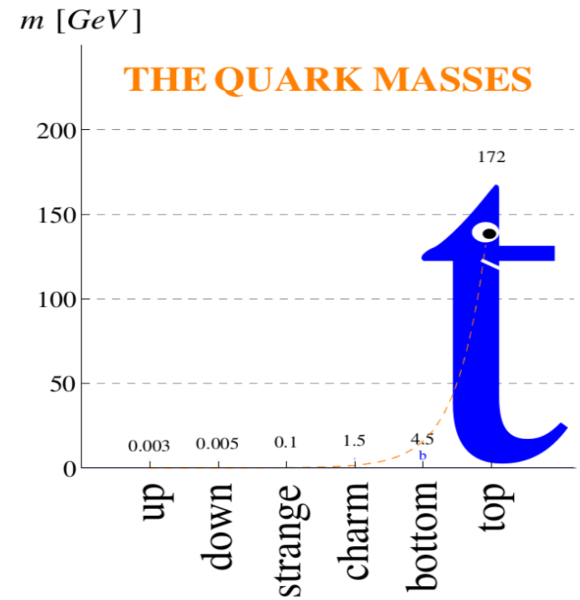
Till Arndt for the CMS Collaboration

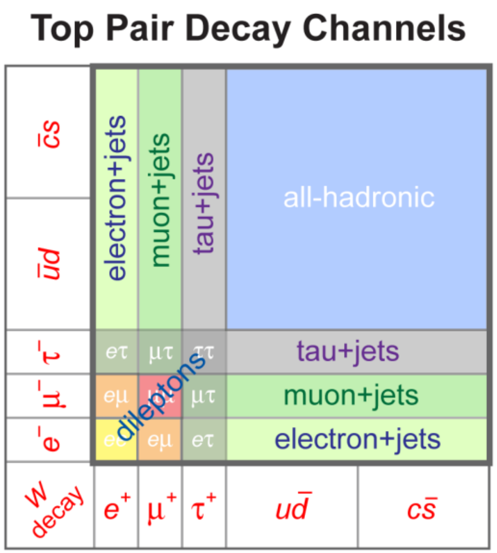
QCD@LHC 2018
Dresden, 27.08.2018

HELMHOLTZ | ASSOCIATION

The top quark

- Heaviest known particle
  - Strong coupling to the Higgs boson
  - Point-like according to current understanding
- Decays before hadronization
  - Does not form bound states
  - Bare quark properties measurable
- Physics goals
  - Increase precision of results
  - Differential distributions
  - Associated production



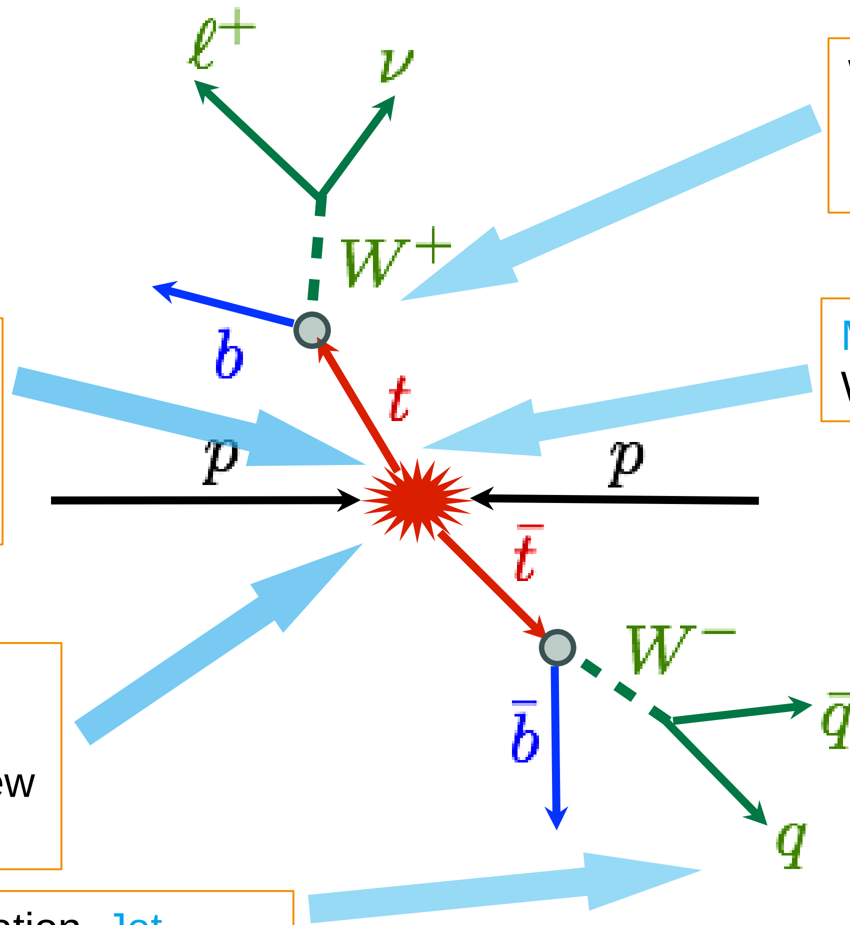


Top pair production and decay

W-Helicity fractions, Branching ratios, V_{tb}, Rare decays, FCNC

Mass, Mass difference, Width, Charge

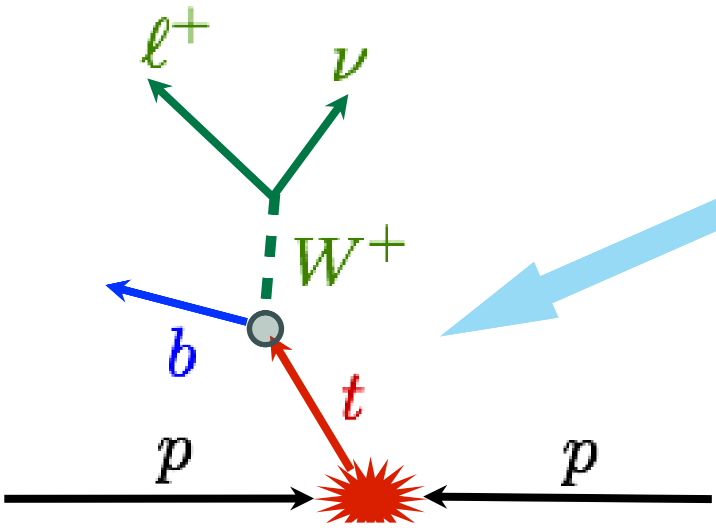
Spin correlations, polarization, asymmetry, underlying event



Cross sections, kinematics, QCD parameters, PDFs, new particles

Hadronization, Jet substructure

Single top production and decay

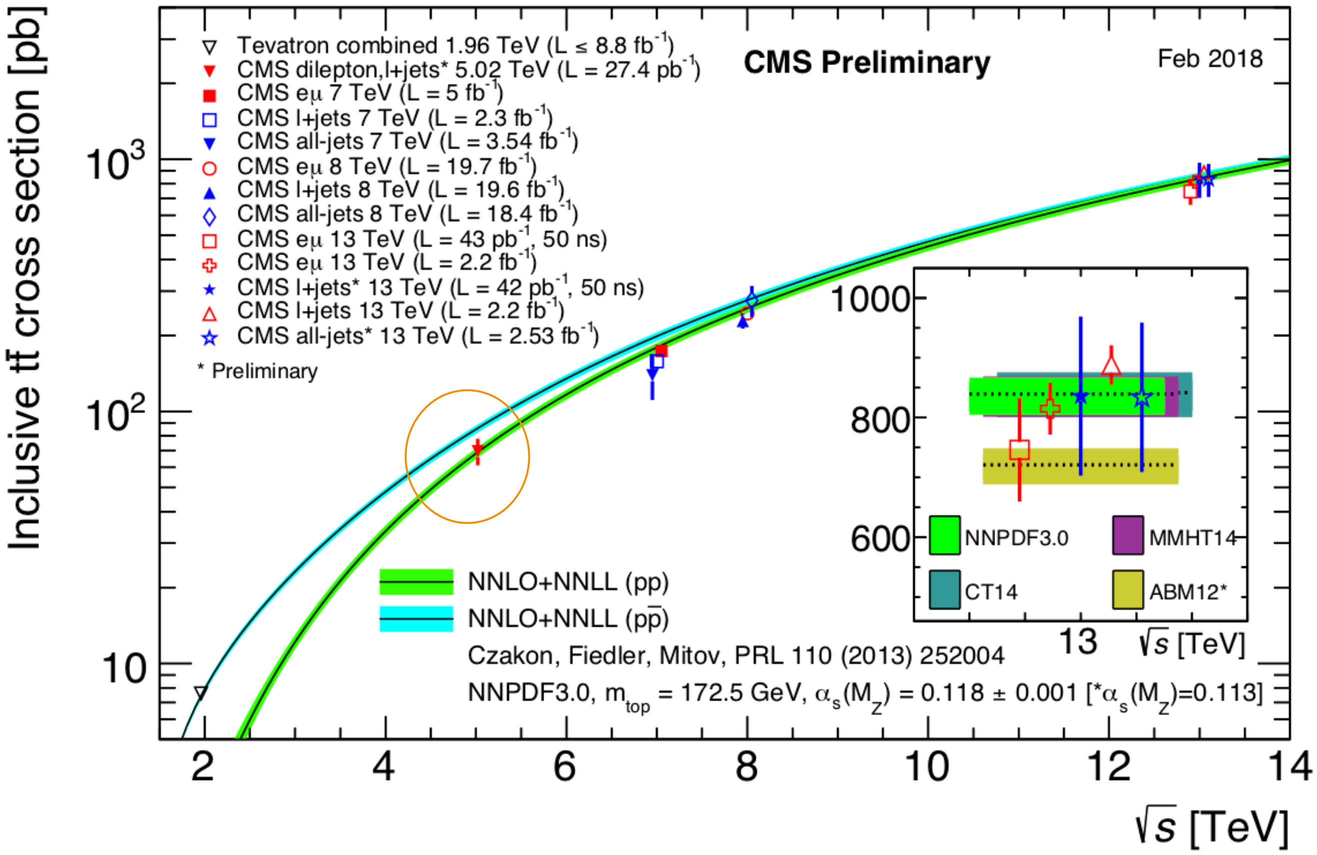


s- and t-channel production, associated production, V_{tb} ,polarization, mass

LHC as a top factory

- LHC is a top factory
  - Roughly 100 million top pairs produced in LHC-Run 2 at 13 TeV
- Todays results mostly with 2016 dataset
  - $35.9\ \mathrm{fb}^{-1}$ taken by CMS

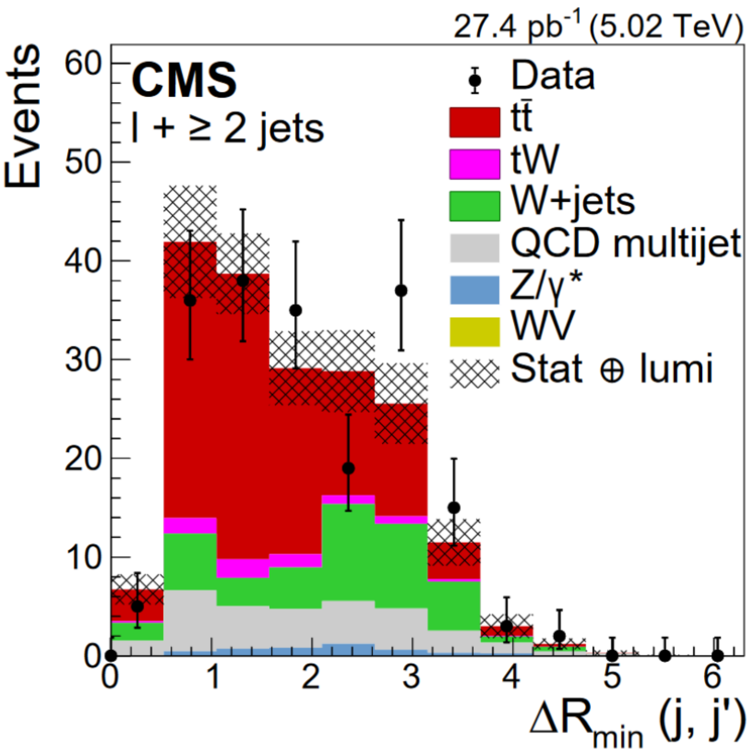
Inclusive top quark pair production

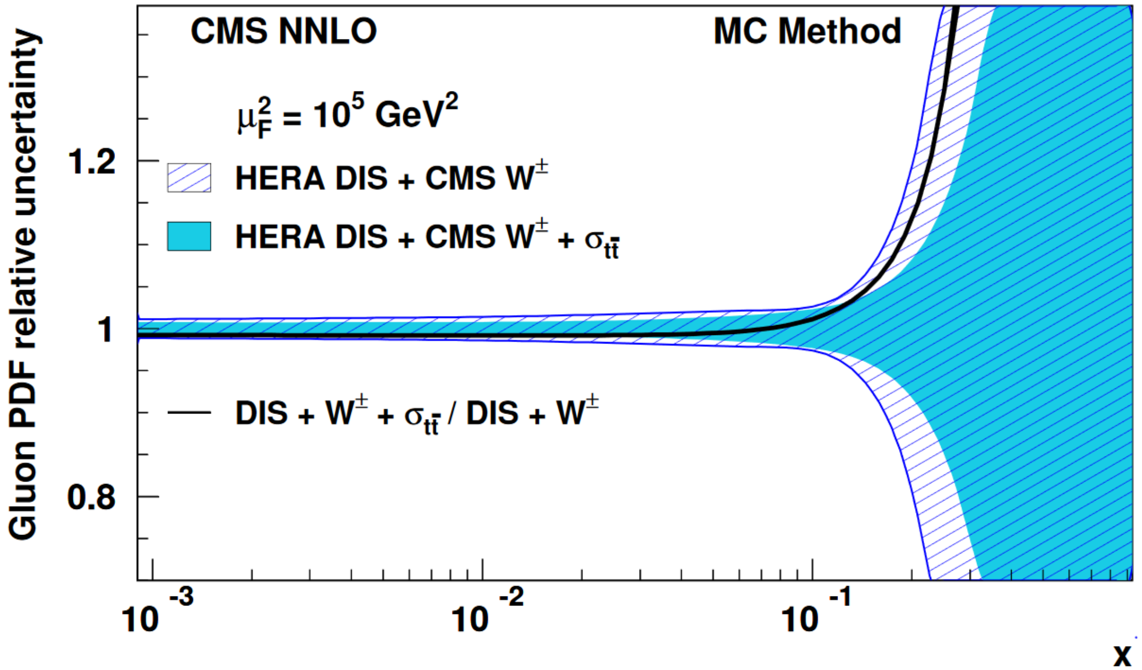


- Measured for multiple decays and energies
  - So far confirms SM

Inclusive $\sigma_{t\bar{t}}$ at 5.02 TeV

Arxiv 1711.03143
JHEP03(2018)115



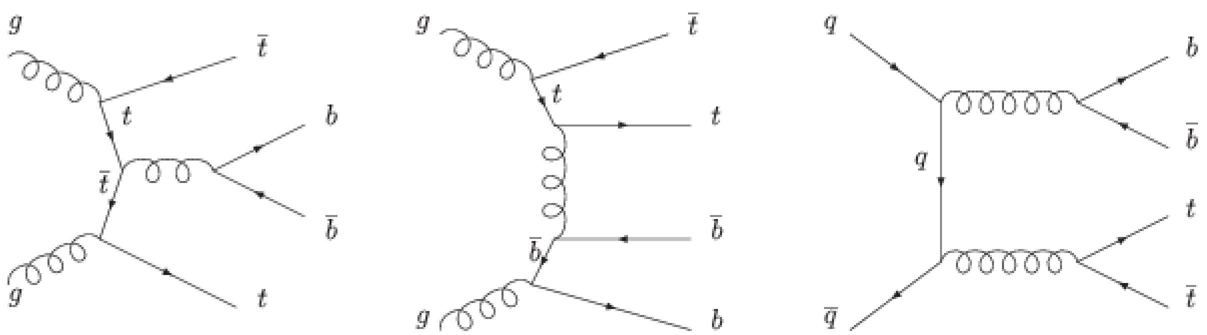


> Combination of l+jets and di-lepton channel

> $\sigma_{\rm NNLO} = 68.9^{+3.3}_{-3.4}$ pb (PRL 110 (2013), 252004)
> $\sigma_{t\bar{t}}(\text{comb}) = 69.5 \pm 6.1(\text{stat}) \pm 5.6(\text{syst}) \pm 1.6(\text{lumi})$ pb

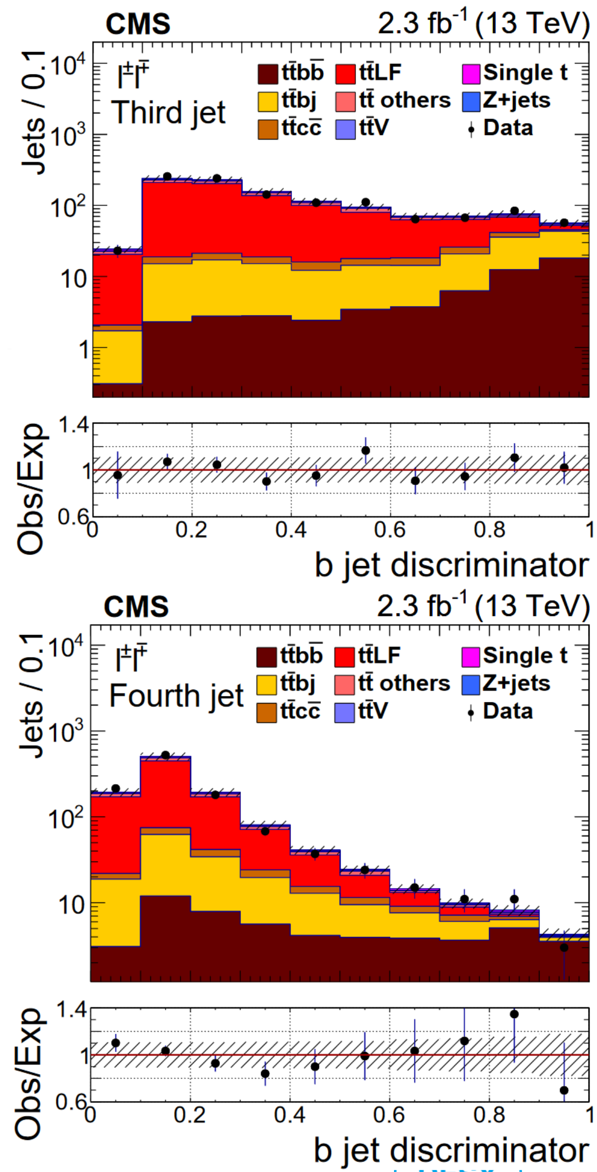
Inclusive $\sigma_{t\bar{t}}$ in association with (b)-jets

arXiv:1705.10141
Phys.Lett.B 776(2018)355



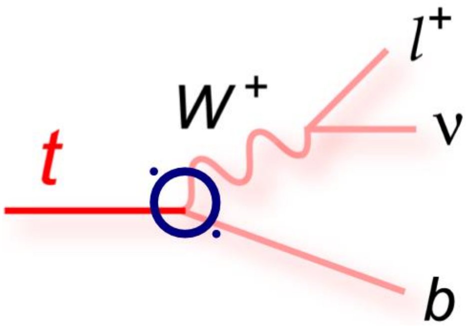
- Measure $\sigma_{t\bar{t}b\bar{b}}$, $\sigma_{t\bar{t}jj}$ and their ratio
  - Test of higher order QCD calculations
  - Depends on two different scales: m_t, $p_T(j)$
- Challenging to separate the processes

Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

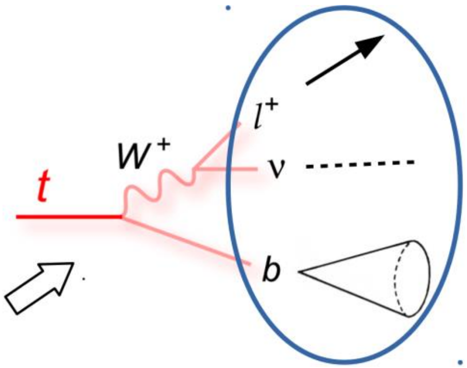


Differential measurements of $\sigma_{t\bar{t}}$

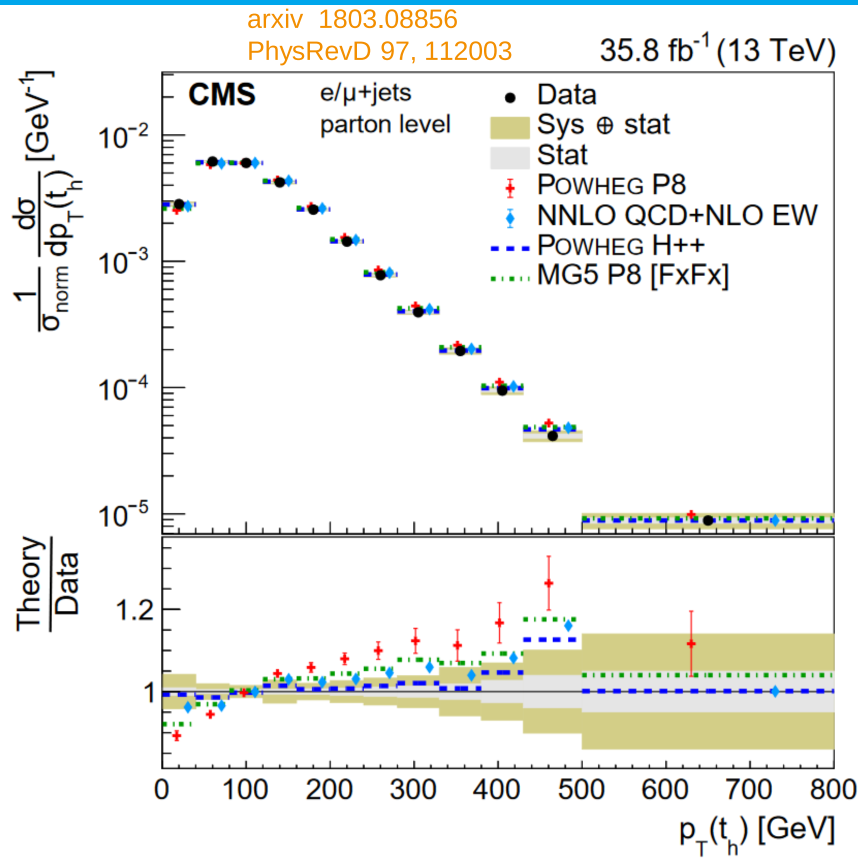
- Test of perturbative QCD
  - $\sigma_{t\bar{t}}$ measured in bins of kinematic variables
  - Unfolding algorithms correct for acceptance, efficiency, resolution
- Defined with respect to $t\bar{t}$ signal:
  Parton level (full phase space)
  - After QCD radiation and before decay
  - Mimics definitions of bare quark widely used in theory calculations
  - Used for extraction of SM parameters

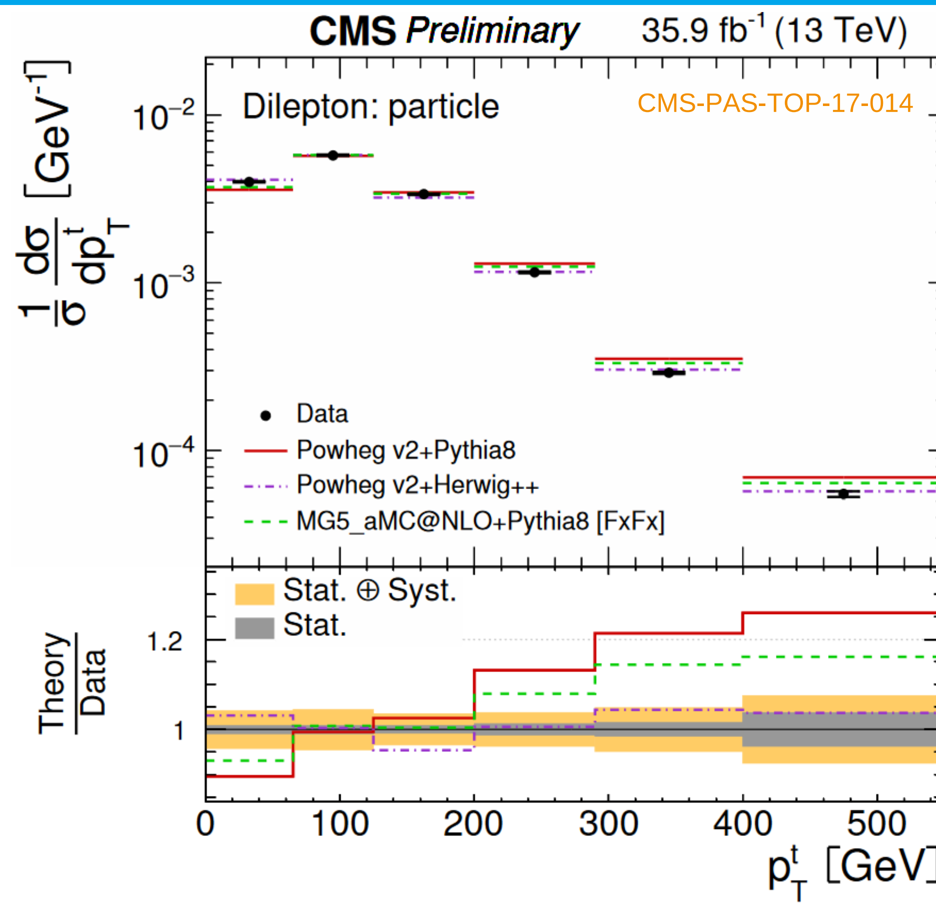


Particle Level (fiducial phase space, CMS-NOTE-17-004)
  - Based on stable particle after hadronization
  - Fiducial phase space defined according to detector level cuts
  - Used for MC tuning and test of BSM models



Differential measurements of $p_T(\mathrm{top})$

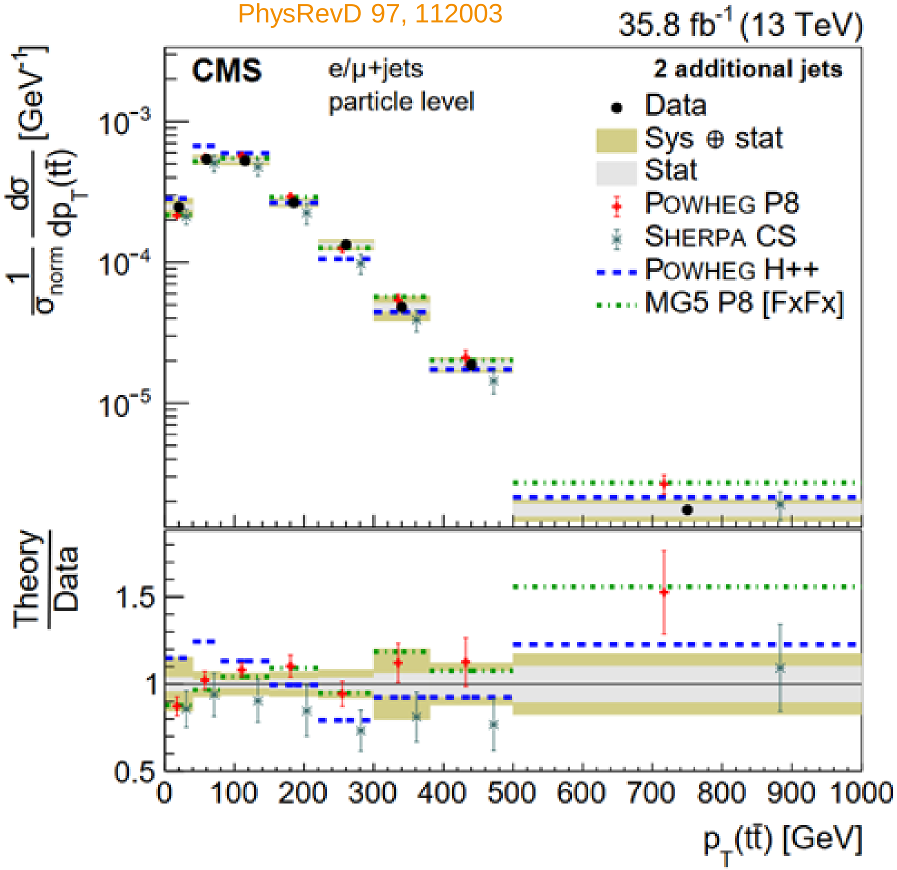


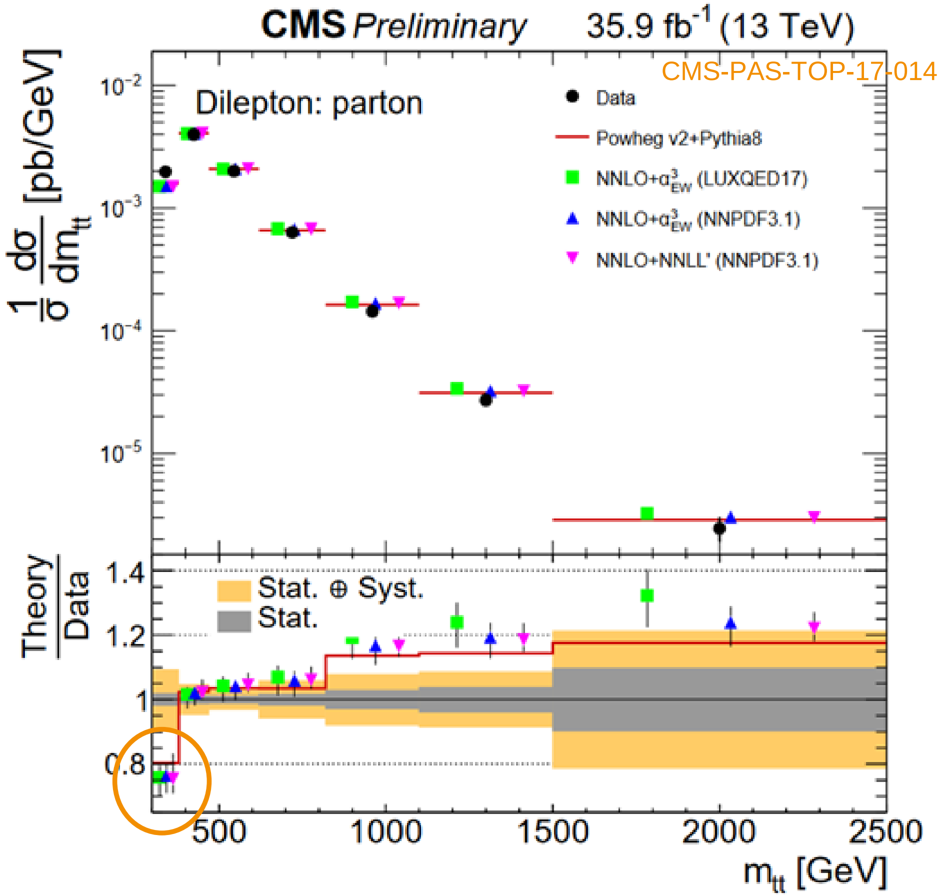


- Measurements softer than predictions
- Measurements and predictions agree for most other distributions

Differential measurements of the $t\bar{t}$ system

arxiv 1803.08856
PhysRevD 97, 112003

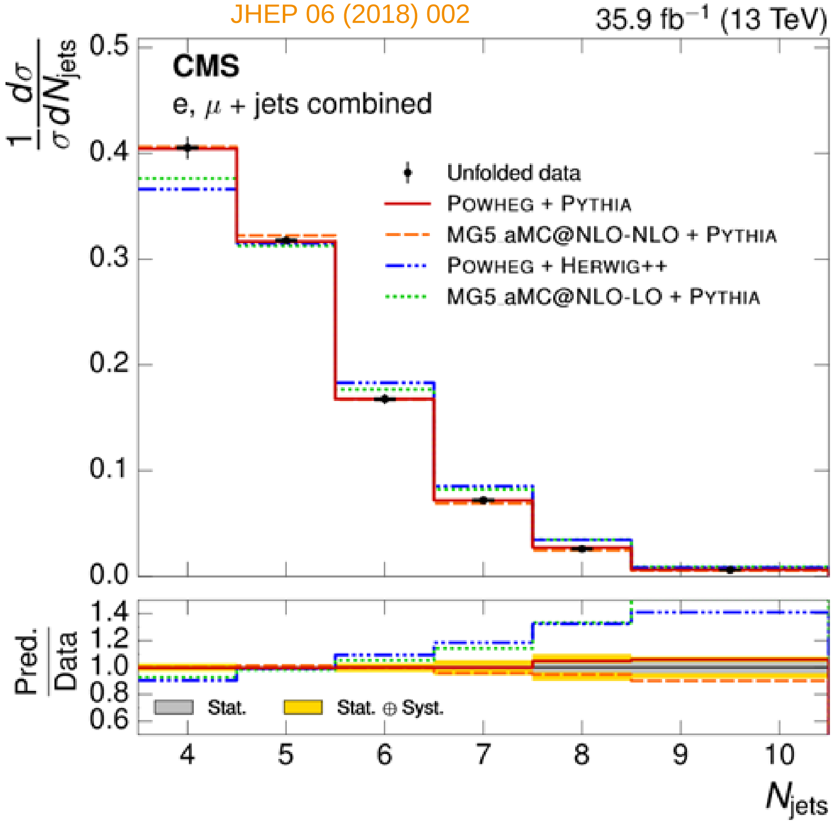


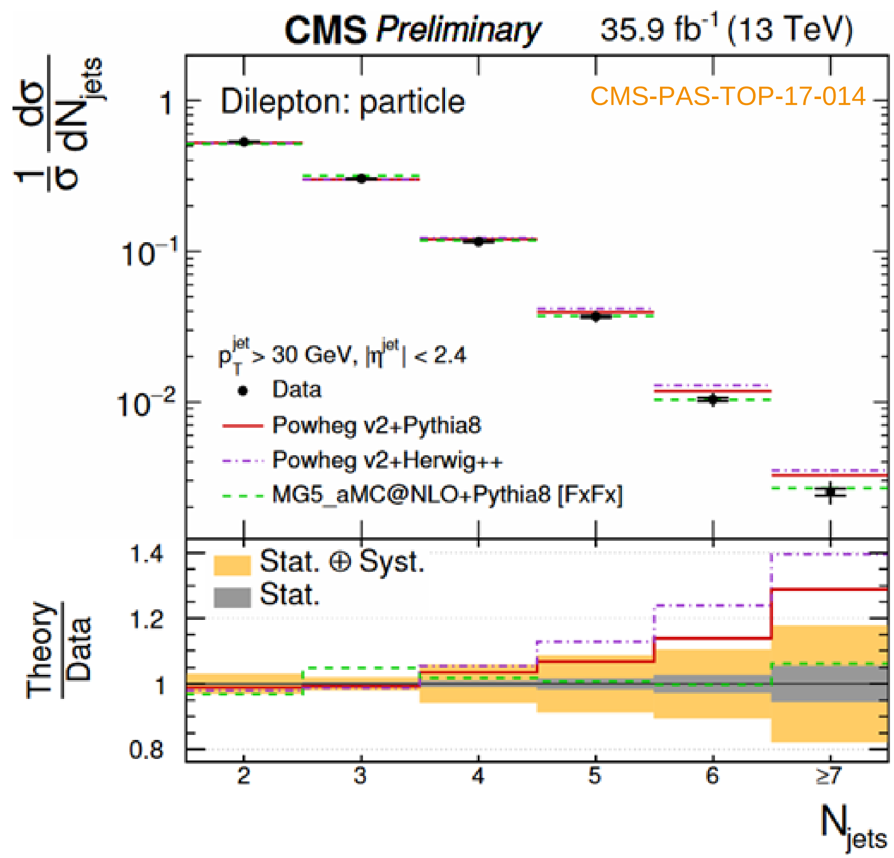


- Most distributions well modeled
- Disagreement for low $m(t\bar{t})$

Differential measurements of additional jets

Arxiv: 1803.03991
JHEP 06 (2018) 002



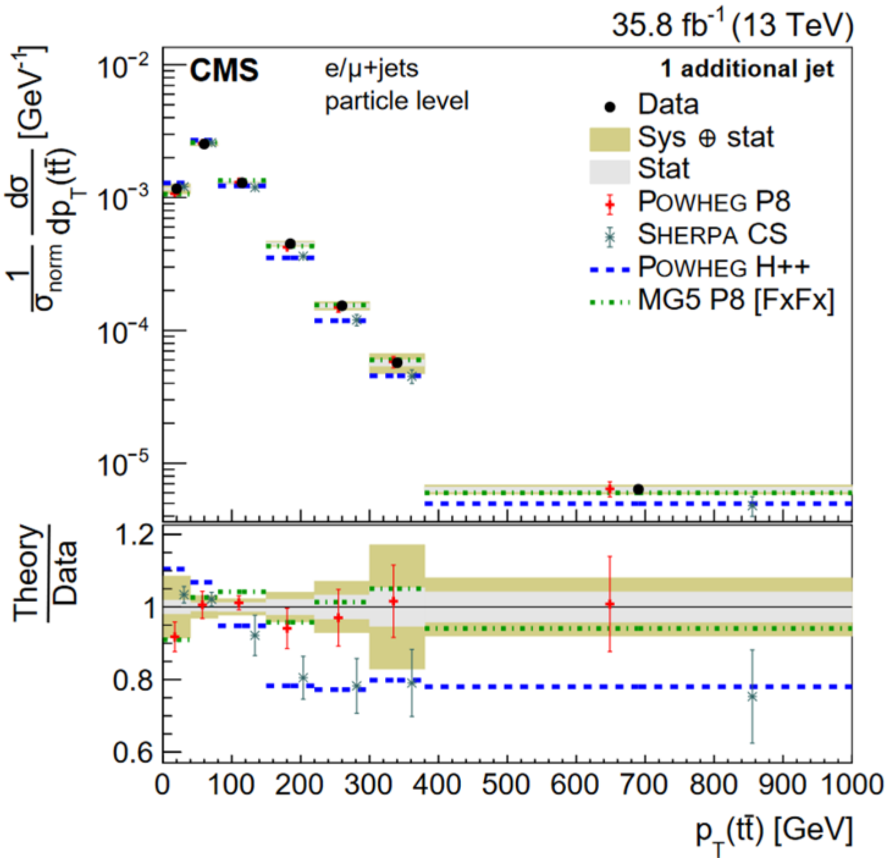


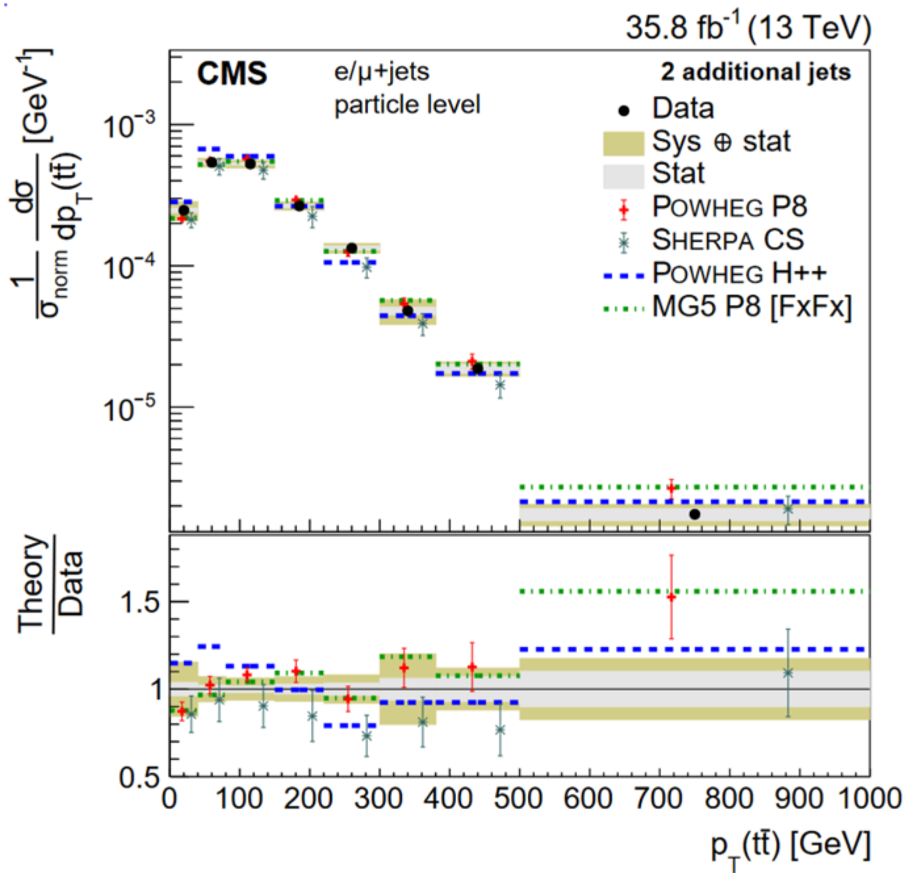
> Powheg/aMC@NLO + Pythia8 describe large parts of the data

- Pythia8 : CUETP8M2T4, Herwig++: EE5C
- No model consistently predicts all results

Double differential measurements

arxiv 1803.08856
PhysRevD 97, 112003

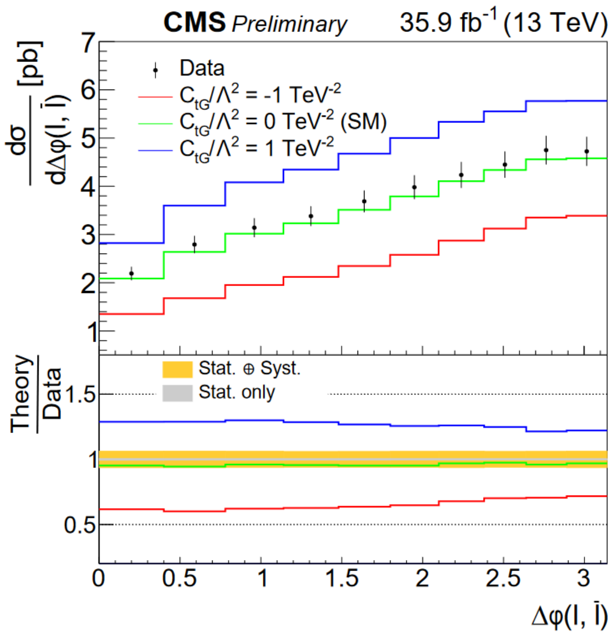


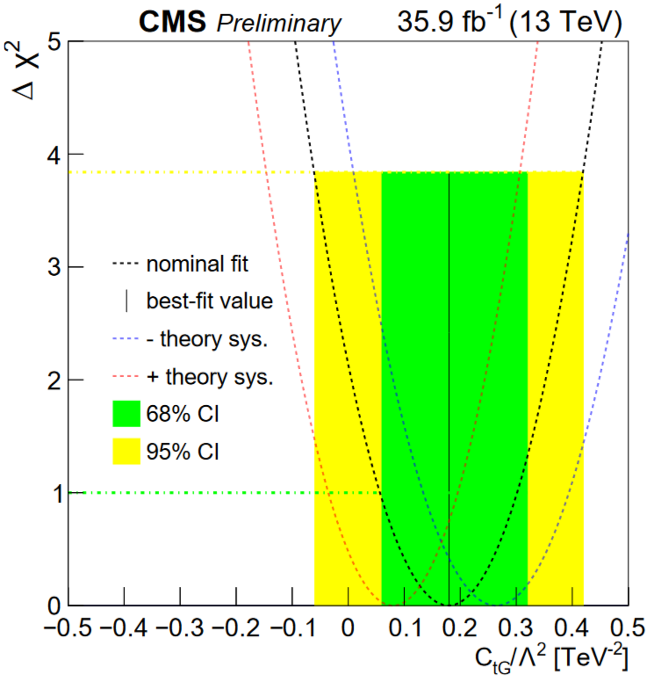


- Most distributions well modeled with Powheg + Pythia
- Without uncertainties no prediction describes data

Interpretation of differential cross sections in an EFT

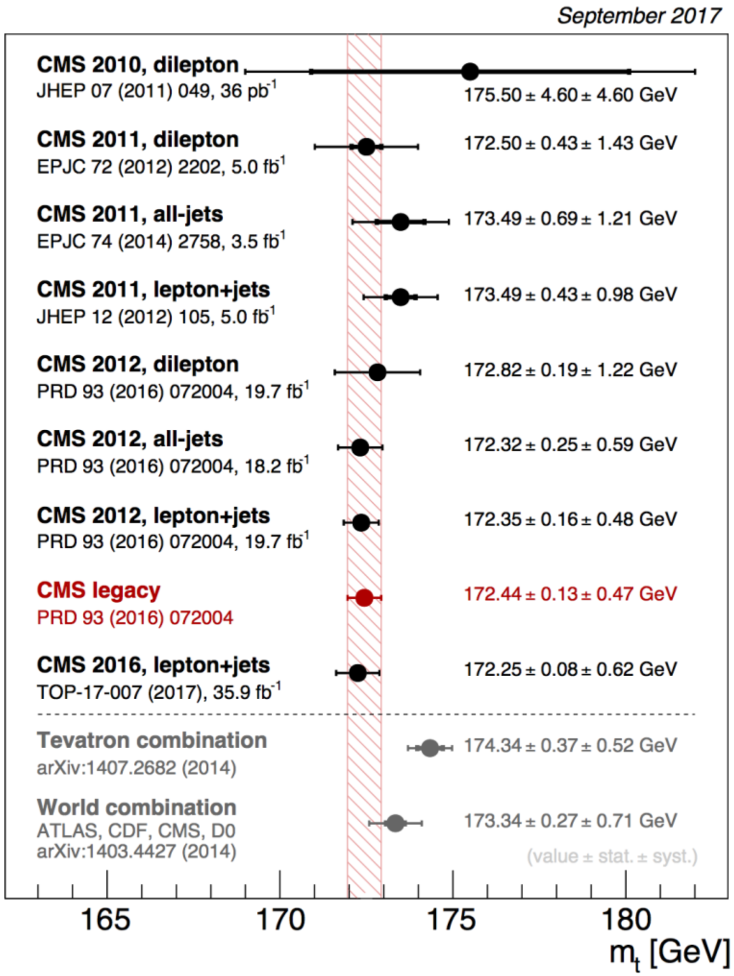
CMS-PAS-TOP-17-014

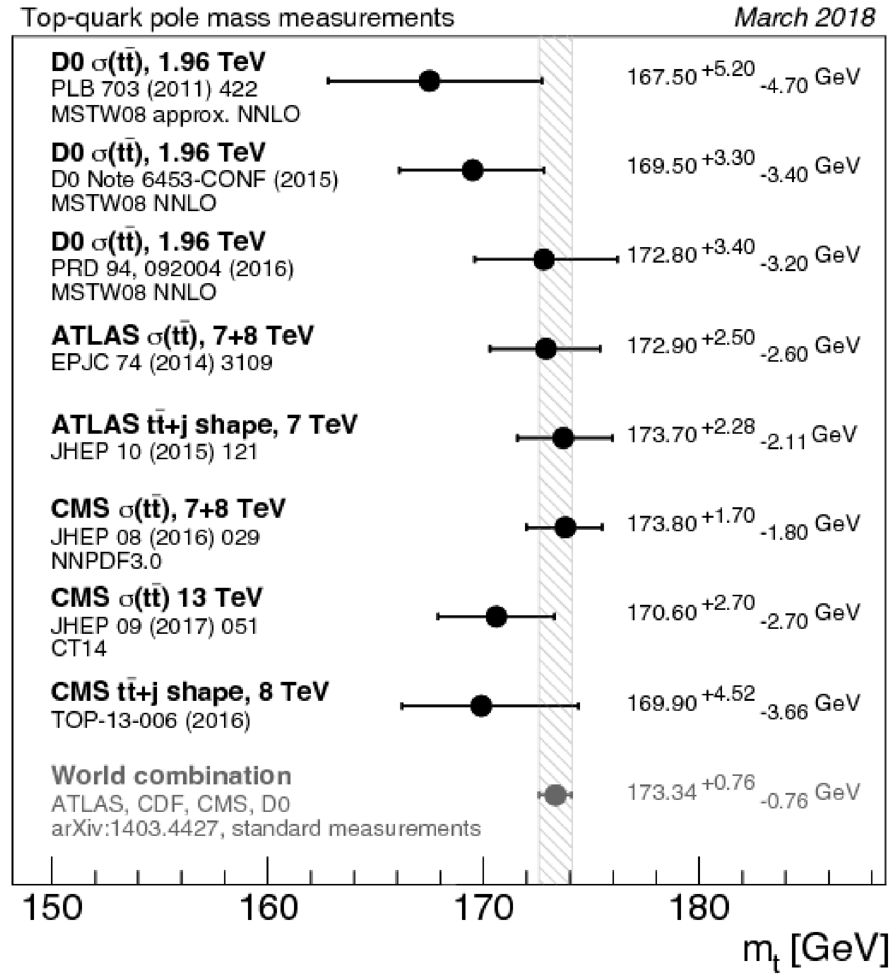


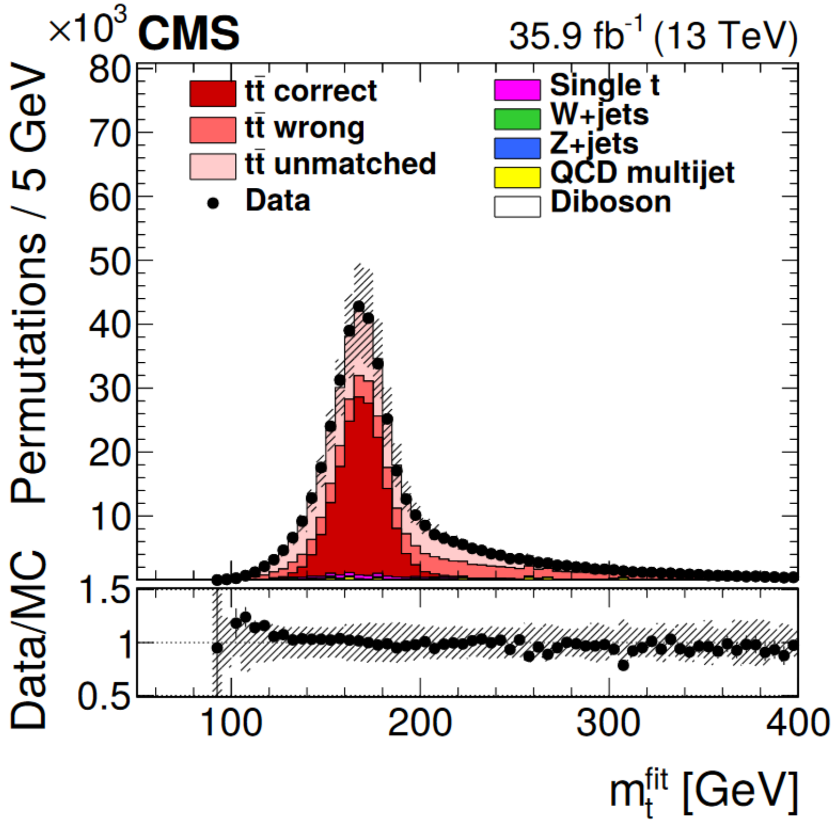


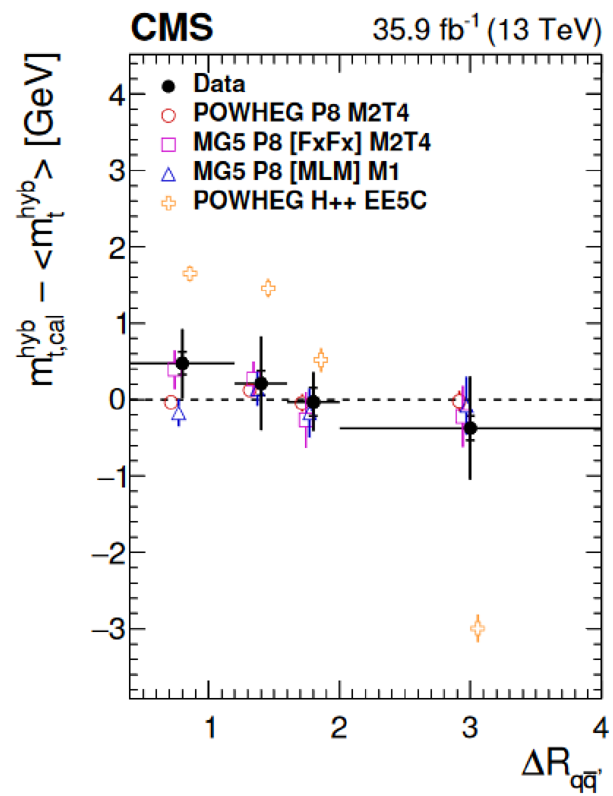
- Several BSM scenarios include anomalous chromomagnetic dipole moment (CMDM)
  - Modelled by higher dimension operator in EFT framework
  - Probes anomalous top-gluon coupling
- No deviation from SM

Top quark mass measurements



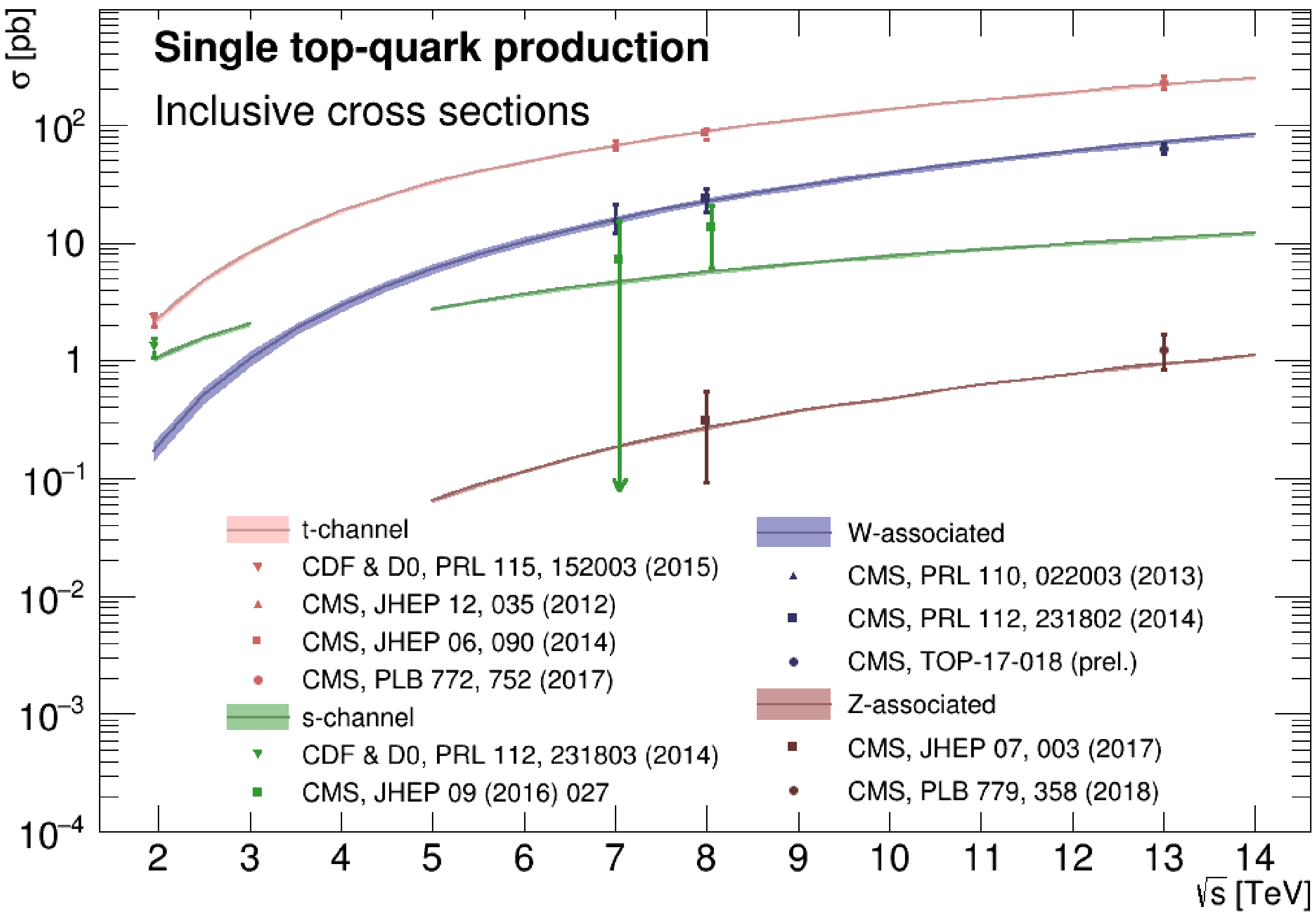




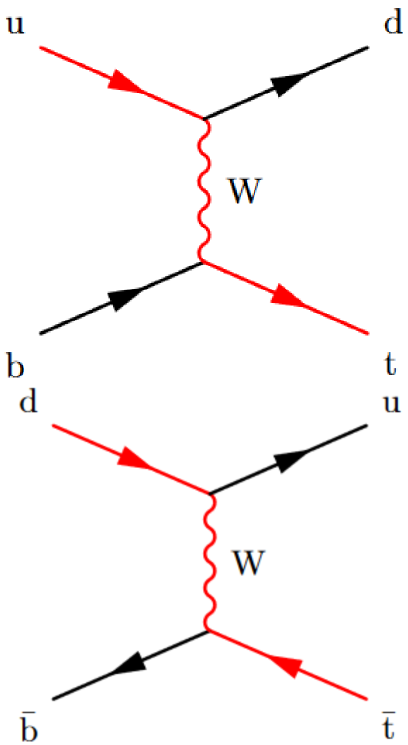


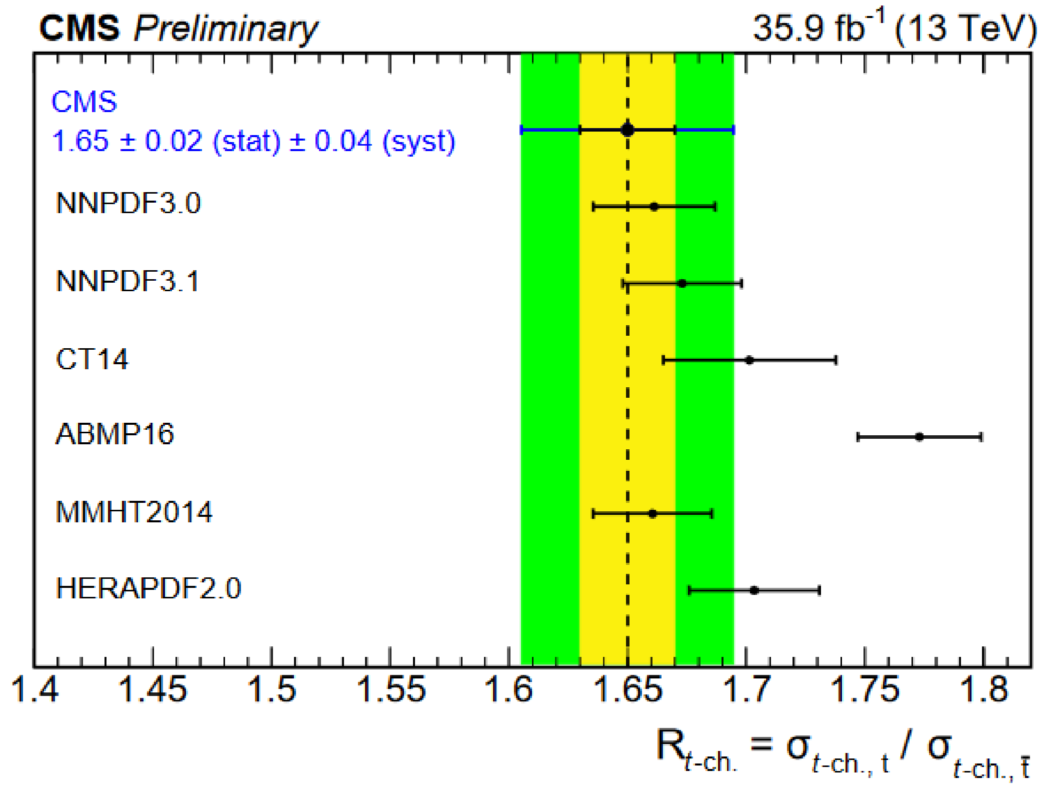
- Measure m_t from the invariant mass of its decay products
  - New color reconnection model in Pythia8 compared to previous measurement
- $m_t = 172.25 \pm 0.08(\text{stat.+JSF}) \pm 0.62(\text{syst})\,\text{GeV}$

Single top production



Single top t-channel production

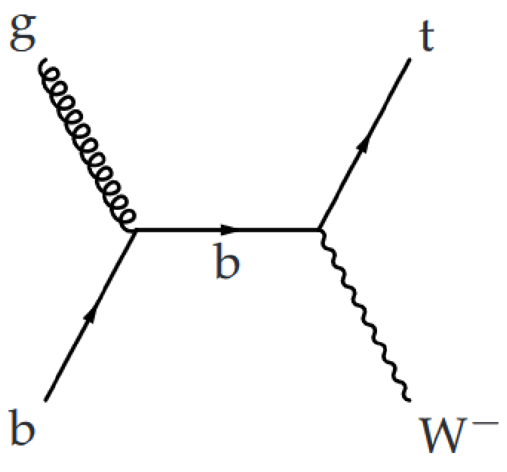


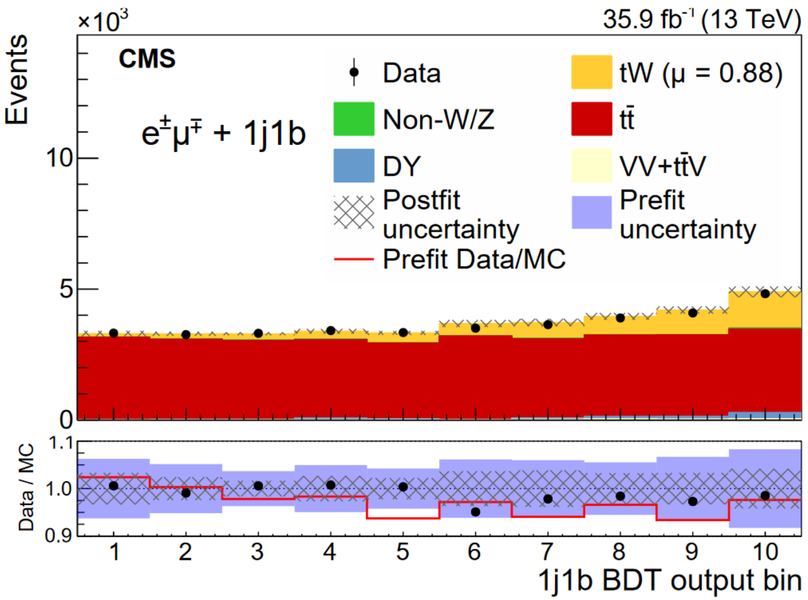


- Ratio of top/anti-top production sensitive to PDF
- CKM element from total x-section: $|V_{tb}| = 1.0 \pm 0.05(\text{exp}) \pm 0.02(\text{theo})$

Single top production in association with W boson

arXiv:1805.07399
submitted to JHEP

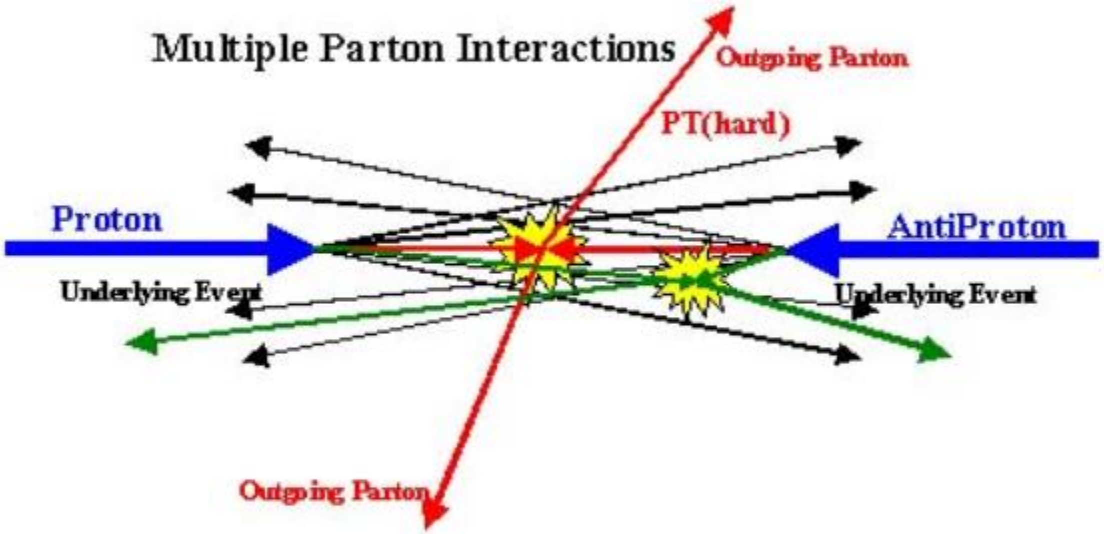




- Interference with $t\bar{t}$ at NLO in $pp \to Wb\,Wb$
- Challenging to separate tW and $t\bar{t}$ experimentally
- $$\sigma_{tW} = 63.1 \pm 1.8(\mathrm{stat}) \pm 6.4(\mathrm{syst}) \pm 2.1(\mathrm{lumi})\mathrm{pb}$$
  $$\sigma_{tW}^{NNLO} = 71.7 \pm 1.8(\mathrm{scale}) \pm 3.4(\mathrm{PDF})\mathrm{pb}$$

Underlying event in $t\bar{t}$ production

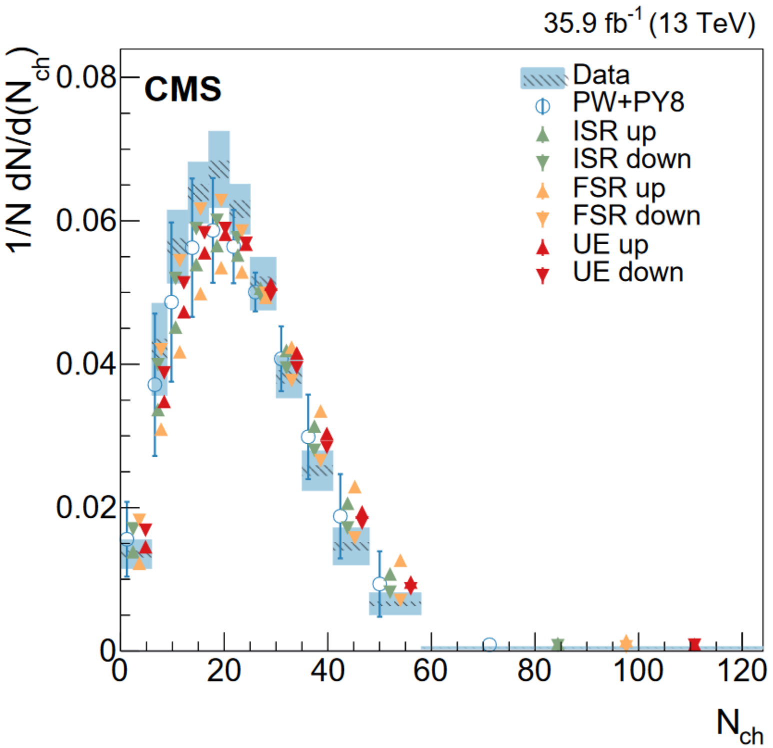
arXiv:1807.02810
sub. to Eur. Phys. J. C.

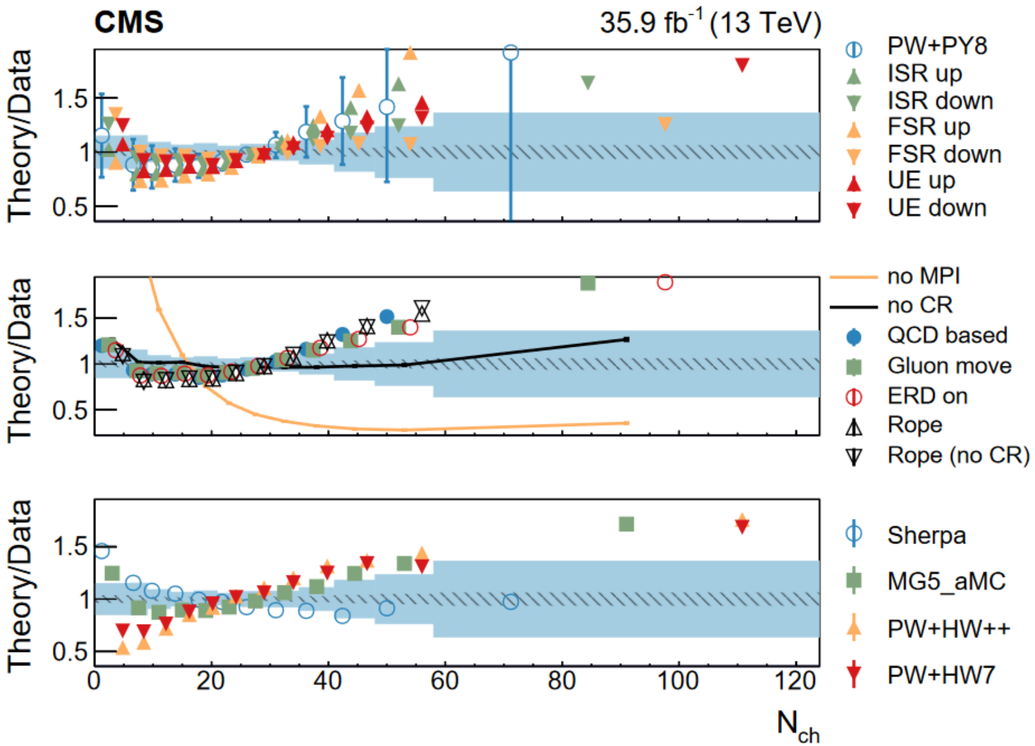


- Hadronic activity not from hard scattering
  - Subtract impact of PU and $t\bar{t}$ decay
- The UE model is tested up to a scale of $\approx 2\mathrm{m}_{\mathrm{top}}$
  - Measurements in m_{ll} categories suggest viability at higher scales
- Differential cross sections in dileptonic $t\bar{t}$ events

Underlying event in $t\bar{t}$ production

arXiv:1807.02810
sub. to Eur. Phys. J. C.

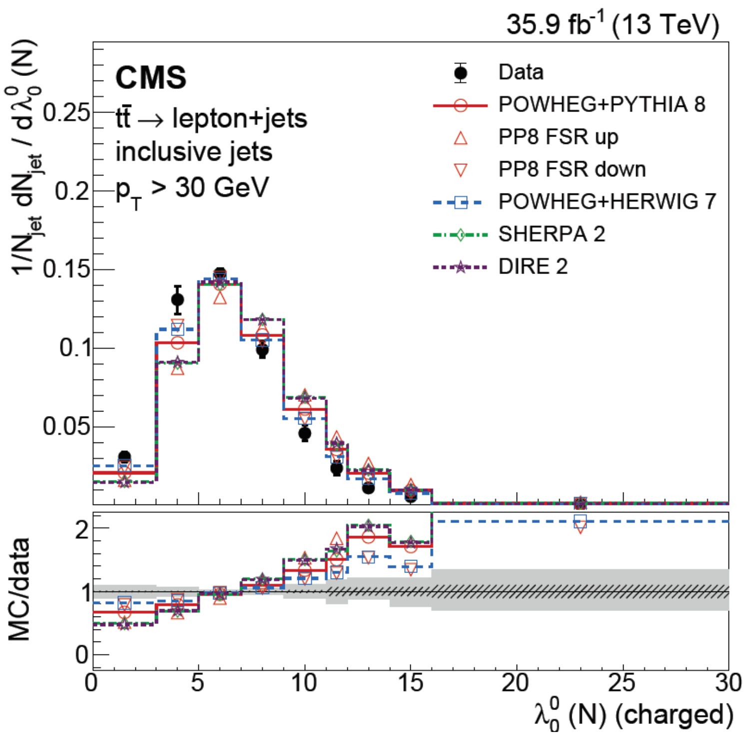


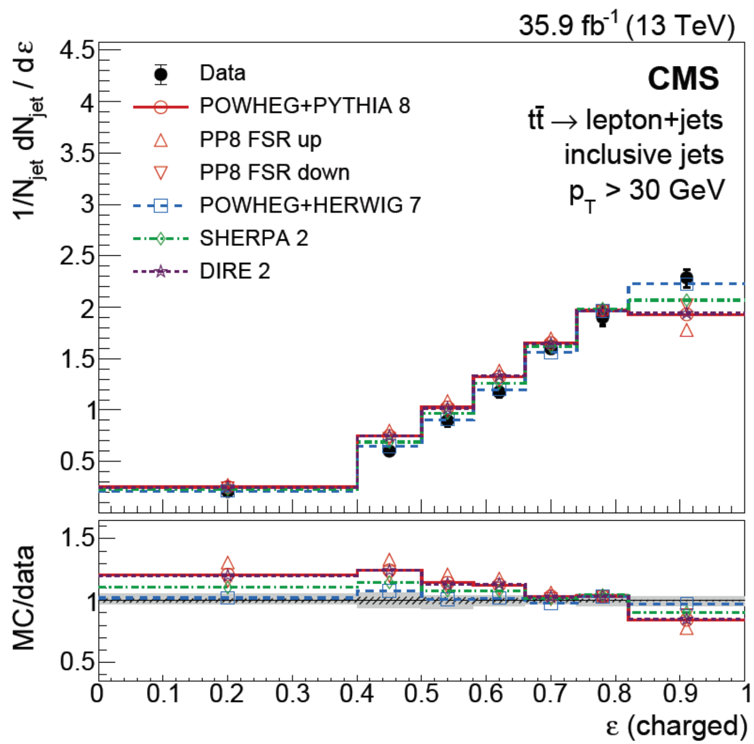


- Measured in many different categories
  - MPI effects important, CR more subtle,
  - Data favors $\alpha_s^{FSR}(m_Z) = 0.120 \pm 0.006$, disfavors high value
- Powheg + Pythia8 [CUETP8M2T4] agrees with data within uncertainties

Jet substructure in $t\bar{t}$ events

arXiv: 1808.07340
sub. to PRD

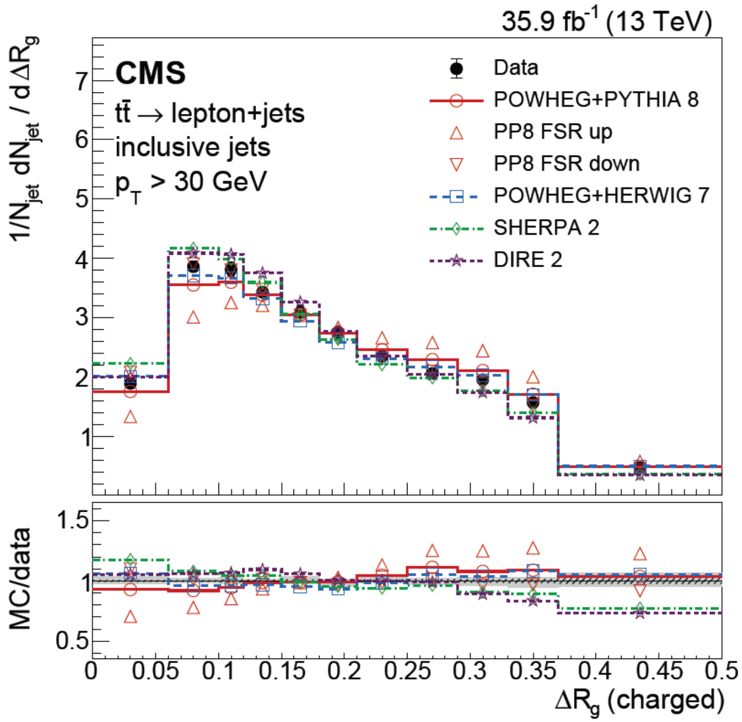


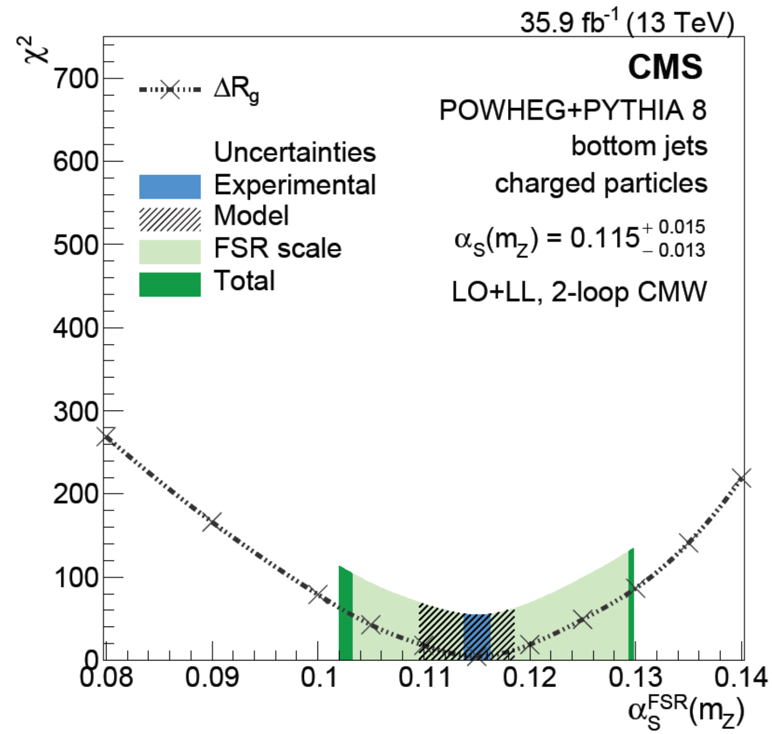


- Differential cross section in semi-leptonic $t\bar{t}$ events
  - Test parton shower and fragmentation models
- With default tunes none of the generators provides good description of data

Jet substructure in $t\bar{t}$ events

arXiv: 1808.07340
sub. to PRD





- Strong coupling preferred by the jet substructure extracted
- Angle between groomed sub-jets for b-jet sample
- $\alpha_S\ (m_Z) = 0.115 \pm 0.015$
  - Constrains renormalization scale of top measurements in CMS

Conclusions

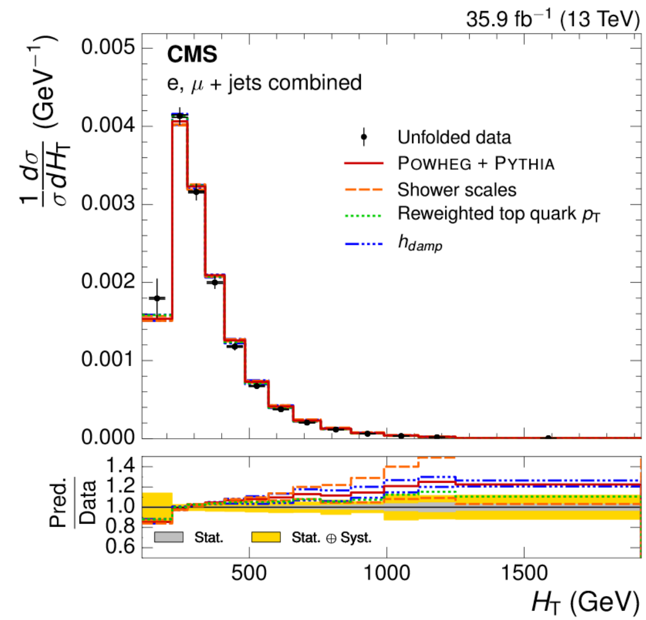
- Top cross quark physics are an important part of research at CMS and provide stringent tests of QCD
  - Differential / inclusive $\sigma_{t\bar{t}}$, associated production, single top, top mass, QCD related observables in $t\bar{t}$ events
  - Compared to MC models and beyond NLO predictions
  - Sensitivity to PDF parameters and α_s
  - Constrain BSM predictions
- Overall good agreement with SM predictions
  - But remaining disagreement in parts of the phase space
  - No single model describes the data
  - Need for further tuning of MC models
- Measurements have reached a precision regime
  - Larger dataset opening new possibilities

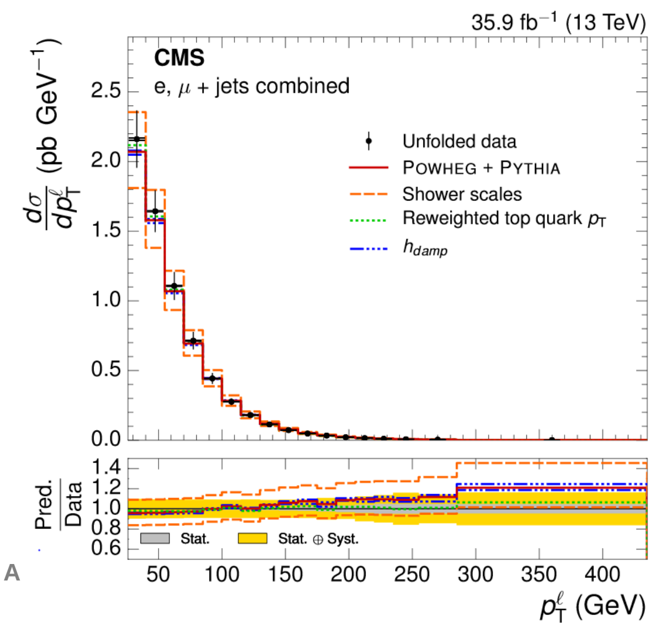
BACKUP

Differential $\sigma_{t\bar{t}}$ for kinematic event variables in the single lepton channel

Arxiv: 1803.03991
JHEP 06 (2018) 002

- Kinematic event variables
  - No need to reconstruct $t\bar{t}$
  - Particle level
- Absolute and normalized differential $\sigma_{t\bar{t}}$
  - Compared to different parameters in Powheg + Pythia
- Dominant uncertainties:
  - Modelling: underlying event, color reconnection
  - Jet energy scale
  - Background estimation

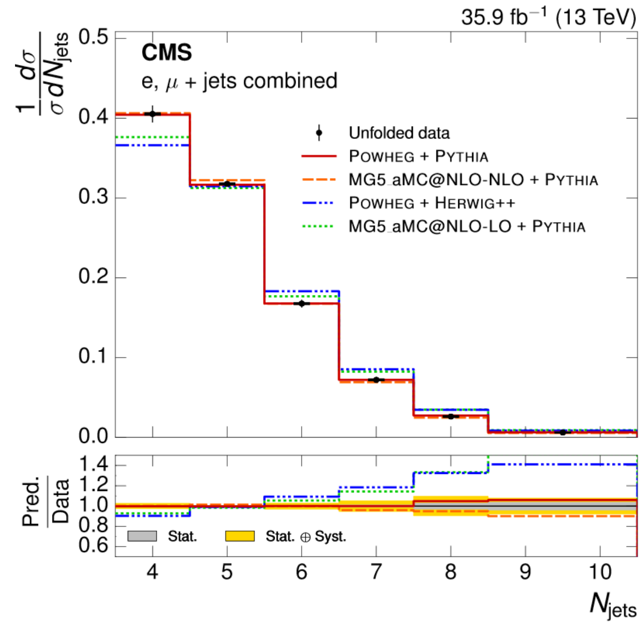


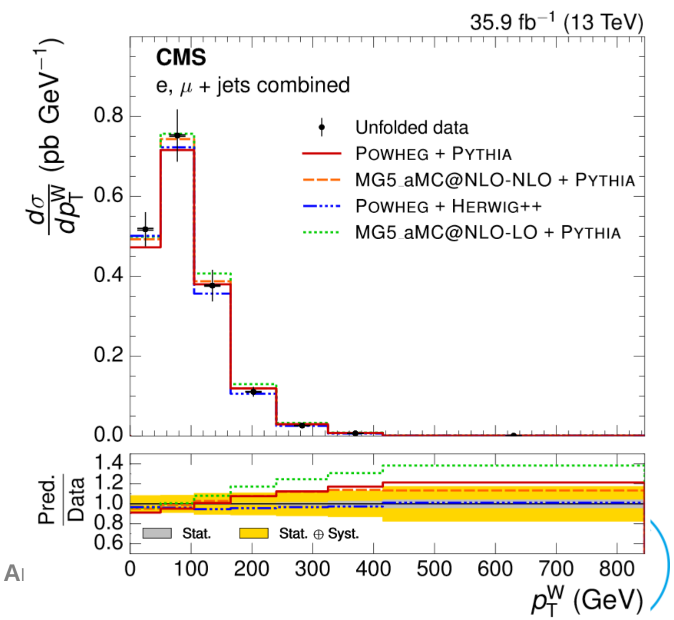


Differential $\sigma_{t\bar{t}}$ for kinematic event variables in the single lepton channel

Arxiv: 1803.03991
JHEP 06 (2018) 002

- Absolute and normalized differential $\sigma_{t\bar{t}}$
  - Compared to predictions with multiple MC algorithms
- Dominant uncertainties:
  - Modelling: shower scales
  - Jet energy scale
  - Background estimation
- Powheg + Pythia model consistent with data within its uncertainties
- Powheg+Herwig++ and aMC@NLO-NLO consistent for most distributions
  - Uncertainties on models not considered

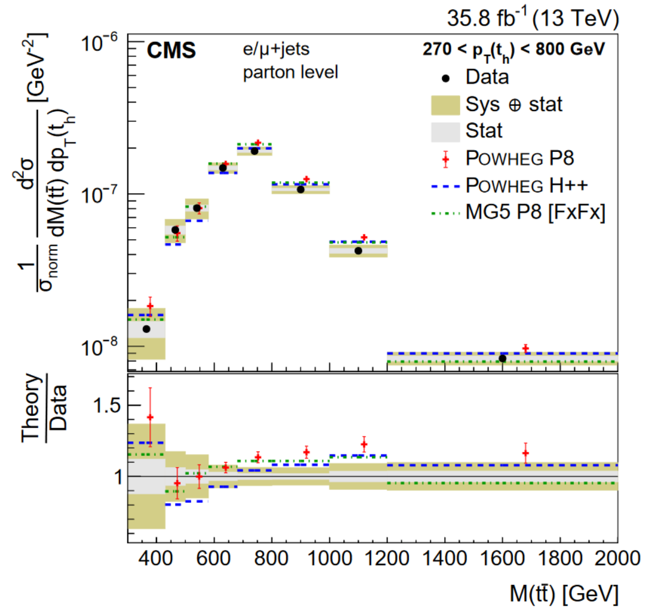


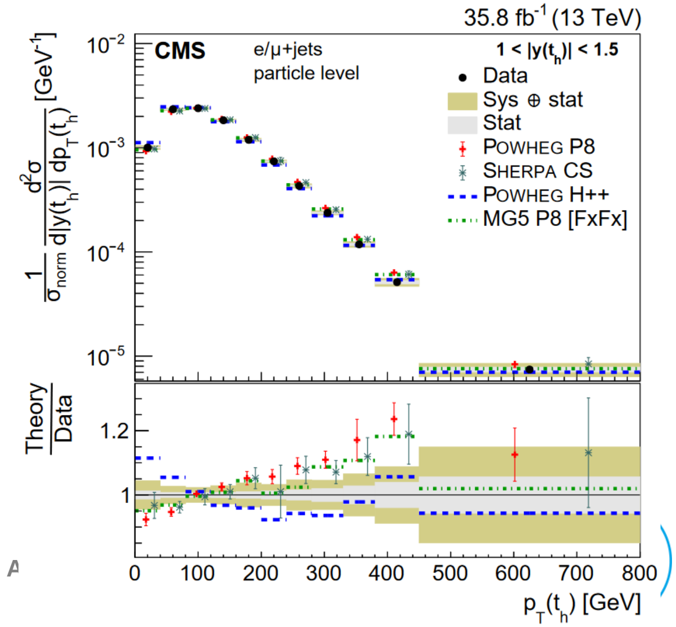


Differential $\sigma_{t\bar{t}}$ in the single-lepton channel

arxiv 1803.08856
PhysRevD 97, 112003

- Double differential $\sigma_{t\bar{t}}$
  - Correlations between kinematic properties
  - Insight into more extreme regions of phase space
- Parton and particle level
  - Compared to MC predictions
- Substantial difference between data and prediction for $\mathrm{p_T(t)}$ vs $\mathrm{M(t\bar{t})}$
- Measured $\mathrm{p_T(t)}$ softer than predictions in all rapidity regions
- Most distributions comparable to Powheg + Pythia and Sherpa within uncertainties

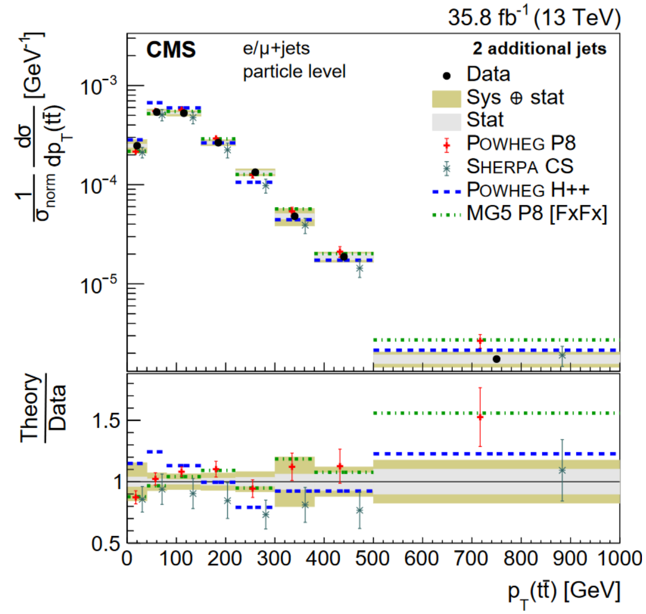


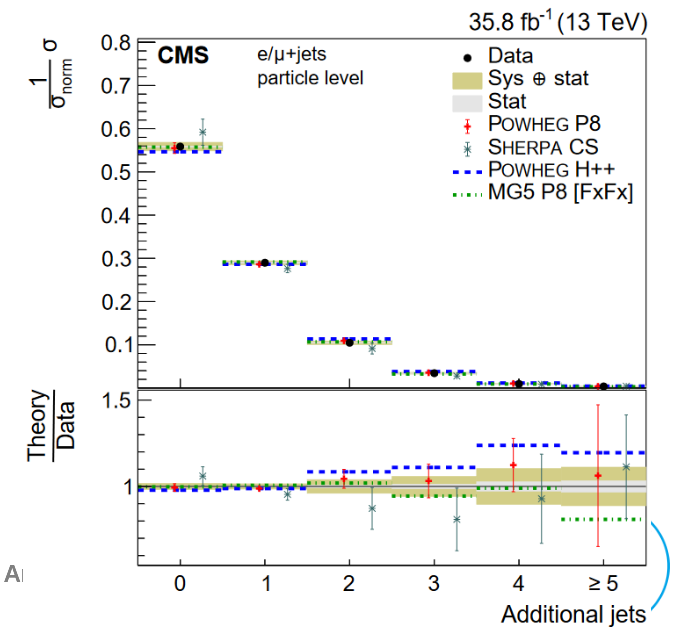


Differential $\sigma_{t\bar{t}}$ in the single-lepton channel

arxiv 1803.08856
PhysRevD 97, 112003

- Double differential $\sigma_{t\bar{t}}$ of jet multiplicities and properties
  - Particle level only
- Compared to MC predictions
- Most distributions well modeled with Powheg + Pythia
  - Inconsistencies for $p_T(j), \eta_j, p_T(t\bar{t})$
  - Other generators mostly fail to describe data at chosen settings
- Without uncertainties on predictions no model describes the data consistently

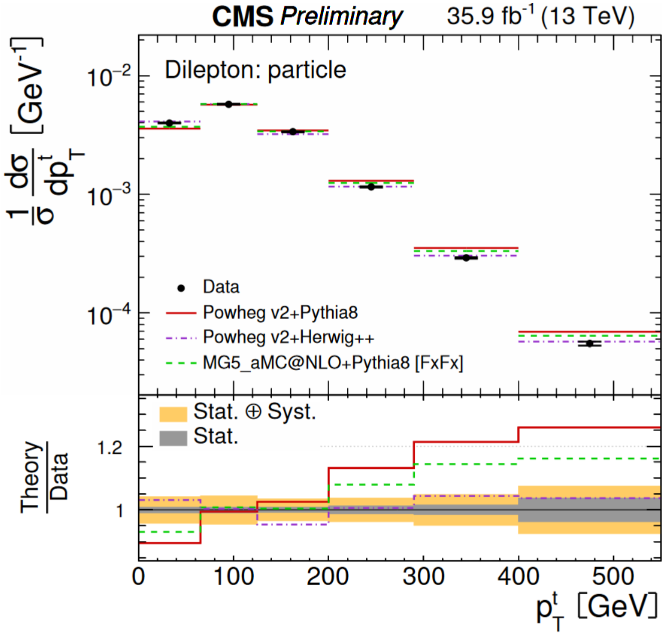


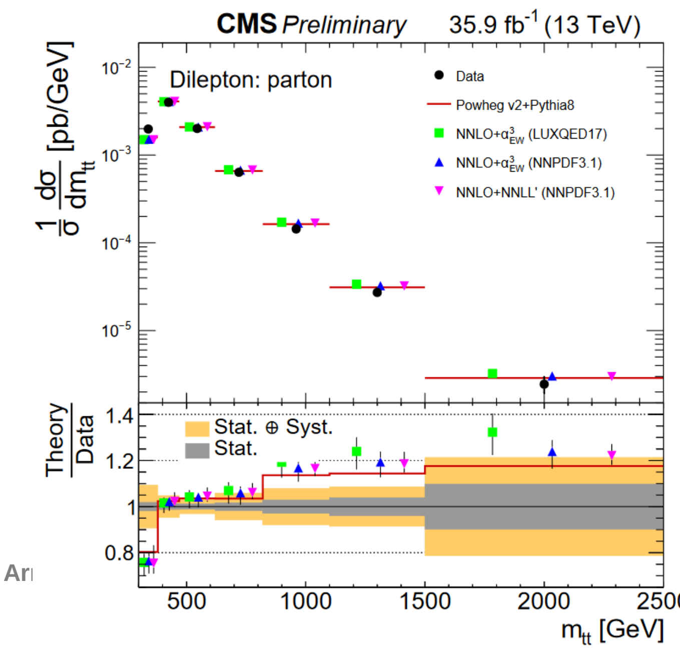


Differential $\sigma_{t\bar{t}}$ in the dilepton channel

CMS-PAS-TOP-17-014

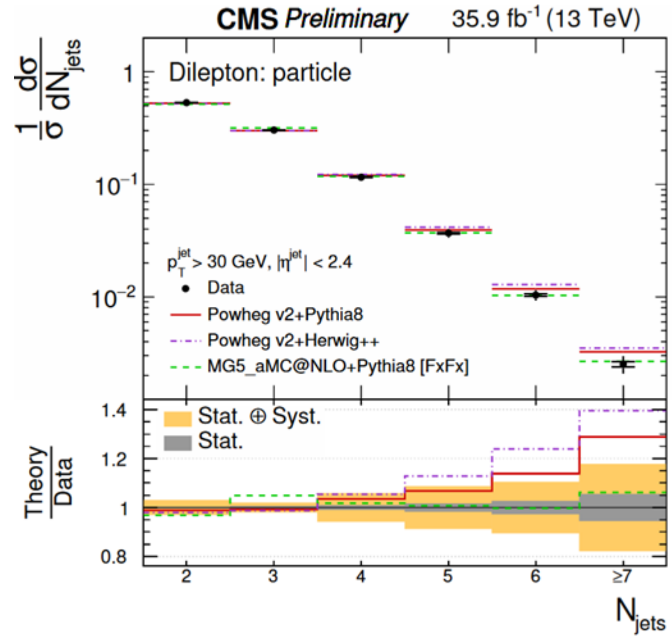
- Absolute and normalized $\sigma_{t\bar{t}}$
- Top quarks are reconstructed
- Parton and particle level
  - Compared to both MC predictions and fixed order calculations
- Generally good agreement between data and prediction
- $p_T(t)$ softer than predictions
  - Described well by Powheg + Herwig++
- No model describes all distributions
- Disagreement between data and prediction for low $M(t\bar{t})$

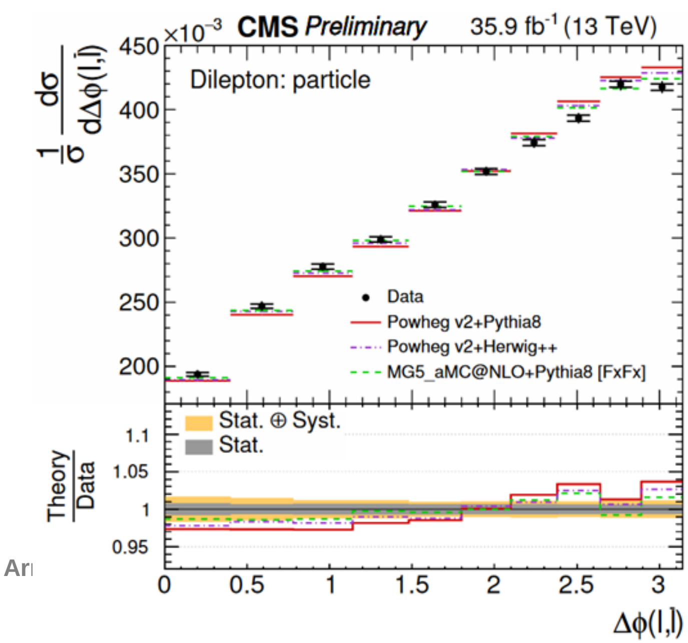




Differential $\sigma_{t\bar{t}}$ in the dilepton channel

- $\sigma_{t\bar{t}}$ in bins of jet and lepton kinematics
  - Particle level only
  - Compared to MC predictions
- No model consistently describes the number of jets
  - Disagreement for either high or low number of jets
- $\Delta\phi(l,\bar{l})$ precisely measured for good lepton resolution
  - Can be used to constrain new physics model

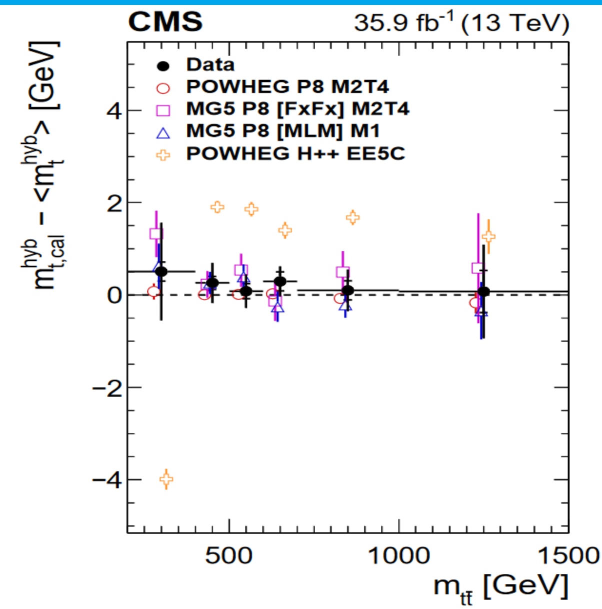


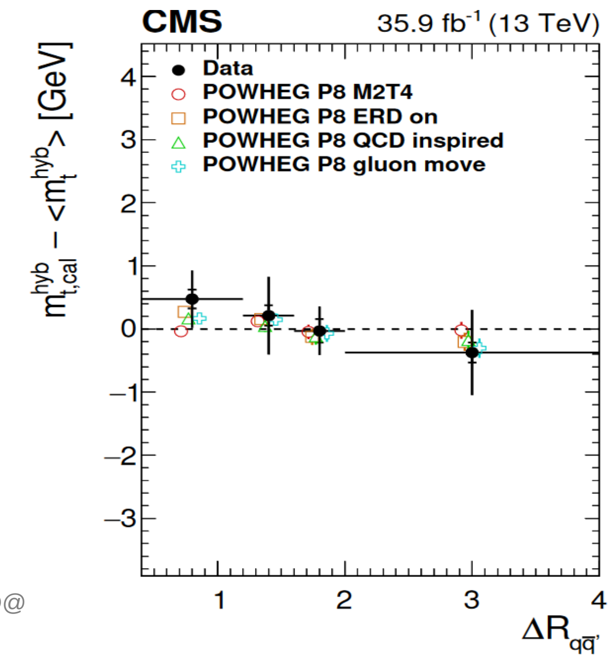


Top quark mass in the single-lepton channel

arXiv:1805.01428
sub. to Eur. Phys. J. C.

- Measure m_t in bins of kinematic properties
  - Probe effects from parton shower scale, color reconnection
  - Difference between each bin and inclusive measurement
- Data compared to multiple MC models
- No evidence of bias for the measurement
  - Only Powheg+Herwig shows deviations
  - Uncertainties to large to rule out differences for CR models





Underlying event in $t\bar{t}$ production

arXiv:1807.02810
sub. to Eur. Phys. J. C.

- Average of differential cross sections in event categories
- Large effect from the number of extra jets
- Dominant uncertainties:
  - Experimental: Tracking efficiency
  - Theoretical: $p_T(t)$, PS scale
- MPI effects are crucial
  - CR effects more subtle
- Powheg + Pythia agrees with data within uncertainties
  - Herwig, Sherpa worse agreement