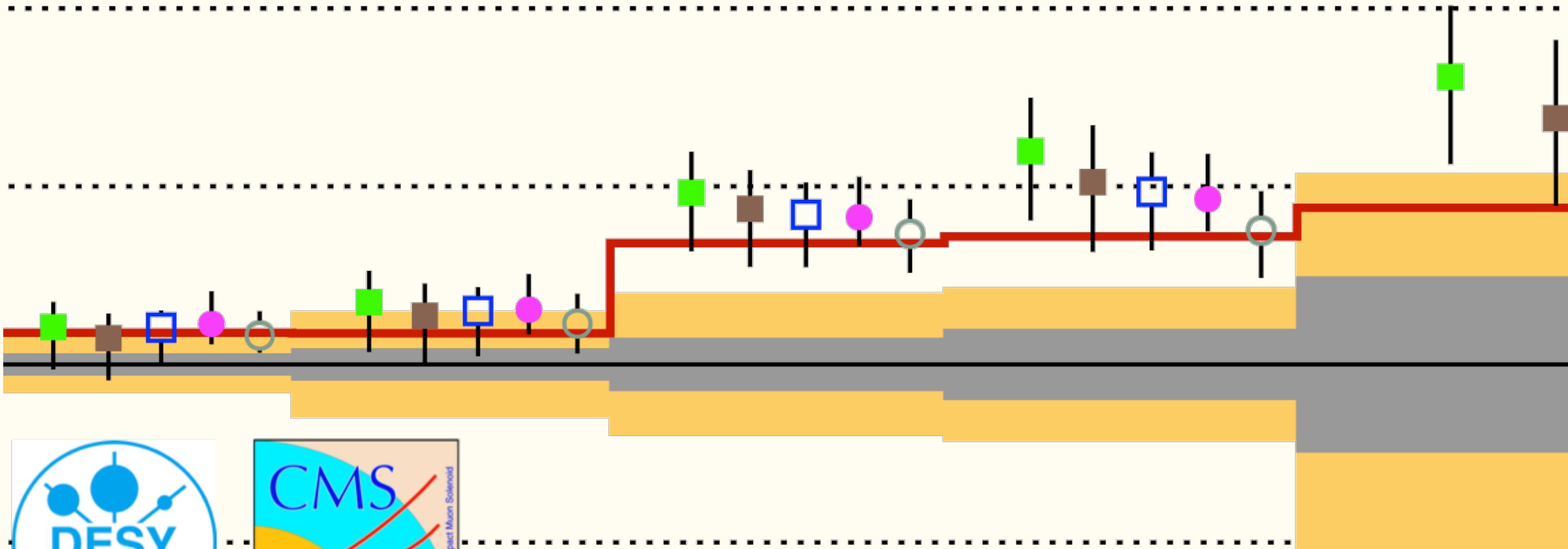
Recent differential tt cross section results from CMS

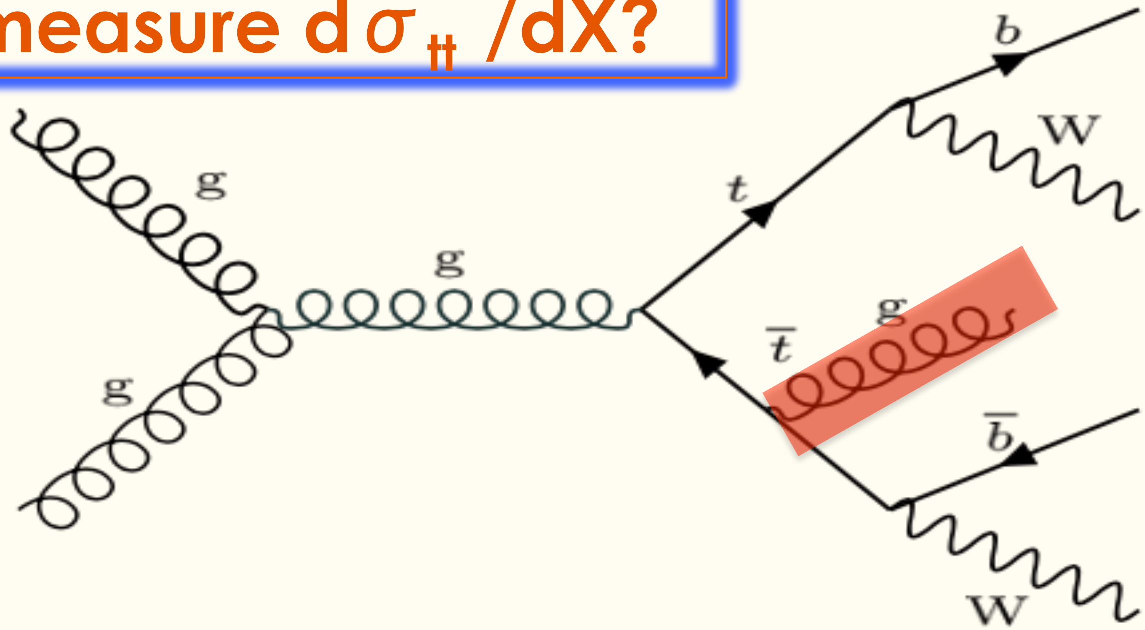
James Keaveney, on behalf of CMS



Terascale meeting, DESY Hamburg, Nov. 2018

tt production at the lhc

Why measure $d\sigma_{tt}$ /dX?

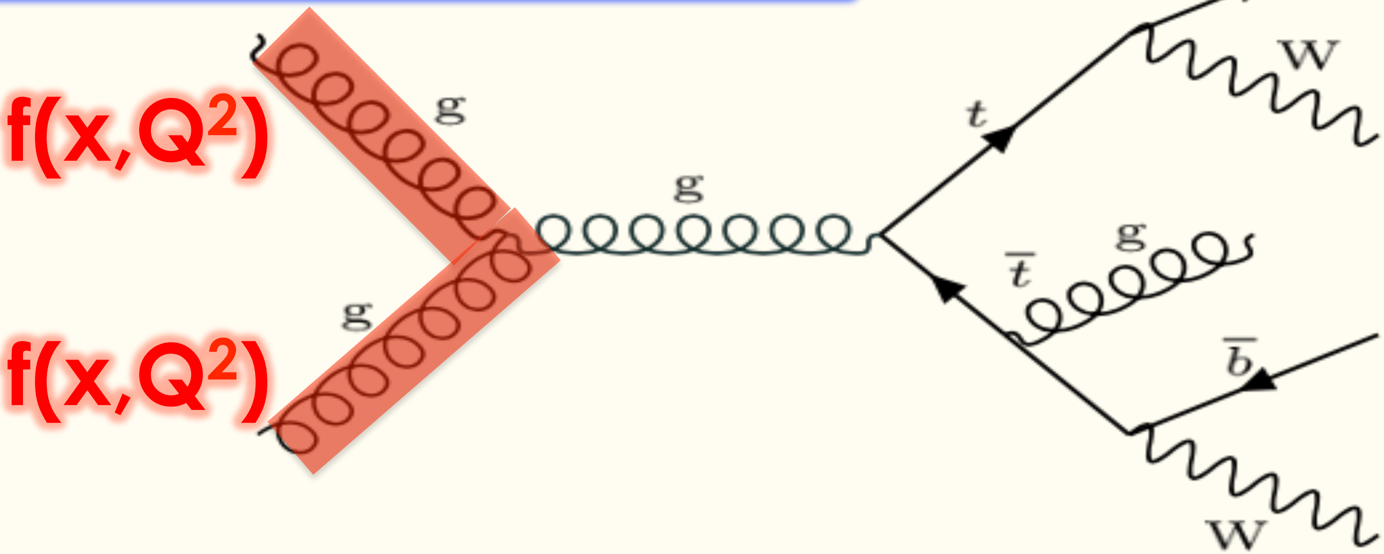


QCD process with significant higher-order corrections

➔ probe pQCD

tt production at the lhc

Why measure $d\sigma_{tt}$ /dX?



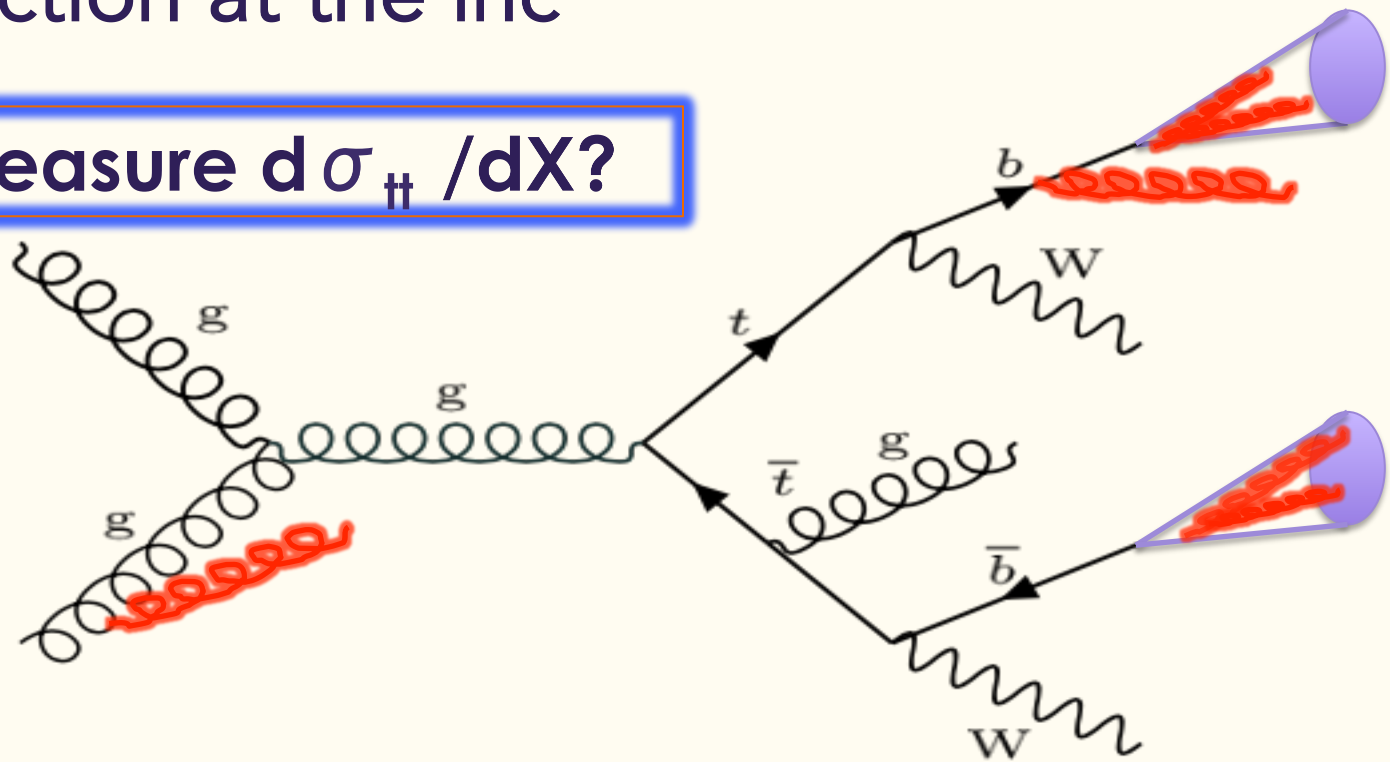
LHC tt produced mainly via by gluon fusion

➔ constrain gluon PDF

➔ extract α_s, m_t

tt production at the lhc

Why measure dσ_{tt} /dX?

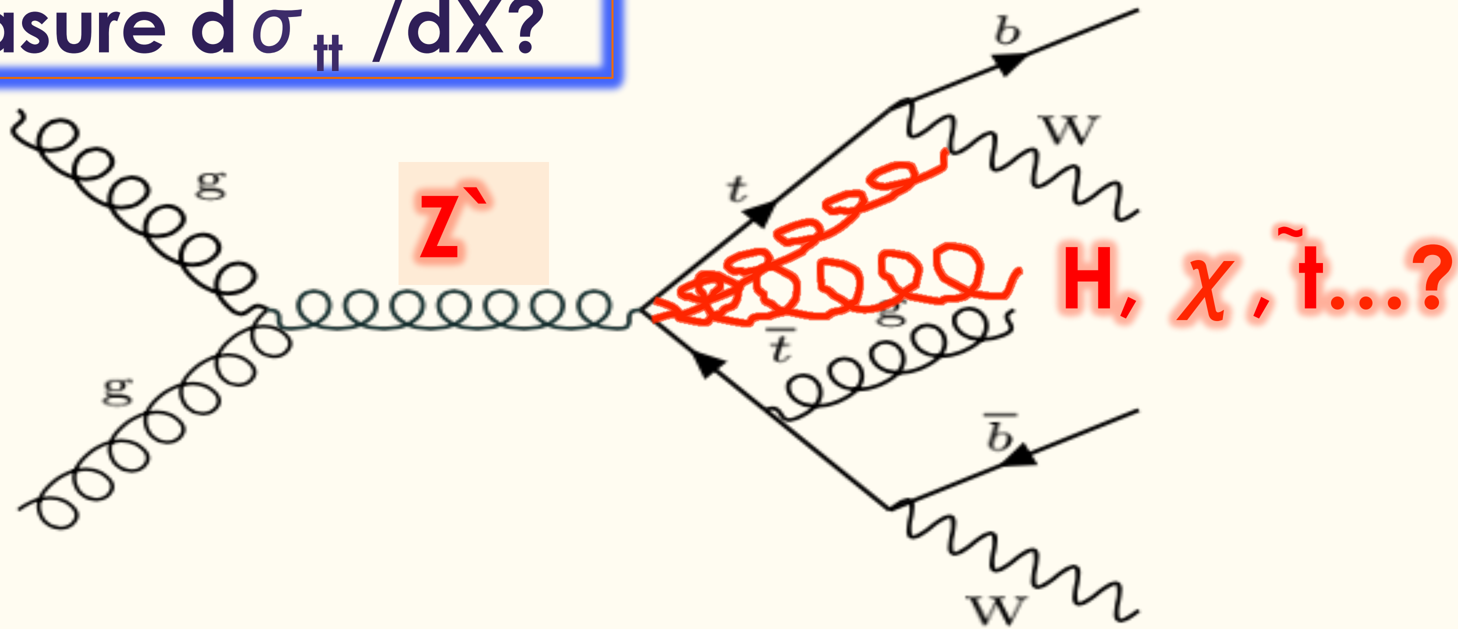


soft radiation in production and decay

➔ constrain modelling of parton shower and hadronisation

tt production at the lhc

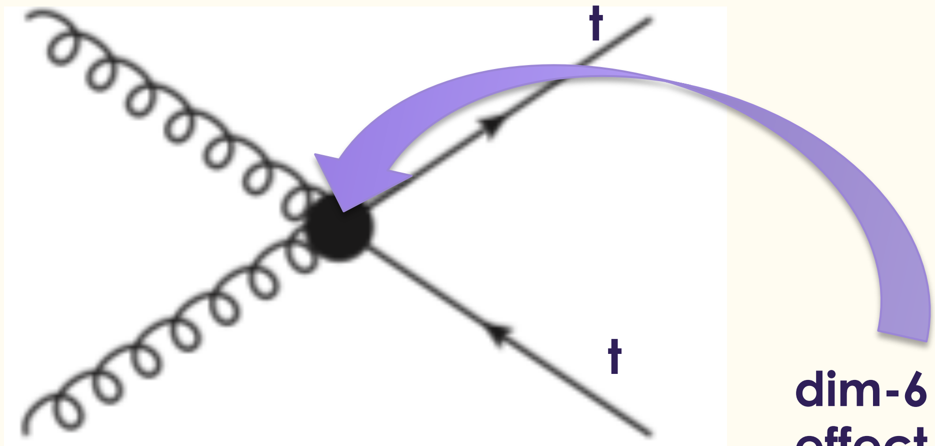
Why measure $d\sigma_{tt}$ /dX?



tt signature similar to many new physics signals
➔ constrain NP & backgrounds for searches

tt production at the lhc

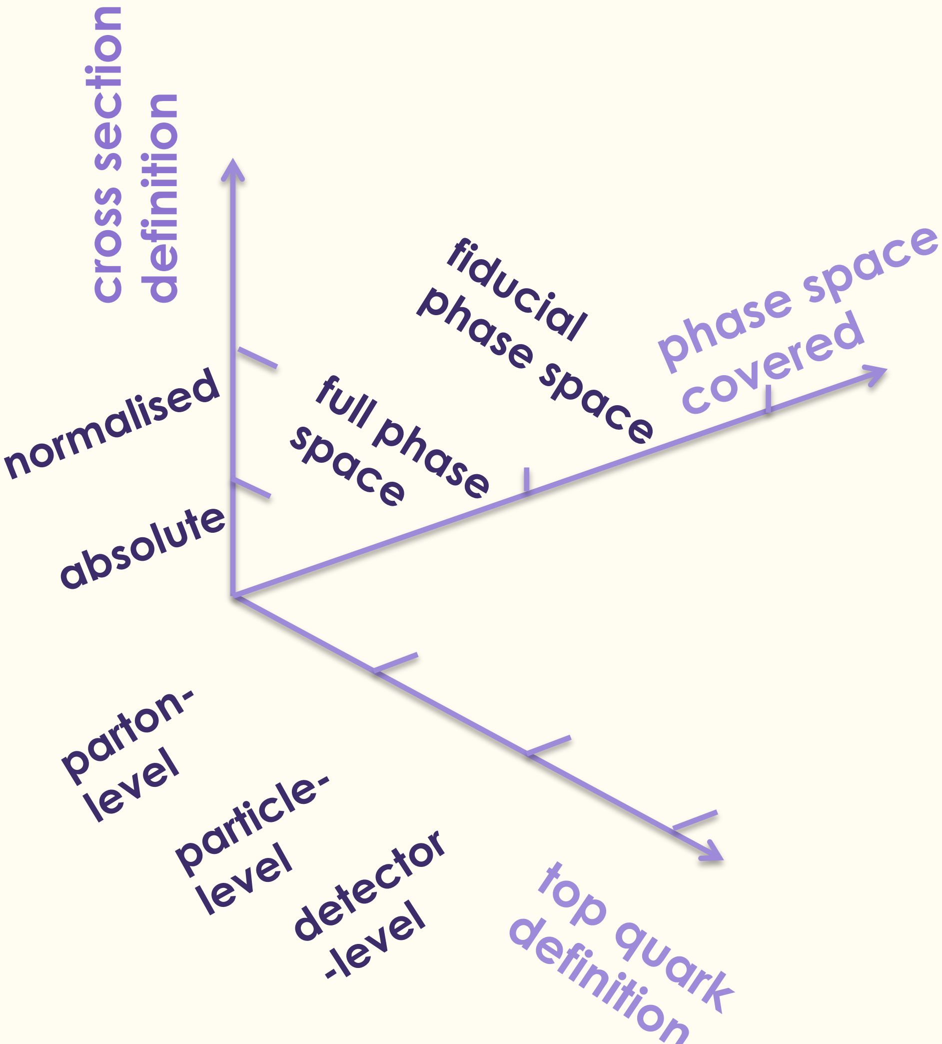
Why measure dσ_{tt} /dX?



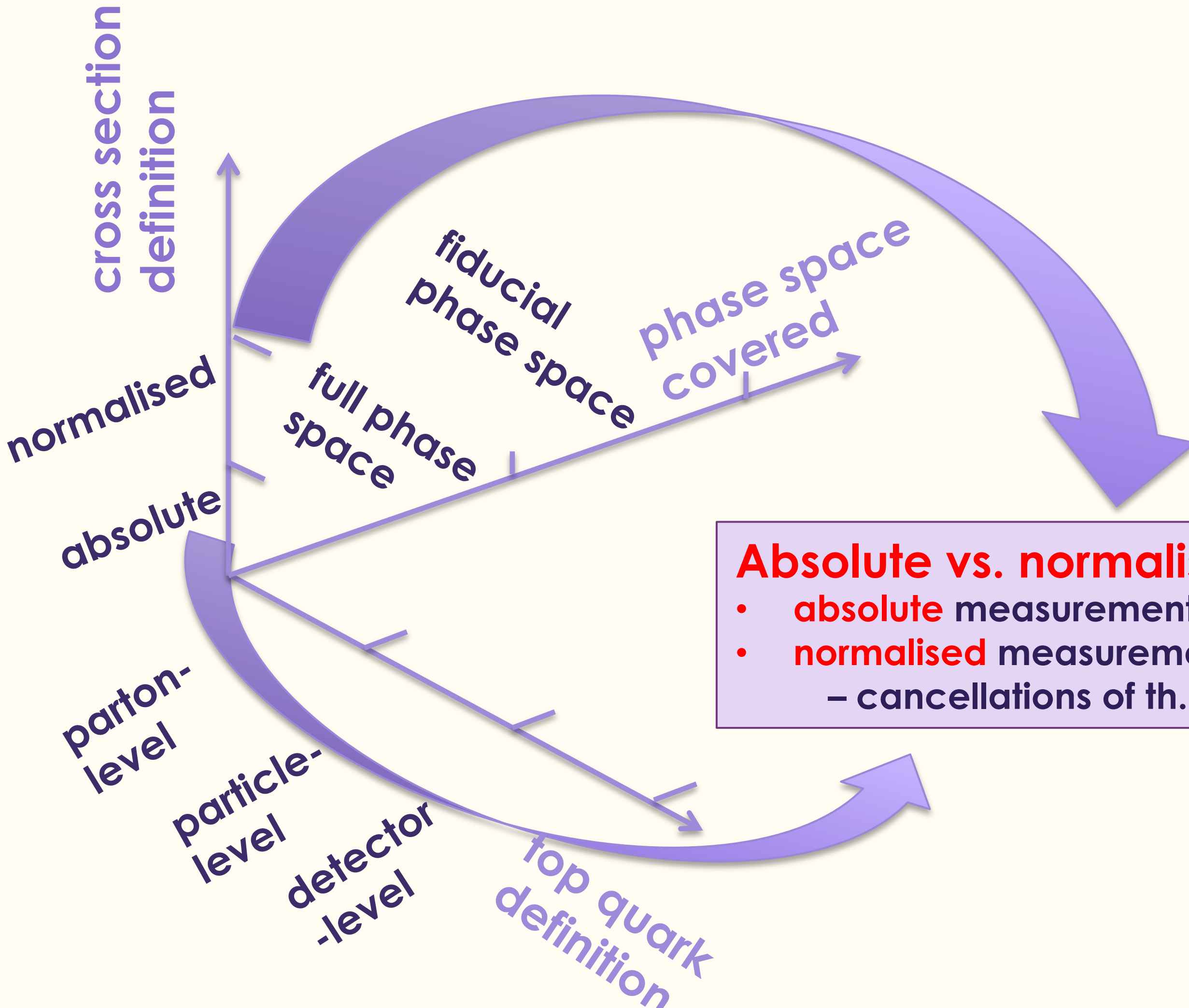
dim-6 operators model effect of high new physics

if new physics lives at large scale Λ
➔ manifested in virtual effects only
➔ constrain EFT with precision measurements

differential measurements



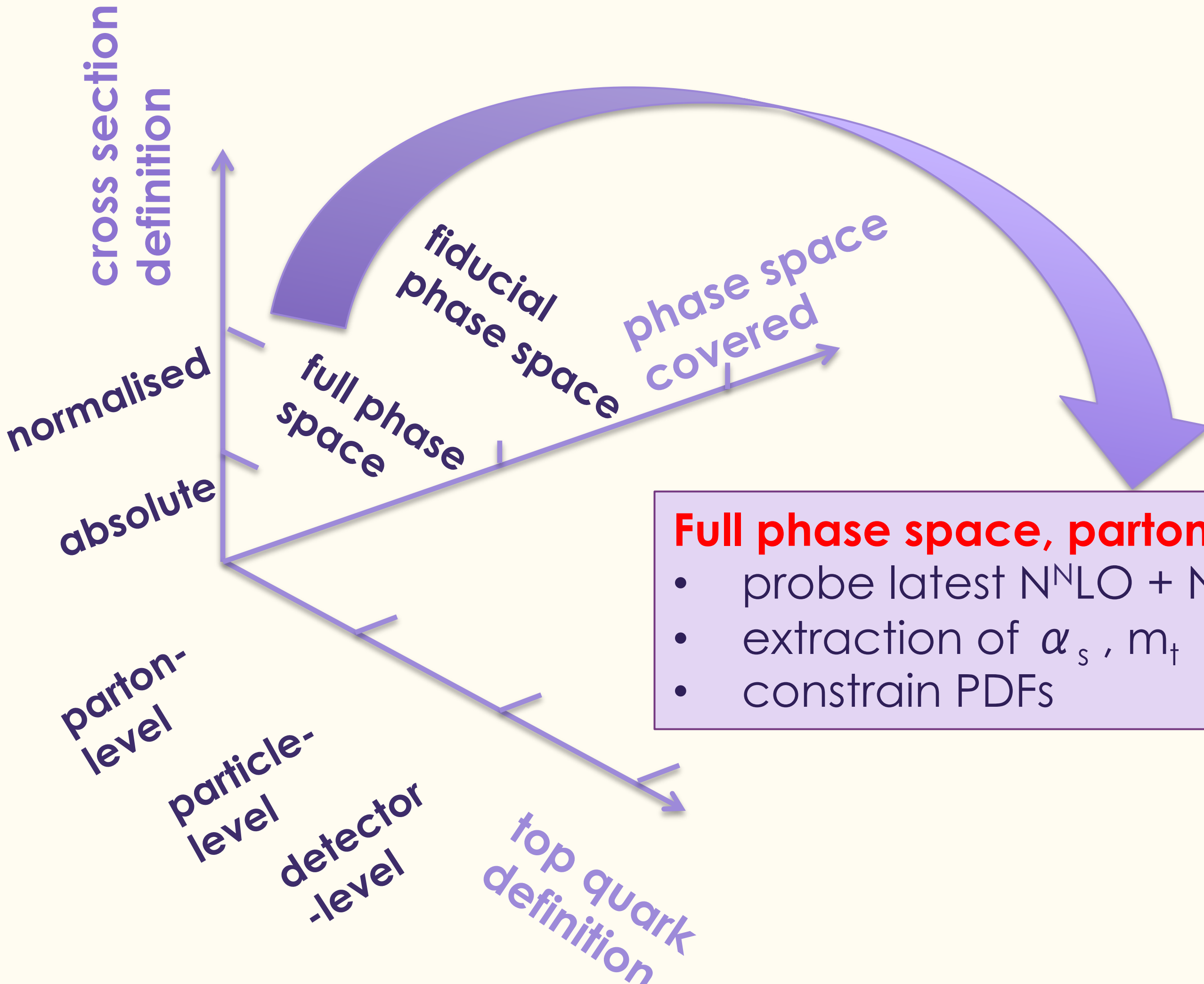
differential measurements



Absolute vs. normalised measurements

- **absolute** measurements reveal maximal information
- **normalised** measurements precisely probe shapes
  – cancellations of th. and exp. uncertainties

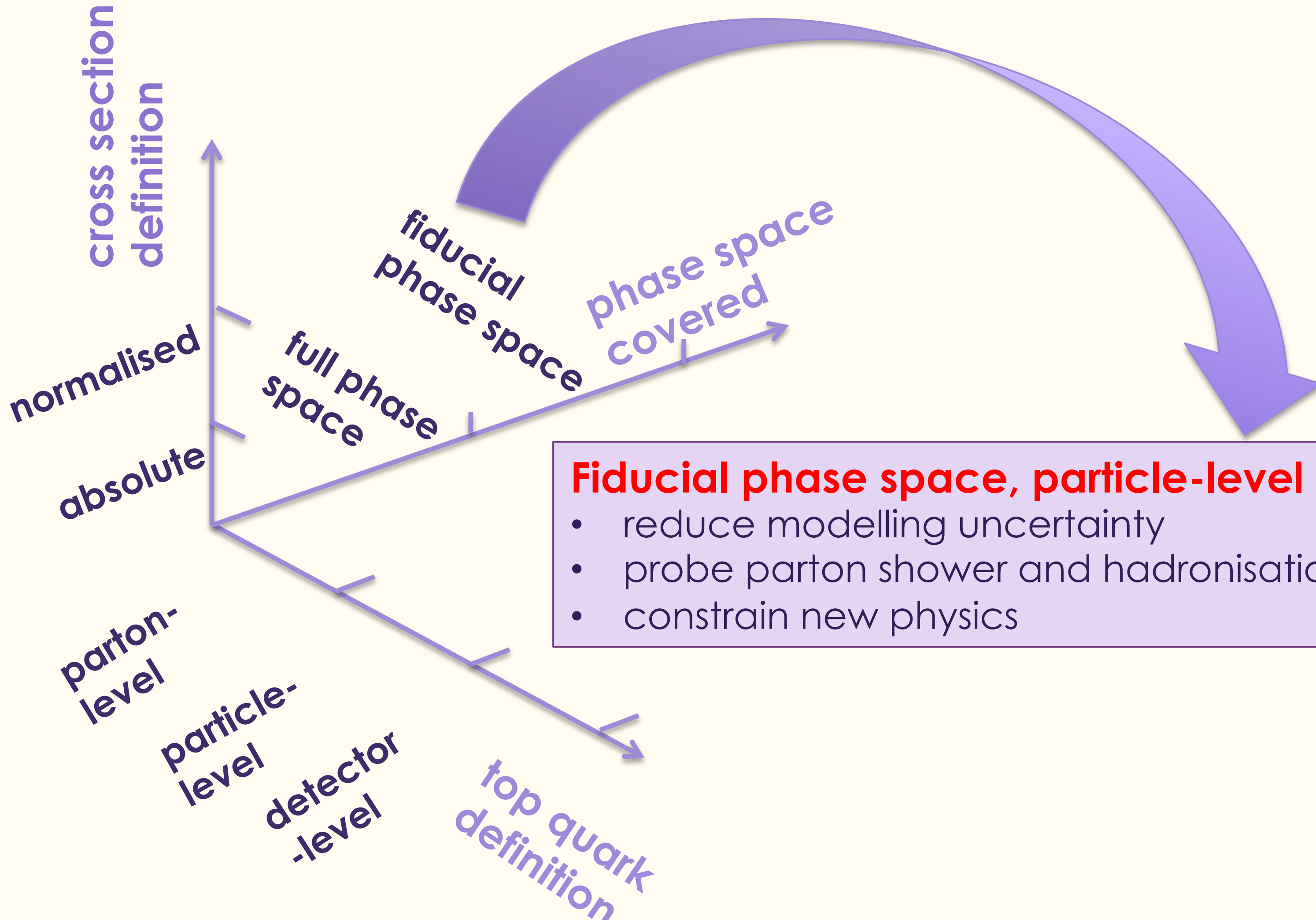
differential measurements



Full phase space, parton-level measurements

- probe latest N^NLO + N^NLL pQCD
- extraction of α_s , m_t
- constrain PDFs

differential measurements



Fiducial phase space, particle-level measurements

- reduce modelling uncertainty
- probe parton shower and hadronisation models
- constrain new physics

the latest from CMS

- two public results in **Nov. 2018** based on full 2016 data and the dilepton channel
  - **arXiv:1811.06625**
    - comprehensive set of **1D** differential cross sections
    - (parton-level, particle-level) X (absolute/normalised) = 94 distributions
    - testing of latest higher order predictions e.g., NNLO+ α^{3}_{EW}, NNLO+NNLL
    - reinterpretation in EFT framework and extraction of charge asymmetry
  - **CMS-PAS-18-004**
    - **2D** and **3D** normalised differential cross sections
    - e.g. y_{tt} vs m_{tt} vs N_{jets}
    - deep probe of NLO modelling
    - simultaneous extraction of m_t , α_S and PDF

Measurements of $t\bar{t}$ differential cross sections in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ using events containing two leptons

The CMS Collaboration

arXiv:1811.06625

arXiv:1811.06625

strategy

fundamental goal

- measure the tt process in as much detail as possible using **1D distributions**

the basic method

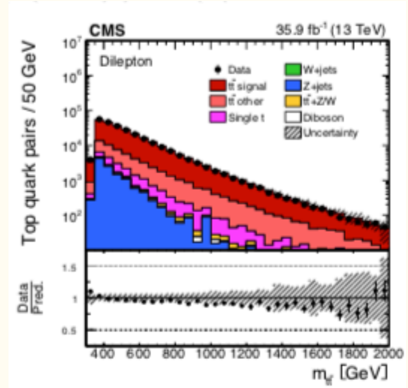
- select dilepton events (minimal backgrounds)
- kinematic reconstruction to define top and tt systems
- cut+count methodology to measure diff. cross sections in bins
  - backgrounds mainly from simulation, except data-driven z+jets
- unfold to **particle** and **parton** levels
- measure **absolute** and **normalised** distributions

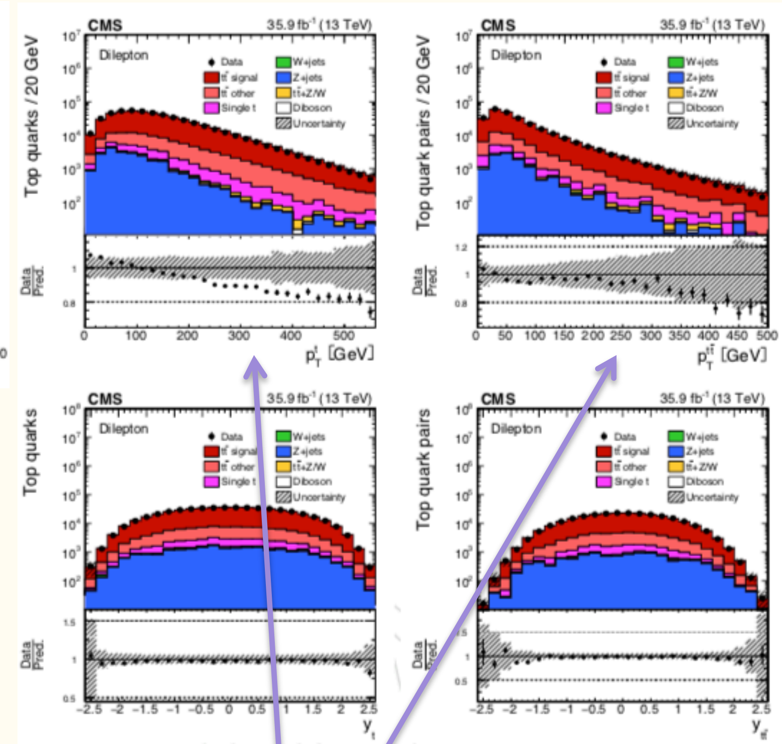
reinterpretations

- extract charge asymmetries
- constrain TOP CMDM in EFT framework

data modelling

arXiv:1811.06625





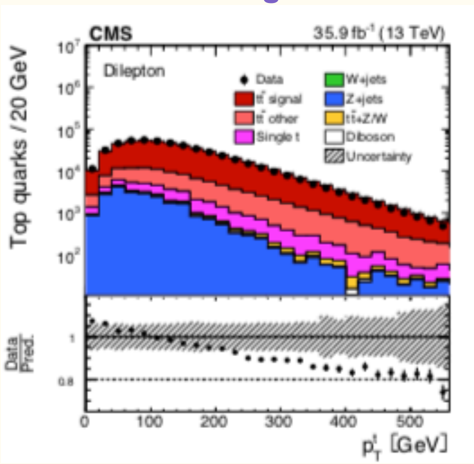
event selection

- *OR* of single and dilepton triggers
- **leptons:** 2 opp-charged: ee, $\mu\mu$, eμ
  - $p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $|\eta| < 2.4$
  - tight ID for electrons and muons
  - $m_{ll} > 20$ GeV
  - ee, $\mu\mu$ channels: Z veto: $|m_Z - m_{ll}| > 15$ GeV
- **jets:**
  - $N_{jets} \geq 2$, ($p_T > 30$ GeV, $|\eta| < 2.4$)
  - ΔR(l, jet) > 0.4
- **b-tags:** ≥ 1 b-tagged jets
- ***MET:*** ee, $\mu\mu$ channels: MET > 40 GeV
- **kinematic reconstruction**
  - event excluded if no solution found

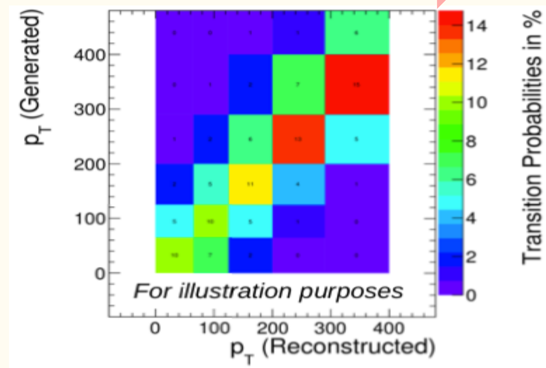
mis-modelling already apparent in top and tt p_T

measuring differential cross sections

Number of signal events

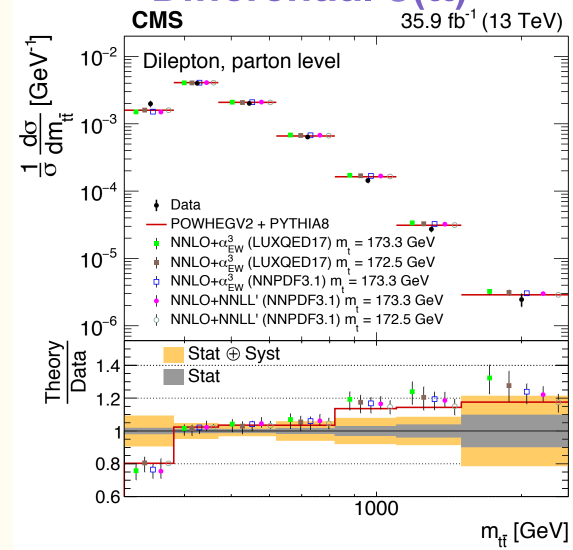


Response matrix



$$\frac{1}{\sigma}\frac{d\sigma}{dX_i}=\frac{1}{\sigma}\frac{unfold\left(N^X_{data,i}-N^X_{BG,i}\right)}{\Delta^i_X\cdot\int\mathscr{L}\,dt}$$

Differential σ(tt)



binning

chosen to limit migration effects in and out of bins:

purity (p_i) & stability (s_i) ≥ ~40%

$$p_i=\frac{N_i^{rec\,\&\,gen}}{N_i^{rec}}\qquad s_i=\frac{N_i^{rec\,\&\,gen}}{N_i^{gen}}$$

- also monitor resolutions, statistical power per bin

unfolding

- regularized unfolding suppresses sharp fluctuations

phase space

- correct back to **parton** or **particle** level in **full** or **fiducial** phase space

final result

“normallised” distributions

- normalized to one

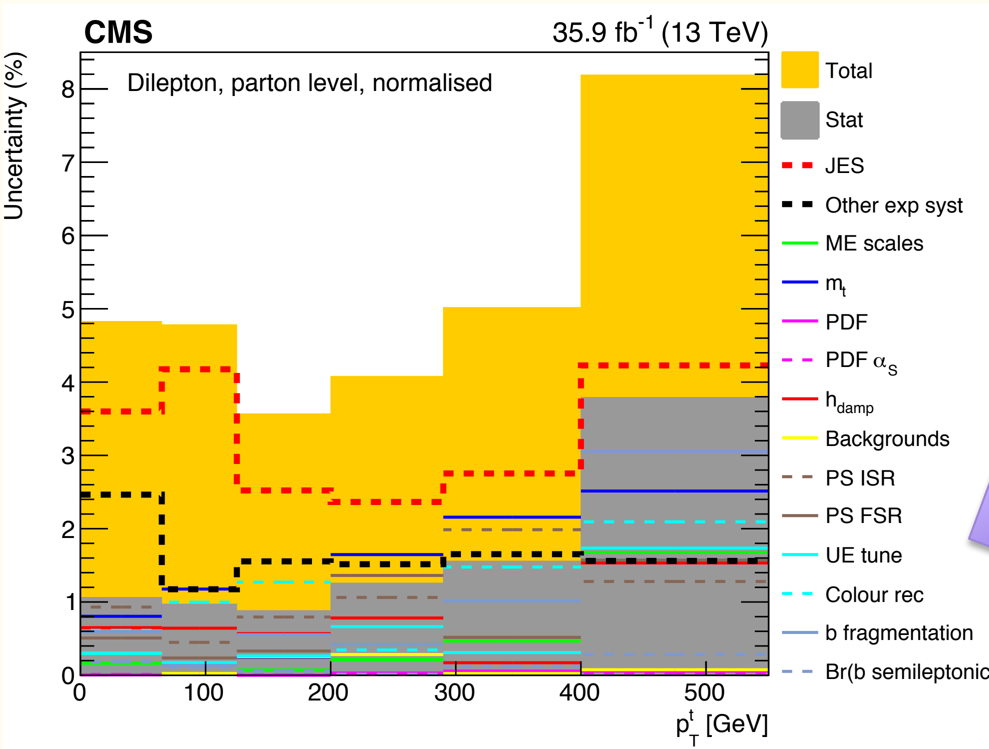
"absolute” distributions

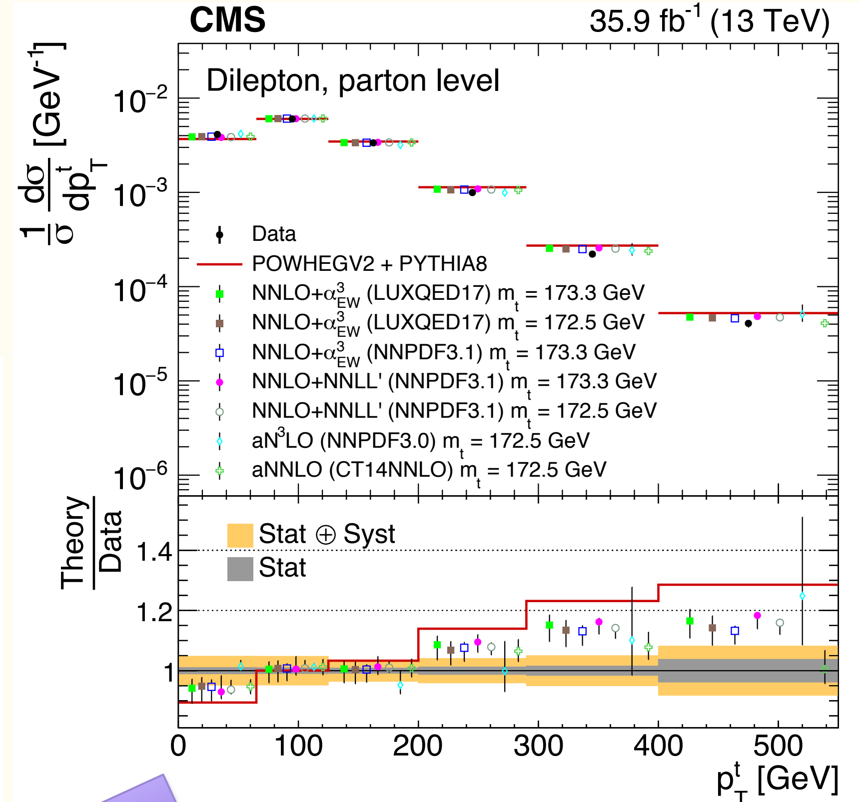
- raw diff. cross section in bin

results – top quark kinematics

arXiv:1811.06625

- pt (top) distribution disagrees with NLO MC predictions
- improved agreement with NNLO predictions



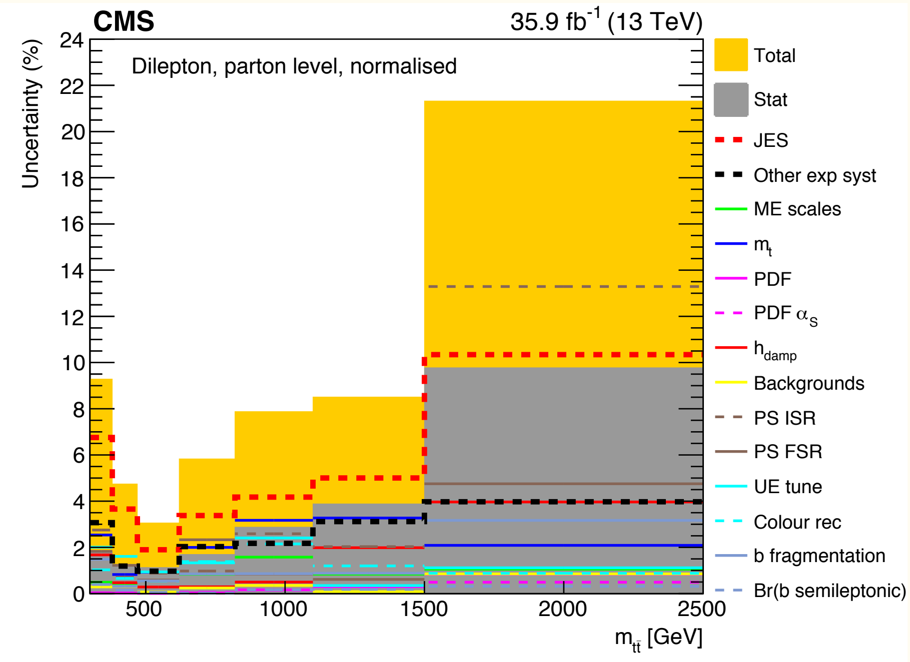


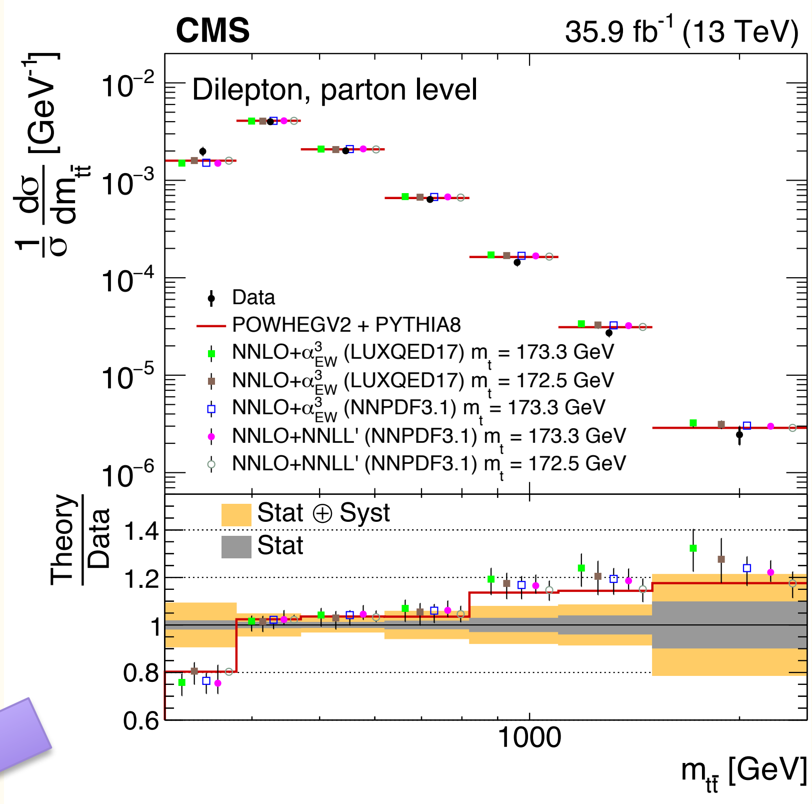
- total uncertainty 5-8%
- strongly systematically limited
- JES dominates

results – tt kinematics

arXiv:1811.06625

- m (tt) all predictions disagree with data at very low and high m(tt)



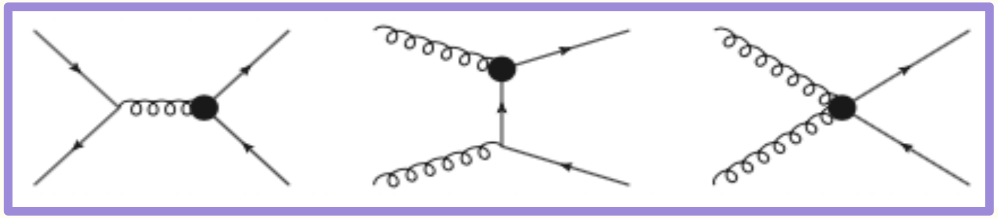


- total uncertainty 9-22%
- JES, ISR modeling dominate

reinterpretations – top quark CMDM in EFT

- in EFTs, dim-6 operators model high-scale new physics
- $\boldsymbol{O_{tG}}$ models the top quark chromomagnetic dipole moment (CMDM)
  - anomalous CMDM arises in many models of new physics

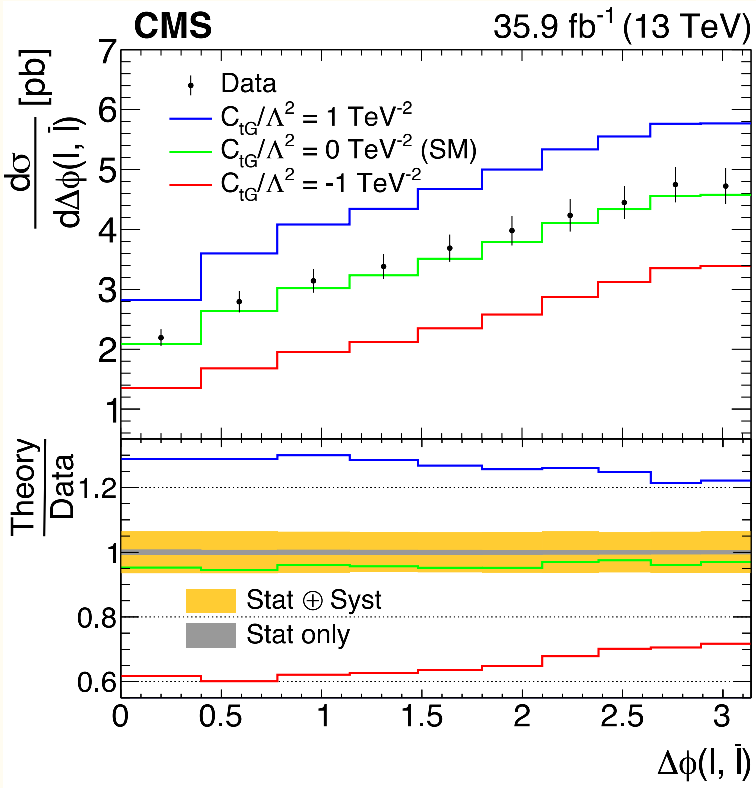
O_{tG}

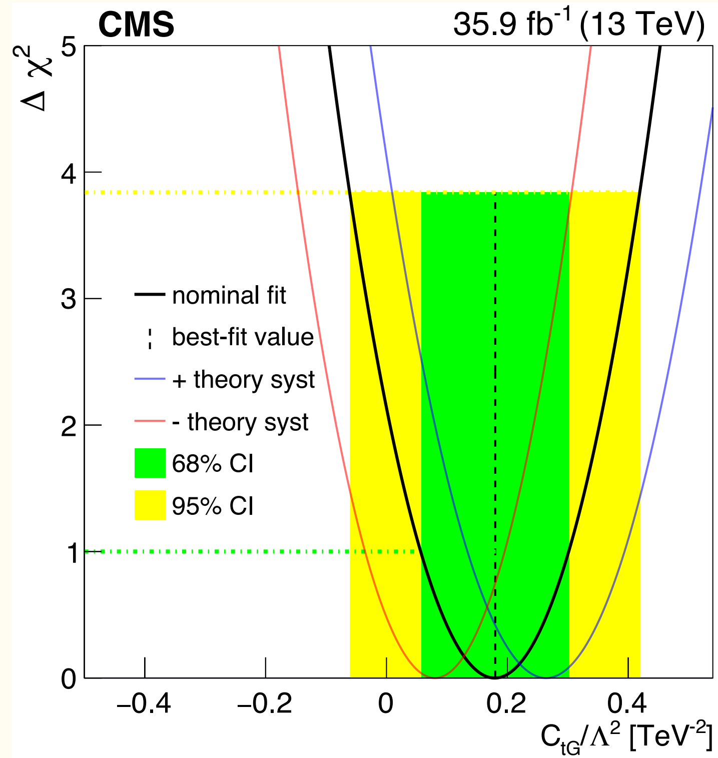


- O_{tG} modifies the gtt vertex and generates new ggtt vertex
- O_{tG} flips the chirality of the top quark
- changes in rate and shape of tt events
  - alters spin correlations of top quarks
  - delta phi of leptons **($\Delta\varphi$(ll))** sensitive to O_{tG}
- particle-level data preferred (minimal model depedence)

strategy:
constrain CMDM with absolute particle-level, $\Delta\varphi$(ll) differential cross section

reinterpretations – top quark CMDM in EFT

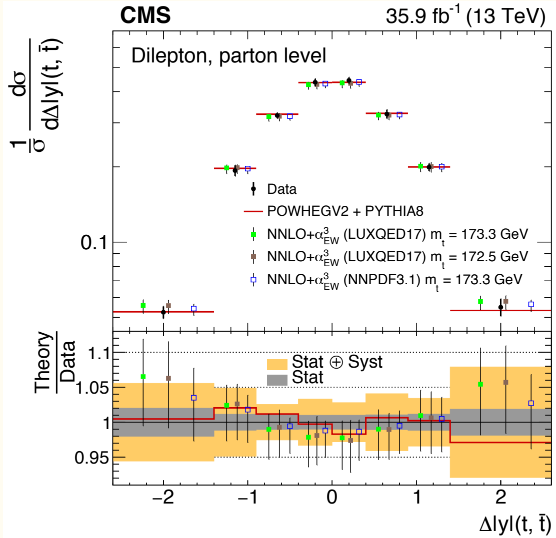


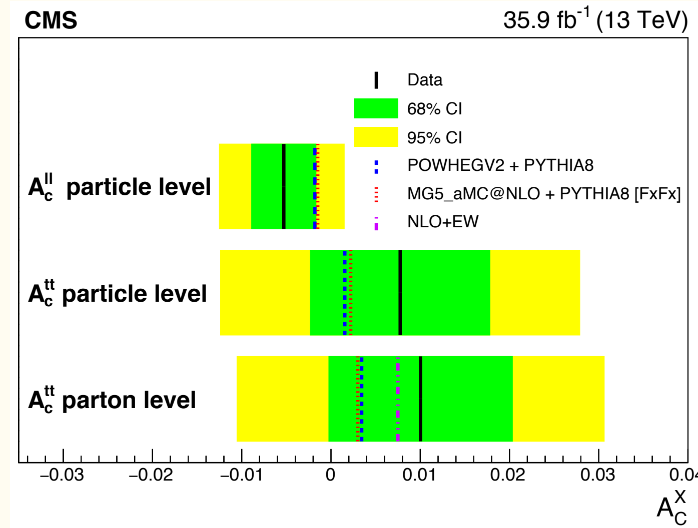


- signal modelled at full NLO with MG5_aMC@NLO
- χ^2 minimisation used to extract best-fit value and CL on C_{tG}/Λ^2
- slight numerical improvement on previous constraints
- particle level means less model dependence in data
  - ease of integration into future global analysis

reinterpretations – charge asymmetries

arXiv:1811.06625





- charge asymmetries (A_C) sensitive to new physics contributions
- measurements of $\Delta|y|(tt)$ and $\Delta|\eta|(ll)$ allow A_C extraction

$$A_c^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}, \quad A_c^{l\bar{l}} = \frac{\sigma_{t\bar{t}}(\Delta|\eta|(l,\bar{l}) > 0) - \sigma_{t\bar{t}}(\Delta|\eta|(l,\bar{l}) < 0)}{\sigma_{t\bar{t}}(\Delta|\eta|(l,\bar{l}) > 0) + \sigma_{t\bar{t}}(\Delta|\eta|(l,\bar{l}) < 0)}$$

- results consistent with SM predictions:
  - NLO QCD
  - NLO QCD + EW

Measurements of normalised multi-differential cross sections for top quark pair production in pp collisions at $\sqrt{s} = 13$ TeV and simultaneous determination of the strong coupling strength, top quark pole mass and parton distribution functions

The CMS Collaboration

CMS-PAS-TOP-18-004

strategy

fundamental goal

measure normalised **2D** and **3D** differential $t\bar{t}$ cross sections using 2016 data

the basic method

- select dilepton events (minimal backgrounds)
- kinematic reconstruction to define top and $t\bar{t}$ systems
- cut+count methodology to measure diff. cross sections in bins
- unfold to **particle** and **parton** levels
- measure **normalised** distributions

almost identical to 1D analysis

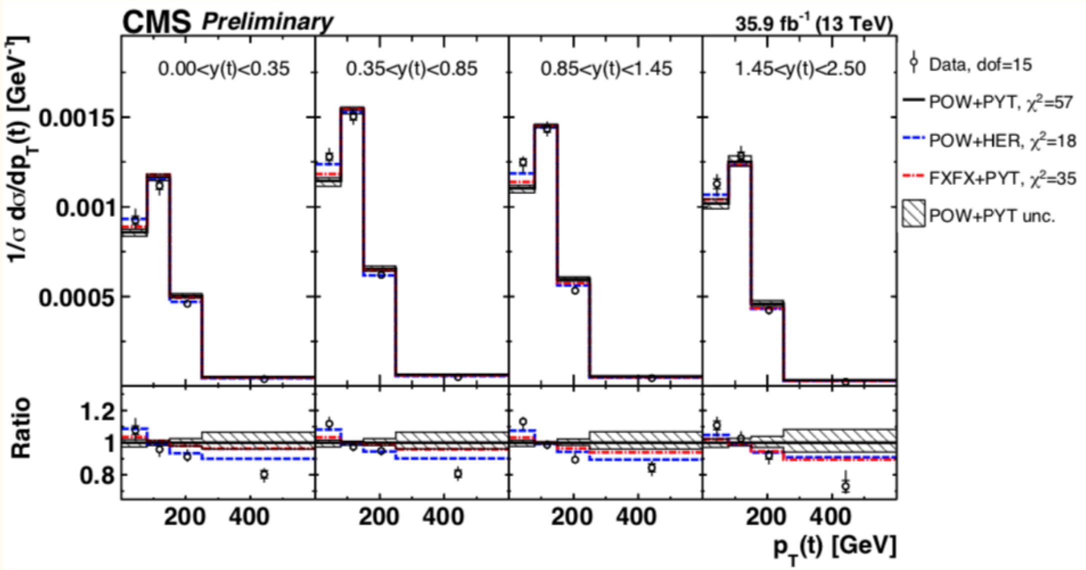
reinterpretations

- extract m_t and α_s using external PDFs and $t\bar{t}$ data only
- simultaneous fit of PDFs, m_t and α_s with $t\bar{t}$ and HERA data

results – 2D cross sections

p_T (top) vs y(top)

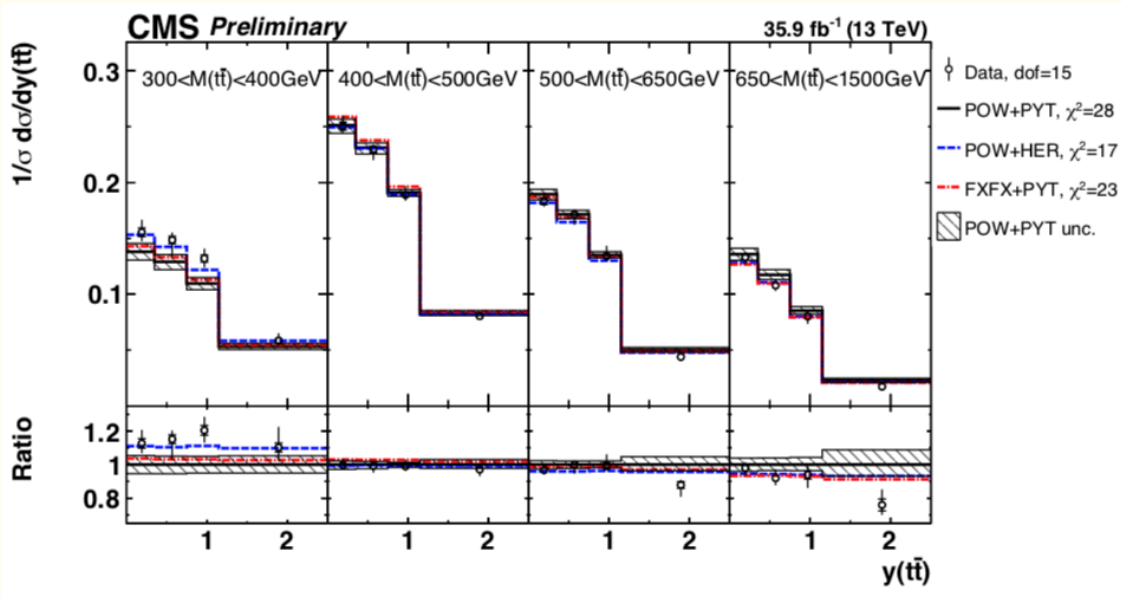
- p_T (top) mis-modelling across y(t) range
- best description by POWHEG+HERWIG



results – 2D cross sections

y (tt) vs m(tt)

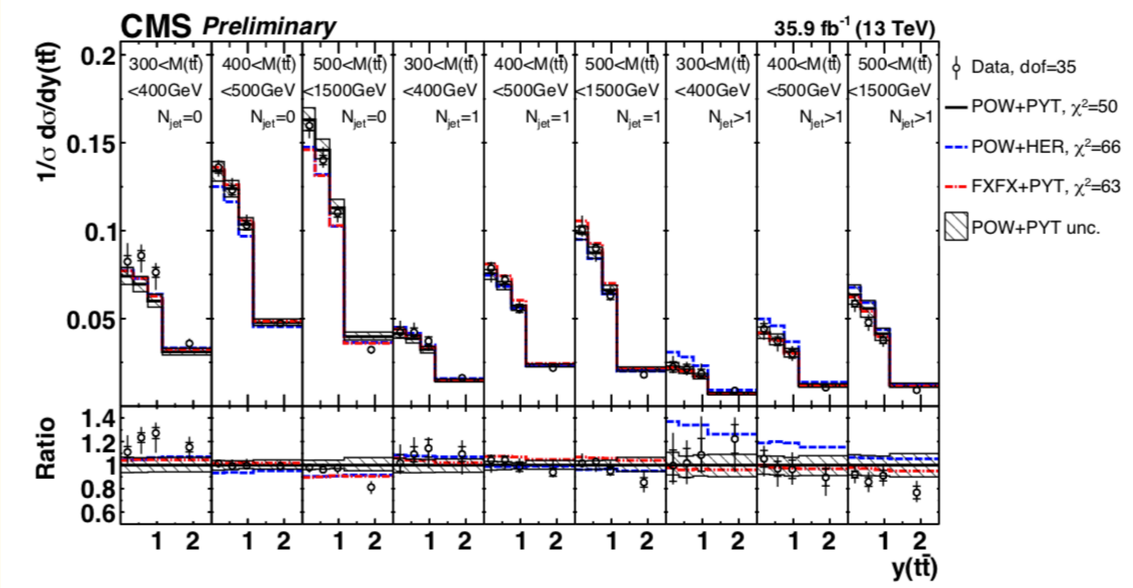
- excess at low m(tt) consistent with 1D analysis
  - no dependence of excess on y(tt)
  - best description vs m(tt) by POWHEG+HERWIG



results – 3D cross sections

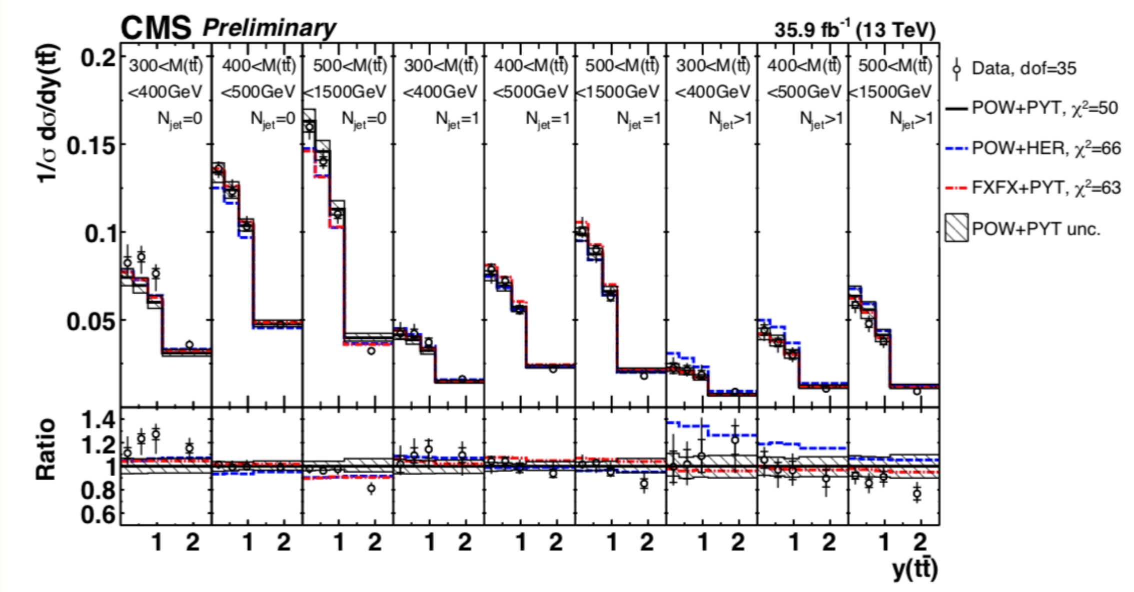
y (tt) vs m(tt) vs N_{jets}

- excess at low m(tt) consistent with 1D analysis
- no dependence of excess on y(tt), N_{jets}
  - best description vs m(tt) by POWHEG+HERWIG



results – 3D cross sections

y (tt) vs m(tt) vs N_{jets}



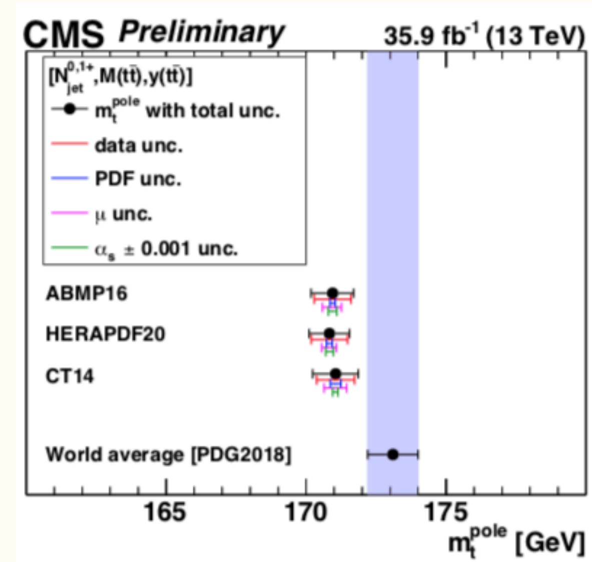
- excess at low m(tt) consistent with 1D analysis
- no dependence of excess on y(tt), N_{jets}
  - best description vs m(tt) by POWHEG+HERWIG

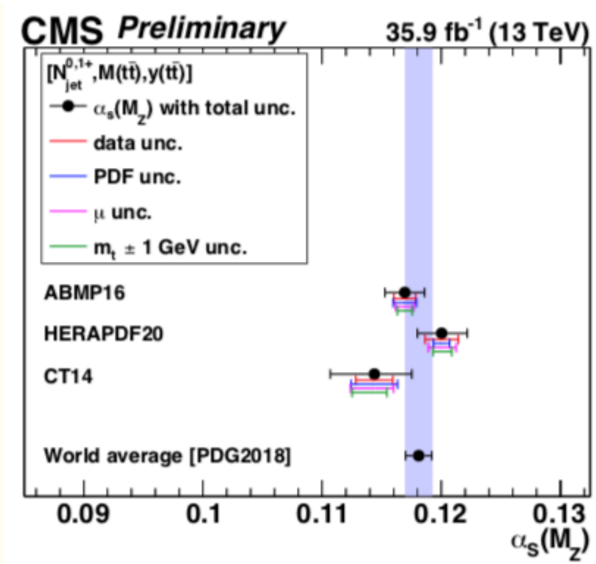
CMS-PAS-TOP-18-004

reinterpretations – m_t and α_s using external PDFs and tt data

- NLO predictions for tt +0,1,2 jets from
  - MadGraph5_aMC@NLO+aMCfast+ApplGrid+xFitter
  - PDFs and α_s from several groups via LHAPDF
  - parton->particle level corrections (<5%)

- **two extractions**
  - **fix α_s, fit m_t (pole)**
    - use α_s from each PDF set
    - no significant dependence on PDF set
  - **fix m_t (pole), fit α_s**
    - use m_t (pole) = 172.5 GeV
    - significant dependence on PDF set

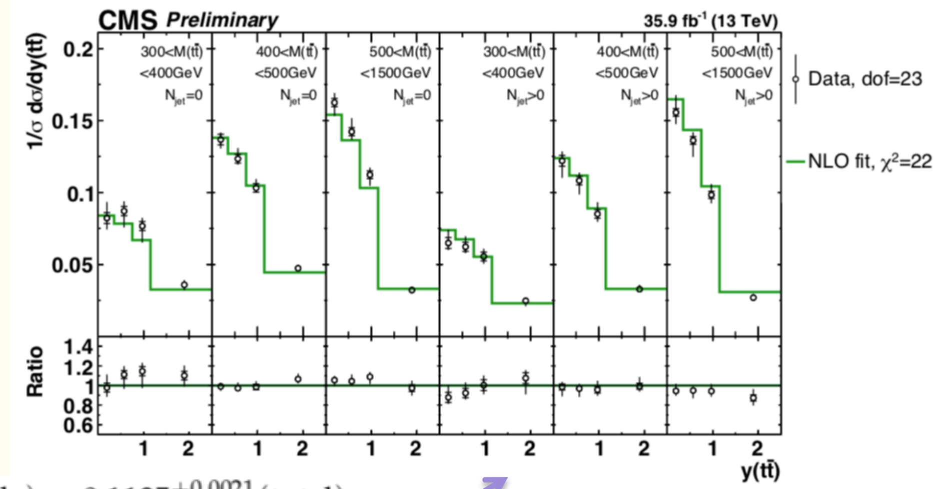




CMS-PAS-TOP-18-004

reinterpretations

- simultaneous (m_t, α_s, PDF) fit



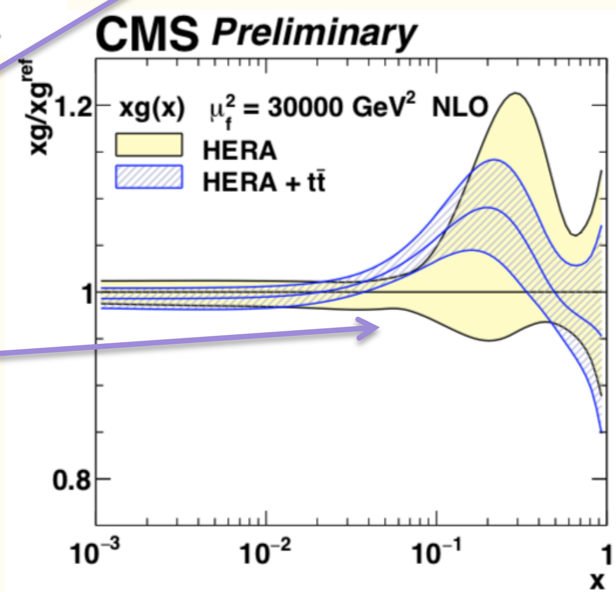
- **standard PDF fit with xFitter**
  - HERA data only
  - HERA + tt data

$$\alpha_s(M_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{mod})^{+0.0008}_{-0.0001}(\text{par})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

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

- m_t, α_s extracted at high precision with only weak (0.3) correlation
- model with best-fit values match data well

- ipact on high-x gluon PDF uncertainty



summary & conclusions

- **CMS has recently published two analyses probing tt in unprecedented detail**
  - **arXiv:1811.06625**
    - comprehensive set of **1D** differential cross sections
    - (parton-level, particle-level) X (absolute/normalised) = 94 distributions
    - test of latest higher order predictions e.g., NNLO+α^3_{EW}, NNLO+NNLL
    - reinterpretation in EFT framework and extraction of charge asymmetry
  - **CMS-PAS-18-004**
    - **2D** and **3D** normalised differential cross sections
    - deep probe of NLO modelling
    - simultaneous extractions of m_t, α_S and PDF

This data will be a crucial ingredient in future QCD, EFT fit and SM parameter extractions

BACKUP

systematics (experimental)

each uncertainty propagated through analysis chain individually

- sys. uncertainty in bin = difference of the changed result wrt nominal
- determined individually for each bin through variation of sys. source
- applying b-tagging efficiency dependent correction for systematic uncertainty estimation due to theory related sources, JES, and JER
- following recommendations in all cases

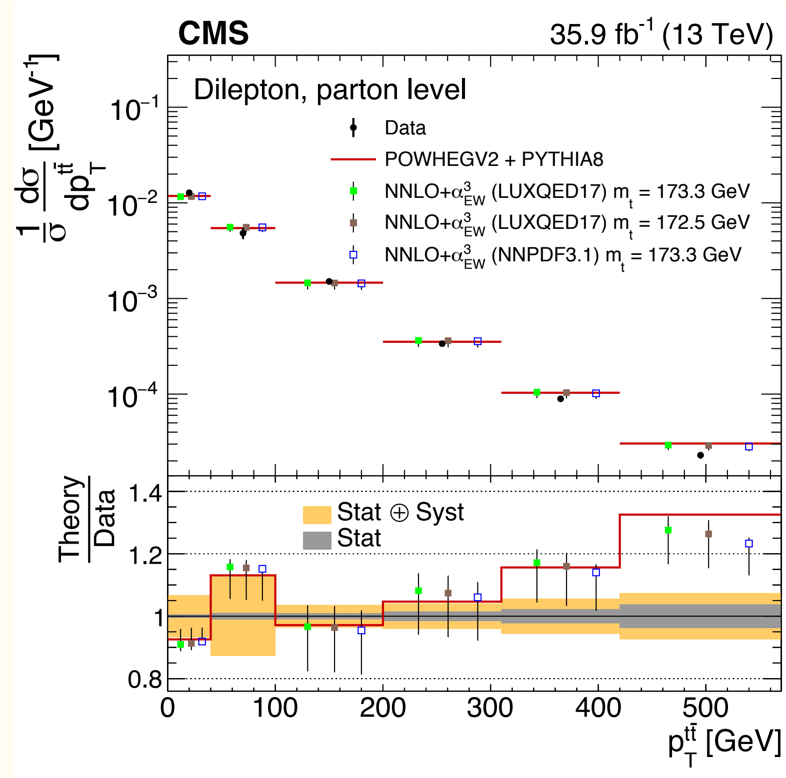
experimental uncertainties considered in this analysis

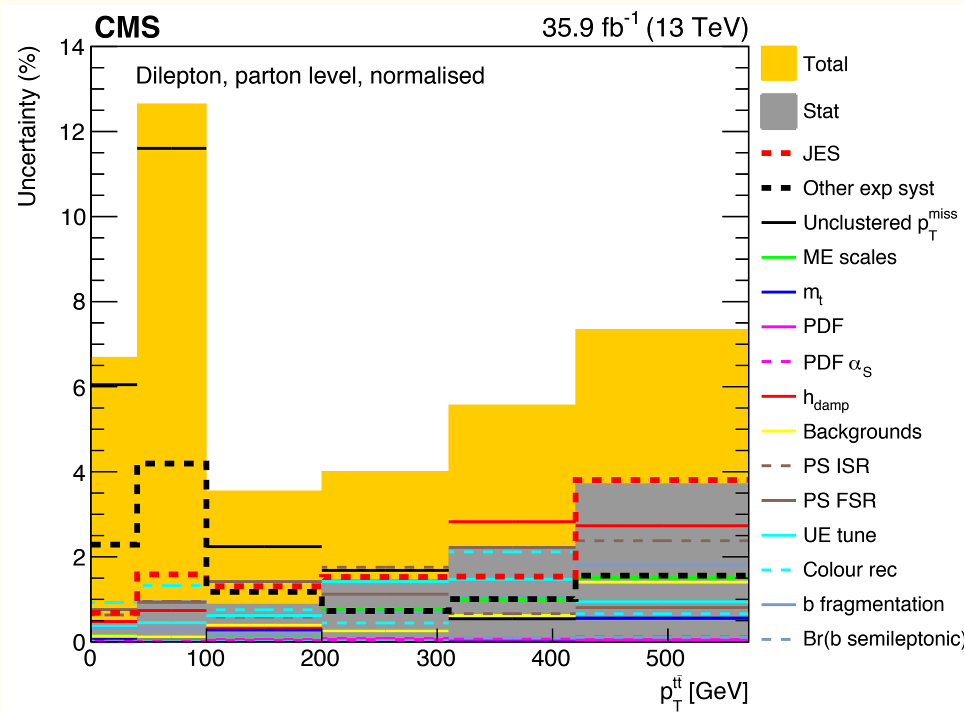
- **trigger eff., lepton ID/Iso, kin. reco. eff.:** vary accordingly to uncertainties
- **JES (individual sources), JER, b-tagging:** prescription by POGs
  - **b-tagging**: additional variations depending on jet kinematics
- **unclustered MET variations**
- **pile-up reweighting:** : +/- 4.6% on min-bias cross section
- **lumi**: 2.5% variation
- **background normalisations**: 30% variations

results – tt kinematics

arXiv:1811.06625

- pt (tt) all predictions disagree with data at large pt (tt)





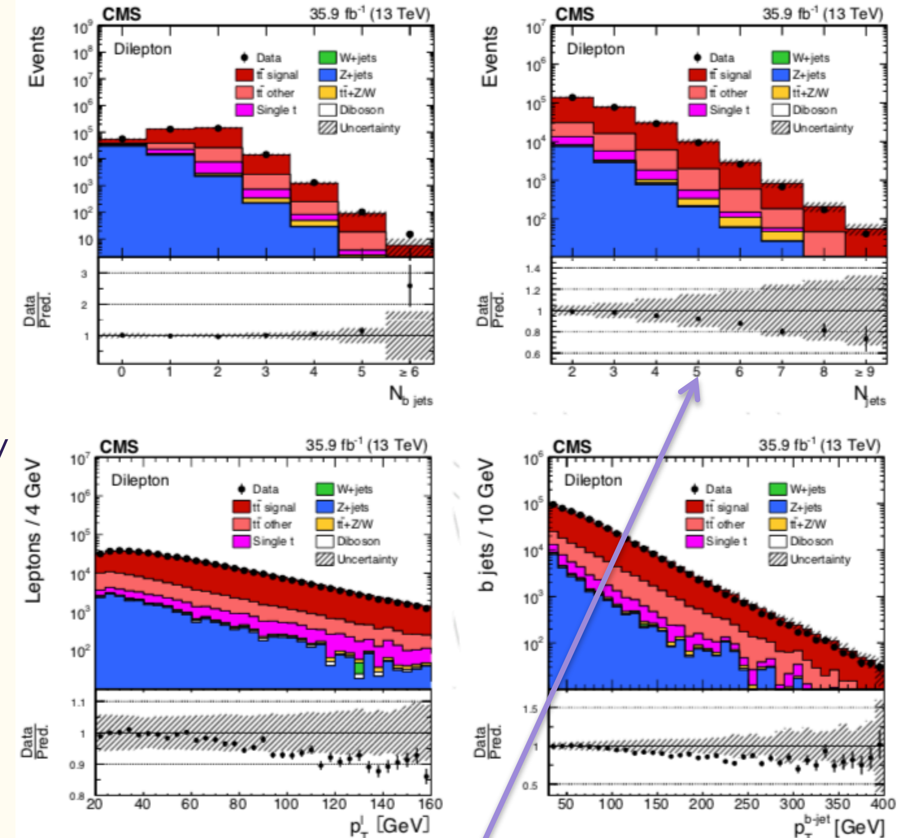
- total uncertainty 6-12%
- MET, JES, modeling dominates

data modelling

arXiv:1811.06625

event selection

- *OR* of single and dilepton triggers
- **leptons:** 2 opp-charged: ee, μμ, eμ
  - $p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $|\eta| < 2.4$
  - tight ID for electrons and muons
  - $m_{ll} > 20$ GeV
  - ee, μμ channels: Z veto: $|m_Z - m_{ll}| > 15$ GeV
- **jets:**
  - $N_{jets} \geq 2$, ($p_T > 30$ GeV, $|\eta| < 2.4$)
  - $\Delta R(l, jet) > 0.4$
- **b-tags:** ≥ 1 b-tagged jets
- **MET:** ee, μμ channels: MET > 40 GeV
- **kinematic reconstruction**
  - event excluded if no solution found



mis-modelling of jet pT and multiplicity

data modelling

arXiv:1811.06625

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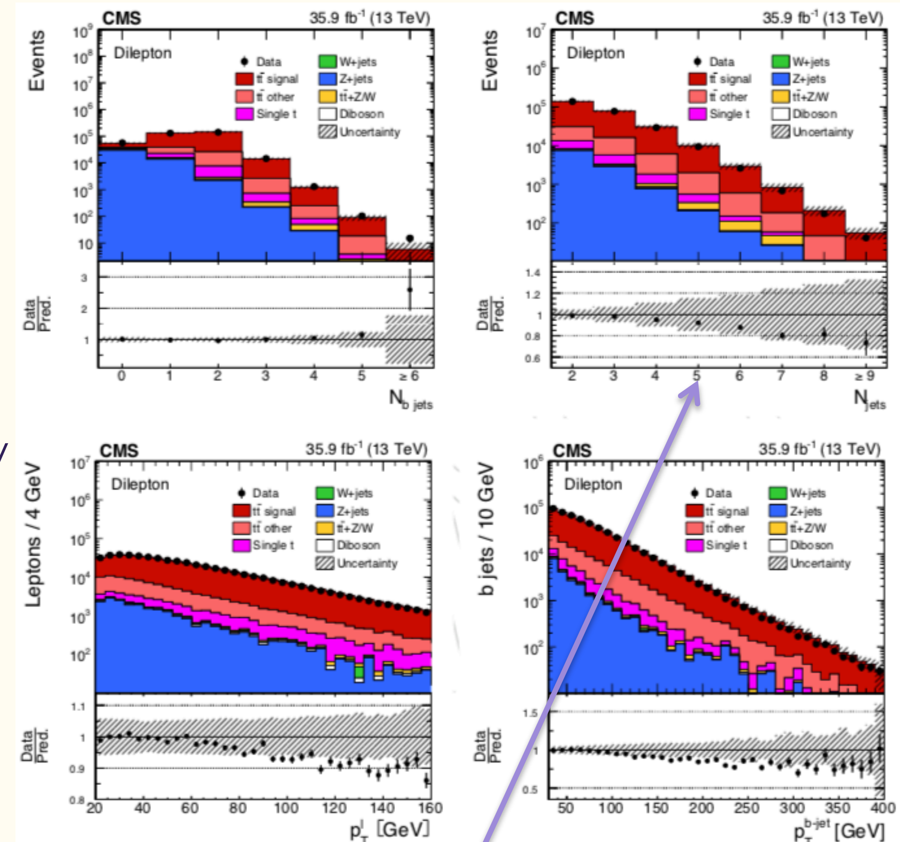

mis-modelling of jet pT and multiplicity