$t\bar{t}$ multi-differential cross sections in dilepton channel

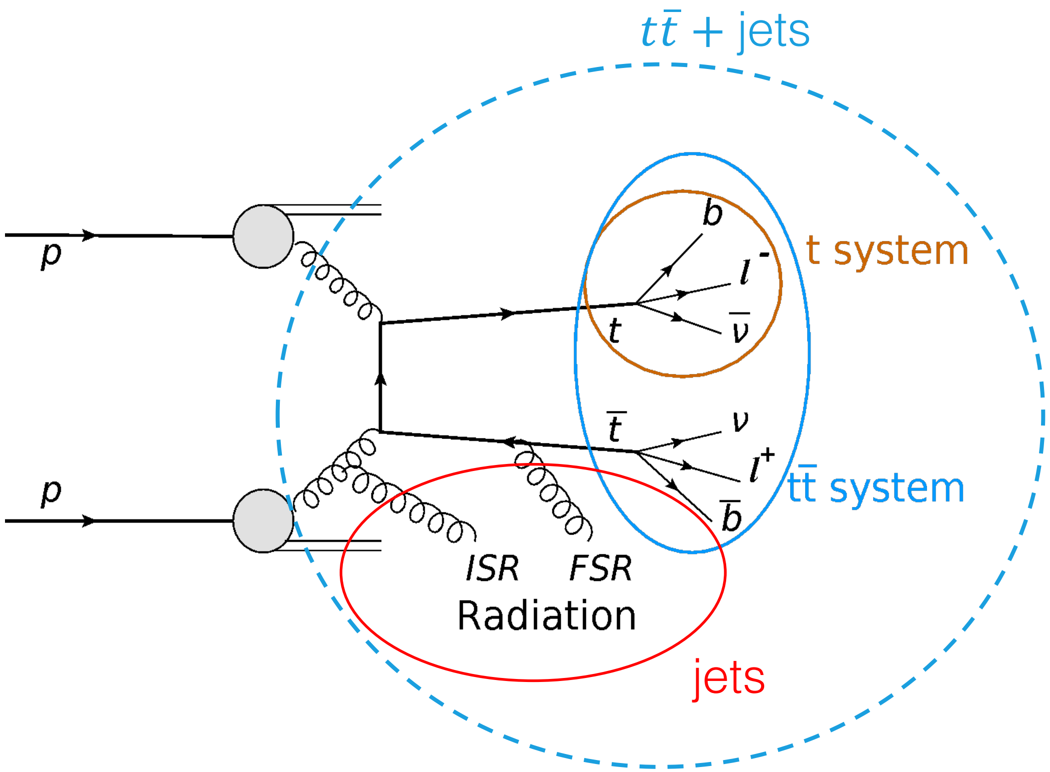
using full Run2 data from the CMS experiment

Maria Aldaya, Olaf Behnke, Henriette Petersen, Mykola Savitskyi, Rafael Sosa, Sebastian Wuchterl

March 16th, 2021.

Analysis description

Motivation



- Aim at a comprehensive set of differential measurements of kinematical and topological spectra in $t\bar{t}$ + additional jet events (dileptonic channel)

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

- Precision tests of perturbative QCD:
  - jet radiation pattern and correlations to $t\bar{t}$ kinematics

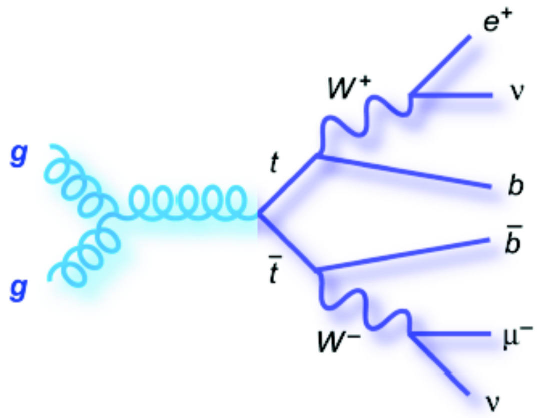
  $[N_j, p_T(t\bar{t})]$ | $[N_j, M(t\bar{t})]$ | ...

- Investigate known problems (e.g. softer $p_T(t)$ in data with respect to predictions) as a function of other observables

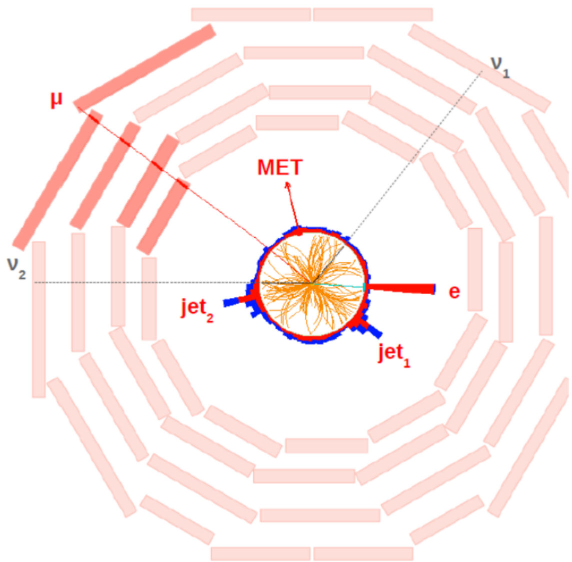
  $[N_j, p_T(t)]$ | $[M(t\bar{t}), p_T(t)]$ | ...

Analysis description

More details in previous talk by H. Petersen



Detector Signature:
- 2 opposite charged leptons
- At least 2 jets (2 b-jets)
- Missing E_T



Measurement strategy follows TOP-17-014 and TOP-18-004 papers

- **leptons:**
  - $p_T(l) > 25(15)\ GeV$
  - $|\eta(l)| < 2.4$ (cut based ID, tight iso)
  - $M(ll) > 20\ GeV$

  For ee and $\mu\mu$ channels:
  - $MET > 40\ GeV$
  - Excluding: $76 < M(ll) < 106\ GeV$

- **jets:**
  - anti-kT, $R = 0.4$
  - $p_T(jet) > 30\ GeV$
  - $|\eta(jet)| < 2.4$
  - $\Delta R(jet, l) > 0.4$
  - at least 1 b-tagged jet (DeepCSV loose WP)

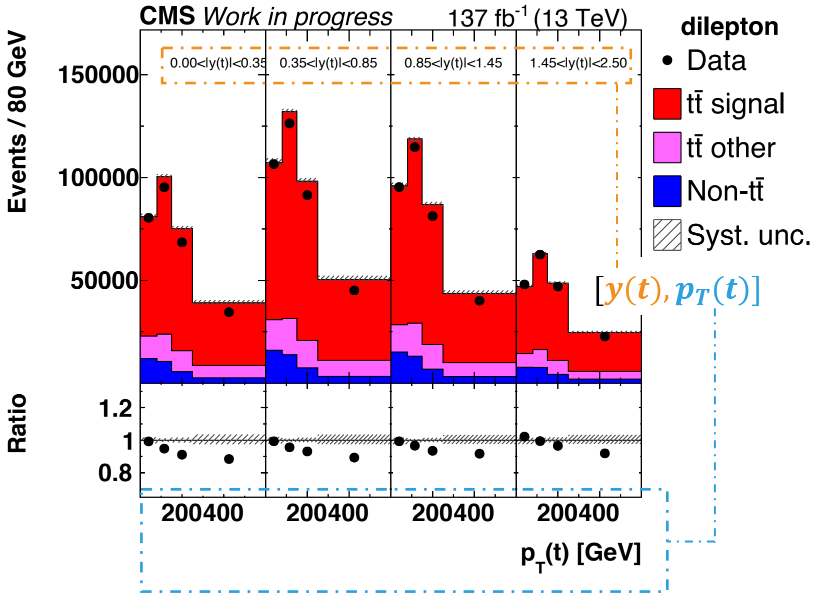
- **extra jets:**
  - $p_T(jet) > 40\ GeV$
  - $\Delta R(jet, b) > 0.8$

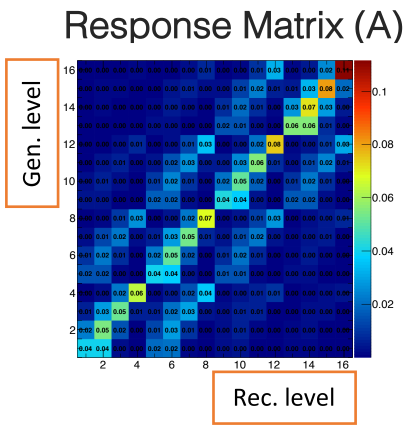
- **Kinematic reconstruction:**
  - full: t and $\bar{t}$
  - loose: only $t\bar{t}$

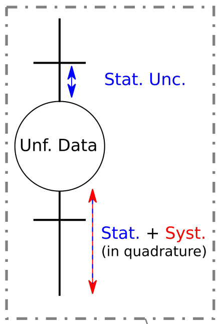
- **Unfolding:**
  - Regularized unfolding using TUnfold

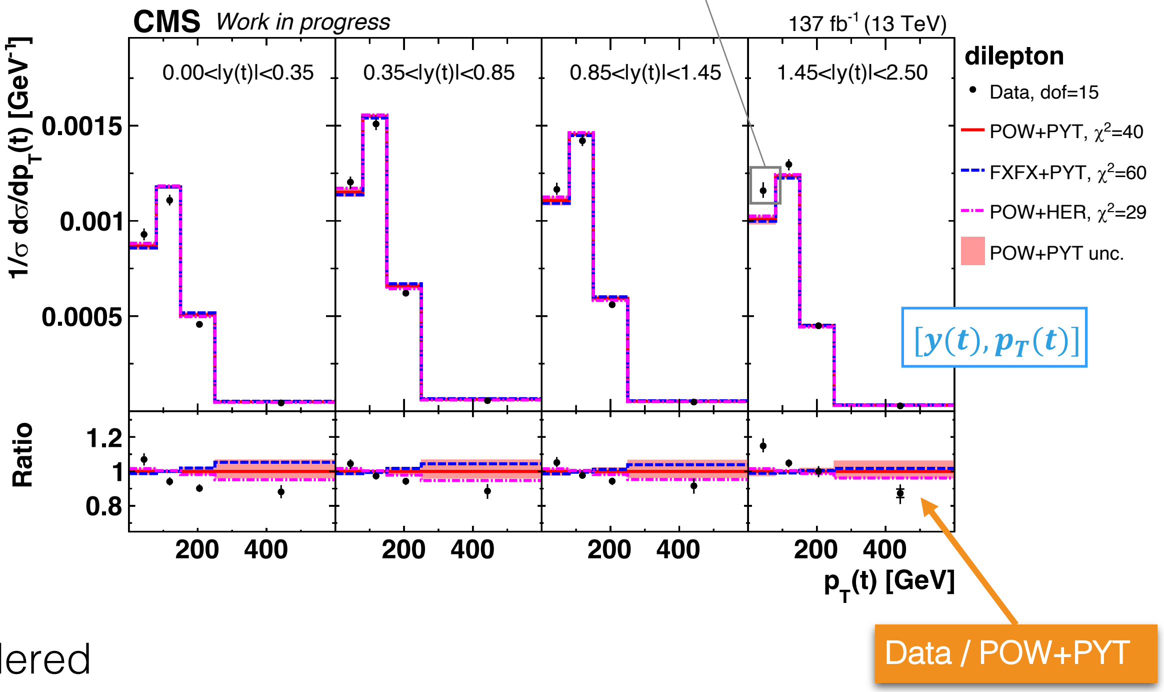
Unfolded cross sections

Event yields are combined for
channels and years before unfolding



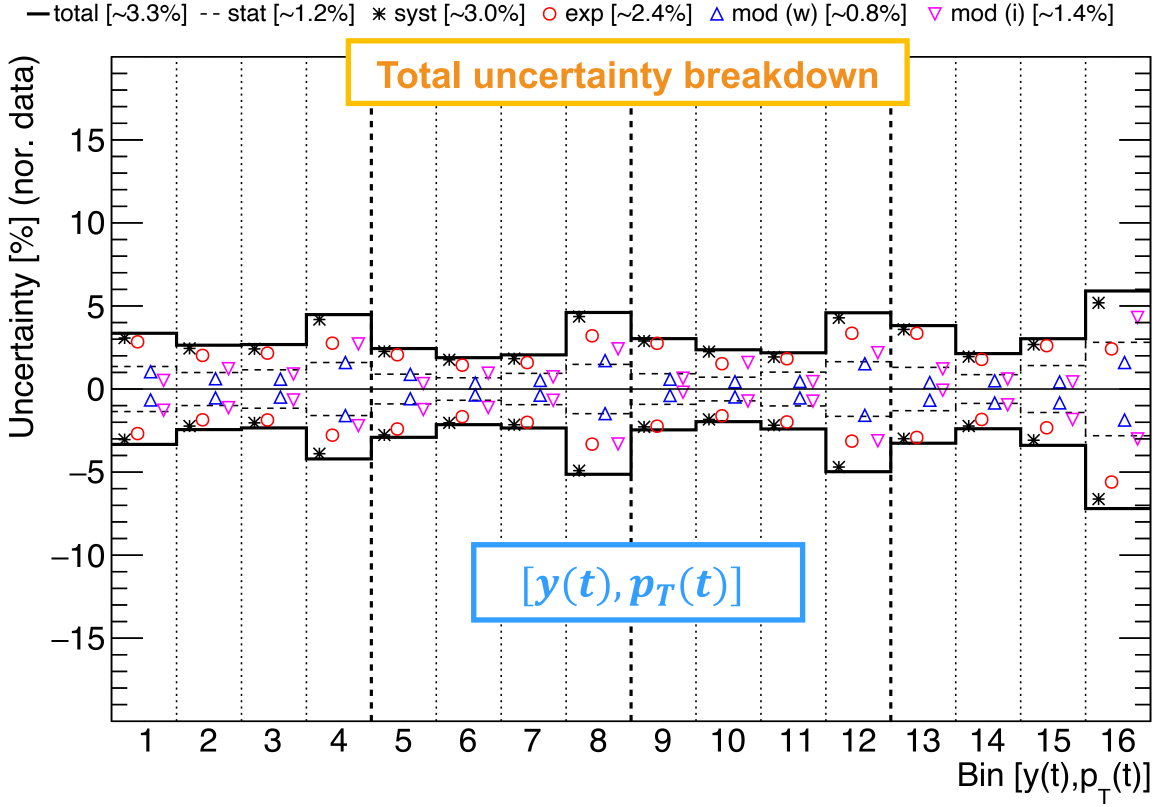




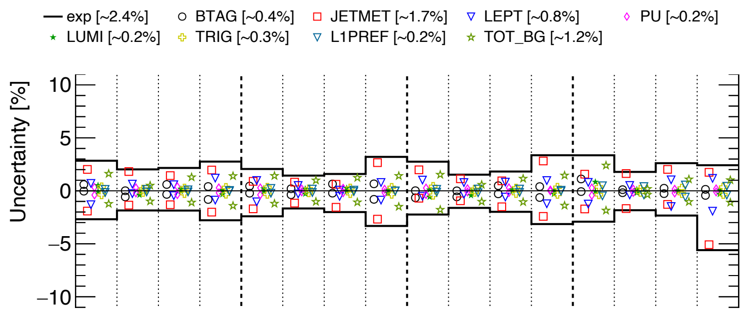


- Systematics: Correlations between the different years are considered
- Using TUnfold regularized unfolding: $\chi^2 = (y - Ax)^T V_{yy}^{-1}(y - Ax) + \tau^2 (x - x_0)^T (L^T L)(x - x_0)$
- Absolute and normalize cross sections are produced for parton and particle level measurements
- Comparisons with MG5_aMC@NLO[FxFx] + Pythia8 (FXFX+PYT) and Powheg + Herwig (POW+HER) are included
  - Shown data-prediction χ^2 considers data bin-by-bin correlations

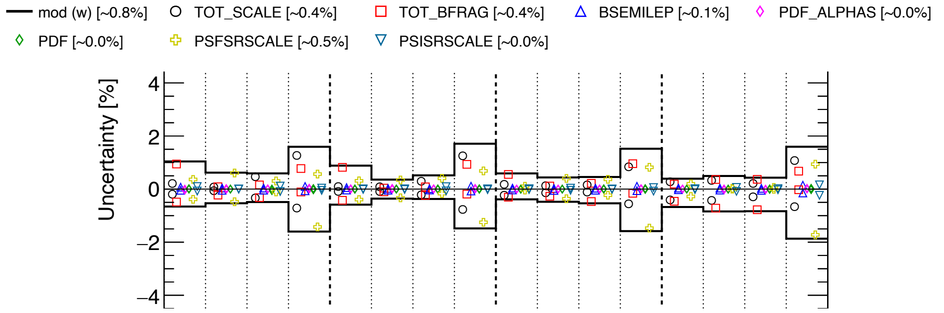
Systematics



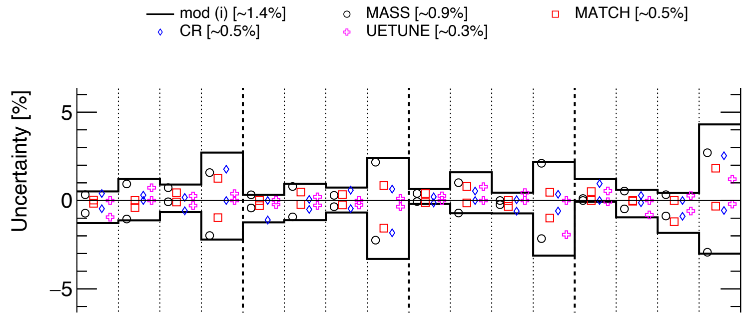
Experimental systematics (exp)



mod(w) theory: as weights in nominal MC sample

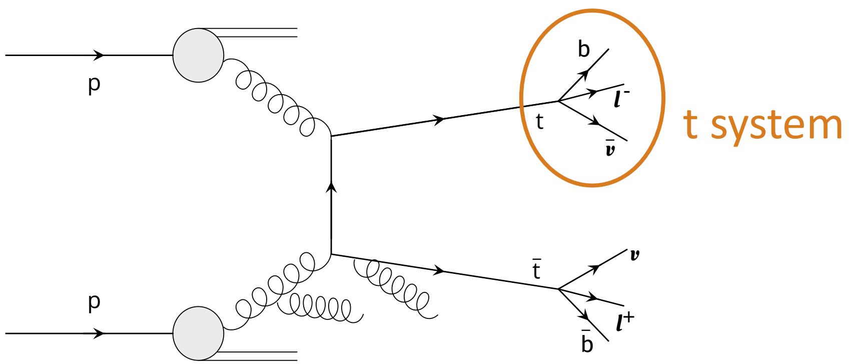


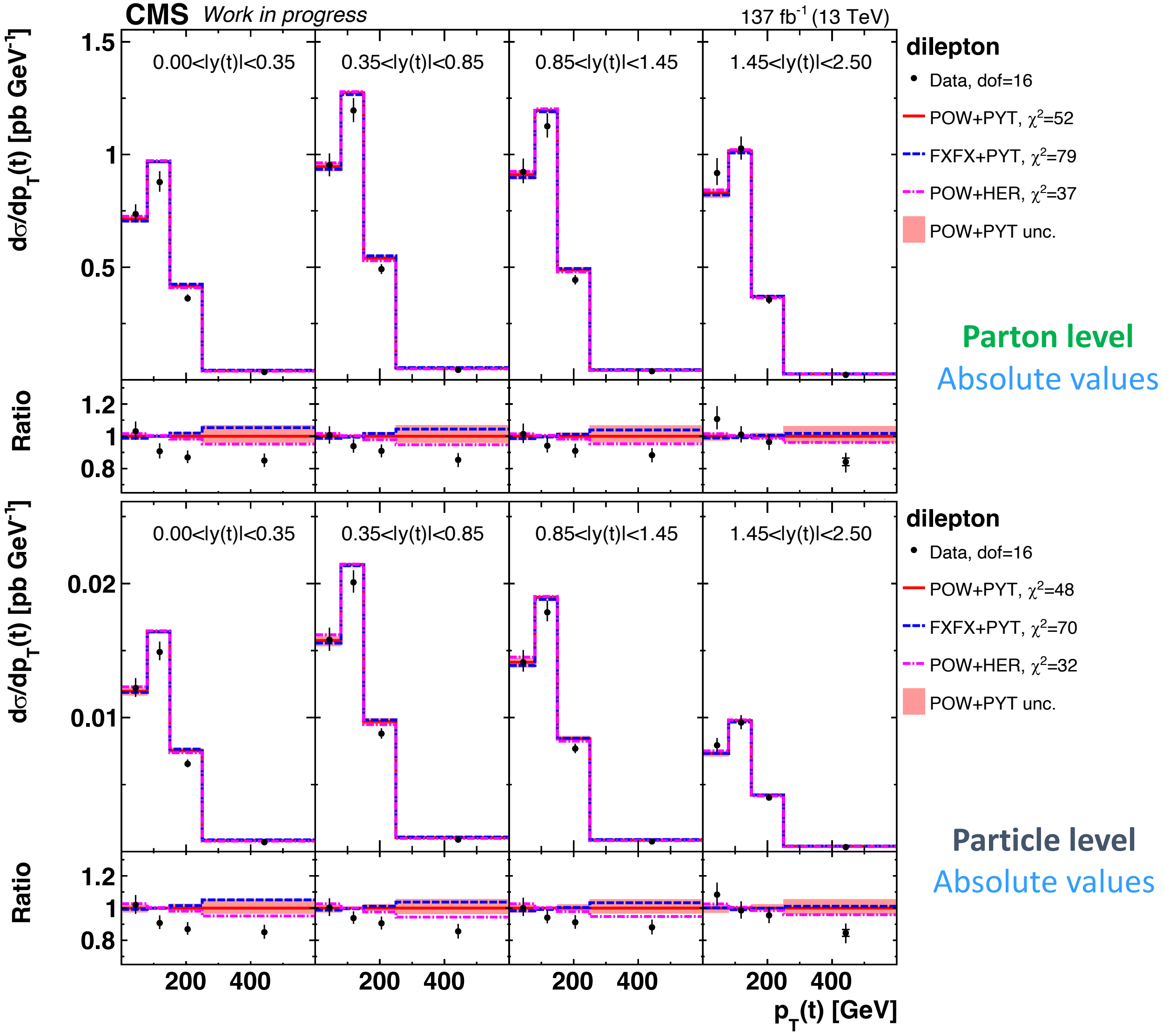
mod(i) theory: independent MC samples used



- Systematics uncertainties dominate over statistical
- Experimental systematics are the main source of uncertainty:
  - Higher contributions are coming from JETMET (mainly JES)
  - Also BG and LEPT are significant
- MASS is the main contribution from theory

top system cross sections: $[y(t), p_T(t)]$



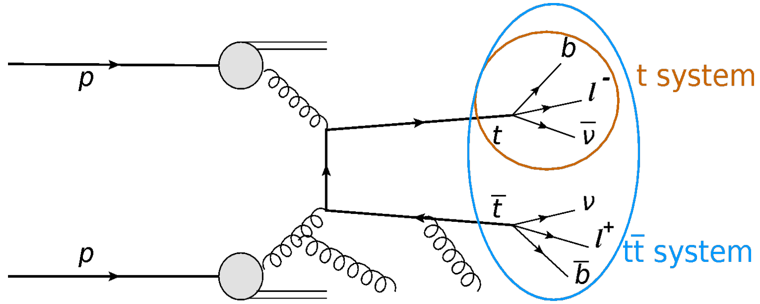


- Slope in Data/MC ratio (p_T-slope) observed in all $y(t)$ bins
- POW+HER shows the best description
- FXFX+PYT has the worst description of the p_T-slope
- No significative difference in shape between parton and particle level results

$t\bar{t}$ kinematics cross sections

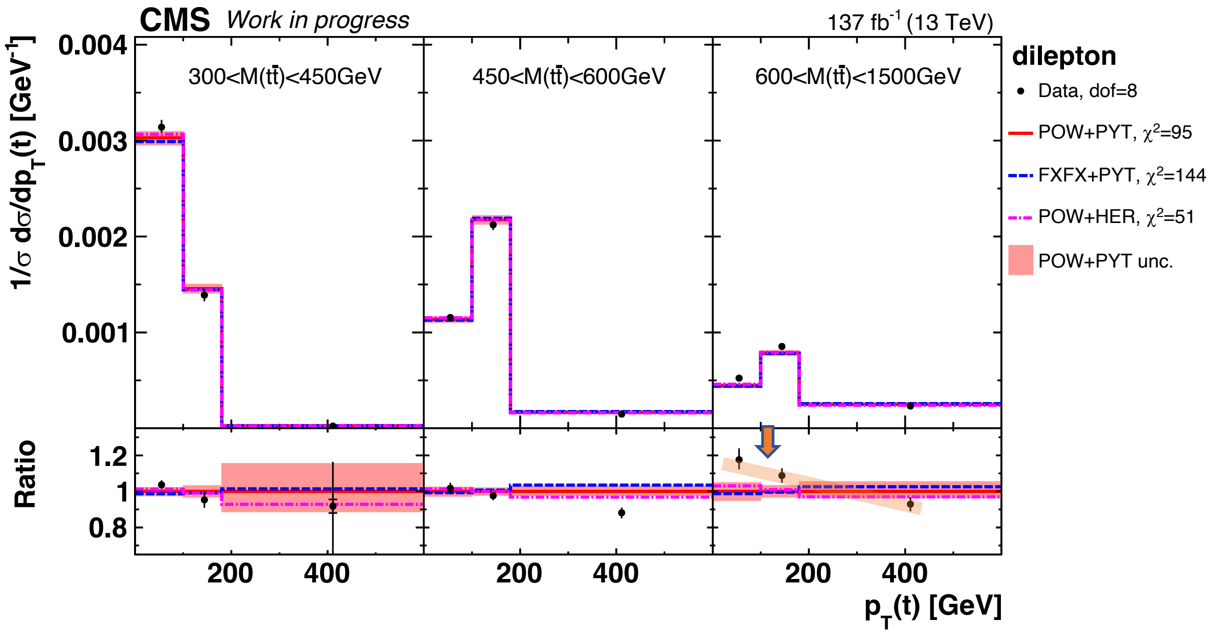
$[M(t\bar{t}), p_T(t)]$:

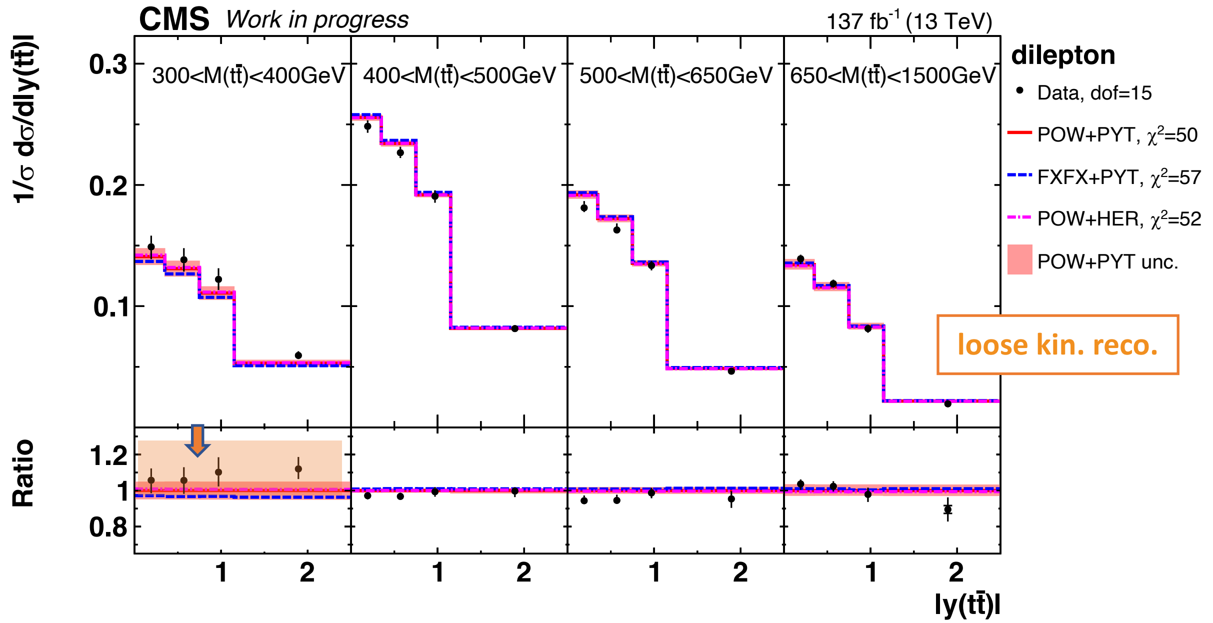
- ➢ p_T-slope for POW-PYTH is more significant at high $M(t\bar{t})$
- ➢ Bad data-MC χ^2 values, in particular for 'FXFX-PYT'



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

- ➢ data higher than predictions in the first $M(t\bar{t})$ bin
- ➢ All predictions agree very well for this measurement

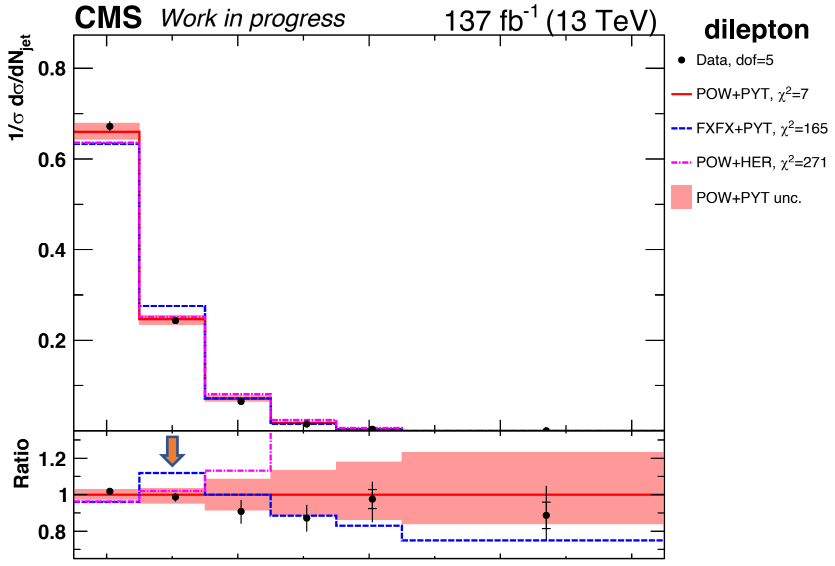




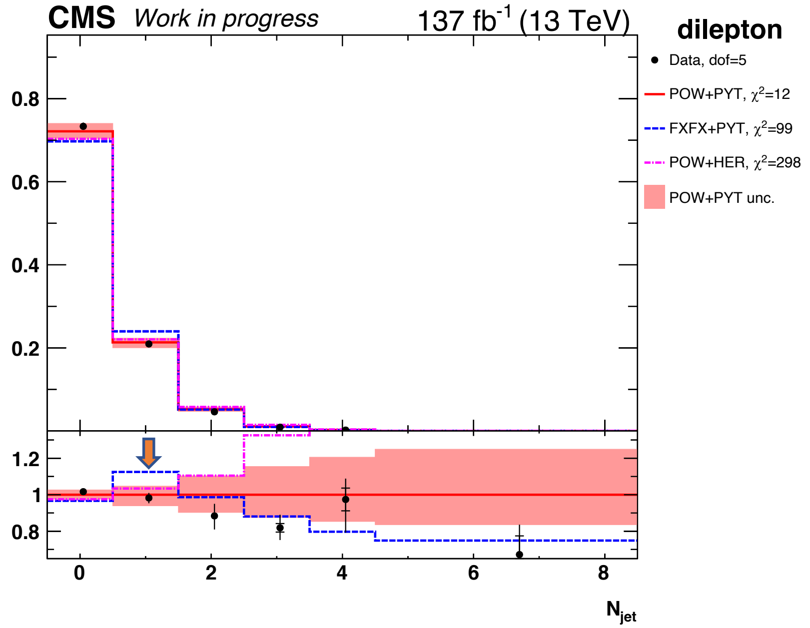
loose kin. reco.

Extra jets multiplicity (N_j) for different minimum jet p_T values

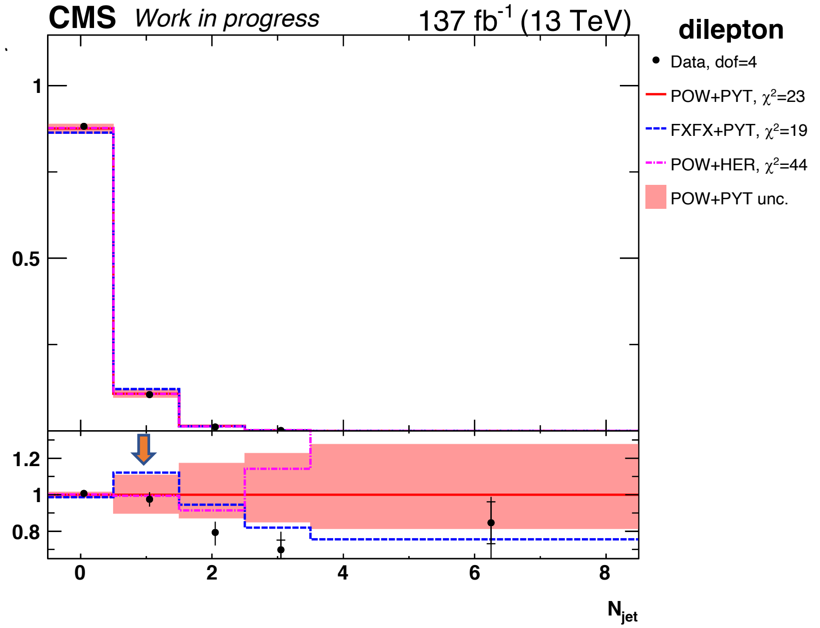
$[N_j]\ (p_T(jet) > 40GeV)$

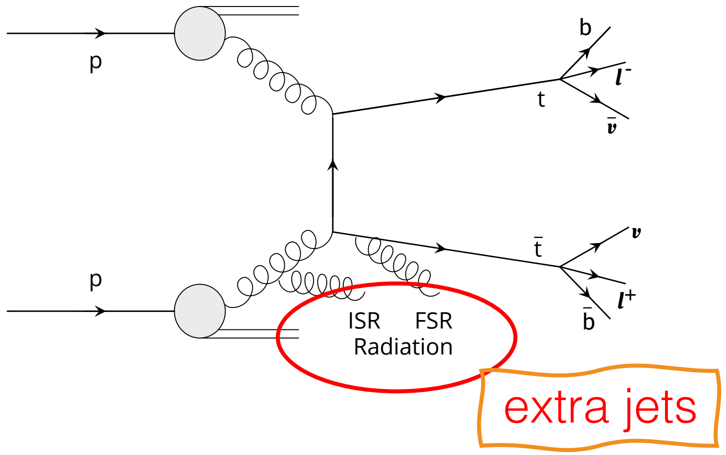


$[N_j]\ (p_T(jet) > 50GeV)$



$[N_j]\ (p_T(jet) > 100GeV)$



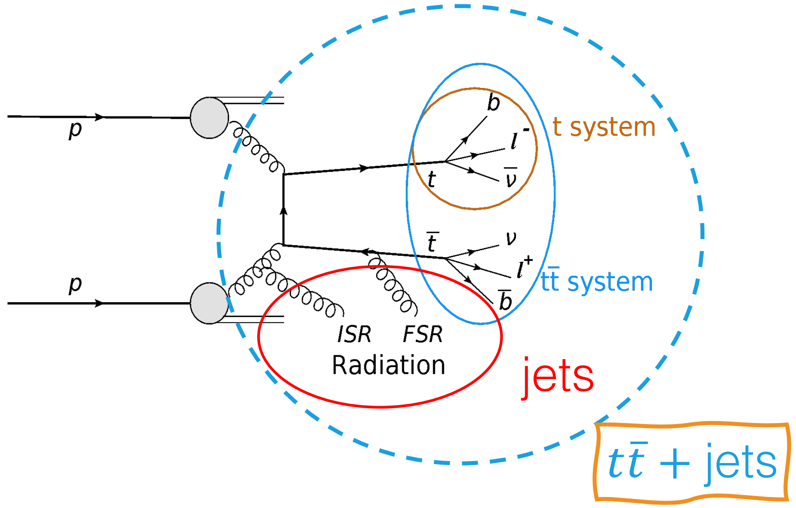


- Reasonably good description in overall by ‘POW-PYT’
- ‘POW+HER’ predicts much more jets compared to data in higher multiplicities
- ‘FXFX-PYT’:
  - Bad description in the bin with 1 extra jet, for all p_T cuts
  - Best description for higher multiplicities
  - Description improves for higher p_T cuts

2D $t\bar{t}$ + extra jets cross sections

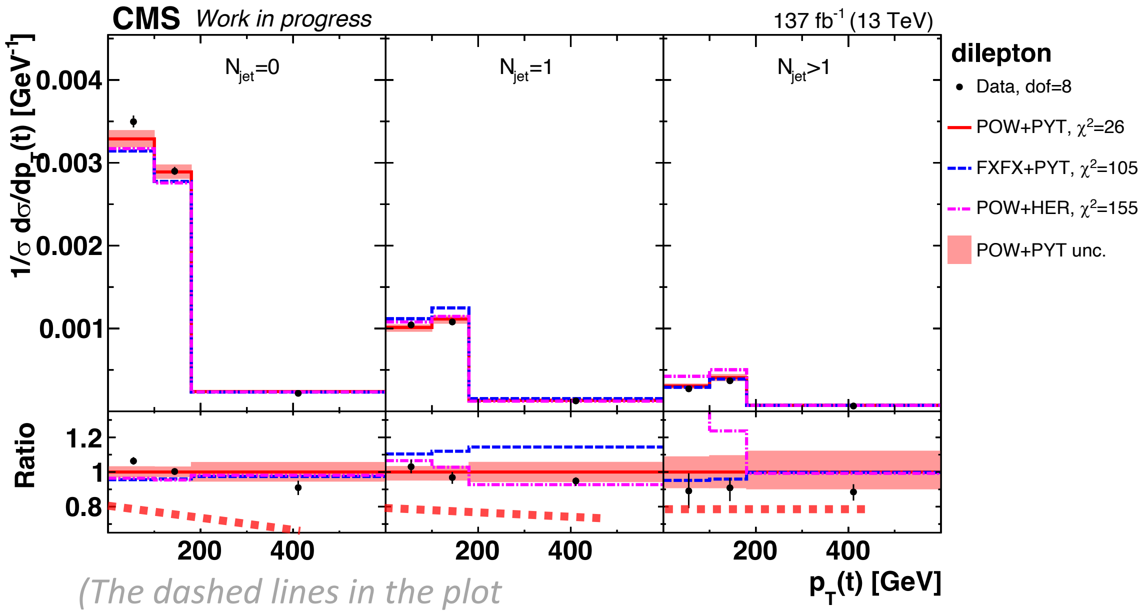
$[N_j(0,1,2+), p_T(t)]$

- ➢ $p_T(t)$-slope problem is smaller at high N_{jet}. This was also observed in TOP-17-002 (lepton+jets channel)

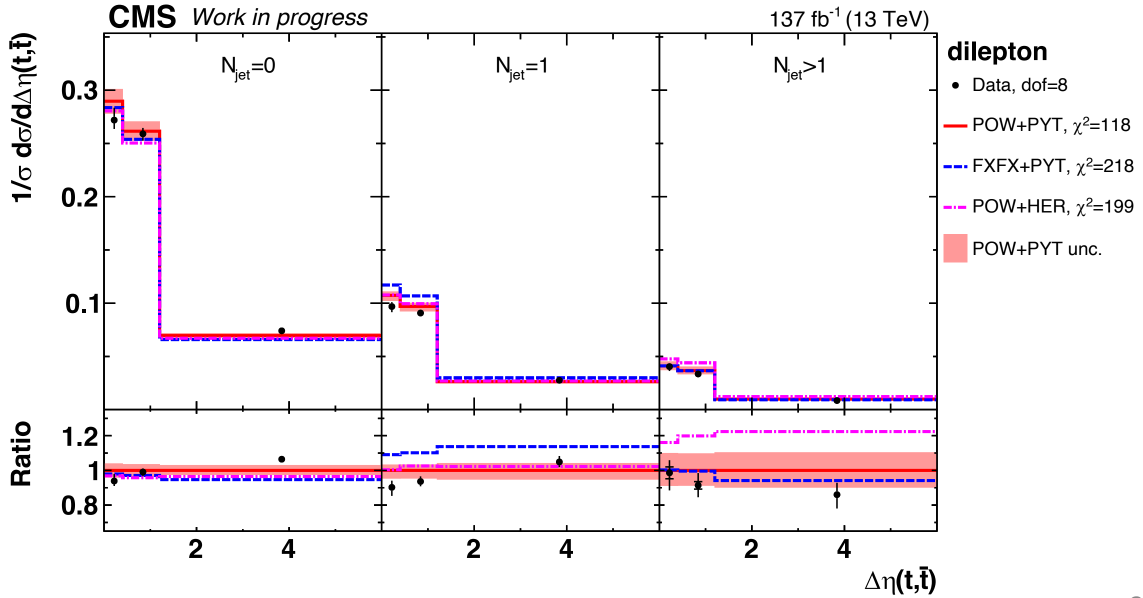


$[N_j(0,1,2+), \Delta\eta(t,\bar{t})]$

- ➢ Dependance with N_{jet} values in the data/'POW-PYT' ratio slope
- ➢ Large chi2 values for MC, especially for FXFX+PYT and POW+HER

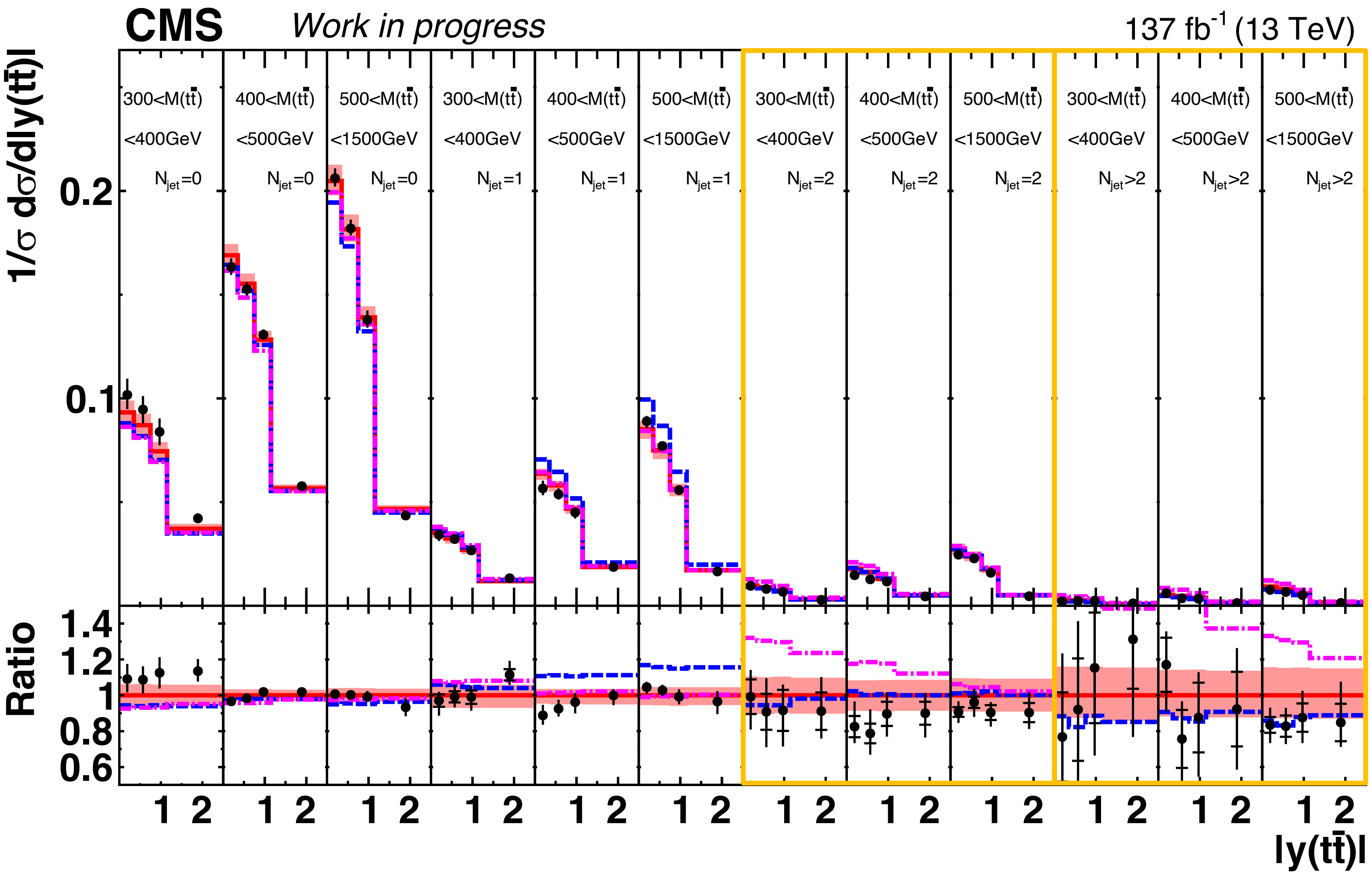


(The dashed lines in the plot are just a visual aid)



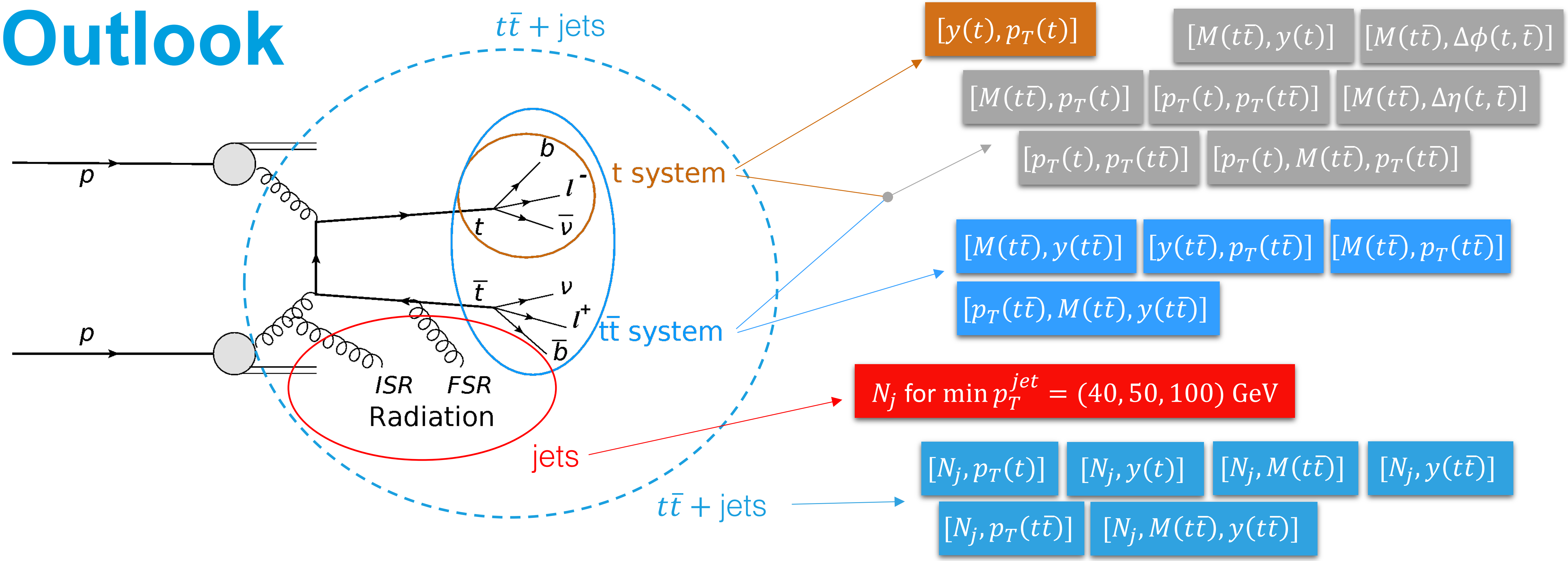
3D cross sections: $[N_j(0,1,2,3+), M(t\bar{t}), y(t\bar{t})]$

Using looseKR



- First time measured in 4 N_j bins
- It can be used for $m_t(pole)$ and α_s extraction

Outlook



- ➢ A wide set of normalized and absolute differential cross sections of the tt̄ + additional jets system have been measured in parton and particle using full Run2 data
- ➢ The obtained cross sections were compared to different NLO MC predictions:
  - Possible correlations between different observables and the $p_T(t)$-slope were investigated
  - Numerous distributions not well described by nominal predictions, like for example $[N_j(0,1,2+), \Delta\boldsymbol{\eta}(t,\bar{t})]$

Thank you

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Rafael E. Sosa Ricardo

CMS – DESY, Top Physics.

rafael.sosa.ricardo@desy.de

+49 40 8998 3264

Full list of measurements

t, $\bar{t}$ and $t\bar{t}$ system

Observables	Remarks
$p_T(t)$ problem:	
$[y(t), p_T(t)]$	study complete top kinematics
$[M(t\bar{t}), p_T(t)]$	test of QCD dynamics
$[p_T(t), p_T(t\bar{t})]$	how gluon radiation affects top kinematics
Complete set of 2D $t\bar{t}$ combinations:	
$[M(t\bar{t}), y(t\bar{t})]$	prime combination for extraction of gluon PDF
$[y(t\bar{t}), p_T(t\bar{t})]$	correlation of gluon radiation with t̄t rapidity
$[M(t\bar{t}), p_T(t\bar{t})]$	test dependence of gluon radiation from $\hat{s}$
$[M(t\bar{t}), y(t)]$	test of QCD dynamics
$[M(t\bar{t}), \Delta y(t, \bar{t})]$	$p_T(t)$ problem
$[M(t\bar{t}), \Delta\phi(t, \bar{t})]$	gluon radiation vs $\hat{s}$
3D:	
$[p_T(t\bar{t}), M(t\bar{t}), y(t\bar{t})]$	complete $t\bar{t}$ kinematics
$[p_T(t), M(t\bar{t}), p_T(t\bar{t})]$	study $p_T(t)$ problem vs implicit radiation

$t\bar{t}$ + additional jets

Observables	Remarks
1D: study jet multiplicity in $t\bar{t}$ events	
N_{jet} for different min jet p_T and ΔR_{iso}	study complete top kinematics
2D: how $t\bar{t}$ dynamics is correlated with additional jets	
$[N_{jet}, p_T(t)]$	how higher order radiation affects $p_T(t)$
$[N_{jet}, y\ (t)]$	how higher order radiation affects y(t)
$[N_{jet}, M(t\bar{t})]$	study jet production as function of $\hat{s}$
$[N_{jet}, \mathrm{y}(t\bar{t})]$	how higher order radiation affects $y(t\bar{t})$
$[N_{jet}, p_T(t\bar{t})]$	recoil of $t\bar{t}$-system against additional jets
3D: Can be used in the future for simultaneous extraction of m_t, α_s and PDFs	
$[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$	potential for improvement upon TOP-18-004
$[N_{jet}^{0,1,2+}, M(t\bar{t}), y(t\bar{t})]$	potential for improvement upon TOP-18-004
$[N_{jet}^{0,1,2,3+}, M(t\bar{t}), y(t\bar{t})]$	extension upon TOP-18-004

Control Plots and systematics

Experimental

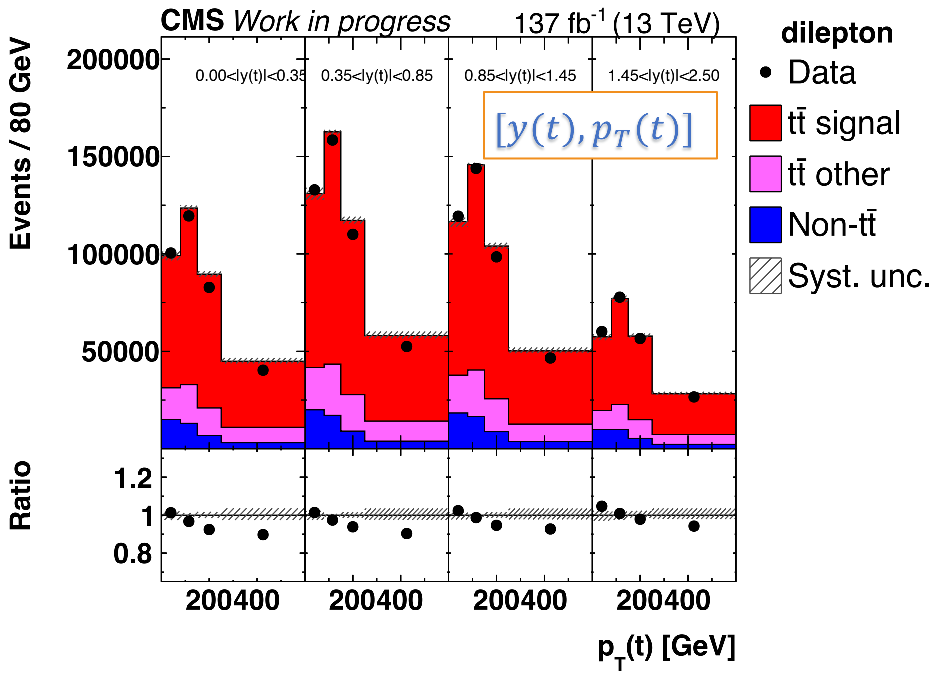
- Systematic uncertainties:
  - JES, JER
  - b-tagging, lepton, trigger, pileup
  - non-$t\bar{t}$ background:
    - DY (20%)
    - TW (30% down and 0% up)
    - Others: 30%
  - Luminosity

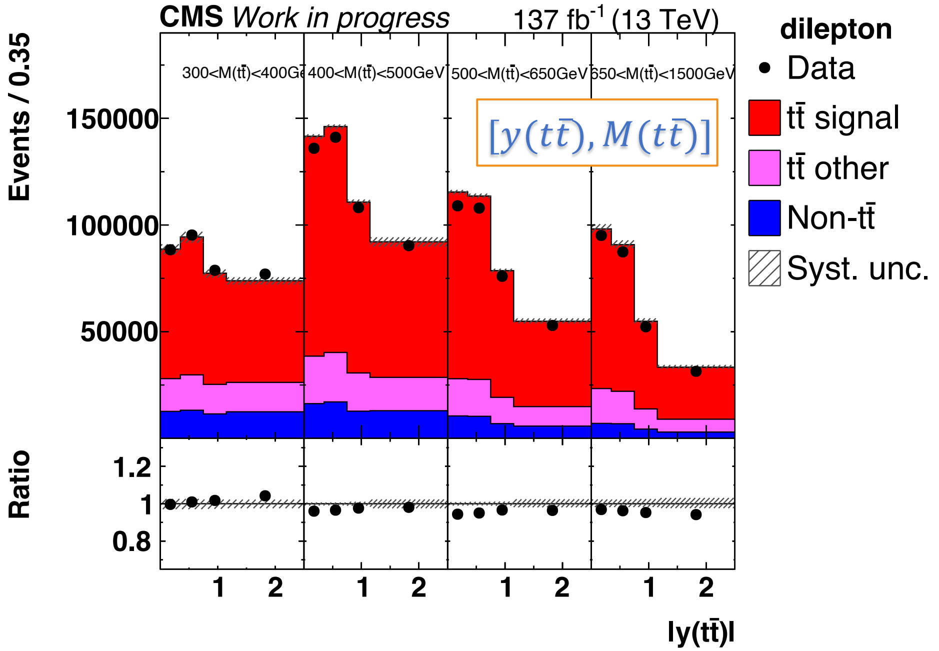
Theory: weight based

- ME scale (envelope)
- PDFs (NNPDF3.1)
- b-quark fragmentation (envelope)
- b-hadron branching ratios

Theory: independent samples

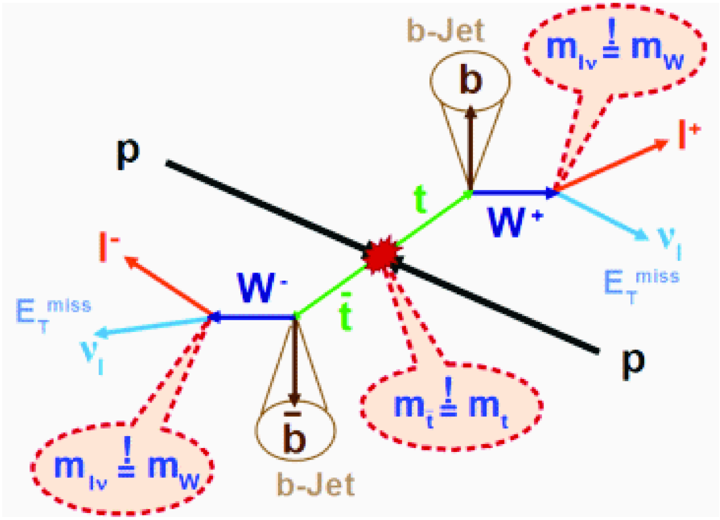
- $m_t \pm 1 GeV$ (using $\pm 3 GeV$ samples and rescaled by 1/3)
- Matching (h_{damp})
- ISR, FSR
- Color reconnection
- Underlying event tune





Kinematic reconstruction

Problem: reconstruct $t, \bar{t}$ from visible objects



- Input for reconstruction: leptons, jets, MET
  - Exactly two leptons in event, one MET
  - ≥ 2 jets (at least one b-tagged)
    - require $M(lb) < 180$ GeV
    - rank jets according to b-tags
    - among equal b-tags, rank jets in p_T

- Full reconstruction (same as in TOP-17-014):
  - Unknowns: $\nu(3)$ and $\bar{\nu}(3)$ momenta
  - constrains: $MET(2)$, $m_t(2)$, $m_W(2)$
  - output: full reconstruction of t and $\bar{t}$

Reconstruction of t and $\bar{t}$
m_t is a constrain

- Loose reconstruction (same as in TOP-18-004):
  - $p_{x,y}(\nu\bar{\nu}) = MET_{x,y}$
  - $p_z(\nu\bar{\nu}) = p_z(l\bar{l})$, $E(\nu\bar{\nu}) = E(l\bar{l})$
  - require: $M(\nu\bar{\nu}) \geq 0$, $M(l\bar{l}\nu\bar{\nu}) \geq 2M_W$ by adjusting $p_z(\nu\bar{\nu})$ and $E(\nu\bar{\nu})$: tiny effect
  - output: recover $t\bar{t}$ only

Reconstruction of $t\bar{t}$
No m_t constraint
Individual information of t and $\bar{t}$ is missed

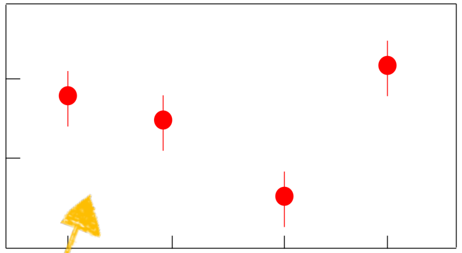
Unfolding

Laws of nature

Theory

Particle level

real particle collisions

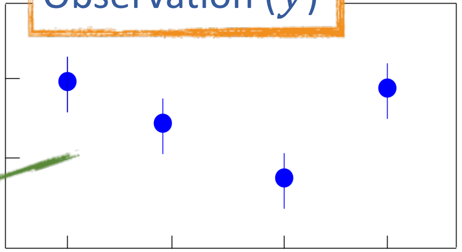


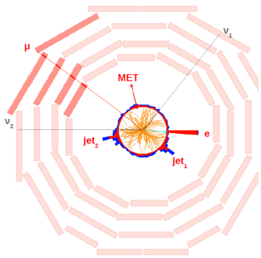
Detector level

real particle detector

Detector effects

Observation (y)





Unfolding

<u>Problem</u>: $\mu = Ax$

μ: detector expectation (observation and its covariance: y and V_{yy})(M_y bins)

A: response matrix (taken from MC)

x: unknown truth, M_x bins ($M_x < M_y$)

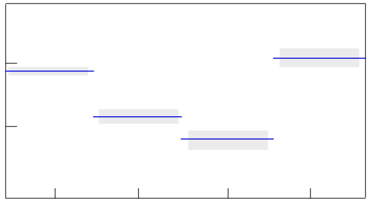
x_0: bias vector for regularization (taken from MC)

$$\mathcal{L} = (y - Ax)^T V_{yy}^{-1} (y - Ax) + \tau^2 (x - x_0)^T (L^T L)(x - x_0)$$

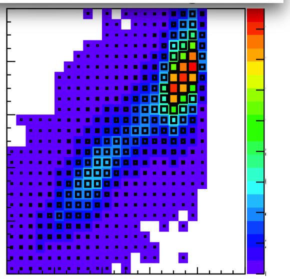
Solution:

$$\frac{\partial \mathcal{L}}{\partial x} = 0 \Rightarrow x = x(y, V_{yy}, x_0) \text{ and } V_{xx}(y, V_{yy}, x_0)$$

Simulation



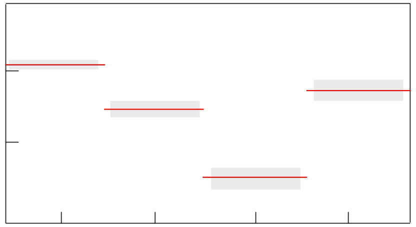
Response matrix (A)



gen level

rec level

Monte Carlo generator



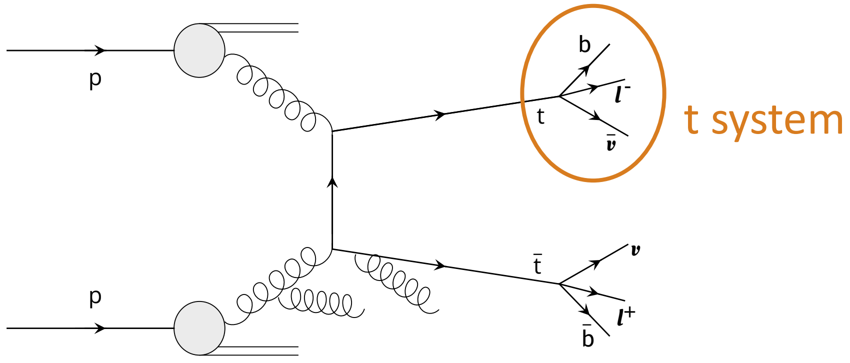
"gen" or "truth" level

detector simulation

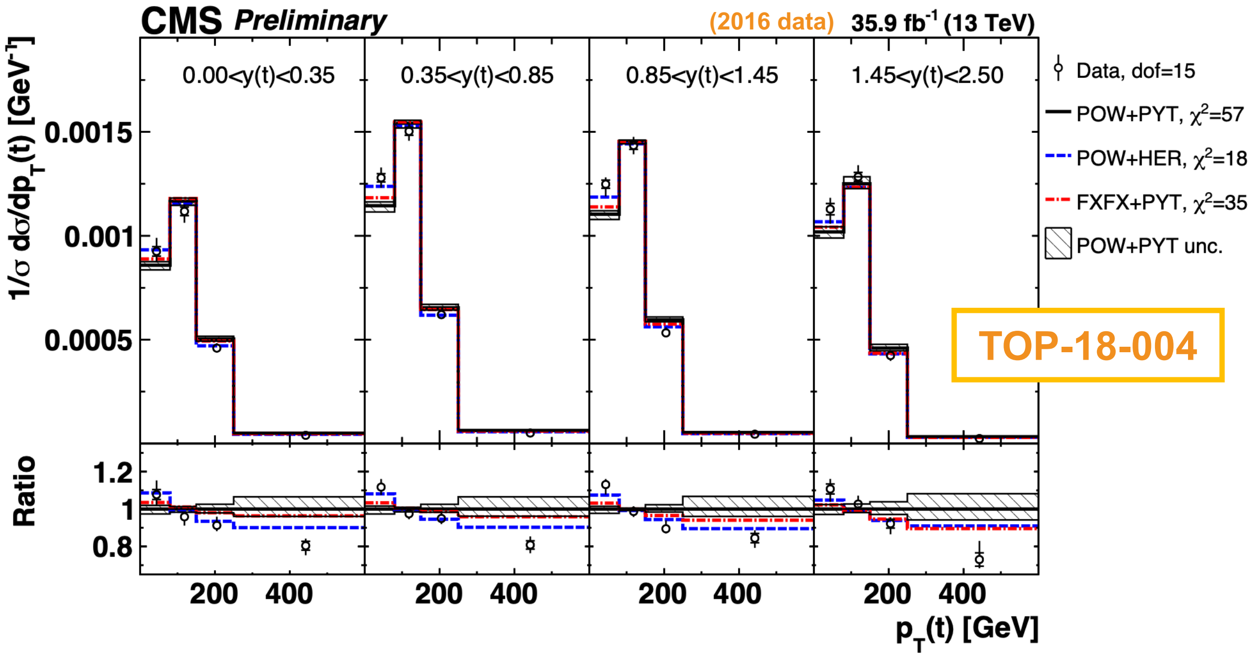
Reconstructed ("rec") level

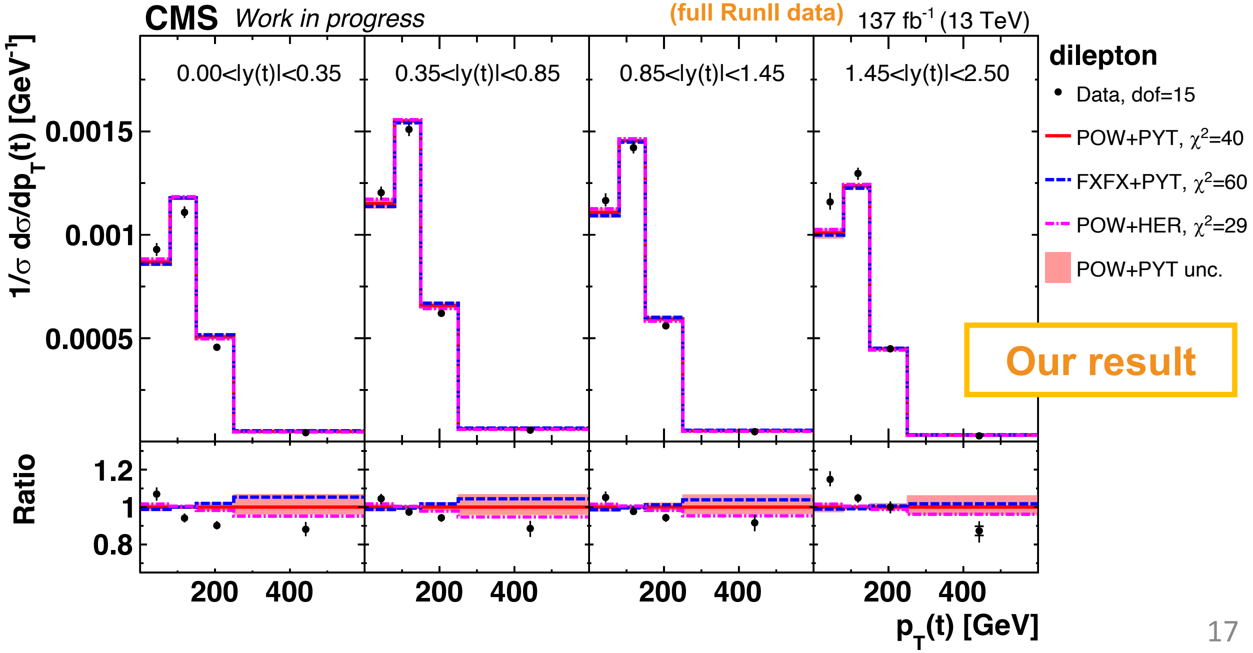
Consistent results with TOP-18-004 measurements

- TOP-18-004 (top figure):
  - 2016 data ($35.9\ \mathrm{fb}^{-1}$)
- Our Analysis (bottom figure):
  - fullRun2 data ($137\ \mathrm{fb}^{-1}$)
- Results in agreement with TOP-18-004
  - Consistently observed p_T-slope in all $y(t)$ bins
  - As expected, improvement in statistical uncertainty with respect to TOP-18-004

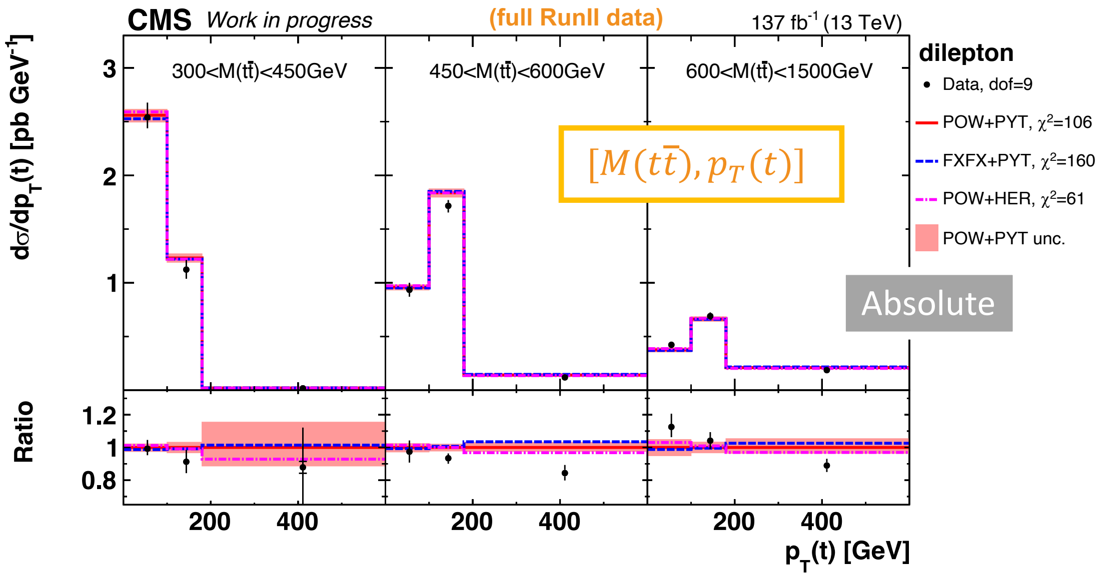


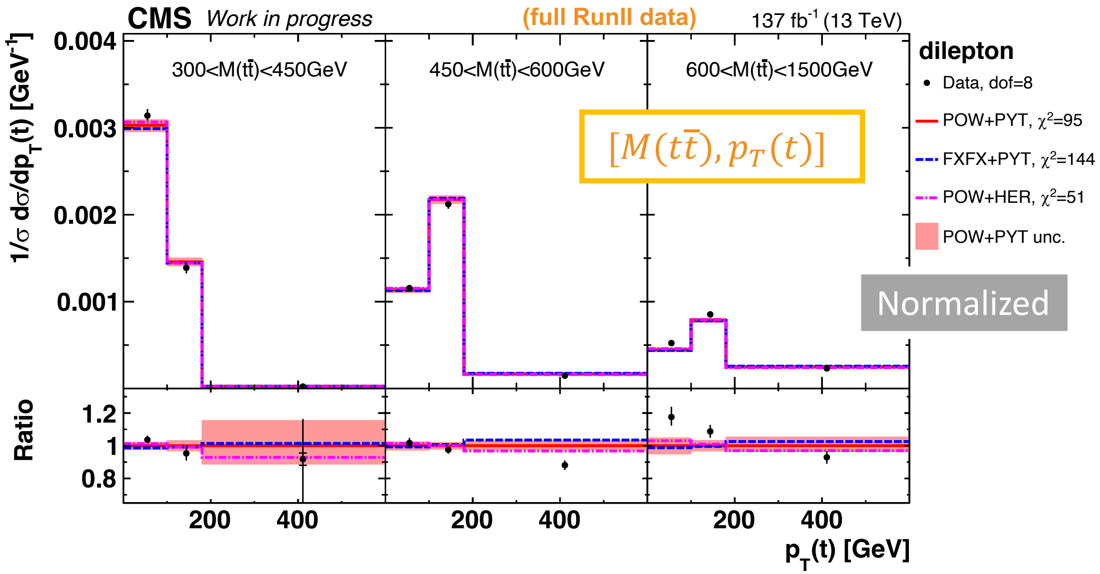
$[y(t), p_T(t)]$





Normalized and absolute cross section





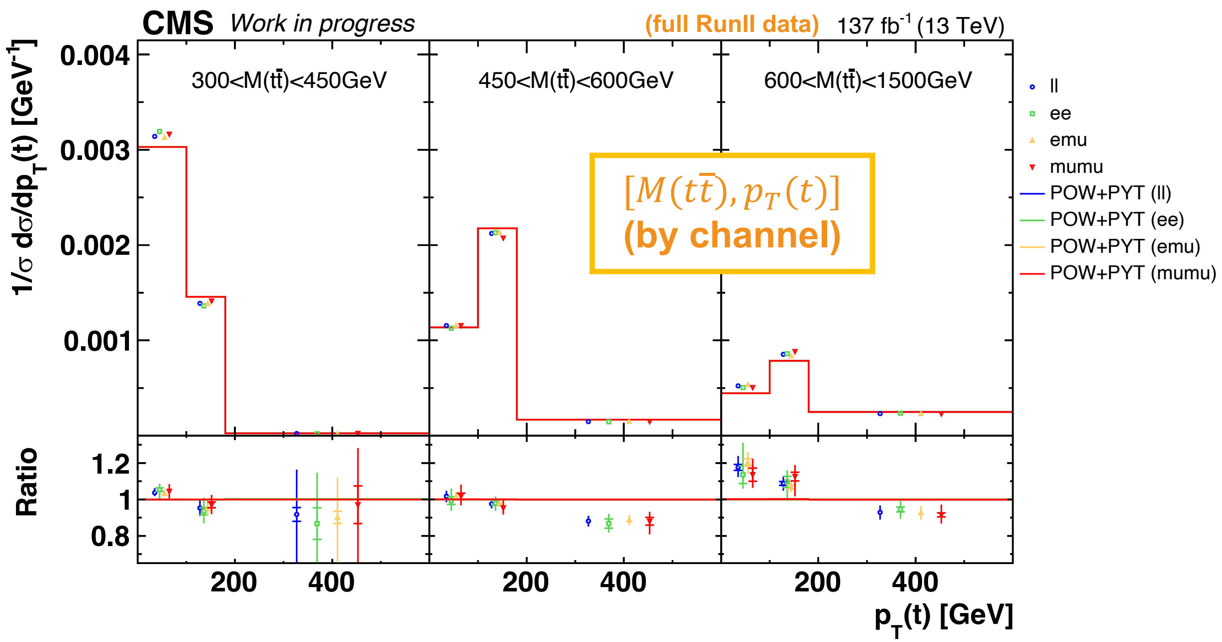
- For all cross sections both absolute and normalized results are obtained:
  - Absolute: $\frac{d\sigma^i}{dX} = \frac{x_i}{\Delta_i^X \cdot L \cdot BR}$
  - Normalized: $\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\Delta_i^X}\frac{x_i}{\sum_i x_i}$

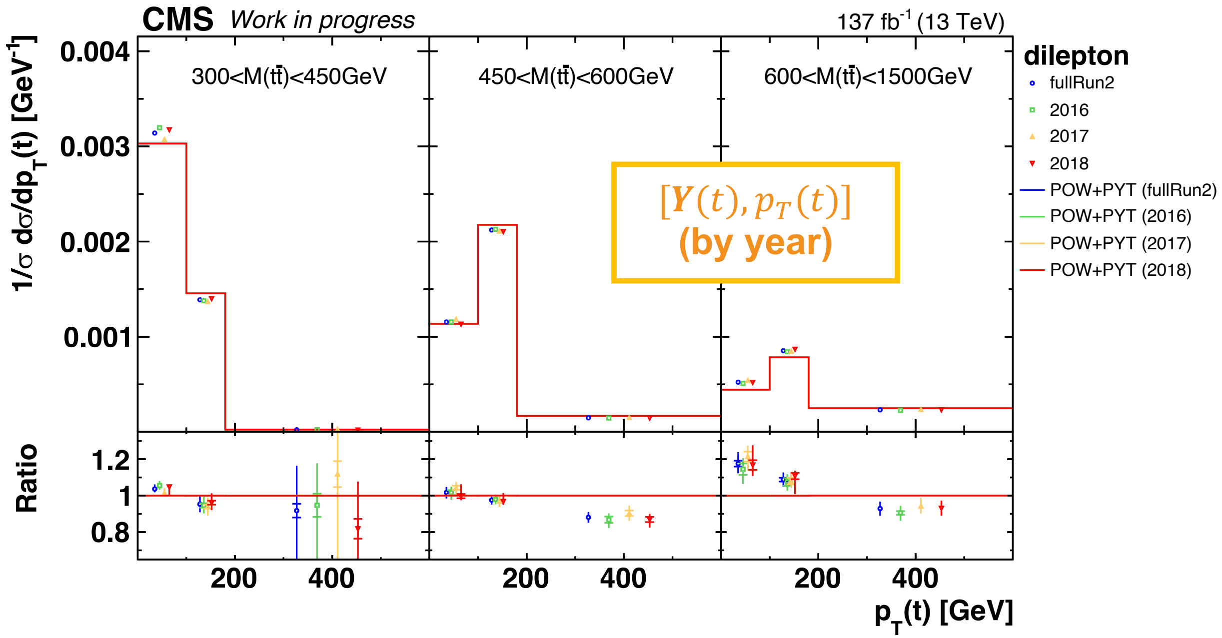
(x_i: signal events, Δ_i^X: bin width, L: luminosity, BR: channel branching ratio)

- Normalized differential cross sections feature better precision than the absolute ones. But they can only be used for the shape comparisons

Consistent results for different years and channels

Normalized values | Using fullKR

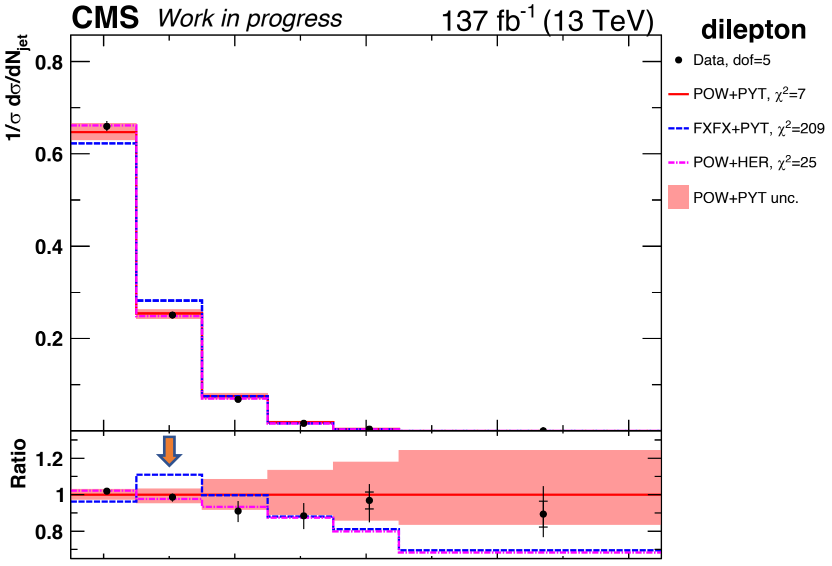




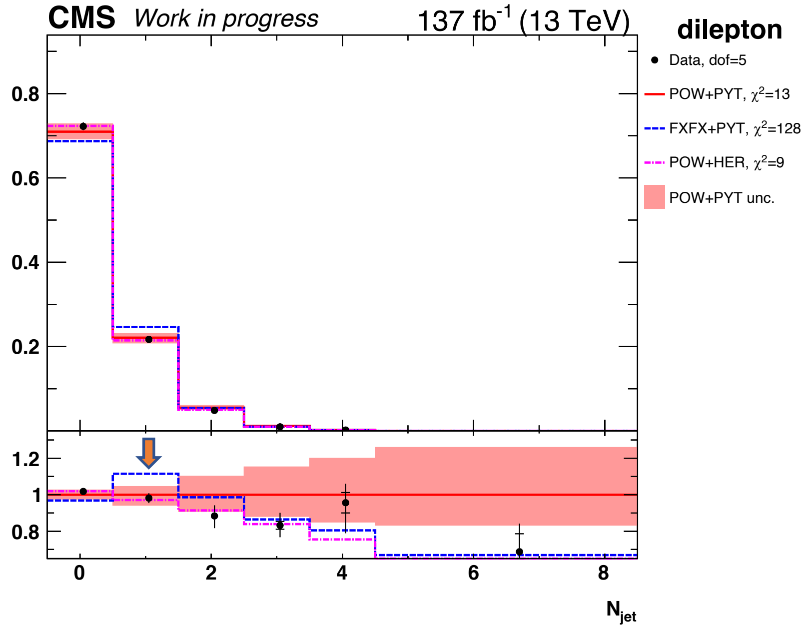
- Why we can combine event yields for channels and years previous unfolding?
  - ➢ Consistent results across all ee, $e\mu$, $\mu\mu$ and ll (combined) channels
  - ➢ Independently unfolded by year values have consistency with the combined full Run2 result
  - ❖ In addition, response matrices have been compared for individual years for nominal and systematics sources $\Longrightarrow$ they have similar values

Extra jets multiplicity (N_j) for different minimum jet p_T values

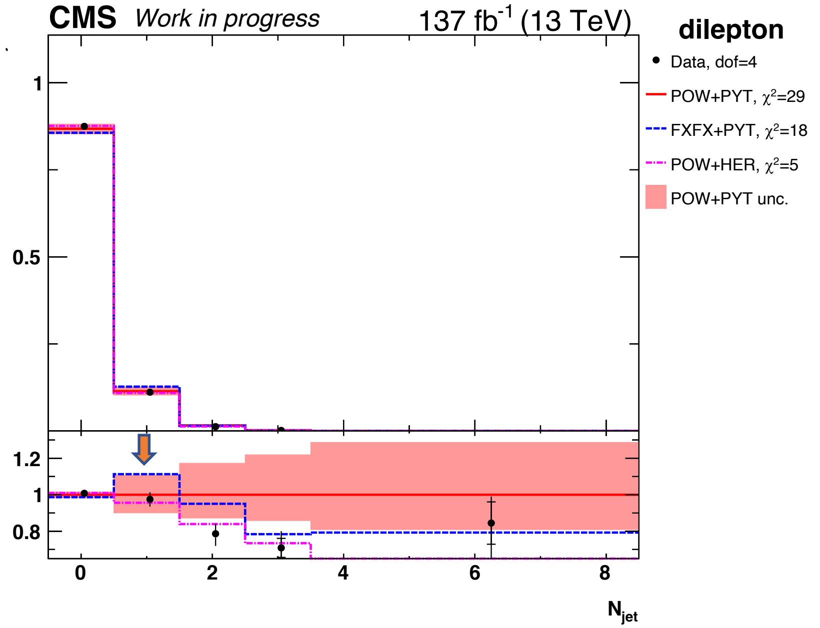
$[N_j]\ (p_T(jet) > 40GeV)$

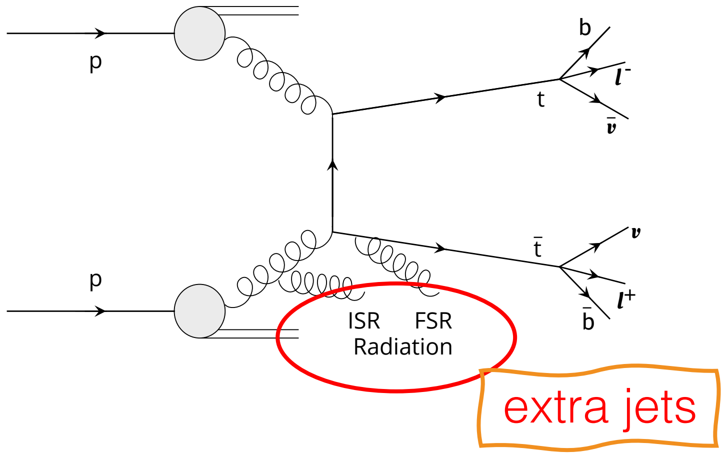


$[N_j]\ (p_T(jet) > 50GeV)$



$[N_j]\ (p_T(jet) > 100GeV)$

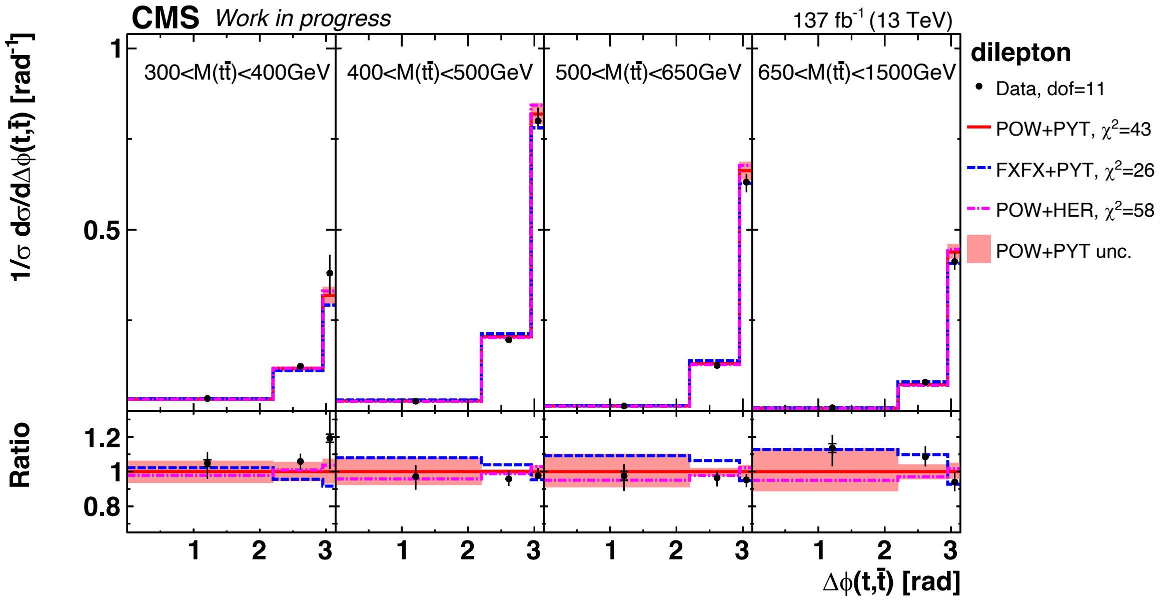




- ‘POW-PYT’: Good data description in overall
- ‘POW+HER’: shows a good agreement with data, specially for higher p_T cuts
- ‘FXFX-PYT’:
  - Bad data description in the bin with 1 extra jet, for all p_T cuts
  - Description of the data improves for higher p_T cuts

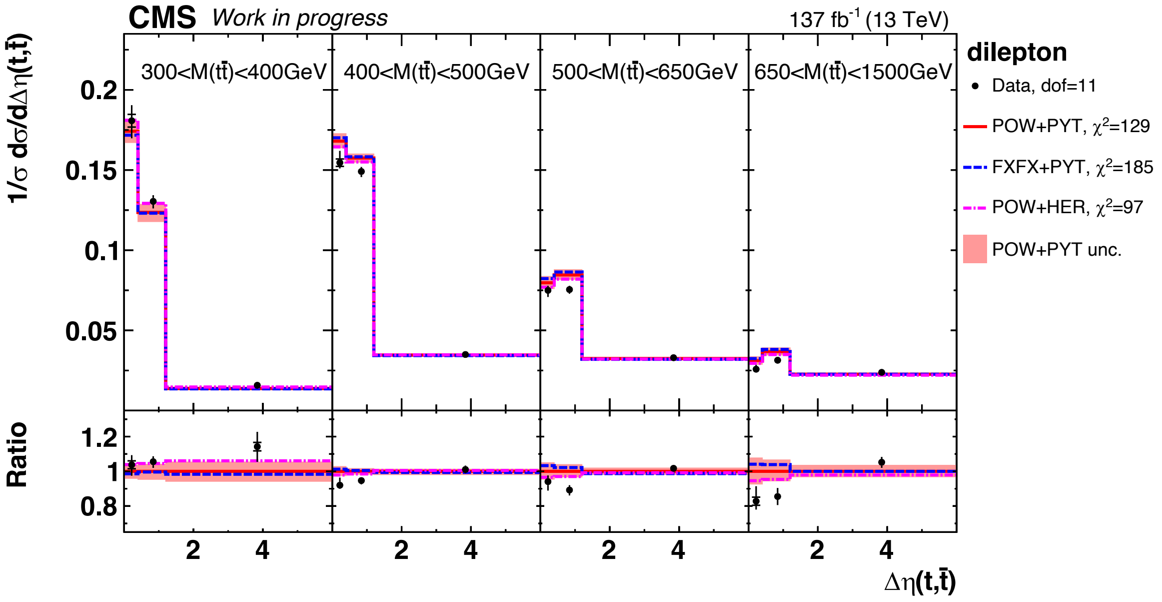
$t\bar{t}$ kinematics cross sections

Normalized values | Using fullKR



$[M(t\bar{t}), \Delta\phi\ (t, \bar{t})]$:

- At small $M(t\bar{t})$ data is more back to back than MC predictions, while at high $M(t\bar{t})$ is less back to back
- Better overall agreement by 'FXFX-PYTH'
- 'FXFX-PYTH' describes the distribution shape very well specially for the higher $M(t\bar{t})$ bin



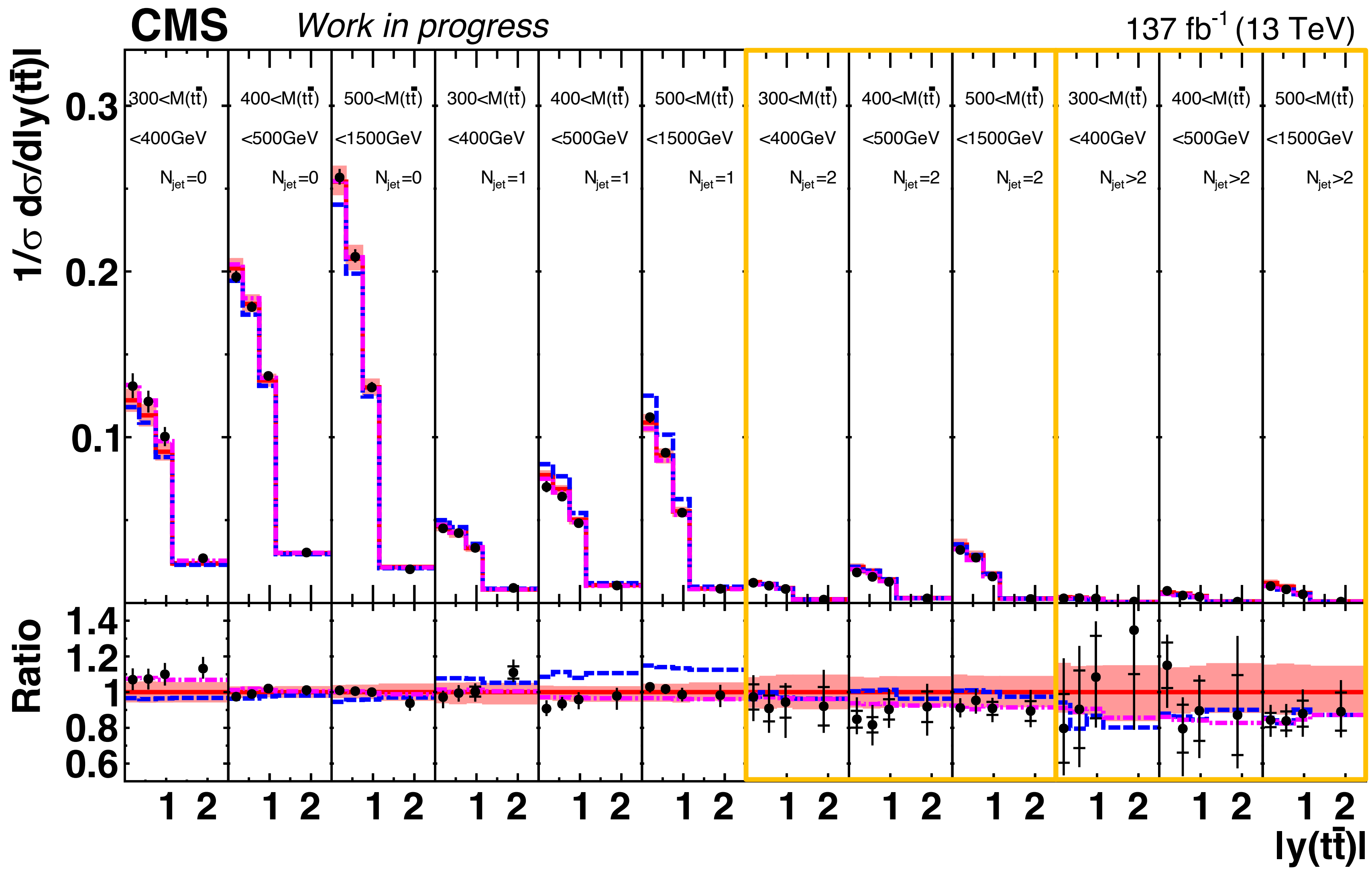
$[M(t\bar{t}), \Delta\eta\ (t, \bar{t})]$:

- Very bad description by all MC
- Larger $\Delta\eta\ (t, \bar{t})$ separation in data than in MC, in particular at higher $M(t\bar{t})$

3D cross sections: $[N_j(0,1,2,3+), M(t\bar{t}), y(t\bar{t})]$

Using looseKR

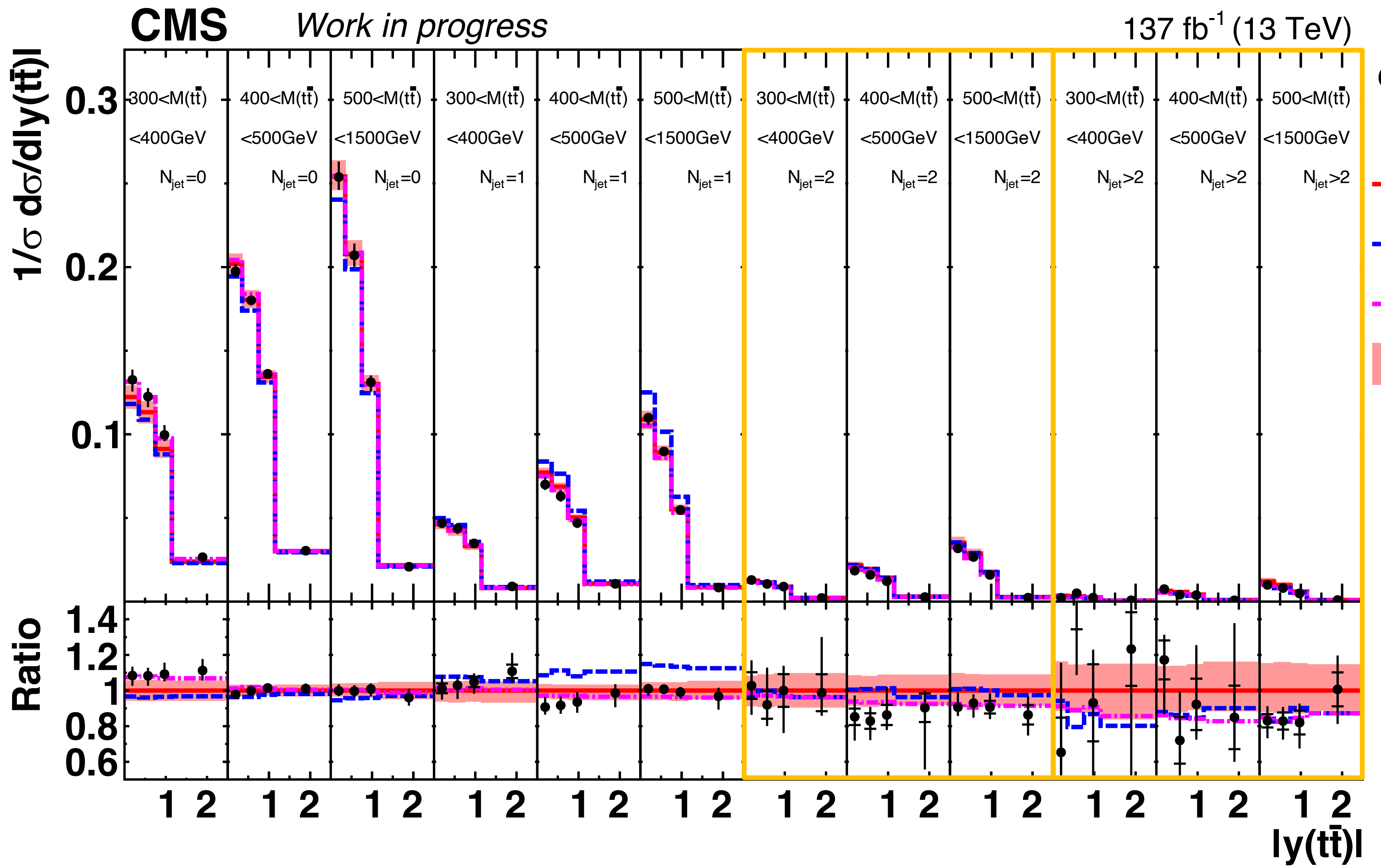
Particle level



- First time measured in 4 N_j bins
- It can be used for $m_t(pole)$ and α_s extraction

3D cross sections: $[N_j(0,1,2,3+), M(t\bar{t}), y(t\bar{t})]$

Using fullKR



- ➢ First time measured in 4 N_j bins
- ➢ The discrepancies between the alternative MC generators is bigger for $N_{jet} > 2$
- ➢ It can be used for $m_t(pole)$ and α_s extraction