Top pair production differential cross sections in the dilepton channel with full Run 2 data (1D measurements)

DPG Dortmund – 16.03.21

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

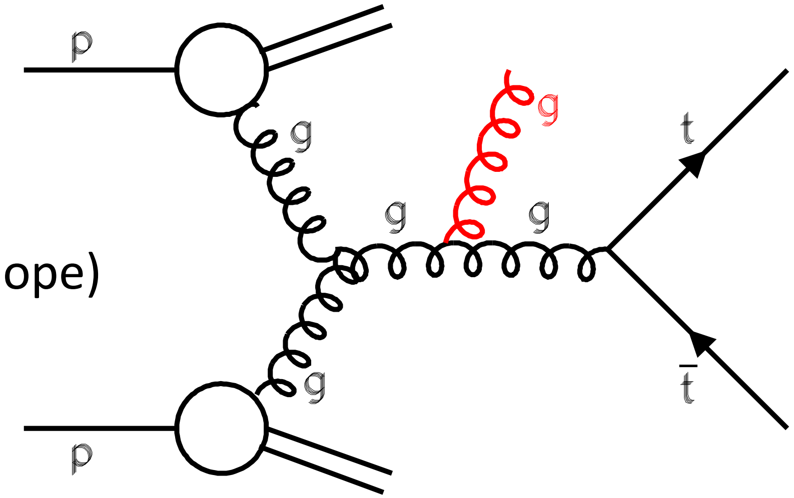
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

$t\bar{t}$ production cross sections

Importance of cross section measurements

- Precision tests of the Standard Model
- Heavy mass suggests possible involvement in production- and decay-processes at higher energy scales
- Significant background for Higgs boson processes, BSM searches etc.

Why measure cross sections (multi)differentially?



- Scrutinize different phase space regions
- 2D and 3D measurements may shed light on 1D trends (e.g. $p_T(\mathrm{t})$ slope)
- Shapes of differential distributions are sensitive to e.g.:

  QCD and electroweak corrections
  top quark properties such as mass and polarization
  α_s and parton distribution functions

Measurements overview

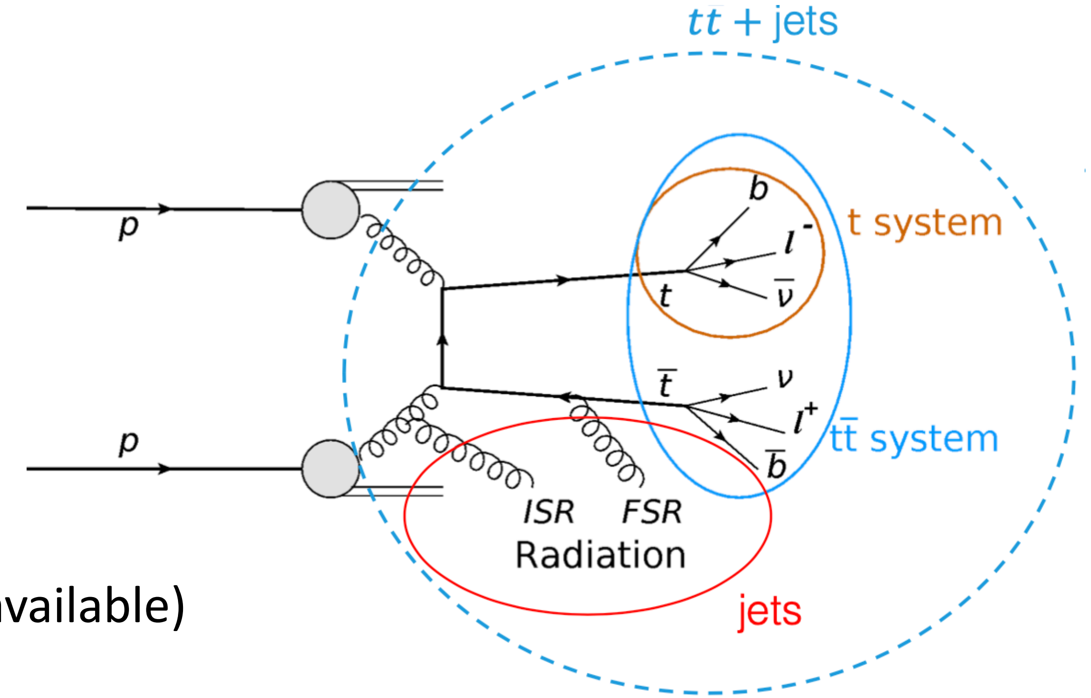
Goal: measurement of $t\bar{t}$ multi-differential production cross sections in dilepton final states (ee, eμ, μμ) using full Run 2 data

1D measurements

- Top quarks and $t\bar{t}$ system (parton- and particle-level)
- Top quark decay products (particle-level only)

2D and 3D measurements – see next talk by Rafael

- Top quarks and $t\bar{t}$ system (parton- and particle-level)
- Investigate cross sections in bins of jet multiplicity
- Scrutinize slope seen in $p_T(\mathrm{t})$ 1D cross section (*new*)



Provide normalized and absolute measurements
(focus is on normalized cross sections in this talk but both are available)

Outlook

- Compare to NNLO theory predictions (not in this talk)

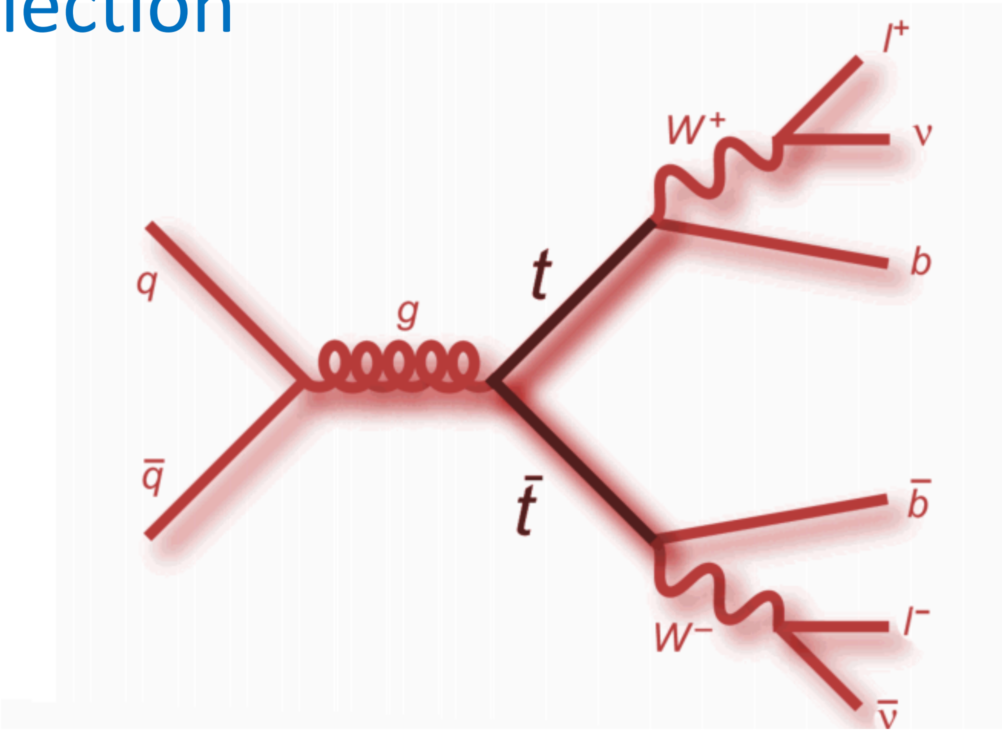
Measurement strategy and event selection

Experimental signature

Two leptons, two b-jets, $E_{\mathrm{T}}^{\mathrm{miss}}$
Only prompt decays to electrons or muons

Dominant backgrounds

$t\bar{t}$ other, single top quark (tW), Z+jets



Note: strategy follows TOP-17-014 and TOP-18-004 for all years

- Combination of single- and dilepton triggers

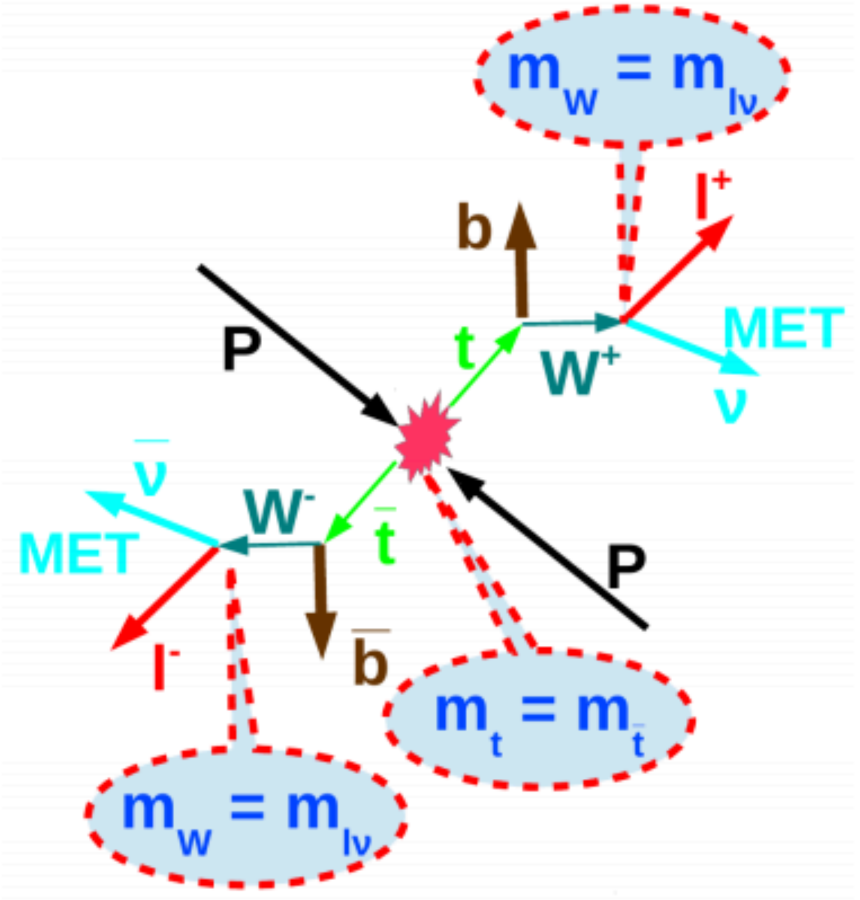
Leptons

- Leading (sub-leading) lepton $P_{\mathrm{T}} \geq 25$ (20) GeV

Jets

Anti-KT $R = 0.4$
$\Delta R(\mathrm{jet}, \mathrm{l}) > 0.4$
≥ 2 jets with $p_T \geq 30$ GeV
≥ 1 b-tag

Kinematic reconstruction



Full kinematic reconstruction

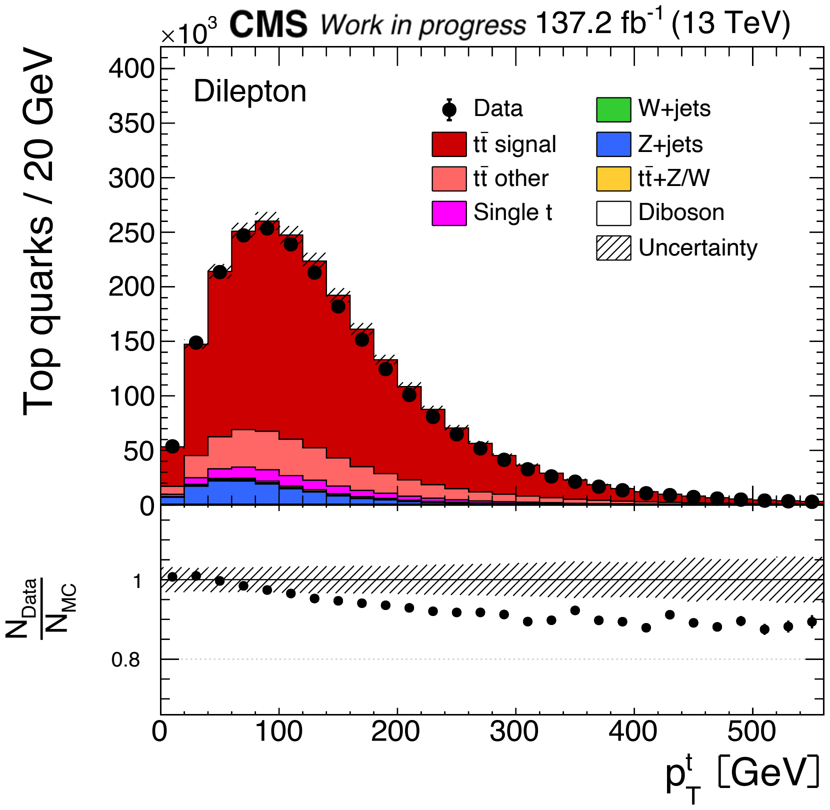
- 6 unknowns (neutrino momenta)
- 6 constraints: top mass, W boson mass and MET
- Used for all distributions and measurements in this talk

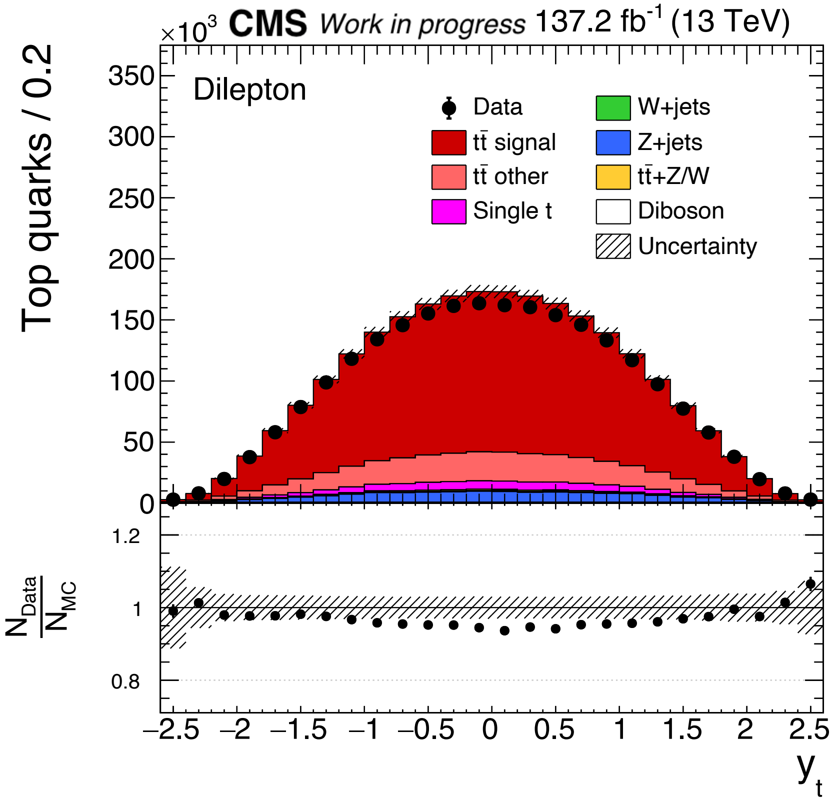
Loose kinematic reconstruction

- No constraint on top mass
- Mass onset is accessible
- Can only reconstruct $t\bar{t}$ system
- Used for m_t extraction from m($t\bar{t}$) spectrum in TOP-18-004

Top-pair production in the dileptonic channel

Control plots





$p_{\mathrm{T}}^{\mathrm{top}}$ (left) ⟶

Data softer than MC as known

y_t (right) ⟶

Good agreement between data and MC.

Unfolding

Regularized unfolding with TUnfold (inputs)

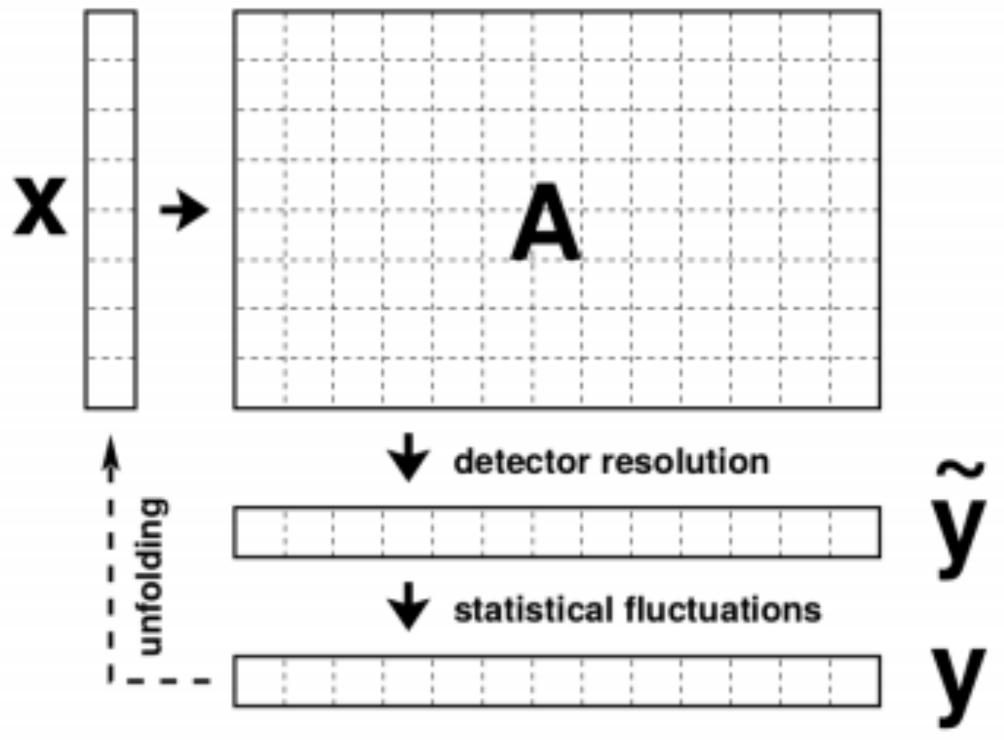
X: true spectrum of e.g. $M^{t\bar{t}}$

y: observed detector level spectrum e.g $M^{t\bar{t}}$ with the background subtracted

A: response matrix to correct for detector effects i.e smearings, acceptances and efficiencies

τ: regularization strength

X_0: bias vector taken from MC



Procedure

Minimize:

$$\mathcal{L} = (y - AX)^T V_{yy}^{-1} (y - AX) + \tau^2 \, (X - X_0)^T L^T L \, (X - X_0)$$

Phase space definitions

Parton level:

After QCD radiation and before decay
Measurements are performed in the full phase space

Particle level:

Consists of stable particles after hadronization
Less dependent on MC generator and tuning
Performed in the fiducial phase space to limit extrapolation effects

Particle objects and selection:

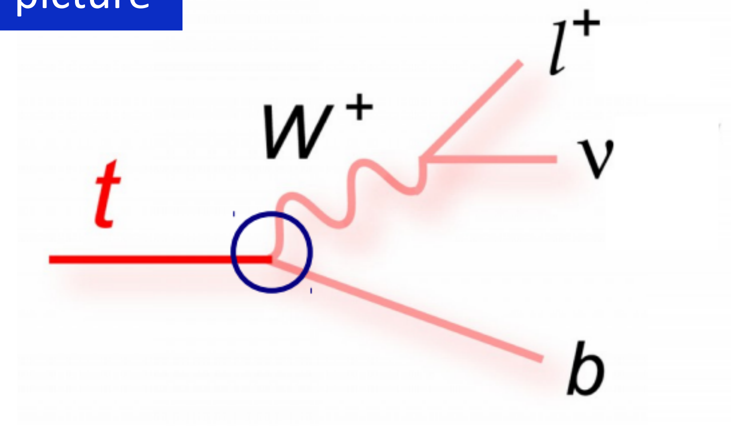
2 oppositely-charged dressed leptons:
prompt leptons not originating from hadrons, clustered with anti-kt jet algorithm and $\mathrm{R} = 0.1$
$p_{\mathrm{T}}(\mathrm{l}) > 20$ GeV, $\eta(\mathrm{l}) < 2.4$, $m_{\mathrm{ll}} > 20$ GeV

$\geq$ **2 neutrinos**
prompt and not from hadrons

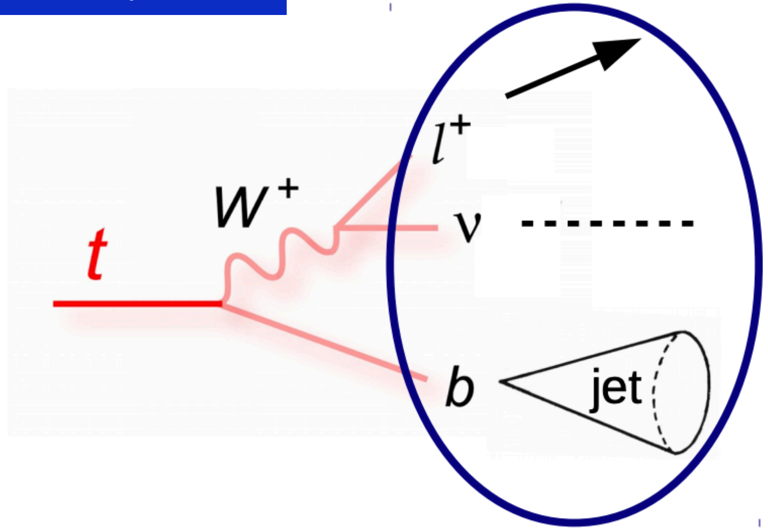
$\geq$ **2 jets:**
all particle candidates except neutrinos and dressed leptons, clustered with anti-kt jet algorithm and $\mathrm{R} = 0.4$

$\geq$ **2 b-jets:**
identified using the ghost B-hadron technique
$p_{\mathrm{T}}(\mathrm{b}) > 30$ GeV, $|\eta(\mathrm{b})| < 2.4$, $\Delta R(\mathrm{b,l}) > 0.4$

Parton picture

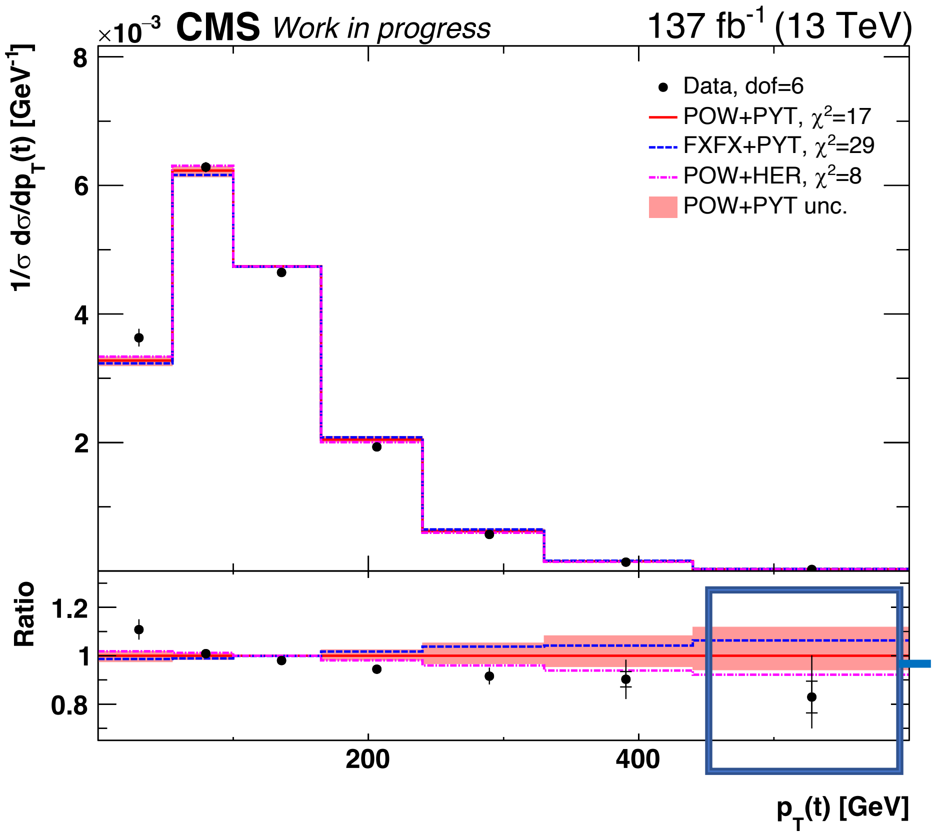


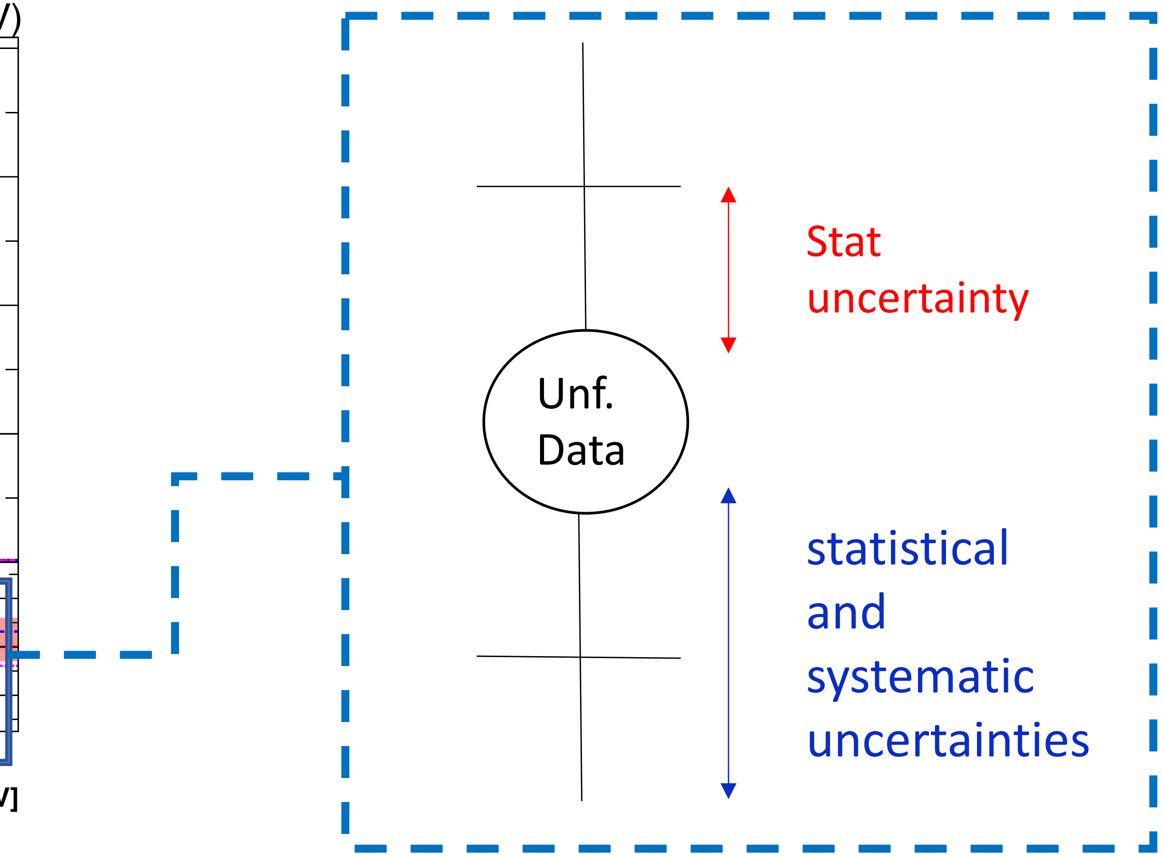
Particle picture



Results

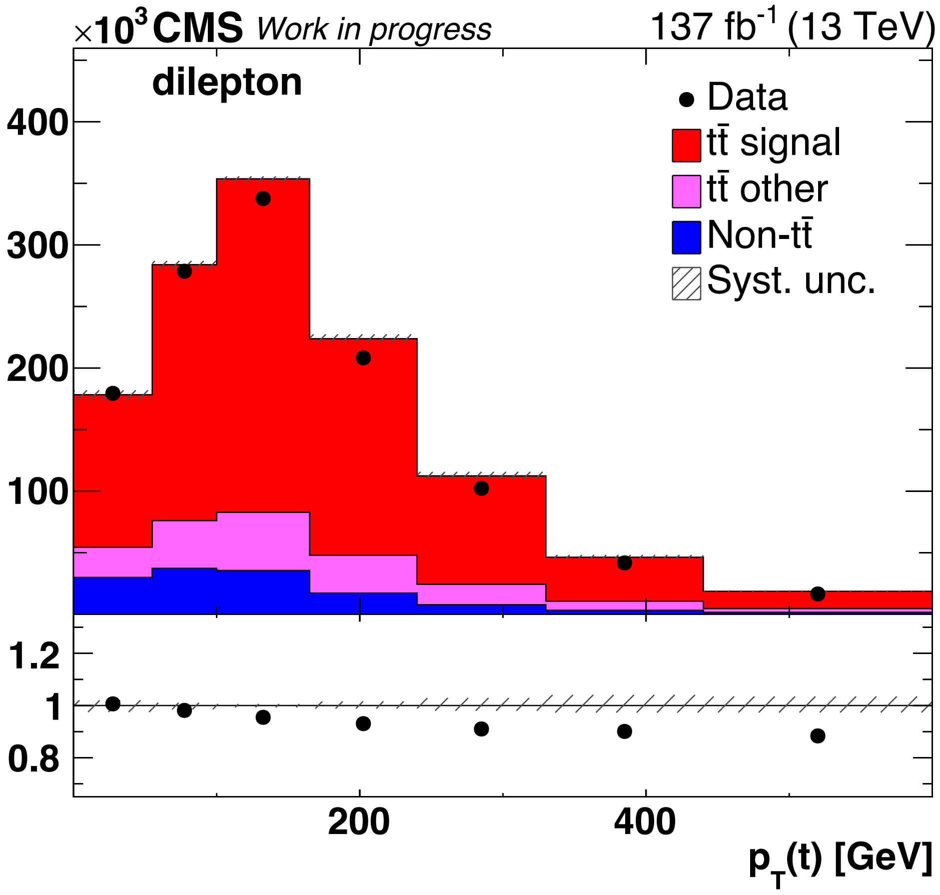
full Run 2

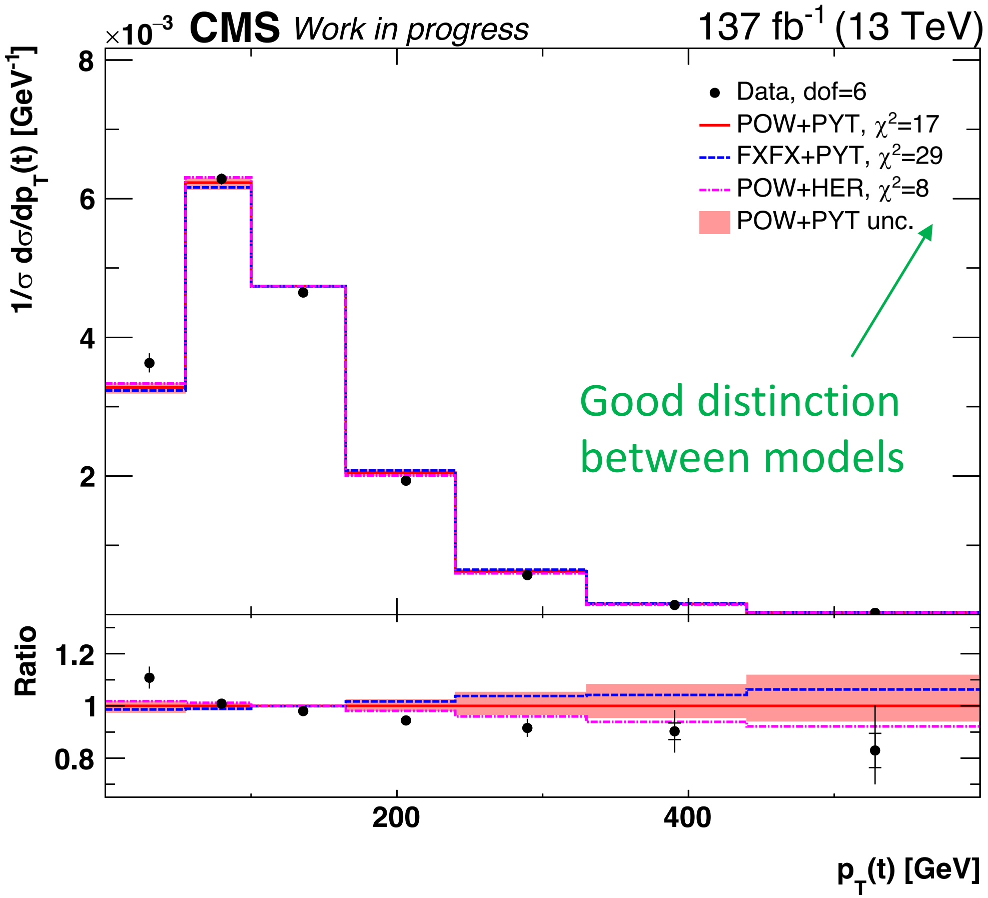




Cross sections

Transverse momentum of the top - $p_T(t)$



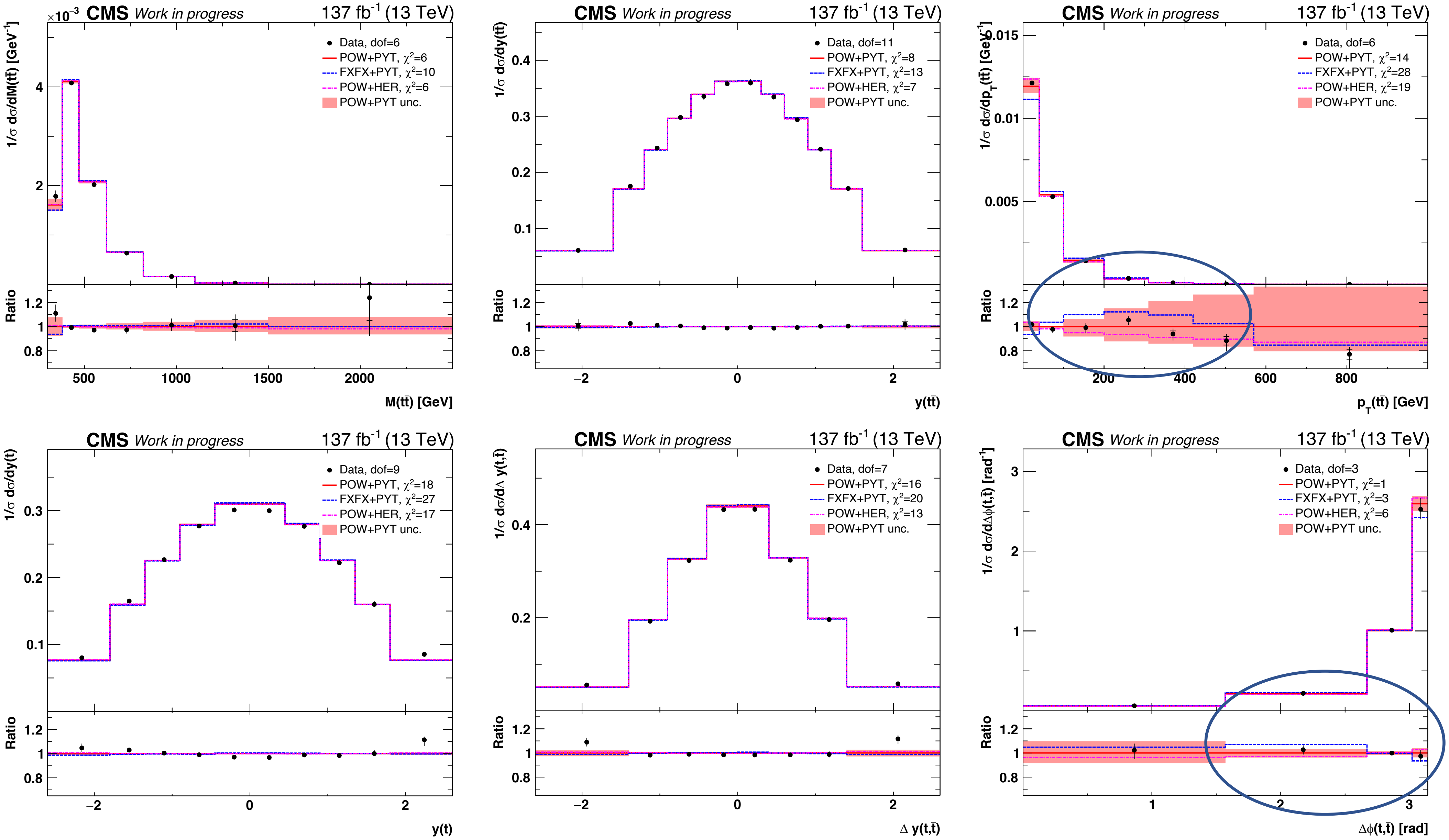


- Event yields are directly combined at detector level before unfolding (resolution matrices are similar for all years)

Cross sections

Parton level - normalized

$M(t\bar{t})$, $y(t\bar{t})$, $p_T(t\bar{t})$ (top row), $y(t)$, $\Delta y(t\bar{t})$, $\Delta\phi(t\bar{t})$ (bottom row)



- $p_T(t\bar{t})$, $\Delta\phi(t\bar{t})$,

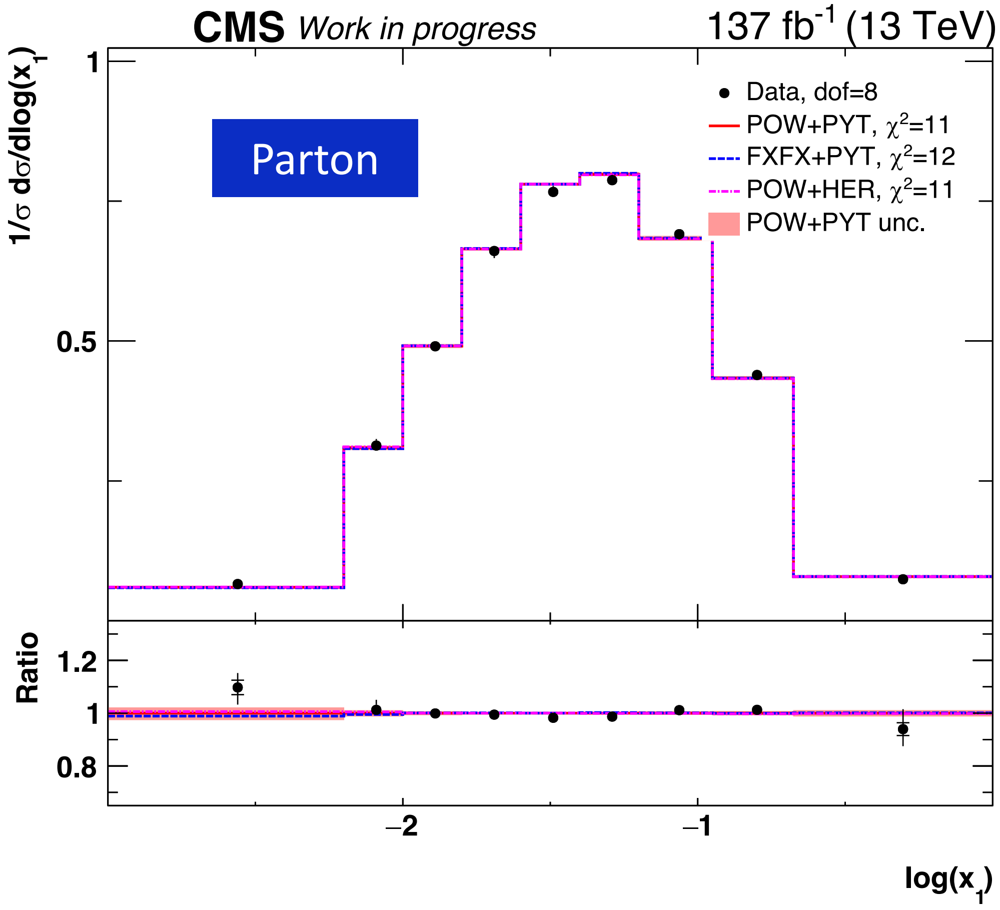
→ Good distinction between MC models

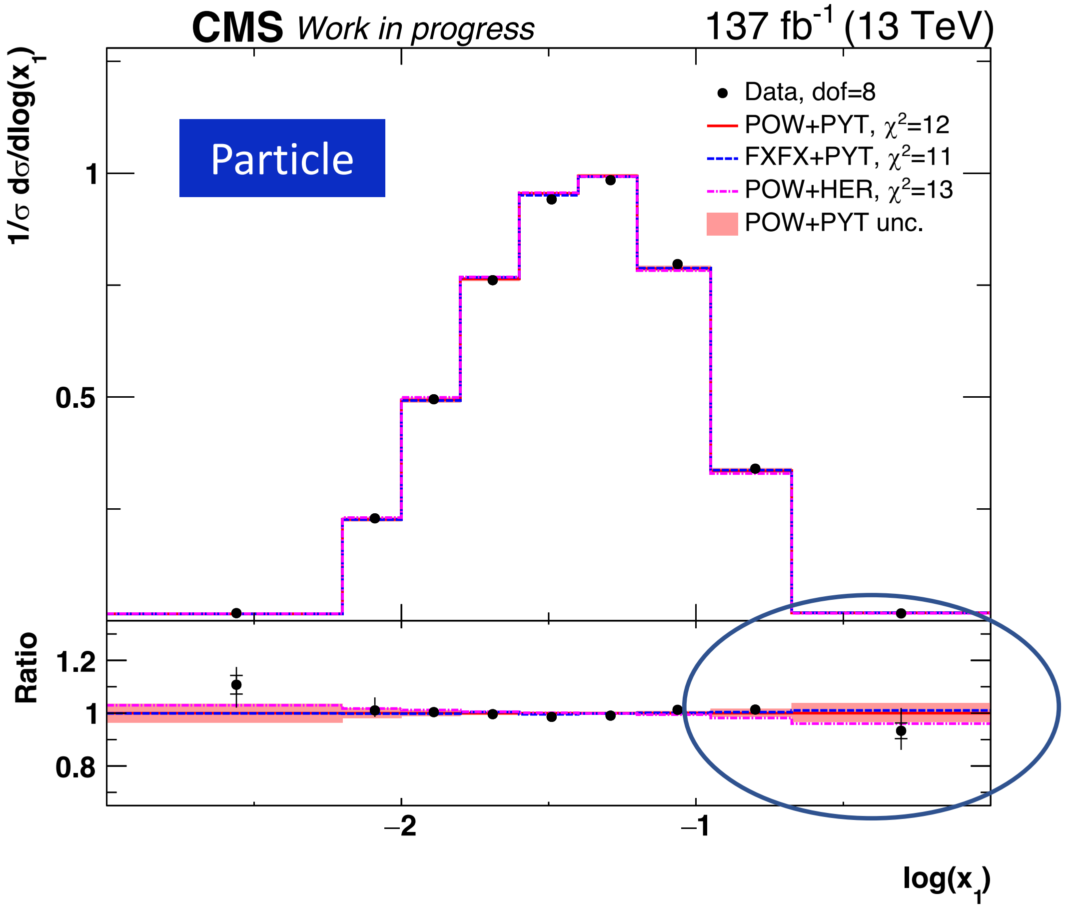
- All spectra

→ Overall good performance of POWHEG (v.2) - PYTHIA8

Cross sections

Log of proton momentum fraction from incoming parton – $\log(x_1)$





Definition:

$x_1 = (\mathrm{E}(\mathrm{t}) - p_z(t) + \mathrm{E}(\bar{t}) - p_z(\bar{t}))/(2\cdot 6.5\ \mathrm{TeV})$

$x_2 = (\mathrm{E}(\mathrm{t}) + p_z(t) + \mathrm{E}(\bar{t}) + p_z(\bar{t}))/(2\cdot 6.5)\ \mathrm{TeV}$

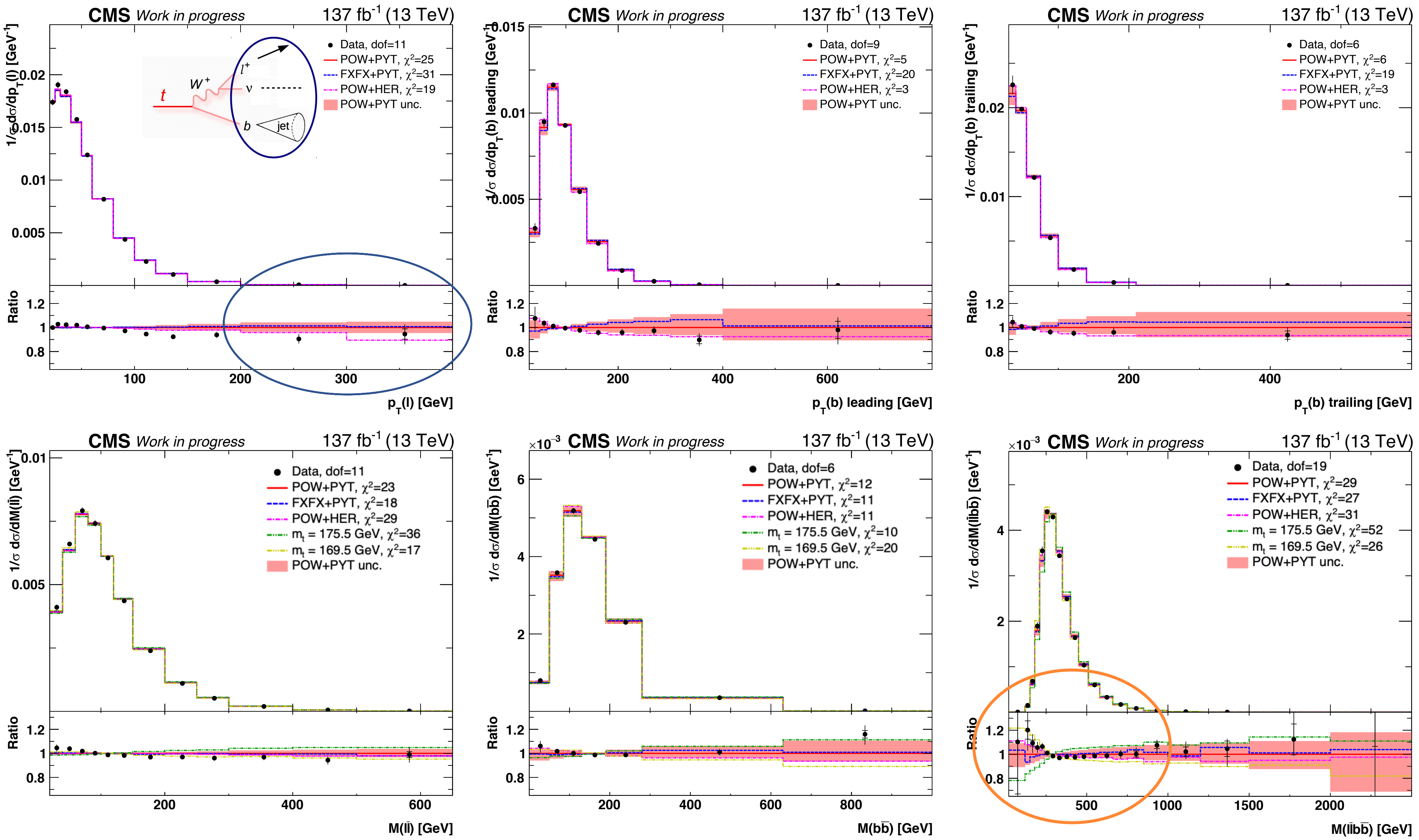
Sensitivity:

- Gluon momentum density fractions up to ≈ 0.3
- Particle level shows additional distinction between MC models

Cross sections

Particle level - normalized

$p_T(\mathrm{l})$, $p_T(\mathrm{b})$ lead, $p_T(\mathrm{b})$ trail (top row), $\mathrm{m}(\mathrm{l\bar{l}})$, $\mathrm{m}(\mathrm{b\bar{b}})$, $\mathrm{m}(\mathrm{l\bar{l}b\bar{b}})$ (bottom row)



- $p_T(\mathrm{l})$, $p_T(\mathrm{b})$ lead and trail (top row)

→

Good distinction between MC models

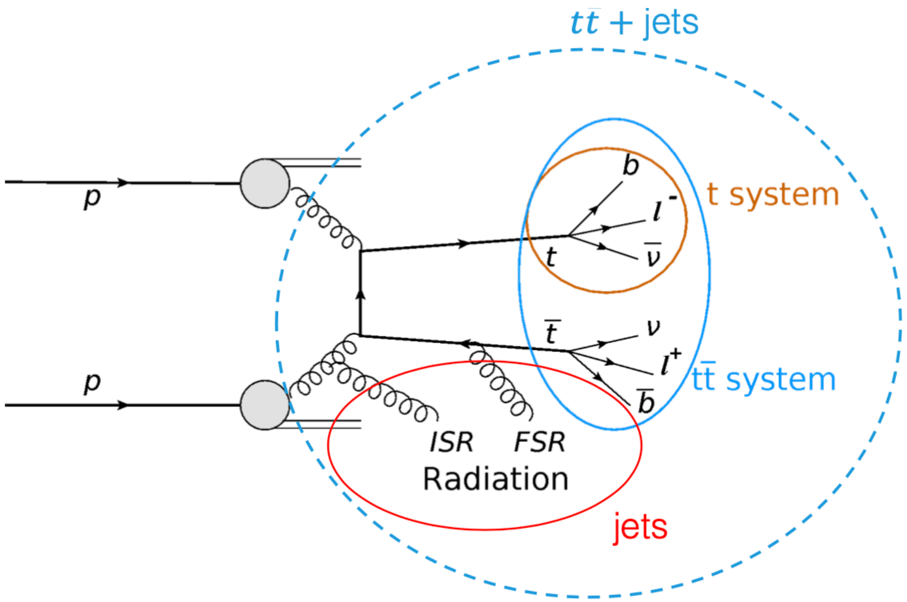
- $\mathrm{m}(\mathrm{l\bar{l}})$, $\mathrm{m}(\mathrm{b\bar{b}})$, $\mathrm{m}(\mathrm{l\bar{l}b\bar{b}})$

→

Alternative top mass samples are shown. Good sensitivity for $\mathrm{m}(\mathrm{l\bar{l}b\bar{b}})$

Summary

- An extensive set of top pair measurements have been performed of
  1. Top quarks and the $t\bar{t}$ system (parton- and particle-level)
  2. Top quark decay products (particle-level only)



- Comparison is done for three generators:
  - POWHEG (v.2) - PYTHIA8 (NLO)
  - MG5_aMC@NLO[FxFx] - PYTHIA8 (NLO)
  - POWHEG (v.2) – Herwig (NLO)

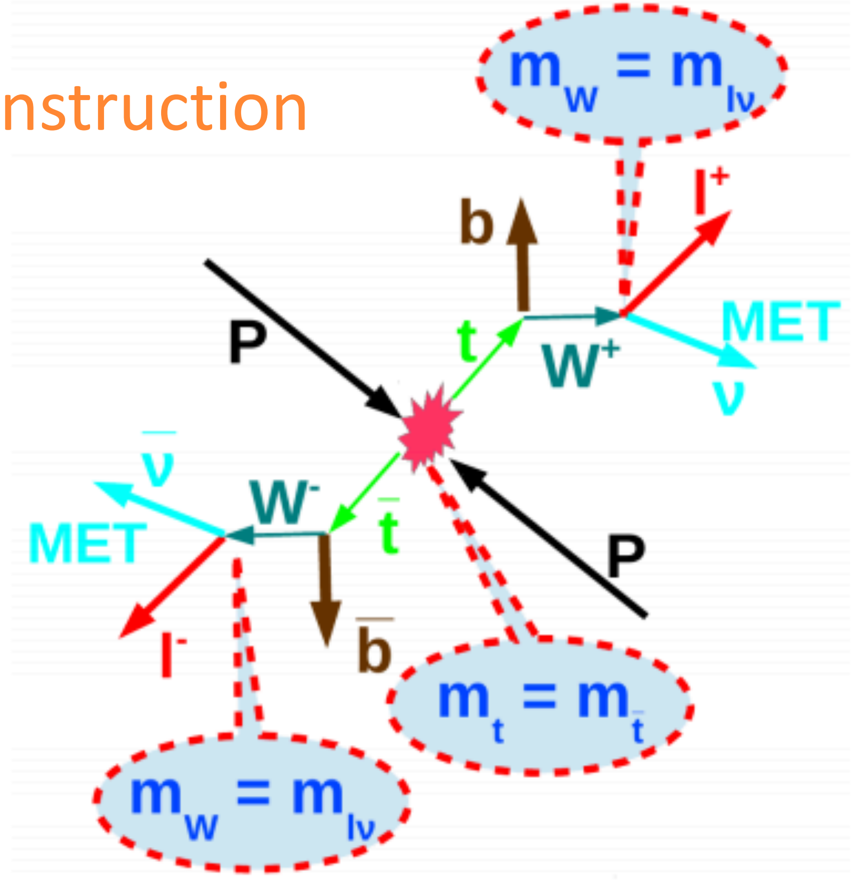
- Good distinction is seen between the models for many observables:
  - overall good description is observed for POWHEG (v. 2) - PYTHIA8
  - MG5_aMC@NLO[FxFx] and POWHEG (v.2) – Herwig describe the data reasonably well but has an overall worse discription compared to POWHEG (v. 2) – PYTHIA8

CADI line – Top-20-006:
http://cms.cern.ch/iCMS/analysisadmin/cadilines?line=TOP-20-006&tp=an&id=2367&ancode=TOP-20-006

Appendix

Kinematic reconstruction

with additional details for loose kinematic reconstruction



Full kinematic reconstruction

- 6 unknowns (neutrino momenta)
- 6 constraints: top mass, W boson mass and MET
- Use all kinematic constraints on visible decay products
- Reconstruct top and anti-top separately
- Unfolded distribution of $M^{\mathrm{t\bar{t}}}$ depends on assumed value of the top mass

Loose kinematic reconstruction

- No constraint on top mass
- Mass onset is accessible
- Can only reconstruct $t\bar{t}$ system

- Kinematic requirements:

$$p_{x,y}(\nu\bar{\nu}) = \mathrm{MET}_{x,y}$$
$$p_z(\nu\bar{\nu}) = p_z(l\bar{l}), E_z(\nu\bar{\nu}) = E_z(l\bar{l})$$
$$M(\nu\bar{\nu}) \geq 0, M(\nu\bar{\nu}l\bar{l}) \geq 2M_W$$