Measurement of double differential $t\bar{t}$ production cross sections with the CMS detector

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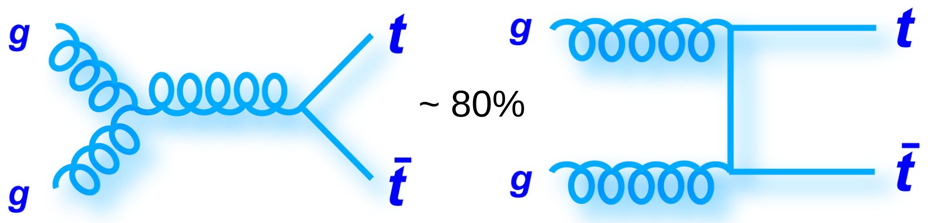
Why measure differential $t\bar{t}$ production at LHC?

Dominant production process:

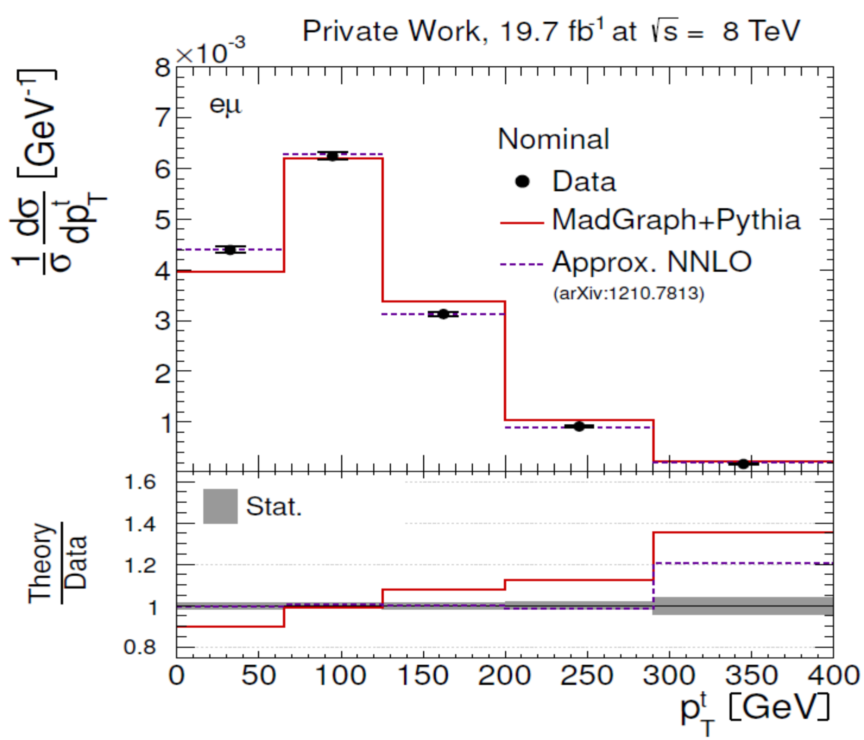


- Probe of the Standard Model / Sensitive to new physics
- Discrepancies seen in differential cross section $\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$

First time measurement of the **double differential** $t\bar{t}$ production cross sections e.g.

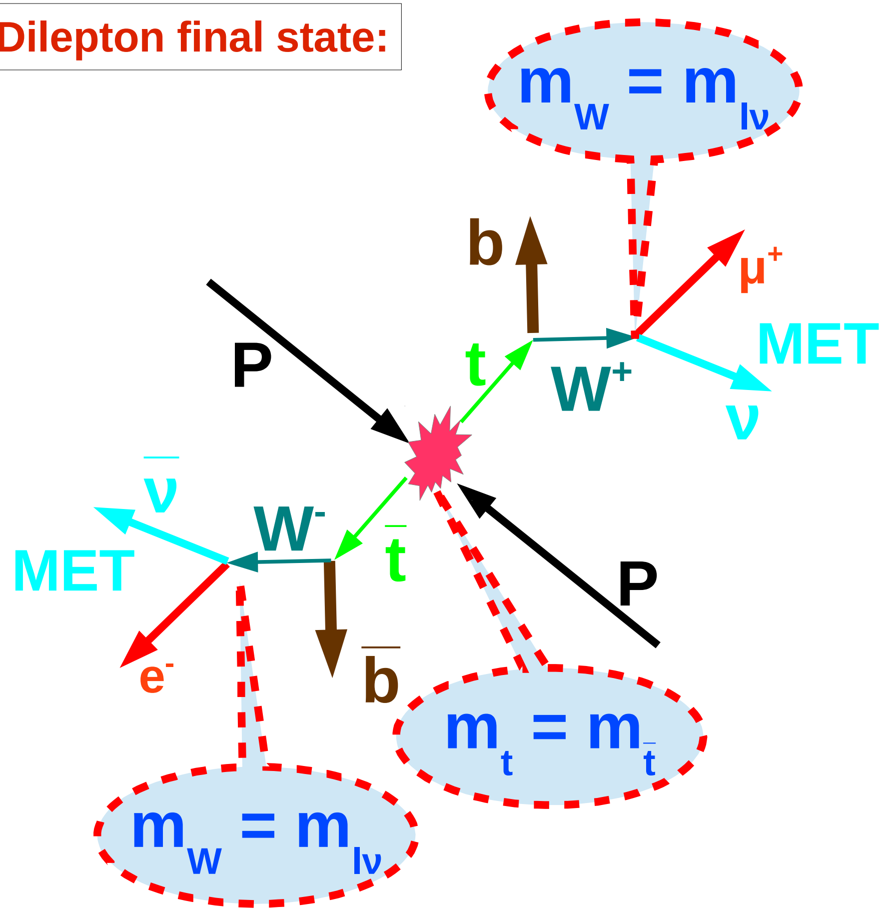
$$\frac{1}{\sigma}\frac{d^2\sigma}{dp_T^t\,dy^t}$$

NNLO for the 2D measurement is not available at the moment



Event Selection and Reconstruction

tt - Dilepton final state:



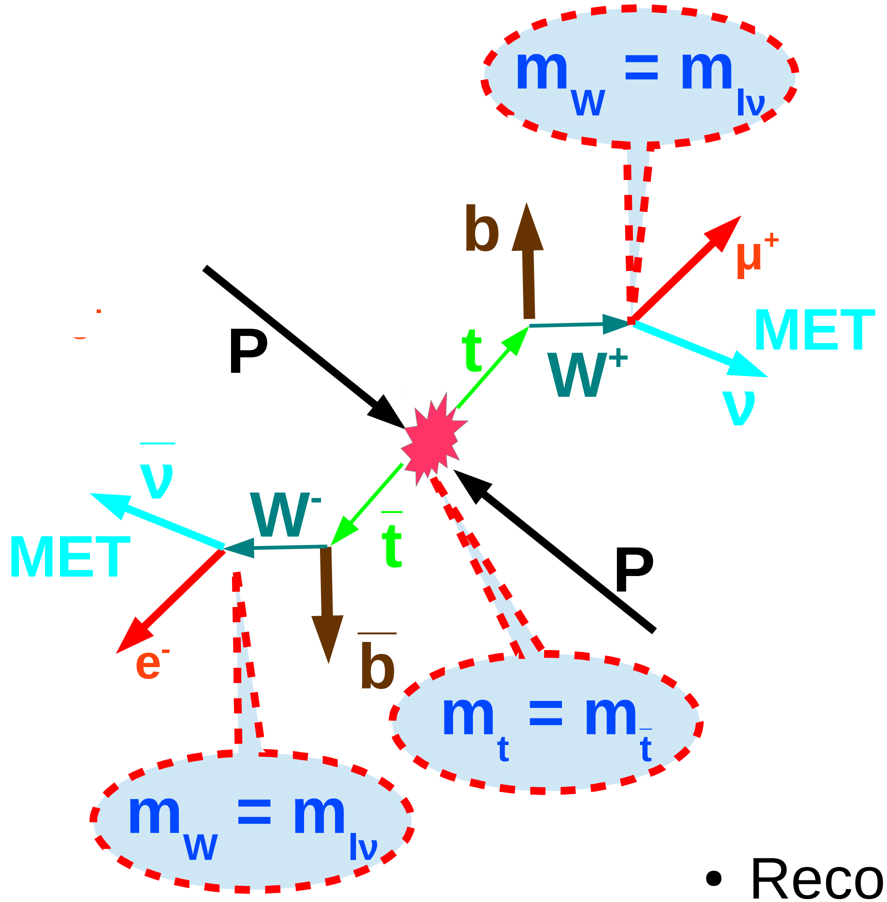
Full reconstruction of t and $\bar{t}$ kinematics
using 6 kinematic constraints

Event Selection

- **$e^{+-}\mu^{-+}$ selection** with
  p_t(leptons) > 20 GeV
  |η(leptons)| < 2.4

- **Jets**
  at least 2
  p_t(jets) > 30 GeV
  |η(jets)| < 2.4
  At least 1 b tagged jet
  (loose working point)

Event Selection and Reconstruction

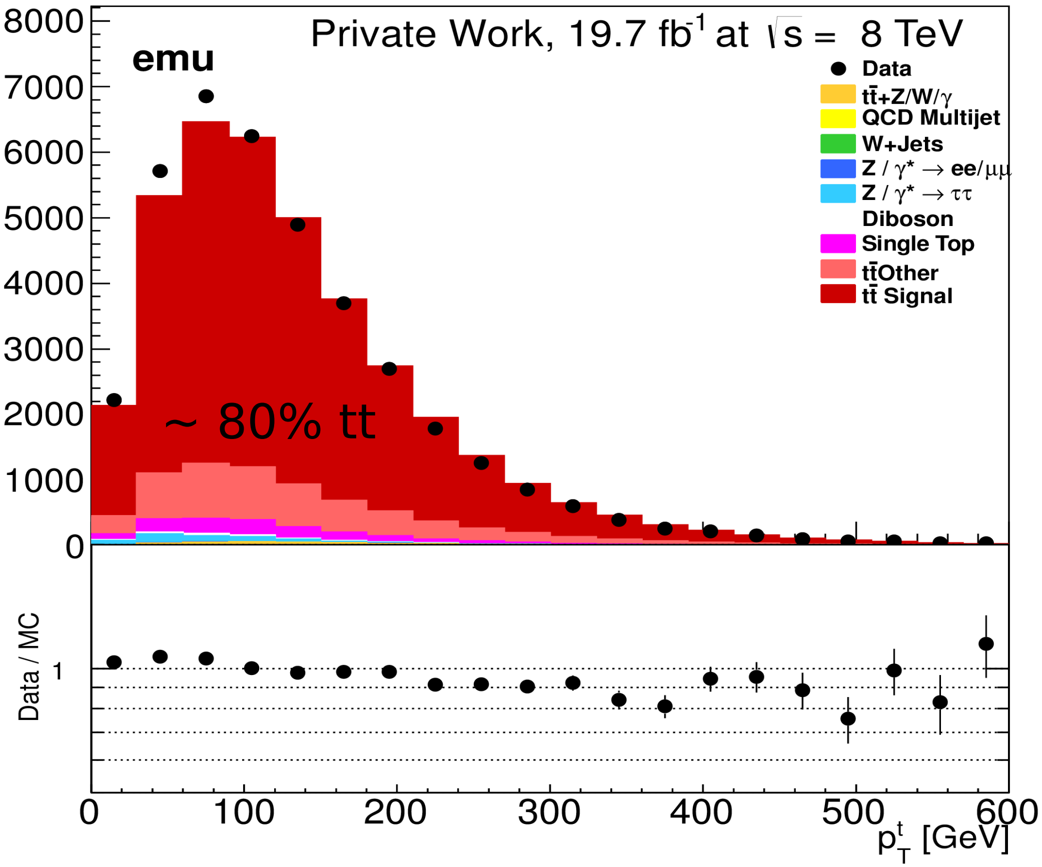


Kinematic Reconstruction

- Measured input
  2 jets, $e^{+-}\mu^{-+}$, MET
- Unknowns
  $\bar{p}_{\nu}, \bar{p}_{\bar{\nu}}$ → 6
- Constraints
  $m_t, m_{\bar{t}}$ → 2
  m_{W^-}, m_{W^+} → 2
  $(\bar{p}_{\nu} + \bar{p}_{\bar{\nu}})_T$ = MET → 2
- Reconstruct each event 100 times smearing inputs by their resolutions
- Take weighted average of solutions

Data and Simulation

- **Data** (Full 2012 data set)
  L = 19.7fb^{-1}
- **$t\bar{t}$ signal MC**
  MadGraph + Pythia
- **Main backgrounds:**
  $t\bar{t}$(other), single top



Normalized 2d Cross Sections

$N^{ij}_{DATA} - N^{ij}_{BG}$ → **Unfolding** (TUnfold) → N^{ij}_{evts}

from signal MC → Migration Matrix → **Unfolding** (TUnfold)

i,j : bins of kinematic variables in which the cross section is calculated

N^{ij}_{BG} : estimate from background MCs

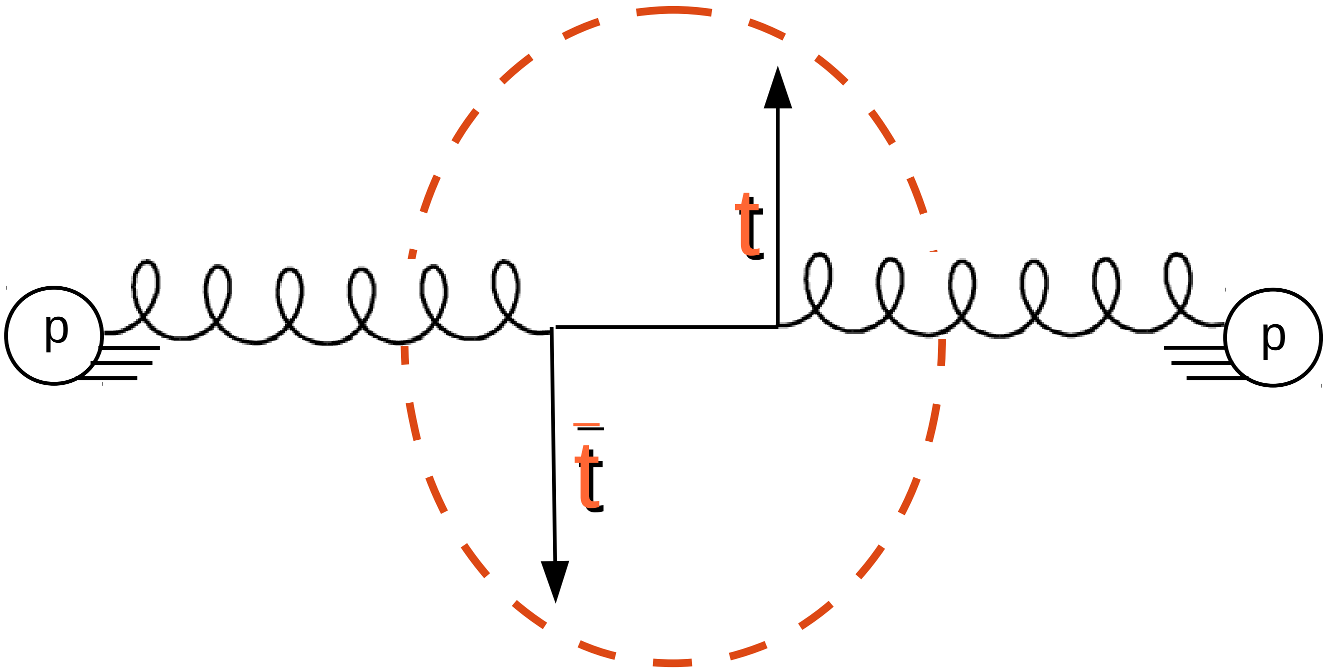
For each ΔY^j:

$$\left(\frac{1}{\sigma}\frac{d\sigma}{dX}\right)^{ij} = \frac{1}{\sigma}\frac{\cdot N^{ij}_{evts}}{L\cdot\Delta X^{i}}$$

σ: inclusive $t\bar{t}$ cross-section in full phase space
σ = 245.10 pb (*private work*)

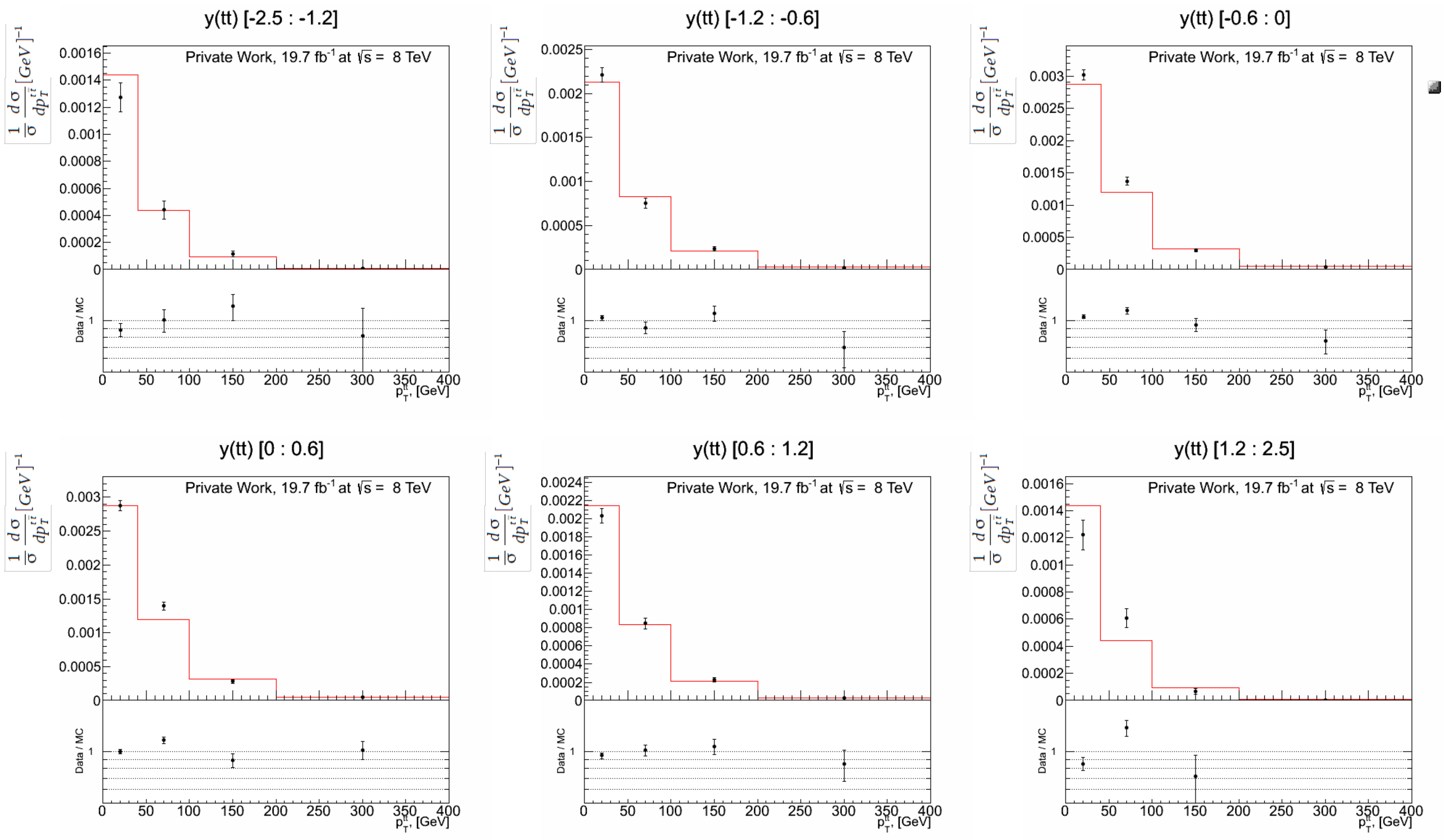
ΔX^i (ΔY^j) : bin width of the variable under test

$t\bar{t}$ dynamics



$p_t(t\bar{t})$ vs $y(t\bar{t})$

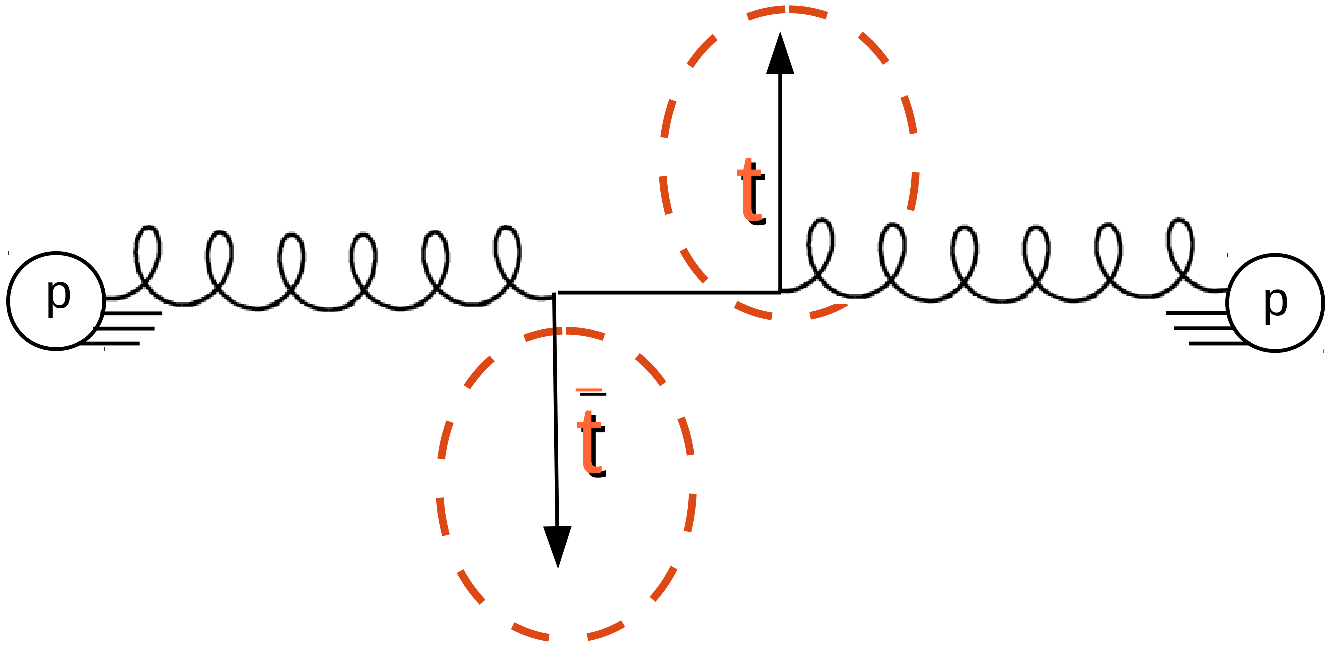
$p_t(t\bar{t})$ in bins of $y(t\bar{t})$, Cross Sections



- *Only statistical errors*

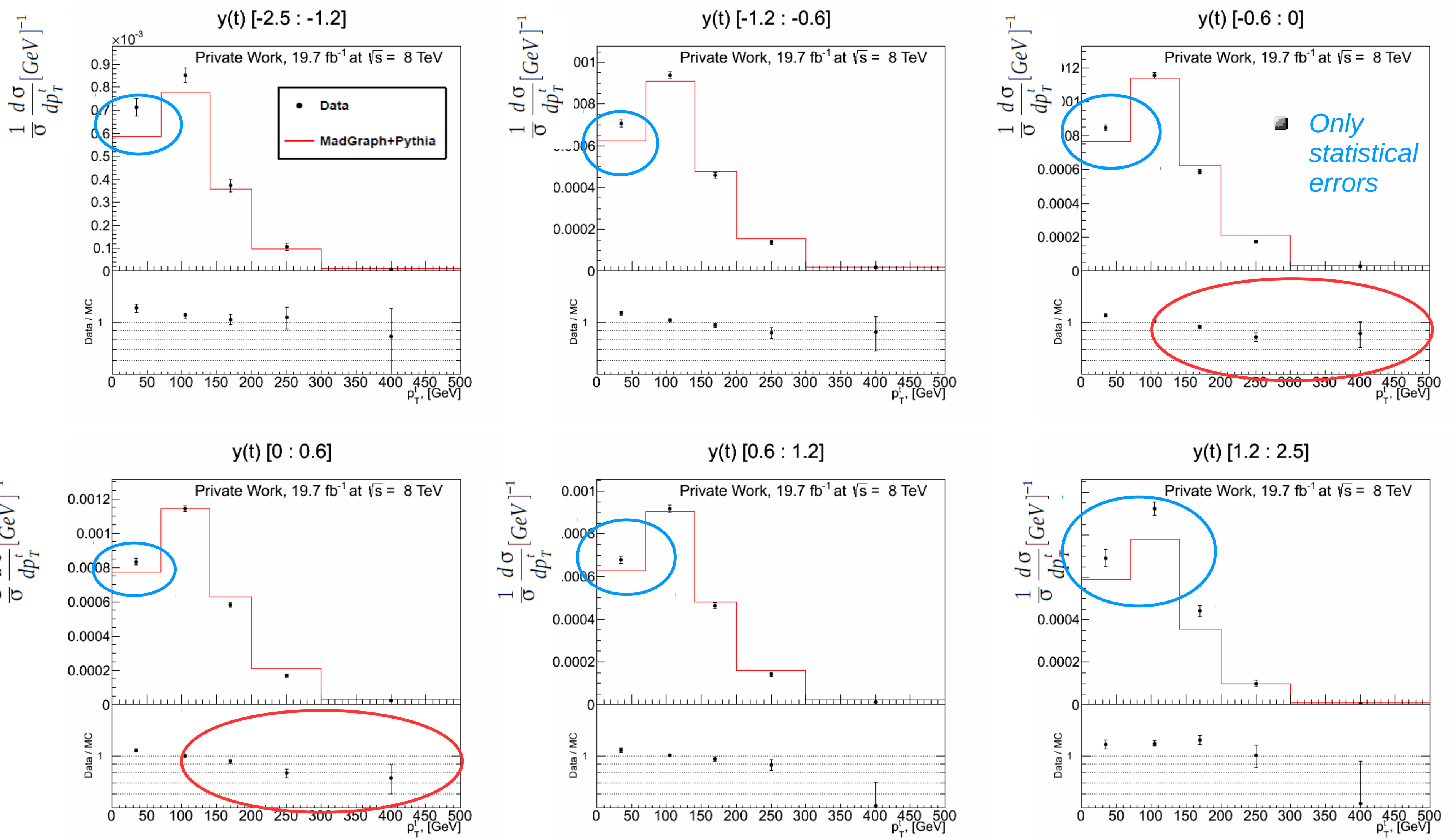
Generally MC describes data reasonably

t ($\bar{t}$) dynamics



p_t(t) vs y(t)

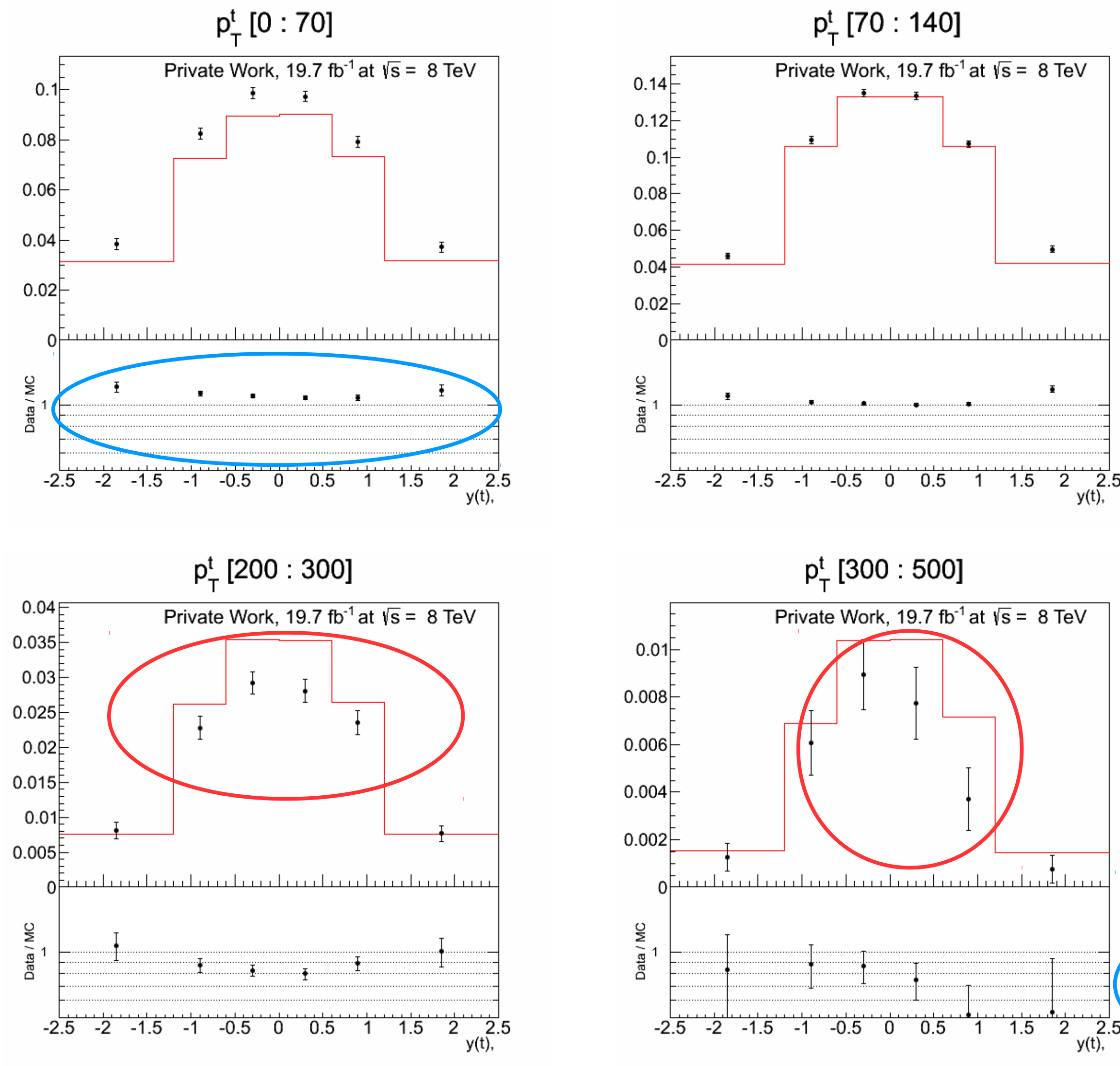
$p_t(t)$ in bins of y(t), Cross Sections



Prediction underestimates signal for small $p_t(t)$ over all y(t) range

Prediction overestimates signal for high $p_t(t)$ at central y(t)

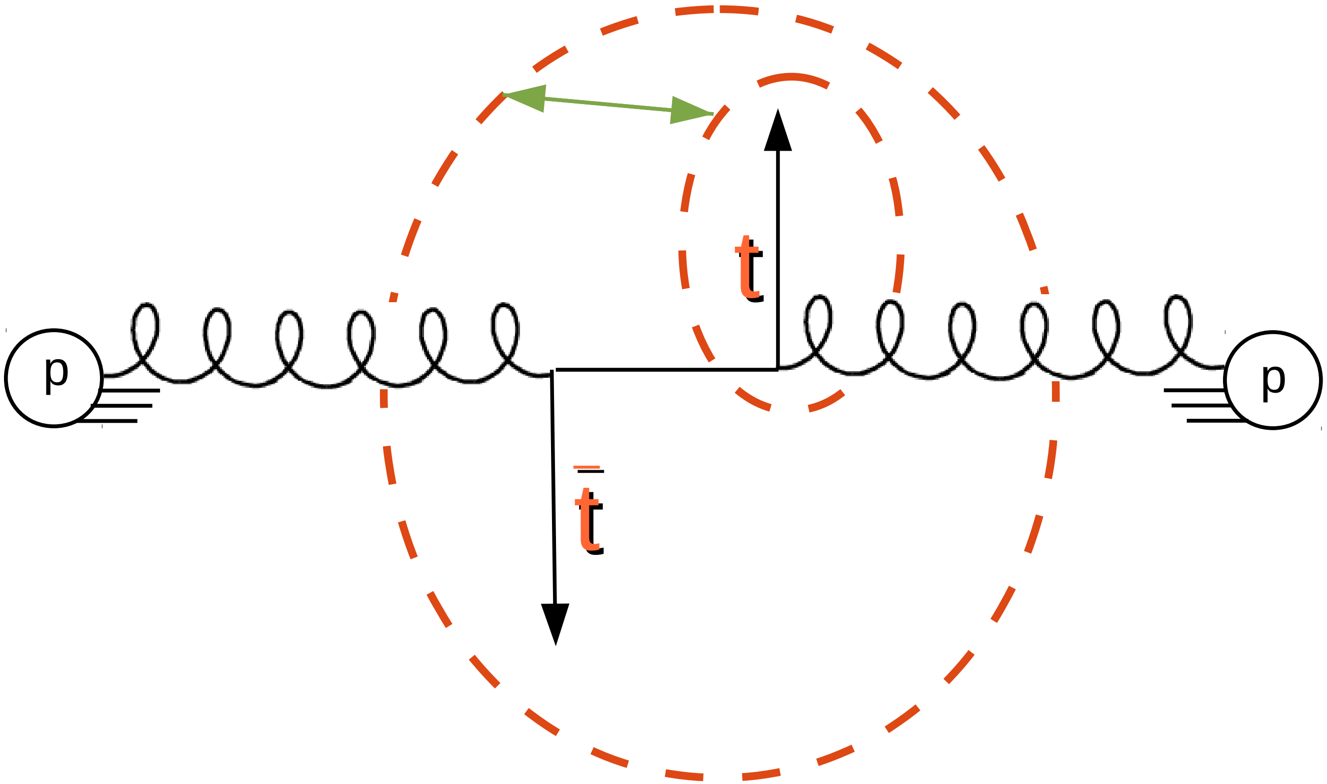
y(t) in bins of p_t(t), Cross Sections



Prediction overestimates signal for high p_t(t) at central y(t)

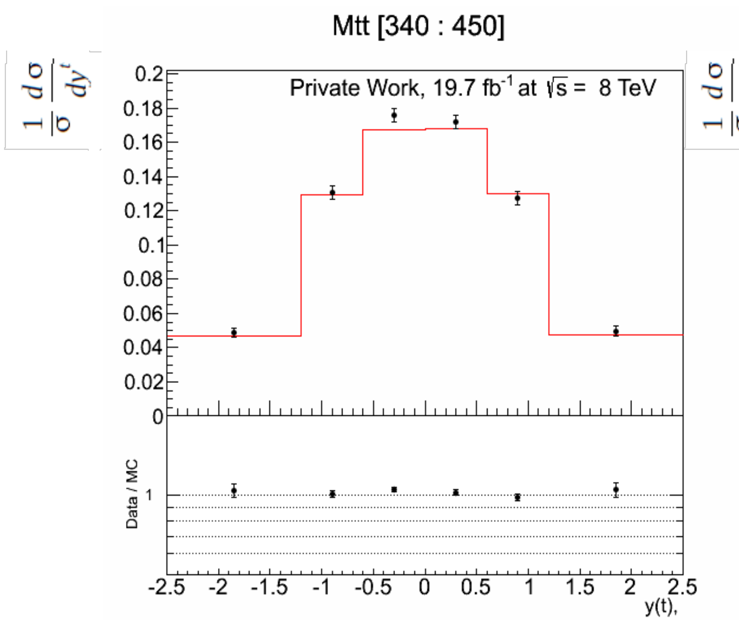
Prediction underestimates signal for small p_t(t) over all y(t) range

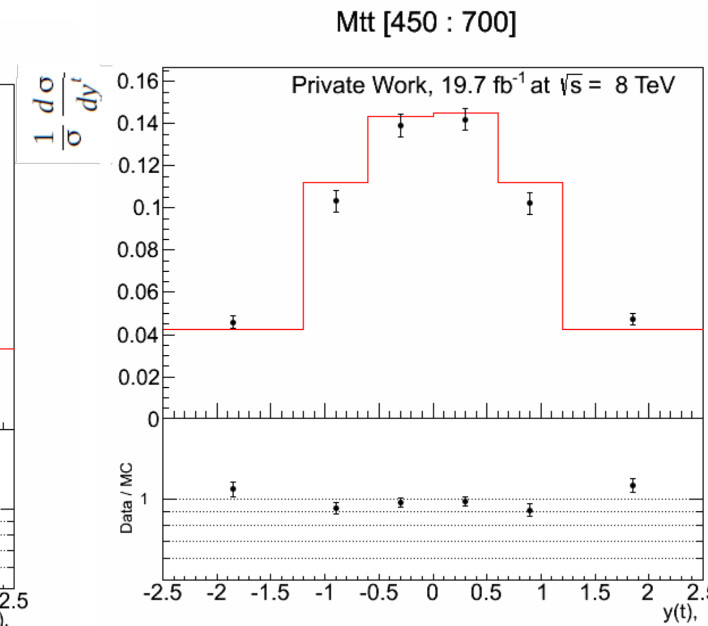
t - $t\bar{t}$ correlation

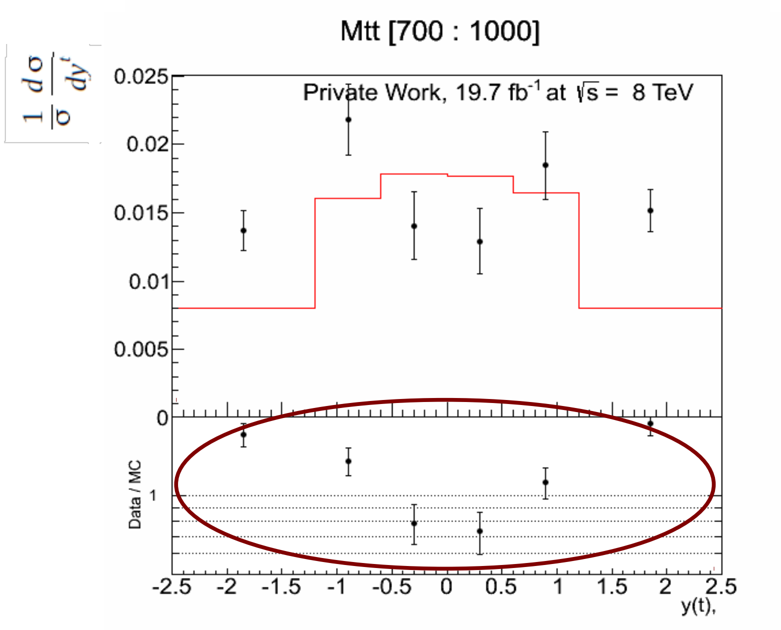


M($t\bar{t}$) vs y(t)

$M(t\bar{t})$ vs $y(t)$, Cross Sections



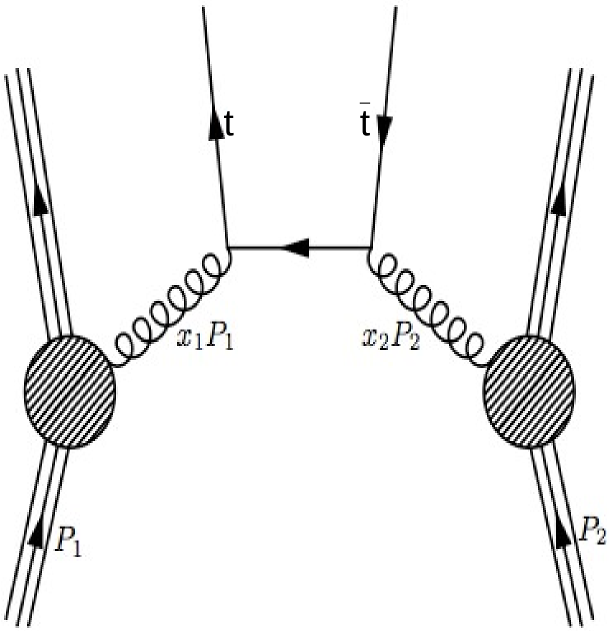




- *Only statistical errors*

Shape is not described

Proton momentum fraction by incoming parton



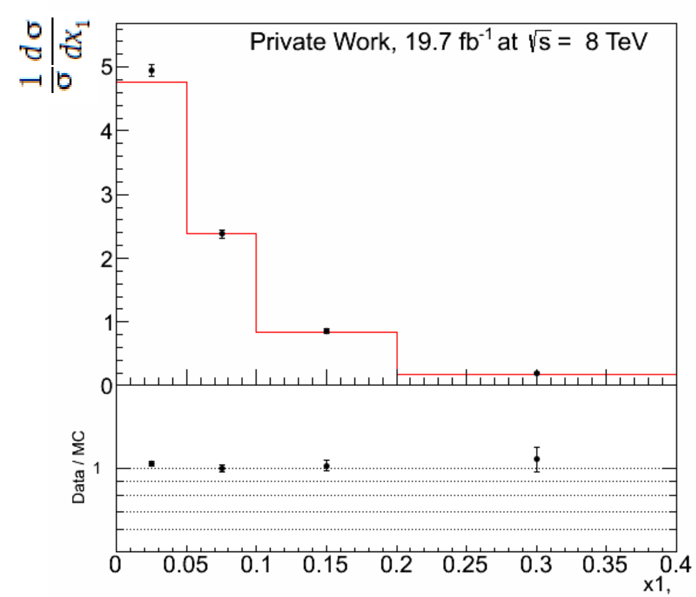
$$x_{1,2}=\frac{\left(E(t)\pm P_Z(t)\right)+\left(E(\bar{t})\pm P_Z(\bar{t})\right)}{2\cdot E(proton)}$$

highly sensitive to PDFs

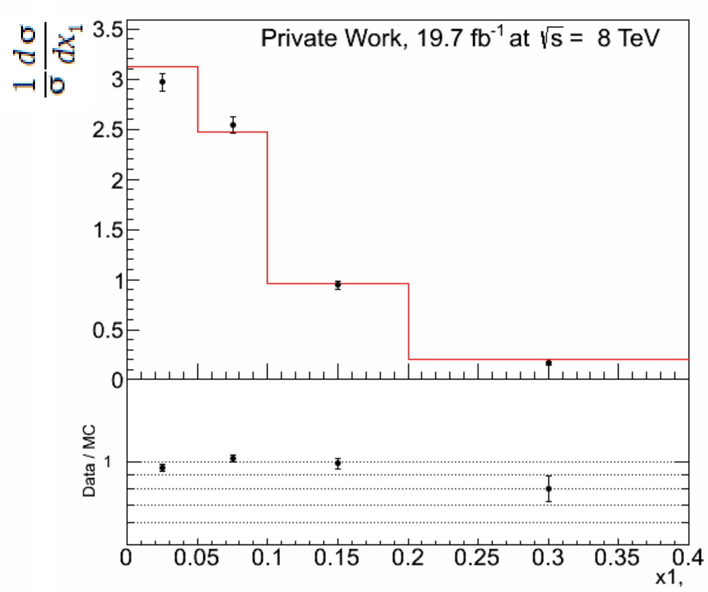
x1 vs M($t\bar{t}$)

x1 vs M($t\bar{t}$), Cross Sections

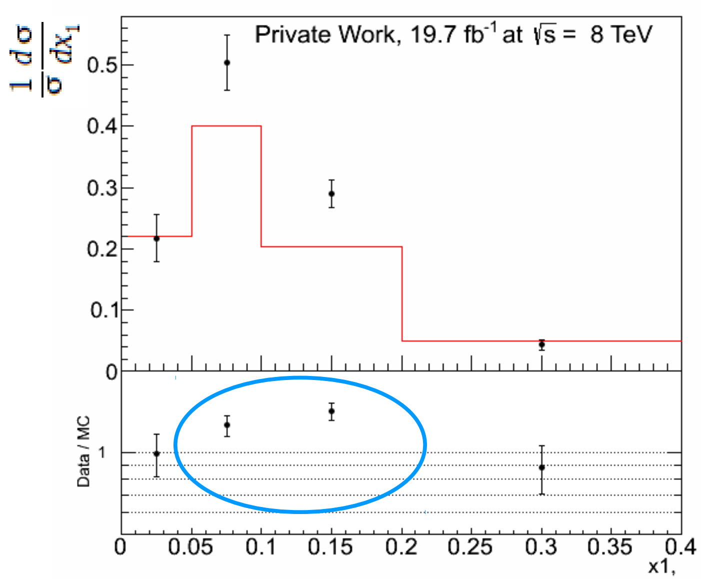
Mtt [340 : 450]



Mtt [450 : 700]



Mtt [700 : 1000]

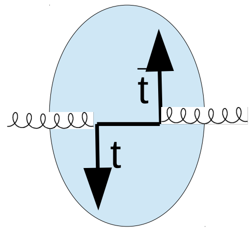


Prediction underestimates signal for some x1 bins with high M($t\bar{t}$)

Summary:

First look at 2d cross sections with 2D unfolding using TUnfold

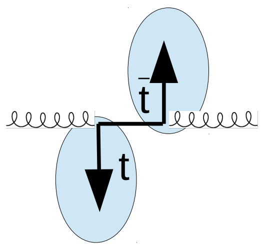
$t\bar{t}$ dynamics:



$y(t\bar{t})$ vs $p_t(t\bar{t})$

- *measurements in **agreement** with predictions*

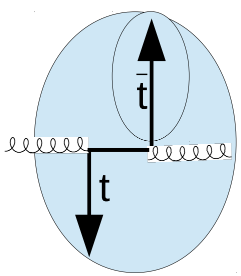
$t(\bar{t})$ dynamics:



$p_t(t)$ vs $y(t)$

- *mc underestimates the data for small $p_t(t)$ and overshoots for the medium $p_t(t)$*

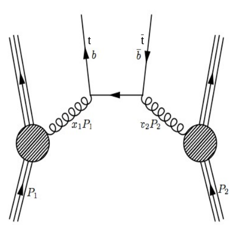
t-$t\bar{t}$ correlation:



$M(t\bar{t})$ vs $y(t)$

- *disagreement between data and mc for high $M(t\bar{t})$*

PDFs:



$x_1(t)$ vs $M(t\bar{t})$

- *for high $M(t\bar{t})$ disagreement within some x1 bins*

MC more central in rapidity for high $M(t\bar{t})$

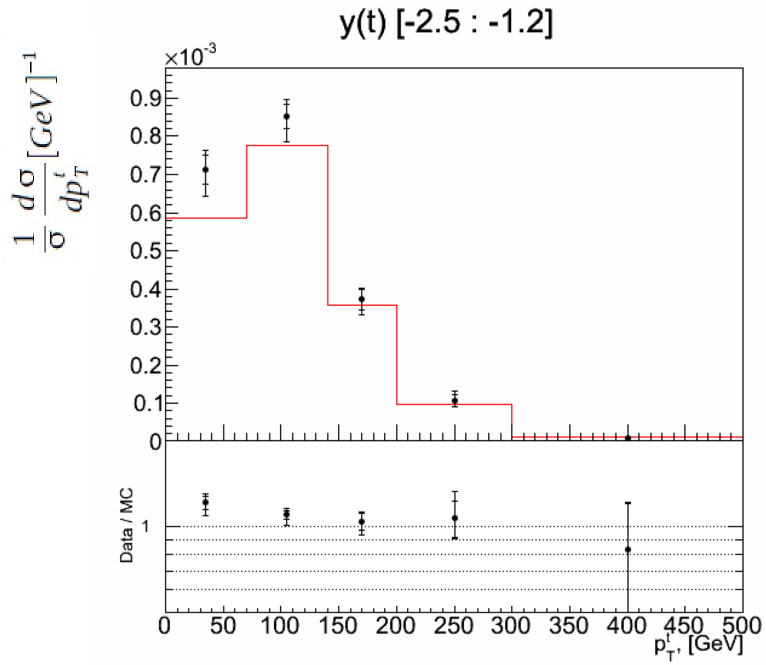
Outlook

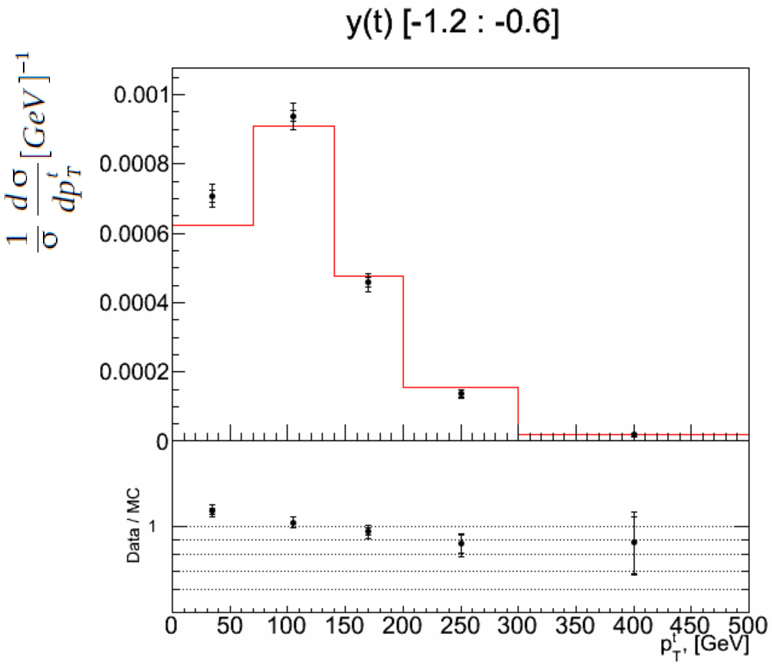
- Determine final results with full systematics
- Comparison to the theory predictions

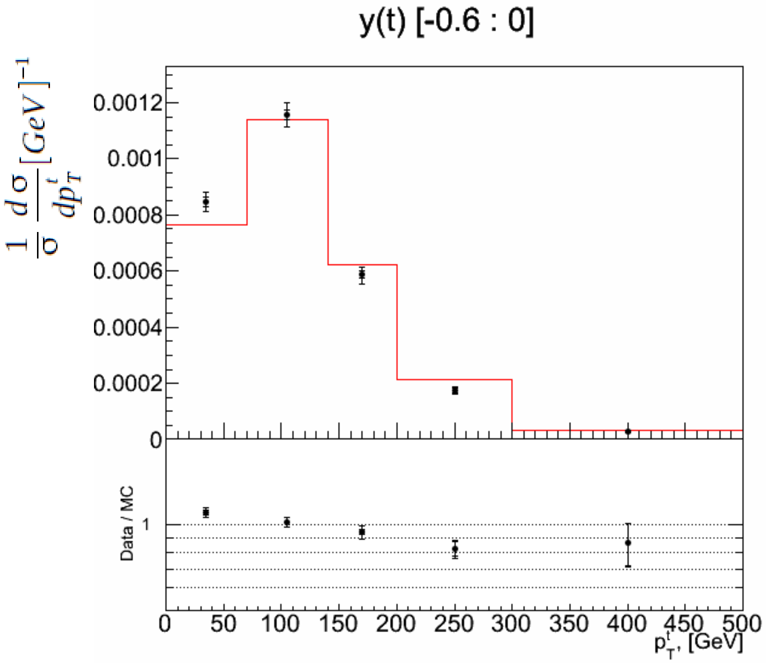
THANK YOU FOR YOUR ATTENTION

Backup

Double differential cross sections







Stat. error – inner error bars

Total error = $\sqrt{stat.error^2 + syst.error^2}$
- outer error bars

Normalized 2d Cross Sections

Bin-by-Bin unfolding:

n - events in data

estimated n bgr. events

$$N^{ij}_{evts} = \frac{(N^{ij}_{DATA} - N^{ij}_{BG})}{\epsilon^{ij} \cdot A}$$

efficiency

acceptance

$i\,,j$: bins of kinematic variables in which the cross section is **calculated**

N^{ij}_{BG} : estimate from background MCs

$$\epsilon^{ij} \cdot A = \frac{N^{ij}_{Reco}}{N^{ij}_{Gen}}$$

from signal MC

TUnfold:

$N^{i'j'}_{DATA} - N^{i'j'}_{BG}$ → TUnfold → N^{ij}_{evts}

Migration Matrix (from signal MC) → TUnfold

described on next slide

$i'\,,j'$: bins of kinematic variables in which the data and BG are **reconstructed**

$i\,,j$: bins of kinematic variables in which the cross section is **calculated**

Migration Matrix : contained **reconstructed** and **generated** information

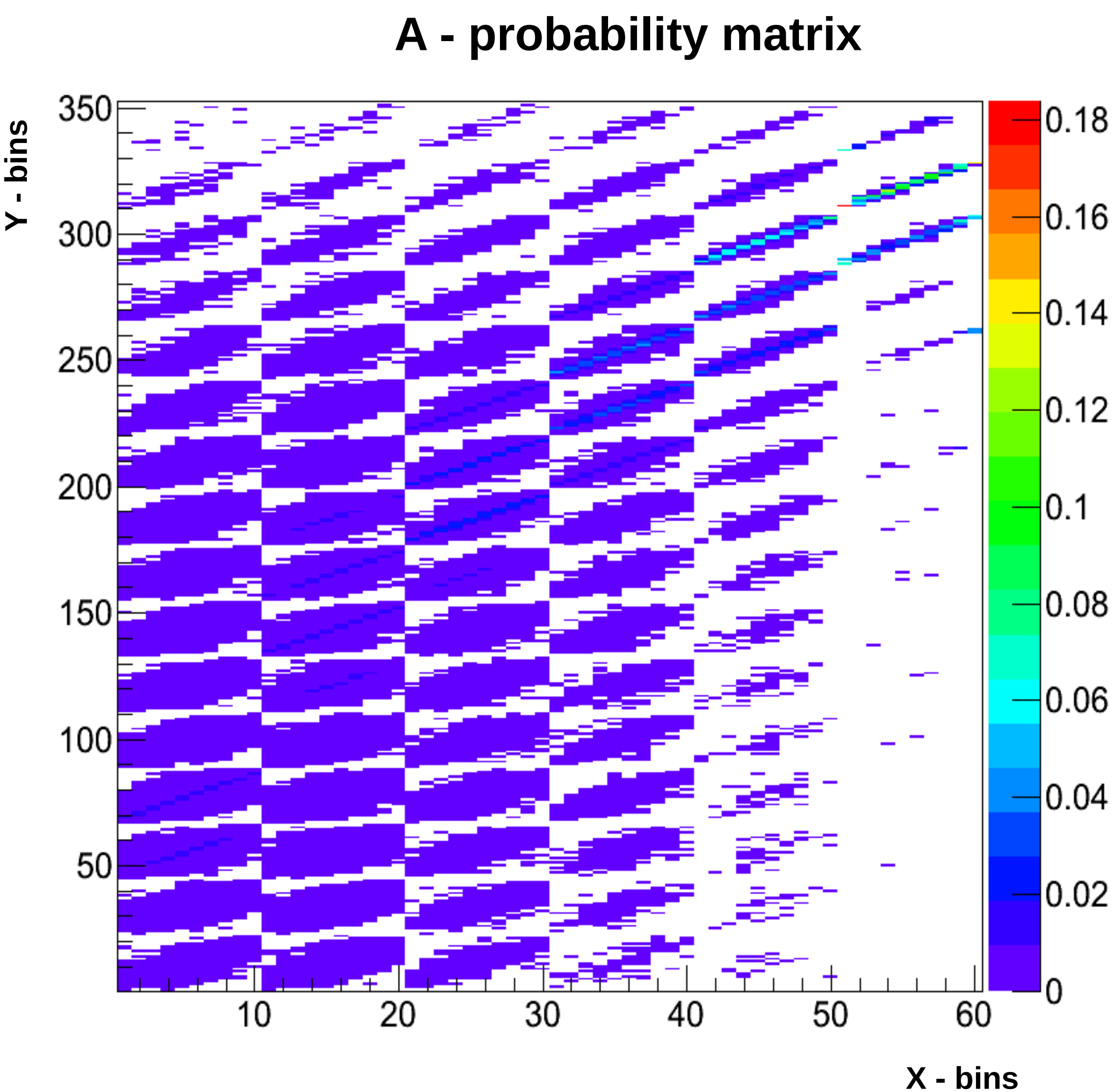
For each ΔY^j:

$$\left(\frac{1}{\sigma}\frac{d\sigma}{dX}\right)^{ij} = \frac{1}{\sigma}\frac{\cdot N^{ij}_{evts}}{L \cdot \Delta X^i}$$

σ: inclusive $t\bar{t}$ cross-section in full phase space

ΔX^i (ΔY^j) : bin width of the variable under test

Probability matrix



$$\chi^2 = (Y - AX)^T V_{YY}^{-1} (Y - AX) + Reg.\,term$$

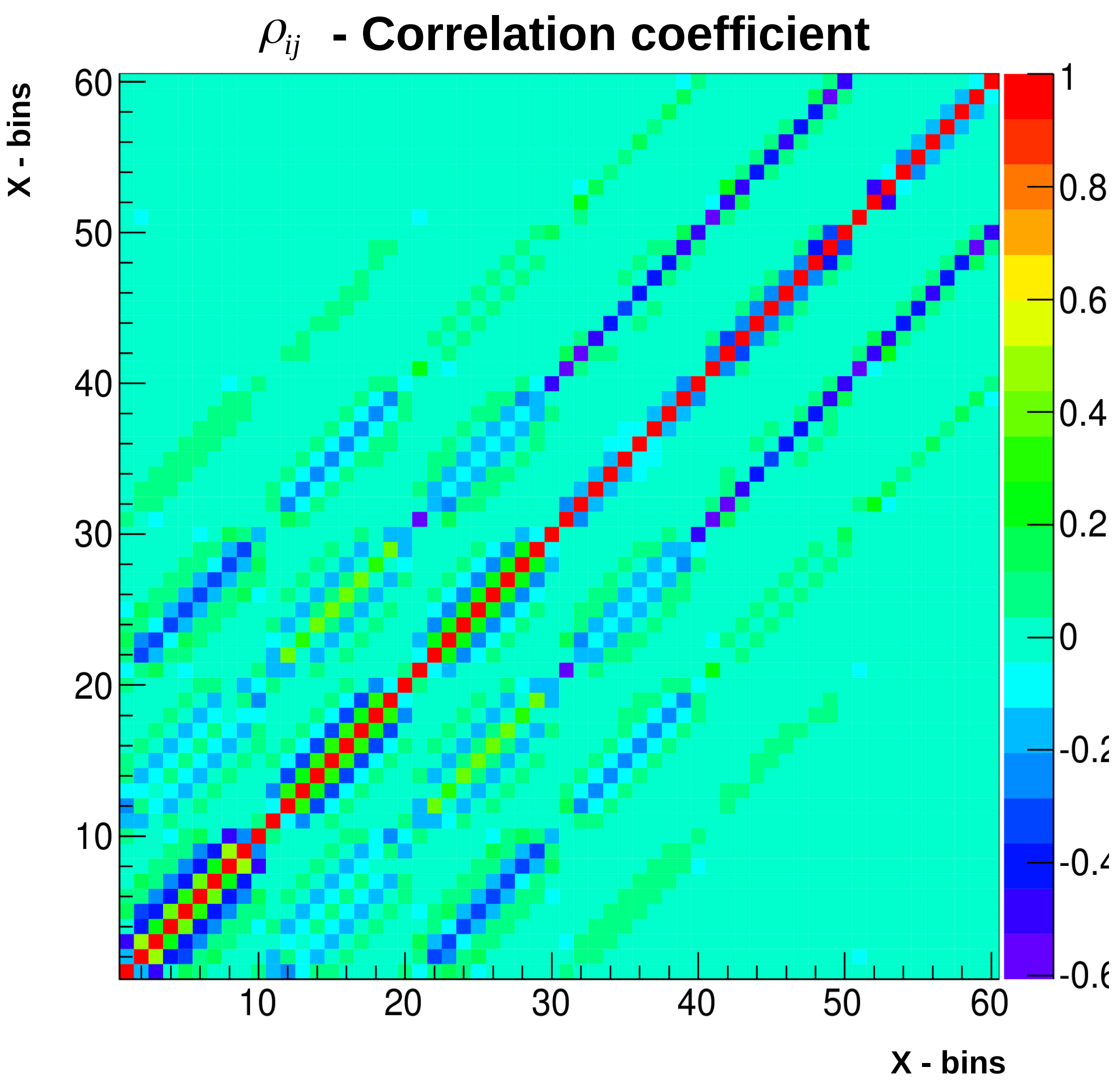
Y - vector of number events in fine bins (reconstructed)

X - unfolded number events in coarse bins ("true")

A - the elements Aij of A describe for each row *j* of X the probabilities to migrate to bin *i* of Y

(migration matrix obtained from signal MC)

Correlation matrix



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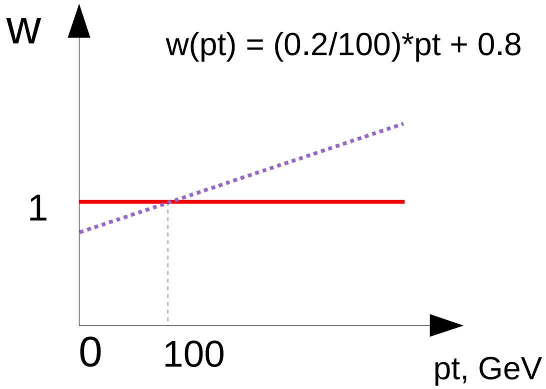
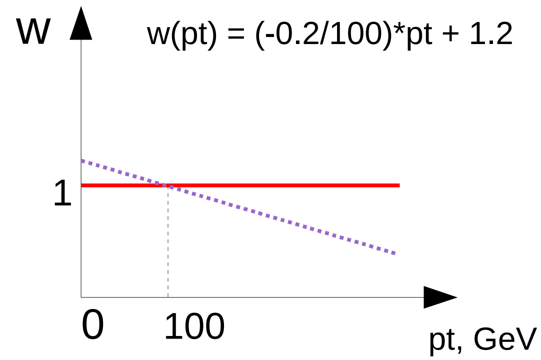
(migration matrix obtained from signal MC)

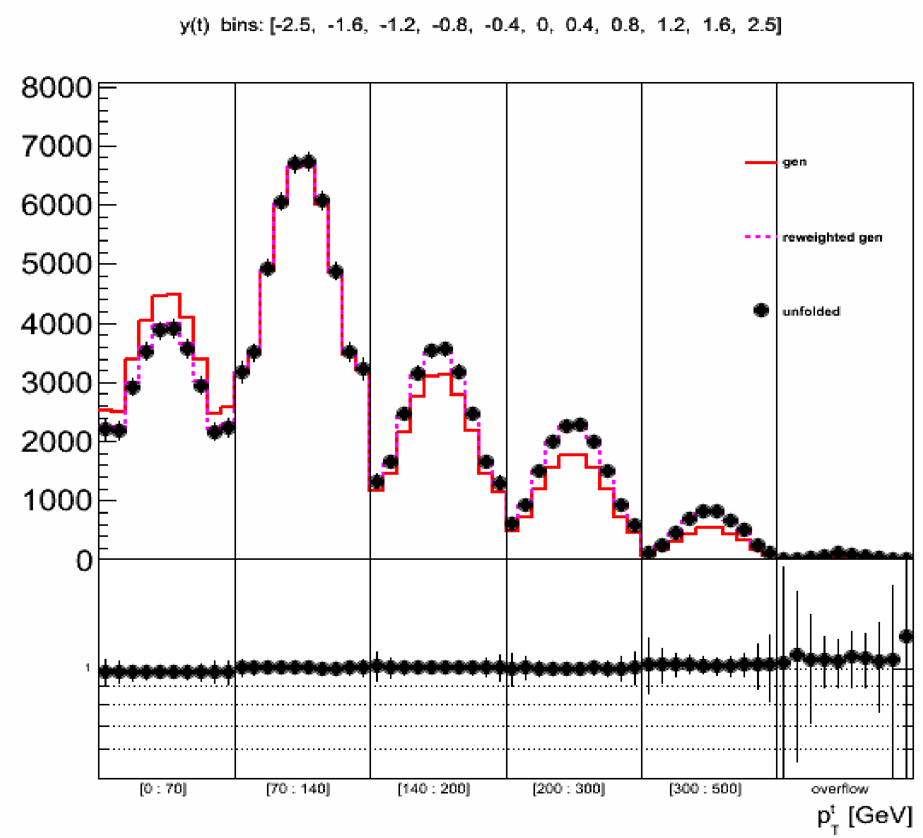
$$\rho_{ij} = \frac{V_{X_{ij}}}{\sqrt{V_{X_{ii}} V_{X_{jj}}}}$$

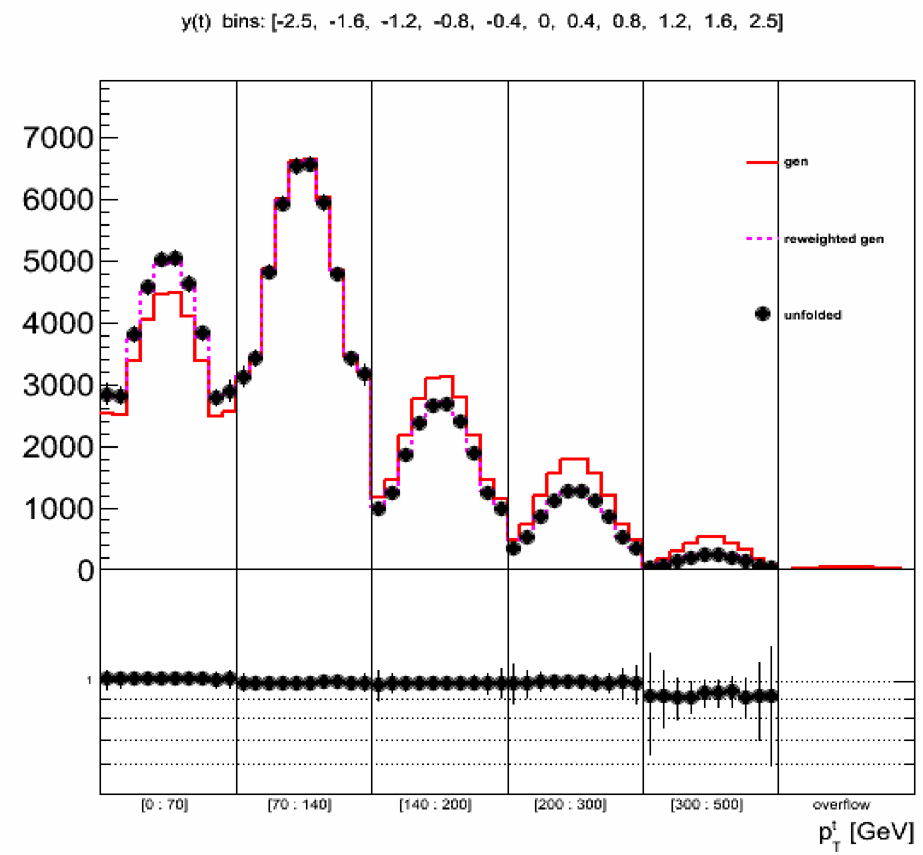
Correlations is up to $|\rho_{ij}| = 0.6$

Closure test: pt(t) reweighting



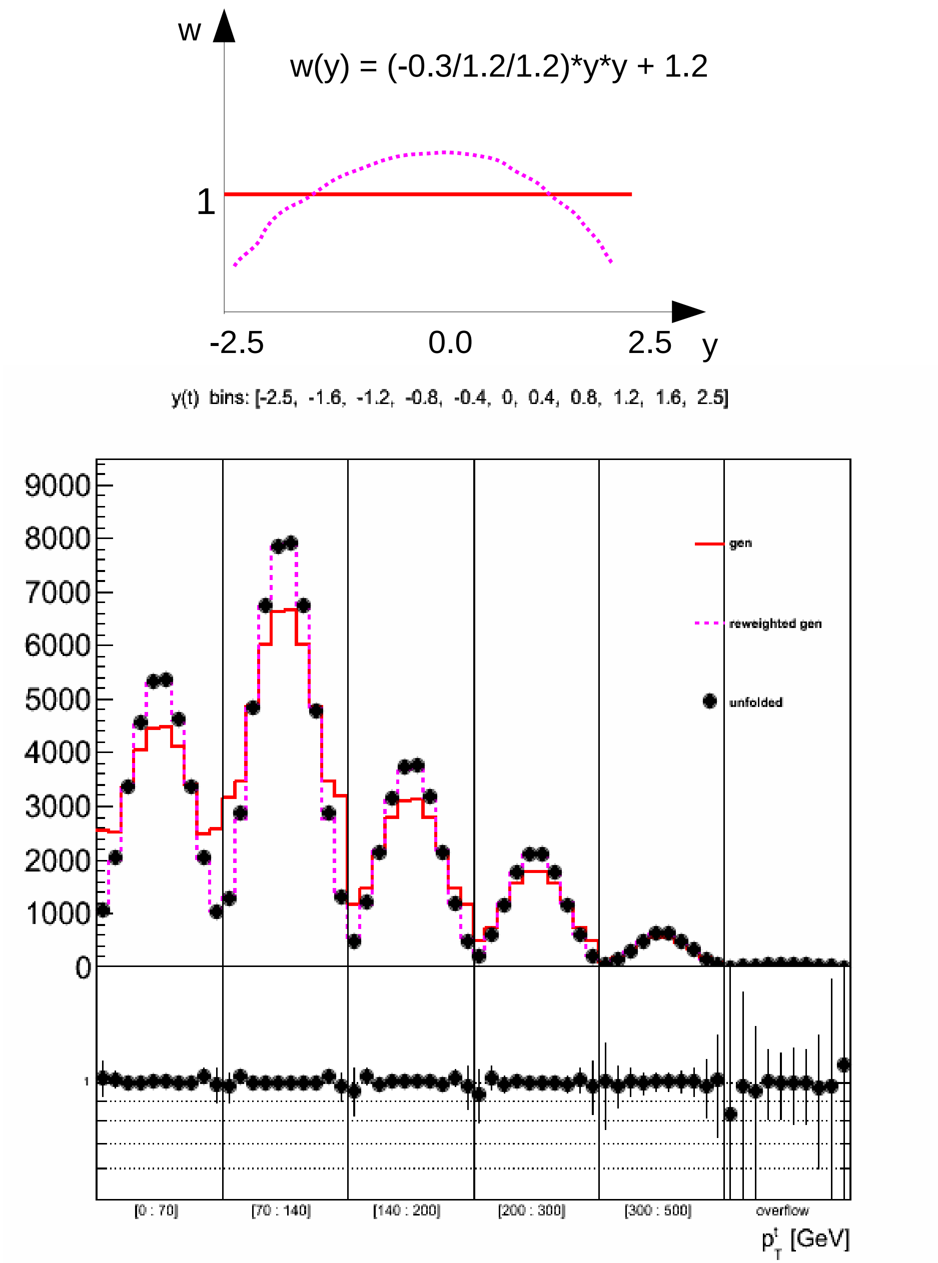


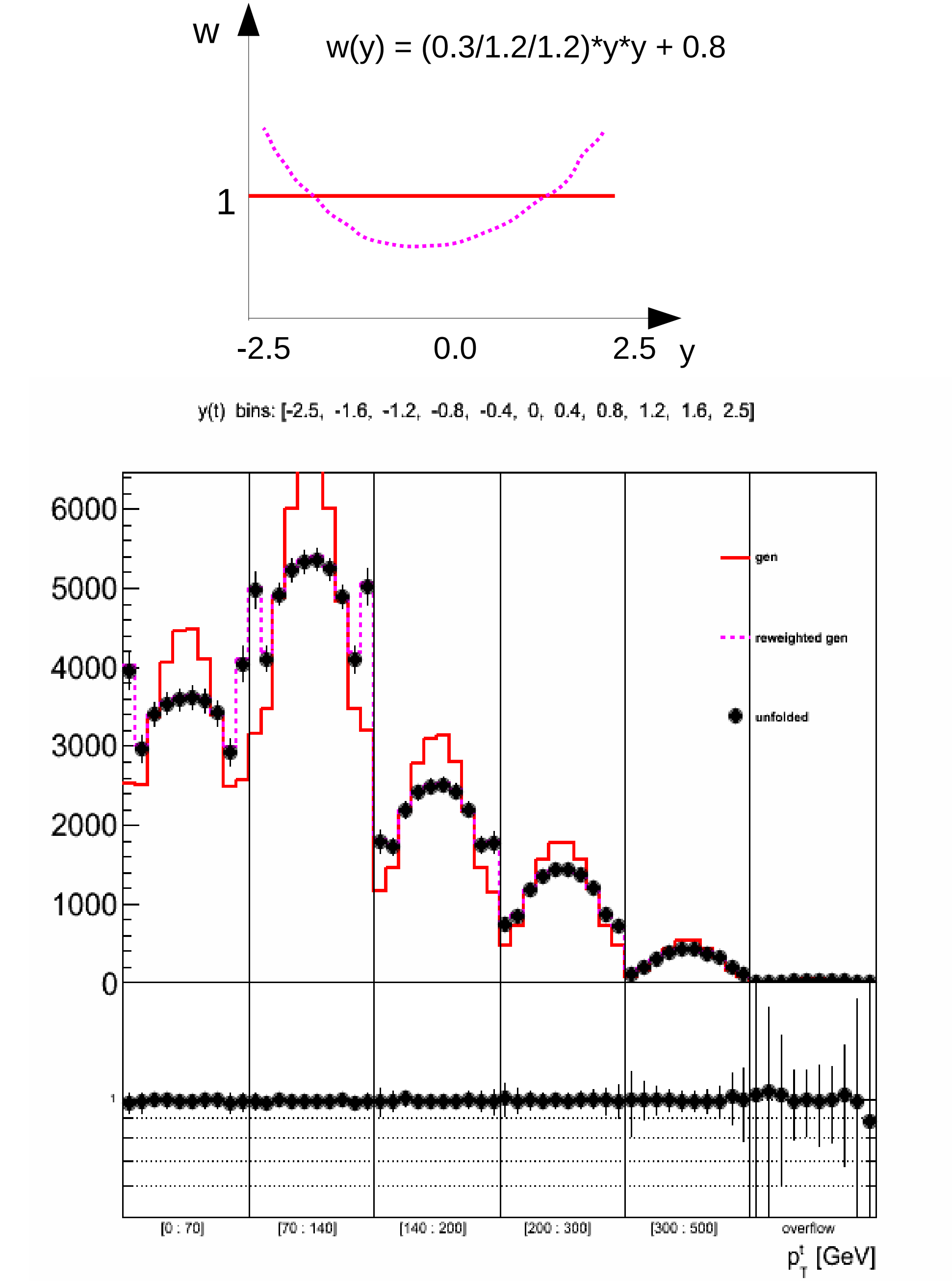




Bias at smallest and largest pT small compared to stat. uncertainty

Closure test: y(t) reweighting





Some biases visible at the outer y regions, but small compared to statistical uncertainty

2d unfolding with TUnfold

- the mathematics and the basic ideas are explained here:
  - **http://arxiv.org/abs/1205.6201**
- a brief user manual:
  - **http://www.desy.de/~sschmitt/TUnfold/tunfold_manual_v17.3.pdf**

Unfolding by χ^2 - minimization

$$\chi^2 = (Y - AX)^T V_{YY}^{-1} (Y - AX) + \tau^2 (X - f_b X_0)^T (L^T L)(X - f_b X_0)$$

Y - vector of number events in fine bins (reconstructed)

X - unfolded number events in coarse bins ("true")

A - the elements A_{ij} of A describe for each row *j* of X the probabilities to migrate to bin *i* of Y (migration matrix obtained from signal MC)

τ^2 - gives the strength of the regularization (defined from L-curve scan)

L - rows of L where three elements are non-zero, corresponding to a regularization of the second derivative (curvature) of X

f_b - normalization factor (= 1 by default)

X_0 - taken from MC

Control plots and Cross sections

2d cross sections pt(t) vs y(t)