# Measurement of the top-anti-top differential production cross section in the all-hadronic final state using the 2016 proton-proton collision data at $\sqrt{s}$ = 13 TeV

National Technical University of Athens

Conference on Recent Developments in
High Energy Physics and Cosmology

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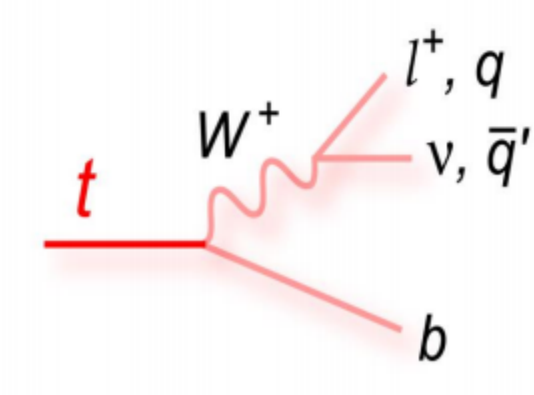
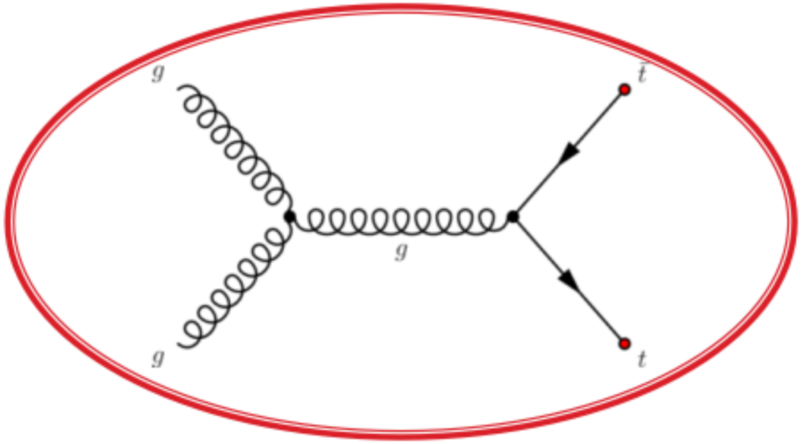
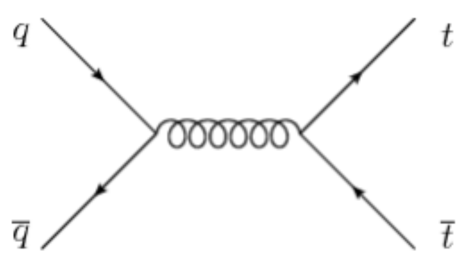
- Top Quark
- Boosted Jets
- CMS Experiment
- Analysis
- Overview

- Mass: $172.44 \pm 0.13 \frac{GeV}{c^2}$
- Top Quark decay:
  - $t \rightarrow W^+ + b \ (\bar{t} \rightarrow W^- + \bar{b})$
- Top quark pair production
  - $q + \bar{q} \rightarrow t + \bar{t}$
  - $g + g \rightarrow t + \bar{t}$




Gluon Fusion is dominant at LHC

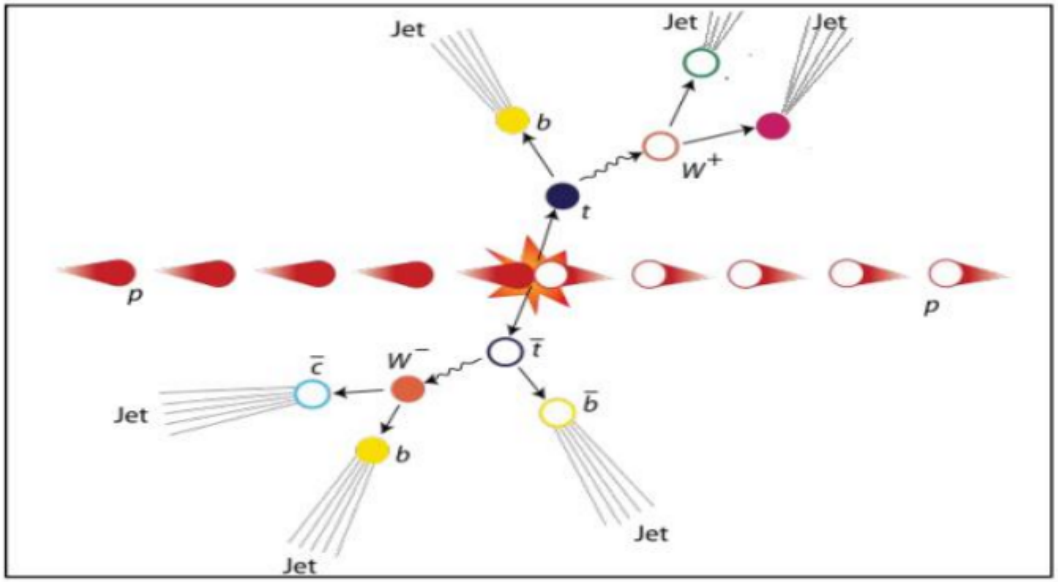


(b)

1. $t\bar{t} \rightarrow W^{+}bW^{-}\bar{b} \rightarrow q\bar{q}b\, q''\bar{b}\bar{q}''$ (45.7 %) → hadronic

2. $t\bar{t} \rightarrow W^{+}bW^{-}\bar{b} \rightarrow q\bar{q}'b\, l^{-}\bar{\nu_l}\bar{b} + l^{+}\nu_l b q''\bar{q}'''\bar{b}$ (43.8 %) → semileptonic

3. $t\bar{t} \rightarrow W^{+}bW^{-}\bar{b} \rightarrow l^{+}\nu_l b l'\bar{\nu}'\bar{b}$ (10.5 %) → dileptonic

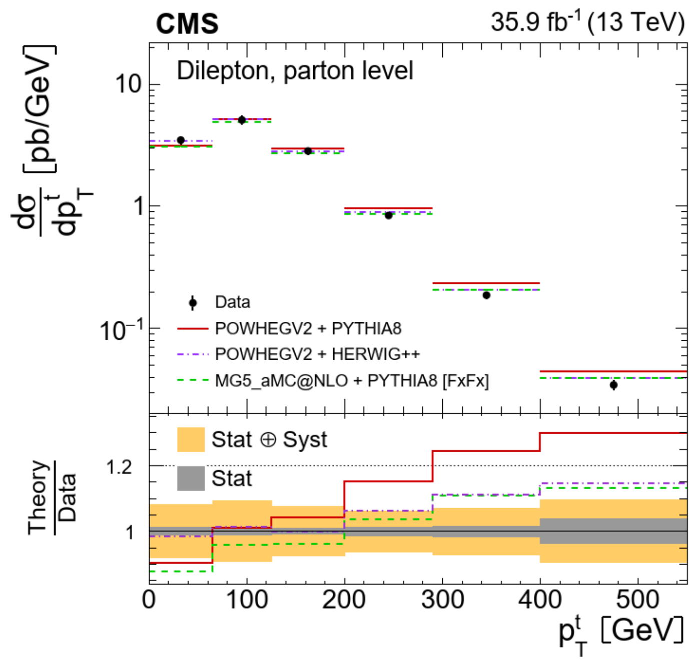


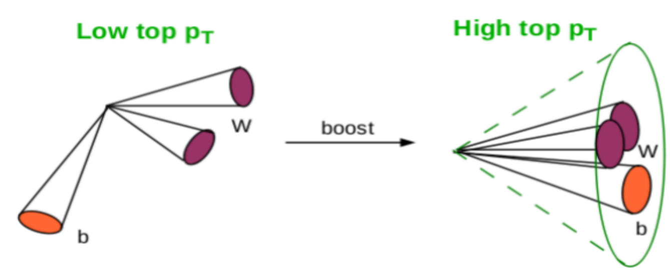
- Boosted Jets are jets with high $p_T$ ( > 400 GeV)
- Aim is the reconstruction of two big jets that contain the decay products of the top-antitop quark pair decay

- Motivation
  - With resolved hypothesis we measure the top pair cross section up to ~500GeV
  - There is an interesting discrepancy with theory ($p_T$ slope)
  - In order to see what happens in bigger $p_T$ ‘s → boosted

- Why Boosted jets?
  - Single “fat” jet: No combinatorial background
  - At high top $p_T$ the hadronic decay is easier to reconstruct than the leptonic

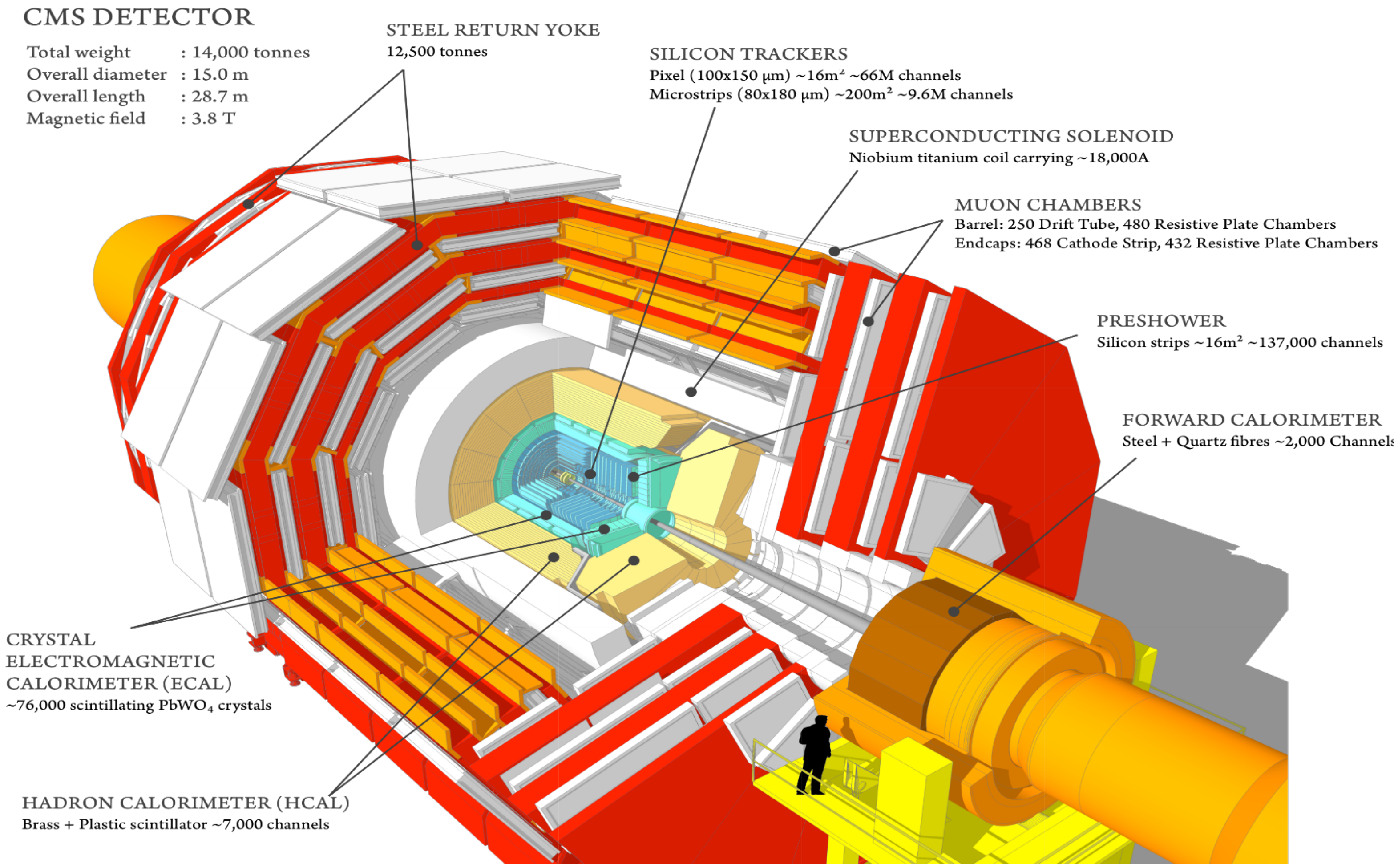
- In order to identify boosted jets
  - Use of sophisticated reconstruction techniques to identify the substructure within the jet
  - SoftDrop technique to eliminate soft contributions



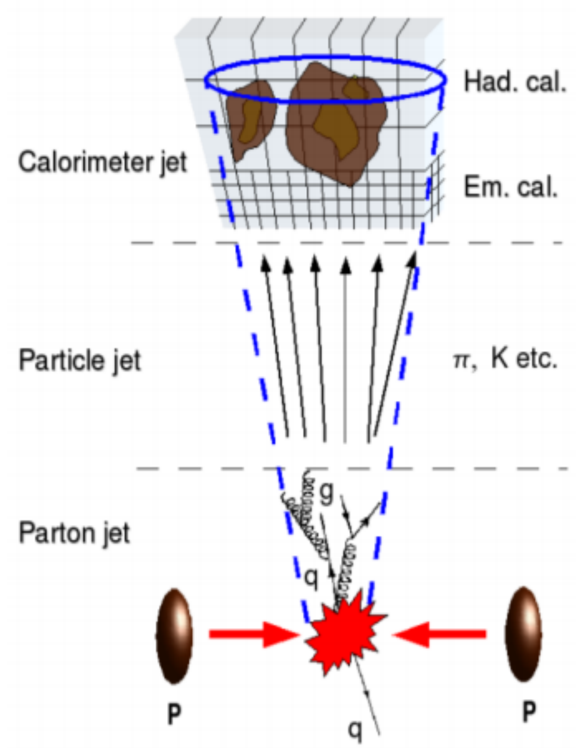
# Compact Muon Solenoid Experiment

- CMS is a general purpose detector and its goal is to investigate a wide range of physics



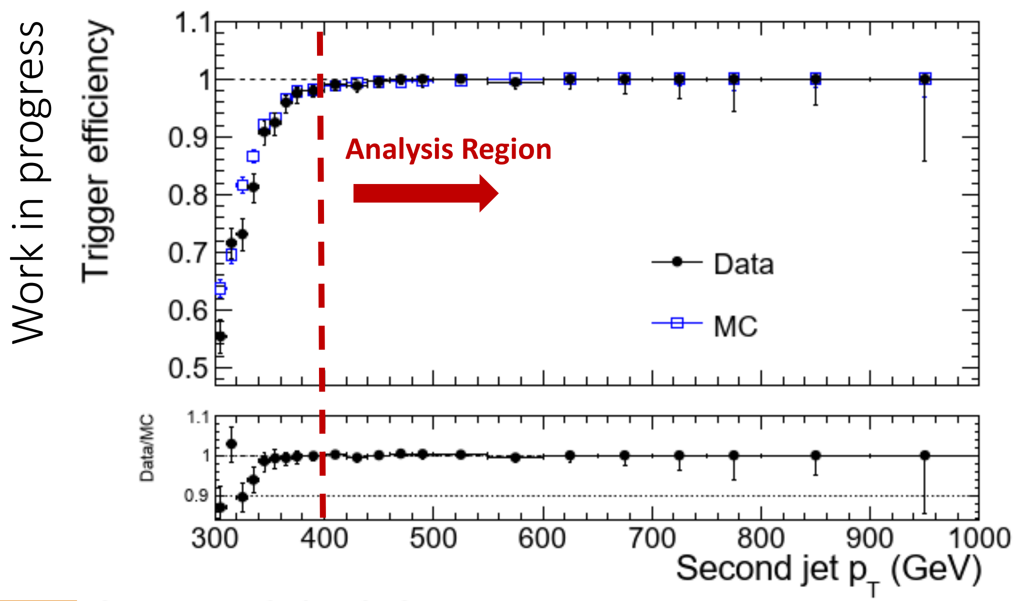
# Analysis Overview

- 2016 dataset
  - Very well understood (calibrations, scale factors, etc)
- Trigger:
  - L1: Single Jet with $p_T > 200$GeV
  - HLT: two AK8 jets, b tagged
- Selection:
  - two AK8 jets with $p_T > 400$ GeV
  - tagged ttbar event with MVA that uses the jet substructure variables as inputs
  - categories based on subjet b-tagging:
    - 0-btag: control region
    - 2-btag: signal region
  - Background
    - QCD dominant: taken from data
    - Single Top, W/Z +jets are negligible
- Deliverables
  - Differential cross sections in parton level (absolute and normalized)
  - Two observables: top $p_T$ , ttbar system mass



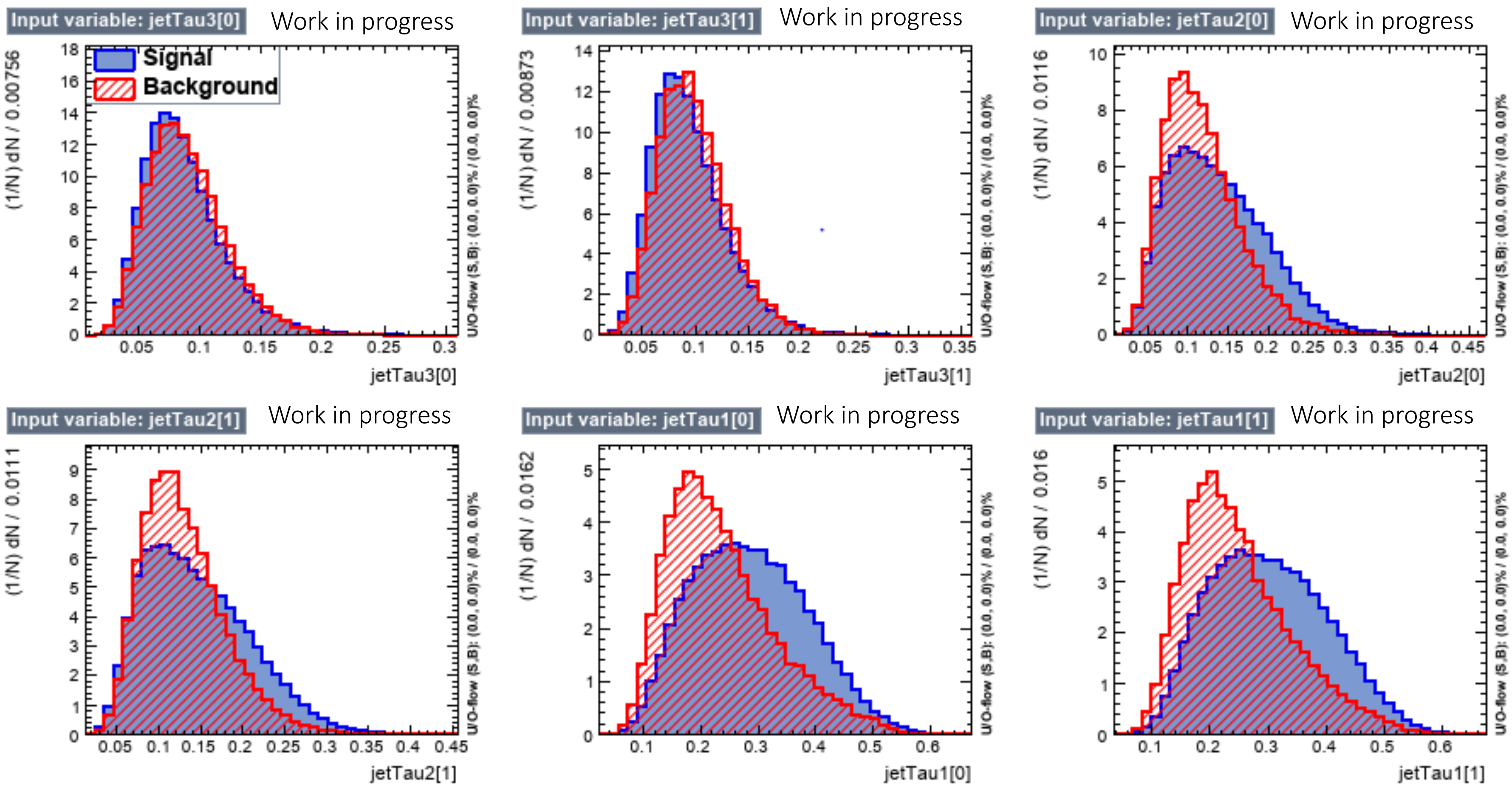
# Trigger

- Level 1 Trigger:
  - L1 SingleJet180 OR L1 SingleJet200
- High Level Trigger:
  - Signal path: HLT_AK8DiPFJet280_200_TrimMass30_BTagCSV p20
    - Aims to capture the decay products of boosted top pair
    - $p_{T,1}$ > 280 GeV and $p_{T,2}$ > 200 GeV
    - Jet mass > 30 GeV
    - At least one of the 2 jets should be b-tagged
    - Efficiency measured wrt orthogonal muon trigger
  - Control path: HLT_AK8DiPFJet280_200_TrimMass30
    - Same kinematics, no HLT b-tagging



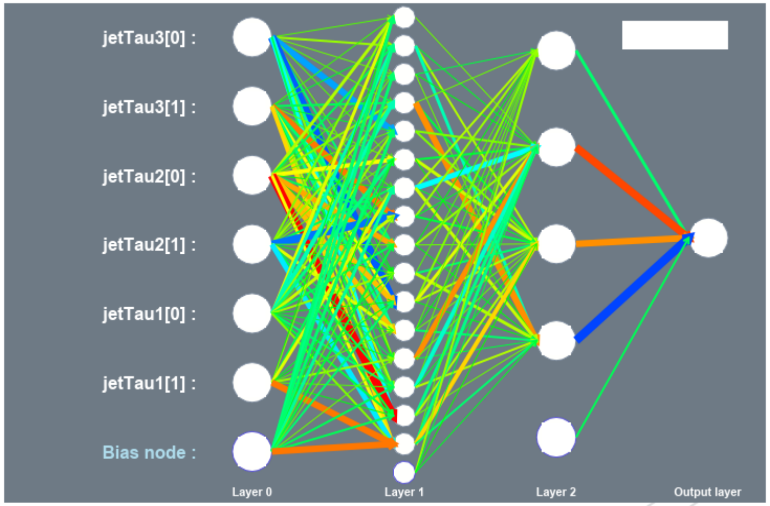

Trigger Efficiency vs Subleading jet $p_T$ (GeV)

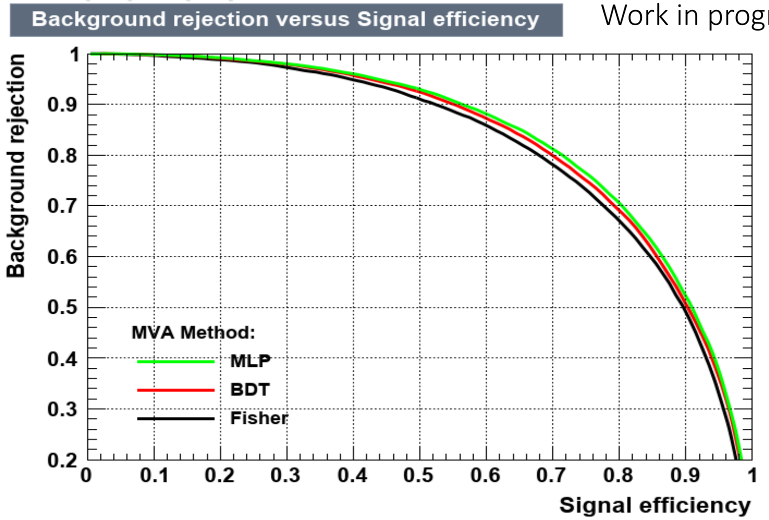
# Multivariate Discriminant Analysis(variables)



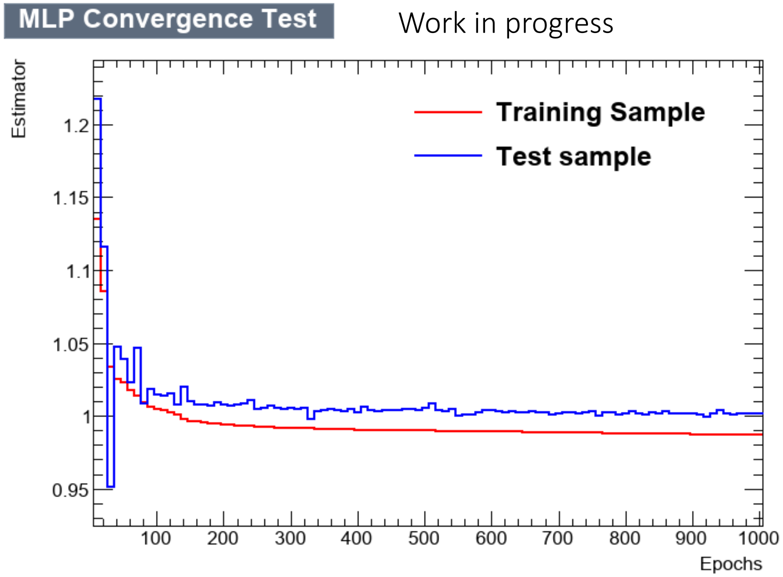

Discriminating variables used for separation of the $t\bar{t}$ from the QCD events

# Multivariate Discriminant Analysis (training)

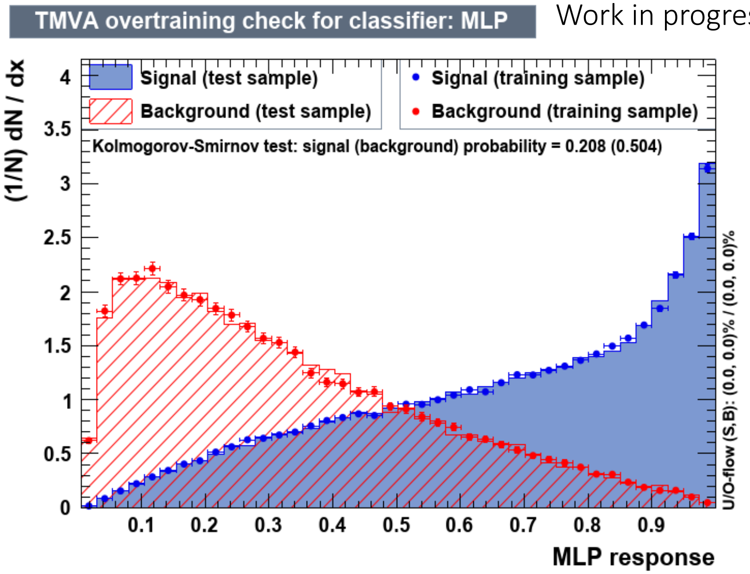



Work in progress




Work in progress



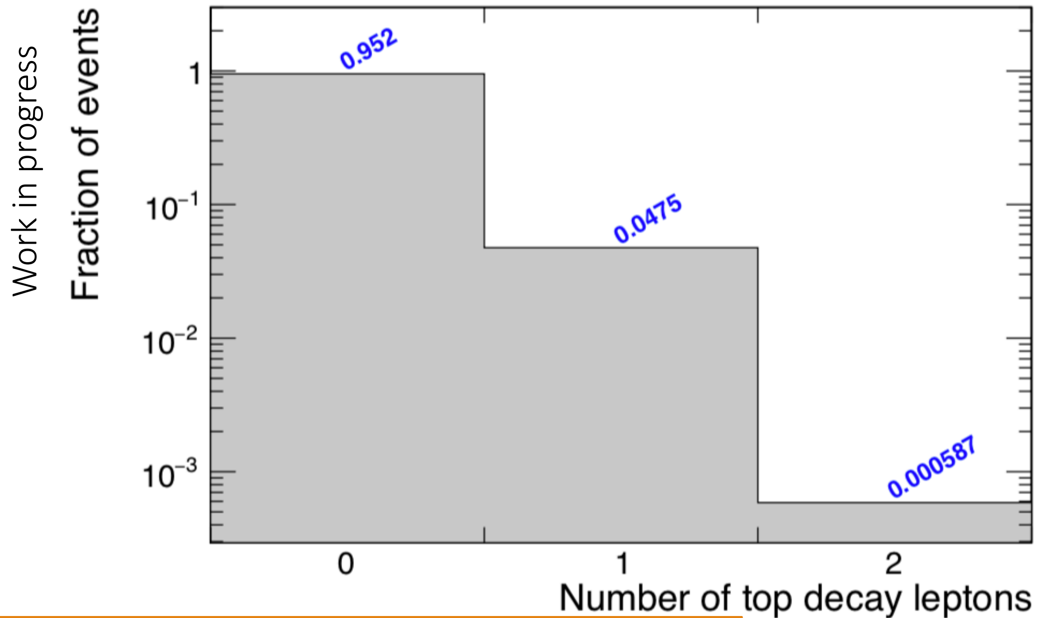

Work in progress

# Selection

## Baseline Selection

| Observable | Requirement |
|---|---|
| $N_{\mathrm{jets}}$ | $> 1$ |
| $N_{\mathrm{leptons}}$ | $= 0$ |
| $p_{\mathrm{T}}^{\mathrm{jet1,2}}$ | $> 400$ GeV |
| $m_{SD}^{\mathrm{jet1,2}}$ | $(50, 300)$ GeV |

Selected jets: AK8 PF+CHS

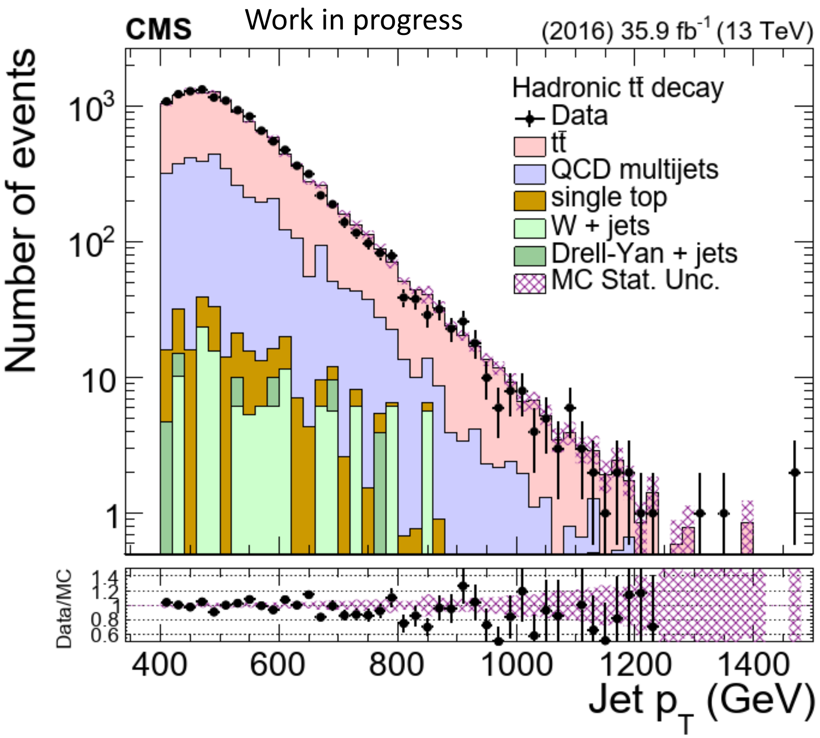


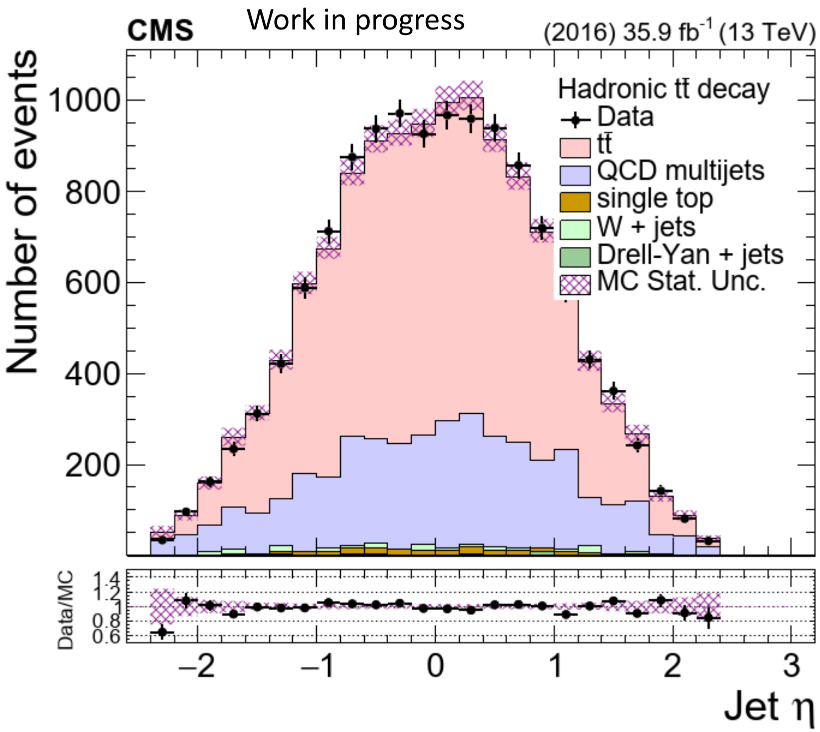

From signal selection almost 95% of the decays are hadronic

Table: Selection requirements per analysis region

| Region | Trigger | Offline Requirements | Purpose |
|---|---|---|---|
| $SR$ | signal | Base+$NN > 0.8$+cat. $= 2$+$m_{SD}^{jet1,2} \in (120, 220)$ GeV | signal region |
| $SR_A$ | signal | Base+$NN > 0.8$+cat. $= 2$ | QCD fit region |
| $SR_B$ | signal | Base+cat. $= 2$+$m_{SD}^{jet1,2} \in (120, 220)$ GeV | signal systematics region |
| $CR$ | control | Base+$NN > 0.8$+cat. $= 0$+$m_{SD}^{jet1,2} \in (120, 220)$ GeV | QCD control region |

| Process | Yield |
|---|---|
| $t\bar{t}$ | 3978 |
| QCD | 2171 |
| W+jets | 51 |
| Z+jets | 12 |
| Single Top | 83 |
| Data | 6295 |


CMS
Work in progress
(2016) 35.9 fb$^{-1}$ (13 TeV)
Hadronic tt̄ decay
Data
tt̄
QCD multijets
single top
W + jets
Drell-Yan + jets
MC Stat. Unc.
Number of events
Data/MC
Jet $p_T$ (GeV)


CMS
Work in progress
(2016) 35.9 fb$^{-1}$ (13 TeV)
Hadronic tt̄ decay
Data
tt̄
QCD multijets
single top
W + jets
Drell-Yan + jets
MC Stat. Unc.
Number of events
Data/MC
Jet η

# Signal Extraction

Fiducial Yield

Transfer factor from $SR_A$ to SR

Bkg Shape Correction
(taken from MC)

$$S_{fid}(x_{reco}) = D(x_{reco}) - R_{yield} N_{qcd} C_{bkg}^{shape} Q(x_{reco})$$

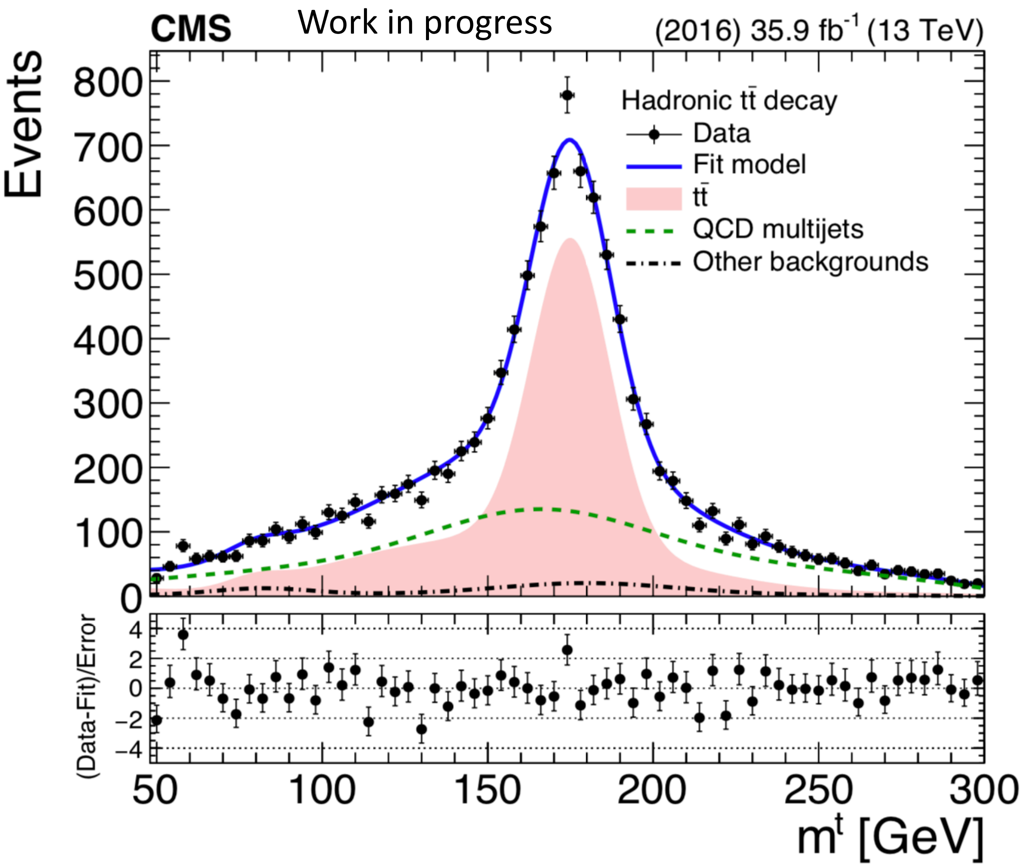
Data

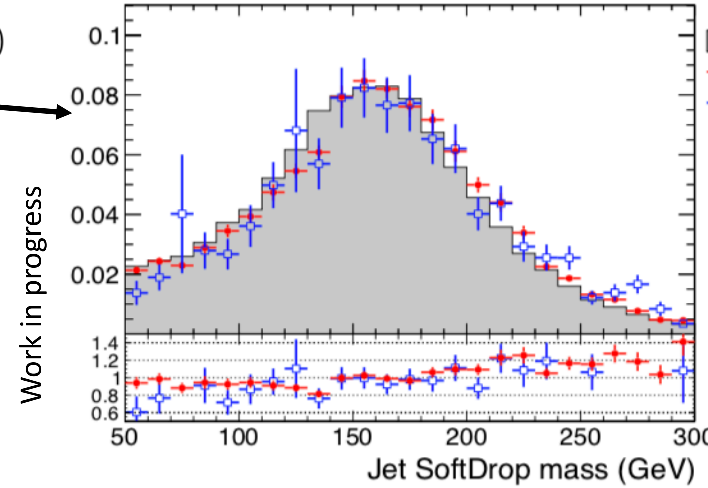
Bkg Yield
(fit in region $SR_A$)

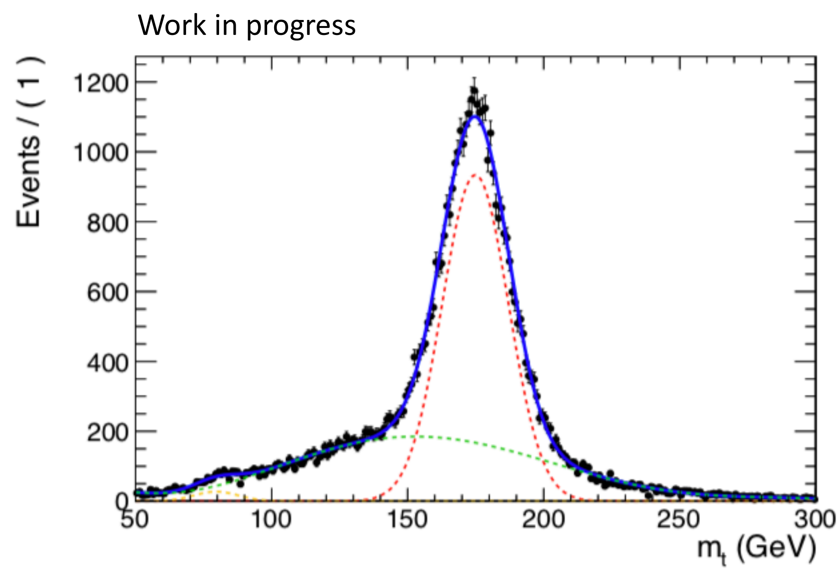
Bkg Shape
(taken from CR in data)

# Fit in the $SR_A$ Region

$$D(m^t) = N_{t}\bar{t}T(m^t; k_{\text{scale}}, k_{\text{res}}) + N_{\text{qcd}}(1 + k_{\text{slope}}m^t)Q(m^t) + N_{\text{bkg}}B(m^t)$$



## Parton Level selection

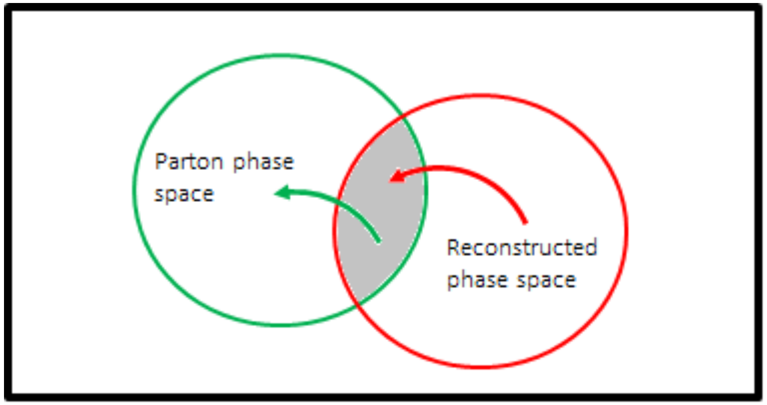
| Observable | Requirement |
|---|---|
| $p_T^{t,\bar{t}}$ | $> 400$ GeV |
| $\lvert\eta^{t,\bar{t}}\rvert$ | $< 2.4$ |
| $m_{t\bar{t}}$ | $> 800$ GeV |

$$\frac{d\sigma_i^{\mathrm{unf}}}{dx} = \frac{1}{\mathcal{L}\cdot\Delta x_i}\cdot\frac{1}{f_{2,i}}\cdot\sum_j\left(R_{ij}^{-1}\cdot f_{1,j}\cdot S_j\right)$$

Reco and parton over reco

Reco and parton over parton

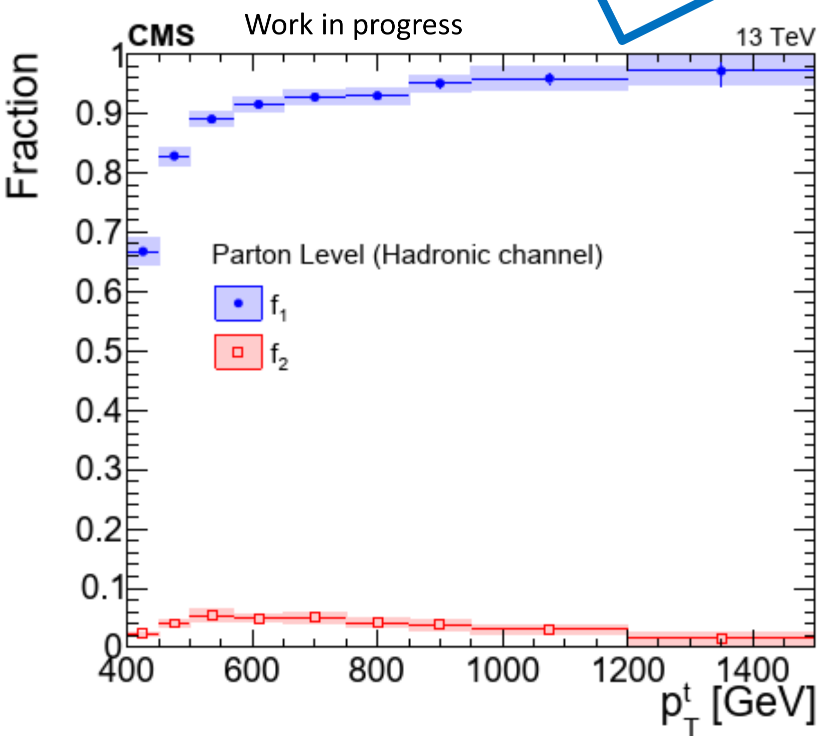
Migration matrix

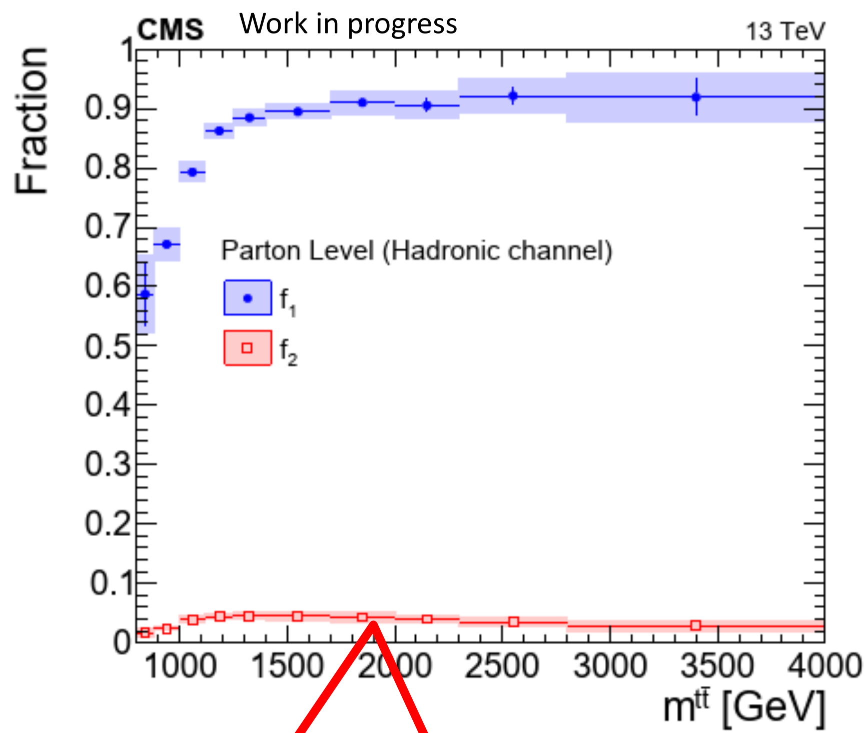



Unfolding is done using simple response matrix inversion without regularization

# Extrapolation factors for parton level

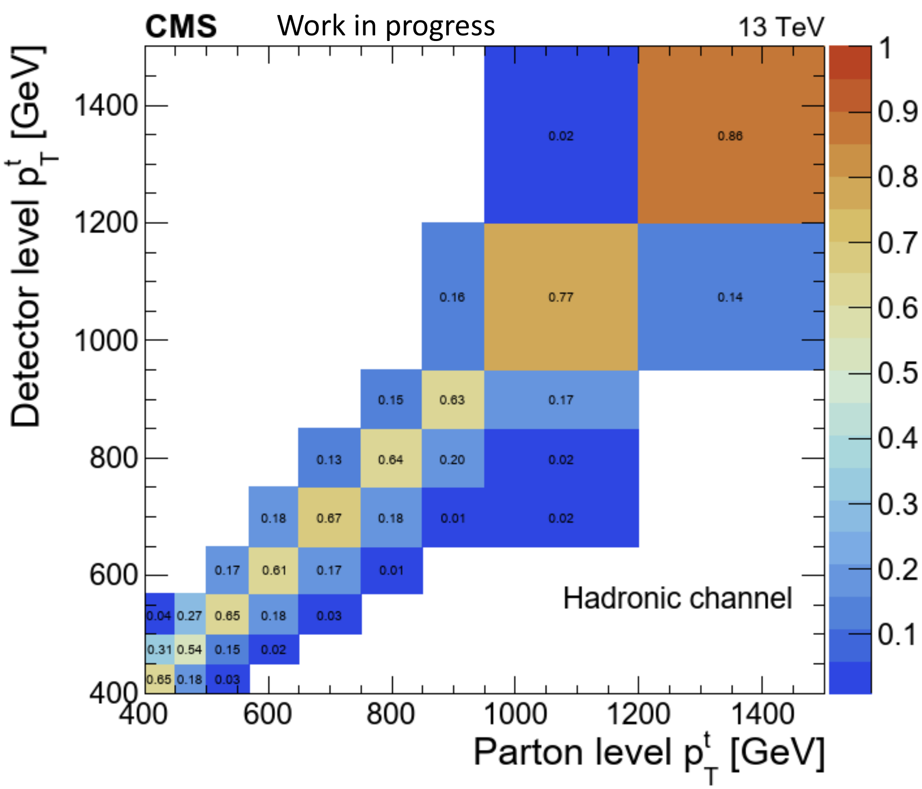
$f_1$: fraction of reco events in the reco+parton phase space

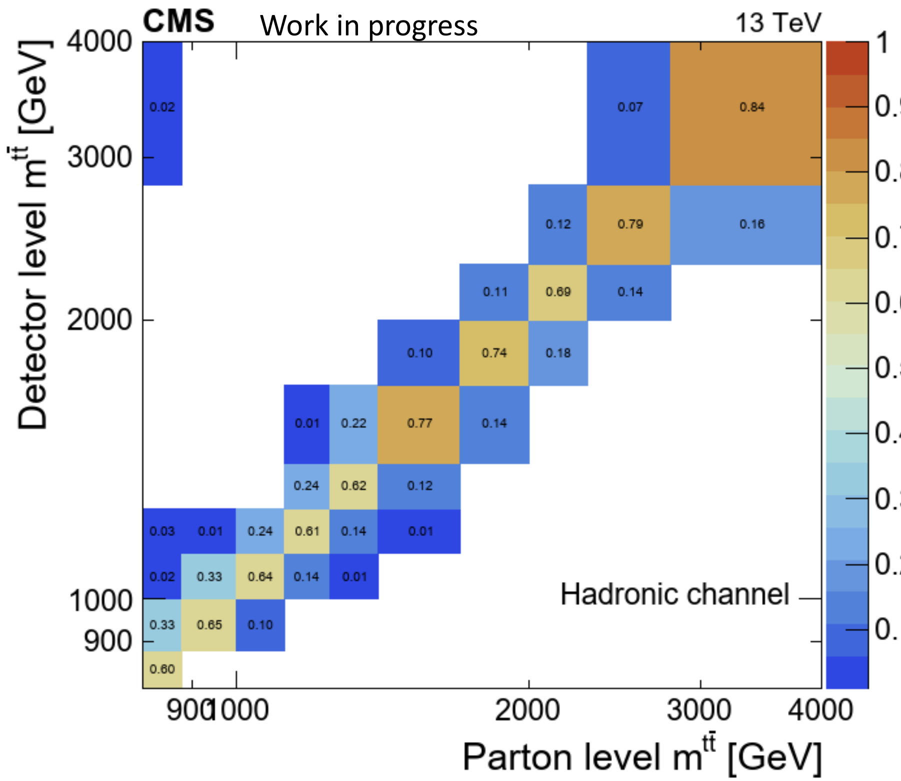



$f_2$: fraction of parton events in the reco+parton phase space

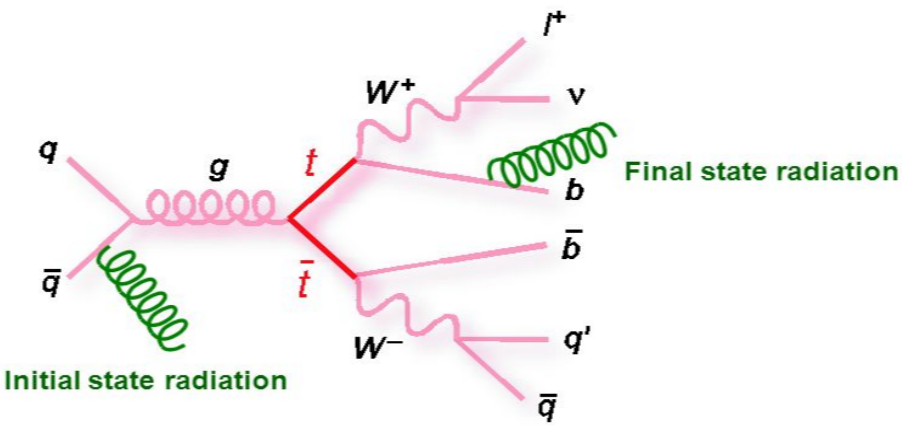
# Migration Matrices



# Uncertainties

- Experimental:
  - QCD background prediction
  - Statistics
  - Jet Energy Scale
  - Jet Energy Resolution
  - B tagging efficiency

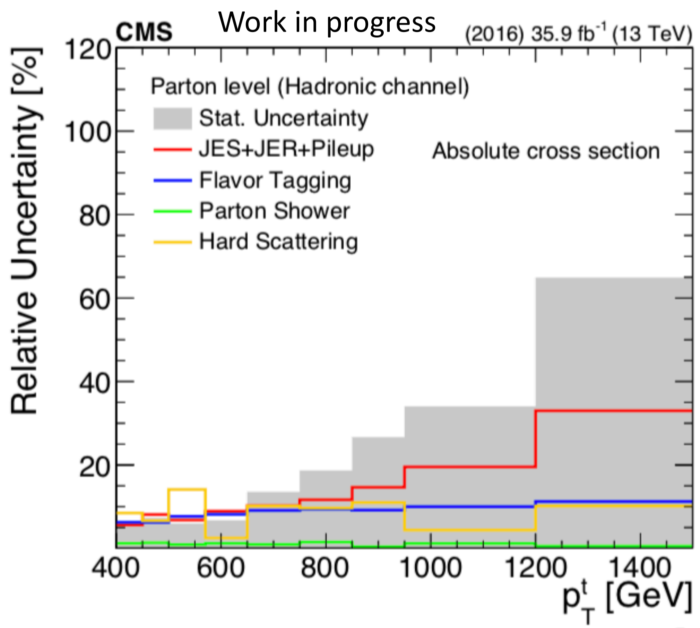


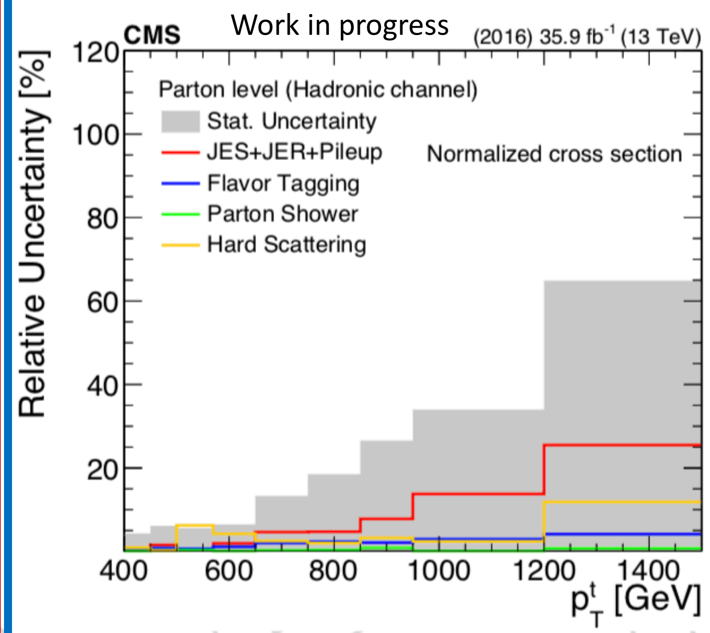

- Theoretical:
  - Affect the extrapolation factors ($f_1$ , $f_2$) and the migration matrices for the unfolding procedure
    - ISR (Initial State Radiation)
    - FSR (Final State Radiation)
    - CMS tuned set of MC parameters for Pythia 8

# Uncertainties

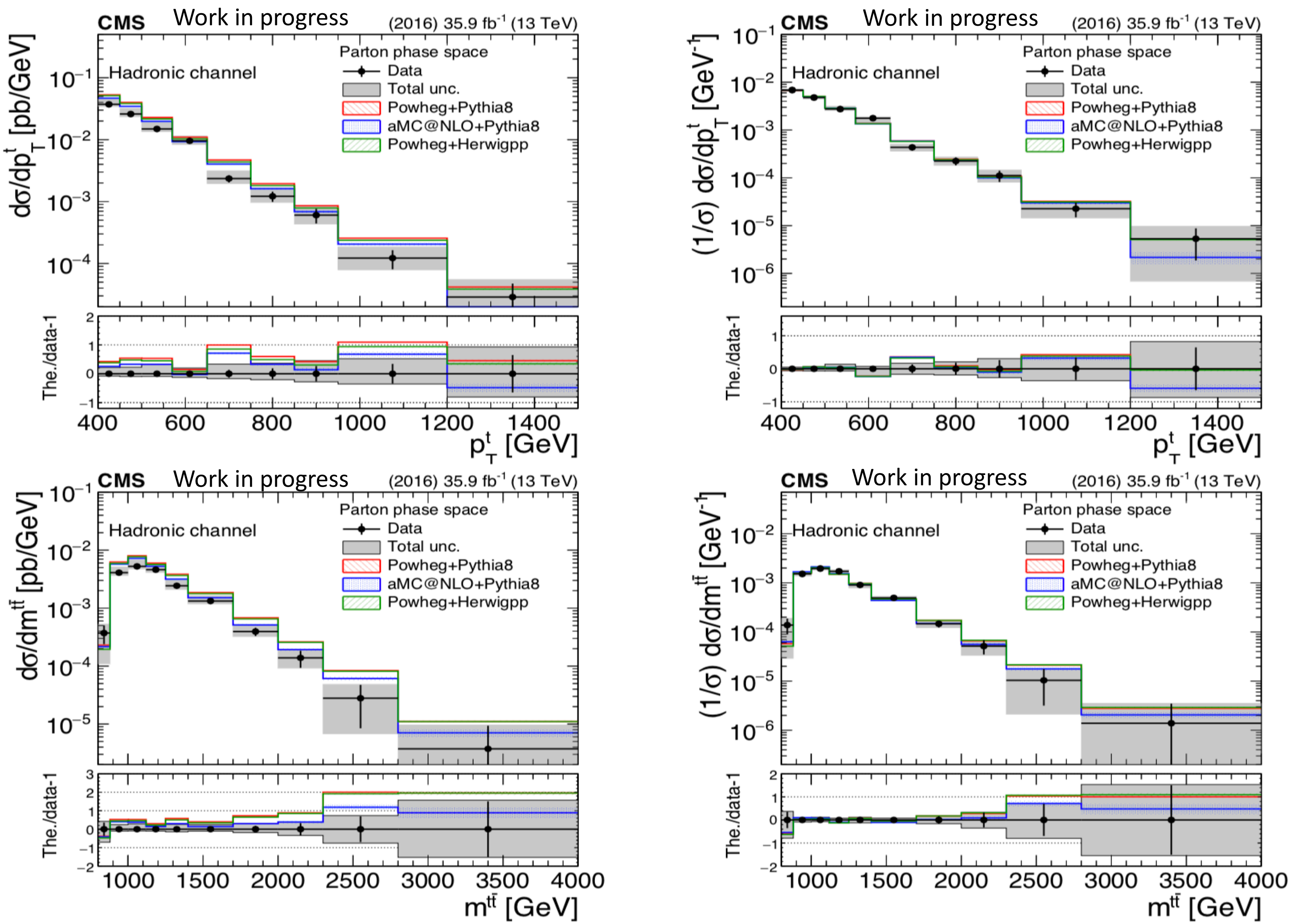
Uncertainties for the parton level measurements (absolute)

Uncertainties for the parton level measurements (normalized)



# Results for Parton Measurement (top $p_T$ , $m_{tt}$)



# Overview

- We have studied the $t\bar{t}$ production in proton-proton collisions at 13TeV energy recorded by the CMS detector

- Performed measurement of the differential ttbar cross section with boosted top quarks in the all hadronic channel , using 2016 data

- Presented the differential ttbar cross sections for two observables: incusive top $p_T$ ,$m_{tt}$
  - The results are presented in the parton phase space
  - Absolute and normalized cross sections

- Results
  - Comparison with MC models: Powheg+Pythia8, Powheg+Hewig++, aMC@NLO+Pythia8
  - Shapes show overall compatibility with theory
  - Systematically lower cross section in data *(this is a known effect also reported by ATLAS and other CMS measurements)*

Thank you for your attention!

# BACKUP SLIDES

# Jet Mass Soft Drop Technique

- Reconstruct the jet mass by removing soft contributions from pileup and collinear emissions

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \times \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

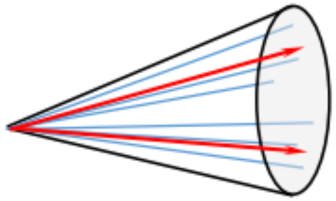
- CMS: $z_{cut} = 0.1$ and $\beta = 0$ , $R_0 = 0.8$
- This means that $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > 0.1$
- Technique goes backwards to de-cluster the jet→ keeps only the objects that have a $p_T$ no smaller than 10% of the "central" $p_T$ of the jet
- Suppress contributions from secondary sources

# N Subjetiness $\tau_N$

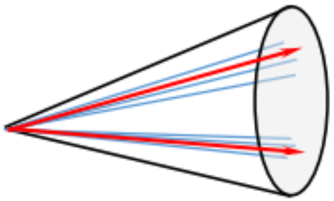
- The NN combines the $\tau_1$ , $\tau_2$ , $\tau_3$ of the two leading jets, where $\tau_N$ is the subjetiness and N is the number of prong jets
- Prong jets are the number of jets that determine the substructure of the boosted jets
- The $\tau_i$ is defined as

$$\tau_i = \frac{1}{\sum_k p_{T,k} R_0} \sum_k p_{T,k} \min(\Delta R_{1k}\,, \Delta \mathrm{R}_{2k}, \ldots \Delta R_{ik})$$

  - Where $\Delta R_{ik}$ is the angular separation between constituent k and candidate subjet i
  - $R_0$ = 0.8  for AK8 clustering



**High $\tau_2$ (consitutents spread out)**

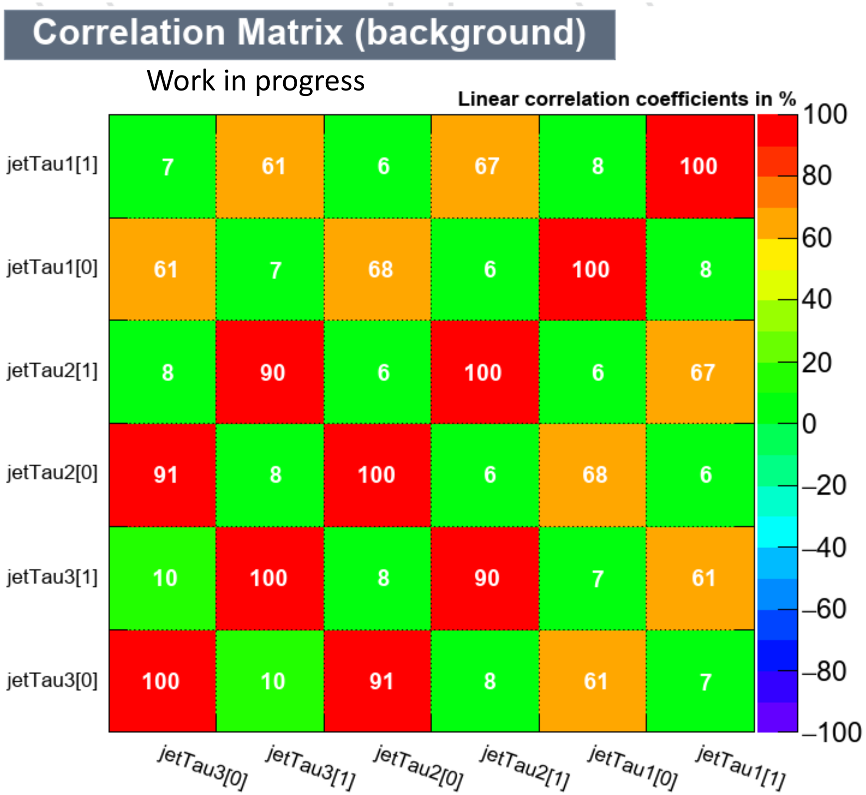


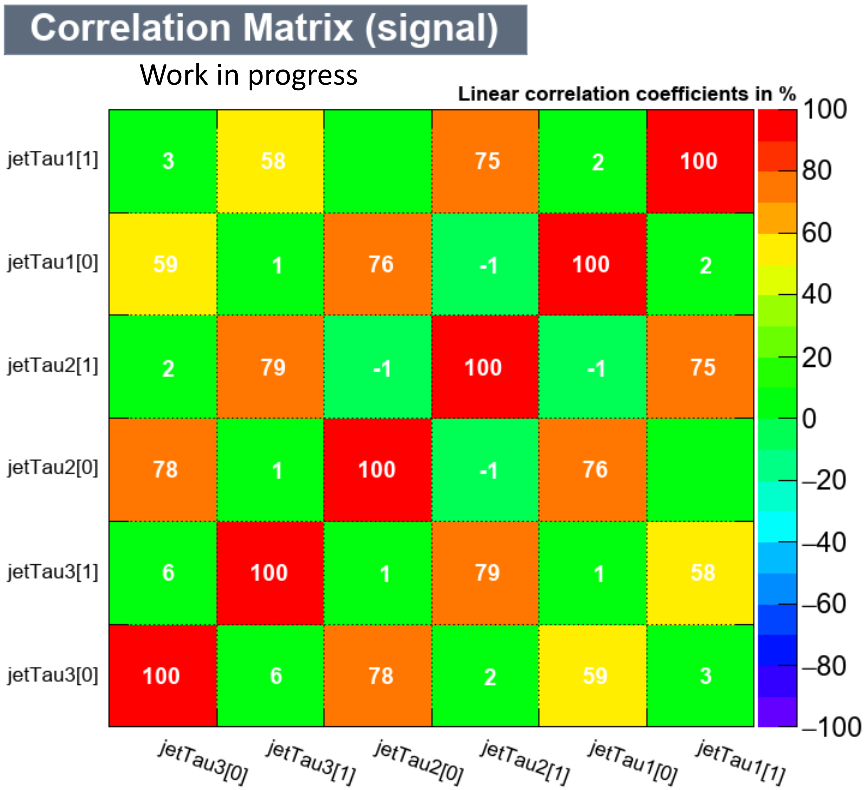
**Low $\tau_2$ (constituents close to subjet axes)**

Clusters with exactly N subjets will have small $\tau_N$

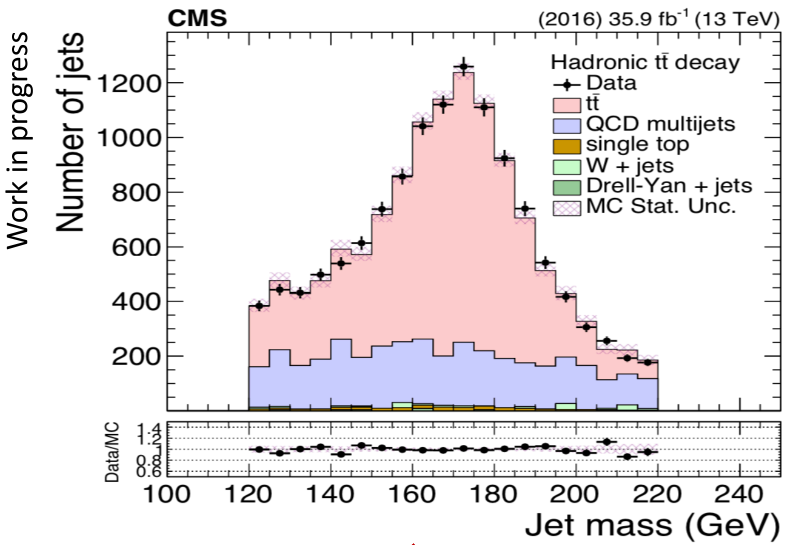
If $\tau_N \simeq 1$, cluster most likely has more than N subjets

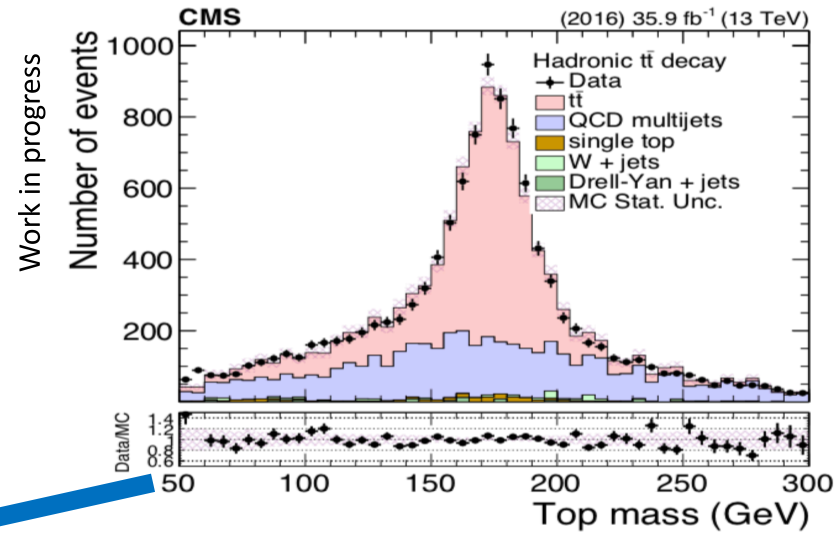
# MVA training: Correlation Matrices

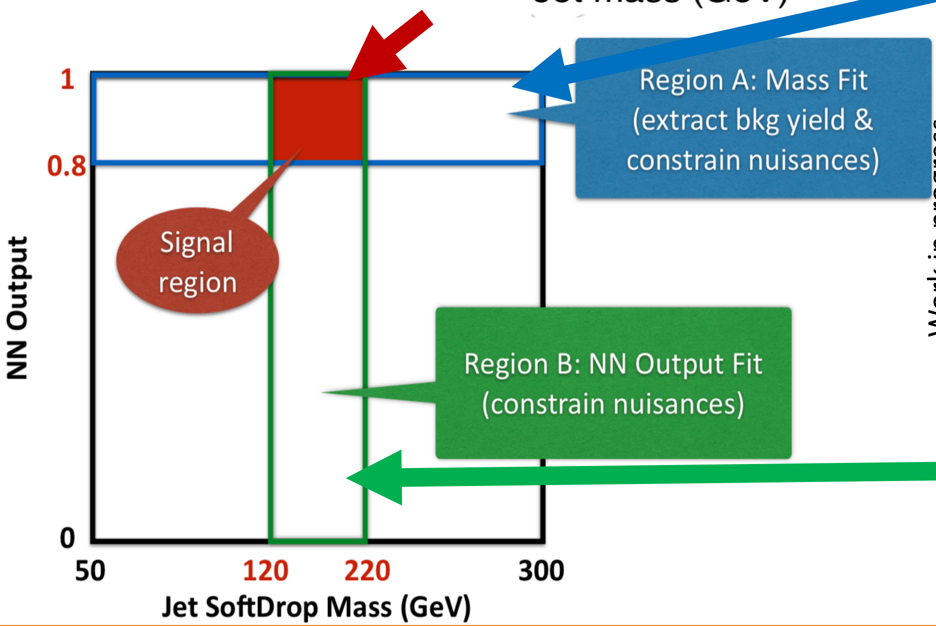


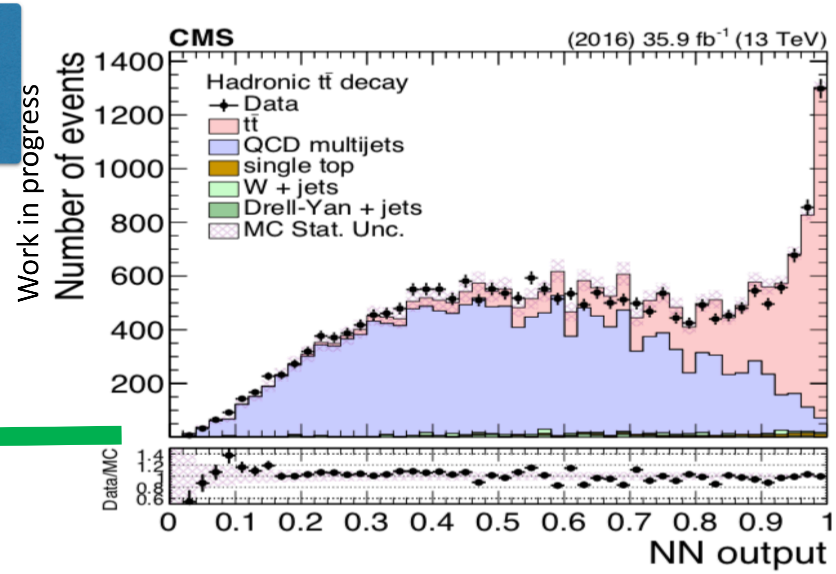



# Analysis Regions

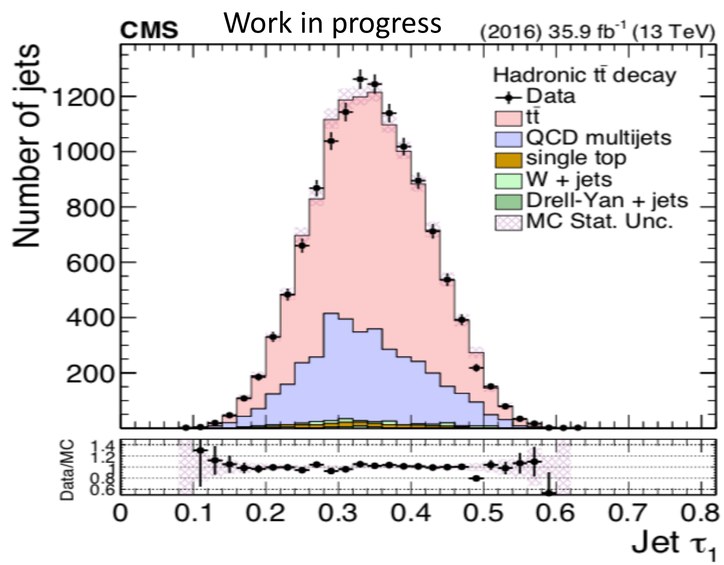


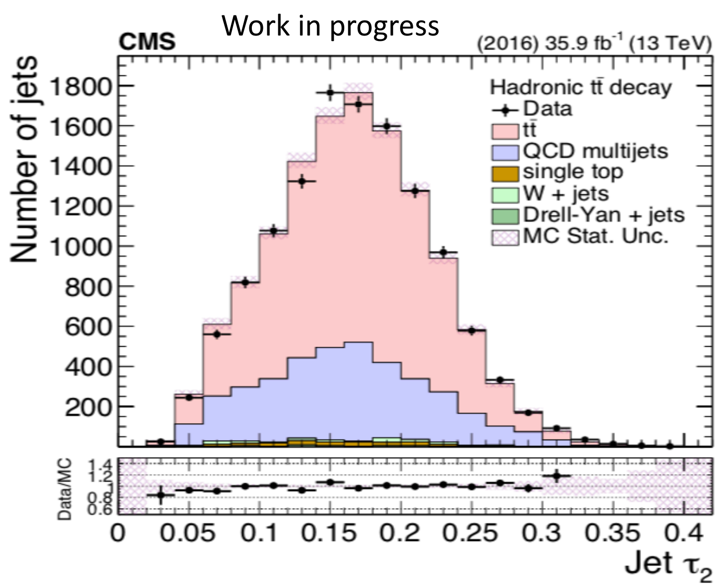



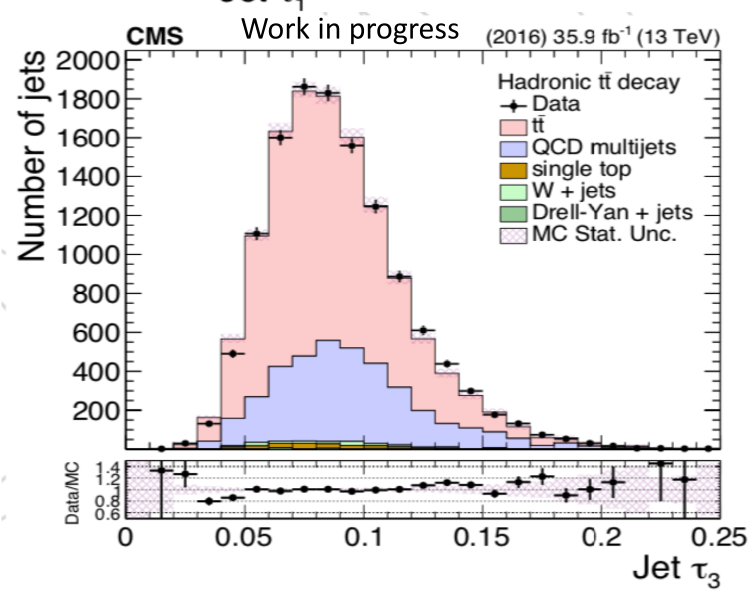



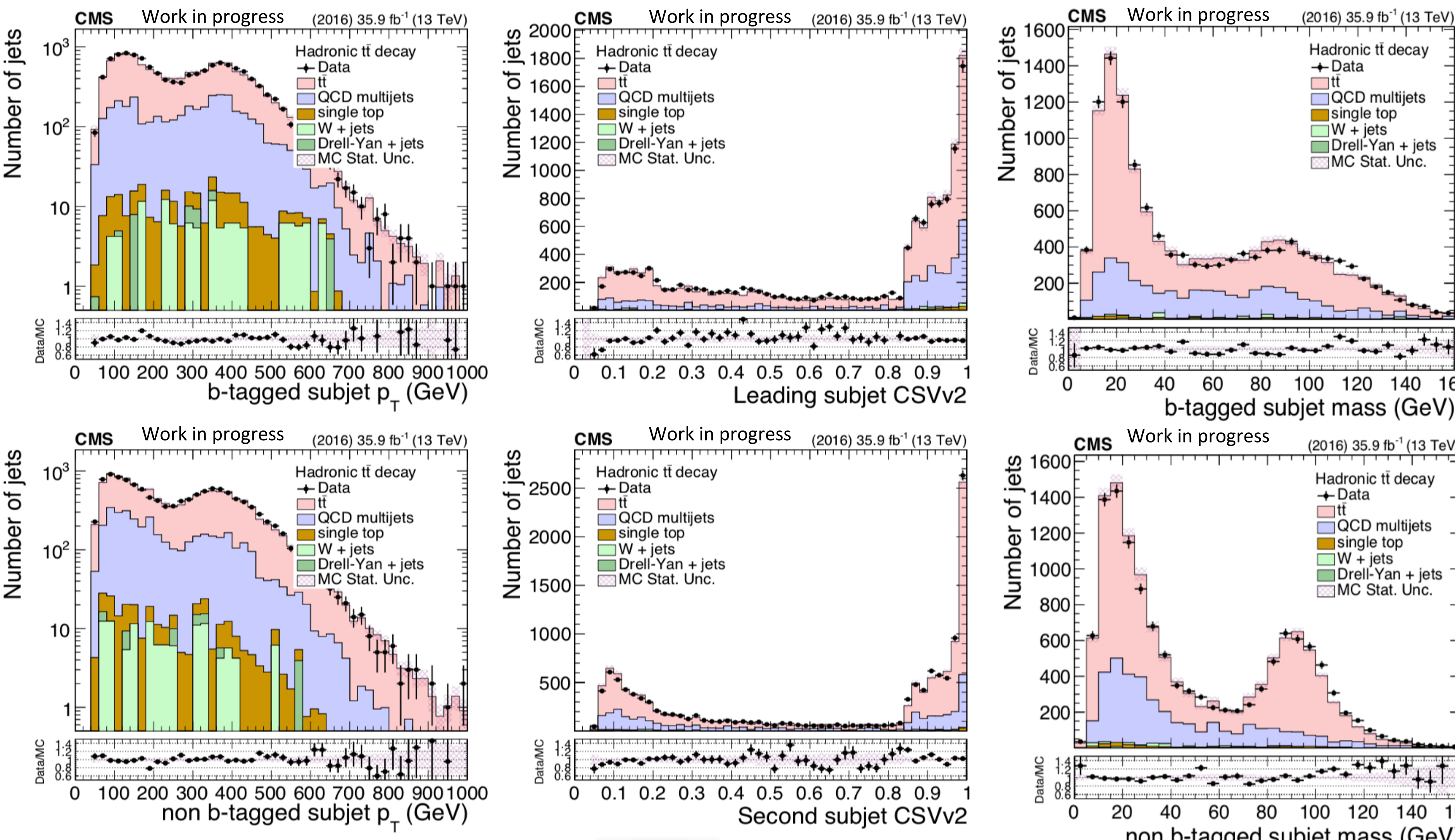
# Data vs MC: Substructure Properties



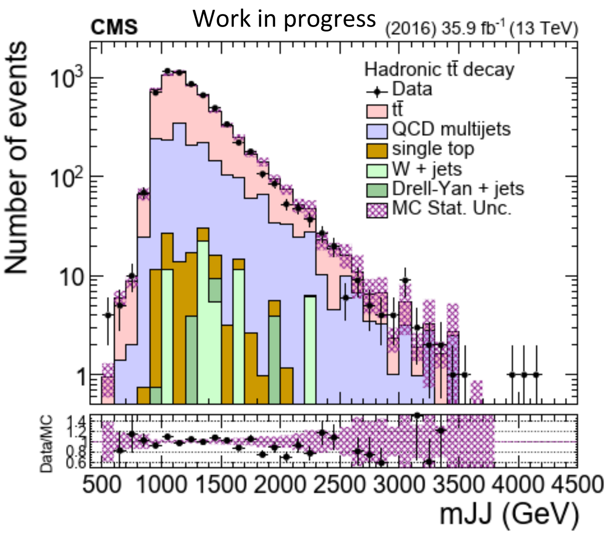



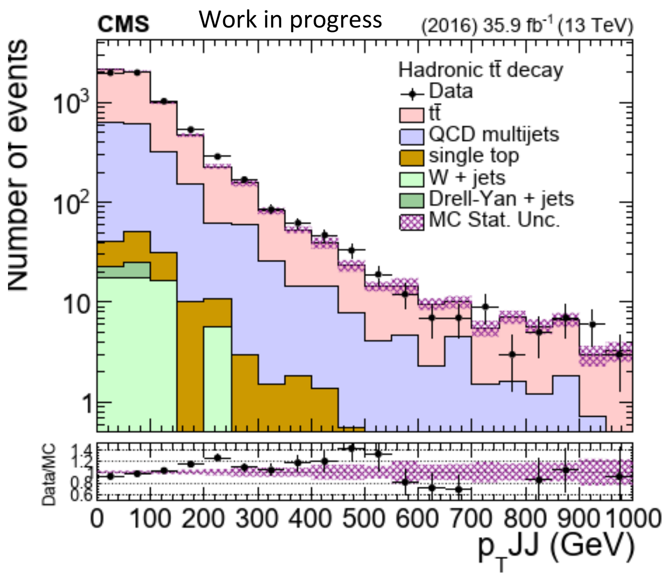



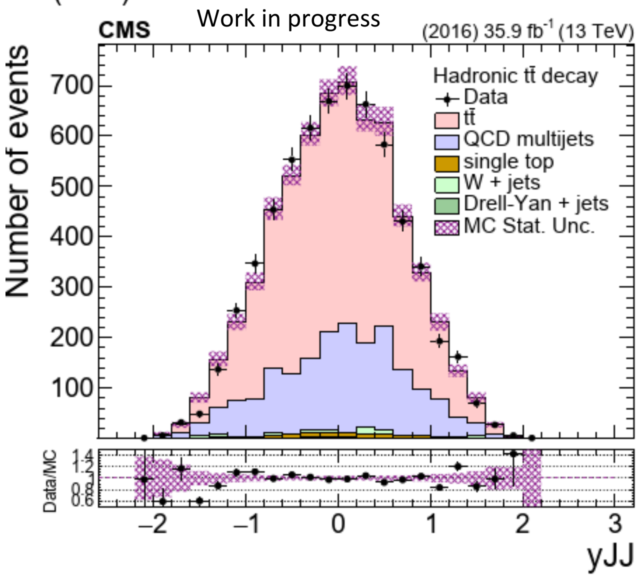
# Data vs MC: Subjet Properties



# Data vs MC: ttbar Kinematics



## Particle Level selection

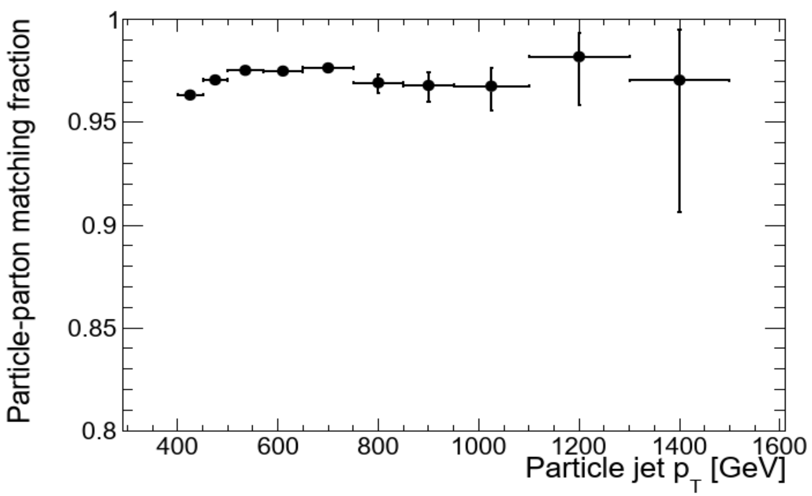
| Observable | Requirement |
|---|---|
| $N_{\text{jets}}$ | $> 1$ |
| $p_{\text{T}}^{\text{jet1,2}}$ | $> 400\,\text{GeV}$ |
| $\lvert\eta^{\text{jet1,2}}\rvert$ | $< 2.4$ |
| $m_{SD}^{\text{jet1,2}}$ | $(120, 220)\,\text{GeV}$ |
| $m_{jj}$ | $> 800\,\text{GeV}$ |

Reco and particle over reco

$$\frac{d\sigma_i^{\text{unf}}}{dx} = \frac{1}{\mathcal{L}\cdot\Delta x_i}\cdot\frac{1}{f_{2,i}}\cdot\sum_j\left(R_{ij}^{-1}\cdot f_{1,j}\cdot S_j\right)$$

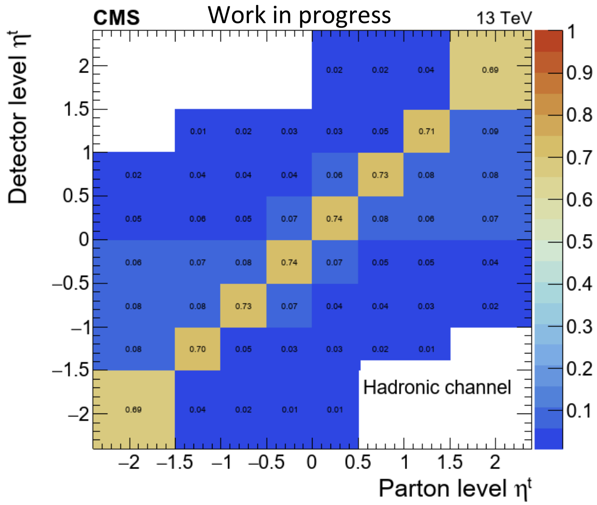
Reco and particle over particle

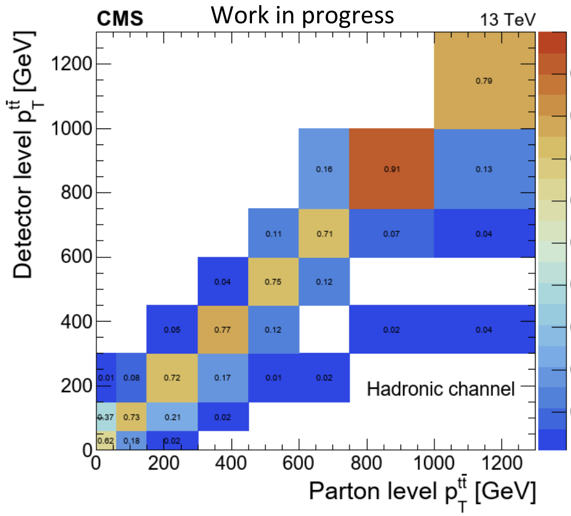
Migration matrix

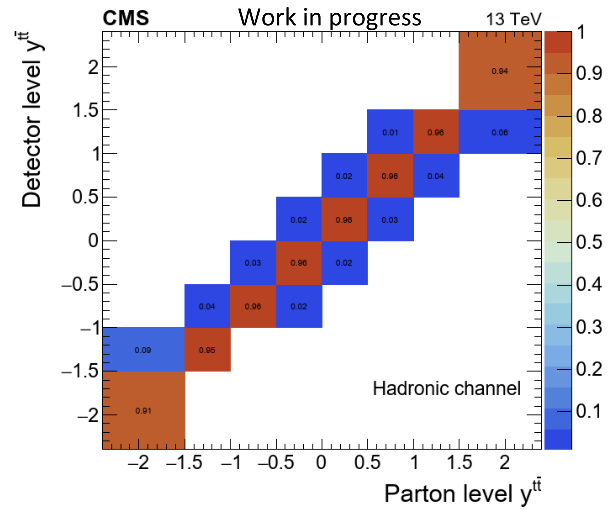


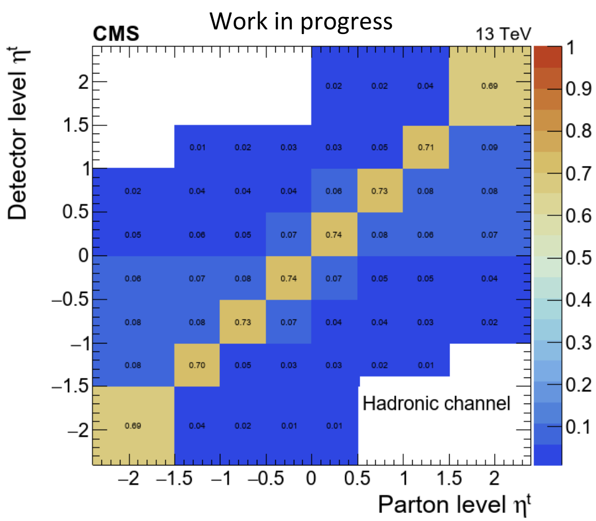

Particle to parton matching efficiency

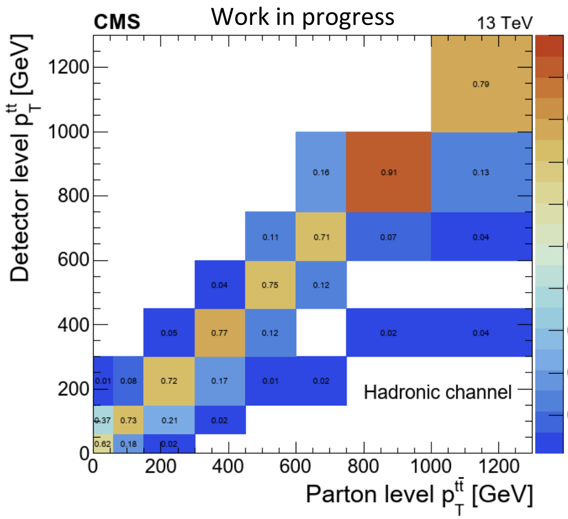
# Migration Matrices

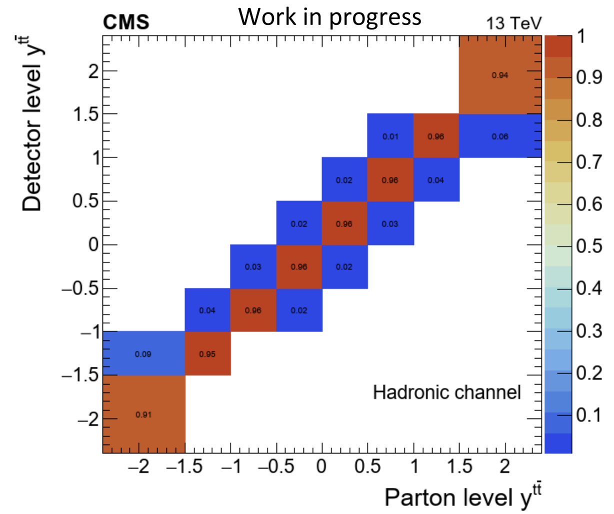


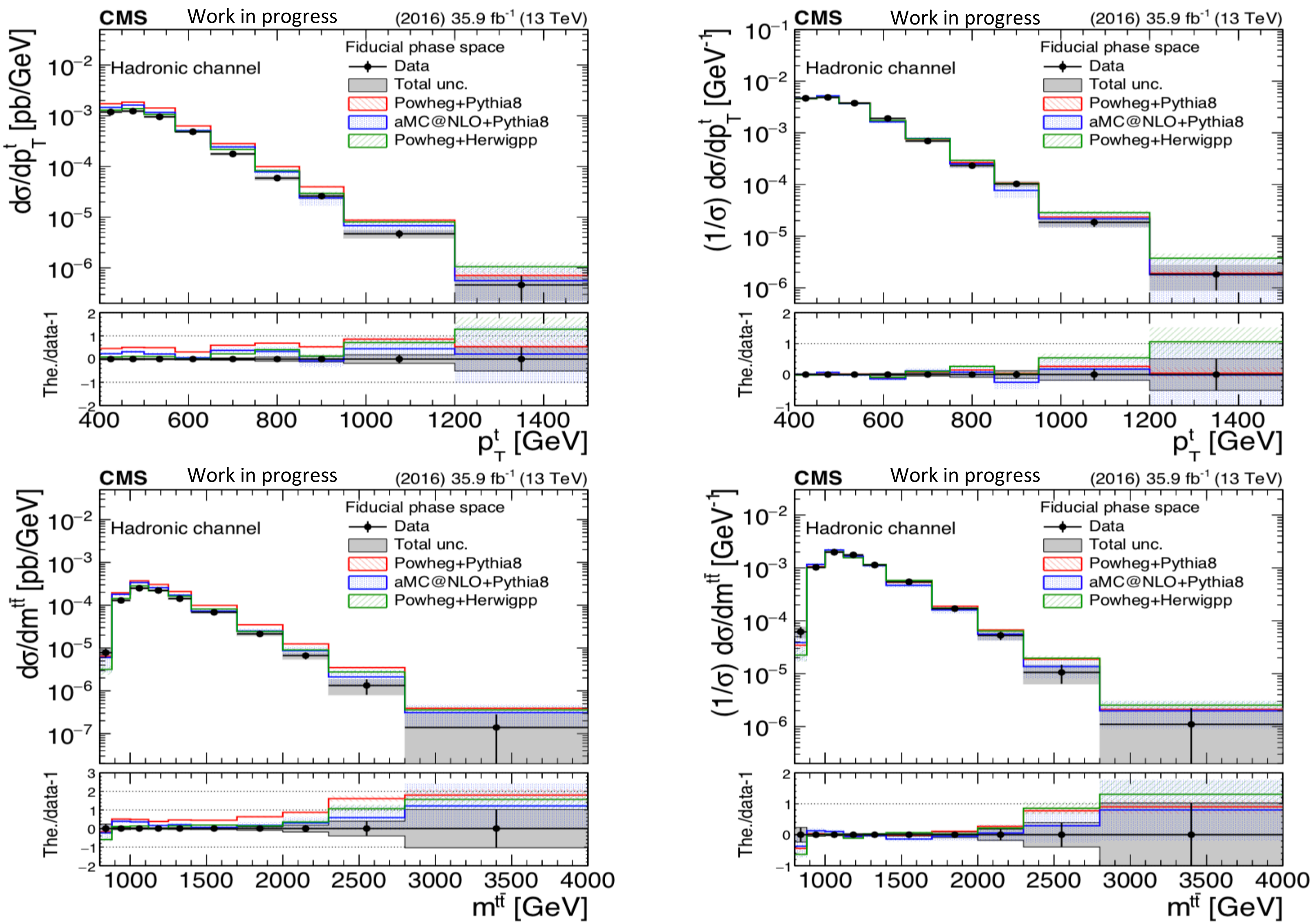



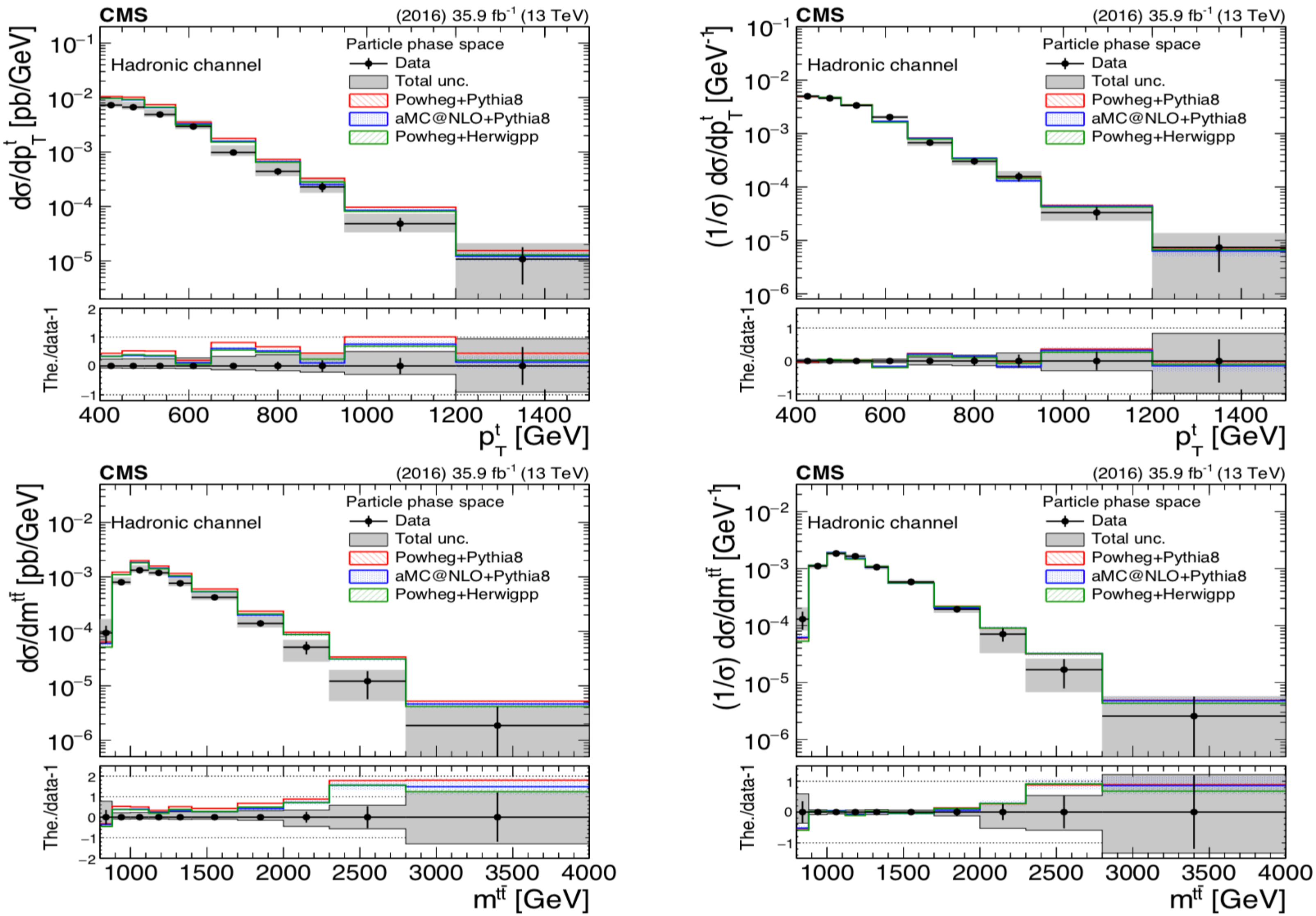



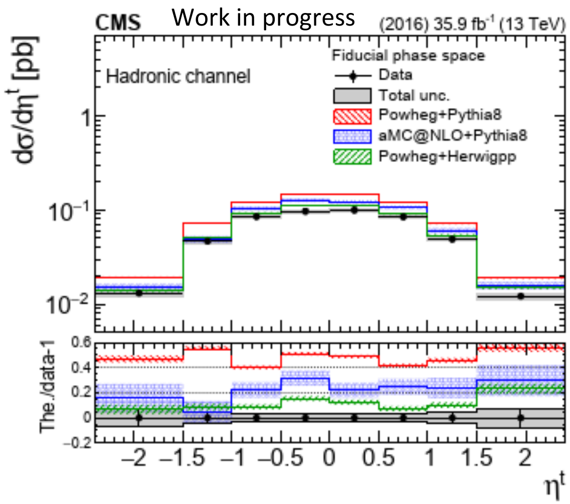
# Results for Fiducial Measurement (top $p_T$ , $m_{tt}$)

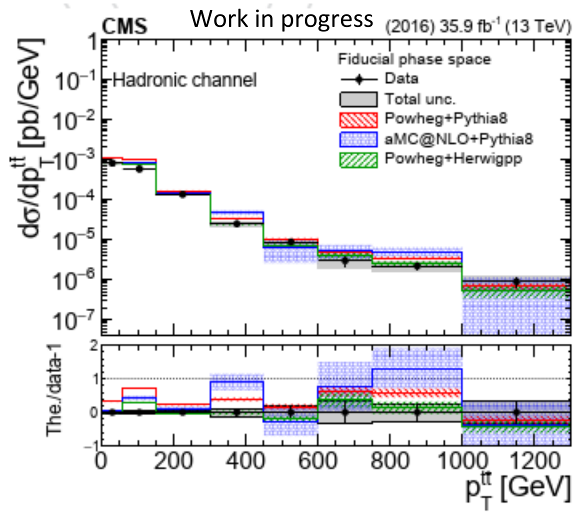


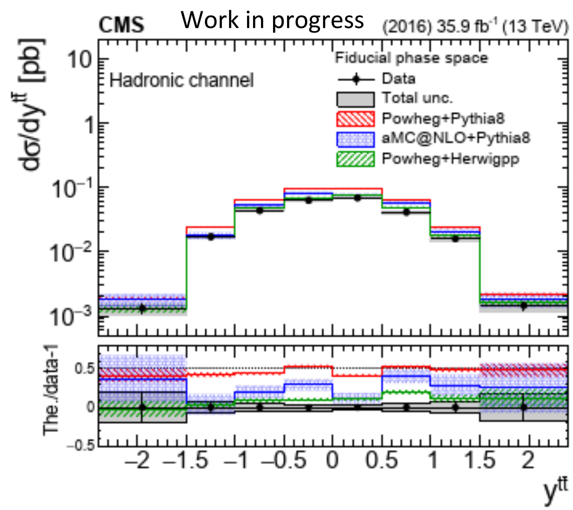
# Results for Particle Measurement (top $p_T$ , $m_{tt}$)

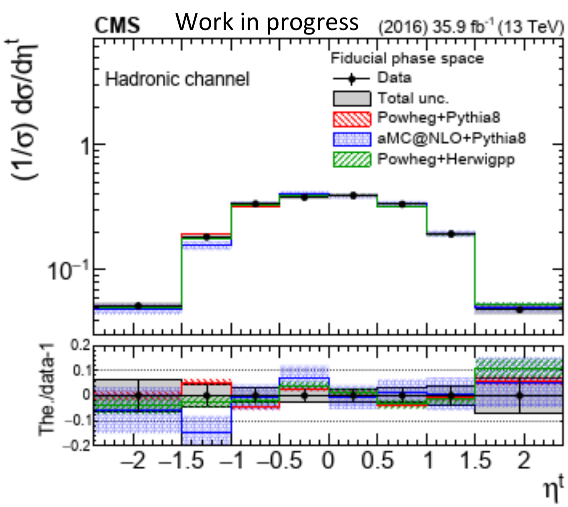


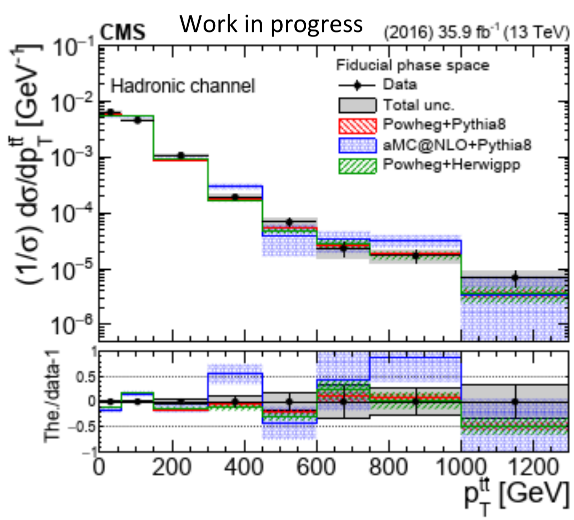
# Fiducial Results for $\eta^{t}$ , $p_{T,tt}$, $y_{tt}$

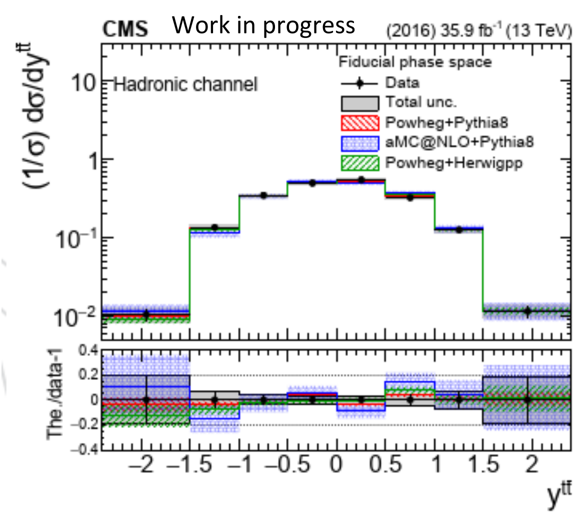


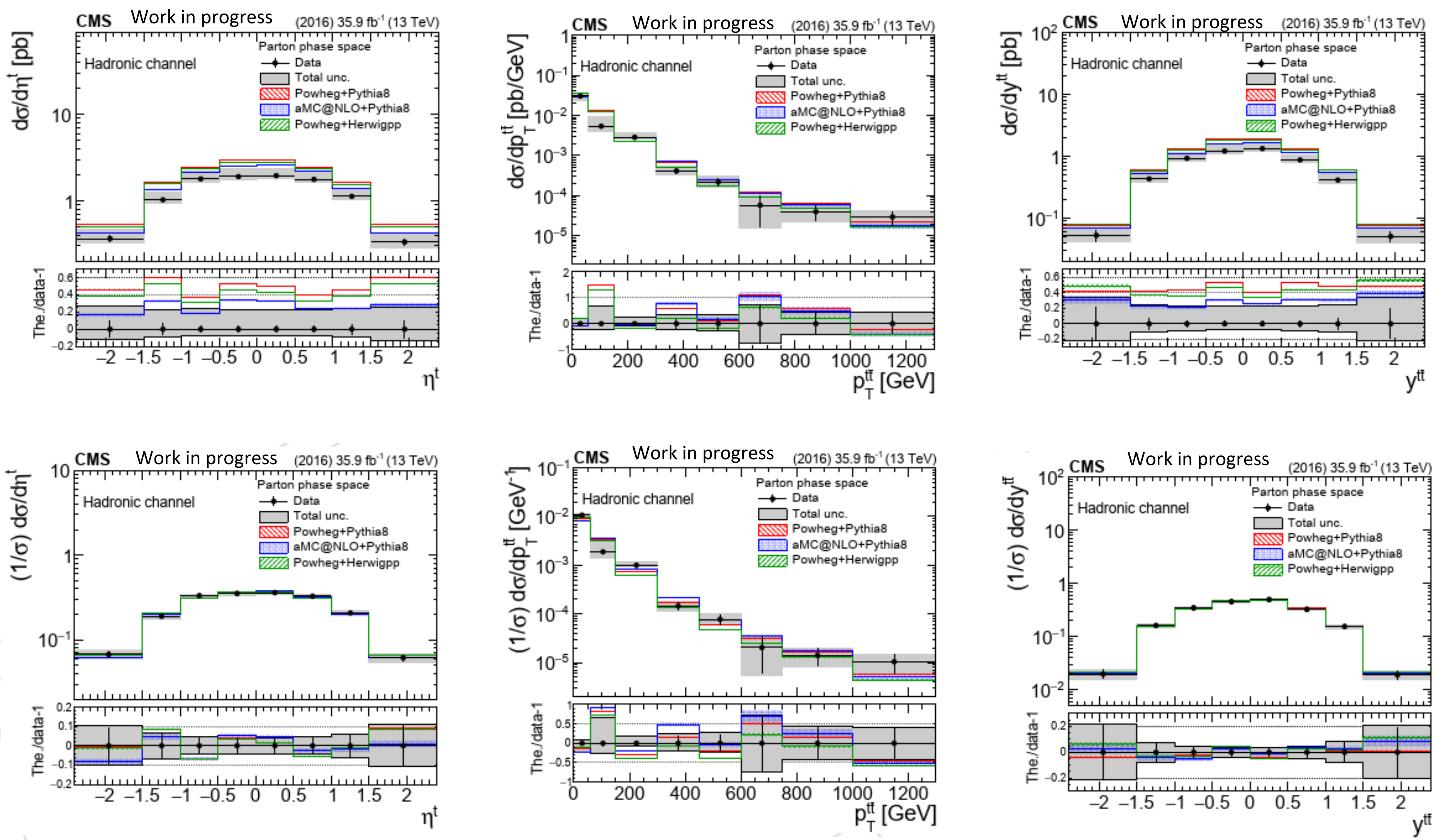



# Parton Results for $\eta^t$ , $p_{T,tt}$, $y_{tt}$



# Particle Results for $\eta^{t}$ , $p_{T,tt}$, $y_{tt}$