



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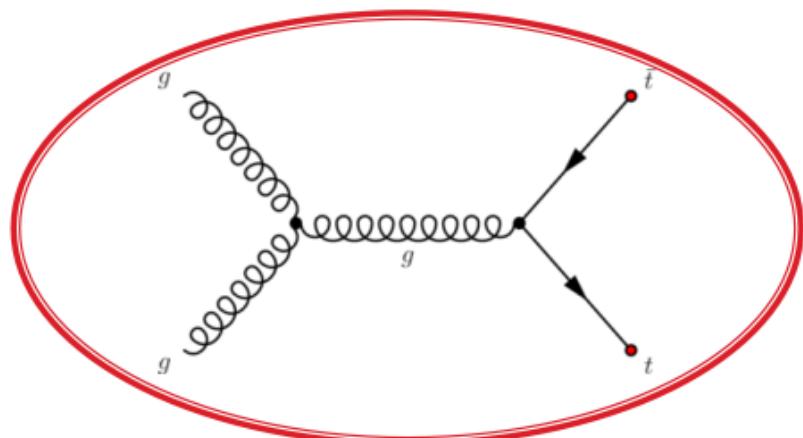
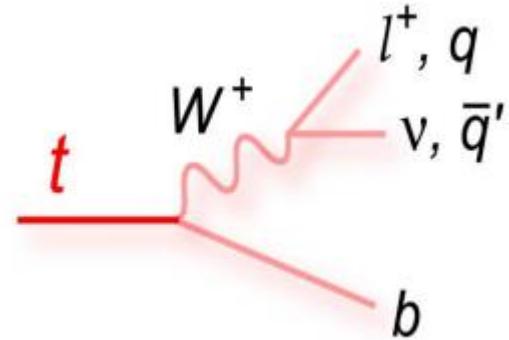
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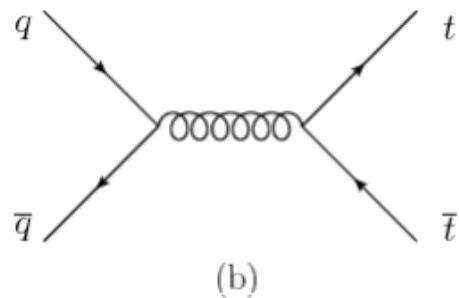
- Top Quark
- Boosted Jets
- CMS Experiment
- Analysis
- Overview

# Top Quark

- 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
  - $q + \bar{q} \rightarrow t + \bar{t}$
  - $g + g \rightarrow t + \bar{t}$

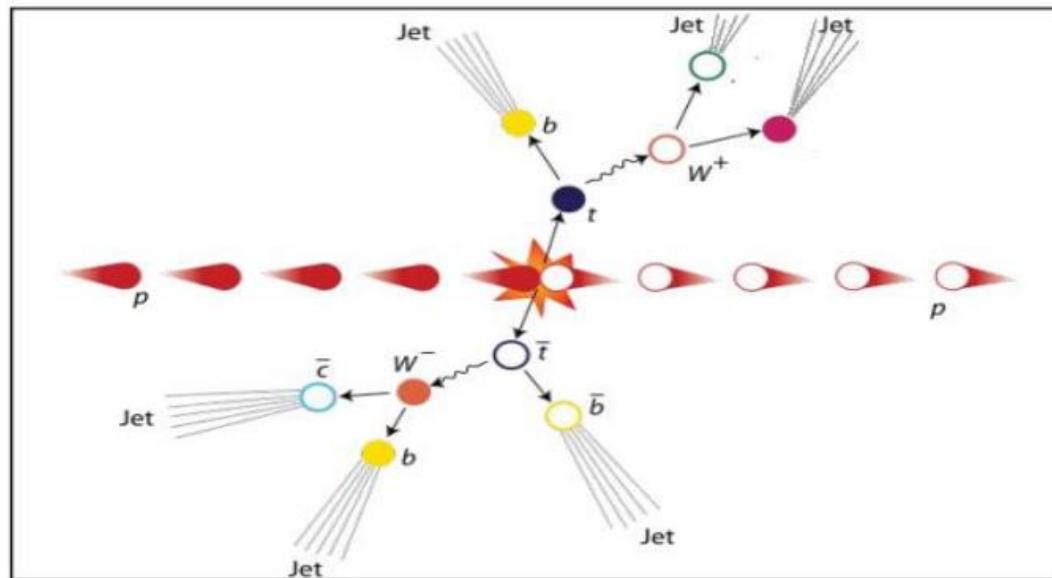


Gluon Fusion is dominant at LHC



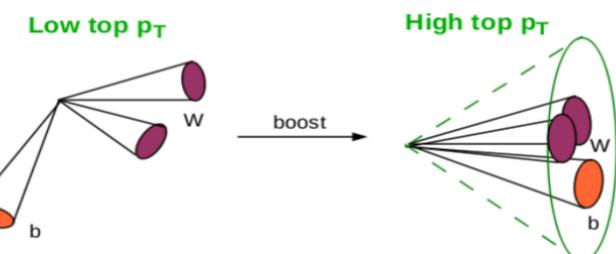
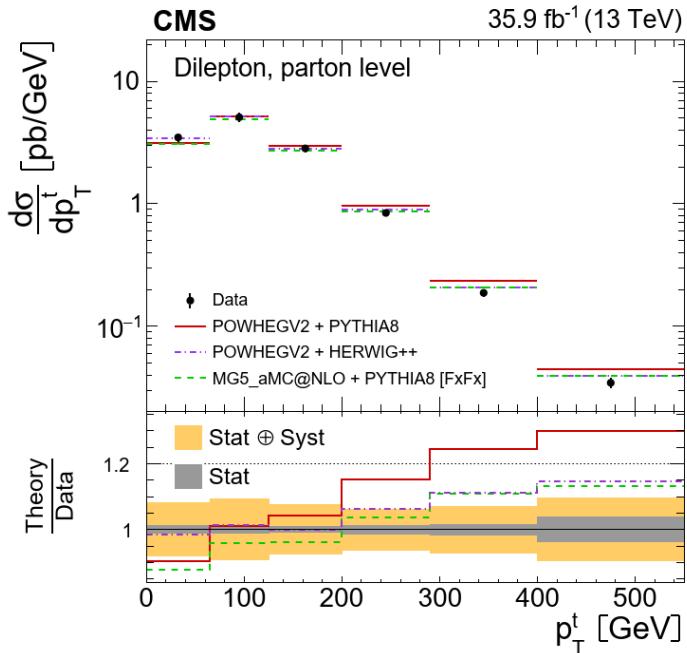
# Top AntiTop system decay

1.  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}b q''\bar{b}\bar{q}''$  (45.7 %)  $\rightarrow$  hadronic
2.  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}'b l^-\bar{\nu}_l\bar{b} + l^+\nu_l b q''\bar{q}''' \bar{b}$  (43.8 %)  $\rightarrow$  semileptonic
3.  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow l^+\nu_l b l'\bar{\nu}'\bar{b}$  (10.5 %)  $\rightarrow$  dileptonic



# Boosted Jets

- 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  $\sim 500$  GeV
  - There is an interesting discrepancy with theory ( $p_T$  slope)
  - In order to see what happens in bigger  $p_T$ 's  $\rightarrow$  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

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

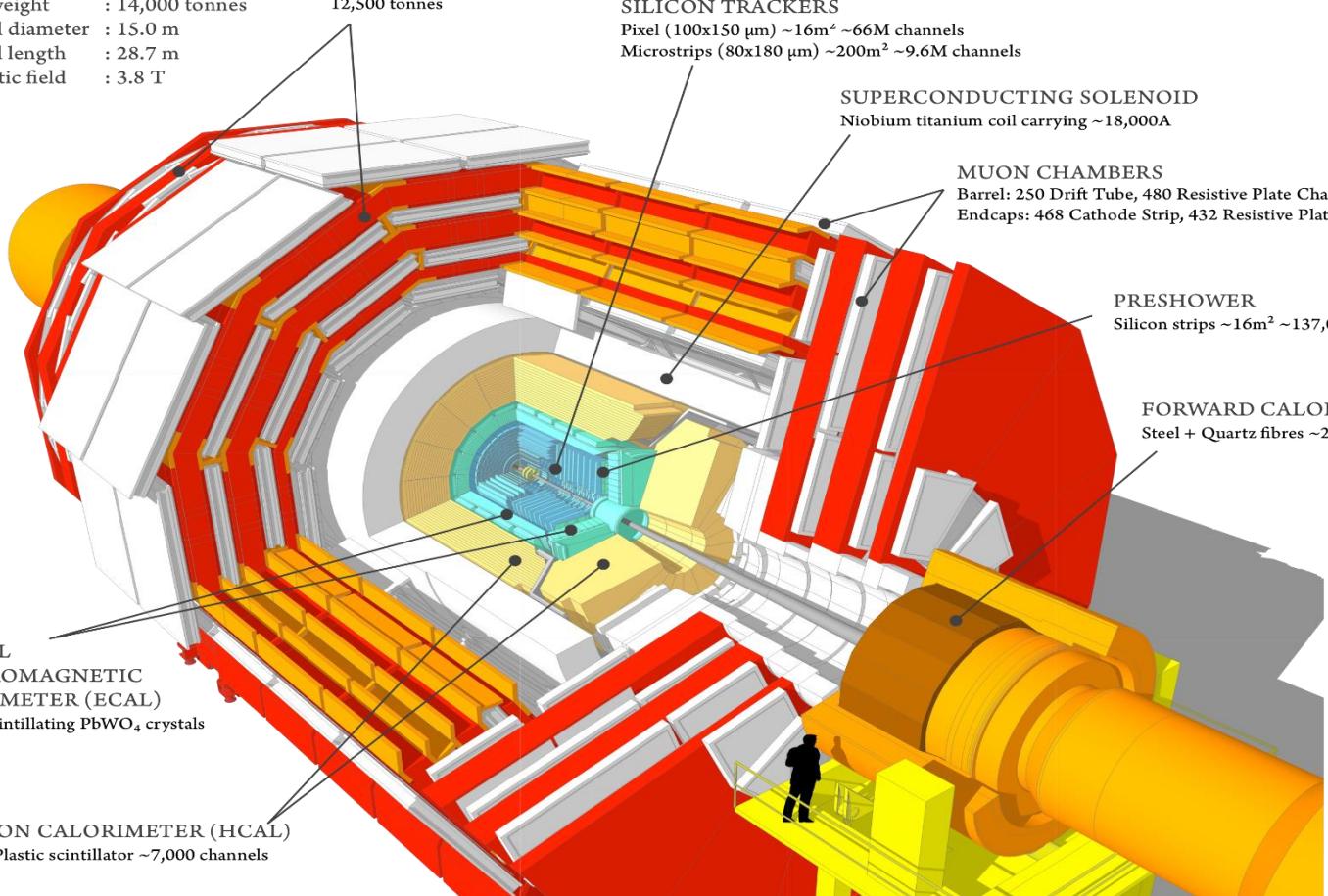
MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

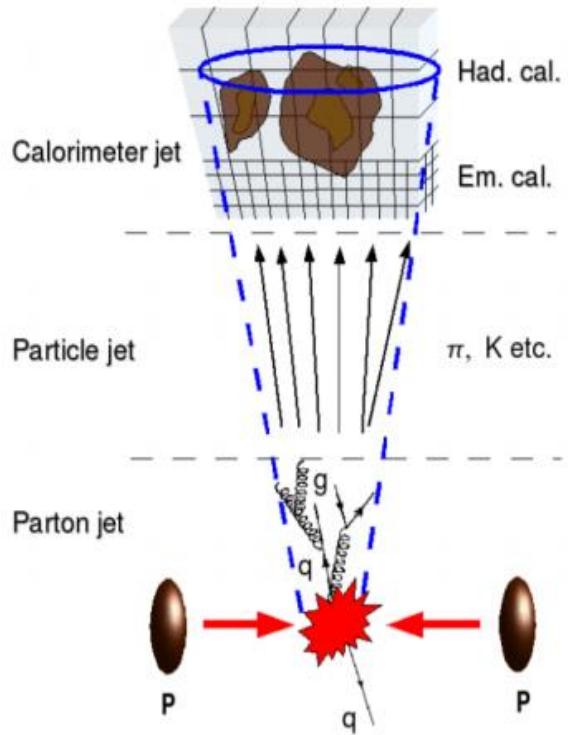
CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels



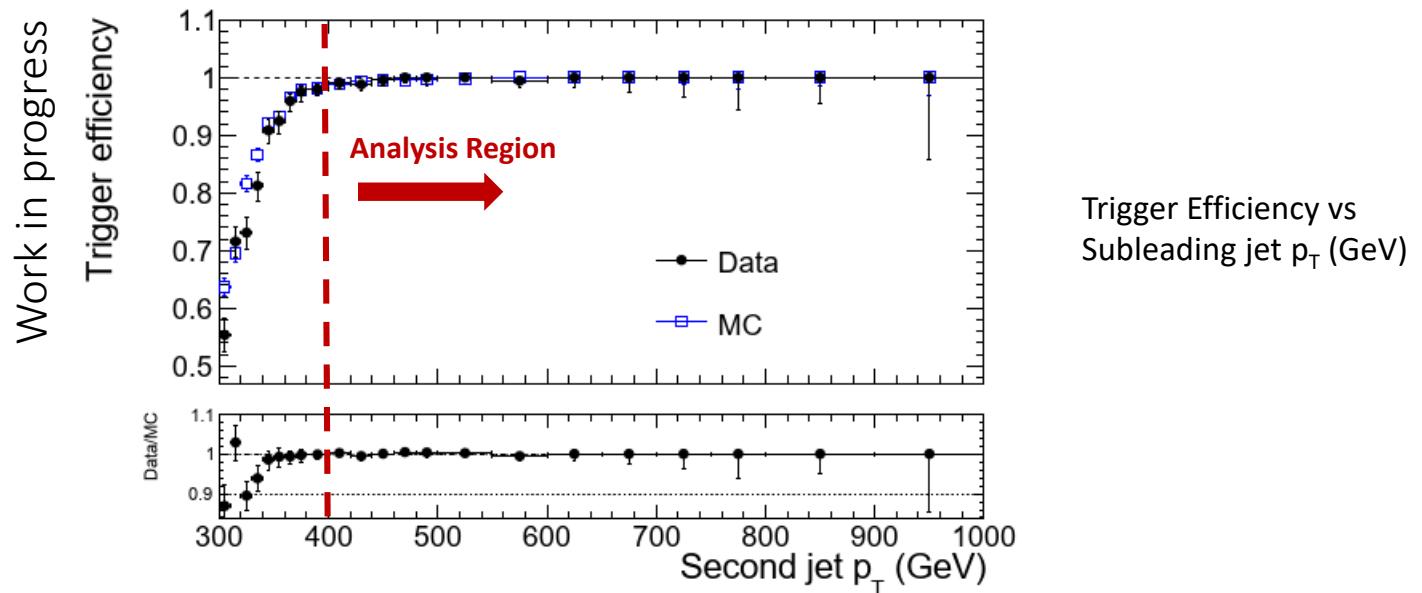
# Analysis Overview

- 2016 dataset
  - Very well understood (calibrations, scale factors, etc)
- Trigger:
  - L1: Single Jet with  $p_T > 200\text{GeV}$
  - HLT: two AK8 jets, b tagged
- Selection:
  - two AK8 jets with  $p_T > 400 \text{ GeV}$
  - 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

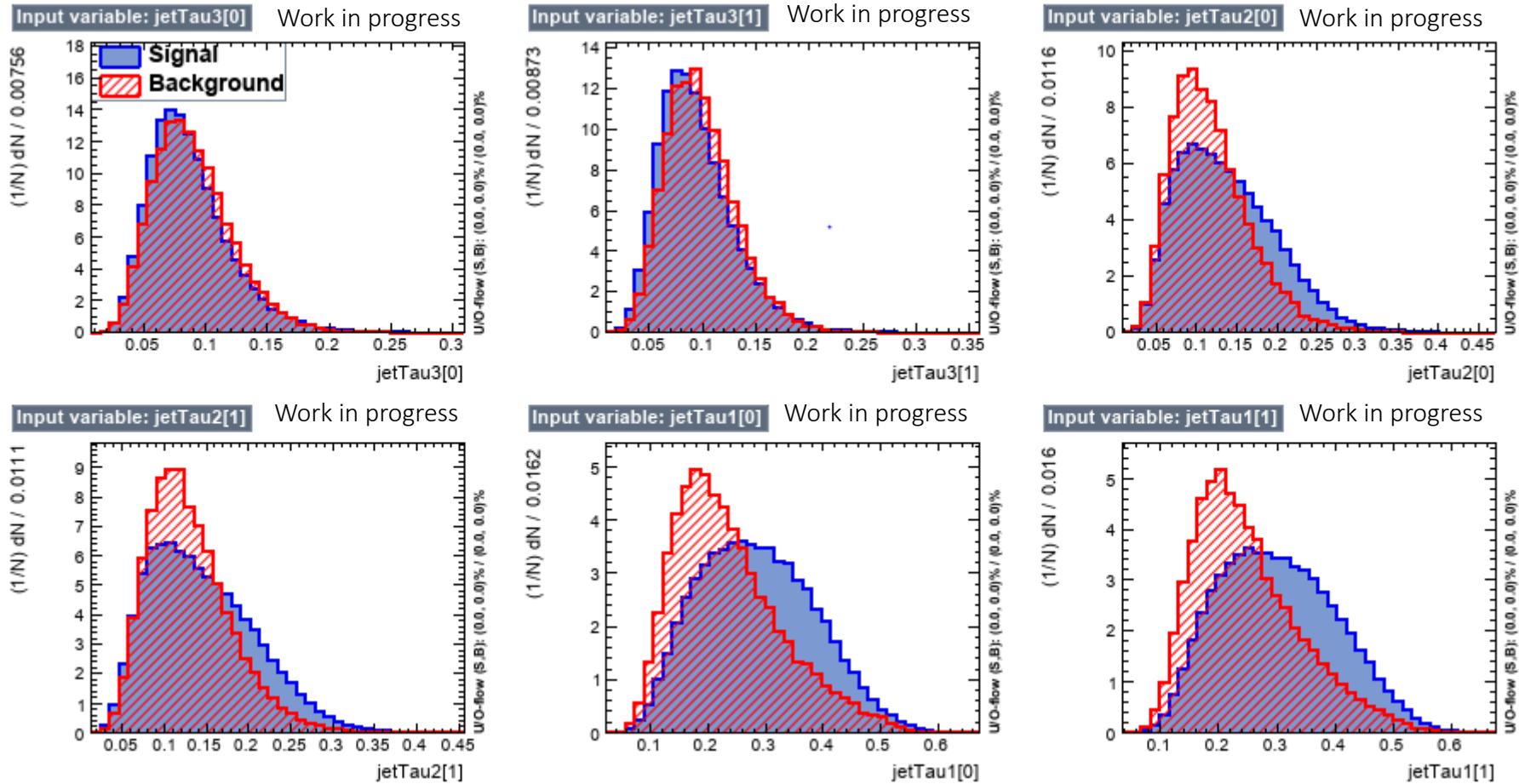


# Trigger

- 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
    - $p_{T,1} > 280 \text{ GeV}$  and  $p_{T,2} > 200 \text{ GeV}$
    - Jet mass  $> 30 \text{ GeV}$
    - 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

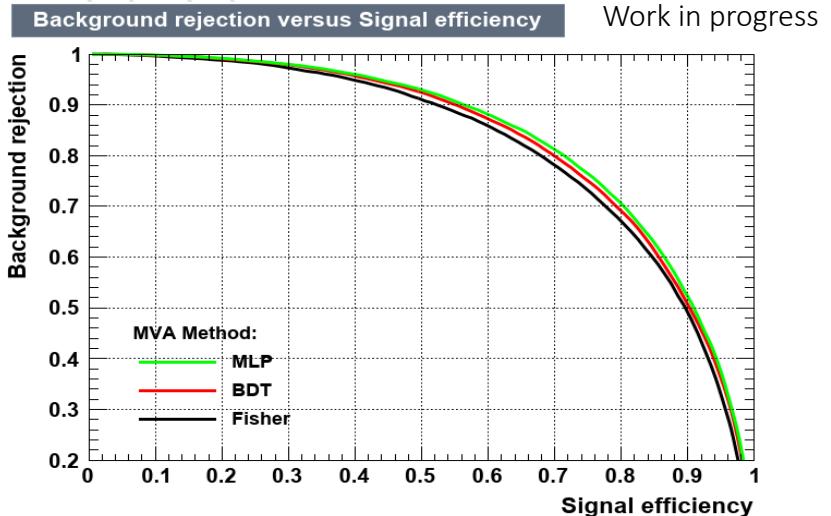
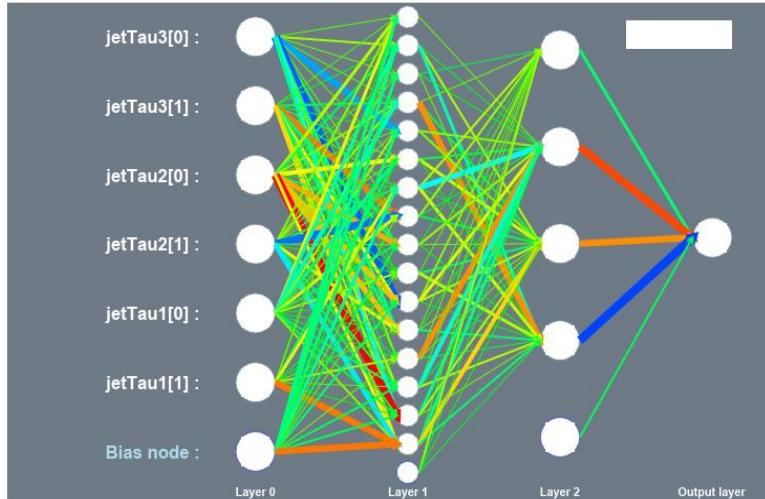


# Multivariate Discriminant Analysis(variables)

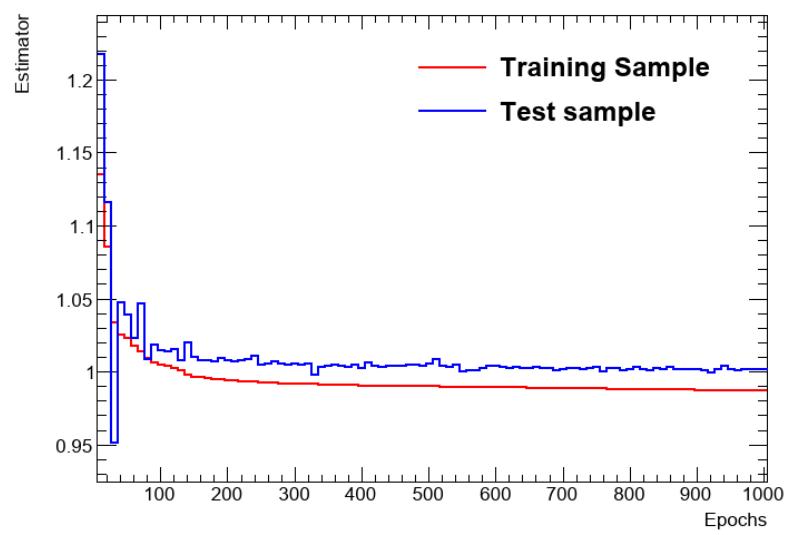


Discriminating variables used for separation of the  $t\bar{t}$  from the QCD events

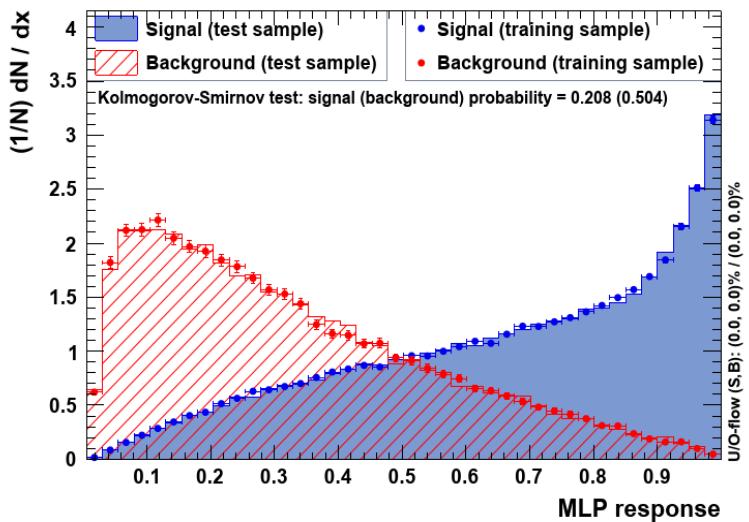
# Multivariate Discriminant Analysis (training)



**MLP Convergence Test** Work in progress



**TMVA overtraining check for classifier: MLP** Work in progress

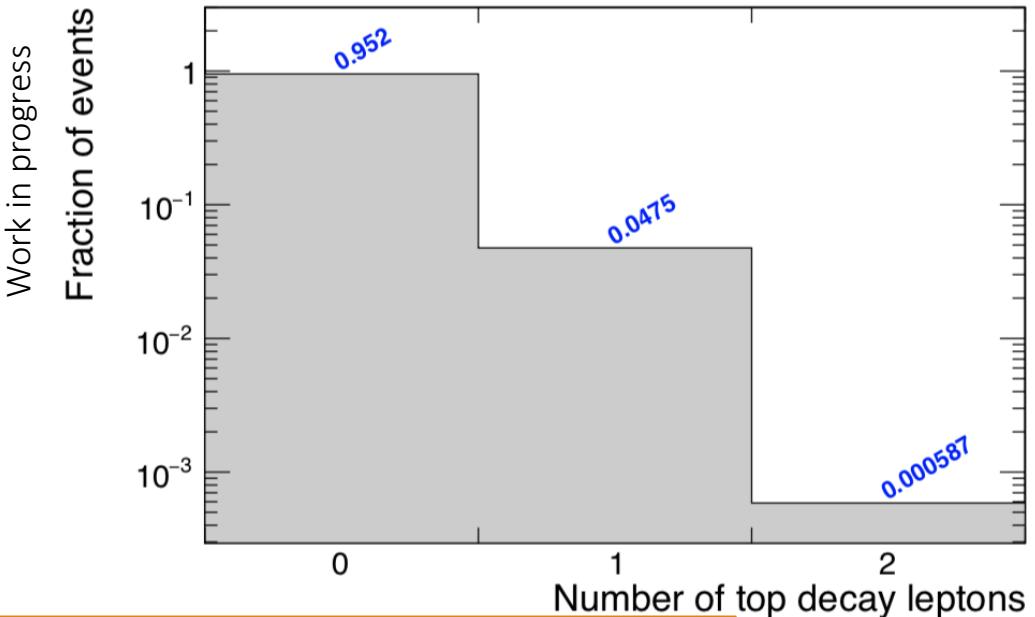


# Selection

## Baseline Selection

| Observable               | Requirement             |
|--------------------------|-------------------------|
| $N_{\text{jets}}$        | $> 1$                   |
| $N_{\text{leptons}}$     | $= 0$                   |
| $p_T^{\text{jet}1,2}$    | $> 400 \text{ GeV}$     |
| $m_{SD}^{\text{jet}1,2}$ | $(50, 300) \text{ GeV}$ |

Selected jets: AK8 PF+CHS



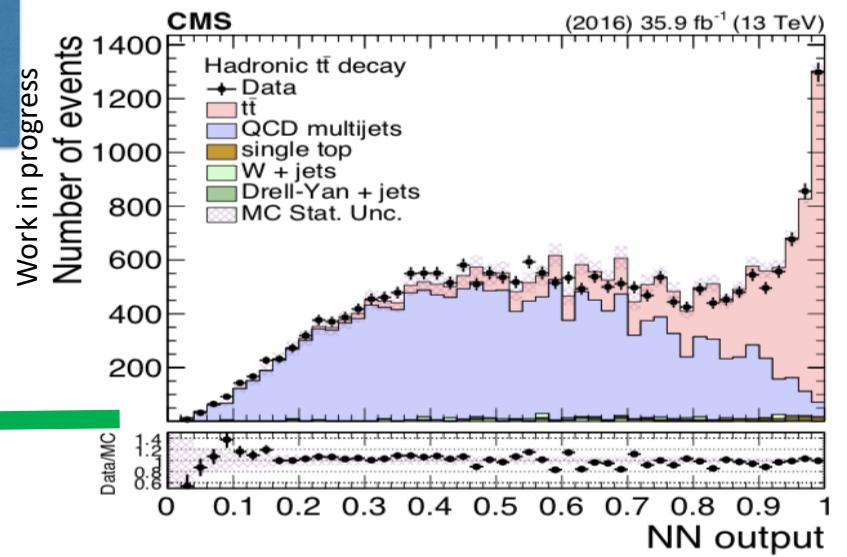
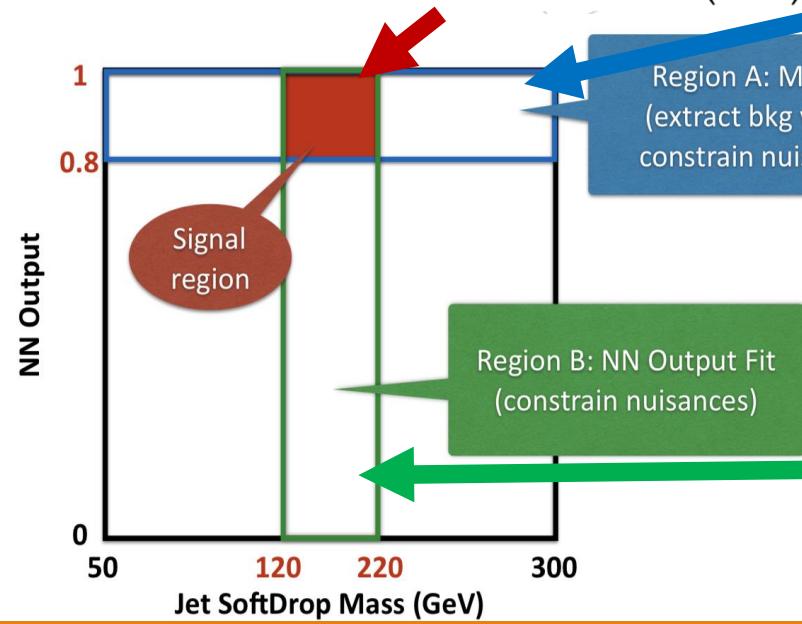
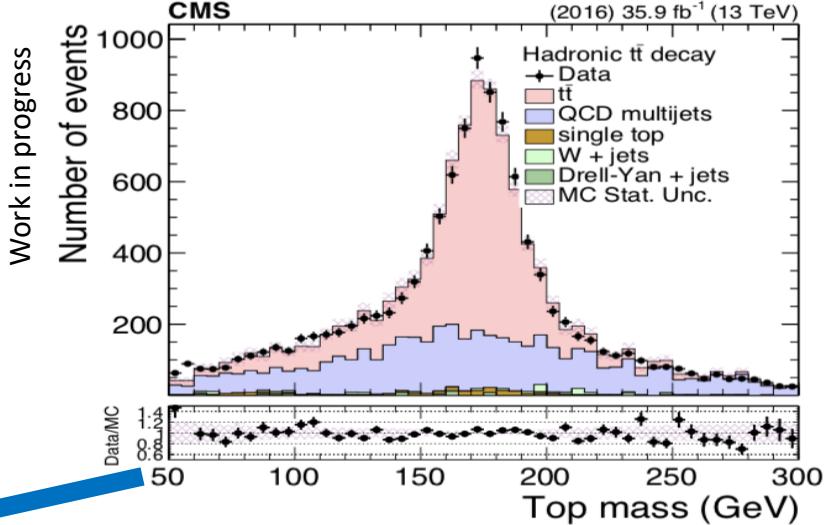
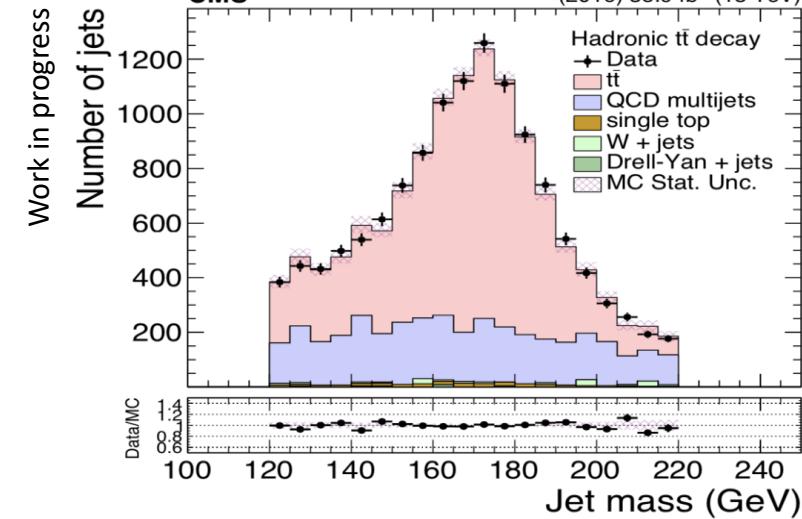
From signal selection almost 95% of the decays are hadronic

Table: Selection requirements per analysis region

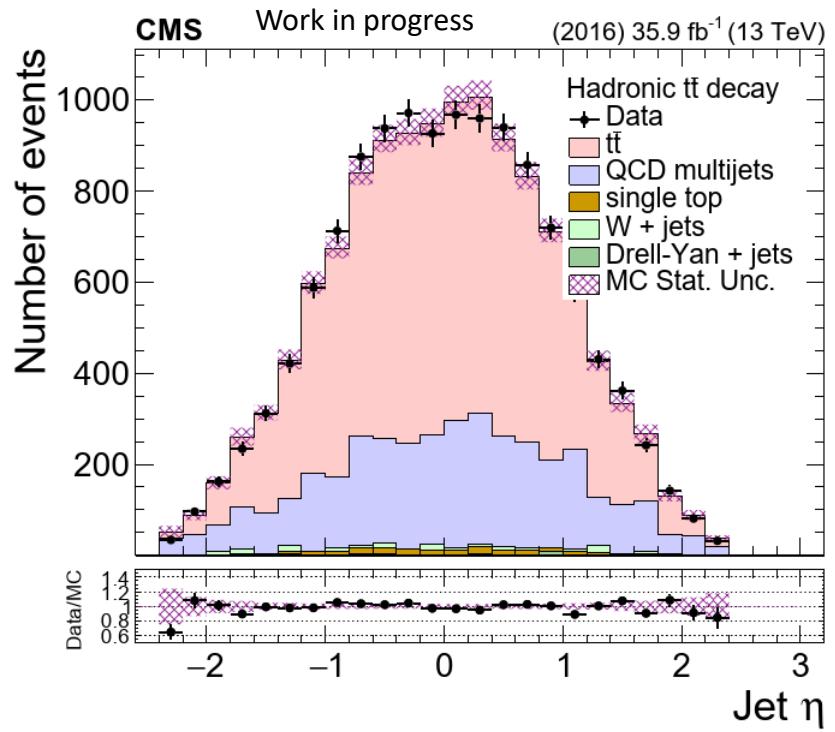
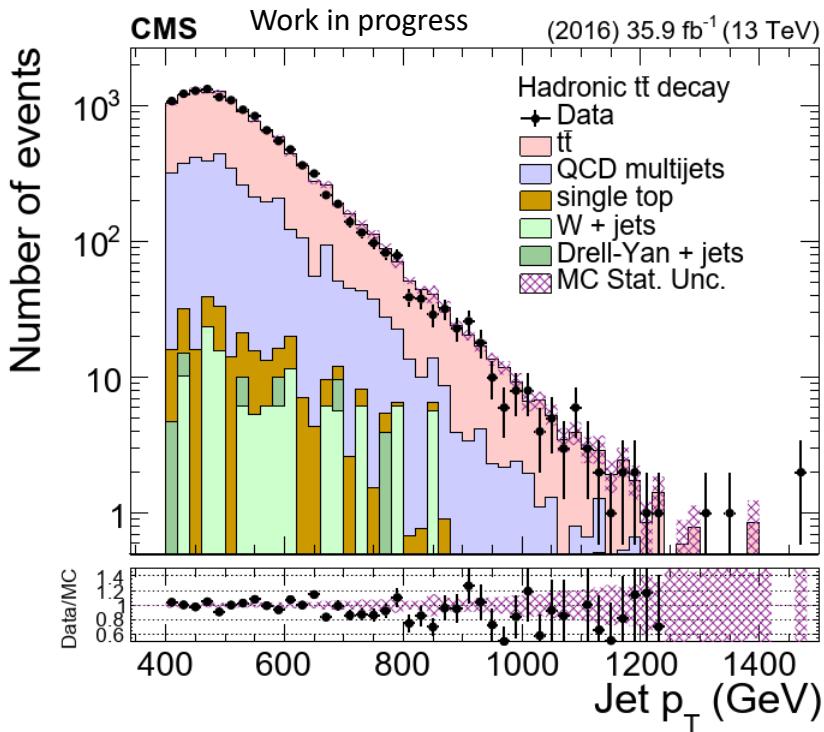
| Region | Trigger | Offline Requirements  | Purpose                   |
|--------|---------|---|---------------------------|
| SR     | signal  | $\text{Base} + \text{NN} > 0.8 + \text{cat.} = 2 + m_{SD}^{\text{jet}1,2} \in (120, 220) \text{ GeV}$ | signal region             |
| $SR_A$ | signal  | $\text{Base} + \text{NN} > 0.8 + \text{cat.} = 2$   | QCD fit region            |
| $SR_B$ | signal  | $\text{Base} + \text{cat.} = 2 + m_{SD}^{\text{jet}1,2} \in (120, 220) \text{ GeV}$                   | signal systematics region |
| CR     | control | $\text{Base} + \text{NN} > 0.8 + \text{cat.} = 0 + m_{SD}^{\text{jet}1,2} \in (120, 220) \text{ GeV}$ | QCD control region        |

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

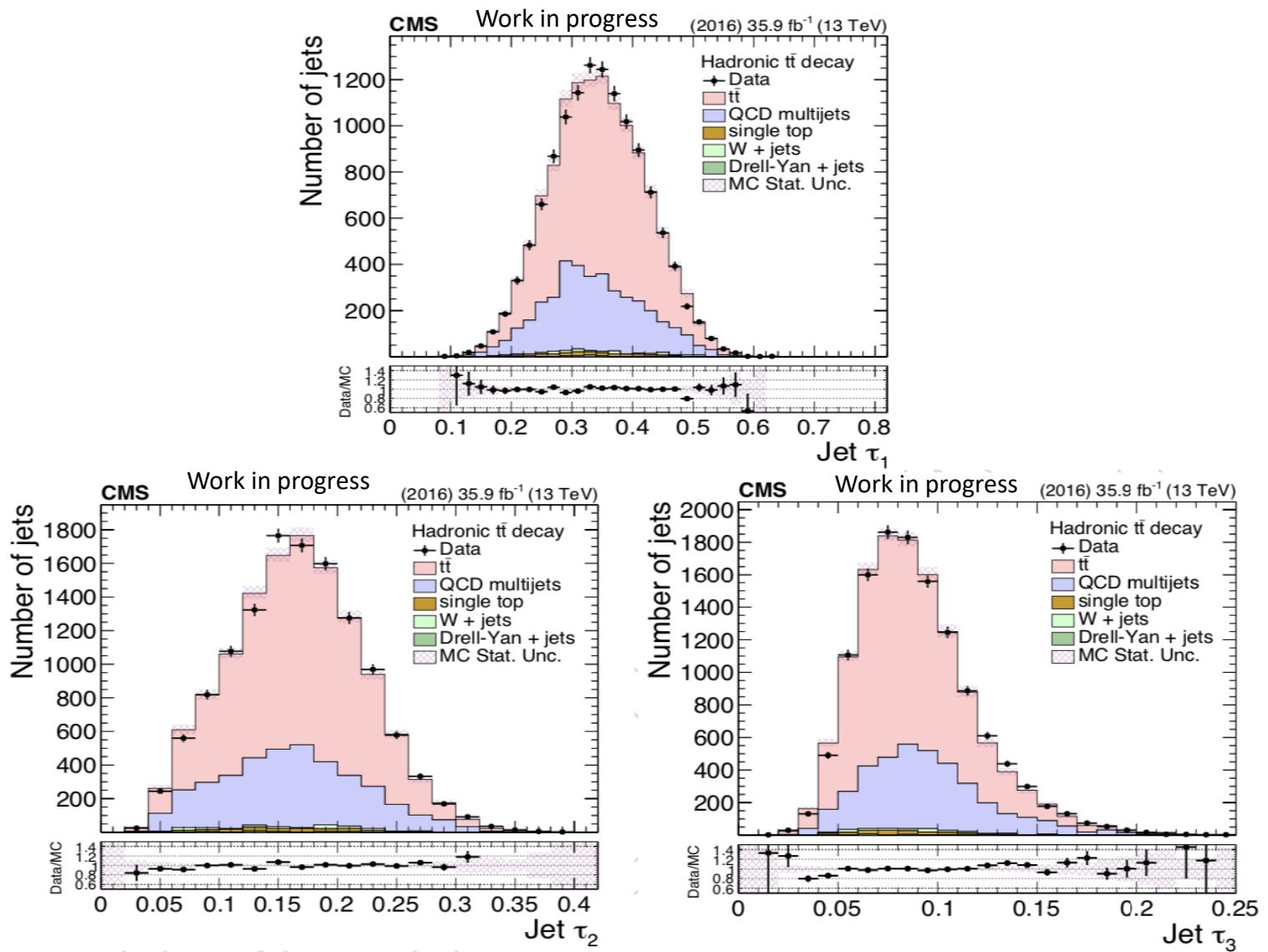
# Analysis Regions



# Data vs MC: Top jet Kinematics



# Data vs MC: Substructure Properties



# Signal Extraction

Fiducial Yield

Transfer factor from SR<sub>A</sub> to SR

Bkg Shape Correction  
(taken from MC)

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

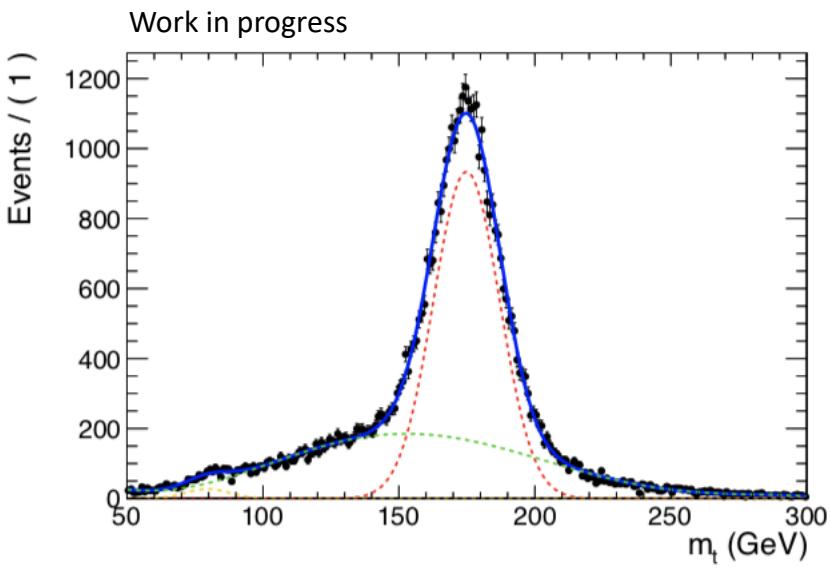
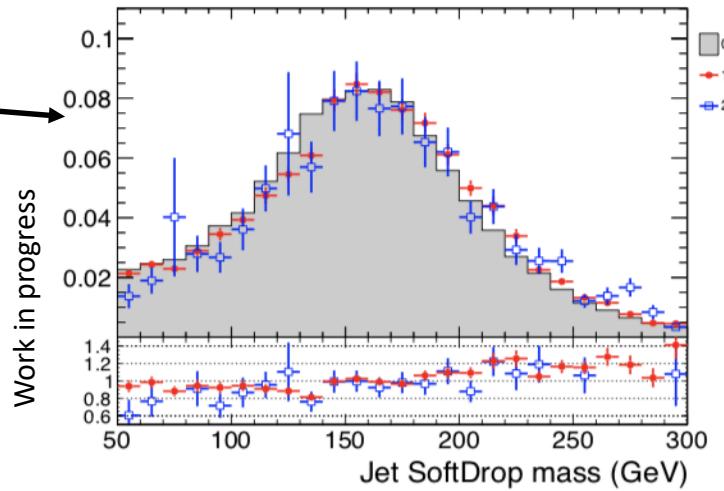
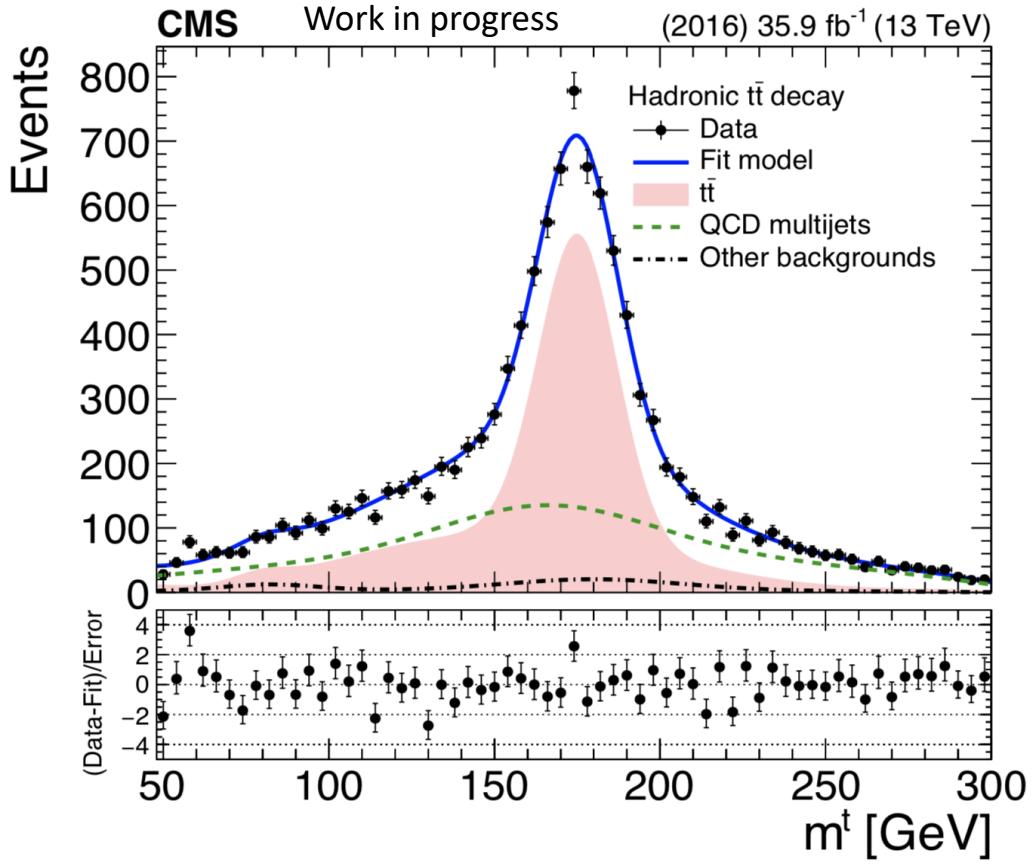
Data

Bkg Yield  
(fit in region SR<sub>A</sub>)

Bkg Shape  
(taken from CR in data)

# Fit in the SR<sub>A</sub> 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

## Parton Level selection

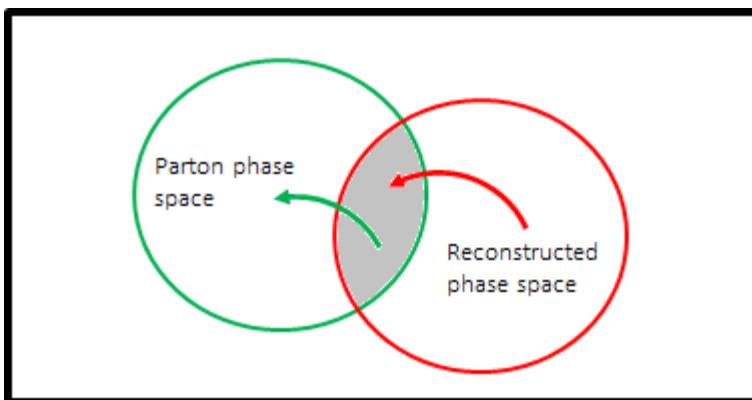
| Observable           | Requirement         |
|----------------------|---------------------|
| $p_T^{t,\bar{t}}$    | $> 400 \text{ GeV}$ |
| $ \eta^{t,\bar{t}} $ | $< 2.4$             |
| $m_{t\bar{t}}$       | $> 800 \text{ GeV}$ |

Reco and parton over reco

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

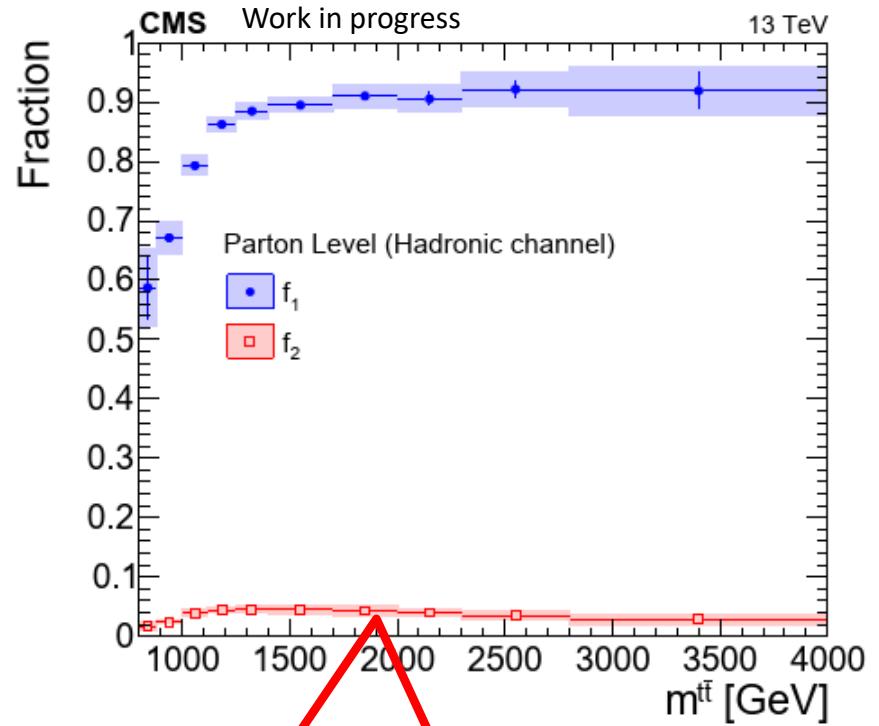
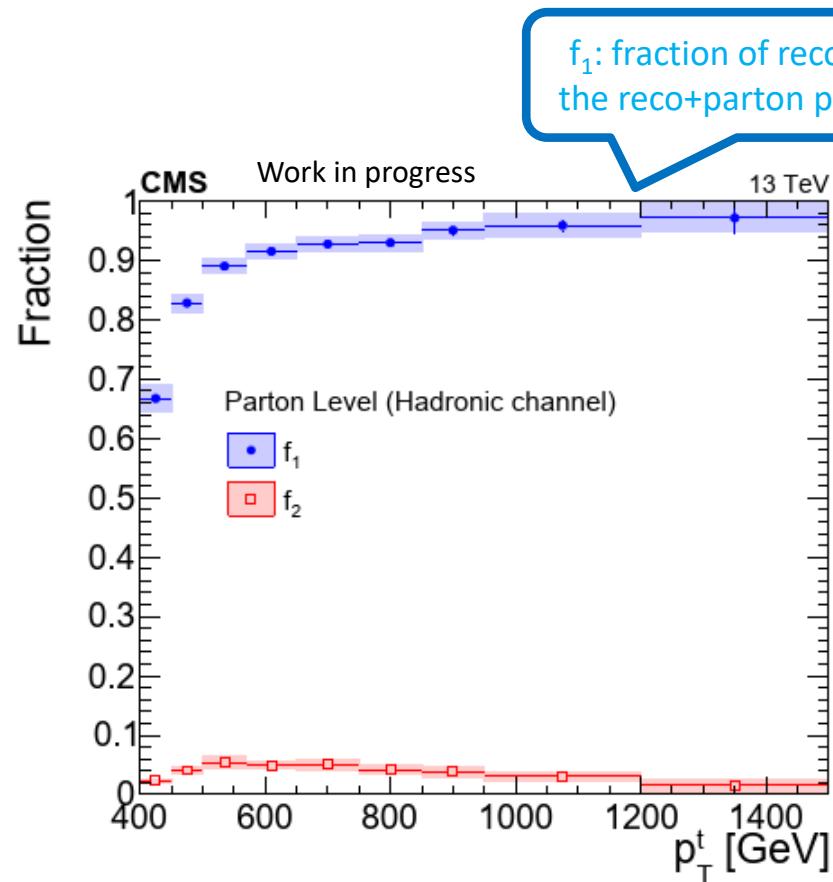
Reco and parton over parton

Migration matrix



Unfolding is done using simple response matrix inversion without regularization

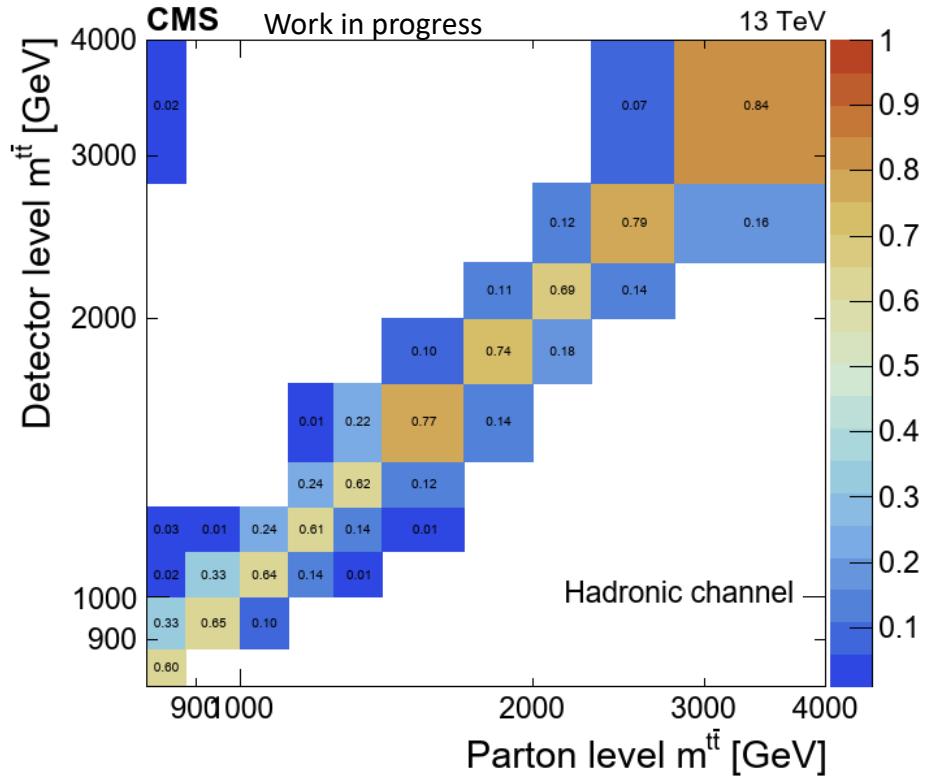
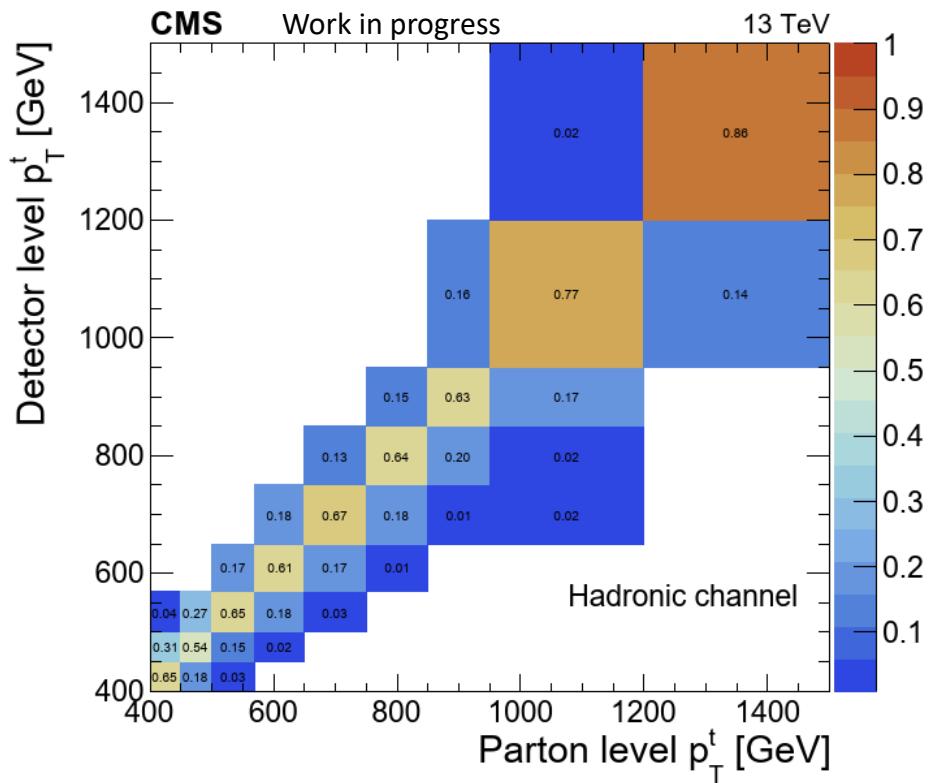
# Extrapolation factors for parton level



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

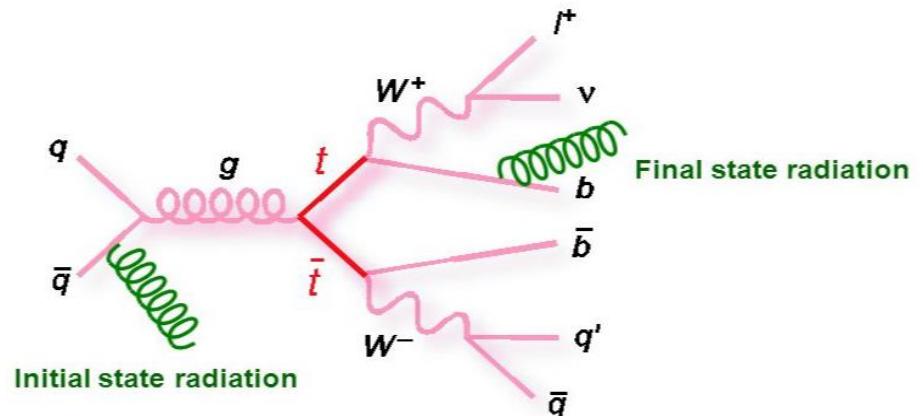


# Migration Matrices

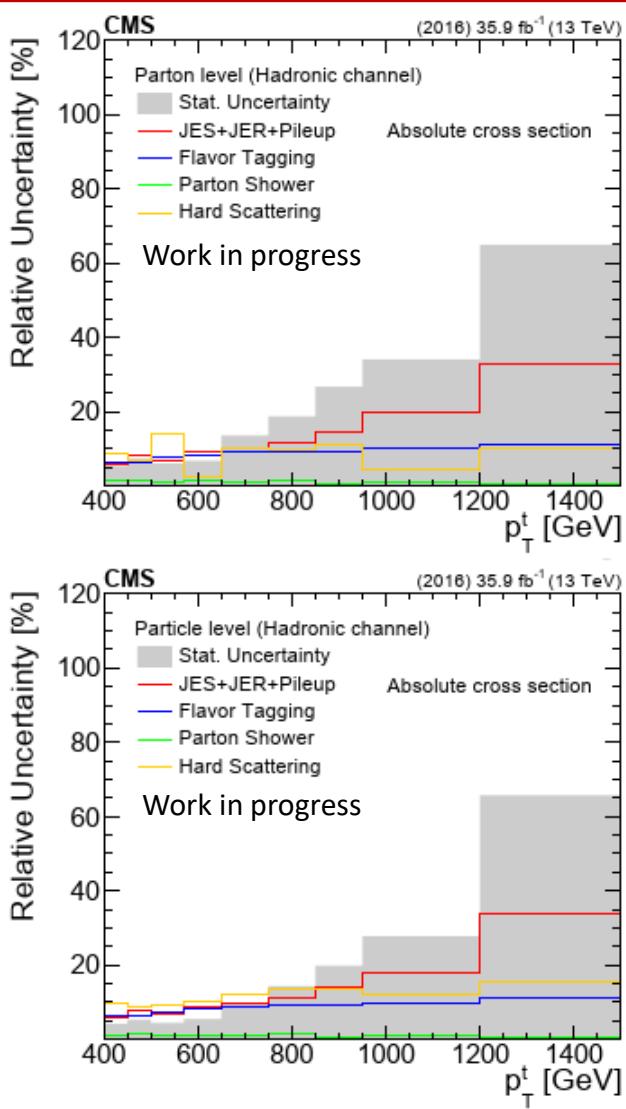


# Uncertainties

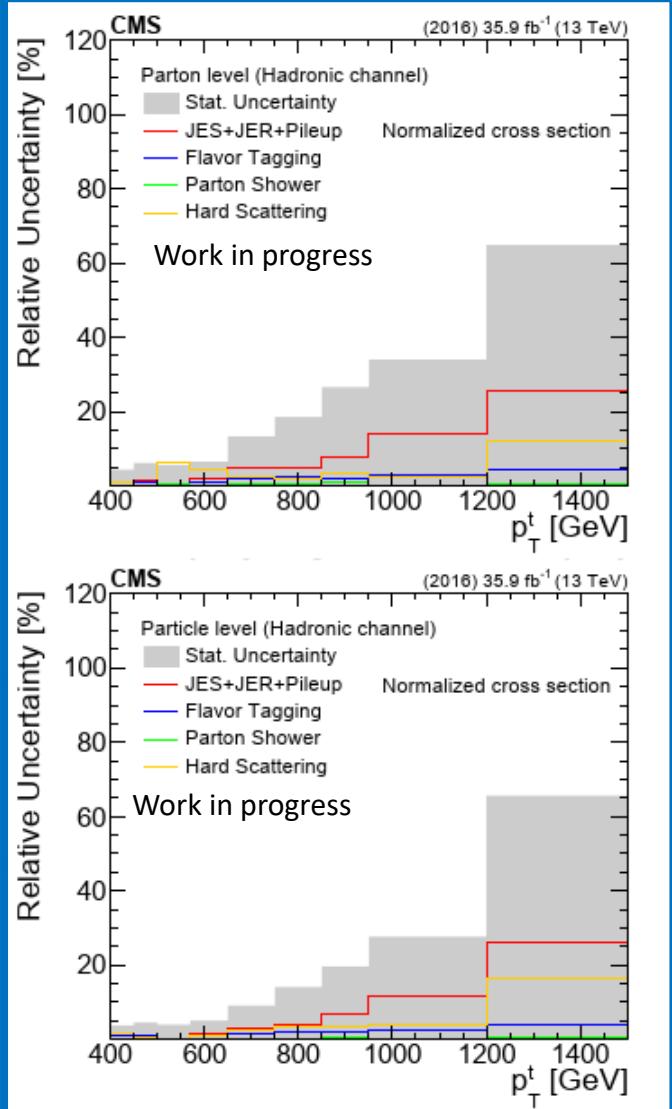
- Experimental:
  - QCD background prediction
  - Statistics
  - Jet Energy Scale
  - Jet Energy Resolution
  - B tagging efficiency
- Theoretical:
  - Affect the extrapolation factors ( $f_1, f_2$ ) and the migration matrices for the unfolding procedure
    - ISR (Initial State Radiation)
    - FSR (Final State Radiation)
    - CMS tuned set of MC parameters for Pythia 8



# Uncertainties

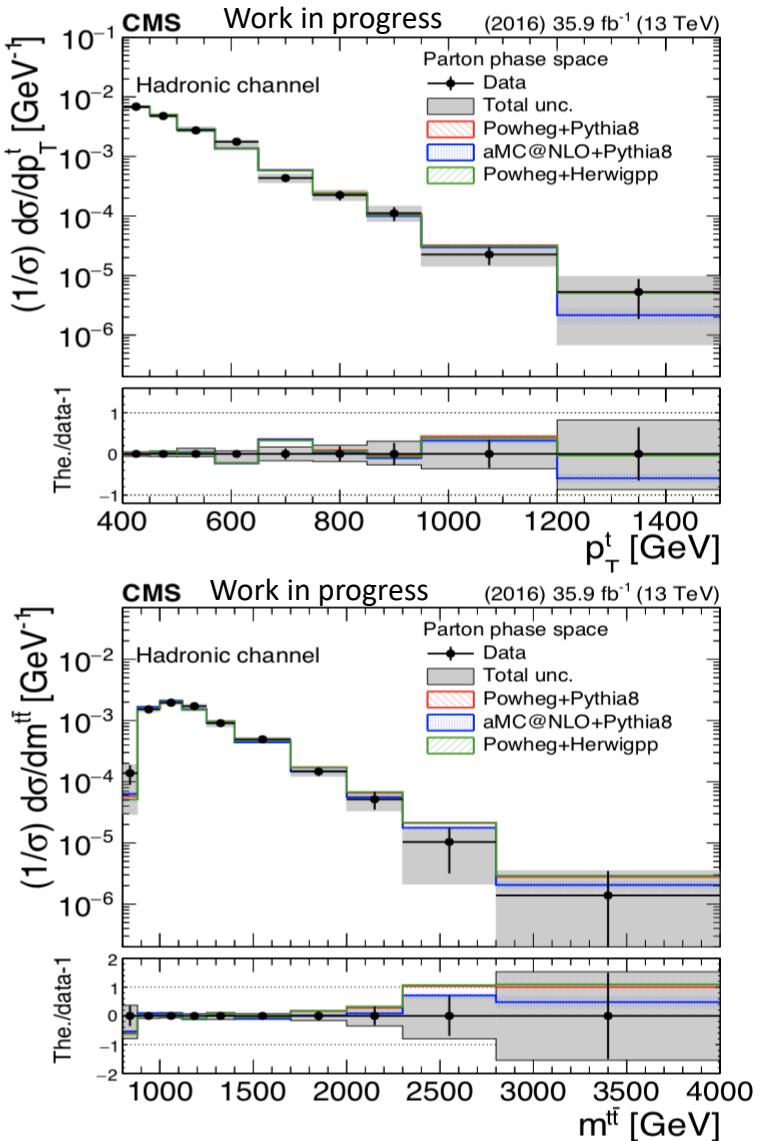
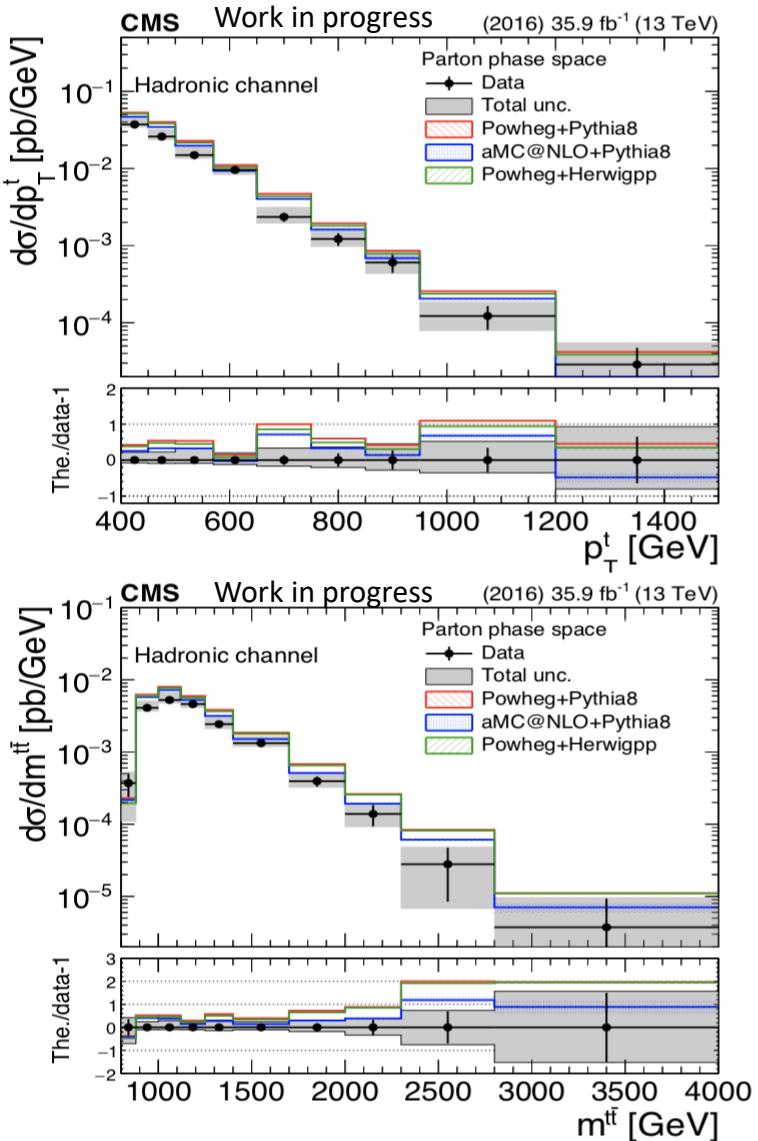


Uncertainties  
for the parton  
and particle  
level  
measurements  
(absolute)



Uncertainties  
for the parton  
and particle  
level  
measurements  
(normalized)

# Results for Parton Measurement (top $p_T$ , $m_{t\bar{t}}$ )





# 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: inclusive 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

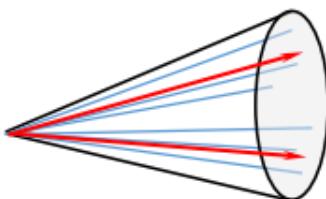
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \times \left( \frac{\Delta R_{12}}{R_0} \right)^\beta$$

- 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

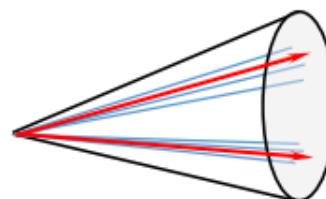
- The NN combines the  $\tau_1, \tau_2, \tau_3$  of the two leading jets, where  $\tau_N$  is the subjetiness and N is the number of prong jets
- Prong jets are the number of jets that determine the substructure of the boosted jets
- The  $\tau_i$  is defined as

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

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



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

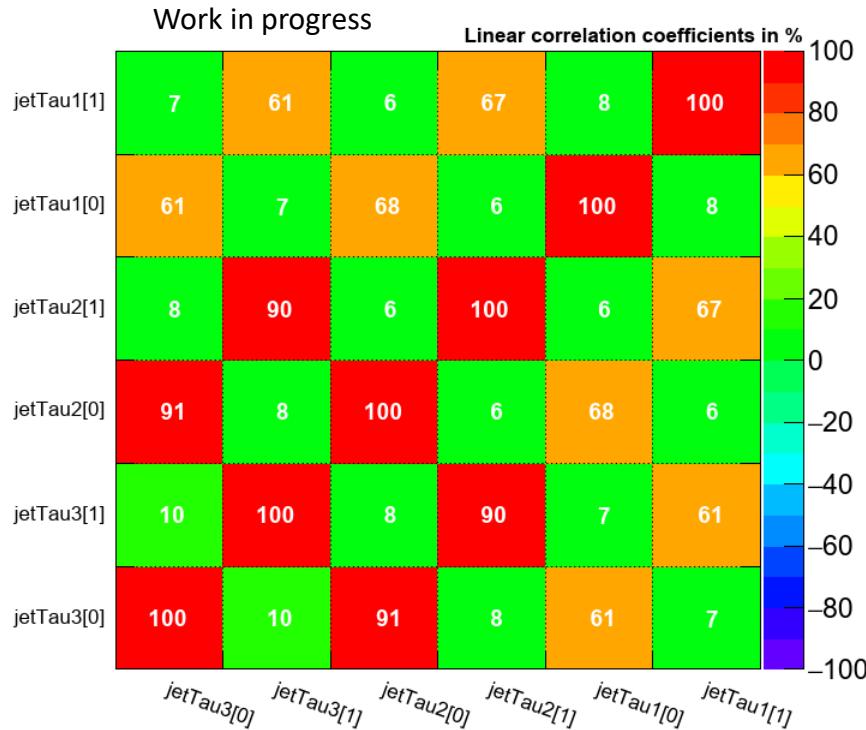


**Low  $\tau_2$  (constituents close to subjet axes)**

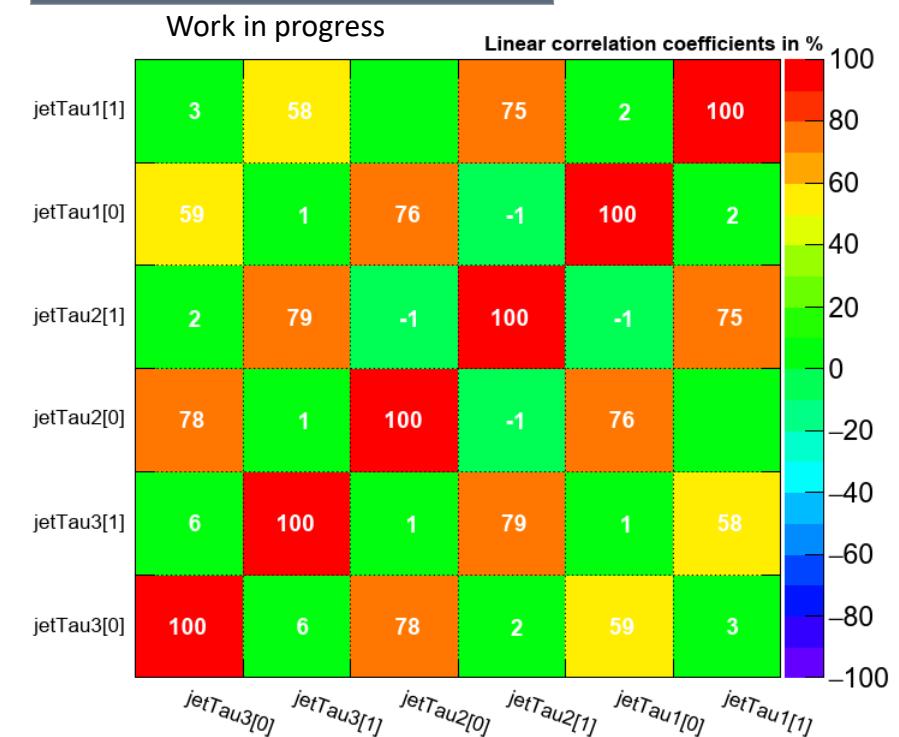
Clusters with exactly N subjets will have small  $\tau_N$   
If  $\tau_N \approx 1$ , cluster most likely has more than N subjets

# MVA training: Correlation Matrices

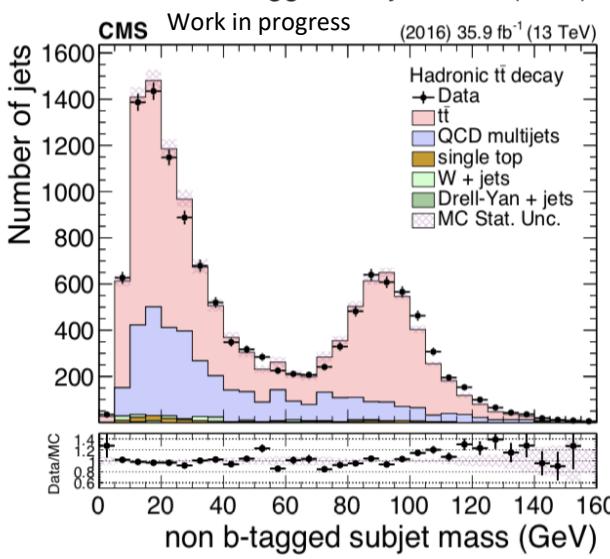
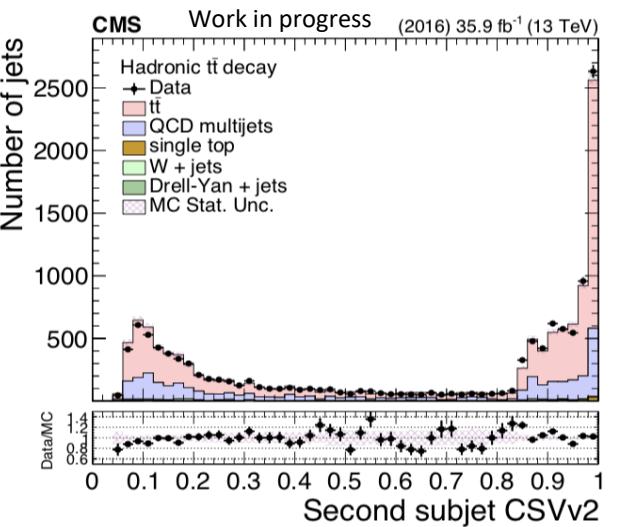
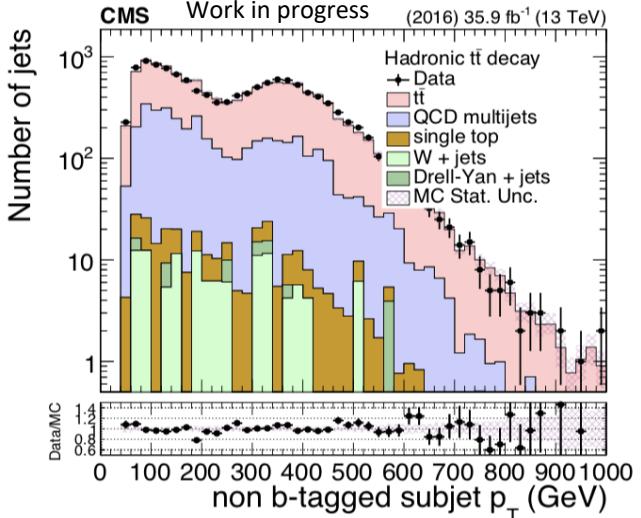
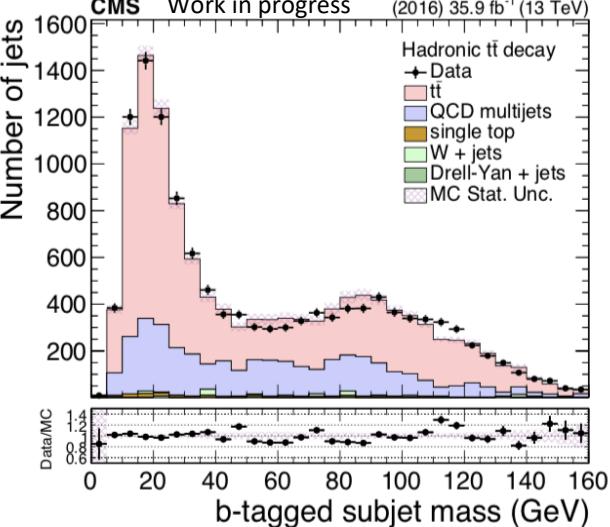
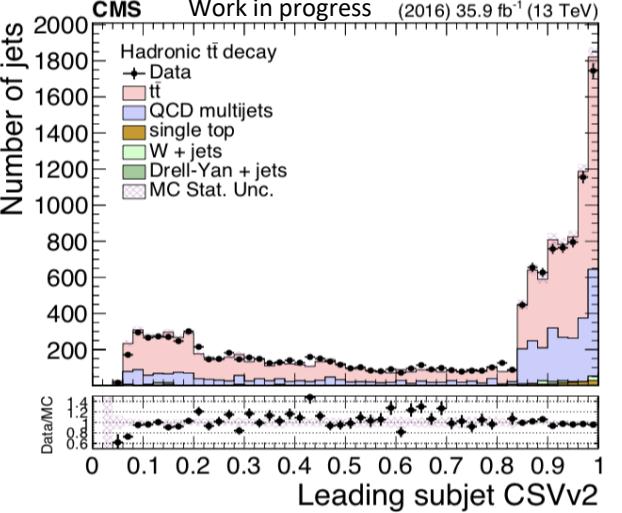
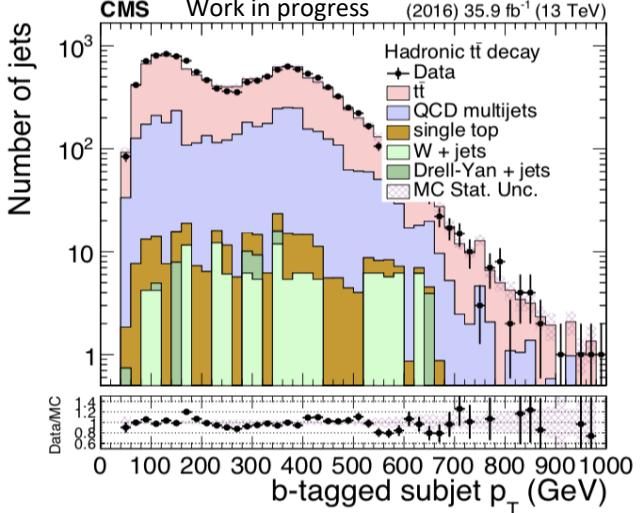
**Correlation Matrix (background)**



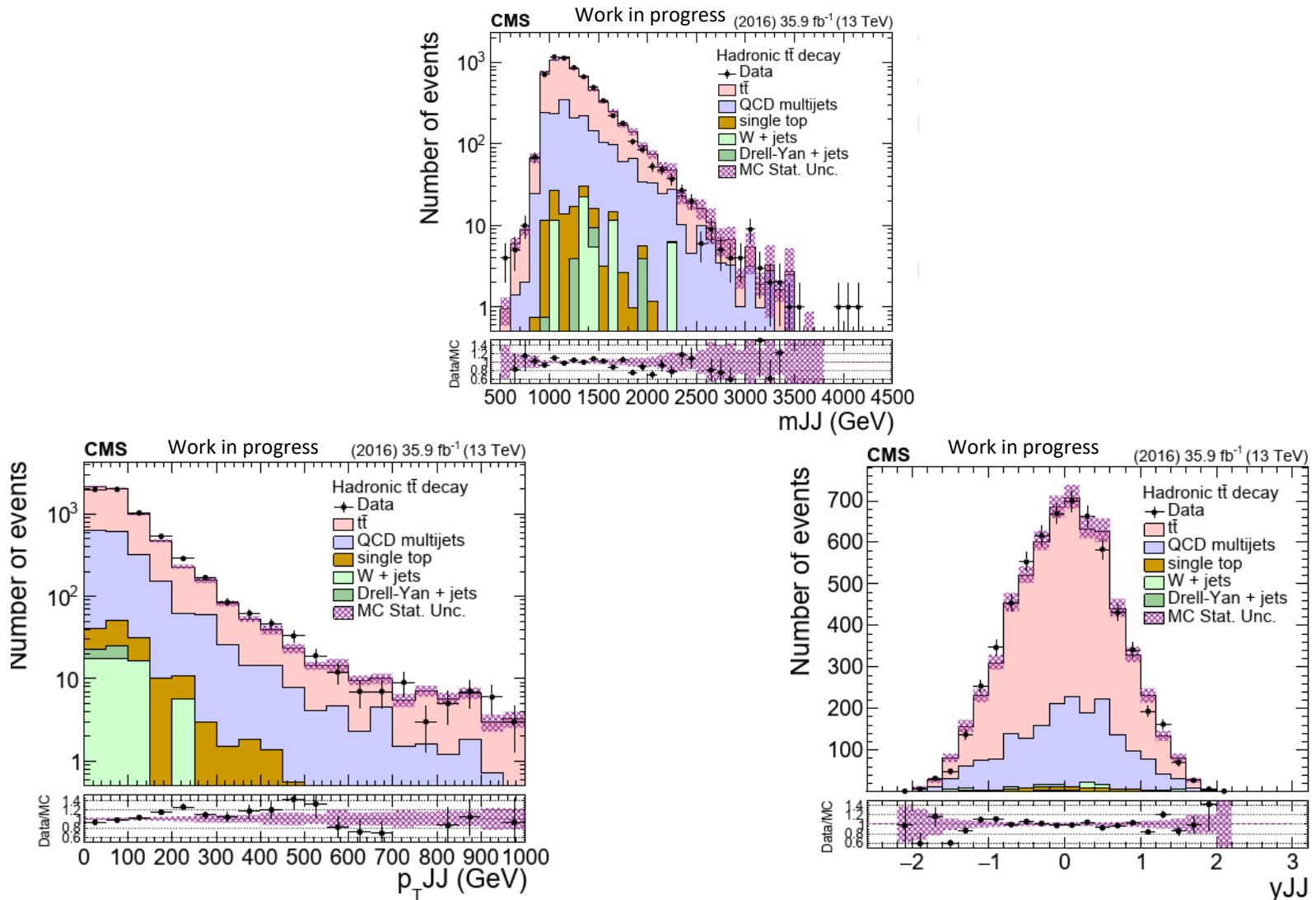
**Correlation Matrix (signal)**



# Data vs MC: Subjet Properties



# Data vs MC: ttbar Kinematics



# Particle Level Selection

## Particle Level selection

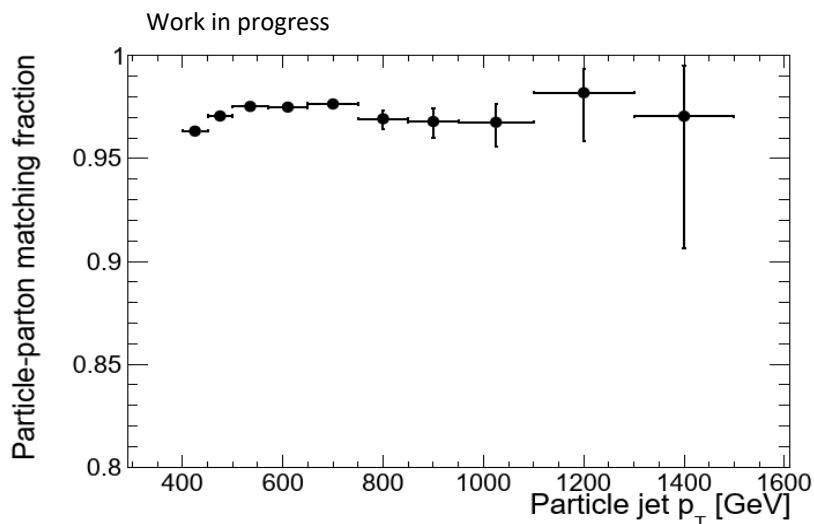
| Observable                     | Requirement              |
|--------------------------------|--------------------------|
| $N_{\text{jets}}$              | $> 1$                    |
| $p_{\text{T}}^{\text{jet}1,2}$ | $> 400 \text{ GeV}$      |
| $ \eta^{\text{jet}1,2} $       | $< 2.4$          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

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

Reco and particle over  
particle

Reco and particle over  
reco

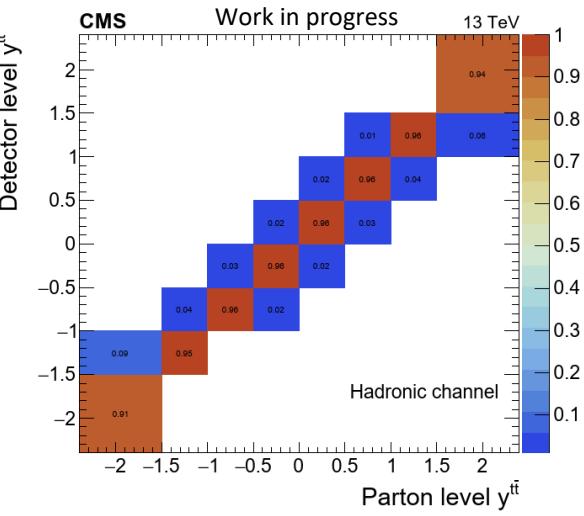
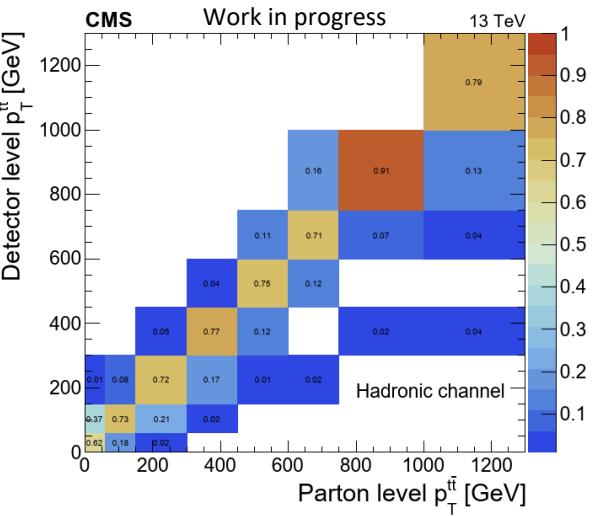
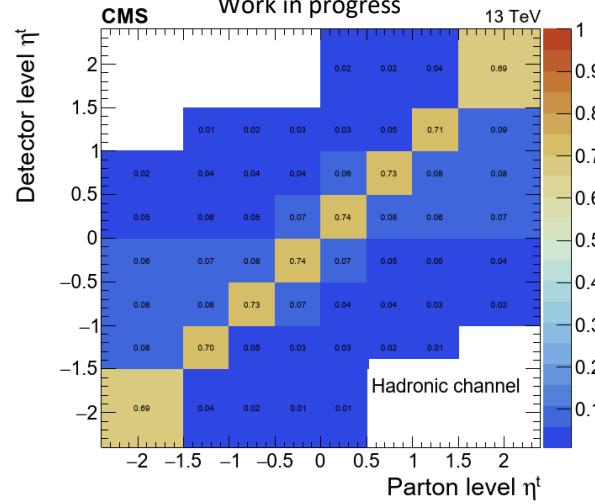
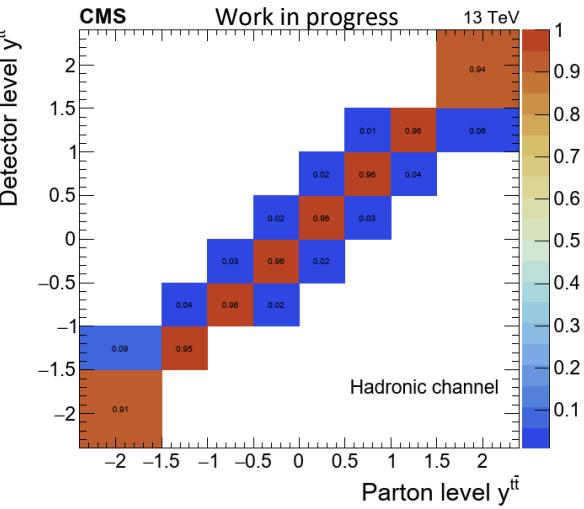
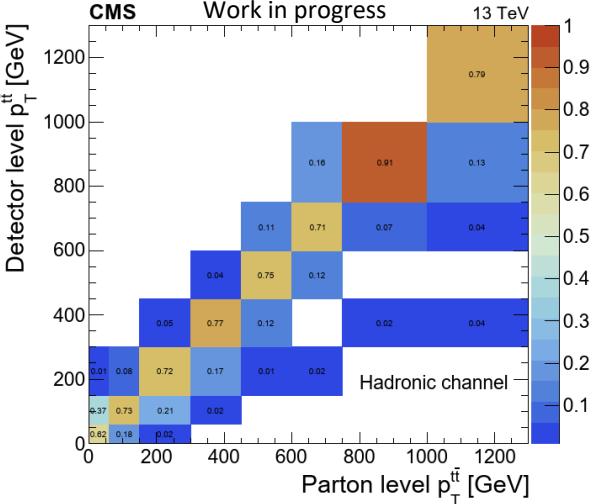
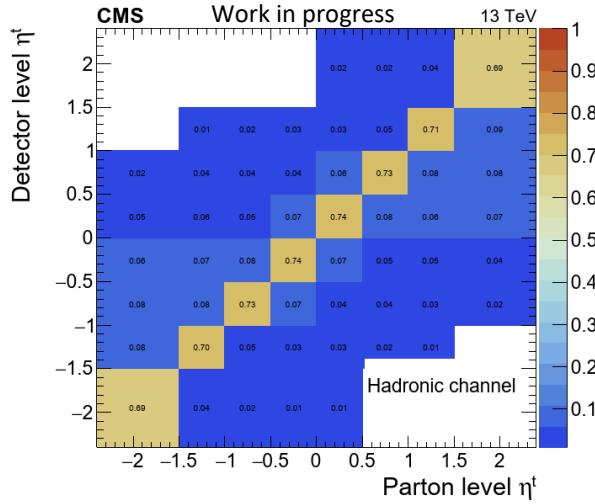
Migration matrix



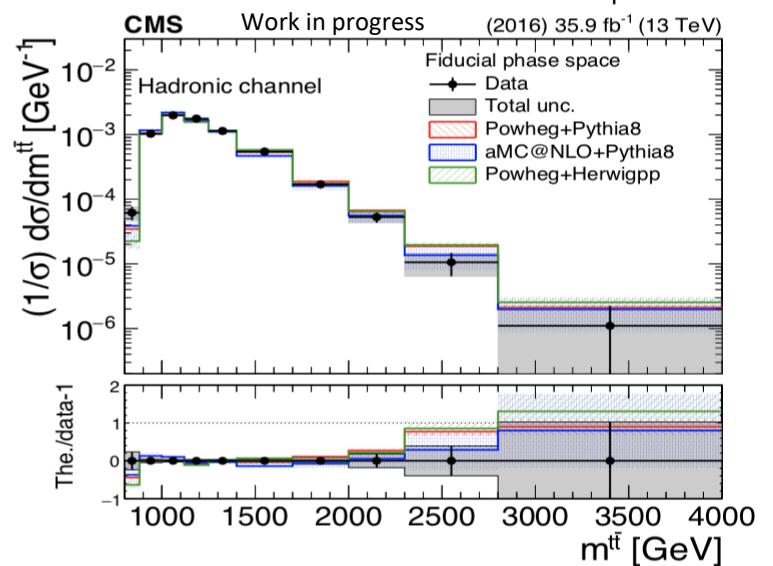
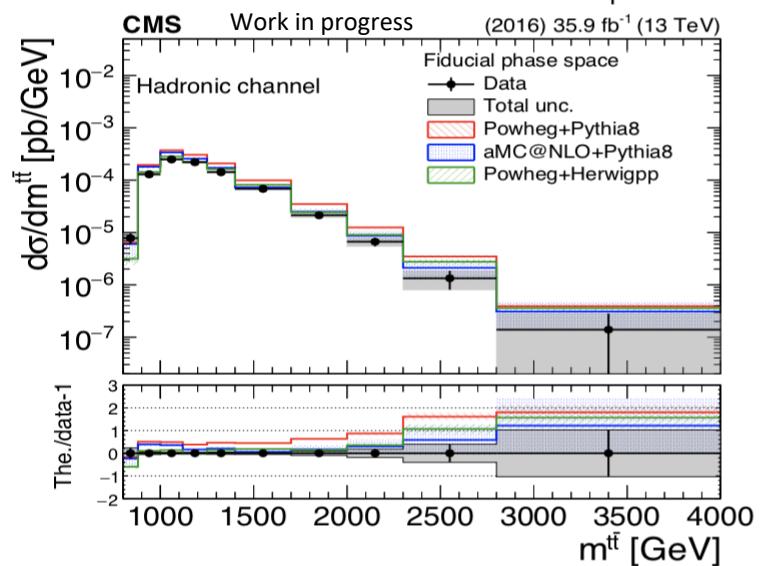
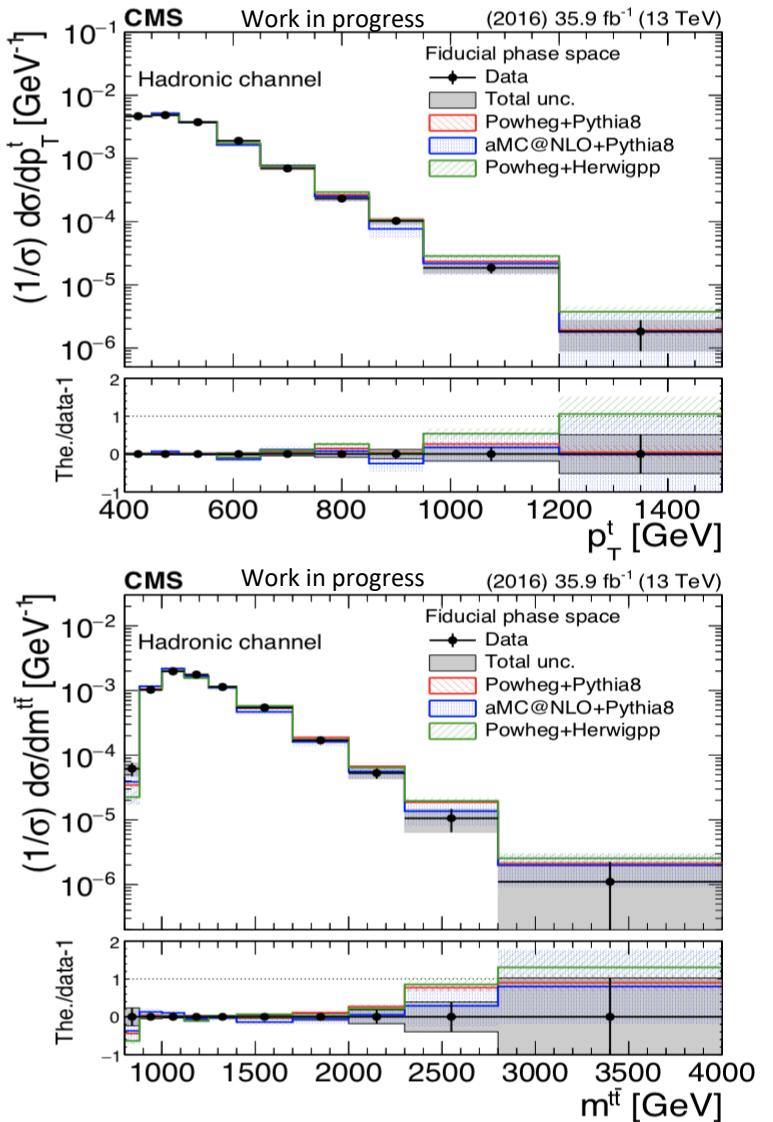
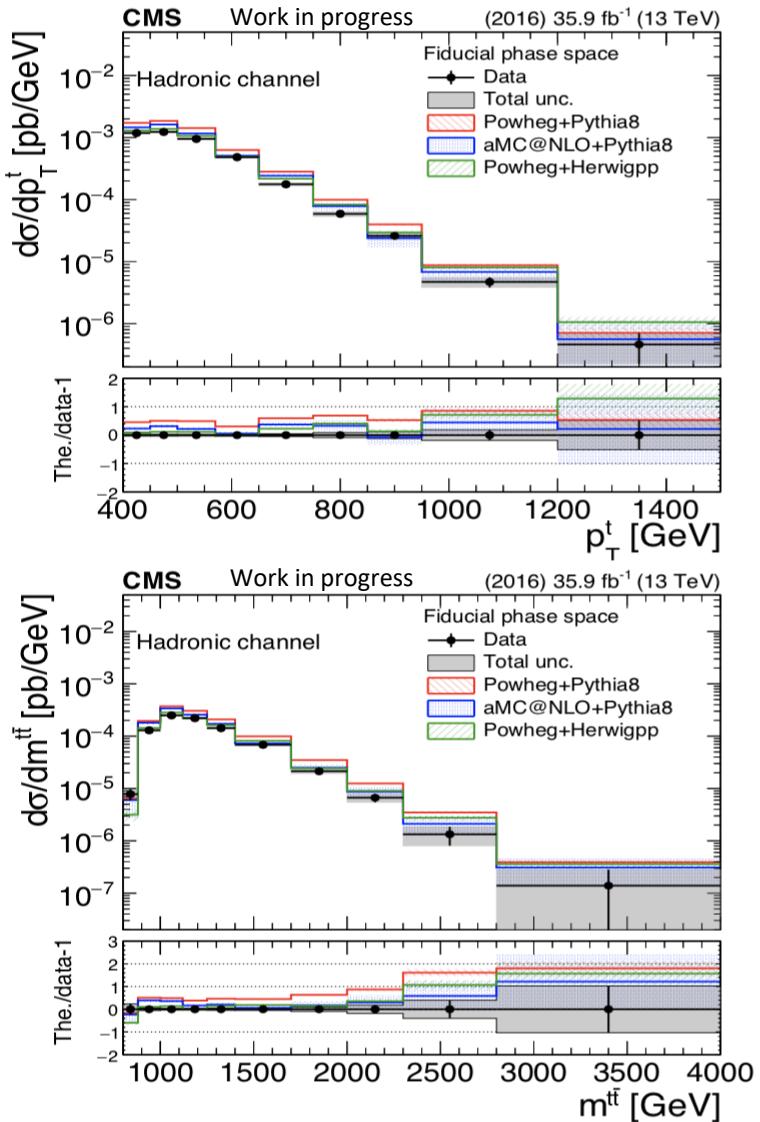
Particle to parton matching efficiency



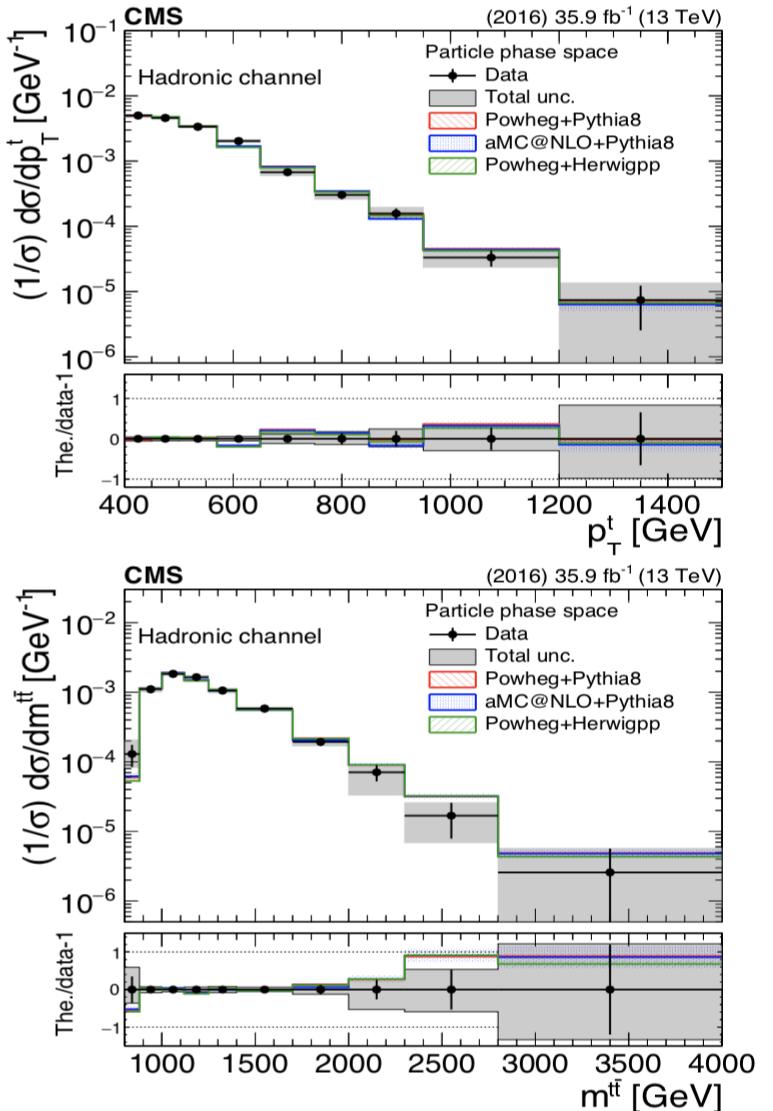
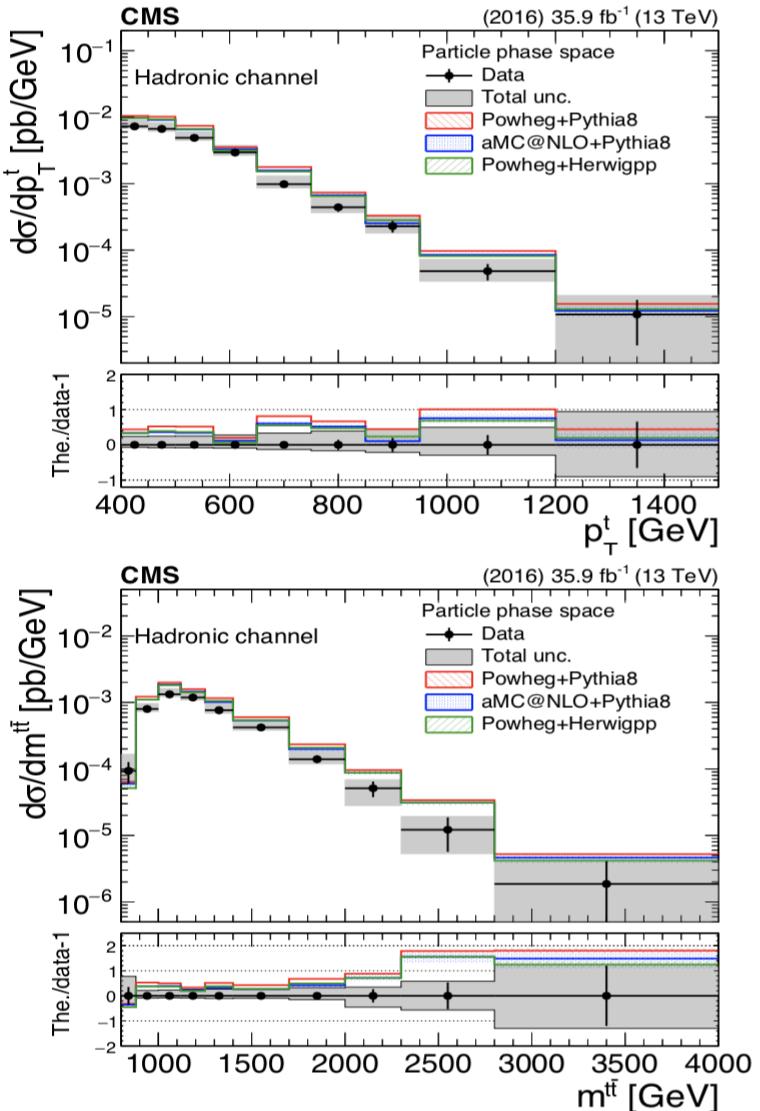
# Migration Matrices



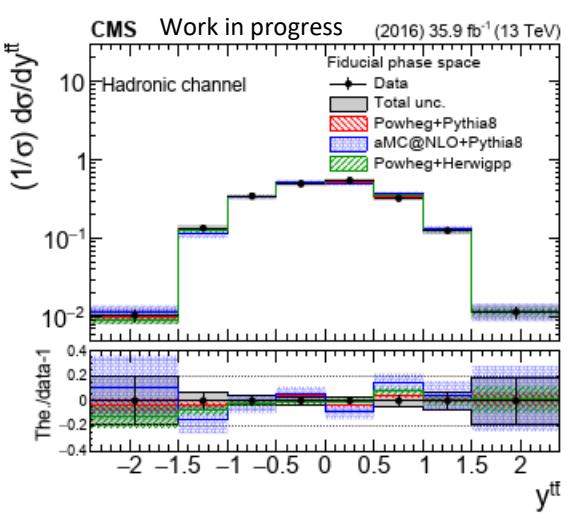
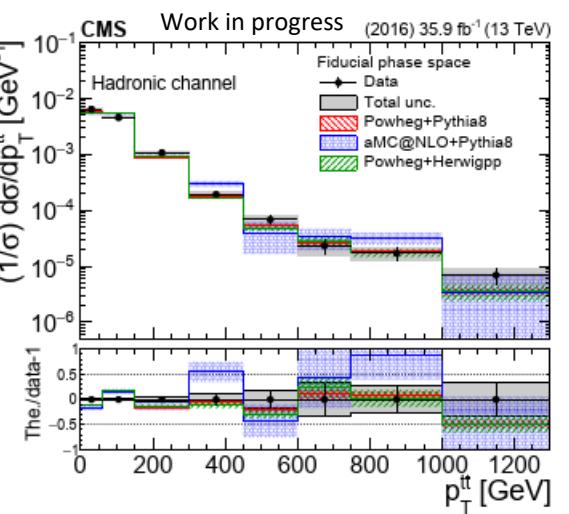
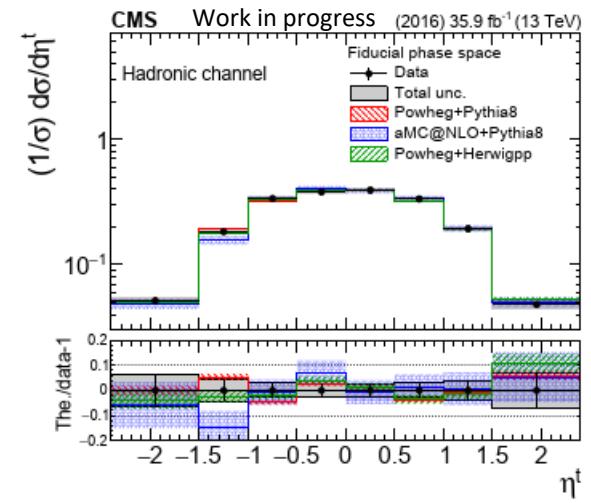
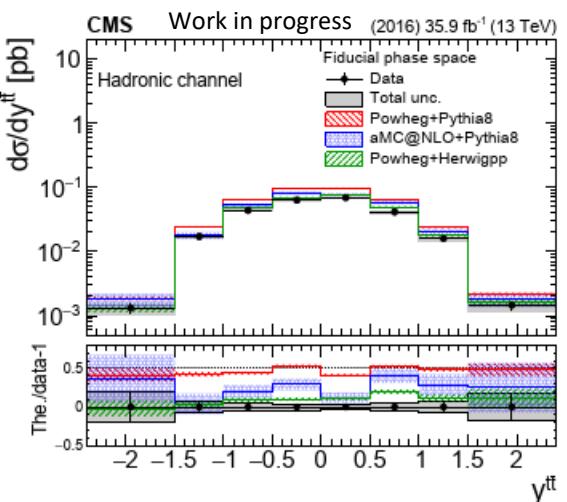
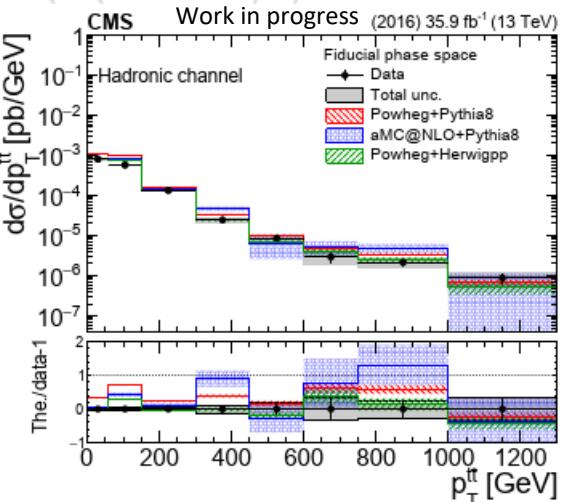
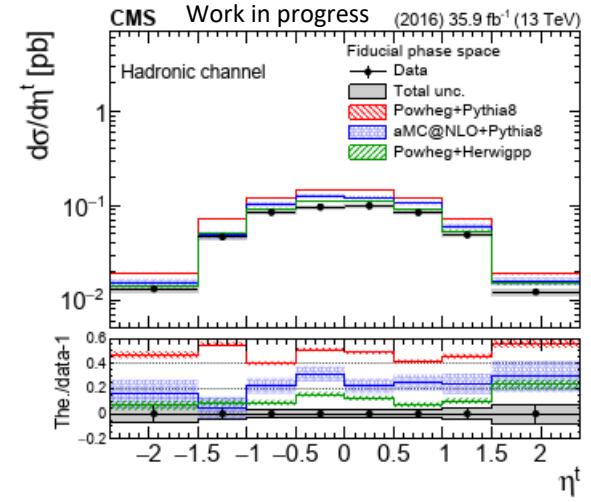
# Results for Fiducial Measurement (top $p_T$ , $m_{t\bar{t}}$ )



# Results for Particle Measurement (top $p_T$ , $m_{t\bar{t}}$ )

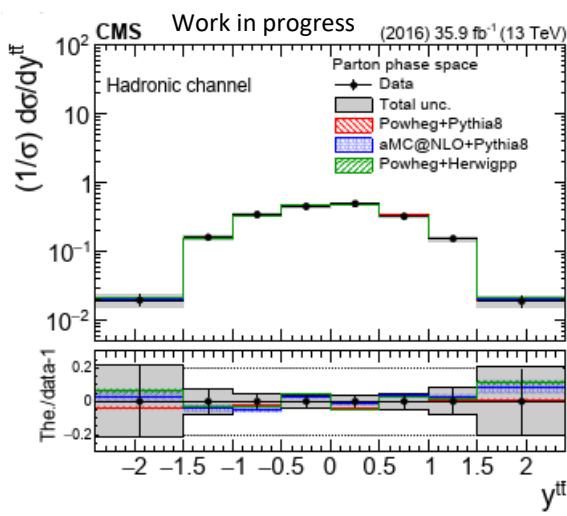
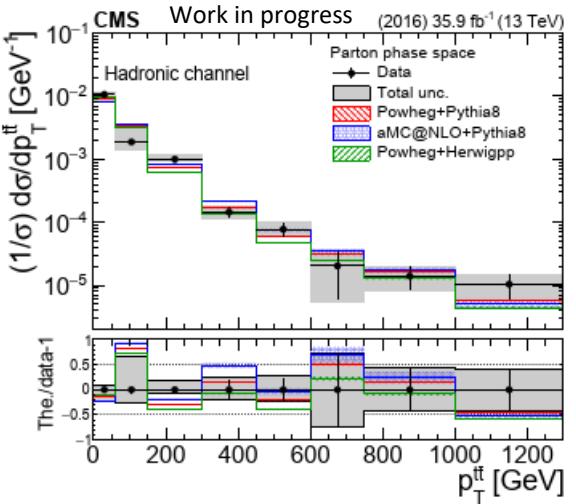
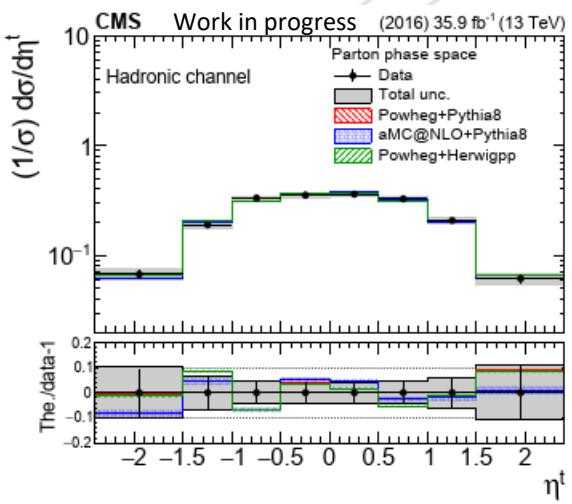
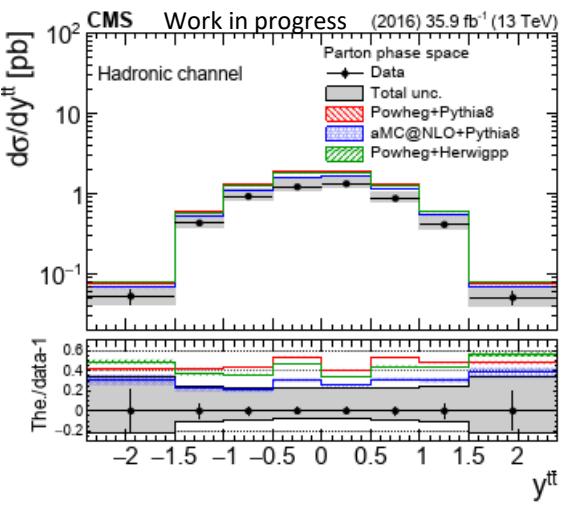
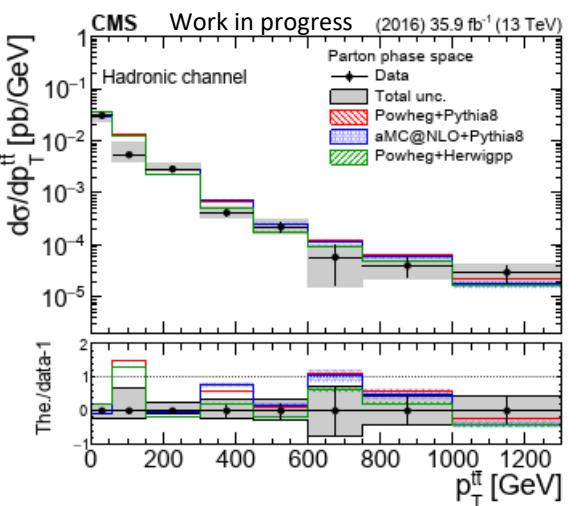
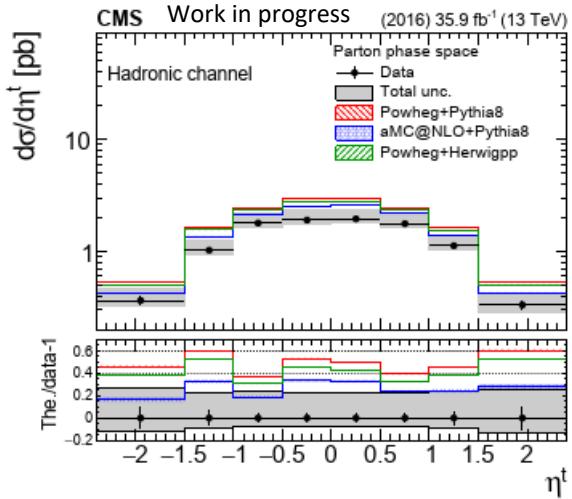


# Fiducial Results for $\eta^t$ , $p_{T,tt}$ , $y_{tt}$





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



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

