



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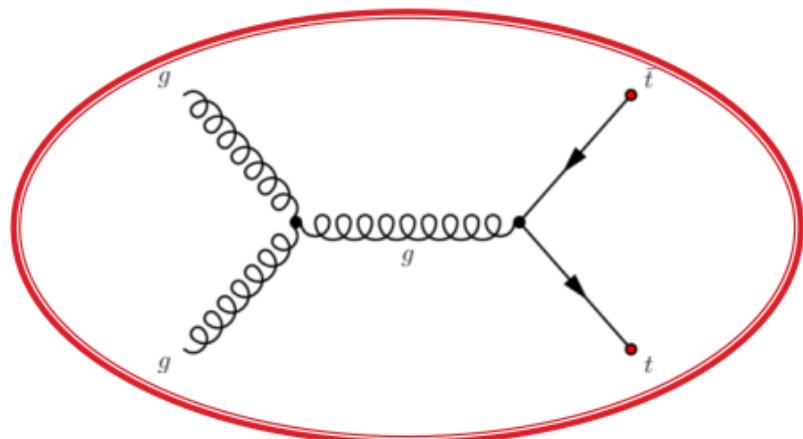
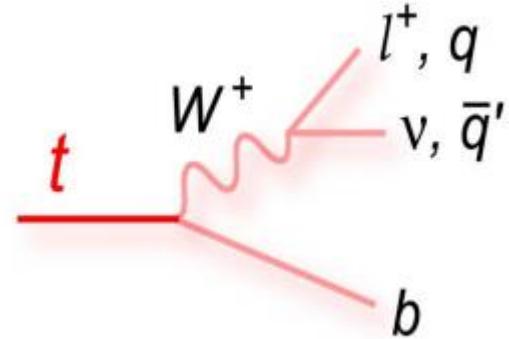
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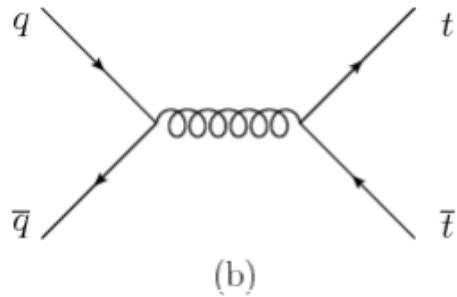
- Top Quark
- Boosted Jets
- CMS Experiment
- Analysis
- Overview

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

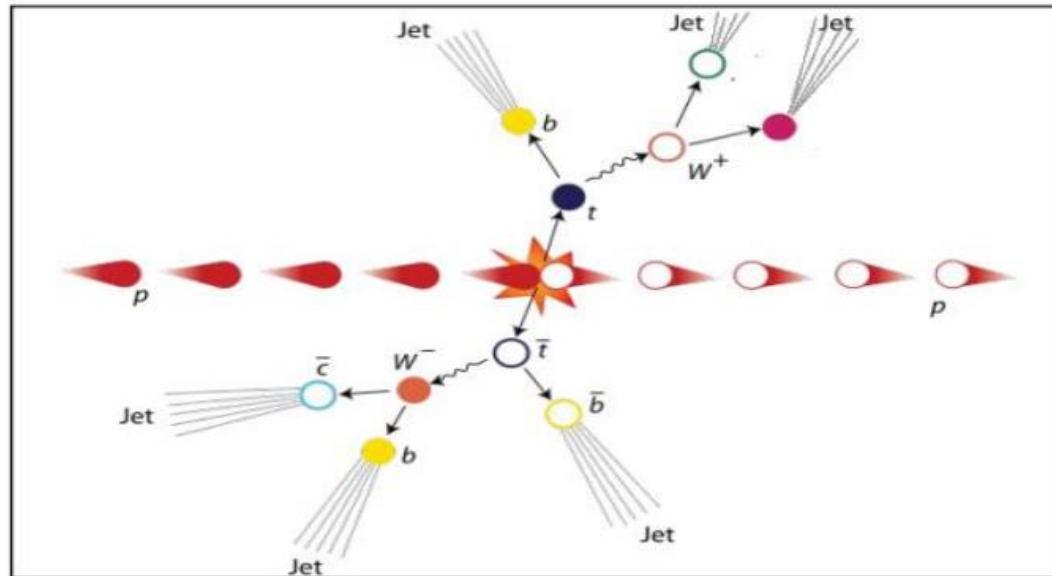


Gluon Fusion is dominant at LHC



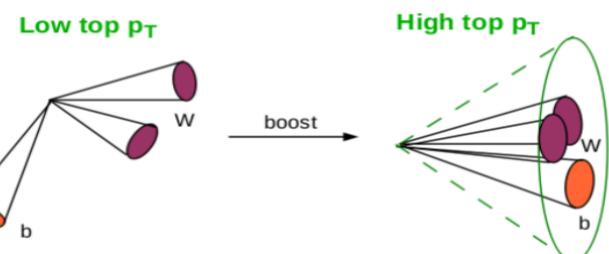
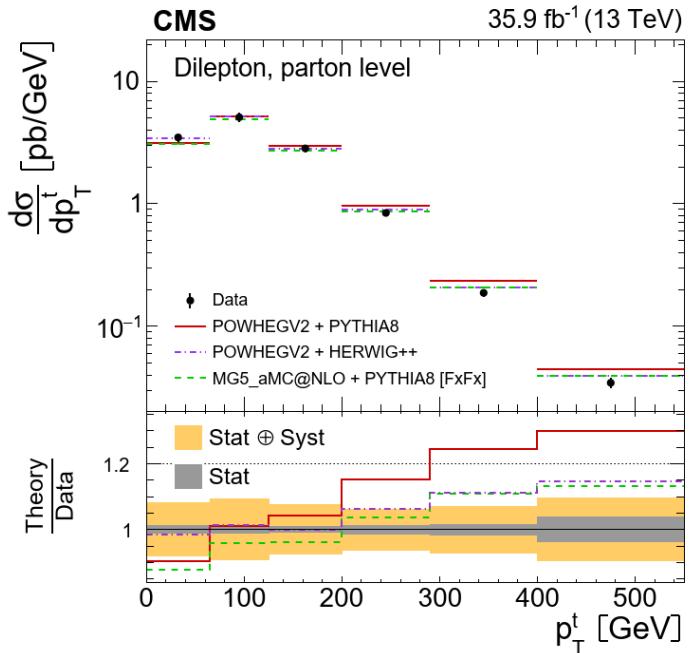
Top AntiTop system decay

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 ~ 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 $\sim 18,000\text{A}$

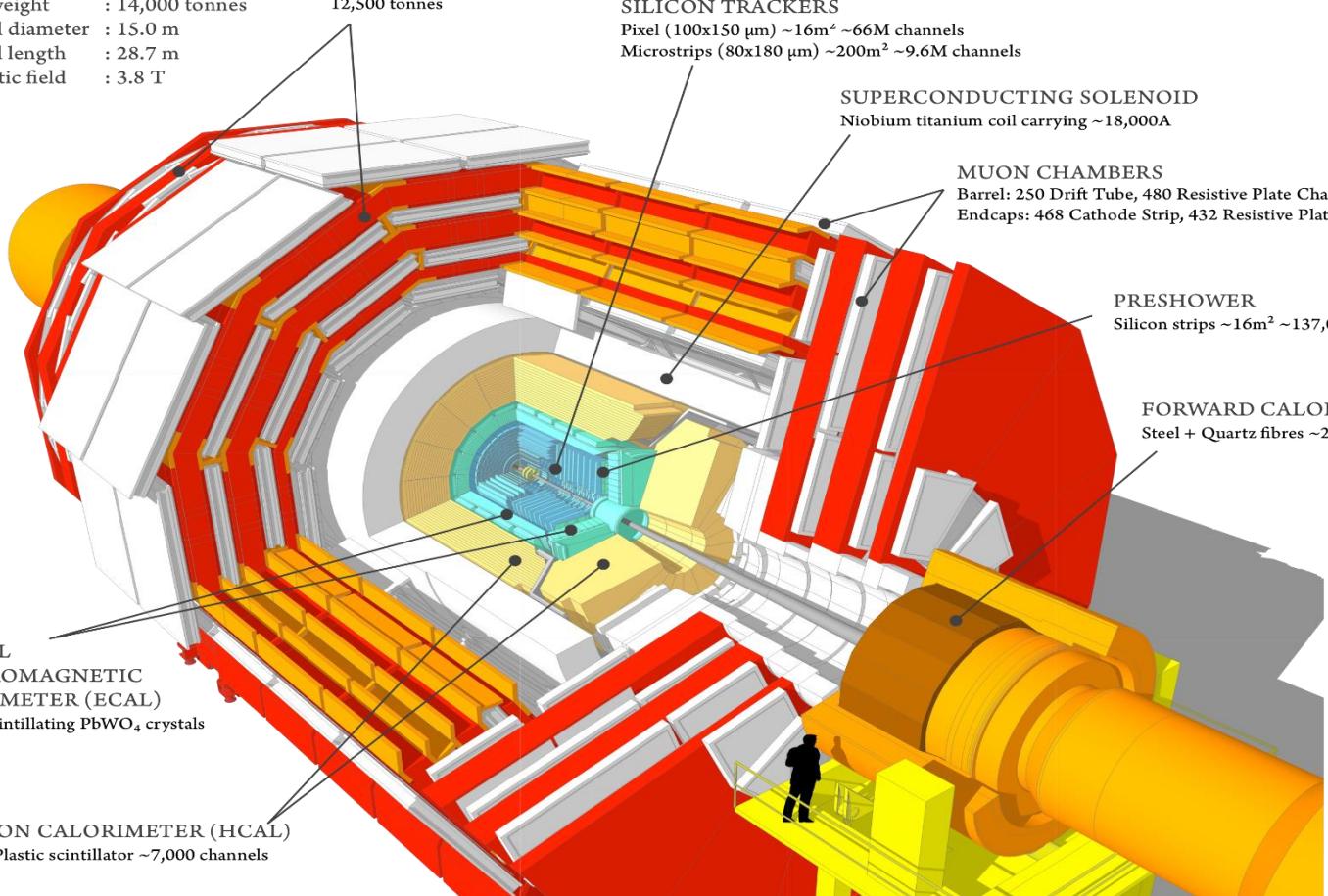
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

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

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

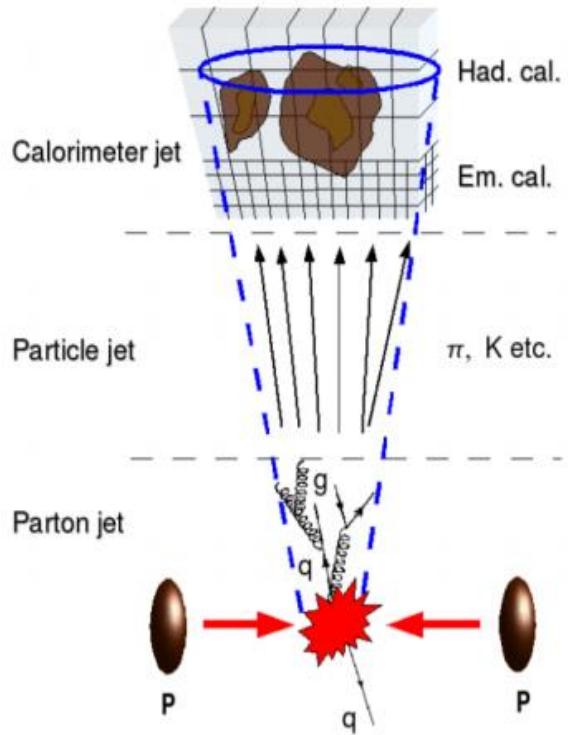
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

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



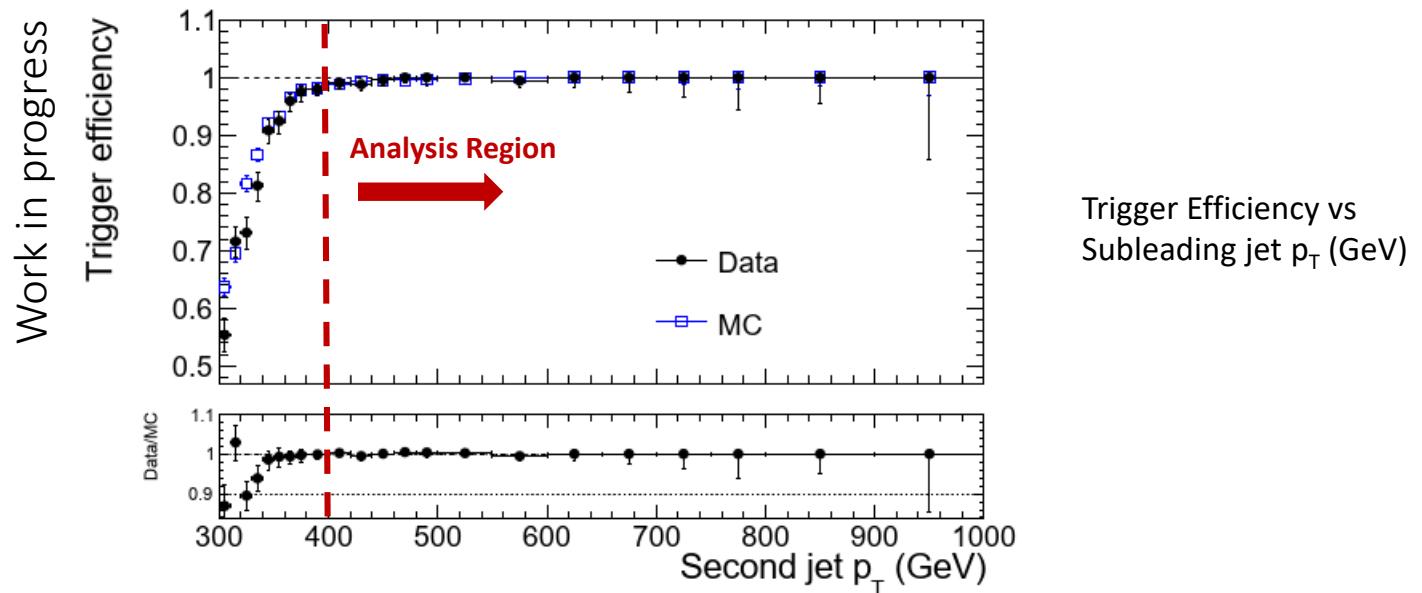
Analysis Overview

- 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

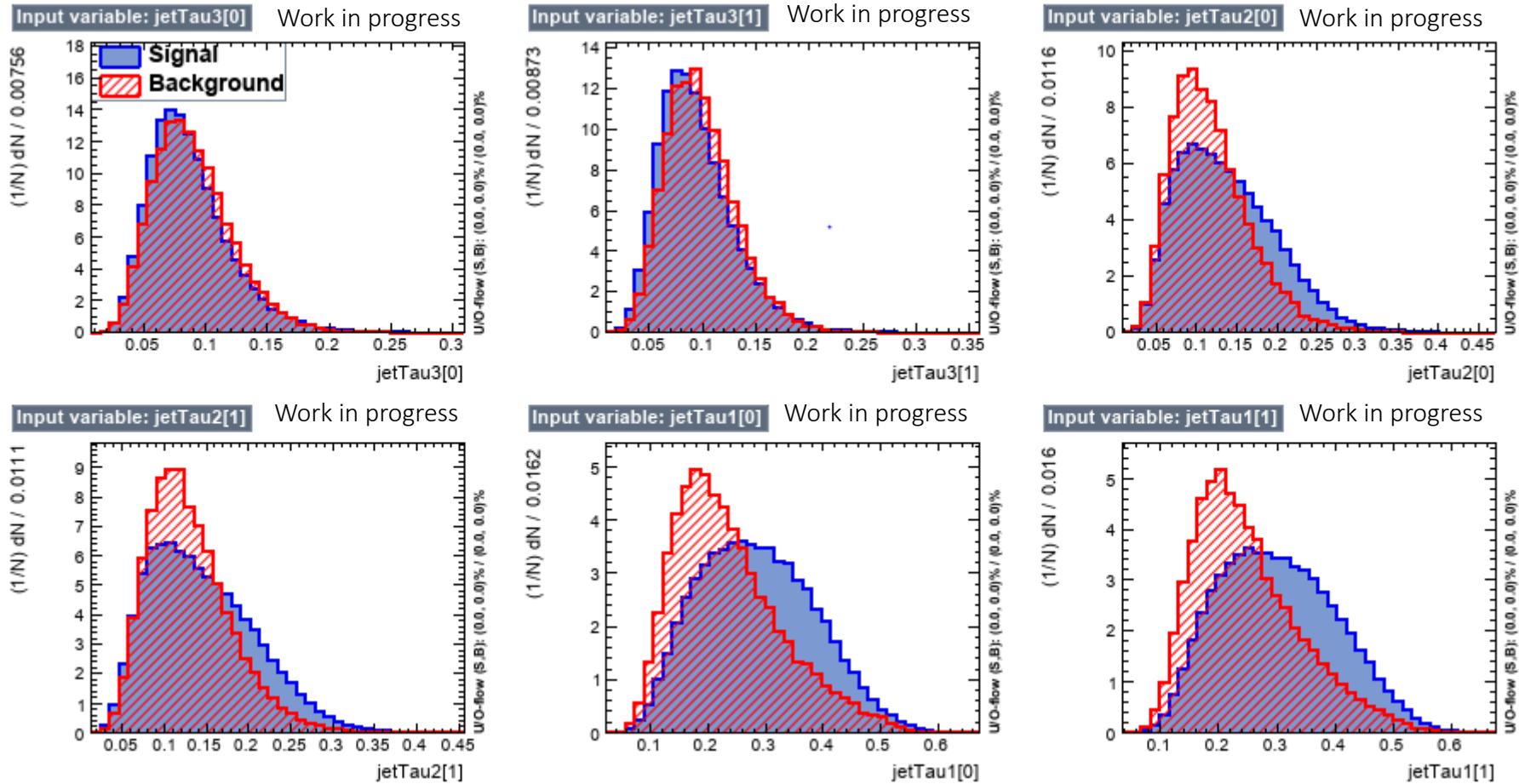


Trigger

- 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

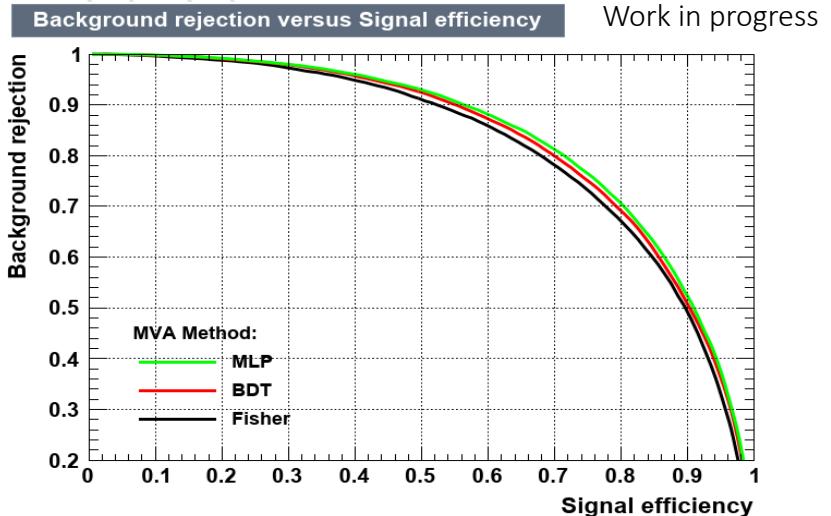
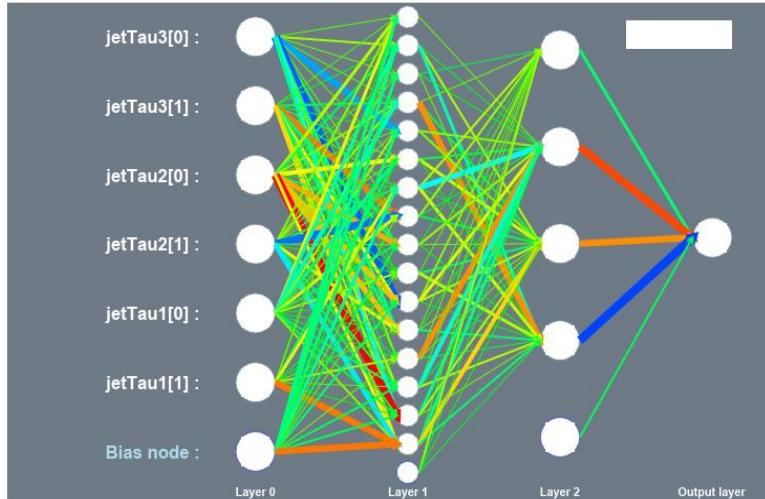


Multivariate Discriminant Analysis(variables)

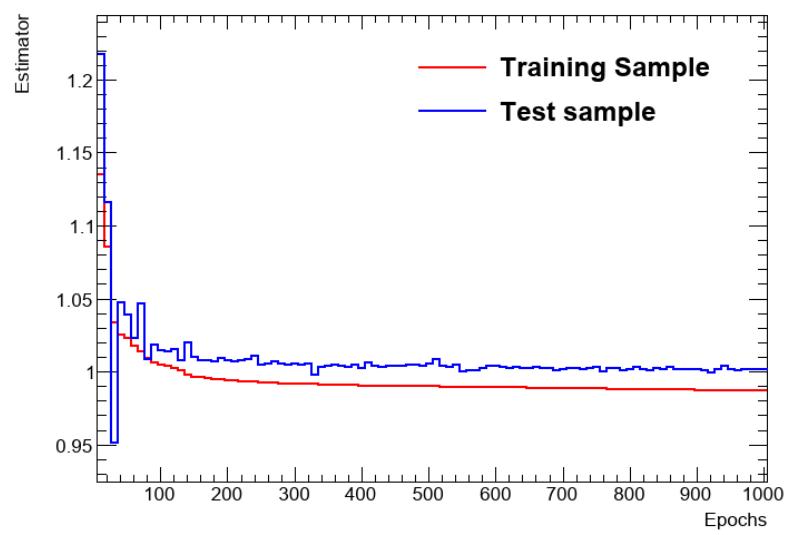


Discriminating variables used for separation of the $t\bar{t}$ from the QCD events

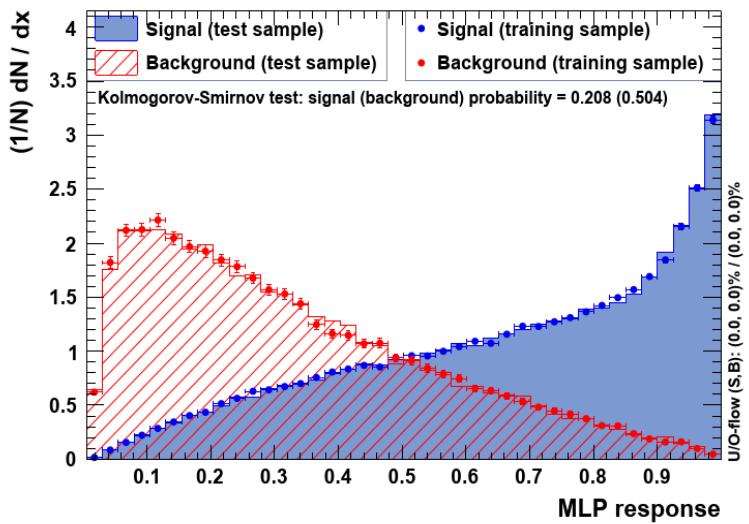
Multivariate Discriminant Analysis (training)



MLP Convergence Test Work in progress



TMVA overtraining check for classifier: MLP Work in progress

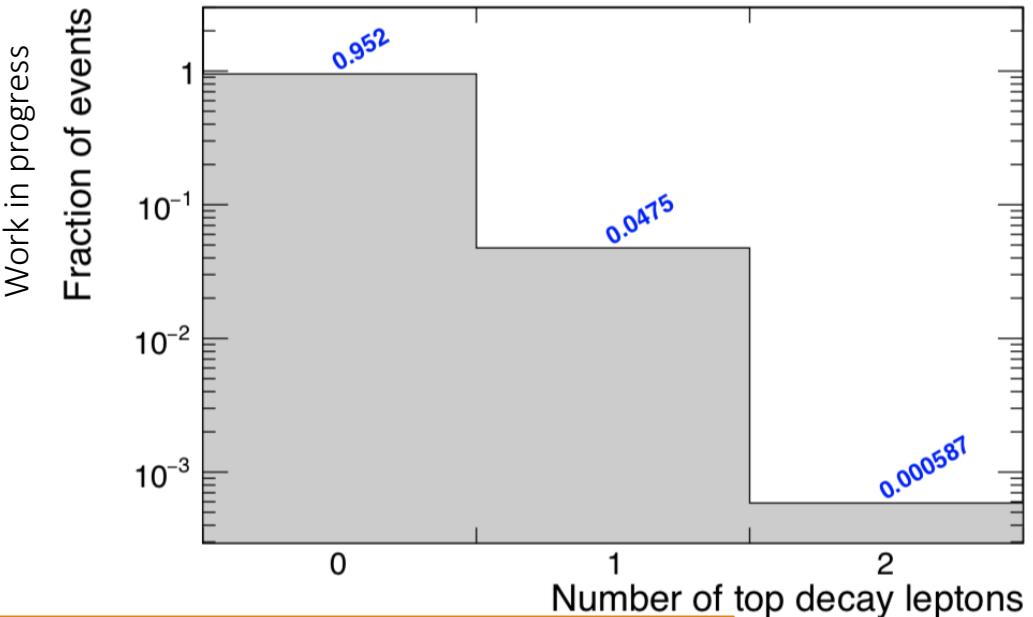


Selection

Baseline Selection

| Observable | Requirement |
|--------------------------|-------------------------|
| N_{jets} | > 1 |
| N_{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



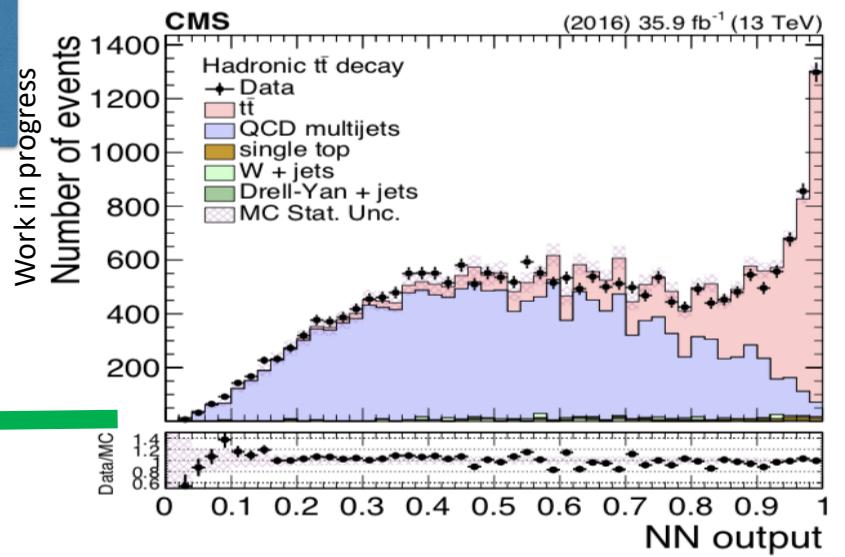
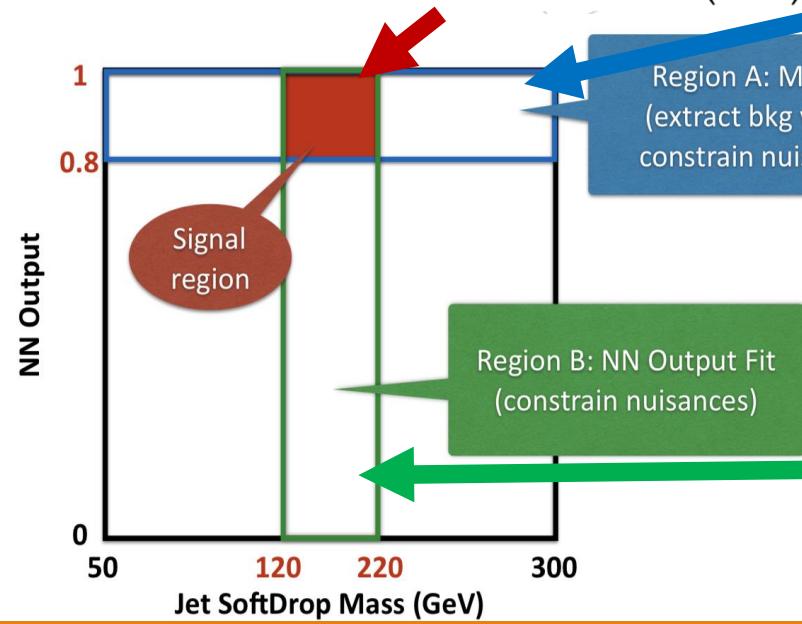
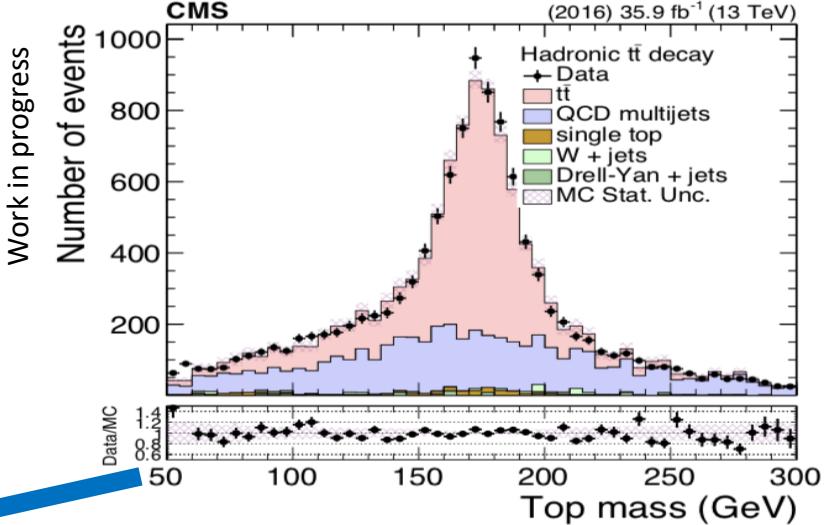
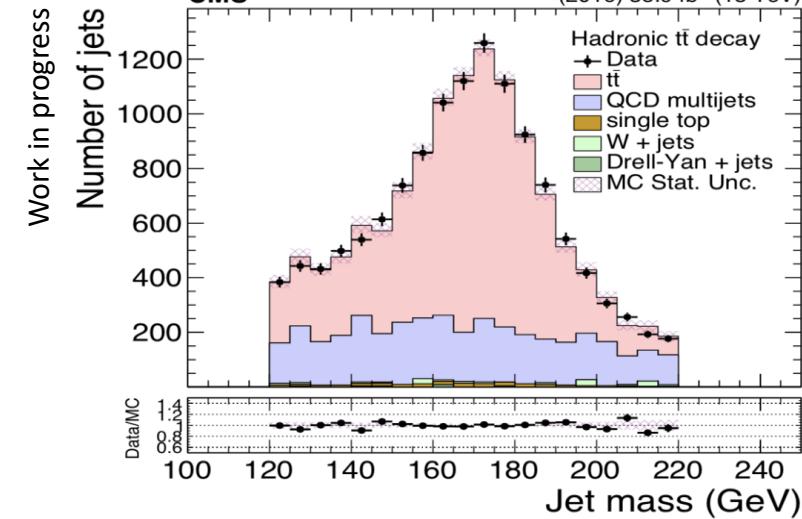
From signal selection almost 95% of the decays are hadronic

Table: Selection requirements per analysis region

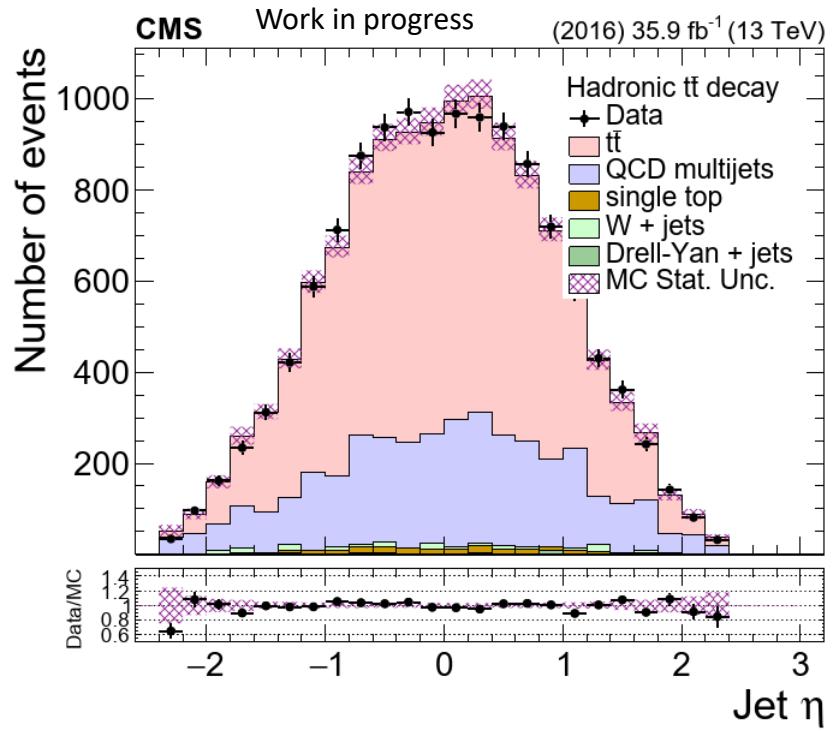
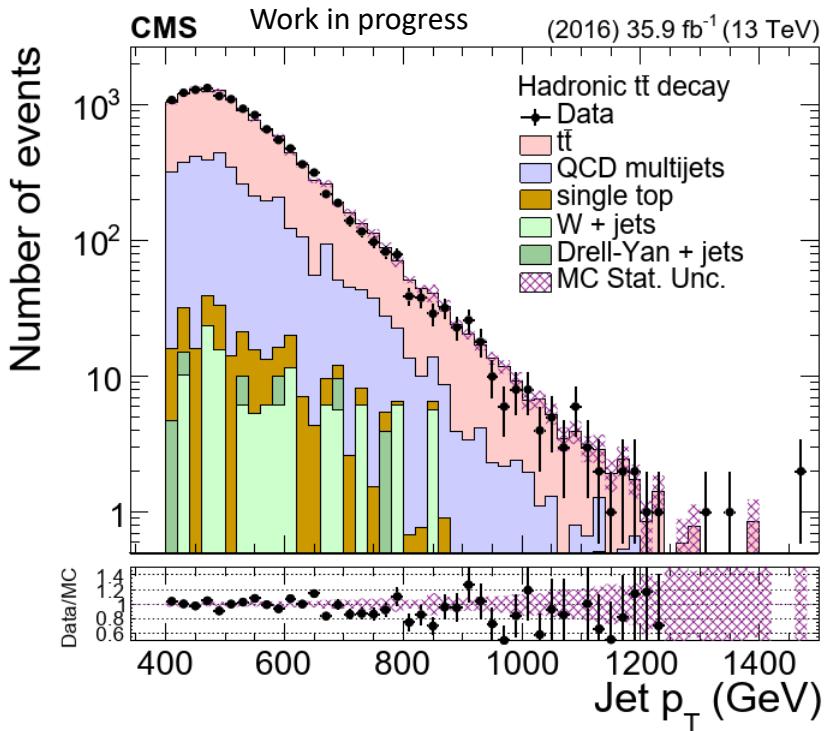
| Region | Trigger | Offline Requirements | Purpose |
|--------|---------|---|---------------------------|
| SR | signal | $\text{Base} + \text{NN} > 0.8 + \text{cat.} = 2 + m_{SD}^{\text{jet}1,2} \in (120, 220) \text{ GeV}$ | signal region |
| SR_A | signal | $\text{Base} + \text{NN} > 0.8 + \text{cat.}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

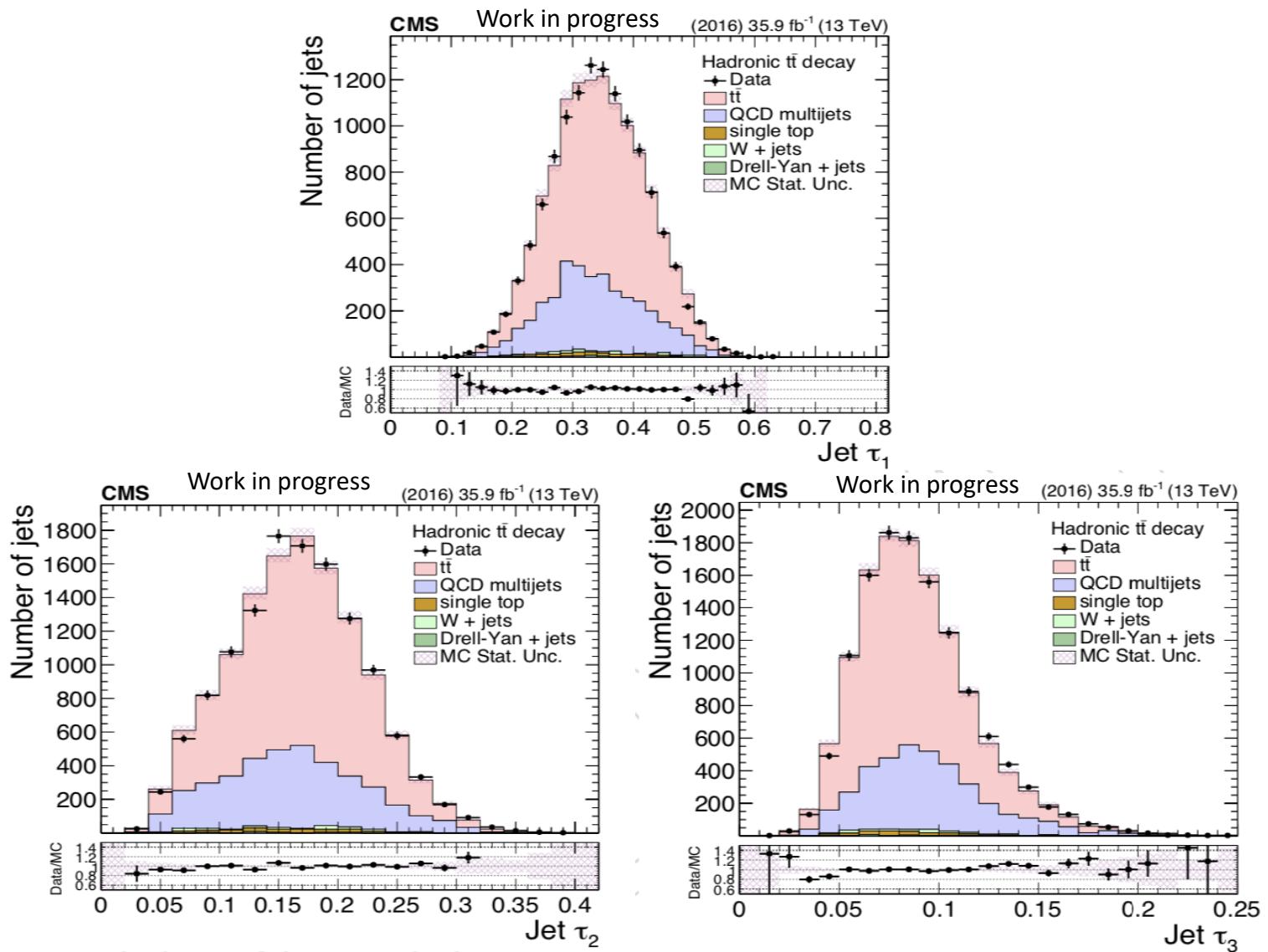
Analysis Regions



Data vs MC: Top jet Kinematics



Data vs MC: Substructure Properties



Signal Extraction

Fiducial Yield

Transfer factor from SR_A to SR

Bkg Shape Correction
(taken from MC)

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

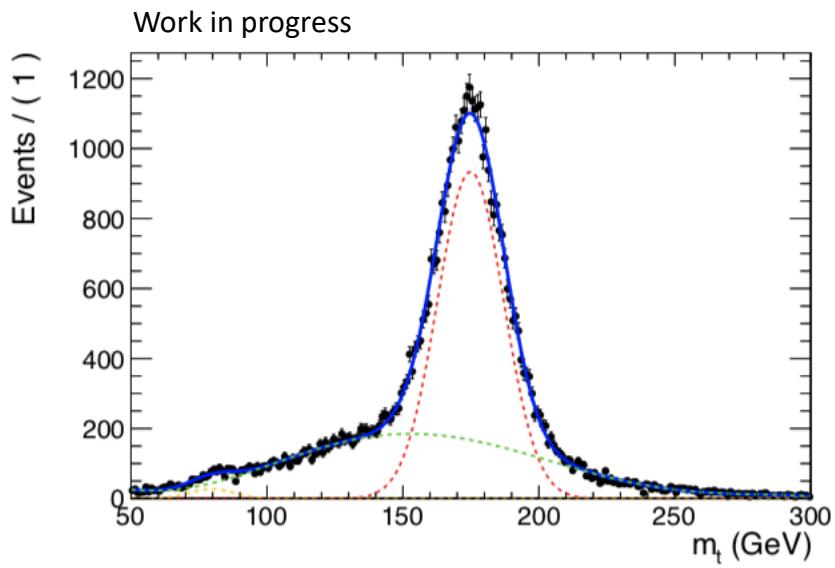
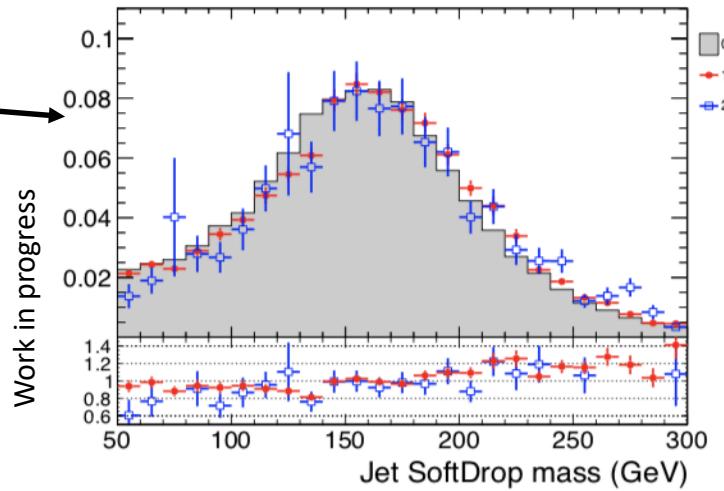
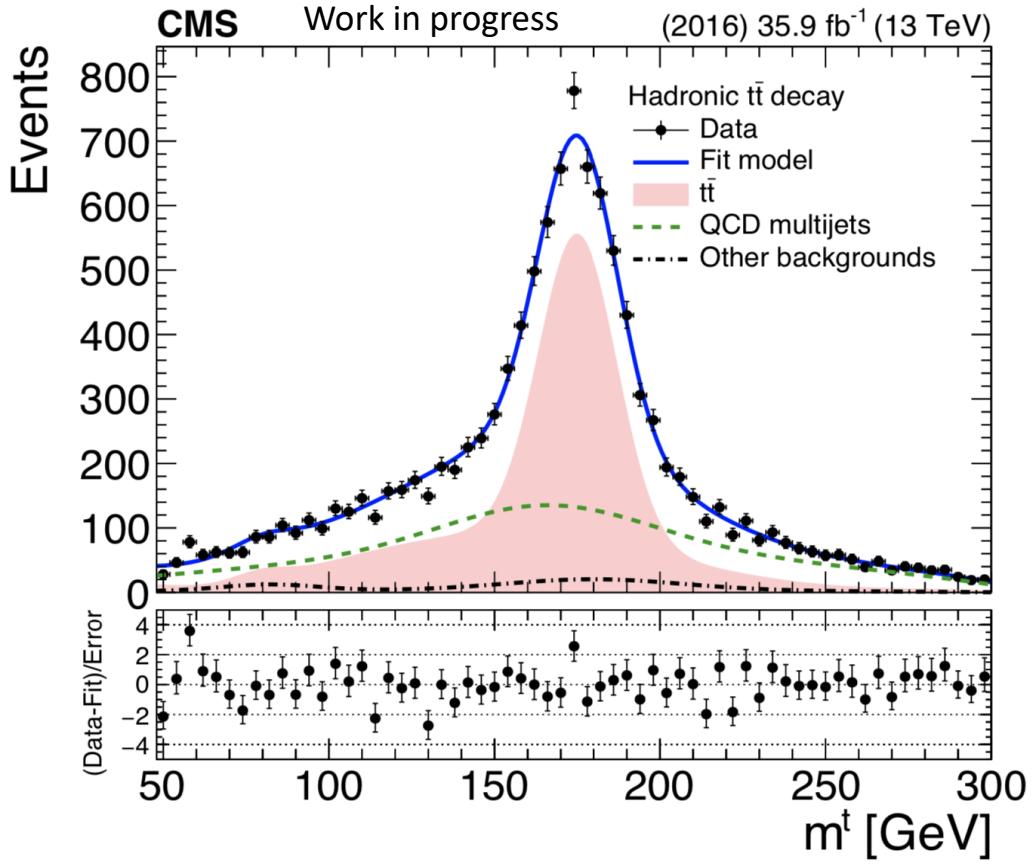
Data

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

Parton Level selection

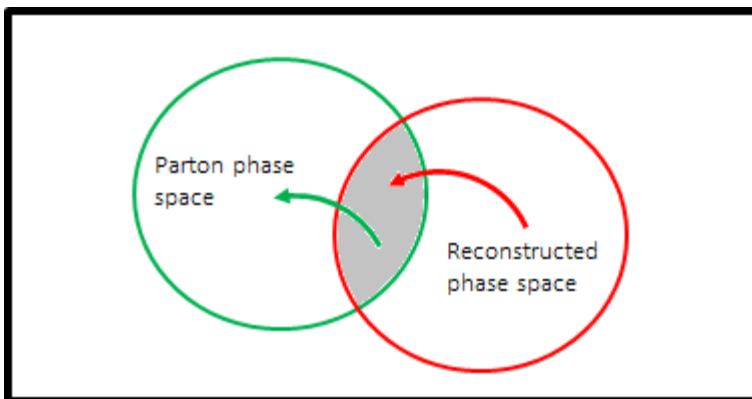
| Observable | Requirement |
|----------------------|---------------------|
| $p_T^{t,\bar{t}}$ | $> 400 \text{ GeV}$ |
| $ \eta^{t,\bar{t}} $ | < 2.4 |
| $m_{t\bar{t}}$ | $> 800 \text{ GeV}$ |

Reco and parton over reco

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

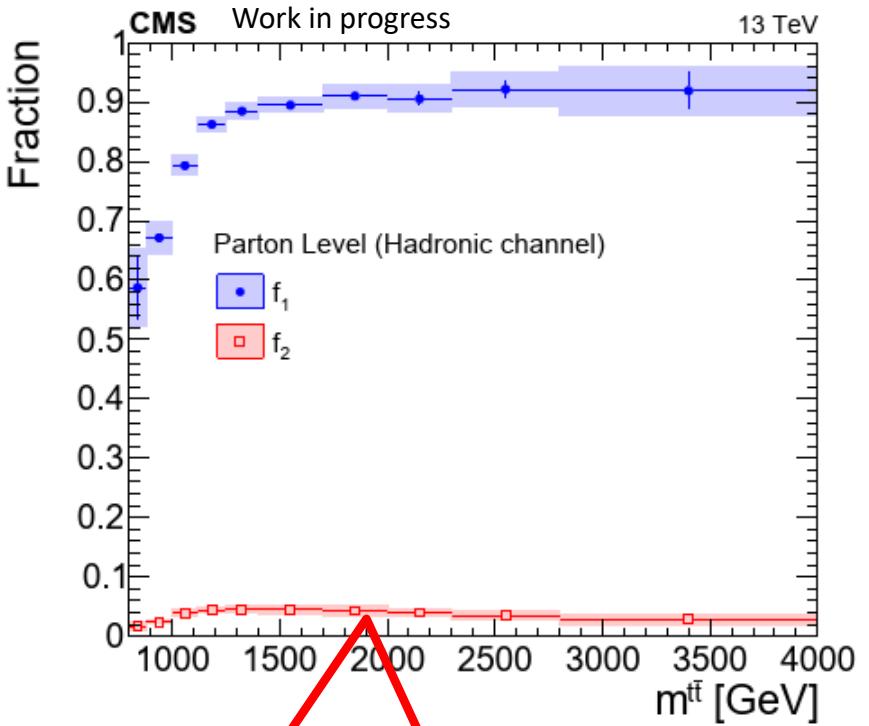
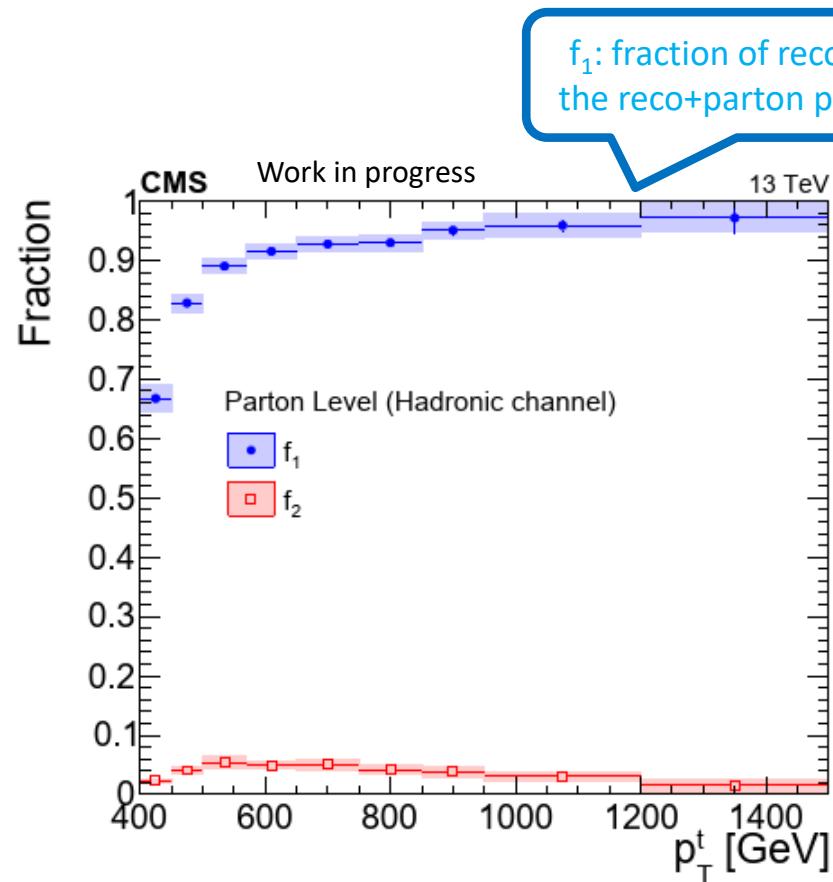
Reco and parton over parton

Migration matrix



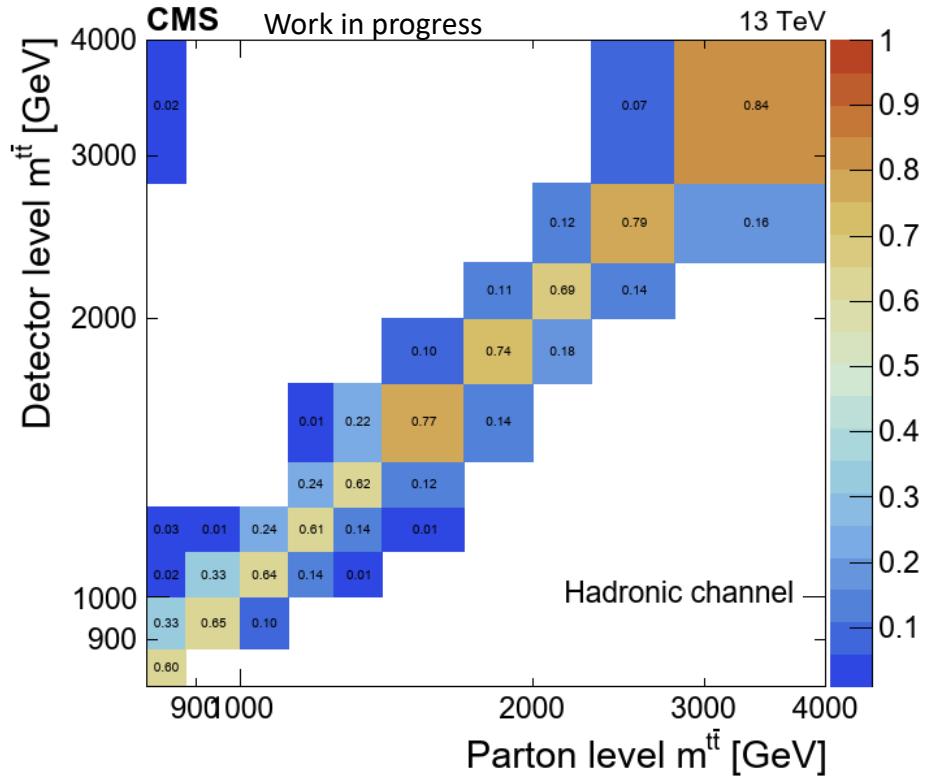
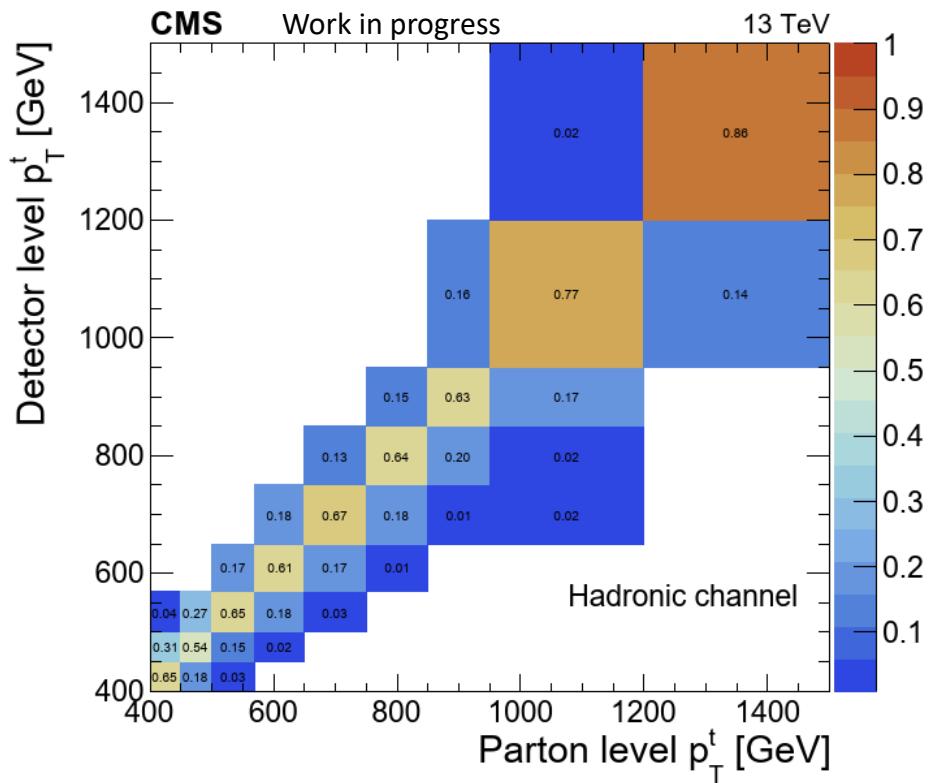
Unfolding is done using simple response matrix inversion without regularization

Extrapolation factors for parton level



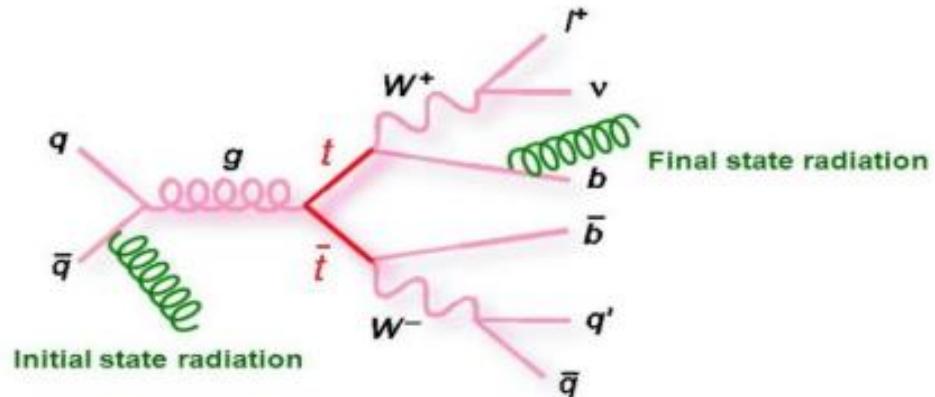


Migration Matrices

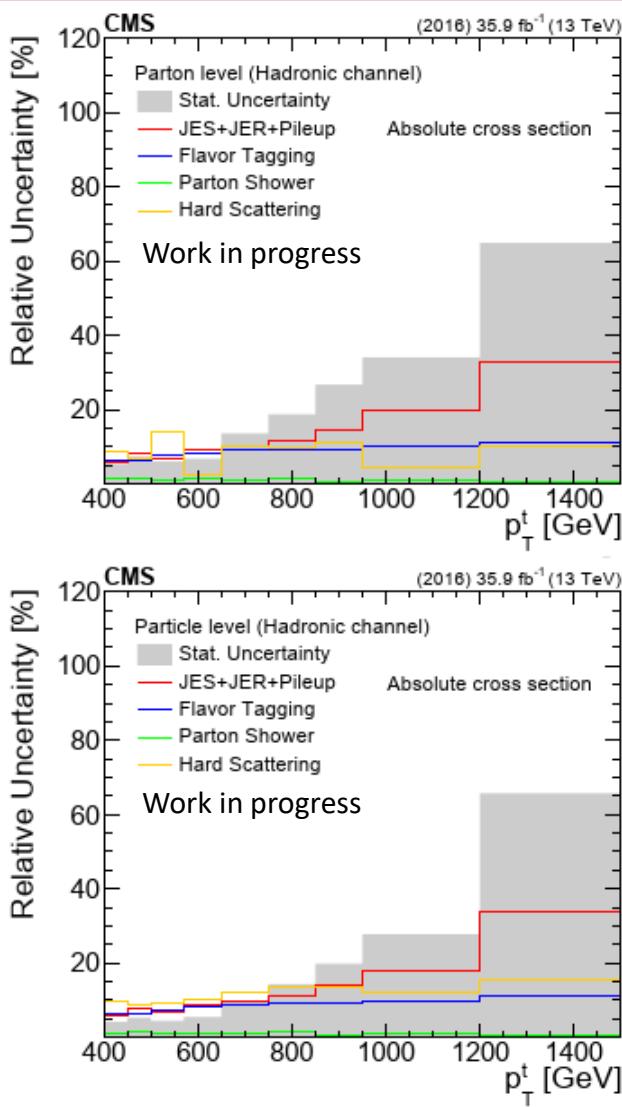


Uncertainties

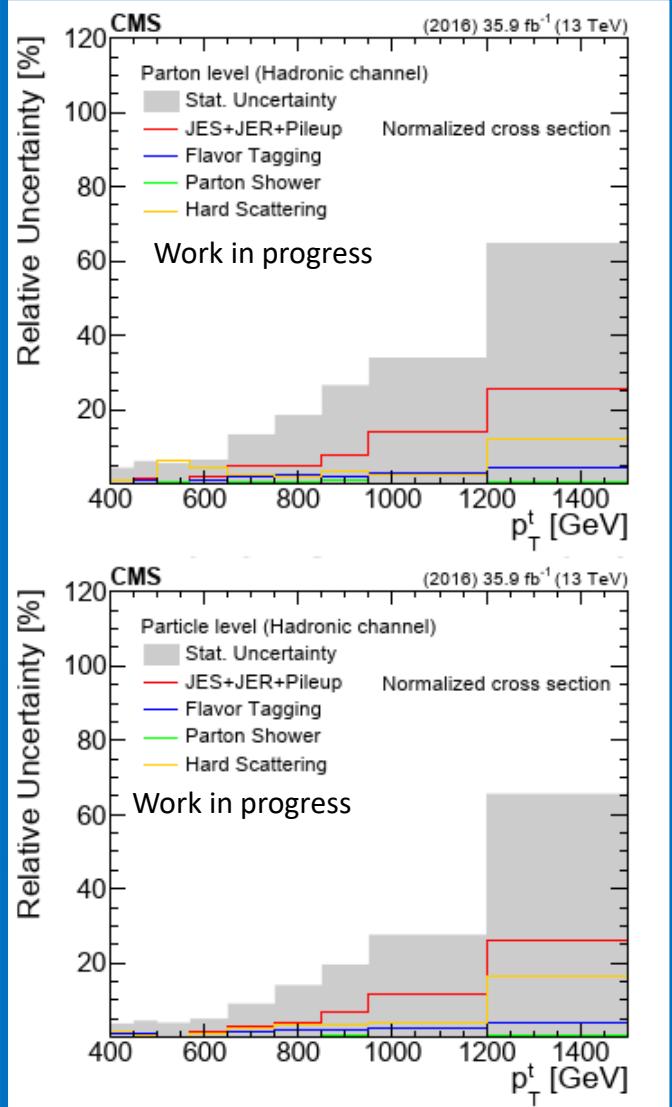
- Experimental:
 - QCD background prediction
 - Statistics
 - Jet Energy Scale
 - Jet Energy Resolution
 - B tagging efficiency
- Theoretical:
 - Affect the extrapolation factors (f_1, f_2) and the migration matrices for the unfolding procedure
 - ISR (Initial State Radiation)
 - FSR (Final State Radiation)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



Uncertainties

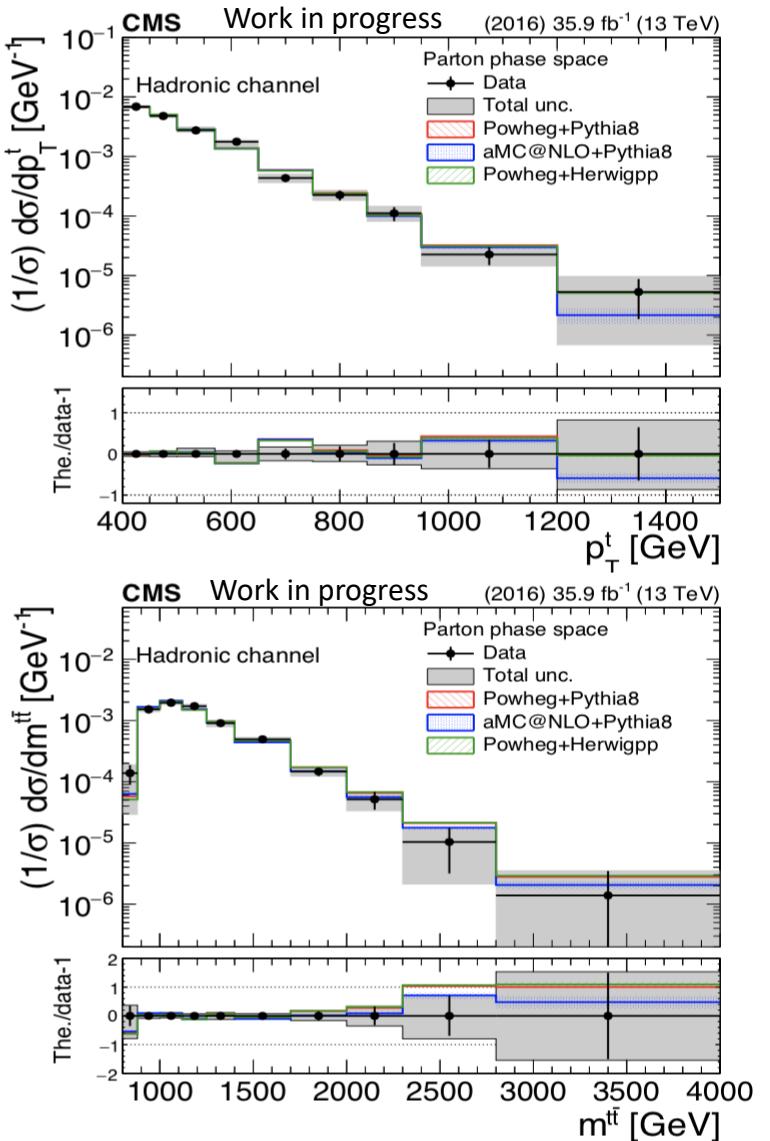
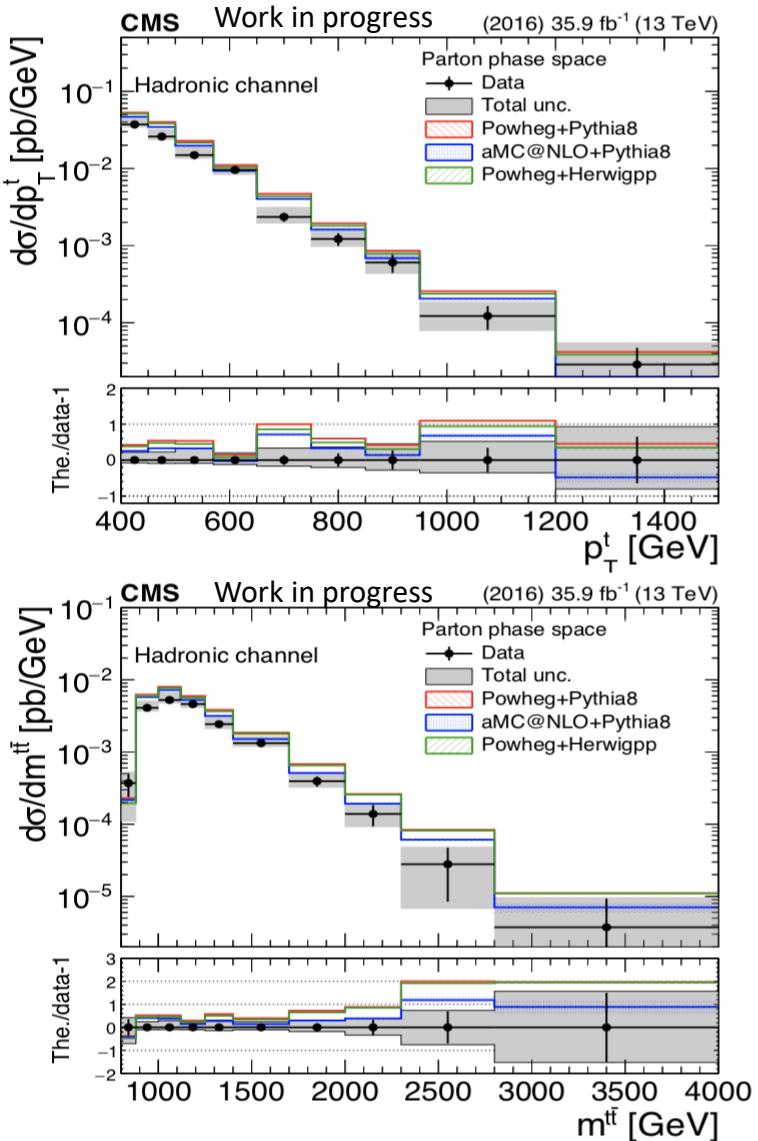


Uncertainties
for the parton
and particle
level
measurements
(absolute)



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*)



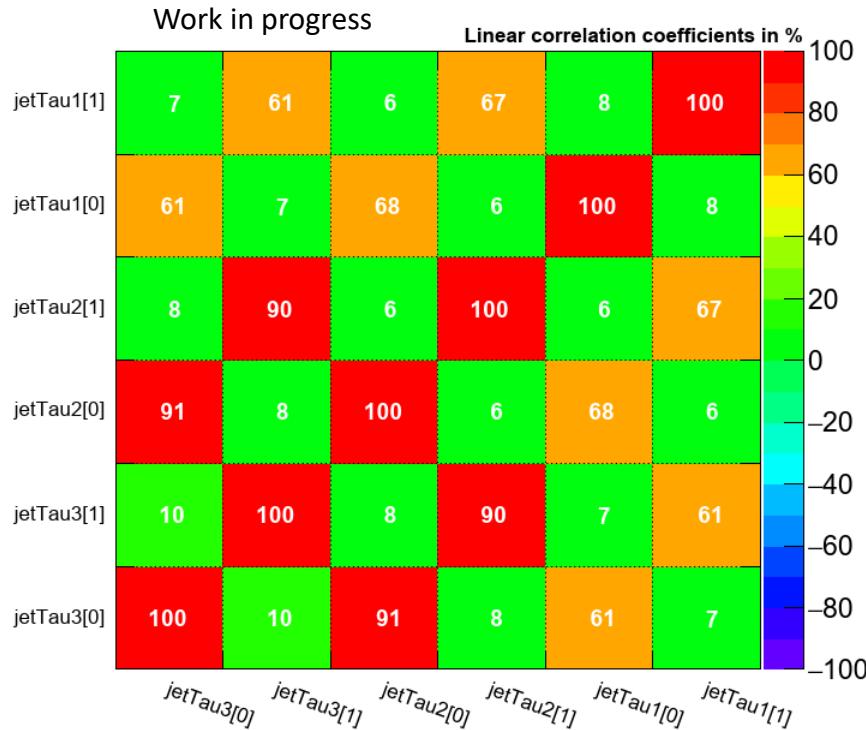
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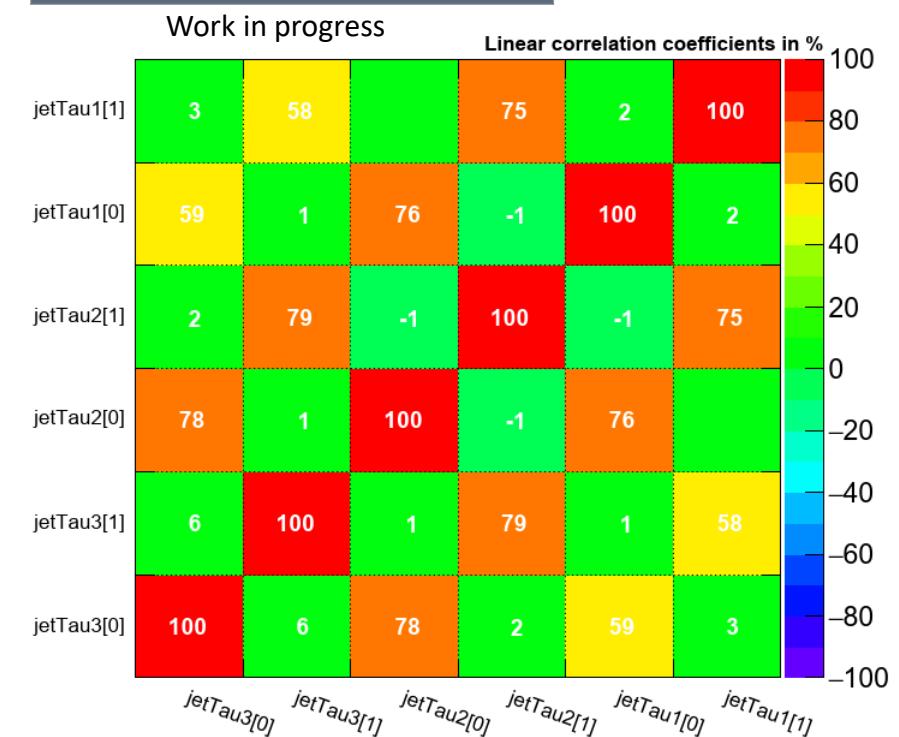
BACKUP SLIDES

MVA training: Correlation Matrices

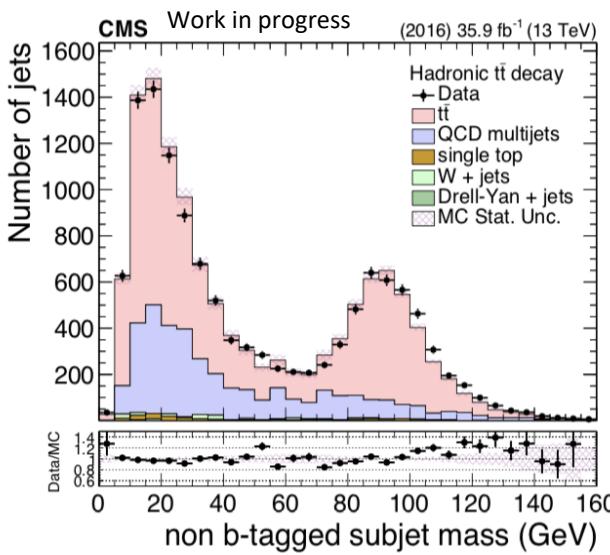
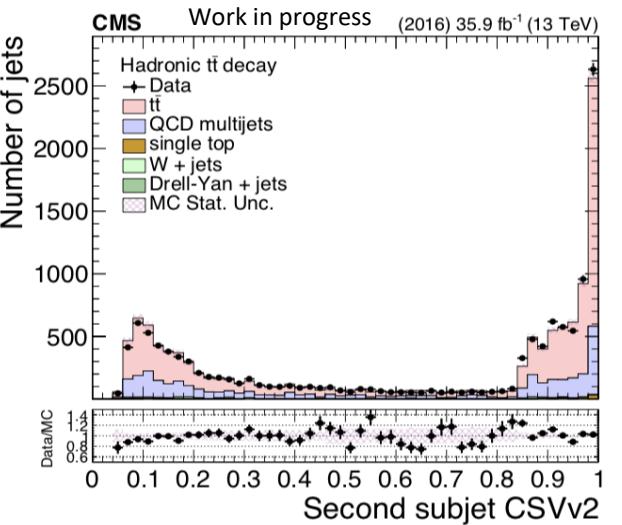
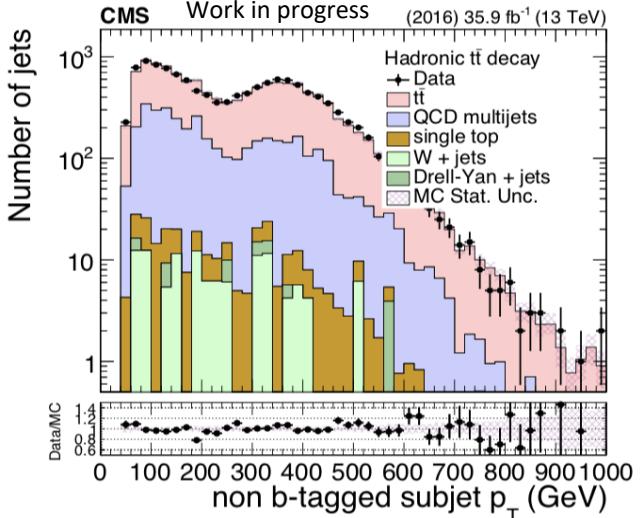
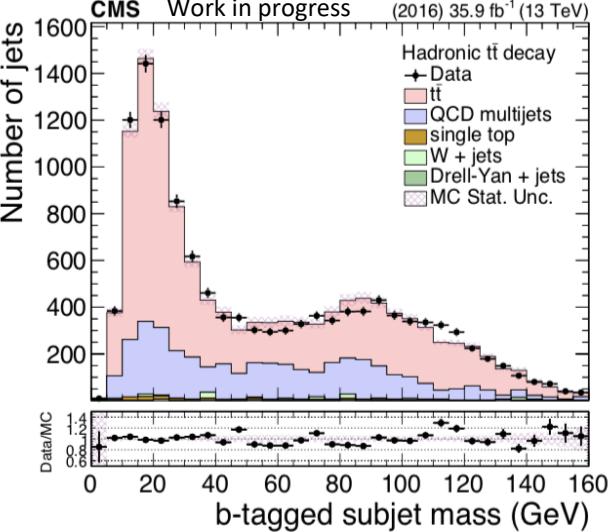
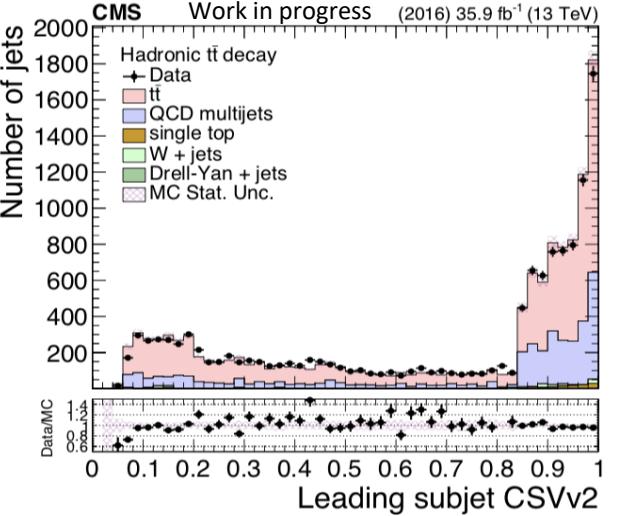
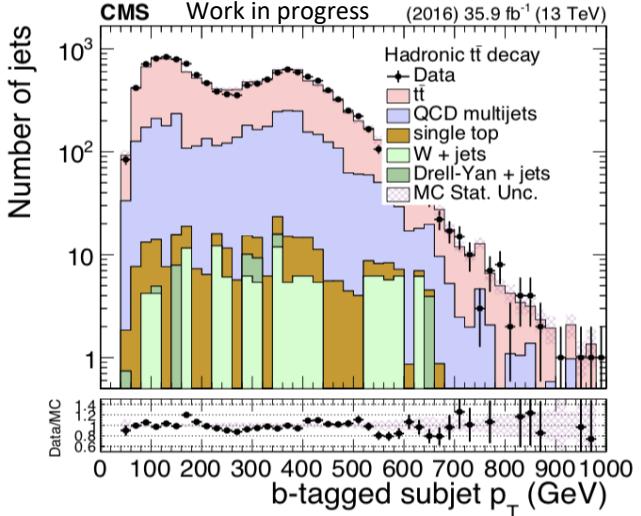
Correlation Matrix (background)



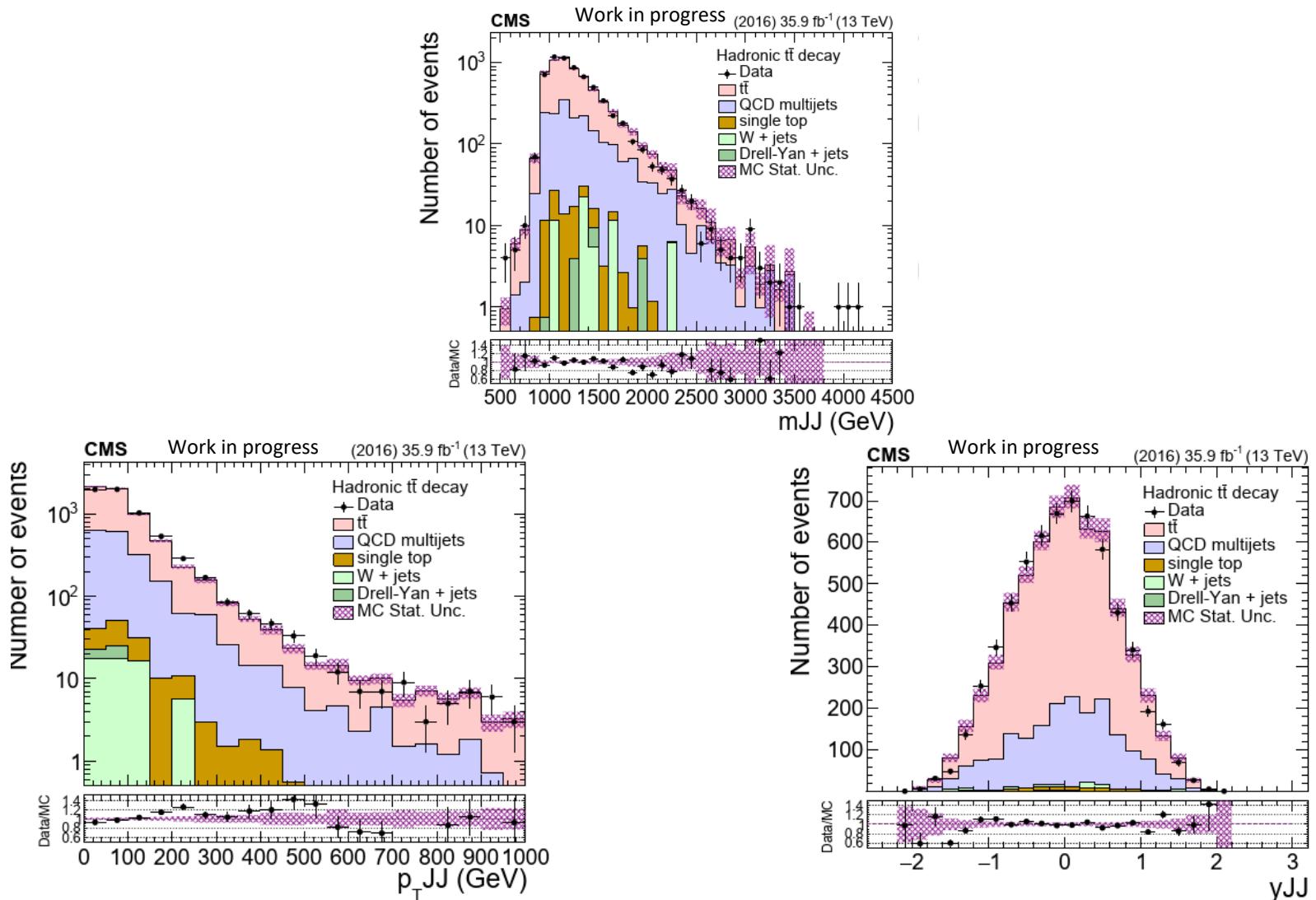
Correlation Matrix (signal)



Data vs MC: Subjet Properties



Data vs MC: ttbar Kinematics



Particle Level Selection

Particle Level selection

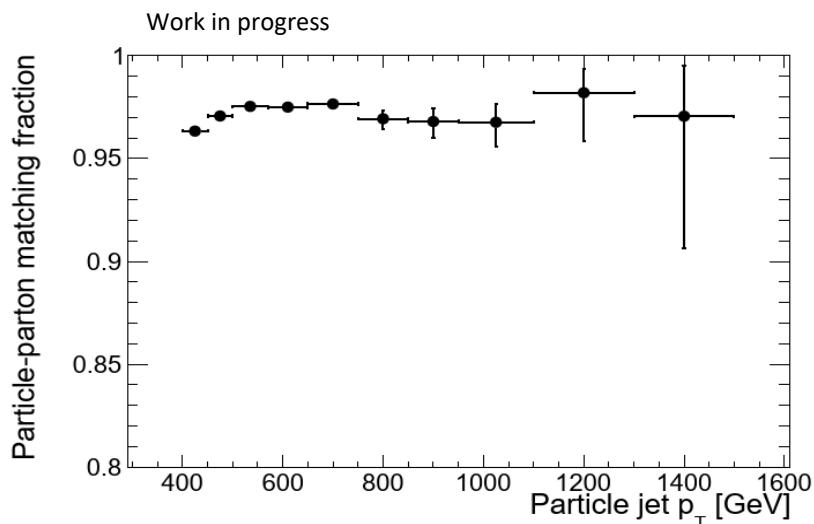
| Observable | Requirement |
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| $p_{\text{T}}^{\text{jet}1,2}$ | $> 400 \text{ GeV}$ |
| $ \eta^{\text{jet}1,2} $ | < 2.4 |
| $m_{SD}^{\text{jet}1,2}$ | $(120, 220) \text{ GeV}$ |
| m_{jj} | $> 800 \text{ GeV}$ |

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

Reco and particle over
particle

Reco and particle over
reco

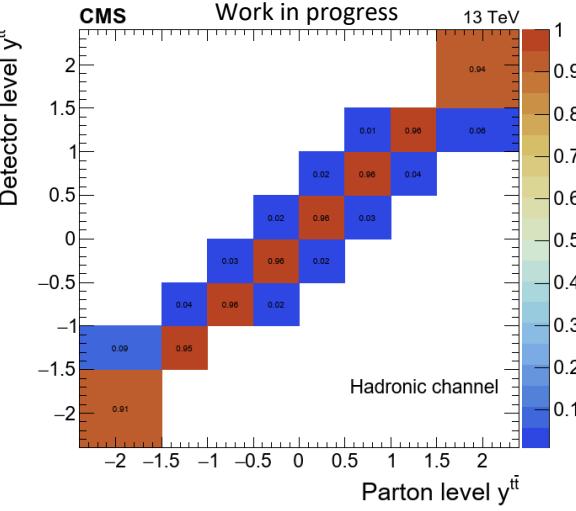
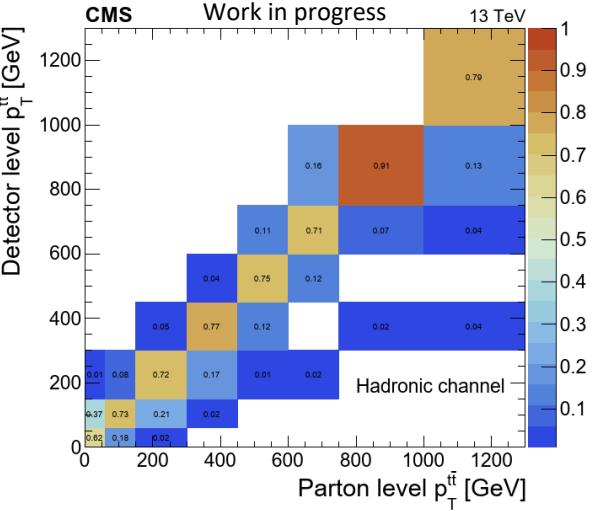
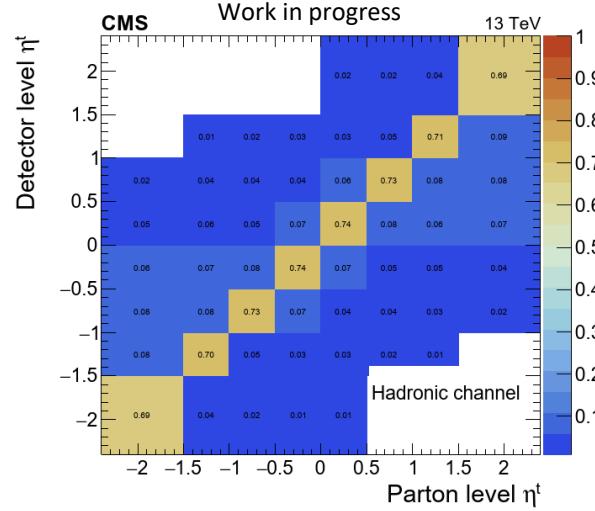
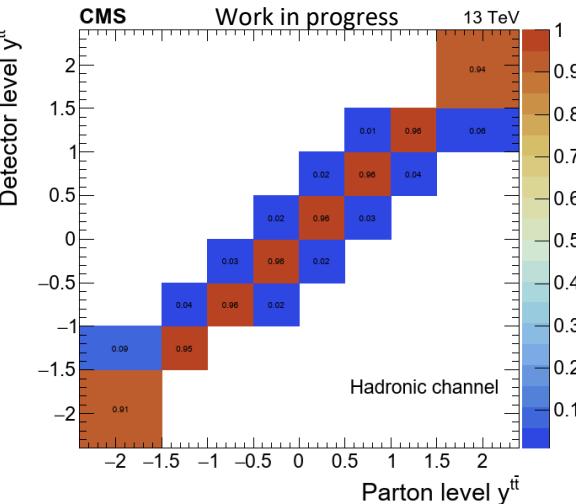
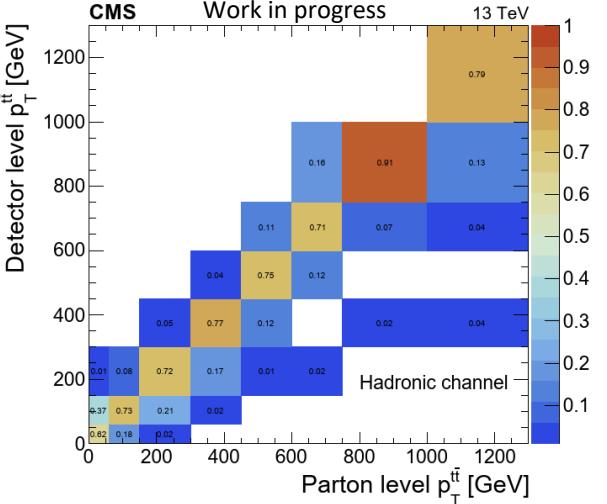
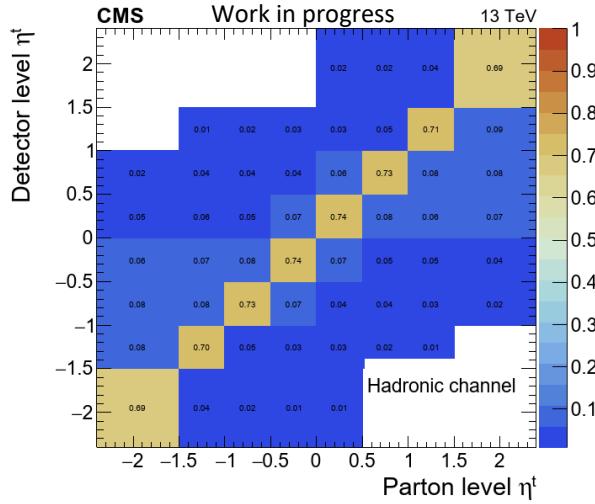
Migration matrix



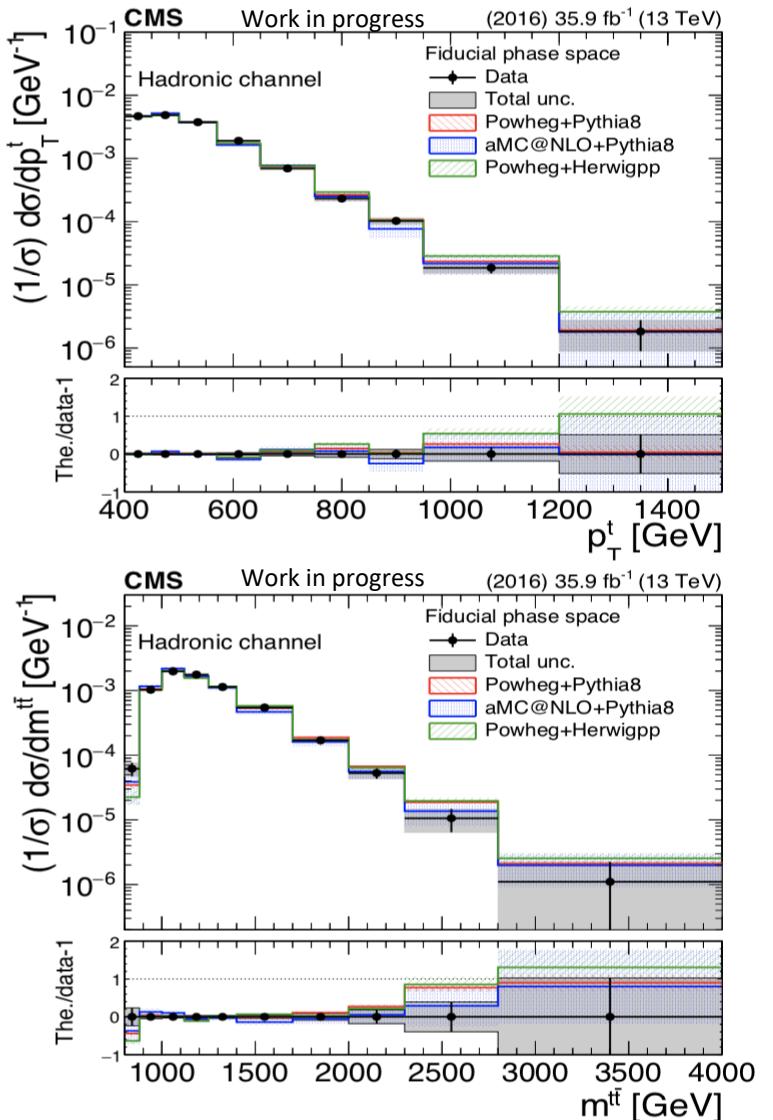
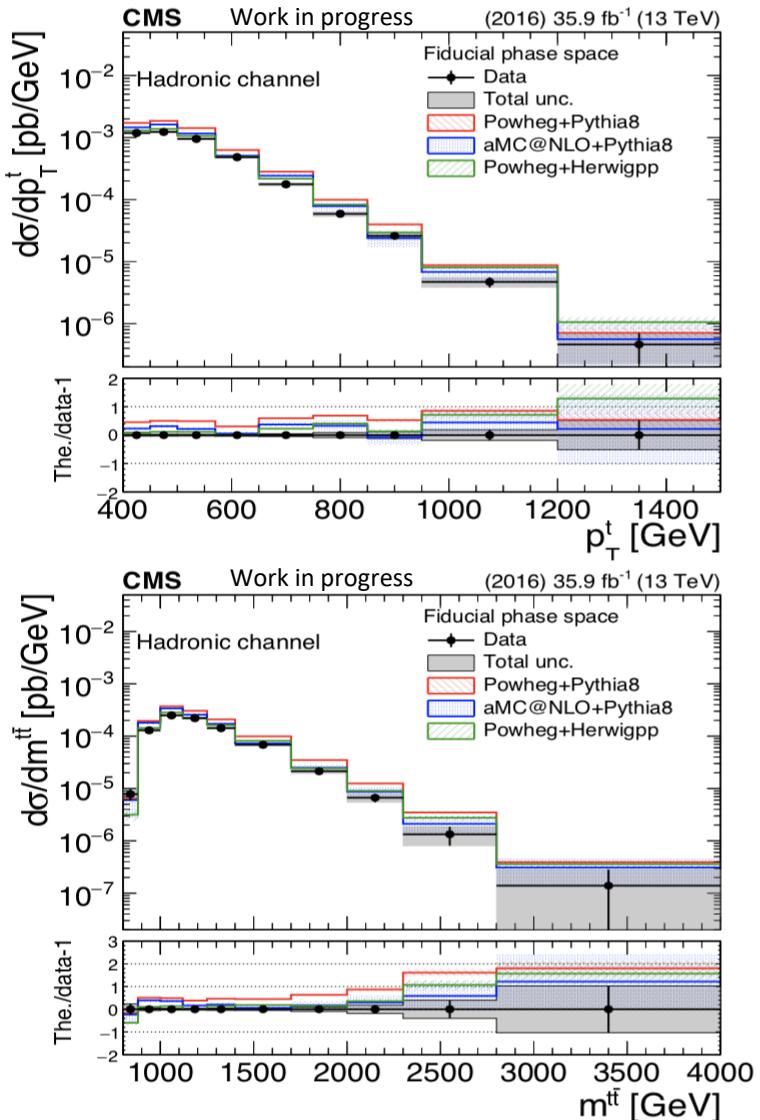
Particle to parton matching efficiency



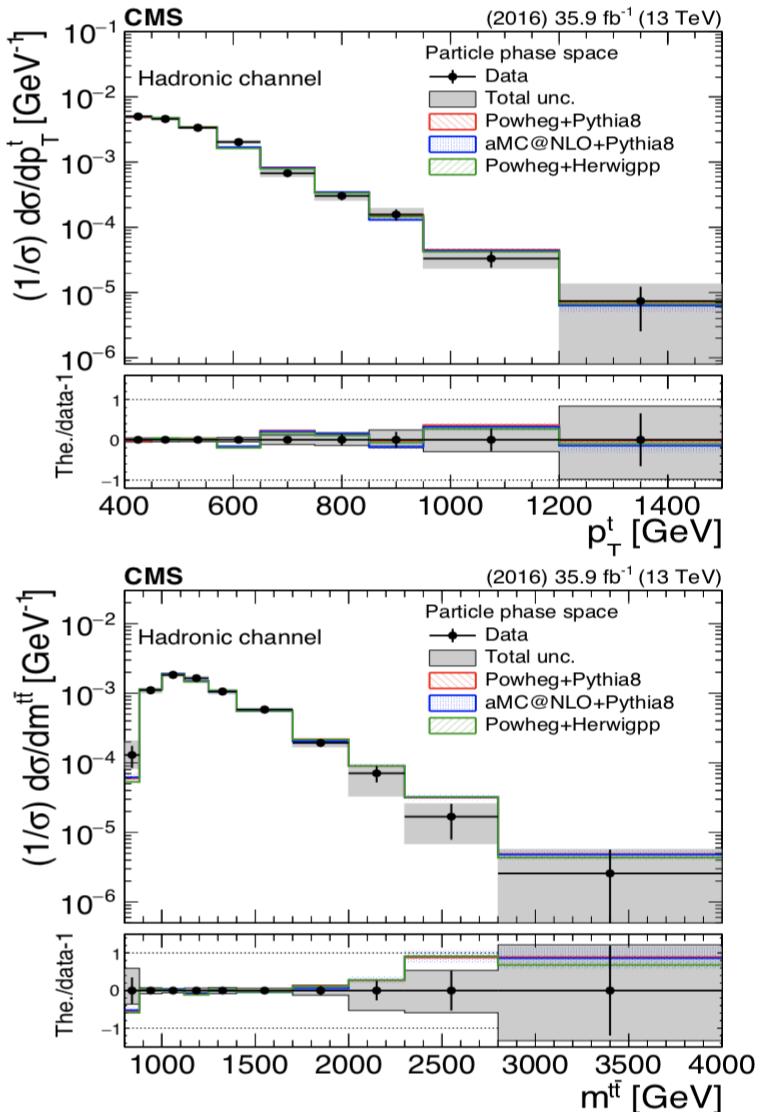
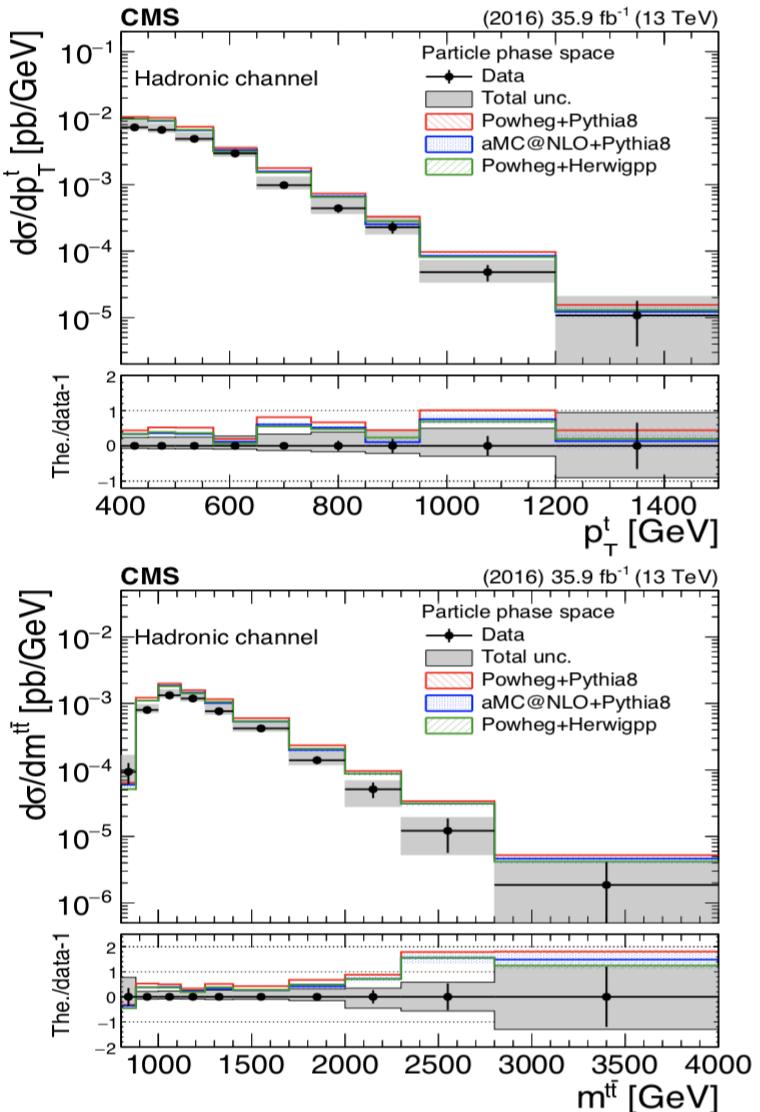
Migration Matrices



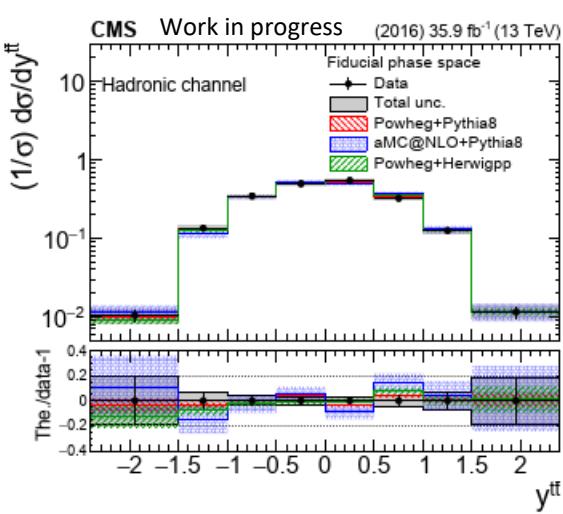
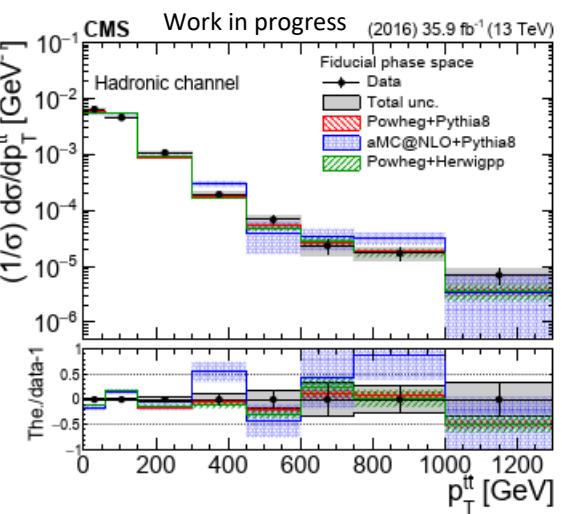
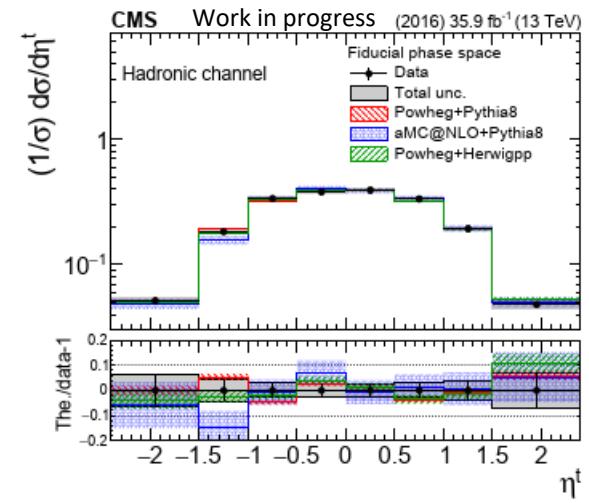
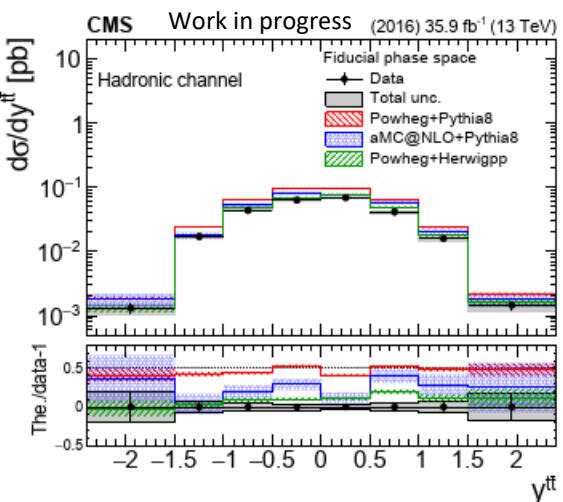
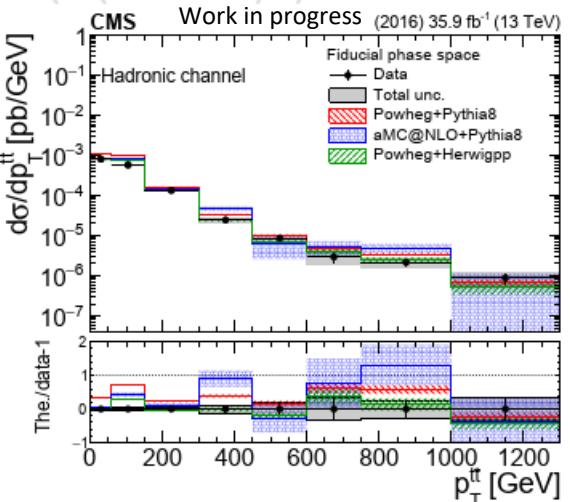
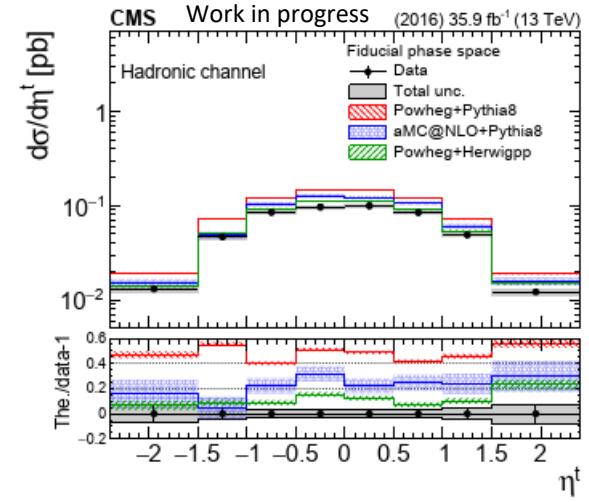
Results for Fiducial Measurement (top p_T , $m_{t\bar{t}}$)



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

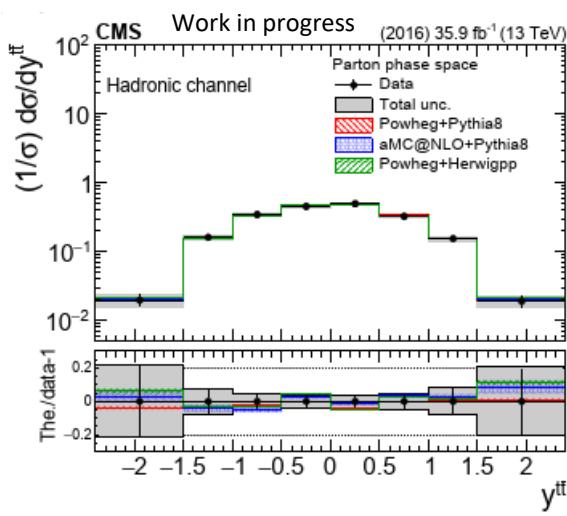
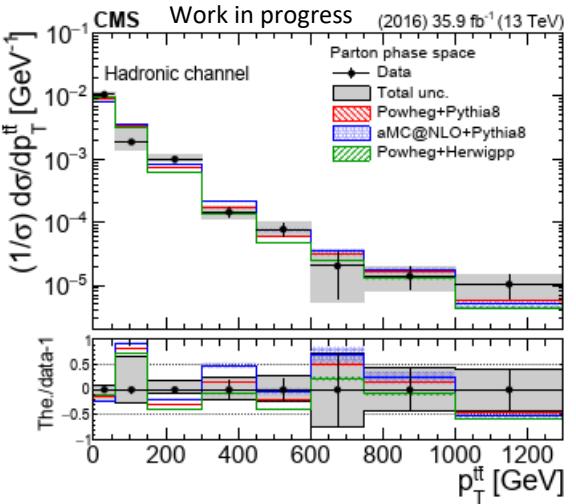
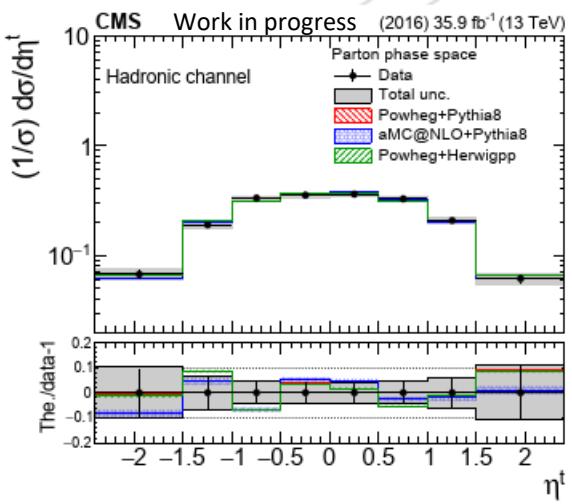
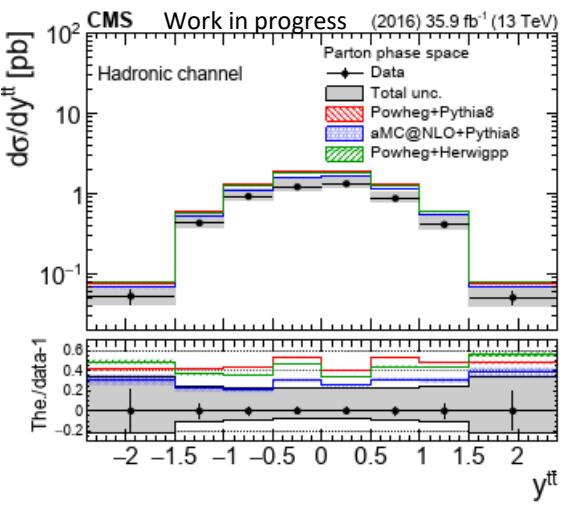
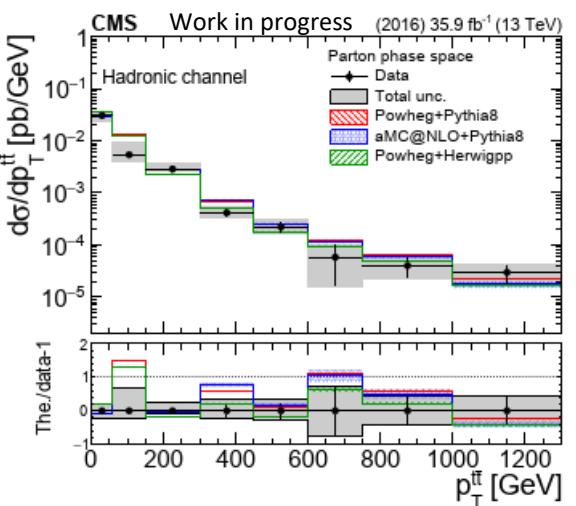
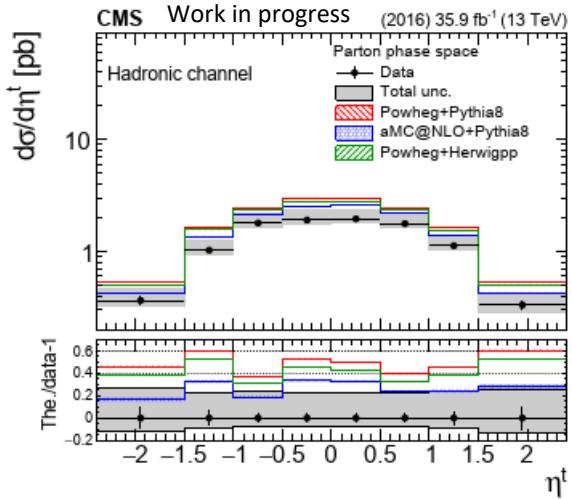


Fiducial Results for η^t , $p_{T,tt}$, y_{tt}





Parton Results for η^t , $p_{T,tt}$, y_{tt}



Particle Results for η^t , $p_{T,tt}$, y_{tt}

