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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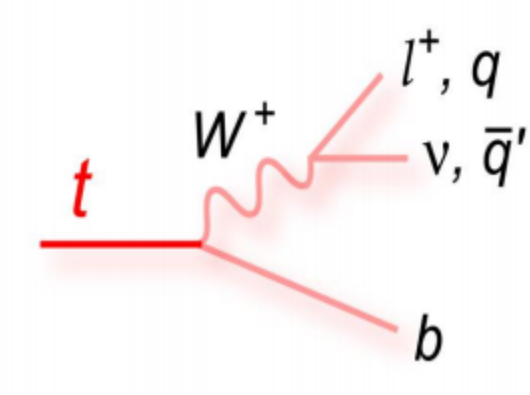
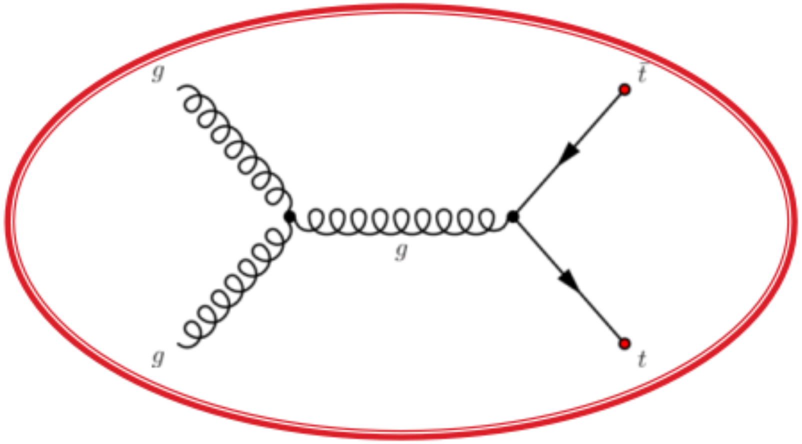
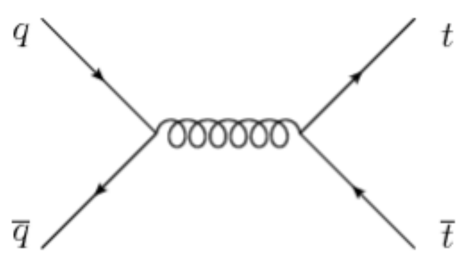
Top Quark

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





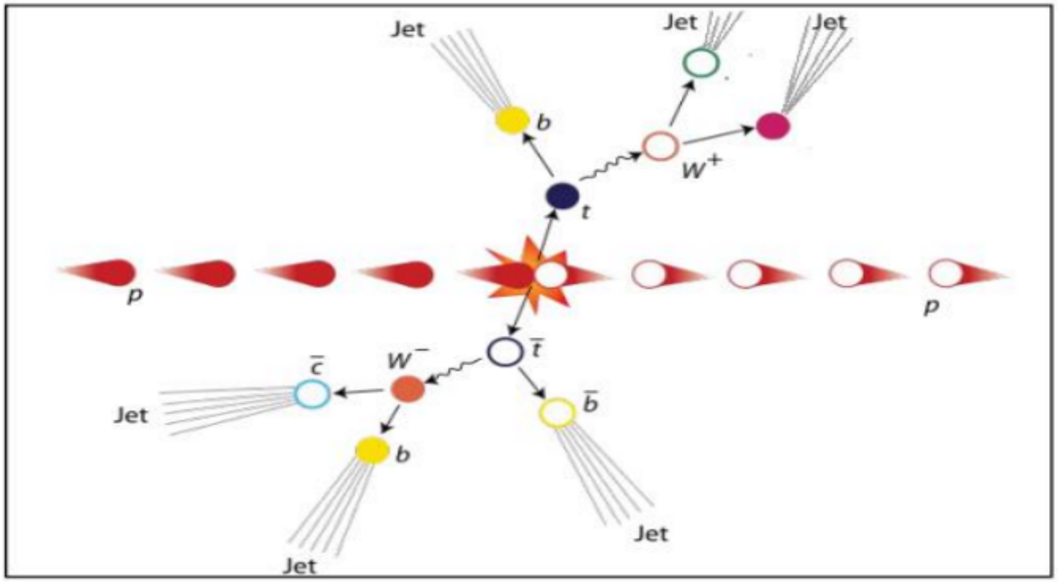


(b)

Gluon Fusion is dominant at LHC

Top AntiTop system decay

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

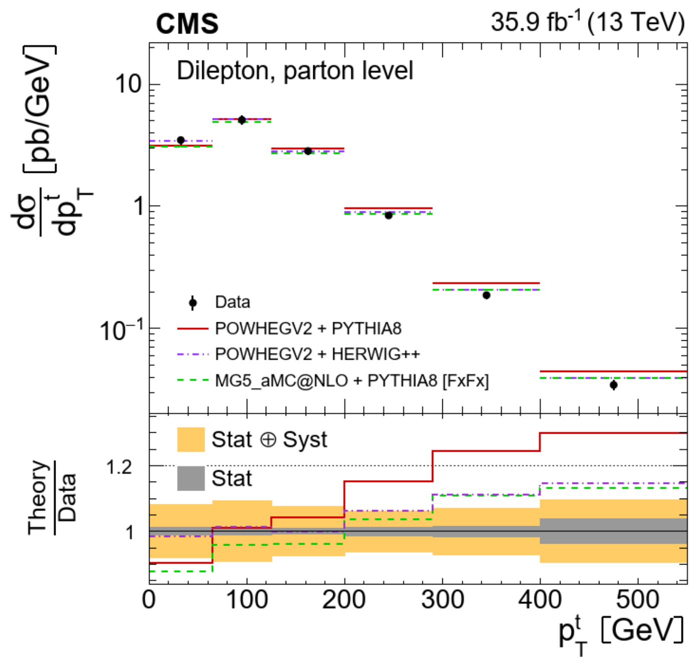


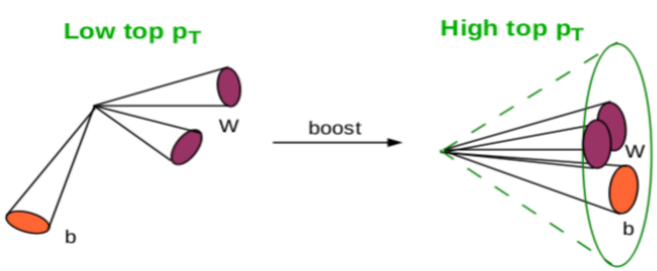
- Boosted Jets are jets with high p_T (> 400 GeV)
- Aim is the reconstruction of two big jets that contain the decay products of the top-antitop quark pair decay

- 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

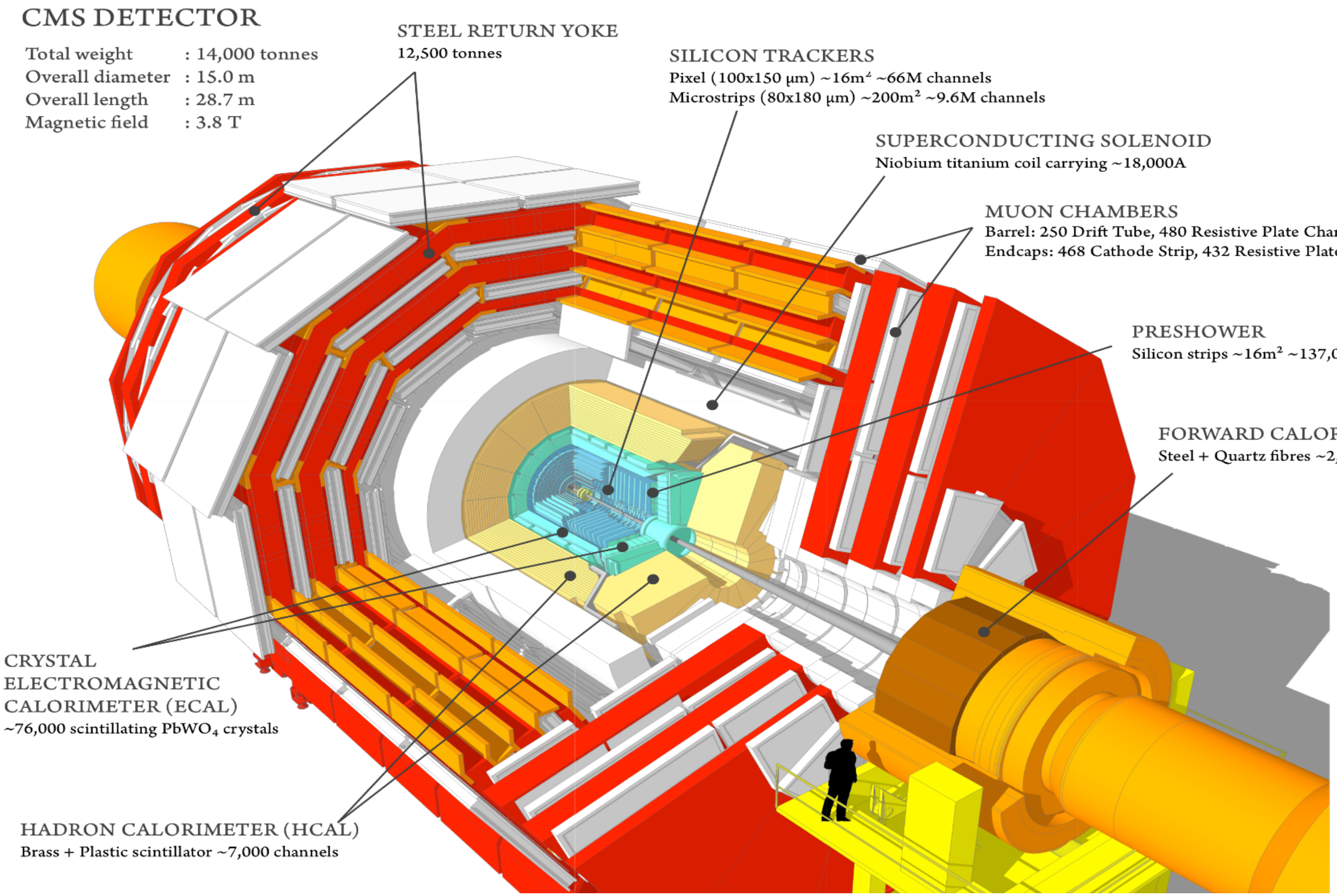
- Why Boosted jets?
  - Single "fat" jet: No combinatorial background
  - At high top p_T the hadronic decay is easier to reconstruct than the leptonic

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



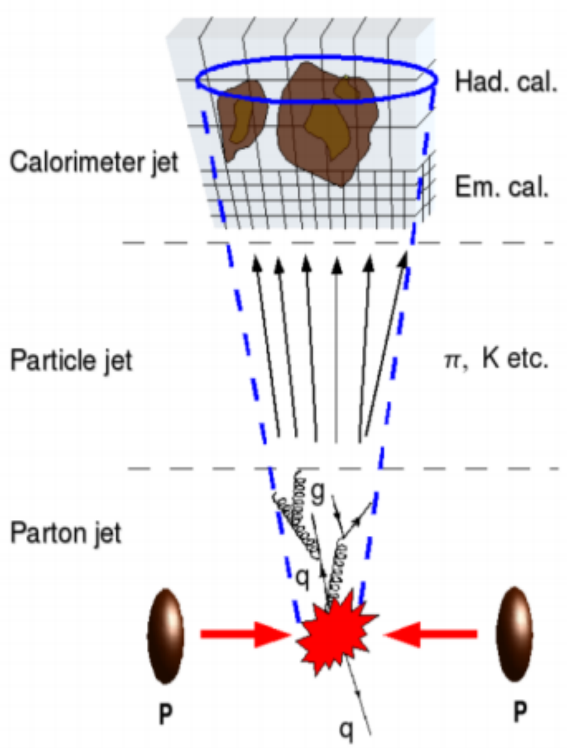


- CMS is a general purpose detector and its goal is to investigate a wide range of physics



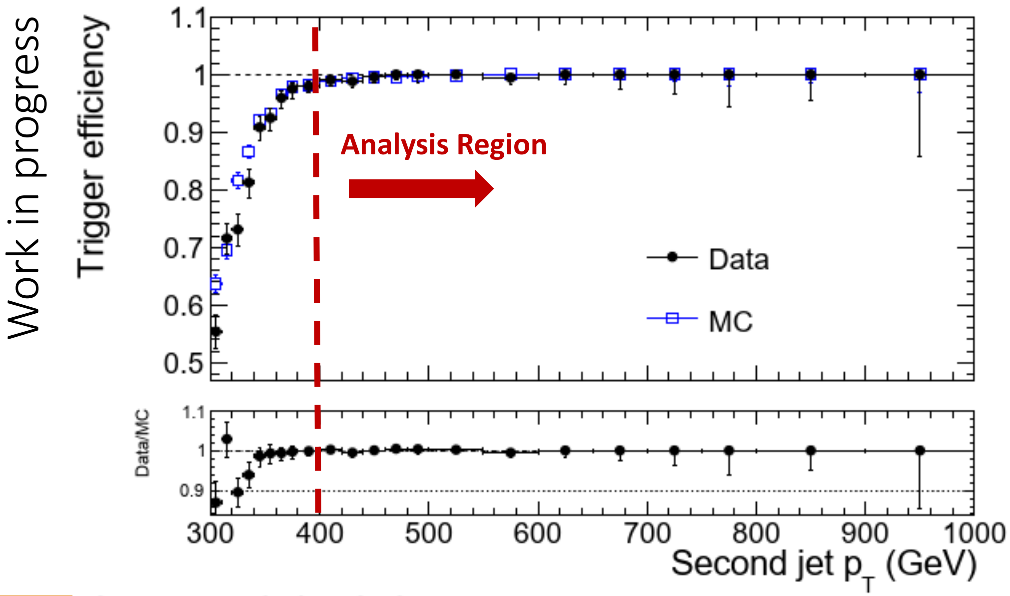
Analysis Overview

- 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



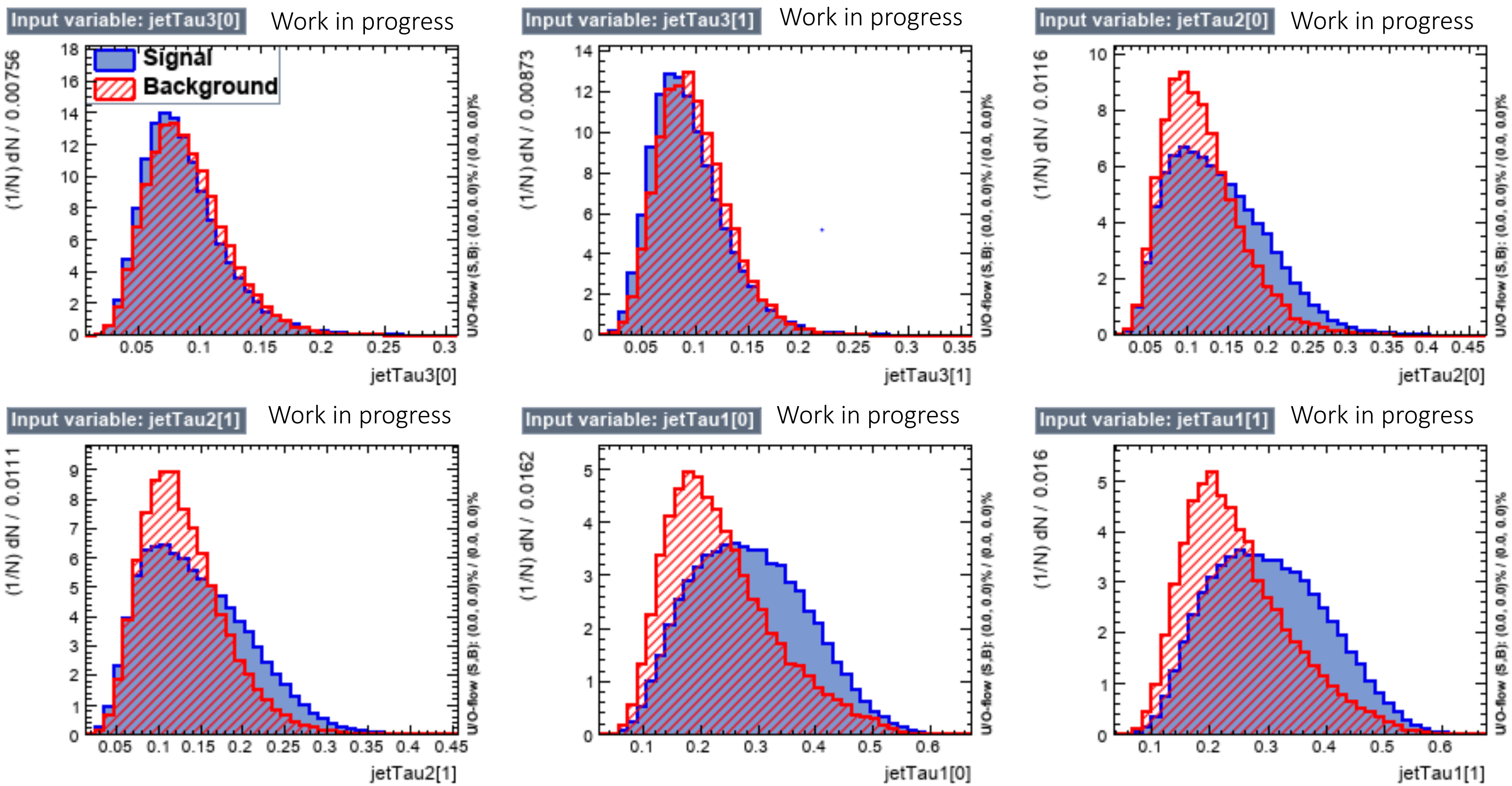
Trigger

- 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

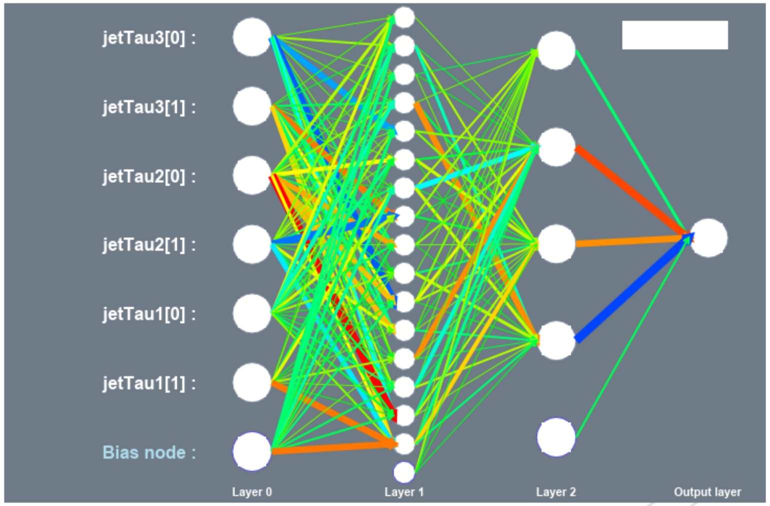


Trigger Efficiency vs Subleading jet p_T (GeV)

Multivariate Discriminant Analysis(variables)

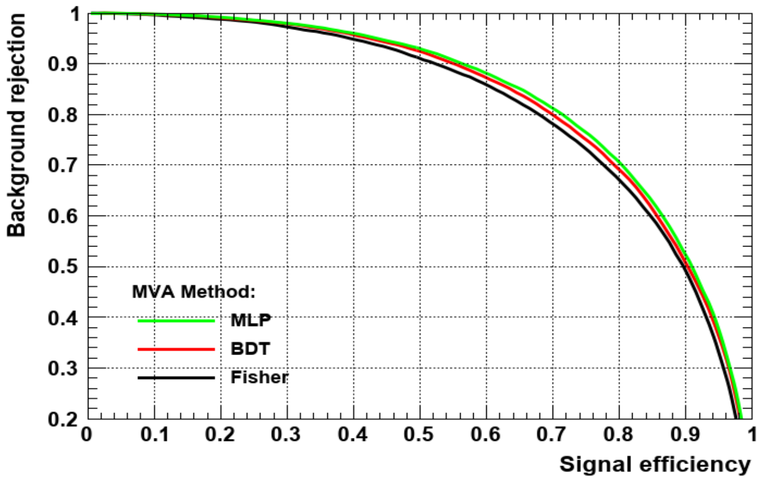


Discriminating variables used for separation of the $t\bar{t}$ from the QCD events



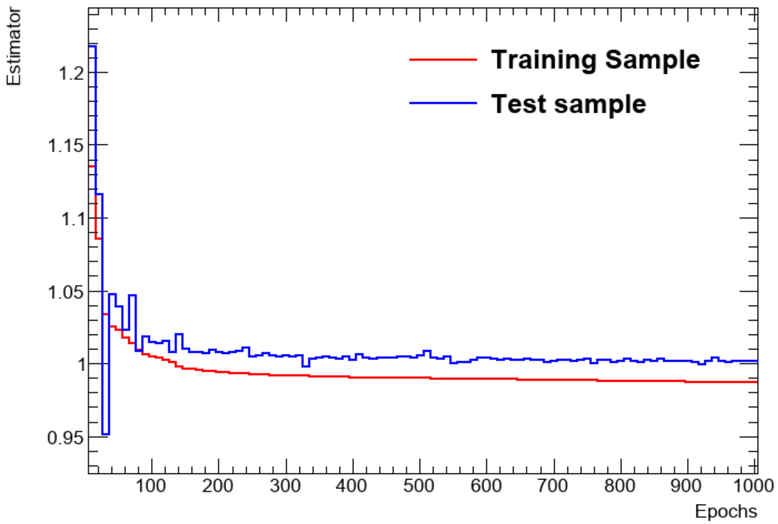
Background rejection versus Signal efficiency

Work in progress



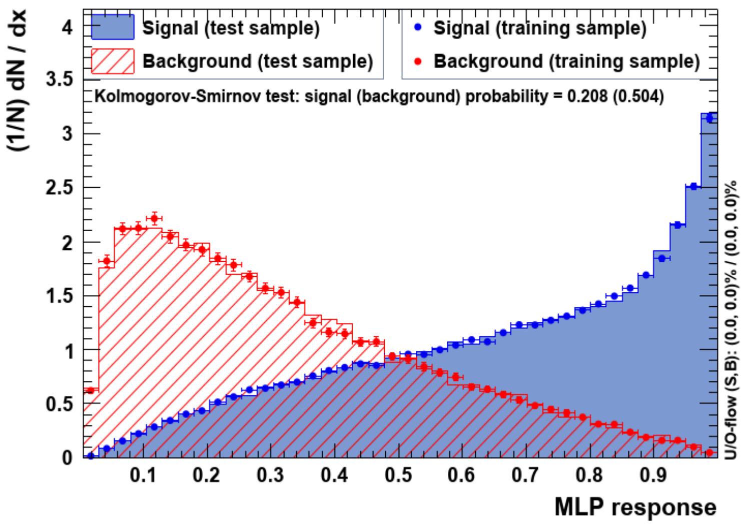
MLP Convergence Test

Work in progress



TMVA overtraining check for classifier: MLP

Work in progress

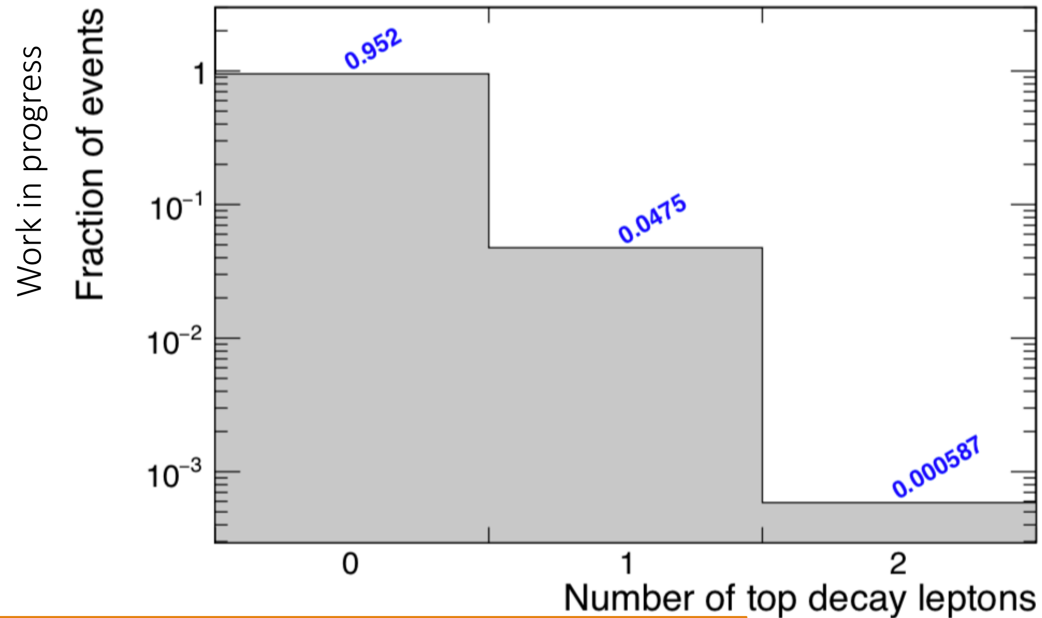


Selection

Baseline Selection

Observable	Requirement
N_{jets}	> 1
N_{leptons}	$= 0$
$p_T^{\text{jet1,2}}$	> 400 GeV
$m_{SD}^{\text{jet1,2}}$	$(50, 300)$ GeV

Selected jets: AK8 PF+CHS



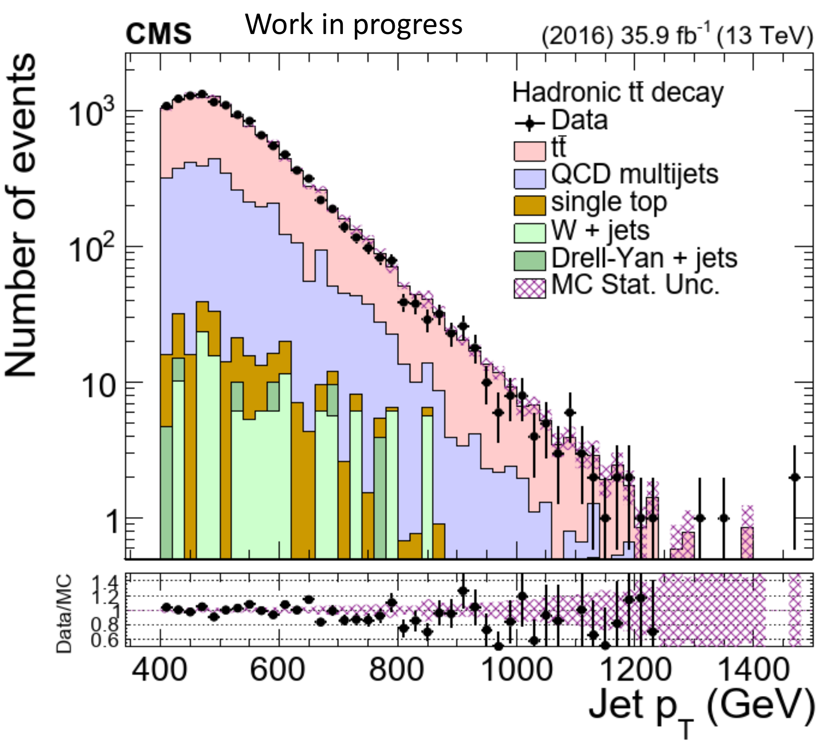
From signal selection almost 95% of the decays are hadronic

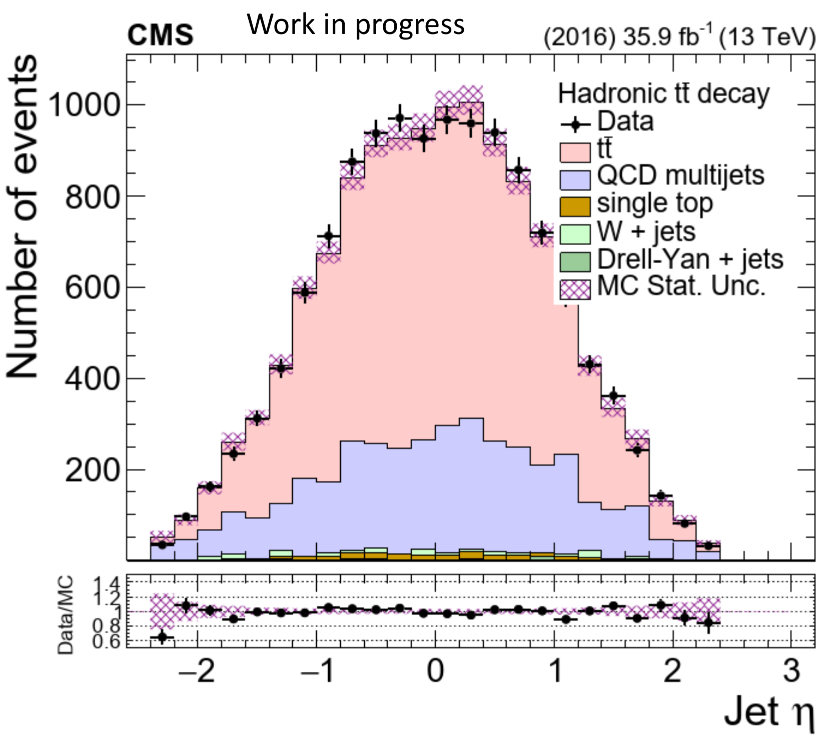
Table: Selection requirements per analysis region

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

Data vs MC: Top jet Kinematics





Signal Extraction

Fiducial Yield

Transfer factor from SR_A to SR

Bkg Shape Correction
(taken from MC)

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

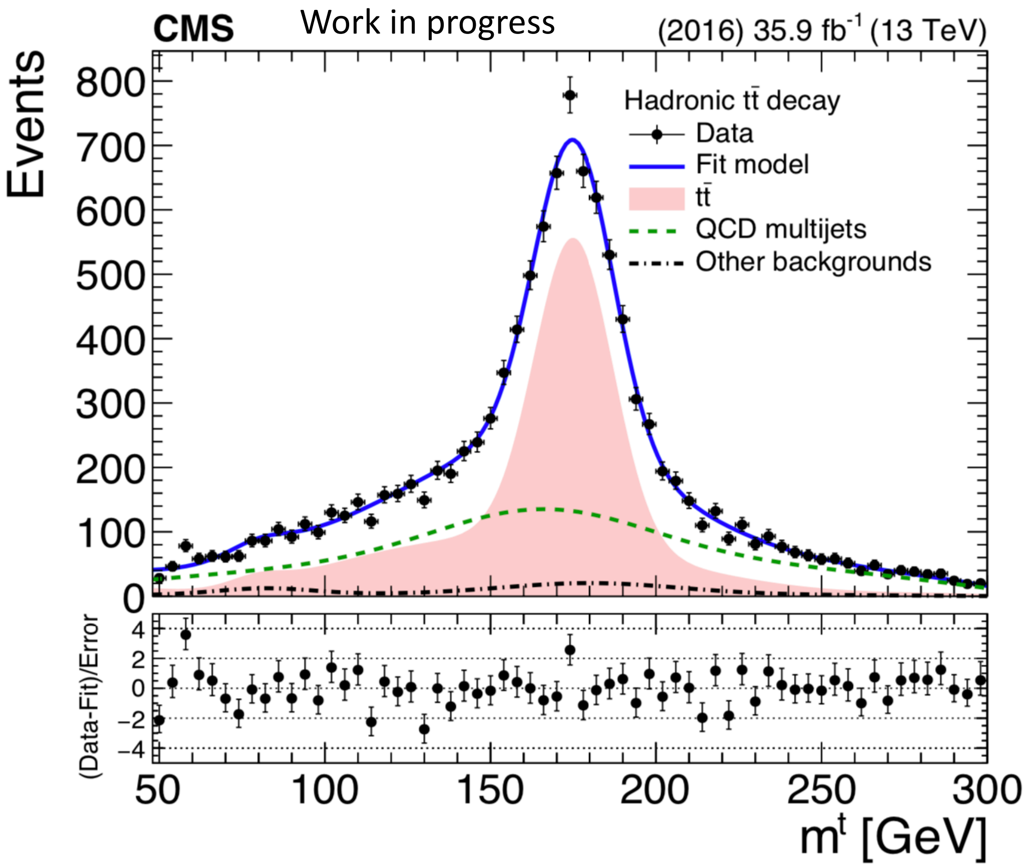
Data

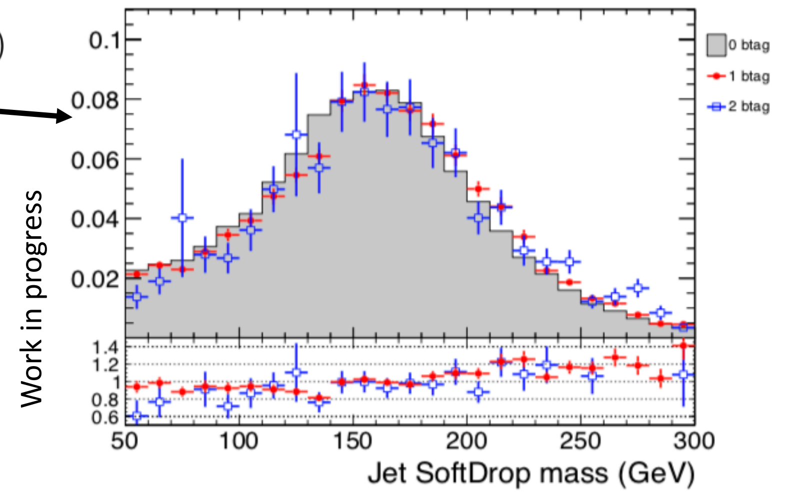
Bkg Yield
(fit in region SR_A)

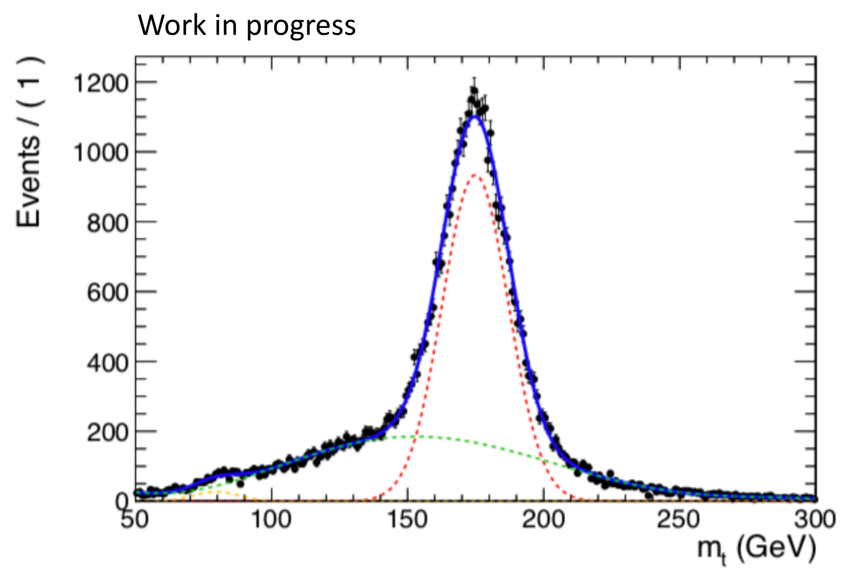
Bkg Shape
(taken from CR in data)

Fit in the SR_A Region

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







Parton Level

Parton Level selection

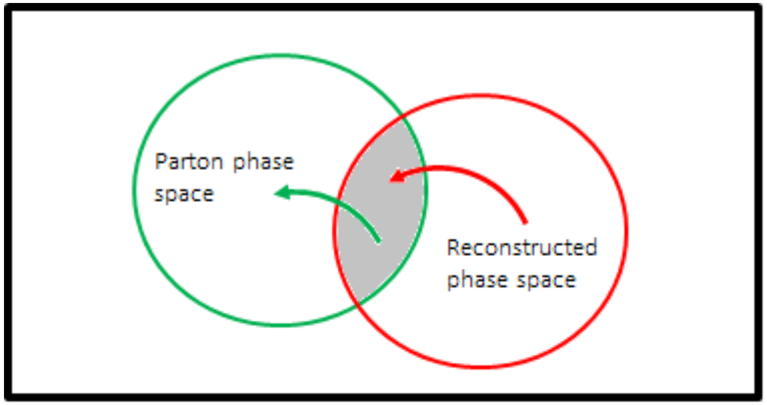
Observable	Requirement
$p_{\mathrm{T}}^{t,\bar{t}}$	$> 400\,\mathrm{GeV}$
$\lvert\eta^{t,\bar{t}}\rvert$	< 2.4
$m_{\mathrm{t\bar{t}}}$	$> 800\,\mathrm{GeV}$

Reco and parton over reco

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

Reco and parton over parton

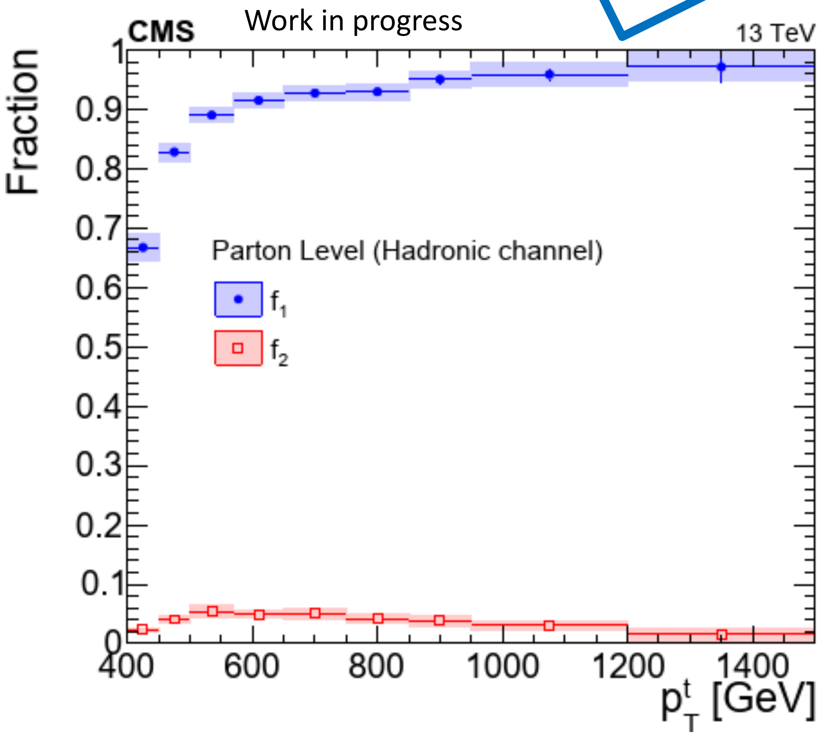
Migration matrix

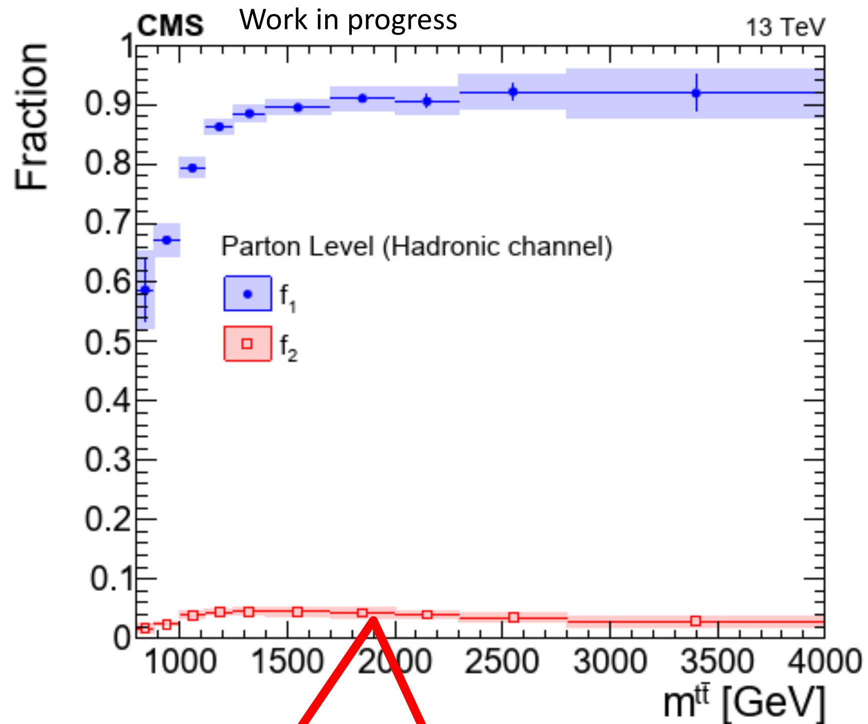


Unfolding is done using simple response matrix inversion without regularization

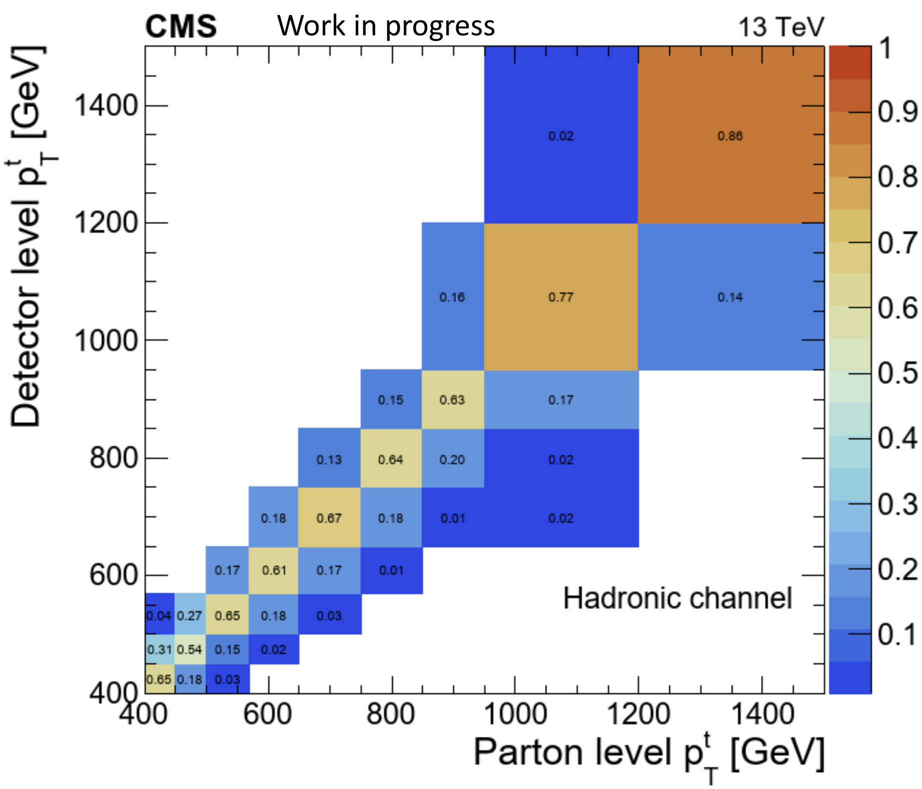
Extrapolation factors for parton level

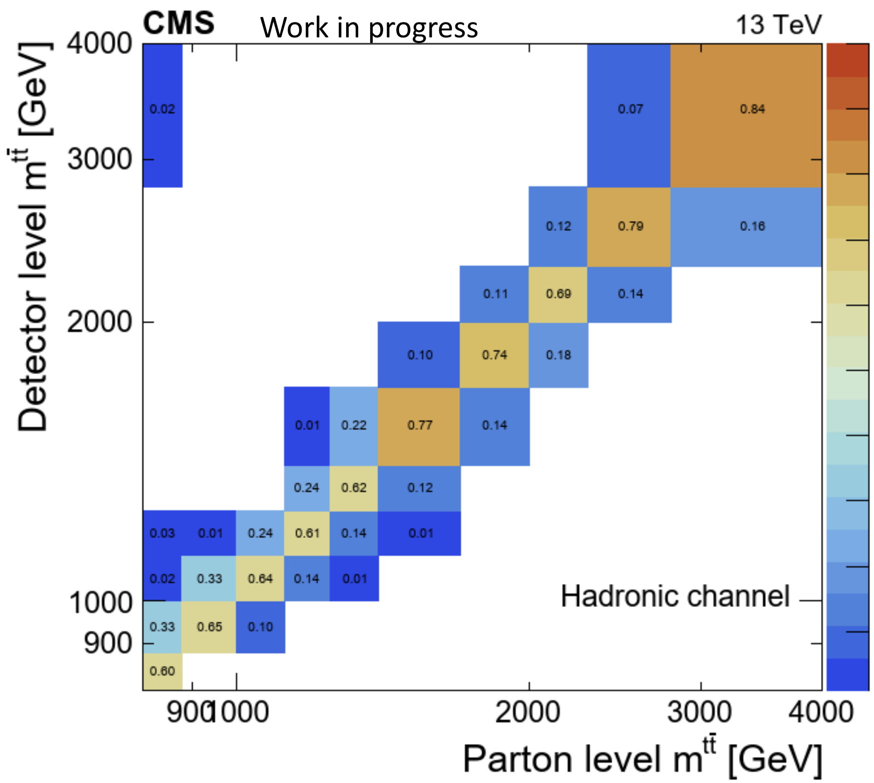
f_1: fraction of reco events in the reco+parton phase space





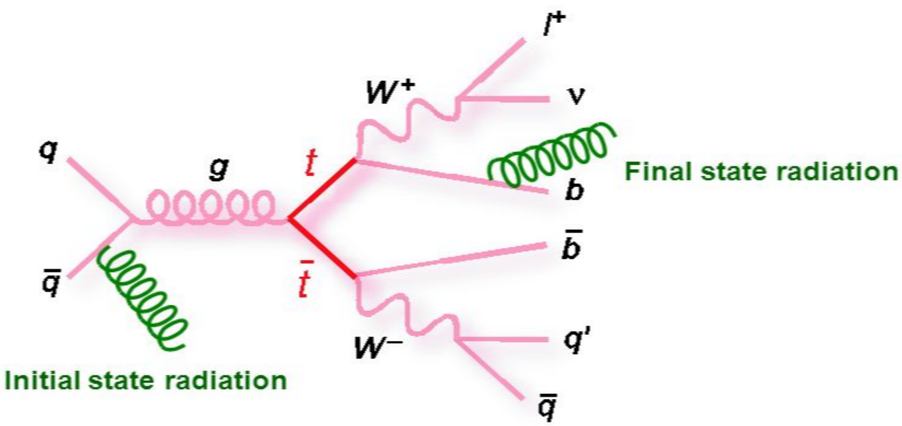
f_2: fraction of parton events in the reco+parton phase space


CMS
Work in progress
13 TeV
Detector level p_T^t [GeV]
Parton level p_T^t [GeV]
Hadronic channel


CMS
Work in progress
13 TeV
Detector level $m^{t\bar{t}}$ [GeV]
Parton level $m^{t\bar{t}}$ [GeV]
Hadronic channel

Uncertainties

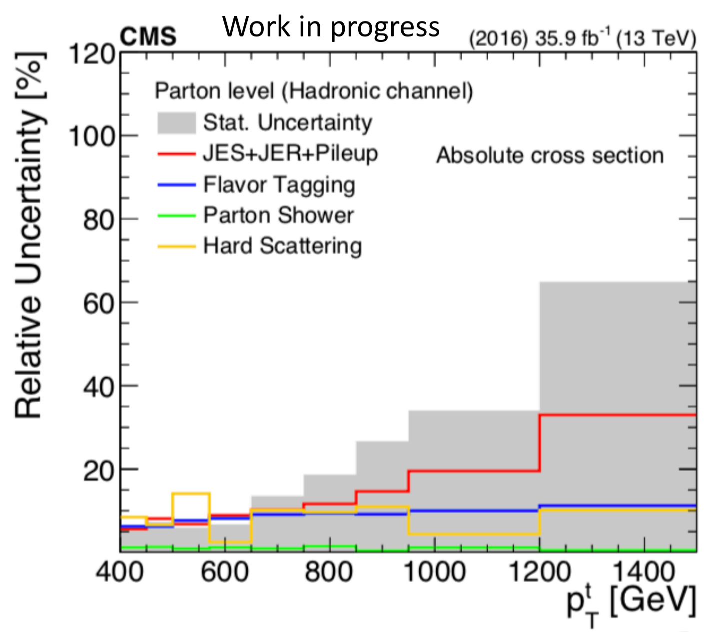
- Experimental:
  - QCD background prediction
  - Statistics
  - Jet Energy Scale
  - Jet Energy Resolution
  - B tagging efficiency

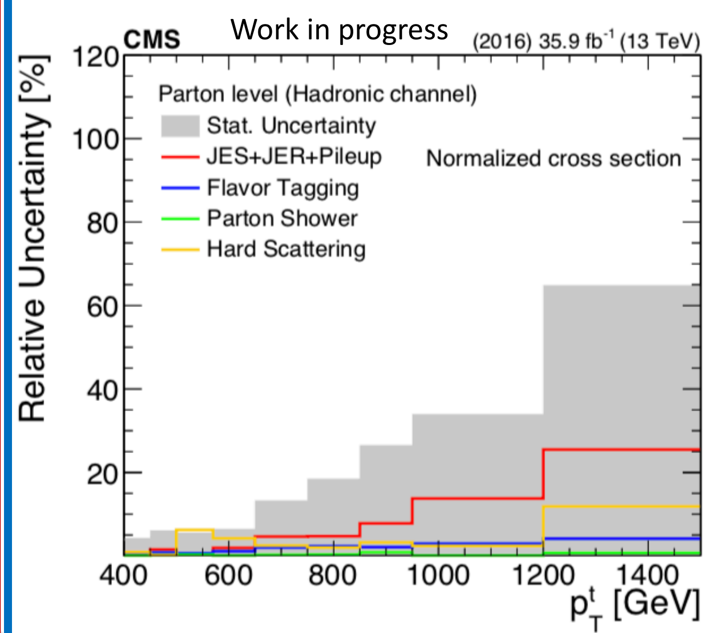


- Theoretical:
  - Affect the extrapolation factors (f_1 , f_2) and the migration matrices for the unfolding procedure
    - ISR (Initial State Radiation)
    - FSR (Final State Radiation)
    - CMS tuned set of MC parameters for Pythia 8

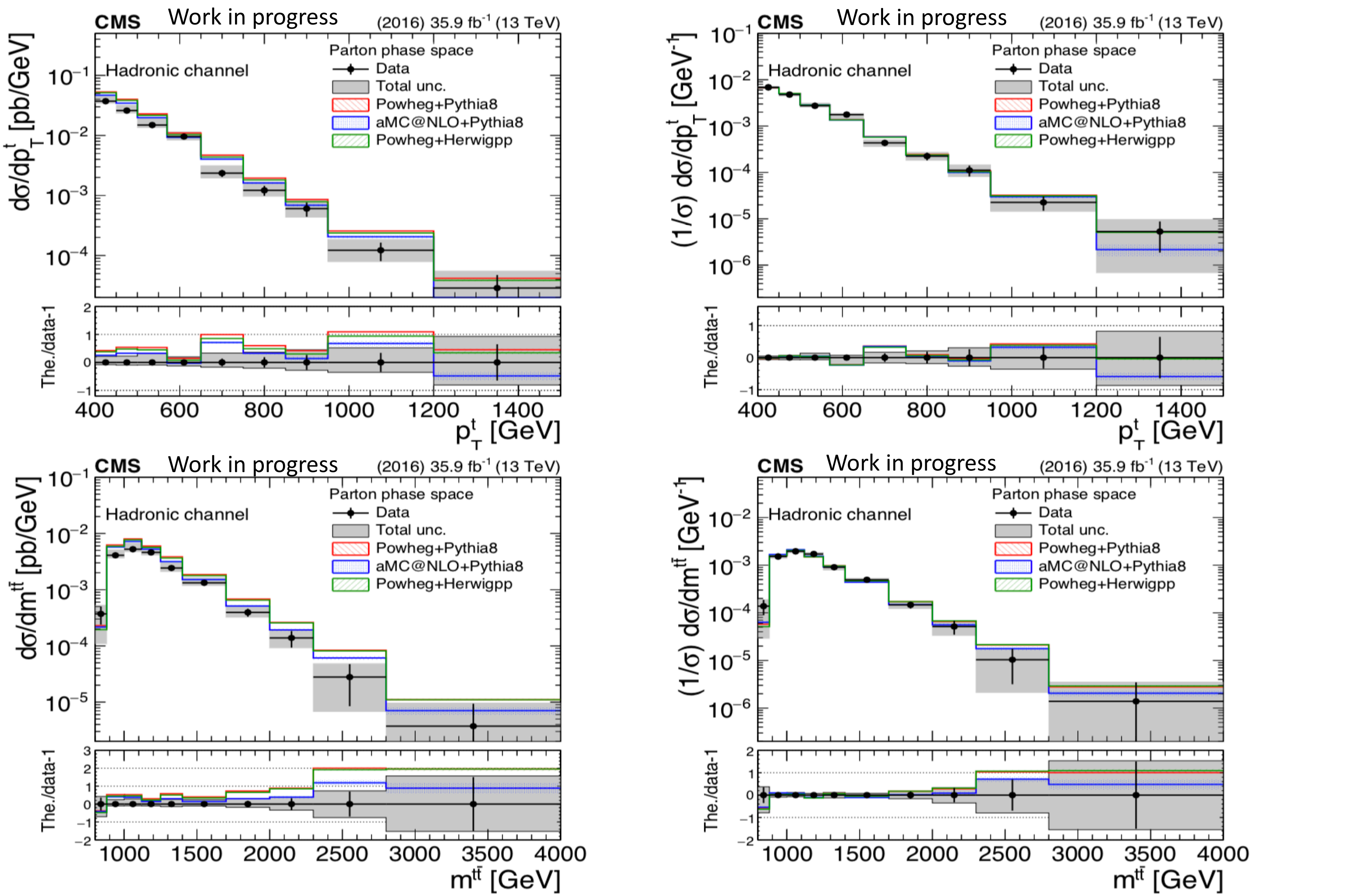
Uncertainties for the parton and particle level measurements (absolute)

Uncertainties for the parton and particle level measurements (normalized)





Results for Parton Measurement (top p_T , m_{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

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

- 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 τ_N

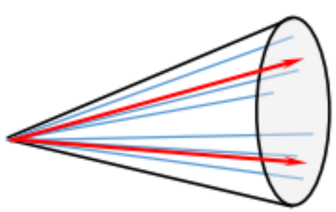
- The NN combines the τ_1 , τ_2 , τ_3 of the two leading jets, where τ_N is the subjetiness and N is the number of prong jets

- Prong jets are the number of jets that determine the substructure of the boosted jets

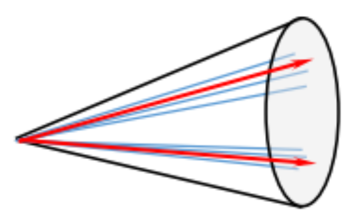
- The τ_i is defined as

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

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



High τ_2 (consitutents spread out)



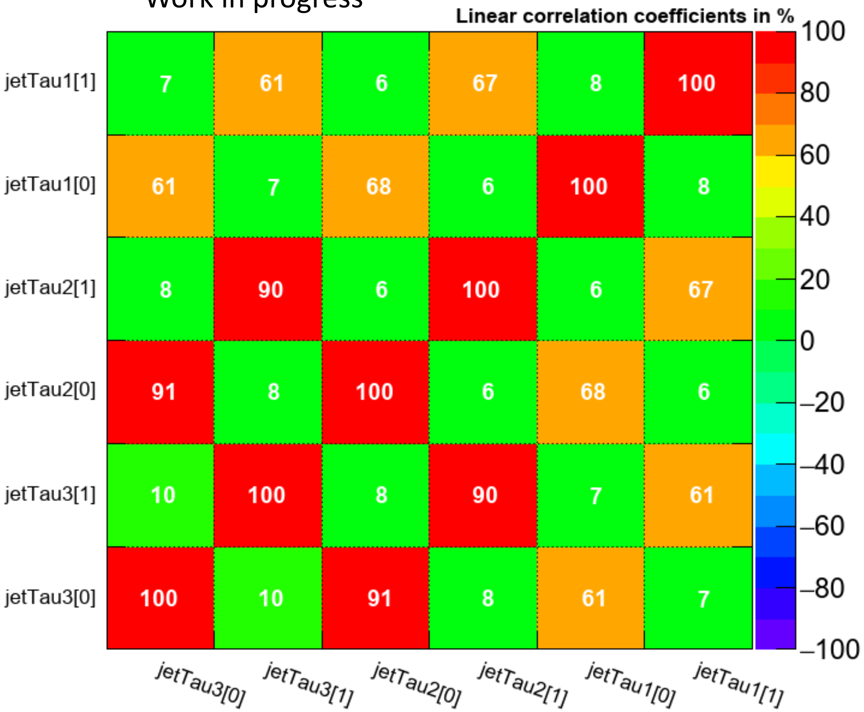
Low τ_2 (constituents close to subjet axes)

Clusters with exactly N subjets will have small τ_N

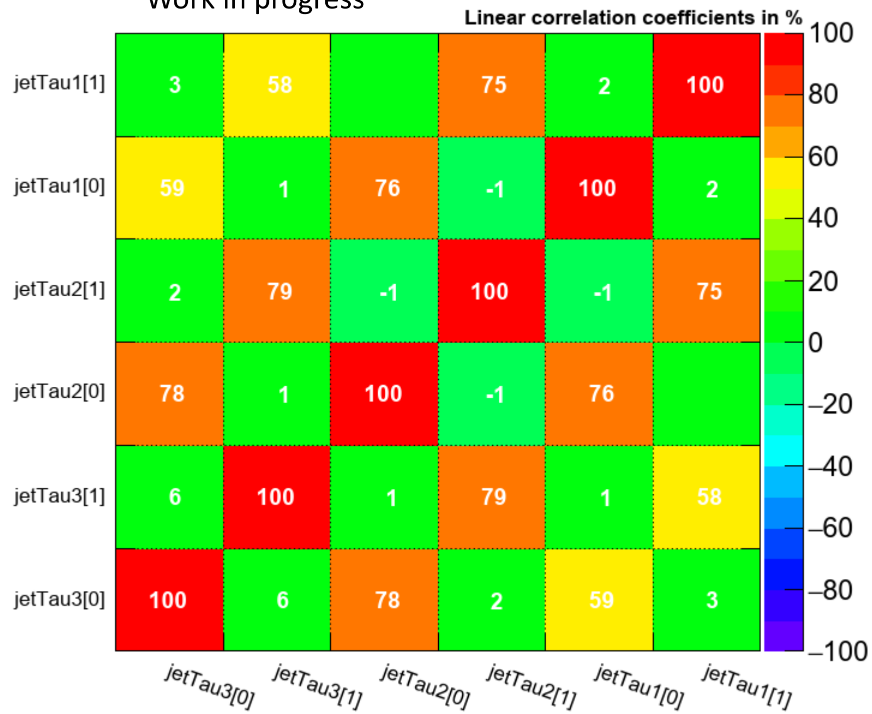
If $\tau_N \simeq 1$, cluster most likely has more than N subjets

MVA training: Correlation Matrices

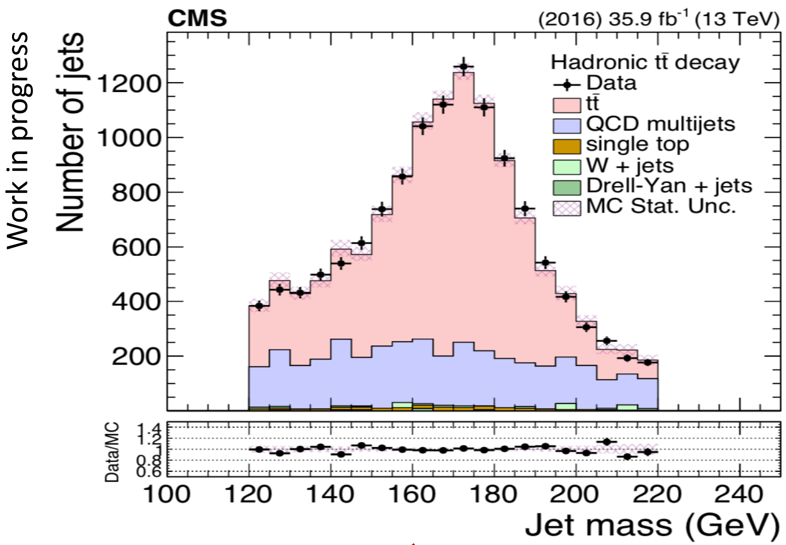
Correlation Matrix (background)

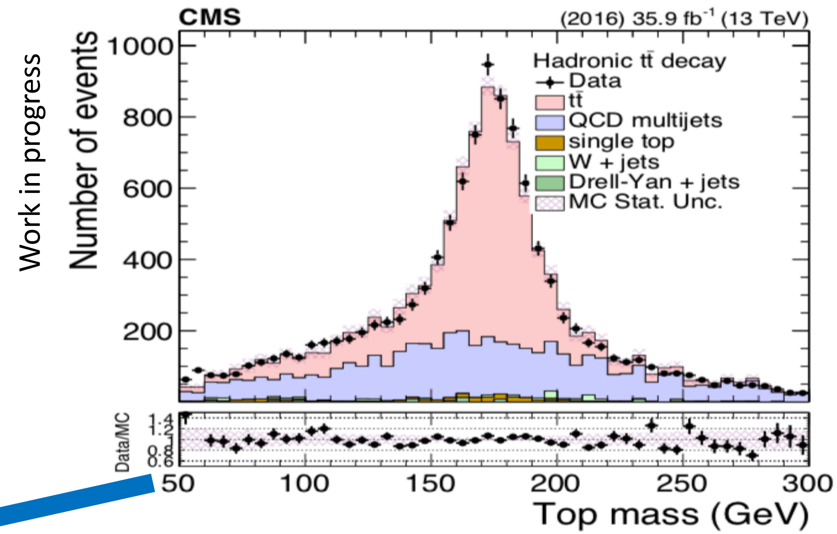


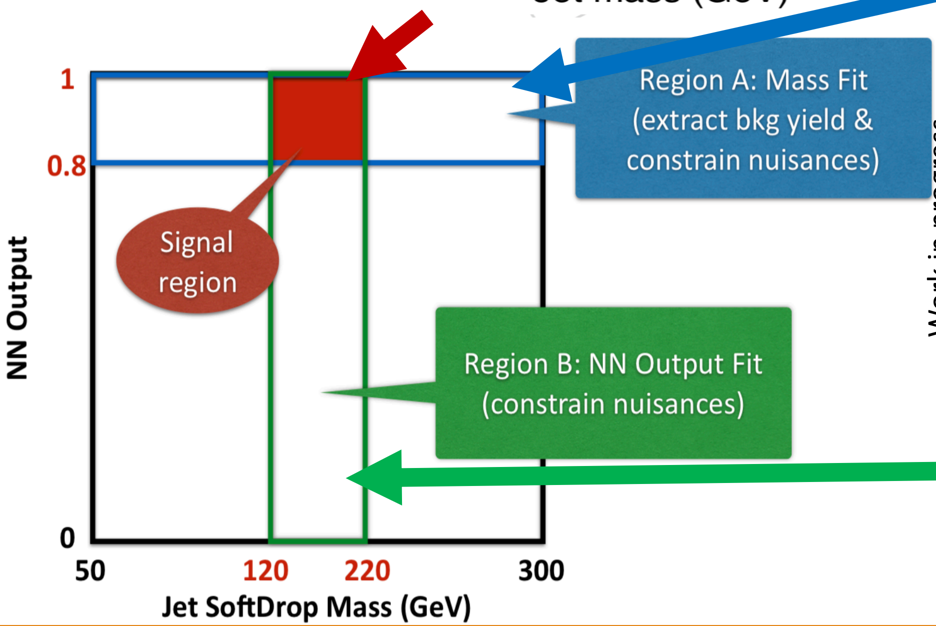
Correlation Matrix (signal)

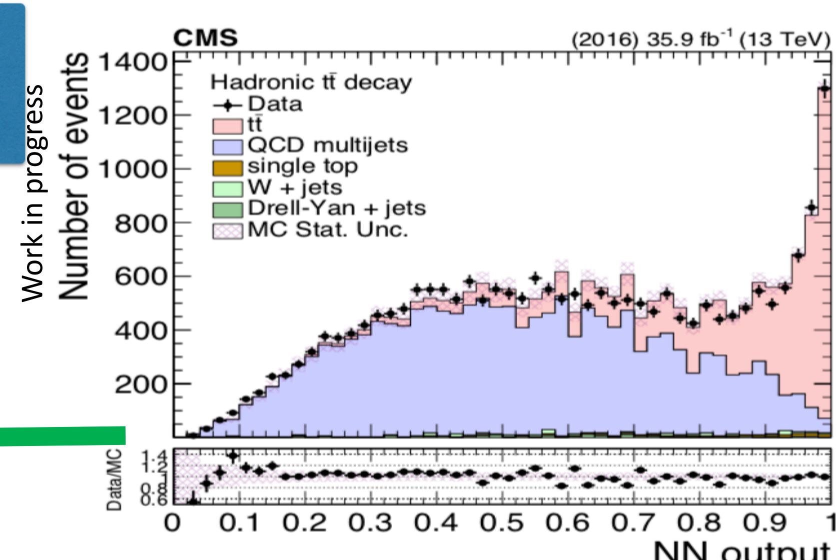


Analysis Regions

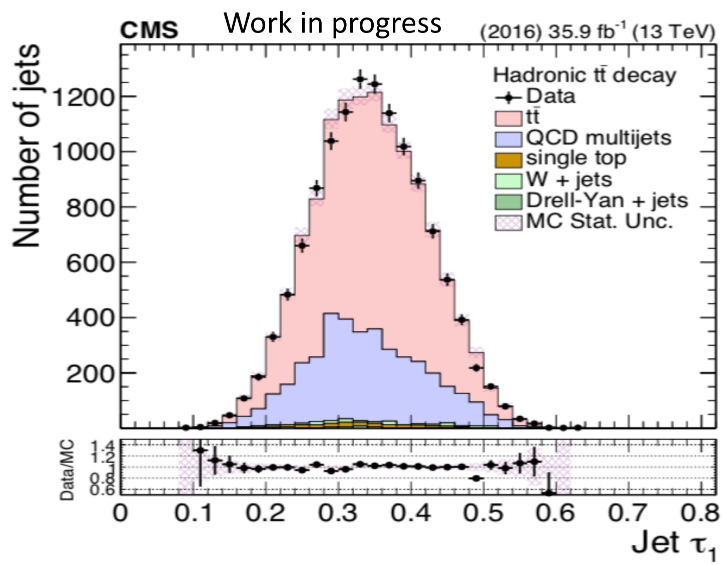


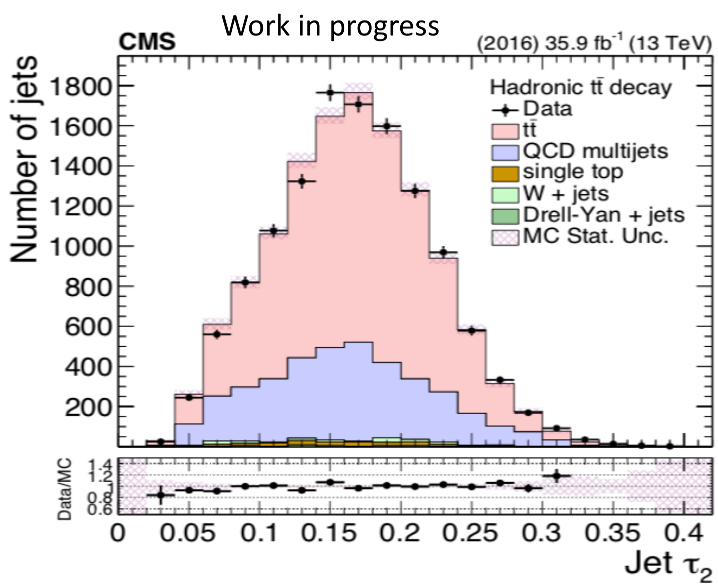


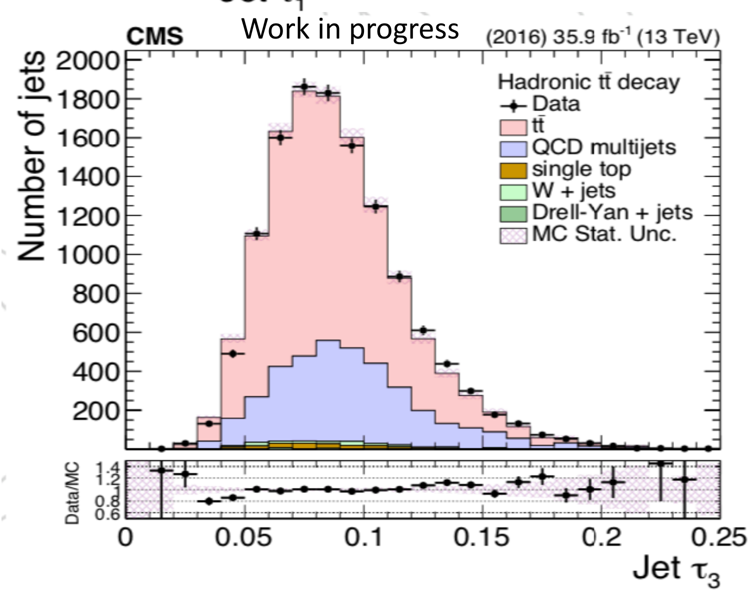




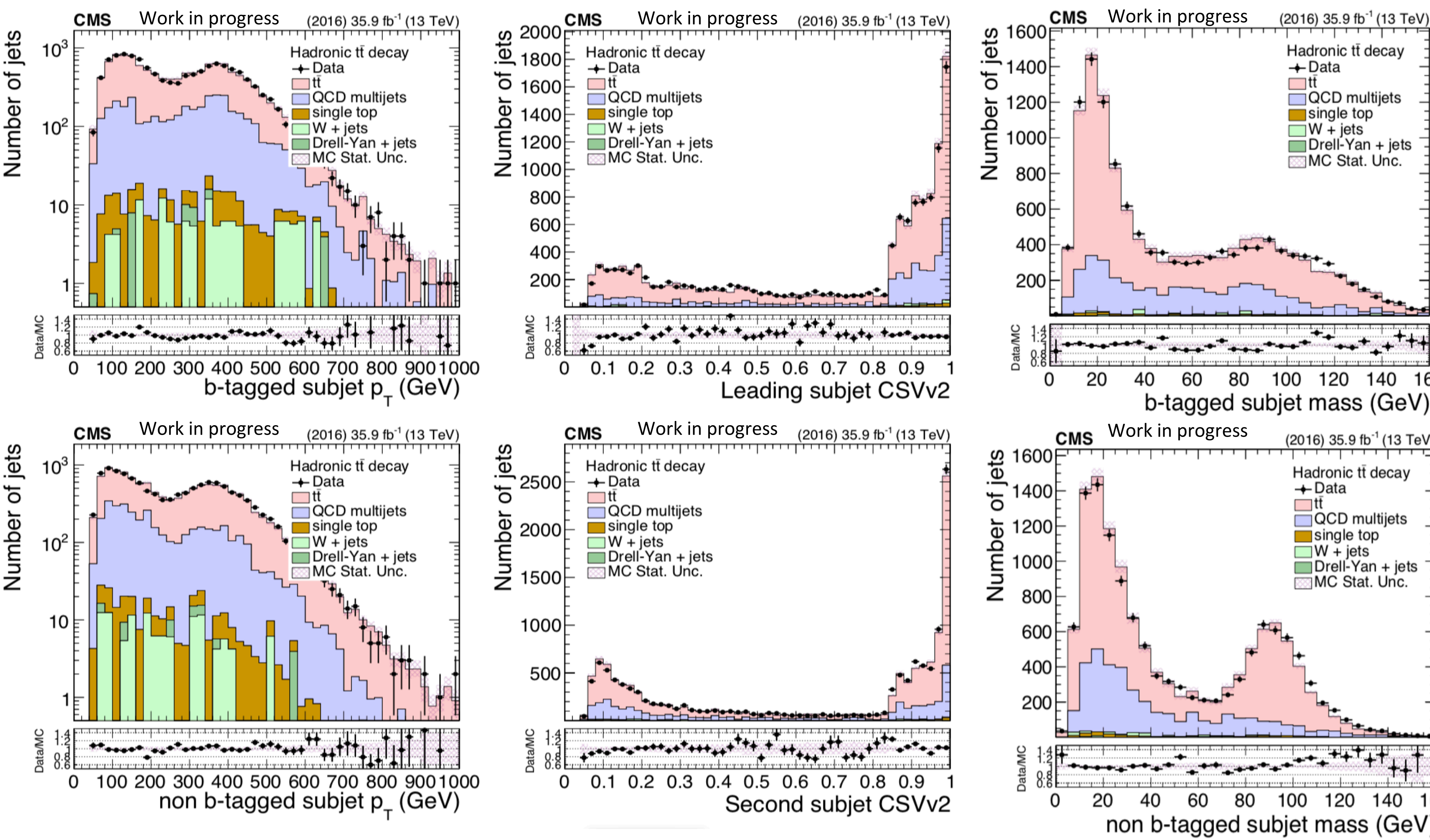
Data vs MC: Substructure Properties



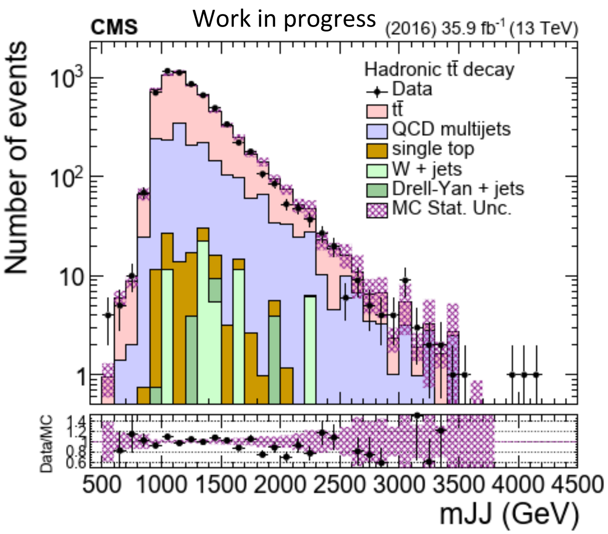


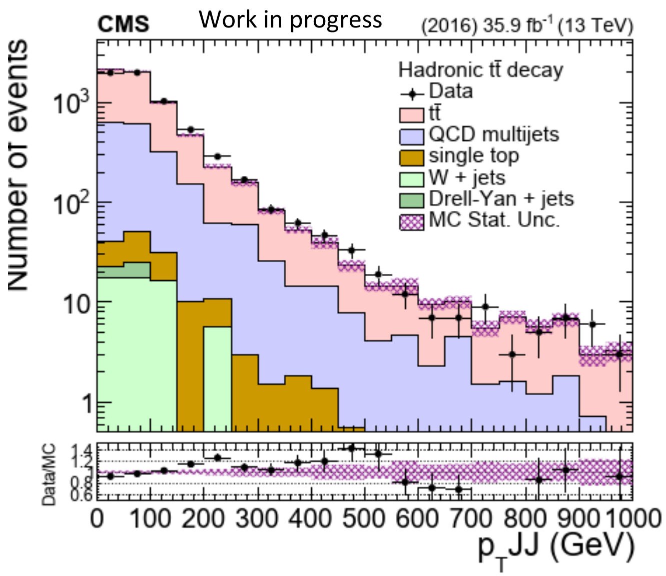


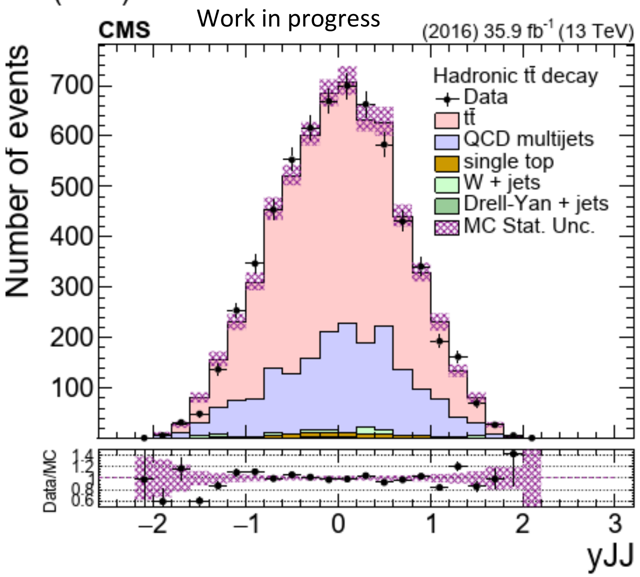
Data vs MC: Subjet Properties



Data vs MC: ttbar Kinematics







Particle Level selection

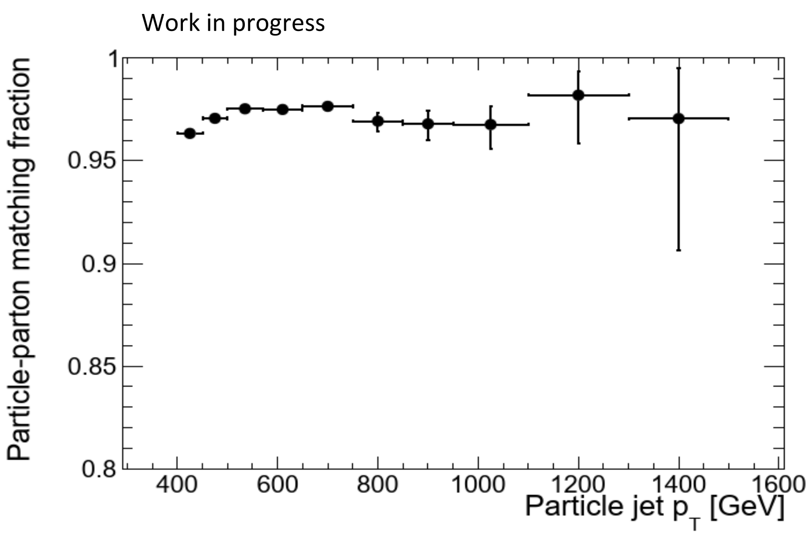
Observable	Requirement
N_{jets}	> 1
$p_T^{\text{jet1,2}}$	$> 400\,\text{GeV}$
$\lvert\eta^{\text{jet1,2}}\rvert$	< 2.4
$m_{SD}^{\text{jet1,2}}$	$(120, 220)\,\text{GeV}$
m_{jj}	$> 800\,\text{GeV}$

Reco and particle over reco

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

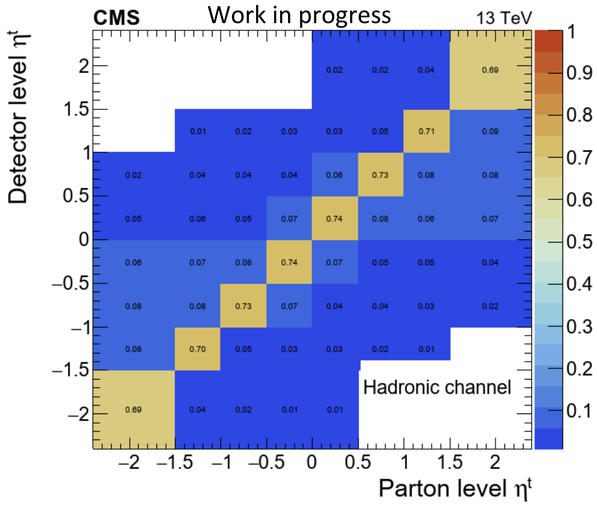
Reco and particle over particle

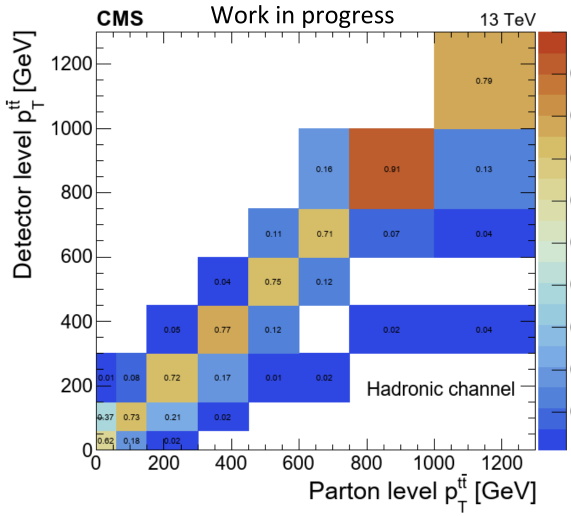
Migration matrix

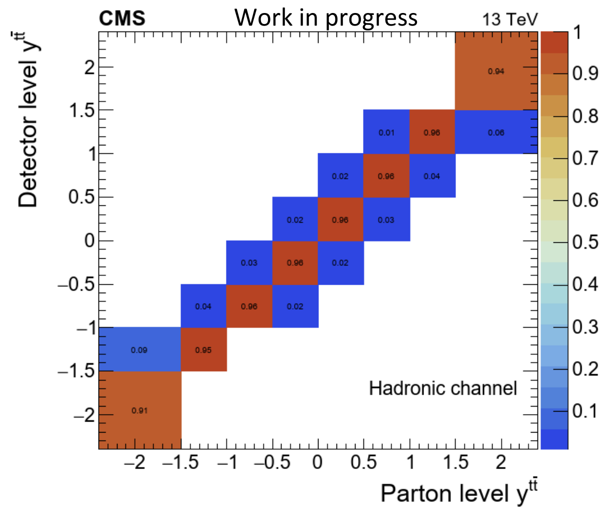


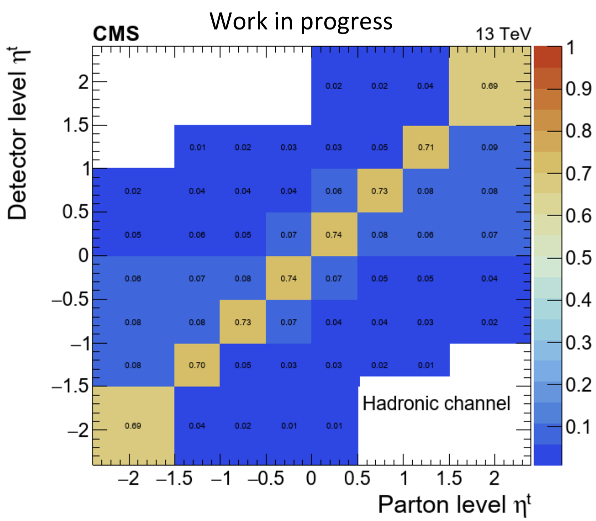
Particle to parton matching efficiency

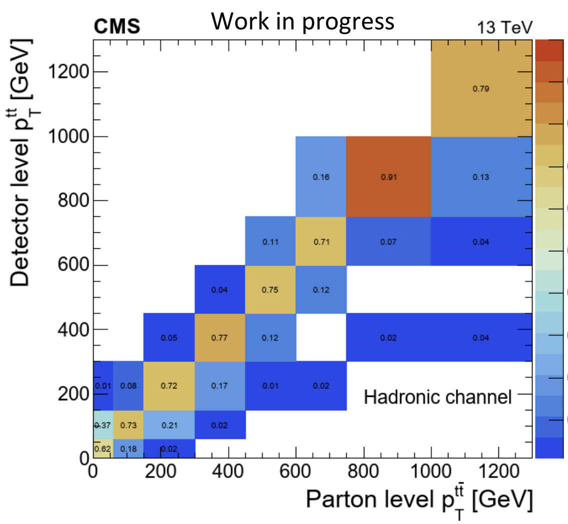
Migration Matrices

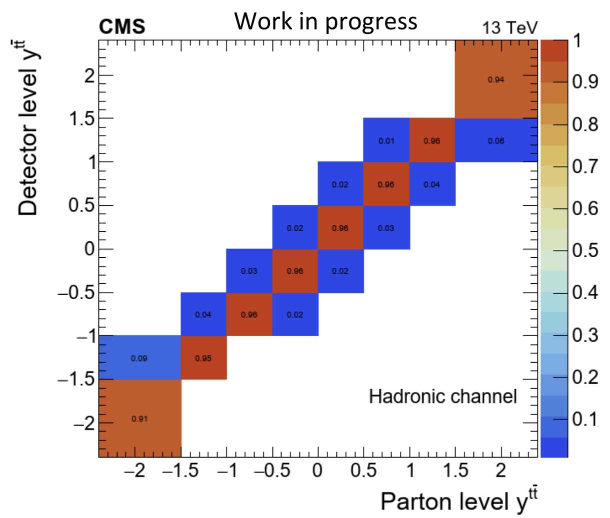




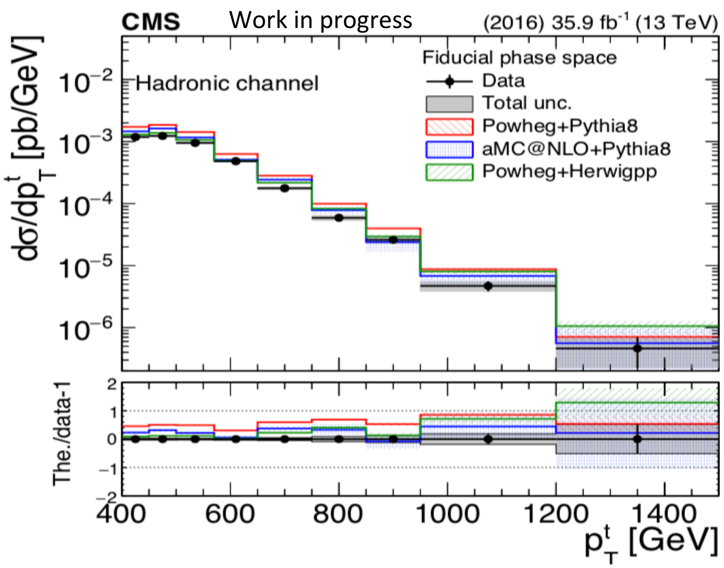


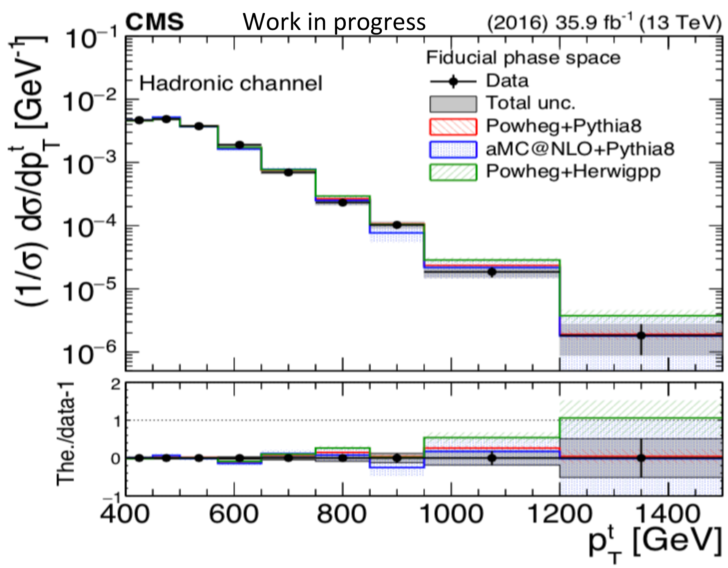


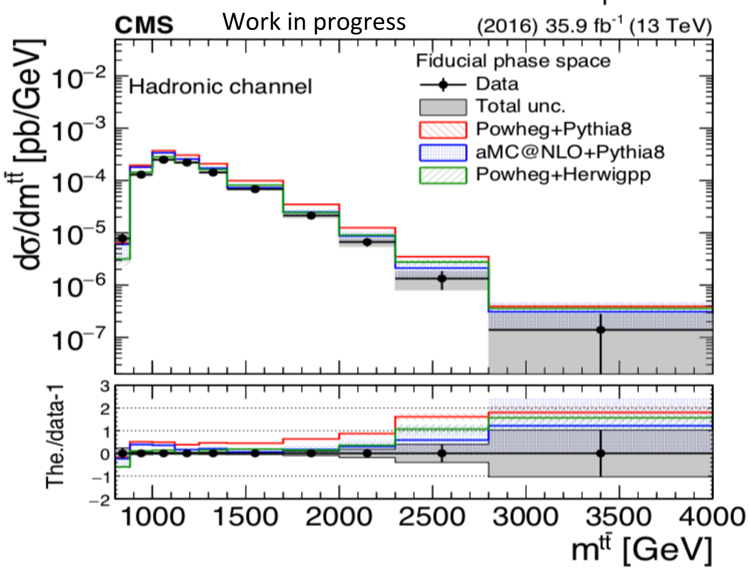


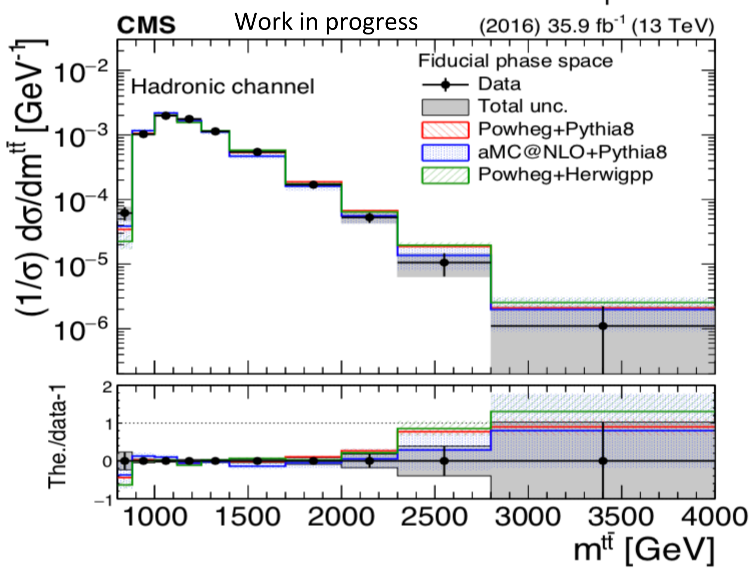


Results for Fiducial Measurement (top p_T , m_{tt})

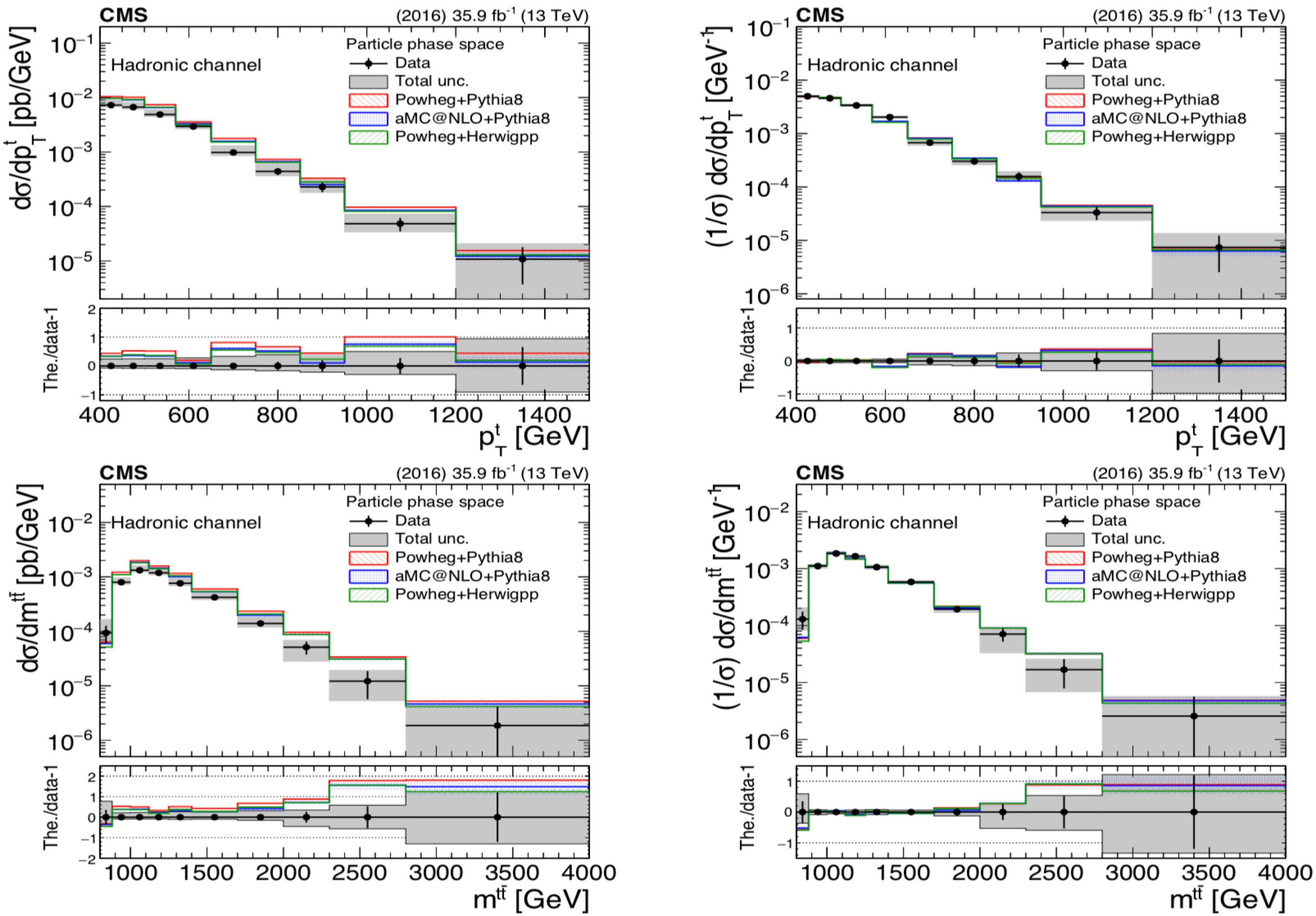




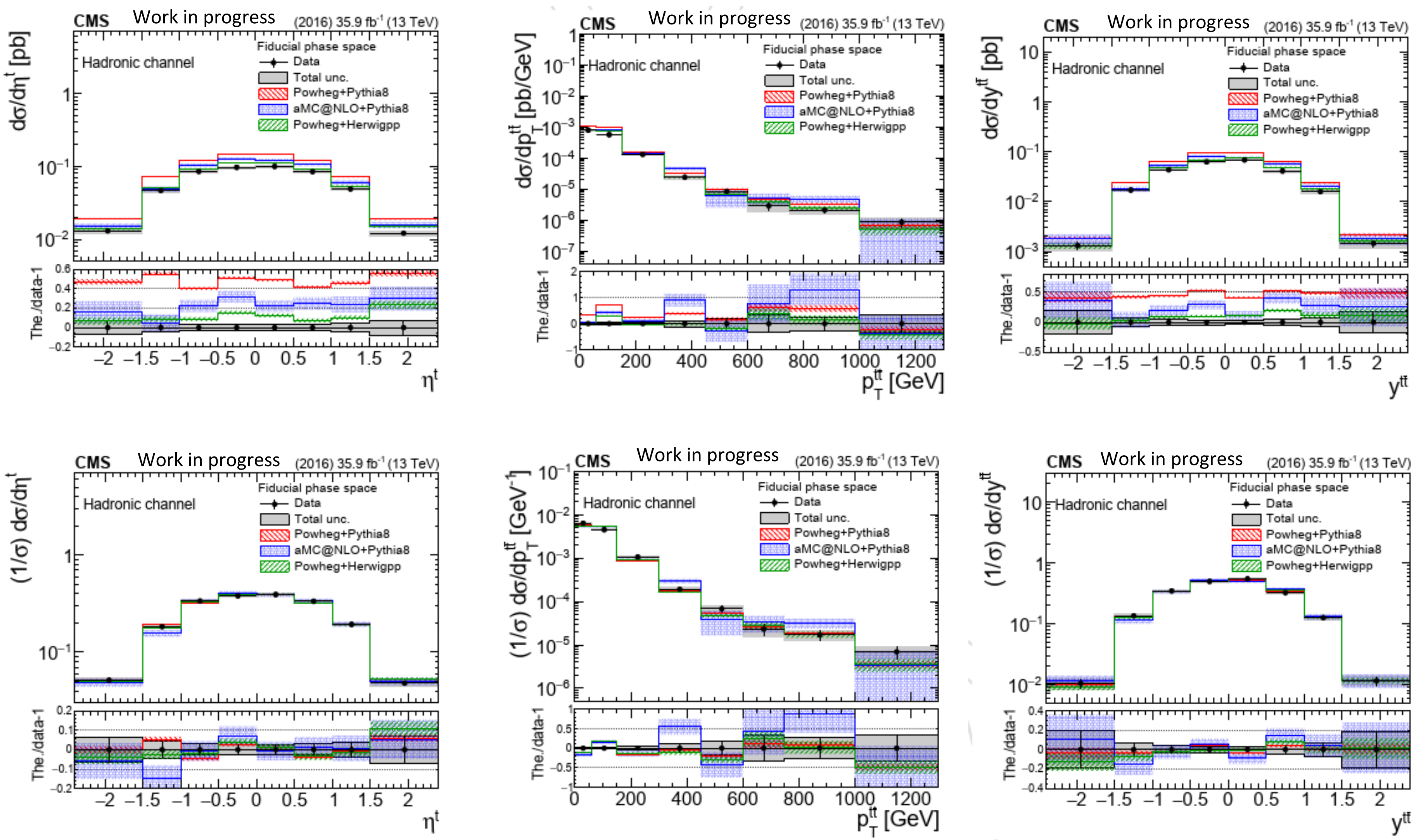




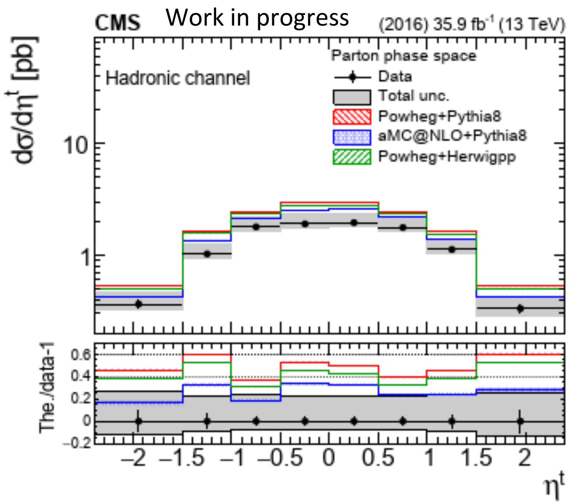
Results for Particle Measurement (top p_T , m_{tt})

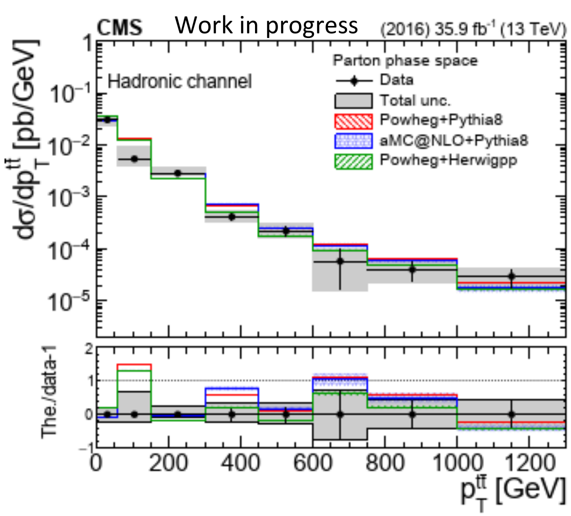


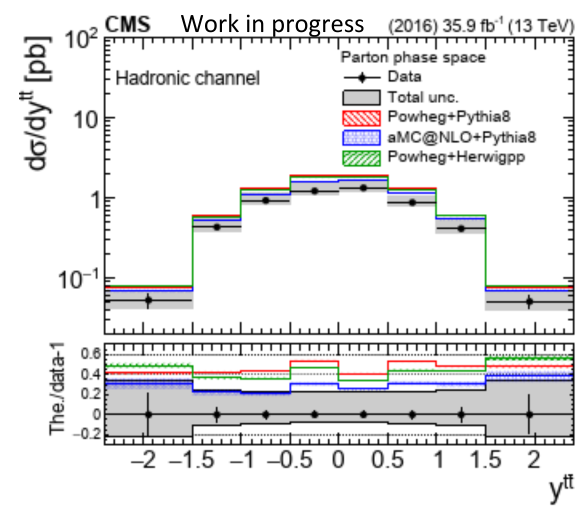
Fiducial Results for η^t , $p_{T,tt}$, y_{tt}

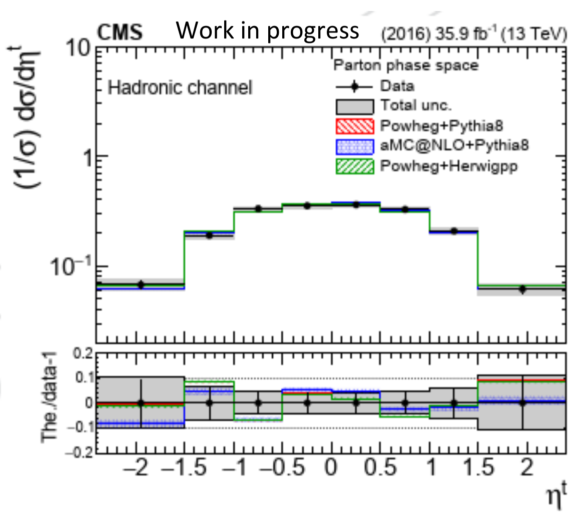


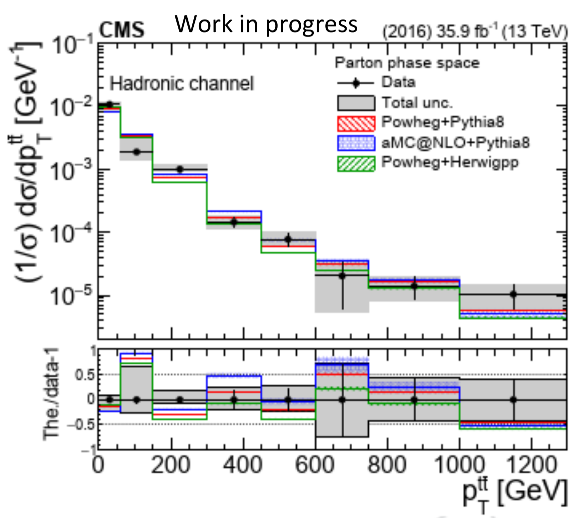
Parton Results for η^{t} , $p_{T,tt}$, y_{tt}

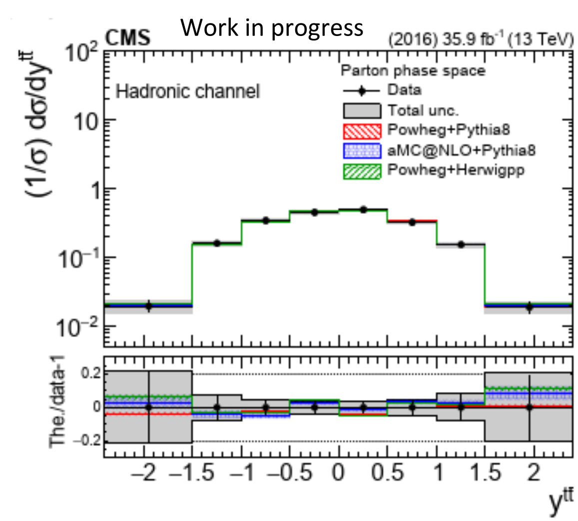












Particle Results for η^t , $p_{T,tt}$, y_{tt}