Z+Jet Center of Momentum Angular Distribution using the Compact Muon Solenoid

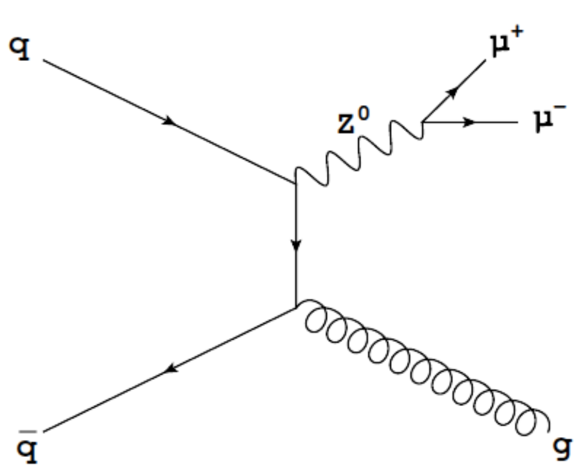
Luis Lebolo
Florida International University
SESAPS 2011

Analysis is a work in progress

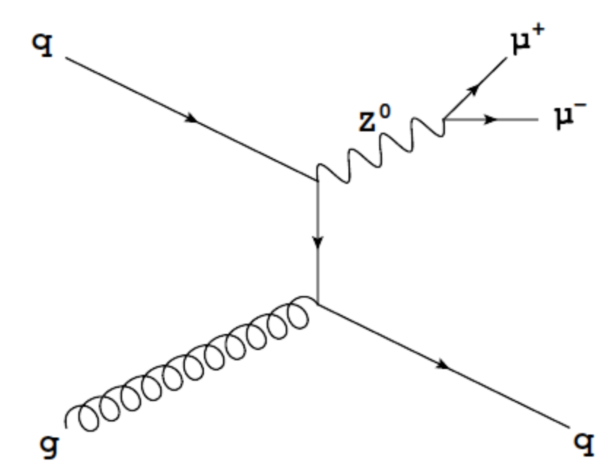
Motivation for the Angular Distribution

- Analysis is a measurement of the Z+jet *partonic* angular distribution (cosθ*) decoupled from the parton distribution functions (^ *and * signify the variable is in CM frame*)
  - Can be seen as a measurement of the partonic matrix element weighted by parton luminosity
- Good test of pQCD; can look for signatures of new physics
- First measurement of Z+jet angular distribution (as opposed to W+jet or dijet)
  - Analogous to ɣ+jet analysis, with the advantage of negligible background
- CMS allows for a high reach in cosθ* (CM energy and rapidity)

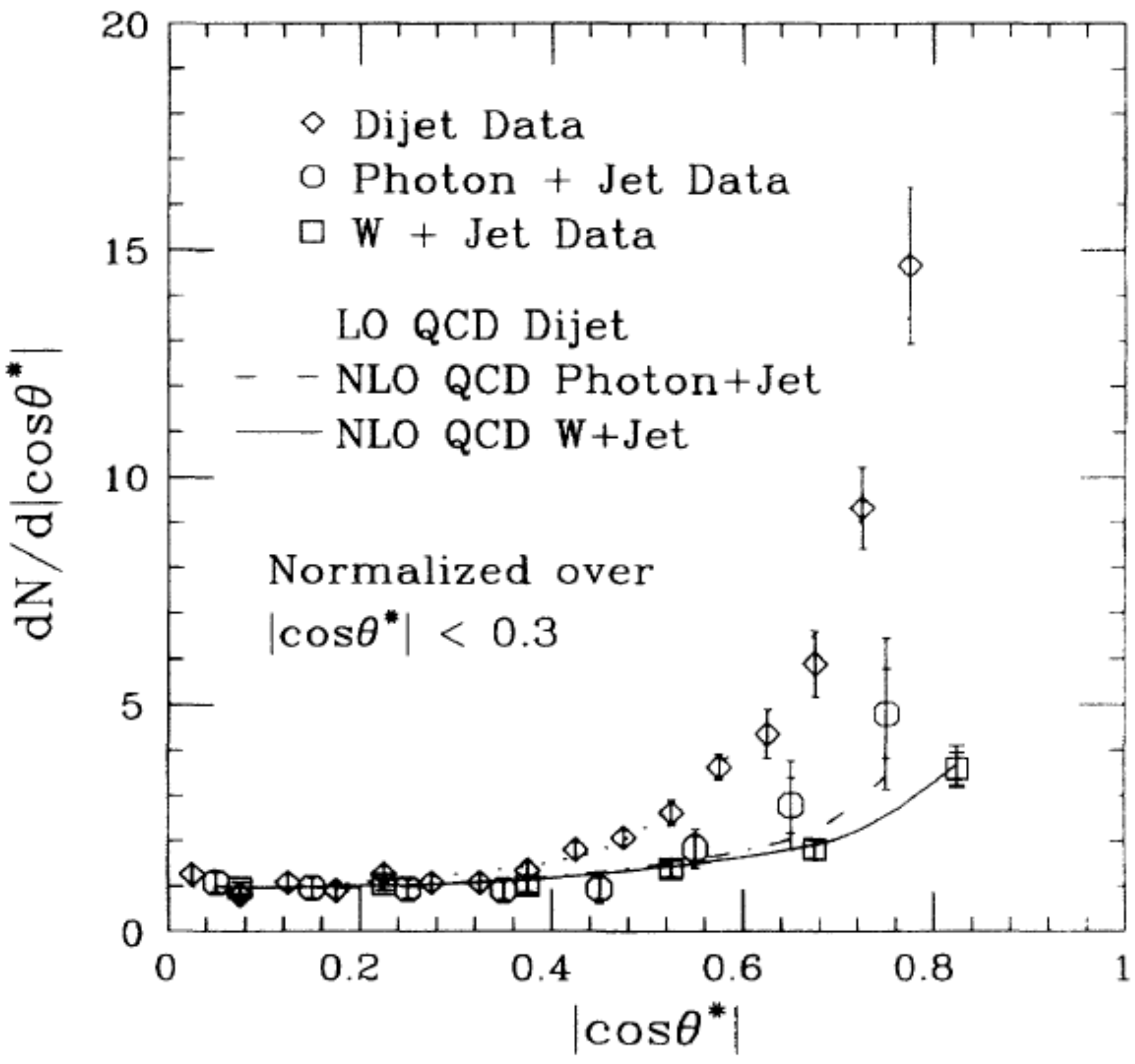
$$E\frac{d^3\sigma}{d\vec{p}} \rightarrow \frac{d^3\sigma}{d(p^*)^2\, dy_B\, d\cos\theta^*} \propto \frac{1}{S}\sum_{i,j}\frac{f_i(x_1)}{x_1}\frac{f_j(x_2)}{x_2}\frac{d\hat{\sigma}_{ij}}{d\cos\theta^*}$$



Process	$\propto \lvert\mathcal{M}\rvert^2$
$q+\bar{q}\rightarrow Z^0+g$	$\frac{8}{9}\left(t^2+u^2+2sm_3^2\right)/tu$
$q+g\rightarrow Z^0+q$	$-\frac{1}{3}\left(s^2+u^2+2tm_3^2\right)/su$



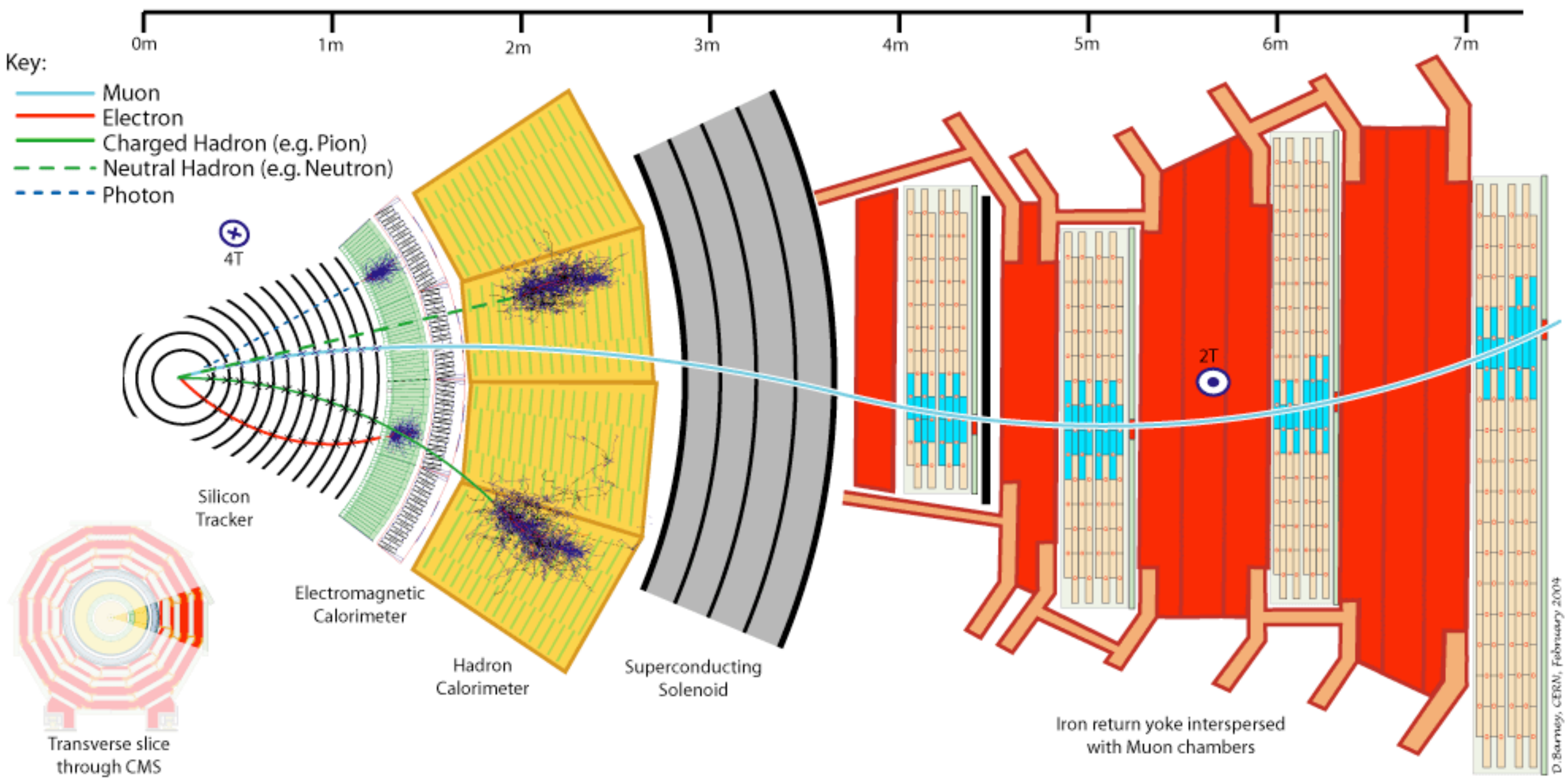
Related Measurements (CDF) [1]



Dijet ~ $(1 - \cos\theta^*)^{-2}$

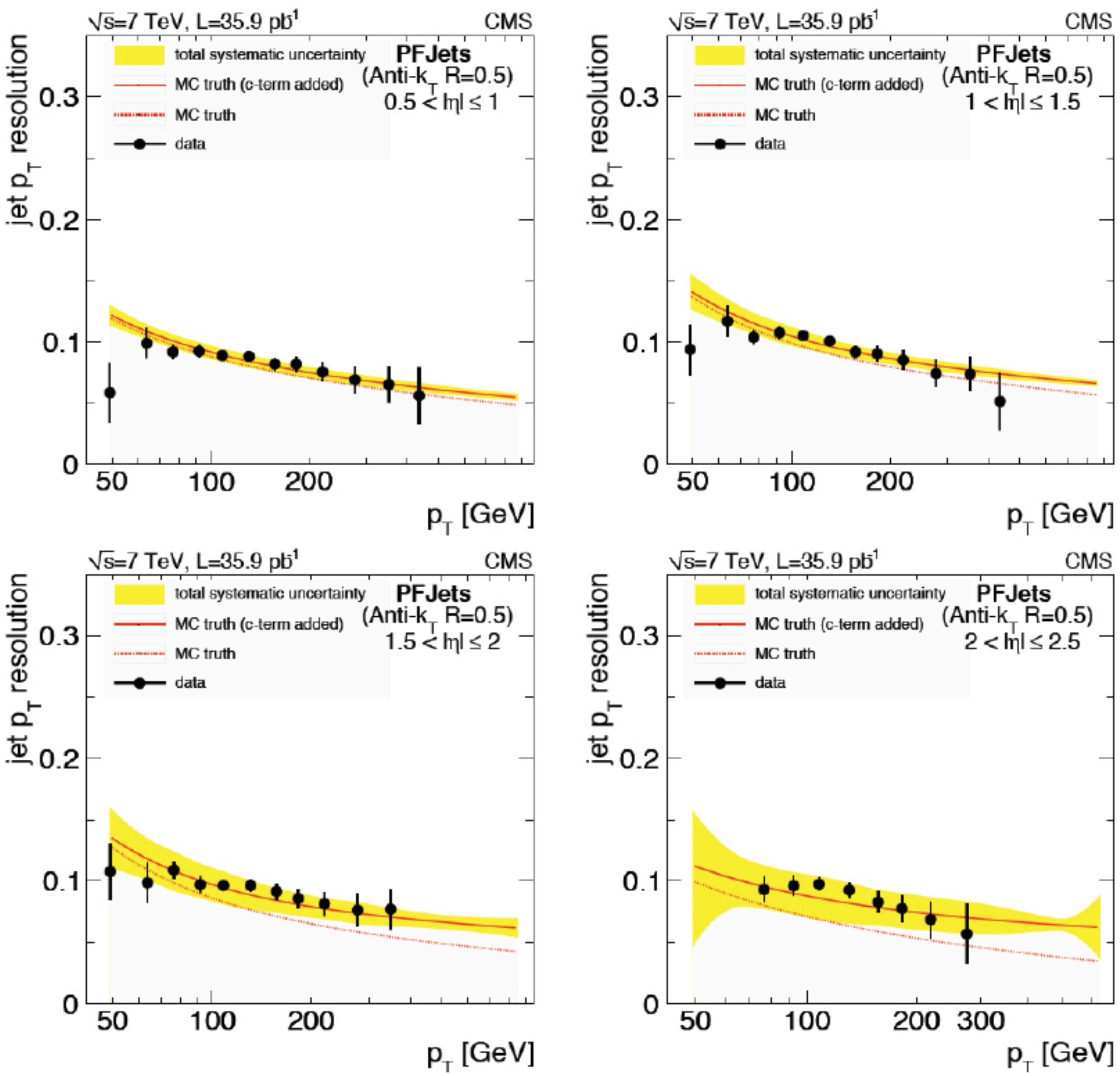
Z^0 ~ $(1 - \cos\theta^*)^{-1}$

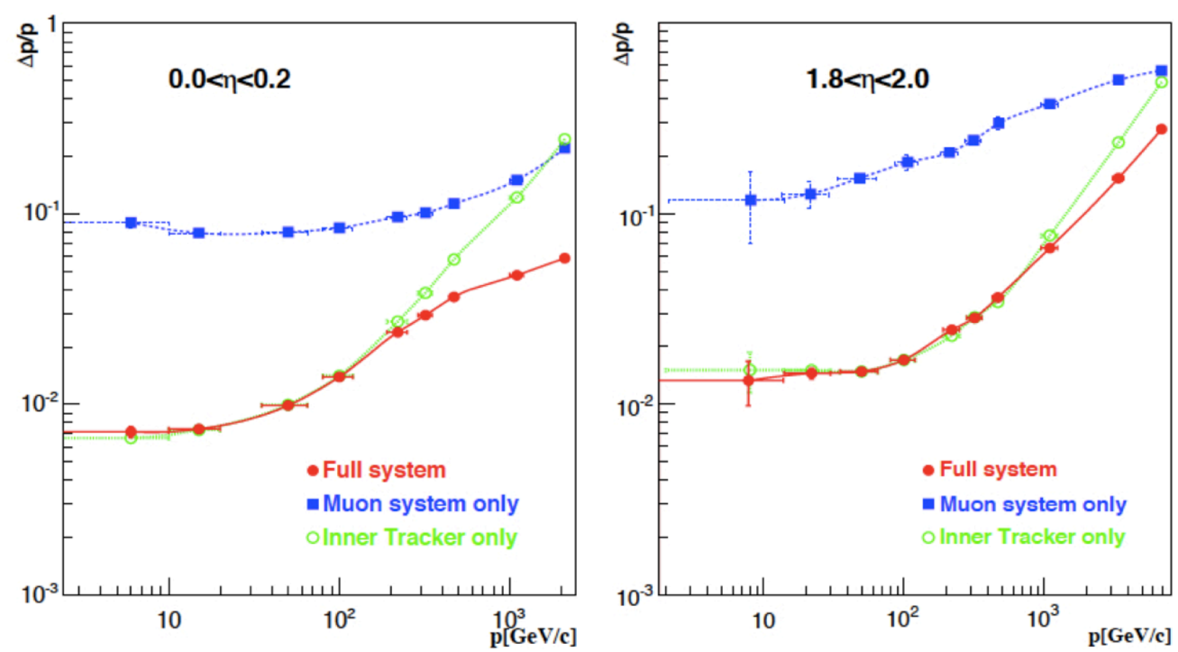
Compact Muon Solenoid



Analysis uses a *particle flow* algorithm that combines information from **all** subdetectors to reconstruct stable particles

PF Jet and Muon Momentum Resolution





Most candidate jets and muons in this analysis have

p_T < 70 GeV

|η| < 2.0

*p_T = Transverse Momentum

Center of Momentum Kinematics

- ✦ Angular distribution is predicted in CM frame - **perform Lorentz boosts on Z^0 and jet four-momentum vectors (measured in lab)**
  - Boosted system = Z^0 + jet 4-vector (gives boost β-vector)
  - Boost the Z^0 and jet into CM frame and calculate *cos*θ*
- Can also derive CM kinematics explicitly

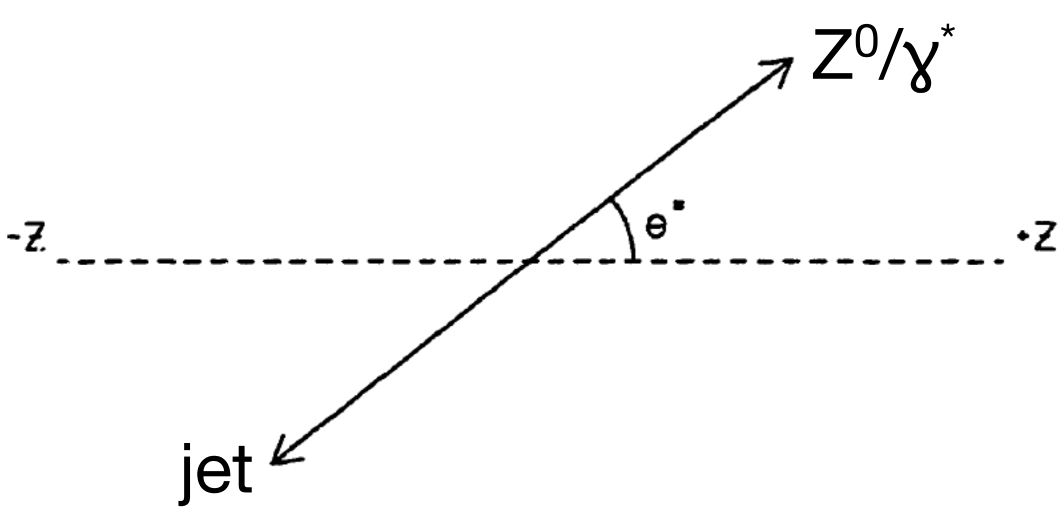
$$y = y_B + y^*$$

$$E^* = m_T \cosh y^*$$

$$P_z^* = m_T \sinh y^*$$

$$m_T \equiv \sqrt{p_T^2 + M^2}$$

$$\tanh y^* = \beta^* \cos\theta^*$$



Datasets

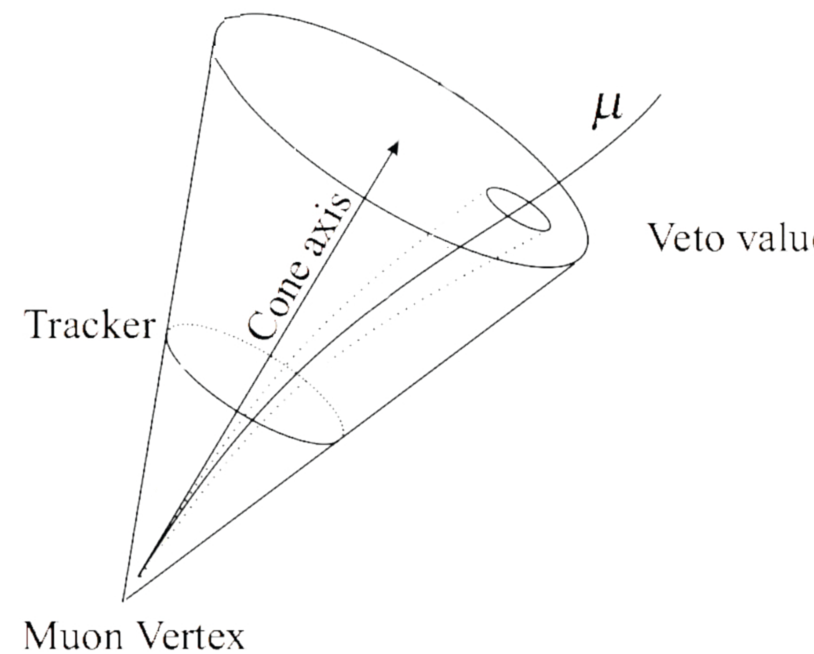
- ✦ Processed LHC collision data taken between May-Nov 2010, corresponding to **L_{int} ~ 36 pb^{-1}** ($\sqrt{S}$ = 7 TeV)
  - Only looking at the Z^0 muon decay (experimentally clean signature)
- ✦ Using a NLO generator (MadGraph) as pQCD prediction/simulation
  - Background is W+jet, ttbar+jet and QCD multijet events

Table 4.1: Simulation datasets used in the analysis, along with kinematic selections and cross sections. The scale and PDF uncertainties for MadGraph samples are also listed.

Process	Generator	Kinematic Selections	Cross Section (pb)
Z^0 + jets	MadGraph	$m_{\ell\ell} > 50$ GeV	$3048 \pm 34 \pm 128$
$W^{\pm}$ + jets	MadGraph	–	$31\,314 \pm 407 \pm 1504$
$t\bar{t}$ + jets	MadGraph	–	$158 \pm 19 \pm 14$
μ-enriched QCD	PYTHIA	$p_T^{boost} > 20$ GeV, $p_T^{\mu} > 5$ GeV, $\lvert\eta_\mu\rvert < 2.5$	3.5×10^6

Particle Identification

- ✦ Events must pass low p_T muon triggers
- ✦ Apply a standard CMS particle identification selection criteria*
  - Muon $p_T > 20$ GeV
  - Jet $p_T > 20$ GeV (Anti-k_T, $R = 0.5$)
  - $60 < M_{\mu\mu} < 120$ GeV
- ✦ Muon relative isolation ($R = 0.4$), $I_{rel} < 15\%$
  - "A muon is considered isolated if the energy in a surrounding hollow cone is less than 15% of its momentum"
  - Removes QCD multijet background

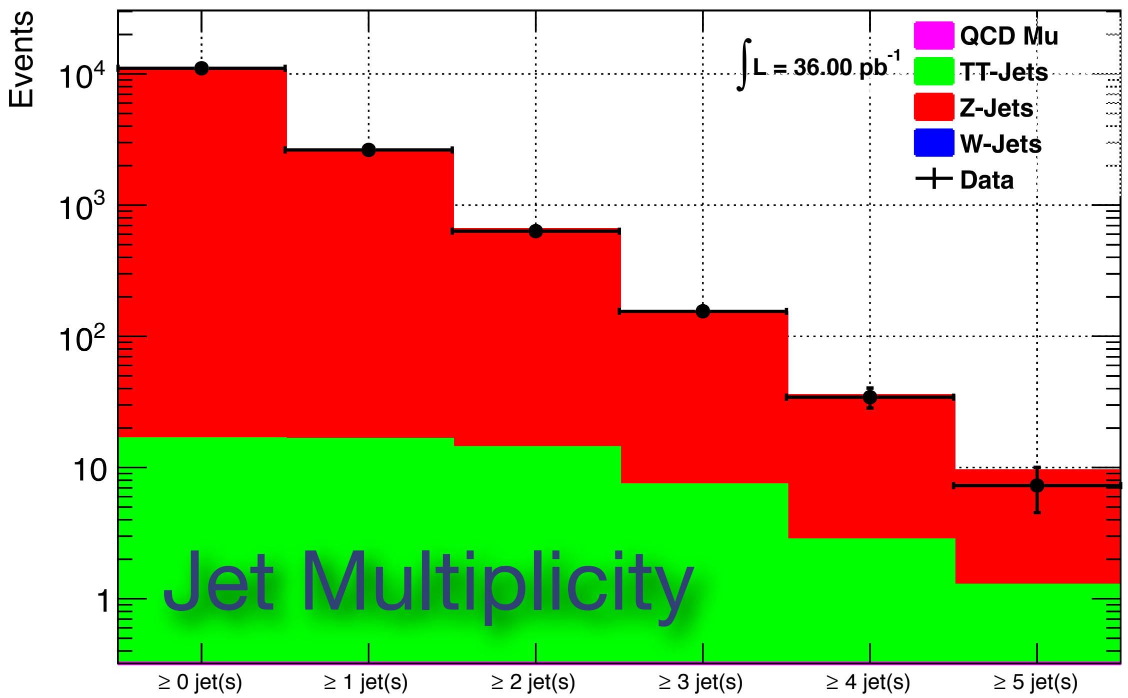


$$I_{rel} = \frac{\sum (p_T^{track} + E_T^{ECAL} + E_T^{HCAL})}{p_T^{\mu}}$$

*using Inclusive W and Z Cross Section [2] muon selections with V+Jet Ratio [3] isolation modifications (see backup slides)

Candidate Z^0 and Jet Distributions

Work in Progress

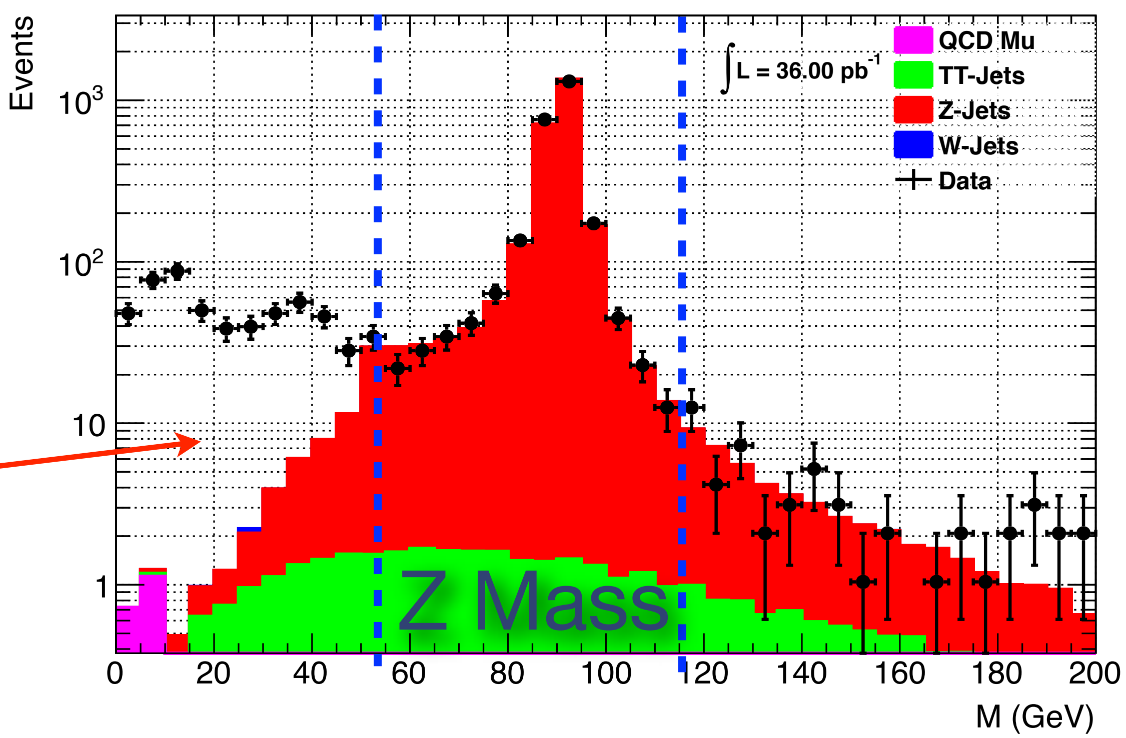


Work in Progress

Generator-level

$M_Z > 50$ GeV

selection

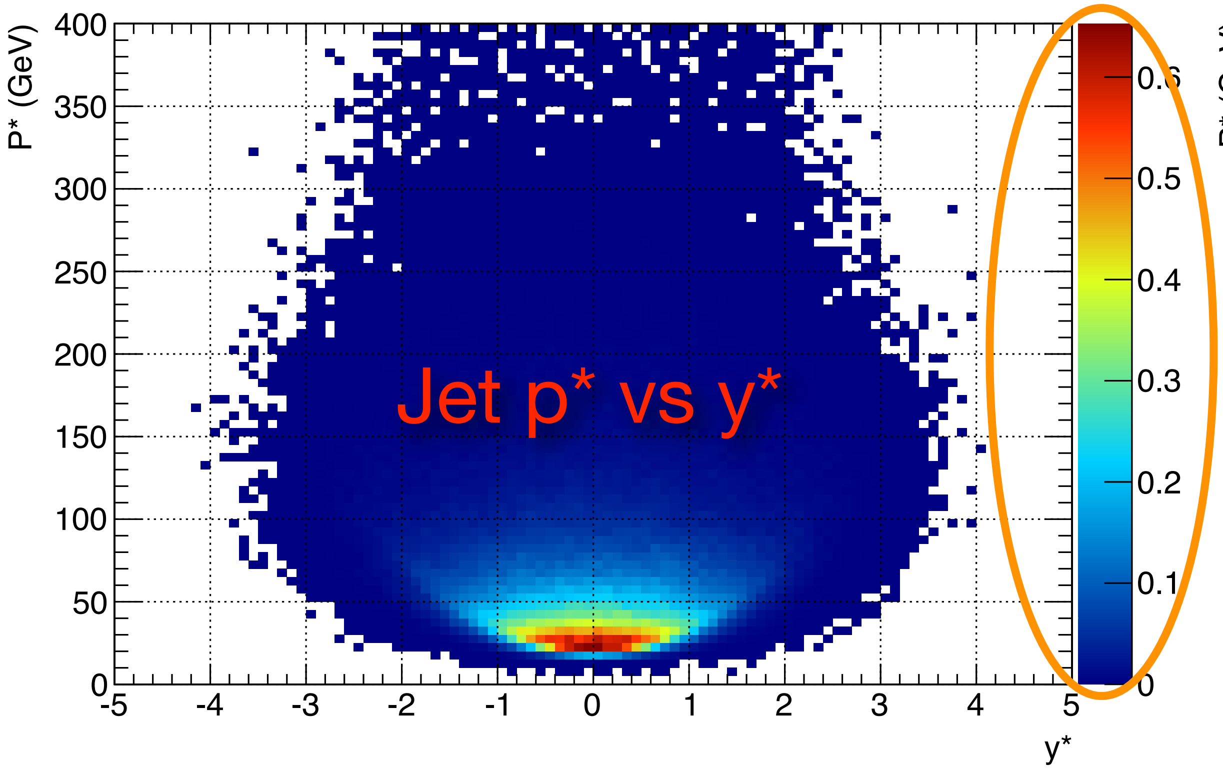


Corrections and Sources of Uncertainty

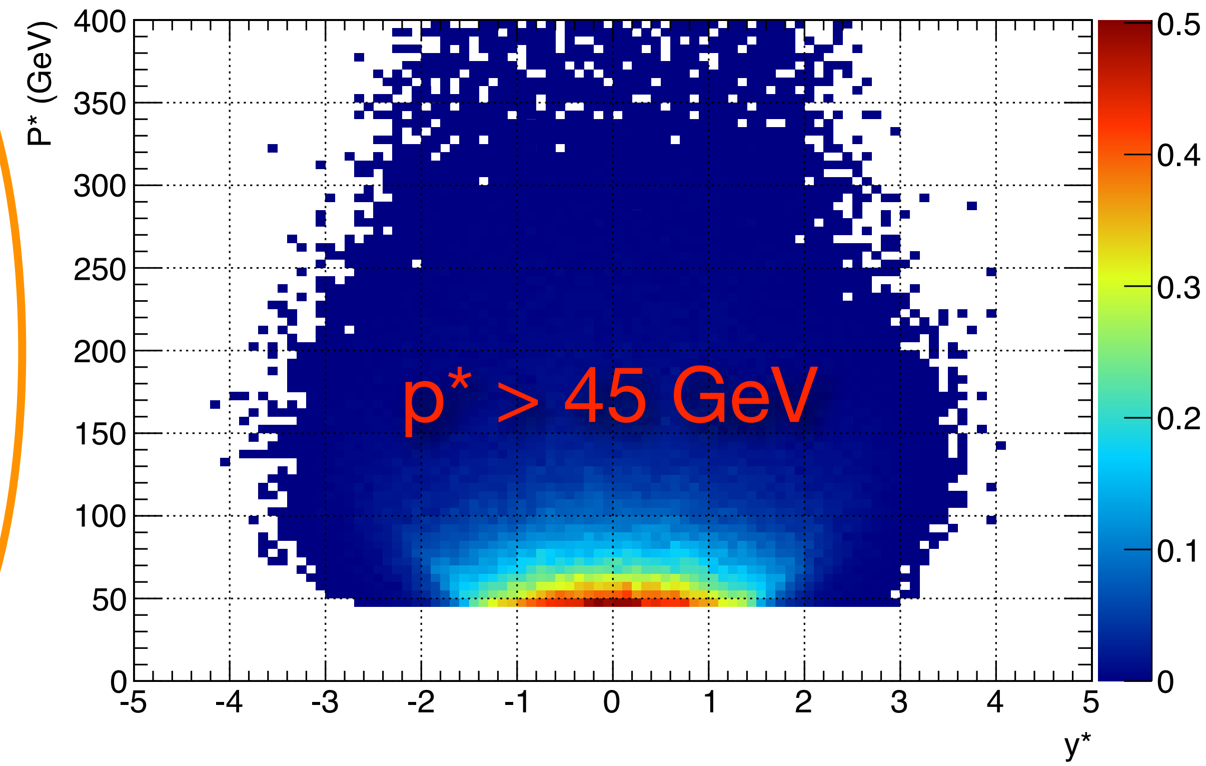
- Trigger momentum thresholds in the lab impose a CM phase space bias
  - Will have to limit CM phase space
- Source of uncertainty
  - Only worry about systematics that have an angular dependence
  - Largest source is the jet energy scale
    - Measured jet energy is different from the true particle energy due to the non-linearity of calorimeters
    - Therefore the jet energy is scaled by a correction factor (with an uncertainty)
    - Relative uncertainty of < 4%
- Other sources (not discussed)
  - Muon resolution negligible compared to jet uncertainty
  - Jet p_T and η resolution is accounted for by unfolding
  - Summarized in conclusion slide

Phase Space Bias

Work in Progress



Work in Progress



Fixed minimum p_T → loss of acceptance that increases with y*

> 20 GeV

$$p^* = p_T \cosh y^*$$

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim (1-\cos\theta^*)^{-1}$$

$$p^* \geq p_{T,\min} \cosh y^*$$

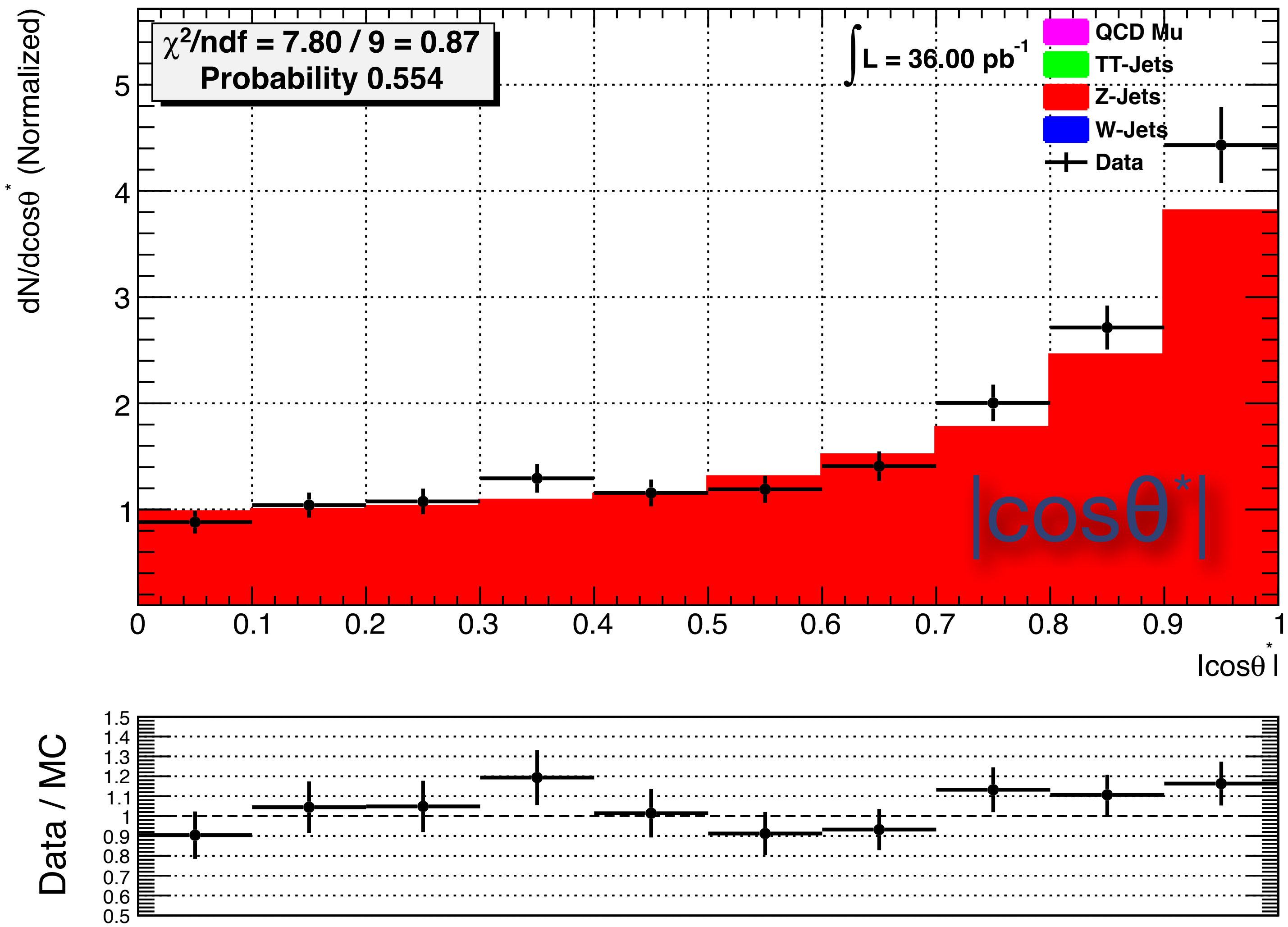
$$45 \geq 20 \cosh y^*$$

$$y^* \leq \cosh^{-1}(2.25) \approx 1.45$$

$$\cos\theta^* \leq \tanh(1.76) \approx 0.90$$

Results and Conclusions

Work in Progress



Source	Relative Value
Theoretical uncertainty (PDF variation)	$< 5\%$
Muon energy scale and resolution	$< 1\%$
Jet energy scale	$< 5\%$
Jet p_{T} and η resolution (unfolding)	$< 4\%$

- First measurement of Z+jet angular distribution shown with LHC 2010 collision data
  - Good agreement with pQCD (NLO)
- Some systematic uncertainties are limited by MC statistics
  - Plan to use full 2011 data (~3 fb^{-1}) for more precise evaluation

Backup Slides

References

[1] pCDF Collaboration. W Boson + Jet Angular Distribution in pp Collsions at sqrt(S) = 1.8 TeV. Phys. Rev. Lett., 73:2296-2300, Oct 1994.

[2] CMS Collaboration. Measurement of the Inclusive W and Z Production Cross Sections in pp Collisions at sqrt(s) = 7 TeV. arXiv e-prints, 2011.

[3] CMS Collaboration. Rates of jets produced in association with w and z bosons. CMS Physics Analysis Summary, CMS-PAS-EWK-10-012, 2011.

[4] CMS Collaboration. Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS. arXiv e-prints, 2011.

[5] S. Alekhin et al. The PDF4LHC Working Group Interim Report. ArXiv e-prints, January 2011.

[6] G. Cowens. A survey of unfolding methods for particle physics. In Proc. Advanced Statistical Techniques in Particle Physics, Durham, 2002.

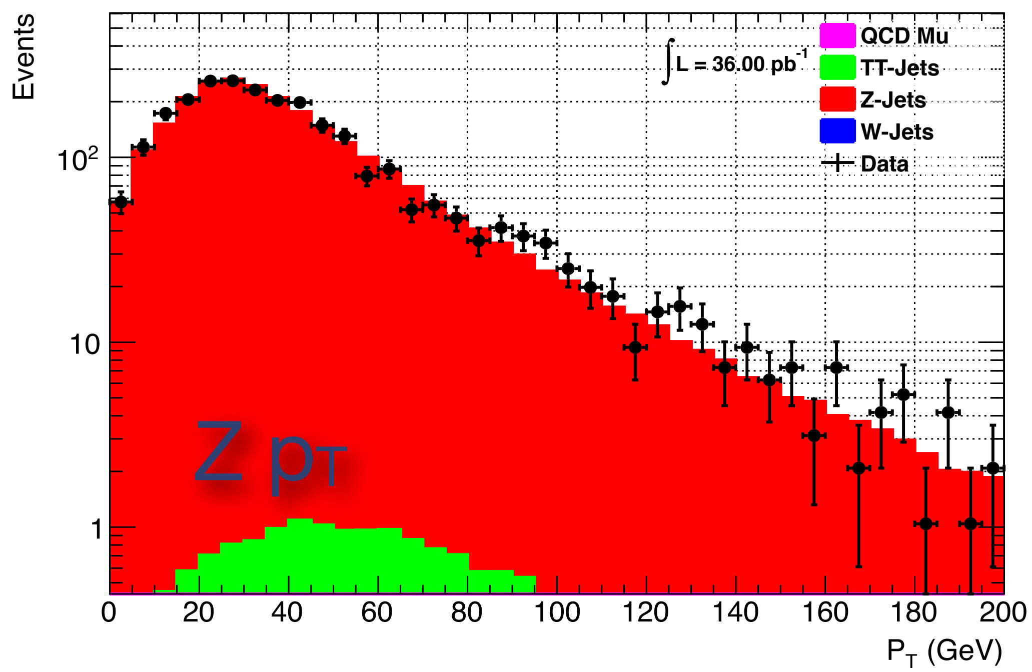
[7] T. Adye. Unfolding algorithms and tests using RooUnfold. ArXiv e-prints, May 2011.

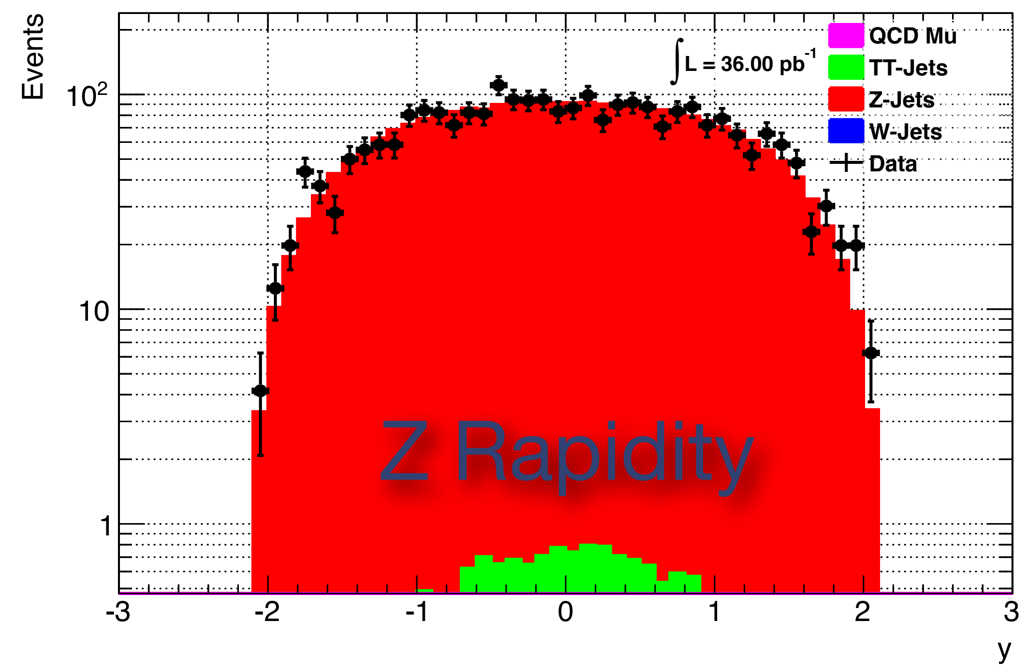
Particle Identification Details

Category	Selection	Motivation
Vertex	$NDOF_{PV} > 4$ $\|z_{PV}\| < 15$ cm $\rho_{PV} < 2$ cm	Non-collision and beam-related background rejection
Muon Acceptance	$p_T^{\mu_1} > 20$ GeV $p_T^{\mu_2} > 10$ GeV $\|\eta_\mu\| < 2.1$	... ... Muon trigger acceptance
Muon Quality	Global Muon & Tracker Muon Number of Pixel Hits > 0 Number of Silicon Hits > 10 Number of Muon Hits > 0 Number of Muon Stations > 1 Normalized $\chi^2 < 10$ $\|d_{xy}\| < 0.2$ cm	Decay-in-flight, punch-through, noise and cosmic ray rejection
Jet Acceptance	$p_T^{jet} > 20$ GeV $\|\eta_{jet}\| < 2.4$	... Tracker and muon spectrometer acceptance
Z Selection	$I_{rel}^{\mu} < 15\%$ $60 < M_{\mu\mu} < 120$ GeV	QCD background rejection Z^0 signal selection

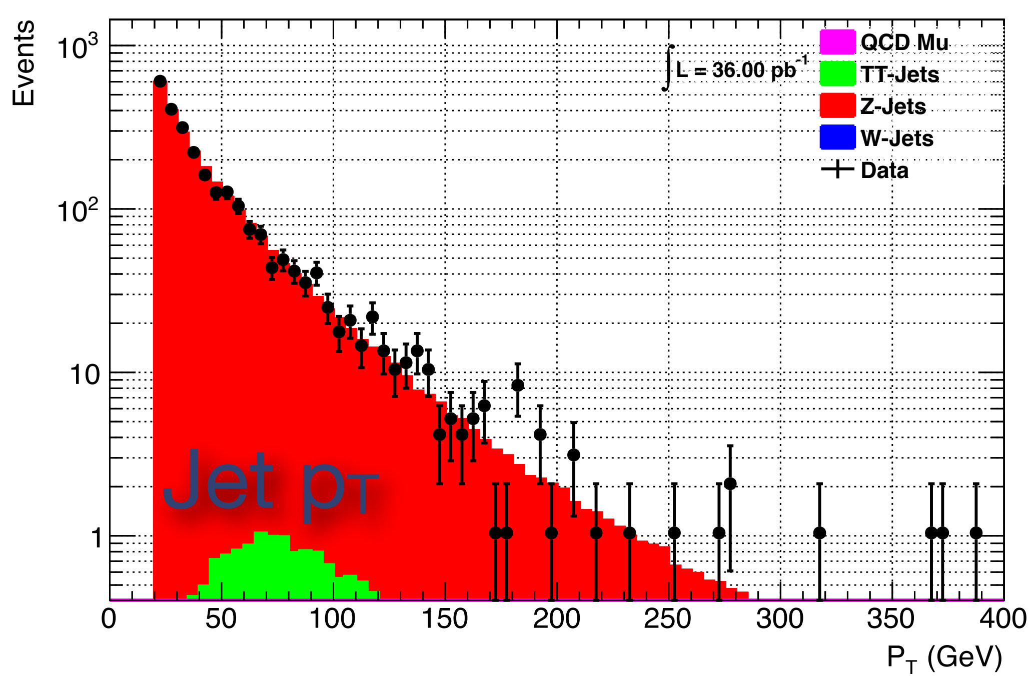
HLT Path	L1 Seed	HLT/L1 p_T Threshold (GeV)
HLT_Mu9	L1_SingleMu7	9 / 7
HLT_Mu11		11 / 7
HLT_Mu13		13 / 7
HLT_Mu15		15 / 7

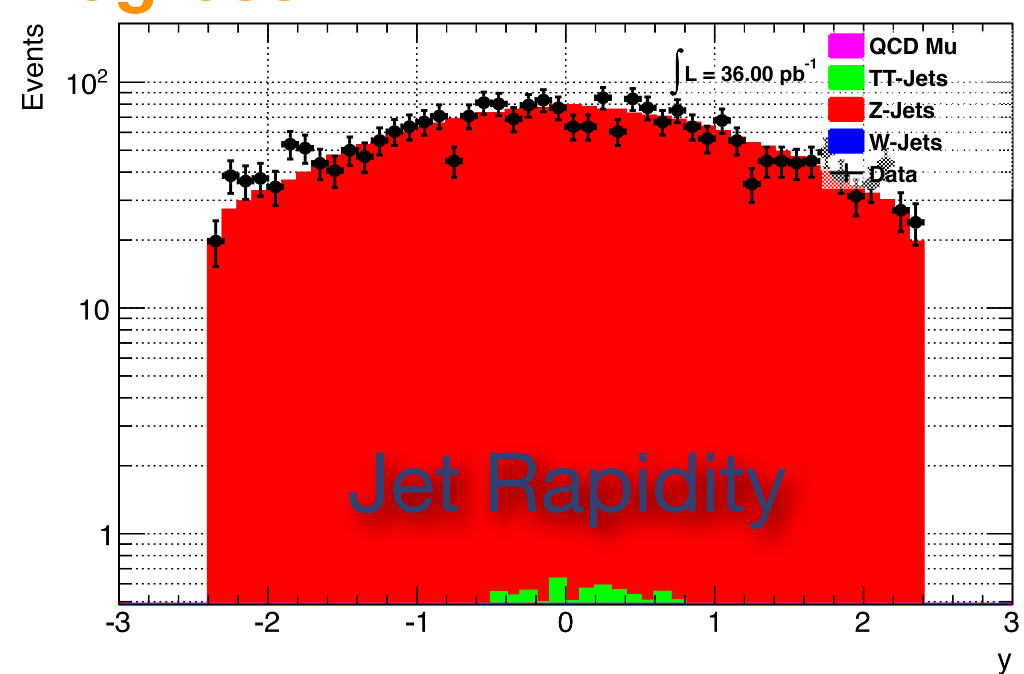
Post-Selection Z^0 and Jet Distributions





Work in Progress



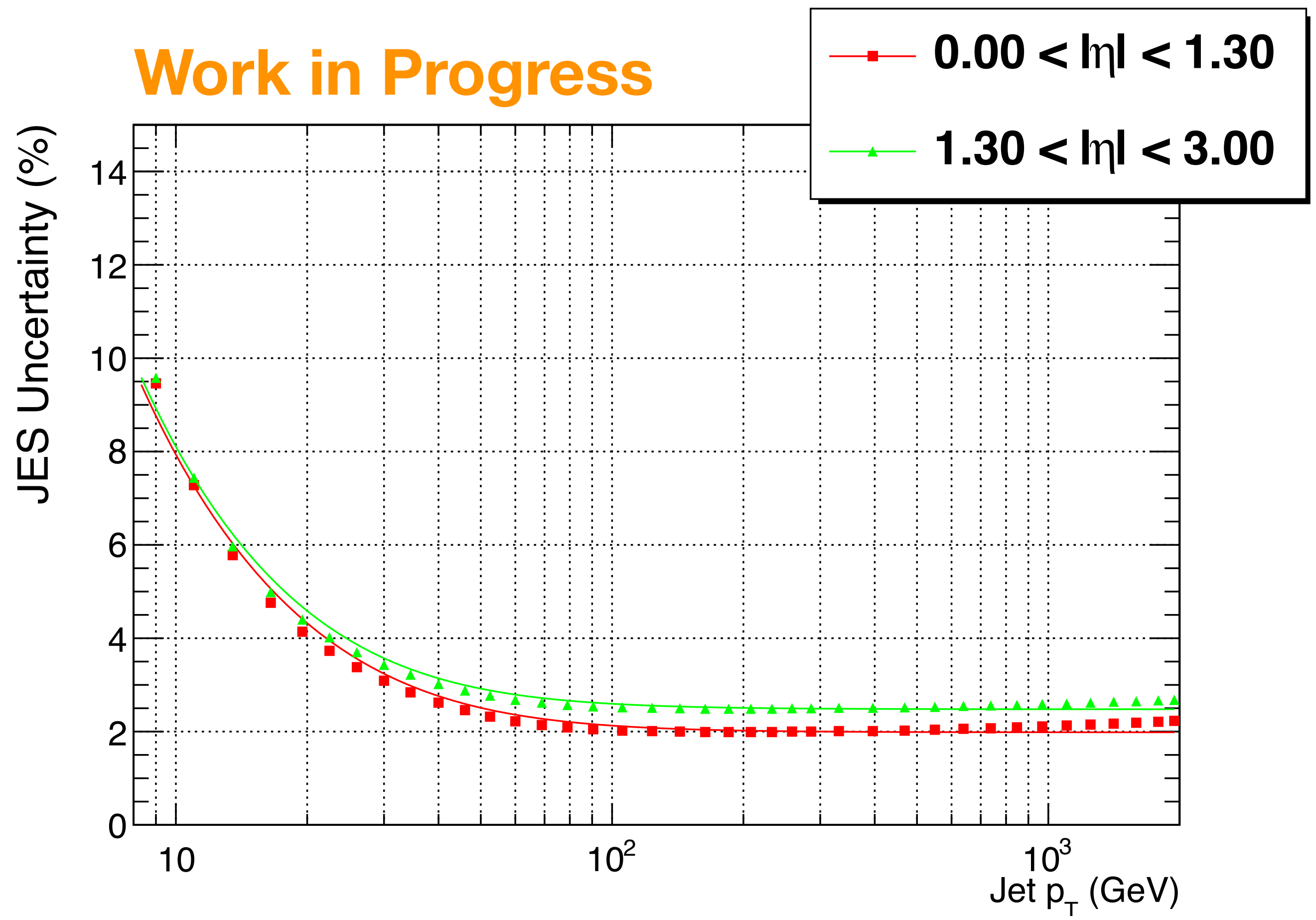


Effect of JES Uncertainty

Jet energy affects cosθ* measurement through the Lorentz boost (lab-to-CM)

$$\cos\theta^* = \frac{p_z}{p} = \frac{\gamma(p_z - \beta E)}{\gamma(E - \beta p_z)} = \frac{\cos\theta - \beta}{1 - \beta\cos\theta}$$

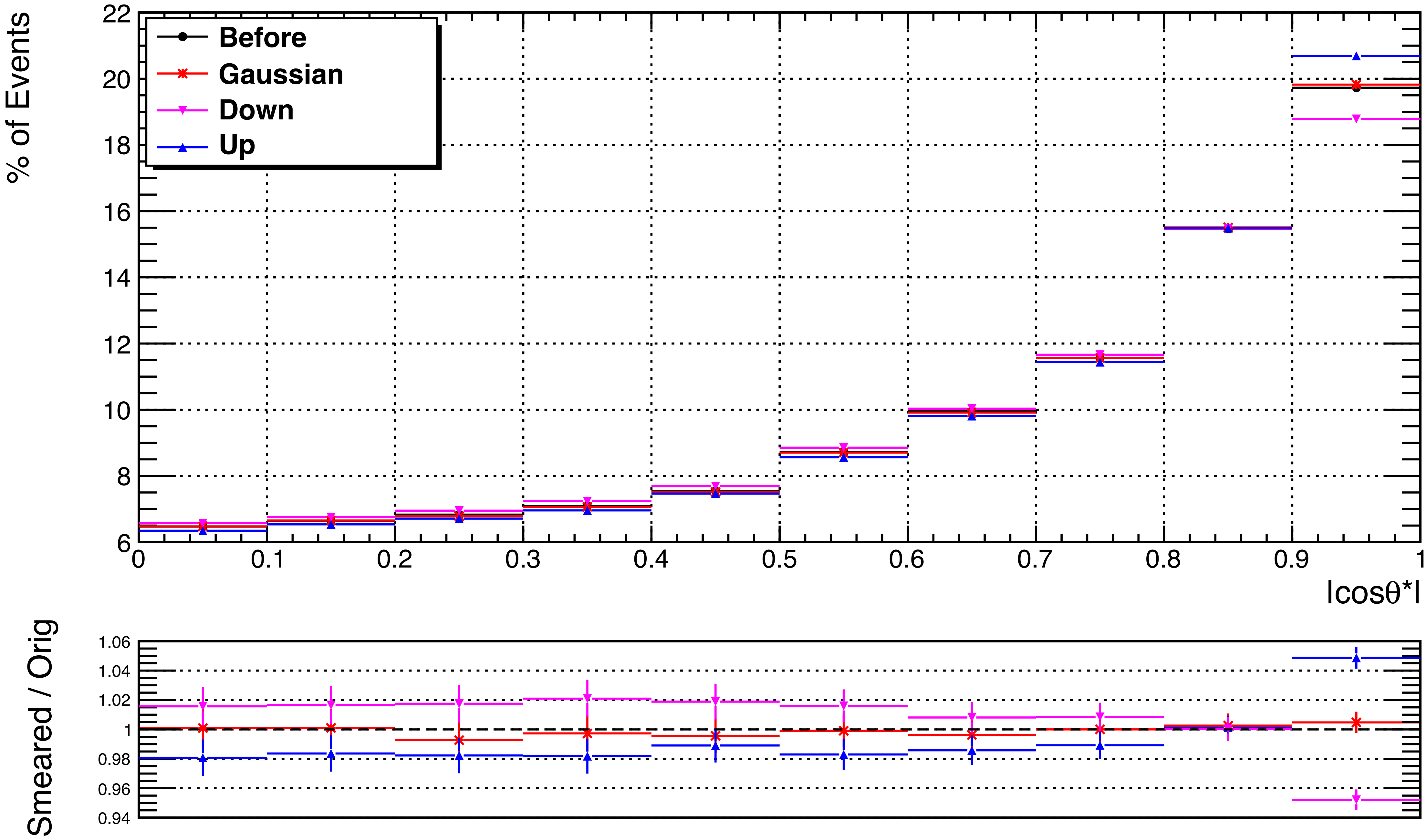
$$\beta \approx \frac{p_z^Z + p_z^j}{E_Z + E_j} = \frac{p_z^Z + p_T^j \cot\theta}{E_Z + p_T^j\sqrt{1 + \cot^2\theta}}$$



Use uncertainty to smear jet p_T then recalculate cosθ*

JES Uncertainty Results

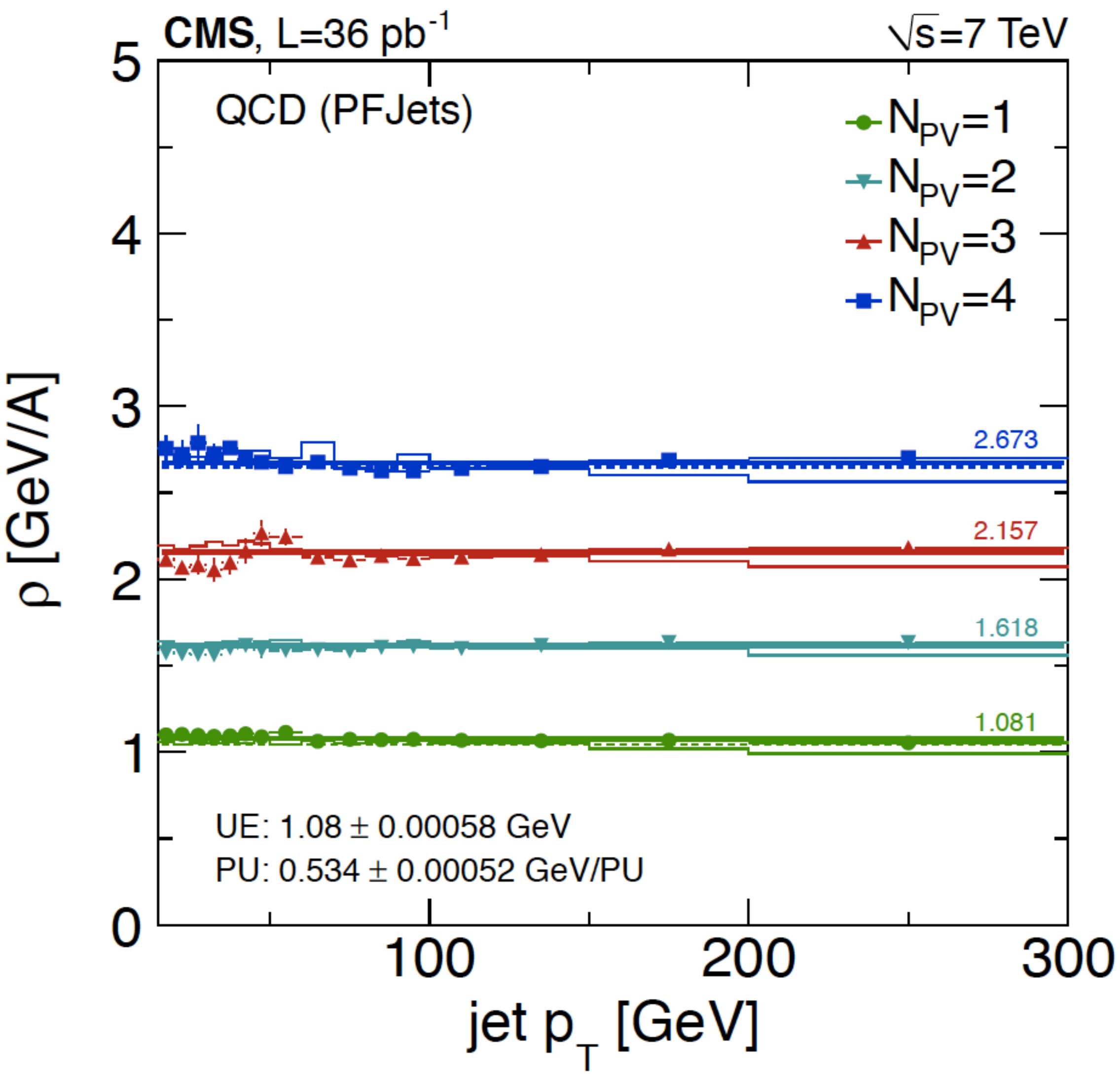
Work in Progress



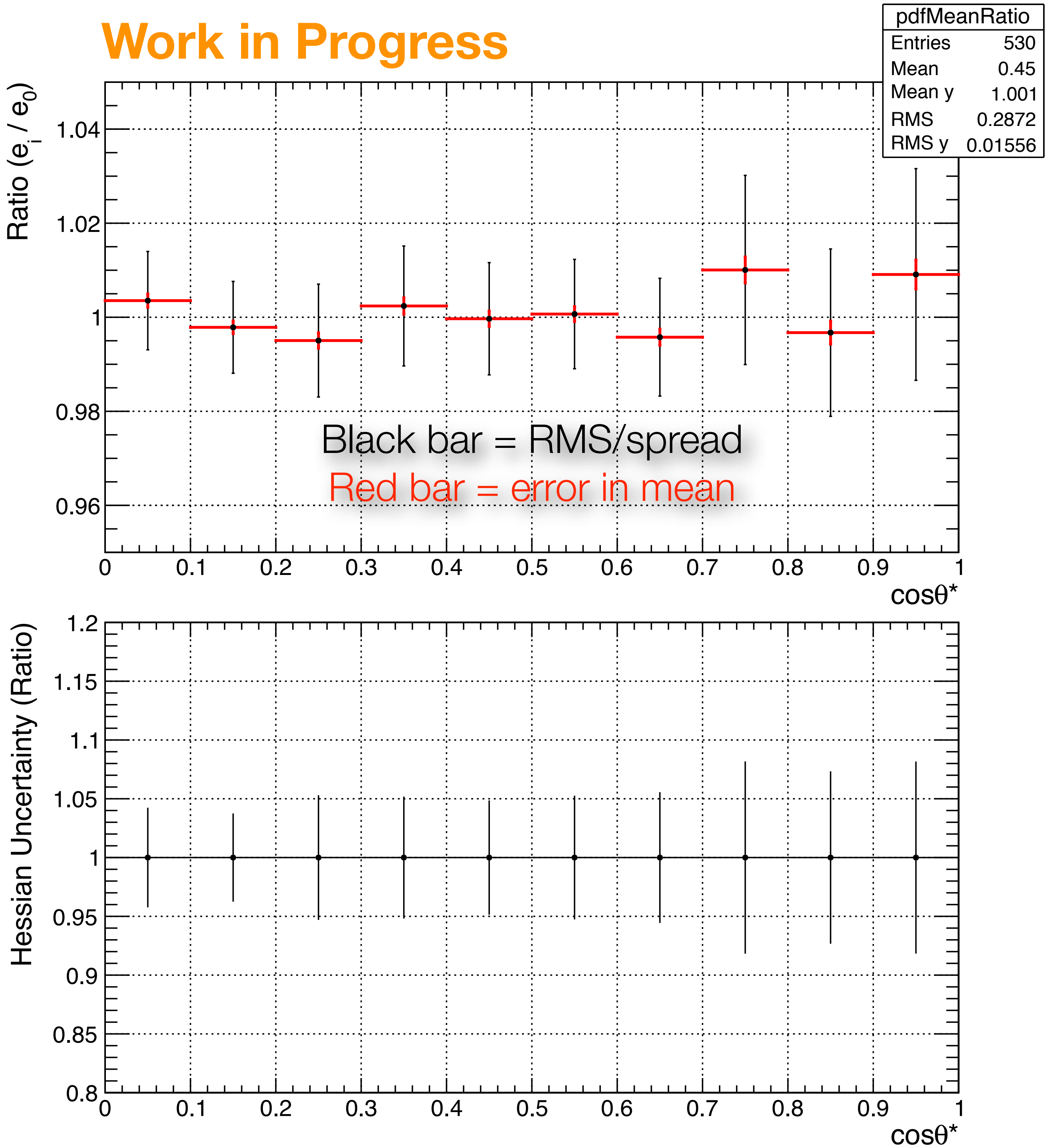
Correcting for Pileup

- ✦ Following recommendations of JEC group for 42X
  - Followed JEC Workbook
- ✦ In short,
  - PU subtraction via L1FastJet (jet area and energy density calculation “ρ”)
  - Also using PF charged hadron subtraction
    - i.e. charged hadrons from secondary vertices are removed
  - See JME-10-011 for details [4]

$$C_{\text{area}}(p_T^{raw}, A_j, \rho) = 1 - \frac{(\rho - \langle \rho_{\text{UE}} \rangle) \cdot A_j}{p_T^{raw}}$$

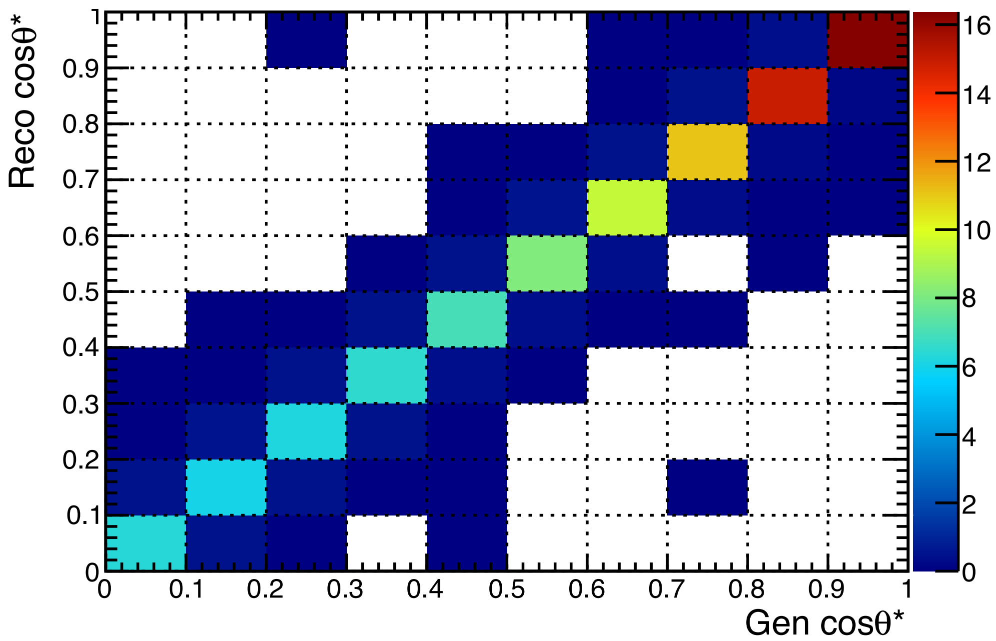


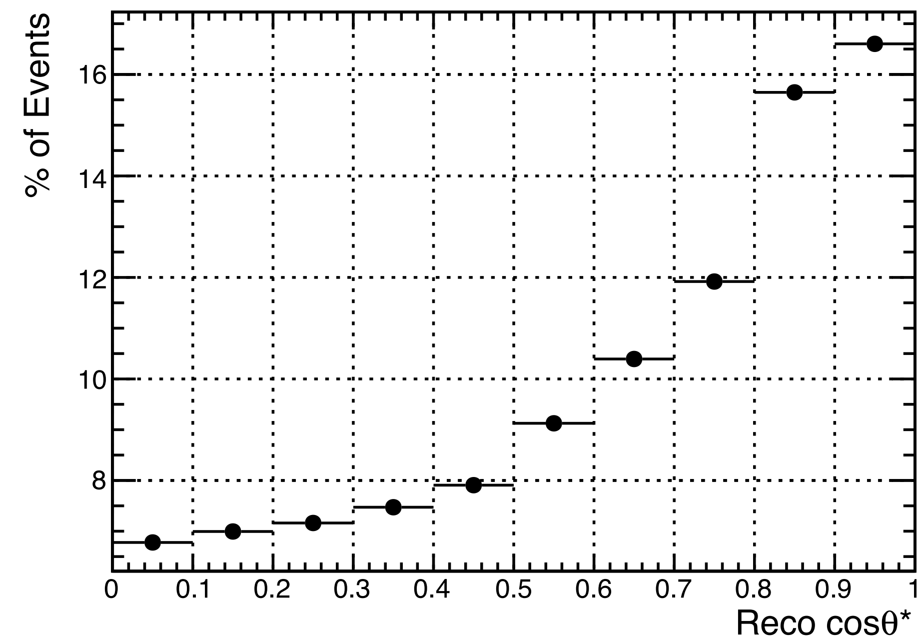
Theoretical (PDF) Uncertainties



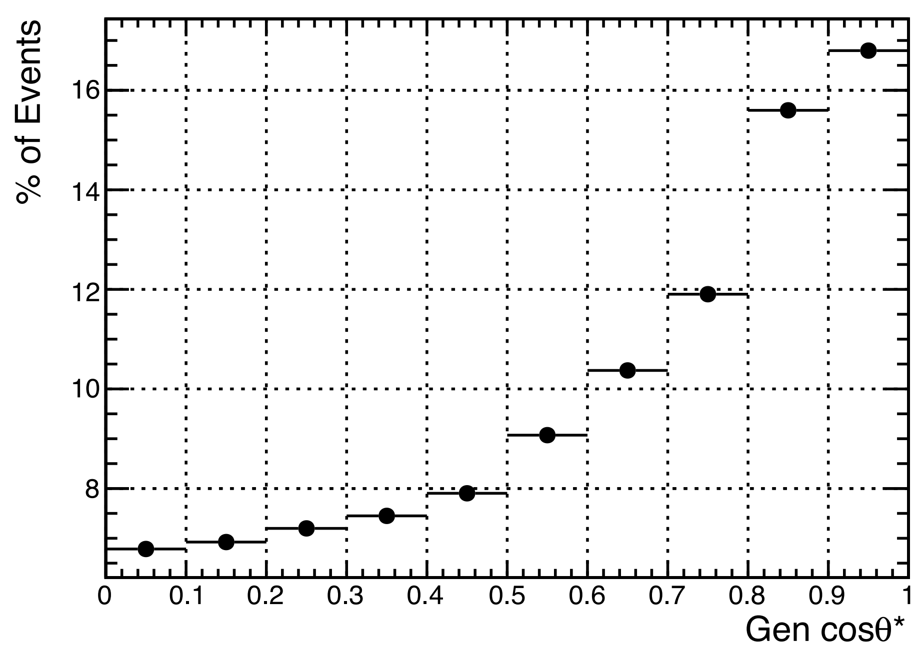
- Idea is to vary sets of PDFs [5]
  - Then take the ratios of the new PDFs w.r.t nominal set
- Analysis was done for a photon +jet cross section
  - However, the Z+jet shape is analogous
- Correct way to determine errors is through a Hessian approach
  - Hessian inflated by lack of MC statistics
  - Conservative relative uncertainty of 5%

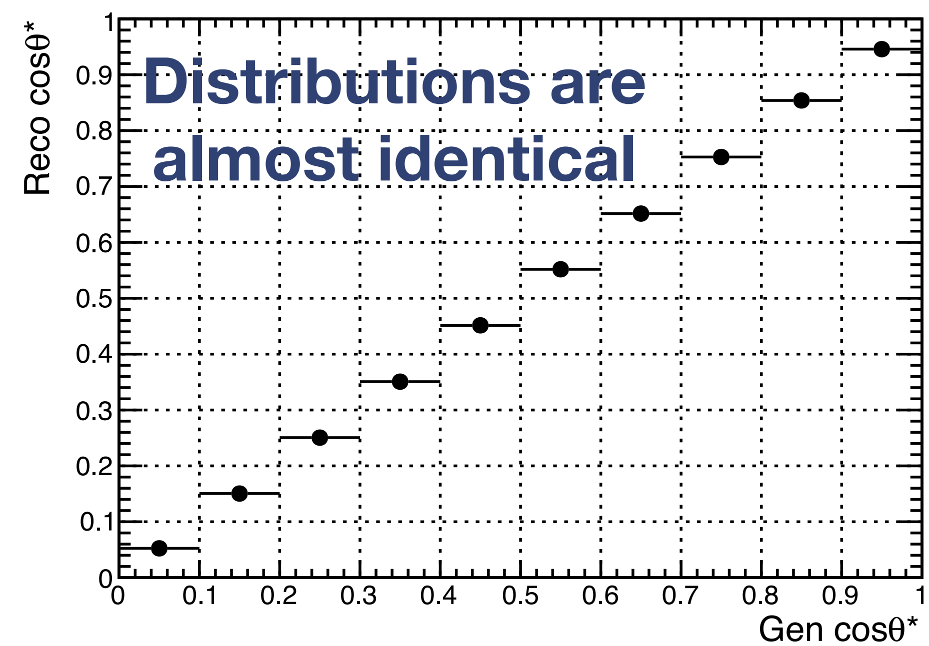
Jet Resolution - Reco vs. Gen





Work in Progress

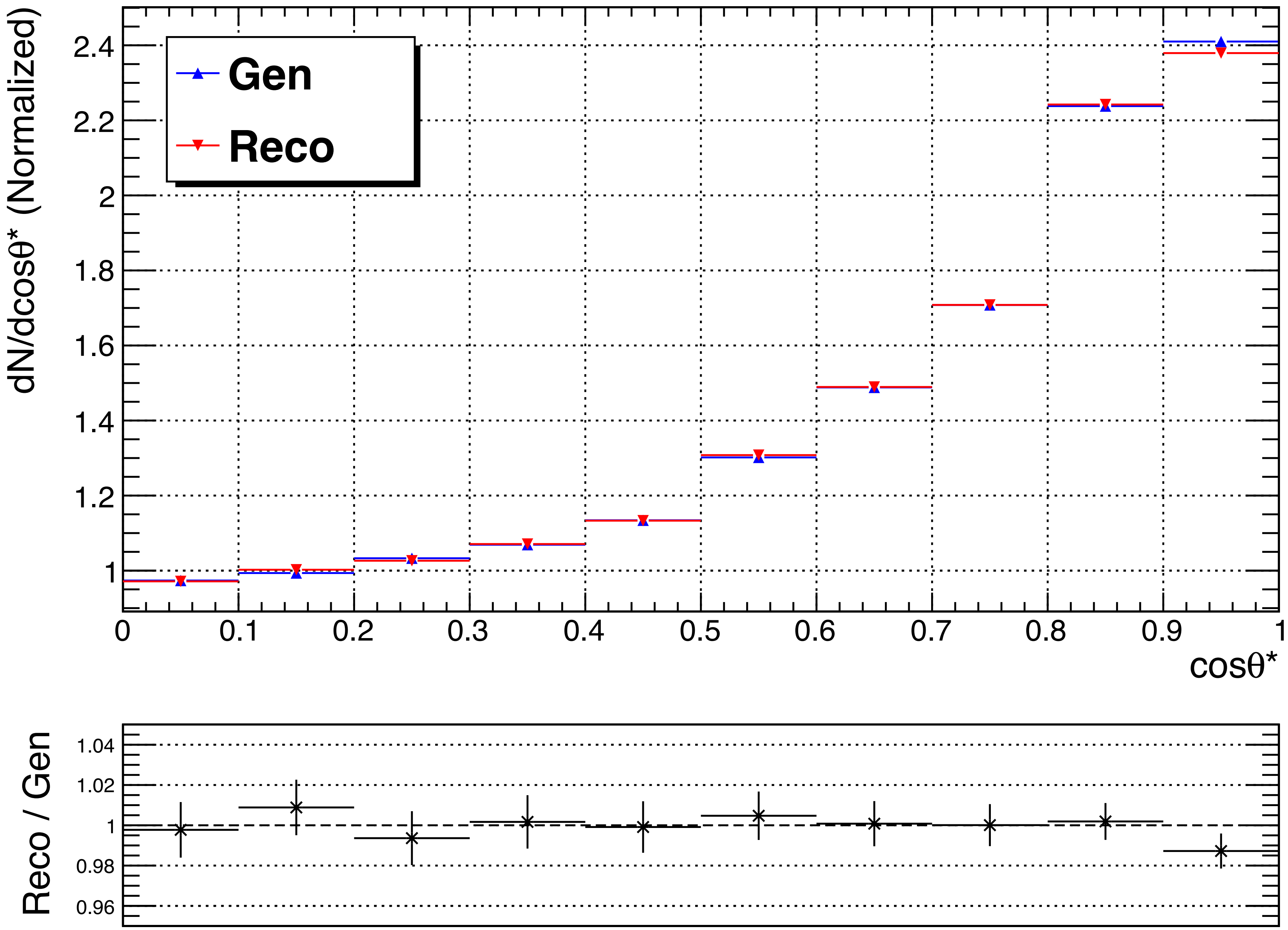




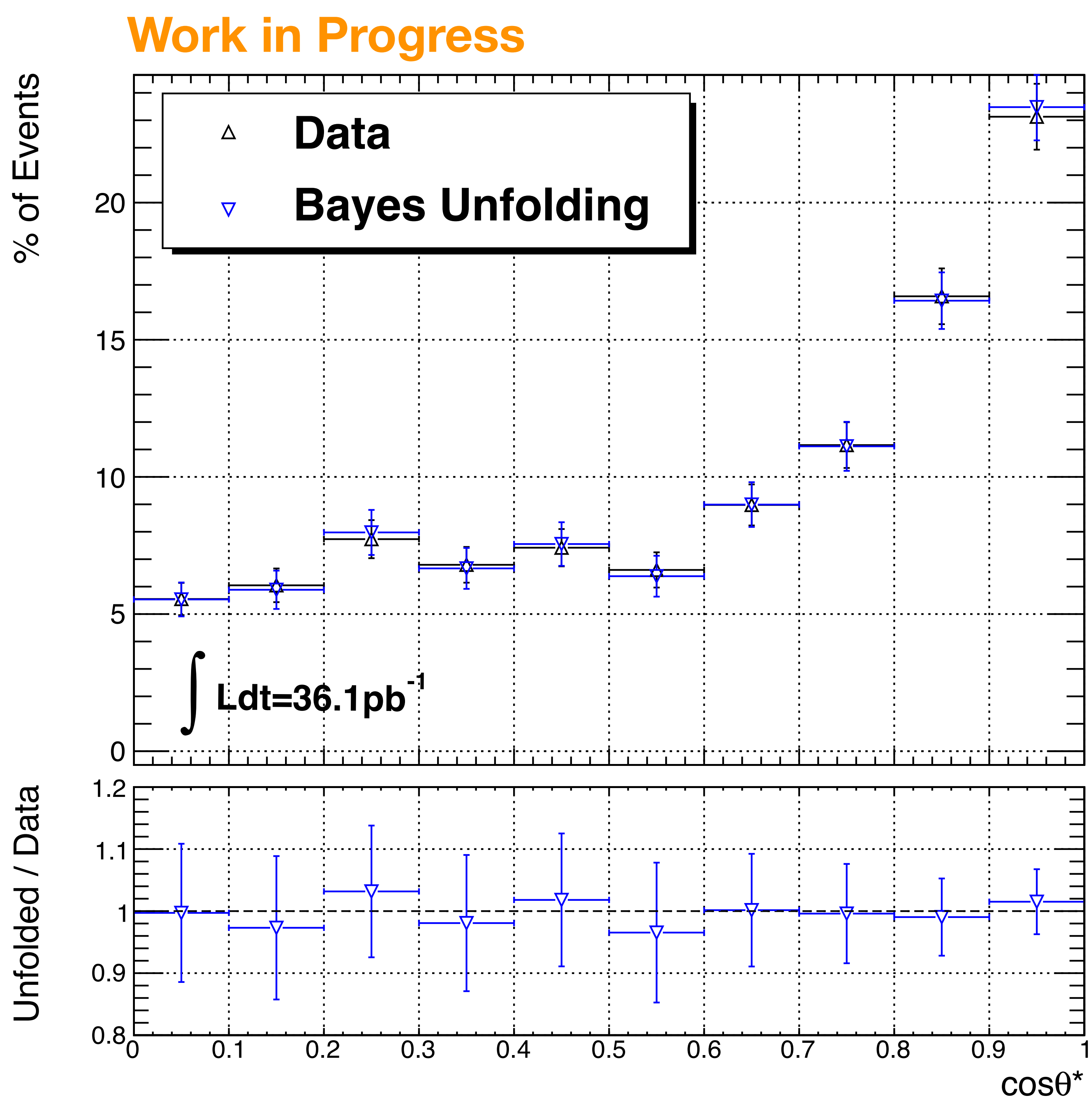
Distributions are almost identical

Jet Resolution - Reco / Gen

Work in Progress

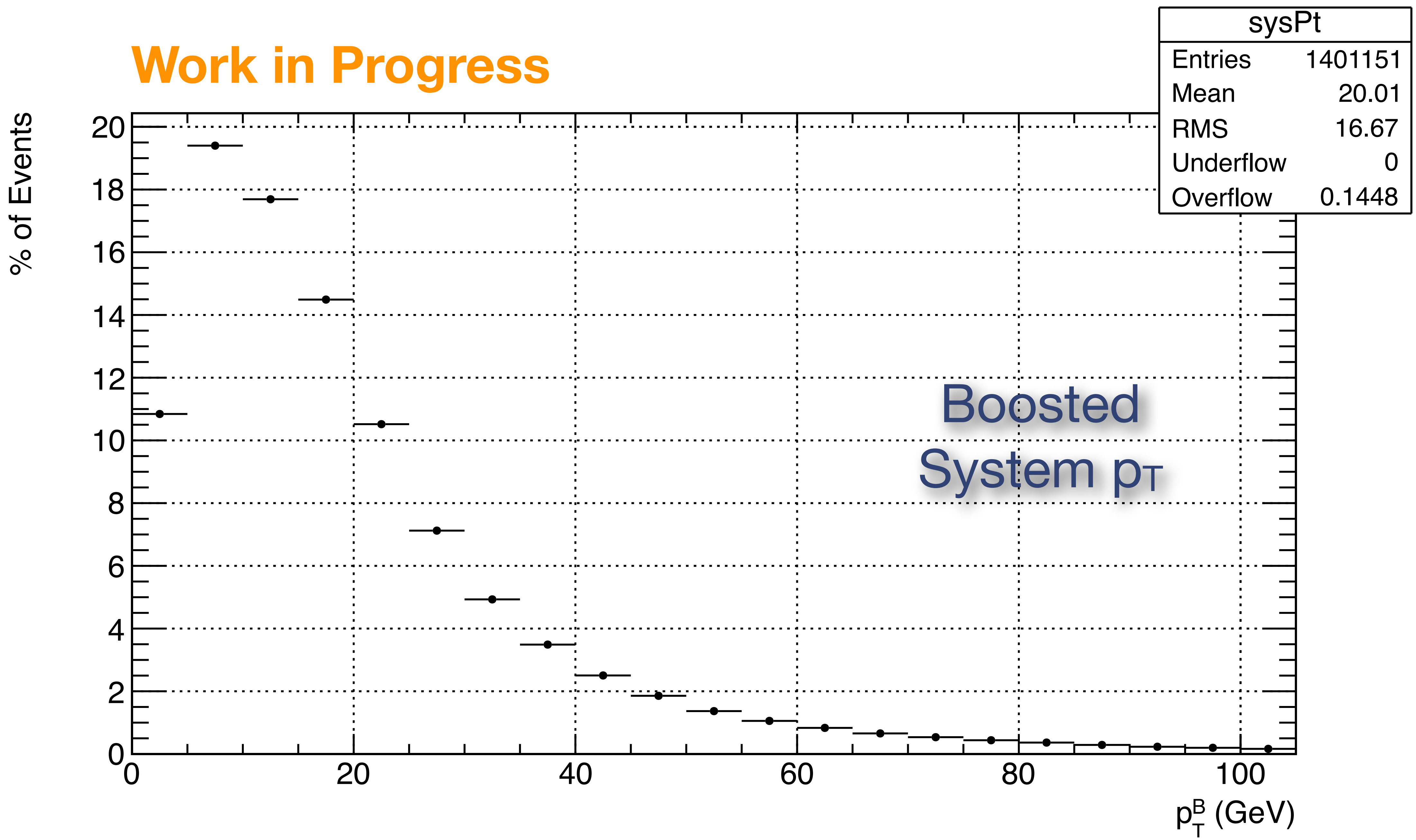


Jet Resolution Unfolding (Bayesian) [6]

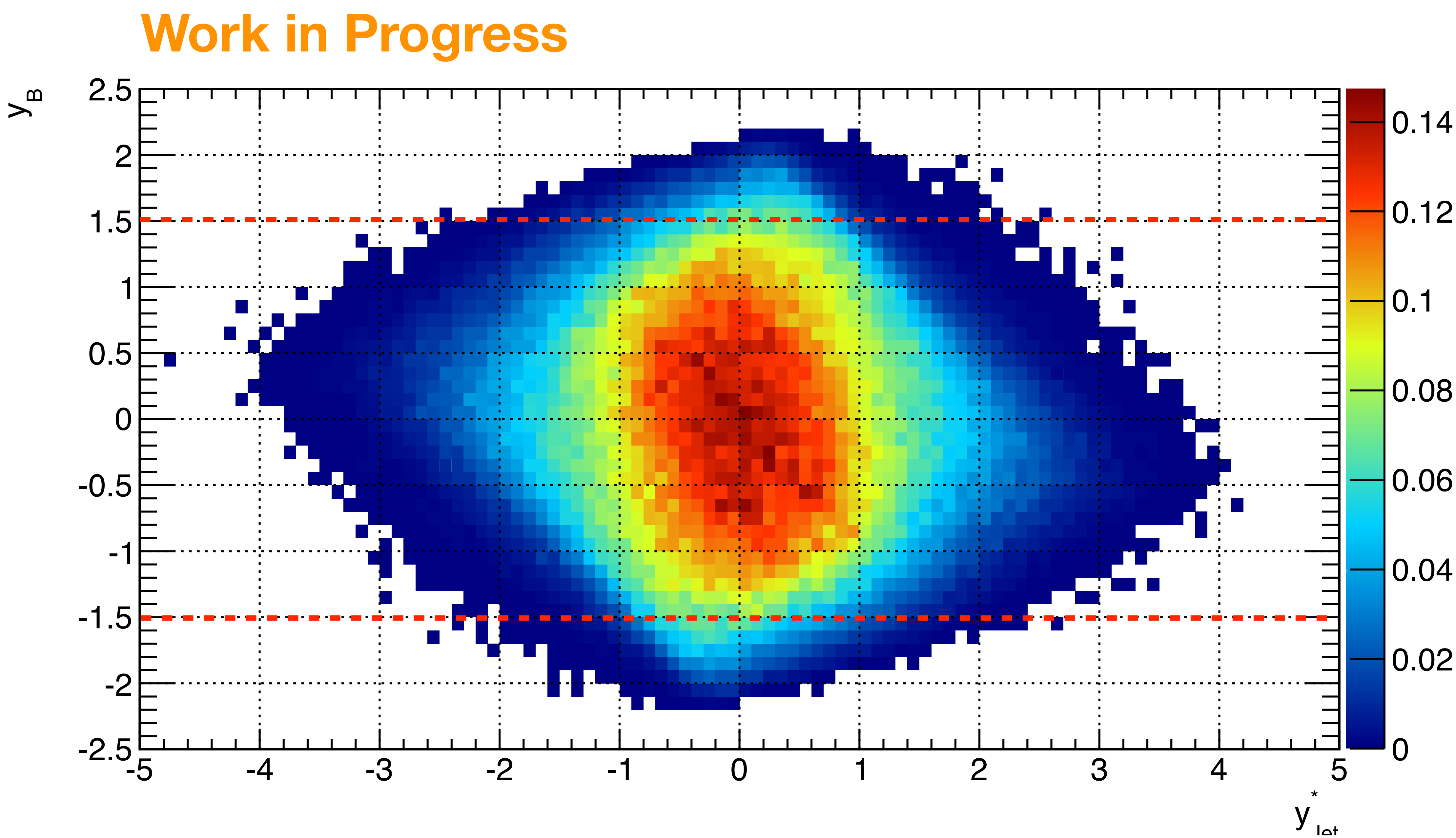


Using RooUnfold package [7]

Boosted System p_T



System vs CM Rapidity



Boosted System Rapidity

$$\frac{d^3\sigma}{dx_1 dx_2 d\hat{t}} \propto \frac{1}{S}\sum_{i,j}\frac{f_i(x_1)}{x_1}\frac{f_j(x_2)}{x_2}\frac{d\hat{\sigma}_{ij}}{d\cos\theta^*}$$

$$x_{i,j} = \frac{2p^*}{\sqrt{S}}e^{\pm y_B}$$

Work in Progress