



Generalized angularities and differential jet shapes measurements from STAR at $\sqrt{s} = 200$ GeV

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Outline

1 Introduction

2 Analysis

3 Results

4 Conclusions



Generalized angularities

$\lambda_\beta^1 \rightarrow$ Infra-red and collinear (IRC) safe angularities

$$\lambda_\beta^\kappa = \sum_{\text{const} \in \text{jet}} \overbrace{\left(\frac{p_{T,\text{const}}}{p_{T,\text{jet}}} \right)^\kappa}^{\text{soft/hard radiation}} \times \overbrace{r(\text{const}, \text{jet})^\beta}^{\text{collinearity sensitive}}$$

$$r(\text{const}, \text{jet}) = \sqrt{(\eta_{\text{jet}} - \eta_{\text{const}})^2 + (\phi_{\text{jet}} - \phi_{\text{const}})^2}$$



Generalized angularities

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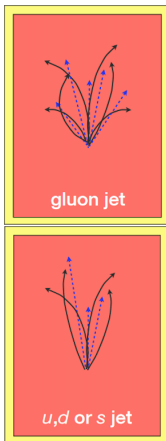
$$r(\text{const, jet}) = \sqrt{(\eta_{\text{jet}} - \eta_{\text{const}})^2 + (\phi_{\text{jet}} - \phi_{\text{const}})^2}$$

$$\langle \text{Radiation} \rangle_{\text{gluon jets}} > \langle \text{Radiation} \rangle_{\text{quark jets}}$$

$$\Rightarrow \langle \lambda_{\beta > 0}^1 \rangle_{\text{gluon jets}} > \langle \lambda_{\beta > 0}^1 \rangle_{\text{quark jets}}$$

$$\Rightarrow \text{quark-gluon discrimination}$$

$\lambda_{\beta}^1 \rightarrow$ Infra-red and collinear (IRC) safe angularities





Generalized angularities

$$\lambda_{\beta}^{\kappa} = \sum_{\text{const} \in \text{jet}} \overbrace{\left(\frac{p_{T,\text{const}}}{p_{T,\text{jet}}} \right)^{\kappa}}^{\text{soft/hard radiation}} \times \overbrace{r(\text{const}, \text{jet})^{\beta}}^{\text{collinearity sensitive}}$$

$$r(\text{const}, \text{jet}) = \sqrt{(\eta_{\text{jet}} - \eta_{\text{const}})^2 + (\phi_{\text{jet}} - \phi_{\text{const}})^2}$$

$\langle \text{Radiation} \rangle_{\text{gluon jets}} > \langle \text{Radiation} \rangle_{\text{quark jets}}$

$\Rightarrow \langle \lambda_{\beta > 0}^1 \rangle_{\text{gluon jets}} > \langle \lambda_{\beta > 0}^1 \rangle_{\text{quark jets}}$

\Rightarrow quark-gluon discrimination

- **Jet girth/broadening:**

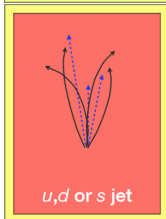
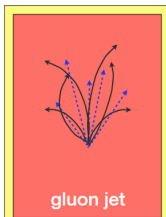
$$g = \lambda_1^1 = \sum_{\text{const} \in \text{jet}} \left(\frac{p_{T,\text{const}} r(\text{const}, \text{jet})}{p_{T,\text{jet}}} \right)$$

- **Momentum dispersion :**

$$p_T^D = \sqrt{\lambda_0^2} = \frac{\sqrt{\sum_{\text{const} \in \text{jet}} p_{T,\text{const}}^2}}{p_{T,\text{jet}}} \text{ soft/hard}$$

fragmentation \Rightarrow low/high p_T^D

$\lambda_{\beta}^1 \rightarrow$ Infra-red and collinear (IRC) safe angularities



Observables

- **Differential jet shapes** : Differential look into jet-broadening

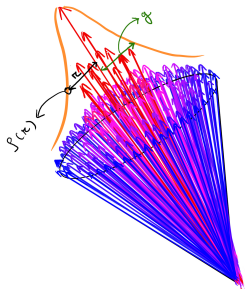
$$\rho(r) = \lim_{\delta r \rightarrow 0} \left\langle \frac{1}{\delta r} \frac{\sum_{|r_{\text{const}} - r| < \delta r/2} p_{T,\text{const}}}{p_{T,\text{jet}}} \right\rangle_{\text{jets}}$$

where,

$$r_{\text{const}} = (\eta_{\text{const}} - \eta_{\text{jet}}) \hat{\eta} + (\phi_{\text{const}} - \phi_{\text{jet}}) \hat{\phi}$$

- $\lambda_{\beta}^1 = \int_0^R r^{\beta} \rho(r) dr$, R = Resolution parameter of the jet

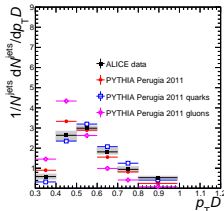
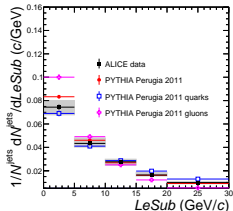
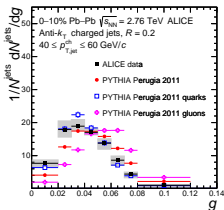
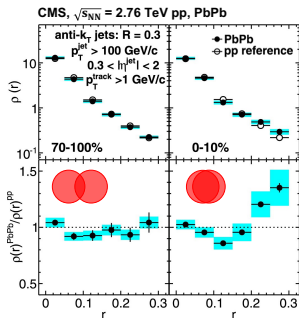
- $\text{LeSub} = p_{T,\text{const}}^{\text{Leading}} - p_{T,\text{const}}^{\text{Subleading}}$, proxy for hardest splitting in jet





Previous measurements from Pb+Pb collisions

- CMS, Phys. Lett. B 730 (2014) 243: $\rho(r)$ modification \implies charged energy move toward jet peripheries
- ALICE, JHEP 10 (2018) 139: jets undergo more quark like fragmentation in medium





Motivation

- **Lower energies at RHIC** → opportunity to further study medium effects using jets from phase space region **complimentary to LHC**



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- Results presented here **establish p+p baseline** at $\sqrt{s} = 200$ GeV for **upcoming Au+Au measurements** at $\sqrt{s_{NN}} = 200$ GeV from STAR

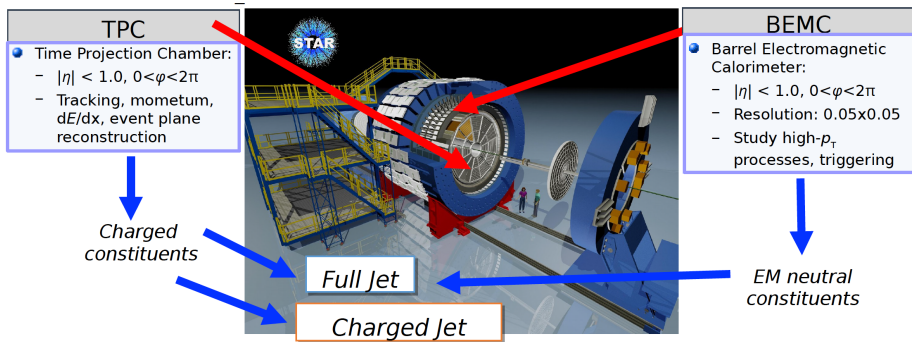


Motivation

- **Lower energies at RHIC** → opportunity to further study medium effects using jets from phase space region **complimentary to LHC**
- Results presented here **establish p+p baseline** at $\sqrt{s} = 200$ GeV for **upcoming Au+Au measurements** at $\sqrt{s_{NN}} = 200$ GeV from STAR
- Inclusive jet measurements in vacuum sensitive to soft radiation and fragmentation serve as tools to **tune and constrain Monte Carlo** event generators (e.g. PYTHIA)



Solenoidal Tracker At RHIC (STAR)



- The **Time Projection Chamber (TPC)** used to detect charged tracks
- The **Barrel Electromagnetic Calorimeter (BEMC)** measures energy deposited by electromagnetic constituents, after full hadronic correction



Outline

1 Introduction

2 Analysis

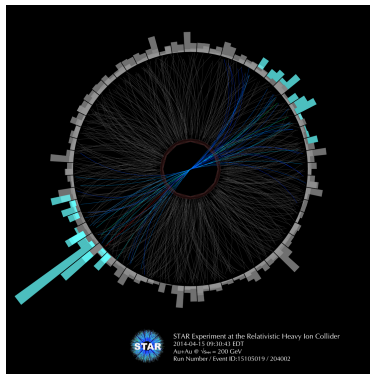
3 Results

4 Conclusions



Dataset and Simulations

- **System:** p+p @ $\sqrt{s} = 200\text{GeV}$ (2012)
- **High Tower (HT) triggered events** (\exists tower with $E_{\text{tower}} > 4.2\text{ GeV}$) to enhance jet signal
- **Embedding simulation:**
 - **GEN:** PYTHIA-6 Perugia¹dijet events
 - **RECO:** PYTHIA-6 Perugia + GEANT3 + STAR p+p Run12 Zerobias
- **PYTHIA-8 simulation:** Detroit/RHIC underlying-event tune ²



From now on,
PYTHIA-6 \equiv PYTHIA-6 Perugia tune
PYTHIA-8 \equiv PYTHIA-8 Detroit tune

¹Phys. Rev. D 82, 074018 (2010)

²Phys. Rev. D 105, 016011 (2022)



Jet Reconstruction

- Jets reconstructed by clustering **TPC tracks** and **calorimeter energy depositions** using the **anti- k_T algorithm** with a **resolution parameter** $R = 0.4$ and using the FASTJET library ³
- **Hard-core constituent cut** of 2 GeV was applied on tracks and tower depositions for jet reconstruction i.e., $p_{T,\text{trk}}(E_{T,\text{tower}}/c) \geq 2 \text{ GeV}/c$, a $p_{T,\text{particle}} \geq 2 \text{ GeV}/c$ is applied on GEN level
- Jet area > 0.3 for p_T^D , LeSub and Girth to suppress fake jets
- For $\rho(r)$ calculation, used tracks with $r(\text{trk}, \text{jet}) = \sqrt{(\eta_{\text{jet}} - \eta_{\text{trk}})^2 + (\phi_{\text{jet}} - \phi_{\text{trk}})^2} < 0.4$ and $p_{T,\text{trk}} > 1 \text{ GeV}/c$

³M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 06



Analysis

- Deconvoluting detector effects by mapping RECO \rightarrow GEN using embedding simulation
- p_T^D , LeSub and Girth - 2D Iterative bayesian unfolding of $p_{T,jet}$ and $\mathcal{O}(= p_T^D, LeSub, g)$ (used RooUnfold package⁴)
- For $\rho(r)$, bin-by-bin corrections done by calculating $\epsilon(r) = \frac{\rho^{GEN}(r)}{\rho^{RECO}(r)}$
- Both deconvolution tactics **passes closure tests**
- Apply deconvolution trained on full embedding to data
- Calculated **systematic uncertainties**

More details on all of these in backup...

⁴arXiv:1910.14654



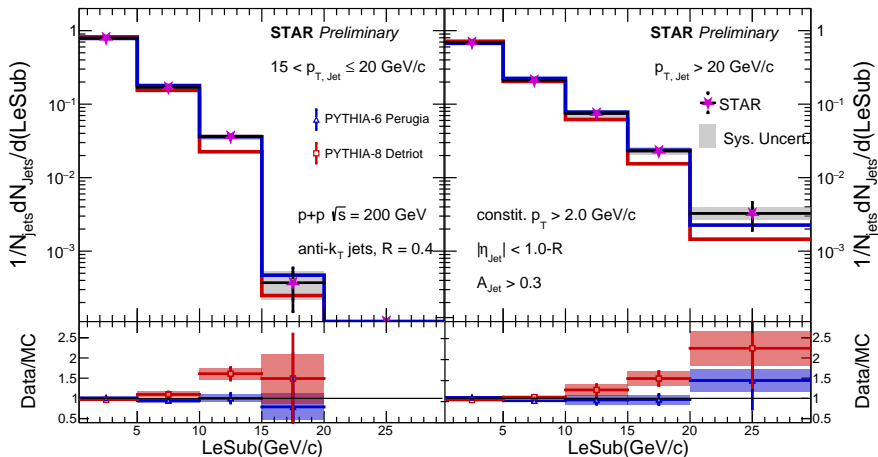
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LeSub

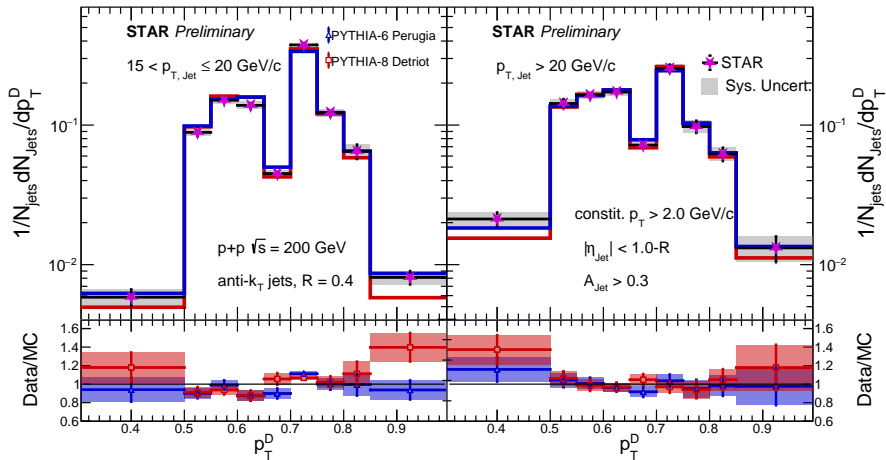
$$\text{LeSub} = p_{T,\text{trk}}^{\text{Lead}} - p_{T,\text{trk}}^{\text{Sublead}}$$



Overall shows preference toward PYTHIA-6, PYTHIA-8 underestimates on average


 p_T^D

$$p_T^D = \frac{\sqrt{\sum_{\text{trk} \in \text{jet}} (p_{T,\text{trk}})^2}}{\sum_{\text{trk} \in \text{jet}} p_{T,\text{trk}}}$$

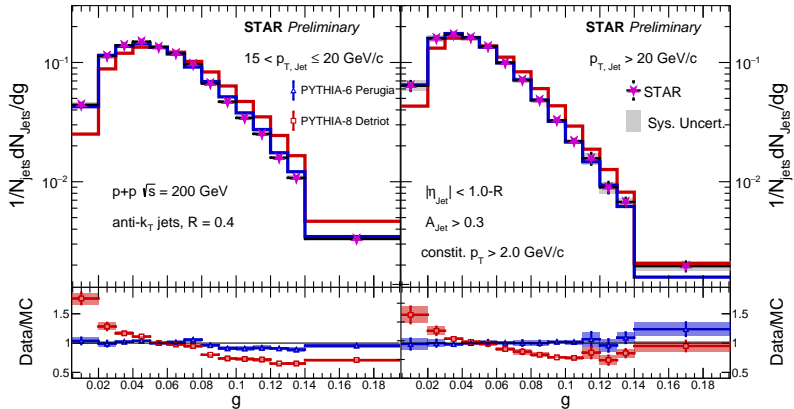


Subtle preference toward PYTHIA-6, PYTHIA-8 underestimates highest and lowest p_T^D 's



Girth

$$g = \frac{\sum_{\text{trk} \in \text{jet}} p_{T,\text{trk}} \Delta R}{p_{T,\text{jet}}}$$

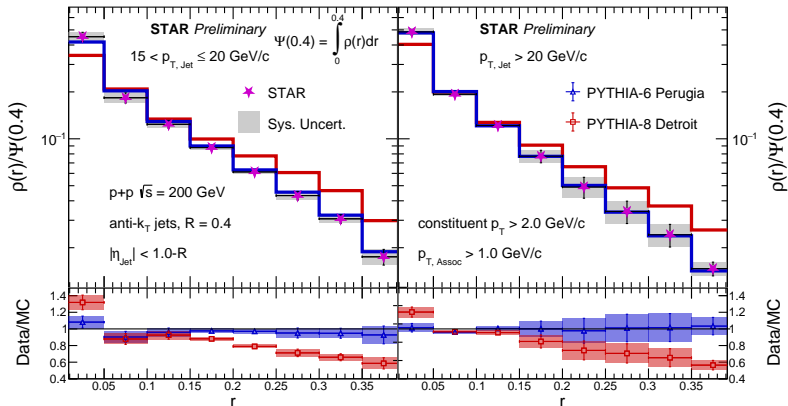


- Girth agrees well with PYTHIA-6, PYTHIA-8 Detroit tune systematically overestimates higher girths
- PYTHIA-8 expects more soft fragmented, broader jets



Differential Jet Shapes ($\rho(r)$)

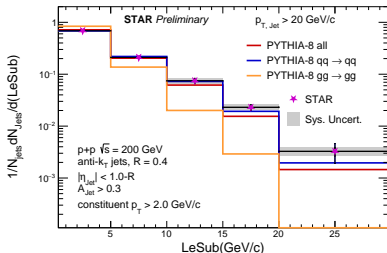
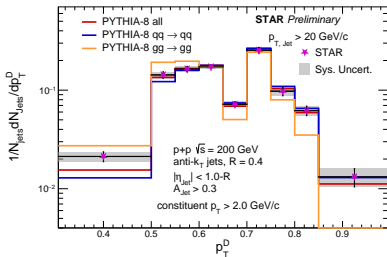
$$\rho(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{1}{\delta r} \frac{\sum_{|r_{\text{assoc}} - r| < \delta r/2} P_{\text{T,assoc}}}{P_{\text{T,jet}}}$$



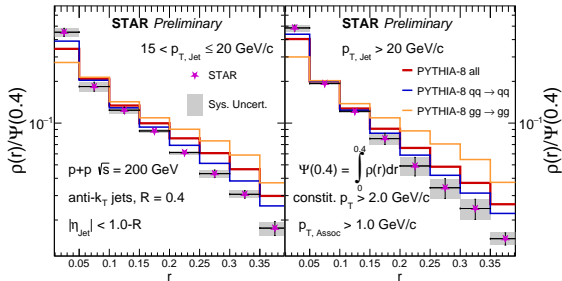
PYHTIA-6 describes data well, PYTHIA-8 overestimates broader (gluon-like?) jets than data



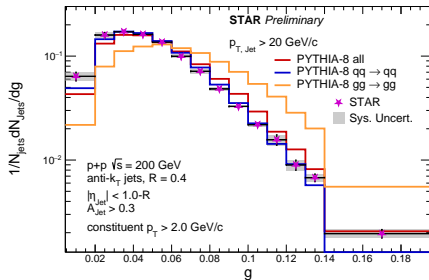
Quark jets vs Gluon Jets from PYTHIA-8



- Quark jets (QJs) from $qq \rightarrow qq$ processes, Gluon jets (GJs) from $gg \rightarrow gg$ processes in PYTHIA-8 HardQCD mode
- $\langle p_T^D \rangle_{QJs} > \langle p_T^D \rangle_{GJs}$,
 $\langle \text{LeSub} \rangle_{QJs} > \langle \text{LeSub} \rangle_{GJs}$,
 $\langle g \rangle_{QJs} < \langle g \rangle_{GJs}$ (next-slide)
- GJs broader, softer than QJs
- QJs closer to data than GJs and nominal PYTHIA-8 Detroit tune for all measured observables



PYTHIA-8
overestimates gluon-like
fragmentations and
underestimates hard
fragmentation of quarks



- Need comparisons for more substructures
- PYTHIA-8 Detroit tune needs more tuning to better explain ungroomed jet substructure



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Conclusions and Outlook

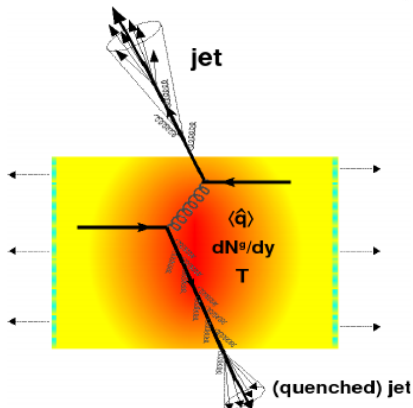
- First measurements of p_T^D , LeSub, Girth and $\rho(r)$ for $R = 0.4$ jets with constituents above 2 GeV from STAR in p+p collisions at $\sqrt{s} = 200$ GeV
 - p+p measurements to be used as baseline to gauge medium-induced jet-modifications in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- Comparisons drawn with Monte-Carlo event generators, PYTHIA-6 Perugia tune and PYTHIA-8 Detroit tune
 - PYTHIA-6 Perugia tune systemically explains the data within uncertainties
 - PYTHIA-8 Detroit tune overestimates broader, softer, more gluon-like jets compared to measurements
- Demonstrated need for further tuning of PYTHIA-8 Detroit tune to better explain ungroomed jet substructure
 - Calculations from quark initiated jets only from PYTHIA-8 closer to measurements than nominal PYTHIA-8

BACK UP...



Jets as probes for QGP

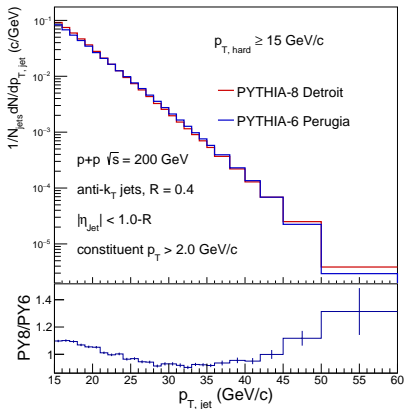
- Jets = collimated sprays of particles from hard scatterings of partons
 - Formed at early stages of heavy ion collisions
 - Travel through Quark Gluon Plasma (QGP), and modified relative to vacuum



Jets as probes to study QGP \equiv Modification of observables related to energy distribution inside jets (relative to vacuum)

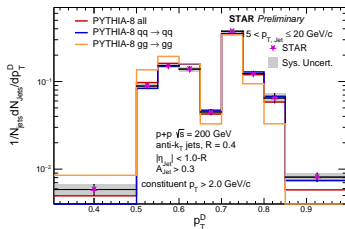
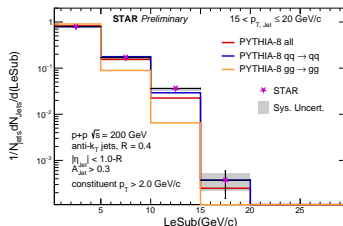
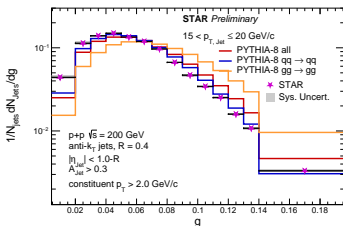


$p_{T,jet}$ PYTHIA-6 vs PYTHIA-8



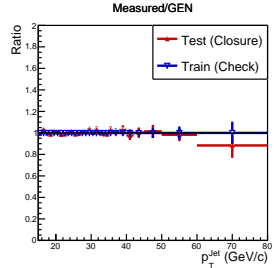
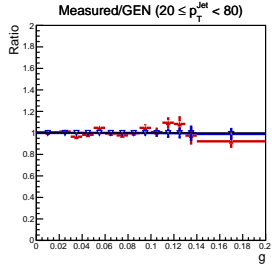
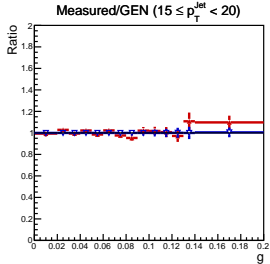
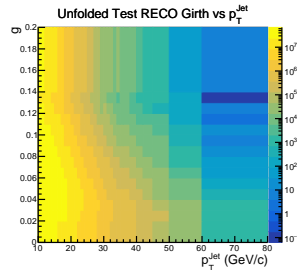
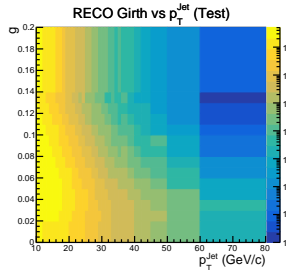
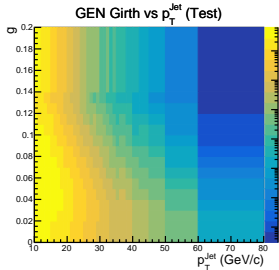
$p_{T,jet}$ varies 5-20% between the two generations

Quark vs Gluon, lower momentum jets:



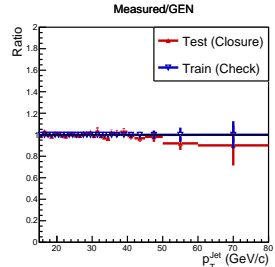
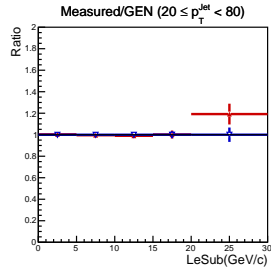
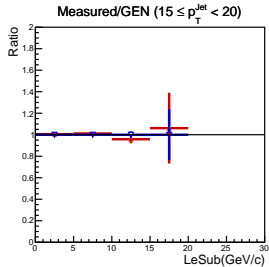
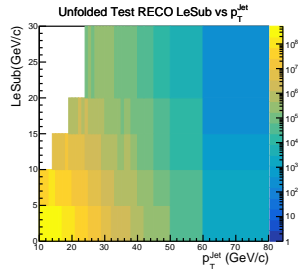
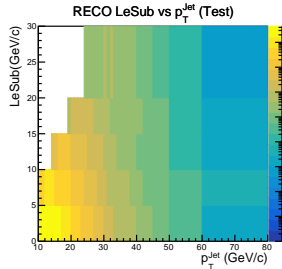
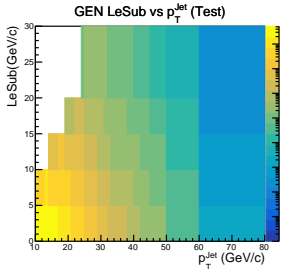


Closure tests - Girth



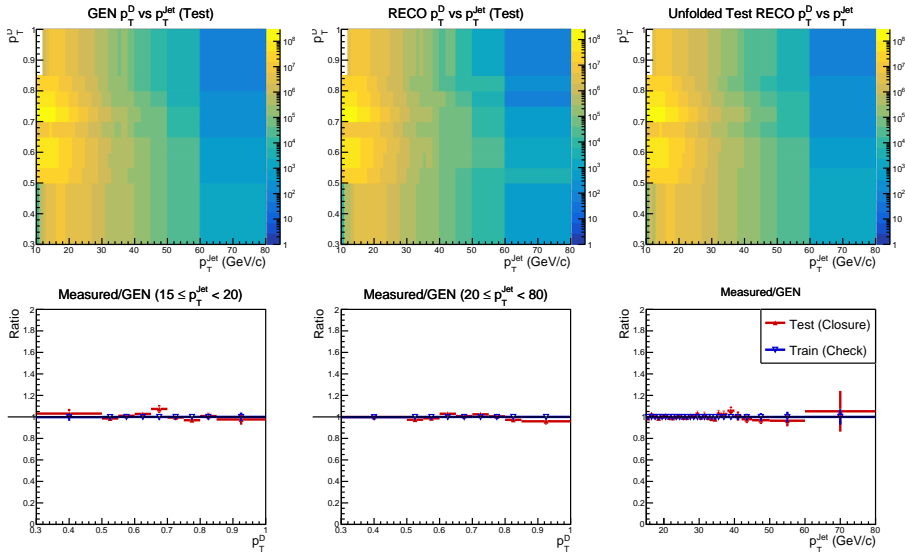


Closure test - LeSub

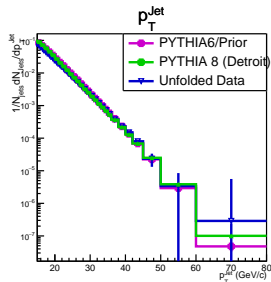
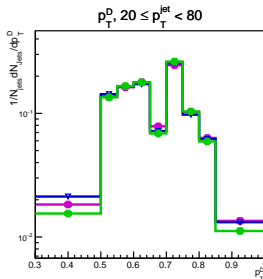
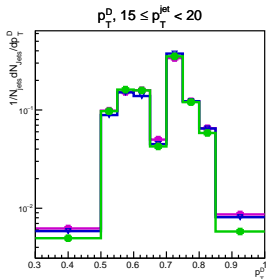
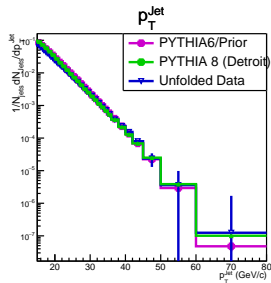
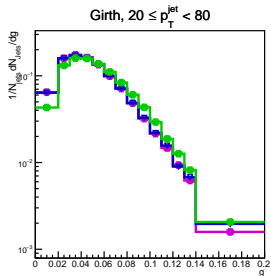
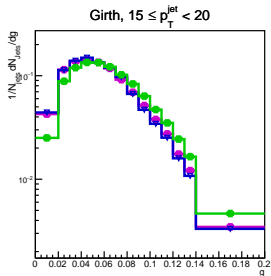




Closure test - PtD



Data Unfolding



Prior Reweighting

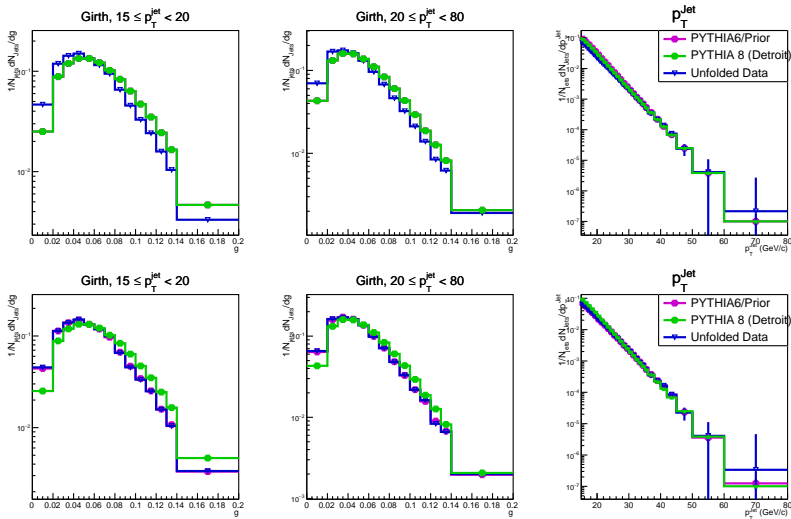


Figure: Upper: Prior reweighed to PYTHIA8; Lower: Prior reweighed to unfolded data



Systematics - p_T^D , LeSub, Girth

To ensure robustness of measurements, varied few details of the analysis within tolerance and added any small variations that arise as **systematic uncertainties**

- **Tracking efficiency:** Tracking efficiency correction applied on tracks before unfolding $\Delta(p_T^D) < 0.5\%$, $\Delta(\text{LeSub}) < 0.3\%$, $\Delta(g) < 2\%$
- **IBU regularization:** Variations with $N_{\text{iterations}} = 3$ and $N_{\text{iterations}} = 6$
 $\Delta(p_T^D) \leq 4\%$, $\Delta(\text{LeSub}) < 1\%$, $\Delta(g) \leq 1\%$
- **IBU prior variation:** Rescaled the nominal prior (PYTHIA6 Perugia) to PYTHIA8 Detroit and the unfolded data $5 < \Delta(p_T^D) < 14\%$,
 $1 < \Delta(\text{LeSub}) \leq 6\%$, $1 < \Delta(g) \leq 10\%$
- **Jet energy scale:** $p_{T,\text{jet}}$ windows shifted 1 GeV/c to the left and right, subtracted the deviation in MC samples from the variation $\Delta(p_T^D) \leq 1\%$,
 $\Delta(\text{LeSub}) \approx 0\%$, $\Delta(g) \leq 0.5\%$



Differential jet shapes ($\rho(r)$)

- To avoid issues from tower pileups, only used charged jet constituents (TPC tracks) to calculate $\rho(r)$, $r_{\text{trk}} = (\eta_{\text{trk}} - \eta_{\text{jet}})\hat{\eta} + (\phi_{\text{trk}} - \phi_{\text{jet}})\hat{\phi}$, $r = |r|$

- Thus,

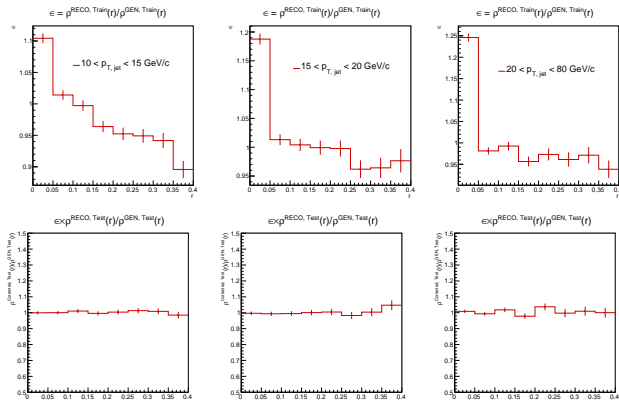
$$\rho(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{1}{\delta r} \frac{\sum_{|r_{\text{trk}}-r| < \delta r/2} p_{\text{T, trk}}}{p_{\text{T, jet}}}$$

- Analysis done in bins of $10 < p_{\text{T, jet}} \leq 15$ GeV/c, $15 < p_{\text{T, jet}} \leq 20$ GeV/c and $p_{\text{T, jet}} > 20$ GeV/c
- Embedding simulation used for deconvoluting detector effects using bin-by-bin correction factors
- 2 levels embedding simulation:
 - GEN**: PYTHA-6 dijet events
 - RECO**: PYTHA-6 + GEANT3 + STAR p+p Run12 Zerobias
 - Correction factors $\epsilon(r) = \frac{\rho_{\text{GEN}}(r)}{\rho_{\text{RECO}}(r)}$ applied to data after closure test
- All tracking inefficiency and acceptance corrections handled by the bin-by-bin corrections



Closure

Unfolding of data here done through Bin-by-Bin corrections, first we make sure the corrections pass a closure test and then apply it to data



Top plots are from the Training set by doing $\epsilon = (\text{Training GEN}) / (\text{Training RECO})$ and the bottom "closure" curves are $((\text{Test RECO}) / \epsilon) / (\text{Test GEN})$



$\rho(r)$ systematics

To ensure robustness of measurements, varied few details of the analysis within tolerance and added any small variations that arise as **systematic uncertainties**

- **Tracking efficiency:** Tracking efficiency correction applied on tracks before bin-by-bin correction $\Delta(\rho) \leq 0.3\%$
- **Non closure of bin/bin corrections:** Any non closure (deviations from 1 in the bottom plots of the slide before) $\Delta(\rho) \leq 2\%$
- **Jet energy scale:** $p_{T,jet}$ windows shifted 1 GeV/c to the left and right, subtracted the deviation in MC samples from the variation $\Delta(\rho) < 20\%$
- $p_{T,jet}$ **resolutions:** Shift $p_{T,jet}$ randomly using a gaussian with σ from $p_{T,jet}$ resolution ($\approx 20\%$) $\Delta(\rho) \leq 20\%$