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

Tanmay Pani

for the STAR Collaboration

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Outline

1. Introduction
2. Analysis
3. Results
4. Conclusions

Generalized angularities

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

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

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

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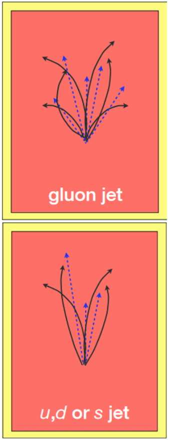
$\langle\text{Radiation}\rangle_{\text{gluon jets}} > \langle\text{Radiation}\rangle_{\text{quark jets}}$

$\implies \langle\lambda^1_{\beta>0}\rangle_{\text{gluon jets}} > \langle\lambda^1_{\beta>0}\rangle_{\text{quark jets}}$

$\implies$ quark-gluon discrimination

λ^1_β → Infra-red and collinear (IRC) safe angularities



Generalized angularities

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

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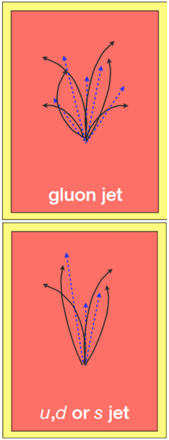
$\langle\text{Radiation}\rangle_{\text{gluon jets}} > \langle\text{Radiation}\rangle_{\text{quark jets}}$

$\Longrightarrow \langle\lambda^{1}_{\beta>0}\rangle_{\text{gluon jets}} > \langle\lambda^{1}_{\beta>0}\rangle_{\text{quark jets}}$

$\Longrightarrow$ quark-gluon discrimination

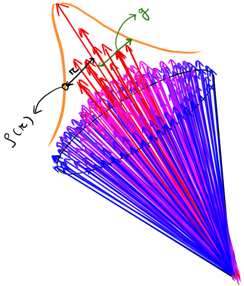
- **Jet girth/broadening:**
  $g = \lambda^{1}_{1} = \sum_{\mathrm{const}\in\mathrm{jet}} \left(\frac{p_{\mathrm{T,const}}\, r(\mathrm{const},\mathrm{jet})}{p_{\mathrm{T,jet}}}\right)$
- **Momentum dispersion :**
  $\mathrm{p}^{\mathrm{D}}_{\mathrm{T}} = \sqrt{\lambda^{2}_{0}} = \frac{\sqrt{\sum_{\mathrm{const}\in\mathrm{jet}} p^{2}_{\mathrm{T,const}}}}{p_{\mathrm{T,jet}}}$ soft/hard fragmentation $\Longrightarrow$ low/high p^{D}_{T}



Observables

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

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



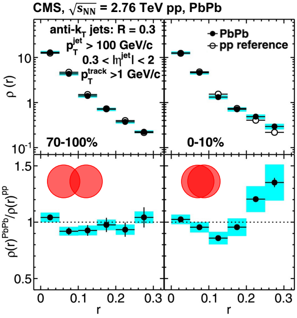
where,

$\mathrm{r}_{\mathrm{const}} = (\eta_{\mathrm{const}} - \eta_{\mathrm{jet}})\hat{\eta} + (\phi_{\mathrm{const}} - \phi_{\mathrm{jet}})\hat{\phi}$

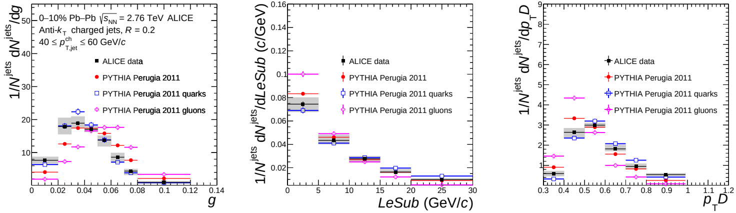
  - $\lambda^1_\beta = \int_0^R r^\beta \rho(r) dr$, R = Resolution parameter of the jet

- LeSub $= p_{\mathrm{T,const}}^{\mathrm{Leading}} - p_{\mathrm{T,const}}^{\mathrm{Subleading}}$, 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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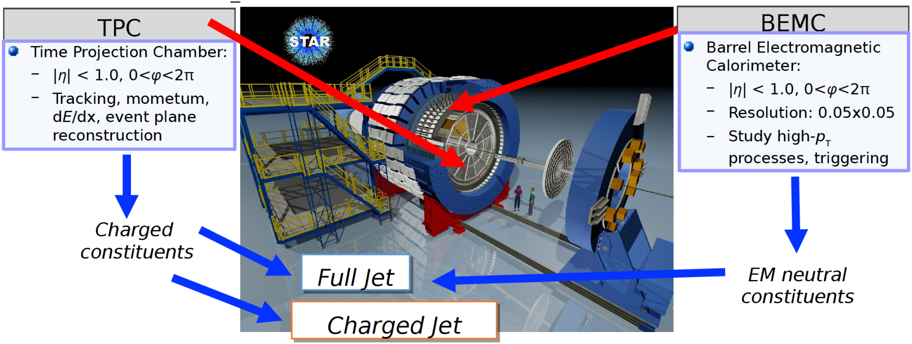
Motivation

- **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)



TPC

- Time Projection Chamber:
  - $|\eta| < 1.0$, $0<\varphi<2\pi$
  - Tracking, mometum, dE/dx, event plane reconstruction

Charged constituents

BEMC

- Barrel Electromagnetic Calorimeter:
  - $|\eta| < 1.0$, $0<\varphi<2\pi$
  - Resolution: 0.05x0.05
  - Study high-p_T processes, triggering

EM neutral constituents

Full Jet

Charged Jet

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

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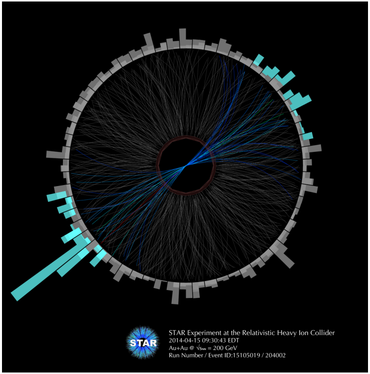
Dataset and Simulations

- **System:** p+p @ $\sqrt{s} = 200$GeV (2012)
- **High Tower (HT) triggered** events ($\exists$ tower with $E_{\text{tower}} > 4.2$ GeV) to enhance jet signal
- **Embedding simulation:**
    - GEN: PYTHIA-6 Perugia[1]dijet 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 ≡ PYTHIA-6 Perugia tune
PYTHIA-8 ≡ PYTHIA-8 Detroit tune

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[1] Phys. Rev. D 82, 074018 (2010)

[2] Phys. 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., $p_{\mathrm{T,trk}}(E_{\mathrm{T,tower}}/c) \geq 2$ GeV/c, a $p_{\mathrm{T,particle}} \geq 2$ 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 $r(\mathrm{trk}, \mathrm{jet}) = \sqrt{(\eta_{\mathrm{jet}} - \eta_{\mathrm{trk}})^2 + (\phi_{\mathrm{jet}} - \phi_{\mathrm{trk}})^2} < 0.4$ and $p_{\mathrm{T,trk}} > 1$ GeV/c

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

Analysis

- Deconvoluting detector effects by mapping RECO → GEN using embedding simulation
- p_T^D, LeSub and Girth - 2D Iterative bayesian unfolding of $p_{\mathrm{T,jet}}$ and $\mathcal{O}(= p_T^D, LeSub, \mathrm{g})$ (used RooUnfold package[4])
- For $\rho(r)$, bin-by-bin corrections done by calculating $\epsilon(r) = \frac{\rho^{\mathrm{GEN}}(r)}{\rho^{\mathrm{RECO}}(r)}$
- 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...

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[4] arXiv:1910.14654

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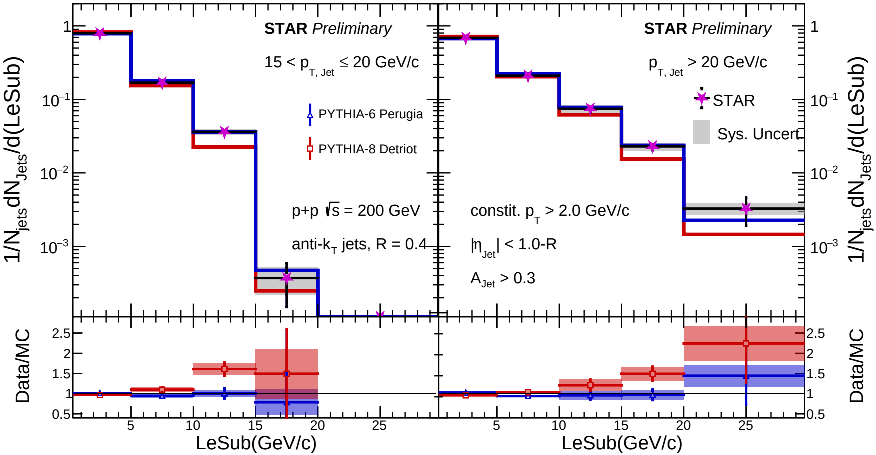
LeSub

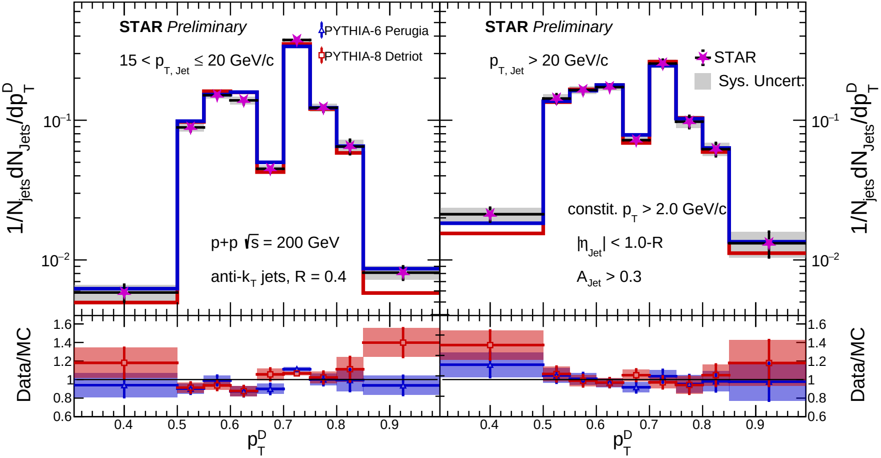
$$\text{LeSub} = p_{\mathrm{T,trk}}^{\mathrm{Lead}} - p_{\mathrm{T,trk}}^{\mathrm{Sublead}}$$



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

p_T^D

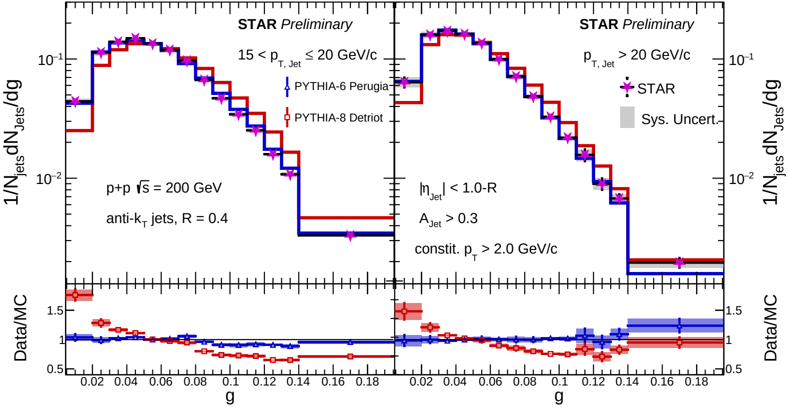
$$p_T^D = \frac{\sqrt{\sum_{\mathrm{trk}\in\mathrm{jet}} \left(p_{\mathrm{T,trk}}\right)^2}}{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}}}$$



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

Girth

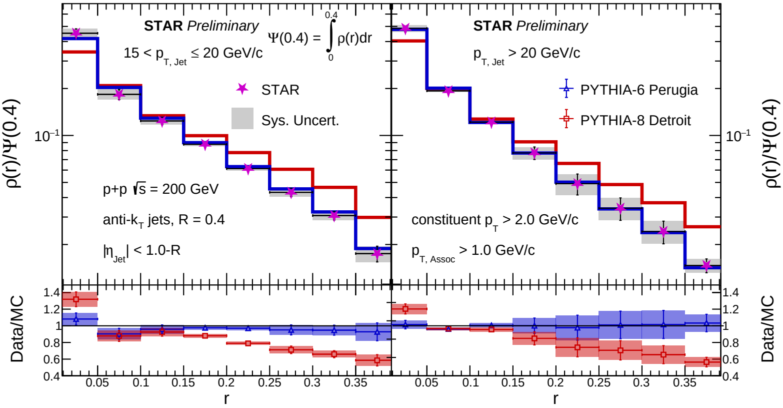
$$g = \frac{\sum_{\text{trk}\in\text{jet}} p_{\text{T,trk}} \Delta R}{p_{\text{T,jet}}}$$



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

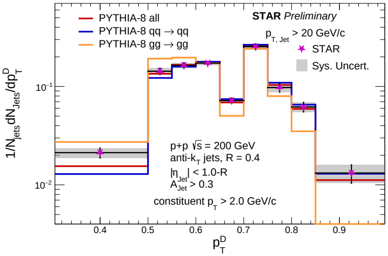
Differential Jet Shapes ($\rho(r)$)

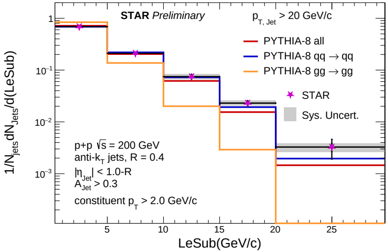
$$\rho(r) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{1}{\delta r} \frac{\sum_{|r_{\rm assoc} - r| < \delta r/2} p_{\rm T,assoc}}{p_{\rm T,jet}}$$



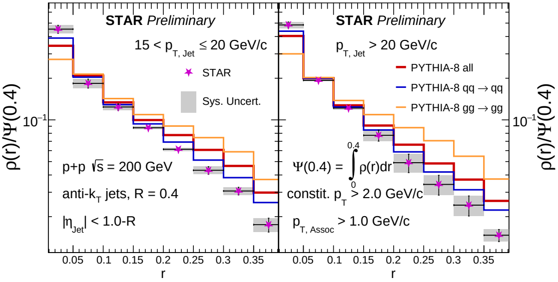
PYHTIA-6 describes data well, PYTHIA-8 overestimates broader (gluon-like?) jets than data

Quark jets vs Gluon Jets from PYTHIA-8

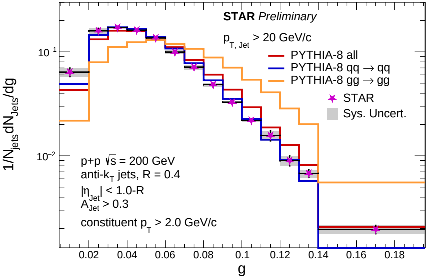




- Quark jets (QJs) from $qq \to qq$ processes, Gluon jets (GJs) from $gg \to gg$ processes in PYTHIA-8 HardQCD mode
- $\langle p_T^D \rangle_{QJs} > \langle p_T^D \rangle_{GJs}$, $\langle LeSub \rangle_{QJs} > \langle LeSub \rangle_{GJs}$, $\langle g \rangle_{QJs} < \langle g \rangle_{GJs}$ (next-slide)
- 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 comparisions for more substructures
- PYTHIA-8 Detroit tune needs more tuning to better explain ungroomed jet substructure

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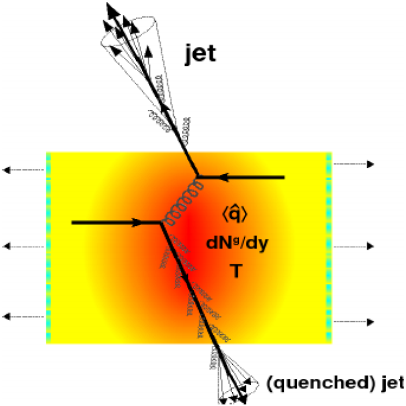
Conclusions and Outlook

- 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 $\sqrt{s_{\mathrm{NN}}} = 200$ GeV
- Comparisions 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...

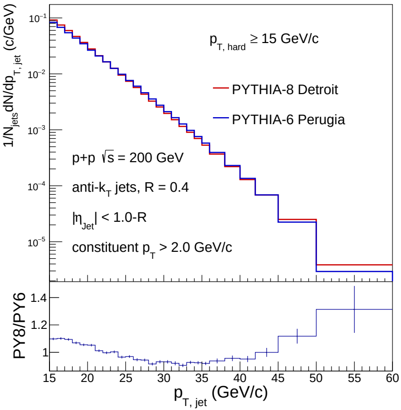
Jets as probes for QGP

- 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 vaccum



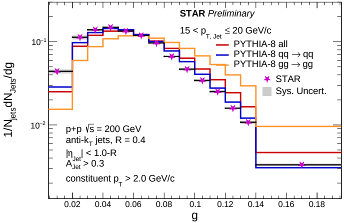
Jets as probes to study QGP ≡ Modification of observables related to energy distribution inside jets (relative to vaccum)

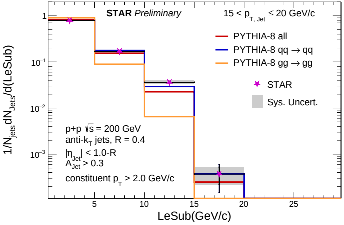
$p_{\mathrm{T,jet}}$ PYTHIA-6 vs PYTHIA-8

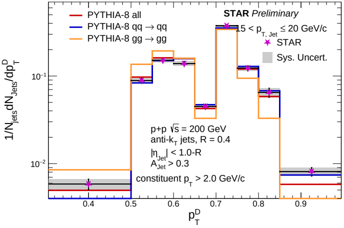


$p_{\mathrm{T,jet}}$ varies 5-20% between the two generations

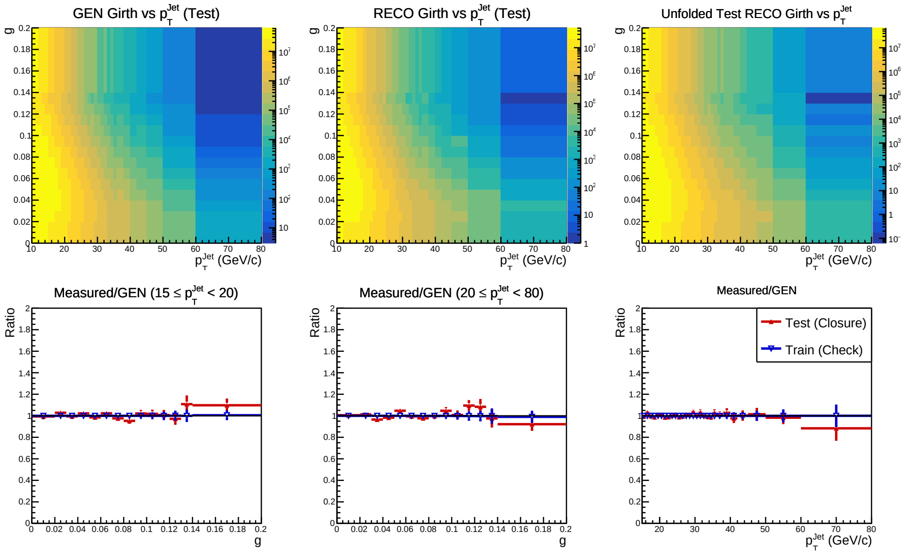
Quark vs Gluon, lower momentum jets:



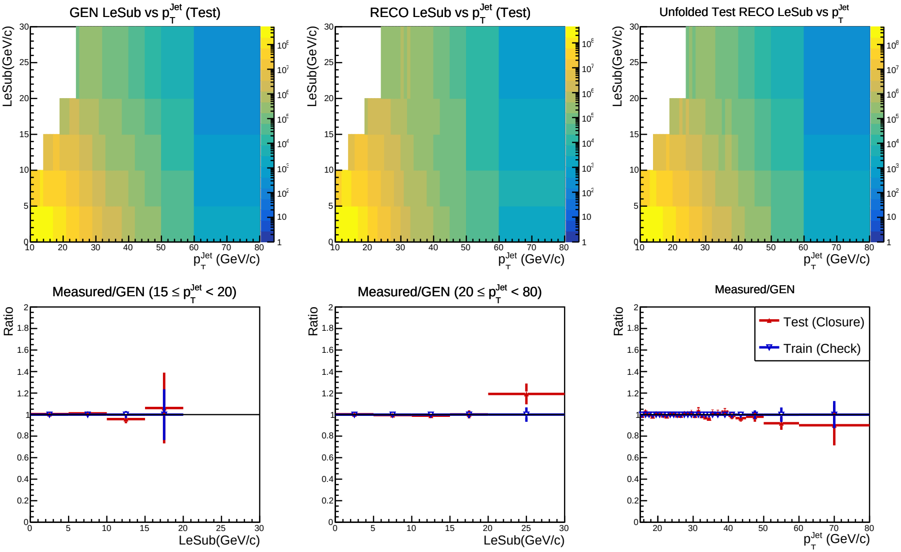




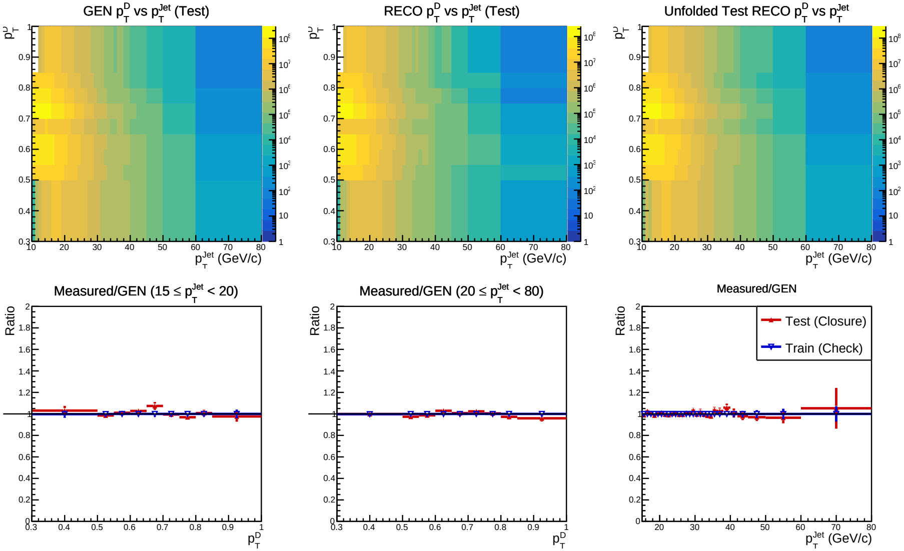
Closure tests - Girth



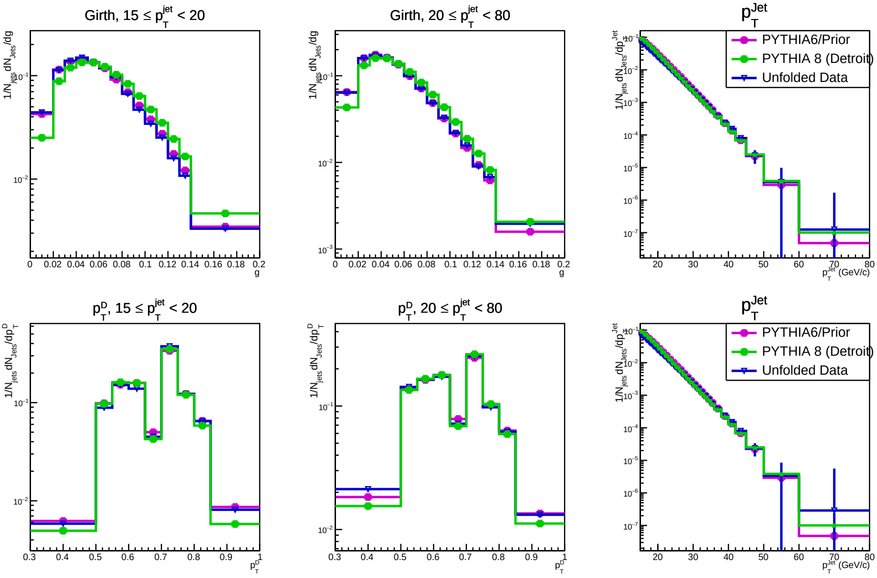
Closure test - LeSub



Closure test - PtD



Data Unfolding



Prior Reweighing

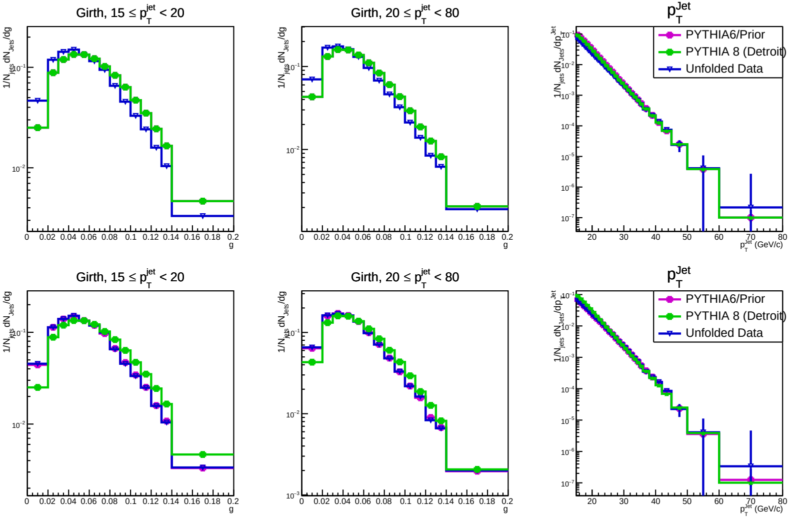


Figure: *Upper: Prior reweighed to PYTHIA8; Lower: Prior reweighred to unfolded data*

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

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

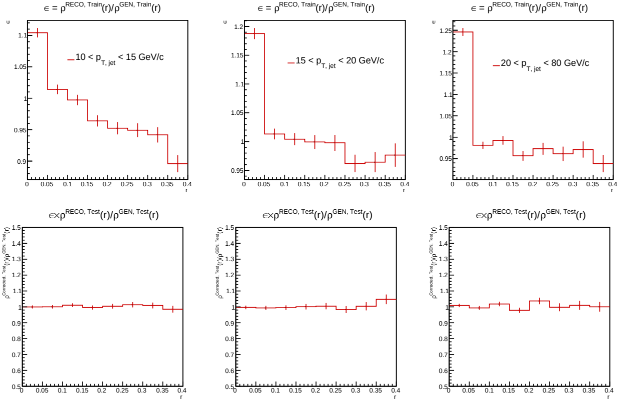
- To avoid issues from tower pileups, only used charged jet constituents (TPC tracks) to calculate $\rho(r)$, $\mathrm{r}_{\mathrm{trk}} = (\eta_{\mathrm{trk}} - \eta_{\mathrm{jet}})\hat{\eta} + (\phi_{\mathrm{trk}} - \phi_{\mathrm{jet}})\hat{\phi}$, $r = |\mathrm{r}|$
- Thus,

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

- Analysis done in bins of $10 < p_{\mathrm{T,jet}} \leq 15$ GeV/c, $15 < p_{\mathrm{T,jet}} \leq 20$ GeV/c and $p_{\mathrm{T,jet}} > 20$ 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 $\epsilon(r) = \frac{\rho_{\mathrm{GEN}}(r)}{\rho_{\mathrm{RECO}}(r)}$ 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 $\epsilon =$(Training GEN)/(Training RECO) and the bottom ”closure” curves are ((Test RECO)/ϵ)/(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:** $p_{\mathrm{T,jet}}$ 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 ($\approx 20\%$) $\Delta(\rho) \leq 20\%$