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

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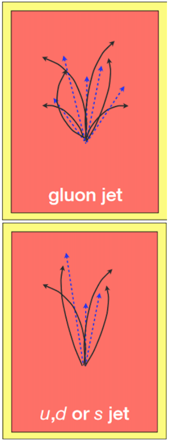
Generalized angularities

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

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

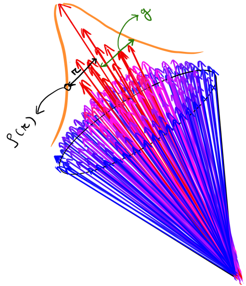
- **Jet girth/broadening:** $\mathbf{g} = \lambda^1_1 = \sum_{\text{const}\in\text{jet}} \left(\frac{p_{\mathrm{T,const}}\, r(\text{const},\text{jet})}{p_{\mathrm{T,jet}}}\right)$
- **Momentum dispersion :** $\mathbf{p_T^D} = \sqrt{\lambda^2_0} = \frac{\sqrt{\sum_{\text{const}\in\text{jet}} p^2_{\mathrm{T,const}}}}{p_{\mathrm{T,jet}}}$ soft/hard fragmentation $\implies$ low/high p_T^D
- **LeSub** $= p^{\text{Leading}}_{\mathrm{T,const}} - p^{\text{Subleading}}_{\mathrm{T,const}}$, proxy for hardest splitting in jet



Observables

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

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



where,

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

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

Dataset and Simulations

- **System:** Au+Au @ $\sqrt{s} = 200\text{GeV}$
- **Production:** Mid-luminosity, 2014
- **High Tower (VPDMB30*BHT2) triggered** events ($\exists$ tower with $E_{\text{tower}} > 5.4$ GeV) to enhance jet signal
- $|Z_{\text{vertex,event}}| < 30$ cm
- A partial set of ≈10 million mid-lumi events used for this update
- **Embedding simulation available:**
  - GEN: PYTHIA-6 Perugia[1] dijet events
  - RECO: PYTHIA-6 Perugia + GEANT3 + STAR Au+Au Run14 Minbias

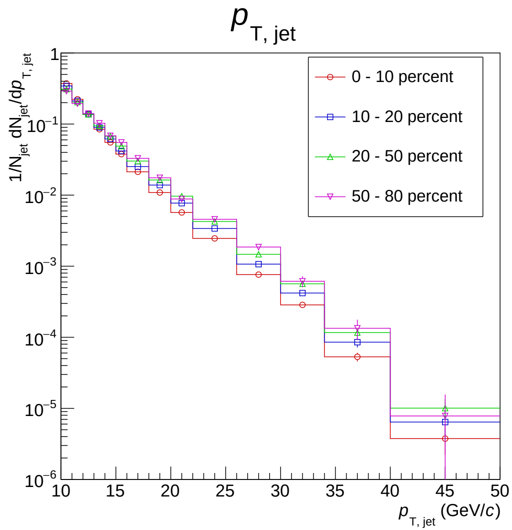
[1] Phys. Rev. D 82, 074018

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 [2]
- **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
- For $\rho(r)$ calculation, used tracks with $r(\mathrm{trk, jet}) = \sqrt{(\eta_{\mathrm{jet}} - \eta_{\mathrm{trk}})^2 + (\phi_{\mathrm{jet}} - \phi_{\mathrm{trk}})^2} < 0.4$ and $p_{\mathrm{T,trk}} > 1$ GeV/c

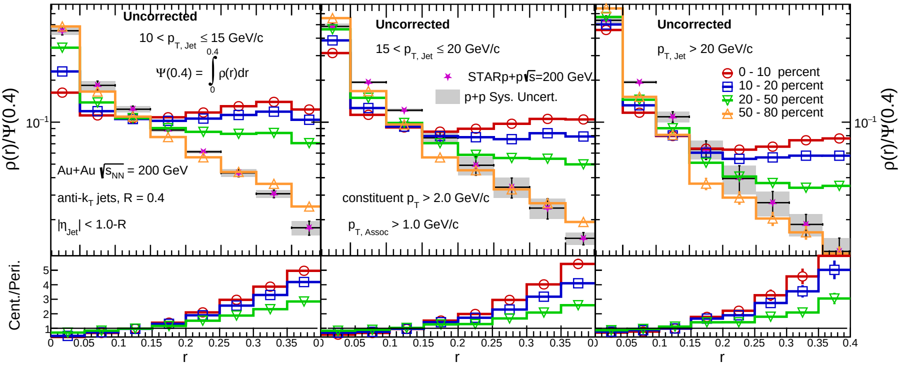
[2] M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 06

Raw $p_{T,jet}$



p T, jet
1/N_jet dN_jet/dp T, jet
1
10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
10
15
20
25
30
35
40
45
50
p T, jet (GeV/c)
0 - 10 percent
10 - 20 percent
20 - 50 percent
50 - 80 percent

Raw $\rho(r)$



Uncorrected
10 < p_{T, Jet} ≤ 15 GeV/c
Ψ(0.4) = ∫_0^0.4 ρ(r)dr
Au+Au √s_NN = 200 GeV
anti-k_T jets, R = 0.4
|η_Jet| < 1.0-R
15 < p_{T, Jet} ≤ 20 GeV/c
STARp+p√s=200 GeV
p+p Sys. Uncert.
constituent p_T > 2.0 GeV/c
p_{T, Assoc} > 1.0 GeV/c
p_{T, Jet} > 20 GeV/c
0 - 10 percent
10 - 20 percent
20 - 50 percent
50 - 80 percent
ρ(r)/Ψ(0.4)
10^{-1}
Cent./Peri.
r

Matching efficiency

Match made between closest possible GEN-RECO pair, with the distance between them being < 0.4

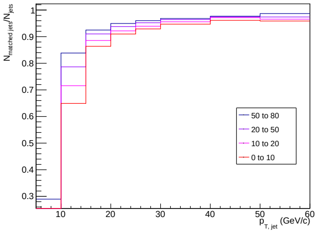


Figure: *RECO Jet Matching Efficiency*

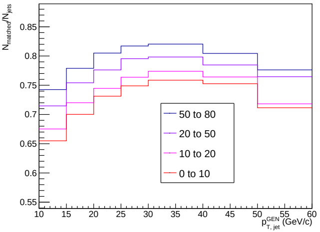


Figure: *GEN Jet Matching Efficiency*

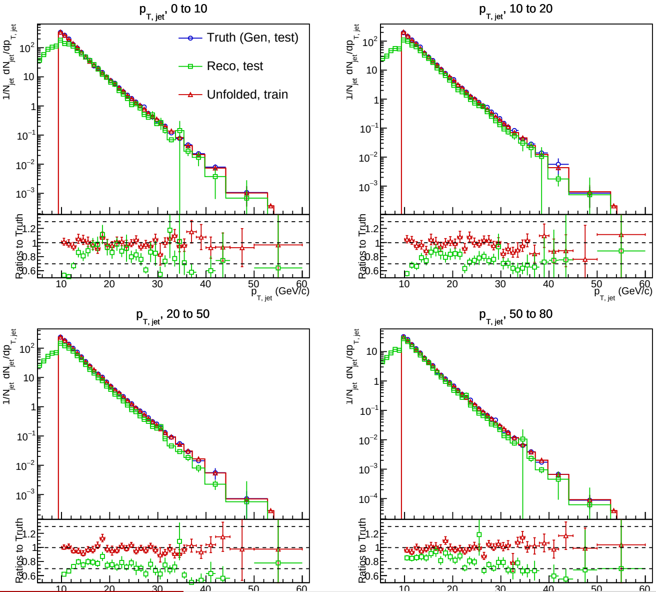
Multifolding

- Iterative unfolding technique that derives reweighing factors using neural networks
- No need to bin data
- Can simultaneously unfold all variables

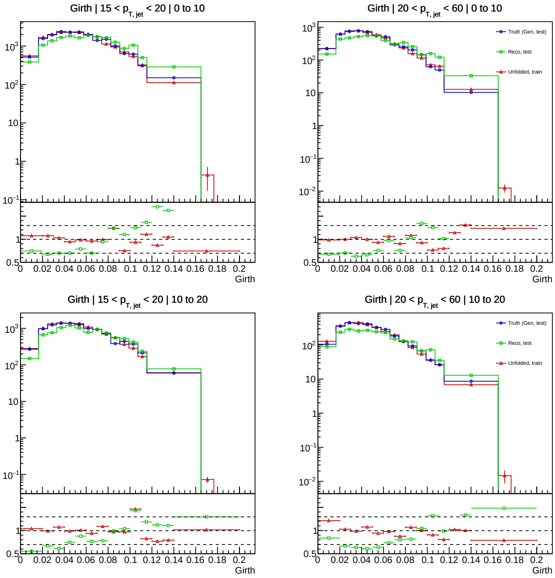
Parameters:

- **Number of iterations** 10 (the unfolding push-pull iterations)
- **Model layer sizes:** 100, 100, 100 (3 hidden layers)
- **Epochs:** 100 (number of times the network sees the training data)
- **Patience:** 20 (number of epochs with no improvement after which training will be stopped)
- **Batch size:** 1000 (number of samples per gradient update)

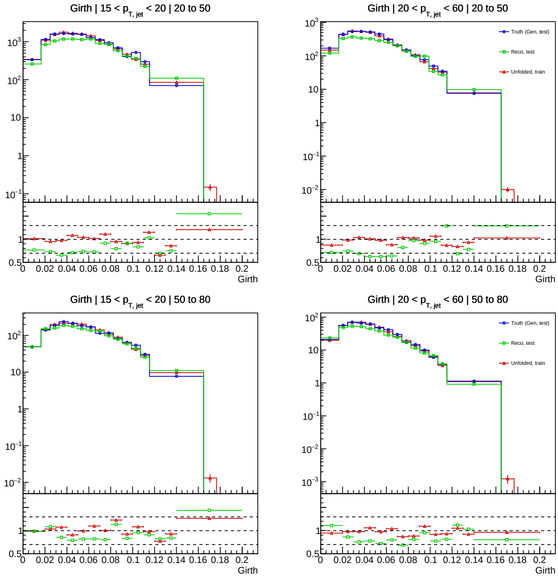
Closure from Multifold



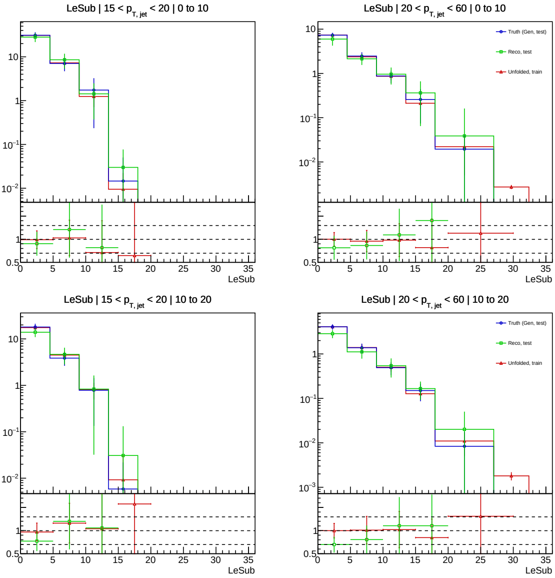
Closure from Multifold



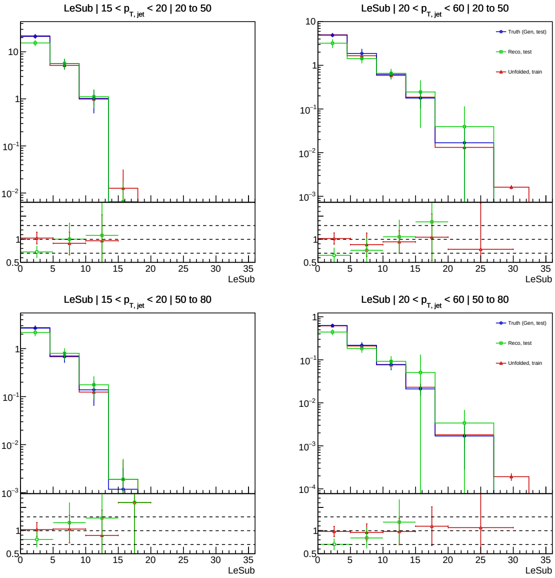
Closure from Multifold



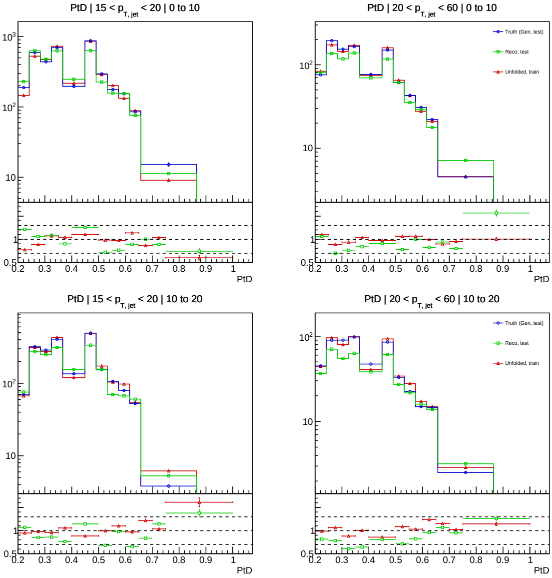
Closure from Multifold



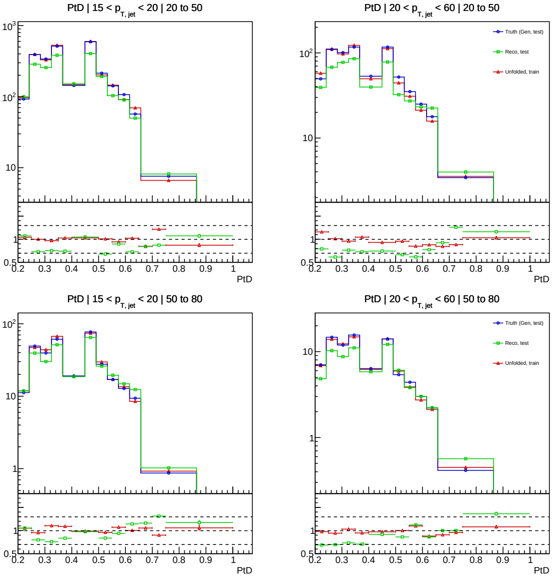
Closure from Multifold



Closure from Multifold



Closure from Multifold



Conclusions and Outlook

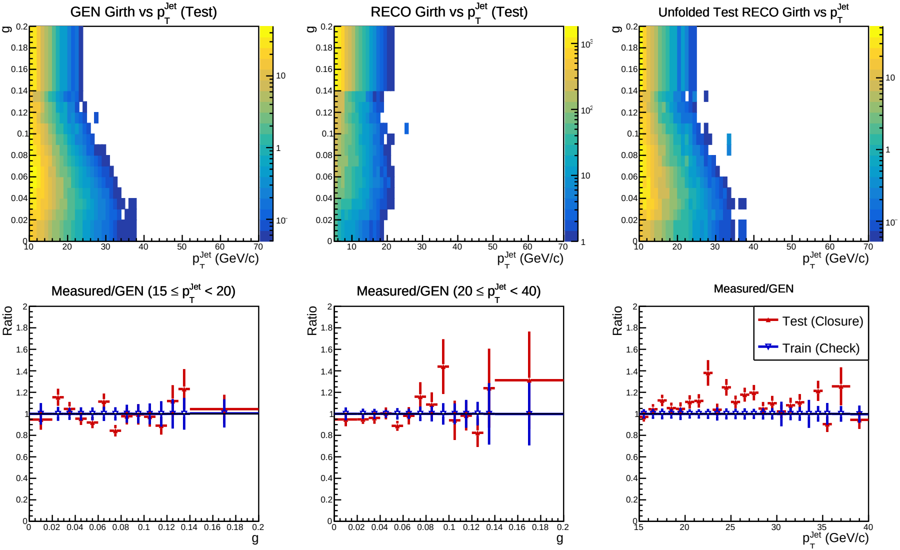
- Closure for simultaneously unfolding p_T^D, LeSub, Girth and $p_{T,jet}$ is established

Ongoing (to be presented on Thursday):

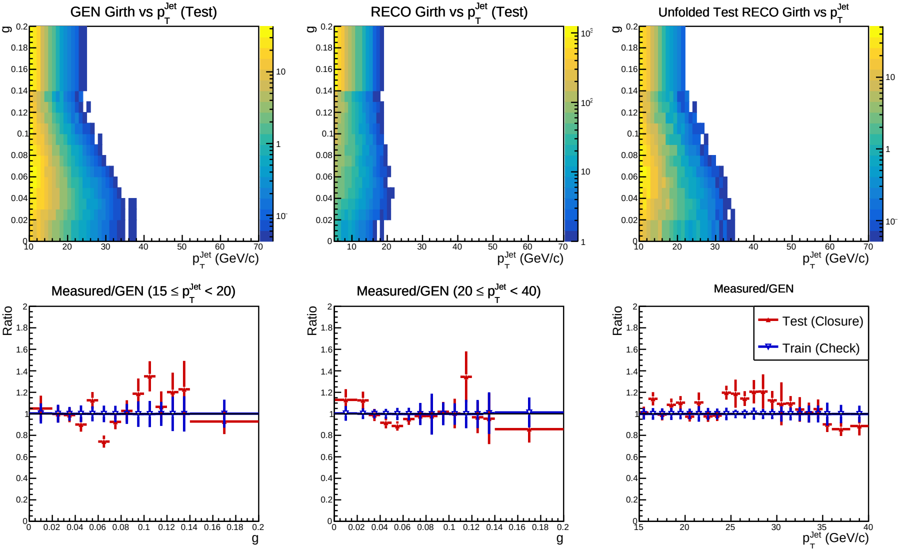
- Background subtraction from $\rho(r)$ measurements using mixed-events
- Unfolding p_T^D, LeSub, Girth and $p_{T,jet}$ data using Multifold
- Multifold closure for $\rho(r)$ and data unfolding.

BACK UP...

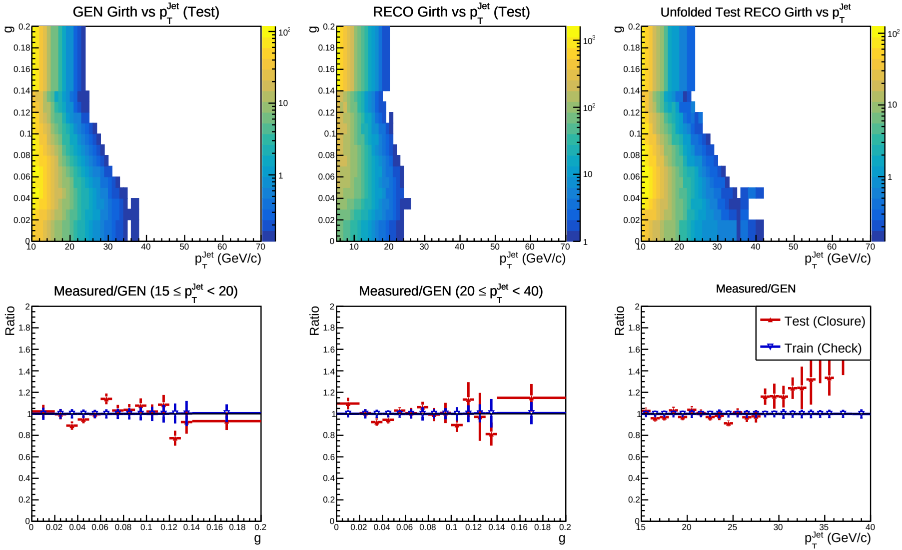
Iterative Bayesian Unfolding Closure (0 to 10 %)



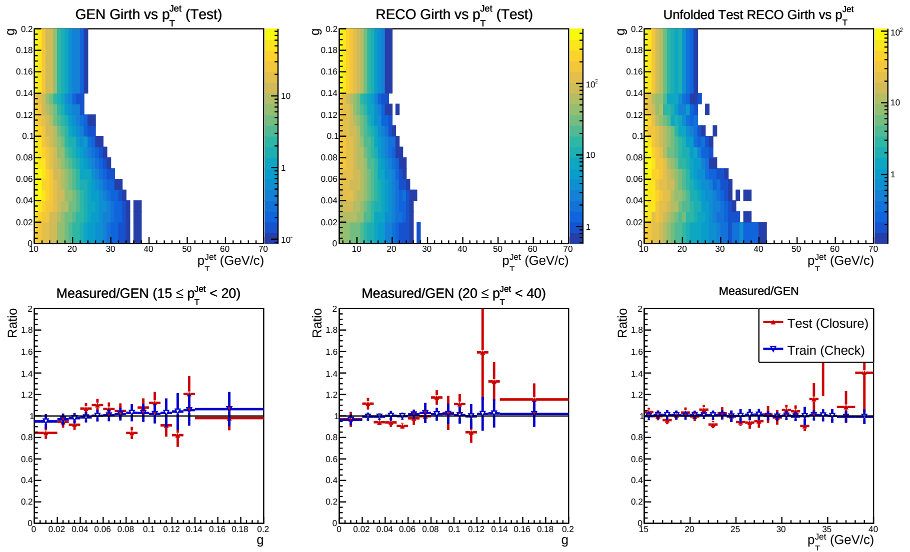
Iterative Bayesian Unfolding Closure



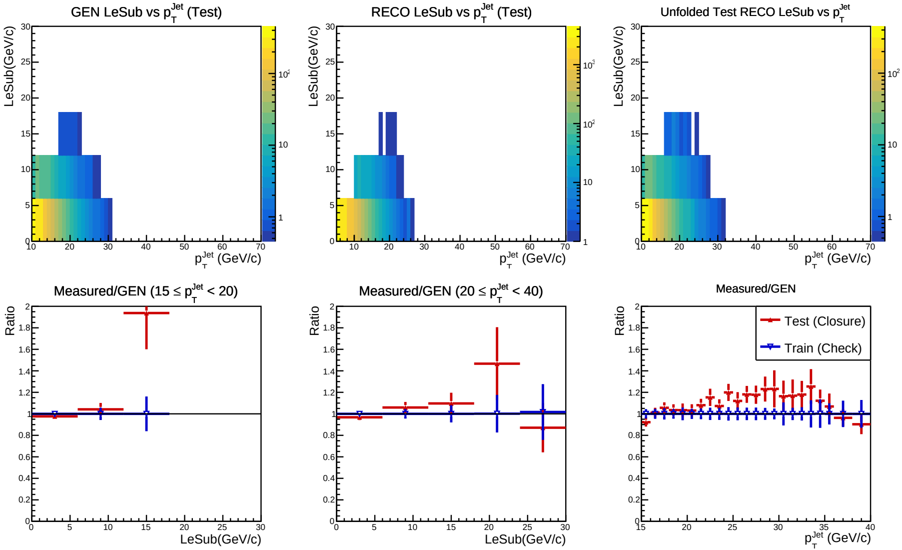
Iterative Bayesian Unfolding Closure



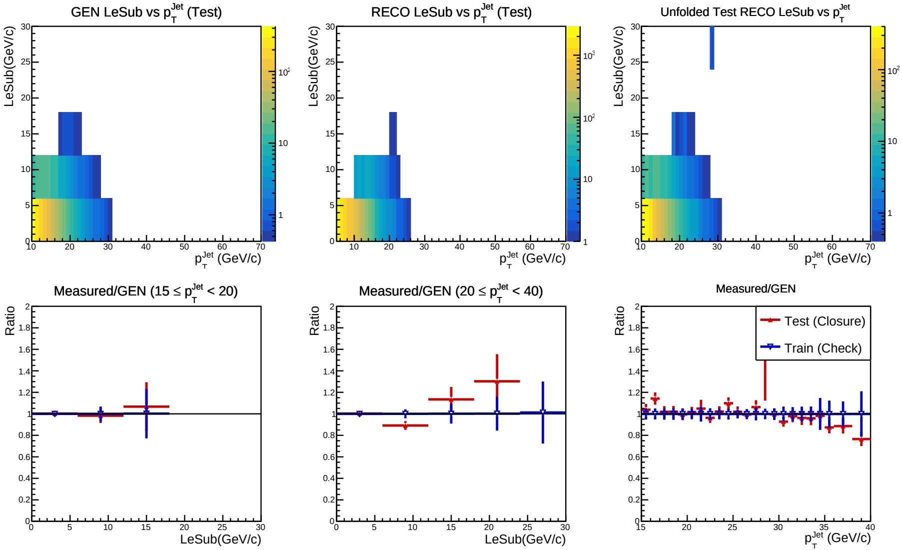
Iterative Bayesian Unfolding Closure



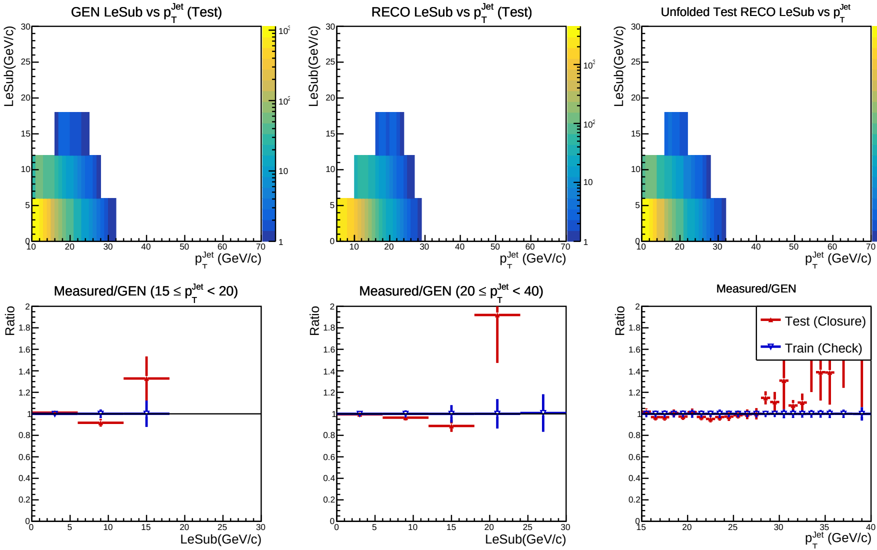
Iterative Bayesian Unfolding Closure



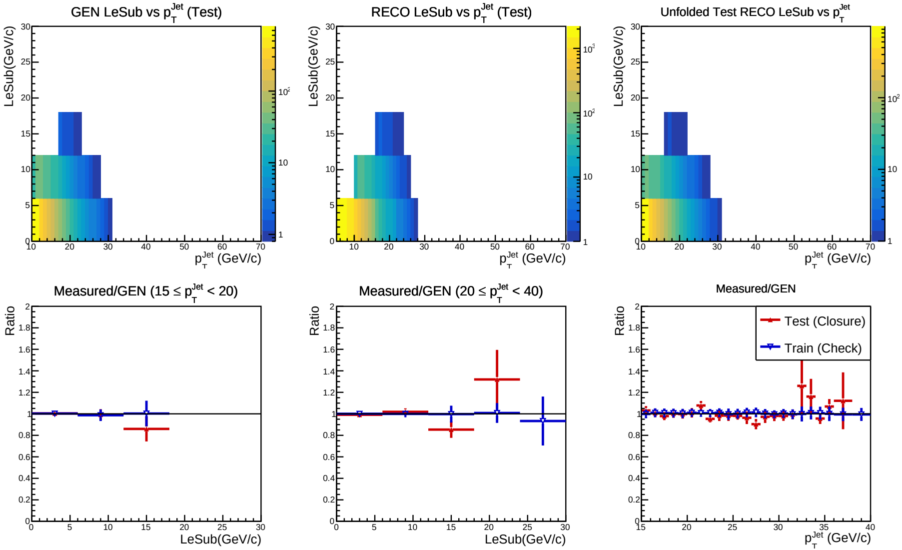
Iterative Bayesian Unfolding Closure



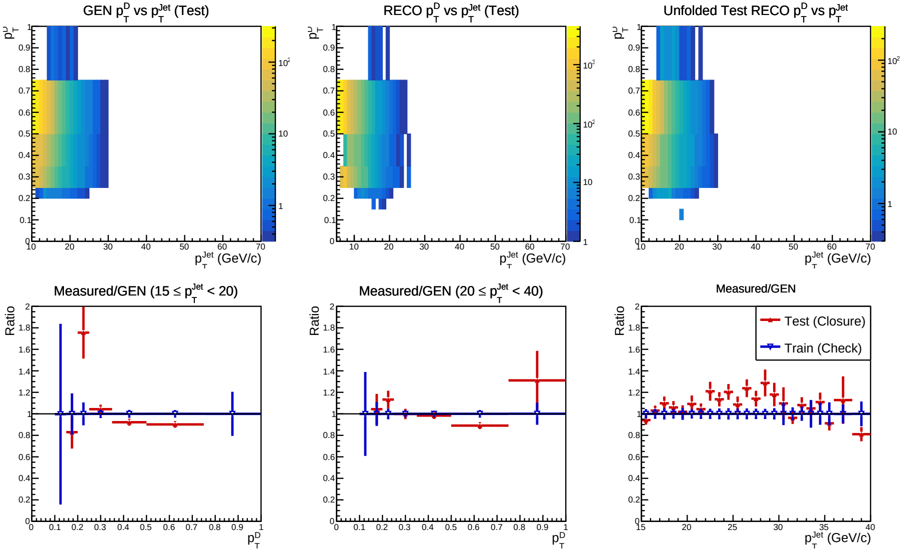
Iterative Bayesian Unfolding Closure



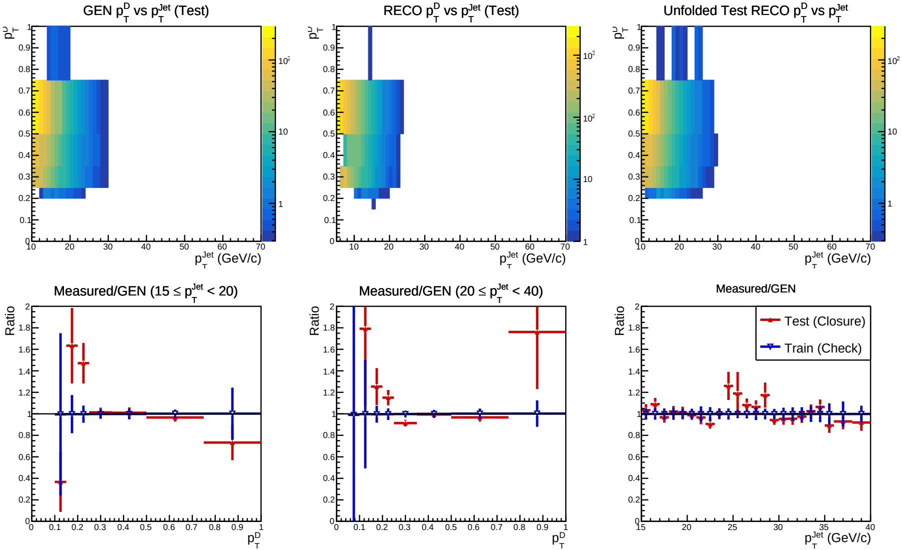
Iterative Bayesian Unfolding Closure



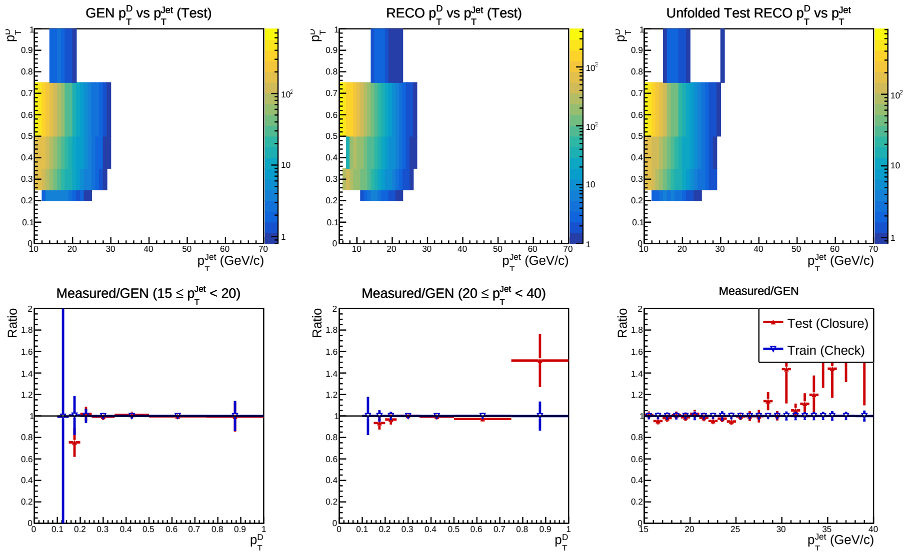
Iterative Bayesian Unfolding Closure



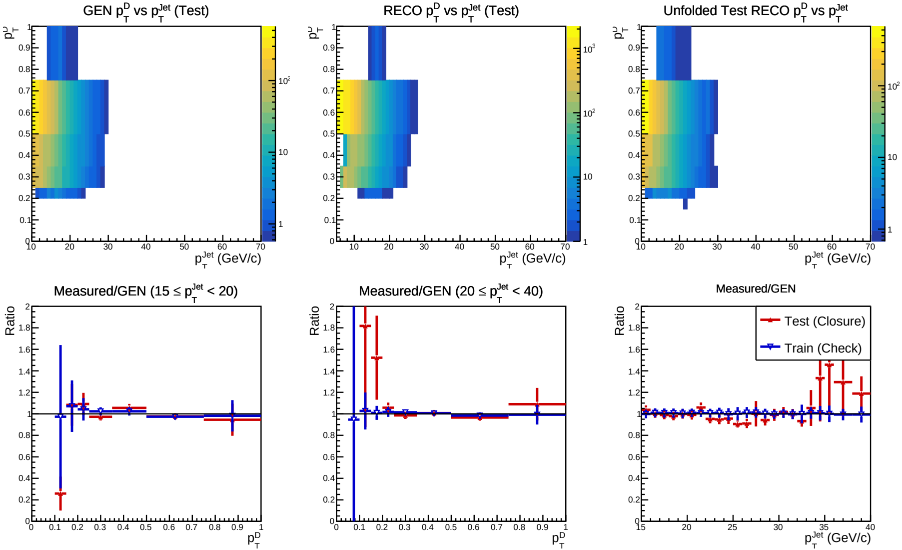
Iterative Bayesian Unfolding Closure



Iterative Bayesian Unfolding Closure

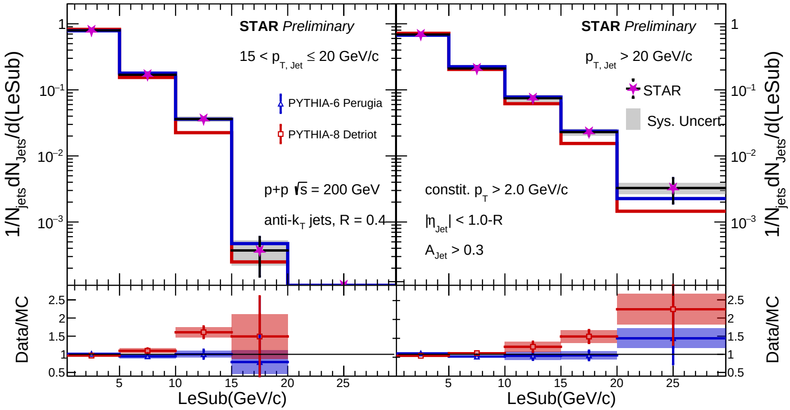


Iterative Bayesian Unfolding Closure



Recap: LeSub (Presented in HP2023)

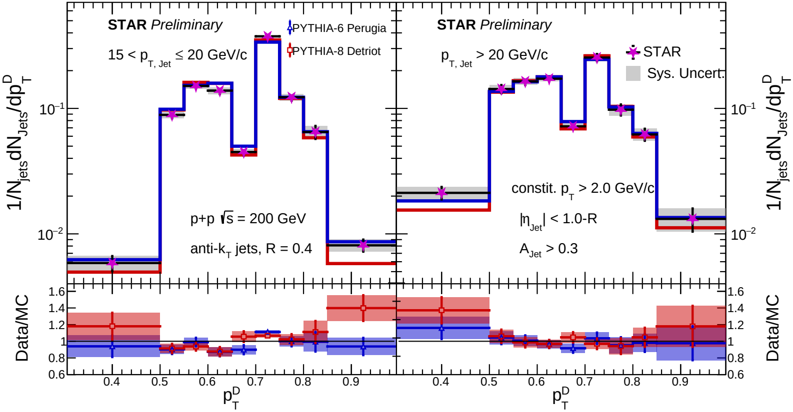
$$\text{LeSub} = p_{\text{T,trk}}^{\text{Lead}} - p_{\text{T,trk}}^{\text{Sublead}}$$



LeSub overall shows slight preference toward PYTHIA-6, PYTHIA-8 underestimates LeSub on average

Recap: p_T^D (Presented in HP2023)

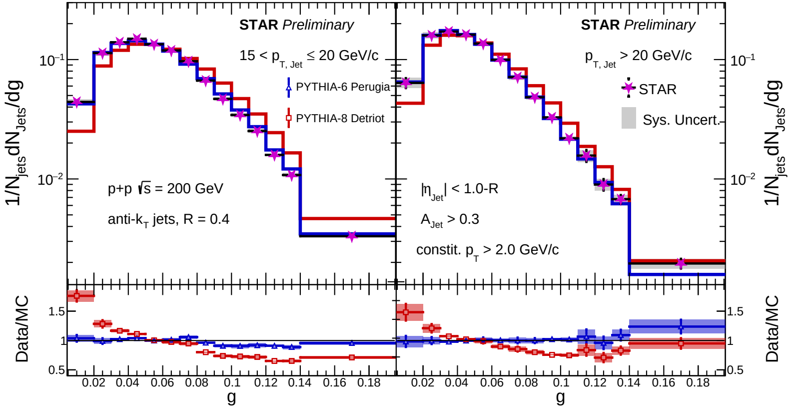
$$p_T^D = \frac{\sqrt{\sum_{\mathrm{trk}\in\mathrm{jet}} (p_{\mathrm{T,trk}})^2}}{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}}}$$



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

Recap: Girth (Presented in HP2023)

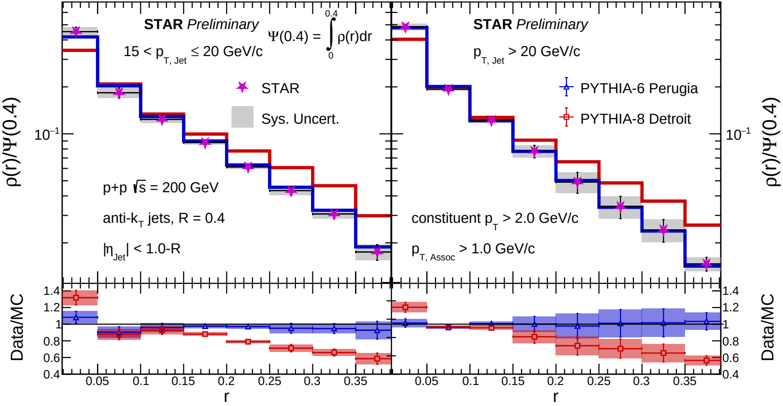
$$g = \frac{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}} \Delta R}{p_{\mathrm{T,jet}}}$$



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

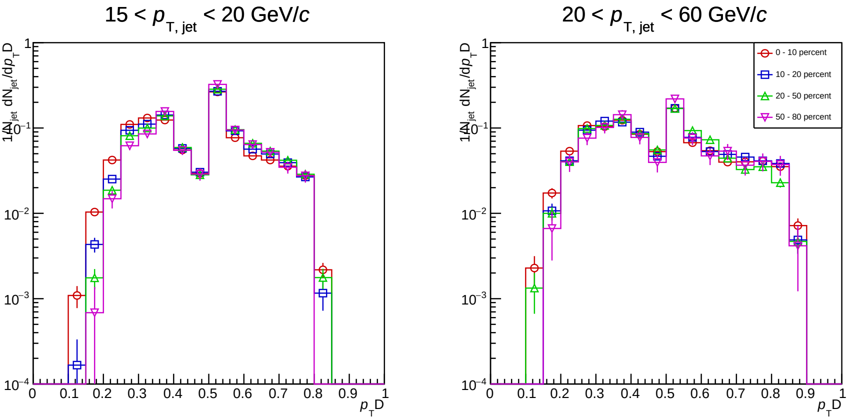
Recap: Differential Jet Shapes ($\rho(r)$) (Presented in HP2023)

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



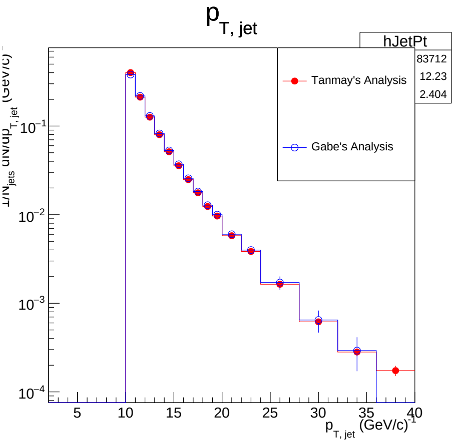
- PYHTIA-6 describes data well, PYTHIA-8 overestimates broader jets

$(p_T^D)^2$

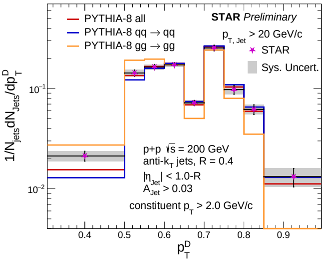

15 < p_T, jet < 20 GeV/c
20 < p_T, jet < 60 GeV/c
1/N_jet dN_jet/dp_TD
p_TD
0 - 10 percent
10 - 20 percent
20 - 50 percent
50 - 80 percent

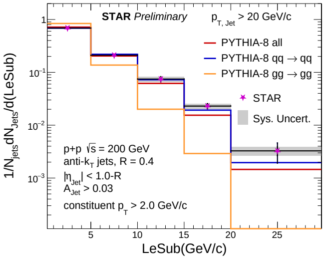
Checking sanity of jet clustering

R = 0.4 Charged hard-core jets, AuAu 200GeV mid-luminosity 2014 production
Centrality: 0 - 20%
Triggers: MB-mon, VPDMB5, VPDMB30, BHT1*VPDMB30, BHT2*VPDMB30, BTHT3

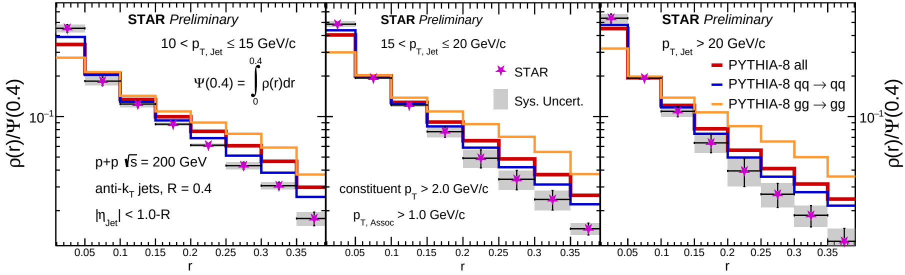


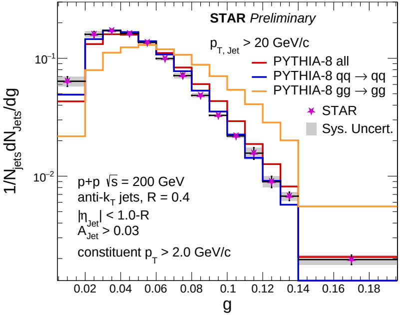
Quark jets vs Gluon Jets from PYTHIA-8





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

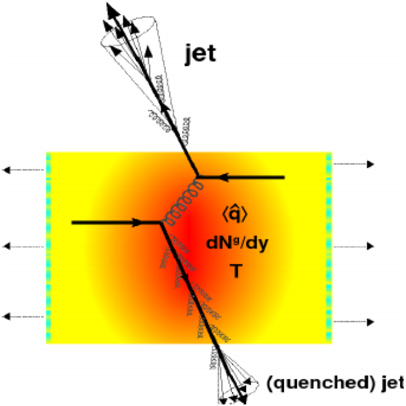




- PYTHIA-8 overestimates gluon-like fragmentations and underestimates hard fragmentation of quarks
- Need comparisions for more substructures
- PYTHIA-8 Detroit tune needs more tuning to better explain ungroomed jet substructure

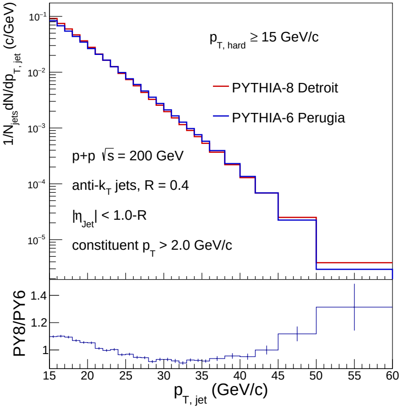
Jets as probes for QGP

- 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



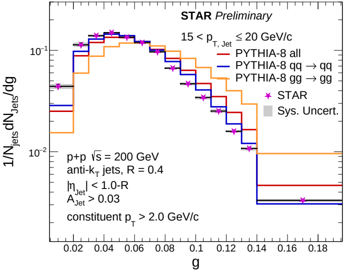
Jets as probes to study QGP ≡ Modification of observables related to energy distribution inside jets (relative to vaccum)

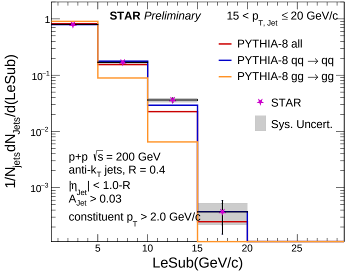
$p_{\mathrm{T,jet}}$ PYTHIA-6 vs PYTHIA-8

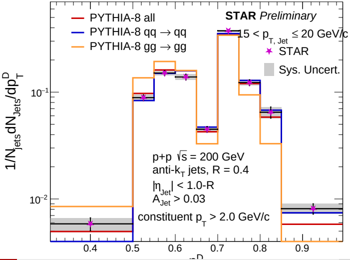


$p_{\mathrm{T,jet}}$ varies 5-20% between the two generations

Quark vs Gluon, lower momentum jets:







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 $N_{iterations} = 3$ and $N_{iterations} = 6$ $\Delta(p_T^D) \leq 4\%$, $\Delta(\text{LeSub}) < 1\%$, $\Delta(g) \leq 1\%$
- **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:** $p_{\mathrm{T,jet}}$ windows shifted 1 GeV/c to the left and right, subtracted the deviation in MC samples from the variation $\Delta(p_T^D) \leq 1\%$, $\Delta(\text{LeSub}) \approx 0\%$, $\Delta(g) \leq 0.5\%$

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

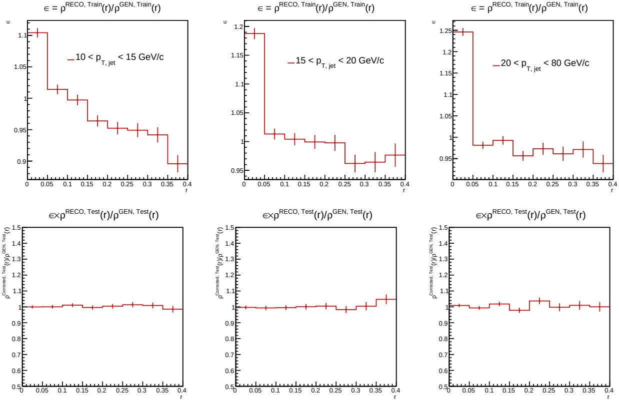
- To avoid issues from tower pileups, only used charged jet constituents (TPC tracks) to calculate $\rho(r)$, $\mathbf{r}_{\rm trk} = (\eta_{\rm trk} - \eta_{\rm jet})\hat{\eta} + (\phi_{\rm trk} - \phi_{\rm jet})\hat{\phi}$, $r = |\mathbf{r}|$
- Thus,

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

- Analysis done in bins of $10 < p_{\rm T,jet} \leq 15$ GeV/c, $15 < p_{\rm T,jet} \leq 20$ GeV/c and $p_{\rm T,jet} > 20$ 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 $\epsilon(r) = \frac{\rho_{\rm GEN}(r)}{\rho_{\rm RECO}(r)}$ 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%) $\Delta(\rho) \leq 20\%$