Jet Shape Observables in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC

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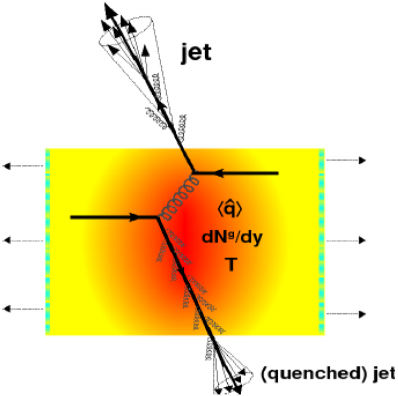
Jets as probes for QGP

- 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



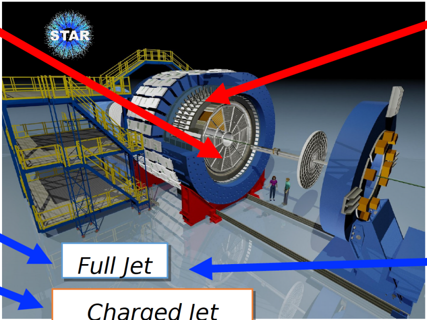
Jets as probes to study QGP ≡ Modification of observables related to energy distribution inside jets (relative to vaccum)

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

- The Time Projection Chamber (TPC) used to detect charged tracks and particle identification.
- The Barrel Electomagnetic Calorimeter (BEMC) gives energy deposited by neutral electomagnetic constituents, after full hadronic correction

Jet Shape Observables

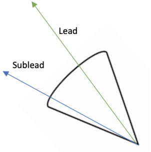
Describe charged energy distribution in a jet :

- **Girth:**

$$g = \frac{\sum_{\text{Tracks}} p_T^{\text{track}} \Delta R}{p_T^{\text{Jet}}}$$

- **LeSub:**

$$\text{LeSub} = p_T^{\text{Lead}} - p_T^{\text{Sublead}}$$



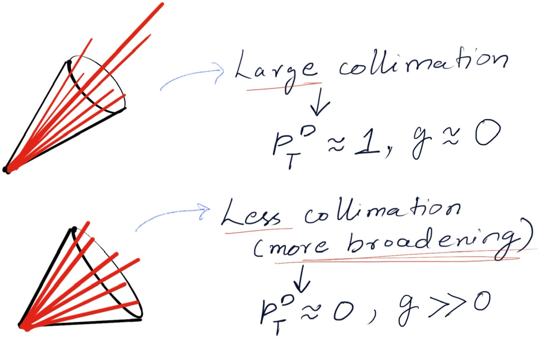
- **p_T dispersion(p_T^D):** 2nd moment of charged momentum distribution.

$$p_T^D = \frac{\sqrt{\sum_{\text{tracks}} \left(p_T^{\text{track}}\right)^2}}{\sum_{\text{tracks}} p_T^{\text{track}}}$$

$p_T^{\text{track}} = p_T$ of jet tracks, $p_T^{\text{Jet}} = p_T$ of jet, $\Delta R = \sqrt{(\eta^{\text{track}} - \eta^{\text{Jet}})^2 + (\phi^{\text{track}} - \phi^{\text{jet}})^2}$

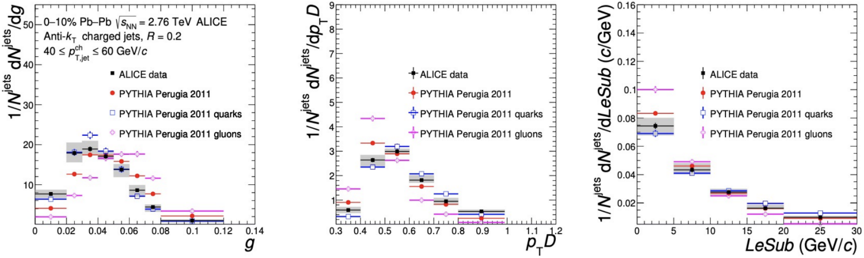
Jet Shape Observables

- Girth shows broadening of p_T distribution
- p_T^D and Girth represent collimation of charged energy in jet.
- **Hard fragmentation** gives $\mathrm{p}_\mathrm{T}^\mathrm{D}$ values **close to 1**; **soft** is closer **to 0**
- Hard fragmentation $\rightarrow$ large LeSub values



Motivation

- ALICE measurements [1] $\Longrightarrow$ Jet Shape Observables distributions consistent with quark-like fragmentation from PYTHIA
- Smaller energies @ RHIC $\Longrightarrow$ smaller p_T^{Jet} $\Longrightarrow$ longer interaction time with QGP medium



[1] ALICE, JHEP 10 (2018) 139

Events, tracks and jets

Event Selection:

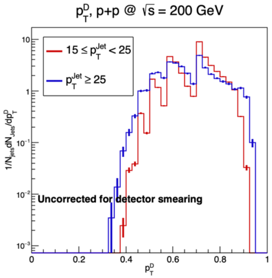
- **System:** p+p @ $\sqrt{s} = 200\text{GeV}$ (2012)
- Minimum bias (MB) + High Tower (HT) triggered event (at least one tower with energy more than 4.2 GeV)

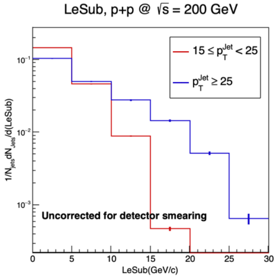
Jet Selection:

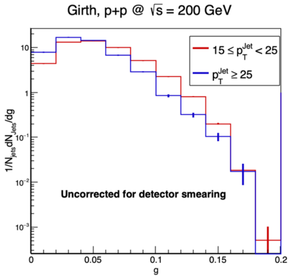
- Jet reconstruction using charged tracks and calorimeter tower energy depositions by anti-k_T algorithm (M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 063) with radius of 0.3
- **Hard-core** requirement of p_T^{track} (E_T^{tower}) > 2.0 GeV/c for the constituents to reduce combinatorial background. (*STAR, Phys. Rev. Lett. 119 (2017) 062301*)
- Jets are required to have at least two charged constituents (TPC tracks)

Raw distributions from data

Raw (Uncorrected) distributions from STAR @ 200 GeV pp data are presented in two p_T^{Jet} bins of $[15, 25)$ GeV/c and ≥ 25 GeV/c

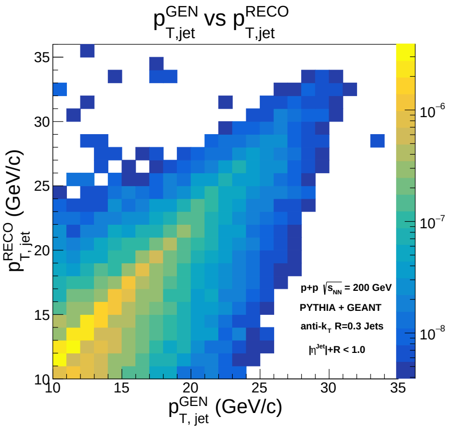






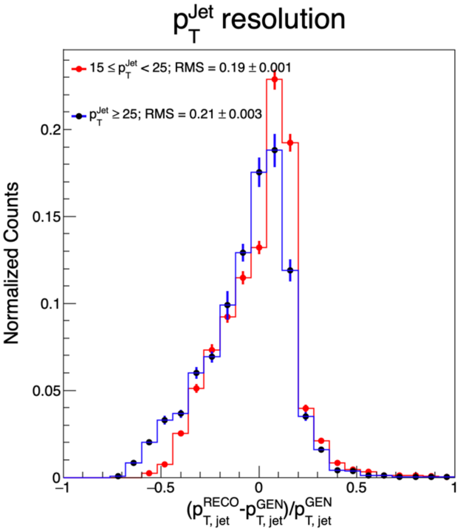
Simulation study

- This simulation is **dijet embedding**
- PYTHIA-8 events generated, run through GEANT-3 simulation of STAR detector
- Events embedded into real zero-bias p+p events (effects of run conditions)
- Jet observables are smeared due to detector effects



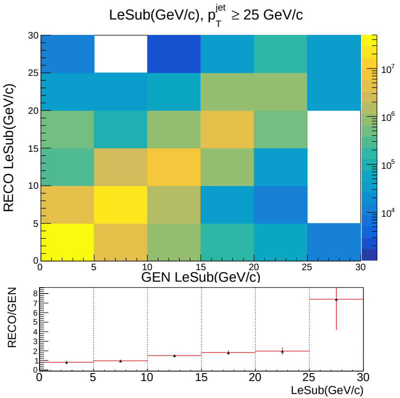
Jets from input PYTHIA-8 tracks (charged and neutral particles)
(**particle/generator/GEN-level**)
VS
Jets from tracks and calorimeter towers after they pass through GEANT
(**detector/reconstructed/RECO-level**)

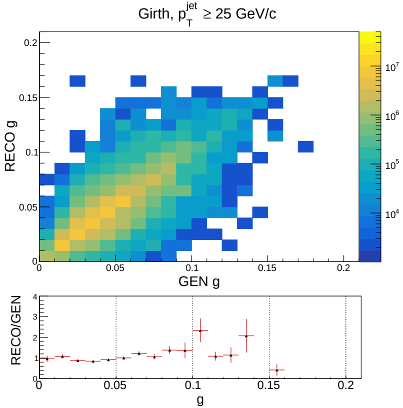
$p_{\mathrm{T}}^{\mathrm{Jet}}$ resolution



- $p_{\mathrm{T}}^{\mathrm{Jet}}$ resolution calculated as RMS of $\frac{p_{\mathrm{T,jet}}^{RECO} - p_{\mathrm{T,jet}}^{GEN}}{p_{\mathrm{T,jet}}^{GEN}}$ histogram
- Resolution of 19-21% for $p_{\mathrm{T}}^{\mathrm{Jet}} \geq 15$ GeV/c

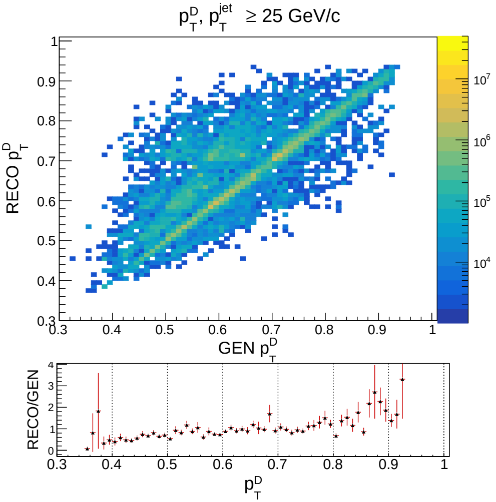
Results from simulation





- Strong diagonal components $\implies$ good GEN $\rightleftarrows$ RECO mapping
- Off diagonal component $\implies$ Smearing due to detector effects
- RECO/GEN ≈ 1 for Girth, show increasing trend for LeSub

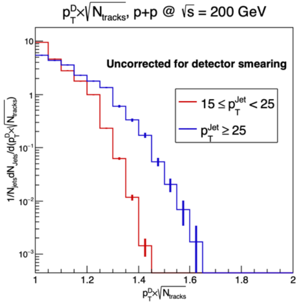
Results from simulation

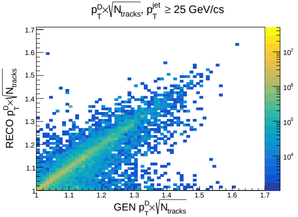


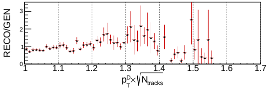
- RECO/GEN ratios show slight increasing trend for p_T^D
- Peaky features in p_T^D 2D plot for different N_{tracks}
- Hard core constituent cut $\Longrightarrow$ raw p_T^D has a jagged, saw tooth structure. Peaks represent a change in number of tracks in a **hard-core** jet

Reweighed p_T^D

- A **soft hard-core jet (all constituents similar** p_T) still has $p_T^D \approx 1/\sqrt{N_{tracks}}$
  $\implies$ p_T^D scales as $1/\sqrt{N_{tracks}}$
- Use $p_T^D \times \sqrt{N_{tracks}} = p_T^{D,Norm}$ (Reweighed p_T^D) to remove this dependence
- Softer jets with more dispersion $\implies$ Lower $p_T^{D,Norm}$
- Harder jets with collimation $\implies$ Higher $p_T^{D,Norm}$
- RECO/GEN ≈ 1







Conclusions and Outlook

Conclusions:

- Raw distributions of p_T^D, LeSub, Girth obtained from p+p@$\sqrt{s} = 200$ GeV
- Enough statistics to do analysis in p_T^{Jet} bins
- p+p dijet embedding studied and shows **good reconstruction** on the detector level
- Embedding results used to set up response matrices for unfolding
- A new variable, $p_T^D \times \sqrt{N_{tracks}}$, discussed

Outlook:

- 2D unfolding to correct the data (simultaneous unfolding of the jet shape observables and $\mathrm{p_T^{Jet}}$)
- Analysis will be extended to Au+Au@$\sqrt{s_{NN}} = 200$ GeV collisions once the p+p baseline is established

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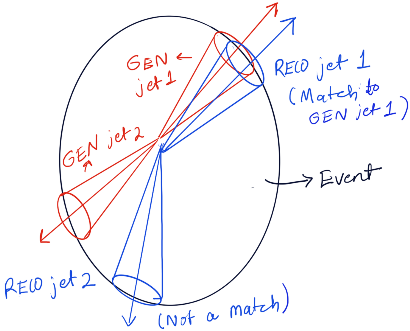
THANK YOU!

BACK UPS

Unfolding

- Need to correct smearing effects observed from embedding simulation
- JSOs are studied in $\mathrm{p_T^{Jet}}$ bins
- Both $\mathrm{p_T^{Jet}}$ and the JSOs show detector smearing $\implies$ 2D unfolding needed
- 4D response matrix objects, $(\mathrm{p_{T,GEN}^{Jet}}, \mathrm{JSO_{GEN}}, \mathrm{p_{T,RECO}^{Jet}}, \mathrm{JSO_{RECO}})$ to be set up for 2D unfolding
  Currently under progress...

Matching between GEN and RECO



Starting with the i^{th} jet at GEN level (that matches analysis cuts), match to the j^{th} RECO level jet iff:

- It's axis is less than 0.3 units away from the GEN jet axis in the $\eta - \phi$ plane
- It jet is the closest to the GEN jet (compared to other RECO jets)
- It passes the analysis cuts

p_T^D for soft jets

Due to almost even dispersion of momentum, all p_T^{track} are roughly the same, so if the soft jet has N_{tracks} charged constituents,

$$
\begin{aligned}
p_T^D &= \frac{\sqrt{\sum_{\text{tracks}} \left(p_T^{\text{track}}\right)^2}}{\sum_{\text{tracks}} p_T^{\text{track}}} \\
&\approx \frac{\sqrt{N_{tracks} \left(p_T^{\text{track}}\right)^2}}{N_{tracks} p_T^{\text{track}}} \\
&= \frac{\sqrt{N_{tracks}}}{N_{tracks}} \\
\implies p_T^D &\approx \frac{1}{\sqrt{N_{tracks}}}
\end{aligned}
$$

Jet reconstruction

- Anti-k_T jet clustering algorithm used through the FASTJET package (*Phys. Lett. B 641 (2006) 57-61*)
- Sequentially clusters softer detected entities (charged particle tracks and calorimeter energy depositions) around harder entities
- Creates approximately conical jets with radii determined by the jet resolution parameter (R)
- R fixed based on various experiment specific considerations

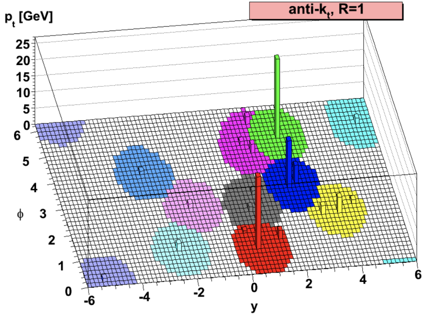


Figure: *M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 063*

What are our jets?

- To cluster entities, define metric in the η-ϕ space:

$$\begin{aligned} d_{ij} &= \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right)\frac{\Delta_{ij}^2}{R^2} \\ d_{iB} &= \frac{1}{p_{ti}^2} \end{aligned} \tag{1}$$

  $\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$, and p_{ti}, is the transverse momentum of entity i.
  - Get minima among all d_{ij}'s and d_{iB}'s
  - If minima is d_{ij} recombine entities i and j,
  - If it is d_{iB} call i a jet and jeep aside.
  - Repeat till all entities are clustered into jet candidates.
- R = jet resolution parameter (determines size of the jets)
- R is arbitrarily chosen depending on the experiment.
- The algorithm discussed is called anti-k_T algorithm, implemented here via FASTJET package

Quantum Chromodynamics (QCD)

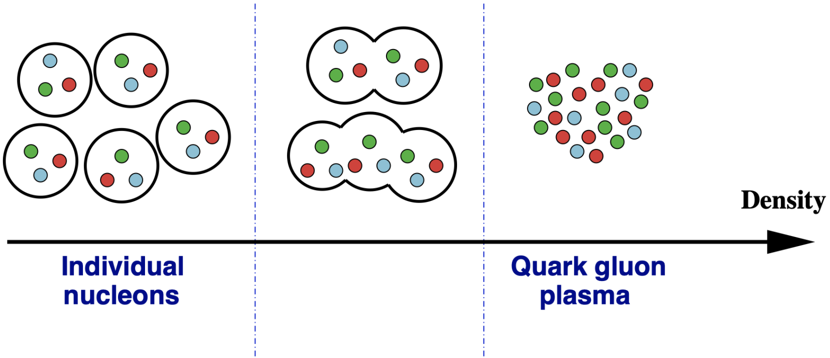
- In the Standard Model the strong force is described by Quantum Chromodynamics (QCD). In QCD, the quarks and gluons are said to have color charge, similar to electric charge in electrodynamics, and they interact via strong force.
- The coupling strength (α_s) of the strong interaction is given by,

$$\alpha_s(Q^2) = \frac{12\pi}{(11n - 2f)\ln(|Q^2|/\Lambda^2)} \tag{2}$$

Where, Q^2 is the momentum transfer, n is the number of colors and f is the number of flavors. The value of Λ lies between the range $100\text{MeV} < \Lambda < 500\text{MeV}$.

Quark Gluon Plasma (QGP)

Temperature increase → particle density increase → hadrons interpenetrate → partonic degrees of freedom expressed over nuclear volumes → QGP

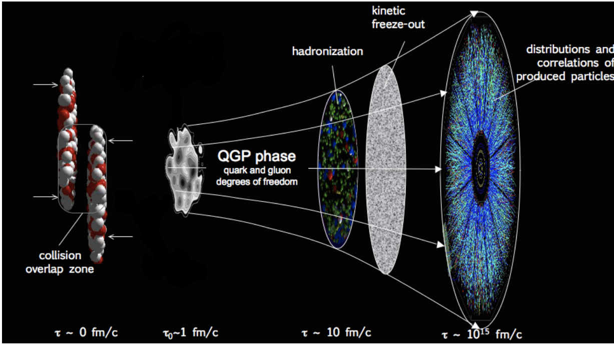


Recipe for QGP - Heavy ion collisions

- QGP $\rightarrow$ Relativistic heavy-ion collisions

Steps:

1. Heavy ion collision
2. Inelastic parton scattering
3. Loss of kinetic energy
4. Creation of particles
5. QGP fireball
6. Hadronization
7. Freezeouts
8. Detected particles and energy depositions



How to study QGP?

- **Hard probes:** Looks at the interaction of species produced before the formation of the QGP fireball.
  Example: Jet modifications, heavy flavour production, dilepton and direct photon production, etc.
- **Bulk probes:** Looks at the properties of the QGP fireball as a whole (bulk probes).
  Example: Collective flow, freezeout parameters, enhanced strangeness, etc.

The work presented here focuses on hard probes known as jets.