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on New Frontiers in Physics

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Recent jet measurements from STAR

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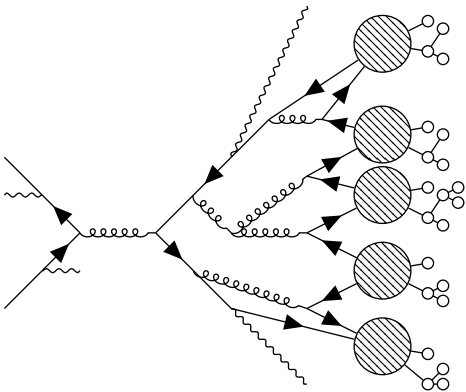
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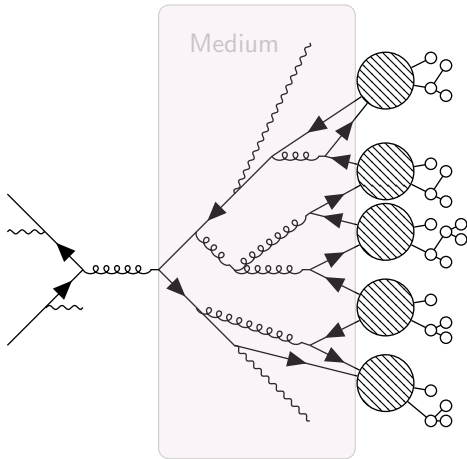


Jets in vacuum

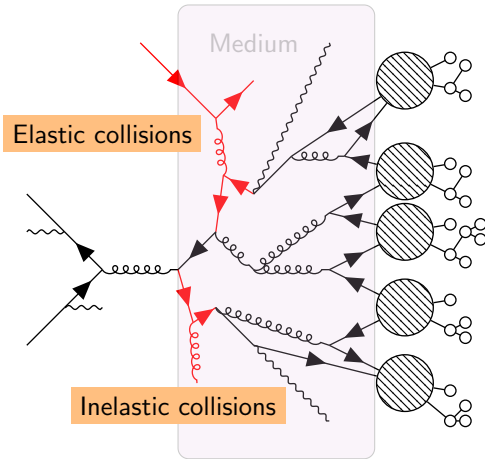


- Collimated sprays of particles, proxies for hard scattered partons
- Produced by parton showering explained by perturbative QCD
- Reconstructed by clustering final state particles after hadronization (non-perturbative)

Jets in medium

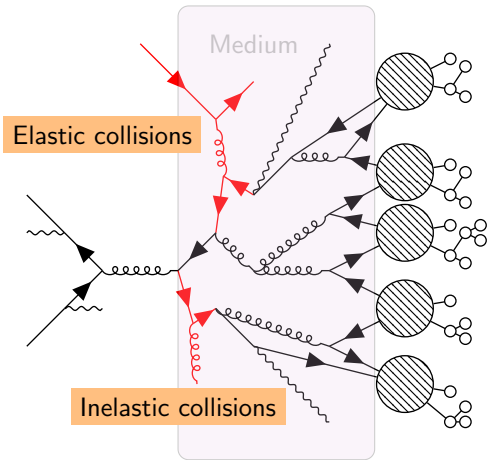


Jets in medium

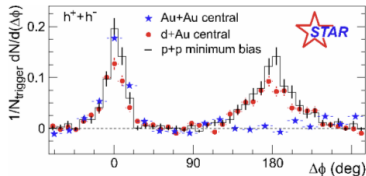


- Elastic and inelastic collisions with medium particles leads to modification of jet properties

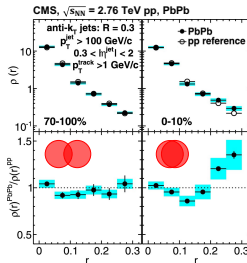
Jets in medium



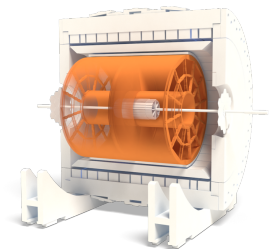
- Energy loss: STAR, Phys.Rev.C 102 (2020) 5

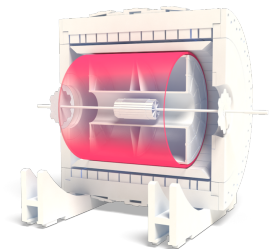


- Jet broadening: CMS, Phys. Lett. B 730 (2014) 243

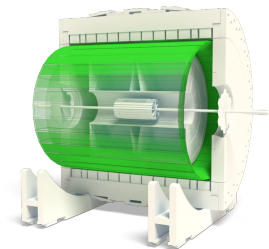


- Time Projection Chamber (TPC)
 - Reconstructs charged particle tracks
 - $|\eta| < 1, 0 < \phi < 2\pi$
 - PID using dE/dx

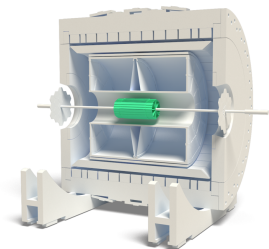




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- Time of Flight (TOF)
 - PID using TOF measurements
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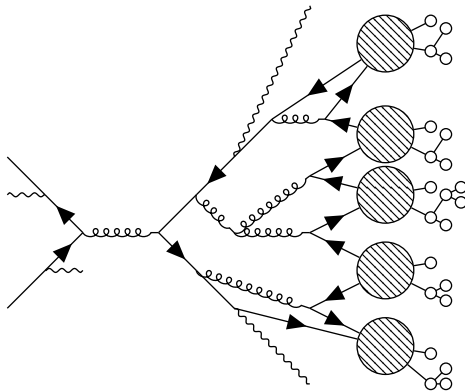


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- Barrel Electromagnetic Calorimeter (BEMC)
 - Measures neutral component of jet energy
 - $|\eta| < 1, 0 < \phi < 2\pi$
 - Used to trigger high energy events



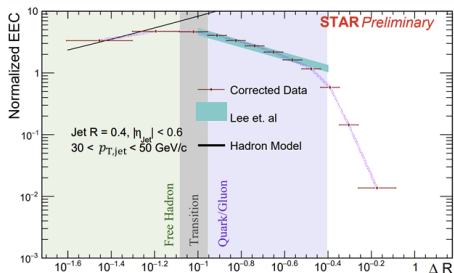
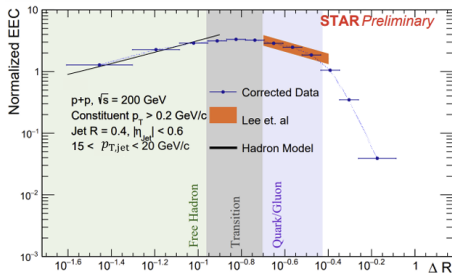
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 - Used to trigger high energy events
- Heavy Flavor Tracker (HFT, 2014-2016)
 - Improves position resolution for secondary vertices

Jets in vacuum



Time evolution of jets, from partons to hadrons

- Normalized EEC =
$$\frac{1}{\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T, \text{Jet}}^2}} \frac{d\left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T, \text{Jet}}^2}\right)}{d(\Delta R)}$$
- Formation time: $t_f \propto \frac{1}{(\Delta R)^2}$ (Apolinário, Cordeiro, & Zapp EPJC 81 (2021))

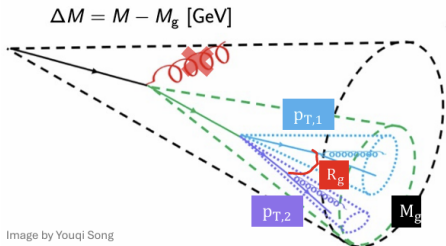


$\Delta R_{\text{Turnover}} \times p_{T, \text{Jet}} \approx 2 - 3 \text{ GeV}$, independent of $p_{T, \text{Jet}}$

Universal energy scale for hadronization

In perturbative (Quark/Gluon) region, next-to-leading log pQCD calculations explain EECs

Separating pQCD and npQCD in vacuum

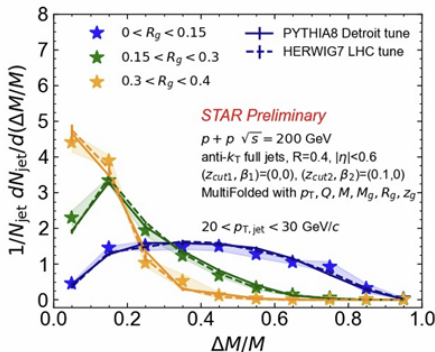
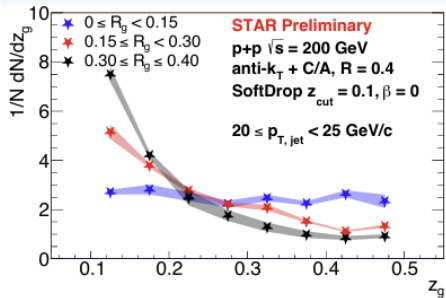


$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (R_g/R_{\text{jet}})^\beta$$

for $z_{\text{cut}} = 0.1$ and $\beta = 0$, $z_g > 0.1$ and R_g is the distance of subjets at split

- **SoftDrop:** Reduce wide-angle, soft radiation from reconstructed jets
(Larkoski, A.J., Marzani, S., Soyez, G. et al. Soft drop. J. High Energ. Phys. 2014, 146 (2014))
- **CollinearDrop:** Soft component of given jet observable (\mathcal{O}).
 $\Delta \mathcal{O} = \mathcal{O} - \mathcal{O}_g$ (Chien, Y.T., Stewart, I.W. Collinear drop. J. High Energ. Phys. 2020, 64 (2020))

Separating pQCD and npQCD in vacuum



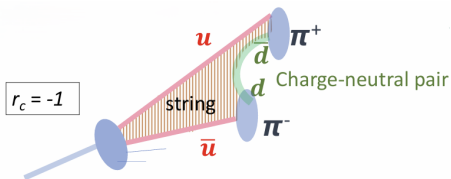
- **Perturbative:** Larger $R_g \implies$ Smaller $\langle \Delta M/M \rangle \implies$ Steeper z_g
- **Non-perturbative:** Smaller $R_g \implies$ Larger $\langle \Delta M/M \rangle \implies$ Flatter z_g
- PYTHIA8 Detroit tune and HERWIG7 LHC tune explain $\Delta M/M$ distributions from data

Probing npQCD region in vacuum

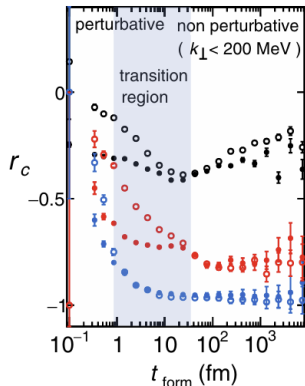
Chien, Deshpande, Mondal, Sterman, PRD 105 (2022) 5, L051502

$$r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 \bar{h}_2}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \bar{h}_2}/dX}$$

$h_1 h_2$: same charge hadrons, $h_1 \bar{h}_2$:
opposite charge hadrons



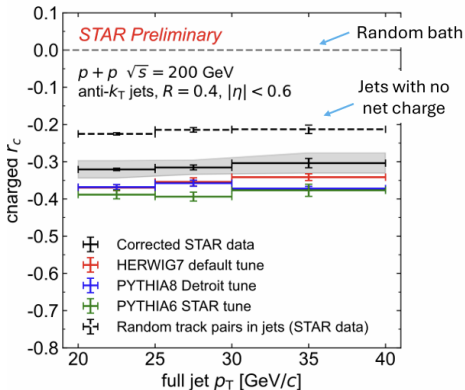
- r_c measures fraction of “string-like hadronization”
- baseline for studying medium modification of hadronization



$$t_{\text{form}} = z(1-z)p/k_T^2$$

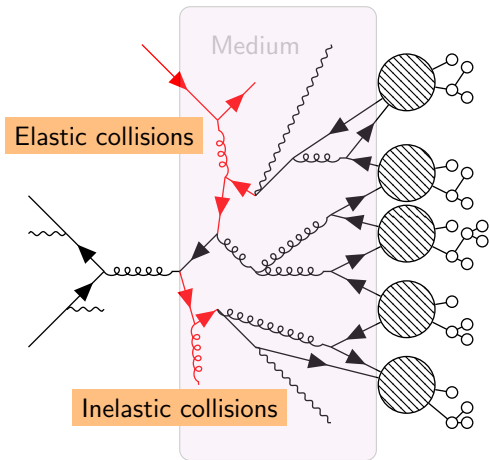
where, $p = p^{h_1} + p^{h_2}$, and $z = p^{h_2}/p$

Probing npQCD region in vacuum



- **First measurement in p+p:** Both string-like and cluster hadronization underpredict STAR data
- More model tuning required

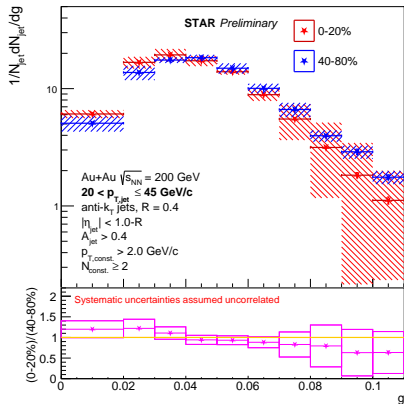
Jets in medium



Jet substructure in medium

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

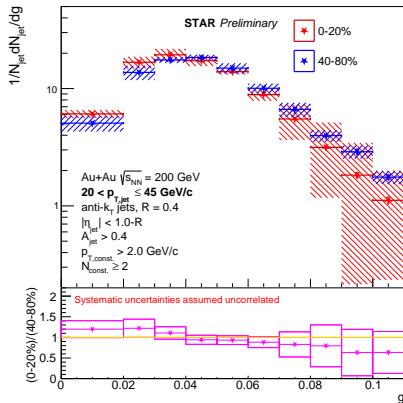
- $\lambda_0^0 = N_{\text{constit.}}$, $\lambda_1^1 = g$ (girth), $\lambda_2^1 = \text{thrust}$, $\sqrt{\lambda_0^2} = p_T^D$
- β , κ control sensitivity to energy and angular scales
- Probe modification of radiation pattern in medium



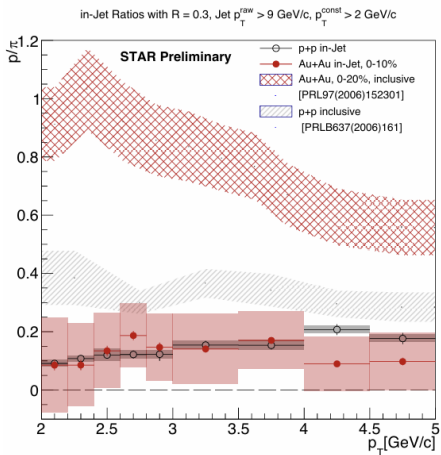
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- Girth consistent within systematic uncertainties between central, peripheral collisions
- Better estimates of systematic uncertainties ongoing

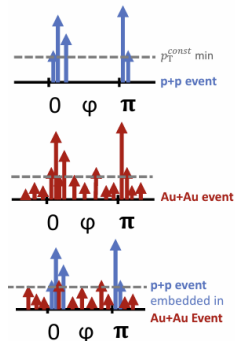


Hadron chemistry in jet cones

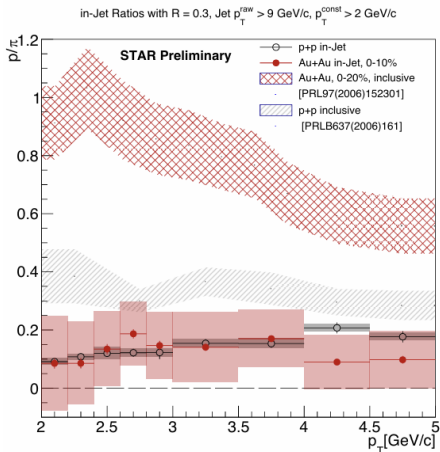


Correlated backgrounds:

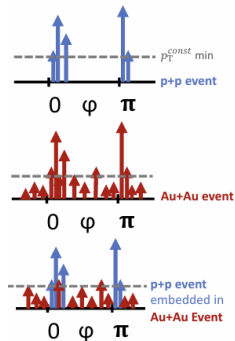
Upward fluctuation into real jets removed using “pseudo-embedding” $p+p$ events into a random central Au+Au events



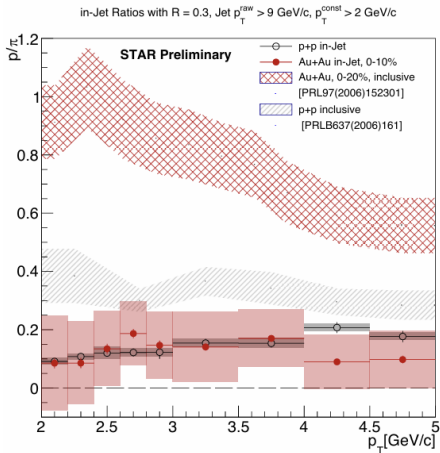
Hadron chemistry in jet cones



Correlated backgrounds:
 Any residual jet - Au+Au hadron correlation \rightarrow bias towards upward fluctuation

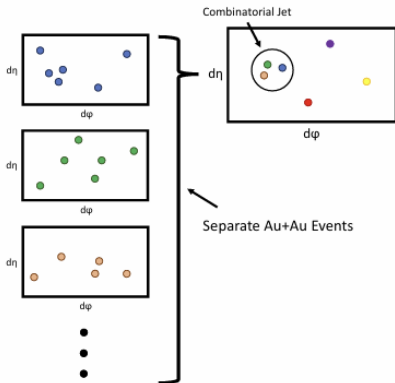


Hadron chemistry in jet cones

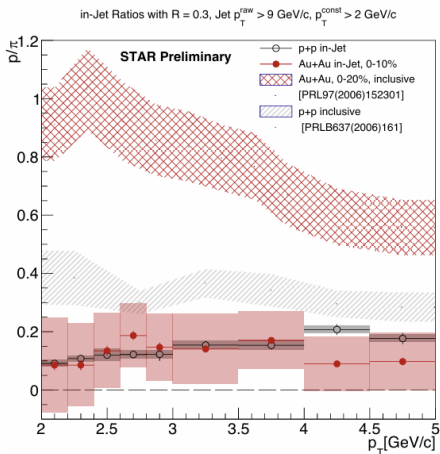


Correlated backgrounds:

Combinatorial jets (jets clustered from low p_T tracks, no hard processes)

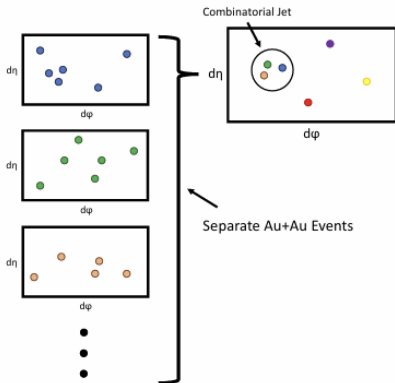


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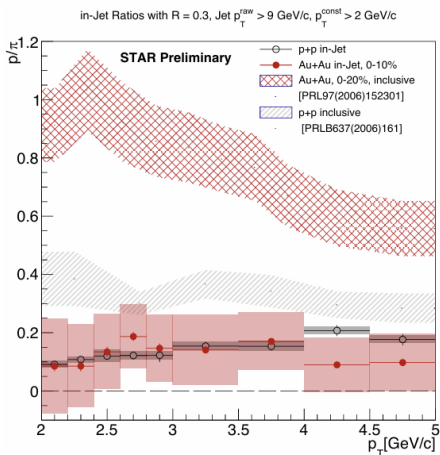


Correlated backgrounds:

Simulated by clustering randomly sampled tracks from separate events (Mixed Constituent Event)



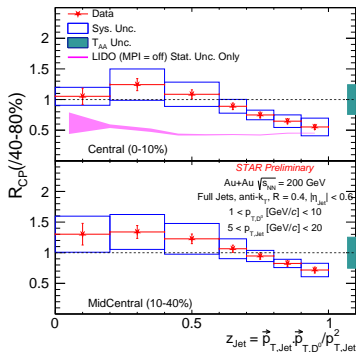
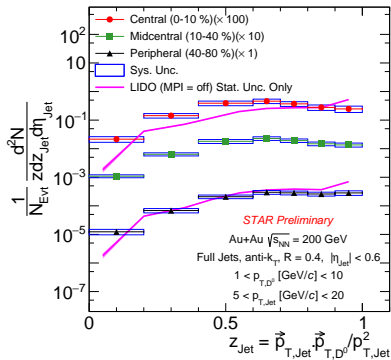
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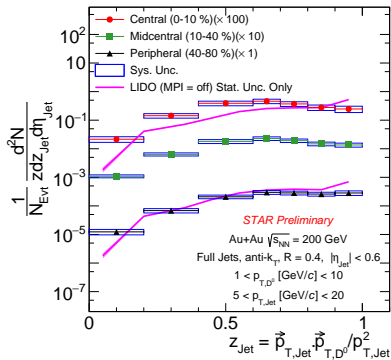
- p/π ratio suppressed inside jet cones compared to inclusive $p+p$
- No significant difference in Au+Au p/π ratio compared to $p+p$

Flavour dependence - D^0 jets

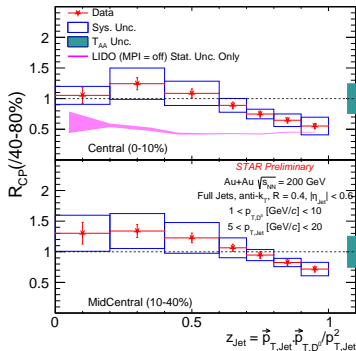
$$z_{\text{Jet}} = \frac{\vec{p}_{T,\text{Jet}} \cdot \vec{p}_{T,D^0}}{|\vec{p}_{T,\text{Jet}}|^2}, \text{ Low/High } z_{\text{Jet}} \rightarrow \text{soft/hard-fragmented } D^0 \text{ jet}$$



Flavour dependence - D^0 jets



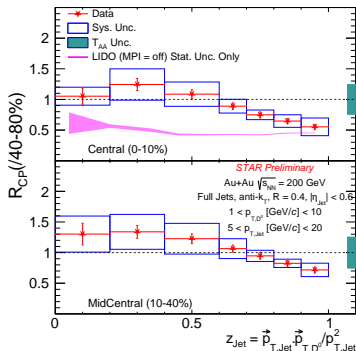
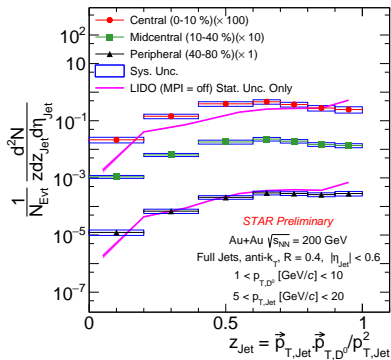
Hard fragmented D^0 jet R_{CP} suppressed in central and midcentral events



Soft fragmented D^0 jet R_{CP} consistent with 1 in central and midcentral events

Flavour dependence - D^0 jets

LIDO, Phys. Rev. C 98, 064901



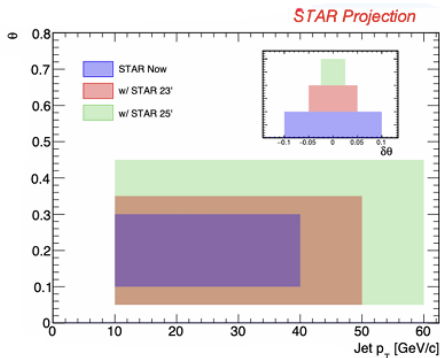
LIDO underpredicts soft-fragmented D^0 jets in central events, overpredicts hard-fragmented D^0 jets

LIDO predicts flat R_{CP} , which agrees with data for D^0 jets with highest z_{Jet} (hardest-fragmented)

$\sqrt{s_{NN}}$ (GeV)	Species	Sampled Luminosity	Year
200	Au+Au&p+Au	AuAu 32.7 nb ⁻¹ / pAu 0.69 pb ⁻¹	2023+2025
200	p+p	142 pb ⁻¹	2024

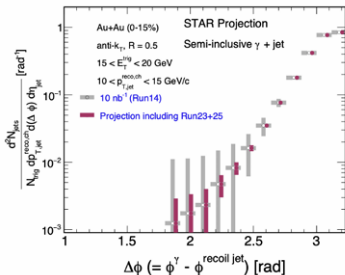
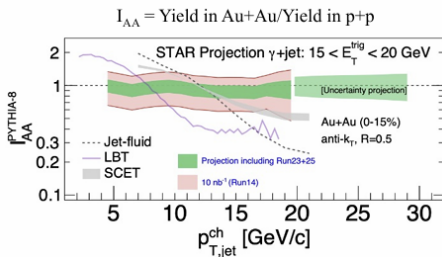
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- Increased statistics for jet substructure measurements
- Access to high p_T jets and wide angle radiation
- Increased angular resolution



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- Wider kinematic range for I_{AA} (current results: <https://arxiv.org/abs/2309.00156>) and acoplanarity measurements
- Larger statistics → Improved uncertainty



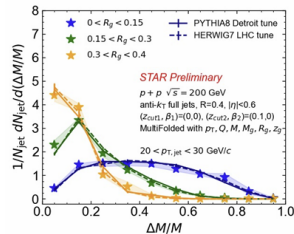
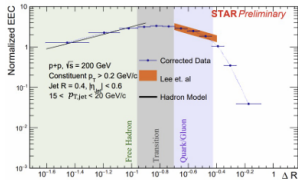


- HERWIG tune to RHIC kinematics ongoing
- Jet chemistry in unbiased sample (constituent p_T dependence)
- Generalized angularities for D^0 -jets
- Higher order EECs, charge dependence, medium modifications

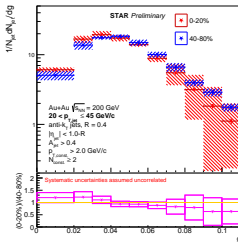
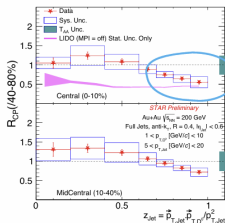
Summary



Precision era of jet substructure



Medium modification of jets



Differential jet yield modifications

