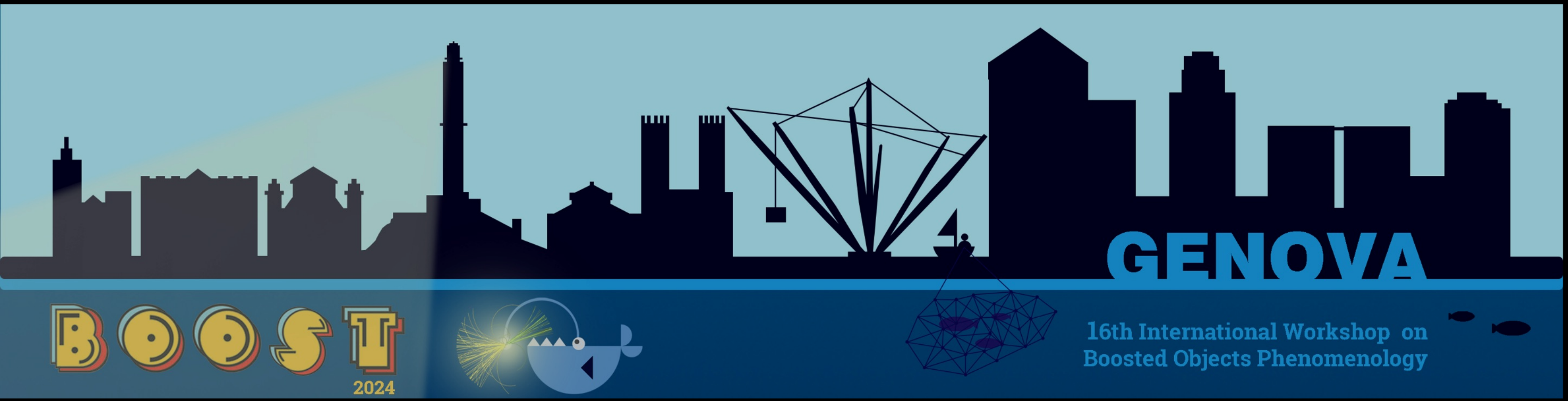

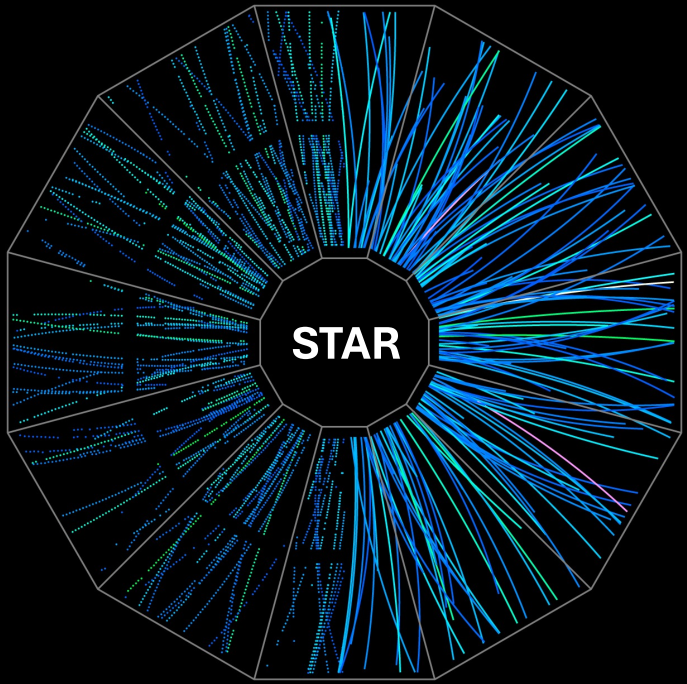

Jet Substructure Measurements at STAR

Diptanil Roy
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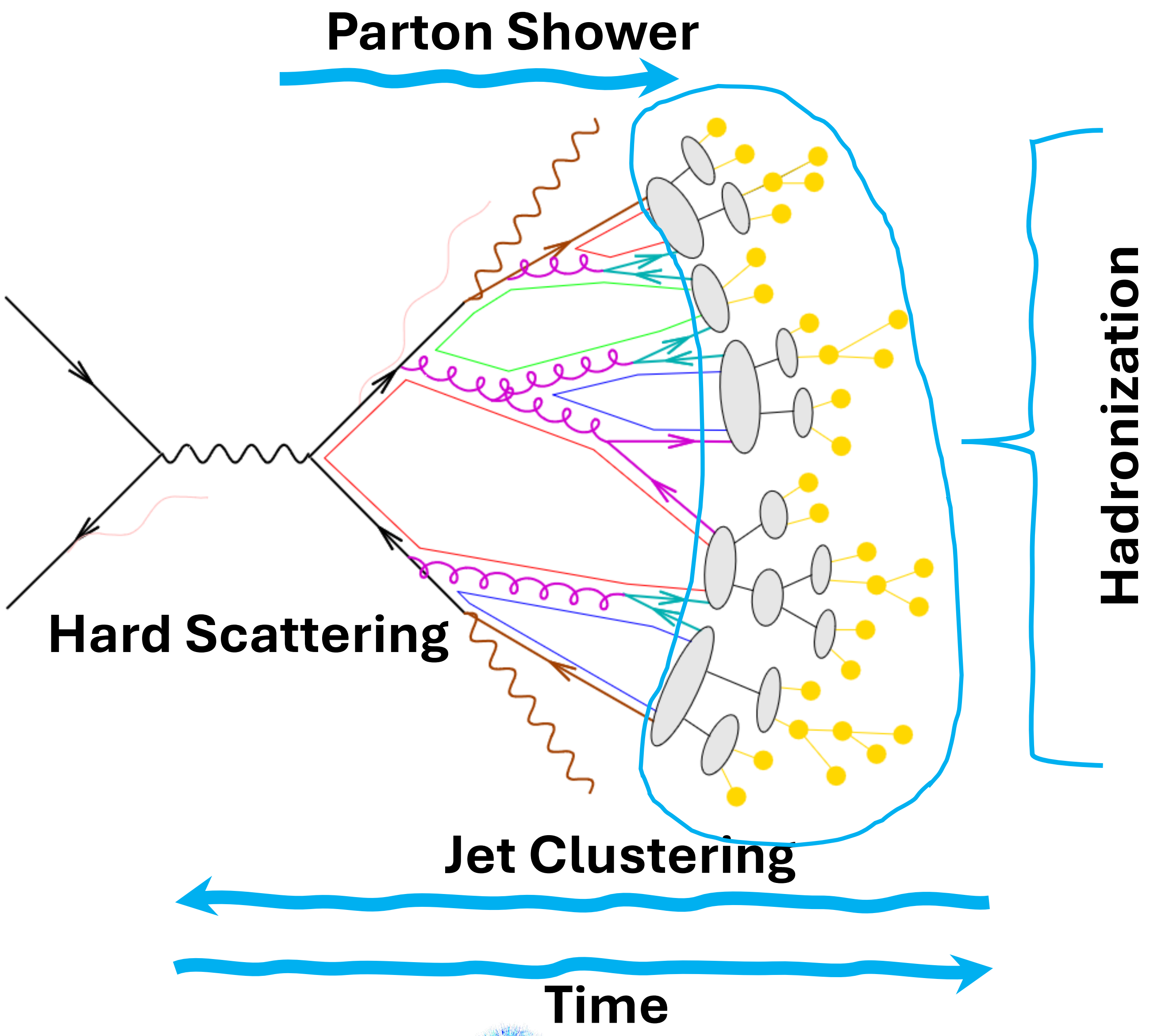
July 28 – Aug 2, 2024

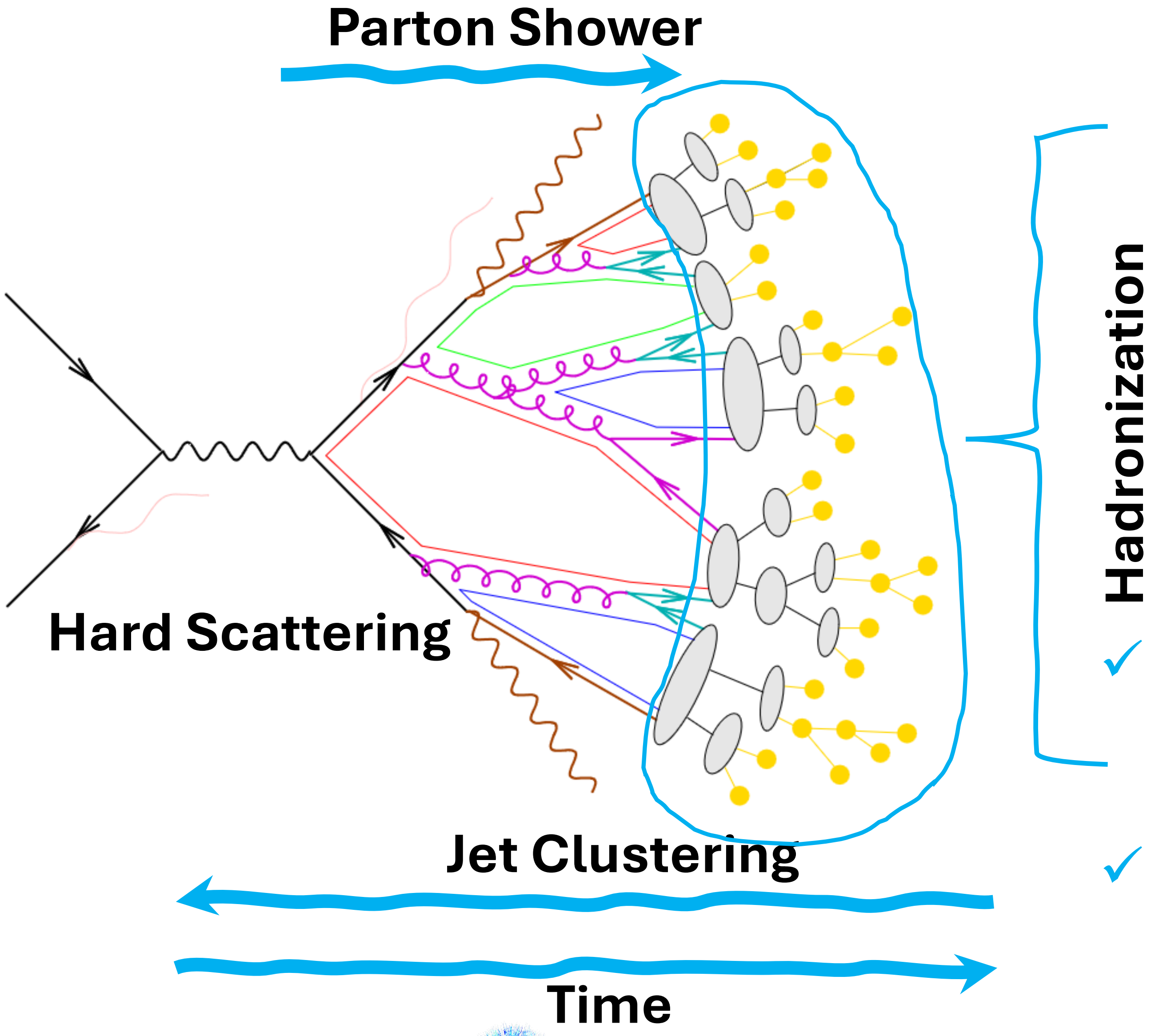
Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

Jets in vacuum



- Proxies for hard scattered partons
- Production explained by pQCD
- Clustering algorithms use final state particles to reconstruct jets
- Jet substructure holds information about fragmentation and hadronization processes

Jets in vacuum

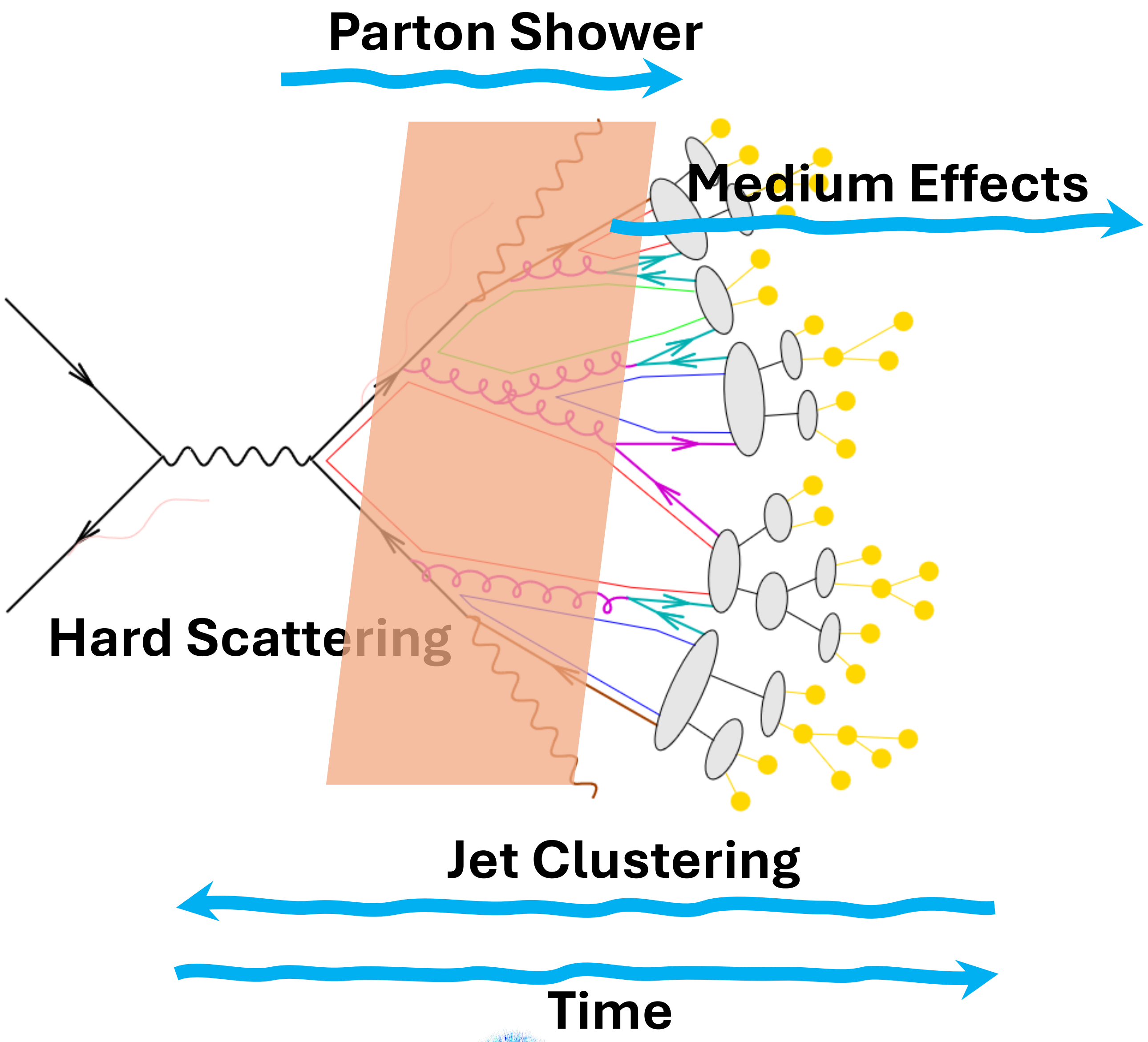


- Proxies for hard scattered partons
- Production explained by pQCD
- Clustering algorithms use final state particles to reconstruct jets
- Jet substructure holds information about fragmentation and hadronization processes

✓ ***Can we disentangle perturbative and non-perturbative physics in vacuum?***

✓ ***Can we use jet substructure to understand hadron formation better?***

Jets in medium

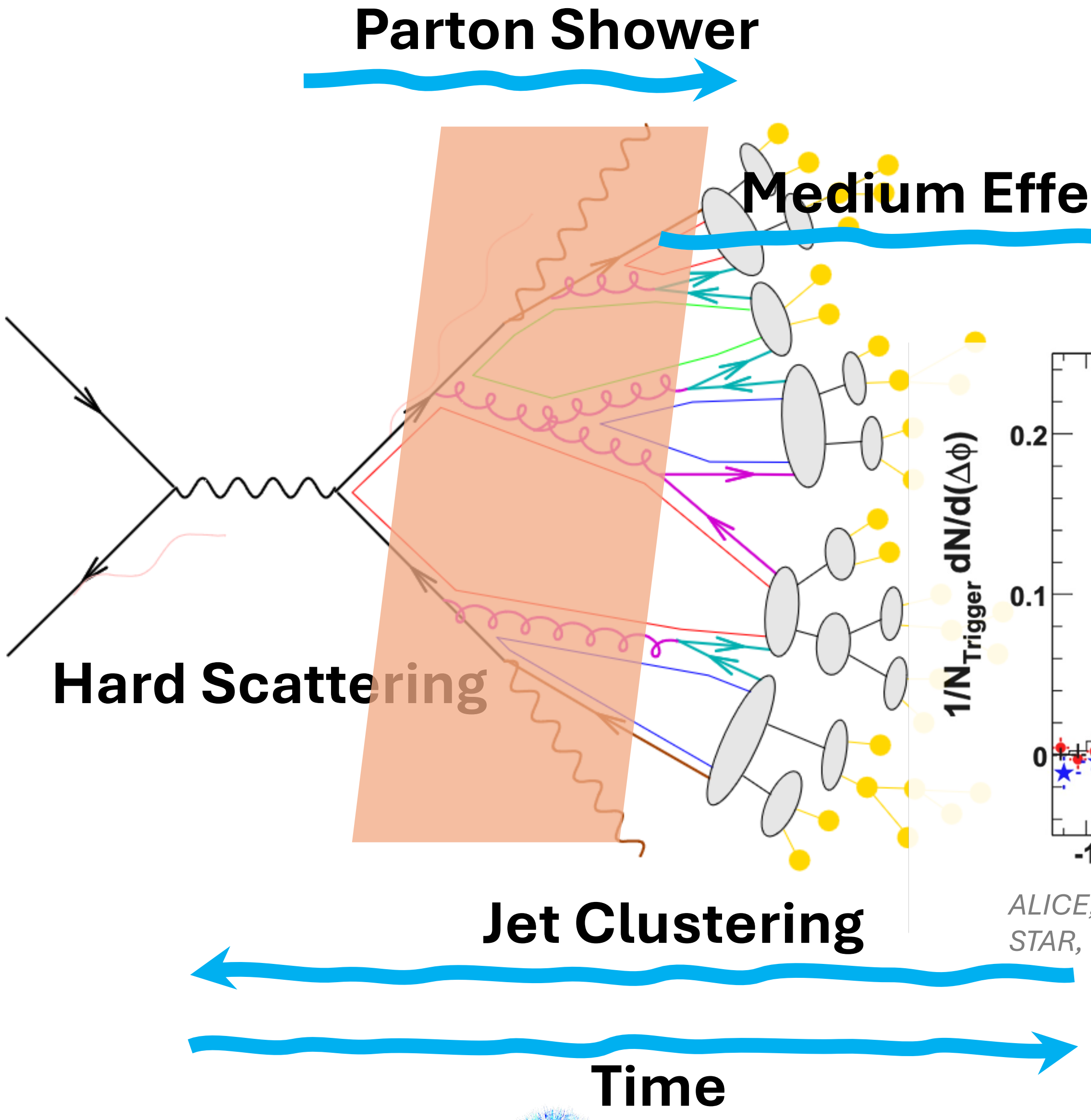


Images by Caitie Beattie

Elastic collisions (collisional)

Inelastic collisions (radiative)

Jets in medium



Images by Caitie Beattie

Elastic collisions (collisional)

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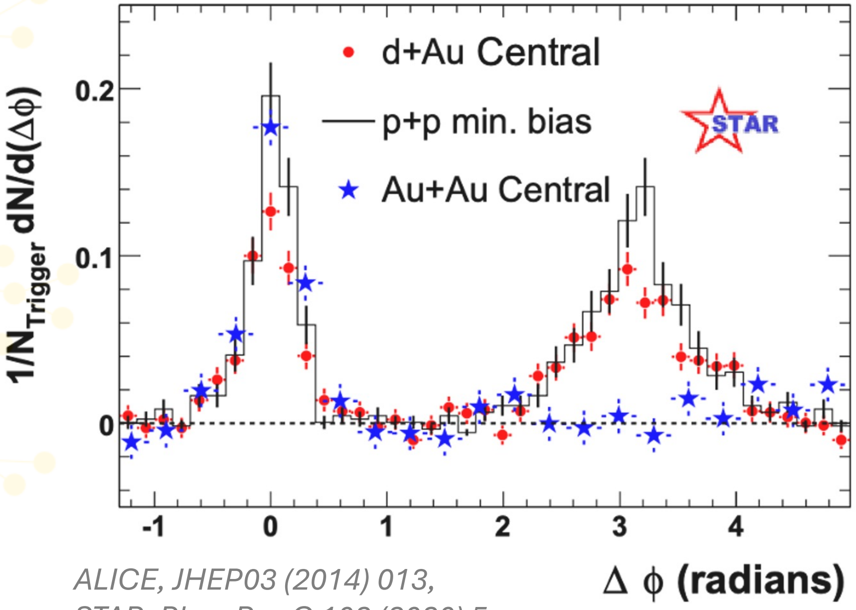
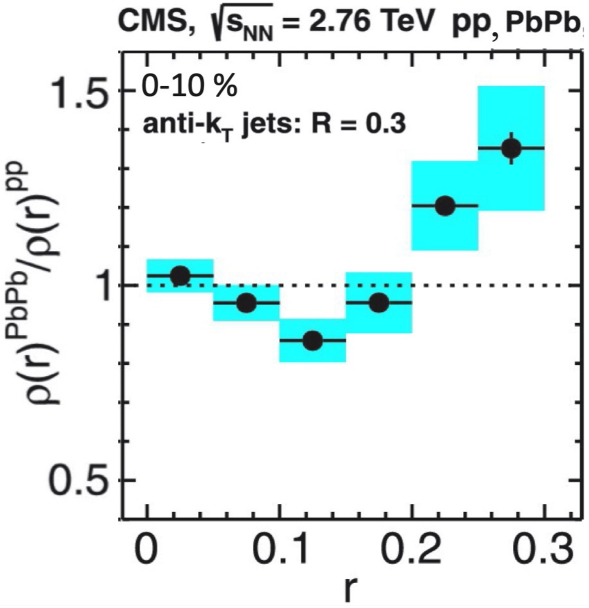


ALICE, JHEP03 (2014) 013,
STAR, Phys.Rev.C 102 (2020) 5

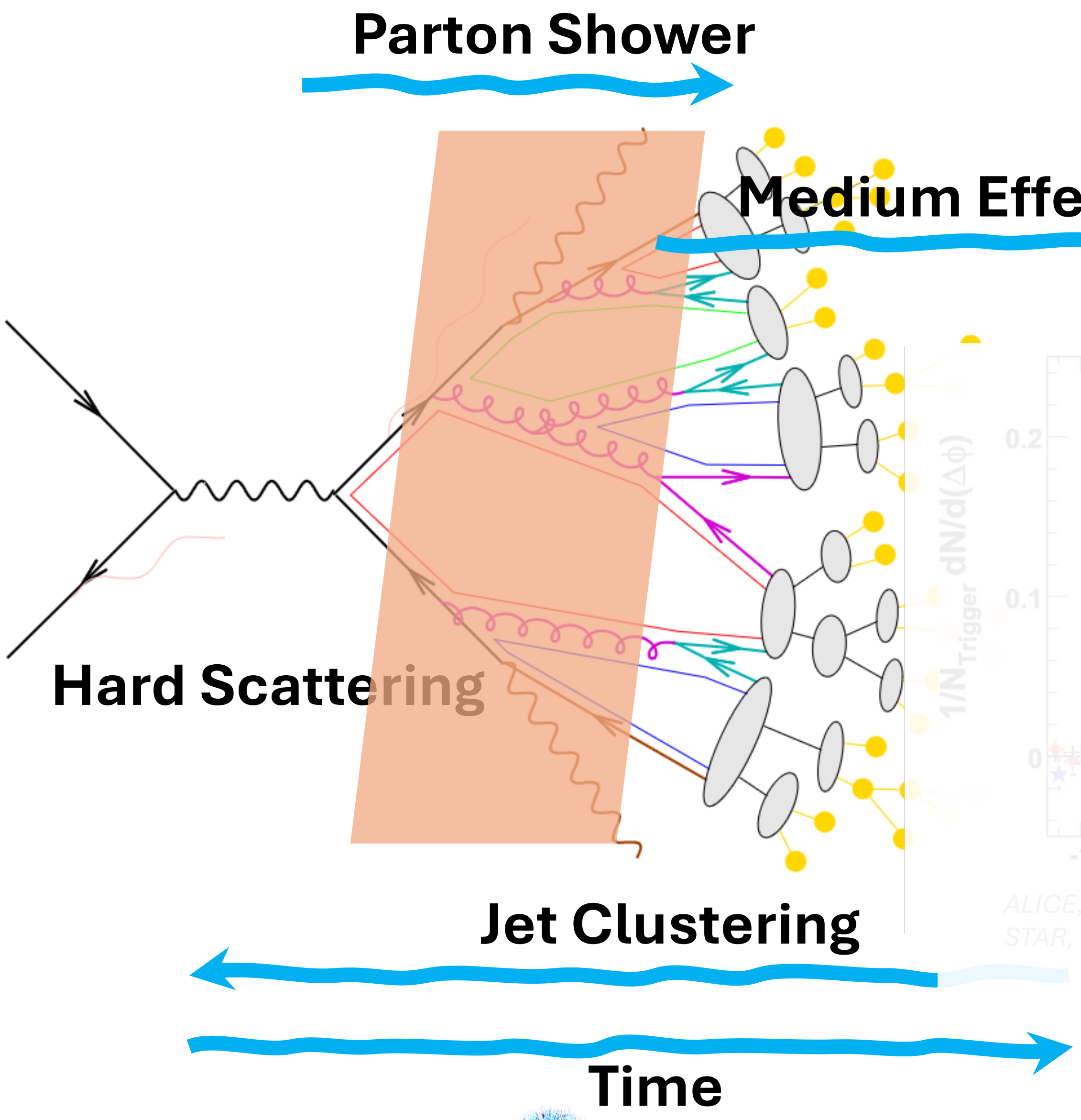
Energy Loss



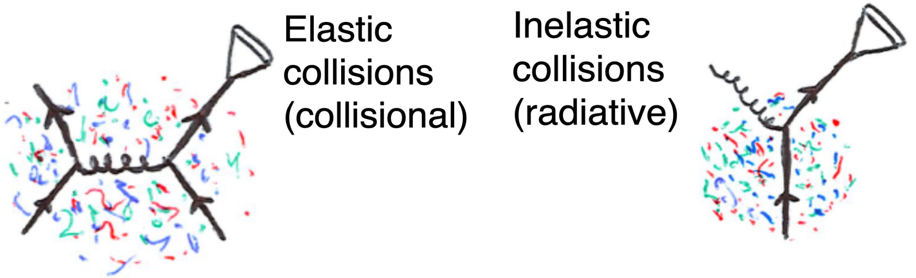
CMS, Phys. Lett. B 730 (2014) 243

Jet Broadening

Jets in medium

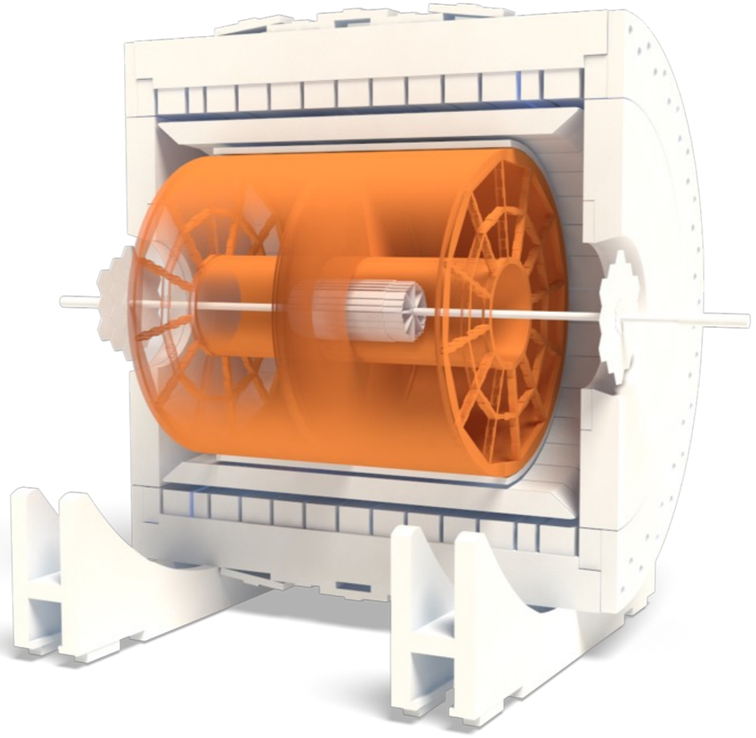


Images by Caitie Beattie



- ✓ ***Is suppression system size and geometry dependent?***
- ✓ ***Does the medium change the chemistry of the hard scattered jets?***
- ✓ ***Does the flavor of the parton influence medium effects?***

STAR at RHIC



Time Projection Chamber

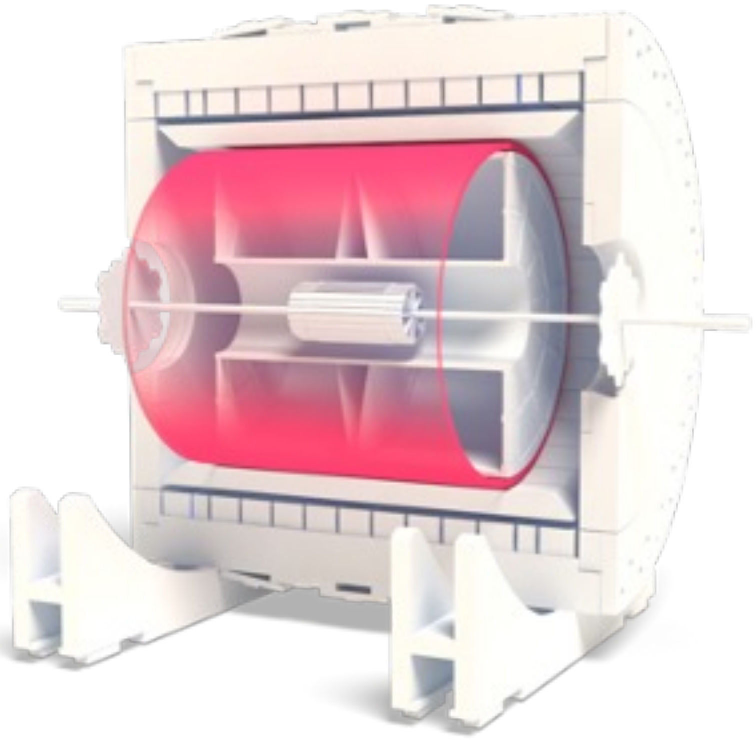
- ✓ Measures momenta of charged tracks $[|\eta| < 1, 0 < \phi < 2\pi]$
- ✓ PID using dE/dx

Images: NSWW

STAR at RHIC

Time-Of-Flight Detector

- ✓ PID using TOF measurement $[|\eta| < 1, 0 < \phi < 2\pi]$



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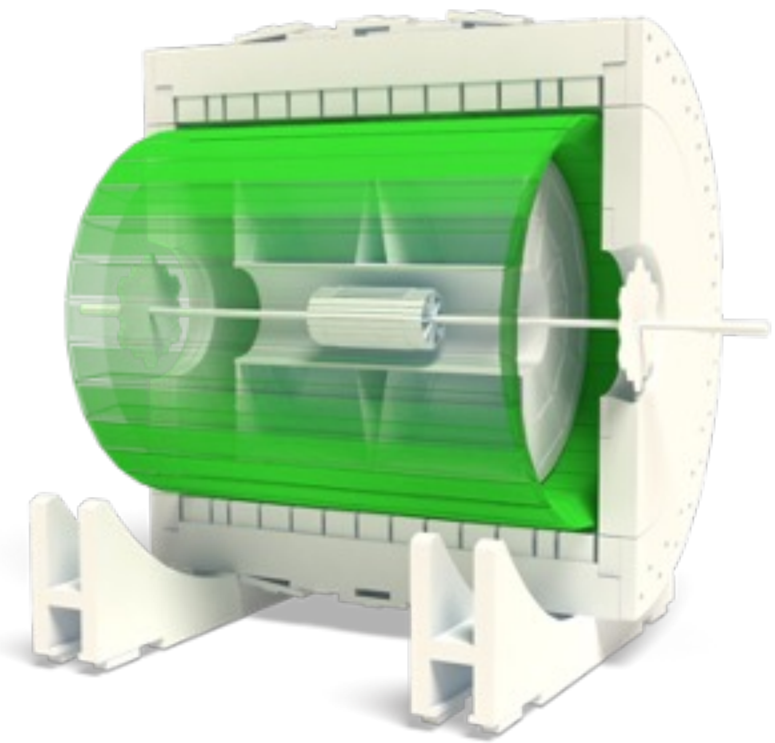
Barrel Electromagnetic Calorimeter

- ✓ Measures neutral component of jet energy $[|\eta| < 1, 0 < \phi < 2\pi]$



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Images: NSWW

STAR at RHIC

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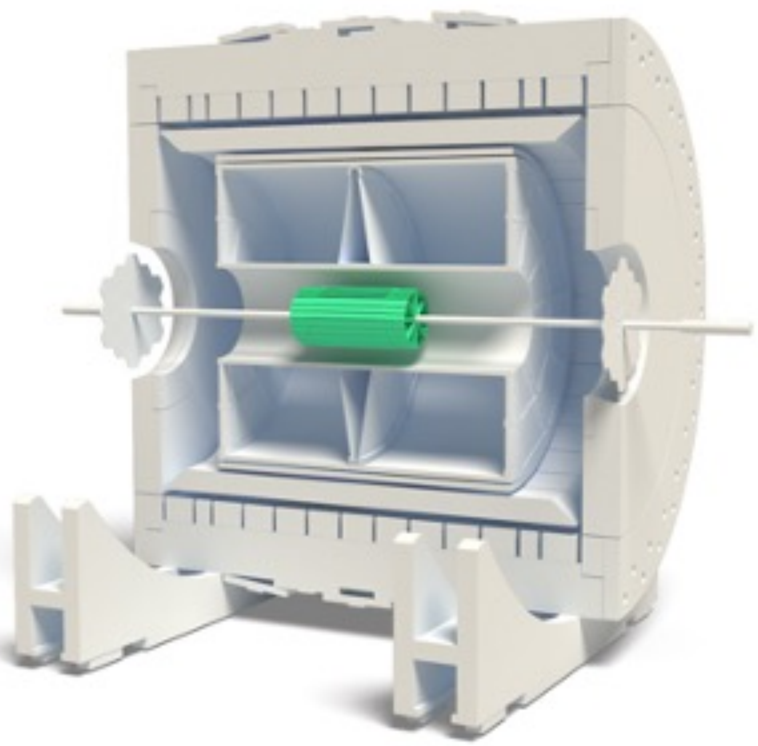


Time Projection Chamber

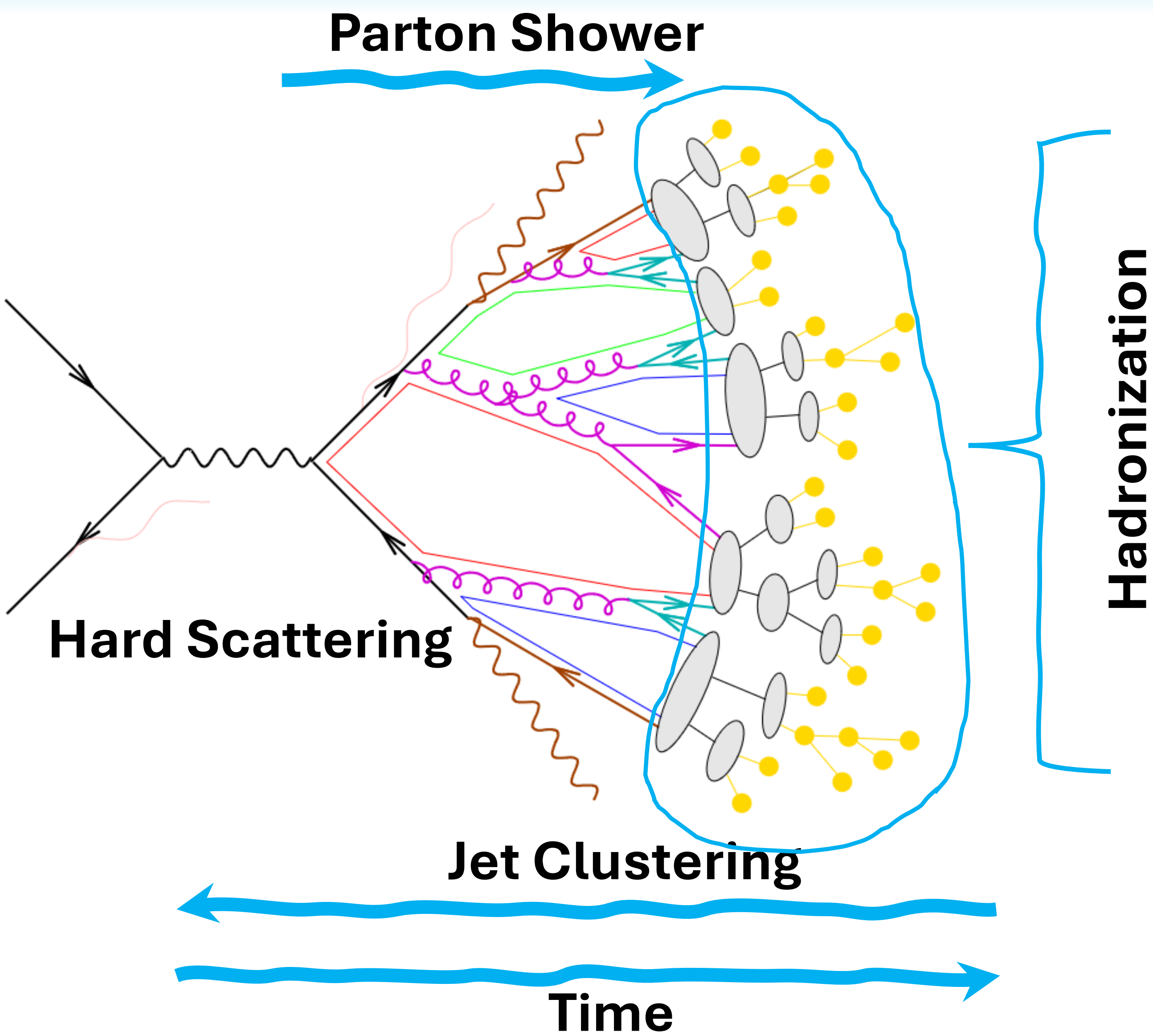
- ✓ Measures momenta of charged tracks $[|\eta| < 1, 0 < \phi < 2\pi]$
- ✓ PID using dE/dx

Heavy Flavor Tracker (2014-2016)

- ✓ Improves position resolution for secondary vertices

Images: NSWW

Jets in vacuum



Isolating pQCD and npQCD in vacuum

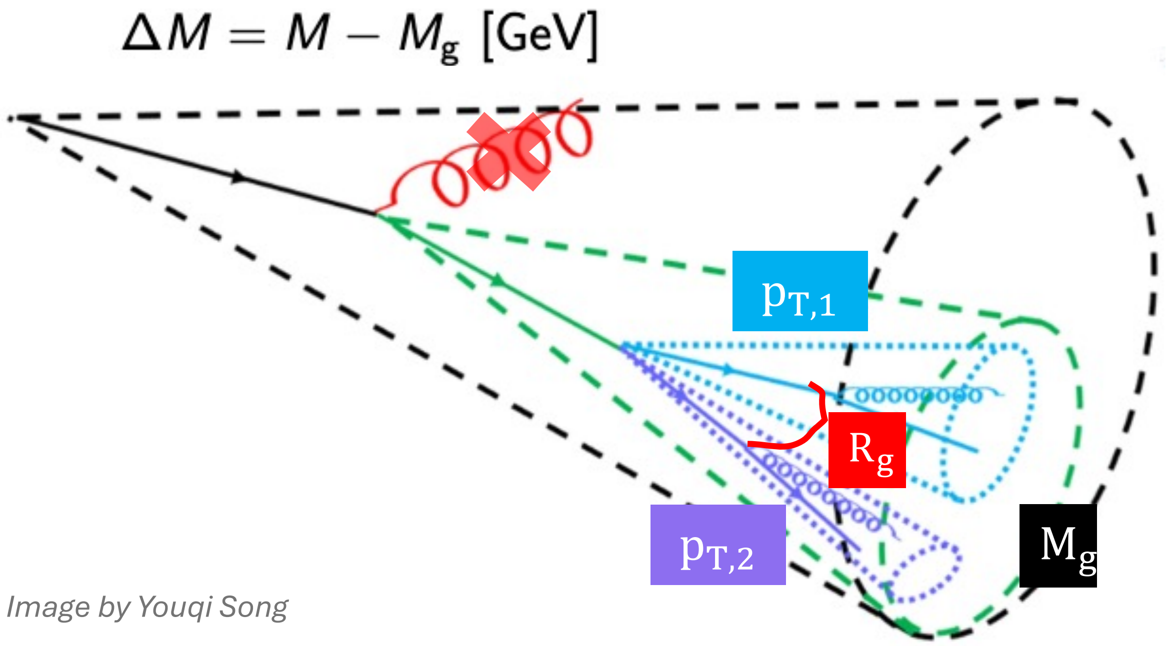
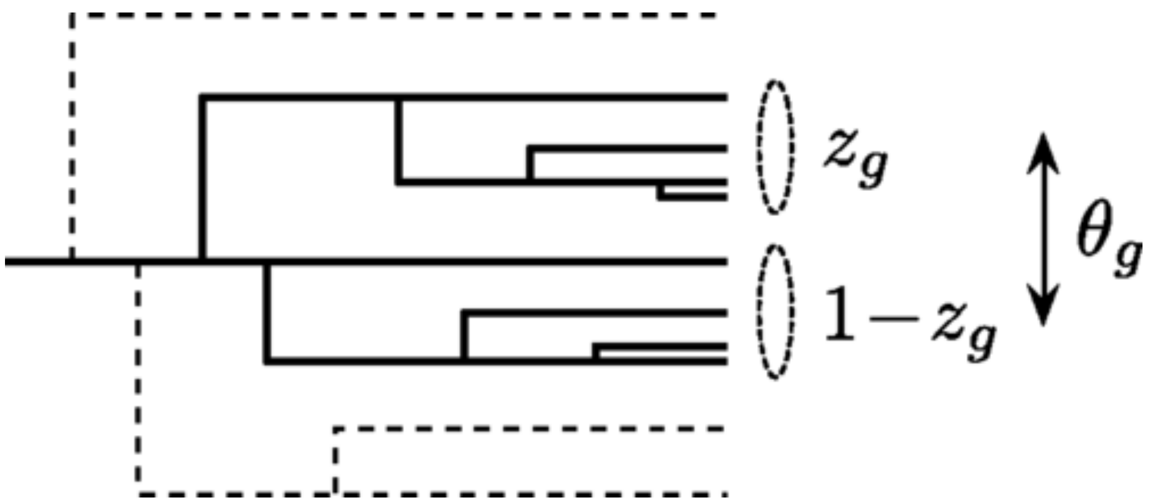


Image by Youqi Song

Image: Larkoski, Marzani, Thaler, Xue, PRL 119 (2017) 13, 132003



- **SoftDrop**: Groom a reconstructed jet to remove wide-angle soft radiation
- **CollinearDrop**: Difference of an observable for an ungroomed vs groomed jet → Access to soft component of jet
- **Iterative SoftDrop:** Access to 1st, 2nd, 3rd splits of the shower

z_g = Shared momentum fraction

R_g = Distance of subjets at split

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

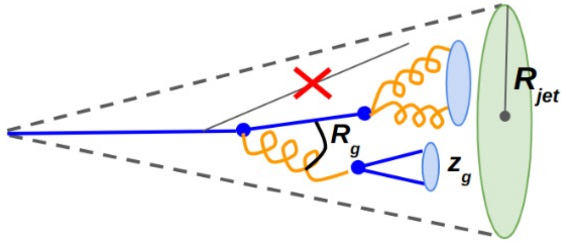
$z_{cut} = 0.1$

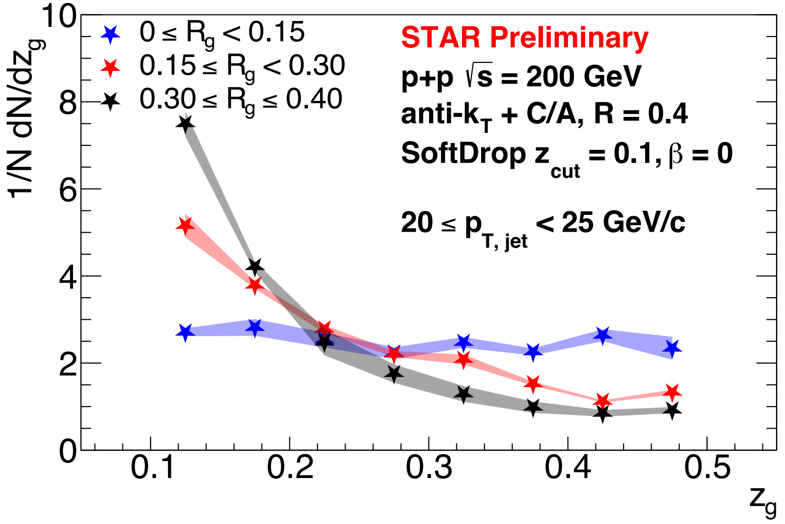
$\beta = 0$

$$\rightarrow \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1$$

Isolating pQCD and npQCD in vacuum

1^{st} split

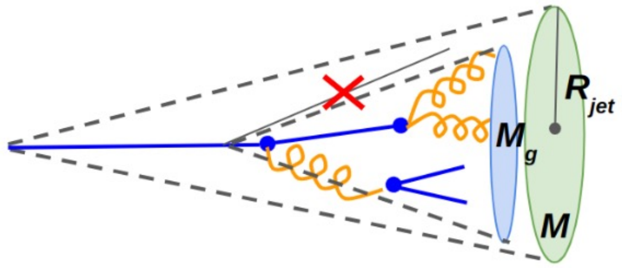


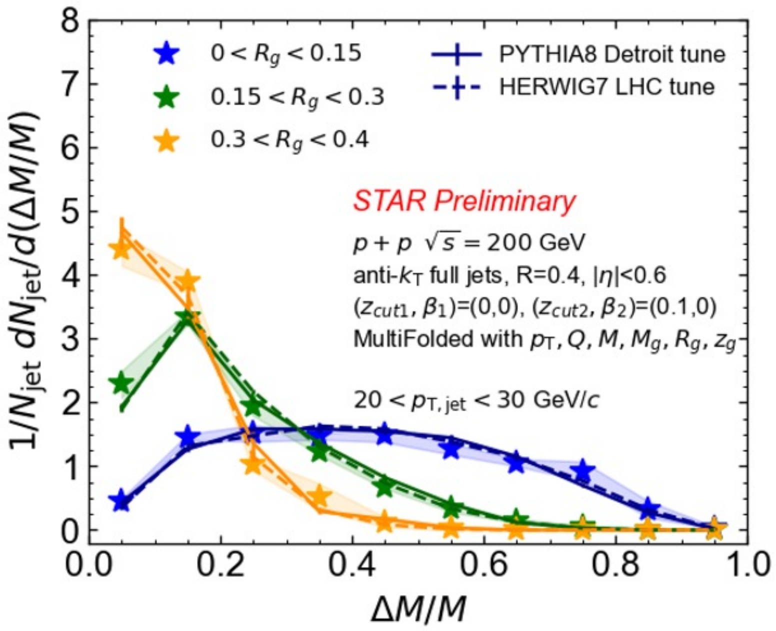


z_g = Shared momentum fraction
R_g = Distance of subjets at split
$\Delta M = M - M_g$ [GeV]

Perturbative

Larger R_g → Smaller $\langle \Delta M / M \rangle$ → Steeper z_g



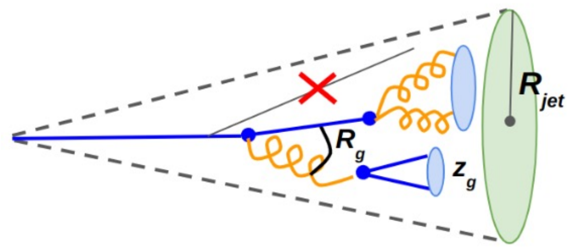


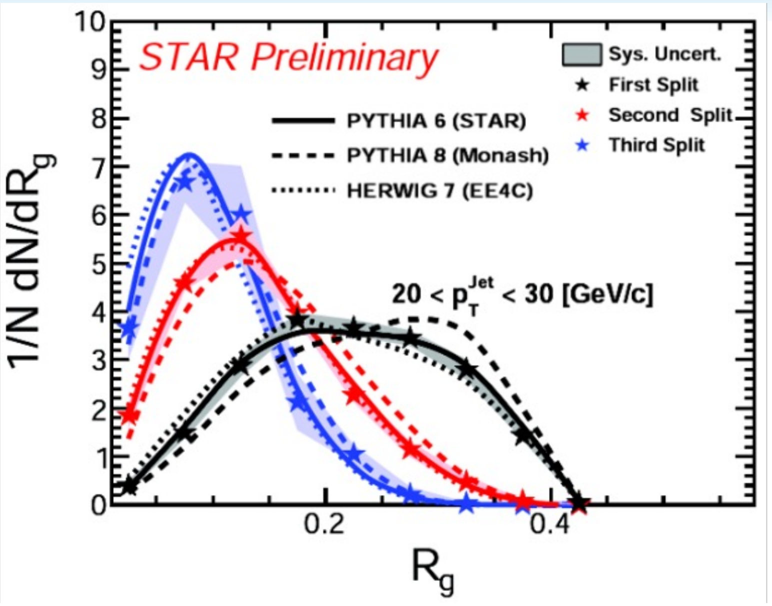
Non-perturbative

Smaller R_g → Larger $\langle \Delta M / M \rangle$ → Flatter z_g

Isolating pQCD and npQCD in vacuum

1^{st}, 2^{nd}, 3^{rd} splits

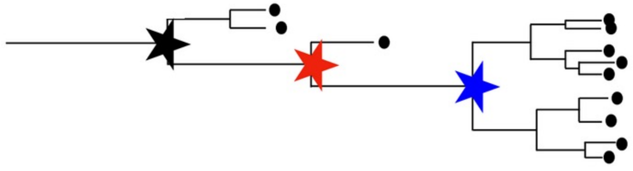




z_g = Shared momentum fraction
R_g = Distance of subjets at split
$\Delta M = M - M_g$ [GeV]

R_g becomes narrower from 1^{st} to 3^{rd} split

Change from soft wide-angle to hard collinear splitting



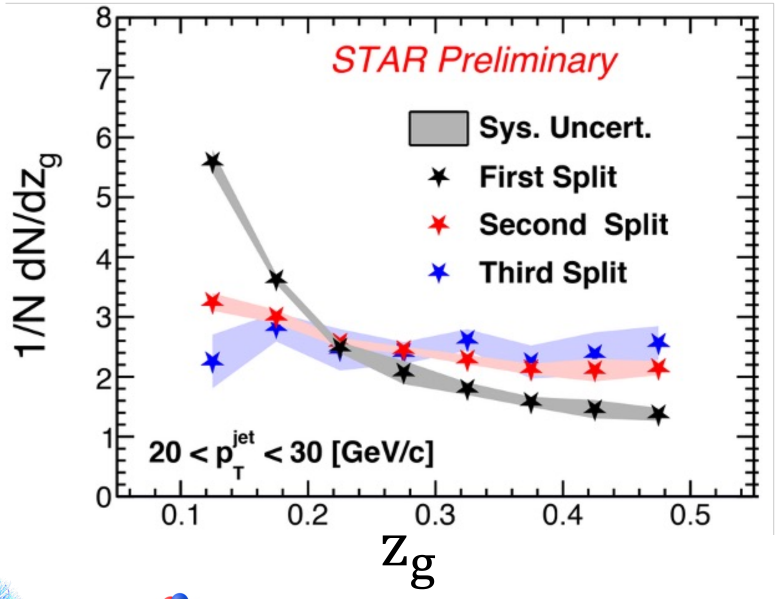


Image by Raghav Kunnawalkam Elayavalli

z_g becomes flatter from 1^{st} to 3^{rd} split

Perturbative to Non-perturbative transition

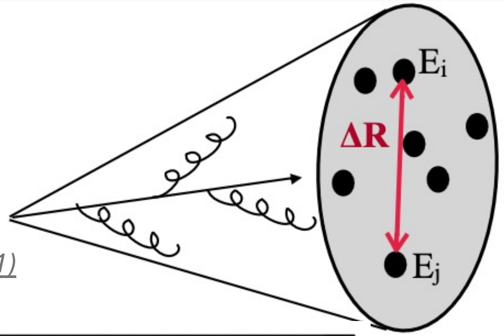
Can we pinpoint a distinct transition region?

Time evolution of jets in vacuum

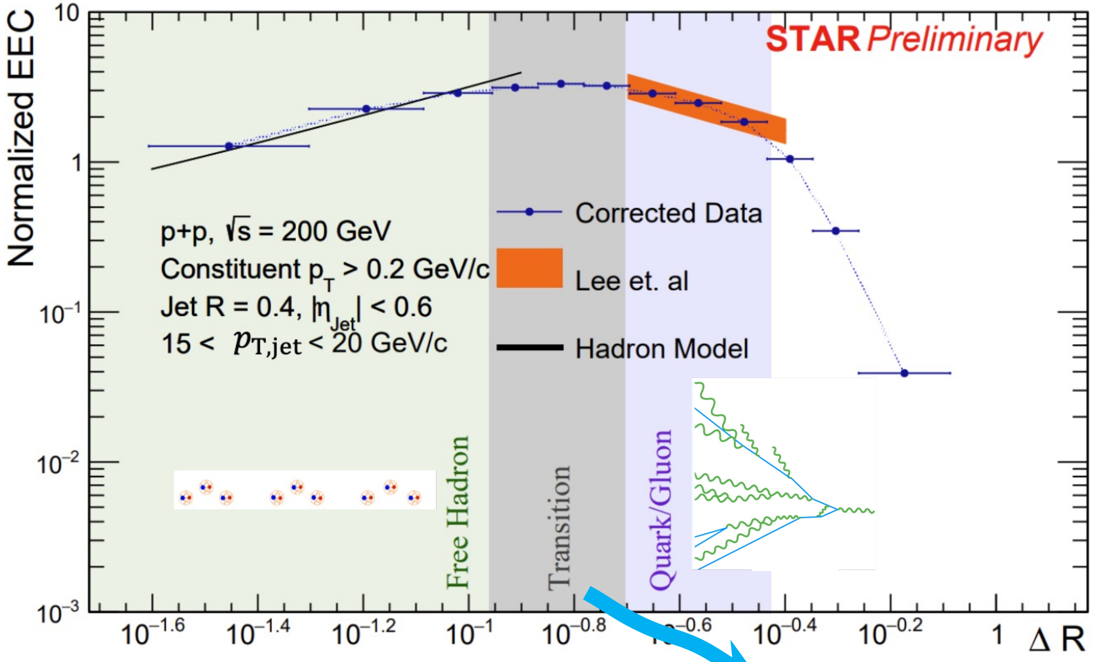
Energy-Energy Correlators

$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{p_{T,Jet}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{p_{T,Jet}^2}\right)}{d\,(\Delta R)}$$

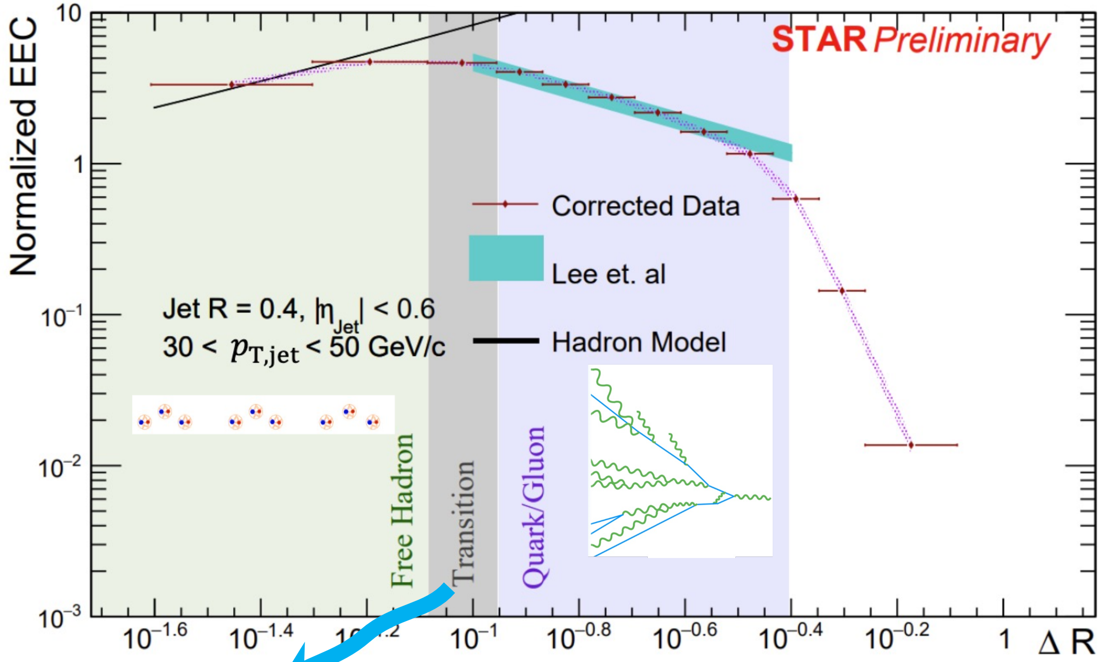
Formation Time: $t_f \propto \frac{1}{\Delta R^2}$



Apolinário, Cordeiro, & Zapp EPJC 81 (2021)



Lee, Mecaj, Moult, arxiv:2205.03414



Transition Region at $\Delta R_{Turnover} \times p_T^{Jet} \sim 2-3$ GeV → No p_T^{Jet} dependence

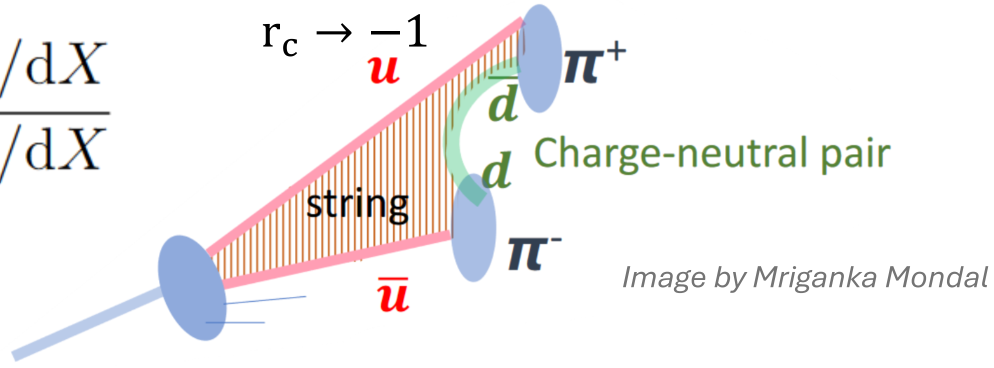
Universal scale for confinement of quark/gluon to hadrons

Probing npQCD region in vacuum

Charge Correlators

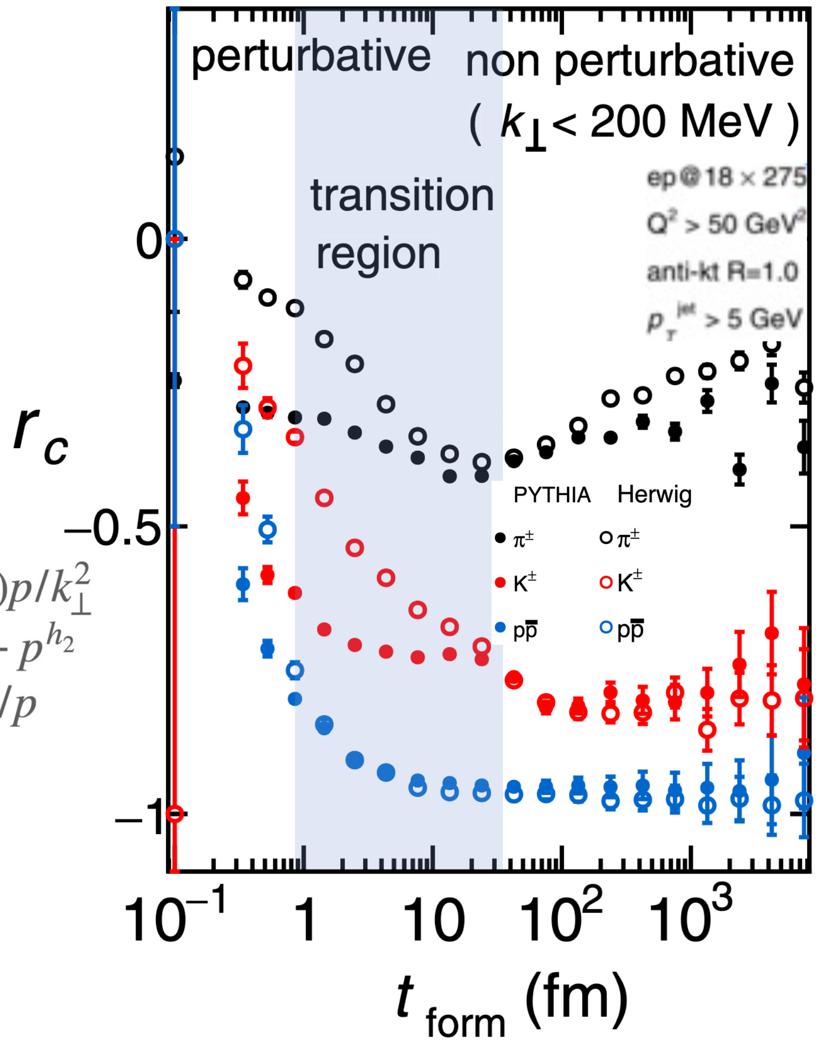
$$r_c(X) = \frac{d\sigma_{h_1h_2}/dX - d\sigma_{h_1\bar{h}_2}/dX}{d\sigma_{h_1h_2}/dX + d\sigma_{h_1\bar{h}_2}/dX}$$

h_1h_2: same charge hadrons,
$h_1\bar{h}_2$: opposite charge hadrons



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

$t_{\text{form}} = z(1-z)p/k_\perp^2$
with $p = p^{h_1} + p^{h_2}$
and $z = p^{h_2}/p$



- r_c can probe for evidence of string-like fragmentation
- In vacuum, can establish baseline for studying medium modification of hadronization

Probing npQCD region in vacuum

Charge Correlators

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1\bar{h}_2}/\mathrm{d}X}$$

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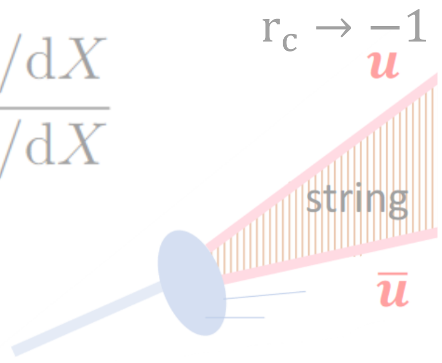
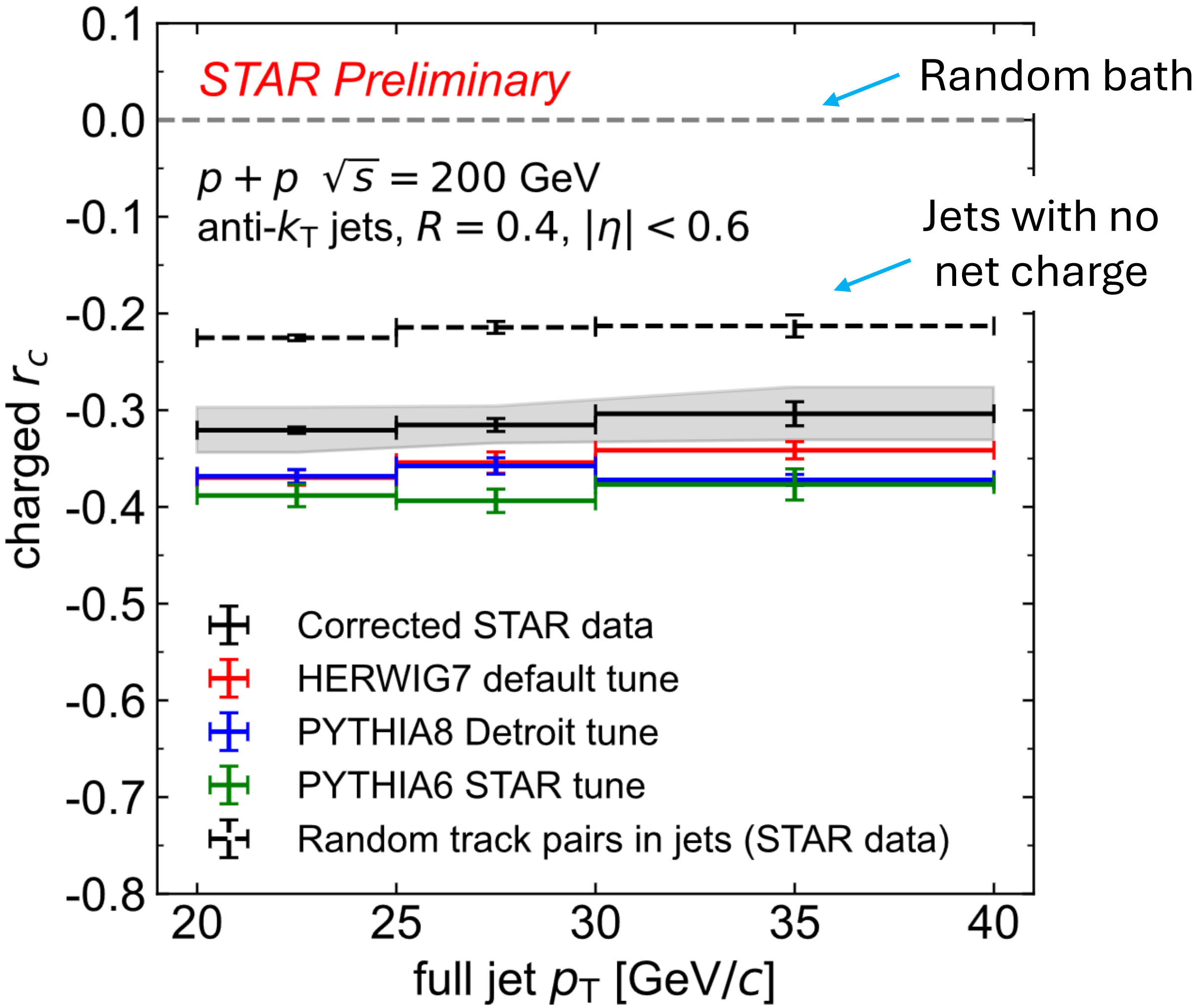


Chien, Deshpande, Mondal, Sterm

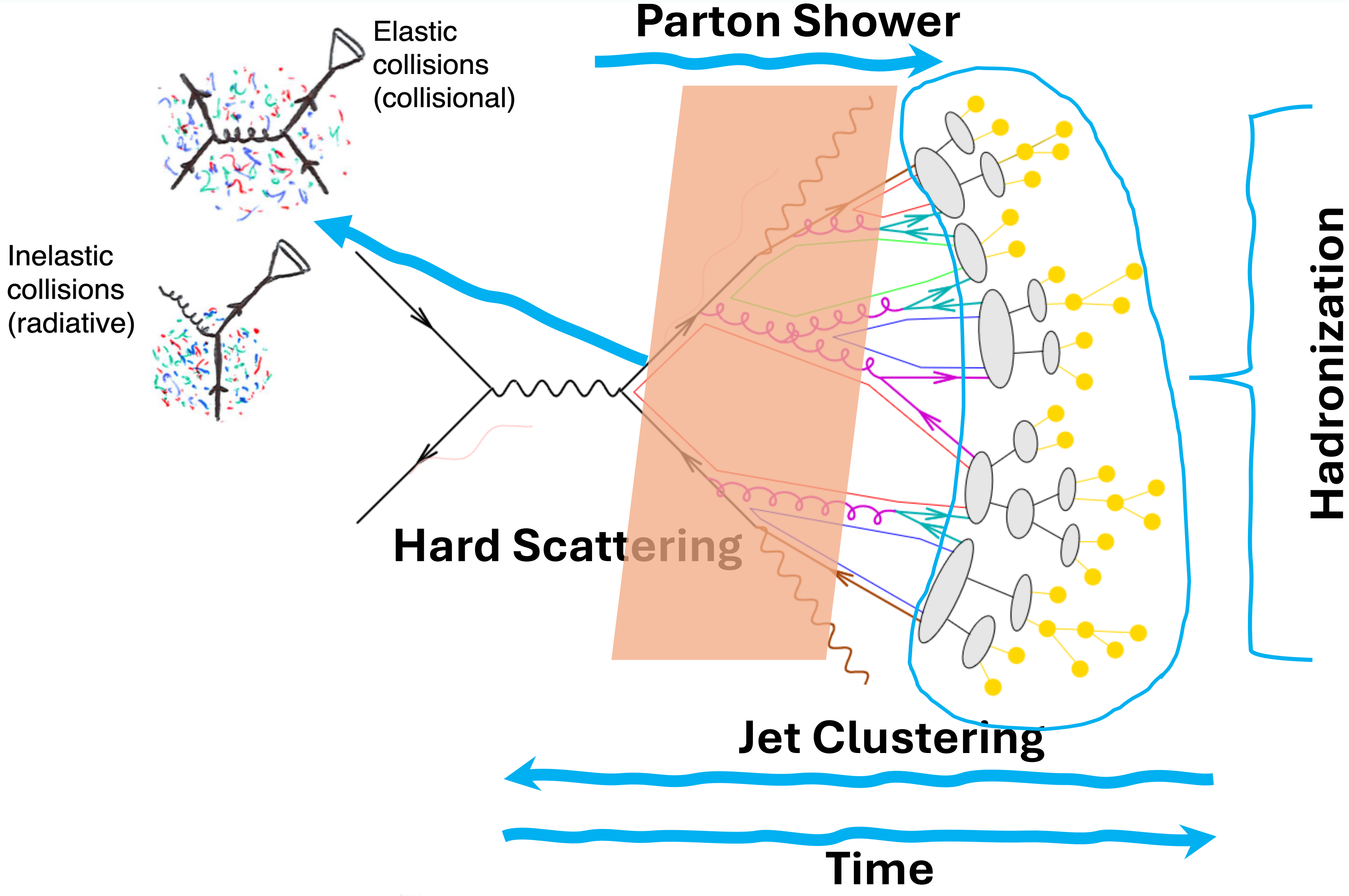
- r_c can probe for evidence of string-like fragmenta
- In vacuum, can establish baseline for studying m modification of hadronization



First measurement in p+p: Both string-like and cluster hadronization underpredict STAR data

More model tuning required.

Jets in medium

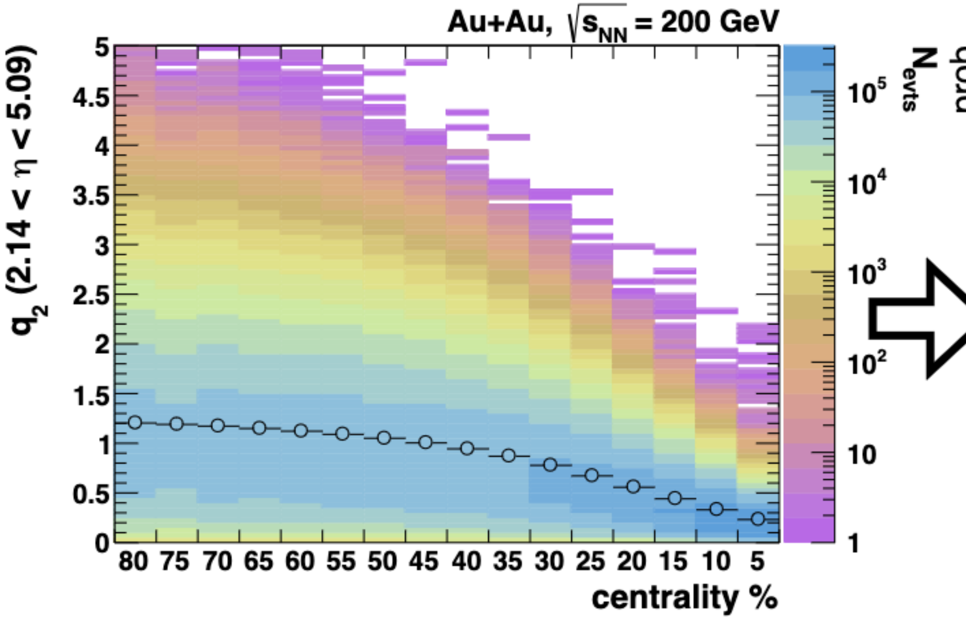


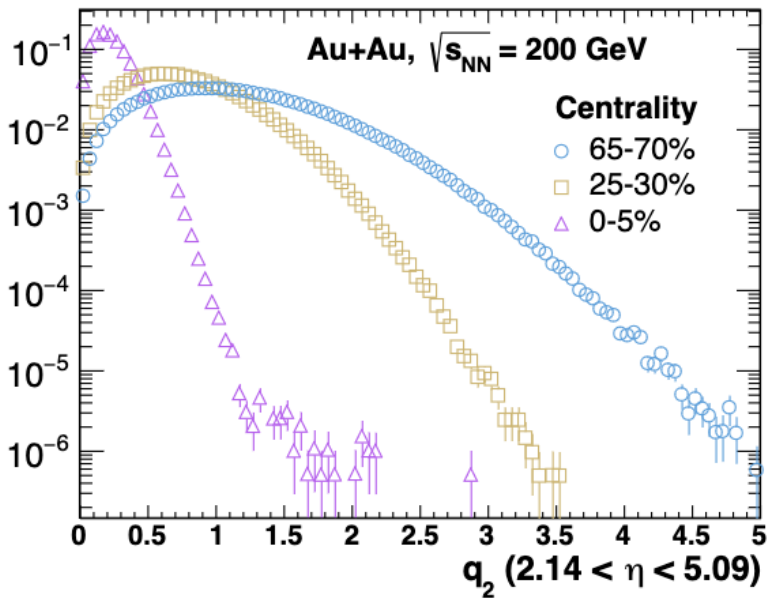
Event shape engineering

$$Q_2 = \left(\sum_{i=1}^{M} w_i \cos(2\phi_i), \sum_{i=1}^{M} w_i \sin(2\phi_i)\right), \; q_2 = |Q_2|/\sqrt{M},$$

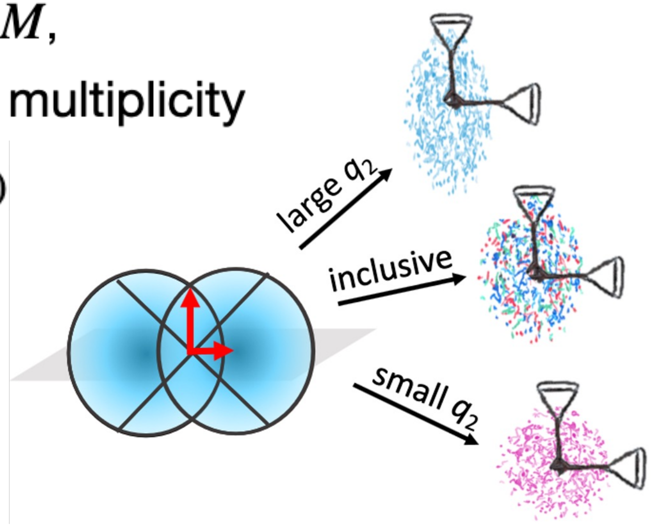
w_i: nMIP weight, M: multiplicity

$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$





Images by Caitie Beattie



- Centrality and q_2 are correlated, event selection based on both centrality and q_2
- Charged particle spectra from TPC, q_2 from EPD-W to avoid autocorrelation

Event shape engineering

$$Q_2 = \left(\sum_{i=1}^{M} w_i \cos(2\phi_i), \sum_{i=1}^{M} w_i \sin(2\phi_i)\right),\ q_2 = |Q_2|/\sqrt{M},$$

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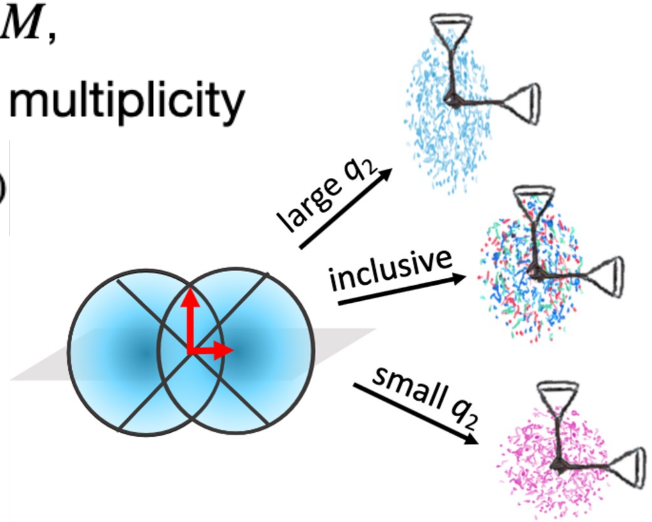
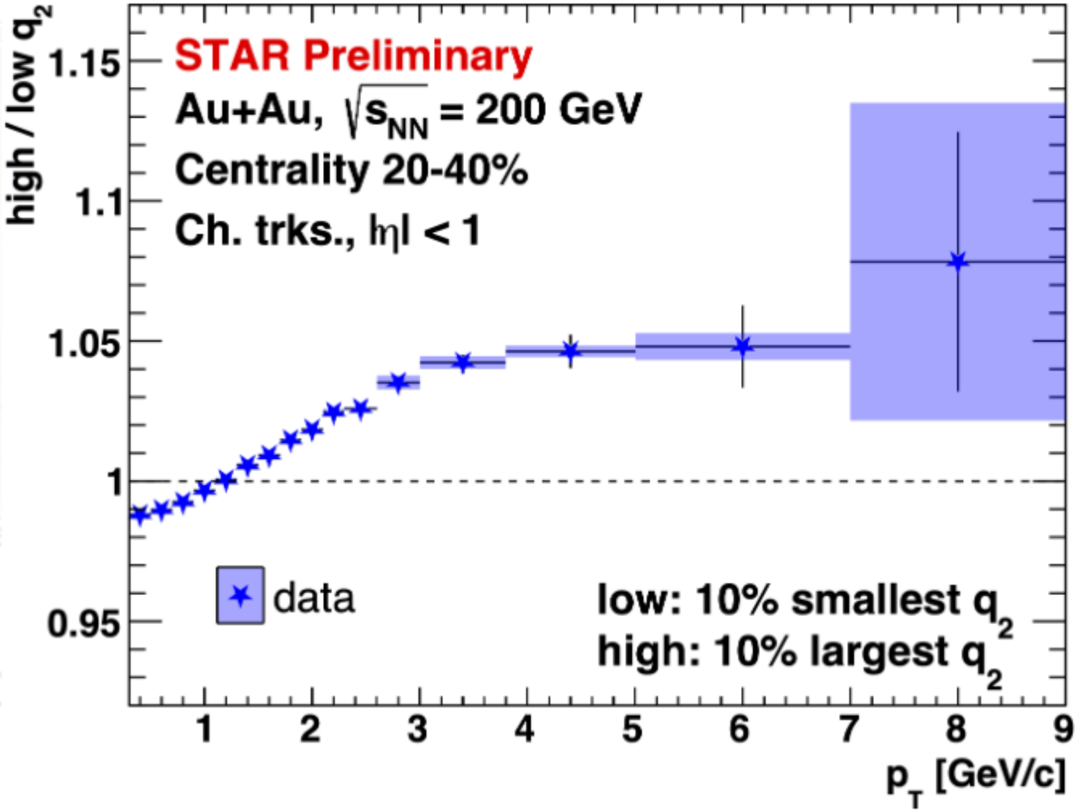
$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$

Images by Caitie Beattie





- Hardened charged particle spectra in high-q_2 events, flattened at high p_T
- Consistent with ALICE results at 2.76 TeV

ALICE, PRC 93 (2016) 3, 034916

Jet substructure in medium

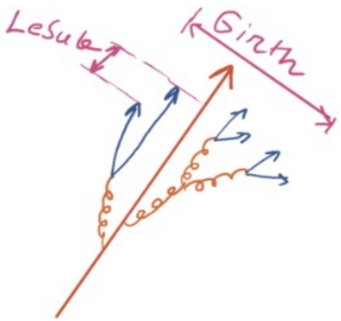
Generalized Angularities

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

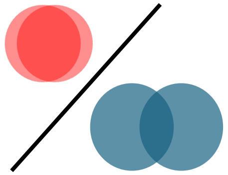
$\lambda_1^1 = g$ - girth

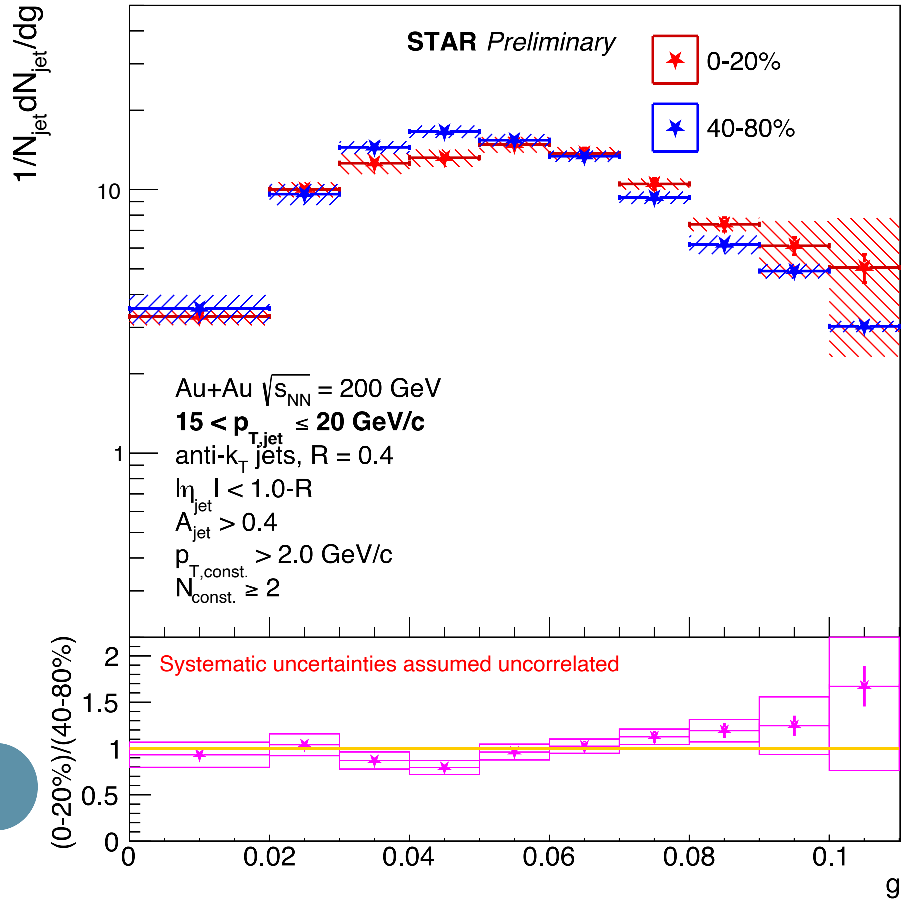
λ_2^1 - thrust

$\lambda_0^2 = (p_T^D)^2$ - momentum dispersion



- Angularities, tunable sensitivities to energy, angular scales – some of them are IRC safe
- Can probe the modification of radiation pattern in medium





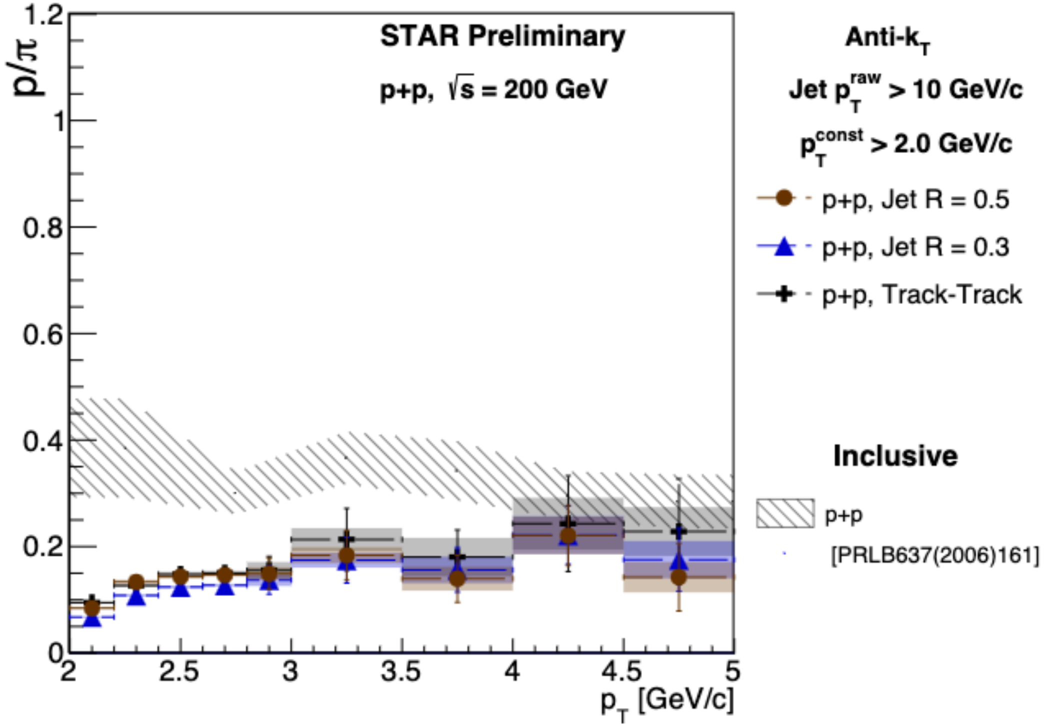
Girth consistent in central and peripheral collisions

Better handle on systematics and sample bias being explored

Jet chemistry

Baryon-To-Meson Ratio in p+p and Au+Au

$$\frac{p^+ + p^-}{\pi^+ + \pi^-}$$



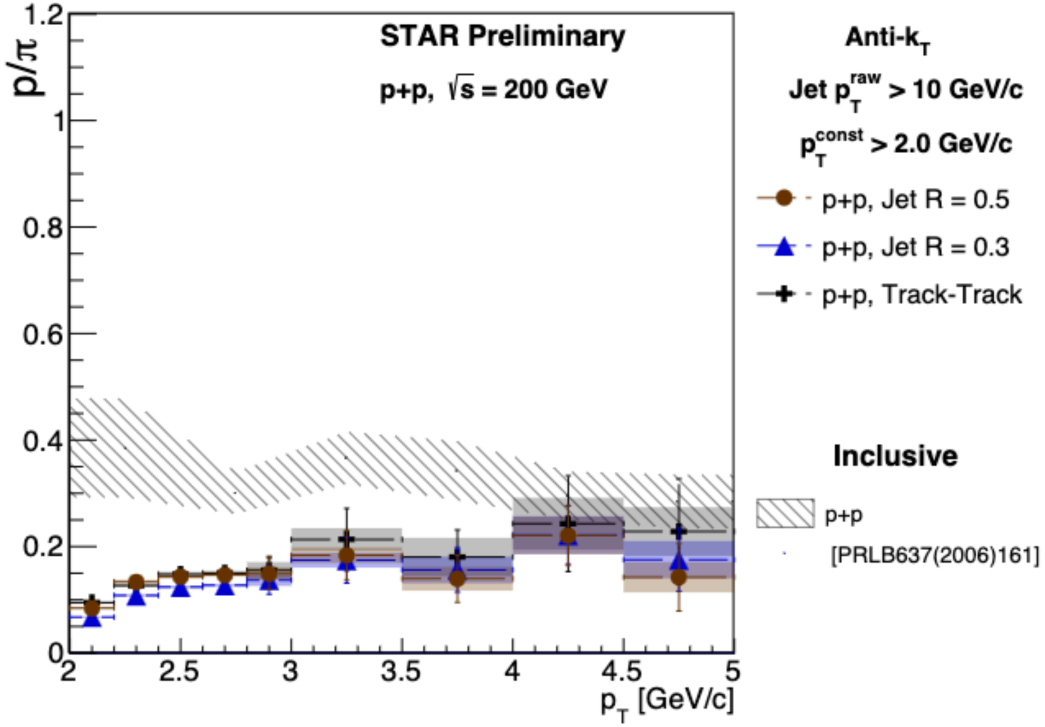
Pion production preferred over proton in jets

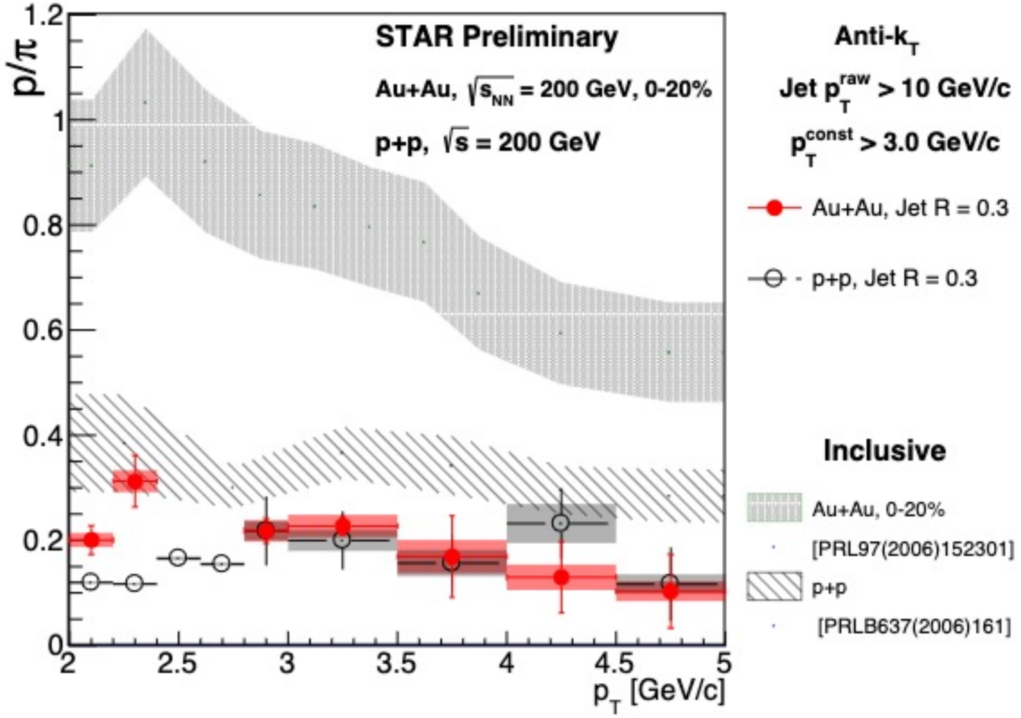
Stronger preference for pions in jets compared to inclusive p+p

Jet chemistry

Baryon-To-Meson Ratio in p+p and Au+Au

$$\frac{p^+ + p^-}{\pi^+ + \pi^-}$$





Pion production preferred over proton in jets

No significant difference in Au+Au p/π ratio compared to p+p

Stronger preference for pions in jets compared to inclusive p+p

Hard-core selection bias (?) Survivor bias(?)

Studies ongoing with jets with different hard-core definitions

Flavor dependence – D^0 jets

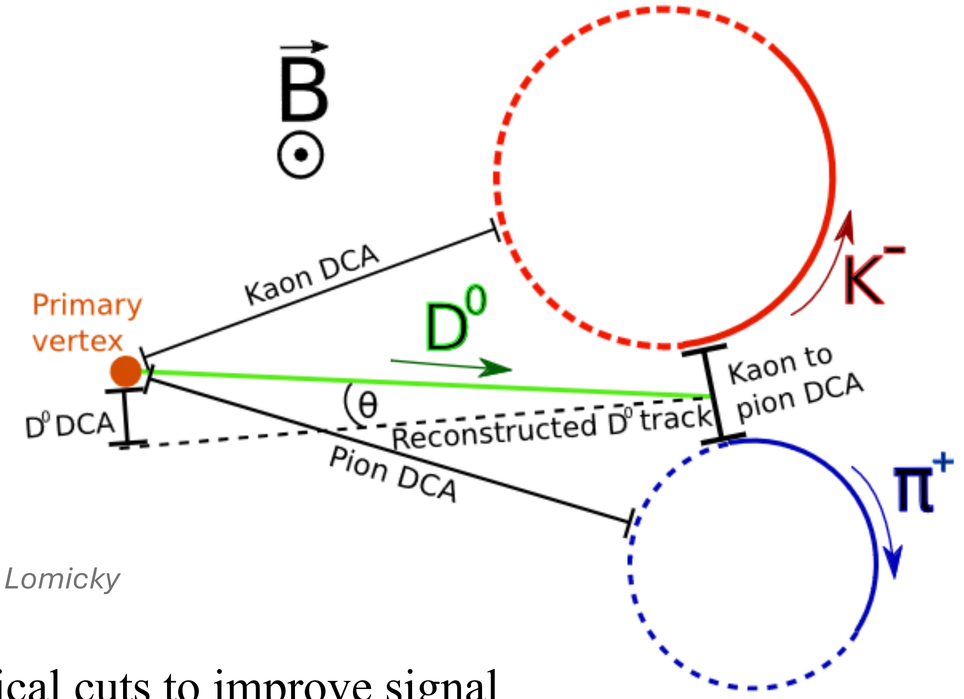
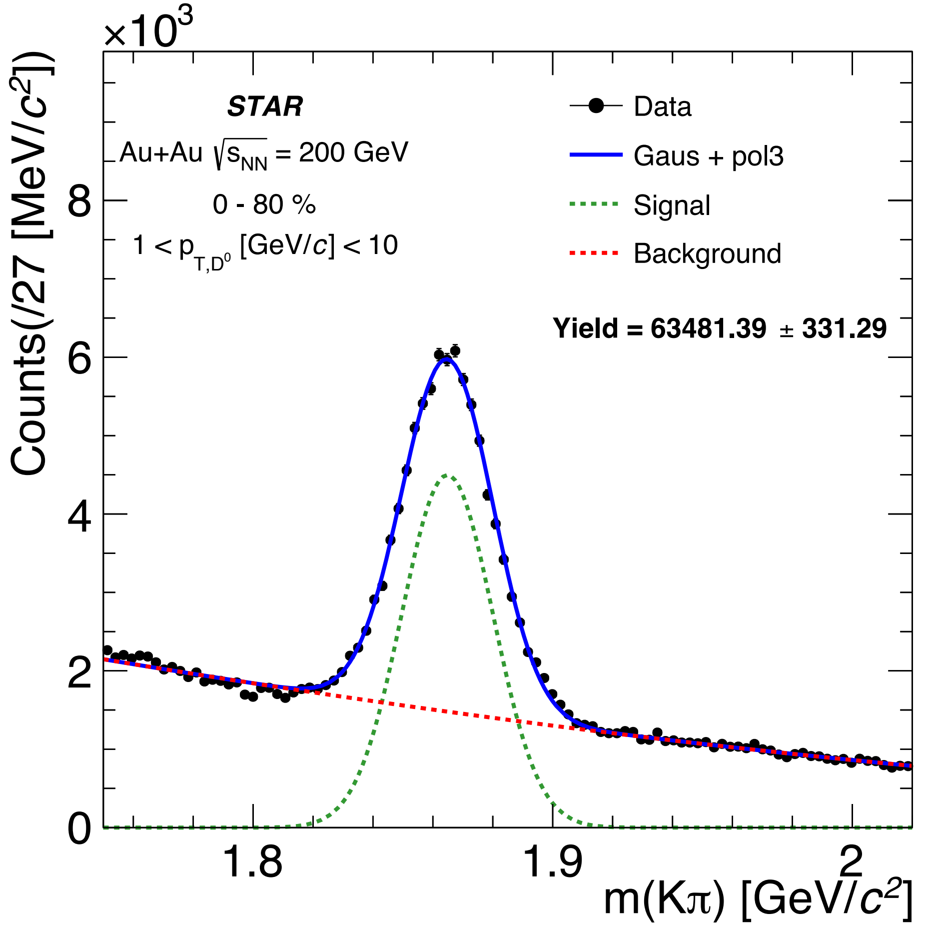


Image by Ondrej Lomicky

- Topological cuts to improve signal significance of D^0
- Yield calculation using sPlot method



${}_s\mathcal{P}lot$

$$ {}_s\mathcal{P}_n(m_{K\pi,i}) = \frac{\sum_{j=1}^{N_T} V_{nj} f_j(m_{K\pi,i})}{\sum_{k=1}^{N_T} N_k f_k(m_{K\pi,i})} $$

Efficiency Correction

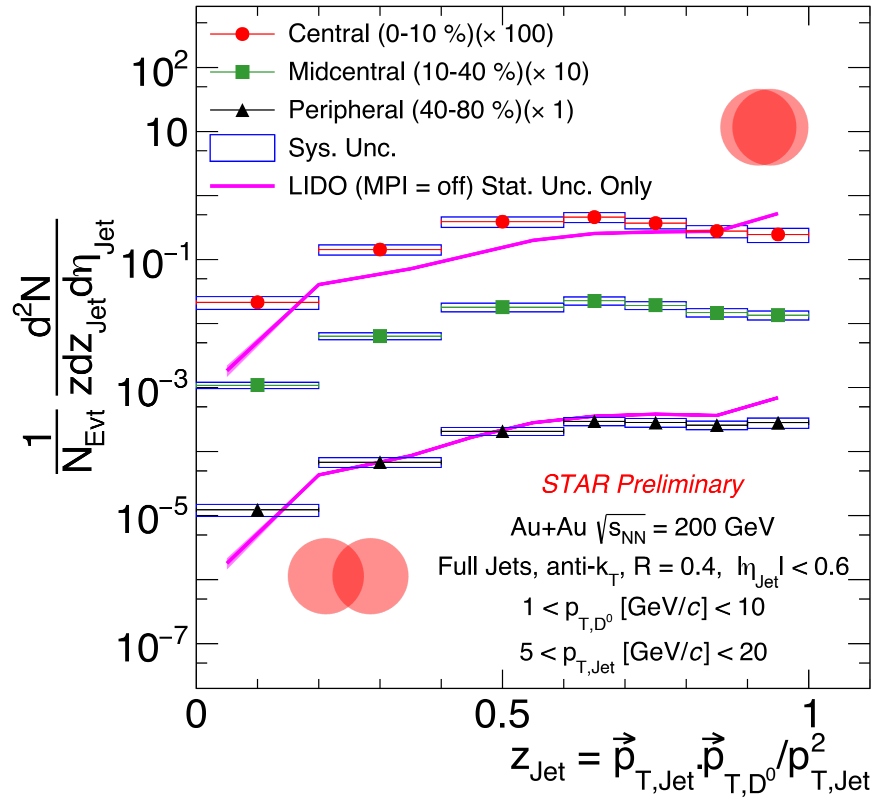
$$ {}_s\mathcal{P}_n(m_{K\pi,i}) \rightarrow \frac{{}_s\mathcal{P}_n(m_{K\pi,i})}{\varepsilon(m_{K\pi,i})} $$

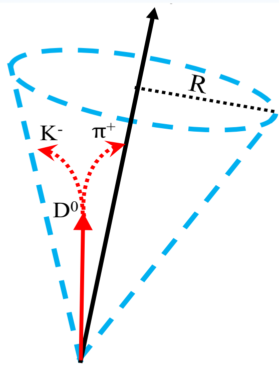
Pivk, Diberder, Nucl. Instrum. Methods Phys. Res., A (2005) 555

Flavor dependence – Fragmentation of D^0 jets

LIDO, Phys. Rev. C 98, 064901

$$z_{\text{Jet}} = \frac{\vec{p}_{\text{T,Jet}} \cdot \vec{p}_{\text{T},D^0}}{|\vec{p}_{\text{T,Jet}}|^2}$$



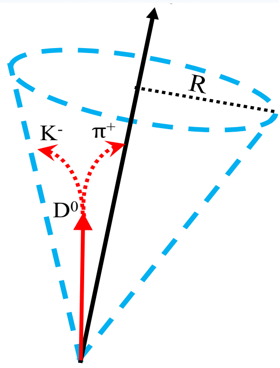


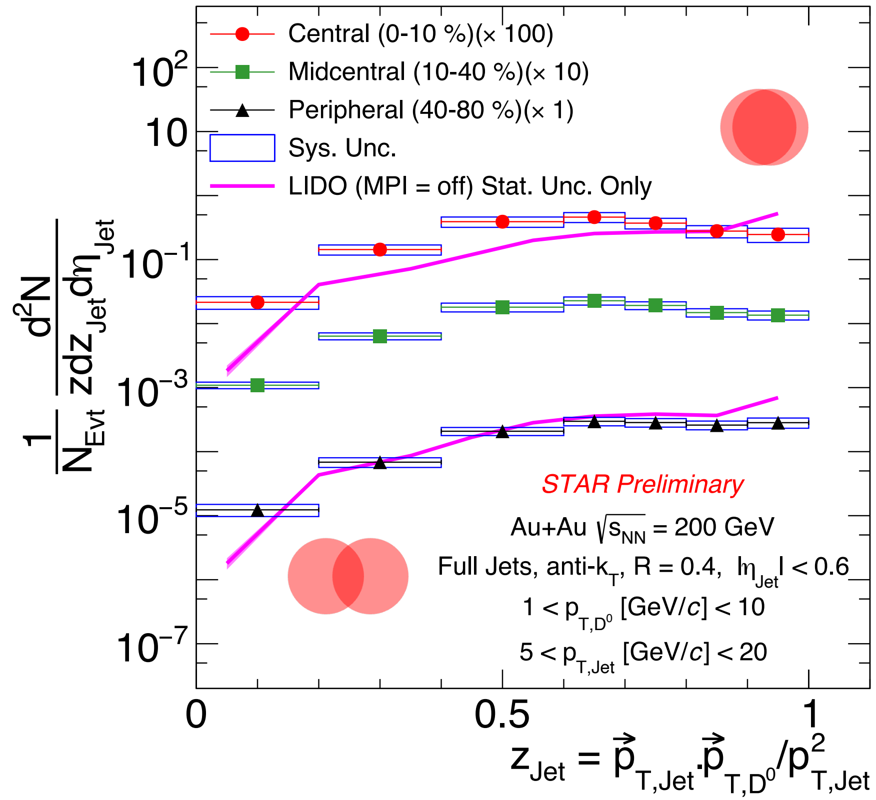
- 2D unfolded with $p_{\text{T,Jet}}$
- LIDO overestimates hard fragmented D^0 jets → Data shows softer fragmentation

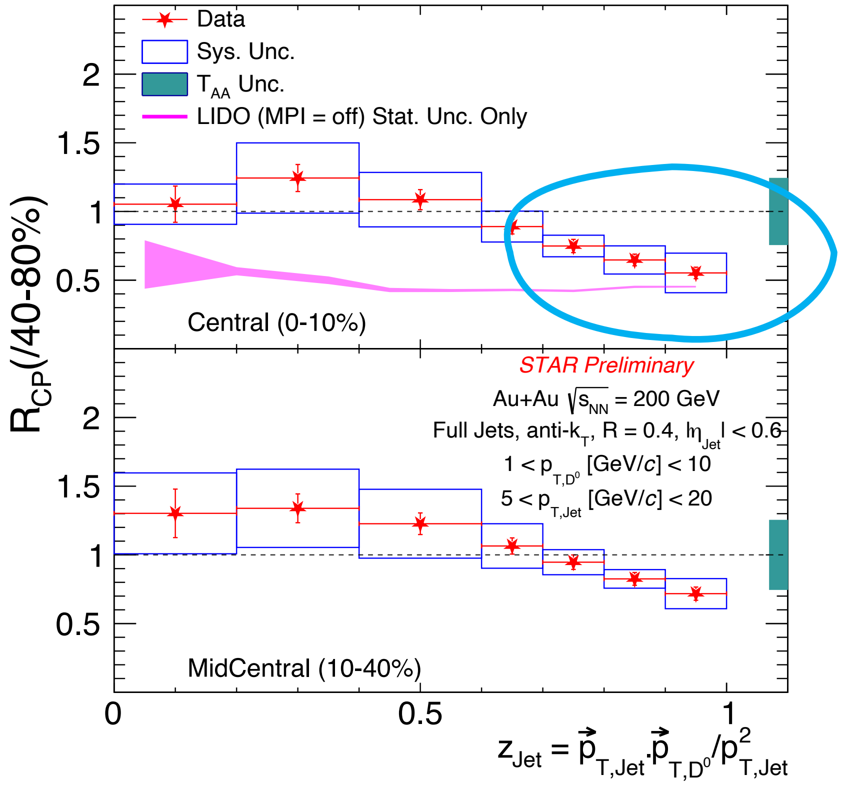
Flavor dependence – Fragmentation of D^0 jets

LIDO, Phys. Rev. C 98, 064901

$$z_{\mathrm{Jet}} = \frac{\vec{p}_{\mathrm{T,Jet}} \cdot \vec{p}_{\mathrm{T,D^0}}}{|\vec{p}_{\mathrm{T,Jet}}|^2}$$





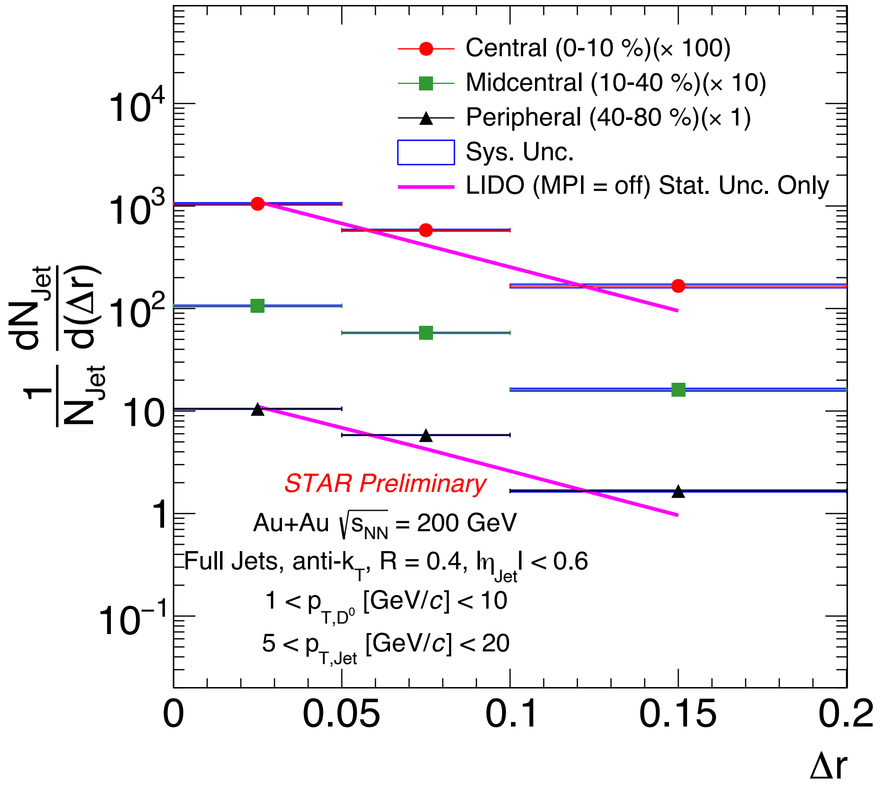


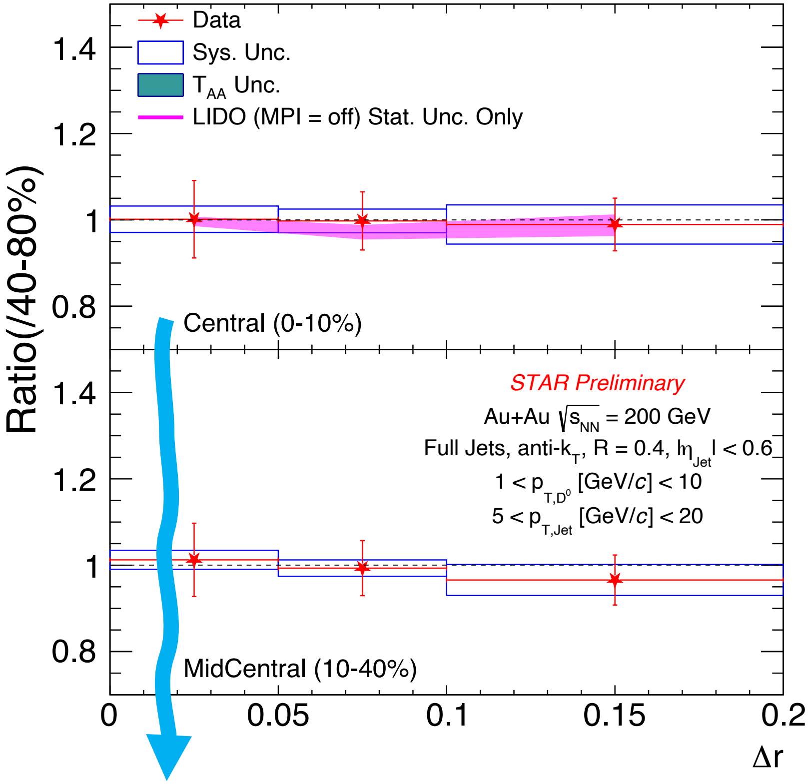
Suppression for hard fragmented D^0 jets in central collisions

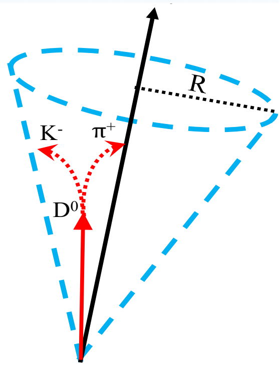
- 2D unfolded with $p_{\mathrm{T,Jet}}$
- LIDO overestimates hard fragmented D^0 jets → Data shows softer fragmentation

Flavor dependence – Radial profile of D^0 jets

LIDO, Phys. Rev. C 98, 064901







- 2D unfolded with $p_{T,Jet}$
- LIDO qualitatively explains radial profile trends, along with ratio of central and peripheral

Ratio of radial profile consistent with 1

What's next for STAR?

√SNN (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

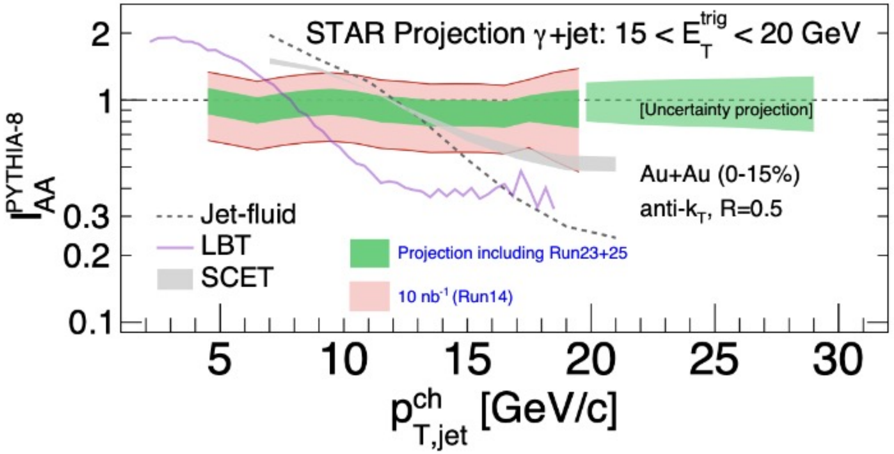
EPD for triggering

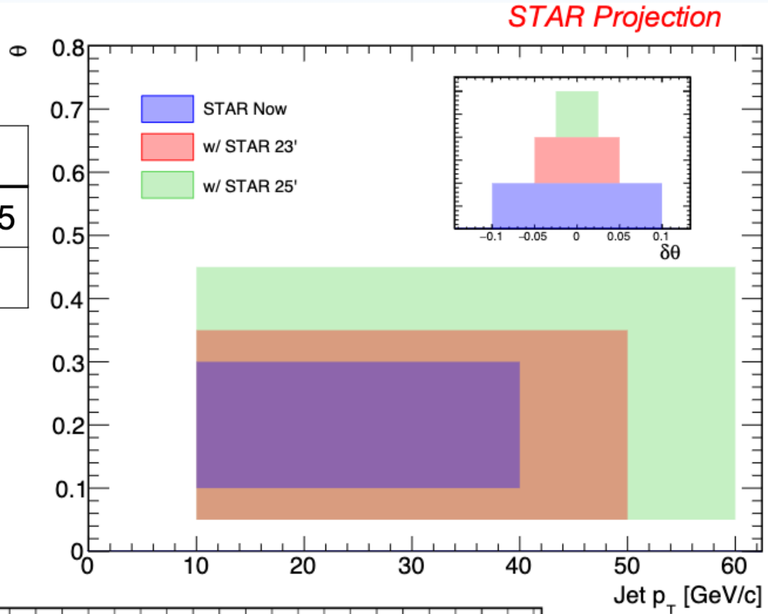
Independent event-plane determination

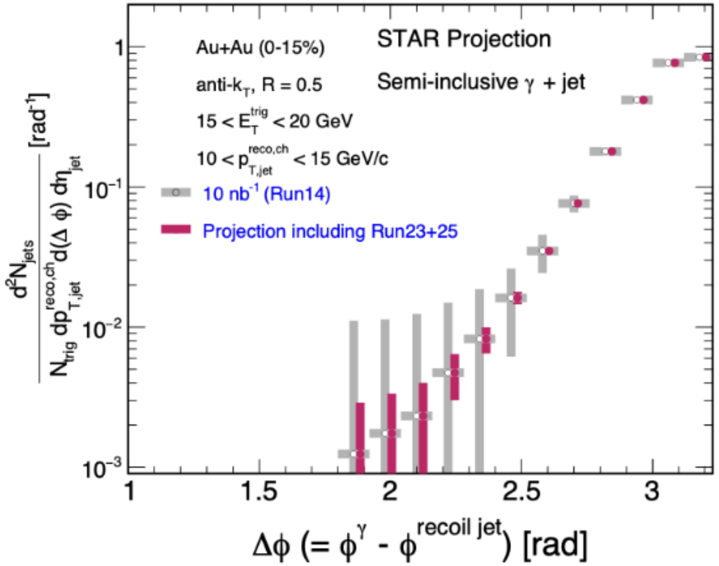
Event shape Engineering

Recoil Jets triggered by γ^{dir}

I_{AA} = Yield in Au+Au/Yield in p+p







Increased statistics for jet-substructure measurements

Use jet substructure as taggers

Access to high p_T jets

Access to wide-angle radiation

Increased resolution in angular scale

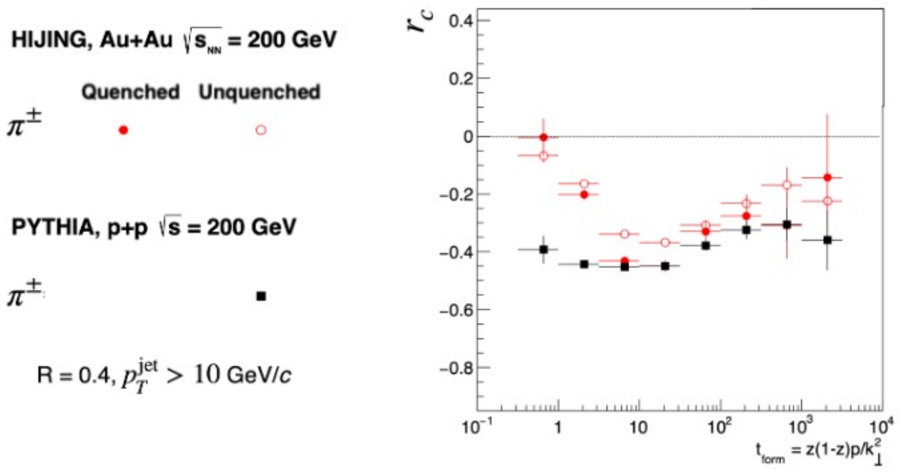
Wider kinematic range for I_{AA} and acoplanarity measurements

Access to forward rapidity

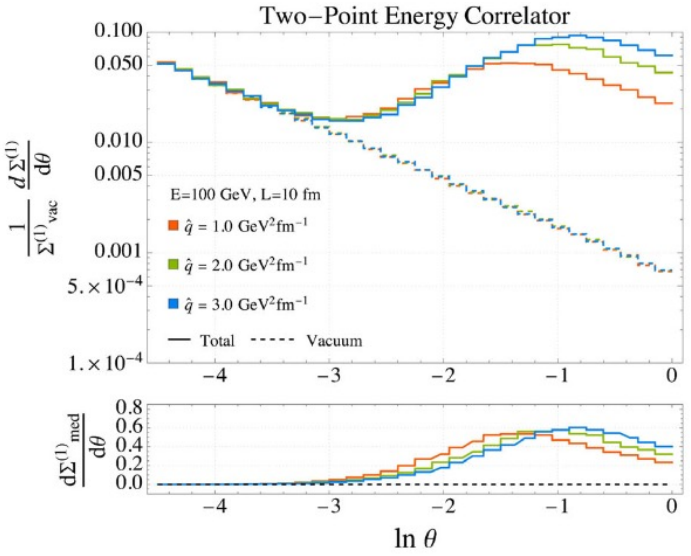
Larger statistics → Improved uncertainty

What's next for STAR?

- Charge correlators in heavy ion collisions
- 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
- Event shape engineering: Probing event-plane angle dependence



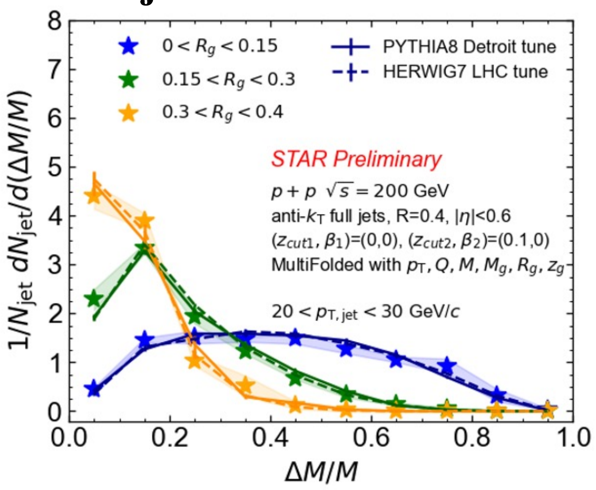
Esha, Hard Probes 2023

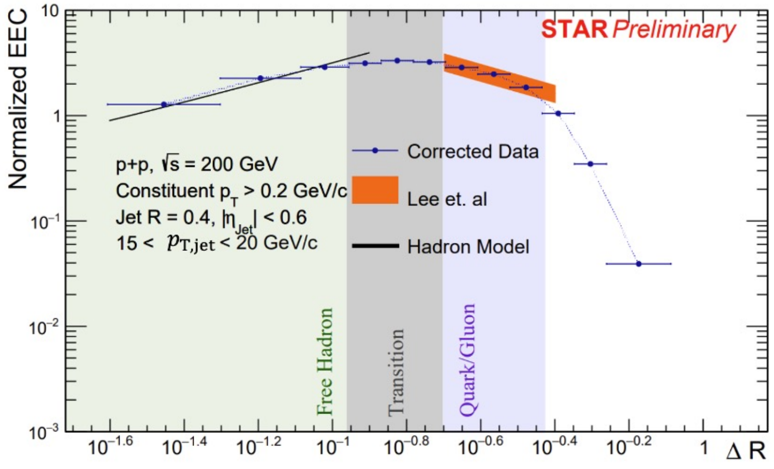


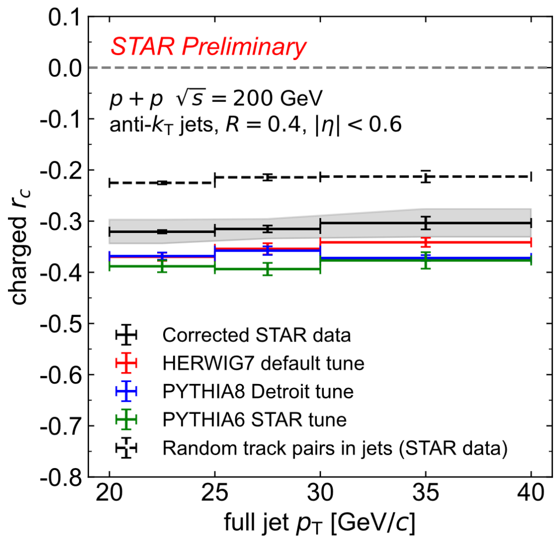
Andres, Dominguez, Kunnawalkam Elayavalli, Holguin, Marquet, Moult, PRL 130 (2023) 26, 262301

Summary

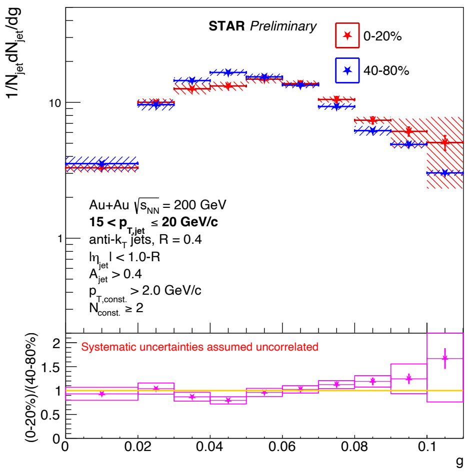
Precision era of jet substructure

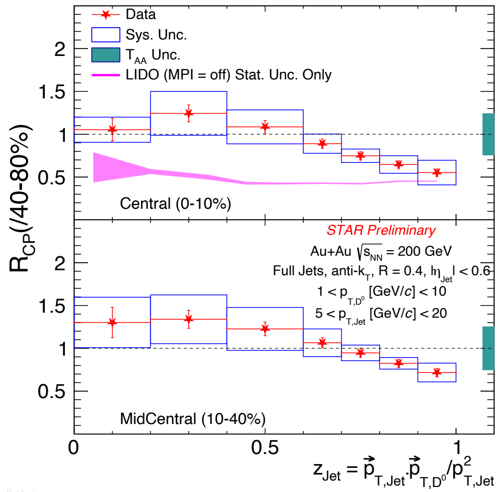




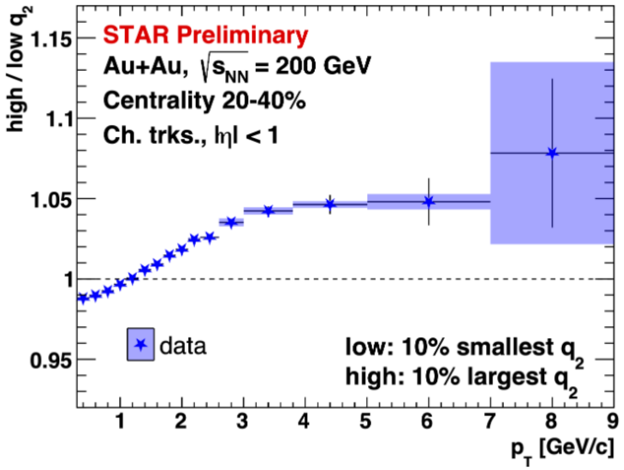


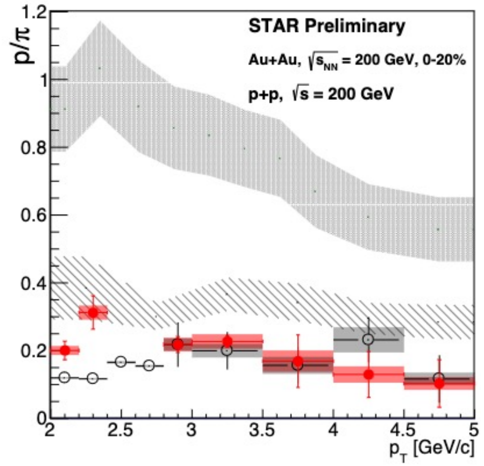
Substructure measurements in medium





Differential look at jet yield modifications





Thank You

Flavor dependence – Generalized angularities

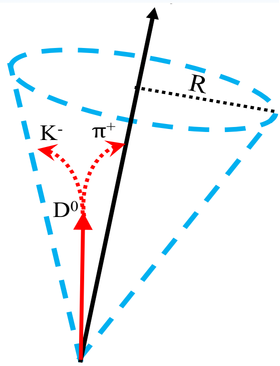
Generalized Angularities

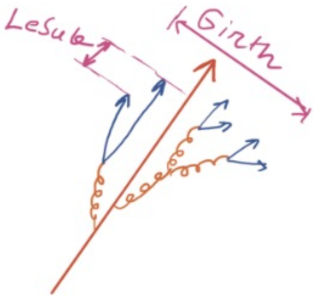
$\lambda_1^1 = g$ - girth

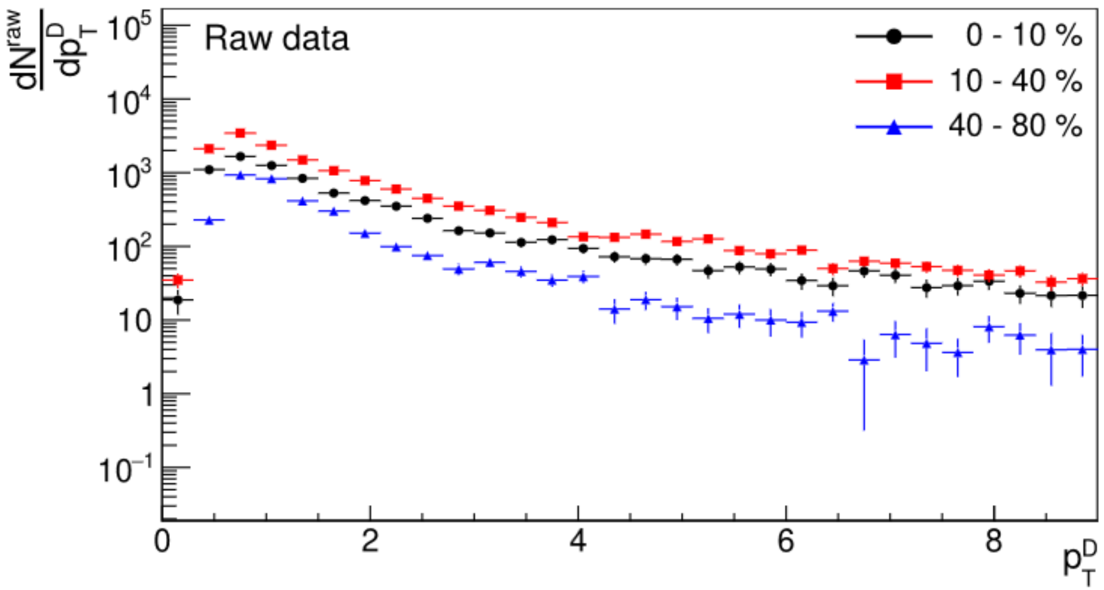
λ_2^1 - thrust

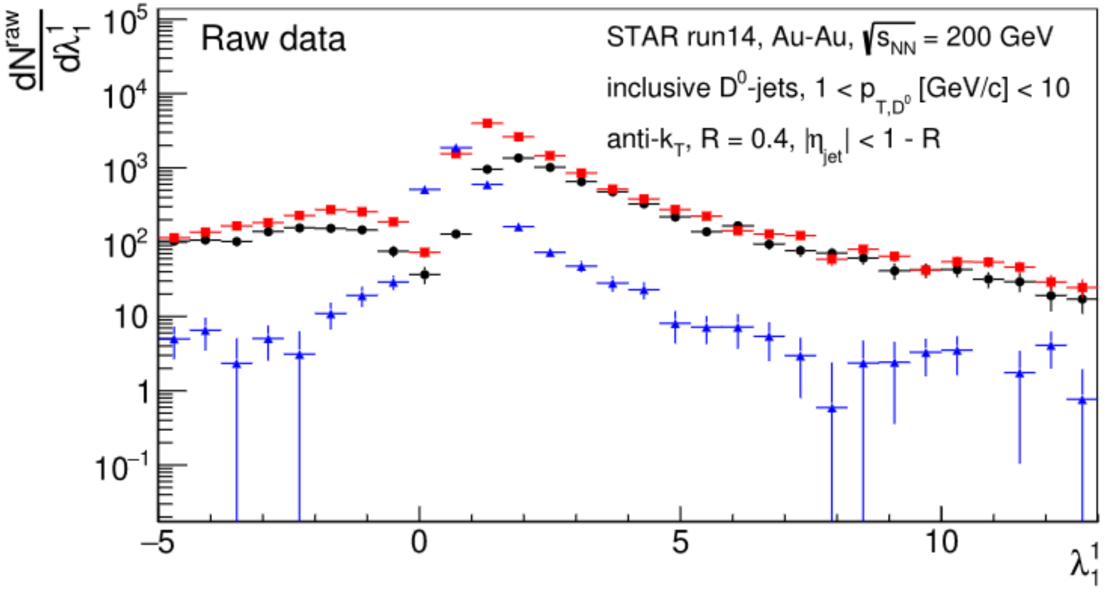
$\lambda_0^2 = (p_T^D)^2$ - momentum dispersion

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









Ongoing measurements for angularities

- Unphysical results caused by median background subtraction → Unfolding required