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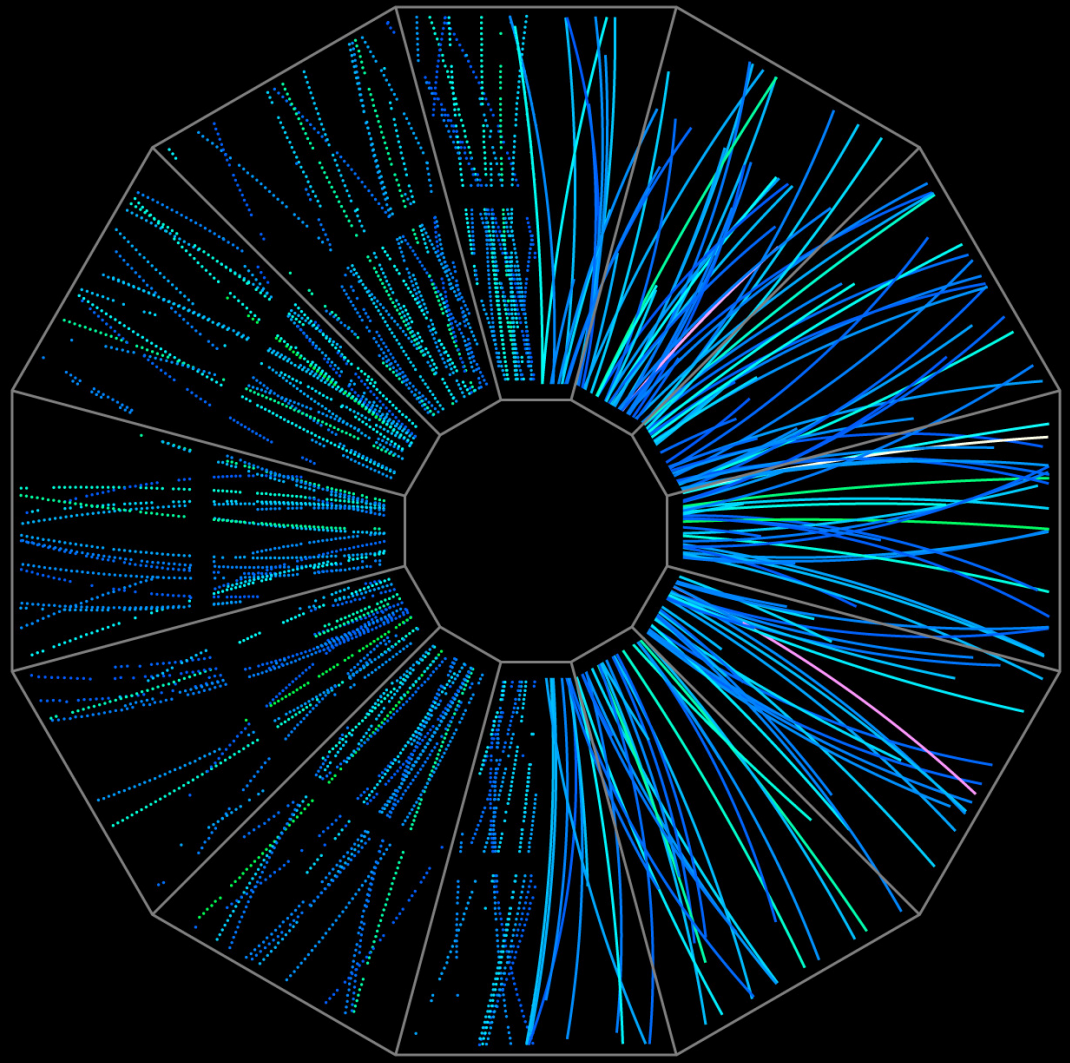
Looking into the QGP



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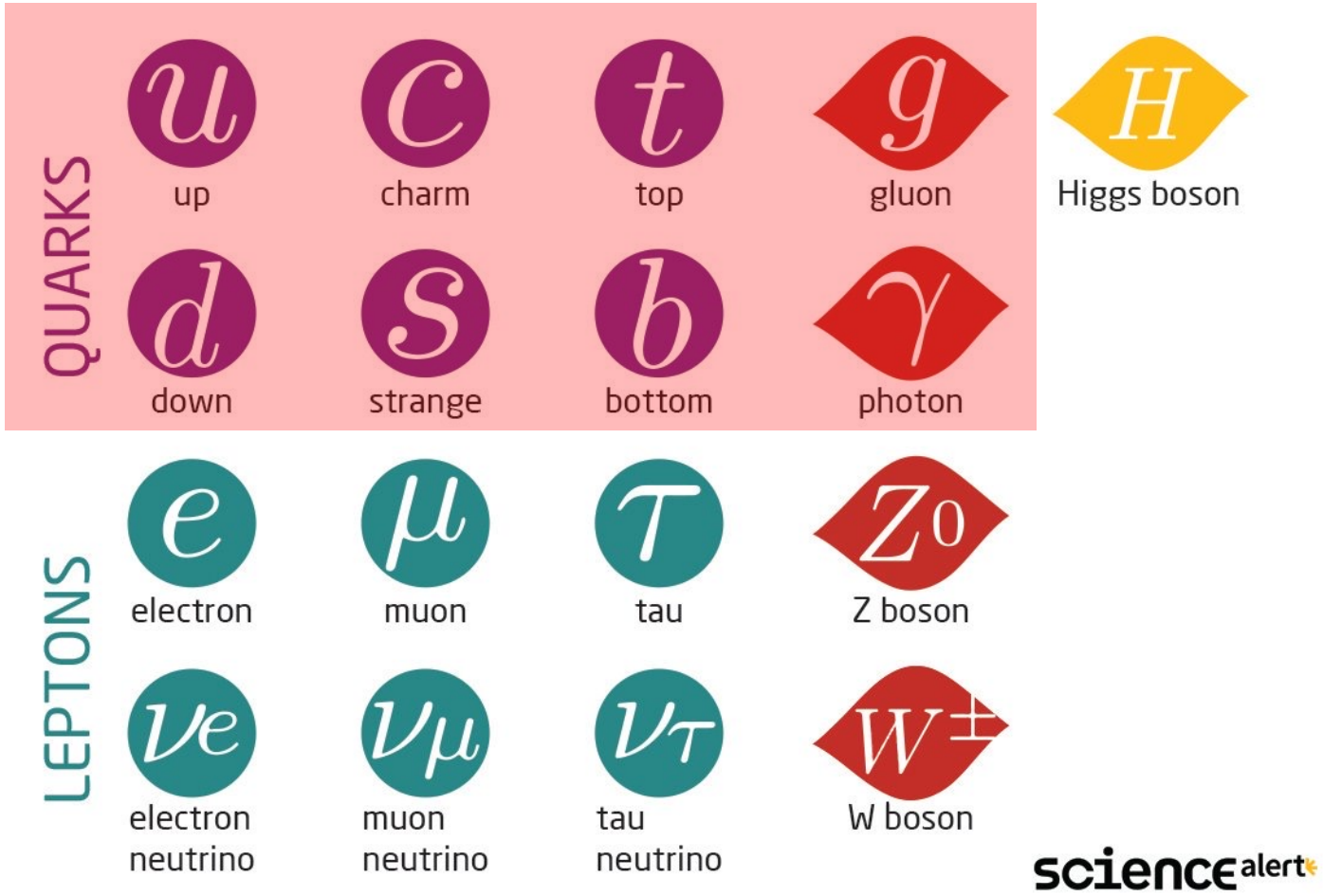
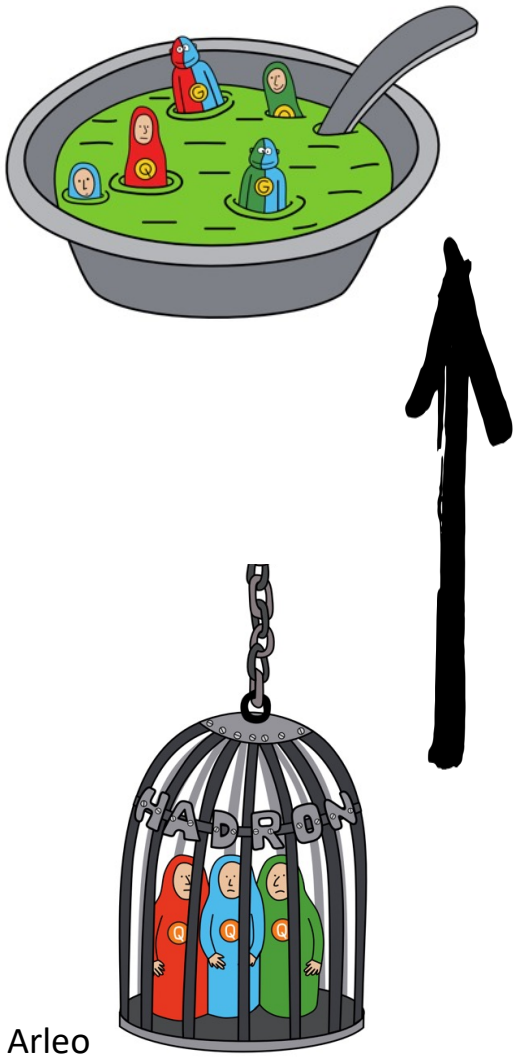
Monday, January 30, 2023

Outline

- ✓ Quark Gluon Plasma
- ✓ Bulk Probes
  - Critical Point
  - Anisotropic Flow
- ✓ Hard Probes
  - Jets
  - Heavy Flavor
  - Heavy Flavor Jets



Quark-Gluon Plasma (QGP)



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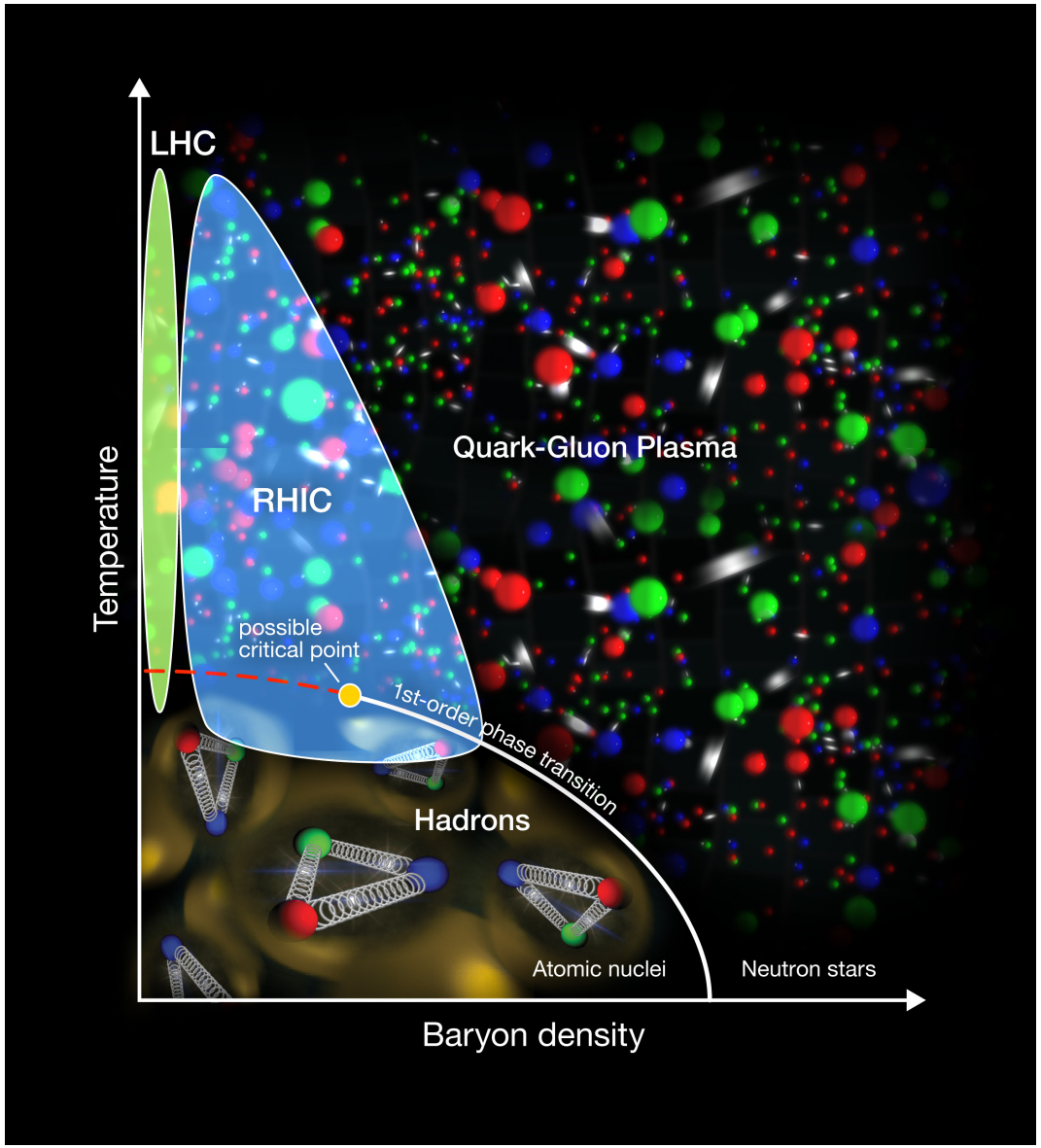
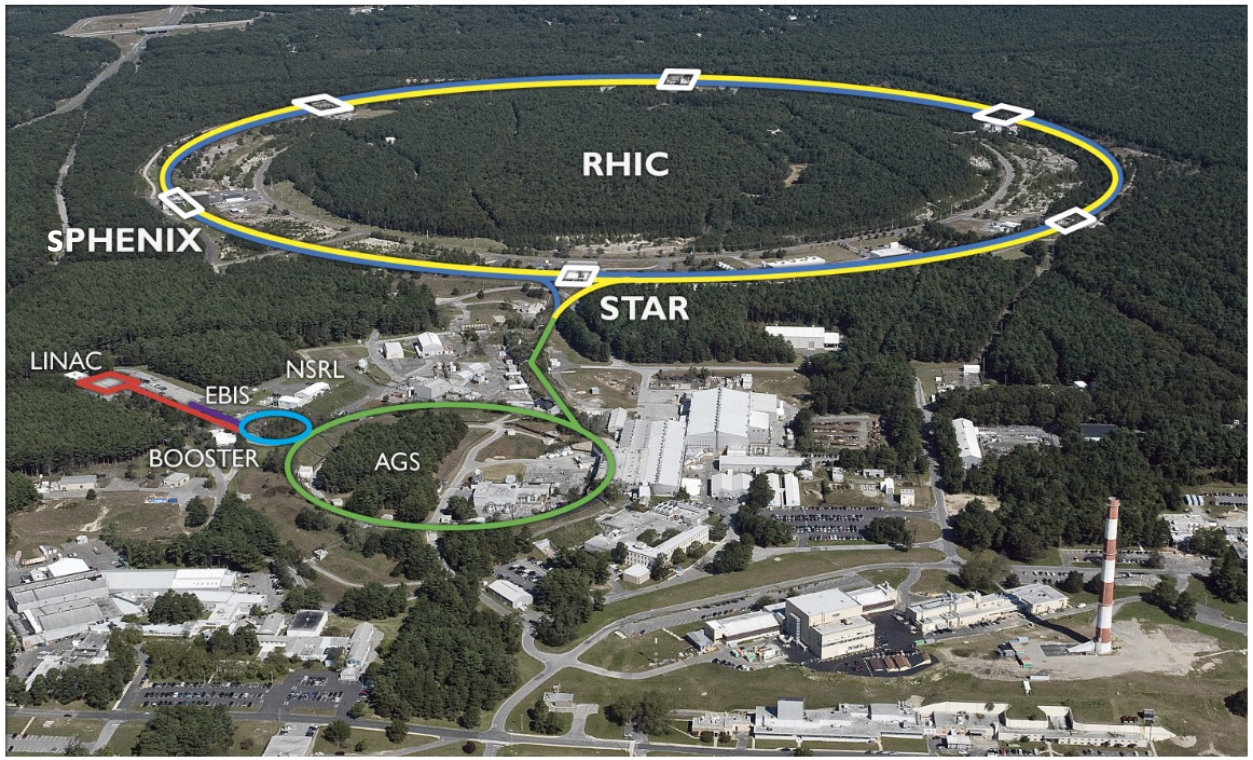
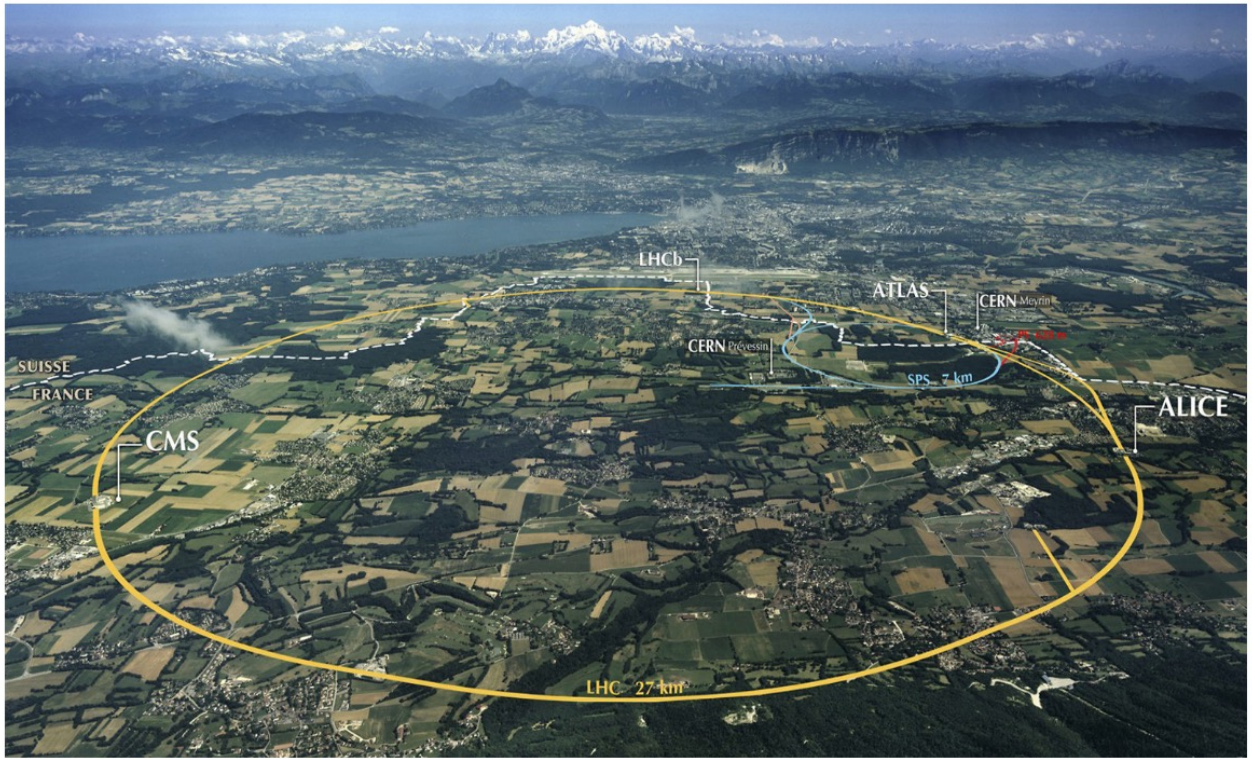


- Continuous transition (crossover) between phases at zero baryon density ~ early universe
- First order phase transition expected at finite baryon density
- Transition from first order behavior to continuous behavior goes through a critical point

QGP Factories

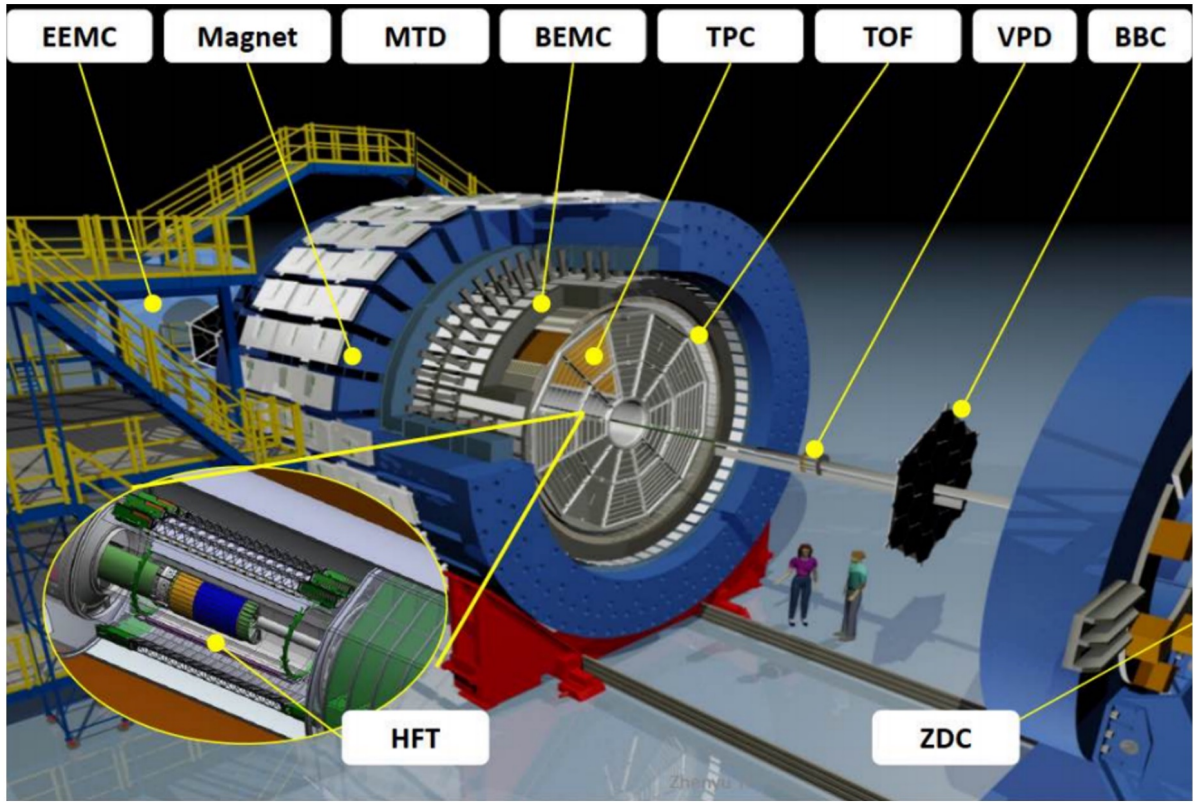


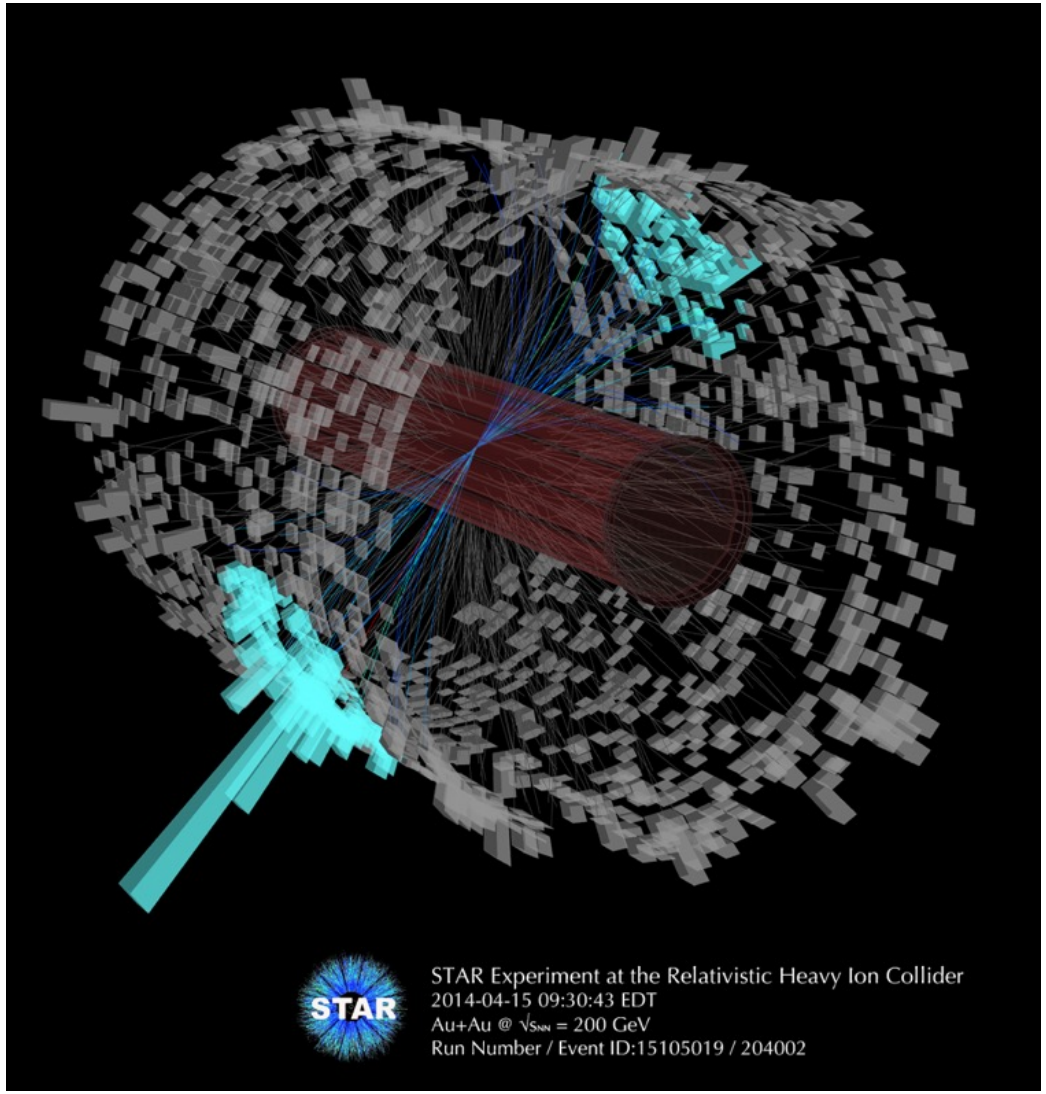


- **Relativistic Heavy Ion Collider**
- $\sqrt{s_{NN}}$ = 3 – 200 GeV (510 GeV for pp)
- Collides p-p, p+Au, d+Au, Au+Au etc

- **Large Hadron Collider**
- $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV(13 TeV for pp)
- Collides p-p, p+Pb, Pb+Pb, Xe+Xe etc

Apparatus

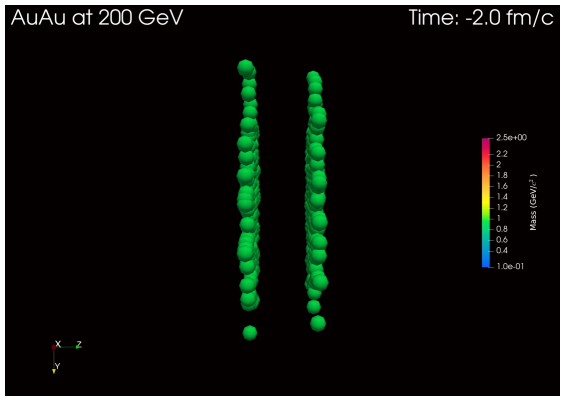


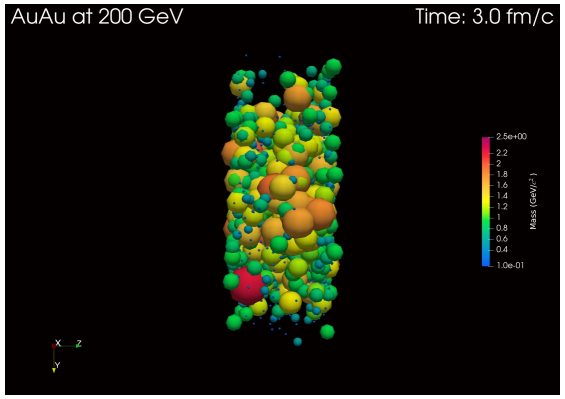


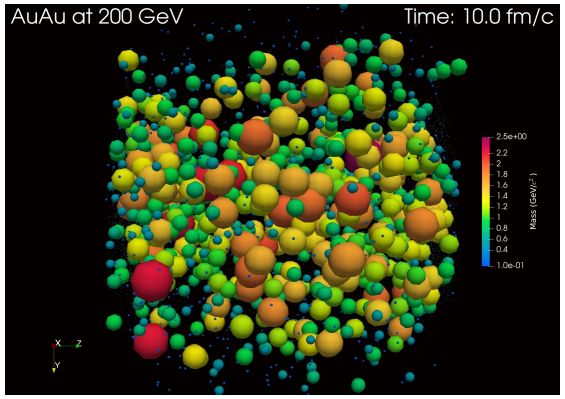
- Capable of colliding both proton and heavy ion beams
- Currently, the only running experiment is STAR, sPHENIX coming up soon
- 3.8 km long, has 6 intersection points

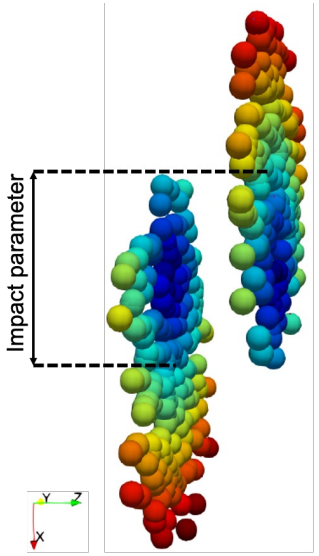
Heavy Ion Collisions

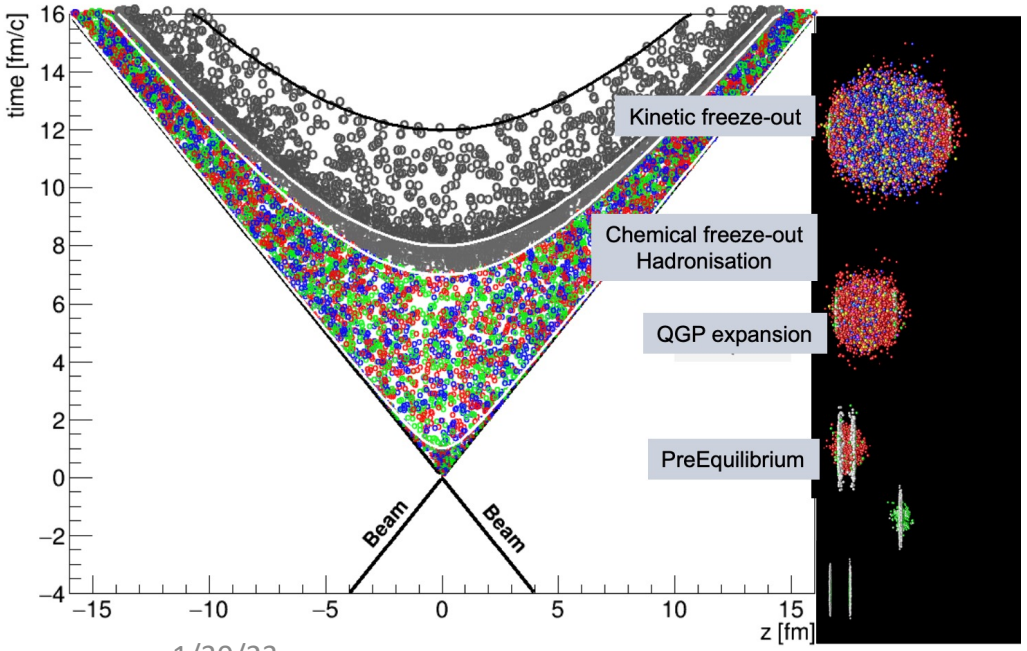
[SMASH] Phys.Rev.C 94 (2016) 5, 054905









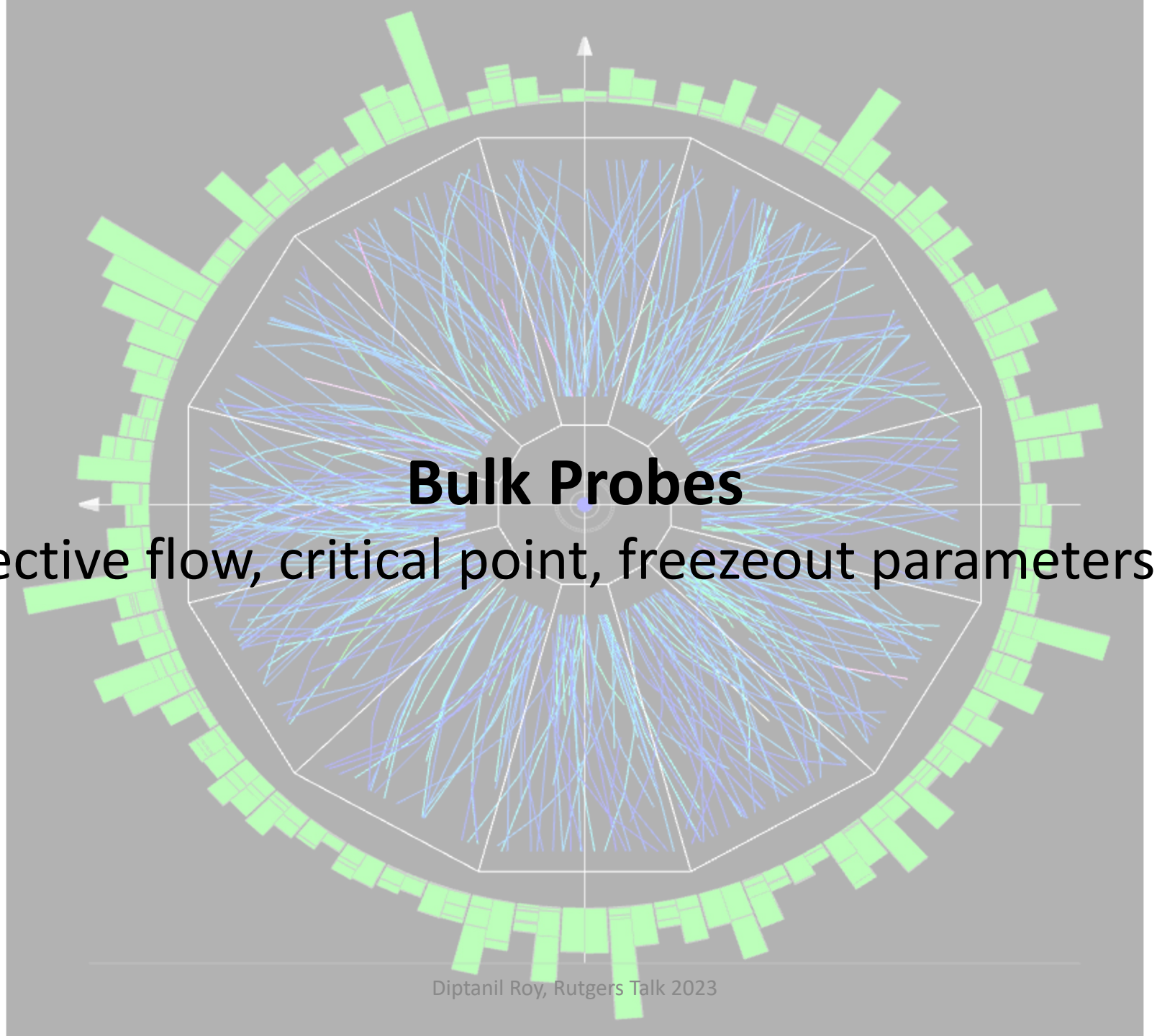


- Lorentz Contracted Nuclei (in the lab frame) collide, and form **Quark-Gluon Plasma**
- New particle formation stops after the first few fm/*c* s

Ways to study the QGP

Bulk Probes
(Collective flow, critical point, freezeout parameters etc.)

Hard (Internal) Probes
(Jet modifications, heavy flavor production etc.)



Bulk Probes

(Collective flow, critical point, freezeout parameters etc.)

Search for the QCD Critical Point

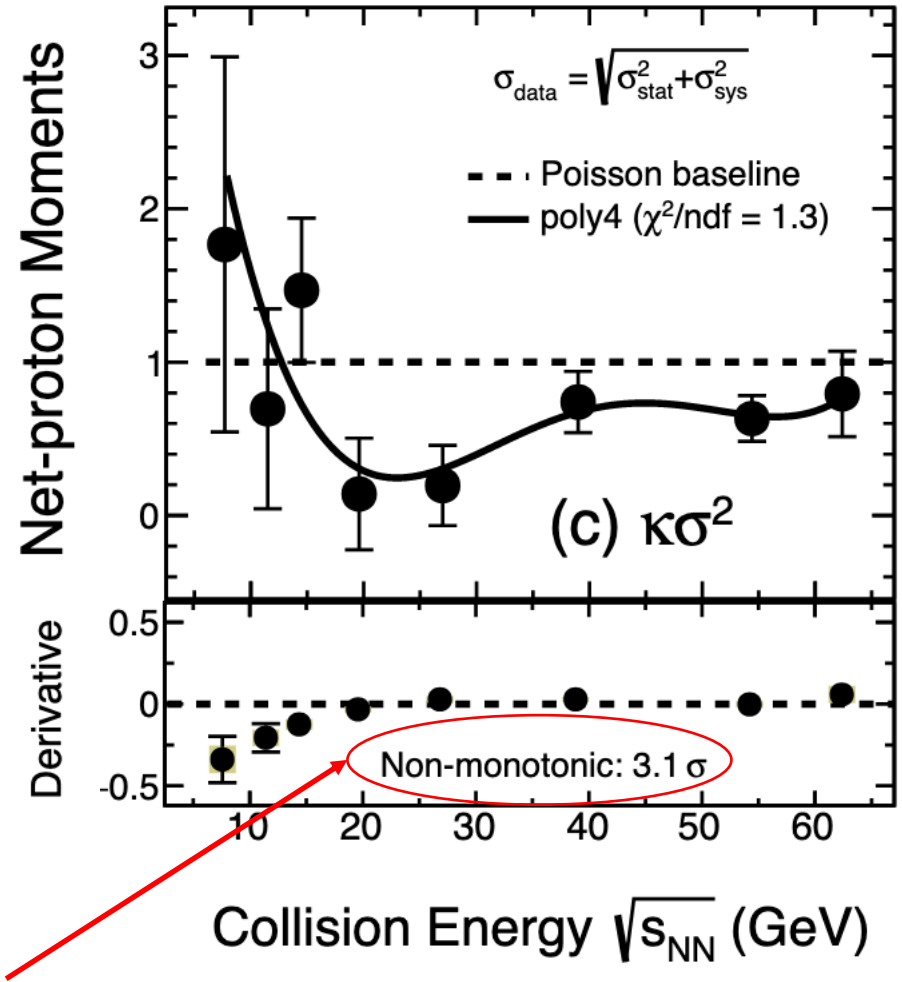
- **Presence of a critical point**: Difference in fluctuations of conserved charges in the hadronic phase vs deconfined phase

- Fluctuations in net-baryon and net-charge → Quantified by the moments of the event-by-event distributions

$$C_1 = \langle N \rangle,$$
$$C_2 = \langle (\delta N)^2 \rangle = \mu_2,$$
$$C_3 = \langle (\delta N)^3 \rangle = \mu_3,$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

$$M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{(C_2)^{3/2}}, \quad \kappa = \frac{C_4}{(C_2)^2}$$

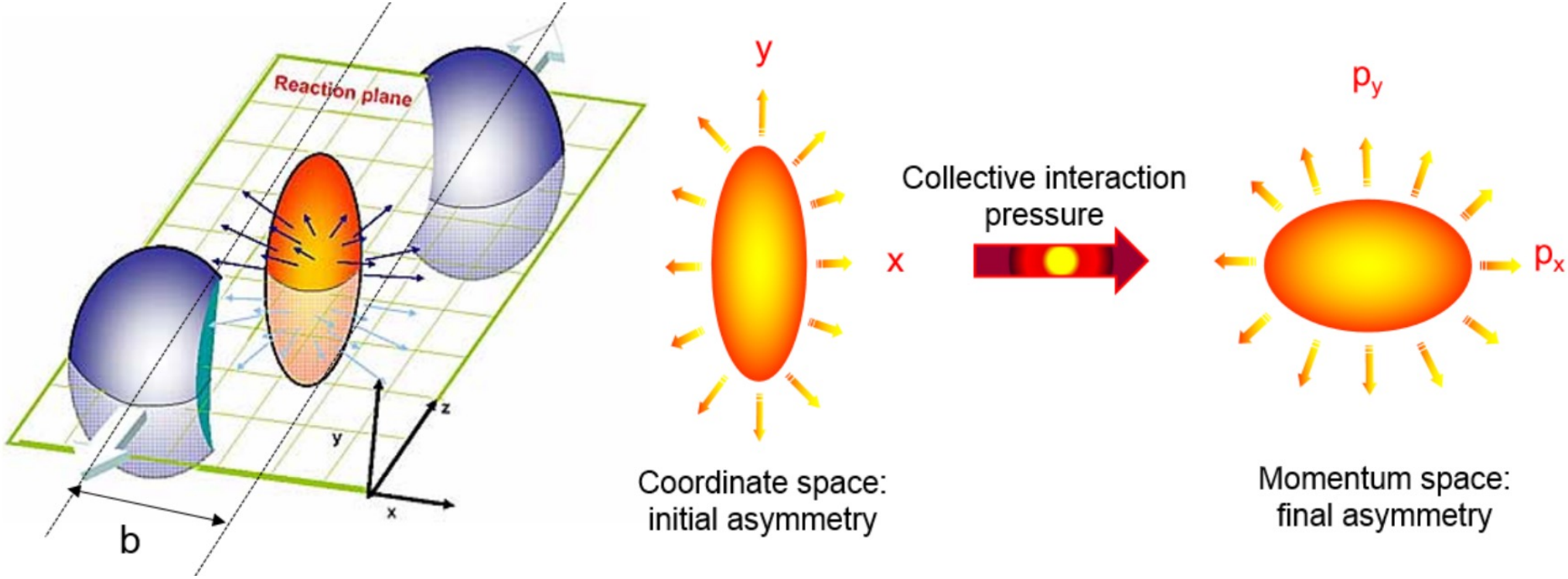
STAR: arXiv 2101.12413 (2021)



Non-monotonicity in $\kappa\sigma^2$ with beam energy → Possible sign of critical point

Awaiting results from Beam Energy Scan II at RHIC

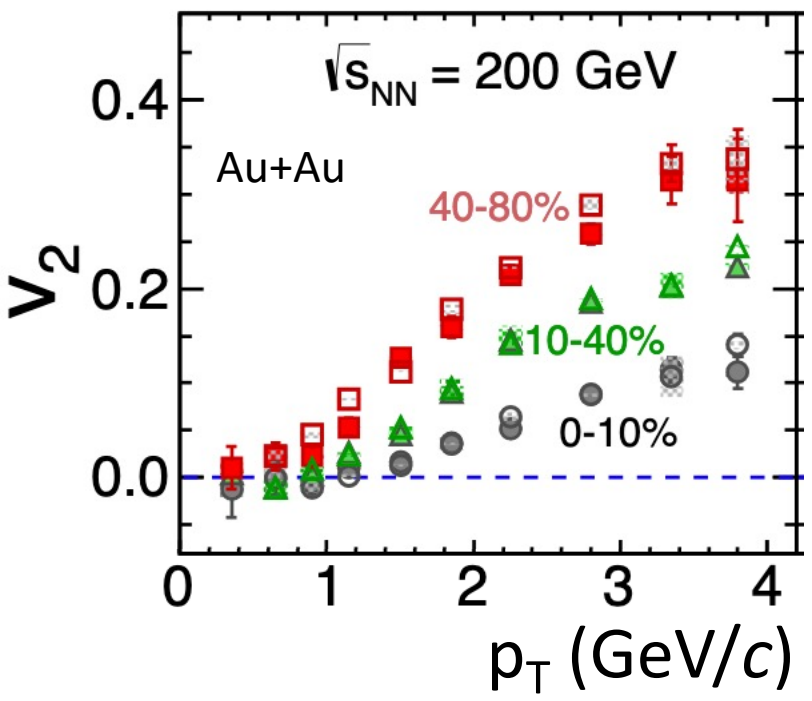
Anisotropic Flow



Quantify anisotropy with Fourier expansion

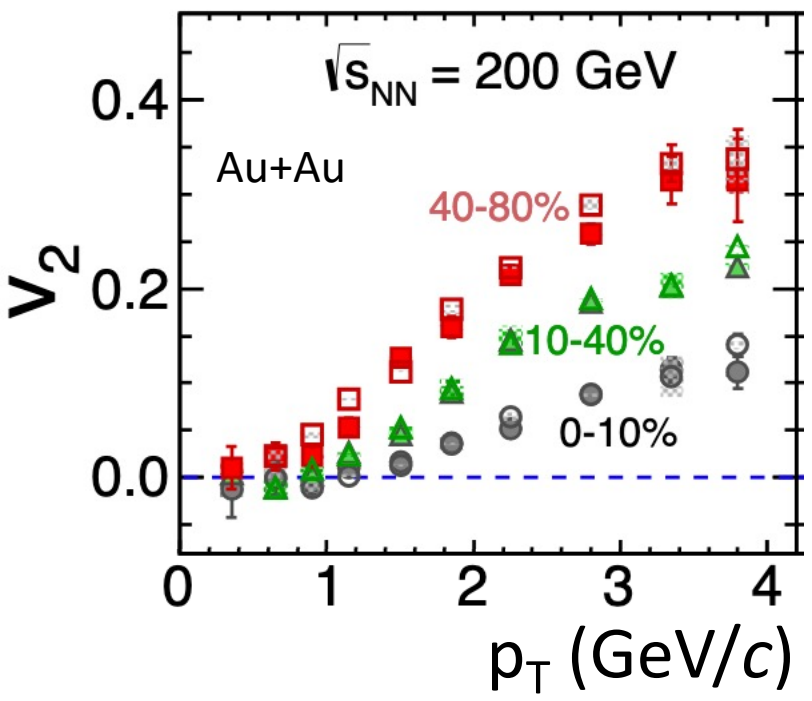
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos(n\phi)\right)$$

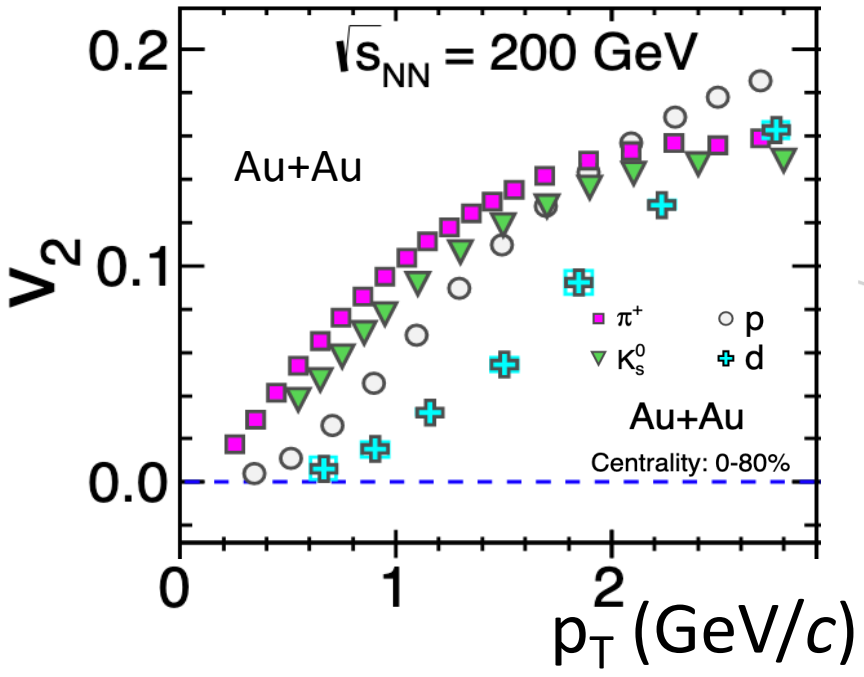
Anisotropic Flow



- Flow increases for peripheral collisions where initial anisotropy is highest
- Flow increases as a function of p_T → Hydrodynamic expansion of QGP
- Flow for identified particles scaled by number of constituent quarks identical → Effects of flow sets in during the QGP phase

Anisotropic Flow





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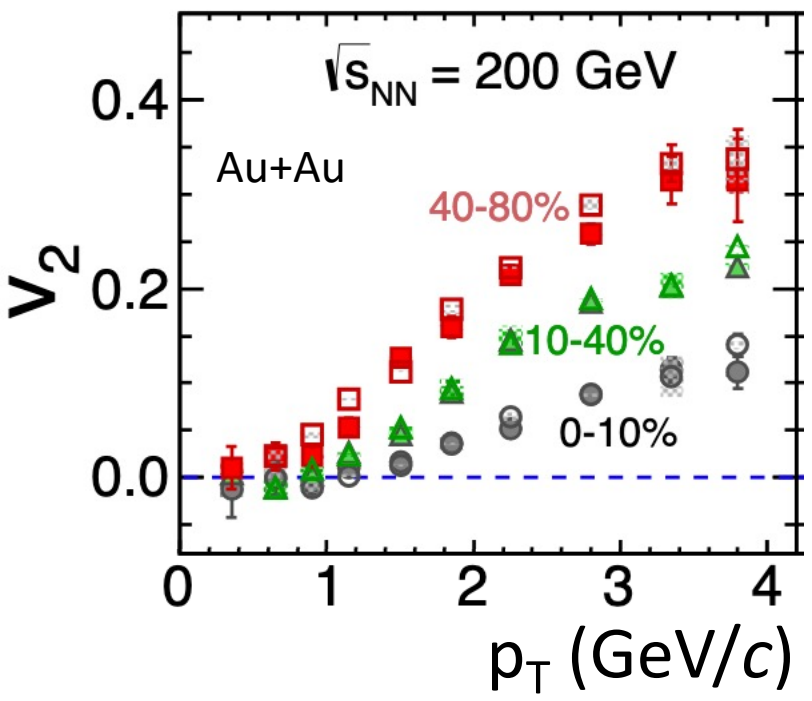

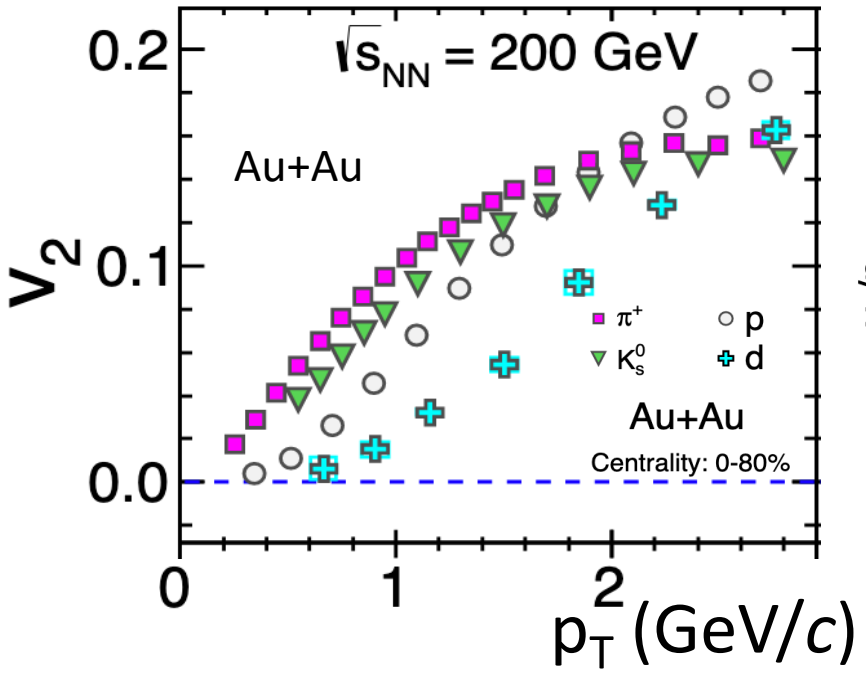

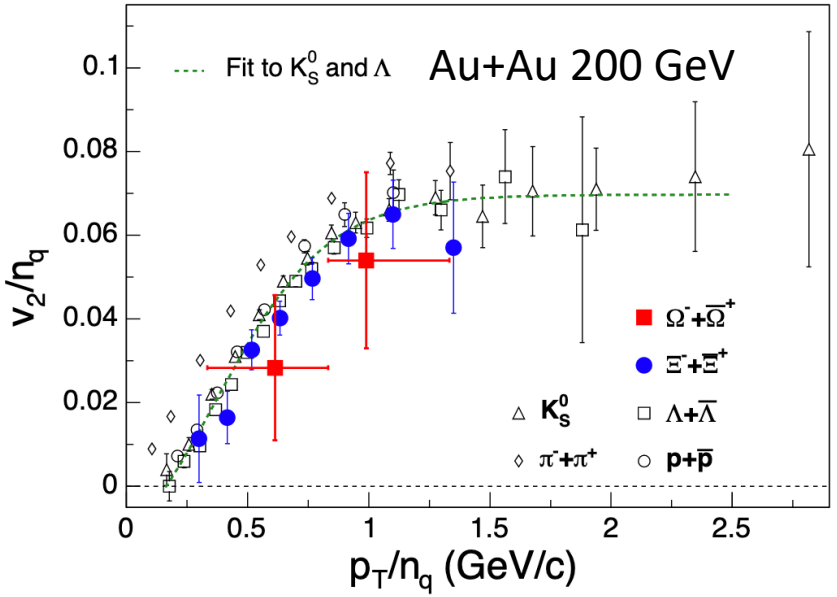

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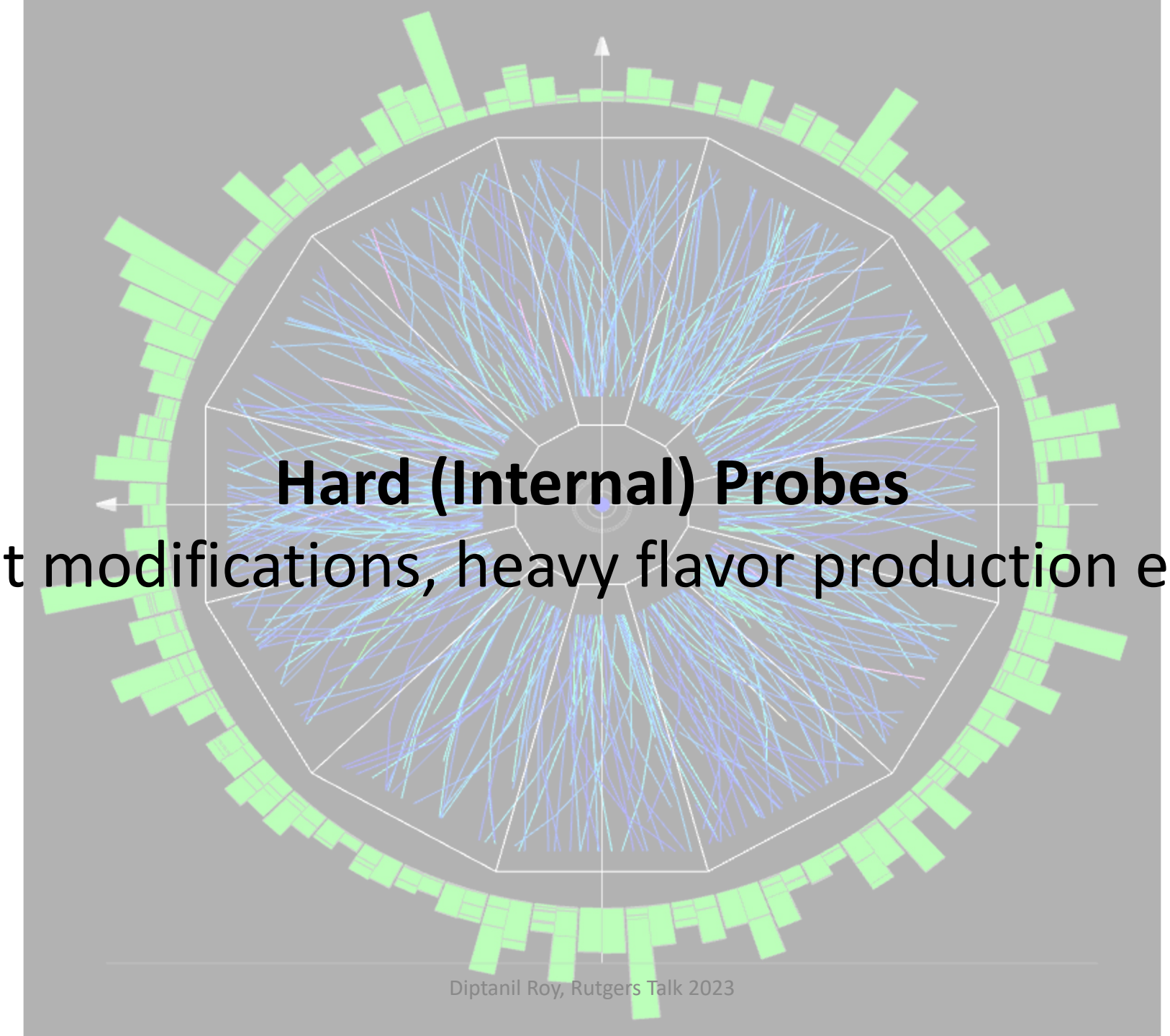


Hard (Internal) Probes

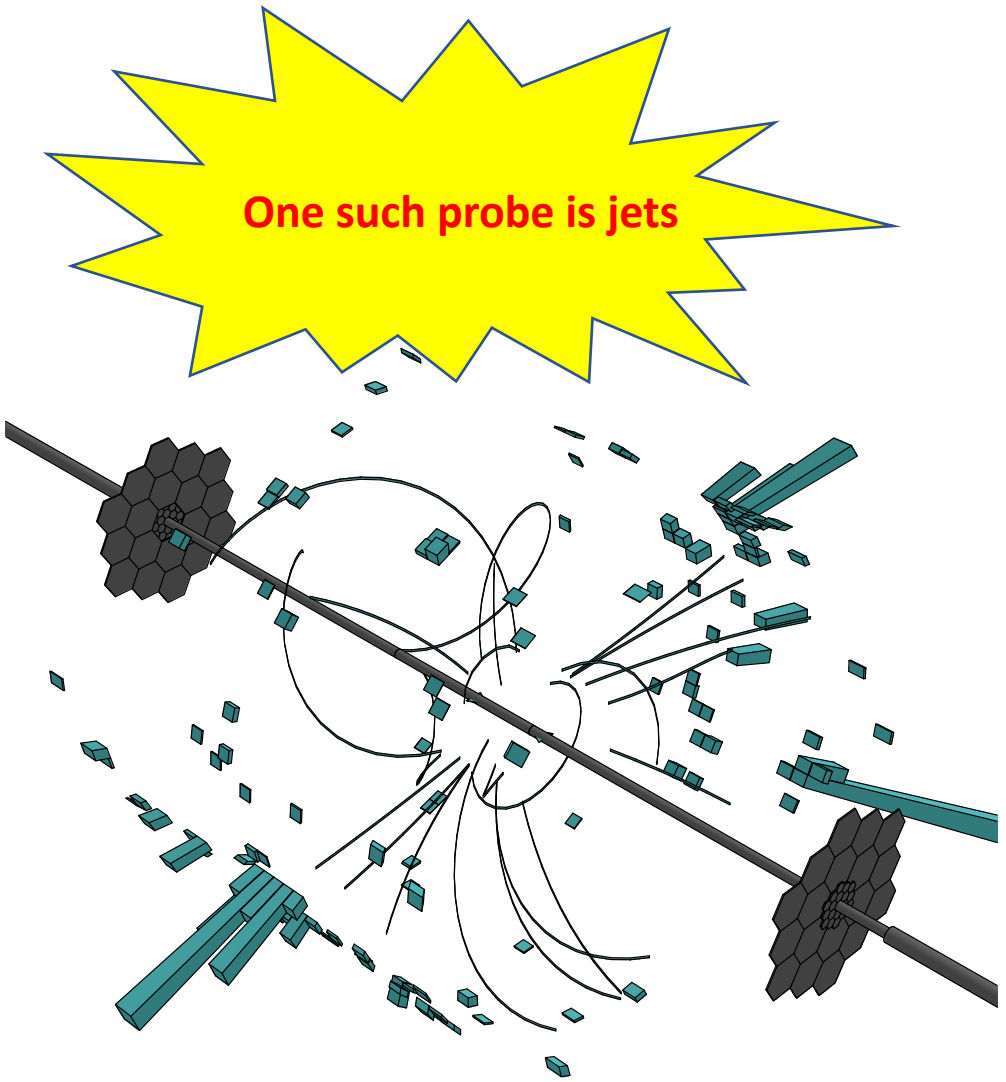
(Jet modifications, heavy flavor production etc.)

How can we study the QGP properties?

1. Lifetime very short ($O(1 – 10\ \text{fm}/c)$)
2. Not feasible to use external probes
3. Instead, pass a QCD-sensitive internal probe through it, then look for any modifications due to the medium

Processes with:
- Large momentum transfer (i.e., high Q^2)

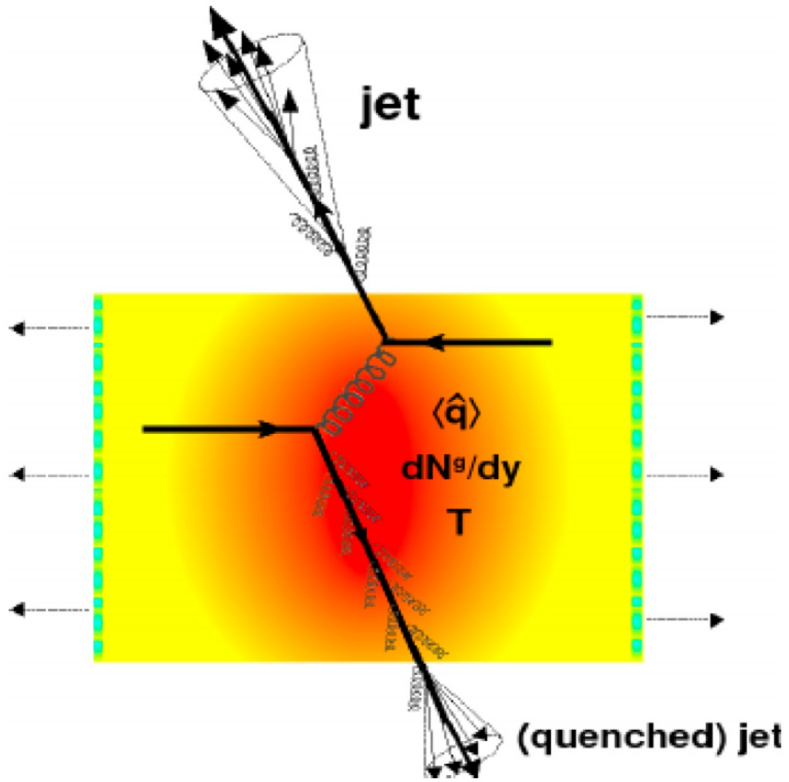
4. Measure an observable in ***p*+*p* & *p*+A** collisions
5. Measure the same observable in **heavy ion** collisions
6. Check for modifications



source: RHIC album © Brookhaven National Laboratory

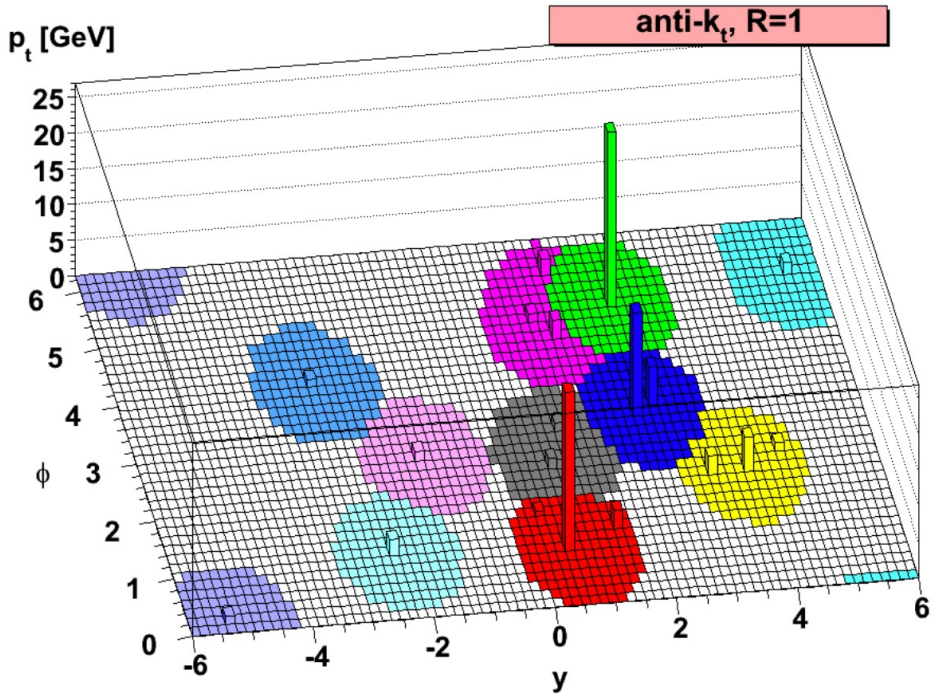
Jets – What are they in an experiment?

- "Jets" are generated after collisions between hard scattered quarks and gluons (partons).
- Outgoing quark or gluon "fragments" into a spray of particles.
- Algorithm clusters tracks and energy depositions using a "**distance measure**" to cluster softer particles around high p_T particles.
- We look at jet observables **in pp collisions** and compare them to **heavy ion collisions** to see the effects of the QGP.

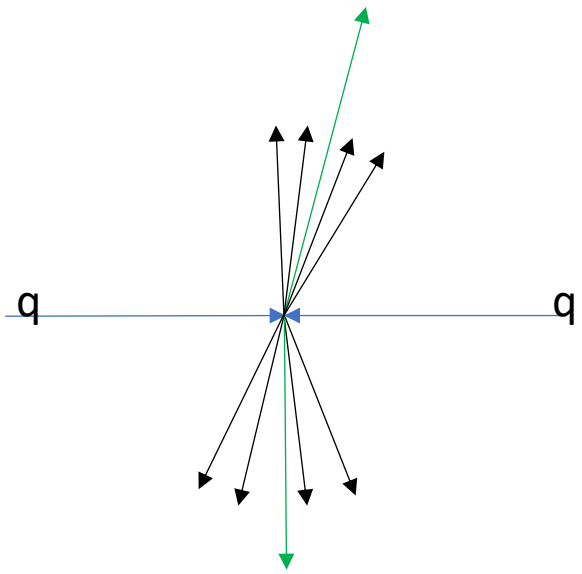


Reconstructing Jets

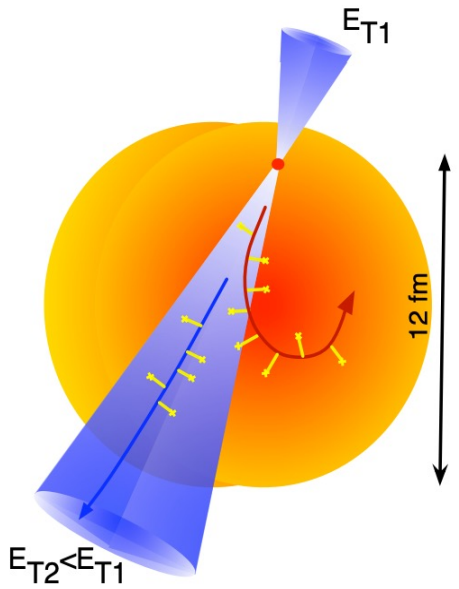
- Anti-k_T jet clustering algorithm used through the FASTJET package (Phys. Lett. B 641 (2006) 57-61)
- Sequentially clusters softer detected entities (charged particle tracks and calorimeter energy depositions) around harder entities
- Creates approximately conical jets with radii determined by the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



Jet Quenching

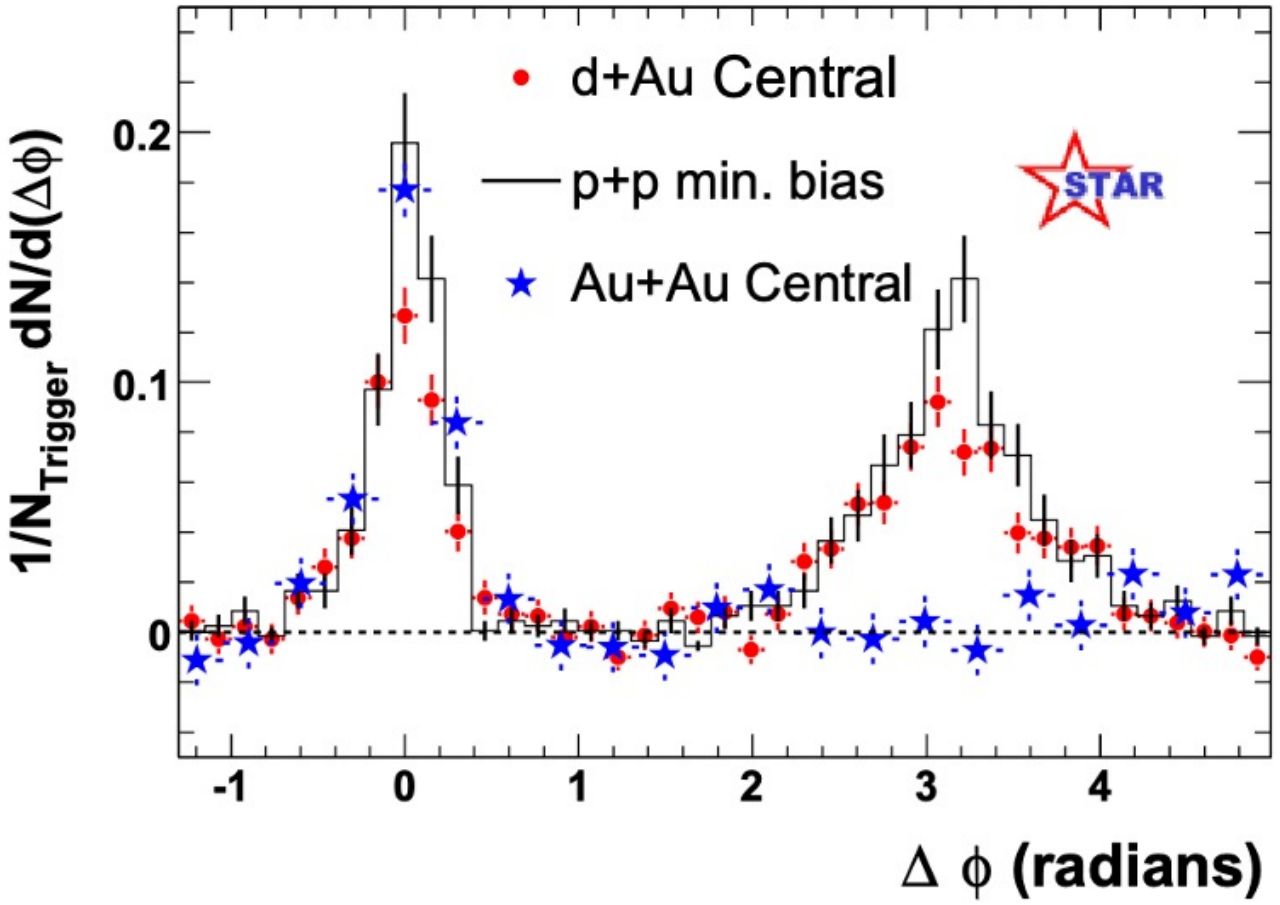


p + p



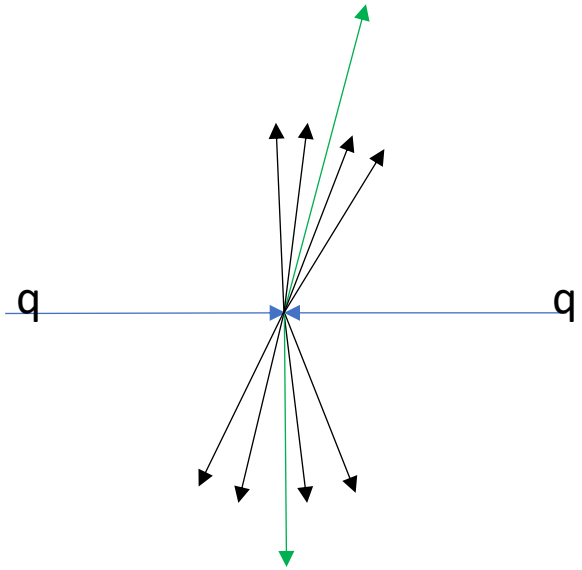
A + A

STAR, Phys. Rev. Lett. 91 (2003) 072304

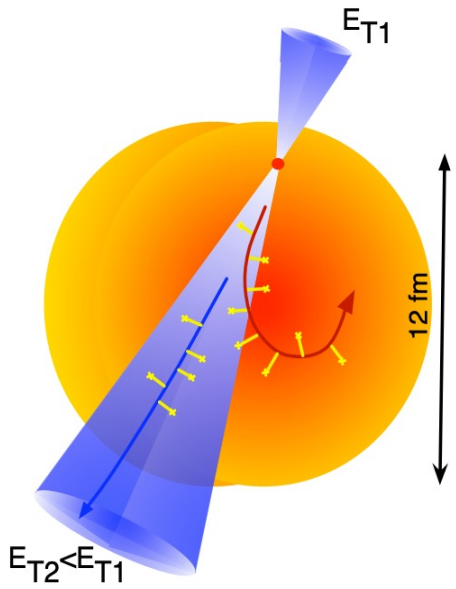


Far side jets are heavily suppressed in the medium.

Jet Quenching



p + p

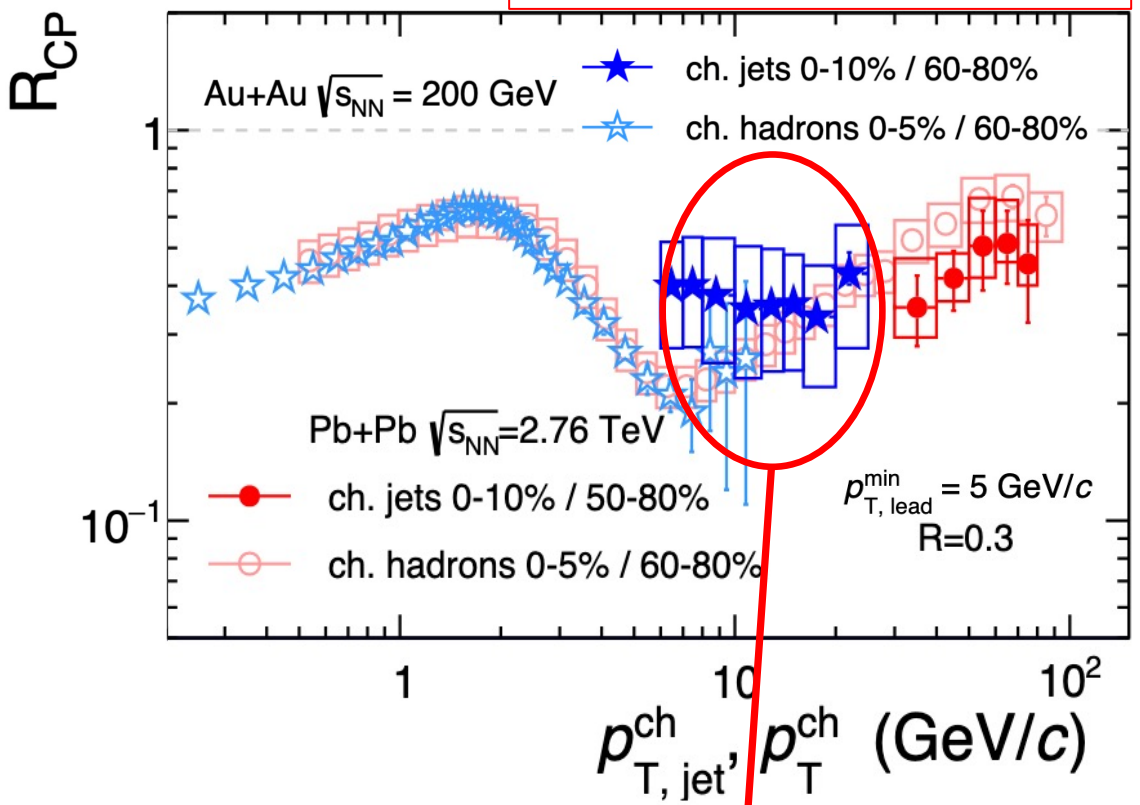


A + A

$$R_{CP} = \frac{\text{(Central)}}{\text{Binary collision scaled} \otimes \text{(Peripheral)}}$$

ALICE, JHEP03 (2014) 013

STAR, Phys.Rev.C 102 (2020) 5, 054913

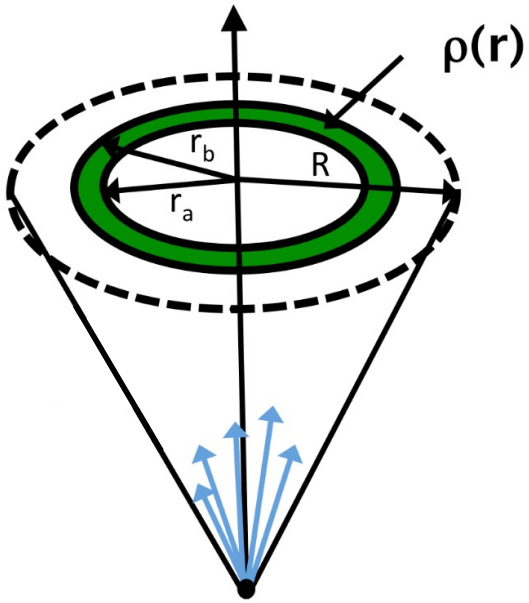


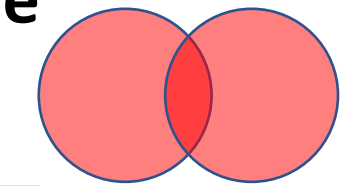
Inclusive jets are heavily quenched in the presence of QGP

Jet Broadening

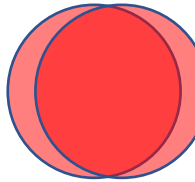
Differential jet shape

$$\rho(R) = \frac{1}{\Delta R}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(R_a,R_b)} p_{\text{T,track}}}{p_{\text{T,jet}}}$$



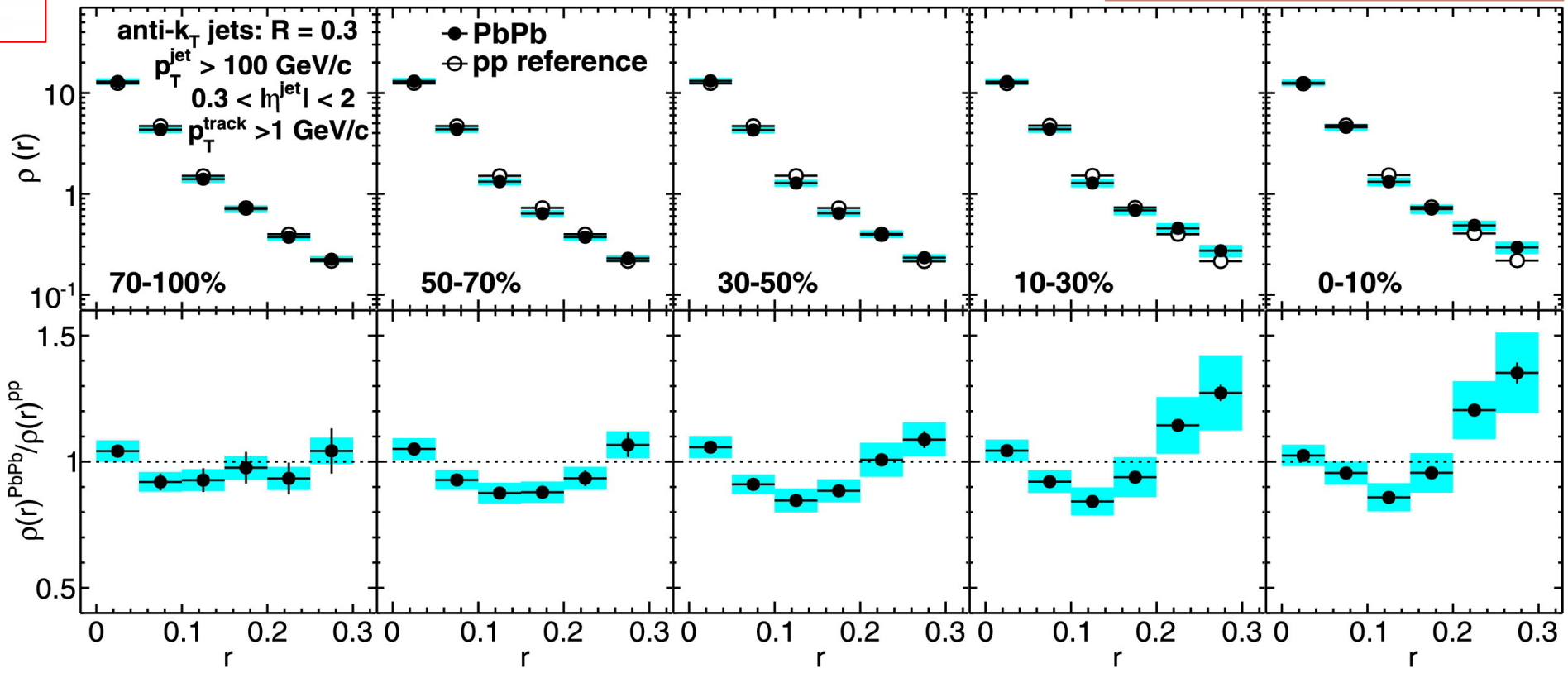


Decreasing centrality



CMS, $\sqrt{s_{NN}}$ = 2.76 TeV pp, $\int L\,dt$ = 5.3 pb^{-1} PbPb, $\int L\,dt$ = 150 μb^{-1}

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



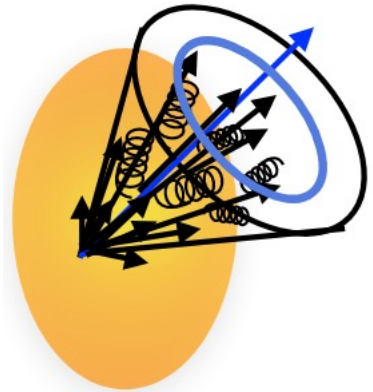
The jet energy is redistributed inside the jet cone in the presence of QGP at the LHC.

Jet Medium Interactions

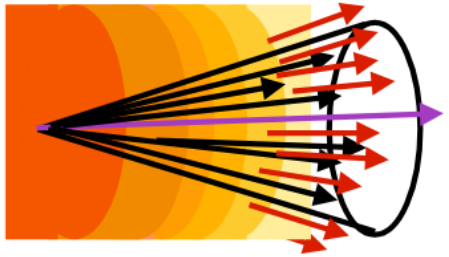
Elastic collisions (collisional)

Inelastic collisions (radiative)

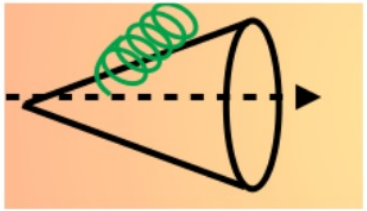
Multiple scattering



Medium Response



Medium-induced splittings



Images from Laura Havener, Yale

Broadens and **Quenches** jets

Dependent on the mass of the underlying quark

$$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$$

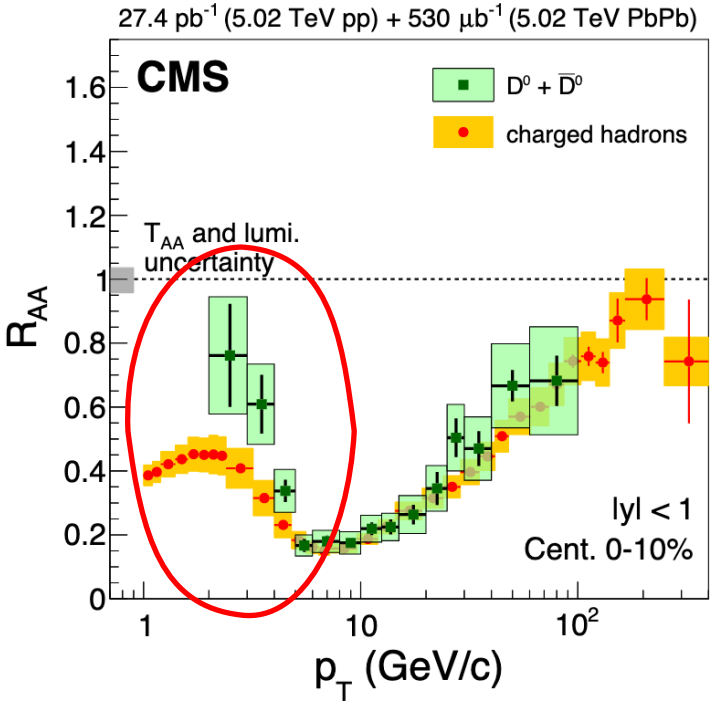
Heavy Quarks (Charm) in Medium

Open heavy flavor

$$R_{AA} = \frac{\text{AA}}{\text{Binary collision scaled pp}}$$

D meson

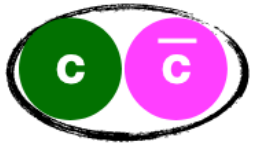
CMS, arXiv:1708.04962



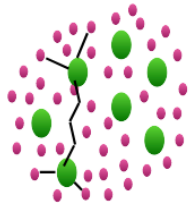
Charm mesons less suppressed than charged hadrons at low p_T

Quarkonia

J/Ψ



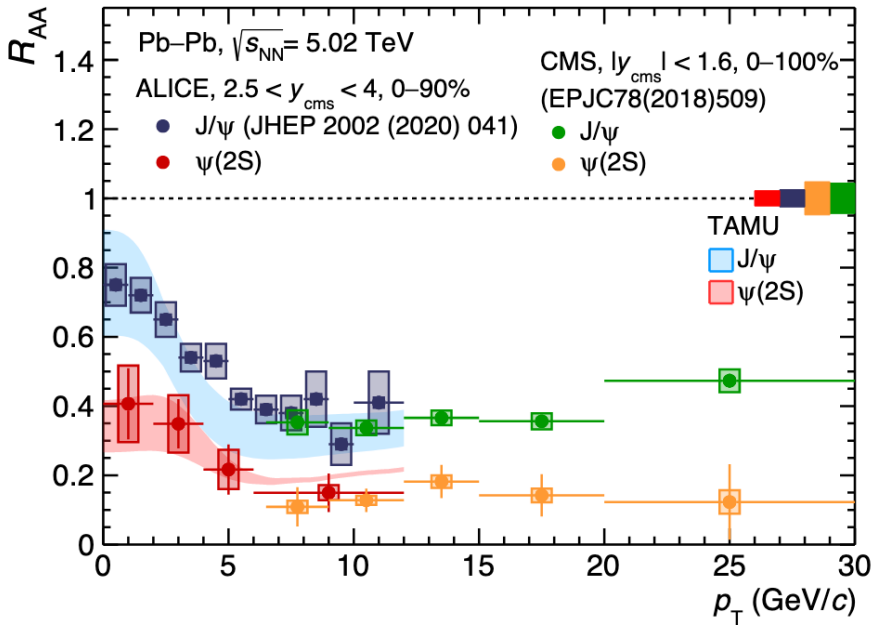
J/Ψ vacuum



J/Ψ in QGP

Debye screening of color charge

ALICE, arXiv:2210.08893

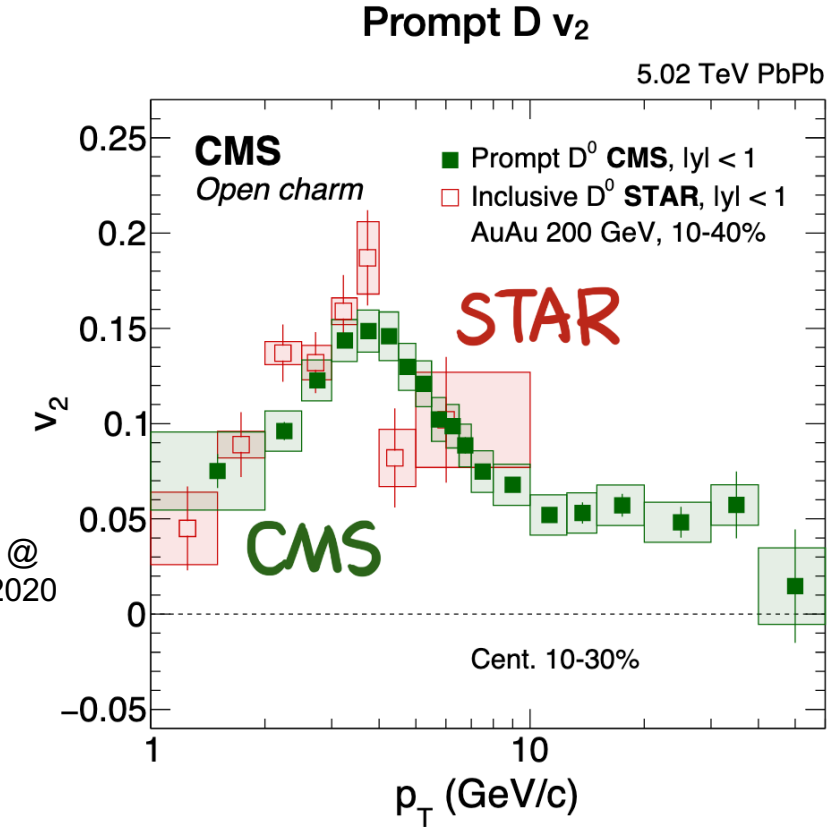


Yield suppression of charmonium states

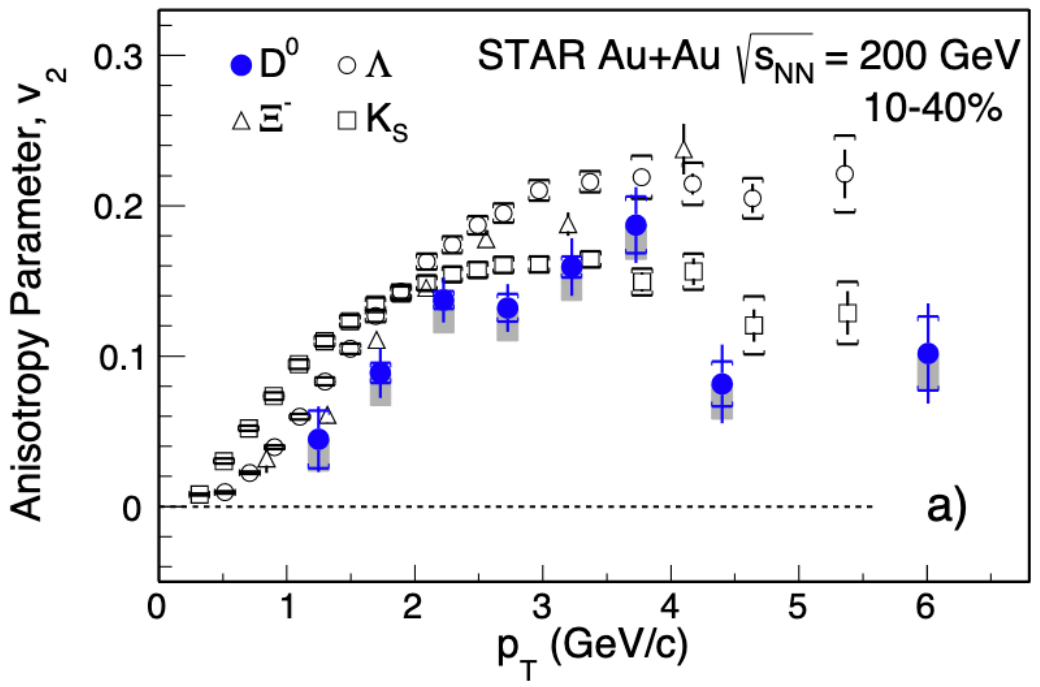
Excited state ($\psi(2S)$) more suppressed than ground state J/ψ

Charm Quark Anisotropy

Jing Wang @ HF-WINC2020



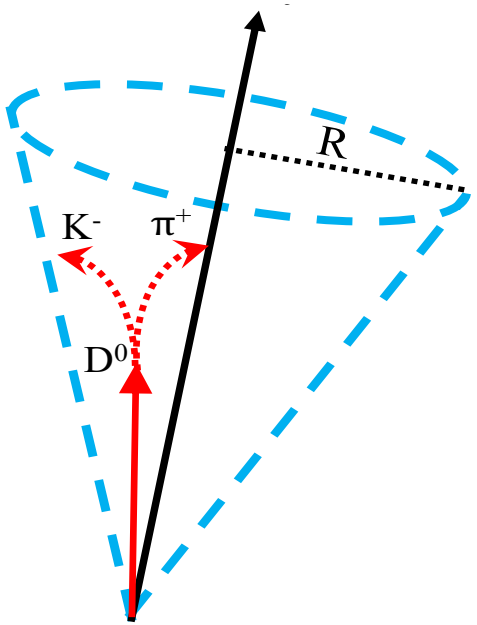
STAR, arXiv: 1701.06060



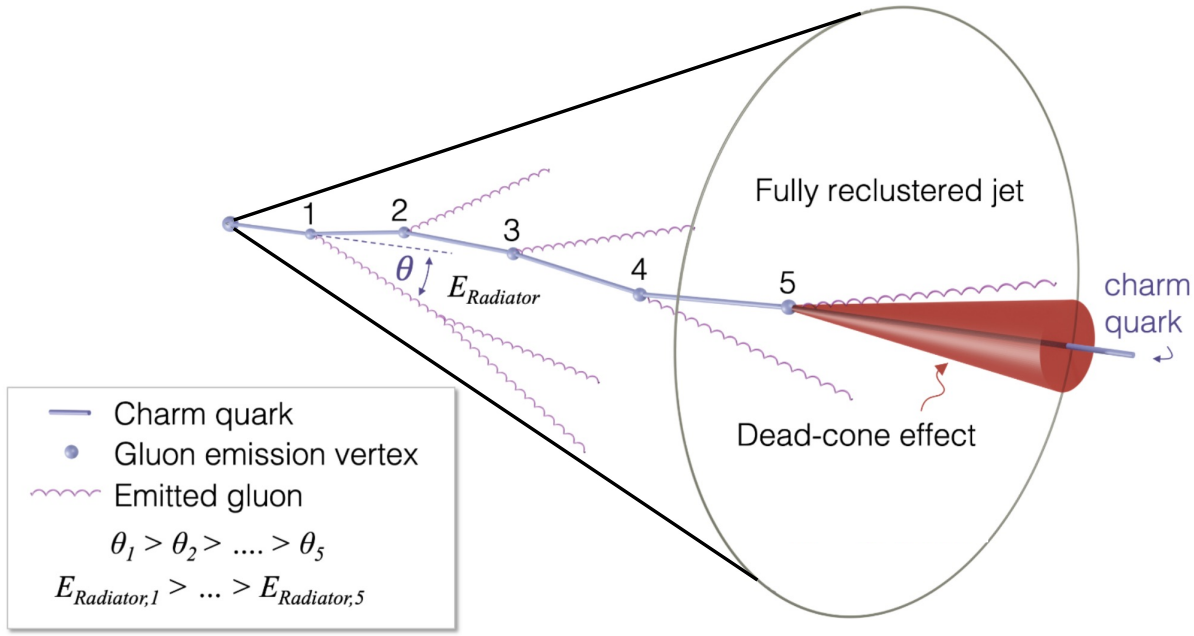
Charm quarks interact strongly with the medium and participate in collective expansion → Non-zero flow

At RHIC energies, open charm quark exhibits similar collective behavior as light hadrons

Open Charm Jets – Looking at the dead cone

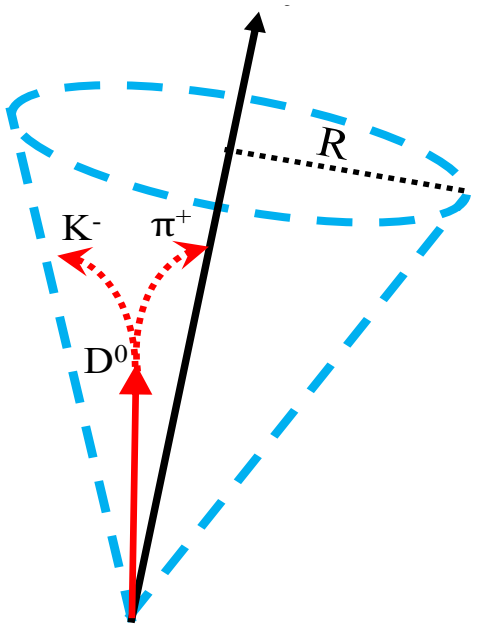


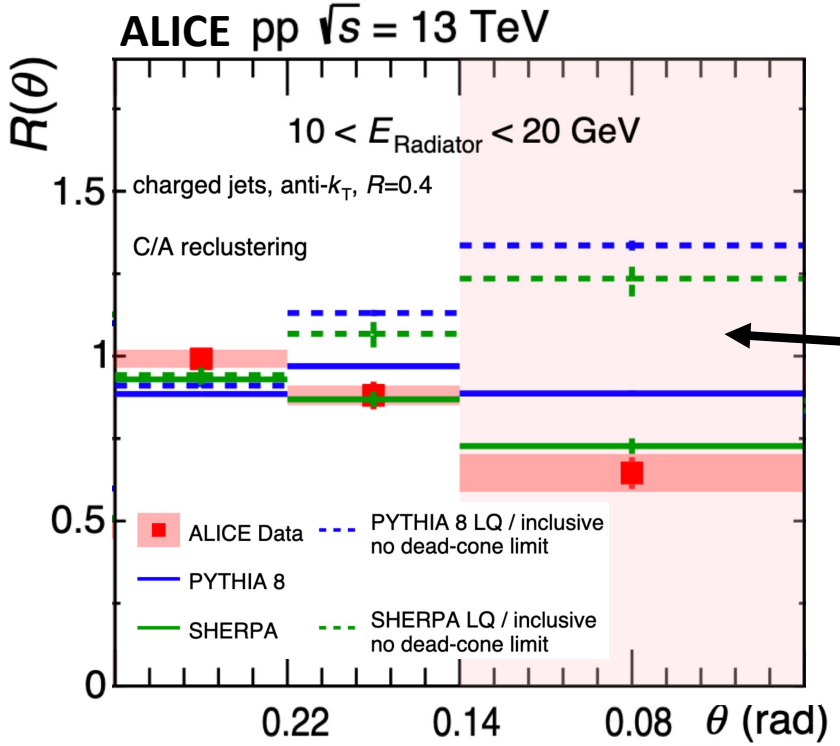
ALICE, arXiv:2106.05713 (2021)



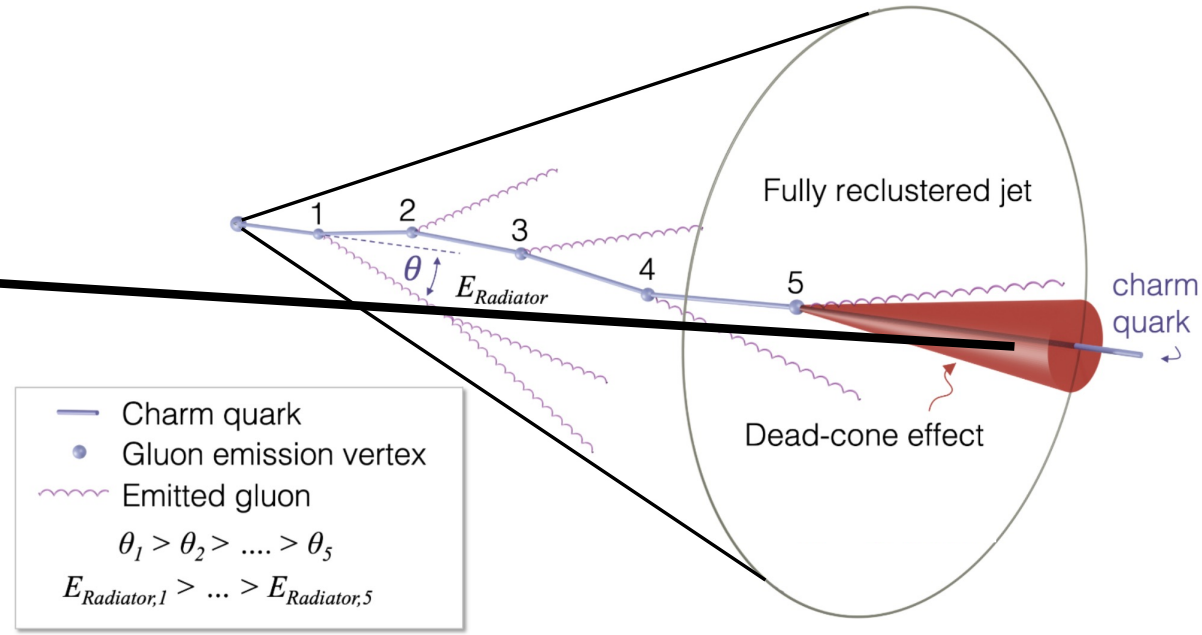
Open Charm Jets – Looking at the 'dead cone'

$$R(\theta) = \frac{1}{N_{D^0\text{jet}}} \frac{\mathrm{d}n_{D^0\text{jet}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N_{\text{inclusive jet}}} \frac{\mathrm{d}n_{\text{inclusive jet}}}{\mathrm{d}\ln(1/\theta)}$$





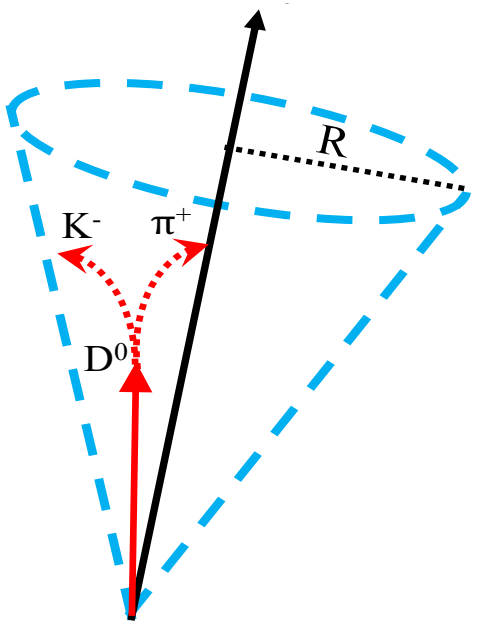
ALICE, arXiv:2106.05713 (2021)



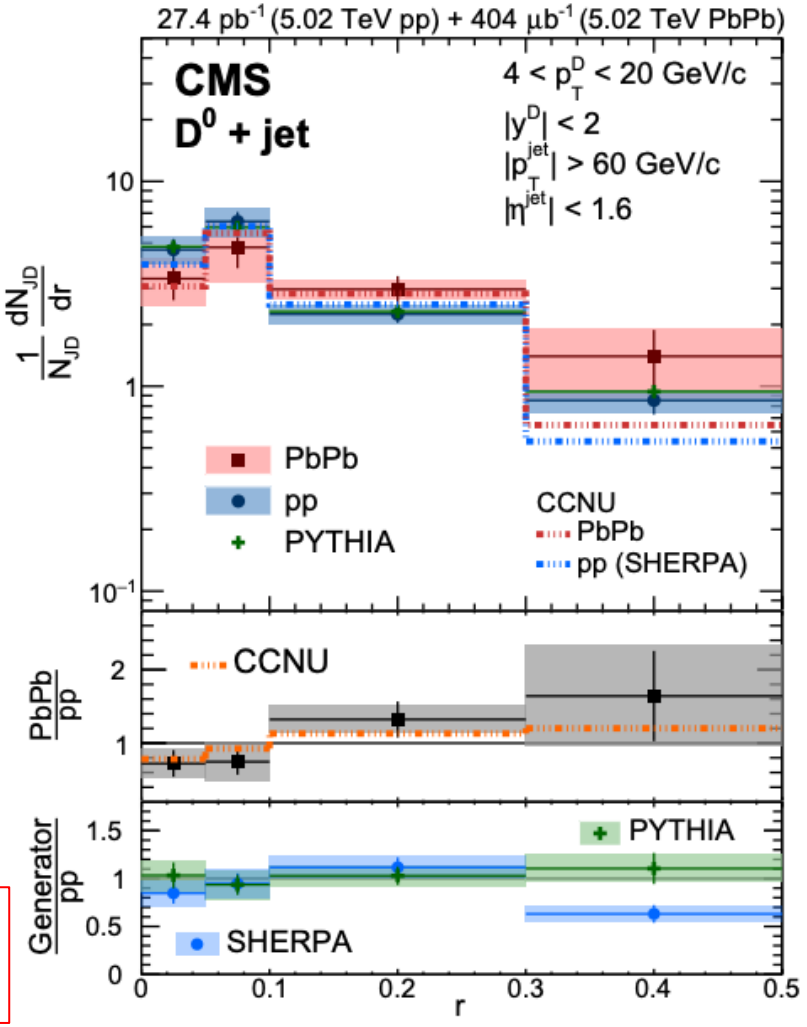
Heavy-flavor emission spectra at small angles suppressed due to dead-cone effect

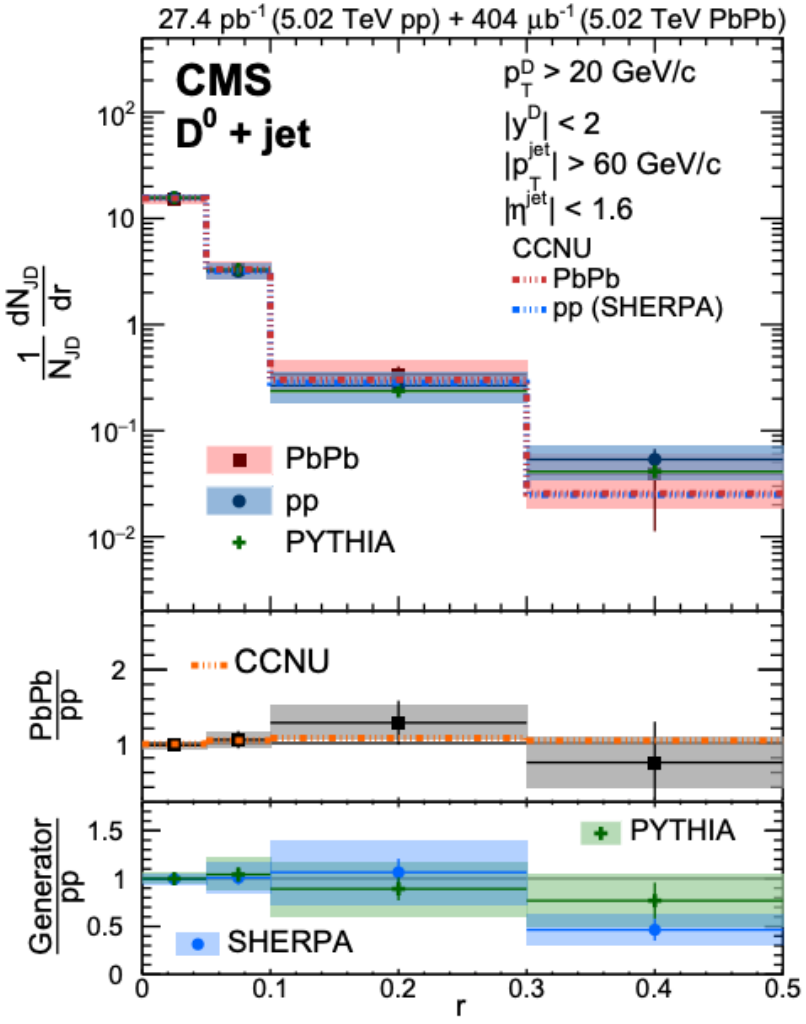
Open Charm Diffusion in Jets (5 TeV)

CMS, Phys. Rev. Lett. 125 (2020) 102001



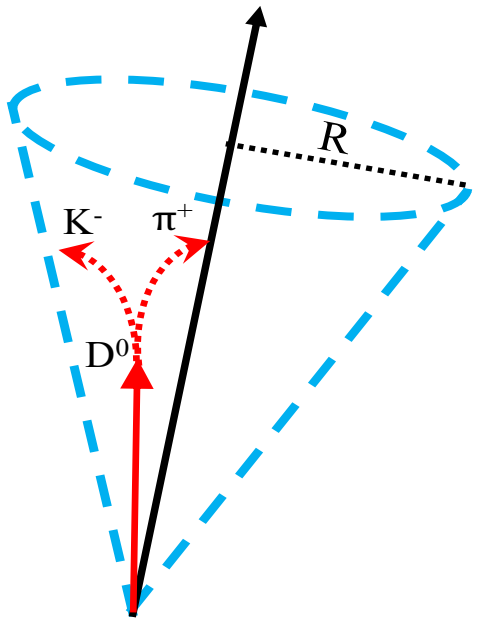
Low p_T D^0 mesons appear to be diffused in the presence of QGP at LHC

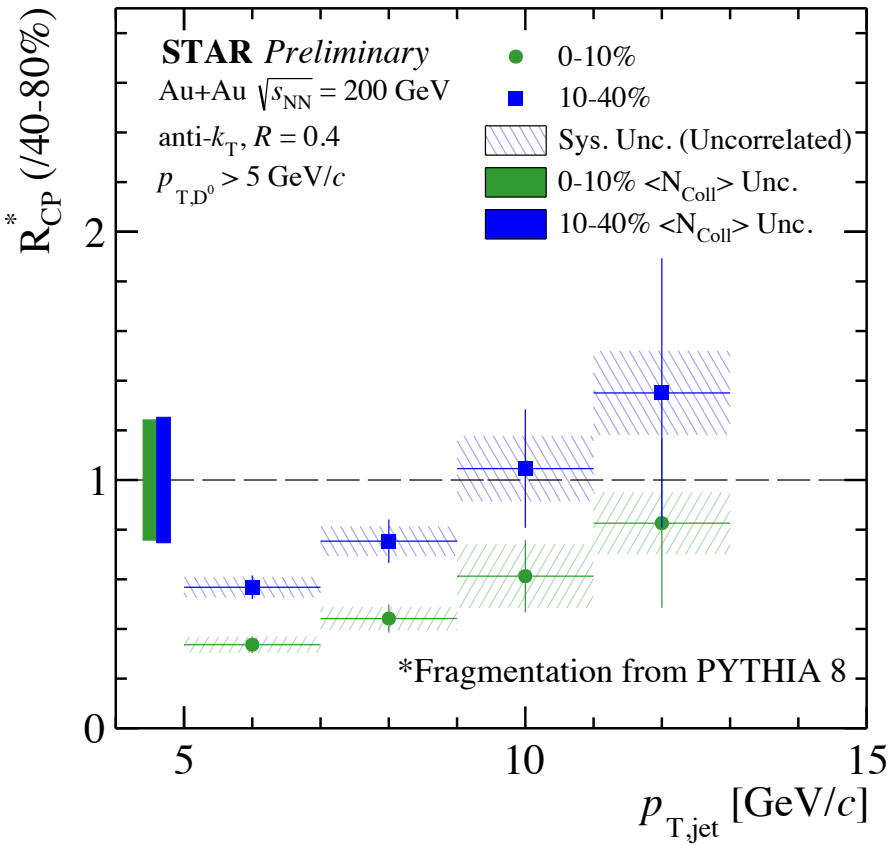


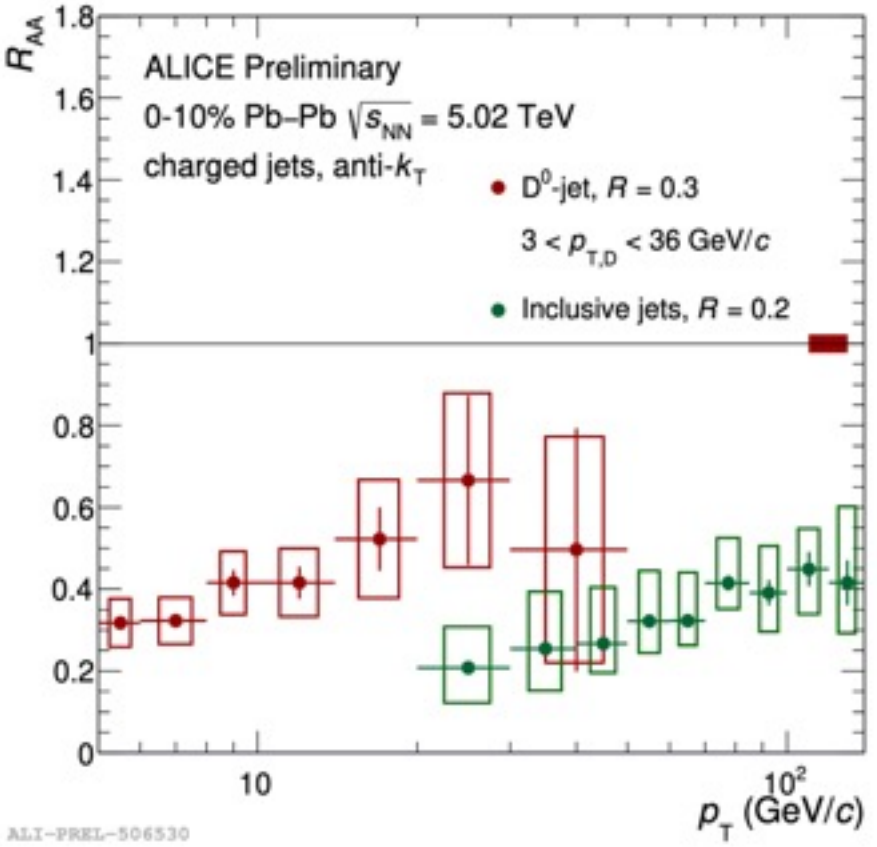


- **Lower p_T D^0 mesons can be reconstructed at RHIC energies**
- **Contribution from the underlying background is smaller at RHIC**

Open Charm Jets in Medium (Quenching)

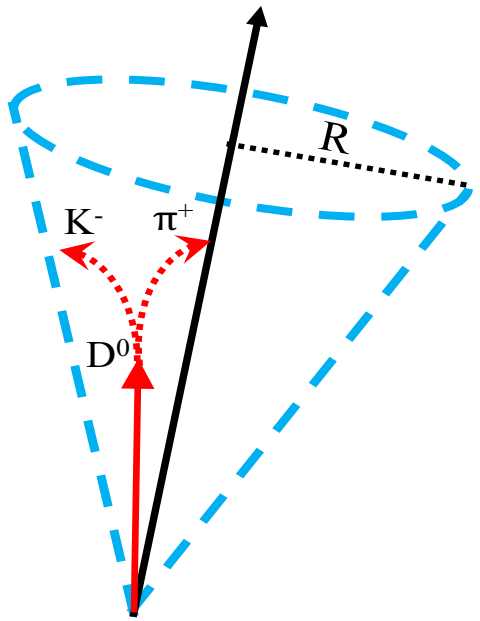


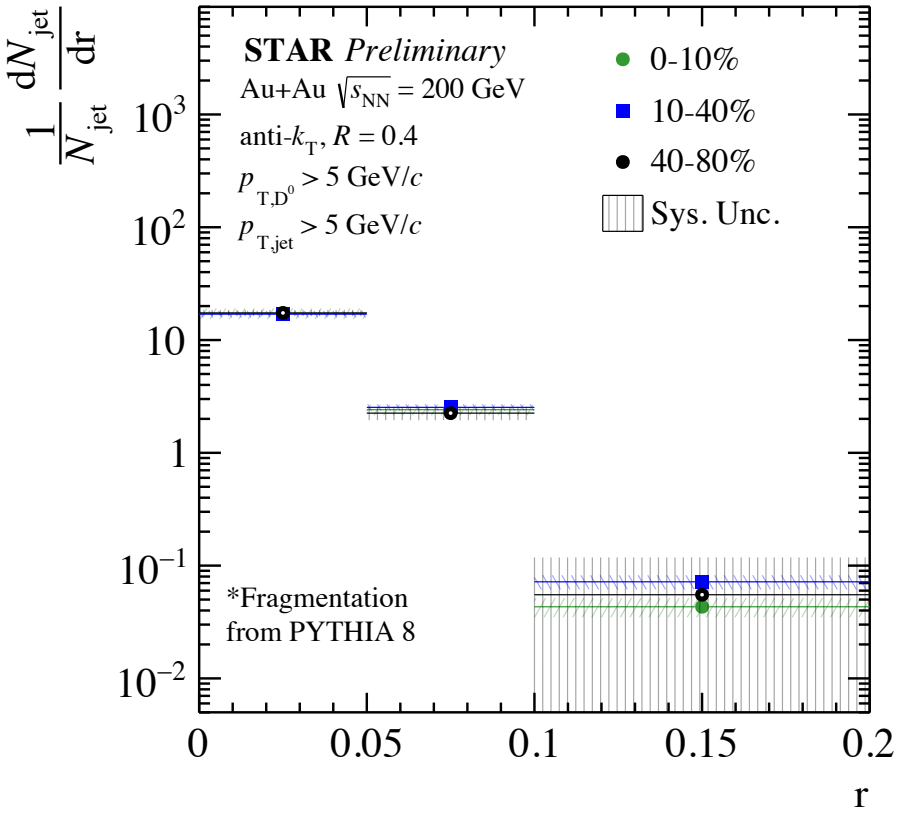


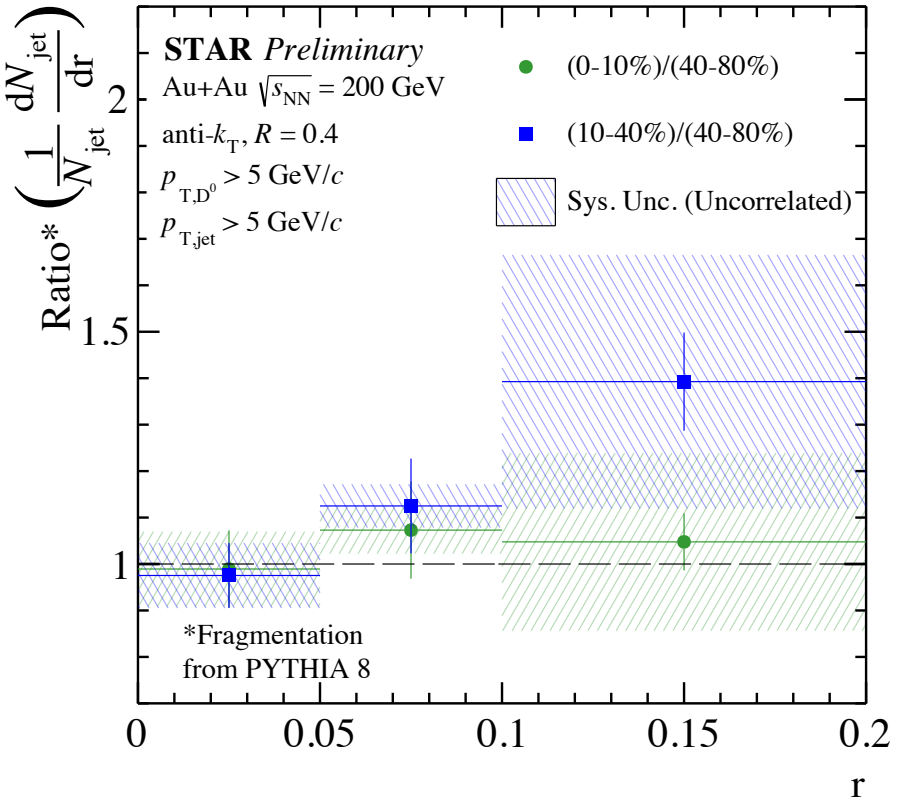


Strong in-medium suppression for D^0-tagged jets at low $p_{T,jet}$ at 200 GeV from STAR and 5.02 TeV from ALICE

Open Charm Diffusion in jet (5 TeV)



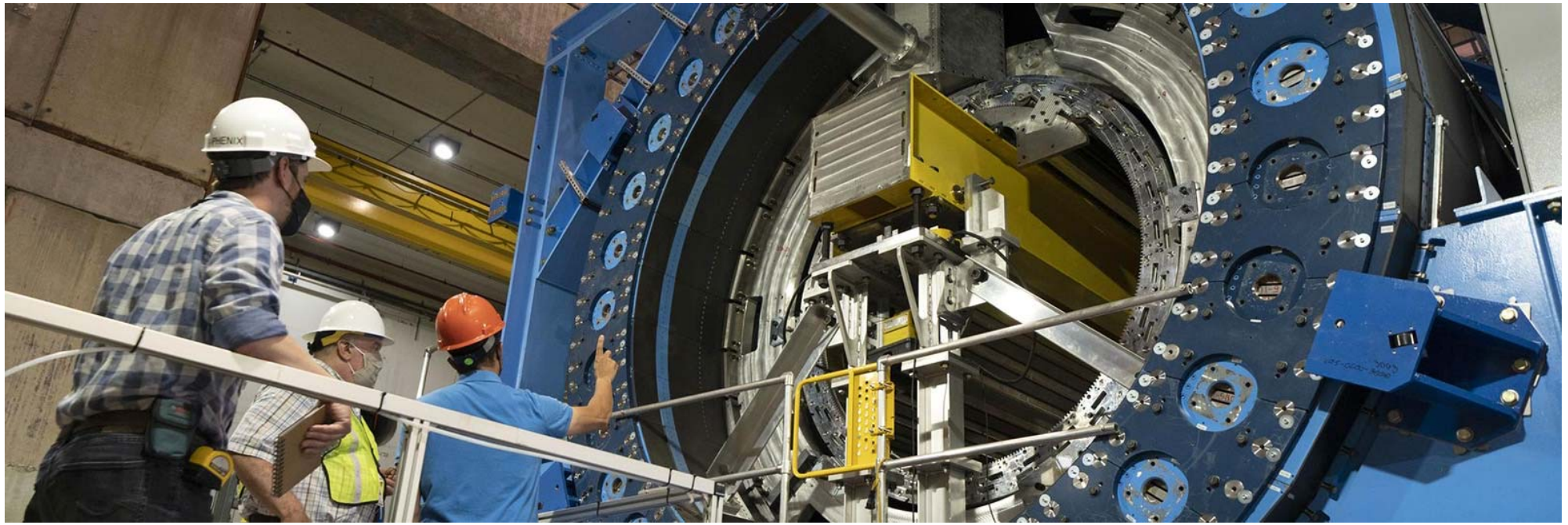




No diffusion observed with D0 p_T > 5 GeV

Summary

- Probes of quark-gluon plasma come in all shapes, sizes, color, and flavor
- Beam Energy Scan II at STAR is hunting for the ever-elusive critical point
- Army of unique and complimentary hard probes at our disposal at LHC and RHIC
- Heavy flavor jets offer a unique perspective into the mass and flavor dependence of interactions with QGP



NEW DETECTOR AT RHIC: sPHENIX

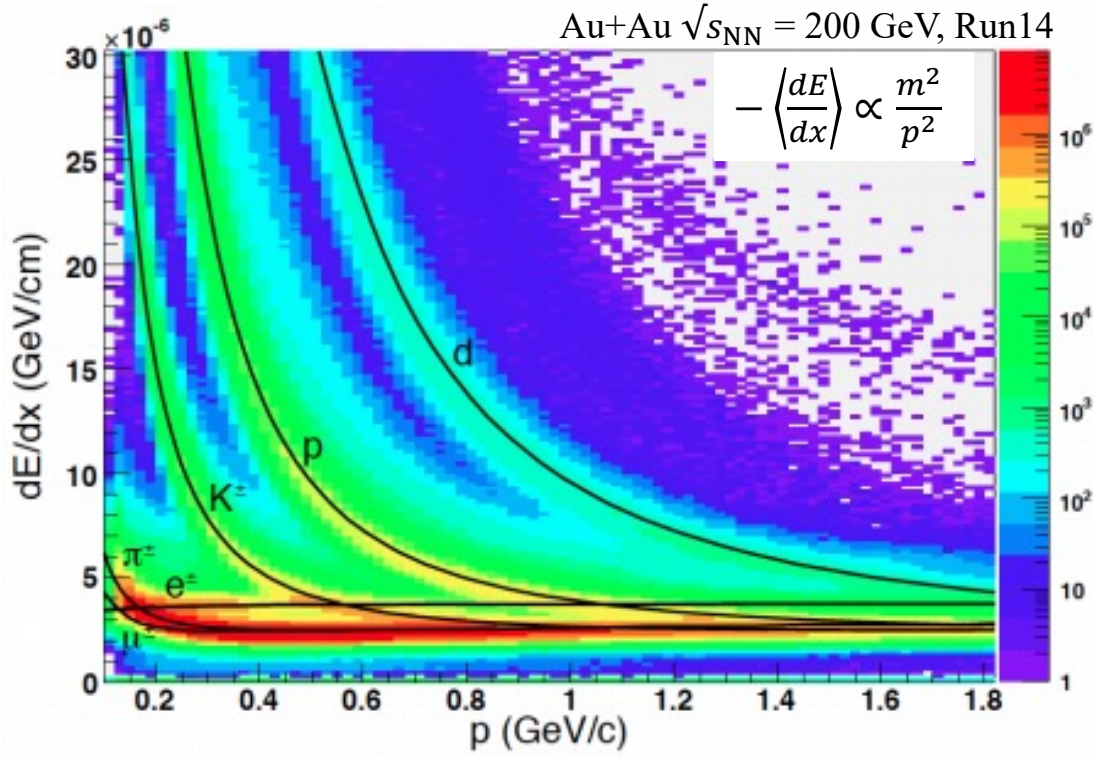
Precision measurements of heavy flavor


Thank you

D^0 Reconstruction

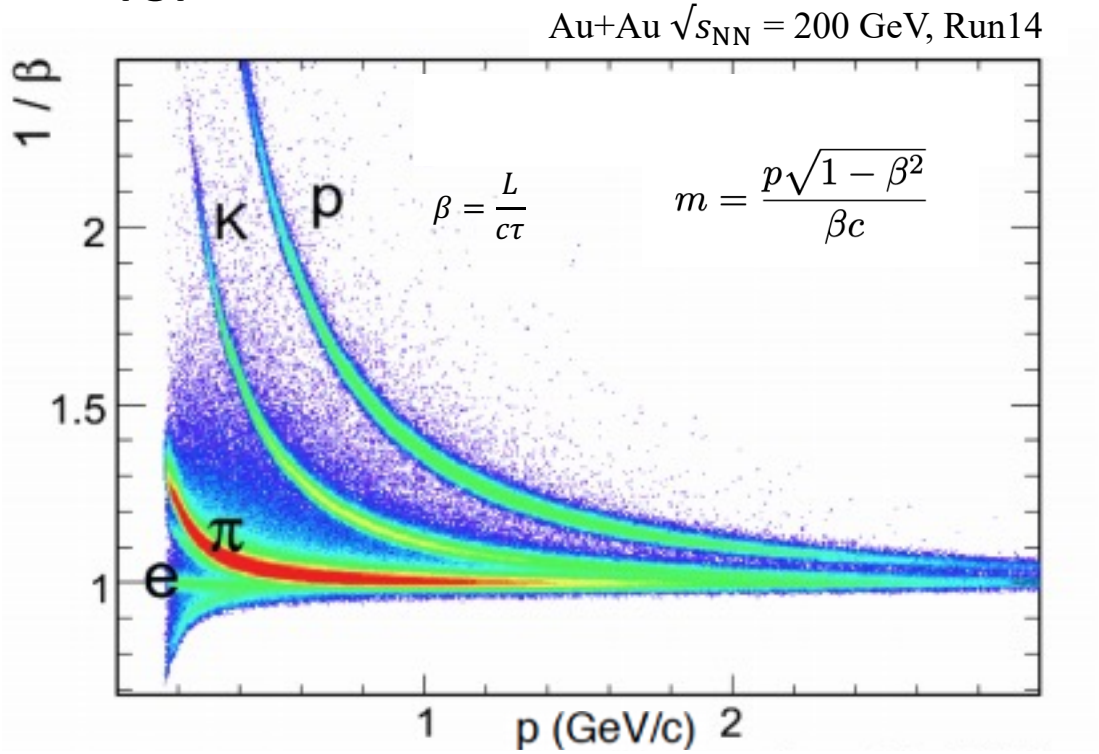
Particle Identification

TPC



- $|n\sigma_{\pi}| < 3.0$
- $|n\sigma_{K}| < 2.0$

TOF



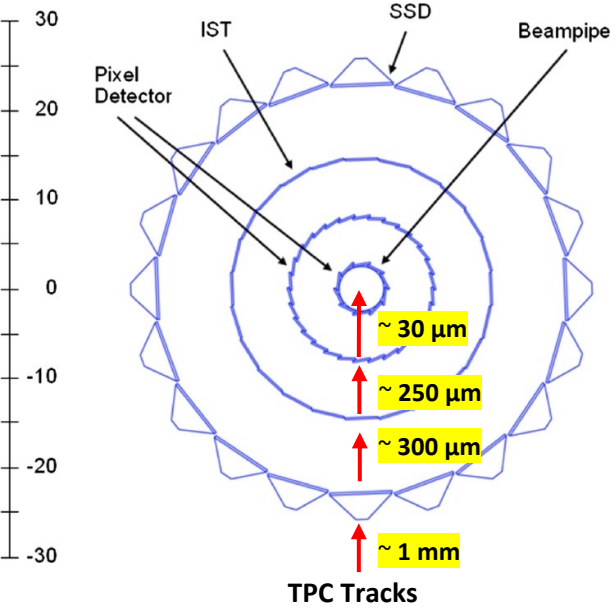
- $|\frac{1}{\beta} - \frac{1}{\beta_{exp}}| < 0.03$

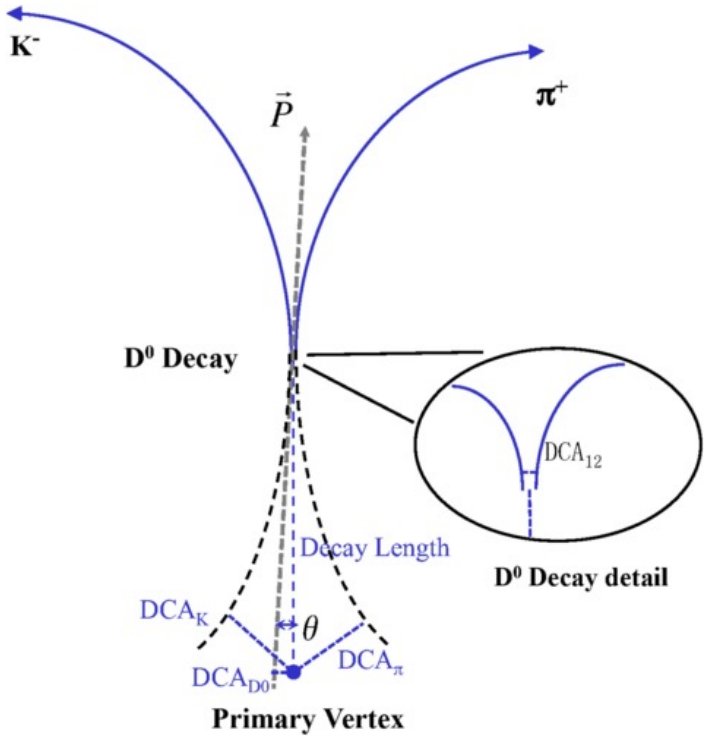
Hybrid PID to identify Pions and Kaons to reconstruct D^0 mesons

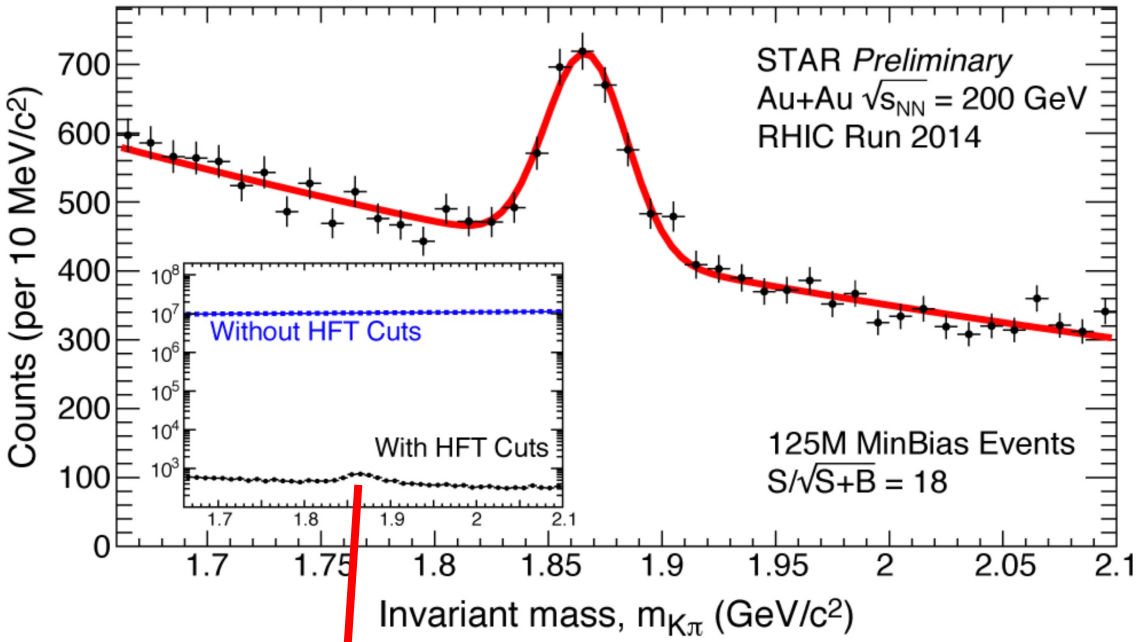
D^0 Reconstruction

Improving signal significance

STAR, Phys. Rev. C 102 (2020) 014905







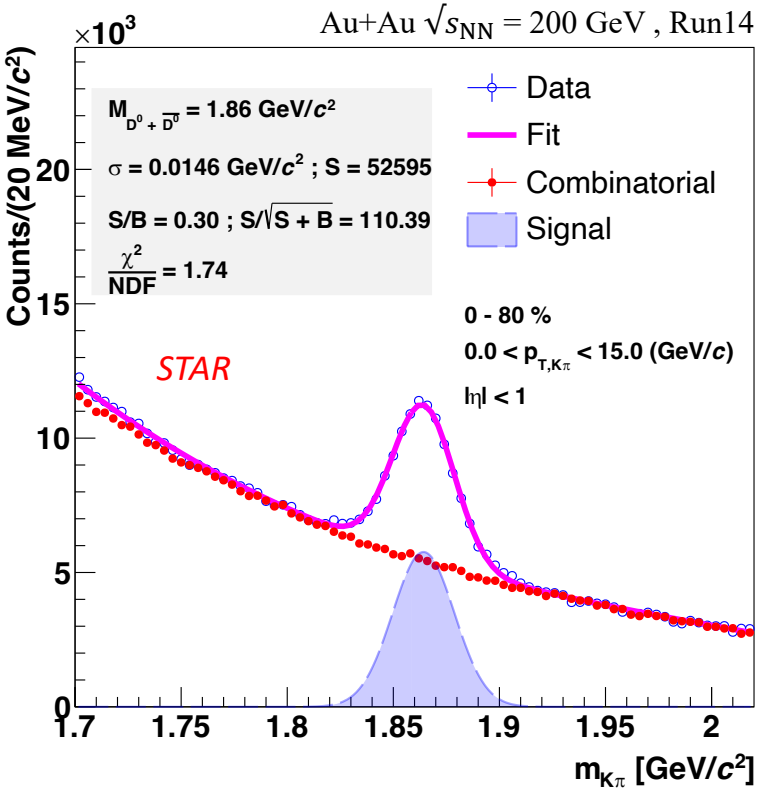
Decay Length of D^0 ~ 123 µm.

HFT has a resolution of 30 µm for kaons at ~ 1.2 GeV/c

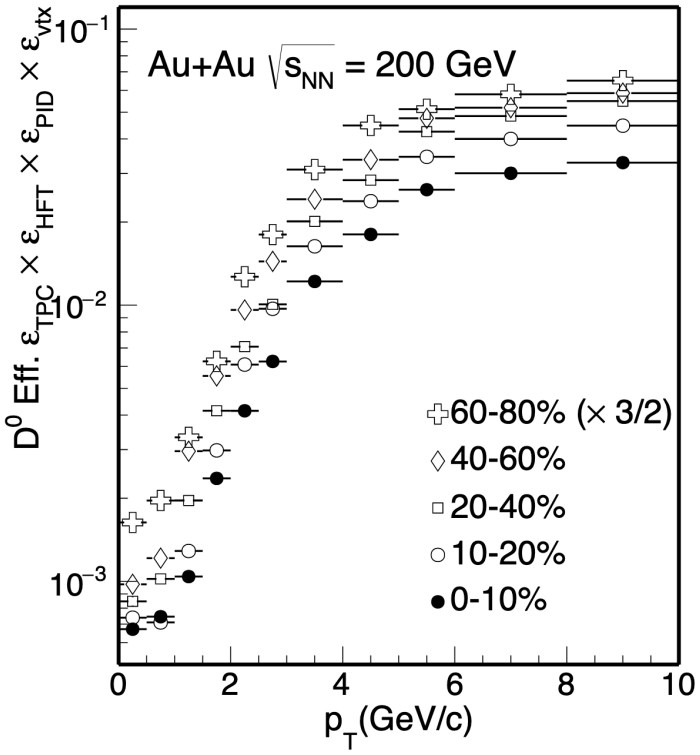
HFT can reconstruct D^0 candidates based on the decay kinematics

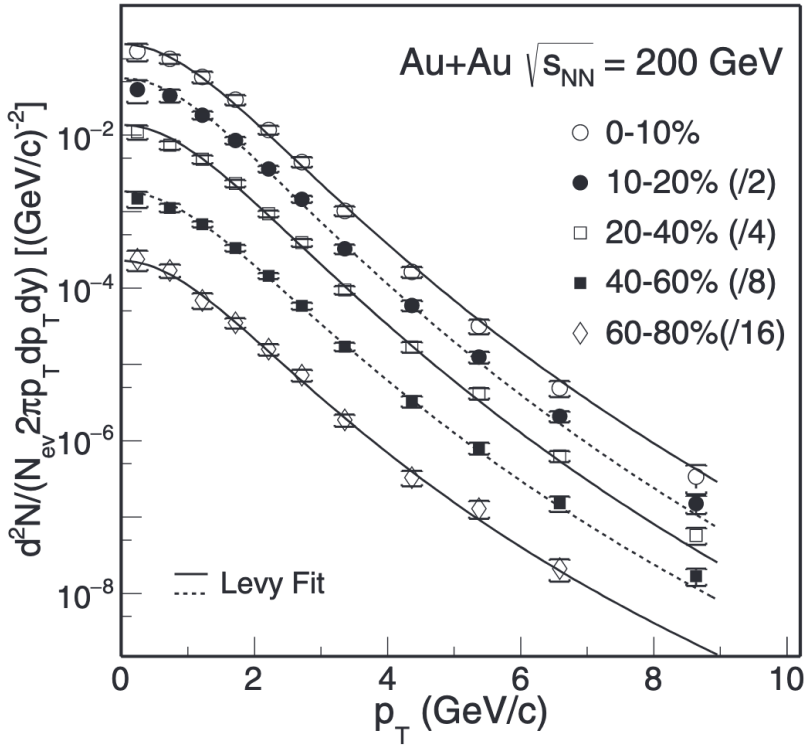
Topological cuts on the D^0 candidates improve signal significance

D^0 Reconstruction



STAR, Phys. Rev. C 99 (2019) 034908





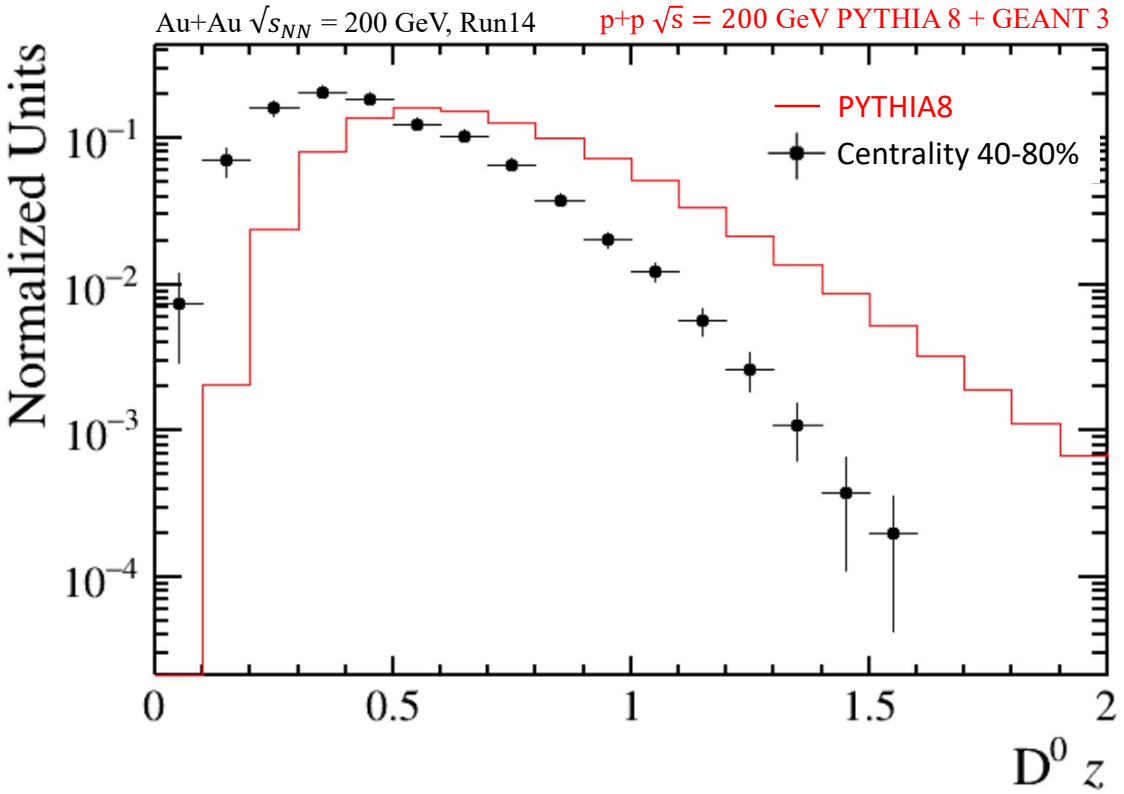
D^0 yield corrected for reconstruction efficiency

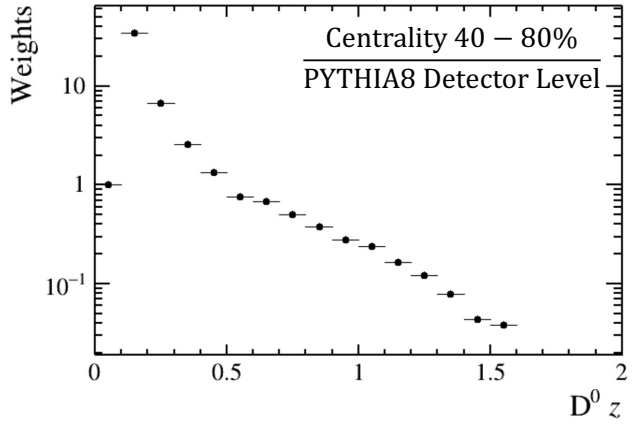
The efficiency weights were derived using a data-driven fast simulation method

Fragmentation Function In PYTHIA8

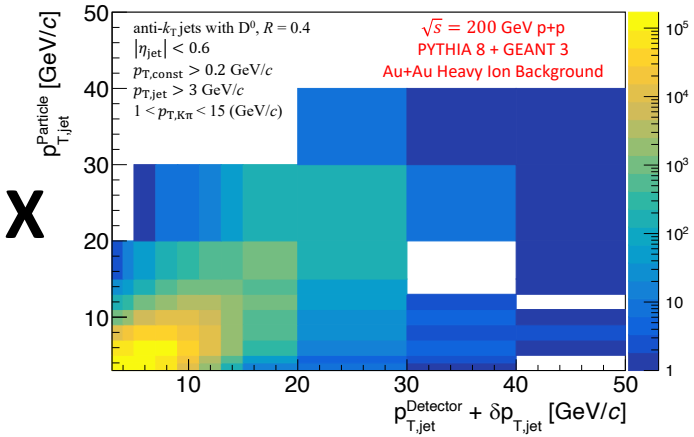
Fragmentation function: Related to cross-section of production processes

In experiment, $z = \frac{\vec{p}_{T,D^0} \cdot \hat{p}_{T,Jet}}{|\vec{p}_{T,Jet}|}$

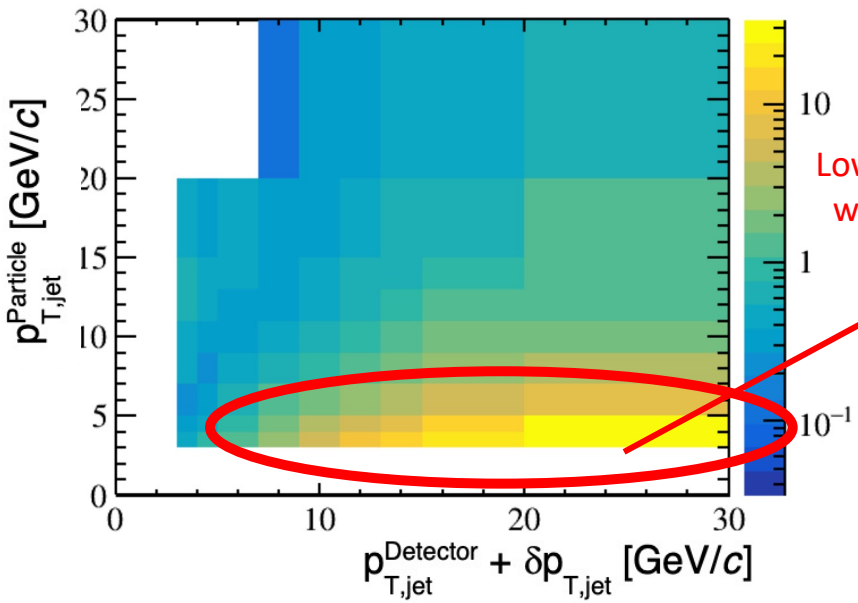




X



Ratio of reweighted and original response matrix



Low p_T particle level jets pick up huge weights → Bias in response matrix

NEED FIXING

Summary and Outlook

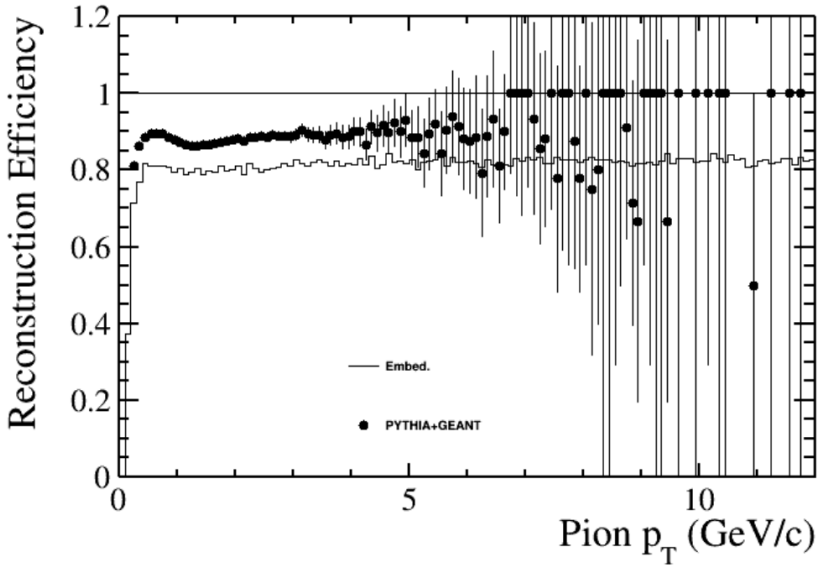
- ✓ First measurements of D^0 meson jet p_T spectra and radial distribution of D^0 mesons in jets for peripheral collisions.
- ✓ PYTHIA simulation along with existing data-driven fast simulation method used to estimate detector effects.
- ✓ 2D Unfolding used to correct the radial distribution of D^0 mesons

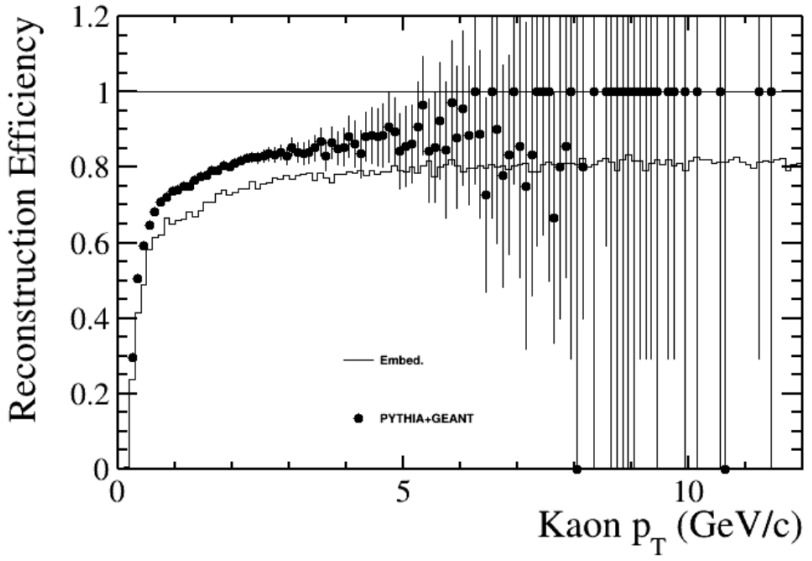
- Need a way to correct for the fragmentation function discrepancy
- Official simulation sample on the way to validate the current results for QM
- R_{CP} values will be reported with the official sample

THANK YOU

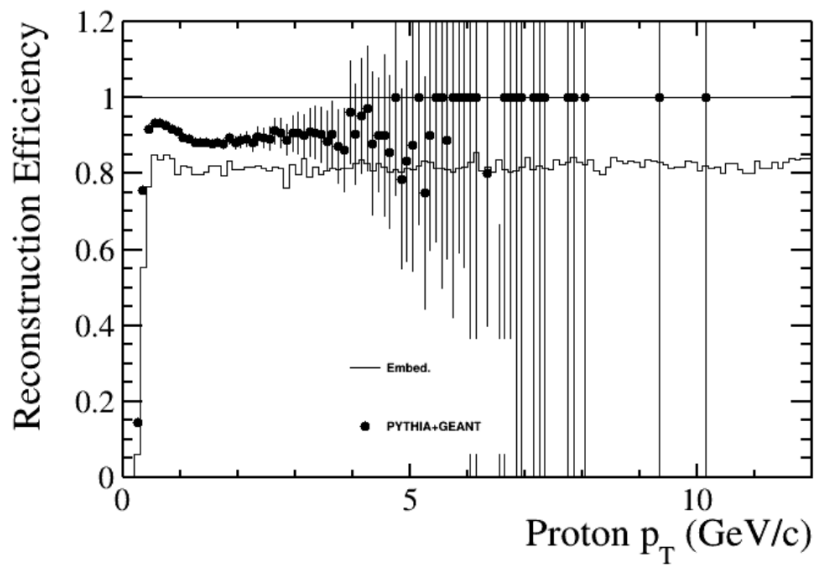
Backup

Au+Au 20-30%





Separate for anti-p

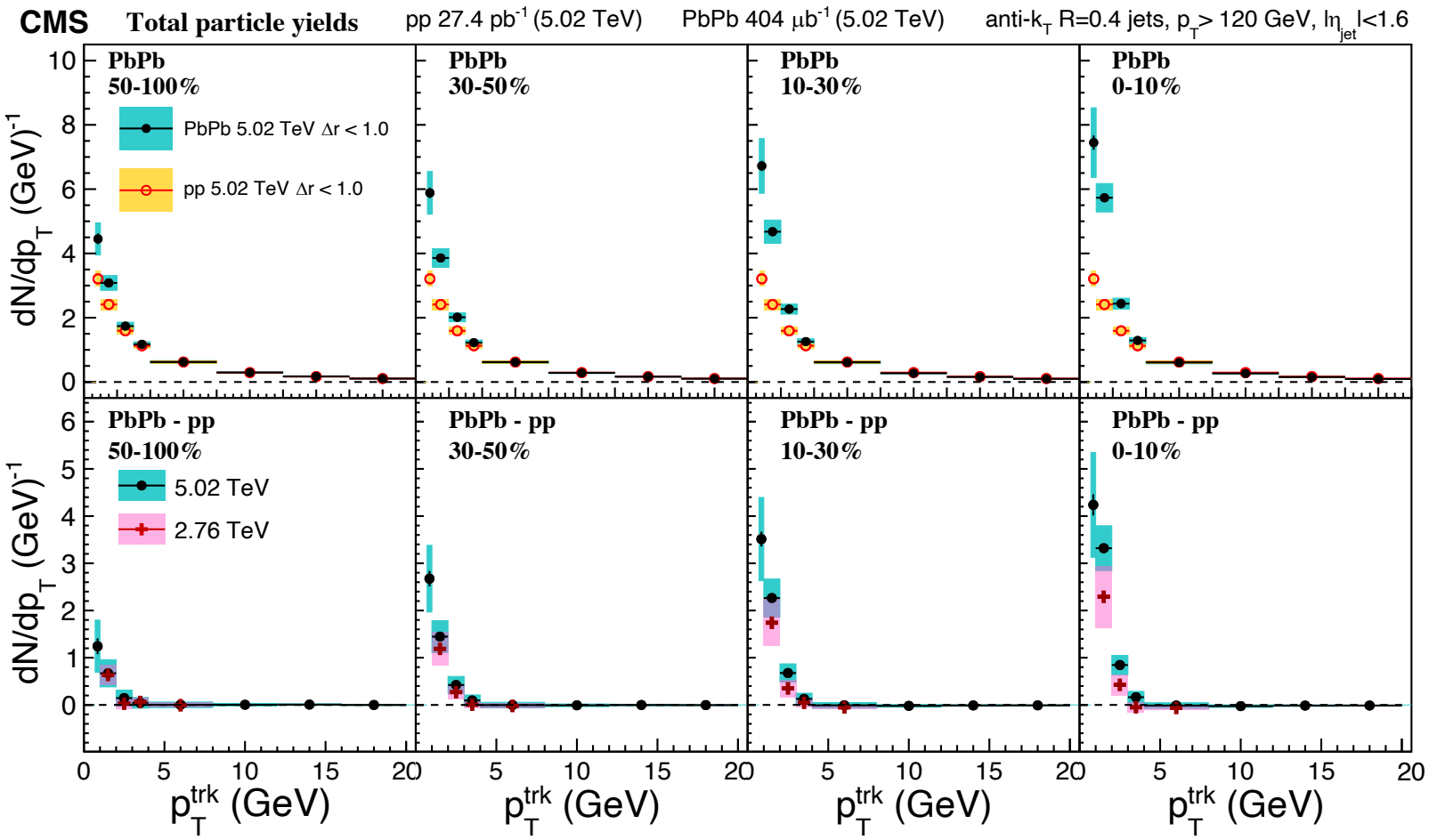


Multiplicity dependence of tracking efficiency not accounted for in PYTHIA samples

Corrections for tracking efficiency by deriving ratios of efficiencies in pure PYTHIA+GEANT (p+p) with single particle embedding (Au+Au)

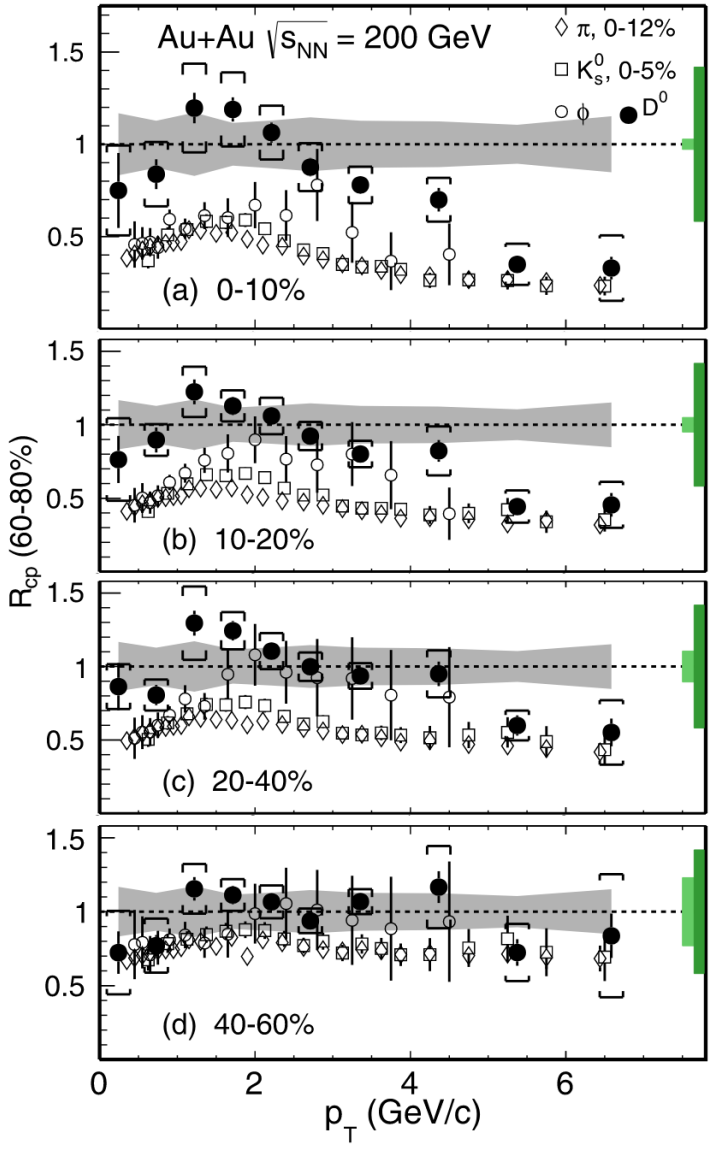
- Single track embedding efficiencies taken from D^0 and Λ_c analyses
- For π, K, p, and anti-p

Backup



CMS, JHEP 05 (2018) 006

Backup


Au+Au $\sqrt{s_{NN}}$ = 200 GeV
π, 0-12%
K^0_s, 0-5%
φ
D^0
(a) 0-10%
(b) 10-20%
(c) 20-40%
(d) 40-60%
R_{cp} (60-80%)
p_T (GeV/c)
1.5
1
0.5
0
2
4
6