Quantifying Jet Quenching And Medium Response With Two Particle Correlations With PHENIX

Anthony Hodges for the PHENIX Collaboration

Hot Jets: Advancing the Understanding of High Temperature QCD With Jets

January 8th, 2024

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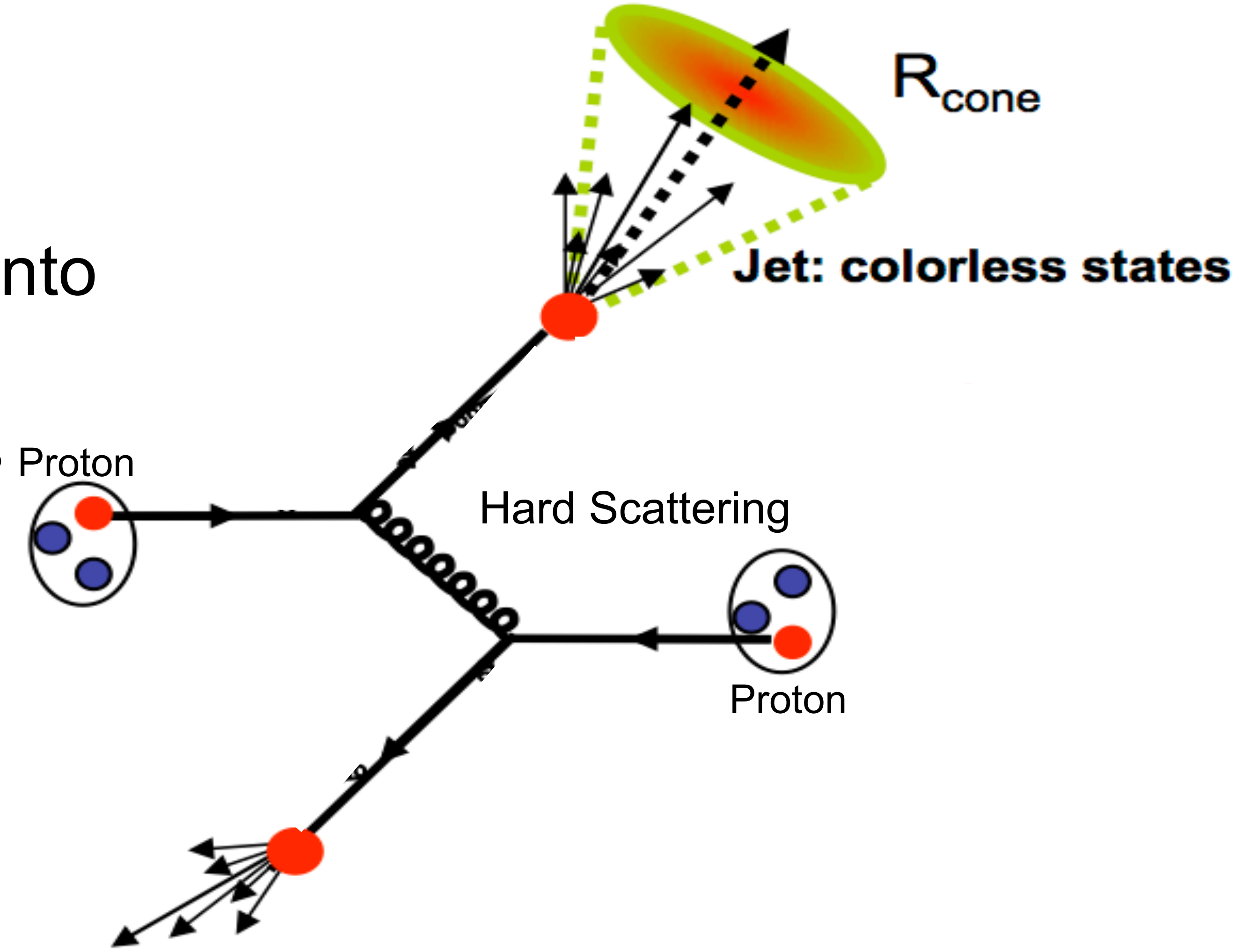
Jets as QCD Probes

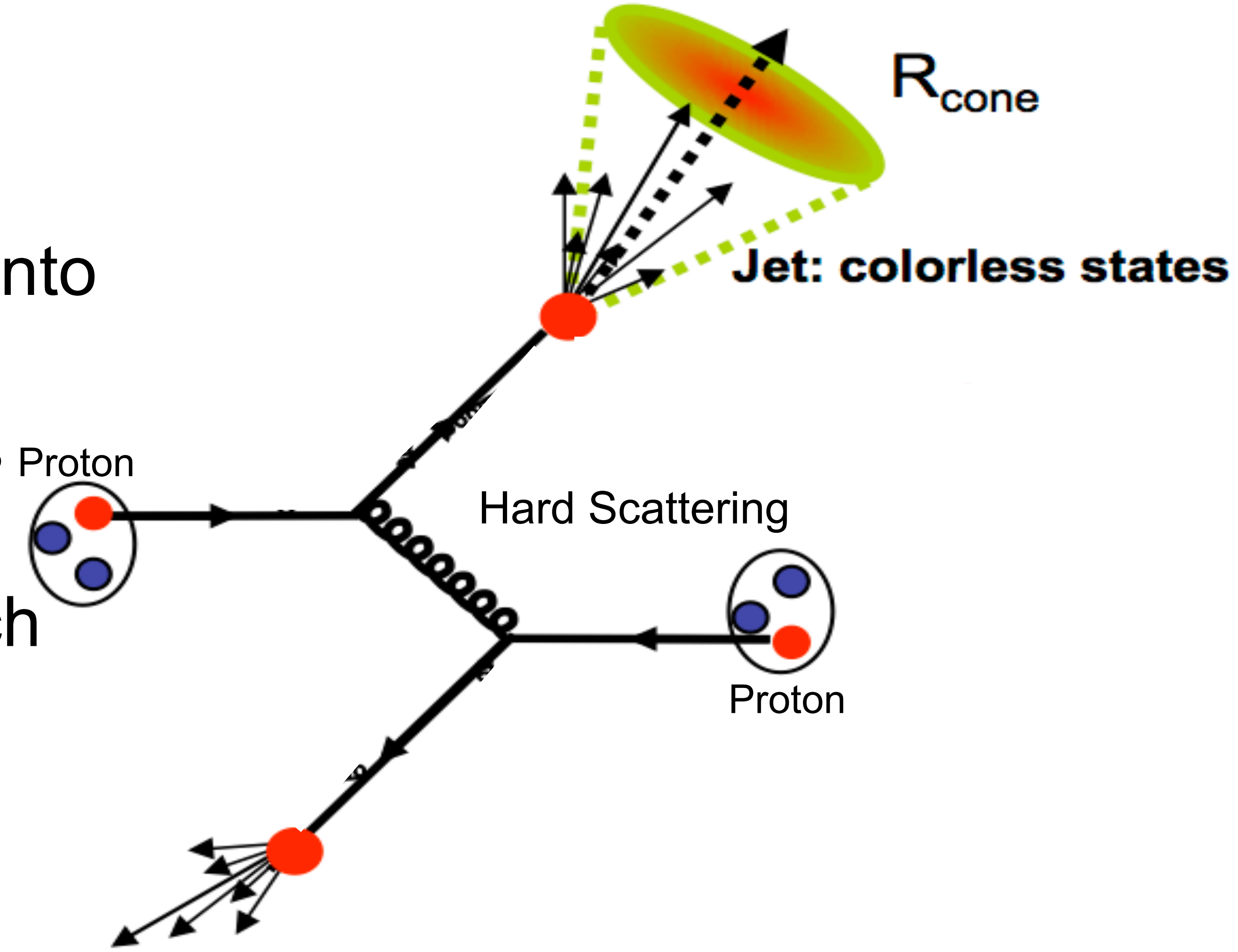
- Partons undergo hard scattering
  - Large momentum transfer (q^2)
- Hard-scattered partons hadronize into jets
- Jet kinematics ≈ parton kinematics good proxy



p+p Collision

Jets as QCD Probes

- Partons undergo hard scattering
  - Large momentum transfer (q^2)
- Hard-scattered partons hadronize into jets
- Jet kinematics ≈ parton kinematics good proxy
- Jets are accessible by pQCD, which makes them very theory-friendly



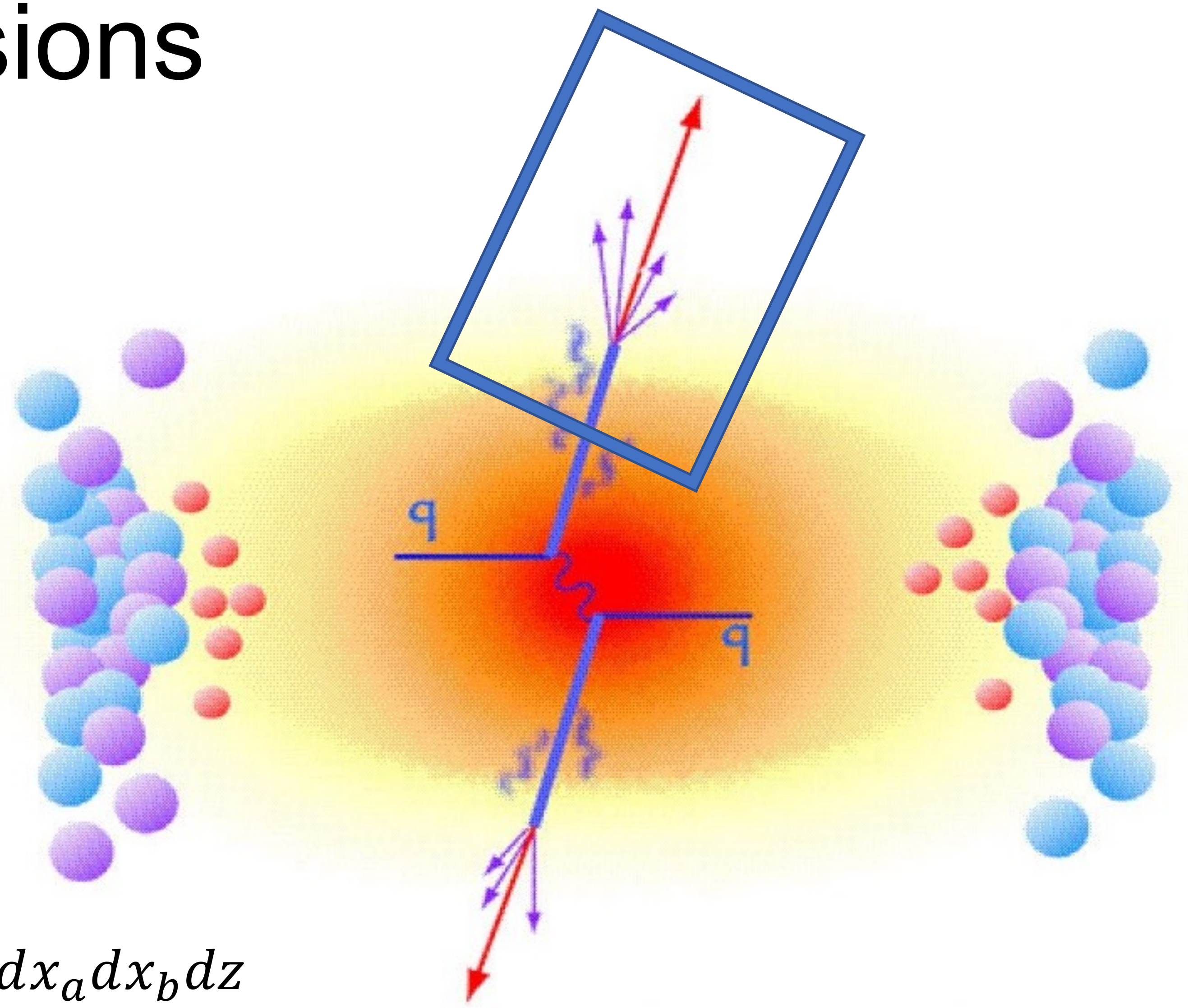
p+p Collision

Differential cross section

$$d\sigma = \int \int \int f_a^A(x_a) f_b^B(x_b) \cdot d\sigma_{ab \to cX} \cdot D_c^h(z) dx_a dx_b dz$$

Jets in Heavy Ion Collisions

- Hard-scattered partons now traverse dense QGP medium
- Energy lost to medium yields modified jets
- Measurement of jet modification allows us to study parton-medium interactions



Differential cross section

$$d\sigma = \int\int\int f_a^A(x_a) f_b^B(x_b) \cdot d\sigma_{ab\to cX} \cdot D_c^h(z) dx_a dx_b dz$$

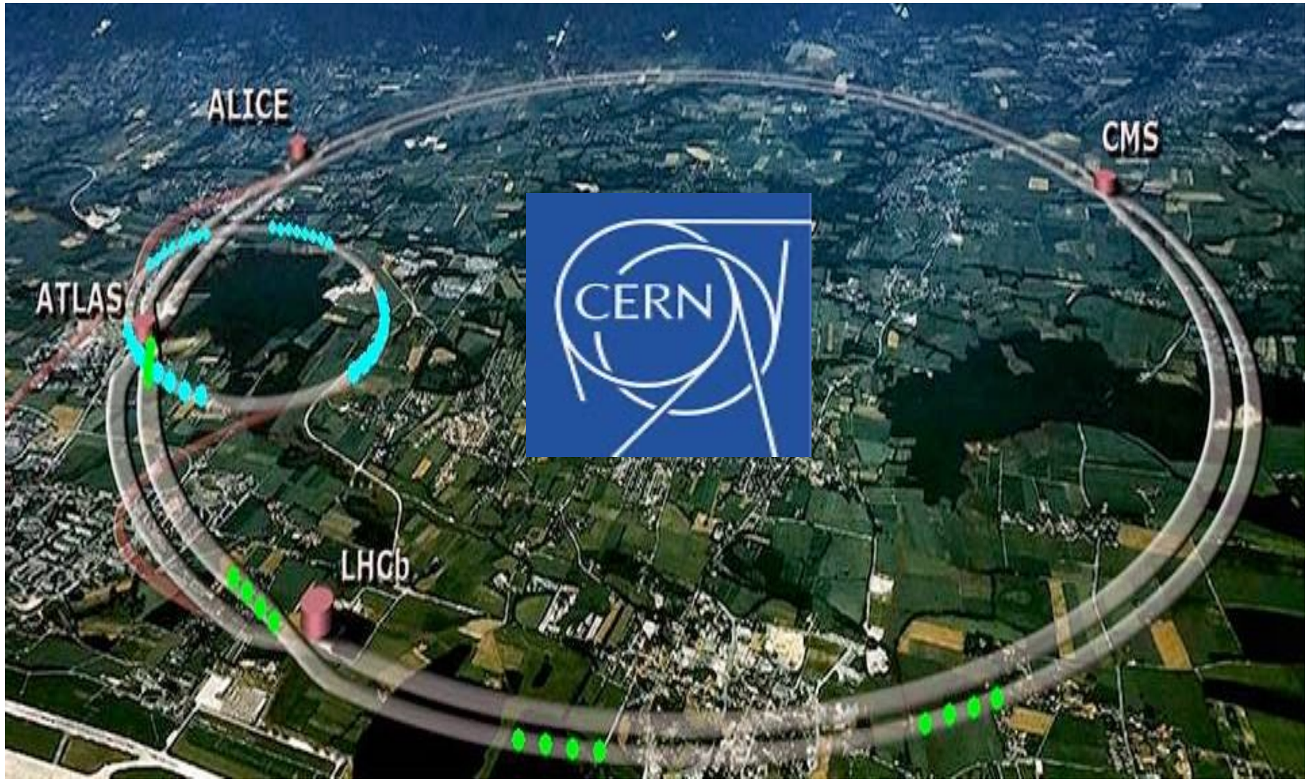
Modification

$D_c^h(z) \to D_c^h(z')$ as $p^{Parton} \to p'^{Parton}$

Heavy Ion Collision

Jet Factories: RHIC and the LHC

Relativistic Heavy Ion Collider



Large Hadron Collider

The Relativistic Heavy-Ion Collider

√s [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

- Highly versatile collider
- Decades of expansive data collected

The Relativistic Heavy-Ion Collider

√s [GeV]	p+p
510	✓
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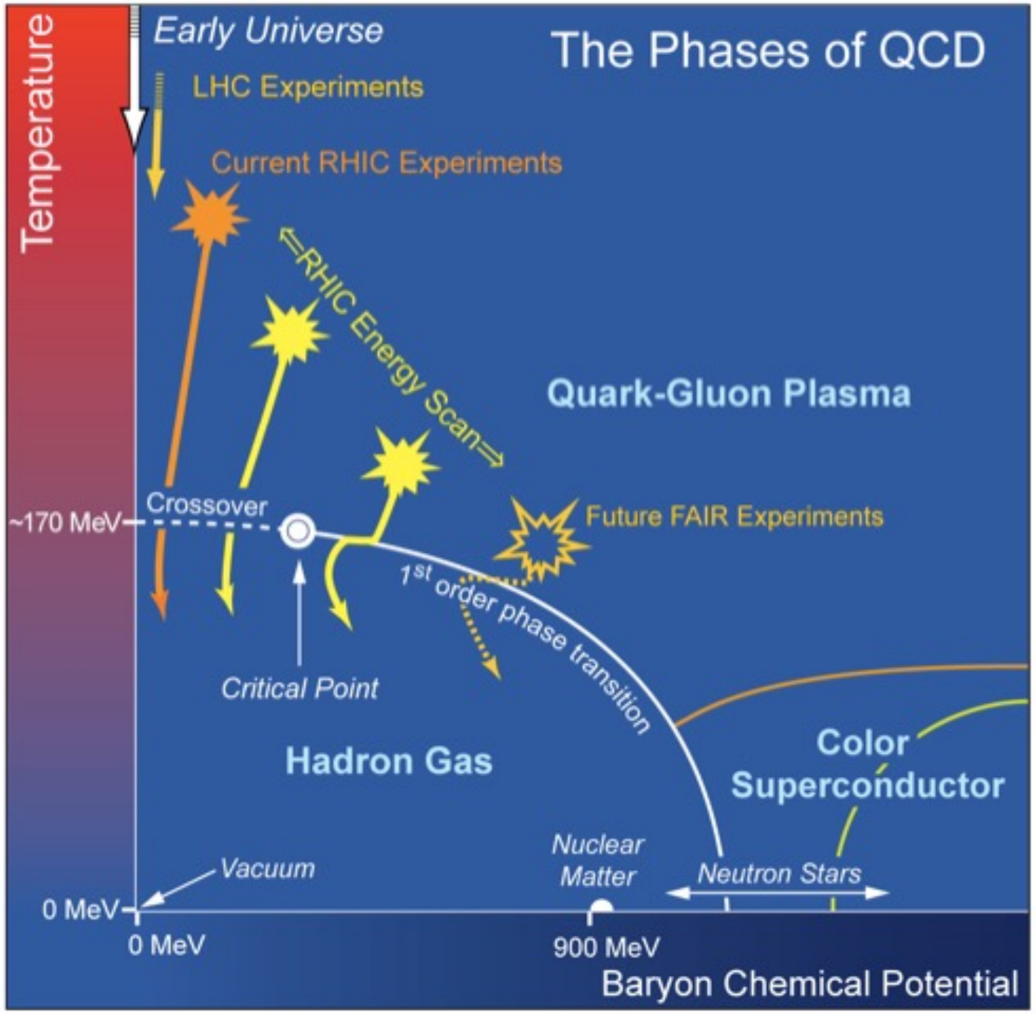
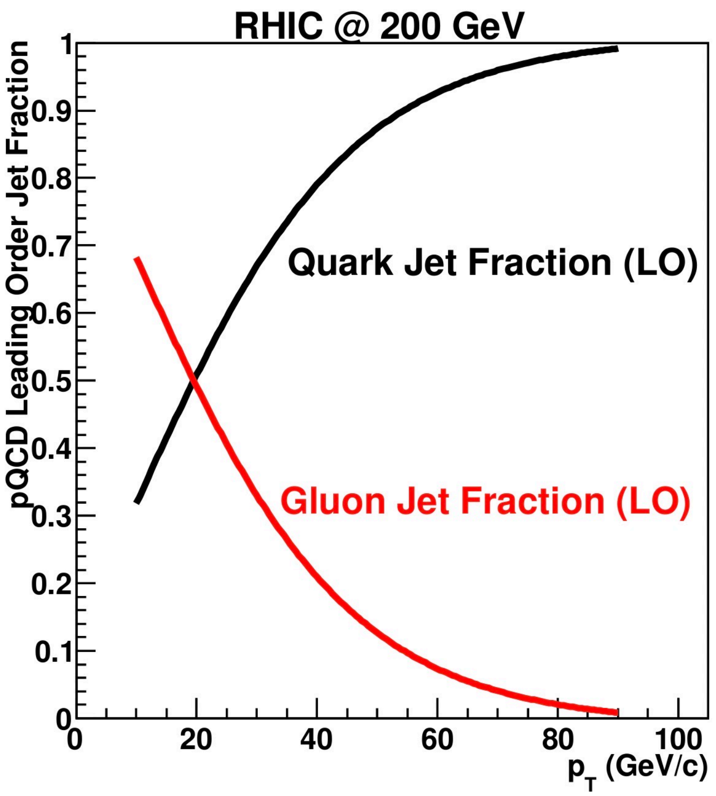
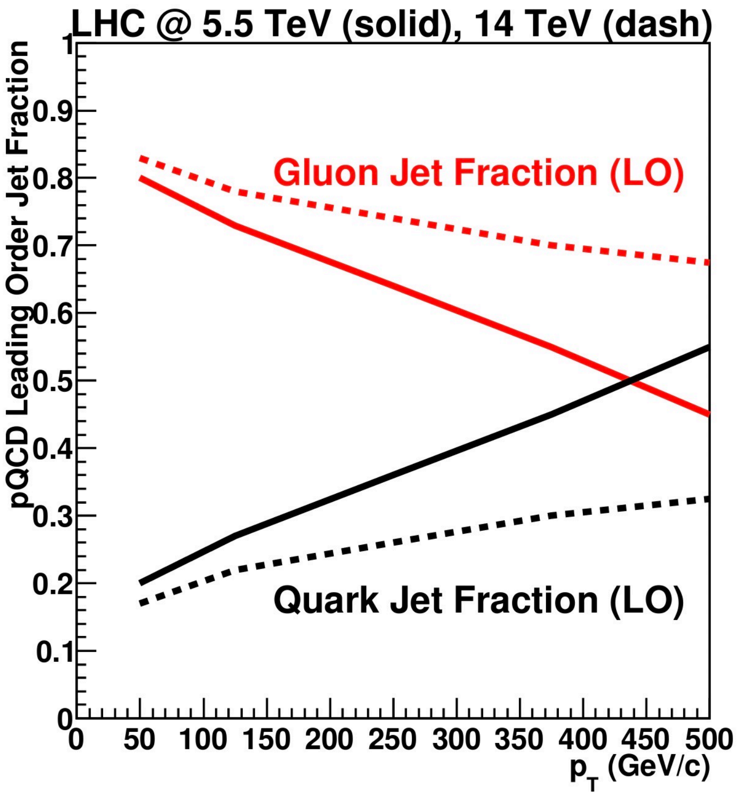


- Capable of probing large swathe of QCD phase space!

Why Jets at RHIC?

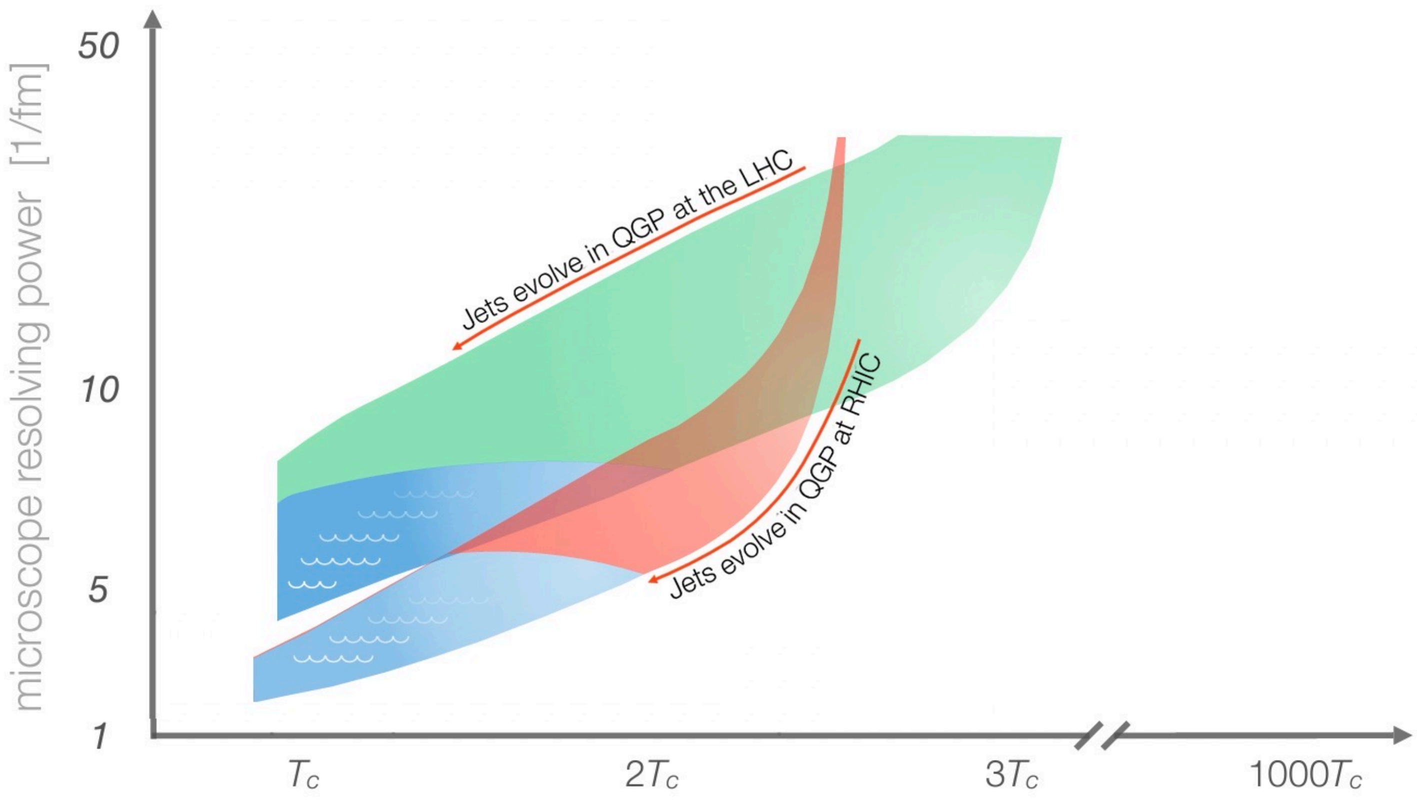
- Different jet populations!
- LHC jets largely initiated by gluons
- RHIC jets dominated by quark-initiated jets



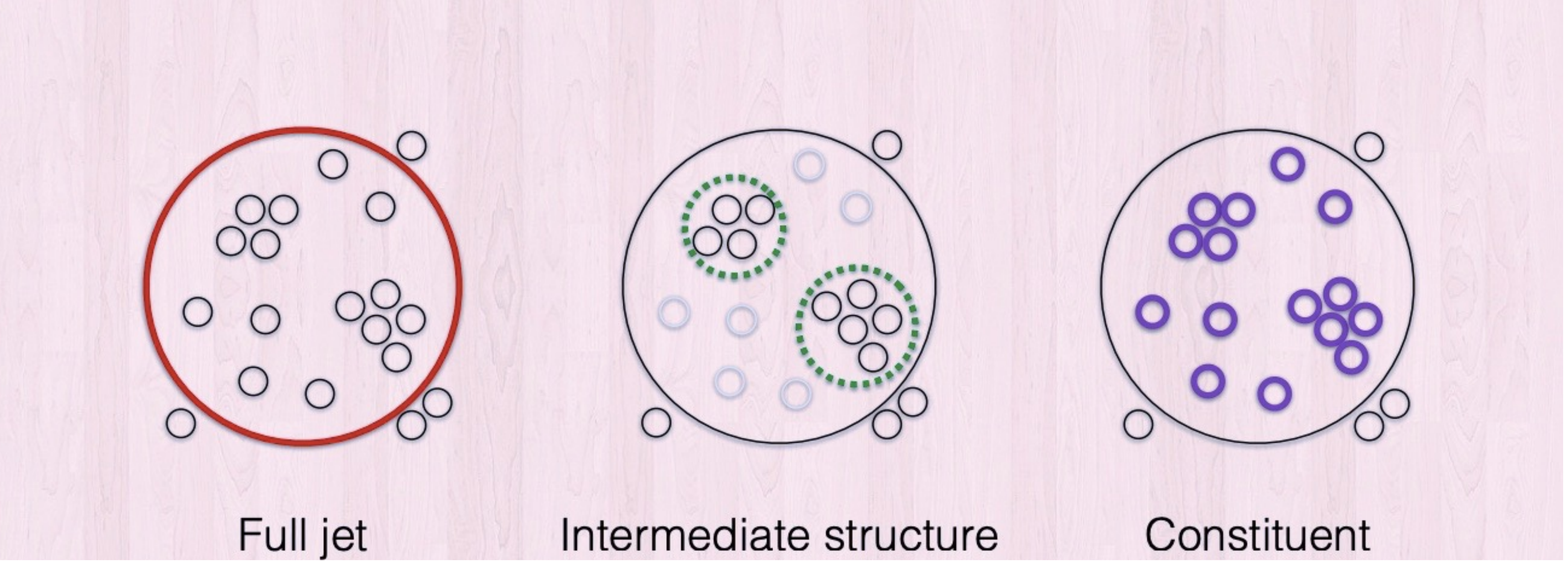


Why Jets in Heavy-Ion Collisions at RHIC?

- Jet-medium interactions at RHIC and the LHC have subtle differences
- Jet energies at RHIC typically closer to medium energy scale
- RHIC jets also spend larger part of their evolution in the medium than LHC jets

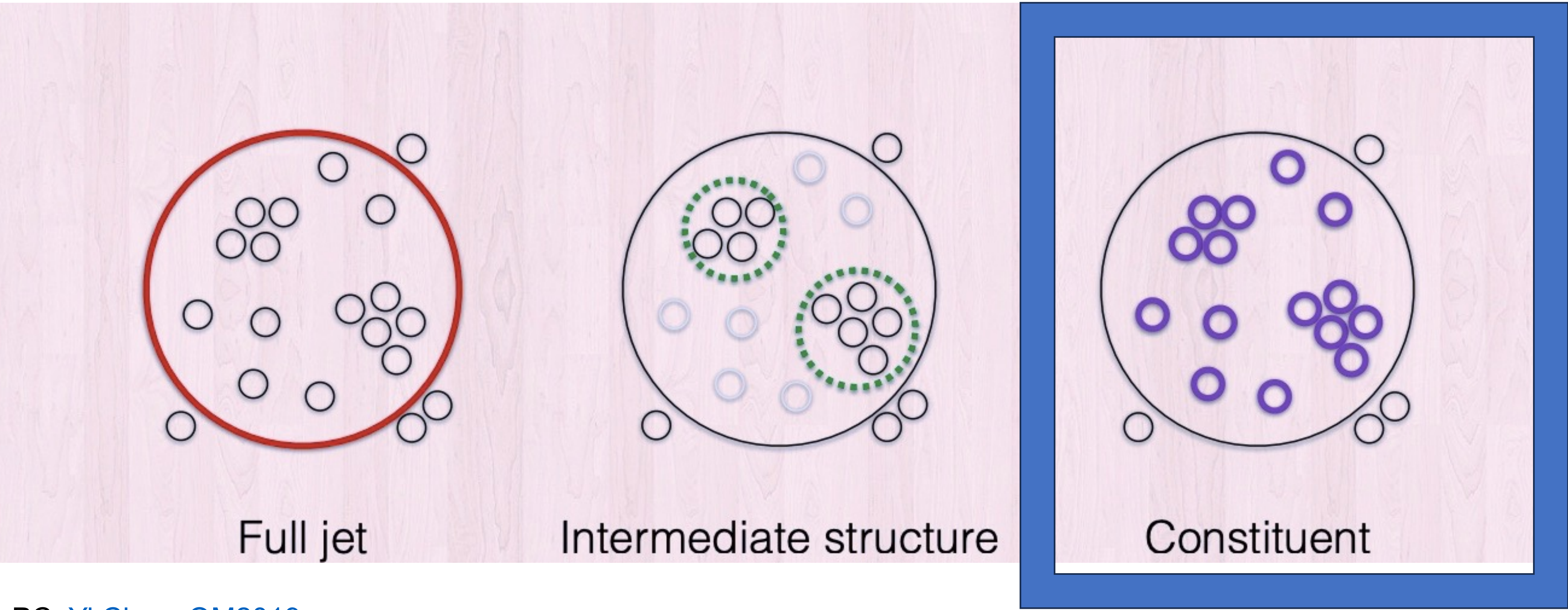


How We Study Jets



PC: [Yi Chen, QM2019]

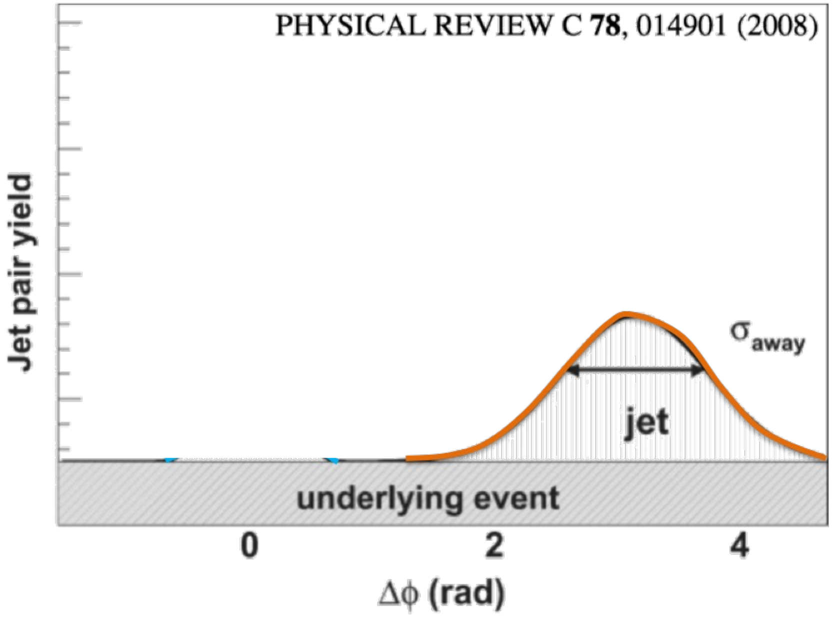
How We Study Jets

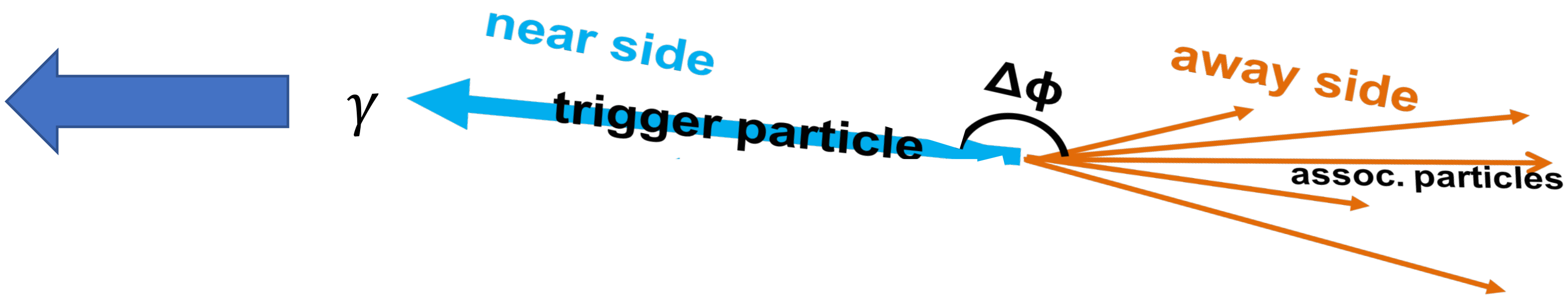


PC: [Yi Chen, QM2019]

Measuring Jets – Two Particle Correlations

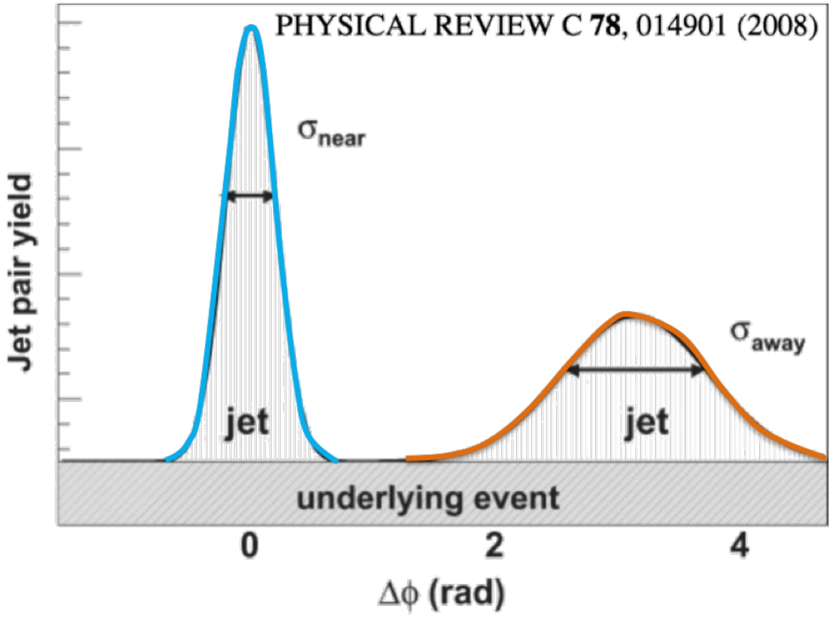
- Direct photons: colorless, well-calibrated probe, but statistically limited

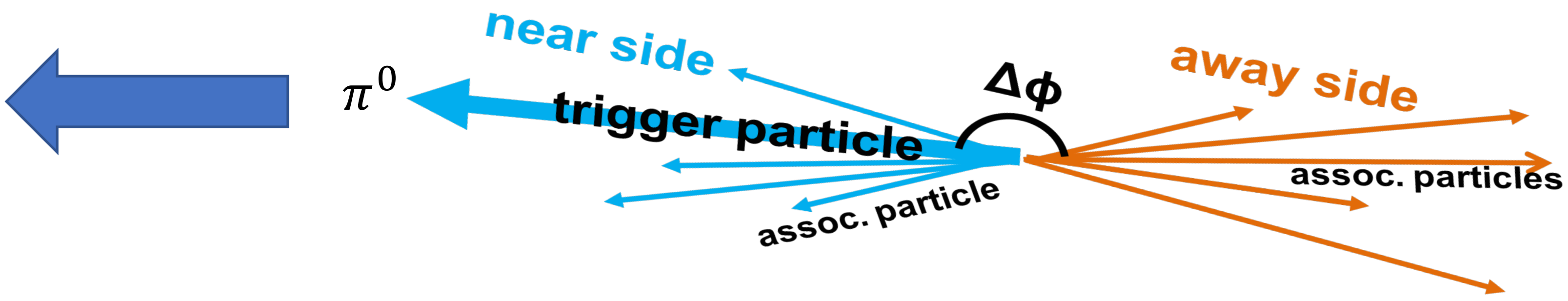




Measuring Jets – Two Particle Correlations

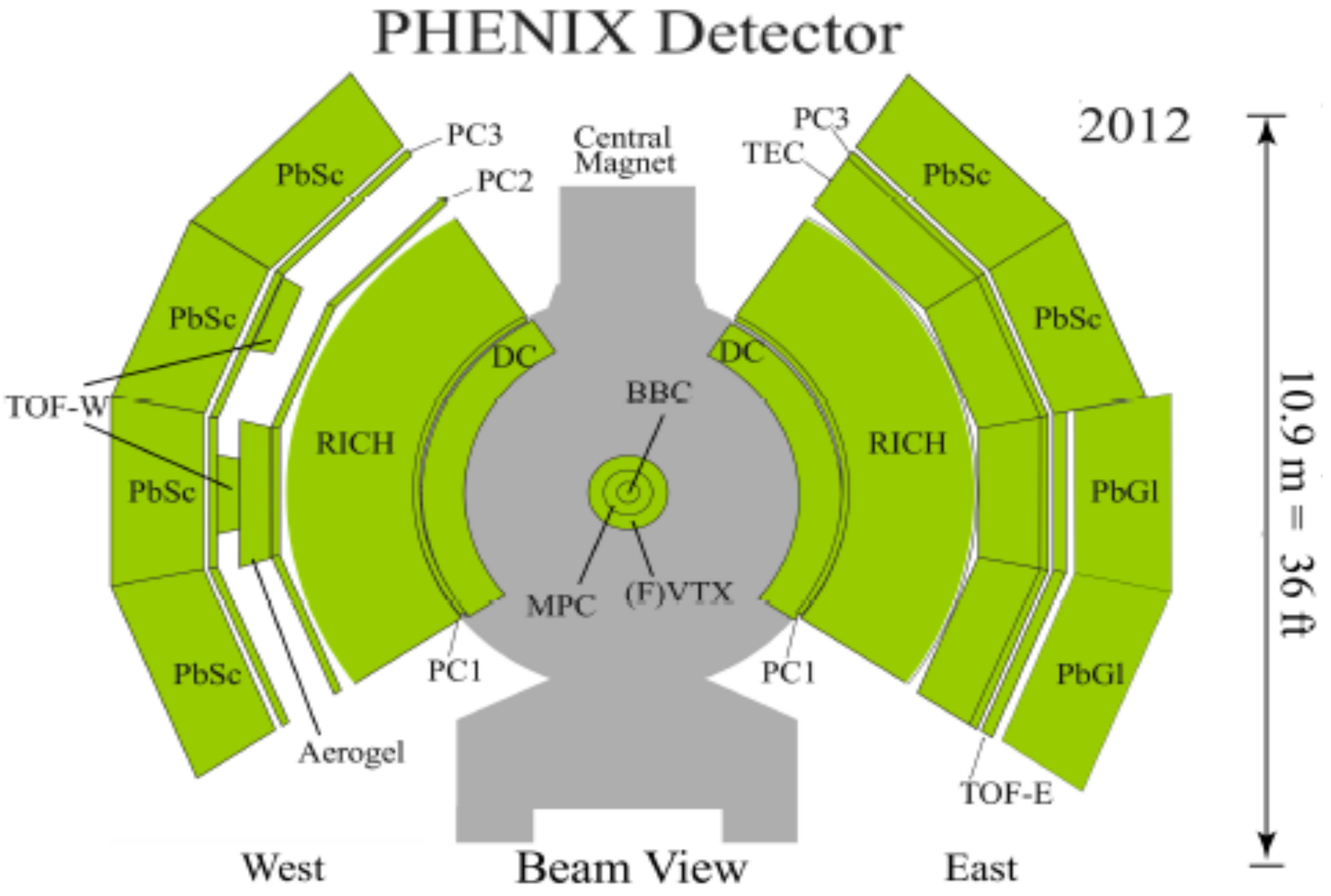
- Direct photons: colorless, well-calibrated probe, but statistically limited
- Neutral pion (π^0): not colorless, but abundant
  - Good for high-precision, differential measurements





The PHENIX Detector

- Central arms
  - π coverage in azimuth
  - Pseudorapidity coverage of $|\eta| < 0.35$
- Electromagnetic calorimeter
  - Photon and electron energy
- Drift/Pad chambers
  - Charged hadron momentum
- Beam-beam counters (BBC)
  - Event characterization



Two-Particle Correlation Anatomy

- $\frac{1}{N_{Trig}} \frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}} \frac{N^{Pair}}{\epsilon^{Hadron} \int \Delta\phi} \left\{ \frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b(1 + 2\sum \langle v_n^t \rangle \langle v_n^a \rangle \cos(n\Delta\phi)) \right\}$

Two-Particle Correlation Anatomy

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Per-trigger (jet) yield of hadrons (what we want to measure)

Two-Particle Correlation Anatomy

- $\frac{1}{N_{Trig}} \frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}} \frac{N^{Pair}}{\epsilon^{Hadron} \int \Delta\phi} \left\{ \frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b(1 + 2\sum \langle v_n^t \rangle \langle v_n^a \rangle \cos(n\Delta\phi)) \right\}$

What we actually measure, the correlation function

Two-Particle Correlation Anatomy

- $\frac{1}{N_{Trig}}\frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}}\frac{N^{Pair}}{\epsilon^{Hadron}\int\Delta\phi}\left\{\frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b(1+2\sum\langle v_n^t\rangle\langle v_n^a\rangle\cos(n\Delta\phi))\right\}$

Correction for detector inefficiencies

Two-Particle Correlation Anatomy

- $\frac{1}{N_{Trig}}\frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}}\frac{N^{Pair}}{\epsilon^{Hadron}\int\Delta\phi}\left\{\frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b\left(1 + 2\sum\langle v_n^t\rangle\langle v_n^a\rangle\cos(n\Delta\phi)\right)\right\}$

Correction for detector effects

Two-Particle Correlation Anatomy

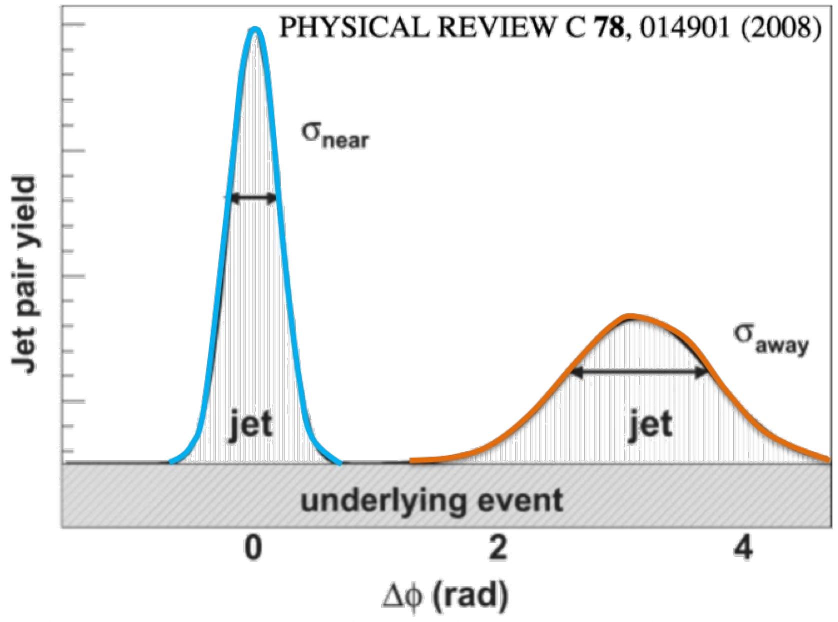
- $\frac{1}{N_{Trig}}\frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}}\frac{N^{Pair}}{\epsilon^{Hadron}\int\Delta\phi}\left\{\frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b\left(1 + 2\sum\langle v_n^t\rangle\langle v_n^a\rangle\cos(n\Delta\phi)\right)\right\}$

Underlying event subtraction

Two-Particle Correlation Anatomy

- $\frac{1}{N_{Trig}} \frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}} \frac{N^{Pair}}{\epsilon^{Hadron} \int \Delta\phi} \left\{ \frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b(1 + 2\sum \langle v_n^t \rangle \langle v_n^a \rangle \cos(n\Delta\phi)) \right\}$

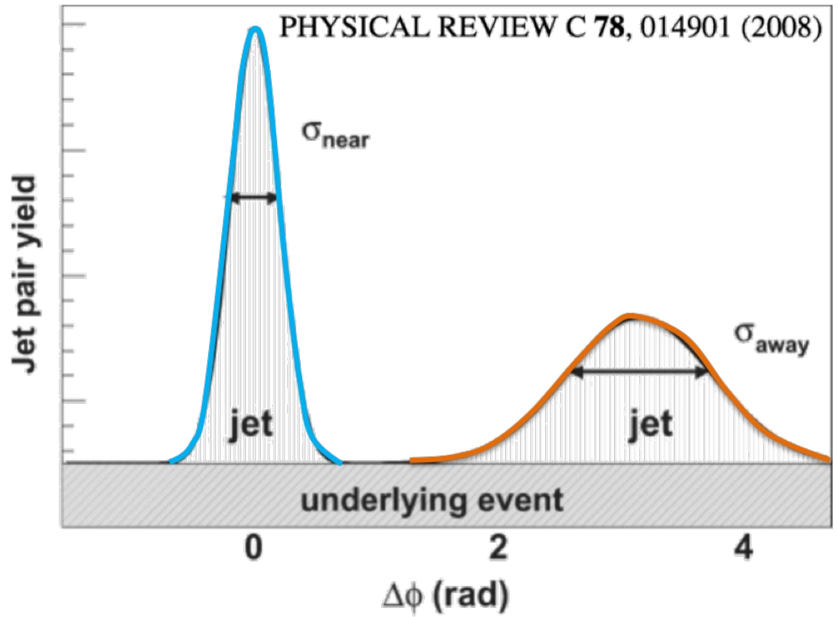
In p+p, nice and flat



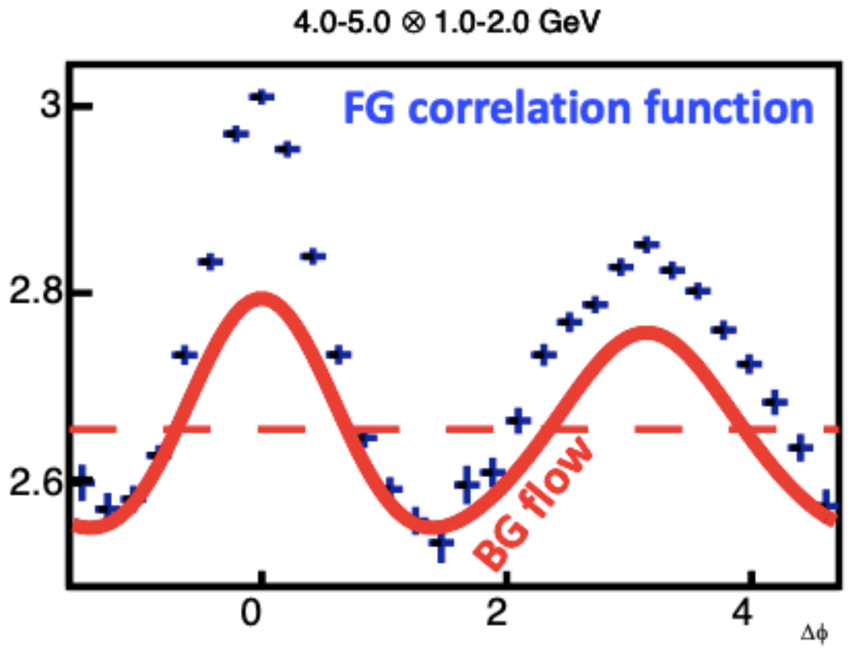
Two-Particle Correlation Anatomy

- $\frac{1}{N_{Trig}}\frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N_{Trig}}\frac{N^{Pair}}{\epsilon^{Hadron}\int\Delta\phi}\left\{\frac{dN^{Pair}_{Real}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - b(1+2\sum\langle v_n^t\rangle\langle v_n^a\rangle\cos(n\Delta\phi))\right\}$

In p+p, nice and flat



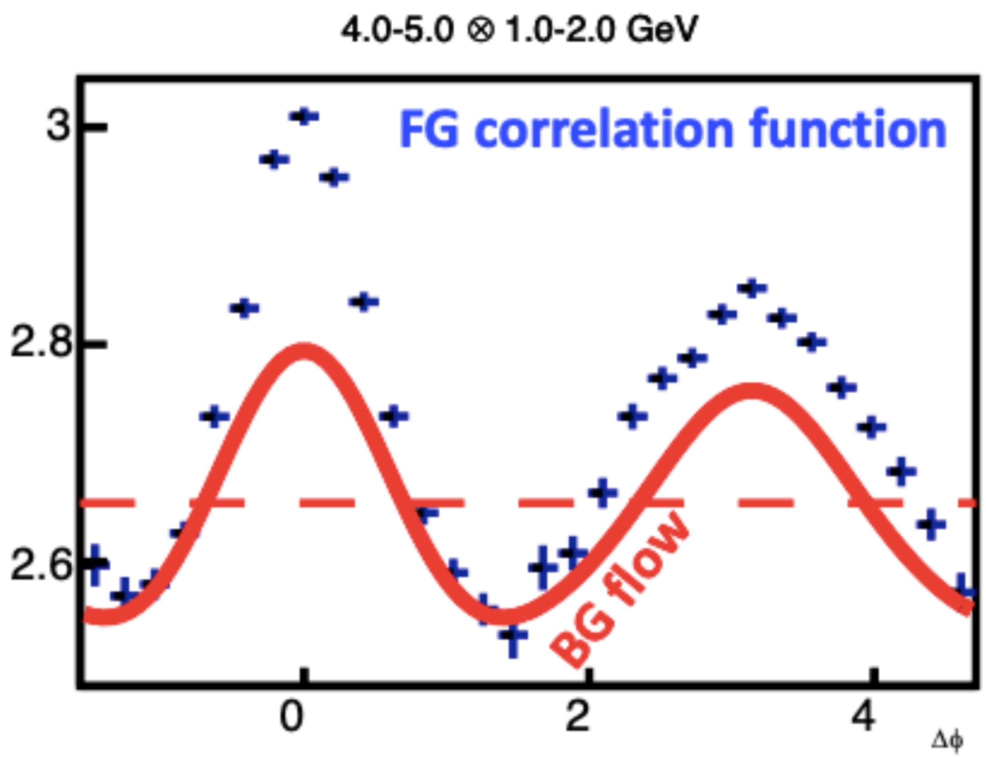
in A+A…



Underlying Event Subtraction

$$\frac{dN}{d\Delta\phi} = \boldsymbol{b}\left(1 + 2\sum \langle v_n^t\rangle\langle v_n^a\rangle \cos(n\Delta\phi)\right)$$

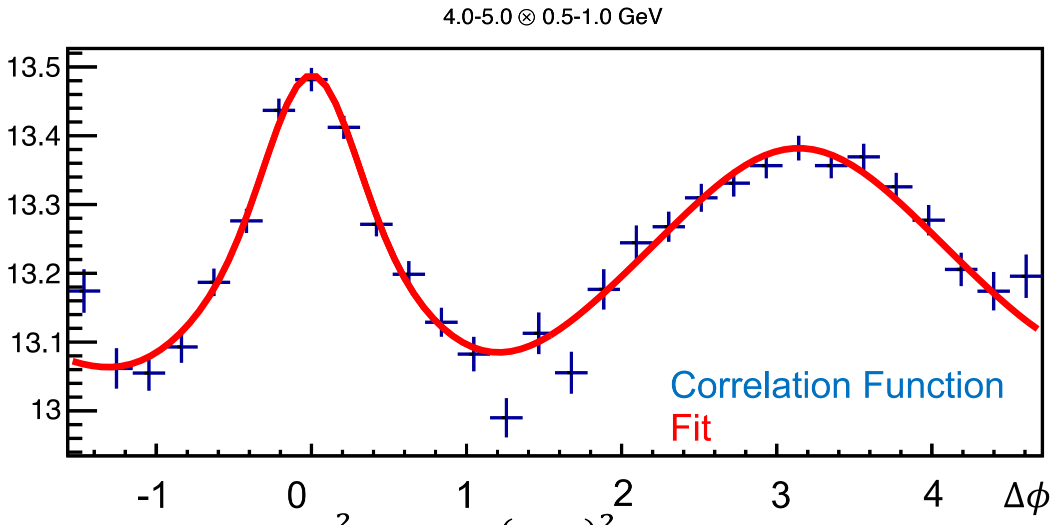
$$b = \frac{\xi\langle N_{Trig}\rangle\langle N_{h^\pm}\rangle}{\langle N_{Pairs}\rangle}$$



- Amplitude given by Absolute Background Subtraction method for $p_T^{Hadron} > 1$GeV/c
  - Phys. Rev. C **81**, 014908

Underlying Event Subtraction

$$\frac{dN}{d\Delta\phi} = \boldsymbol{b}(1 + 2\sum \langle v_n^t \rangle \langle v_n^a \rangle \cos(n\Delta\phi))$$



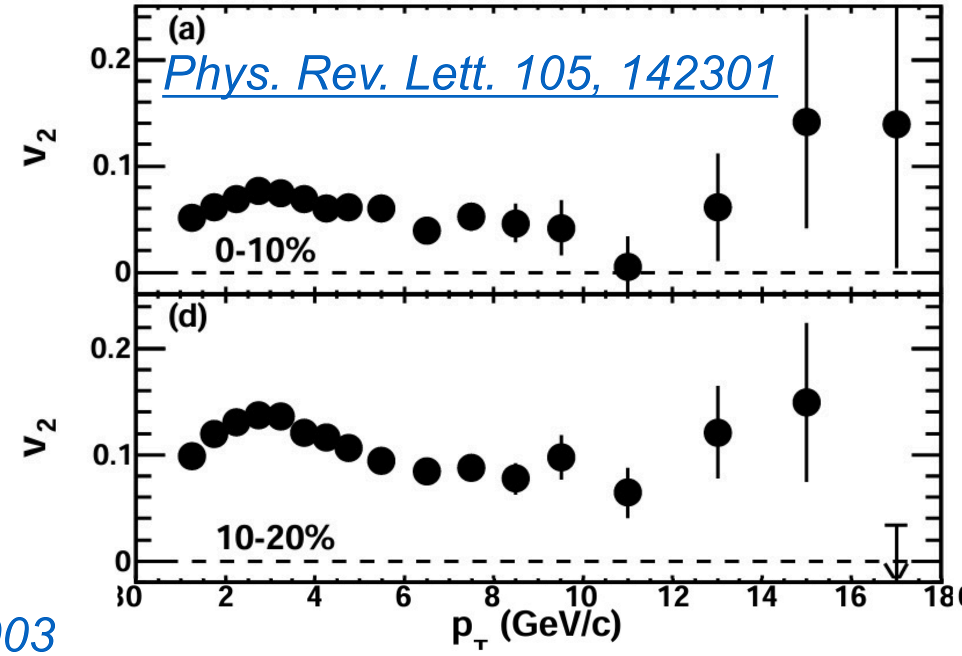
$$Corr(\Delta\phi) = Ae^{\frac{-x^2}{C}} + De^{\frac{-(x-\pi)^2}{E}} + \boldsymbol{b}(1 + 2\sum \langle v_n^t \rangle \langle v_n^a \rangle \cos(n\Delta\phi))$$

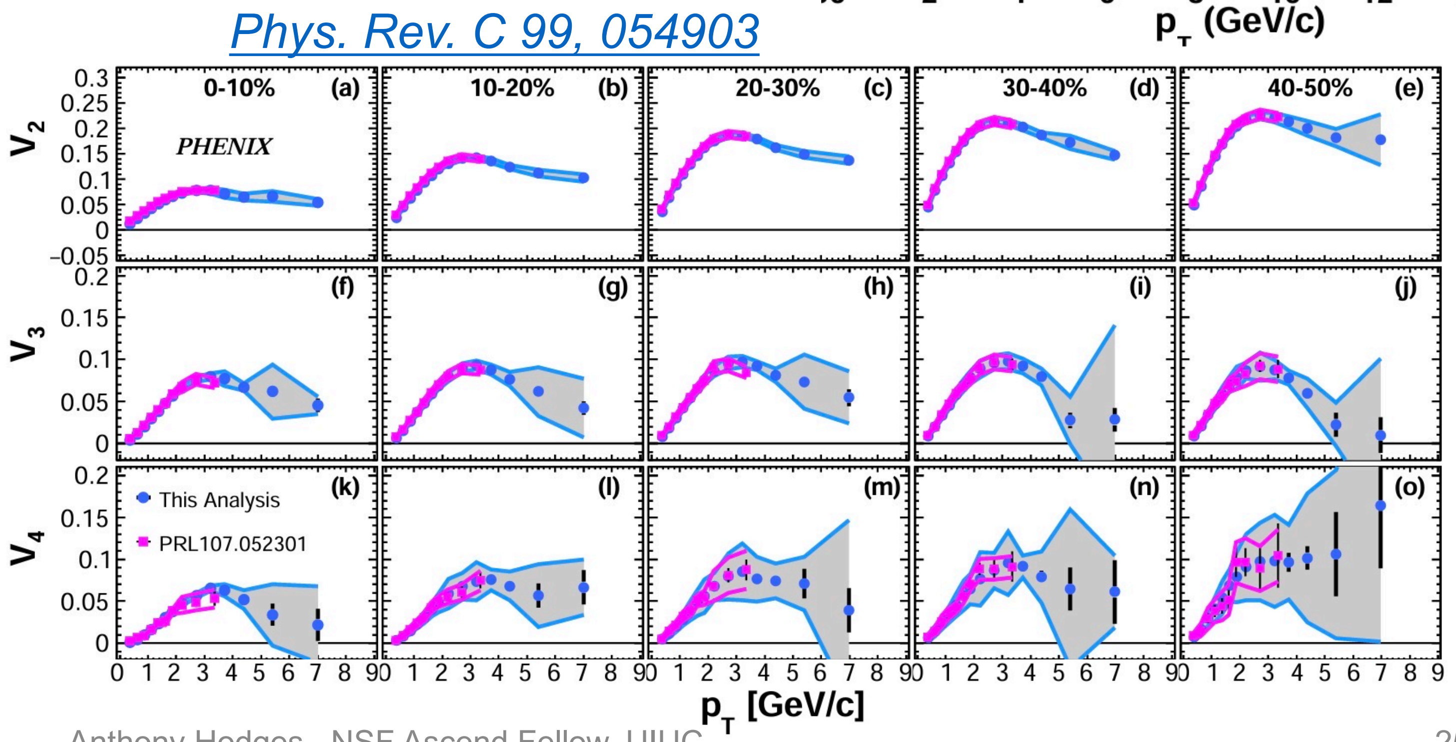
- b from ZYAM (Zero Yield At Minimum) for $p_T^{Hadron} < 1$GeV/c to account for over-subtraction

Underlying Event – Flow

$$\frac{dN}{d\Delta\phi} = b\left(1 + 2\sum \langle \boldsymbol{v_n^t} \rangle \langle \boldsymbol{v_n^a} \rangle \cos(n\Delta\phi)\right)$$

- v_n terms quantify background shape, come from previous PHENIX analyses

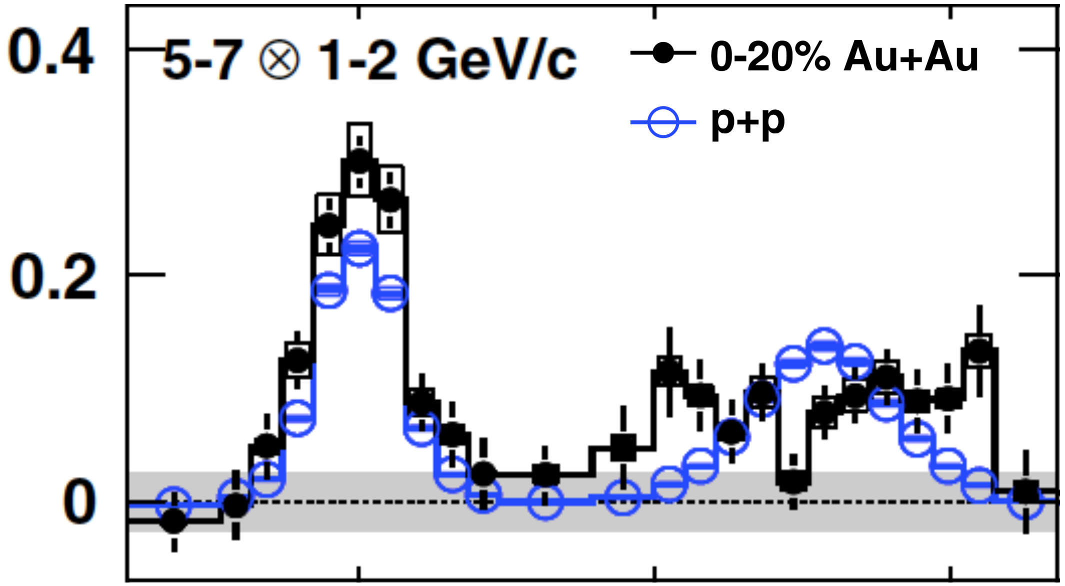




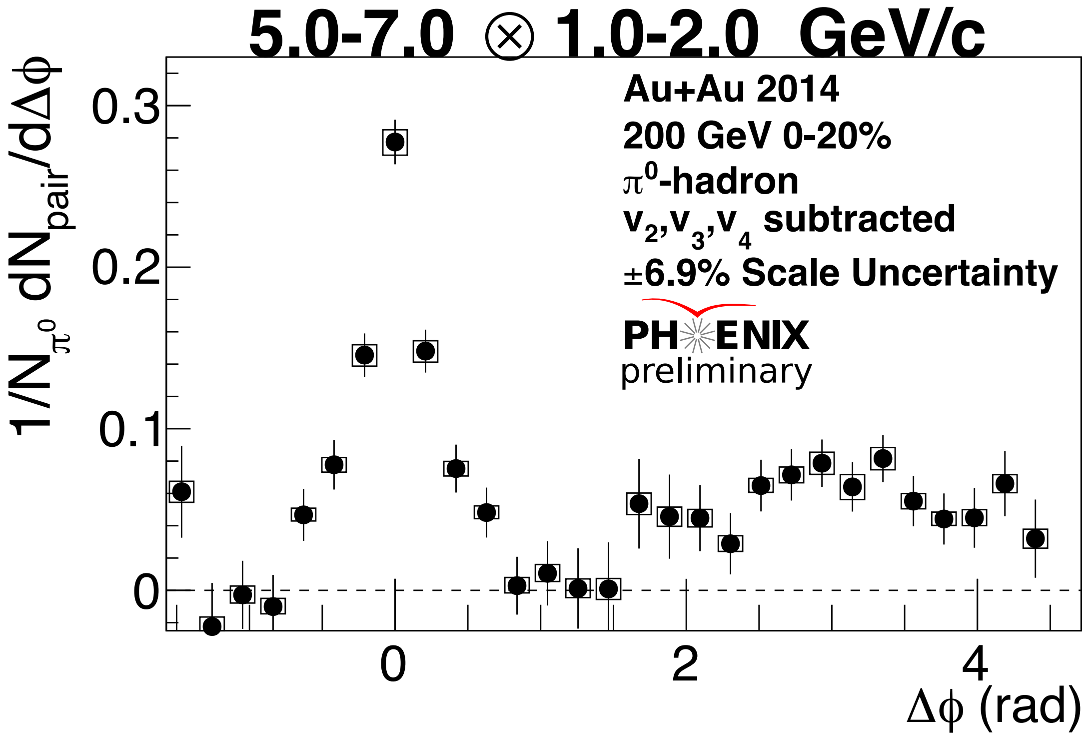
Improved Background Subtraction

Previous

PRL 104 252301 (2010)

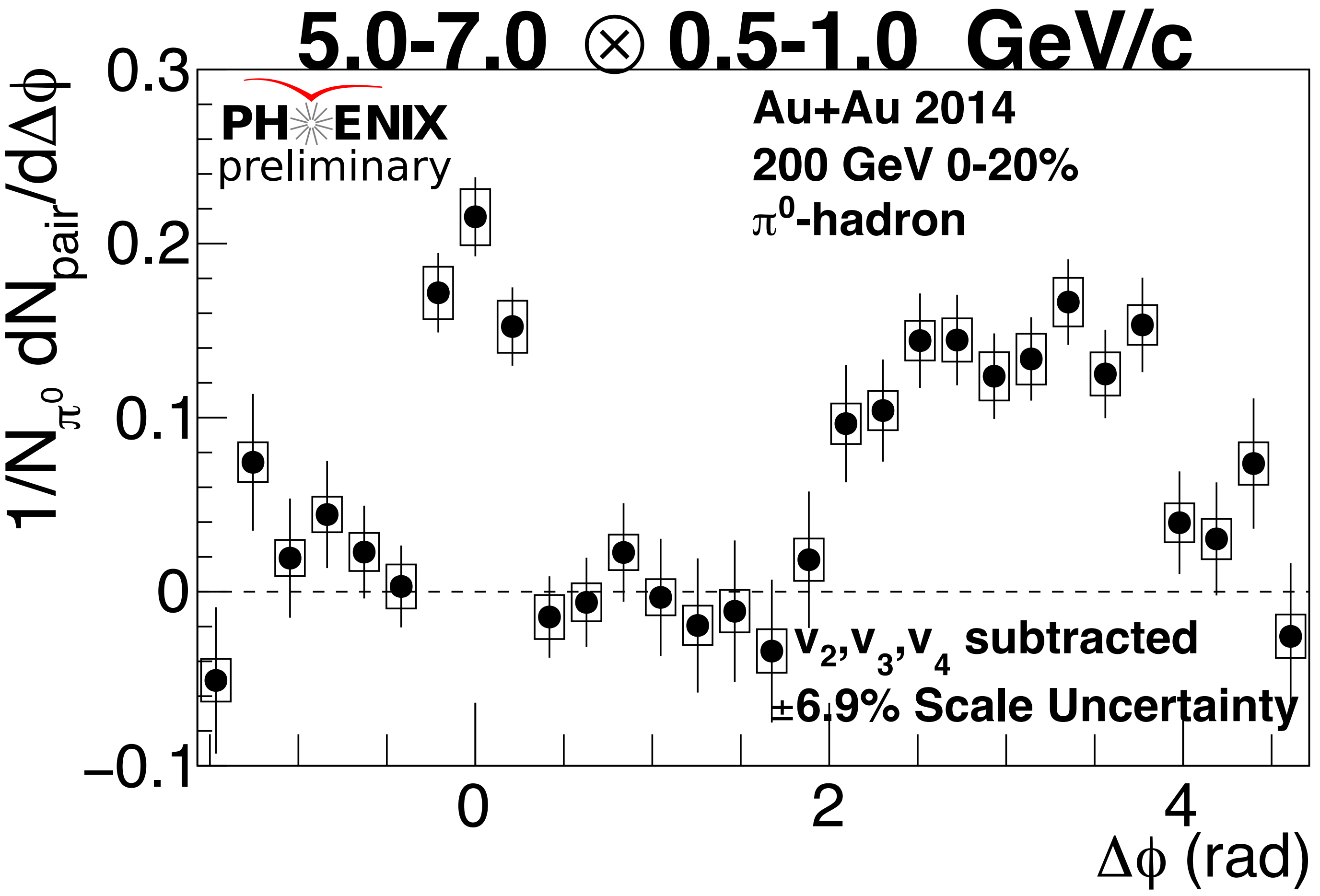


New



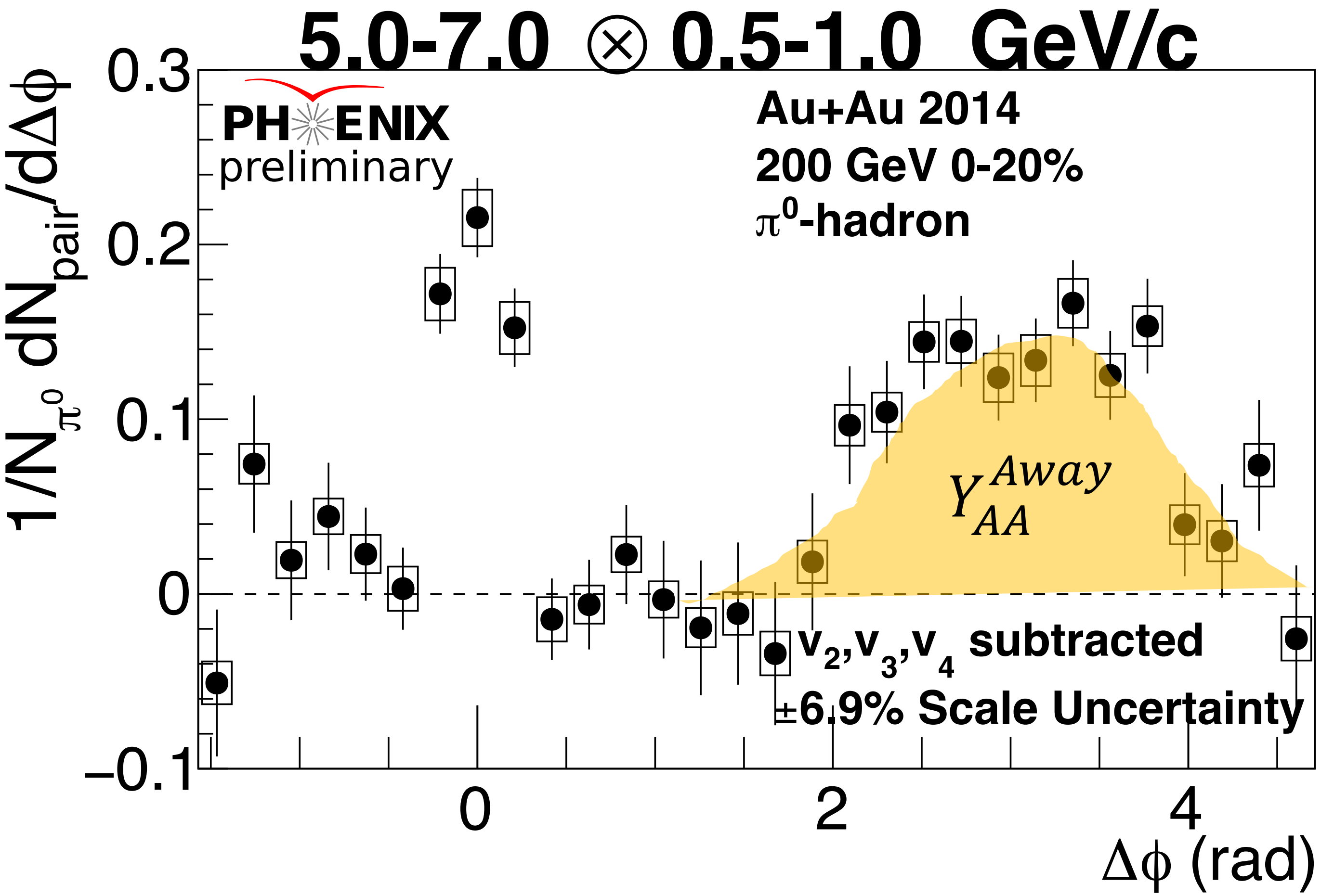
- New results (right) from data from 2014, 3.3x more trigger π^0's
- v_2, v_3, and v_4 subtracted in new results → flow contamination removed

Jet Modification: $I_{AA}(p_T)$



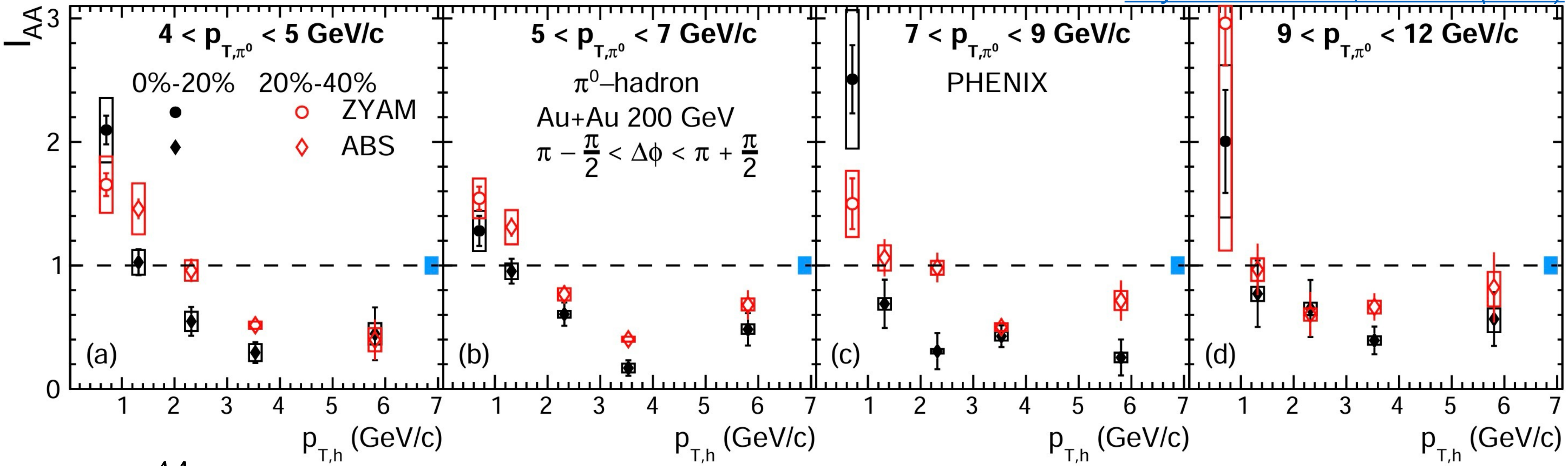
Jet Modification: $I_{AA}(p_T)$

- $I_{AA} = \frac{Y_{AA}^{Away}}{Y_{pp}^{Away}}$, bread-and-butter 2PC measurement
- $I_{AA} = 1 \rightarrow$ No modification
- $I_{AA} < 1 \rightarrow$ Suppresion
- $I_{AA} > 1 \rightarrow$ Enhancement
- $I_{AA} = \frac{Y_{AA}}{Y_{pp}} \approx \frac{D_{AA}(z')}{D_{pp}(z)}$



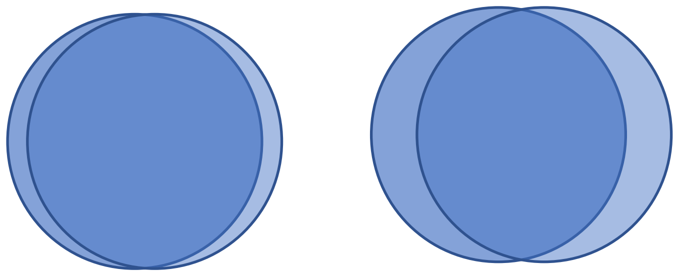
π^0-Hadron Correlations - $I_{AA}(p_T)$

Phys. Rev. C 110, 044901 (2024)



$$I_{AA} = \frac{Y^{AA}_{Away}}{Y^{pp}_{Away}}$$

Newly Published!

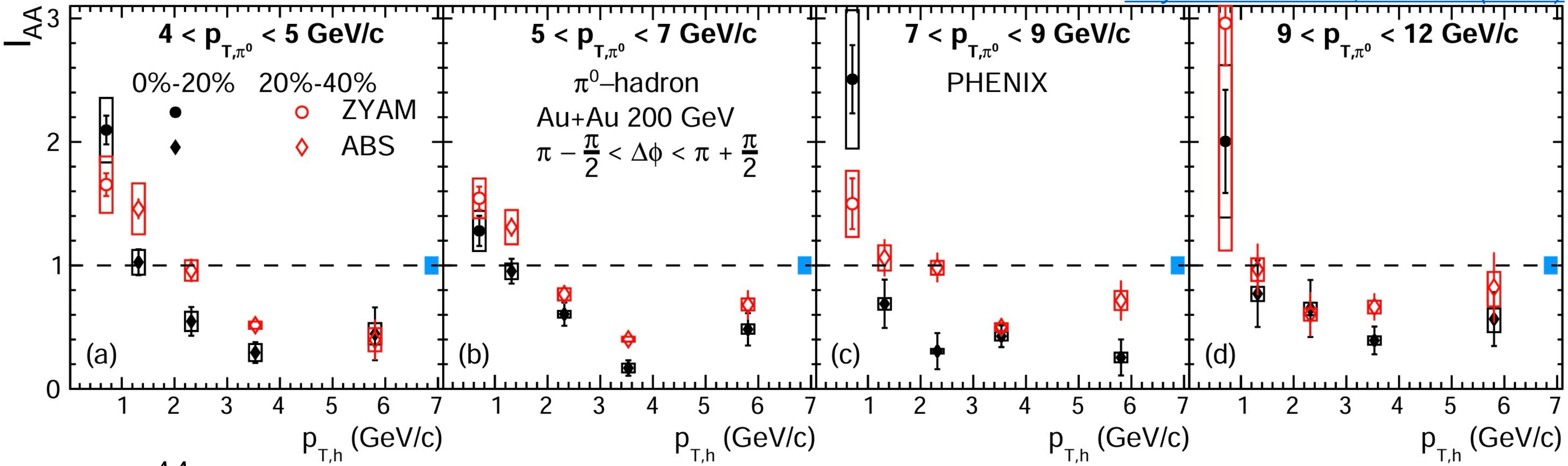


0-20% 20-40%

- Enhancement of yield (I_{AA} > 1) at low associate particle momentum
- Depletion (I_{AA} < 1) at high associate particle momentum

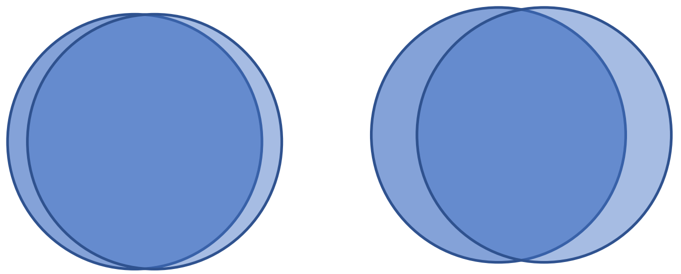
π^0-Hadron Correlations - $I_{AA}(p_T)$

Phys. Rev. C 110, 044901 (2024)



$$I_{AA} = \frac{Y_{Away}^{AA}}{Y_{Away}^{pp}}$$

Newly Published!

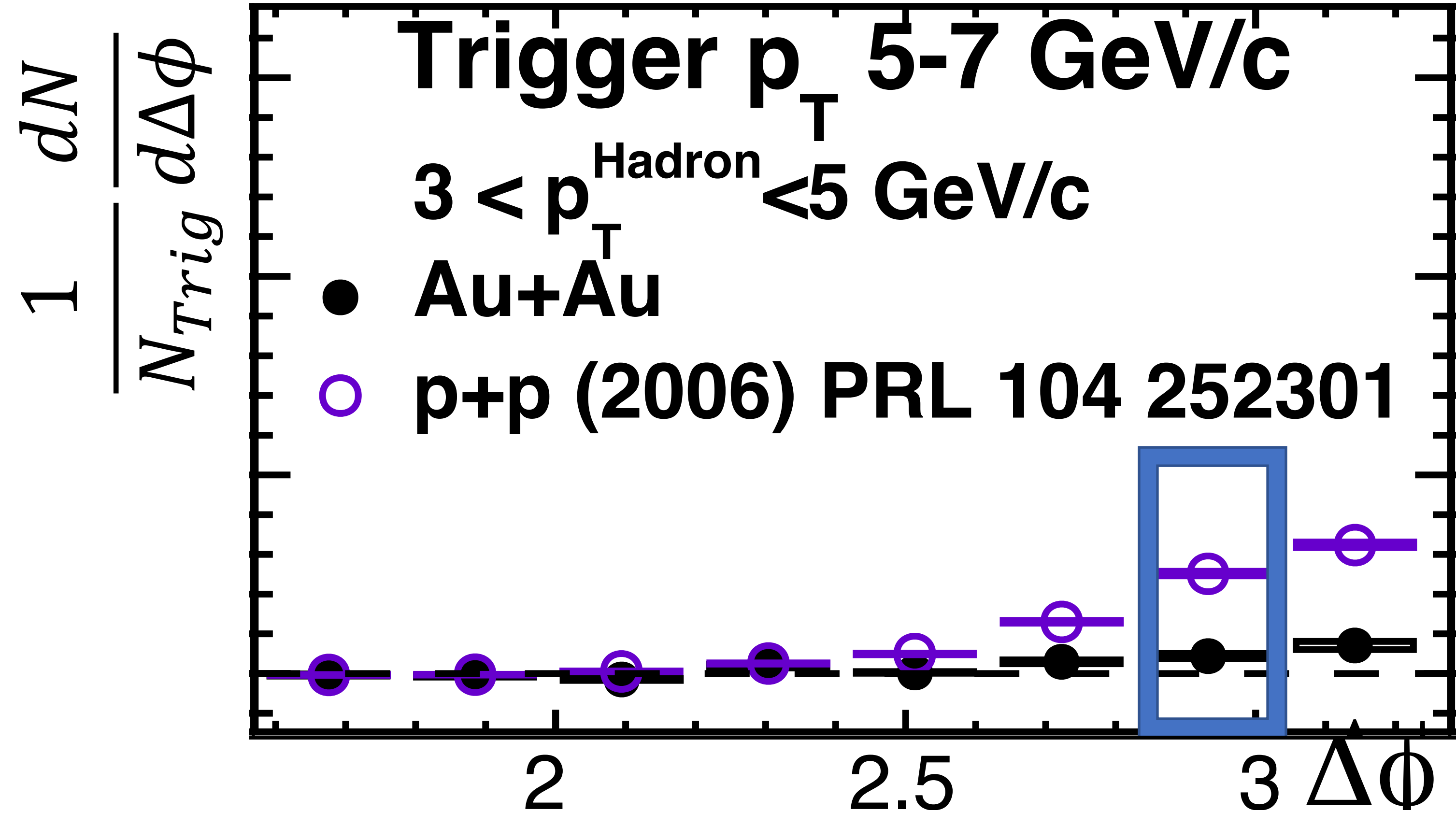


- Suppression phenomenon is consistently more severe in most central collisions (black points)

Jet Structure Modification: Δ_{AA} vs. $\Delta\phi$

- Can we look at modification "inside" the jet?
- Can take difference between *differential* yields rather than integrated
- How is the actual distribution of particles changed within a jet?

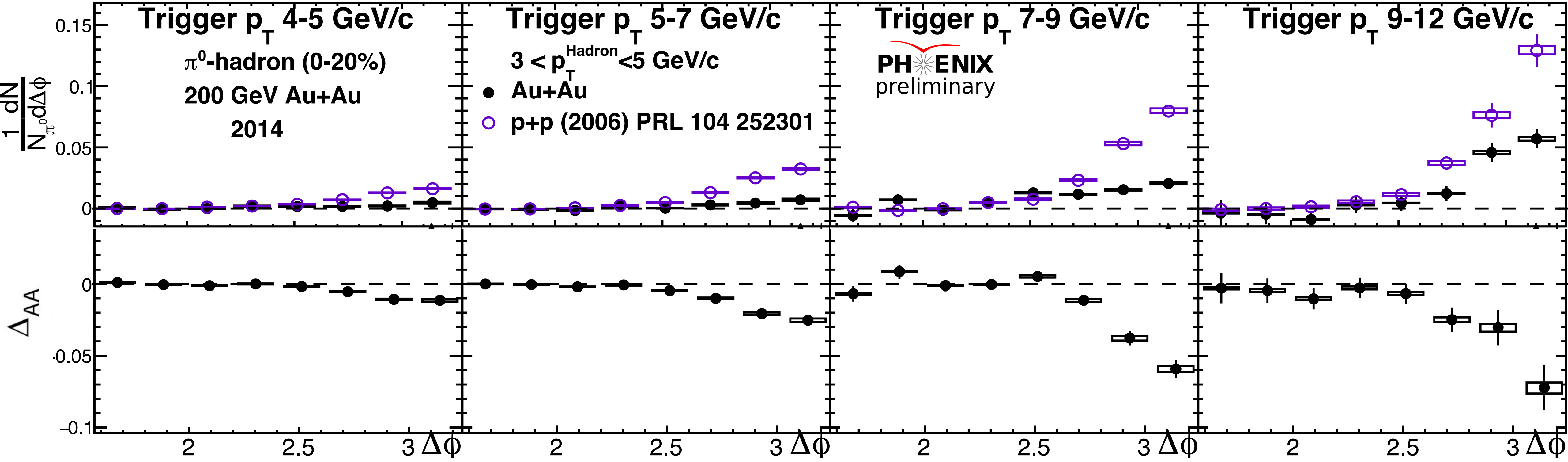
Phys. Rev. C 110, 044901 (2024)



Jet Structure Modification: Δ_{AA} vs. $\Delta\phi$

- $\Delta_{AA} = Y_{AA} - Y_{pp}$
- Captures jet modification across wide range of $\Delta\phi$ values
- Difference, rather than ratio, better behaved for yields ~ 0

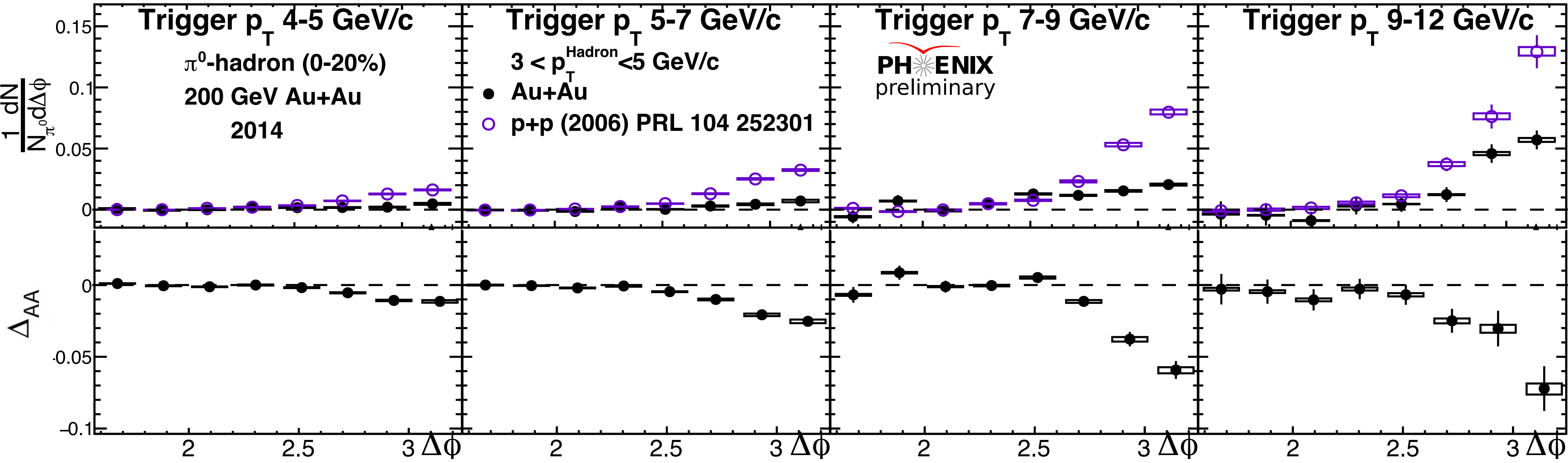
[Phys. Rev. C 110, 044901 (2024)]



Jet Structure Modification: Δ_{AA} vs. $\Delta\phi$

- For high p_T constituents, can see suppression ($\Delta_{AA} < 0$)
- Suppression is most severe at jet core ($\Delta\phi \sim \pi$)

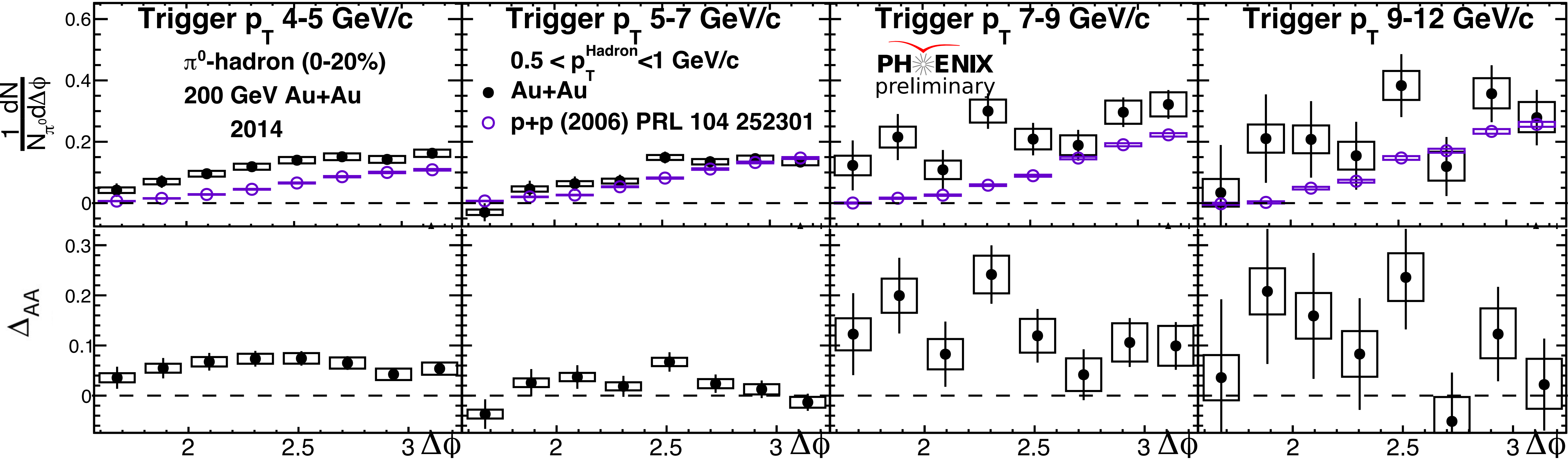
Phys. Rev. C 110, 044901 (2024)



Jet Structure Modification: Δ_{AA} vs. $\Delta\phi$

- Enhancement of soft particles seen at wide angles
- For softest jets, this enhancement even appears at the core

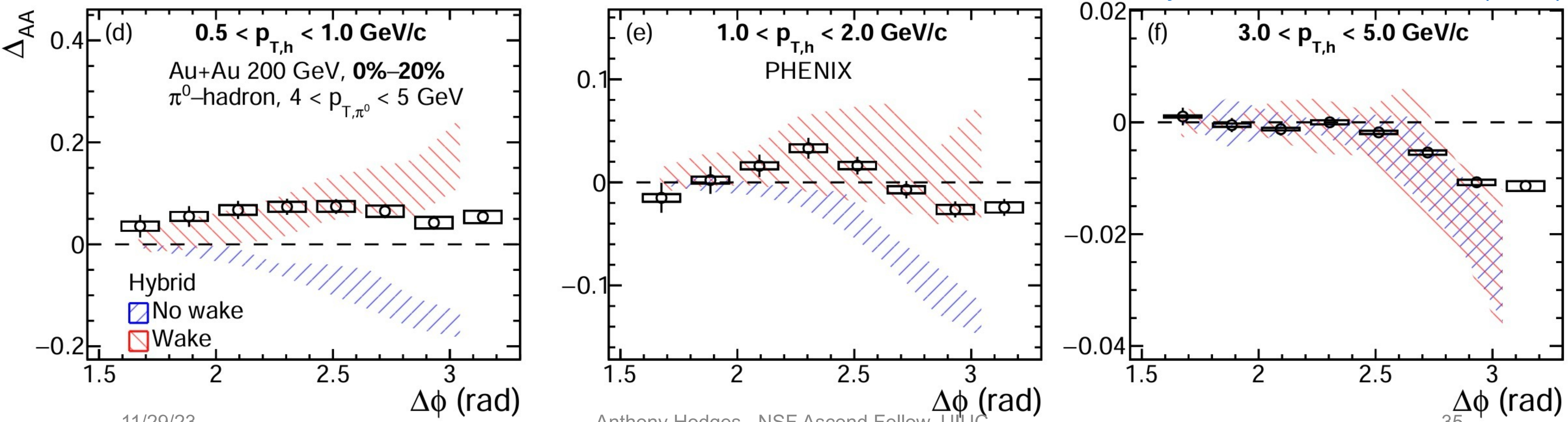
Phys. Rev. C 110, 044901 (2024)



Model Comparisons

- Here, Hybrid model is shown with two configurations
- Wake: includes a medium response in the form a hydrodynamic wake of low p_T particles
- No wake: energy loss via pQCD only

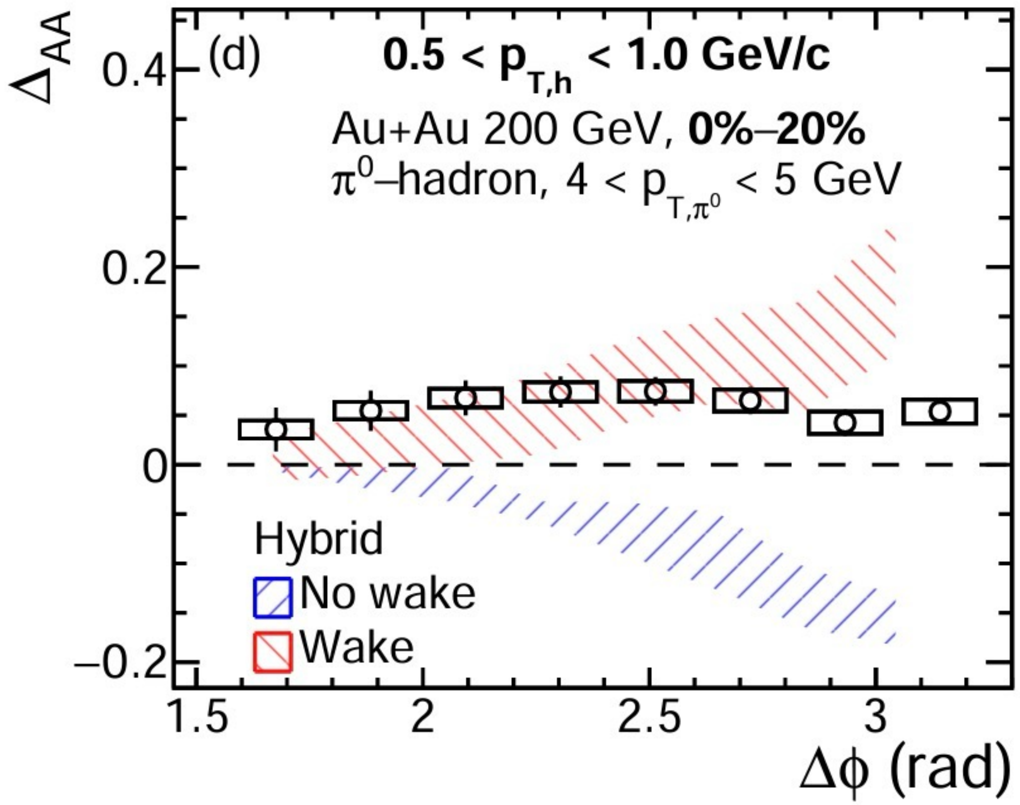
[Phys. Rev. C 110, 044901 (2024)]



The Importance of Medium Response

- Jet modification is an interplay between energy loss *and* the medium's response to that energy

[Phys. Rev. C 110, 044901 (2024)](https://journals.aps.org/prc/)



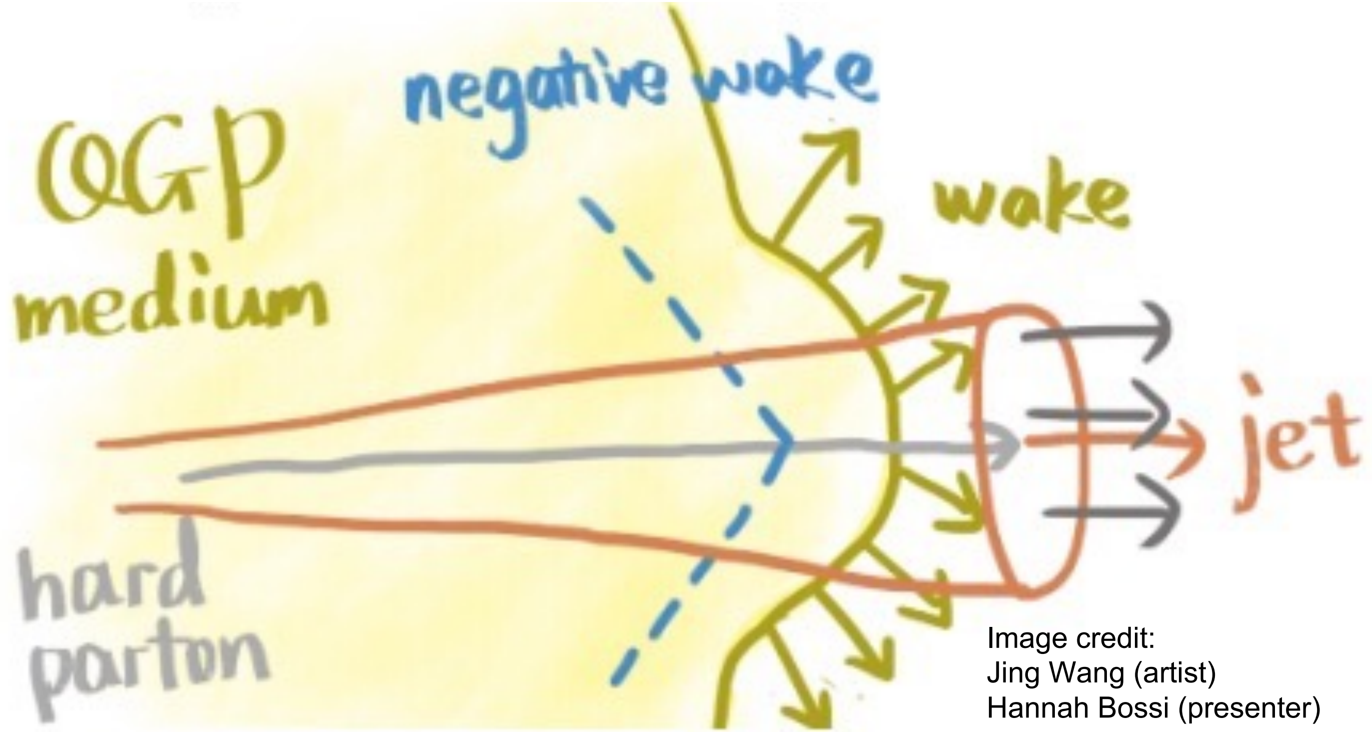
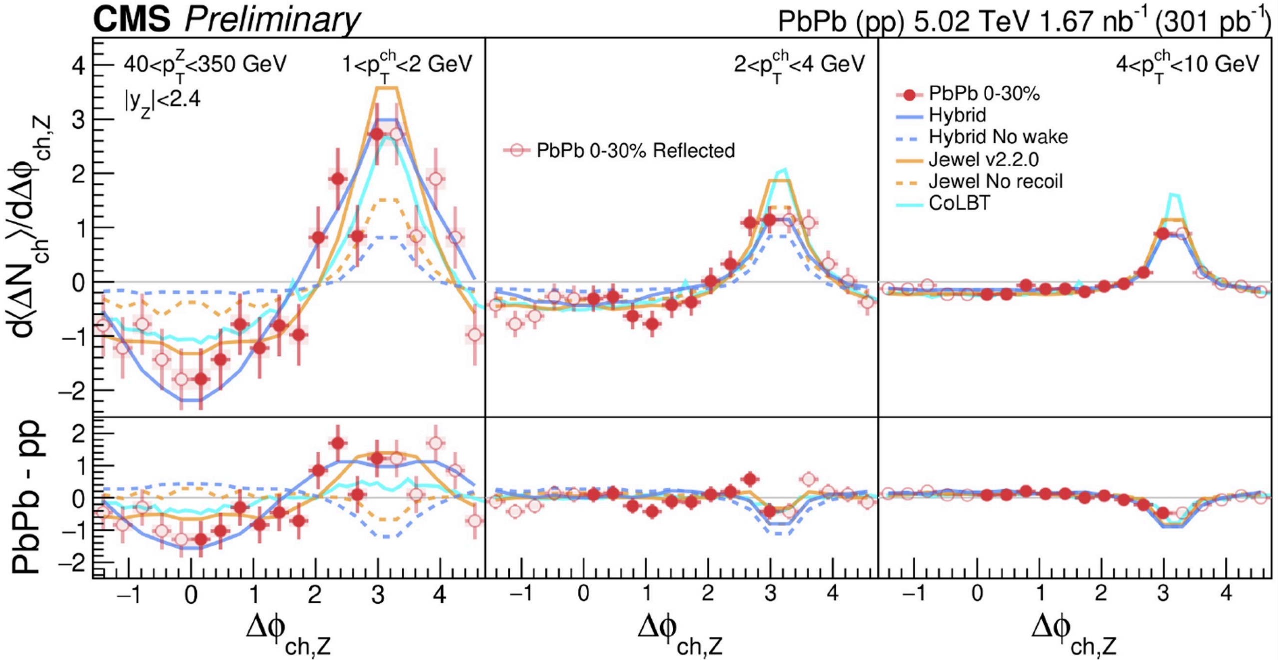


Image credit:
Jing Wang (artist)
Hannah Bossi (presenter)

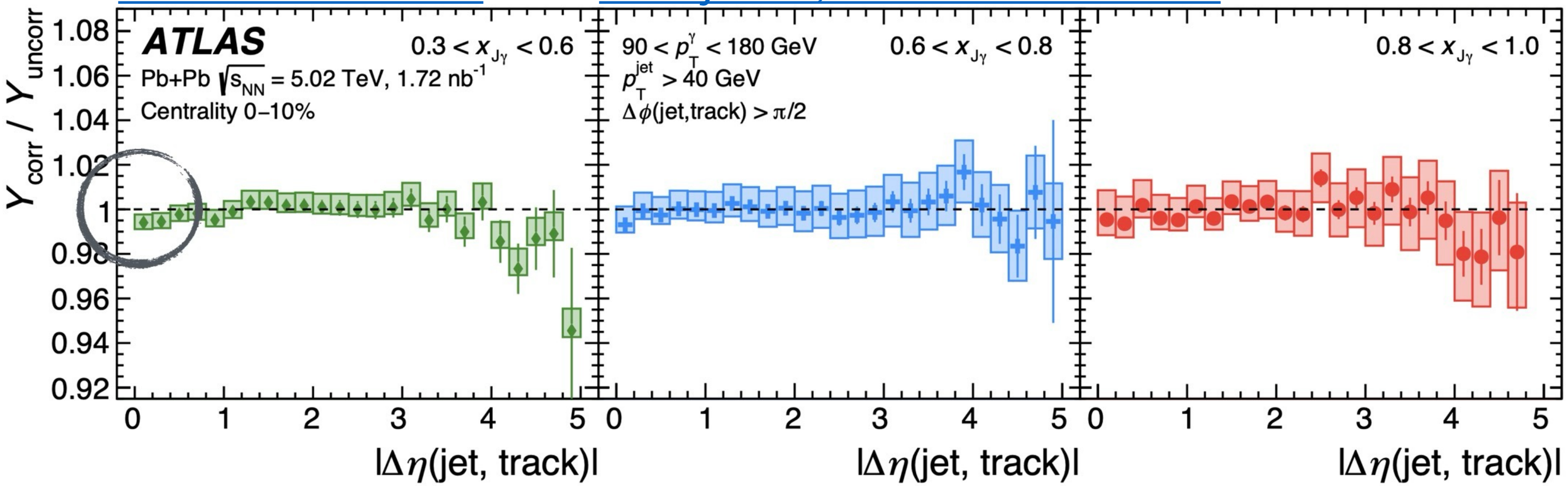
Turning 180°: The Diffusion Wake

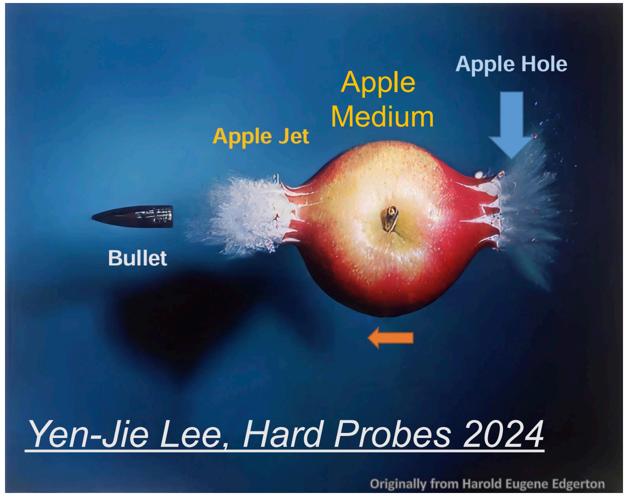
CMS-PAS-HIN-23-006

- In addition to enhancement wake, recent studies have also sought a corresponding depletion wake near $\Delta\phi \sim 0$



arXiv:2408.08599 Yeonju Go, Hard Probes 2024

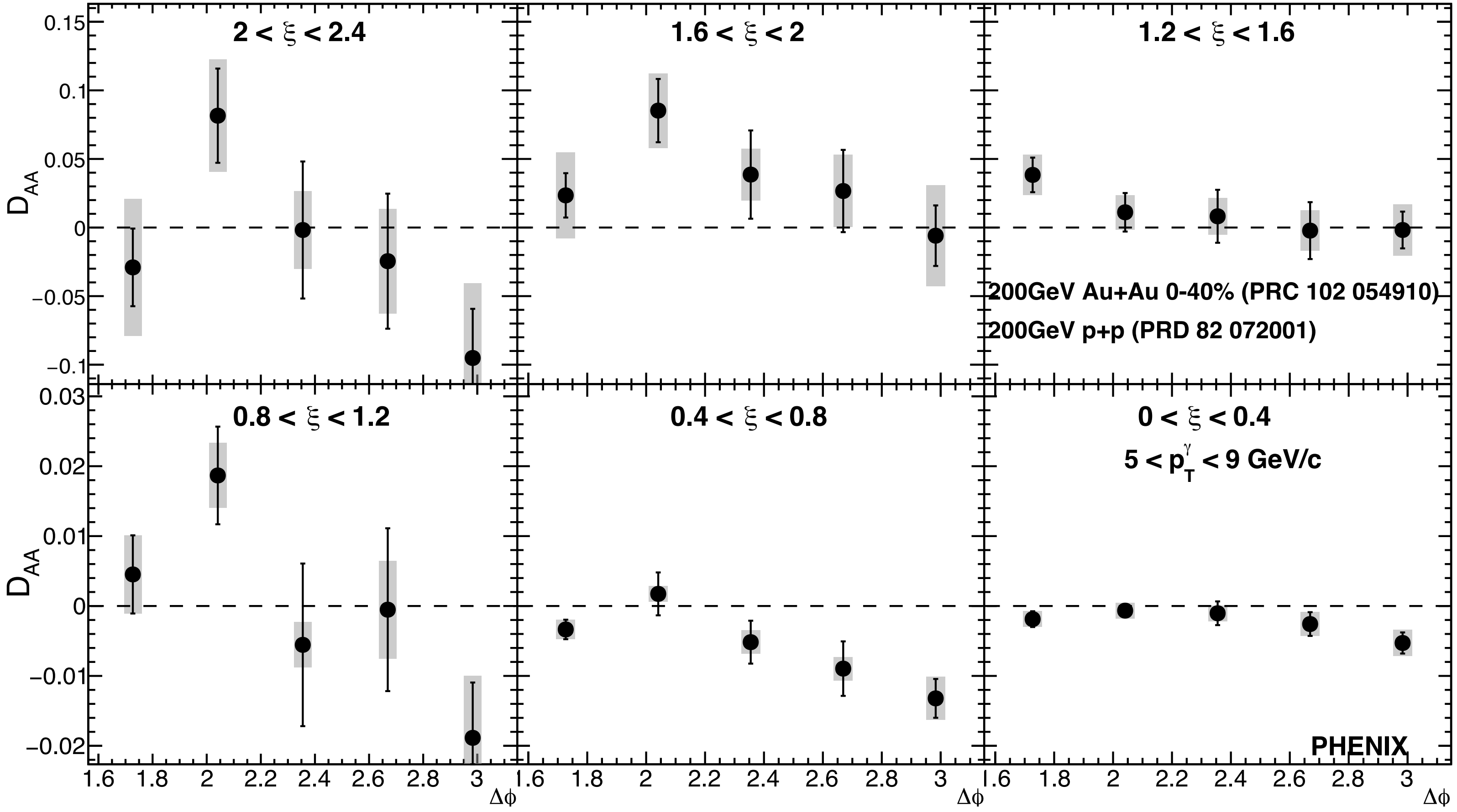




Future PHENIX Results

[Phys. Rev. C 102, 054910 (2020)]

- Δ_{AA} extracted from previously published results
- Familiar depletion signal for low ξ (high p_T) bins
- High ξ (low p_T) bins will benefit from larger Run 14 dataset in ongoing analysis



$$\xi = \log(1/z_t)$$

High $\xi \rightarrow$ low p_T

Low $\xi \rightarrow$ high p_T

Summary and Conclusion

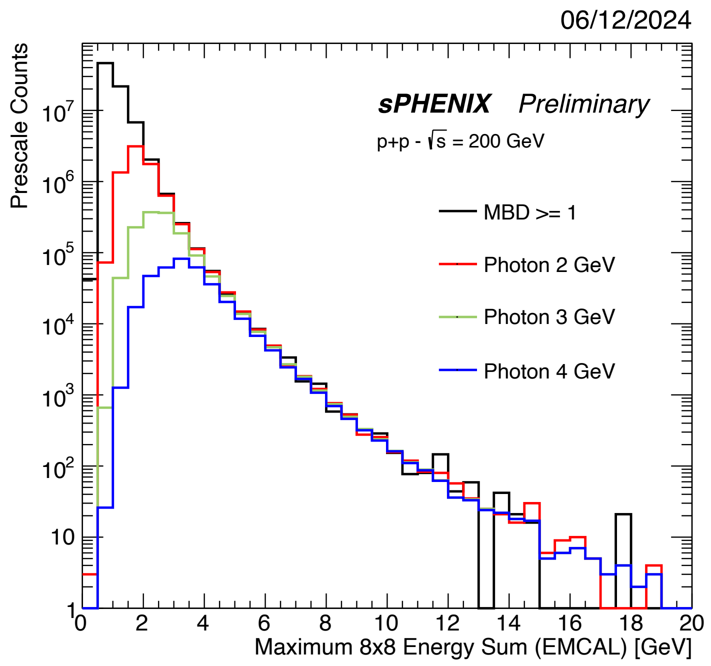
- New two-particle correlation results from PHENIX probe modification to the structure of recoil jets
- The yield of high p_T hadrons associated with jets is found to be suppressed, especially at the jet core
- The yield of low p_T hadrons is enhanced, with this enhancement appearing as far as $\frac{\pi}{2}$ [rad] away from the jet peak
- Enhancement phenomenon is captured well by HYBRID model, where it is owed to a hydrodynamic wake of low p_T particles
- Future PHENIX measurements will employ the large-statistics Run 14 dataset to probe jet modification via prompt photon-hadron correlations

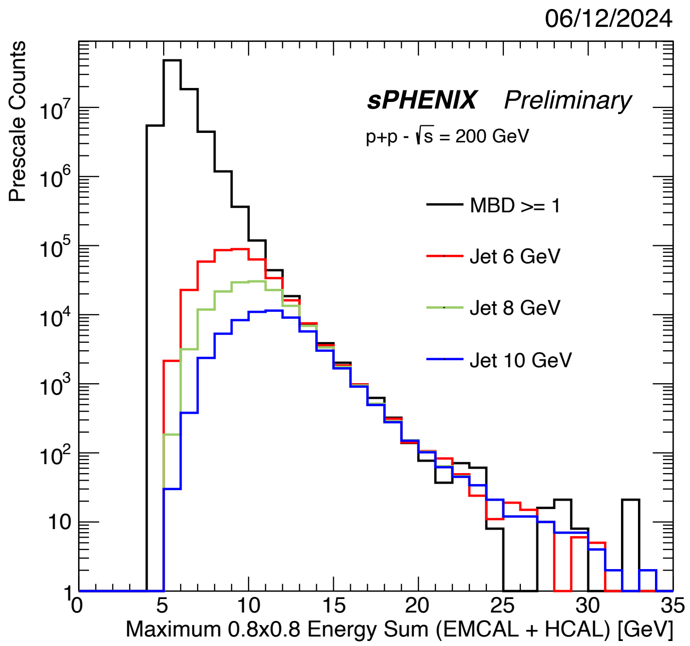
Thank You! Questions?

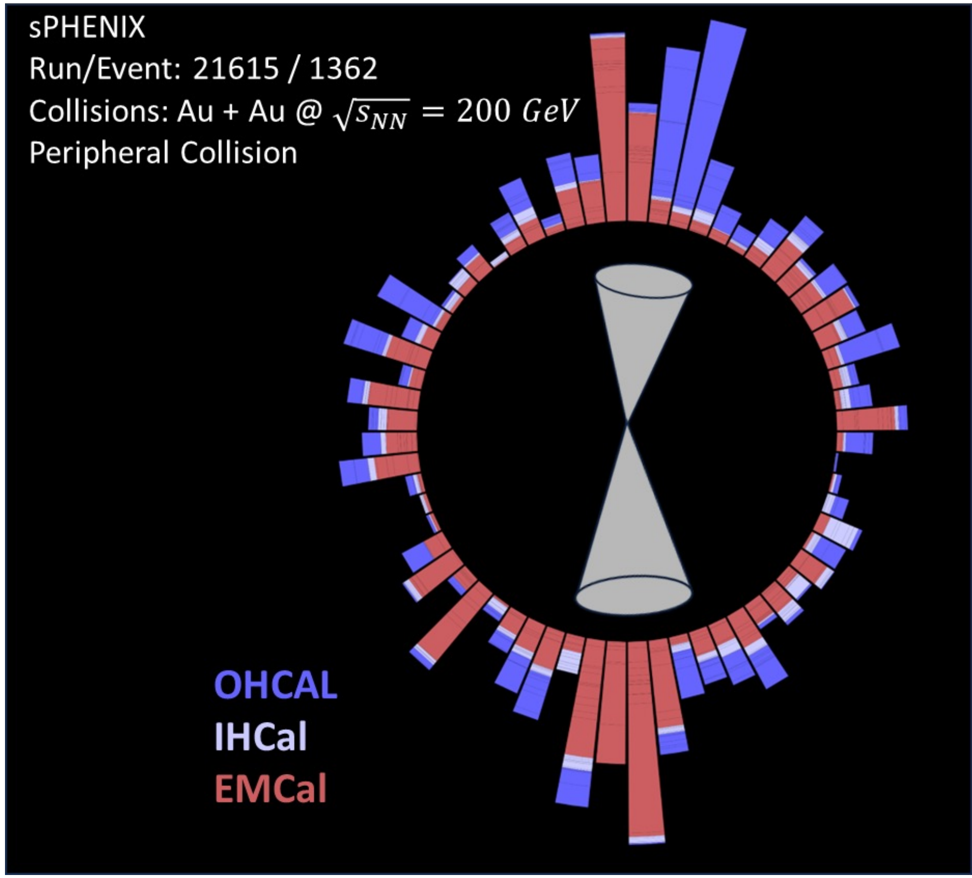
Back-Up

Future Jet-Medium Studies at RHIC

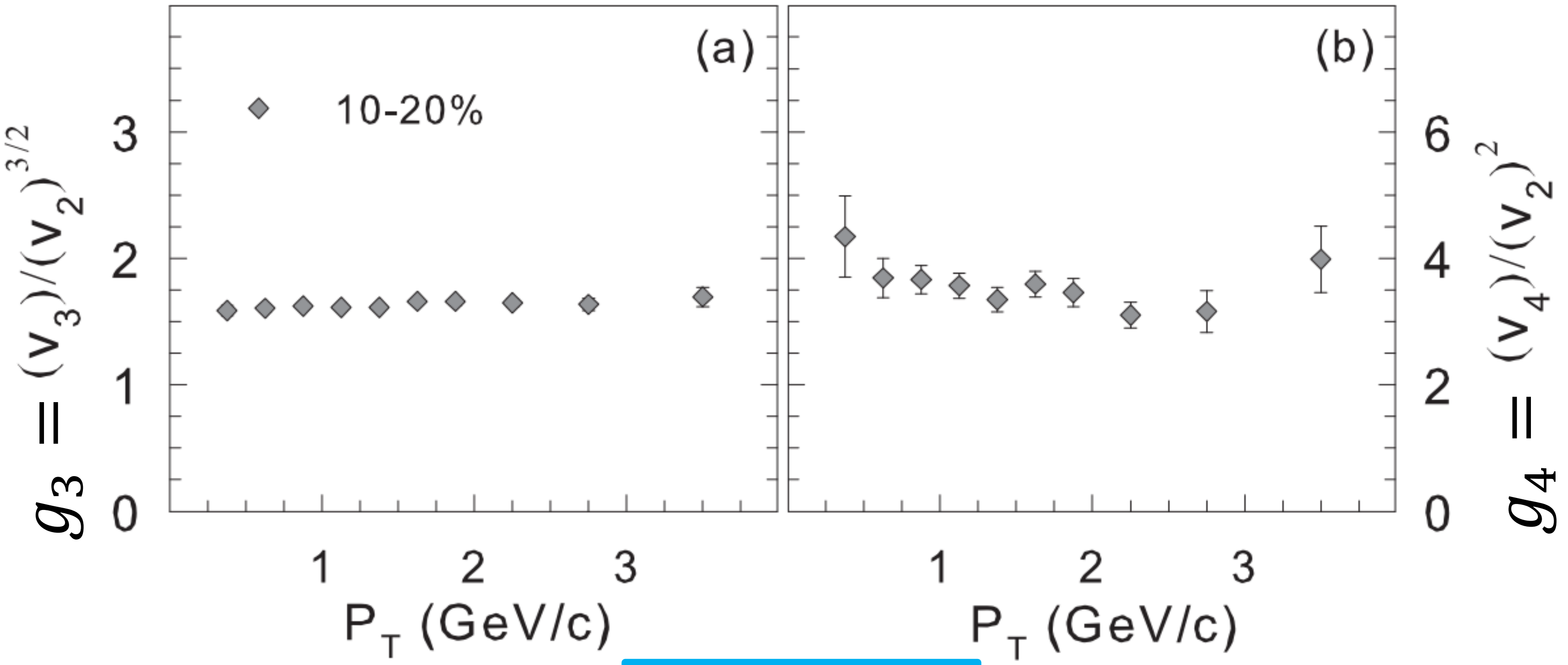
- sPHENIX completed reference $p+p$ run in 2024 exceeding luminosity projections by 200%
- $Au+Au$ run in a matter of months!
- Exciting era of jet-medium interactions awaits!







Flow Subtraction – Acoustic Scaling

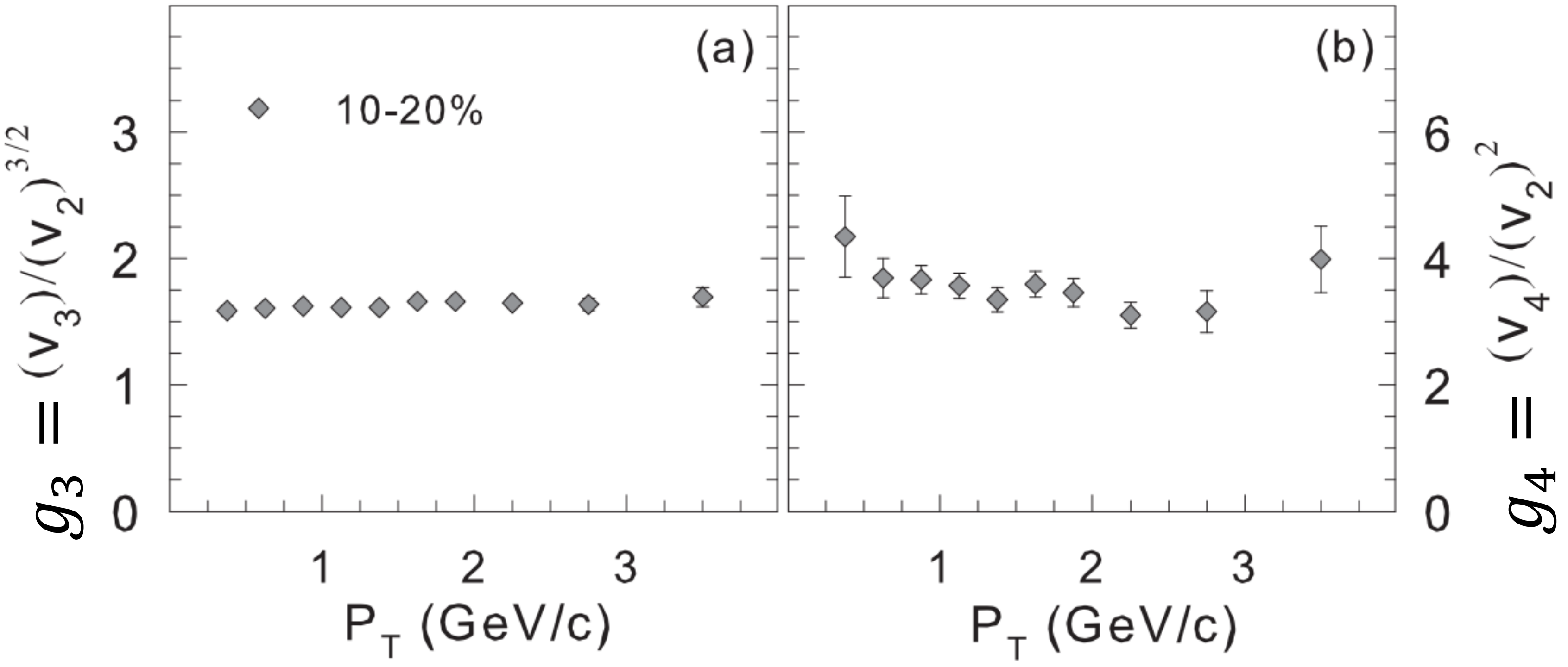


$$g_n = \frac{v_n}{(v_2)^{n/2}}$$

arXiv:1105.3782v2

- Have charged hadron v_n^a for $(n = 2,3,4)$ from PHENIX results
- No π^0 v_3 or v_4 measured at RHIC energies
- v_n harmonics can be scaled to one another via value g_n

Flow Subtraction – Acoustic Scaling



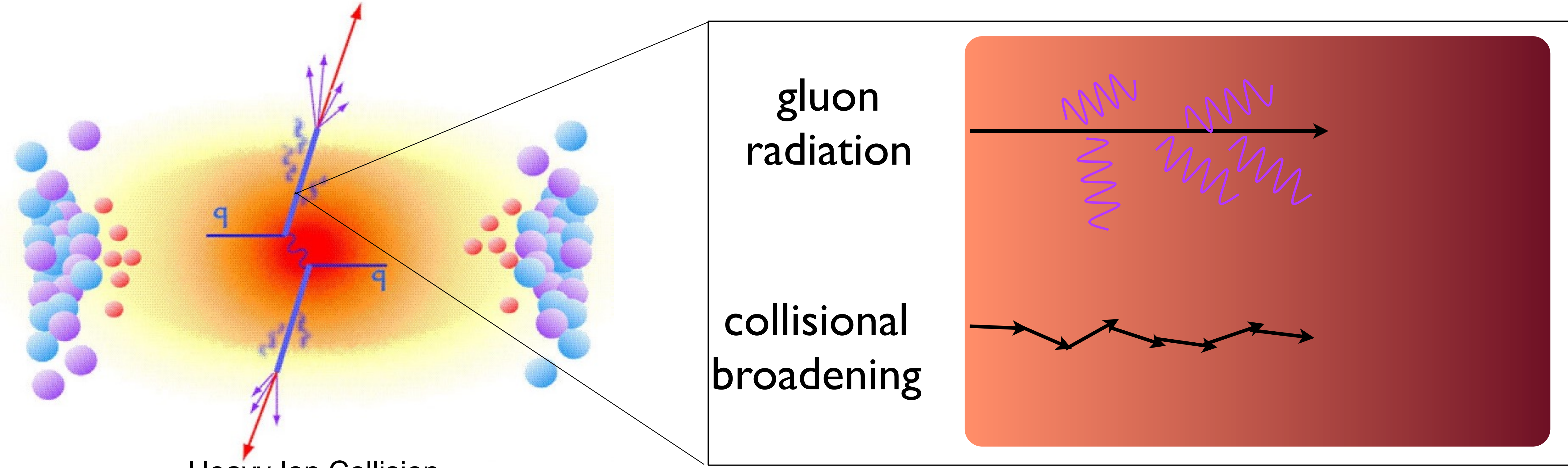
arXiv:1105.3782v2

$$v_n^{\pi^0} = g_n^h \left(v_2^{\pi^0}\right)^{n/2}$$

- Can calculate π^0 v_3, v_4 by scaling π^0 v_2 with charged hadron g_n

Jets in Heavy Ion Collisions

Inside the medium…



Heavy Ion Collision