Photon-hadron, Isolated Photon-hadron, and Related Two-Particle Azimuthal Correlations Results in PHENIX

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SANTA FE JETS AND HEAVY FLAVOR WORKSHOP

Outline

Background info

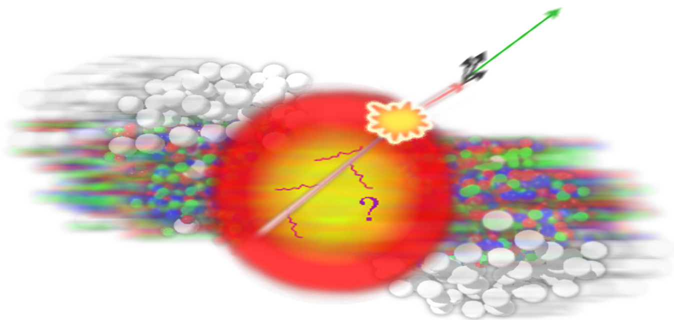
1st part: Review Iso g-h Results in PHENIX

2nd part: Review Interesting Small System d+Au Jet Modification

3rd part: NEW RESULT: ^{3}He+Au Confirmation of d+Au

Two particle correlation

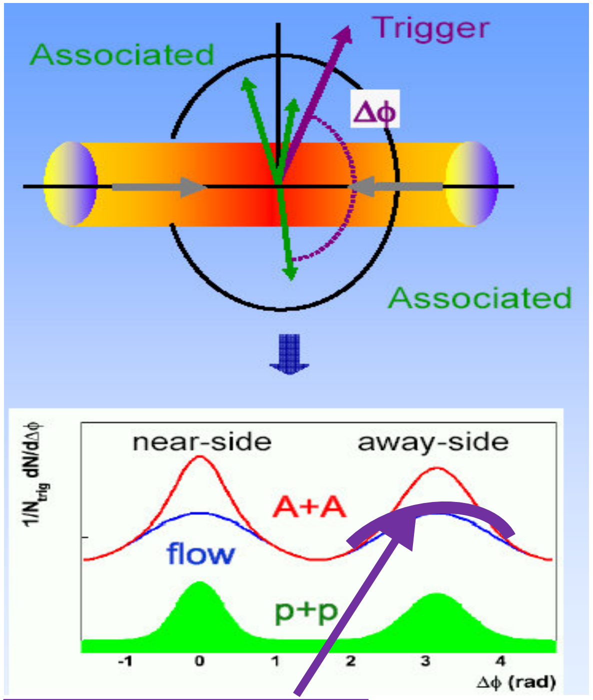
Jets must be produced in back to back pairs to conserve momentum



- Trigger particle → high momentum pi0 → proxy for jet
- Partner (Associated) particle → charged hadron from same jet or "awayside" jet
- Correlation function: C(ΔΦ)

$$C(\Delta\phi) \propto \frac{N^{AB}_{same}(\Delta\phi)}{N^{AB}_{mixed}(\Delta\phi)}$$

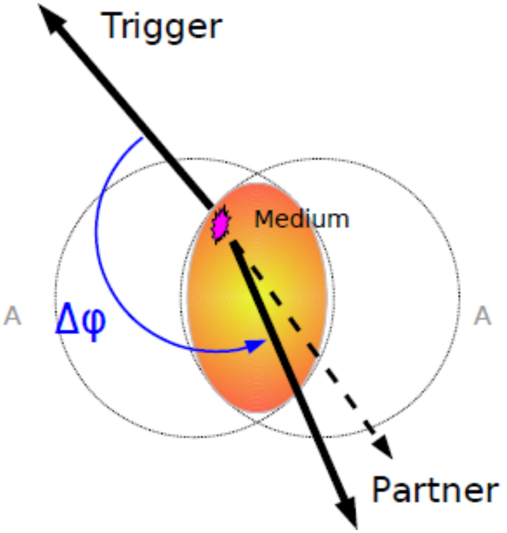
Corrects for imperfect detector



Awayside suppression

Source: http://puma.uio.no/trine/ALICE-Oslo/angular_correlations.html

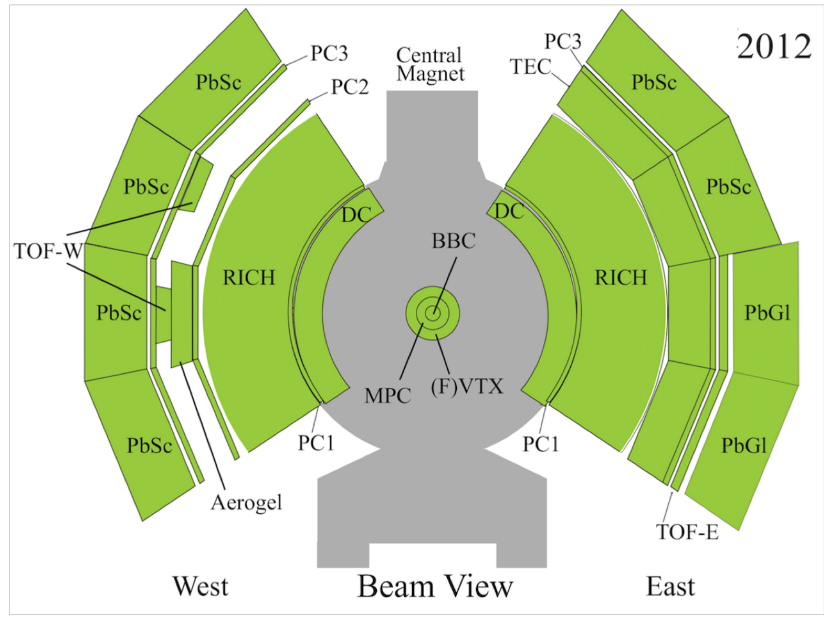
Why direct photon-hadron correlations?



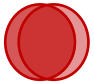
- High p_T direct photons
  - Color neutral – no strong interactions, no E_{loss}
  - Originate from initial hard scattering, ~ no flow
  - Produced alone, opposite direction of jet
  - Generally Isolated
- Direct photon energy is proxy of the opposing jet energy
  - Can study energy loss of awayside jets as they traverse medium
- Two methods of obtaining direct photons in PHENIX
  - Statistical subtraction method – previously used in Au+Au
  - Isolation cut method + modified statistical subtraction

PHENIX Detector overview

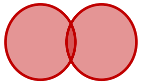
- Two Central Arms: cover $\phi \sim \pi$ and $|\eta| < 0.35$ $\eta \equiv -ln(tan\frac{\theta}{2})$
- Electro-magnetic Calorimeter (EMCal): measures γ, $\pi^0 \rightarrow \gamma\gamma$
- Drift Chamber (DC) and Pad Chamber (PC): charged particle tracking
- Beam-Beam Counters (BBC) and Zero-Degree Calorimeters (ZDC): measures collision centrality



Source: https://www.phenix.bnl.gov/WWW/run/drawing/



Central collision



peripheral collision

2-p Correlation Analyses - Methods

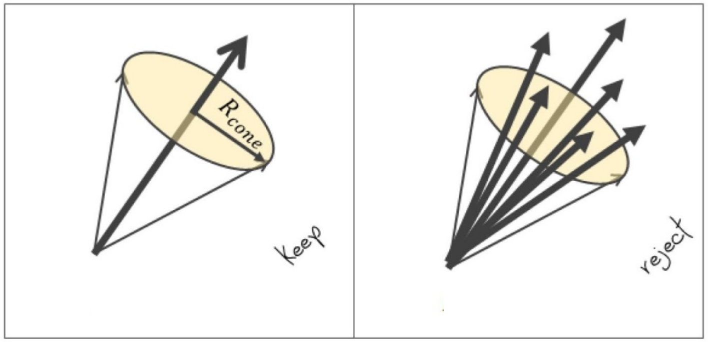
- Need to measure per-trigger yield (aka jet function)
  - Correlation Function – bkgd (Flow)

$$C(\Delta\phi_{AB}) = J(\Delta\phi_{AB}) + b_0 \frac{dN^{AB}_{comb}}{d\Delta\phi_{AB}}$$

$$\frac{dN^{AB}_{comb}}{d\Delta\phi_{AB}} \propto 1 + 2v_2^A v_2^B \cos(2\Delta\phi_{AB})$$

- Isolation cut
  - Prompt g : no jet—Iso improves S/B
  - R_{cone} = 0.4, E_{cone}<0.1E_γ (in pp)
  - Cone Parameters depend on underlying event size in Au+Au

$$R_{cone} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



Statistical Subtraction:

g-h: double subtraction of 2-particle measurements:

$$Y_{direct} = \frac{R_\gamma Y_{inclusive} - Y_{decay}}{R_\gamma - 1}$$

$$Y_{direct} \propto C_{incl} - Bkgd_{incl}(Flow) - \left[C_{decay} - Bkgd_{decay}(Flow)\right]$$

$$Y_{xxx} \propto C_{xxx} - b_0\left(1 + 2\langle v_2^\gamma\rangle\langle v_2^h\rangle\cos 2\Delta\phi\right)$$

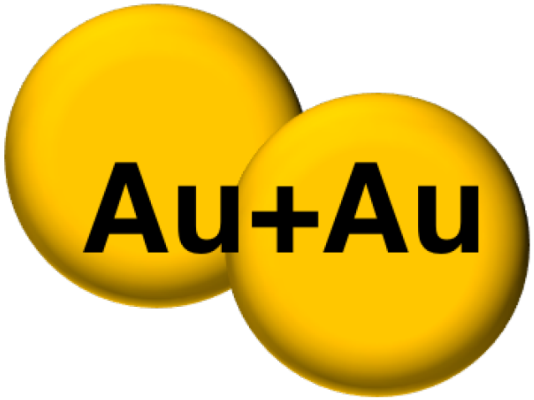
Norm

Bkgd(Flow)

$$R_\gamma = 1 + \frac{N_{direct}}{N_{decay}}$$

- For isolation cut - $Y_{inclusive} = Y_{isolated}$
- For p+p – no flow background subtraction
- No flow subtracted in small systems (e.g. p+Au and d+Au)

1st part

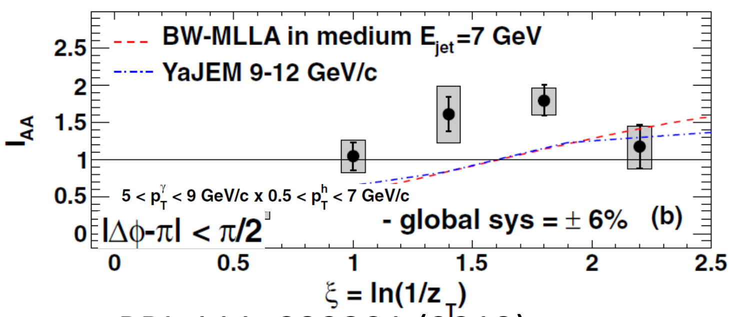


$$\sqrt{s_{NN}} = 200 \text{ GeV}$$

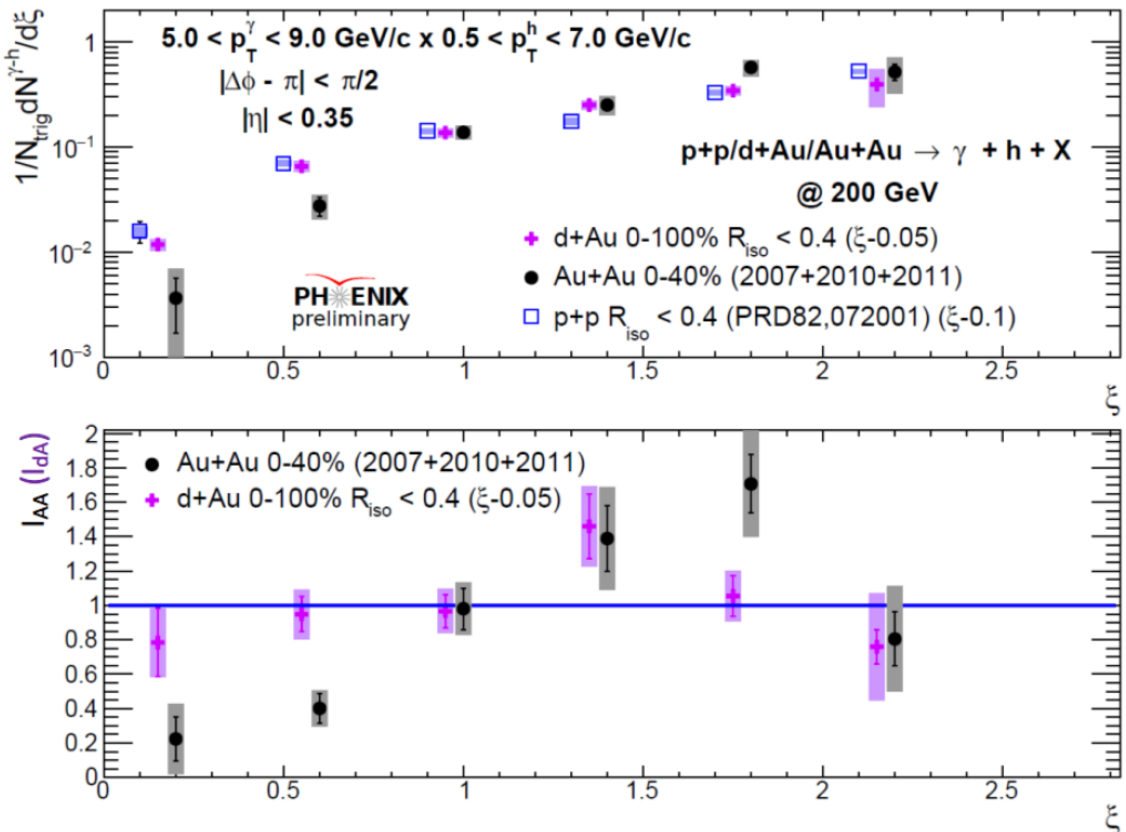
Goal: Study Jet energy loss in QGP especially improving information about how the lost energy is distributed within the plasma

Fragmentation Function Modification in Au+Au : REMINDER

- 0-40% events – Most central Au+Au
- No clear modification in d+Au
- Enhancement in Au+Au
- Run 7+10+11 Au+Au more precise than previous measurement (Run 7+Run 10)



PRL 111, 032301 (2013)



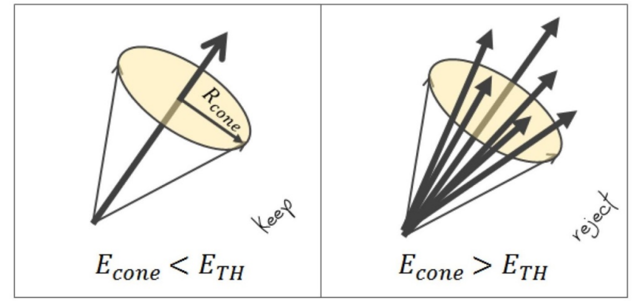
$\xi=\ln(1/z_T)$

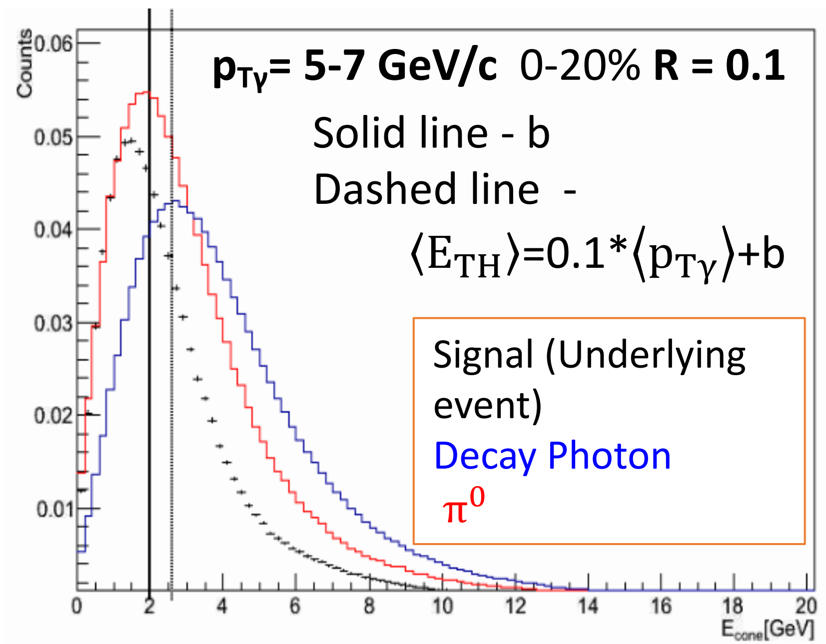
How does enhancement behave with centrality?

New Method - Isolation Cut in Au+Au

- Use cone method
  - Sum energy in cone around particle, if less than threshold, particle is isolated
  - Optimal threshold depends on centrality, background event energy, and central photon energy

$$R_{cone} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$
$$E_{TH} = aE_\gamma + b.$$





Centrality (%)	R_{cone}	a	b (GeV)
0 - 20	0.1	0.1	2.0
20 - 40	0.2	0.1	4.0
40 - 60	0.2	0.1	2.0
60 - 92	0.3	0.1	1.0

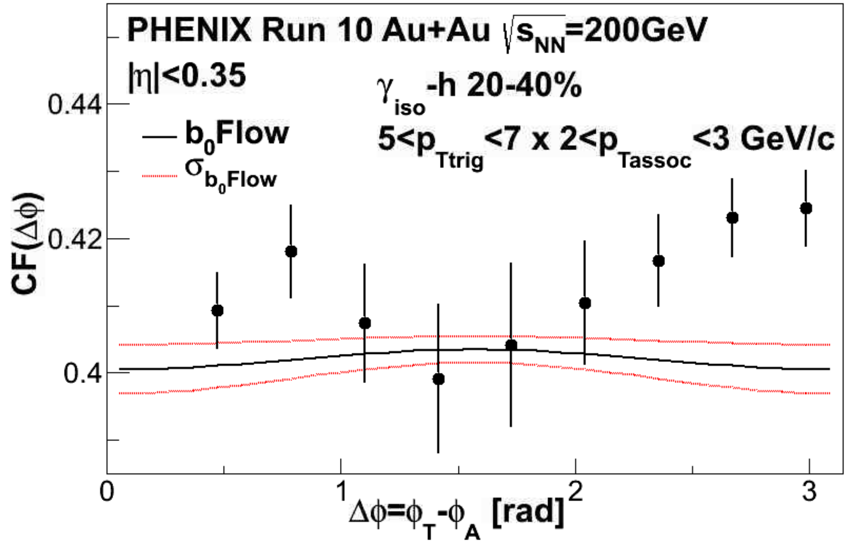
N. Riveli,, Ph.D. thesis, Ohio University (2014).

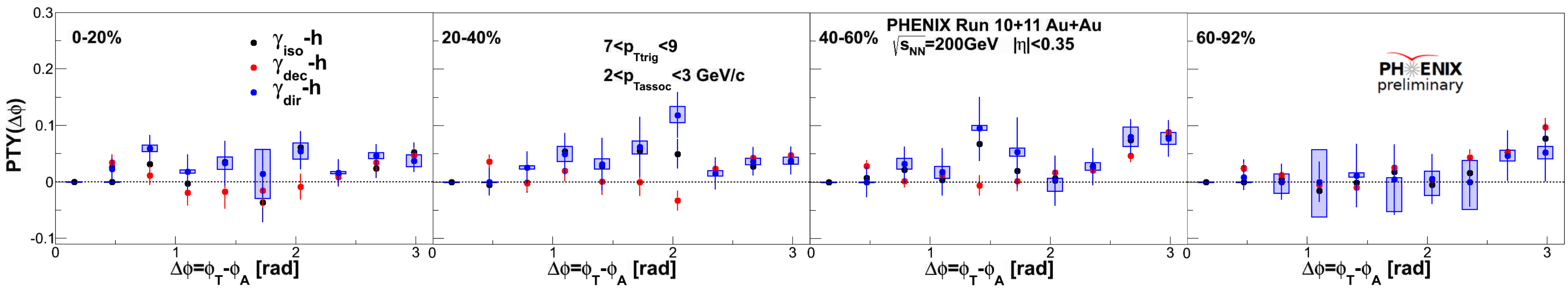
Causes complications to normal 2PC

- Measuring isolated particle v_2 for 2-p background subtraction
- Background level – using abs norm method

Correlation and Jet Functions

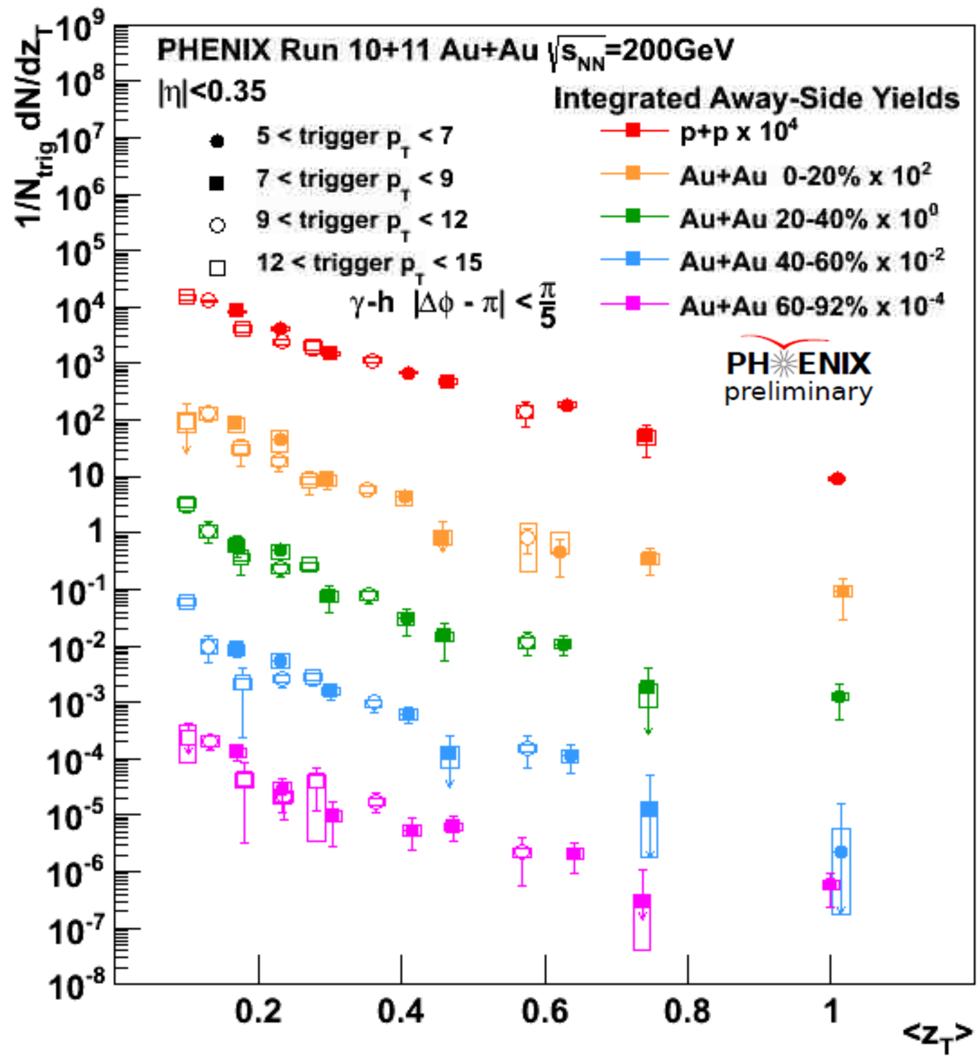
- Background level matches the minimum of CF
  - We understand the background modification from iso cut
  - Notice the negative flow shape
- Subtract this background to get per-trigger yields





Away-side Yield

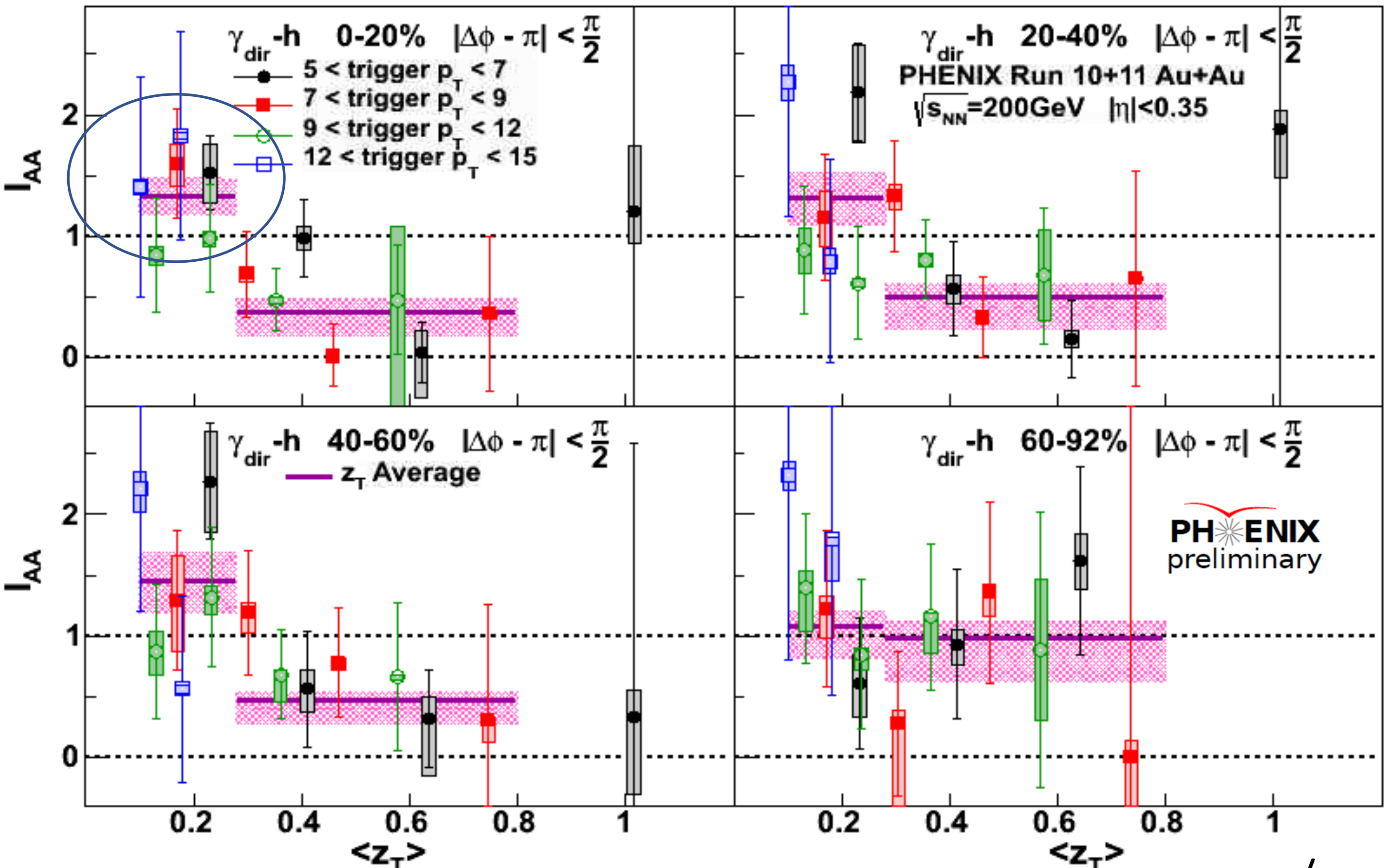
- Integrate away-side of per-trigger yield
- Seems to scale with $z_T = p_{Th}/p_{T\gamma}$



I_{AA} as a function of z_T

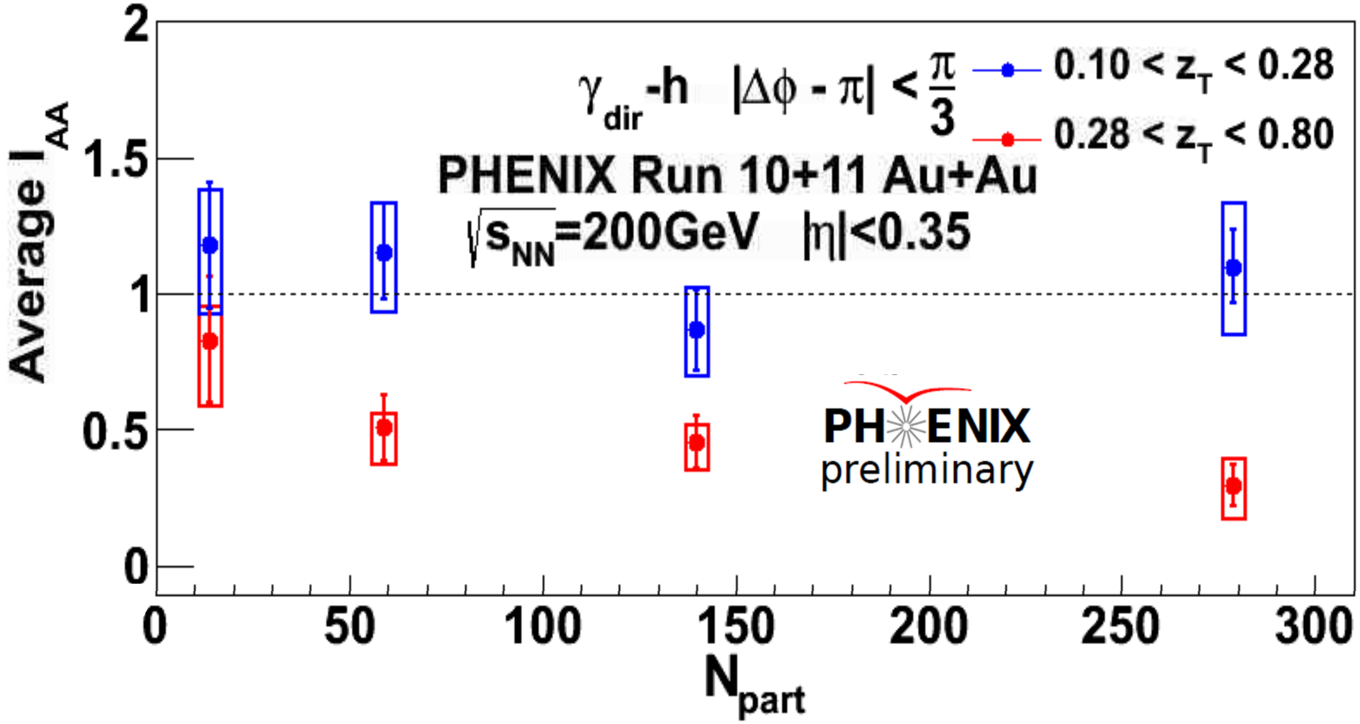
$$I_{AA}(p_T^\gamma, p_T^h) = \frac{Y^{Au+Au}(p_T^\gamma, p_T^h)}{Y^{p+p}(p_T^\gamma, p_T^h)}$$

- Fit all I_{AA} points in two z_T regions to a constant to extract the average I_{AA} for each z_T region and centrality bin



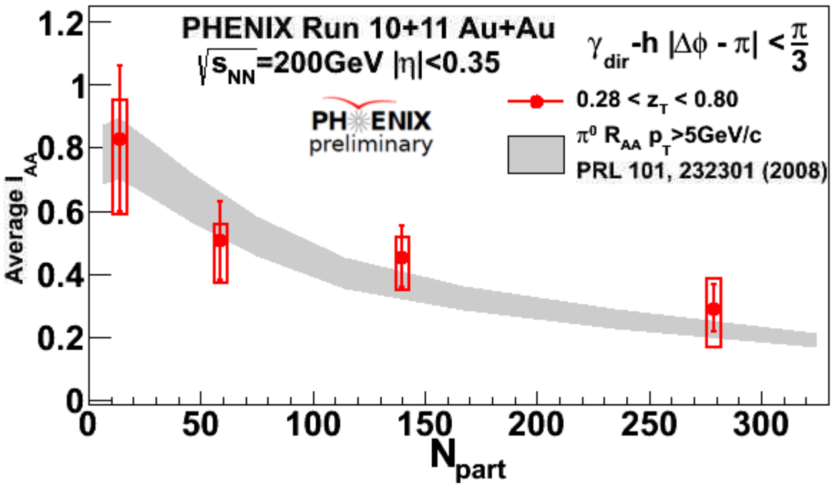
$z_T = p_{Th}/p_{T\gamma}$

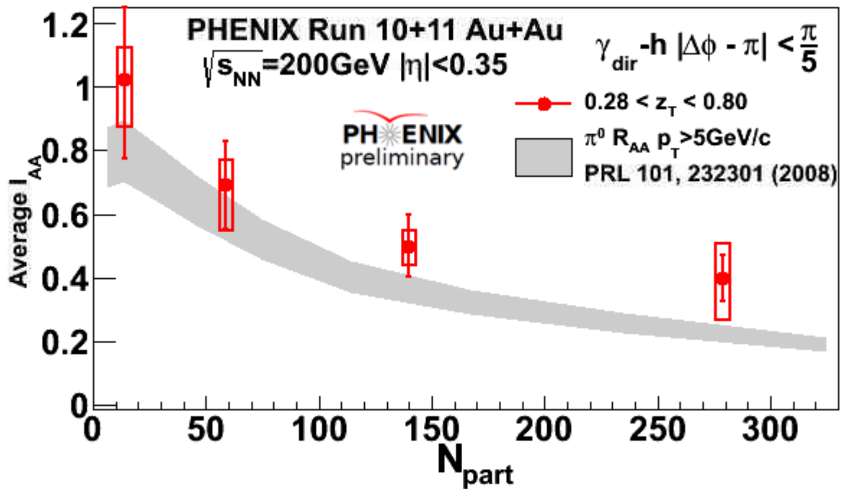
Average I_{AA} vs. Centrality



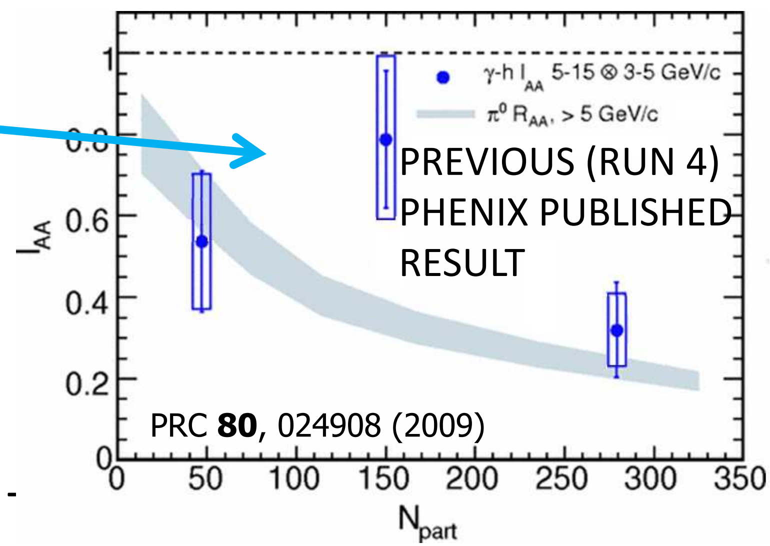
- Low z_T and High z_T behaviors different.
- High z_T suppression for all centrality bins
- Low z_T NOT SUPPRESSED, relatively flat with centrality-- E_{loss} Recovery
- Isolation cut allows more precise analysis of the semi-peripheral and peripheral centralities

High z_T Average I_{AA} Centrality Dependence



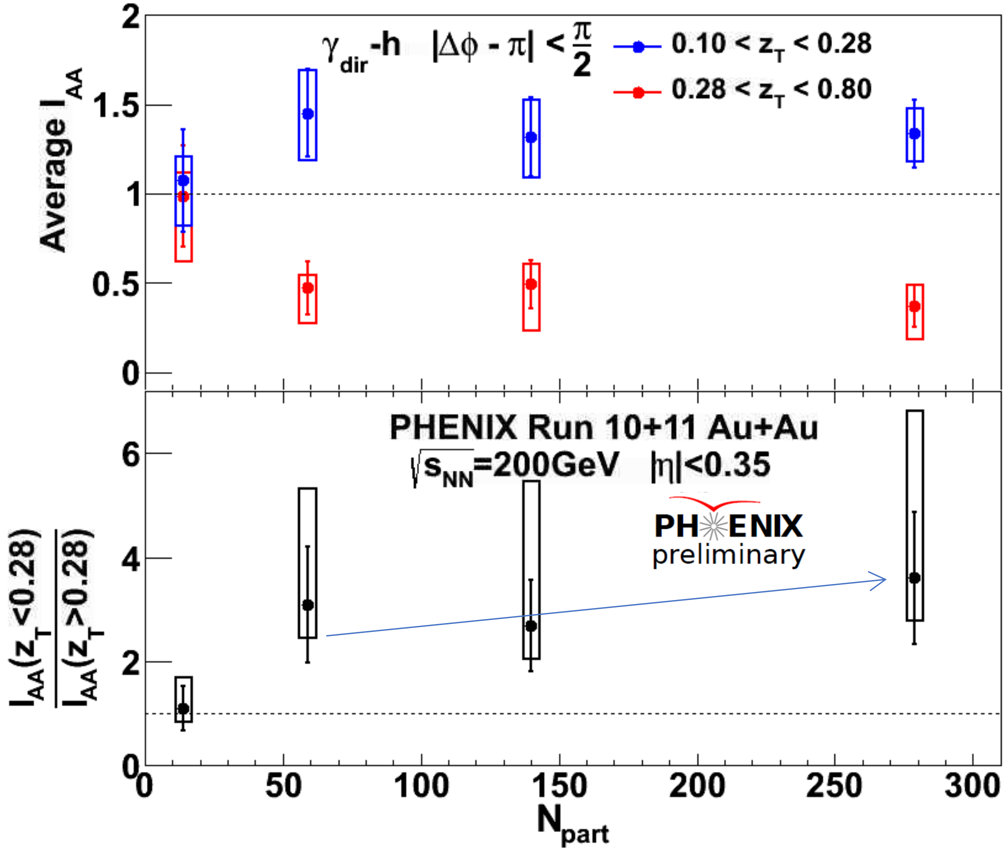


- Isolation cut/New stats substantial improvement in precision
- Detailed centrality shape of suppression
- High z_T Average I_{AA} and π^0 R_{AA} approximately match
  - Photon tagged jet geometric distribution (E_{loss} geometry) is exactly the same as single inclusive jet geometric distribution - so $R_{AA} \approx \gamma$-jet I_{AA} expected



Average I_{AA} – π/2 away-side

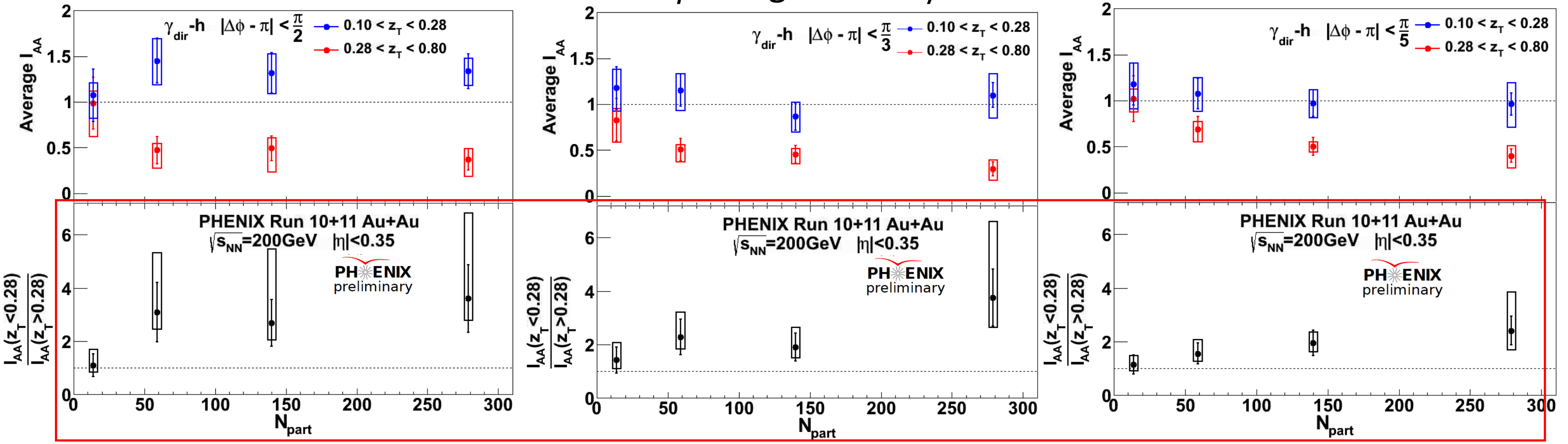
- High z_T energy loss enhances low z_T production
- 1st measurement of centrality dependence of low z_T enhancement
- To judge true centrality dependence of enhancement, must account for overall reduction of jets due to suppression
- *Relative* Enhancement Factor – High z_T/ low z_T ratio – is:
  - Larger than low z_T I_{AA}
  - shows increase in most central event



Average I_{AA}

Enhancement and suppression for all away-side regions!

AS $\Delta\phi$ Integration: $\pi/2$ | AS $\Delta\phi$ Integration: $\pi/3$ | AS $\Delta\phi$ Integration: $\pi/5$



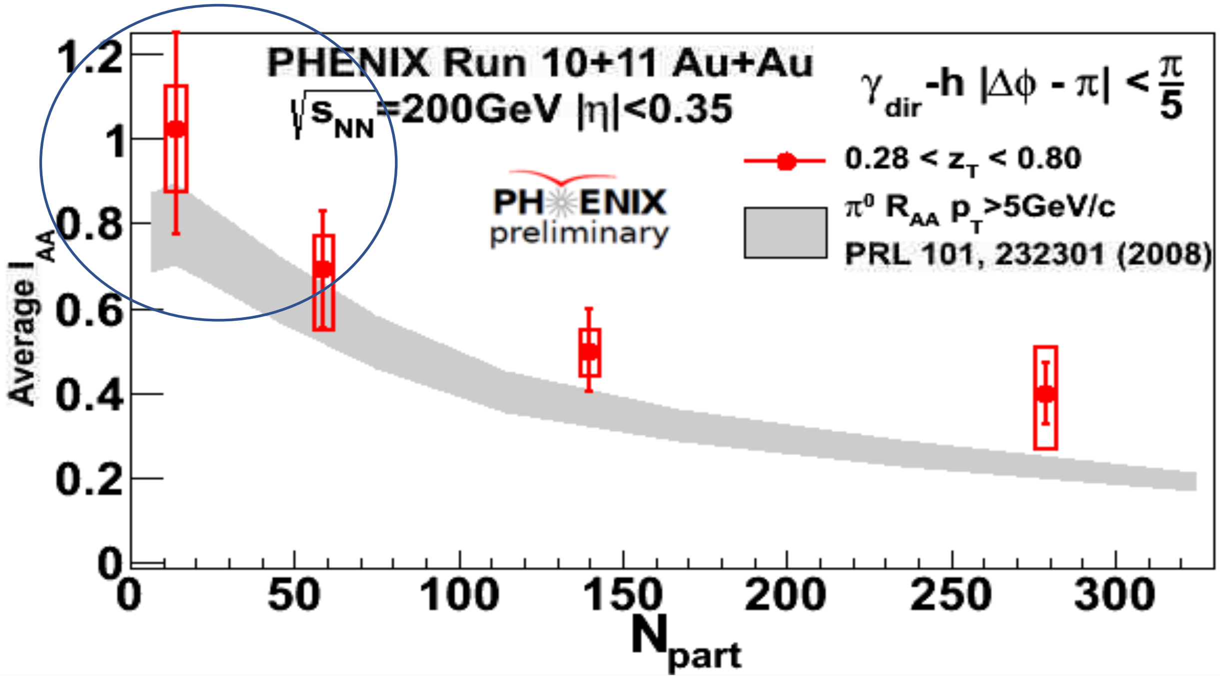
- Increasing low z enhancement for wider integration regions (blue points right to left)
  - Seen by previous gamma-jet and LHC jet reconstruction analyses
- Both high z suppression and low z enhancement
- *Relative* enhancement above suppressed jet level (black ratio) much larger than 1 in all bins even where low z I_{AA} consistent with p+p level of 1
  - reveals monotonic increase towards central events

Conclusions 1:

- **Au+Au at $\sqrt{s_{NN}}$ =200 GeV with isolation cut – first results**
- Isolation cut allows more precise analysis of the semi-peripheral and peripheral centralities
- 1st ever study of enhancement pattern as a function of centrality at RHIC
  - Enhancement is monotonically increasing with centrality
- PHENIX still has high statistics data sets (2014, 2016 long Au+Au runs) that need to be analyzed!
- **Future: focus on studying Eloss in semi-peripheral and peripheral centralities – most interesting region?**
- **Why?...**

E_{loss} Turn-off? E_{loss} in Small systems?

- We want to focus on region where E_{loss} is small to study whether it may be expected in small systems and how large does a system have to be?
- Isolation cut helps most in mid-central to periph: but low statistics, we need analyze Run14/Run16 statistics (beyond-sphenix?) to gain sufficient statistical precision



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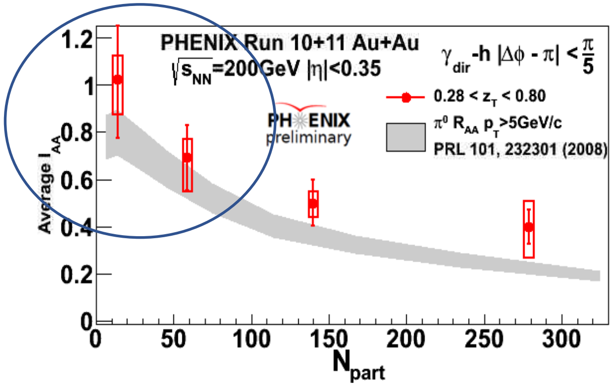
Alternative solution:

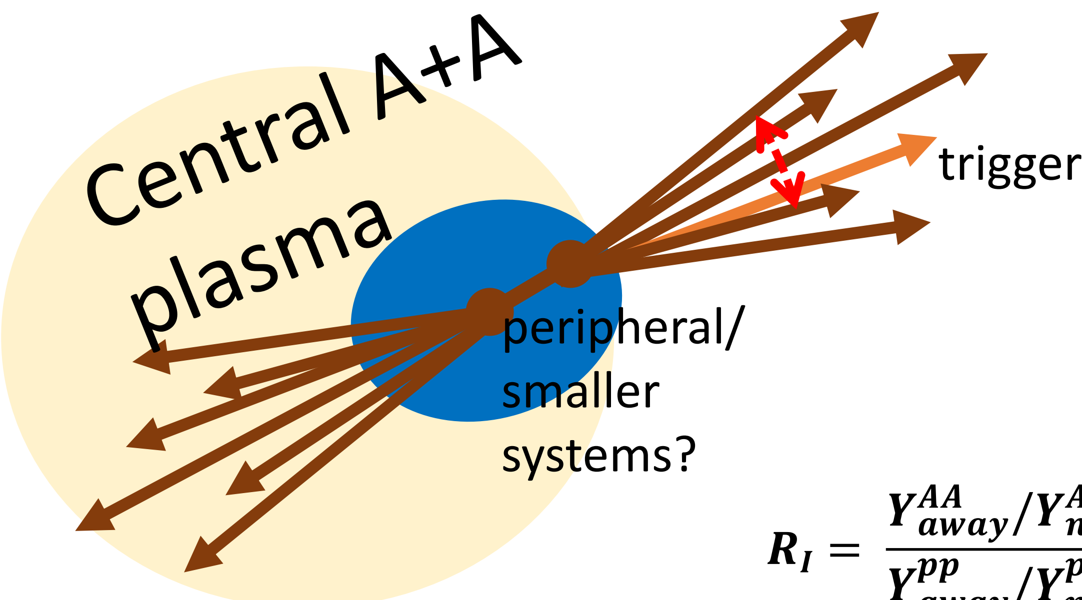
1. Using pi0-h correlation has better statistical precision, can make many more differential measurements– but suffers from other systematics and trigger biases compared to γ-h
2. Find new 2PC observable other than I_{AA} to reduce systematic errors.

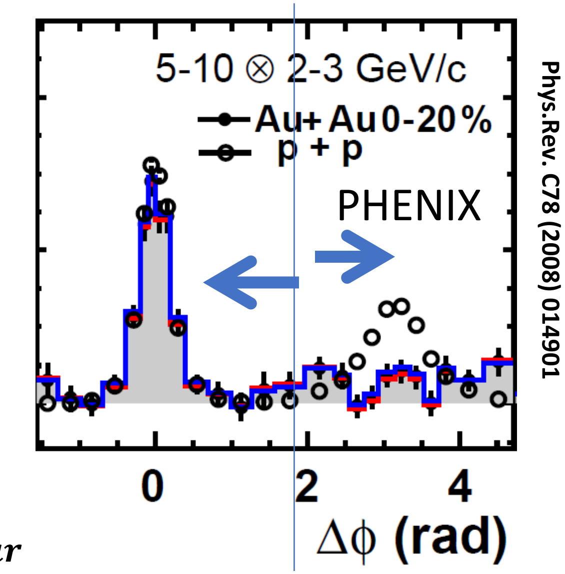
Need best possible precision and differential measurements to go to most peripheral where Eloss effects smallest and mixed with cold matter effects



NS/AS Ratios: A Nice Observable for searching for small E_{loss} ?

- For E_{loss} search, assume well-known surface bias picture for Au+Au should apply as the system goes peripheral—possibly even in "small systems" d+Au, He+Au?
- Look for Differences in Awayside Modification compared to Nearside



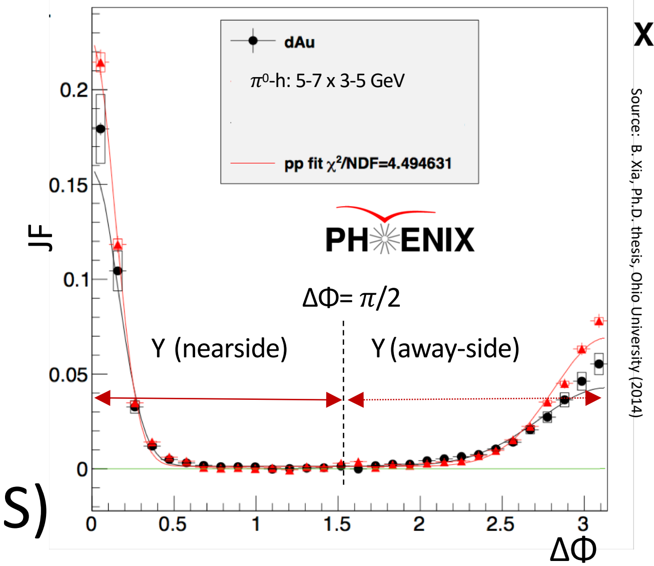


$$R_I = \frac{Y^{AA}_{away}/Y^{AA}_{near}}{Y^{pp}_{away}/Y^{pp}_{near}}$$

Set up for 2nd part

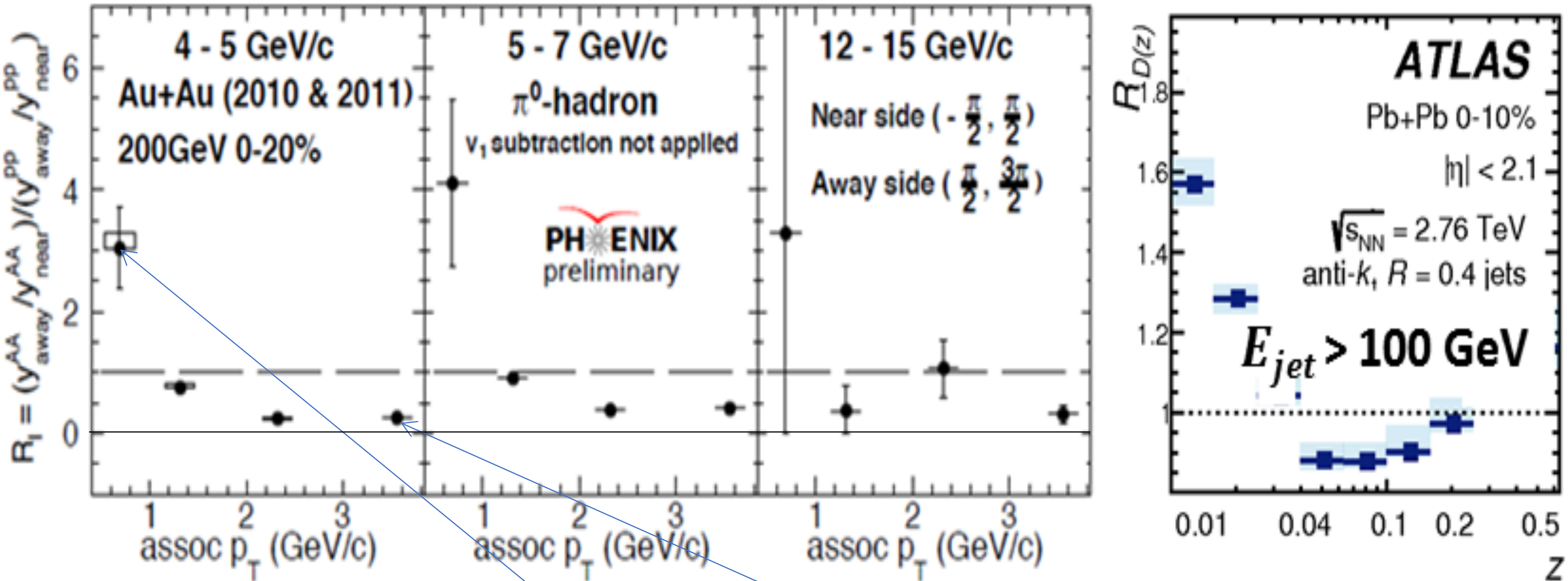
Jet Pair Quantification

Double Ratio: $R_I = \frac{Y^{AA}_{away}/Y^{AA}_{near}}{Y^{pp}_{away}/Y^{pp}_{near}}$



- NO EFFICIENCIES NEEDED (Cancels in AS/NS)
  - Dominant systematic errors due to single charge hadron efficiency are completely removed
- Surface Bias: levels of modification mostly unchanged (going from IAA to R_I)
- No Contribution of v_{2n} even harmonics from hydrodynamic flow **is zero** (e.g. v_2)
- Contribution of higher order odd harmonics (>= v_3) can be neglected--only sensitive to v_1
- ZYAM systematic is also small since residual mis-subtraction contribute to both NS and AS.

Energy loss ?: Double Ratio (R_I)



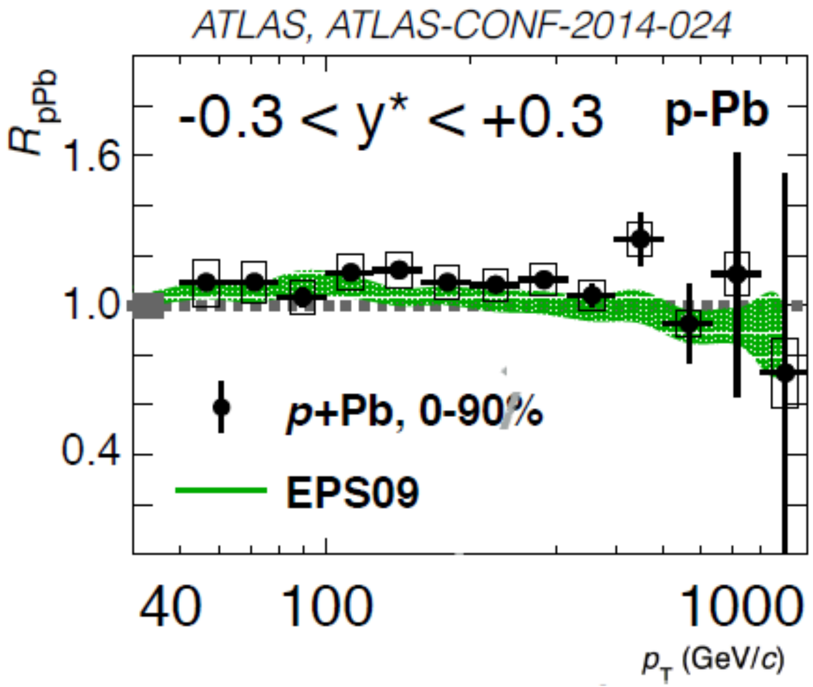
Eur.Phys.J. C77 (2017) no.6, 379

- **Recent PHENIX's result in AuAu R_I :**
- Very similar to I_{AA} previously shown **but effects more pronounced**
  - relative rise from high p_{Ta} (R_I = ~0.3) to low p_{Ta} (R_I= 3.5) is factor of 12!

- Still qualitatively similar to LHC Frag. Function Ratio results but enhancement relatively larger partially due to LHC results only including surface-biased reco'd jets.

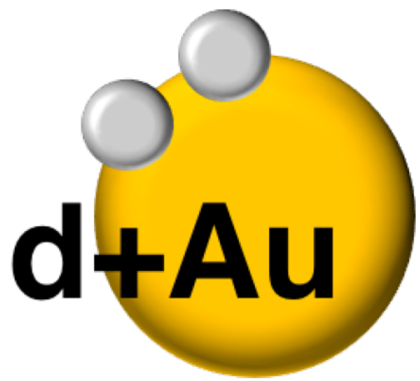
Other end of spectrum: Small Systems:?

- No E_{loss} in p+Pb at LHC? –LHC only very high energy observables.
  - npdfs account for ALL jet modifications?
- LHC focus on found jets, observables like x.s. excludes largest modification e.g. for A+A jets (ΔR > 1 enhancement)
- Greater sensitivity in low E_{jet}?
  - lowest possible "jet" pt: 5-10 GeV.
- Exploit enhancement—Exploit trigger bias for sensitivity, Exploit lowest E_{jet}: 2PC/RI can do all



2nd part: d+Au: pi0-h correlation

-Slightly older PHENIX result already explored this idea by creating the RI observable in d+Au
-RI precision revealed interesting jet modifications

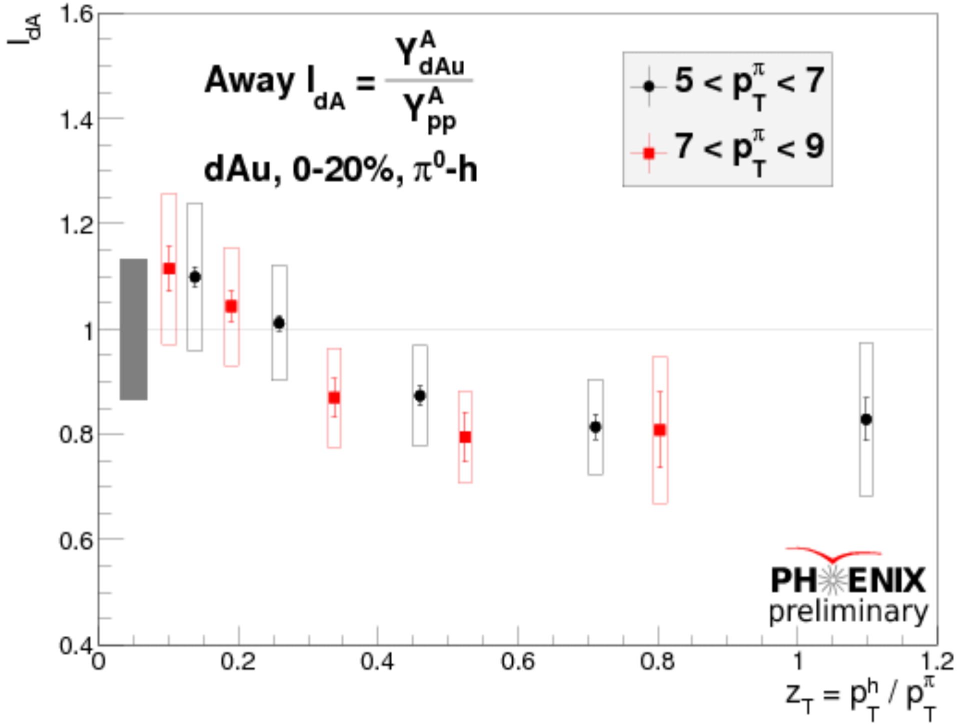


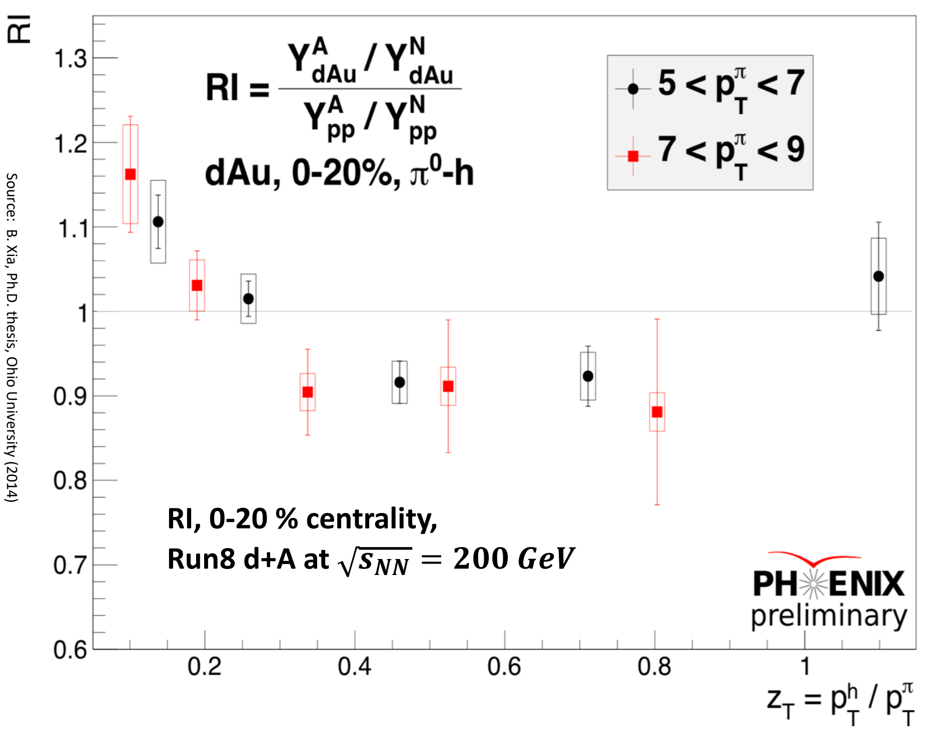
$$\sqrt{s_{NN}} = 200 \text{ GeV}$$

Reminder of some of what was observed:

I_{AA} vs R_I

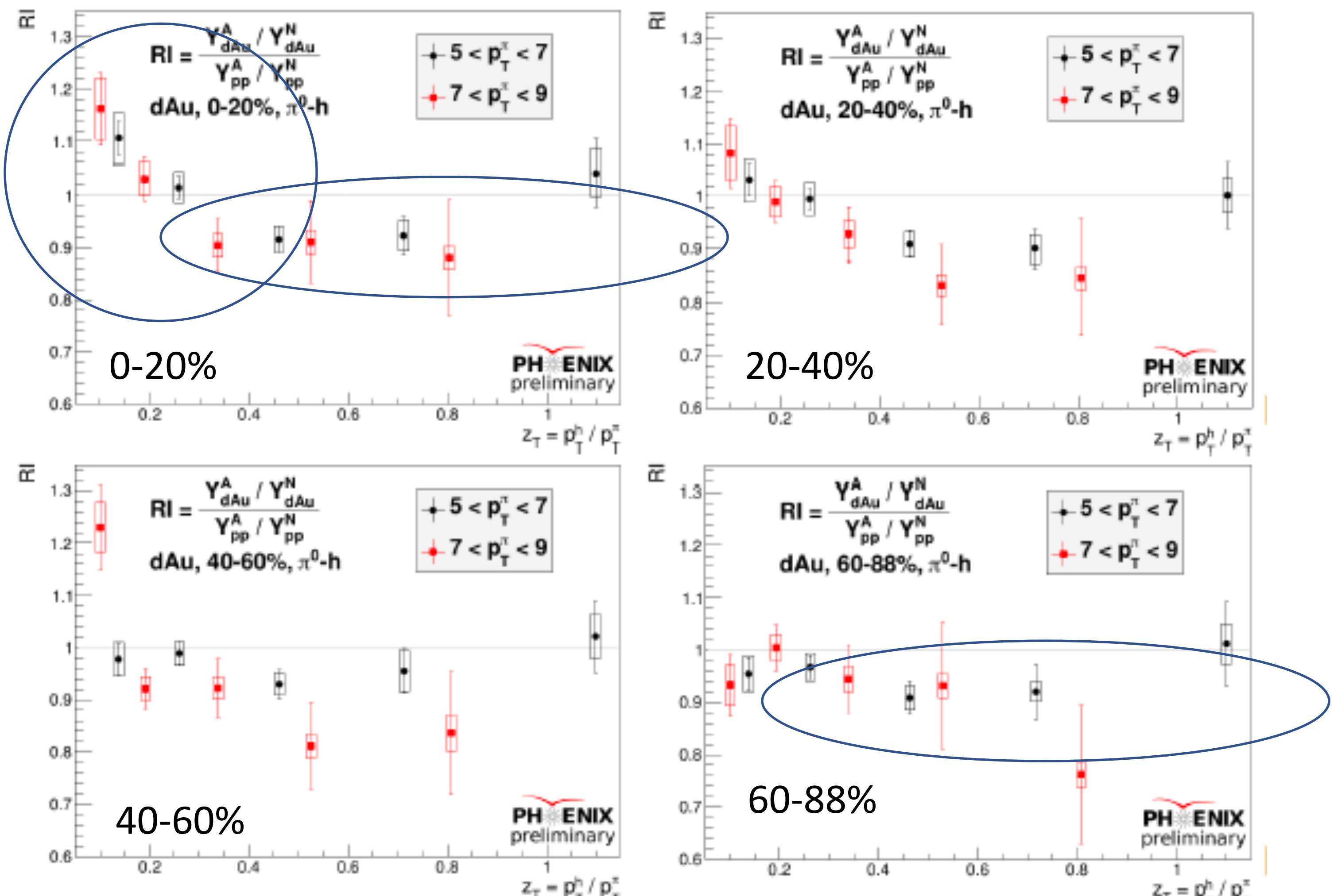
- Clear improvement of uncertainties in R_I compared to I_{AA}
- RI can be more sensitive to small levels of suppression or small cold nuclear effects
- Shows small high z suppression and low z enhancement in d+Au





Source: B. Xia, Ph.D. thesis, Ohio University (2014)

dAu R_I Ratio Centrality Dependence



System size evolution in d+Au? Peripheral to Central? More low z_T enhancement at low z_T → High pt suppression? Not clear? Can we confirm this with another system? (Motivation for next result)

Causes?

- Many potential Trivial or Cold Nuclear Explanations—but also shares qualitative features of E_{loss}
- "Trivial" explanations we could test:
  - ✓ "Hydro" v3, v1
  - ✓ Trivial Rapidity Distributions Mismatching p+p vs d+Au?
  - ✓ HIJING show anything like this?

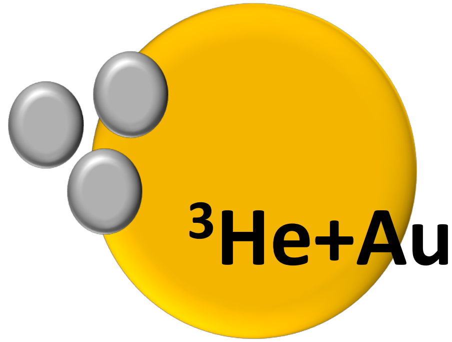
None of these could reproduce the effect

- "Cold Nuclear Effects":
  - ✓ Enhanced Nuclear k_T (based on STAR jet-broadened d+Au k_T result)
  - ✓ Initial State nPDF effects (partial—EPS09(s) only checked)
  - Check other npdf's?
  - Get bonafide theory calcs from theorists (need input from theorists)
- Could QGP/Hot Eloss cause something like this?
  - Get bonafide theory calcs from theorists (need input from theorists)

First since this is (WAS) only one channel in one system, can we confirm the result in other data ?

3rd part: NEW RESULT: ^{3}He+Au Confirmation of d+Au

3rd part



2014 Run (^{3}He+Au)
2015 Run (p+p)
2016 Run (new d+Au)

- d+Au result was from 2008 data set - using 2006 p+p reference
- A lot of newer data can shed light on these questions
- How about ^{3}He+Au? Next bigger system
- What physics causing d+Au modifications should be interesting to compare to ^{3}He+Au?
  - Bigger geometry than dAu– Central 0-20% N_{part} values have good overlap with PHENIX AuAu peripheral data
  - **He+Au 0-20% Npart = ~22.5 comparable to 65-70% Au+Au!**

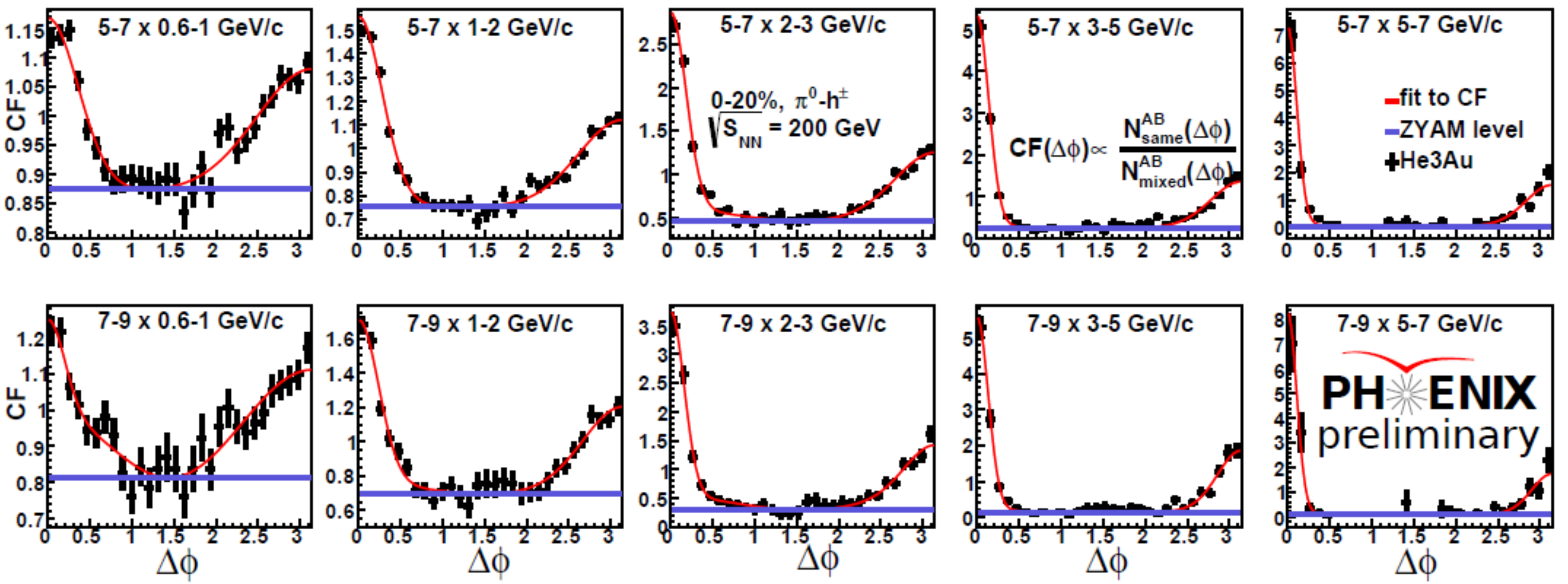
Newer Datasets

2014 Run (^{3}He+Au)
2015 Run (p+p)
2016 Run (new d+Au)

- **^{3}He+Au ($\sqrt{s_{NN}} = 200$ GeV)**
  - 0-20% Centrality Triggered Dataset
  - PHENIX Emcal-Rich (ERT)
  - N^{π^0}: **386 k** (**Run8 dAu: 5 m**)
- Run 15 p+p ($\sqrt{s_{NN}} = 200$ GeV) improves statistics of pp reference
  - N^{π^0} **: 6.9 m** (vs . **Run6 pp: 1.5** m)
- Run 16 d+Au data also available
  - Initial rough (pre-) re-analysis also confirms 2008 result - TBA

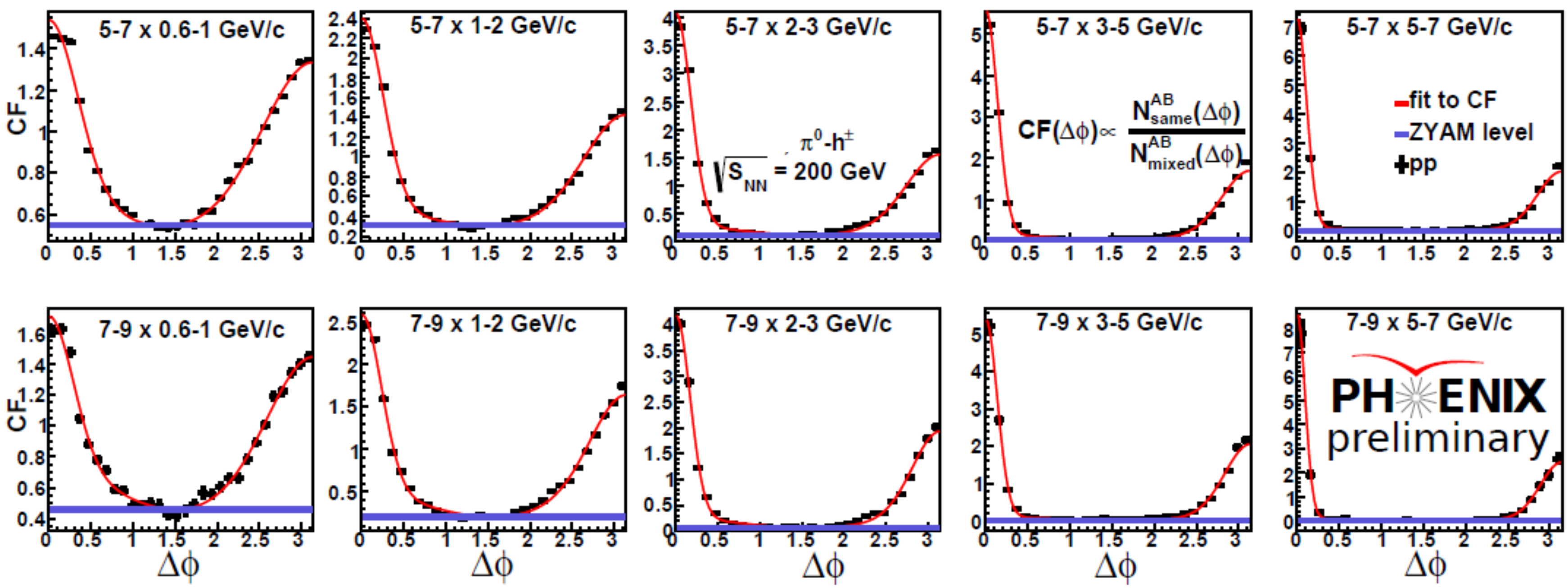
Correlation Functions - ^{3}He+Au

- Run14 ^{3}He+Au at $\sqrt{s_{NN}} = 200$ GeV
- As in 2008 d+Au Analysis:
- Background level subraction: ZYAM method
- Two Trigger(π^0) bins: [5-7, 7-9] GeV/c
- 5 Partner(h$^{\pm}$) bins:[0.6-1, 1-2, 3-5, 5-7] GeV/c



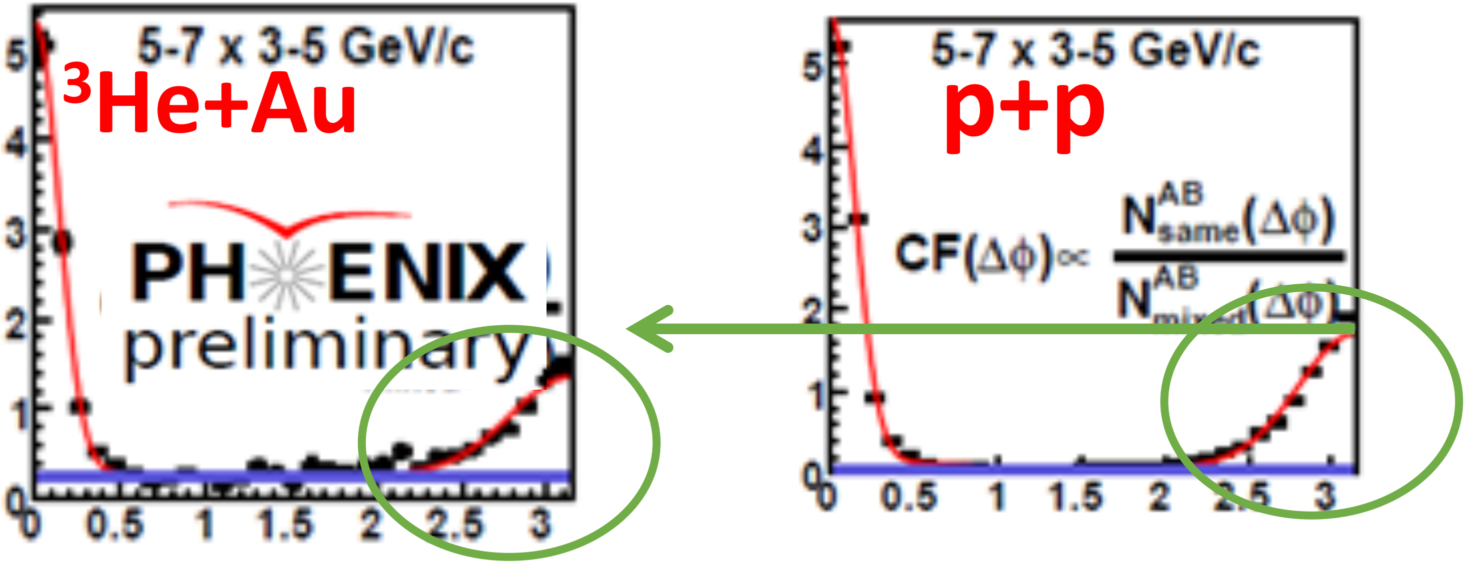
Correlation Functions -2015 p+p

- Run15 p+p at $\sqrt{s_{NN}} = 200$ GeV
- Background level: ZYAM method
- Excellent p+p statistics helps improve comparison to d+Au
  - Will eventually also be applied to Run 8/Run 16 d+Au analysis as well

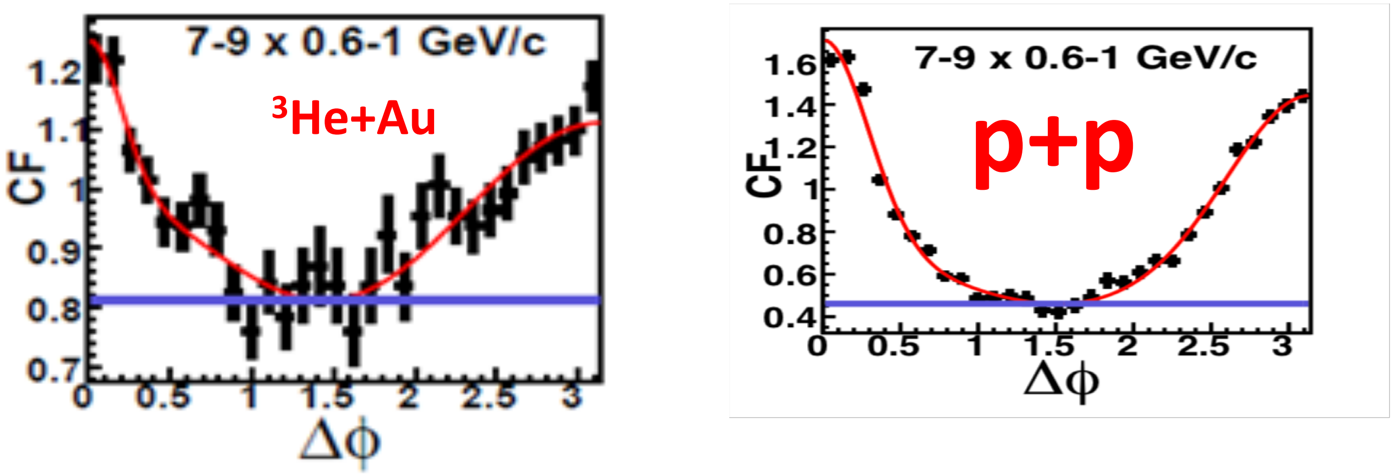


Modifications in ^{3}He+Au?

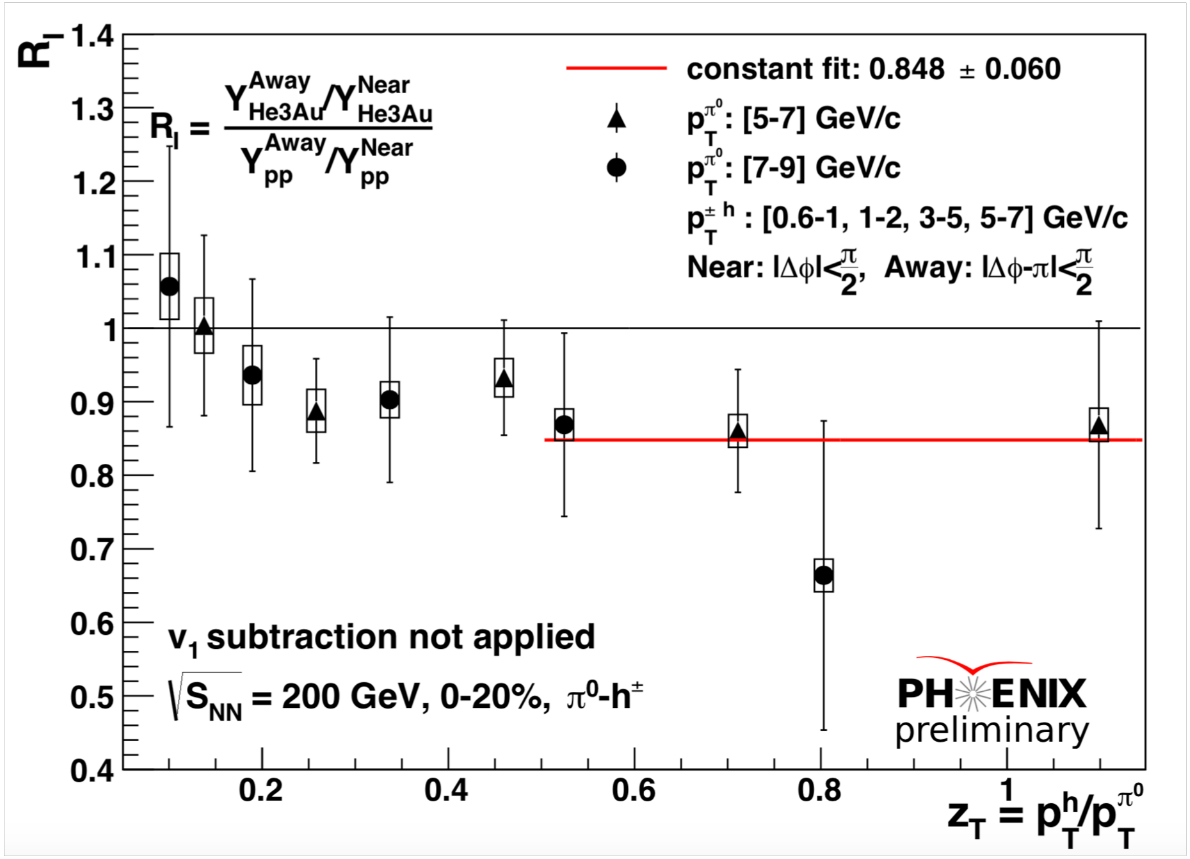
By eye can see suppression in the AS Shape



At low z statistical precision of He+Au is limited to see small modifications :

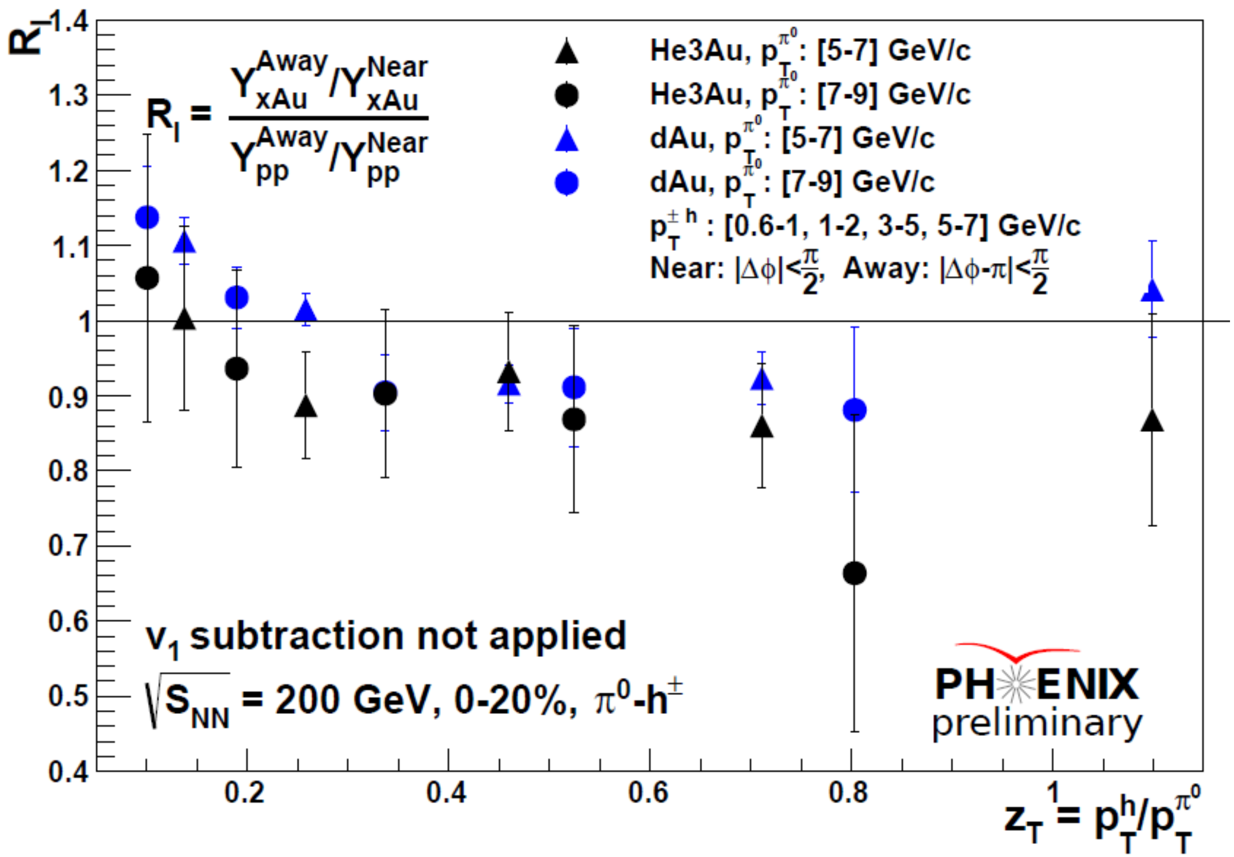


R_I: ^{3}He+Au



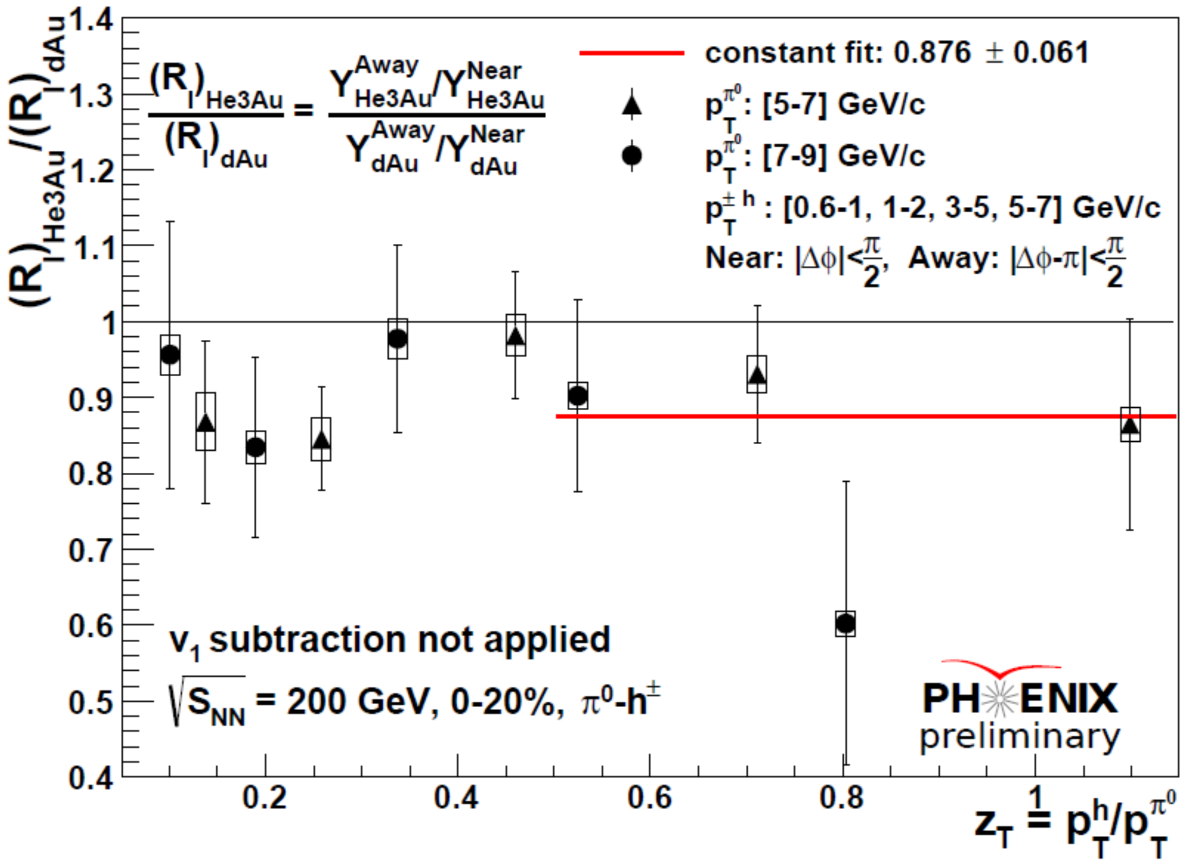
- Significant Suppression at high z_T in ^{3}He+Au
- Trends similar to d+Au, w/rise at low z_T, although unlike d+Au, uncertainties too large to confirm low z_T shape with significance

Comparison of ^{3}He+Au and d+Au R_I



- He+Au confirms behavior of d+Au: similar trends overall, and suppression at high z_T
- He+Au is more suppressed than d+Au --> More modification for larger system geometry
- How statistically significant is this size dependence of ^{3}He+Au R_I < d+Au R_I ?

Ratio of RI's of ^{3}He+Au to that of d+Au



- High z_T suppression in ^{3}He+Au is about 12% larger than d+Au with at least 2-sigma significance.

Conclusion 2:

- ^{3}He+Au shows similar behavior to d+Au: Suppression at high z_T and possible rise at low z_T
- Ordering of increase in suppression with volume/system size is confirmed
  - ^{3}He+Au R_I is more suppressed than d+Au R_I in high z_T
  - Ratio of ^{3}He+Au to d+Au at high z_T (>0.48) is more than 2 sigma below the unity
- Motivations to theorists to determine possible explanations : both Cold and Hot in order to evaluate the likeliness whether it could be consistent with Hot QGP Eloss?

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Implication: Causes?

In other words, results are pretty well studied and now confirmed in ^{3}He+Au – Need Theory Input—Important Question!

- Many potential Trivial or Cold Nuclear Explanations—but also shares qualitative features of Eloss
- "Trivial" explanations we could test:
  - ✓ "Hydro" v3, v1
  - ✓ Trivial Rapidity Distributions Mismatching p+p vs d+Au?
  - ✓ HIJING show anything like this?

None of these could reproduce the effect

- "Cold Nuclear Effects":
  - ✓ Enhanced Nuclear k_T
  - ✓ Initial State nPDF effects (partial—EPS09(s) only checked)
  - Check other npdf's?
  - Get bonafide theory calcs from theorists (need input from theorists)
- Could QGP/Hot Eloss Cause This?
  - Get bonafide theory calcs from theorists (need input from theorists)

Thank you

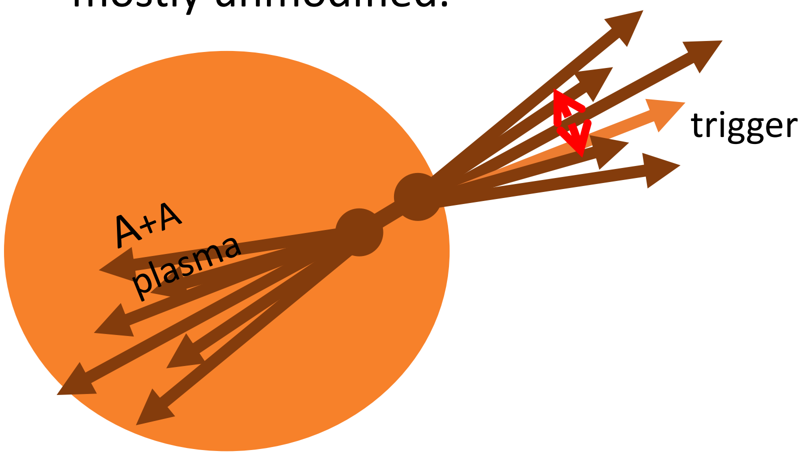
Back up

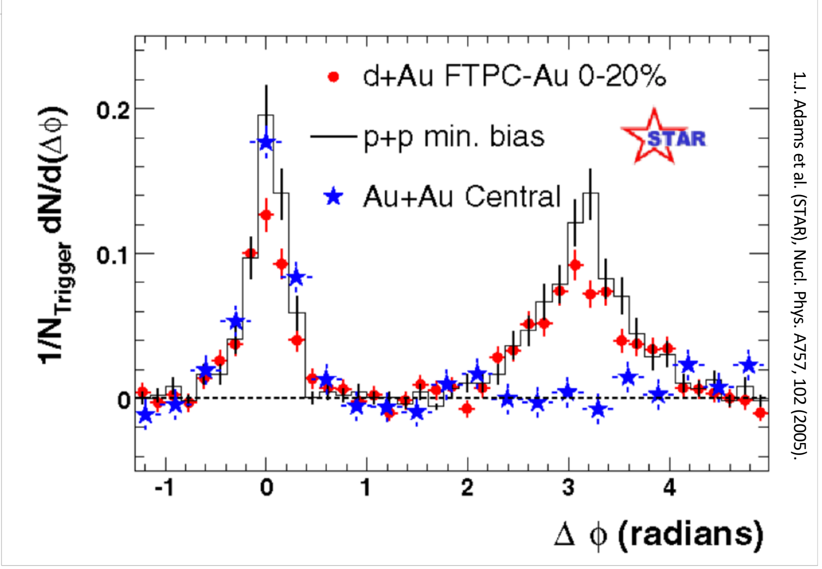
2-Particle Jet Function Basics

Two source model: Same event pair distribution = jet pair distribution + background pairs

$$C(\Delta\phi_{AB}) = J(\Delta\phi_{AB}) + b_0\left[(1 + 2v_2^A v_2^B cos(\Delta\phi_{AB})\right]$$

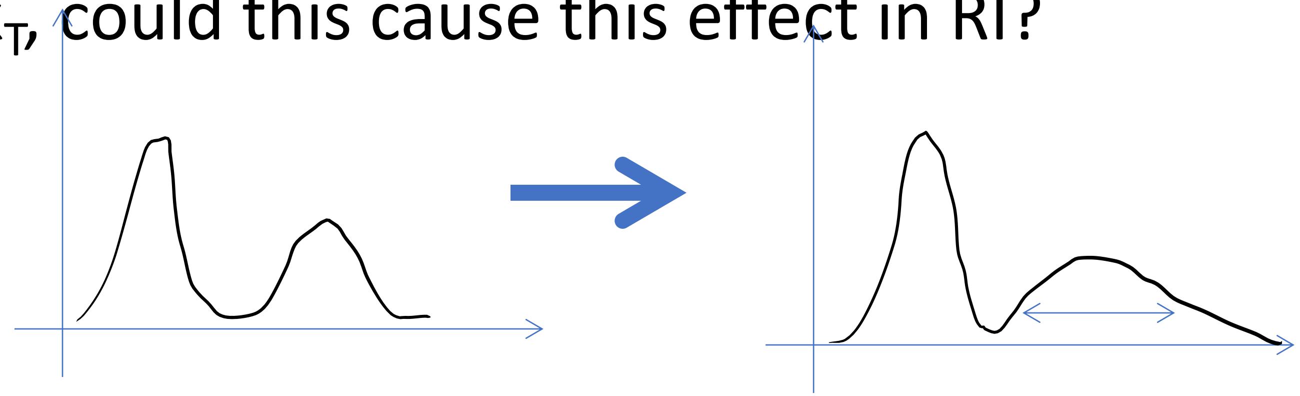
- Because of well-known surface bias picture, near-side in A+A is mostly unmodified.





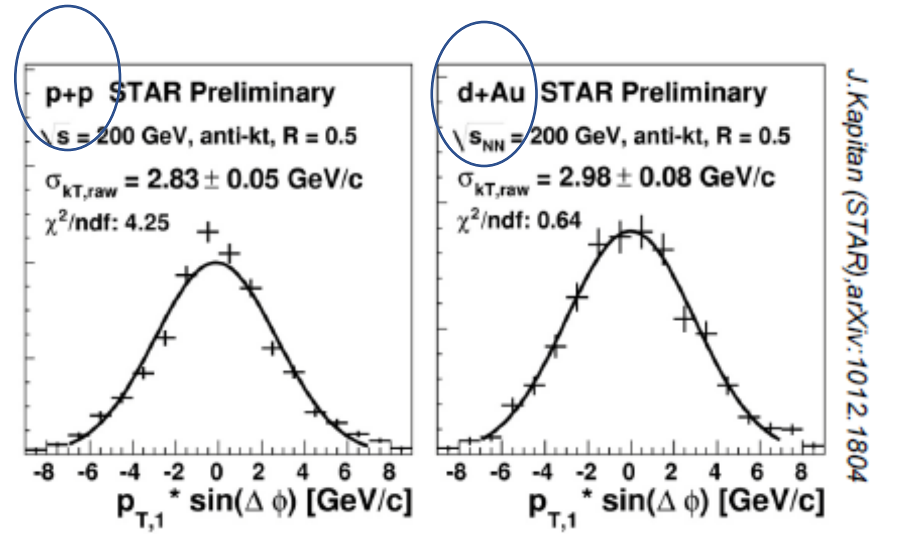
Enhanced Nuclear k_T ?

- kT == Acoplanarity of di-jets
- Smears Awayside → Known part of the 2pc AS width
- If d+Au had long sought after enhanced nuclear k_T, could this cause this effect in RI?

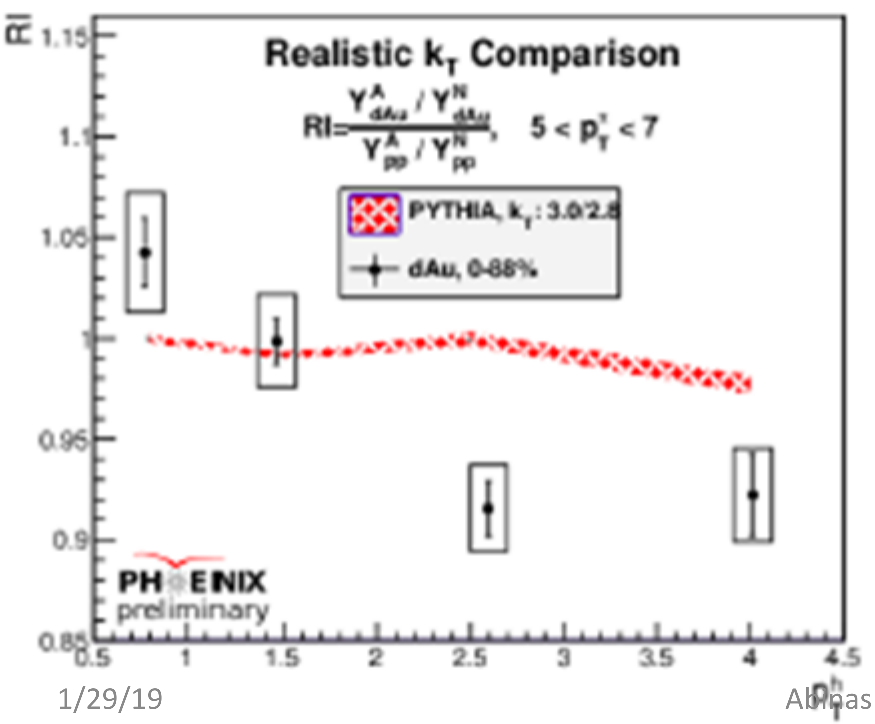


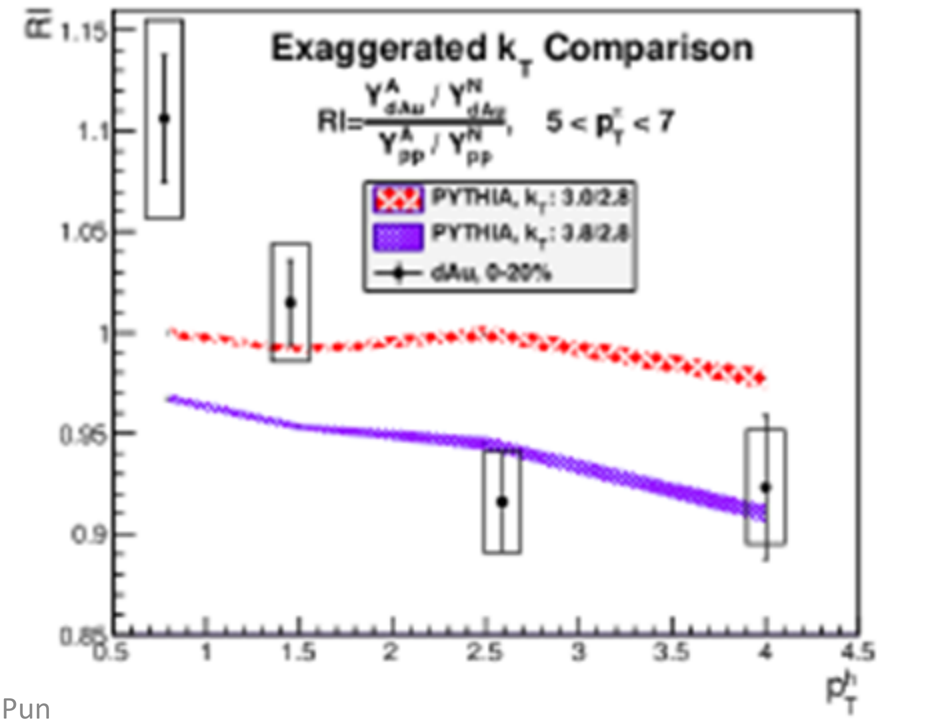
PYTHIA Nucl k_T Test

- Using k_T constraints from STAR jet measurements → No effect for 0-100% Minbias
- However, k_T smear larger in Central?



Using STAR k_T Increase (Minbias)





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“Trivial” Causes?

- Strategy: address all “trivial” explanations we can test:

- ~~“Hydro” v3, v1~~
- ~~Enhanced Nuclear k_T~~
- Initial State nPDF effects
- Trivial Rapidity Distributions Mismatching p+p vs d+Au?
- HIJING show anything like this?

- If none of above → INTERESTING
  - Looking for other ideas?

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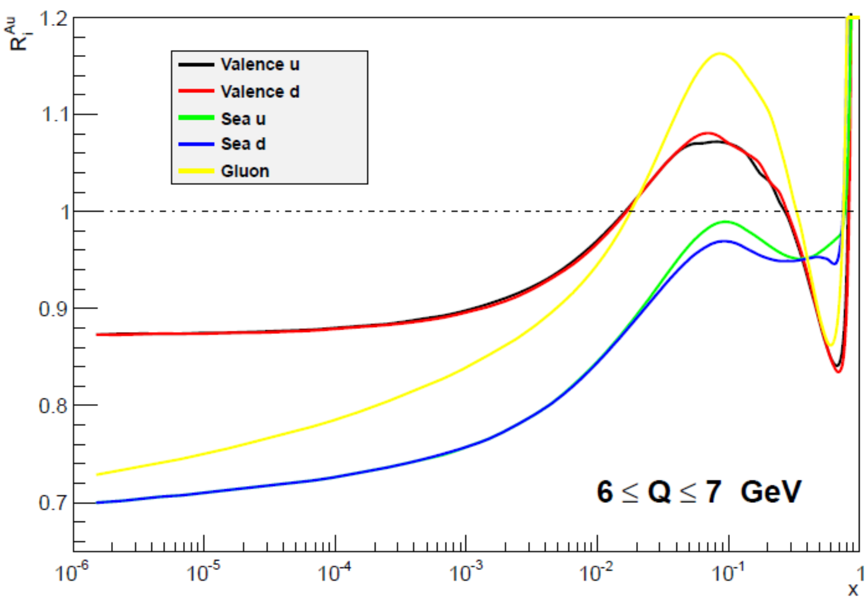
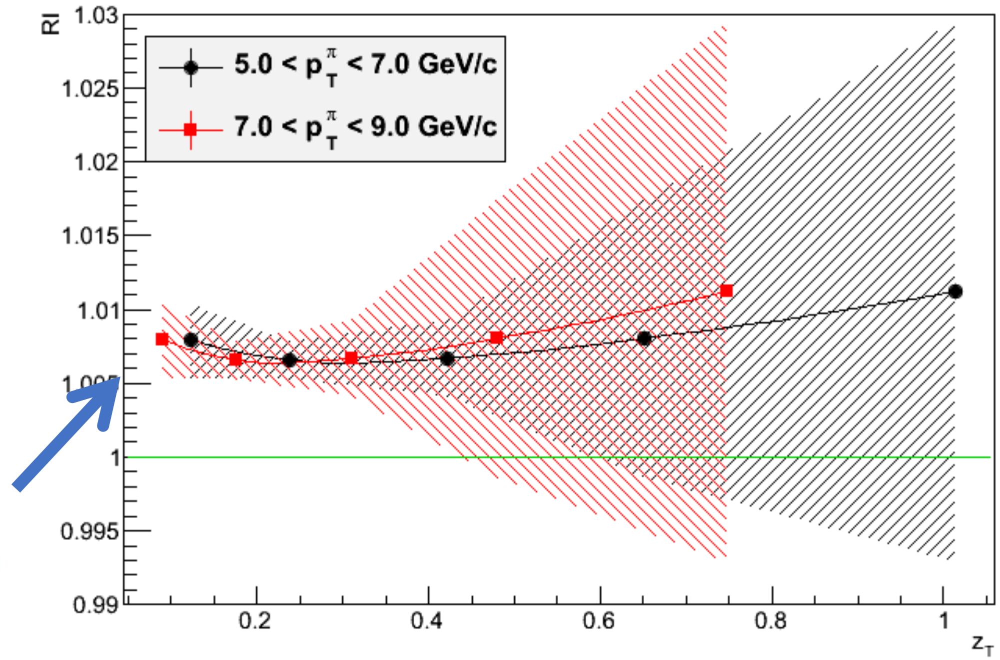
Initial State Nuclear PDF's?

- nPDF effects would seem unlikely to cause this, since they probably often affect *both* jets in a di-jet
- Studies with EPS09 (and 09s) confirm this expectation
  - NOTE UNITS: << 1% negligible effect

nPDF extracted from EPS09 code



RI Extracted from EPS09 Study



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“Trivial” Causes?

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- ~~Enhanced Nuclear k_T~~
- ~~Initial State nPDF~~ effects
- Trivial Rapidity Distributions Mismatching p+p vs d+Au?
- HIJING show anything like this?

- If none of above → INTERESTING
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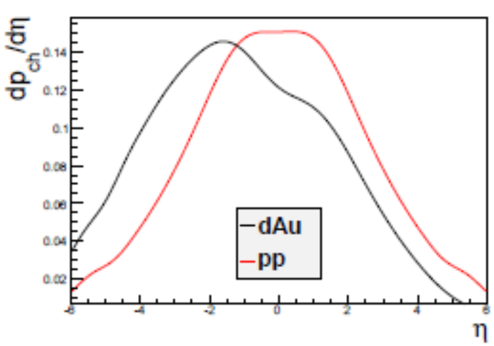
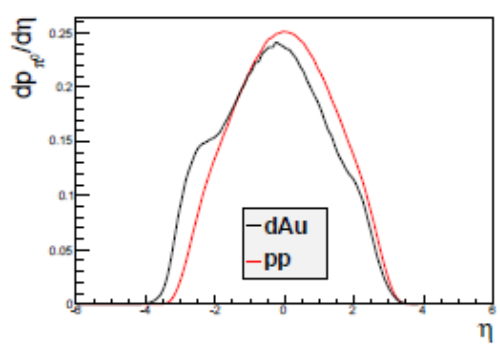
HIJING

- We ran HIJING with default settings
- First, this can test for ***very*** trivial effects e.g. due to the 2p method and to the mismatch in rapidity distributions
- More importantly any other “cold” nuclear physics embedded in HIJING (mini-jets, momentum conservation (?), etc…)



(a) Charged hadrons in central HIJING

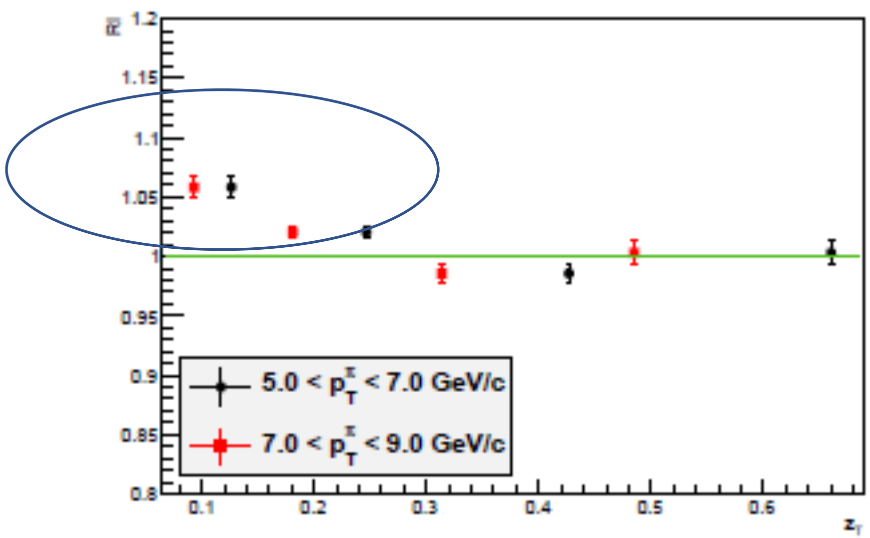


(b) π^0 triggers in central HIJING

HIJING RI

- With default settings, HIJING does not reproduce the effect
- Small enhancement at low z_T appears to be due to default nuclear k_T in HIJING consistent with PYTHIA study

RI from HIJING simulation with $k_T = 0.44$ GeV/c.



Au+Au's Back up

Illustration of v_2 Measurement With Isolation Cone

- Underlying event shape

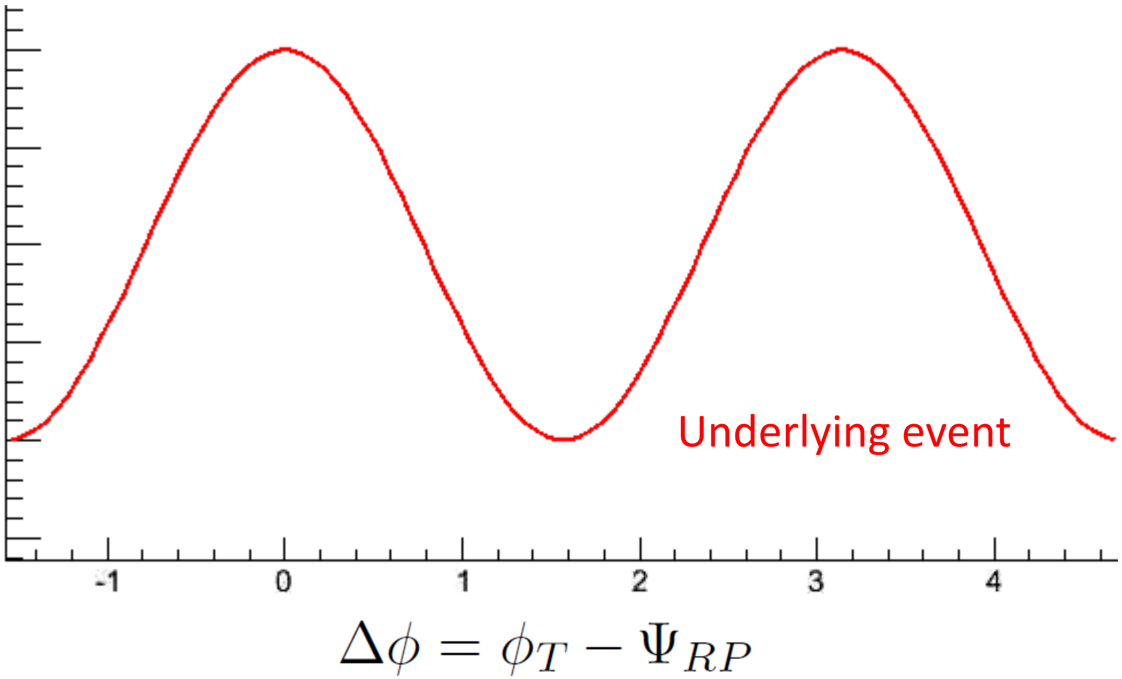


Illustration of v_2 Measurement With Isolation Cone

- Underlying event shape
- Isolation cone

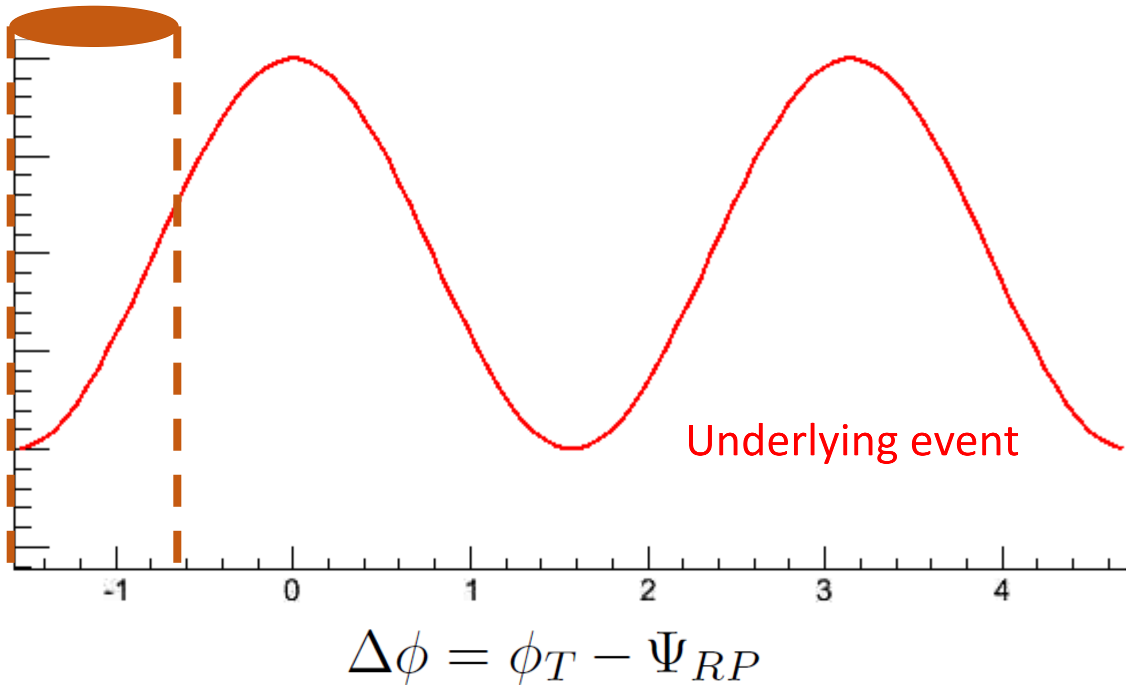


Illustration of v_2 Measurement With Isolation Cone

- Underlying event shape
- Isolation cone
- Accept more particles when number of underlying event particles is low

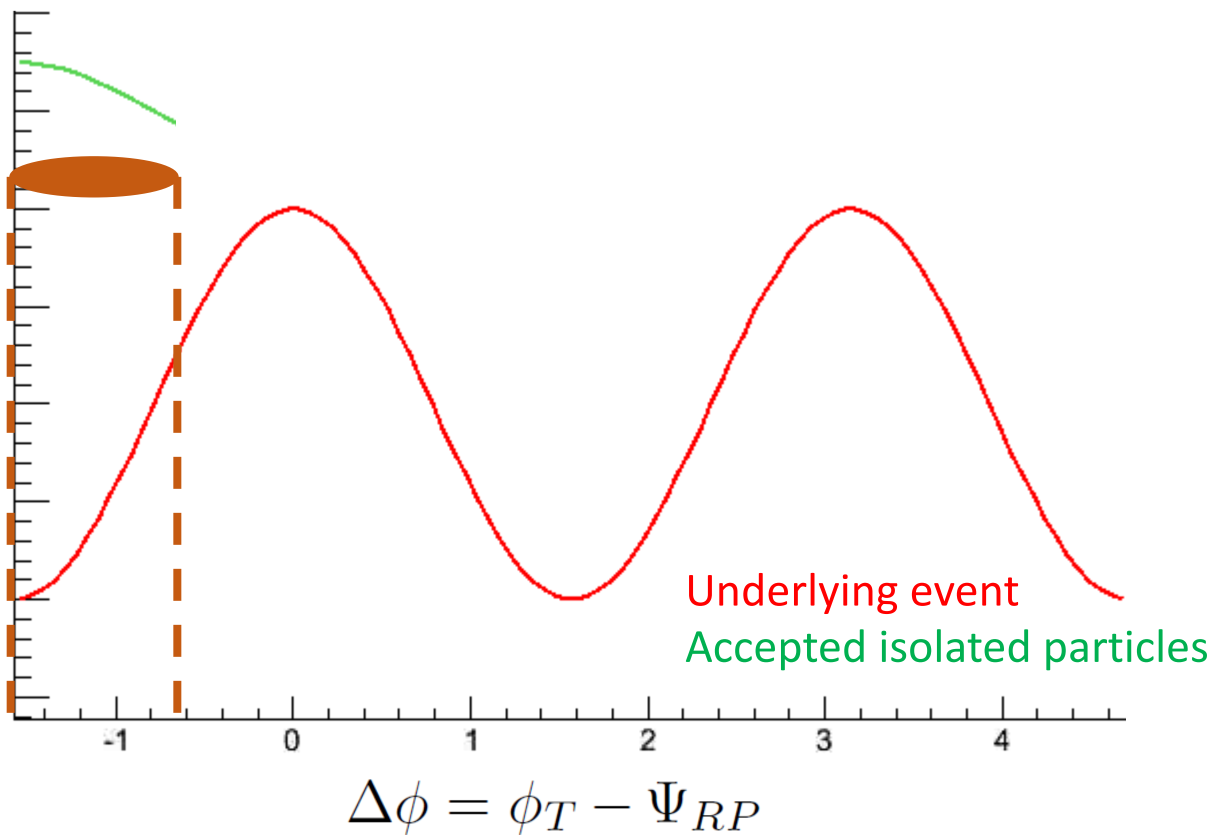
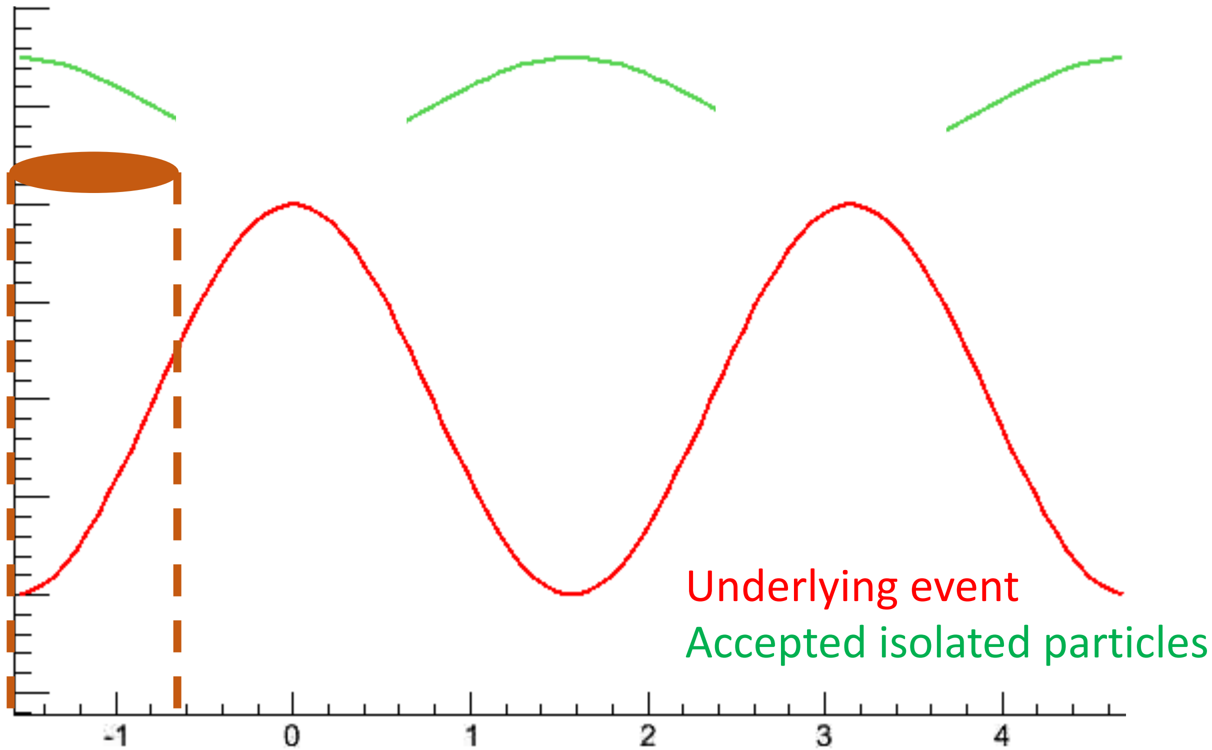


Illustration of v_2 Measurement With Isolation Cone

- Underlying event shape
- Isolation cone
- Accept more particles when number of underlying event particles is low (out of event plane)



$$\Delta\phi = \phi_T - \Psi_{RP}$$

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Illustration of v_2 Measurement With Isolation Cone

- Underlying event shape
- Isolation cone
- Accept less particles when number of underlying event particles is high

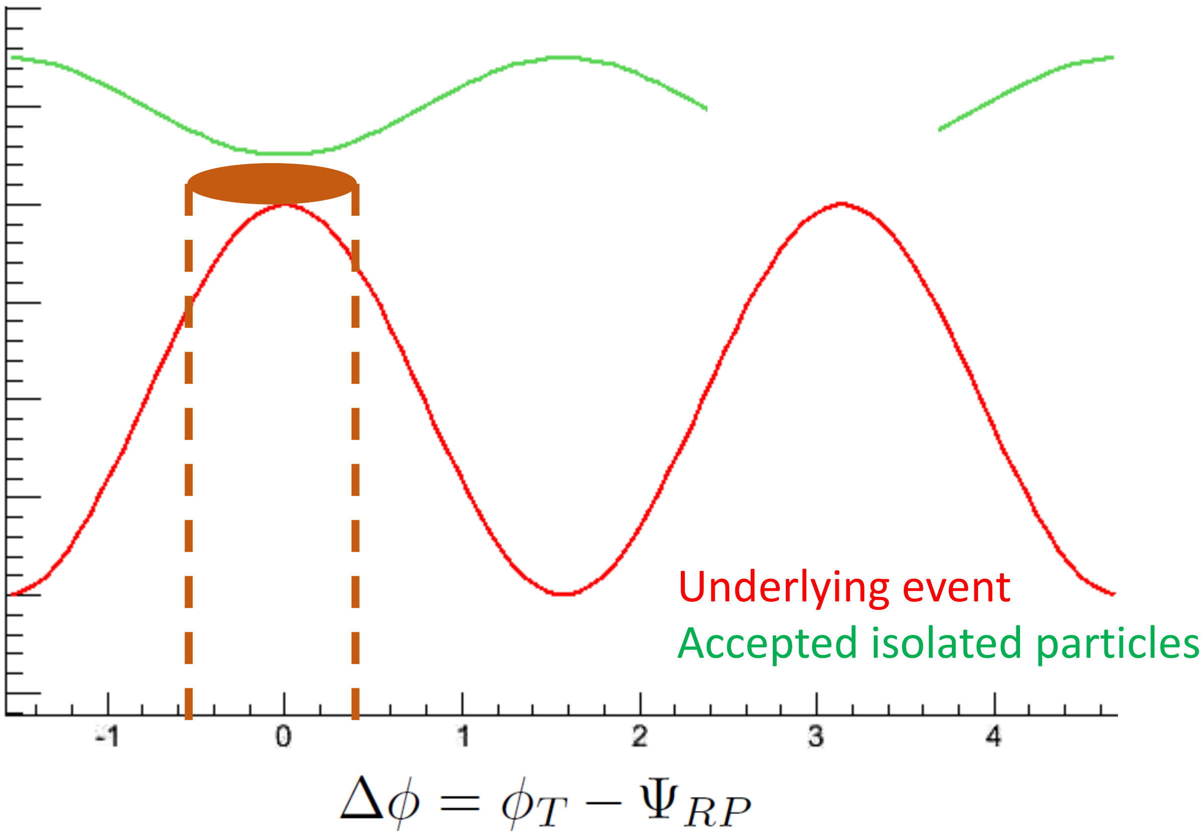
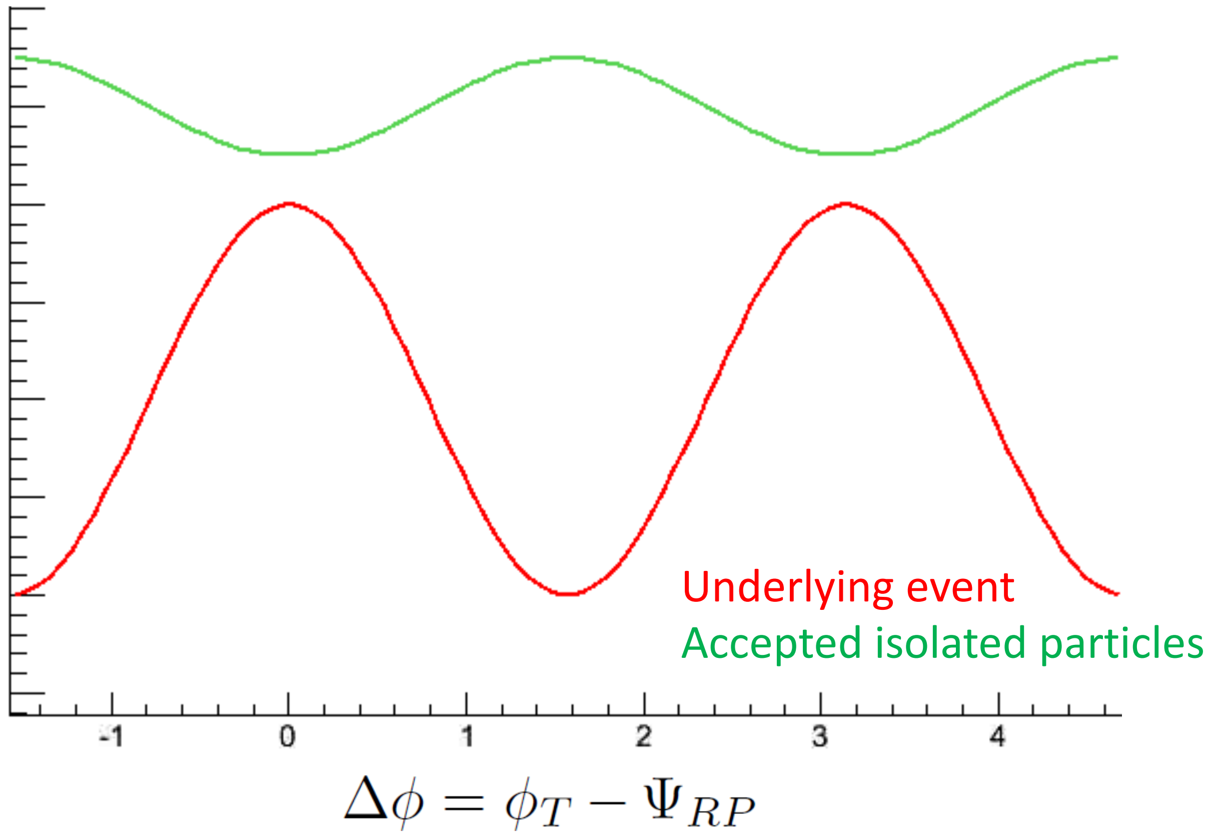


Illustration of v_2 Measurement With Isolation Cone

- Underlying event shape
- Isolation cone
- Accept less particles when number of underlying event particles is high (in event plane)
- Must correct for this bias.



Complications of v_2 Measurement with Isolation Cut

- Isolation cut efficiency

$$\epsilon = \epsilon_0 \big(1 + 2v_{2E}\cos(2\Delta\phi)\big) \qquad \Delta\phi = \phi_T - \Psi_{RP}$$

- How does it effect the trigger particle's distribution?

$$\frac{dN_{TE}}{d\Delta\phi} = \mathcal{A}\big(1 + 2\mathcal{B}\cos(2\Delta\phi) + 4\mathcal{C}\cos^2(2\Delta\phi)\big)$$

$$\mathcal{B} = v_{2T} + v_{2E}$$
$$\mathcal{C} = v_{2T}v_{2E}.$$

- How does the event plane resolution effect this distribution?

$$\frac{dN_{STSE}}{d\Delta\phi} = \mathcal{I}\left(1 + 2\mathcal{J}\cos(2\Delta\phi) + \mathcal{K}\cos^2(2\Delta\phi) - 4\mathcal{L}\cos(4\Delta\phi)\right)$$

$$\mathcal{J} = (v_{2T} + v_{2E})\langle\cos(2\delta\Psi)\rangle,$$
$$\mathcal{K} = v_{2T}v_{2E}, \quad \text{and}$$
$$\mathcal{L} \propto v_{2T}v_{2E}.$$

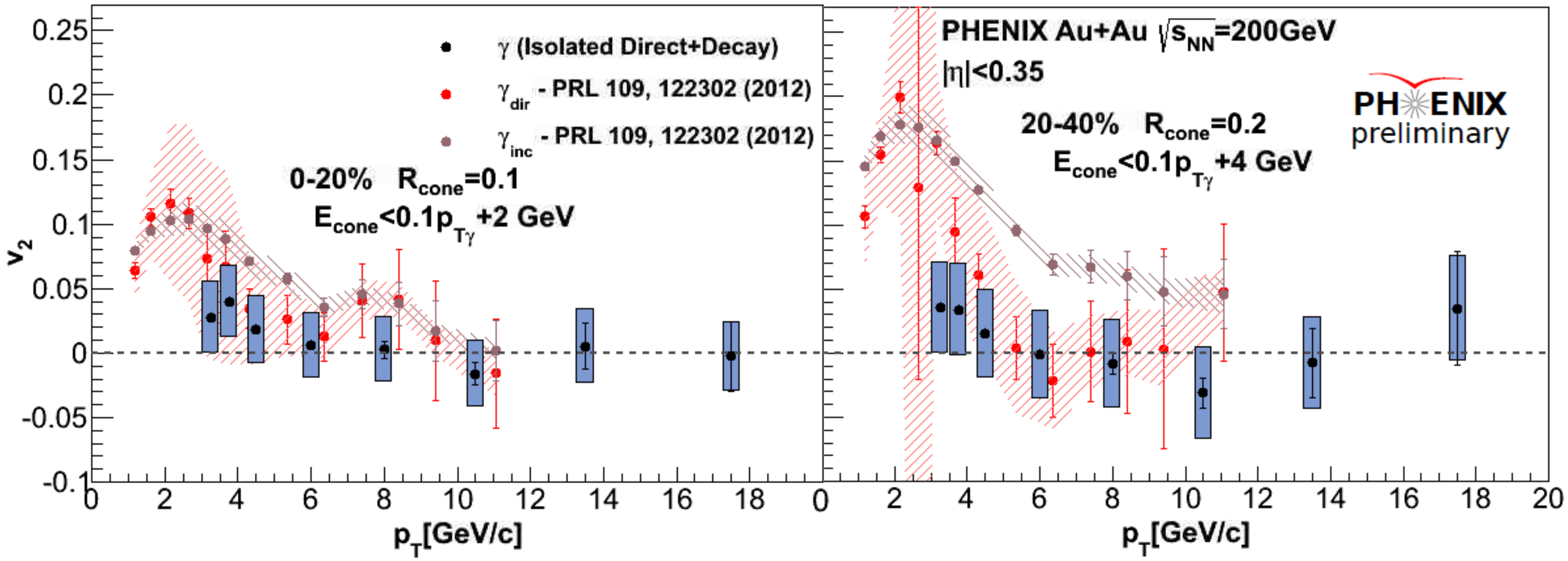
- How does it effect the correlation function background distribution?

$$\frac{dN_{TA}}{d\Delta\phi} = \mathcal{F}\big(\mathcal{G} + 2\ \mathcal{H}\ \cos(2\Delta\phi_{TA})\big)$$
$$\Delta\phi_{TA} = \phi_T - \phi_A$$

$$\mathcal{G} = 1 + 2v_{2T}v_{2E},$$
$$\mathcal{H} = v_{2A}\big(v_{2T} + v_{2E}\big)$$

- For 2 particle correlations, only need sum $v_{2iso} = v_{2T} + v_{2E}$ which is what is ~directly measured from isolated triggers using 'typical' event plane method
- These equations have been verified using toy MC simulation

Measuring v_2 of Isolated Photons



- Inclusive photon v_2 is large and not consistent with 0 for most p_T
- Isolation cut reduces the v_2 to be more comparable to the direct photon v_2
- Some decay photons survive isolation cut
  - No decay photon subtraction here
- This v_2 is subtracted from γ_{iso}-h correlation functions