Jet, Di-jet, and γ-jet Probes in PHENIX

Michael P. McCumber
(University of Colorado)
for the PHENIX Collaboration

INT: Quantifying the Properties of Hot QCD Matter
27 May 2010

Jet, Di-Jet, and γ-jet Probes in PHENIX

Can we catch energy loss
in the act?

Topics this morning:

(Conditional) Spectra modification

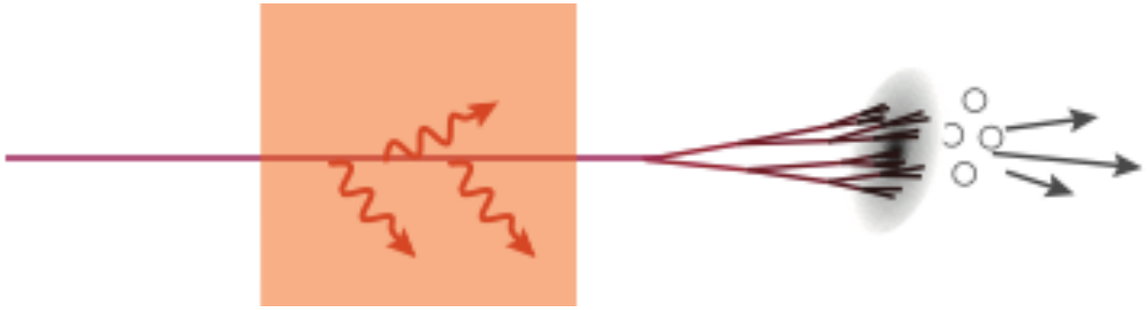
Jet broadening

Fragmentation Function modification

Jet, Di-Jet, and γ-jet Probes in PHENIX

Can we catch energy loss **in the act**?

Experimental signature of partial energy loss



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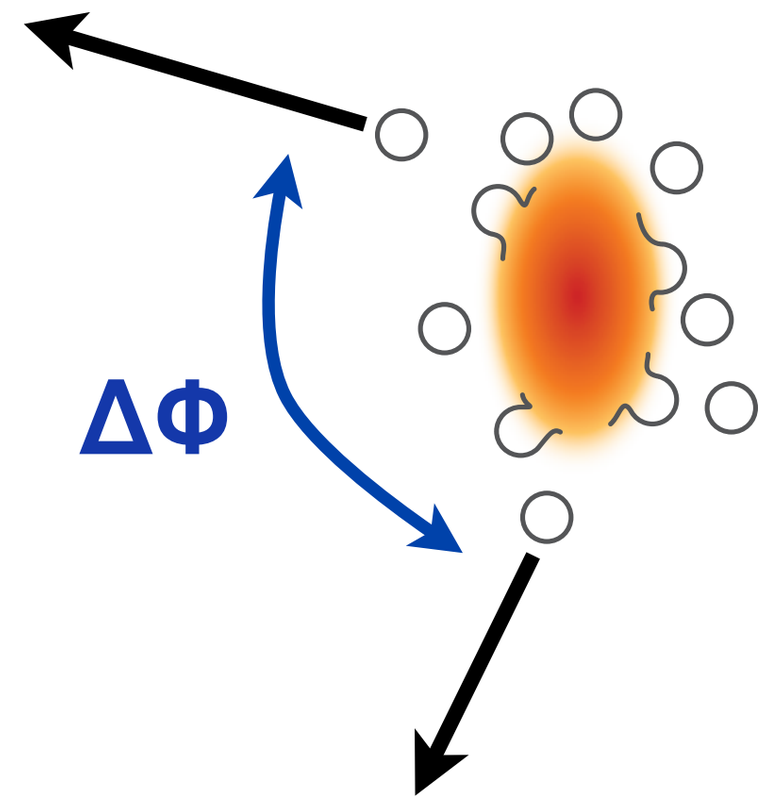
Medium Response?

Is “medium response” actually related to energy loss?

Correlations between lower p_T ($\lesssim$4 GeV/c) particles



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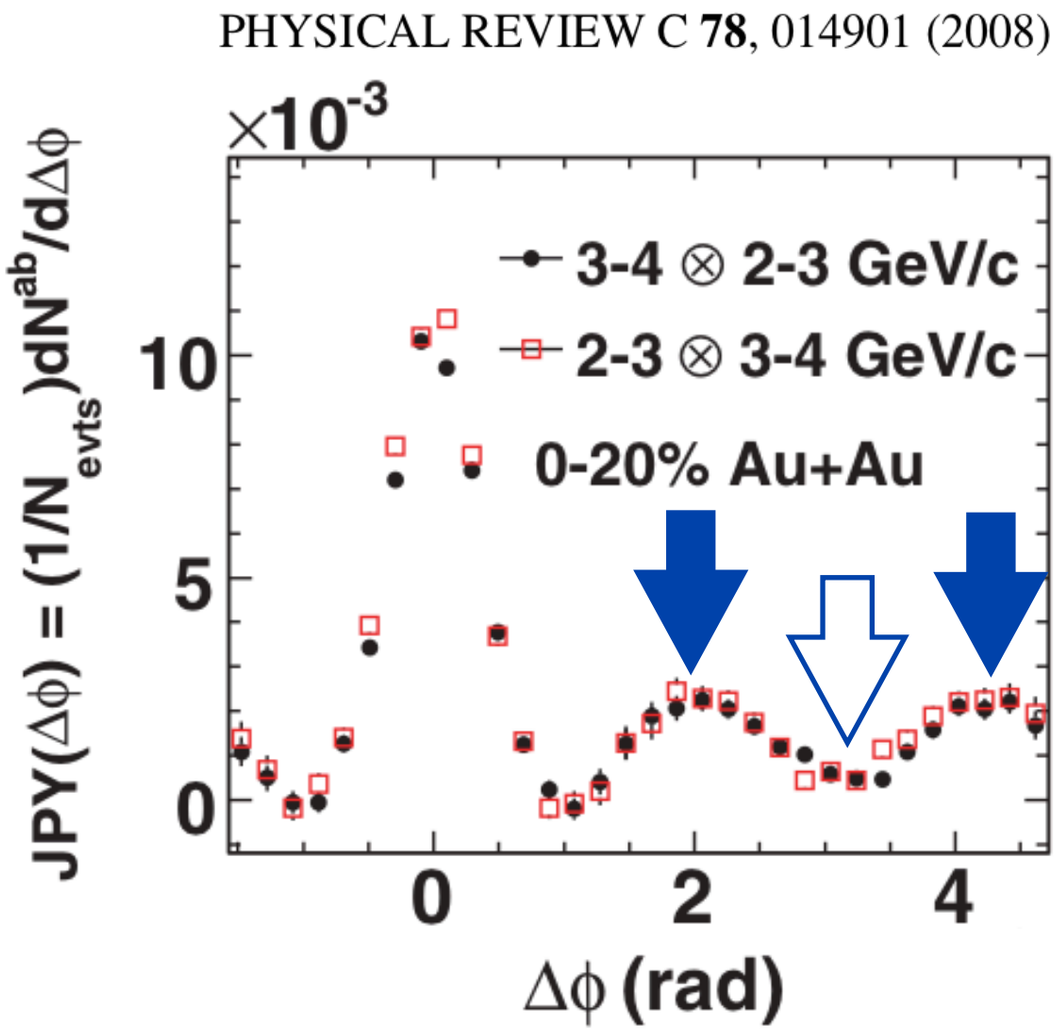
Away-side “shoulder”



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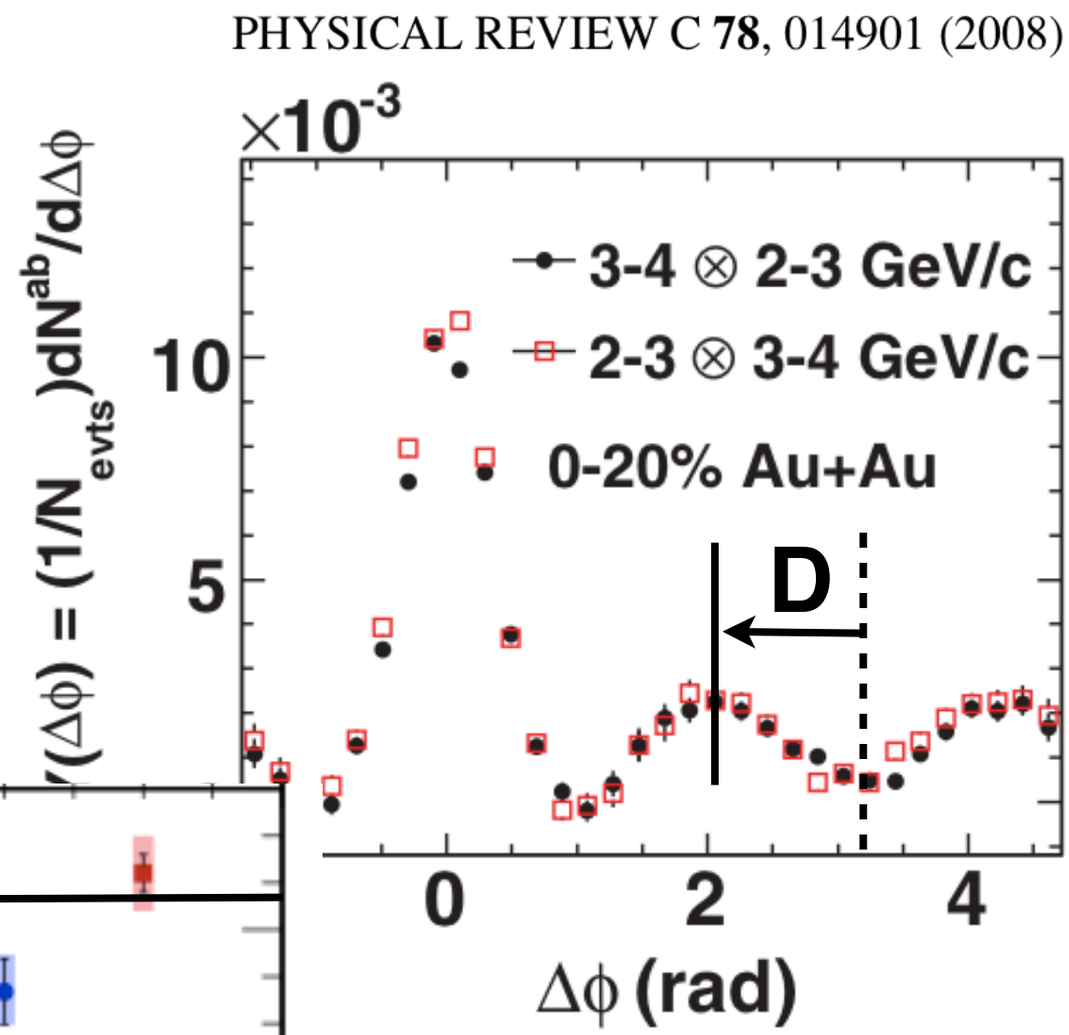

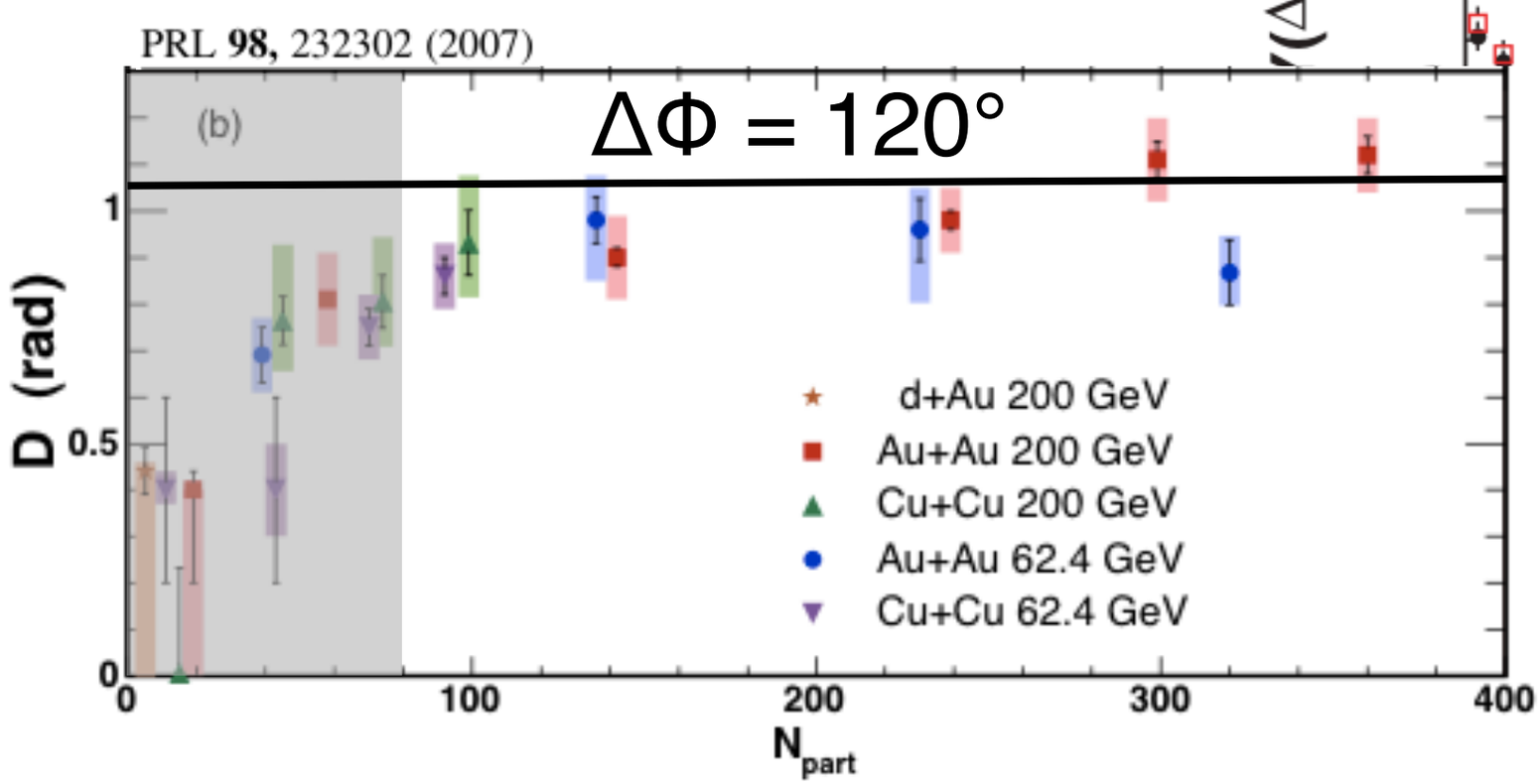

Medium Response?

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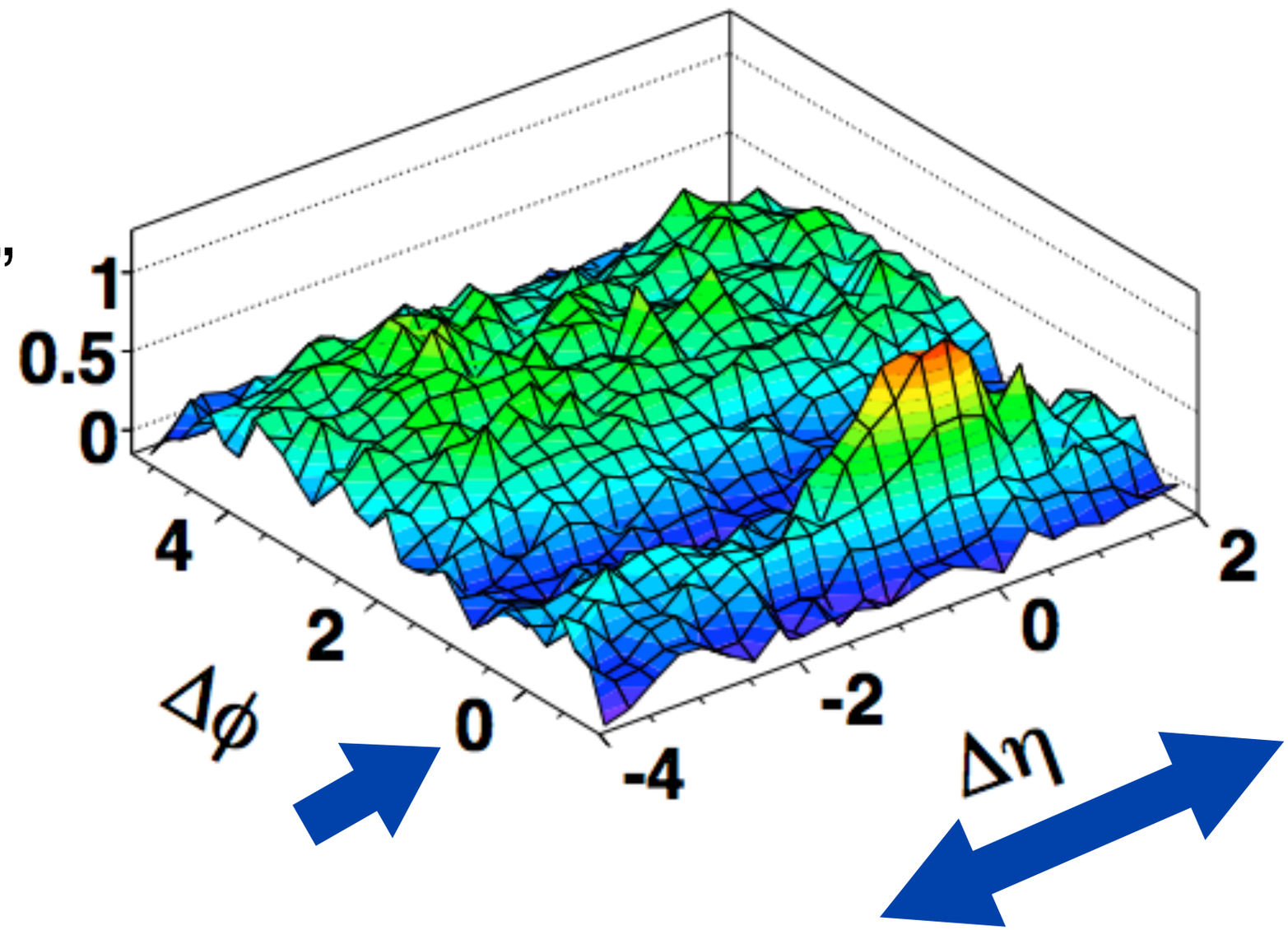
Correlations between lower p_T (≲4 GeV/c) particles

Away-side “shoulder”

Near-side “ridge”

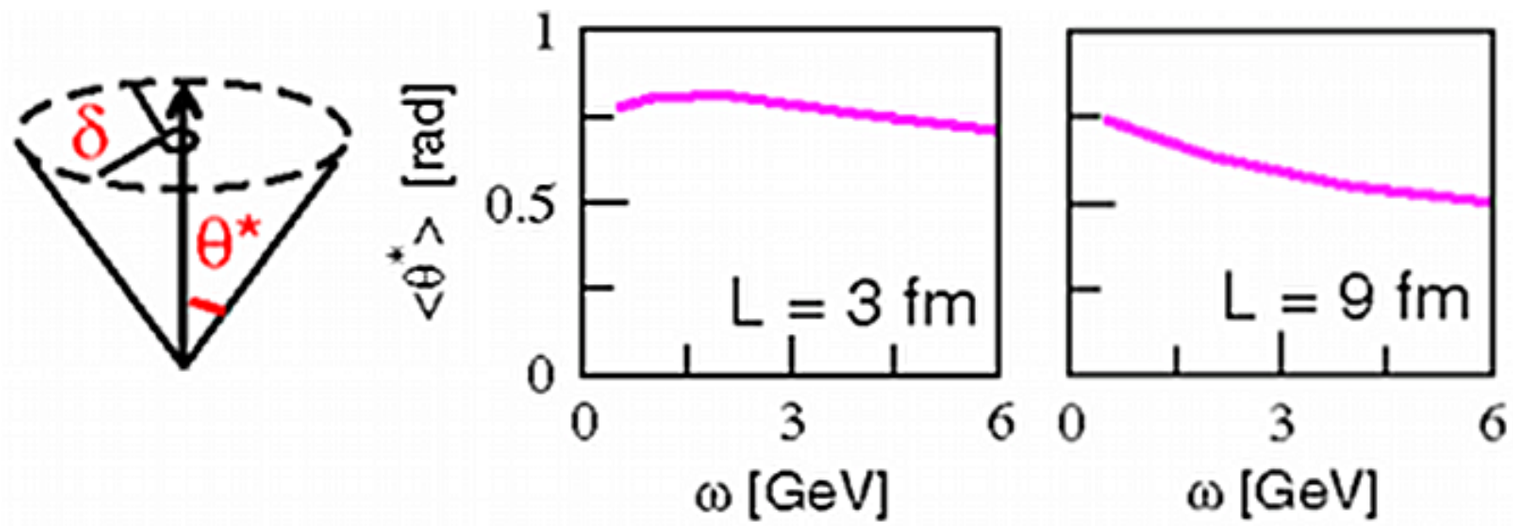
B. Alver, et al, (PHOBOS) Phys.Rev.Lett.104:062301,2010



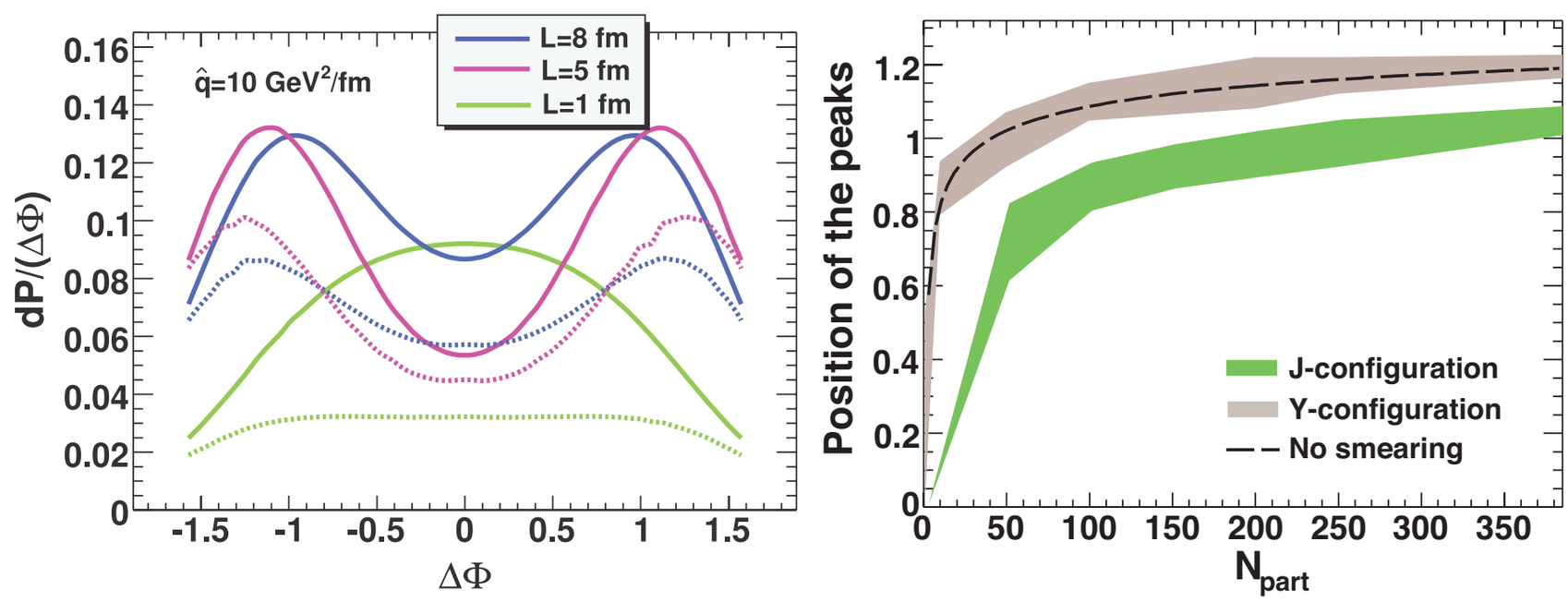
Medium Response?

Large Angle Radiation

Large angle hadron correlations from medium-induced gluon radiation, Vitev, Phys. Lett. B 630, 78 (2005)



Jet shapes in opaque media, Polosa & Salgado, PRC 75, 041901(R) (2007)

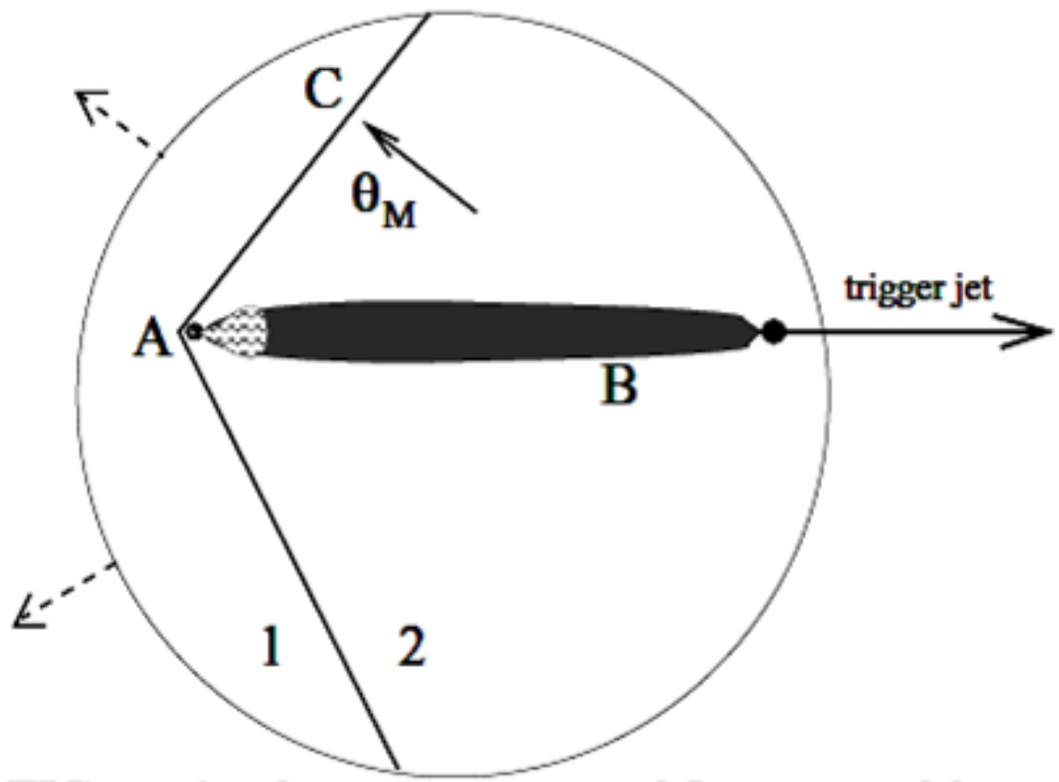


Medium Response?

Mach Cones

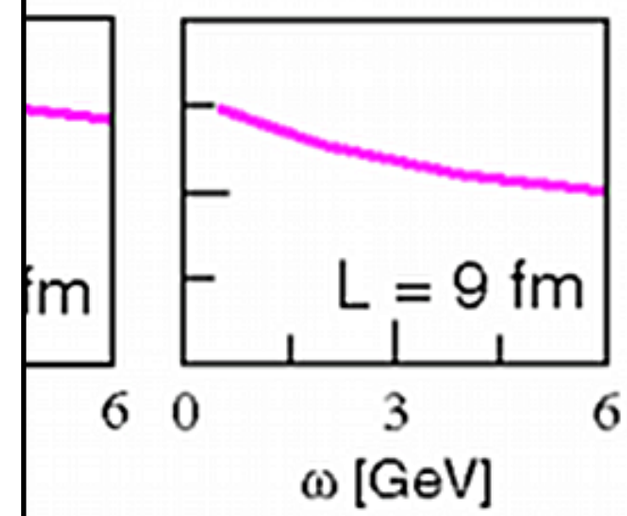
Hydrodynamic Flow from Fast Particles

J. Casalderrey-Solana, E. V. Shuryak, D. Teaney



adiation

edium-induced gluon radiation,
0, 78 (2005)



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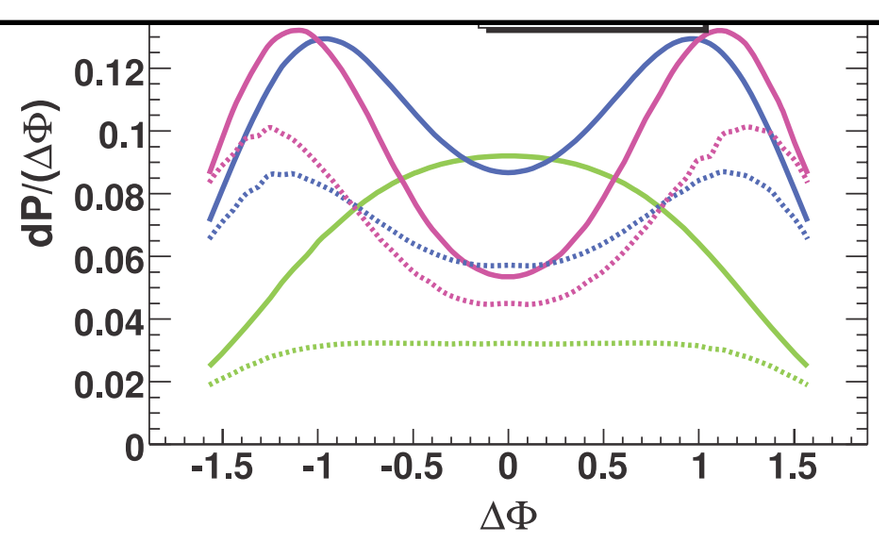

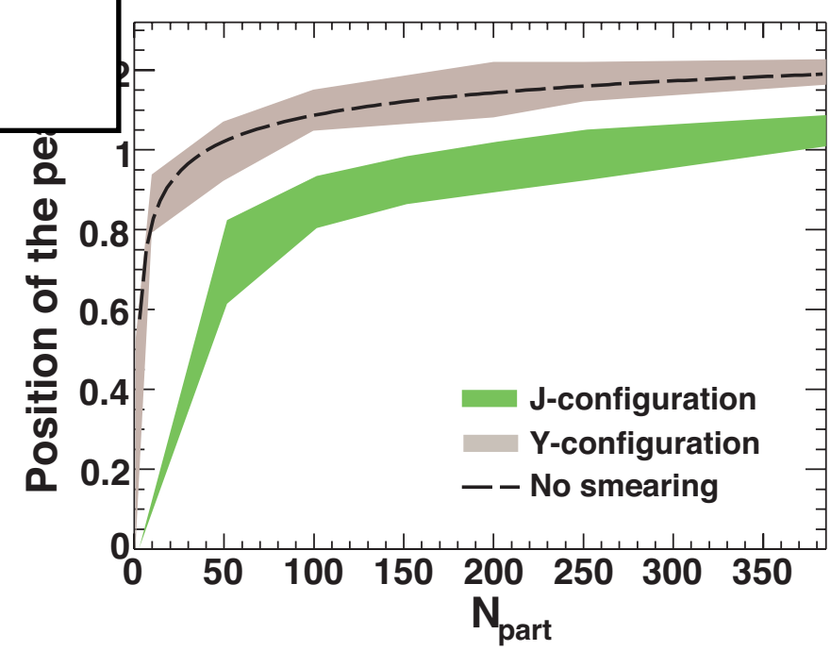

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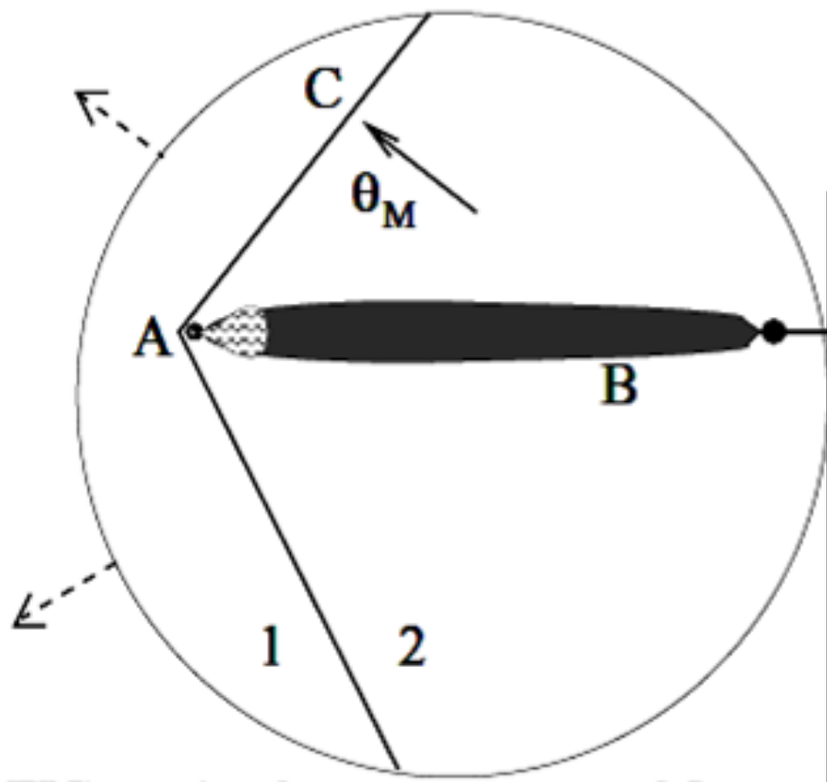

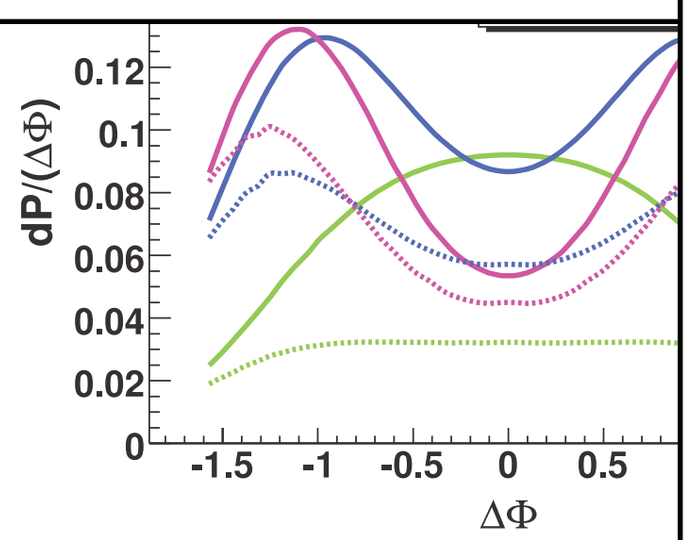

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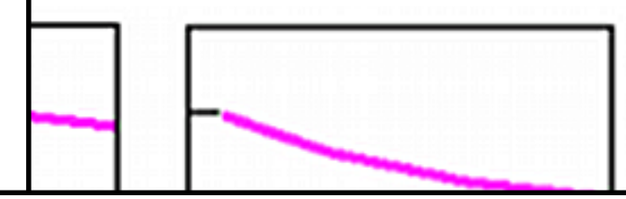
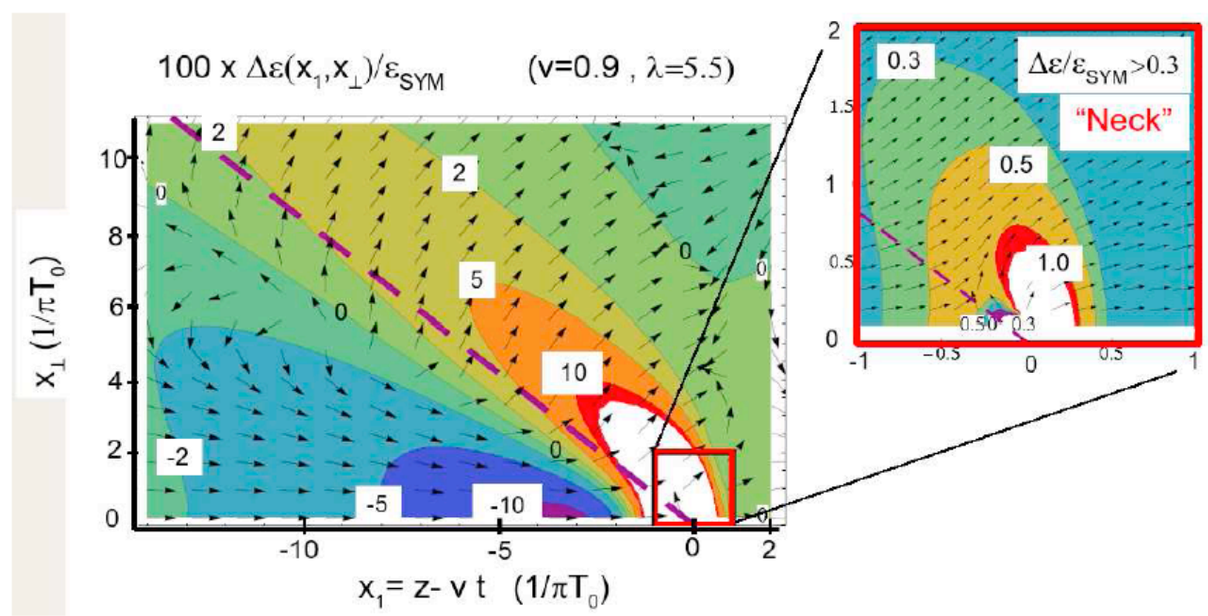


Non-Equilibrium Effects

MACH CONES IN HEAVY ION COLLISIONS*

Giorgio Torrieri, Barbara Betz
Jorge Noronha, Miklos Gyulassy



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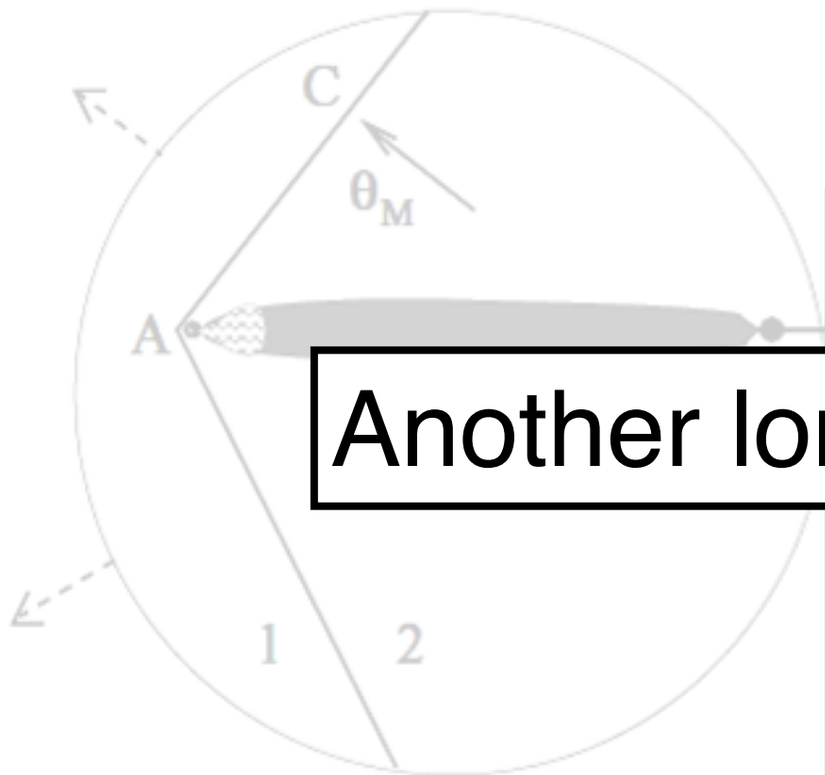

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Parton-Medium Coupling

COLLISIONS*

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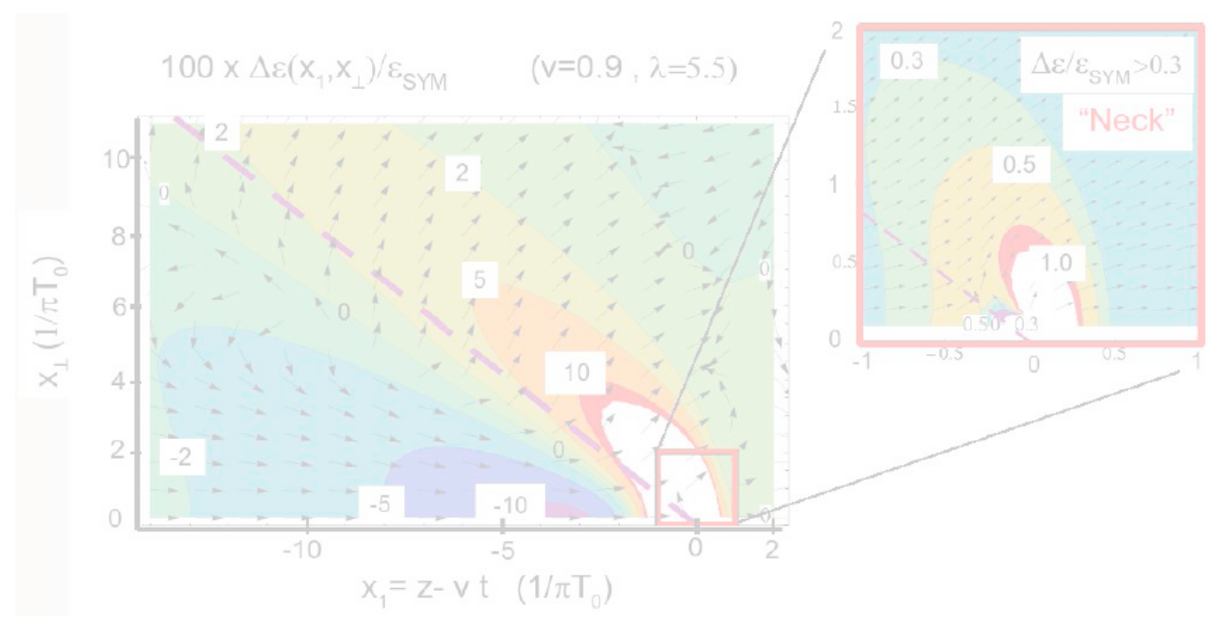


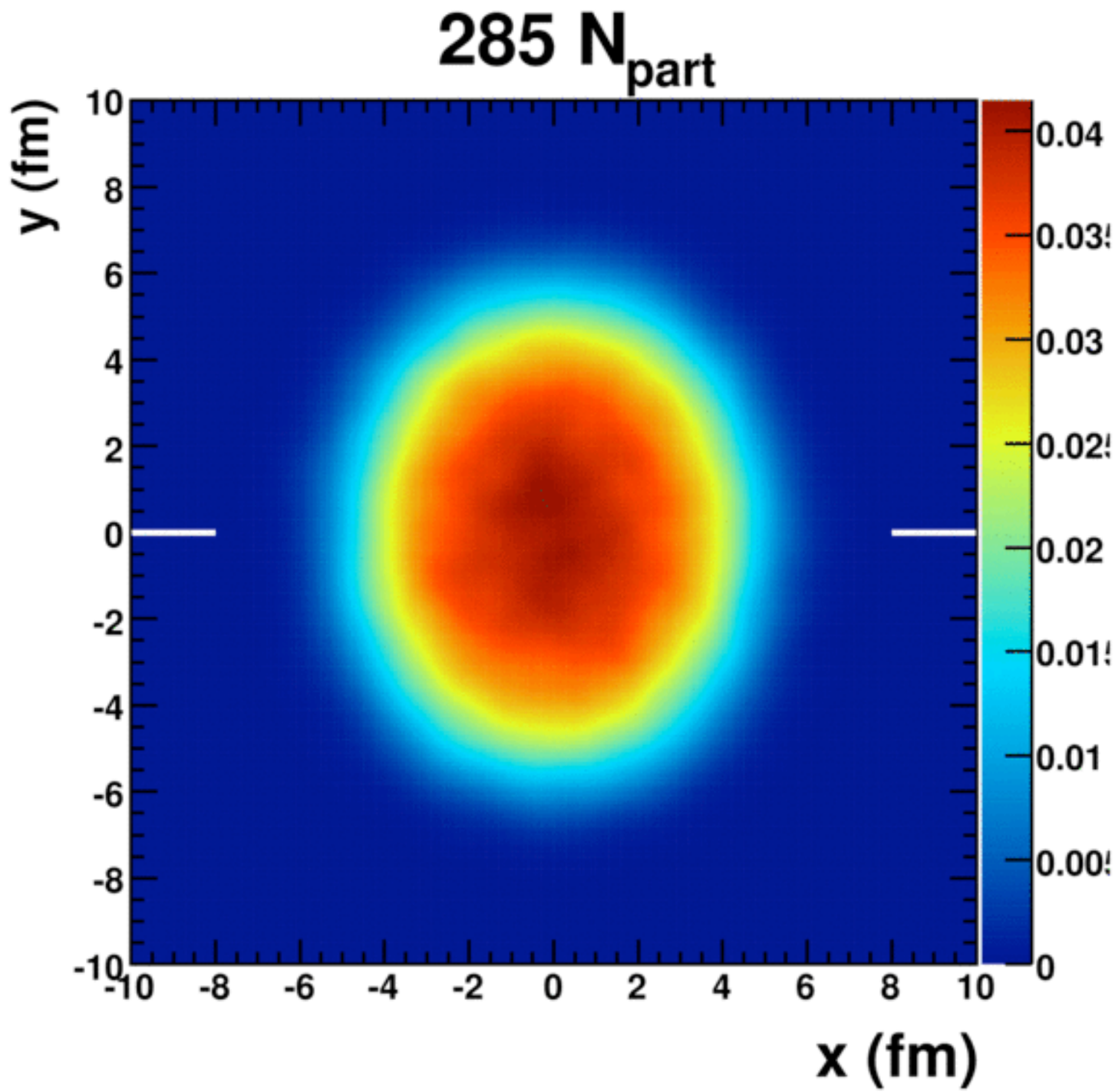
Another long list for the "ridge"

Or Triangular Flow?

Is “medium response” actually related to energy loss?

The canonical initial condition for nucleus-nucleus collisions

“the almond”

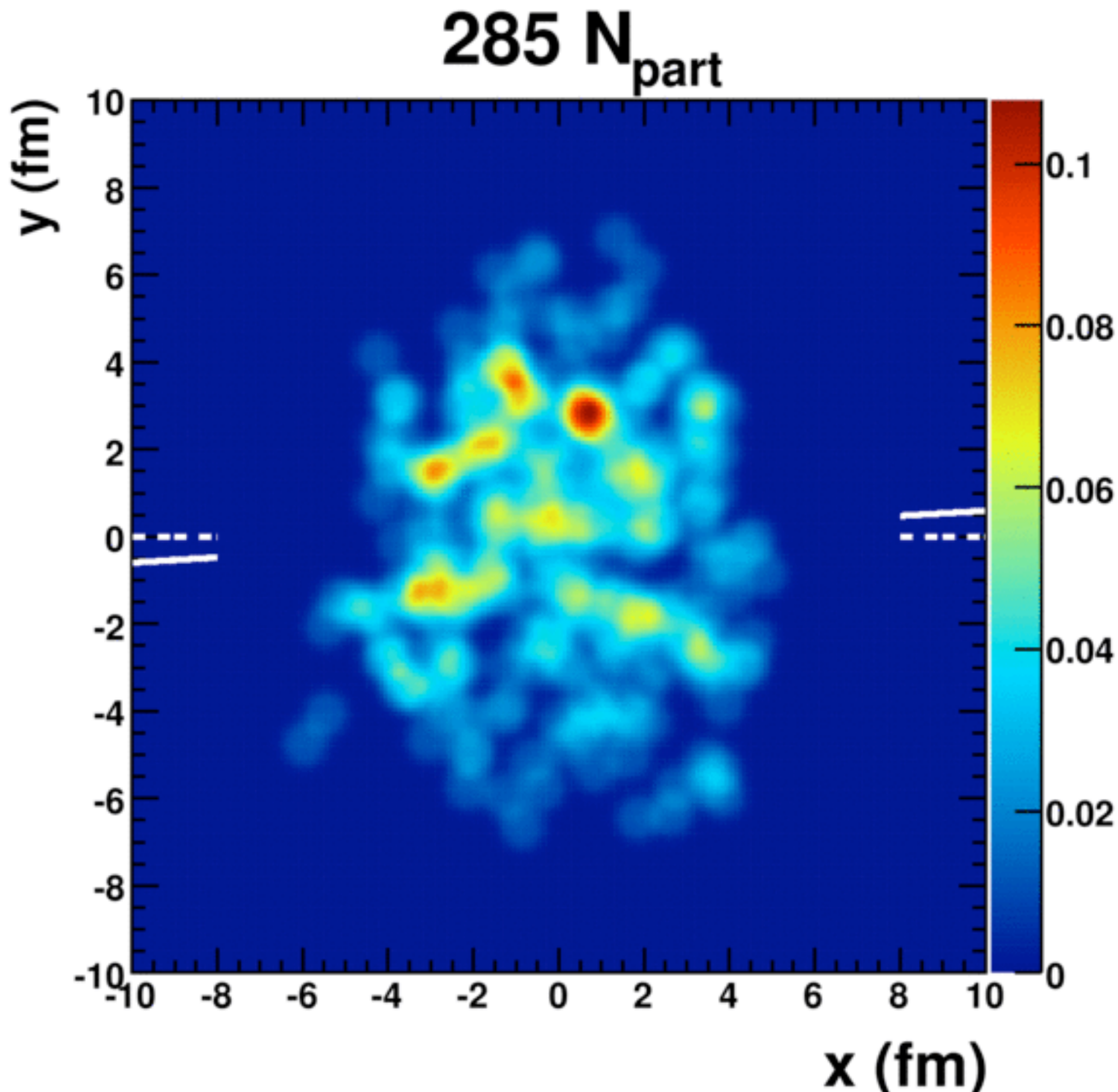


1000 event average

Or Triangular Flow?

Is “medium response” actually related to energy loss?

Real collisions start from lumpy initial conditions and break symmetry



a single event

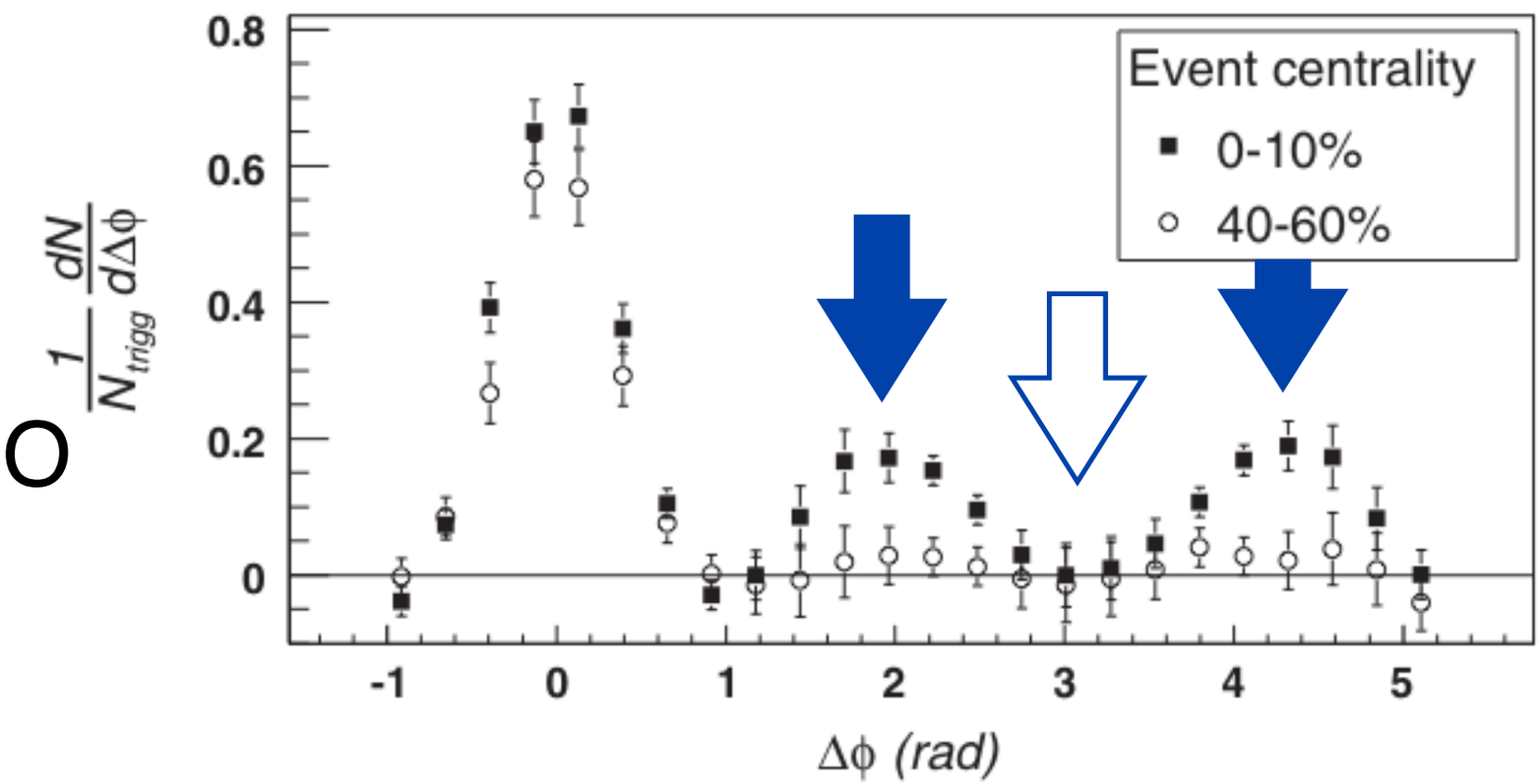
Or Triangular Flow?

Is “medium response” actually related to energy loss?

Real collisions start from lumpy initial conditions and break symmetry

through NEXSPHERIO hydrodynamics

Takahashi, et.al. PRL **103,** 242301 (2009)



No parton-medium coupling required

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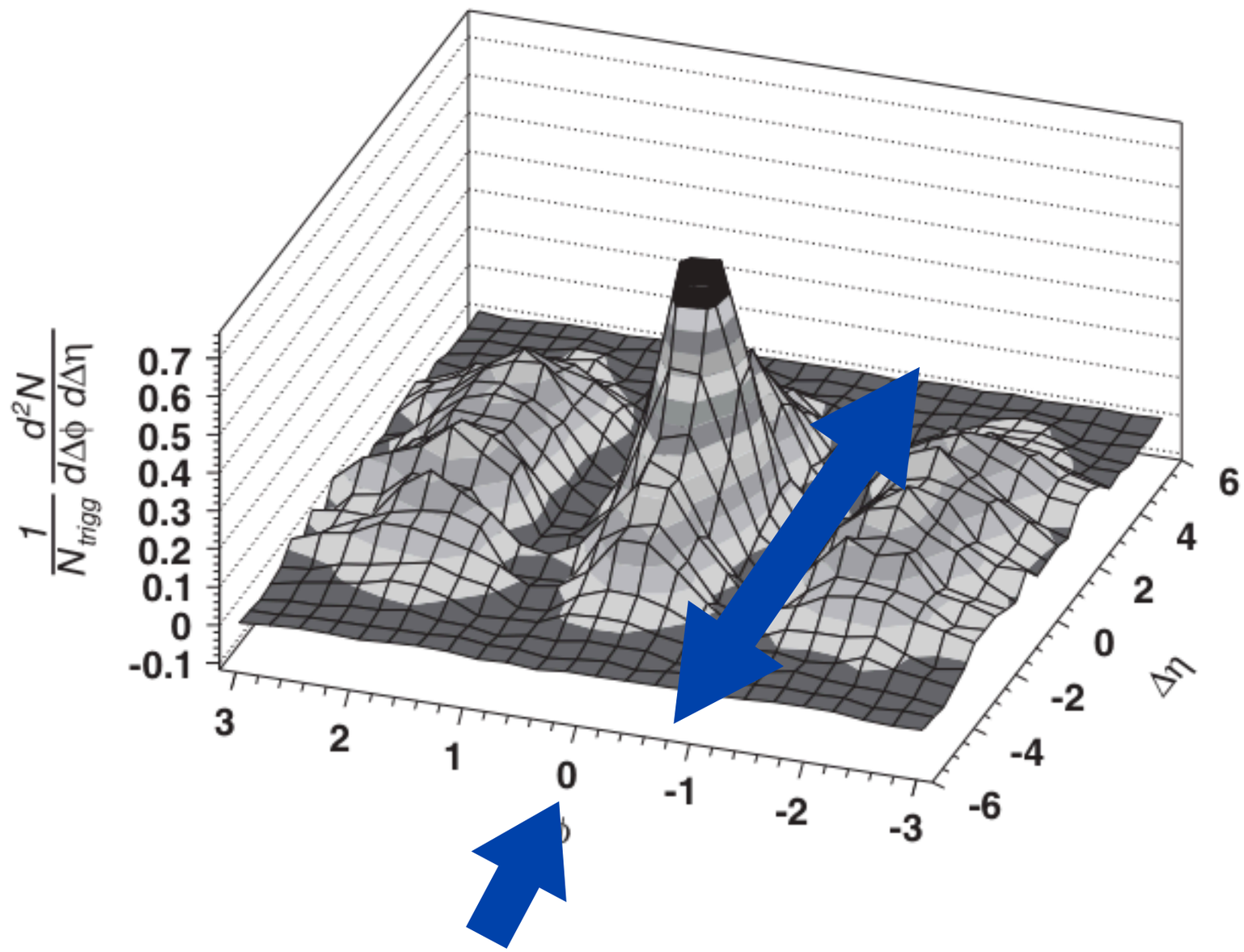

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Could explain both “ridge” and “shoulder”

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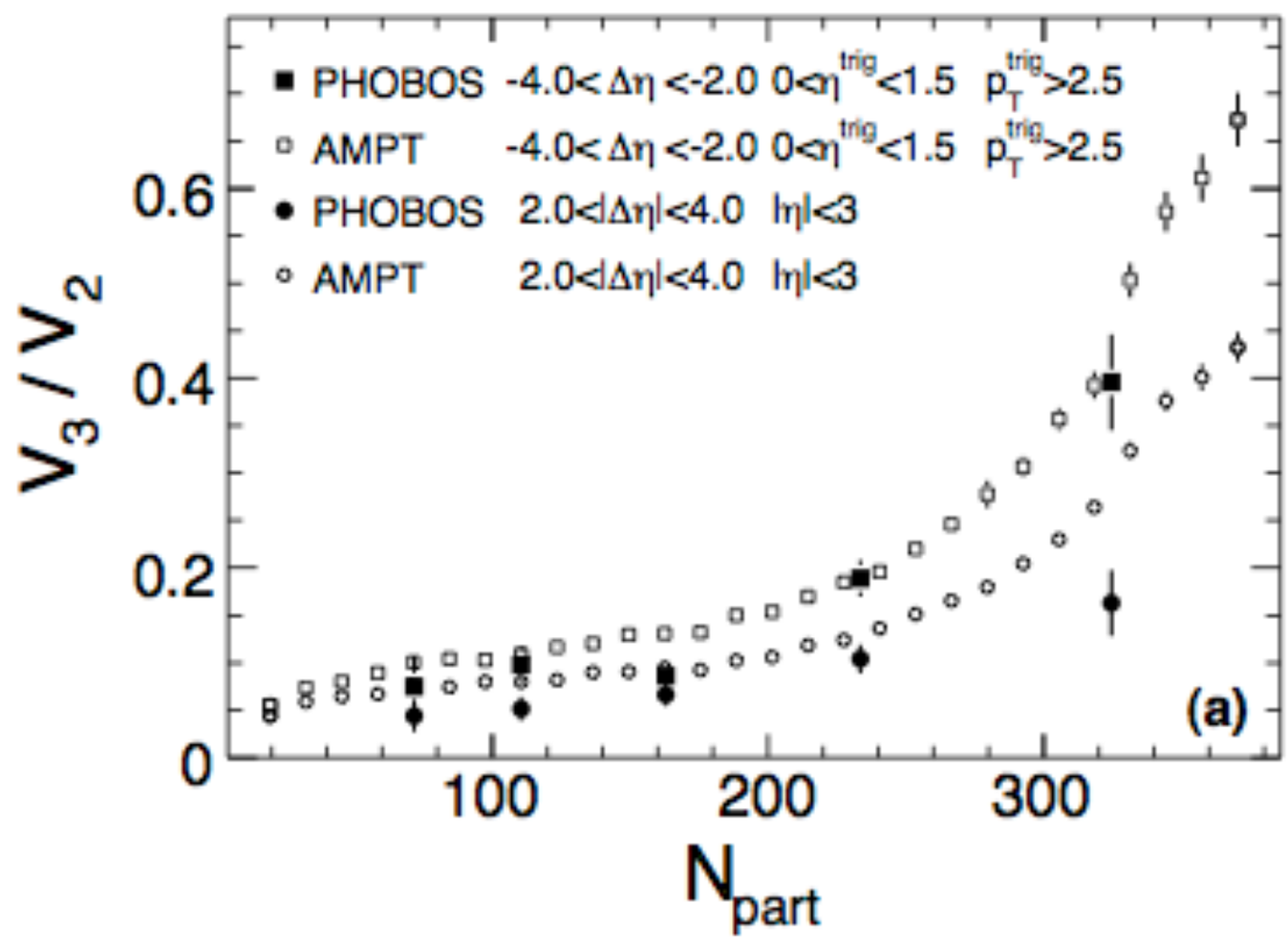
Alver & Roland, arXiv:1003.0194v1

Real collisions start from lumpy initial conditions and break symmetry

through NEXSPHERIO hydrodynamics

and through AMPT



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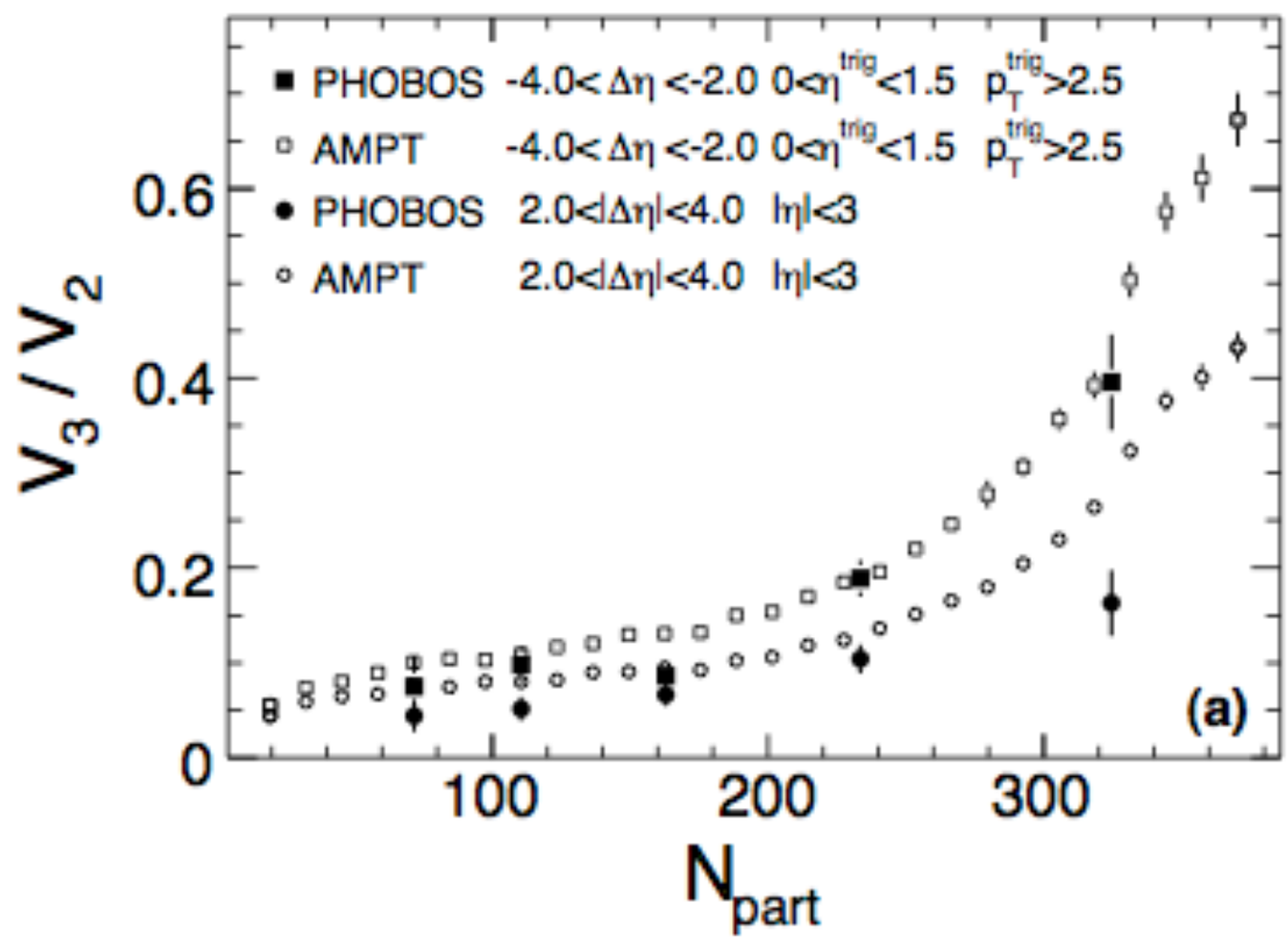

Triangular flow ➜ Initial Conditions, Medium Properties but not Energy Loss

Open Questions: Can triangular flow explain all the data? What about even higher order terms?

Meanwhile...

So how do we catch energy loss **in the act**?

4 basic high p_T measurements above "medium response" of:

	Energy Loss Mechanism	Event Geometry
Single particle	$\mathbf{R_{AA}}$	$R_{AA}(\Phi_s)$, v_2
Two particle	$\mathbf{I_{AA}}$	$I_{AA}(\Phi_s)$, $v_2^{I_{AA}}$

Energy Loss

Two trivial limits of energy loss modifications to spectra: “Loss” and “Shift”

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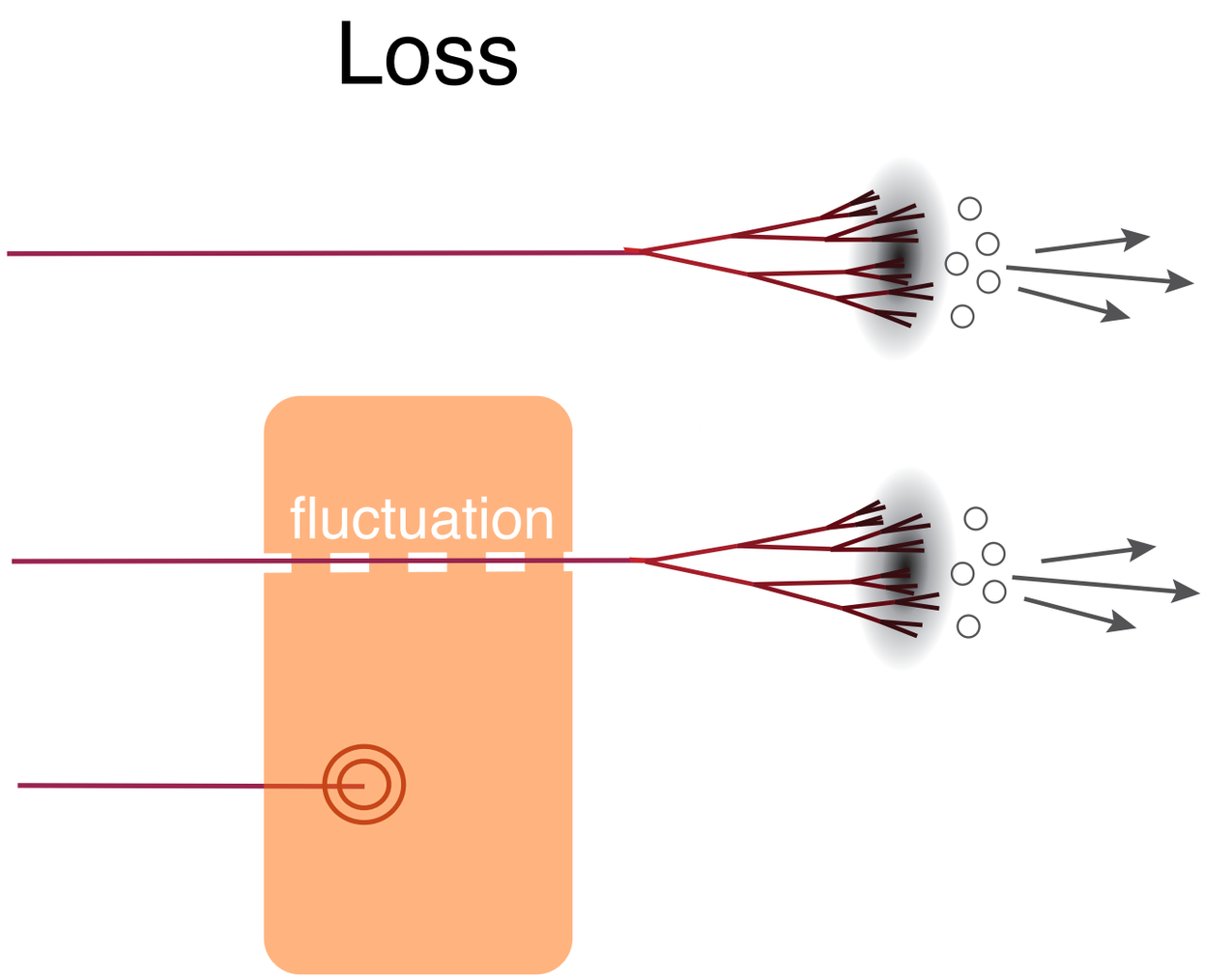

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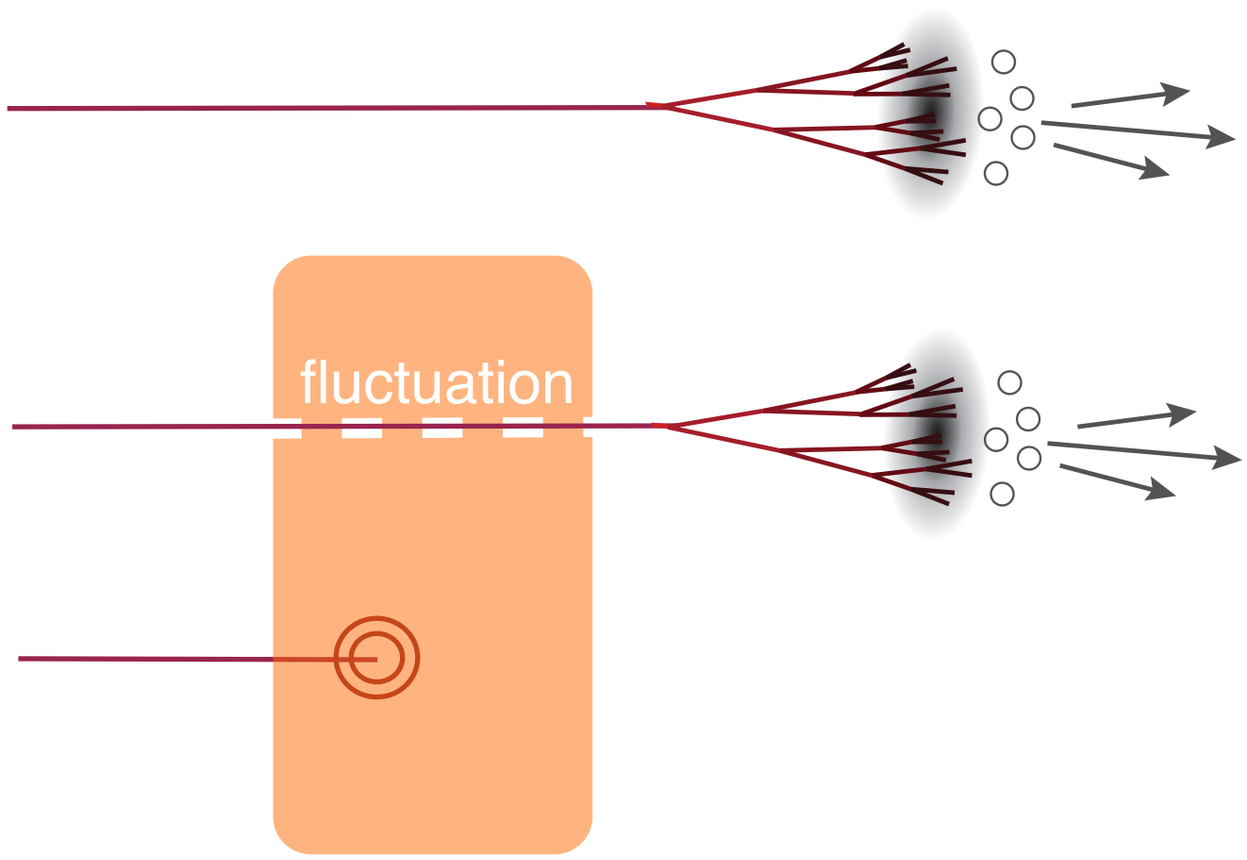

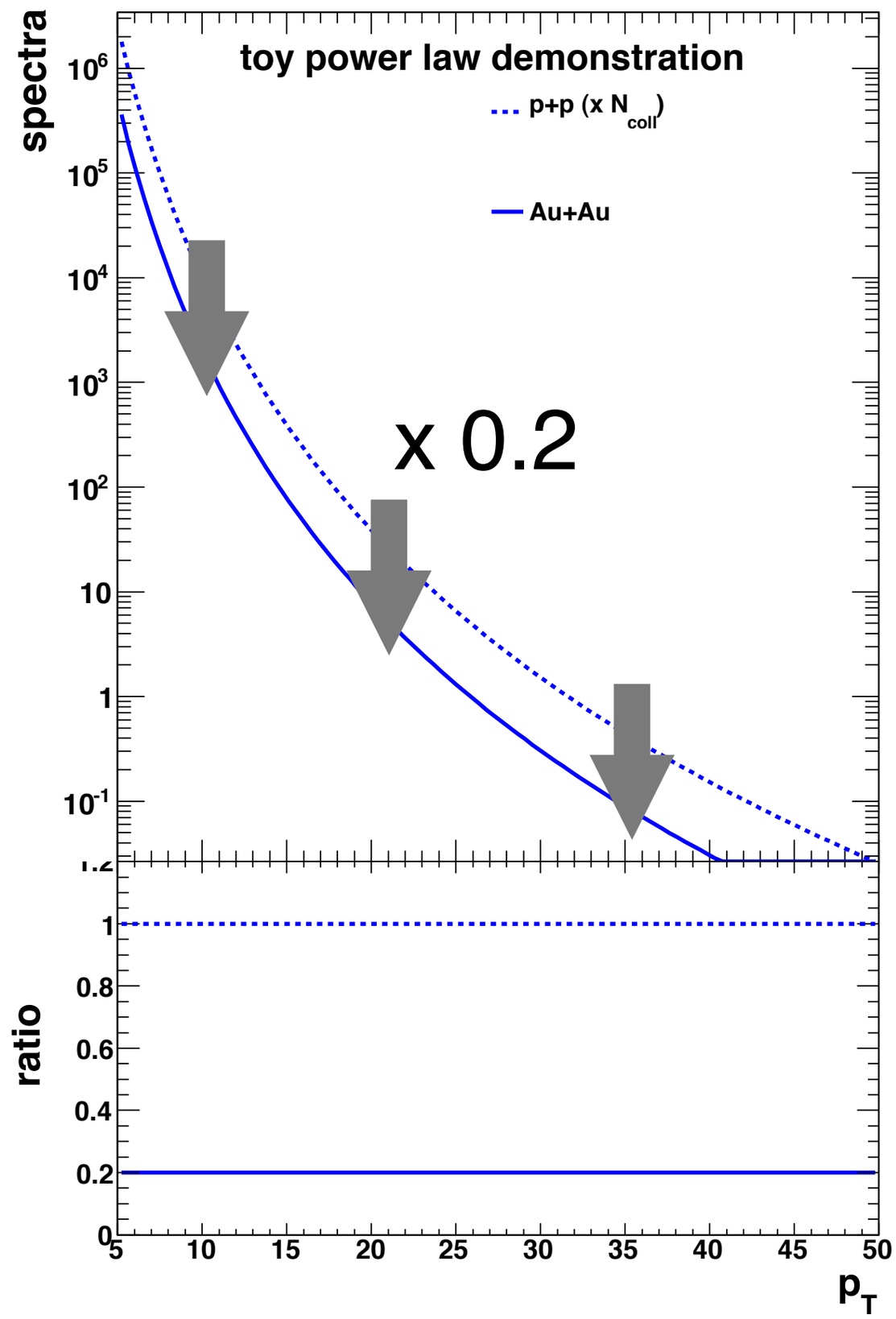

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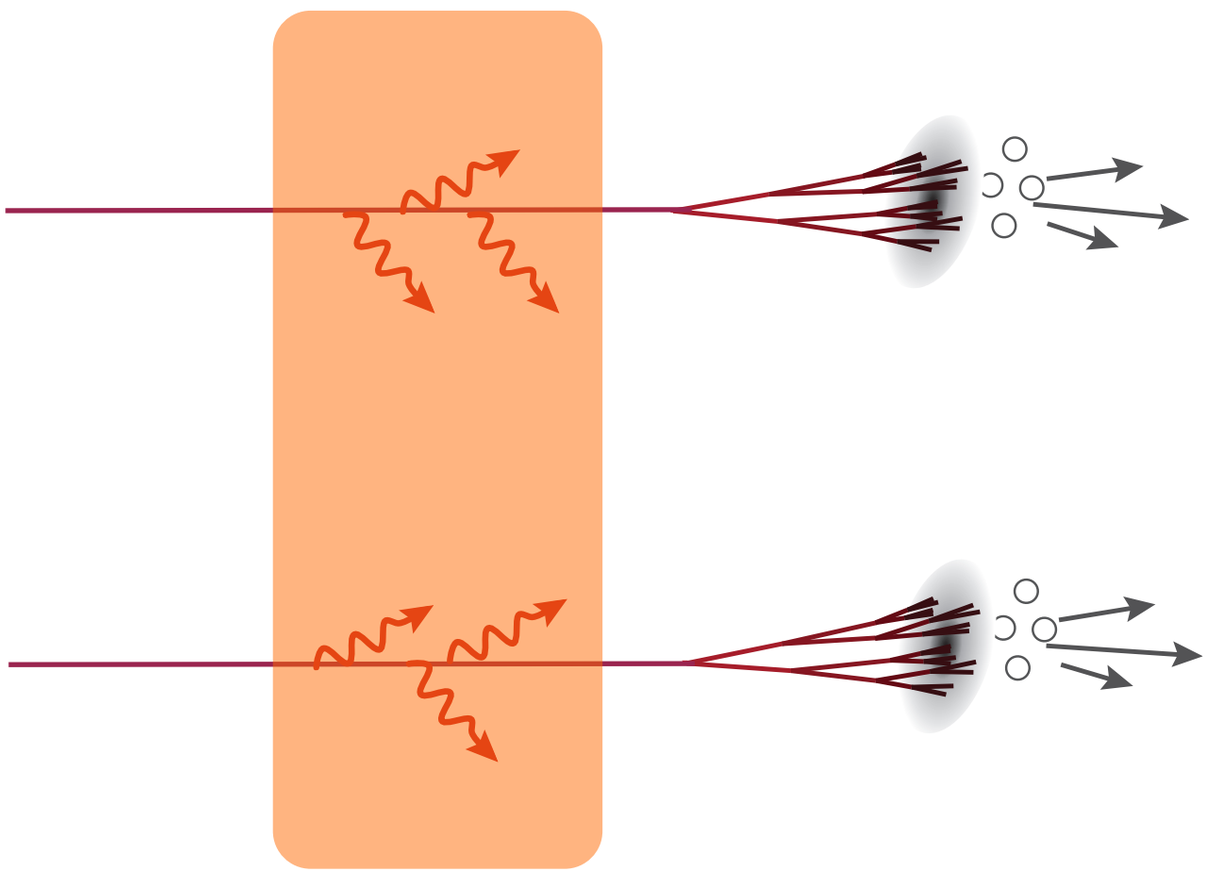

More information!

Energy Loss

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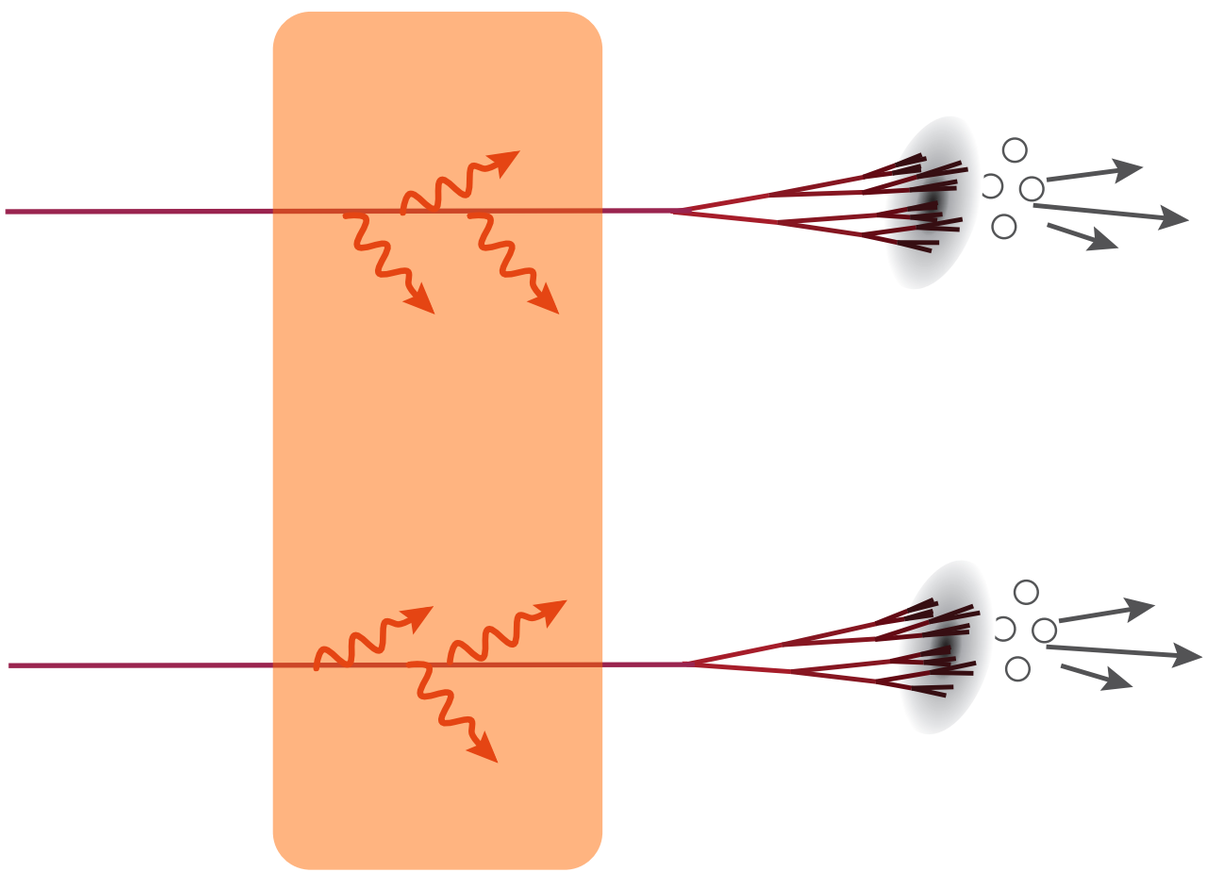
Shift



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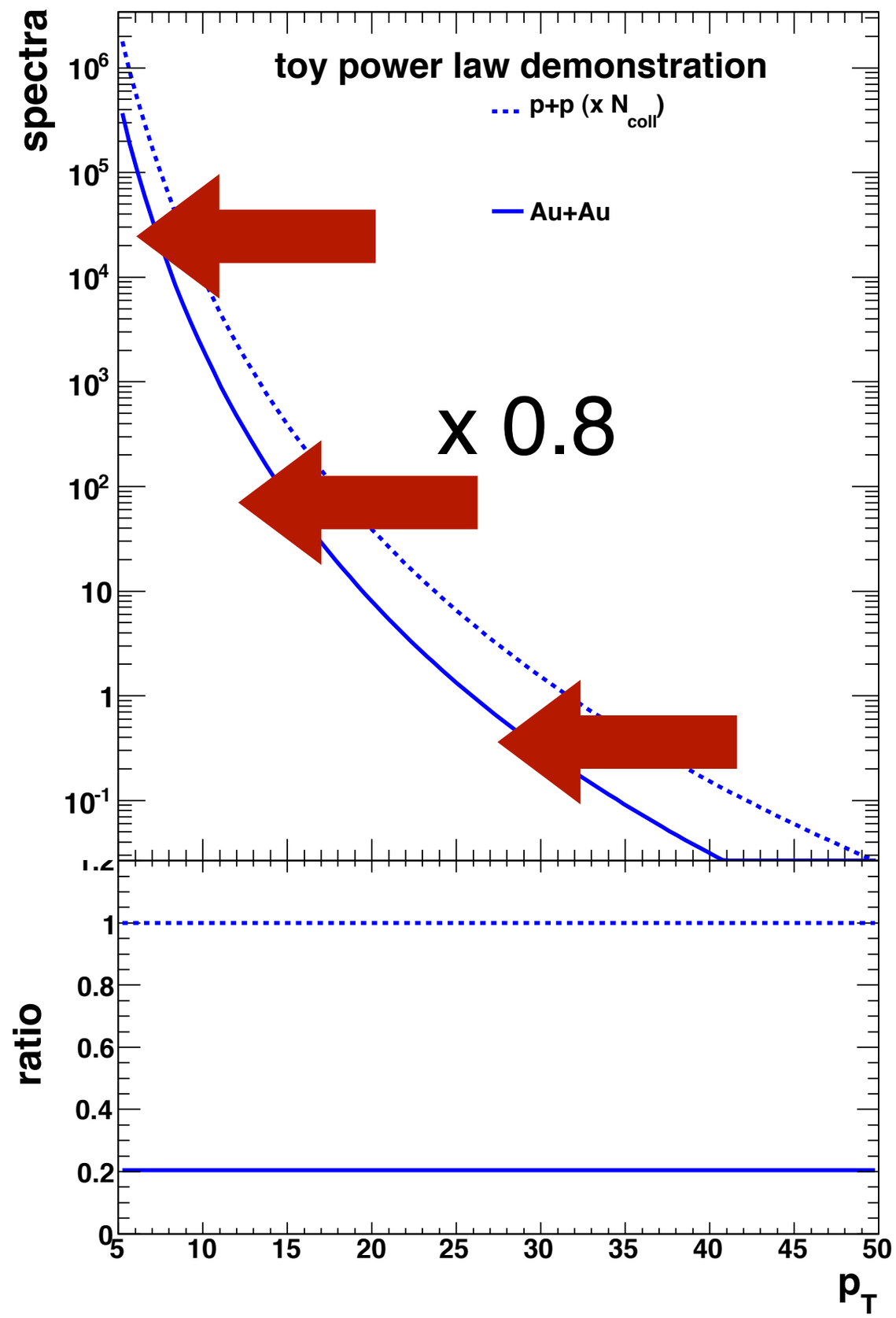
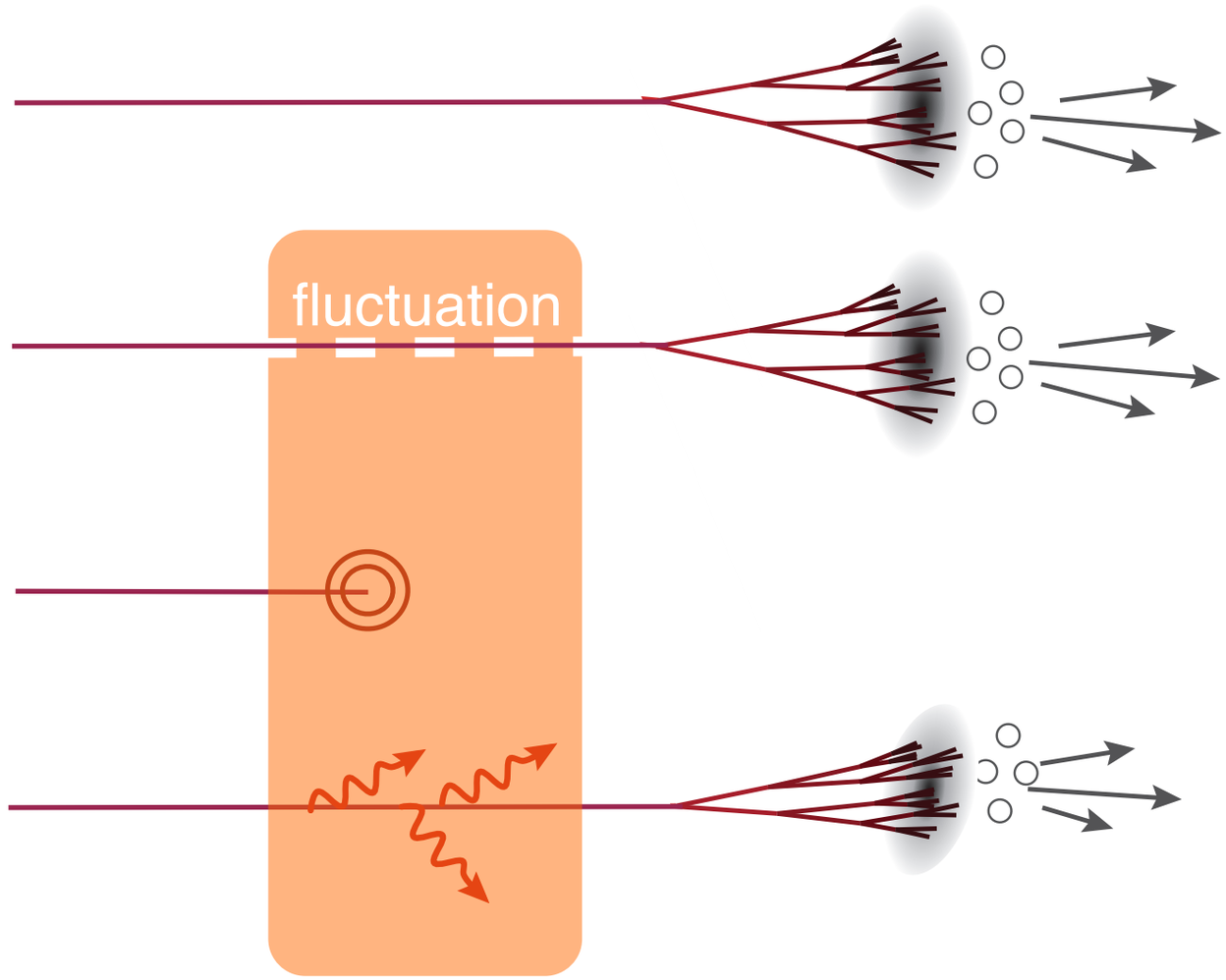


Energy Loss

Reality likely lies in between:
(and probably depends on p_T)

Loss + Shift



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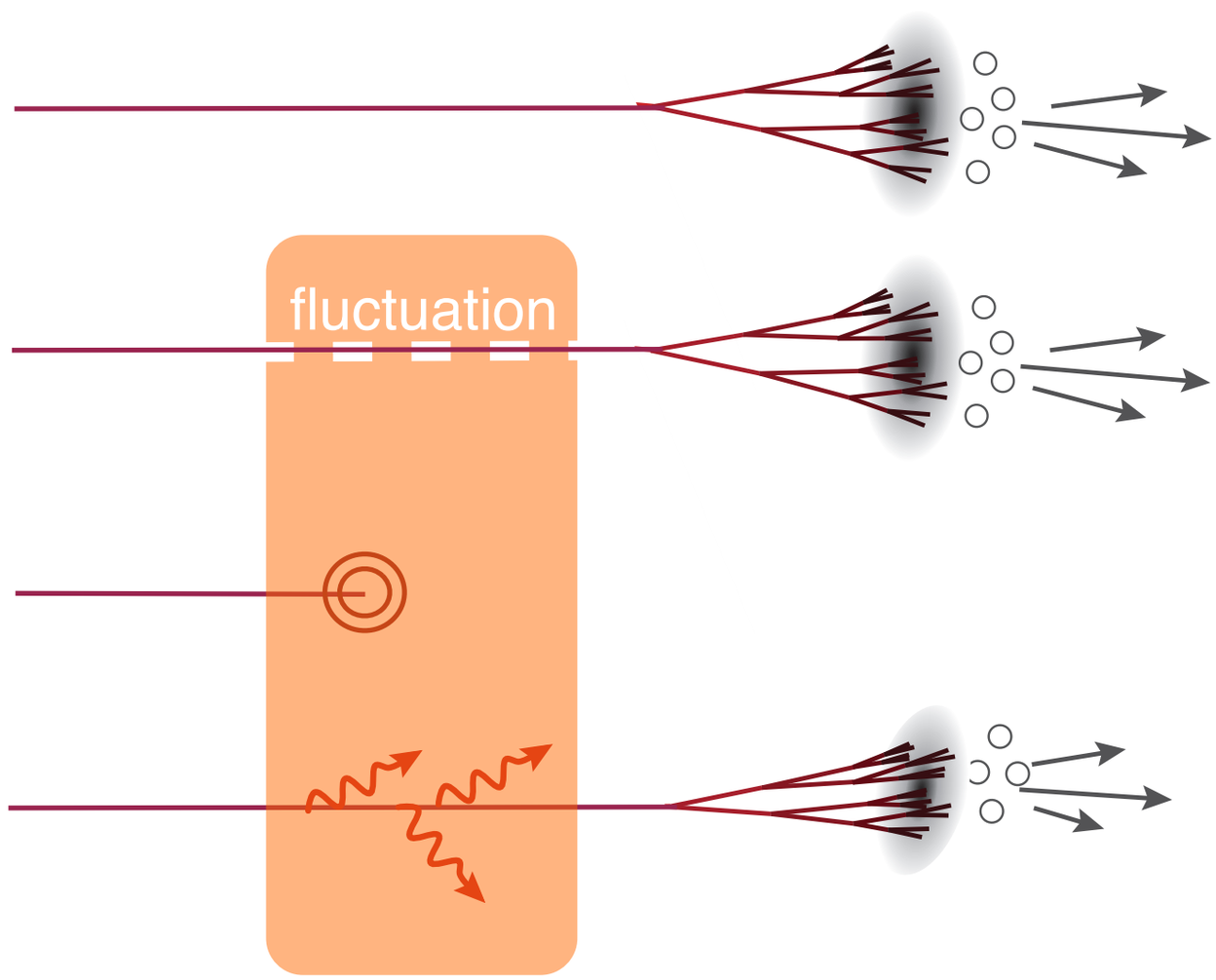
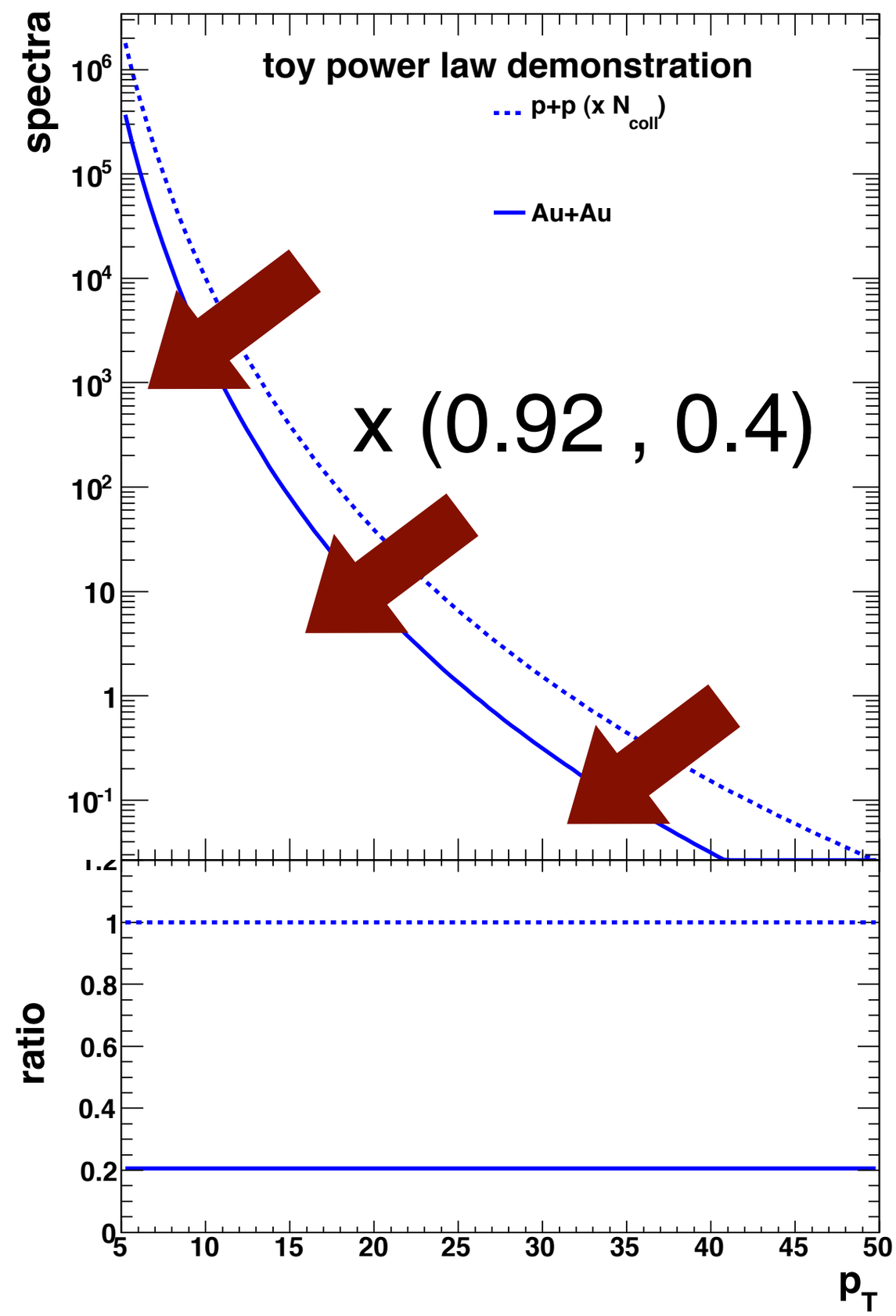




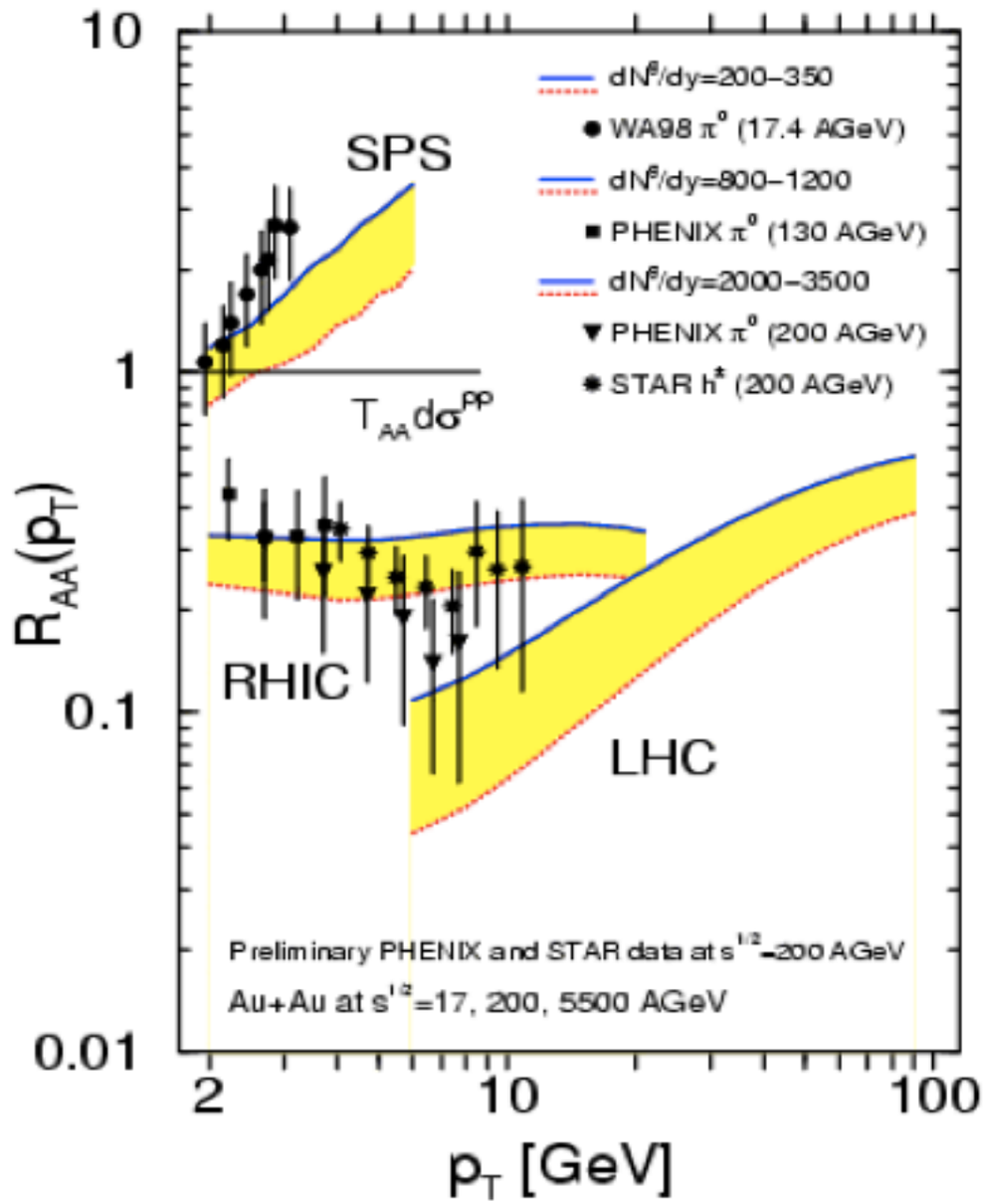
Trivial or not?

Is a flat $R_{AA}(p_T)$ dependence really this simple?

Gyulassy, Erice, 9/5/2004

Single Hadron Tomography from SPS, RHIC, LHC

Ivan Vitev and MG, Phys.Rev.Lett. 89 (2002)



1) Cronin *enhancement* dominates at SPS

2) Cronin+Quench+Shadow conspire to give ~ flat $R_{AA} \sim N_{part}/N_{bin}$ at RHIC

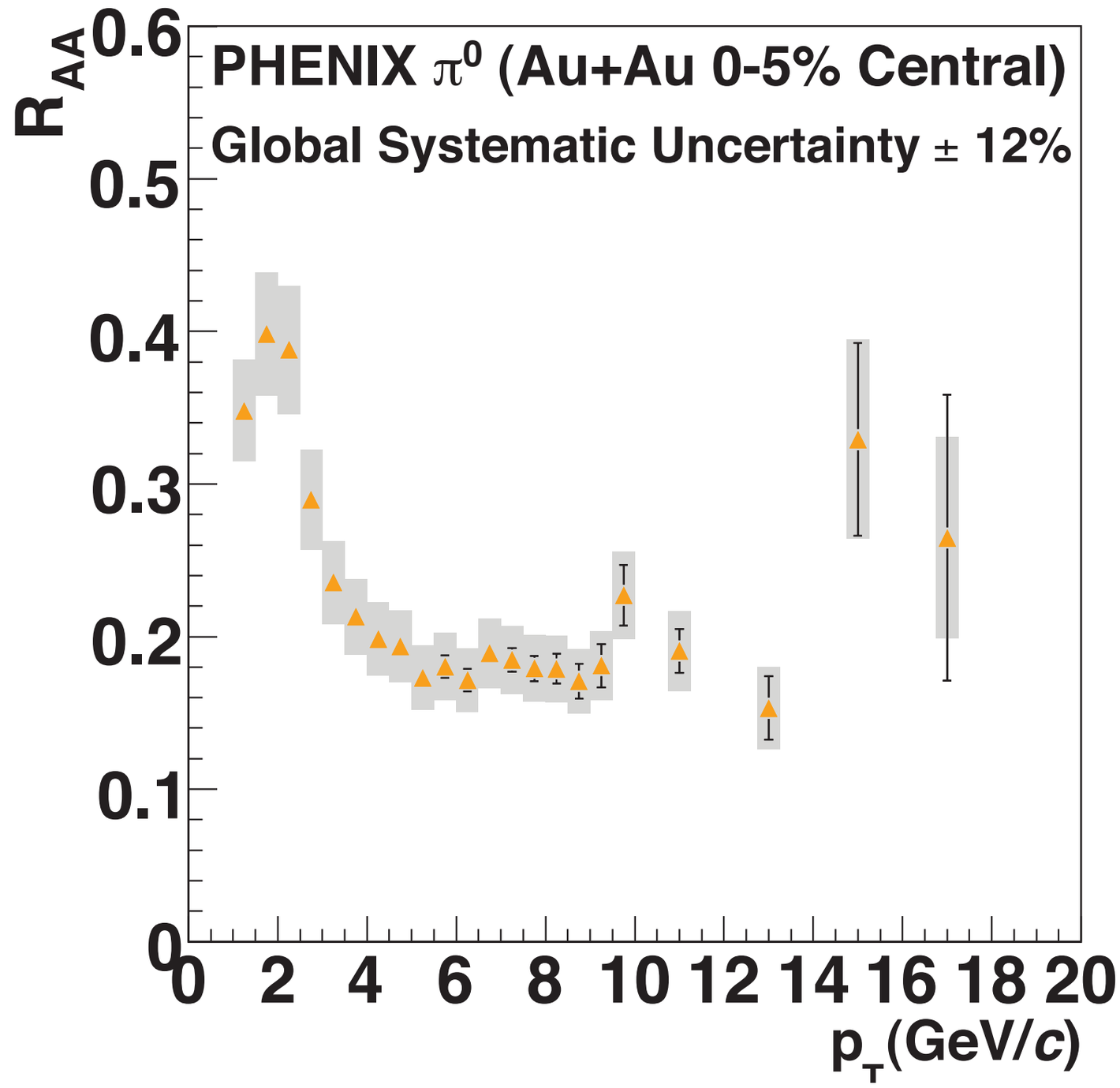
3) R_{AA} + I_{AA} data indicate $dN_g/dy \sim 1000 \rightarrow \rho_g \sim 100\ \rho_0$

Gyulassy 21

The First Look (2 years ago)

Does R_{AA} rise at large p_T?

PHYSICAL REVIEW C **77**, 064907 (2008)



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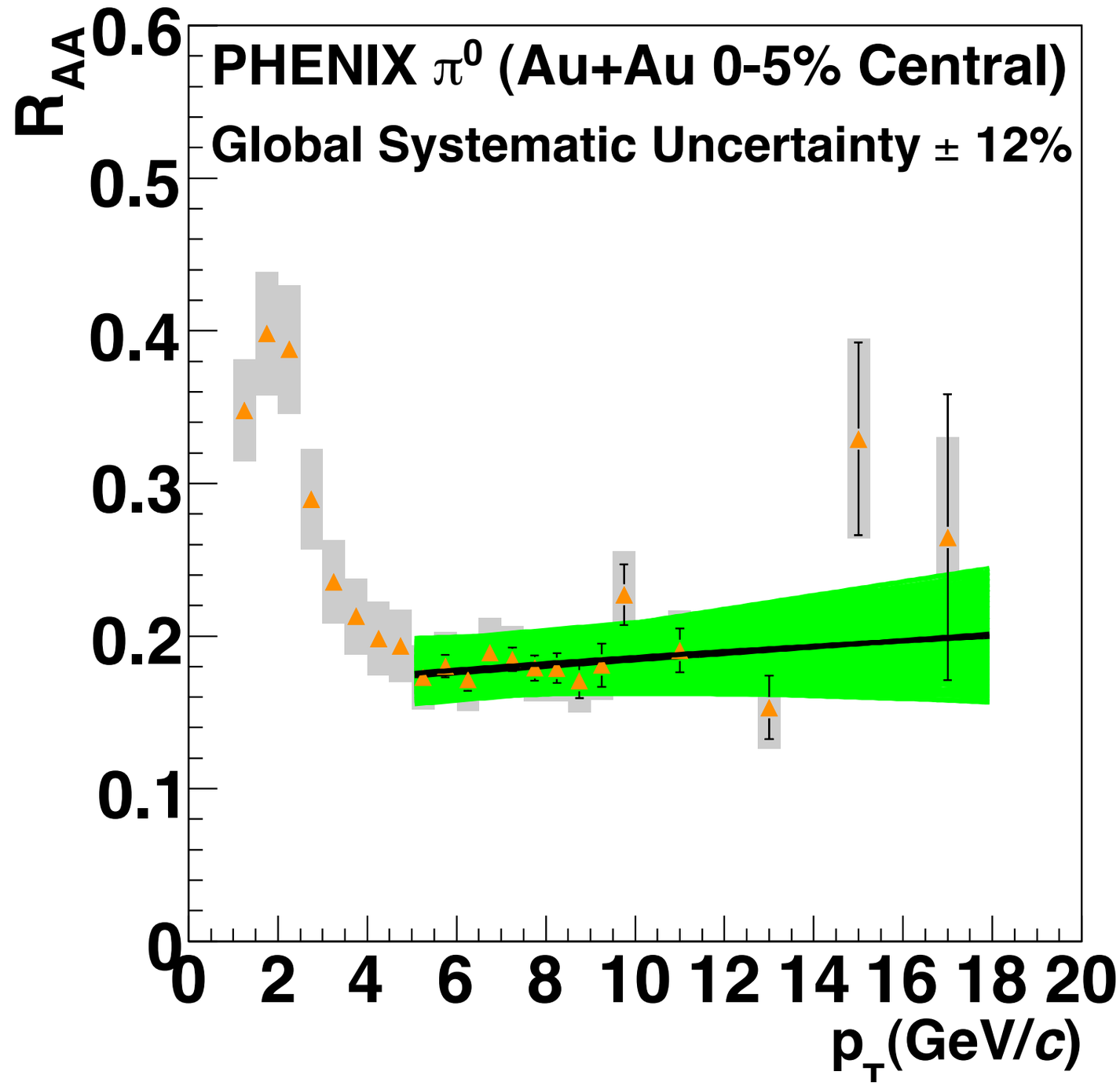
Fit requires proper accounting of correlated systematic uncertainties



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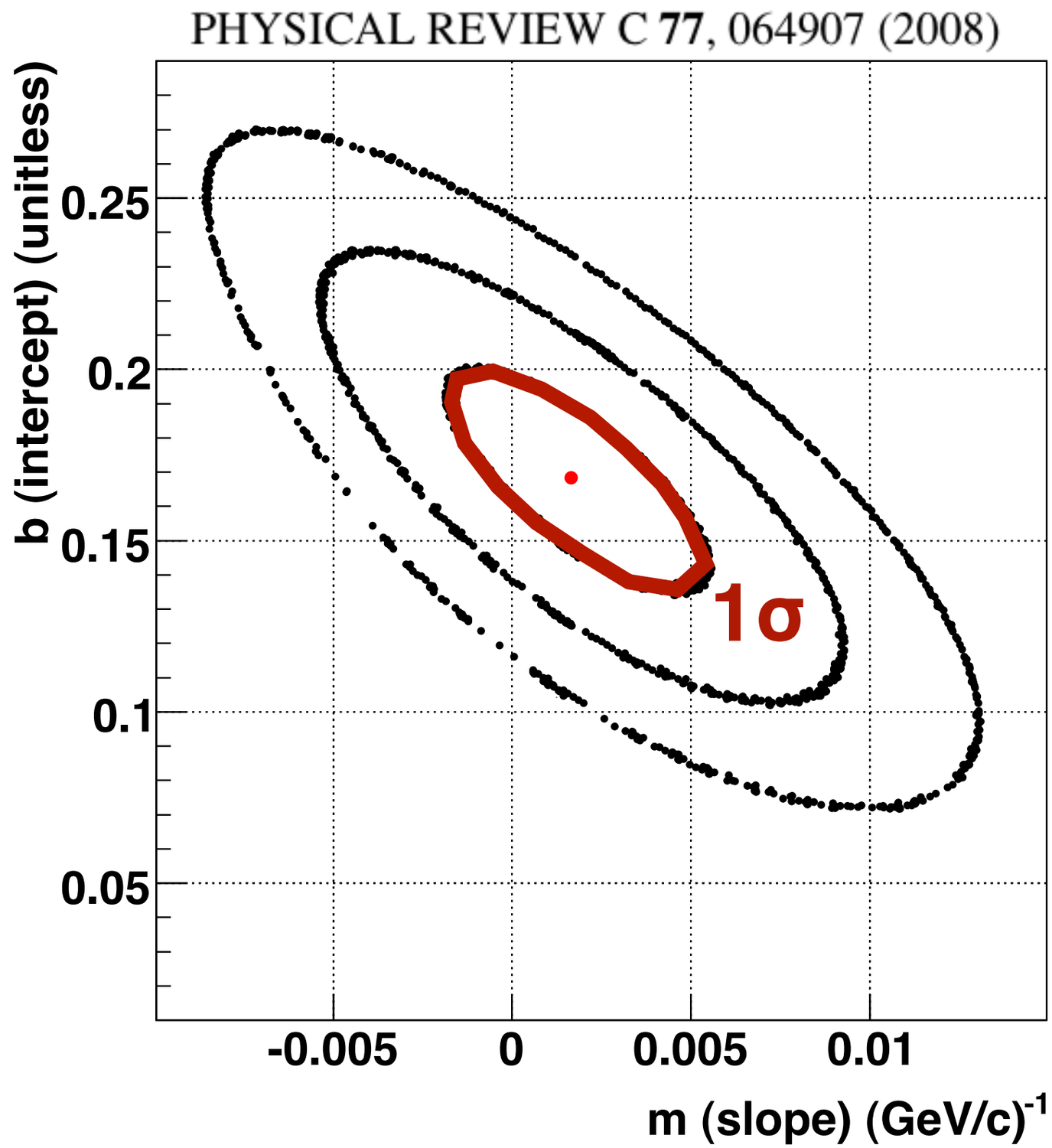

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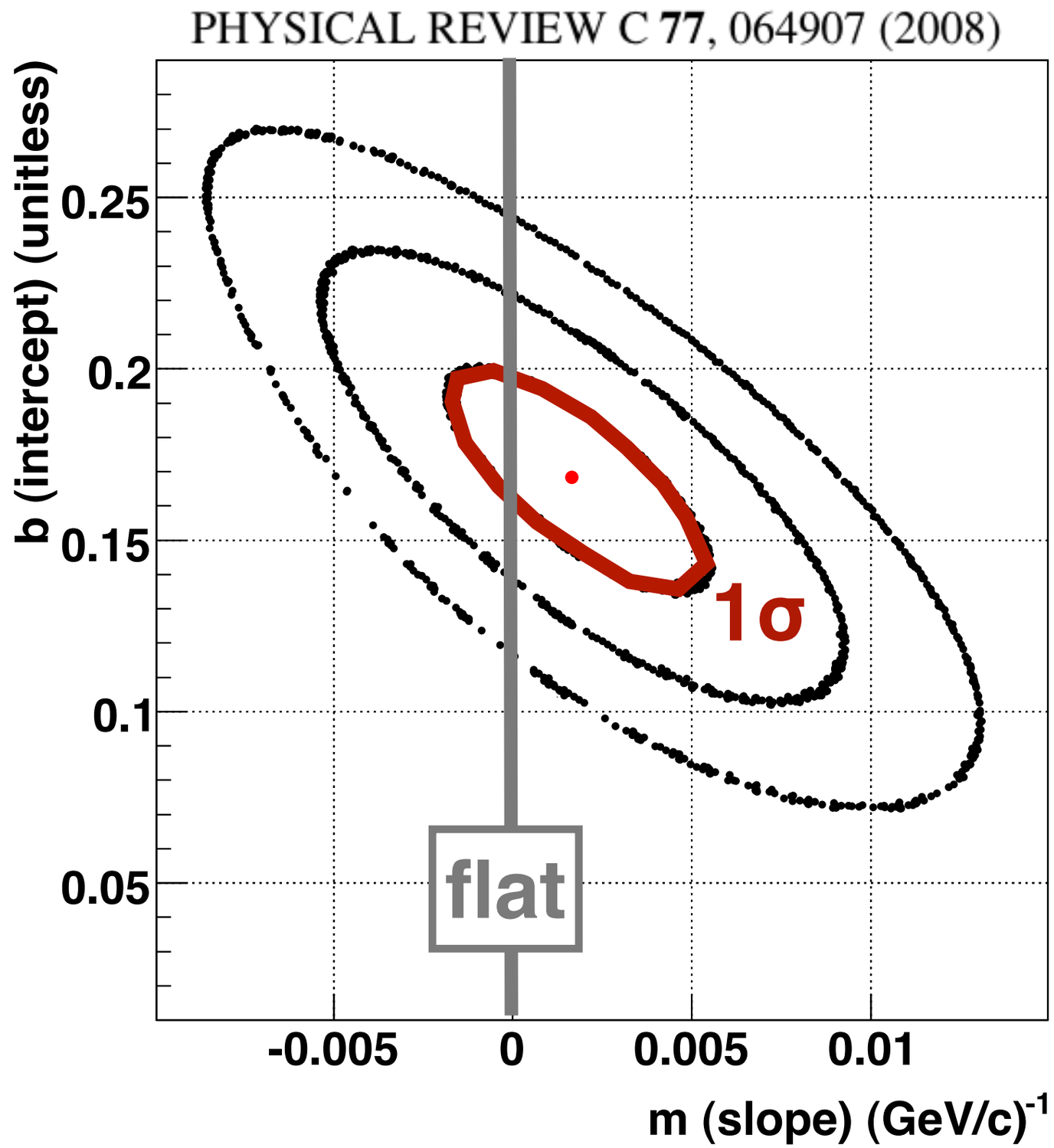

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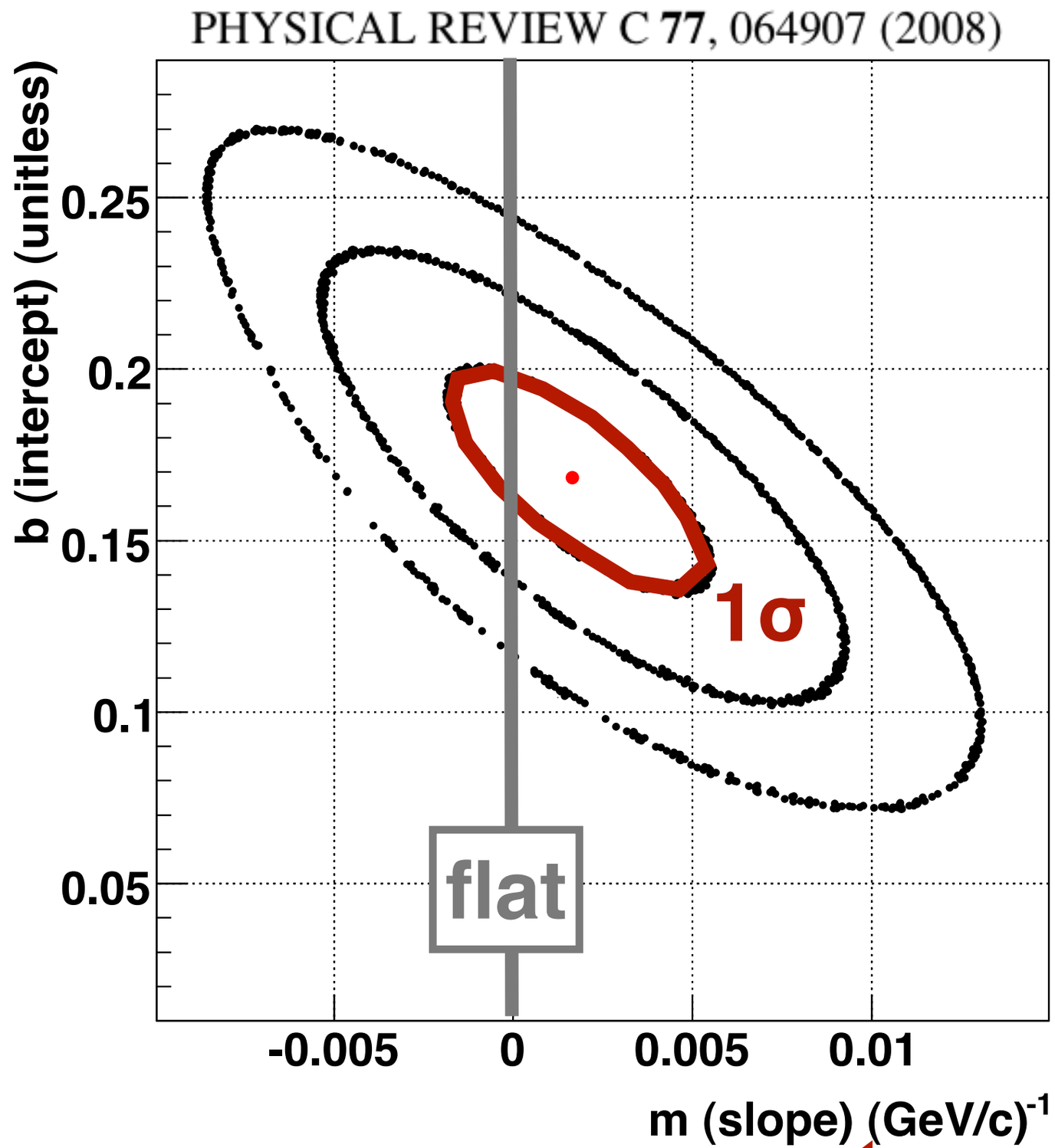

Consistent with constant loss and shift

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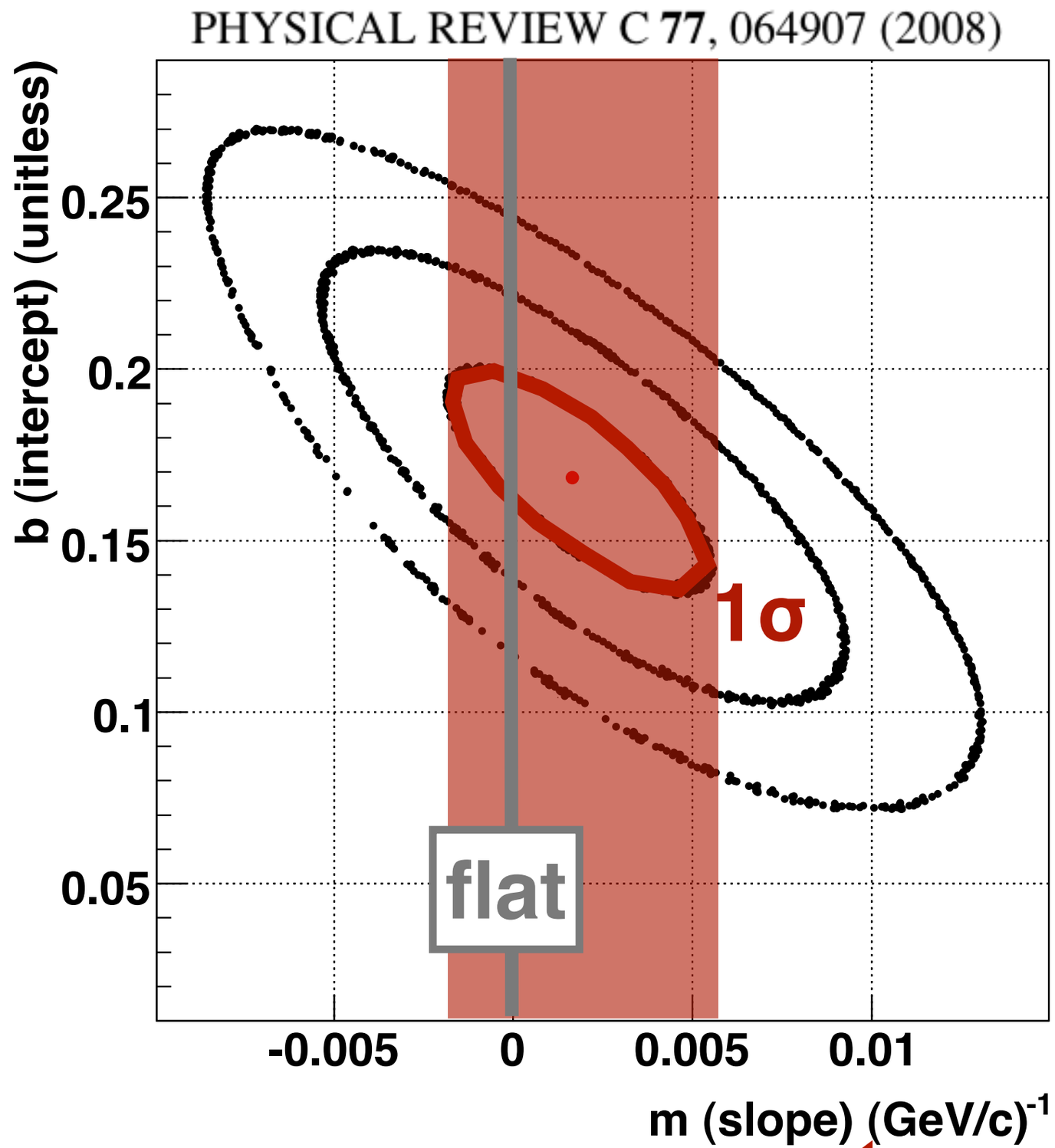

Consistent with constant loss and shift but also small trends

Second Look (yesterday!)

Does R_{AA} rise just a little at large p_T?

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Examined η meson R_{AA}

- Advantage:
  Larger opening angle

- Disadvantage:
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➤ Different mix of uncertainties than π^0

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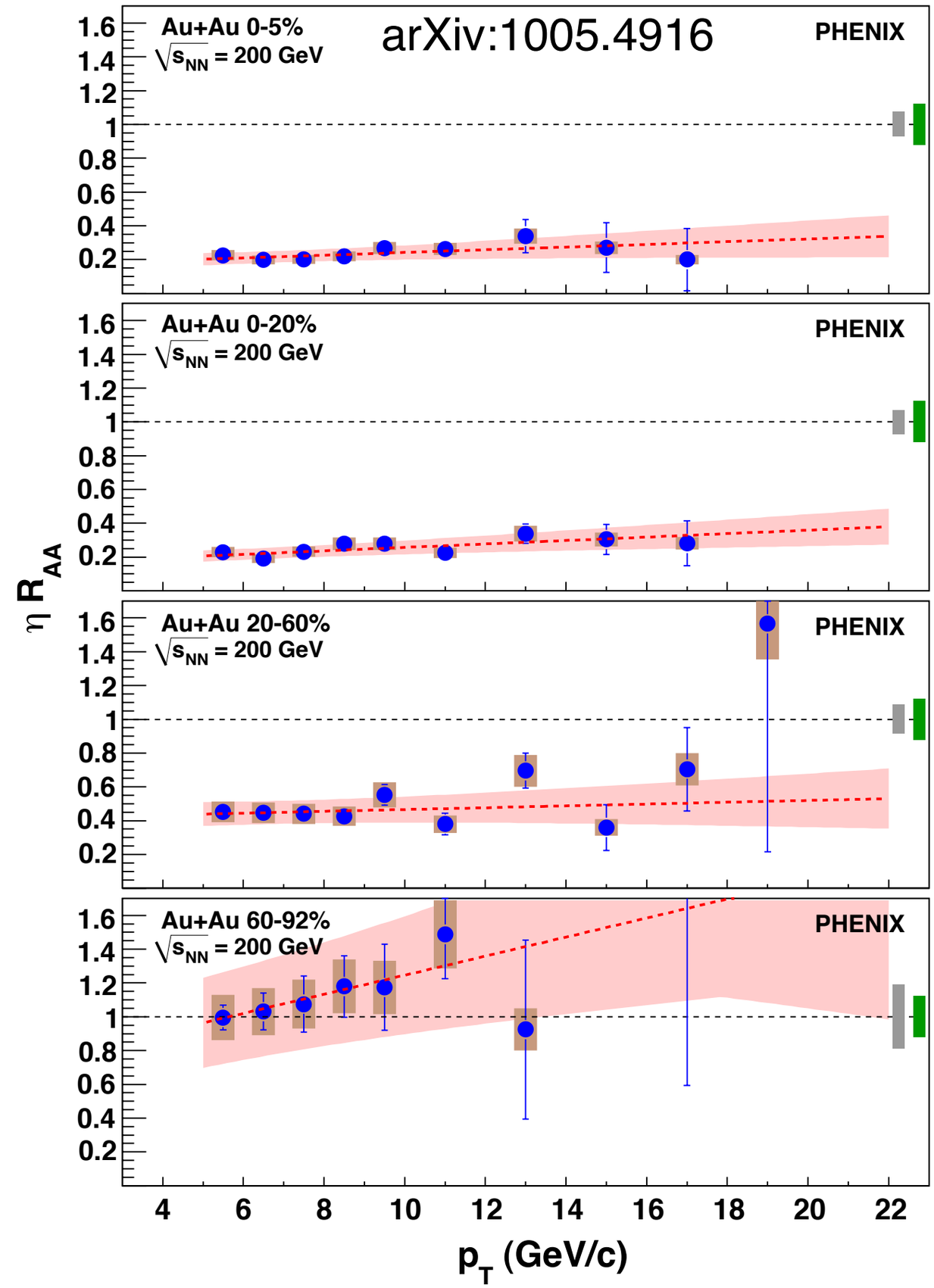

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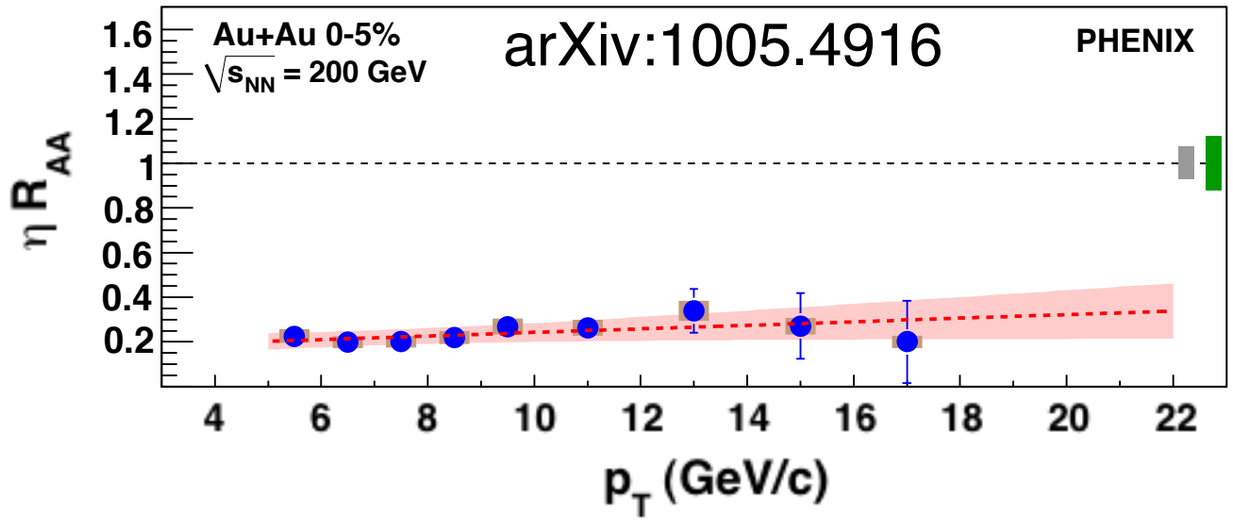

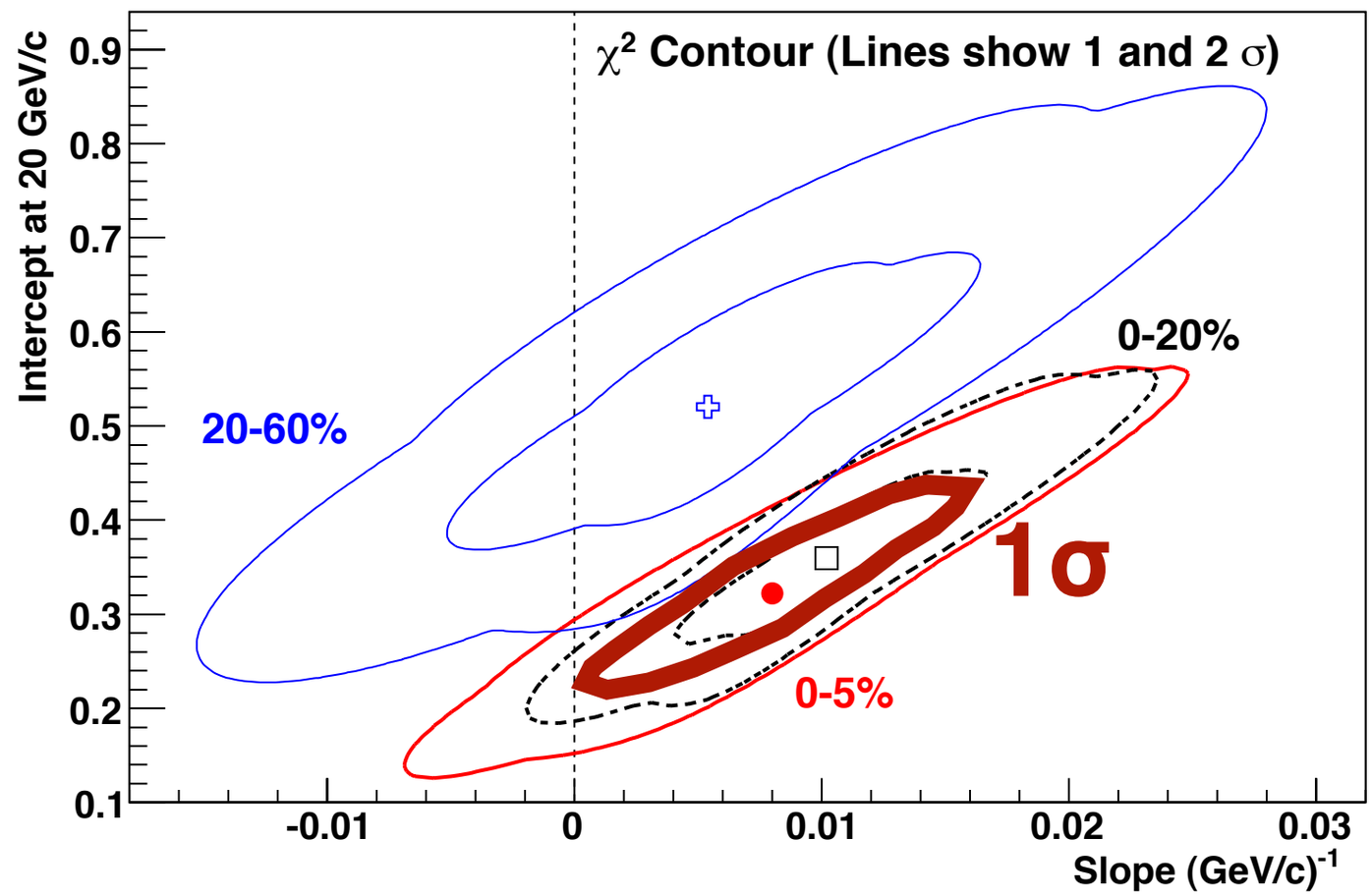

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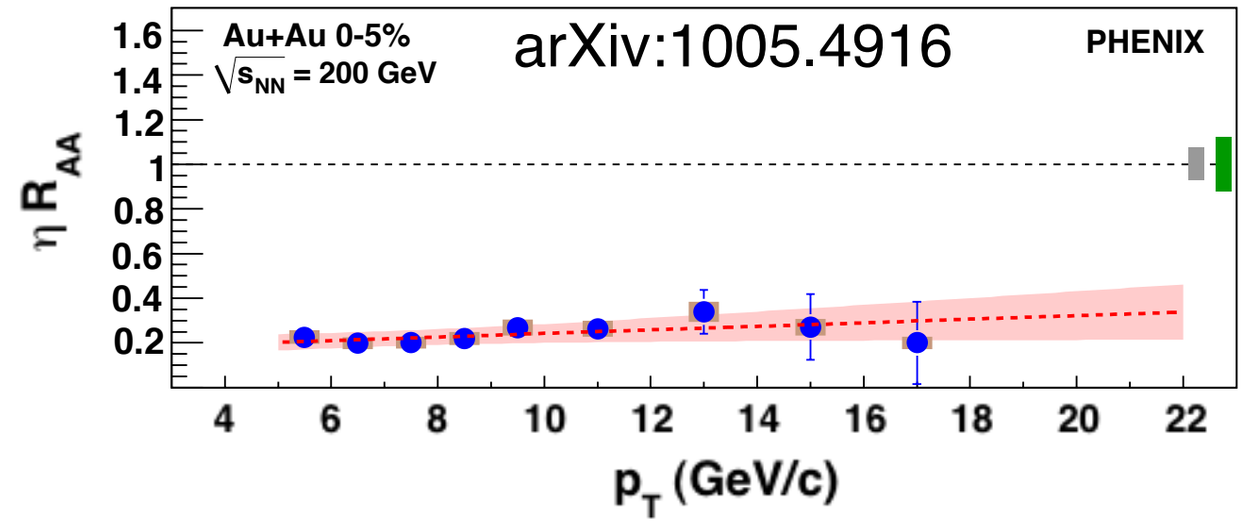

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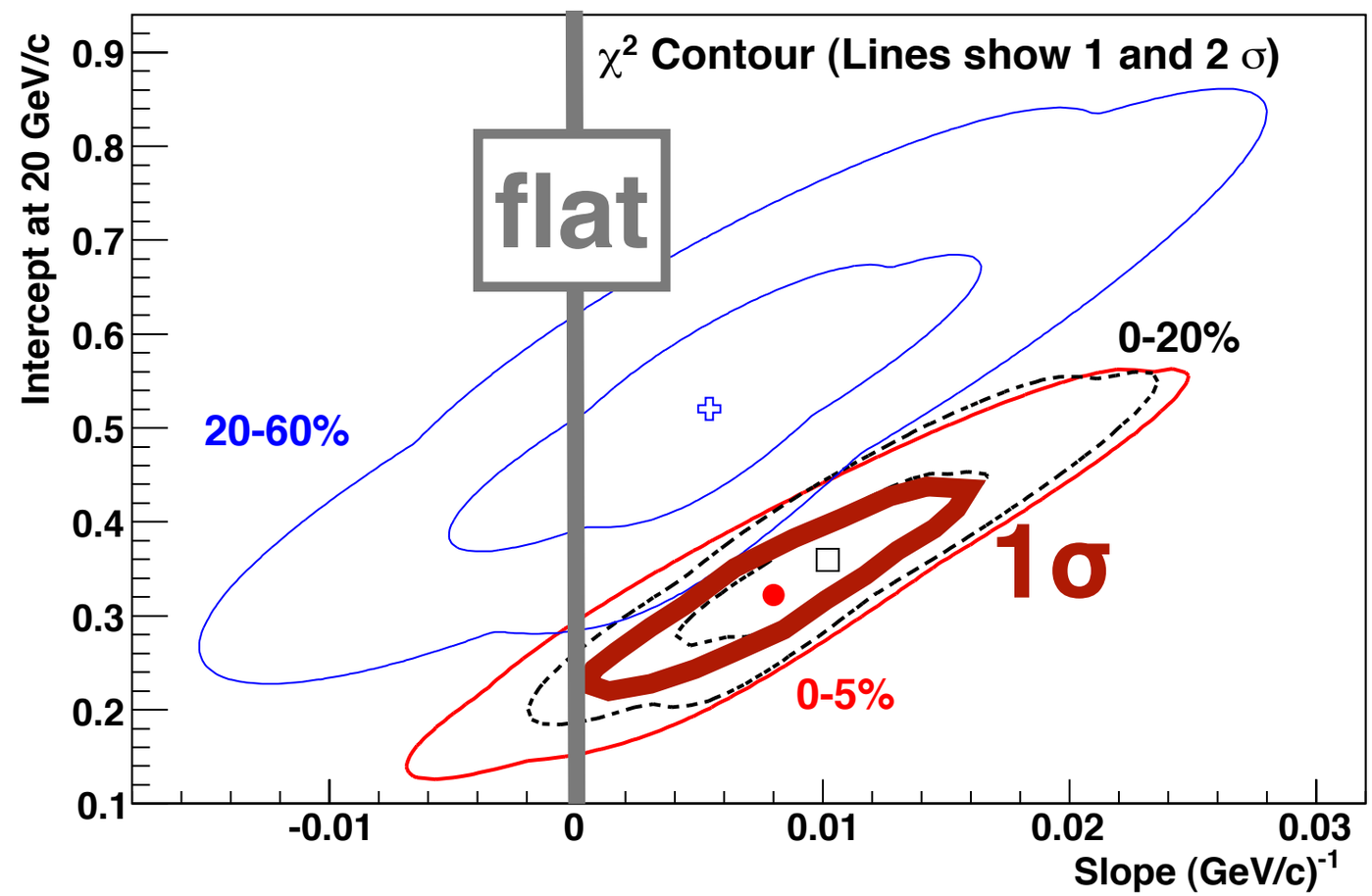
Individually the data are still consistent with flat p_T trend

Some preference for small increasing R_{AA}

Falling trends disfavored



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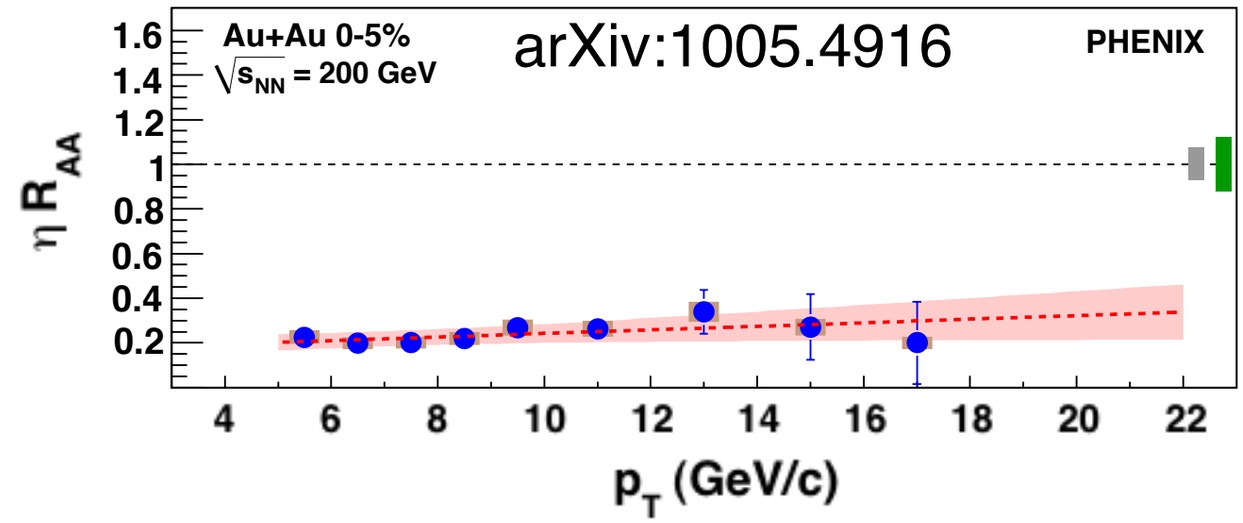

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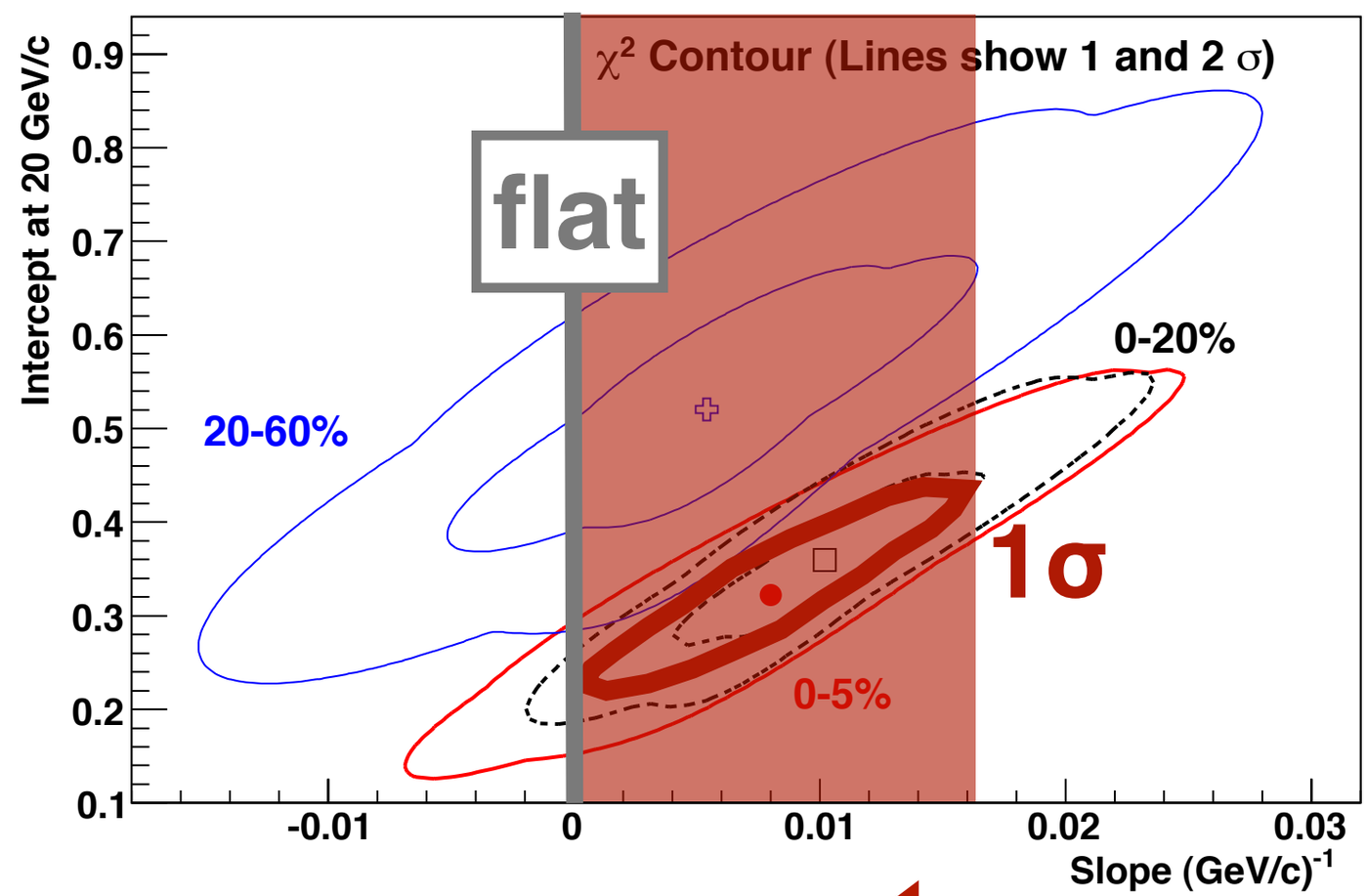
Some preference for small increasing R_{AA}

Falling trends disfavored



Still consistent with constant loss and shift

Moving on...

So how do we catch energy loss **in the act**?

4 basic high p_T measurements above "medium response" of:

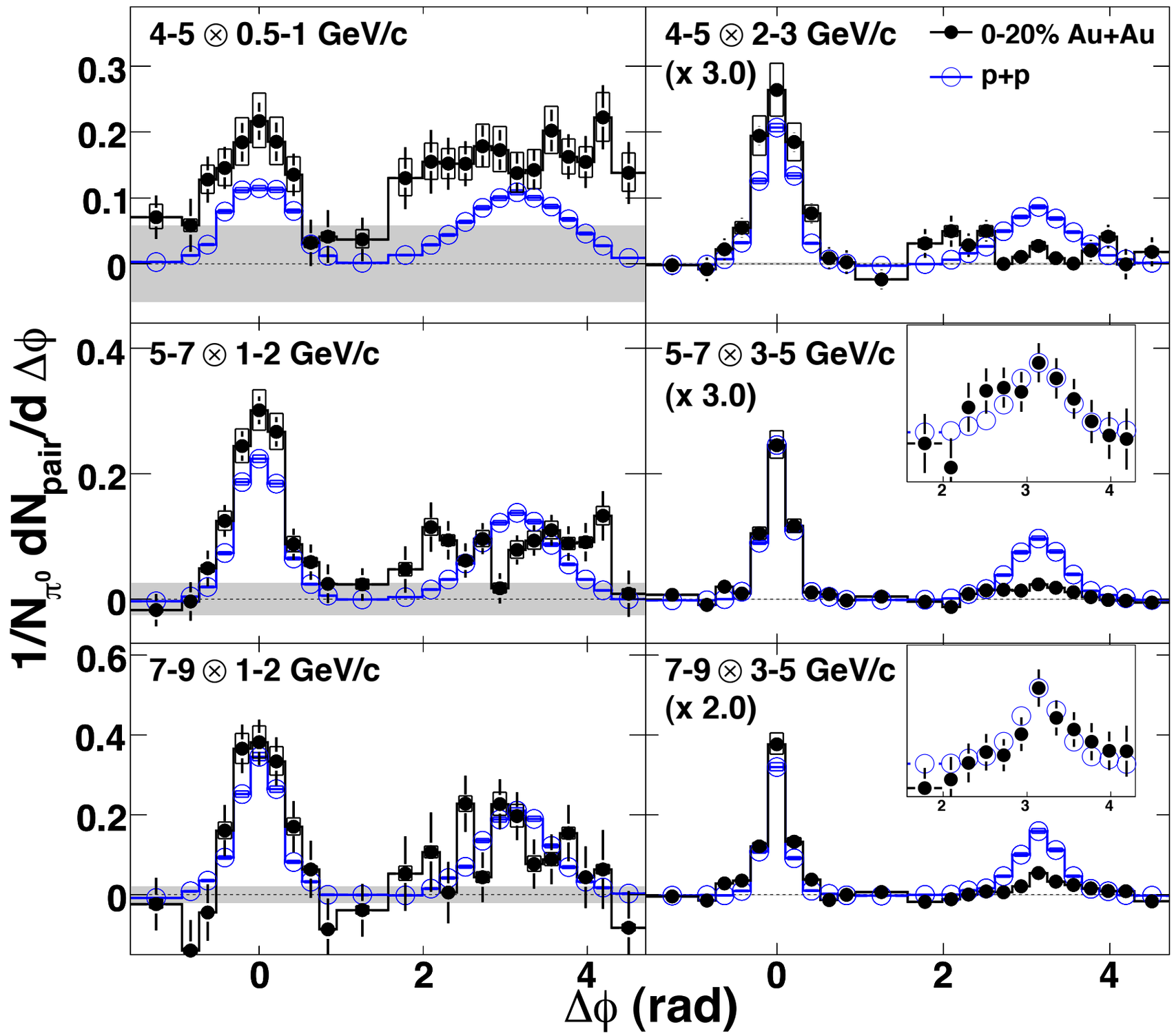
	Energy Loss Mechanism	Event Geometry
Single particle	$\cancel{R_{AA}}$	$R_{AA}(\Phi_s)$, v_2
Two particle	I_{AA}	$I_{AA}(\Phi_s)$, $v_2^{I_{AA}}$

Two-Particle Correlations

π^0: 4-12 GeV/c
$h^{\pm}$: 0.5-7 GeV/c

Broad range of trigger p^t_T

arXiv:1002.1077v2, Accepted by PRL



Two-Particle Correlations

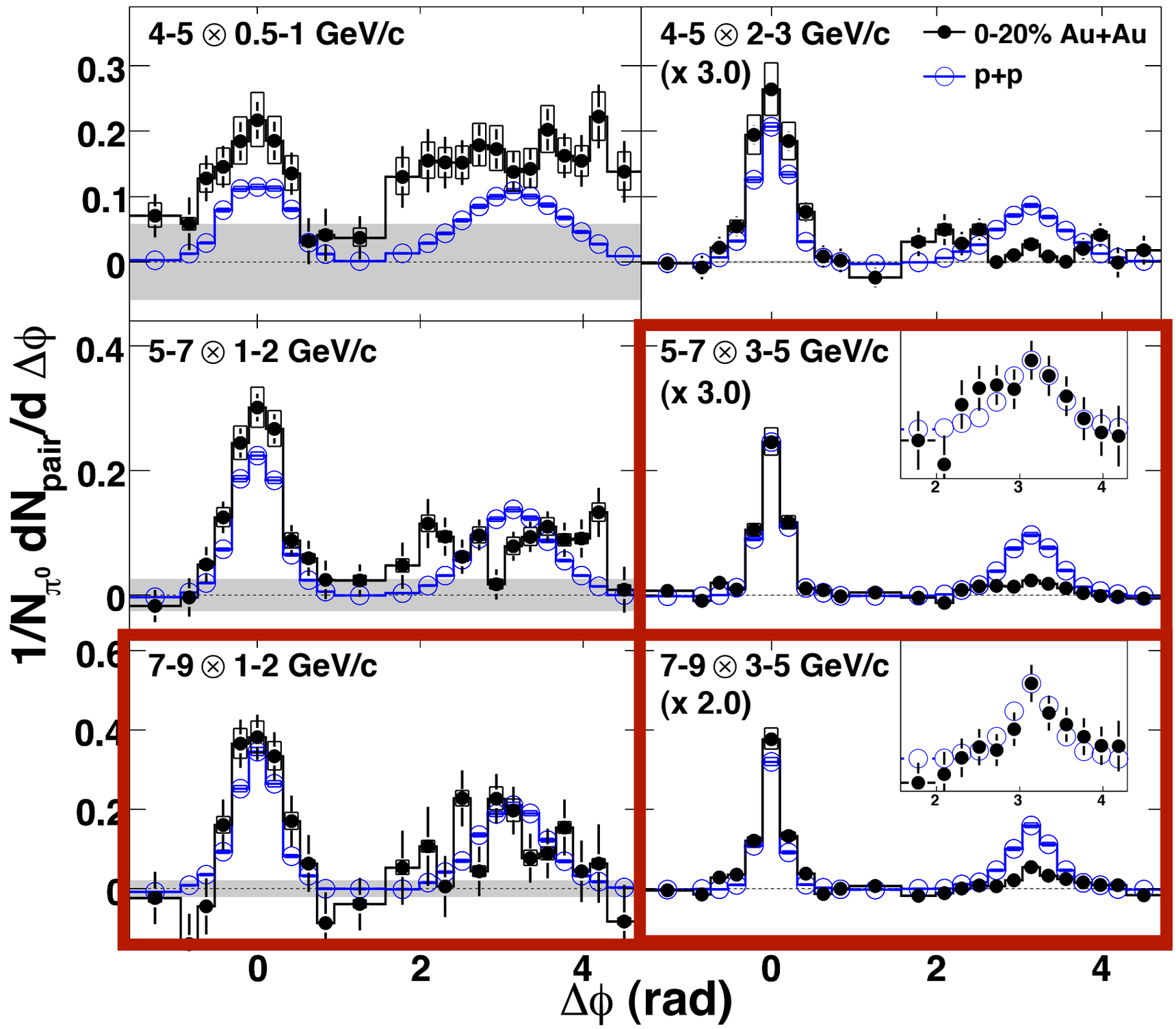
π^0: 4-12 GeV/c
$h^{\pm}$: 0.5-7 GeV/c

Broad range of trigger p^t_T

$p^t_T > 7$ GeV/c

Back-to-back peaks for all measured associated p_T

arXiv:1002.1077v2, Accepted by PRL



Two-Particle Correlations

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$h^{\pm}$: 0.5-7 GeV/c

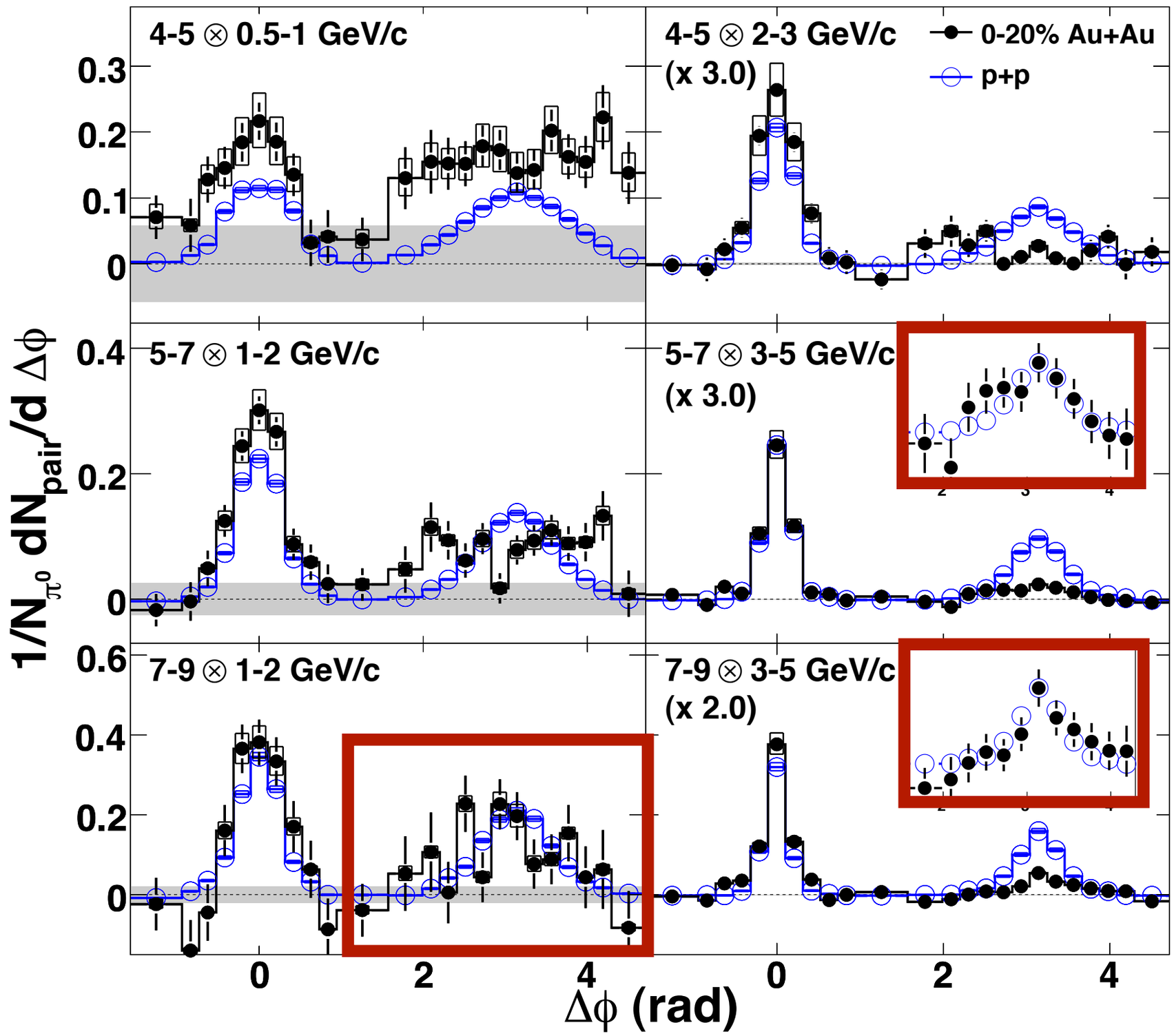
Broad range of trigger p^t_T

$p^t_T > 7$ GeV/c

Back-to-back peaks for all measured associated p_T

Still no evidence for jet broadening

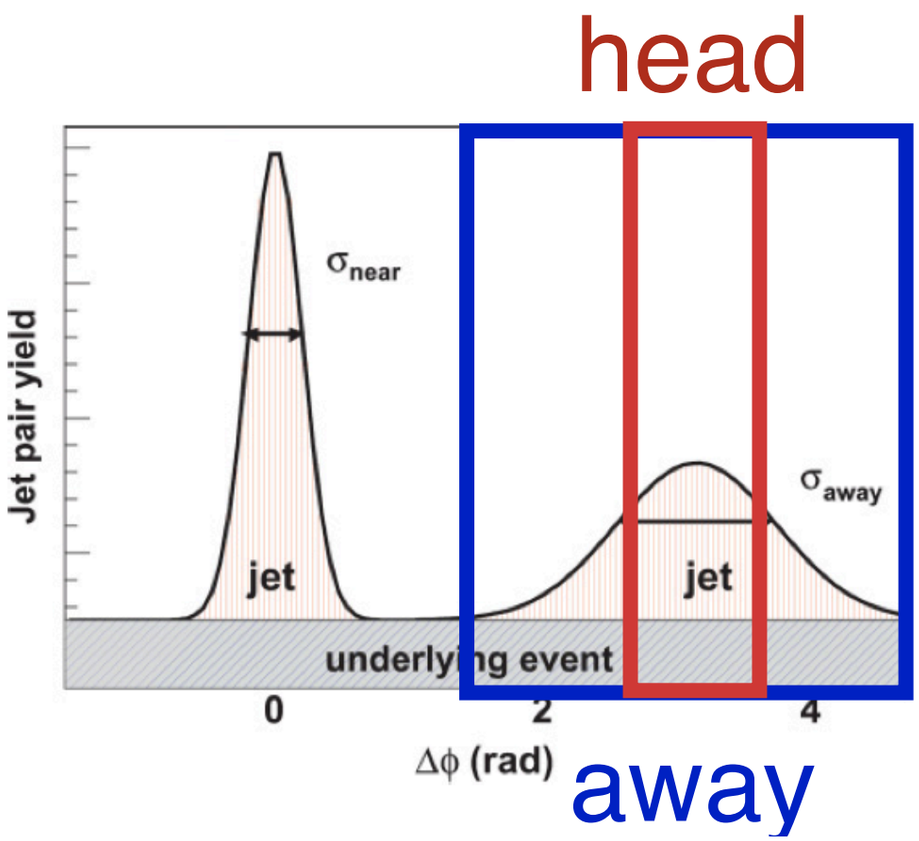
arXiv:1002.1077v2, Accepted by PRL



Away-side suppression at large associated p_T

Away-side I_{AA}

$$I_{AA} = \frac{(N^{ta}/N^{t})_{Au+Au}}{(N^{ta}/N^{t})_{p+p}}$$



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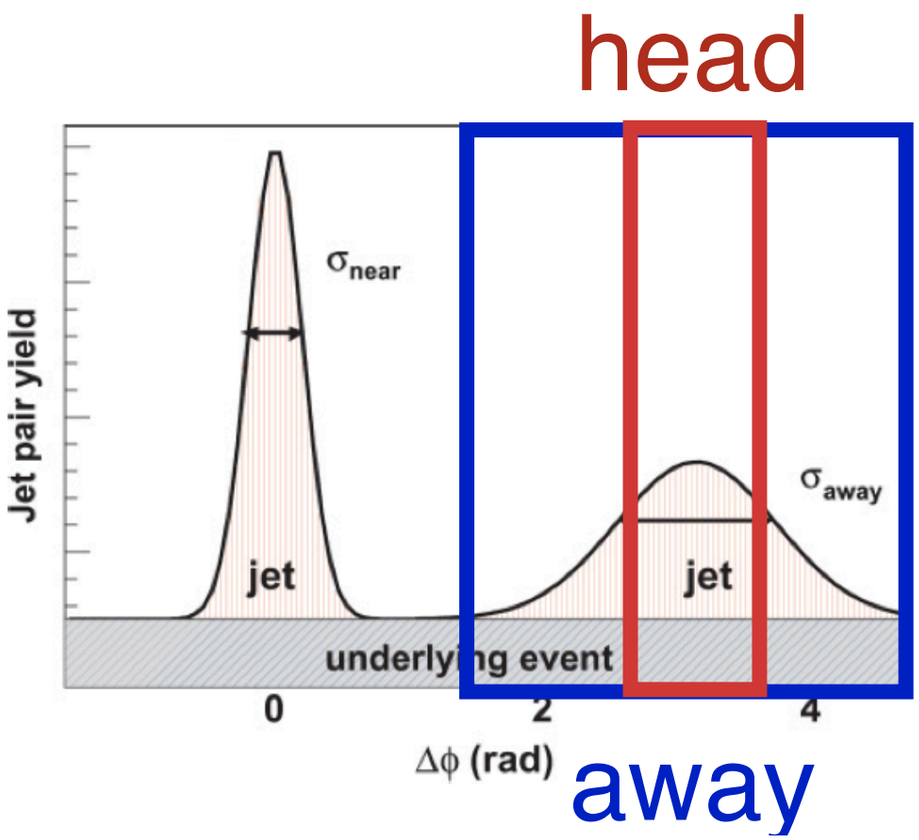

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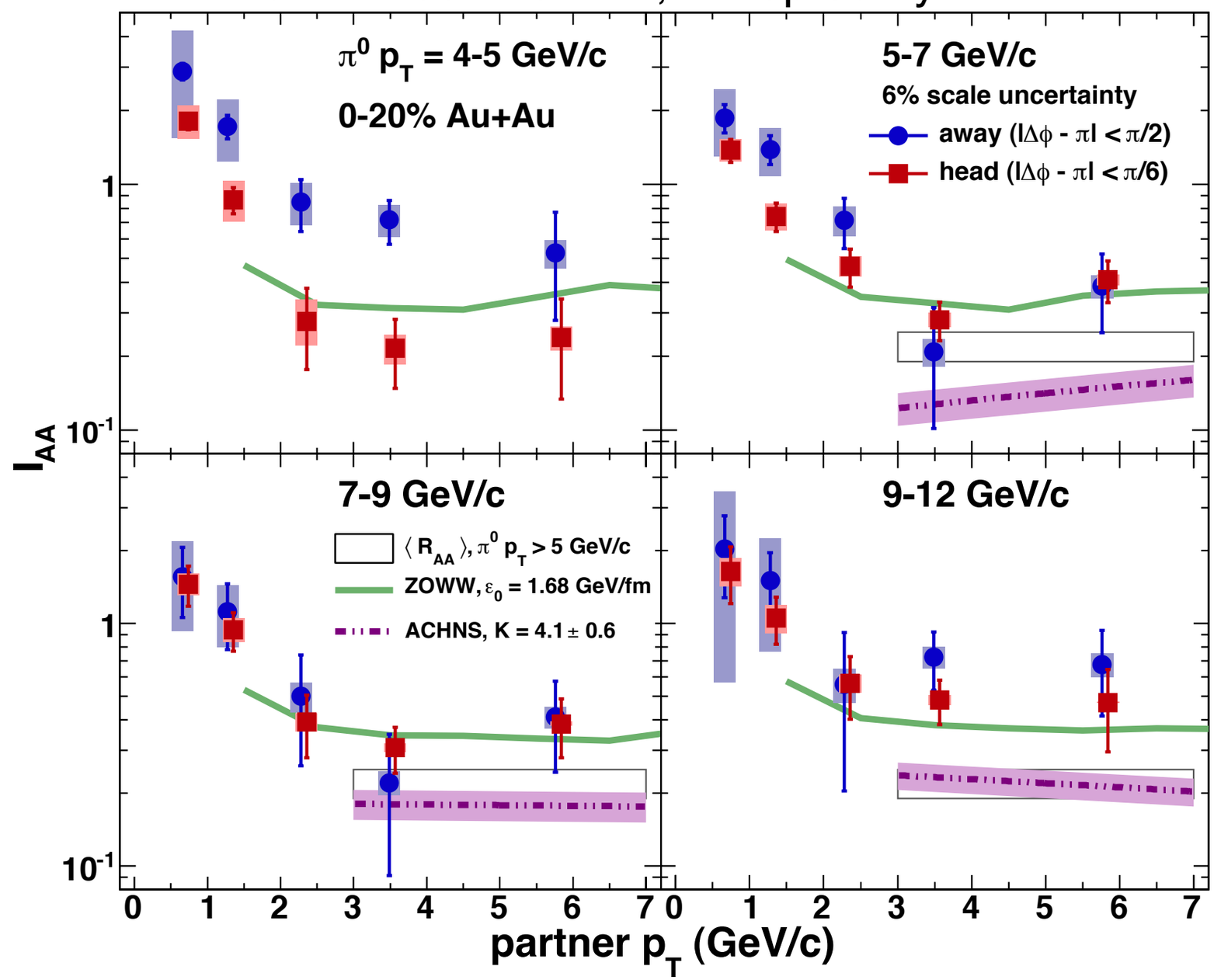

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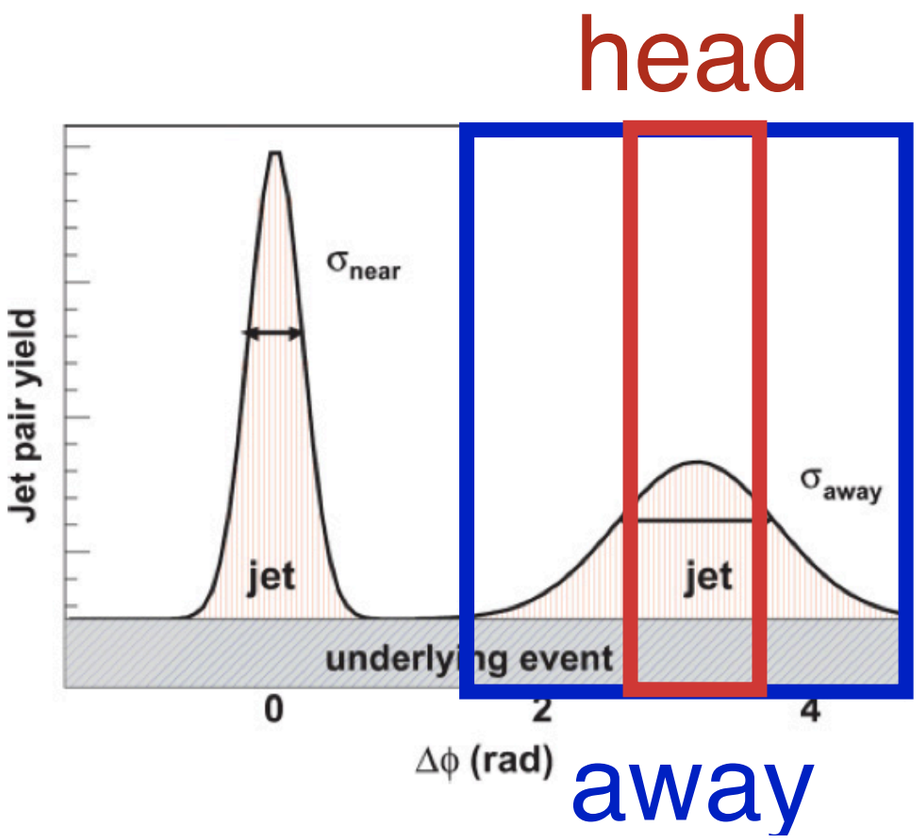

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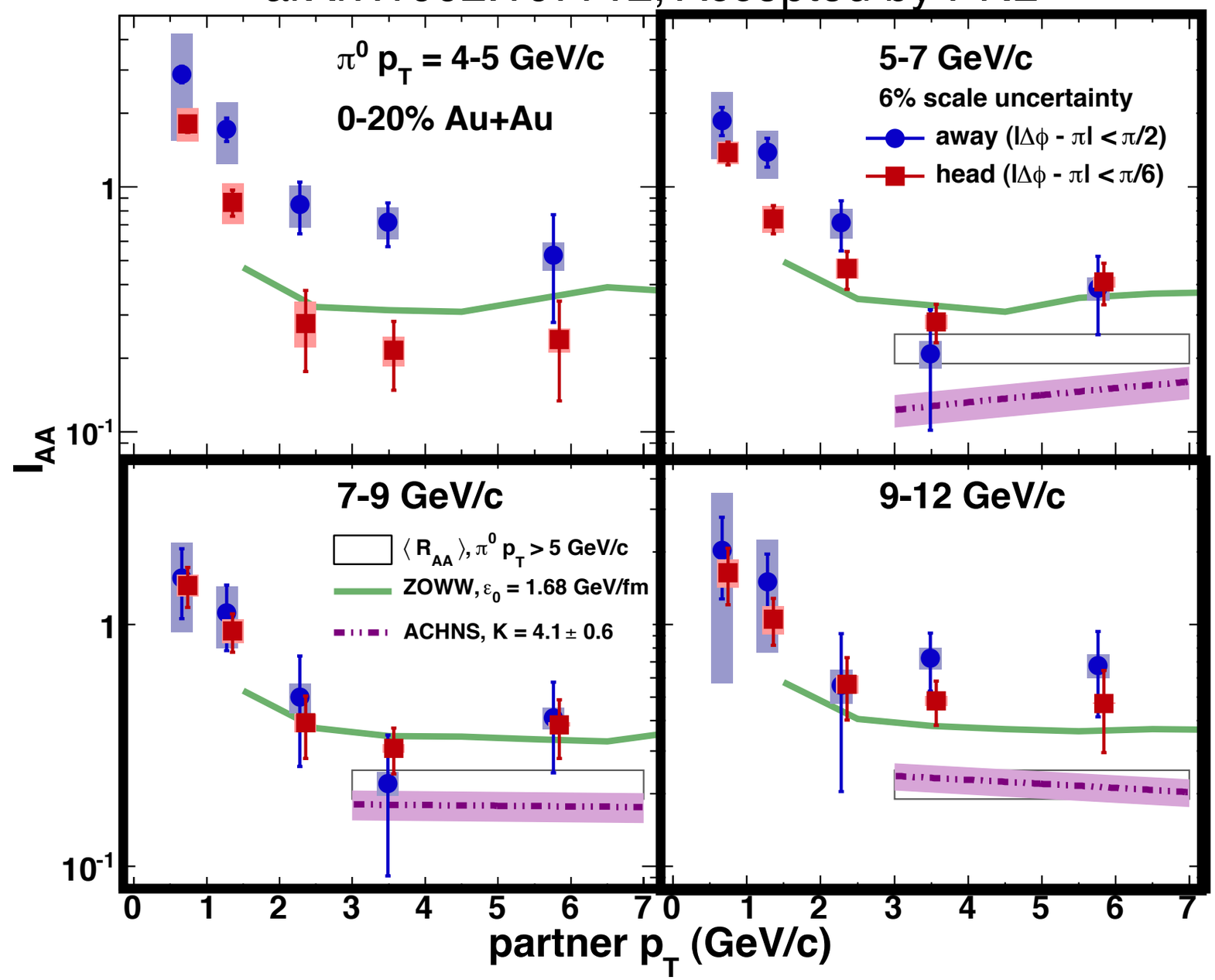
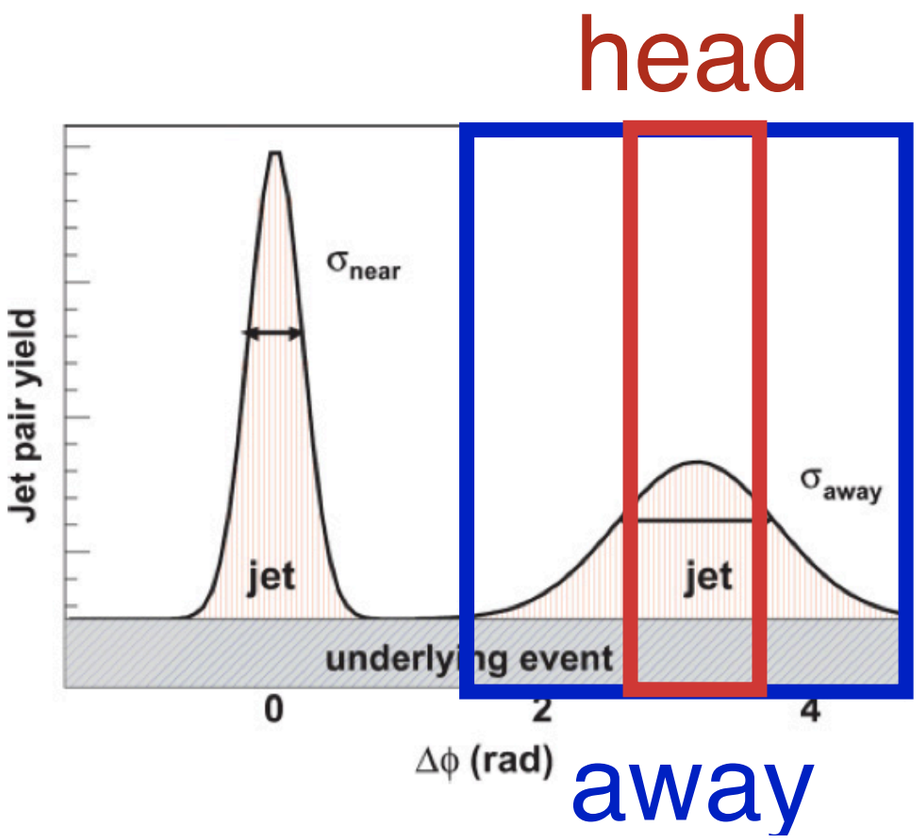


No shape change implies: $I_{AA}^{away} = I_{AA}^{head}$

Away-side I_{AA}

$$I_{AA} = \frac{(N^{ta}/N^{t})_{Au+Au}}{(N^{ta}/N^{t})_{p+p}}$$



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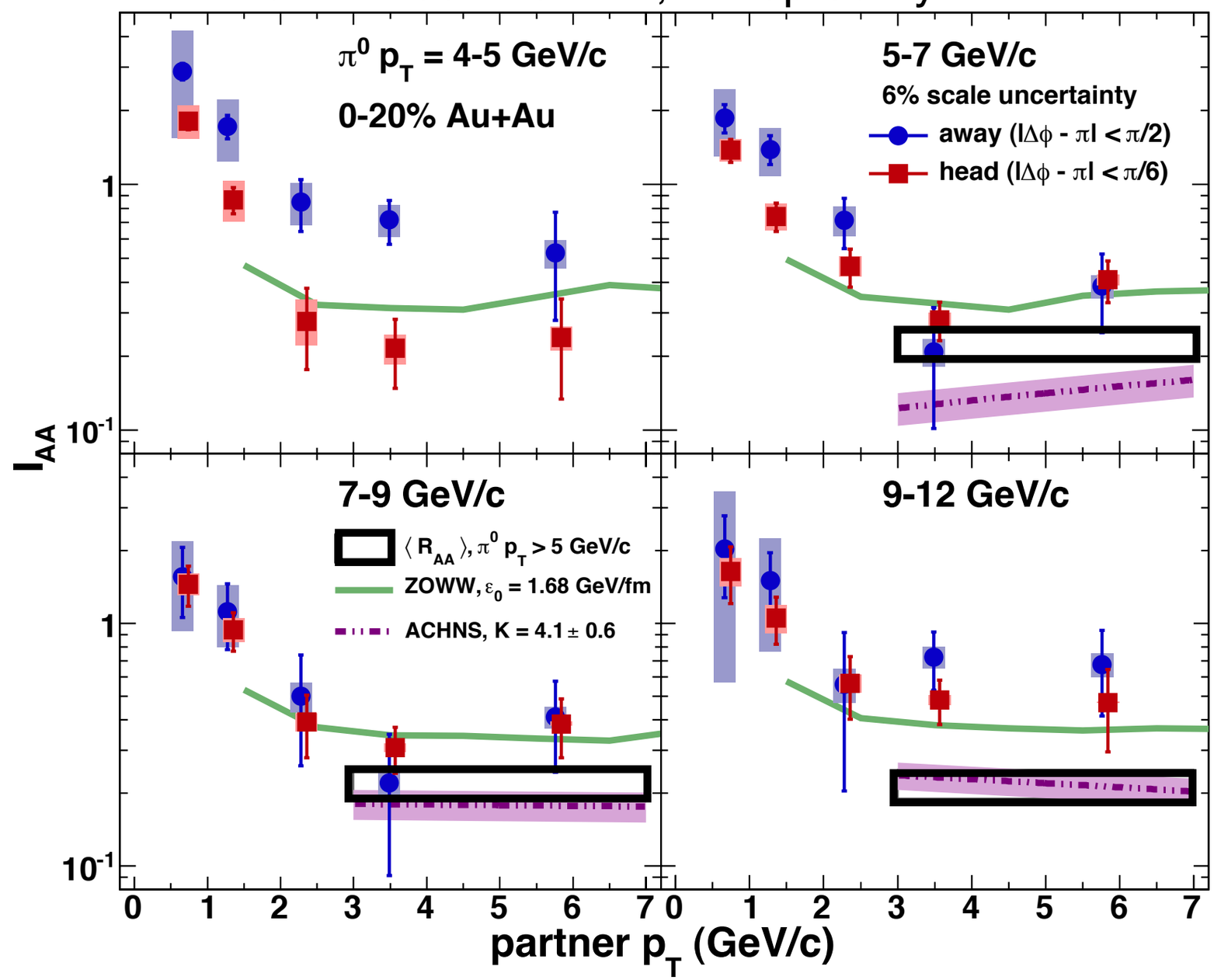
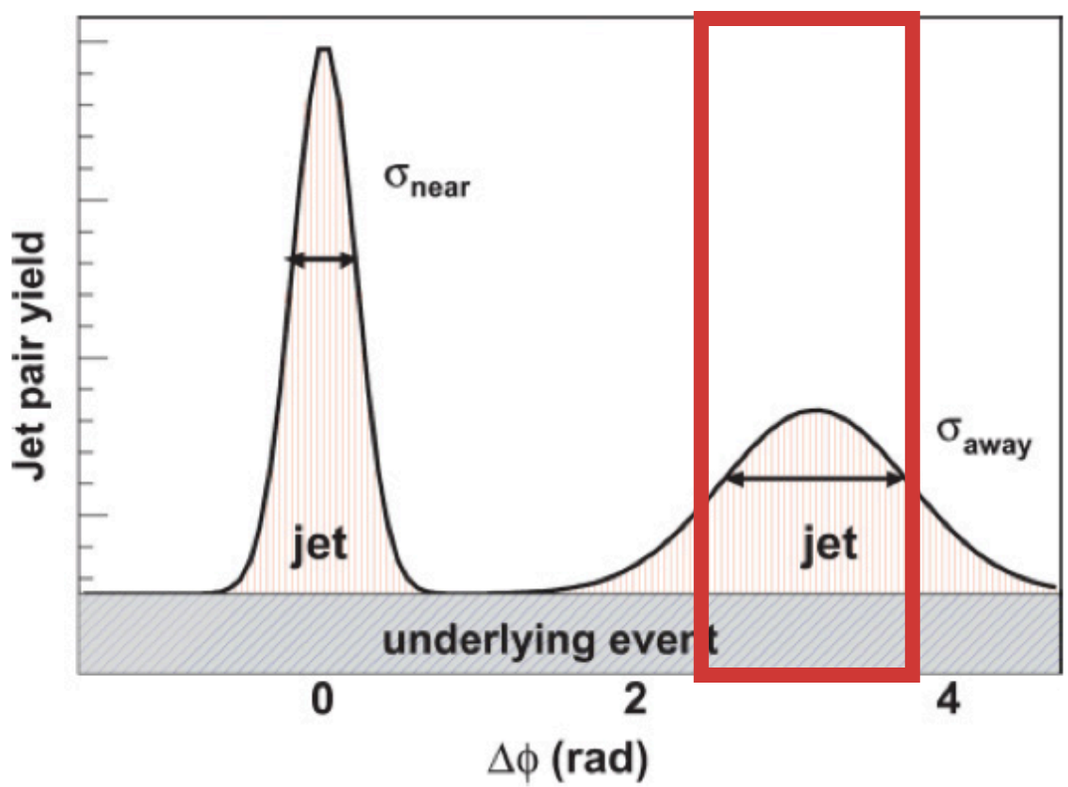


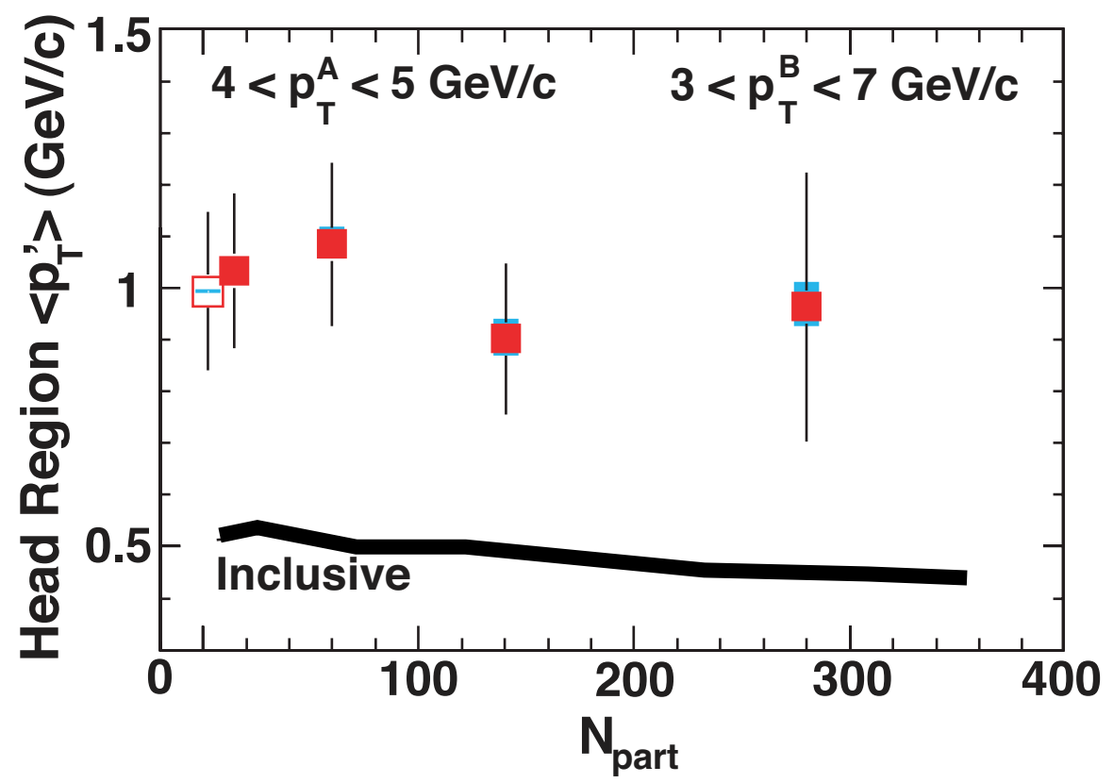
Observation: Surprisingly at high p_T, $I_{AA} > R_{AA}$

How can $I_{AA} > R_{AA}$?

Important: Conditional away-side spectra are hard



PHYSICAL REVIEW C **78**, 014901 (2008)



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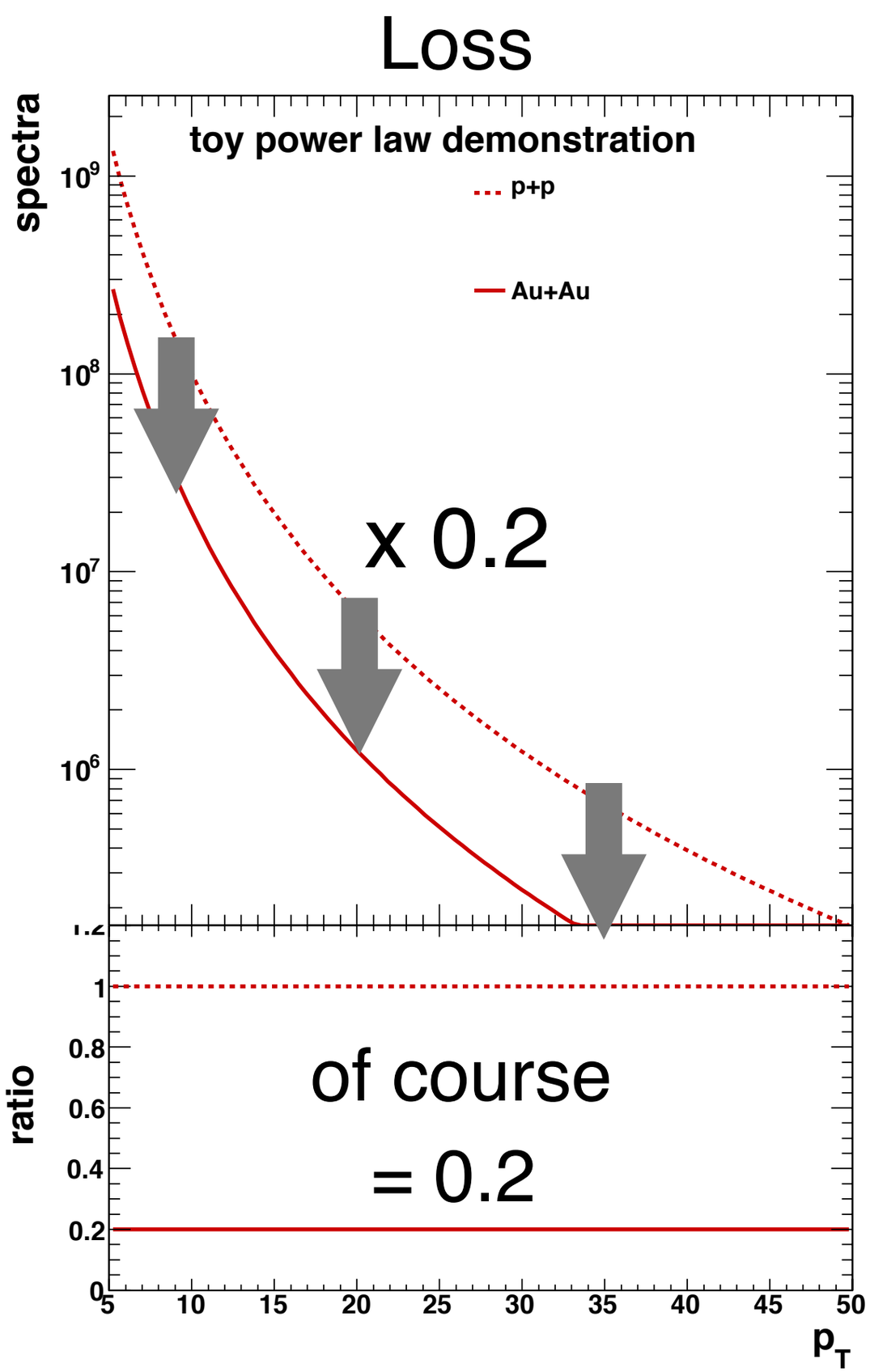

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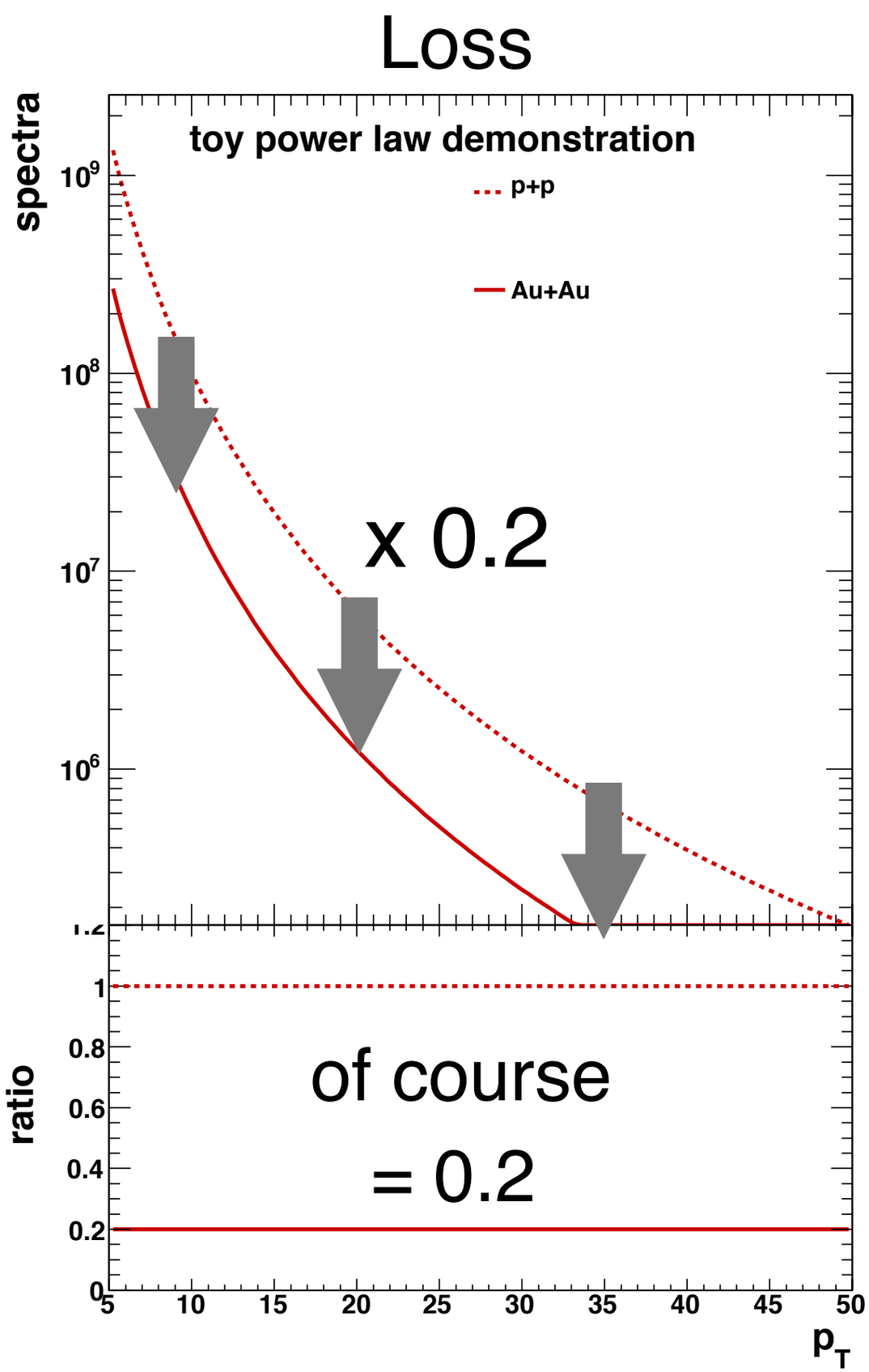

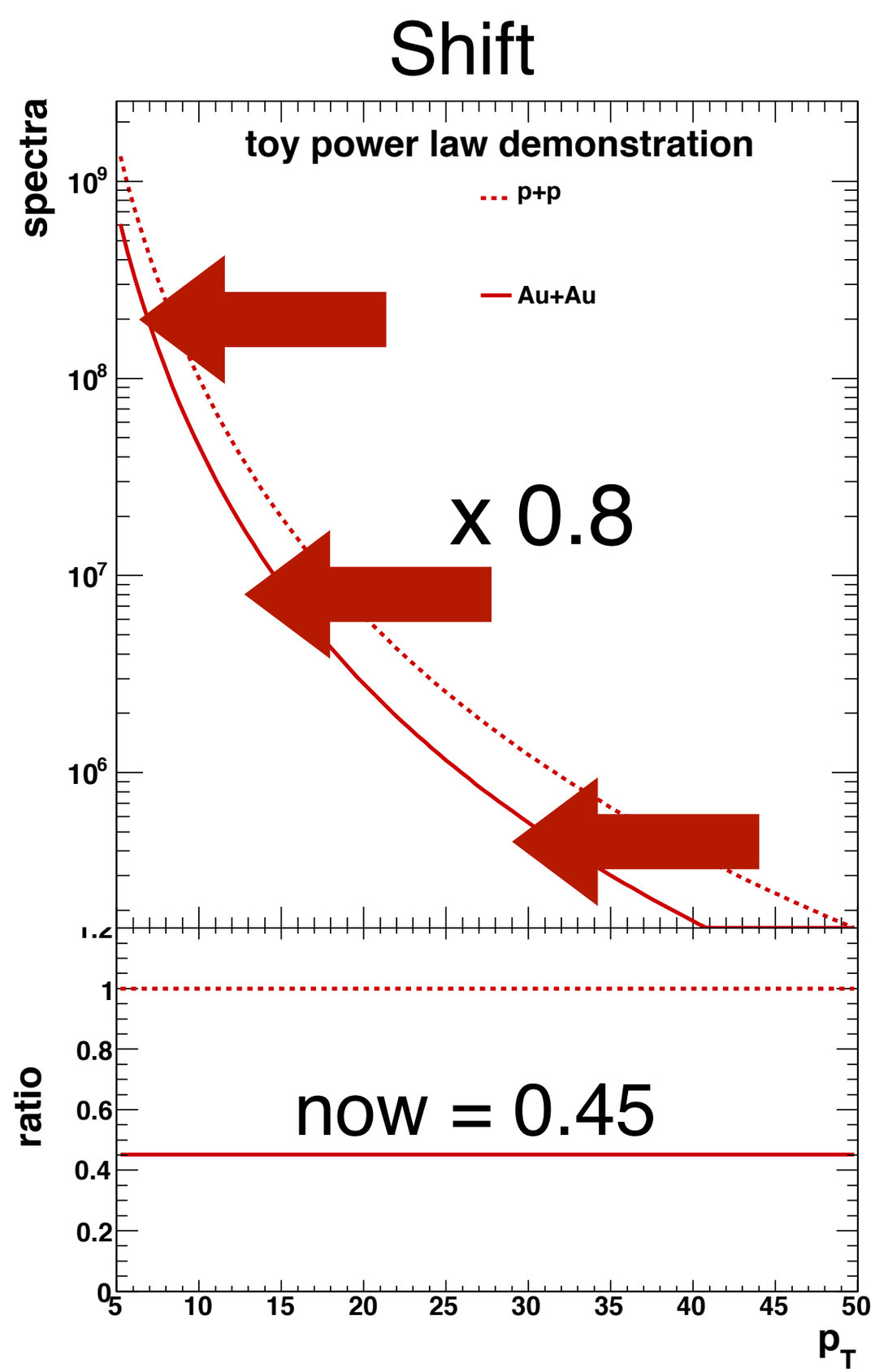

Away-side I_{AA}

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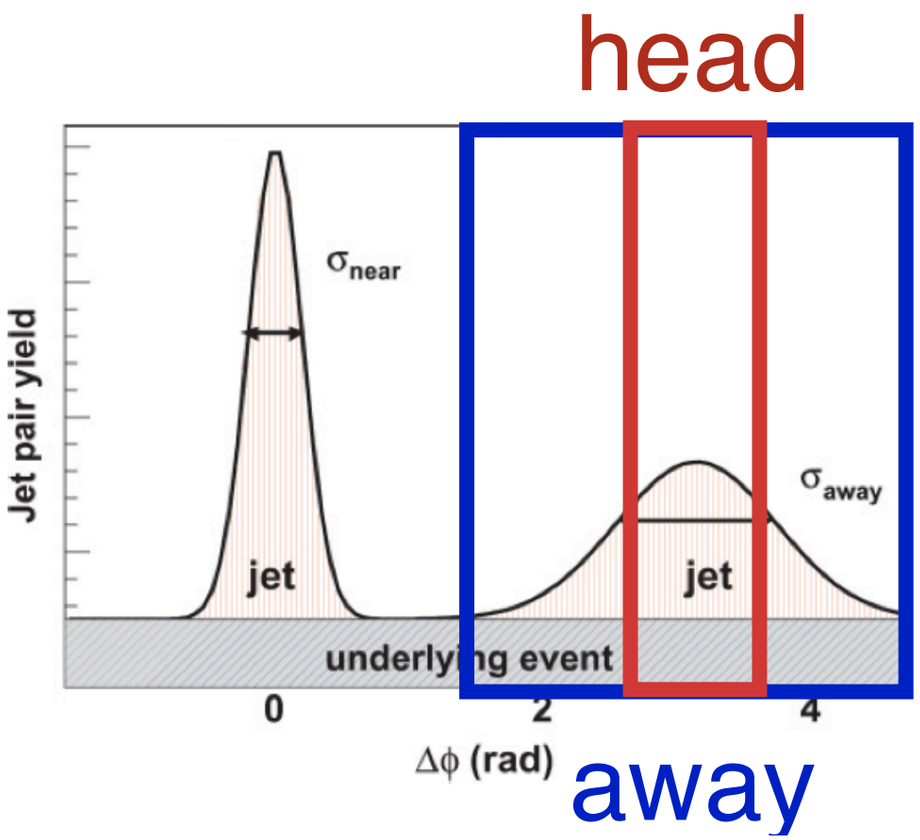

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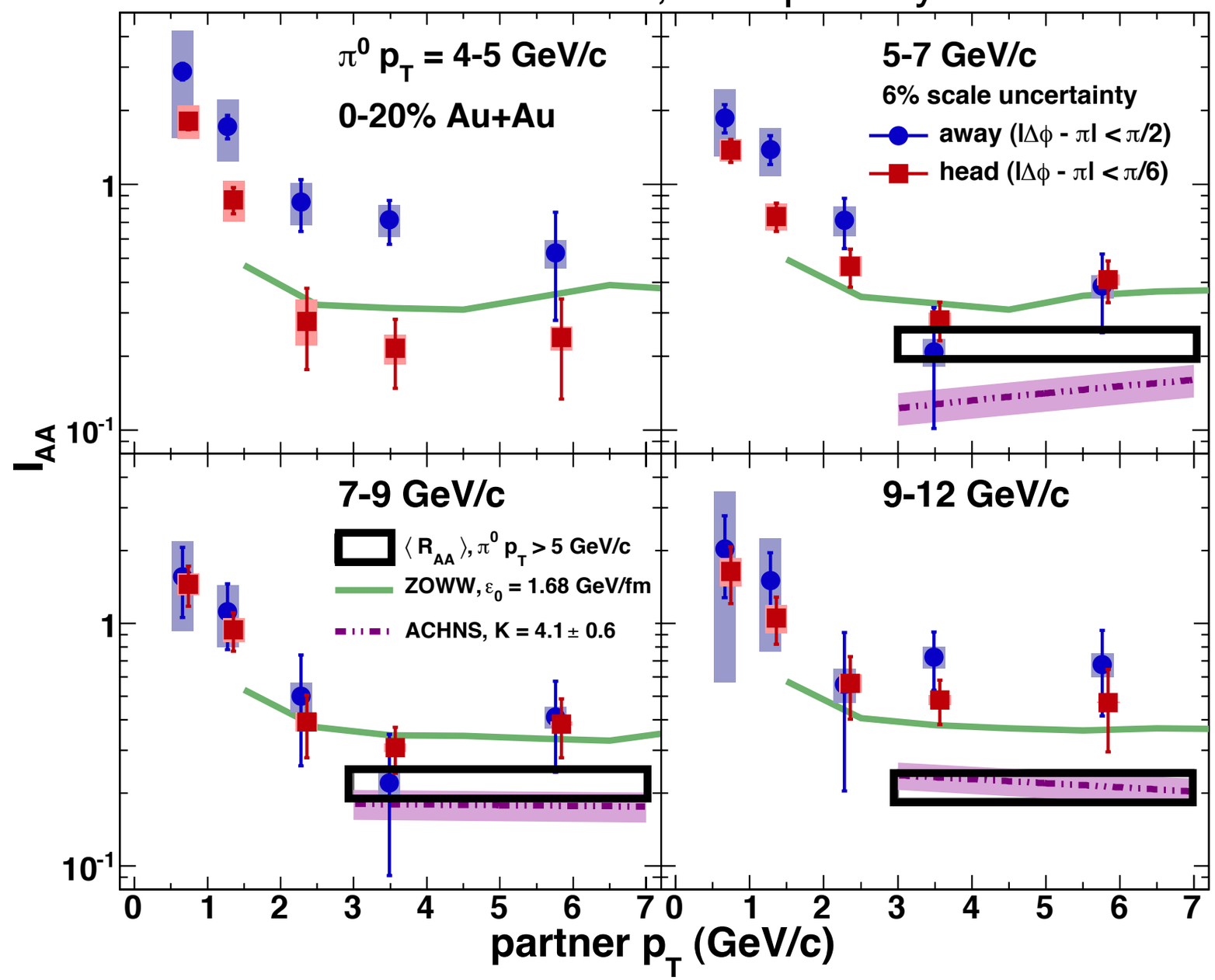
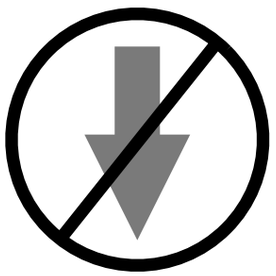


Observation: Surprisingly at high p_T, $I_{AA} > R_{AA}$

No longer fully consistent with pure loss

Energy loss in the act!



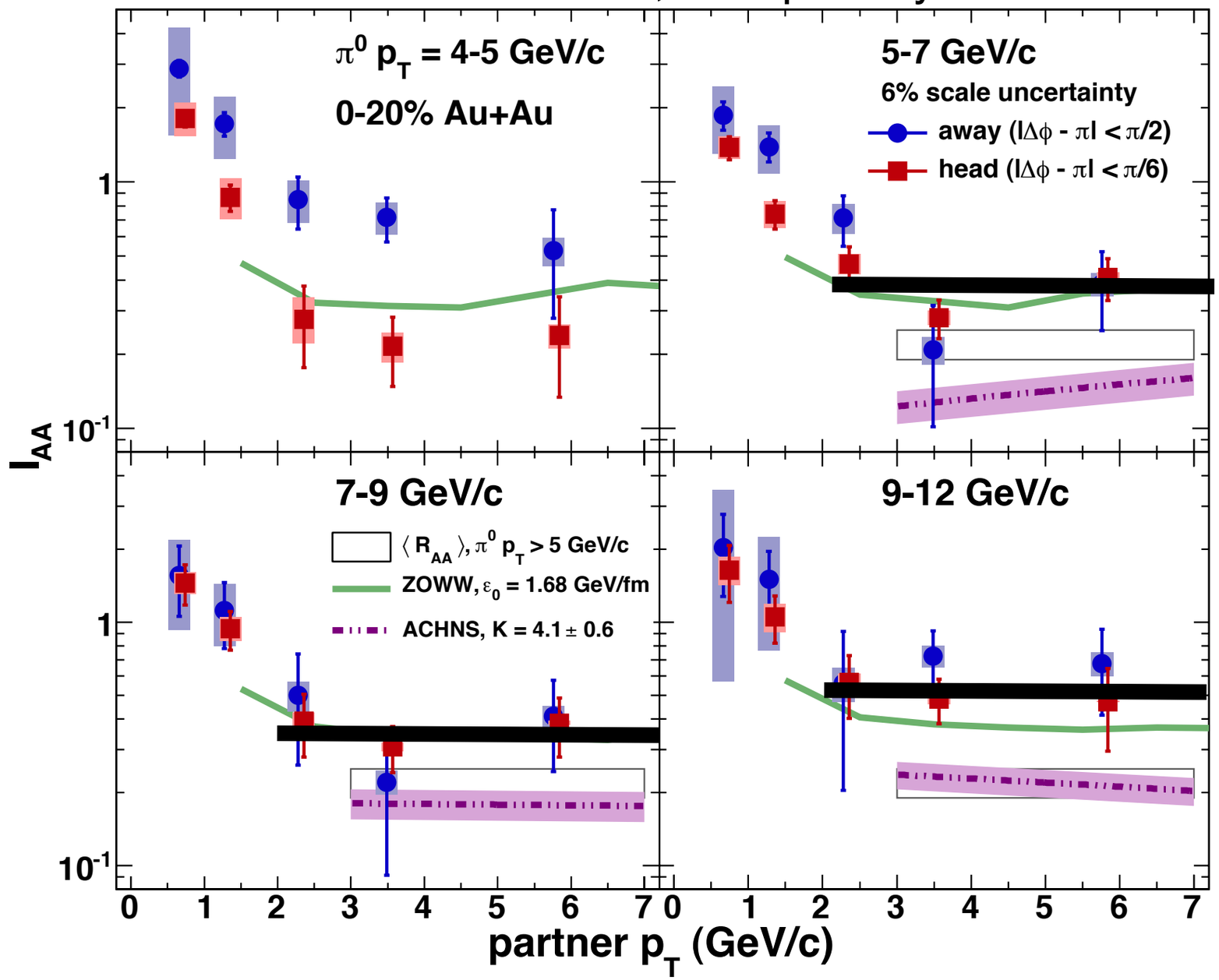
Away-side I_{AA}

Increasing trigger p_T:

- further hardens the away-side spectrum

- results in larger I_{AA} values

arXiv:1002.1077v2, Accepted by PRL



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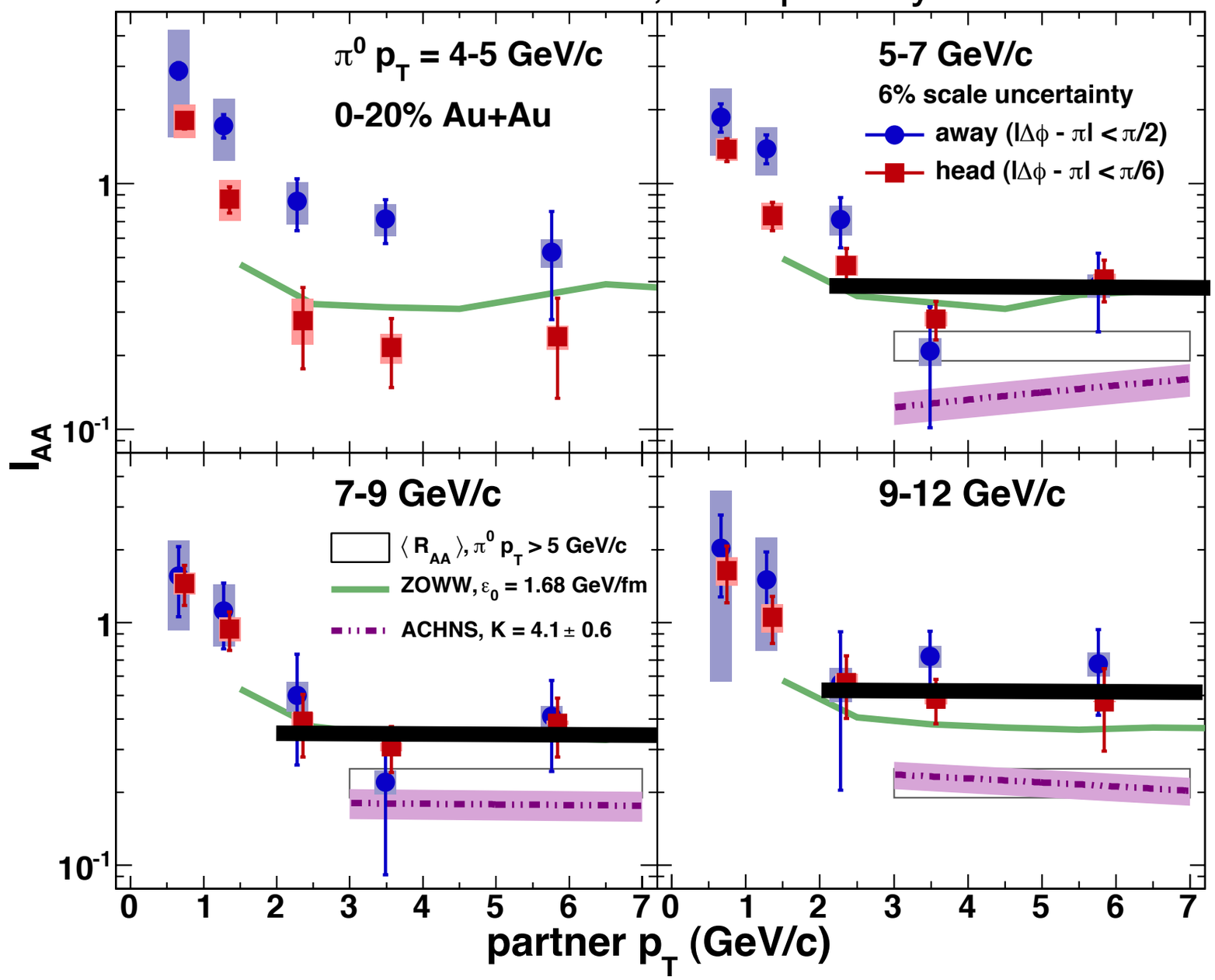


increasing p_T^t

	Cent 0–20%			Cent 20–60%		
p_T^t	I_{AA}^{head}	$\pm\sigma_{stat}$	$\pm\sigma_{syst}$	I_{AA}^{head}	$\pm\sigma_{stat}$	$\pm\sigma_{syst}$
5–7	0.35	0.04	0.03	0.55	0.02	0.04
7–9	0.34	0.05	0.03	0.64	0.04	0.02
9–12	0.50	0.08	0.02	0.73	0.06	0.02

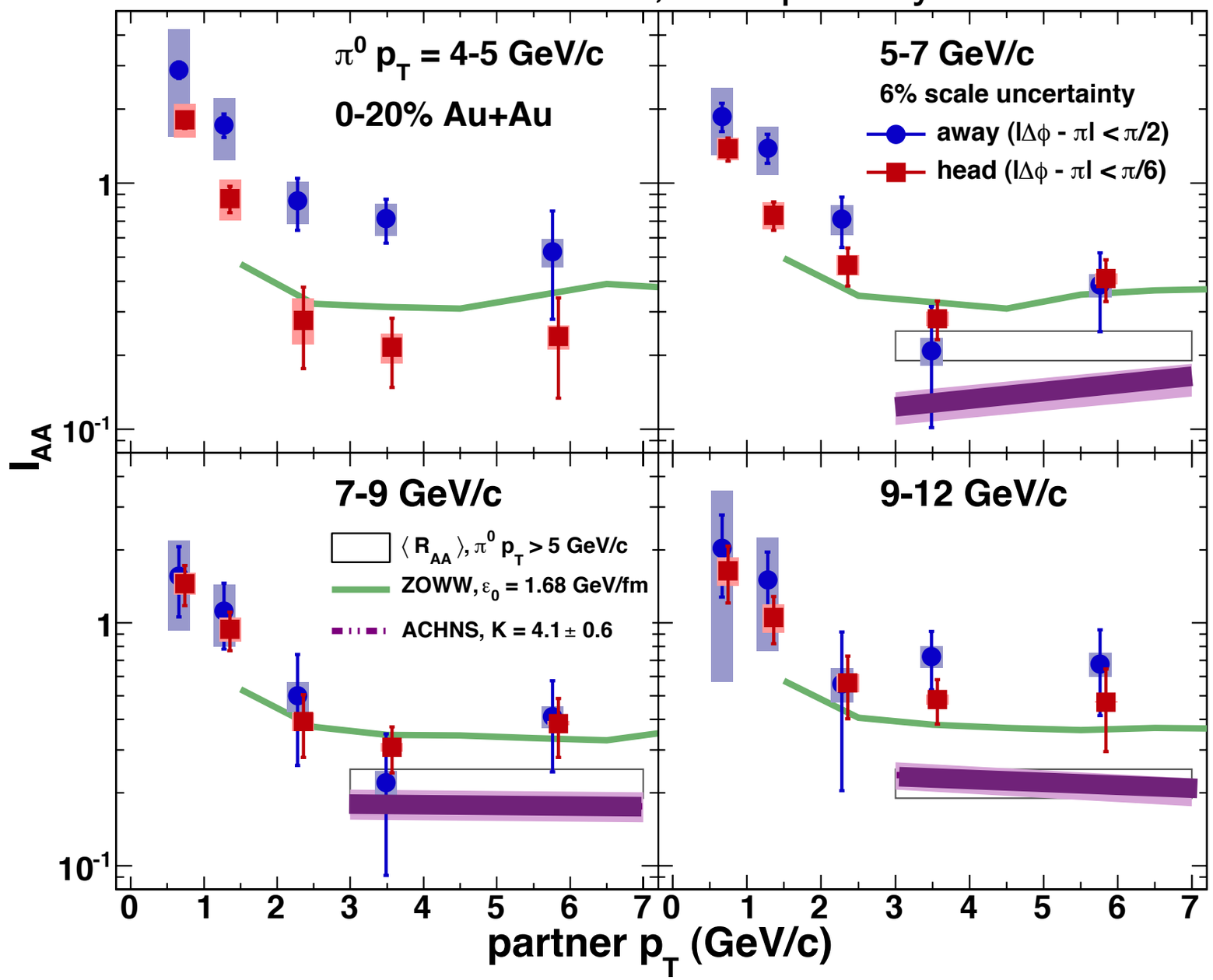
Theoretical Away-side I_{AA}

arXiv:1002.1077v2, Accepted by PRL

ACHNS

Consistently falls below data

ASW energy loss + full hydro evolution (gives correct R_{AA})



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Consistently falls below data

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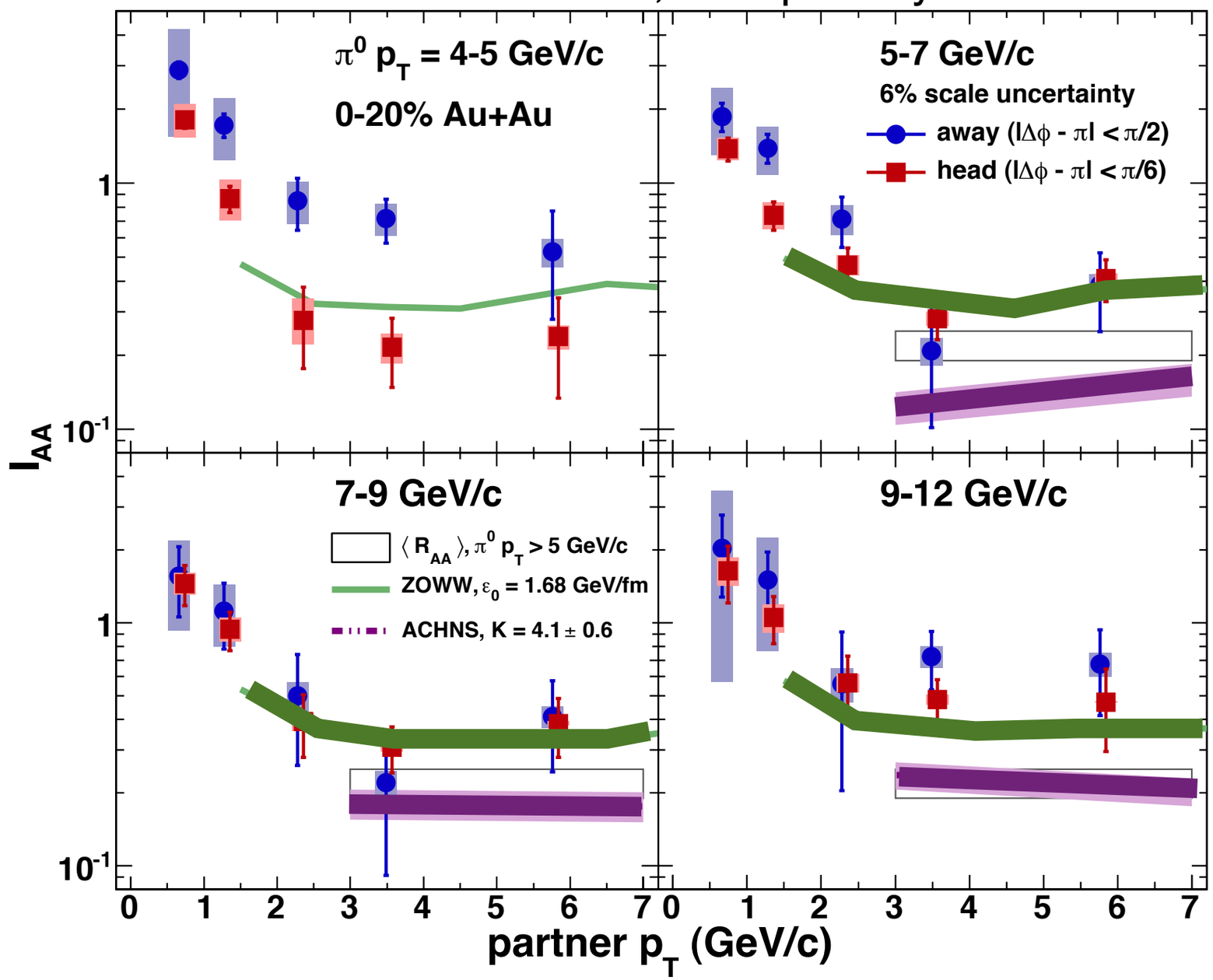
ZOWW

Follows data reasonably well

Uses a simple hard sphere geometry



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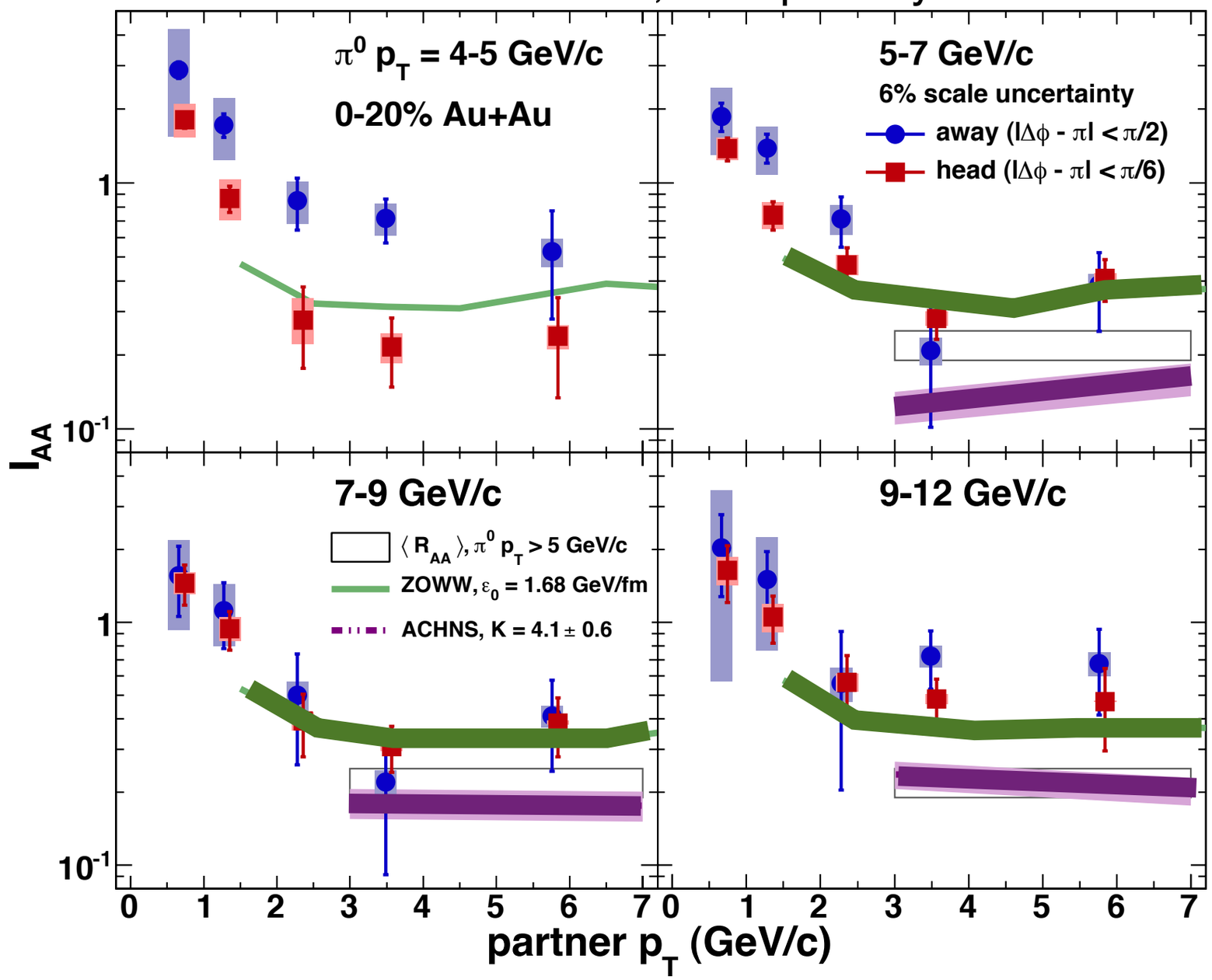

Is energy loss or medium geometry the crucial difference?

Theoretical Away-side I_{AA}

arXiv:1002.1077v2, Accepted by PRL

ACHNS

Consistently falls below data

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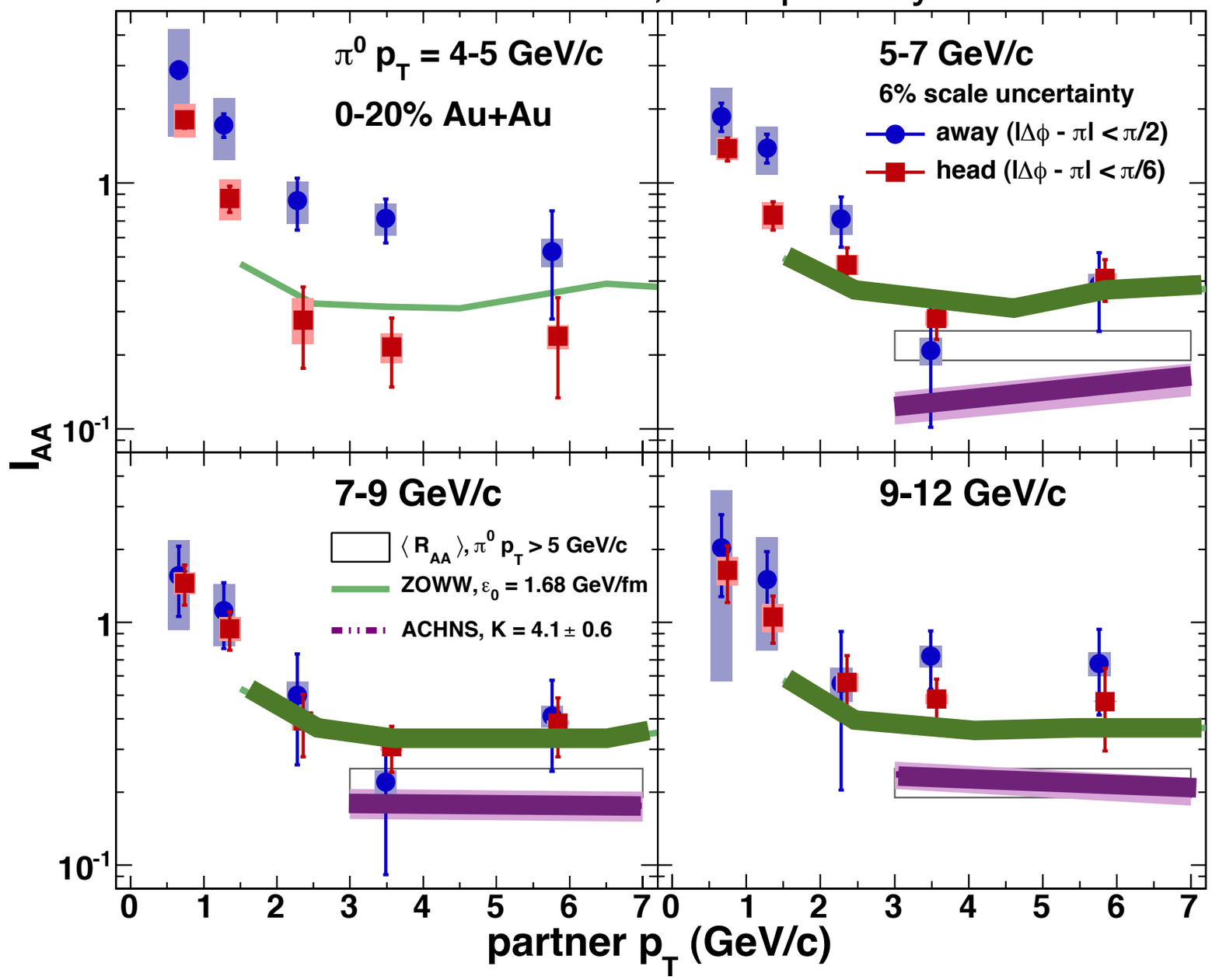


Is energy loss or medium geometry the crucial difference?

Any full description requires realistic: geometry, spectra, energy loss

Pinning Down the Geometry...

So how do we catch energy loss **in the act**?

4 basic high p_T measurements above "medium response" of:

	Energy Loss Mechanism	Event Geometry
Single particle	$\cancel{R_{AA}}$	$R_{AA}(\Phi_s)$, v_2
Two particle	I_{AA}	$I_{AA}(\Phi_s)$, $v_2^{I_{AA}}$

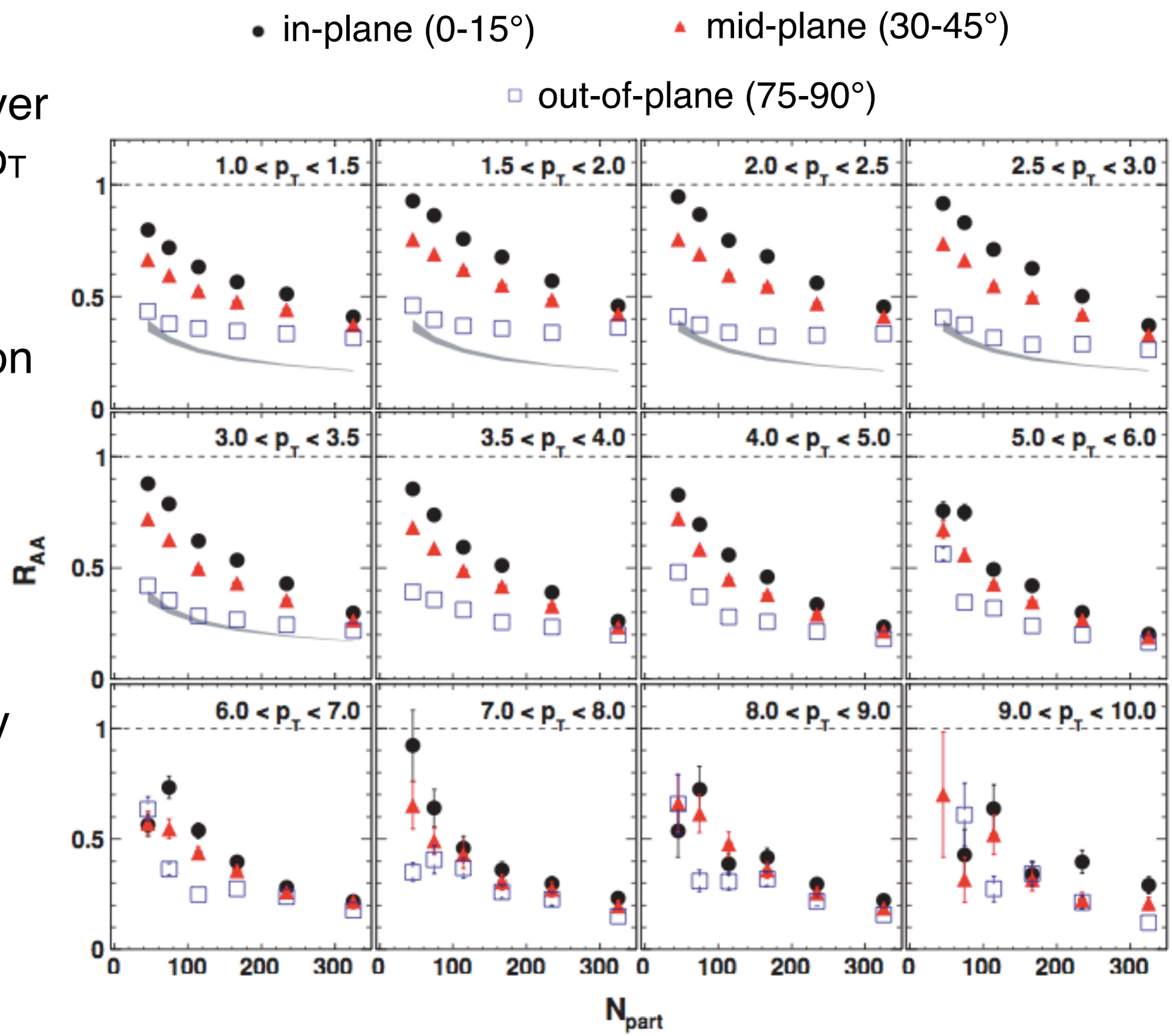
$R_{AA}(\Phi_S)$

Measurement over a large span of p_T

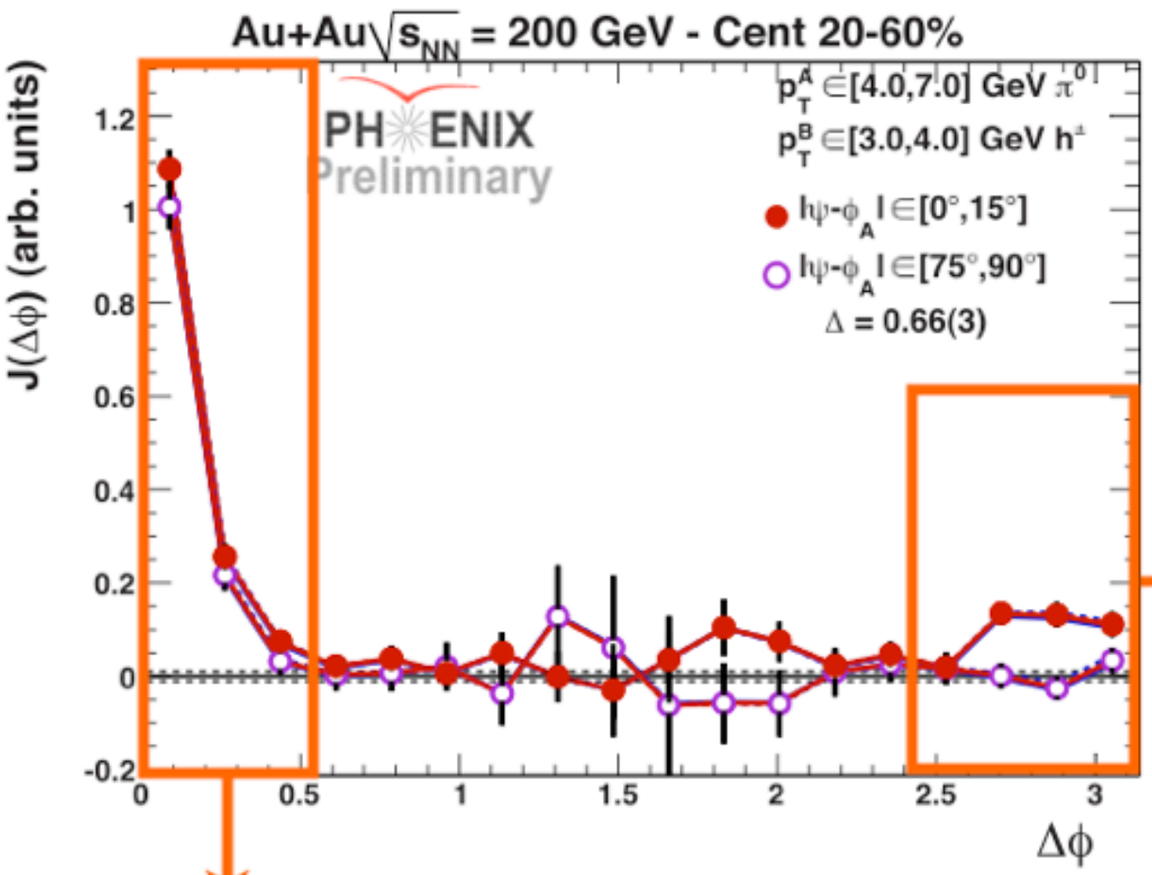
Low p_T
Hydro evolution

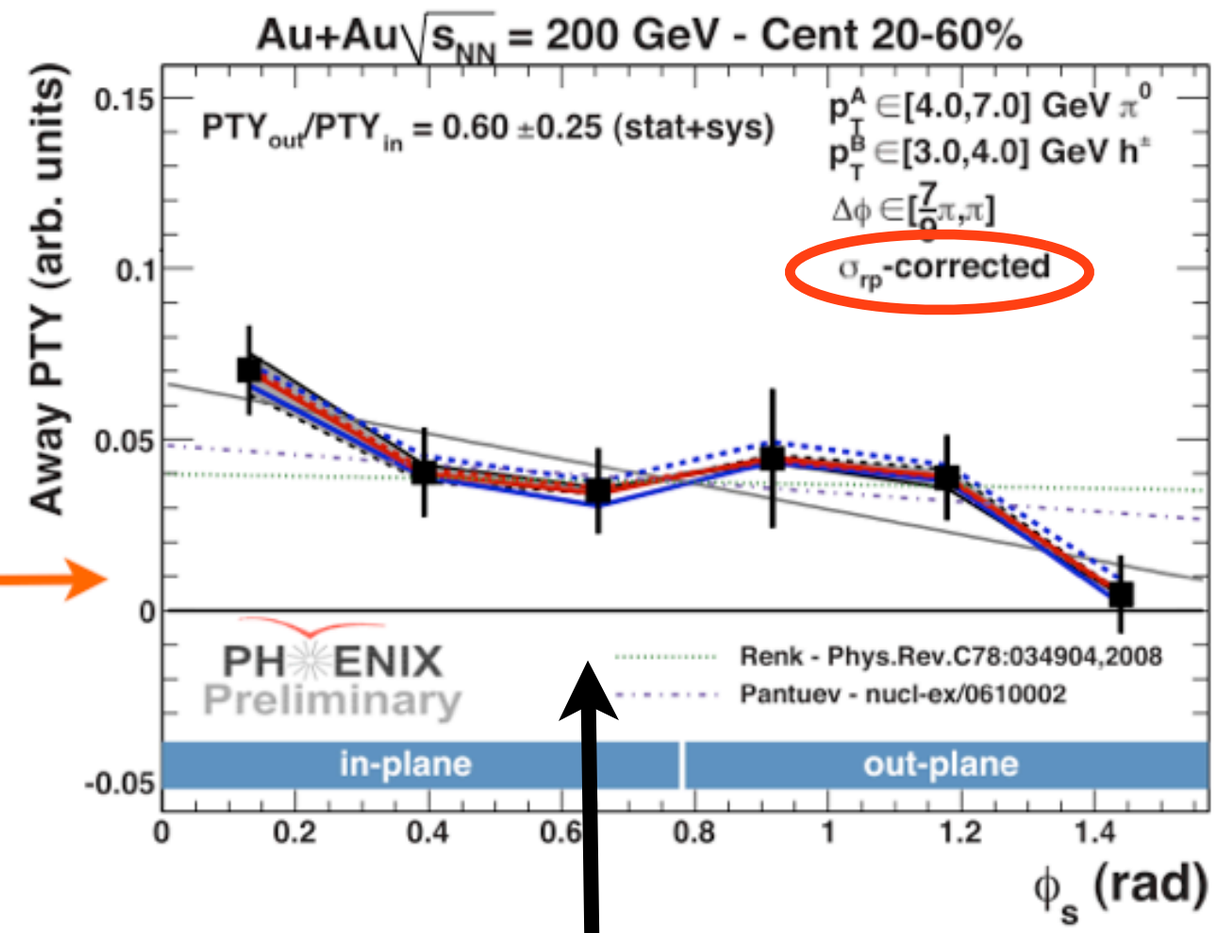
High p_T
Jet quenching

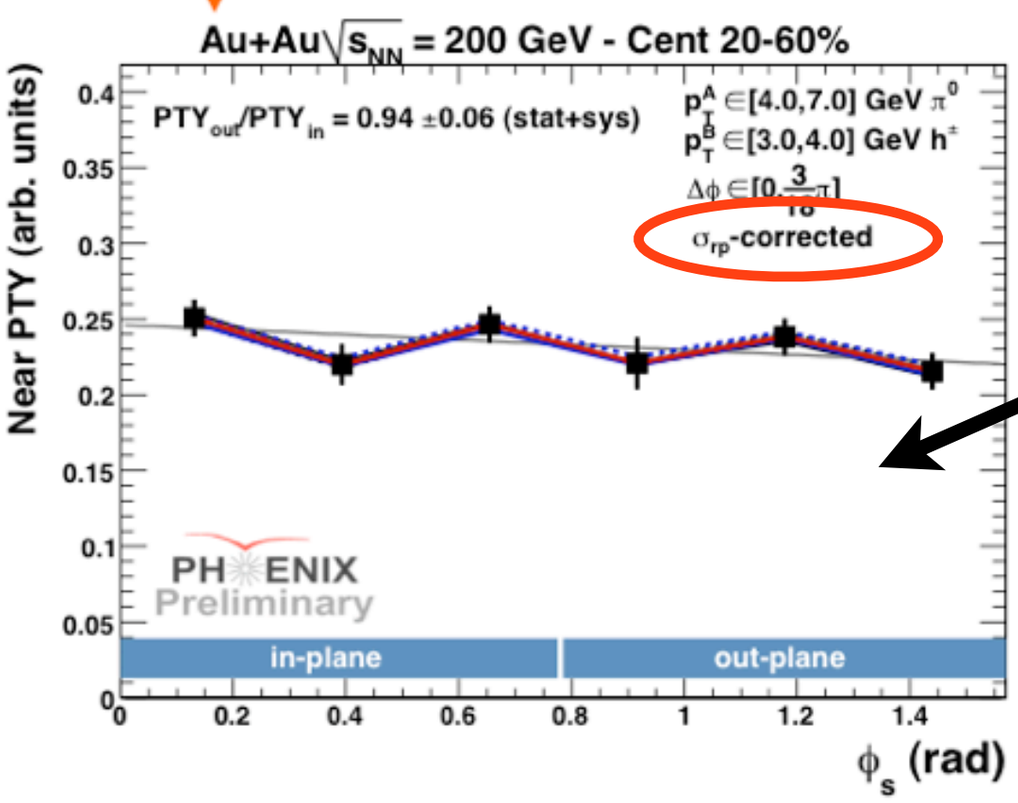
Event geometry
+
path-length dependence



Away-side PTY(Φs)







falling away-side trend

insignificant near-side trend

Particle selections just above the medium response

- π^0 triggers: 4-7 GeV/c
- $h^\pm$ partners: 3-4 GeV/c

Beyond the Basics

So how do we catch energy loss **in the act**?

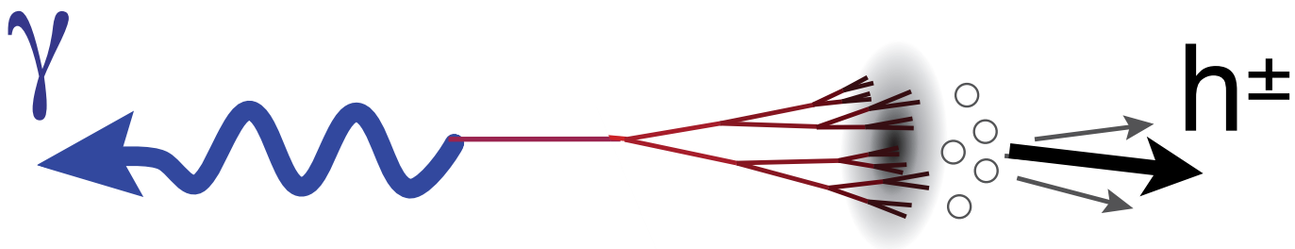
4 basic high p_T measurements above "medium respons

Can we get a second witness?

	Energy Loss Mechanism	Event Geometry
Single particle	R_{AA}	$R_{AA}(\Phi_s)$, v_2
Two particle	I_{AA}	$I_{AA}(\Phi_s)$, $v_2^{I_{AA}}$

Direct Photon Correlations

At leading order:



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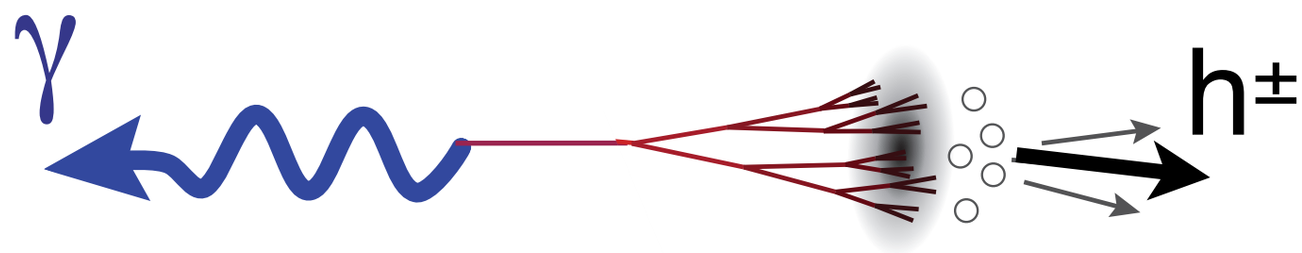
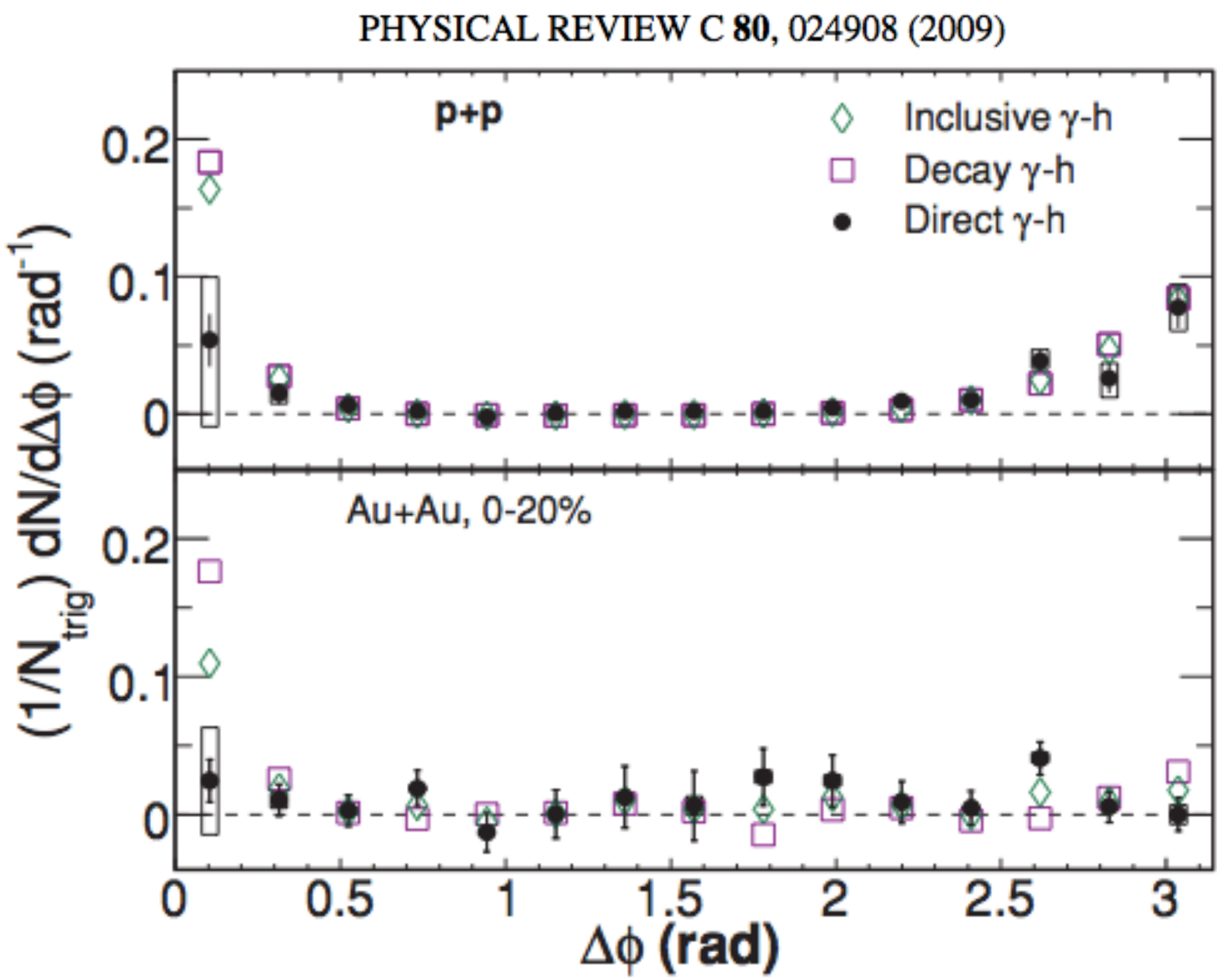


Direct γ-h:

Measured statistically

Dominated prompt photons

Little near-side yield (fragmentation photons)



Direct Photon Correlations

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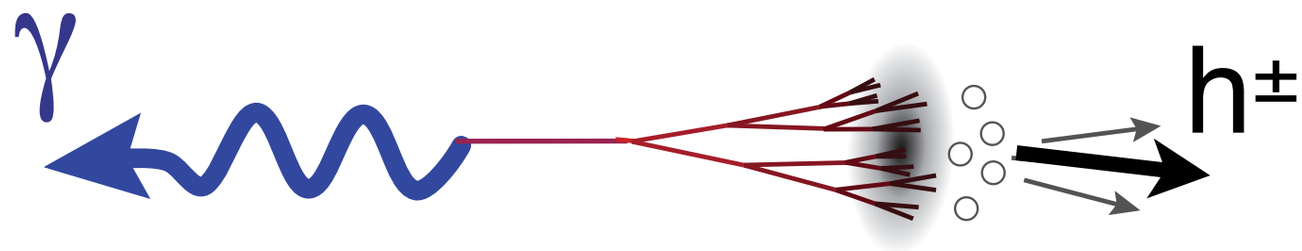


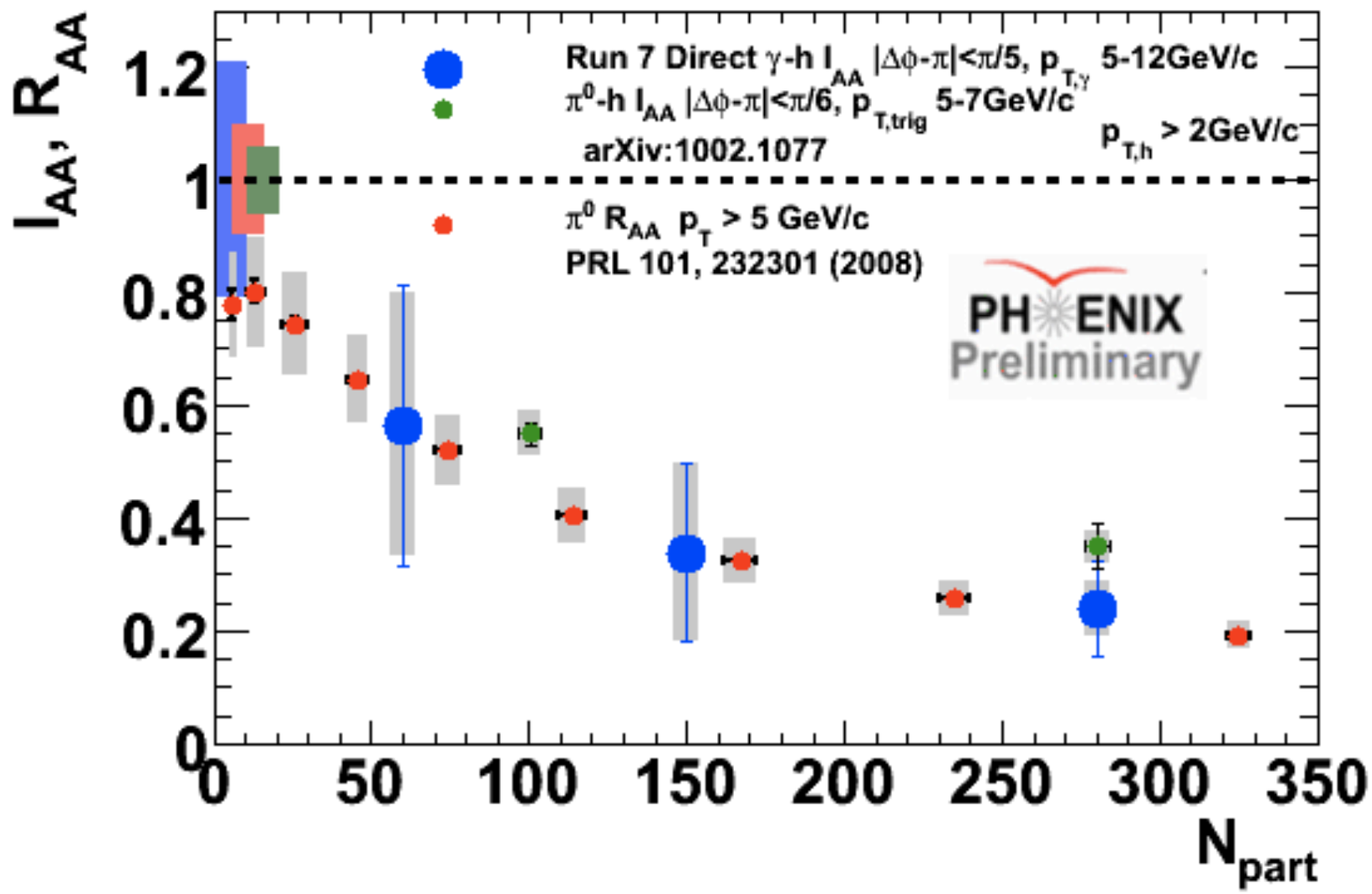
Away-side γ-h:

suppression similar to both R_{AA} and I_{AA}

similar path as R_{AA}

quark jet dominated

Megan Connors (PHENIX) QM09



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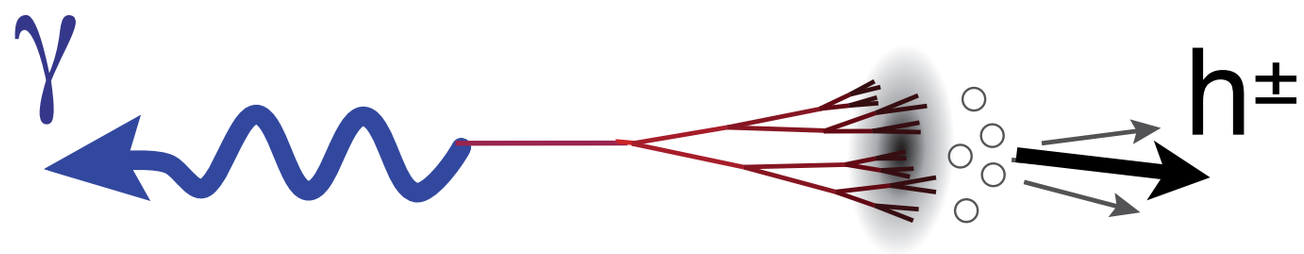


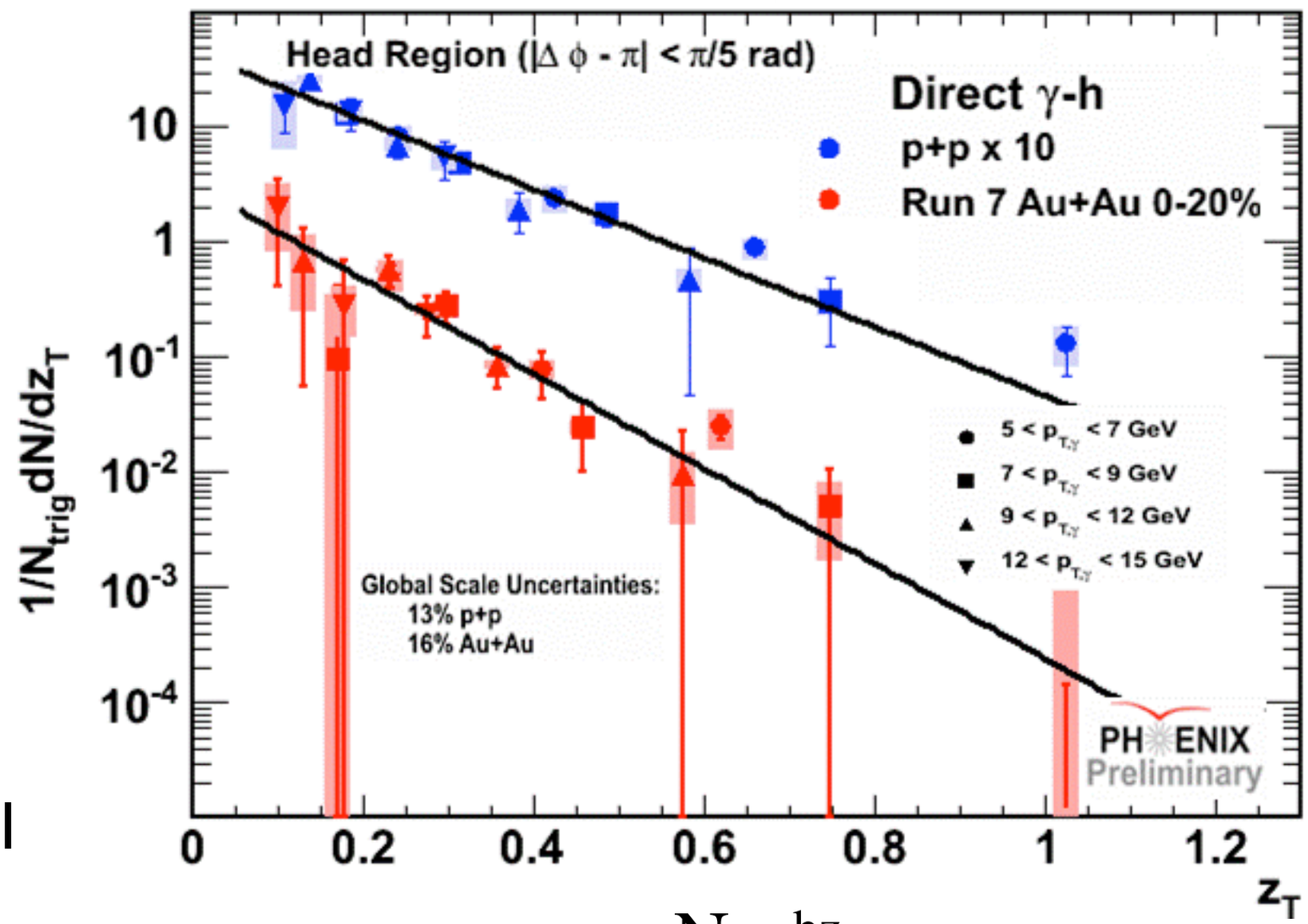
Megan Connors (PHENIX) QM09

Away-side γ-h:

suppression similar to both R_{AA} and I_{AA}

fragmentation function somewhat steeper than p+p (only 1.3σ significance)

improved experimental uncertainties pin down these trends

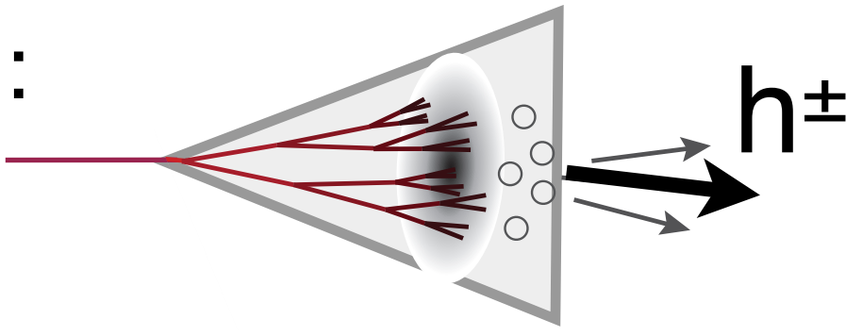


$$Ne^{-bz_T}$$

$b = 6.89 \pm 0.64$ $\quad$ $b = 9.49 \pm 1.37$

Jets and Partons

Another path to parton LO information:



Jets are not directly partons

but they are more closely connected than leading fragments

Jets and Partons

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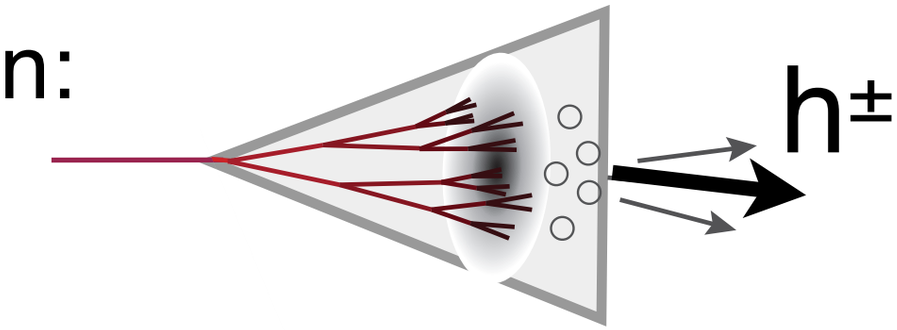

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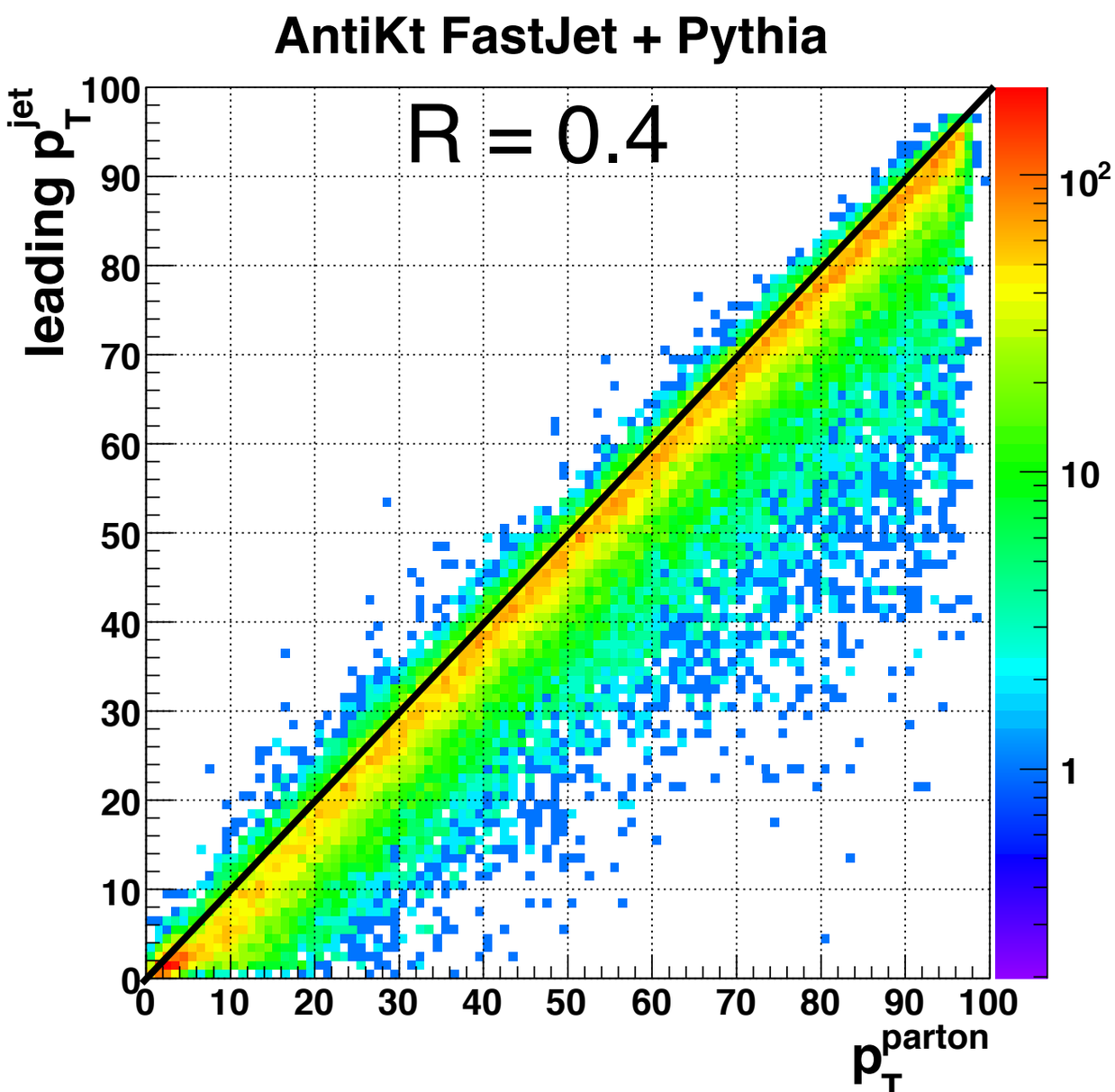

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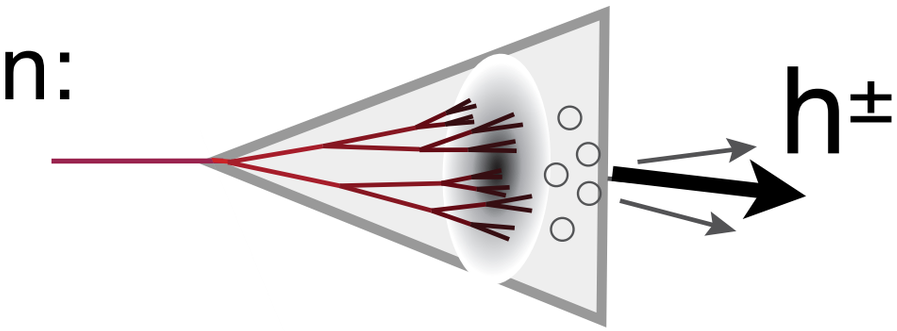

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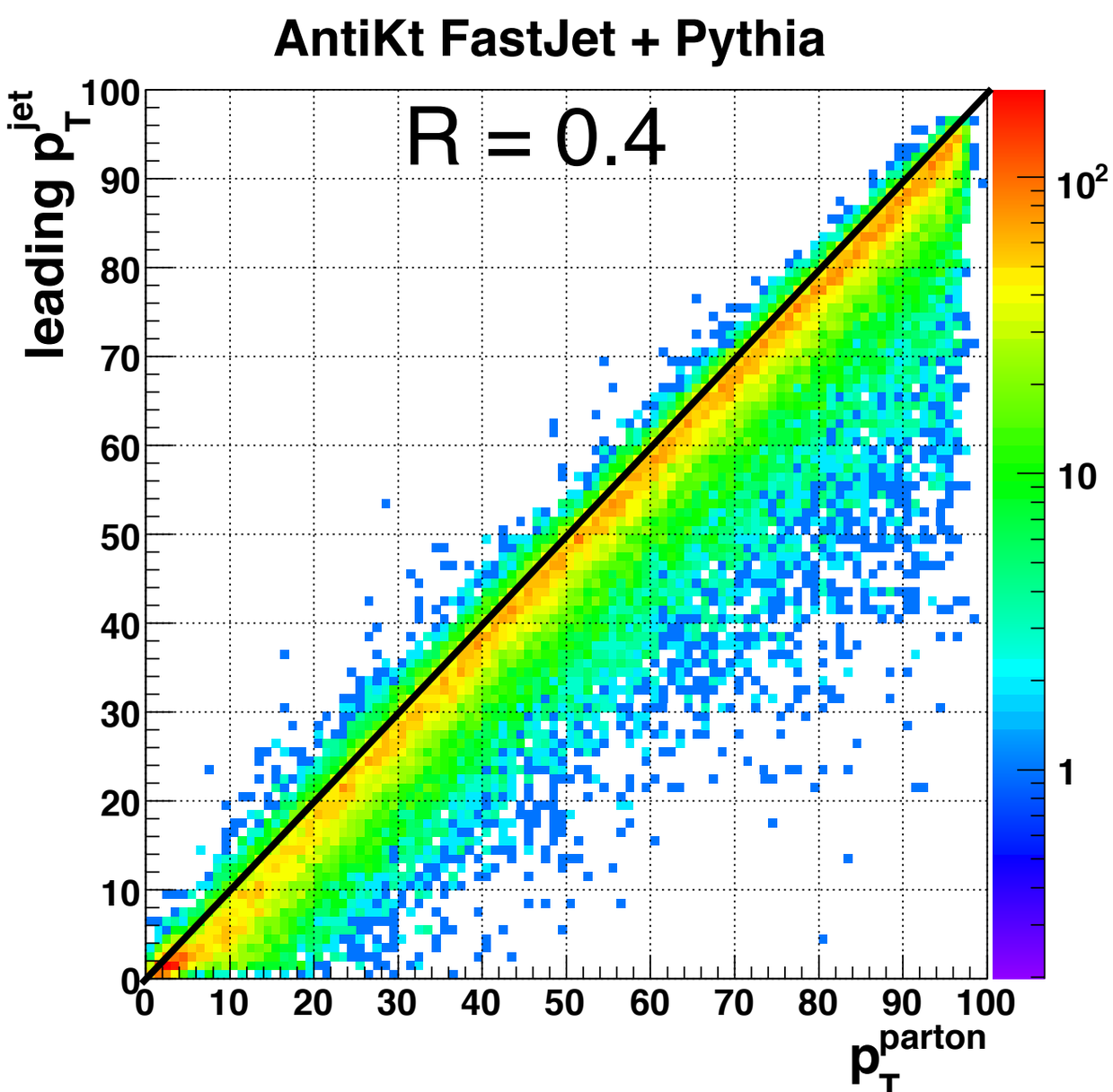

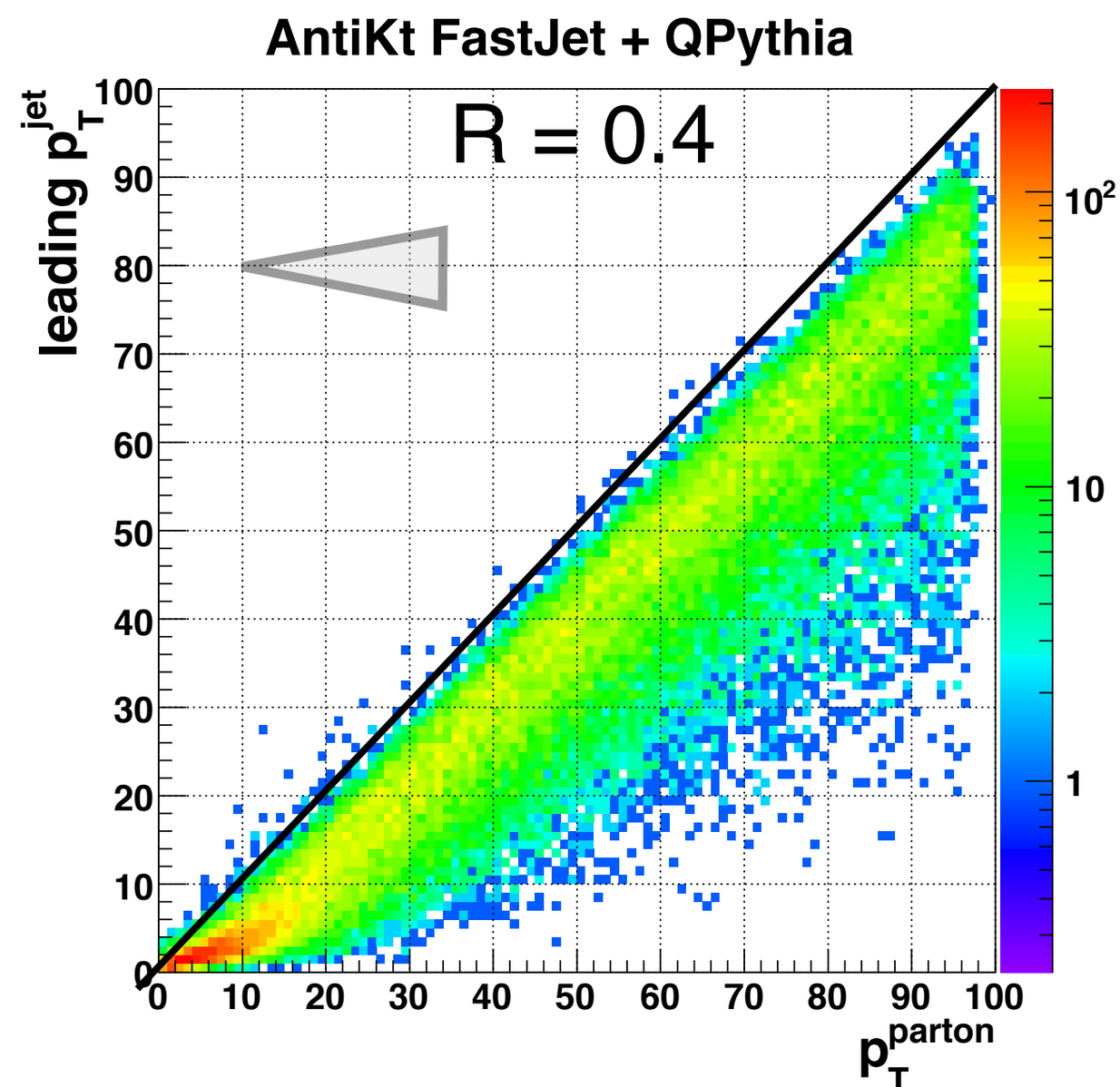

Jets and Partons

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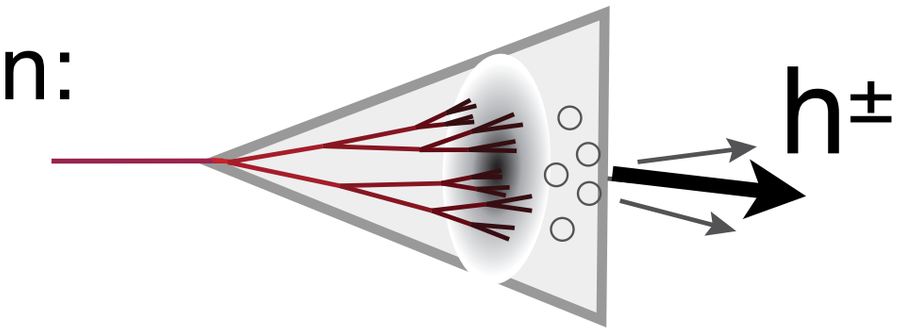

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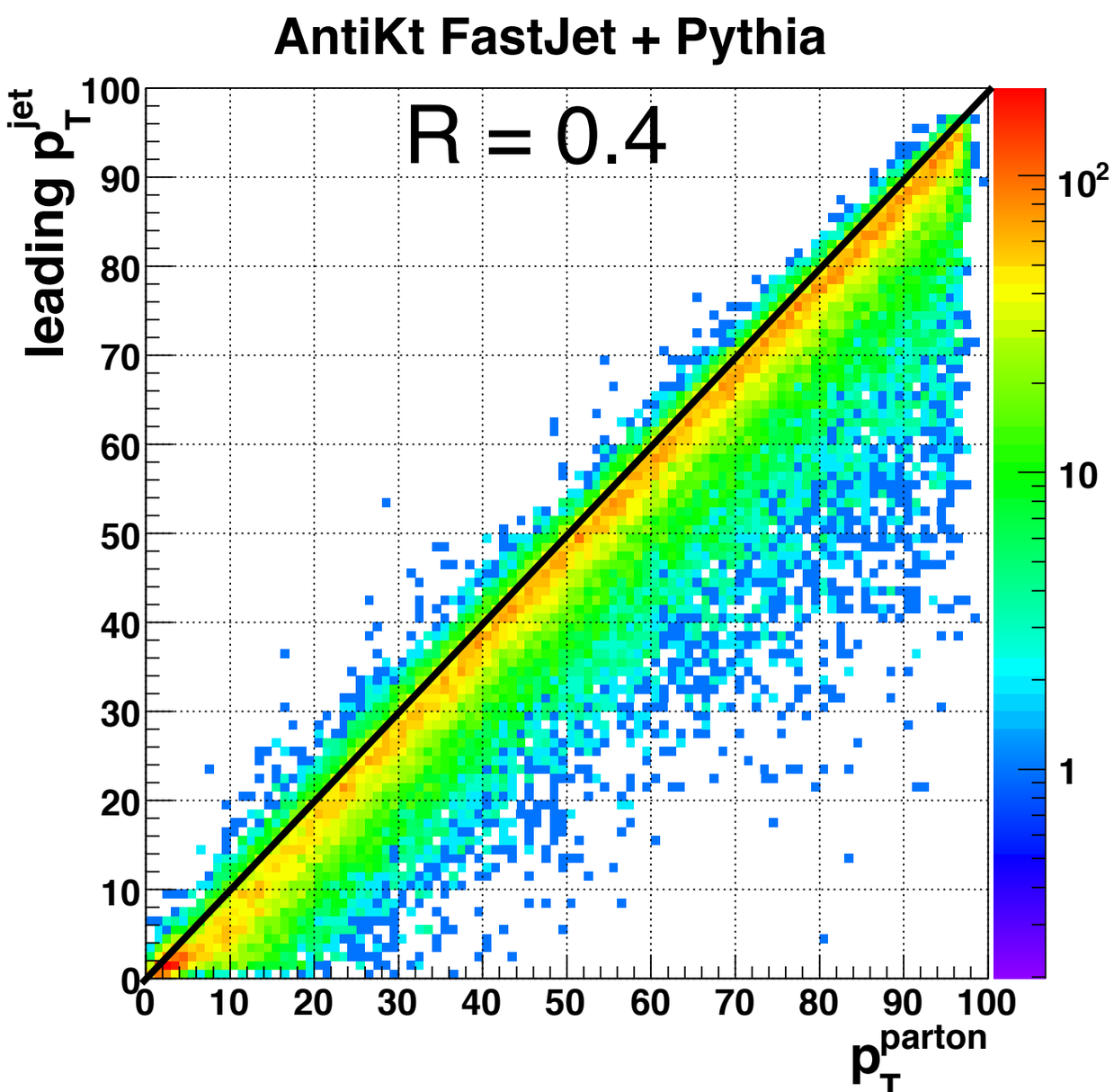

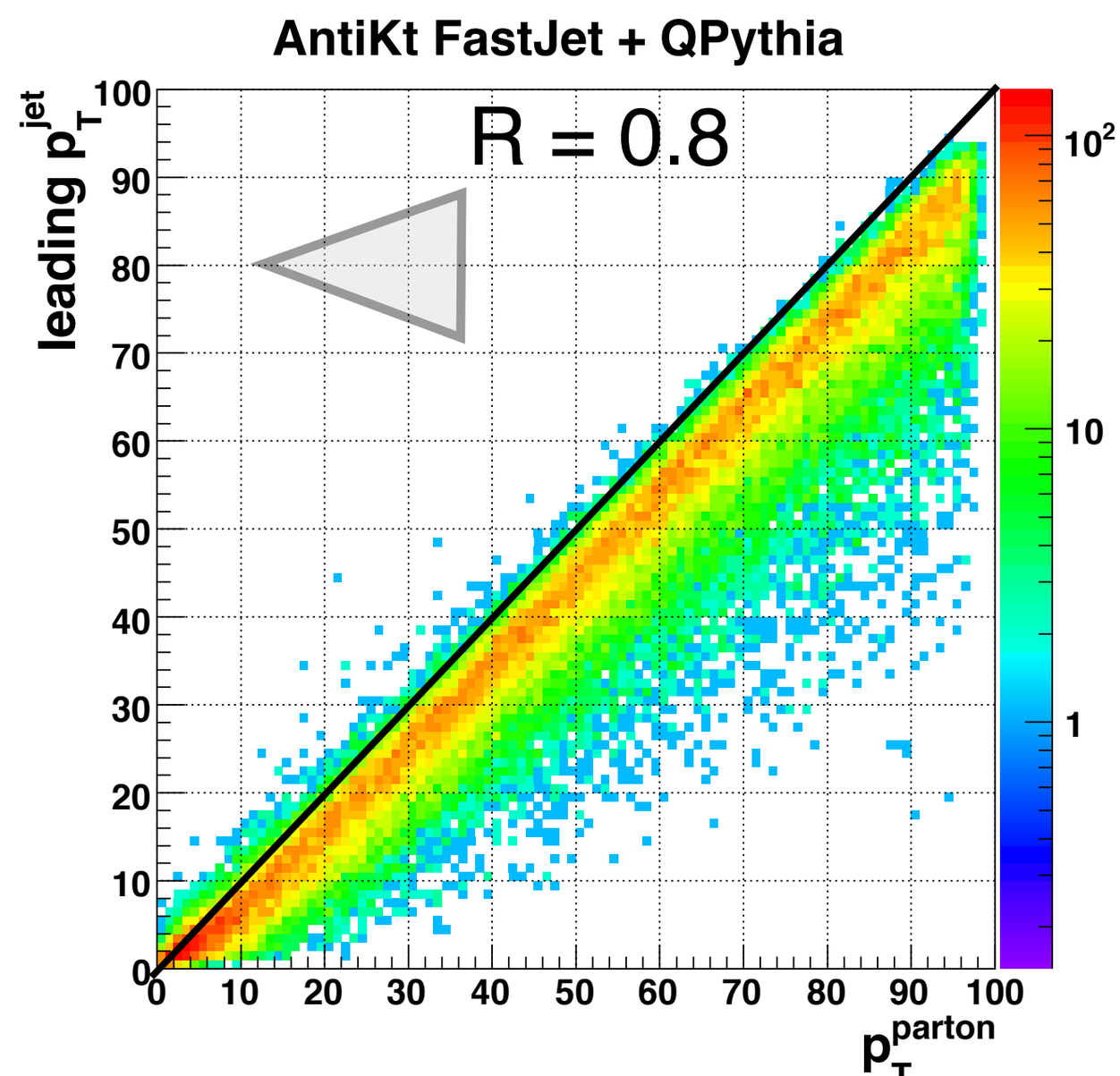

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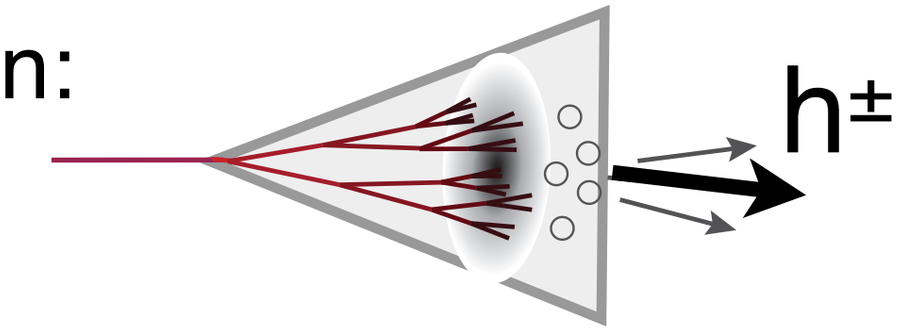
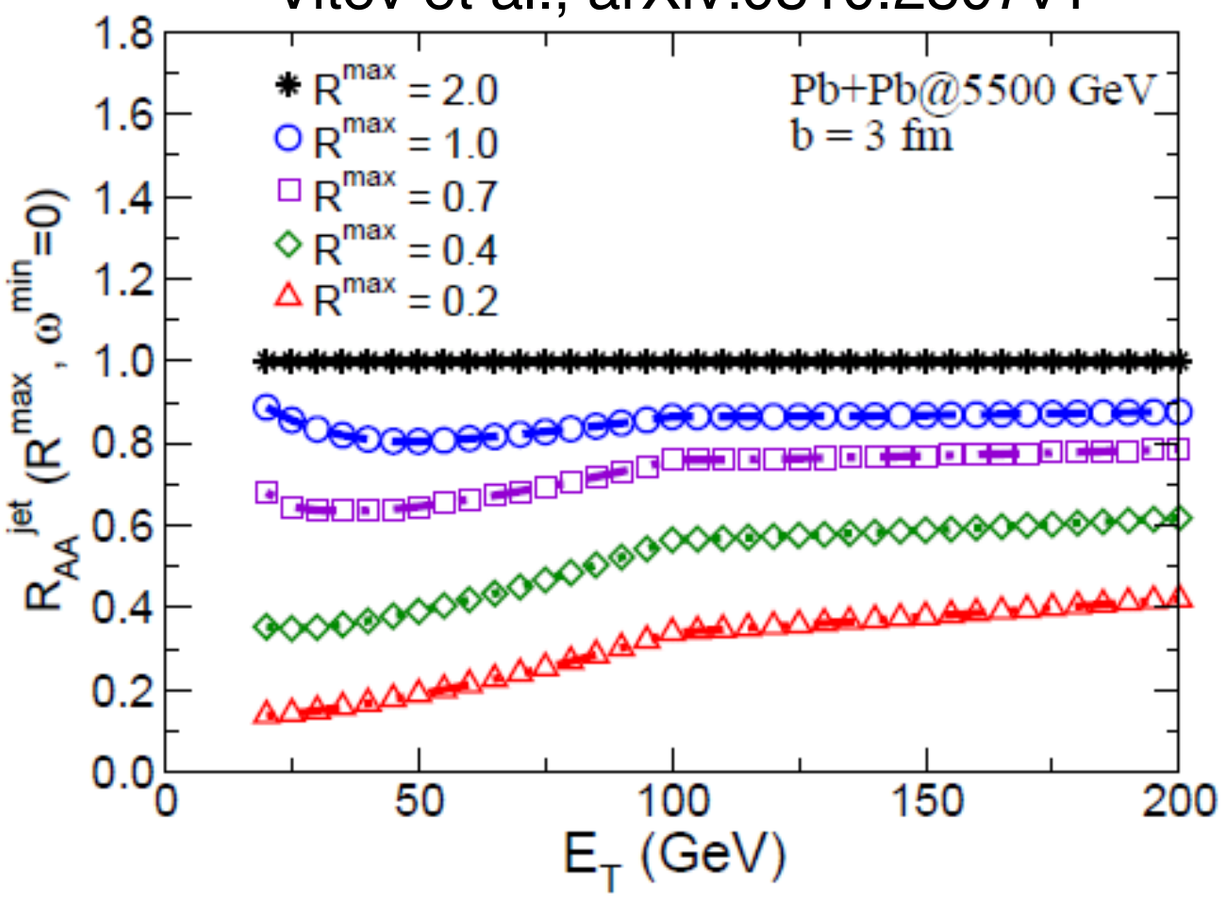


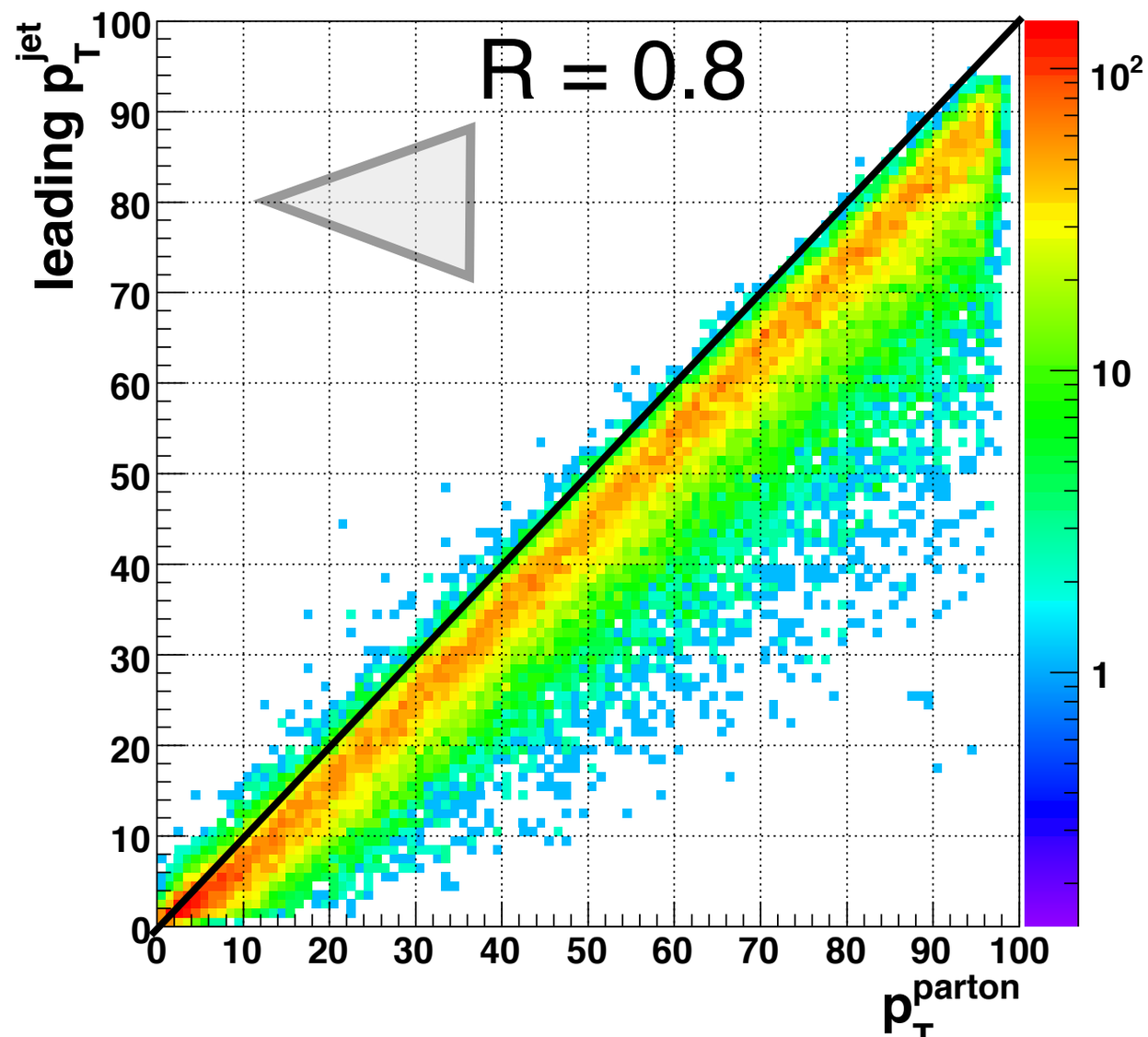
Jets are not directly partons

but they are more closely connected than leading fragments

Vitev et al., arXiv:0810.2807v1

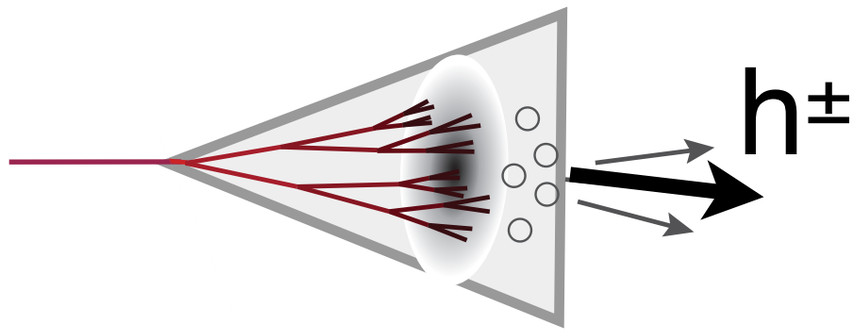


AntiKt FastJet + QPythia



may access the lost energy

Jet Reconstruction



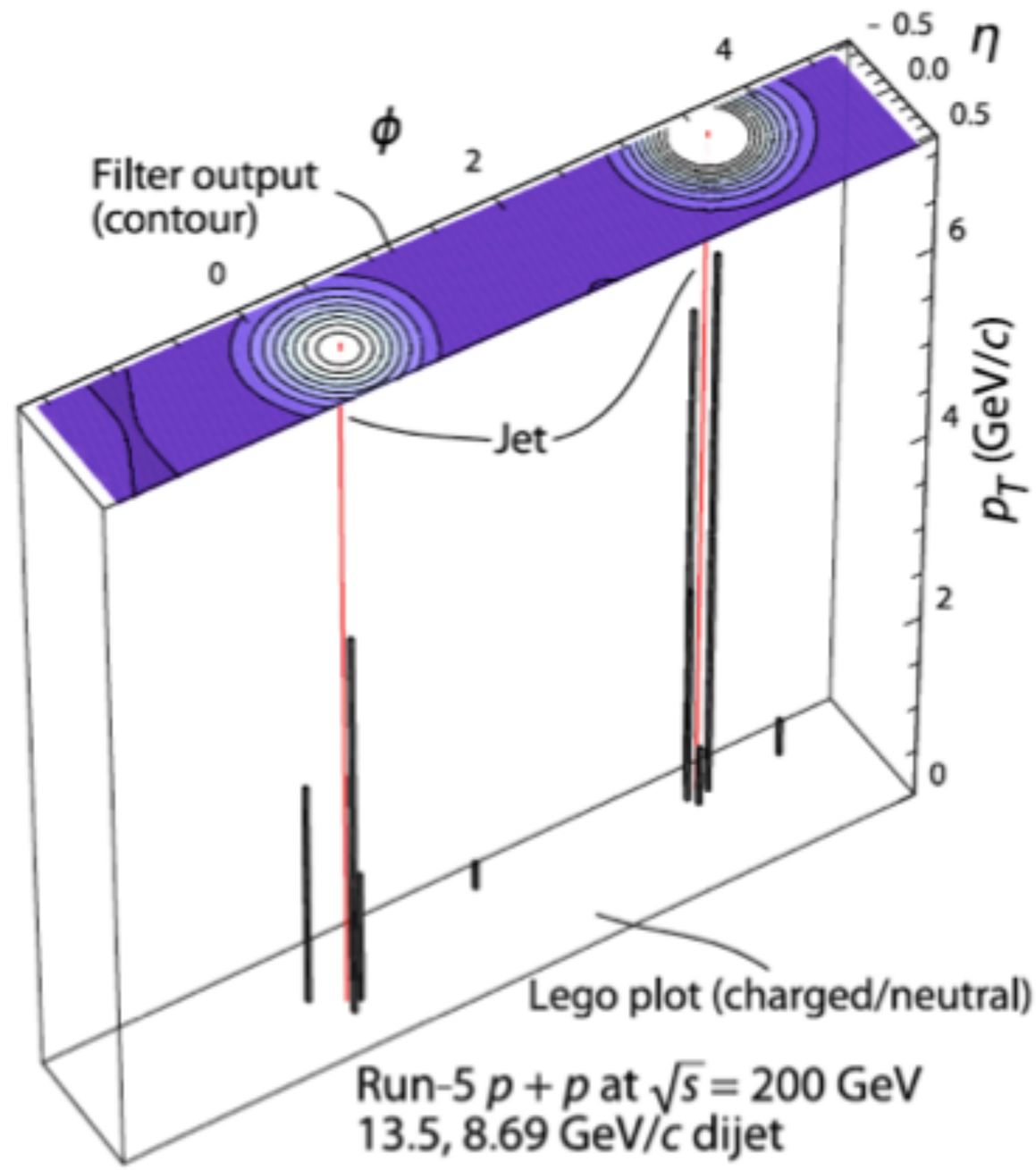
INT Schedule for Wednesday, June 23:
==========
9:00: Y.S. Lai: "Reconstructed jets in PHENIX"

Methodology:

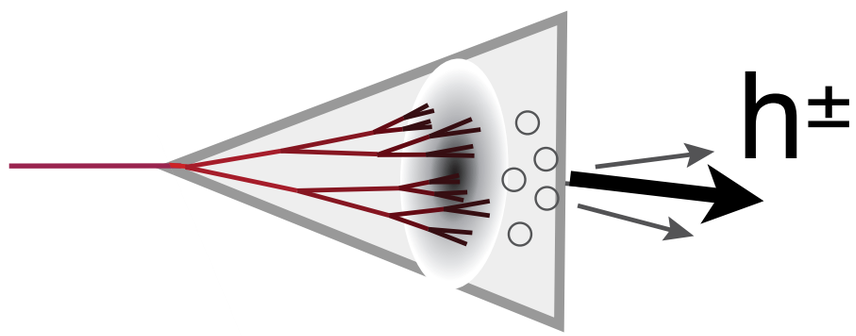
Gaussian filter

Better weighted to jet signal than a cone algorithm

Less influenced by non-jet particles



Jet Reconstruction



INT Schedule for Wednesday, June 23:
==========
9:00: Y.S. Lai: "Reconstructed jets in PHENIX"

Methodology:

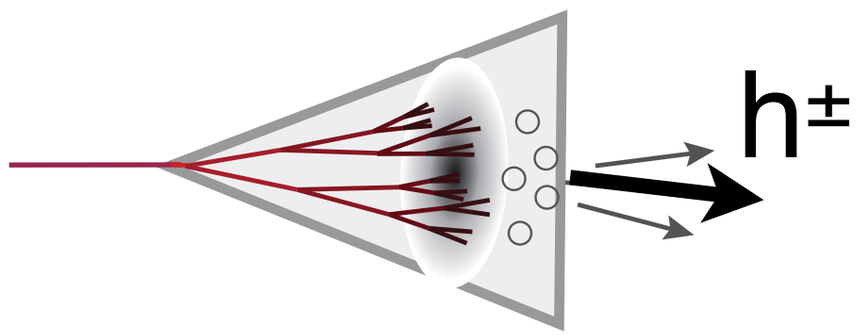
Gaussian filter

2D ($p^{particle}$,p^{jet}) Unfolding

Simultaneous extraction of spectra and fragmentation funcs

Requires careful examination of systematics

Jet Reconstruction



INT Schedule for Wednesday, June 23:
==========
9:00: Y.S. Lai: "Reconstructed jets in PHENIX"

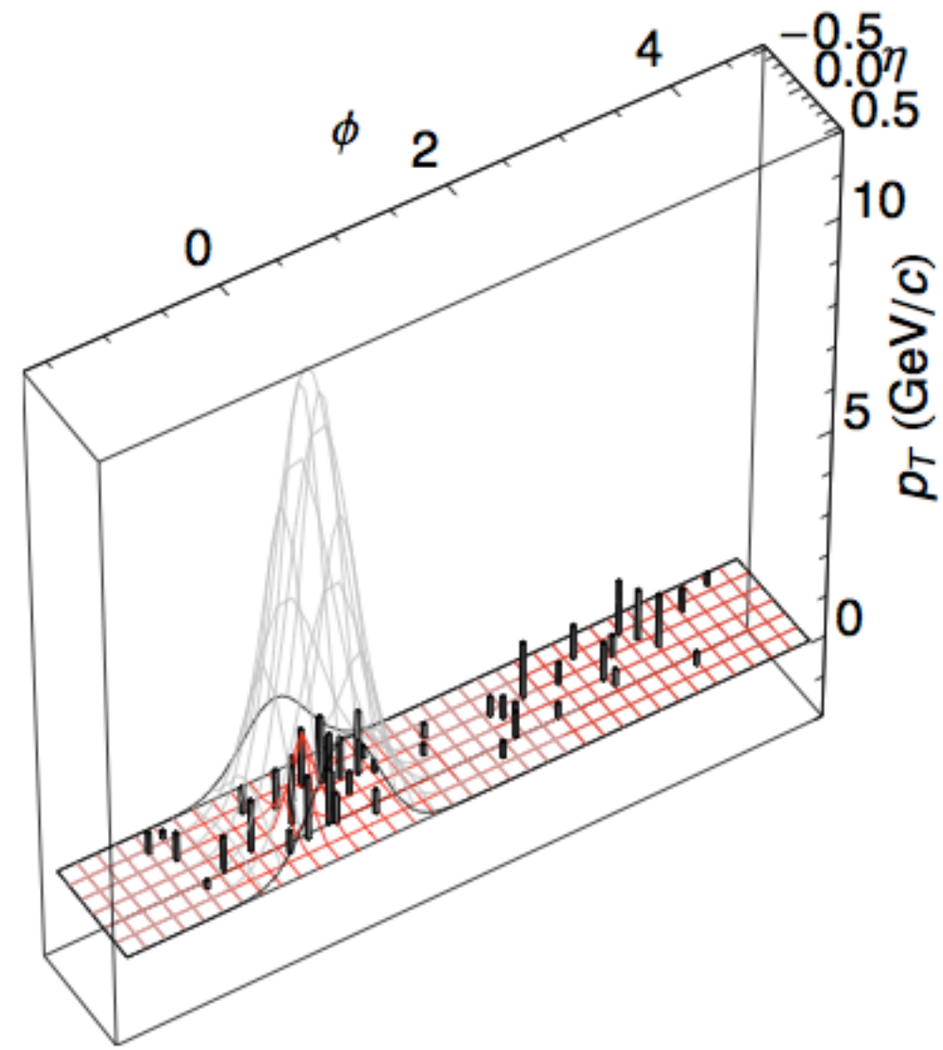
Methodology:

Gaussian filter

2D ($p^{particle}$,p^{jet}) Unfolding

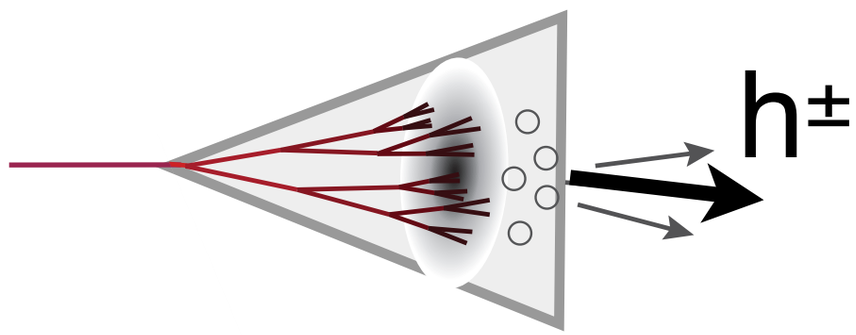
Fake rejection for heavy ion backgrounds

Gaussian shape cut on momentum distribution in filter

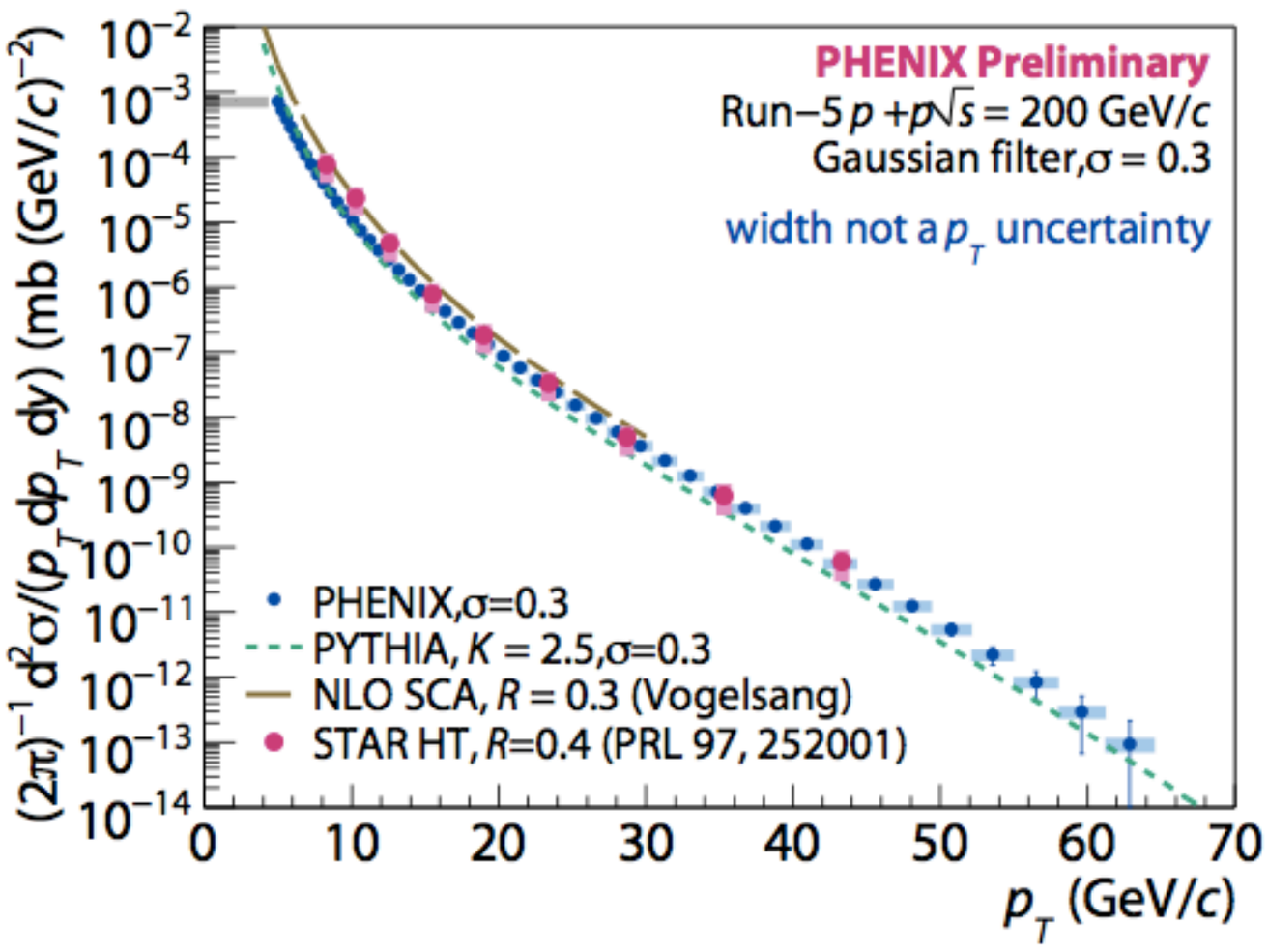


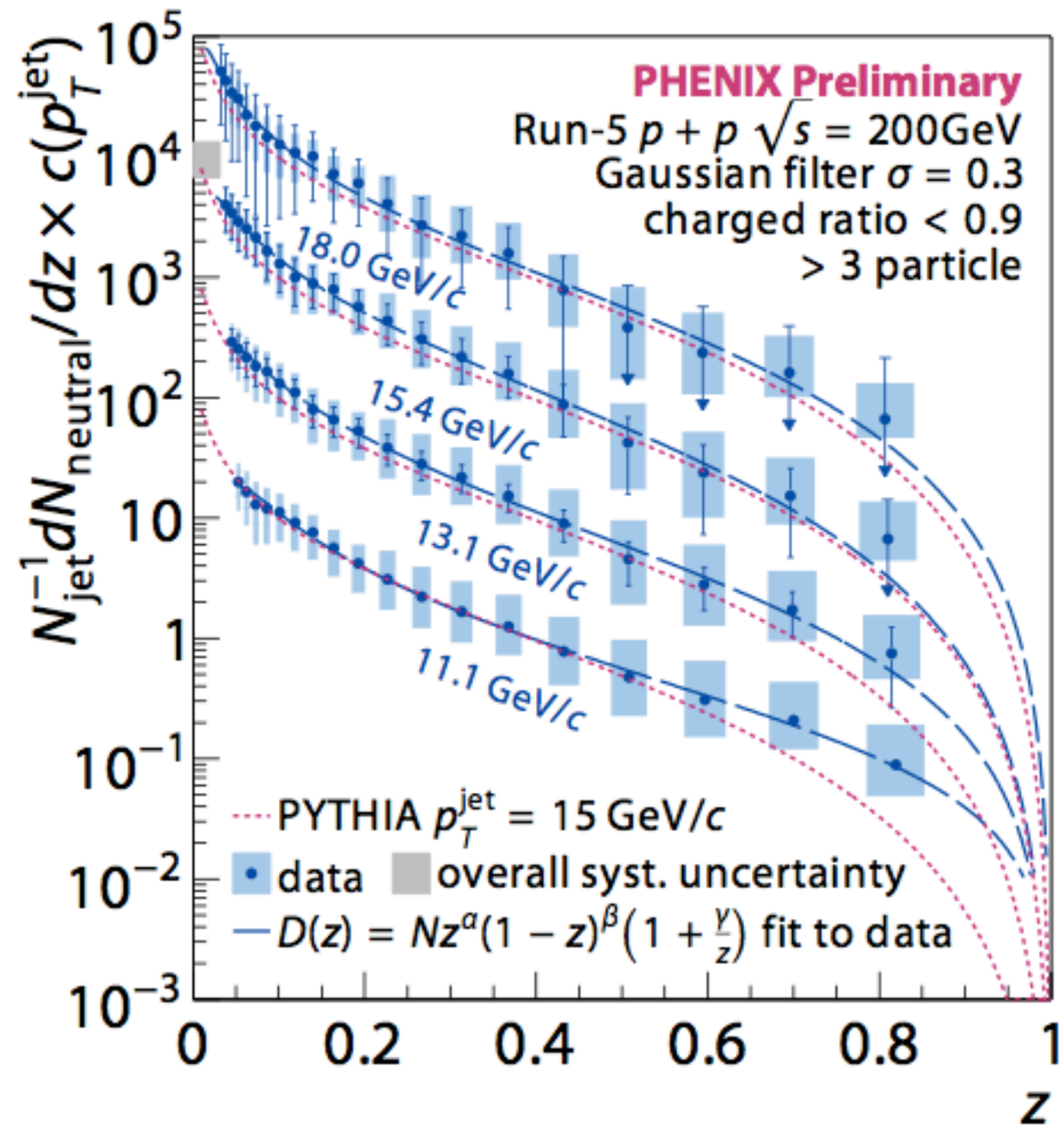
Rejected 10.8 GeV/c background fluctuation

Jet Reconstruction



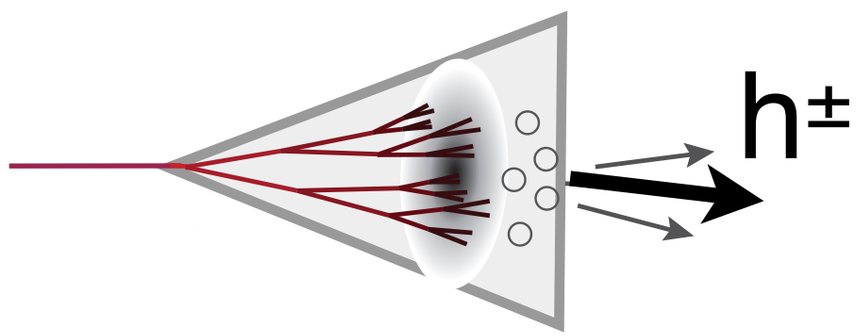
INT Schedule for Wednesday, June 23:
==========
9:00: Y.S. Lai: "Reconstructed jets in PHENIX"





p+p consistent with NLO and PYHIA

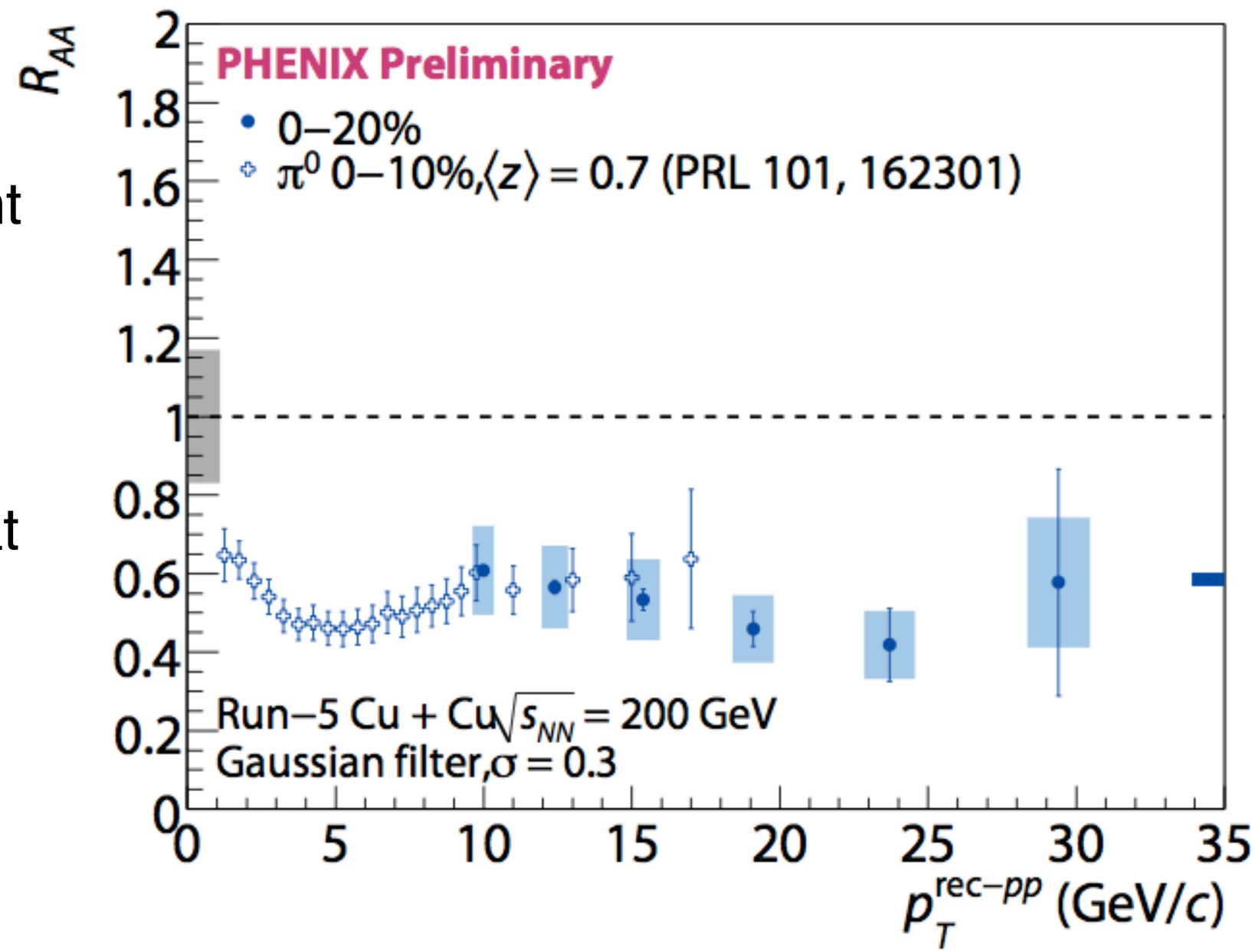
Jet Reconstruction



INT Schedule for Wednesday, June 23:
==========
9:00: Y.S. Lai: "Reconstructed jets in PHENIX"

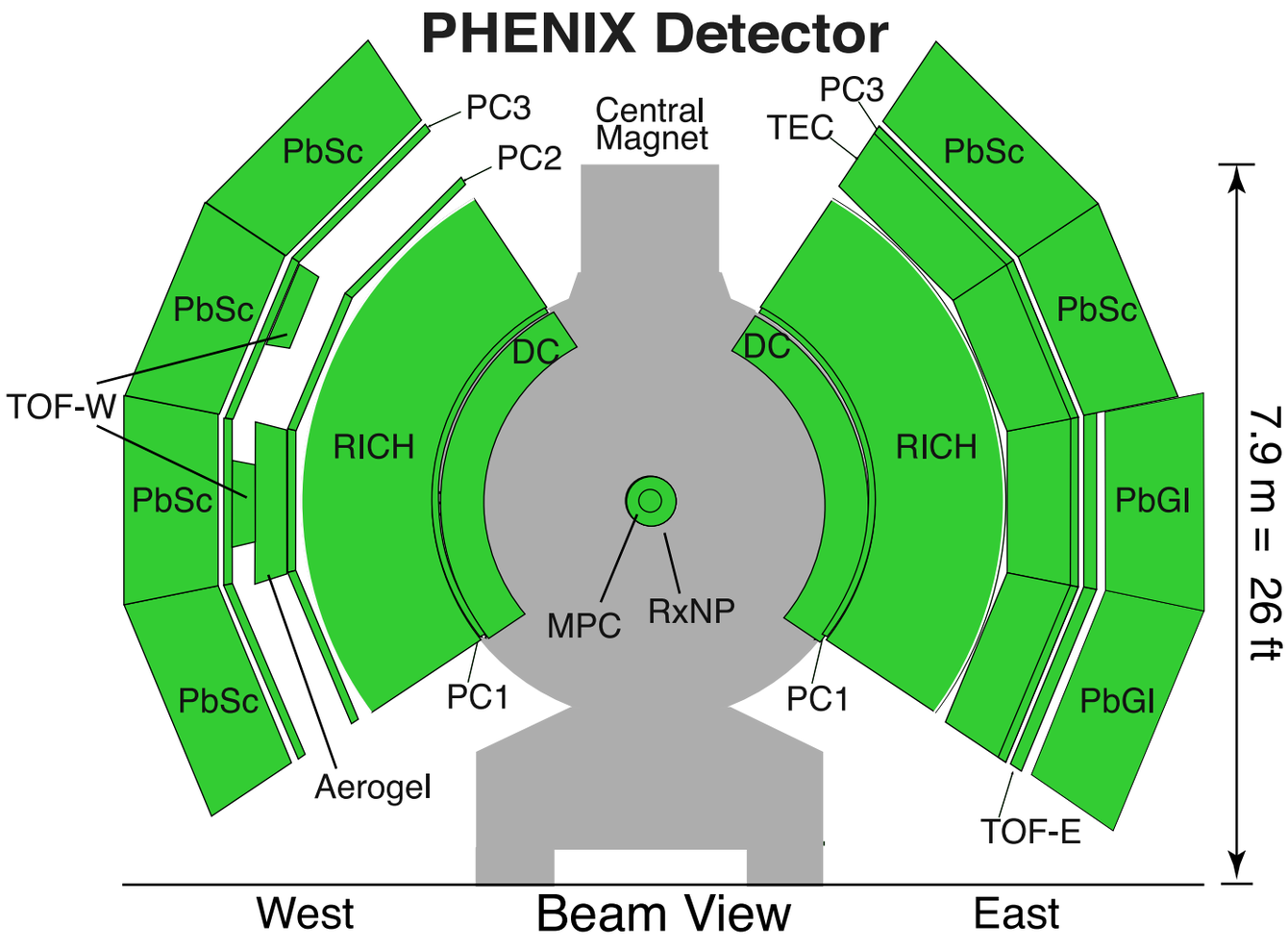
RAA roughly consistent with single particles

Also consistent with flat dependence in p_T



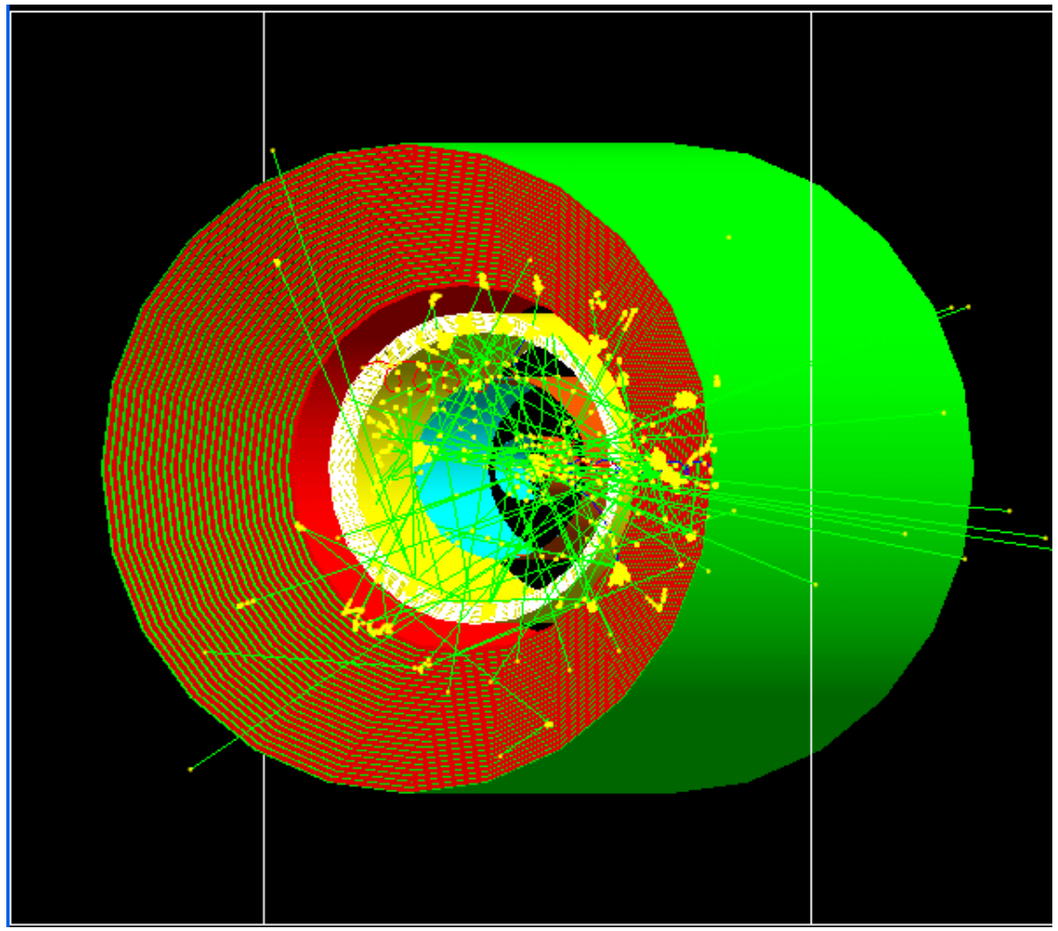
PHENIX Central Upgrade

Step #1: Remove the outer PHENIX Central Arms
Step #2: Replace Axial Field Magnet with Solenoid
(2 Tesla with inner radius = 70 cm).

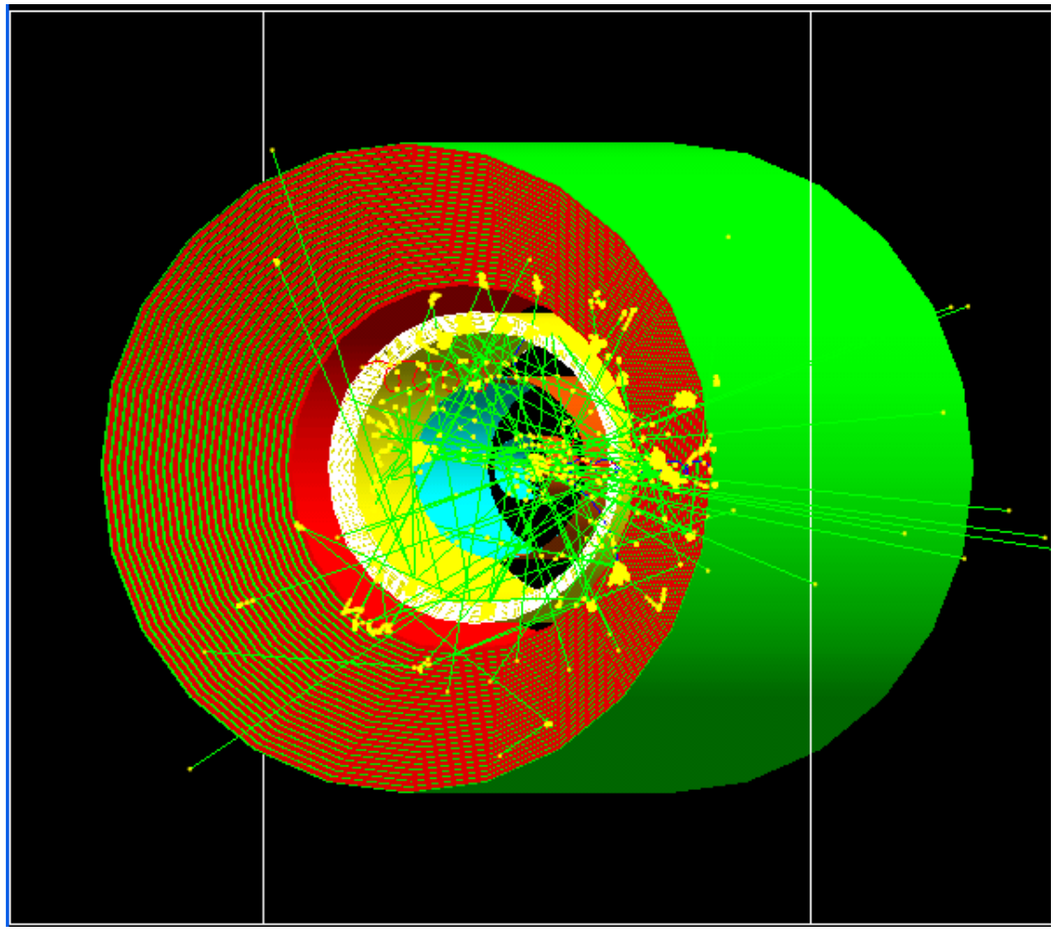


PHENIX Central Upgrade

Step #1: Remove the outer PHENIX Central Arms
Step #2: Replace Axial Field Magnet with Solenoid
(2 Tesla with inner radius = 70 cm).
Step #3: New silicon tracking layers at 40 and 60 cm
Step #4: Compact EmCal (Silicon/Tungsten) $|\eta|<1.0$
8 cm total depth and preshower layer
Step #5: Hadronic Calorimeter Outside Magnet
Step #6: Maintain high DAQ bandwidth and triggers

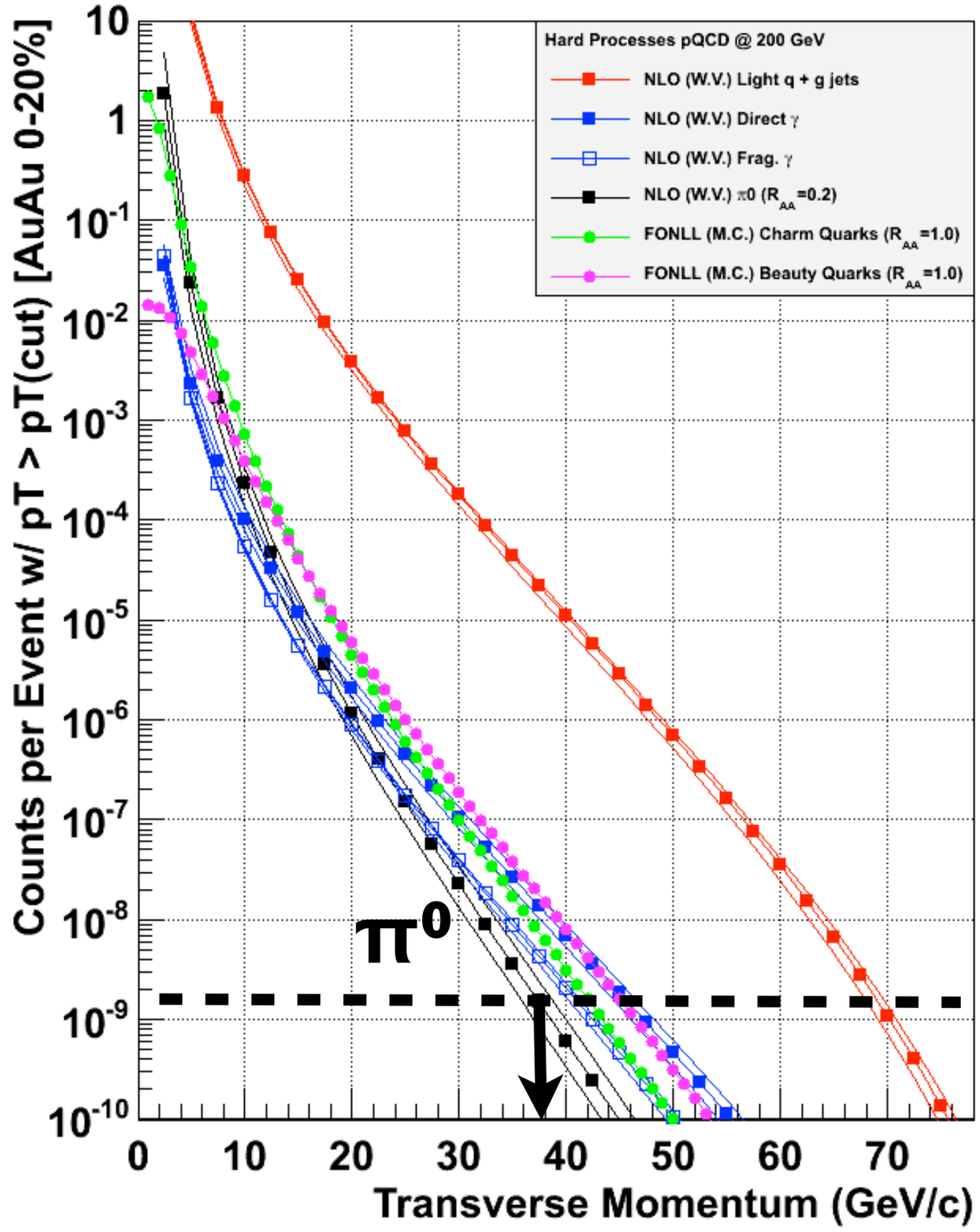


Jet Capabilities

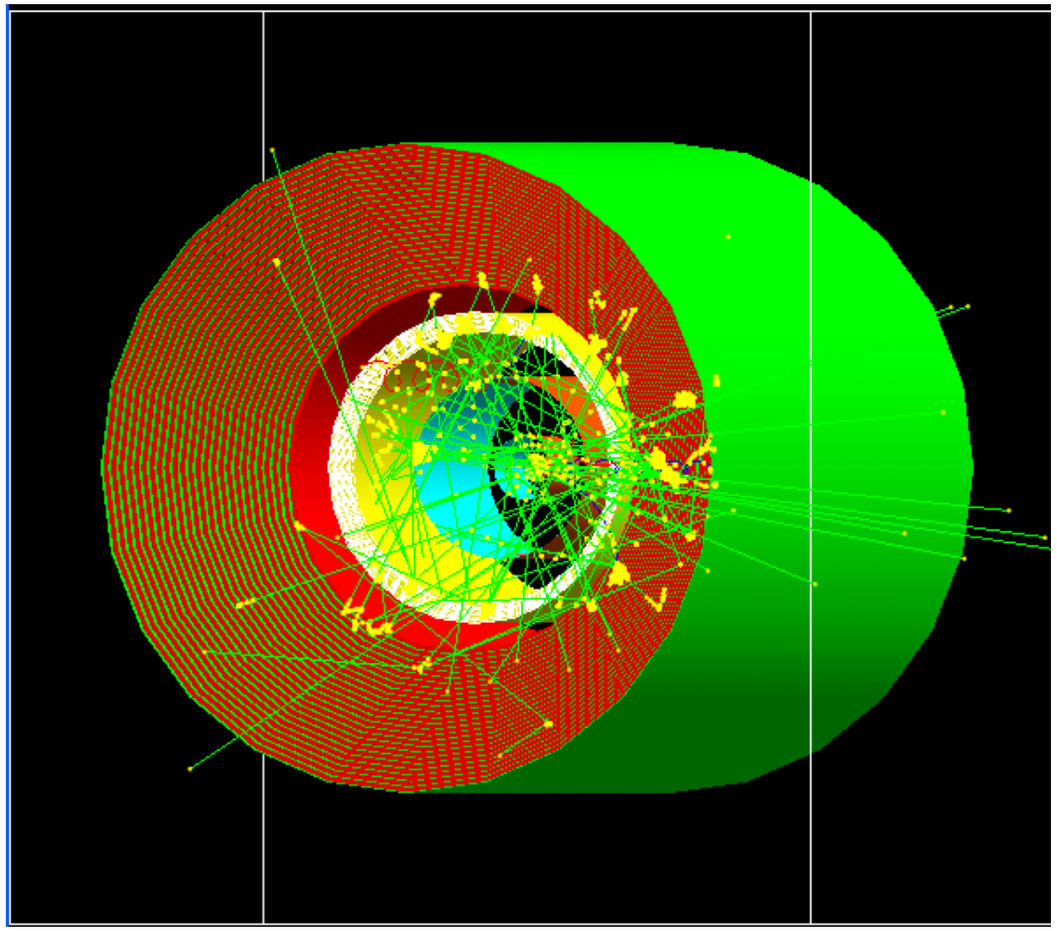


Central collisions:

π^0 out to 38 GeV/c



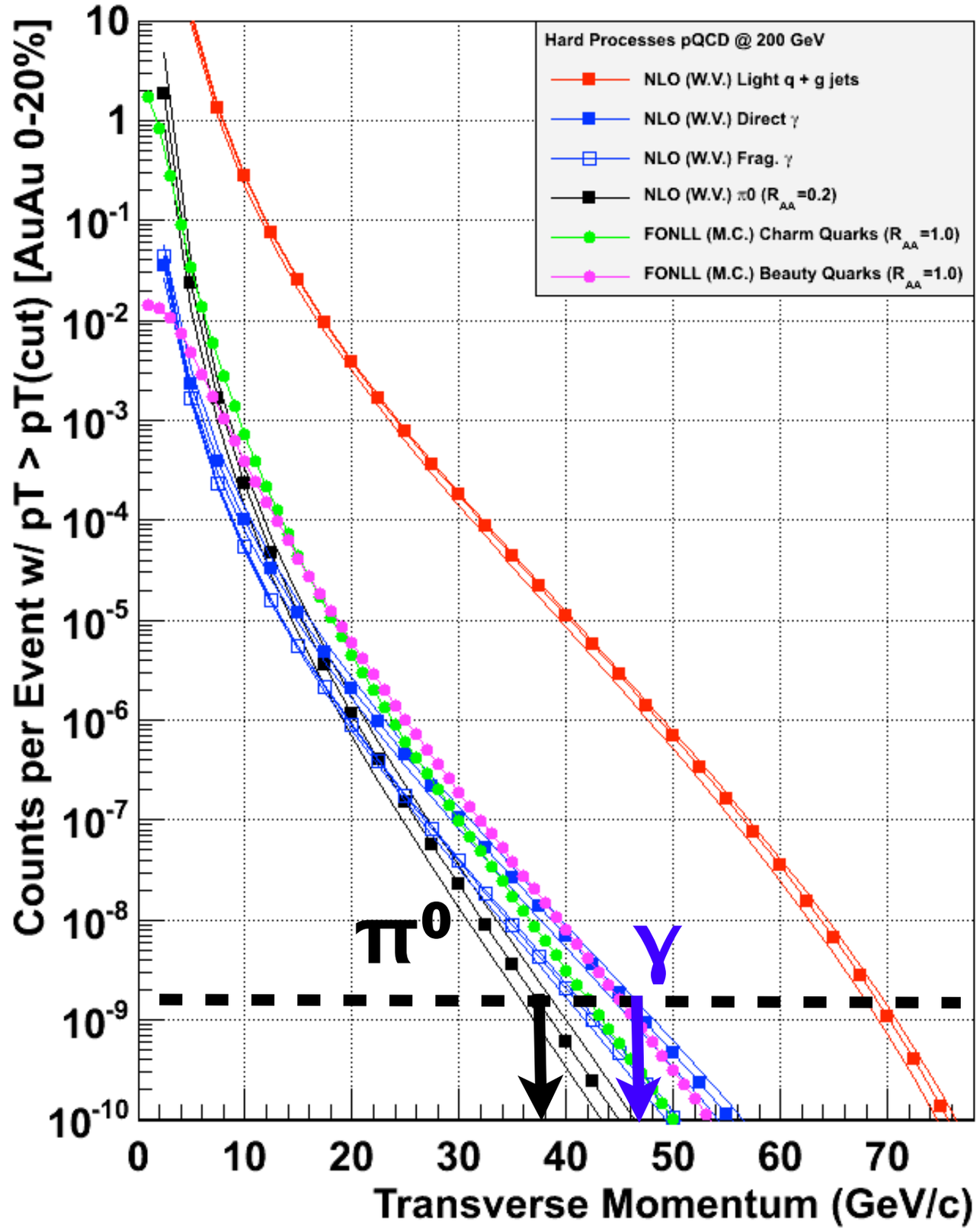
Jet Capabilities



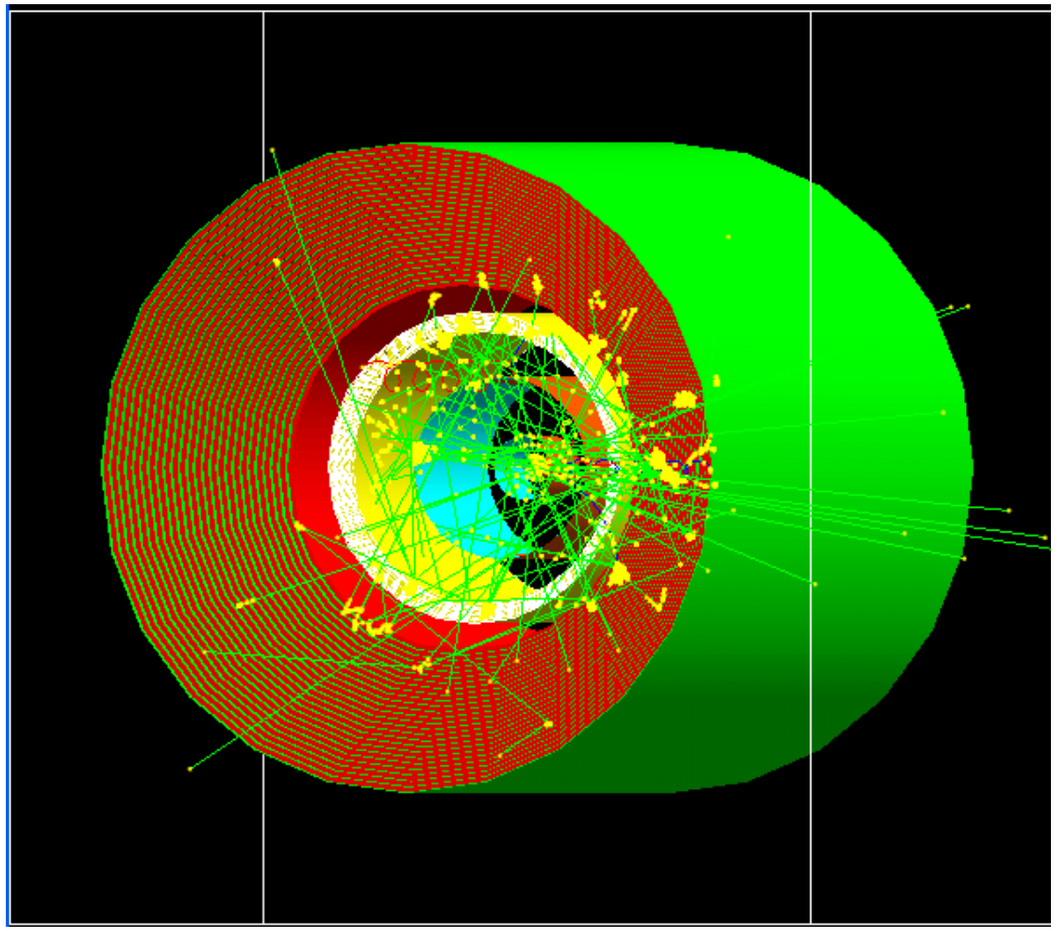
Central collisions:

π^0 out to 38 GeV/c

Direct photons out to 46 GeV/c



Jet Capabilities

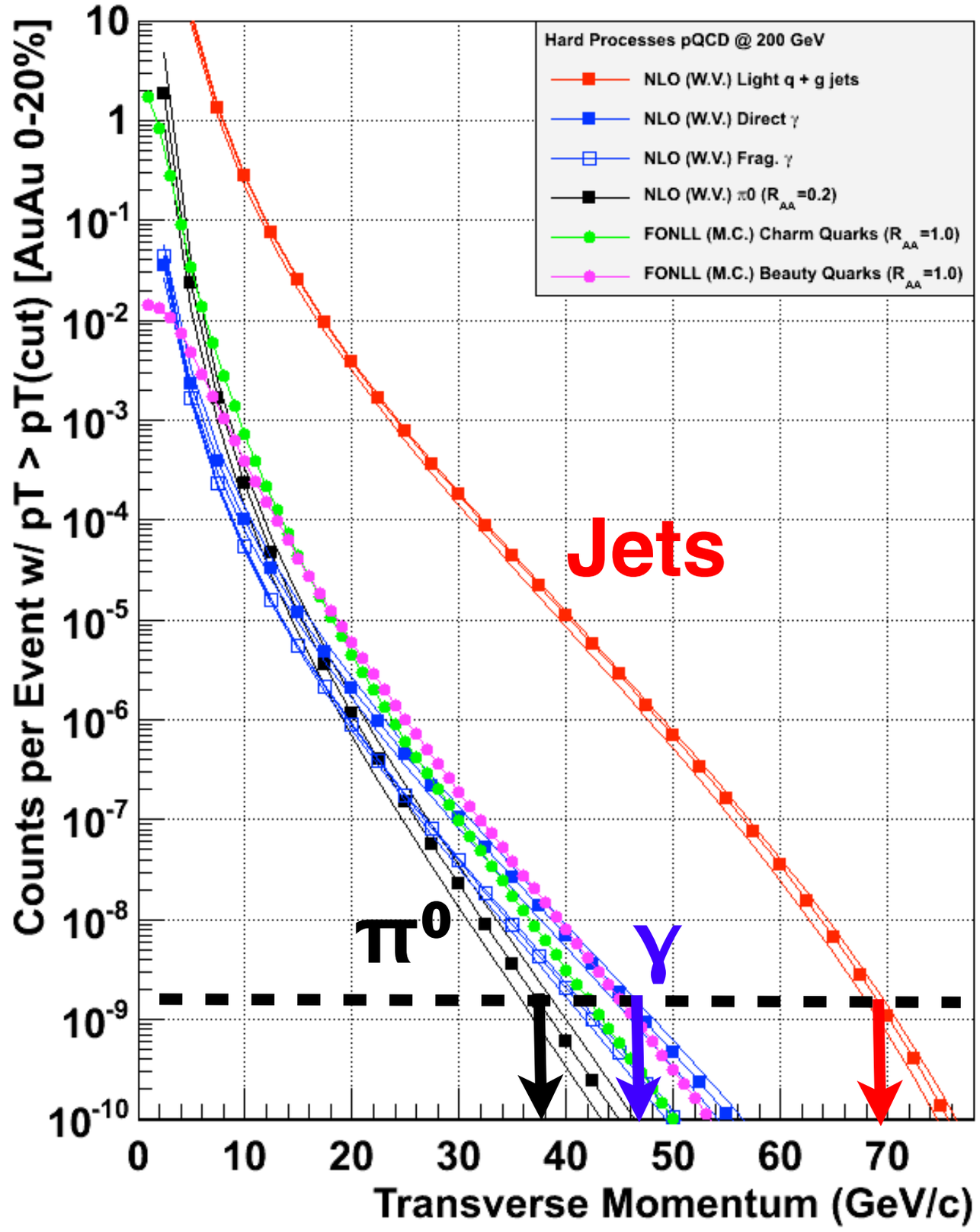


Central collisions:

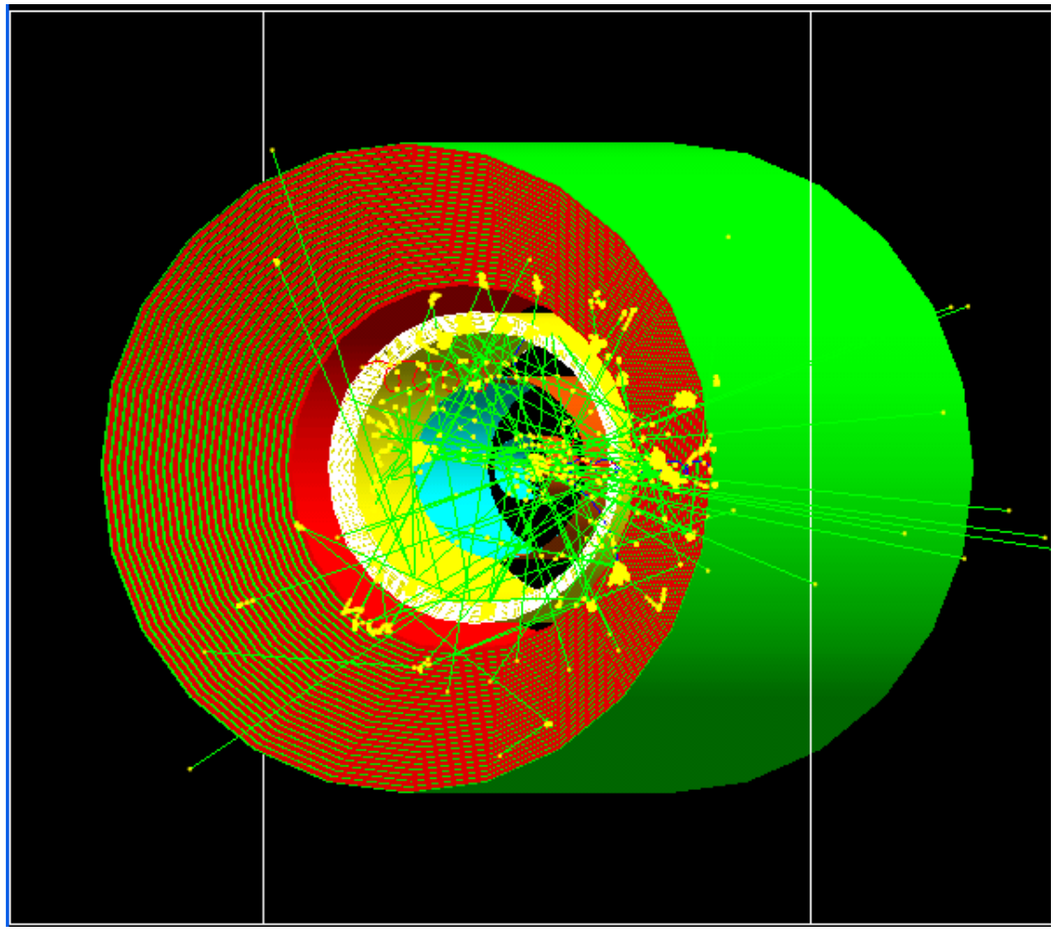
π^0 out to 38 GeV/c

Direct photons out to 46 GeV/c

Jets out to 70 GeV/c



Jet Capabilities



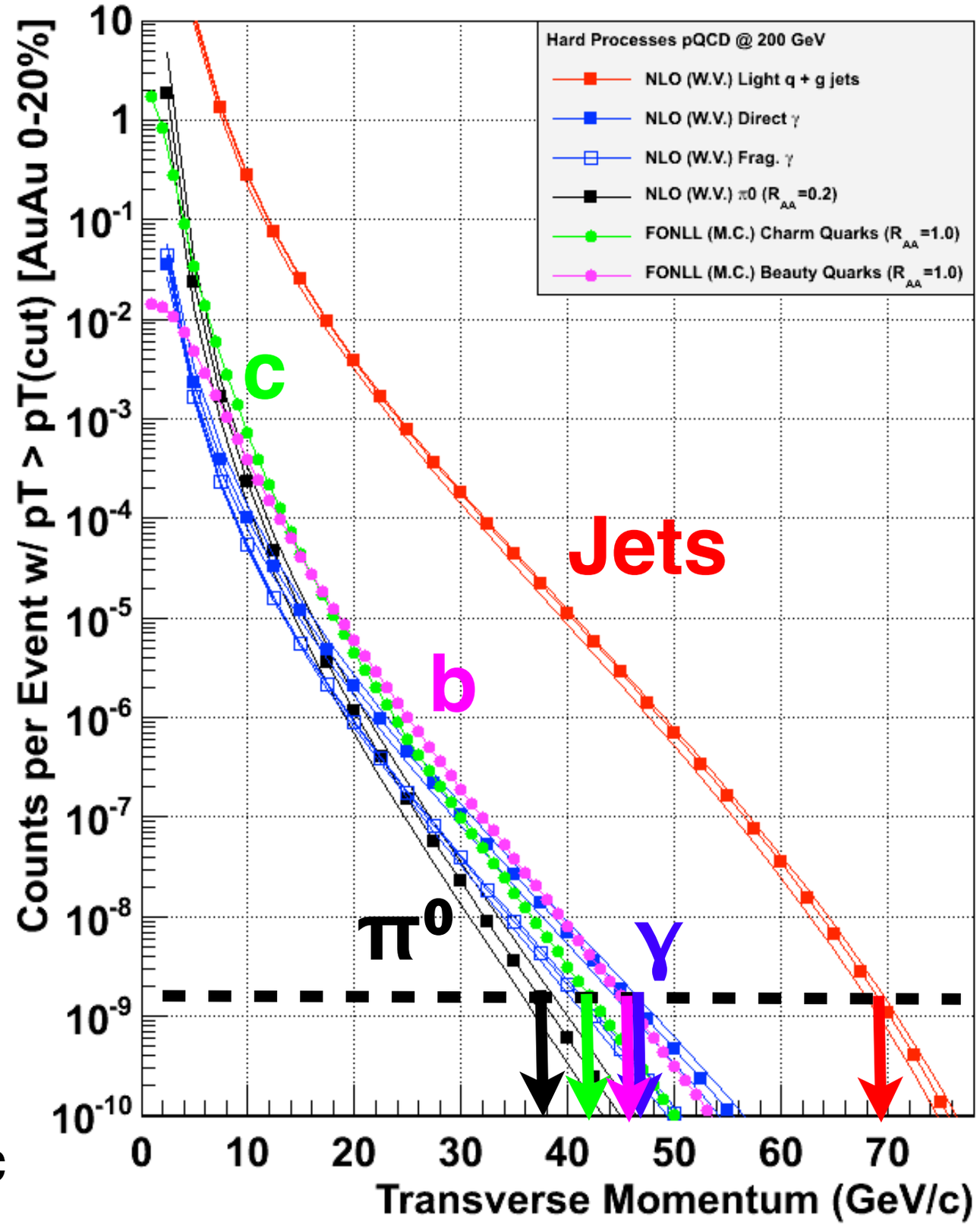
Central collisions:

π^0 out to 38 GeV/c

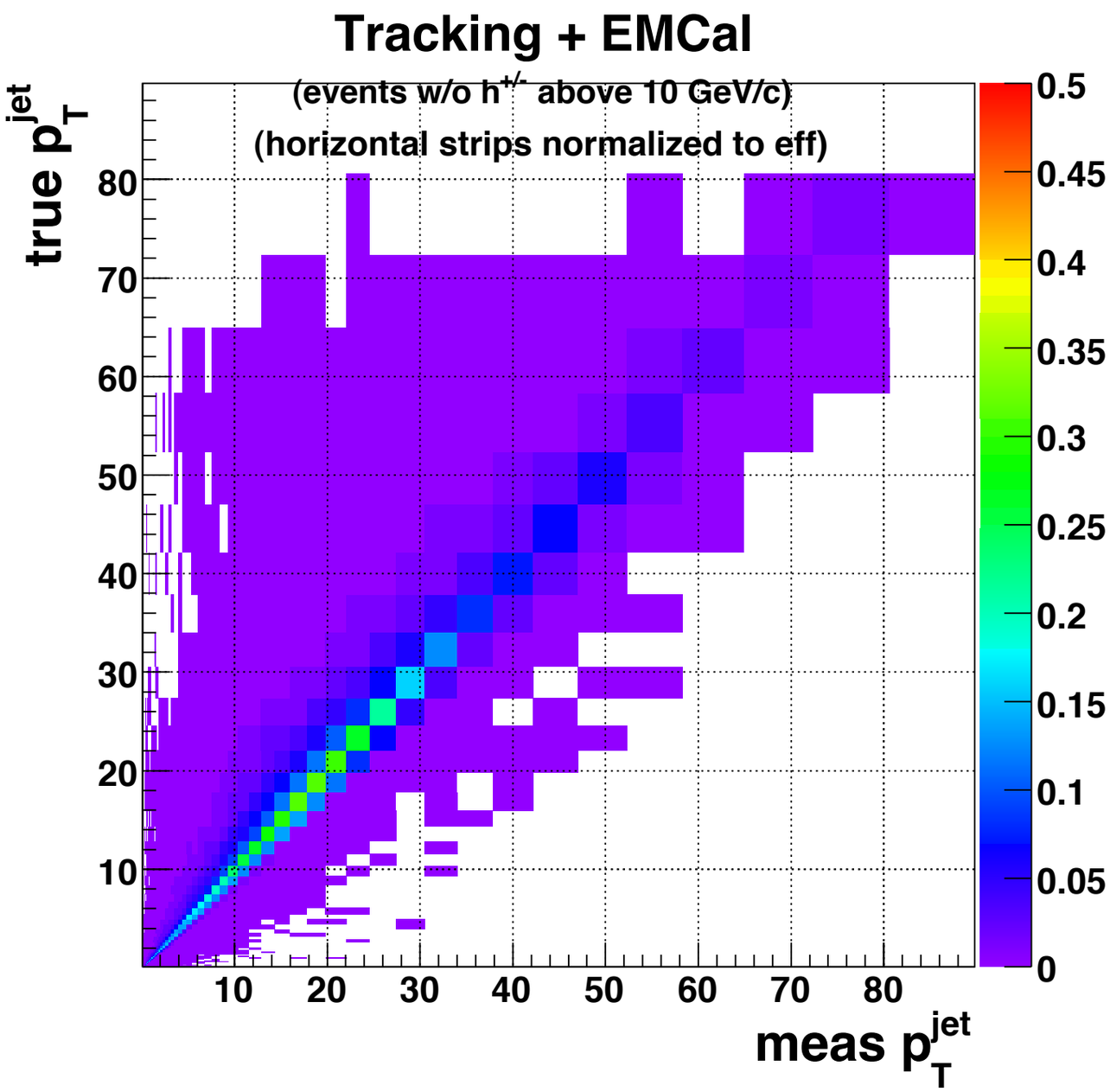
Direct photons out to 46 GeV/c

Jets out to 70 GeV/c

Charm (beauty) jets 42(45) GeV/c

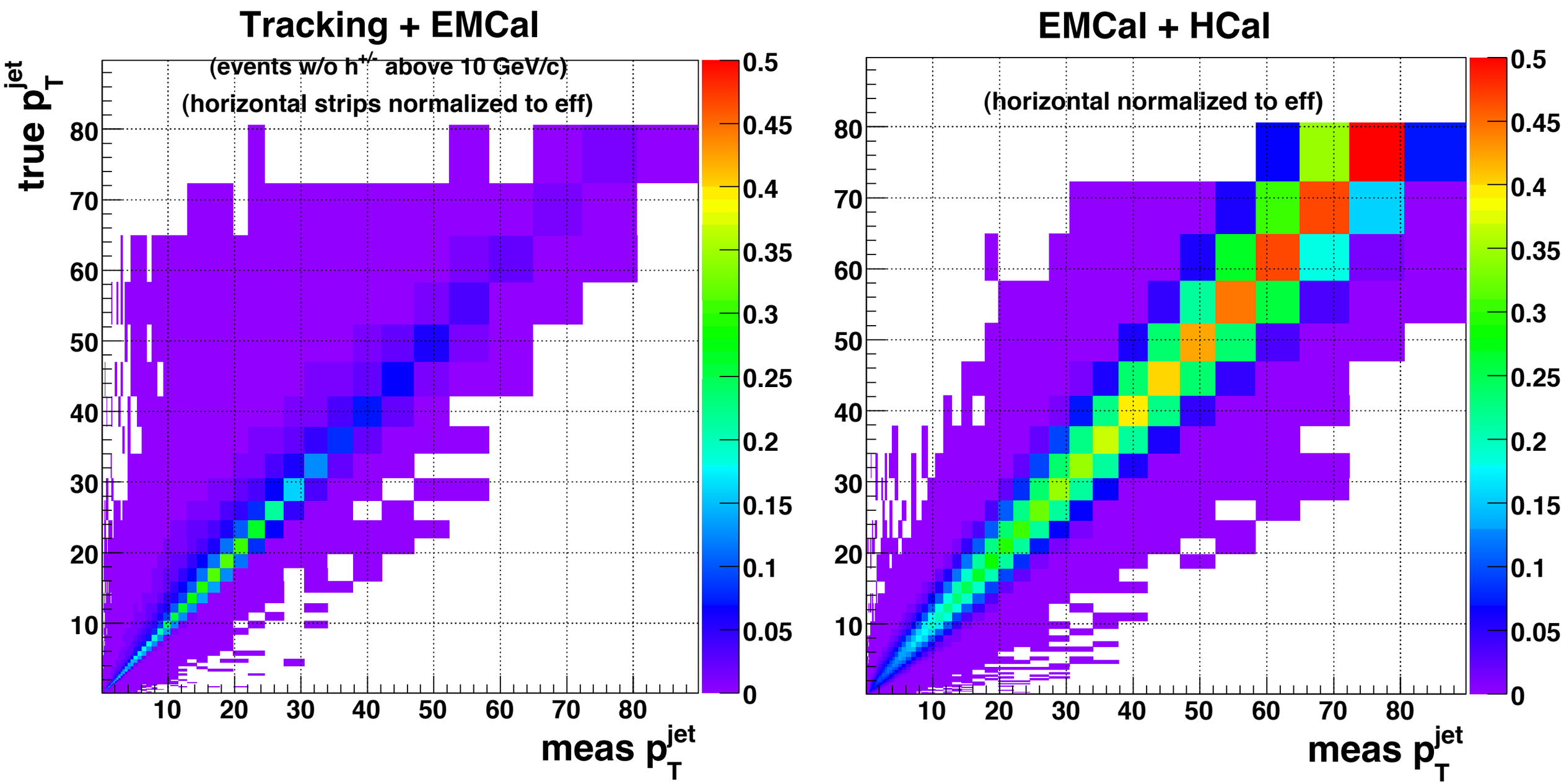


Jet Response



With tracking, dominated by “fakes” above some p_T (here p_T > 10 GeV). Thus, low overall efficiency for true high energy jets. Bias in spectra reconstruction when FF is uncertain.

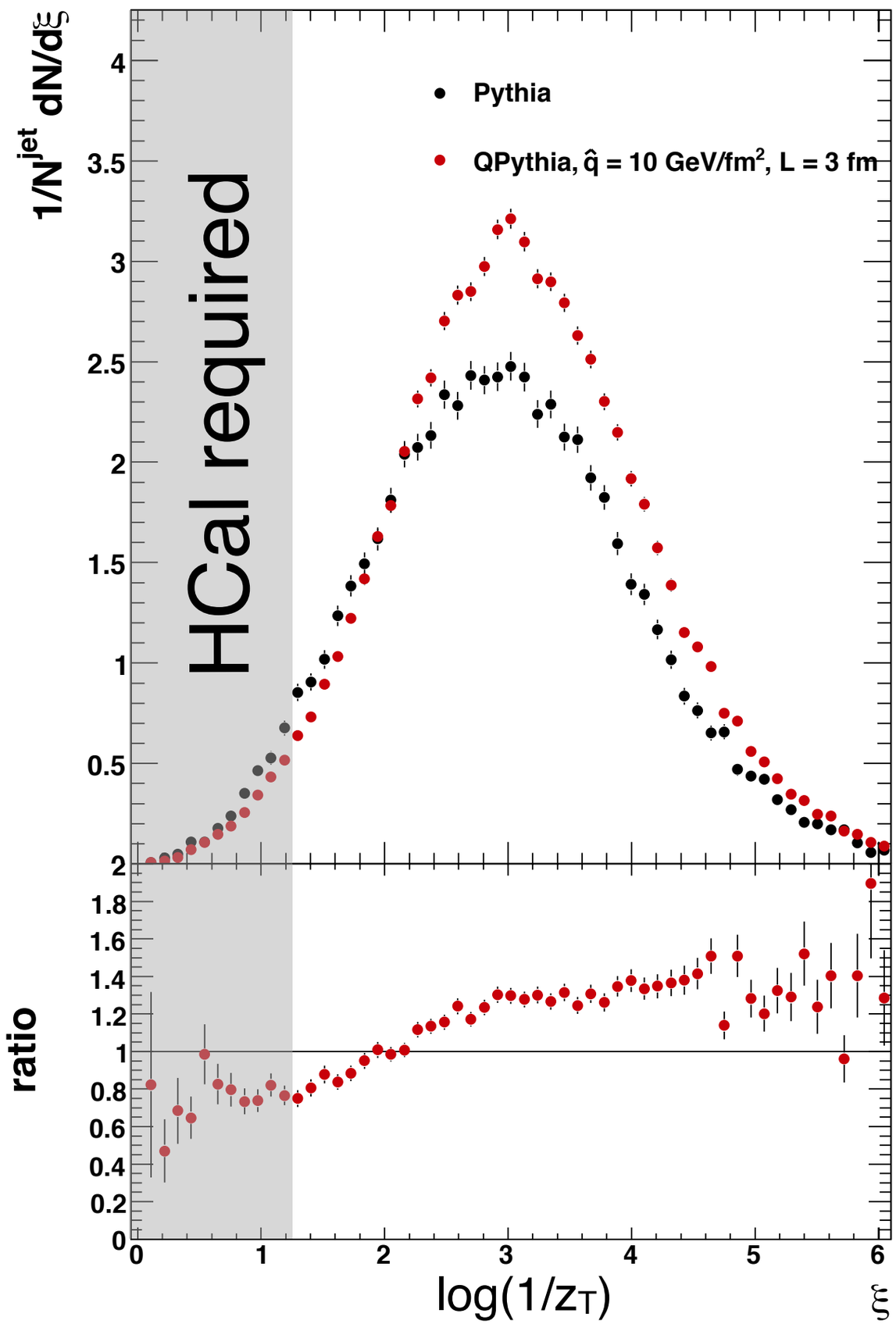
Jet Response



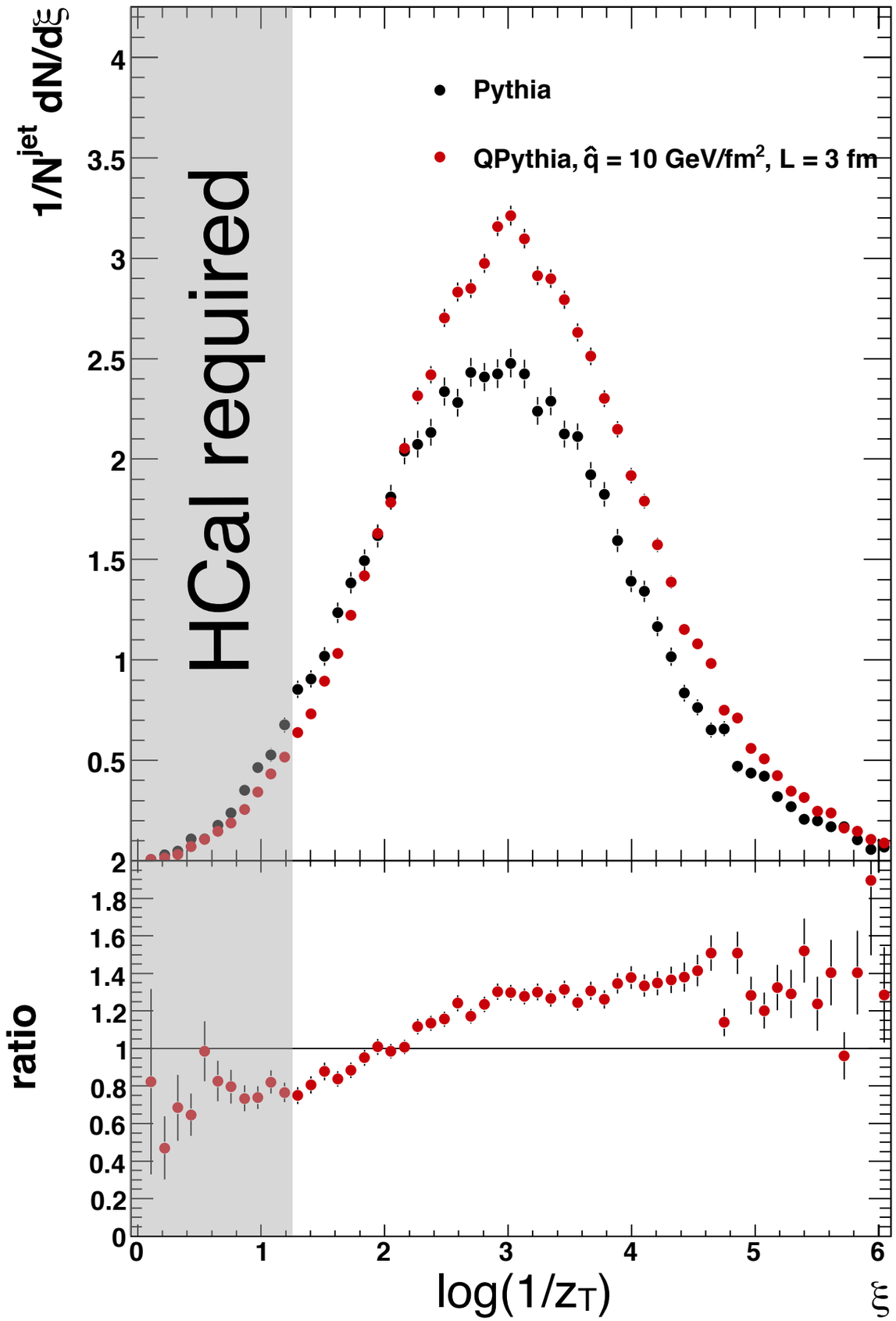
With tracking, dominated by “fakes” above some p_T (here p_T > 10 GeV). Thus, low overall efficiency for true high energy jets. Bias in spectra reconstruction when FF is uncertain.

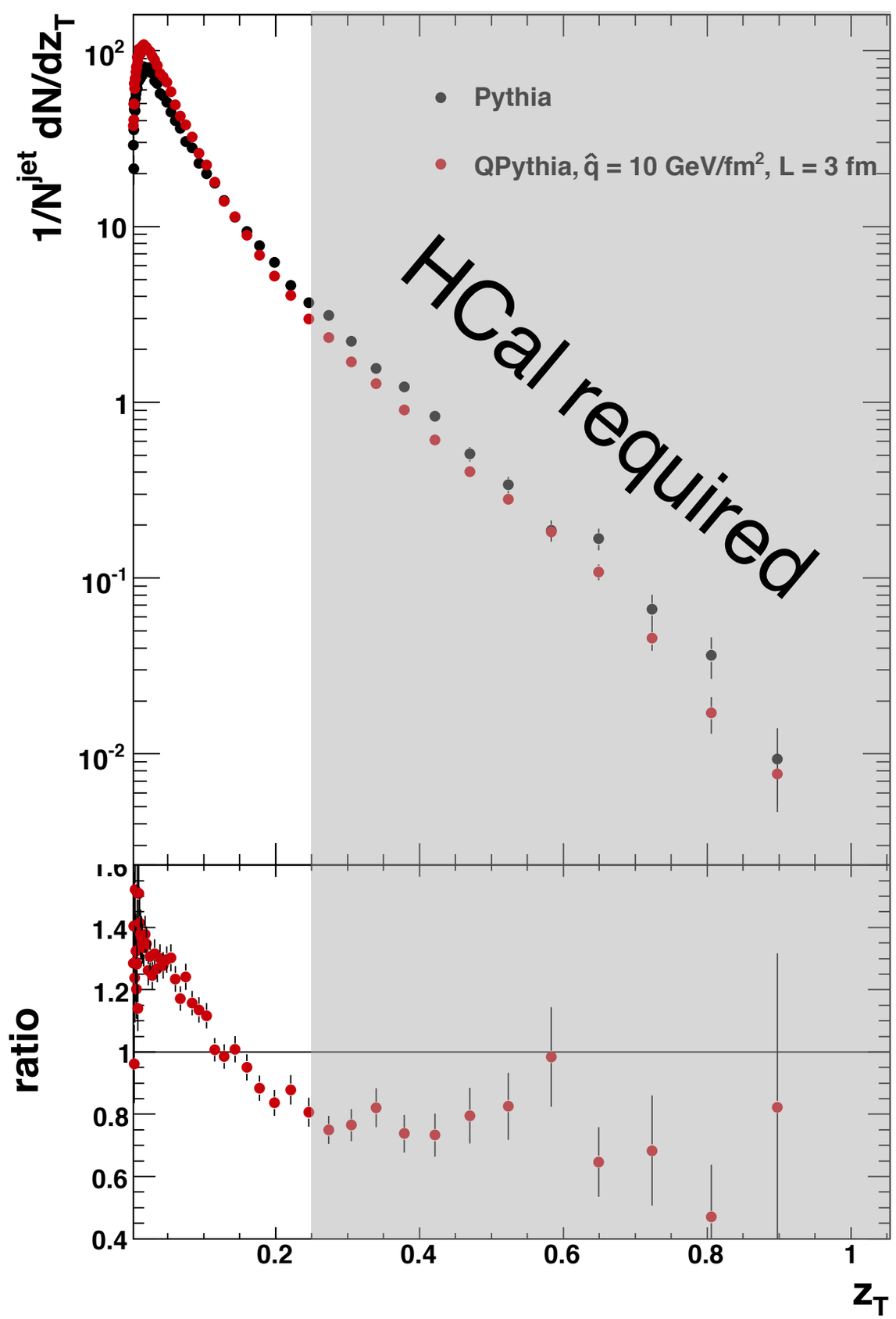
Issue largely solved with EMCal + HCal for jet energy!

Frag Func Range



Frag Func Range





Summary

Triangular flow is a promising explanation for “ridge” and “shoulder” phenomena

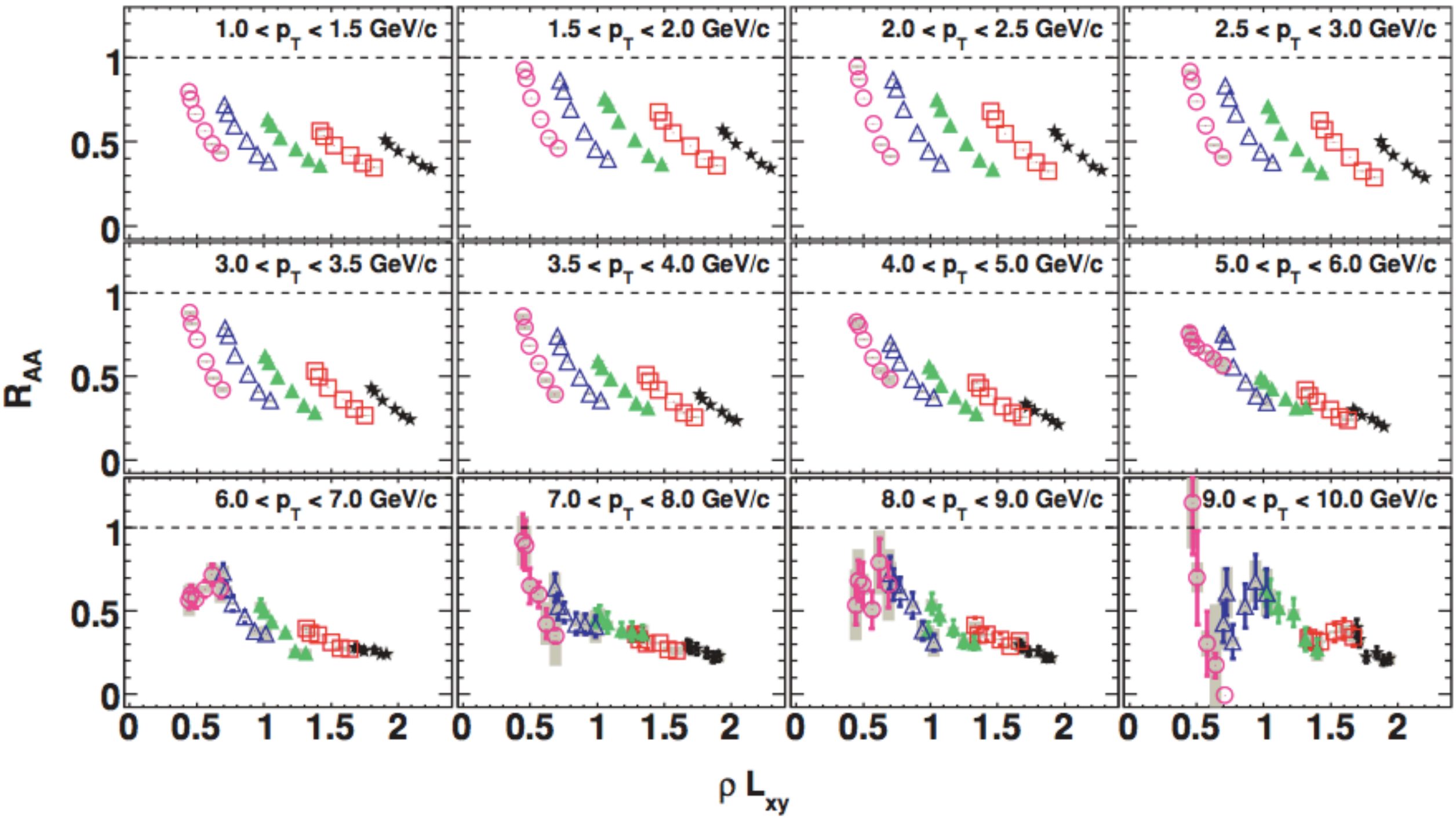
- Definitive only when full quantitative reproduction of the data (eliminate the possibility of some degree of medium response)

R_{AA}, I_{AA}, $R_{AA}(\Phi_s)$, $I_{AA}(\Phi_s)$ provide a basic but useful set of observables from testing theory

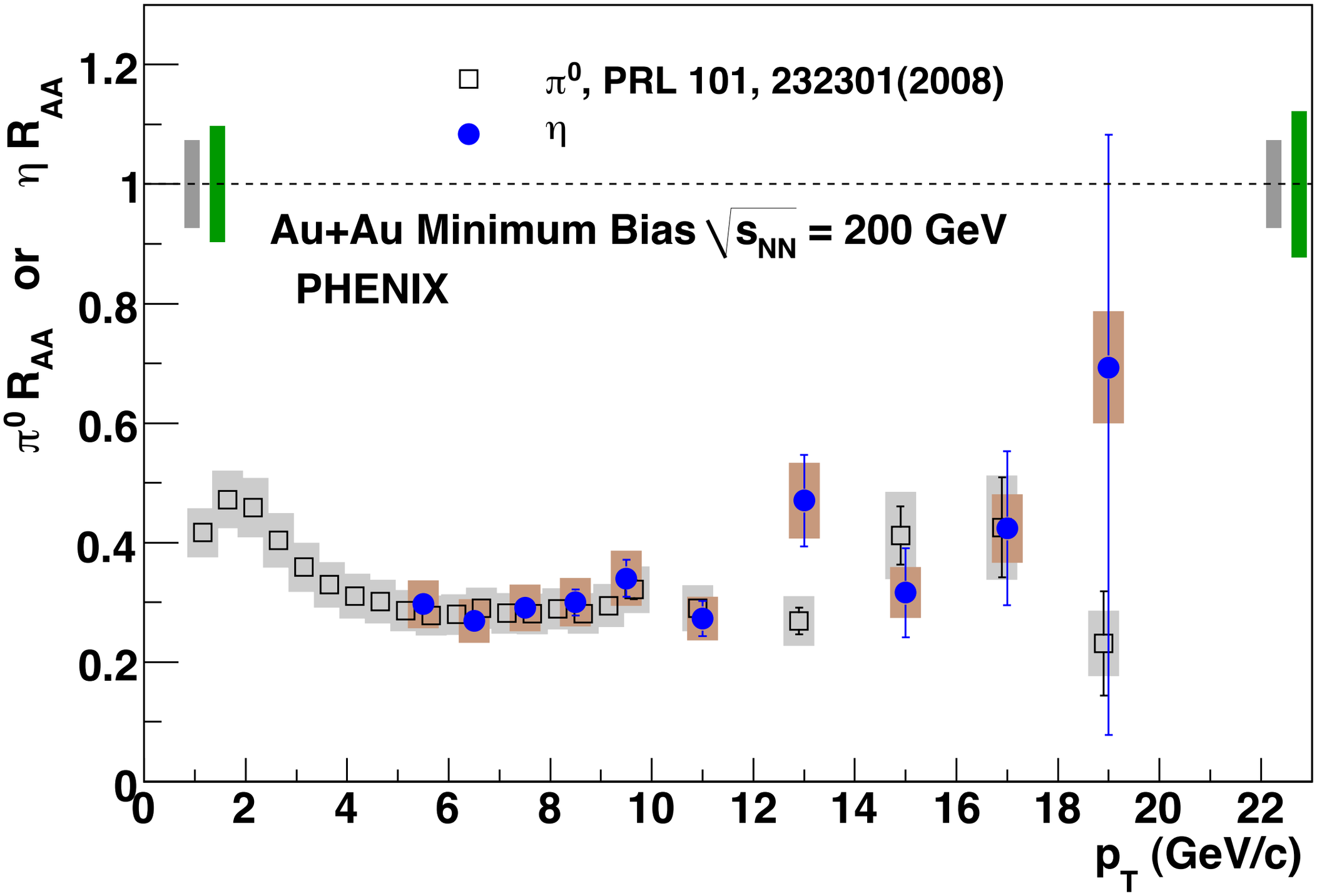
Additional observations will give us more information

Backup

$R_{AA}(\Phi s)$

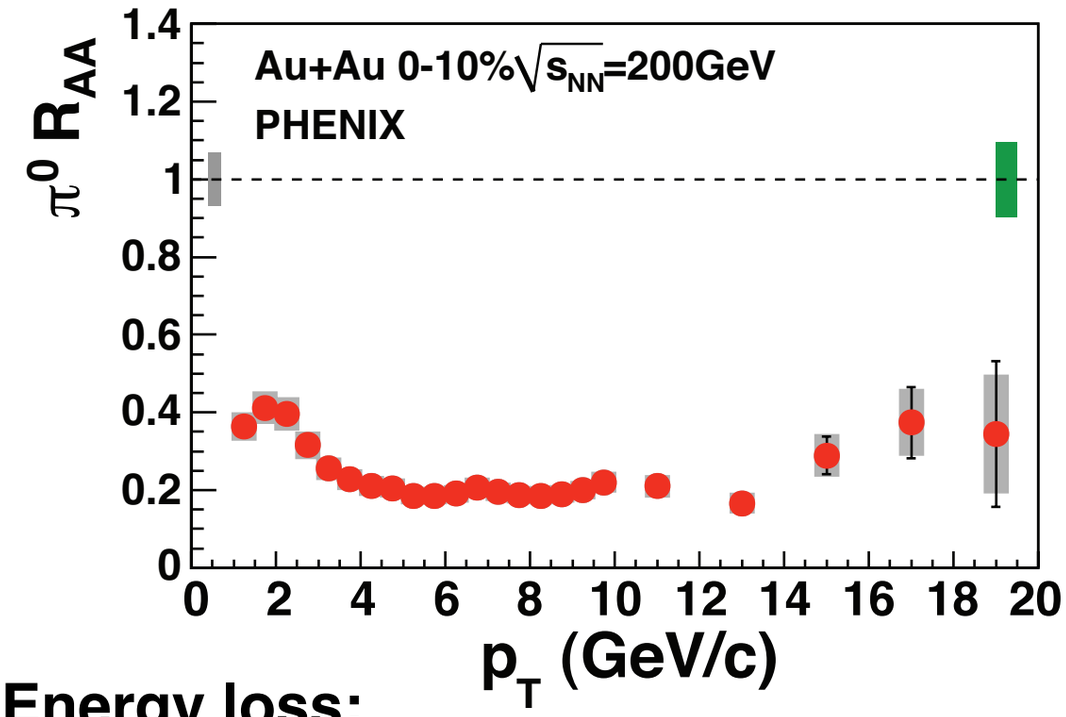

1.0 < p_T < 1.5 GeV/c
1.5 < p_T < 2.0 GeV/c
2.0 < p_T < 2.5 GeV/c
2.5 < p_T < 3.0 GeV/c
3.0 < p_T < 3.5 GeV/c
3.5 < p_T < 4.0 GeV/c
4.0 < p_T < 5.0 GeV/c
5.0 < p_T < 6.0 GeV/c
6.0 < p_T < 7.0 GeV/c
7.0 < p_T < 8.0 GeV/c
8.0 < p_T < 9.0 GeV/c
9.0 < p_T < 10.0 GeV/c
R_AA
ρ L_xy
0
0.5
1
1.5
2

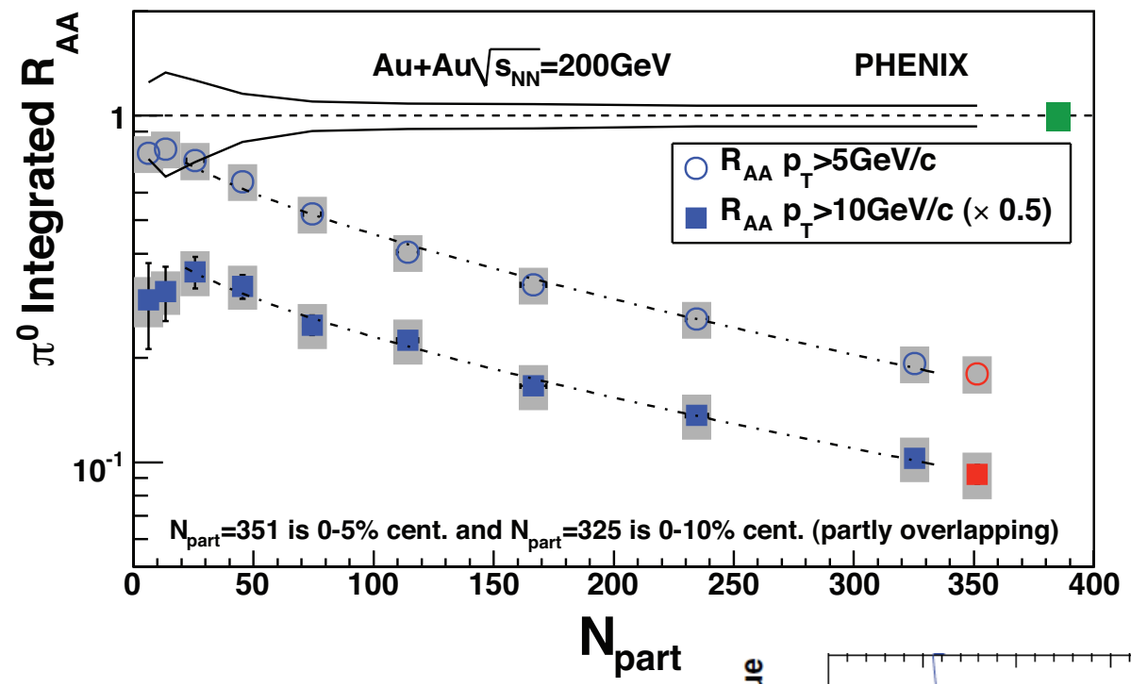
eta Raa


π^0, PRL 101, 232301(2008)
η
Au+Au Minimum Bias $\sqrt{s_{NN}}$ = 200 GeV
PHENIX
π^0 R_{AA} or η R_{AA}
p_T (GeV/c)
0
0.2
0.4
0.6
0.8
1
1.2
0
2
4
6
8
10
12
14
16
18
20
22

Fast Parton Energy Loss

$$R_{AA}(p_T) \equiv \left(\frac{d\sigma_{AA}}{dp_T}\right) \Big/ \left(T_{AB}\frac{d\sigma_{pp}}{dp_T}\right) = \left(\frac{dn_{AA}}{dp_T}\right) \Big/ \left(N_{coll}\frac{dn_{pp}}{dp_T}\right)$$





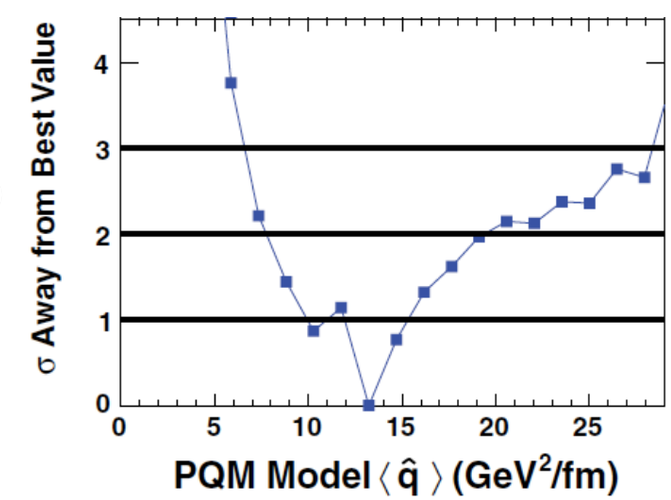
Energy loss:

- large suppression = opaque medium

- found by many models, but these differ on characteristics of fast parton interactions:
  - few large interactions, GLV, AMY
  - many small interactions, BDMPS

...but also on path length dependence
  - $\Delta E \sim L^2$ (weak coupling, BDMPS-Z)
  - $\Delta E \sim L^3$ (strong coupling, AdS/CFT)

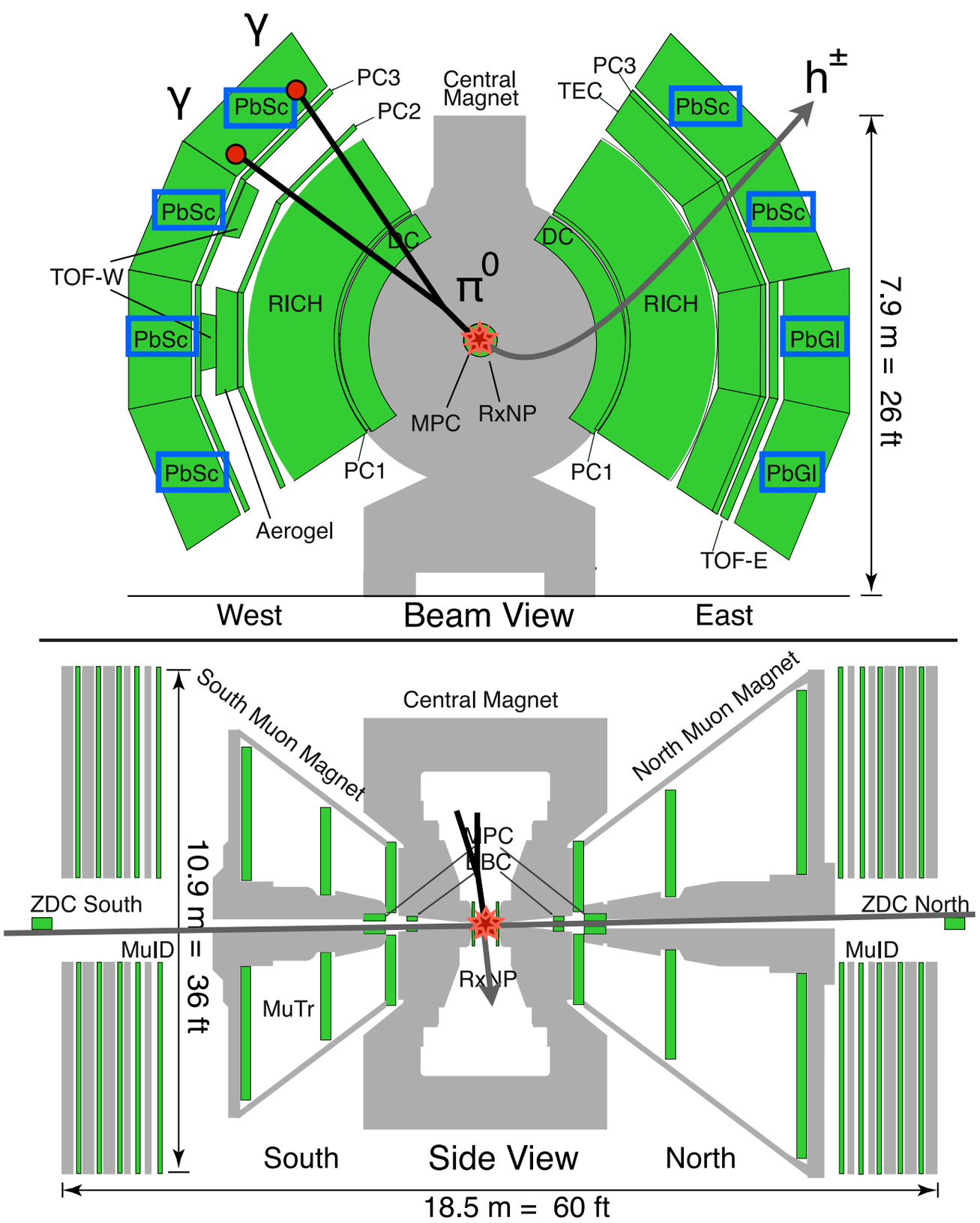
Comparison to PHENIX data



$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

Bass, et al., PRC79, 024901

PHENIX Detector



Event Characterization

- Vertex, Centrality, Reaction Plane (BBC, ZDC, RXPN)

Single Particle Reconstruction

- Charged Particle Tracking (DC, PC1, PC3, *RICH*)
- Photon and π^0 Reconstruction (PbSc, PbGl, *PC3*)

Charge Particle Tracking

Challenging high multiplicity environments

$$dN_C/dy \lesssim 700$$

Drift Chamber:

- north-south division
- two X-layers (phi-separation)
- two UV-layers (z-separation)

PC1:

- small pads, ~8 mm
- better z-separation

Track resolution

- fine DC spacial resolution

$$150\mu m$$

- large field integral

1.15 *Tesla-meters*

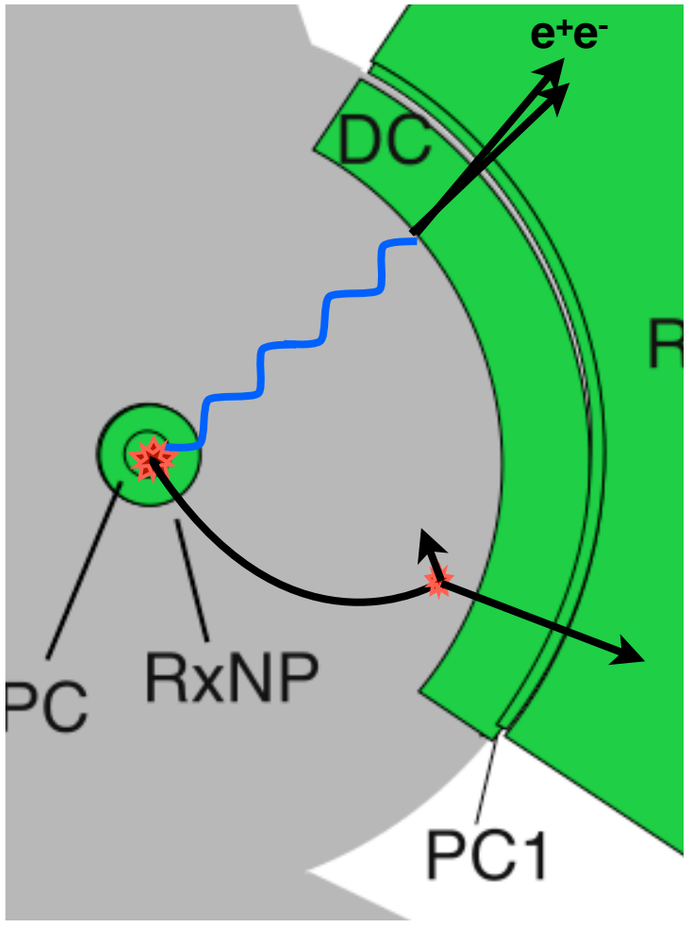
- fine momentum resolution

$$\delta p/p \approx 0.7\% \otimes 0.1\% p$$

low p_T - multiple scattering
high p_T - angular resolution

~1% at 7 GeV/c

High momentum background



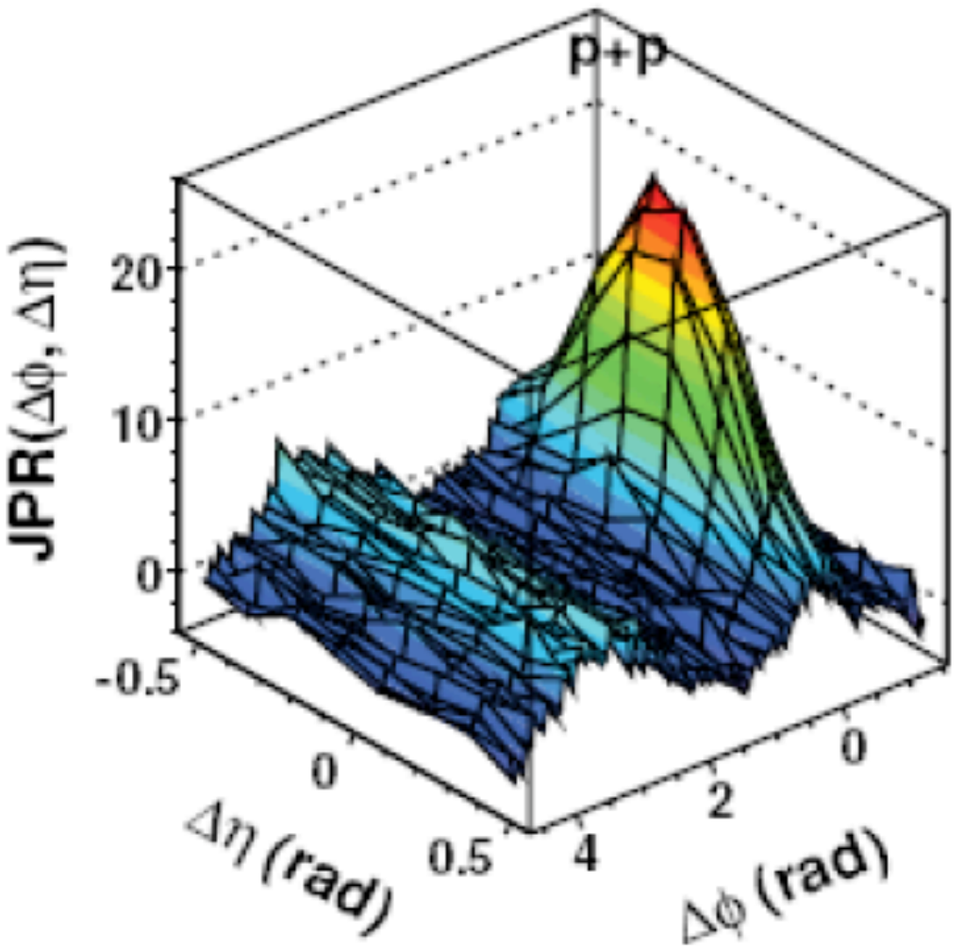
$p_T > 5$ GeV/c

- photon conversion
- post-field decay
- albedo

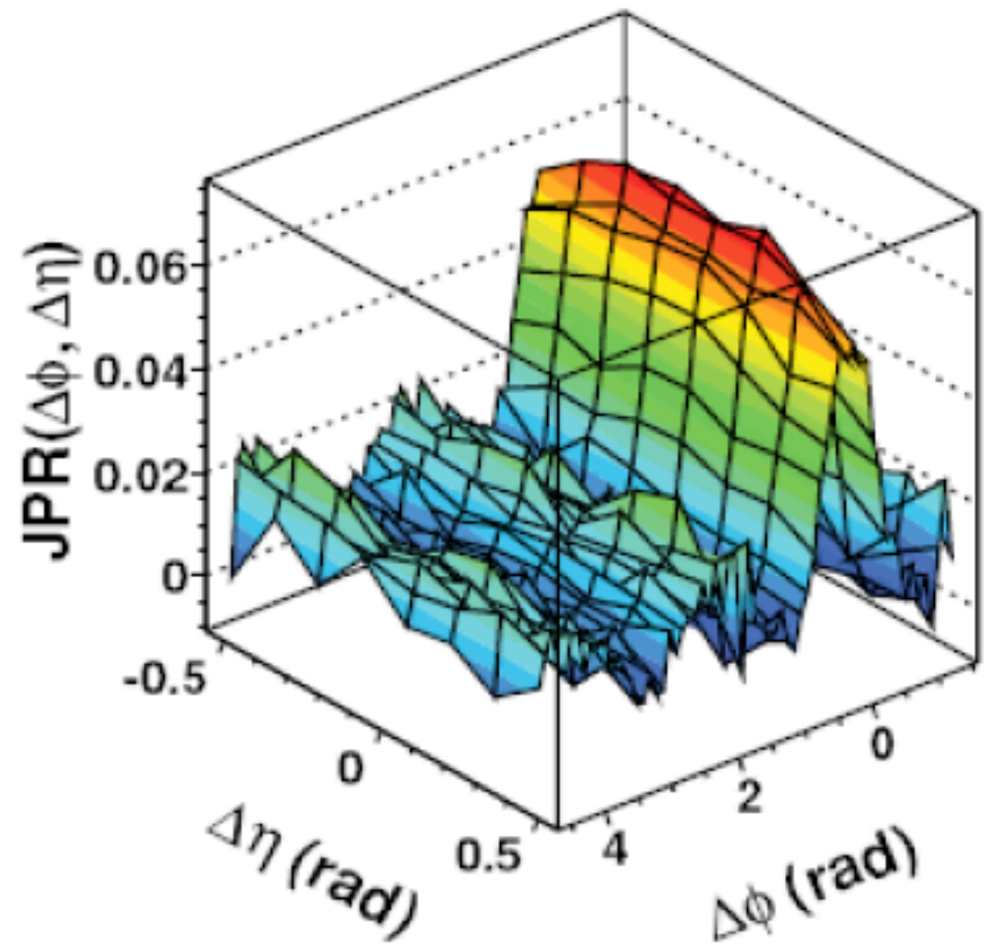
Extend matching requirement in PC3

Intermediate p_T Medium Response

p+p (similar in peripheral Au+Au)



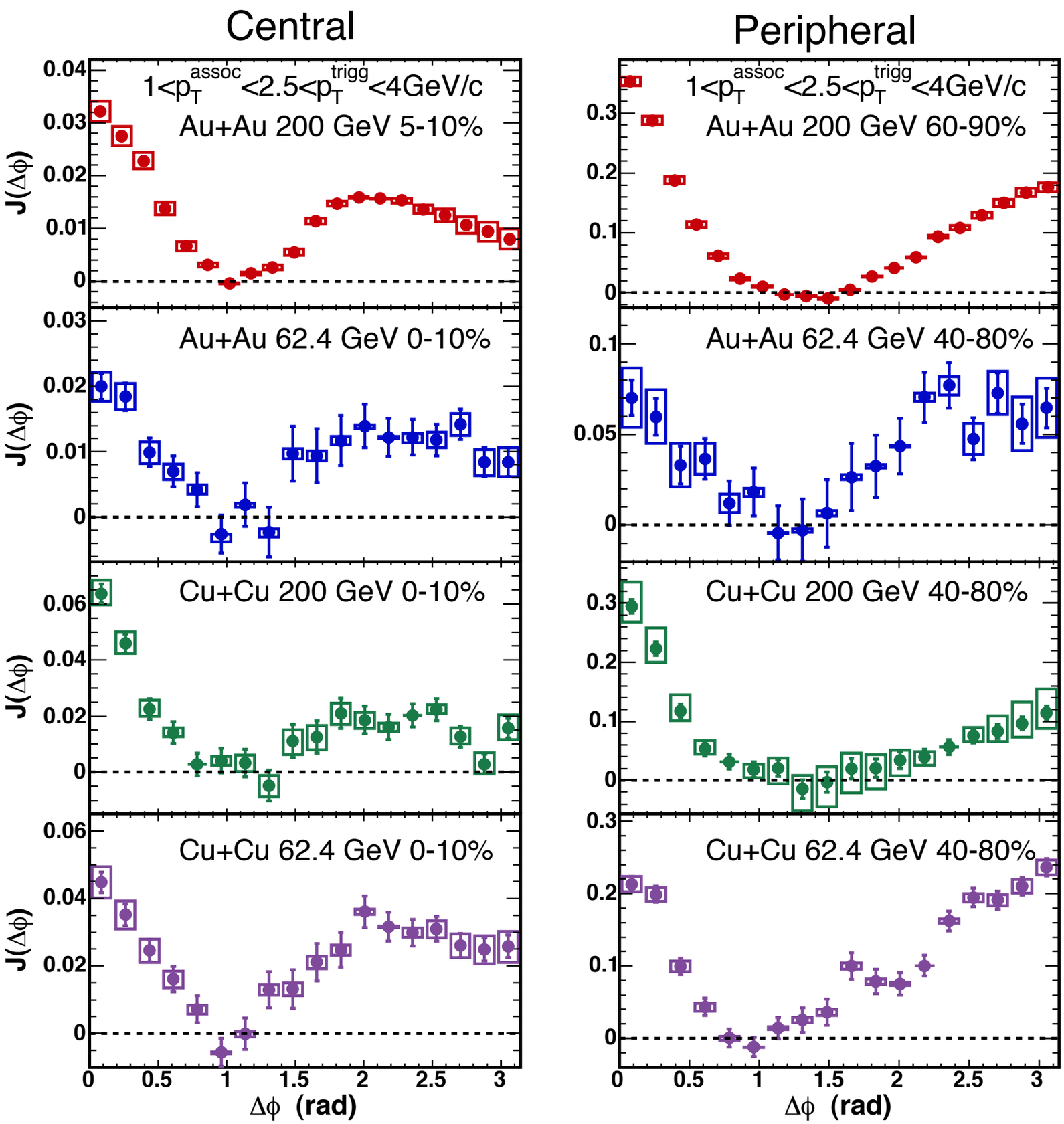
central Au+Au



Typical:
- Near-side Jet
- Away-side Jet - "Head"

New:
- Near-side Modification- "Ridge"
- Away-side Modification - "Shoulder"

System and Energy Scan

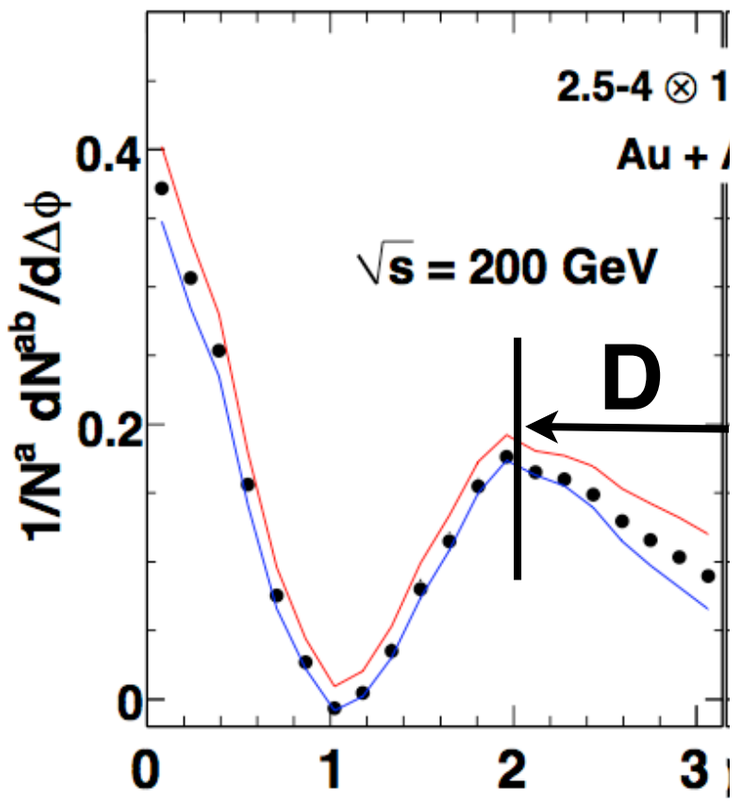


Away-side structure vs. beam species, beam energies, and centrality

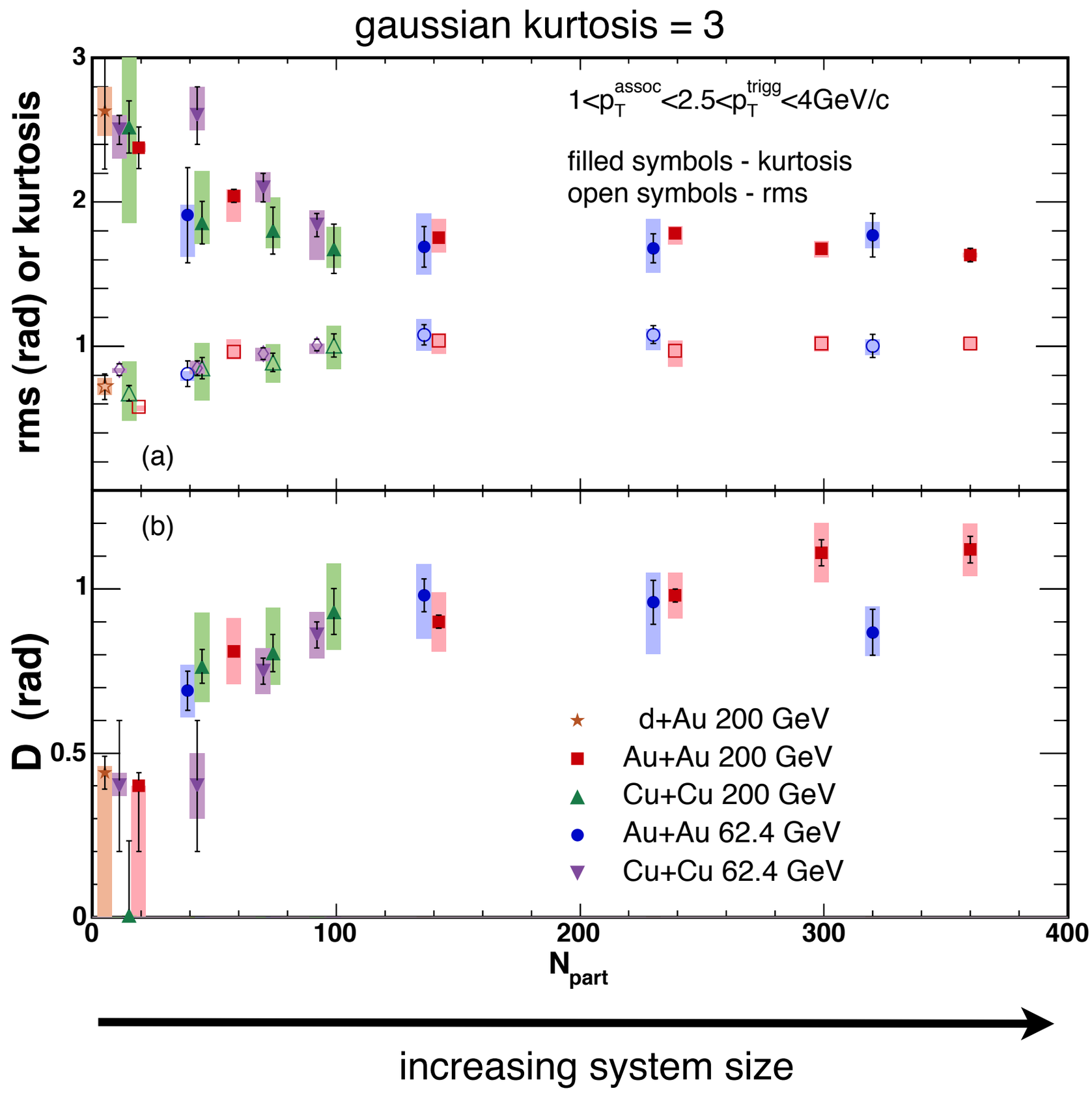
<u>All cases:</u>

- Peripheral similar to p-p
- Central shows development of shoulder structure in all cases

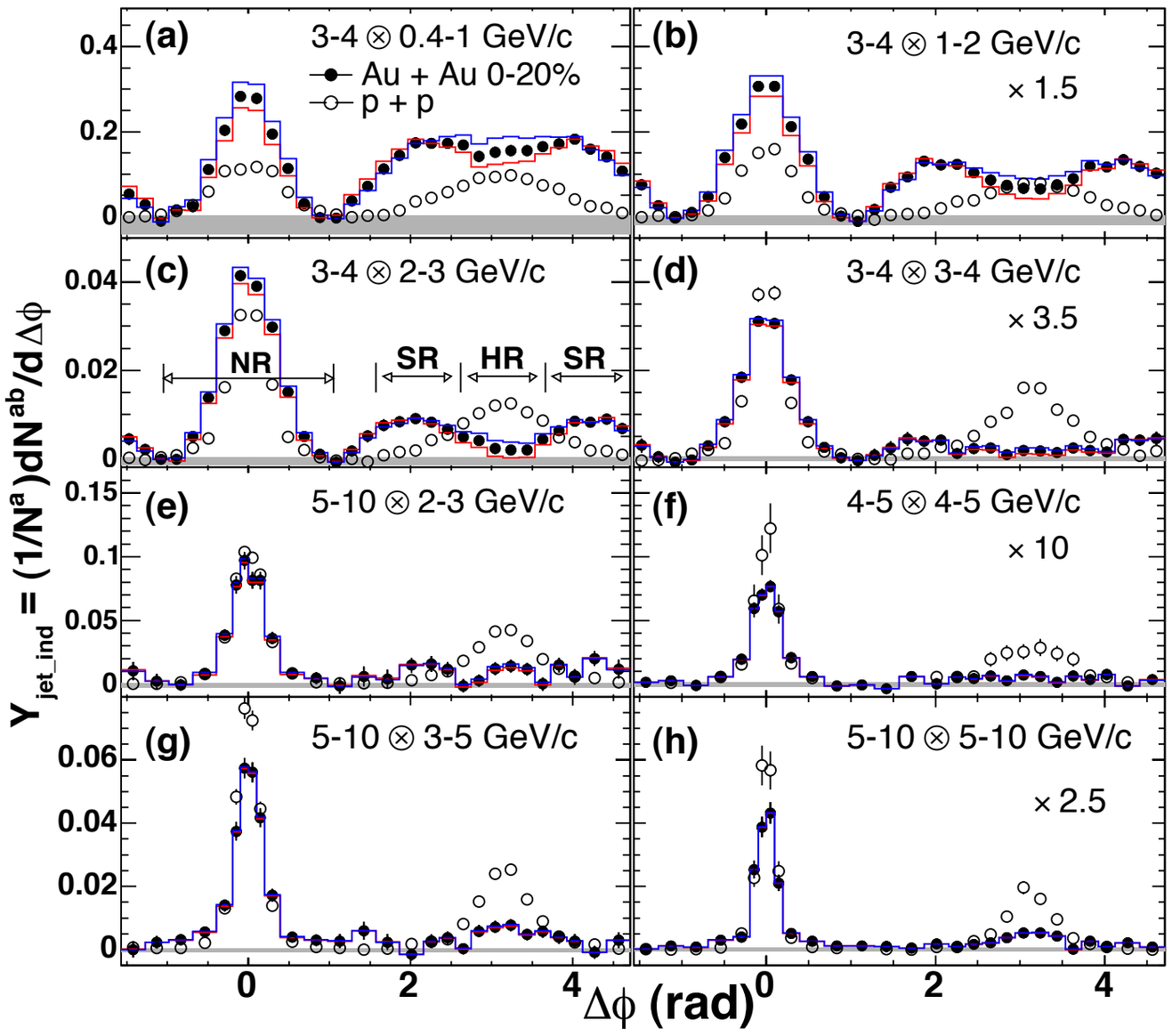
System Size



- Common trend with system size
- Transition region between 0 and 100 N_{part}
- Shape saturates above 100 N_{part}
- No observed energy dependence at RHIC

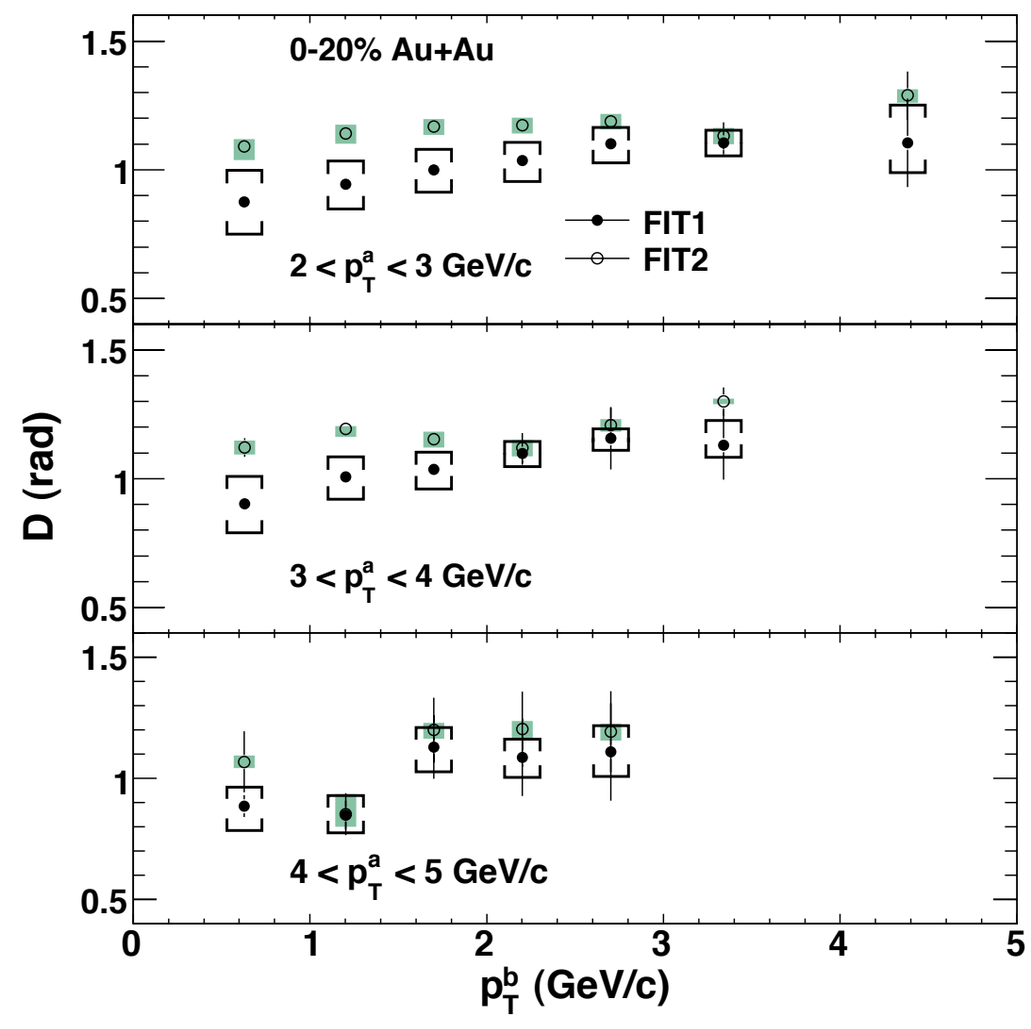


Transverse Momentum, p_T



- Away-side shoulder and near-side enhancement is seen in all intermediate p_T correlations
- Normal, but suppressed, away-side at high p_T

- Position of intermediate p_T away-side relatively insensitive to trigger and partner selection

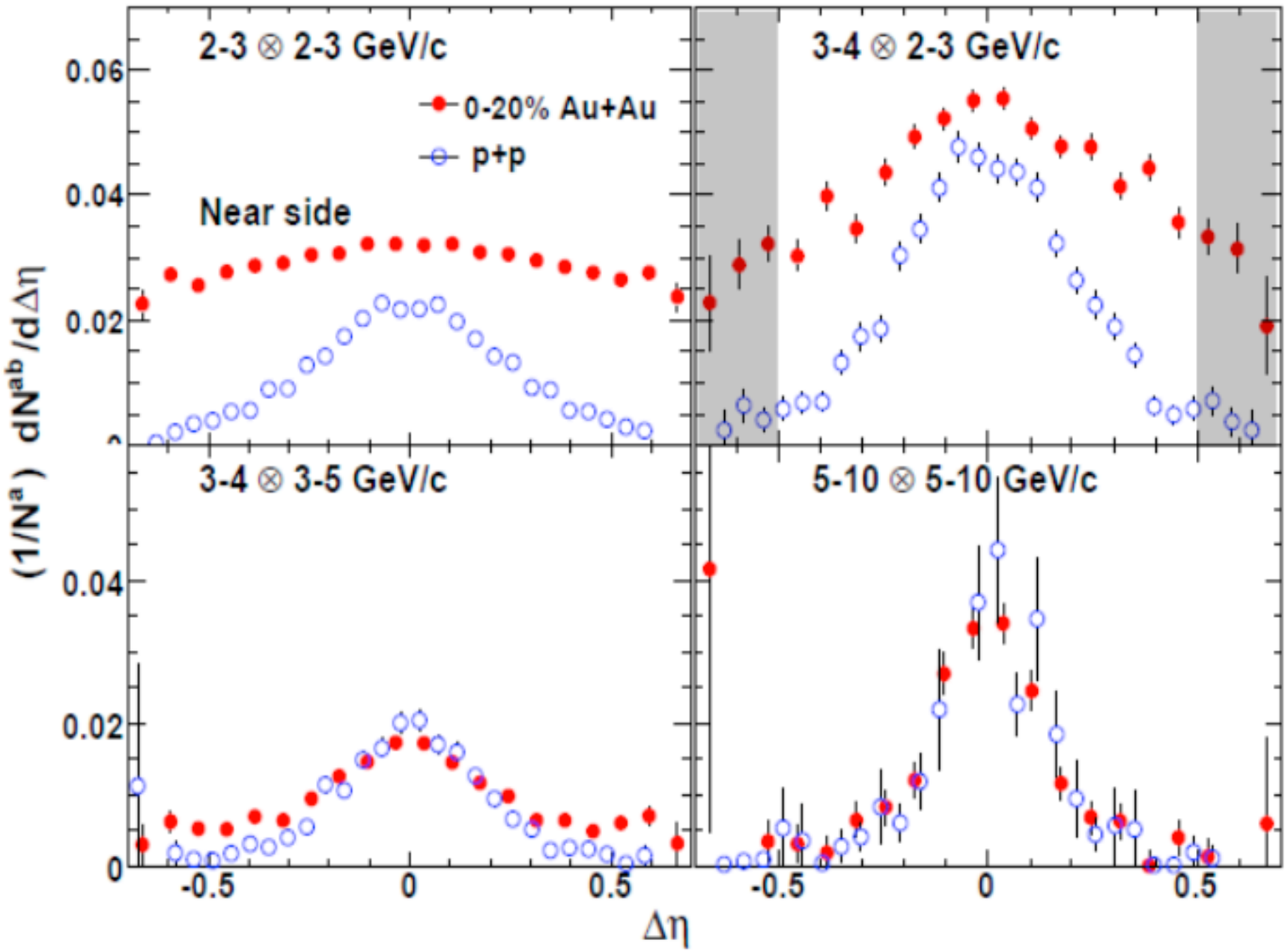


Near-side Ridge

- Broad Δη near-side enhancement measured in Au+Au collisions at intermediate p_T

- High p_T near-sides are similar

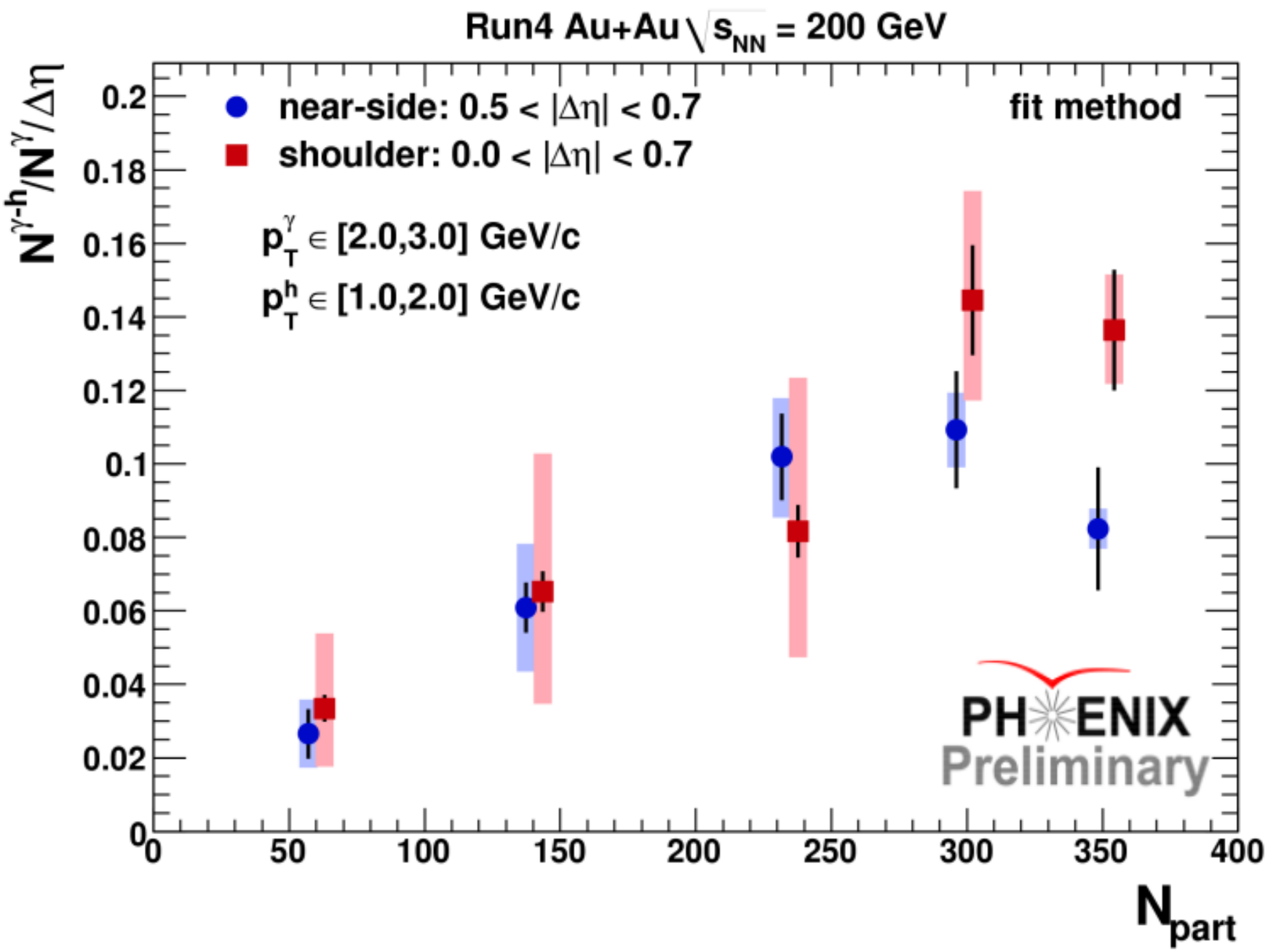
- Intermediate p_T p+p near-side is narrower in Δη than central collisions



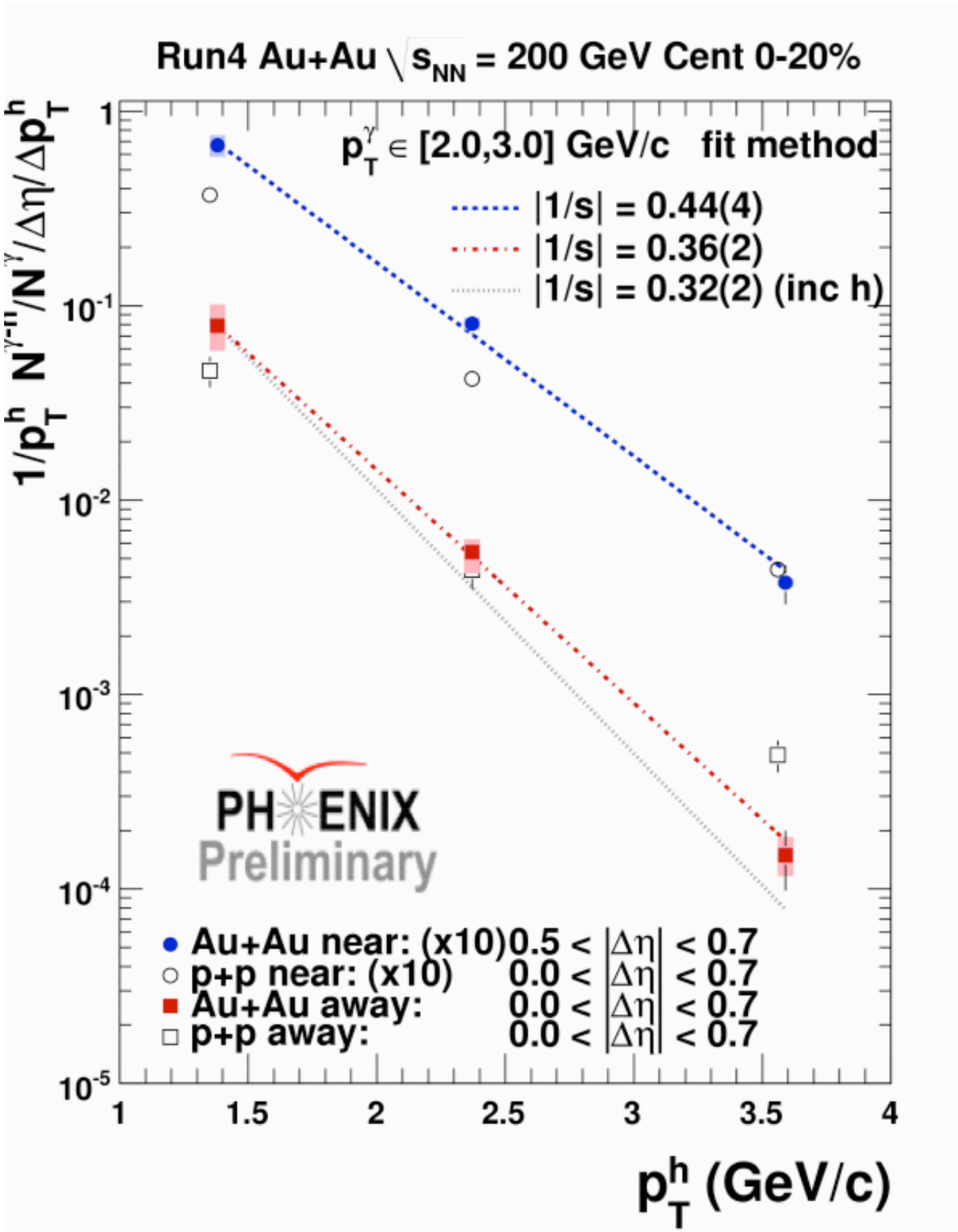
- At intermediate p_T, little p-p jet beyond Δη > 0.5

Ridge and Shoulder - Centrality

- Away-side shoulder and near-side ridge share a common centrality dependence
- Scale similarity here is largely a factor of p_T selection



Ridge and Shoulder - Spectrum



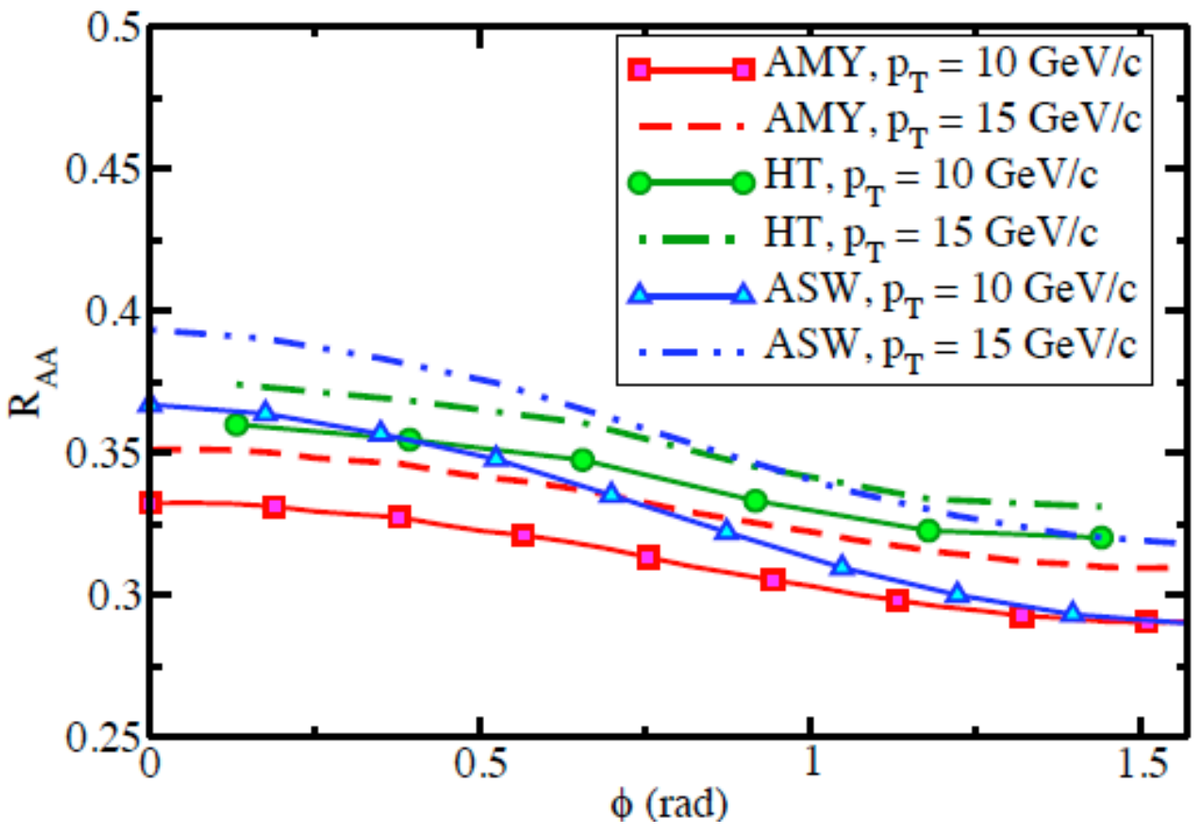
- Near-side ridge and away-side shoulder are both softer than p-p counterparts
- Near-side ridge is possibly harder than away-side shoulder
- Away-side shoulder is closest to inclusive hadron slope

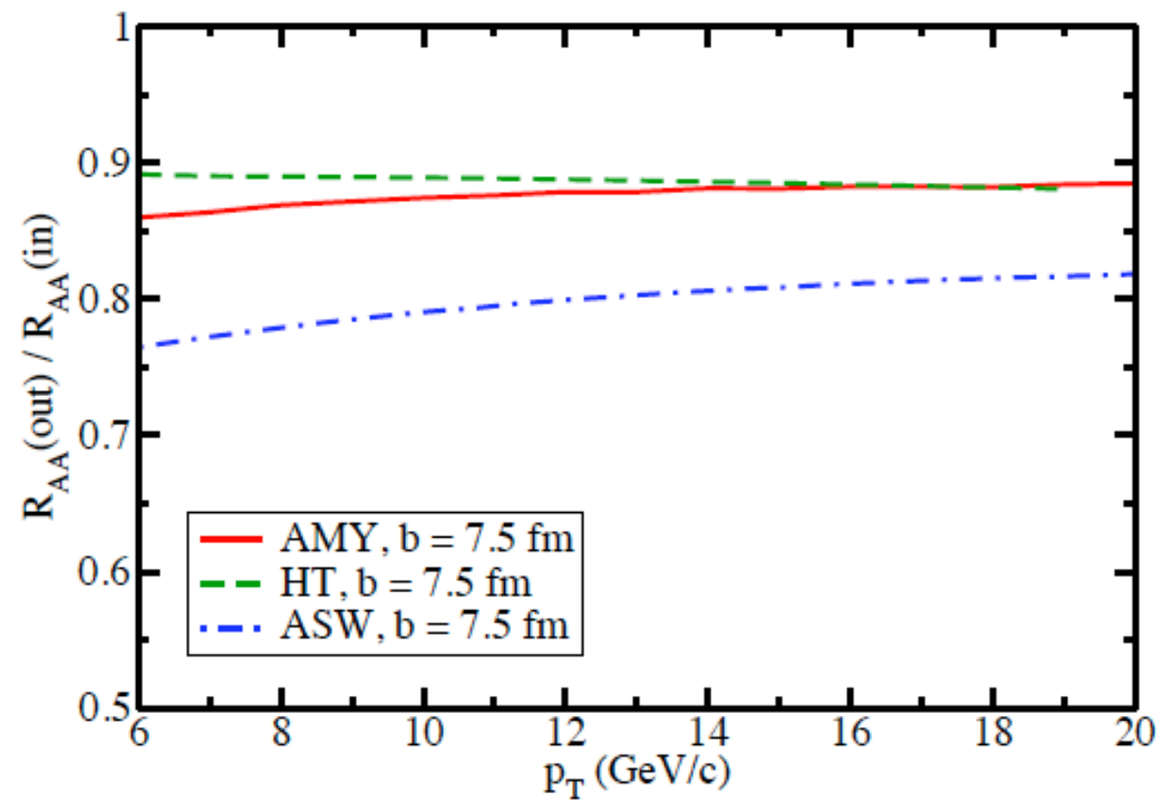
Also:

- Ridge and shoulder have more bulk-like particle ratios

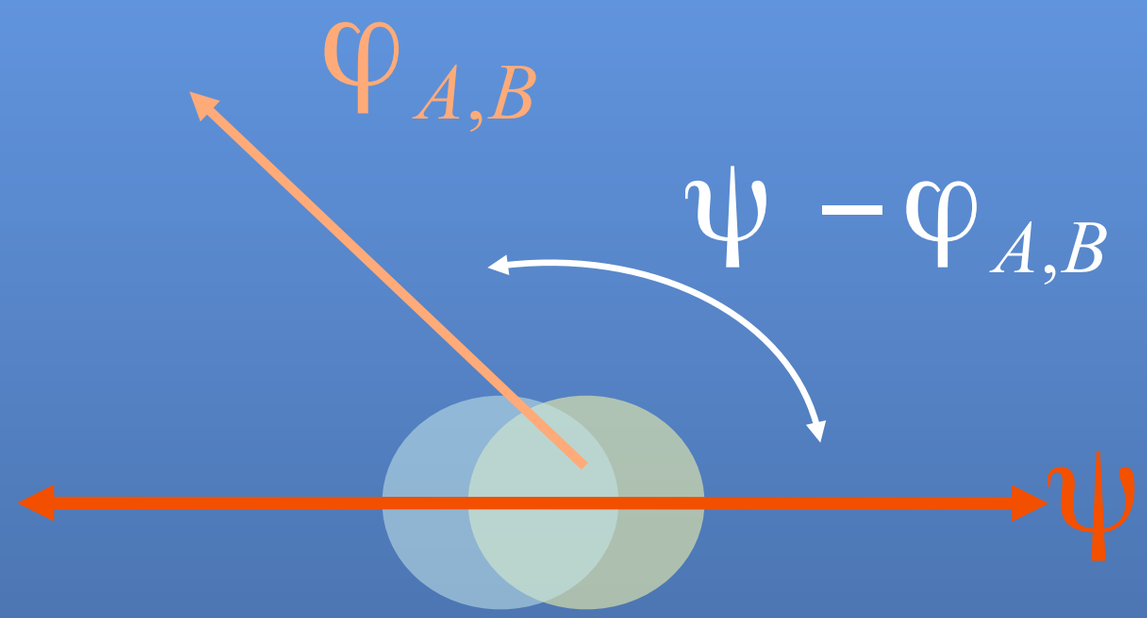
Raa x phiS

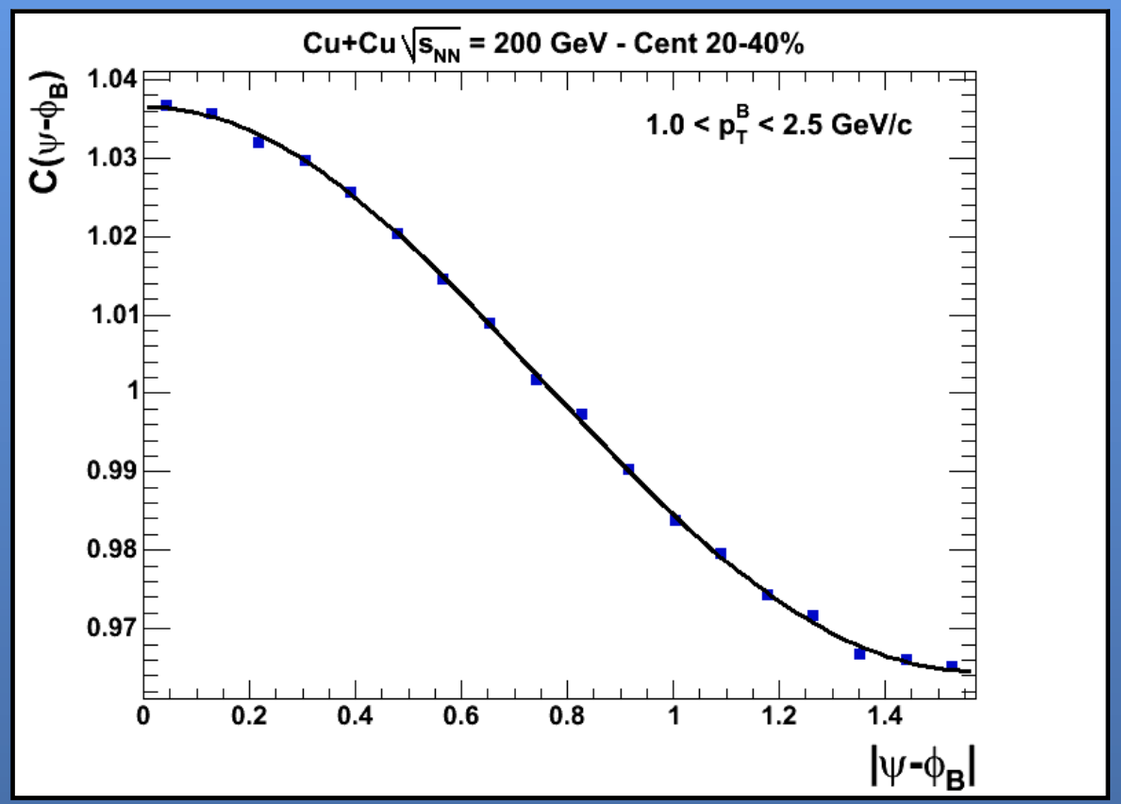
Bass, et al., PRC79, 024901





Measuring Elliptic Flow, v_2





Rx-pn ⇔ Track

Mean Projection:

$$v_2^{obs} = \sqrt{2\left\langle \cos\left(2\left(\psi - \varphi_{A,B}\right)\right)\right\rangle}$$

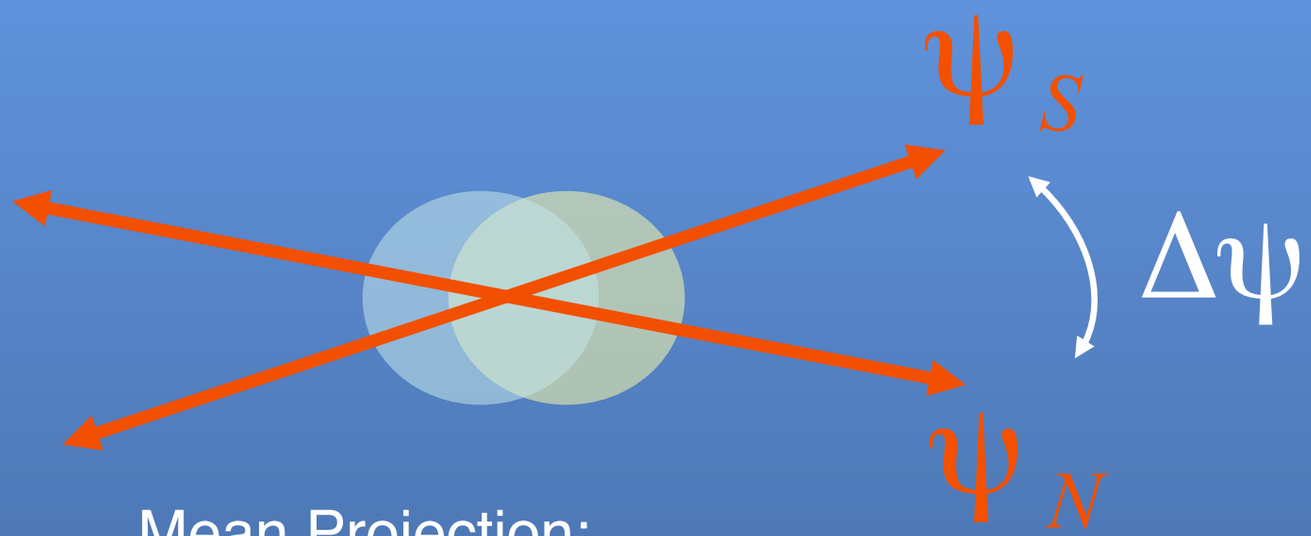
$$0 \cong \sqrt{2\left\langle \sin\left(2\left(\psi - \varphi_{A,B}\right)\right)\right\rangle}$$

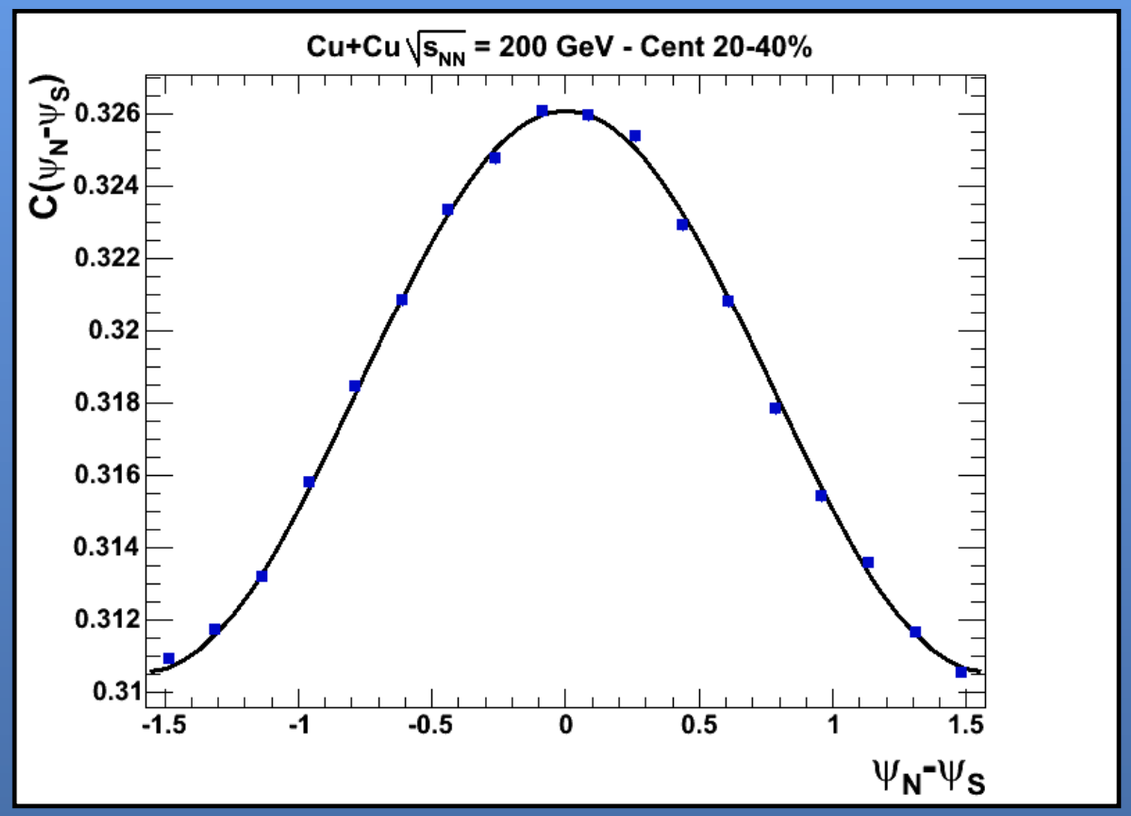
$$v_2 = \frac{v_2^{obs}}{\Delta}$$

Fit:

$$C\left(\psi - \varphi_{A,B}\right) = 1 + 2v_2^{obs}\cos\left(2\left(\psi - \varphi_{A,B}\right)\right)$$

Measuring Reaction-Plane Resolution, Δ





Rx-pn ⇔ Rx-pn

Mean Projection:

$$\Delta = \sqrt{2\langle\cos(2(\psi_N - \psi_S))\rangle}$$

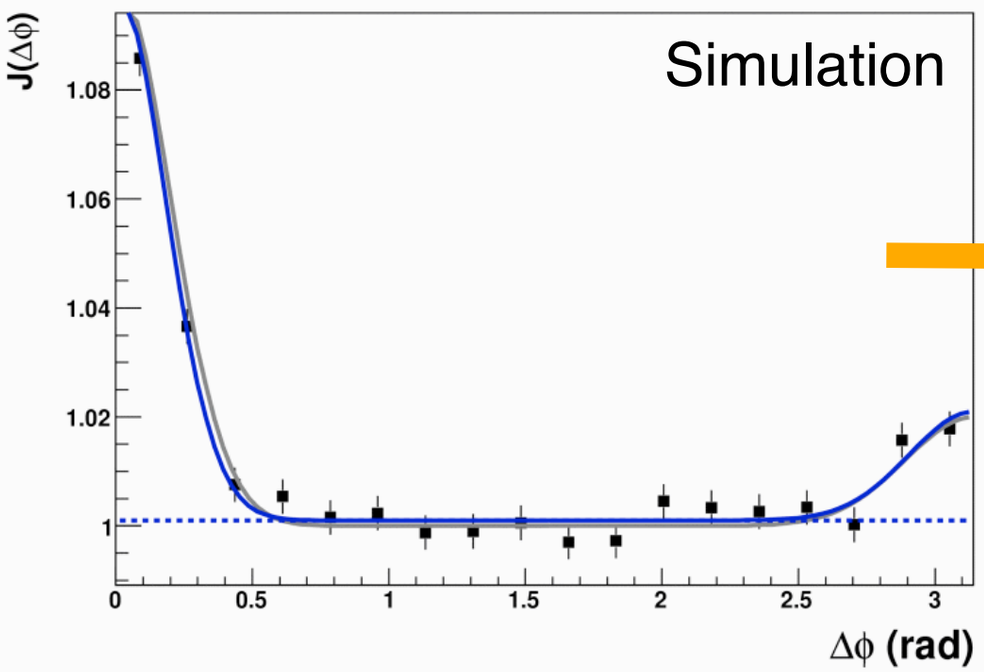
$$0 \cong \sqrt{2\langle\sin(2(\psi_N - \psi_S))\rangle}$$

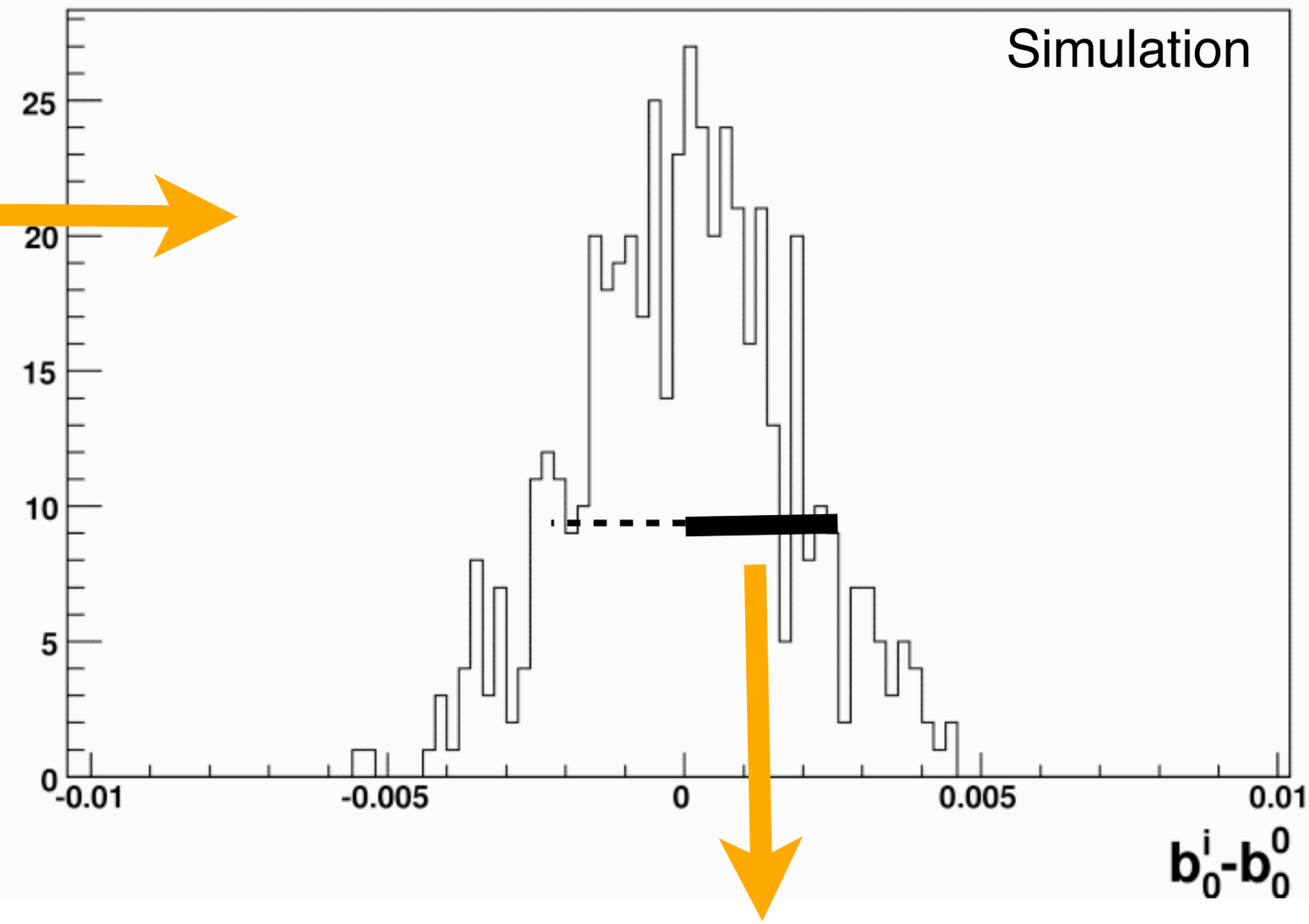
Ollitrault-Voloshin:

$$C(\Delta\psi) = \frac{1}{2}e^{-\frac{1}{2}\chi^2}\left\{\frac{2}{\pi}\left(1+\frac{\chi^2}{2}\right) + z\left(I_0(z)+L_0(z)\right) + \frac{\chi^2}{2}\left(I_1(z)+L_1(z)\right)\right\} \qquad z \equiv \frac{\chi^2}{2}\cos(2\Delta\psi)$$

$$\Delta = \frac{\sqrt{\pi}}{2}\chi e^{-\frac{1}{2}\chi^2}\left(I_0\left(\frac{\chi^2}{2}\right) + I_1\left(\frac{\chi^2}{2}\right)\right)$$

ZYAM Statistical Uncertainty





Bin Methods typically use statistical error of points (not a real estimate)

Proper Error Calculation:

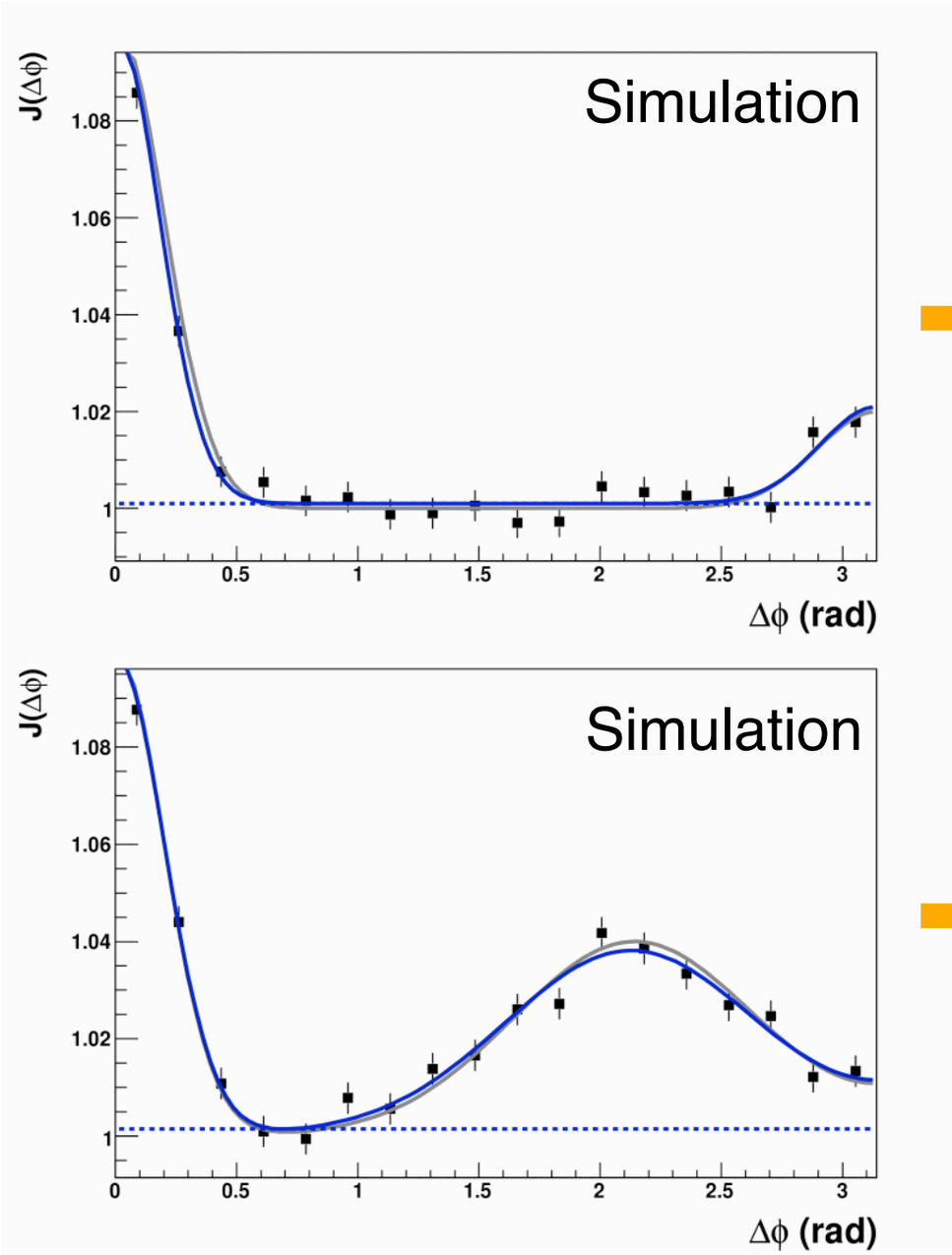
- Toss new C(Δϕ) against measurement(fit)
- Fit new C(Δϕ) (fit method only)
- Extract b_0, & repeat

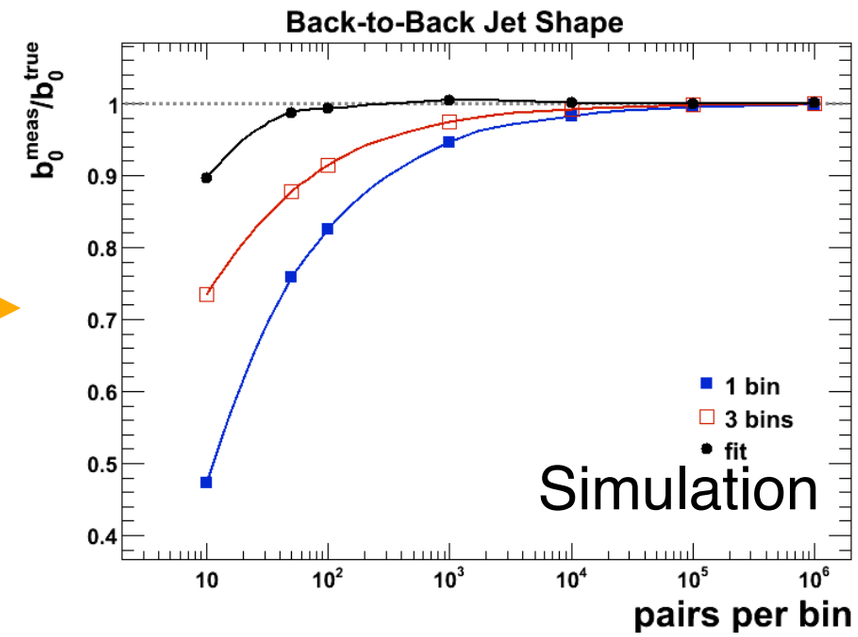
Scatter of b_0 in tossed C(Δϕ)s is the estimation of statistical error

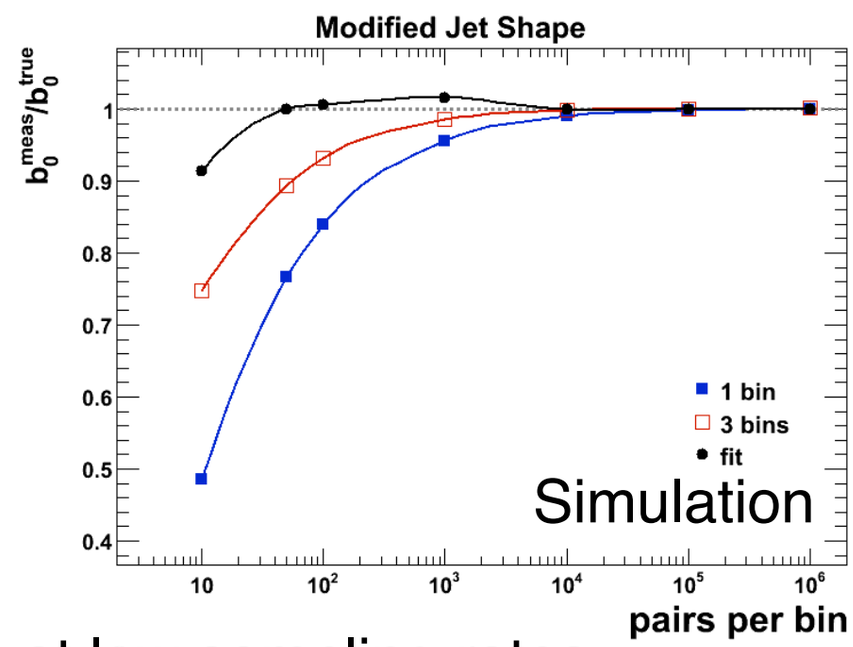
σ_{b0}

Don't trust ZYAM yields without this error bar!

ZYAM Systematic Uncertainty



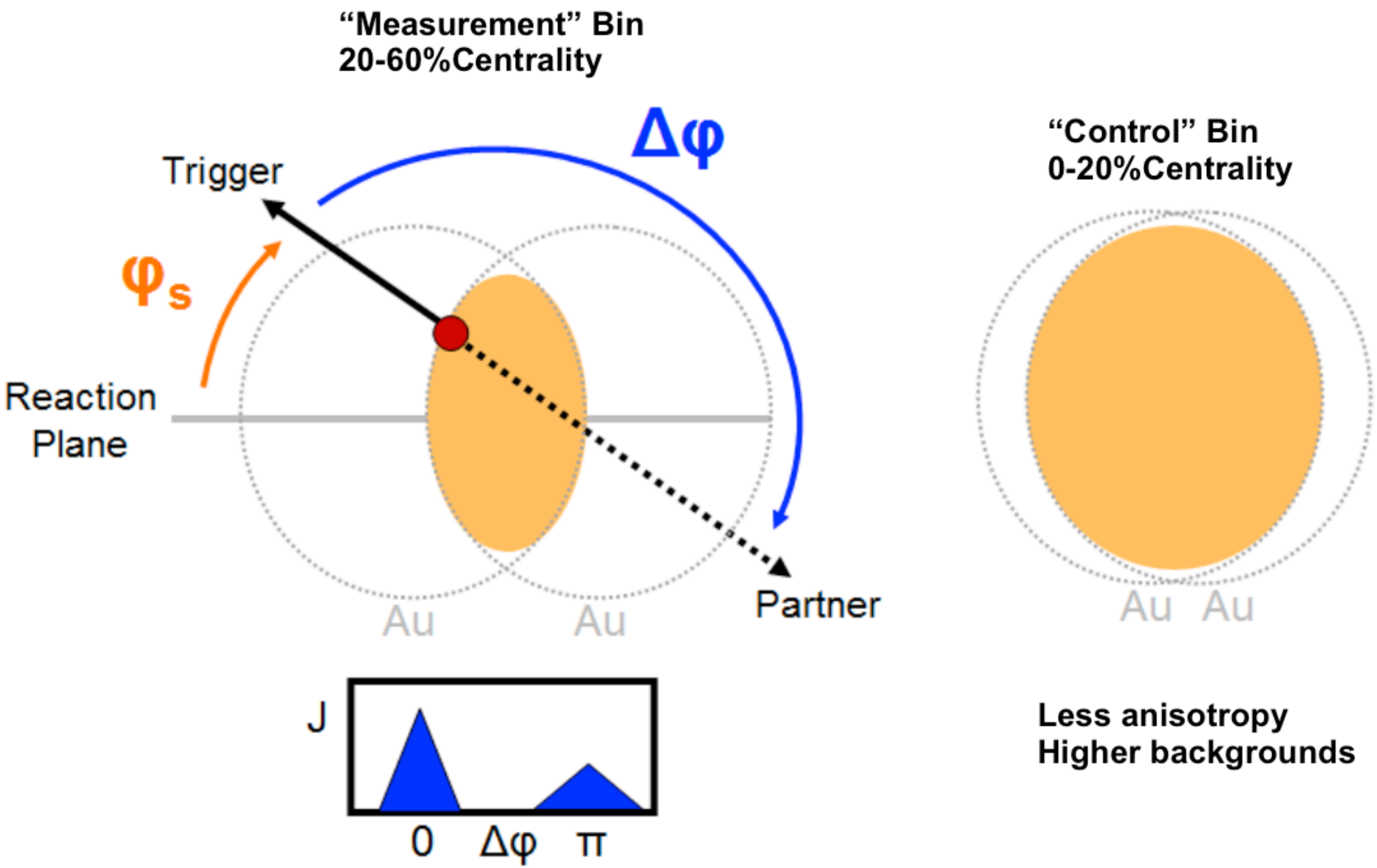




Binned ZYAMs deviate significantly from true value at low sampling rates
Fit method deviates most slowly (no effort to recover failed fits made here)
These jet shapes show only minor effects on

ZYAM applied at sufficiently low statistics requires an additional systematic!
(this is ~~usually not~~ <u>never</u> done)

High π^0-$h^\pm$ by Reaction Plane Analysis



Pair Analysis with Reaction Plane

Two source model is now:

$$C(\Delta\phi) = J(\Delta\phi)) + b_0^{ZYAM}\left(1 + \frac{\beta}{\alpha}\cos(2\Delta\phi) + \frac{\gamma}{\alpha}\cos(4\Delta\phi)\right)$$

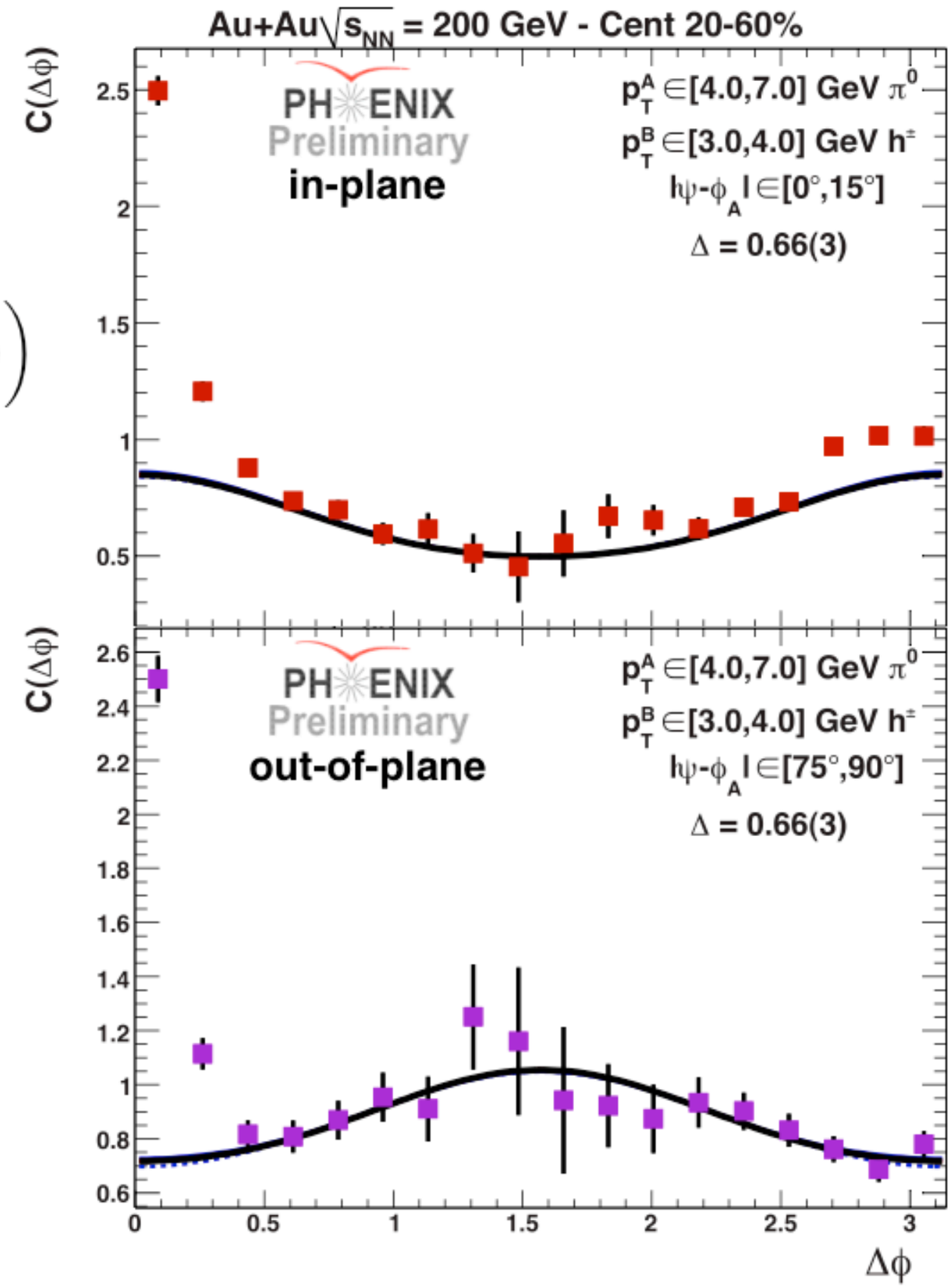
and rxpn-binning requires:

$$\alpha = 1 + 2v_2^A cos(2\phi_s)\frac{sin(2c)}{2c}\Delta + 2\,v_2^A cos(4\phi_s)\Delta_4$$

$$\beta = 2v_2^A v_2^B + 2v_2^B\left(1 + v_4^A\right)cos(2\phi_s)\frac{sin(2c)}{2c}\Delta + 2v_2^A v_2^B cos(4\phi_s)\frac{sin(4c)}{4c}\Delta_4 + 2v_2^B v_4^A cos(6\phi_s)\frac{sin(6c)}{6c}\Delta_6$$

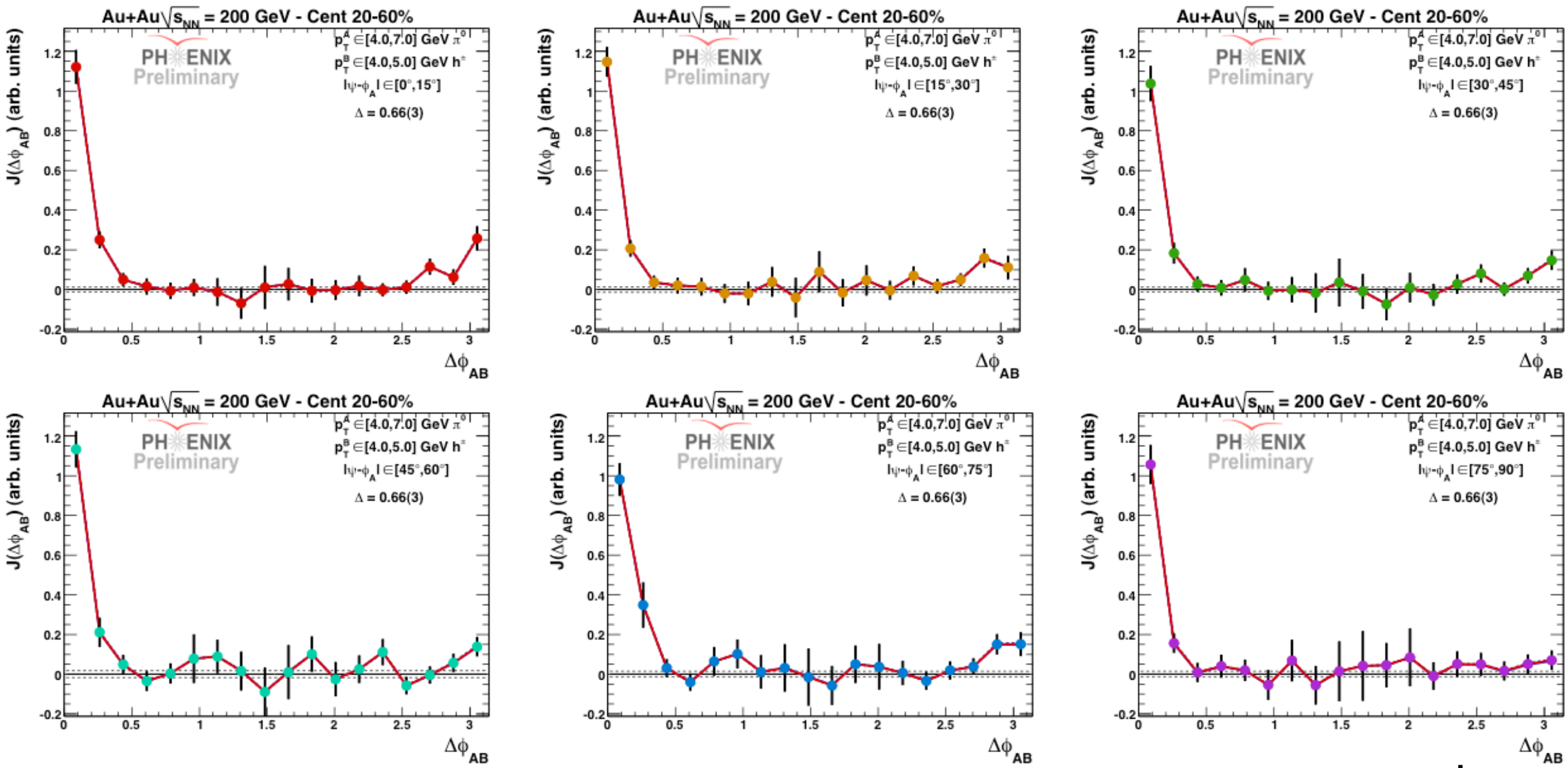
$$\gamma = 2v_4^A v_4^B + 2v_4^B\left(1 + v_2^A\right)cos(4\phi_s)\frac{sin(4c)}{4c}\Delta_4 + 2v_2^A v_4^B\left(cos(2\phi_s)\frac{sin(2c)}{2c}\Delta + cos(6\phi_s)\frac{sin(6c)}{6c}\Delta_6\right) + 2v_4^A v_4^B cos(8\phi_s)\frac{sin(8c)}{8c}\Delta_8$$

high order



Jet Functions - Full Set @ 4-5 GeV/c

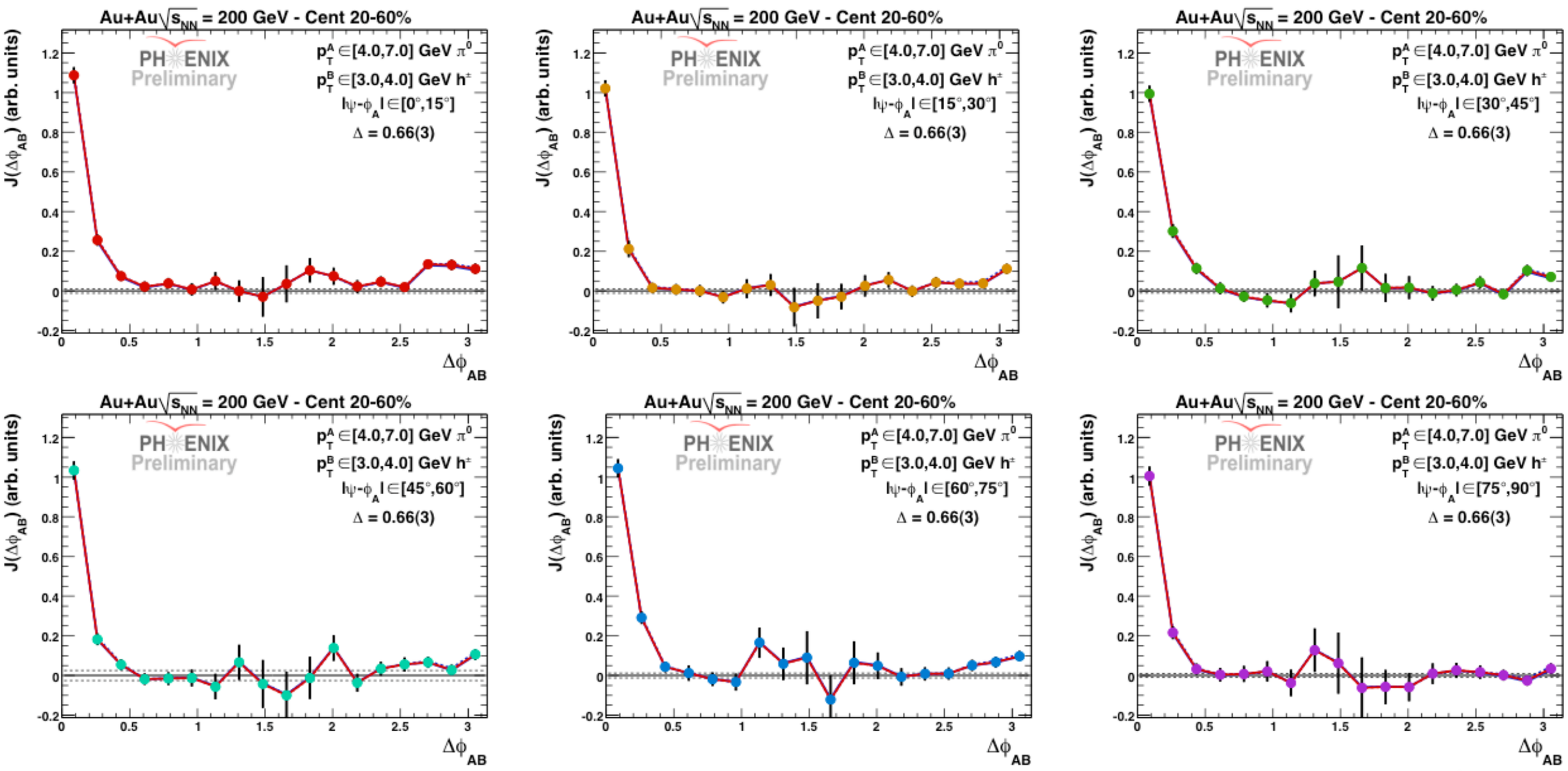
most in-plane



most out-of-plane

Jet Functions - Full Set @ 3-4 GeV/c

most in-plane



most out-of-plane