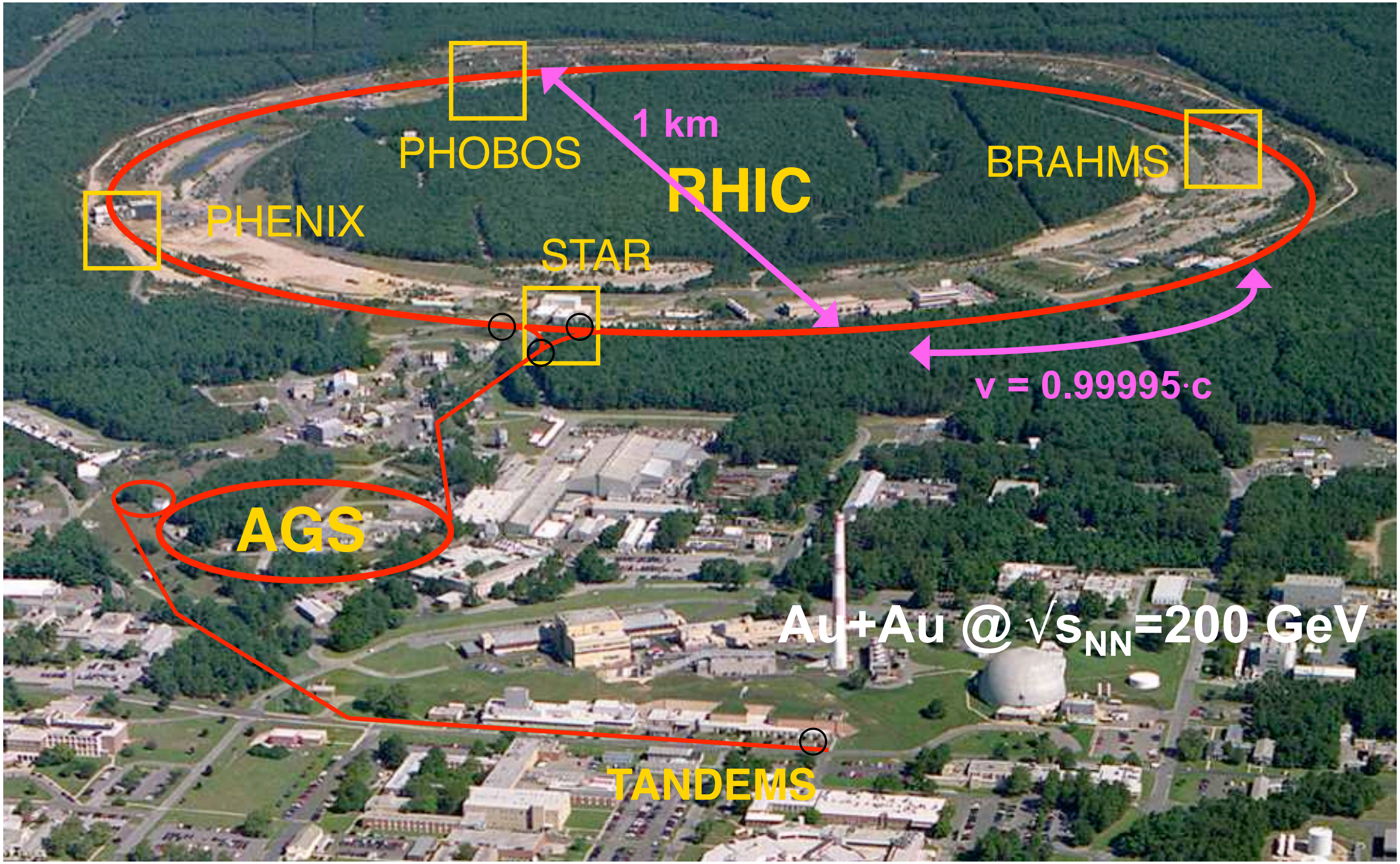
Using particle correlations to probe the medium produced at RHIC

Helen Caines - Yale University

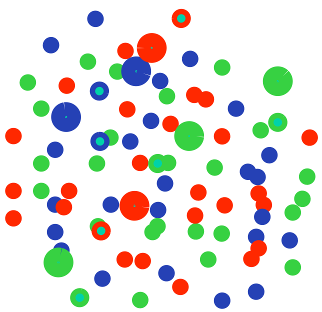
Oxford/RAL
November 2008

Relativistic Heavy-Ion Collider (RHIC)

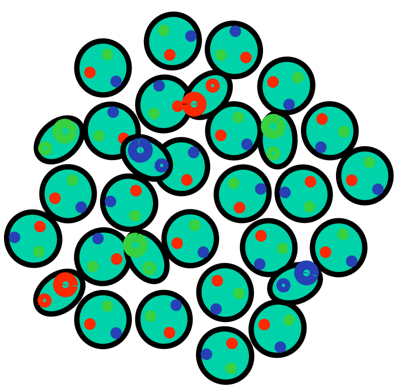


QGP expectation came from Lattice

ε/T^4 ~ # degrees of freedom



deconfined:
many d.o.f.



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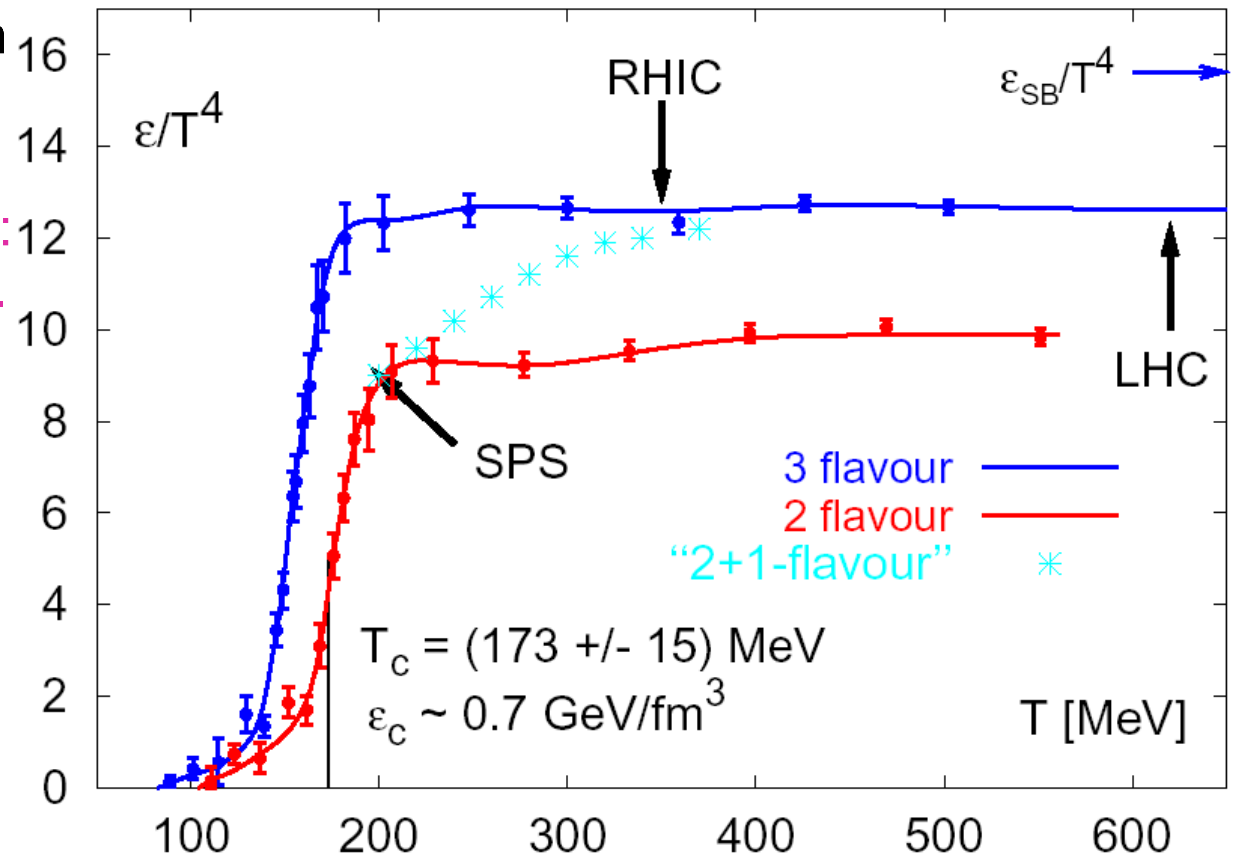

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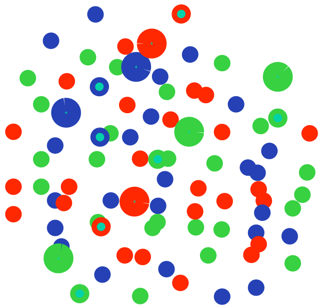

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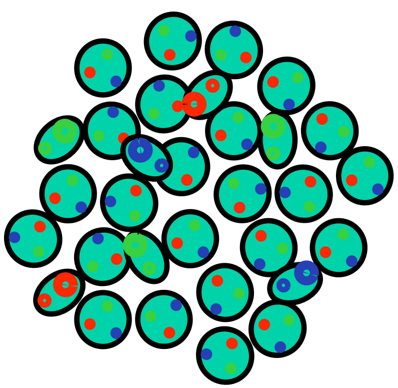

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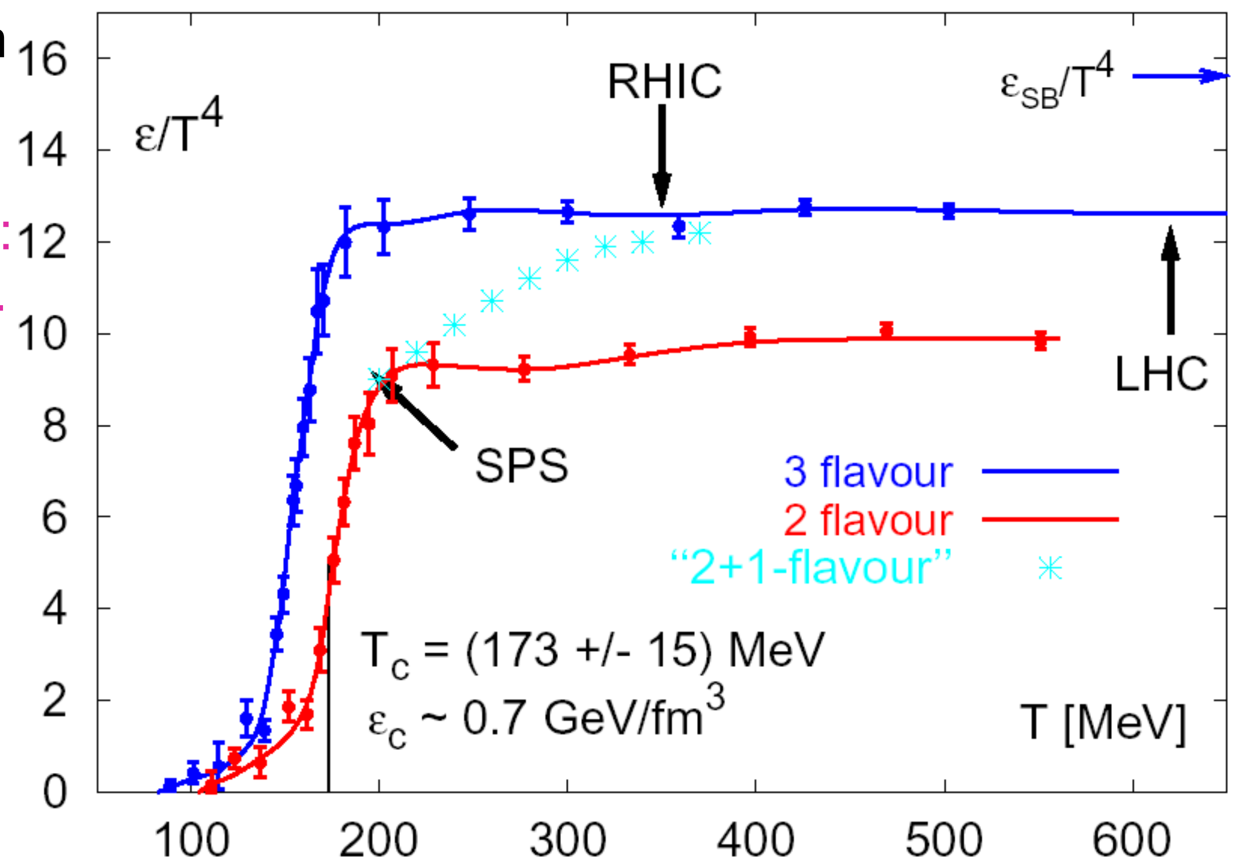

$T_C \approx 173$ MeV $\approx 2{\cdot}10^{12}$ K
$\varepsilon_C \approx 0.7$ GeV/fm^3 (~6x normal nuclear densities)

RHIC has created a new state of matter

The QGP is the:

hottest (T=200-400 MeV ~ 2.5 10^{12} K)

densest (ε = 30-60 $\varepsilon_{\text{nuclear matter}}$)

matter ever studied in the lab.

It flows as a

(nearly) perfect fluid

with systematic patterns, consistent with

quark degree of freedom

and a viscosity to entropy density ratio

lower

than any other known fluid.

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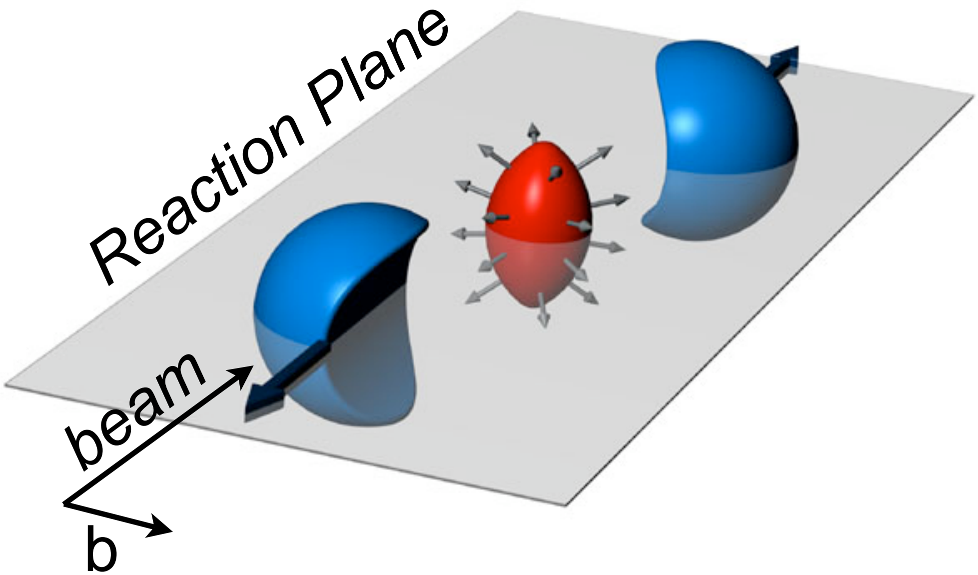
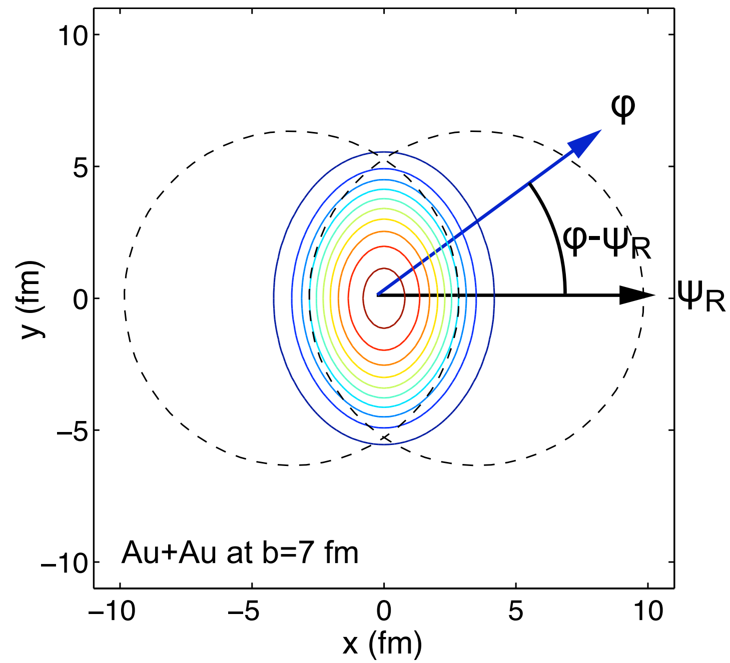
Want to learn more about the properties

Elliptic flow – rapid thermalization





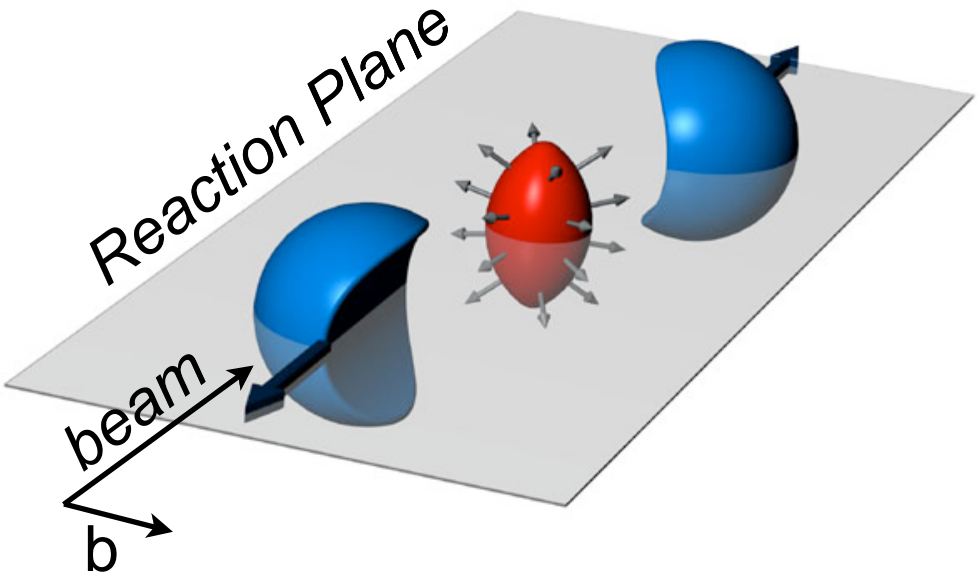
Interactions

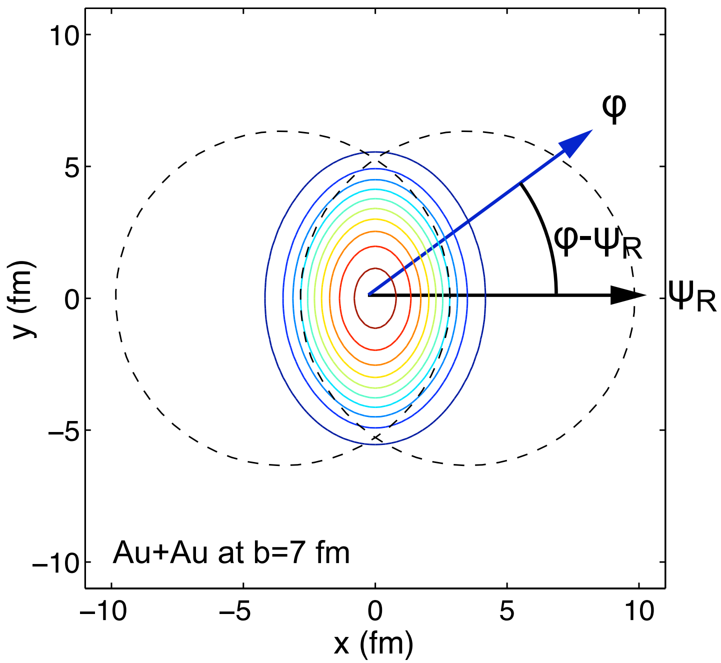
Initial spatial anisotropy → Final momentum anisotropy

A Fourier expansion used to describe the angular distribution of the particles

$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

Elliptic flow – rapid thermalization





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Driving spatial anisotropy vanishes ⇒ self quenching

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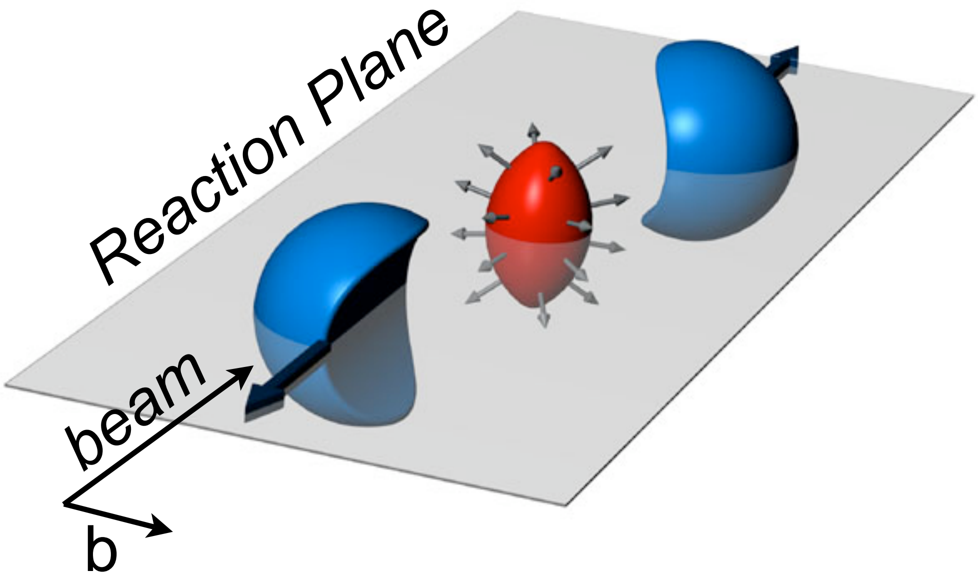

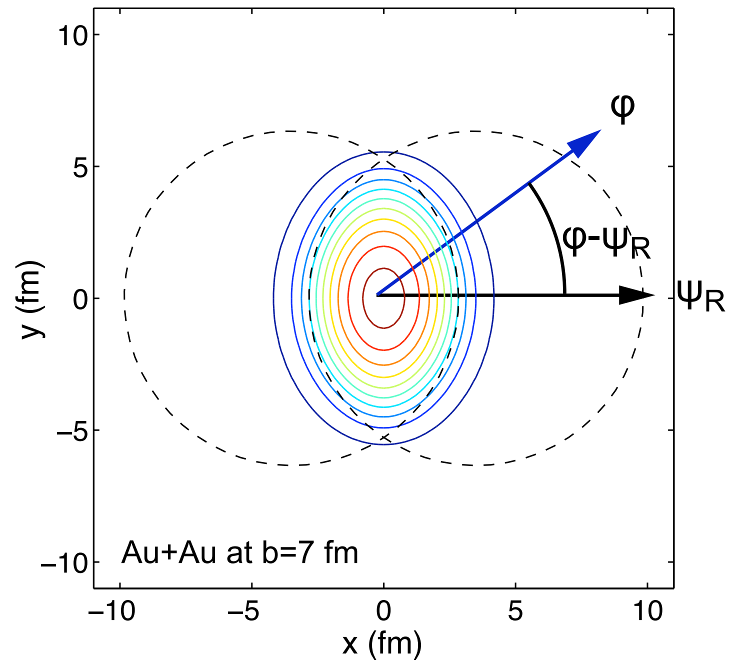

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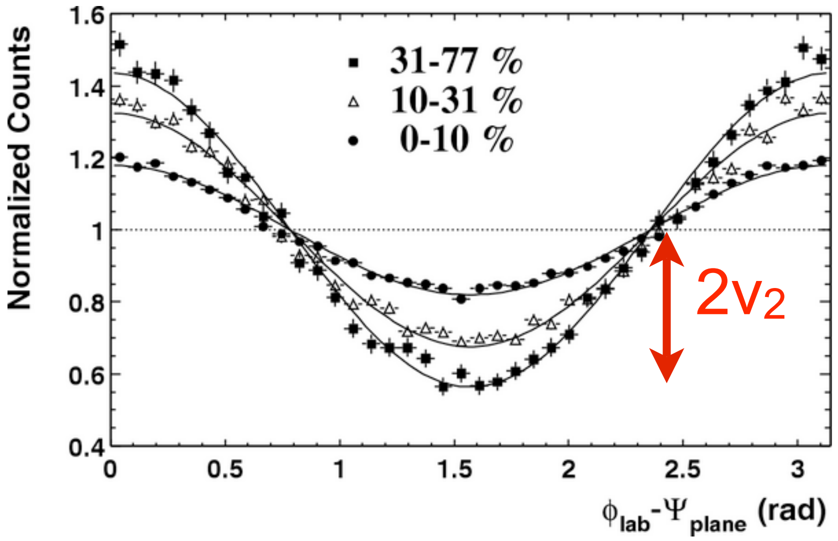
Sensitive to **early** interactions and pressure gradients

The flow is ~Perfect



Huge asymmetry found at RHIC

- massive effect in azimuthal distribution w.r.t reaction plane
- At higher p_T: Factor 3:1 peak to valley from 25% v_2

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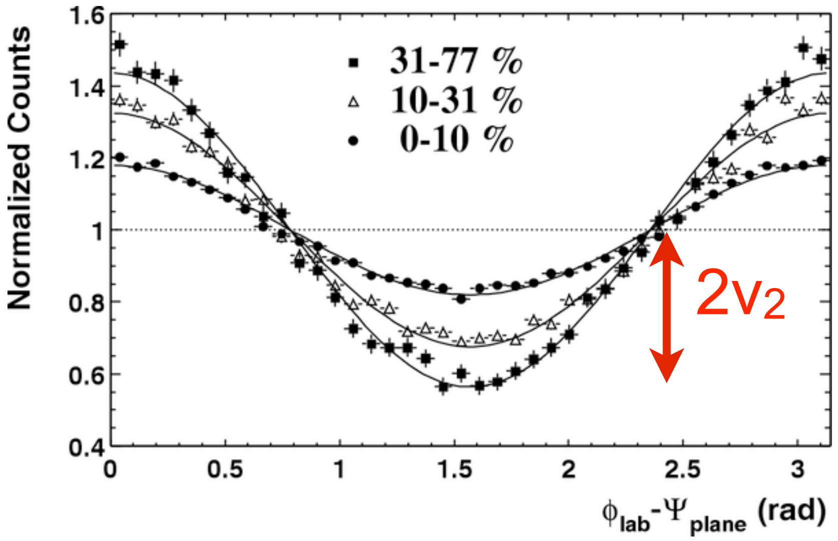

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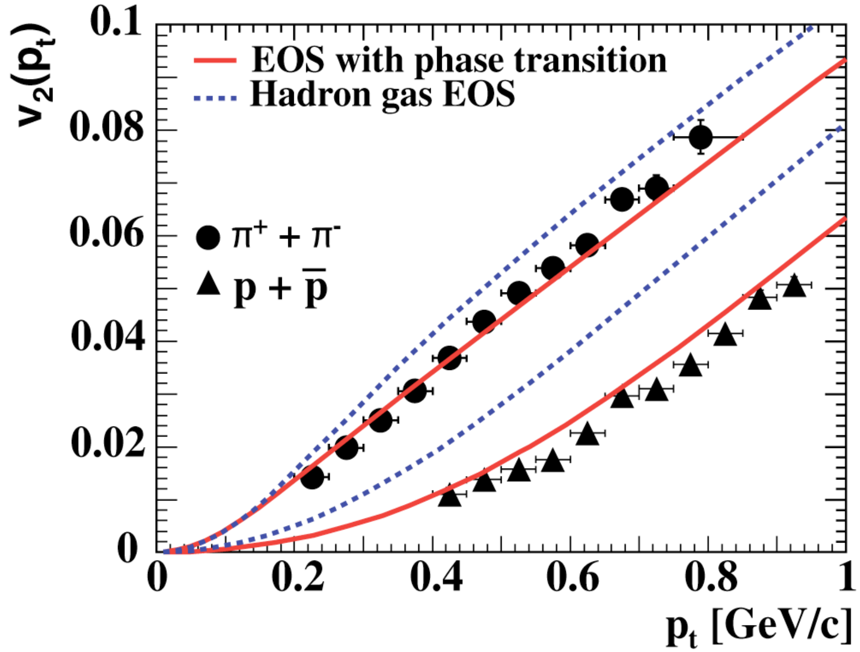
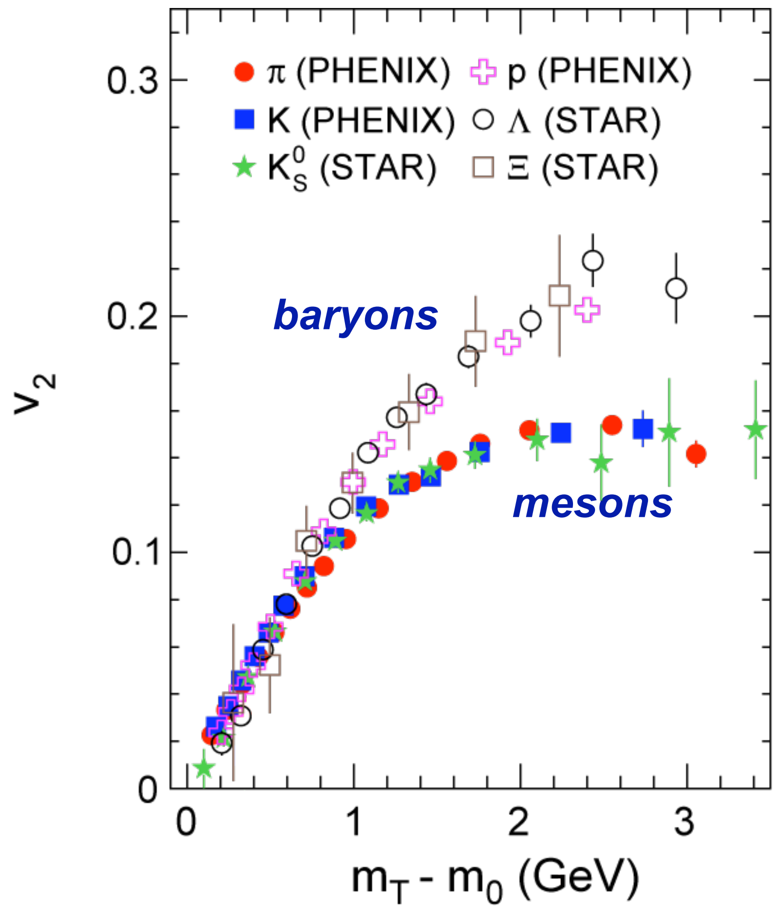
"fine structure" $v_2(p_T)$

- ordering with mass of particle
- good agreement with ideal hydrodynamics (zero viscosity, λ=0)



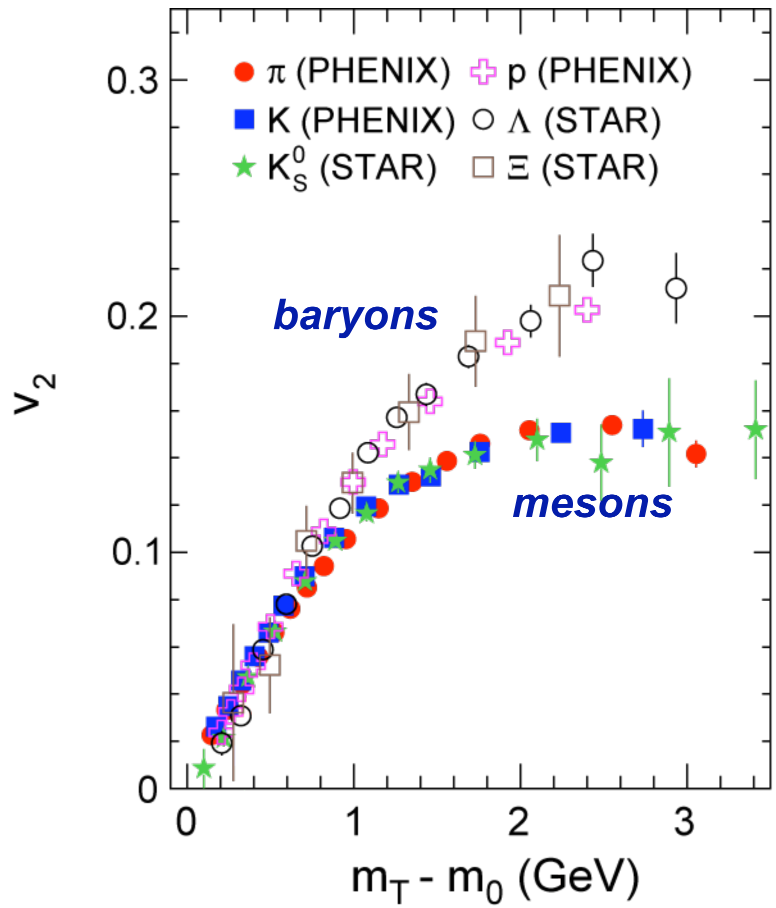
⇒ "perfect liquid"

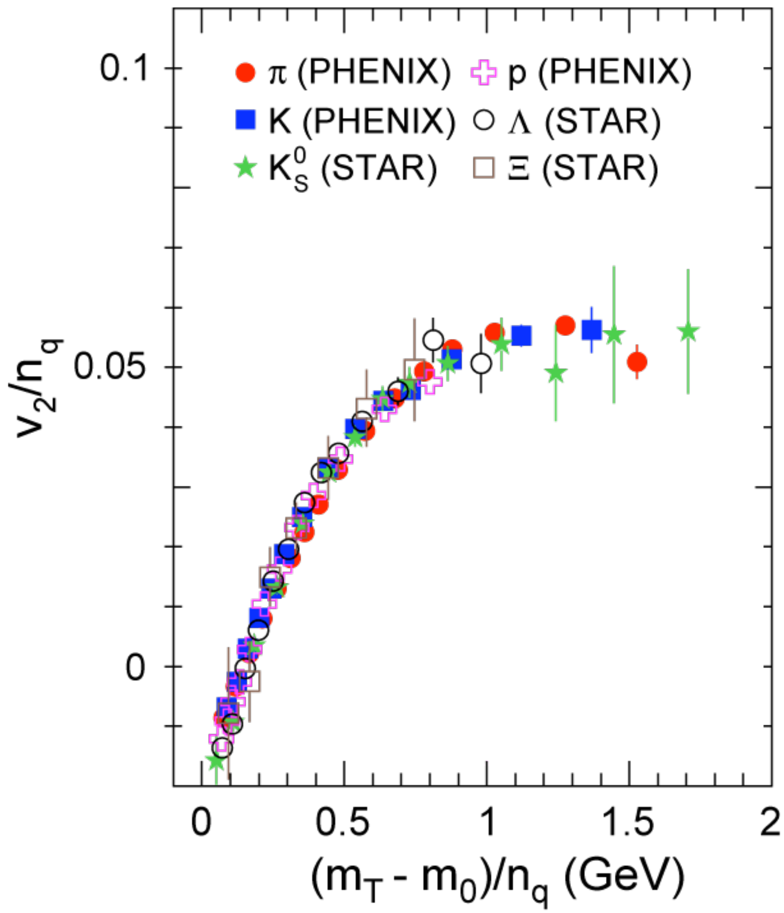
The constituents "flow"



$$m_T = \sqrt{p_T^2 + m_0^2}$$

The constituents “flow”





- Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

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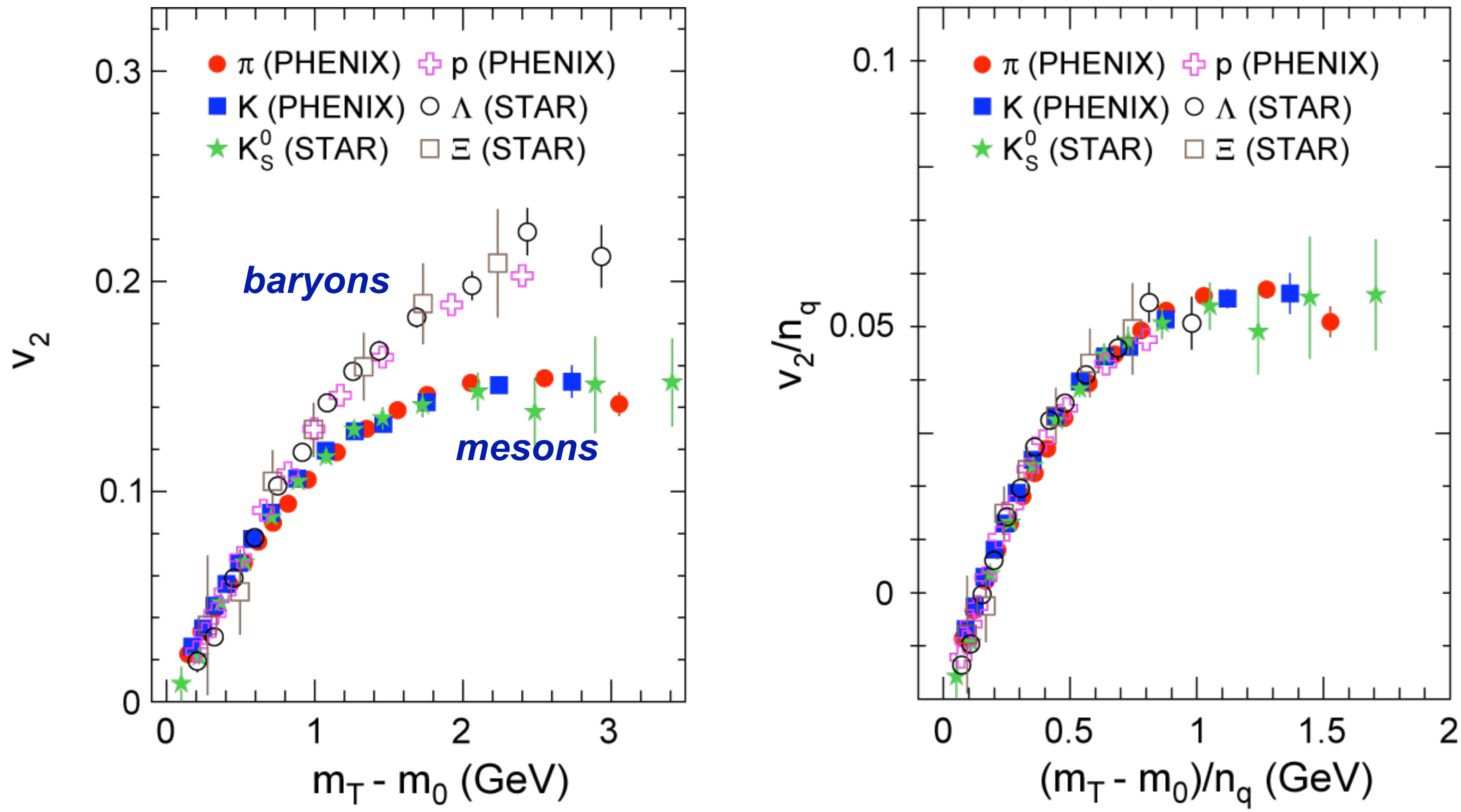

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Constituents of liquid are partons

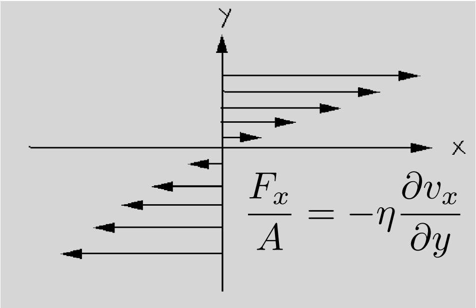
How perfect is "Perfect" ?

Viscous fluid

- supports a shear stress
- viscosity η:

$$\eta \approx \text{momentum density} \times \text{mean free path}$$
$$\approx n\bar{p}\lambda = n\bar{p}\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}$$

- small η ⇒ large σ ⇒ strong couplings



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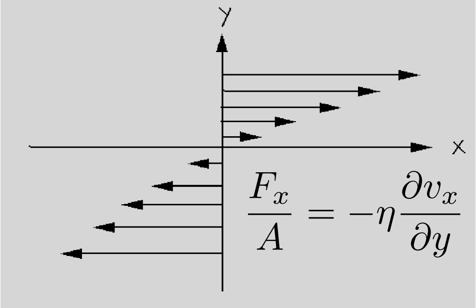


Hydrodynamic calculations for RHIC assumed zero viscosity

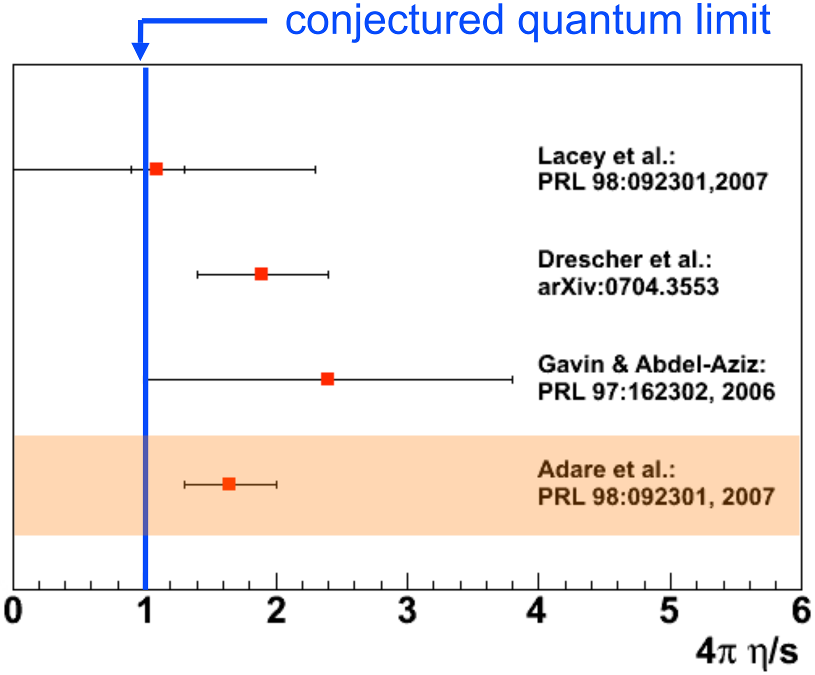
η = 0 ⇒ “perfect fluid”

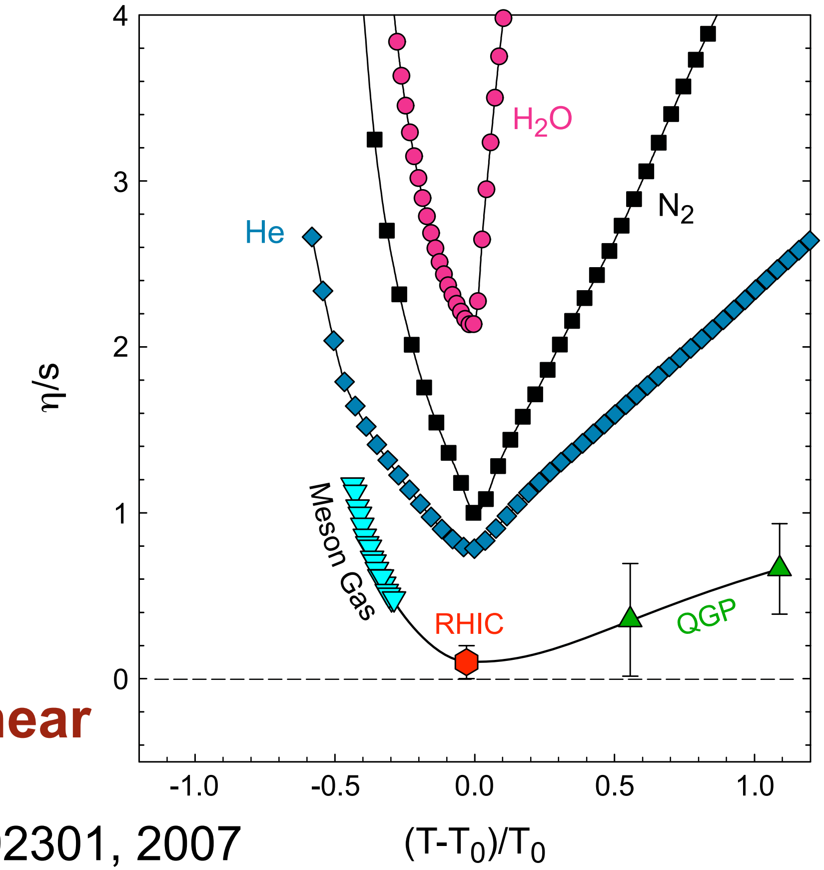
- But there is a (conjectured) quantum limit:
  - derived first in (P. Kovtun, D.T. Son, A.O. Starinets, PRL.94:111601, 2005) motivated by AdS/CFT correspondence

$$\eta \geq \frac{\hbar}{4\pi}(\textit{Entropy Density}) \equiv \frac{\hbar}{4\pi}s$$

N.B.: water (at normal conditions) η/s ~ 380 ħ/4π

What is η/s at RHIC ?





Observables that are sensitive to shear

- Elliptic Flow
  - R. Lacey et al.: Phys. Rev. Lett. 98:092301, 2007
  - H.-J. Drescher et al.: Phys. Rev. C76:024905, 2007
- p_T Fluctuations
  - S. Gavin and M. Abdel-Aziz: Phys. Rev. Lett. 97:162302, 2006
- Heavy quark motion (drag, flow)
  - A. Adare et al. : Phys. Rev. Lett. 98:092301, 2007

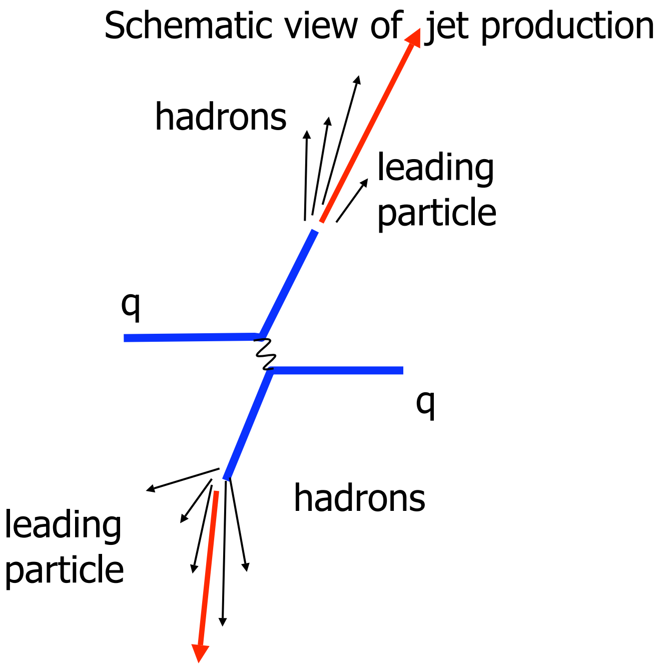
Probing the medium - Jet production

Early production in parton-parton scatterings with large Q^2.

Direct interaction with partonic phases of the reaction

From p+p

- Obtain jet rate
- Obtain fragmentation functions



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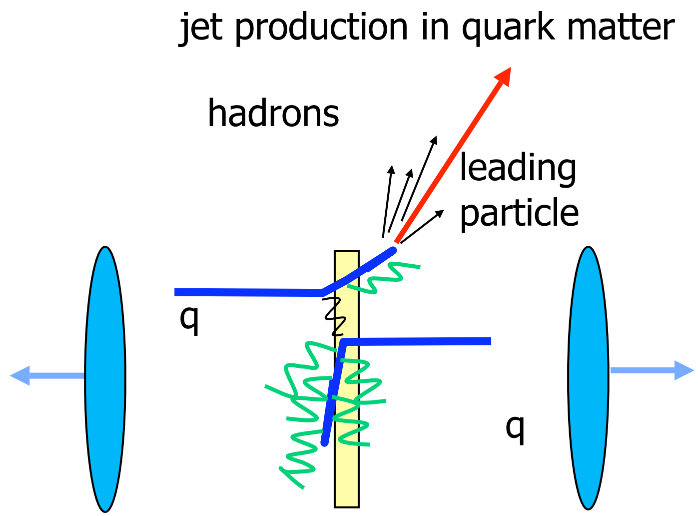
In A+A look at
- attenuation or absorption of jets: "jet quenching"
- suppression of high p_T hadrons
- modification of angular correlation
- changes of particle composition



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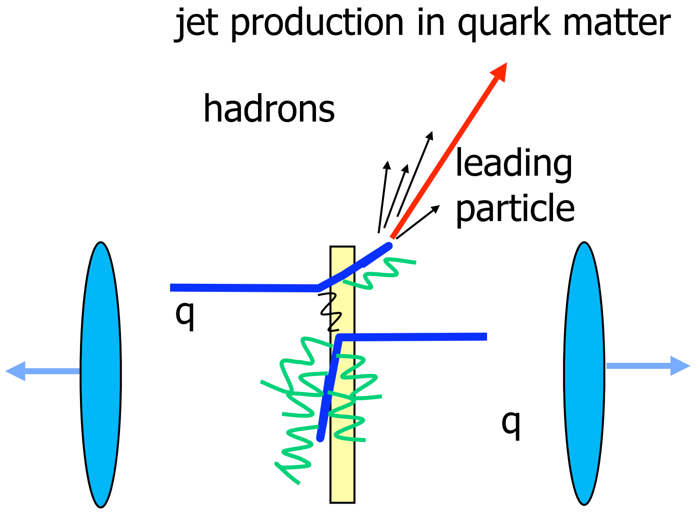
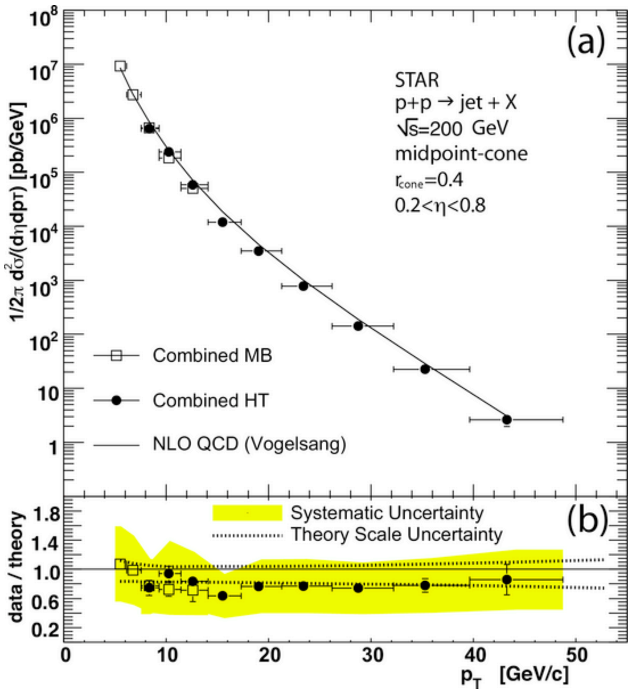


Differences due to medium

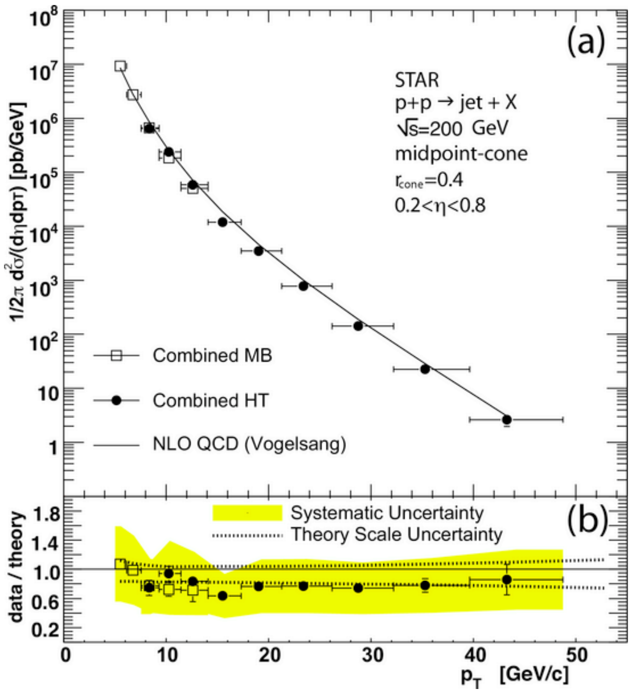
Jets – a calibrated probe?



STAR : PRL 97 (2006) 252001

Jet production in p+p understood in pQCD framework

Jets – a calibrated probe?



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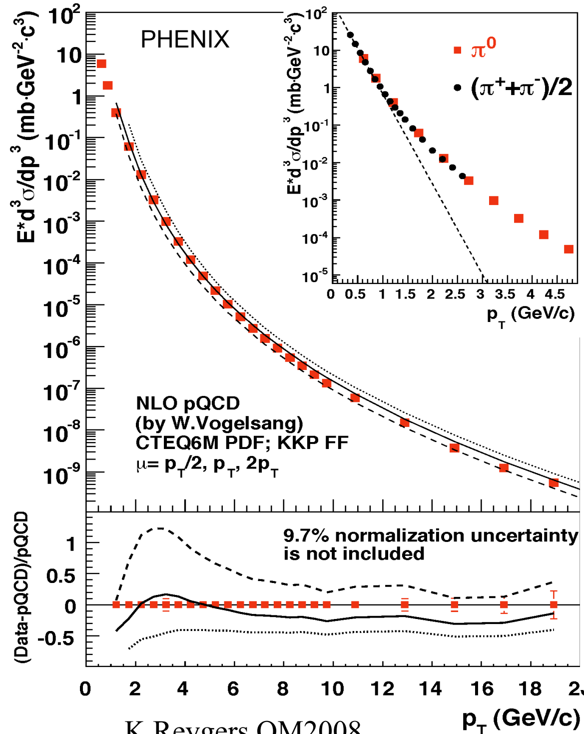
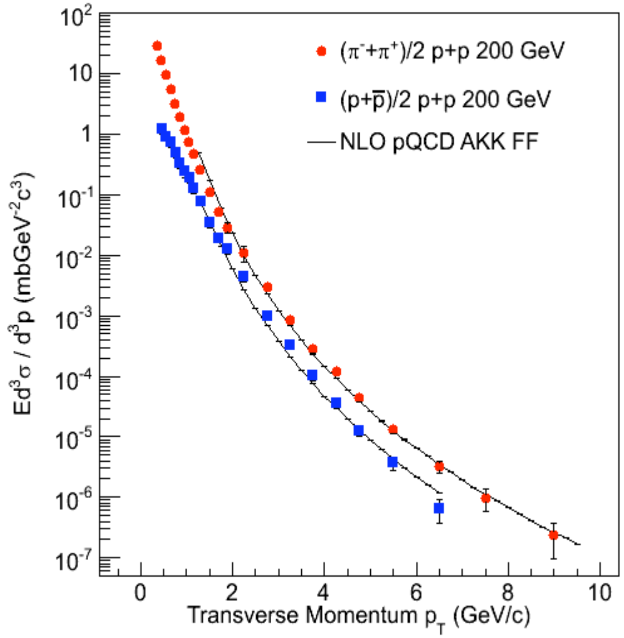


K.Reygers QM2008



STAR : PLB 637 (2006) 161

S. Albino et al, NPB 725 (2005) 181

Jet production in p+p understood in pQCD framework

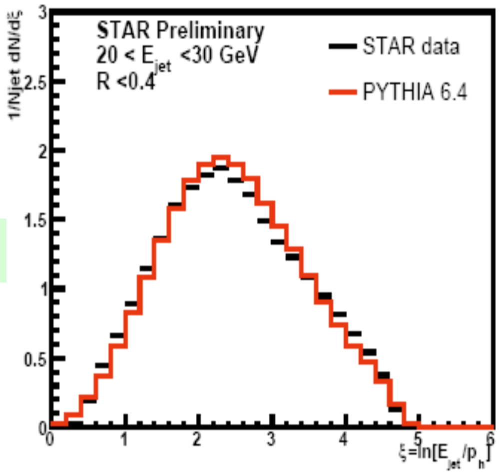
Particle production in p+p also well modeled.

Seems we have a reasonably calibrated probe

Charged hadron ξ in p+p 200 GeV

R<0.4

20<E^{reco}<30 GeV



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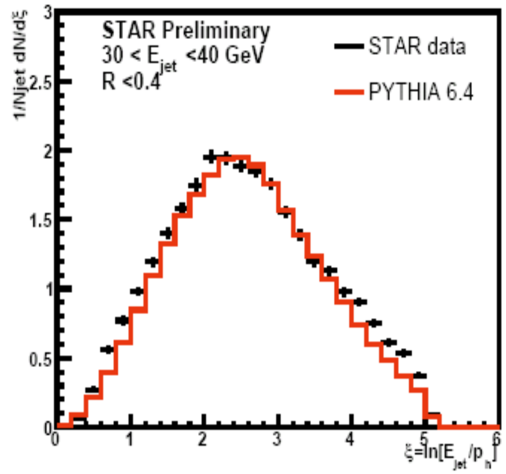
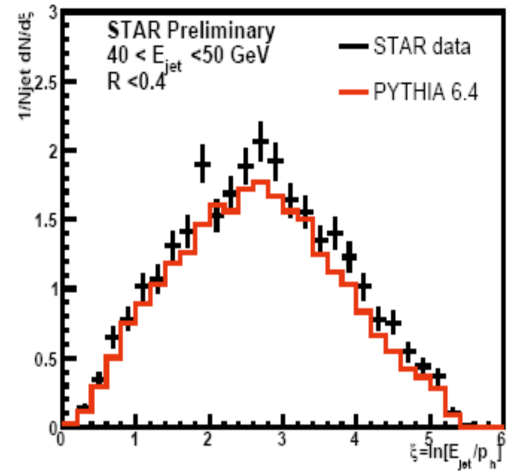


40<E^{reco}<50 GeV



M. Heinz
Hard Probes 2008

Reasonable agreement between Pythia and data

Charged hadron ξ in p+p 200 GeV

20<E^reco<30 GeV | 30<E^reco<40 GeV | 40<E^reco<50 GeV

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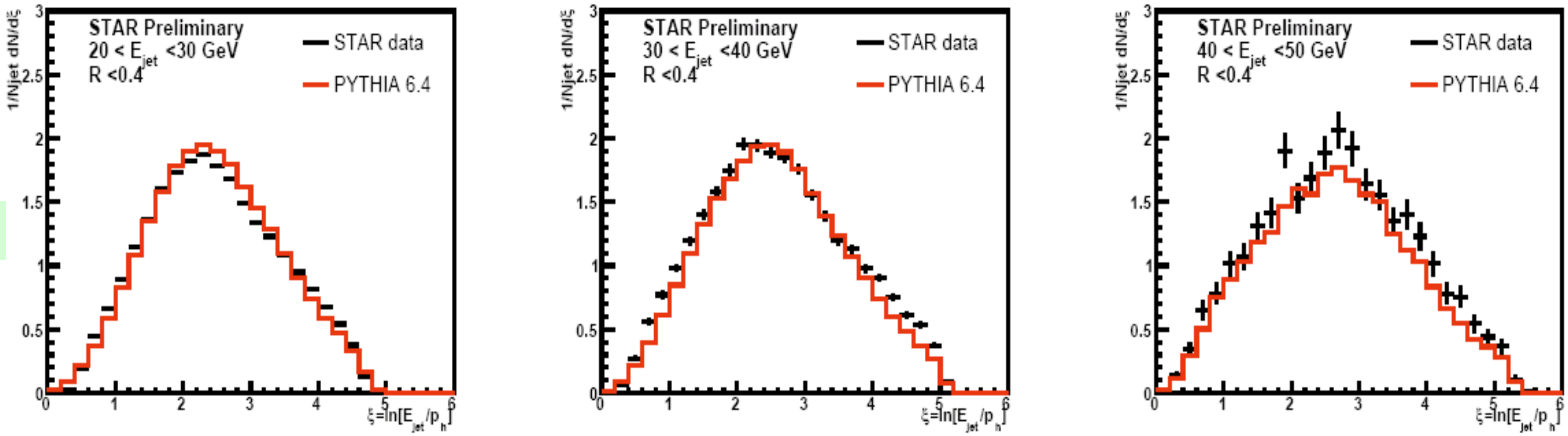
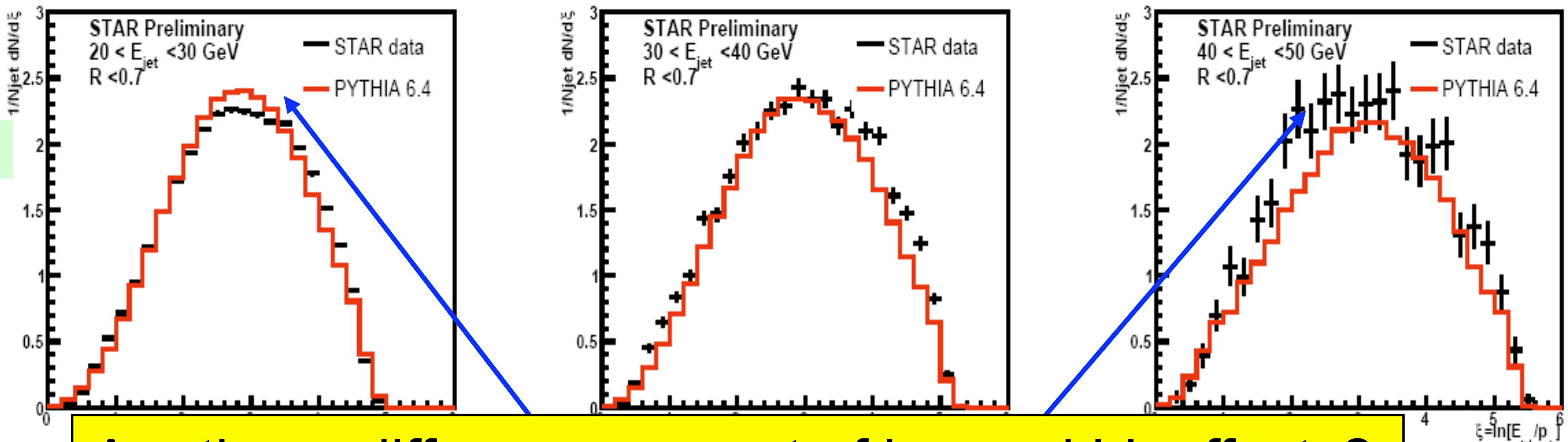


M. Heinz
Hard Probes 2008

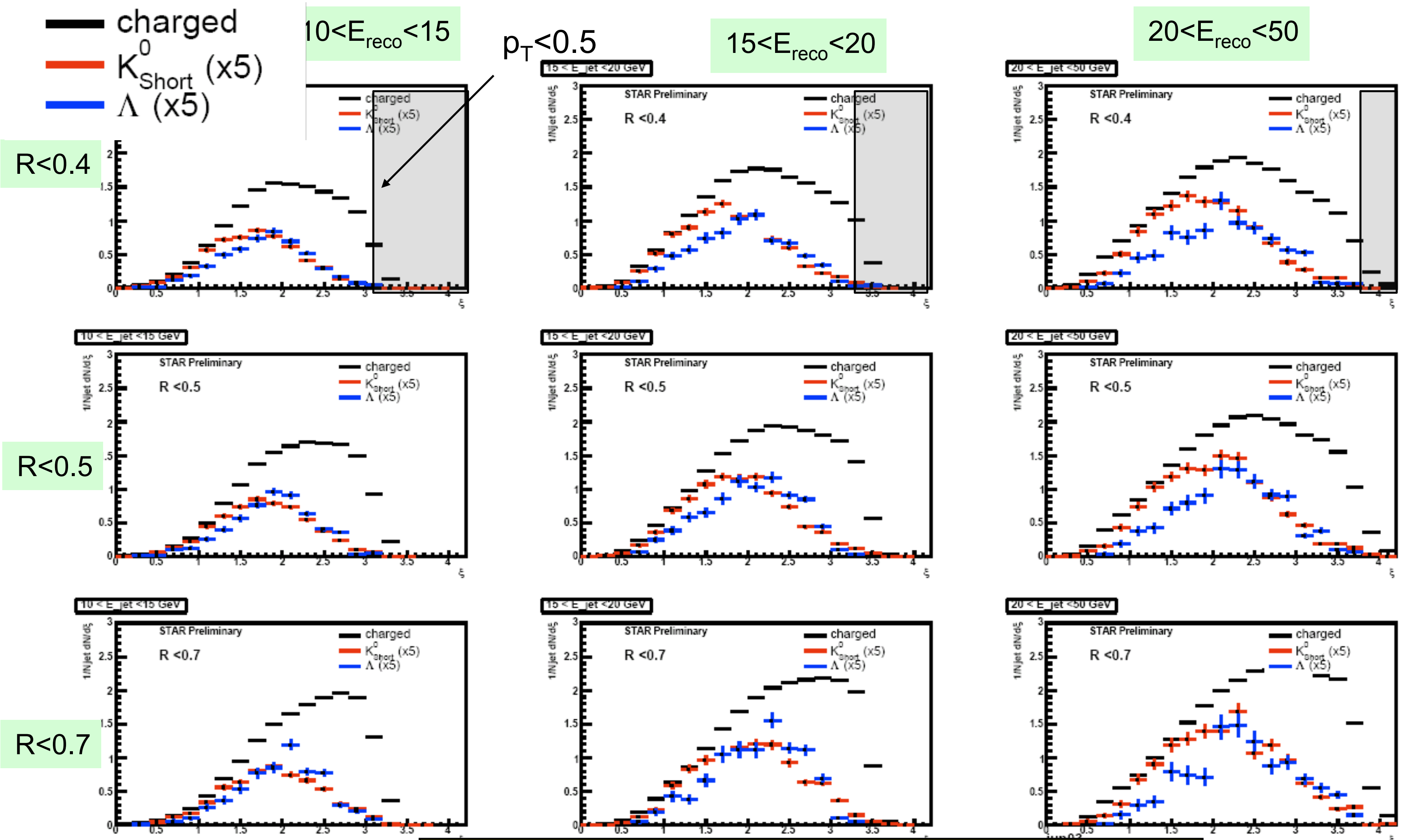
Reasonable agreement between Pythia and data

R<0.7



Are these differences onset of beyond LL effects?

ξ for strange hadrons



M. Heinz Hard Probes 2008

Clear differences between particles

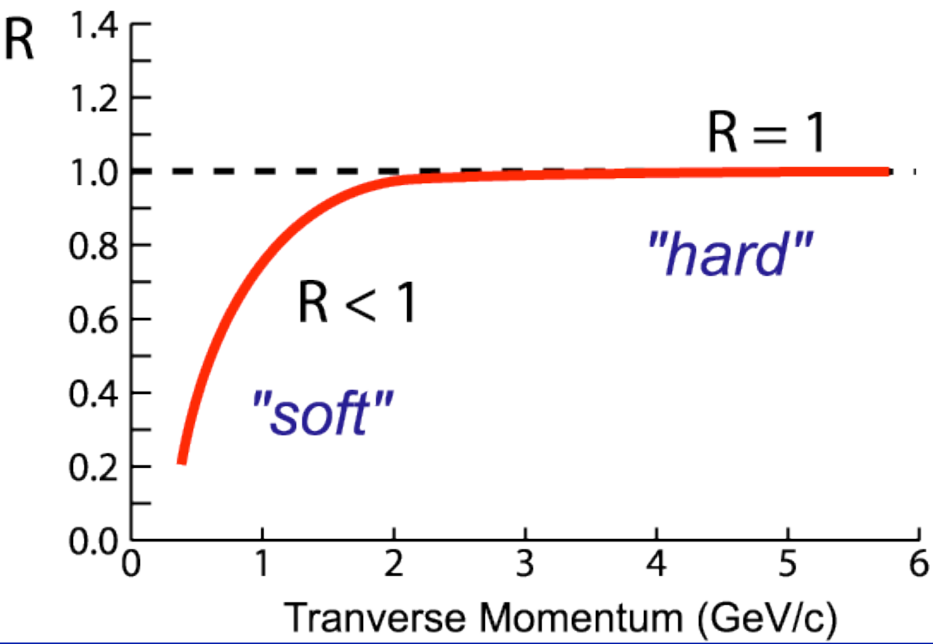
Back to probing the medium

Compare Au+Au with p+p Collisions ⇒ R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

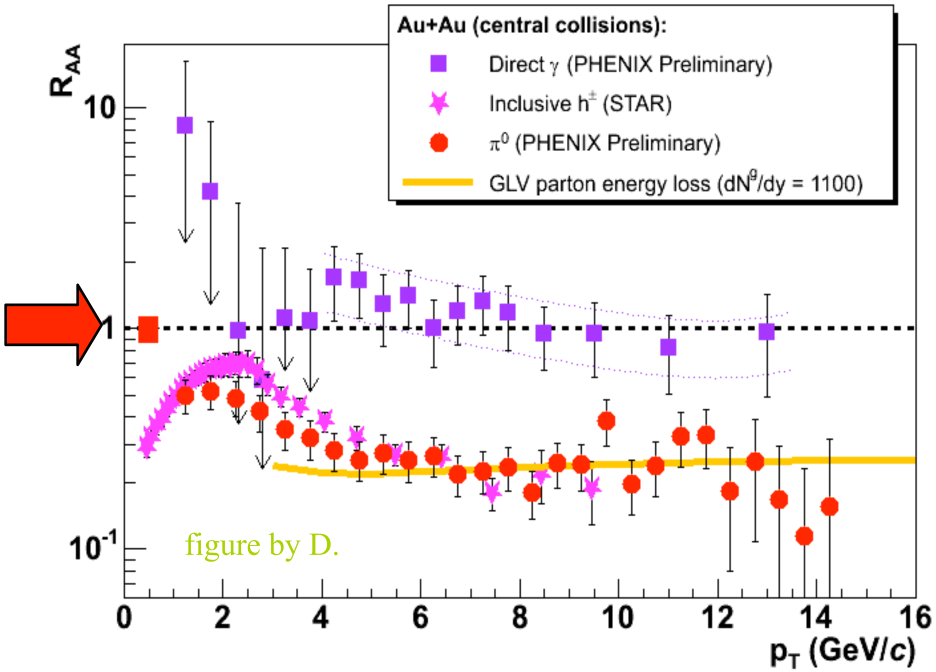
Average number of NN collision in an AA collision



No "Effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

Suppression: R < 1

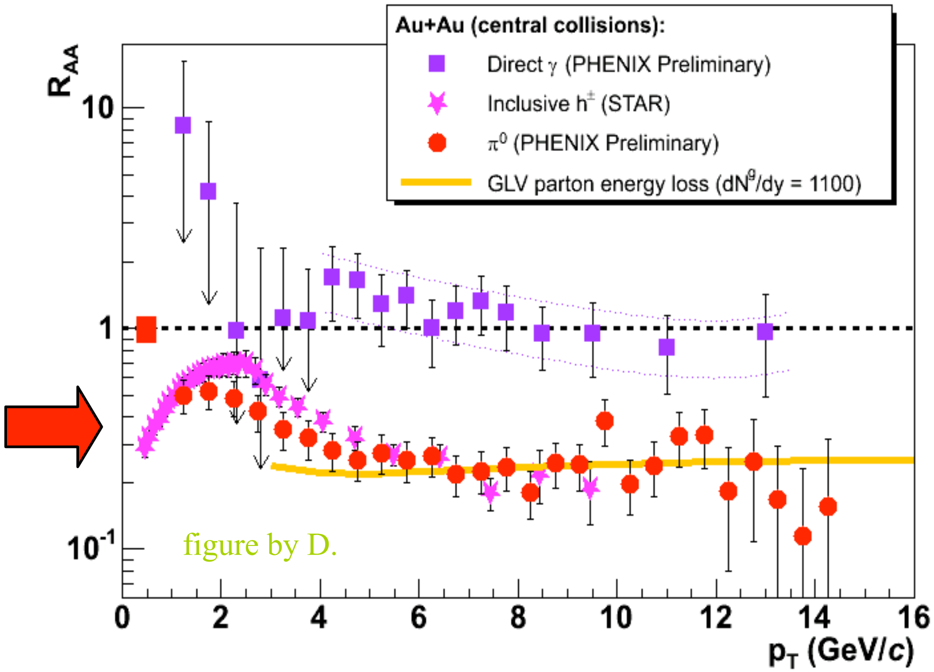
High-p_T suppression



Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works

High-p_T suppression



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   - Huge: factor 5

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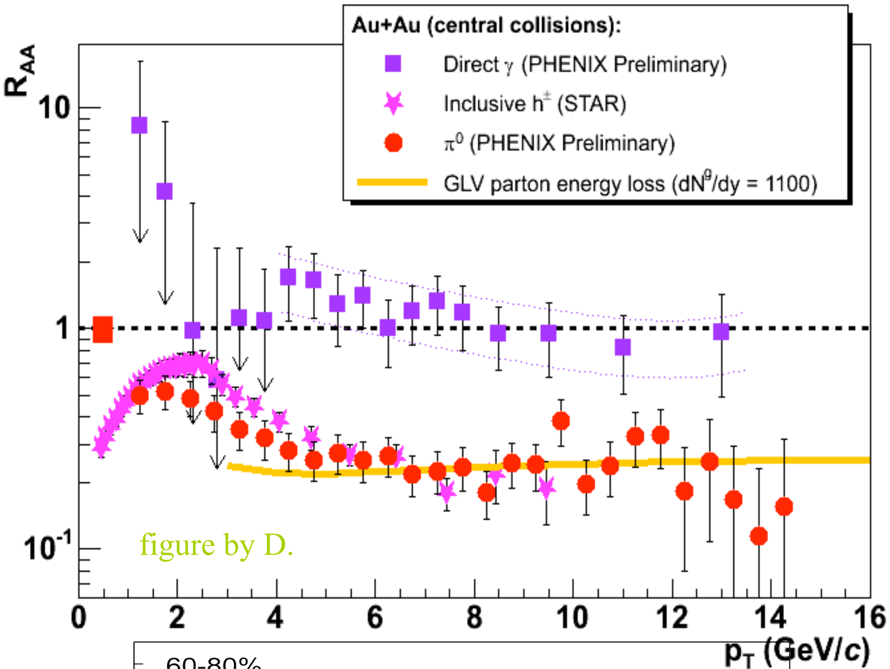
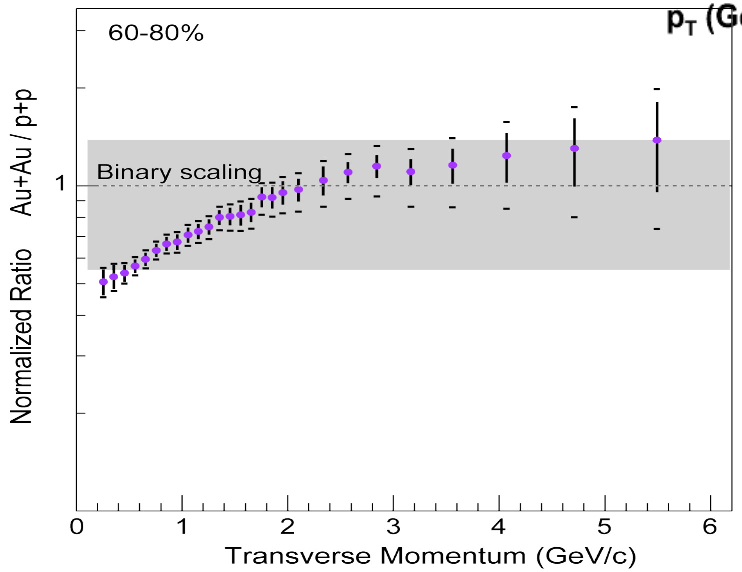


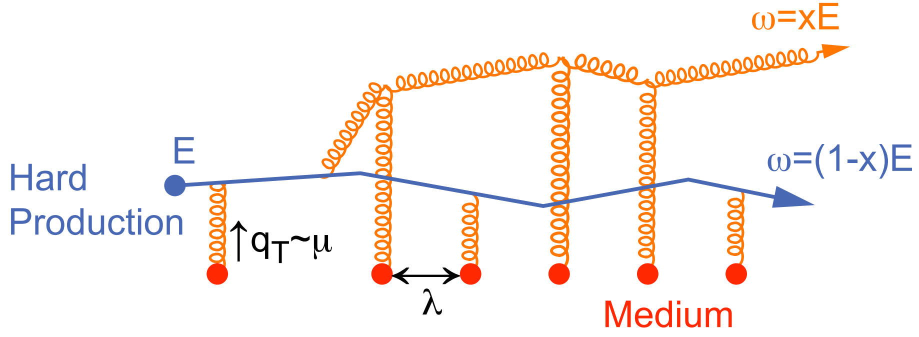


Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5
3. Hadrons are not suppressed in peripheral collisions
   - Good! medium not dense

Interpretation

Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium



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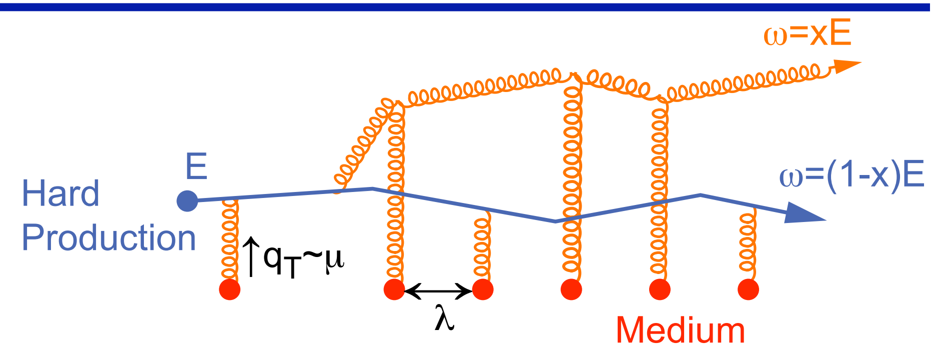
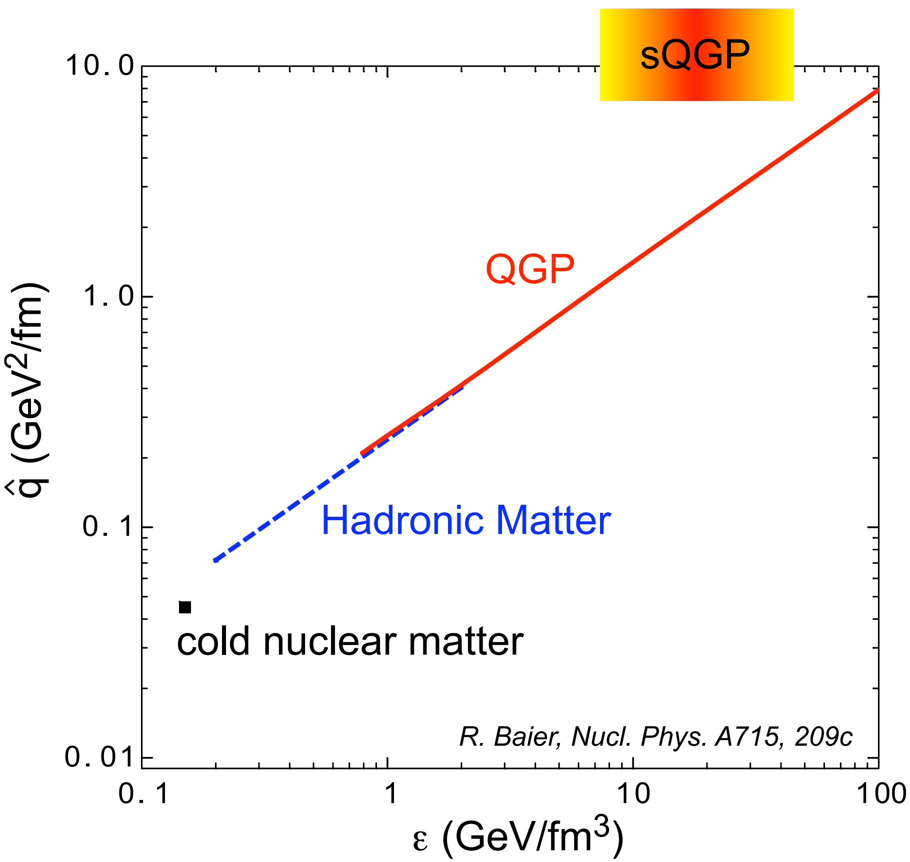




- Mean parton energy loss ∝ medium properties:
    - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - Coherence among radiated gluons
    - $\Delta E_{loss} \sim \Delta L^2$ (medium length)

      $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$

  is $\langle k_T^2 \rangle$ transferred per unit path length

$$\hat{q} = \frac{\langle k_T^2 \rangle}{L} \approx \frac{\mu^2}{\lambda} \qquad \hat{q} = \hat{q}(\vec{r}, \tau)$$

  - gluon density dN_g/dy

The model landscape (not exhaustive)

PQM (Parton Quench model)

Implementation of BDMPS (calc. E loss via coherent gluon radiation - many soft scattering approx.

- Realistic geometry
- Static medium, q time average (i.e. depends on initial density, scheme evolution dependent)
- No initial state multiple scatterings
- No modified PDFs

GLV

Implementation of GLV formalism (calc. E loss via gluon brehmsstralung -few hard scatterings.)

- Realistic geometry
- Bjorken expanding medium - Calc. a priori (w/o E loss) average path length - use to calc. partonic E loss

WHDG

Implementation of GLV formalism (calc. E loss via gluon brehmsstralung -few hard scatterings) + collisional energy loss.

- Realistic geometry - integral over all paths
- Expanding medium
- No initial state multiple scatterings

ZOWW

Modified fragmentation model (radiative gluon E loss incorporated into effective medium modified FF)

- Hard sphere geometry
- Expanding medium

Constraining $\hat{q}$

Model	Opacity Parameter
PQM	$\langle \hat{q} \rangle$ = 13.2 (+ 2.1 - 3.2)
GLV	dN_g/dy = 1400 (+270 -150)
WHDG	dN_g/dy = 1400 (+200 -375)
ZOWW	ϵ_0 = 1.9 (+0.2 - 0.5) $(\langle \hat{q} \rangle \sim 1)$

$(\langle \hat{q} \rangle \sim 7)$

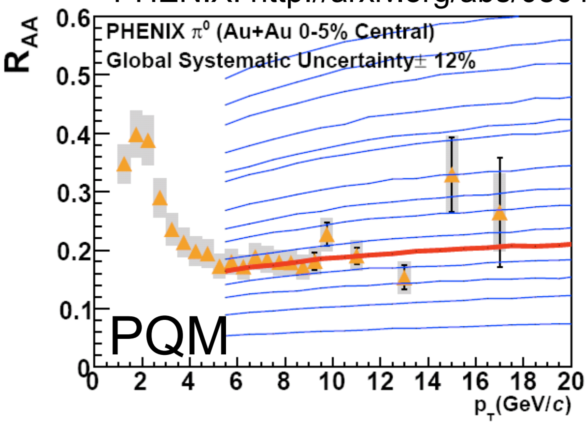
PQM: A. Dainese, C. Loizides, G. Paic, Eur. Phys. J C38: 461 (2005). C. Loizides, Eur. Phys. J.C49, 339 (2007).

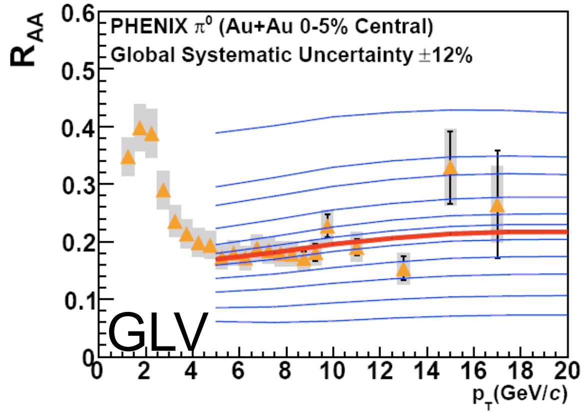
GLV: I. Vitev, Phys. Lett. B639, 38 (2006). M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B571, 197 (2000).

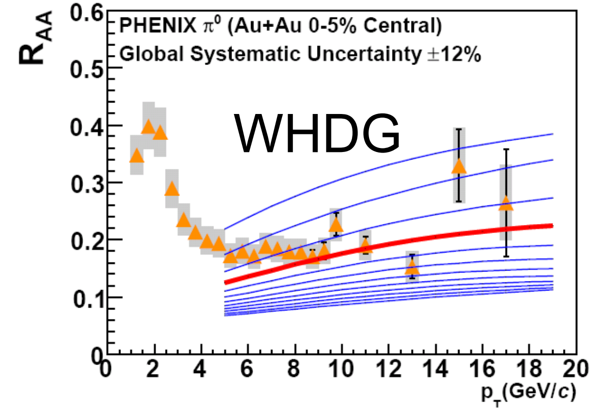
WHDG: W.A. Horowitz, S. Wicks, M. Djordjevic, M. Gyulassy,in preparation; S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A 783, 493 (2007); S. Wicks, W. Horowitz, M. Djordjevic,M. Gyulassy, Nucl. Phys. A 784, 426 (2007).

ZOWW: H. Zhang, J.F. Owens, E. Wang, X-N Wang, Phys Rev. Lett. 98: 212301 (2007).

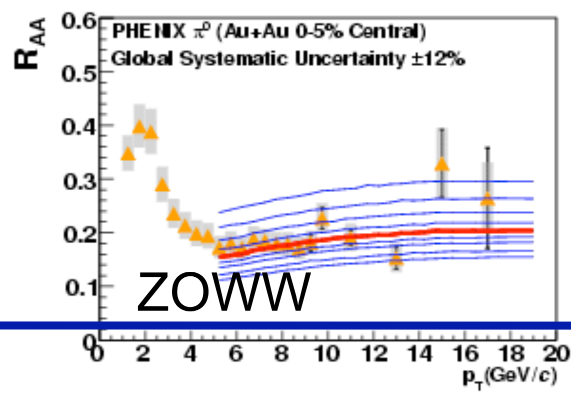
PHENIX: http://arxiv.org/abs/0801.1665







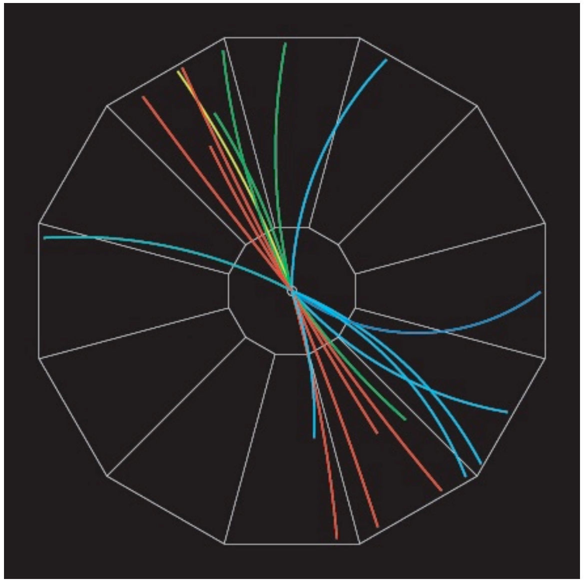
$\langle \hat{q} \rangle$ only the natural unit in PQM



Need other observables to dis-entangle all the possible effects

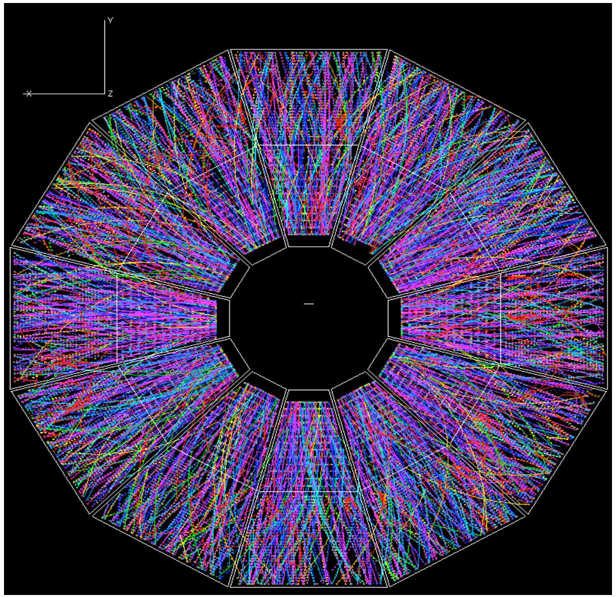
Jet correlations in heavy-ion collisions

- Full jet reconstruction very challenging
  background from bulk similar to signal for jet p_T<~30 GeV



p+p collisions

Au+Au collisions



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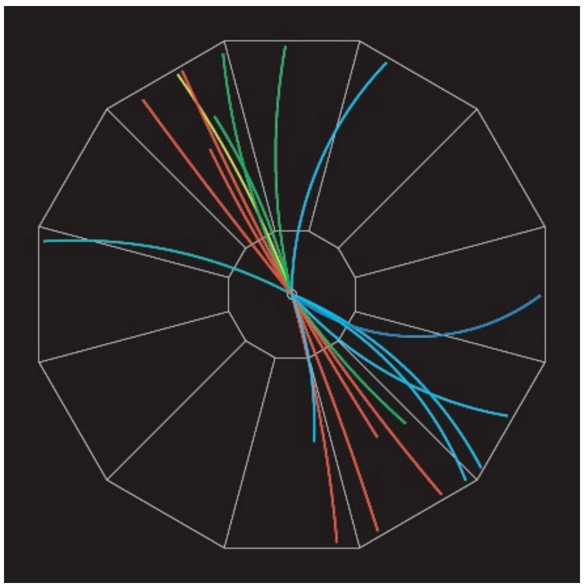

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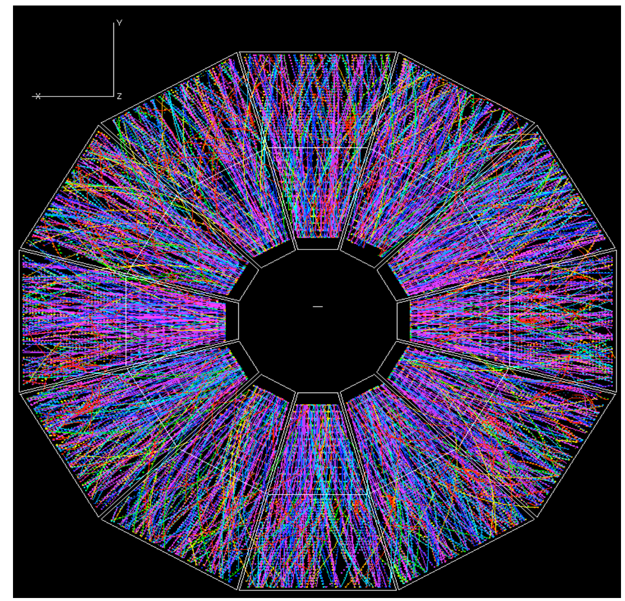
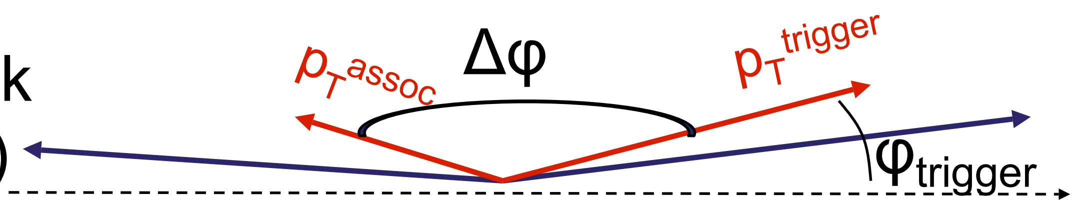


Use di-hadron correlations

Back-to-back (away side) jet



Trigger (near side) jet

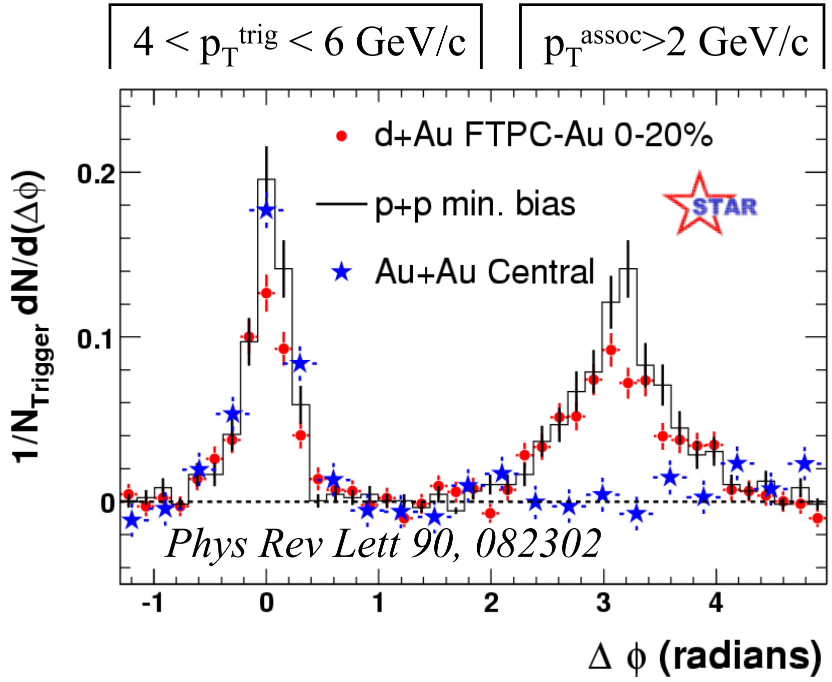
RHIC seminal di-hadron results

"The disappearance of the away-side jet"

d+Au results similar to p+p

→ final state interaction

→ d+Au can be used as the reference measurement instead of p+p



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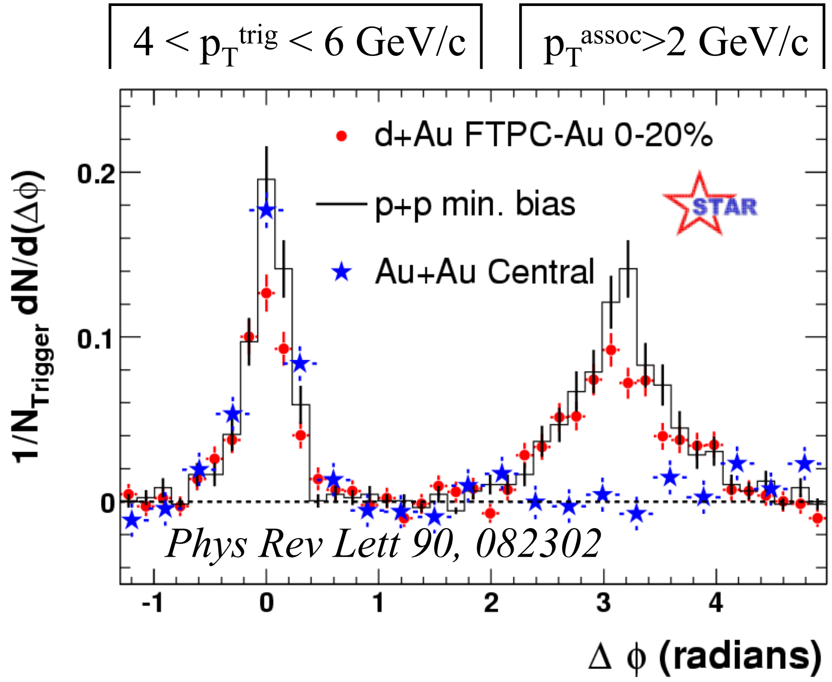
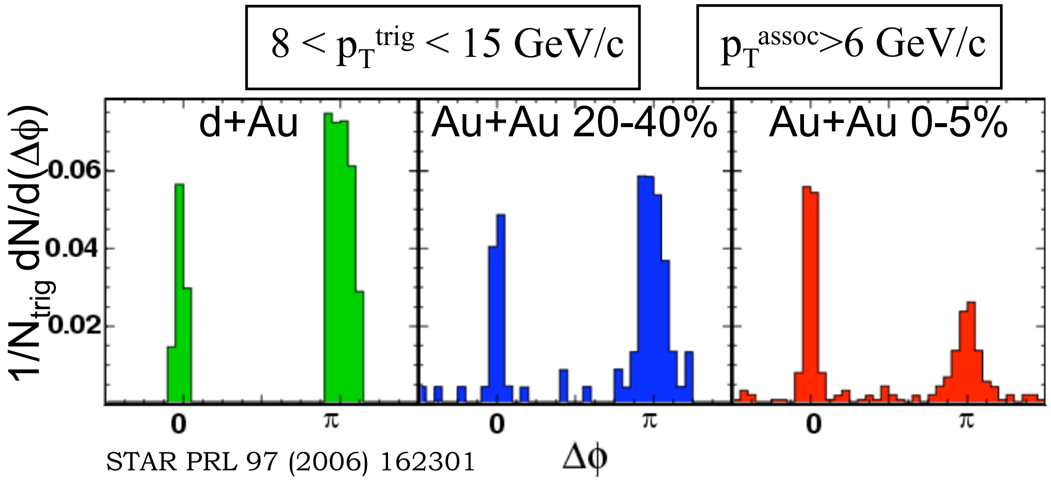


"High p_T Punch-through"

Away side correlation reappears for high p_T correlations

→ yield reduced compared to d+Au



Away-side di-hadron fragmentation

- Study medium-induced modification of fragmentation function due to energy loss
- Without full jet reconstruction, parton energy not measurable
  - z not measured ($z=p_{hadron}/p_{parton}$)
  - $z_T=p_{T,assoc}/p_{T,trig}$

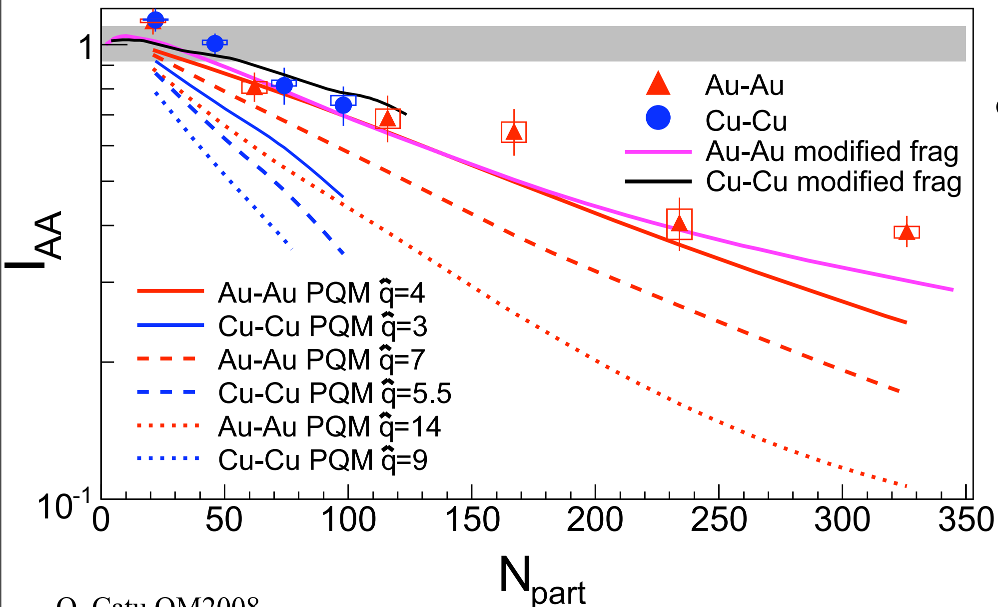
$$D^{h_1h_2}(z_T, p_T^{\rm trig}) = p_T^{\rm trig} \frac{d\sigma_{AA}^{h_1h_2}/dp_T^{\rm trig}dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\rm trig}}$$

$$I_{AA} = \frac{D_{AA}(z_T, p_T^{\rm trig})}{D_{pp}(z_T, p_T^{\rm trig})}$$

Away-side di-hadron fragmentation

H. Zhong et al., PRL 97 (2006) 252001
C. Loizides, Eur. Phys. J. C 49, 339-345 (2007)

6< $p_{T\ trig}$ < 10 GeV



O. Catu QM2008

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Inconsistent with *Parton Quenching* Model calculation

Modified fragmentation model better

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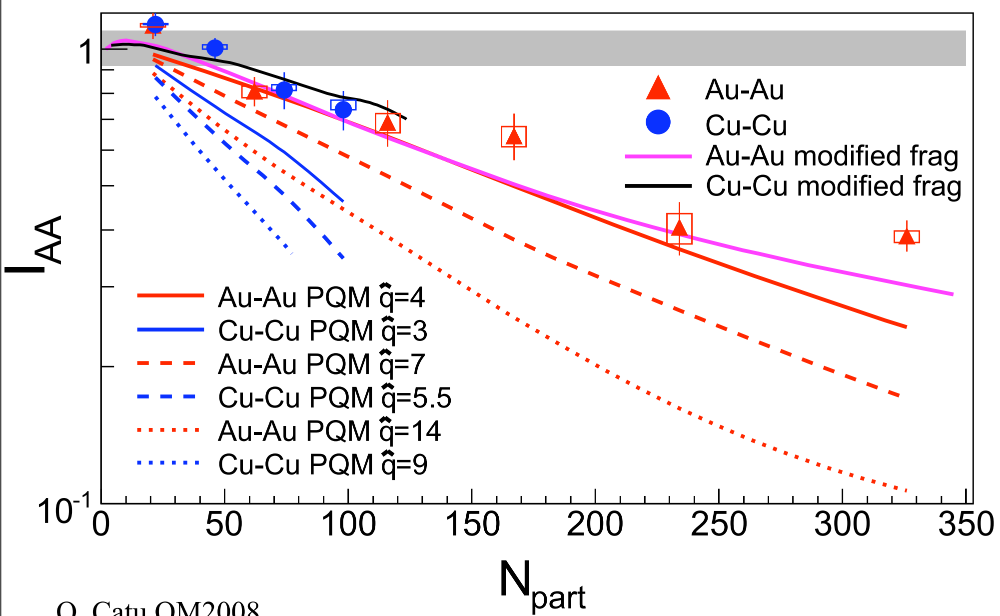

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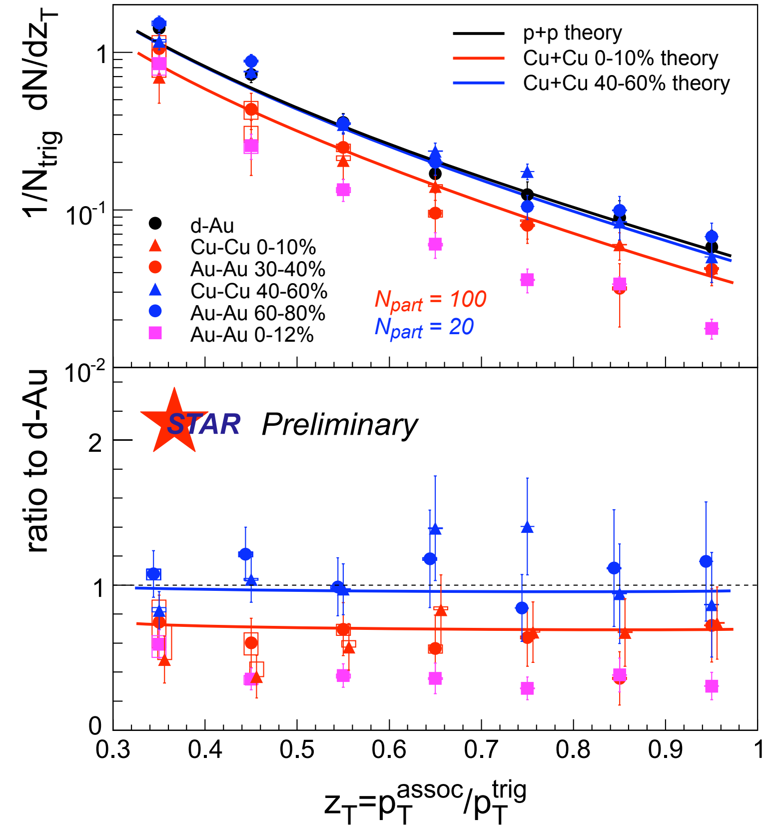


Inconsistent with *Parton Quenching* Model calculation

Modified fragmentation model better

Denser medium in central Au+Au than central Cu+Cu

Similar medium for similar N_{part}

Vacuum fragmentation after parton E_{loss} in the medium

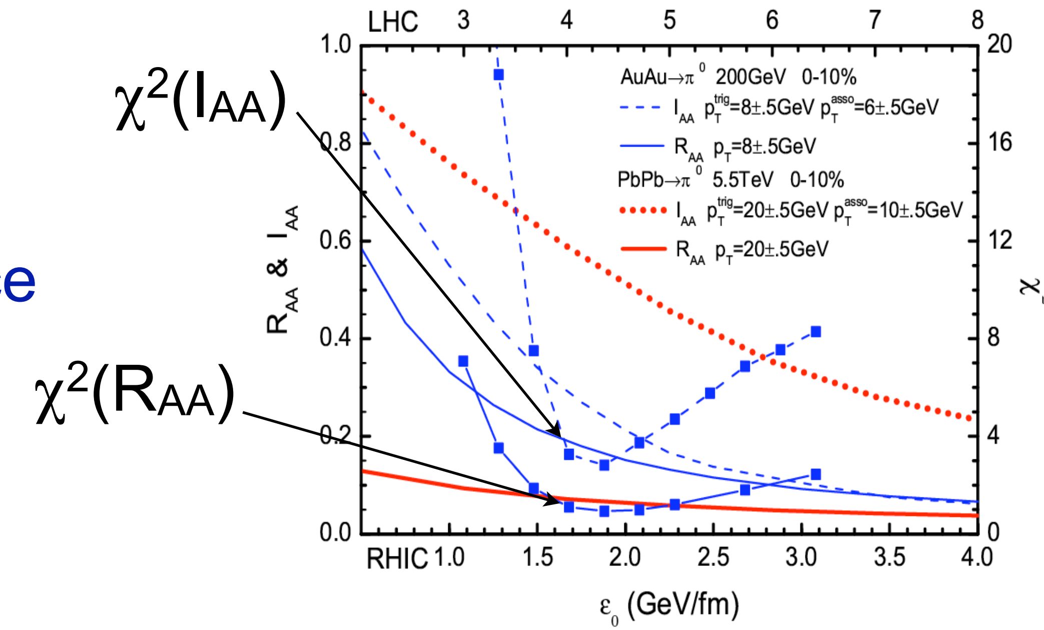
Two particles are better than one

Compare fits to R_{AA} and I_{AA}

H. Zhang, J.F. Owens, E. Wang, X.N. Wang
Phys. Rev. Lett. 98: 212301 (2007)

- Minima of data in same place
- Sharper for di-hadrons

$q_0\tau_0 \sim \hat{q} = 2.8 \pm 0.3\ GeV^2/fm$



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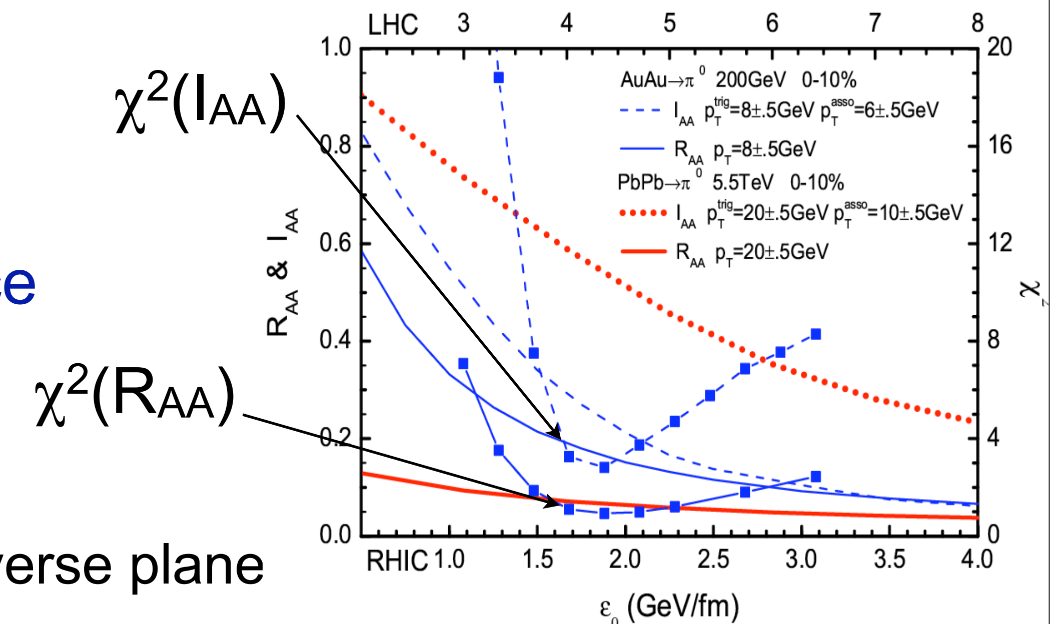

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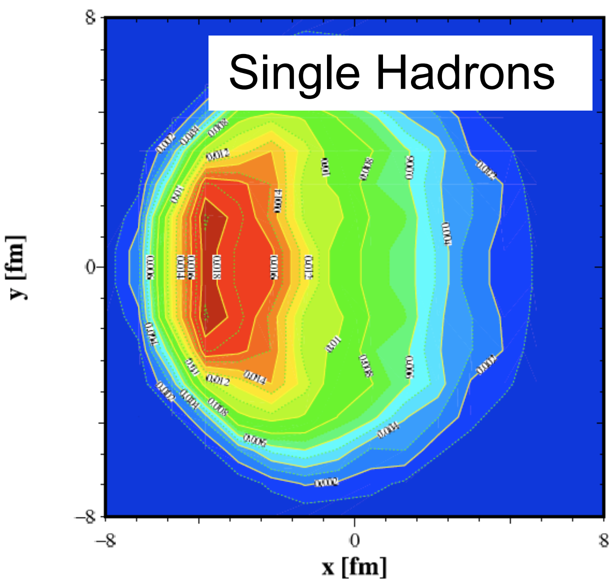
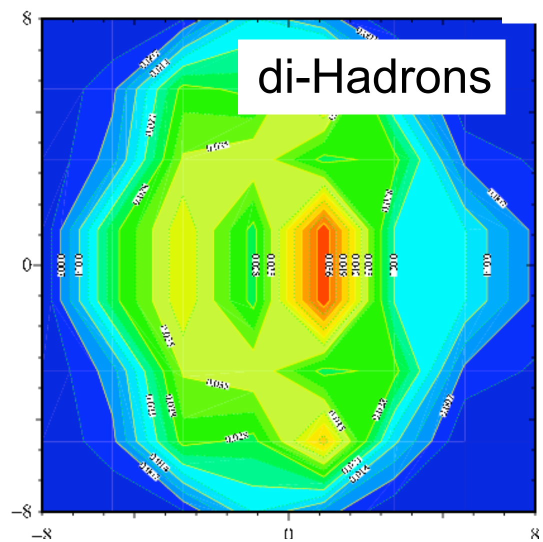
Parton production points in transverse plane





Renk and Eskola, hep-ph/0610059

- Surface bias effectively leads to saturation of R_{AA} with density

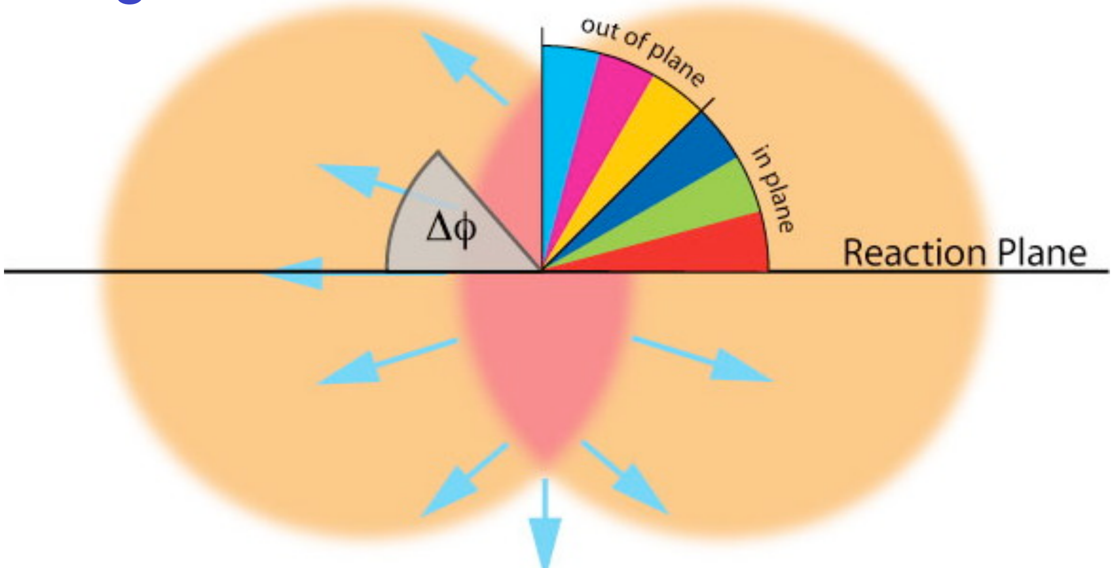
minimize bias:
di-hadron correlations
full jets

Path length dependencies

Non-central events have “elliptic” overlap geometries

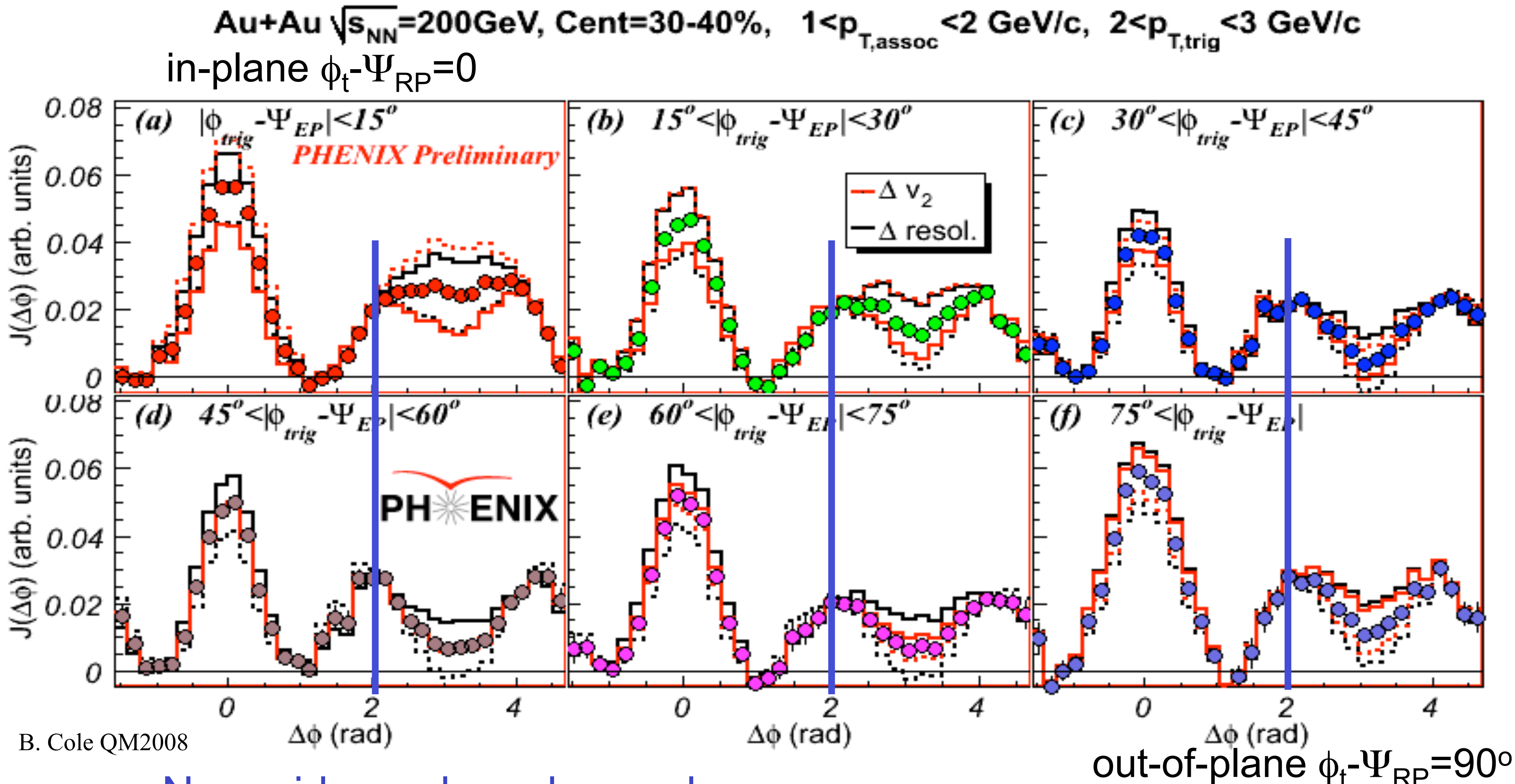
Measurements w.r.t reaction plane angle:

Change path length
Keep everything else same



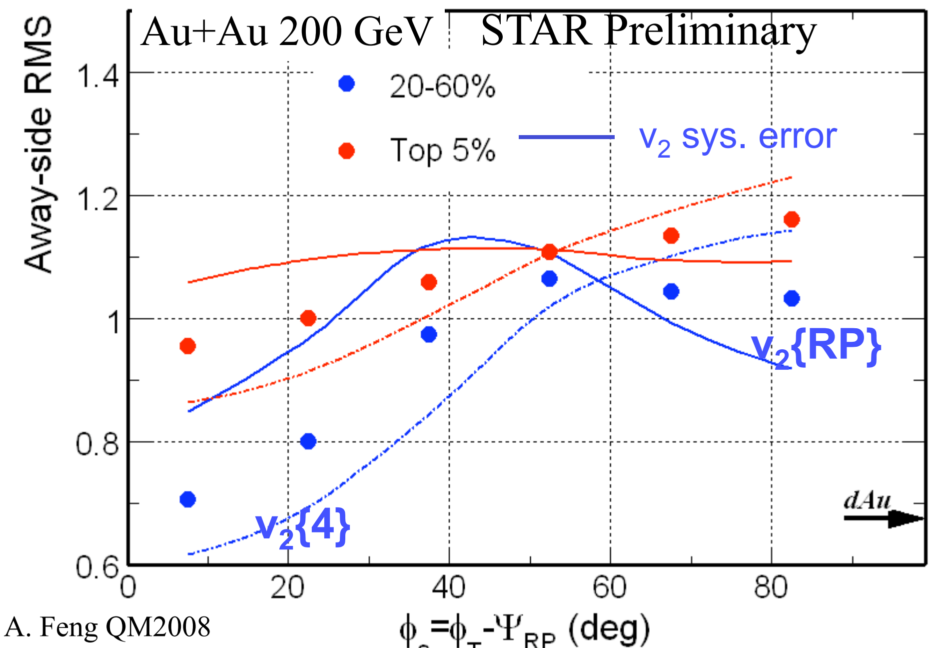
Isolate effects due to path length

Path length effect on di-hadron correlation



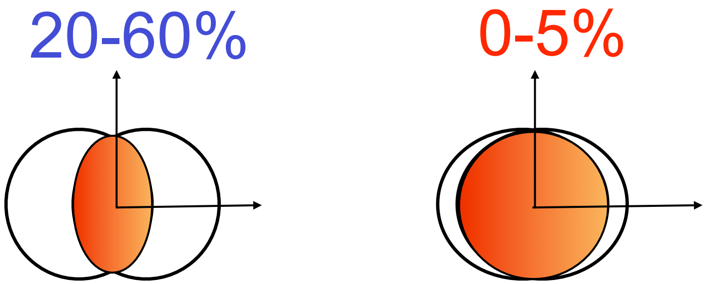
– Near side peak unchanged
– Shoulder peaks emerge as ϕ_t - Ψ increases but are at fixed $\Delta\phi$
– Head peak (di-jet remnant) decreases as ϕ_t - Ψ_{RP} increases

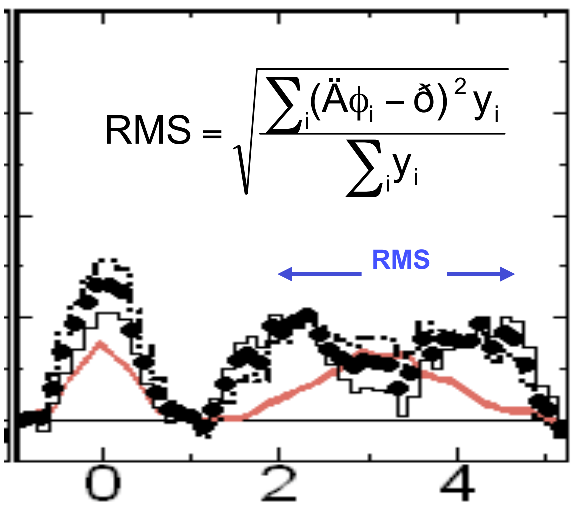
Centrality and path length effects



A. Feng QM2008

$3 < p_T^{trig} < 4$ GeV/c, $1.0 < p_T^{asso} < 1.5$ GeV/c





In-plane: 20-60% ~ d+Au

0-5% > d+Au

Out-of-plane: 20-60% ~ 0-5%

Au+Au > d+Au

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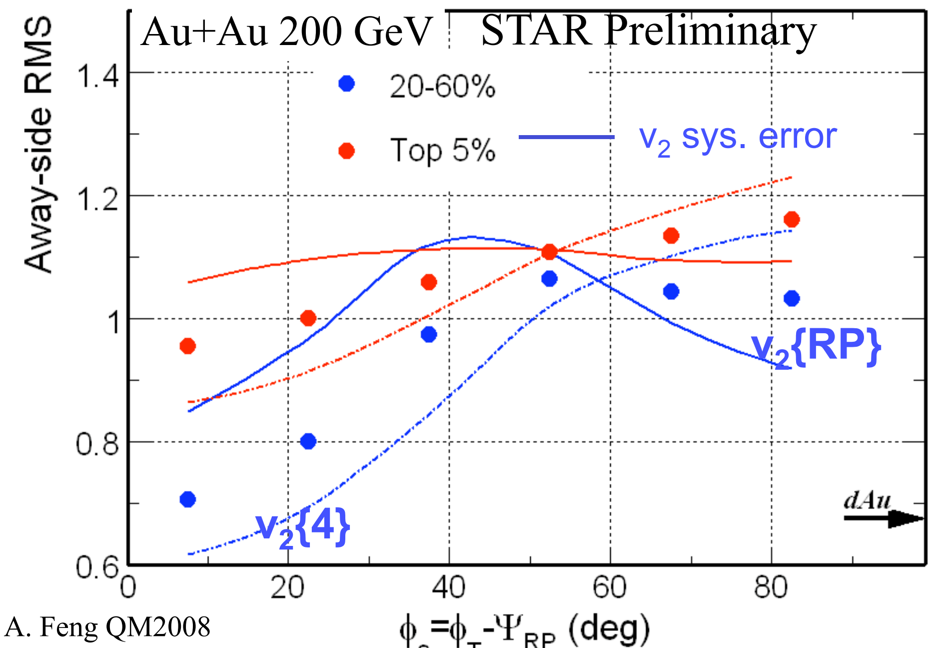

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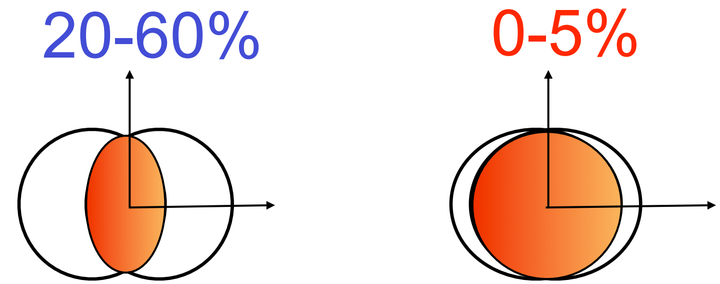

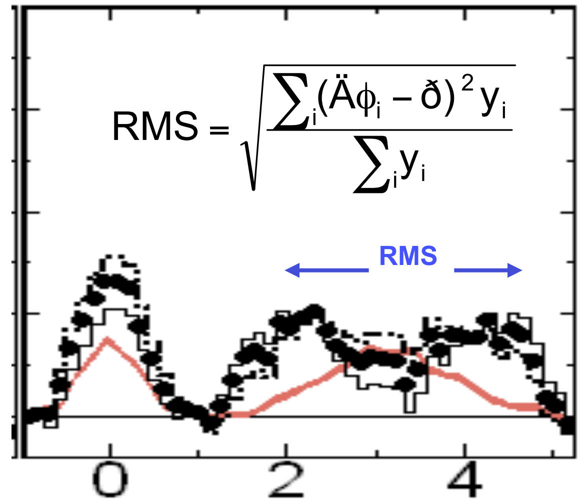

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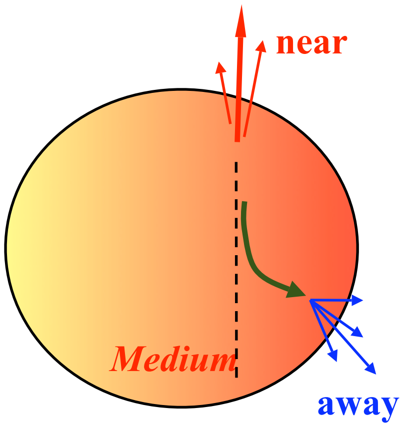
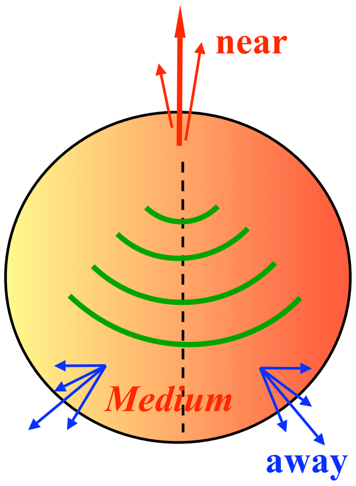
Away-side features reveal path length effects

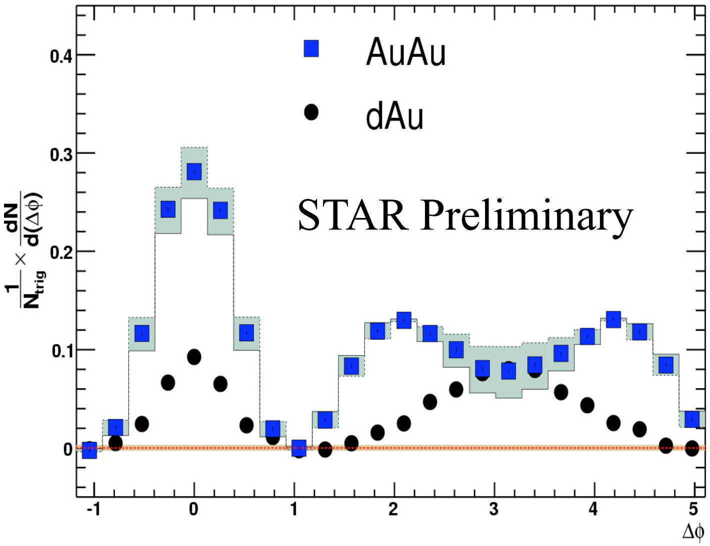
Deflected jets or conical emission?



Deflected jets



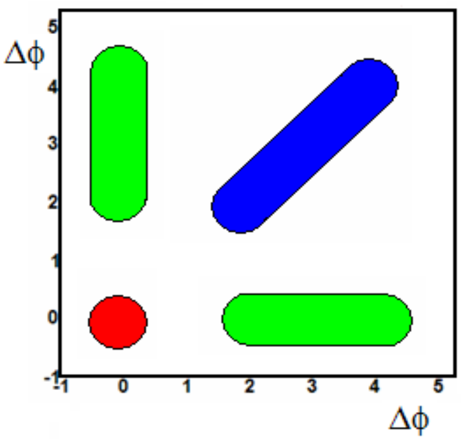
Conical Emission



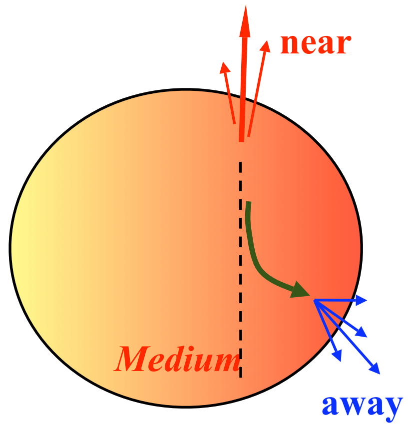
Conical emission or deflected jets?

Distinguish between models using 3-particle correlations

Deflected jets or conical emission?



Deflected jets



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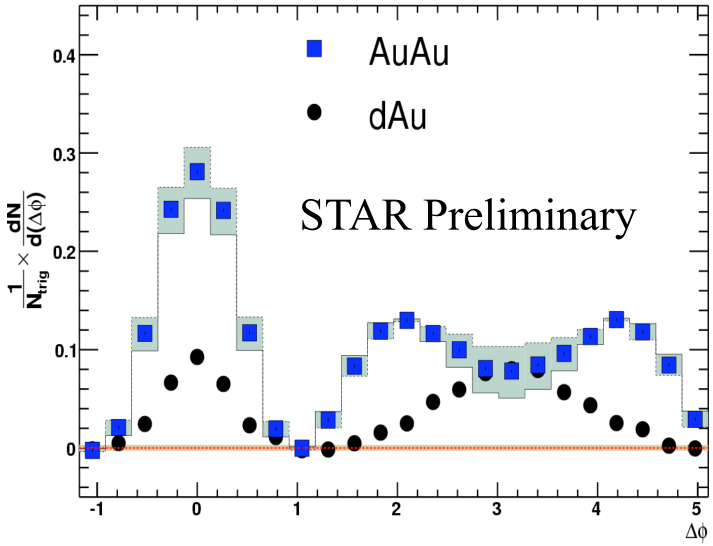

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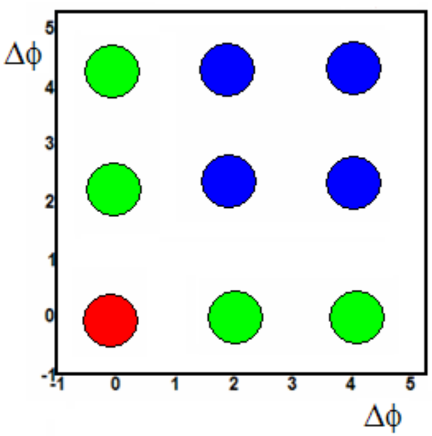

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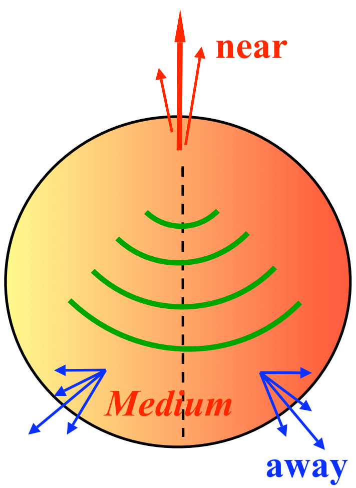

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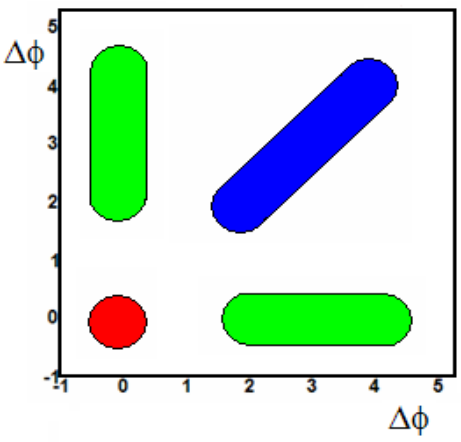

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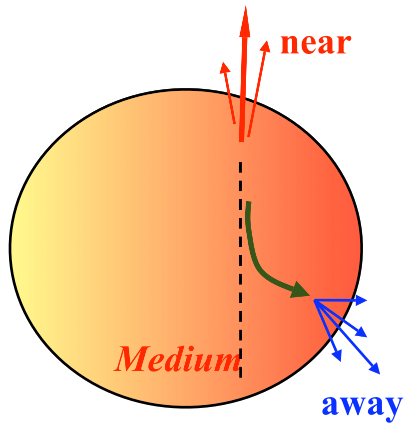

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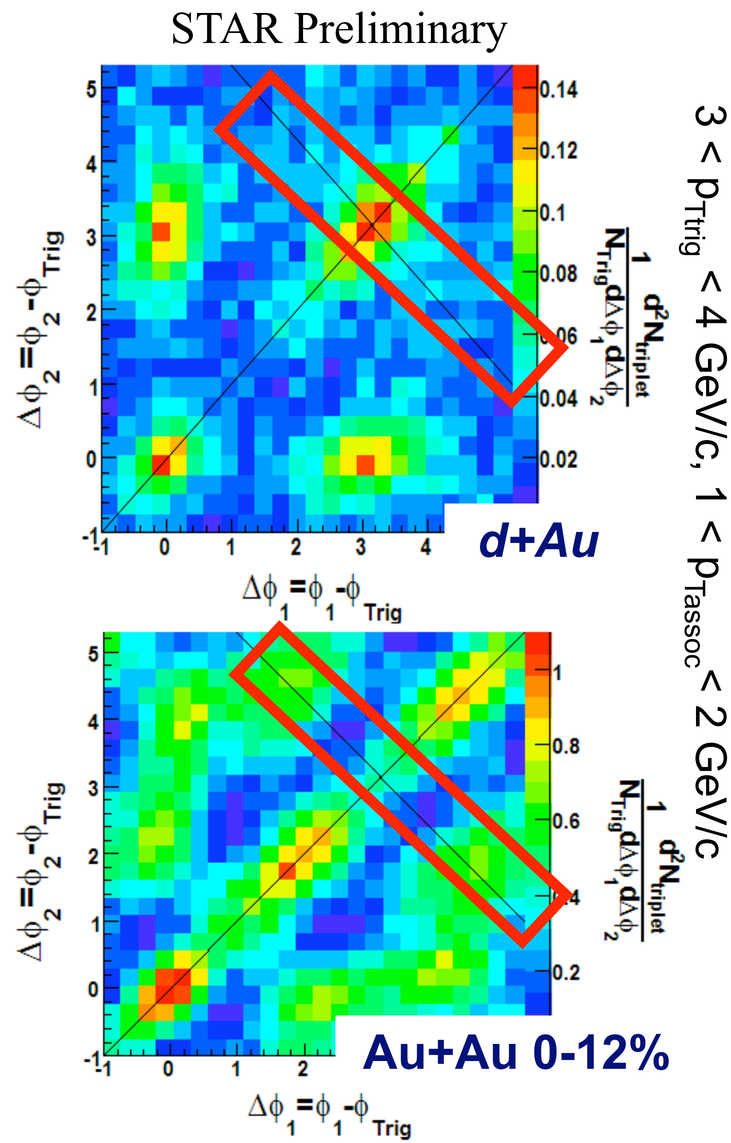

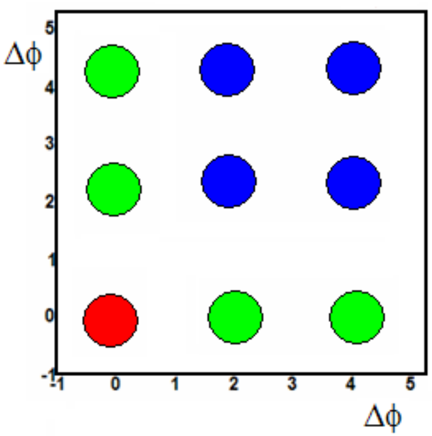

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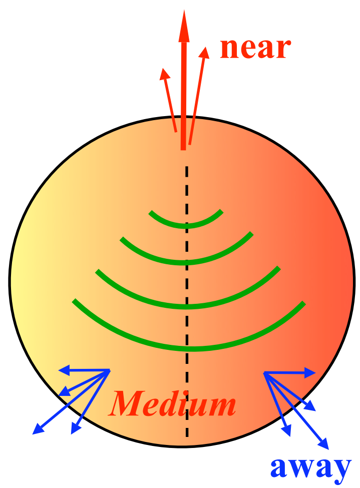

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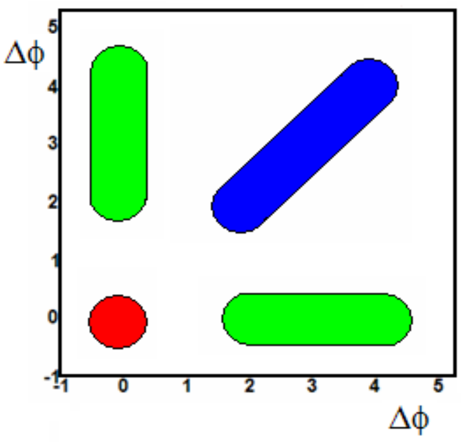

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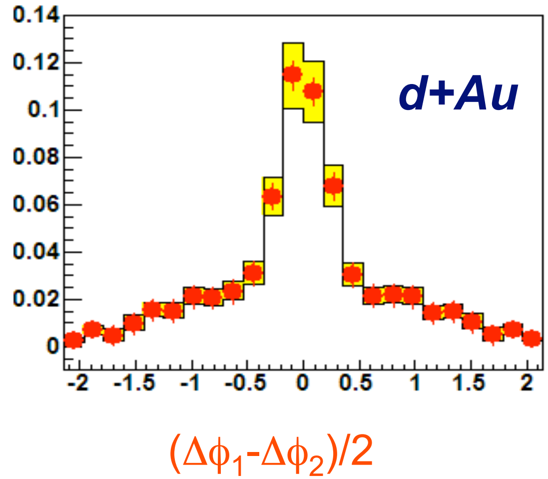

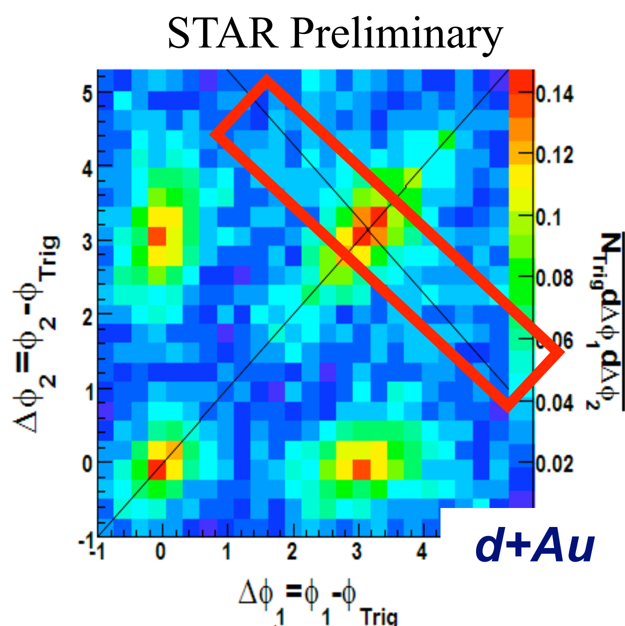

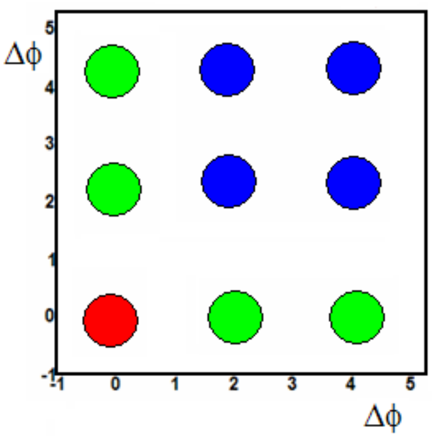

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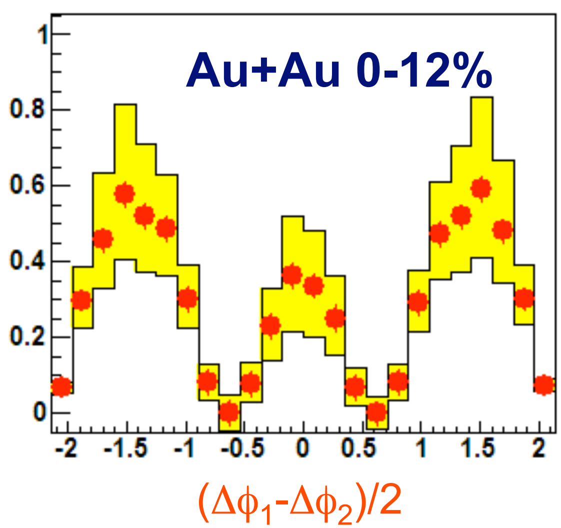

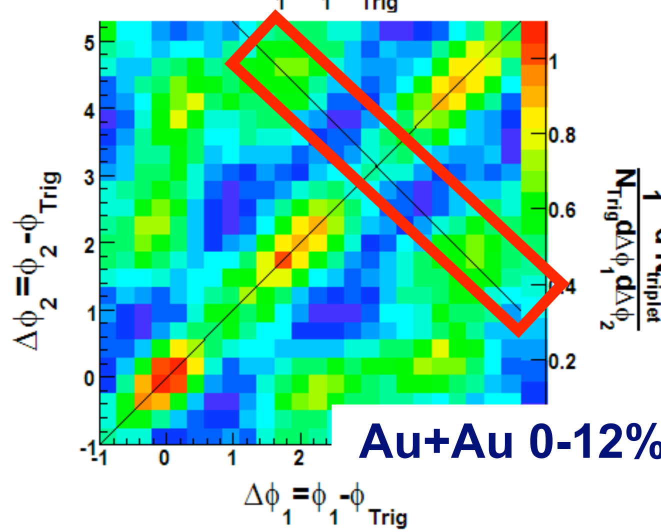

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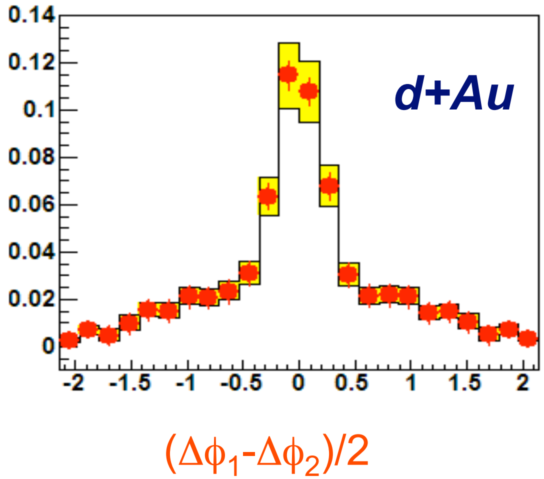
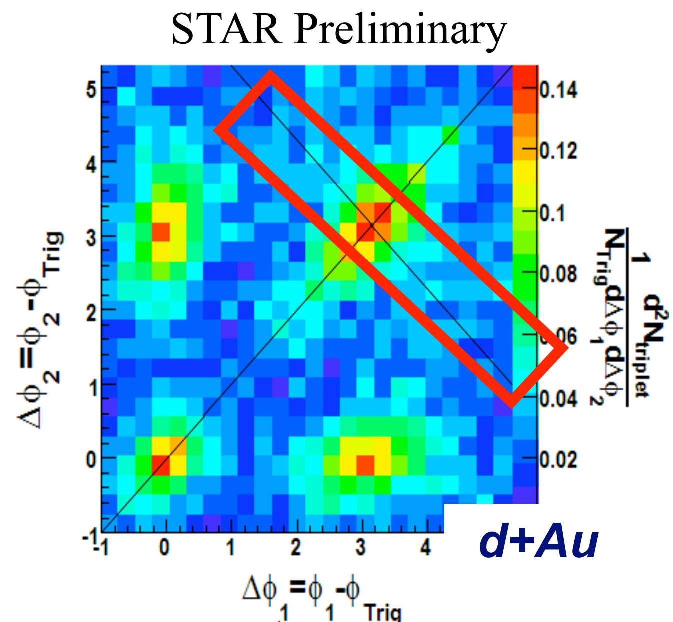
Deflected jets or conical emission?

Au+Au data consistent with Conical emission





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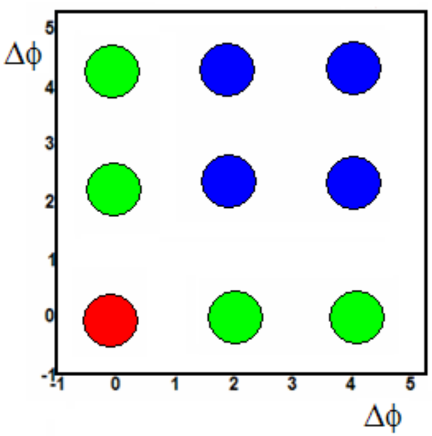

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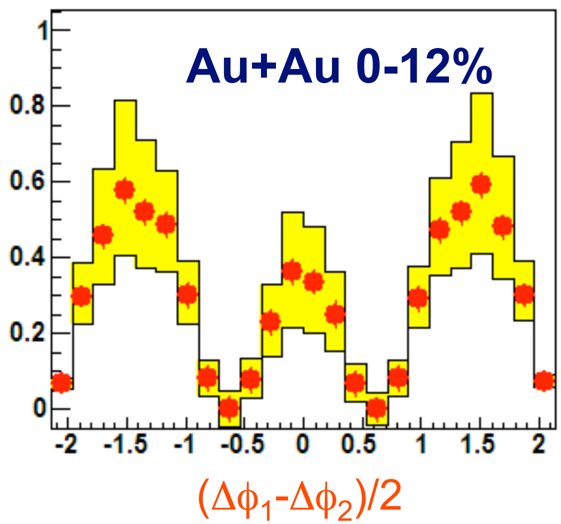

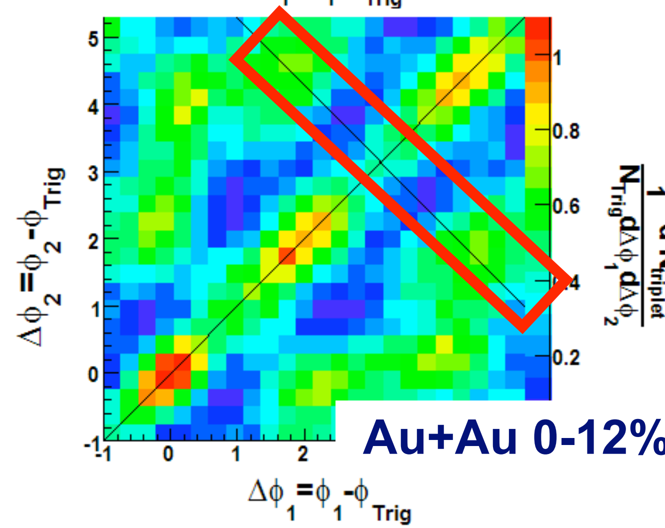

Possible causes of conical emission

Mach Cone

Similar to jet creating sonic boom in air.

Energy radiated from parton deposited in collective hydrodynamic modes.

- Mach angle depends on C_s
  - T dependent

$$\frac{c_s}{v_{parton}} = \cos(\theta_M)$$

- Angle independent of p_T^{assoc}

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Čerenkov Gluon Radiation

Gluons radiated by superluminal parton.

$$\frac{c_n}{v_{parton}} = \cos(\theta_c)$$

$$= \frac{c}{n(p)v_{parton}}$$

$$\approx \frac{1}{n(p)}$$

Angle dependent on p_T^{assoc}

Mach cone or Čerenkov gluons?

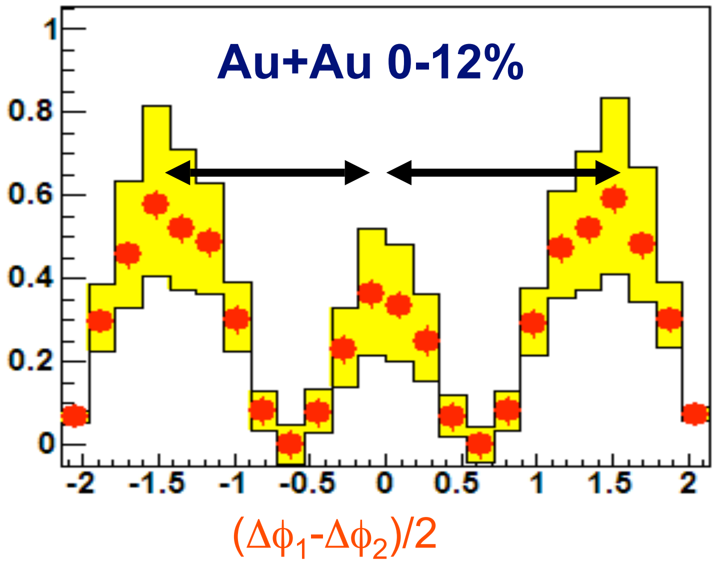
Angle predictions:

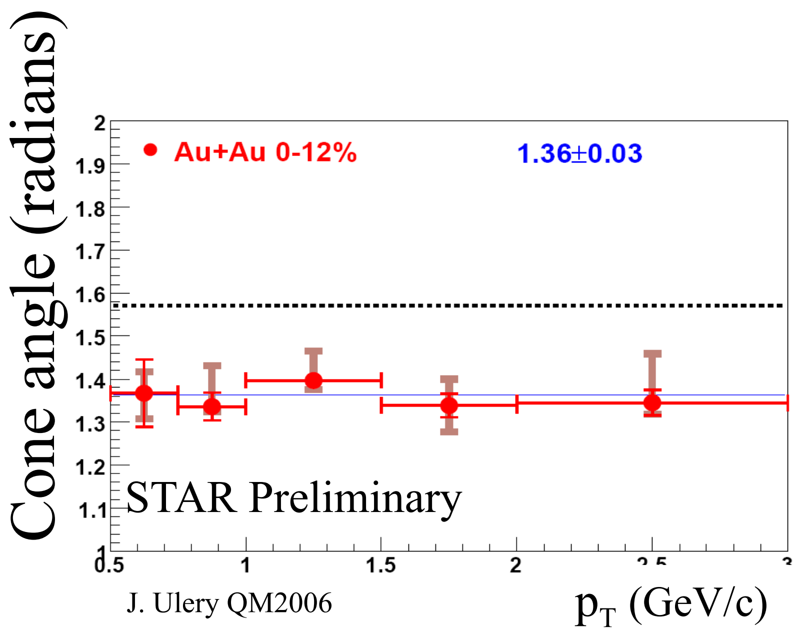
- Mach-cone:

  Angle independent of associated p_T

  Čerenkov gluon radiation:

  Angle decreases with associated p_T





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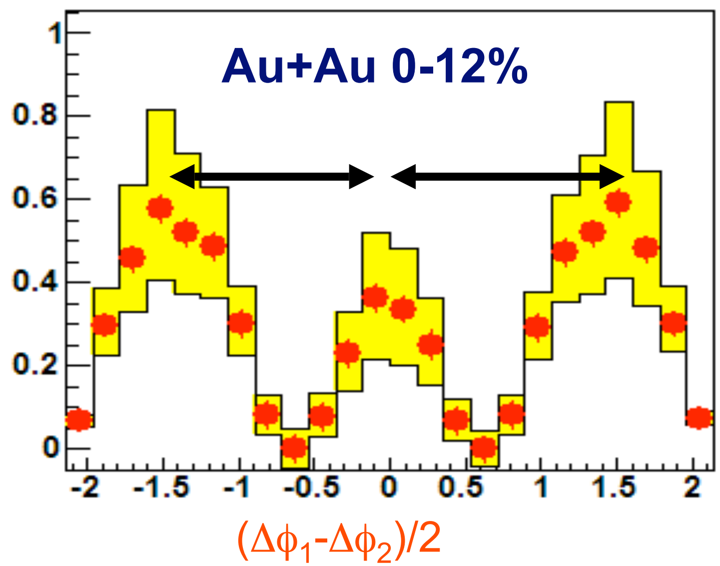
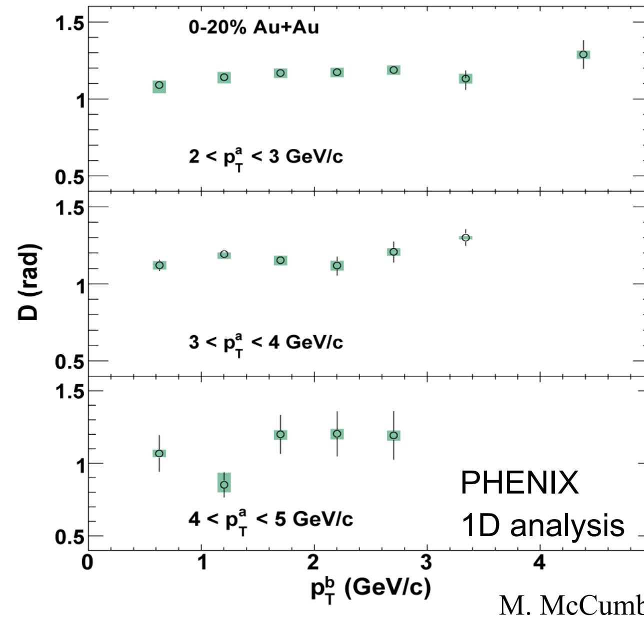
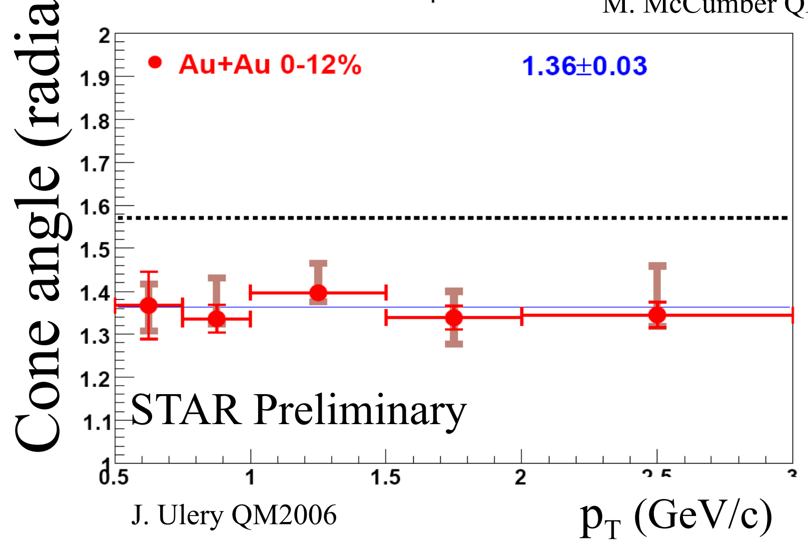




M. McCumber QM2008



J. Ulery QM2006

Mach cone or Čerenkov gluons?

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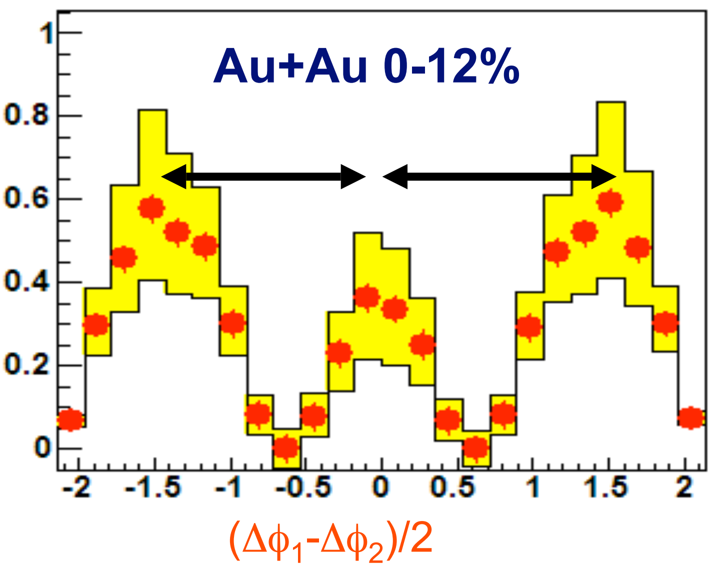
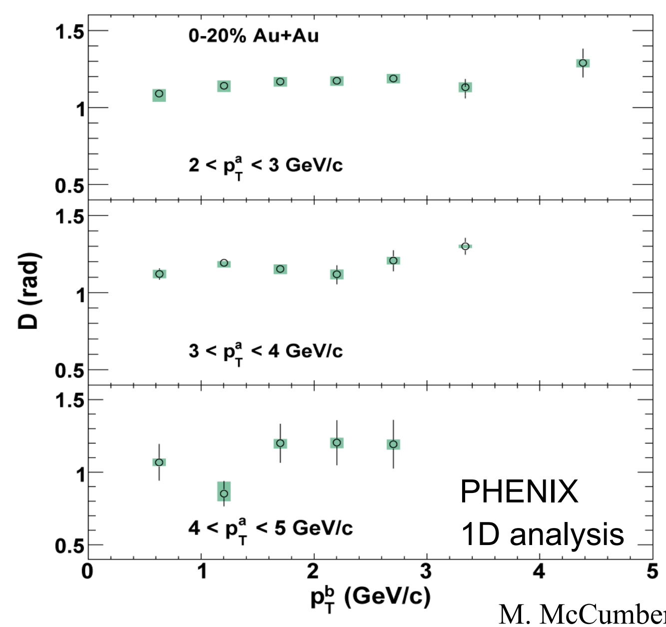
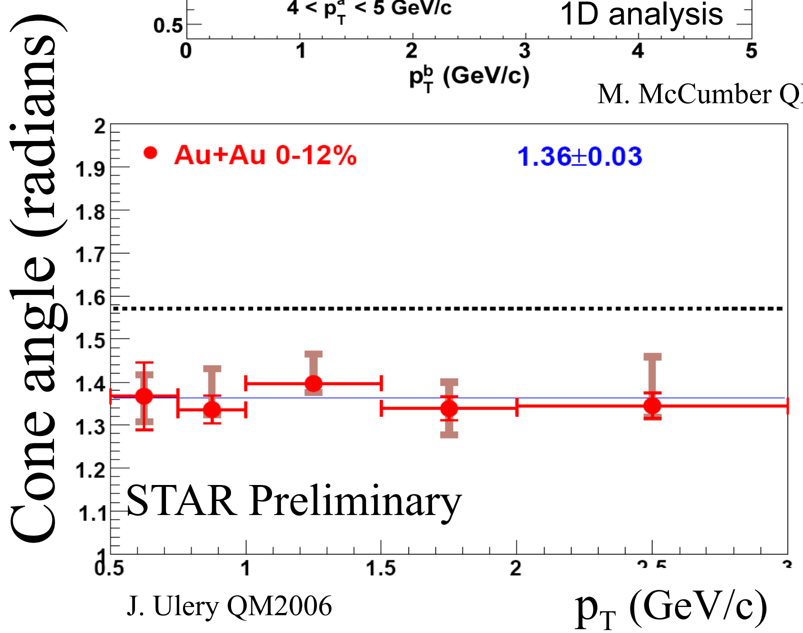
  Angle decreases with associated p_T





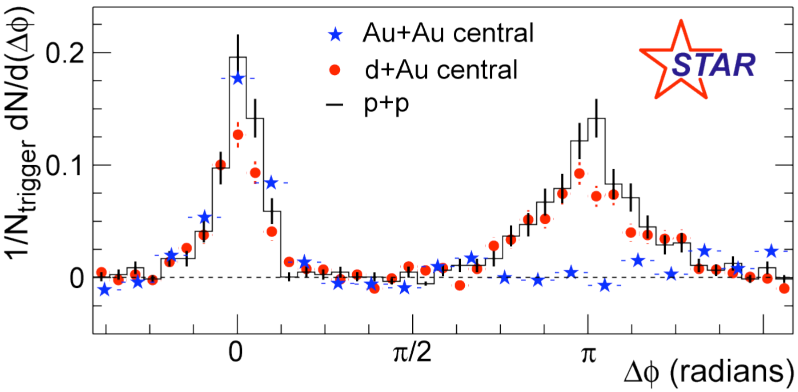
M. McCumber QM2008



J. Ulery QM2006

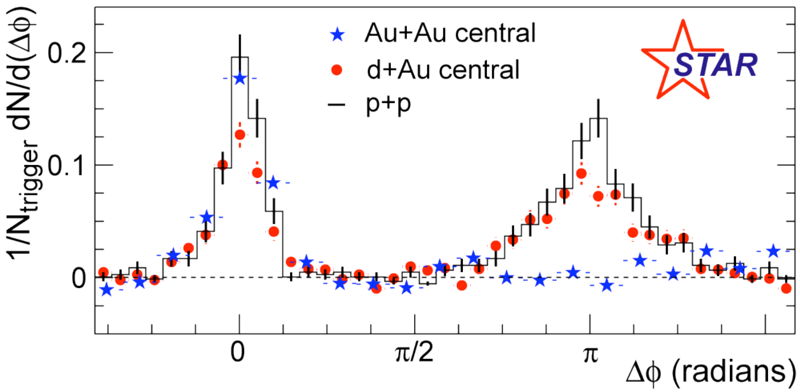
Parton interactions on near side

Δ(φ) correlations

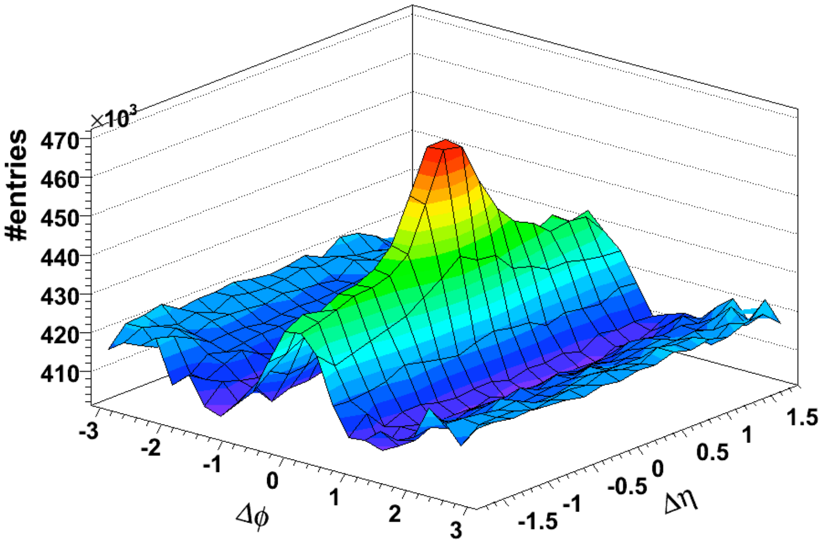


Parton interactions on near side

$\Delta(\phi)$ correlations



$\Delta(\eta) - \Delta(\phi)$ correlations

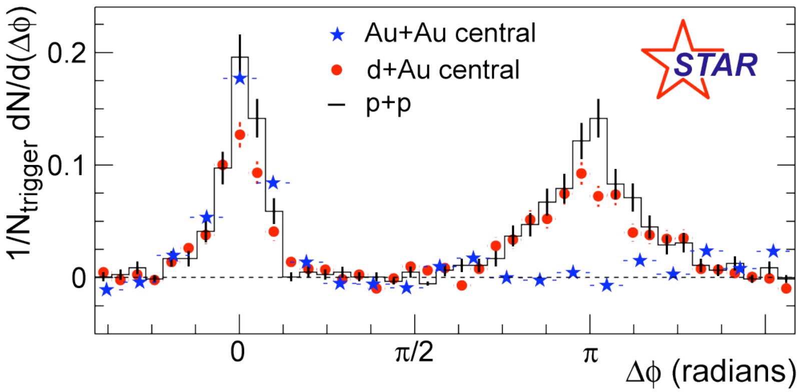


Long range $\Delta(\eta)$ correlation

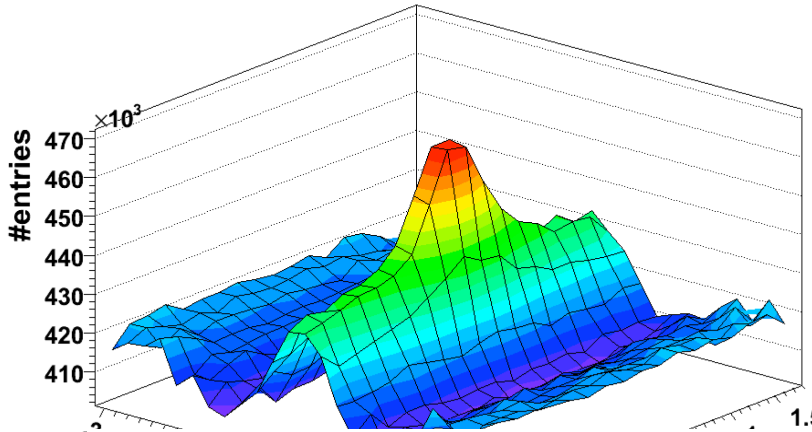
– the "Ridge"

Parton interactions on near side

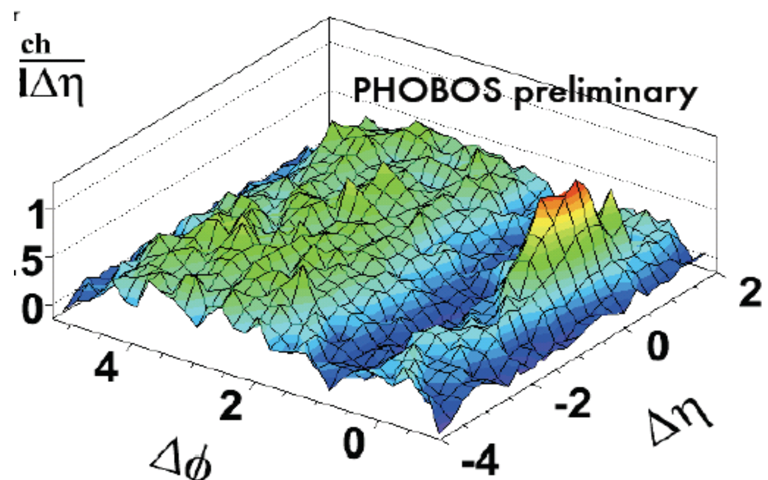
Δ(φ) correlations



Δ(η) – Δ(φ) correlations



Au+Au 0-30% central

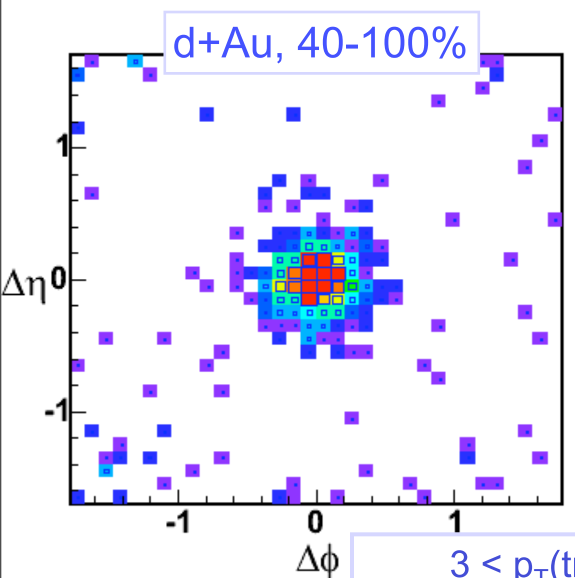


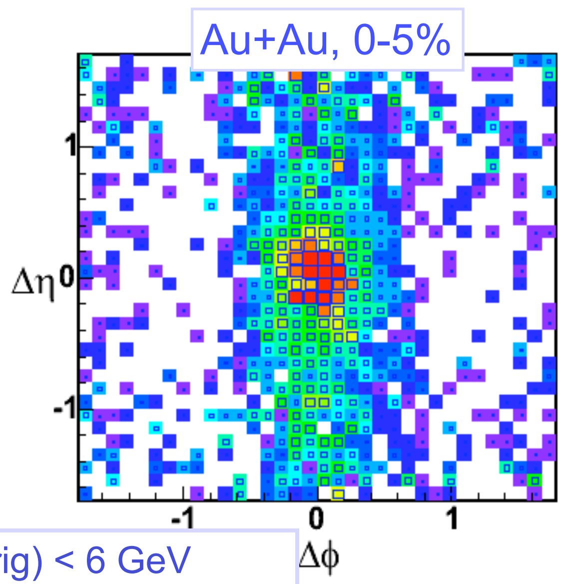
Long range Δ(η) correlation

– the “Ridge”

Persists out to very large Δ(η) >2

Energy loss of trigger -“The ridge”

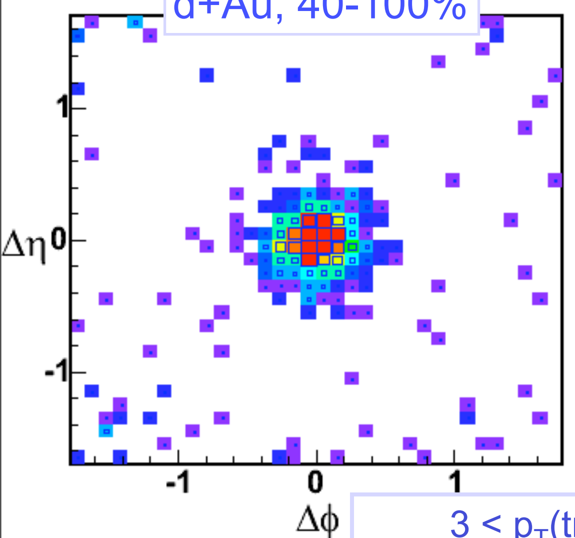


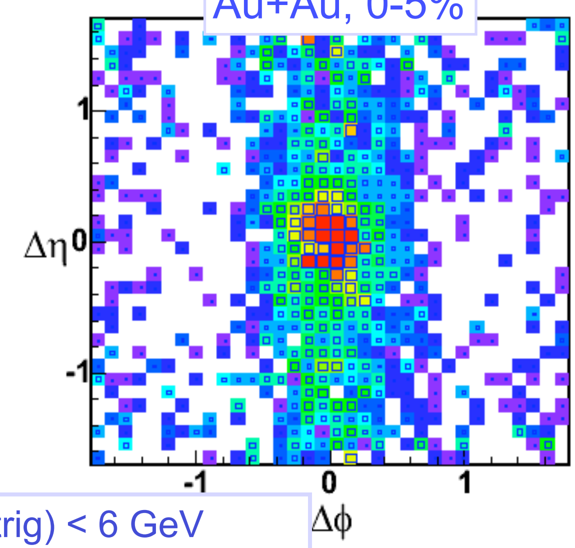


$3 < p_T(\text{trig}) < 6$ GeV

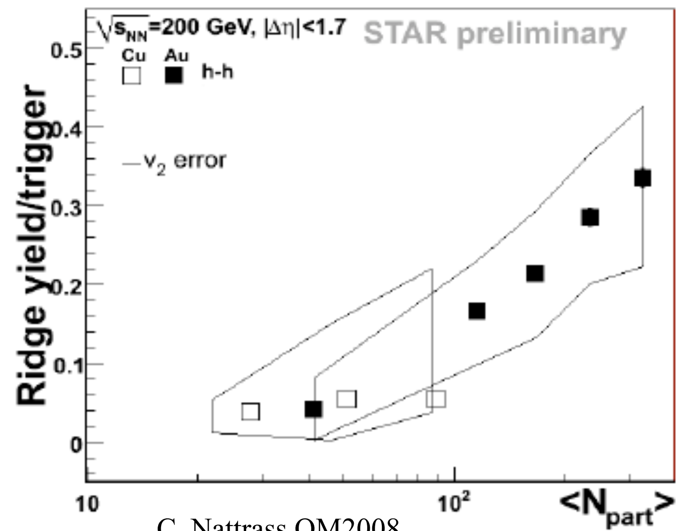
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

Energy loss of trigger -“The ridge”





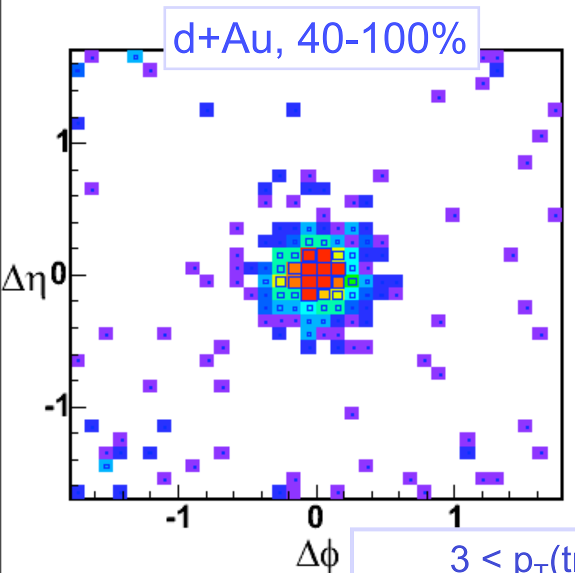
3 < p_T(trig) < 6 GeV
2 < p_T(assoc) < p_T(trig)

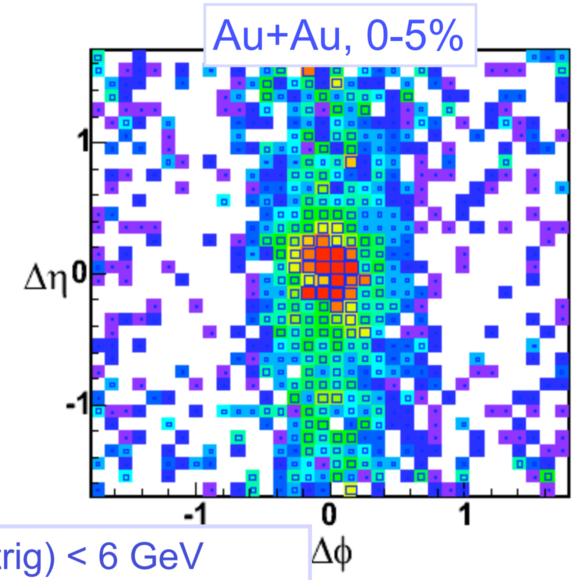


C. Nattrass QM2008

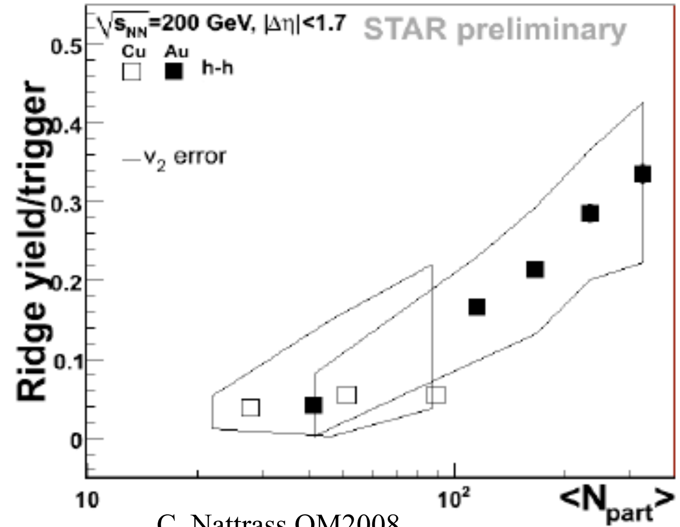
Ridge: Increases with N_{part}
Independent of colliding system

Energy loss of trigger -“The ridge”

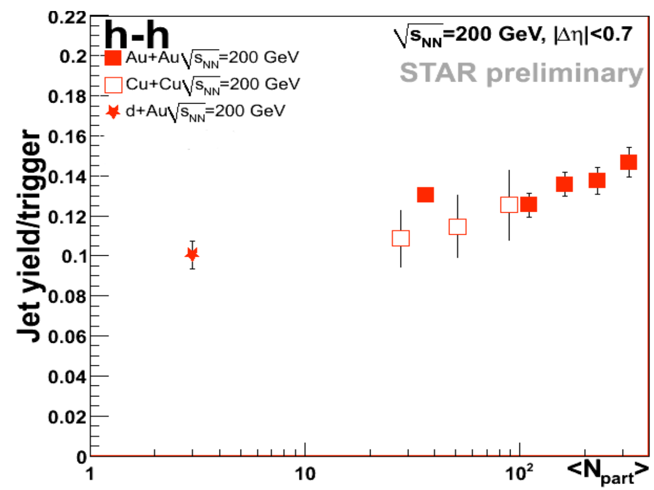




$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$



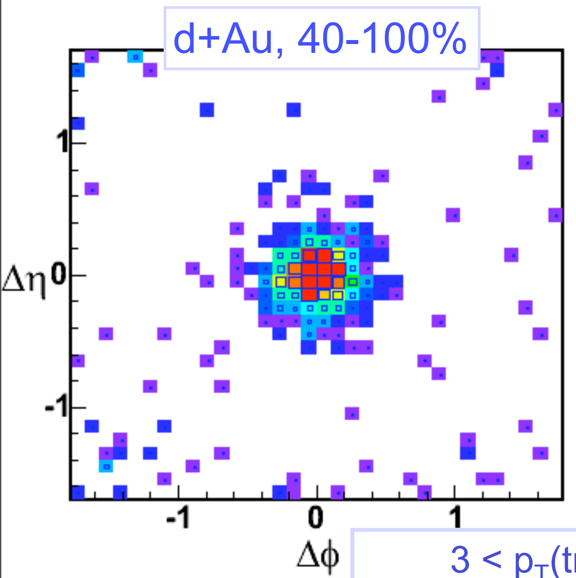
C. Nattrass QM2008

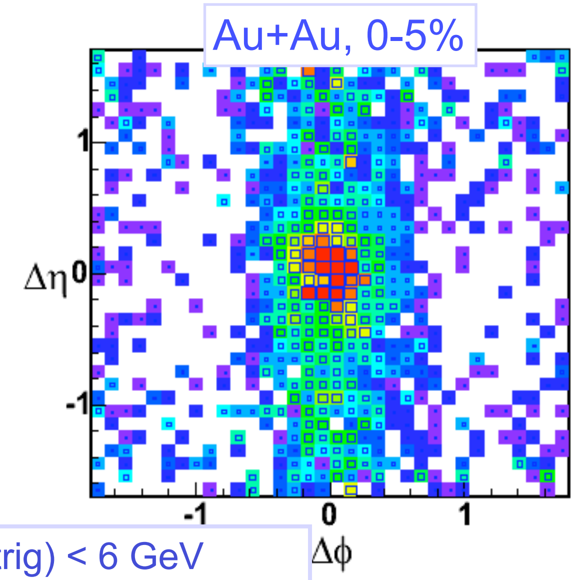


Ridge: Increases with N_{part}
Independent of colliding system

Jet: Approx. flat with N_{part}
Independent of colliding system

Energy loss of trigger -"The ridge"





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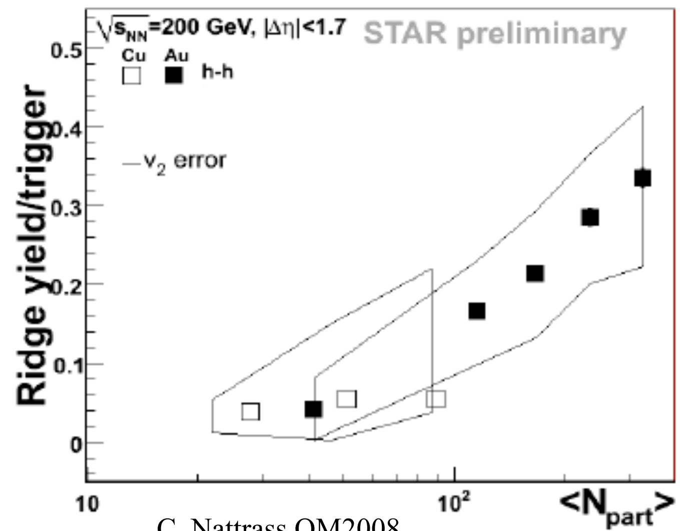
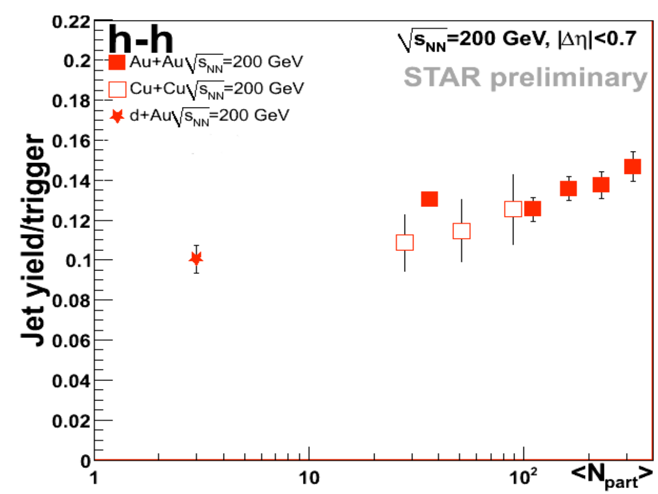


C. Nattrass QM2008

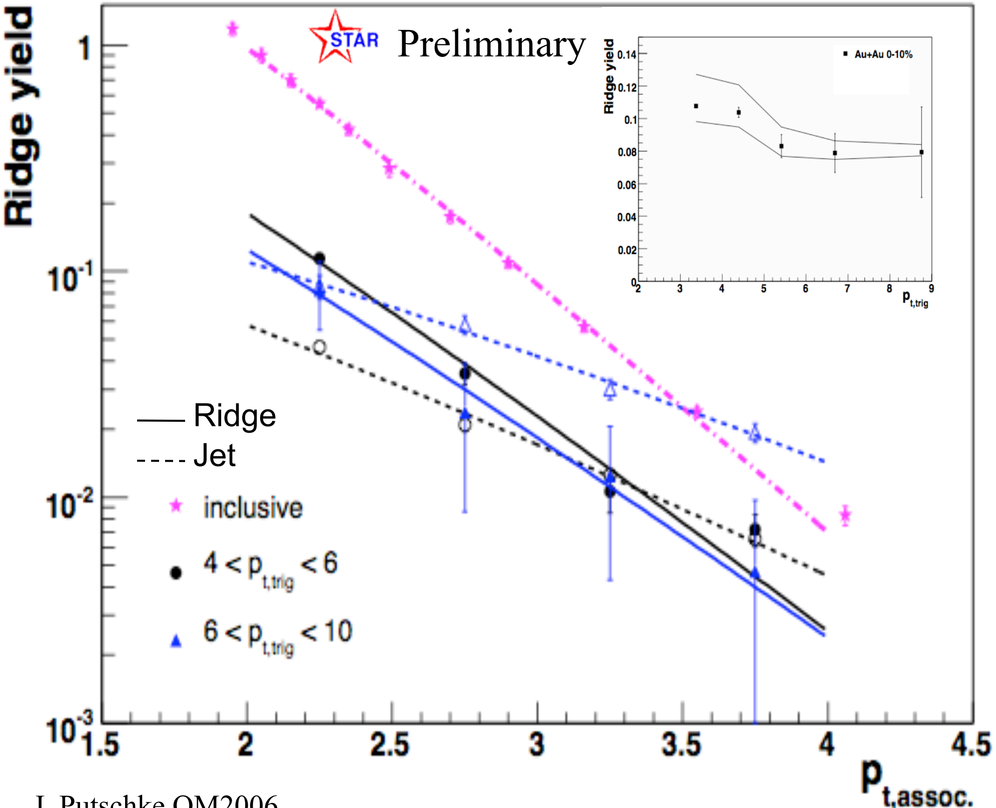


Ridge: Increases with N_{part}
Independent of colliding system

Jet: Approx. flat with N_{part}
Independent of colliding system

Parton interacts with medium (ridge), then vacuum fragments (jet)?

Spectra of ridge and shoulder particles

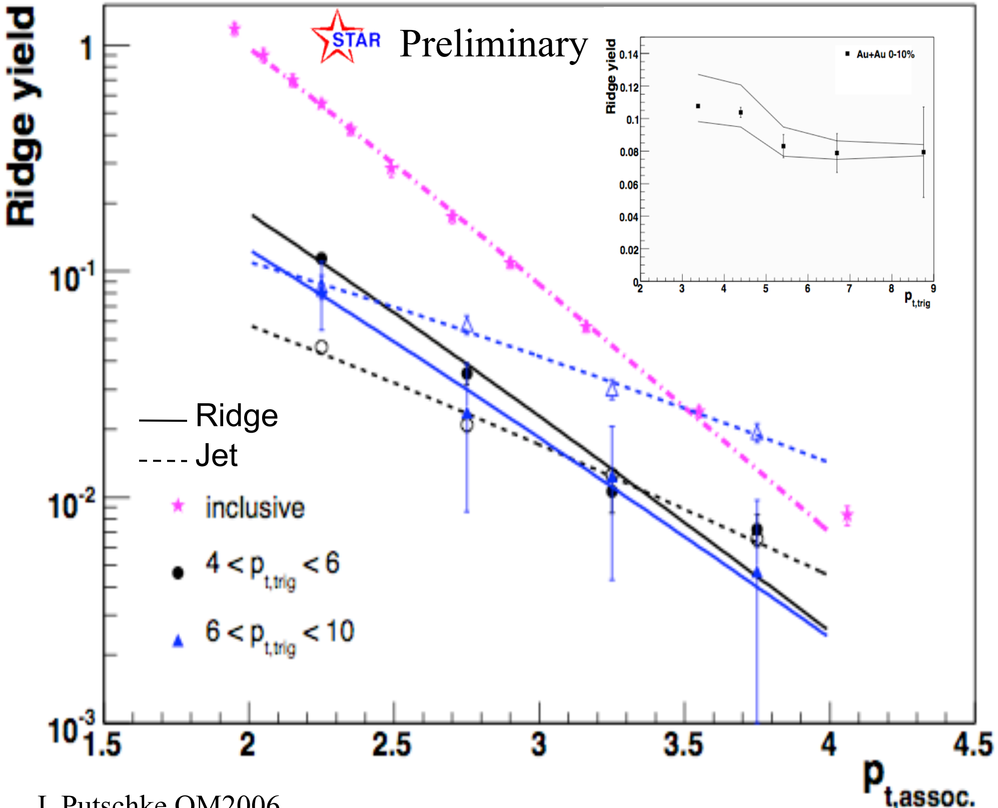


J. Putschke QM2006

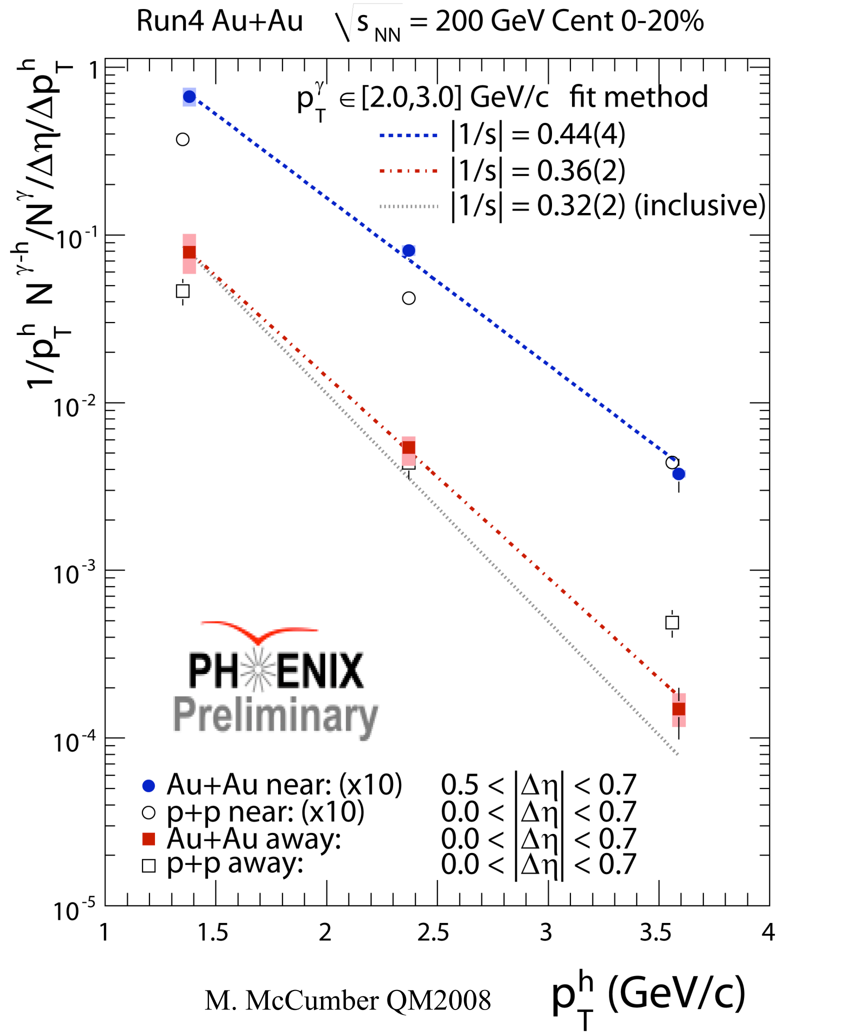
$\text{slope}_{\text{ridge}} > \text{slope}_{\text{jet}}$

$\sim \text{slope}_{\text{inclusive}}$

Spectra of ridge and shoulder particles



J. Putschke QM2006



M. McCumber QM2008

$slope_{ridge} > slope_{jet}$

$\sim slope_{inclusive}$

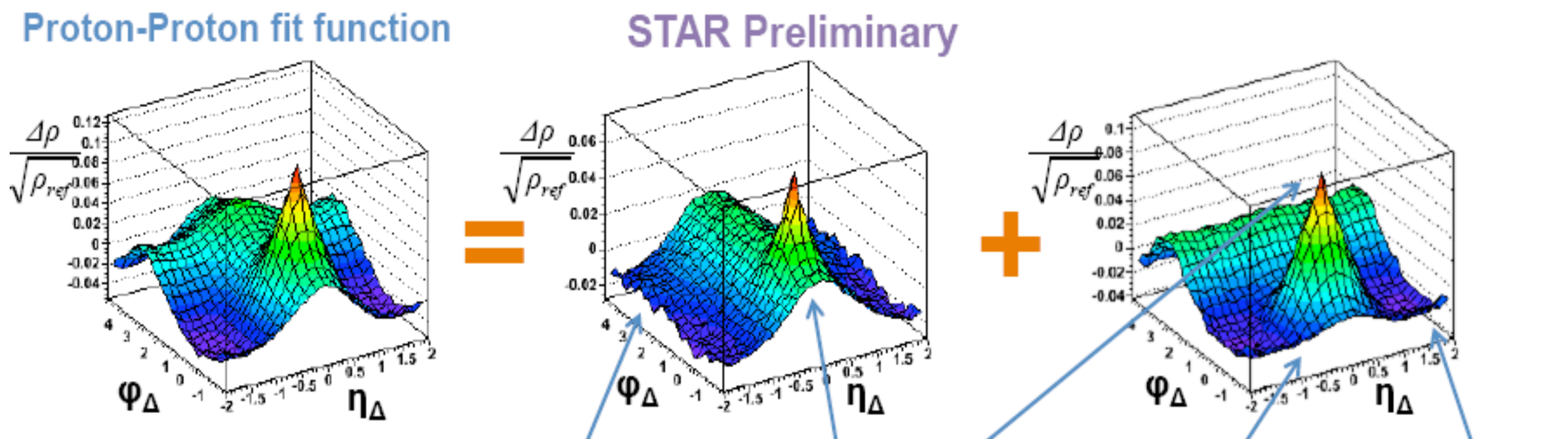
$\geq slope_{shoulder}$

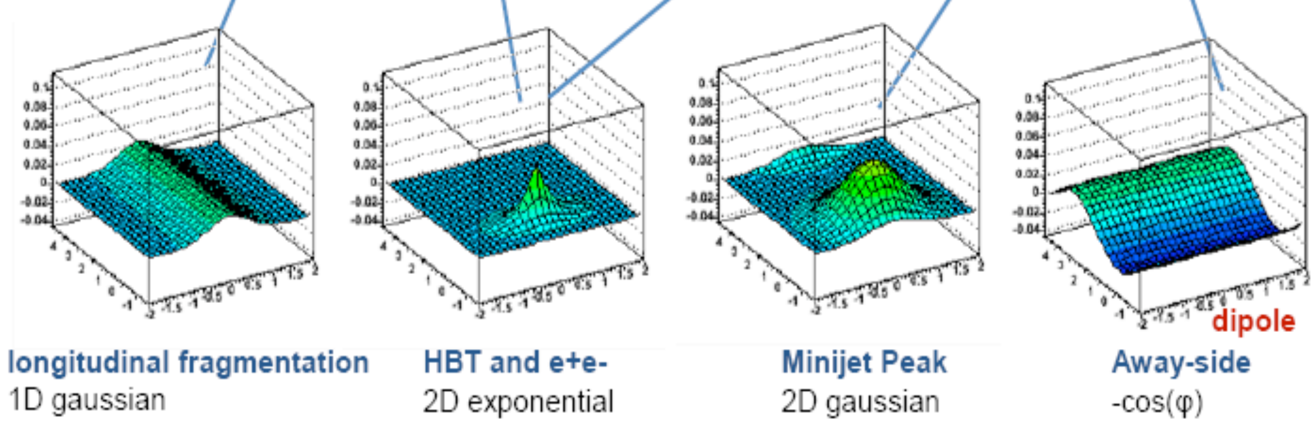
Un-triggered pair correlations

Method: measure pair densities $\rho(\eta_1-\eta_2,\varphi_1-\varphi_2)$ for *all possible pairs* in same and mixed events.

Define correlation measure as:

$$\frac{\rho_{same}-\rho_{mixed}}{\sqrt{\rho_{mixed}}} \equiv \frac{\Delta\rho}{\sqrt{\rho_{ref}}} \propto \frac{\#\,\text{correlated pairs}}{\text{particle}}$$





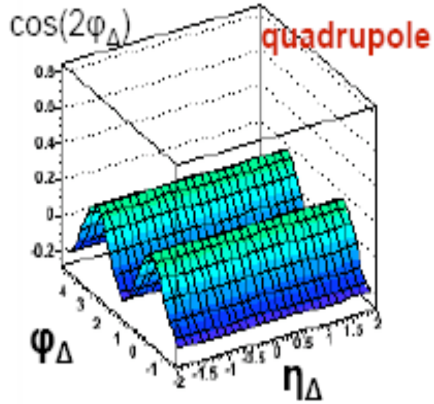
M. Daugherty QM2008

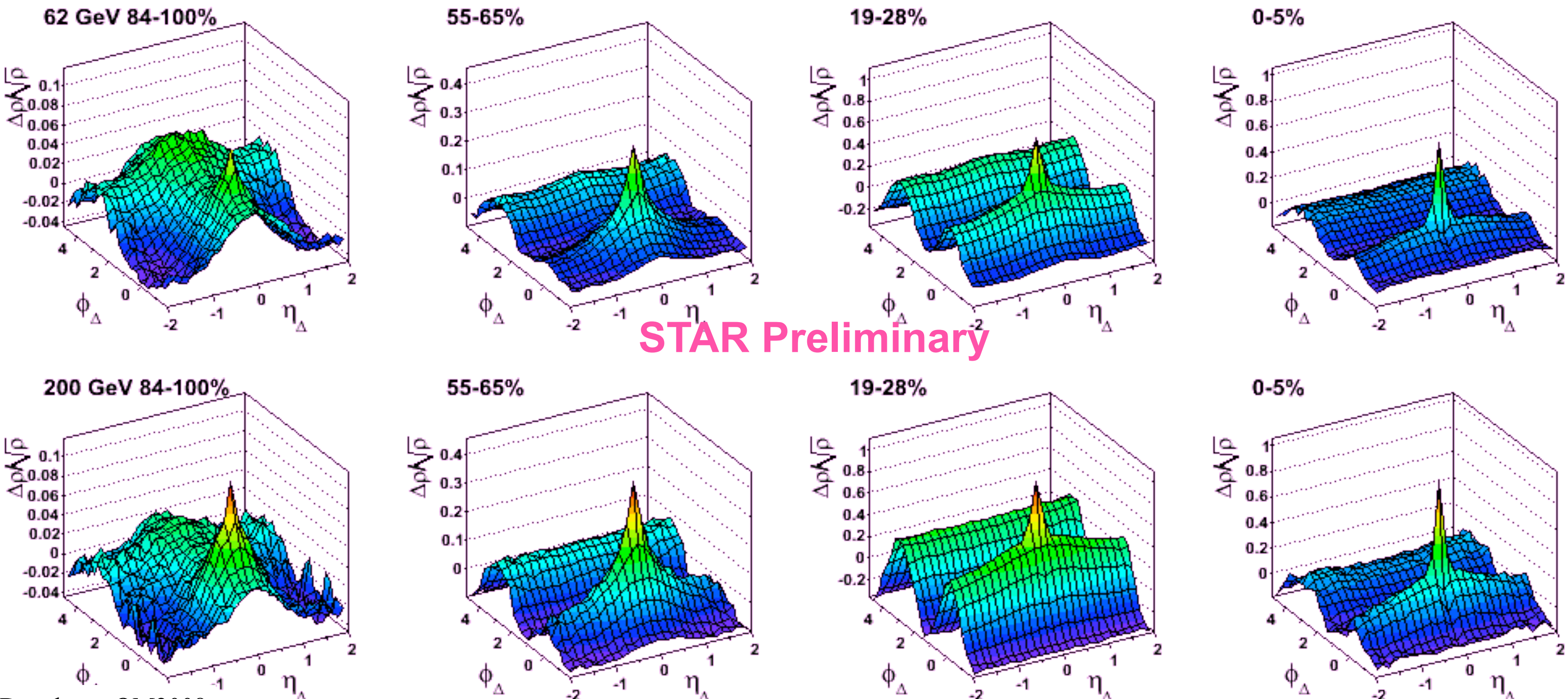
Minijet:
Same-side jet-like correlations with no trigger particle

Un-triggered pair correlations

Au-Au fit function

Use proton-proton fit function + $\cos(2\varphi_\Delta)$ quadrupole term ("flow").
This gives the ***simplest possible*** way to describe Au+Au data.





Un-triggered pair correlations

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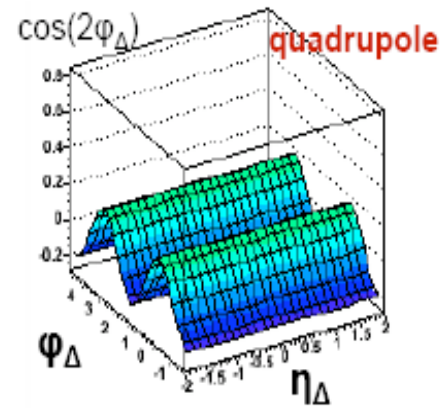
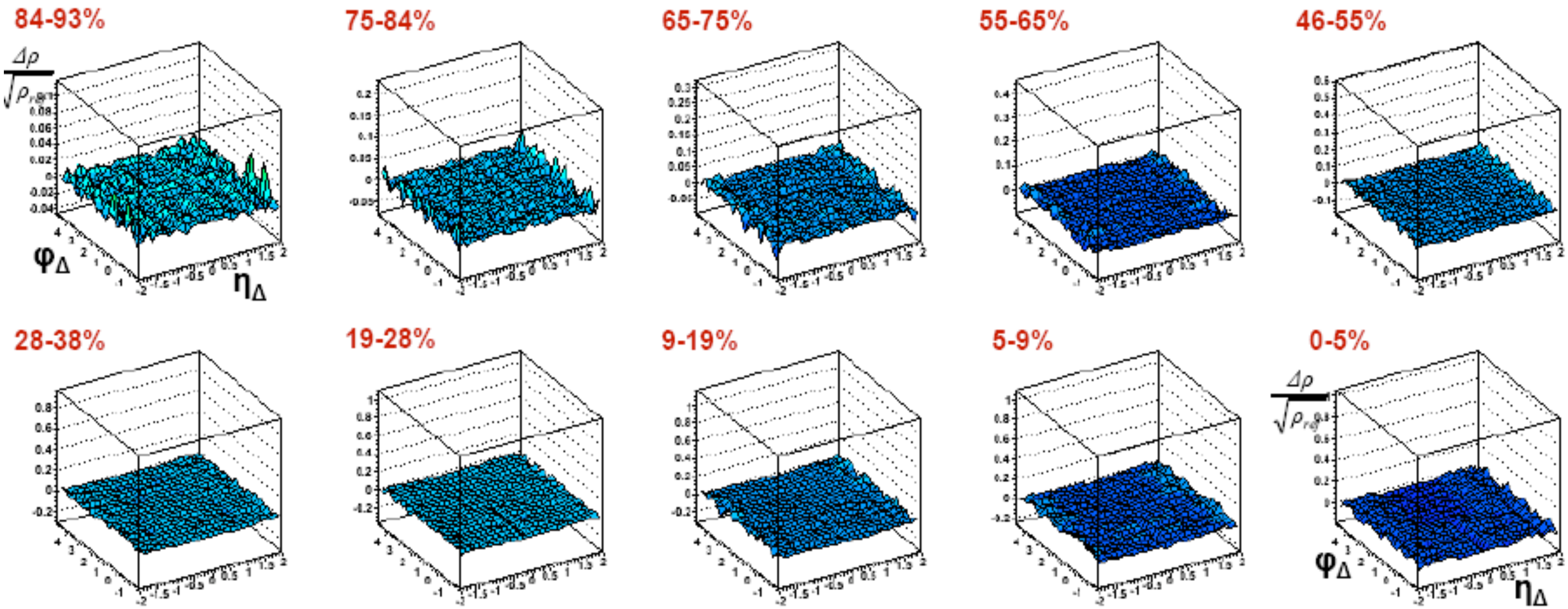


Small residual indicates goodness of fit

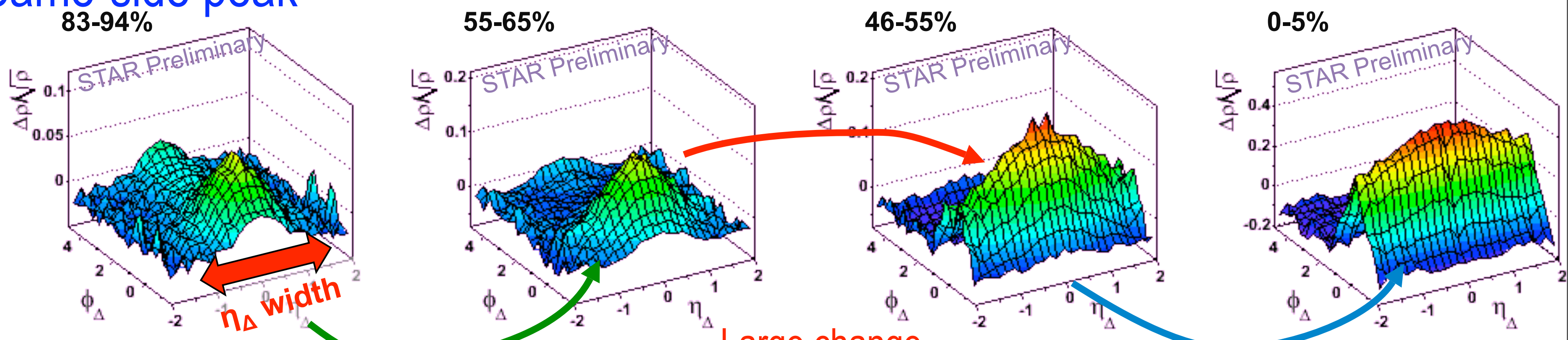
Fit residual = data - model

STAR Preliminary



Evolution of mini-jet with centrality

Same-side peak



Little shape change from peripheral to 55% centrality

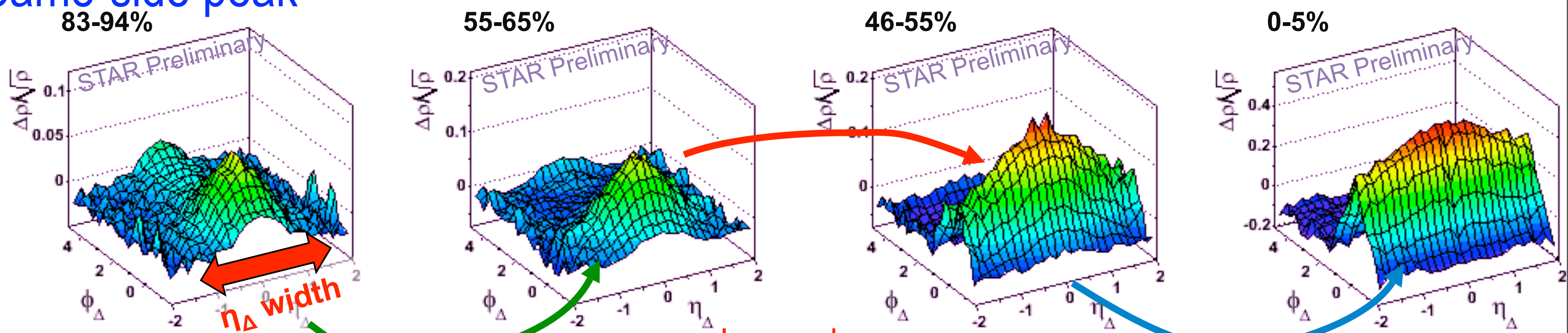
Large change within ~10% centrality

Smaller change from transition to most central

M. Daugherty QM2008

Evolution of mini-jet with centrality

Same-side peak



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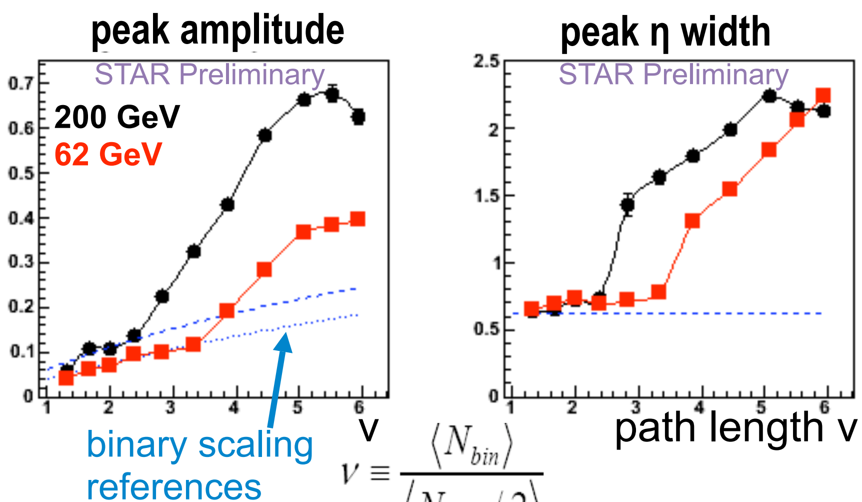
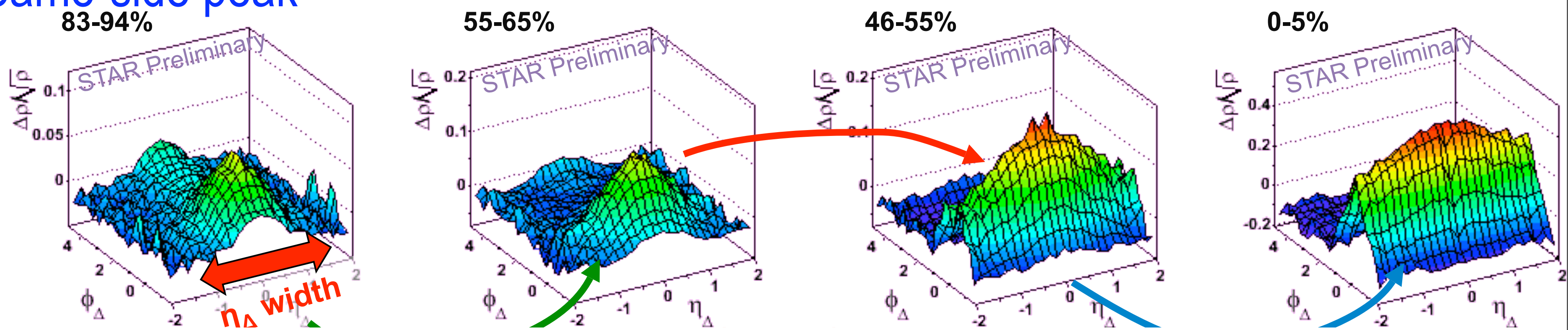


$$\nu \equiv \frac{\langle N_{bin} \rangle}{\langle N_{part}/2 \rangle}$$

M. Daugherty QM2008

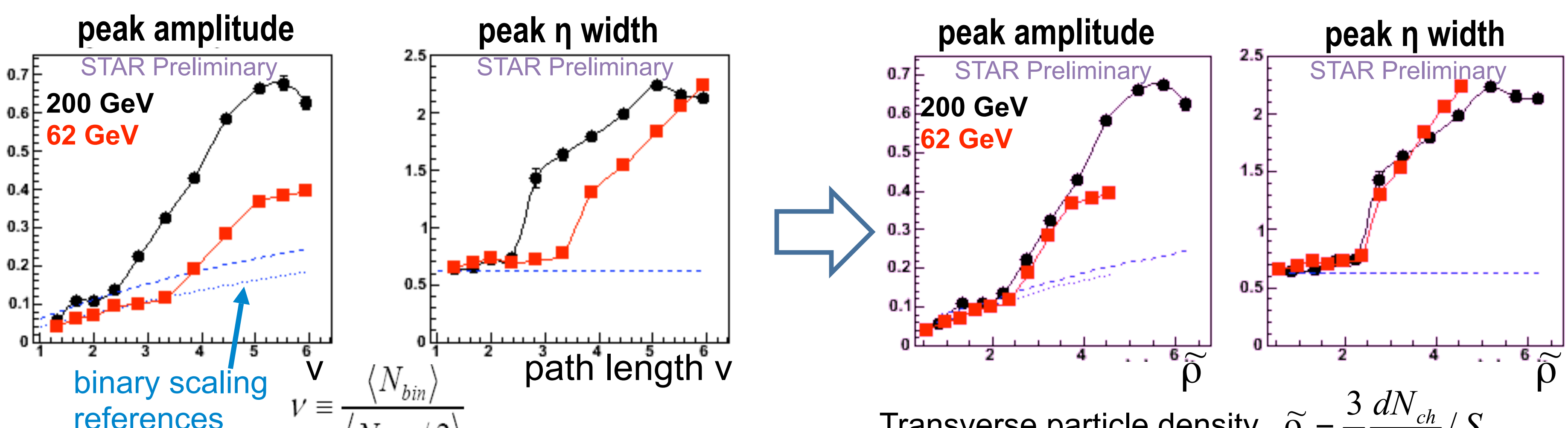
Evolution of mini-jet with centrality

Same-side peak



Binary scaling reference followed until sharp transition at ρ ~ 2.5

~30% of the hadrons in central Au+Au participate in the same-side correlation

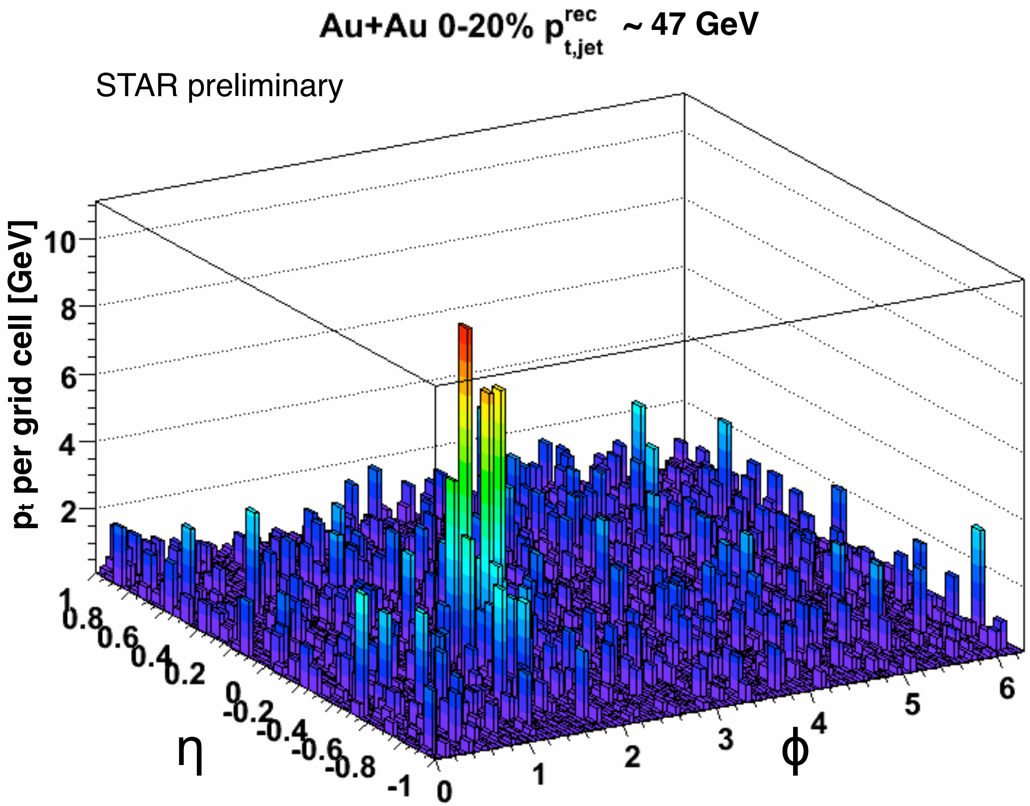


$$\nu \equiv \frac{\langle N_{bin} \rangle}{\langle N_{part}/2 \rangle}$$

M. Daugherty QM2008

Transverse particle density $\tilde{\rho} = \frac{3}{2}\frac{dN_{ch}}{d\eta}/S$

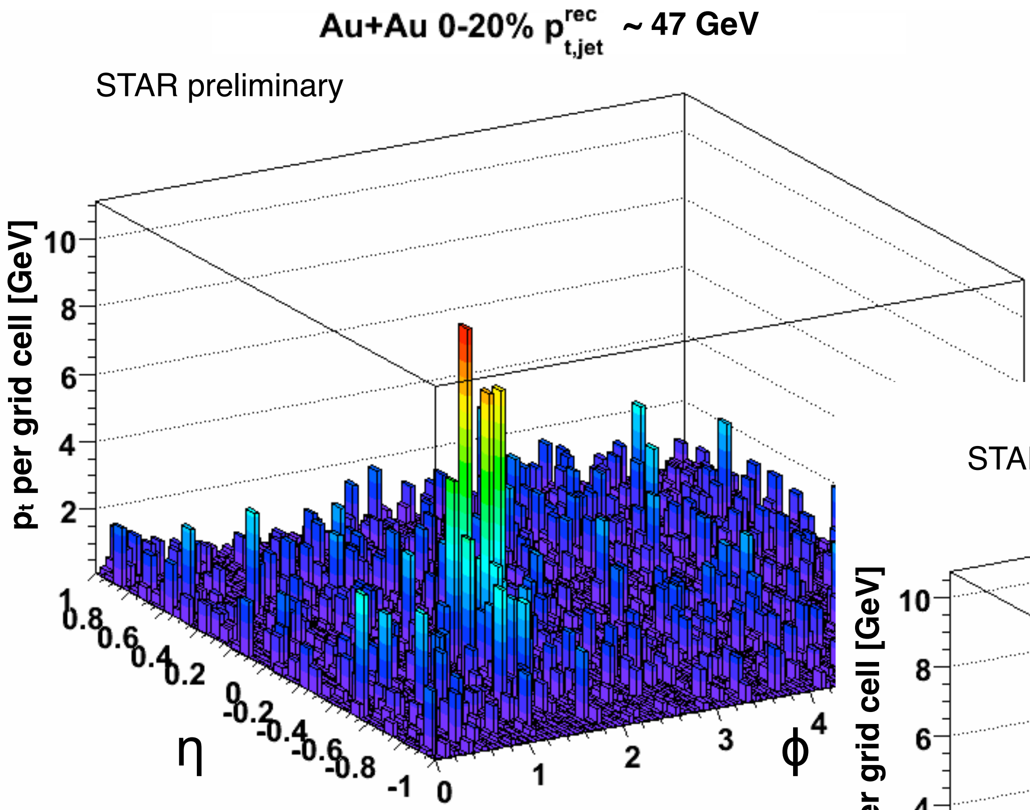
Jets @ RHIC in Au-Au collisions



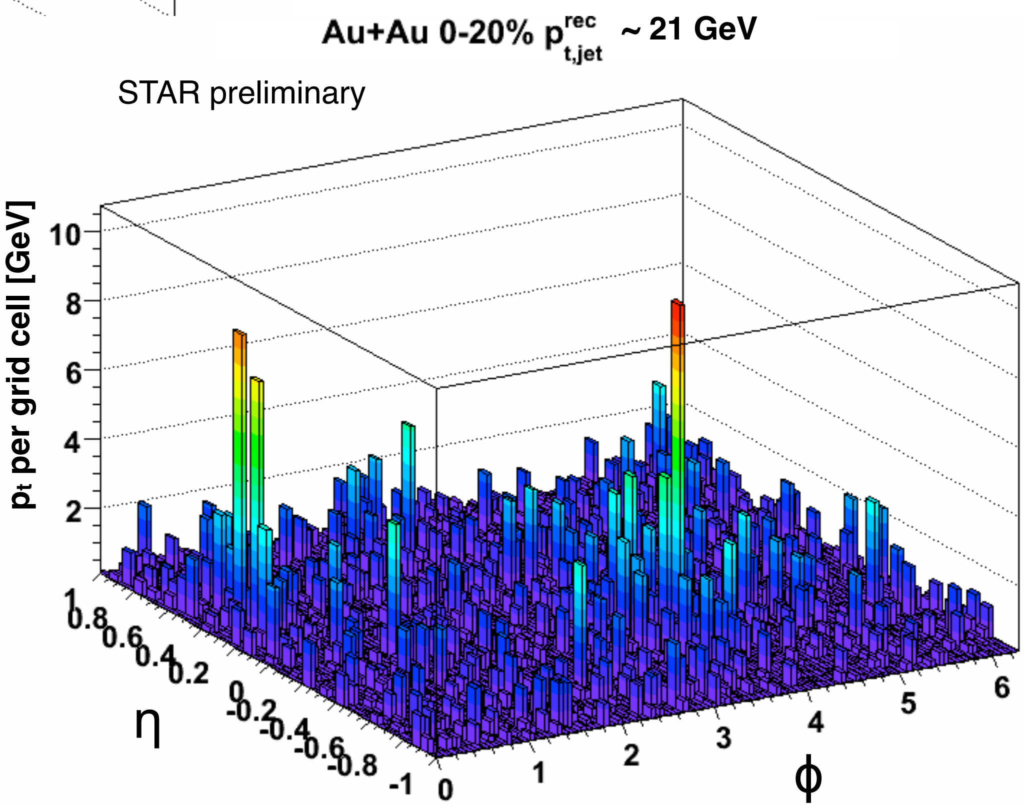
Clearly visible in central events on E-by-E basis

J. Putschke Hard Probes 2008

Jets @ RHIC in Au-Au collisions



Clearly visible in central events on E-by-E basis



Energies as low as 20 GeV resolvable

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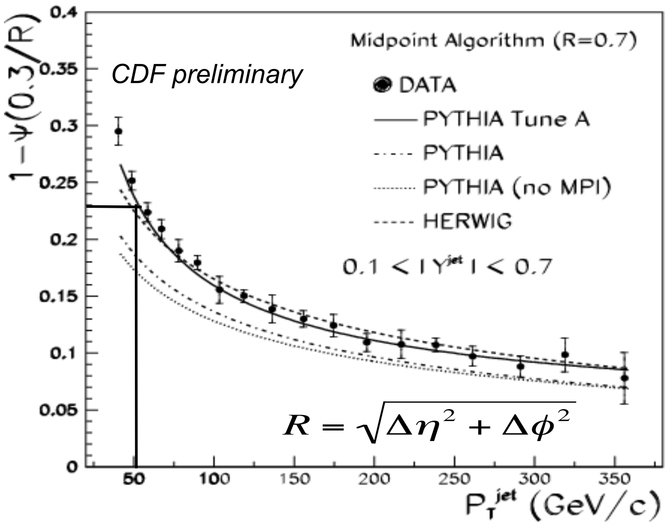
Jet-finding strategies in heavy-ion

Jet energy fraction outside cone



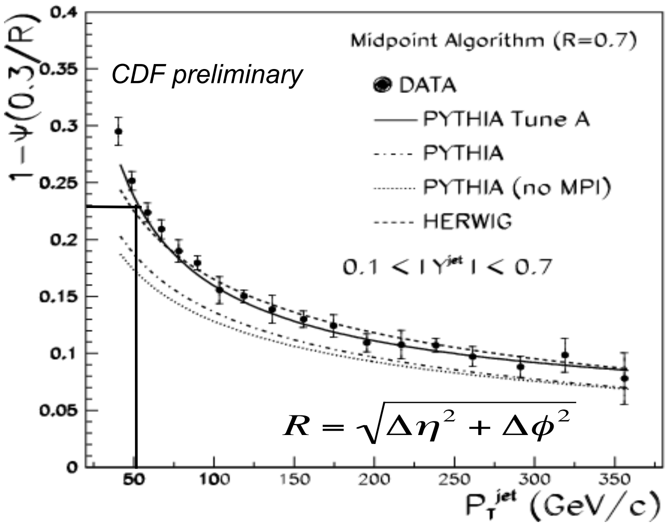
- Unmodified (p+p) jets:
  ~ 80% of energy within R~0.3

- Need to suppress heavy-ion background:
  small jet cones areas
  R~0.3-0.4
  remove underlying event
  $p_{t,track}$,$E_{t,tower}$ >1-2 GeV

J. Putschke Hard Probes 2008

Jet-finding strategies in heavy-ion

Jet energy fraction outside cone



- Unmodified (p+p) jets:
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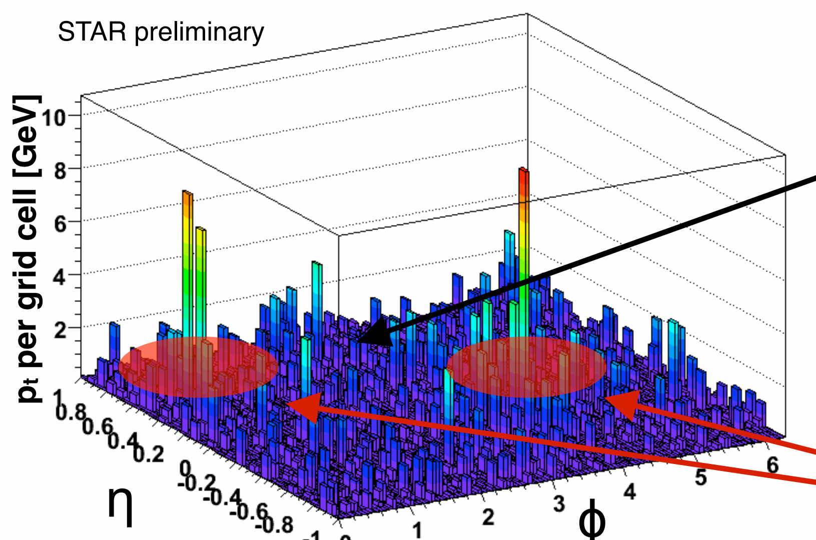
- Need to suppress heavy-ion background:
  small jet cones areas
  R~0.3-0.4
  remove underlying event
  $p_{t,track}$, $E_{t,tower}$ >1-2 GeV

Estimate background E-by-E by sampling Out-of-Cone area:



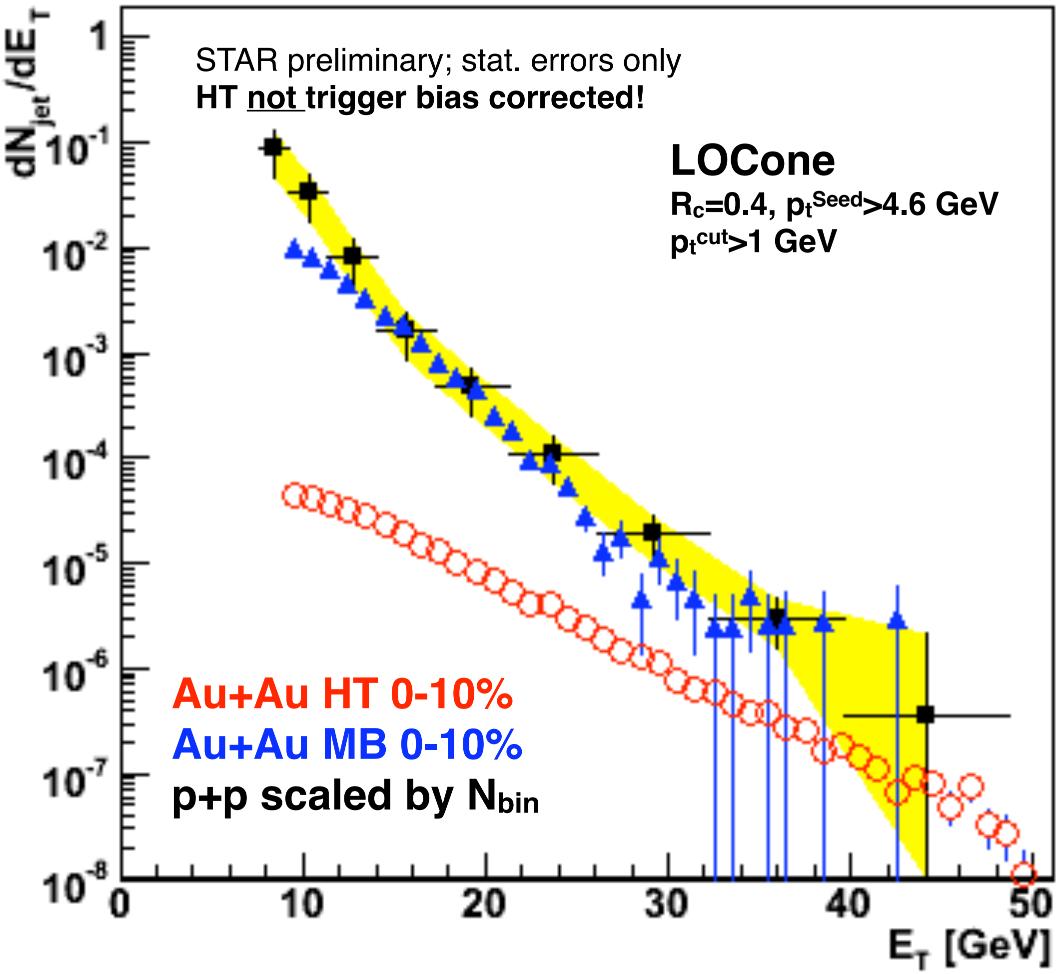
Out-of-Cone area:
used to estimate mean background energy and "mean background FF function"

Caveat: Precision depends on acceptance, event-by-event fluctuations and elliptic flow (small effect for central heavy-ion collisions) …

reconstructed jets

J. Putschke Hard Probes 2008

Jet spectrum in Au+Au collisions



MB-Trig: Good agreement with N_{bin} scaled p+p collisions

HT-Trig: Large trigger bias how far up does it persist? (in p+p at least to 30 GeV)

Relative normalization systematic uncertainty: ~50%.

Further statistics of MB is needed to assess the bias in HT Trigger.

First reconstructed jets in central heavy ion collisions.

black points: p+p mid-cone corrected to particle level (scaled by N_{bin})

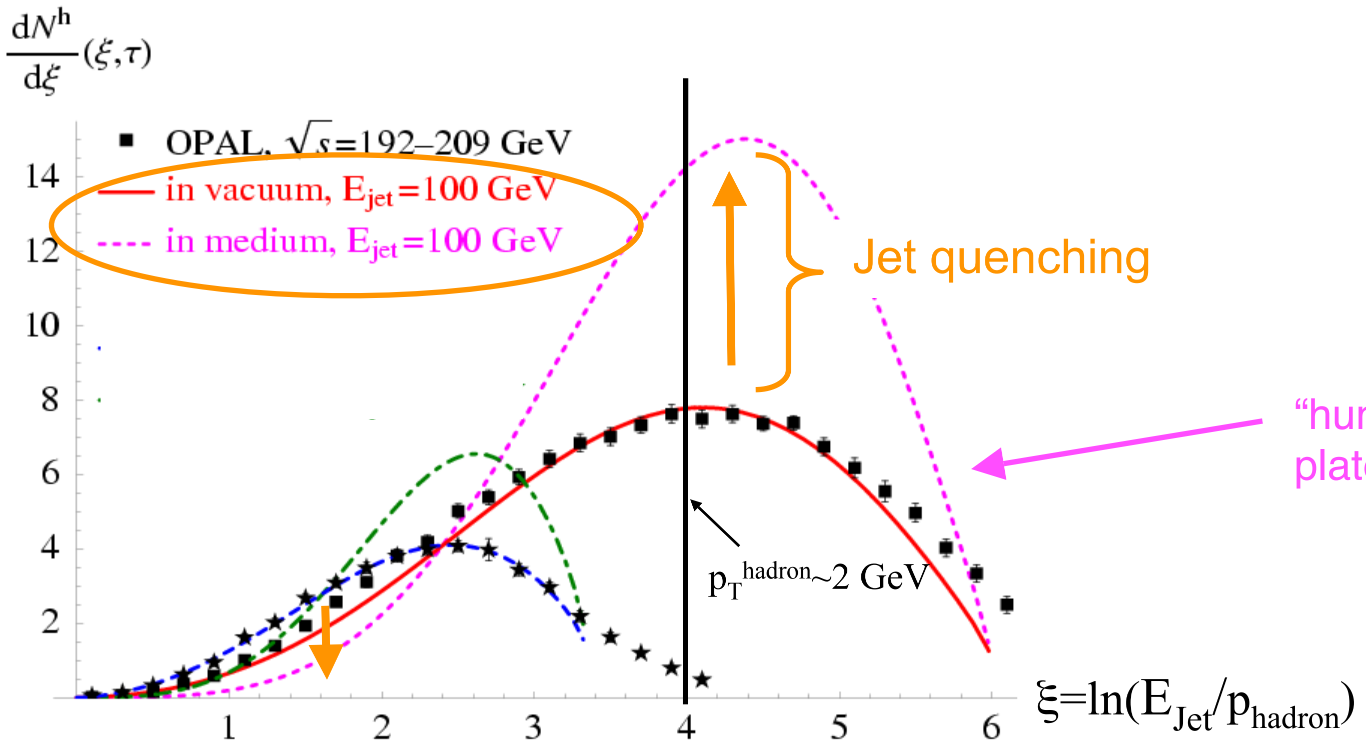
blue solid points: Au+Au minbias corrected for p_t^{cut} and eff. using Pythia

red open points: Au+Au HT trigger not corrected for p_t^{cut} and eff. using Pythia

S. Salur Hard Probes 2008

Modification of fragmentation function

- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*



Jet quenching ⇒ fragmentation should be strongly modified at p_T^{hadron}~1-5 GeV

Can we measure this at RHIC?

RHIC "Summary"

We create a strongly coupled medium ⇒ sQGP

- **not** the asymptotically plasma of "free" quarks and gluons as expected - high p_T partons interact very strongly with it
- It *flows* like a (nearly) perfect fluid with *quark degrees of freedom* and a *viscosity to entropy* density ratio lower than any other known fluid

We are past the discovery stage ⇒ towards the quantitative

- i.e. η/s, transport coefficients
- First full jet reconstruction in heavy-ion collisions - probing medium
- How medium varies as a function of collision energy/centrality/species
- New phenomena (e.g. ridge) challenge our understanding
- much remains to be done: EOS, initial conditions (ultimately needs EIC)

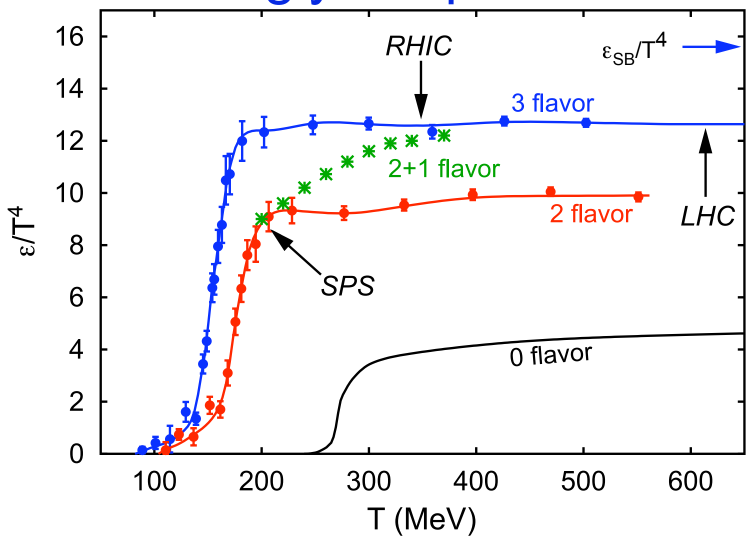
Next steps

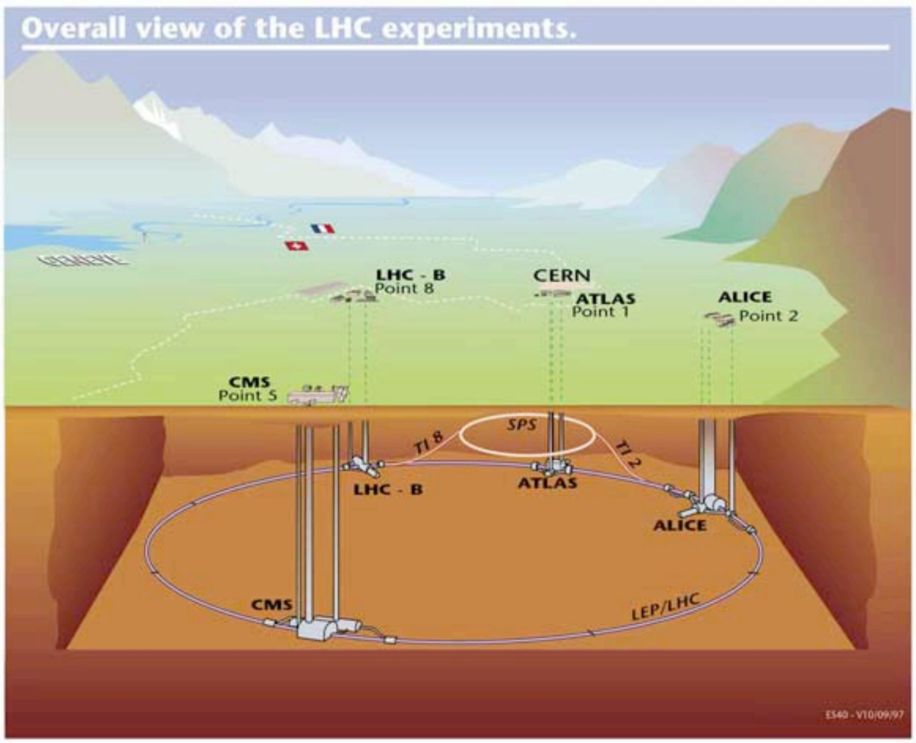
- Ongoing upgrades to STAR and PHENIX
  - Vertex detectors, increased coverage and PID, improved triggering capabilities ⇒ rare probes, heavy flavor, γ-jet, ...
- Electron Beam Ion Source (EBIS) to extend ranges of species (U+U)
- RHIC-II: increase luminosity by factor 5 using stochastic cooling

The Next Energy Frontier: LHC

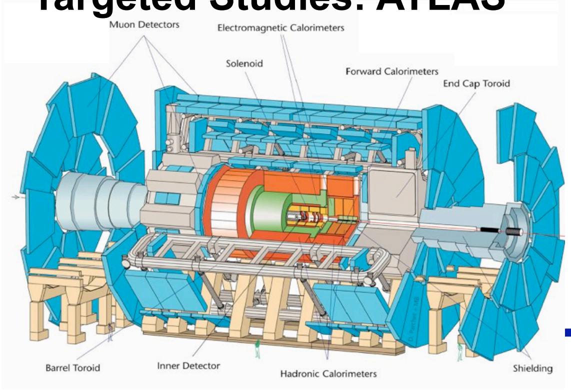
A unique opportunity to investigate "QGP" at unparalleled high √s

Will this too create a strongly-coupled fluid?

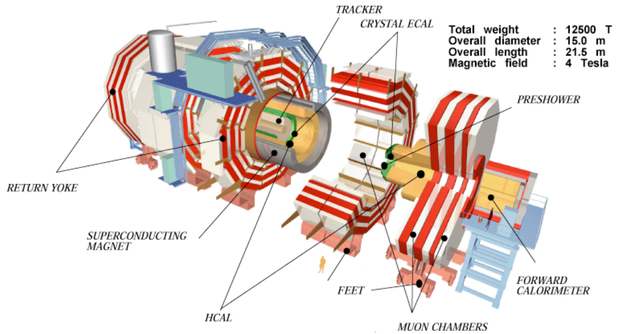




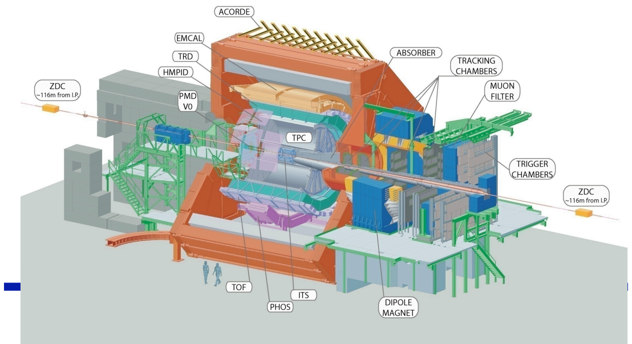
Targeted Studies: ATLAS



Targeted Studies: CMS



Dedicated Experiment: ALICE



END

Some possible explanations of the ridge

Recombination between thermal and shower partons at intermediate p_T

R.C. Hwa & C.B. Chiu Phys. Rev. C 72 (2005) 034903

QCD bremsstrahlung radiation boosted by transverse flow

S.A. Voloshin, Phys. Lett. B 632 (2007) 490
E. Shuryak, hep-ph:0706.3531

In medium radiation and longitudinal flow push

N. Armesto et.al Phys. Rev. Lett. 93 (2007) 242301

Broadening of quenched jets in turbulent color fields

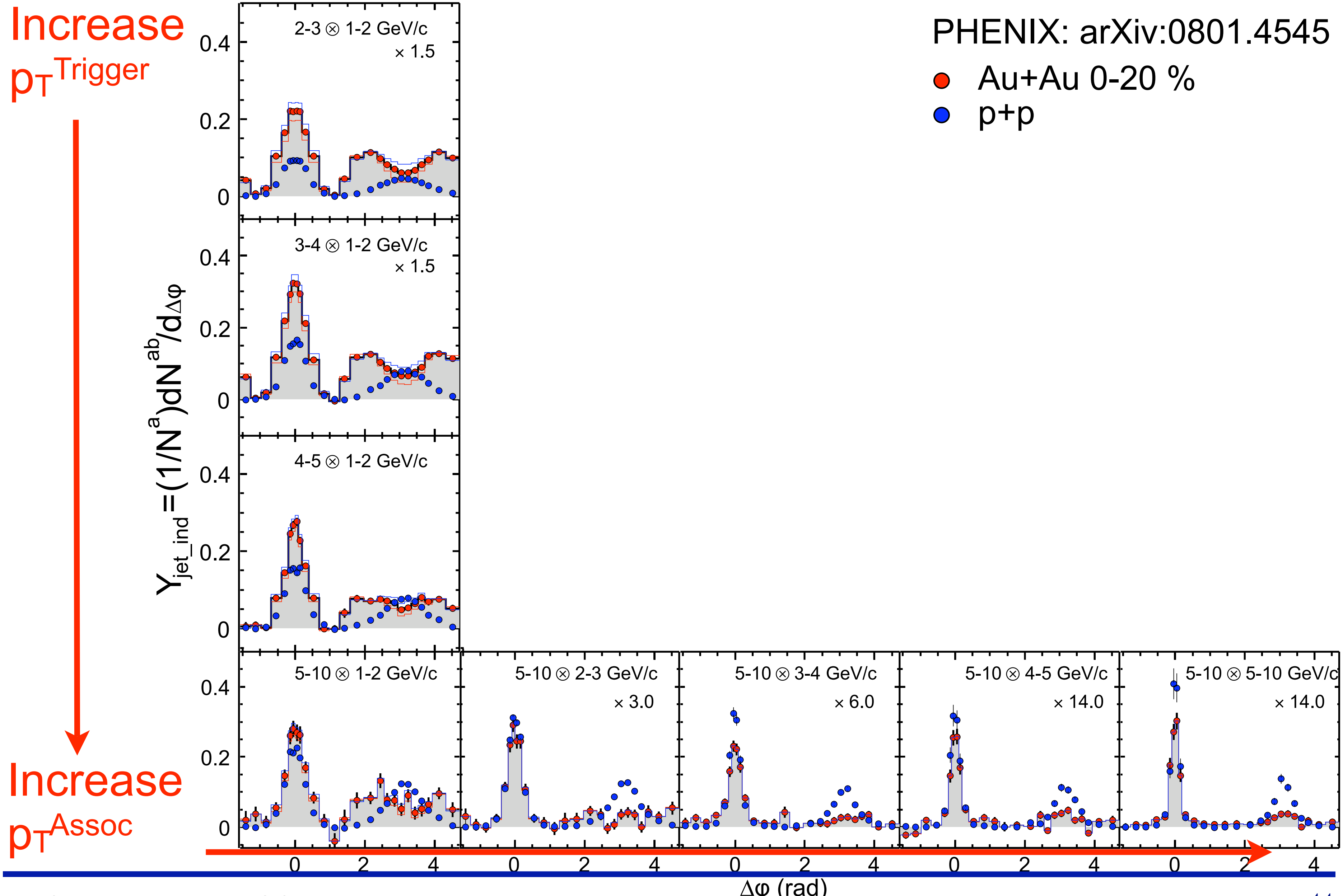
A. Majumder et.al Phys. Rev. Lett. 99 (2004) 042301

Momentum Kick Model

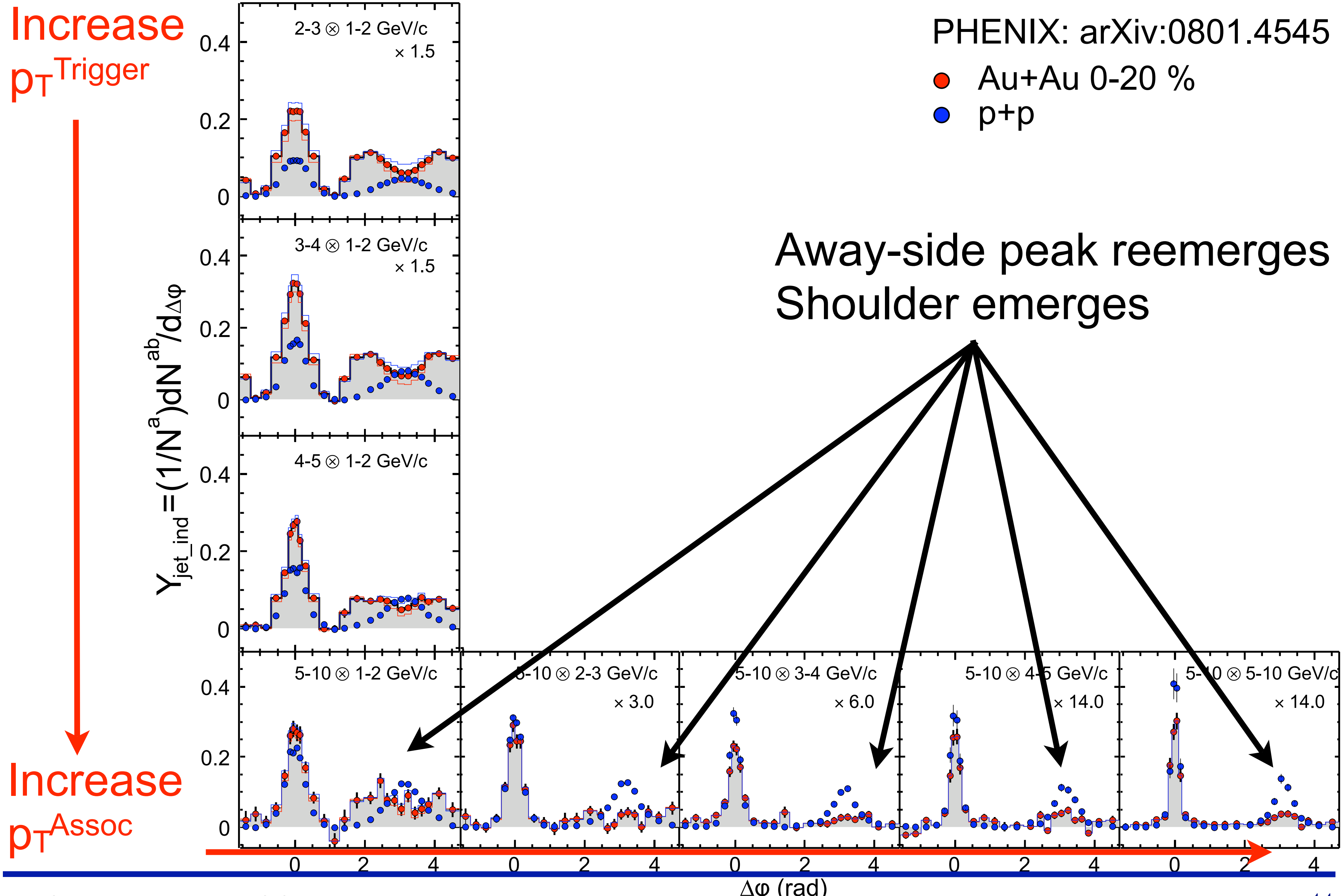
C.Y. Wong hep-ph:0712.3282

All qualitatively consistent with the features of the ridge

p_T systematics of di-hadron correlations



p_T systematics of di-hadron correlations

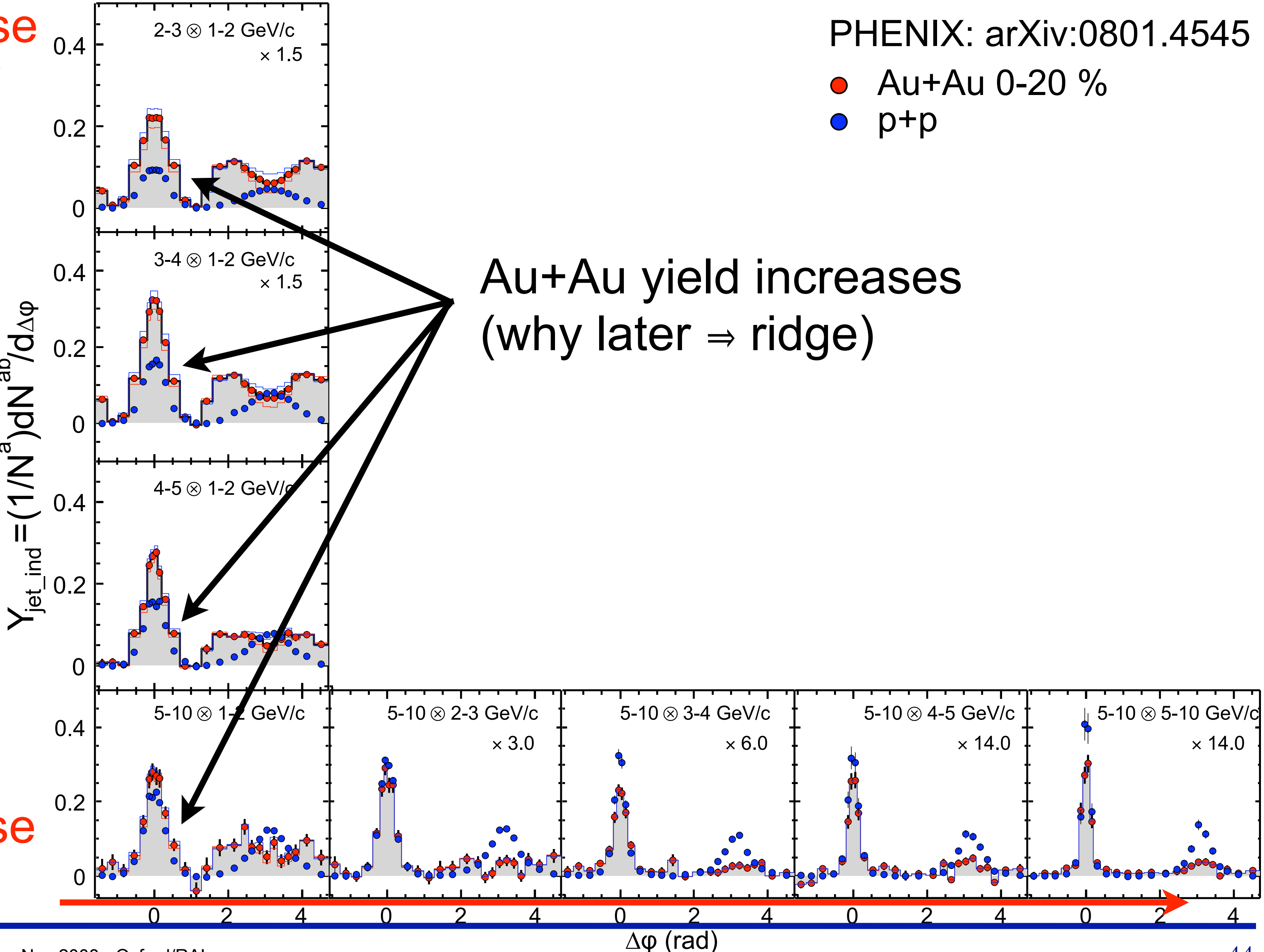


p_T systematics of di-hadron correlations

Increase $p_T^{Trigger}$

Increase p_T^{Assoc}

PHENIX: arXiv:0801.4545

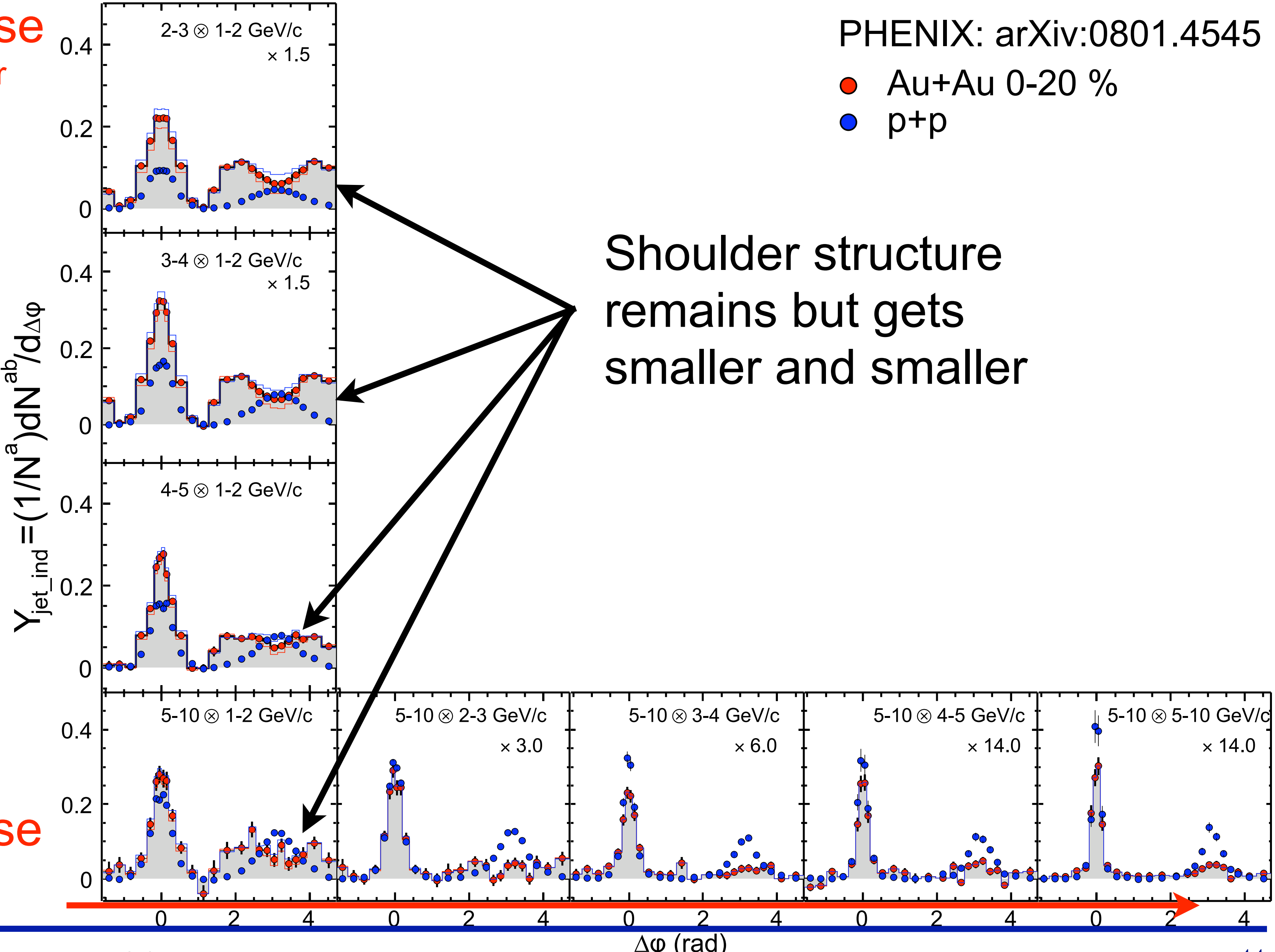


Au+Au yield increases (why later ⇒ ridge)

p_T systematics of di-hadron correlations

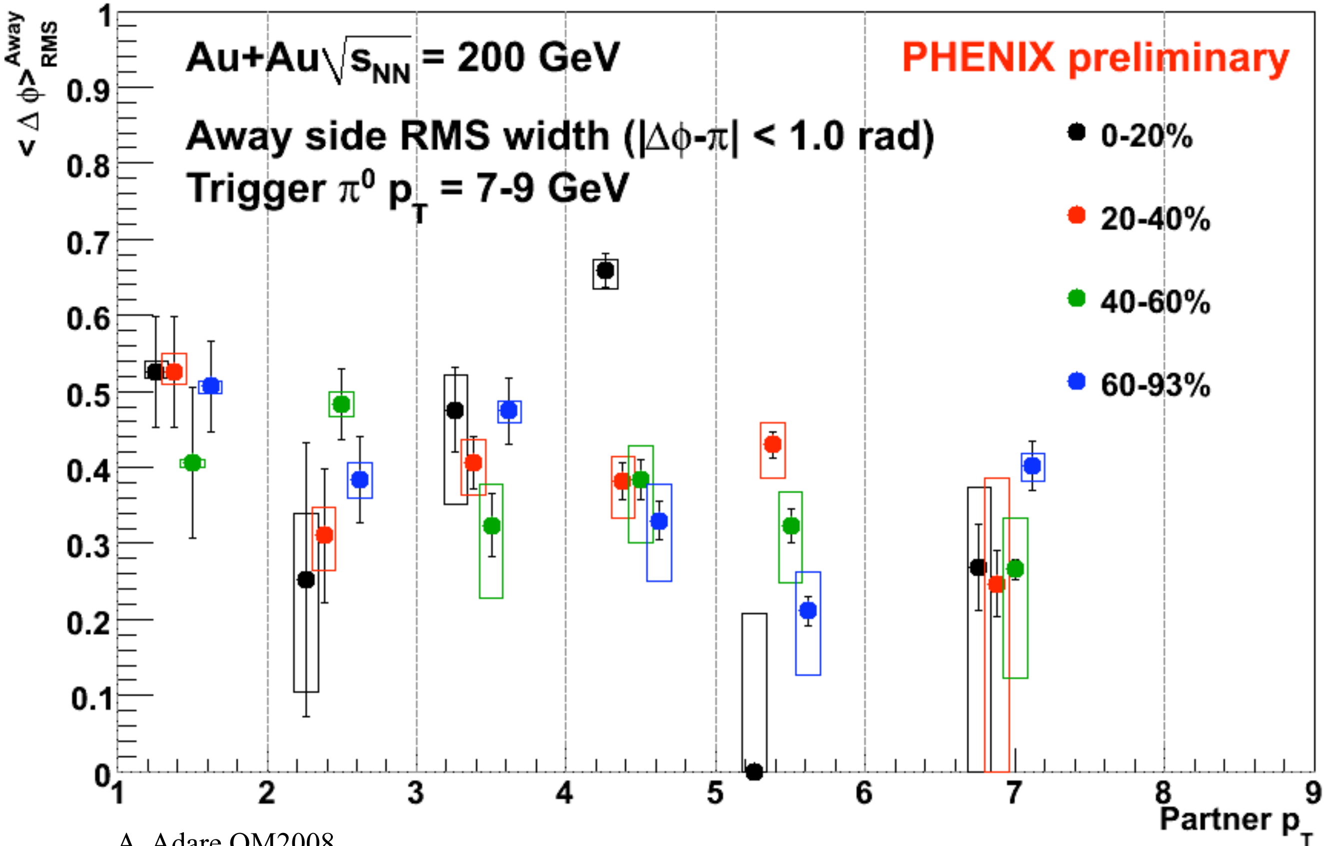
Increase $p_T^{Trigger}$

Increase p_T^{Assoc}



Shoulder structure remains but gets smaller and smaller

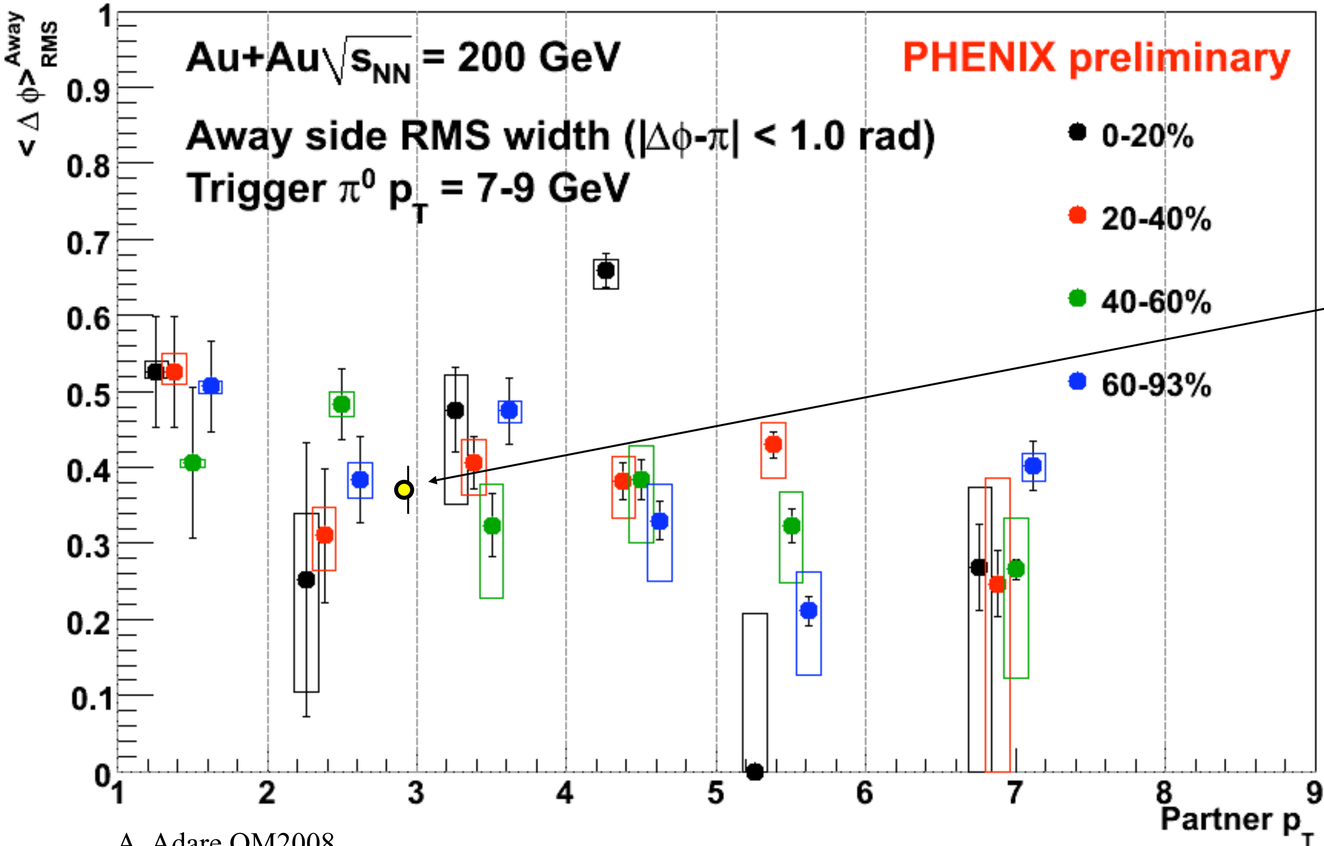
High p_T triggered away side RMS width



A. Adare QM2008

RMS Width - centrality independent

High p_T triggered away side RMS width



A. Adare QM2008

p+p π^0-h:

p_T^{trig} = 6.5-8 GeV/c

p_T^{assoc} = 1.4-5 GeV/c

RMS = 0.350 ± 0.03

PHENIX:

Phys Rev D 74 072002

RMS Width - centrality independent

Consistent with p+p data

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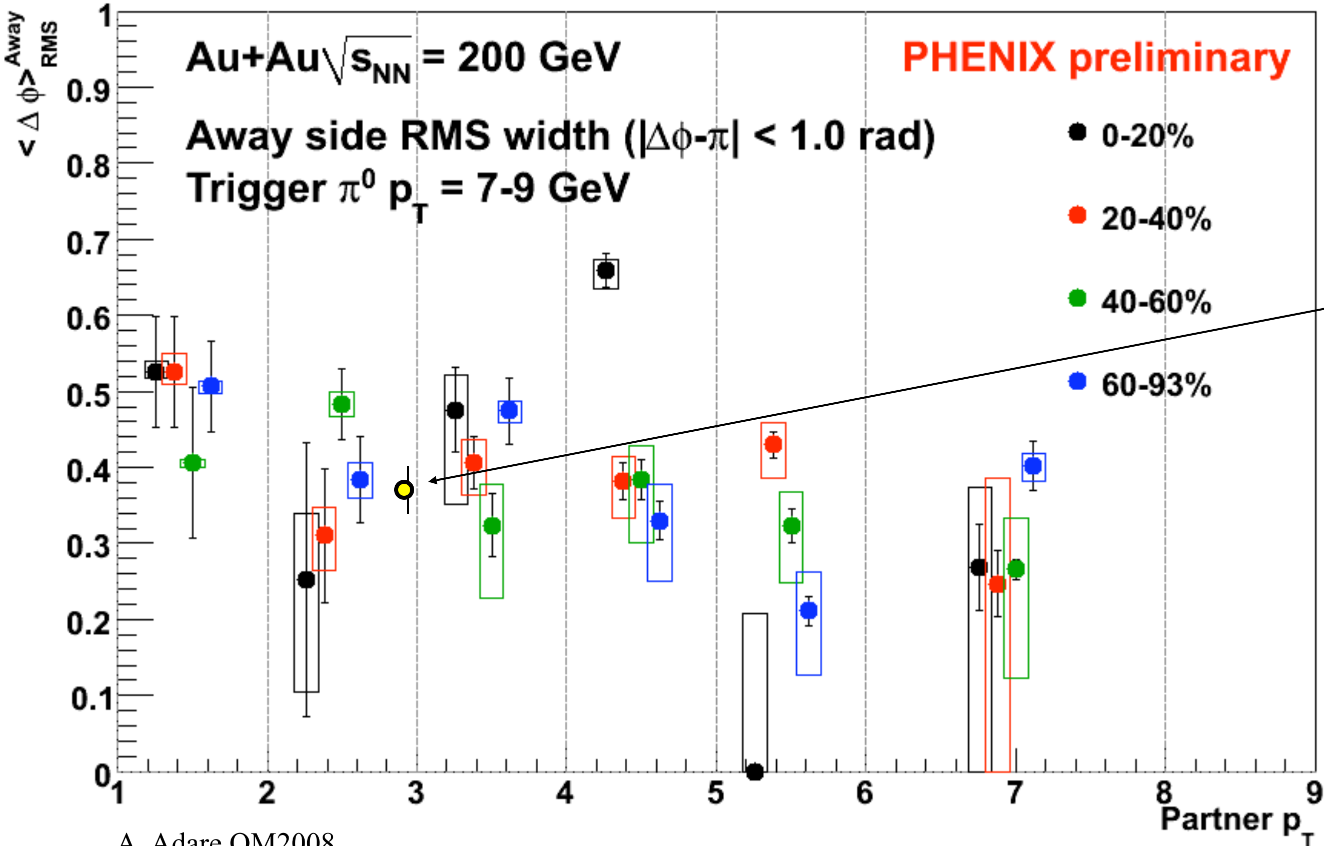

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PHENIX: Phys Rev D 74 072002

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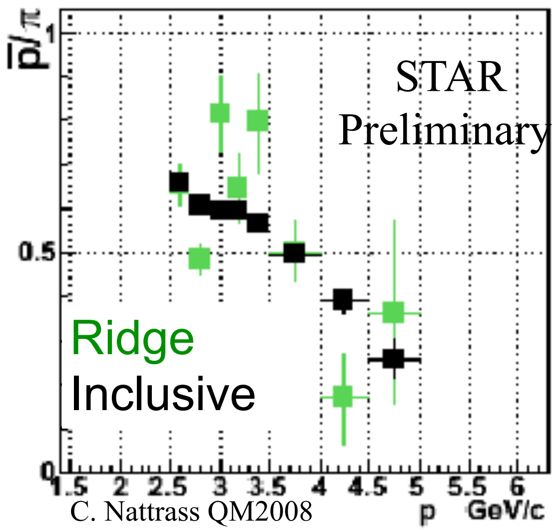
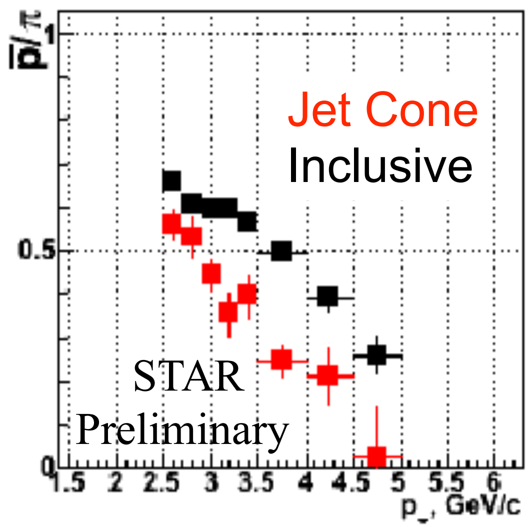
Vacuum fragmentation?

Composition of ridge and shoulders





ridge ratio ~ inclusive ratio
> jet ratio

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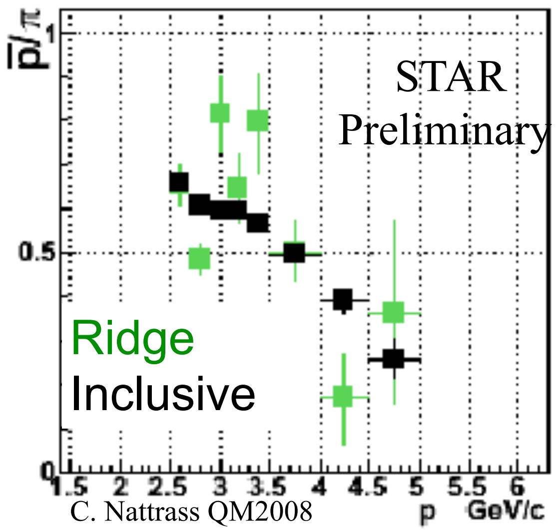
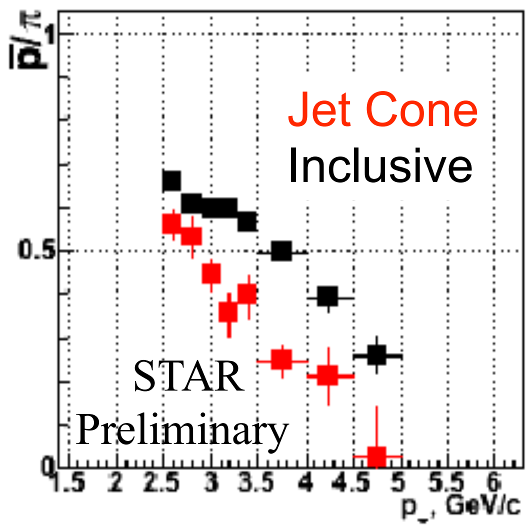
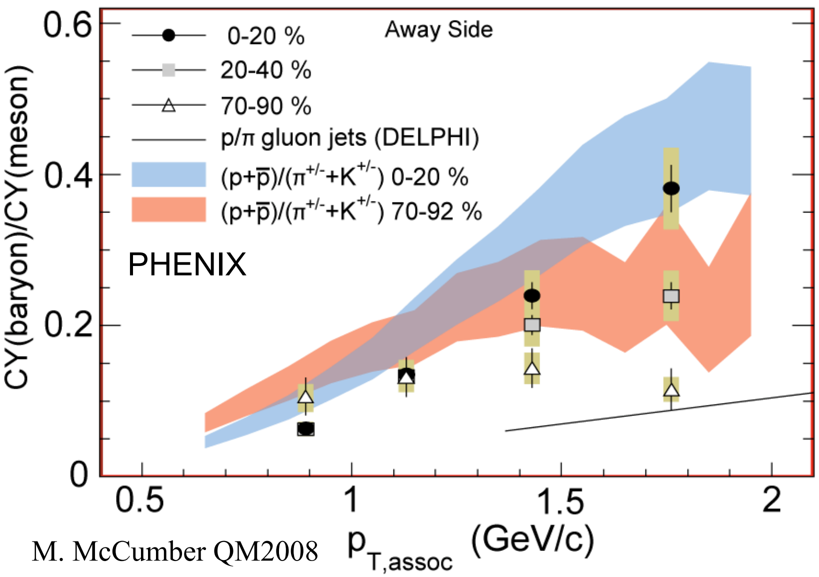




ridge ratio ~ inclusive ratio > jet ratio

shoulder ratio ~ inclusive ratio > jet ratio



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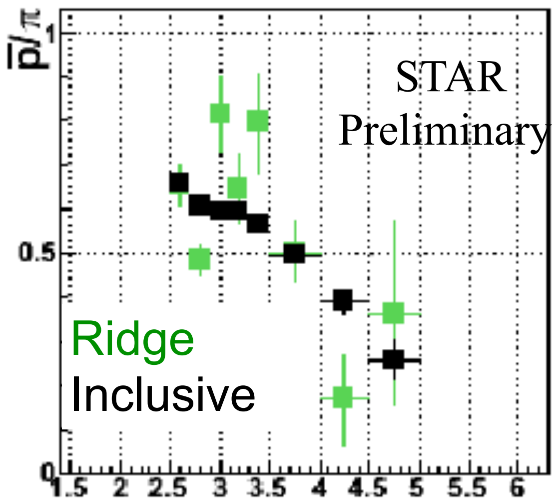
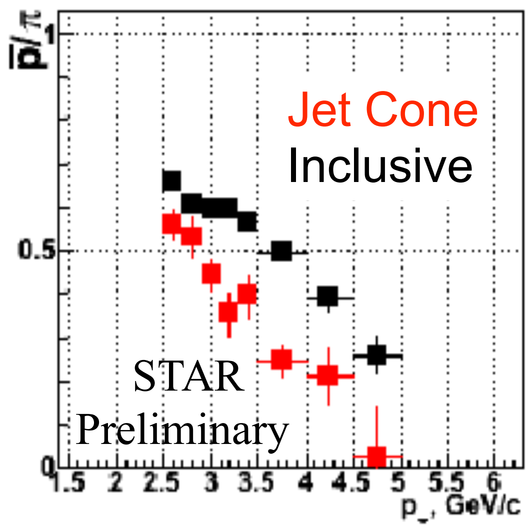


C. Nattrass QM2008



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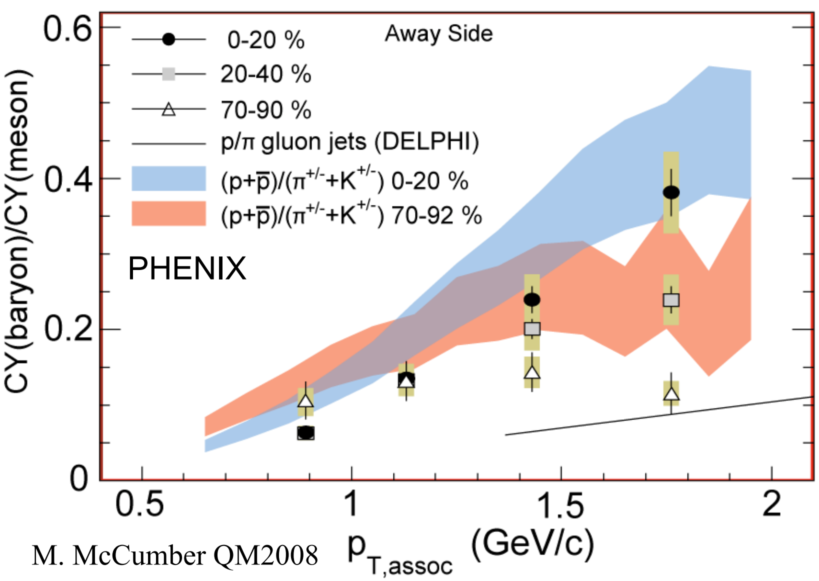
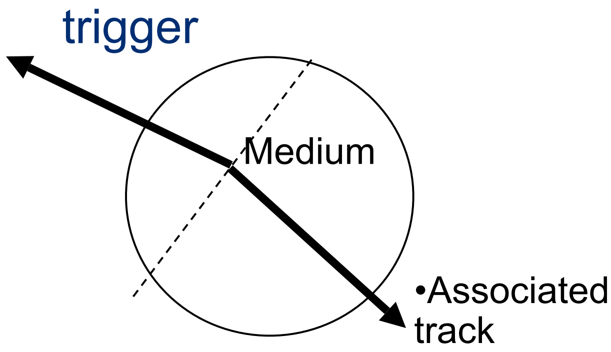
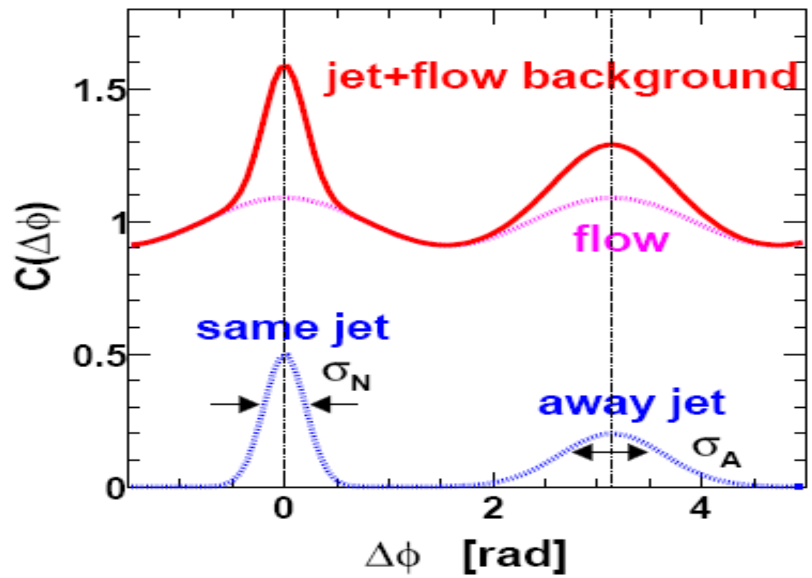


M. McCumber QM2008

Ridge and Shoulder similar properties
NOT vacuum fragmentation

Energy lost by jet partons seems to be re-distributed into the medium and freezes out in similar fashion





$$C(\Delta\phi) \equiv \frac{Y_{same}(\Delta\phi)}{Y_{mixed}(\Delta\phi)} \times \frac{\int Y_{mixed}(\Delta\phi)d\phi}{\int Y_{same}(\Delta\phi)d\phi}$$

$$C(\Delta\phi) \equiv b_0\left[1 + 2\left\langle v_2^{assoc}\right\rangle\left\langle v_2^{trig}\right\rangle \cos(2\Delta\phi)\right] + J(\Delta\phi)$$

•Trigger

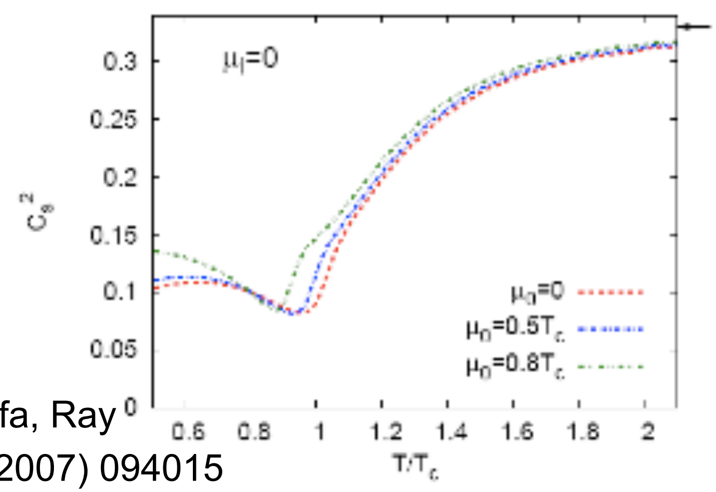
$$\frac{c_s}{v_{parton}} = \cos(\theta_M)$$

$$c_s^{\ 2} = \frac{\partial p}{\partial \varepsilon};\ v_{parton} \approx c$$

•Away-side

- Mach angle depends on speed of sound in medium
  - T dependent
- Angle independent of associated p_T.

•PNJL Model



•Mikherjee, Mustafa, Ray

•Phys. Rev. D75 (2007) 094015

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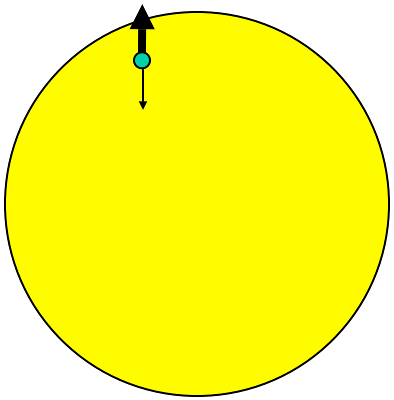

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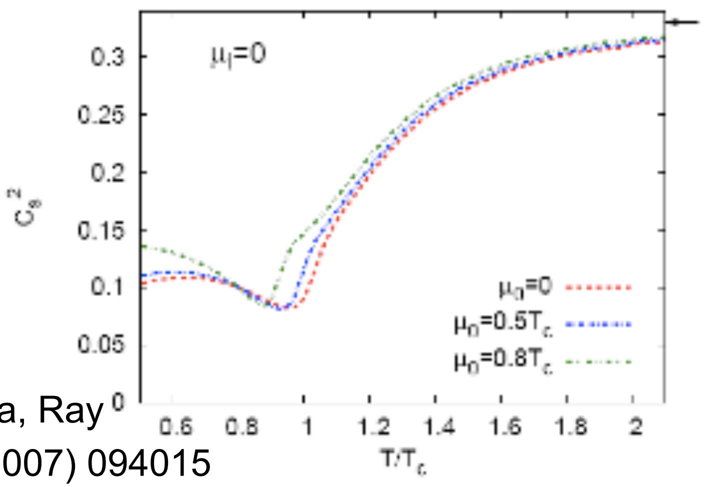

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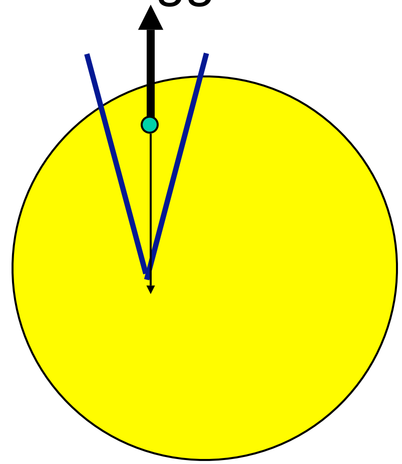

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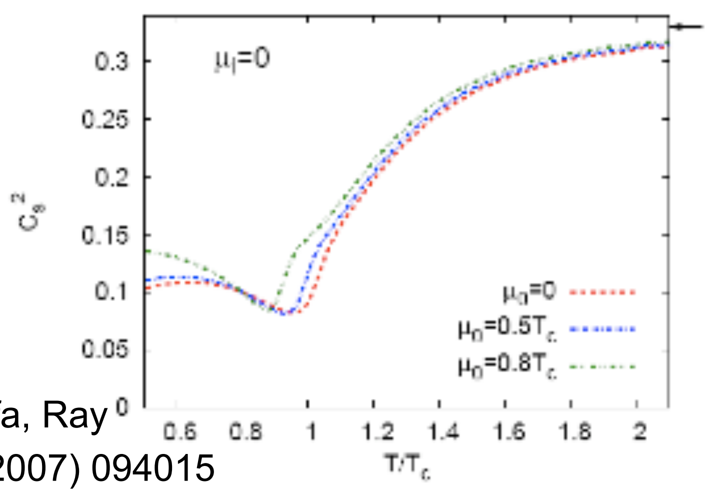
•PNJL Model



•Mikherjee, Mustafa, Ray
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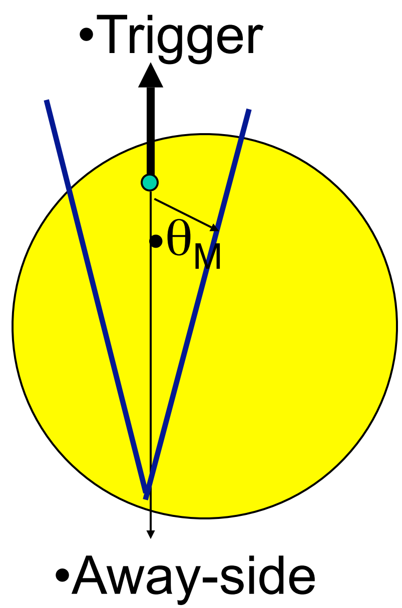

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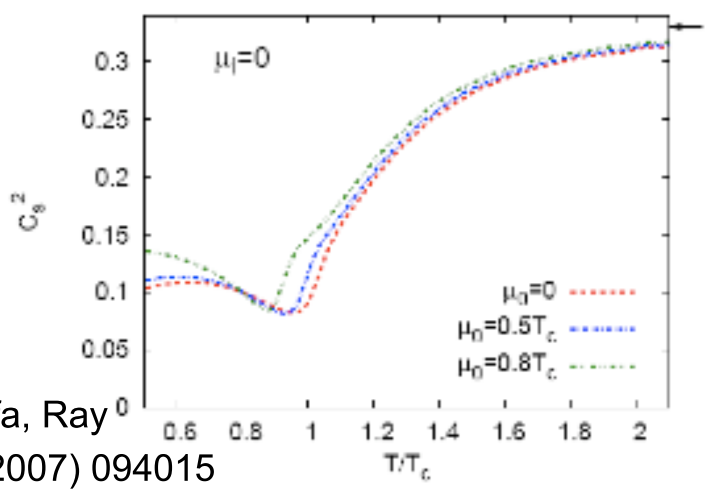

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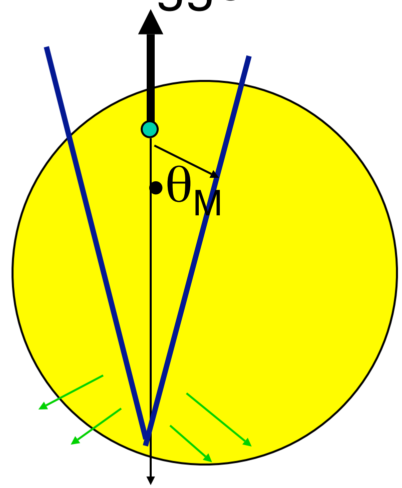

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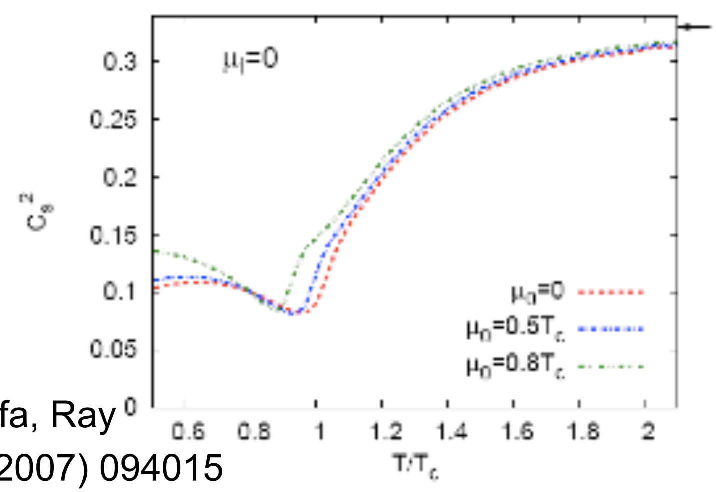

•Mikherjee, Mustafa, Ray

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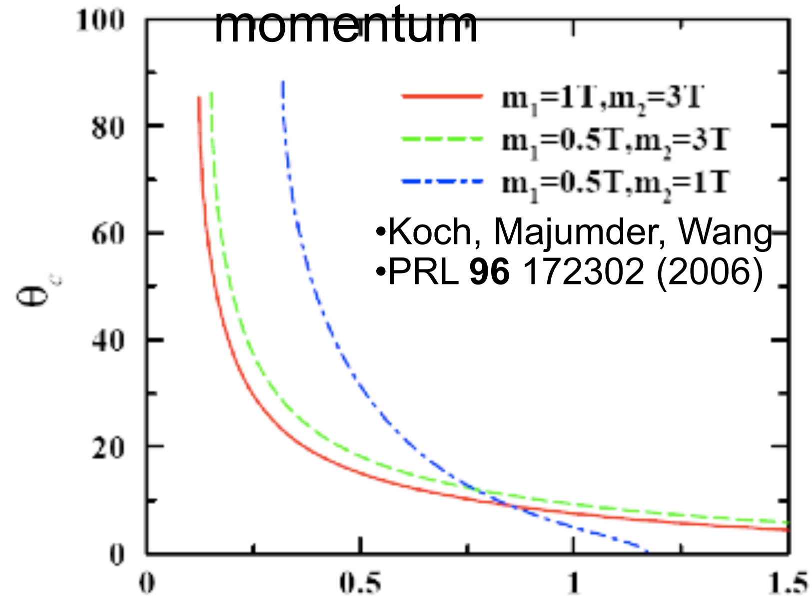
- Čerenkov angle vs
- emitted particle momentum

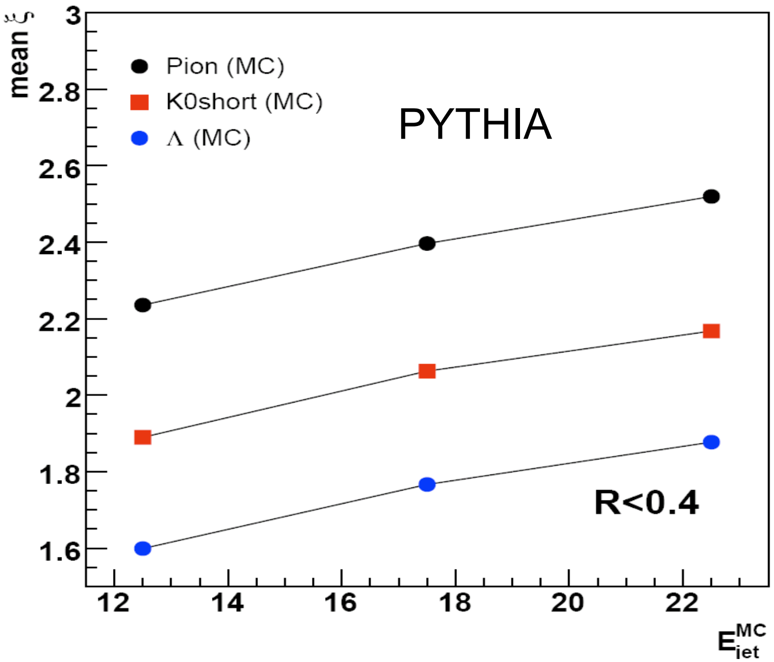


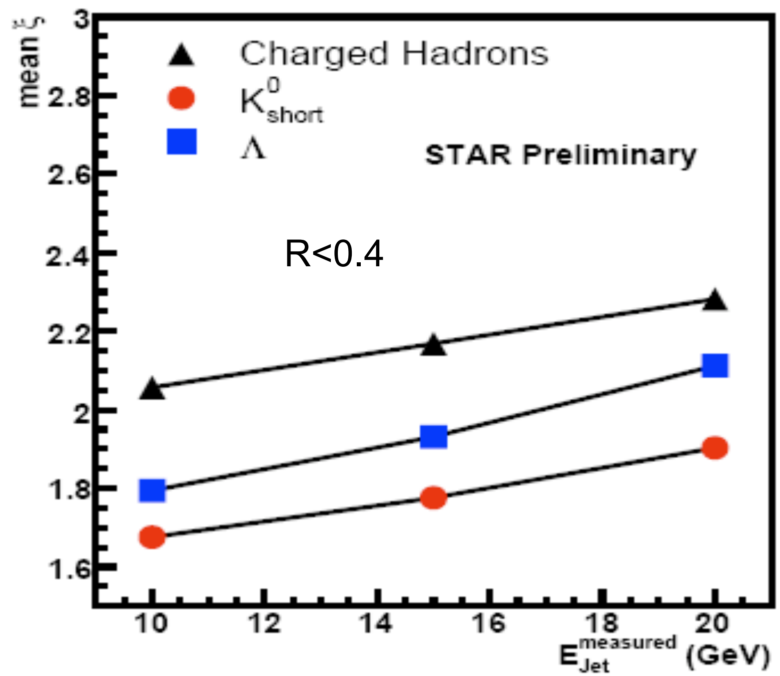
- Koch, Majumder, Wang
- PRL **96** 172302 (2006)

- p (GeV/c)

$$\frac{c_n}{v_{parton}} = \cos(\theta_c) = \frac{c}{n(p)v_{parton}} \approx \frac{1}{n(p)}$$

⟨ξ⟩ for strange hadrons

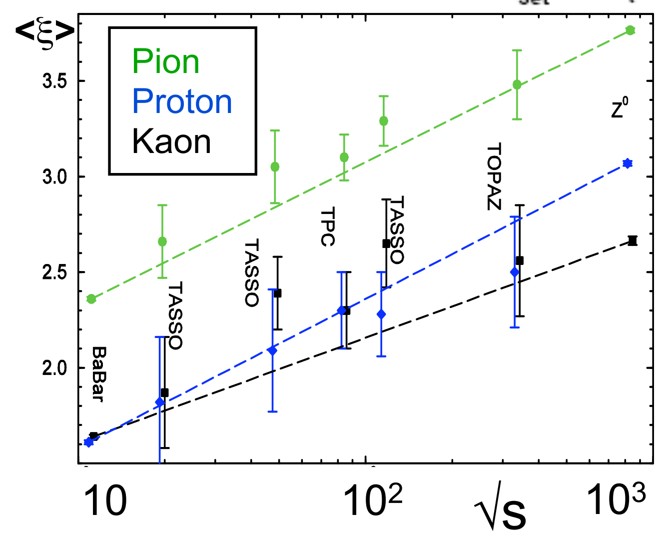




- QCD predicts a <ξ> p mass ordering

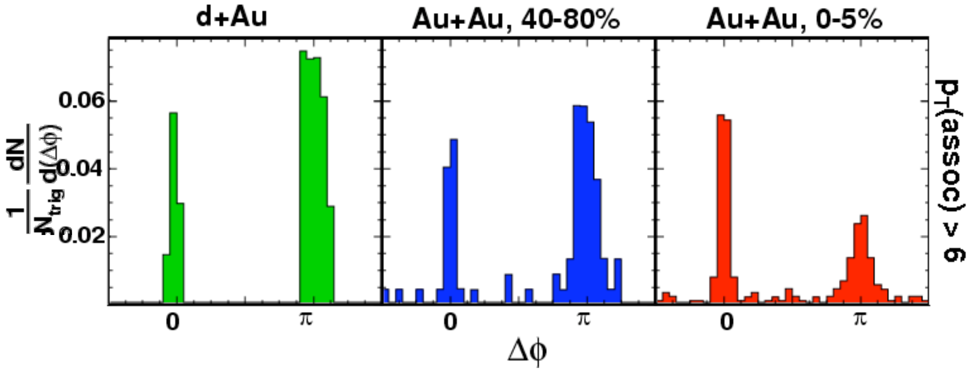
We observe an inversion of K^0_s and Λ

- Similar observation from BABAR for K and p



BABAR preliminary
(Trento 2008 hep-ph/0804.2021)

Observation of di-jets: punch through



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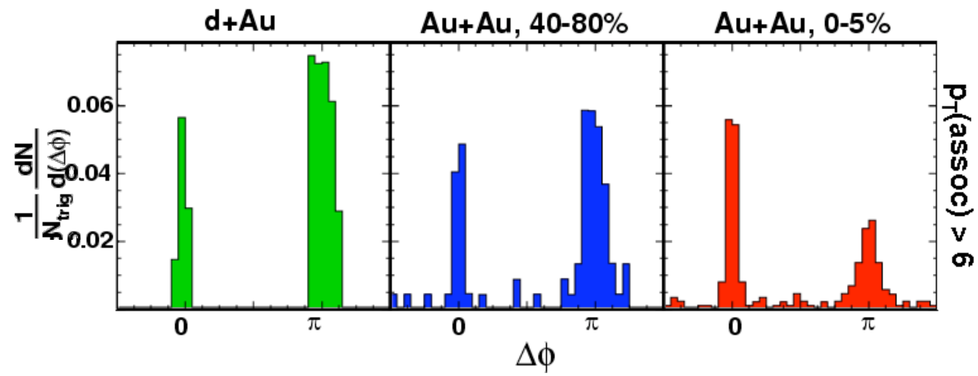

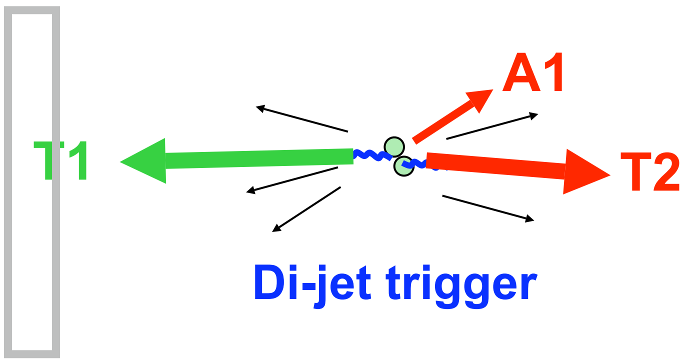

Select di-jets events:
Require T1 and T2 b-to-b

T1: p_T>5GeV/*c* **T2**: p_T>4GeV/*c*

A1: p_T>1.5GeV/*c*

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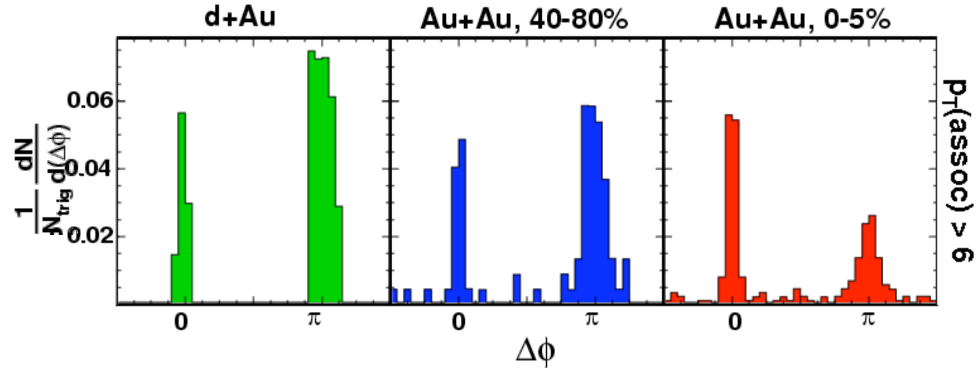

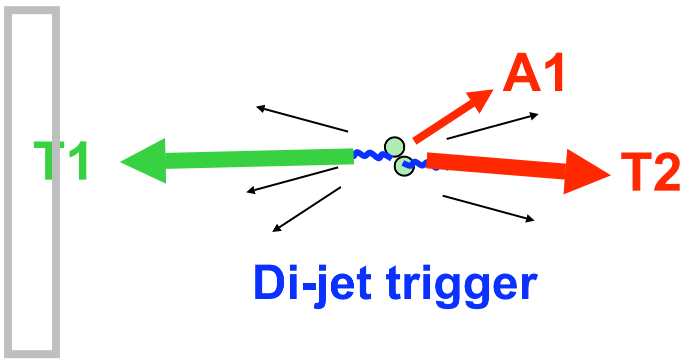

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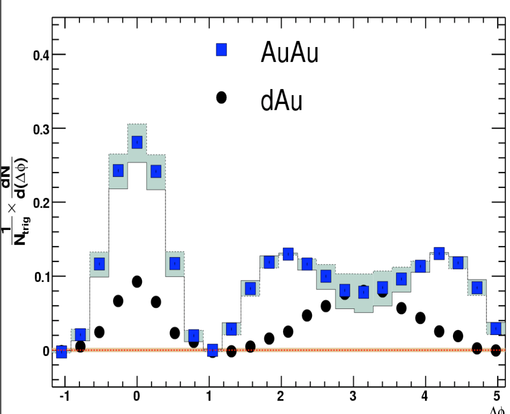
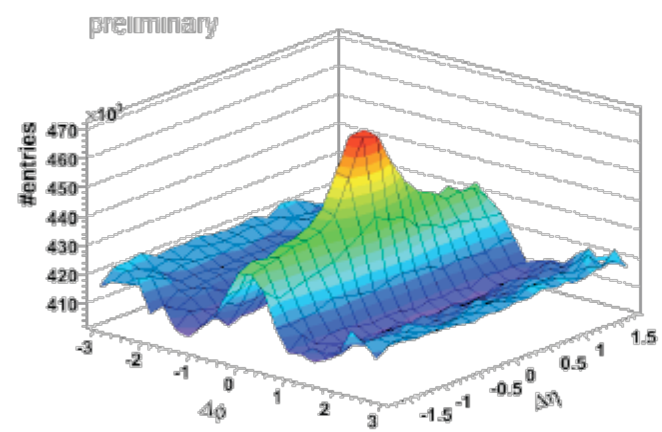
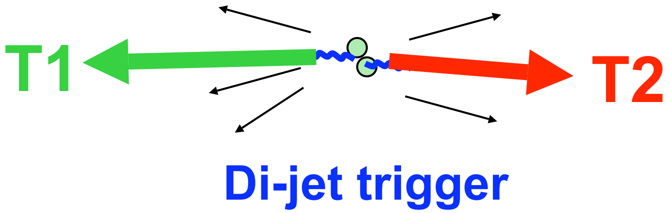


What happens to away-side hump and near-side ridge if we trigger on di-jets ?



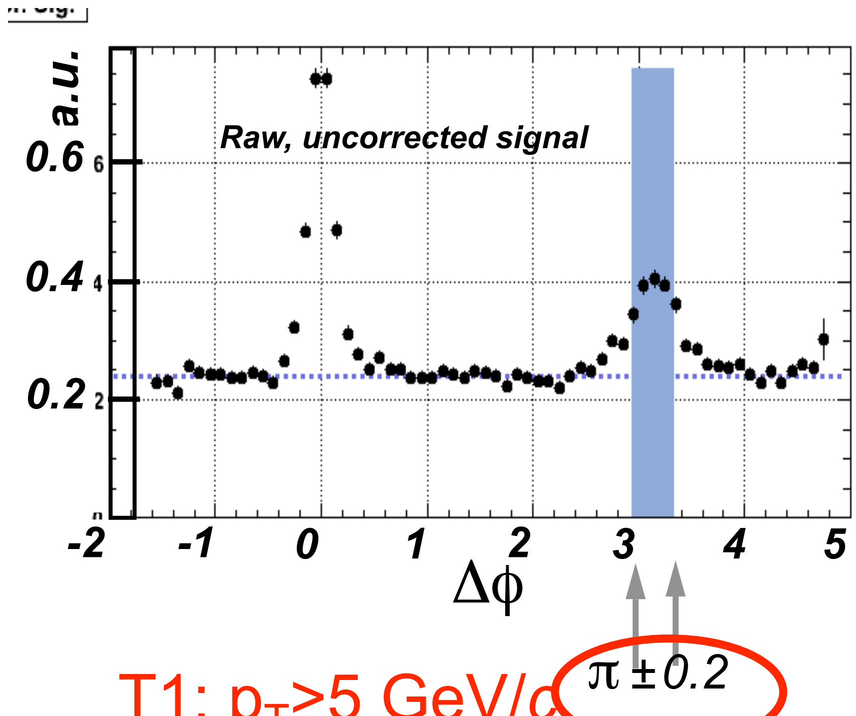
Data analysis: di-jet selection

- Correlation between primary trigger (T1) and "away-jet-axis trigger" (T2).



- Require that the 2 highest p_T particles are back-to-back in ϕ.

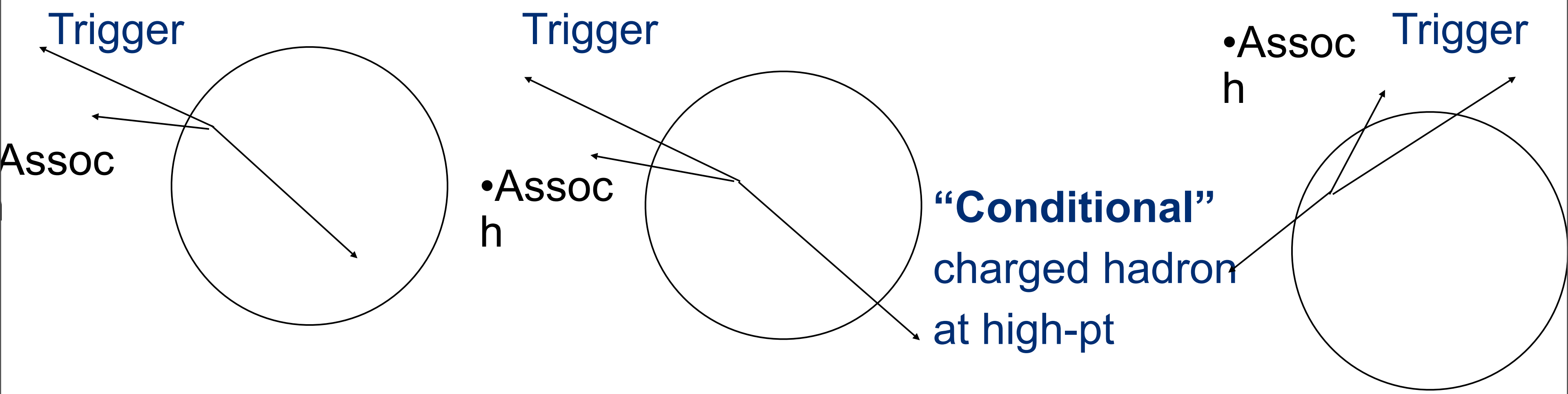
T1T2 correlation



T1: p_T>5 GeV/*c*

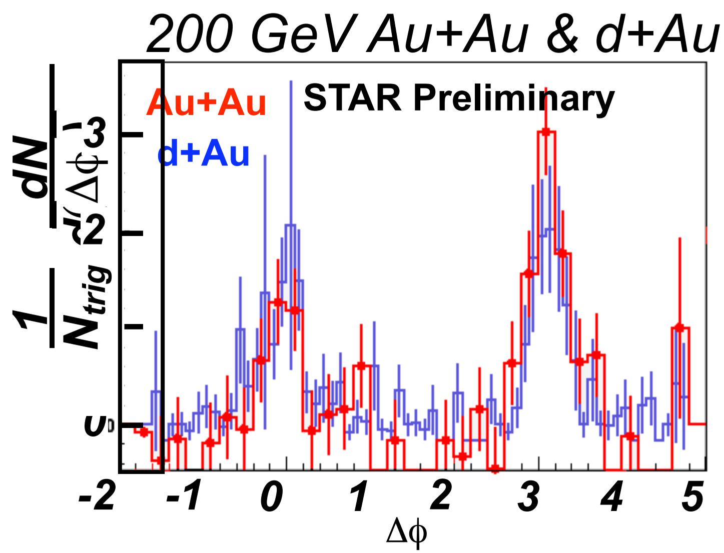
T2: p_T>4 GeV/*c*

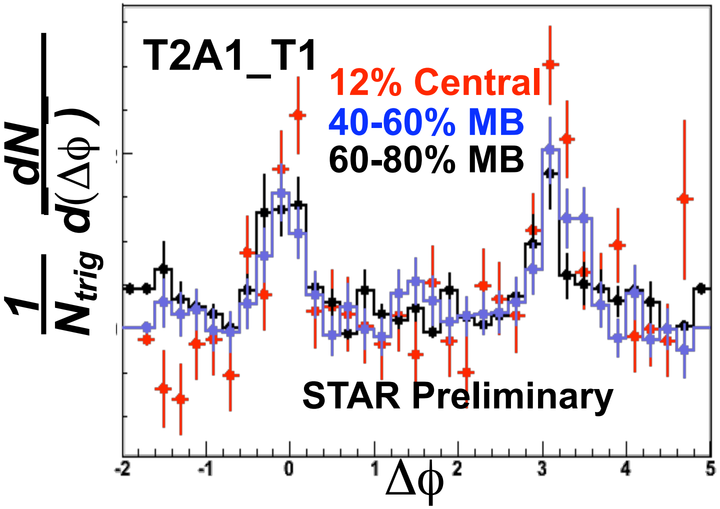
- Hope to shift distribution of hard scattering towards center of medium. Near-side parton travels through more medium



Create path lengths **comparable** in dense medium.

However not always from center could be tangential

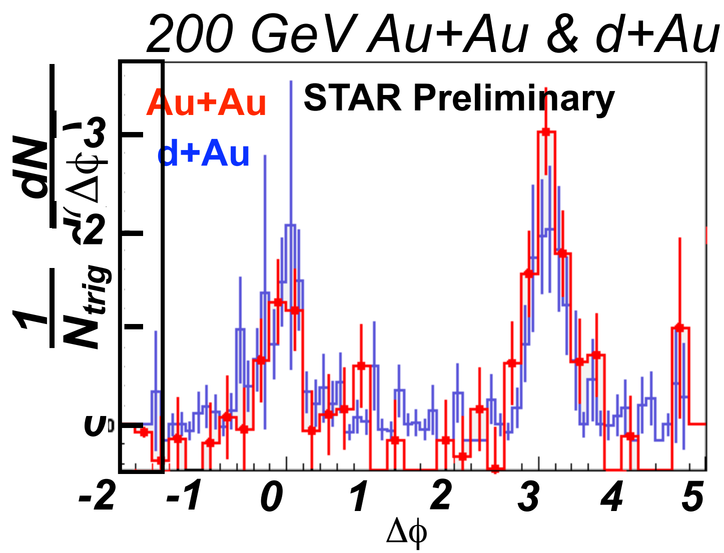


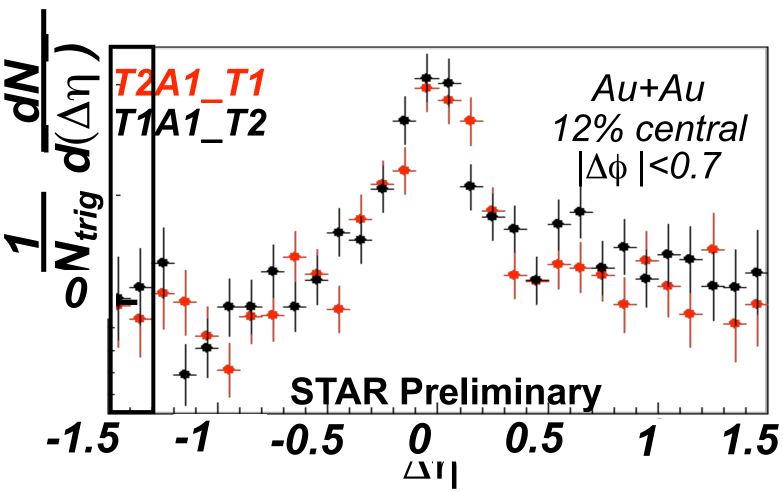


Di-jets are suppressed

Once selected:

- No Away-side suppression
  Au+Au ~ d+Au
- No Away-side shape modification





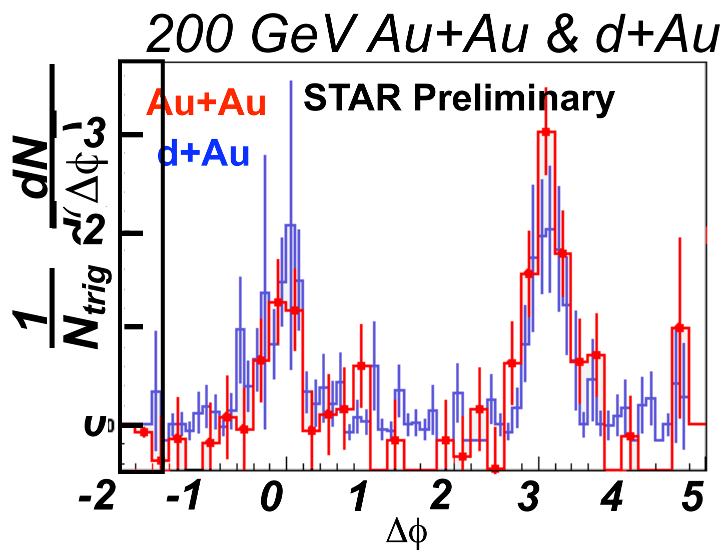
Di-jets are suppressed

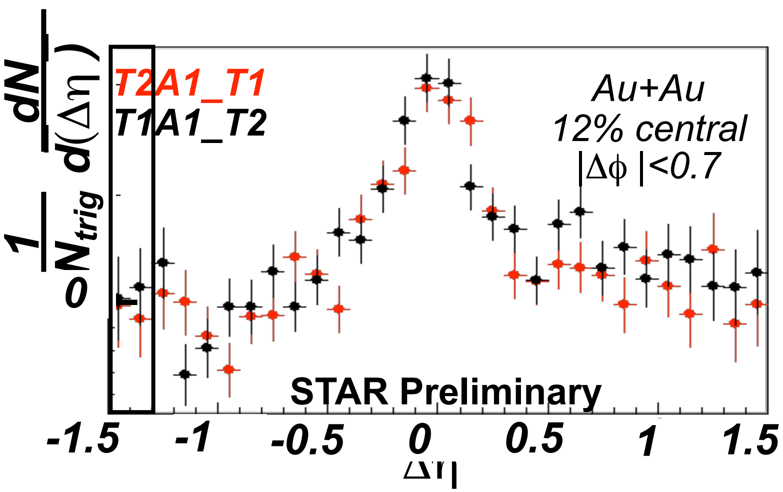
Once selected:

- No Away-side suppression
  Au+Au ~ d+Au

- No Away-side shape modification

- No Ridge





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Di-Jets don’t interact with medium. Tangential jets or punch through without interaction ?