Recent Heavy-Ion Results from RHIC
Evidence for a New State of Matter

Helen Caines - Yale

Low-x Meeting: Crete, Greece

July 2008

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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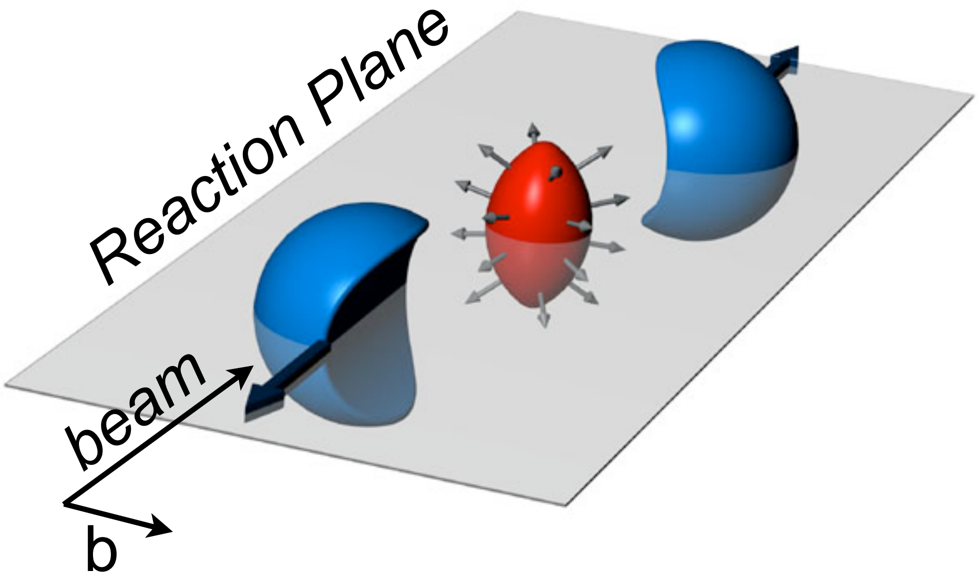
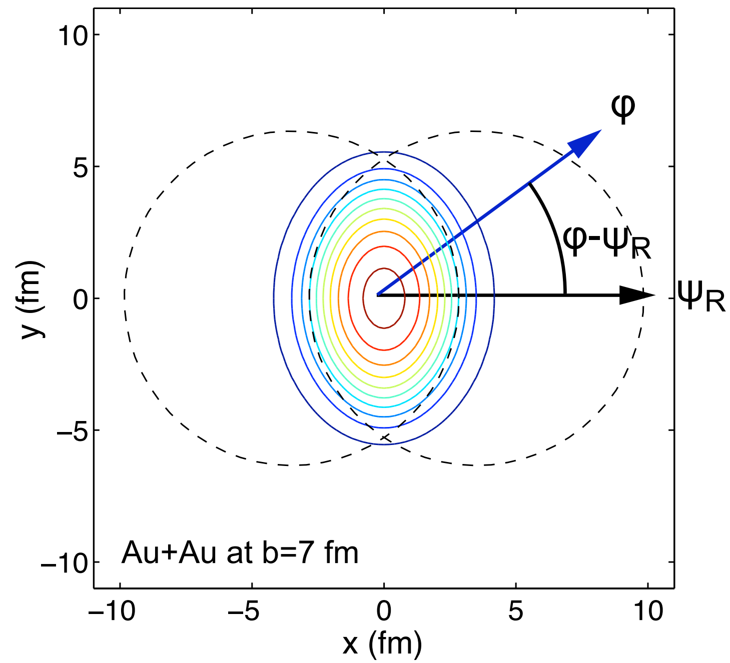
Want to learn more about the properties

Elliptic flow – rapid thermalization





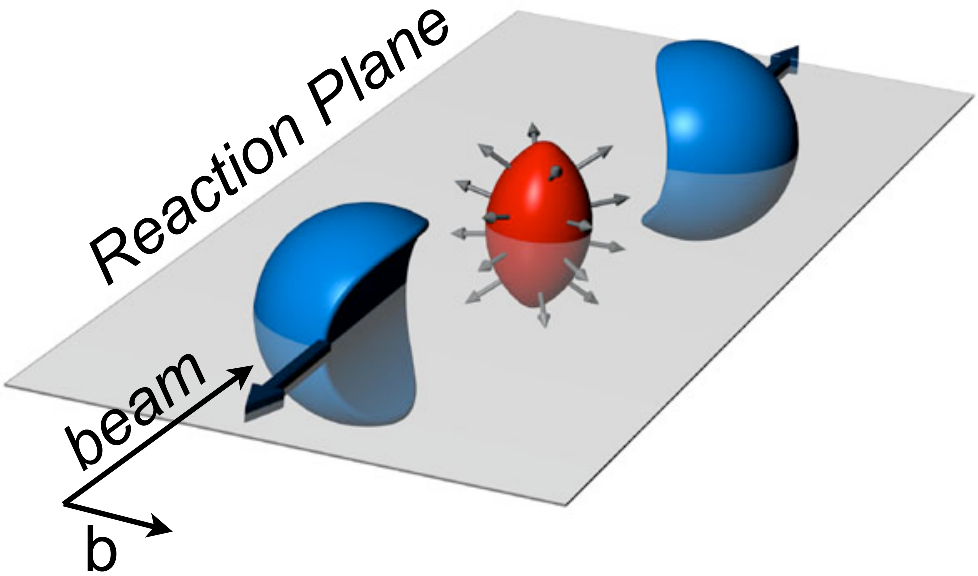
Interactions

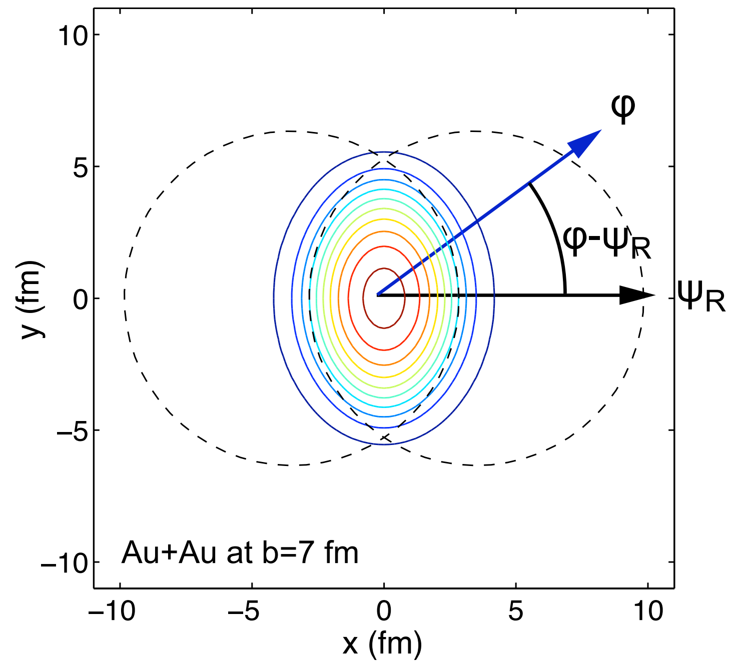
Initial spatial anisotropy → Final momentum anisotropy

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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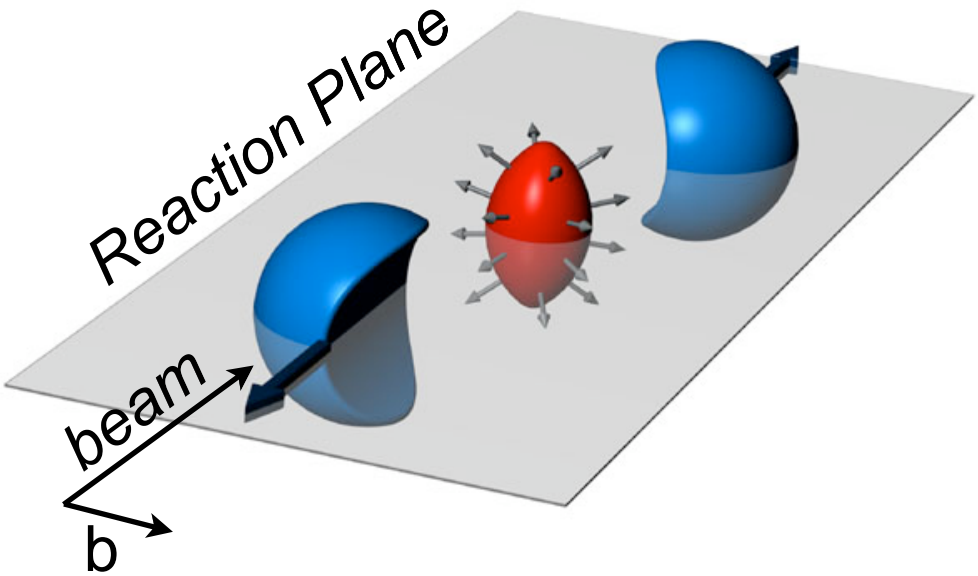

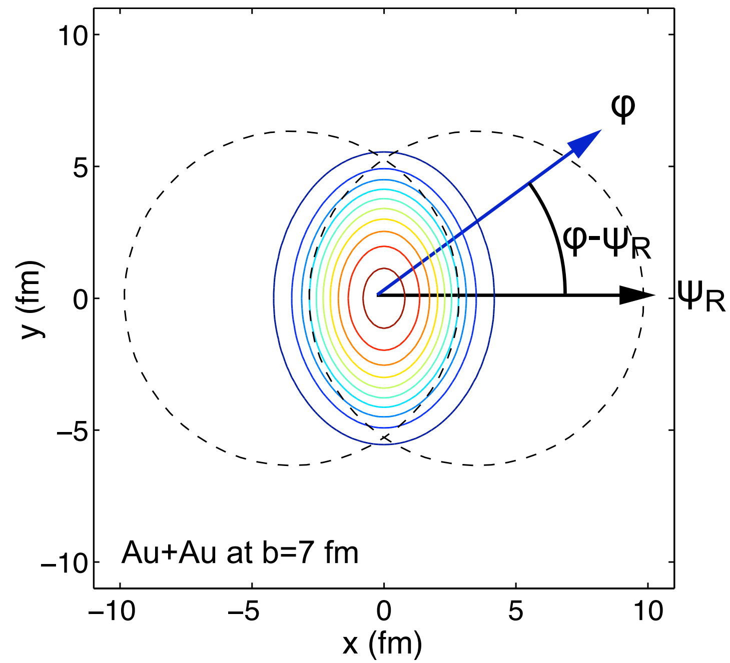

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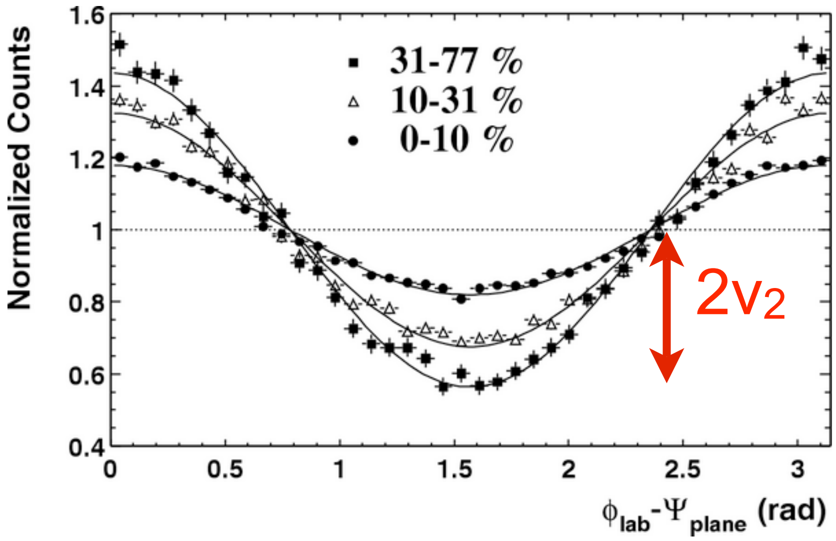
Driving spatial anisotropy vanishes ⇒ self quenching

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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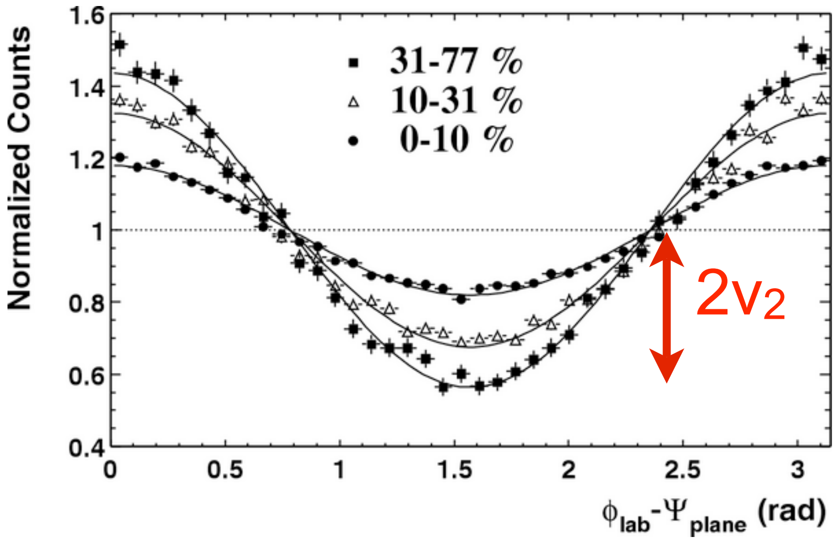

Huge asymmetry found at RHIC

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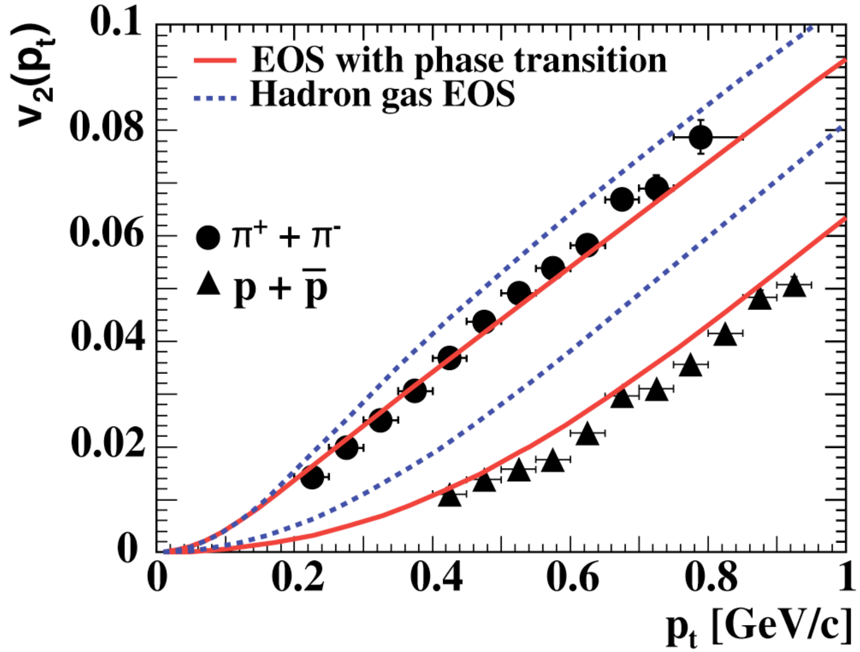
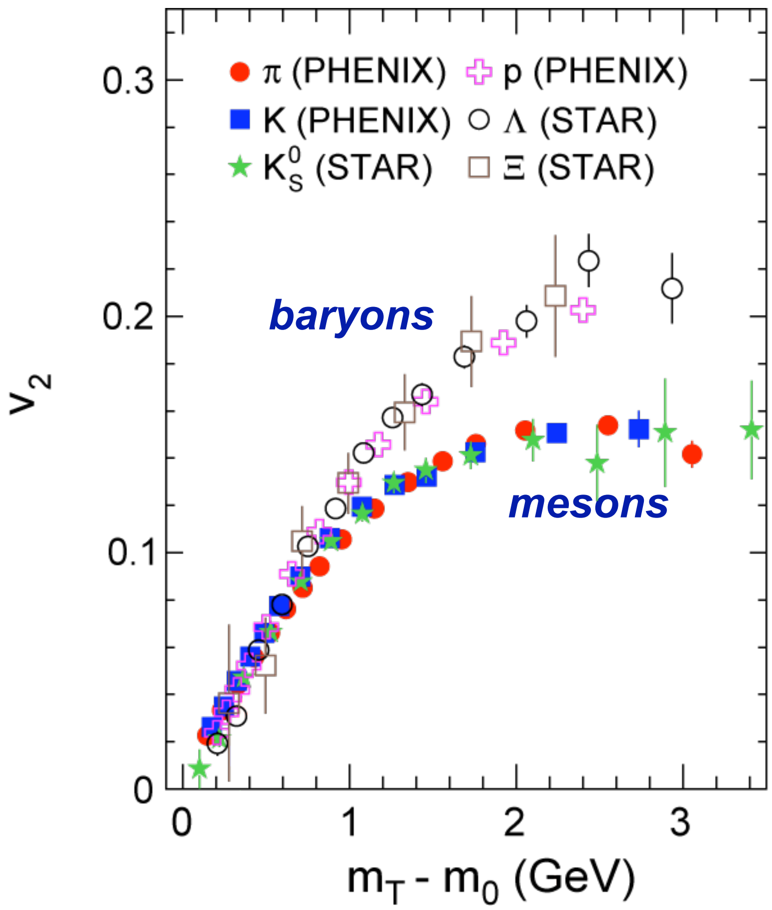
"fine structure" $v_2(p_T)$

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



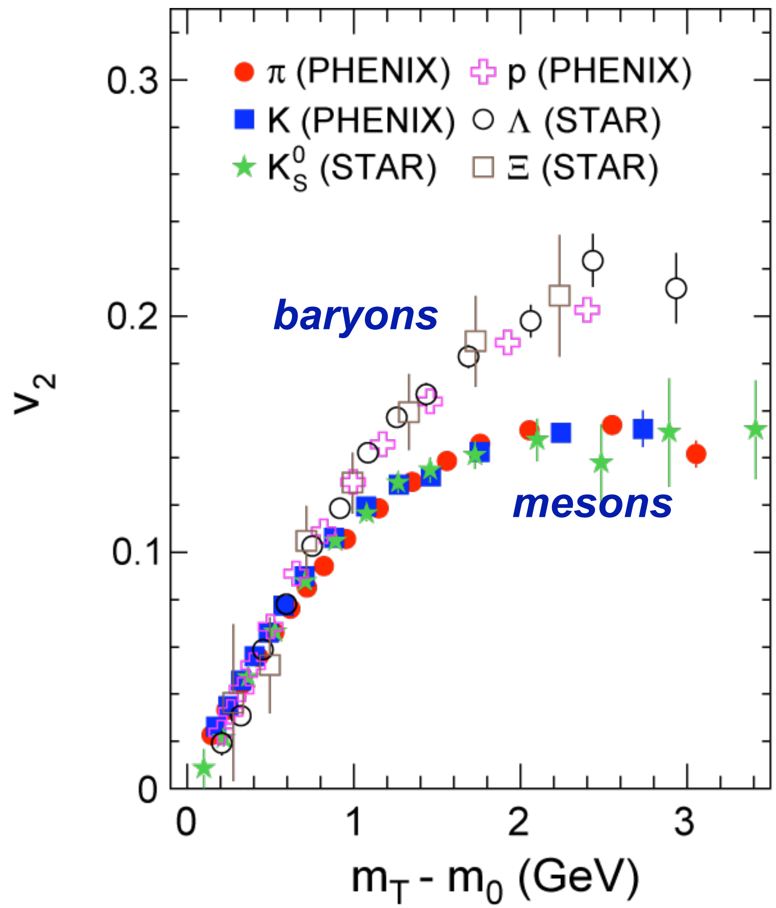
⇒ "perfect liquid"

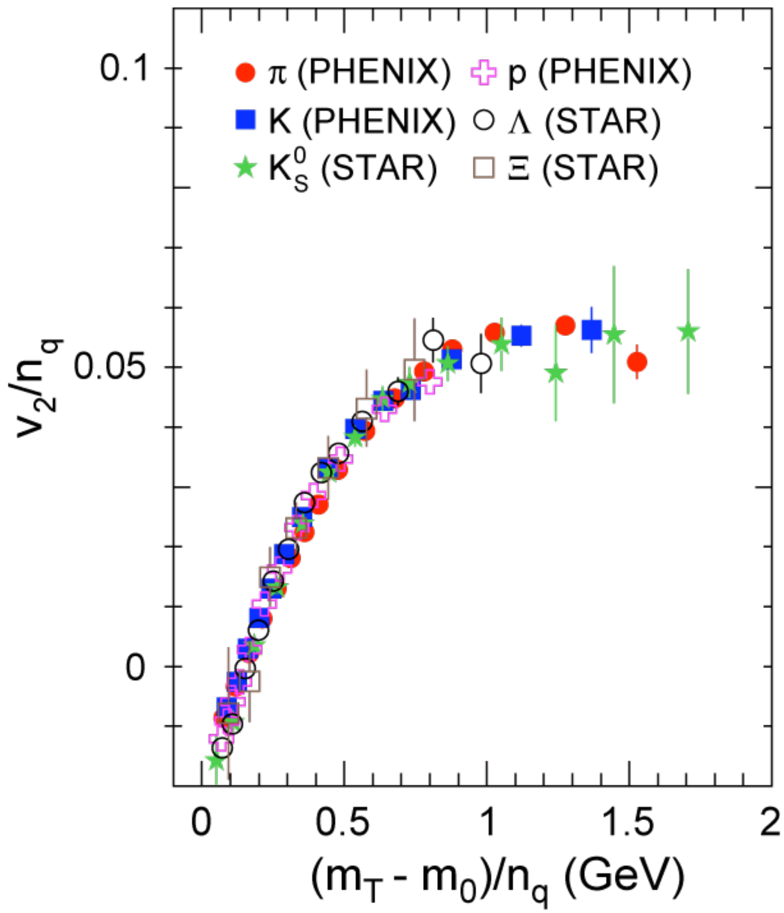
The constituents “flow”



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

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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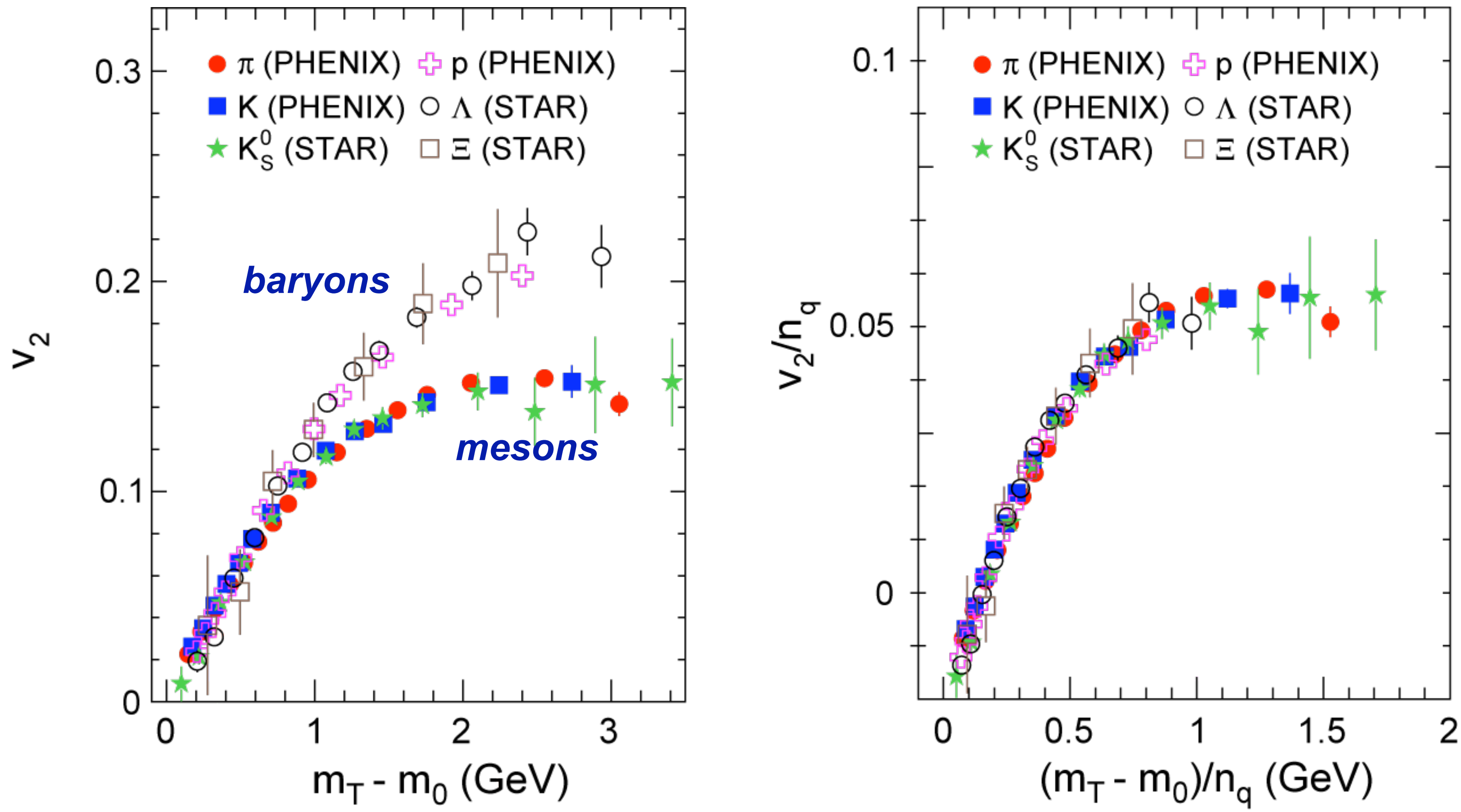
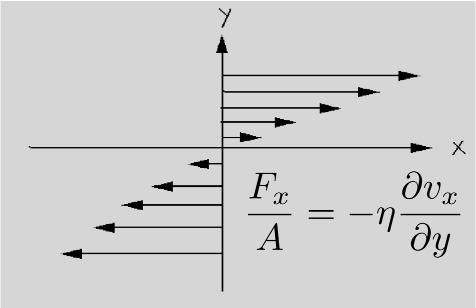


- Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

Constituents of liquid are partons

How perfect is “Perfect” ?

Viscous fluid

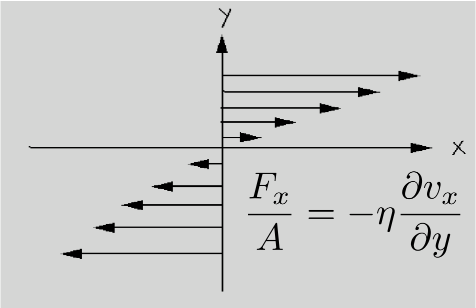


- supports a shear stress
- viscosity η:

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

- small η ⇒ large σ ⇒ strong couplings

How perfect is “Perfect” ?



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Hydrodynamic calculations for RHIC assumed zero viscosity

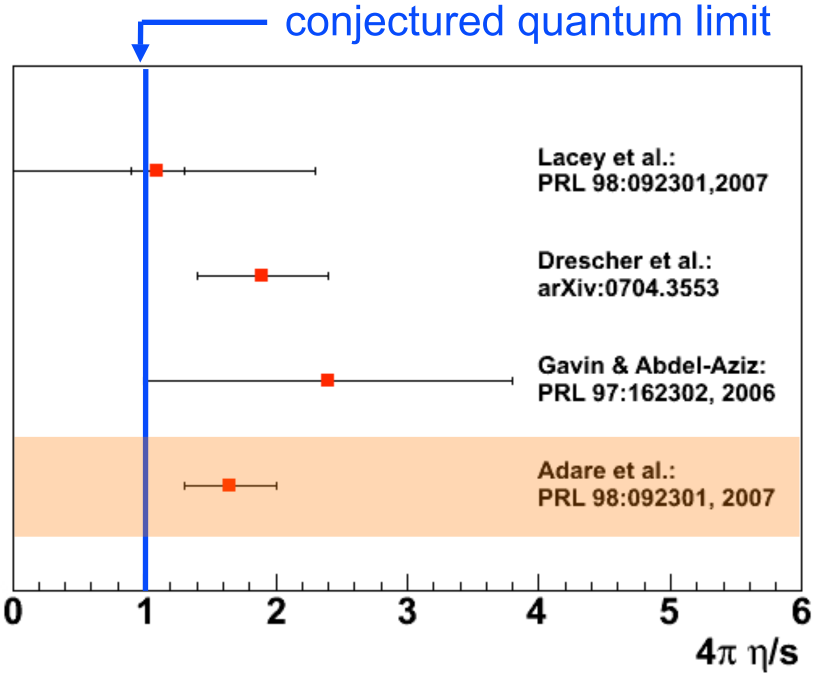
η = 0 ⇒ “perfect fluid”

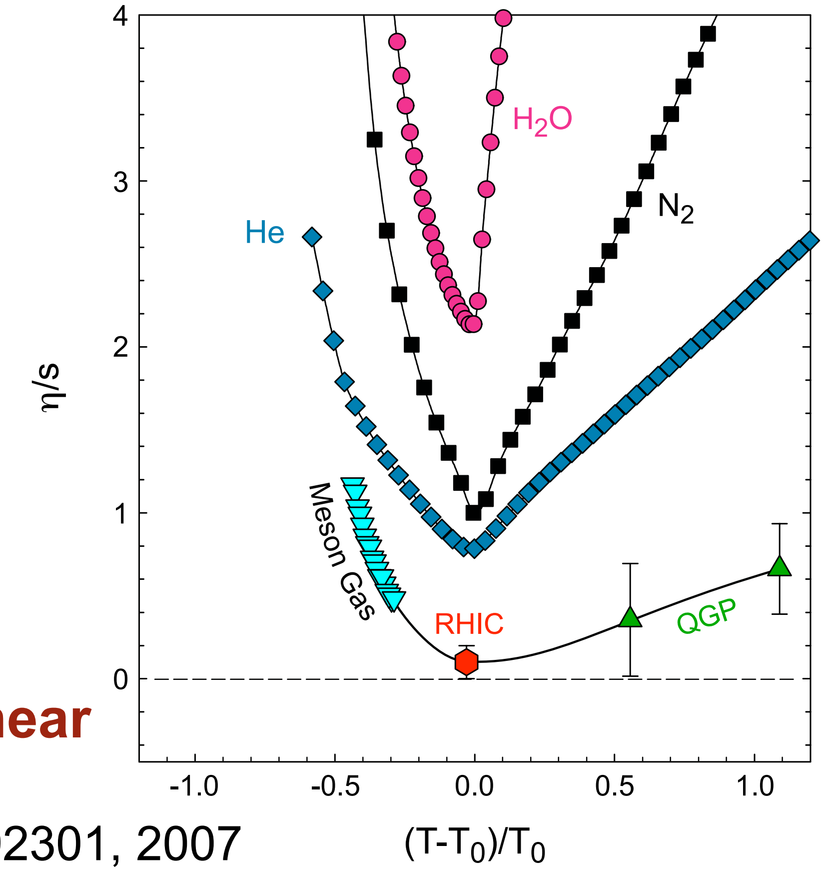
- But there is a (conjectured) quantum limit:
  - derived first in (P. Kovtun, D.T. Son, A.O. Starinets, PRL.94:111601, 2005) motivated by AdS/CFT correspondence

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

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

What is η/s at RHIC ?





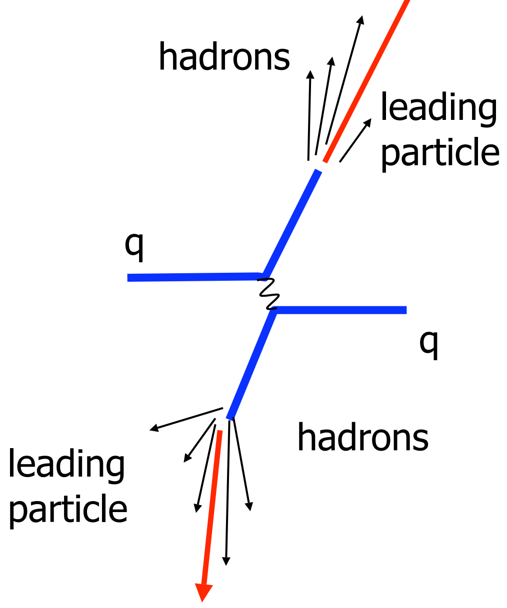
Observables that are sensitive to shear

- 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



Probing the medium - Jet production

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

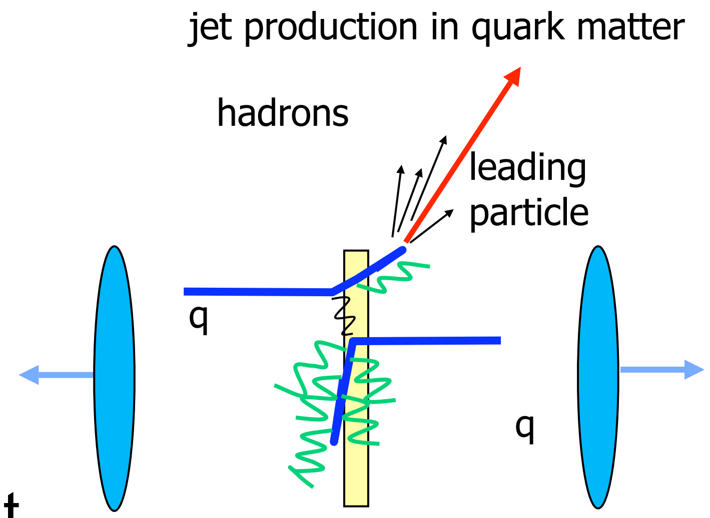
Direct interaction with partonic phases of the reaction

Use “jets” as probes at RHIC

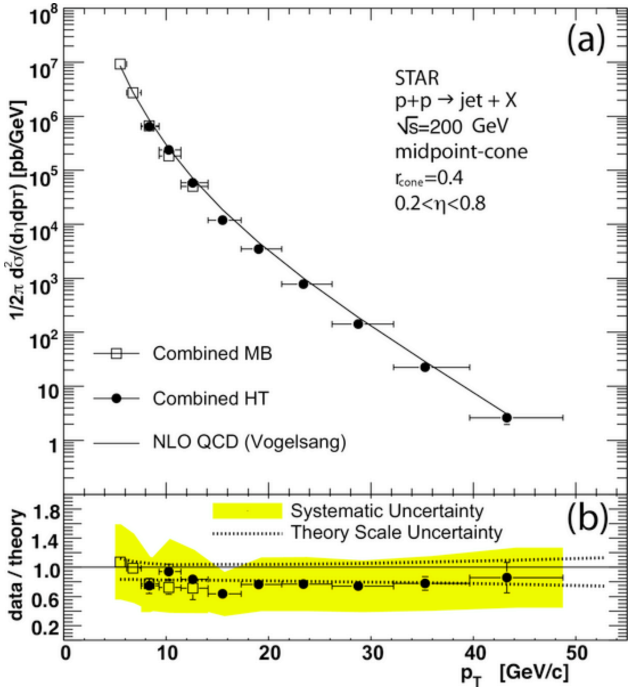
From p+p

- Have a known jet rate
- Have a known energy

Use suppression pattern to learn about medium



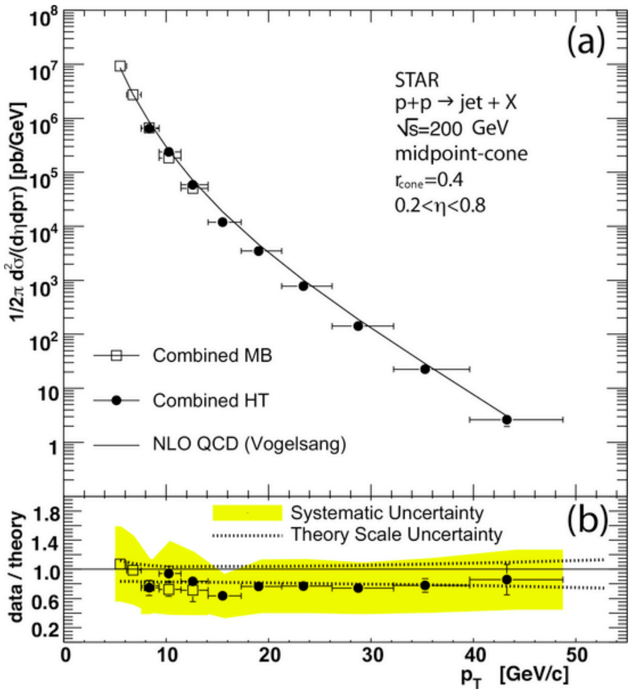
Jets – a calibrated probe?



STAR : PRL 97 (2006) 252001

Jet production in p+p understood in pQCD framework

Jets – a calibrated probe?



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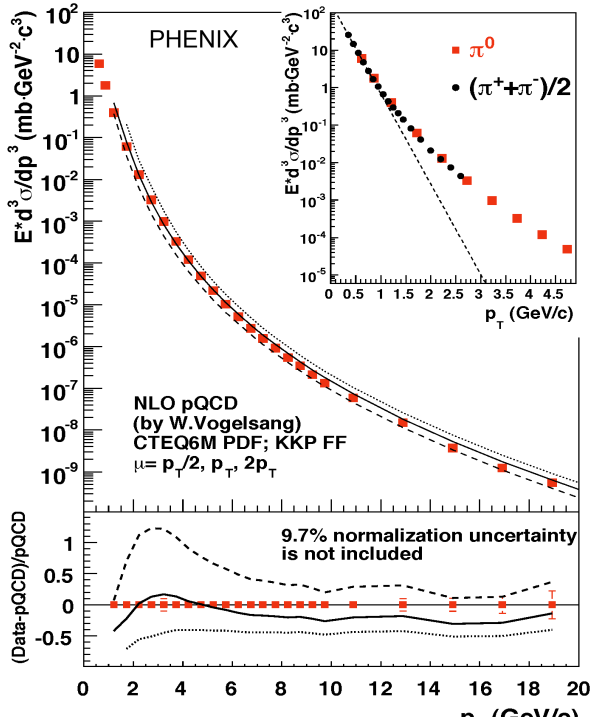
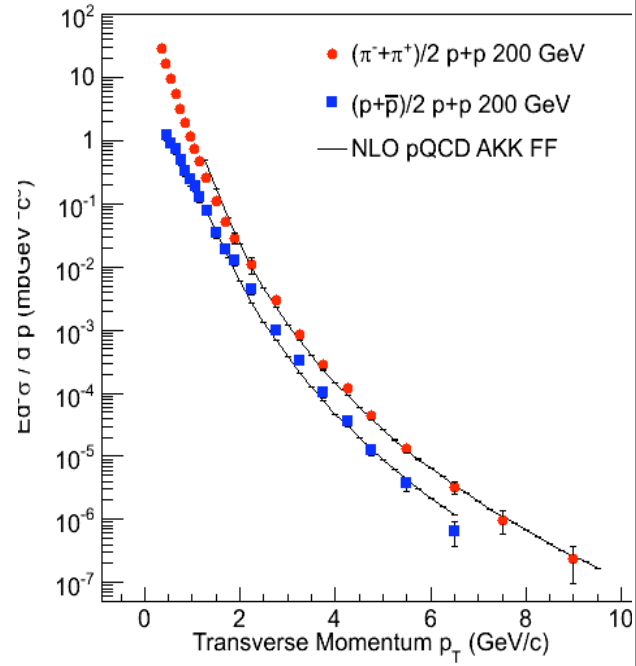


K.Reygers QM2008



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

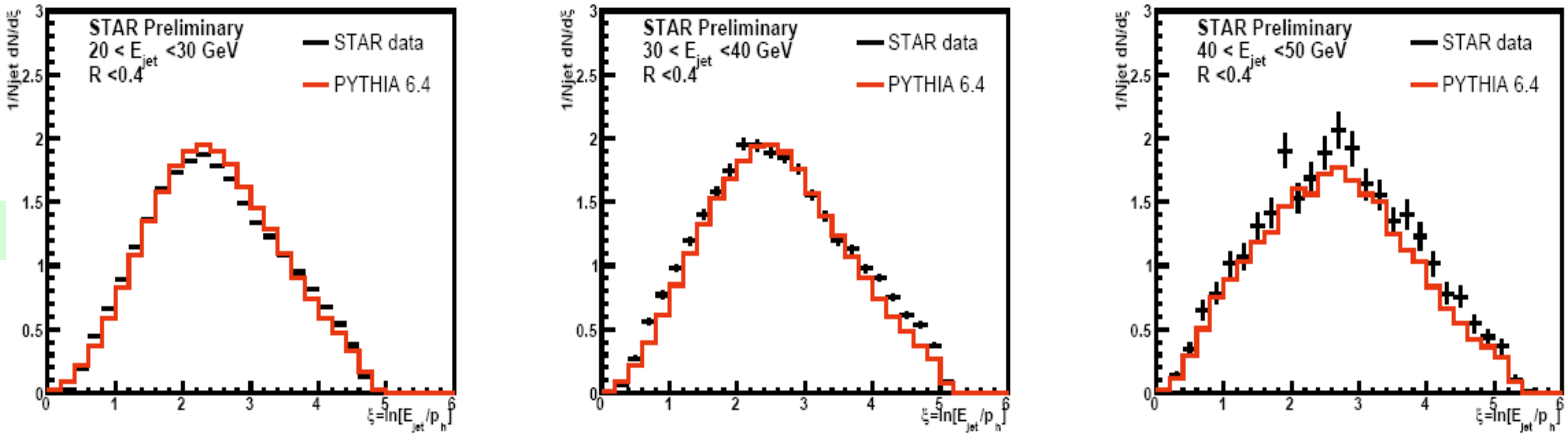
Charged hadron ξ in p+p 200 GeV

20<E^{reco}<30 GeV

30<E^{reco}<40 GeV

40<E^{reco}<50 GeV

R<0.4



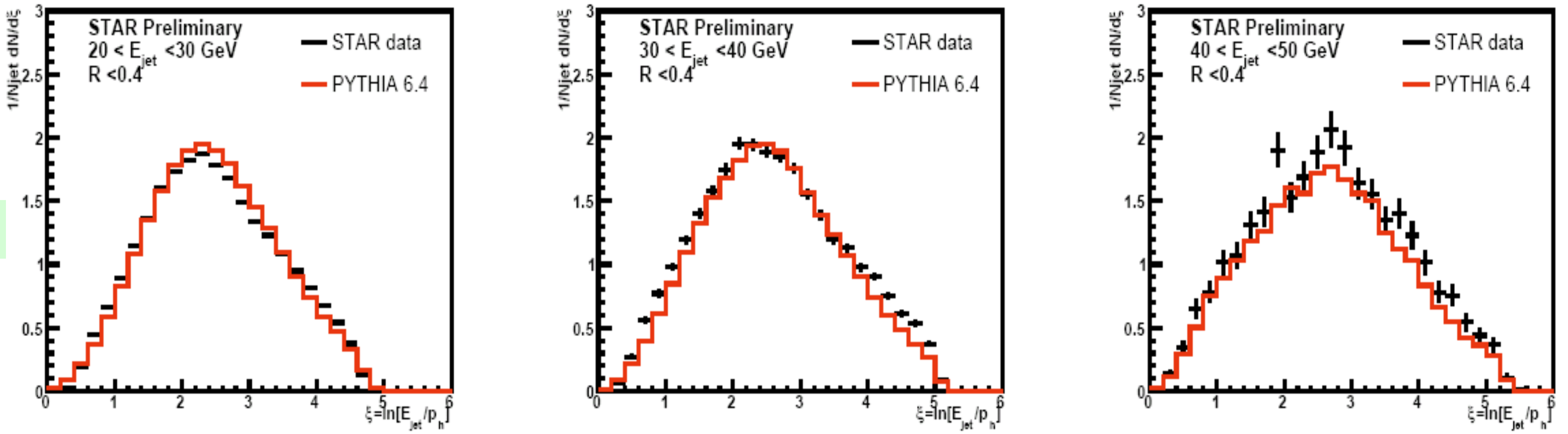
M. Heinz
Hard Probes 2008

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

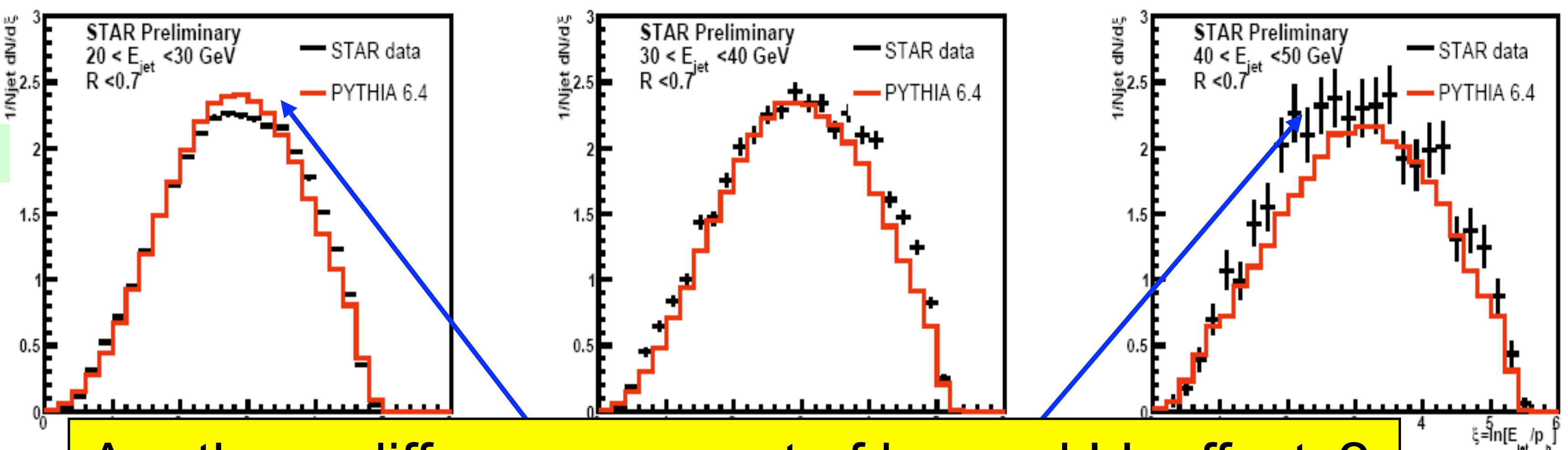
R<0.4



M. Heinz
Hard Probes 2008

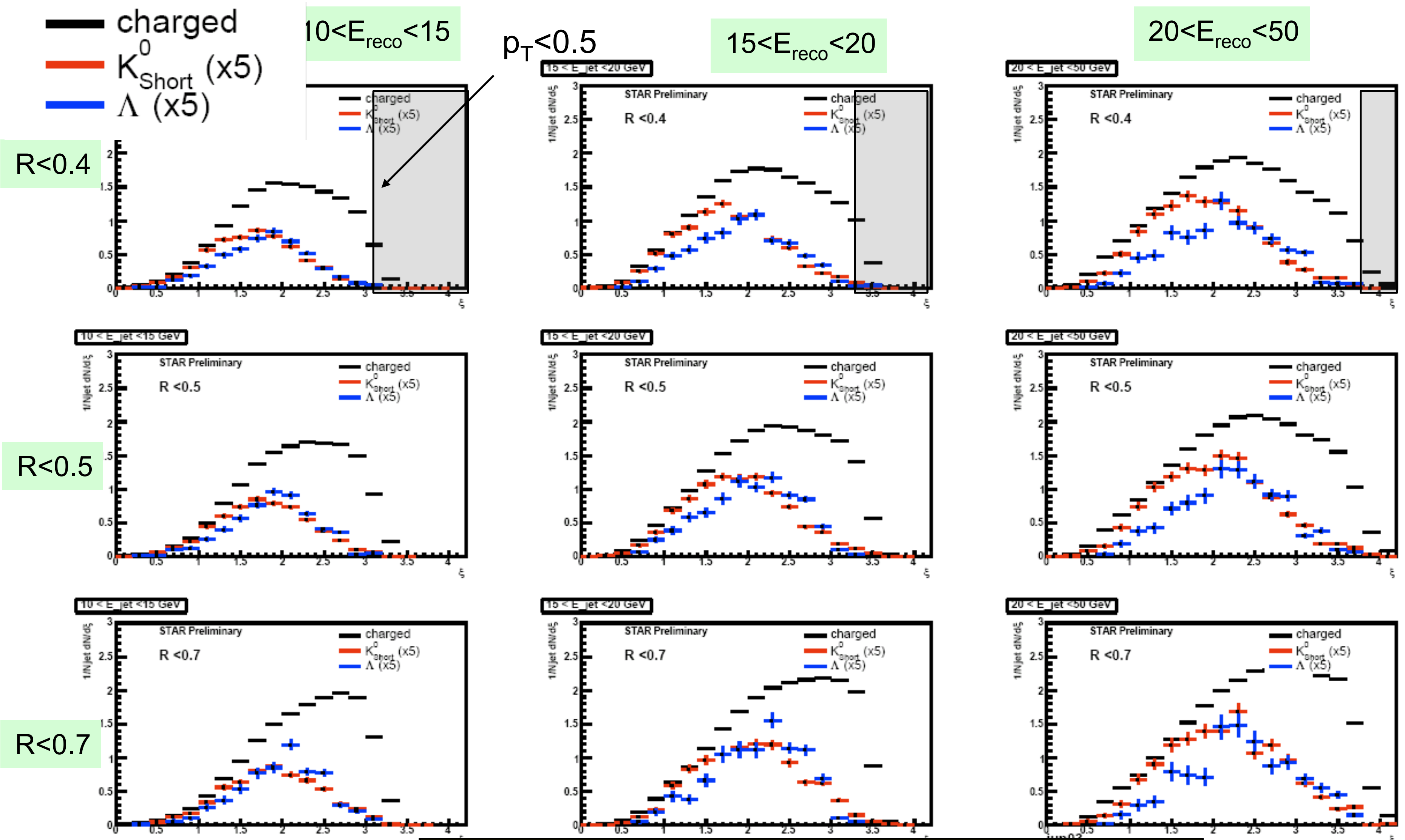
Reasonable agreement between Pythia and data

R<0.7



Are these differences onset of beyond LL effects?

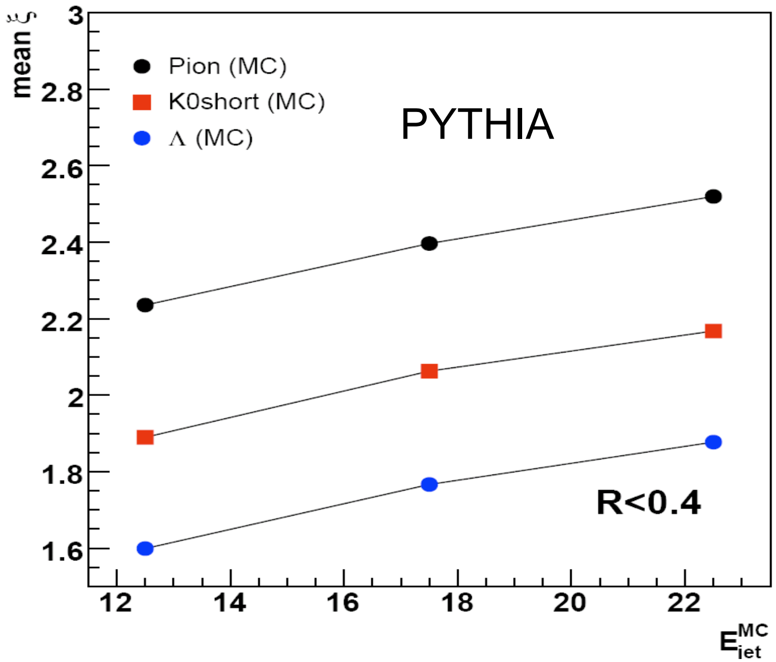
ξ for strange hadrons

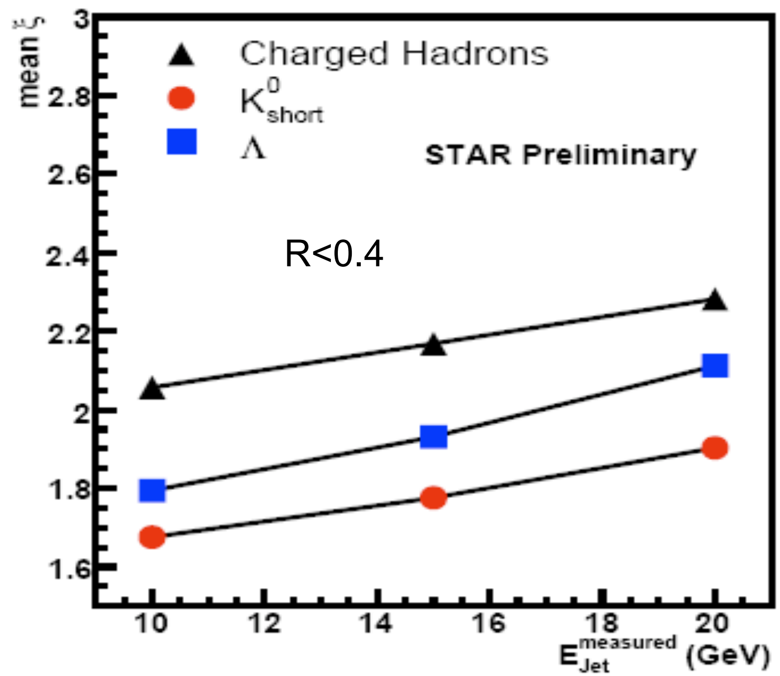


M. Heinz Hard Probes 2008

Clear differences between particles

⟨ξ⟩ for strange hadrons

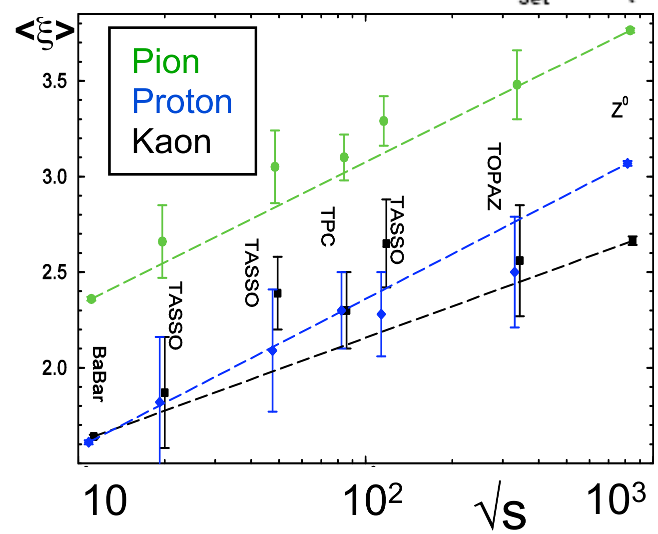




- QCD predicts a <ξ> p mass ordering

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)

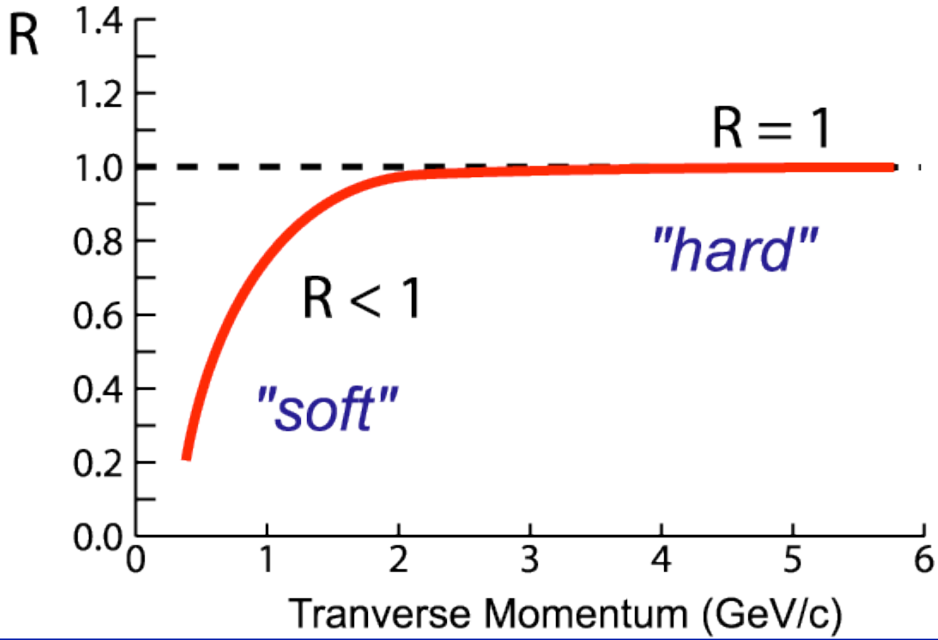
Back to probing the medium

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

Nuclear Modification Factor:

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

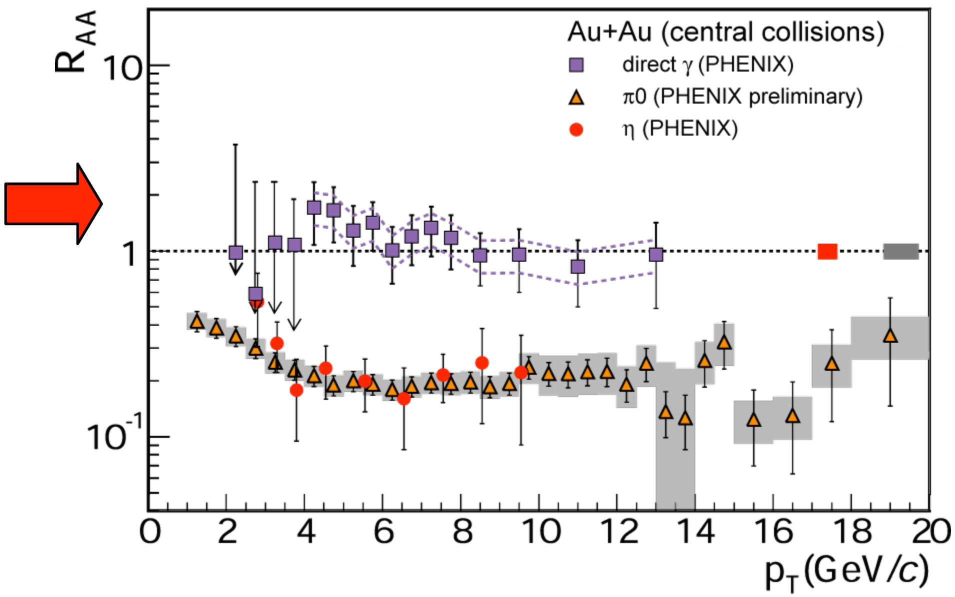
Average number of NN collision in an AA collision



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

Suppression: R < 1

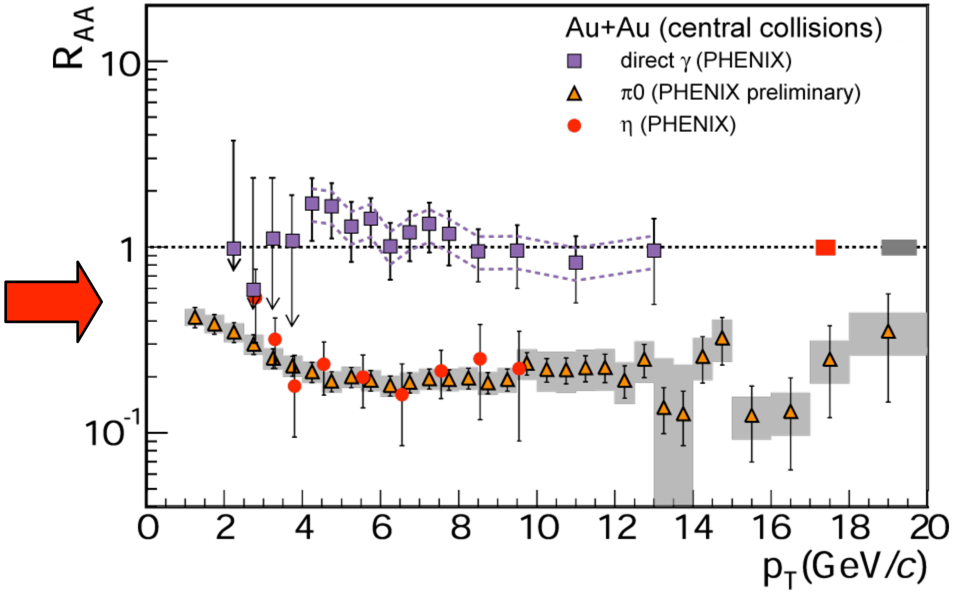
High-p_T suppression



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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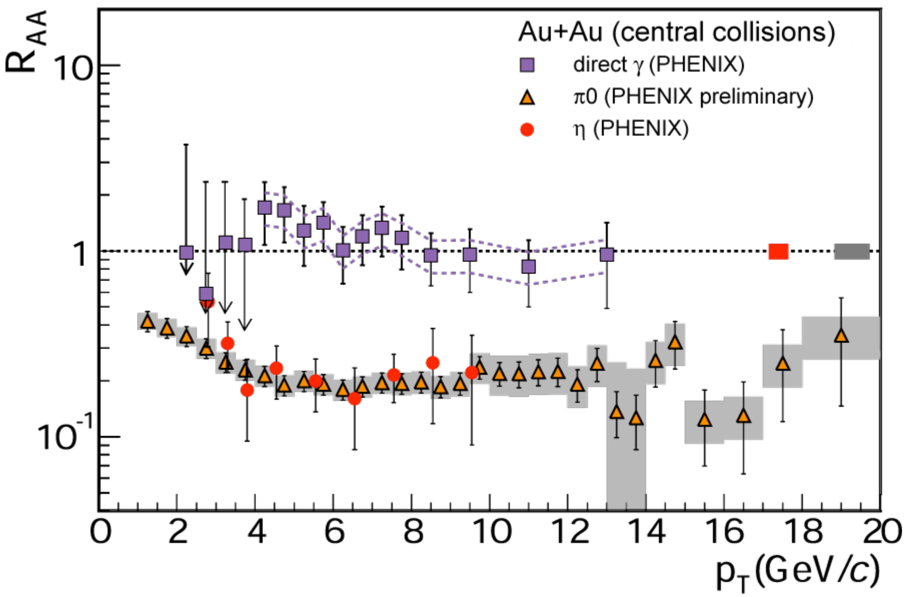
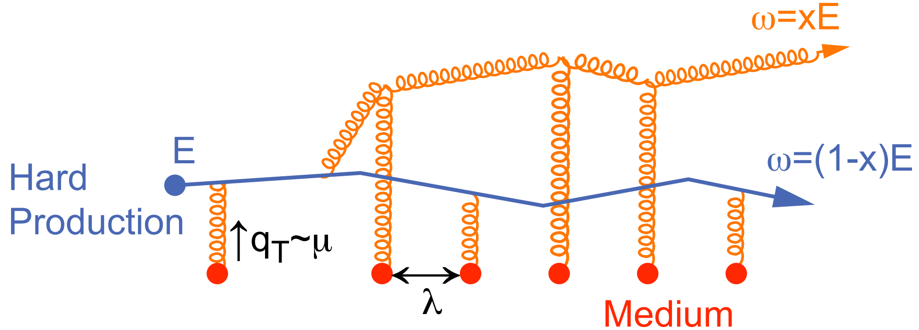


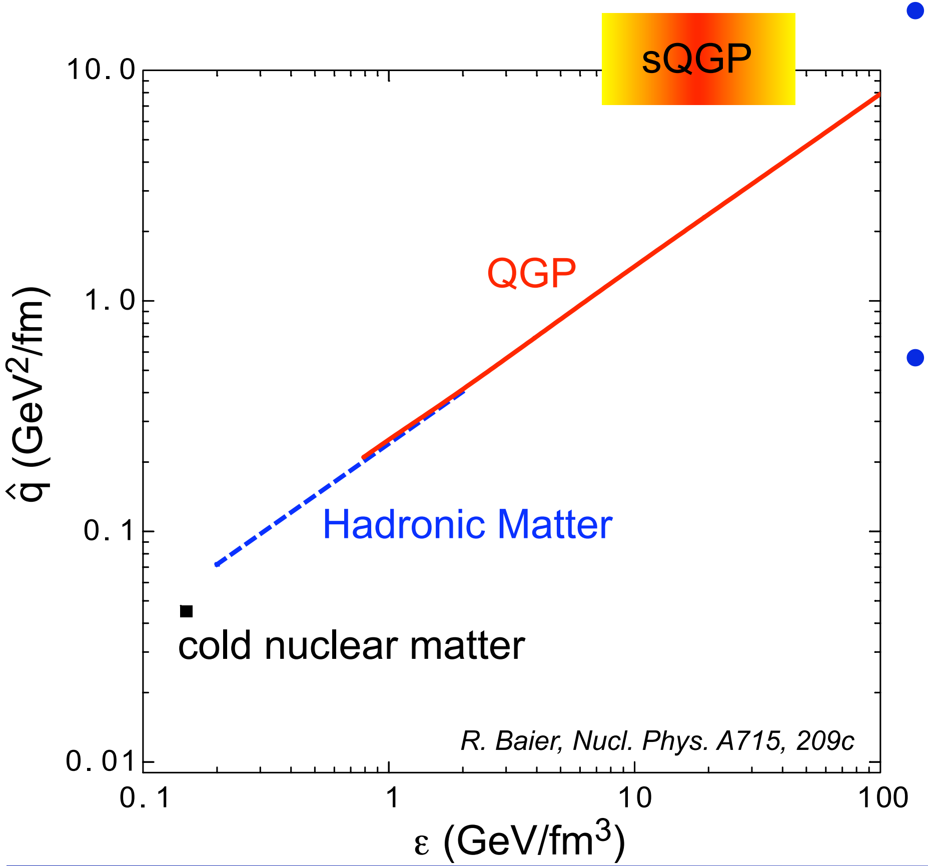
Observations at RHIC:

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





- Mean parton energy loss ∝ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim \Delta L^2$ (medium length)
    $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$

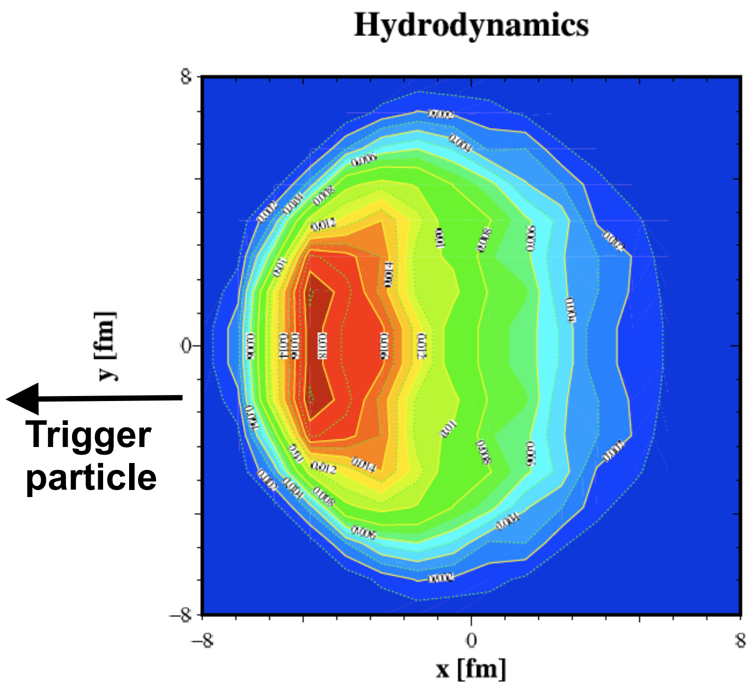
  is $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length

  - gluon density dN_g/dy
  - Note: expanding medium

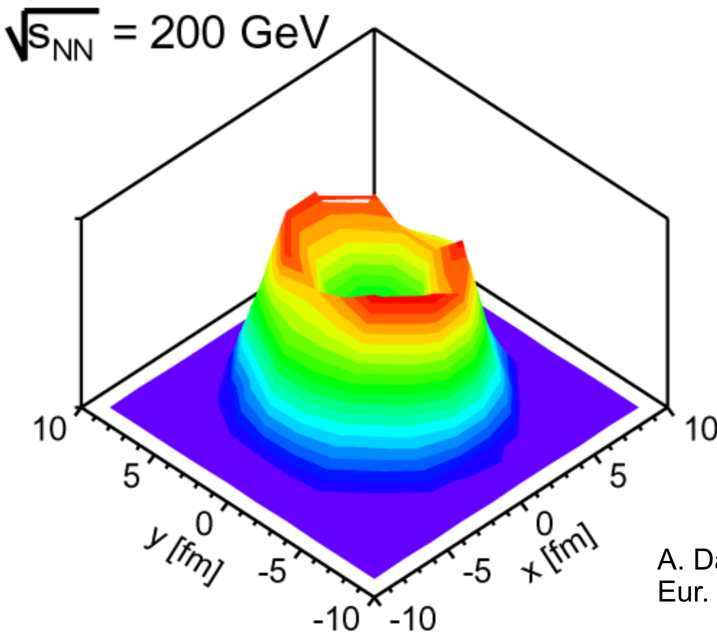
$$\hat{q} = \hat{q}(\vec{r}, \tau)$$

Surface Bias

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



Renk and Eskola, hep-ph/0610059



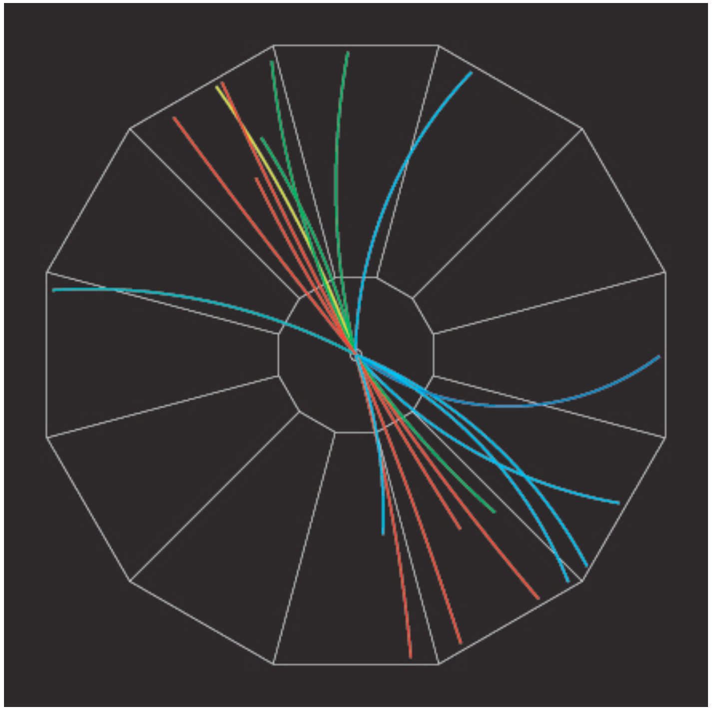
Distributions of parton production points in the transverse plane

A. Dainese et al., Eur. Phys. J. C38(2005) 461

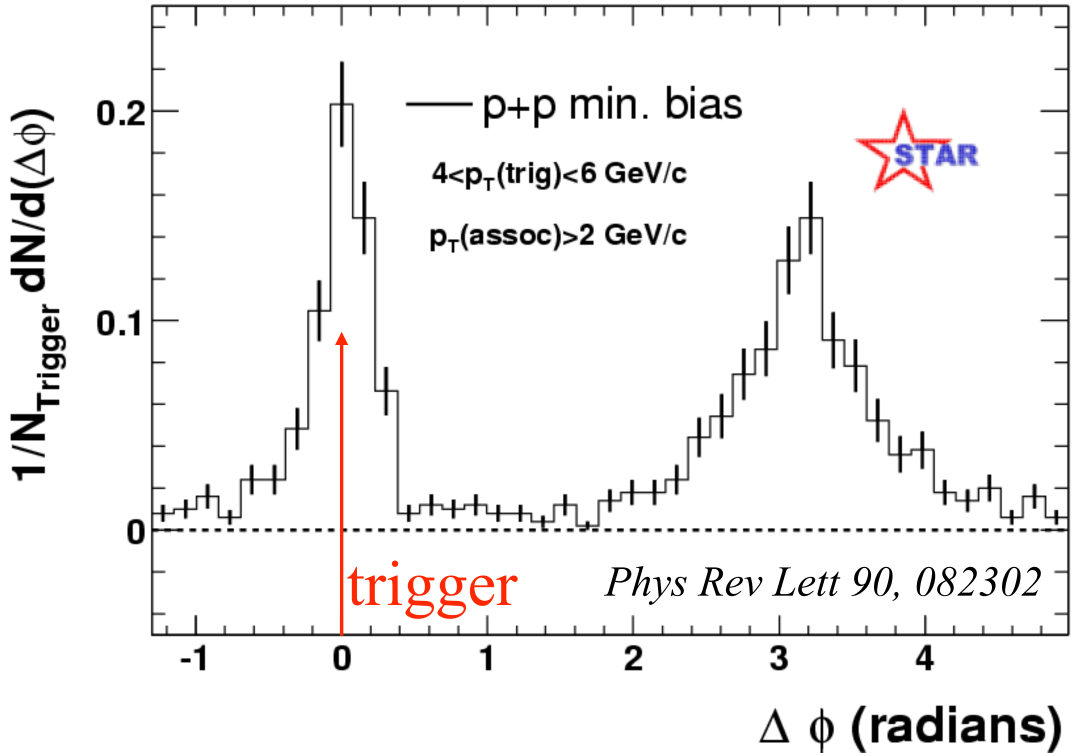
- Need realistic medium profile: 3-D viscous hydro, correct initial states
- Ways to minimize bias
  - di-hadron correlations
  - full jets
  - γ-Jet
  - Heavy flavour measurements

Jet correlations in Au+Au collisions!

p+p → dijet



min. bias p+p collisions



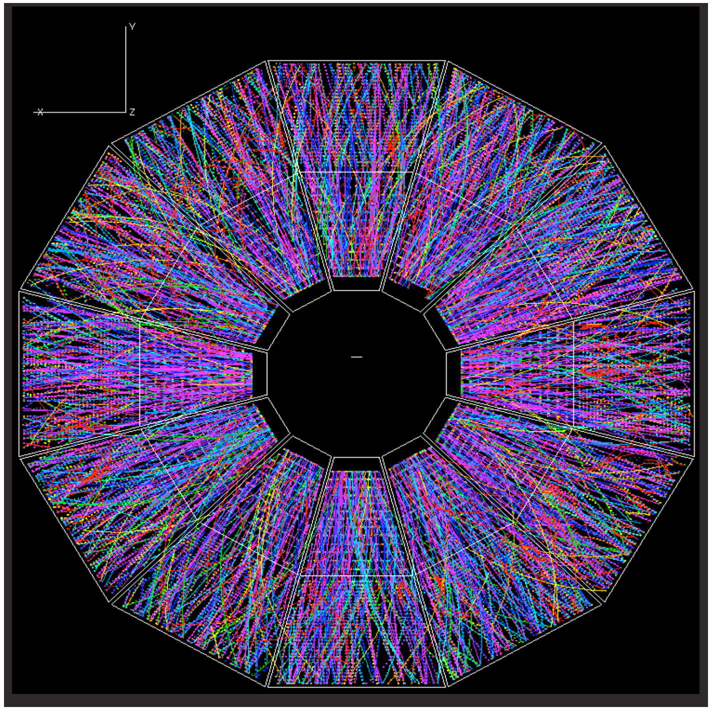
Trigger: highest p_T track

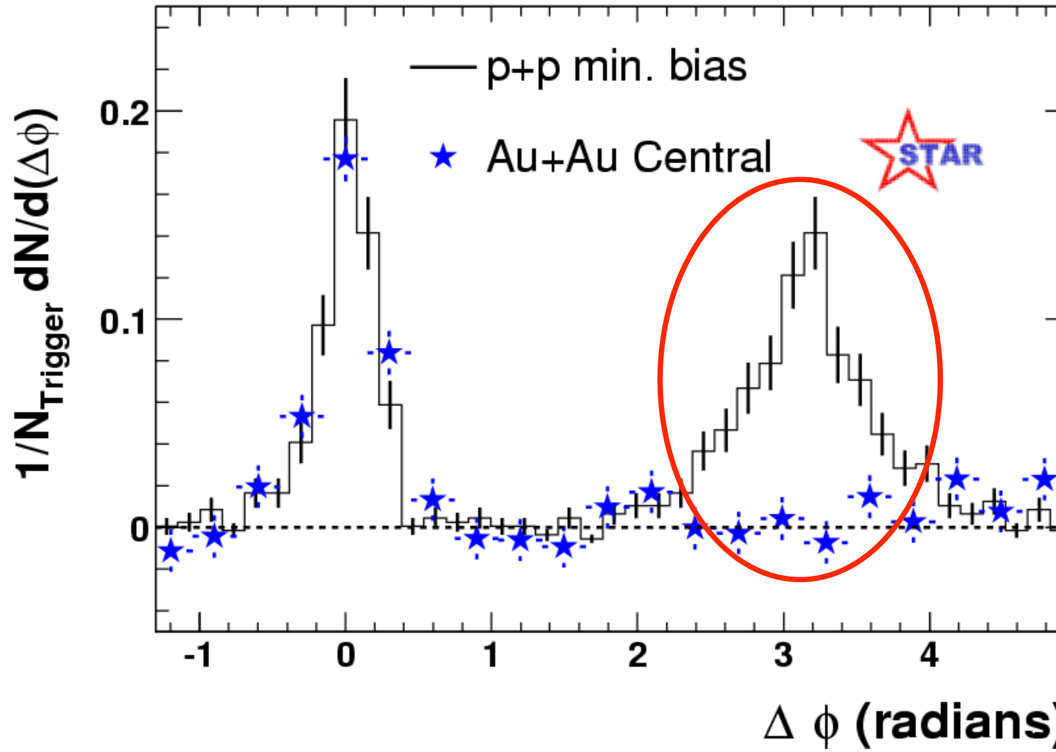
Δφ distribution:

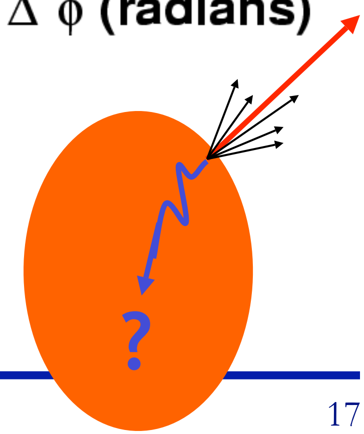
Jet correlations in Au+Au collisions!

Au+Au → dijet

central Au+Au collisions





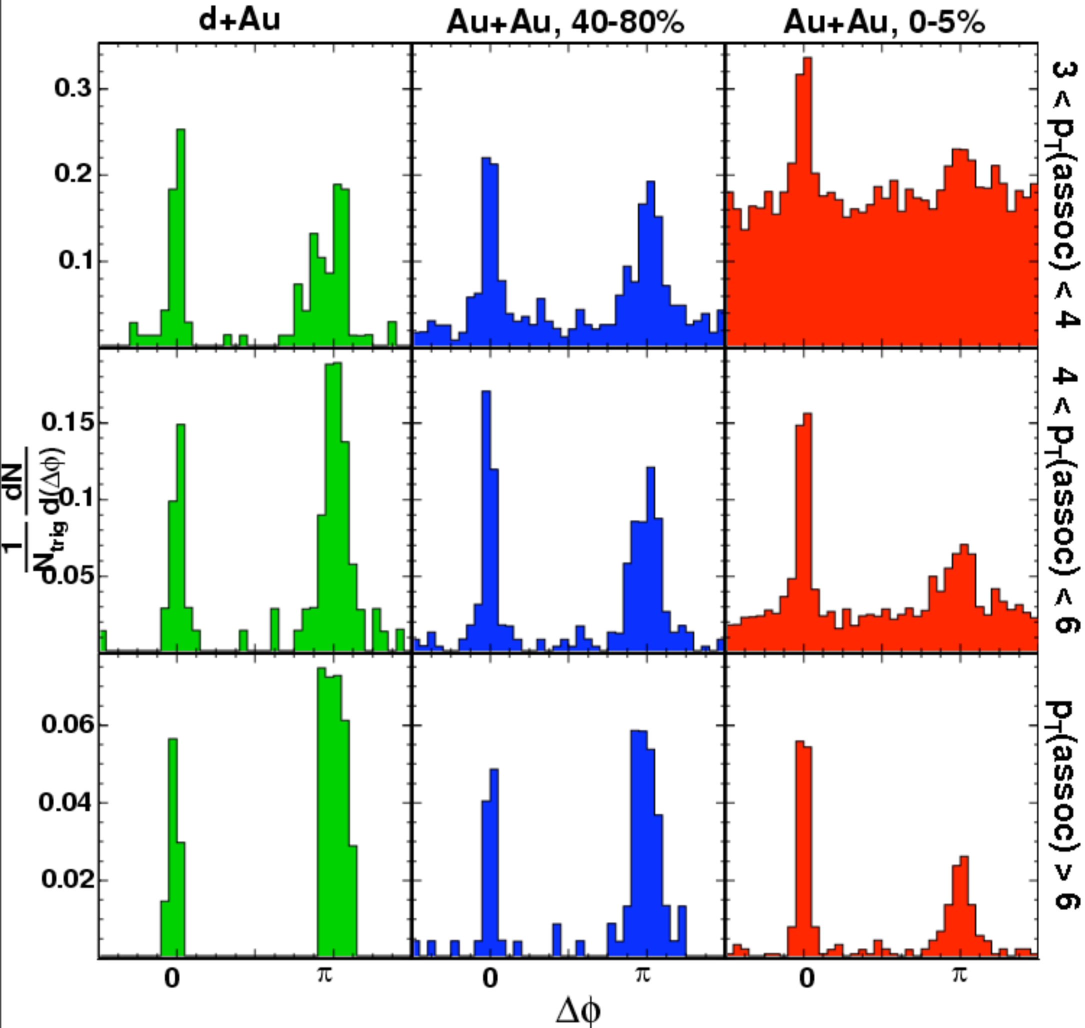


$\Delta\phi \approx 0$: central Au+Au similar to p+p

$\Delta\phi \approx \pi$: strong suppression of back-to-back correlations in central Au+Au

Observation of "Punch through"

$8<p_T^{trig}<15$ GeV/c

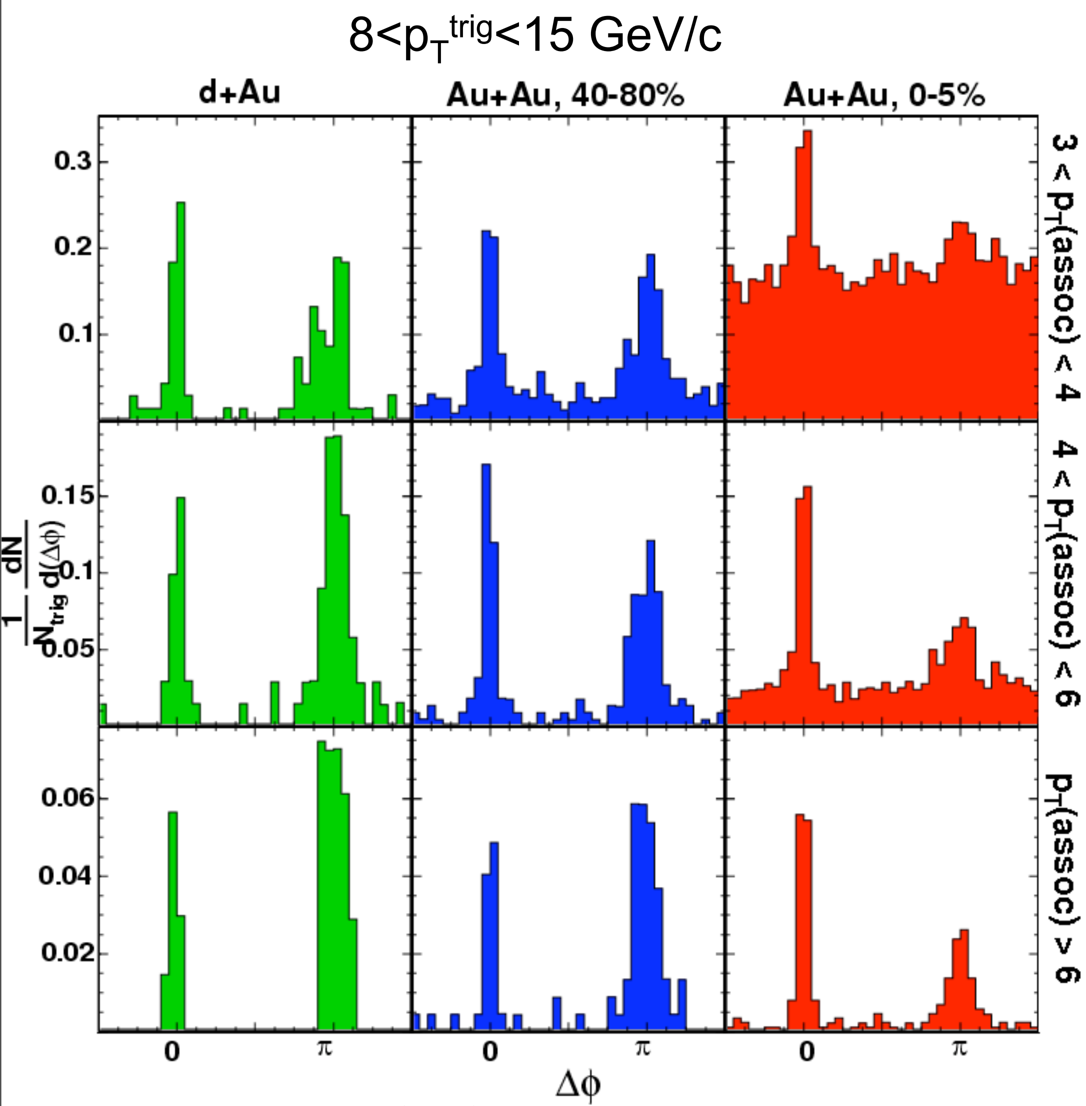


STAR PRL 97 (2006) 162301

If use high-p_T triggers:

- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background

Observation of "Punch through"



STAR PRL 97 (2006) 162301

If use high-p_T triggers:

- Away-side peak re-emerges
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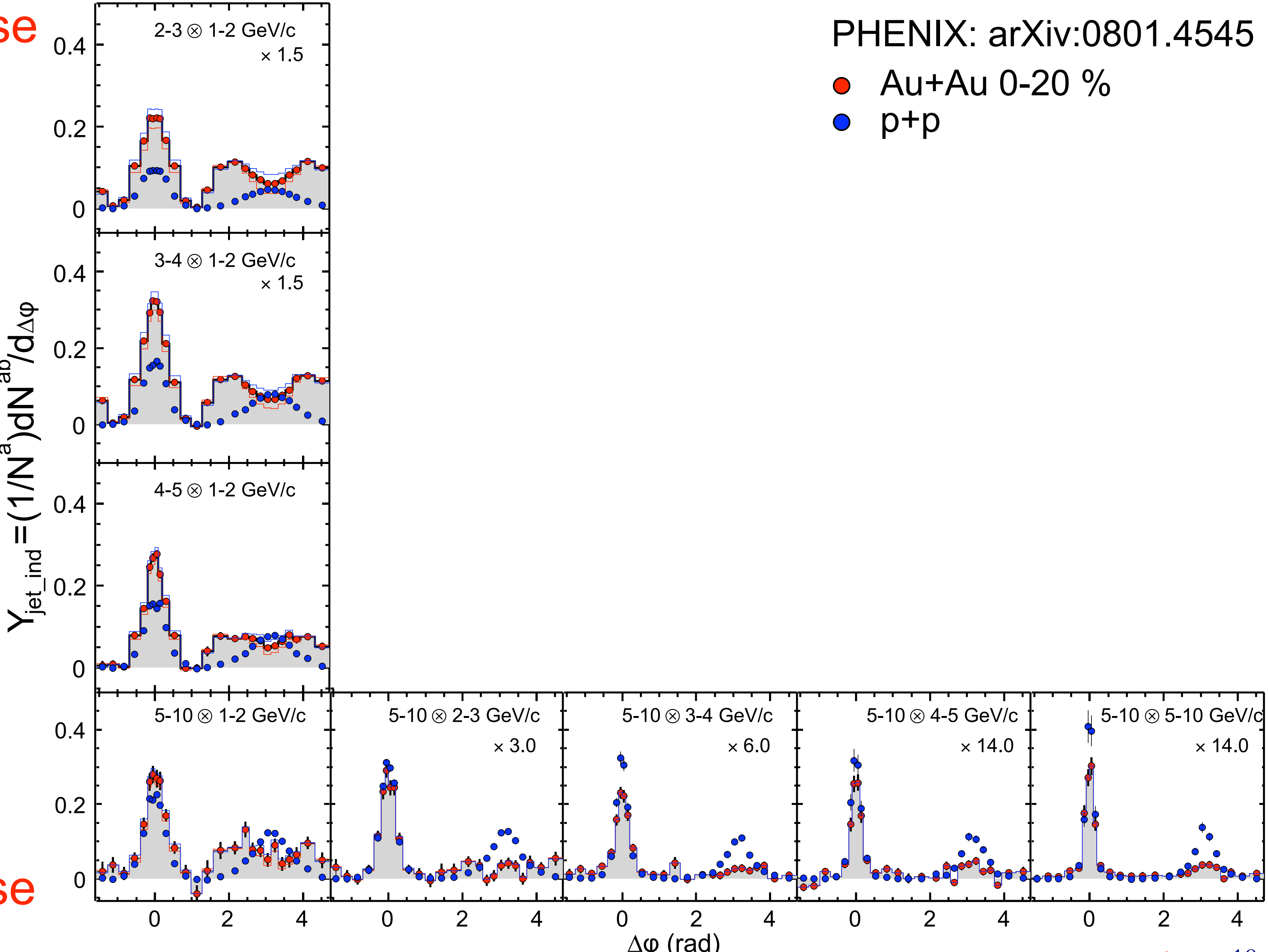
High energy jets *"punch through"* the medium.

Really passing through medium or edge effects?

p_T systematics of di-hadron correlations

Increase $p_T^{Trigger}$

Increase p_T^{Assoc}



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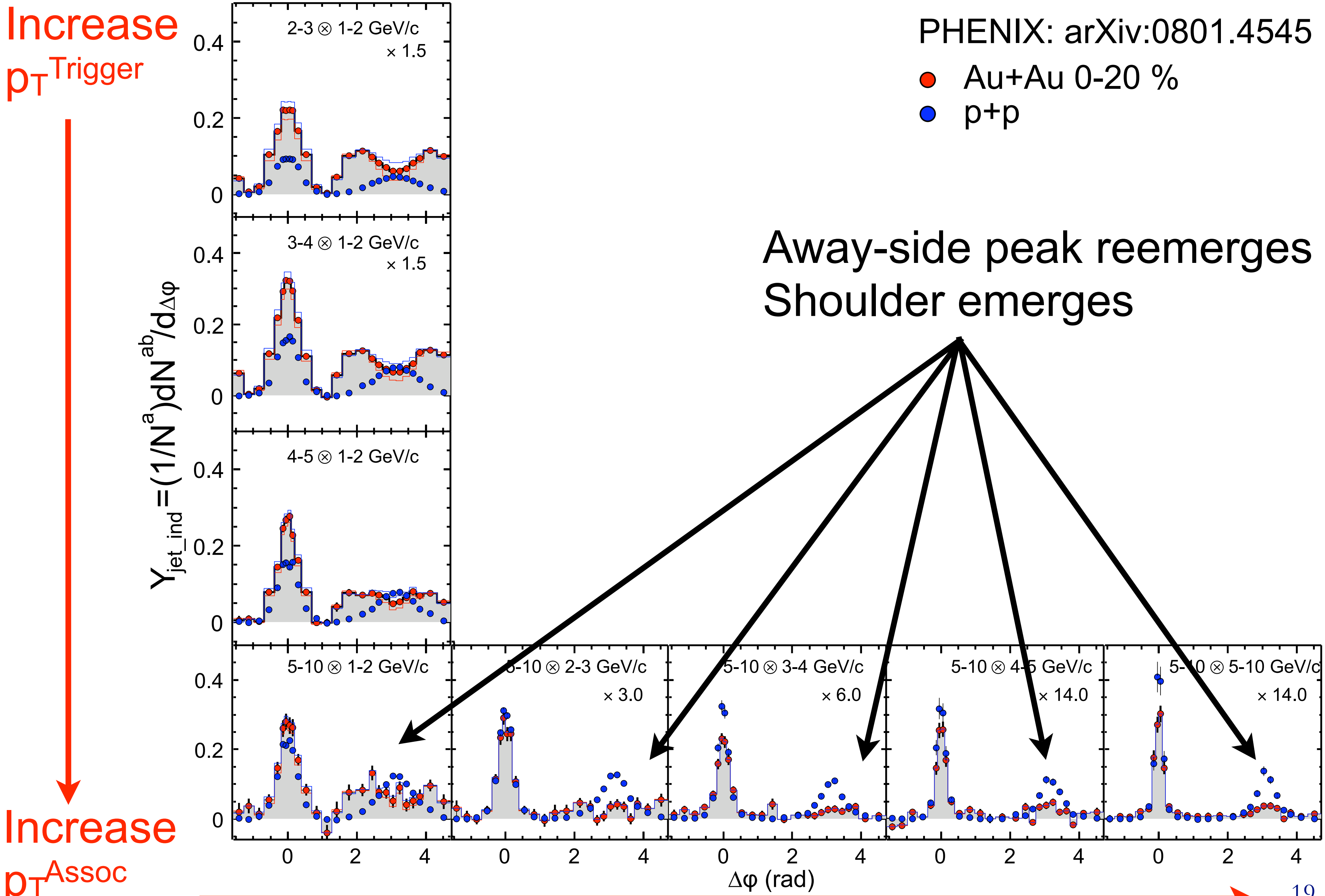

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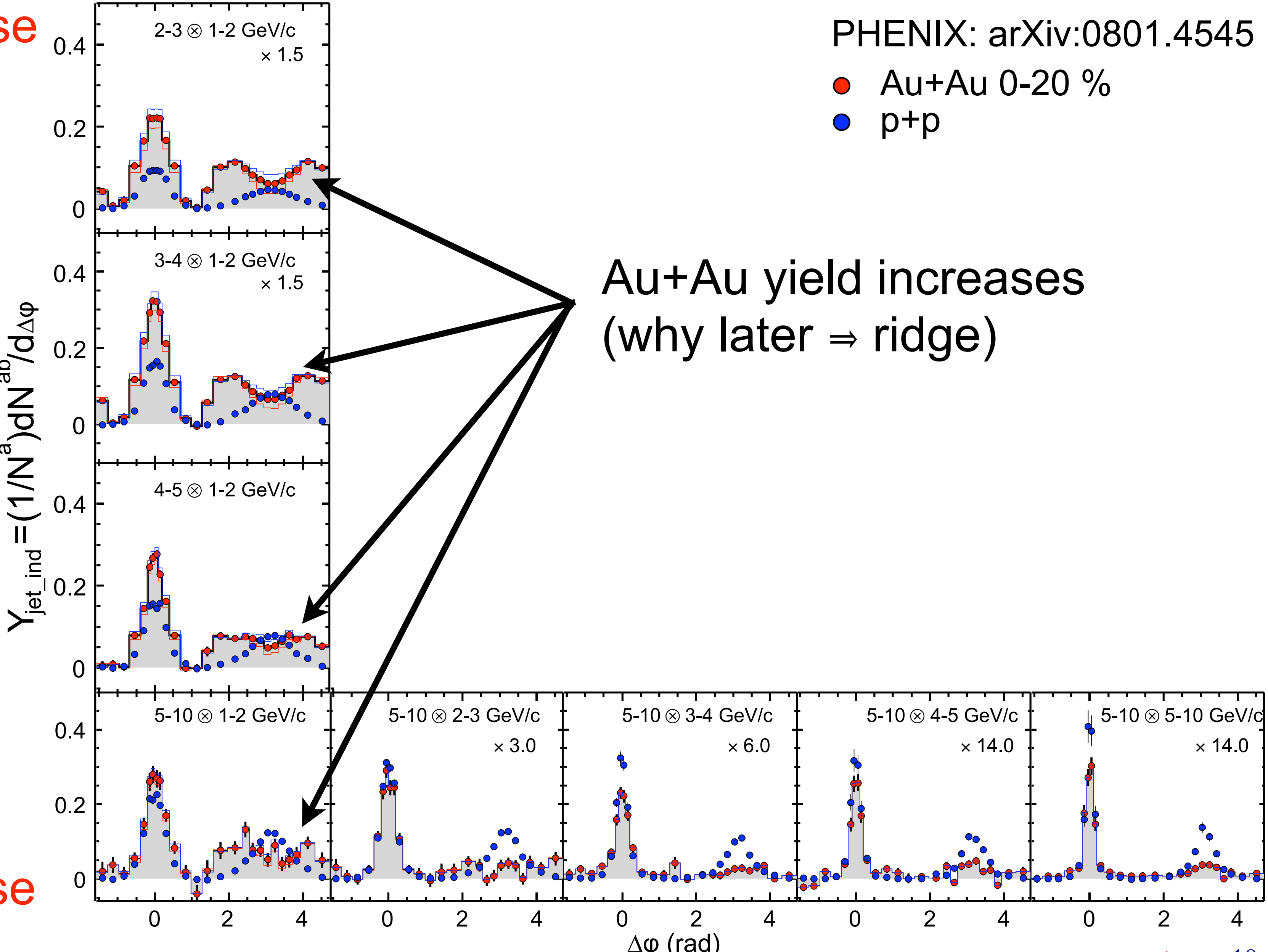
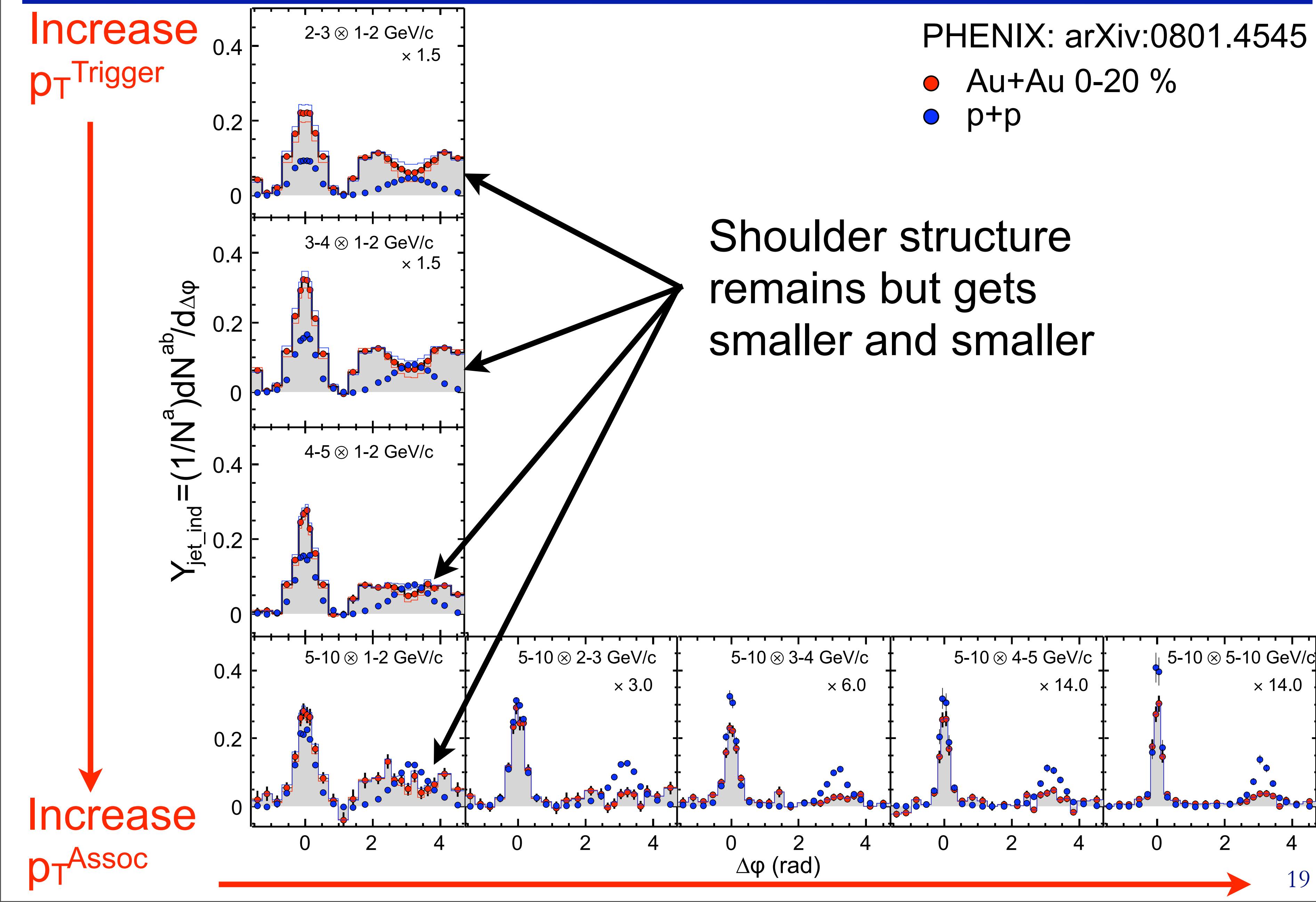


Au+Au yield increases
(why later ⇒ ridge)

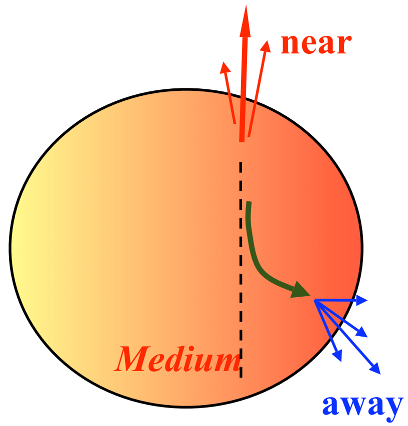
Increase p_T^{Assoc}

p_T systematics of di-hadron correlations

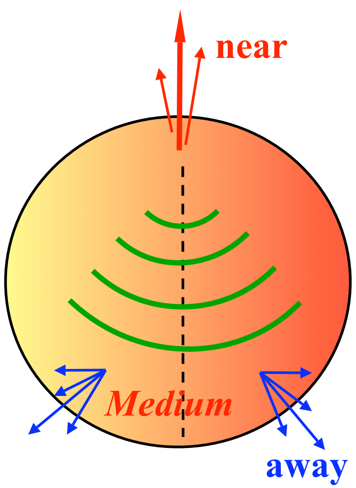


Shoulder structure remains but gets smaller and smaller

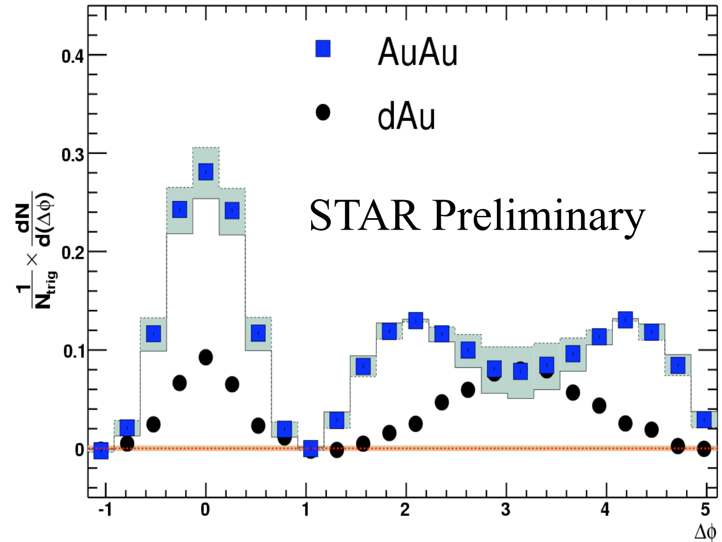
Deflected jets or conical emission?



Deflected jets



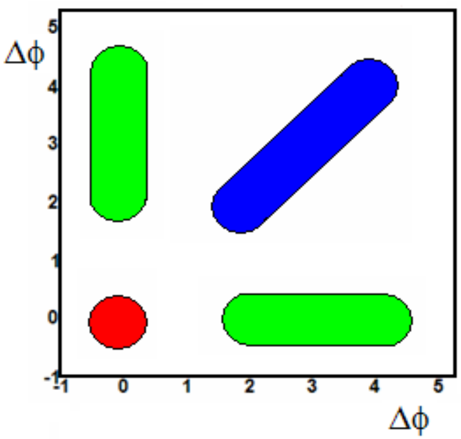
Conical Emission



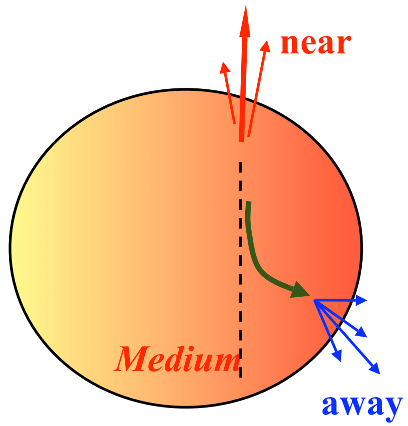
Conical emission or deflected jets?

Distinguish between models using 3-particle correlations

Deflected jets or conical emission?



Deflected jets



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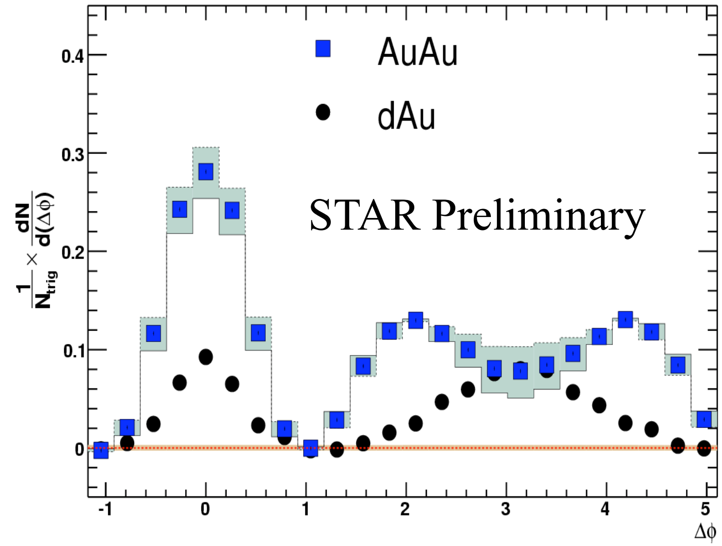

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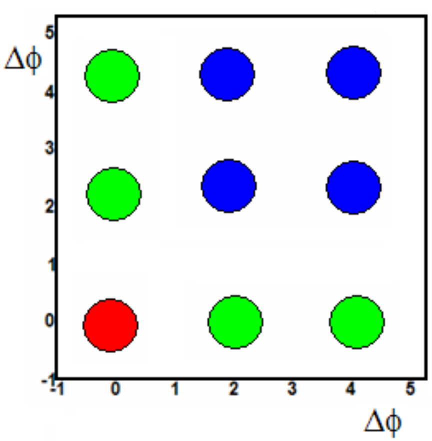

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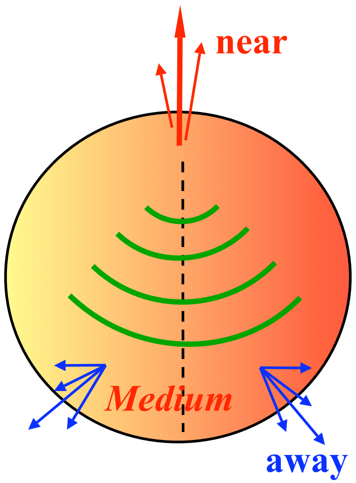

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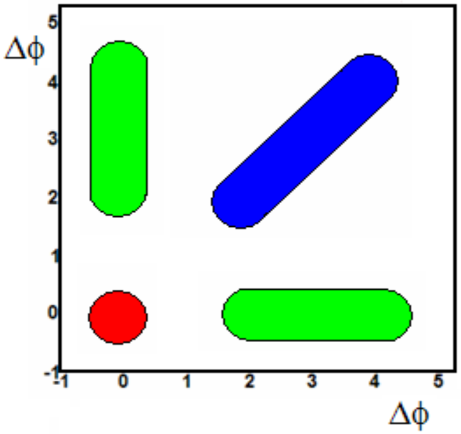

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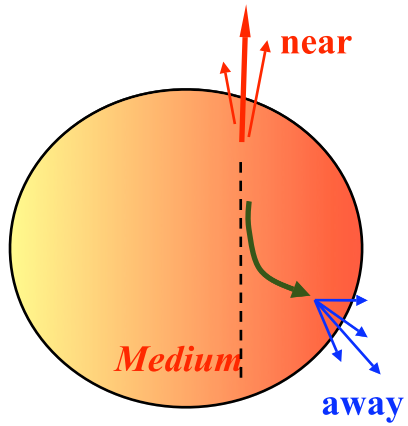
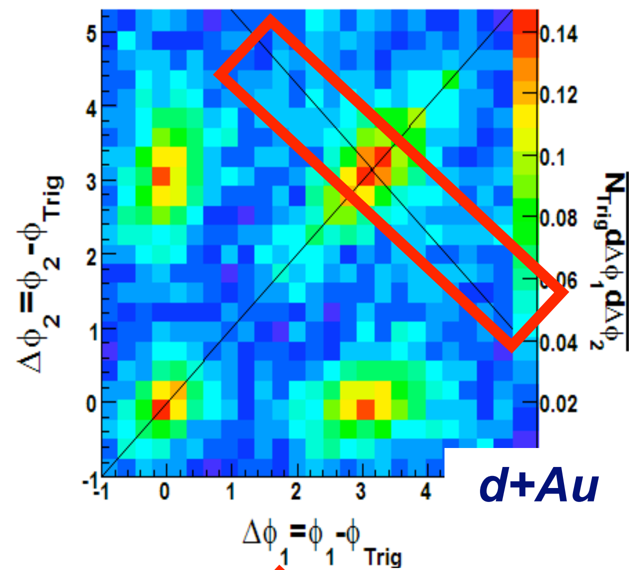
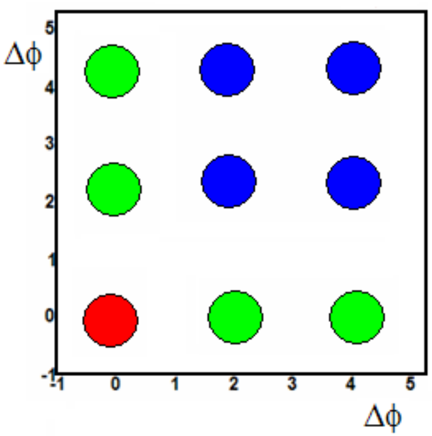


Deflected jets

STAR Preliminary



$3 < p_{Trig} < 4$ GeV/c, $1 < p_{Tassoc} < 2$ GeV/c



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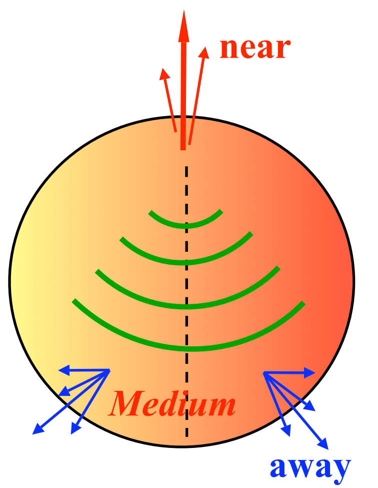

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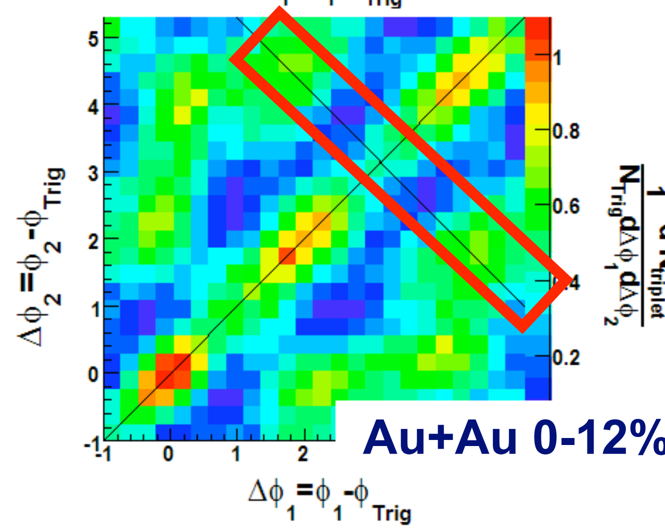

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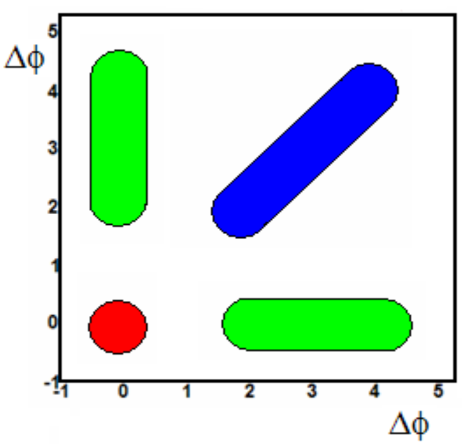

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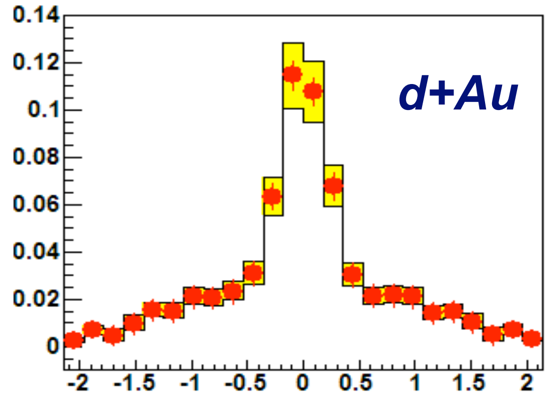
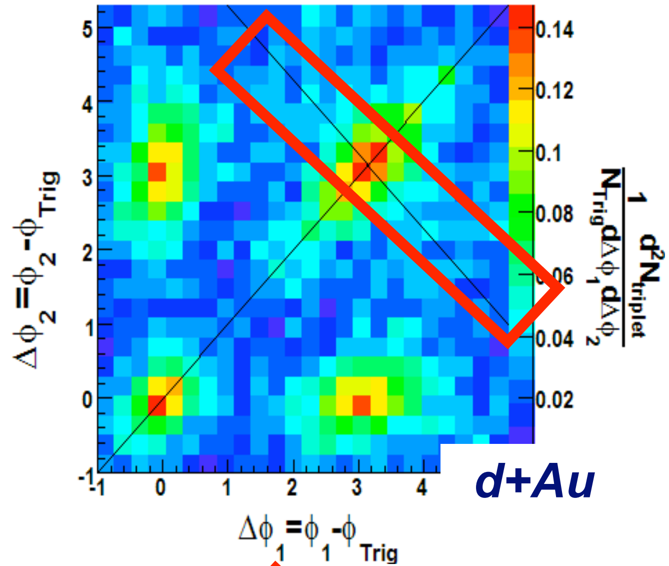


$(\Delta\phi_1-\Delta\phi_2)/2$

STAR Preliminary



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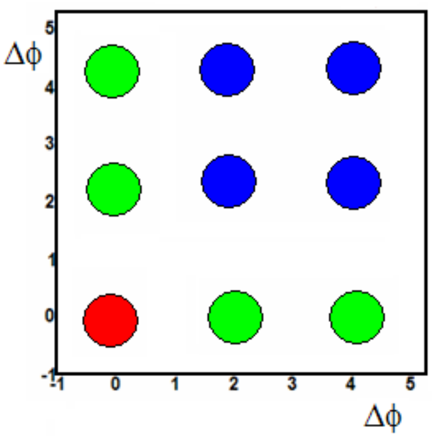

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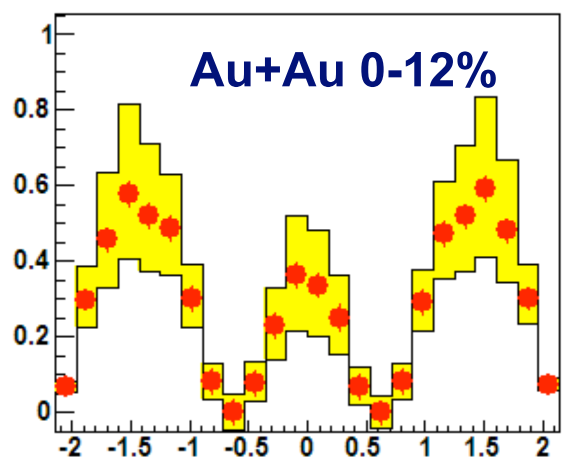

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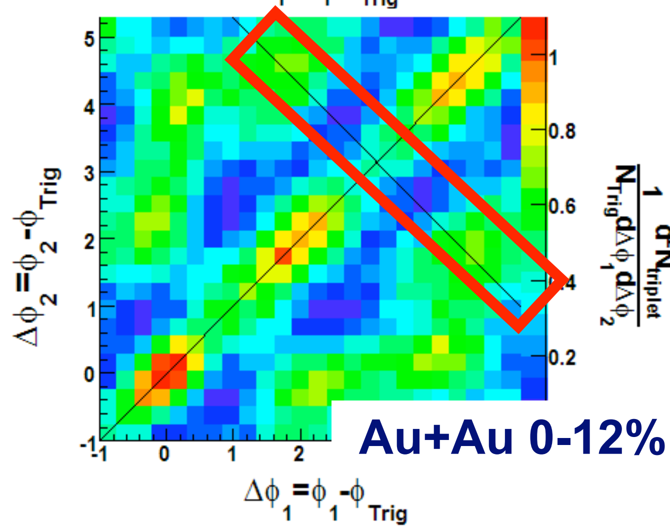

Possible causes of conical emission

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

- Angle independent of p_T^{assoc}

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?

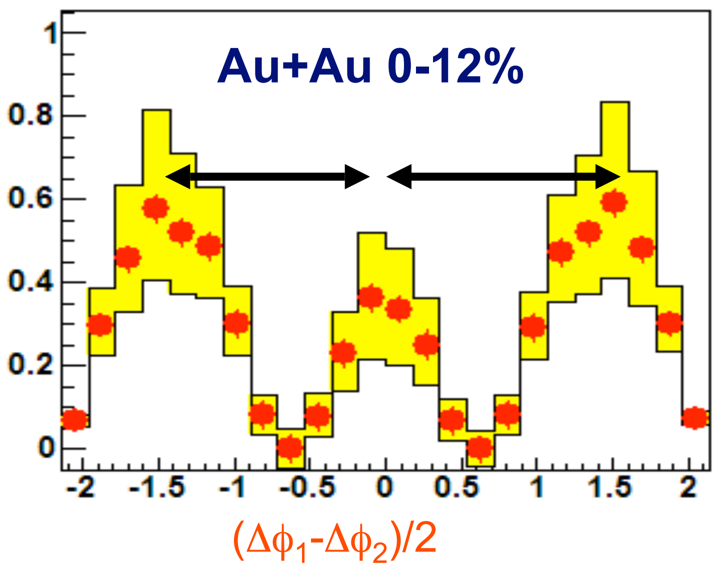
Angle predictions:

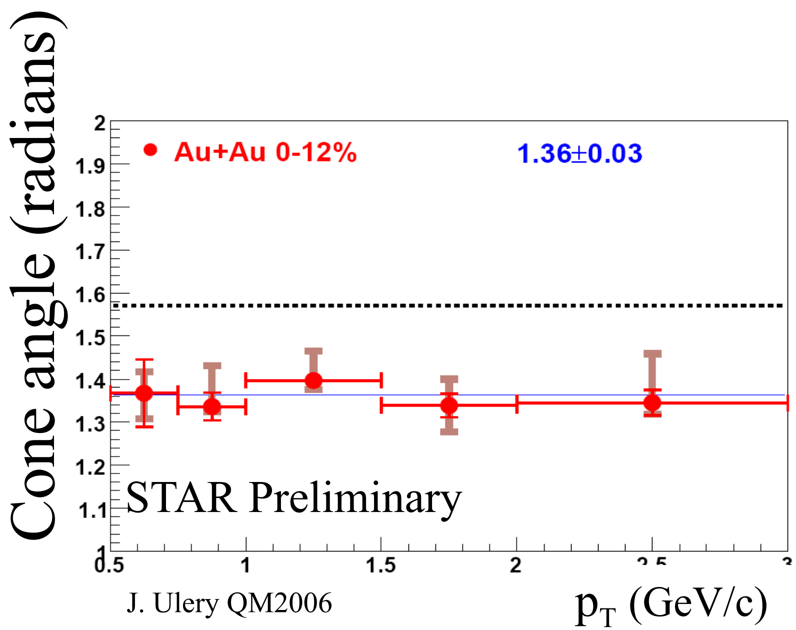
- Mach-cone:

  Angle independent of associated p_T

  Čerenkov gluon radiation:

  Angle decreases with associated p_T





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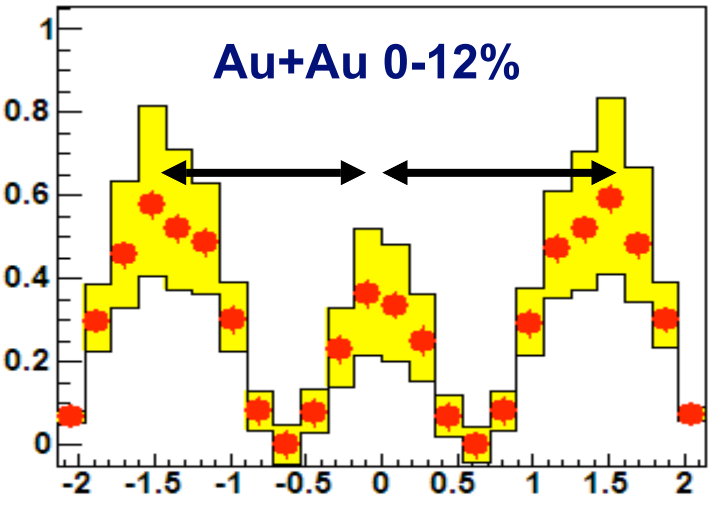
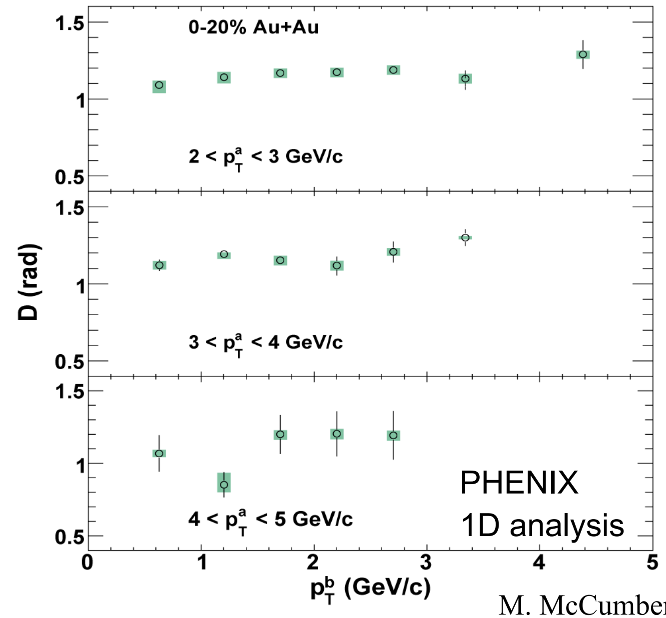
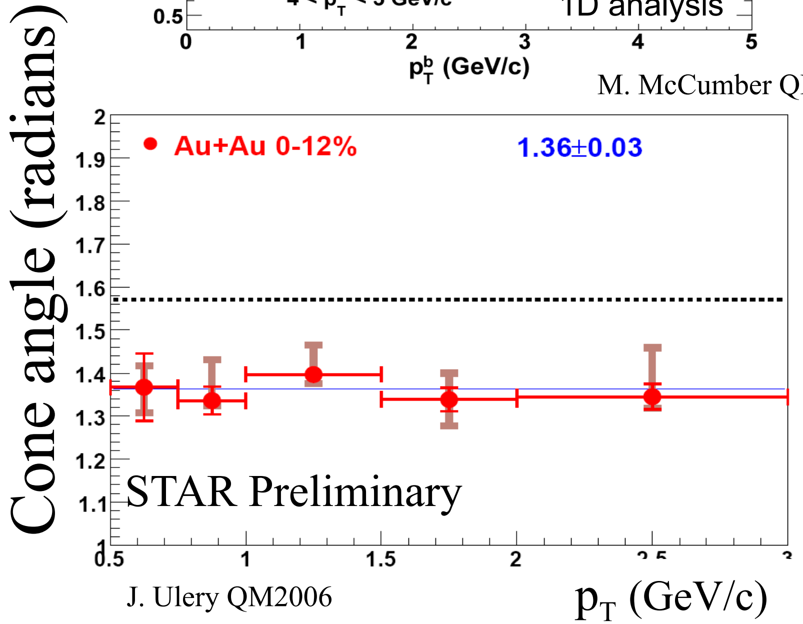




M. McCumber QM2008



J. Ulery QM2006

Mach cone or Čerenkov gluons?

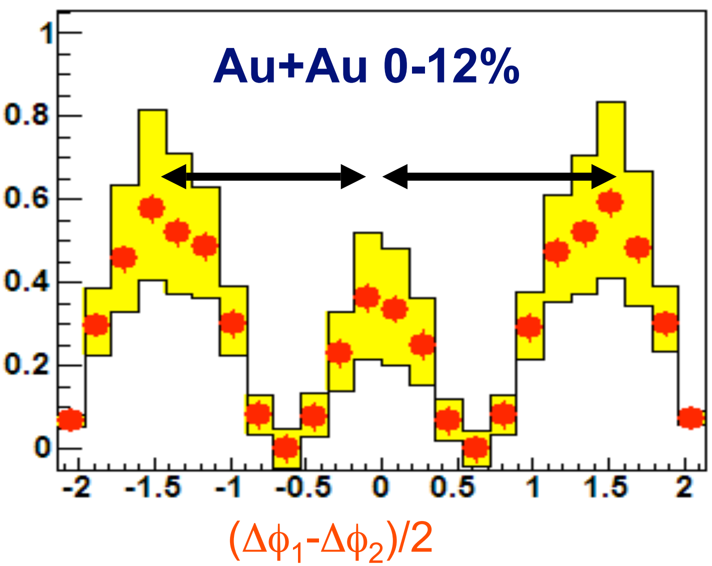
Angle predictions:

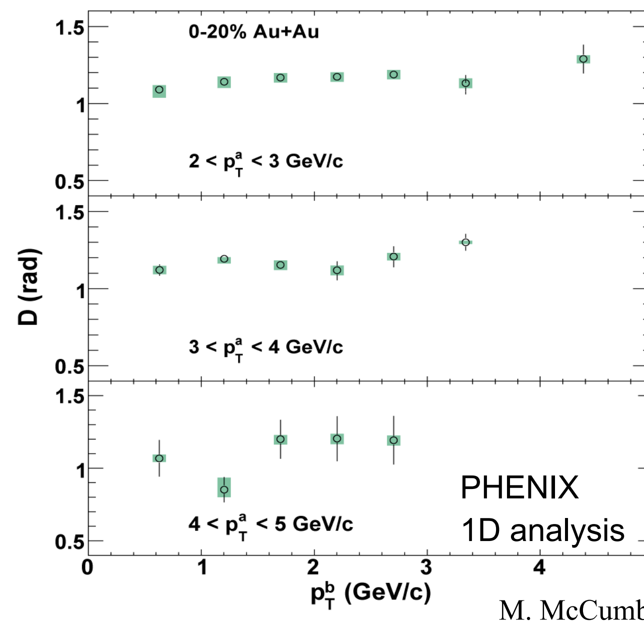
- Mach-cone: ✓

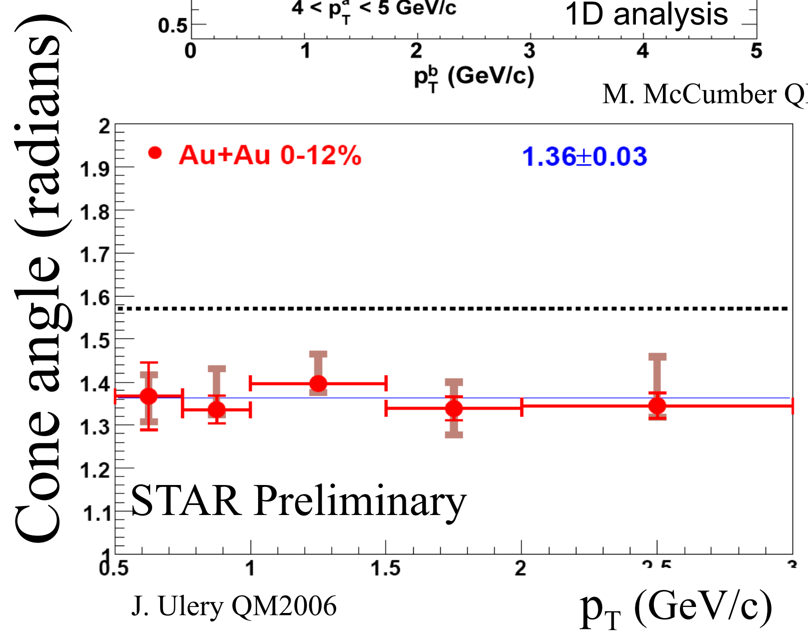
  Angle independent of associated p_T

- Čerenkov gluon radiation: ✗

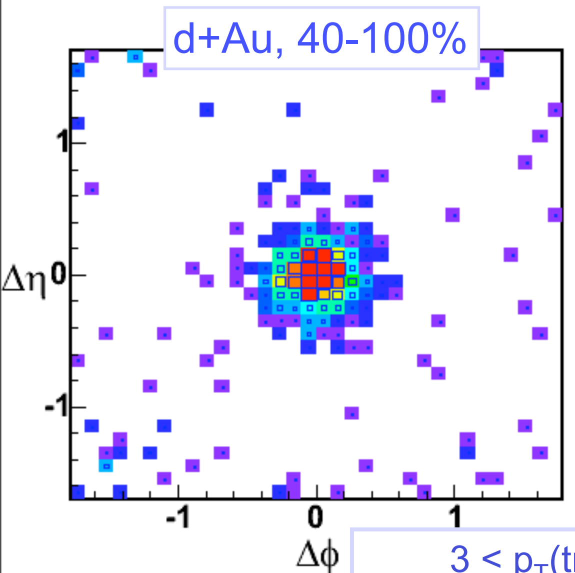
  Angle decreases with associated p_T







Energy loss of trigger -"The ridge"



3 < p_T(trig) < 6 GeV

2 < p_T(assoc) < p_T(trig)

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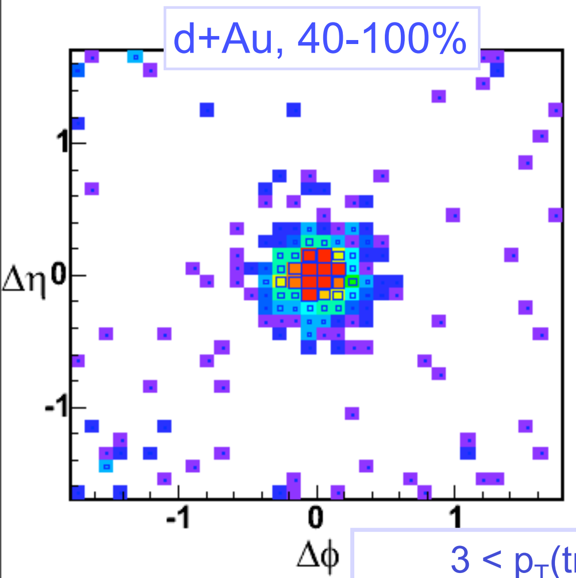

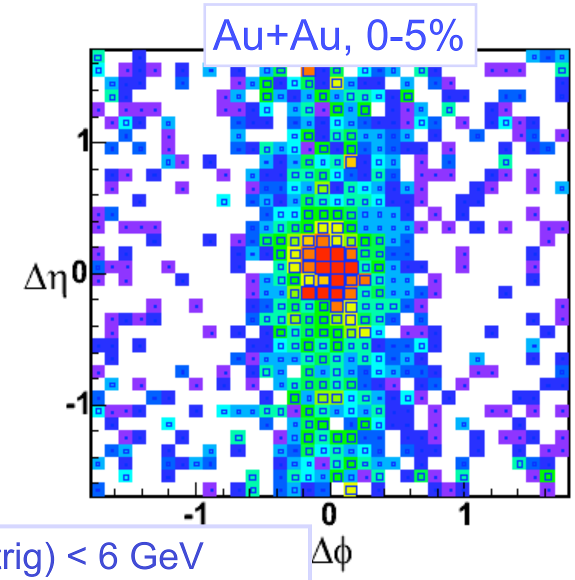

$3 < p_T(\text{trig}) < 6$ GeV
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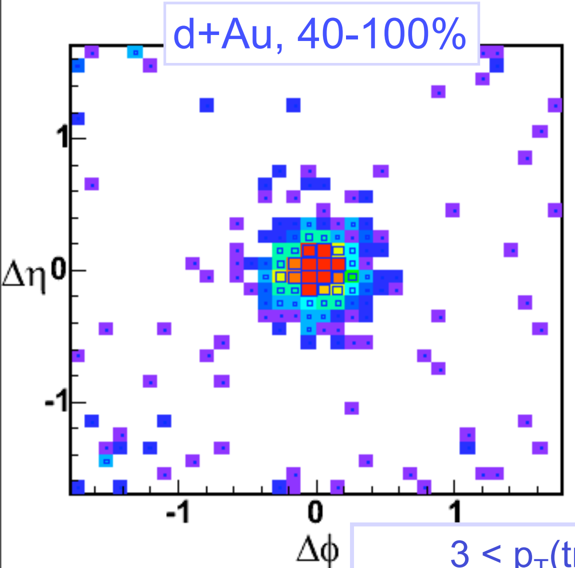

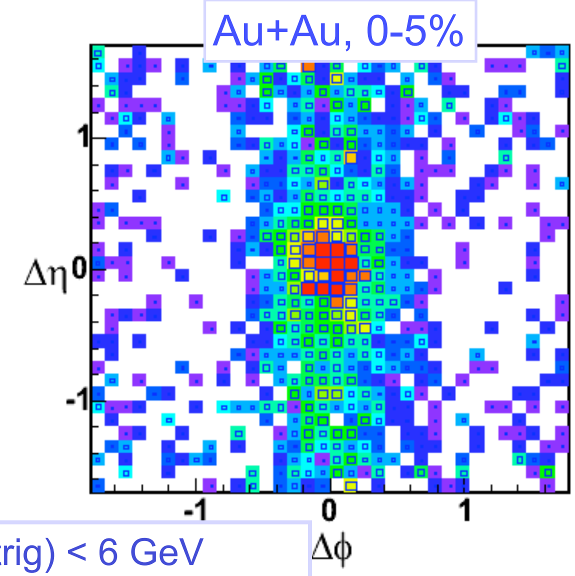

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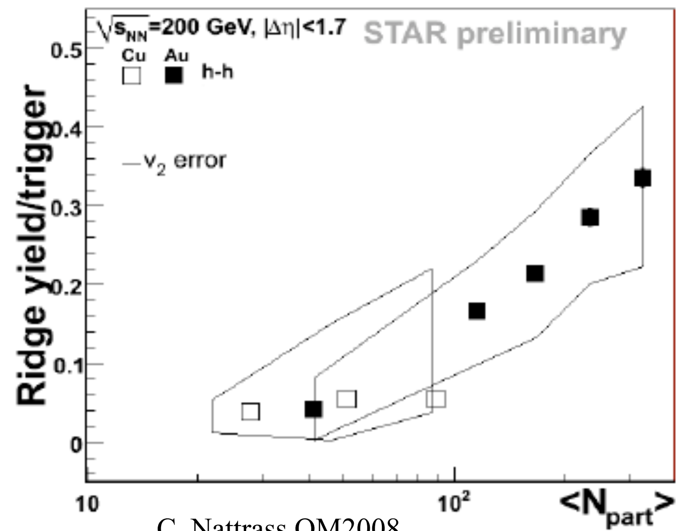
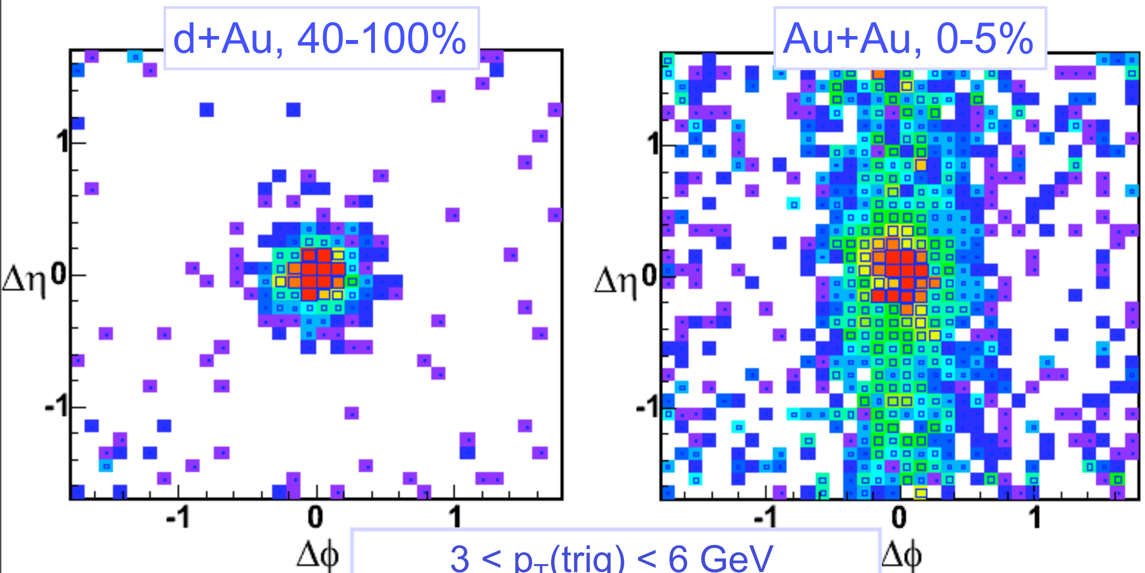


C. Nattrass QM2008

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

Energy loss of trigger -“The ridge”



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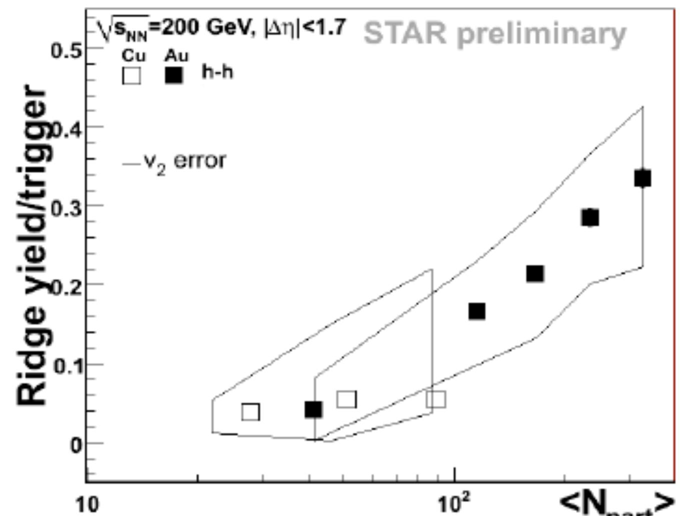
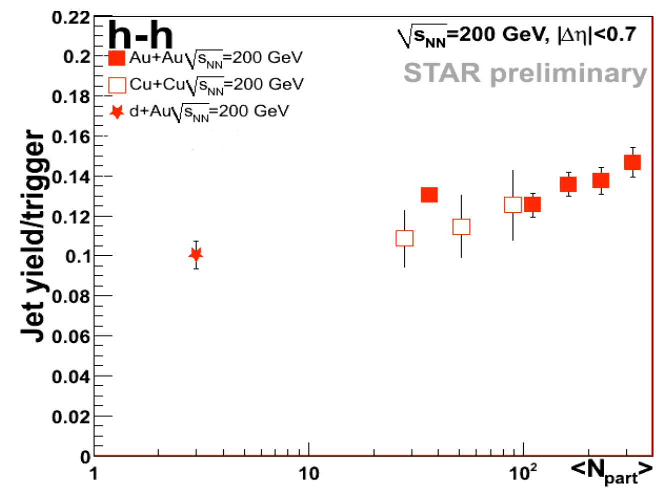


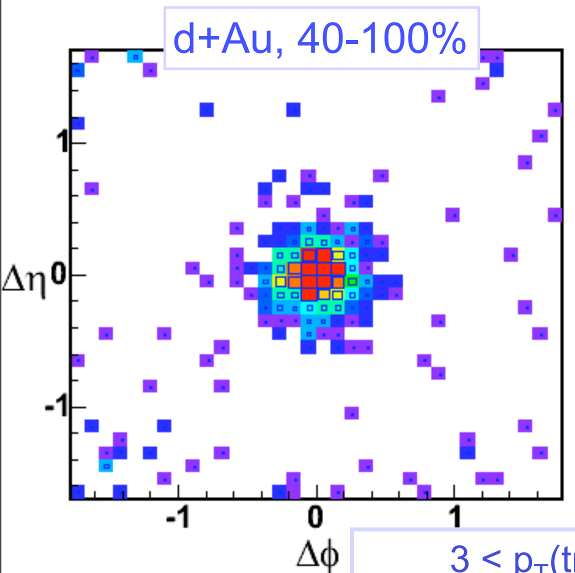
C. Nattrass QM2008

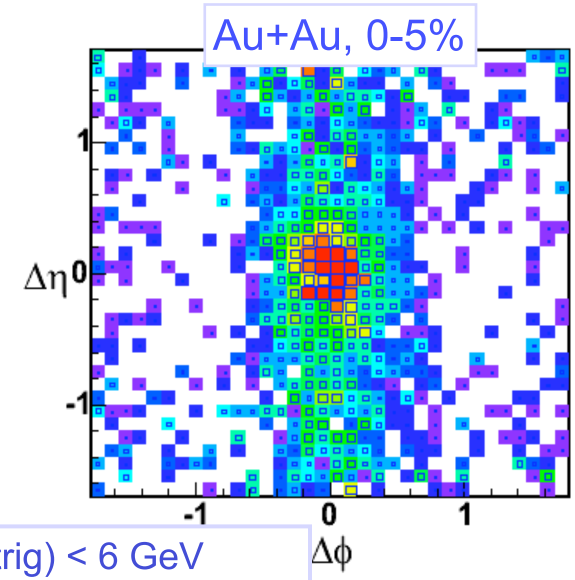


Ridge: Increases with N_{part}
Independent of colliding system

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

Energy loss of trigger -“The ridge”





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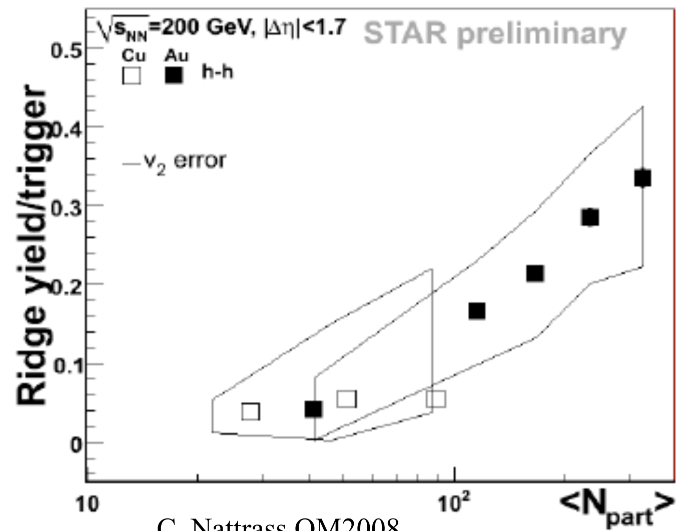

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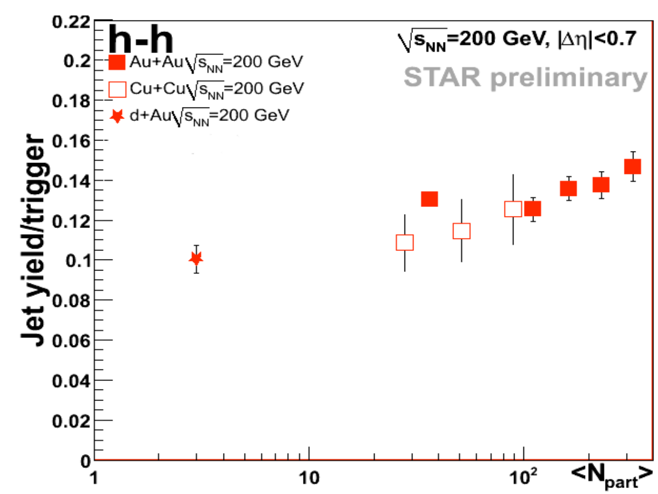


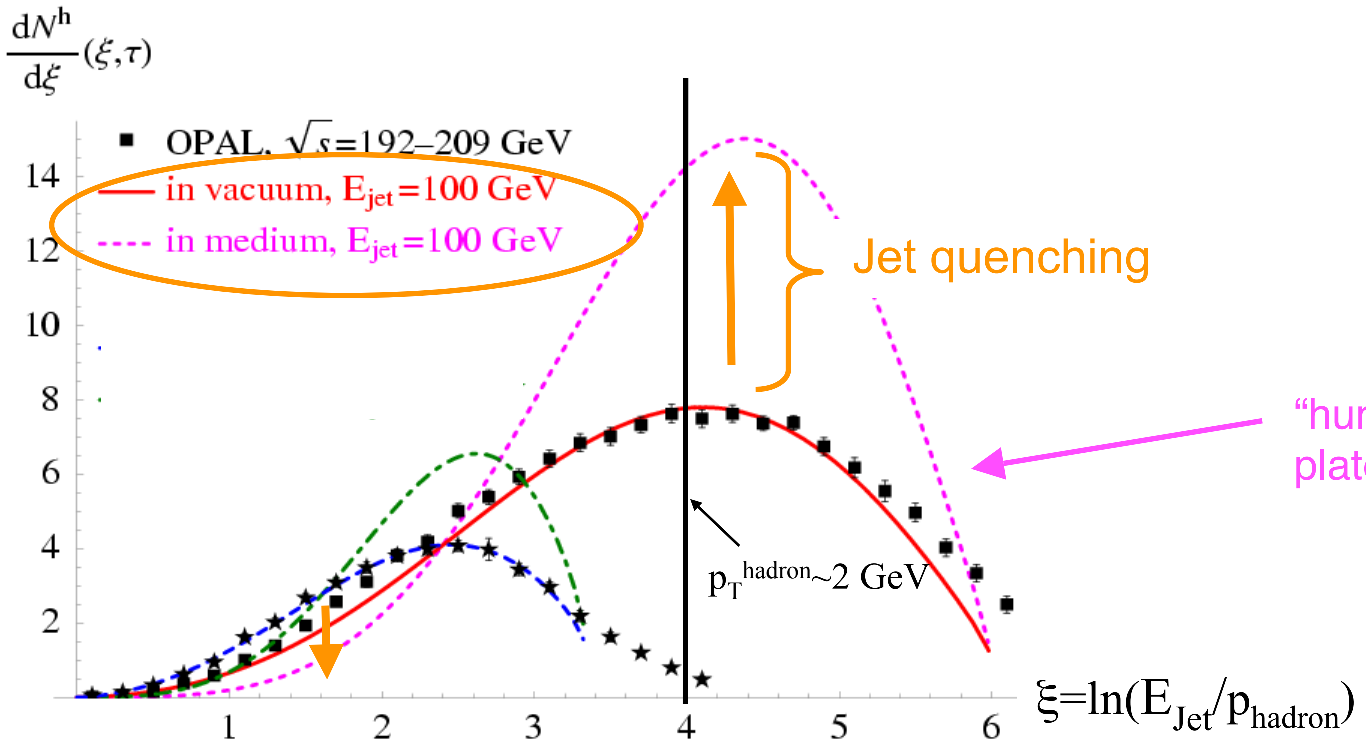
Ridge: Increases with N_{part}
Independent of colliding system

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

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

Modification of fragmentation function

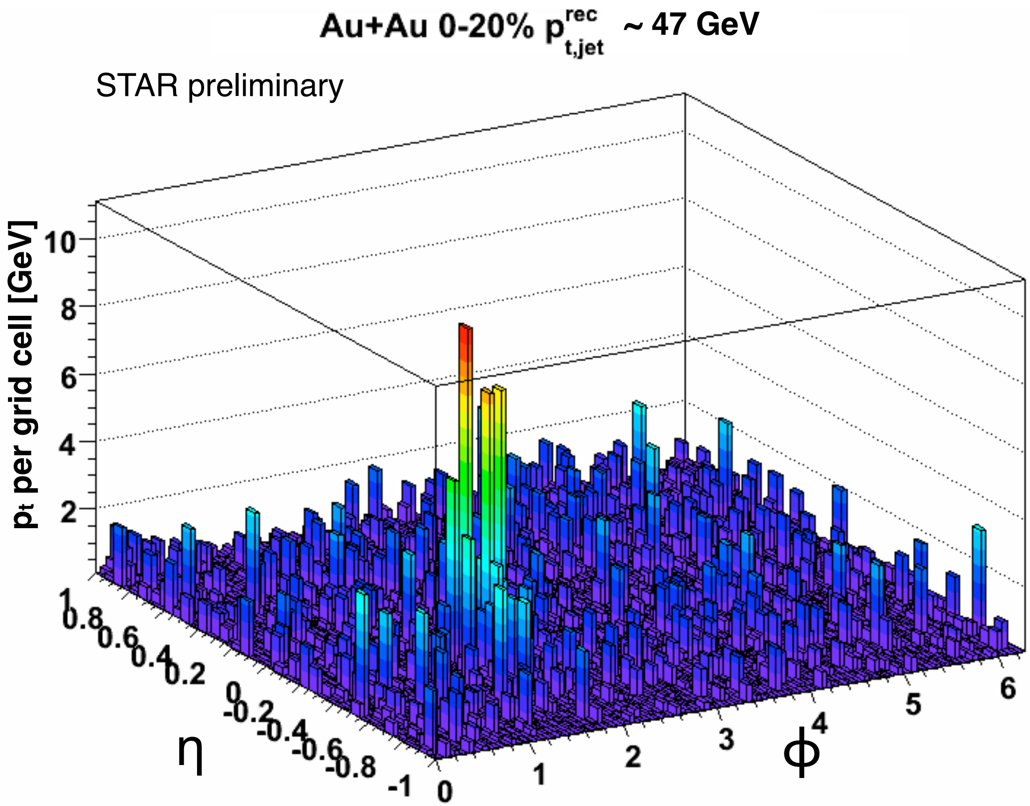
- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*



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

Can we measure this at RHIC?

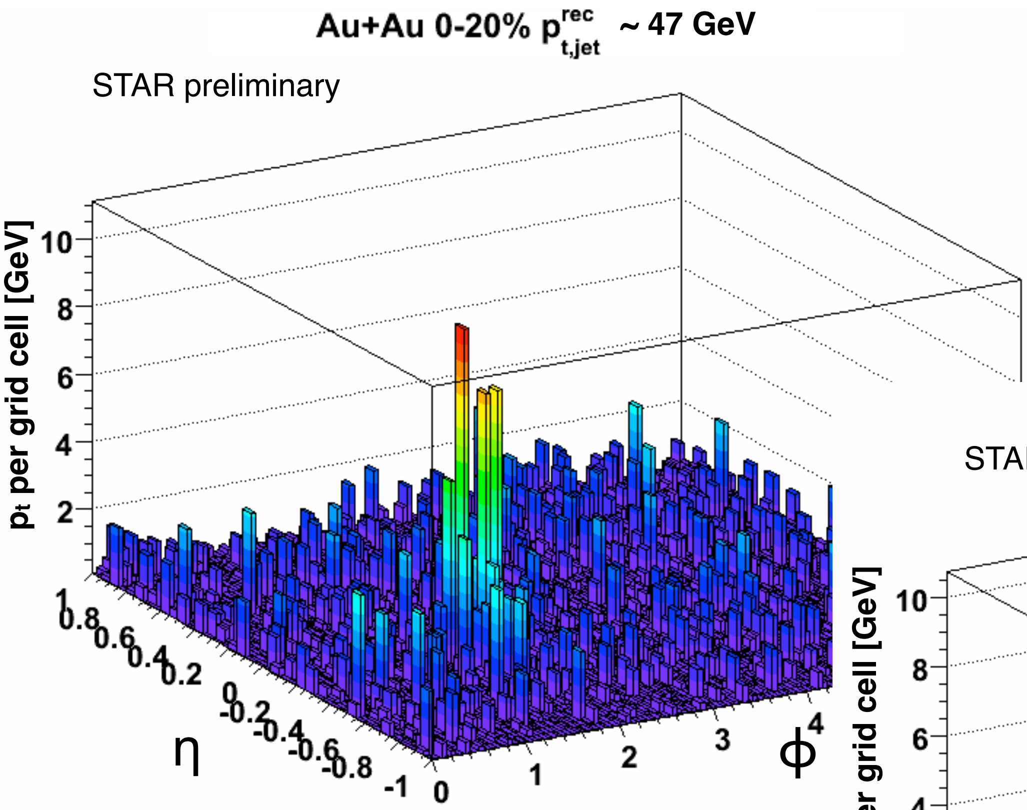
Jets @ RHIC in Au-Au collisions



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

J. Putschke Hard Probes 2008

Jets @ RHIC in Au-Au collisions



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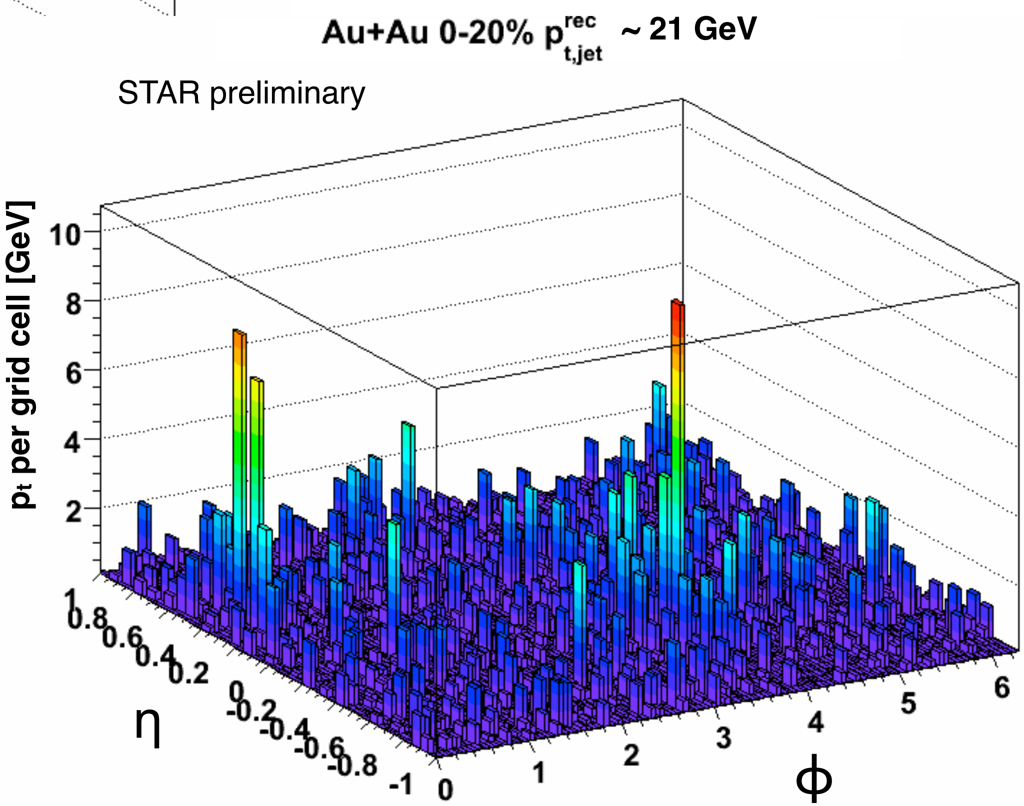

Energies as low as 20 GeV resolvable

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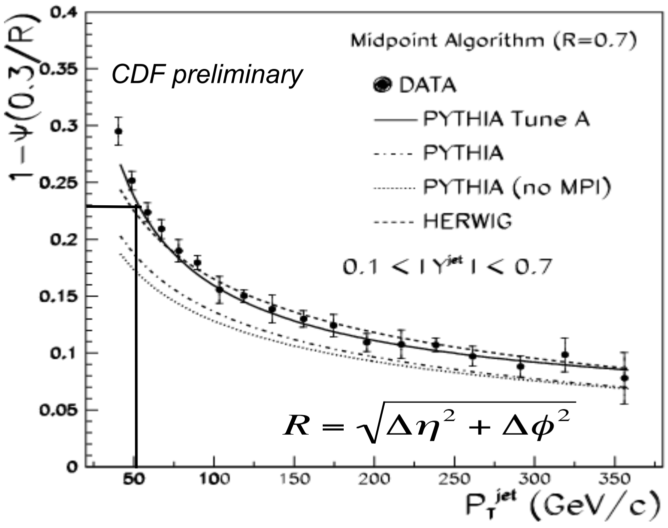
Jet-finding strategies in heavy-ion

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

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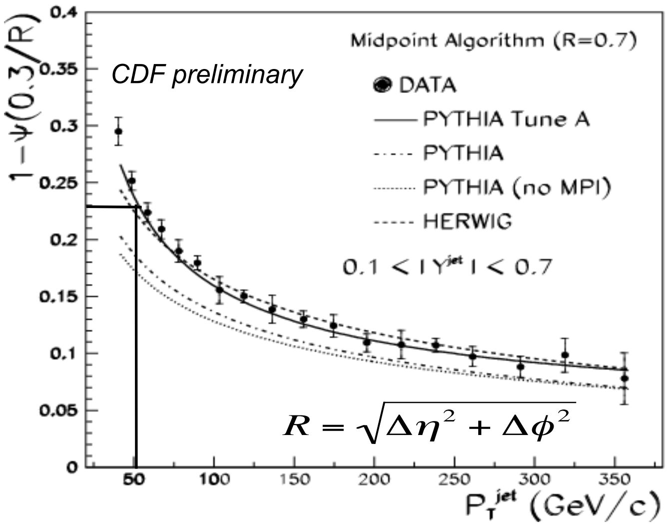

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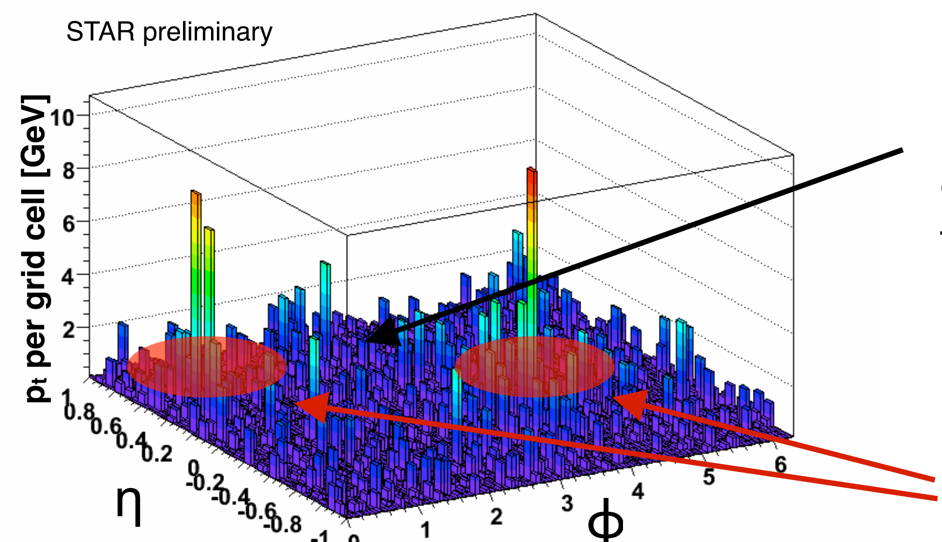
Estimate background E-by-E by sampling Out-of-Cone area:



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

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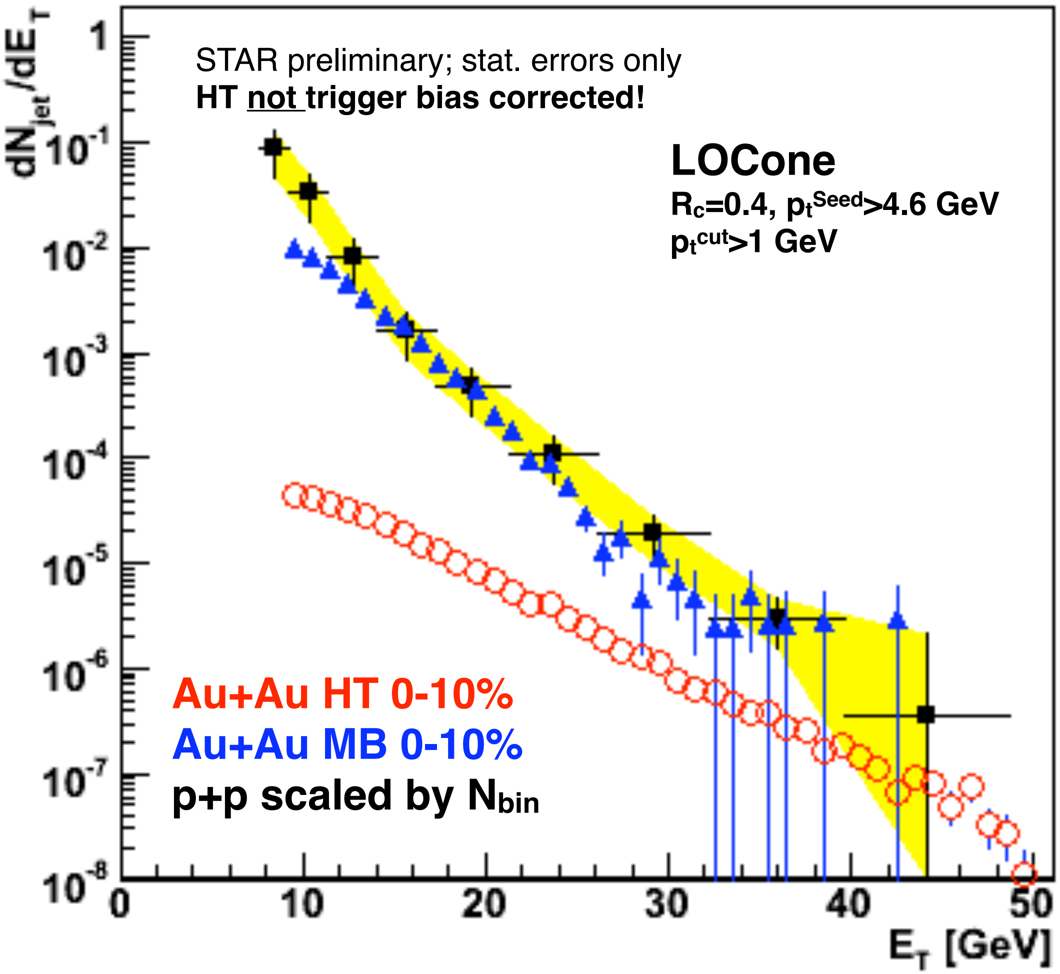
Jet spectrum in Au+Au collisions



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.

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

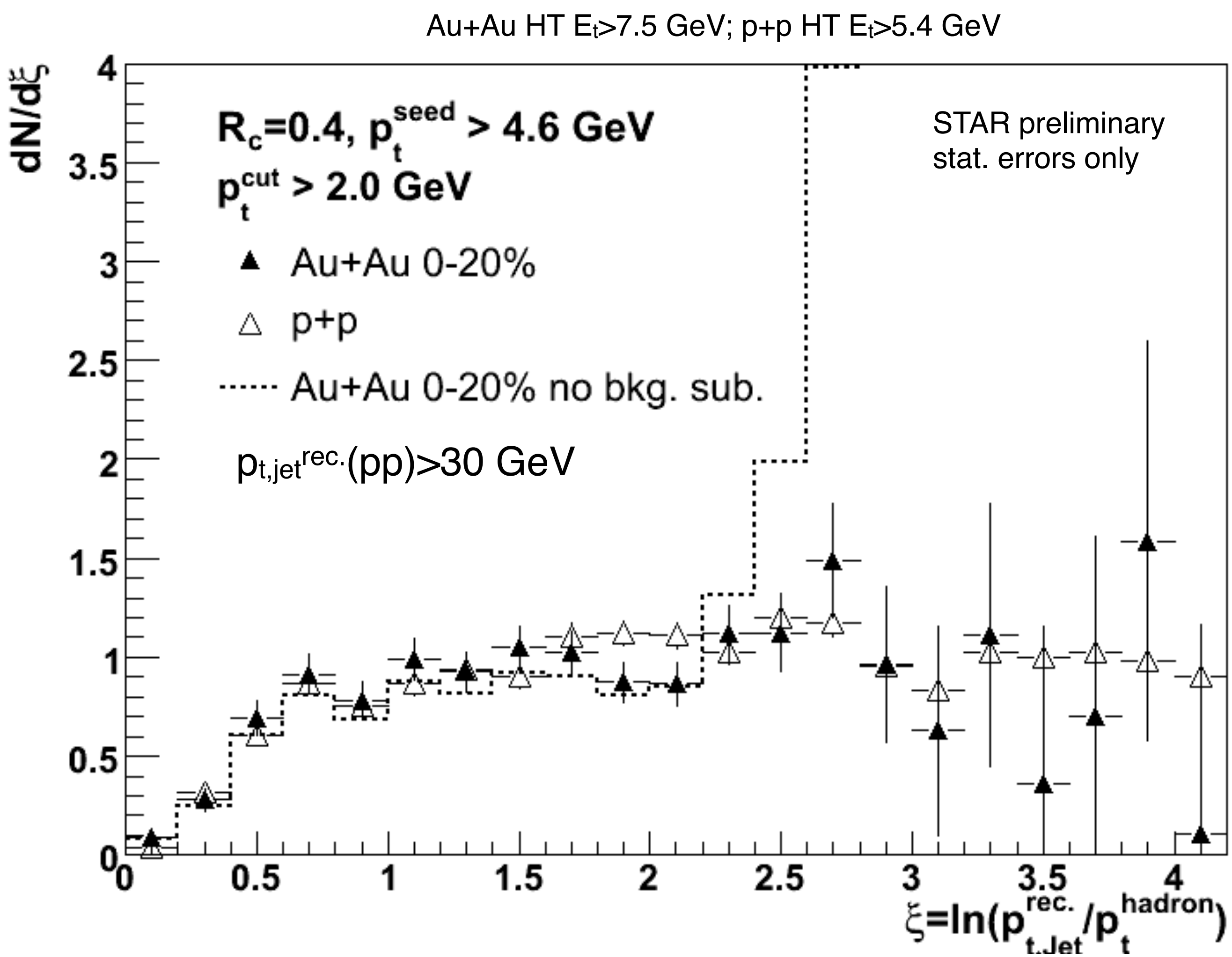
blue solid points: Au+Au minbias corrected for p_t^{cut} and eff. using Pythia

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

First reconstructed jet in central heavy ion collisions.

S. Salur Hard Probes 2008

Fragmentation function ratio Au+Au



$p_{t,jet}^{rec.}$(pp)>30 GeV

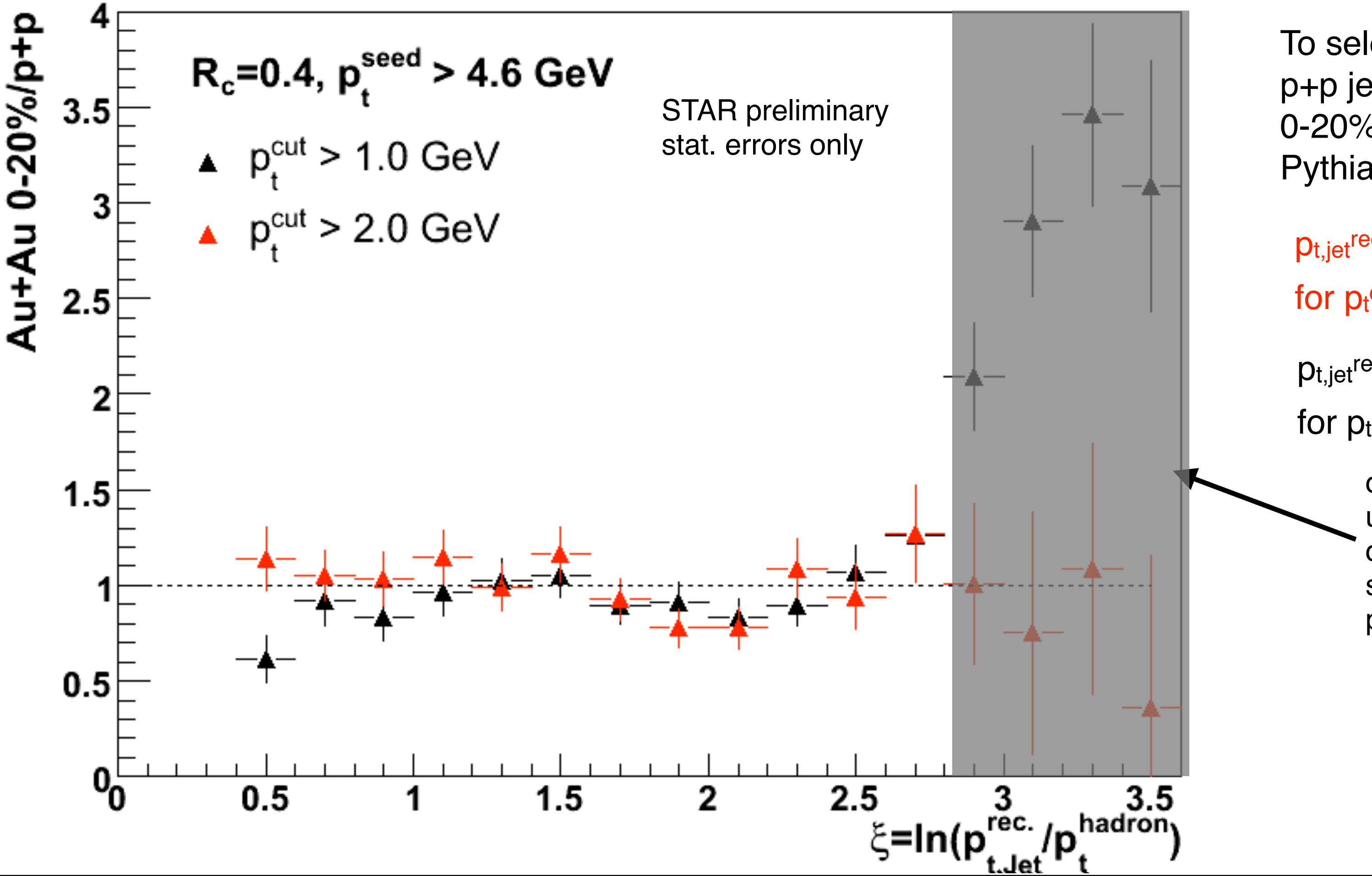
To select corresponding p+p jet-population in 0-20% Au+Au based on Pythia simulations:

$p_{t,jet}^{rec.}$(Au+Au)>31 GeV for p_t^{cut}>2 GeV

$p_{t,jet}^{rec.}$(Au+Au)>35 GeV for p_t^{cut}>1 GeV

J. Putschke Hard Probes 2008

Fragmentation function ratio Au+Au



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No apparent modification in the fragmentation function with respect to p+p !?

Caveat: ξ not corrected for jet energy shift due to quenching. Need MC quenching models !

J. Putschke Hard Probes 2008

RHIC "Summary"

We create a strongly coupled medium ⇒ sQGP

- **not** the asymptotically plasma of "free" quarks and gluons as expected
- 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
- New phenomena (e.g. ridge) challenge our understanding
- much remains to be done: EOS, initial conditions (ultimately needs EIC)

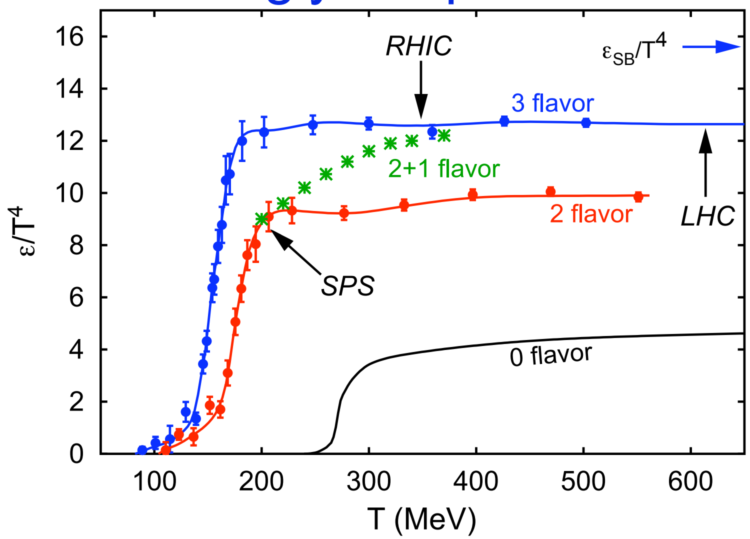
Next steps

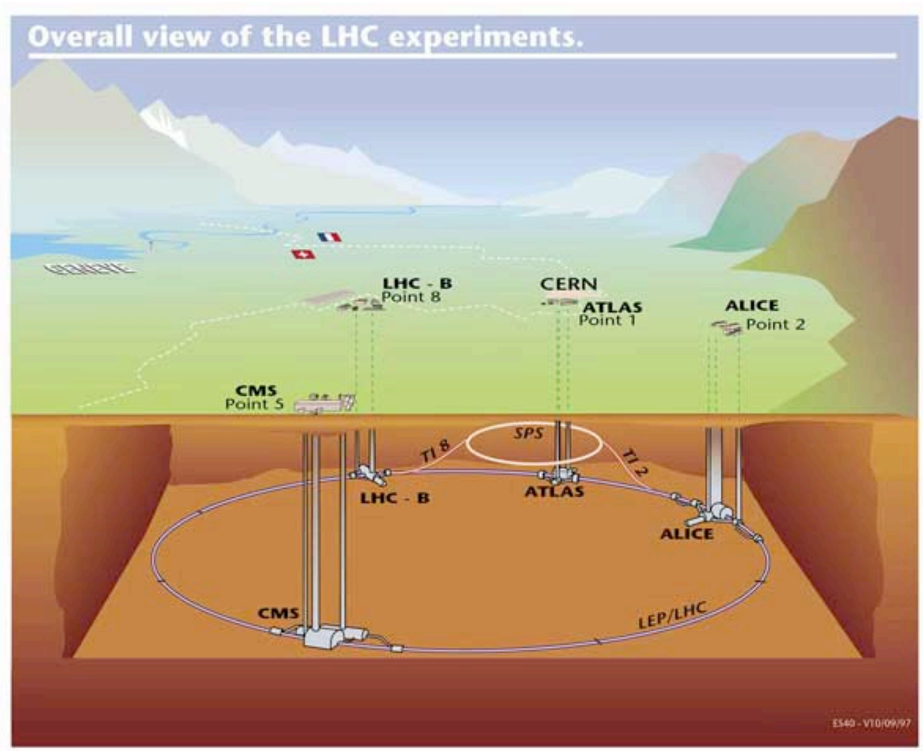
- Ongoing upgrades to STAR and PHENIX
  - Vertex detectors, increased coverage and PID, improved triggering capabilities ⇒ rare probes, heavy flavor, γ-jet, ...
- Electron Beam Ion Source (EBIS) to extend ranges of species (U+U)
- RHIC-II: increase luminosity by factor 5 using stochastic cooling

The Next Energy Frontier: LHC

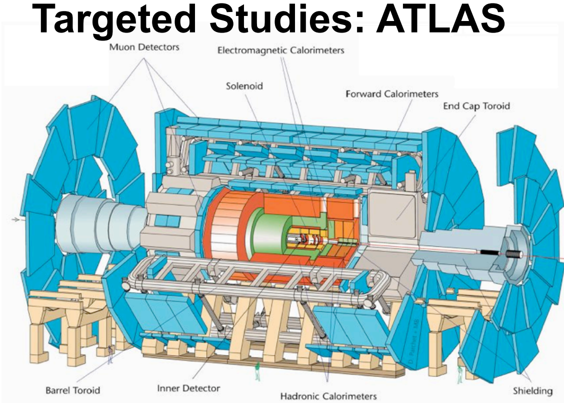
A unique opportunity to investigate "QGP" at unparalleled high √s

Will this too create a strongly-coupled fluid?

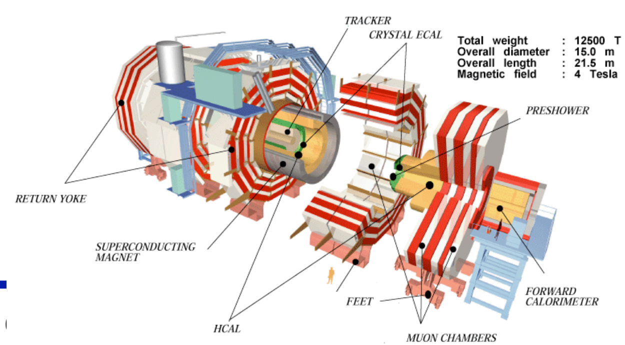




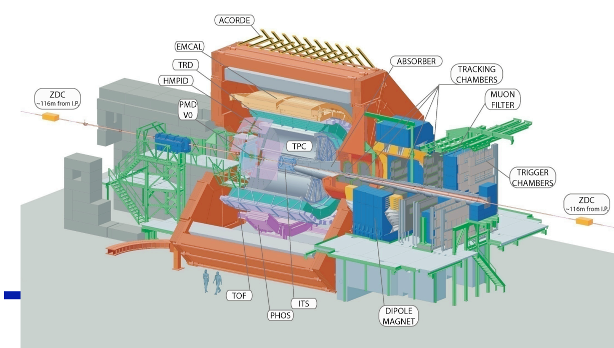
Targeted Studies: ATLAS



Targeted Studies: CMS



Dedicated Experiment: ALICE

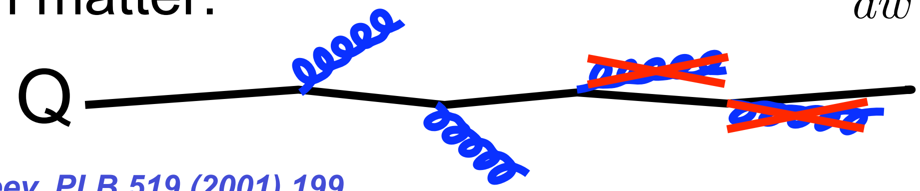


END

High-p_T Heavy Quarks are Gray Probes

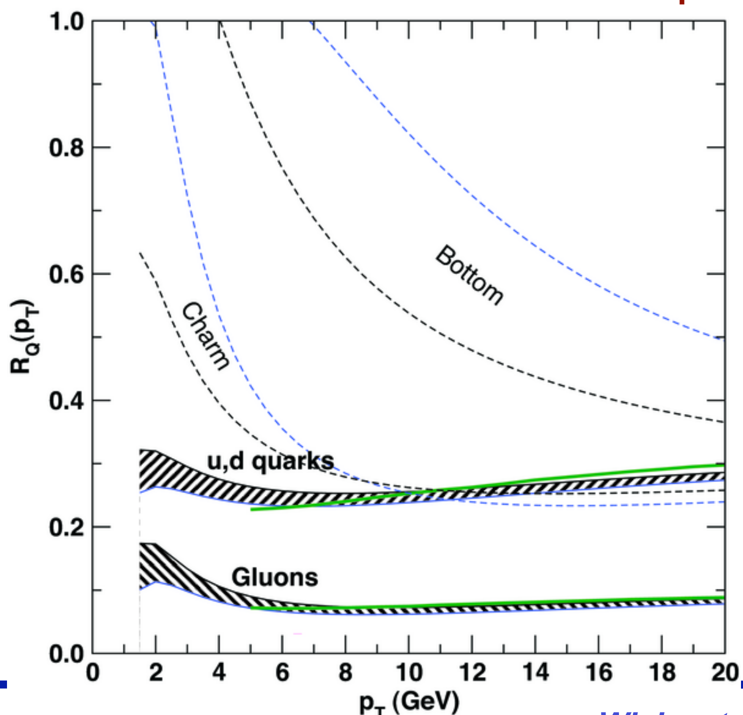
Dead cone effect implies lower heavy quark energy loss in matter:

$$\omega \frac{dI}{dw}\Big|_{\mathrm{HEAVY}} = \frac{\omega \frac{dI}{dw}\Big|_{\mathrm{LIGHT}}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

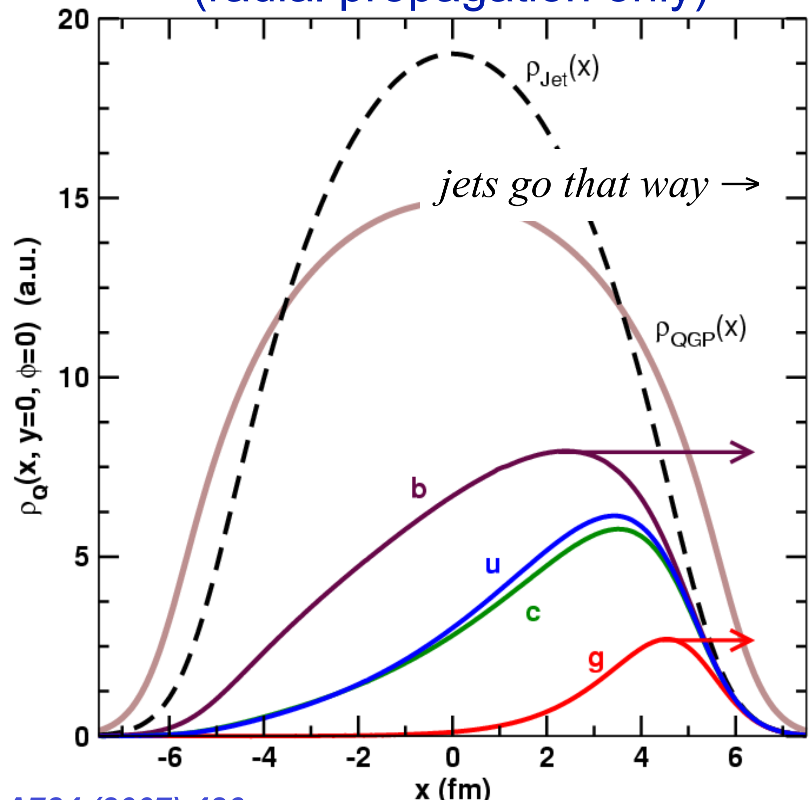


Dokshitzer and Kharzeev, PLB 519 (2001) 199.

- Problem: interaction with the medium so strong that information lost: “Black”⇒ use different probe



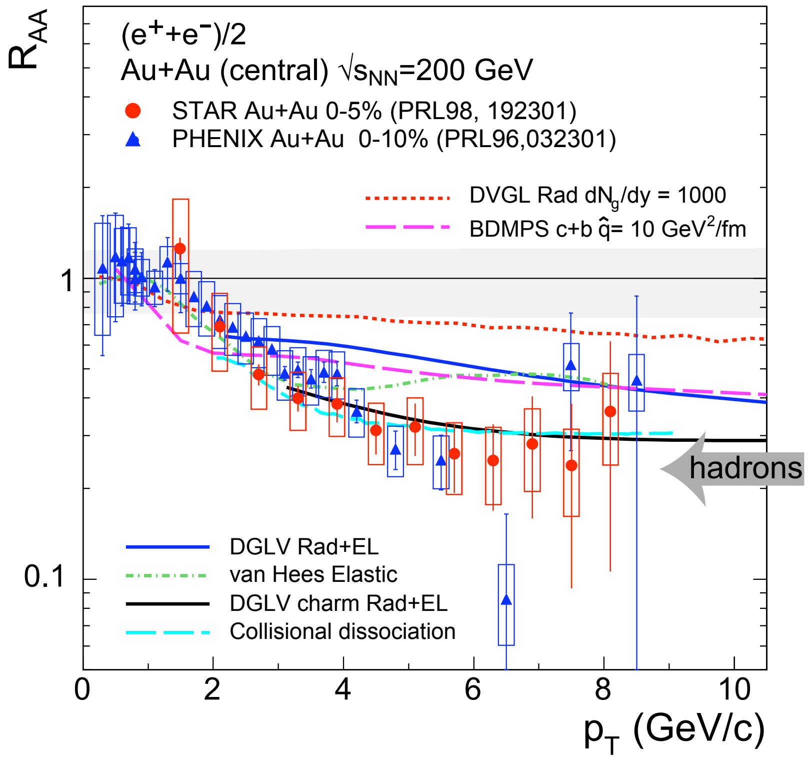
Origin of surviving jets p_T= 15 GeV (radial propagation only)



Wicks et al, Nucl. Phys. A784 (2007) 426

Big Surprise: Charm is Suppressed (is not Gray)

electrons from heavy flavor c,b → e K ν NLO (FONLL): c/b → e X



- Substantial suppression on same level to that of light mesons
- Describing the suppression is difficult for models
  - radiative energy loss | collisional E-loss | fragmentation and dissociation in medium
- What's about bottom?

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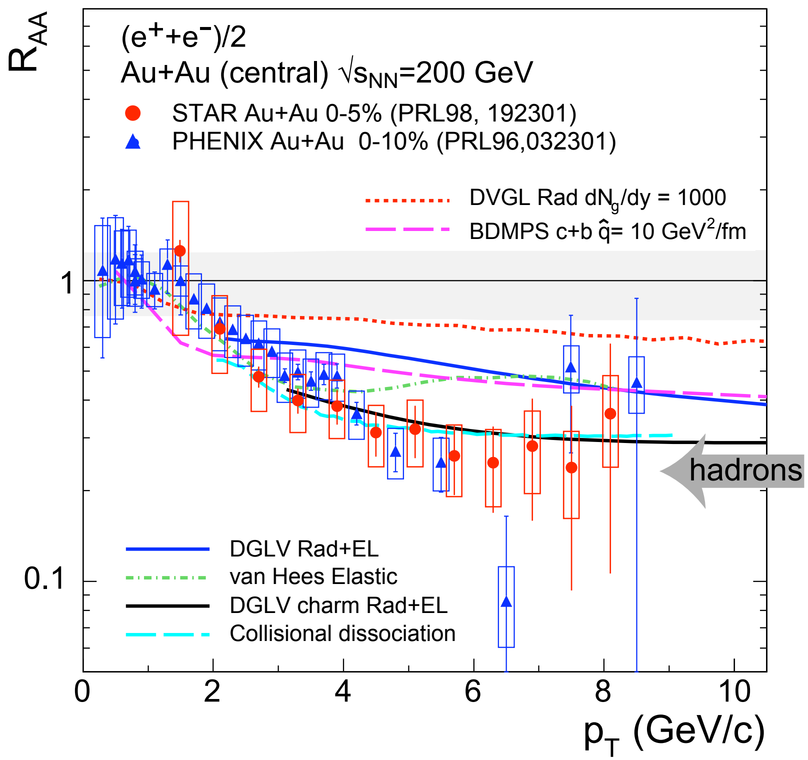
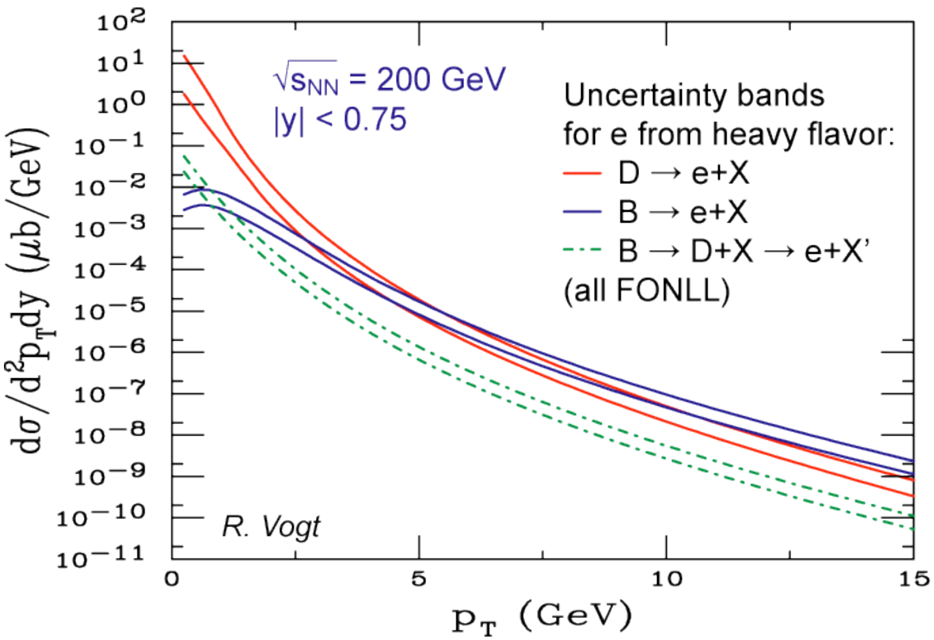


NLO (FONLL): c/b → e X



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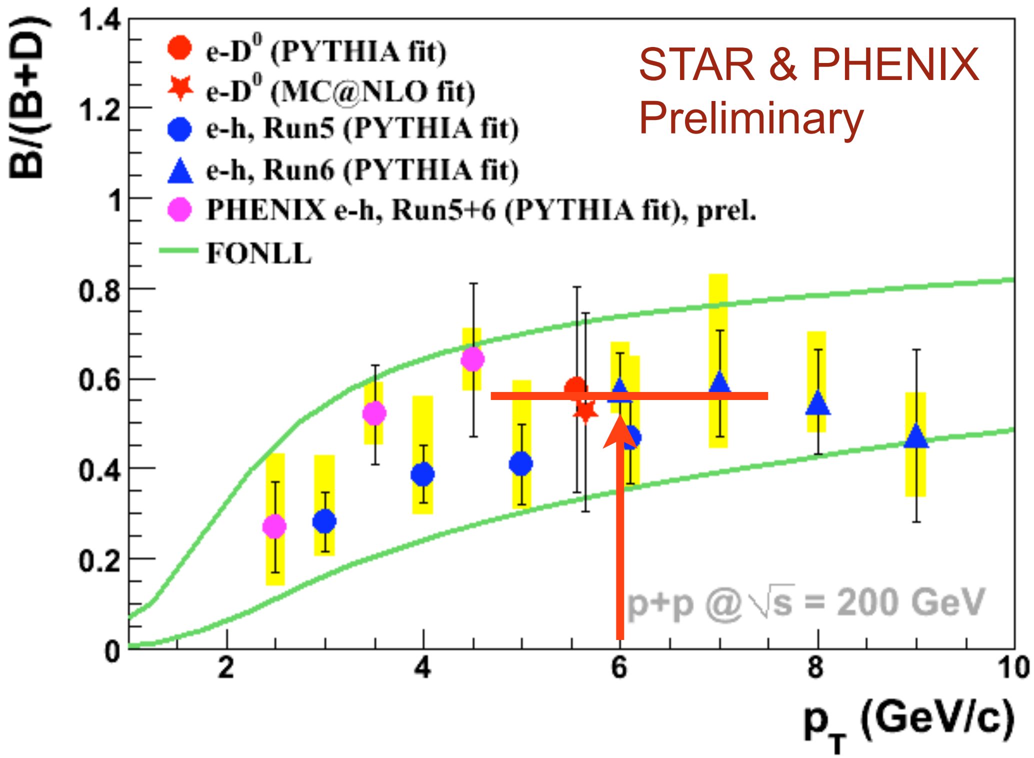
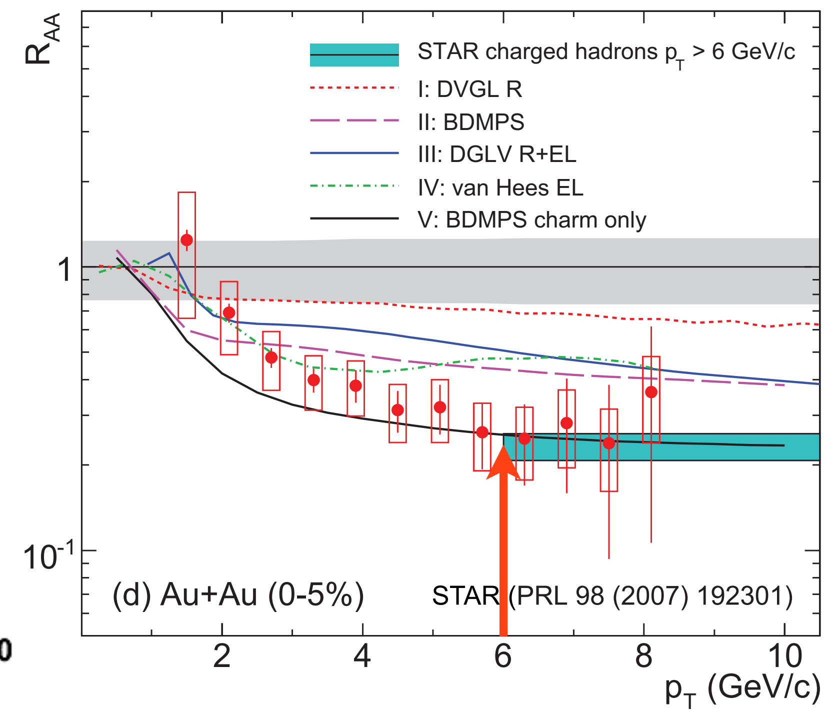
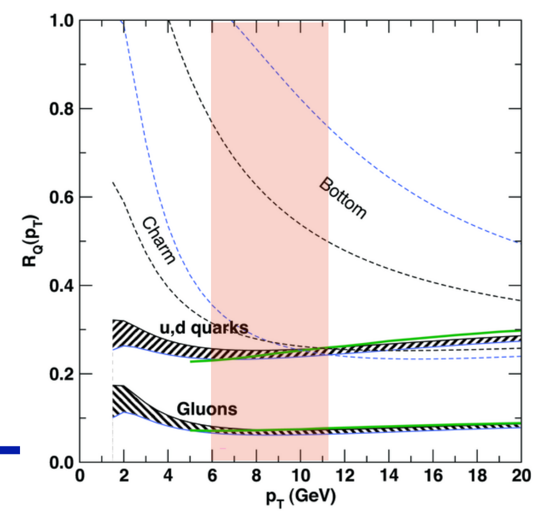
It Gets Worse ... Bottom Not Gray Either







Correlation measurements in STAR and PHENIX constrain beauty contribution to non-photonic electrons in p+p collisions

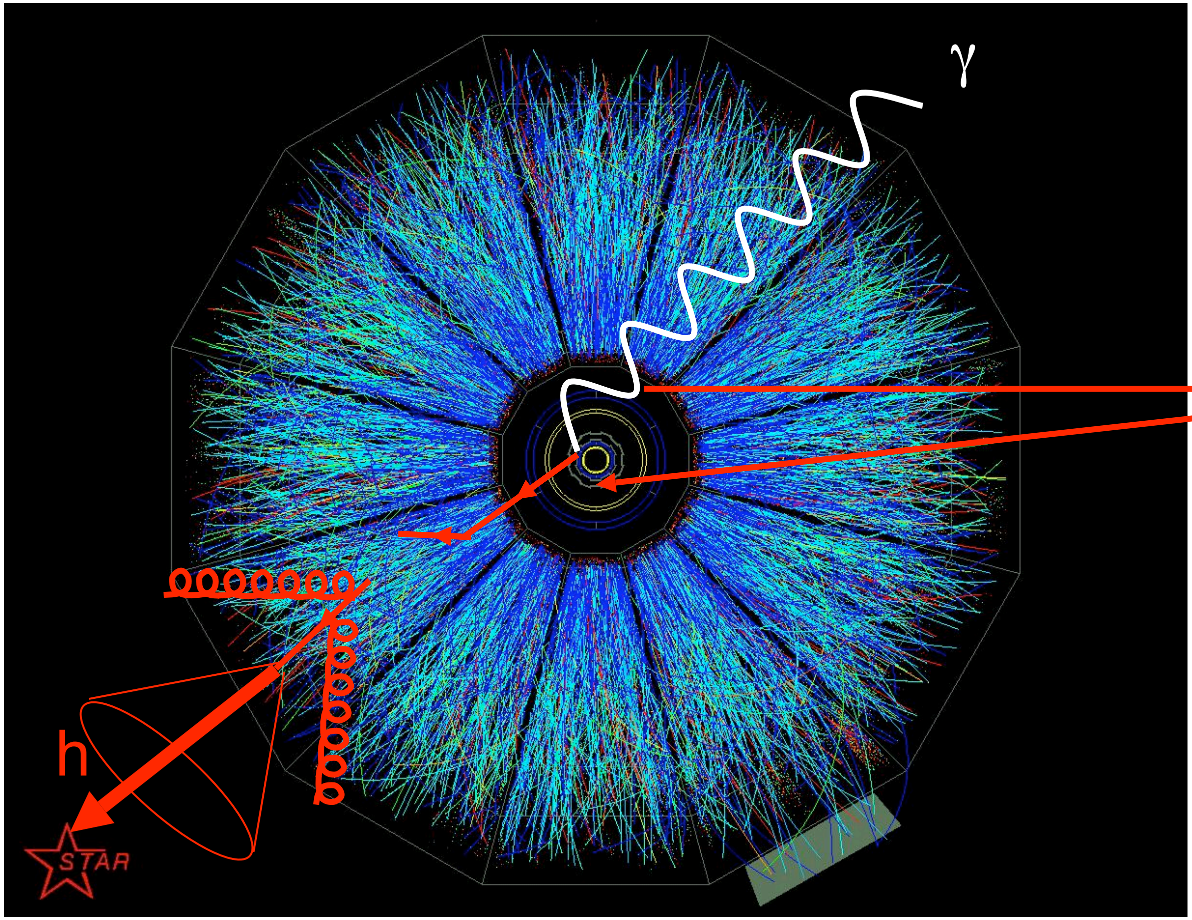
⇒ ~55% at p_T^e = 6 GeV/c

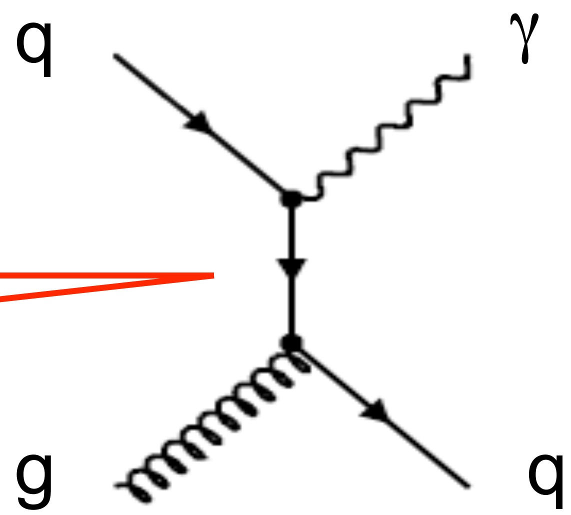
Beauty appears to be suppressed by more than predicted

Do we really understand energy loss ?

Detector upgrades still sorely needed to measure b and c R_{AA} accurately

Golden Probe of QCD Energy Loss - γ-

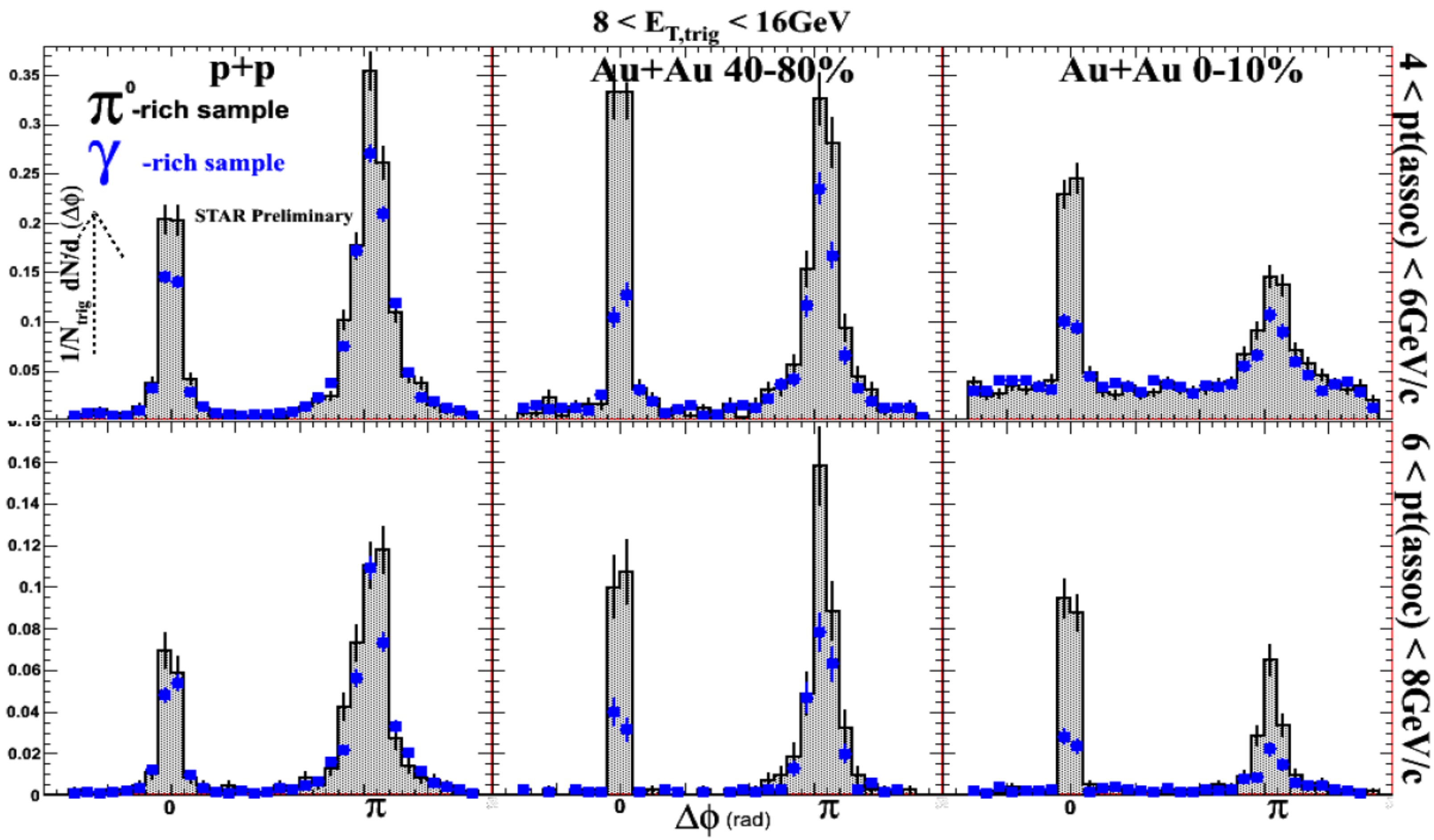




QCD analog of Compton Scattering

- γ emerges "unscathed" from medium
  - Full reconstruction of kinematics: real fragmentation function (D(z))

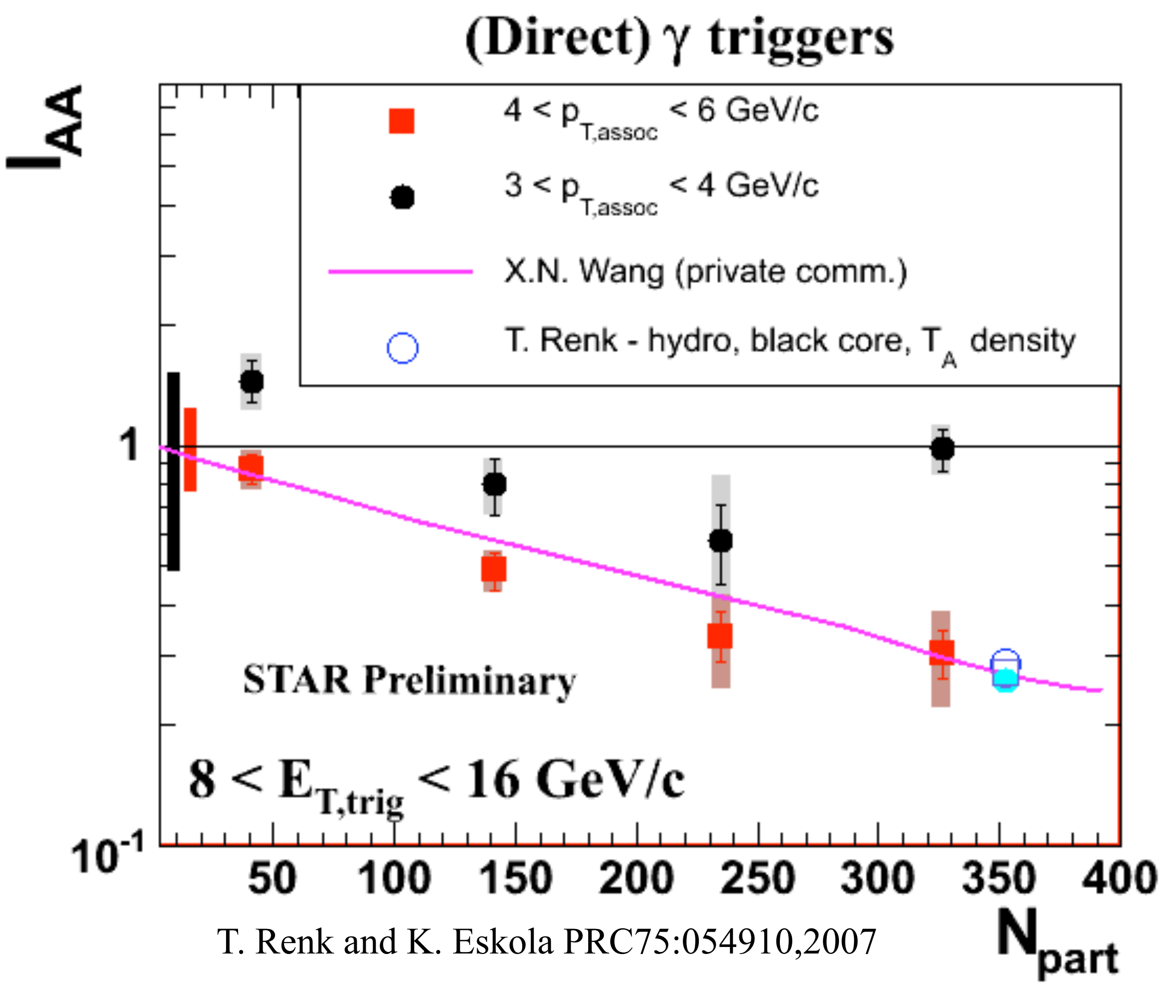
γ-hadron and π^0-hadron correlations



Shower shape in Shower Maximum Detector gives γ-, π^0-enriched samples

The γ-rich sample has lower near-side yield than π^0.

First measure of away-side I_{AA} for γ-h



T. Renk and K. Eskola PRC75:054910,2007

$E_{jet} = E_{\gamma} = E_{trig}$

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

$$D^{h_1 h_2}(z_T, p_T^{\rm trig}) = p_T^{\rm trig} \frac{d\sigma_{AA}^{h_1 h_2}/dp_T^{\rm trig} dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\rm trig}}$$

Good agreement between theory and measurement for higher p_{Tassoc}

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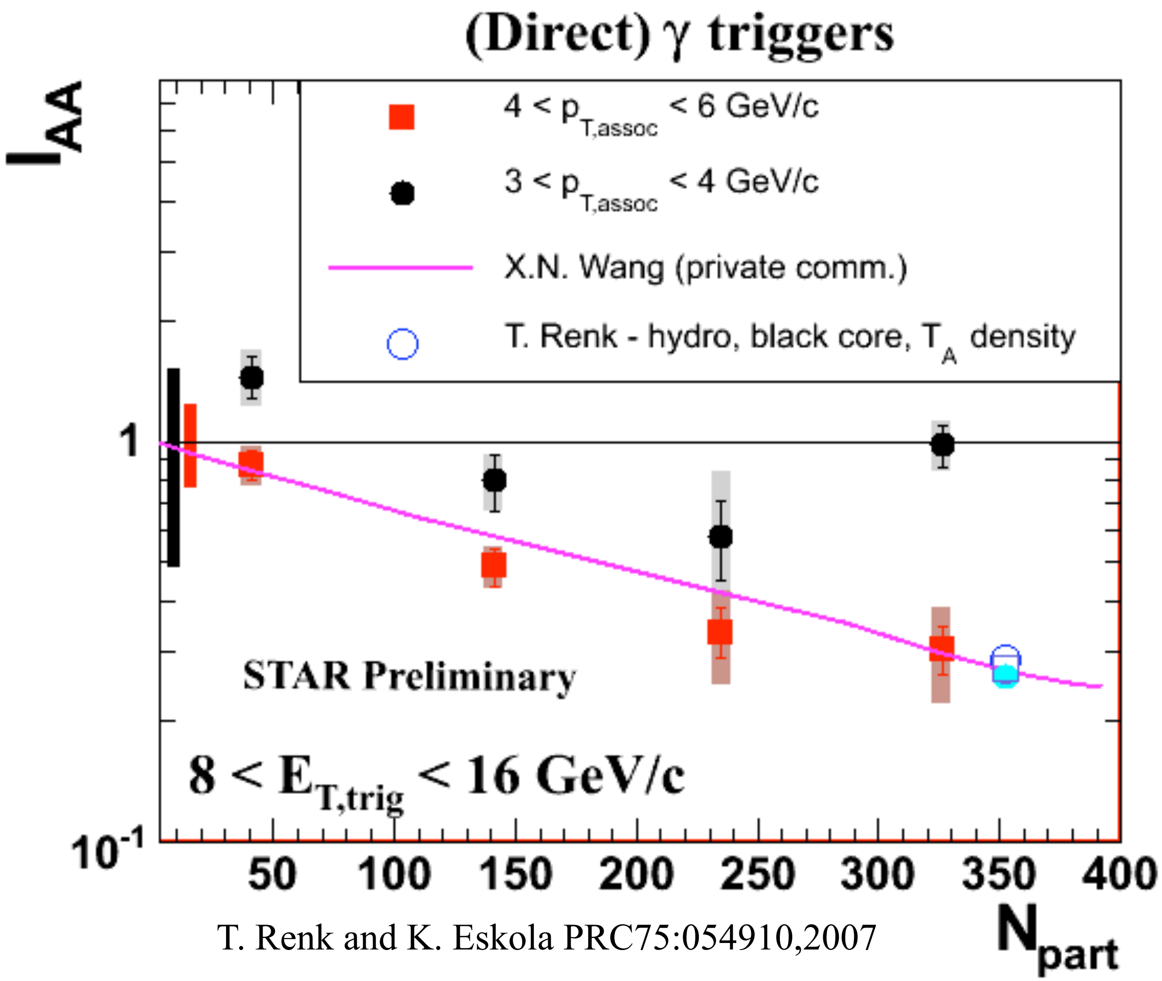

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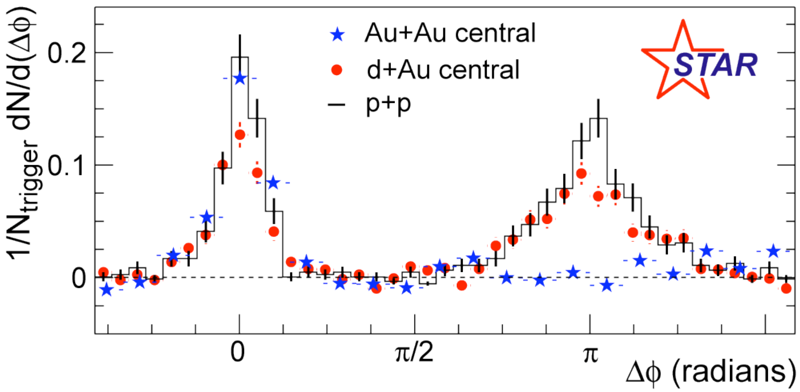
Suppression similar level to inclusives in central collisions

Parton interactions on near side

$\Delta(\phi)$ correlations



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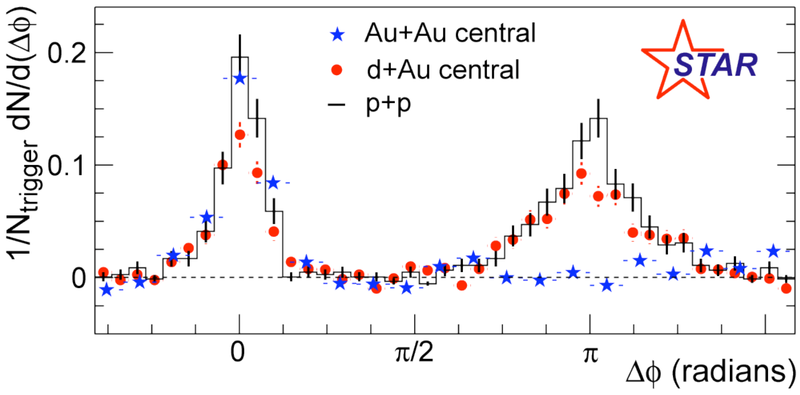
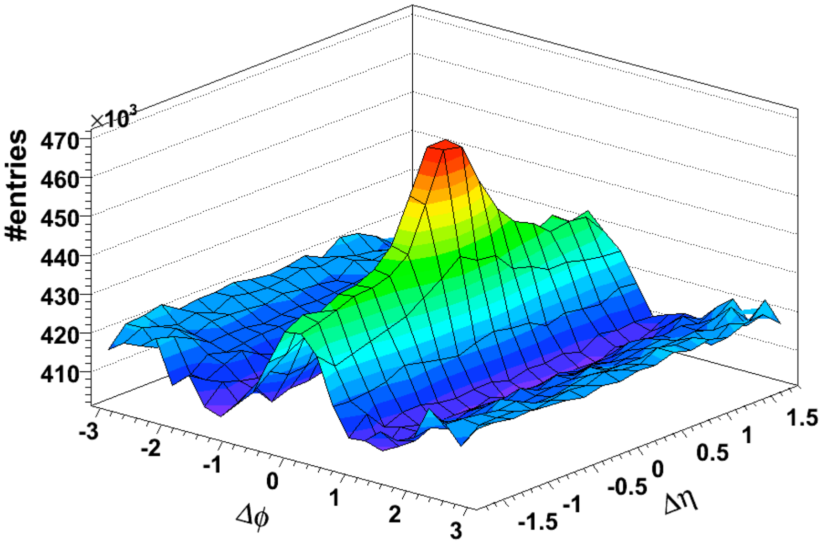


$\Delta(\eta)$ – $\Delta(\phi)$ correlations

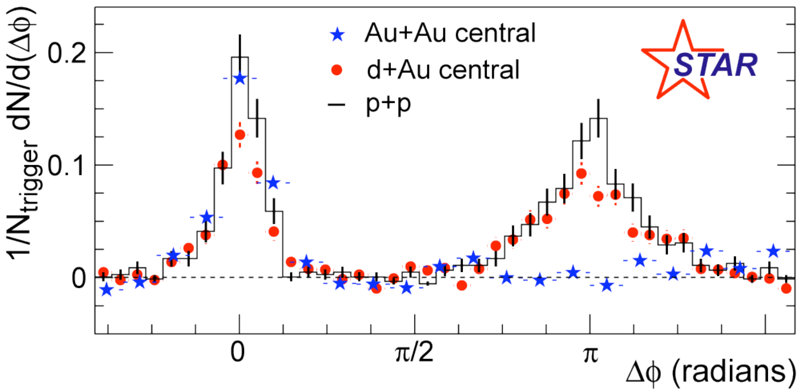


Long range $\Delta(\eta)$ correlation

– the "Ridge"

Parton interactions on near side

$\Delta(\phi)$ correlations



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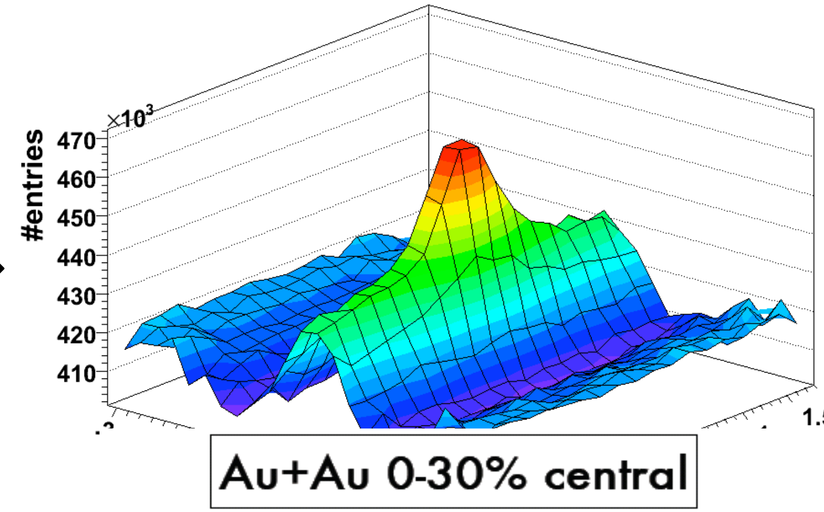

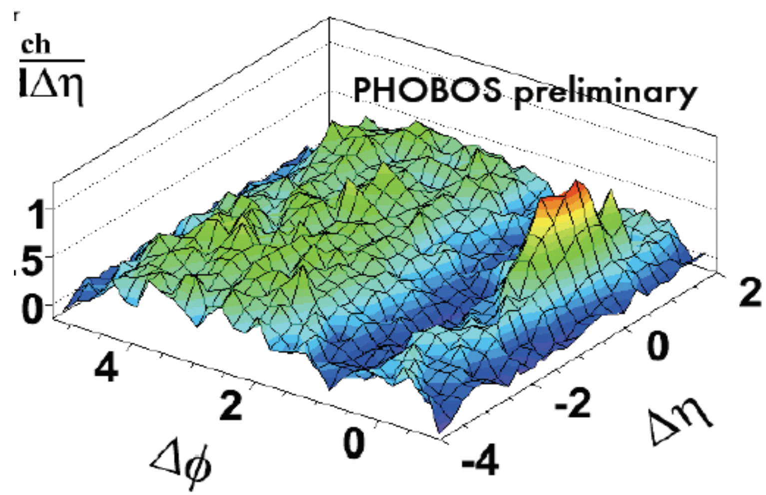

Long range $\Delta(\eta)$ correlation

– the "Ridge"

Persists out to very large $\Delta(\eta) > 2$