Highlights of the Highlights from STAR at QM 2008

Helen Caines - Yale University

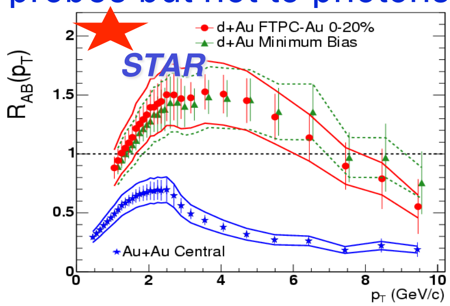
BNL QM 2008 Overview Symposium
Feb. 27th-29th 2008

Unashamedly derived from talks of B. Mohanty and T. Hallman

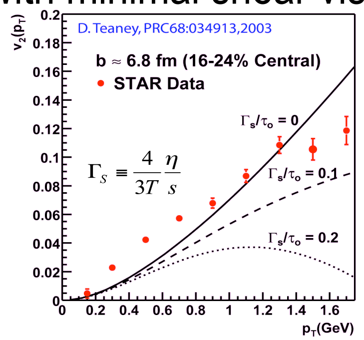
What we knew after QM2006

We make the hottest, densest matter yet examined in the laboratory

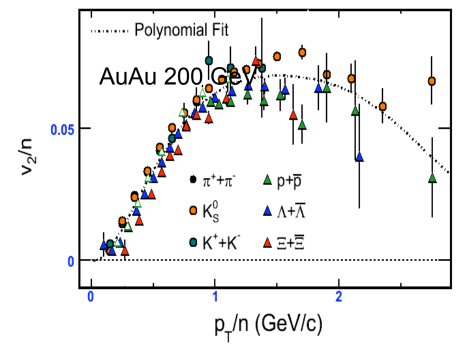
Highly opaque to colored probes but not to photons



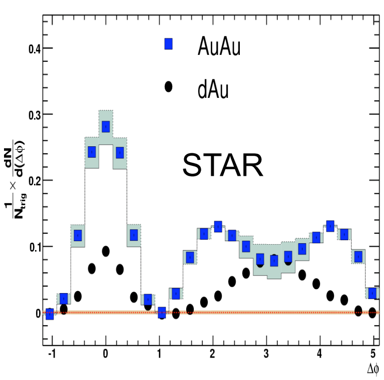
Flows as a relativistic quantum liquid with minimal shear viscosity



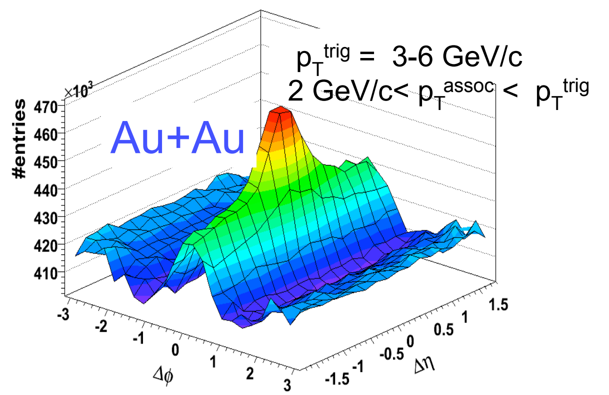
Particle formation via valence quark coalescence



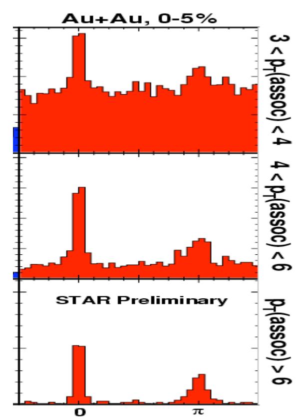
Away-side correlation shape modified



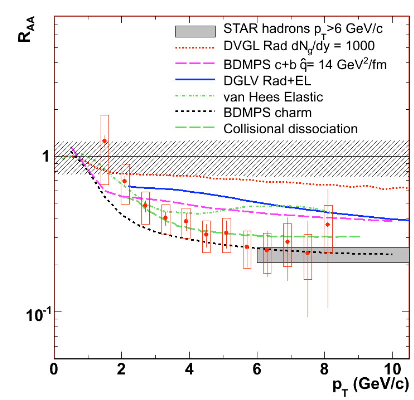
Enhance correlation in $\Delta\eta$ on the near-side - The "Ridge"



At high p_T di-jets re-emerge



Heavy quarks are also suppressed



Outline – What we've been looking at since

Medium properties	Physical phenomenon	Experimental probes
Energy density	Parton E_{loss} in the medium	High p_T particles, $\Delta\phi$ and $\Delta\eta$ correlations
Velocity of sound	Mach cones	3-particle correlations
Partonic interactions, Mechanism of E_{loss}	Non-Abelian features of QCD - Color factor effects, path length effects of E_{loss} Jet-medium coupling	High p_T particle production $\Delta\phi$ and $\Delta\eta$ correlations, correlations with respect to reaction plane
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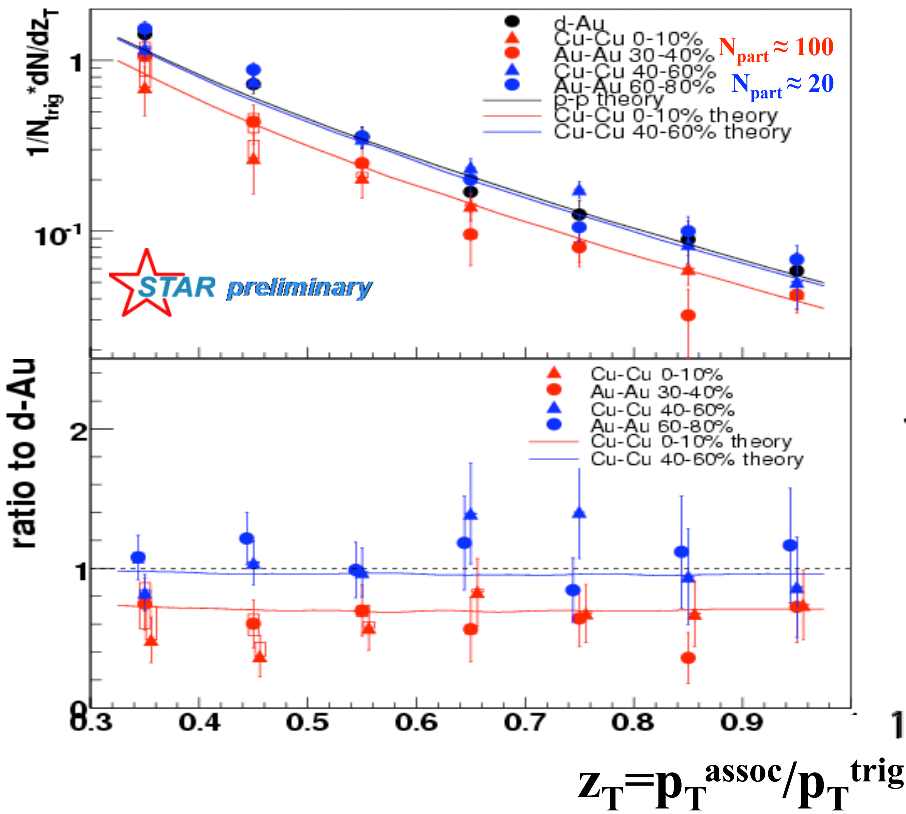
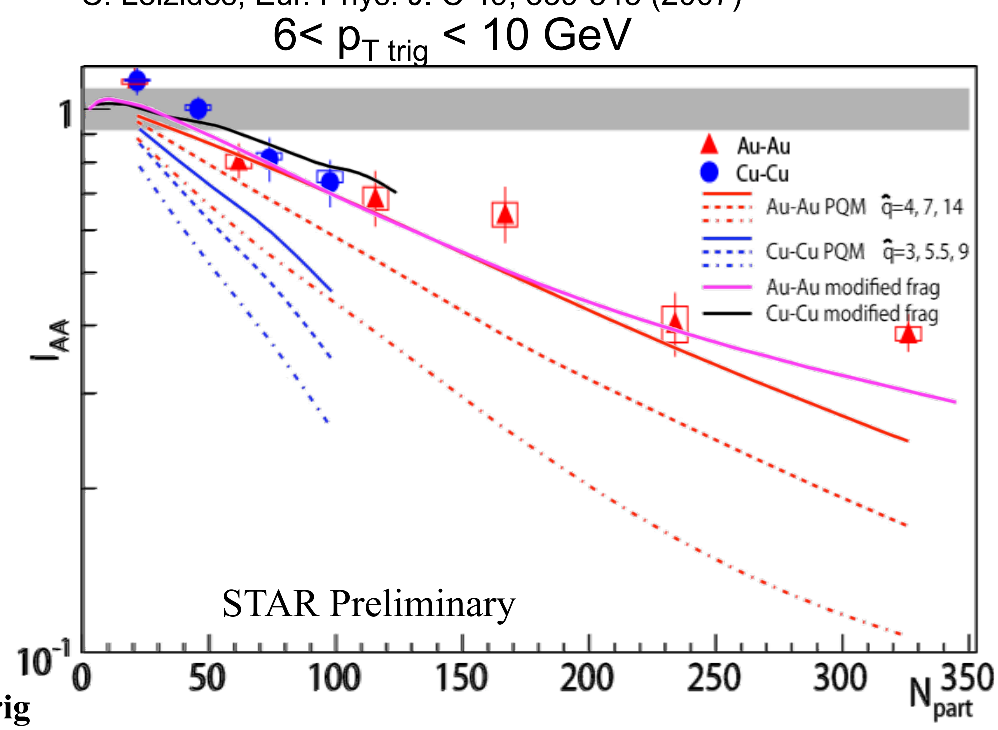
Away-side di-hadron fragmentation functions



H. Zhong et al., PRL 97 (2006) 252001

C. Loizides, Eur. Phys. J. C 49, 339-345 (2007)



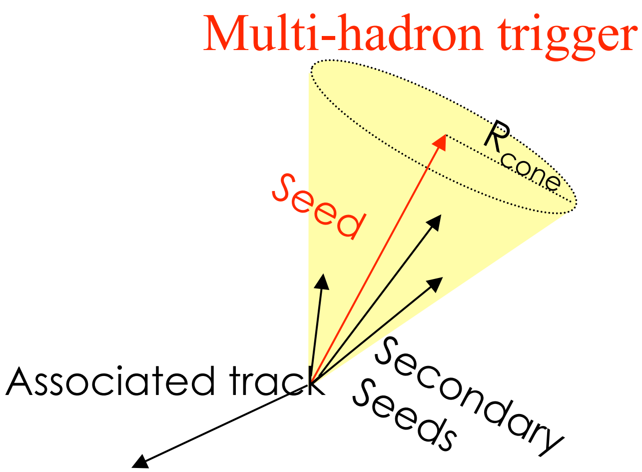
- Denser medium in central Au+Au than central Cu+Cu
- Similar medium for similar N_{part}
- Vacuum fragmentation after parton E_{loss} in the medium

- Inconsistent with Parton Quenching Model calculation
- Modified fragmentation model better

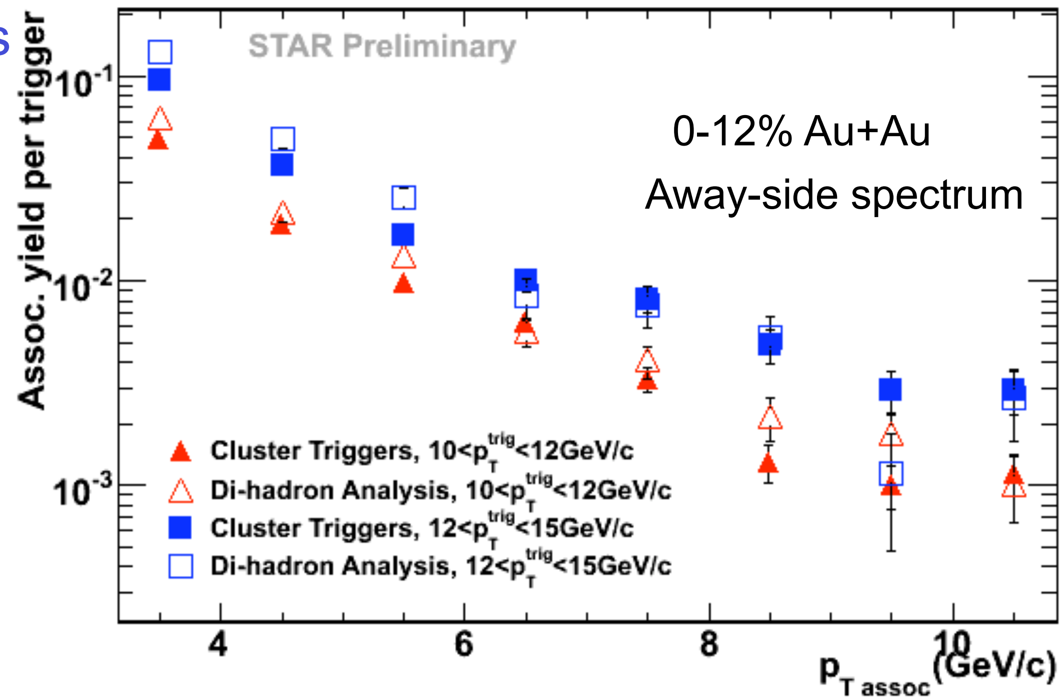
Towards true jet reconstruction

- Reduce leading trigger particle biases from di-hadron correlations

- First step to jet reconstruction in A+A



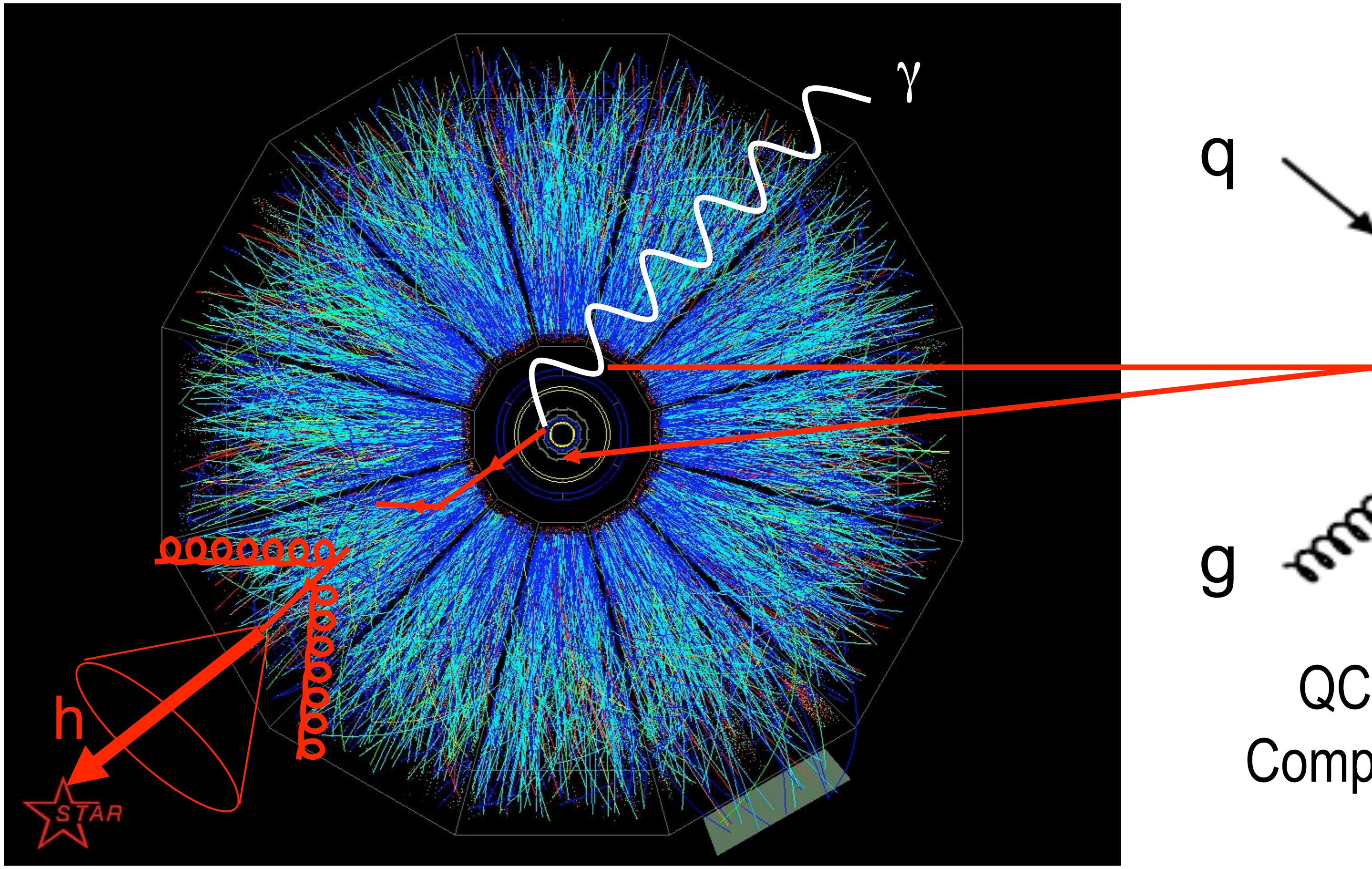
Use "cluster energy" as trigger:
- R_{cone} = 0.3
- $p_{T,seed}$ > 5 GeV
- $p_{T,sec\ seed}$ > 3 GeV

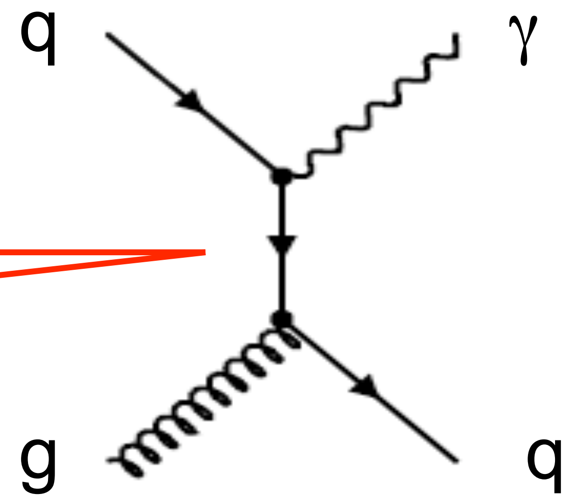


- Single-hadron trig. ≈ multi-hadron trig.

- Single high p_T triggered correlations probe jet-like correlations

Golden Probe of QCD Energy Loss - γ-Jet

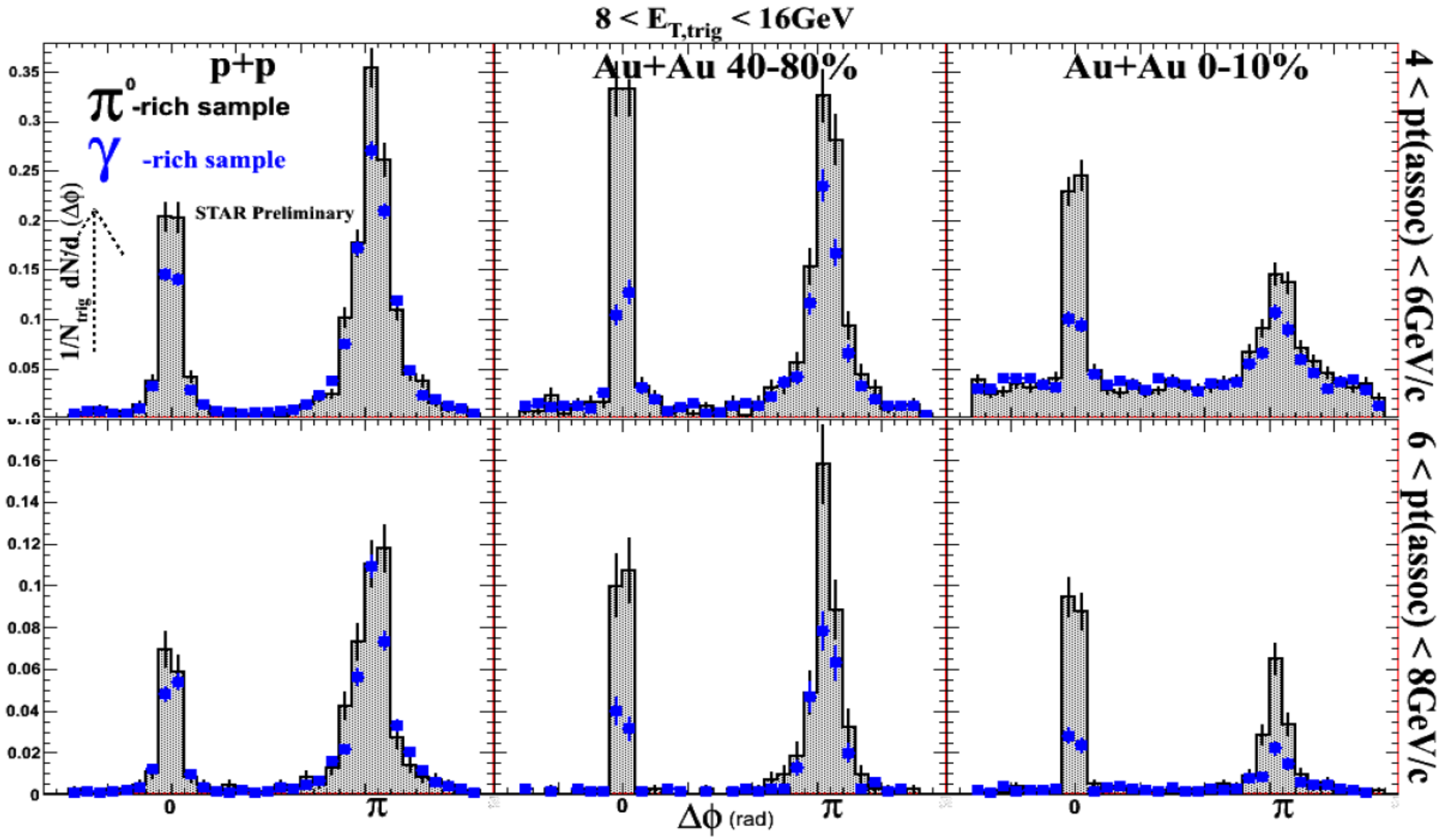




QCD analog of Compton Scattering

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

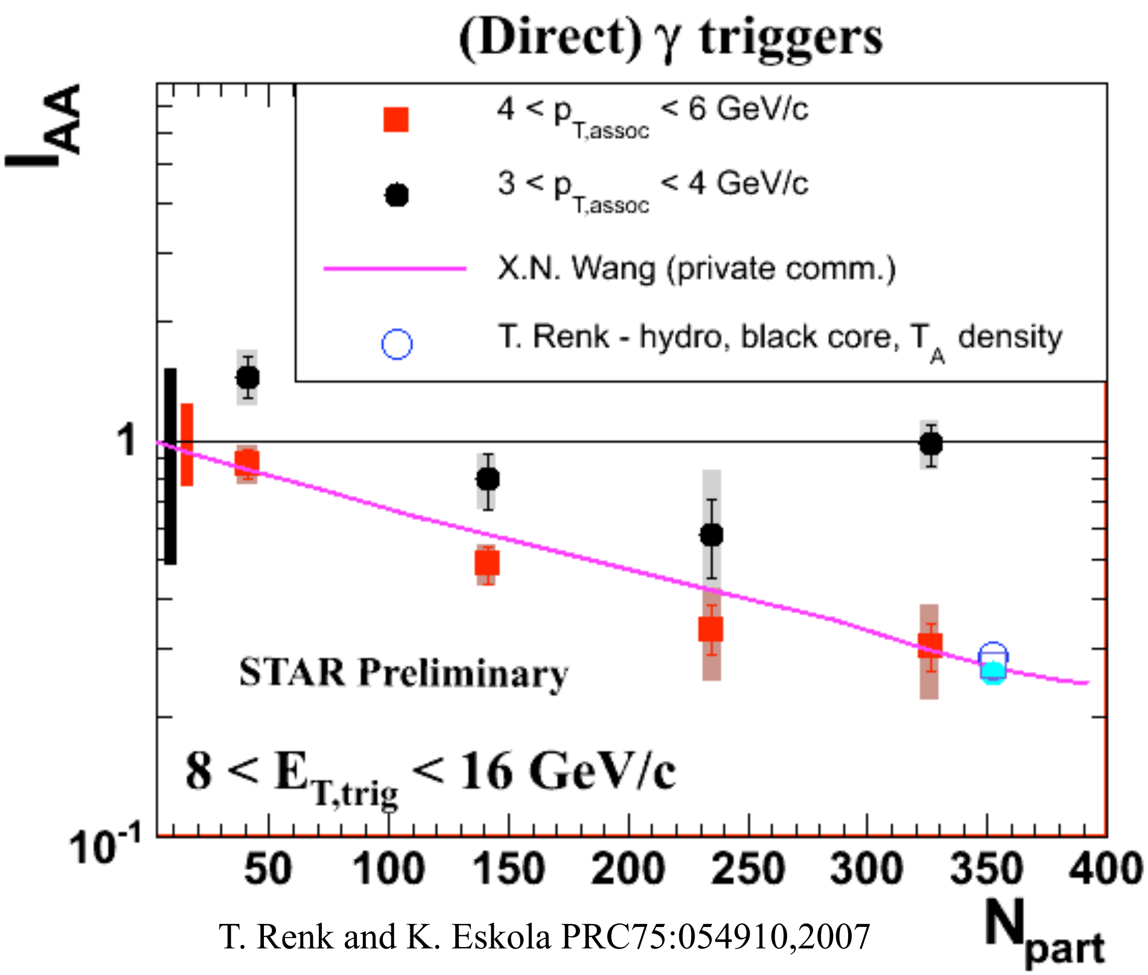
γ-hadron and π^0-hadron correlations



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

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

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

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

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

Suppression similar level to inclusives in central collisions

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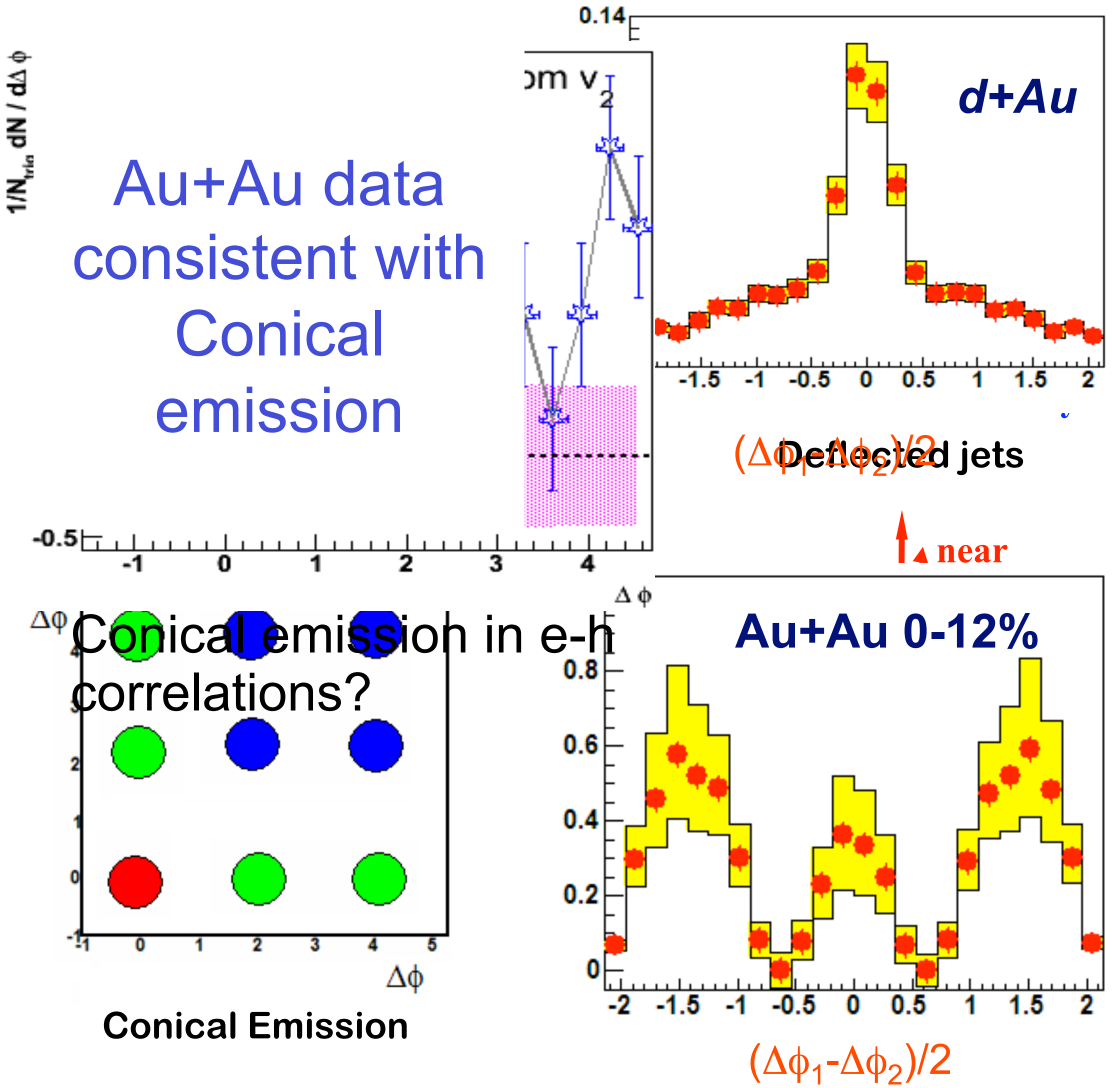
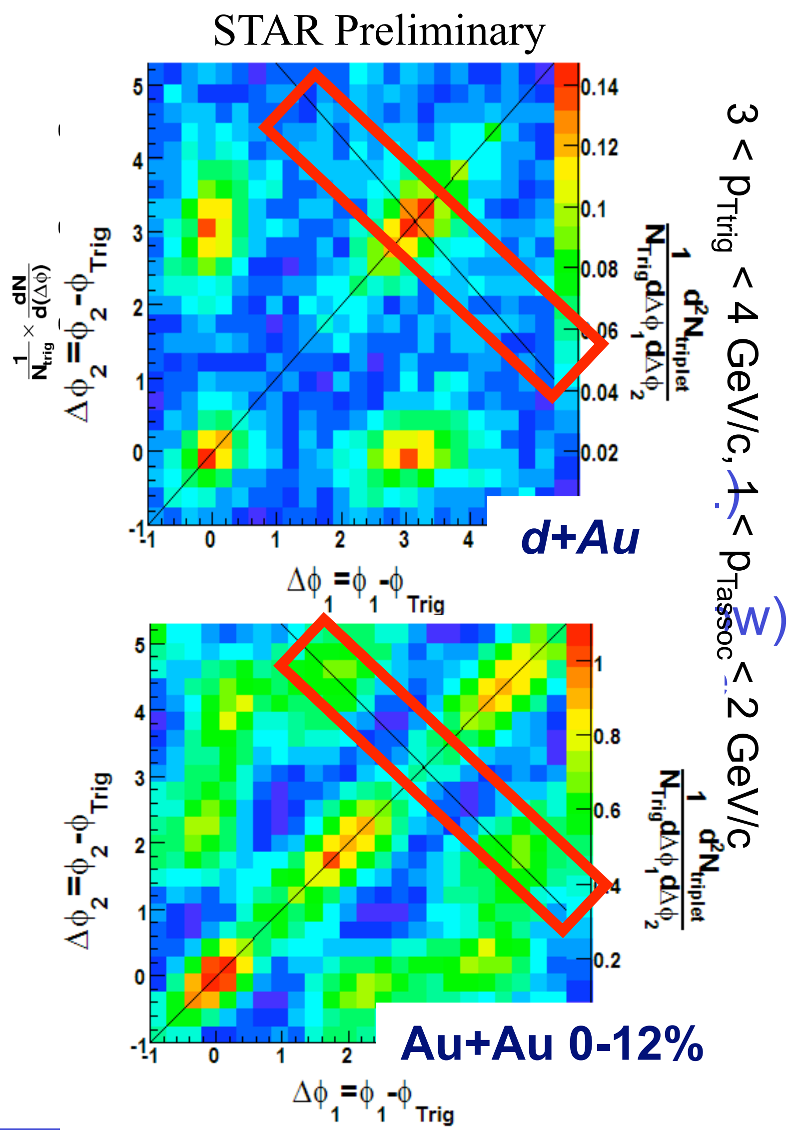
Deflected jets or conical emission?

Au+Au data consistent with Conical emission





Mach cone or Cerenkov gluons?

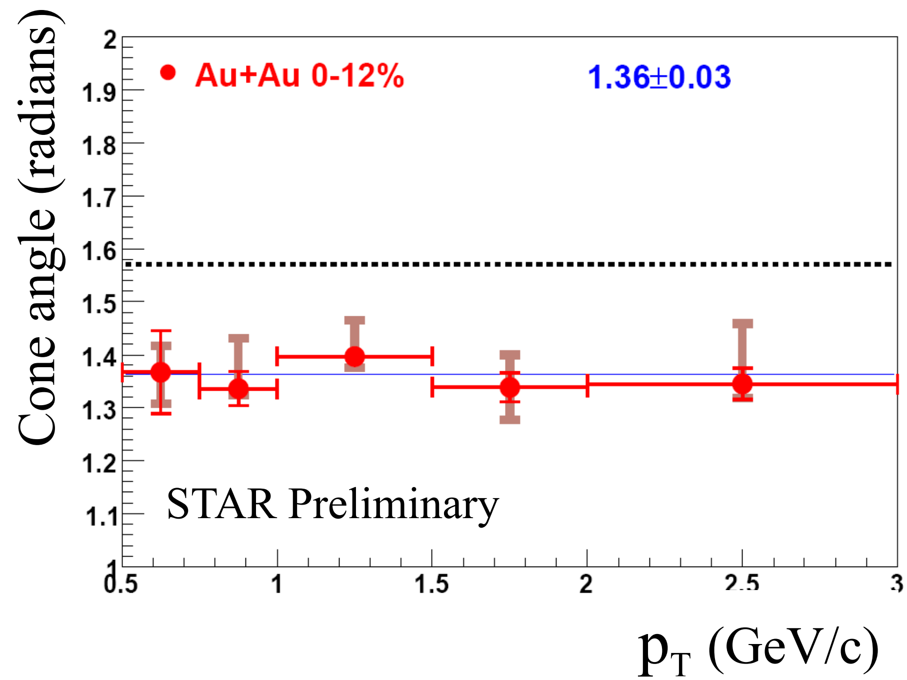
Angle predictions:

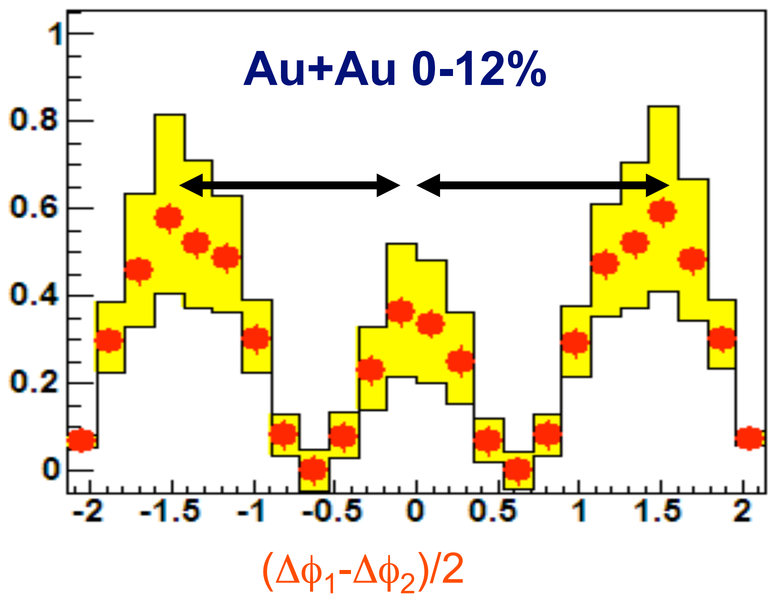
- Mach-cone:

  Angle independent of associated p_T

- Cerenkov gluon radiation:

  Angle decreases with associated p_T





Central Au+Au results consistent with Mach cone emission

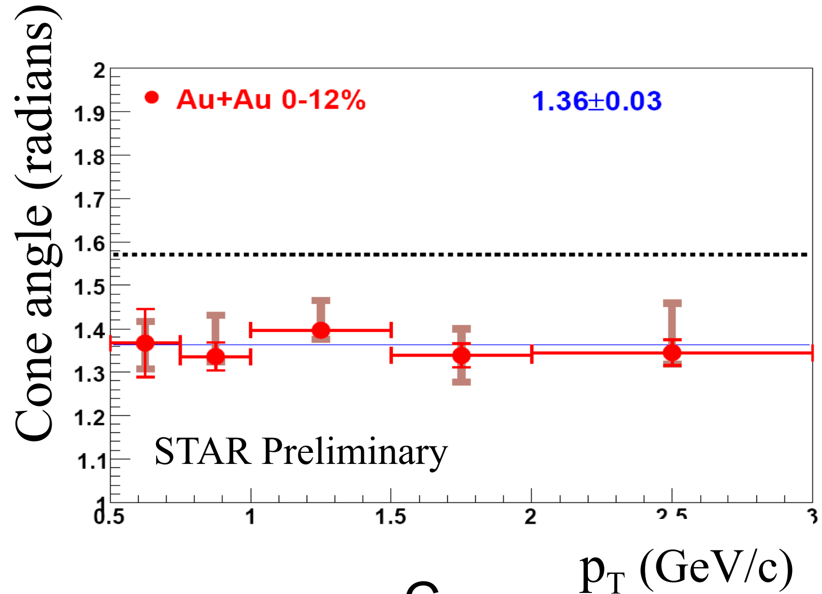
Mach cone?

Naive calc. of time averaged velocity of sound in medium:

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

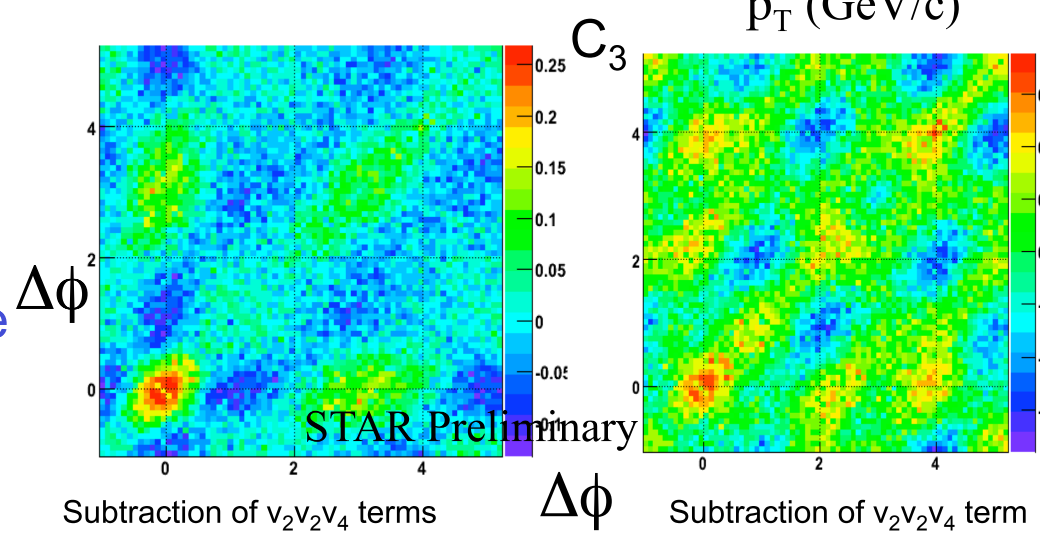
Cone angle ~ 1.36 radians

$c_s = 0.2c!$



- In cumulant approach: no conclusive evidence for conical emission so far

- Strength and shape of away side structures observed depends on assumed magnitude of flow coefficients



Subtraction of $v_2v_2v_4$ terms using on $v_2 = 0.06$

Subtraction of $v_2v_2v_4$ term using $v_2 = 0.12$

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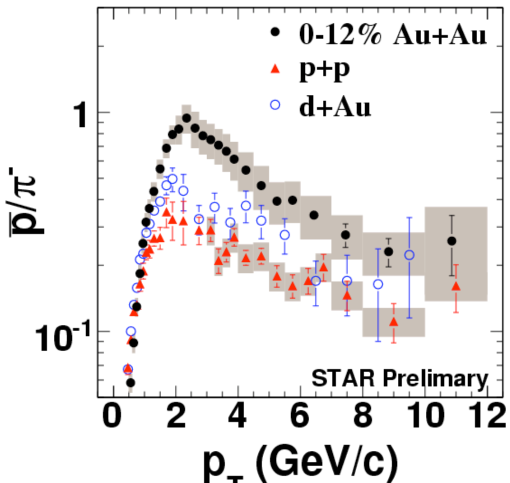
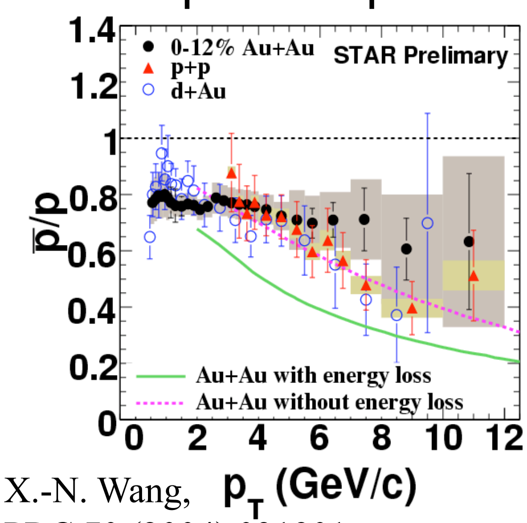
Is there a difference in E_{loss} of q and g

Anti-Baryon/meson



Anti-particle/particle



X.-N. Wang, PRC 70 (2004) 031901

Mechanism of energy loss : Medium induced gluon radiation

$$\langle \Delta E \rangle \sim \alpha_s C < \hat{q} > L^2$$

The Color Factor Effect

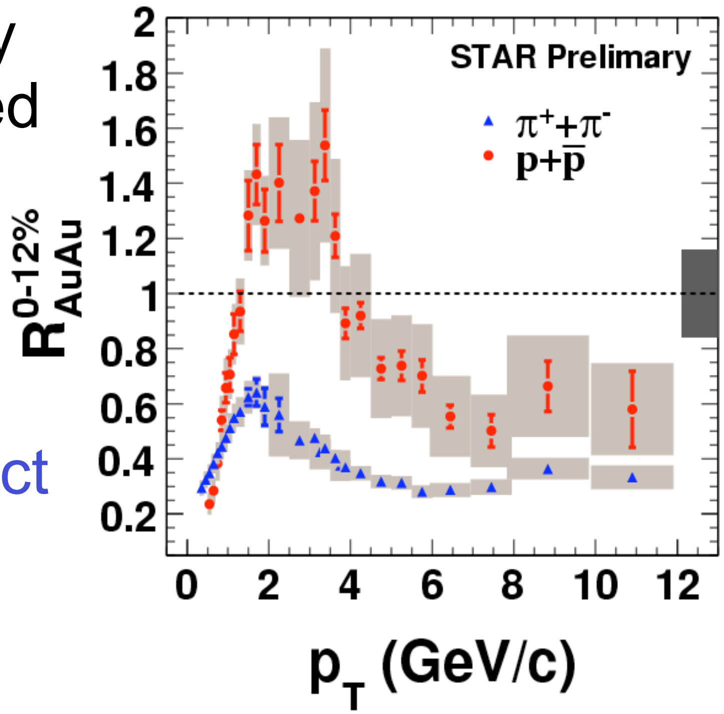
$$\frac{\Delta E_g}{\Delta E_q} \sim 9/4$$

STAR : PLB 637 (2006) 161

PRL 97 (2006) 152301

PLB 655 (2007) 104

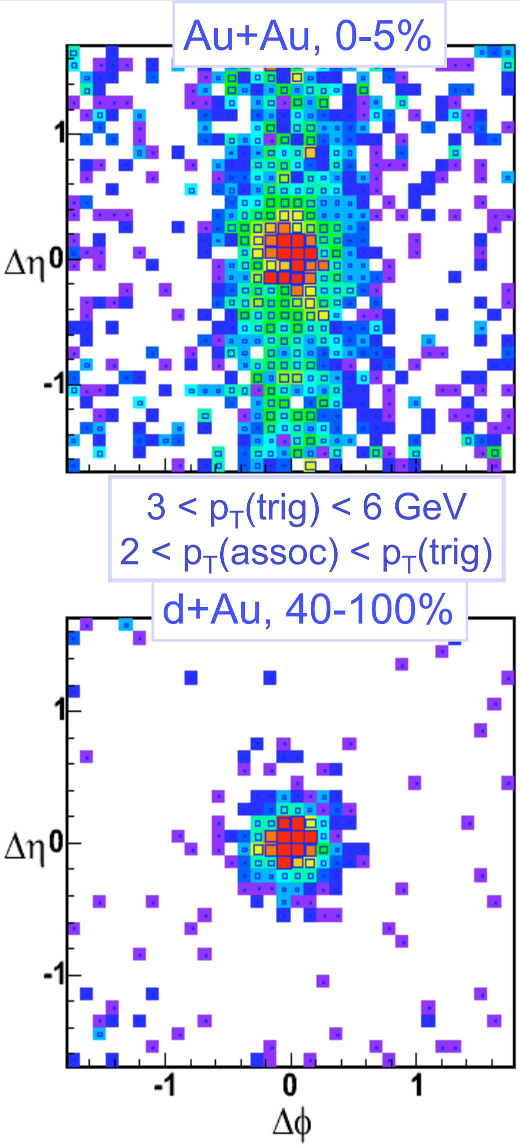
Baryon & meson NMF



Factor 9/4 Color effects not observed up to $p_T \sim 12$ GeV/c

Maybe just not sensitive!

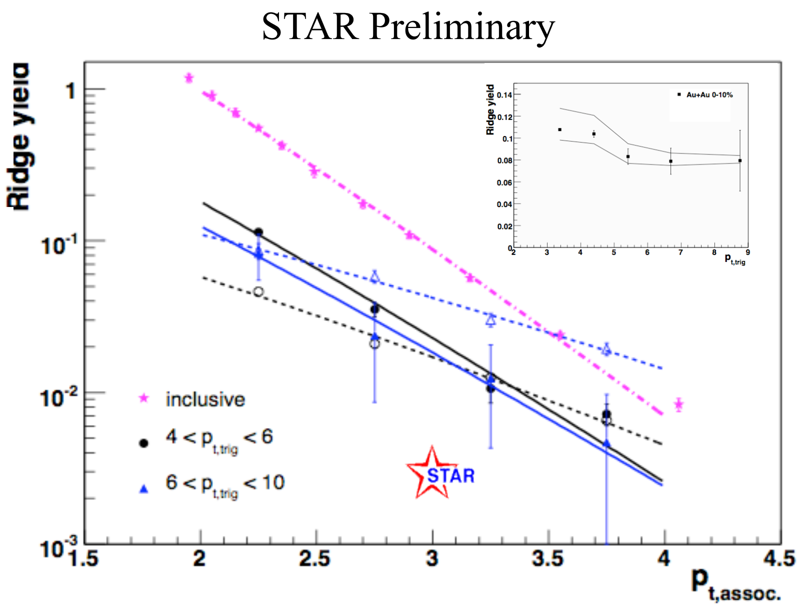
Ridgeology – QM2006



The Ridge:

Long range $\Delta\eta$ correlations in A+A collisions.

Persists up to high p_T-trig.



$T_{Ridge} \sim T_{inclusive} < T_{jet}$

Is this feature showing us how the energy lost by parton in the medium is distributed?

Some possible ridge explanations

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

Recombination between thermal and shower partons at intermediate p_T
R.C. Hwa & C.B. Chiu
Phys. Rev. C 72 (2005) 034903

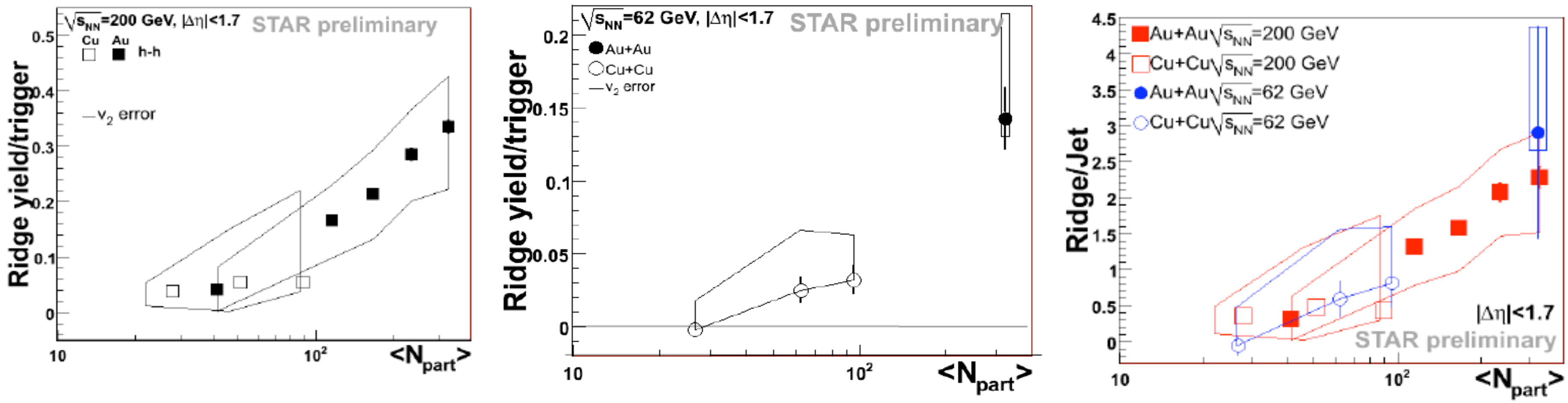
Momentum Kick Model
C.Y. Wong hep-ph:0712.3282

All qualitatively consistent with the features of ridge

New approaches used in to attempt to disentangle

- System size dependence
- Identified particle correlation
- Di-hadron correlation with respect to reaction plane
- 3-particle correlation

Centrality, system, √s dependences

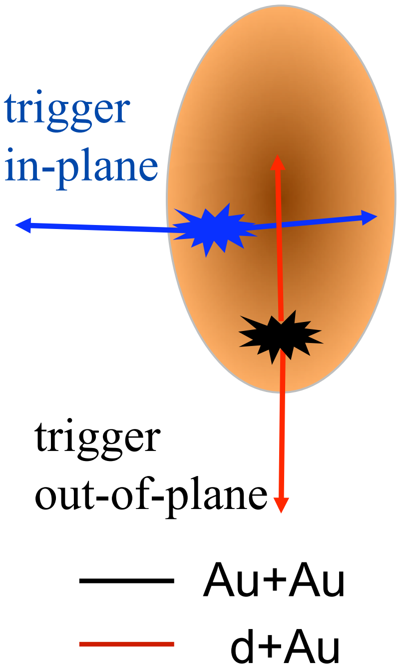


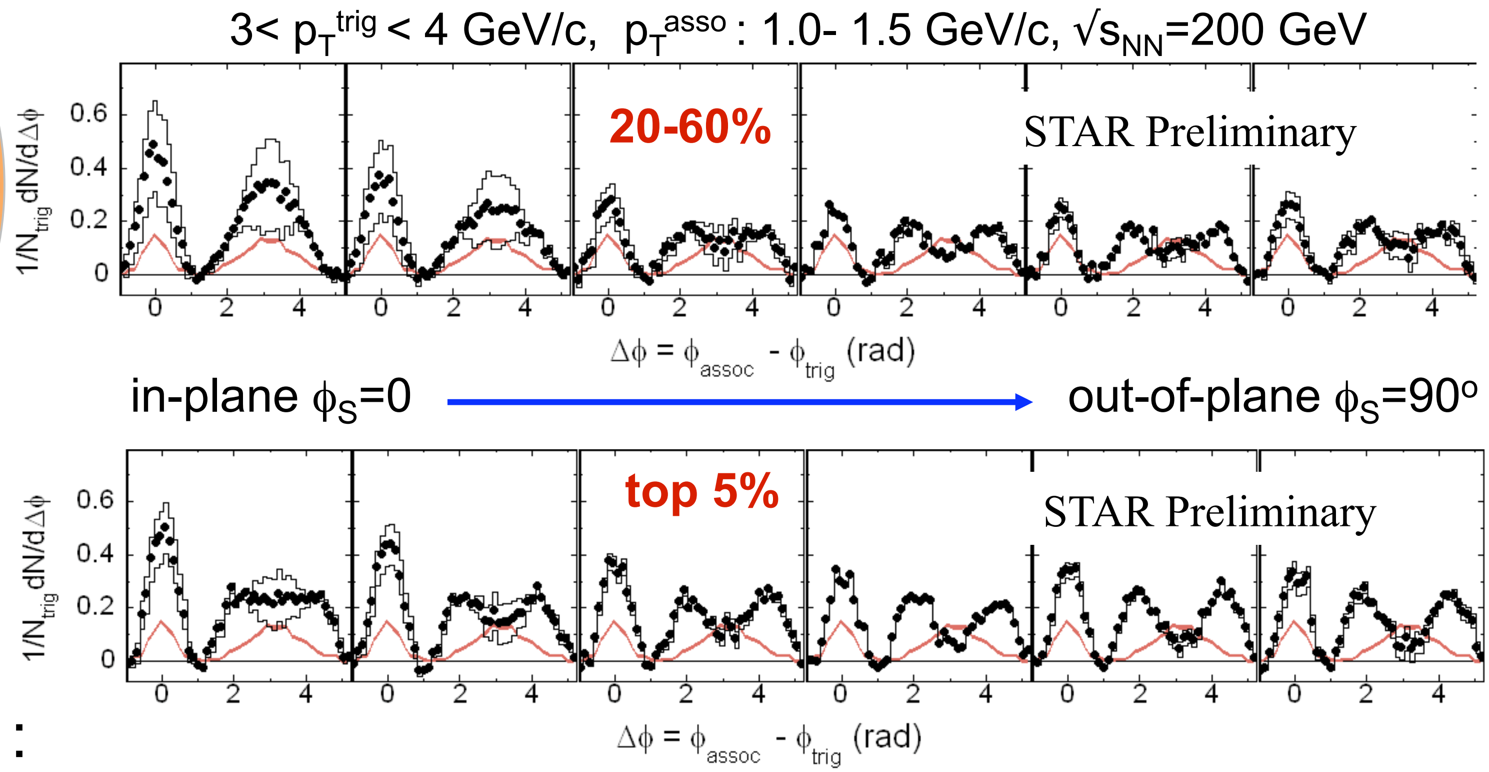
Ridge yield – increases with N_{part}
independent of colliding system, trigger species (not shown)
increases with √s

Ridge/Jet yield - increases with N_{part}
independent of √s

Different medium at different energies?

Di-hadrons correlated to event plane





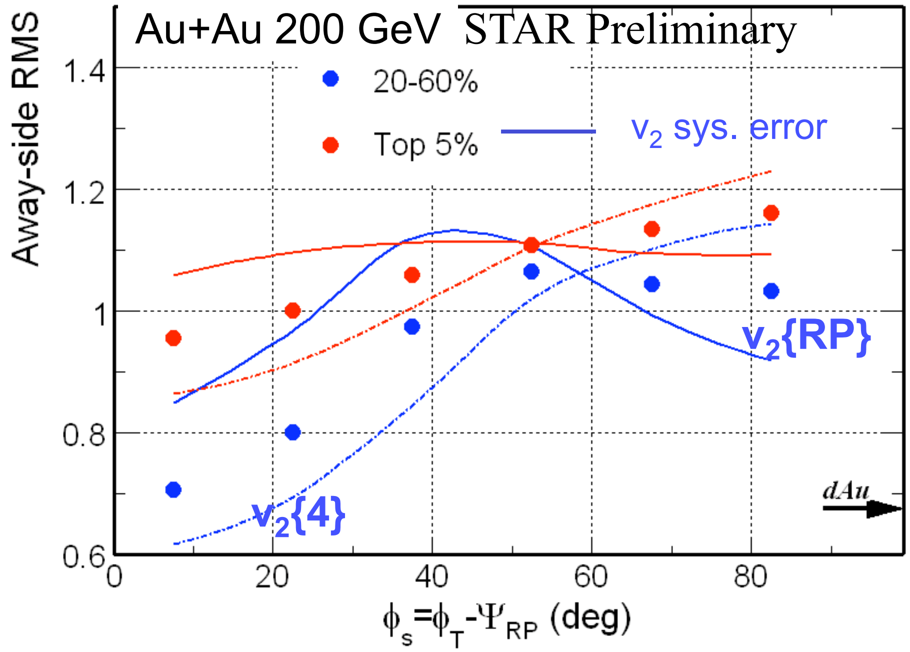
Observations :

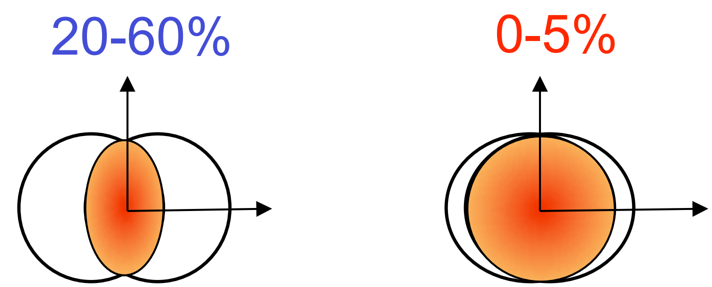
20-60% : away-side : from single-peak (φ_S =0) to double-peak (φ_S =90°)

Top 5% : double peak shows up at a smaller φ_S

At large φ_S, little difference between two centrality bins

Path length effect on di-hadron correlations

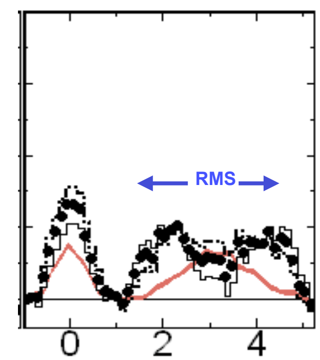




$$\mathrm{RMS} = \sqrt{\frac{\sum_i (\Delta\phi_i - \pi)^2 y_i}{\sum_i y_i}}$$

$3 < p_T^{trig} < 4$ 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

Away-side features reveal path length effects

Path length effect on ridge correlations

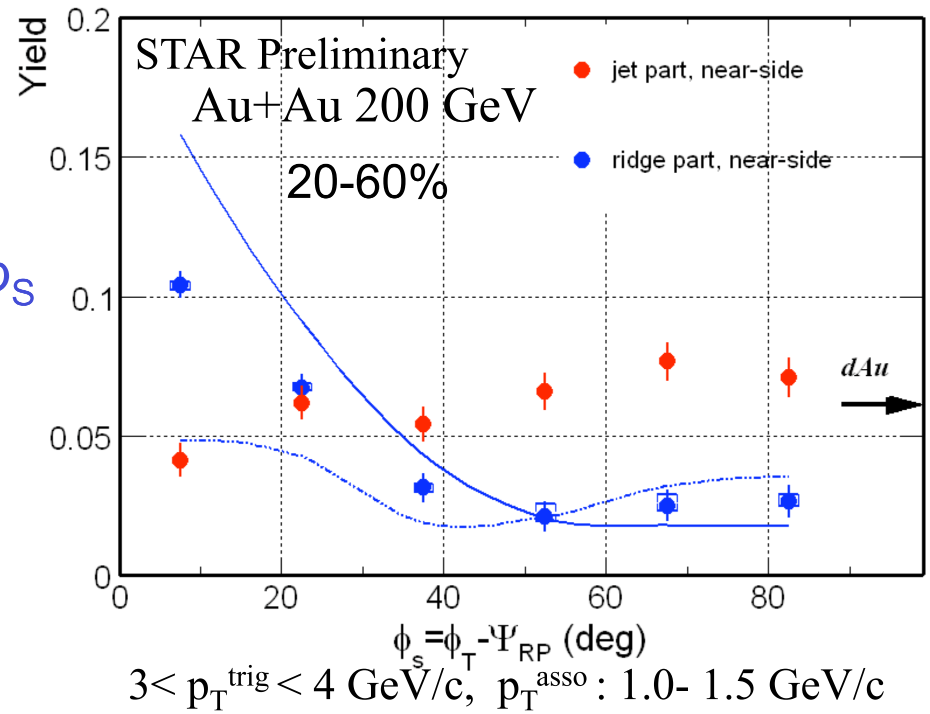
Observations :

Ridge: Decreases with φ_S

Little to no ridge at larger φ_S

Jet: Slight to no increases with φ_S.

Au+Au ~ d+Au



Strong near-side jet-medium interaction when in reaction plane

generates sizable ridge

Minimal near-side jet-medium interaction when perp. to reaction plane

generates very little ridge

Chemistry and v_2 associated with Jet and Ridge

Using Identified associateds

Jet:

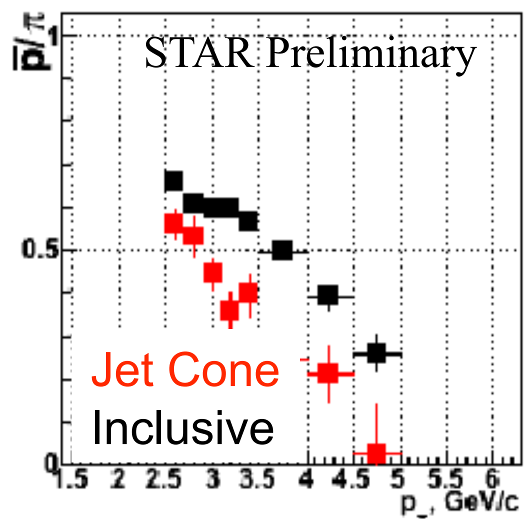
Λ/K^0_s ~ 0.5 < inclusive

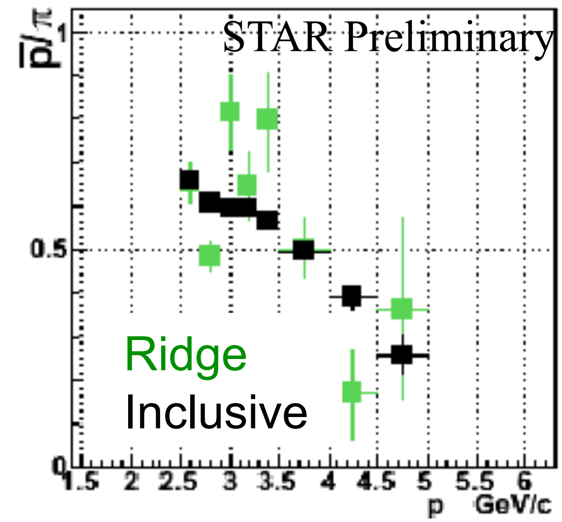
(anti)p/π < inclusive

Ridge:

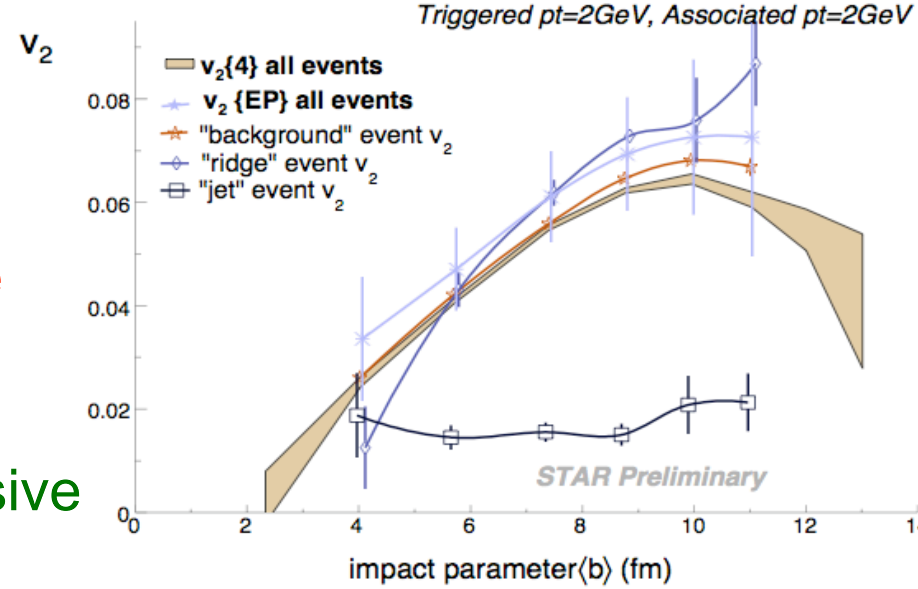
Λ/K^0_s ~ 1 ~ inclusive

(anti)p/π ~ inclusive





Triggered pt=2GeV, Associated pt=2GeV



Jet:

Inferred v_2 jet pair events < inclusive

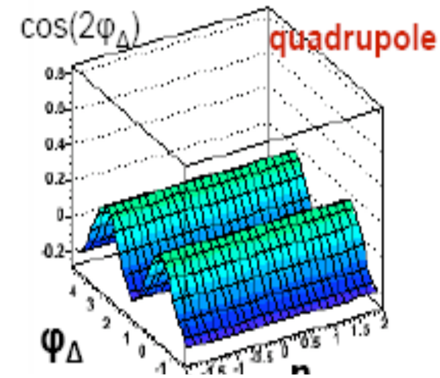
Ridge:

Inferred v_2 ridge pair events ~ inclusive

Un-triggered pair correlations

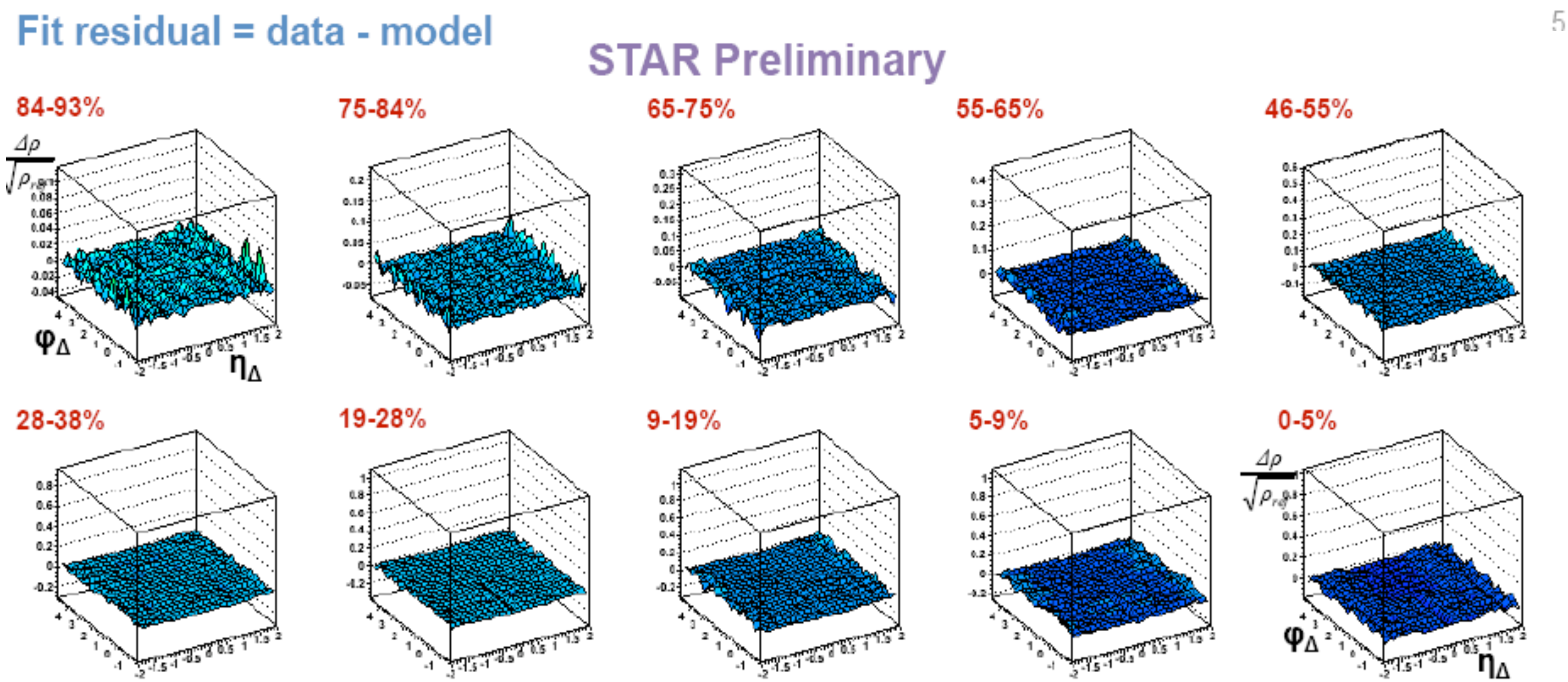
Au-Au fit function

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



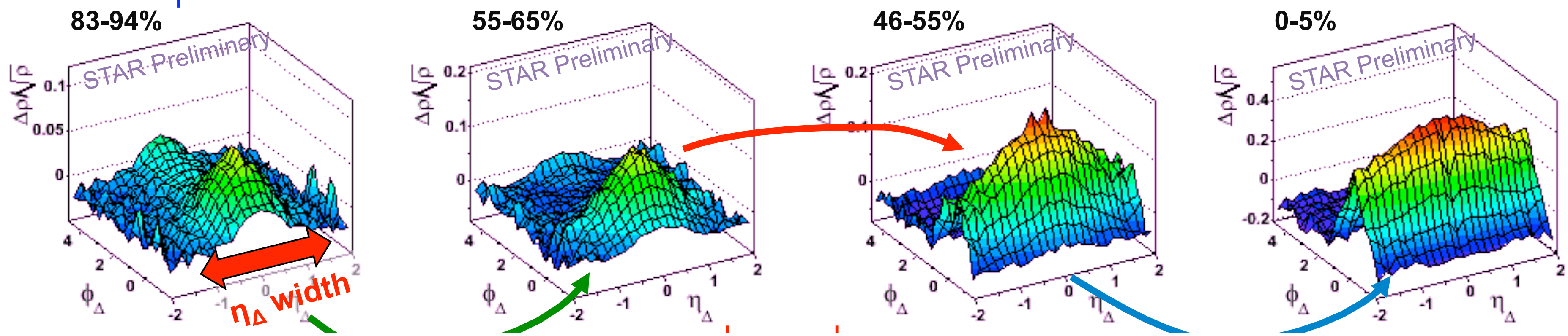
Small residual indicates goodness of fit

Fit residual = data - model



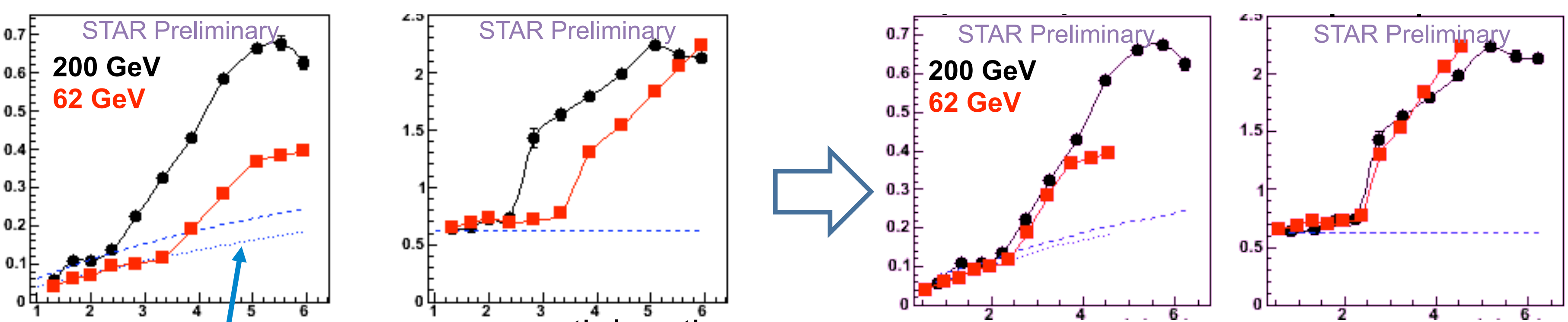
Evolution of mini-jet with centrality

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

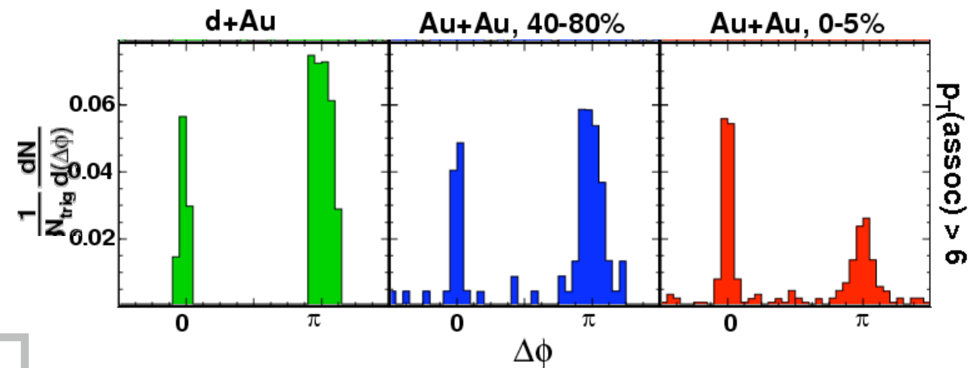


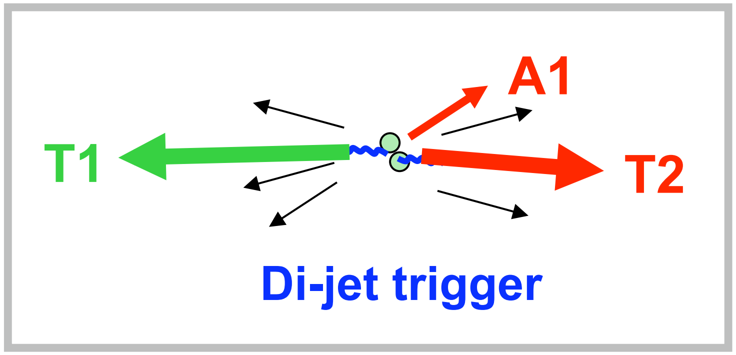
$$\nu \equiv \frac{\langle N_{bin} \rangle}{\langle N_{part}/2 \rangle}$$

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

Di-jet triggered correlations

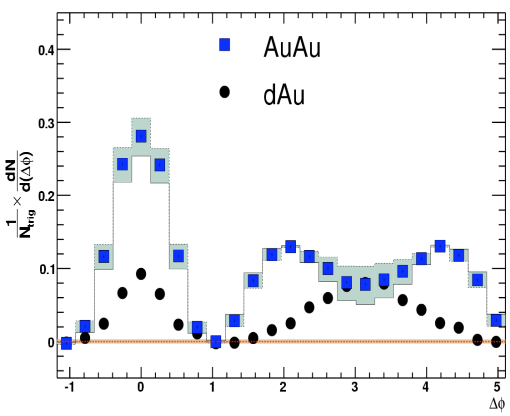
Observation of di-jets:
punch through



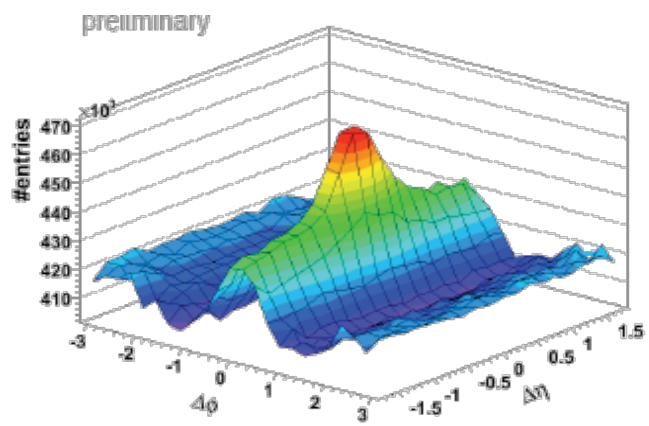


Select di-jets events:

T1: p_T>5GeV/*c* **T2**: p_T>4GeV/*c*
A1: p_T>1.5GeV/*c*

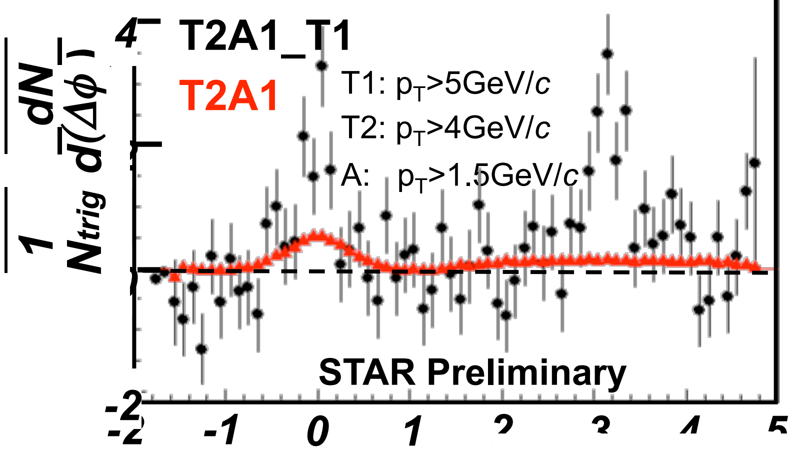


What happens to away-side hump and near-side ridge if we trigger on di-jets ?

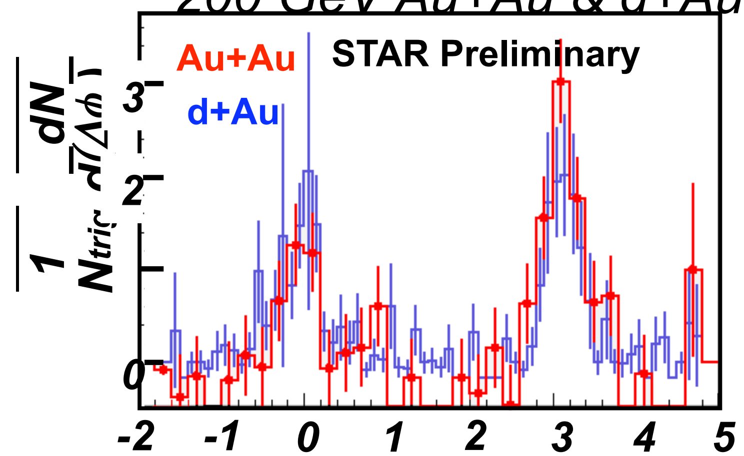


Di-jet triggered correlations

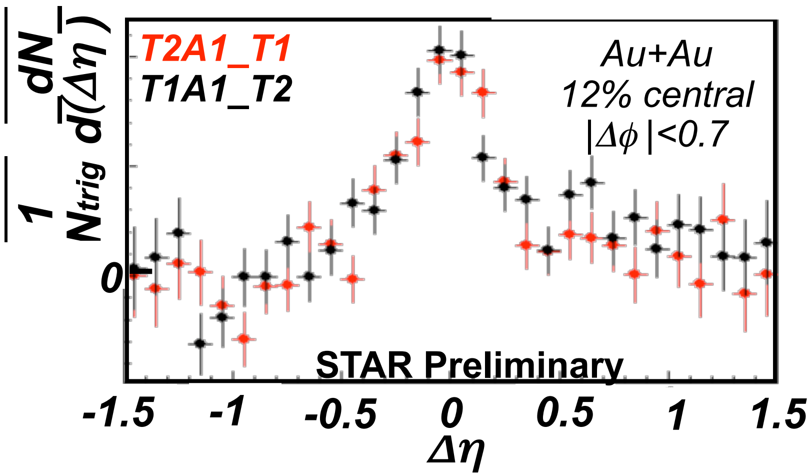
200 GeV Au+Au, 12% central

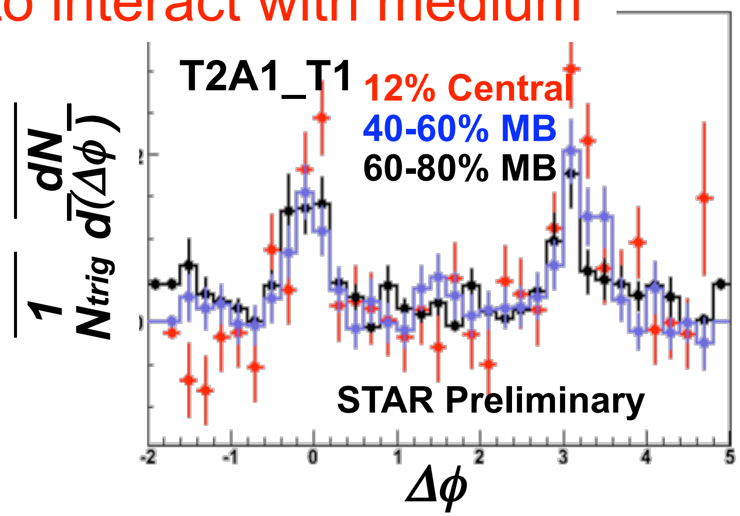


200 GeV Au+Au & d+Au



$\Delta\phi$ Di-Jets don't seem to interact with medium





No Away-side suppression, No shape modification, No ridge

Outline – What we've been looking at since

Medium properties	Physical phenomenon	Experimental probes
Energy density	Parton E_{loss} in the medium	High p_T particles, $\Delta\phi$ and $\Delta\eta$ correlations
Velocity of sound	Mach cones	3-particle correlations
Partonic interactions, Mechanism of E_{loss}	Non-Abelian features of QCD - Color factor effects, path length effects of E_{loss} Jet-medium coupling	High p_T particle production $\Delta\phi$ and $\Delta\eta$ correlations, correlations with respect to reaction plane
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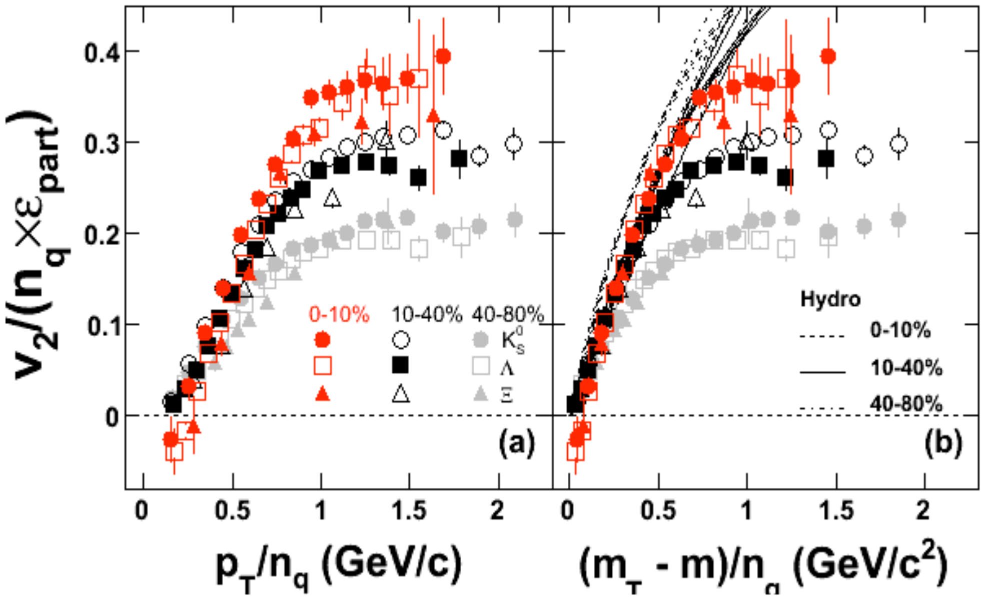
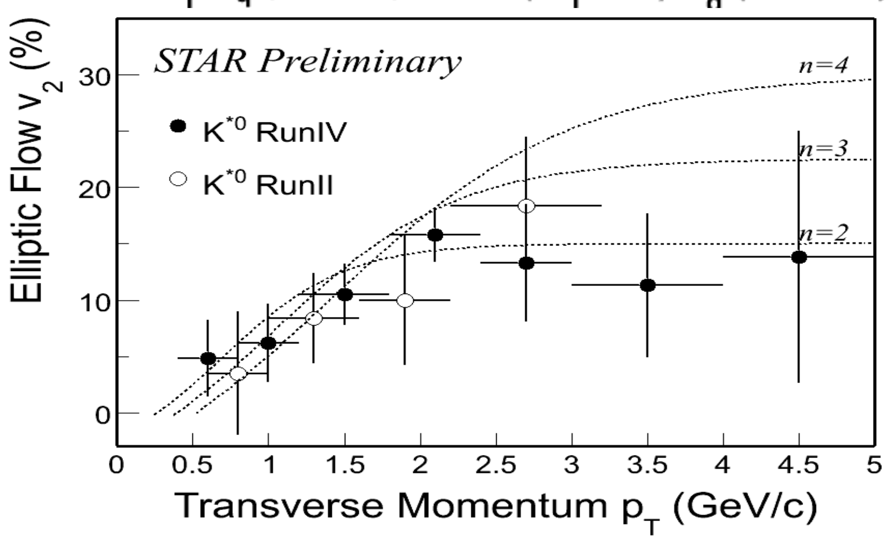
Identified particle v_2

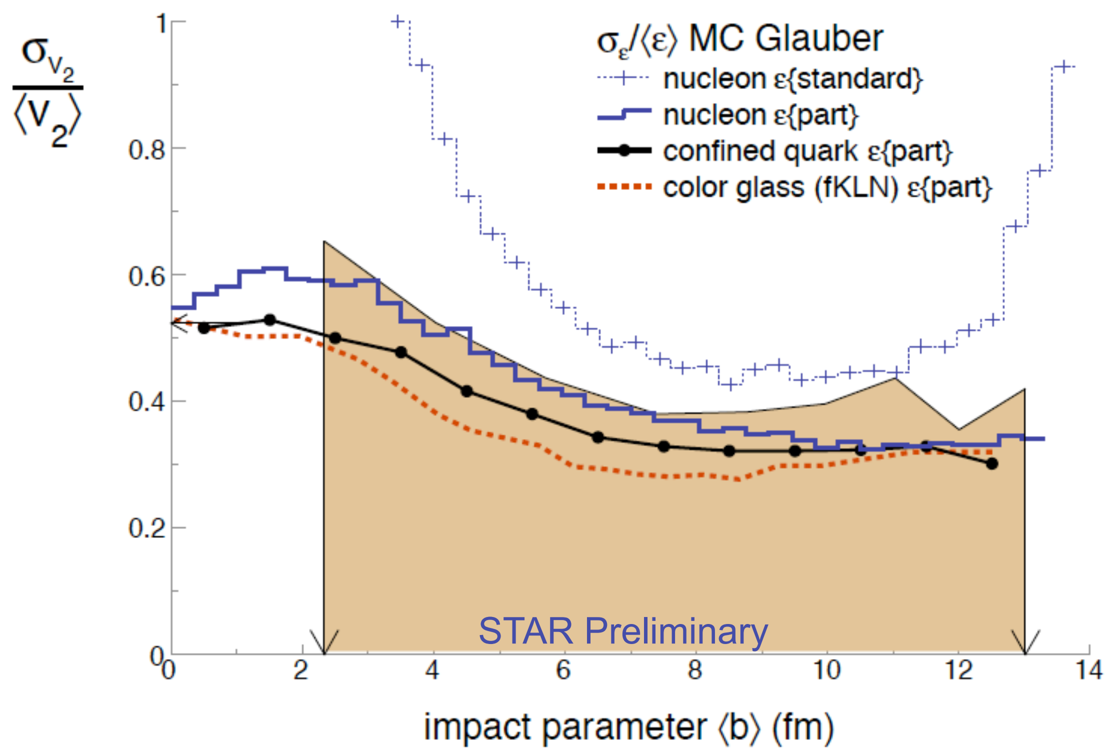




- v_2 precisely follows NCQ scaling for all centralities and all identified particles
- Suggests coalesence from a hot thermal bath
- Additional data for γ at high η
- For different systems, common scaling with ε, both at forward- and mid-rapidity
- v_2/ε increases with centrality
- K* v_2 consistent with meson scaling
- Constrains level of regeneration

Initial conditions: Glauber or CGC?

v_2 fluctuations may provide some insight/constraints



$$\left(\frac{\sigma_{v_2}}{\langle v_2 \rangle}\right)_{meas.} \approx \left(\frac{\sigma_{\varepsilon}}{\langle \varepsilon \rangle}\right)_{calc.}$$

Confined quark MC:
- constituent quark participants
- decreases ε fluctuations

Color glass MC:
- includes effects of saturation
- increases the mean ε

- Upper limit challenges models of initial eccentricity fluctuations
- Nucleon Glauber leaves no room for other fluctuations & correlations
- Data calls for different model of initial eccentricity (e.g. CGC)

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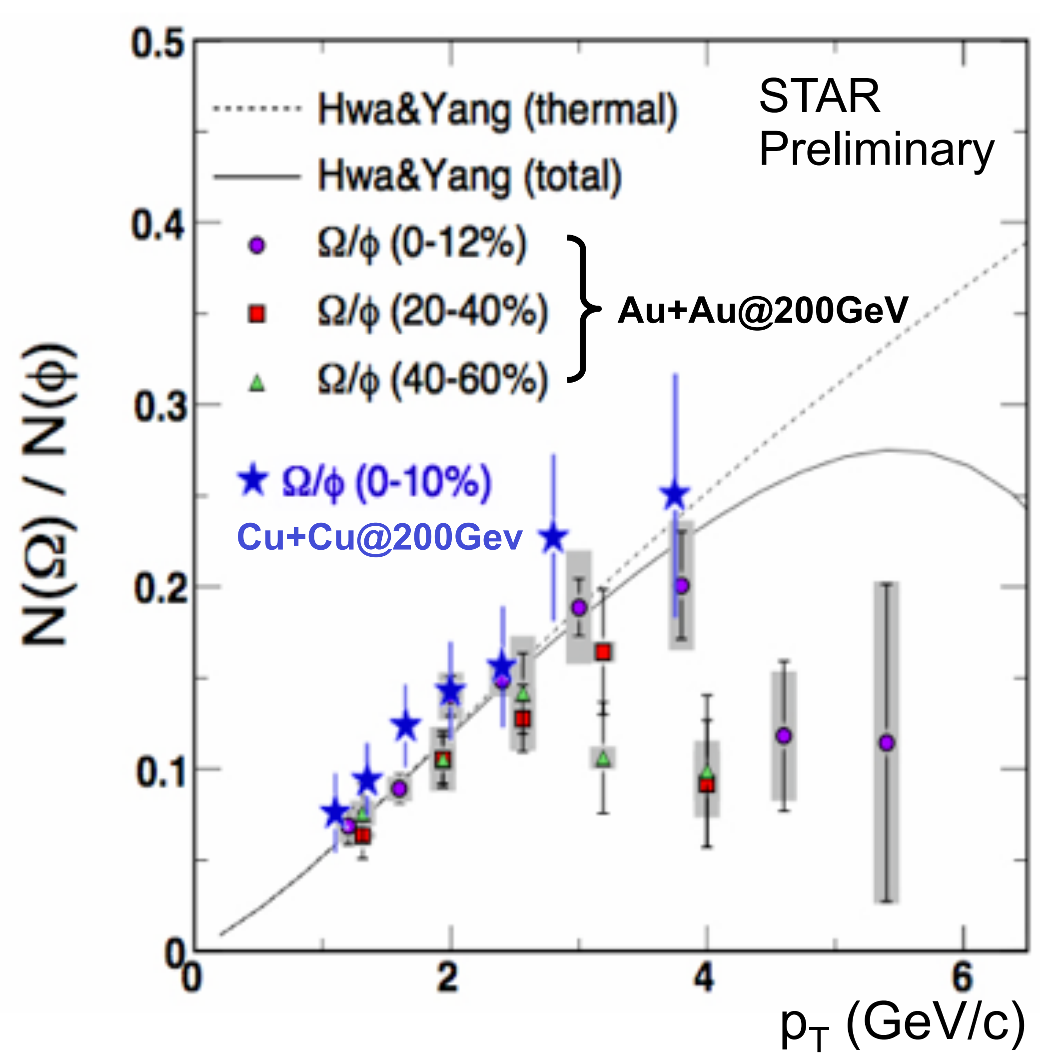
Testing constituent quark scaling



At intermediate p_T Ω (sss) and ϕ ($s\bar{s}$) should be dominated by bulk thermal quark coalescence – no jet contribution

(Hwa and Yang PRC 75, 054904 (2007))

Central Au+Au data agrees with model up to p_T~ 4 GeV/c

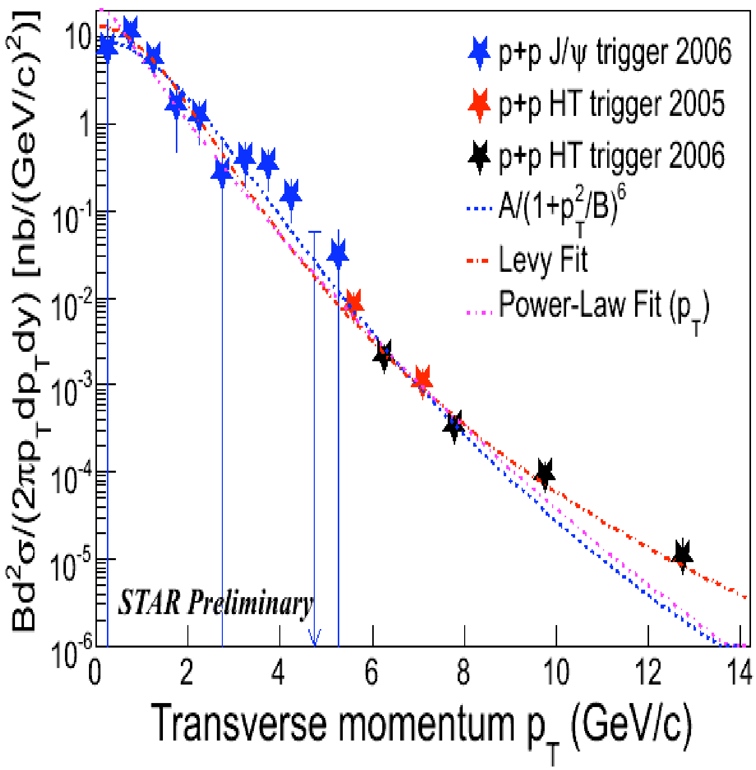
Peripheral data pulls away earlier

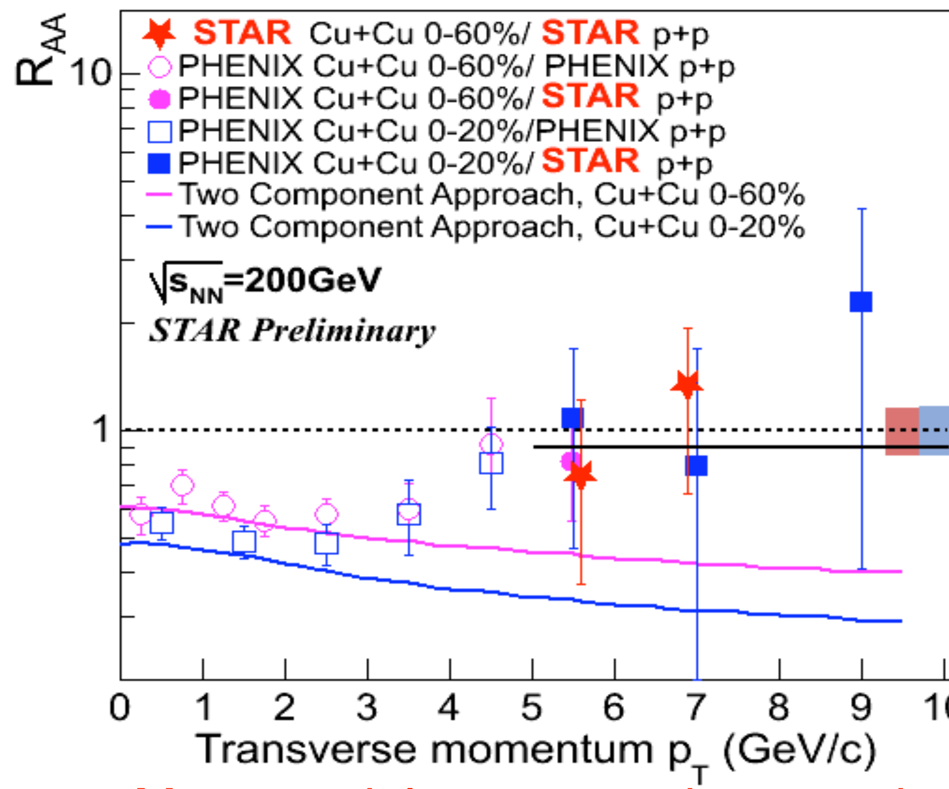
Cu+Cu data agrees with Au+Au of same centrality NOT same N_{part}

Hidden charm: R_{AA} J/Ψ

Provides means to investigate heavy quarkonium production mechanisms

Two Component Approach: *X. Zhao and R. Rapp, hep-ph/07122407*





R_{AA} (p_T < 4 GeV/c) : 0.5-0.6

R_{AA} (p_T > 5 GeV/c) : 0.9±0.2 consistent with no suppression

Many models expect a decrease in R_{AA} as function of p_T

Next step the ϒ - almost there

J/Ψ – hadron correlations in p+p

1) $g + g \to \chi + g$

$\to J/\psi + \gamma$

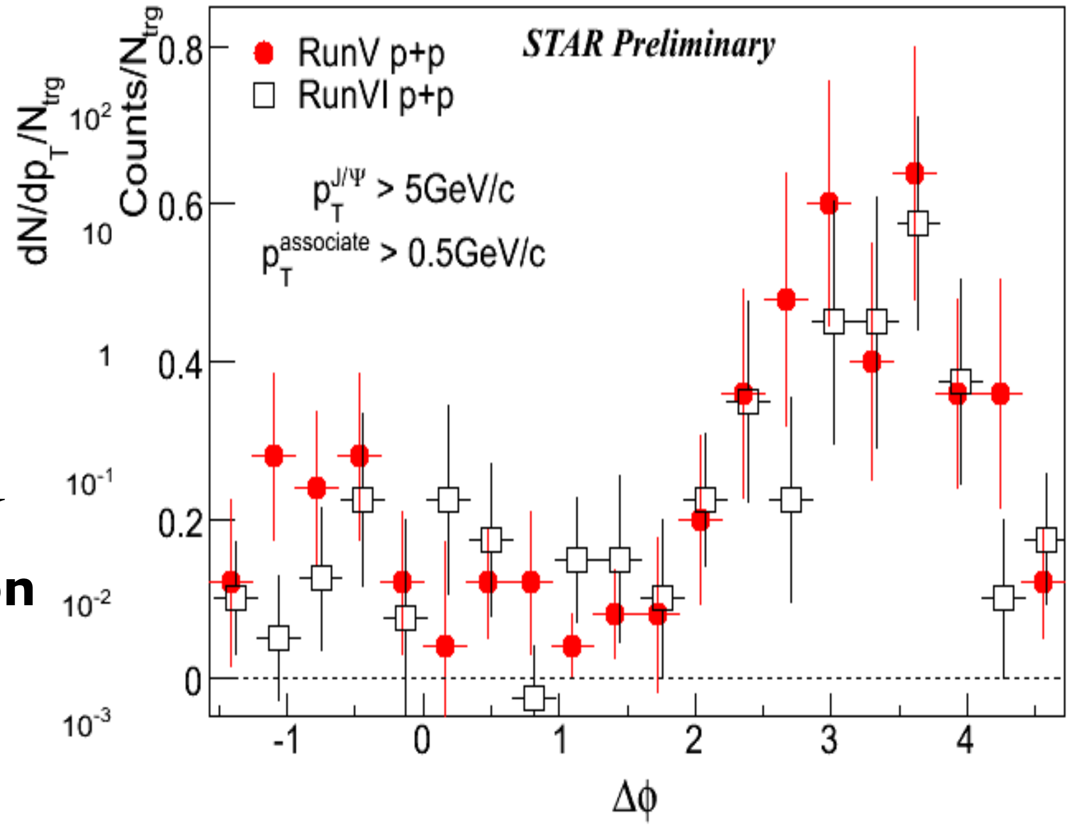
no near side correlation

2) $g + g \to b + \overline{b}$

$\to B_{hadron} + X$

$\to J/\psi + X$

strong near side correlation



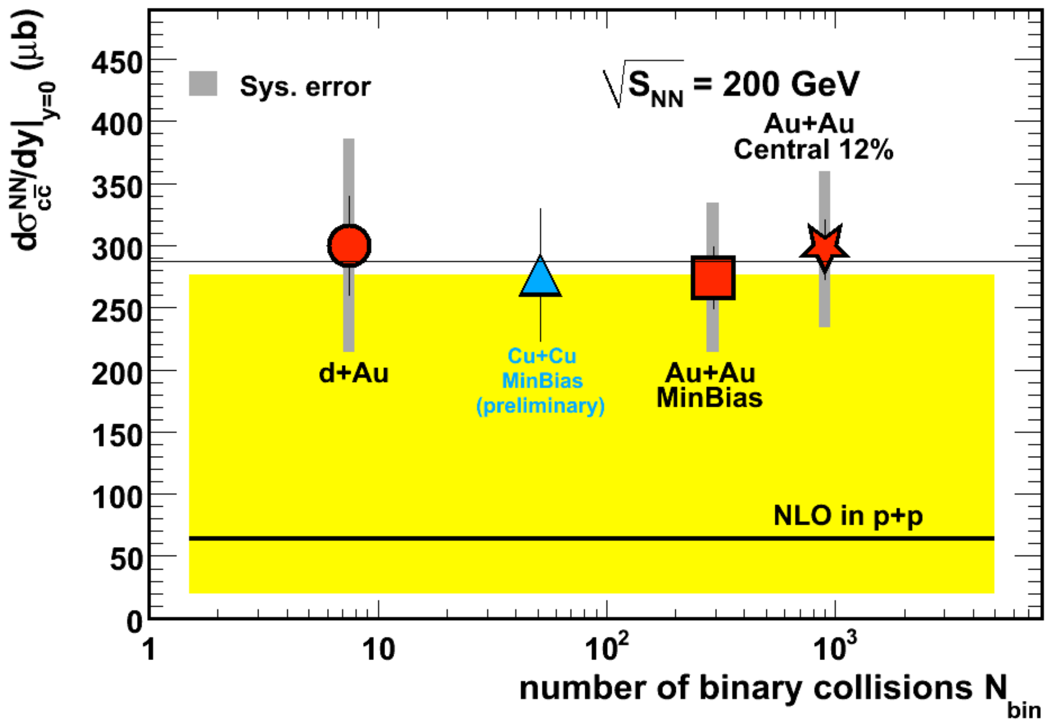
No near side correlation seen!

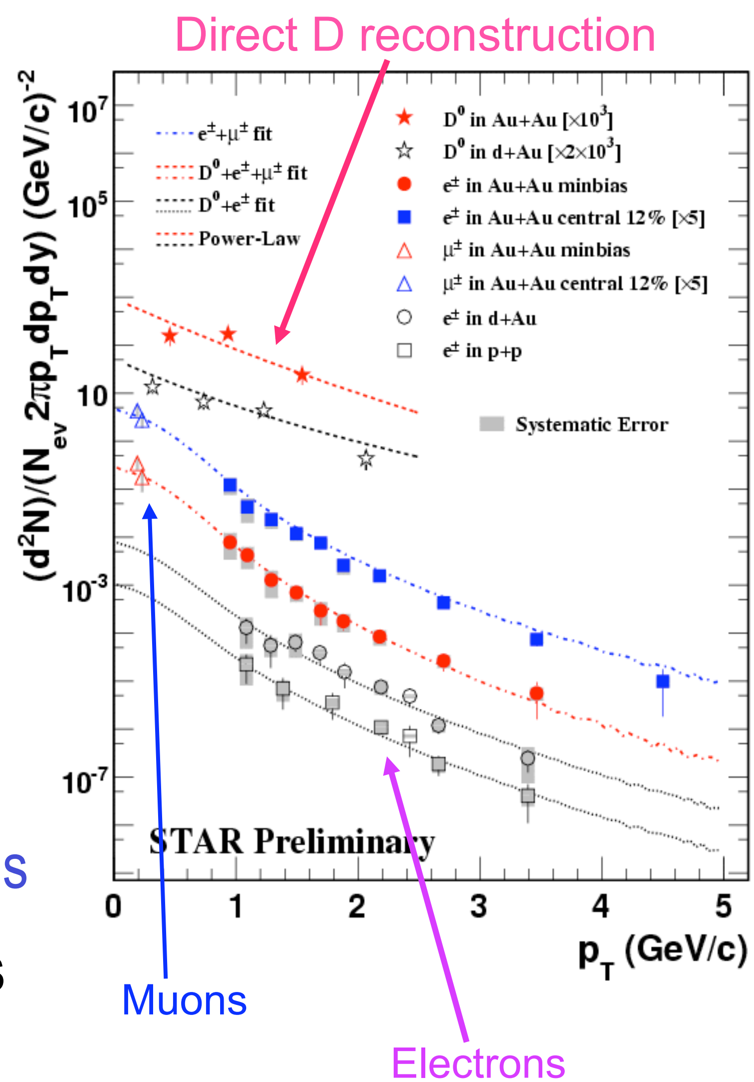
Away side: consistent with leading charged hadron correlations

Near side: consistent with no associated hadron production

B→J/ψ not a dominant contributor to inclusive J/ψ

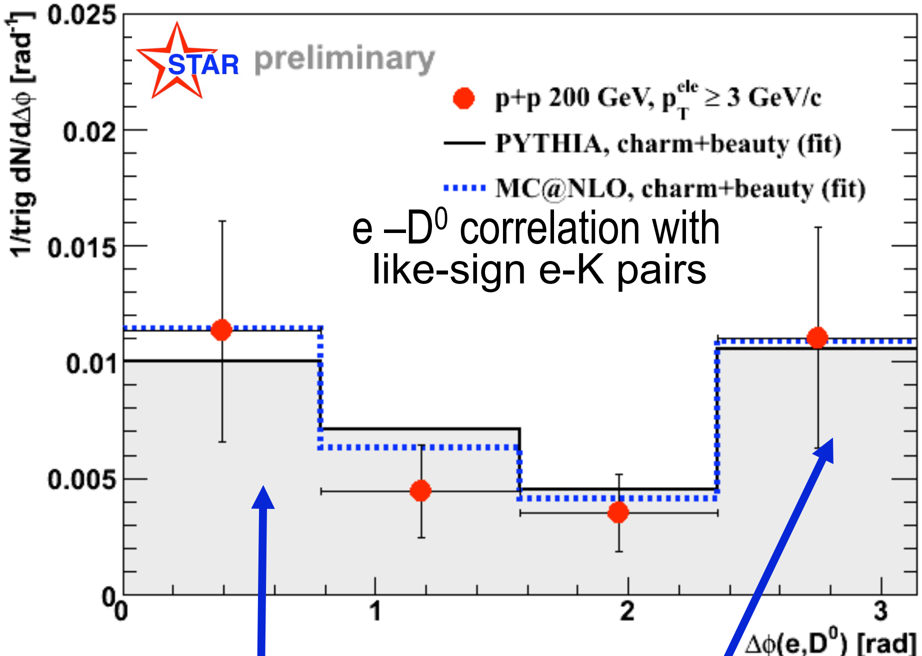
The total charm cross-section

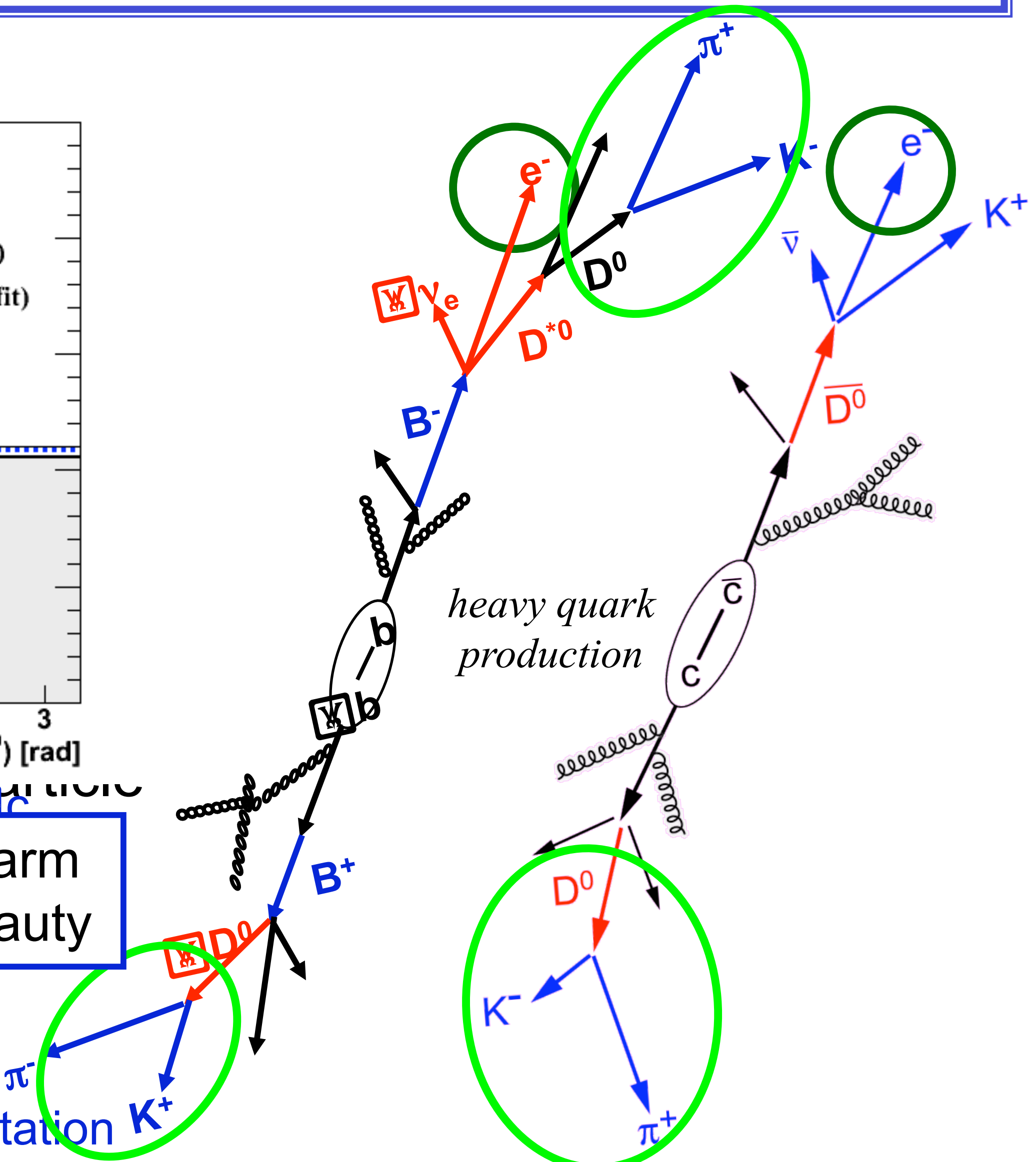




- Charm cross section scale with N_{bin} collisions
- Multiple measurements in different channels all give the same result

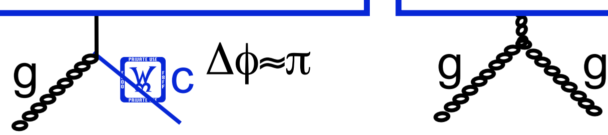
Electron tagged correlations





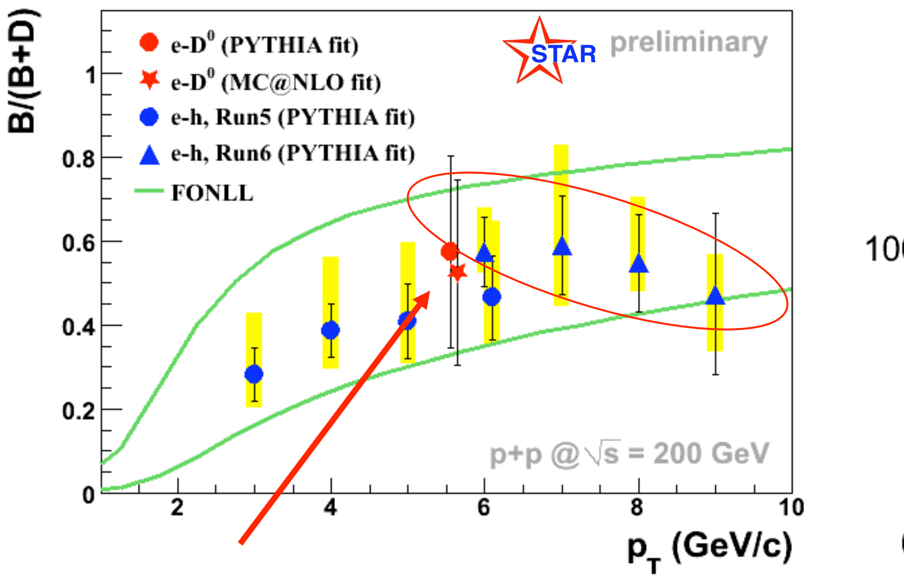
essentially from
B decays only

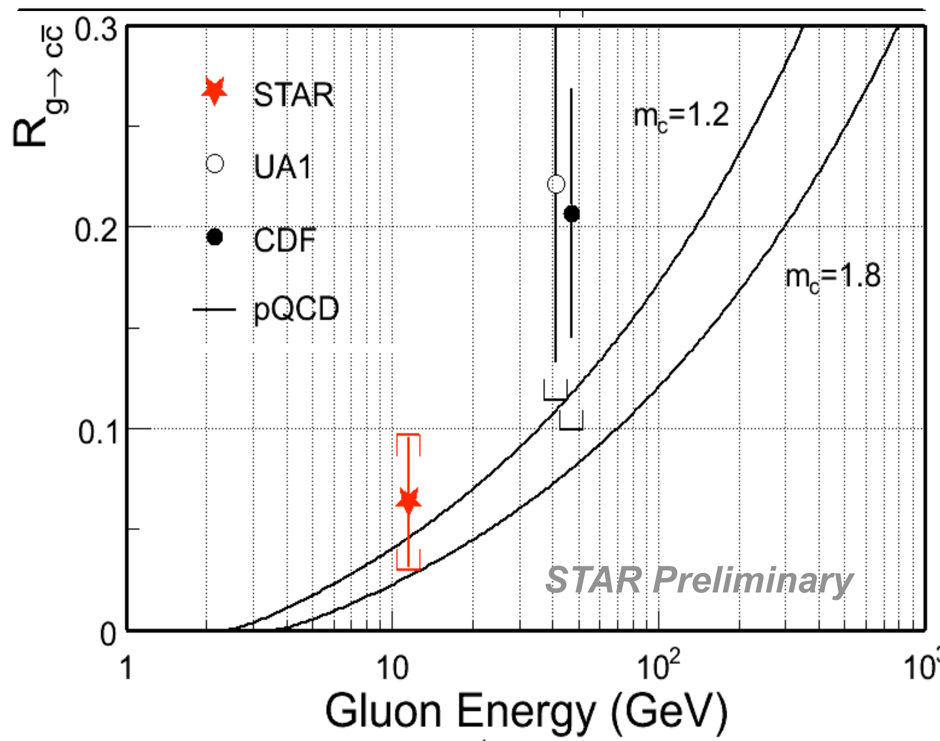
≈75% from charm
≈25% from beauty



flavor creation gluon splitting/fragmentation

Unraveling heavy quark production in p+p at √s = 200 GeV





e-D^0 correlation agree with e-h results

In p+p collisions:

- The B contribution to non-photonic electrons is sizeable based on e-h and e-D correlations
- Gluon splitting contribution to charm is as expected (~6%)

Taken together with suppression of non-photonic electrons in Au+Au suggests significant suppression of non-photonic electrons from bottom in medium

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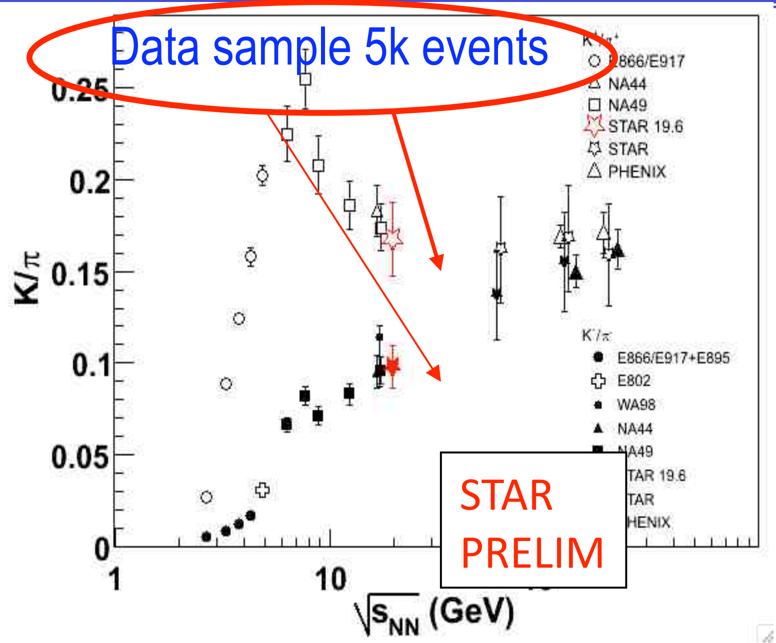
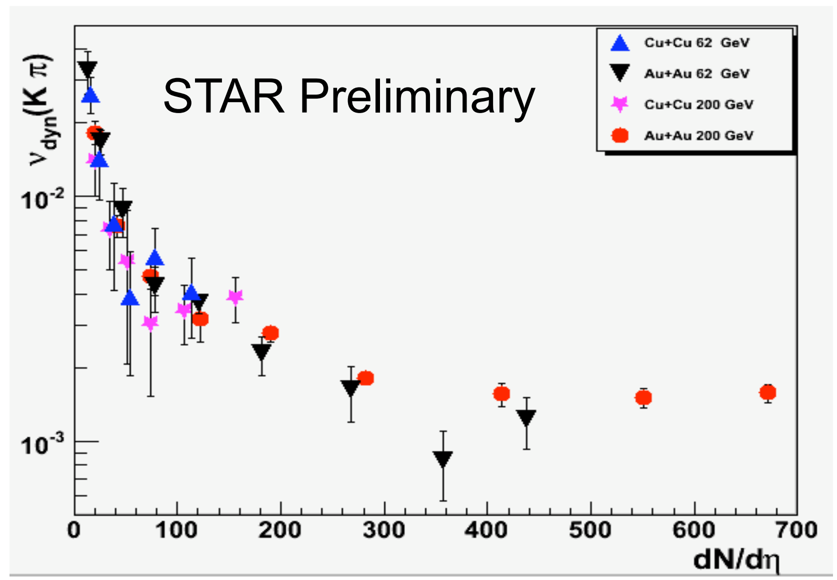
Fluctuations and the Critical Point search





- 20 GeV data consistent with systematics observed at SPS

- Rise in fluctuations (Kπ and γ-h) scale roughly with dN/dη across energy and centrality – consistent with NA49

Ready for the Energy scan Critical point (and DCC) search
Large acceptance means can do a lot with small amount of data

Conclusions

Too much data to give a one slide summary

Taken as a whole STAR's results make important steps towards in constraining models that try to explain:

- How partons interact with and lose energy in the medium
- How the medium changes with $\sqrt{s}$, centrality and ion collided
- Where that energy goes
- How particles are created out of the medium
- What the initial conditions look like and how much they fluctuate
- How charm quarks are created and distributed among particles
- How much bottom is produced

RHIC on the threshold of new era of quantitative comparison between theory and experiment that will characterize the properties of the remarkable new matter discovered at here

STAR presentations at QM2008

Timothy Hallman	Plenary I	Recent Highlights from STAR
Bedanga Mohanty	Plenary III	Medium properties and response to highly energetic particles
Pawan Kumar Netrakanti	Plenary IV	The ridge via 3-particle $\Delta\eta$-$\Delta\eta$ correlations in STAR
Guoji Lin	Session I	First results on π^0 production over extended p_T range
Yan Lu	Session III	System Size Dependence Of Strange Hadron Elliptic Flow
J. H. Chen	Session III	Energy and System Size Dependence of φ-meson
Sadhana Dash	Session III	K* production in Cu+Cu and Au+Au collisions
Patricia Fachini	Session V	ρ^0 production at High-pt in Au+Au and p+p Collisions
Xiaobin Wang	Session VII	Multi-strange hyperon Xi and Ω production in Cu+Cu
Aoqi Feng	Session VIII	Away-side Modification and Near-side Ridge
Michael Daugherity	Session IX	Anomalous centrality variation of minijet correlations
Oana Catu	Session IX	System size dependence of jet-like di-hadron correlations
Olga Barannikova	Session IX	Back-to-back di-jet triggered multi-hadron correlations
Zubayer Ahammed	Session X	Energy and System Size dependence of K/π Fluctuations at RHIC
Sunil Dogra	Session X	Correlation & fluctuations between photons & Charged particles
Rashmi Raniwala	Session XII	Elliptic Flow of Inclusive Photons in AuAu & CuCu collisions at 200 GeV
Paul Sorensen	Session XII	Elliptic flow fluctuations and non-flow correlations measured by STAR
Christine Nattrass	Session XIII	System size dependence of di-hadron correlations
Gang Wang	Session XIII	Study of Conical Emission of Particles from Heavy Quark Energy Loss
Andre Mischke	Session XIV	Heavy-flavor correlations via electron correlations with open charm
Alexandre Shabetai	Session XIV	The Open Charm Cross-Section in sqrt(s_NN) = 200 GeV Cu+Cu
Ahmed Hamed	Session XV	Probing the medium with γ-jet correlation measurements
Daniel Cebra	Session XVII	Charged Hadron Spectra in 19.6 GeV Au+Au collisions
Zebo Tang	Session XVII	High-pt J/Psi production in p+p and A+A collisions
Brijesh K. Srivastava	Session XIX	Long-range forward-backward multiplicity correlations
Debashish Das	Session XXII	Upsilon production in p+p and Au+Au collisions in STAR
Grazyna Odyniec	Session XXIV	The RHIC Energy Scan

Thanks to the whole STAR Collaboration

Argonne National Laboratory
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University of California - Los Angeles
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Carnegie Mellon University
University of Illinois at Chicago
Creighton University
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Laboratory of High Energy Physics - Dubna
Particle Physics Laboratory - Dubna
Institute of Physics. Bhubaneswar
Indian Institute of Technology. Mumbai
Indiana University Cyclotron Facility
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