Results from STAR

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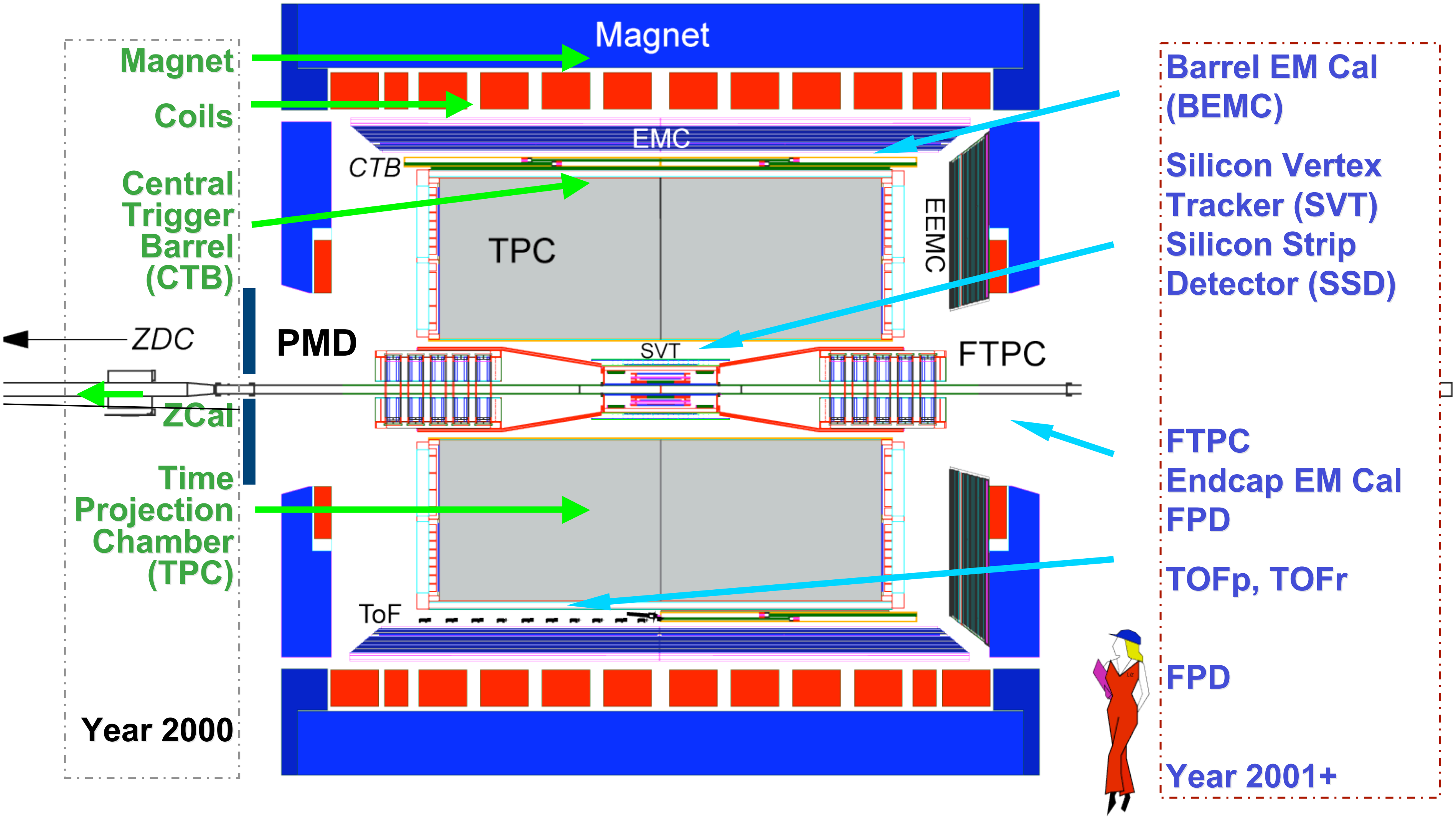
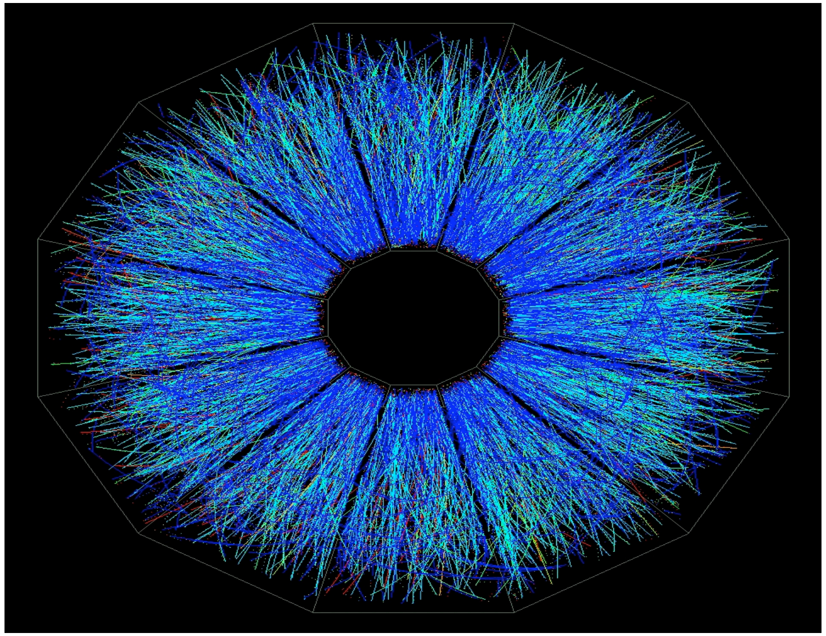
For the STAR Collaboration

The STAR Detector

Large acceptance: 2p coverage at mid-rapidity



Measurements



- AuAu: 200, 62.5, 20 GeV
- CuCu: 200, 62.5 GeV
- Pp: 200 GeV
- dAu: 200 GeV

Global Characteristics:

multiplicity, Et

Rapidity and azimuthal distribution

for charge and neutral particles

for identified particles:

pion,K,lambda,cascade,omega,electron

Charm, resonances.

Coverage:

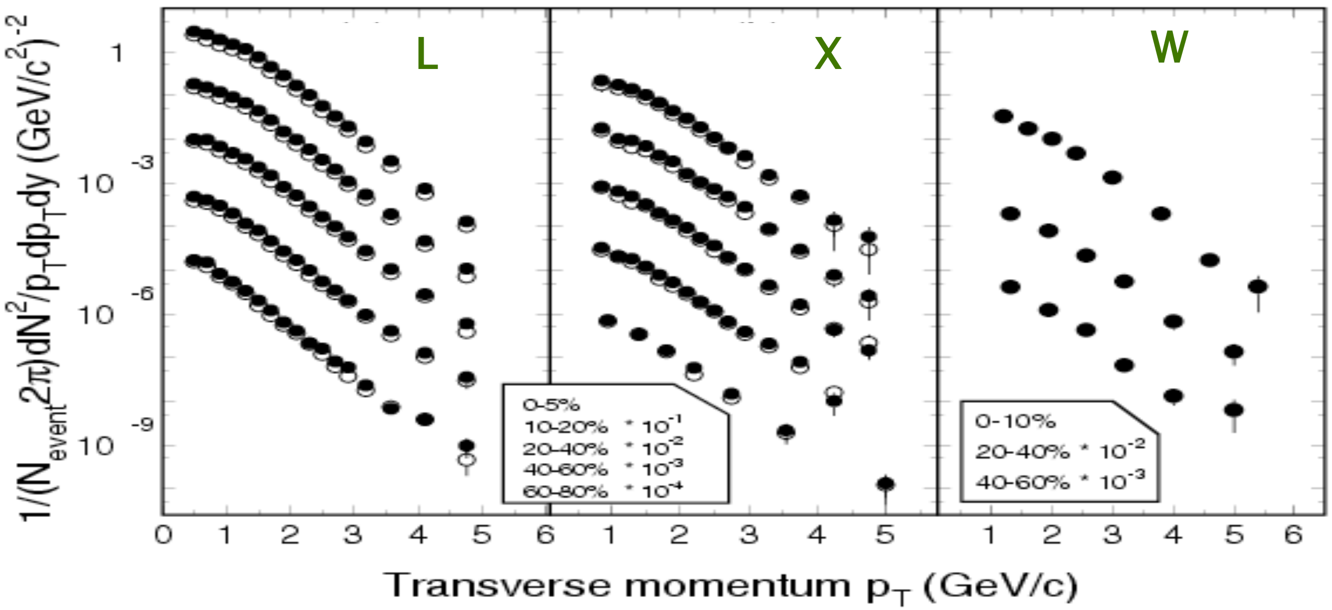
Eta ranges +-1, 2.3 to 3.8,

Full azimuth

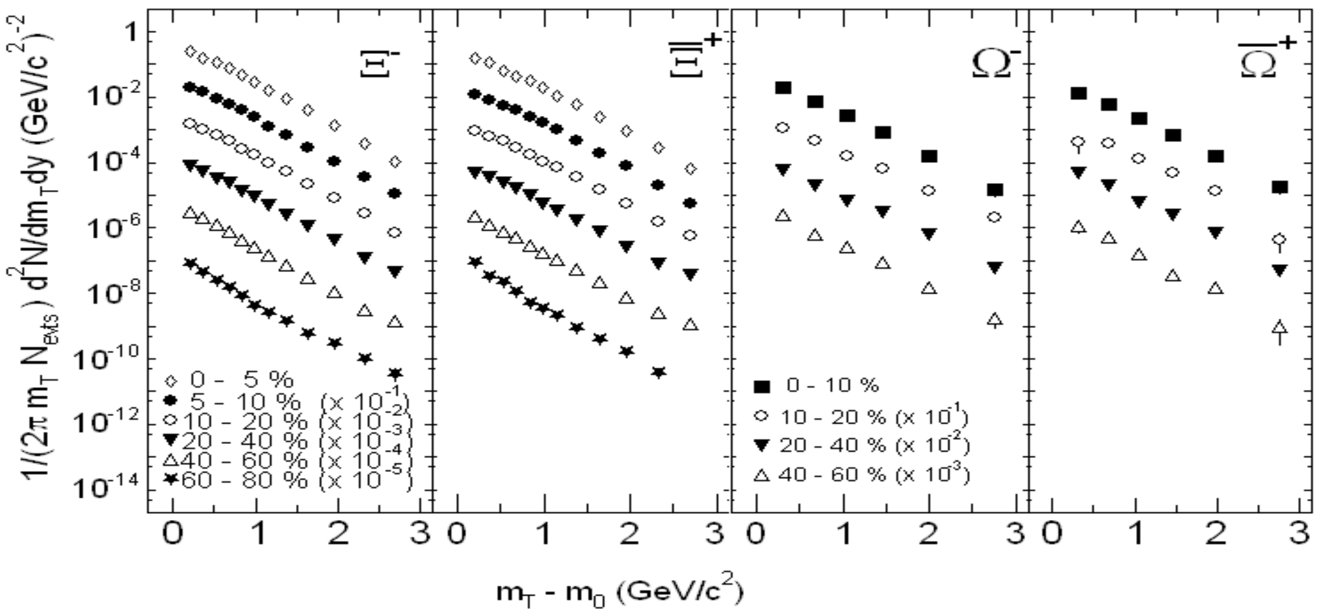
Pt from 50 MeV/c to 15 GeV/c

WHITE PAPER

strange baryon spectra



200 GeV
Au+Au



62.4 GeV
Au+Au

tools

- Global observables
- Rapidity, azimuthal and pT distributions of (non) identified particles

Radial, elliptic, directed flow

Rapidity and azimuthal correlations for (non)identified particles

Particle ratios

Fluctuations (number, pT, ratio..) and correlations

Heavy flavor

It is a partial journey

A Definition of the Quark-Gluon Plasma

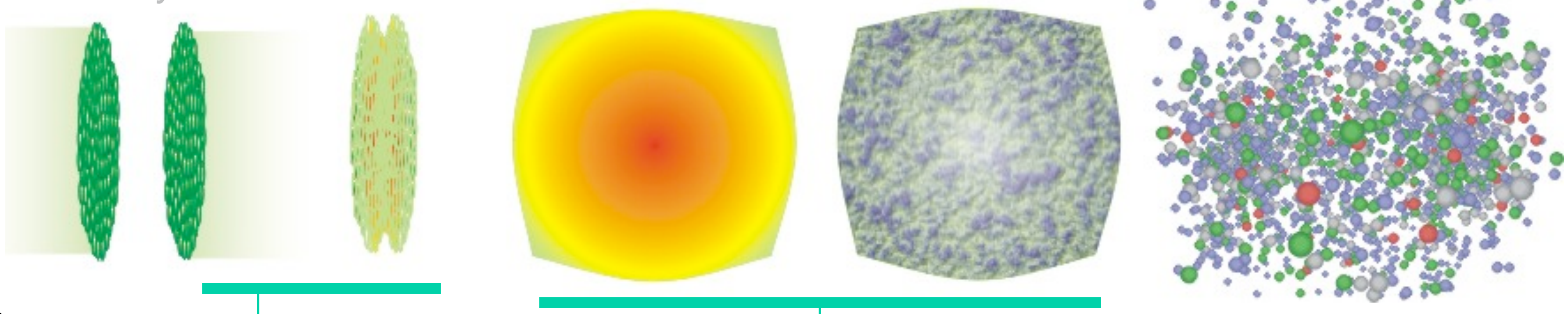
QGP ≡ *a (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes.*

Not required:

- *non-interacting quarks and gluons*
- *1st- or 2nd-order phase transition*
- *evidence of chiral symmetry restoration*

timeline

Courtesy of S. Bass



1

Initial condition: CGC
high-Q^2 interactions
medium formation

2

hot, dense medium
expansion
hadronization

3

hadrons
hadronic scatterings
freeze-out

Medium and properties

Tool:

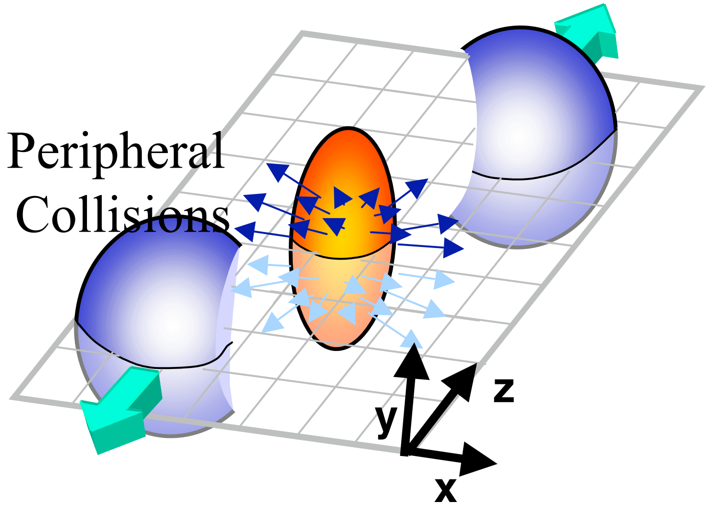
Elliptic Flow

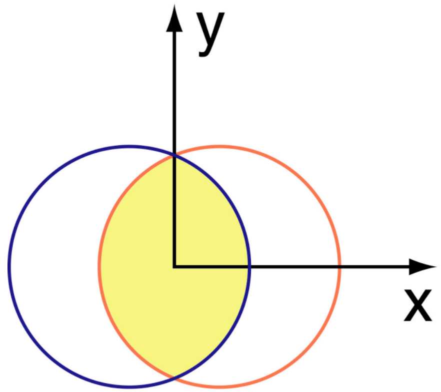
Understanding:

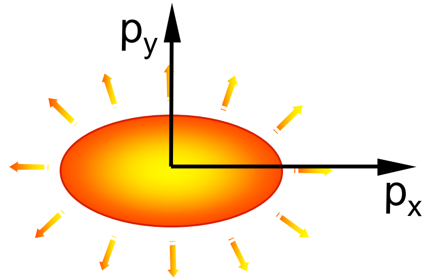
Thermalization?

EOS?

Time scale?



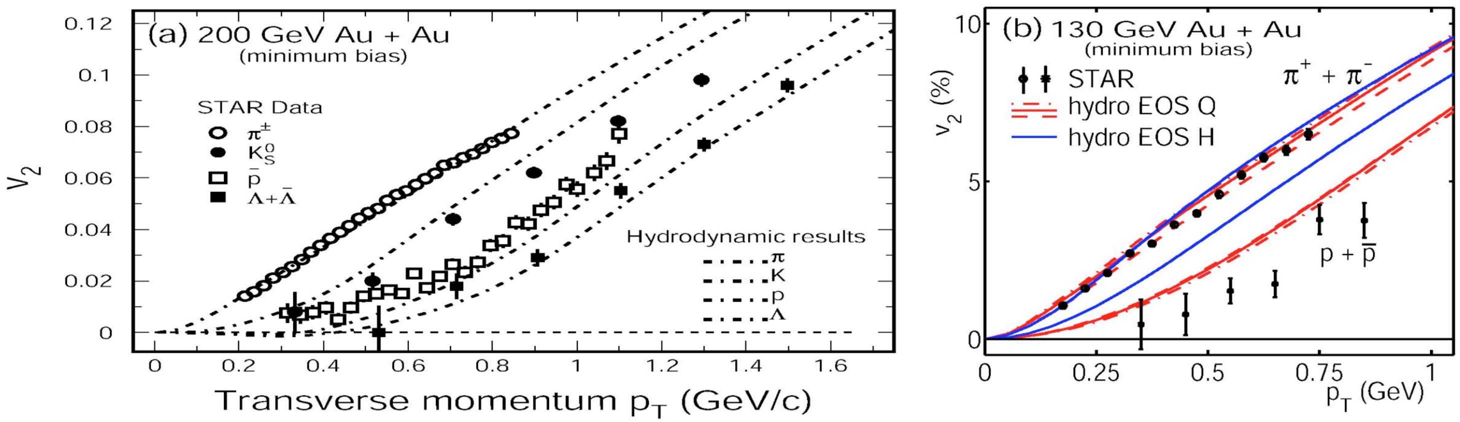




$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

Anisotropic Flow

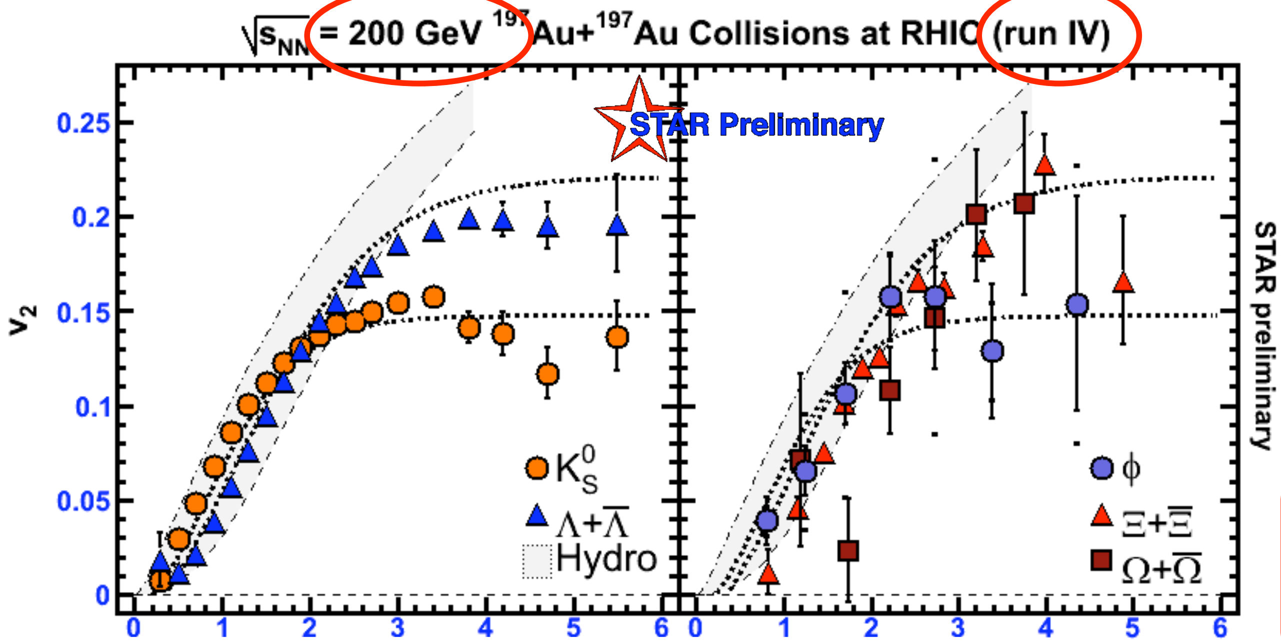
$$v_2 = \langle \cos 2\phi \rangle$$



The Strongest Evidence For (Locally)Thermalized State of Matter and EOS with a soft point : Observed Elliptic Flow vs the Predictions of Hydro

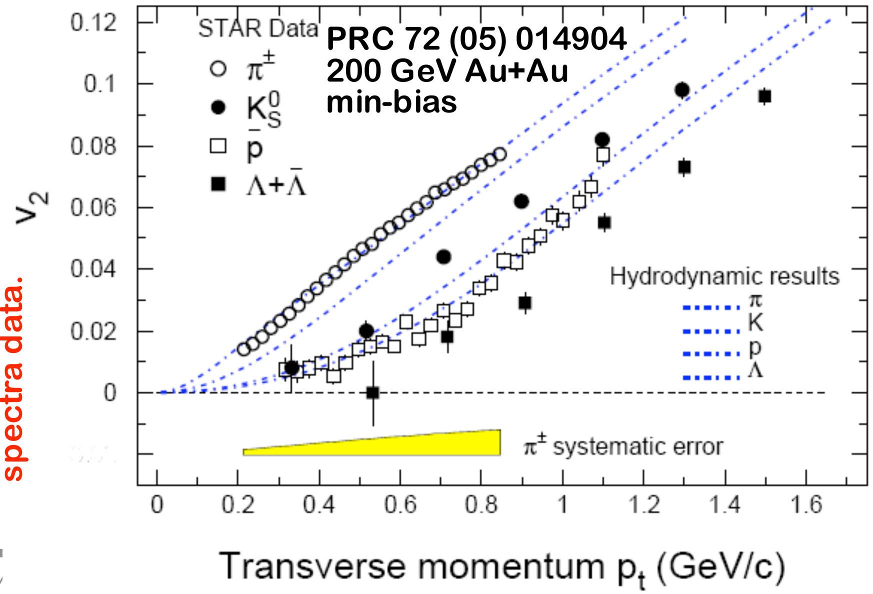
Hydro calculations: Kolb, Heinz and Huovinen

elliptic flow v_2



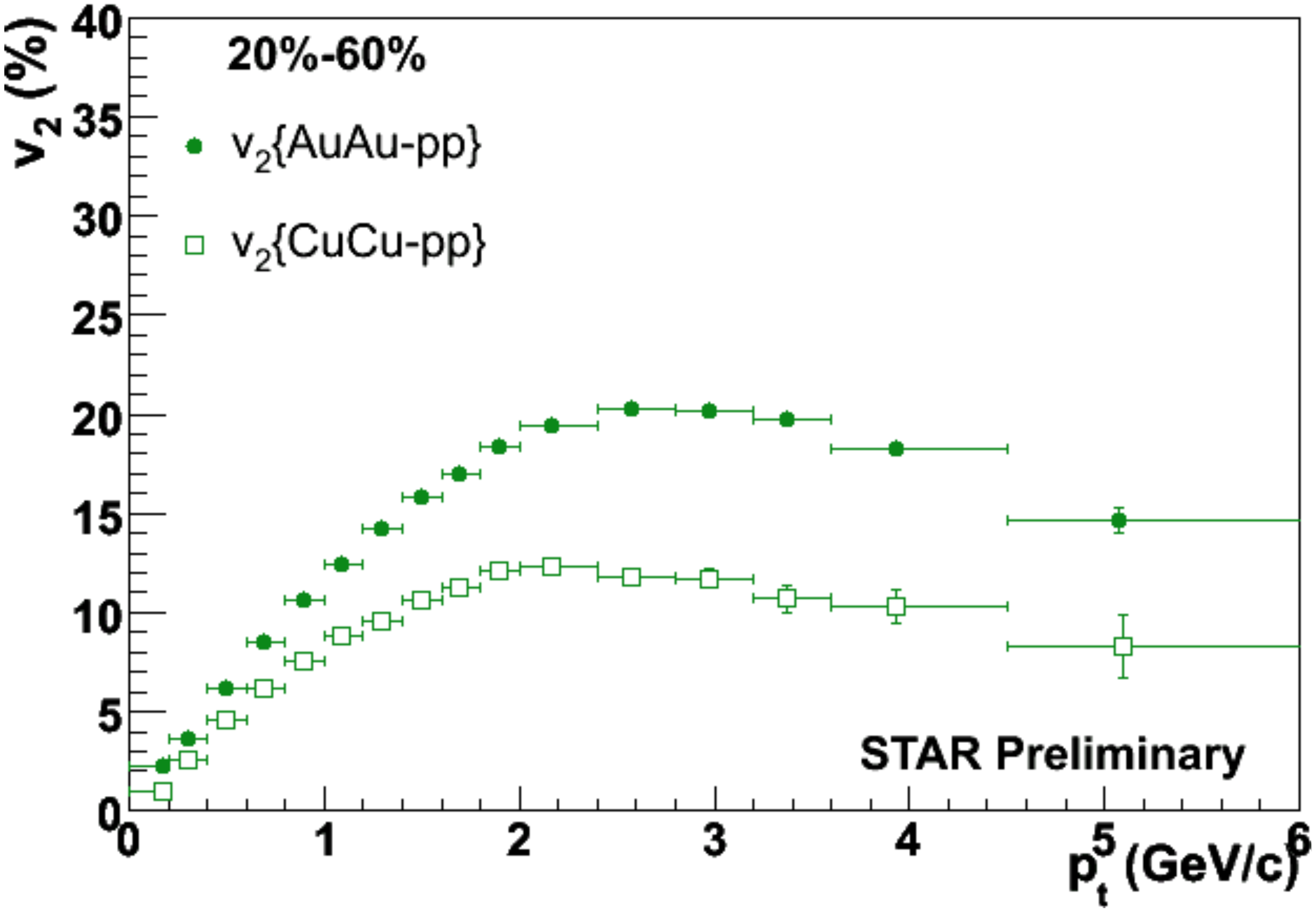
large v2 (even f , X, W):
strong interactions
at early stage

Hydro by Huovinen et al.
hydro tuned to fit central
spectra data.



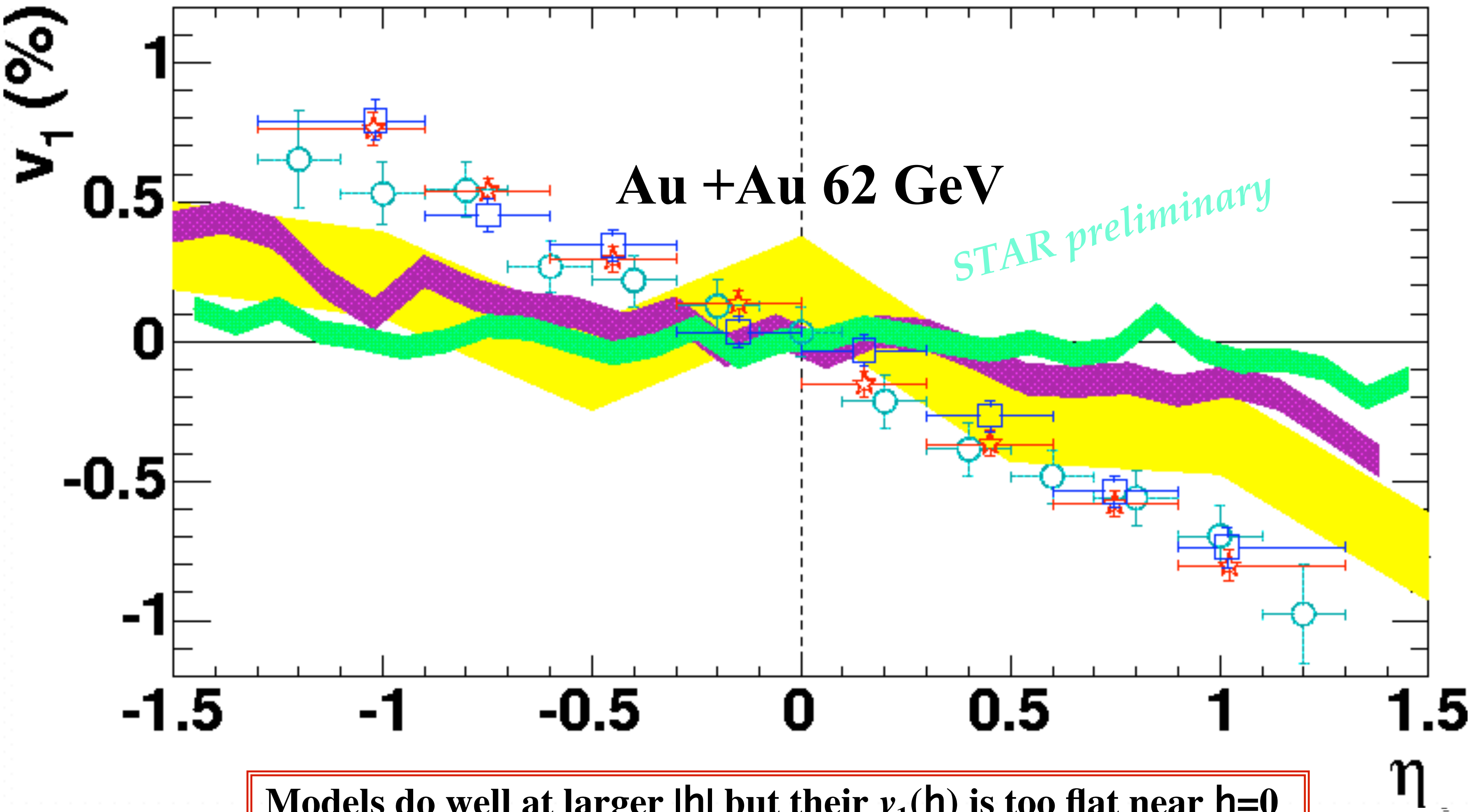
- m-dependence: common v_T field.
- hydro works: suggests early thermalization.
- soft (QGP) EOS favored: sub-hadronic DOF.

Charged hadrons: v_2 at 200 GeV in Cu+Cu



- Non-flow effects large at high p_T and for lighter systems.
- multiple methods to remove non-flow: 4-particle cumulants, subtraction of pp.
- Significantly smaller v_2 in Cu+Cu than in Au+Au.

Charged hadrons: v_1 in 62 GeV Au +Au



Models do well at larger |h| but their v_1(h) is too flat near h=0

Soft Sector: Evidence for Thermalization and EOS with Soft Point?

What do the v_2 and Hydro results tell us ?

- *Systematic m-dependence of $v_2(p_T)$ suggests common transverse vel. Field*
- *m_T spectra and v_2 systematics for mid-central collisions at low p_T are well (~20-30% level) described by hydro expansion of ideal relativistic fluid*
- *Hydro success suggests early thermalization, very short mean free path and high initial energy density (e > 10 GeV/fm^3)*

Best agreement with v_2 and spectra for τ_{therm} < 1 fm/c and soft (mixed-phase-dominated) EOS ~ consistent with LQCD expectations for QGP → hadron

What do we need to understand better ?

- *Real sensitivity of the Hydro predictions to the EOS and the Freeze-out Treatment*

E-by-E Fluctuations

- Net Charge Fluctuations
  - Prediction by Jeon & Koch, PRL83 (99) 5435, + others…
    - Net charge fluctuations ***dramatically reduced*** in a QGP compared to a hadron or resonance gas.
  - Published STAR results at 130 GeV: C. Adler, *et al.*, Phys. Rev. **C68**, 044905 (2003).
- **K/Pi fluctuation**:

reflects strangeness fluctuation

$$R = \frac{N_+}{N_-}$$

$$D \equiv \langle N_{ch} \rangle \langle \delta R^2 \rangle = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{CH} \rangle} = 4\varpi_Q$$

Model	D	$\nu_{+-,dyn}$
Poisson, Hadron Gas	4	0
Resonance Gas (Koch et al)	2.8	$-1.2/n_{ch}$
Quark Coalescence (Bialas)	3.33	$-0.7/n_{ch}$
QGP (Koch et al)	0.75	$-3.25/n_{ch}$
Lattice	1	$-3/n_{ch}$

- Momentum Fluctuations
  - Predictions by M. Stephanov *et al* PRL81 (98) 4816; S. Mrowczynski, PLB314 (93) 118.
  - Large Transverse Momentum Fluctuations
    - Sensitive to 1st order phase transition - QGP Droplets.
    - Sensitive to 2nd order phase transition Near critical point.

Study beam energy & collision centrality dependence

Specific Fluctuation Measures

Net Charge & K/π Fluctuations

Instead of measuring the variance of a yield ratio,

$$r_{12} = \frac{n_1}{n_2} \quad \rightarrow \quad \frac{\langle(\Delta r_{12})^2\rangle}{\langle r_{12}\rangle^2} \approx \frac{\langle(\Delta n_1)^2\rangle}{\langle n_1\rangle^2} + \frac{\langle(\Delta n_2)^2\rangle}{\langle n_2\rangle^2} - 2\frac{\langle \Delta n_1 \Delta n_2\rangle}{\langle n_1\rangle\langle n_2\rangle}$$

Study the "dynamical fluctuations":

$$\nu_{12,dyn} = \left\langle \left(\frac{n_1}{\langle n_1\rangle} - \frac{n_2}{\langle n_2\rangle} \right)^2 \right\rangle - \frac{1}{\langle n_1\rangle} - \frac{1}{\langle n_2\rangle} = \tilde{R}_{11} + \tilde{R}_{22} - 2\tilde{R}_{12}$$

Side Note: $D \equiv \langle n_1 + n_2\rangle\langle(\Delta r_{12})^2\rangle$

$$\frac{D}{4} \approx 1 + \frac{(\tilde{R}_{++} + \tilde{R}_{--} - 2\tilde{R}_{+-})\langle n_+ + n_-\rangle}{4}$$

p_t Fluctuations

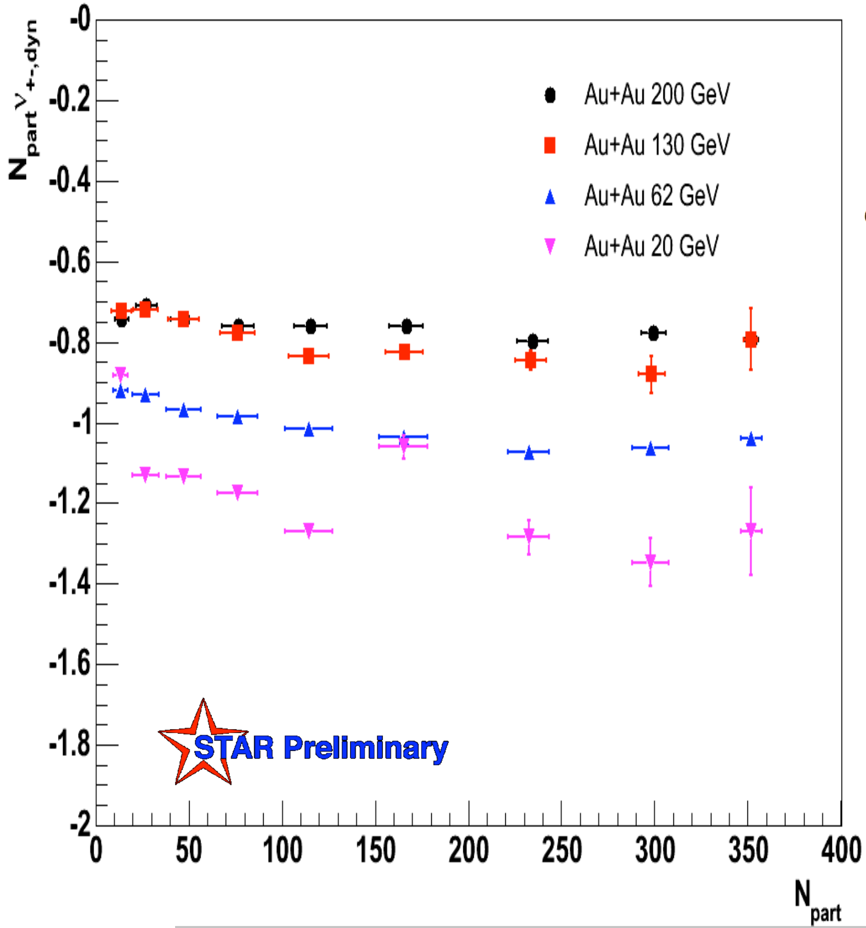
$$\langle \Delta p_{t,1} \Delta p_{t,2}\rangle = \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_k(N_k - 1)}$$

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left(p_{t,i} - \langle\langle p_t\rangle\rangle\right)\left(p_{t,j} - \langle\langle p_t\rangle\rangle\right)$$

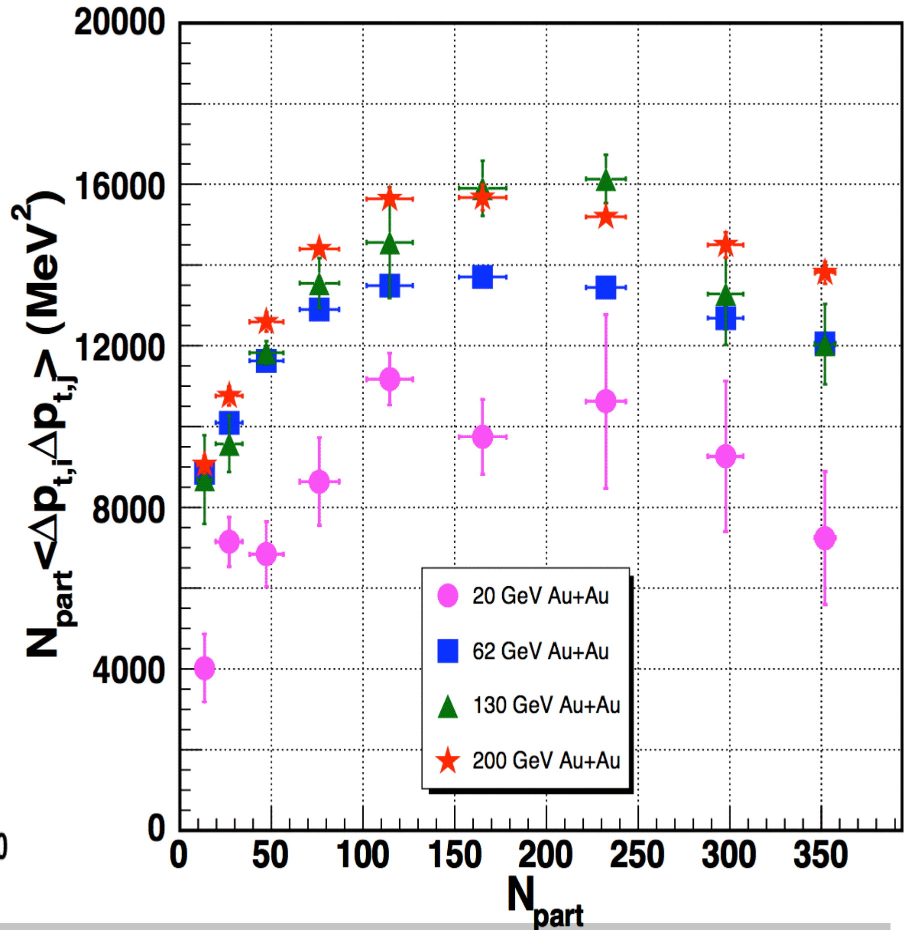
and $\langle\langle p_t\rangle\rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t\rangle_k\right) / N_{event}$ and $\langle p_t\rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i}\right) / N_k$

$1/N_{part}$ Scaling?

Net Charge



pT fluctuation

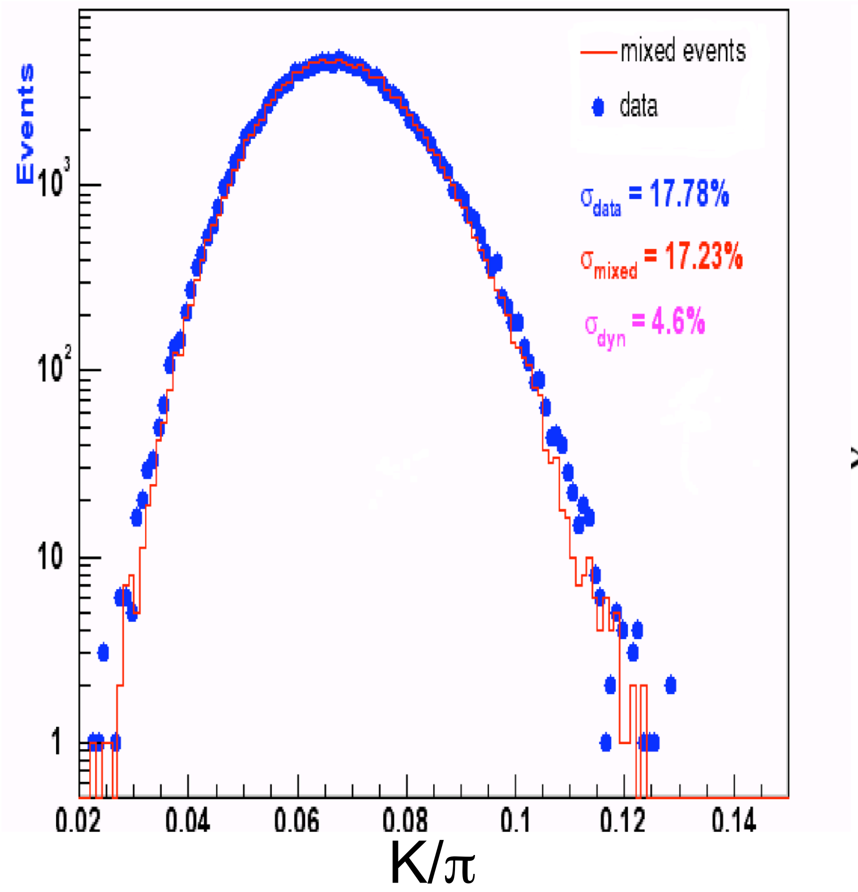


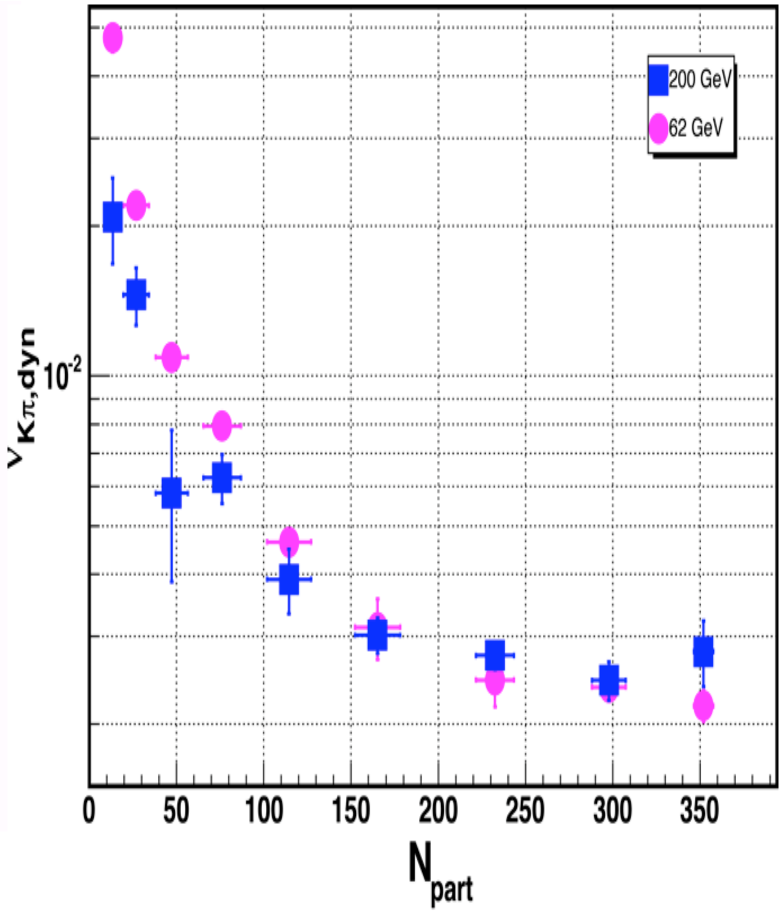
$N_{part}\,\nu_{+-dyn}$ exhibits small dependence on N_{part}

$N_{part}\,\langle\Delta p_{t,1}, \Delta p_{t,2}\rangle$ exhibits large dependence on N_{part}

K vs π multiplicity fluctuations

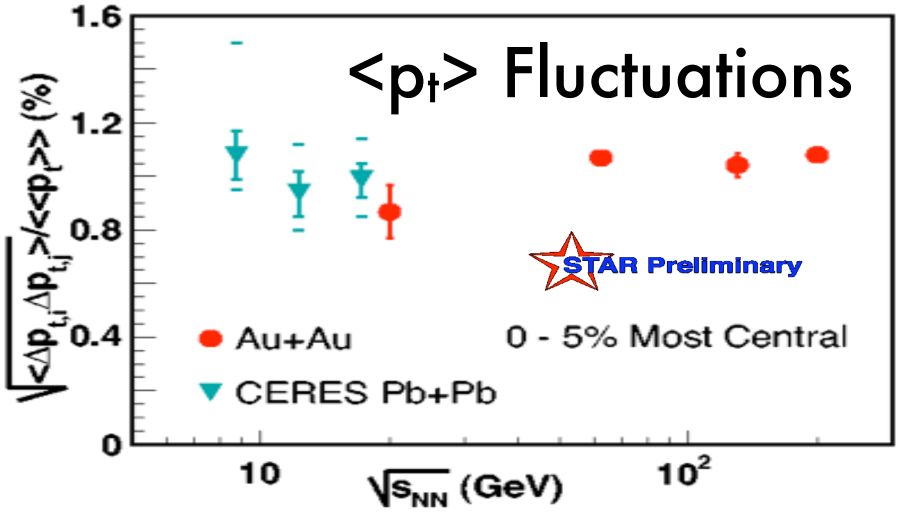
Au + Au @ 200 GeV

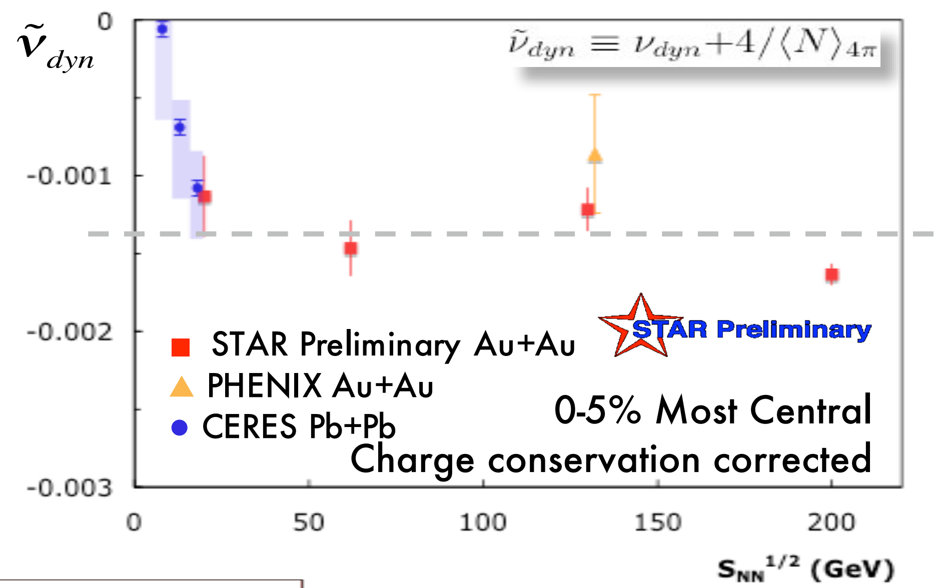


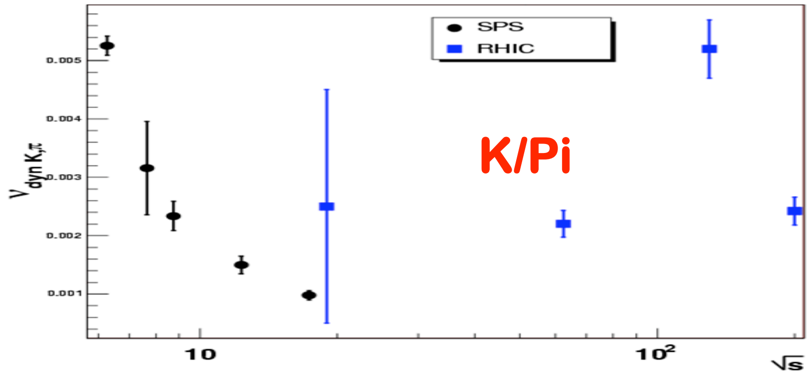


Finite Dynamical k vs π Fluctuations

event-by-event fluctuations





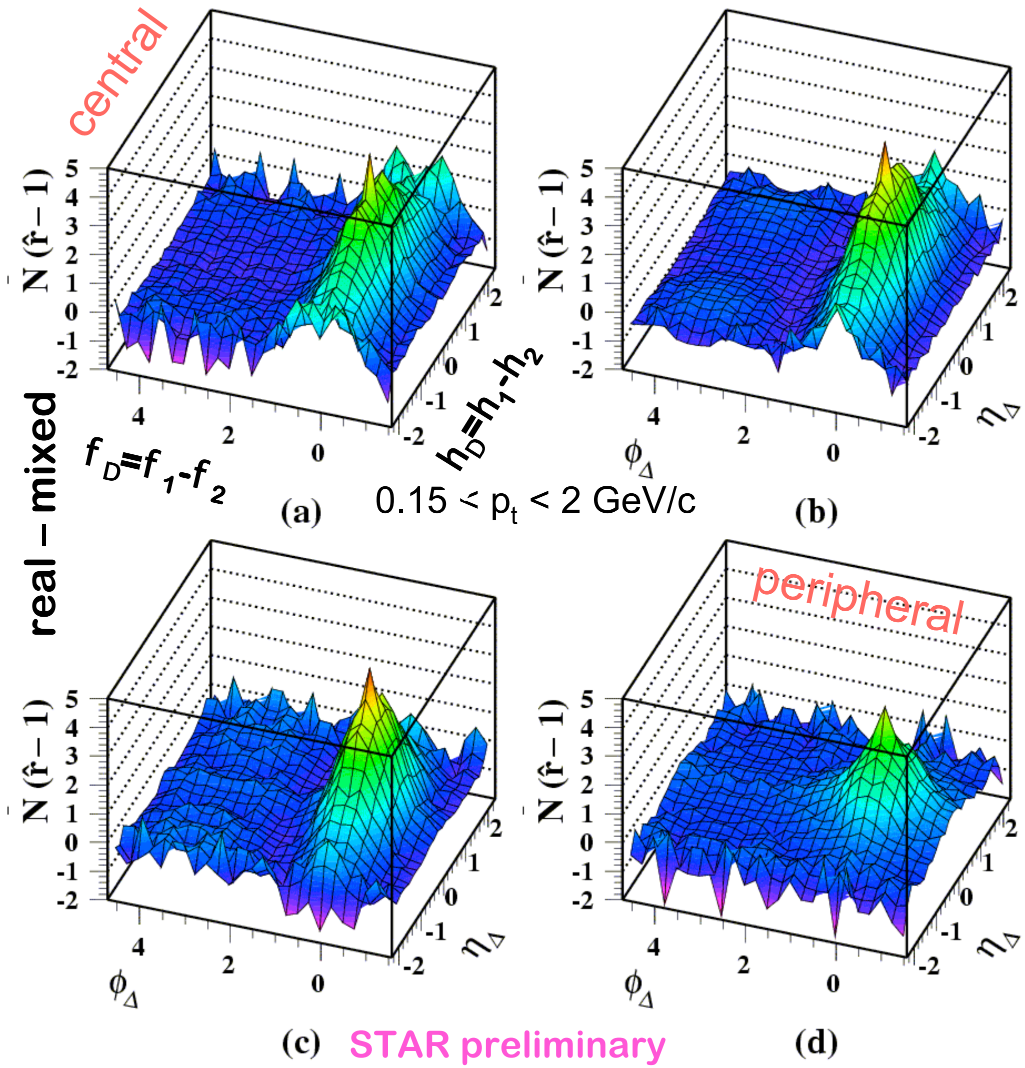


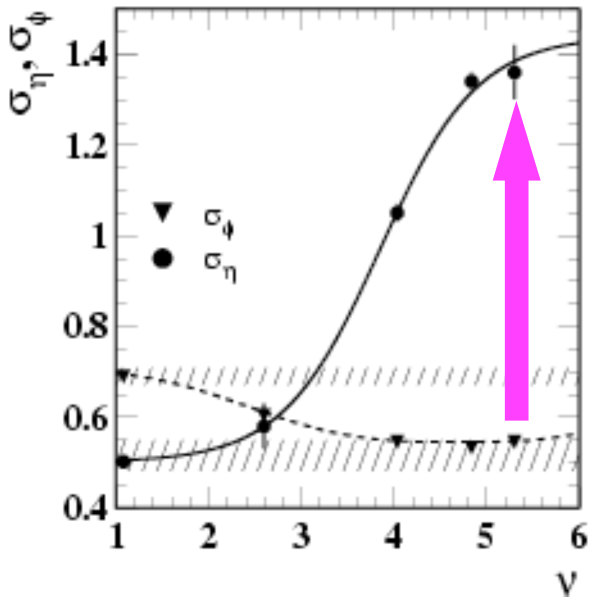
- Smooth √s dependence (?), no threshold effect.
- Original QGP signal in inclusive net charge fluctuation is excluded. More differential studies are needed.

soft-soft correlations

130 GeV Au+Au: STAR, nucl-ex/0411003.
cos(f D), cos(2f D) subtracted correlations.

p-p 200 GeV





$$\nu \equiv 2N_{BC} / N_{part} \approx (N_{part} / 2)^{1/3}$$

- even at low pt, remnants of jet-like structure survive.
- strongly coupled to the medium, elongated along h.

High (??) pT

- Jet Quenching via

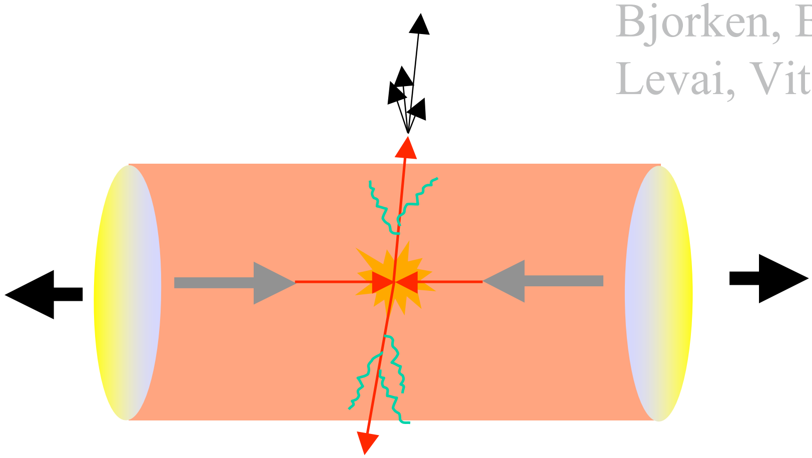
  Spectra

  azimuthal anisotropy

  Correlation

Partonic energy loss in dense matter

Bjorken, Baier, Dokshitzer, Mueller, Pegne, Schiff, Gyulassy, Levai, Vitev, Zhakarov, Wang, Wang, Salgado, Wiedemann,…



Gluon bremsstrahlung

Multiple soft interactions:

$$\Delta E \approx \frac{C_R \alpha_S}{4} \hat{q} L^2$$

$$\hat{q} = \frac{\langle k_T^2 \rangle_{medium}}{\lambda} \propto \alpha_S \rho_{glue}$$

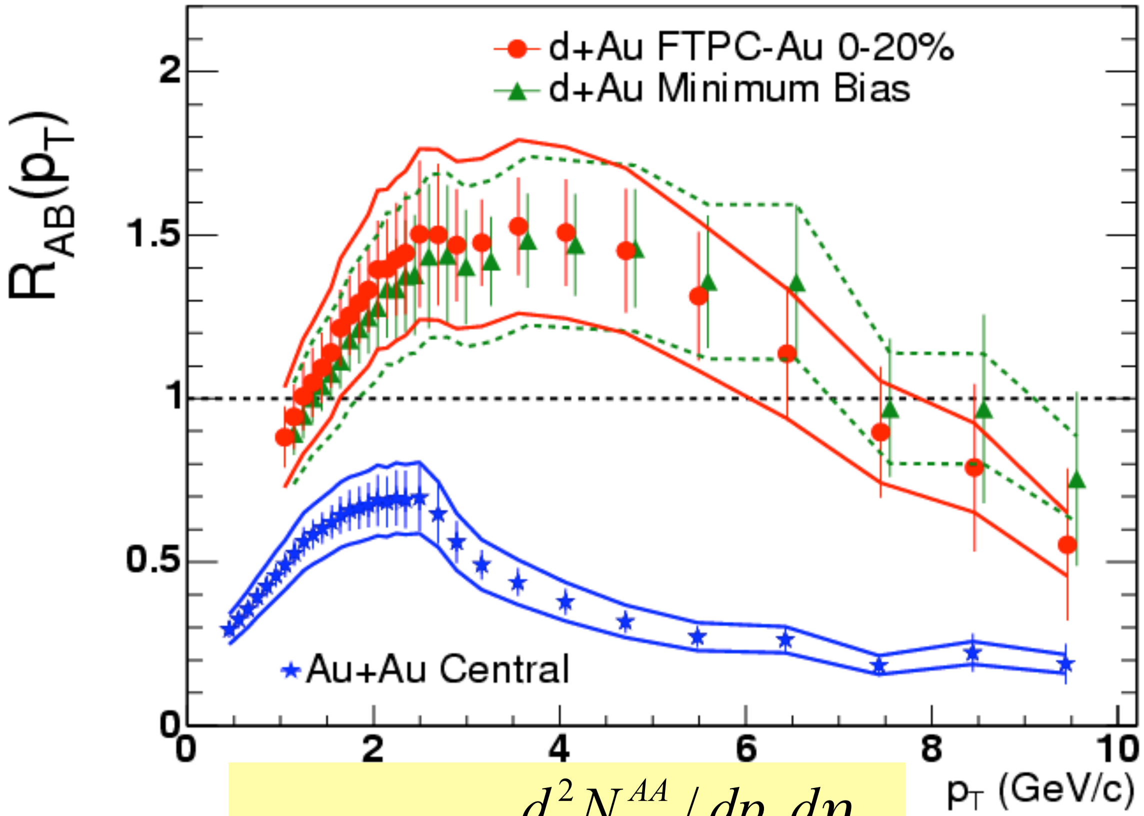
Opacity expansion:

$$\Delta E = \pi C_A C_a \alpha_S^3 \int d\tau \rho_{glue}(\tau, r(\tau)) \tau Log\left(\frac{2E_{jet}}{\mu^2 L}\right)$$

Strong dependence of energy loss on gluon density ρ_{glue}:

measure DE ⇒ color charge density at early hot, dense phase

Inclusive Suppression



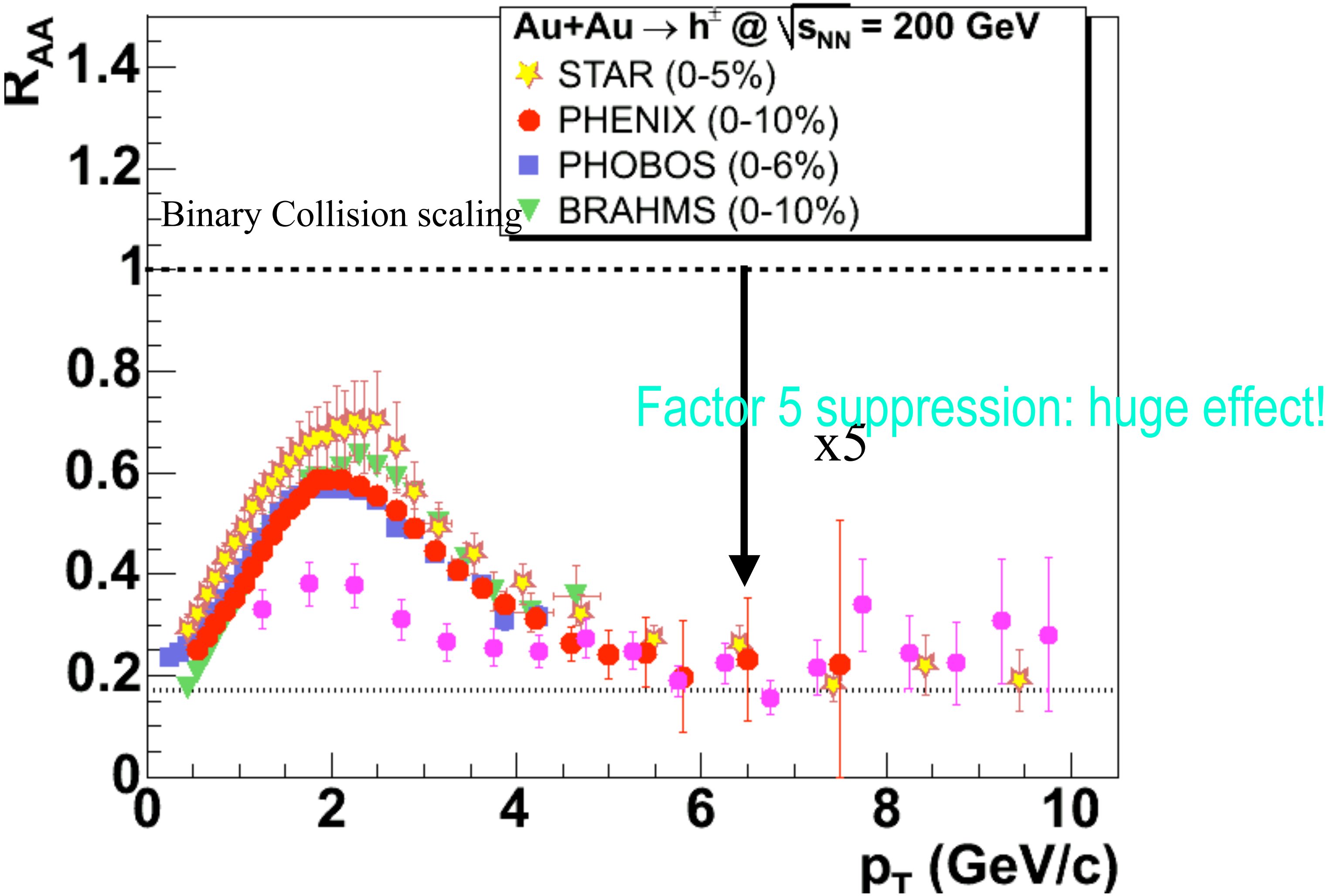
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Binary collision scaling p+p reference

J. Adams et al, Phys. Rev. Lett. 91 (2003) 072304

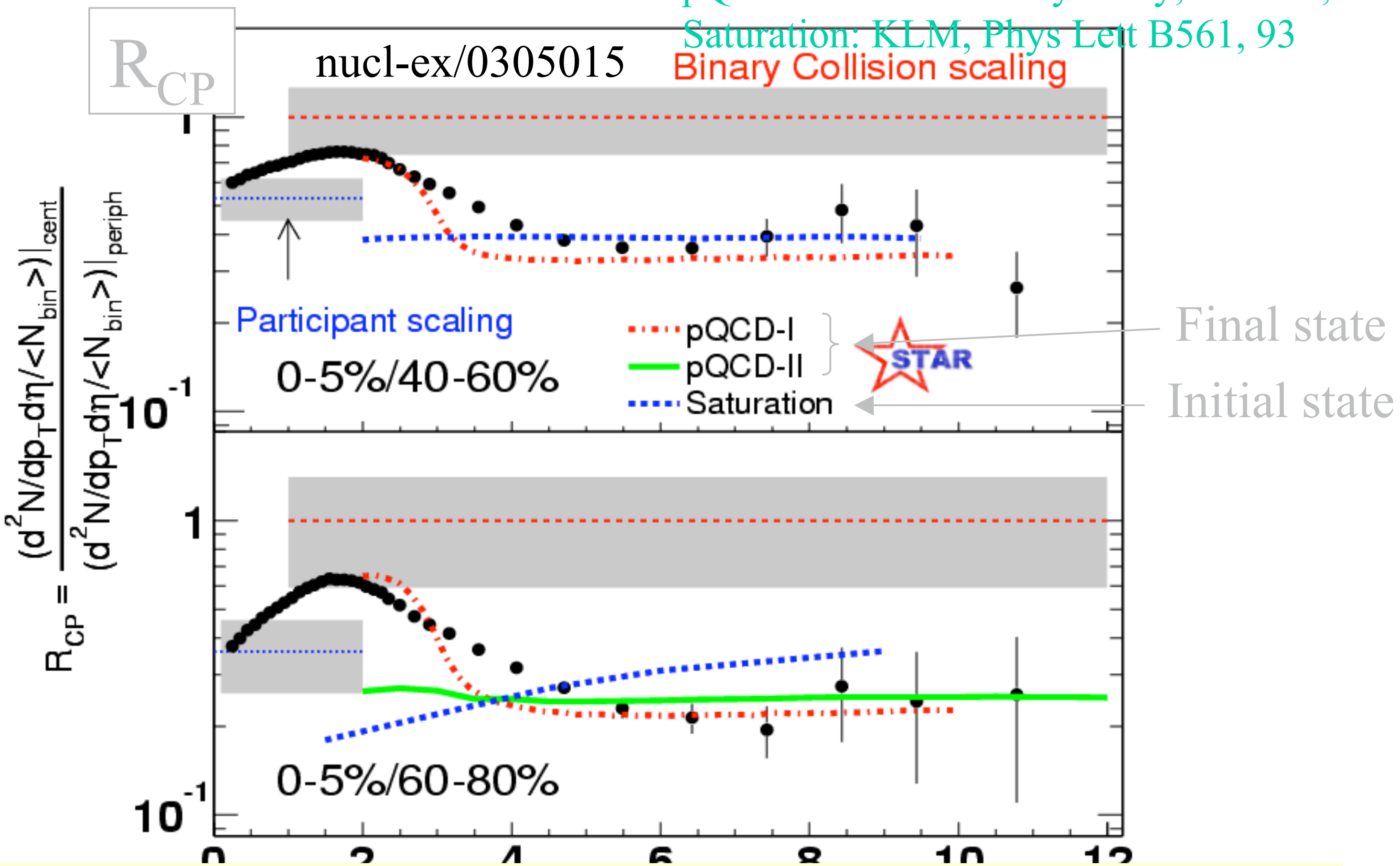
Suppression an established probe of the density of the medium

High p_T yields in central Au+Au are suppressed



Inclusive suppression: theory vs. data

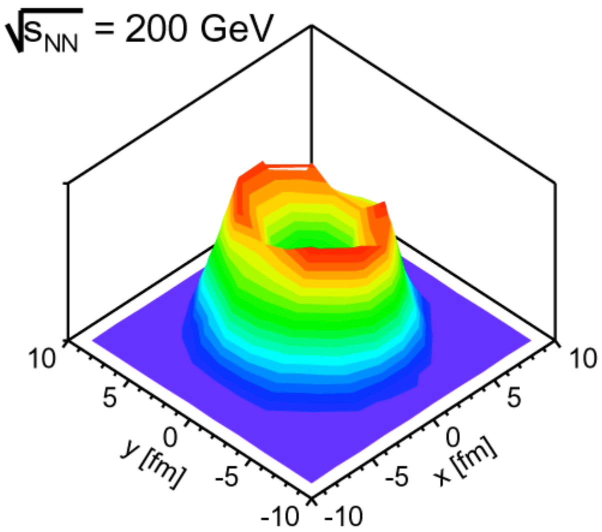
pQCD-I: Wang, nucl-th/0305010
pQCD-II: Vitev and Gyulassy, PRL 89, 252301
Saturation: KLM, Phys Lett B561, 93

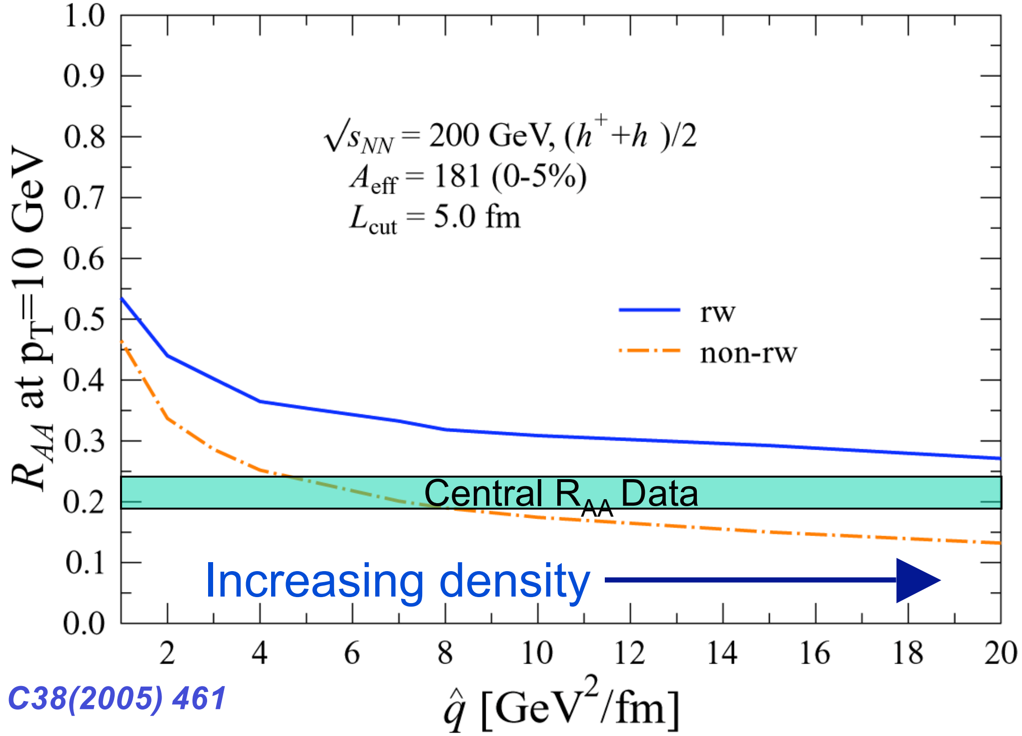


p_T>5 GeV/c: well described by KLM saturation model (up to 60% central) and pQCD+jet quenching

The Limitations of R_{AA}

K.J. Eskola, H. Honkanken, C.A. Salgado, U.A. Wiedemann, Nucl. Phys. A747 (2005) 511





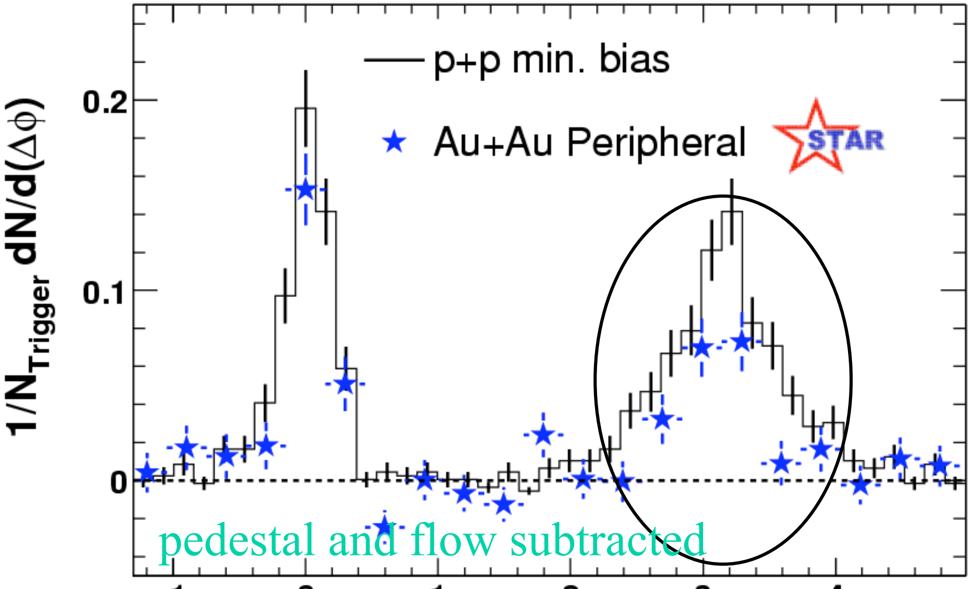
A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C38(2005) 461

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

Challenge: Increase sensitivity to the density of the medium

Azimuthal distributions in Au+Au

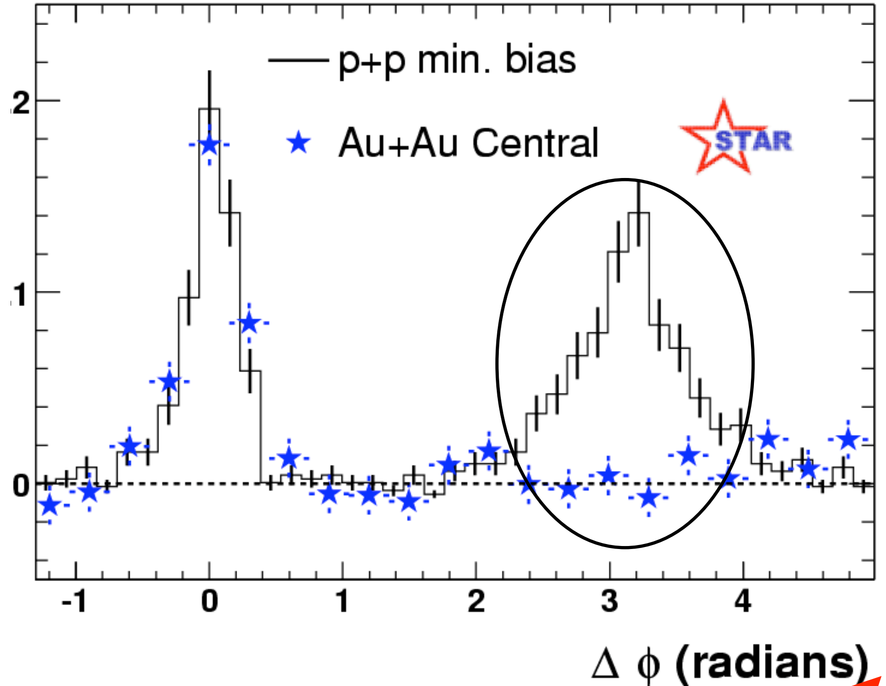
Au+Au peripheral



Phys Rev Lett 90, 082302

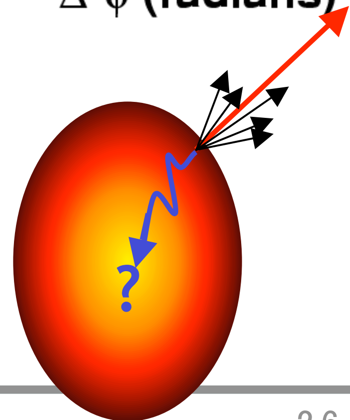
Δ φ (radians)

Au+Au central



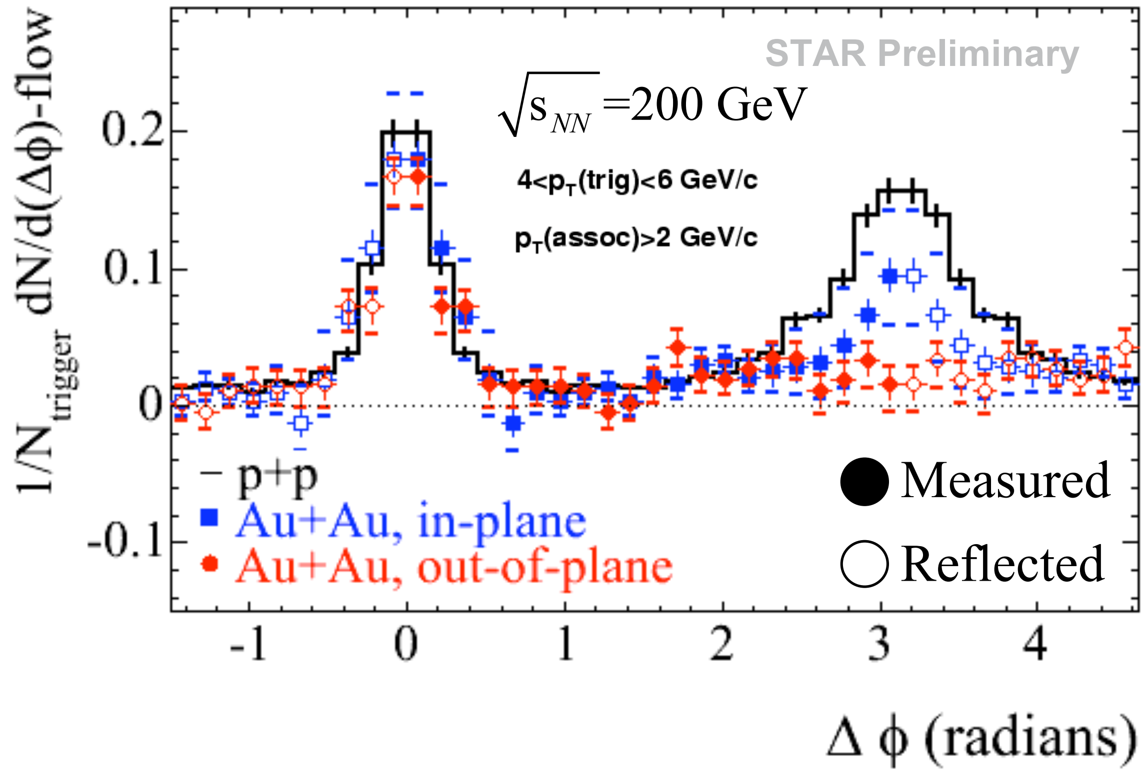
Near-side: peripheral and central Au+Au similar to p+p

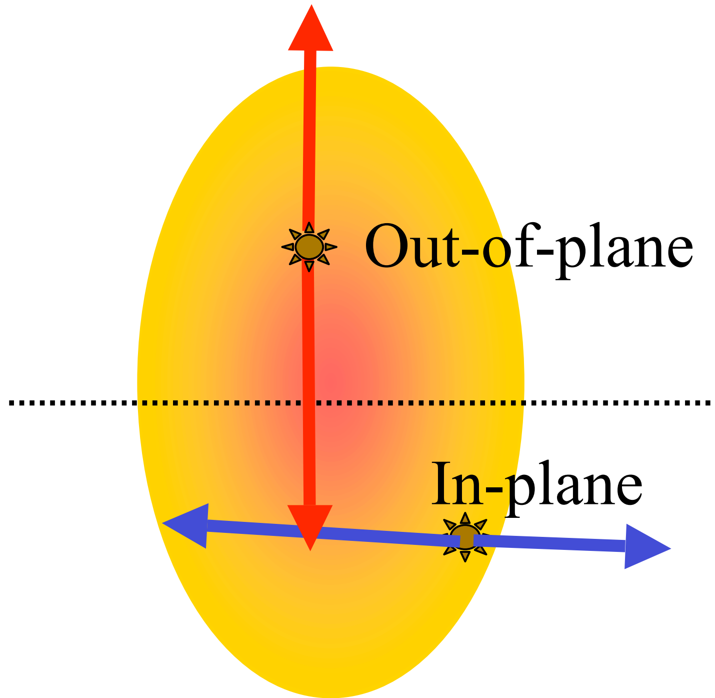
Strong suppression of back-to-back correlations in central Au+Au



Path Length Dependence

di-hadron, 20-60% Central

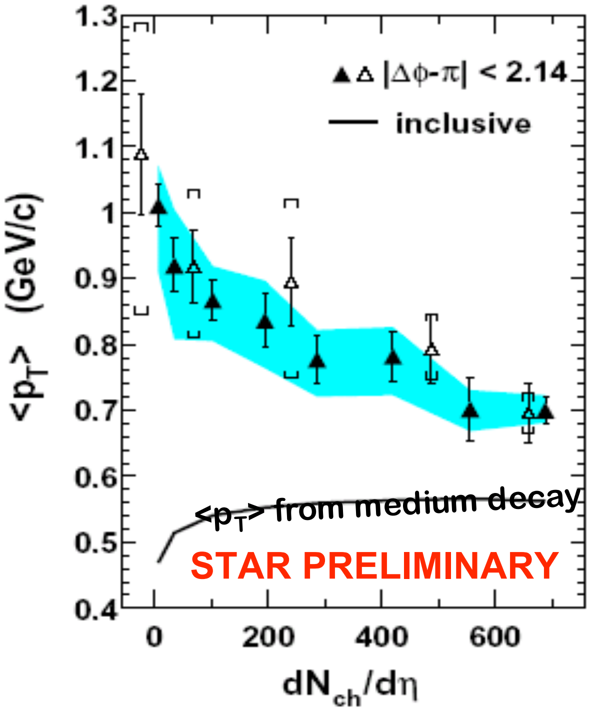


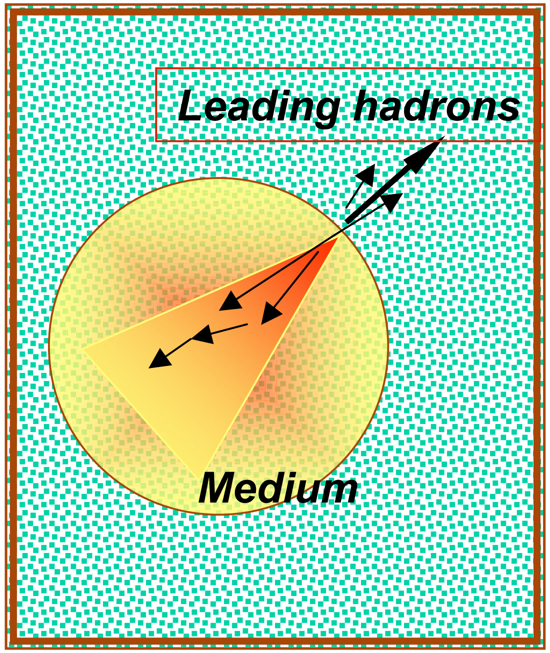


Suppression larger out-of-plane

$\Delta E_{GLV} \quad L^n(\phi)$

Soft-Hard Correlations: Partial Approach Toward Thermalization?



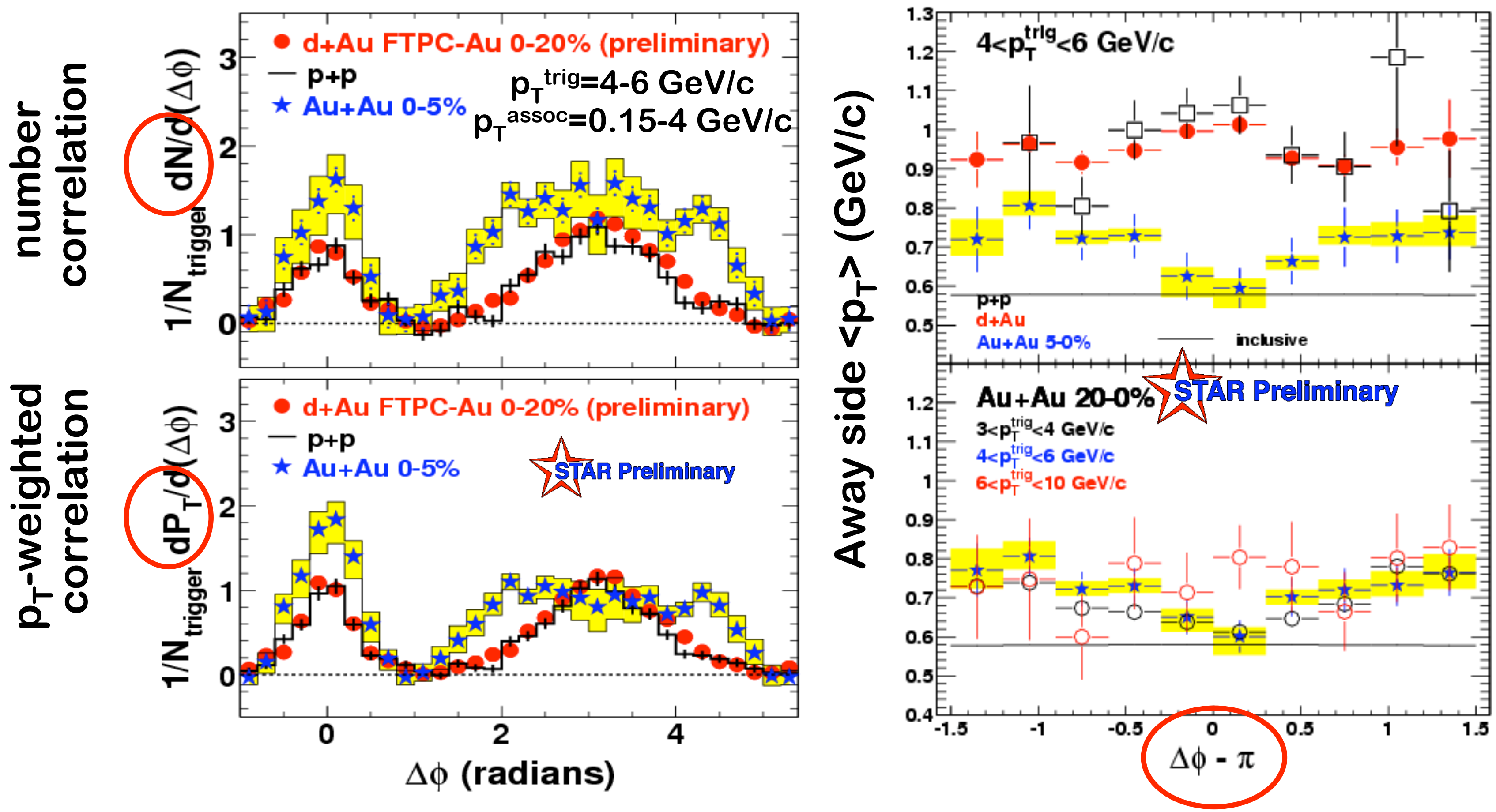


$\sqrt{s_{NN}}$ = 200 GeV Au+Au results: { Closed symbols ⇔ $4 < p_T^{trig} < 6$ GeV/c Open symbols ⇔ $6 < p_T^{trig} < 10$ GeV/c } Assoc. particles: $0.15 < p_T < 4$ GeV/c

Away side not jet-like! In central Au+Au, the balancing hadrons are greater in number, softer in p_T, and distributed ~statistically [~ cos(Δφ)] in angle, relative to pp or peripheral Au+Au.

⇒ away-side products seem to approach equilibration with bulk medium traversed, making thermalization of the bulk itself quite plausible.

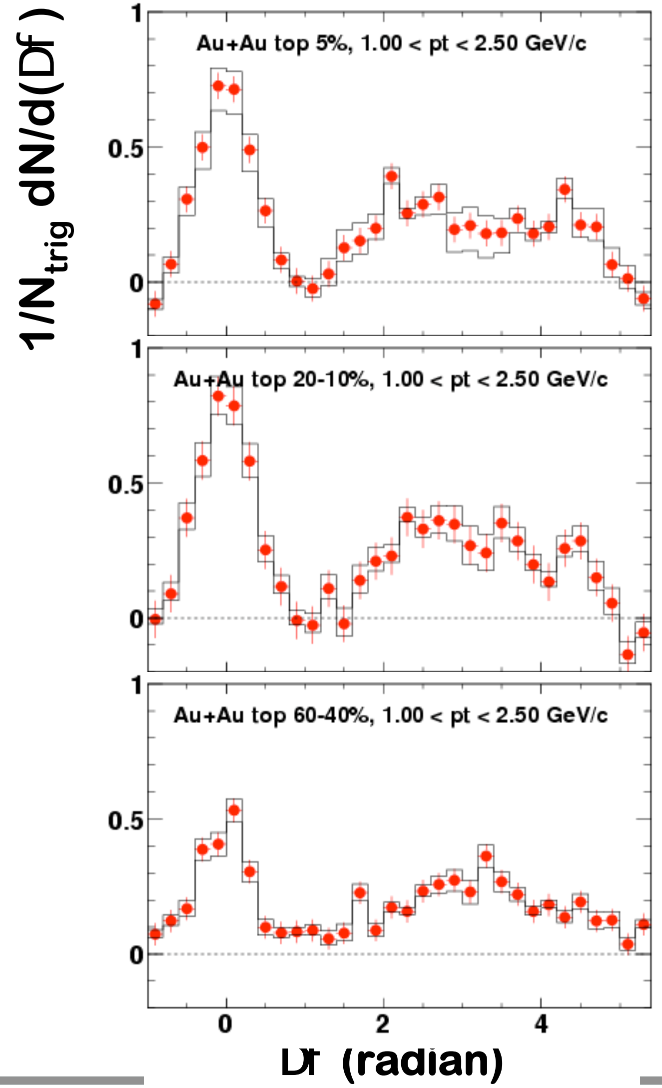
hard-soft angular correlations



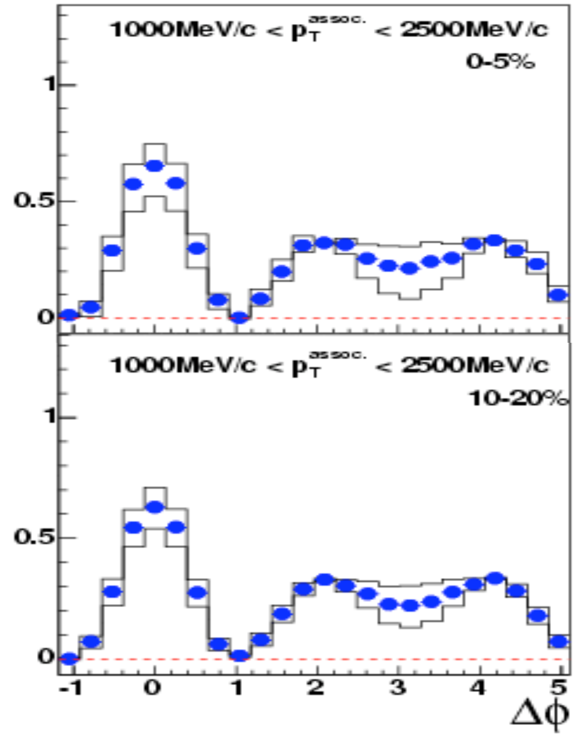
- Broader away-side correlations in central Au+Au.
- Novel dip at p in away $<p_T>$ for $p_T^{trig}<6$ GeV/c. Associated hadrons at p appear more equilibrated.

correlation functions

$4 < p_T^{trig} < 6$ GeV/c
$1 < p_T^{assoc} < 2.5$ GeV/c



$2.5 < p_T^{trig} < 4$ GeV/c
$1 < p_T^{assoc} < 2.5$ GeV/c

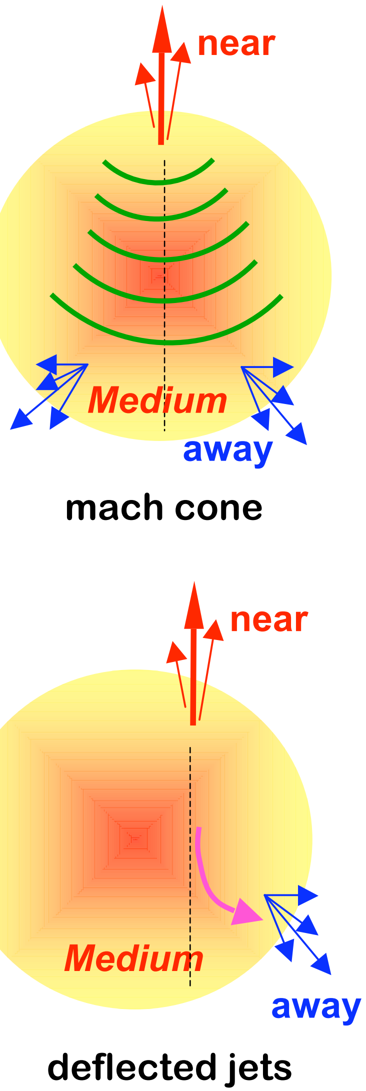


broad away-side correlations.

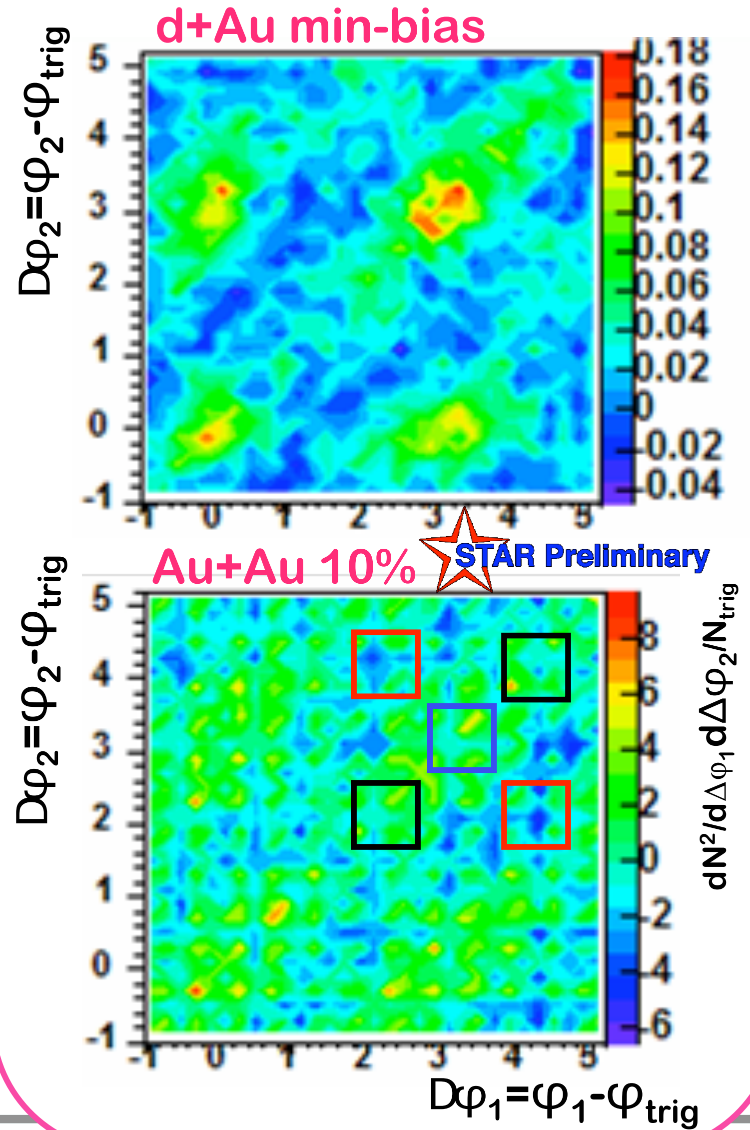
consistent with flat.

- large angle gluon radiation: Vitev
- conical flow: Stoecker,Shuryak,Muller
- jets deflected by medium flow

conical flow? 3-particle correlation



p_T^{trig}=3-4, p_T^{assoc}=1-2 GeV/c
2-particle corr, bg, v2 subtracted



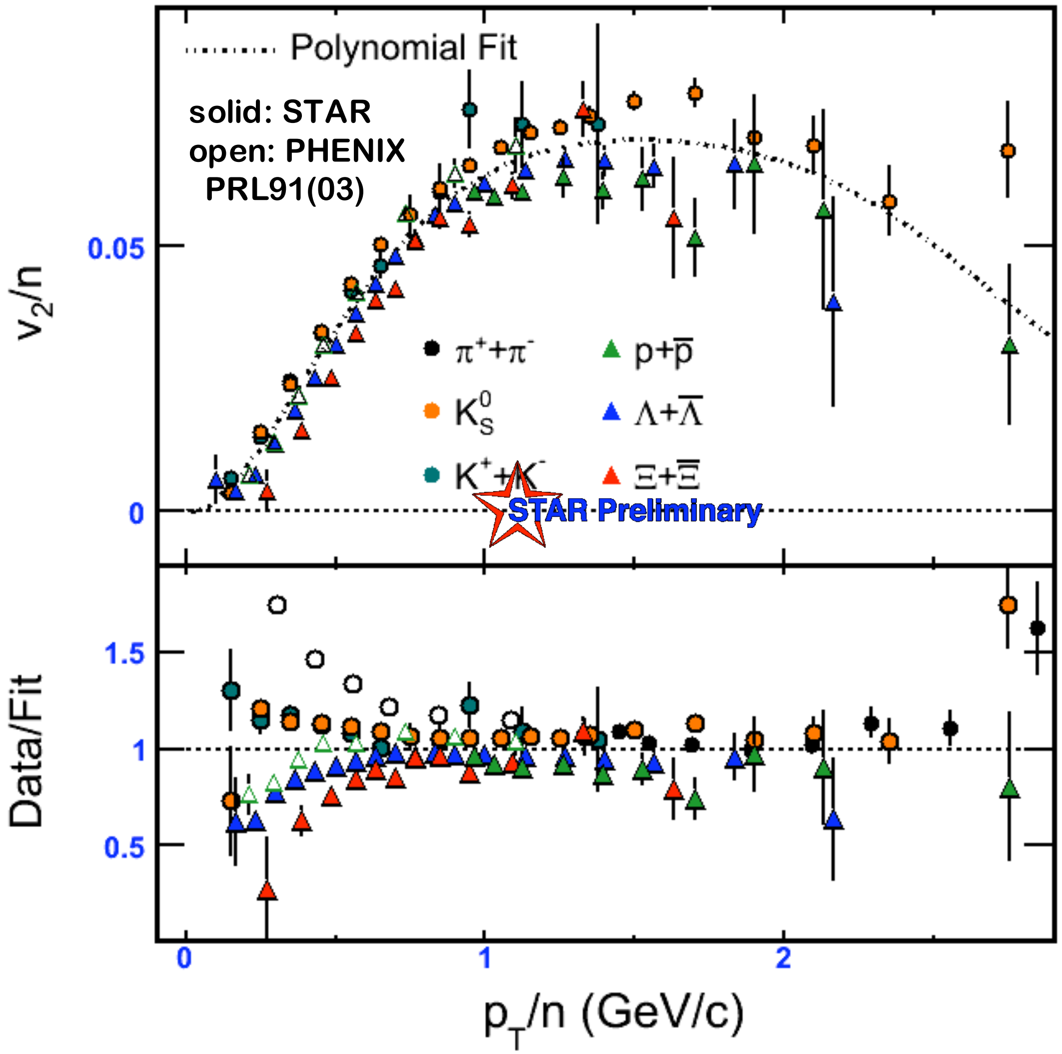
Three regions on away side:
center = (p, p) ±0.4
corner = (p+1,p+1) ±0.4 x2
cone = (p+1,p-1) ±0.4 x2

difference in Au+Au
average signal per radian^2:
center – corner =
0.3 ± 0.3 (stat) ± 0.4 (syst)
center – cone =
2.6 ± 0.3 (stat) ± 0.8 (syst)

d+Au and Au+Au elongated along diagonal: k_T effect, and deflected jets?

Distinctive features of conical flow are not seen in present data with these p_T windows.

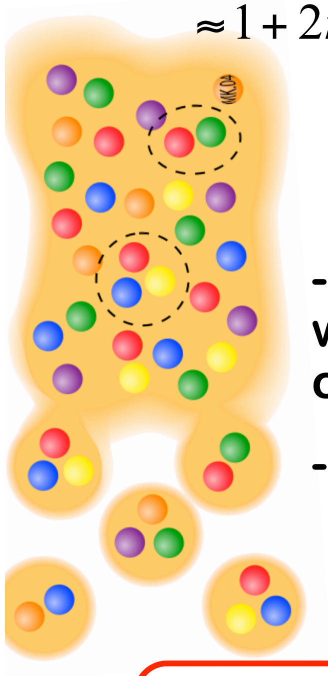
constituent quark scaling



$$\frac{dN}{d\phi} \propto \left[1 + 2v_2(p_T)\cos(2\phi) + \cdots\right]$$

$$= \left[1 + 2v_2^q(p_T^q)\cos(2\phi) + \cdots\right]^{n_q}$$

$$\approx 1 + 2n_q v_2^q\left(\frac{p_T}{n_q}\right)\cos(2\phi) + \cdots$$

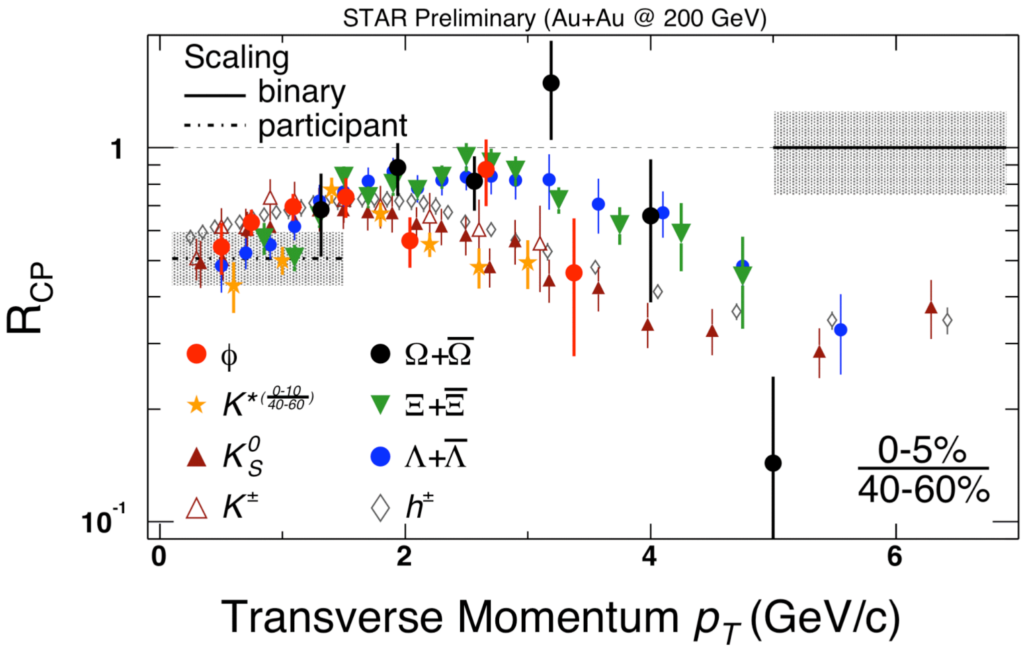


- v_2 appears to scale with number of constituent quarks.
- quark coalescence.

Constituent quark DOF.

Deconfinement?

Mesons and baryons behave differently

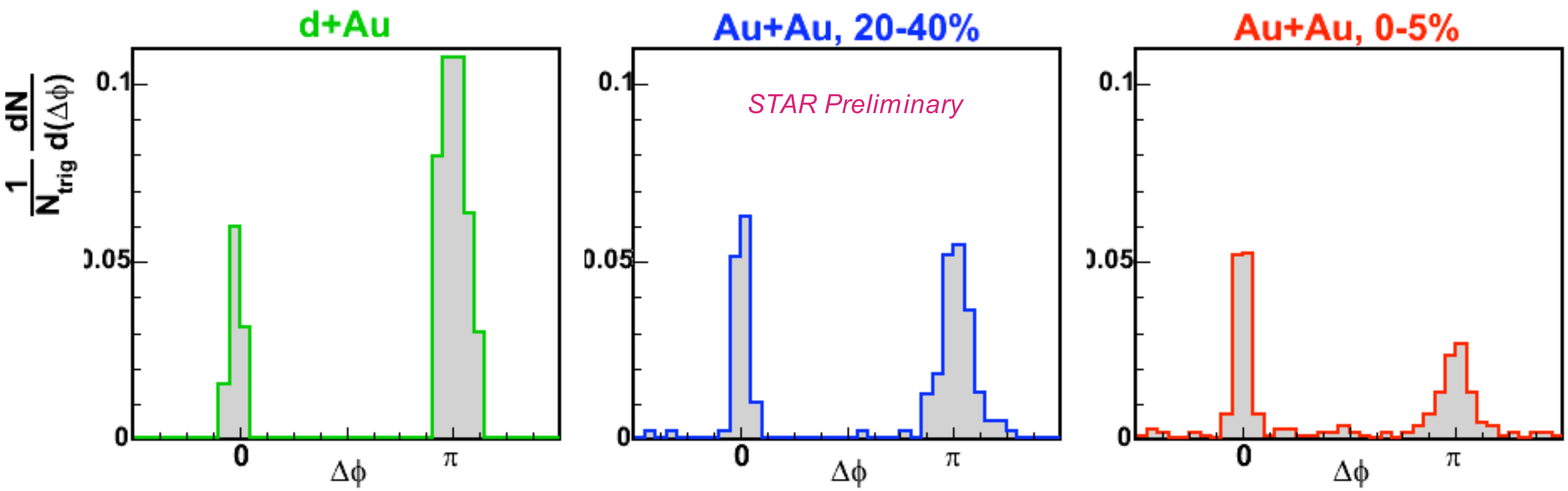


- Two groups ($2<p_t<6$GeV/c):
  - K^0_s, $K^\pm$, K^*, f → mesons
  - L, X, W → baryons
- dependence on number of valence quarks
- limited to $p_t<6$GeV/c ?
- hadron production from quark recombination/ coalescence ?

Emergence of dijets

8 < p_T(trig) < 15 GeV/c

p_T(assoc)>6 GeV



Increase associated p_T threshold also

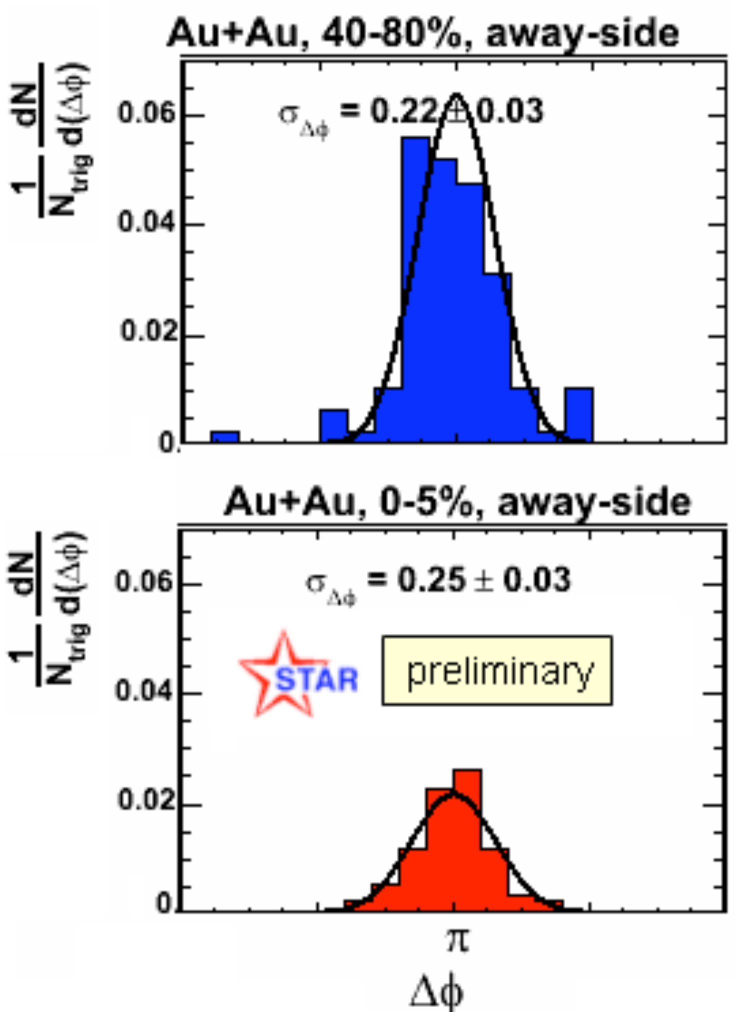
For the first time: clear jet-like peaks seen on near and away side in central Au+Au collisions

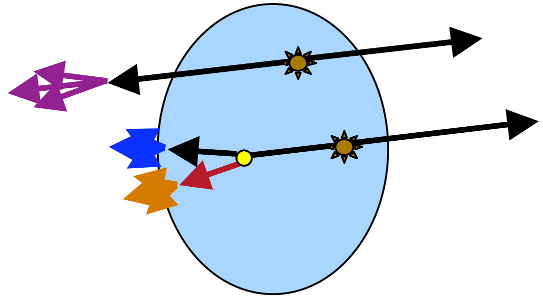
Observation 1 on away-side peaks: Widths

8 < p_T(trig) < 15 GeV/c

p_T(assoc)>6 GeV

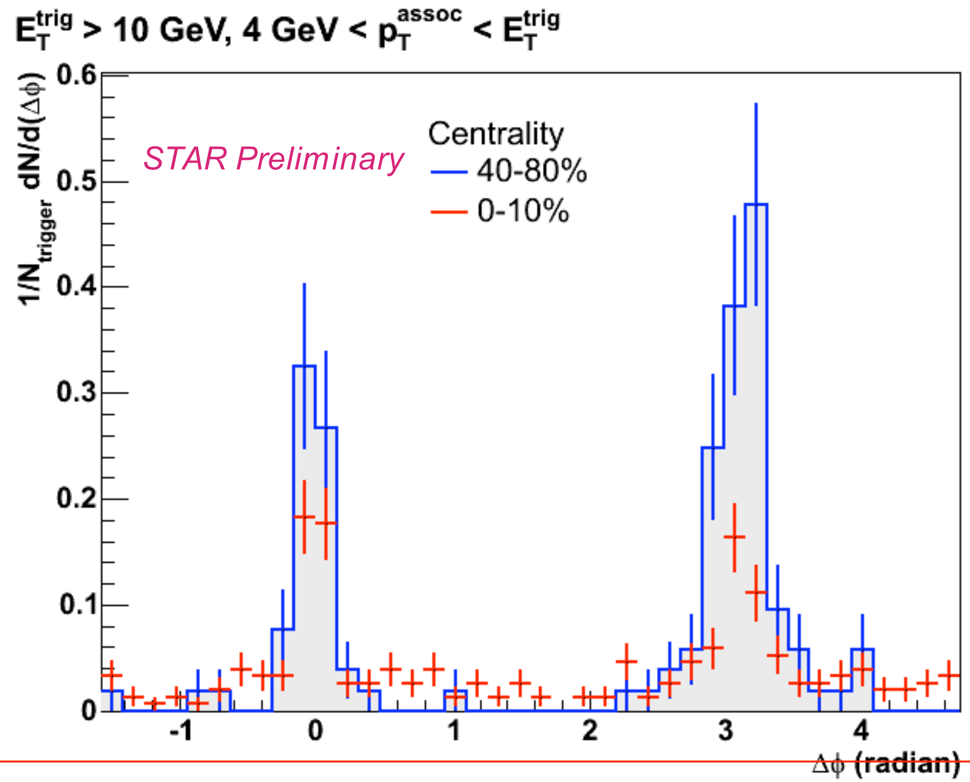
Away-side widths similar for central,
pe





Widths unchanged with centrality: seeing those partons that fragment in vacuum?

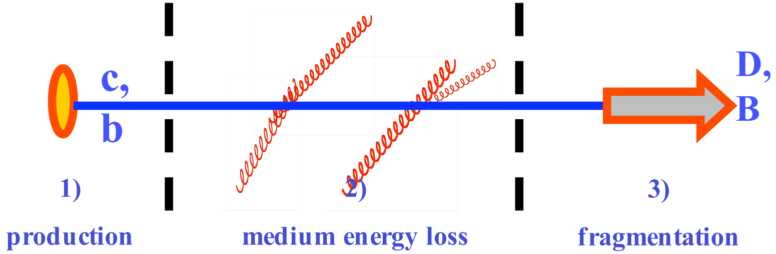
Changing the probe: towards g-jet in Au+Au



- **Direct g does not couple to medium or fragment into jets**
  - **remove from trigger both surface bias, fragmentation uncertainty in Q^2**
- **Correlations triggered on g: clear near and away-side peaks**
- **Strong contamination remains from p^0 decay daughters**
  - **Work in progress to separate out direct g**

Heavy quark production at RHIC

- Can we learn something from the difference between heavy and light quarks?
- How do heavy quarks interact with the medium?
  - Thermalization, suppression?



- Important test of transport properties of sQGP
- Heavy quark energy loss is expected to be smaller because of dead cone
- D,B spectra are affected by energy loss

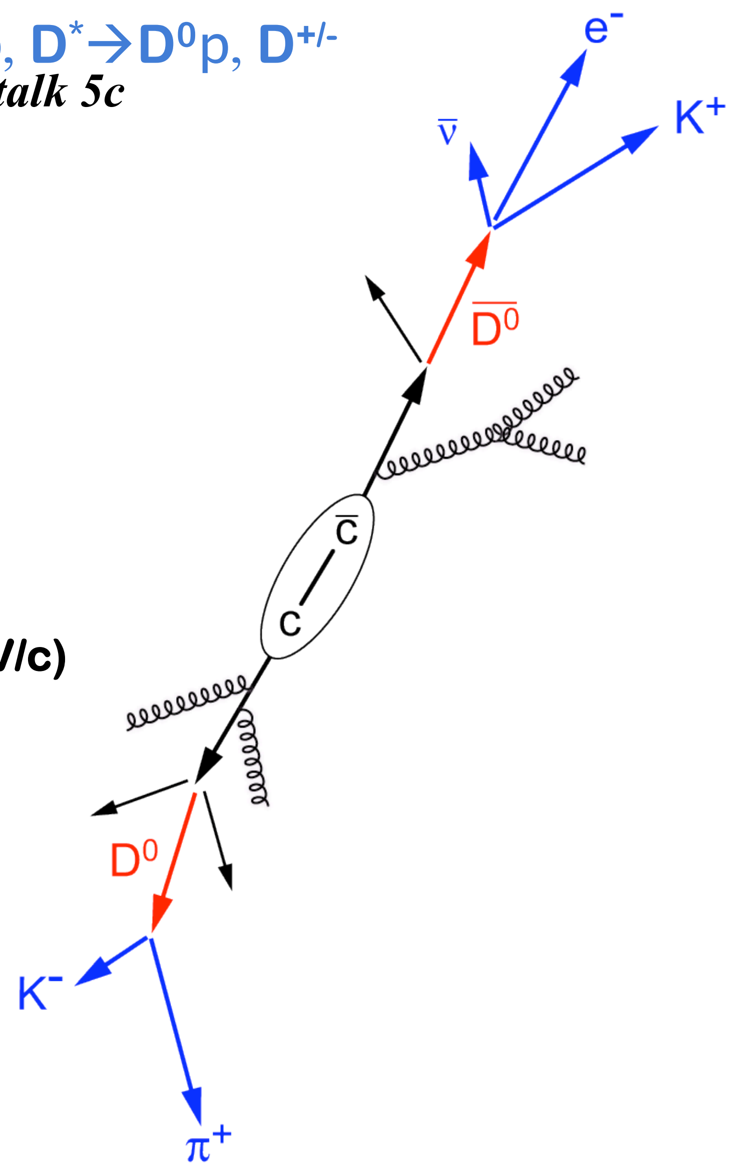
Detecting charm/beauty via semileptonic D/B decays

- **Hadronic decay channels:** $D^0 \rightarrow Kp$, $D^* \rightarrow D^0 p$, $D^{+/-} \rightarrow Kpp$

  See H.Zhang talk 5c

- ***Non-photonic*** **electrons:**
  - **Semileptonic channels:**
    - **$c \rightarrow e^+$ + anything (B.R.: 9.6%)**
      - **$D^0 \rightarrow e^+$ + anything (B.R.: 6.87%)**
      - **$D^\pm \rightarrow e^\pm$ + anything (B.R.: 17.2%)**
    - **$b \rightarrow e^+$ + anything (B.R.: 10.9%)**
      - **$B^\pm \rightarrow e^\pm$ + anything (B.R.: 10.2%)**
  - **Drell-Yan (small contribution for p_T < 10 GeV/c)**

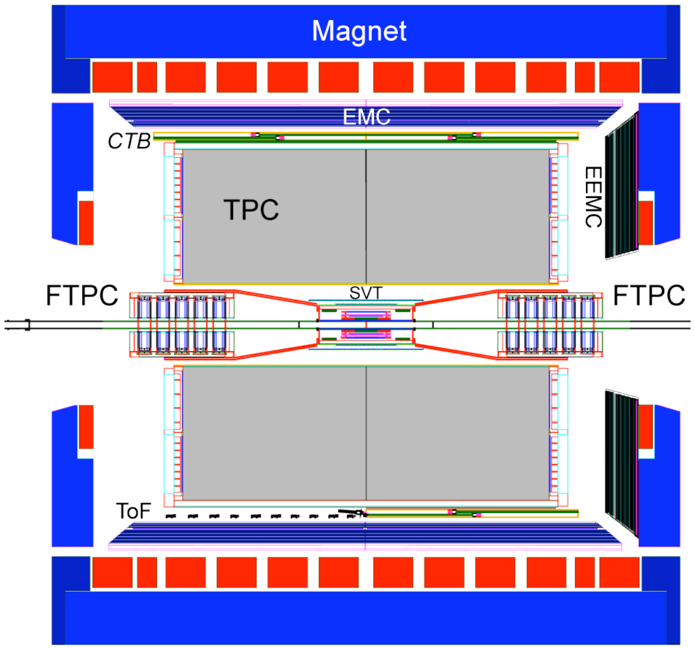
- ***Photonic*** **electron background:**
  - **g conversions ($p^0 \rightarrow gg$; $g \rightarrow e^+e^-$)**
  - **p^0, h, h' Dalitz decays**
  - **r , f ... decays (small)**
  - **K_{e3} decays (small)**



STAR Detector and Data Sample

Electrons in STAR:

- TPC: tracking, PID |h|<1.3 f =2p
- BEMC (tower, SMD): PID 0<h<1 f =2p
- TOF patch



HighTower trigger:

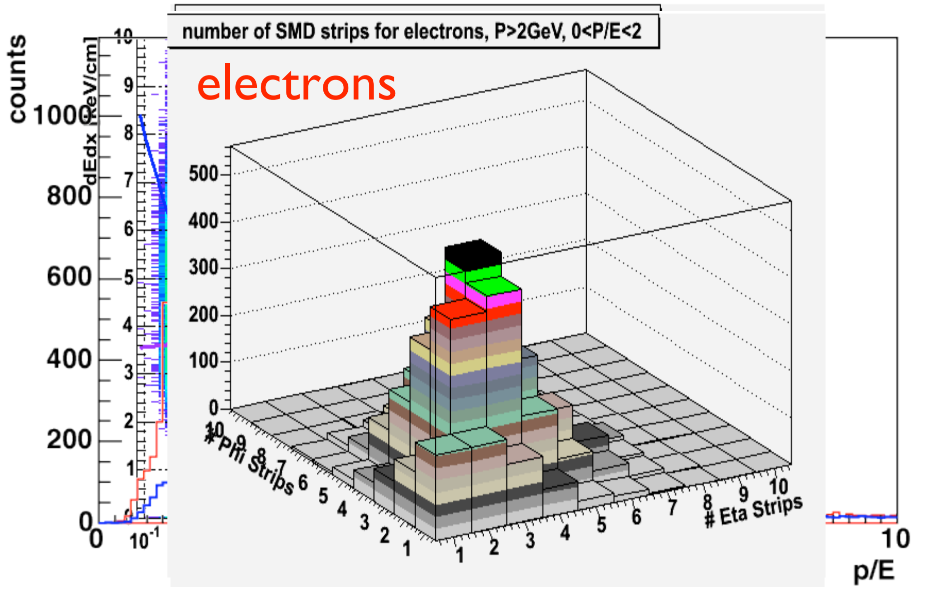
- Only events with high tower E_T>3 GeV/c^2
- Enhancement of high p_T

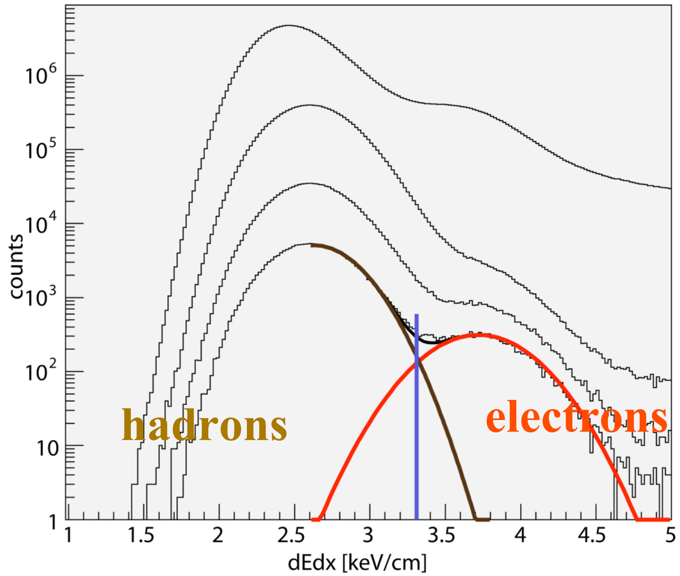
Processed:

Run2003/2004	min. bias.	6.7M	events with half field
	high tower trigger	2.6M	events with full field (45% of all)
	10% central	4.2M	events (15% of all)

Electron ID in STAR – EMC

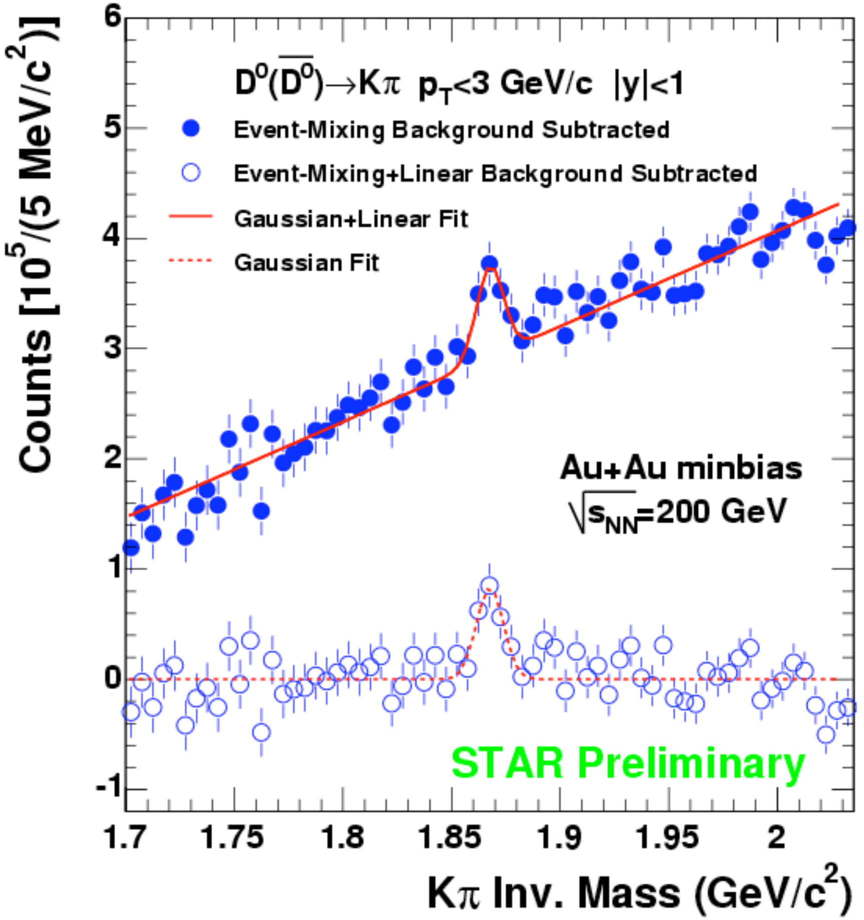
1. TPC: dE/dx for p > 1.5 GeV/c
   - Only primary tracks
     (reduces effective radiation length)
   - Electrons can be discriminated well from hadrons up to 8 GeV/c
   - Allows to determine the remaining hadron contamination after EMC
2. EMC:
   a) Tower E ⇒ p/E
   b) Shower Max Detector (SMD)
      - Hadrons/Electron shower develop different shape
      - Use # hits cuts

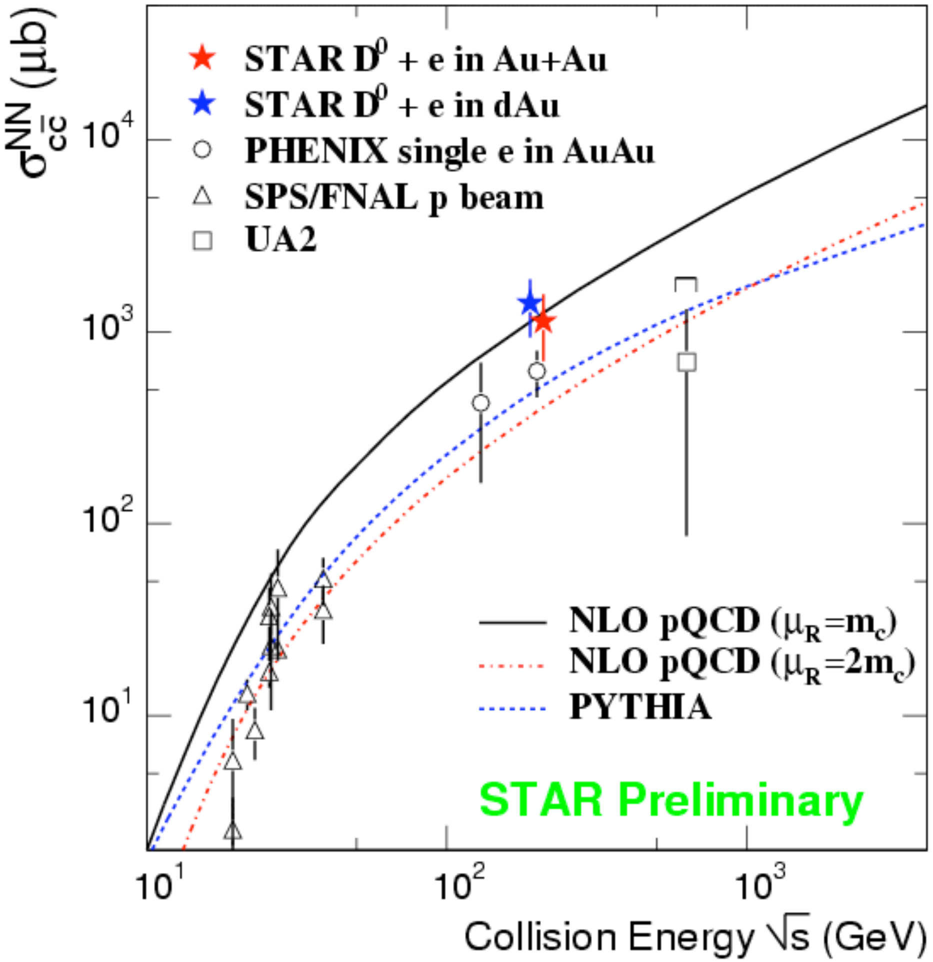




85-90% purity of electrons
(p_T dependent)

Heavier: Charm production

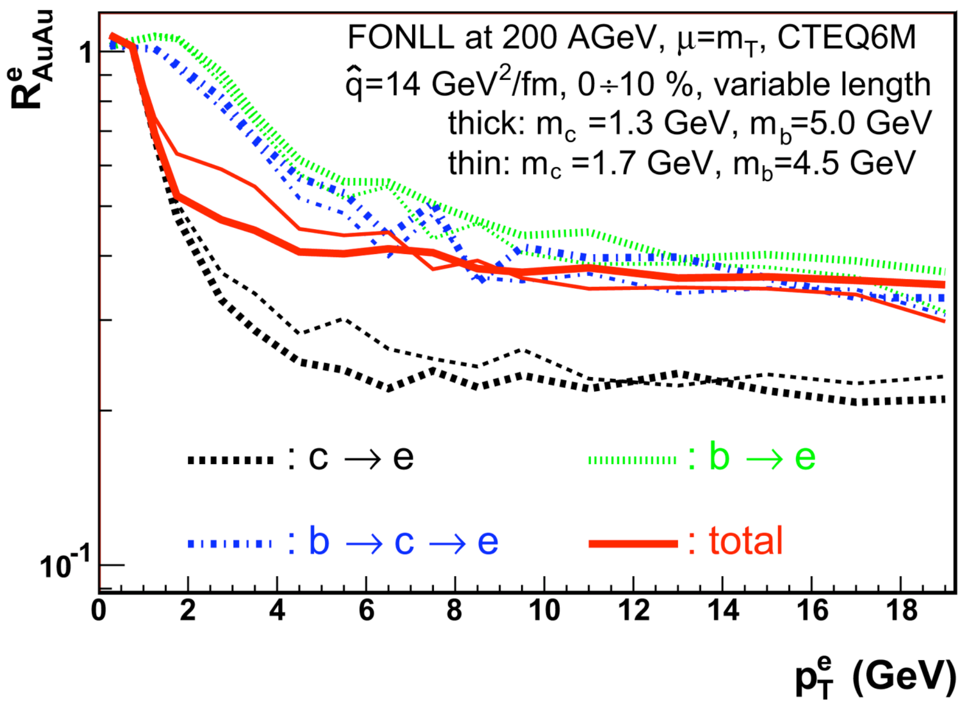




- First direct measurement of open charm in Au+Au Collisions
- Total charm cross-section in Au+Au: N_{binary} scaling from d+Au

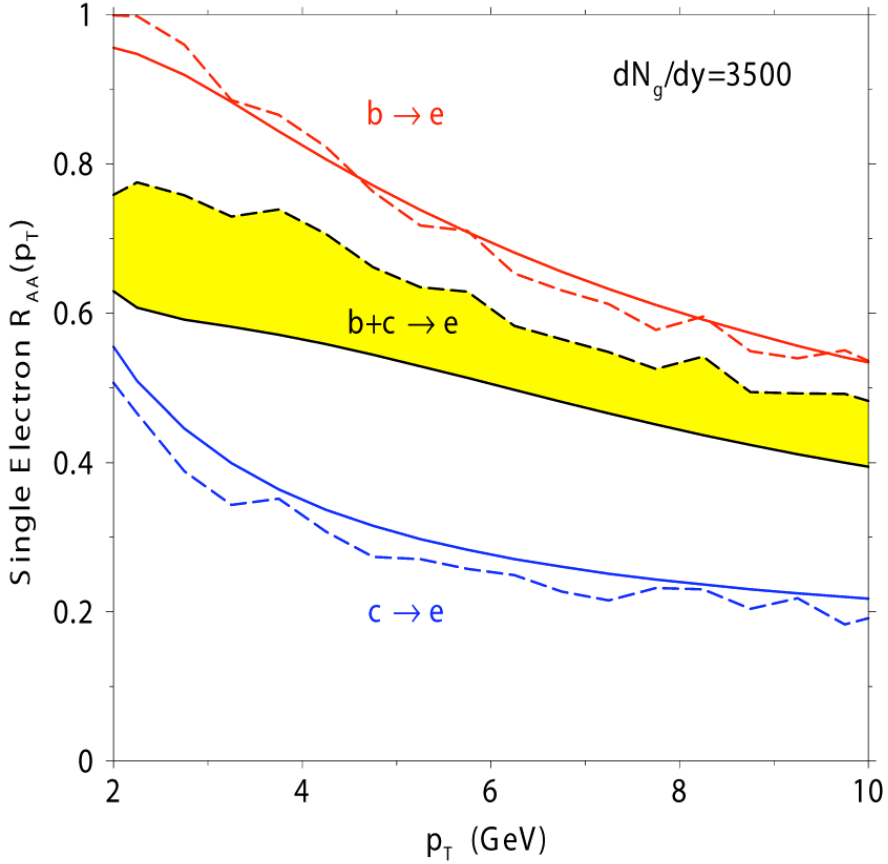
Expectation: Radiative Energy Loss of Heavy Quarks

N. Armesto et al., private communication



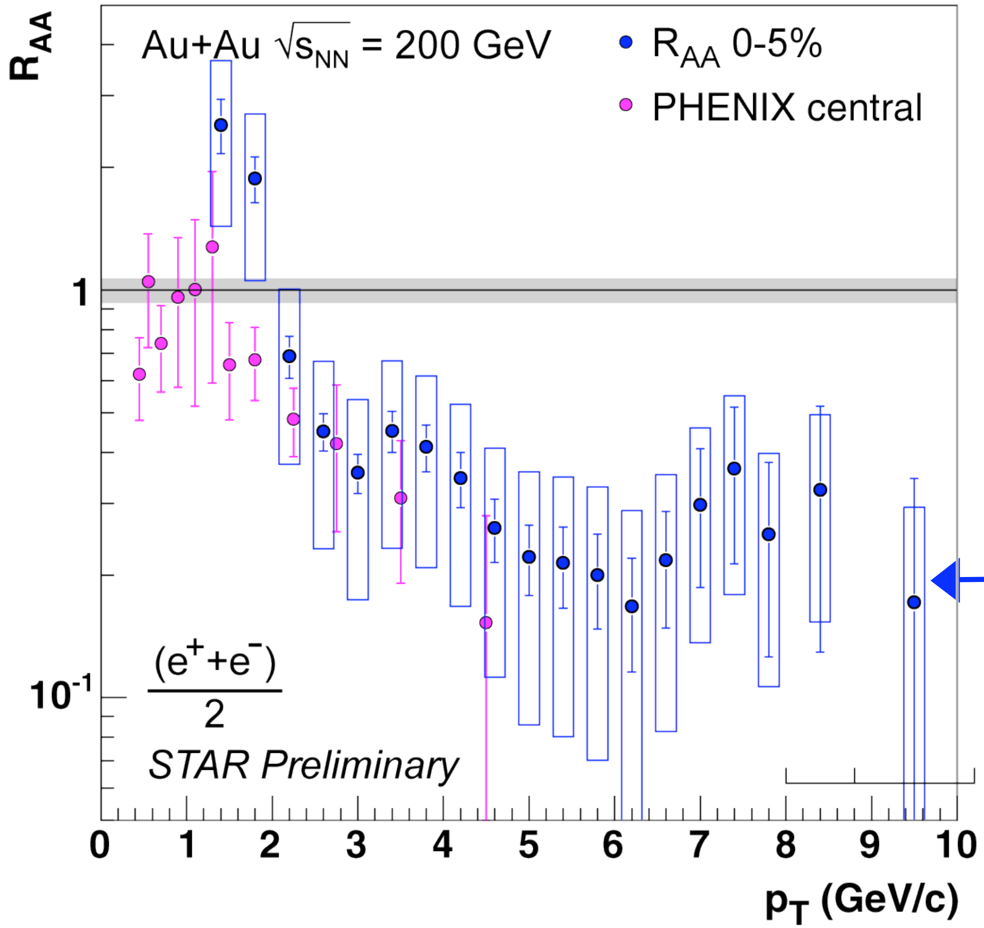
See also Armesto et al, Phys. Rev. D71 (2005) 054027

Djordjevic et al, nucl-th/0507019

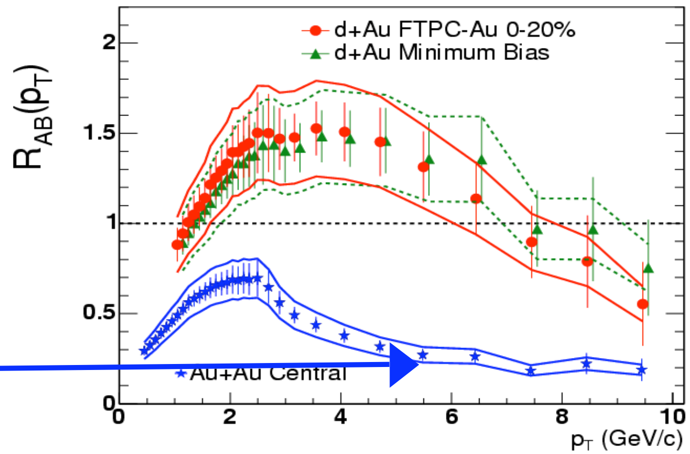


- **Coupling of heavy quarks to the medium reduced due to mass**
- **Expectation: even for high medium density, higher R_{AA} for single electrons from heavy flavor than for light hadrons**

Heavy Flavor R_{AA}



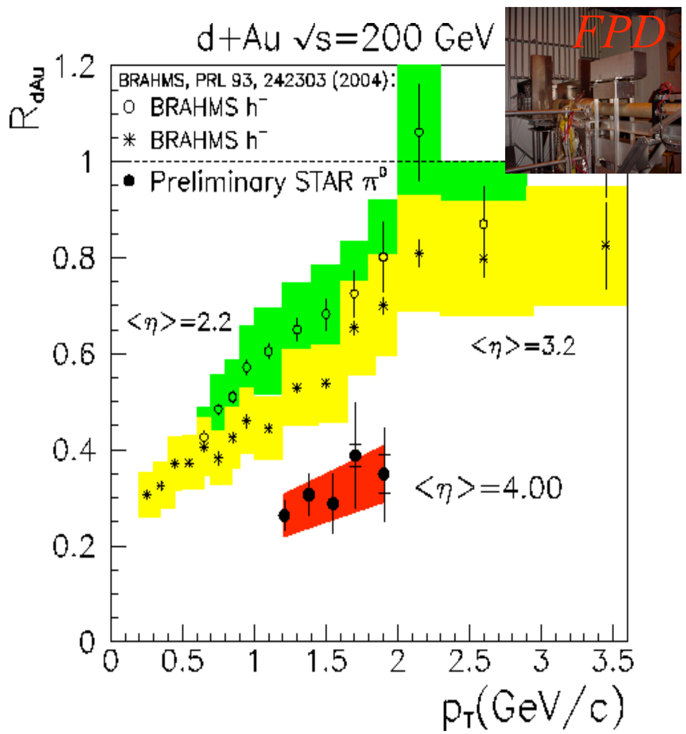
Charged Hadron R_{AA}

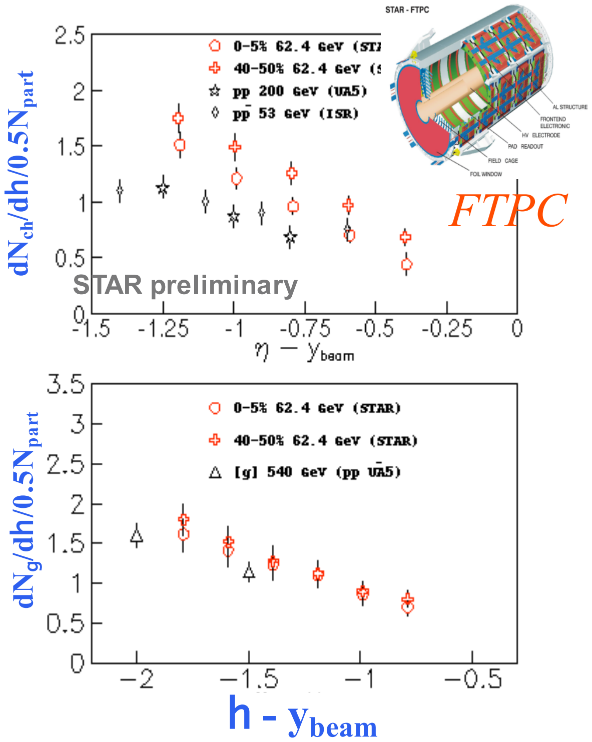


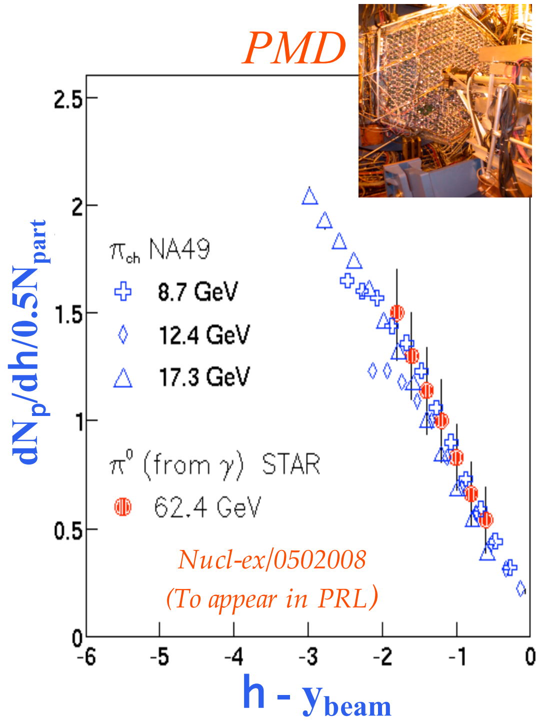
- R_{AA} to 10 GeV/c in non-photonic electrons
- Suppression is approximately the same as for hadrons
- B contribution? Challenge for radiative picture?

forward physics

Forward rapidity at RHIC probes CGC.
CGC will be even more important at LHC (and at mid-rapidity).







- ❑ Consistent with the CGC framework.
- ❑ R_{dAu}-p^0 lower than h^-: p+p→ h^- is isospin suppressed at large h.

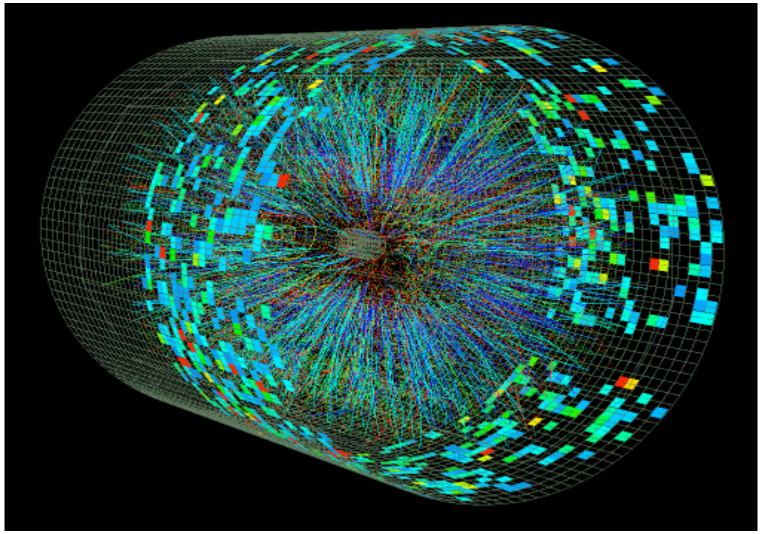
- ❑ Photons: centrality independent limiting fragmentation.
- ❑ Charged particles: centrality dependent limiting fragmentation.
- ❑ Pions follow limiting fragmentation in heavy-ion collisions.

Summary

- New, precision data from STAR.
- Jet-medium interaction:
  - strong indication of thermalization processes
  - distinctive features of conical flow not seen
  - Dijet reappears at larger pT
  - Heavy flavor shows similar quenching as of light ones
- Elliptic flow and spectra data show:
  - early thermalization
  - partonic collectivity
  - relevance of constituent quark DOF

  - Limiting fragmentations have been investigated

Future Outlook



- Rich physics still on tape: Half of year 4 Au+Au, 80% of year 5 Cu+Cu statistics still to be processed
- Future runs:
  - Full EMC barrel installed and ready for use for triggered data over 2 units in η
  - Full barrel TOF upgrade for identified correlations, resonances, electrons
  - DAQ1000 upgrade of DAQ to remove deadtime, increase dataset size
  - Forward Meson Spectrometer upgrade for definitive measurements on CGC
  - Heavy Flavor Tracker for definitive measurements of open charm

The STAR Collaboration

U.S. Labs:
Argonne, Lawrence Berkeley, and Brookhaven National Labs

U.S. Universities:
UC Berkeley, UC Davis, UCLA, Caltech, Carnegie Mellon, Creighton, Indiana, Kent State, MIT, MSU, CCNY, Ohio State, Penn State, Purdue, Rice, Texas A&M, UT Austin, Washington, Wayne State, Valparaiso, Yale

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Croatia:
Zagreb University

Czech Republic:
Nuclear Physics Institute

England:
University of Birmingham

France:
Institut de Recherches Subatomiques Strasbourg, SUBATECH - Nantes

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Switzerland:
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