Soft Physics from STAR

Bulk properties

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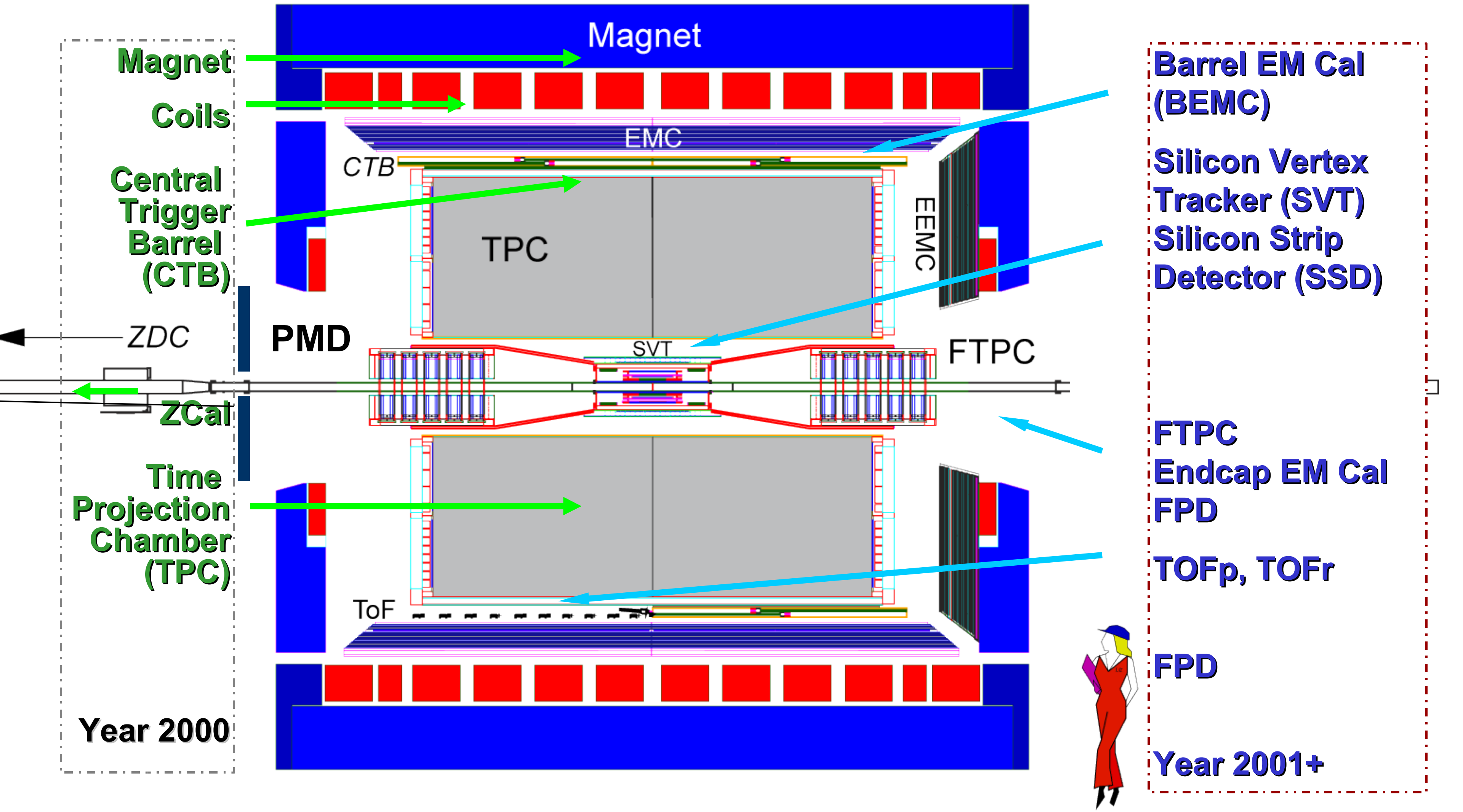
For the STAR Collaboration

The STAR Detector

Large acceptance: 2π coverage at mid-rapidity

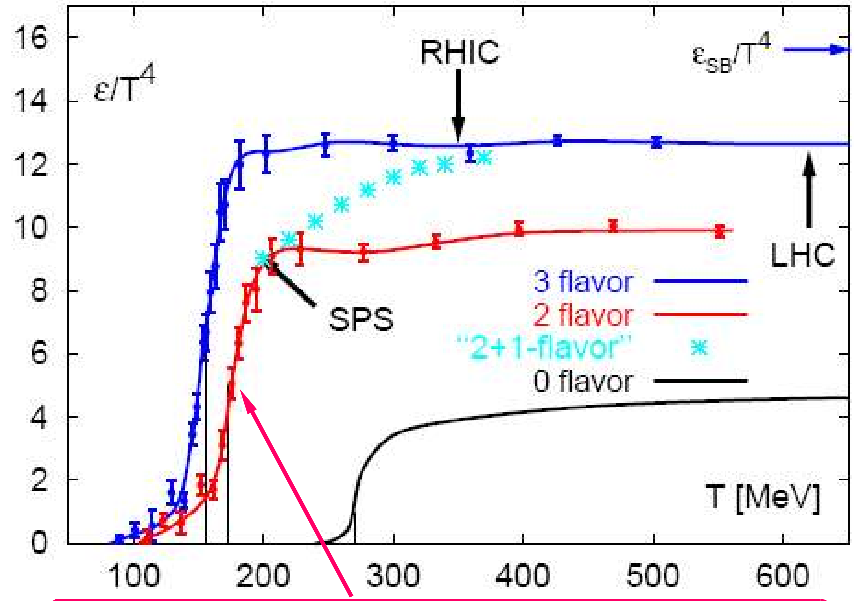


the Quark-Gluon Plasma

The goal: To create and study QGP – a state of deconfined, thermalized quarks and gluons over a large volume predicted by QCD at high energy density.

Lattice QCD prediction:

F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)



$T_c \approx 170 \pm 8$ MeV, $\varepsilon_c \approx 1$ GeV/fm^3

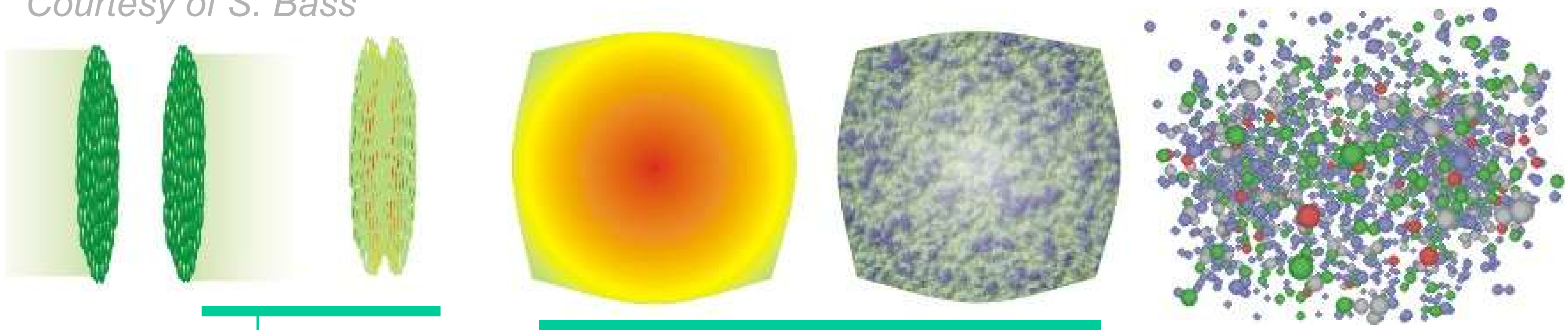
QGP is a bulk, soft physics phenomenon.

Questions:
- energy density?
- degree of thermalization?
- deconfinement, DOF, EOS?

Tools:
- jets & interactions with bulk
- elliptic & radial flow
- hadron distributions

outline

Courtesy of S. Bass



1

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

correlations:
(1) thermalization?
(2) is there conical flow?

2

hot, dense medium
expansion
hadronization

elliptic flow:
(2) does hydro work?
(3) what EOS?

3

hadrons
hadronic scatterings
freeze-out

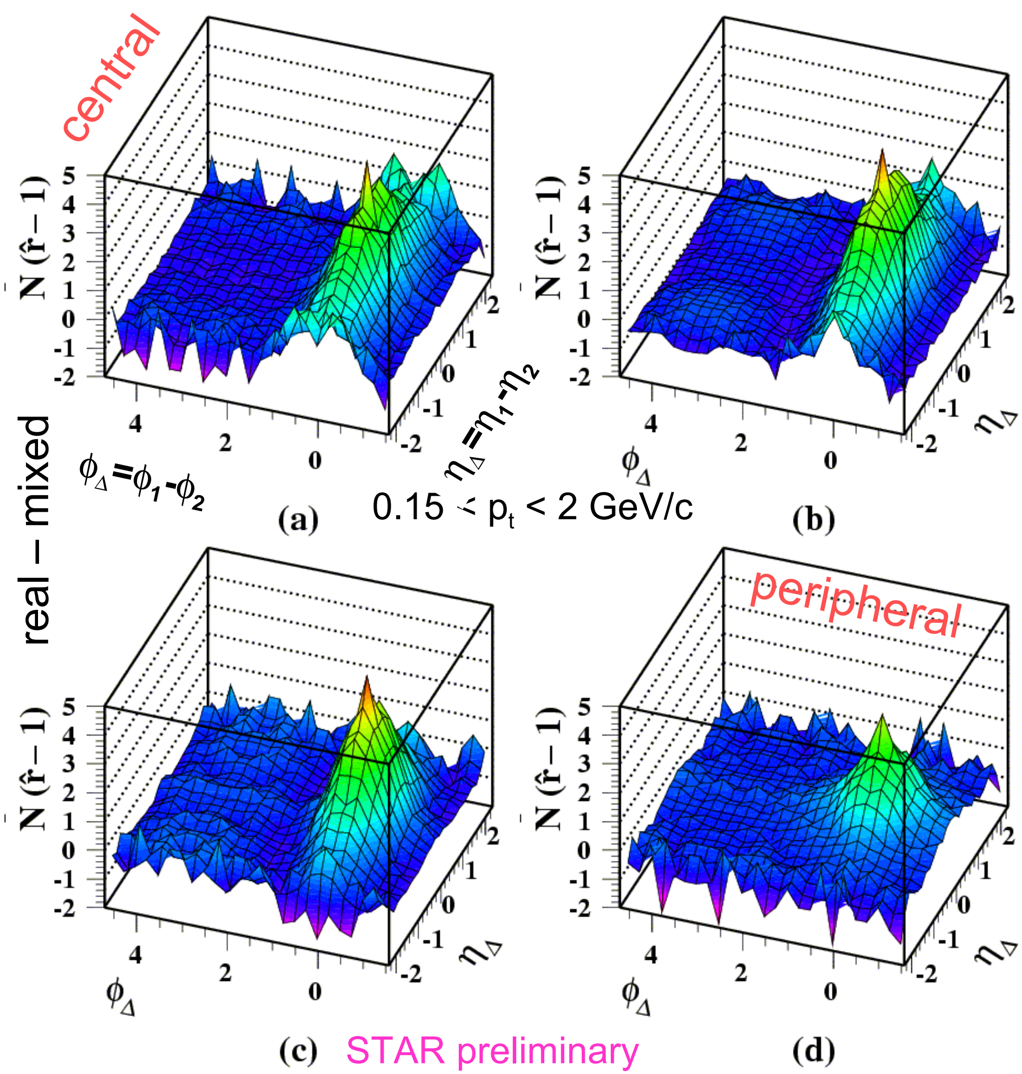
ratios, spectra:
freeze-out properties
fluctuations, etc.

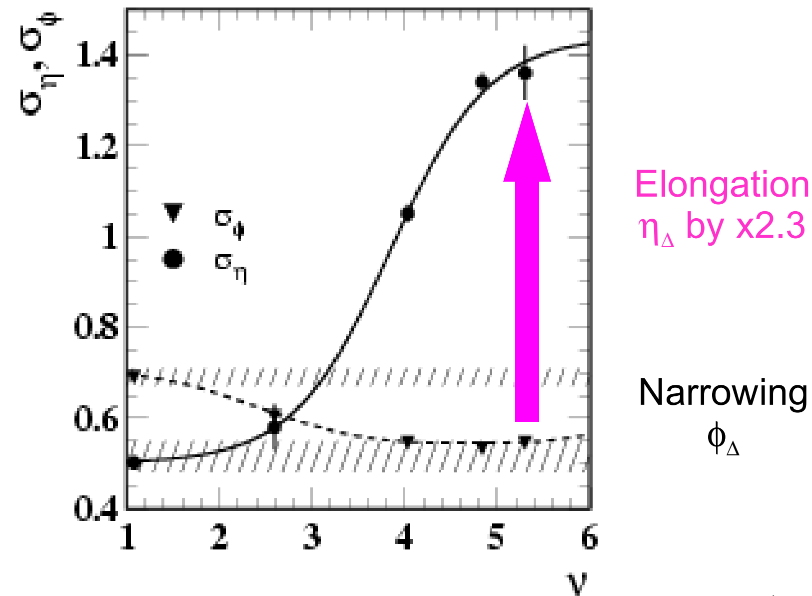
soft-soft correlations

130 GeV Au+Au: STAR, nucl-ex/0411003.
$\cos(\phi_\Delta)$, $\cos(2\phi_\Delta)$ subtracted correlations.

p-p 200 GeV

See posters, Prindle (#111), Ray(#87) , Trainor (#31)





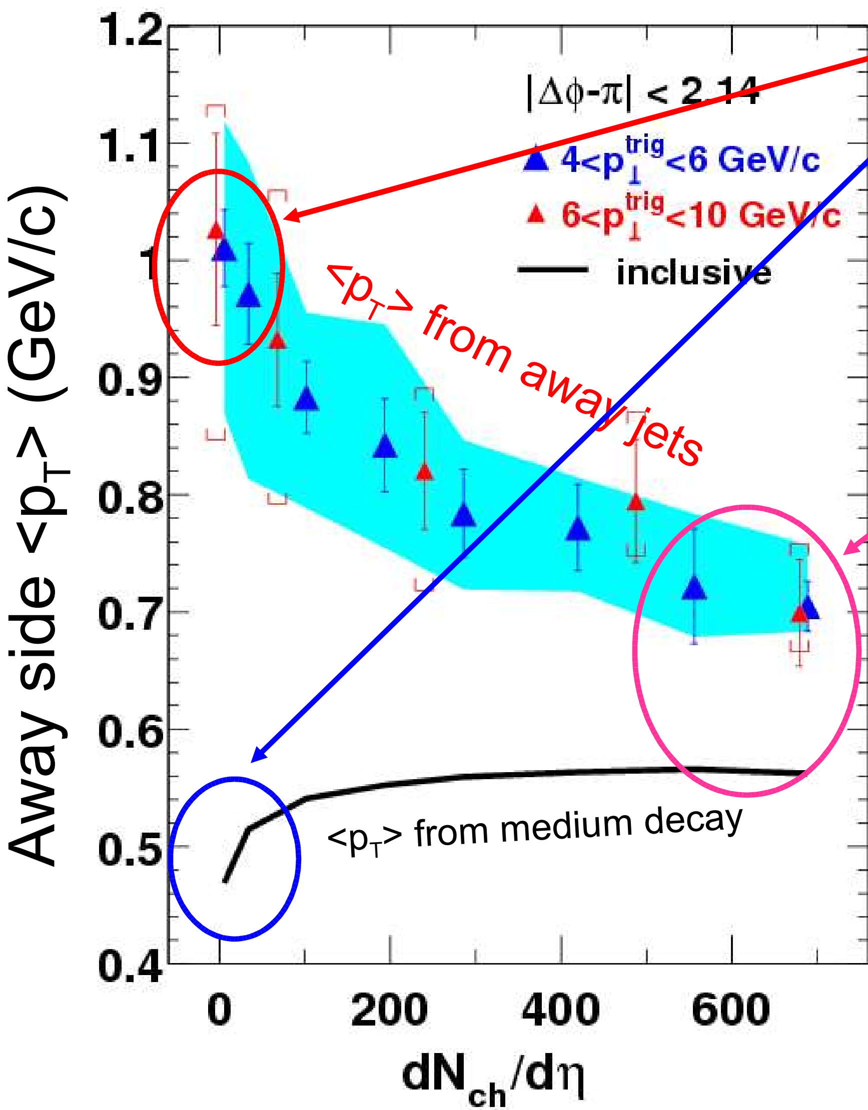
$$\nu \equiv 2N_{BC} / N_{part} \approx (N_{part}/2)^{1/3}$$

even at low pt, remnants of jet-like structure survive.

strongly coupled to the medium, elongated along η.

hard-soft interactions

STAR, nucl-ex/0501016.



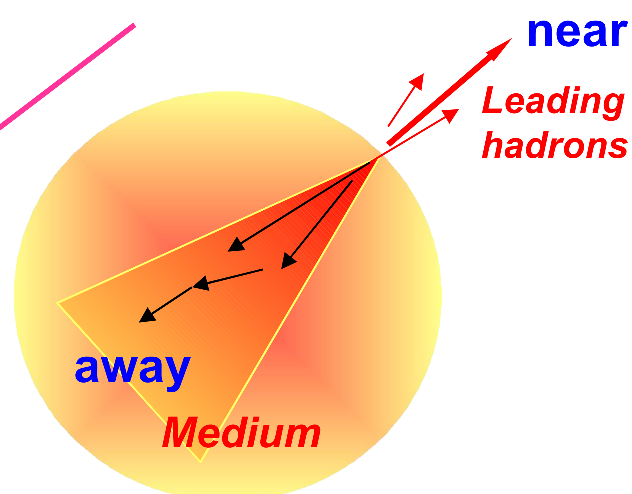
Two sources of particles:

hard: hard scattering products.

soft: bulk medium constituents.

Very different as seen in peripheral.

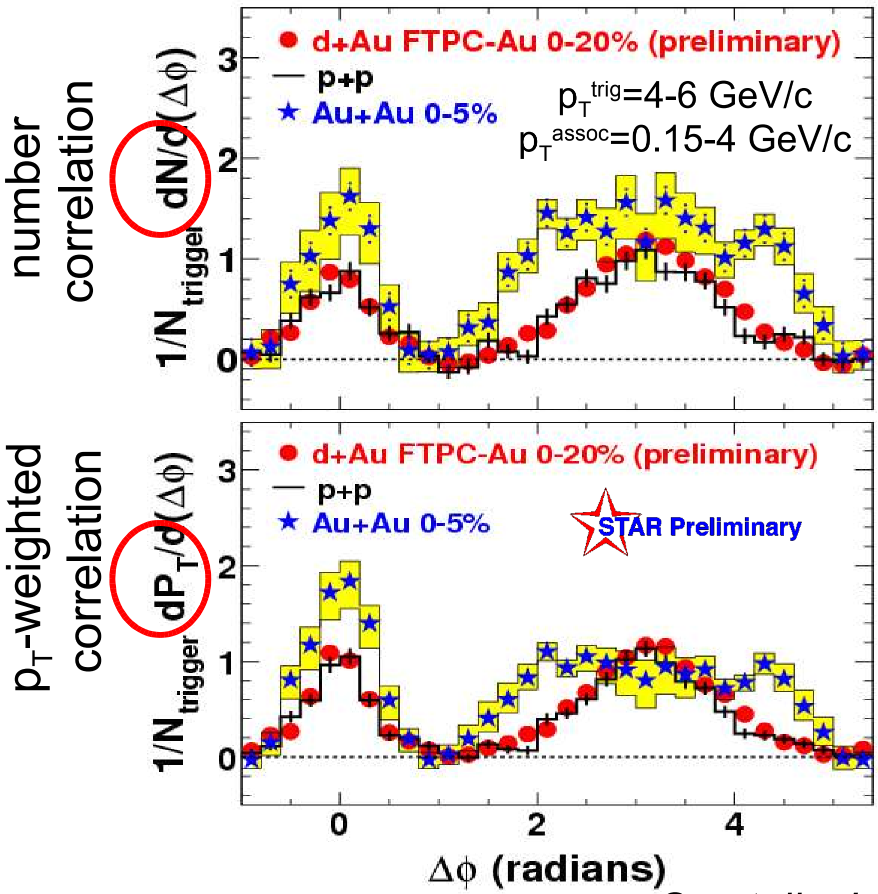
Become similar in central.

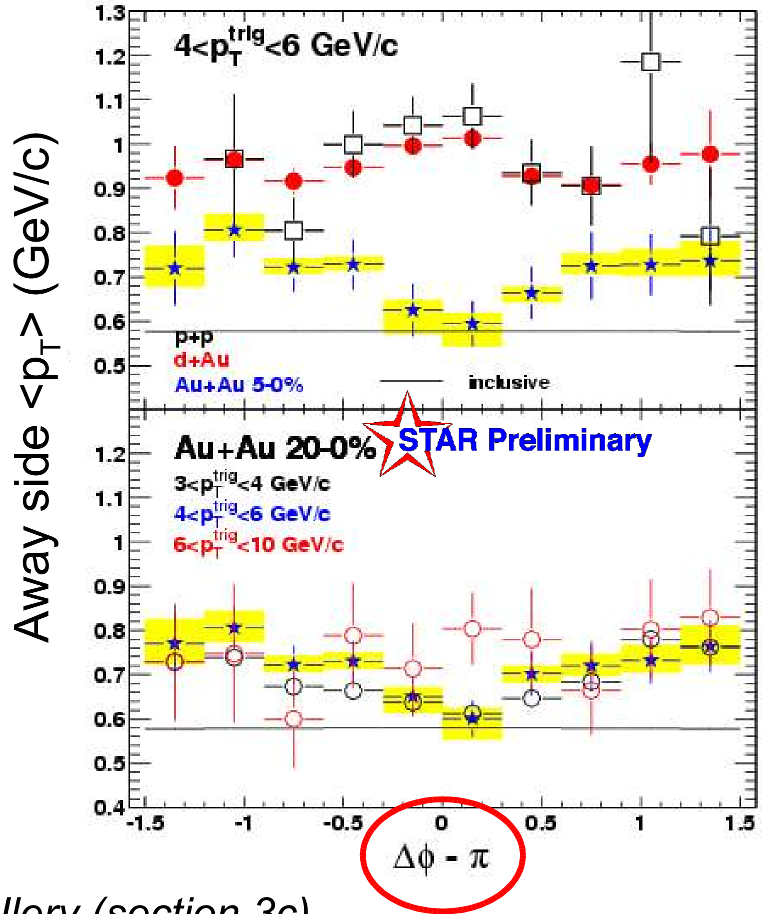


hard-soft: approach thermalization.

soft-soft (larger x-section): higher degree of thermalization.

hard-soft angular correlations





See talk, J. Ulery (section 3c)

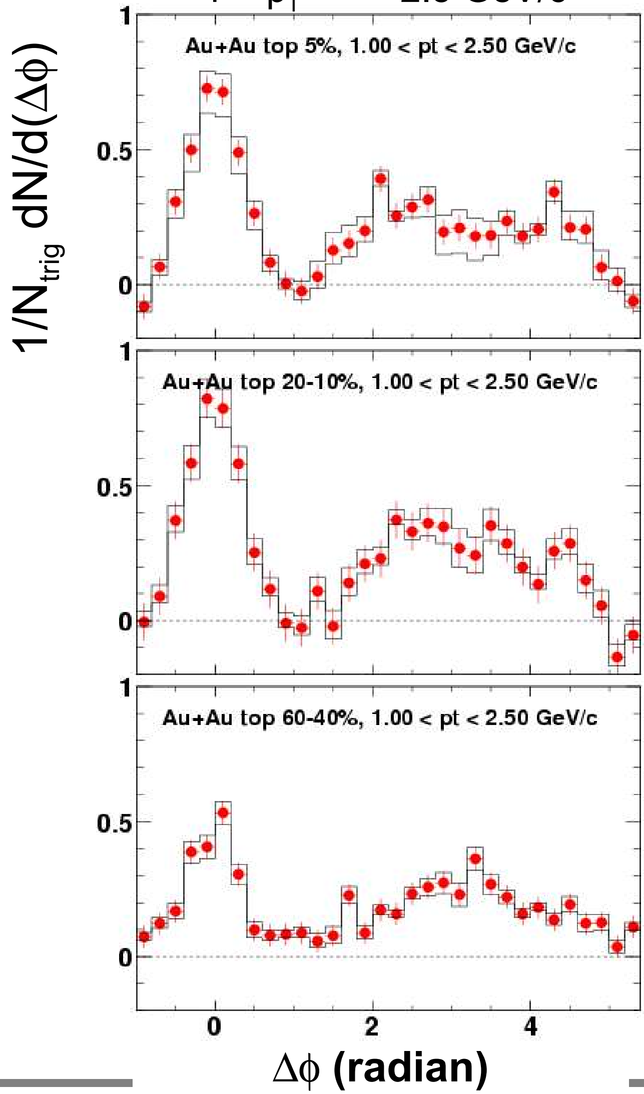
Broader away-side correlations in central Au+Au.

Novel dip at π in away $\langle p_T \rangle$ for p_T^{trig}<6 GeV/c. Associated hadrons at π appear more equilibrated.

correlation functions

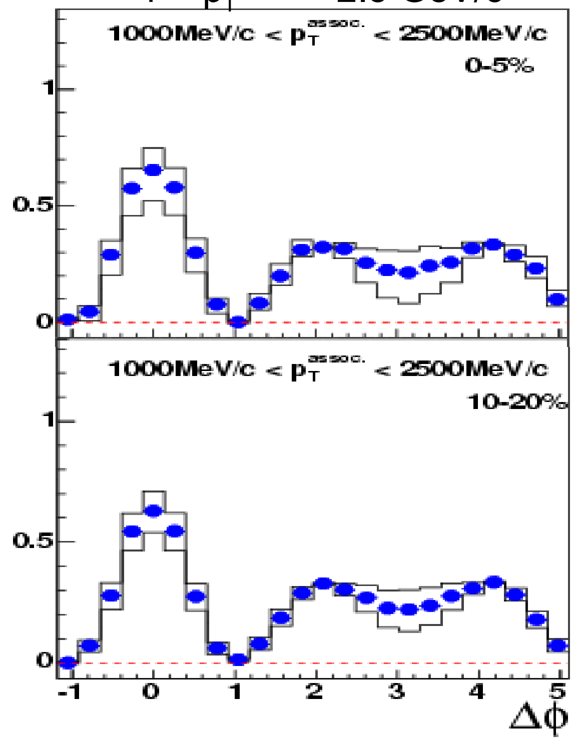
$4 < p_T^{trig} < 6$ GeV/c

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



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

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



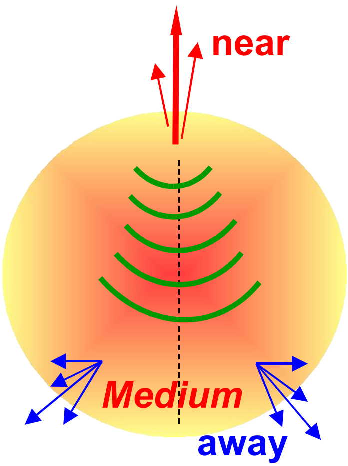
See talk, J. Ulery (section 3c) and poster, M. Horner (#70)

broad away-side correlations.

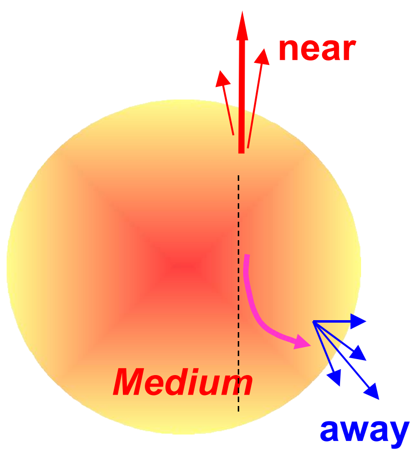
consistent with flat.

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

conical flow? 3-particle correlation



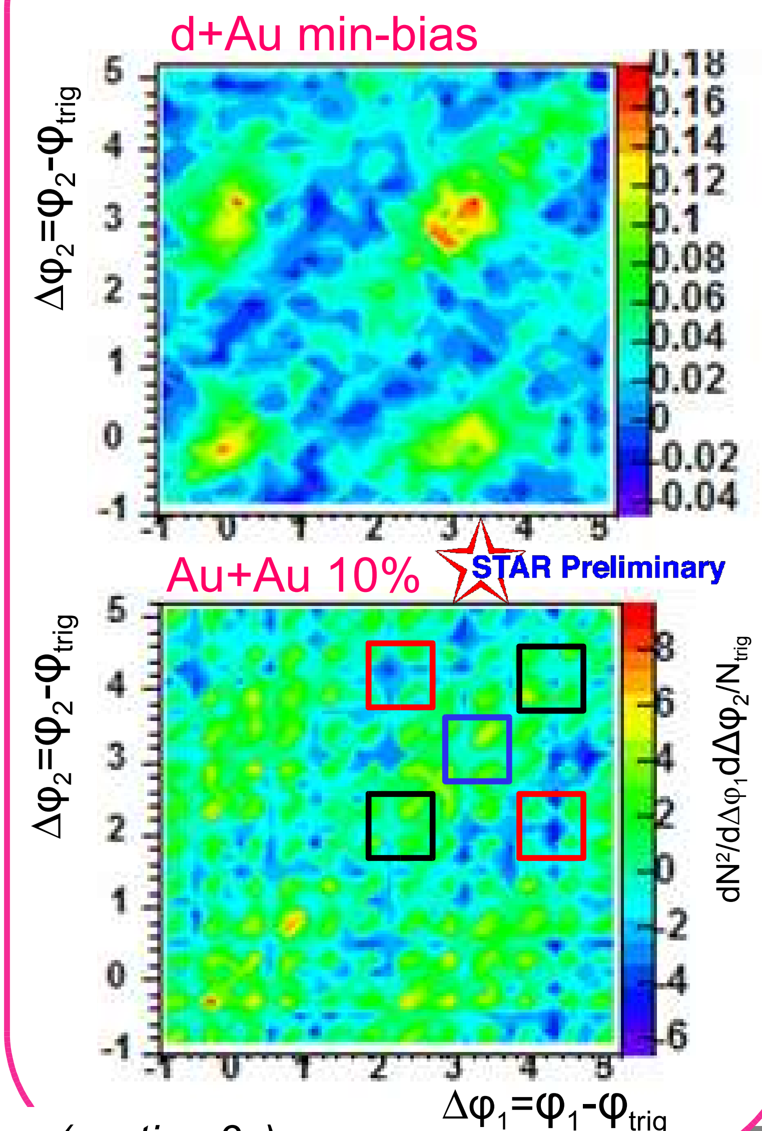
mach cone



deflected jets

p_T^{trig}=3-4, p_T^{assoc}=1-2 GeV/c

2-particle corr, bg, v2 subtracted



Three regions on away side:

center = $(\pi, \pi) \pm 0.4$

corner = $(\pi+1, \pi+1) \pm 0.4$ x2

cone = $(\pi+1, \pi-1) \pm 0.4$ 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)

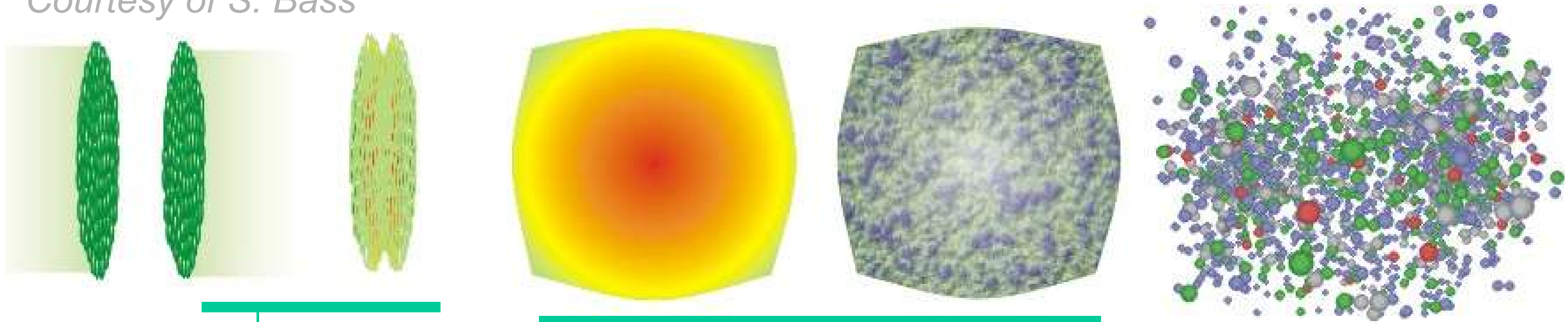
d+Au and Au+Au elongated along diagonal: k_T effect, and deflected jets?

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

See talk, J. Ulery (section 3c)

outline

Courtesy of S. Bass



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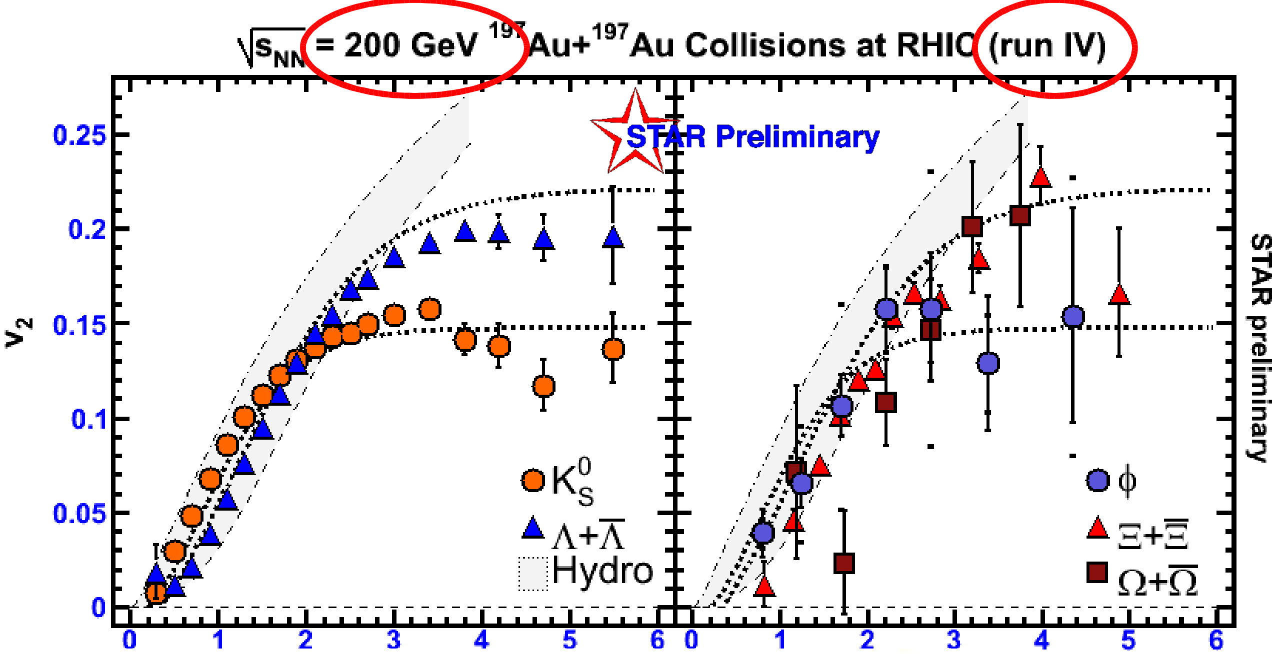
elliptic flow v_2

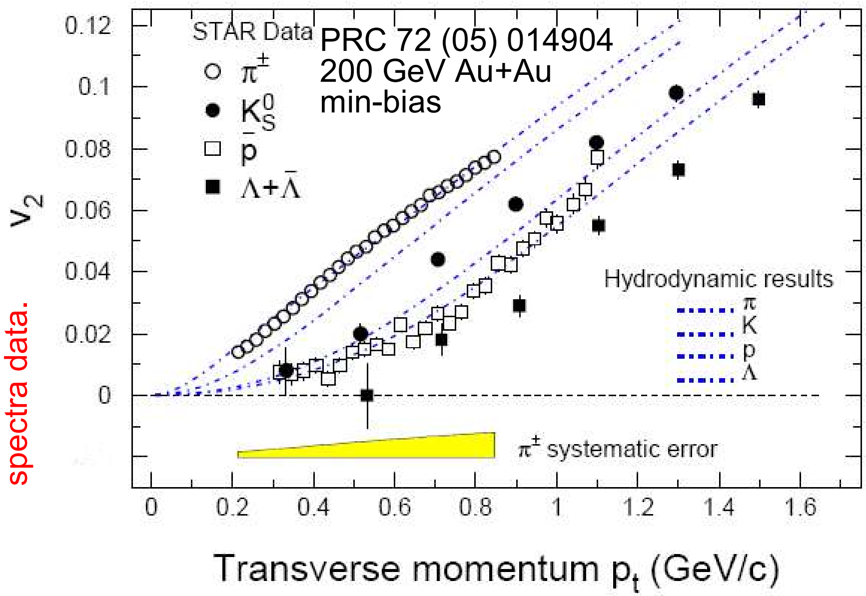


See talks, X. Cai (section 1)
M.D. Oldenburg (section 2a)
and poster, J. Speltz (#164)

large v2 (even ϕ, Ξ, Ω): strong interactions at early stage

large v2 of ϕ, Ξ, Ω (low hadronic x-sections): partonic collectivity at RHIC.

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

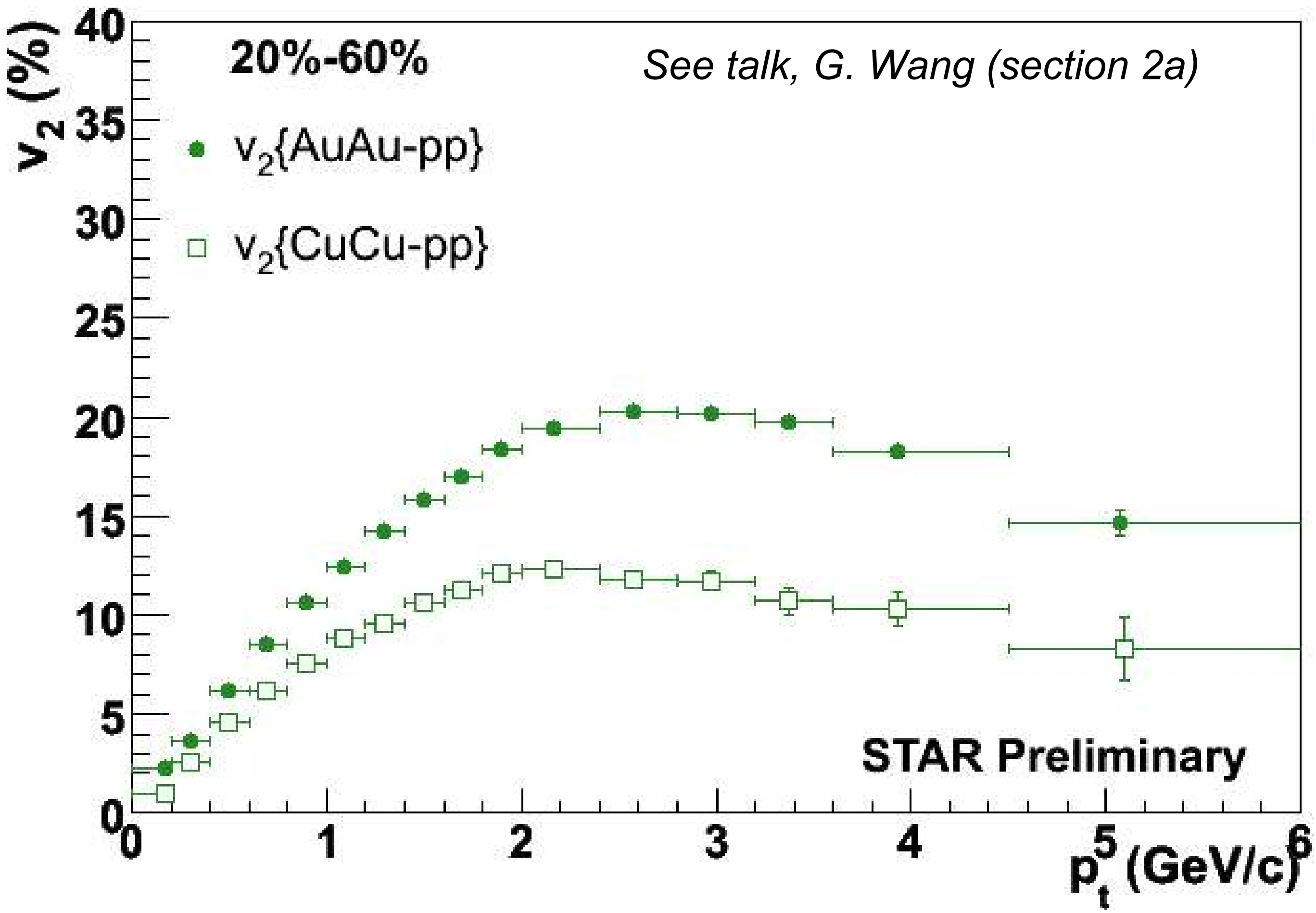


m-dependence: common v_T field.

hydro works: suggests early thermalization.

soft (QGP) EOS favored: sub-hadronic DOF.

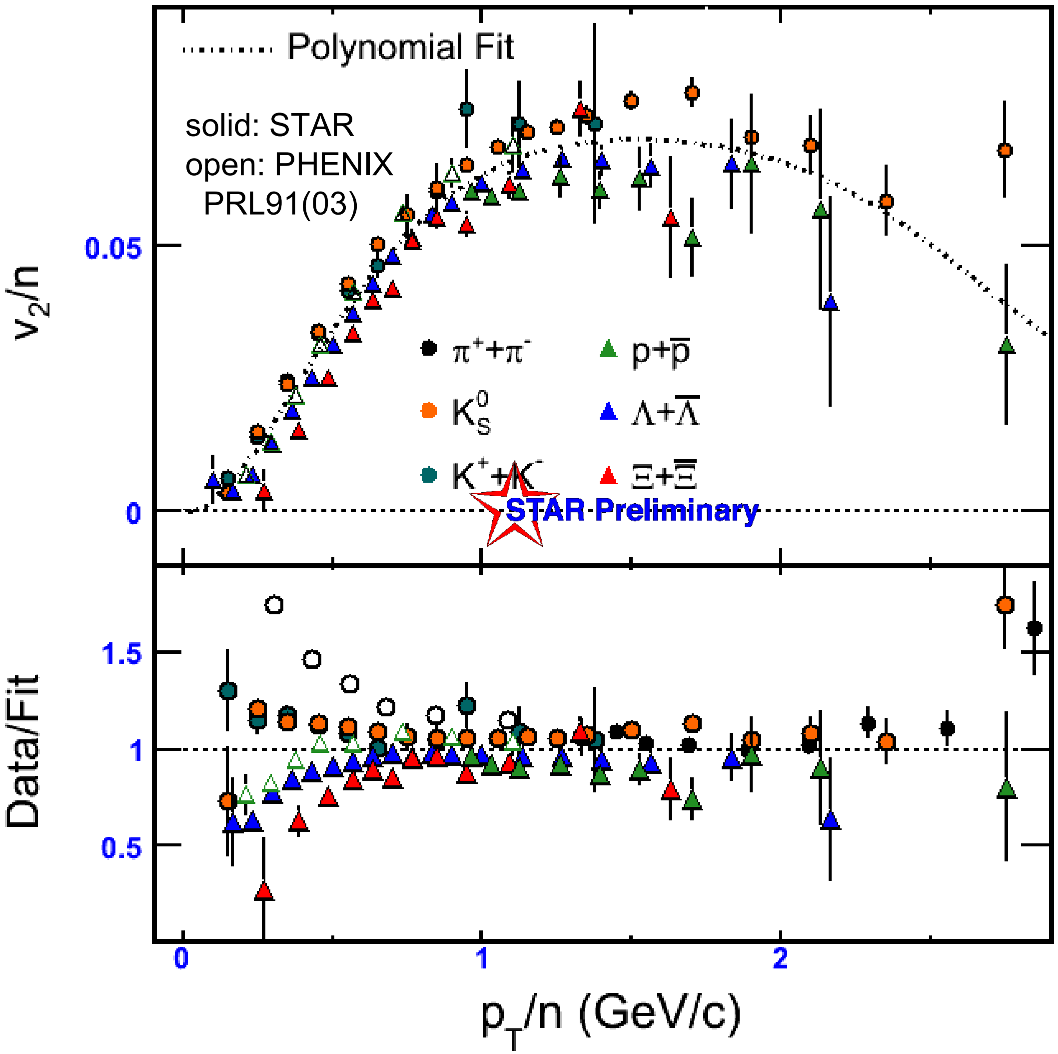
Charged hadrons: v_2 at 200 GeV in Cu+Cu



- 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.

constituent quark scaling

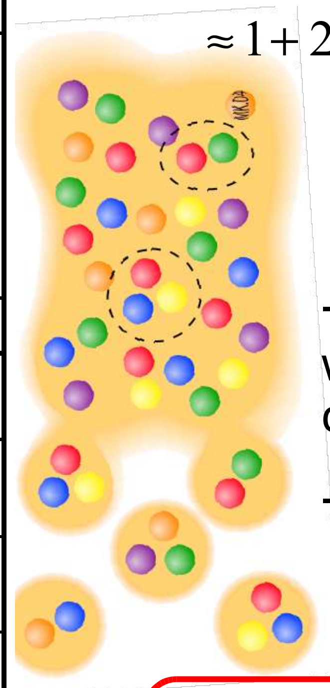
See talk: Oldenburg (section 2a)



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

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

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



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

Constituent quark DOF.

Deconfinement?

hadronization via quark coalescence?

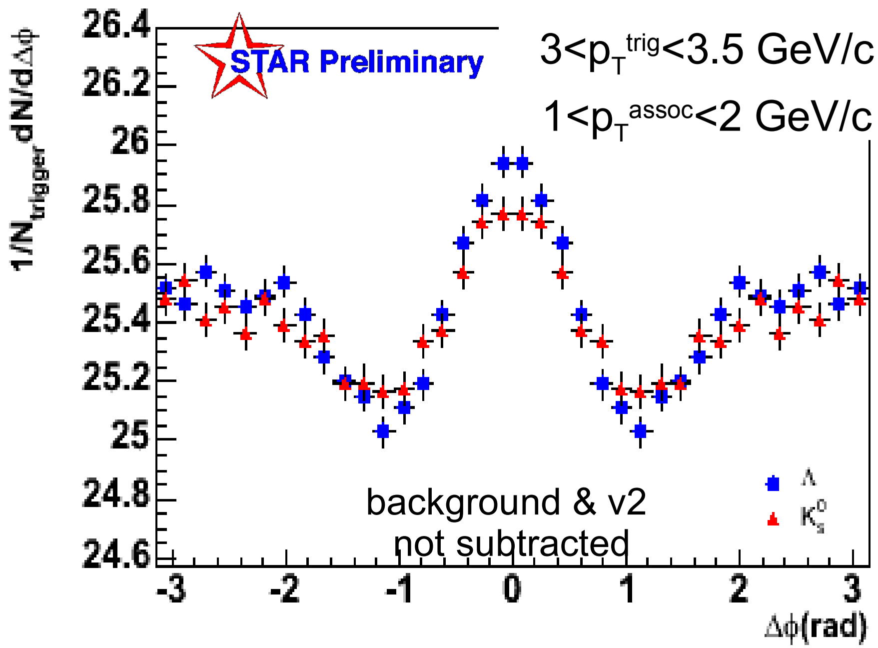
Molnar, Voloshin, Ko, Fries, Hwa, et al.

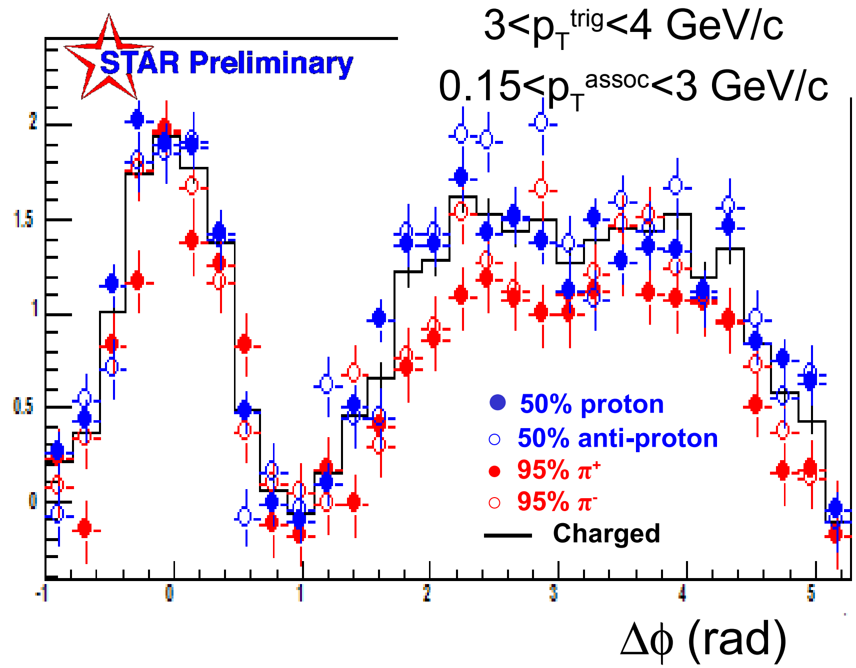
explains

baryon/meson enhancement

NCQ scaling of v_2.

But no intrinsic angular correlations.





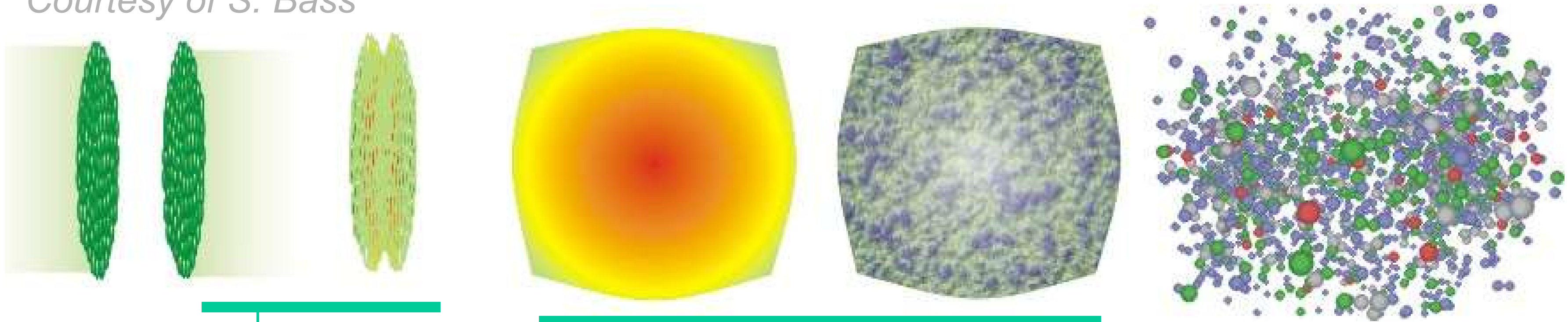
See talk, J. Ulery (section 3c)

No significant difference in angular correlations.

More work for coalescence approach.

outline

Courtesy of S. Bass



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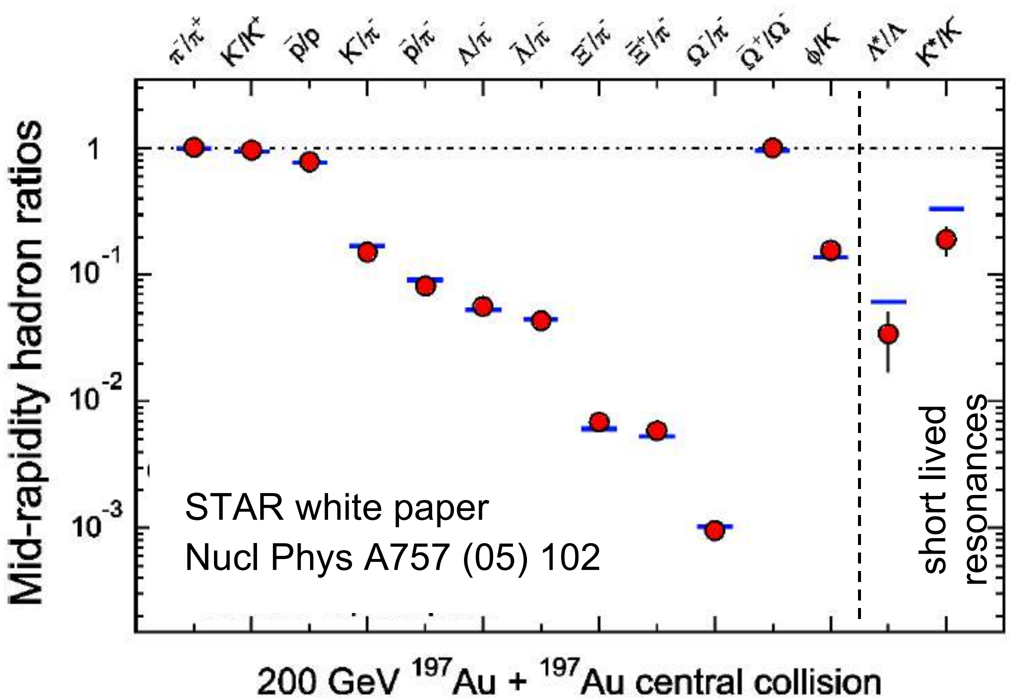
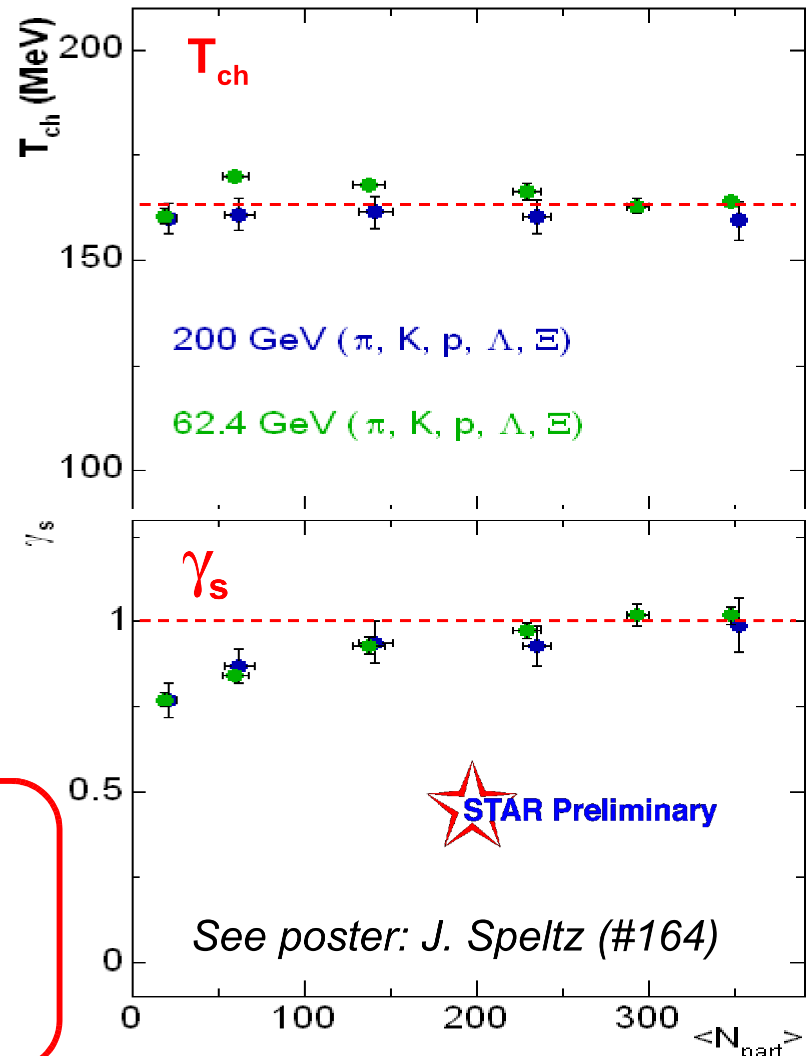
chemical freeze-out

hadron-chemistry: particle ratios   chemical freezeout properties



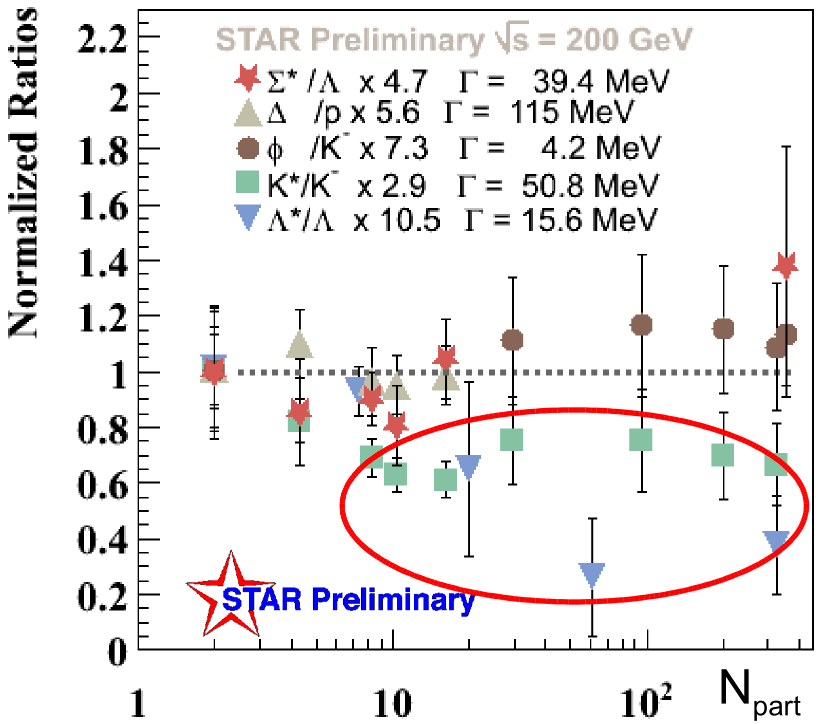


- **$T_{ch} \approx T_C \approx 165 \pm 10$ MeV**
  Chemical freezeout ≈ hadronization.
- **s ~ u, d**
  Strangeness is chemically equilibrated.

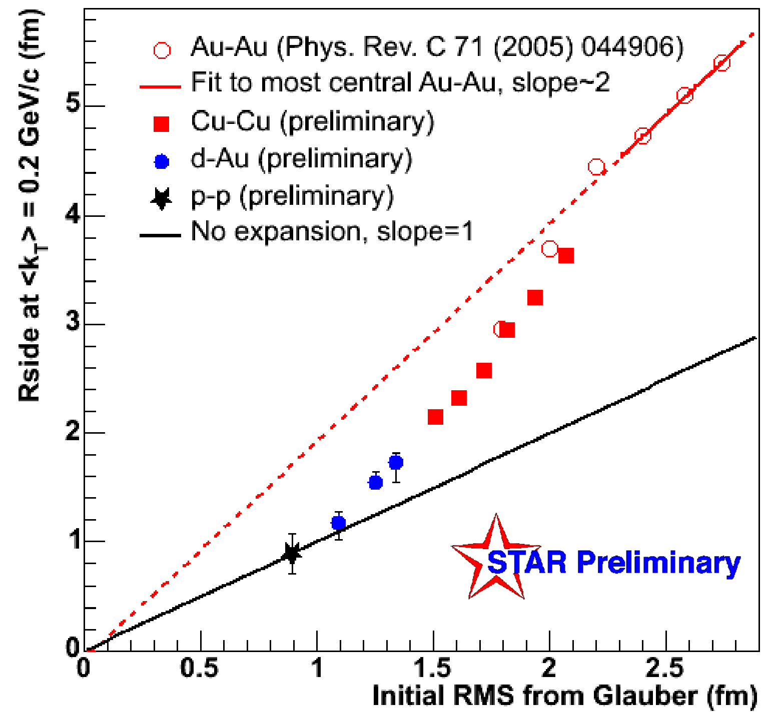
time and size

resonance decays and regeneration: measure kinetic freezeout – life time.

HBT: measures freeze-out source sizes (marked by collective flow).



Re-scattering and regeneration is needed! Finite time span from chemical to kinetic freeze-out.



HBT size (low k_T): x2 expansion

initial   final in Au+Au.

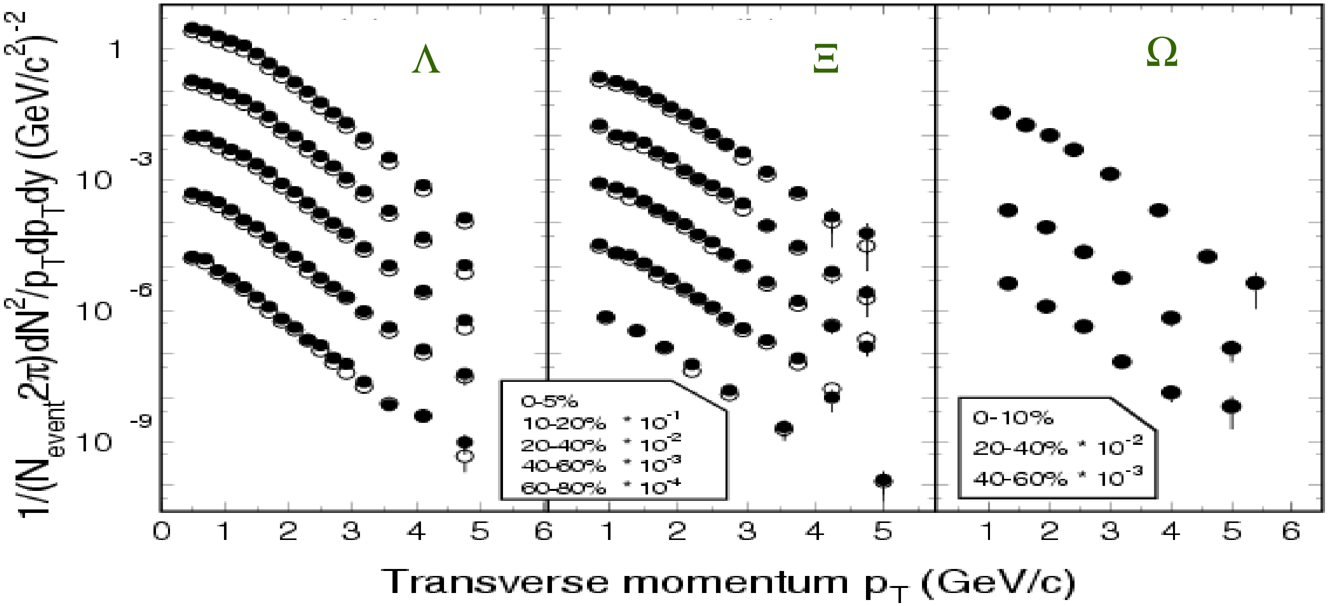
What is the size at chemical freeze-out?

may be assessed via π-Ξ correlations.

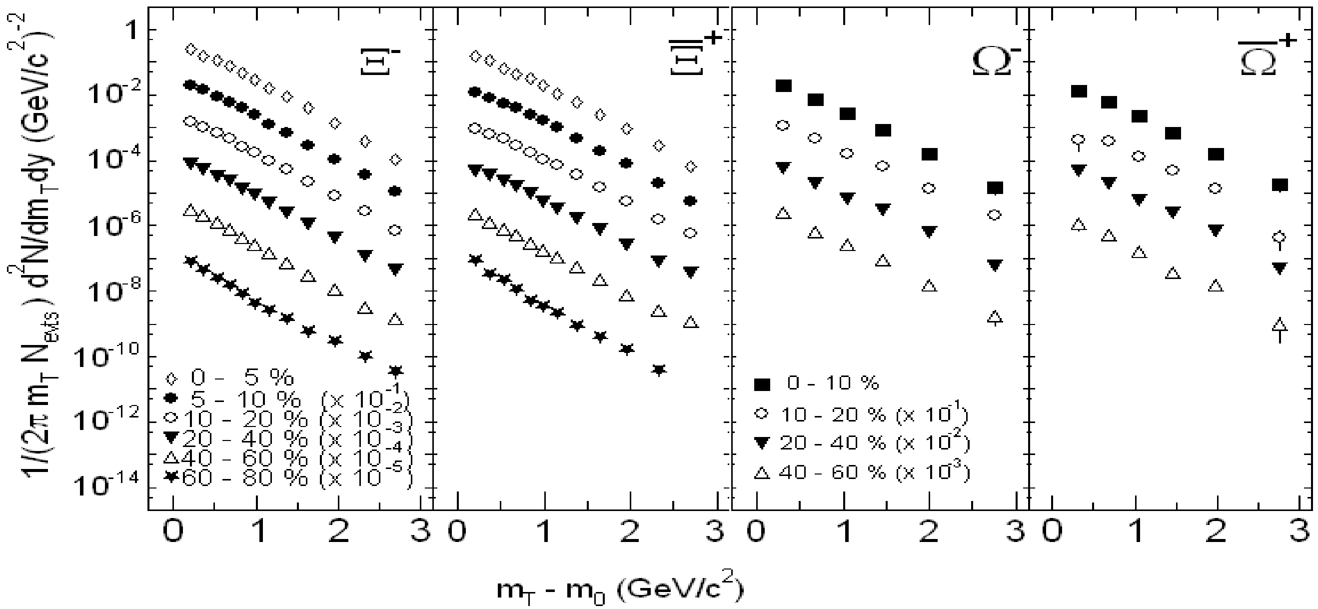
See talk, S. Salur (section 5a) and posters, C. Markert (#151), D. Mishra (#19)

See talks, Z. Chajęcki, P. Chaloupka (section 4a)

strange baryon spectra



200 GeV
Au+Au

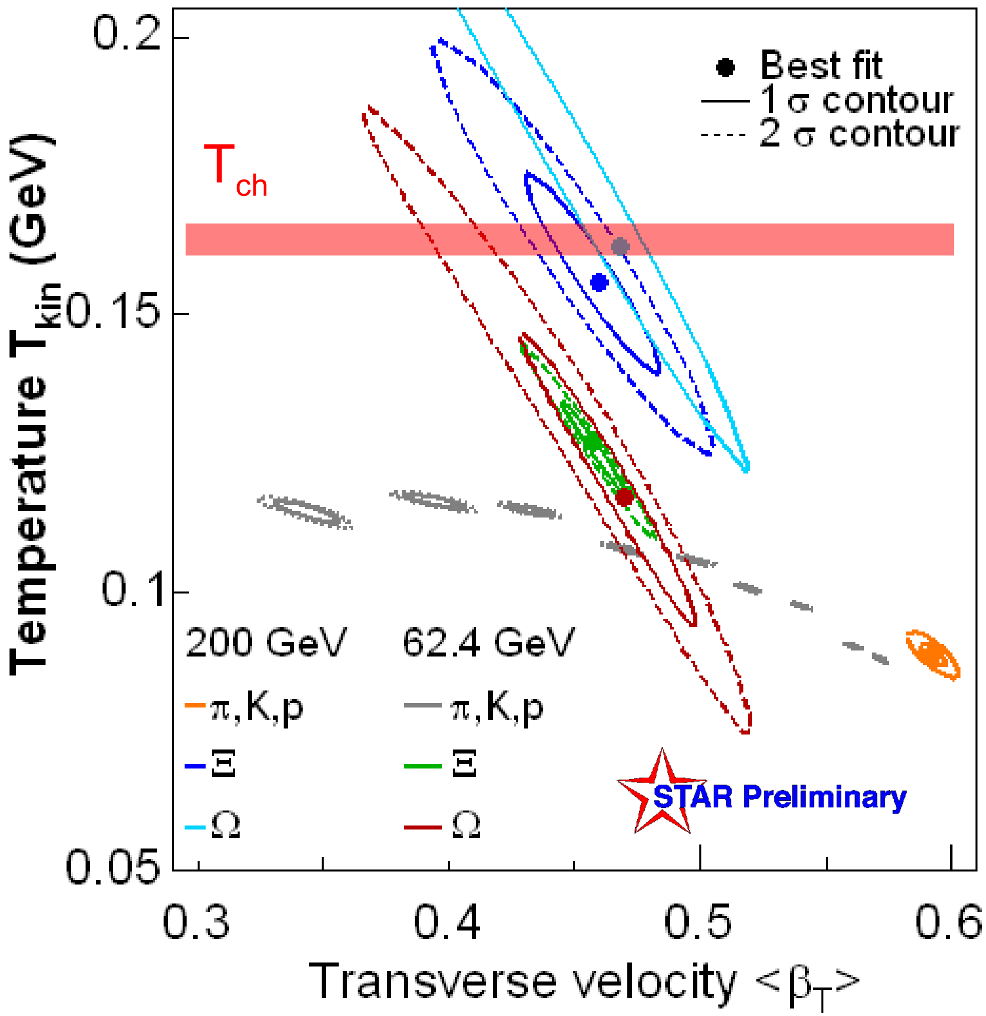


62.4 GeV
Au+Au

See talk, S. Salur (section 5a)

kinetic freeze-out

particle spectra   kinetic freezeout properties, total collective radial flow.



Blast wave fit

See poster, J. Speltz (#164)

π,K,p,Λ: T_{kin} decreases, β increases with centrality.

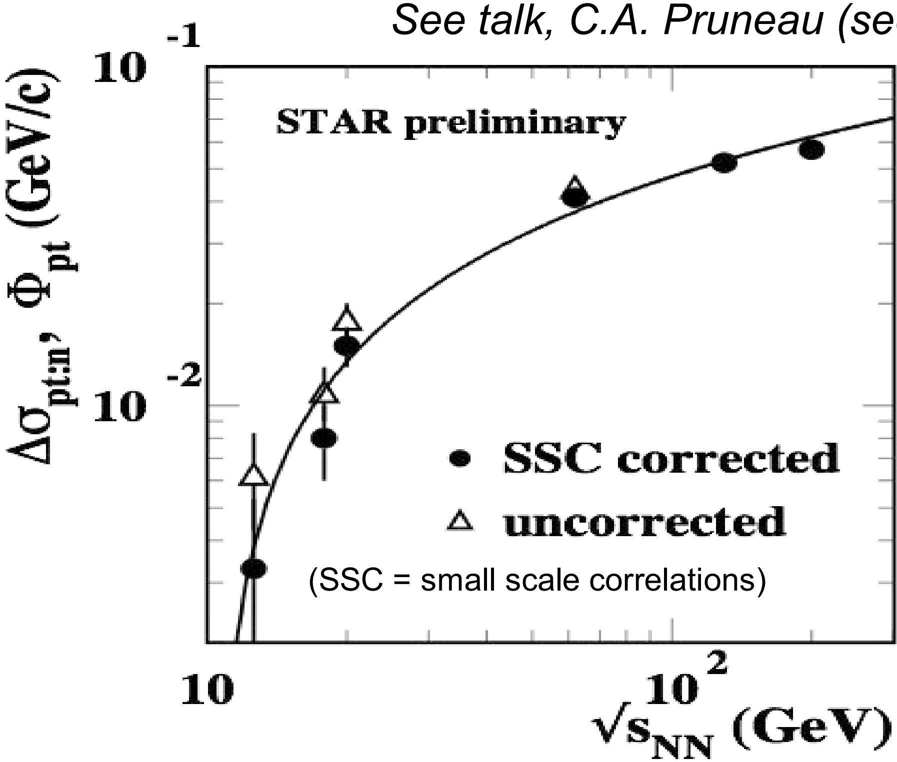
Ξ, Ω (low hadronic x-sections): higher $T_{kin} \approx T_{ch}$, still significant radial flow.

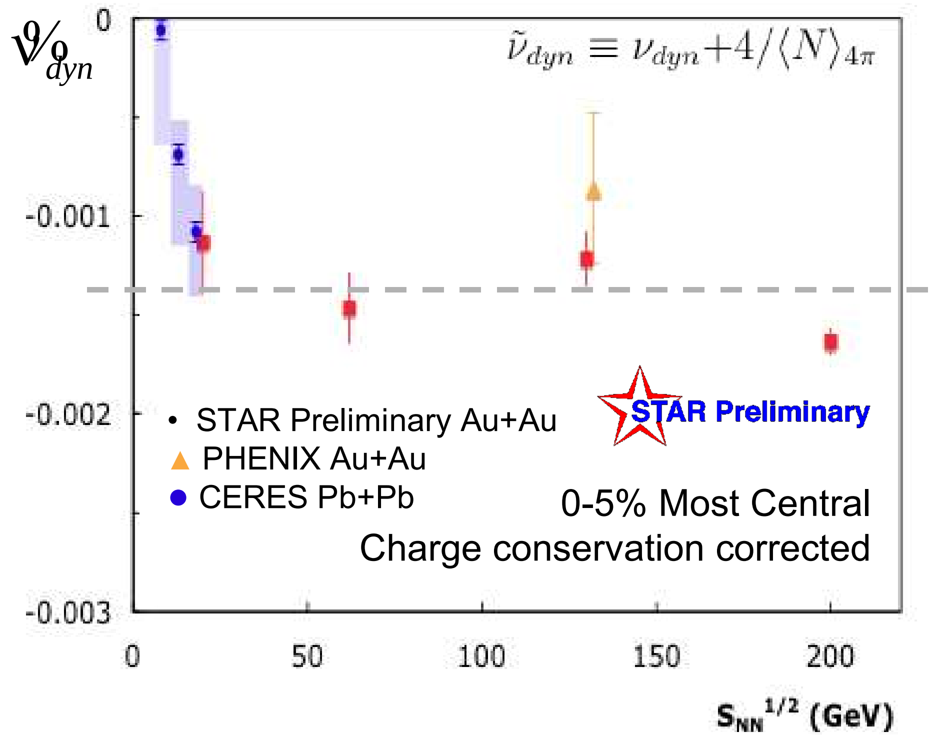
Rare particles:
kinetic freeze-out ≈
chemical freeze-out ≈
hadronization

event-by-event fluctuations

Phase transition   large event-by-event fluctuations

See talk, C.A. Pruneau (section 4c) and poster, L. Ray (#87)



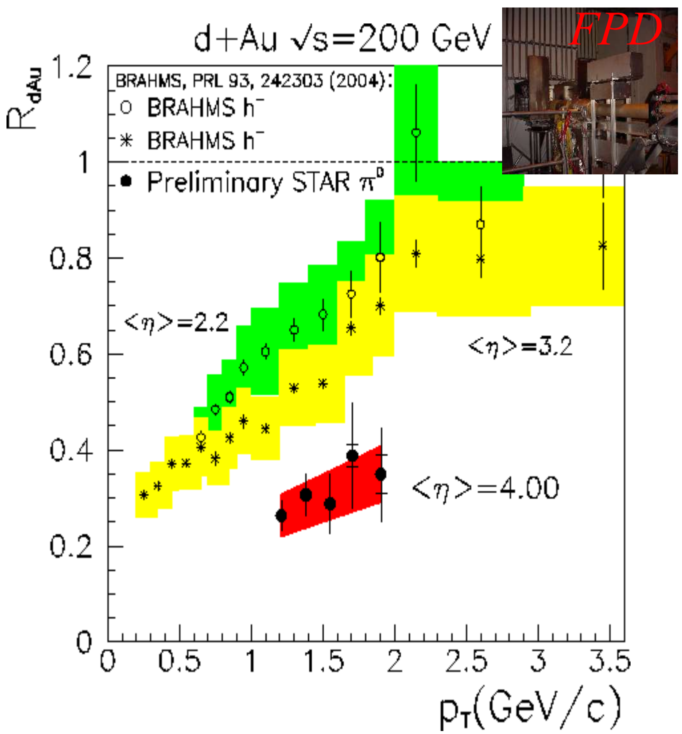


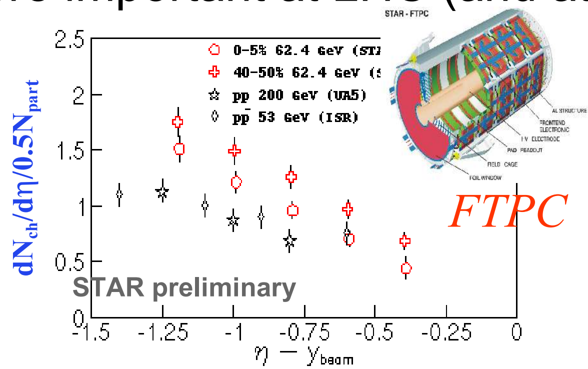
Smooth √s dependence, no threshold effect.

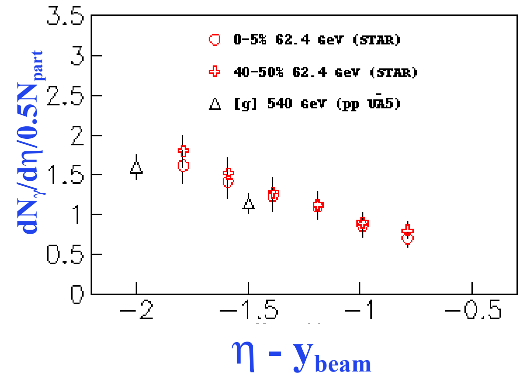
Original QGP signal in inclusive net charge fluctuation is excluded. More differential studies are needed.

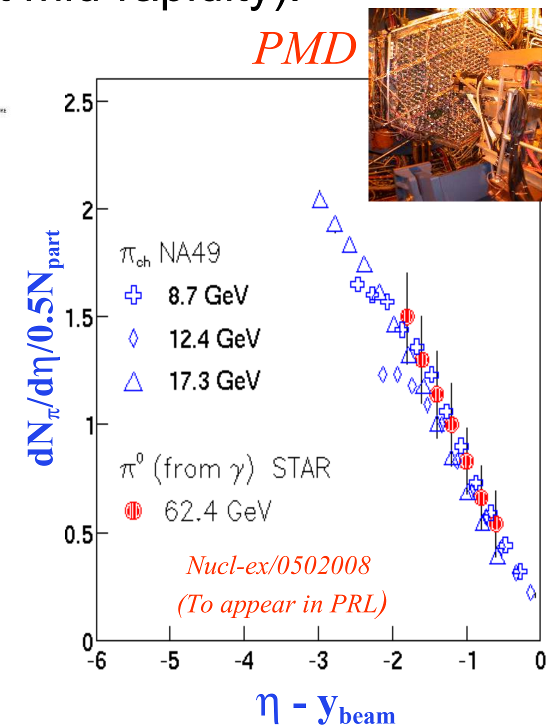
forward physics

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









See talk, B. Mohanty (section 1b)

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

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
- Elliptic flow and spectra data show:
  - early thermalization
  - partonic collectivity
  - relevance of constituent quark DOF
- Particle distributions with equilibrium models:
  - chemical freeze-out ≈ hadronization
  - finite span from chemical to kinetic freeze-out

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

Brazil:
Universidade de Sao Paolo

China:
IHEP - Beijing, IPP - Wuhan, USTC, Tsinghua, SINAP, IMP Lanzhou

Croatia:
Zagreb University

Czech Republic:
Nuclear Physics Institute

England:
University of Birmingham

France:
Institut de Recherches Subatomiques Strasbourg, SUBATECH - Nantes

Germany:
Max Planck Institute – Munich
University of Frankfurt

India:
Bhubaneswar, Jammu, IIT-Mumbai, Panjab, Rajasthan, VECC

Netherlands:
NIKHEF/Utrecht

Poland:
Warsaw University of Technology

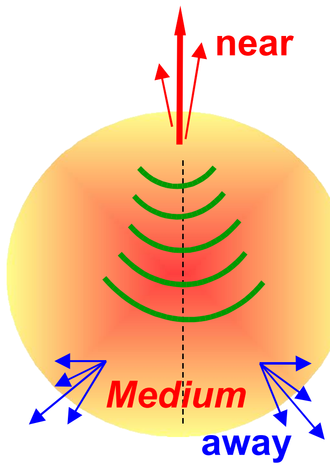
Russia:
MEPHI – Moscow, LPP/LHE JINR – Dubna, IHEP – Protvino

South Korea:
Pusan National University

Switzerland:
University of Bern

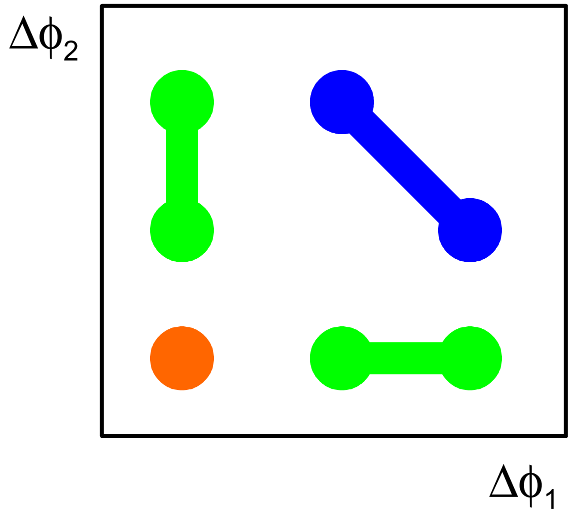
---Backup slides---

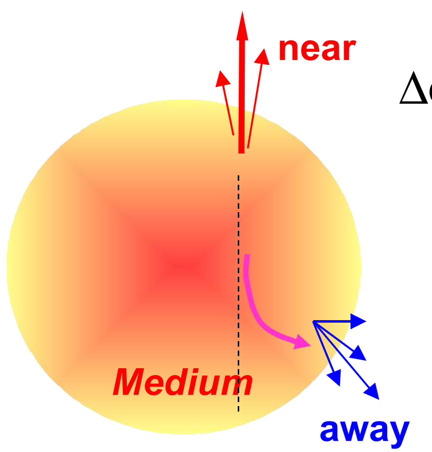
Is there conical flow?



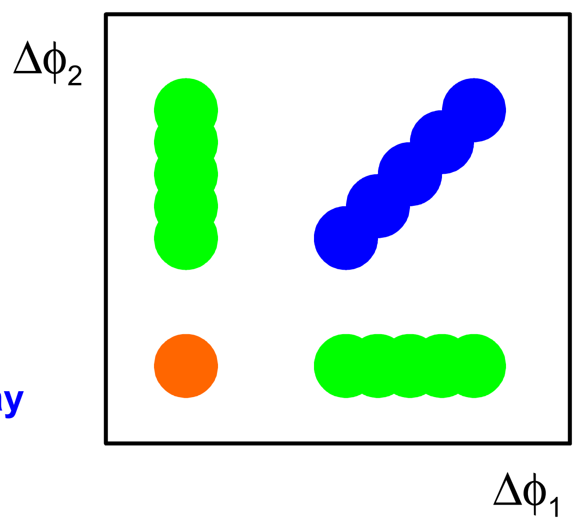
mach cone

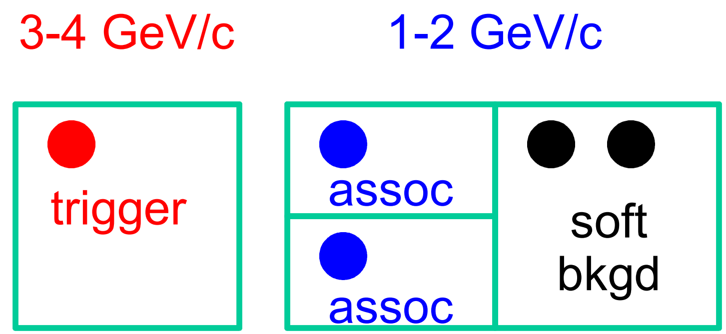
See talk, J. Ulery (section 3c)





deflected jets





3-particle correlation

hard-soft-corr + soft-bkgd.

flow modulated background:

$$1 + 2v_2^{trig} v_2^{(1)} \cos[2(\varphi_1 - \varphi_{trig})]$$
$$+2v_2^{trig} v_2^{(2)} \cos[2(\varphi_2 - \varphi_{trig})]$$
$$+2v_2^{(1)} v_2^{(2)} \cos[2(\varphi_1 - \varphi_2)]$$

soft-soft-corr in underlying event.

existing v_2 scaling data