Collective Expansion in Relativistic Heavy Ion Collisions

-- Search for the partonic EOS at RHIC

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Many Thanks to Organizers!

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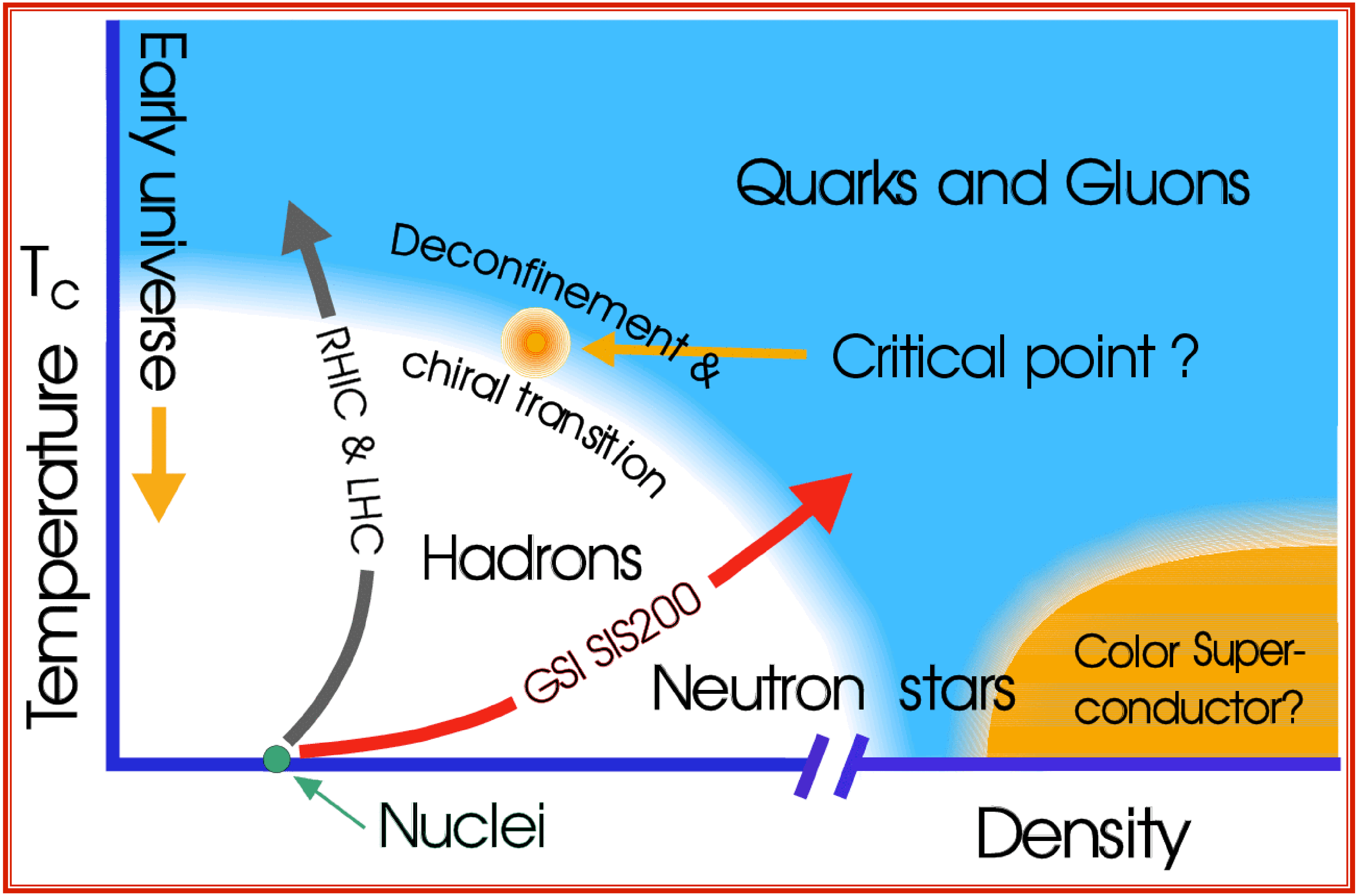
Outline

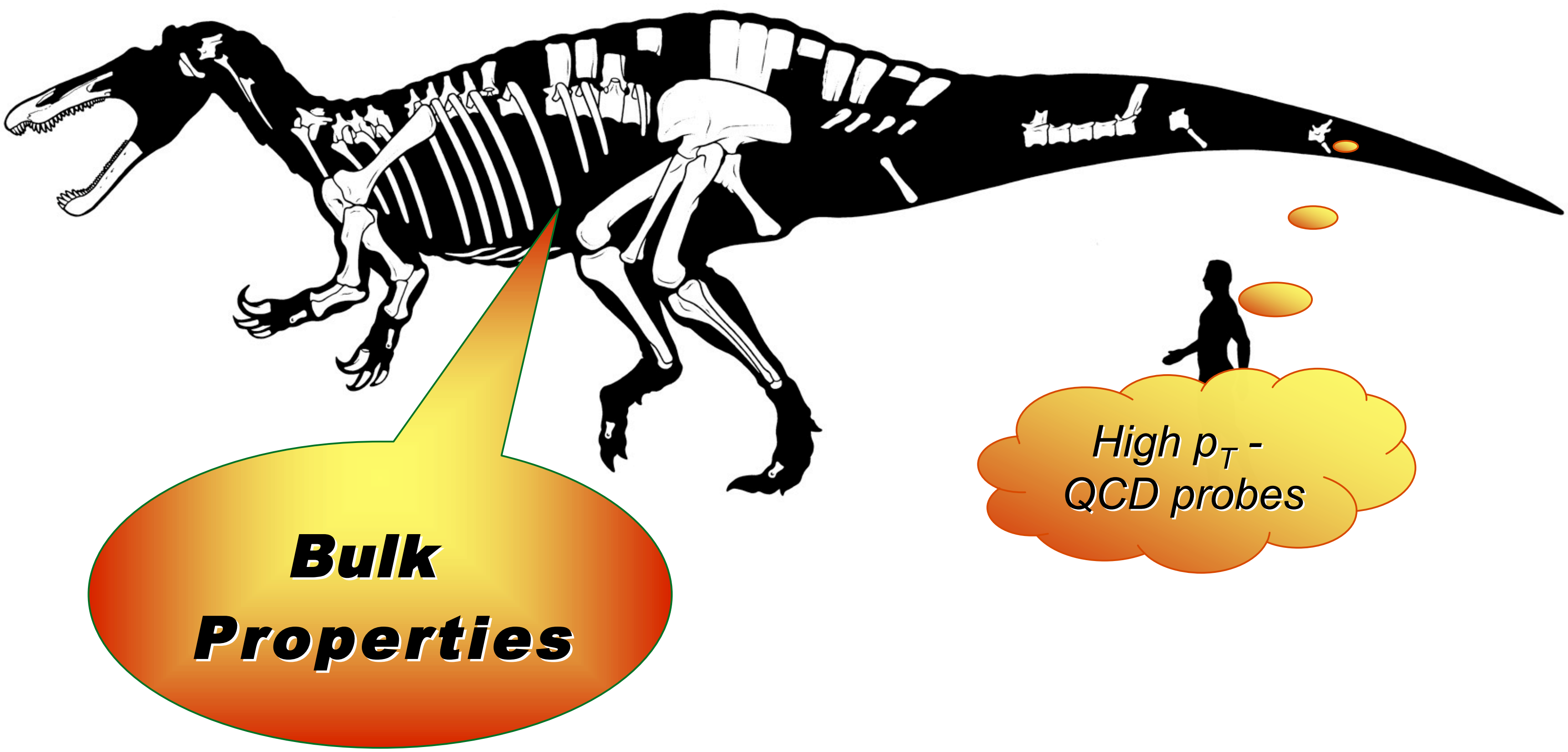
- Introduction
- Energy loss - QCD at work
- Bulk properties - ∂P_{QCD}
  - hadron spectra
  - elliptic flow v_2
- Summary and Outlook

http://www4.rcf.bnl.gov/brahms/WWW/brahms.html
http://www.phobos.bnl.gov/
http://www.phenix.bnl.gov/
http://www.star.bnl.gov/


Quarks and Gluons
Early universe
Tc
Temperature
Deconfinement &
chiral transition
Critical point ?
RHIC & LHC
Hadrons
GSI SIS200
Neutron stars
Color Super-
conductor?
Nuclei
Density

Study of Nuclear Collisions Like…

P.C. Sereno *et al*. **Science**, Nov. 13, 1298(1998).
(Spinosaurid)



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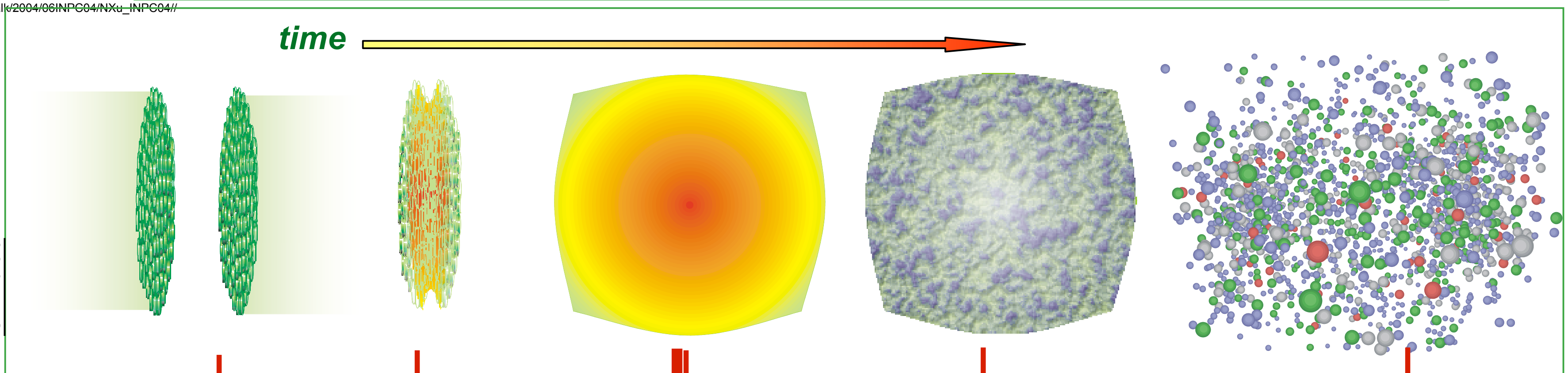
High-energy Nuclear Collisions



Initial conditions

Initial high Q²
interactions

Parton matter - QGP
- The hot-QCD

Hadronization
and Freeze-out

Experimen ... ch

1) Energy l
2) Elliptic fl
3) Heavy fl... ... 1) and 2)

(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

(1) Initial condition in high-energy nuclear collisions
(2) Cold-QCD-matter, small-x, high-parton density
- parton structures in nucleon / nucleus

High-energy Nuclear Collisions

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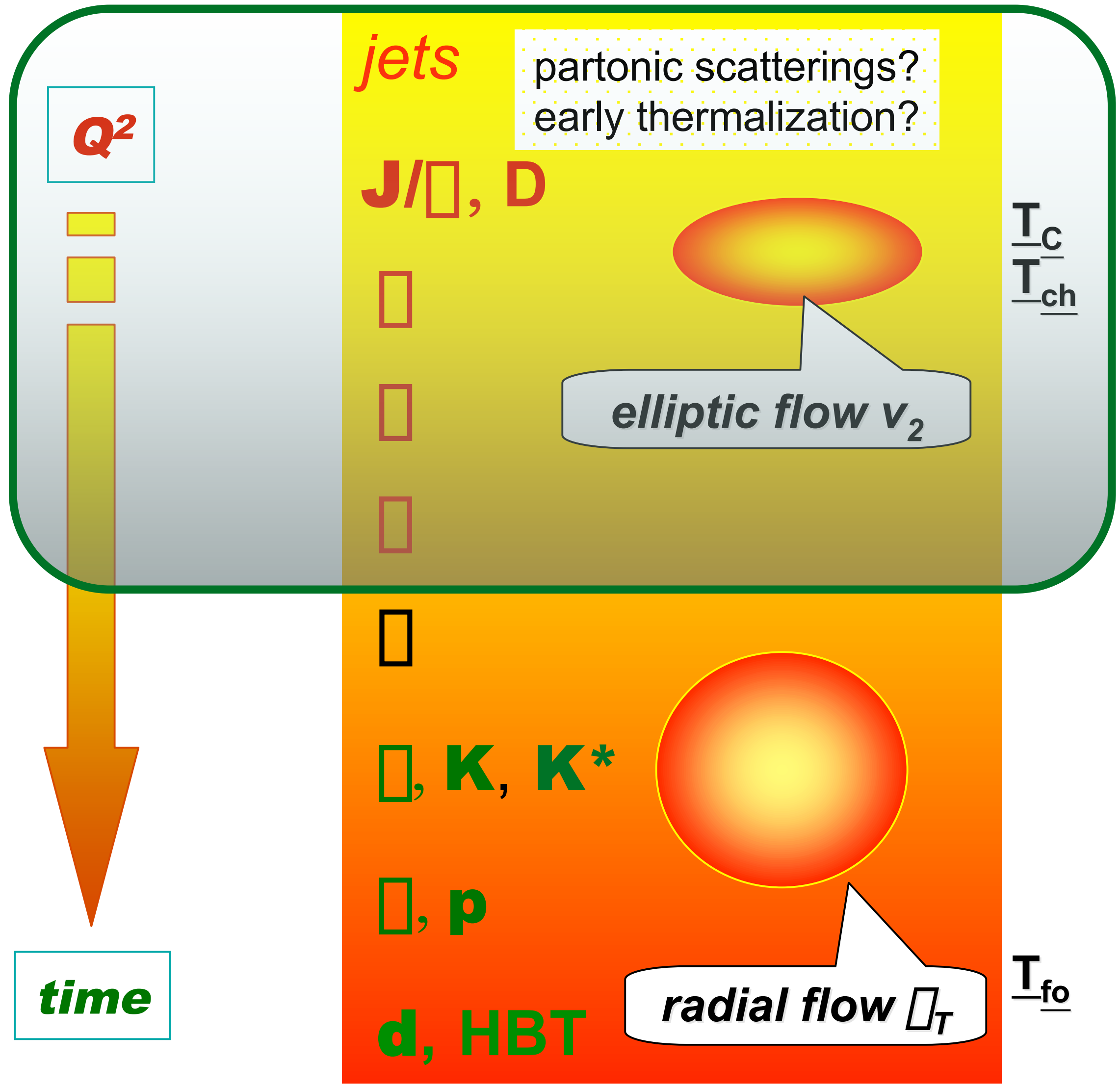
Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



Physics Goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

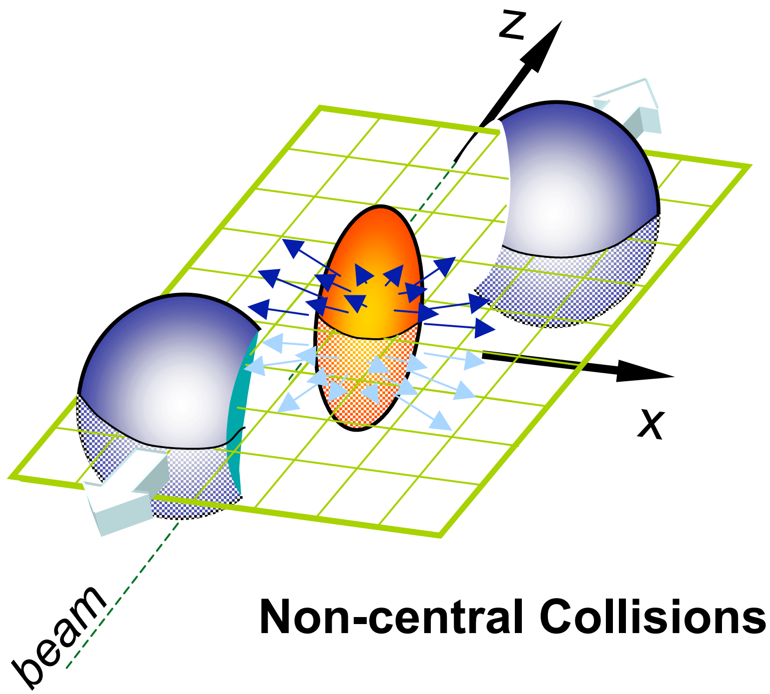
- direct photons, leptons
- "jets" and heavy flavor

Bulk probes

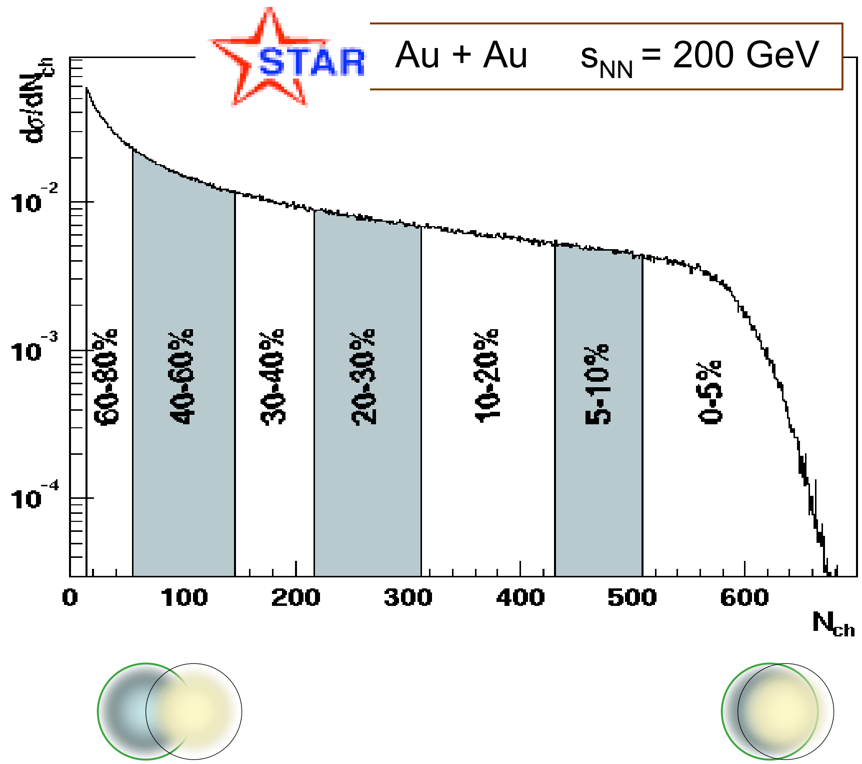
- spectra, v_1, v_2 …
- partonic collectivity
- fluctuations

Hydrodynamic Flow = Collectivity Local Thermalization

Collision Geometry

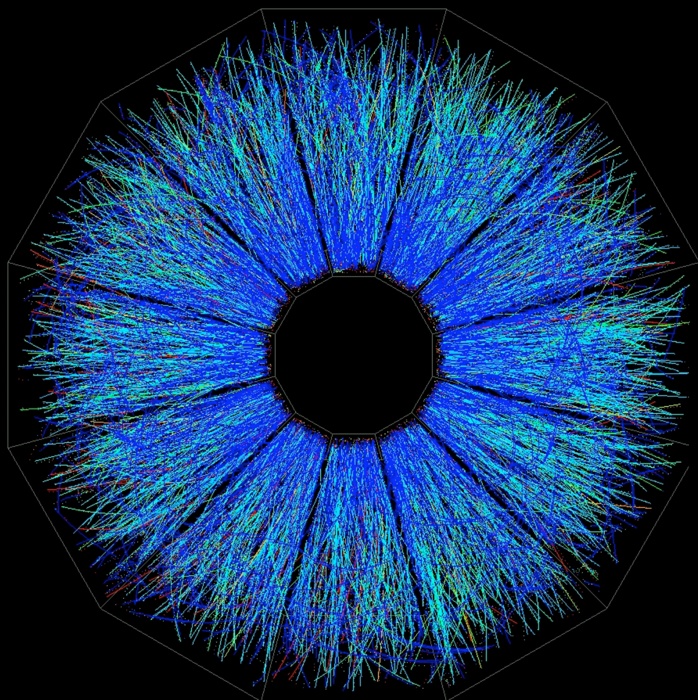


Non-central Collisions

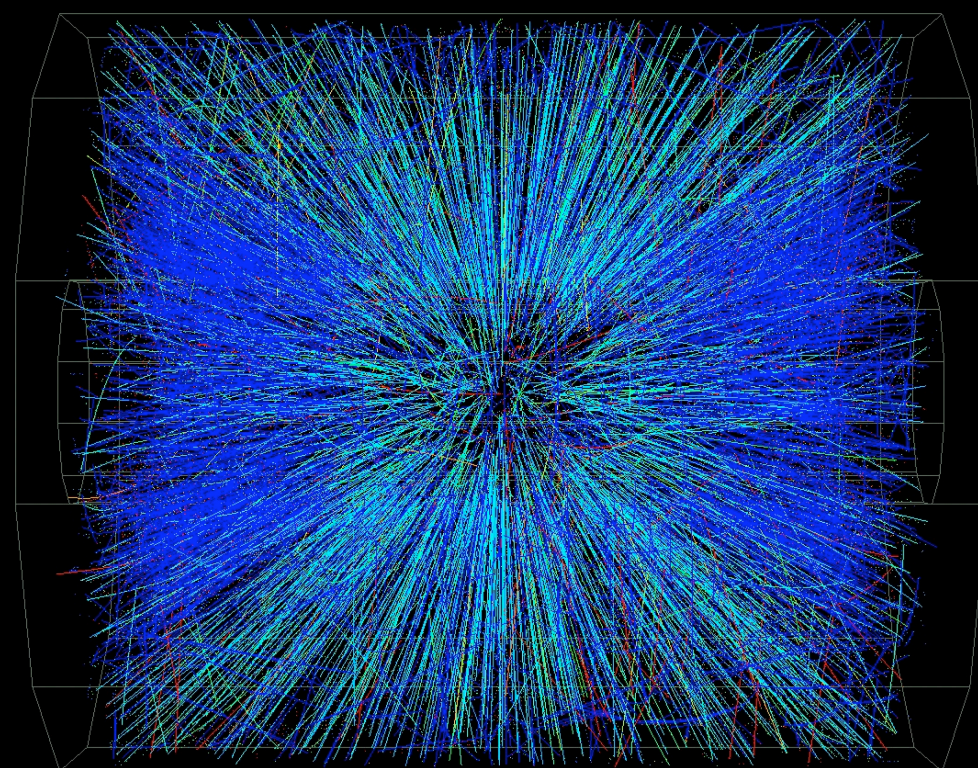


Number of participants: number of incoming nucleons in the overlap region
Number of binary collisions: number of inelastic nucleon-nucleon collisions
Charged particle multiplicity collision centrality
Reaction plane: x-z plane

Au + Au Collisions at RHIC



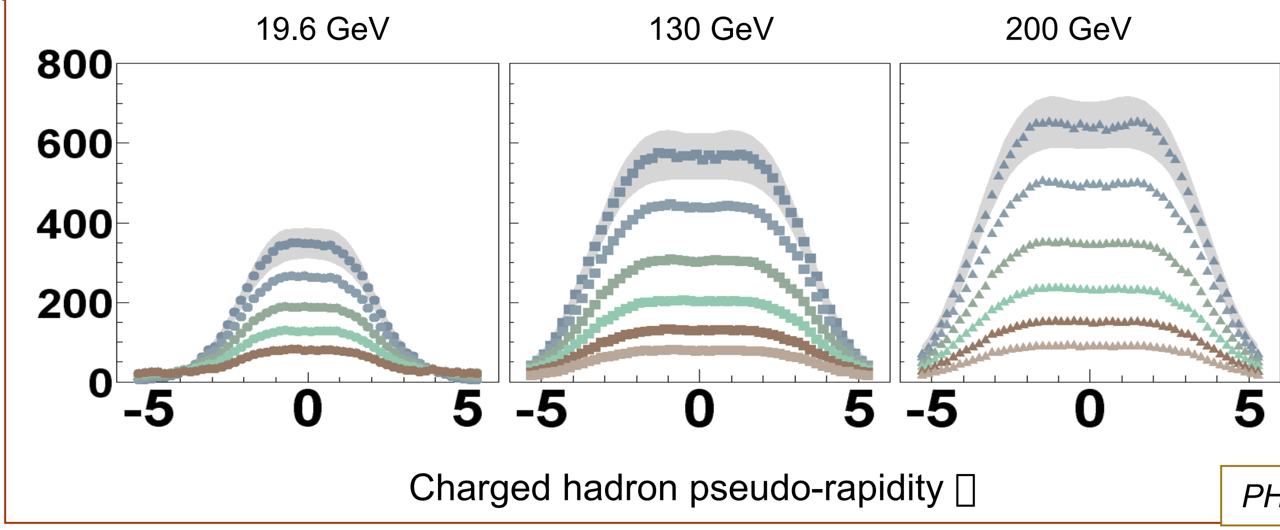
Central Event



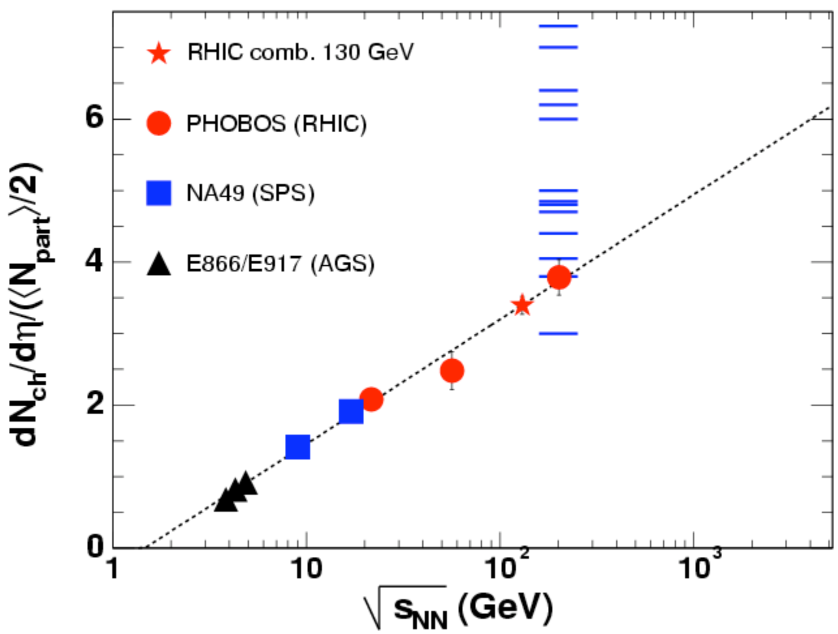
STAR

(real-time Level 3)

Charged Hadron Density



PHOBOS Collaboration

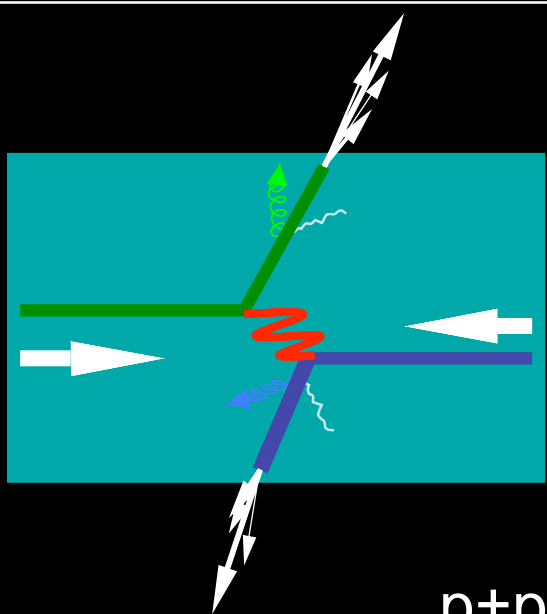


1) High number of N_{ch} indicates initial high density;
2) Mid-y, N_{ch} N_{part} ➪ nuclear collisions are not incoherent;
3) Saturation model works

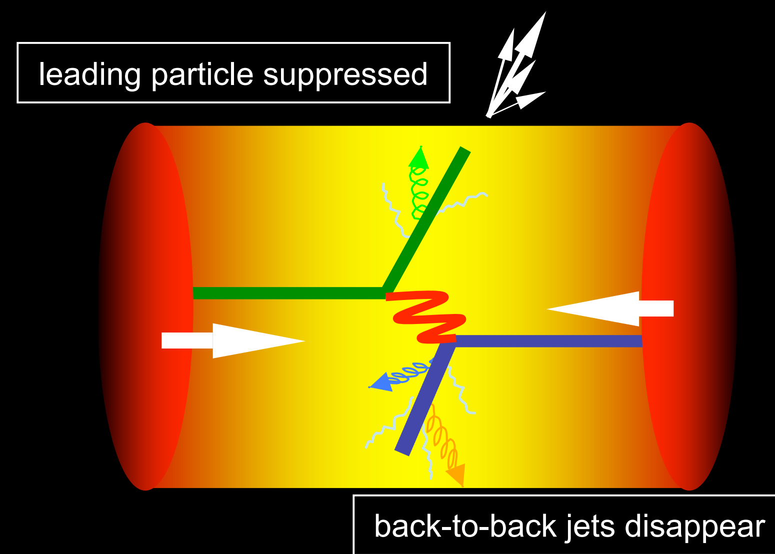
Initial high parton density at RHIC

*PRL **85**, 3100 (00); **91**, 052303 (03); **88**, 22302(02); **91**, 052303 (03)*

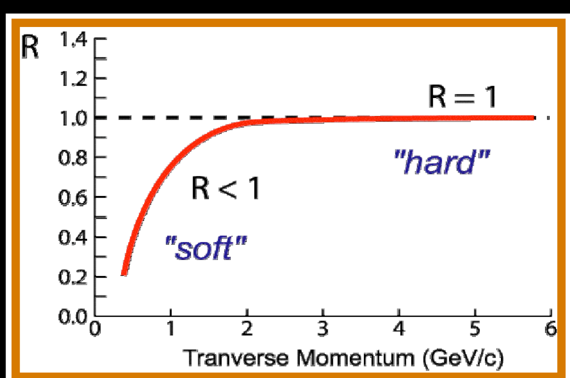
Energy Loss in A+A Collisions



p+p



Au + Au

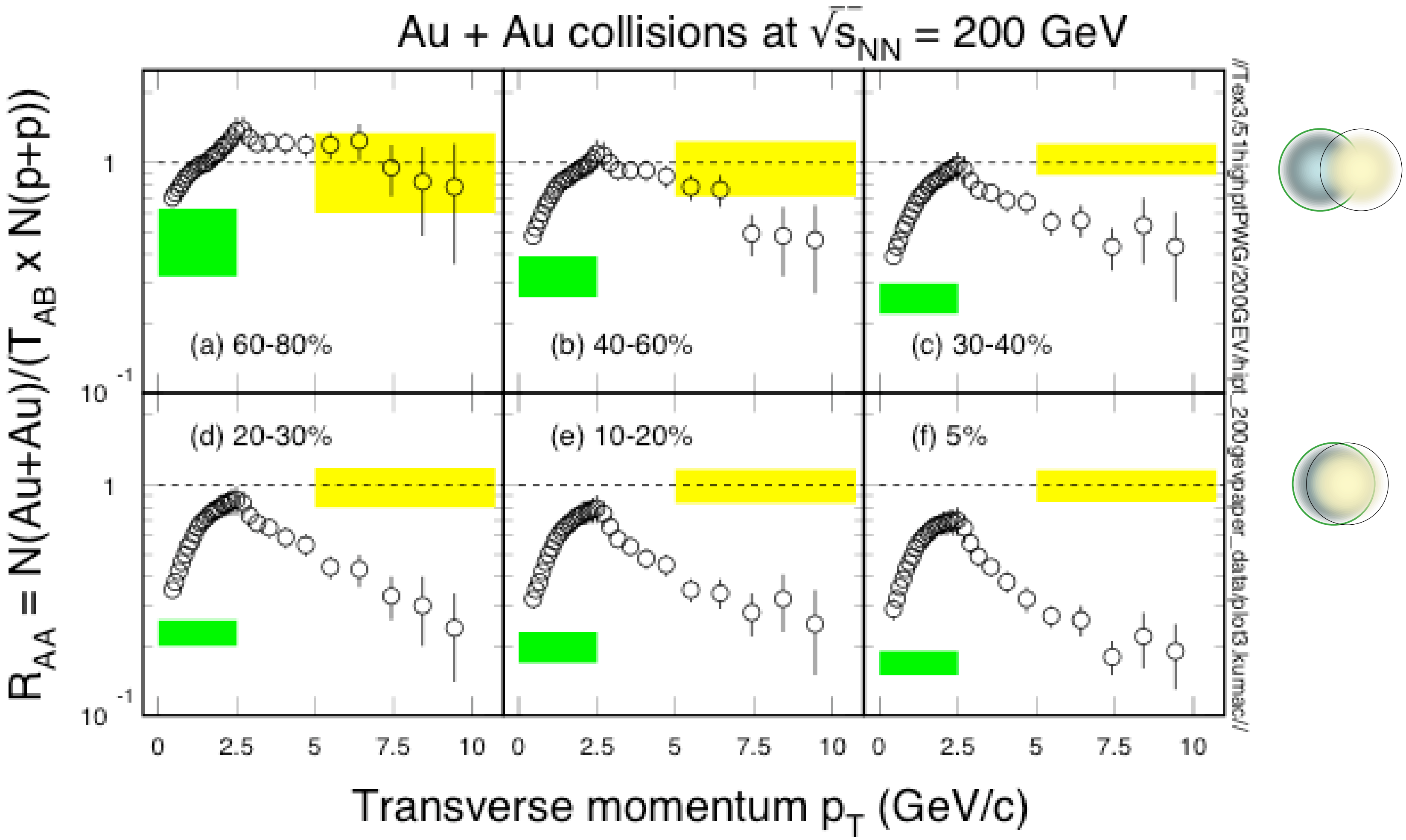


Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

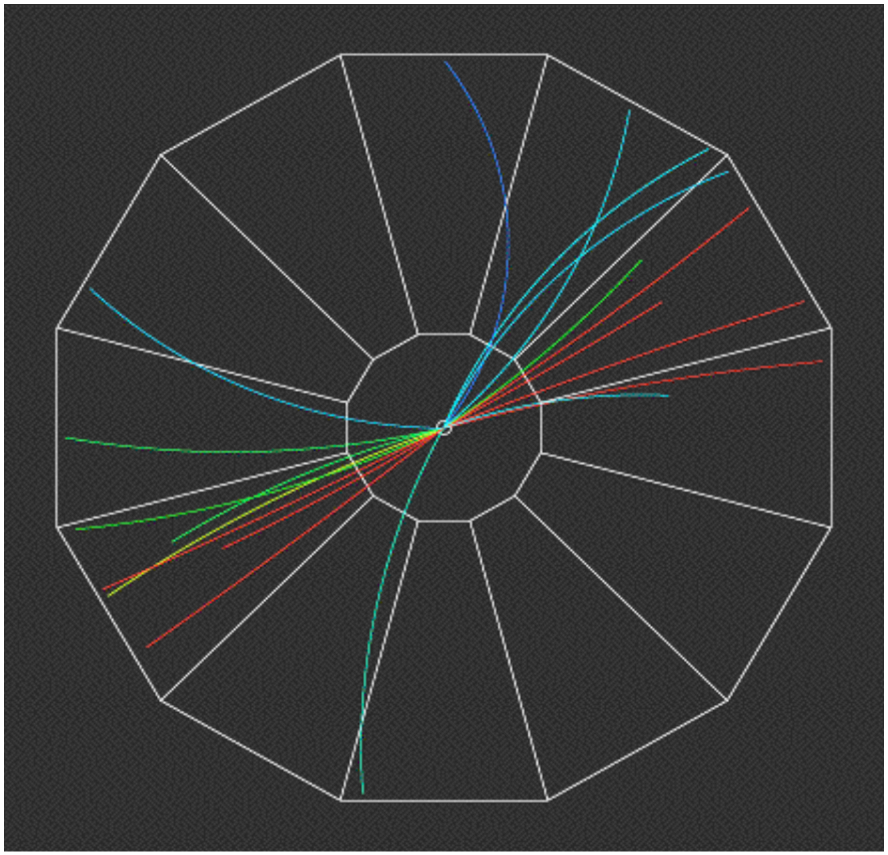
Hadron Suppression at RHIC

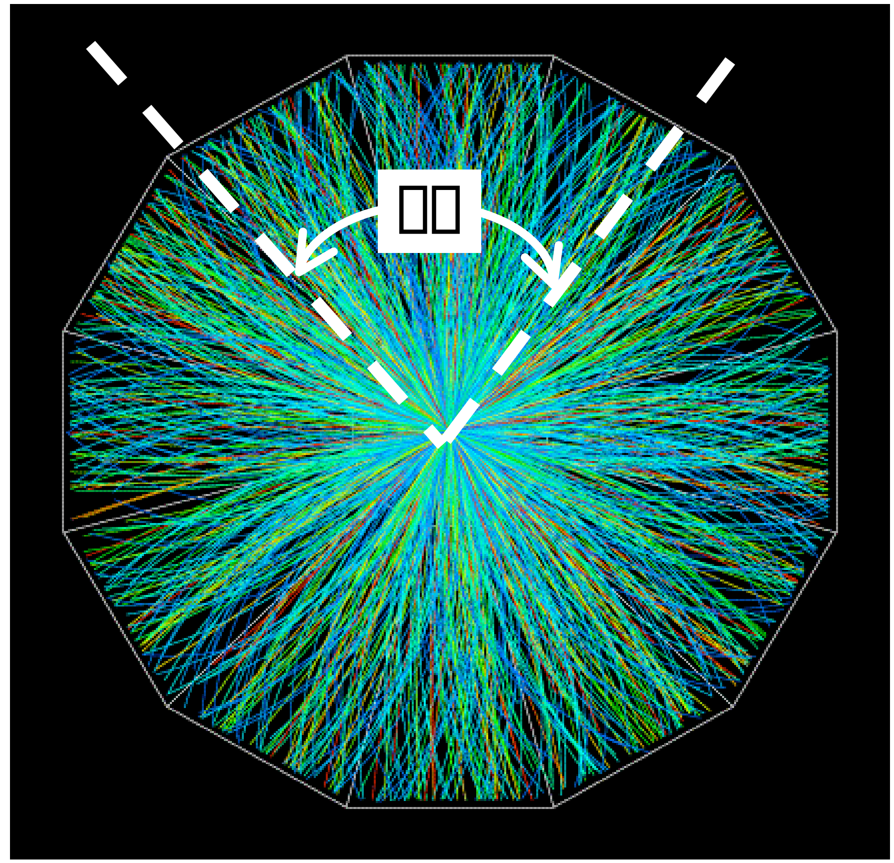
//Talk/2004/06INPC04/NXu_INPC04//



Hadron suppression in more central Au+Au collisions!

Jets Observation at RHIC

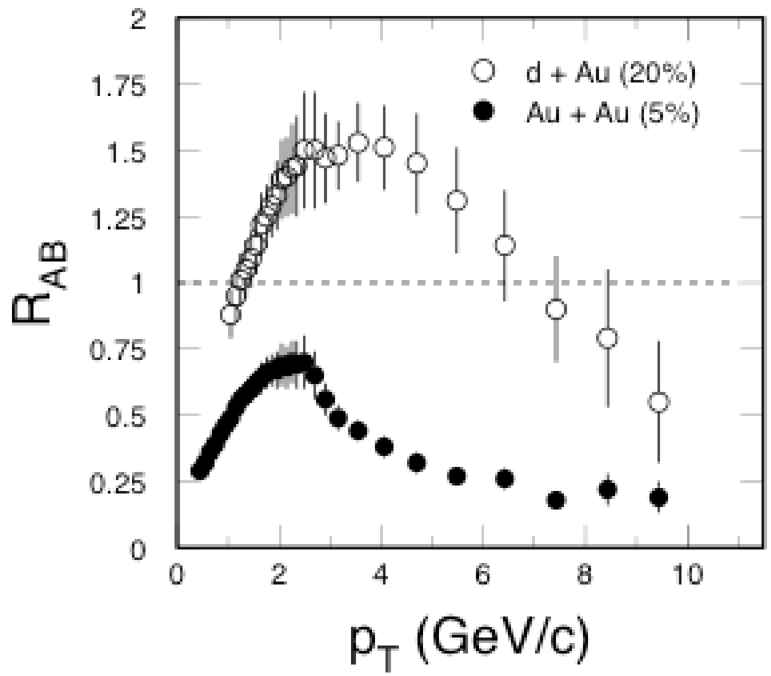


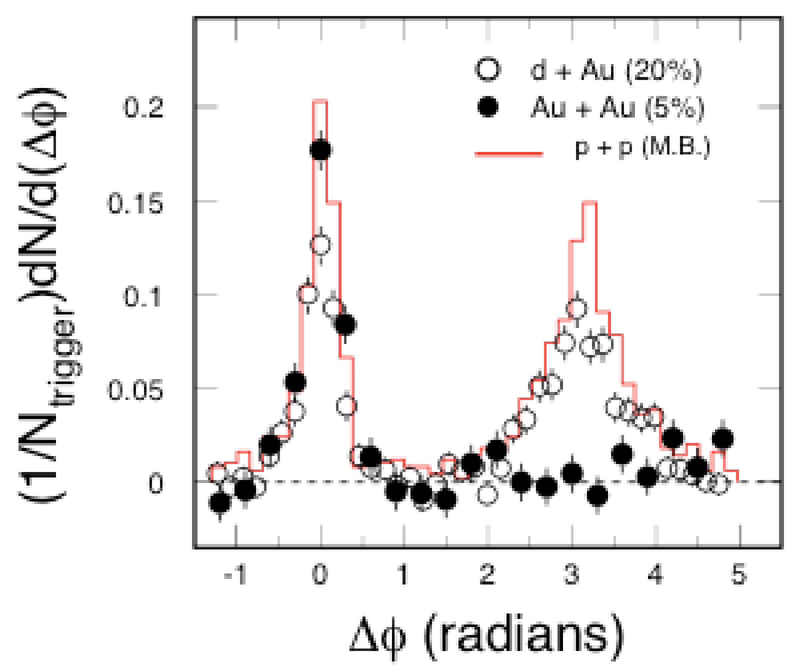


p+p collisions at RHIC
Jet like events observed

Au+Au collisions at RHIC
Jets?

Suppression and Correlation





In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ϵ > 5 GeV/fm^3 ~ 30ϵ_0

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…

Energy Loss and Equilibrium

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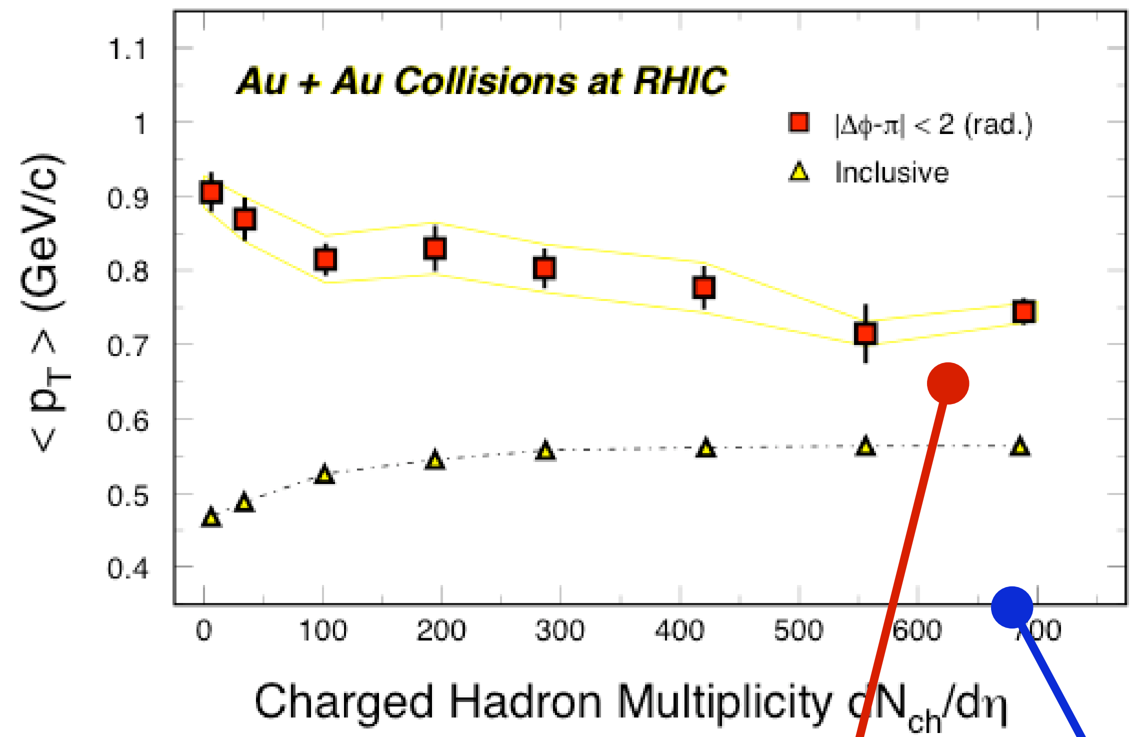

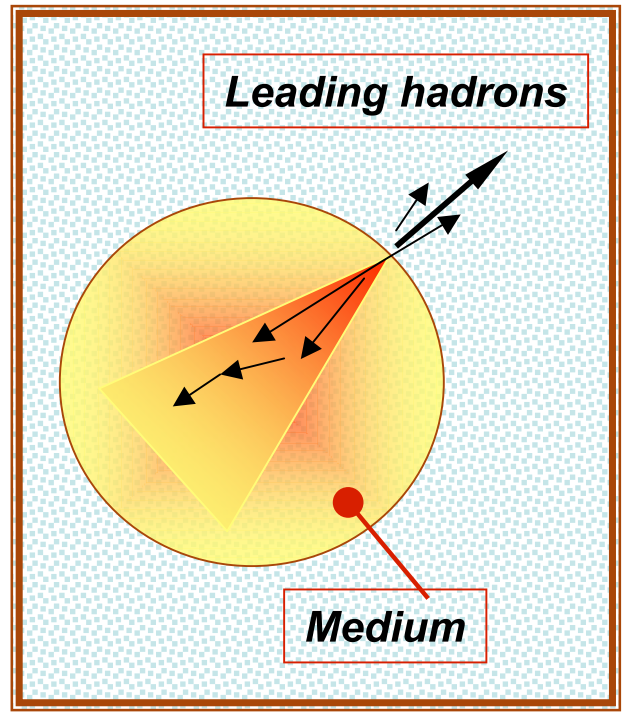

In Au +Au collision at RHIC:

- Suppression at the intermediate p_T region - energy loss

- The energy loss leads to progressive equilibrium in Au+Au collisions

STAR: nucl-ex/0404010

Parton Energy Loss

//Talk/2004/06INPC04/NXu_INPC04//

(1) Measured spectra show evidence of suppression
up to $p_T \sim 6$ GeV/c;

(2) Jet-like behavior observed in correlations:
- hard scatterings in AA collisions
- disappearance of back-to-back correlations

⇨ ***"Partonic" Energy loss process leads to progressive equilibrium in the medium***

Next step: fix the partonic Equation of State, bulk properties

Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\phi} = \frac{1}{2\pi} \frac{dN}{p_t dp_t dy} \left[1 + \sum_{i=1} 2 v_i \cos(i\phi) \right]$$

$$p_t = \sqrt{p_x^2 + p_y^2}, \qquad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass:

- Directed flow (v_1) – early
- Elliptic flow (v_2) – early
- Radial flow – integrated over whole evolution

Note on collectivity:

1) Effect of collectivity is accumulative – final effect is the sum of all processes.
2) Thermalization is not needed to develop collectivity - pressure gradient depends on ***density gradient*** and ***interactions***.

Hadron Spectra From RHIC

mid-rapidity, p+p and Au+Au collisions at 200 GeV

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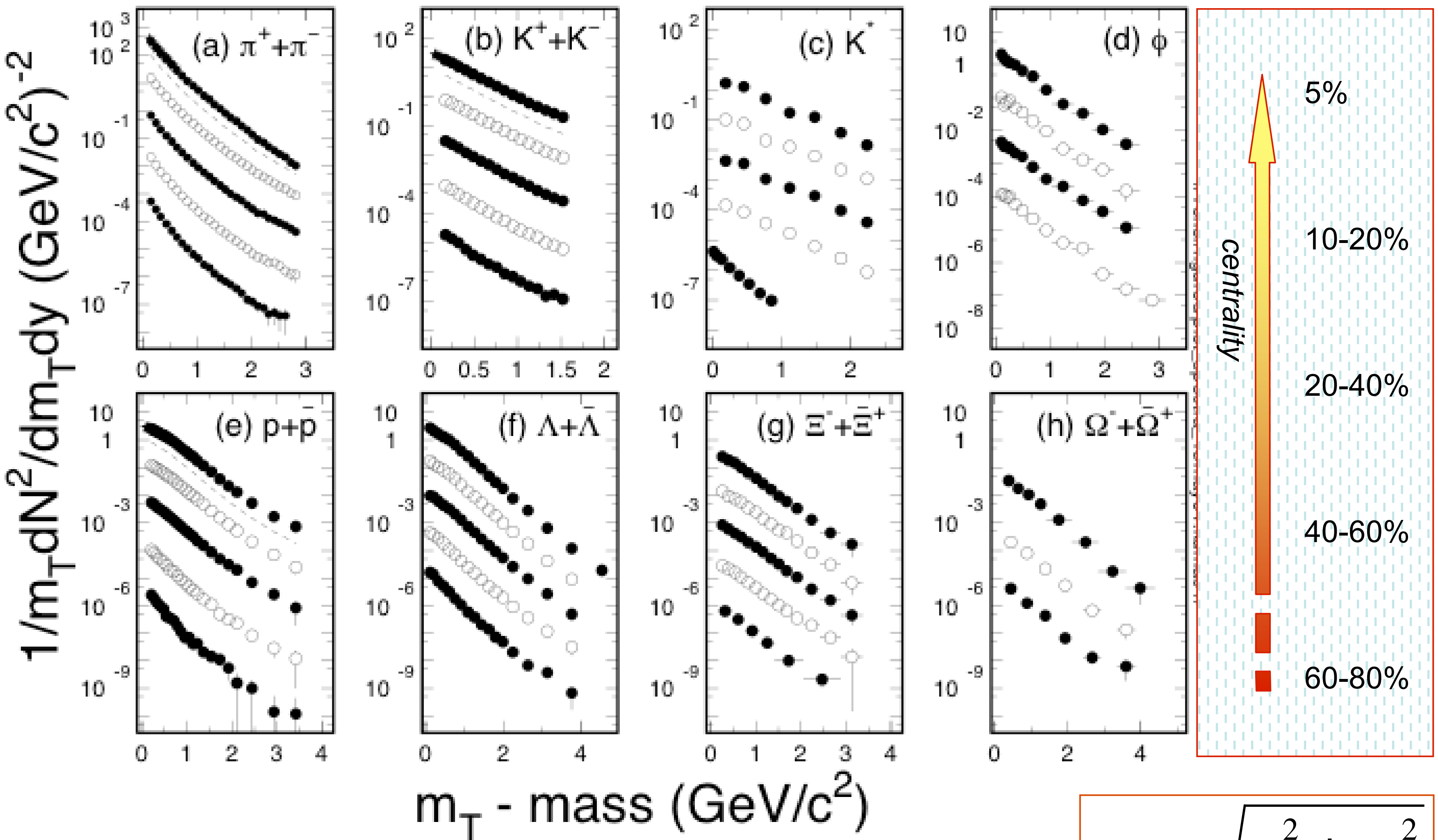
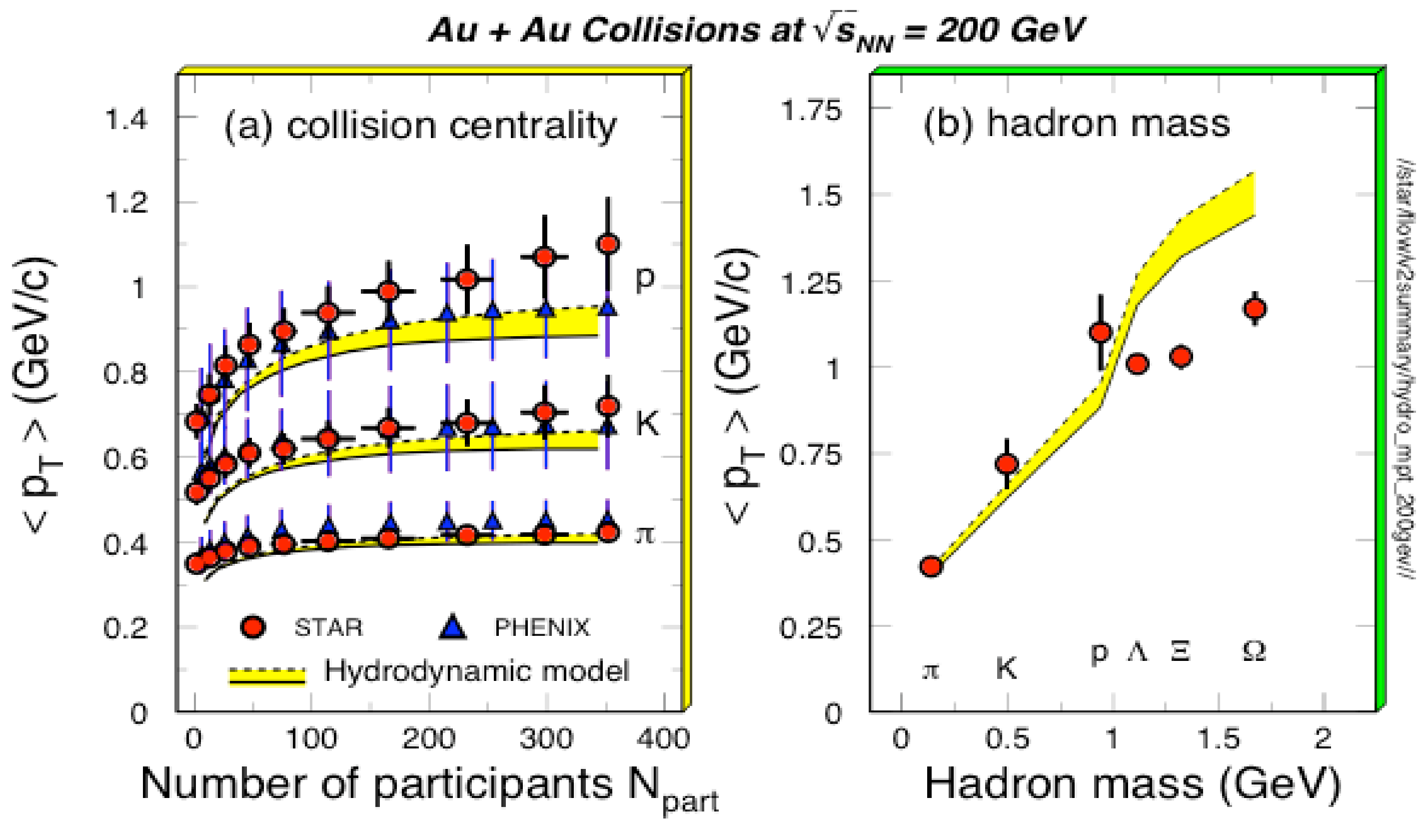


$$m_T = \sqrt{p_T^2 + m^2}$$

Compare with Model Results

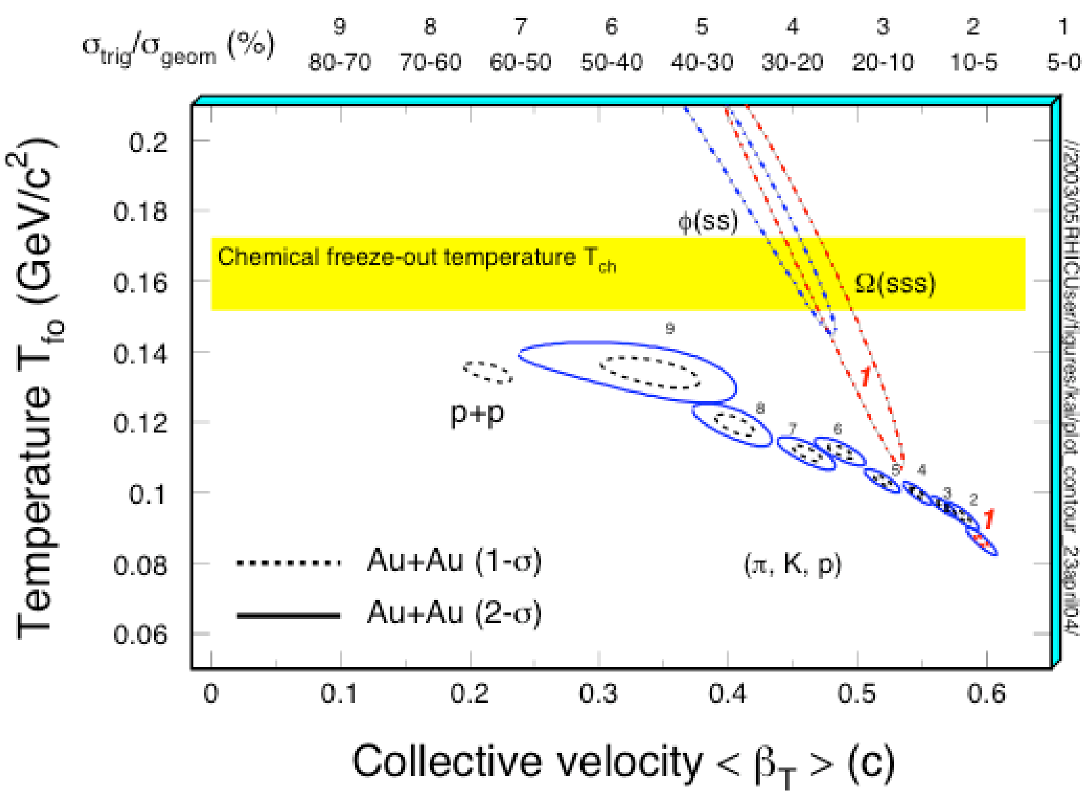


Model results fit to π, *K*, *p* spectra well, but over predicted <p_T> for multi-strange hadrons - **Do they freeze-out earlier?**

Phys. Rev. ***C69*** *034909 (04); Phys. Rev. Lett.* ***92****, 112301(04);* ***92****, 182301(04); P. Kolb et al., Phys. Rev.* ***C67*** *044903(03)*

Thermal fits: T_{fo} vs. < β_T >

200GeV Au + Au collisions



1) π, *K*, and *p* change smoothly from peripheral to central collisions.

2) At the most central collisions, <β_T> reaches 0.6c.

3) Multi-strange particles Φ, Ω are found at higher T_{fo} ($T \sim T_{ch}$) and lower <β_T>

➪ **Sensitive to early partonic stage!**

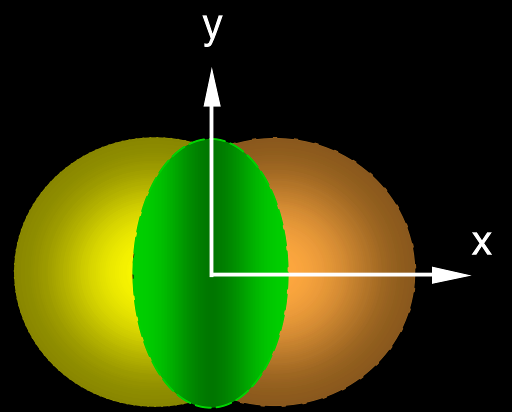
➪ **How about v_2?**

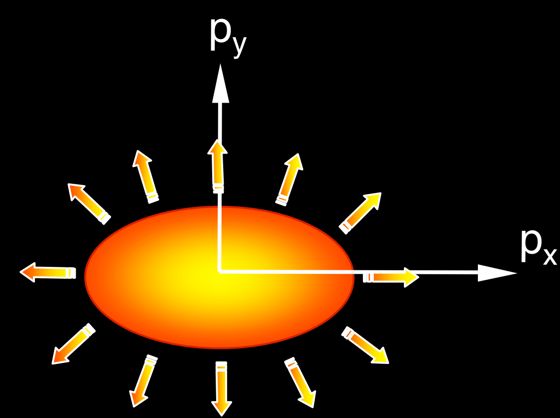
STAR: NP**A715**, 458c(03); *PRL* ***92****, 112301(04);* ***92****, 182301(04).*

<u>Chemical Freeze-out:</u> inelastic interactions stop
<u>Kinetic Freeze-out:</u> elastic interactions stop

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇒ momentum-space-anisotropy





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\phi \rangle, \ \ \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

v_2 at Low p_T

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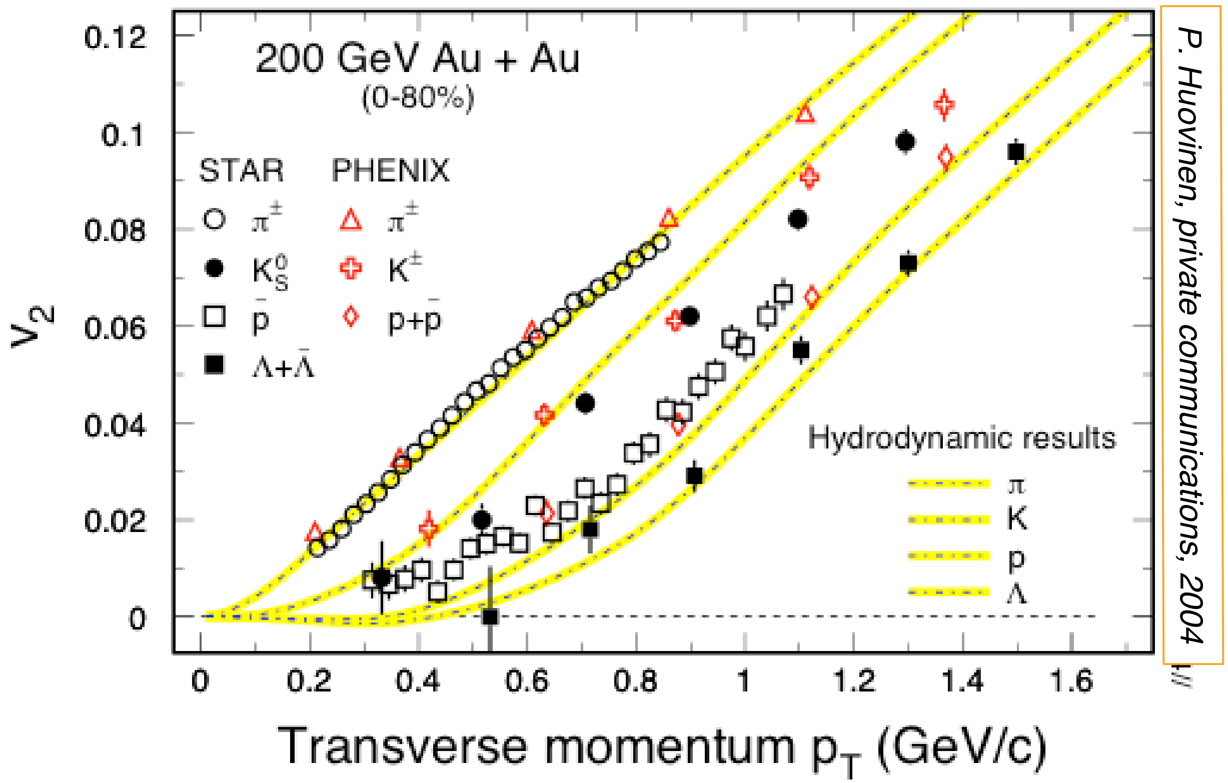
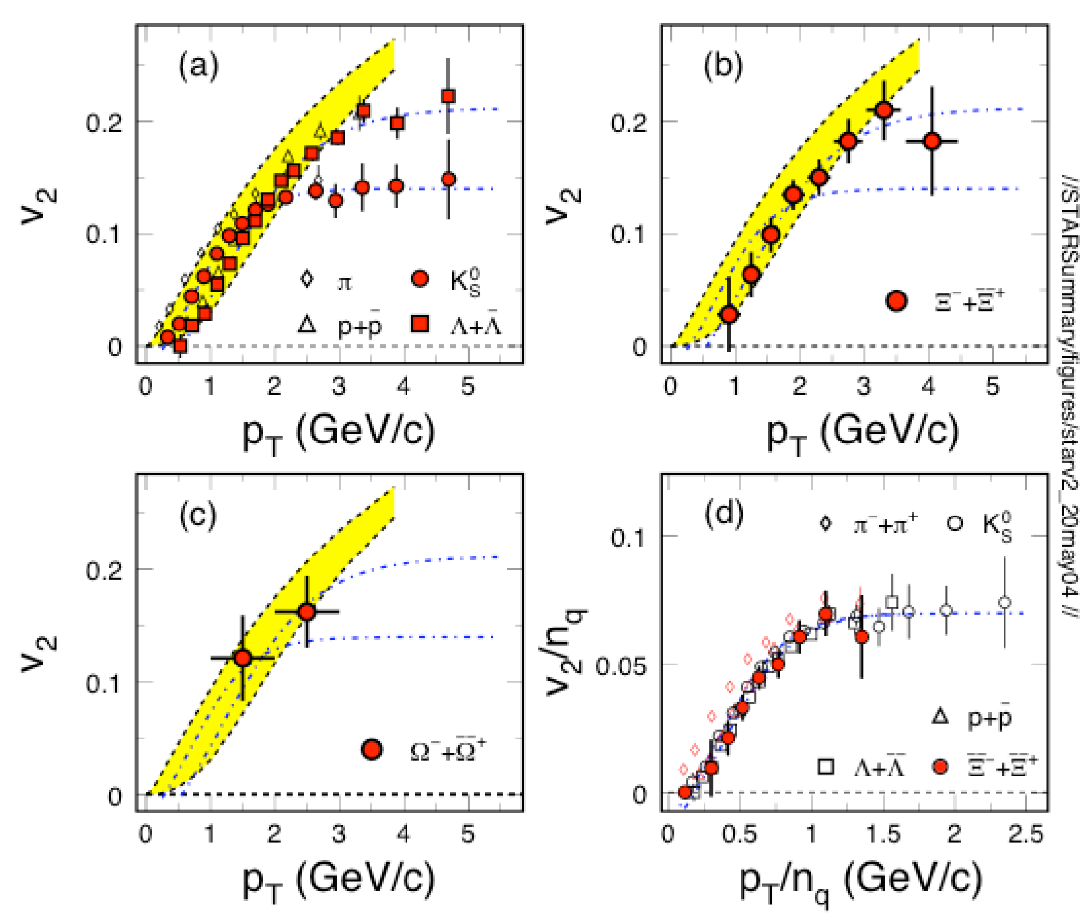


- At low p_T, hydrodynamic model fits well for minimum bias events indicating early thermalization in Au+Au collisions at RHIC!
- More theory work needed to understand details such as v_2 centrality dependence, consistence with spectra.

v_2 at All p_T

//Talk/2004/06INPC04/NXu_INPC04//

PHENIX: PRL91, 182301(03) STAR: PRL92, 052302(04)
*Models: R. Fries et al, PR**C68**, 044902(03), Hwa, nucl-th/0406072*



v_2, the spectra of multi-strange hadrons, and the scaling of the number of constituent quarks

- **Partonic collectivity has been attained at RHIC!**
- **Deconfinement, model dependently, has been attained at RHIC!**

Next question is the thermalization of light flavors at RHIC:

- v_2 of charm hadrons
- J/ψ distributions !!

Nuclear Modification Factor

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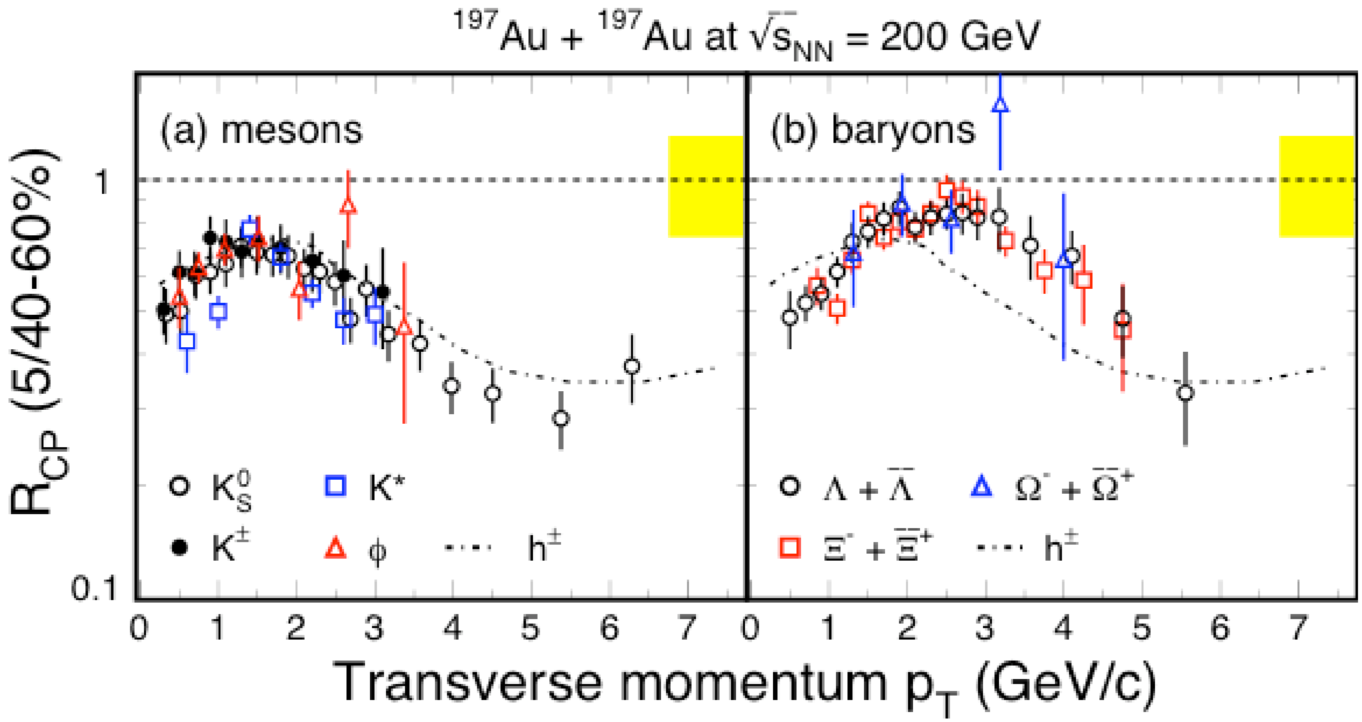


$$R_{CP}(p_T) = \frac{d^2N^{central} / (N^{central}_{binary}\, dp_T dy)}{d^2N^{peripheral} / (N^{peripheral}_{binary}\, dp_T dy)}$$

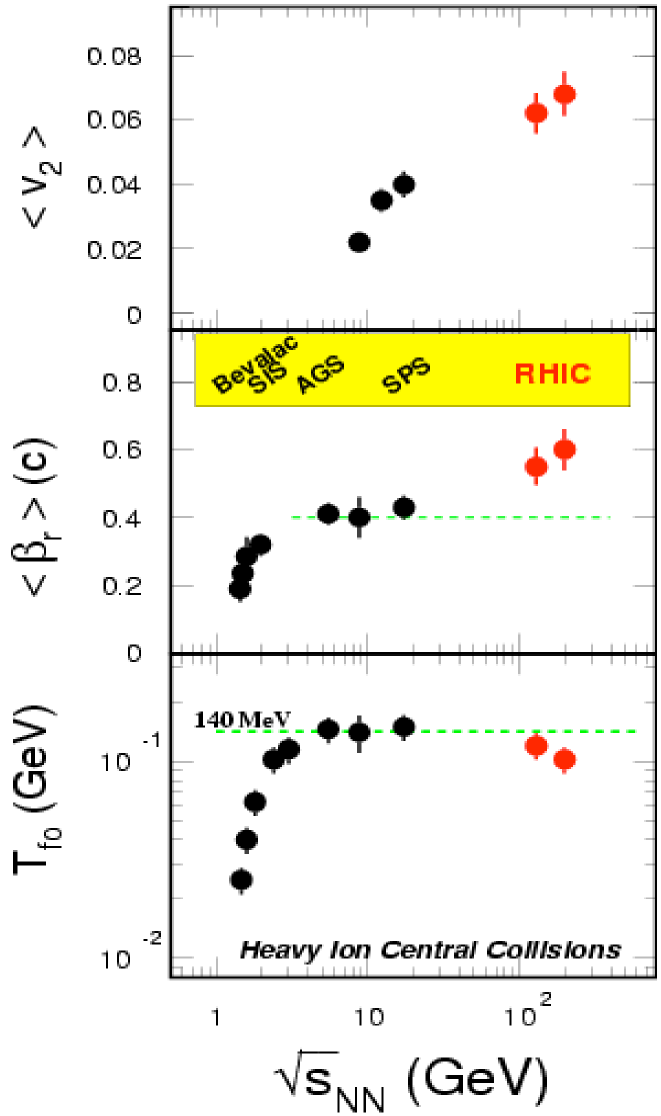
1) Baryon vs. meson effect!

2) Hadronization via coalescence

3) Parton thermalization (model)

- (K^0, □): *PRL* ***92***, *052303(04); NP* ***A715***, *466c(03);*
- *R. Fries et al, PRC* ***68***, *044902(03)*

Bulk Freeze-out Systematics



The additional increase in β_T is likely due to partonic pressure at RHIC.

1) v_2 self-quenching, hydrodynamic model works at low p_T
2) Multi-strange hadron freeze-out earlier, $T_{fo} \sim T_{ch}$
3) Multi-strang hadron show strong v_2

Partonic Collectivity at RHIC

1) Copiously produced hadrons freeze-out:
T_{fo} = 100 MeV, $\square_T$ = 0.6 (c) > $\square_T$(SPS)

2)* Multi-strange hadrons freeze-out:
T_{fo} = 160-170 MeV (~ T_{ch}), $\square_T$ = 0.4 (c)

3)** Multi-strange v_2:
Multi-strange hadrons □ and □ flow!

4)*** Constituent Quark scaling:
Seems to work for v_2 and R_{AA} (R_{CP})

Partonic (*u,d,s*) collectivity at RHIC!

Summary & Outlook

(1) Charged multiplicity - high initial density

(2) Parton energy loss - ***QCD*** at work

(3) Collectivity - pressure gradient ∂P_{QCD}

⇨ **Deconfinement and Partonic collectivity**

Open issues - partonic (***u,d,s***) thermalization

- heavy flavor v_2 and spectra
- di-lepton and thermal photon spectra

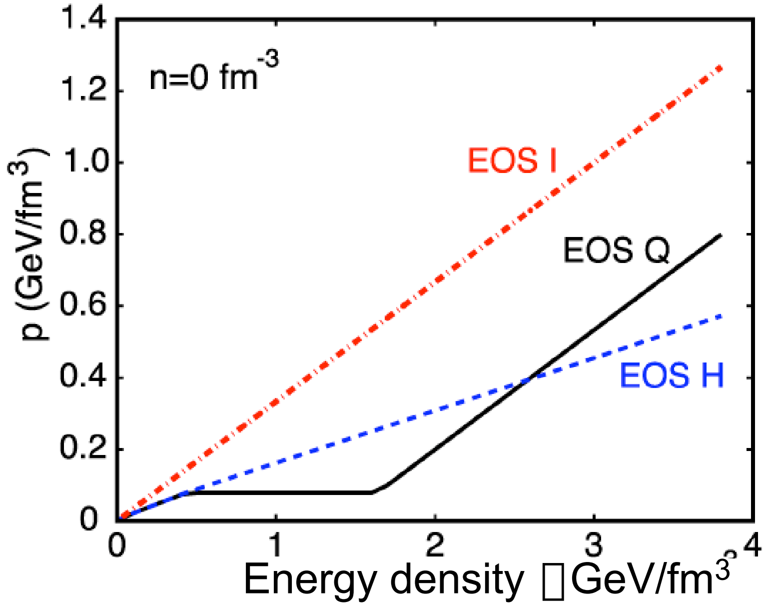
Equation of State

//Talk/2004/06INPC04/NXu_INPC04//

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \qquad j^\mu(x) = n(x)u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)]u^\mu u^\nu - g^{\mu\nu} p(x)$$

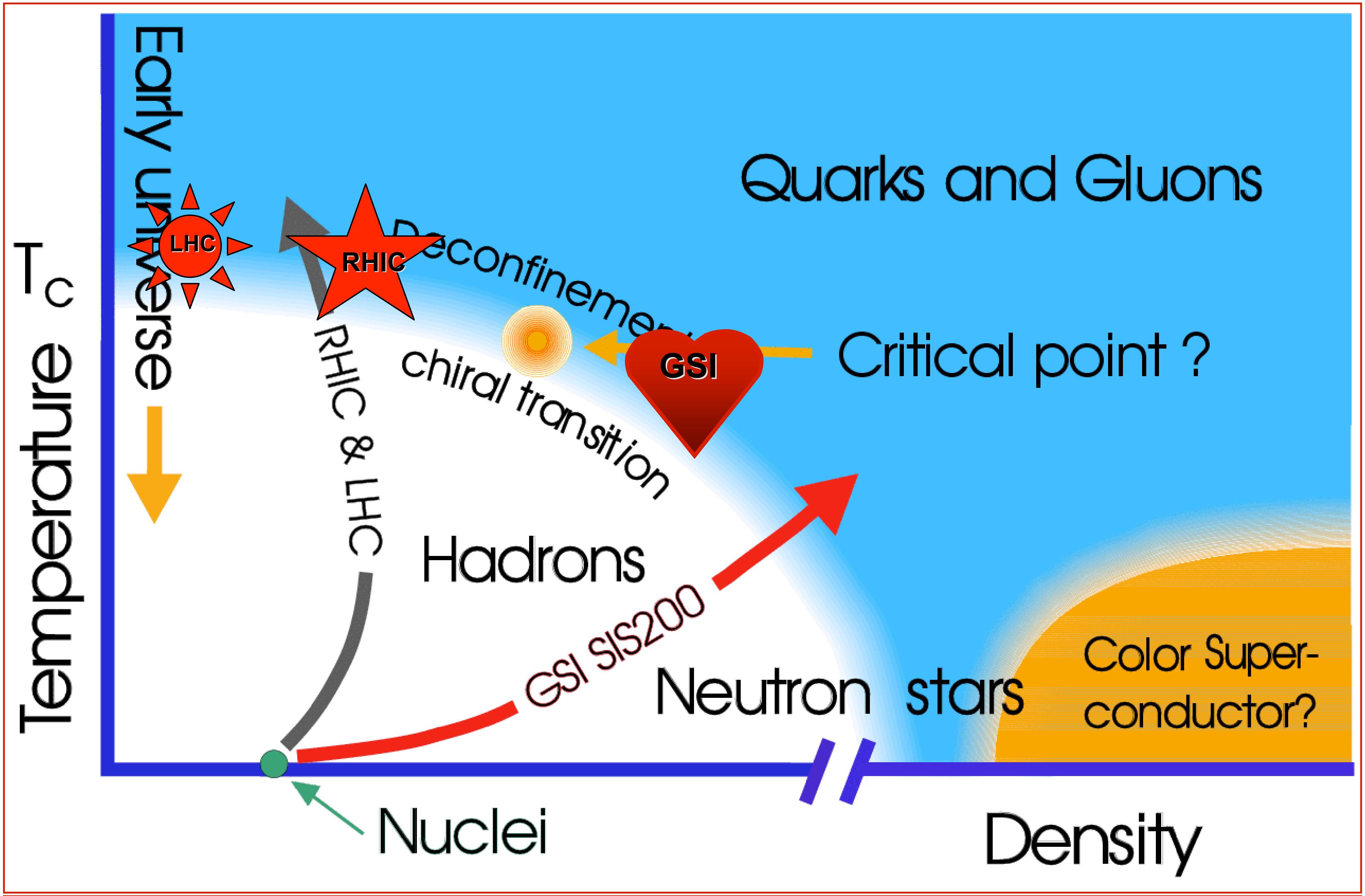


With given degrees of freedom, the EOS - the system response to the changes of the thermal condition - is fixed by its ***p*** and ***T*** or ***ε***

Equation of state:

- **EOS I** : relativistic ideal gas: $p = \varepsilon/3$
- **EOS H**: resonance gas: $p \sim \varepsilon/6$
- **EOS Q**: Maxwell construction:
  T_{crit}= 165 MeV, $B^{1/4}$ = 0.23 GeV
  ε_{lat}=1.15 GeV/fm^3

P. Kolb et al., Phys. Rev. ***C62****, 054909 (2000).*


Quarks and Gluons
Early universe
LHC
RHIC
Deconfinement
Critical point ?
GSI
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Color Super-conductor?
Temperature
T_C
Nuclei
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