Some Highlights from the STAR Experimental Program at RHIC

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The RHIC Accelerator Facility

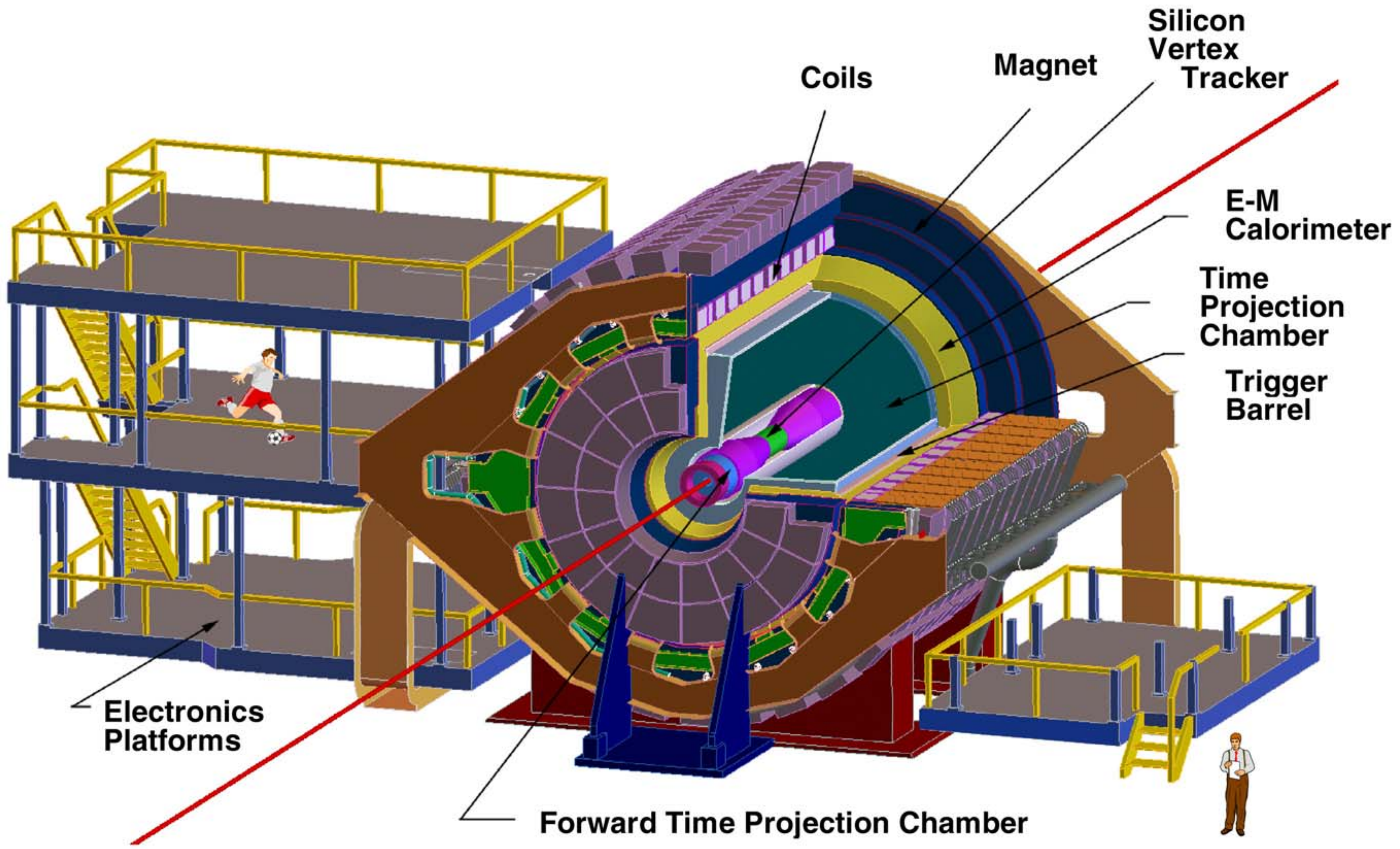
RHIC

- Two independent accelerator rings
- 3.83 km in circumference
- Accelerates everything, from p to Au

	$\sqrt{s}$	L
p-p	500	10^{32}
Au-Au	200	10^{26}
1	GeV	$cm^{-2}\ s^{-1}$

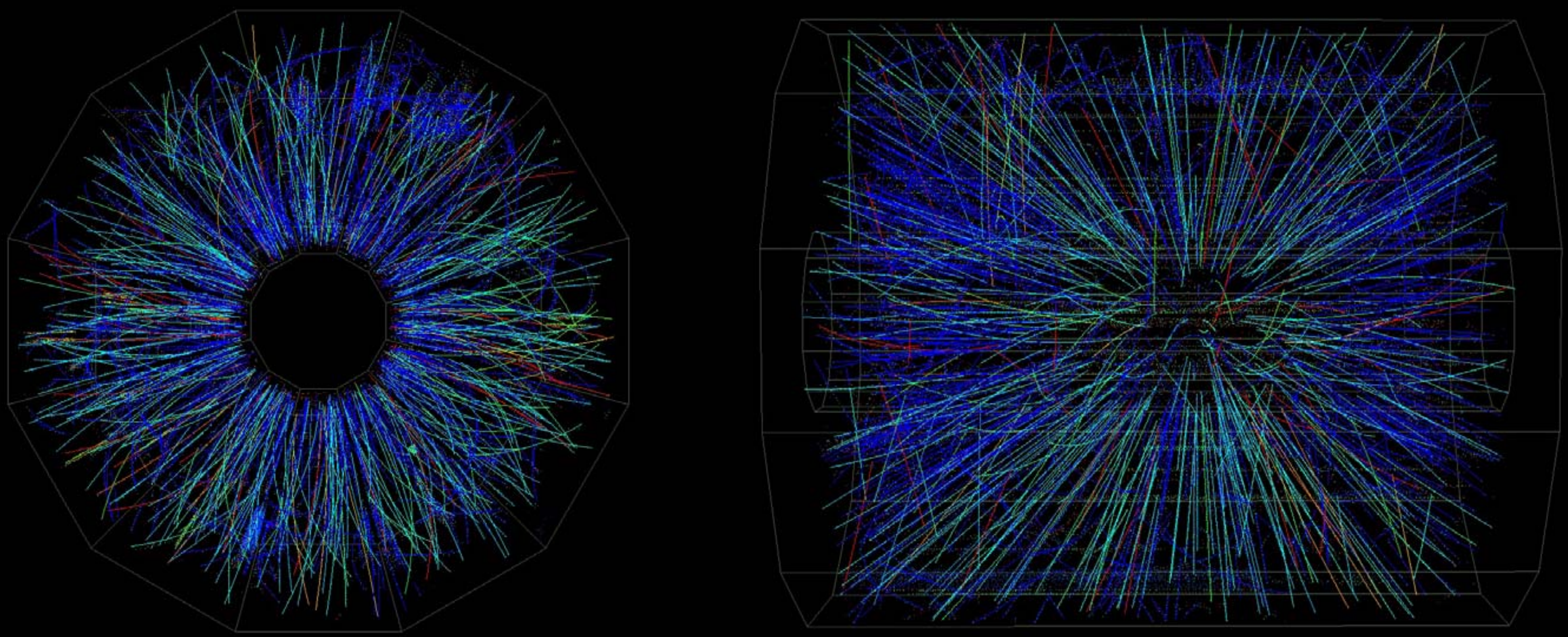
- Polarized protons
- STAR is the *Hadronic Signals* experiment
- At its heart is a large **T**ime **P**rojection **C**hamber

The STAR Detector at RHIC



STAR uses the world's largest Time Projection Chamber

Au on Au Event at CM Energy   130 GeV*A



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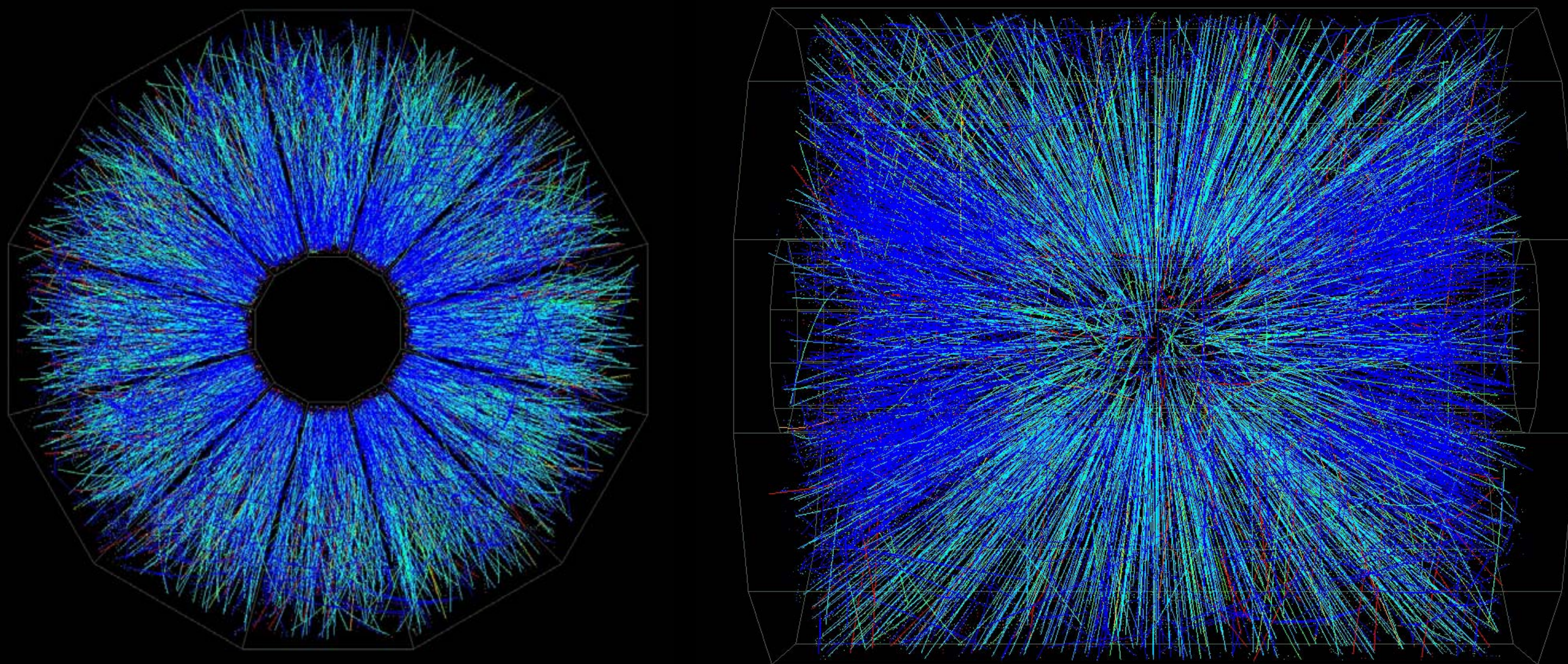
Data Taken June 25, 2000

Au on Au Event at CM Energy   130 GeV*A



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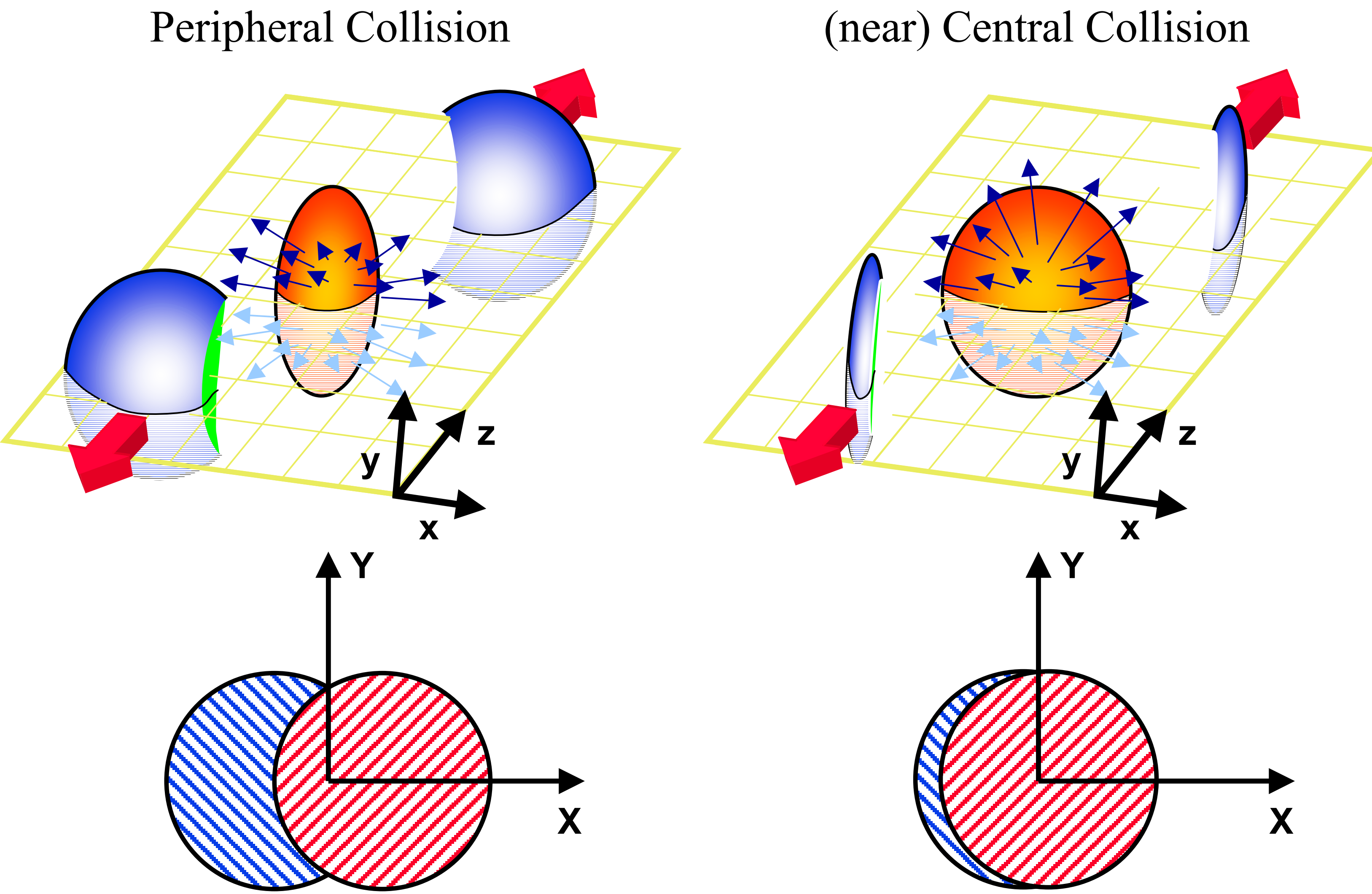
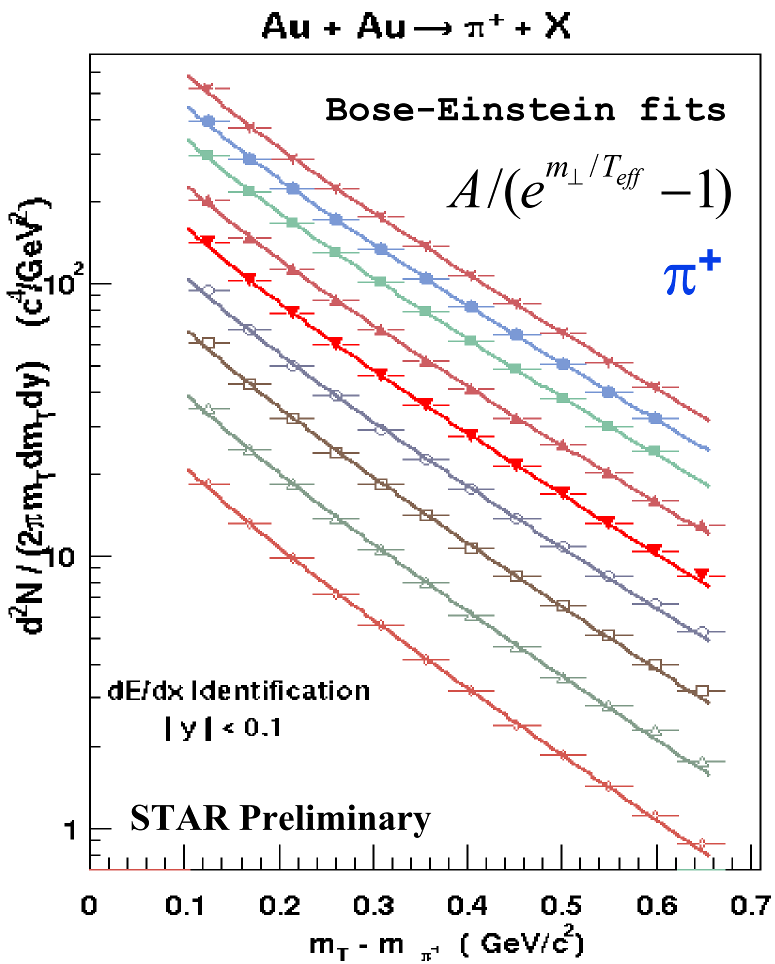
Pictures from Level 3 online display.   Data Taken June 25, 2000

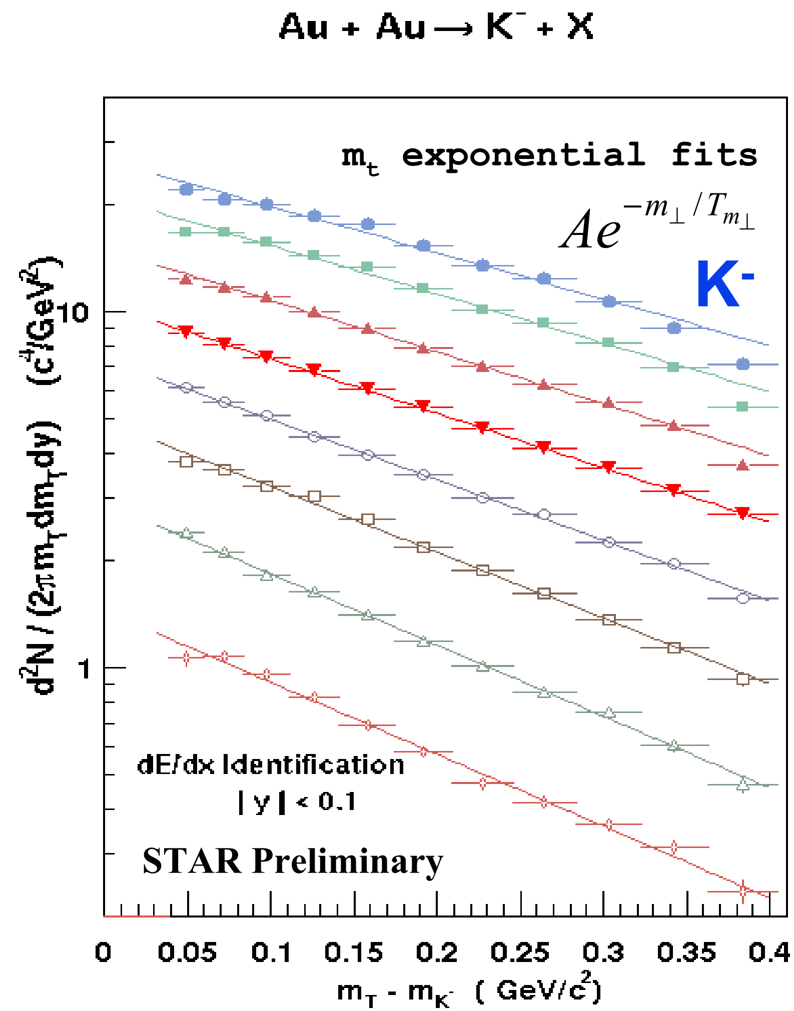
Spectra Measured .vs. Centrality (impact parameter)



central collision ⇒ high multiplicity in CTB & low multiplicity in Zcal

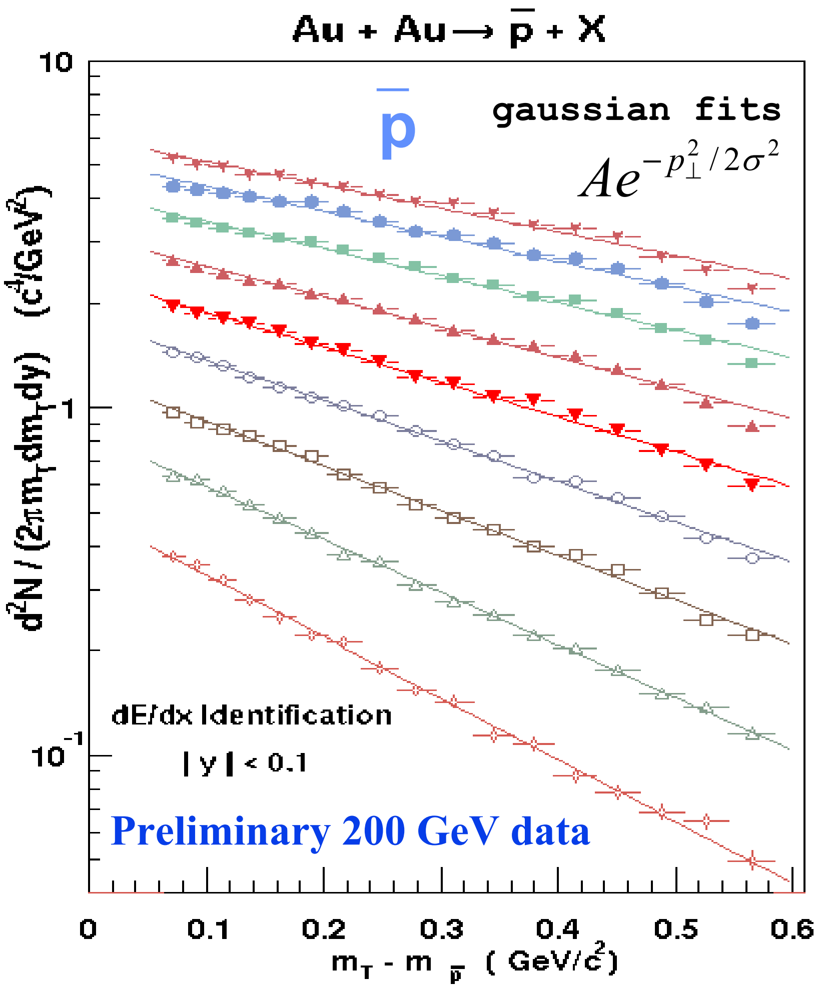
What's New? Identified Particle Spectra at 200 GeV

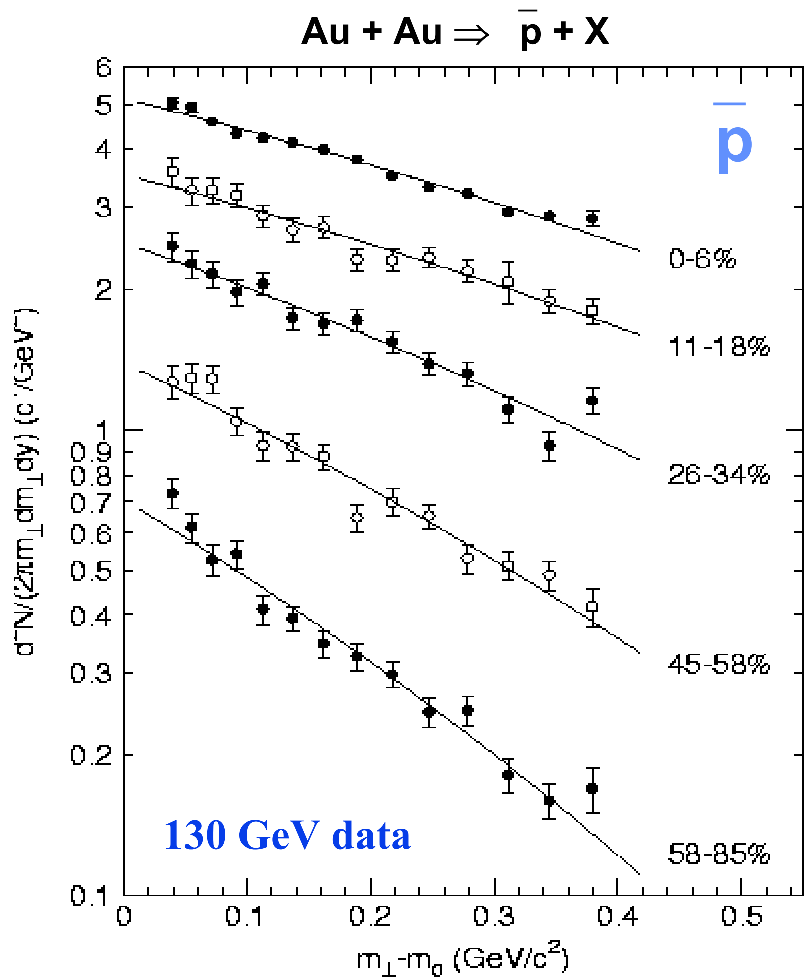




π^+, π^-, K^+, K^- spectra versus centrality
(130 GeV/N data in *nucl-ex/0206008*)

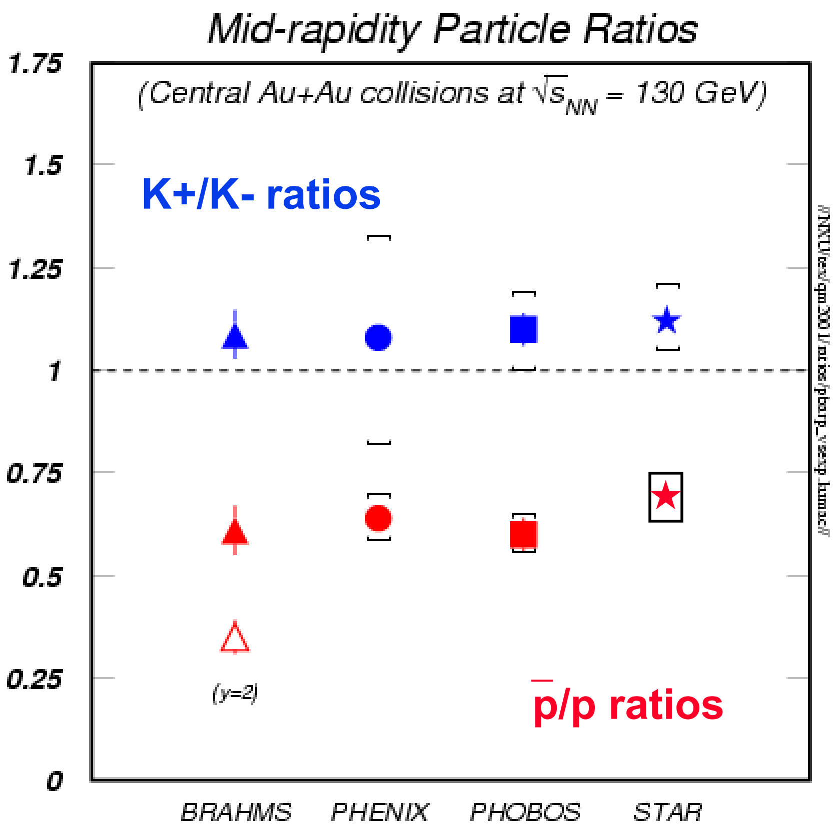
Anti-Proton Spectra at 200 & 130 GeV / N

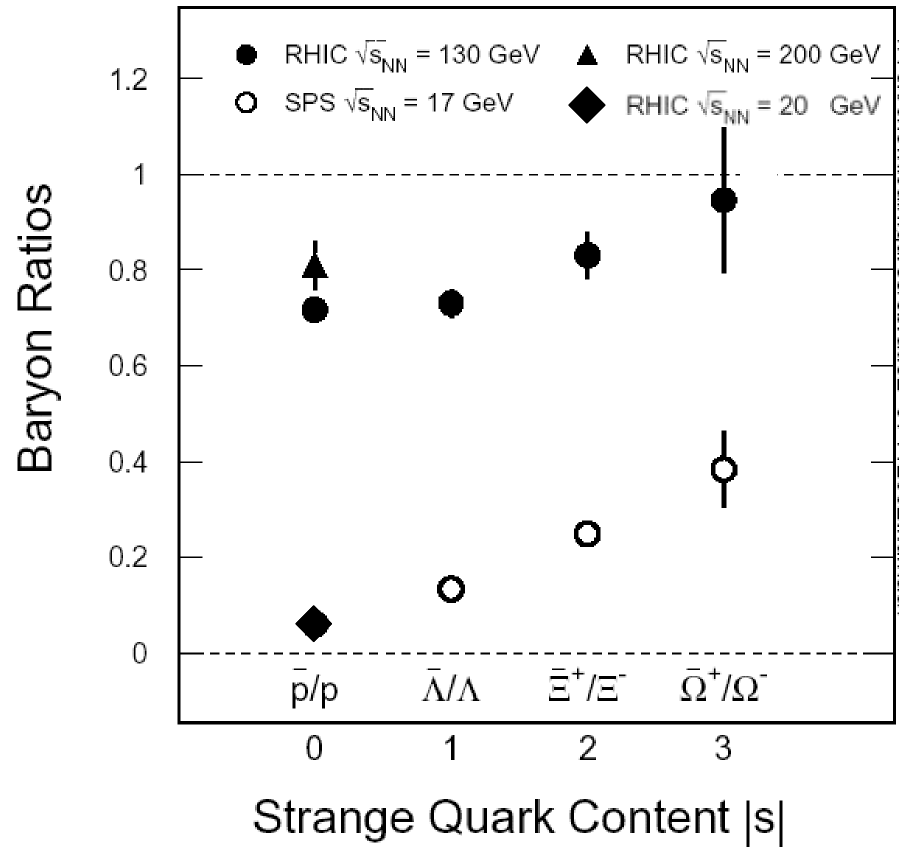




p and p̄ spectra versus centrality
[130 GeV data in PRL 87 (2002)]

Anti-Particle to Particle Ratios



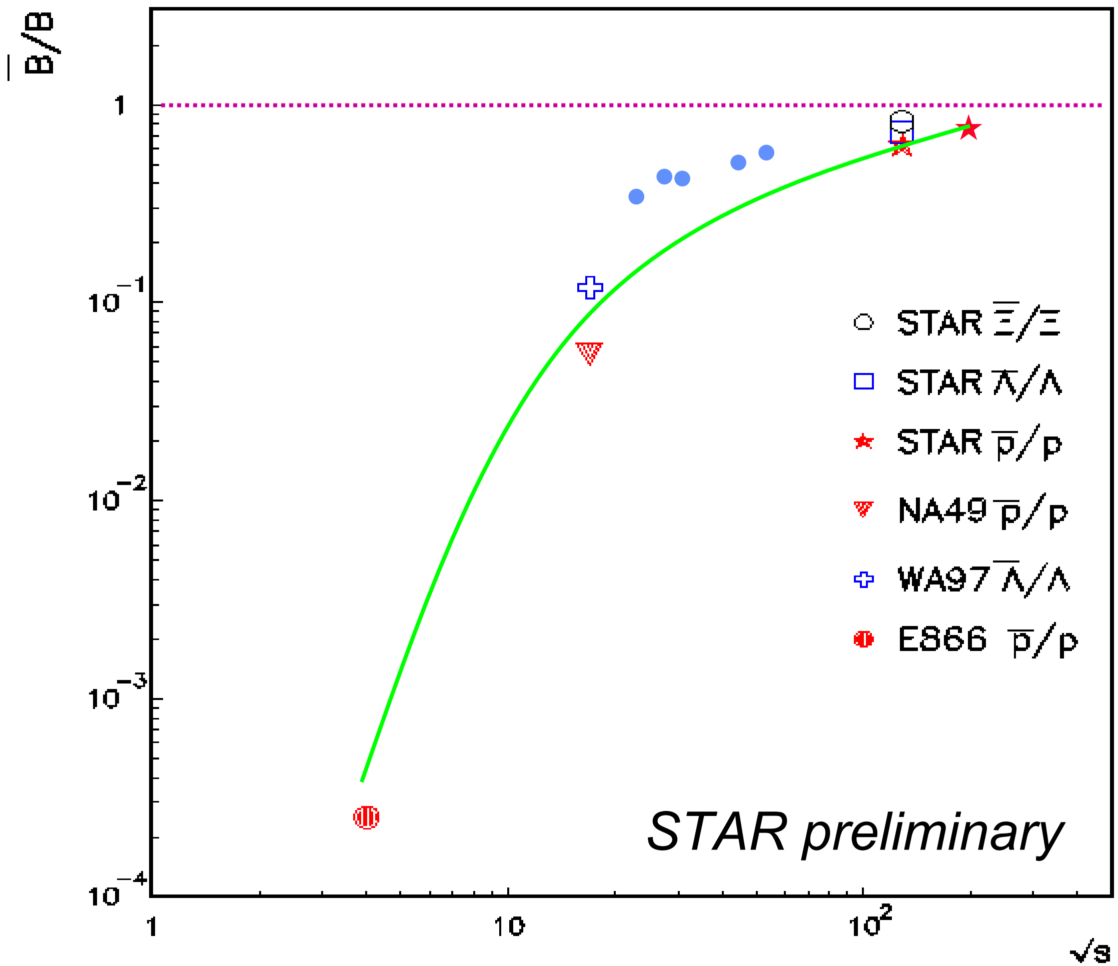


Excellent agreement between experiments at y = 0, √s = 130

STAR results on the $\bar{p}/p$ ratio

- $\bar{p}/p$ = 0.11 ± 0.01 @ 20 GeV
- $\bar{p}/p$ = 0.71 ± 0.05 @ 130 GeV
  - Previously reported as 0.60 ± 0.06
- $\bar{p}/p$ = 0.80 ± 0.05 @ 200 GeV

Anti-Baryon/Baryon Ratios versus $\sqrt{s}_{NN}$



In HI collisions at RHIC, more baryons are pair produced than are brought in by the initial state

In the early universe

- **$\bar{p}$ / p ratio = 0.999999**

At RHIC, pair-production increases with √s

Mid-rapidity region is not yet yet baryon-free!

$$\frac{Y_{pbar}}{Y_p} = \frac{Y_{pair}}{Y_{pair} + Y_{Trans}} \approx 0.8$$

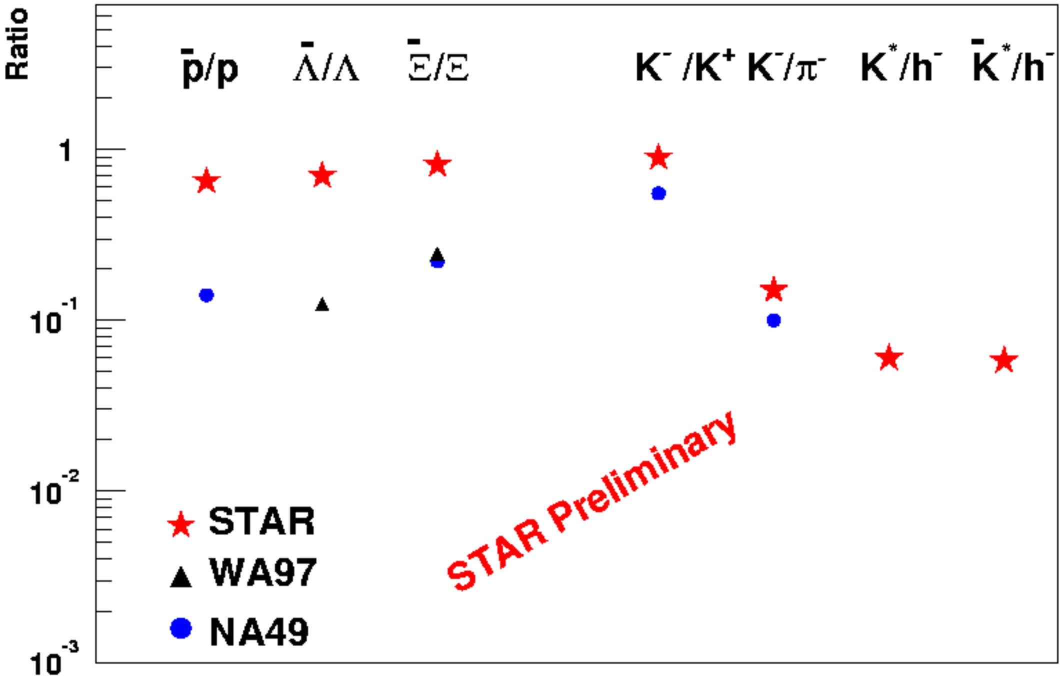
Pair production is larger than baryon transport

$$\frac{Y_{pair}}{Y_{Tr}} \approx 4$$

80% of protons from pair production

- **20% from initial baryon number transported over 5 units of rapidity**

Particle Ratios at RHIC



$\bar{p}/p$ = 0.71 ± 0.02(stat) ± 0.05 (sys)
= 0.60 ± 0.04(stat) ± 0.06 (sys)
= 0.64 ± 0.01(stat) ± 0.07 (sys)
= 0.64 ± 0.04(stat) ± 0.06 (sys)

$\bar{\Lambda}/\Lambda$ = 0.73 ± 0.03(stat)

Ξ^+/Ξ^- = 0.83 ± 0.03(stat.)±0.05(sys.)

K^-/π^- = 0.15 ± 0.01 (stat) ± 0.02 (sys)

K^+/π^+ = 0.16 ± 0.01 (stat) ± 0.02 (sys)

$\pi+/\pi-$ = 1.00 ± 0.01(stat) ± 0.02 (sys)
= 0.95 ± 0.03(stat) ± 0.05 (sys)

K-/K+ = 0.89 ± 0.008(stat) ± 0.05 (sys)
= 0.91 ± 0.07(stat) ± 0.06 (sys)
= 0.89 ± 0.07(stat) ± 0.05 (sys)

K+/K- = 1.08 ± 0.03(stat) ± 0.22(sys) *min. bias*

K-/ π- = 0.15 ± 0.01 (stat) ± 0.02 (sys)

K+/ π+ = 0.16 ± 0.01 (stat) ± 0.02 (sys)

$\bar{K}^*/K^*$ = 0.92 ± 0.14(stat.)

ϕ/h^- = 0.021 ± 0.001 (stat) ± 0.005 (sys)

Λ/h^- = 0.060 ± 0.001 (stat) ± 0.006 (sys)

$\bar{\Lambda}$ / h^- = 0.043 ± 0.001 (stat) ± 0.004(sys)

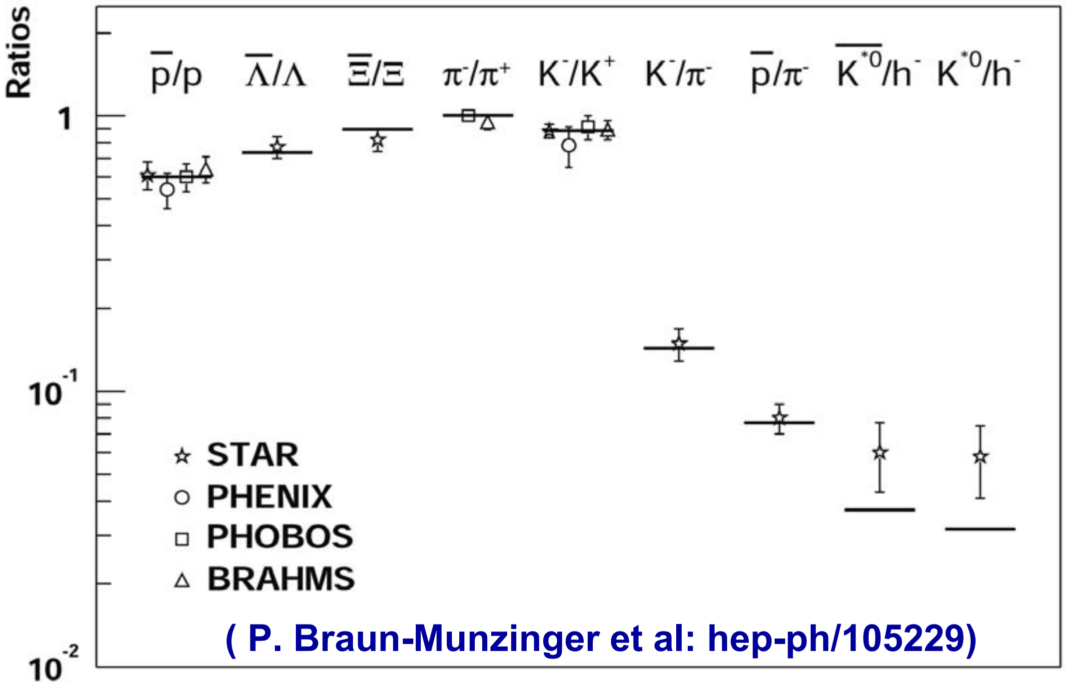
K^0_s / h^- = 0.124 ± 0.001 (stat)

($\bar{K}^*+K^*$) / 2 h^- = 0.032 ± 0.003(stat.) ± 0.008 (sys.)

2 ϕ/($\bar{K}^*+K^*$) = 0.64 ± 0.06 (stat) ± 0.16 (sys)

Good agreement between the 4 experiments STAR, PHOBOS, PHENIX, BRAHMS

Chemical Freeze-out – from a thermal model



Thermal model fits

$T_{ch}(RHIC) = 175 \pm 7$ MeV

$\mu_B(RHIC) = 51 \pm 6$ MeV

$T_{ch}(SPS) = 160 - 170$ MeV

$\mu_B(SPS) \cong 270$ MeV

Compare to QCD on Lattice:

$T_c = 154 \pm 8$ MeV (N_f=3)

$T_c = 173 \pm 8$ MeV (N_f=2)

(ref. Karsch QM01)

Assume:

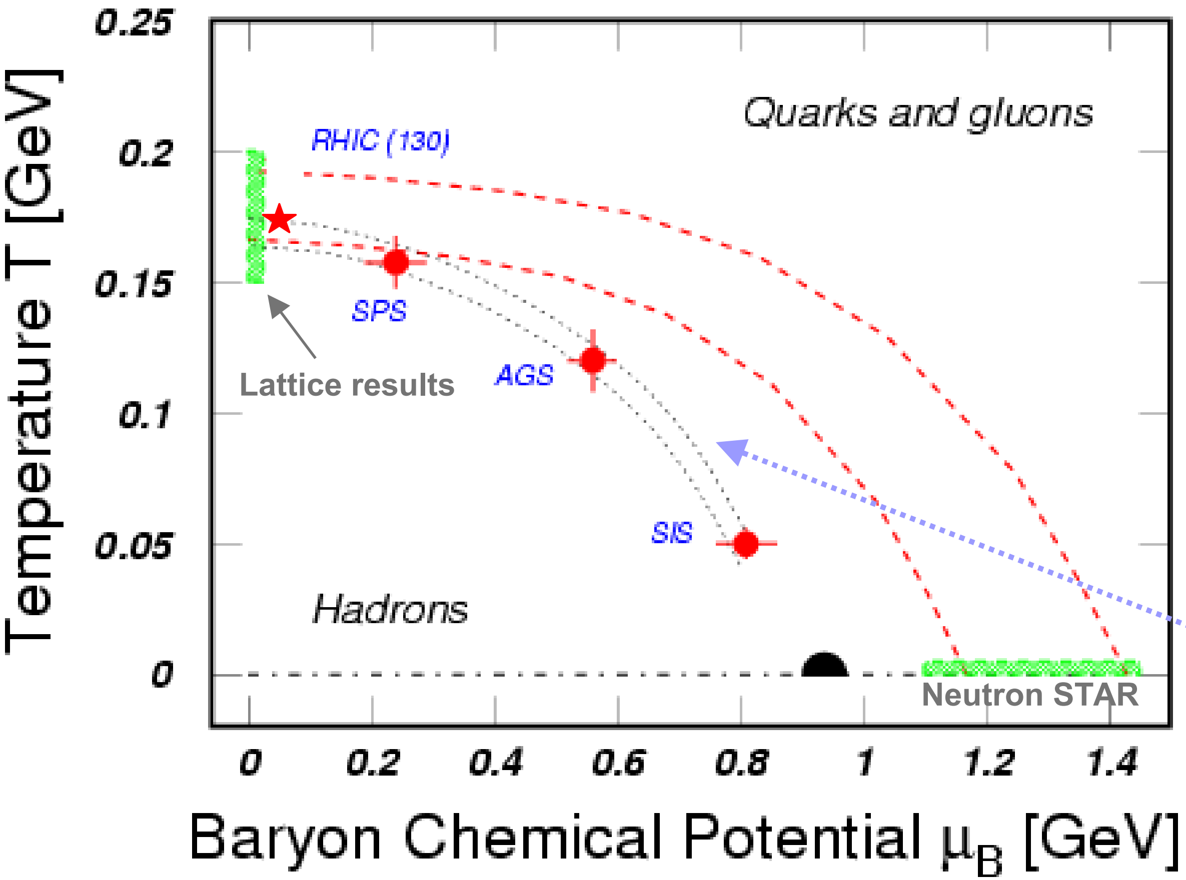
- Thermally and chemically equilibrated fireball at hadro-chemical freeze-out
- Law of mass action is applicable

Recipe:

- Grand canonical ensemble to describe partition function $\Rightarrow$ density of particles of species ρ_i
- Fixed by constraints: Volume V, strangeness chemical potential μ_S, and isospin

input: measured particle ratios output: temperature T and baryo-chemical potential μ_B

Putting STAR on the Phase Diagram

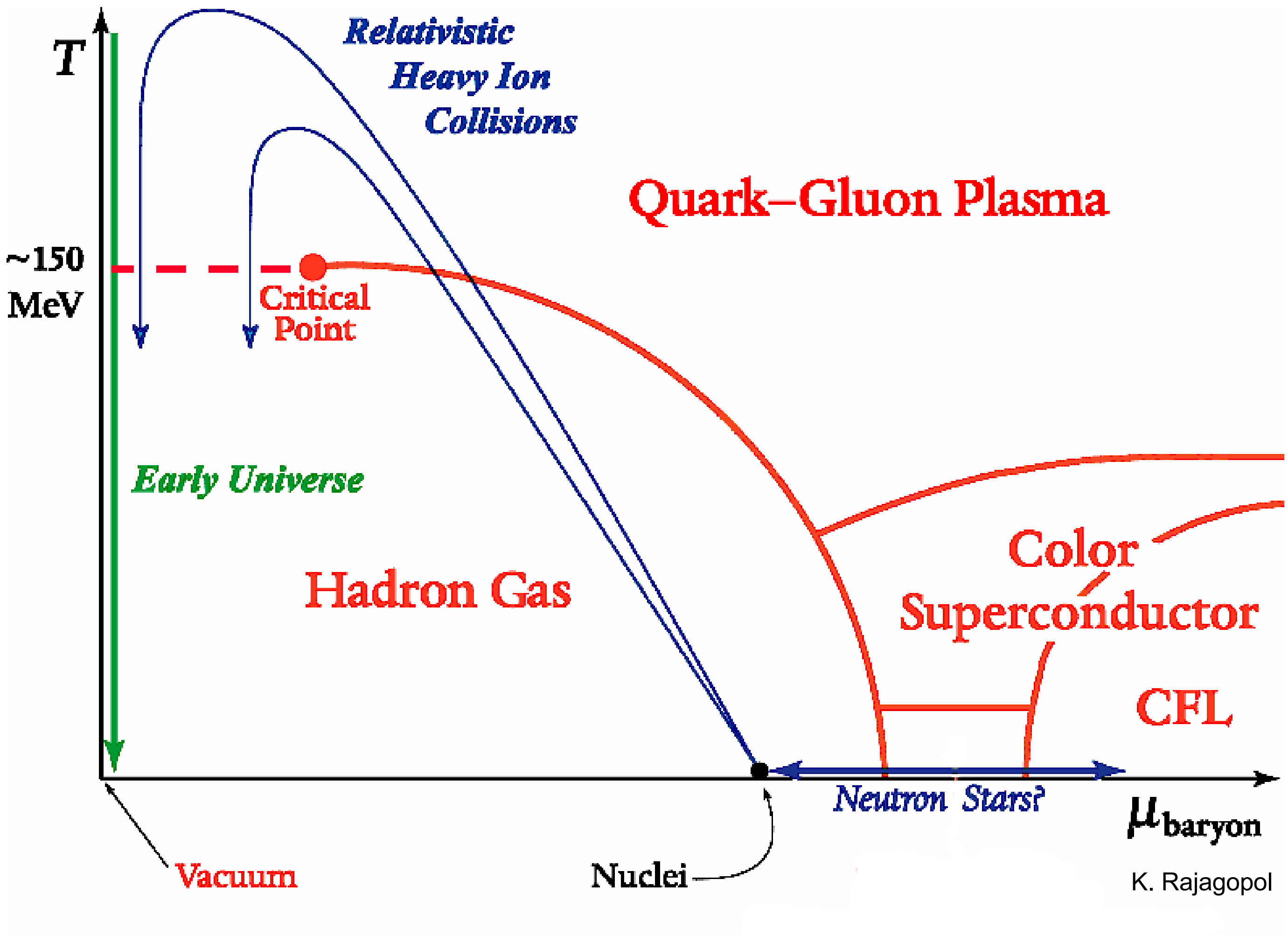


- **Final-state analysis suggests RHIC reaches the phase boundary**
- **Hadron resonance ideal gas** (M. Kaneta and N. Xu, nucl-ex/0104021 & QM02)
  - T_{CH} = 175 ± 10 MeV
  - μ_B = 40 ± 10 MeV
- **<E>/N ~ 1 GeV**

(J. Cleymans and K. Redlich, Phys.Rev.C, 60, 054908, 1999)

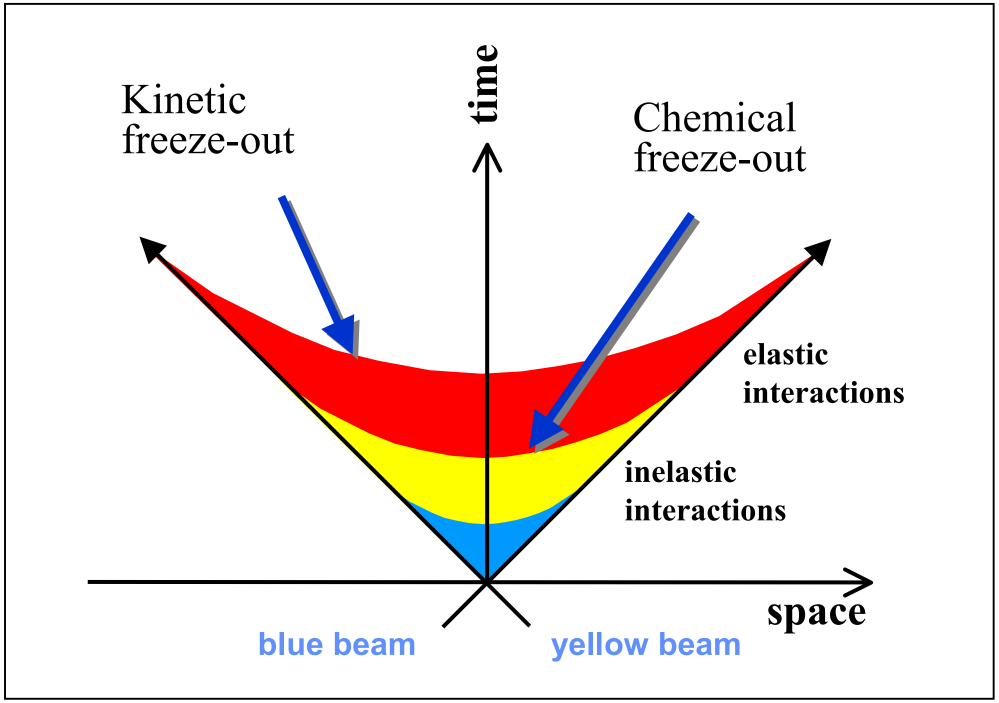
We know where we are on the phase diagram but now we want to know what other features are on the diagram

The Phase Diagram for Nuclear Matter



The goal is to explore nuclear matter under extreme extreme conditions – $T > m_\pi c^2$ and $\rho > 10 * \rho_0$

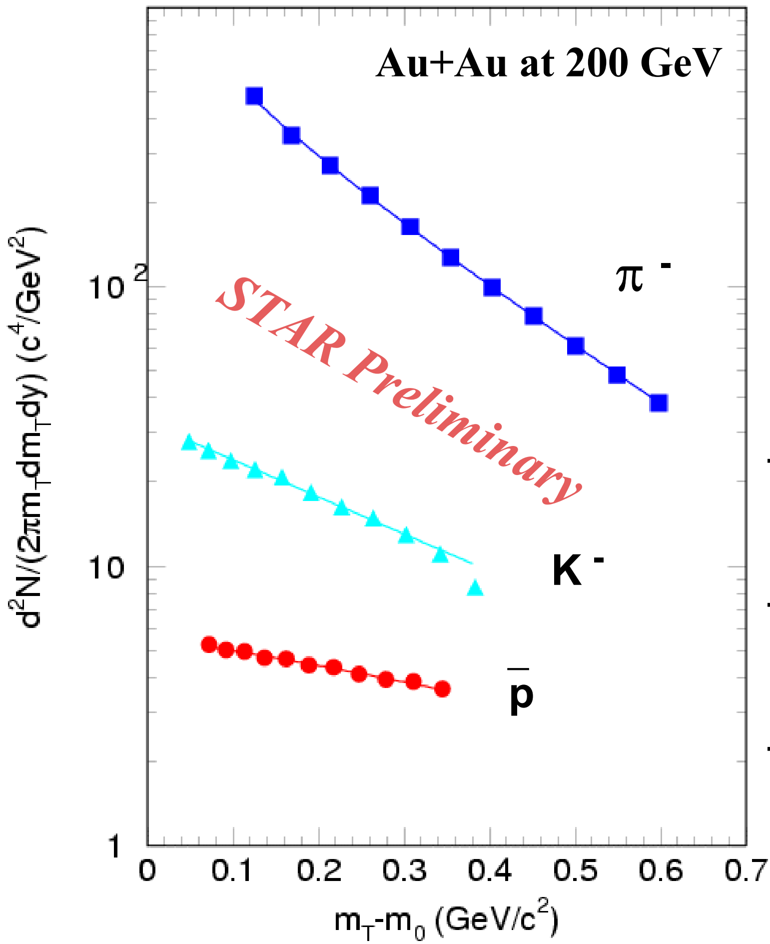
Chemical and Kinetic Freeze-out



- Chemical freeze-out (first)
  - End of inelastic interactions
  - Number of each particle species species is frozen
- Useful data
  - Particle ratios

- Kinetic freeze-out (later)
  - End of elastic interactions
  - Particle momenta are frozen
- Useful data
  - Transverse momentum distributions
  - and Effective temperatures

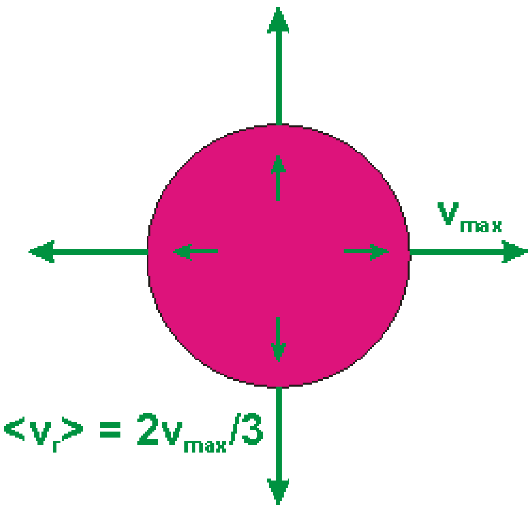
Transverse Flow



T ≈ 215 MeV

T ≈ 310 MeV

T ≈ 575 MeV



The transverse radial expansion of the source (flow) adds kinetic energy to the particle distribution. So the classical expression for E_{Tot}

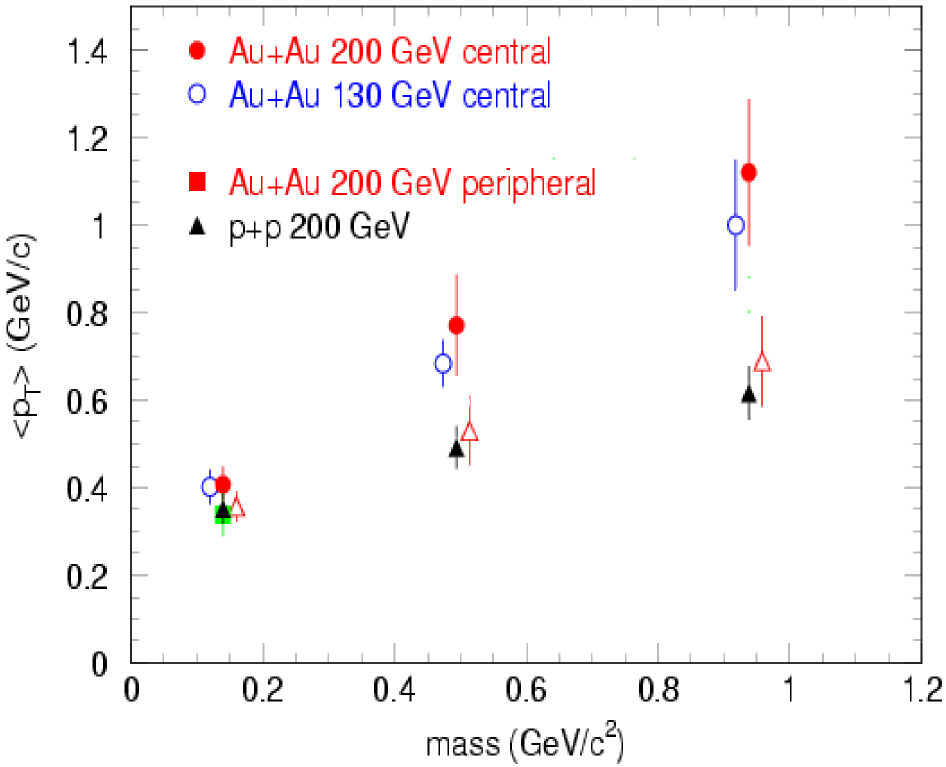
$$\bar{E} = \frac{3}{2}T + \frac{1}{2}mv^2$$

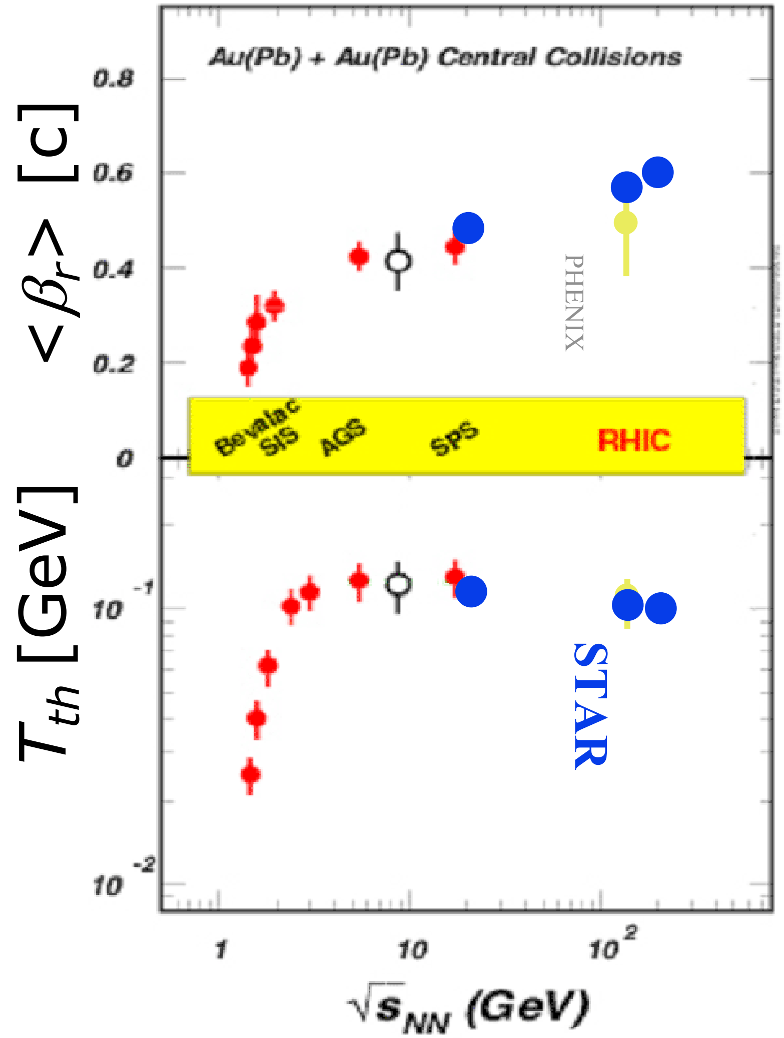
suggests a linear relationship

$$T_{Obs} = T_{KFO} + mass \times \overline{\beta}^{\,2}$$

Slopes decrease with mass. $\langle p_T \rangle$
$\langle p_T \rangle$ and the effective temperature increase with mass.

Kinetic Freezeout from Transverse Flow





$<\beta_r>$ (RHIC) = 0.55 ± 0.1 c

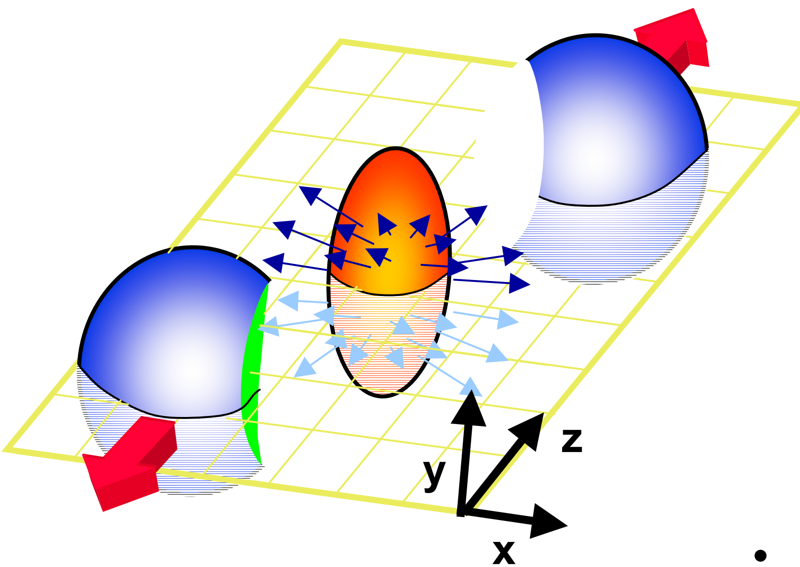
T_{KFO} (RHIC) = 100 ± 10 MeV

Thermal freeze-out determinations are done with the blast-wave model to find $<p_T>$

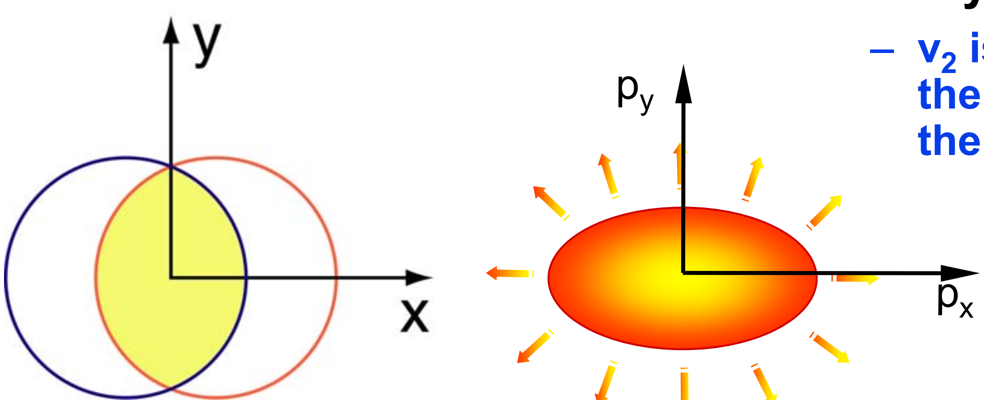
Explosive Transverse Expansion at RHIC ⇒ High Pressure

Anisotropic (Elliptic) Transverse Flow

Peripheral Collisions



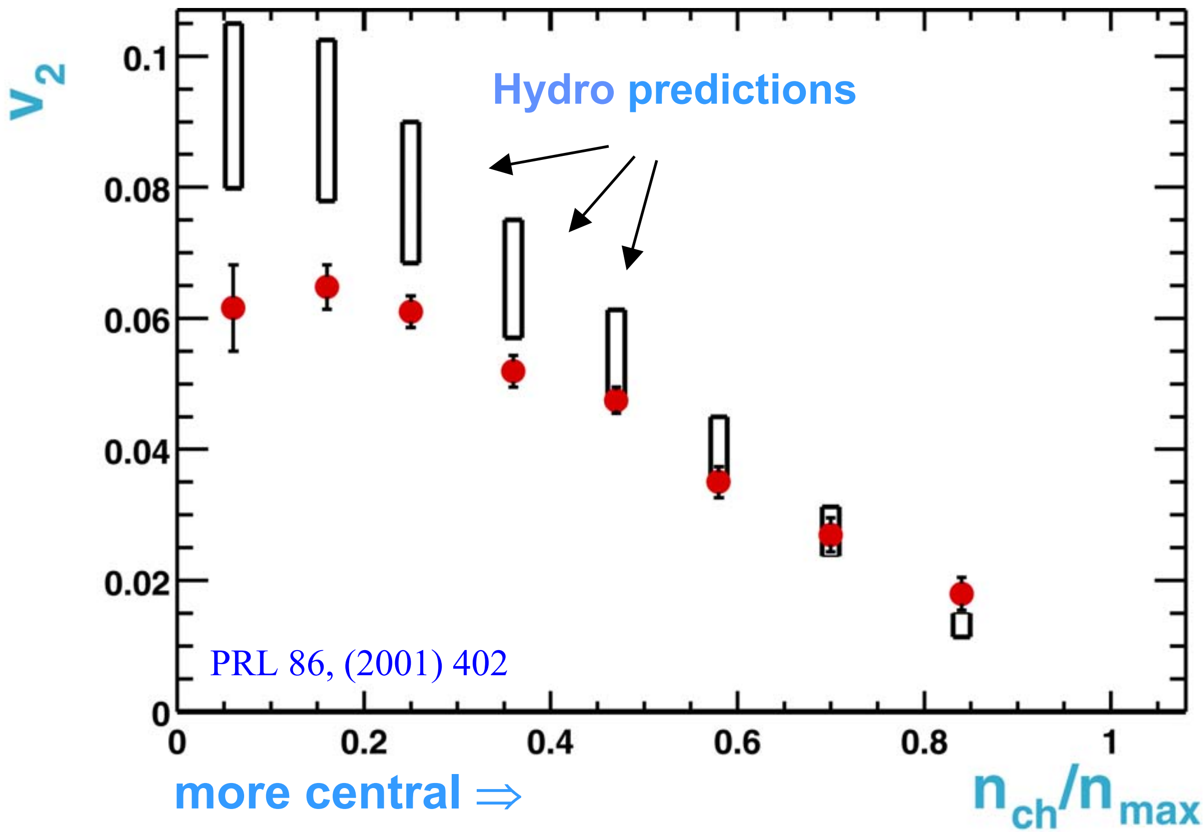
Anisotropic Flow



- **The overlap region in peripheral collisions is is not symmetric in coordinate space**
  - **Almond shaped overlap region**
    - **Easier for particles to emerge in the direction of x-z plane**
    - **Larger area shines to the side**
  - **Spatial anisotropy → Momentum anisotropy**
    - **Interactions among constituents generates a pressure gradient which transforms the initial initial spatial anisotropy into the observed momentum anisotropy**
- **Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane**
  - **v_2 is the 2nd harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane**

$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \operatorname{atan}\frac{p_y}{p_x}$$

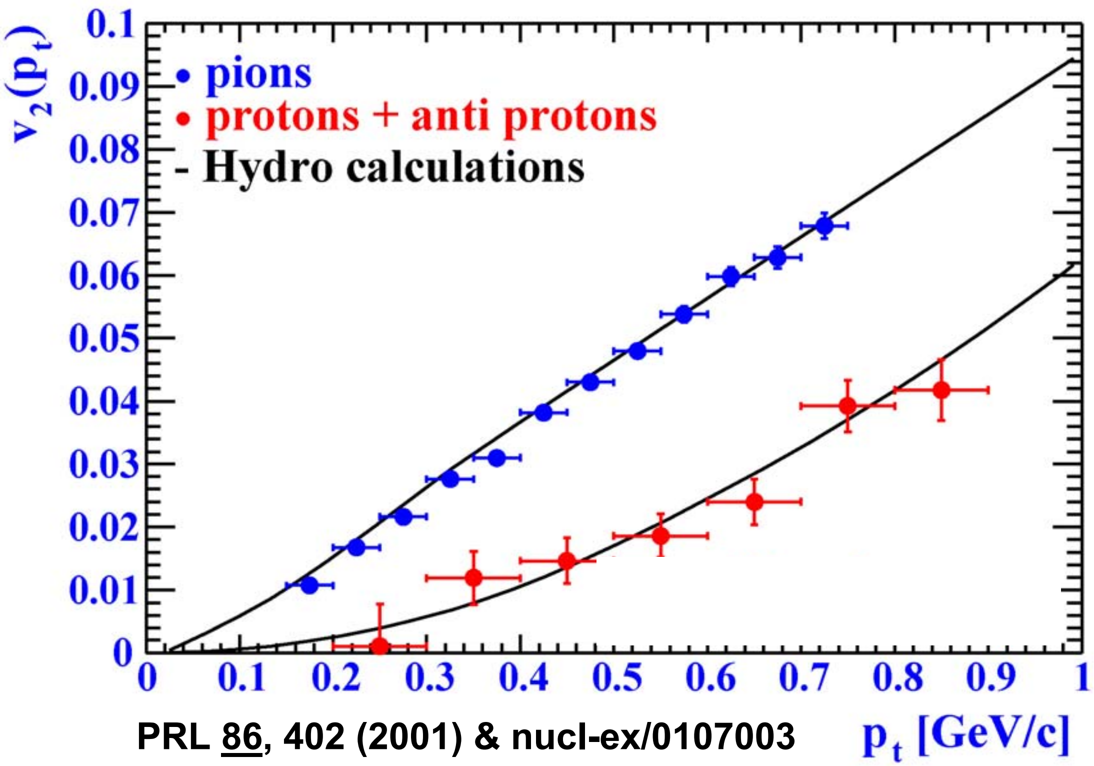
v_2 vs. Centrality



Anisotropic transverse flow is large at RHIC

- v_2 is large
  - 6% in peripheral collisions
  - Smaller for central collisions
- Hydro calculations are in reasonable agreement with the data
  - In contrast to lower collision energies where hydro over-predicts anisotropic flow
- Anisotropic flow is developed by rescattering
  - Data suggests early time history
  - Quenched at later times

v_2 vs. p_T and Particle Mass



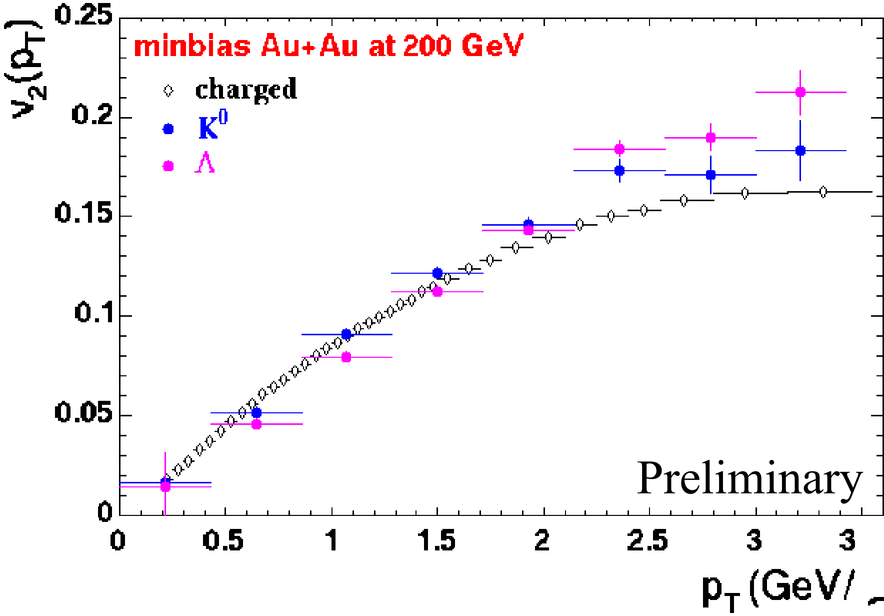
PRL 86, 402 (2001) & nucl-ex/0107003

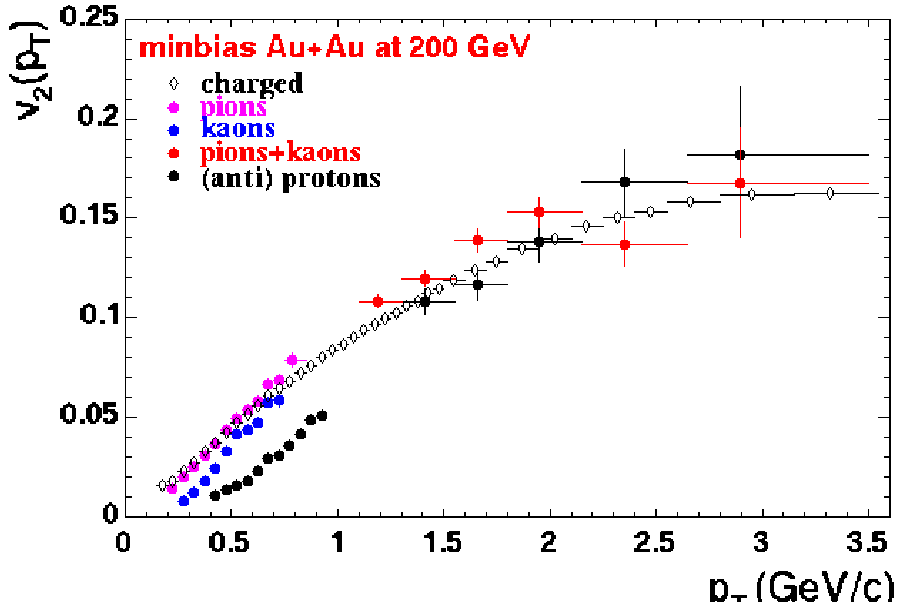
- **The mass dependence is reproduced by hydrodynamic models**
  - **Hydro assumes local thermal equilibrium**
  - **At early times**
  - **Followed by hydrodynamic expansion**

Hydro does a surprisingly good job!

D. Teaney et al., QM2001 Proc.
P. Huovinen et al., nucl-th/0104020

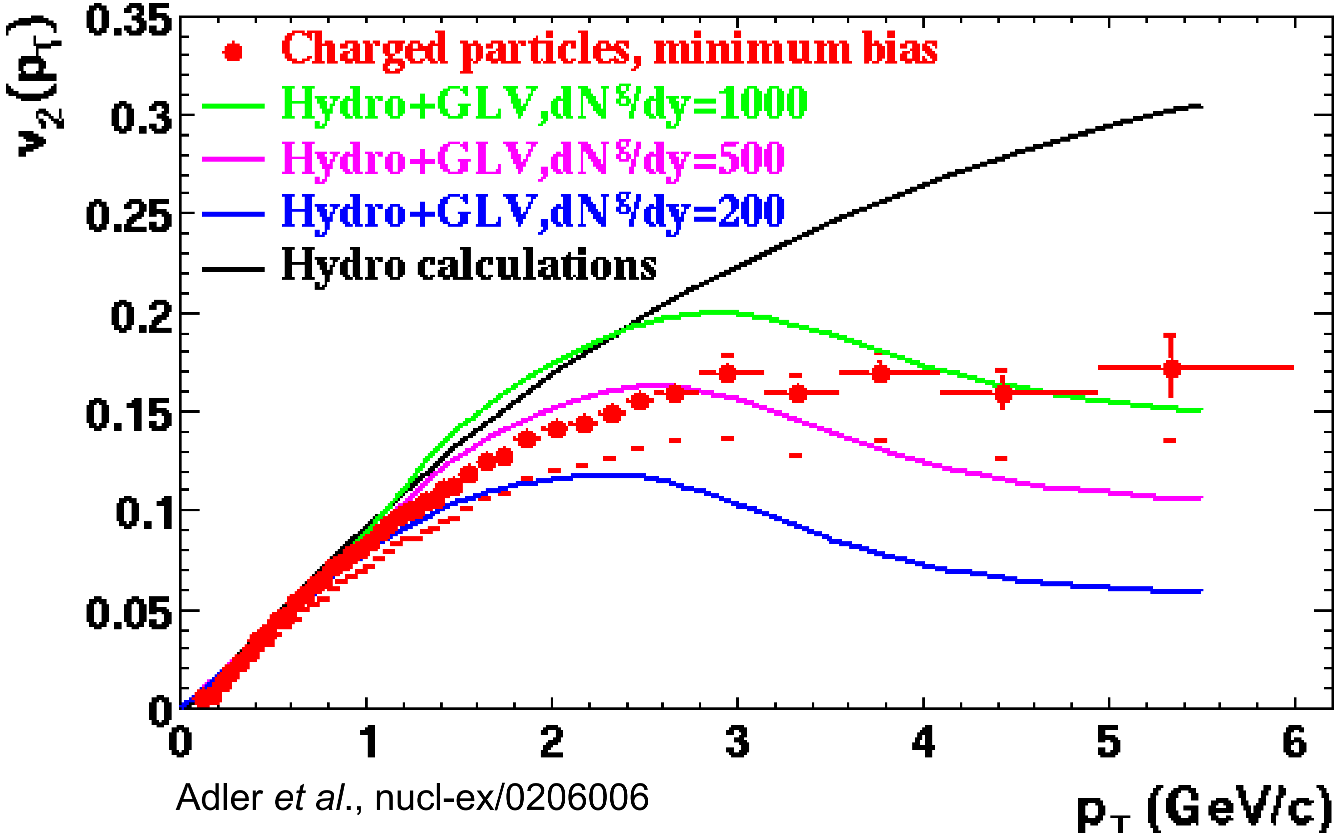
v_2 for π, K, K^0, $\bar{p}$ and Λ





v_2 for High p_t Particles

See also, M. Gyulassy, I. Vitev and X.N. Wang, nucl-th/00012092



Adler *et al.*, nucl-ex/0206006

v_2 is large … but at p_t > 2 GeV/c the data starts to deviate from hydrodynamics

Centrality Dependence of $v_2(p_T)$

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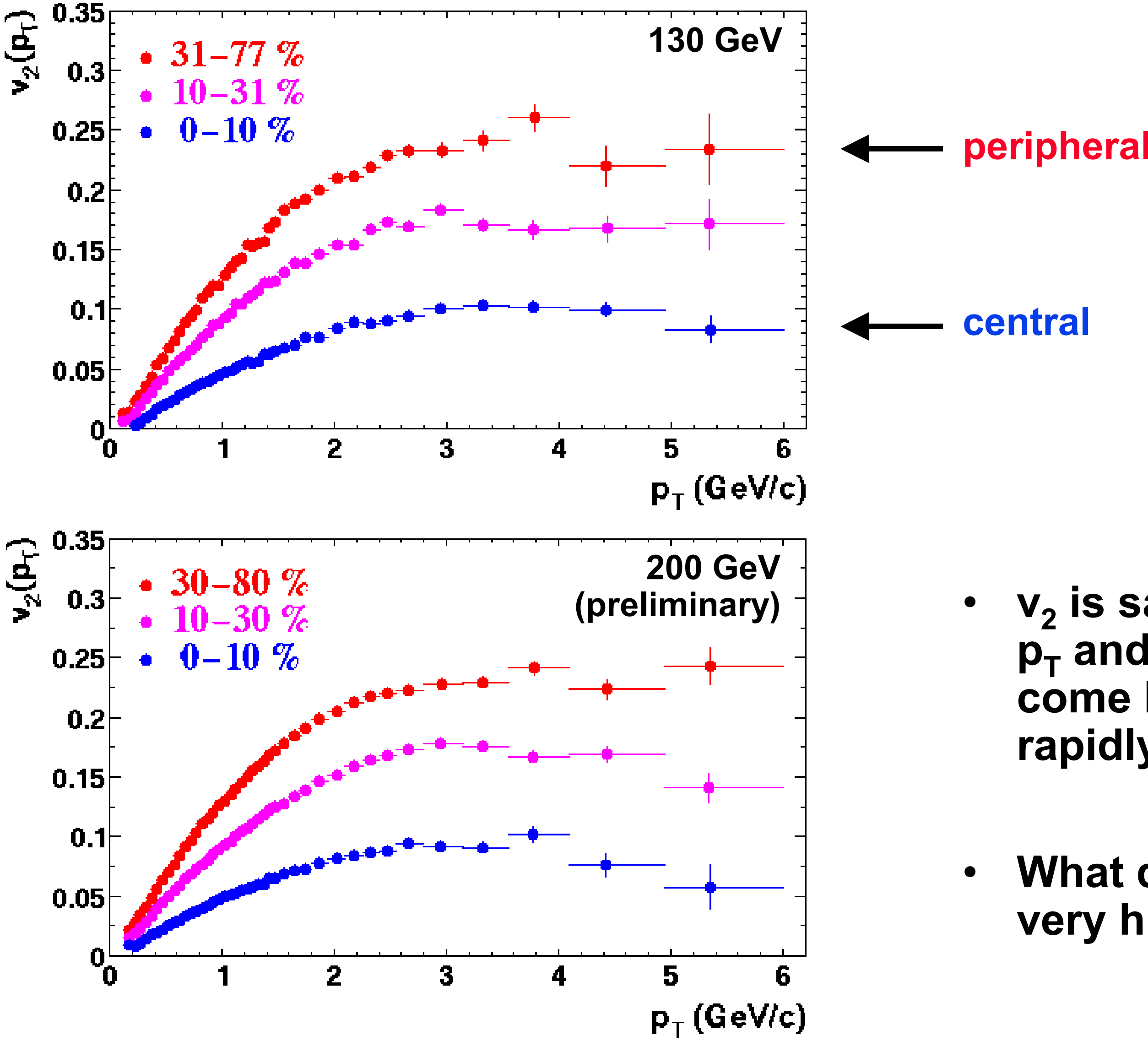
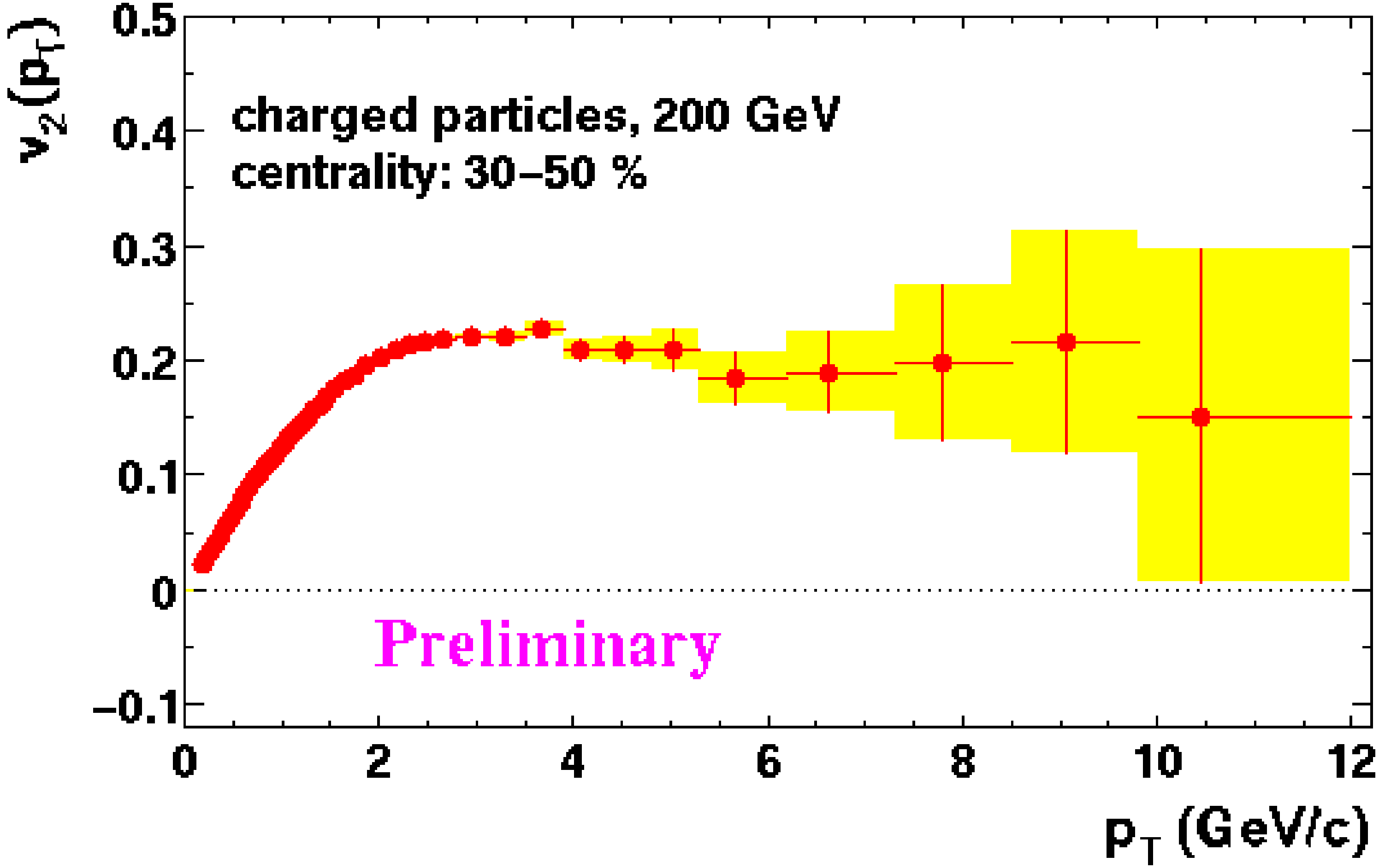


- v_2 is saturated at high p_T and it does not come back down as rapidly as expected

- What does v_2 do at very high p_T ?

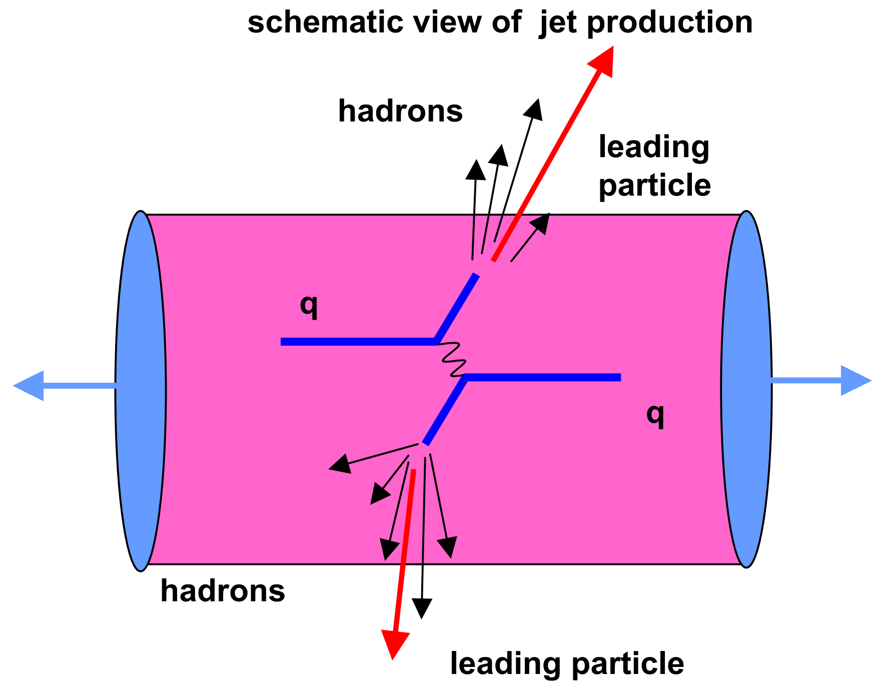
v_2 up to 12 GeV/c



v_2 remains saturated

Hard Probes in Heavy-Ion Collisions

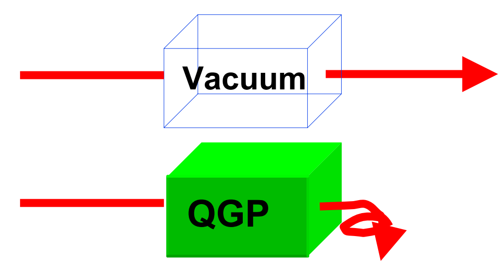
- **New opportunity using Heavy Ions at RHIC → *Hard Parton Scattering***
  - $\sqrt{s_{NN}}$ = 200 GeV at RHIC
  - 17 GeV at CERN SPS



- **Jets and mini-jets**
  - 30-50 % of particle production
  - High p_t leading particles
  - Azimuthal correlations

- **Extend into perturbative regime**
  - Calculations reliable (?)

- **Scattered partons propagate through matter & radiate energy (dE/dx ~ x) in colored medium**
  - Interaction of parton with partonic matter
  - Suppression of high p_t particles "jet quenching"
  - Suppression of angular correlations



Scaling pp to AA … including the Cronin Effect Effect

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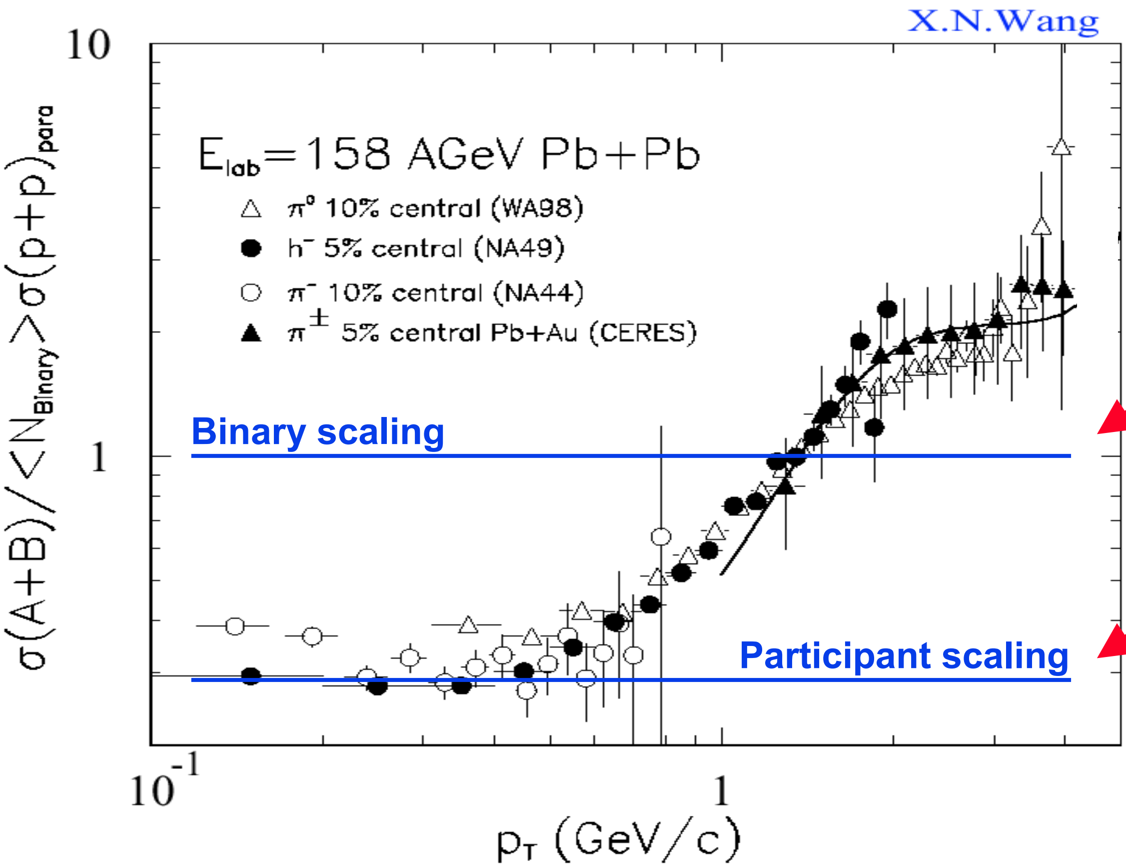
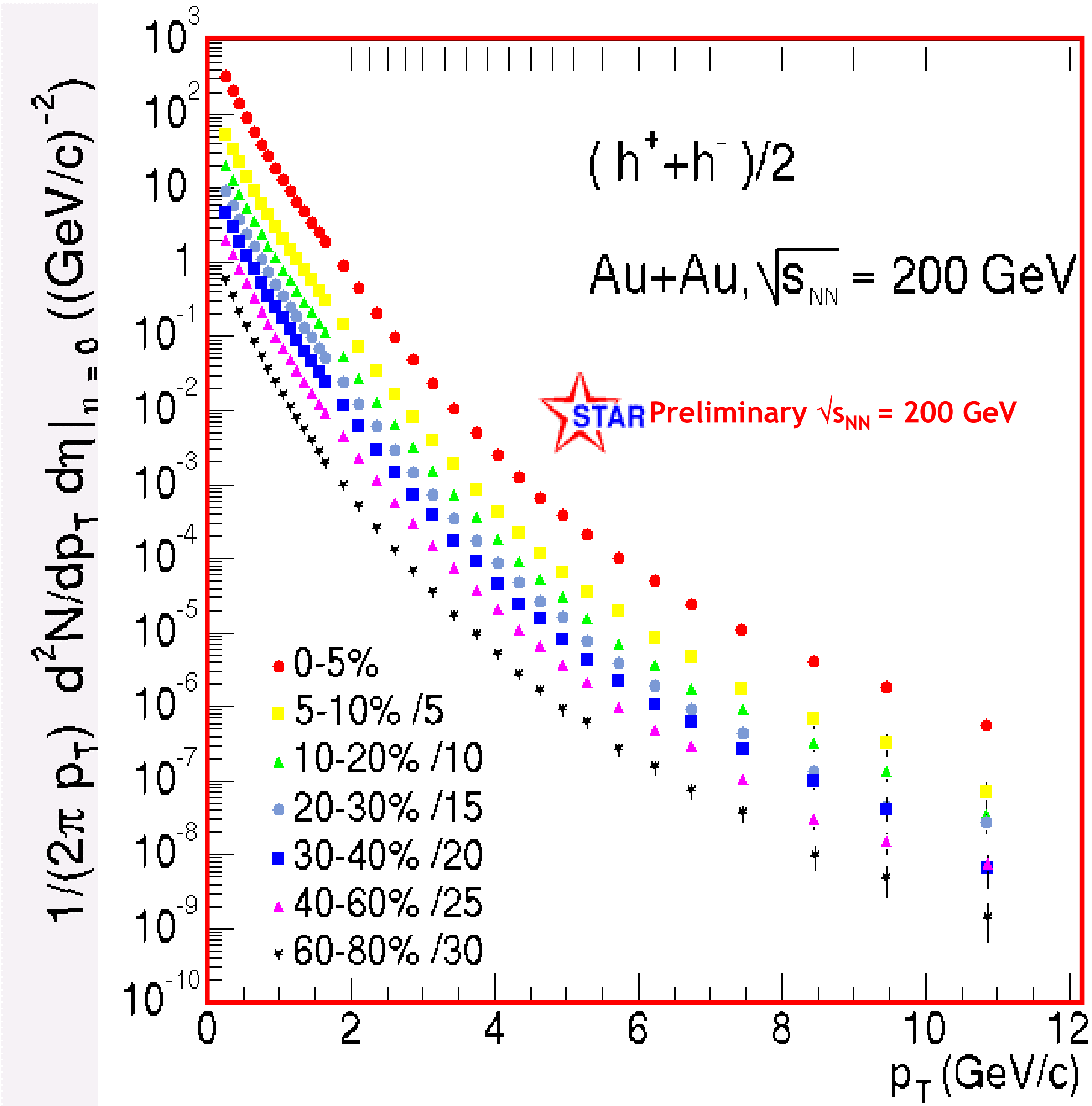


$$\frac{\text{Yield}_{\text{central}} / \langle N_{\text{binary}} \rangle_{\text{central}}}{\text{Yield}_{\text{pp}}} > 1$$

At SPS energies:

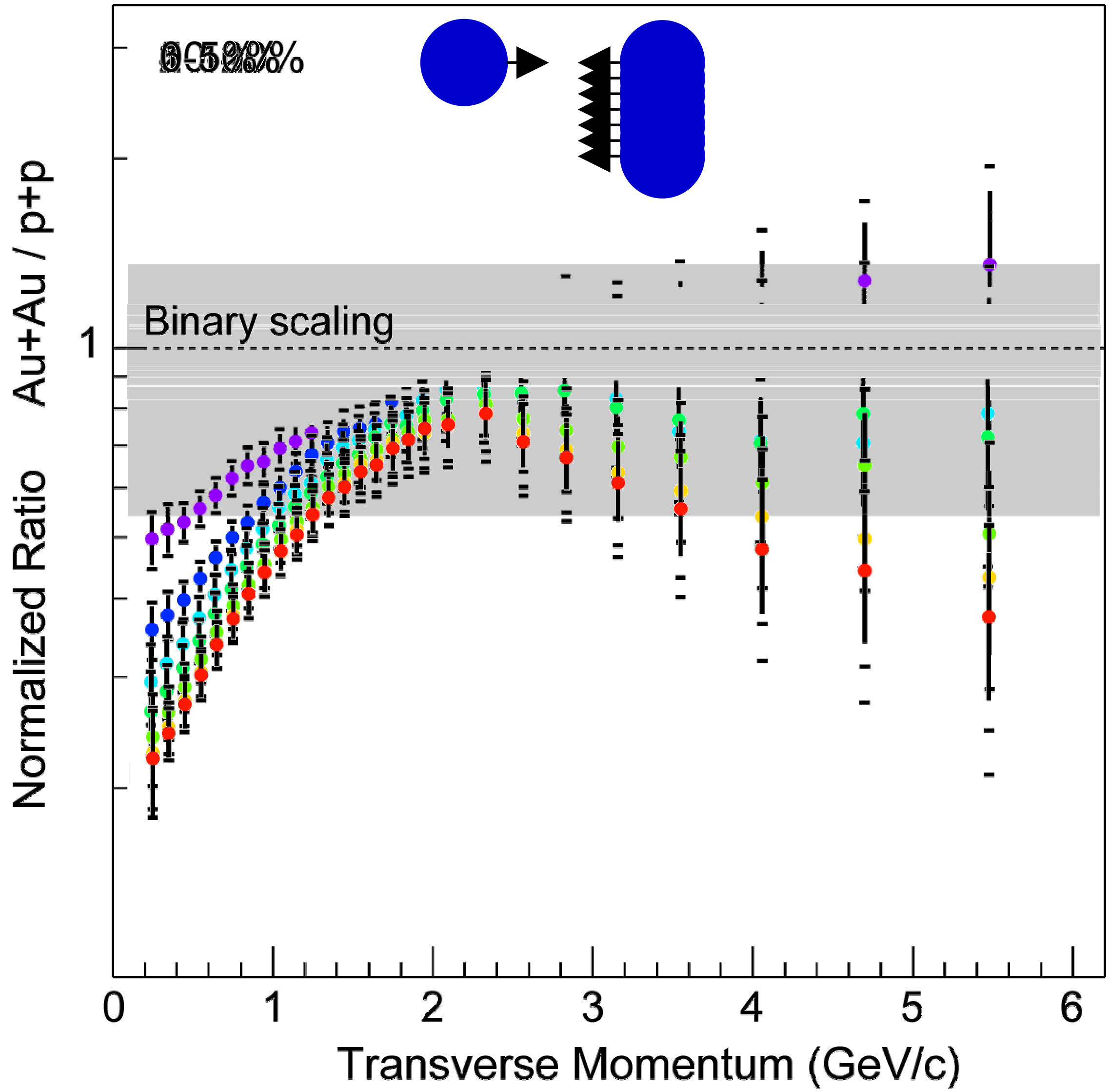
- High p_t spectra evolves systematically from pp → pA → AA
- Hard scattering processes scale with the number of binary collisions
- Soft scattering processes scale with the number of participants
- The ratio exhibits "Cronin effect" behavior at the SPS
- No need to invoke QCD energy loss

Inclusive p_T Distribution of Hadrons at 200 GeV



- **Scale Au-Au data by the number of binary collisions**
- **Compare to UA1 $p\bar{p}$ reference data measured at 200 GeV**

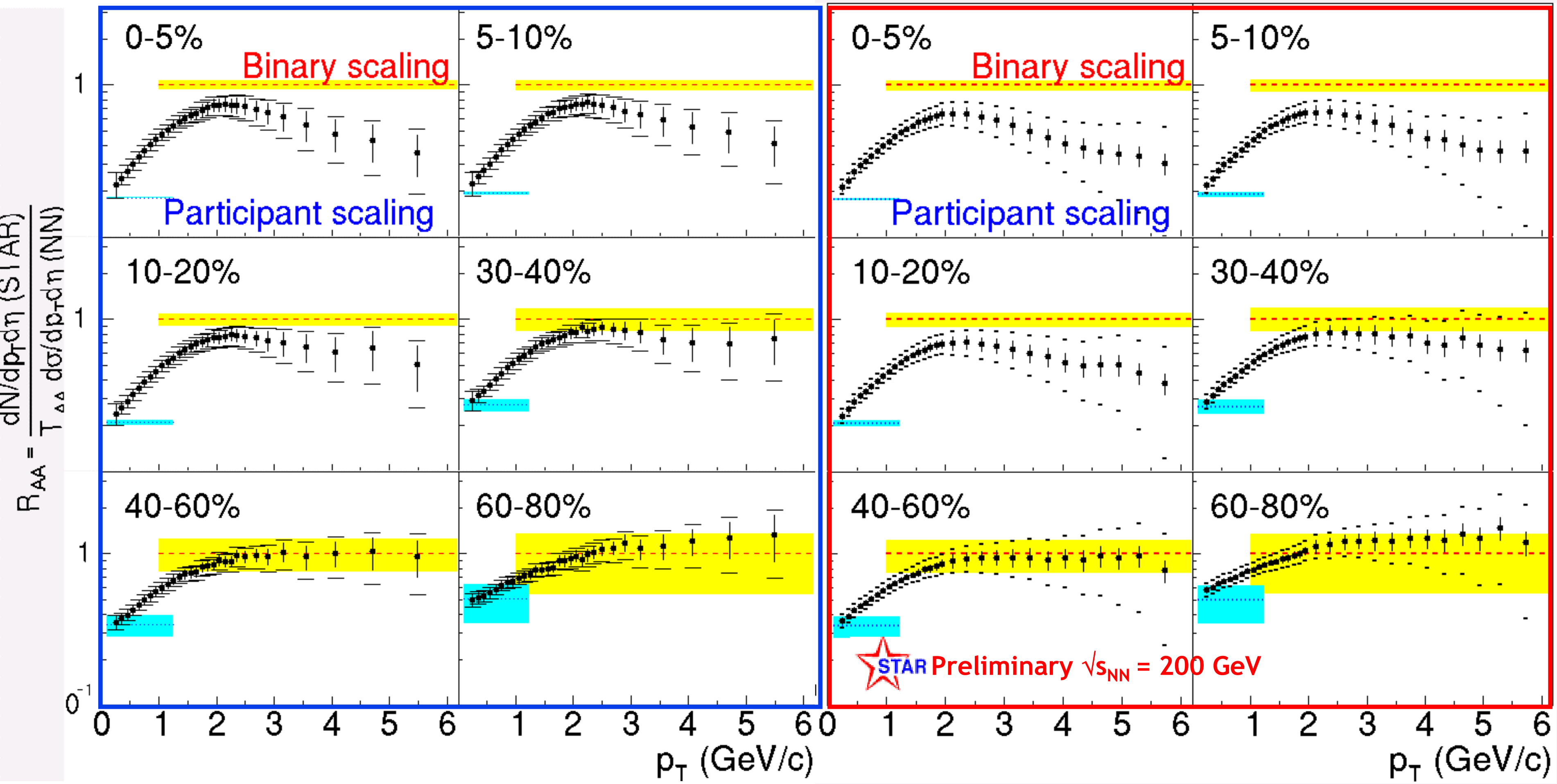
Comparison of Au+Au / p+p at 130 GeV



R_{AA} Comparison to p_T = 6 GeV/c

130 GeV nucl-ex/0206011

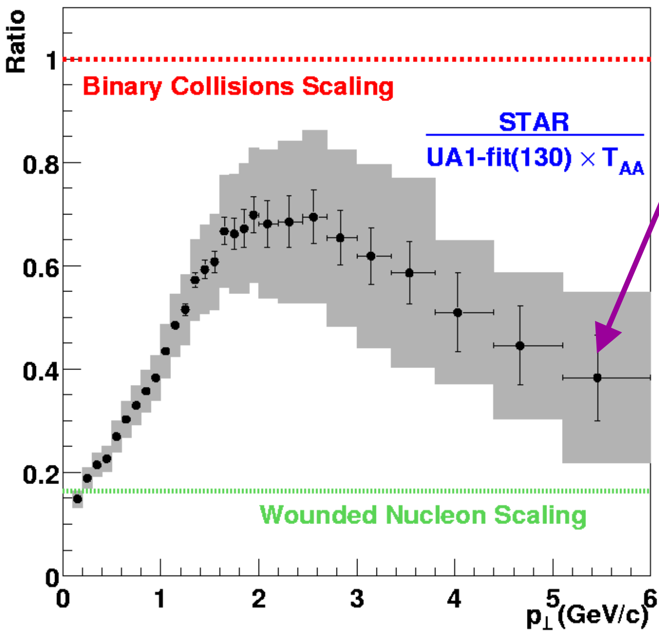
STAR Preliminary $\sqrt{s_{NN}}$ = 200 GeV

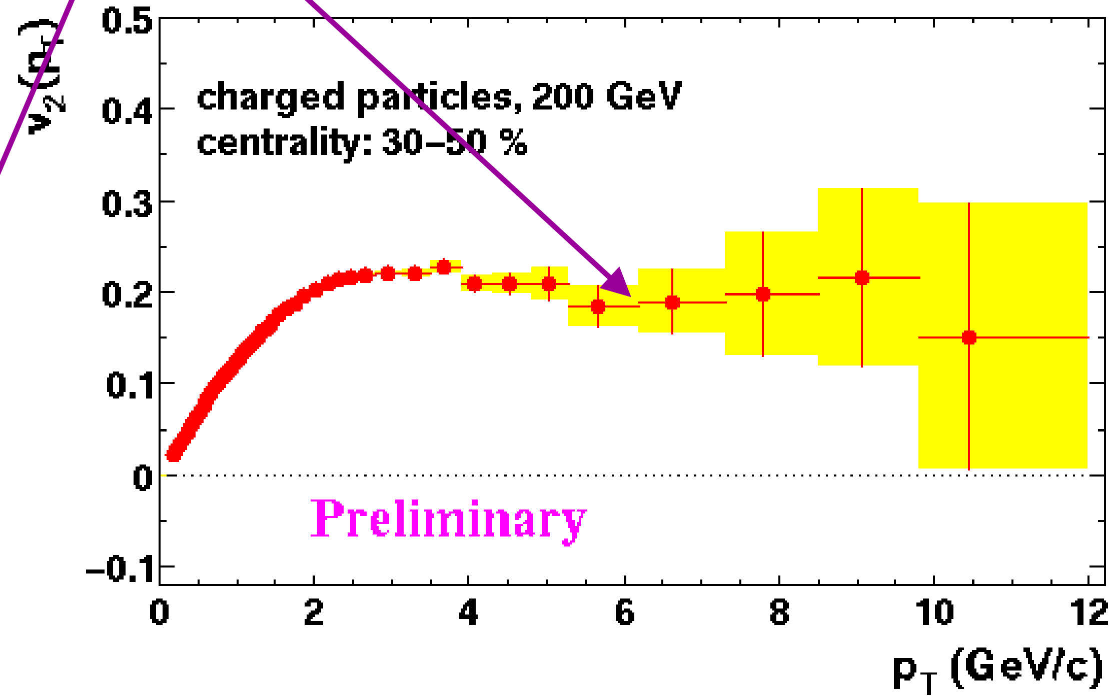


Similar Suppression at high p_T in 130 and 200 GeV data

Flow vs. Inclusive Hadron Spectra

Different views of same physics?



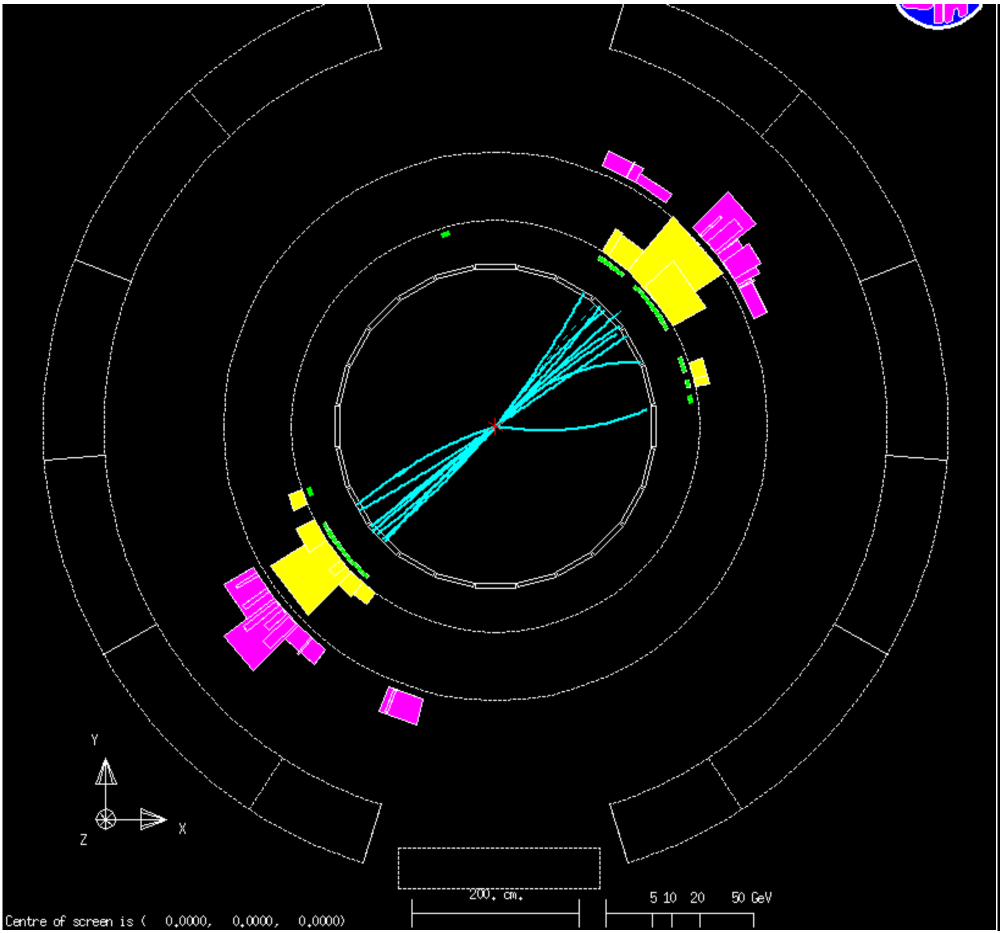


Evidence for hadron suppression at high p_T

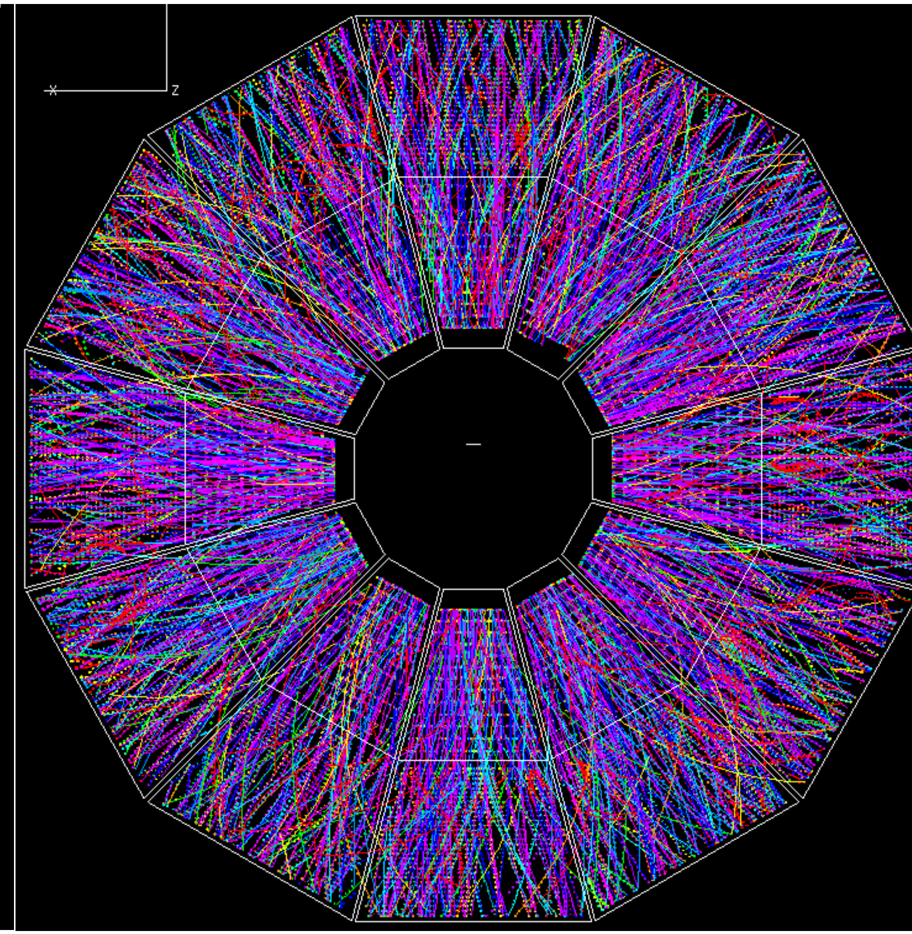
Partonic interaction with matter? dE/dx?

Jet Physics … it is easier to find one in e^+e^- e^+e^-

Jet event in e^+e^- collision

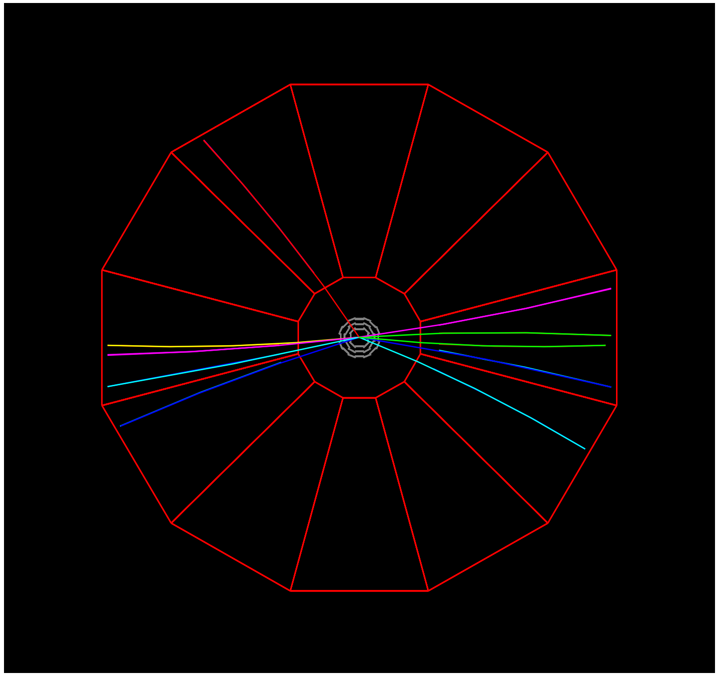


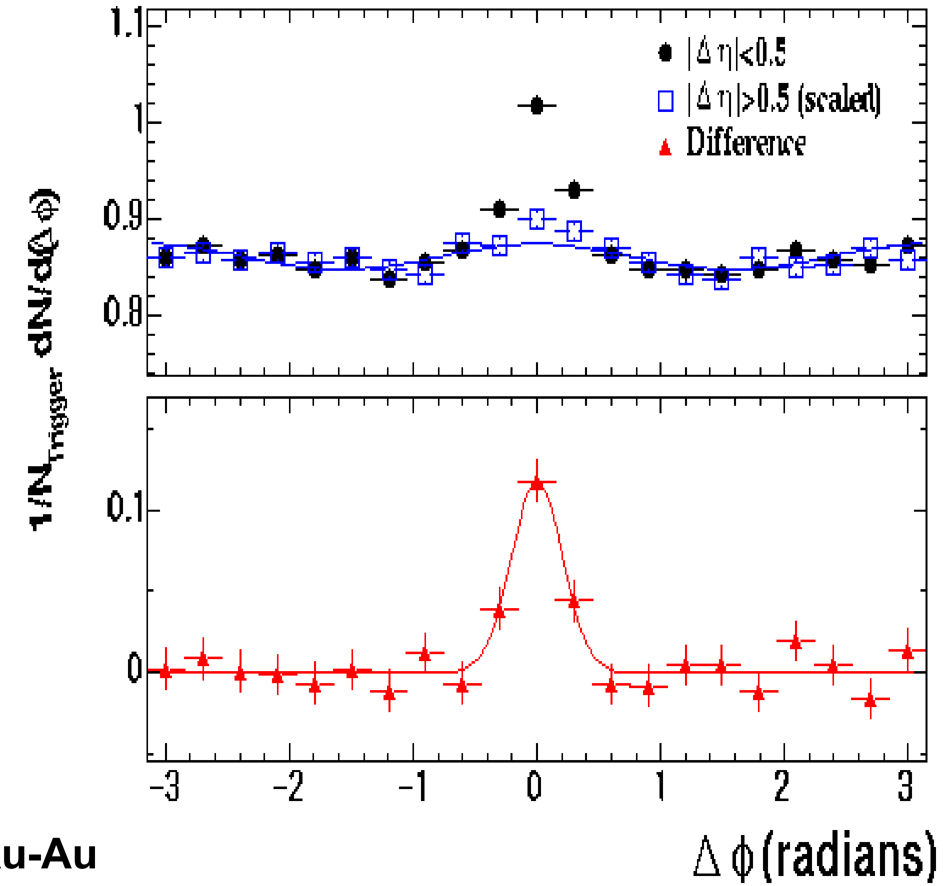
STAR Au+Au collision



Identifying jets on a *statistical* basis in Au-Au

- **You can see the jets in p-p data at RHIC**





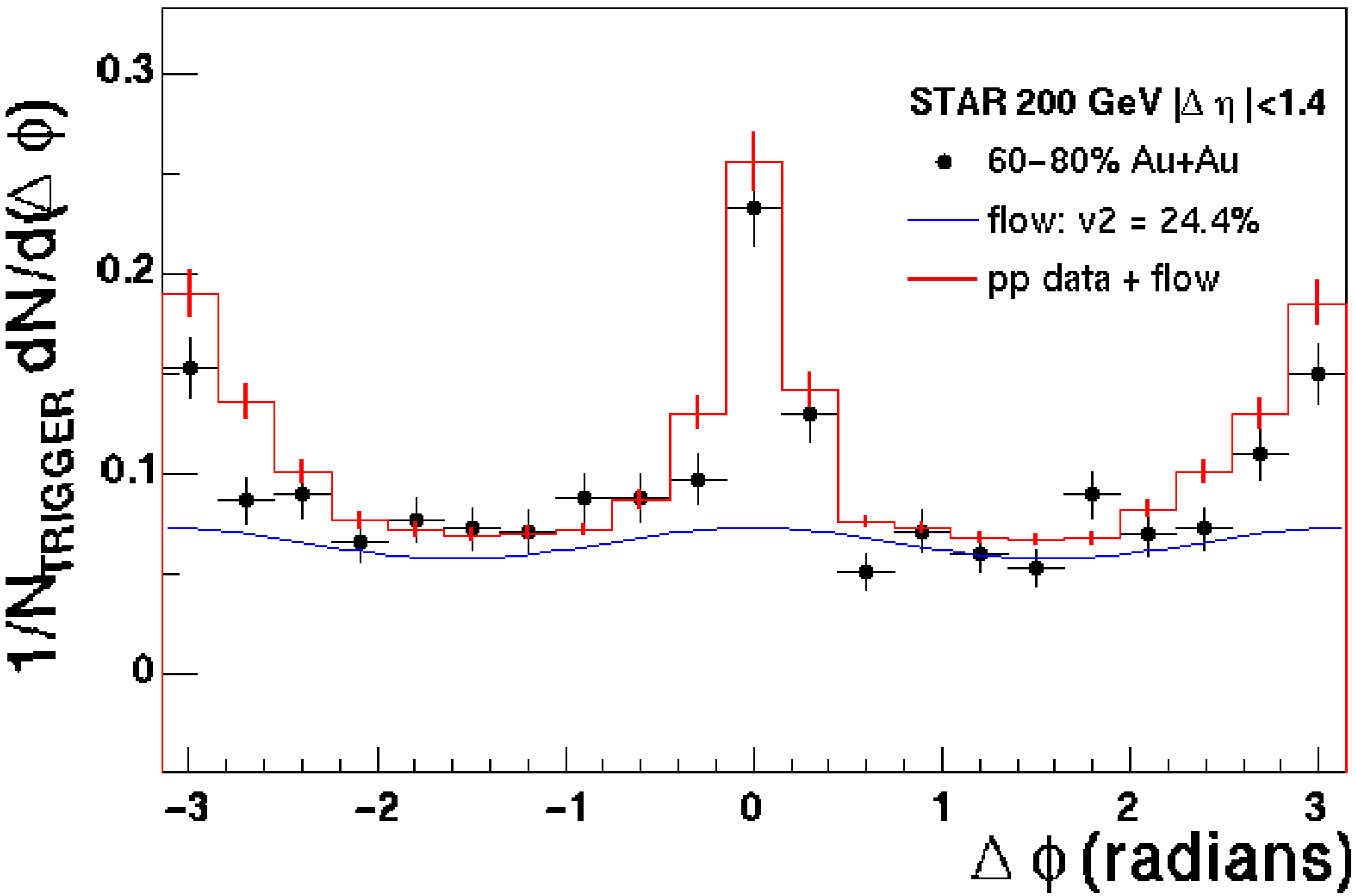
- **Identify jets on a *statistical* basis in Au-Au**
- **Given a trigger particle with $p_T > p_T$ (trigger), associate particles with $p_T > p_T$ (associated)**

$$C_2(\Delta\phi,\Delta\eta) = \frac{1}{N_{TRIGGER}} \frac{1}{Efficiency} N(\Delta\phi,\Delta\eta)$$

STAR Preliminary
Au+Au @ 200 GeV/c
0-5% most central
$4 < p_T(\text{trig}) < 6$ GeV/c
$2 < p_T(\text{assoc.}) < p_T(\text{trig})$

Peripheral Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$



Ansatz:

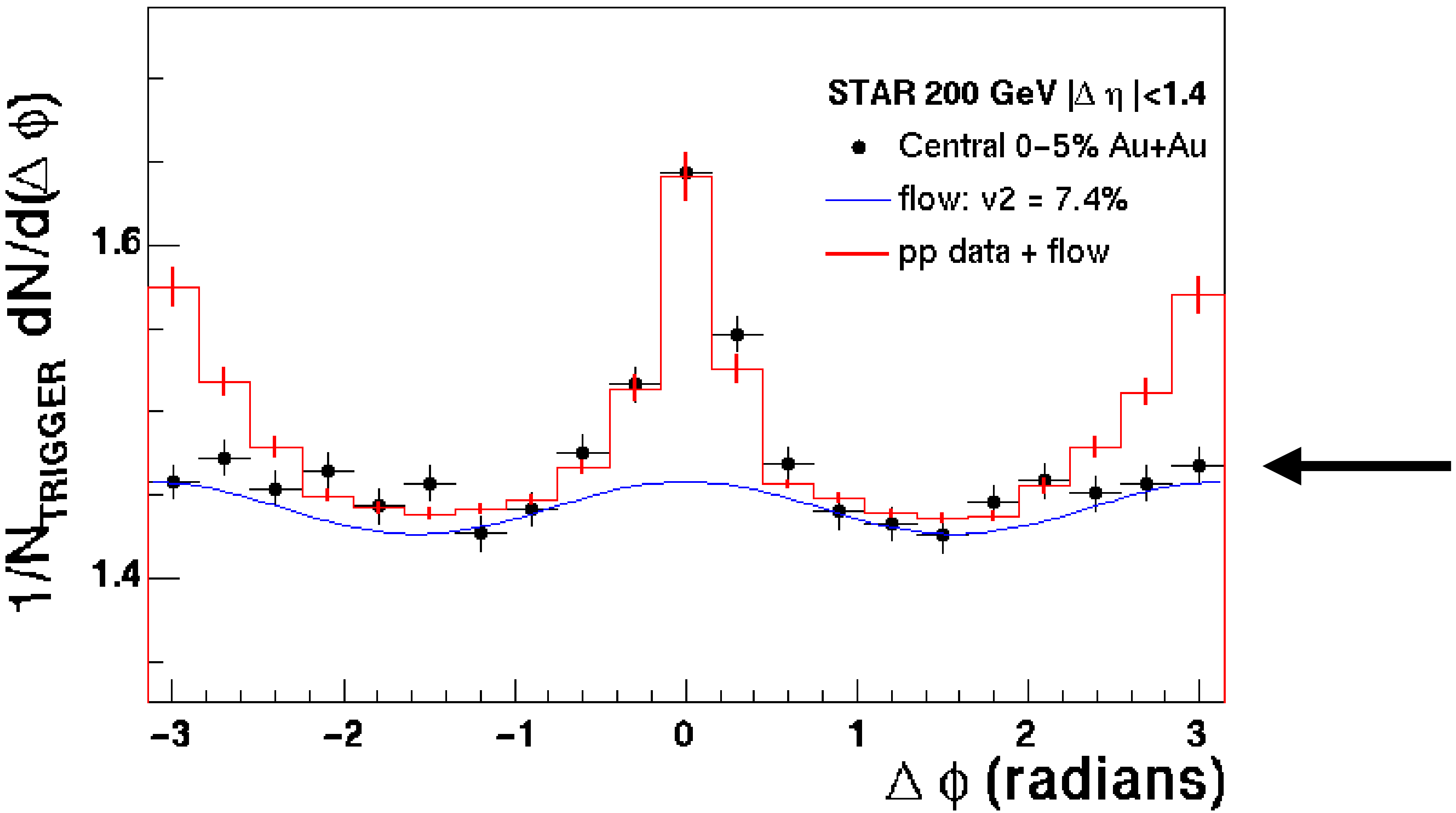
A high p_T triggered Au+Au event is a superposition of a high p_T triggered p+p event plus anisotropic transverse flow

v_2 from reaction plane analysis

"*A*" is fit in non-jet region (0.75<|Δφ|<2.24)

Central Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$



Jets at RHIC

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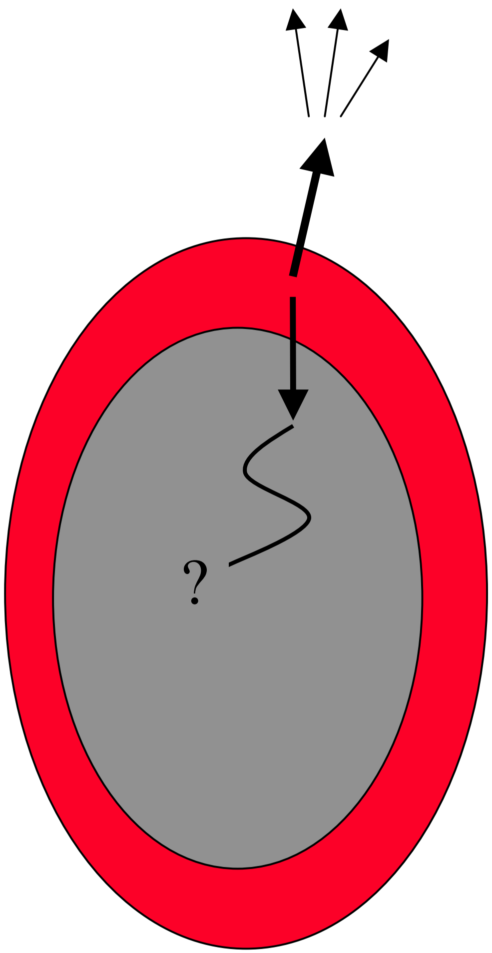
- The backward going jet is missing in central Au-Au collisions when compared to p-p data + flow

- Other features of the data
  - High p_T charged hadrons dominated by jet fragments
    - Relative charge
    - Azimuthal correlation width
    - Evolution of jet cone azimuthal correlation strength with centrality

- Other explanations for the disappearance of back-to-back correlations in central Au-Au?
  - Investigate nuclear k_T effects
    - Experiment: p+Au or d+Au
    - Theory: Add realistic nuclear k_T to the models

Surface emission?



Suppression of back-to-back correlations in central Au+Au collisions

Conclusions About Nuclear Matter at RHIC

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- Its hot
  - Chemical freeze out at 175 MeV
  - Thermal freeze out at 100 MeV
  - The universal freeze out temperatures are surprisingly flat as a function of $\sqrt{s}$ $\sqrt{s}$
- Its fast
  - Transverse expansion with an average velocity of 0.55 c
  - Large amounts of anisotropic flow (v_2) suggest hydrodynamic expansion and high pressure at early times in the collision history
- Its opaque
  - Saturation of v_2 at high p_T
  - Suppression of high p_T particle yields relative to p-p
  - Suppression of the away side jet
- And its nearly in thermal equilibrium
  - Excellent fits to particle ratio data with equilibrium thermal models
  - Excellent fits to flow data with hydrodynamic models that assume equilibrated systems

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Encore Slides

STAR Institutions

STAR

U.S. Labs:

Argonne, Brookhaven, and
Lawrence Berkeley National Labs

U.S. Universities:

UC Berkeley, UC Davis,
UCLA, Carnegie Mellon,
Creighton, Indiana,
Kent State, Michigan State,
CCNY, Ohio State,
Penn State, Purdue,
Rice, UT Austin,
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IPP - Wuhan, IMP - Lanzhou
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India

Institute of Physics - Bhubaneswar
IIT - Mumbai, VECC - Calcutta
Jammu University, Panjab University
University of Rajasthan

Poland:

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Russia:

MEPHI - Moscow, IHEP - Protvino
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The STAR Collaboration