Energy Loss and Flow in Heavy Ion Collisions at RHIC

Preparing to open a new chapter at RHIC with Charm + Beauty

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Who is RHIC and What Does He Do?

RHIC

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

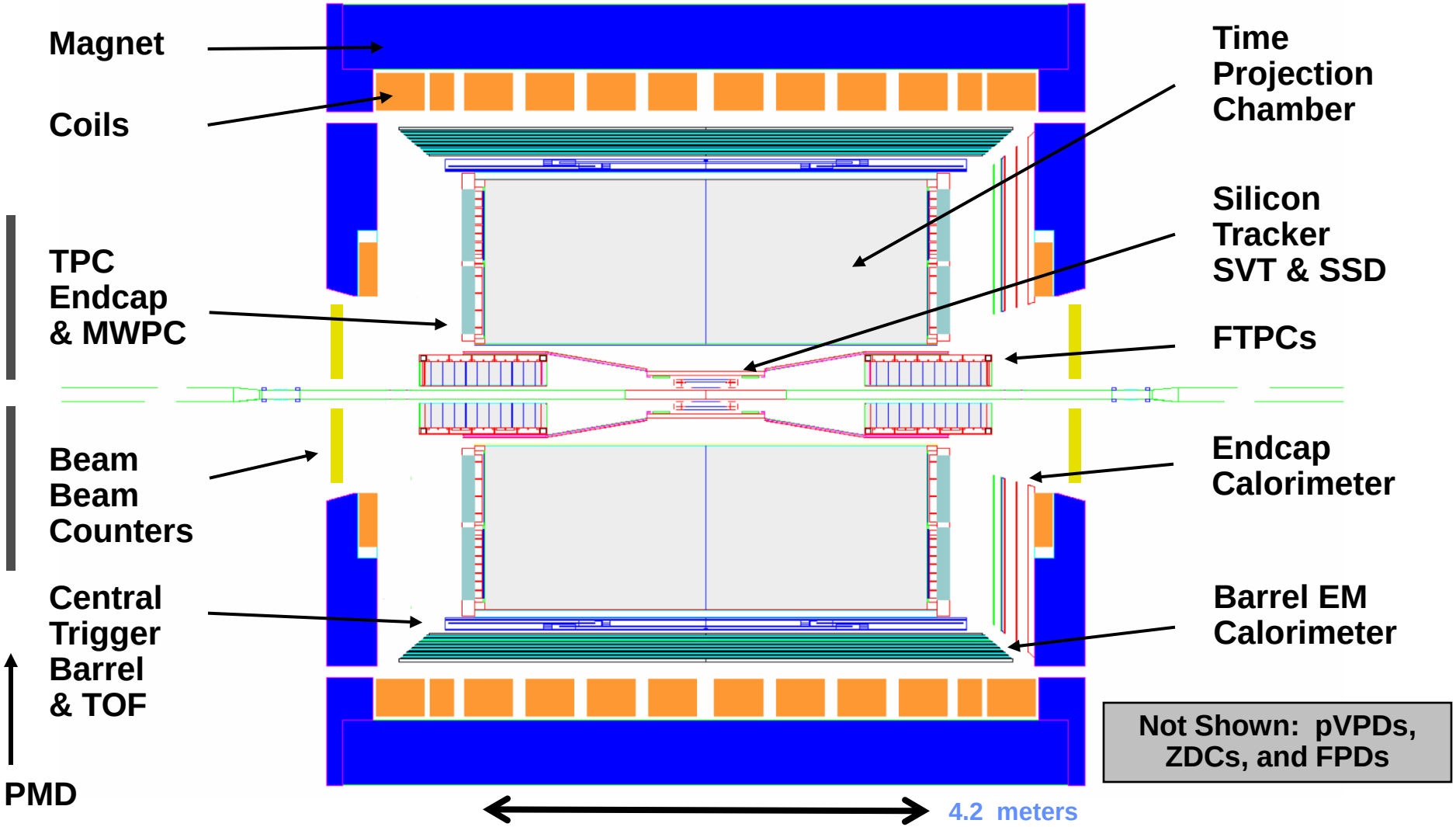
	√s	L
p-p	500	10^{32}
Au-Au	200	10^{27}

(GeV and $cm^{-2}\ s^{-1}$)

- **Polarized protons**
- **Two Large and two small detectors were built**

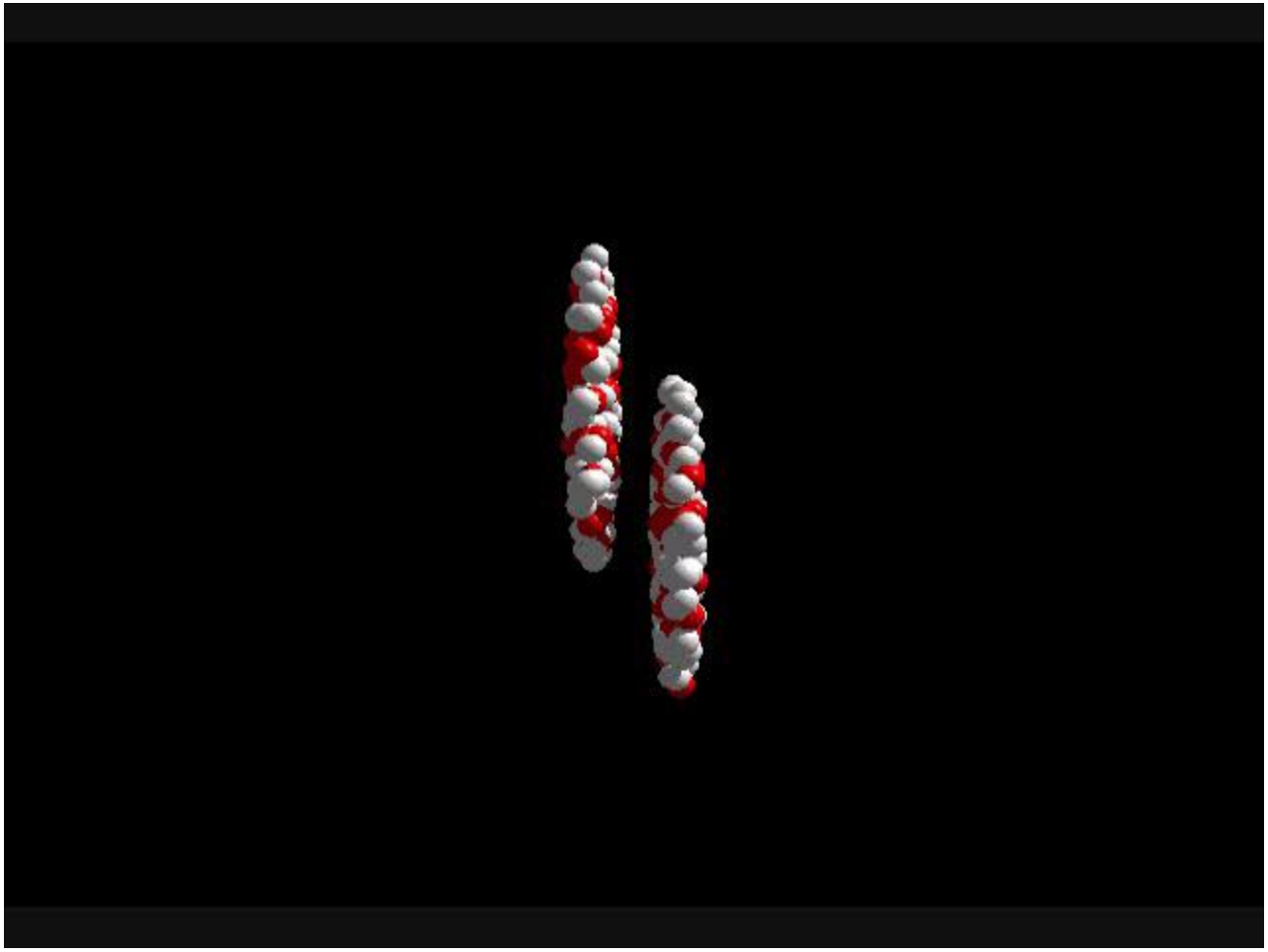
And for a little while longer, it is the highest energy heavy ion collider in the world

STAR is a Suite of Detectors

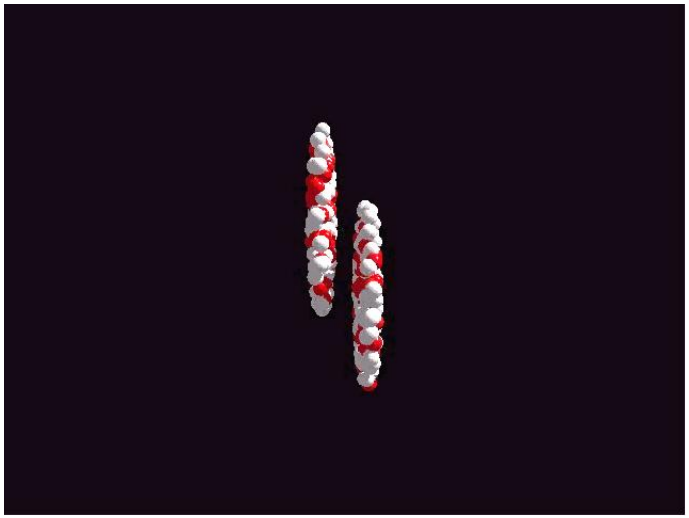


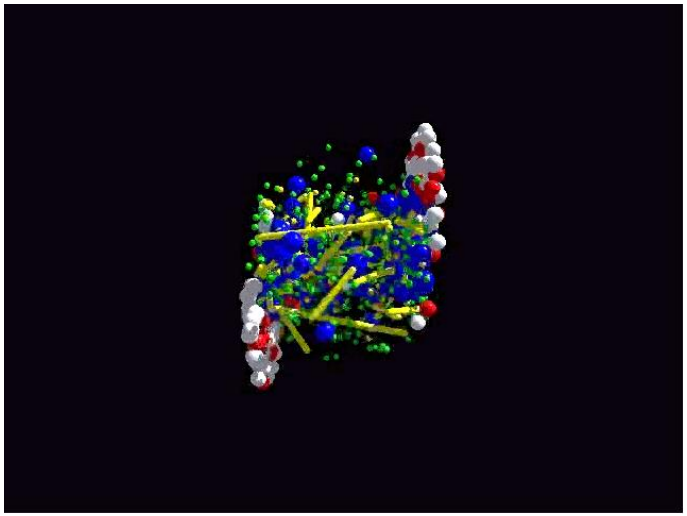
A TPC lies at the heart of STAR

RHIC Physics is Relativistic Nuclear Physics



Unlike Particle Physics, the initial state is important

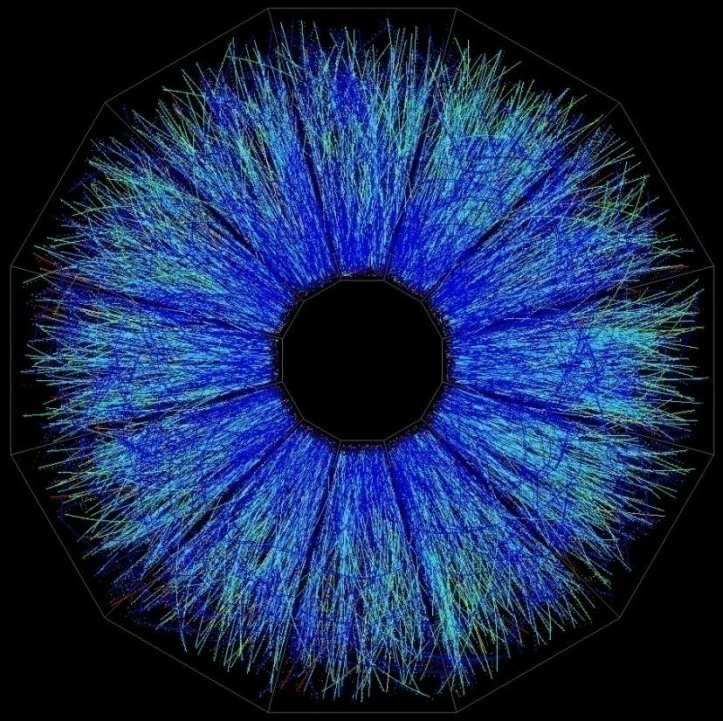




proton neutron delta pion string

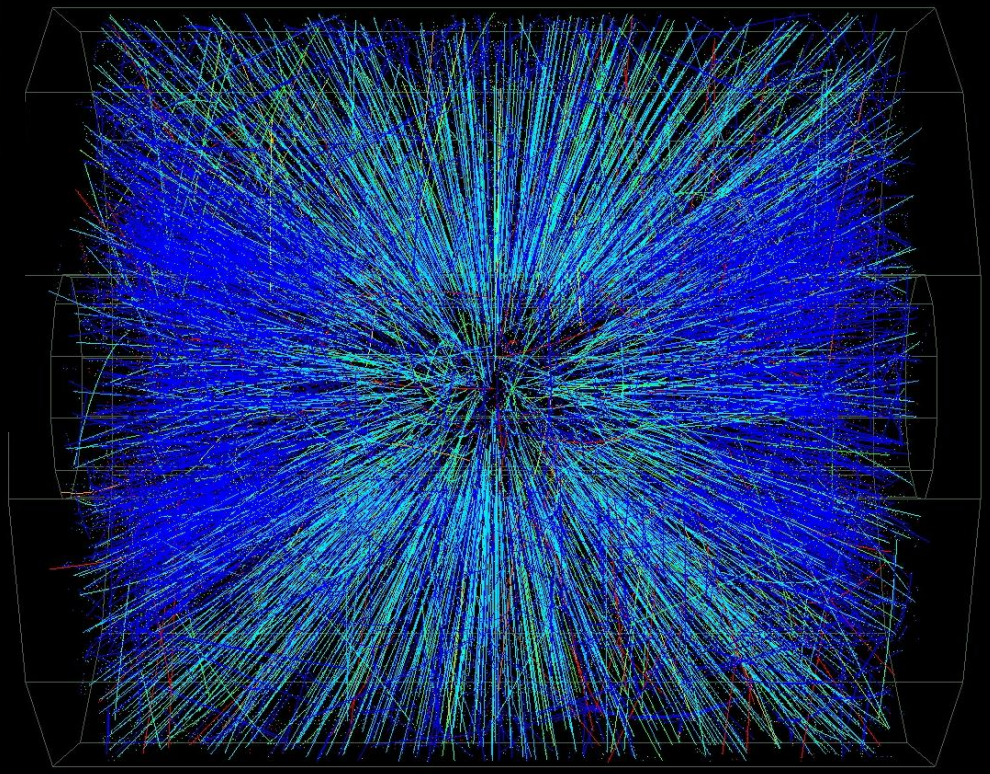
- The nucleus is not a point like particle, it is macroscopic
- Only a few of the nucleons <u>participate</u> in the collision as determined by the impact parameter
- The initial state is Lorentz contracted
- There is multiple scattering in the initial state before the hard collisions take place
  - Cronin effect
- Cross-sections become coherent.
  - The uncertainty principle allows wee partons to interact with the front <u>and</u> back of the nucleus
  - The interaction rate for wee partons saturates ($\rho\sigma = 1$)
- The intial state is even time dilated
  - A color <u>glass</u> condensate

Au on Au Event at CM Energy ~ 130 GeV*A



A Central Event

Typically 1000 to 2000 tracks per event into the TPC



Two-track separation 2.5 cm

Momentum Resolution < 2%

Space point resolution ~ 500 μm

Rapidity coverage $-1.8 < \eta < 1.8$

Particle ID using Topology & Combinatorics

Secondary vertex:

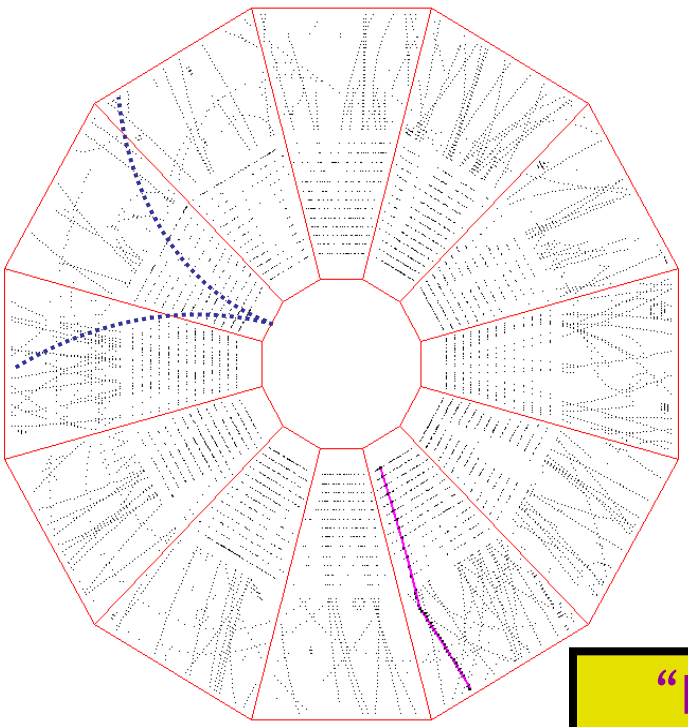
$K_s \rightarrow \pi + \pi$ $\Lambda \rightarrow p + \pi$

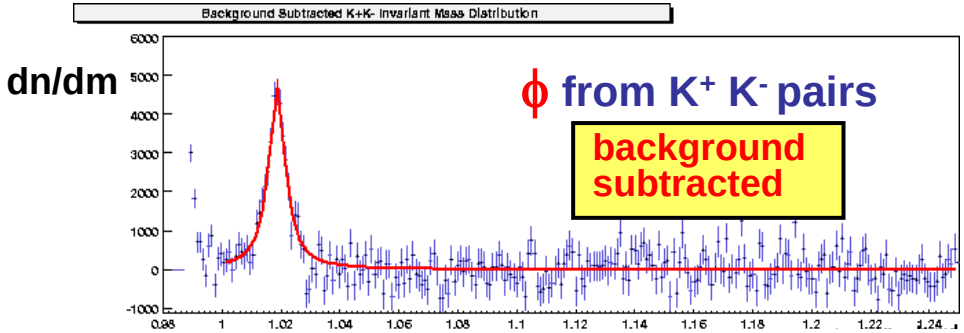
$\Xi \rightarrow \Lambda + \pi$ $\Omega \rightarrow \Lambda + K$

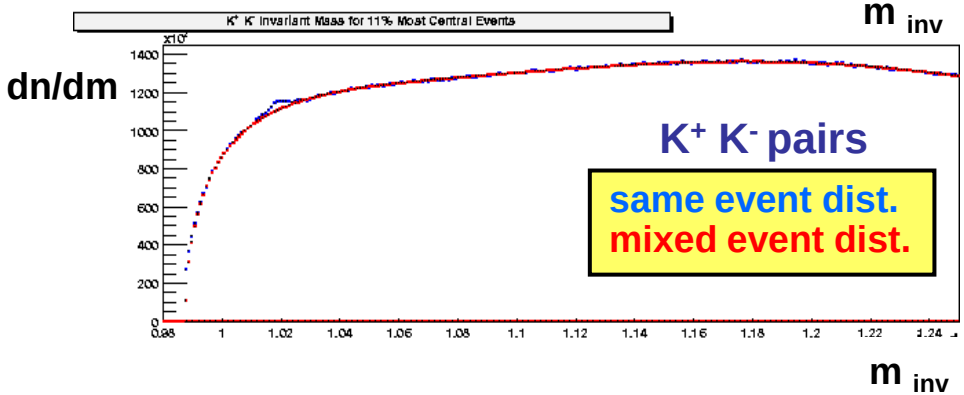
$\gamma \rightarrow e^+ + e^-$

$K_s \rightarrow \pi^+ + \pi^-$ $\phi \rightarrow K^+ + K^-$

$\Lambda \rightarrow p + \pi^-$ $\rho \rightarrow \pi^+ + \pi^-$



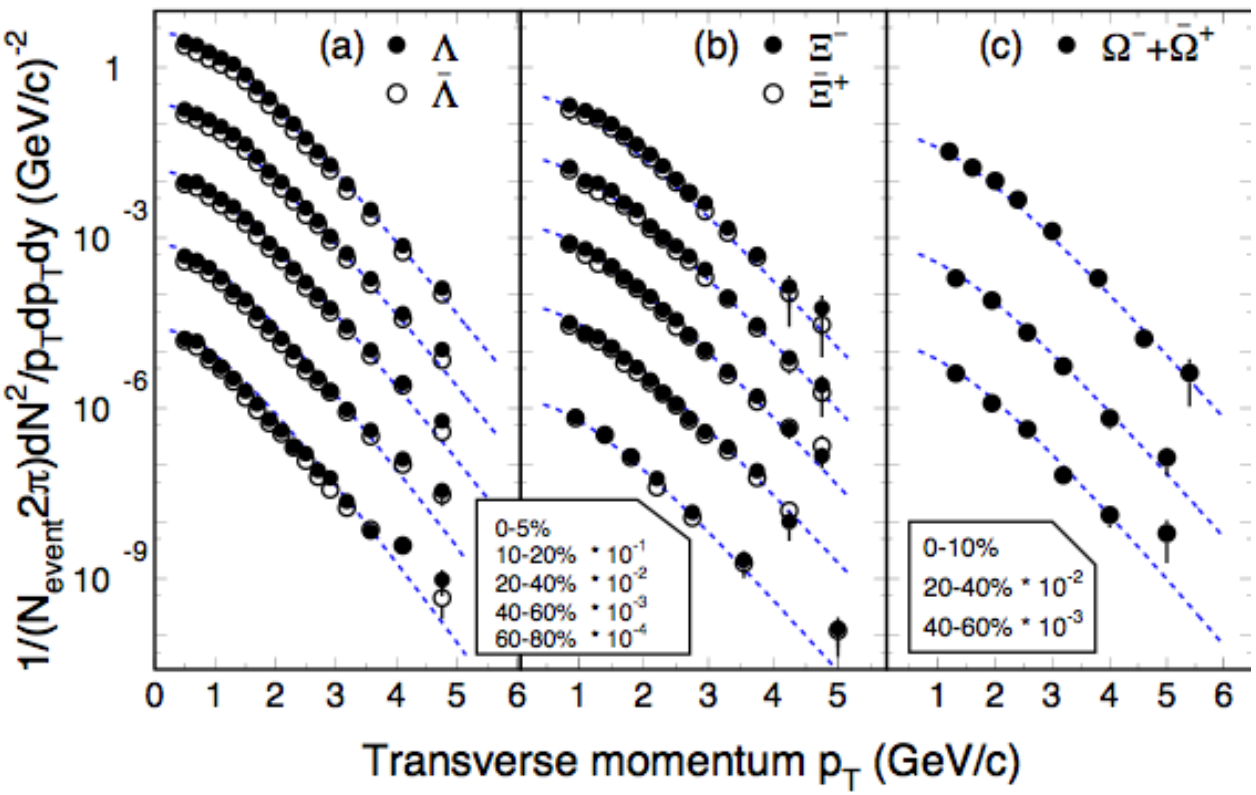


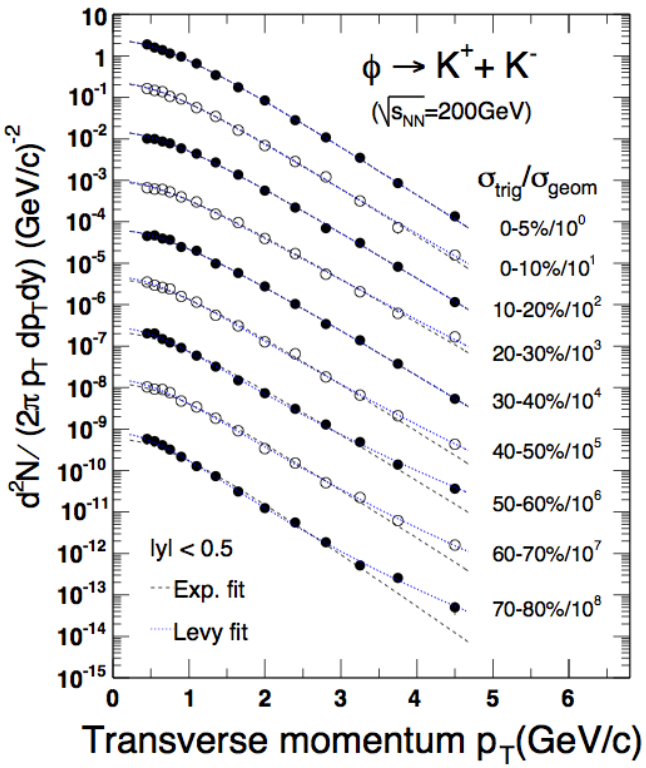


"kinks"

$K^{\pm} \rightarrow \mu^{\pm} + \nu$

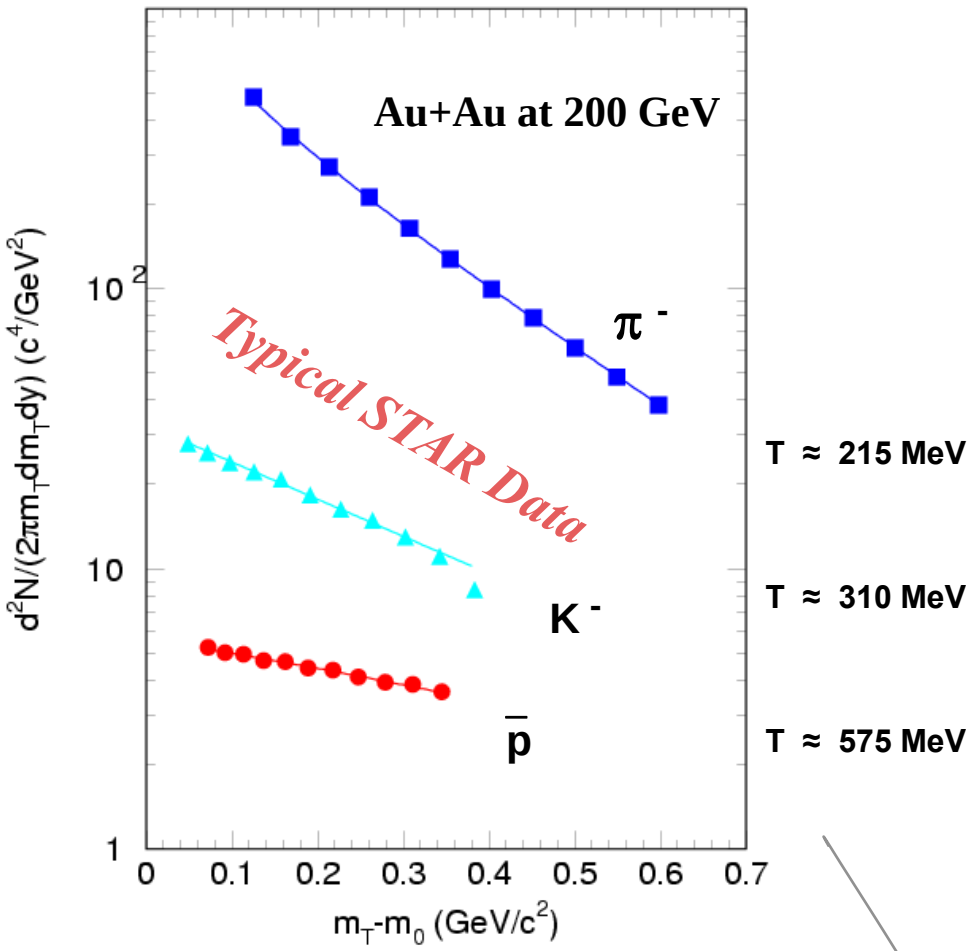
Strange Baryons and Mesons: Au+Au @ 200 GeV

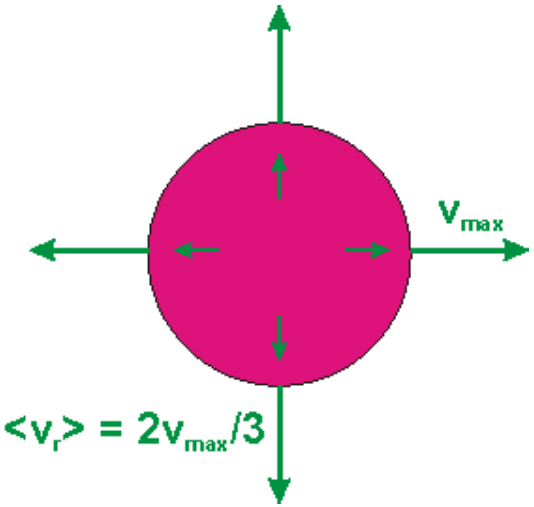




Λ, Ξ, Ω and φ yields .vs. p_T
Phys. Rev. Lett. 98 (2007) 060301

Transverse Radial Expansion: Isotropic Flow





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

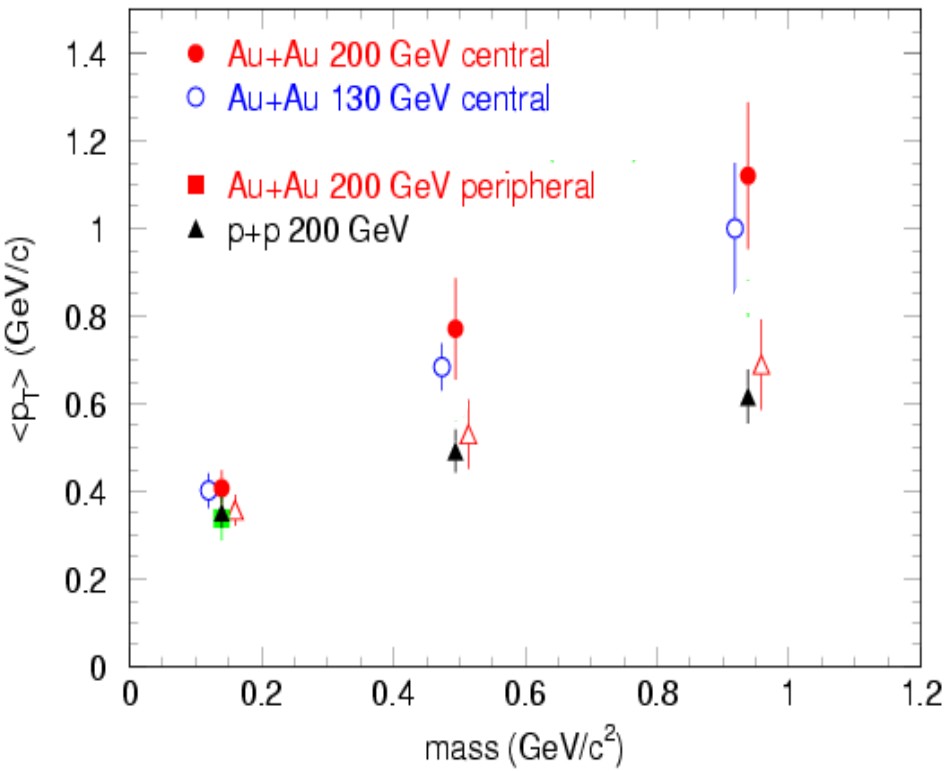
$$\bar{E} = \frac{3}{2}T + \frac{1}{2}mv^2$$

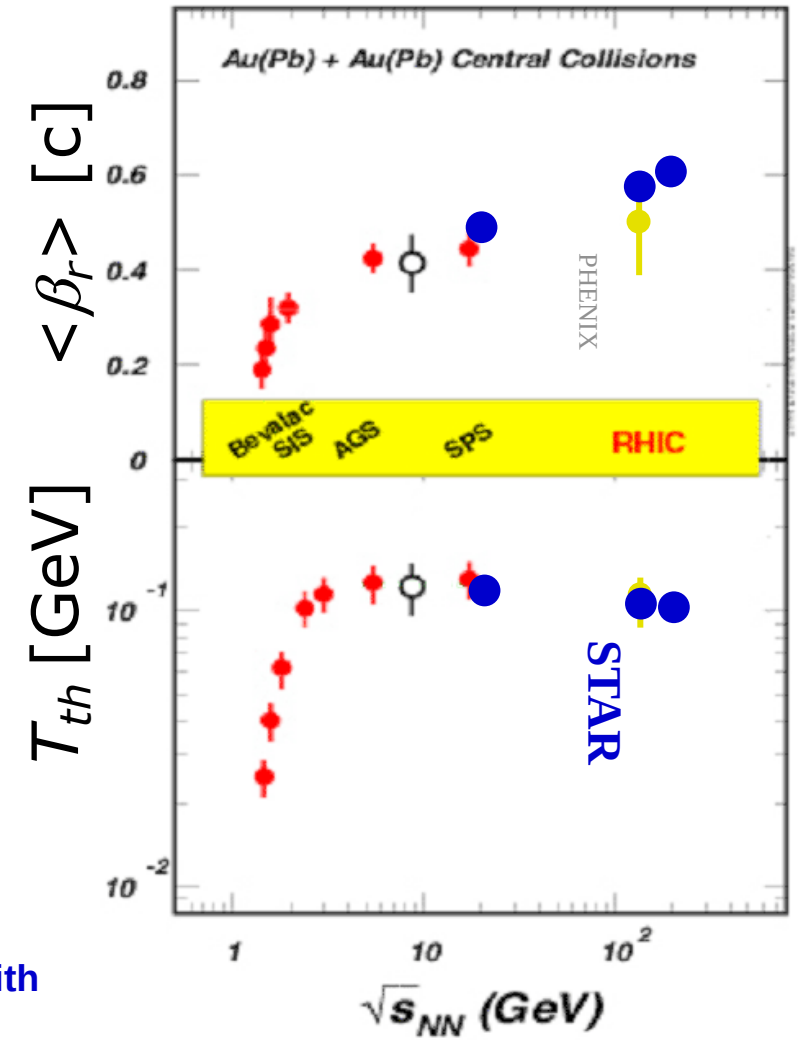
suggests a linear relationship

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

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

Kinetic Freezeout from Transverse Radial Flow





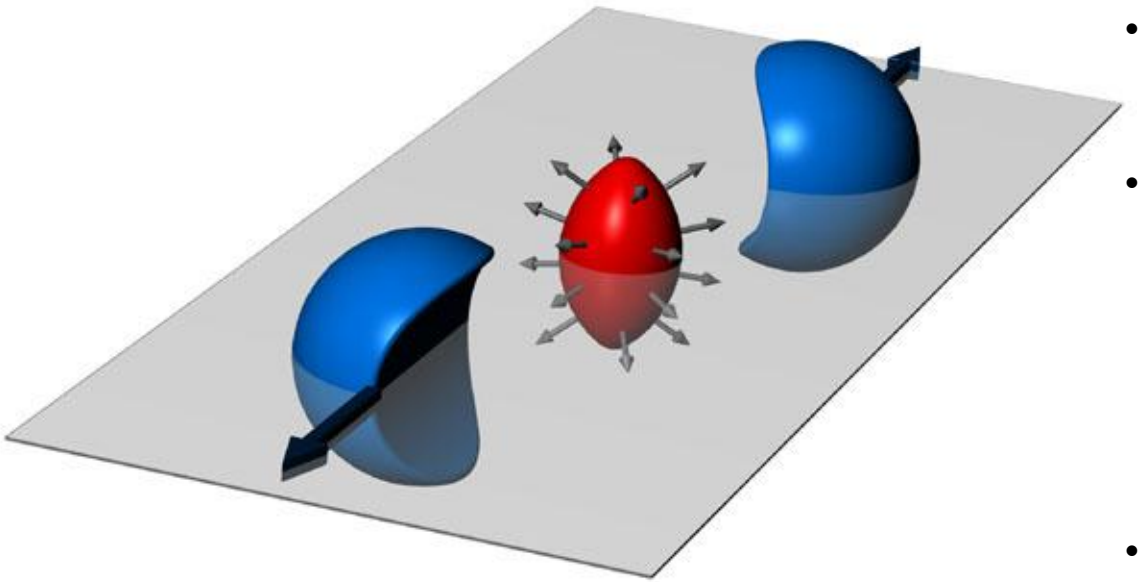
$\langle \beta_r \rangle$ (RHIC) = 0.55 ± 0.1 c

T_{KFO} (RHIC) = 100 ± 10 MeV

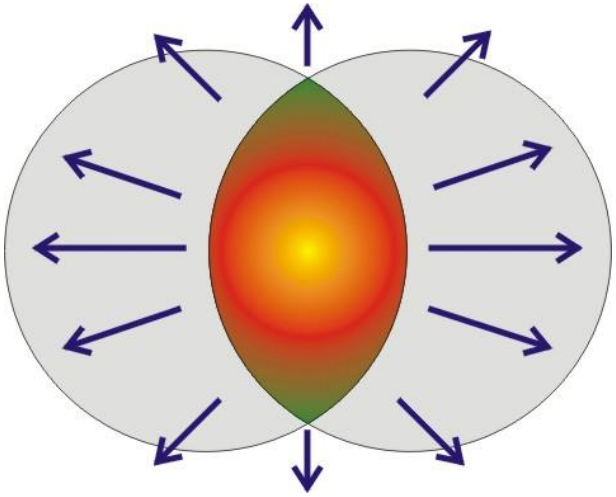
Thermal freeze-out determinations are done with the blast-wave model to find $\langle p_T \rangle$

Explosive Transverse Expansion at RHIC ⇒ High Pressure

ϕ Dependent Distributions – Flow



- **The overlap region in peripheral collisions is not symmetric in coordinate space**
- **Almond shaped overlap region**
  - **Larger pressure gradient in the x-z plane drives flow in that direction**
  - **Easier for high p_T particles to emerge in the direction of x-z plane**
- **Spatial anisotropy → Momentum anisotropy**



- **Perform a Fourier decomposition of the momentum-space particle distribution in the ⊥ plane**
  - **For example, v_2 is the 2nd harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane**

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

isotropic **directed** **elliptic**

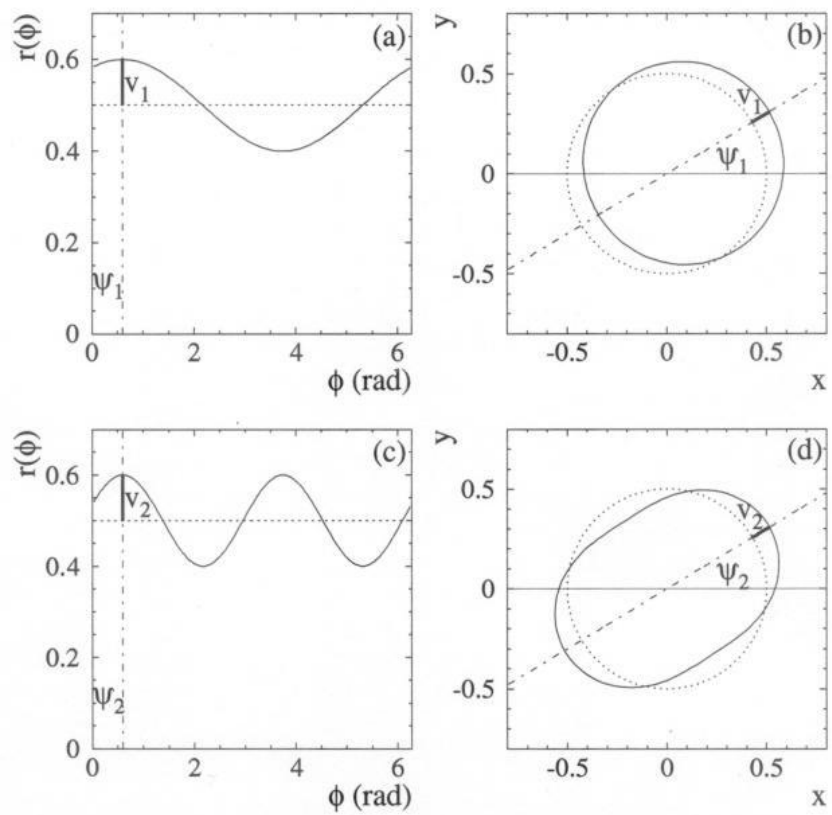
Interpreting Flow – order by order

n=1: Directed Flow has a period of 2π (only one maximum)

- **v_1 measures whether the flow goes to the left or right – whether the momentum goes with or against a billiard ball like bounce off the collision zone**

n=2: Elliptic flow has a period of π (two maximums)

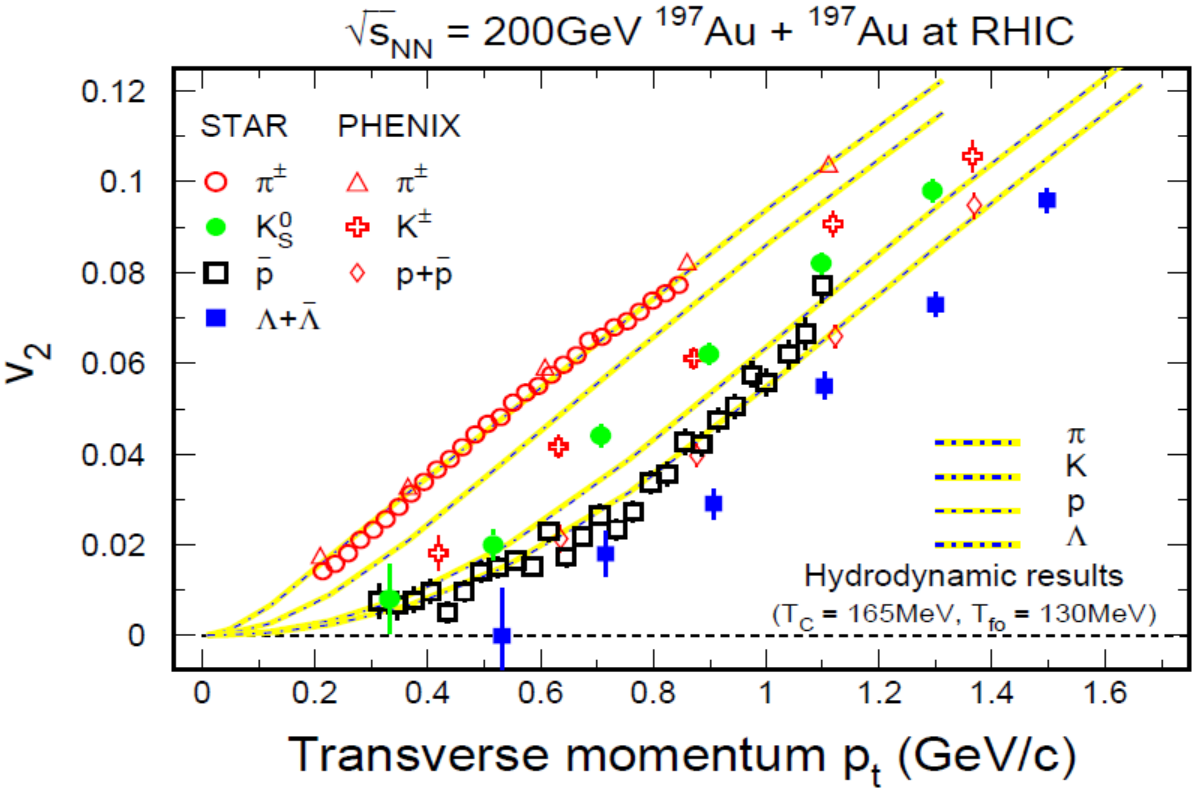
- **v_2 represents the elliptical shape of the momentum distribution**



$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \ldots\right)$$

isotropic directed elliptic higher order terms

v_2 vs. p_T and Particle Mass

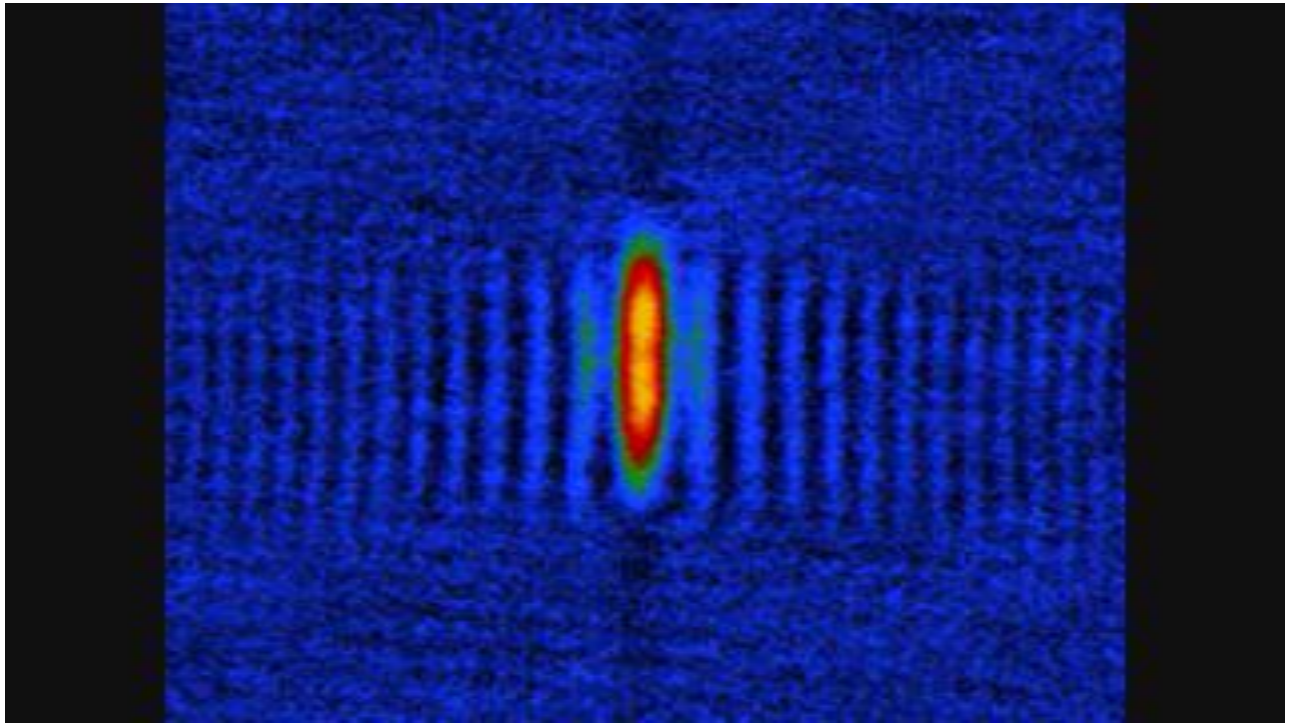


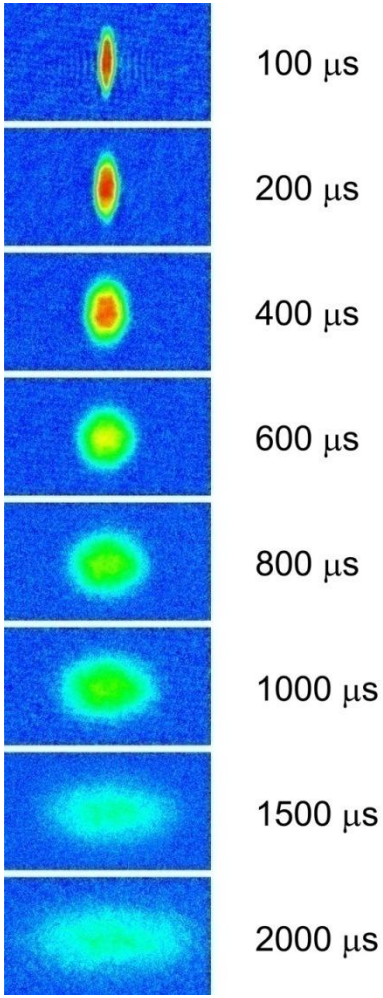
M. Oldenberg, nucl-ex/0412001.
P. Huovinen et al., QM04

Anisotropic transverse flow is large at RHIC

- **v_2 is large**
  - **6% in peripheral collisions (for pions average over all p_T)**
- **Flow is developed very rapidly**
  - **Data suggests very early times ~ fm/c**
- **Hydro calculations are in good agreement with the data**
  - **Hydro assumes local thermal equilibrium**
  - **Followed by hydrodynamic expansion**
  - **The mass dependence is reproduced by the models**

Elliptic Flow in an Ultra-Cold Fermi-Gas

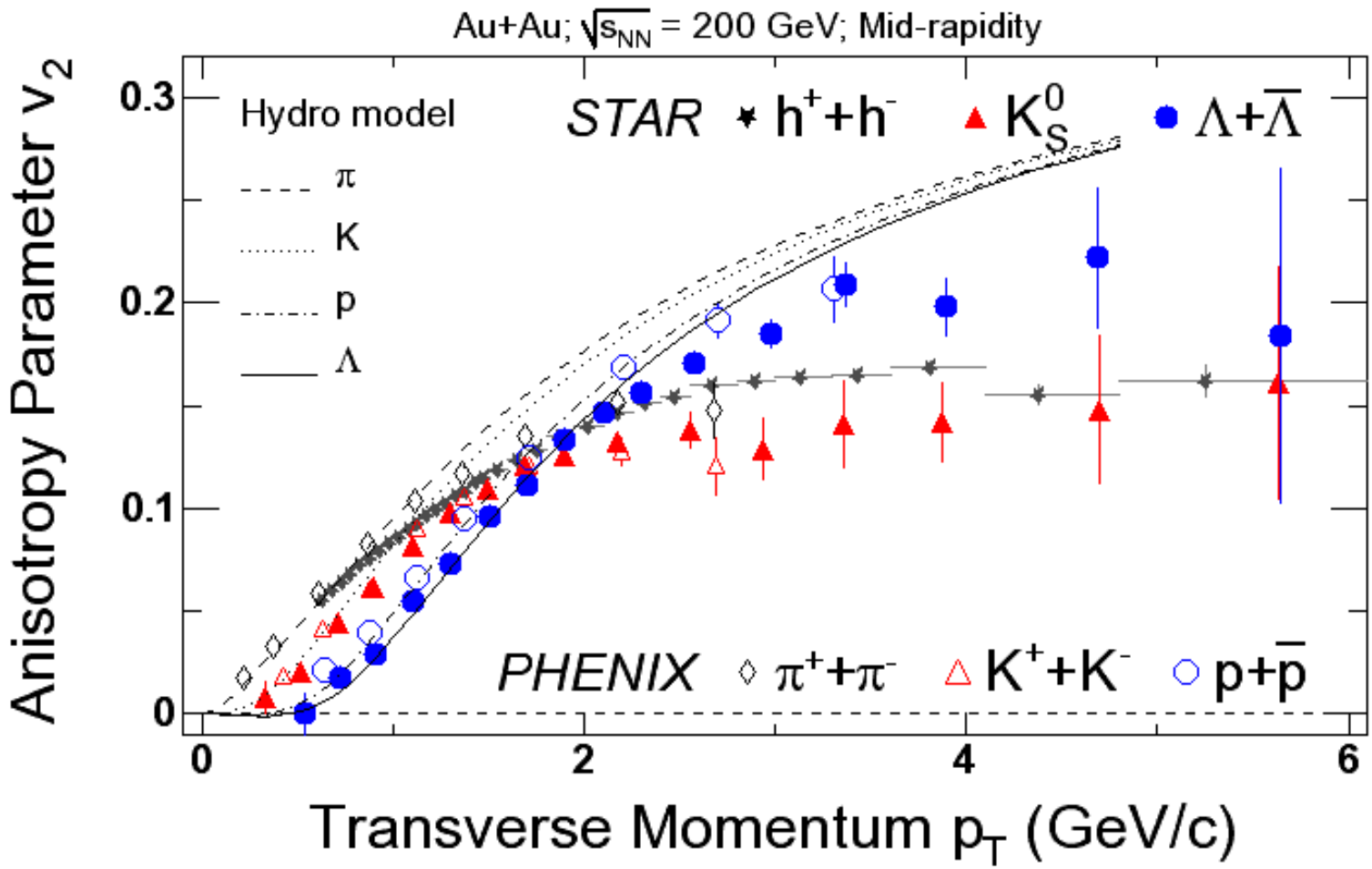




Li-atoms released from an optical trap exhibit elliptic flow analogous to what is observed in ultra-relativistic heavy-ion collisions

- **Elliptic flow is a general feature of strongly interacting systems!**

v_2 at high p_T shows meson / baryon differences

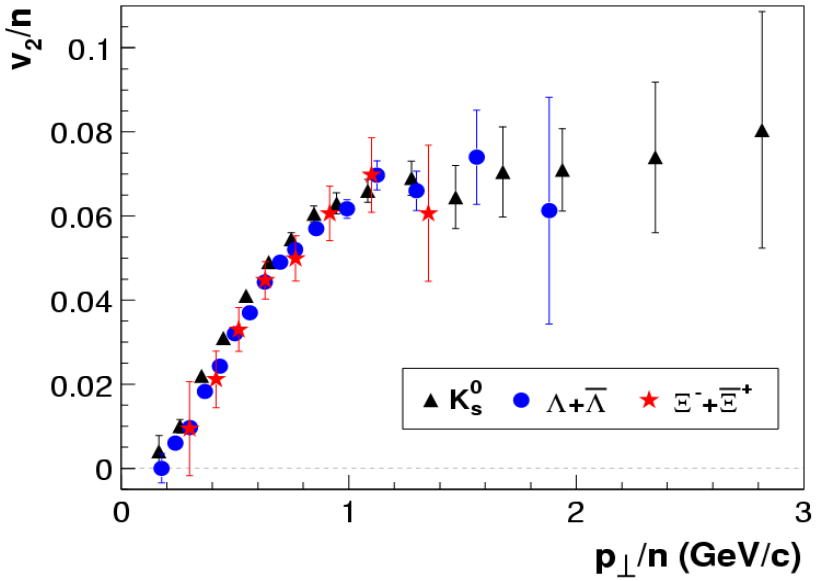


Bulk P_{QCD} Hydro

Asym. pQCD Jet Quenching

q^n Coalescence

The Recombination Model (Fries et al. PRL 90 (2003) 202303)

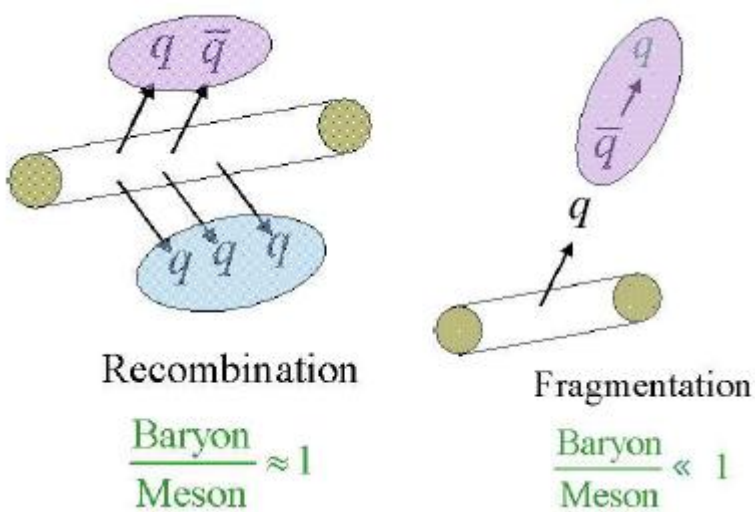


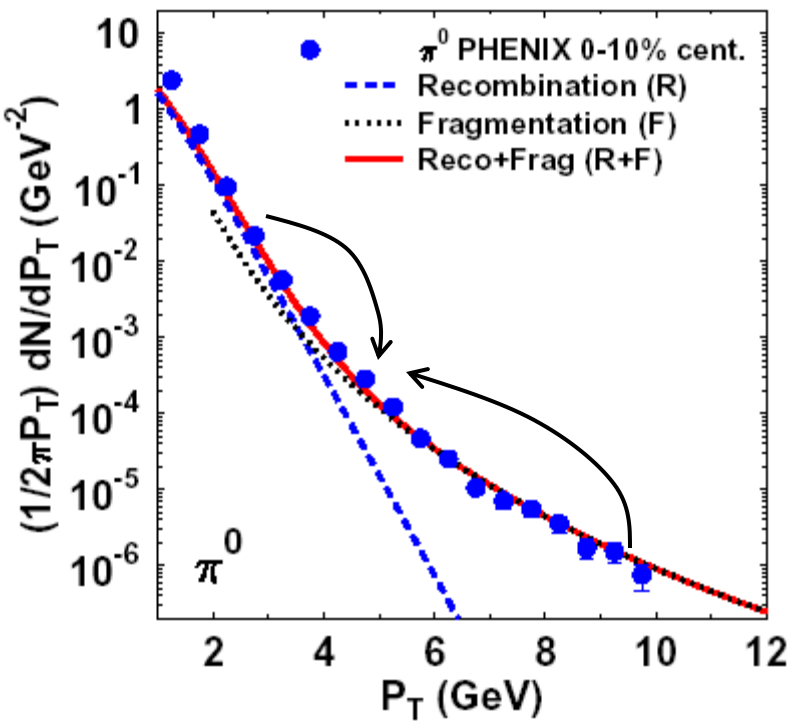
The flow pattern in $v_2(p_T)$ for hadrons is predicted to be simple <u>if</u> flow is developed at the quark level

$p_T \rightarrow p_T/n$

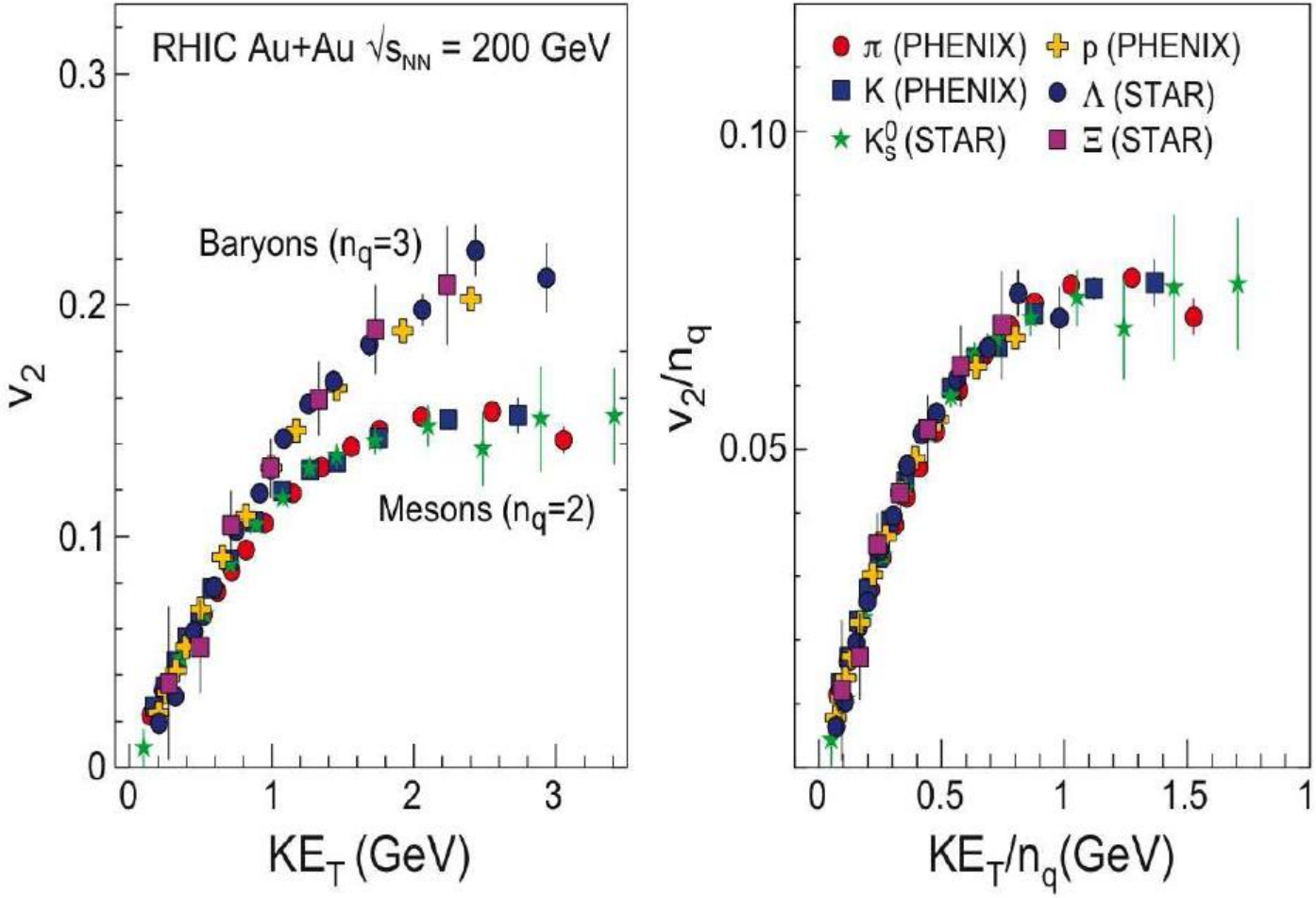
$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)



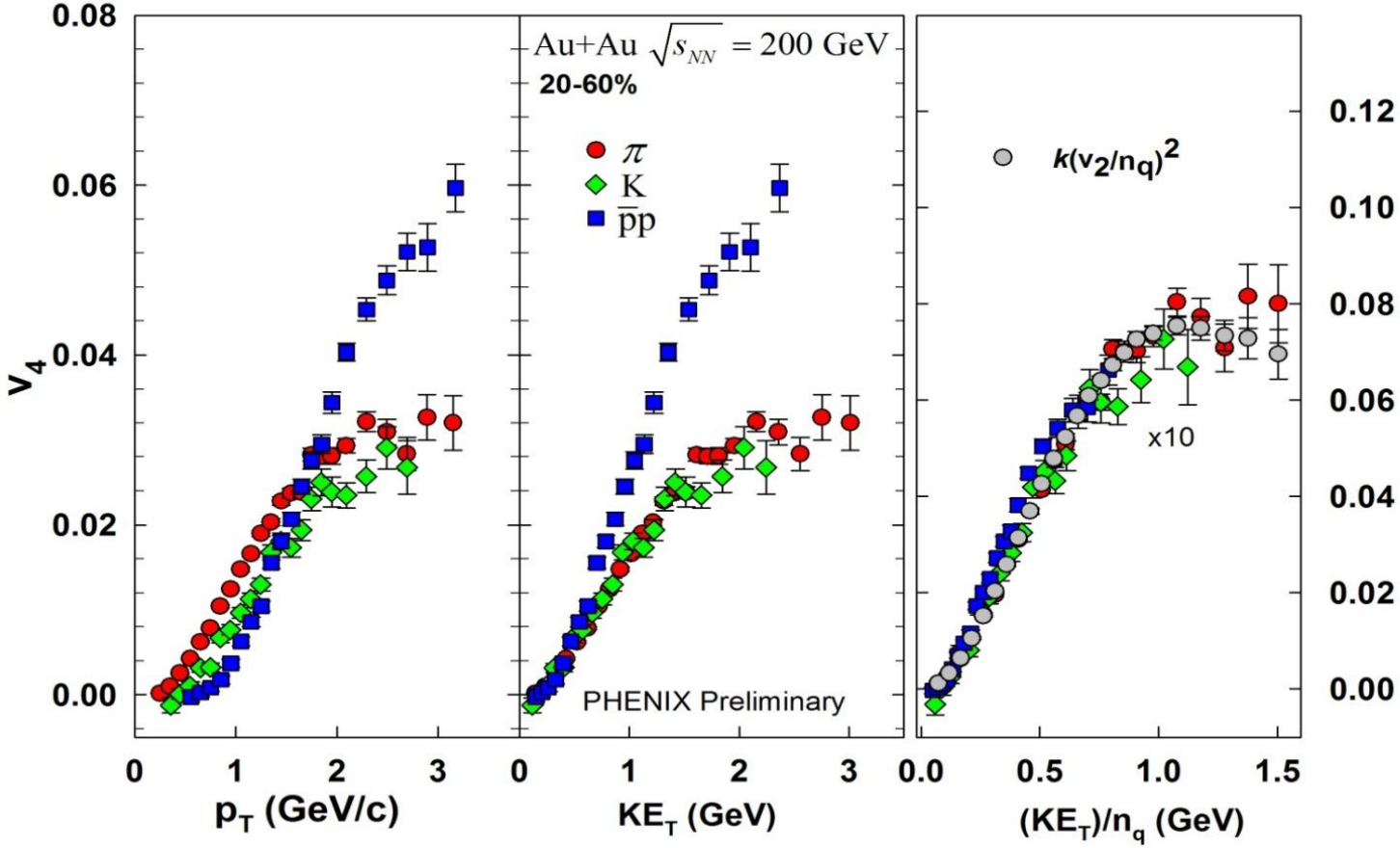


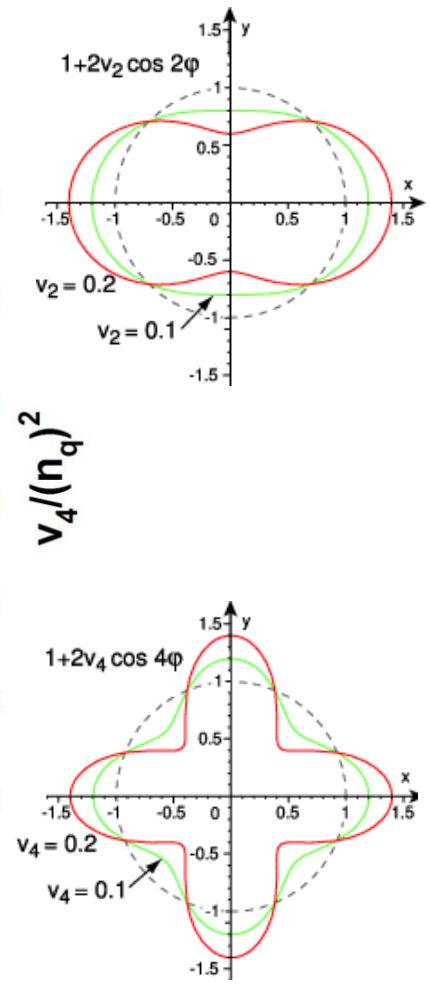
Elliptic flow scales with the number of quarks



Implication: (uds) quarks, not hadrons, are the relevant degrees of freedom at early times in the collision history

v_4 Exhibits Constituent Quark Scaling, too





S.L. Huang QM08

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \ldots\right)$$

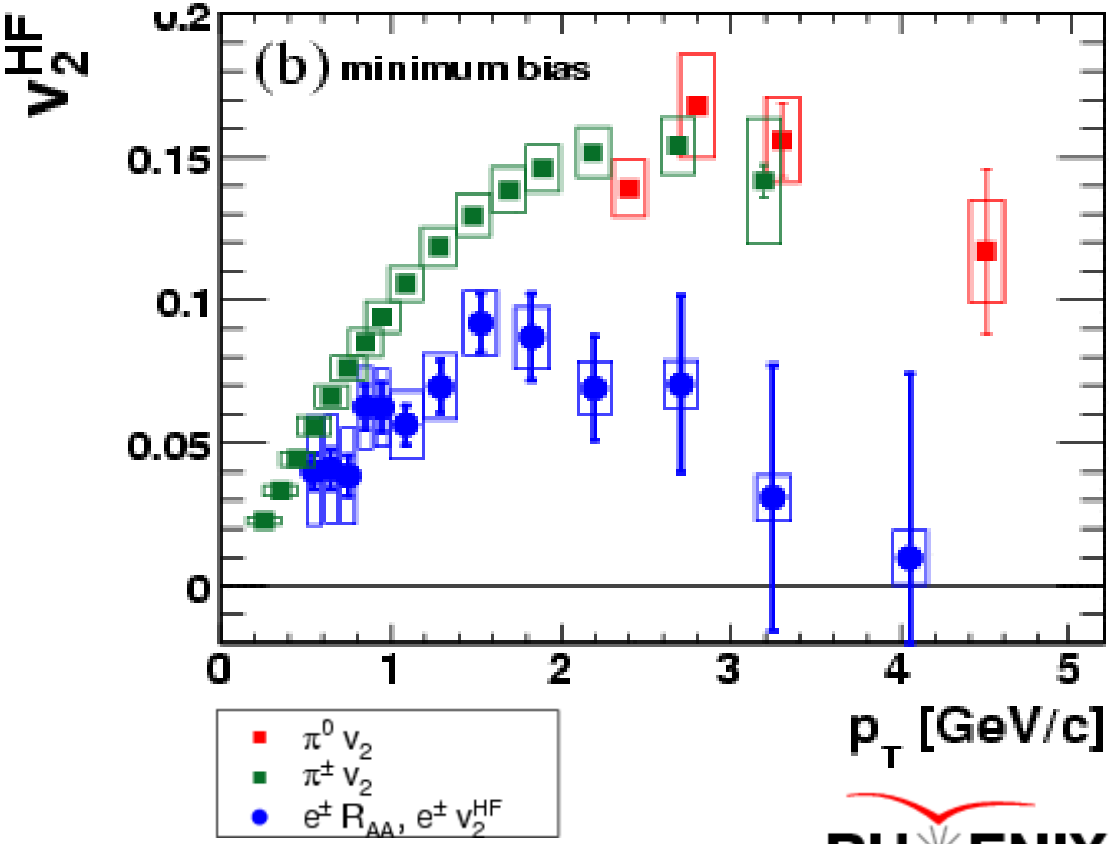
isotropic directed elliptic higher order terms

Constituent Quark Scaling?

- **Hadrons are created by the recombination of quarks and this appears be the dominant mechanism for hadron formation at intermediate p_T**
- **Baryons and Mesons are produced with equal abundance at intermediate p_T**
- **The collective flow pattern of the hadrons appears to reflect the collective flow of the constituent quarks.**
- **up, down, and strange quarks do it … despite the difference in their masses**

Partonic Collectivity

Hints of Elliptic Flow with Charm



Shingo Sakai, QM 2006
PRL 98, 172301 (2007)

A Look to the Future: better if we can do direct topological identification of Charm

- **D $\rightarrow$ e +X**

  Single electron spectra from PHENIX show hints of elliptic flow

  Is it charm or beauty?

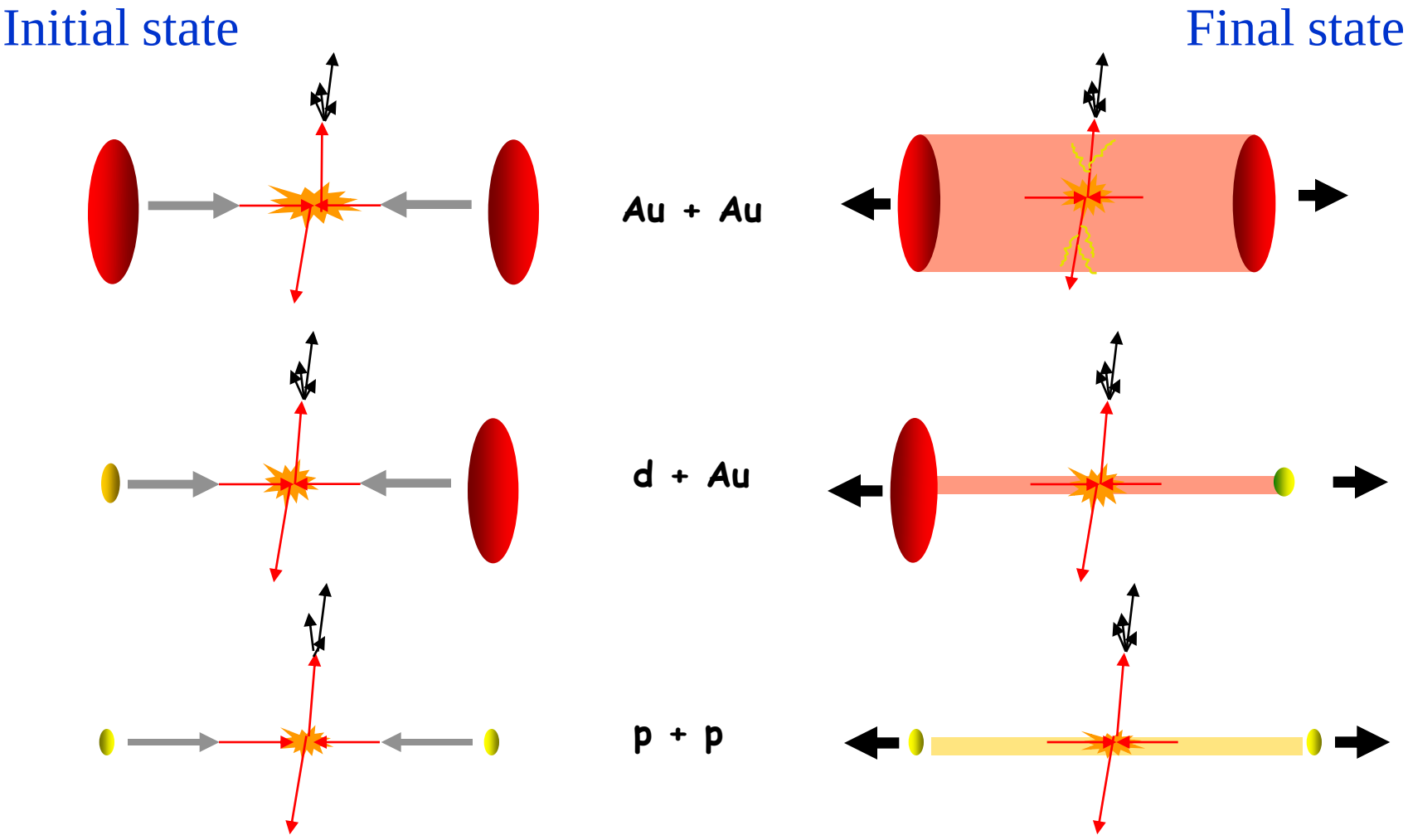
- **Very profound, if it is true, because the Charm quark is rare and heavy compared to u, d, or s quarks**
  - **Indicator for rapid thermalization**

- **Their will be RHIC upgrades to cut out large photonic backgrounds:**

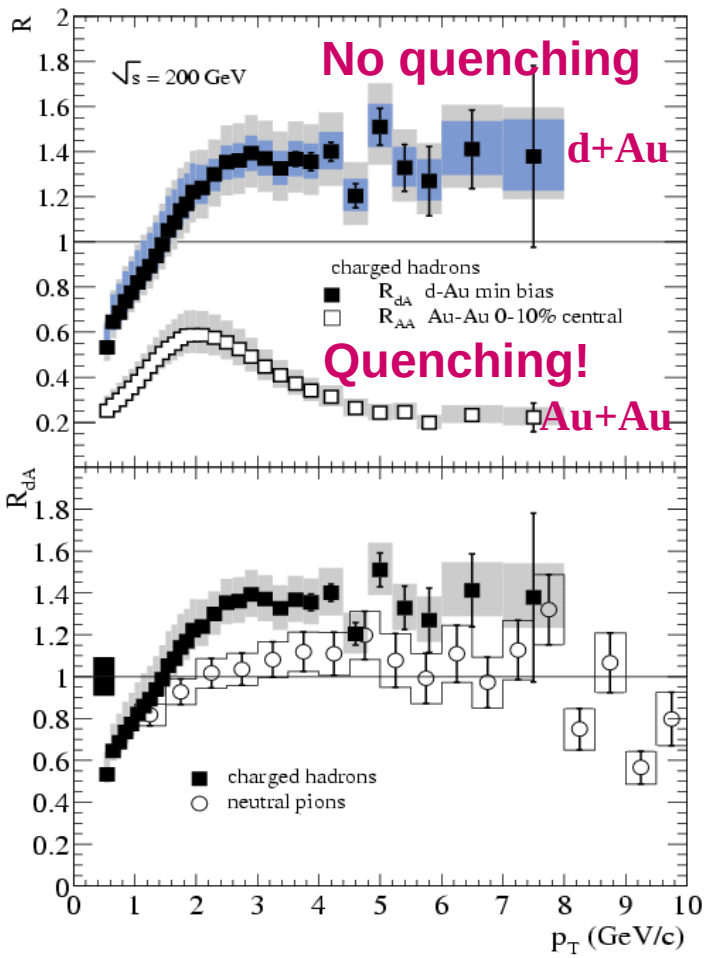
  $\gamma \rightarrow e^+e^-$

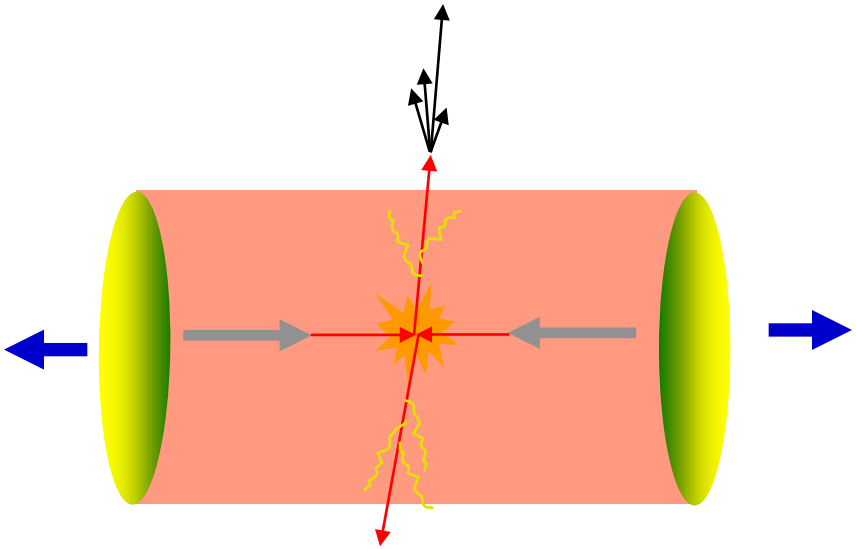
  and reduce other large statistical and systematic uncertainties

Lets look at some collision systems in detail …



Partonic Energy Loss and Jet Quenching



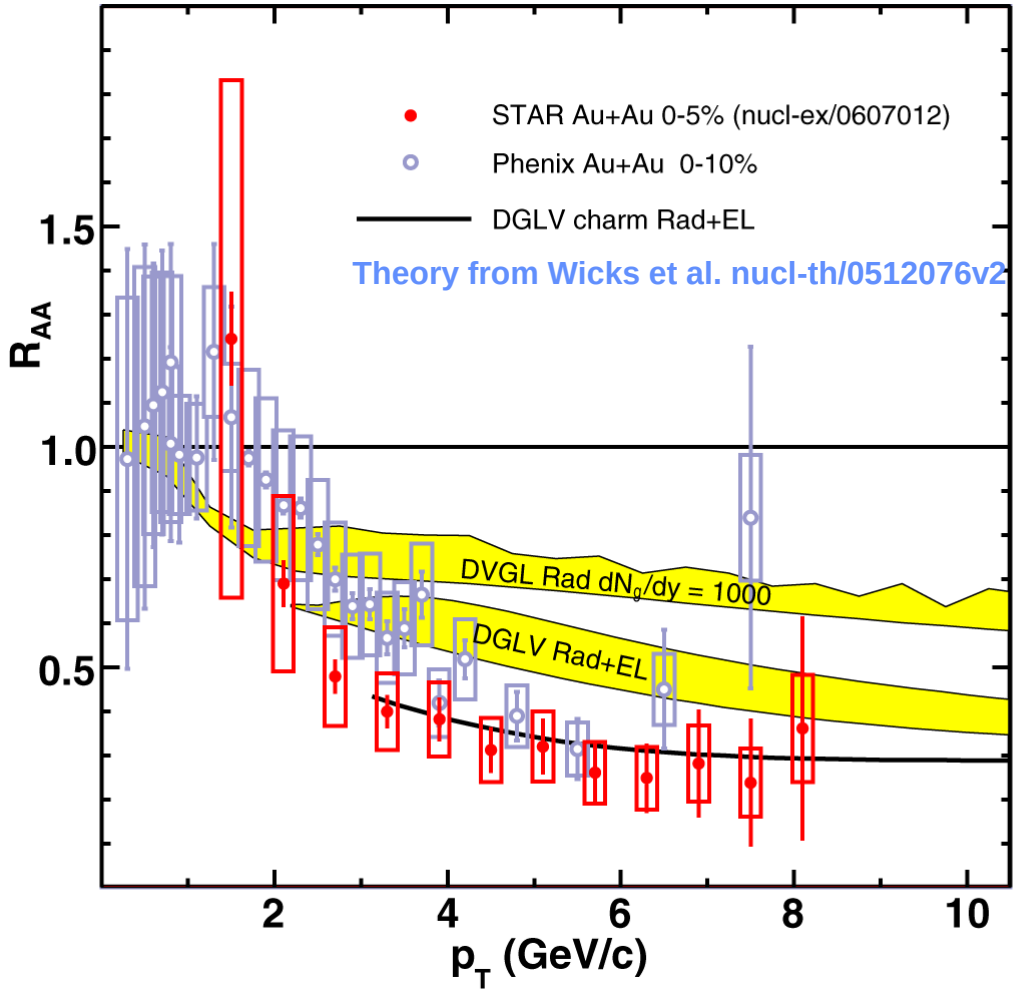


Energy loss $\Rightarrow$
suppression of leading hadron yield
The jet can't get out!

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

Binary collision scaling p+p reference

Heavy Flavor Energy Loss … R_{AA} for Charm

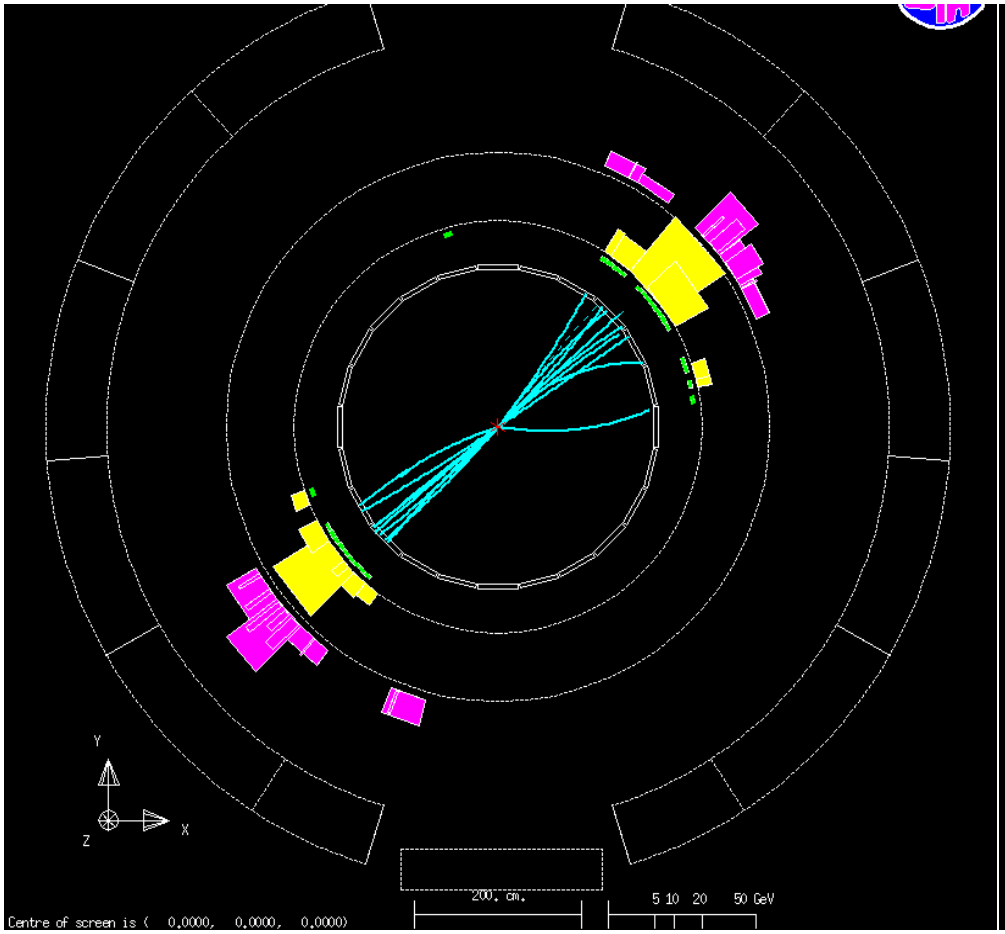


Where is the contribution from Beauty?

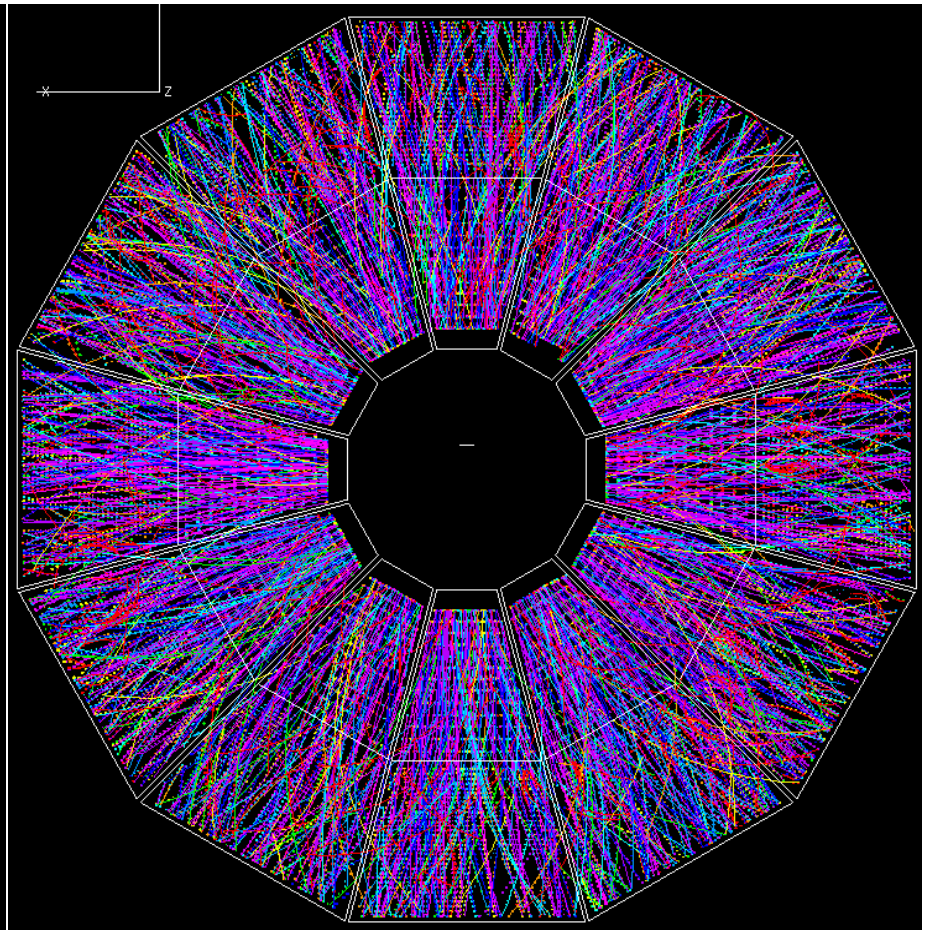
- **Heavy Flavor energy loss is an unsolved problem**
  - **Gluon density ~ 1000 expected from light quark data**
  - **Better agreement with the addition of inelastic E loss**
  - **Good agreement only if they ignore Beauty …**
- **Beauty dominates single electron spectra above 5 GeV**
- **In the future, RHIC upgrades will separate the Charm and Beauty contributions**

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

Jet event in e^+e^- collision

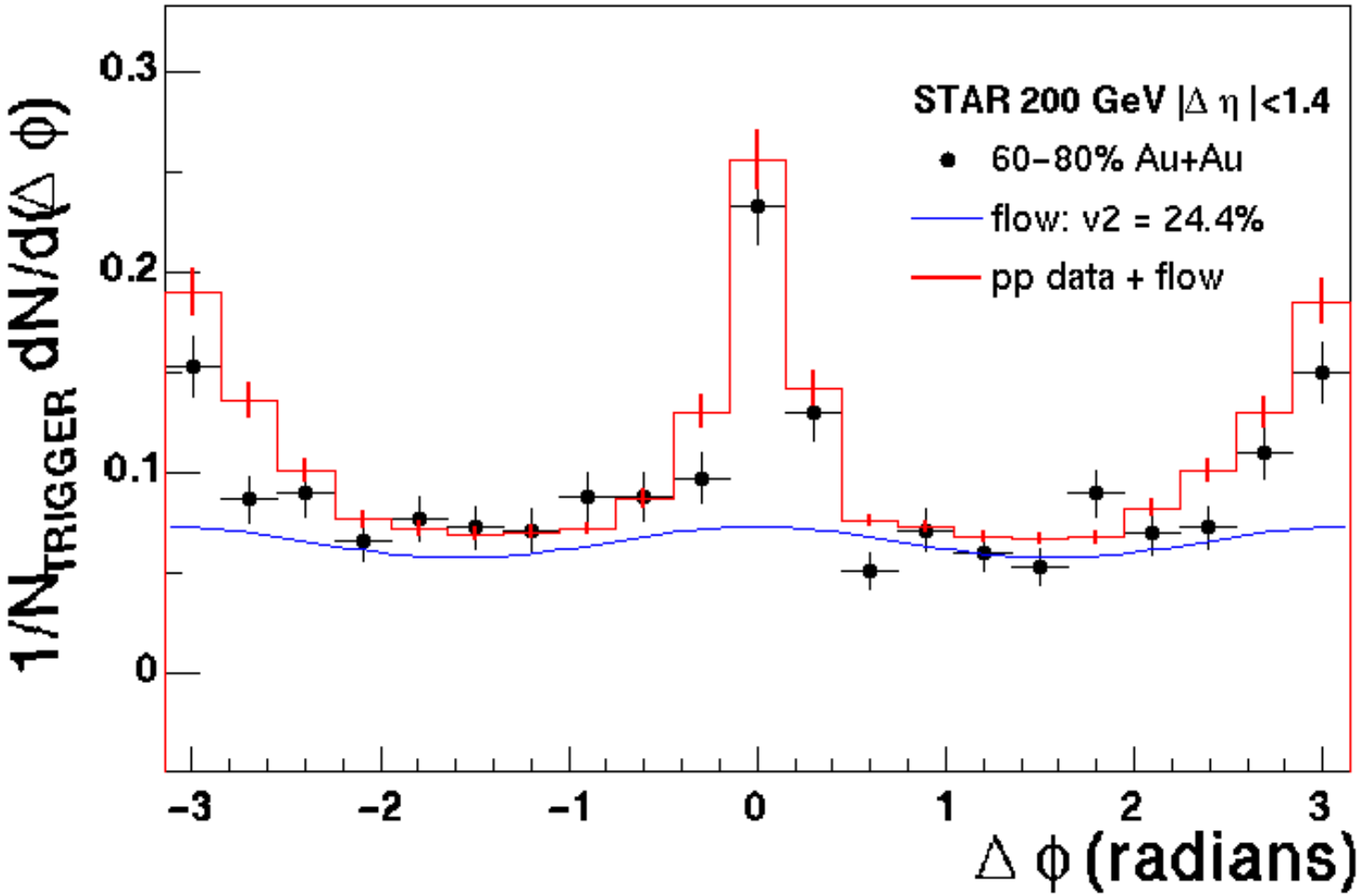


STAR Au+Au collision



Angular Distribution: 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:

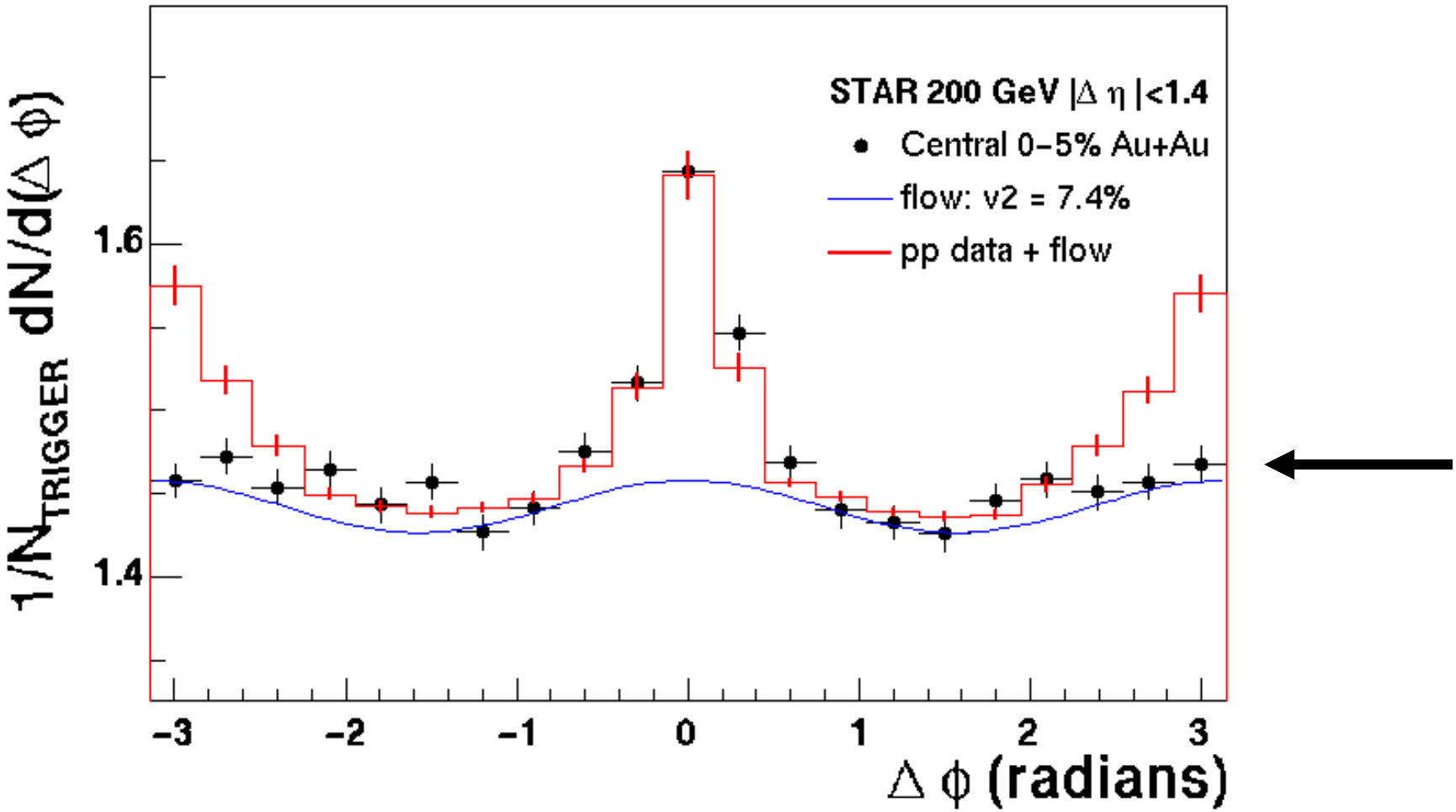
A high p_T triggered Au+Au event is a superposition of a high p_T triggered p+p event plus anisotropic transverse flow

***v_2* from reaction plane analysis**

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

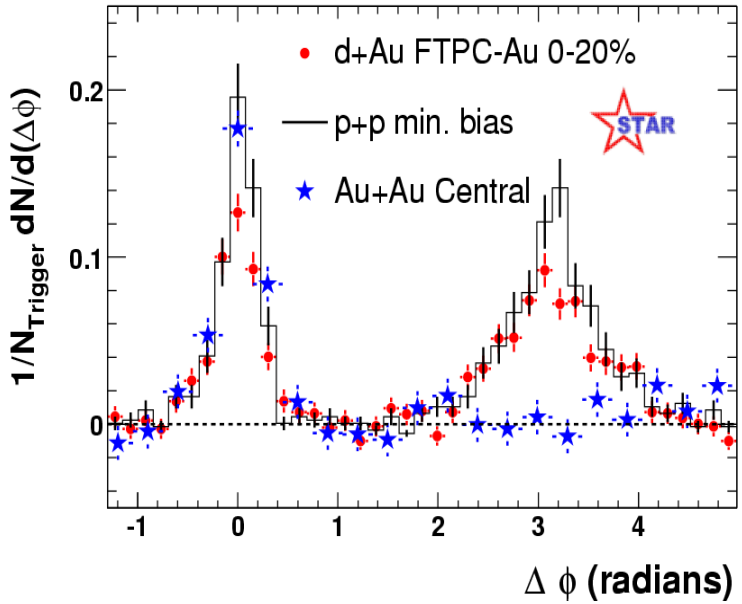
Angular Distribution: Central Au+Au data vs. pp+flow

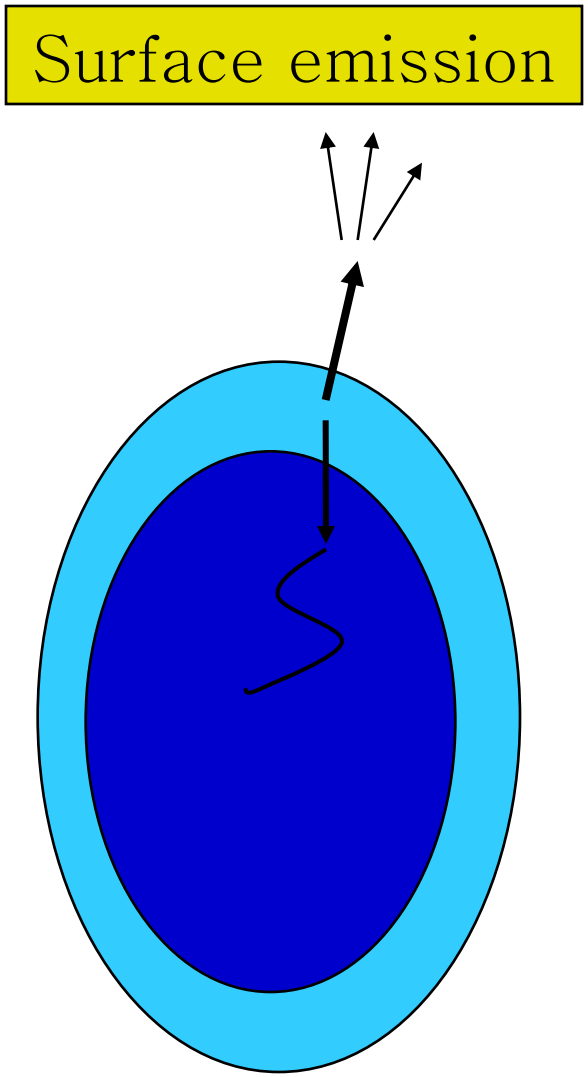
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$



Lessons learned – Dark Matter … its opaque

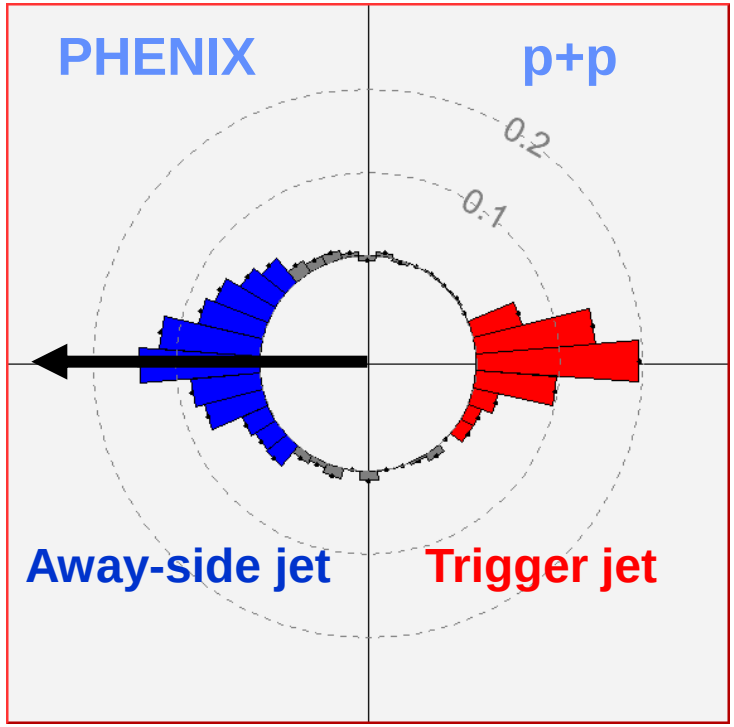
- **The backward going jet is missing in central Au-Au collisions when compared to p-p data + flow**
- **The backward going jet is not suppressed in d-Au collisions**
- **These data suggest opaque nuclear matter and surface emission of jets**

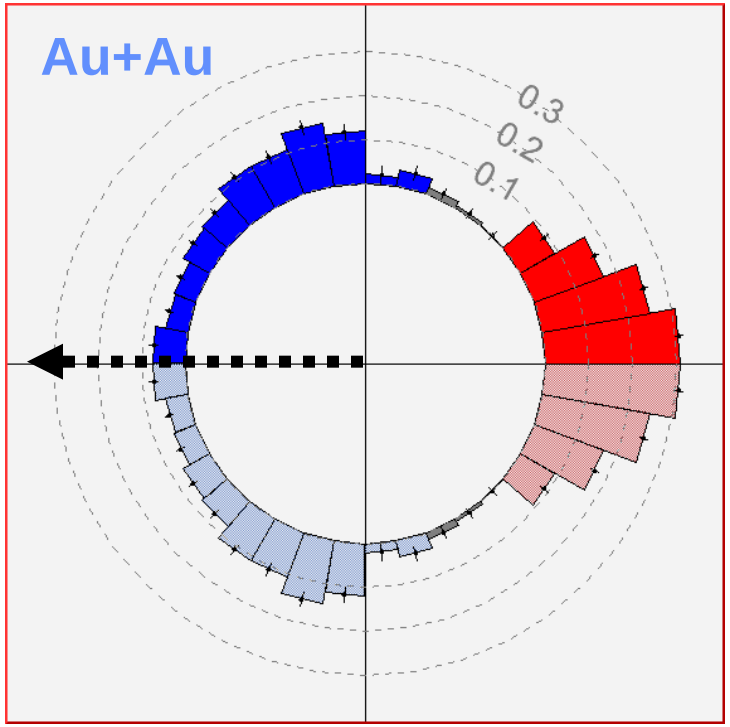




Suppression of back-to-back correlations in central Au+Au collisions

Where does the E_{loss} go?

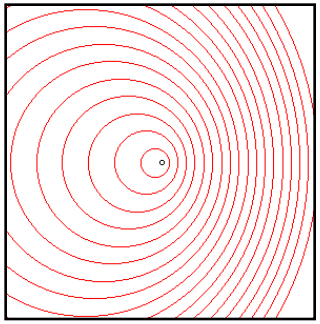




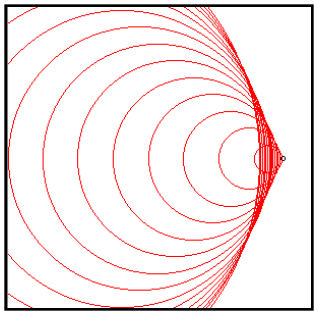
Lost energy of away-side jet is redistributed to rather large angles!

Mach Cone: Theory vs Experiment

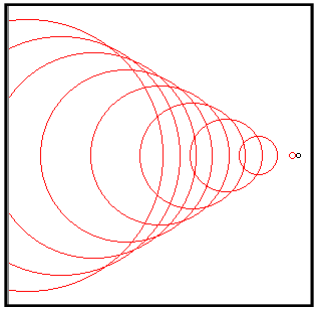
$v/u = 0.5$

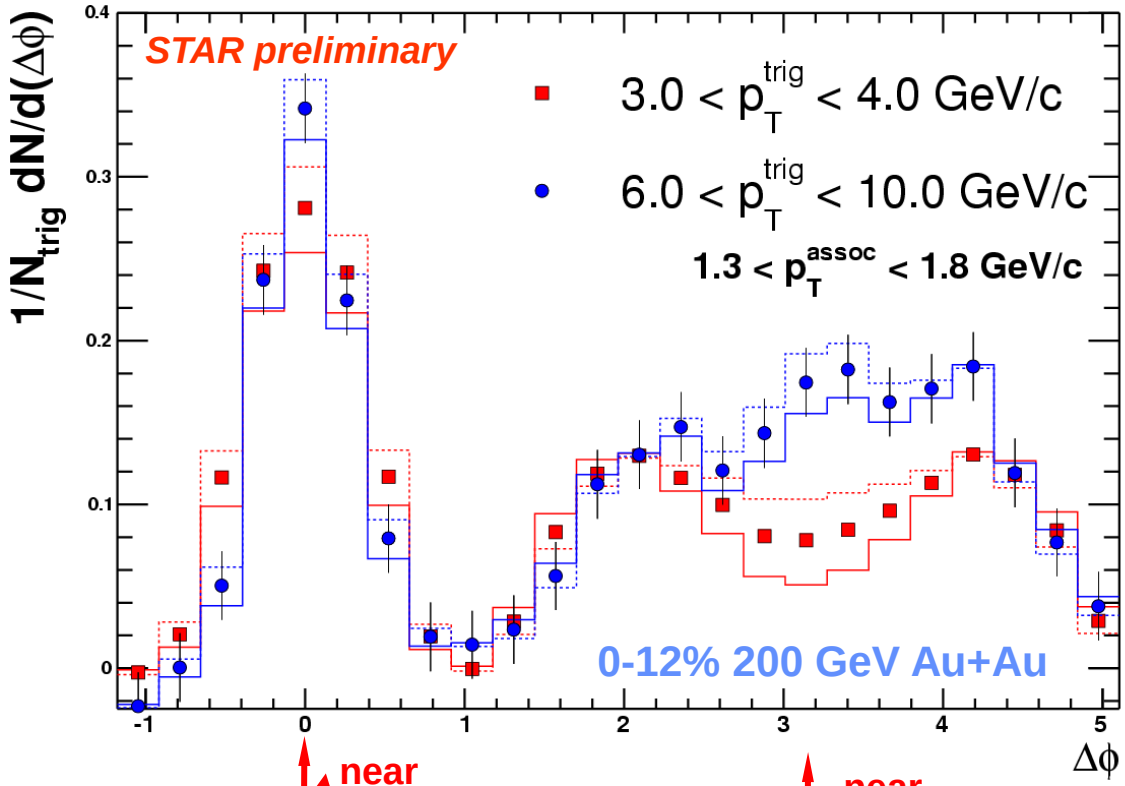


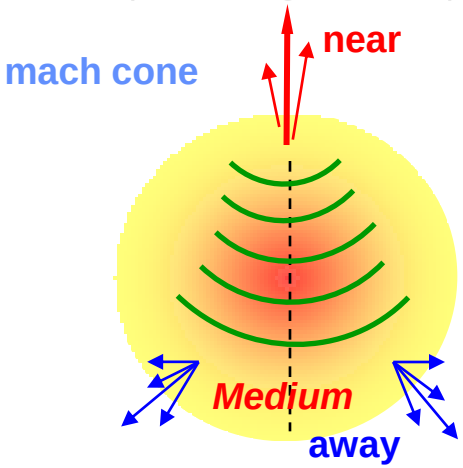
$v/u = 1.1$

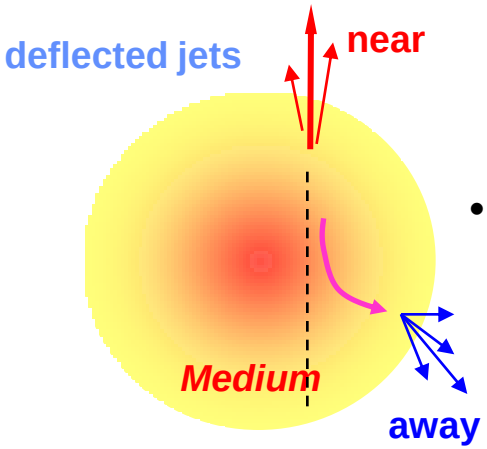


$v/u = 2$



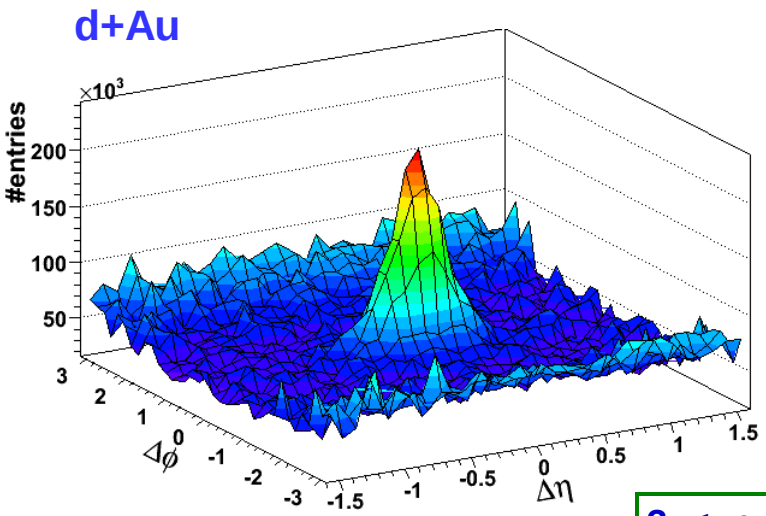


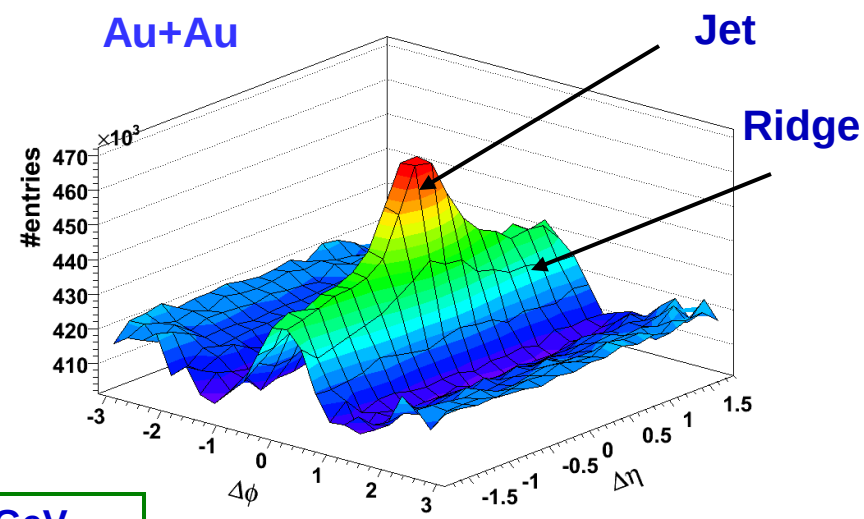




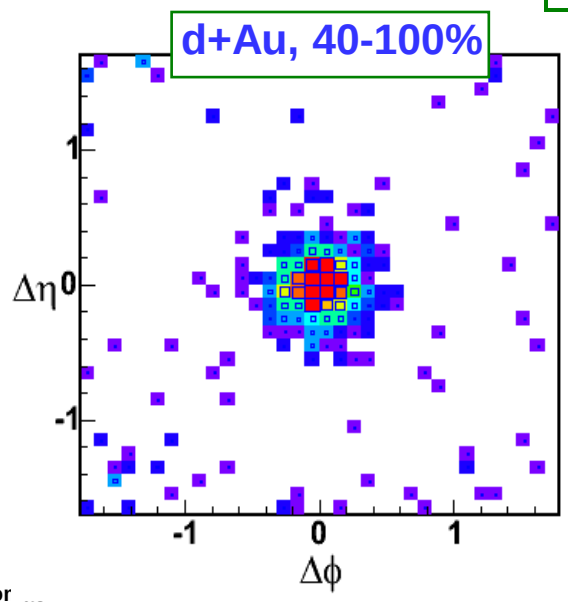
- **Hint of a Mach Cone?**

The Ridge (after v_2 subtraction)

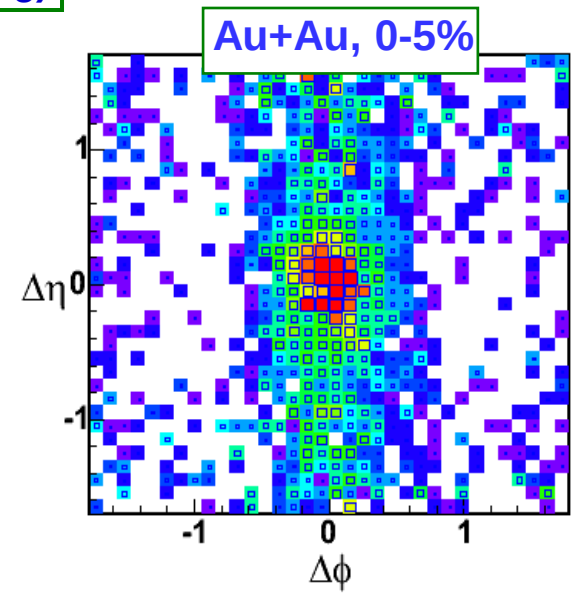




$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

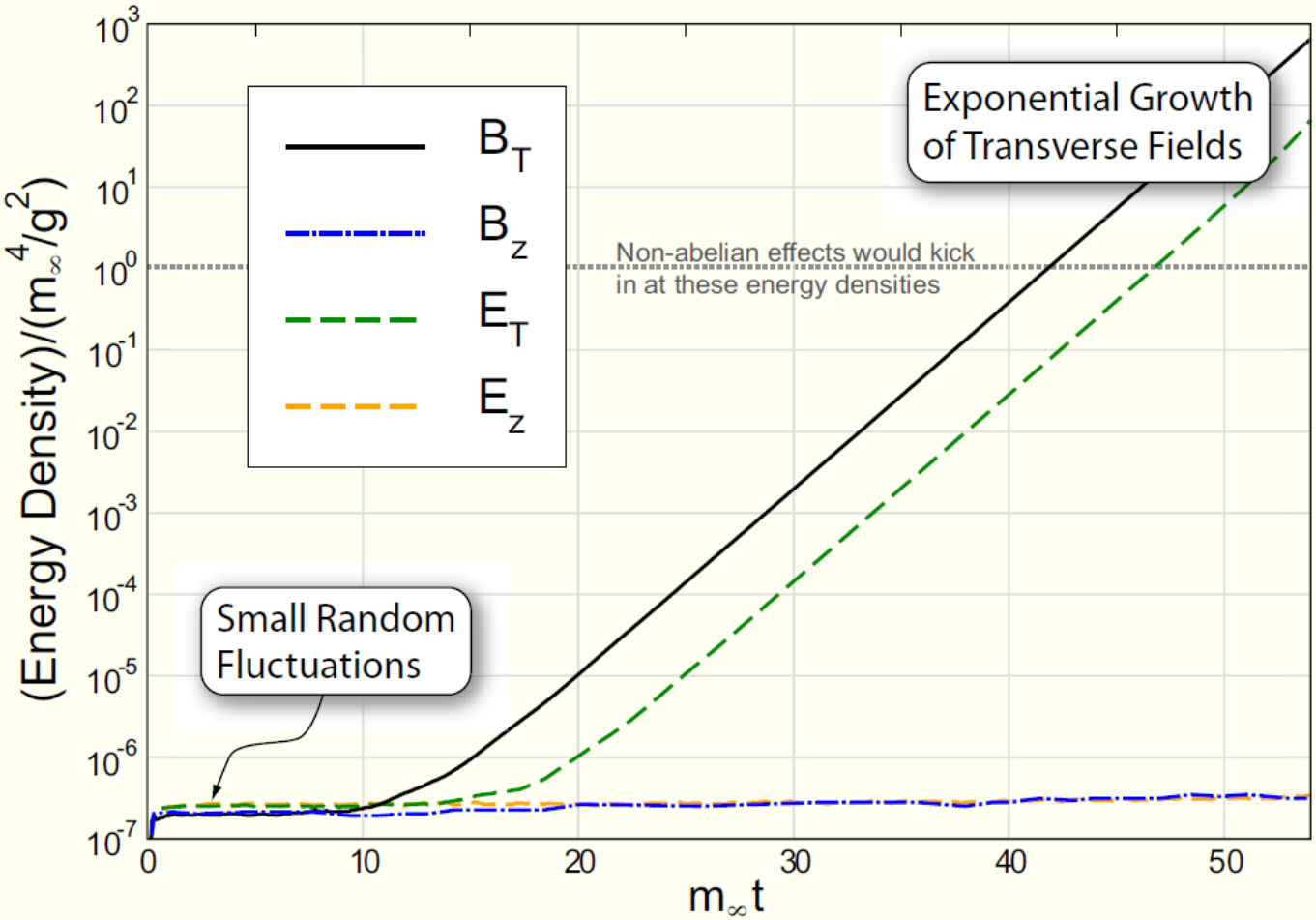


STAR Preliminary



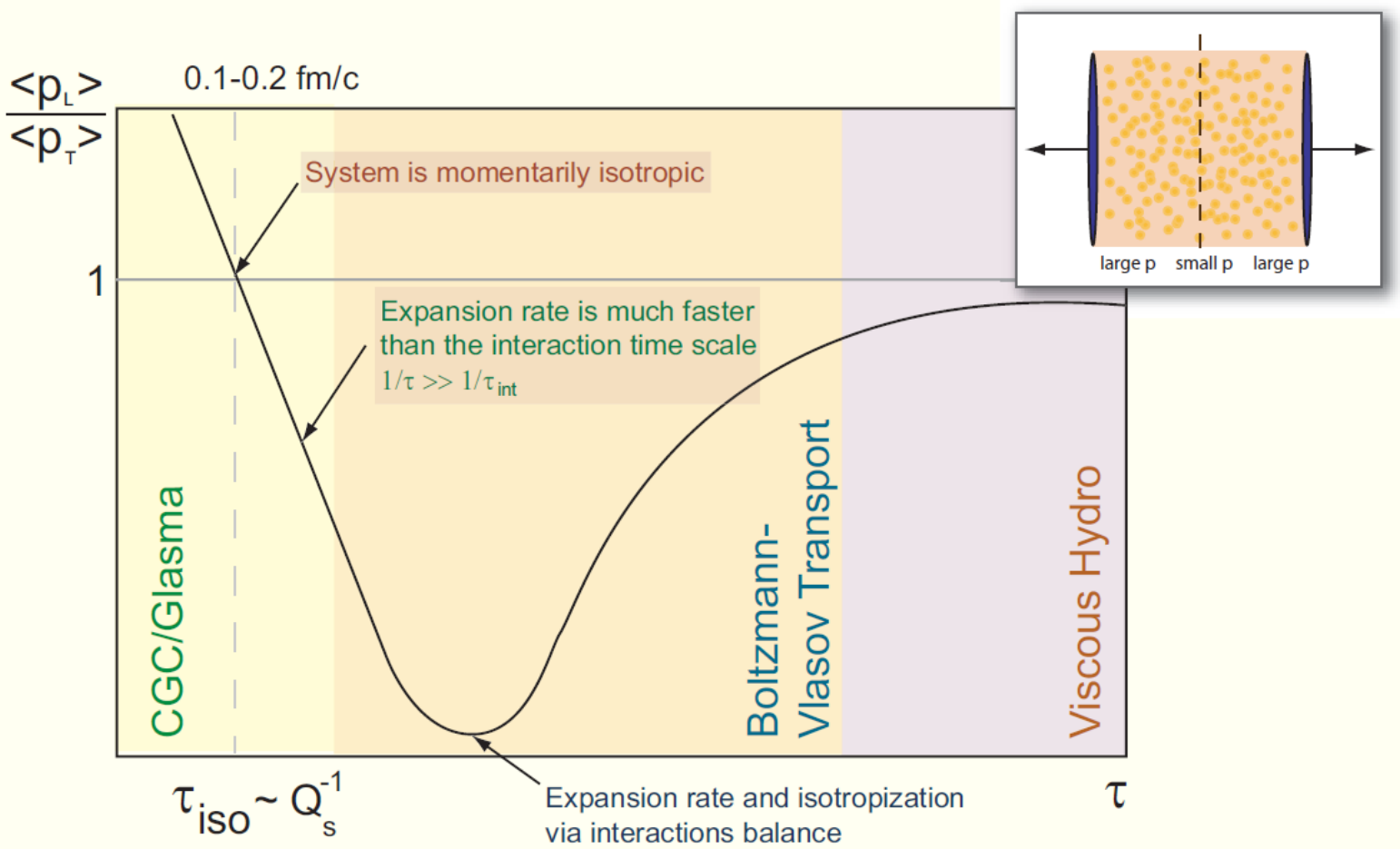
The Ridge May be due to Very Strong Fields

Anisotropic Abelian Plasma – Weibel Instability (1959)



Strong Fields Run Away ⇒ Thermalisation

Momentum Space Anisotropy Time Dependence



AdS/CFT correspondence (from H. Liu)

Maldacena (1997) Gubser, Klebanov, Polyakov, Witten

N = 4 Super-Yang-Mills theory with SU(N) ⟺ **A string theory in 5-dimensional anti-de Sitter spacetime**

anti-de Sitter (AdS) spacetime: homogeneous spacetime with a negative cosmological constant.

***N* = 4 Super-Yang-Mills (SYM):**

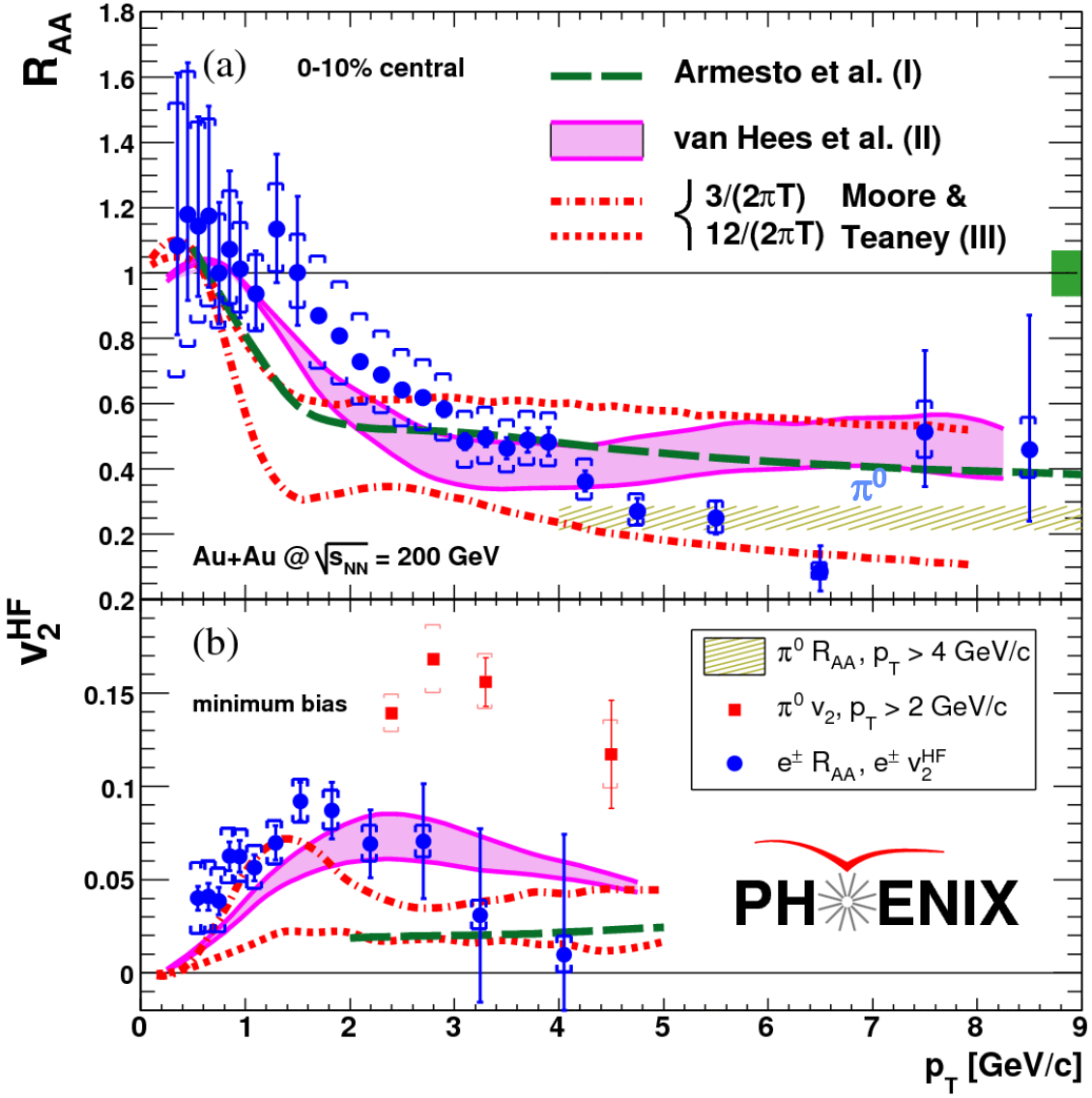
maximally supersymmetric gauge theory

scale invariant

A special relative of QCD

The value $\frac{\eta}{s} = \frac{1}{4\pi}$ **turns out to be universal for all strongly coupled QGPs with a gravity description. It is a universal lower bound.**

PHENIX PRL 98, 172301 (2007)



- R_{AA} of heavy-flavor electrons in 0%–10% central collisions compared with π^0 data and model calculations
- V_2 of heavy-flavor electrons in minimum bias collisions compared with π^0 data and the same models.
- Conclusion is that heavy flavor flow corresponds to η/s at the conjectured QM lower bound

Old Chinese Proverb

Beware of theorists waiting for data

- **Confusion**

Nuclear Fluid Dynamics ... with friction

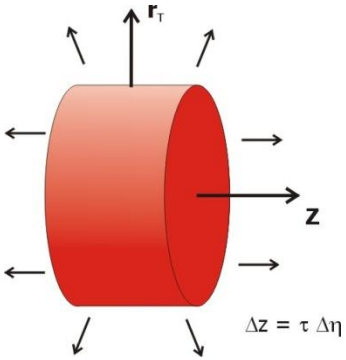
- **The energy momentum tensor for a viscous fluid**

$$T^{\mu\upsilon} = (\varepsilon + p)\, u^{\mu} u^{\upsilon} - p g^{\mu\nu} + \Pi^{\mu\nu}$$

- **Conservation laws:** $\partial_{\mu} T^{\mu\upsilon} = 0$ **and** $\partial_{\mu} j^{\mu} = 0$ **where** $j_i^{\mu} = \rho_i\, u^{\mu}$

- **The elements of the shear tensor, $\Pi^{\mu\nu}$, describe the viscosity of the fluid and can be thought of as velocity dependent 'friction'**

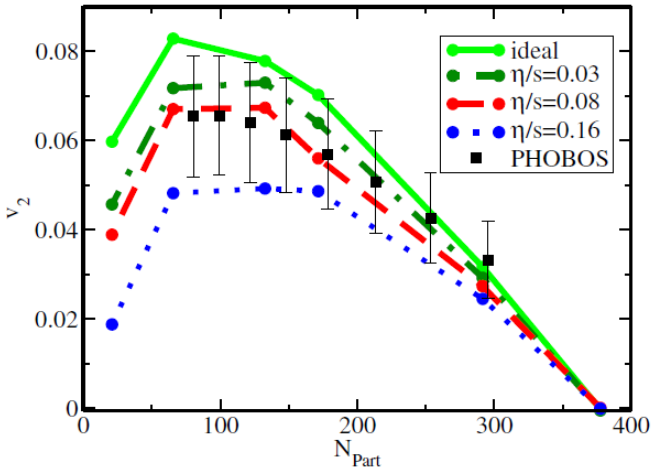
- **Simplest case: scaling hydrodynamics**
  - **assume local thermal equilibrium**
  - **assume longitudinal boost-invariance**
  - **cylindrically symmetric transverse expansion**
  - **no pressure between rapidity slices**
  - **conserved charge in each slice**

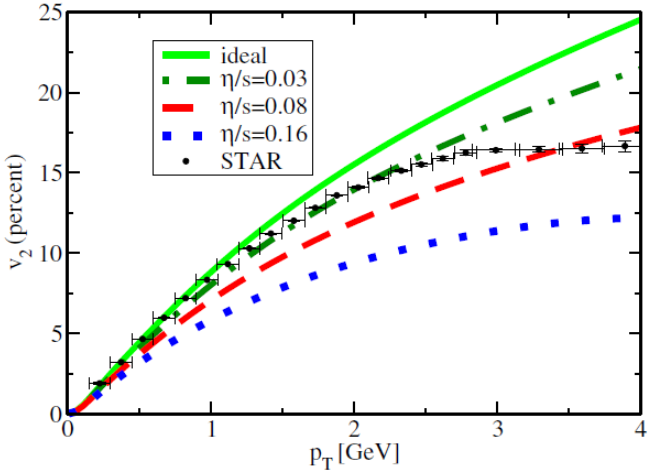


- **Initially expansion is along the Z axis, so viscosity resists it**
  - **Conservation of $T^{\mu\nu}$ means that energy and momentum appear in the transverse plane … viscosity drives radial flow**

- **Viscosity is velocity dependent friction so it dampens v_2**
  - **Viscosity (η/s) must be near zero for large elliptic flow to be observed**

3D Hydro … new insights

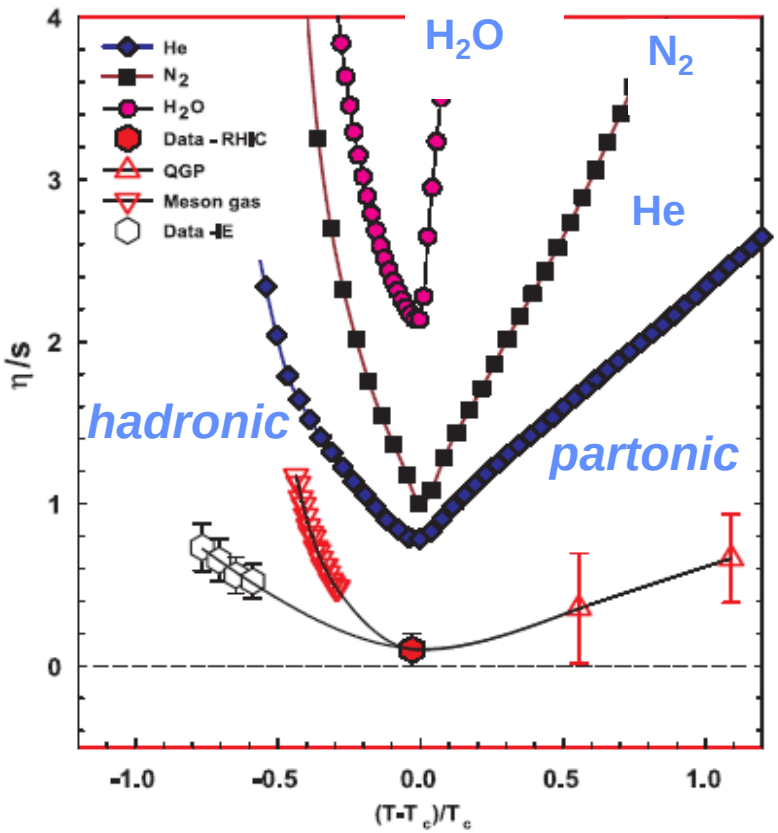




PRL 99, 172301 (2007)

- **Romatschke[2] performed relativistic viscous hydrodynamics calculations including the new 2nd order terms beyond Landau's prescription**
- **Data on the integrated elliptic flow coefficient v_2 are consistent with a ratio of viscosity over entropy density up to $\eta/s \approx 0.16$**
- **But data on minimum bias v_2 seem to favor a much smaller viscosity over entropy ratio, below the bound from the anti–de Sitter conformal field theory conjecture**

Viscosity and the Perfect Fluid



Caption: *The viscosity to entropy ratio versus a reduced temperature.*

Lacey et al. PRL 98:092301(07)
hep-lat/0406009; hep-ph/0604138
Csernai et al, PRL97, 152303(06)

The universal tendency of flow to be dissipated due to the fluid's *internal friction* results from a quantity known as the shear viscosity. All fluids have non-zero viscosity. The larger the viscosity, the more rapidly small disturbances are damped away.

Quantum limit: $\eta/s_{AdS/CFT} \sim 1/4\pi$

pQCD limit: ~ 1

At RHIC: ideal ($\eta/s = 0$) hydrodynamic model calculations fit to data ⇒

Perfect Fluid at RHIC?!

STAR Upgrades to keep the discoveries rolling …

In the queue

- **Forward Meson Spectrometer**
  - Gluon density distributions, saturation effects, and transverse spin
- **DAQ Upgrade**
  - order of magnitude increase in rate
  - extra bandwidth opens the door to ‘small’ physics
- **Full Barrel MRPC TOF**
  - extended particle identification at intermediate p_T

Engines running

- **Forward GEM Tracker**
  - end cap tracker for W sign determination
- **Heavy Flavor Tracker**
  - high precision Heavy Flavor Tracker near the vertex
  - opens the door to direct topological ID of Charm & Beauty

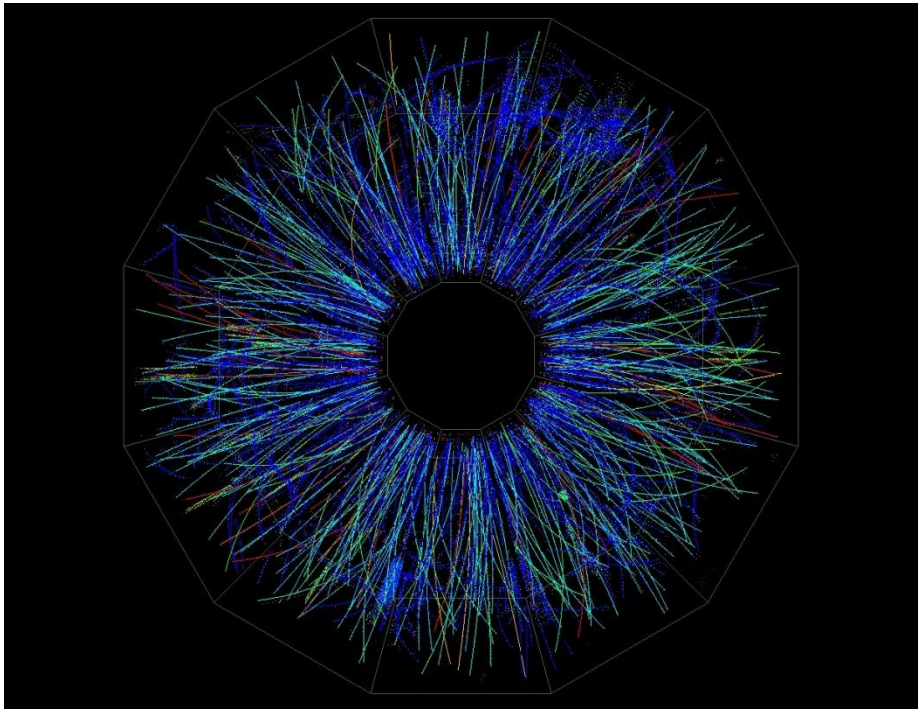
Warming Up

- Muon Telescope
- Forward Reaction Plane Detector
- A Crystal Calorimeter for low E photons
- γ-γ HBT

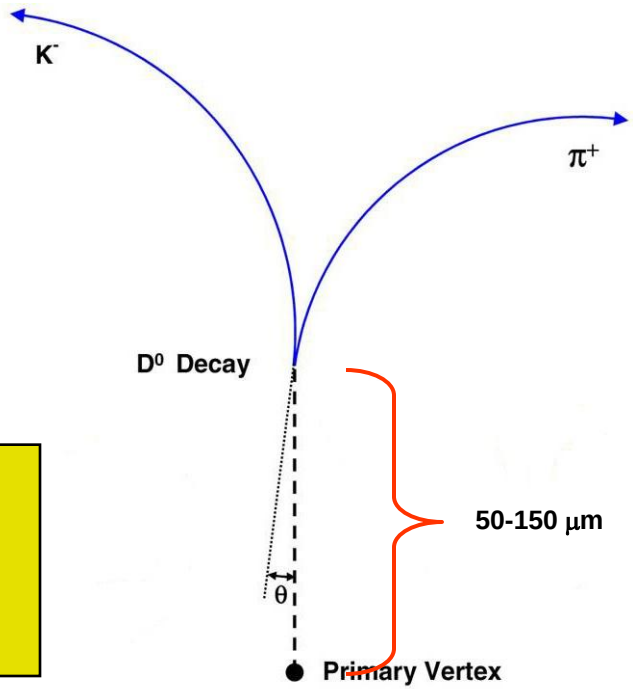
The Properties of the Open Charm Hadrons

Particle	Decay Channel	$c\tau$ (μm)	Mass (GeV/c^2)
D^0	$K^- \pi^+$ (3.8%)	123	1.8645
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312	1.8694
D_s^+	$K^+ K^- \pi^+$ (5.2%) $\pi^+ \pi^+ \pi^-$ (1.2%)	150	1.9683
Λ_c^+	$p K^- \pi^+$ (5.0%)	59.9	2.2865

Direct Topological Identification of Open Charm



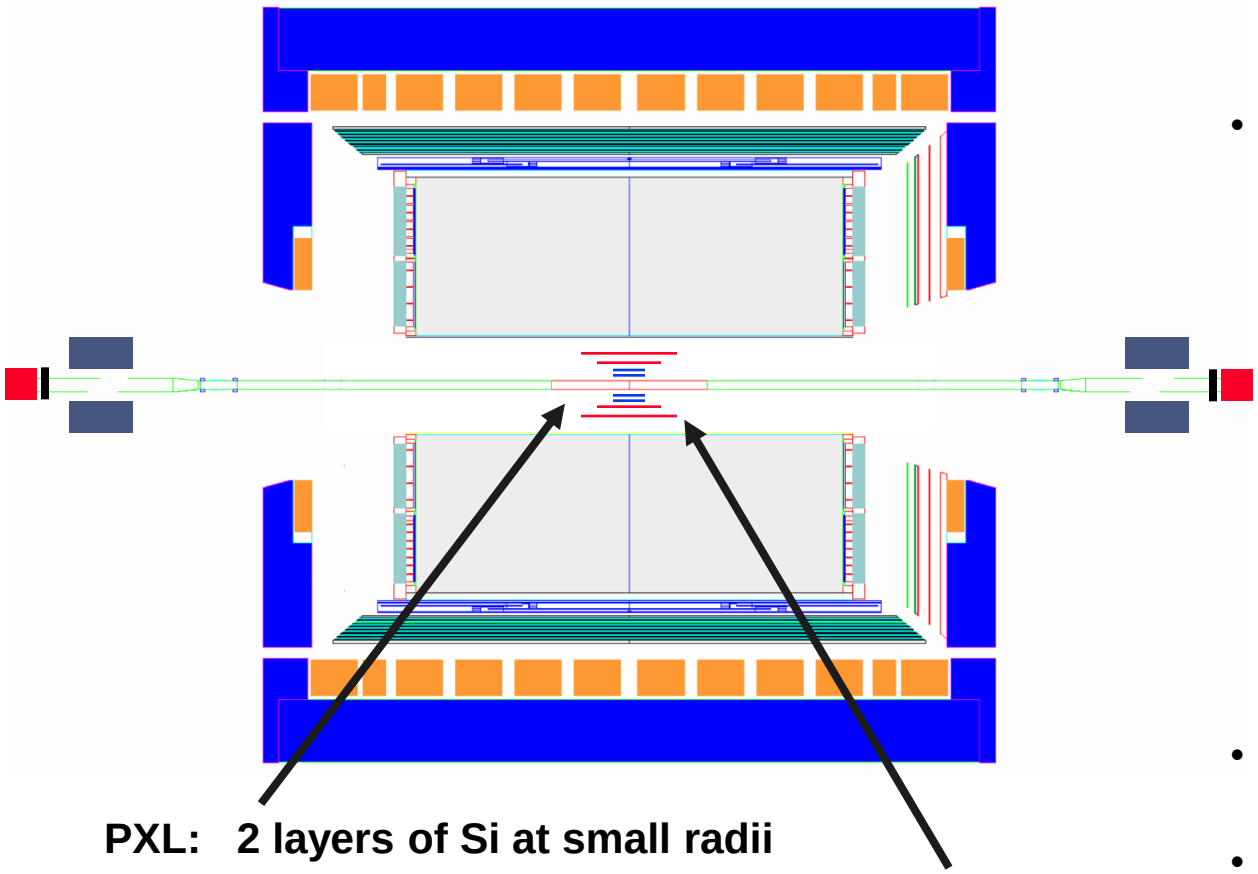
Goal: Distinguish secondary from primary vertices by putting a high precision detector near the IP to extend the TPC tracks to small radius



The STAR Inner Tracking Upgrades will identify the daughters in the decay and do a direct topological reconstruction of the open charm hadrons.

No ambiguities between charm and beauty.

The Heavy Flavor Tracker = PXL + IST + SSD



PXL: 2 layers of Si at small radii

IST: 1 layer of Si at intermediate radius

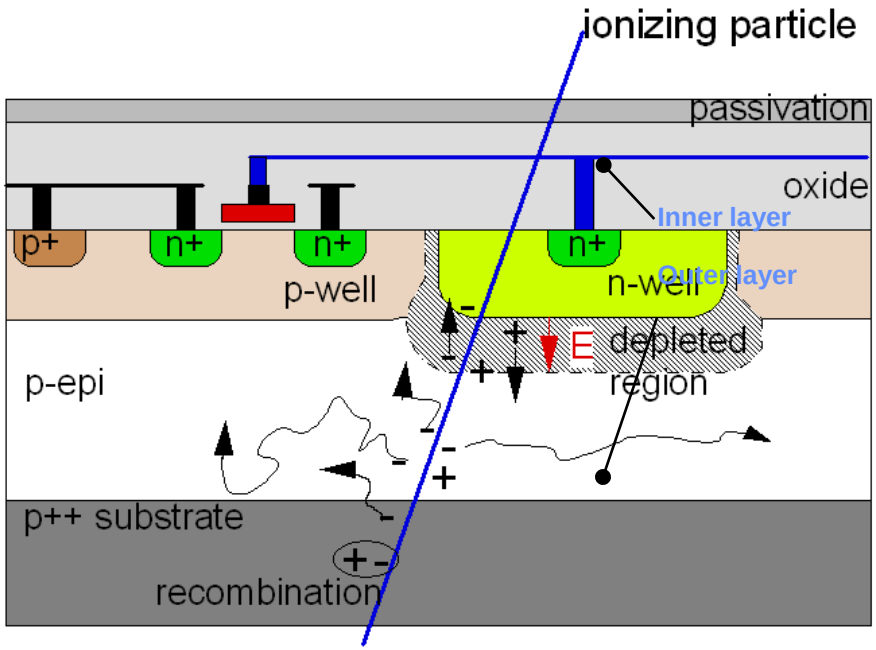
SSD: an existing detector at 23 cm radius

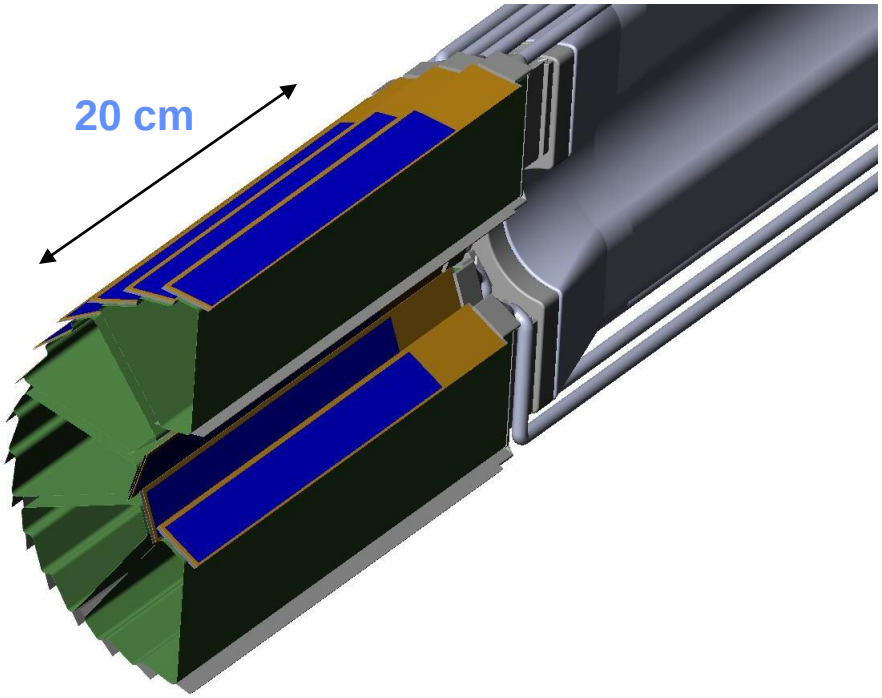
- **A new detector**
  - **30 μm silicon pixels to yield 10 μm space point resolution**
- **Direct Topological reconstruction of Charm**
  - **Detect charm decays with small cτ, including $D^0 \rightarrow K\,\pi$**
- **New physics**
  - **Charm collectivity and flow to test thermalization at RHIC**
  - **Charm Energy Loss to test pQCD in a hot and dense medium at RHIC**
- **The SSD … is part of the plan for tracking TPC ⇒ HFT**
- **The technical design is evolving but converging rapidly to final form.**

Active Pixel Sensors from IPHC Strasbourg

- 30 μm pixels
- 640 x 640 pixels per chip
- 10 chips per ladder
- 100 – 200 μsec integration time
- 164 M pixels, total
- 300 kRad hardness

  (~1 yr under certain conditions)



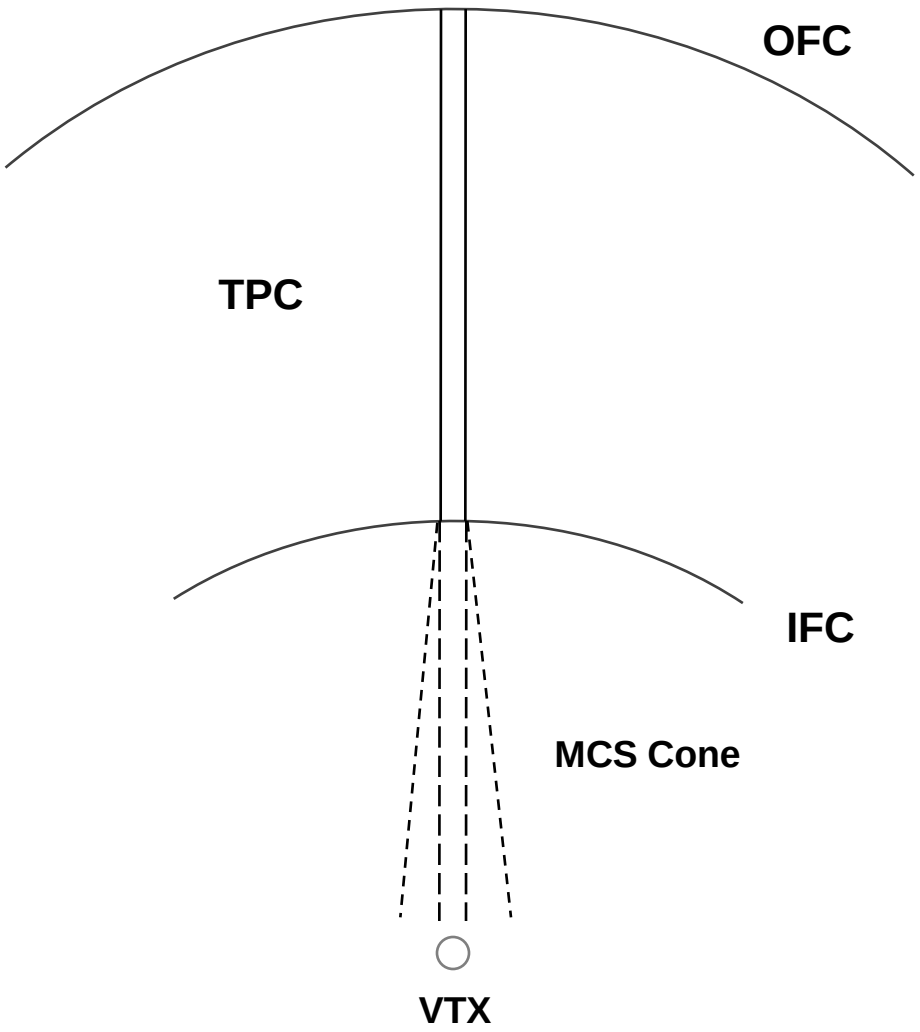


Properties:

- Signal created in low-doped epitaxial layer (typically ~10-15 μm)
- Sensor and signal processing integrated in the same silicon wafer
- Standard commercial CMOS technology

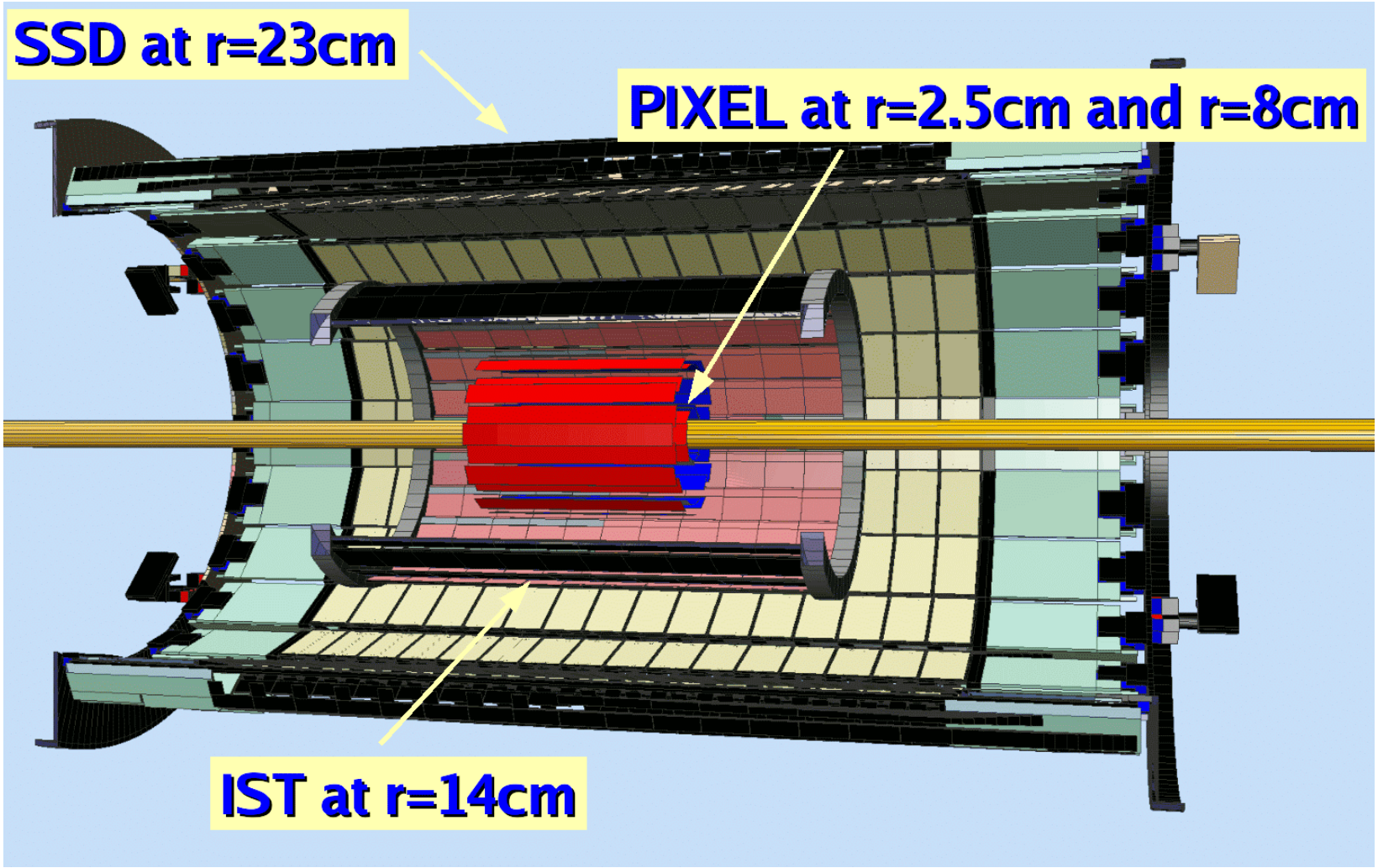
Getting a Boost from the TPC

- **The TPC provides good but not excellent resolution at the vertex and at other intermediate radii**
  - **~ 1 mm**
- **The TPC provides an excellent angular constraint on the path of a predicted track segment**
  - **This is very powerful.**
  - **It gives a parallel beam with the addition of MCS from the IFC**
- **The best thing we can do is to put a pin-hole in front of the parallel beam track from the TPC**
  - **This is the goal for the Si trackers: SSD, IST, and PXL**
- **The SSD and IST do not need extreme resolution. Instead, the goal is to maintain the parallel beam and not let it spread out**
  - **MCS limited**
  - **The PXL does the rest of the work**



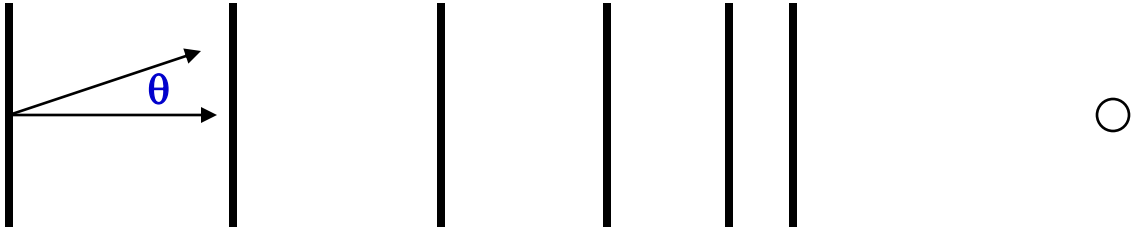
The Gift of the TPC

Optimized HFT Configuration



The HFT configuration described in the Addendum

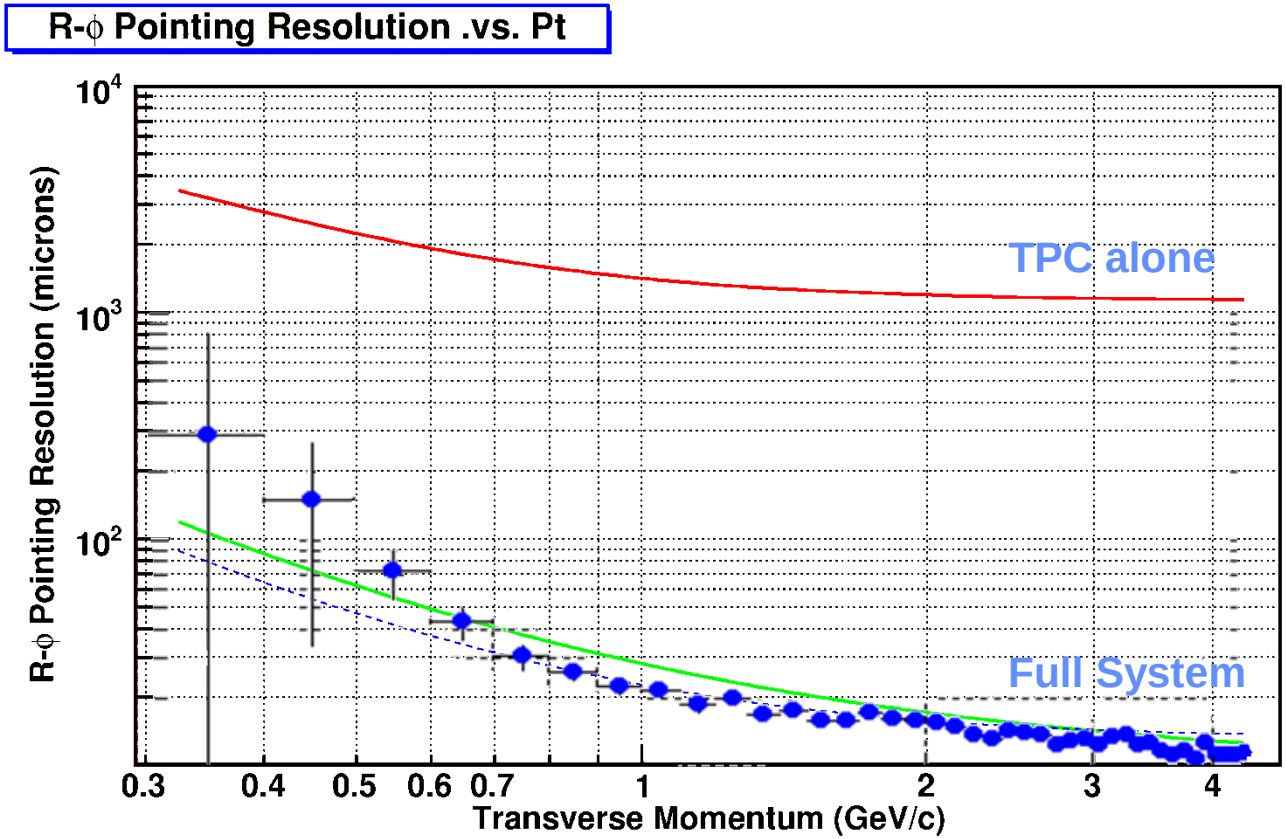
Calculating the Performance of the Detector



$$[MCS][D][M][MCS][D]\,|\,[M][MCS] \quad \bullet \quad \bullet \quad \bullet$$

- **Billoir invented a matrix method for evaluating the performance of a detector system including MCS and dE/dx**
  - **NIM 225 (1984) 352.**
- **The 'Information Matrices' used by Billoir are the inverse of the more commonly used covariance matrices**
  - **thus, σ's are propagated through the system**
- **ITTF tracking software uses a similar method (aka a Kalman Filter)**
  - **The 'hand calculations' go outside-in**
  - **STAR Software goes outside-in and then inside-out, and averages the results, plus follows trees of candidate tracks. It is 'smart' software.**

Hand Calculations .vs. GEANT & ITTF



- - - - PXL stand alone configuration

——— Paper Proposal configuration

● ● ● GEANT & ITTF

——— Updated configuration … no significant changes in pointing at VTX

MinBias Pileup – The PXL Layers Integrate over Time

Integrate over time and interaction diamond

$$\frac{dN}{dA}(MinBias, z, r, \sigma) = \frac{dN}{d\eta} \times \frac{1}{2\pi r} \times ZDC \times \tau \times \int_{-a}^{a} \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-z_0^2}{2\sigma^2}} \frac{d\eta}{d(z-z_0)} dz_0$$

200 μsec

$$\frac{dN}{dA}(MinBias, z, r, \sigma) = \frac{2720}{2\pi r} \times \int_{-a}^{a} \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-z_0^2}{2\sigma^2}} \frac{1}{\sqrt{r^2 + (z-z_0)^2}} dz_0$$

	PIXEL-1 Inner Layer	PIXEL-2 Outer Layer
Radius	2.5 cm	8.0 cm
Central collision hit density	17.8 cm^{-2}	1.7 cm^{-2}
Integrated MinBias collisions (pileup)	23.5 cm^{-2}	4.2 cm^{-2}
UPC electrons	19.9 cm^{-2}	0.1 cm^{-2}
Totals	**61.2 cm^{-2}**	**6.0 cm^{-2}**

Pileup is the bigger challenge

A full study of the integrated hit loading on the PIXEL detector includes the associated pileup due to minBias Au-Au collisions and the integration time of the detector.

Efficiency Calculations in a high hit density environment

The probability of associating the right hit with the right track on the first pass through the reconstruction code is:

P(good association) = 1 / (1+S)

where $S = 2\pi\, \sigma_x\, \sigma_y\, \rho$

P(bad association) = (1 – Efficiency) = S / (1 + S)

and when S is small

P(bad association) $\approx 2\pi\, \sigma_x\, \sigma_y\, \rho$

An area

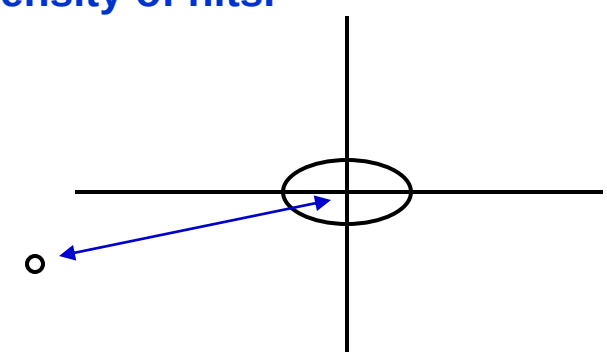
A density, depends on τ and pileup

σ_x is the convolution of the detector resolution and the projected track error in the 'x' direction, and ρ is the density of hits.

The largest errors dominates the sum

$$\sigma_x = \sqrt{(\sigma^2_{xp} + \sigma^2_{xd})}$$

$$\sigma_y = \sqrt{(\sigma^2_{yp} + \sigma^2_{yd})}$$



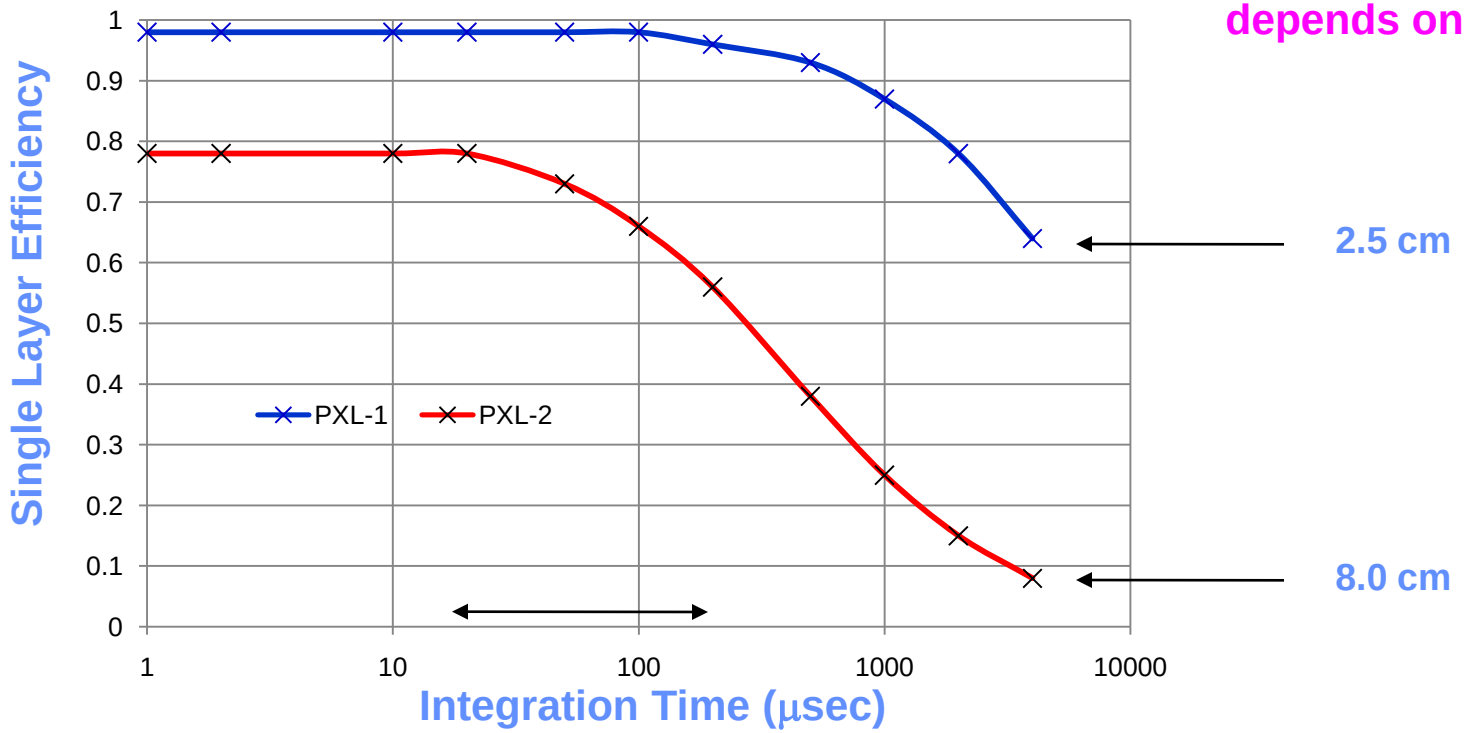
Asymmetric pointing resolutions are very inefficient … try to avoid it

The performance of the TPC pointing at the PXL

- **The performance of the TPC acting alone to point at the PXL detector depends on the integration time of the PXL chips**

P(good association) = 1 / (1+S) **where $S = 2\pi\sigma_x\sigma_y\rho$**

depends on τ

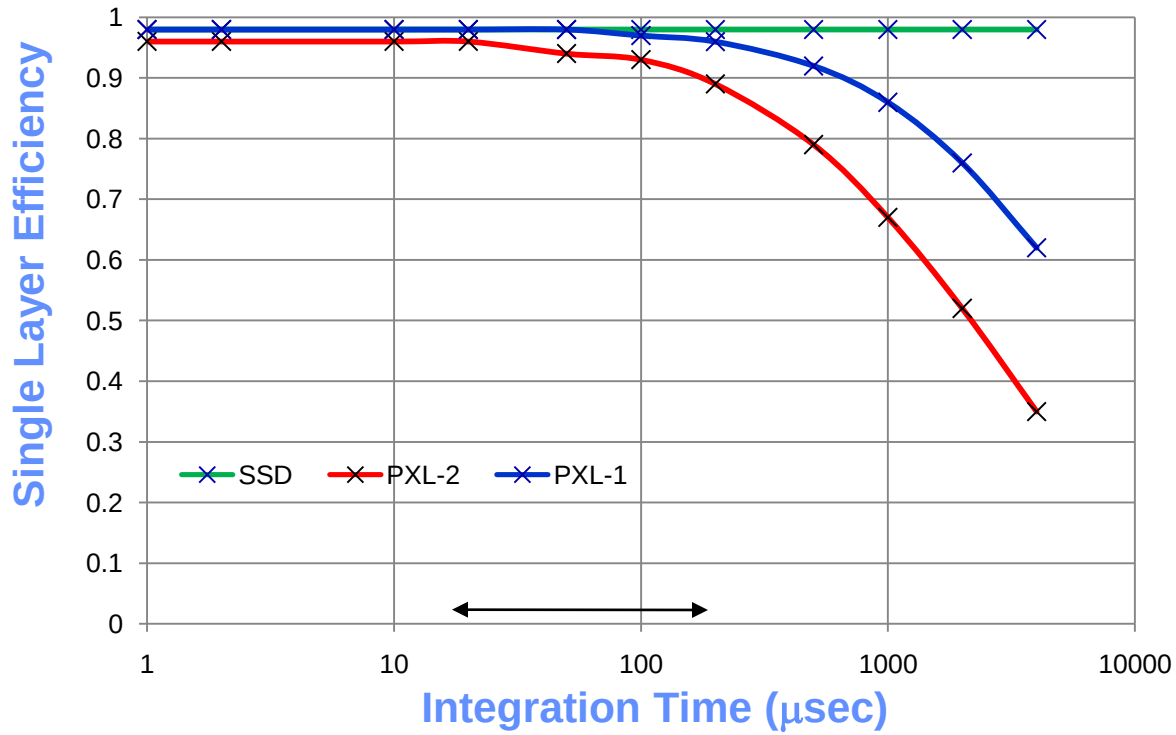


The purpose of intermediate tracking layers is to make 55% go up to ~100%

The performance of the TPC + SSD + PXL

- **The performance of the TPC + HFT acting together depends on the integration time of the PXL chip … but overall the performance is very good**

P(good association) = 1 / (1+S) where $S = 2\pi\, \sigma_x\, \sigma_y\, \rho$

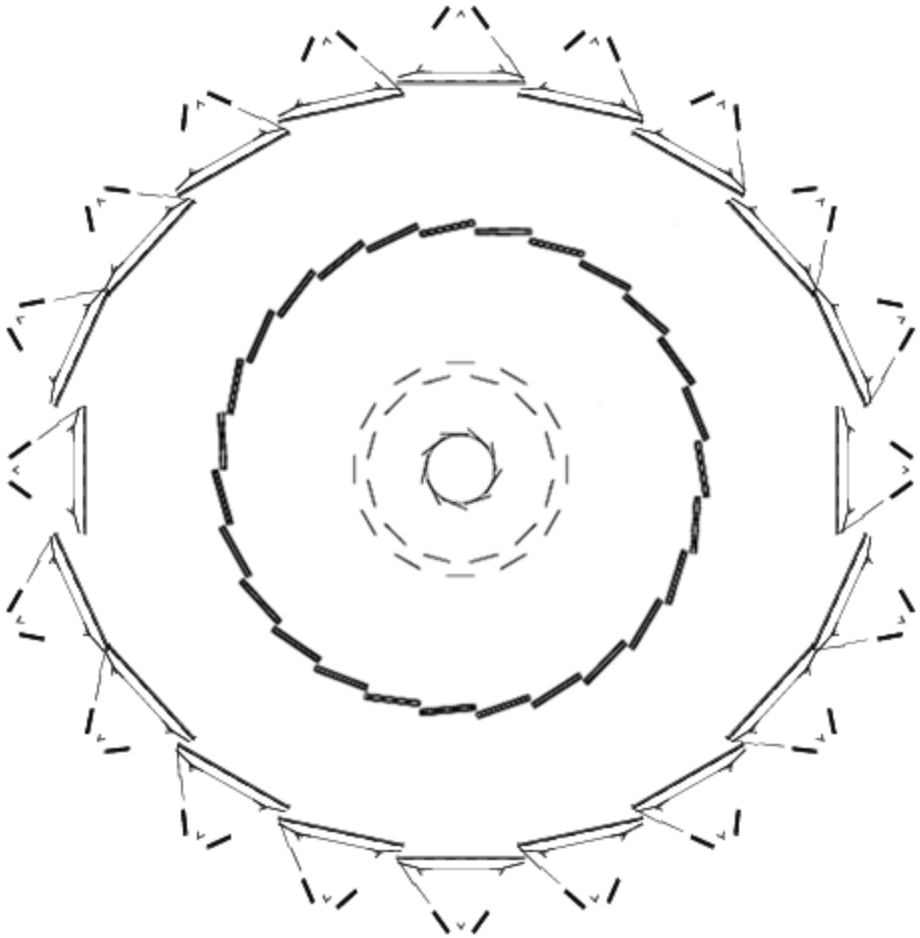


Note that systematic errors are not included in the hand calculations nor in the GEANT Simulations

Random errors <u>only</u> included in hand calculations and in GEANT/ITTF simulations

The performance of the TPC + SSD + IST + PXL

- Goal: graded resolution and high efficiency from the outside → in
- TPC – SSD – IST – PXL
- TPC pointing resolution at the SSD ~ 1 mm $\varepsilon = 0.98$
- SSD pointing at the IST is ~ 400 μm $\varepsilon = 0.98$
- IST pointing at PXL 2 is ~ 400 μm $\varepsilon = 0.93$
- PXL 2 pointing at PXL1 is ~ 125 μm $\varepsilon = 0.94$
- PXL1 pointing at the VTX is ~ 40 μm



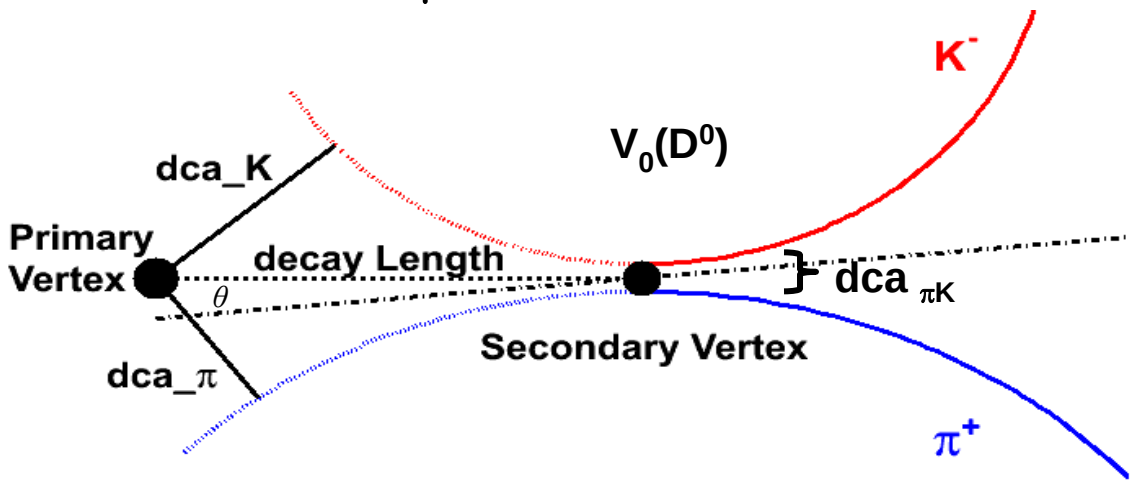
~ 50 cm

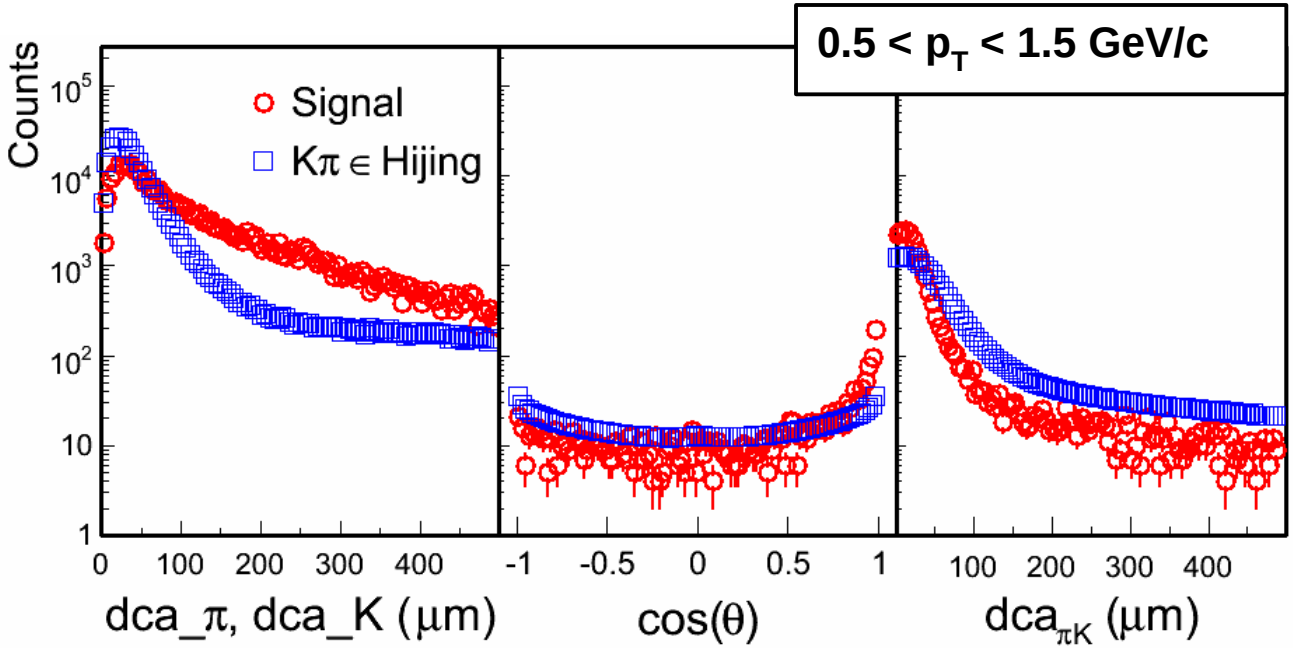
Raw HFT Tracking Efficiency: 0.98 x 0.98 x 0.93 x 0.94 = 0.84

Geometric acceptance and TPC track finding efficiencies
0.9 x 0.9 x 0.8 = 0.65 In this example Tot = 0.55

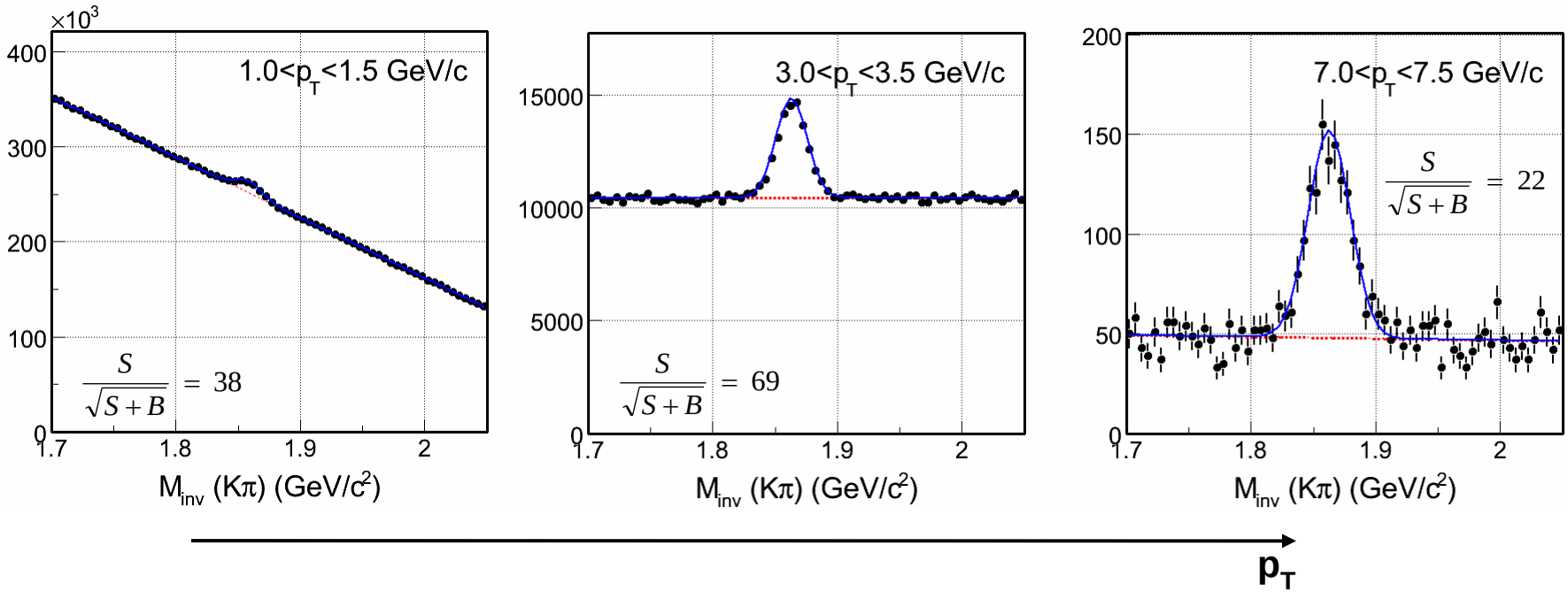
D^0 reconstruction

M_{D0} = 1.8645 GeV/c^2 $c\tau$ = 123 μm





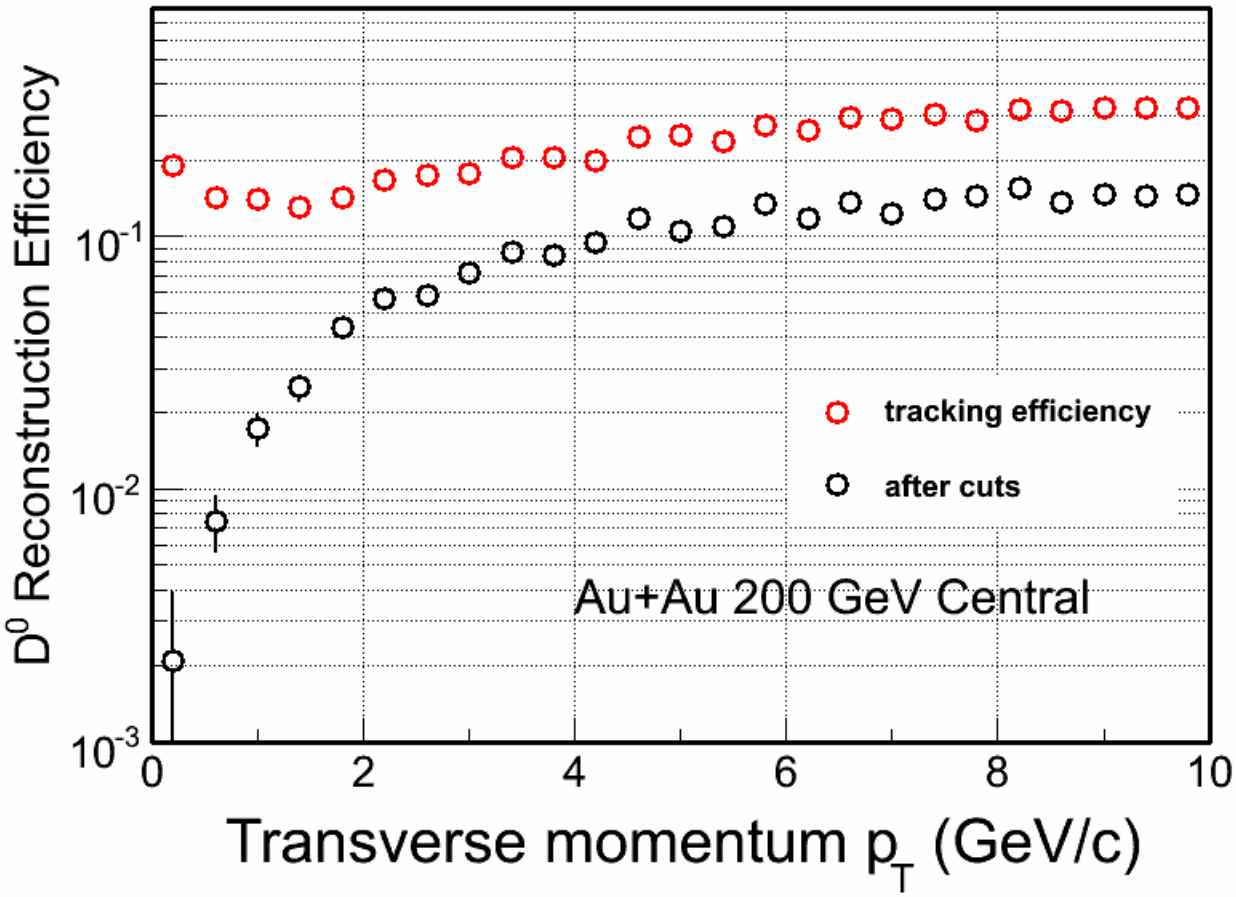
D^0 expected invariant mass distributions



For 100 M Au+Au central collisions at 1x RHIC II luminosity

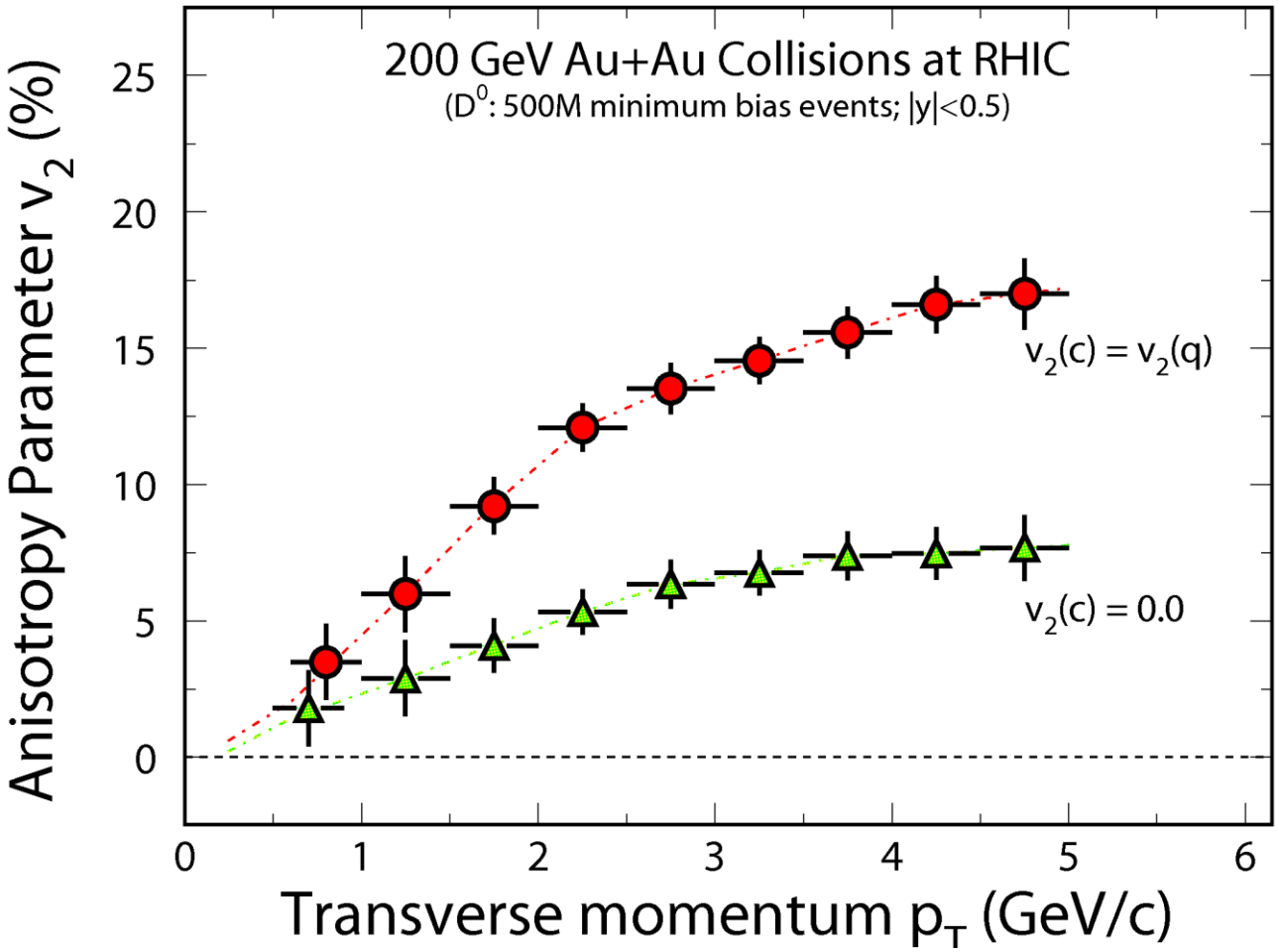
p_T distributions for (S,B) at high p_T are from power-law guess and Hijing, respectively. D^0 Background slope at high p_T could be uncertain due to limited statistics in MC.

D^0 Reconstruction Efficiency



- **The predicted <u>absolute</u> efficiency of the HFT detector.**
  - **The red squares show the efficiency for finding the D^0 meson with the full set of Geant/ITTF techniques. The black circles show the efficiency AFTER cuts.**
- **The tracking efficiency is improved by 20-30% compared to the simulation in the proposal. Mostly due to improved hit selection in PXL.**

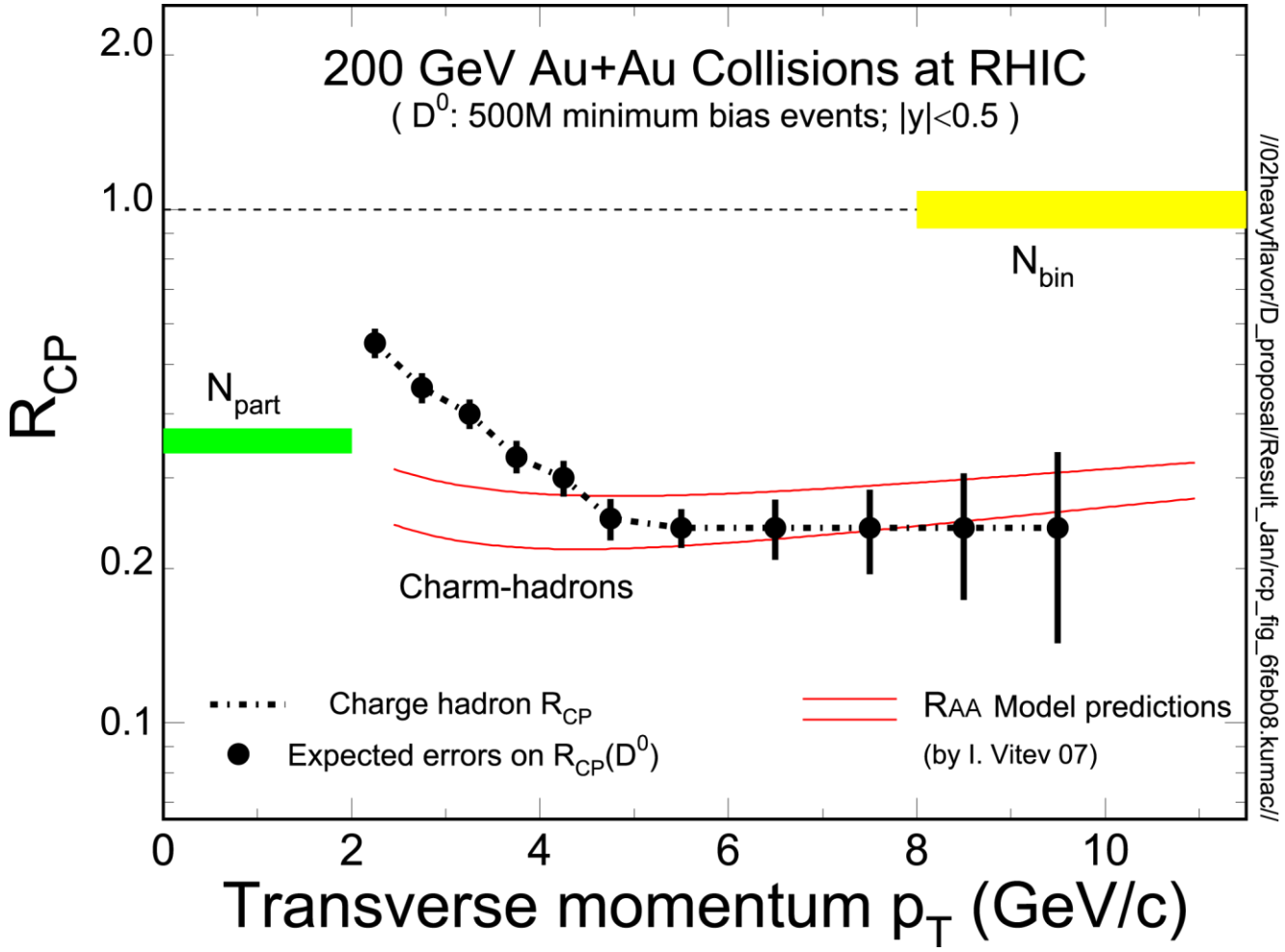
Estimate v_2 sensitivity – focus on the error bars



From central to minimum bias, assume:

- **D^0 scaled by N_{bin}**
- **Hijing background scaled by N_{part}**

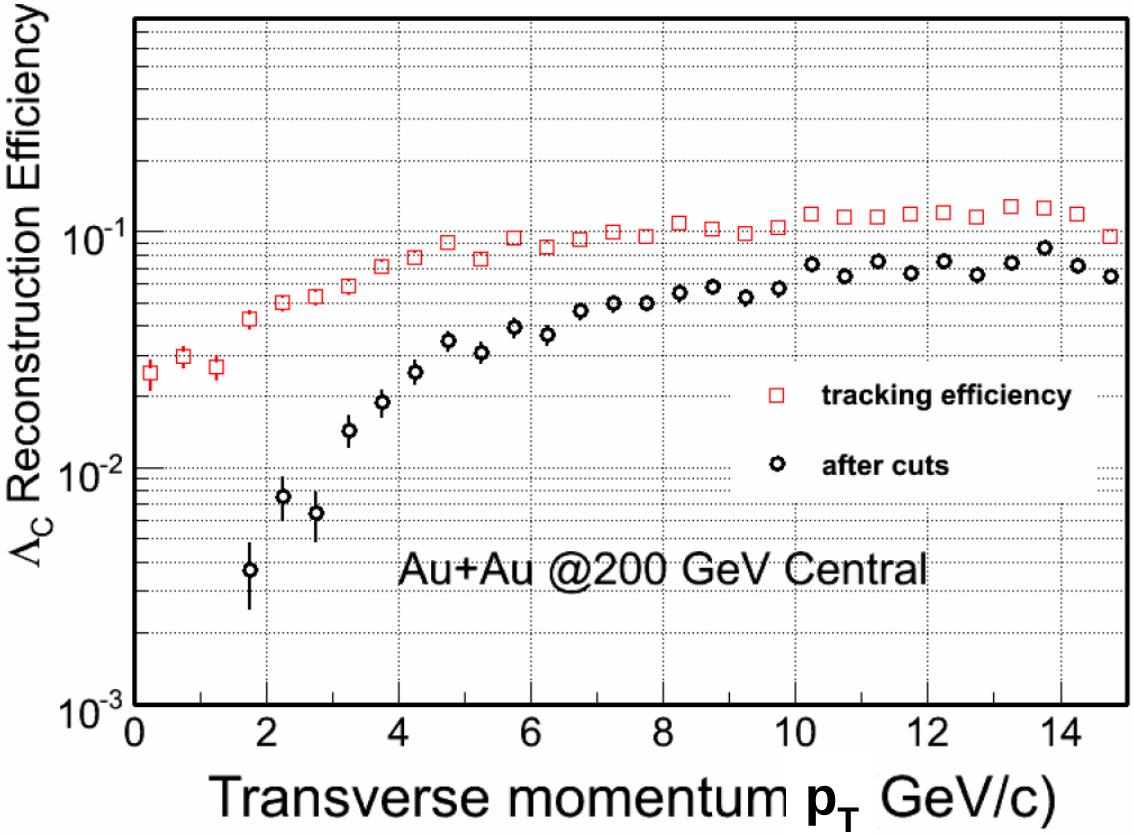
Estimate R_{cp} sensitivity: focus on the error bars



The next level of difficulty: Charm baryon - Λ_c

$$\Lambda_c \rightarrow pK^-\pi^+$$

M = 2.286 GeV/c^2 cτ = 60 μm



Nuclear Matter at RHIC … a perfect liquid … an sQGP

- **Its hot**
  - Chemical freeze out at 175 MeV & Thermal freeze out at 100 MeV
- **Its fast**
  - Transverse expansion with an average velocity greater than 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 and strongly interacting**
  - Saturation of v_2 at high p_T
  - R_{AA} … suppression of high p_T particle yields relative to p-p
  - Jet Quenching … suppression of the away side jet
- **It has partonic degrees of freedom**
  - Constituent quark scaling of v_2 and v_4 for u, d, s and perhaps charm
- **There are hints that it is thermally equilibrated**
  - Excellent fits to particle ratio data with equilibrium thermal models
- **And it has nearly zero viscosity and perhaps a Mach cone**
  - Perhaps it is at or below the quantum bound from the AdS/CFT conjecture

The next step is to see if these results hold in the charm sector