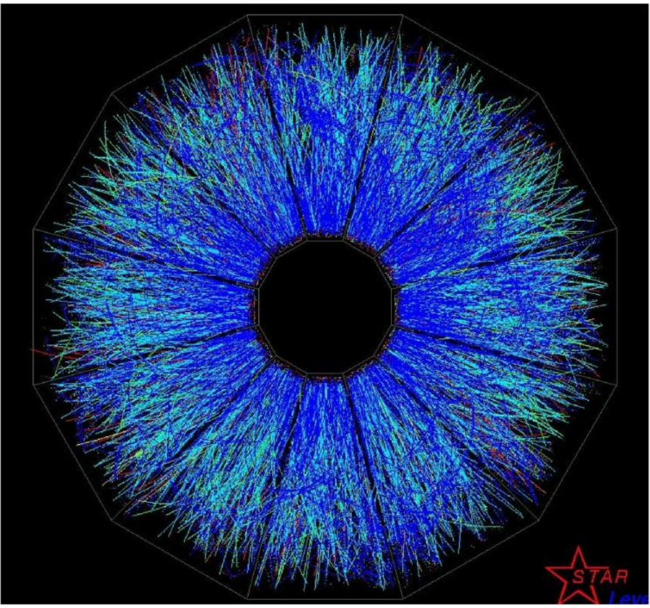
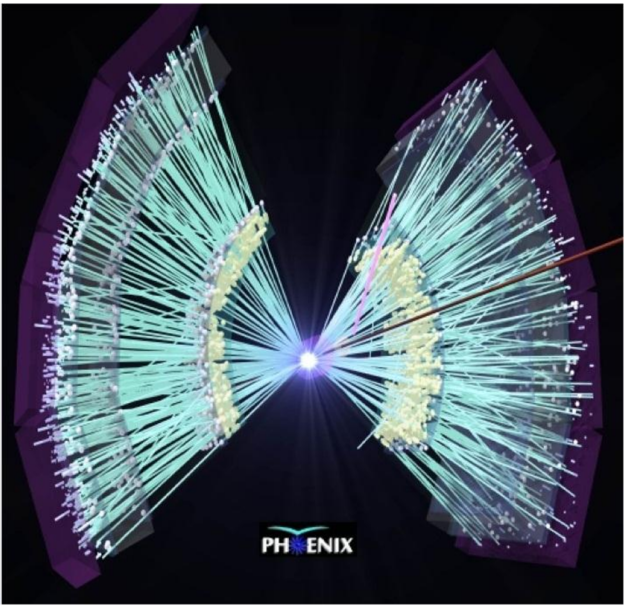
Probing the QCD medium at RHIC collective behavior and the quenching of jets





Julia Velkovska

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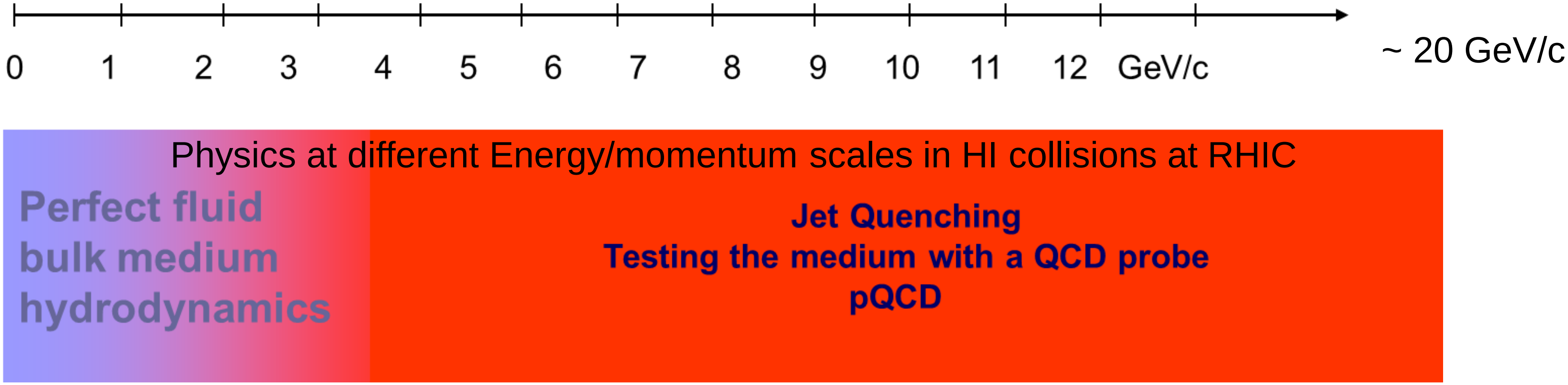
Trends in Particle Physics Summer School
Primorsko, Bulgaria
June 21-26, 2010

Outline of lectures

- Preliminaries:
  - Motivation for heavy ion experiments at relativistic energies
  - Introduction to RHIC and its experimental program
- RHIC discoveries:
  - enormous collective motion of the medium: Perfect fluid behavior
  - quenching of jets in the QCD medium



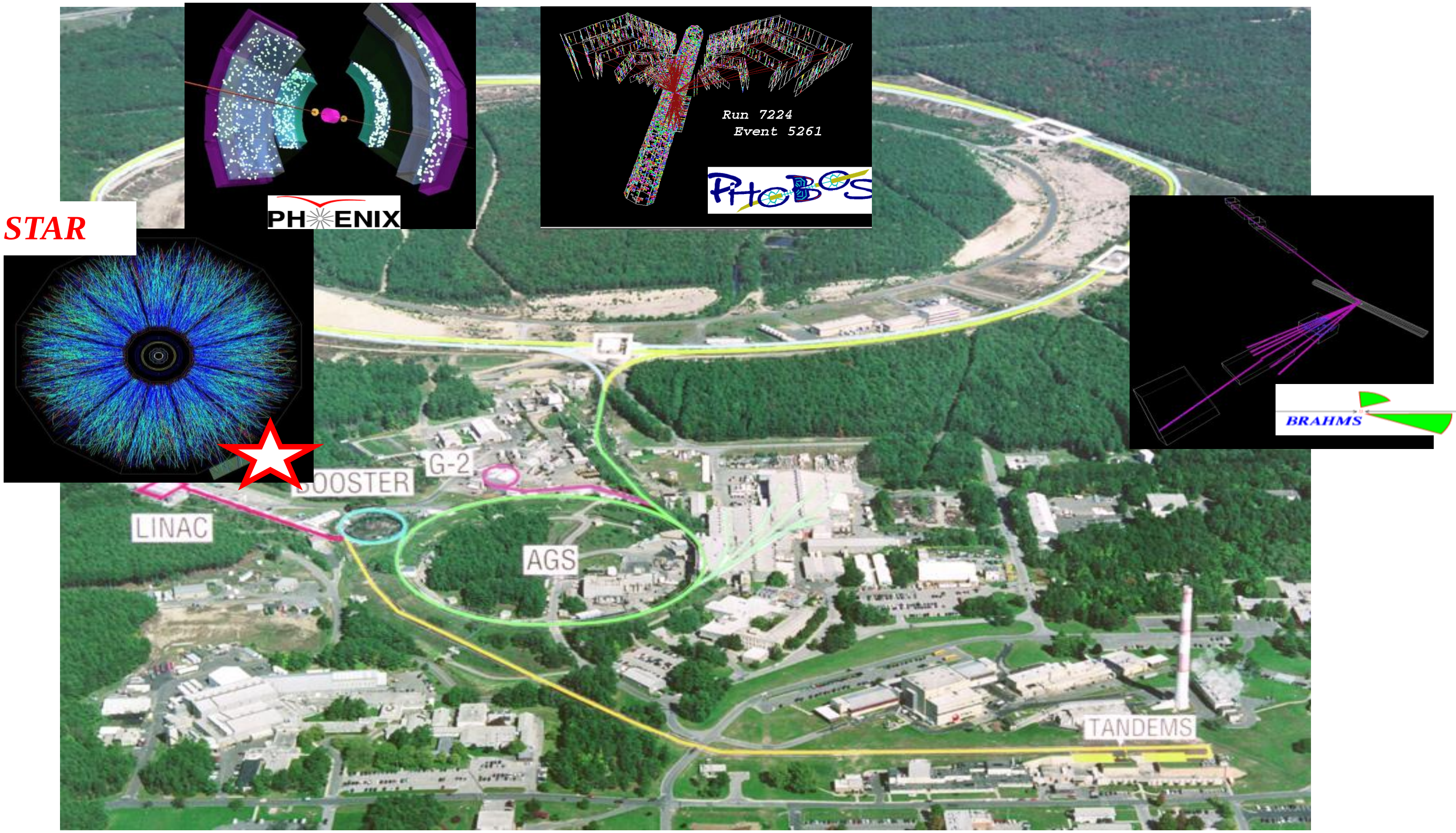
Physics at different Energy/momentum scales in HI collisions at RHIC

Perfect fluid
bulk medium
hydrodynamics

Jet Quenching
Testing the medium with a QCD probe
pQCD

Long Island, NY, USA

RHIC at Brookhaven National Lab

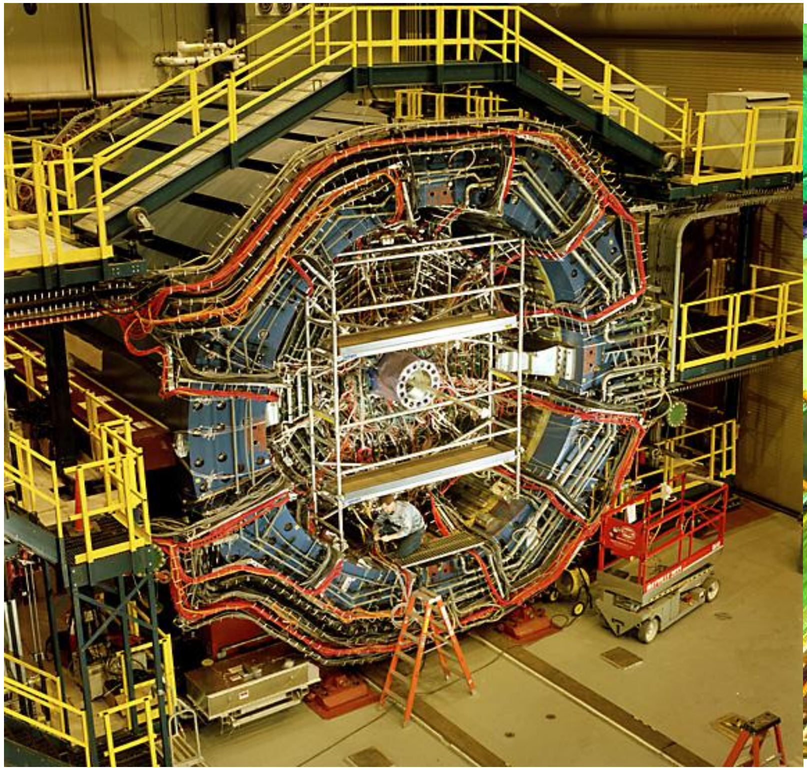


10 years at RHIC: Collide Au + Au ions for maximum volume

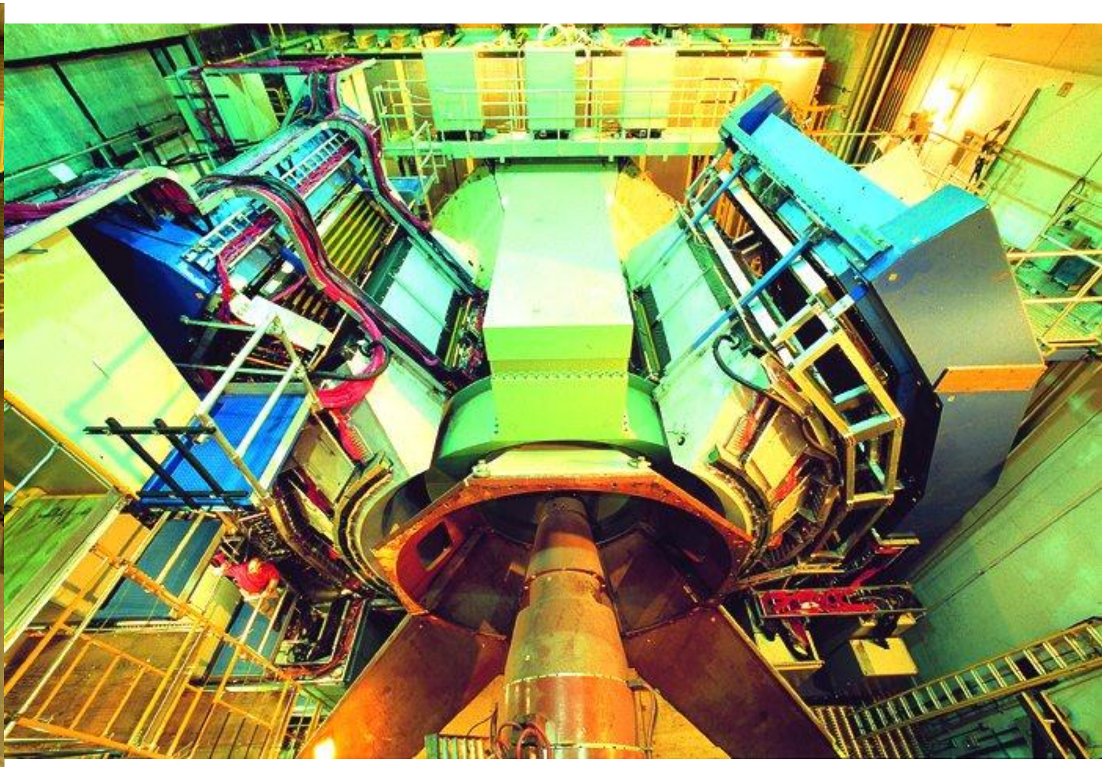
$\sqrt{s}_{NN}$= 200 GeV, p+p, d+A and Cu+Cu to compare

Energies $\sqrt{s}_{NN}$ = 7,11, 22, 39, 56, 62, 130, 200 GeV

The Present Experiments at RHIC



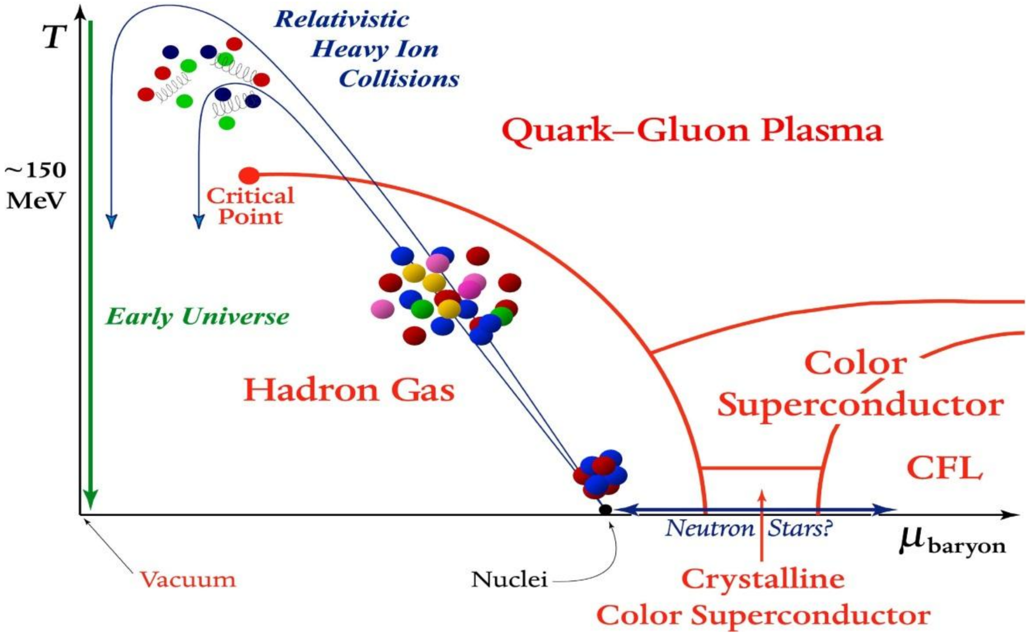
STAR
specialty: large acceptance measurement of hadrons



PHENIX
specialty: rare probes, leptons, and photons

Both experiments undergoing extensive upgrades: vertex tracking, calorimetry, forward coverage.

Why collide HI at high energy?



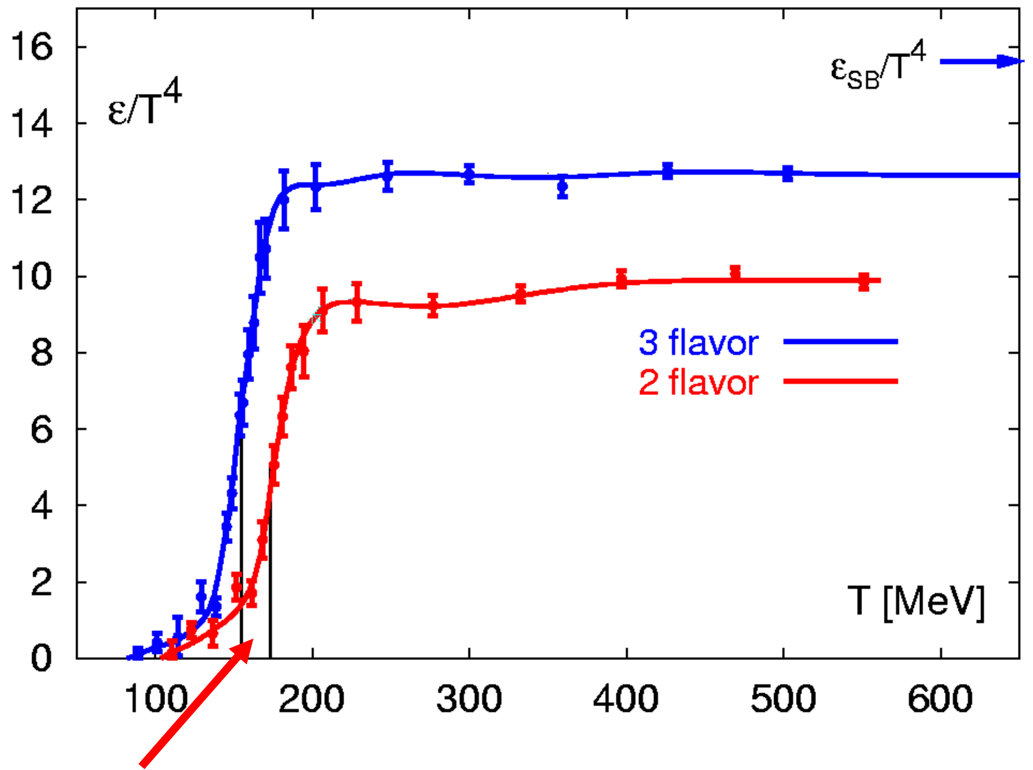
- Motivation: HI experiments at high energy give access to a (simpler) QCD phase at high T that existed in the early Universe
- Goals:
  - ☐ **to create matter above the phase transition**
  - ☐ **study its structure and thermodynamics properties**

Lattice QCD at Finite Temperature

F. Karsch, hep-ph/010314

$$\varepsilon = g\,\frac{\pi^2}{30}T^4$$

(μ_B=0)



Hadronic Matter:
quarks and gluons confined
For T ~ 200 MeV, **3** pions with spin=0

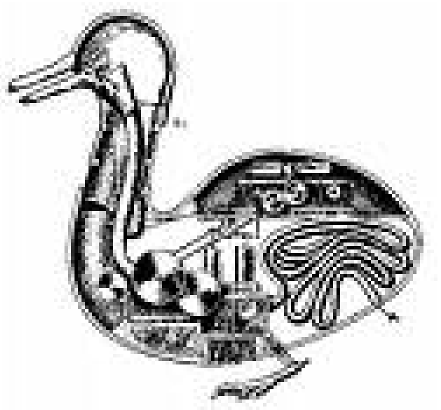
Quark Gluon Matter:
8 gluons;
2(3) quark flavors, antiquarks,
2 spins, 3 colors

$$\varepsilon = \left\{2_s \cdot 8_g + \frac{7}{8}\cdot 2_s \cdot 2_a \cdot 2_f(3)\cdot 3_c\right\}\frac{\pi^2}{30}T^4$$

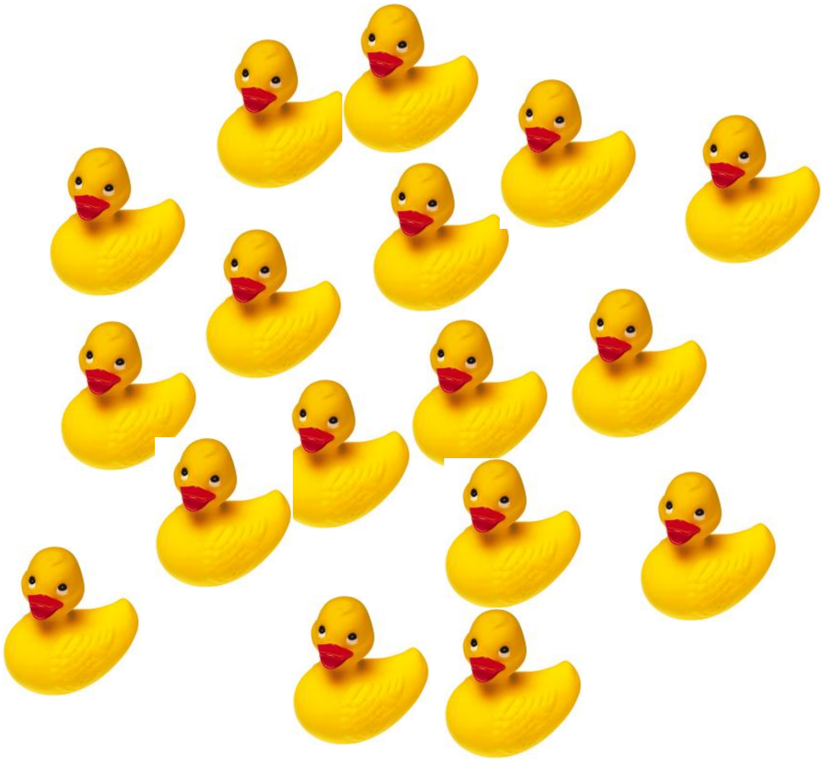
$$\varepsilon = 37(48)\cdot\frac{\pi^2}{30}T^4$$

Critical Temperature, **T_C ~ 135 -170 MeV**
Critical Energy Density, **ε_C ~ 1 GeV/fm^3**

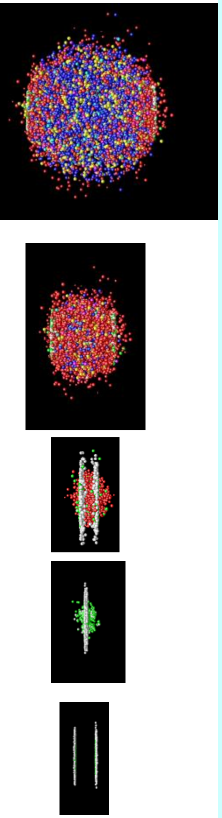
HEP

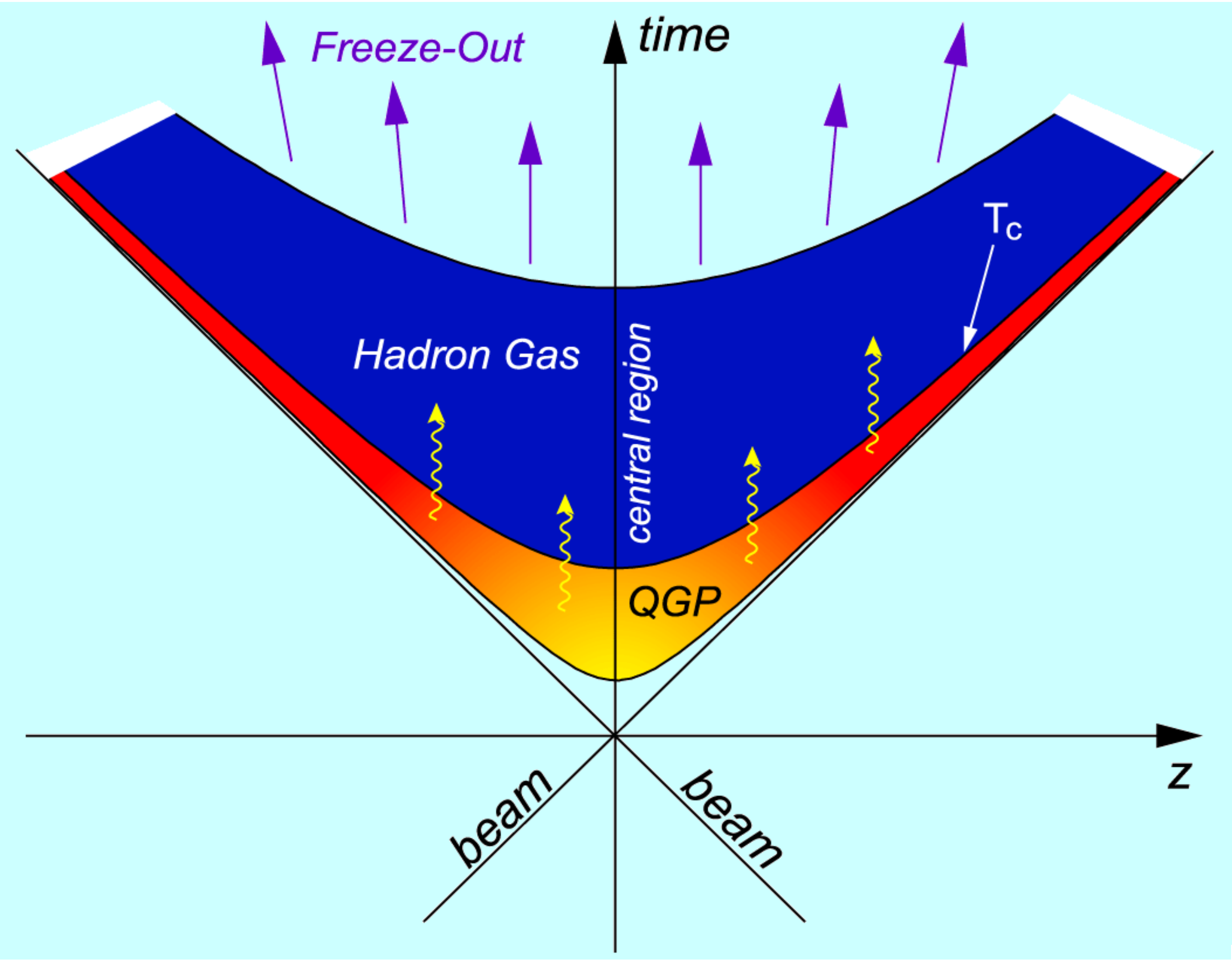


HEN



Evolution of a heavy ion collision





Freeze-out

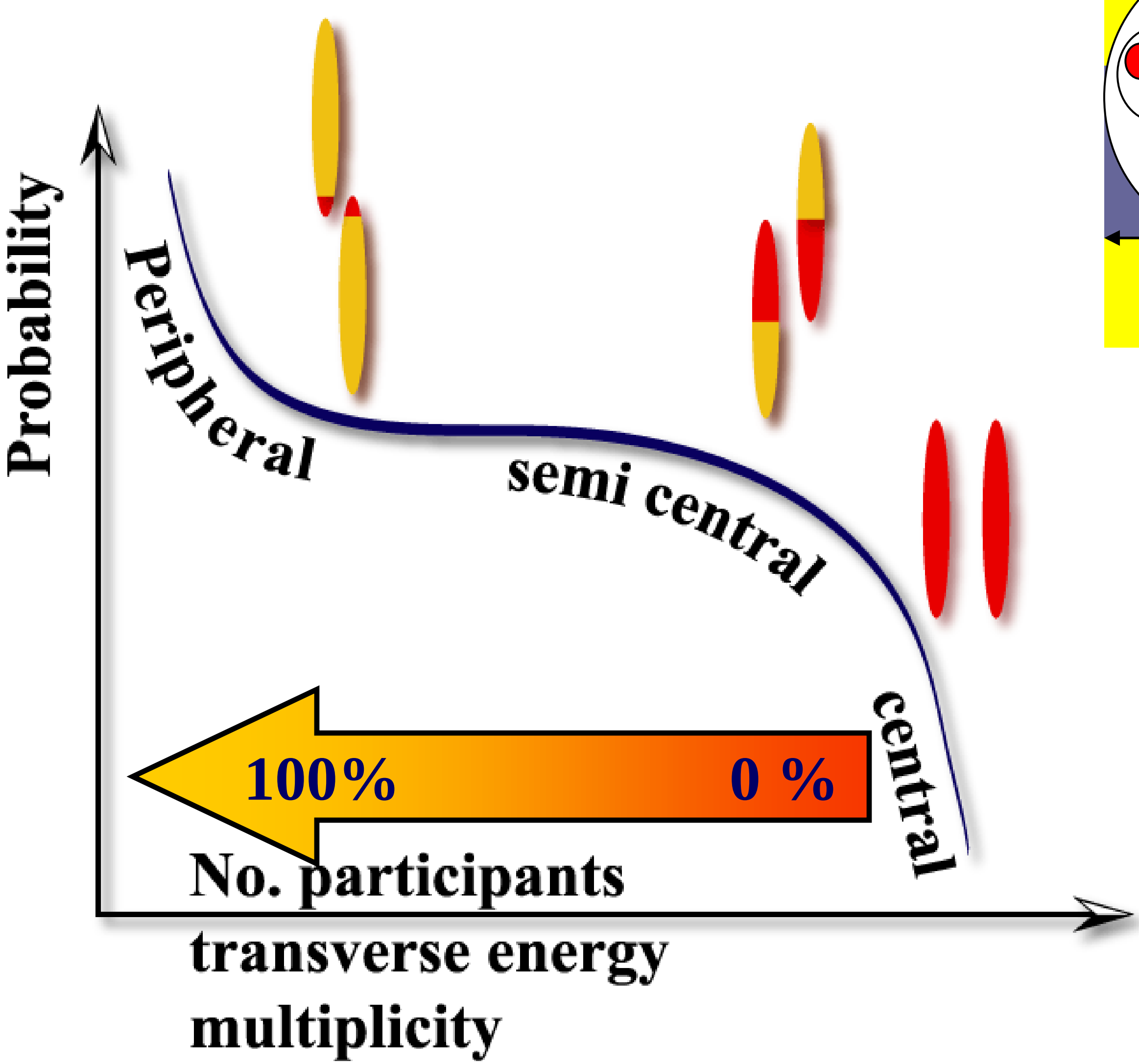
Hadron Gas

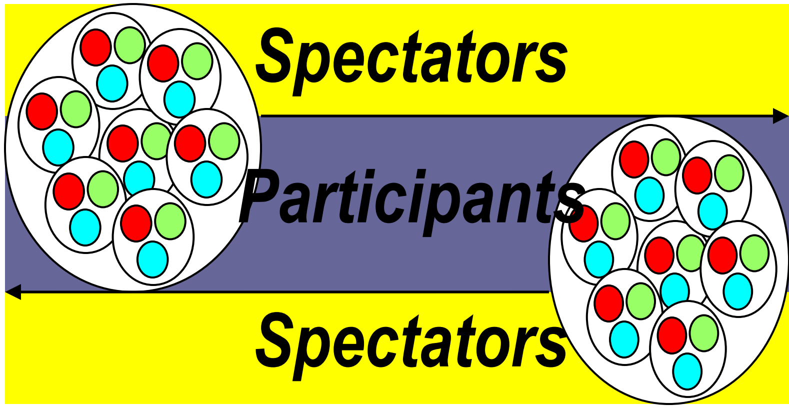
Phase Transition

Plasma-phase

Pre-Equilibrium

AA collisions are not all the same





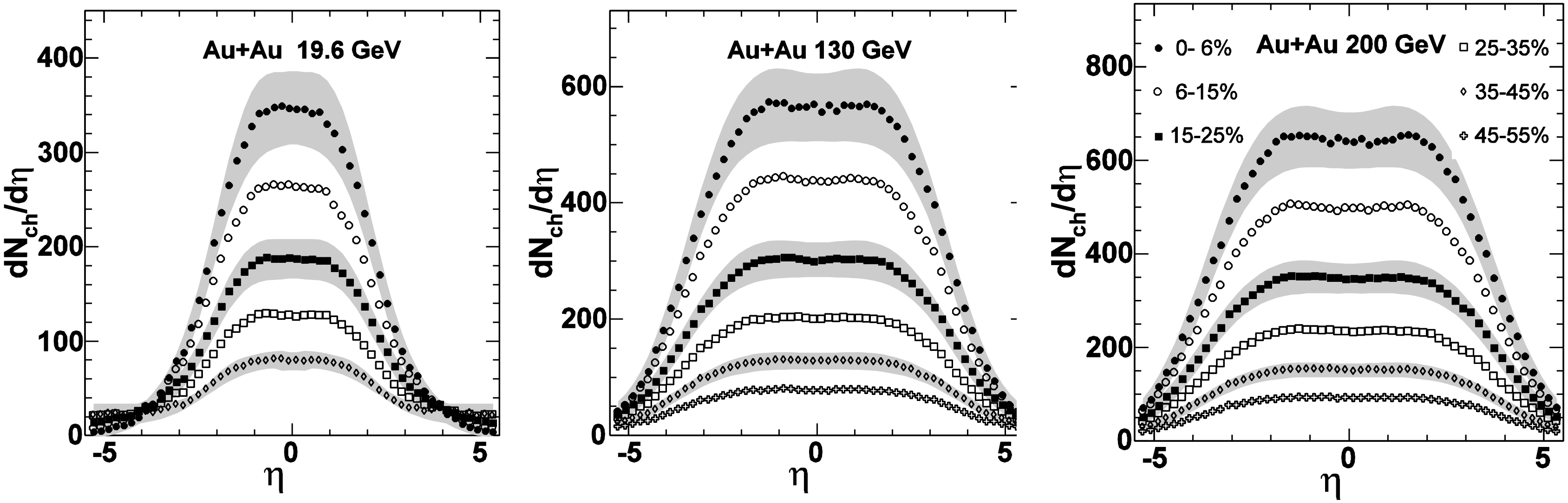
Nuclei are extended objects

- ☐ **Impact parameter**
- ☐ **Number of participants**
- ☐ **Centrality**

(% from total inelastic cross-section)

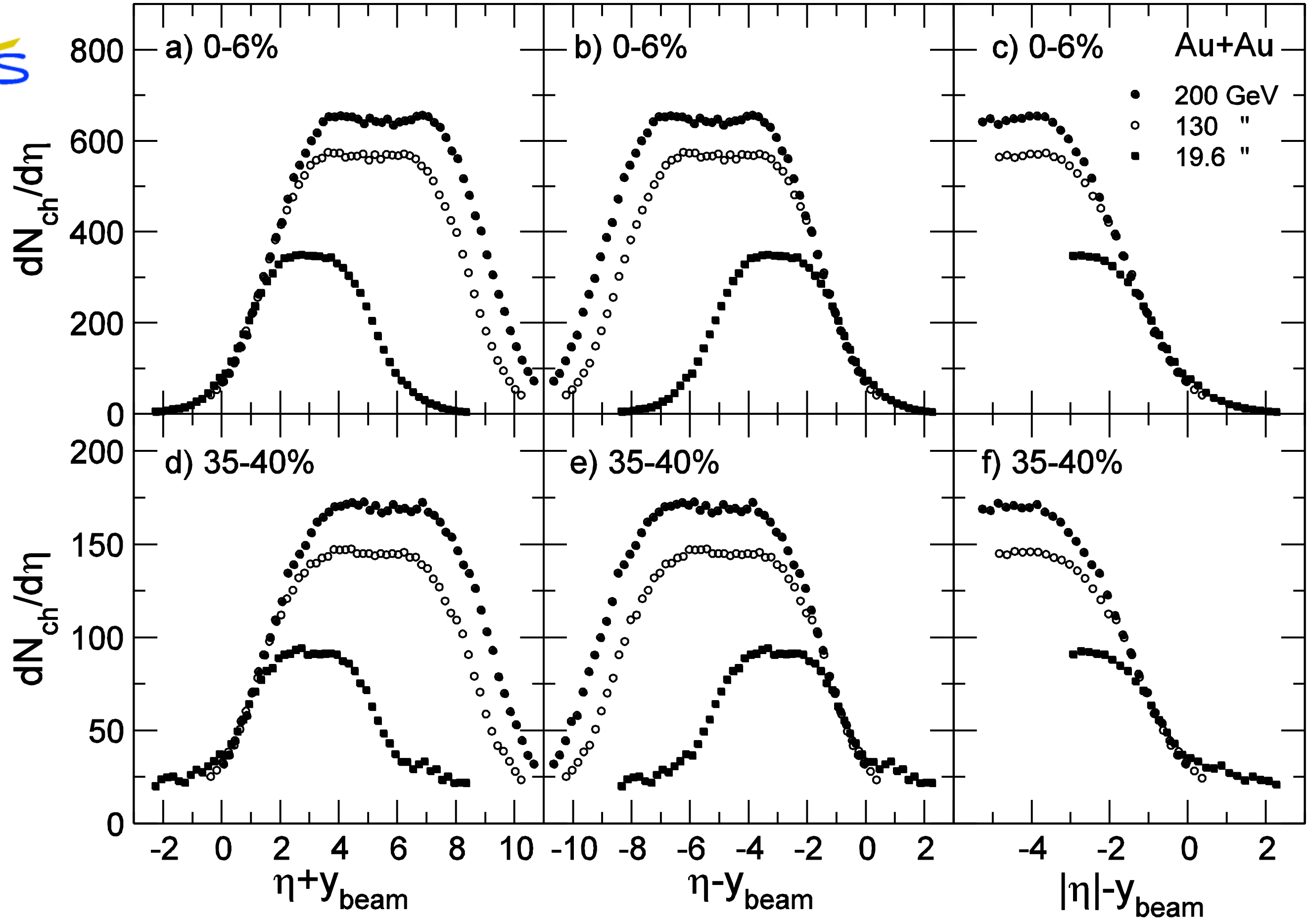
J.Velkovska

N_{ch} rapidity dependence



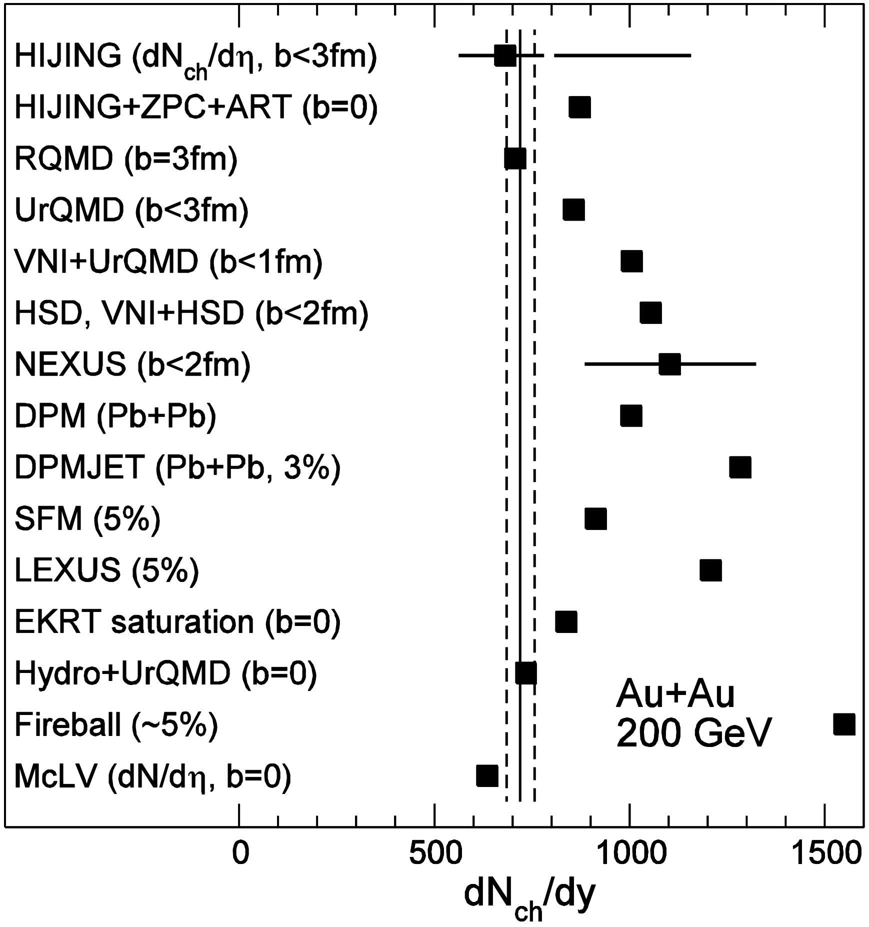
- Integrate the distribution to get total multiplicity – study the production as a function of energy
- Explore scaling behavior
  - ☐ **Is there longitudinal boost invariance ?**
  - ☐ **What is the entropy of the system ?**
  - ☐ **How are hadrons produced ?**

Longitudinal scaling

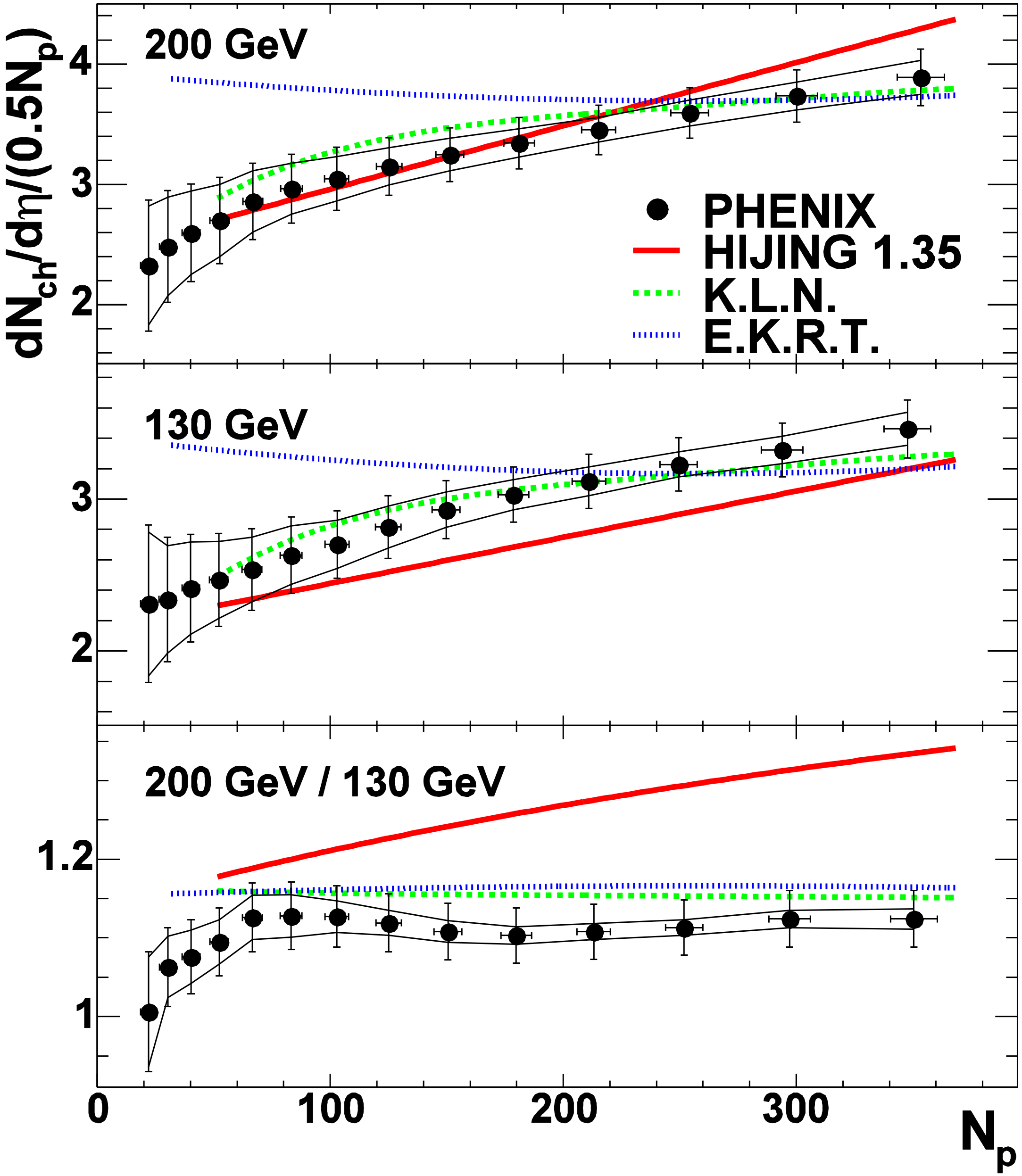


- Particles near beam and target rapidity governed by limiting fragmentation
- Projectile hadron viewed in the rest frame of the target is highly Lorenz contracted. It passes through the target leaving it in an excited state which is independent of energy or even the identity of the projectile. It then fragments to produce hadrons

And a full pallet of N_{ch} to theory comparison from PHOBOS



N_{ch} as a model killer (PHENIX)



- HIJING – pQCD based model with soft and hard component of particle production

X.N.Wang and M.Gyulassy,
PRL 86, 3498 (2001)

- KLN – gluon saturation in the initial state

D.Kharzeev and M. Nardi,
Phys.Lett. B503, 121 (2001)

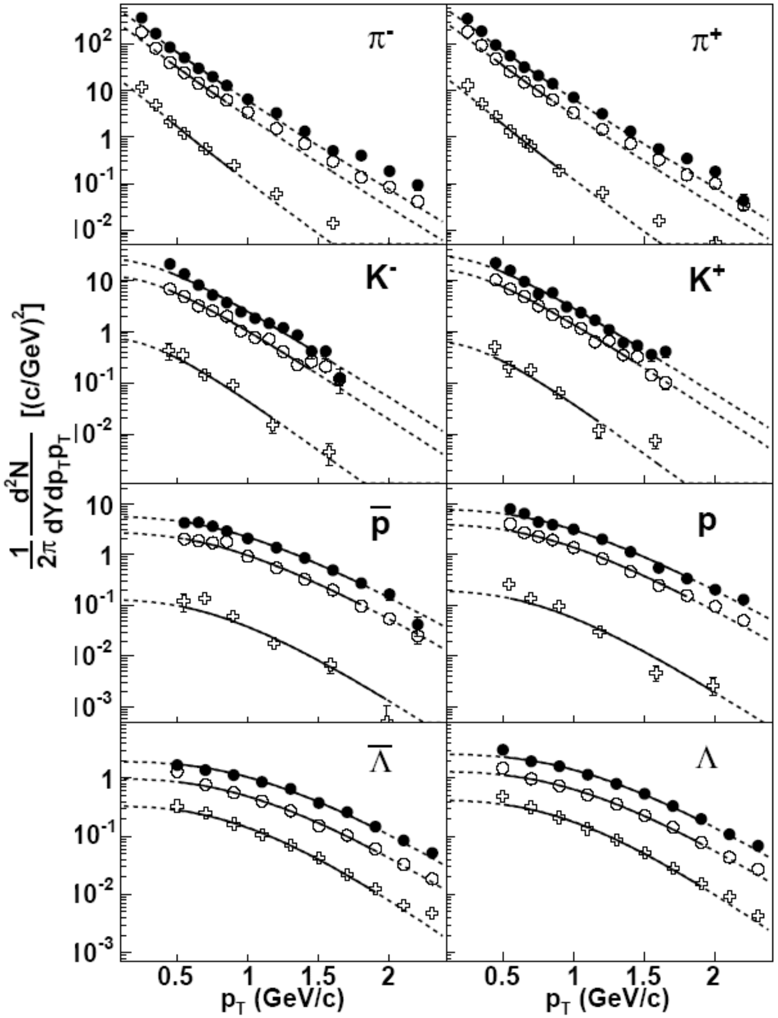
D.Kharzeev and E.Levin,
Phys.Lett. B523, 79 (2001)

- EKRT – saturation in the final state

K.J.Eskola et al,
Nucl Phys. B570, 379 and
Phys.Lett. B 497, 39 (2001)

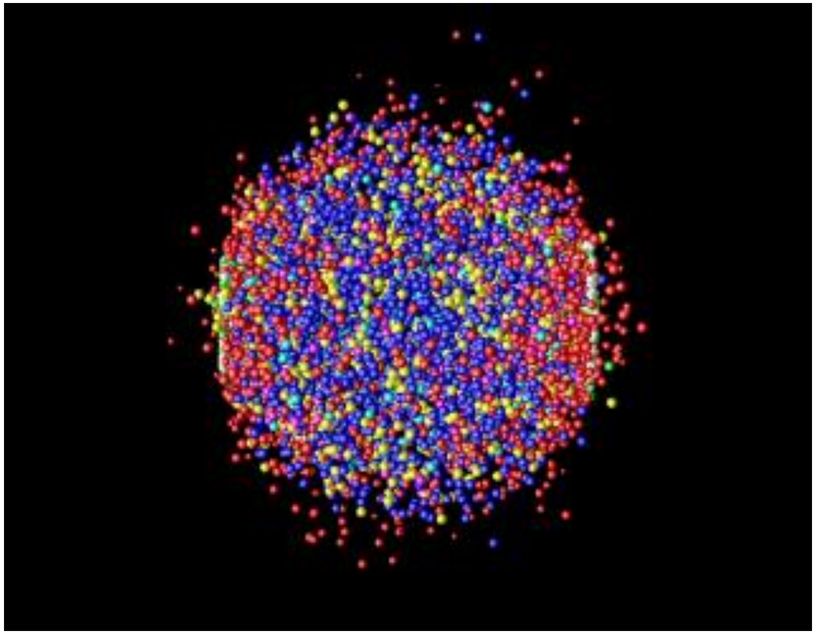
Hadron spectral shapes (low-p_T)

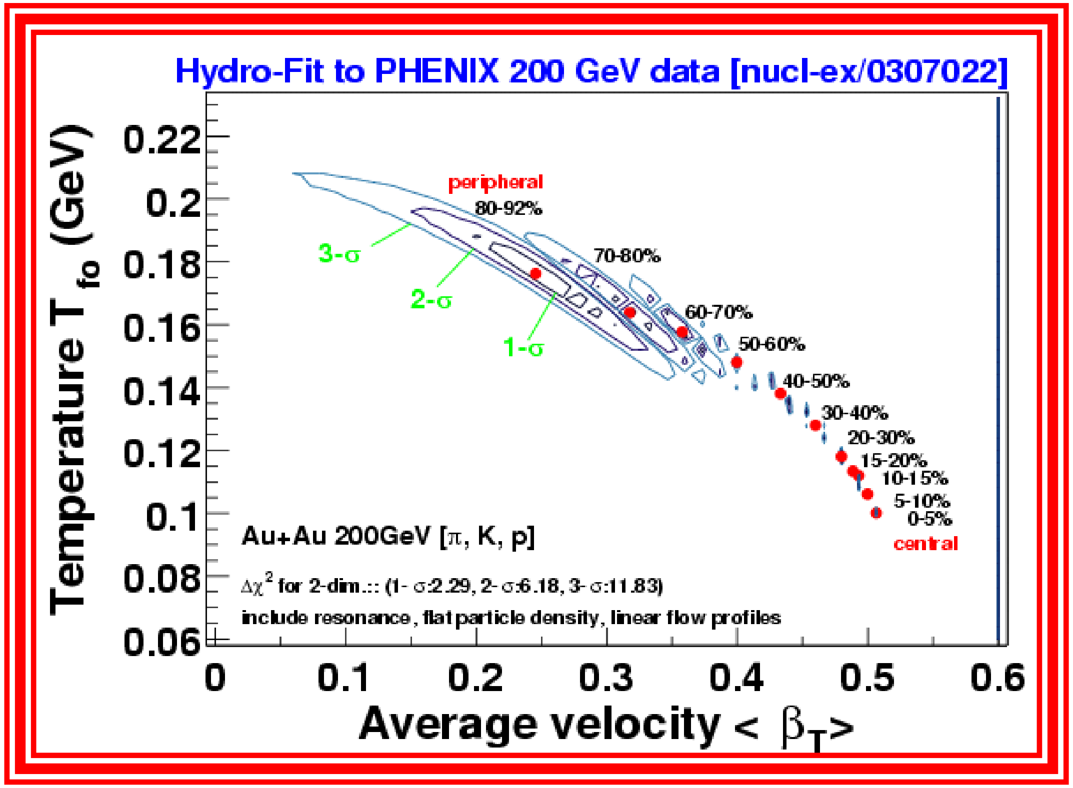
Retiere and Lisa – nucl-th/0312024



- Central Au+Au collisions
- Boltzmann distribution modified to include a common flow velocity ("blast-wave" fit) in good agreement with data
- Rapid expansion with $<\beta_T>$ ~0.5 c and T_{fo} ~110 MeV

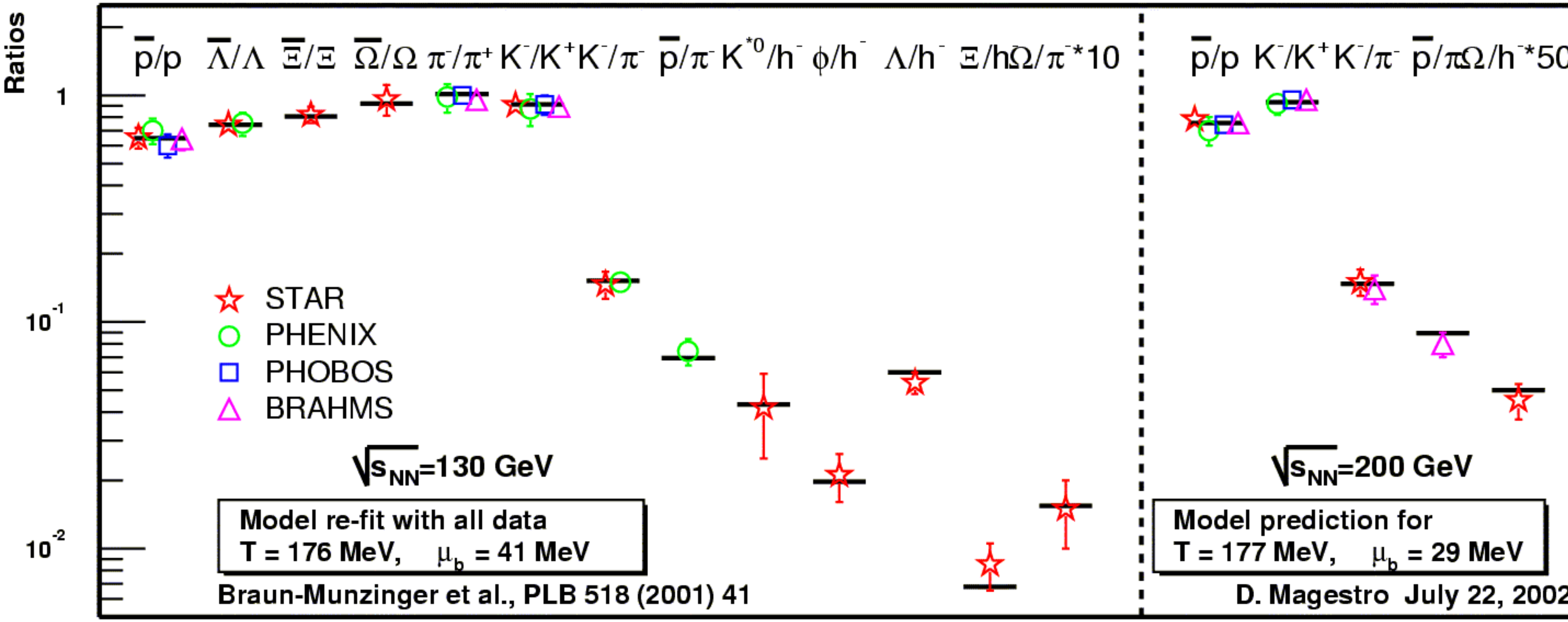
Radial flow and T at kinetic freeze-out

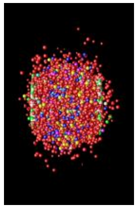




- Explosive collective expansion (centrality dependent)
- Next: Integrate specta to get hadron yields
  - ☐ Compare to thermal models of hadron production
  - ☐ Determine the chemical freeze-out conditions

Chemical freeze-out at ~T_c

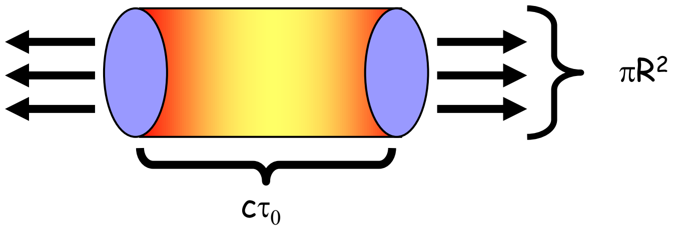




- Thermally equilibrated final state, including strangeness
  - ☐ **When and how is thermalization achieved ?**
  - ☐ **Did the system spend time in a QGP phase ?**

Is the energy density high enough ?

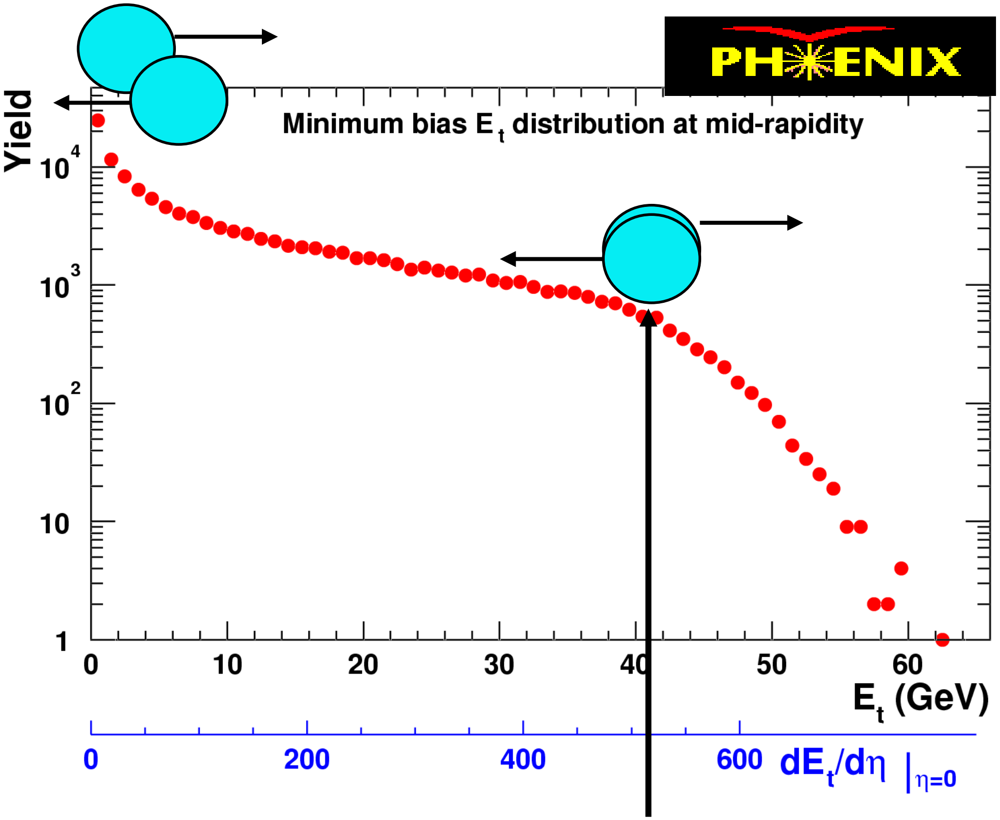
Colliding system expands:



Energy ⊥ to beam direction

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)$$

per unit velocity || to beam



$\rightarrow \varepsilon \geq 5.5$ *GeV/fm³* (200 GeV Au+Au)

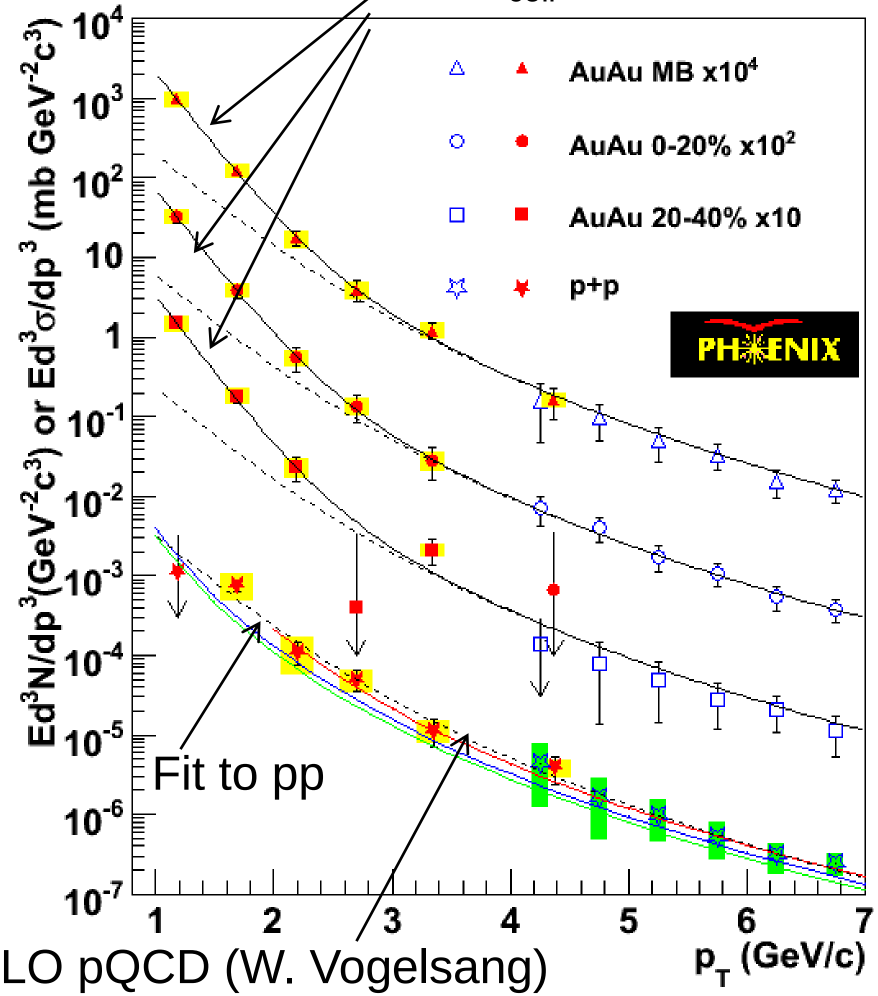
well above predicted transition!

value is lower limit:

longitudinal expansion rate, formation time overestimated

Radiated photons →T_{init}

exp + N_{coll} scaled pp



Fit to pp

NLO pQCD (W. Vogelsang)

Phys. Rev. Lett. 104, 132301 (2010)

- Measure:
  - ☐ γ **(direct)**
  - ☐ **γ*→e+e-**
- Compare spectra in p+p and Au+Au
  - ☐ In p+p: pQCD works to low p_T
  - ☐ In Au+Au: soft (thermal) excess fit with exponential
- Extract initial temperature:

T = 221 ± 23 ± 18 MeV (central)

T = 224 ± 16 ± 19 MeV (MB)

arXiv: 0804.4168

- The initial T and energy density are above the critical values predicted by l-QCD
- Matter appears to be in thermal equilibrium with hadron abundances frozen at T_C ; μ_b is small (as expected)
  - **Hence thermodynamics description is applicable**
- Next: describe evolution and properties
  - **Equation of state ?**
  - **Transport properties ?**
  - **Interactions ?**

Basics of Hydrodynamics

Hydrodynamic Equations

$$\partial_\mu T^{\mu\nu} = 0,$$ Energy-momentum conservation

$$\partial_\mu n_i^\mu = 0$$ Charge conservations (baryon, strangeness, etc…)

For perfect fluids (neglecting viscosity),

$$T^{\mu\nu} = (\underbrace{\boxed{e}}_{\text{Energy density}} + \underbrace{\boxed{P}}_{\text{Pressure}})u^\mu \underbrace{\boxed{u^\nu}}_{\text{4-velocity}} - Pg^{\mu\nu}$$

Need equation of state (EoS)

$$P(e,n_B)$$

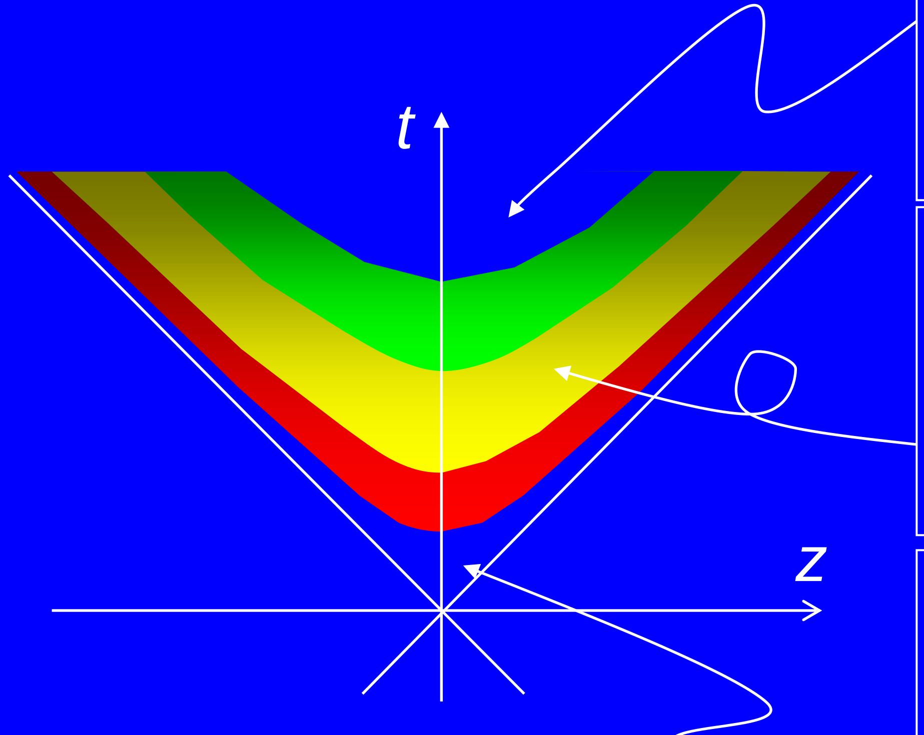
to close the system of eqs.
→ Hydro can be connected directly with lattice QCD

Within ideal hydrodynamics, pressure gradient *dP/dx* is the driving force of collective flow.

→ Collective flow is believed to reflect information about EoS!
→ Phenomenon which connects 1st principle with experiment

Caveat: Thermalization, λ << (typical system size)

Inputs to Hydrodynamics



Final stage:
Free streaming particles
→Need decoupling prescription
→Constrained by identified particle spectra

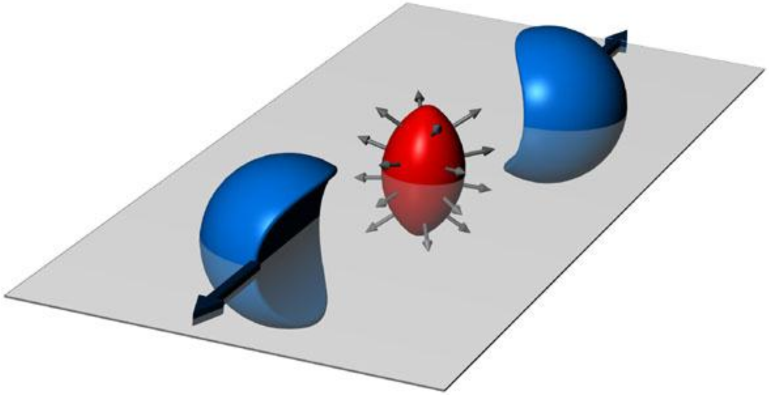
Intermediate stage:
Hydrodynamics can be valid if thermalization is achieved.
→ Need EoS

Initial stage:
Particle production and pre-thermalization beyond hydrodynamics
→Instead, initial conditions for hydro simulations

Need modeling
(1) EoS, (2) Initial cond., and (3) Decoupling

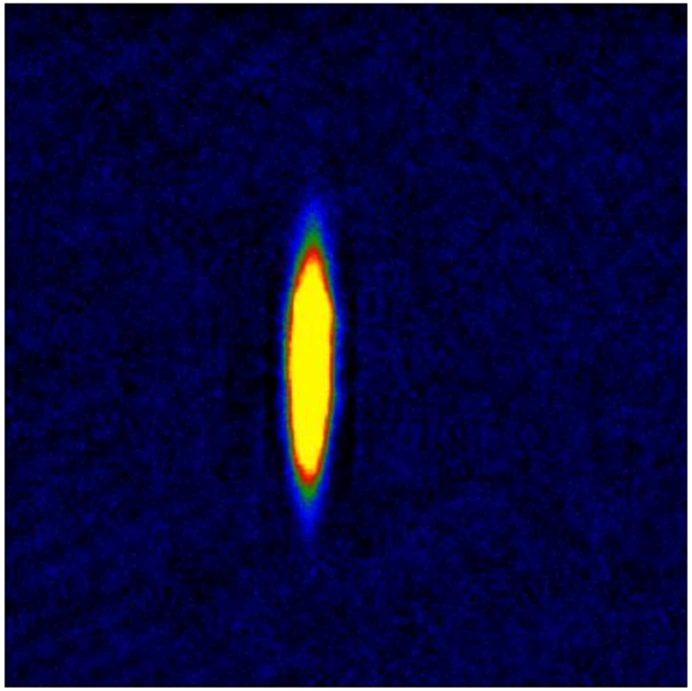
Gas vs liquid

- Start with asymmetric initial conditions
- Apply pressure
- What happens next ?

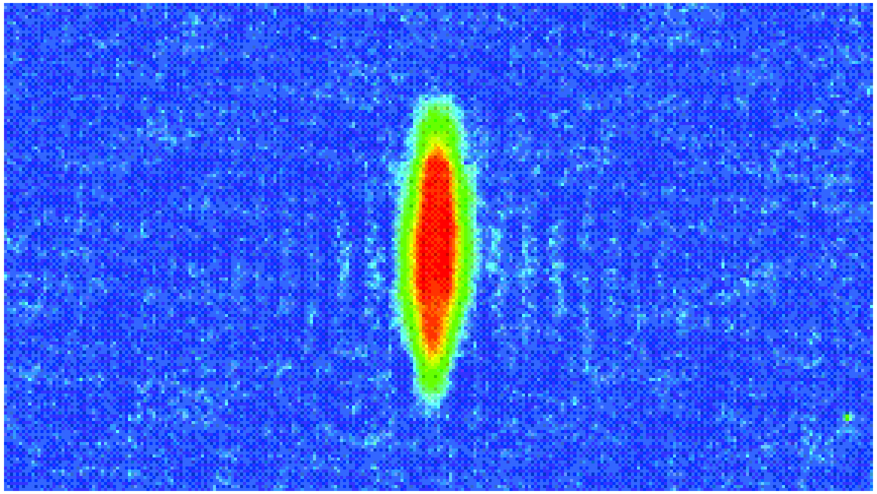


Gas vs liquid

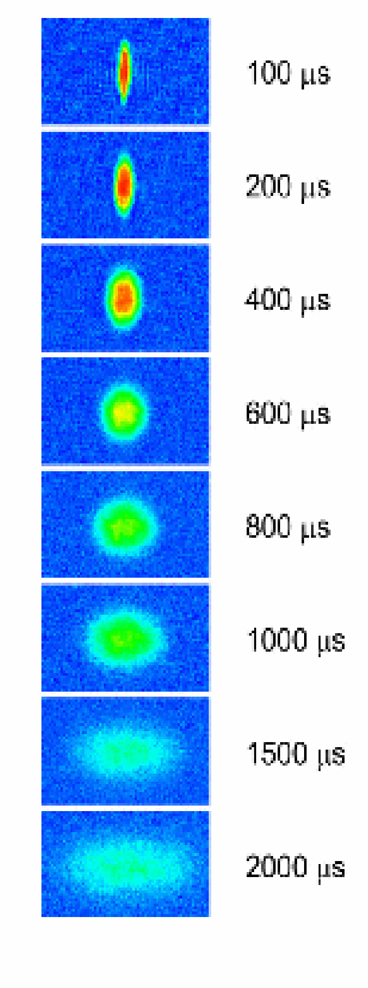
GAS: Large mean free path
isotropic expansion

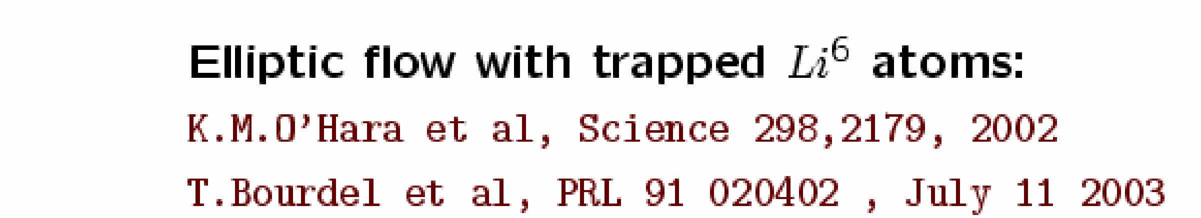


Liquid: small mean free path
anisotropic expansion



Explore a system where we control over mfp





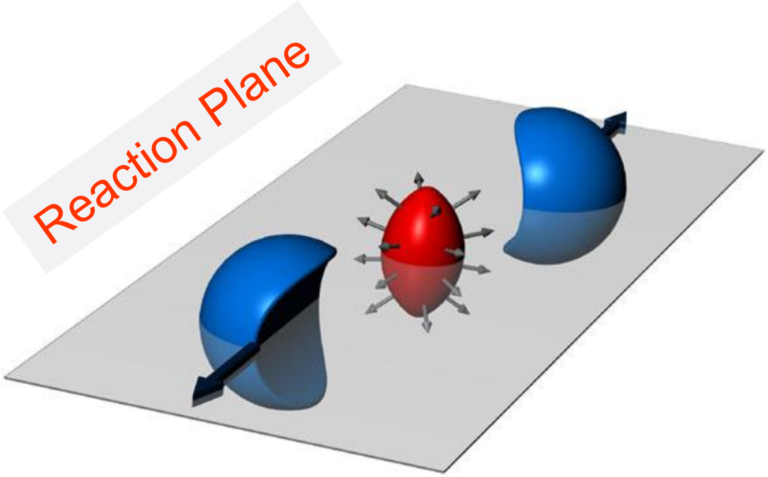
Elliptic flow with trapped Li^6 atoms:

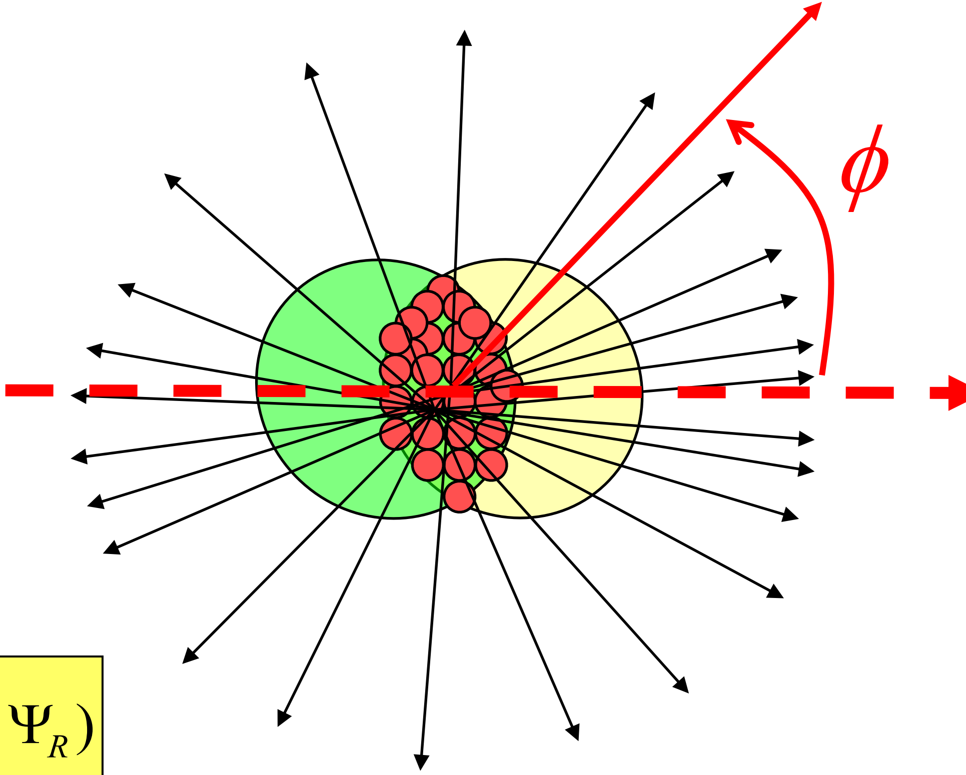
K.M.O'Hara et al, Science 298,2179, 2002

T.Bourdel et al, PRL 91 020402 , July 11 2003

- nano-Kelvin gas of ^{6}Li atoms in magnetic trap
- Feschbach resonance tuned for large cross-section (i.e. small mean free path)
- nearly ideal hydrodynamics
- anisotropic expansion when trapping field dropped
- THIS IS A LIQUID

The elliptic flow “barometer”



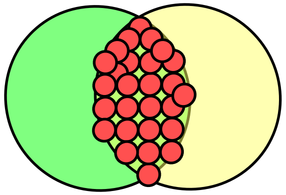


$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_R)$$

- Measure the azimuthal distribution of particle emission with respect to the reaction plane. Fourier expansion
- Driven by pressure gradients => barometer
- Self-quenching due to expansion=> sensitive to early times

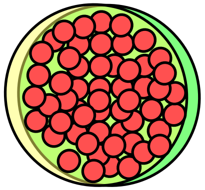
… and the RHIC data show

Increasingly peripheral

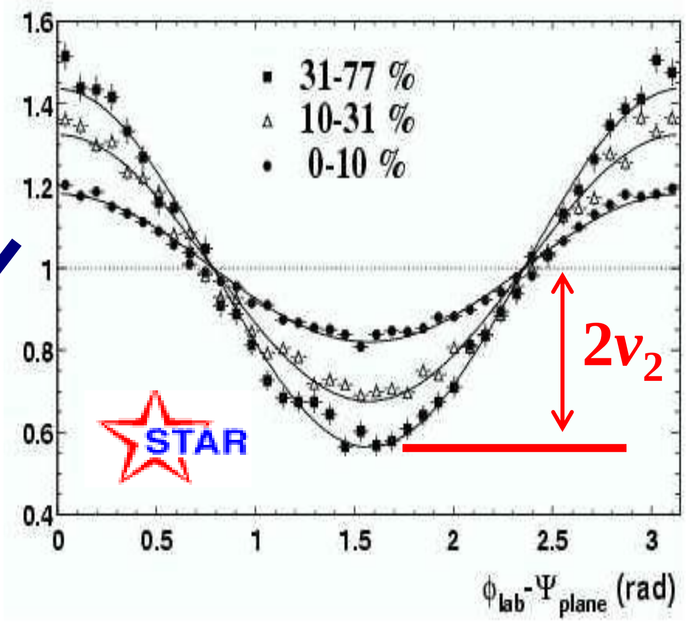


Larger eccentricity (and v_2)

0-10% = central collisions



Smaller eccentricity (and v_2)

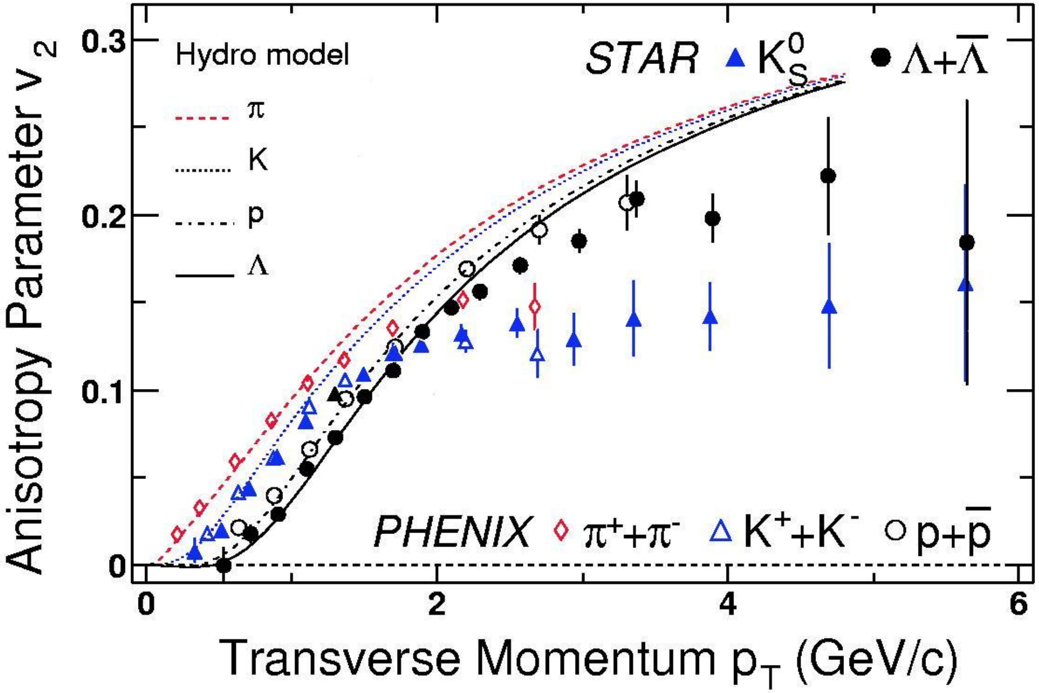


$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_R)$$

- Enormous asymmetry in particle emission

=> Strong pressure gradients and liquid properties

Hydrodynamics at RHIC



- Ideal hydrodynamics (i.e. – zero viscosity) describes with great precision the mass ordering in v_2 vs p_T
- What can we learn from this comparison ?

- Elliptic flow develops early in the collisions: => early thermalization $\tau < 1$ fm/c
- EoS with phase transition describes the data, while hadron gas EoS does not
- Recent viscous hydro estimates show that the data indeed require very low η/s close to conjectured lower limit of $1/4\pi$

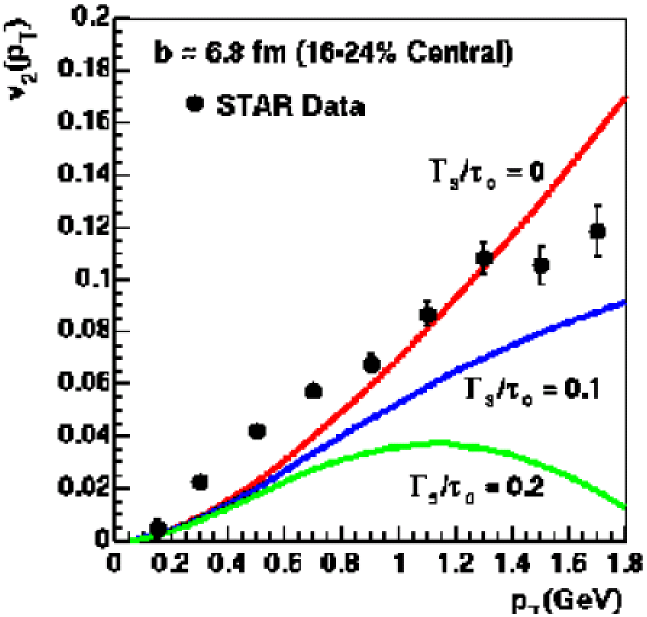
How small is the viscosity ?

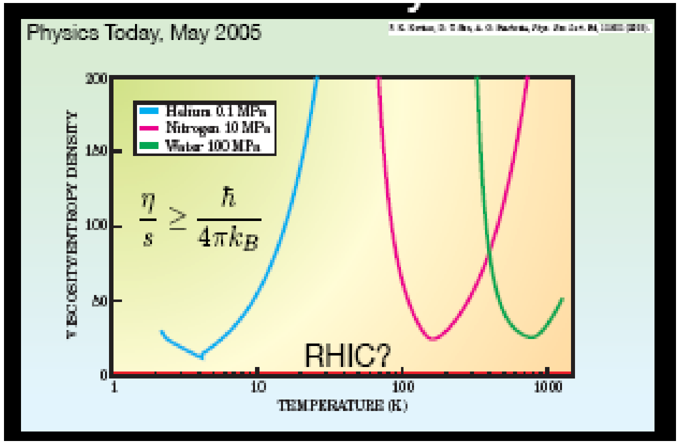
- Solving hydro with viscosity is hard
- In 2003 the viscous corrections were estimated in a simplified numerical model
- Even small viscosity breaks agreement with data

$$\frac{\text{viscosity}}{\text{entropy density}} = \frac{\eta}{s} \leq \sim 0.1??$$

RHIC produces the most perfect fluid in nature !

D. Teaney, nucl-th/0301099




Physics Today, May 2005

QGP perfect liquid makes the top

1931-2006
AMERICAN INSTITUTE OF PHYSICS
75 Years of Service

Physics News Update
The AIP Bulletin of Physics News

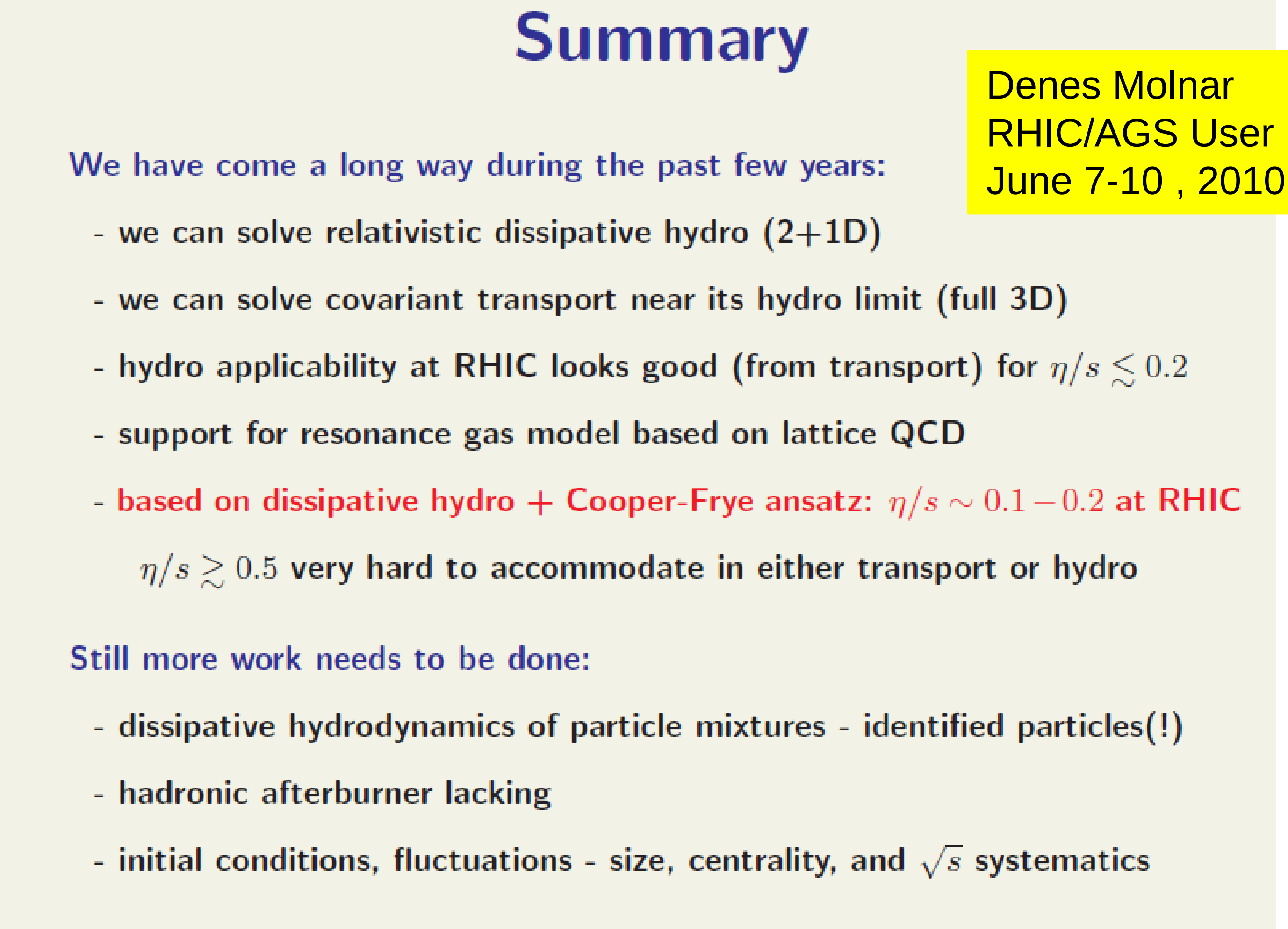
Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

The Top Physics Stories for 2005

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year’s worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

What's new on this front ?

- A lot of theoretical development recently



Summary

We have come a long way during the past few years:

- we can solve relativistic dissipative hydro (2+1D)
- we can solve covariant transport near its hydro limit (full 3D)
- hydro applicability at RHIC looks good (from transport) for $\eta/s \lesssim 0.2$
- support for resonance gas model based on lattice QCD
- based on dissipative hydro + Cooper-Frye ansatz: $\eta/s \sim 0.1 - 0.2$ at RHIC

  $\eta/s \gtrsim 0.5$ very hard to accommodate in either transport or hydro

Still more work needs to be done:

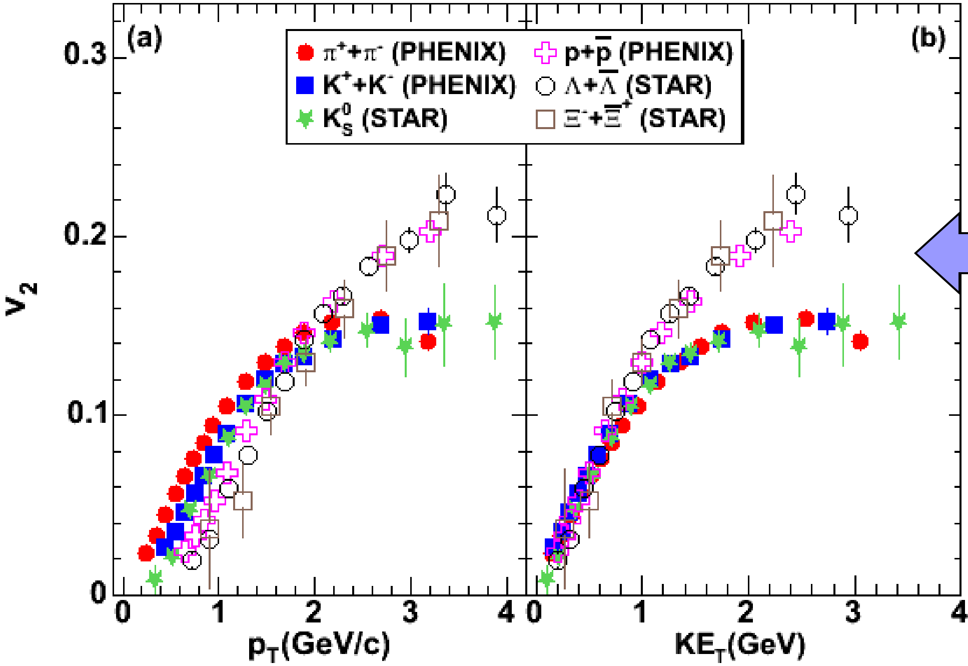
- dissipative hydrodynamics of particle mixtures - identified particles(!)
- hadronic afterburner lacking
- initial conditions, fluctuations - size, centrality, and $\sqrt{s}$ systematics

Denes Molnar
RHIC/AGS User meeting
June 7-10 , 2010

What we learn from hydro and thermal models

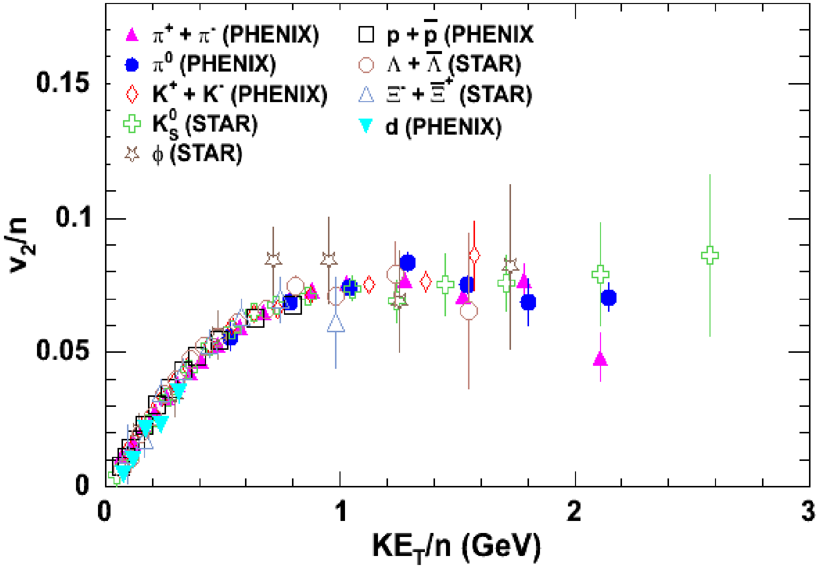
- The medium has achieved (at least local) thermal equilibrium on a very short time scale (< 1 fm/c)
- The medium flows with very small viscosity
- The system expands radially with $\beta_T \sim 0.7$ c
- Total particle production is governed by thermal rates and chemical potentials (observed in particle ratios)
- The temperature at hadronization is ~ 170 MeV~ T_c
- The temperature at freeze-out is ~ 100 MeV
- EoS with a phase transition is favored by the data

What are the quanta that flow ?



- Complicated dependence on mass and p_T
- Simplifies when plotted vs transverse kinetic energy
  - **Two groups: baryons and mesons**

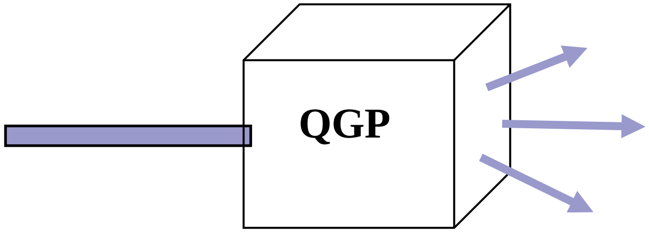
- Now scale both axes with the number of constituent quarks
  - **2 for mesons**
  - **3 for baryons**
- Uniform behavior observed in flow/per constituent quark



THE BULK SYSTEM HAS UNIQUE PROPERTIES AND IS SURELY NOT A HADRON GAS !

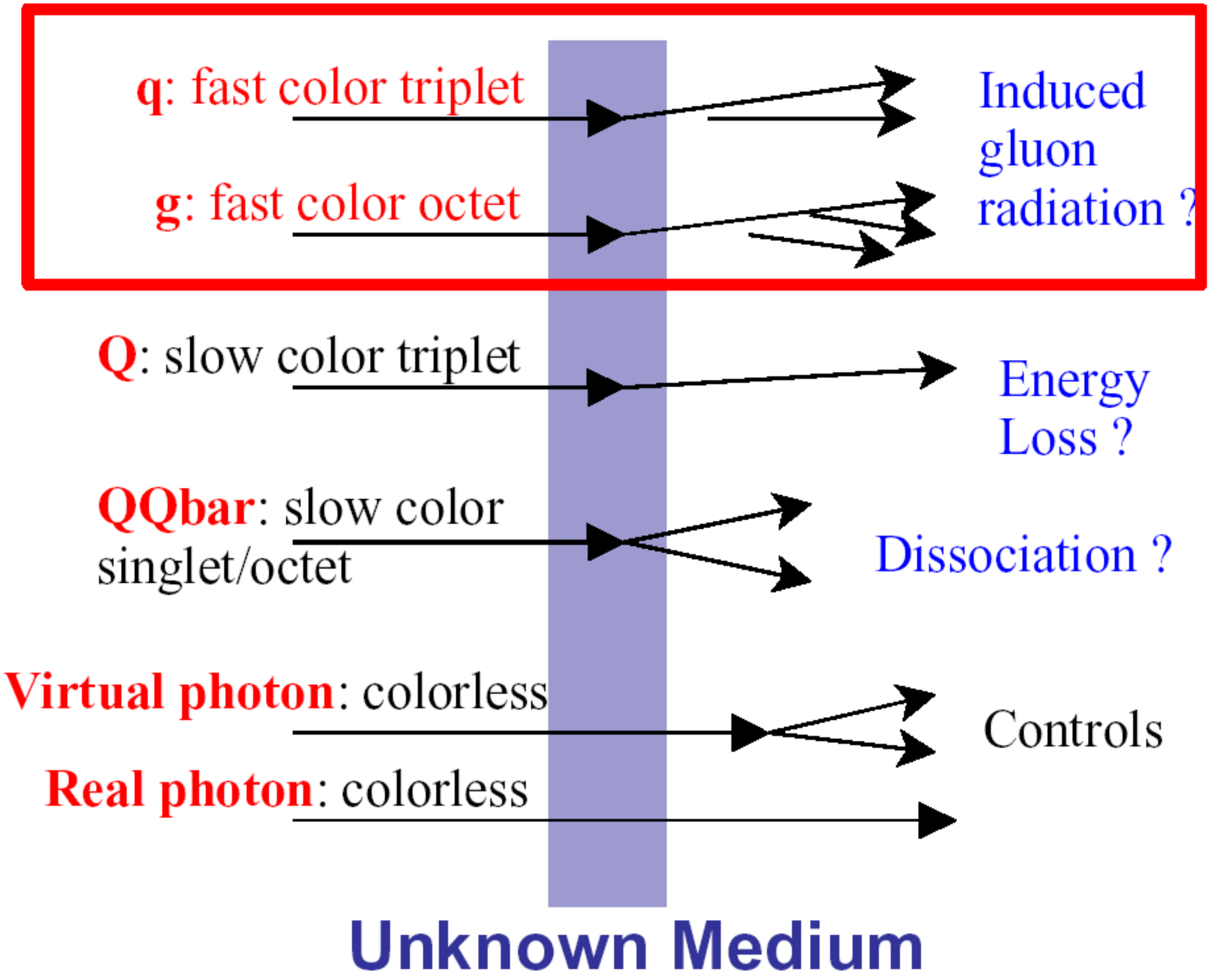
Now lets switch gears to "hard" physics

- I will make an artificial distinction of the "medium" and "the probe"
- In fact: both are produced in the collision
  - ☐ **Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.**
  - ☐ **<u>Probe</u>: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.**
- The basic idea:



- Things to learn
  - ☐ **Measure the density of the medium**
  - ☐ **Is the medium colored (i.e. deconfined) ? Specific pQCD predictions for induced gluon radiation since 1990s**

The Probes Gallery:



q: fast color triplet

g: fast color octet

Induced gluon radiation ?

Q: slow color triplet

Energy Loss ?

QQbar: slow color singlet/octet

Dissociation ?

Virtual photon: colorless

Real photon: colorless

Controls

Unknown Medium

Jet Suppression

charm/bottom dynamics

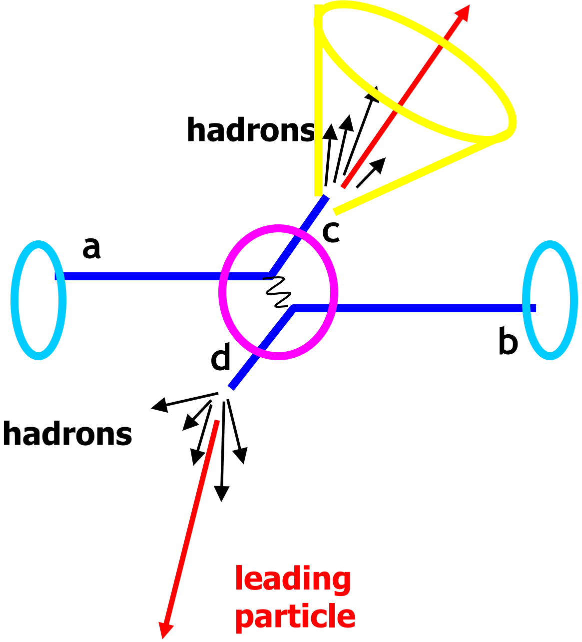
J/Ψ & Υ

direct photons
CONTROL

The importance of the control measurement(s) cannot be overstated!

High p_T Particle Production in pp

Jet: A localized collection of hadrons which come from a fragmenting parton



Parton Distribution Functions

Hard-scattering cross-section

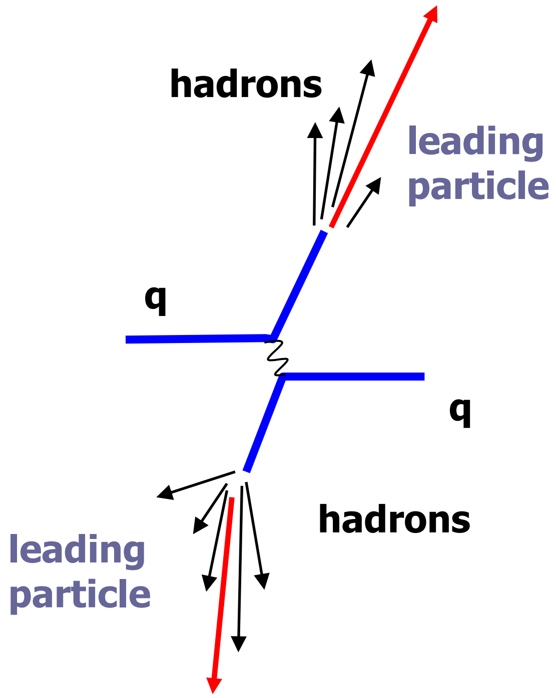
Fragmentation Function

"Collinear factorization"

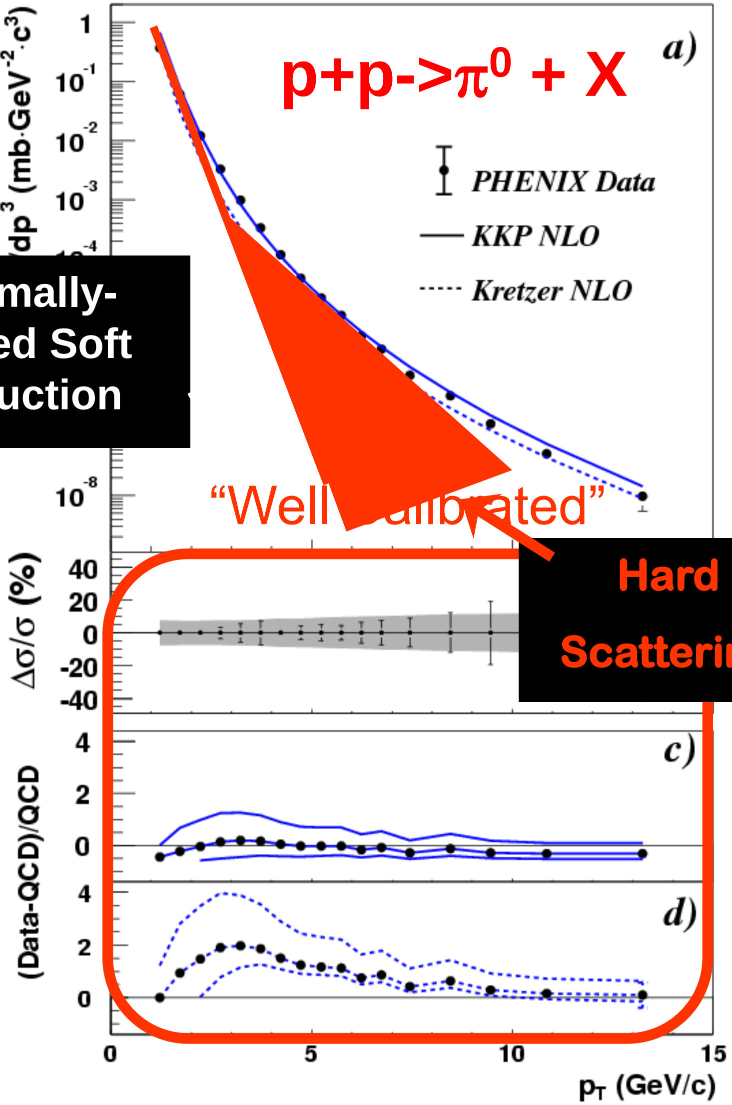
$$\frac{d\sigma_{pp}^{h}}{dy\,d^{2}p_{T}} = K\sum_{abcd}\int dx_a dx_b\, f_a(x_a,Q^2)\, f_b(x_b,Q^2)\, \frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\, \frac{D_{h/c}^{0}}{\pi z_c}$$

Calibrating the Probe(s)

schematic view of jet production



- Measurement from elementary collisions. Leading particles spectra used as a "proxy" to jets.



$p+p \rightarrow \pi^0 + X$

Thermally-shaped Soft Production

"Well calibrated"

Hard Scattering

hep-ex/0305013 S.S. Adler et al.

High p_T Particle Production in A+A

$$\frac{dN^h_{AB}}{dyd^2p_T} = ABK\sum_{abcd}\int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

(pQCD context…)

$$\otimes f_{a/A}(x_a,Q^2)\, f_{b/B}(x_b,Q^2)$$

Parton Distribution Functions

$$\otimes g(\mathbf{k}_a)g(\mathbf{k}_b)$$

Intrinsic k_T , Cronin Effect

$$\otimes S_A(x_a,Q_a^2)S_B(x_b,Q_b^2)$$

Shadowing,

$$\otimes \frac{d\sigma}{d\hat{t}}(ab\to cd)$$

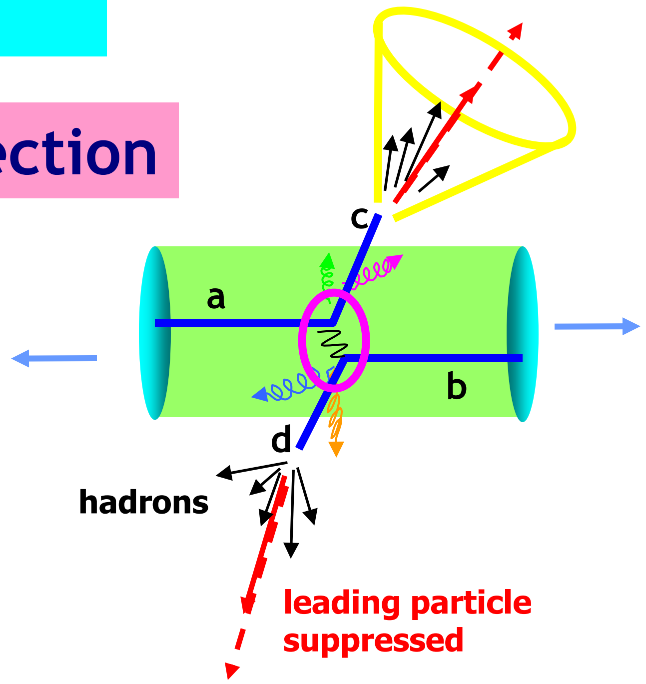
Hard-scattering cross-section

$$\otimes \int_0^1 d\varepsilon P(\varepsilon)\frac{z_c^*}{z_c}$$

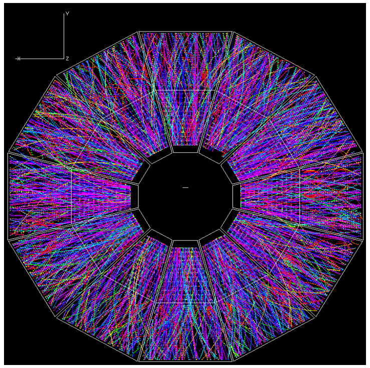
Partonic Energy Loss

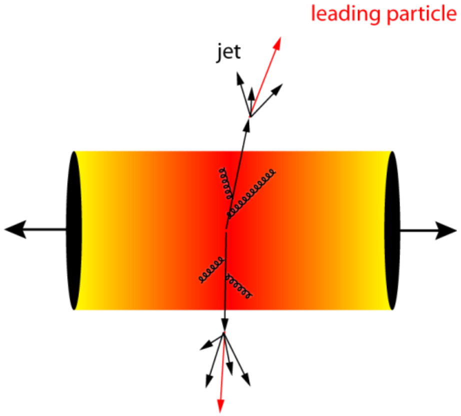
$$\otimes \frac{D^0_{h/c}(z_c^*,Q_c^2)}{\pi z_c}$$

Fragmentation Function



Quantifying the nuclear effect





Energy loss depends on

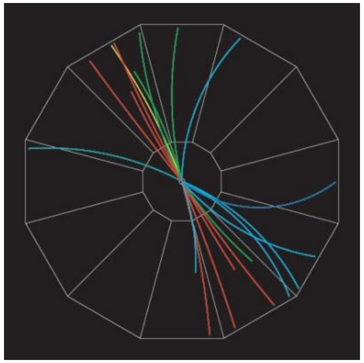
properties of medium

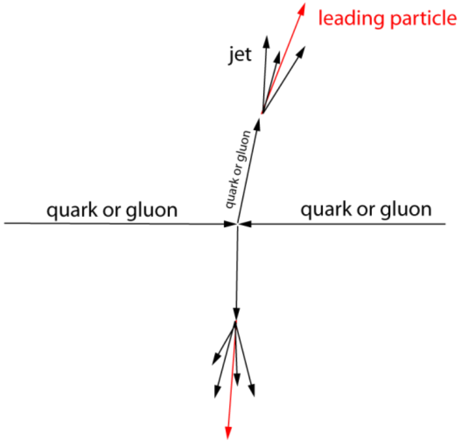
(gluon densities, size, transport coefficients)

properties of “probe”

(color charge, mass)

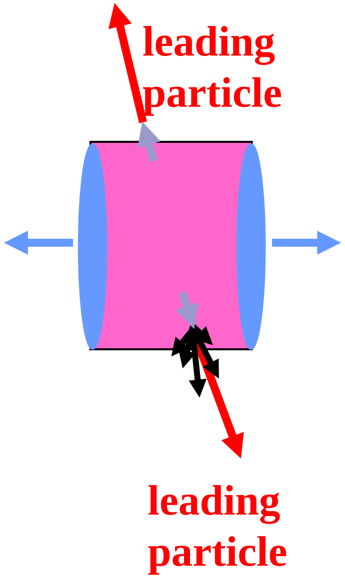
$$R_{AA} = \frac{\text{yield in A+A/number of equivalent p+p collisions}}{\text{yield in p+p}}$$

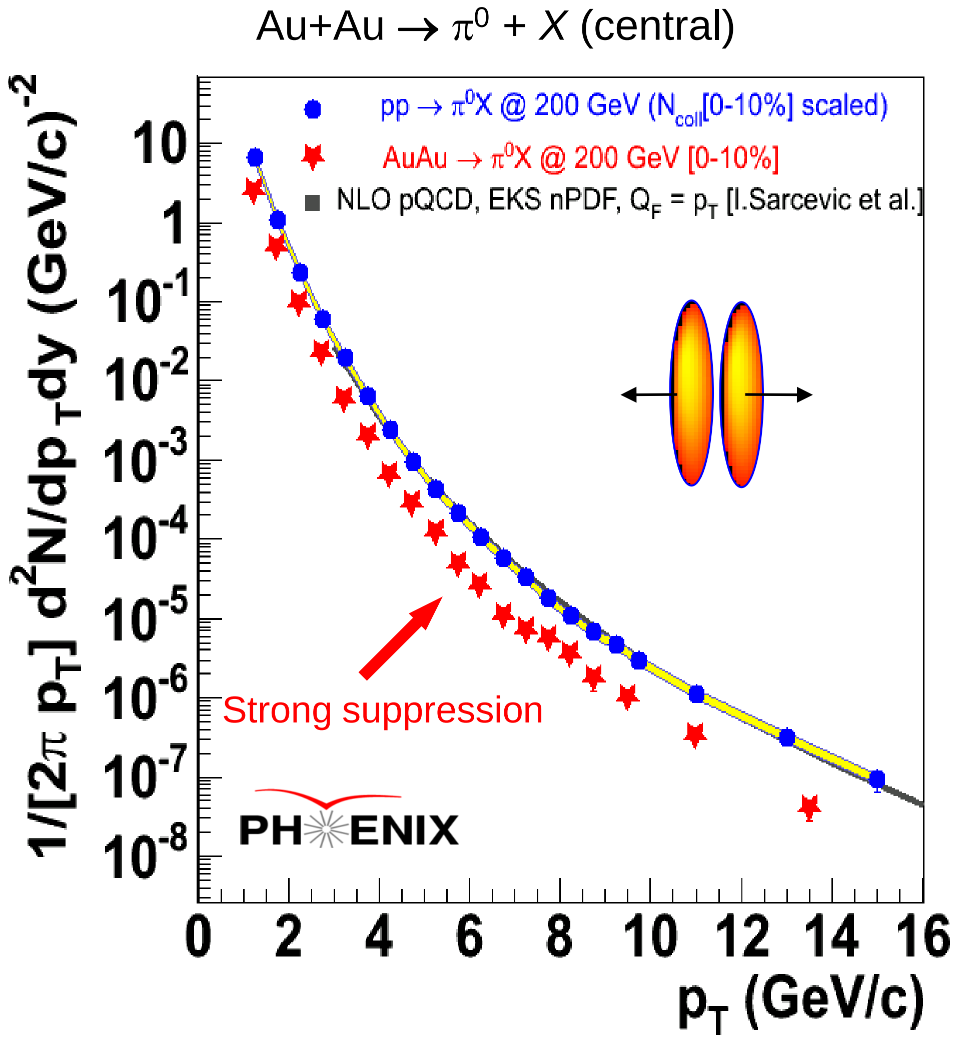




Calibrate the probe and then use it !

- Single-particle spectrum and QCD predictions

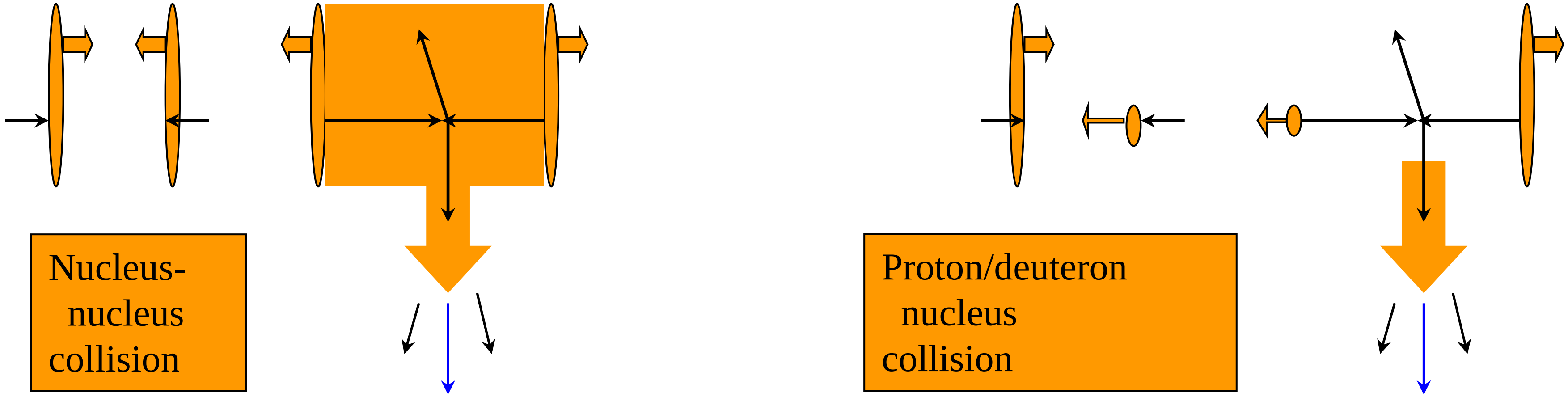




Peripheral spectra agree well with p+p (data & pQCD) scaled by N_{coll}

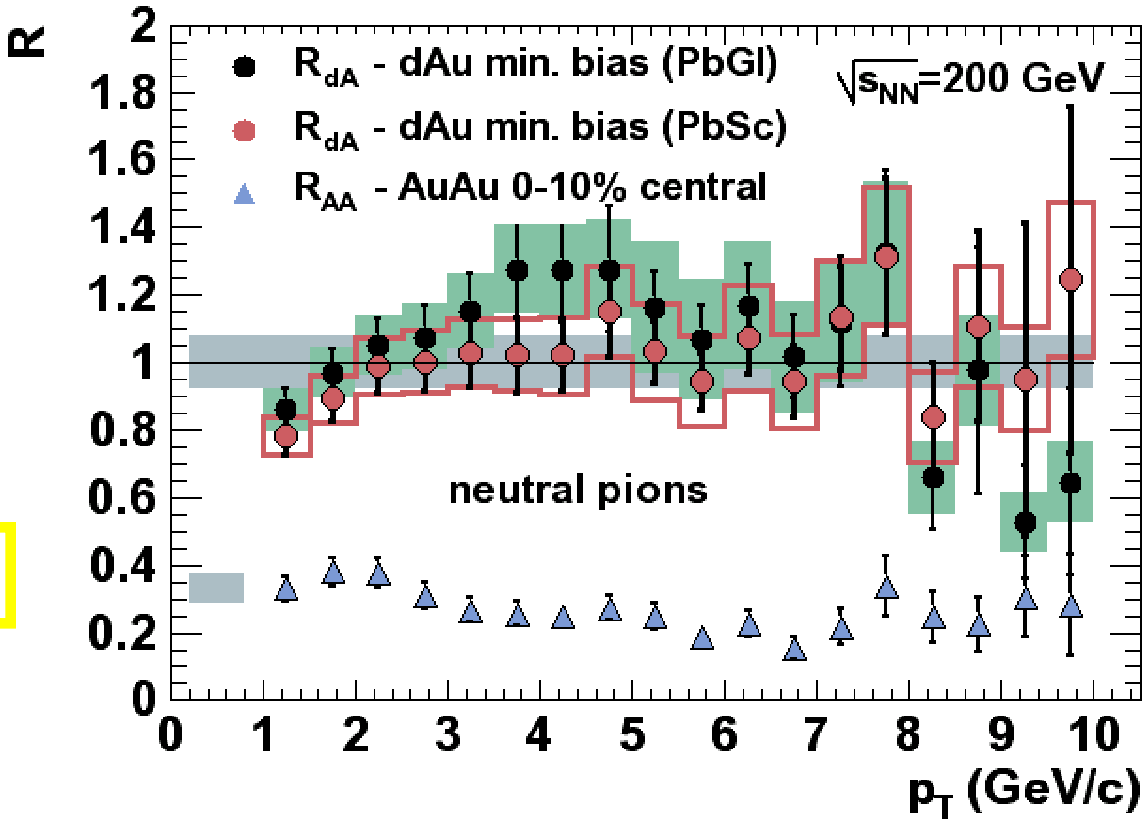
Central data exhibits suppression!

d+Au Control Experiment #1



- Collisions of small with large nuclei are usually considered necessary to quantify cold nuclear matter effects.
- At RHIC , theoretical prediction from "Color Glass Condensate" model provides alternative explanation of data:
  - Jets are not quenched, but are a priori made in fewer numbers.
  - Color Glass Condensate **hep-ph/0212316; Kharzeev, Levin, Nardi, Gribov, Ryshkin, Mueller, Qiu, McLerran, Venugopalan, Balitsky, Kovchegov, Kovner, Iancu**
- Small + Large distinguishes all initial and final state effects.

R_{AA} vs. R_{dA} for Identified π^0



d+Au

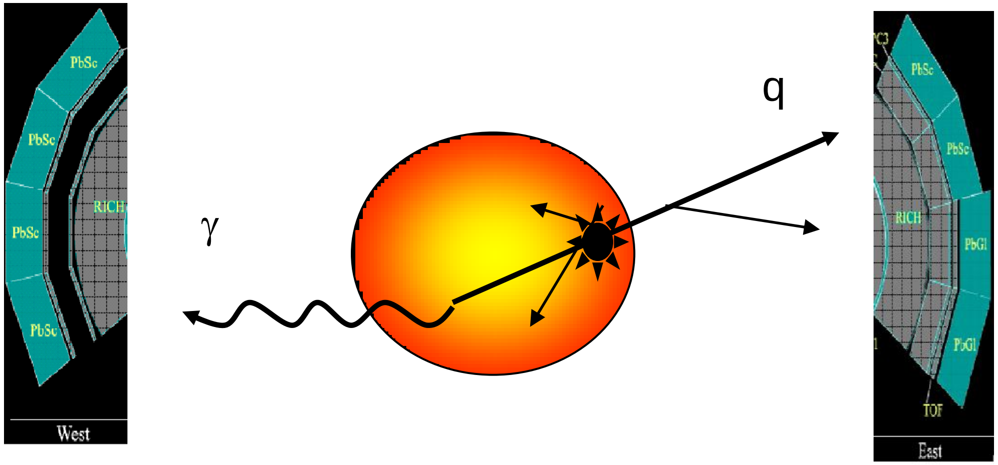
Au+Au

Initial State Effects Only

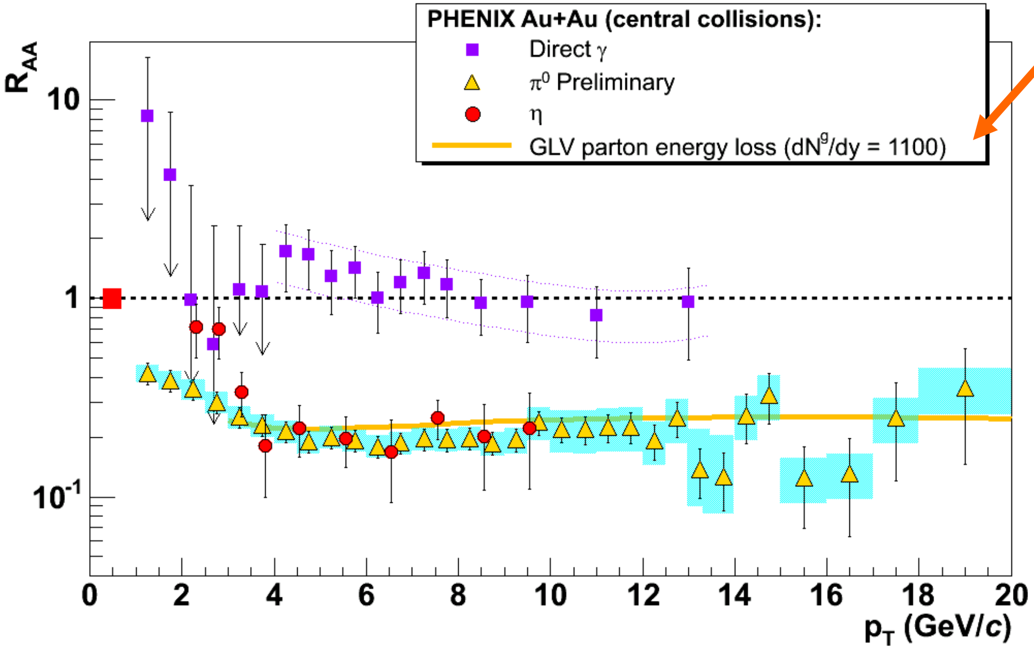
Initial + Final State Effects

- **d-Au results rule out CGC as the explanation for Jet Suppression at Central Rapidity and high p_T**

Control experiment #2: colorless probe



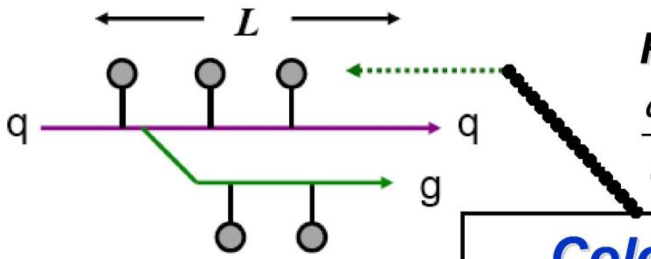
Confirm that jet quenching is due to energy loss in the medium. Deduce the medium density.



Photons shine !

Pions and etas – suppressed !

Quantify energy loss from data



Radiative:

$$\frac{dE}{dx} \sim \sigma\rho L\left\langle k_T^2\right\rangle$$

Color charge scattering centers

k_T transfer per collision

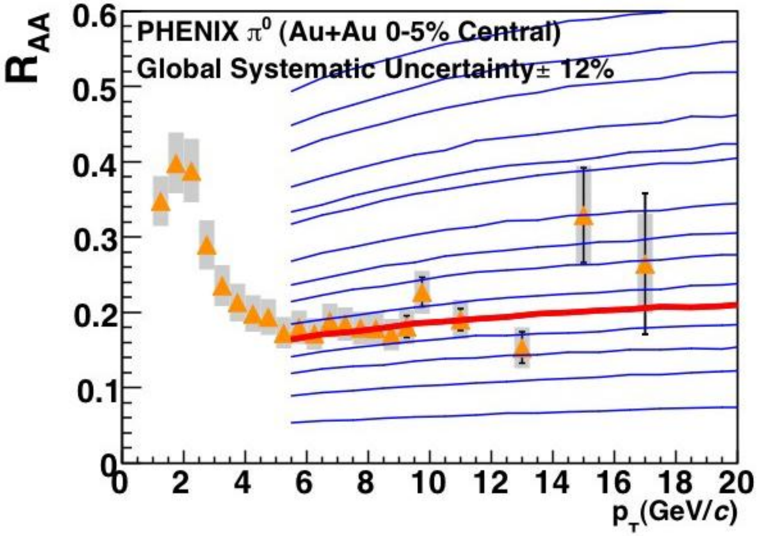
$$\hat{q} \sim \rho\sigma\left\langle k_T^2\right\rangle$$

Can access
ρ and $\hat{q}$

Scattering Power Of Medium

Density of Scattering centers

C. Loizides Eur.Phys.J. C49 (2007) 339: theory
PRC77, 064907 (2008): data

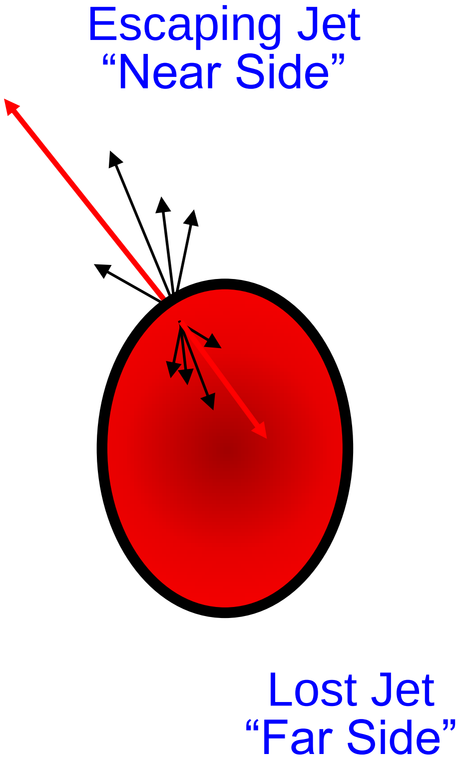


Data with sufficient precision to constrain model parameters to 20-25%. arXiv: 0801.1665

Back to back jets (di-jets)

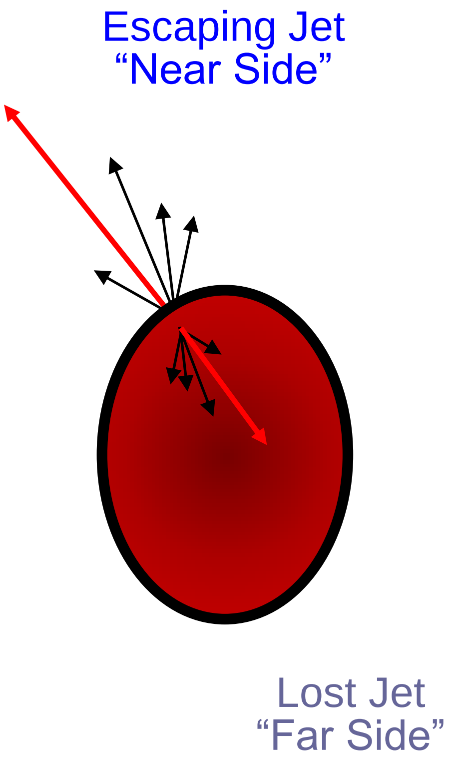
single particle spectra tell you a lot, but you should be able to learn even more from di-jets

Tomographic information on the medium



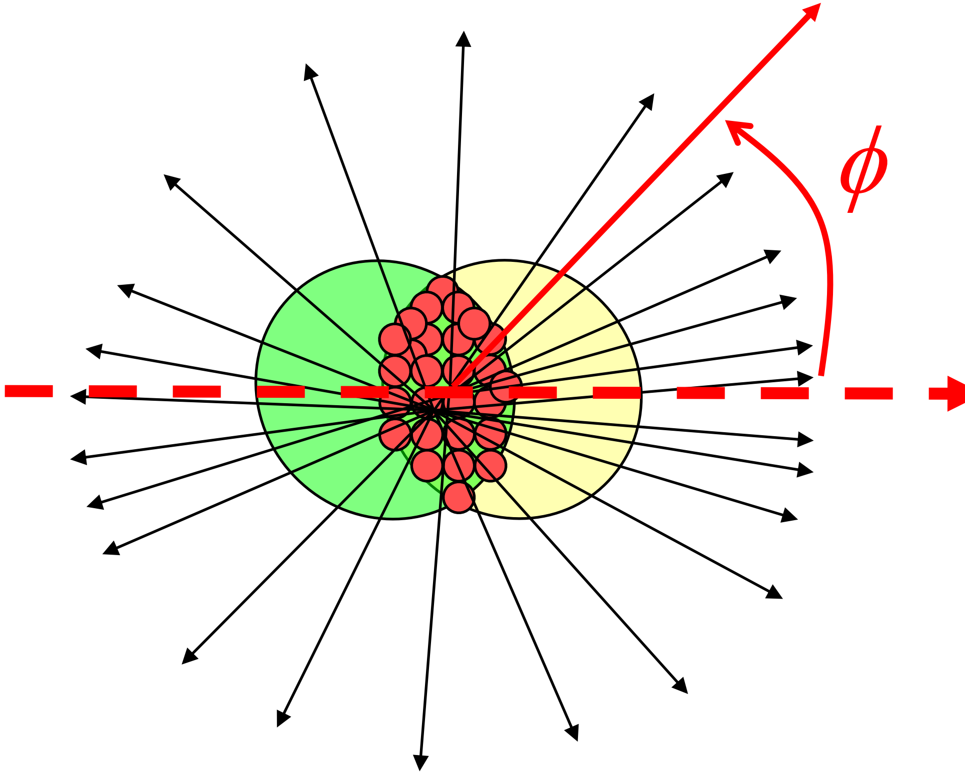
Back-to-back jets and flow

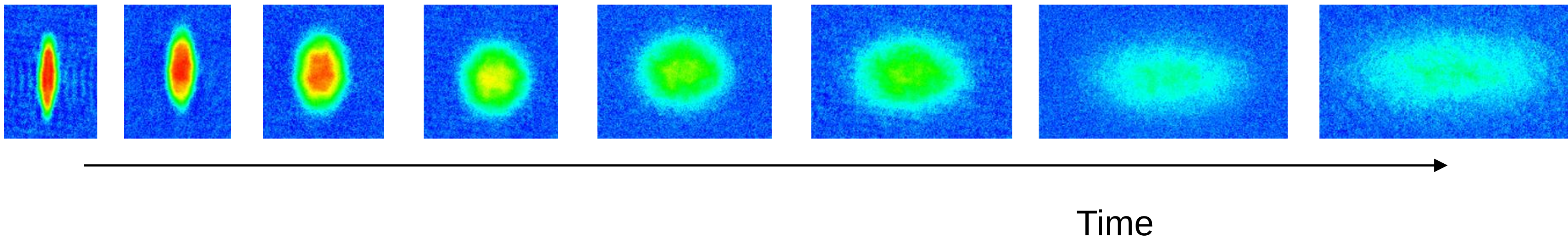
Tomographic information on the medium



Escaping Jet
“Near Side”

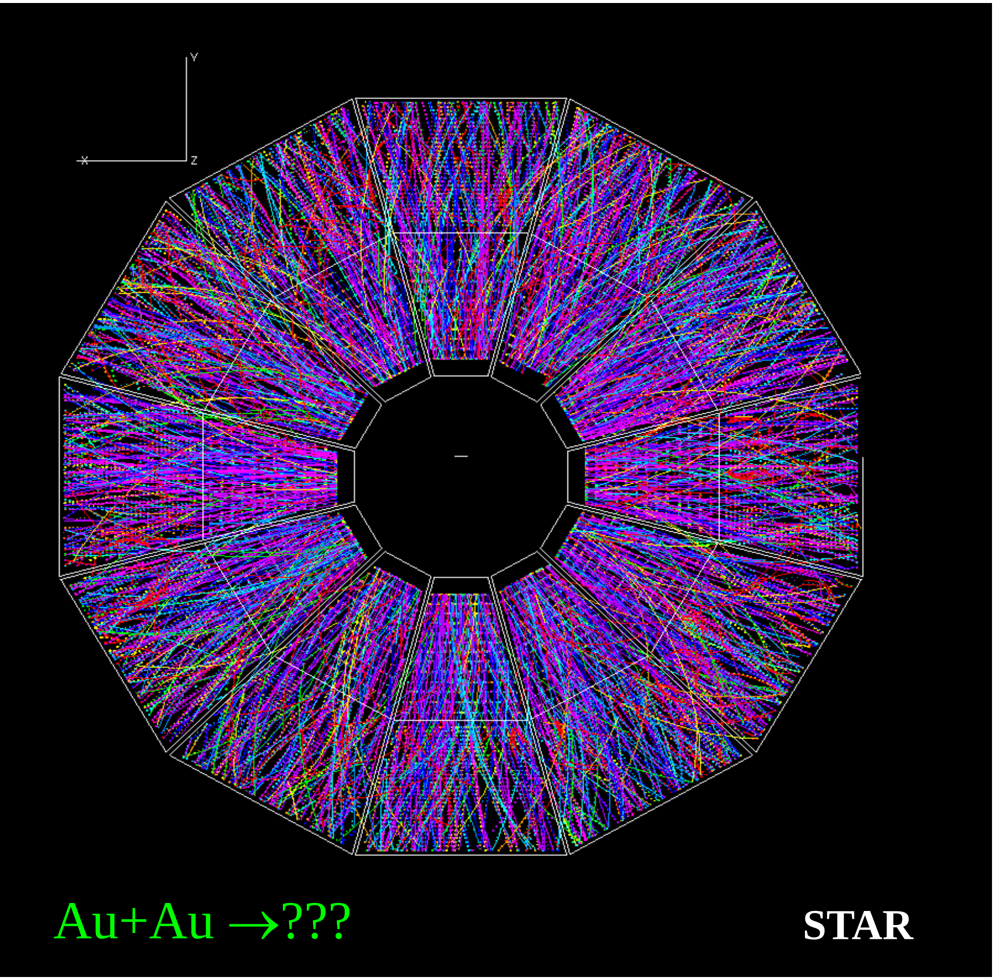
Lost Jet
“Far Side”



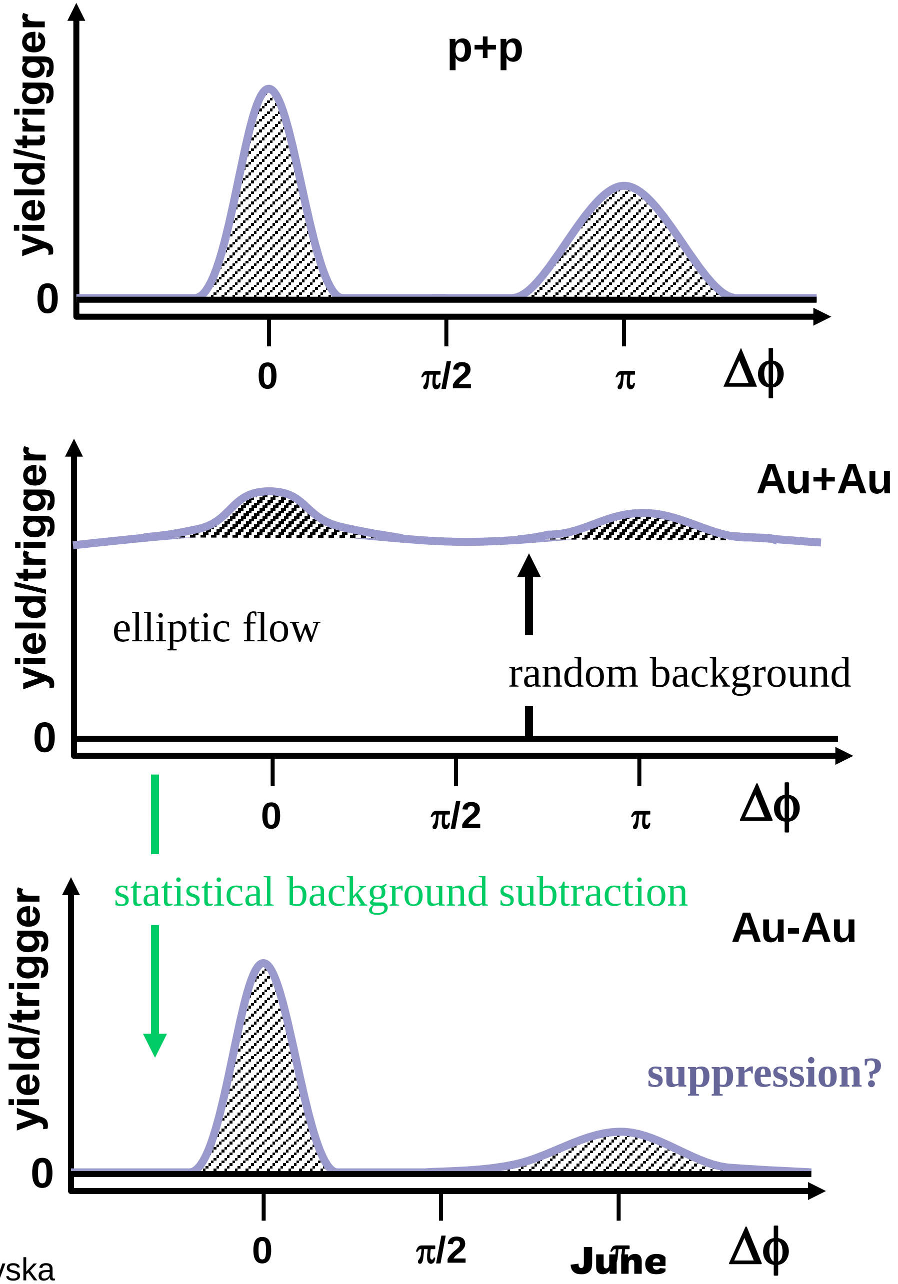


Time

Azimuthal Correlations from Jets



Au+Au →???



elliptic flow

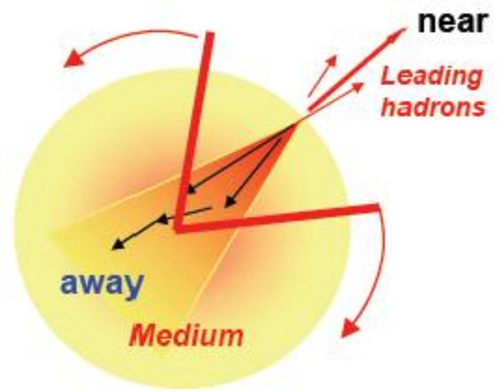
random background

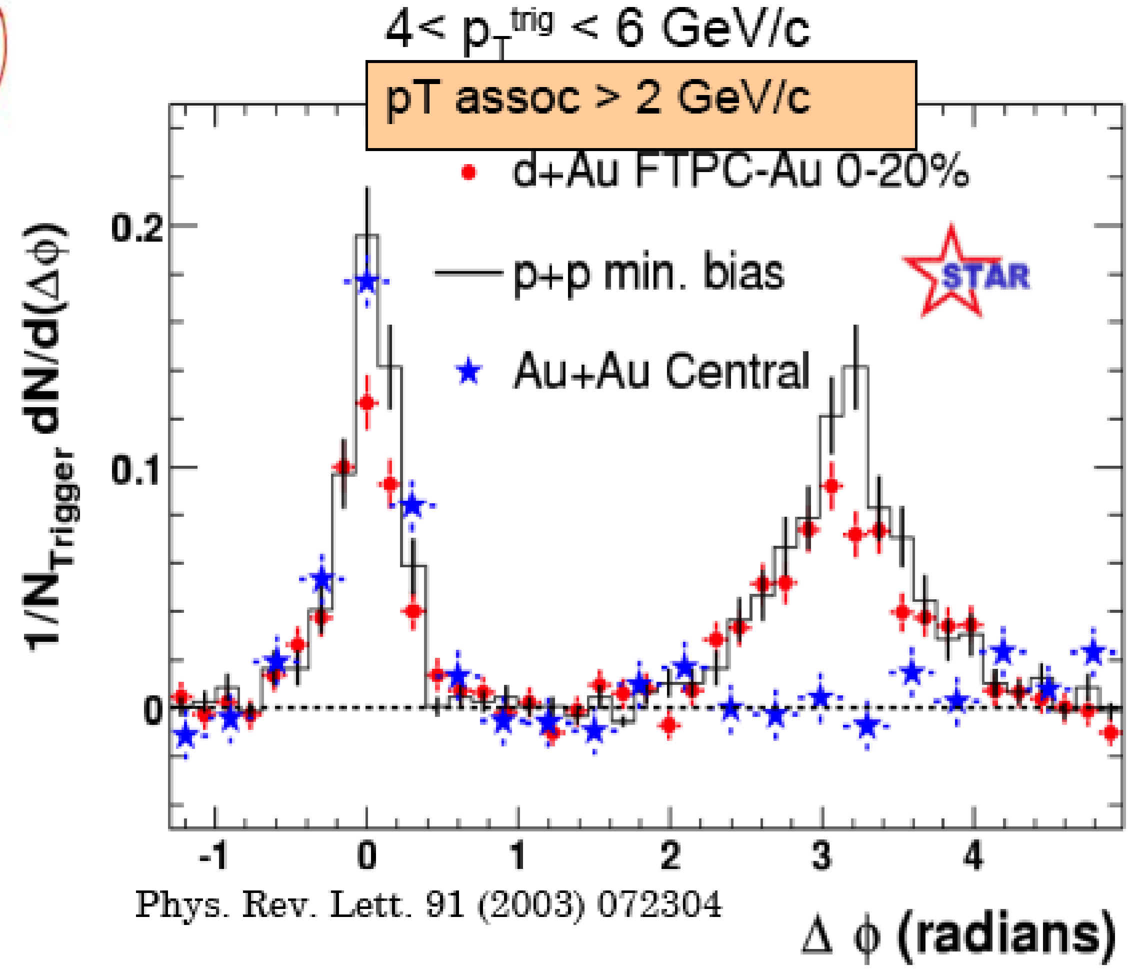
statistical background subtraction

suppression?

Jet correlations in Au-Au via statistical background subtraction

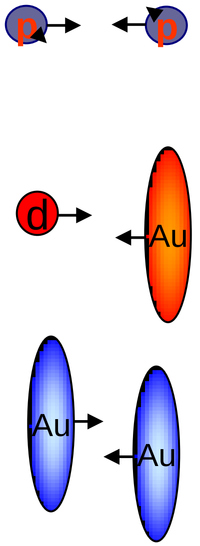
Dijets are suppressed



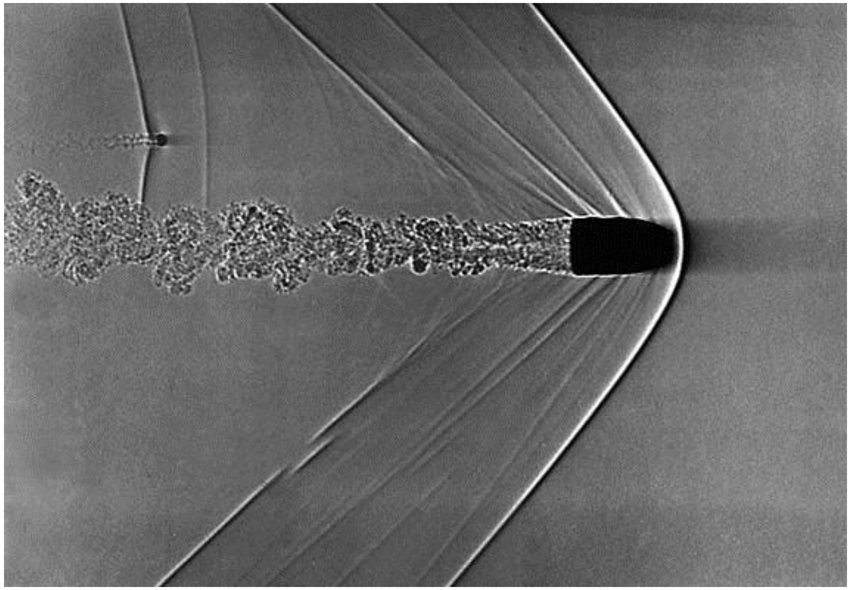


Phys. Rev. Lett. 91 (2003) 072304

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

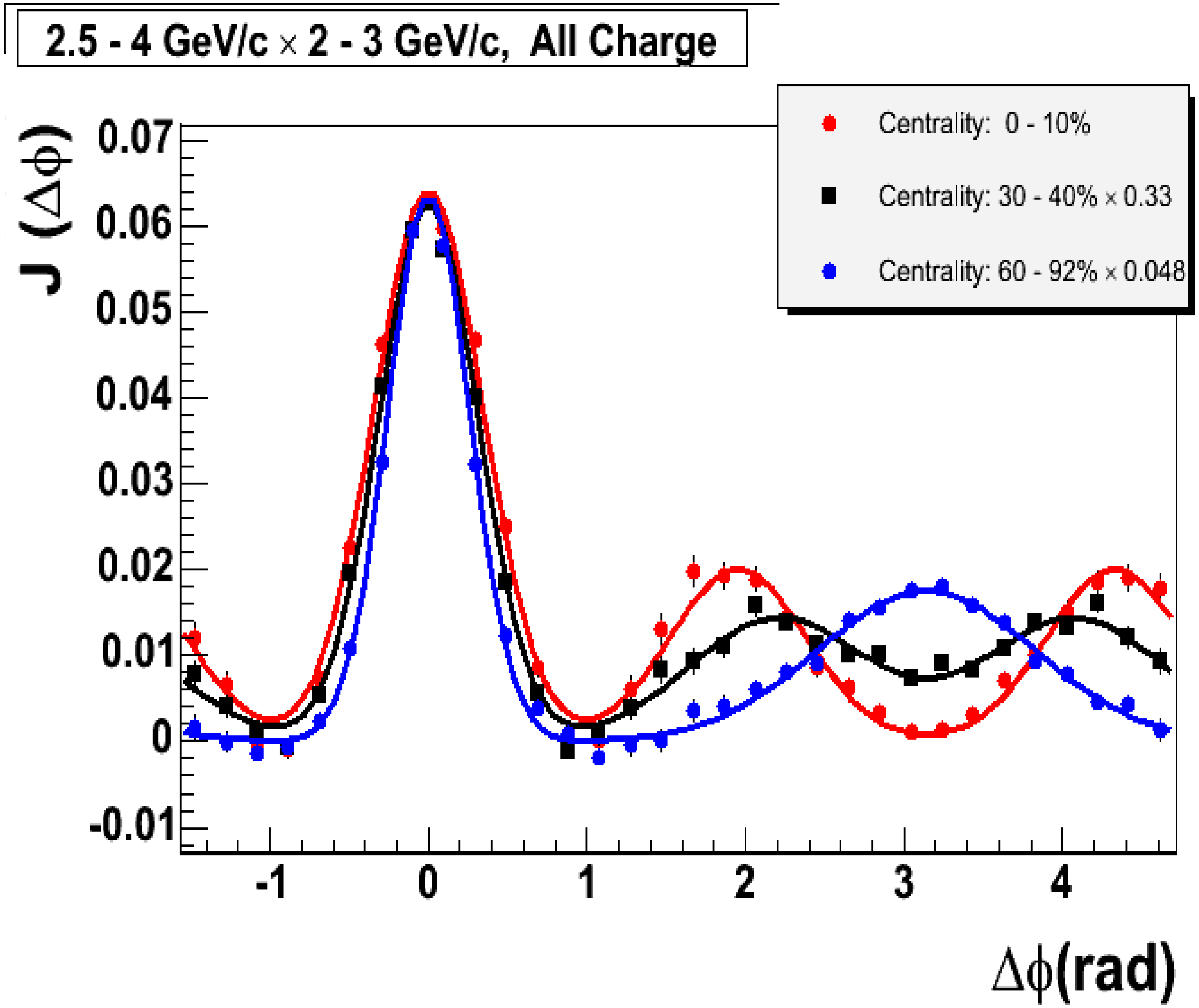


Shock waves ?

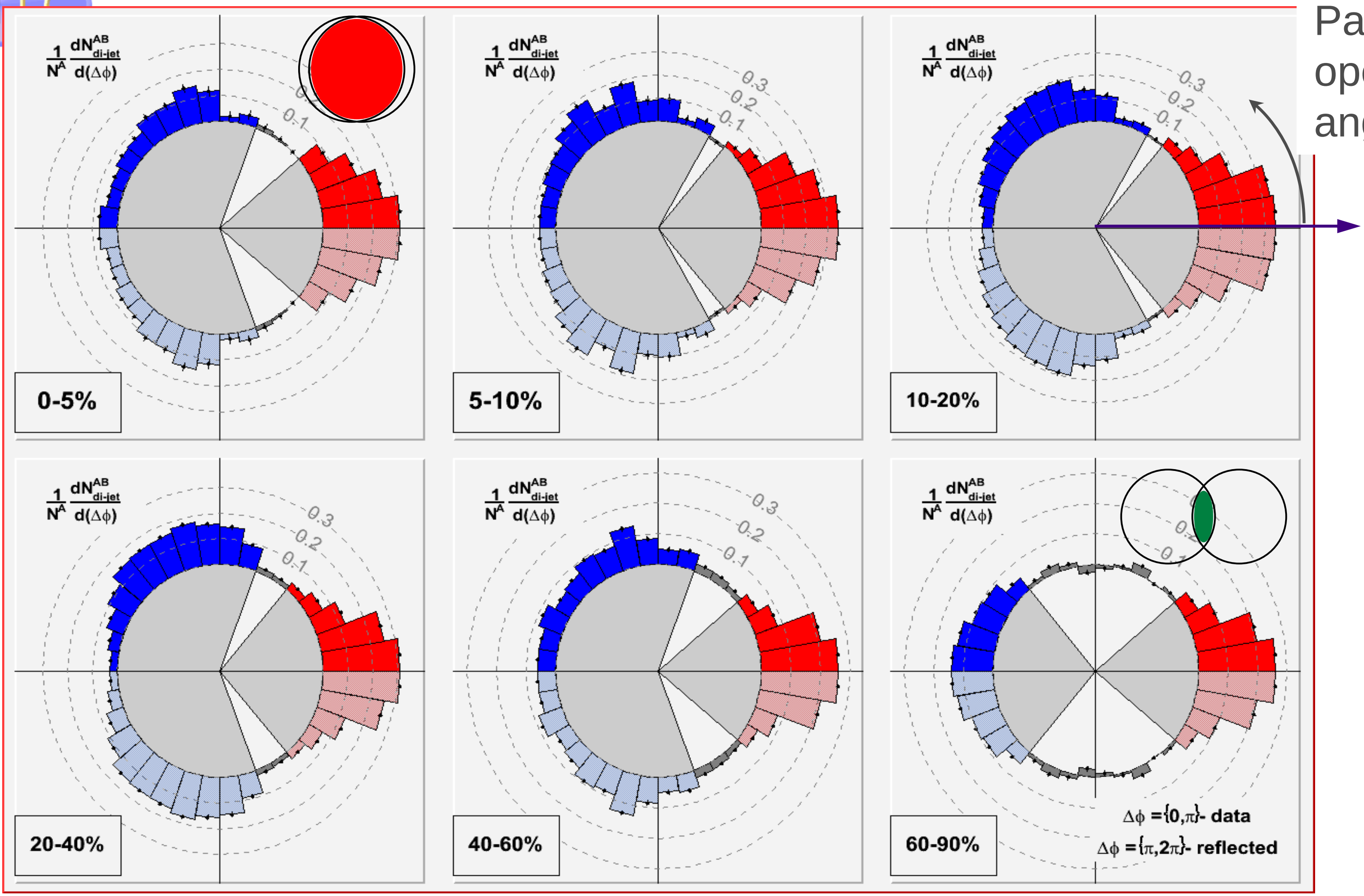


- It looks like the medium quenches the jets, but it also responds to the propagation of the fast moving parton
- If you look closely, you will find the lost energy at lower momenta !

Here is what the data look like

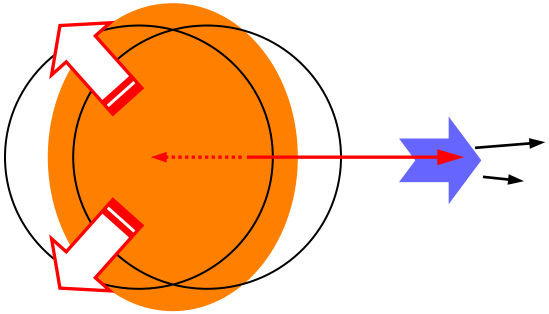


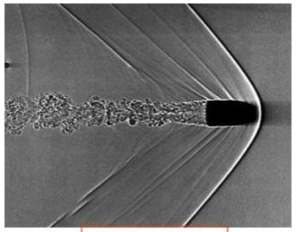
- The shapes of jets are modified by the matter.
  - Mach cone?
  - Cerenkov?
- Can the properties of the matter be measured from the shape?
  - Sound velocity
  - Di-electric constant



Pair opening angle

Trigger particle





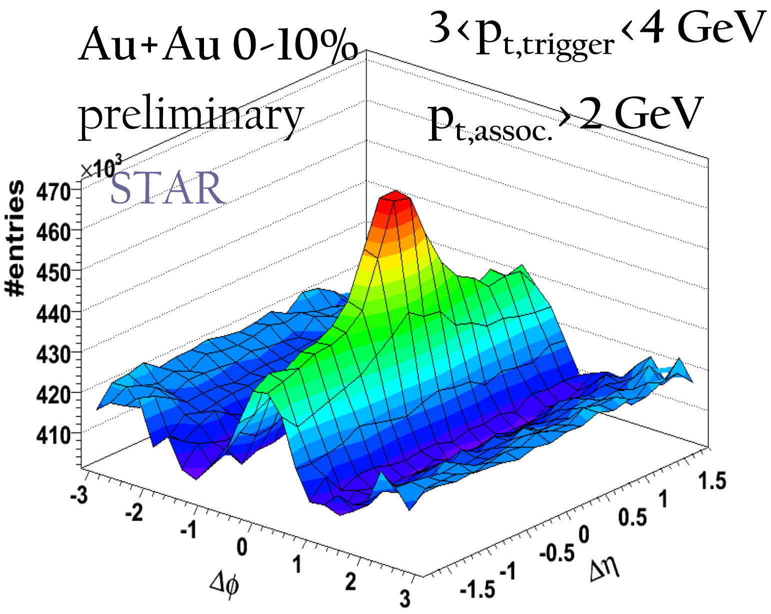
$\cos(\theta_M) = c_s$

Peak: $\phi=\pi$ -(1.2-1.38)

→ **speed of sound**

c_s~0.2-0.4 c

Other interesting structures

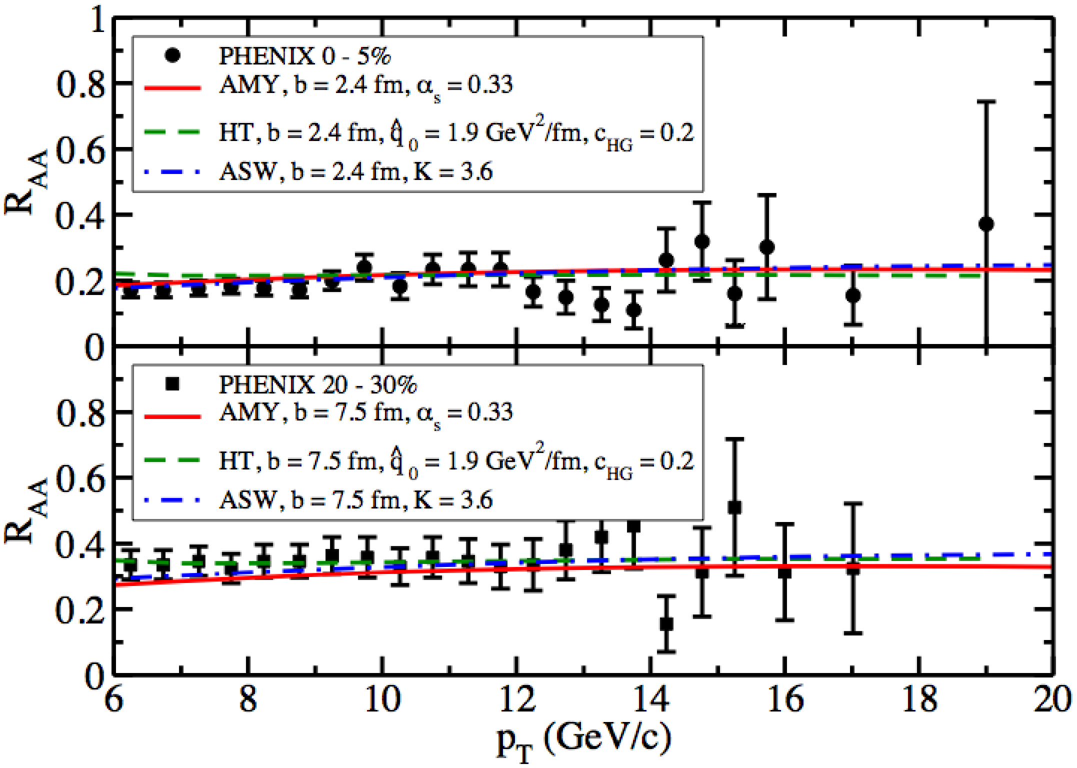


The near side shows interesting structures as well: "the ridge".

These phenomena are presently studied with multi-particle correlations as well.

Comparing to energy loss models

Look into models that describe $R_{AA}(p_T)$ well at high-p_T



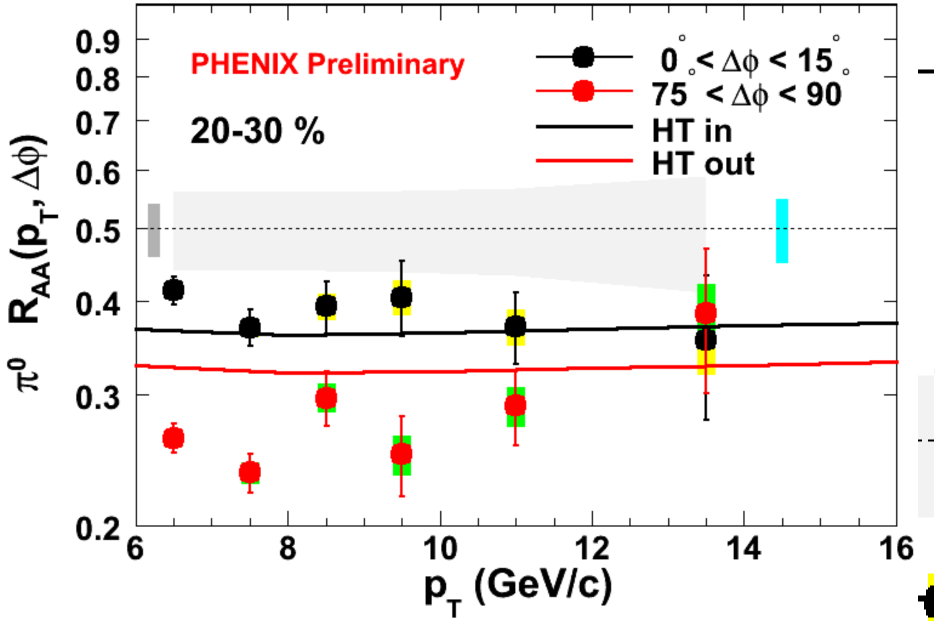
Large discrepancy of extracted transport coefficient q-hat:

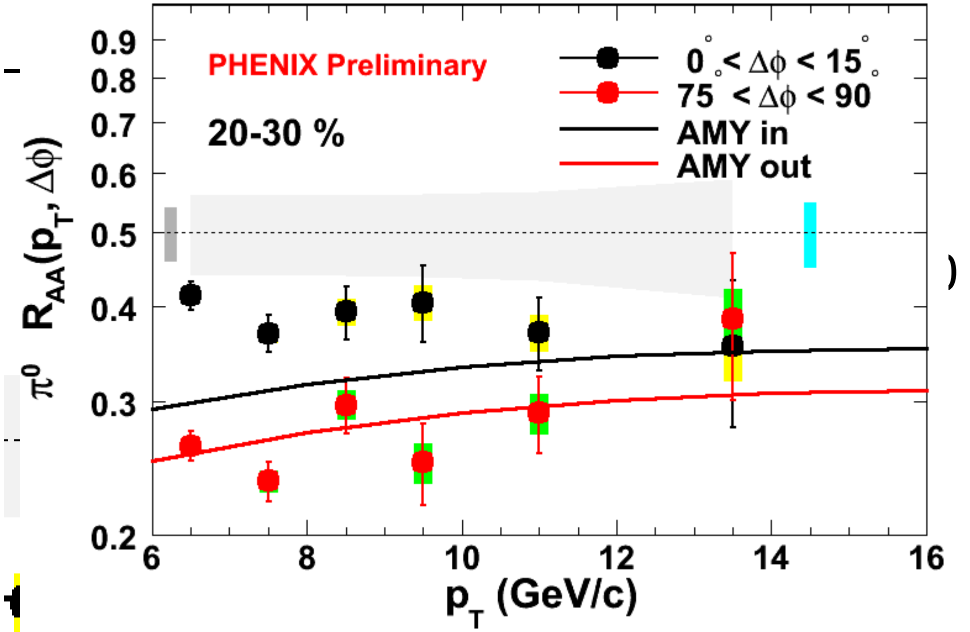
HT:	2.3 $\mathrm{GeV}^2/\mathrm{fm}$
AMY:	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
ASW:	10 $\mathrm{GeV}^2/\mathrm{fm}$

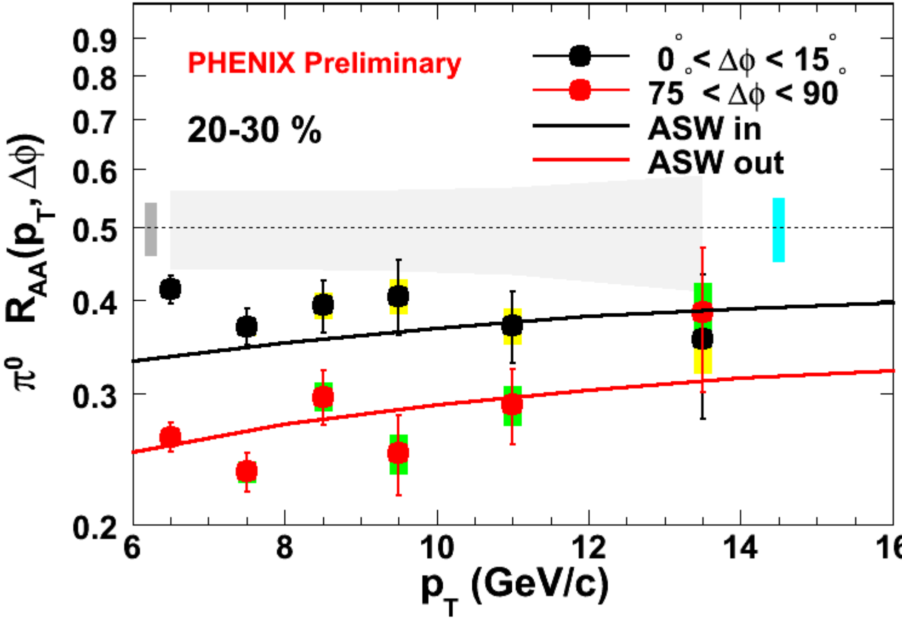
Discriminating power of inclusive R_{AA} is not enough

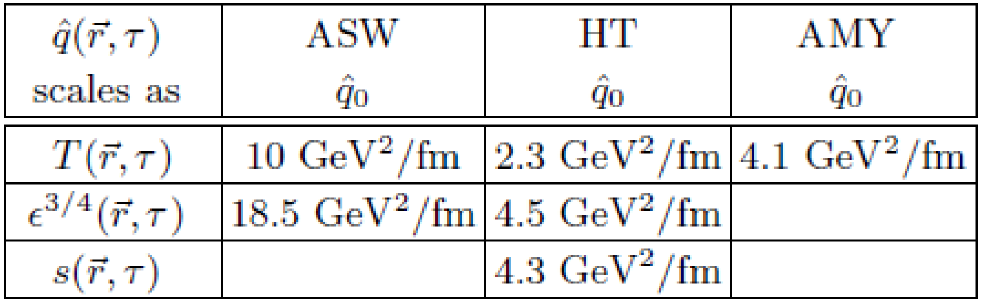
Calculations by S.Bass *et al* in arXiv:0808.0908

Comparisons to model calculations: 20-30% centrality









$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

Calculation from S.Bass et al arXiv:0808.0908

Heavy quarks as a probe

- p+p data:

→ baseline of heavy ion measurements
→ test of pQCD calculations

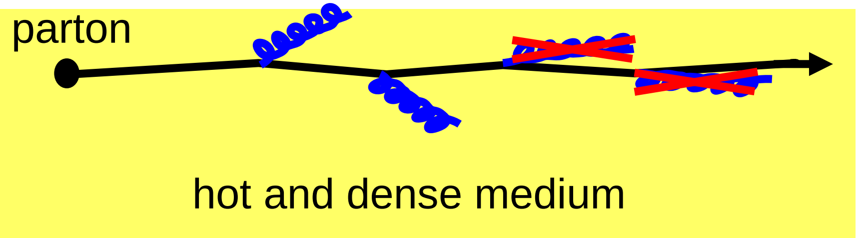
- Due to their large mass heavy quarks are primarily produced by gluon fusion in early stage of collision

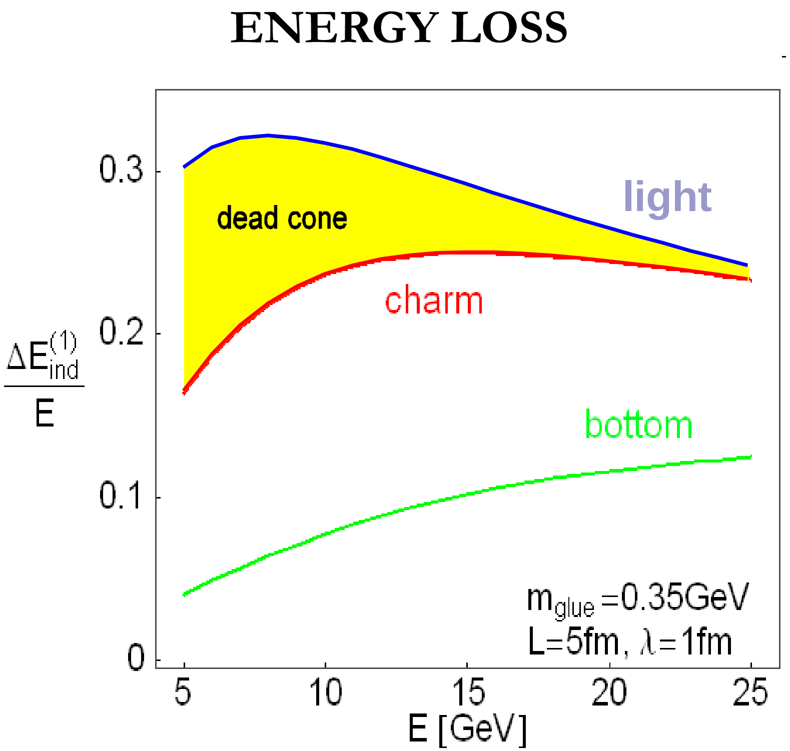
→ production rates calculable by pQCD
M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)

- heavy ion data:

- Studying energy loss of heavy quarks

→ independent way to extract properties of the medium





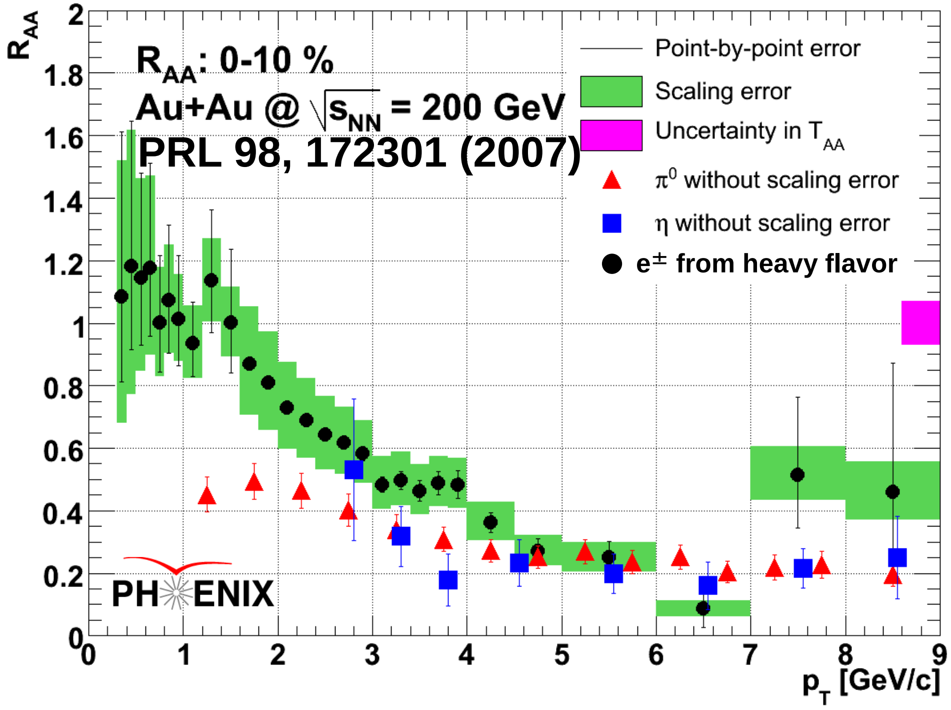
M.Djordjevic PRL 94 (2004)

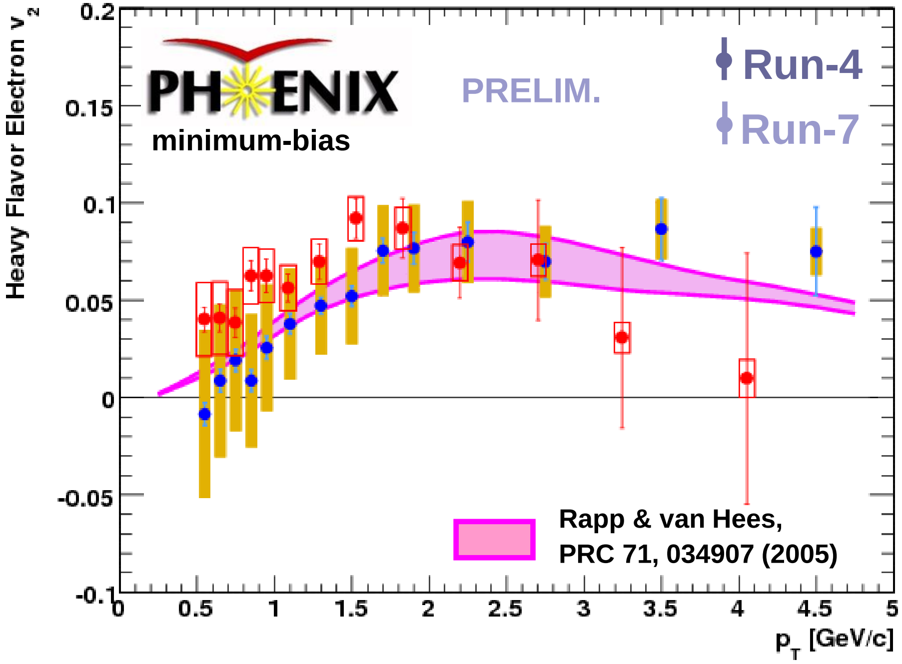
dead-cone effect:

Dokshitzer and Kharzeev, PLB 519, 199 (2001)

Discovery: Heavy quarks flow and lose energy

00-10 %





Lose ~ as much energy as light quarks & gluons!

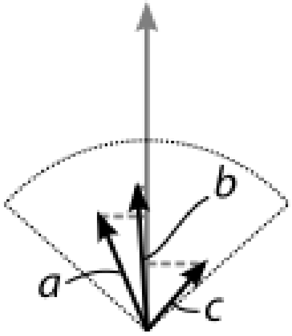
Actually flow along with the bulk medium!

** Measured via $c \rightarrow e^{\pm}$, reconstructed D at low p_T*

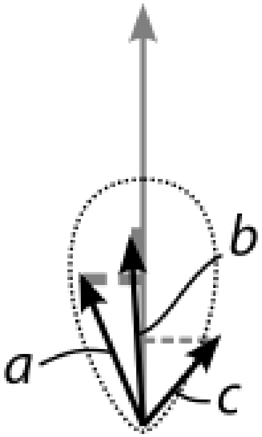
Full jets in PHENIX

- Cone-like algorithm but with angular weight
  - **Implementation naturally seedless, (analytically) collinear , infrared safe**
- Considerations:
  - **Flat angular weight of cone algorithms**
  - **Small cones susceptible to bkgd fluctuations**
  - **Limited angular coverage of PHENIX needs control of edge effects**

Y. Lai, BAC, arXiv:0806.1499

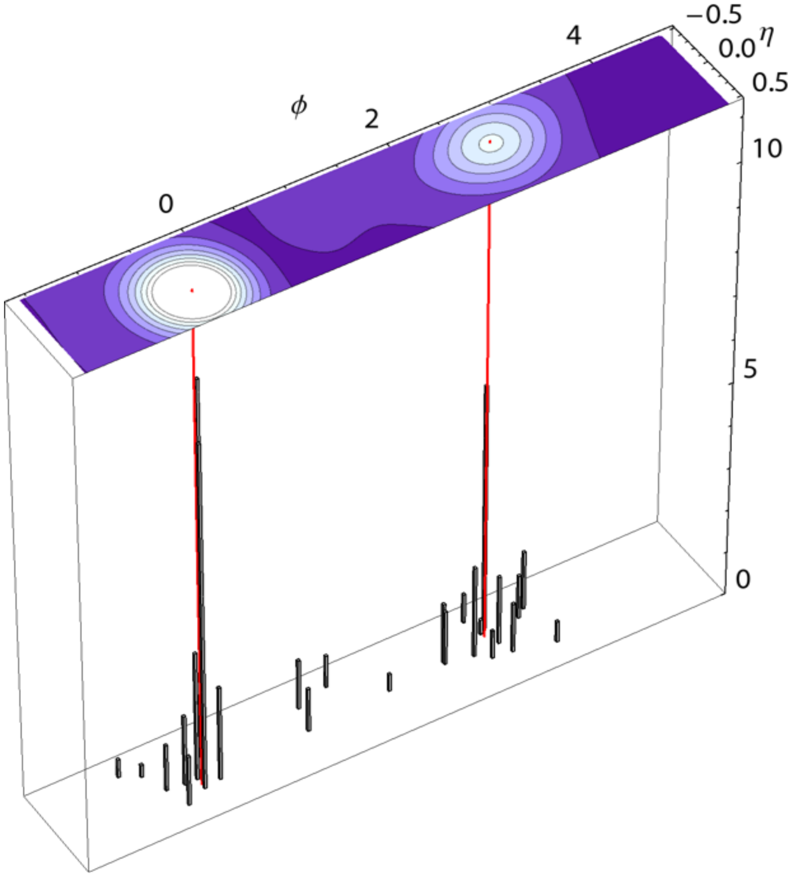


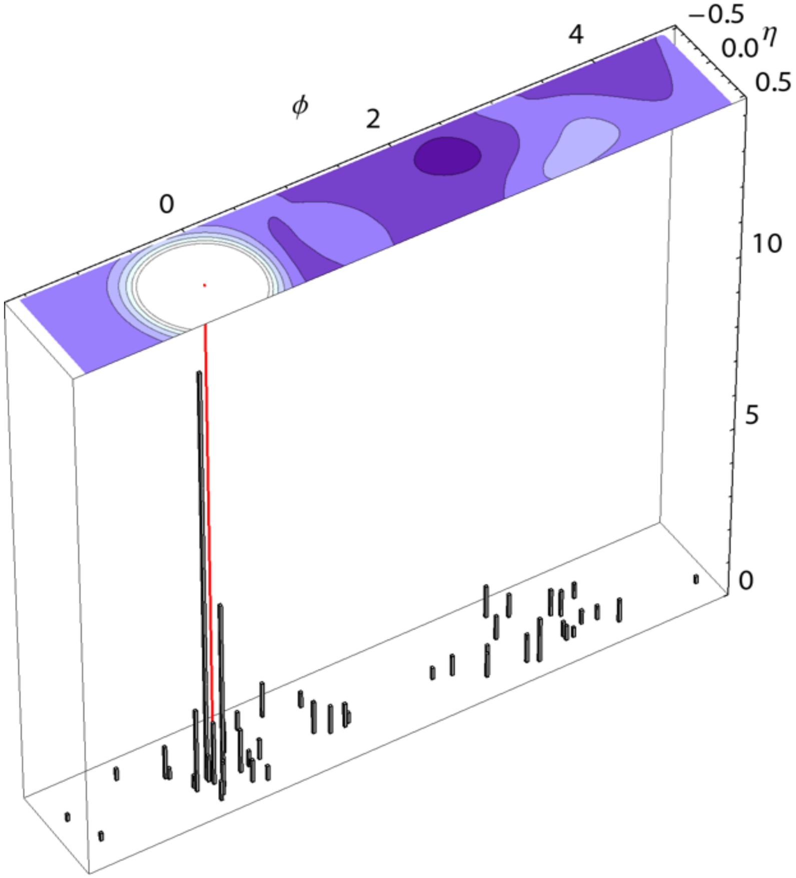
Cone



Filter

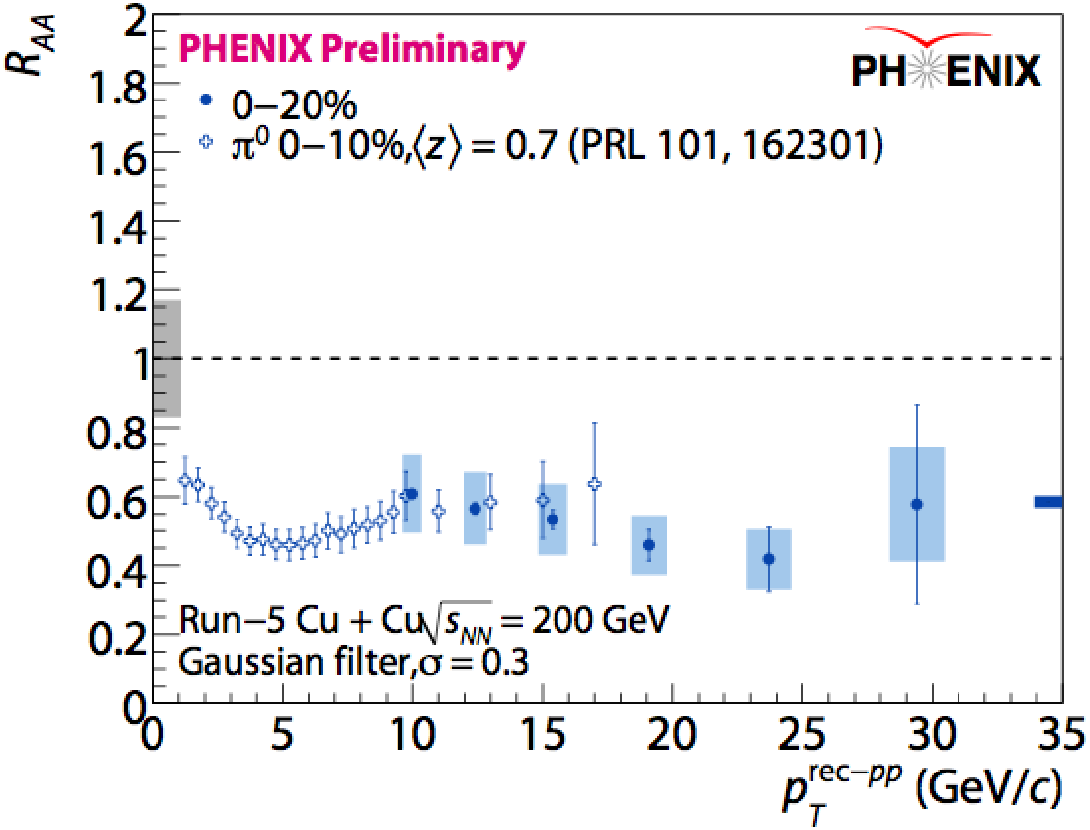
Cu+Cu Event Display





- **Event display of two Cu+Cu events**
  - Di-jet event
  - Single-jet event, other outside acceptance (?)

R_{AA} of jets in CuCu



- Jet RAA comparable to π^0 R_{AA} . Suggest we are not “seeing” quenched jets
  - ☐ **Due to algorithm, “Out of cone radiation”, collisional energy loss, other ? We don’t know yet**

Summary

- Extremely dense and strongly coupled medium has been produced at RHIC.
- The medium quenches the jets , but it is also modified by them.
- Even heavy quarks flow with the bulk.
- After 10 years, the RHIC program has moved beyond the initial exploration phase and is now producing detailed and precise measurements that need detailed and precise theoretical descriptions
- Recent progress in theory gives insight in the collective hydrodynamic behavior
- Calculations in the perturbative regime (“easy”) need to follow suite
- Experiments and the accelerator are being upgraded
- Stayed tuned for more RHIC results in the LHC era !