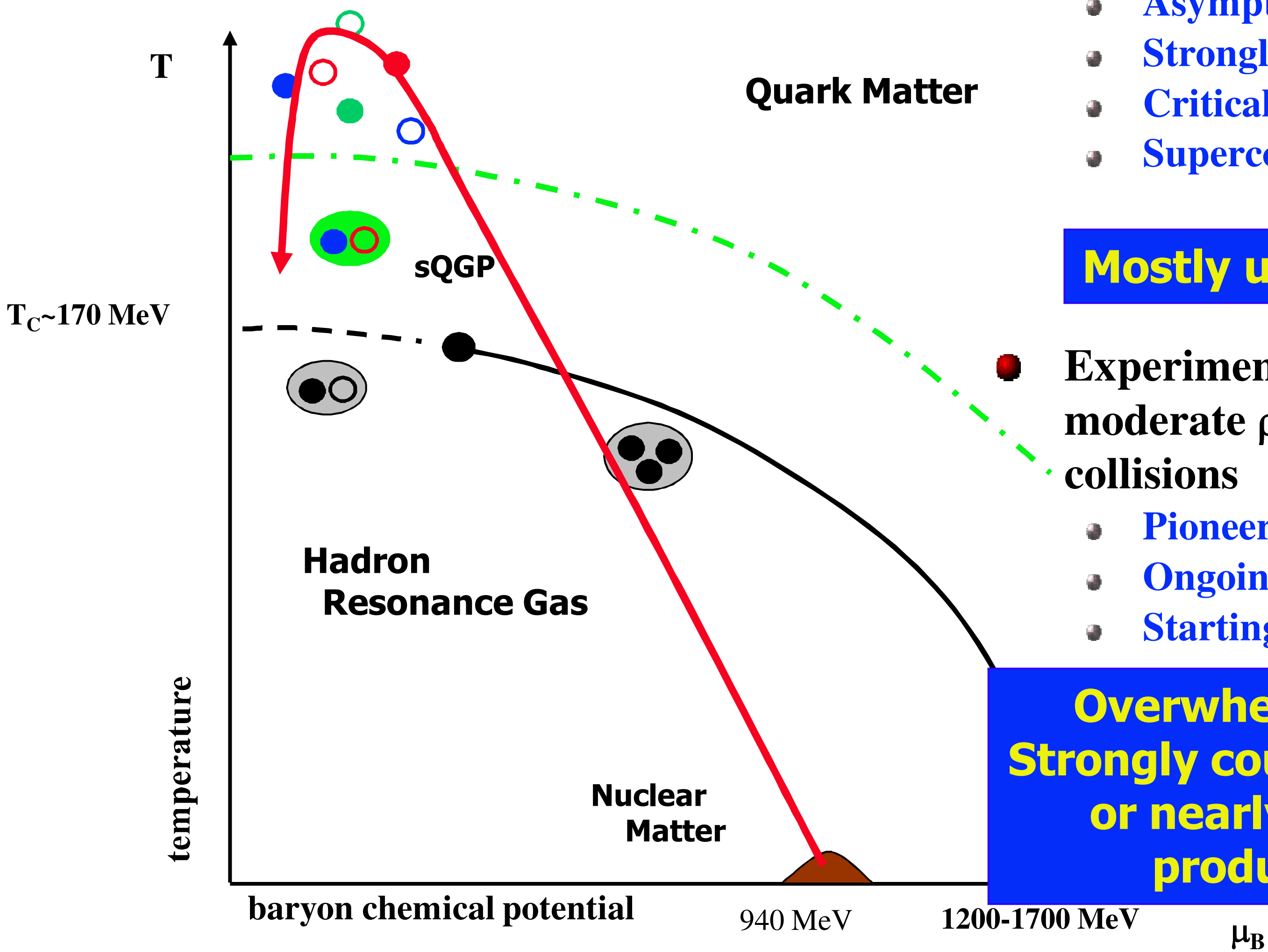
Heavy Ion Physics at RHIC: The Strongly Coupled Quark Gluon Plasma

Axel Drees, Stony Brook University
19/11/2009 HCP2009, Evian, France

- **High temperature and density QCD**
  - QCD phase transition
  - The RHIC program
- **Experimental Results**
  - Energy density and temperatures
  - Quenching of penetrating probes
  - Anisotropic flow of matter
  - Local flow of matter
- **Outlook and Summary**

Study high T and ρ QCD in the Laboratory

Exploring the Phase Diagram of QCD



- **Quark Matter: Many new phases of matter and features**
  - Asymptotically free quarks & gluons
  - Strongly coupled plasma
  - Critical point (?)
  - Superconductors, CFL ….

Mostly uncharted territory

- **Experimental access to "high" T and moderate ρ region: heavy ion collisions**
  - Pioneered at AGS and SPS
  - Ongoing program at RHIC
  - Starting program at LHC

**Overwhelming evidence:
Strongly coupled quark matter
or nearly perfect liquid
produced at RHIC**

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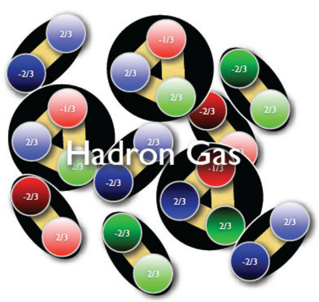
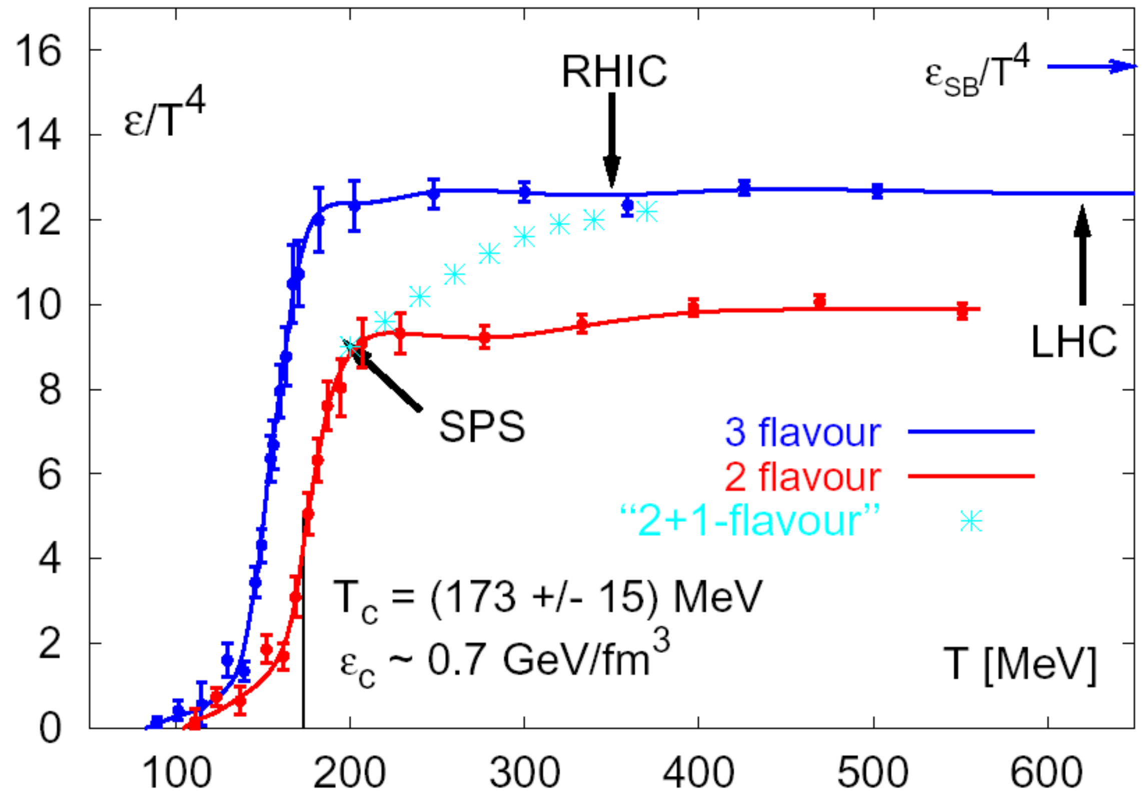
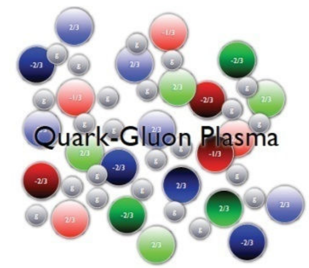
Numerical QCD Calculations on the Lattice







- **Hadron ←degrees of freedom→ Parton**
- **Change at $\varepsilon_C \sim 0.7$ GeV/fm^3**
- **Critical temperature $T_C \sim 170$ MeV**

Phase transition well established from lattice calculations

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A New Approach to Non-perturbative Calculations

- **Duality of theories**
- **Tool in string theory for 10 years**
- **Strong coupling in one theory correspond weak coupling in other theory**

- **AdS/CFT duality (Anti deSitter Space/ Conformal field theory)**

QGP

⇕

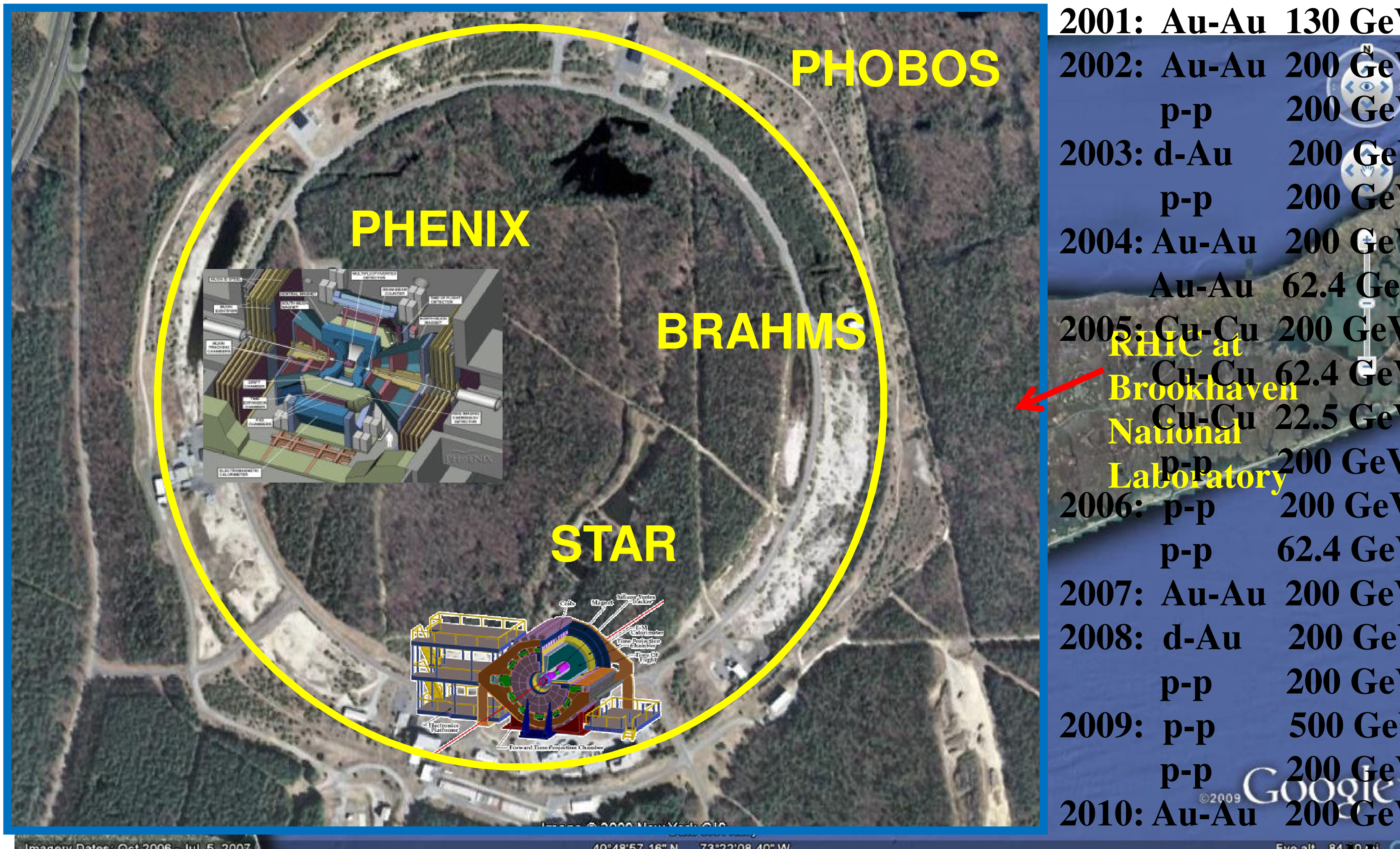
Finite temperature gauge theory ⇔ Black hole
at strong coupling ⠀⠀⠀⠀⠀⠀ in AdS space

⇓ thermal

⇓ thermal due to the Hawking radiatio

Recent success: 1/4π quantum bound on shear viscosity

Relativistic Heavy Ion Collider

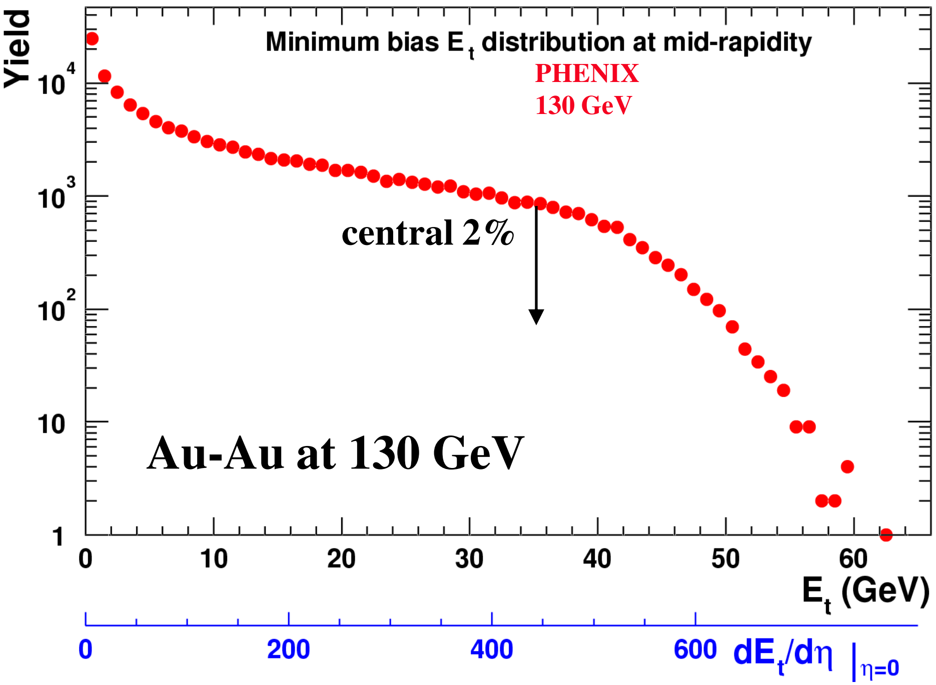


2001: Au-Au 130 GeV
2002: Au-Au 200 GeV
p-p 200 GeV
2003: d-Au 200 GeV
p-p 200 GeV
2004: Au-Au 200 GeV
Au-Au 62.4 GeV
2005: Cu-Cu 200 GeV
Cu-Cu 62.4 GeV
Cu-Cu 22.5 GeV
p-p 200 GeV
2006: p-p 200 GeV
p-p 62.4 GeV
2007: Au-Au 200 GeV
2008: d-Au 200 GeV
p-p 200 GeV
2009: p-p 500 GeV
p-p 200 GeV
2010: Au-Au 200 GeV
and lower

Huge sets of data from 9 years operation!

Estimate of Initial Energy Density

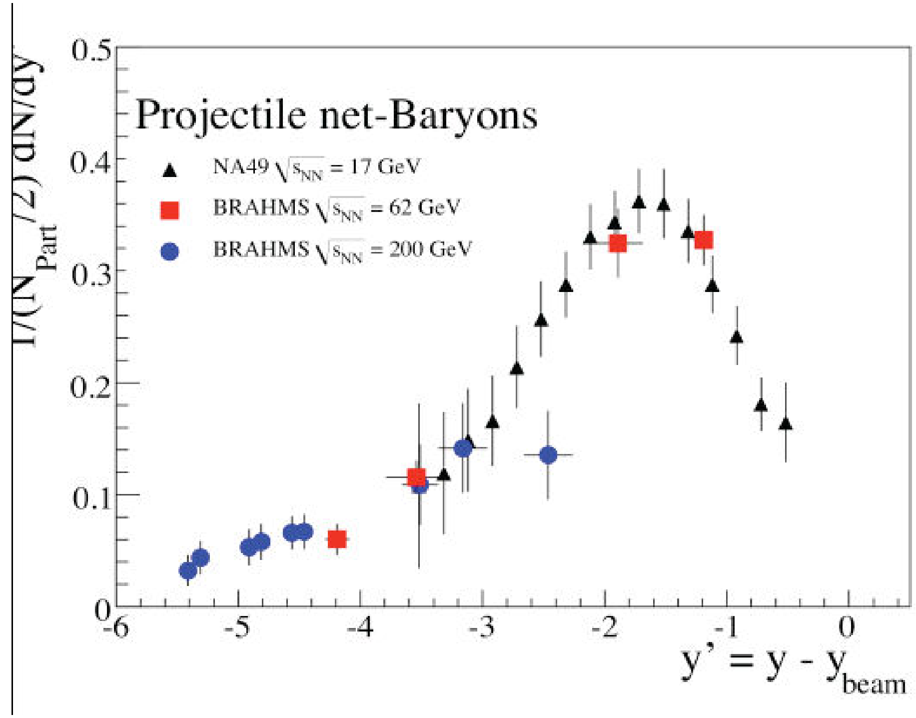
I. Transverse Energy



Bjorken estimate:

$\tau_0 \sim 0.3$ fm

II. Baryon Stopping



Rapidity shift: $\Delta y \sim 1.6$

$\tau_0 \sim 0.3$ fm

$\varepsilon_{initial} > 10\text{-}20\ \mathrm{GeV/fm^3} > \varepsilon_C$

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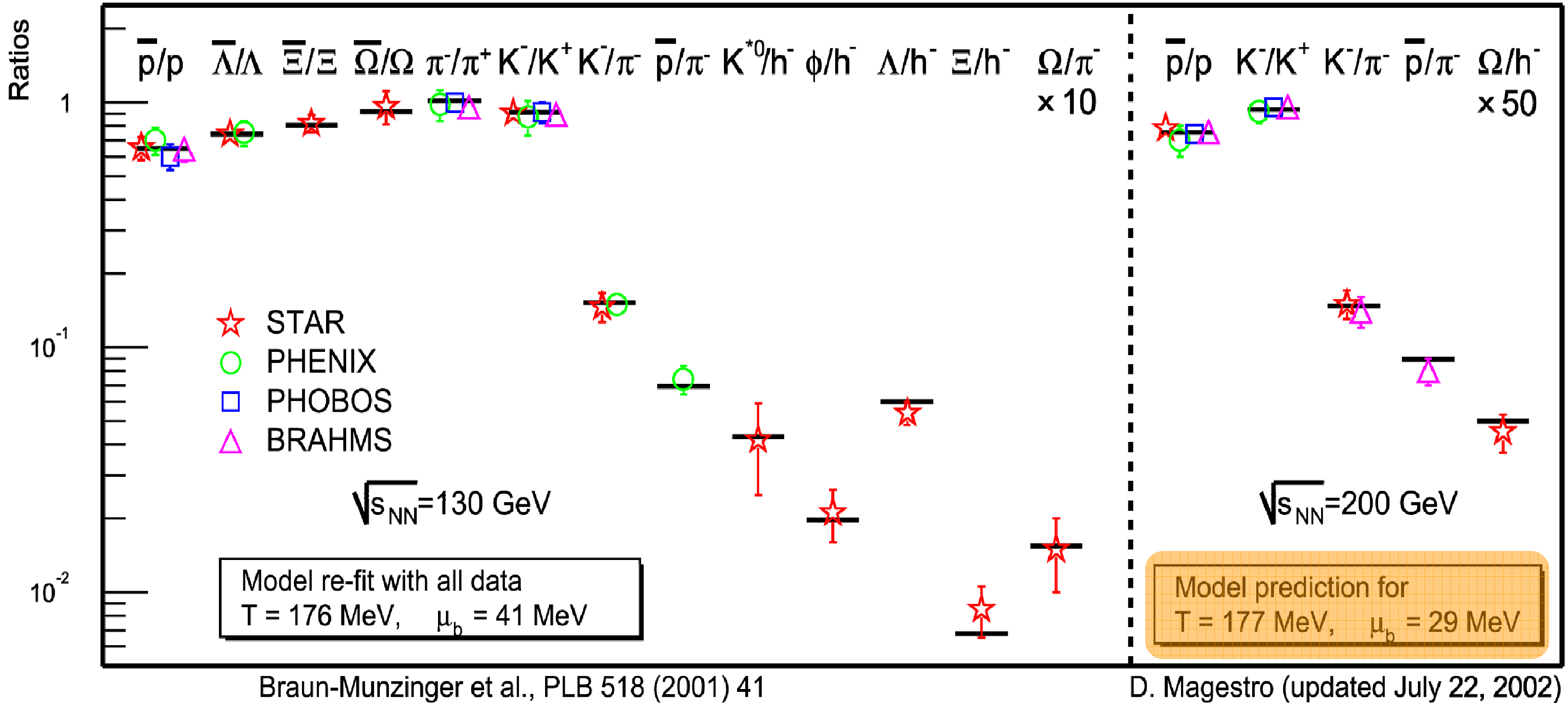
Temperature Estimate from Hadron Yields

- **Statistical description of hadron yields**
  - **chemical freezeout temperature T_C**
  - **baryochemical potential μ_B**

$$N_h \propto V \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\left(\sqrt{p^2+m_h^2}-\mu_B\right)/T} \pm 1}$$



Braun-Munzinger et al., PLB 518 (2001) 41

D. Magestro (updated July 22, 2002)

All hadron species apparently emitted from thermal source at T = 170 MeV close to phase boundary

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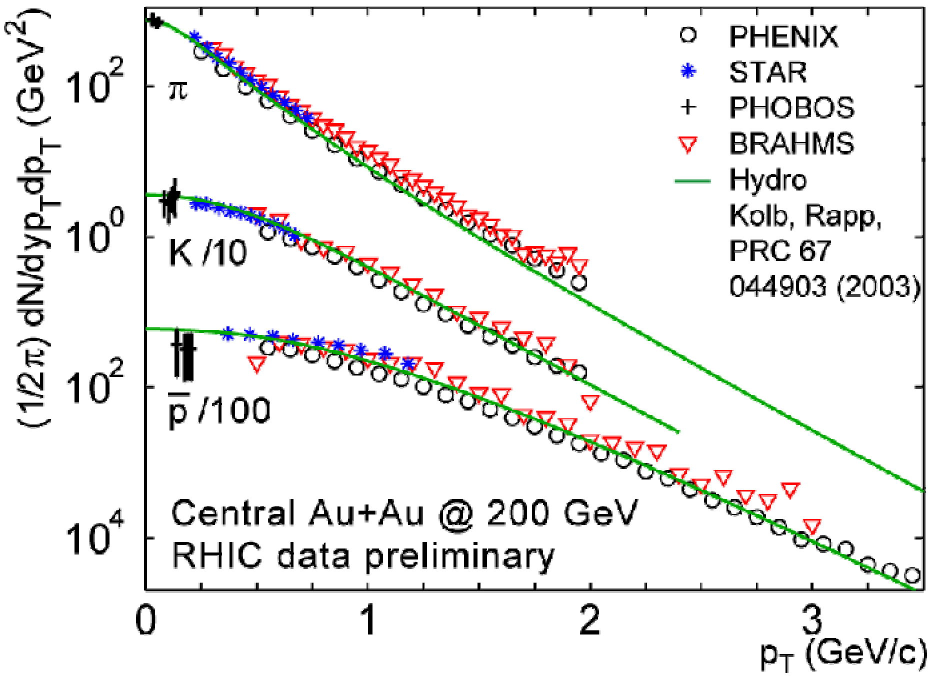
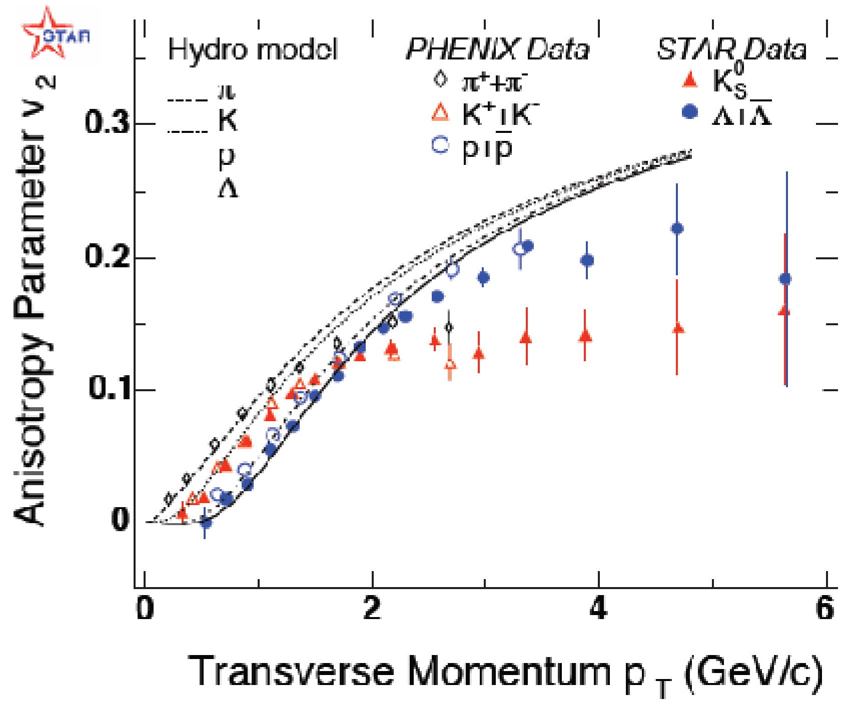
Hydrodynamic Description of Particle Production

- **Bulk hadron production well described by liquid (ideal hydrodynamics)**
  - **Thermal momentum spectra modified by collective radial expansion**
  - **Anisotropy of particle emission for collisions with finite impact parameter**

$T_f \sim 100$ MeV $< T_C$ and $\langle\beta_r\rangle \sim 0.55$ c





Indirect estimate of initial conditions at 0.6 fm:
$\varepsilon \sim 20$ GeV/fm^3 $T_i \sim 350$ MeV

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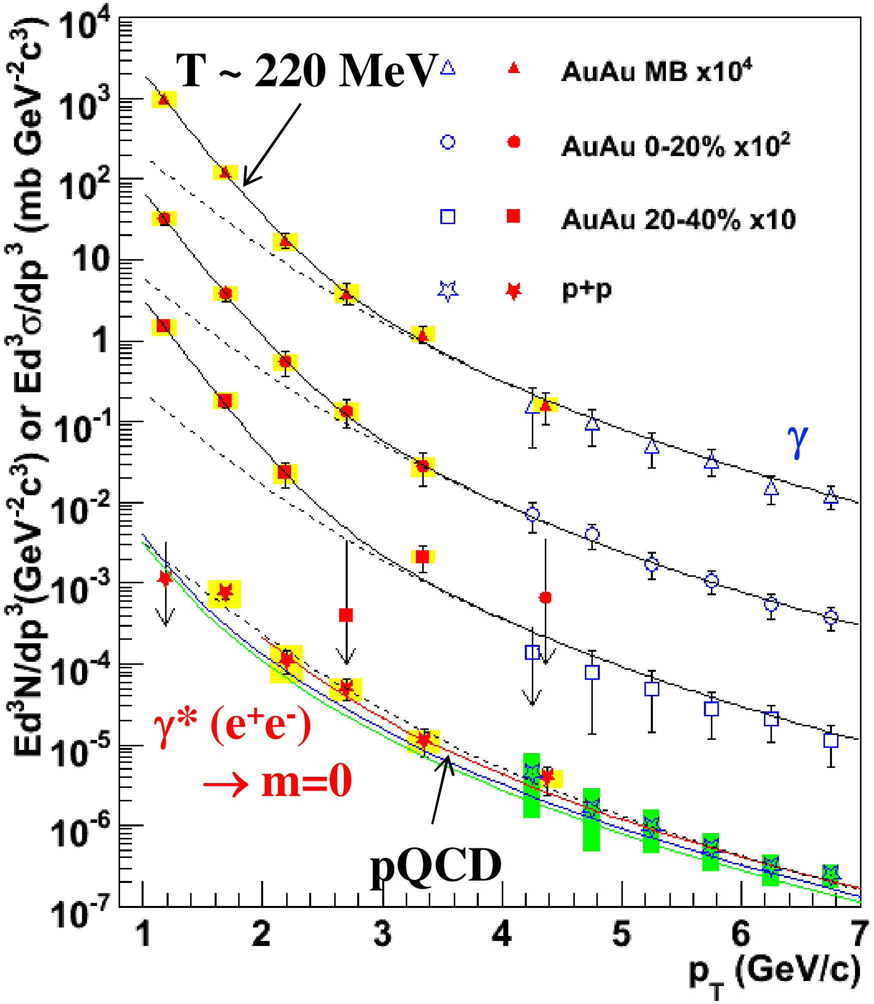
Radiation from Plasma: Direct Photons



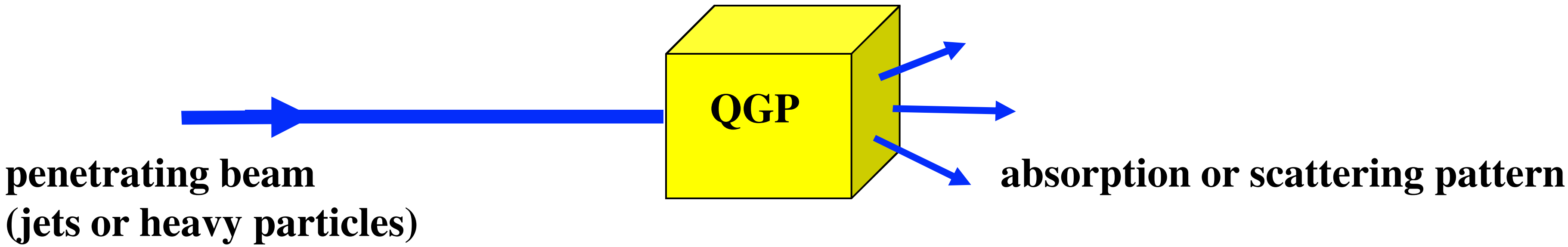
Notoriously difficult measurement

- **Direct photons from real photons:**
  - Measure inclusive photons
  - Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV
- **Direct photons from virtual photons:**
  - Measure e^+e^- pairs at $m_\pi < m << p_T$
  - Subtract η decays at S/B ~ 1:1
  - Extrapolate to mass 0

From data: T_{ini} > 220 MeV > T_C
From models: T_{ini} = 300 to 600 MeV

Penetrating Probes of Quark Matter

- Rutherford experiment $\alpha \rightarrow$ atom discovery of nucleus
  SLAC electron scattering $e \rightarrow$ proton discovery of quarks

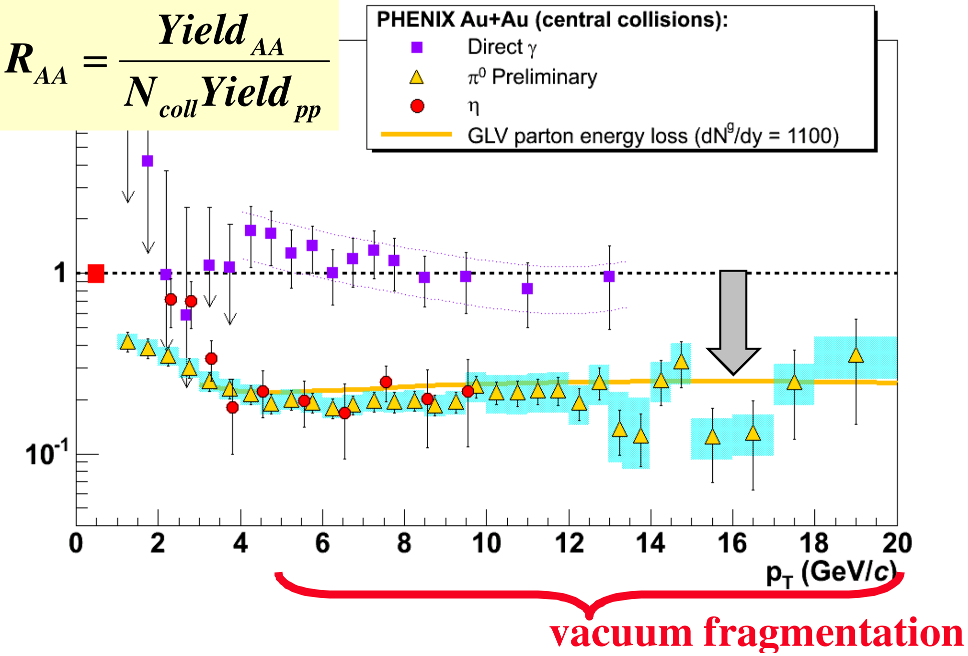


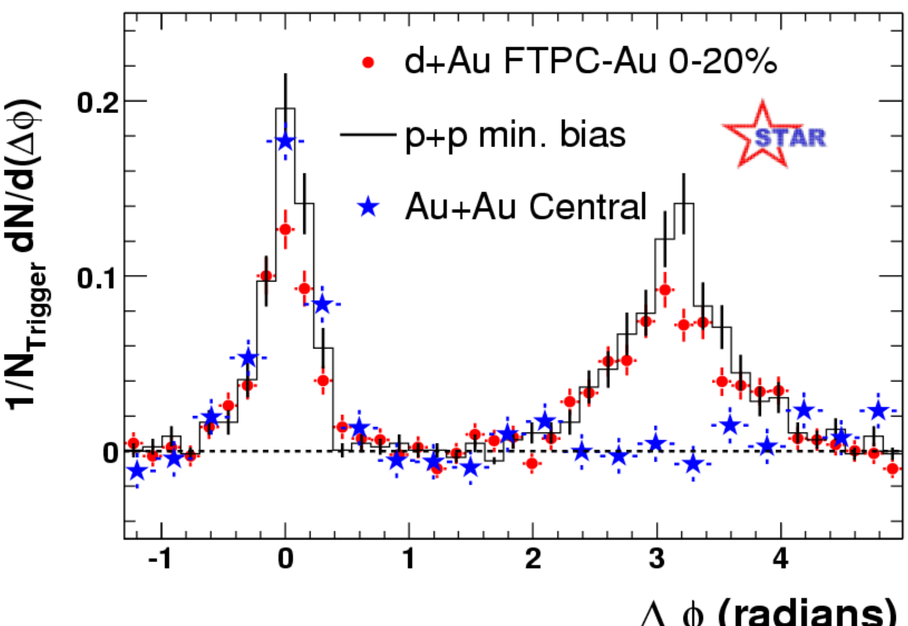
Nature provides penetrating beams or "hard probes" and the QGP in A-A collisions

- Penetrating beams created by parton scattering before QGP is formed
  - High transverse momentum particles $\rightarrow$ jets: high p_T back-to-back particles
  - Heavy particles $\rightarrow$ open and hidden charm or bottom
  - Calibrated probes calculable in pQCD
- Probe QGP created in A-A collisions as transient state after ~ 1 fm

Hard Probes: Light Quark/Gluon Jets

$$R_{AA} = \frac{Yield_{AA}}{N_{coll} Yield_{pp}}$$





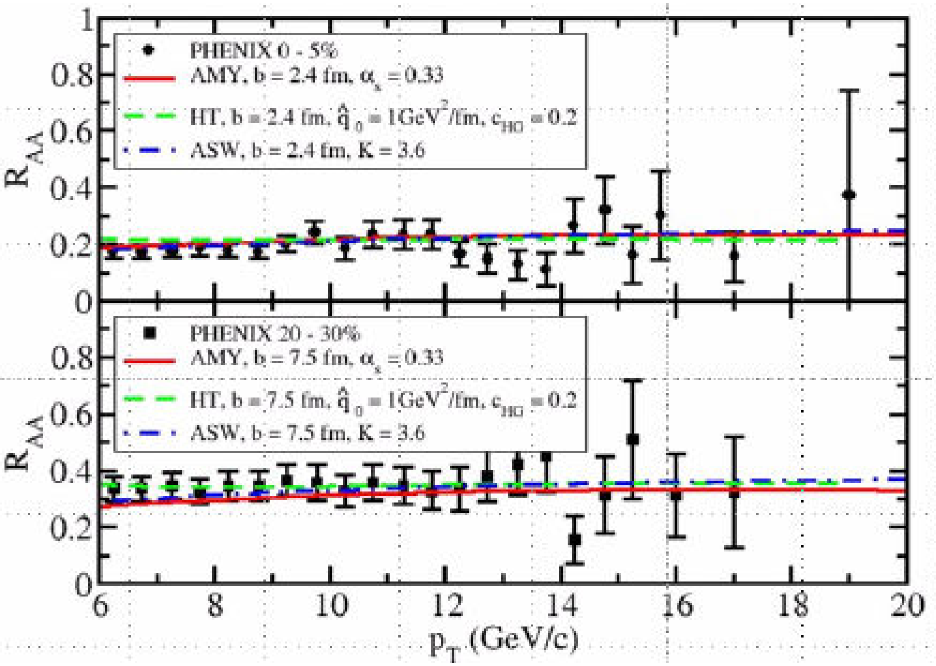
trigger 6 <pt< 8 GeV
partner 2 < pt < 6 GeV

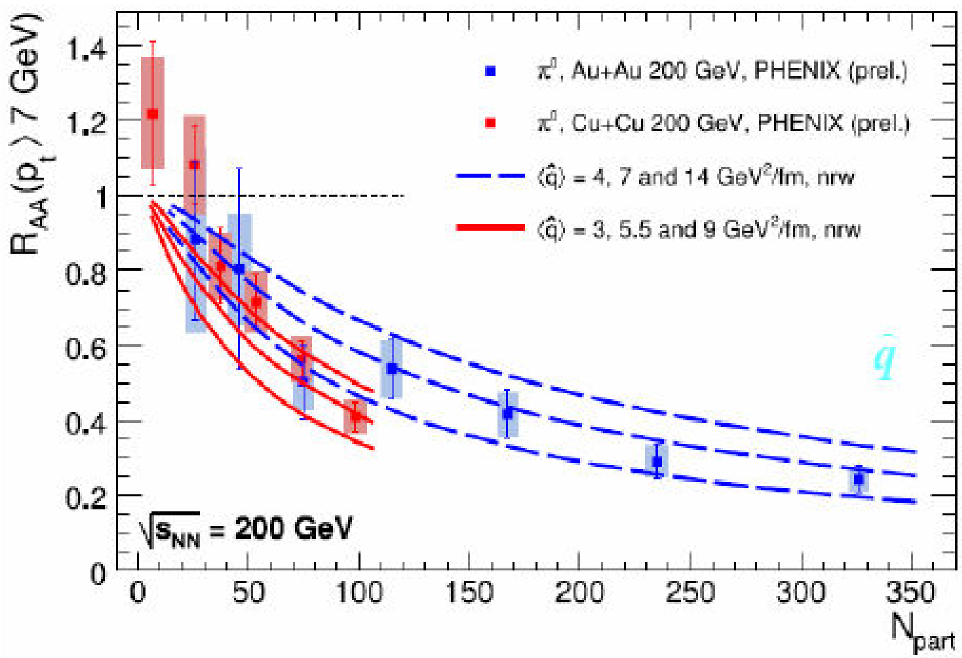
- **Experimental evidence**
  - **Well established baseline**
    - **pQCD works for prompt photons**
  - **High p_T particles quenched**
    - **π and η suppressed by factor 5**
    - **Remaining jet fragments in vacuum**
  - **Back-to-back correlation lost**

Matter is opaque to penetrating probes!

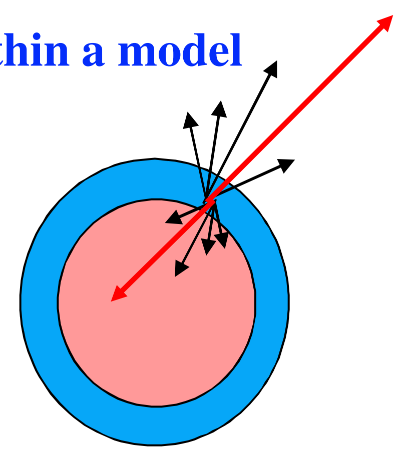
- **Theory comparision: Radiative parton energy loss**
  - **Consistent with data (GLV)**
  - **$dN^g/dy \sim 1100$**
  - **energy density $\varepsilon \sim 20\ GeV/fm^3$**

Closer Look at More Model Comparisons





- **Many models agree with data**
  - dN^g/dy or $\langle\hat{q}\rangle$ and other parameters can be constraint within a model
- **Energy loss governed by geometry**
  - Observed yield strongly biased towards surface
  - Little sensitivity to energy loss mechanism



Matter is really opaque to penetrating probes!

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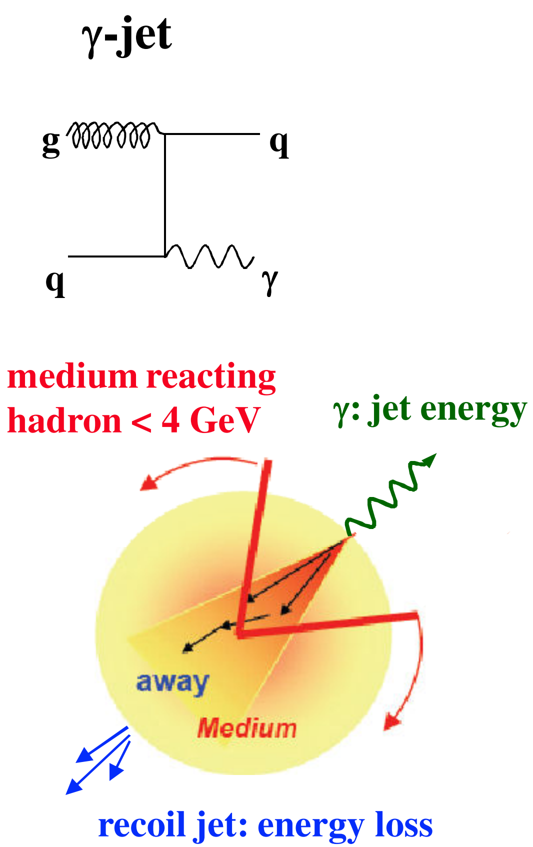
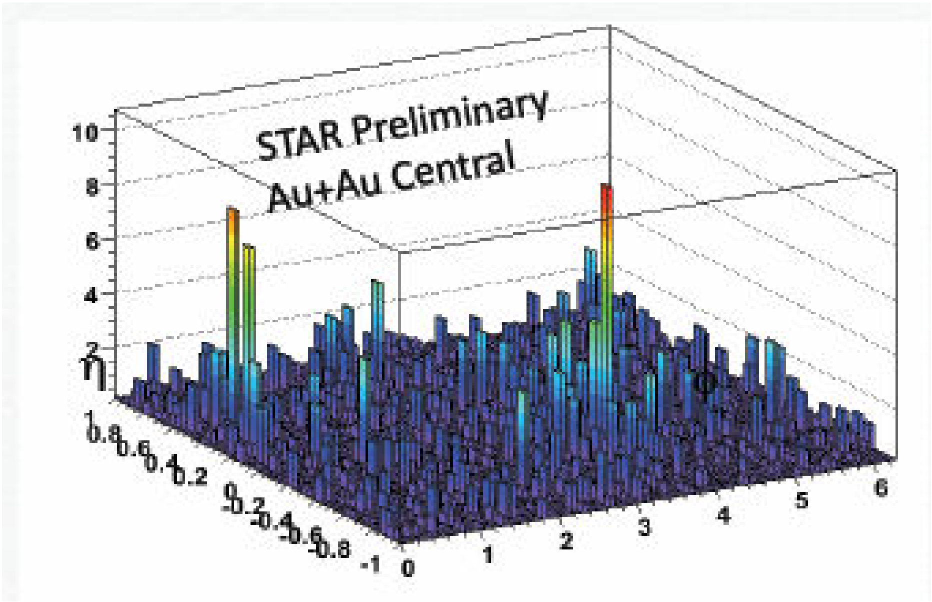
Sensitivity to Energy Loss: Jet Tomography



- At high enough p_T jets fully reconstructed in Au+Au
  - Seen in range 20 to 40 G

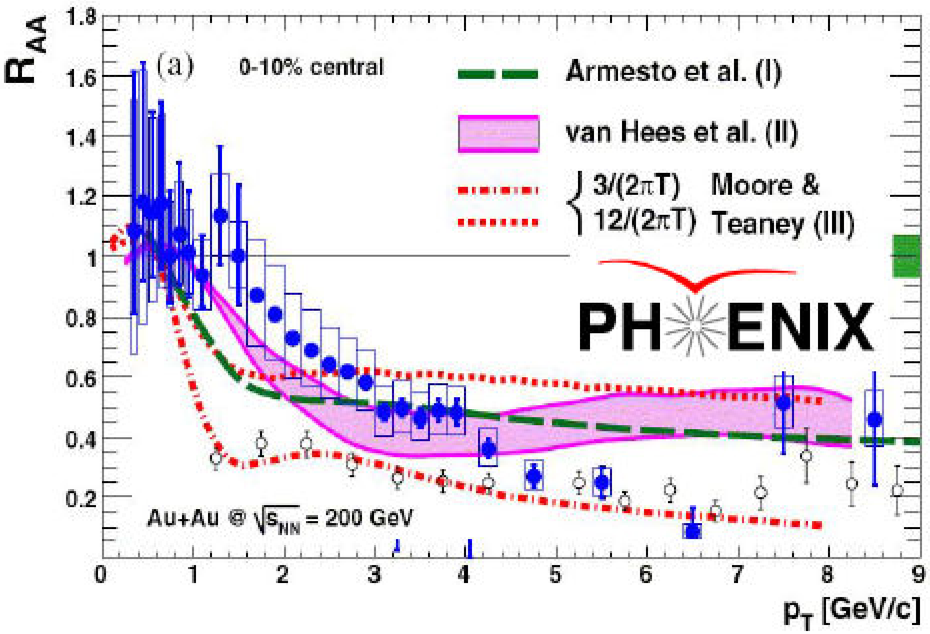


- Some sensitivity at RHIC after luminosity upgrade

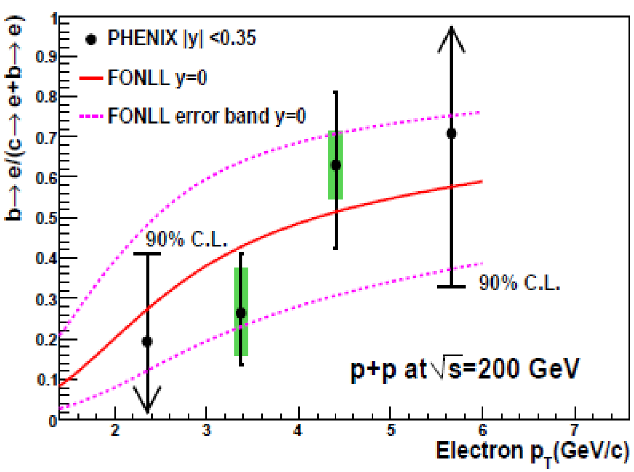
Sensitivity to Energy Loss Mechanism
→ LHC

Hard Probes: Open Heavy Flavor

Electrons from c/b hadron decays



more b than c

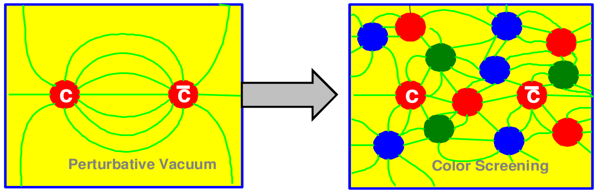


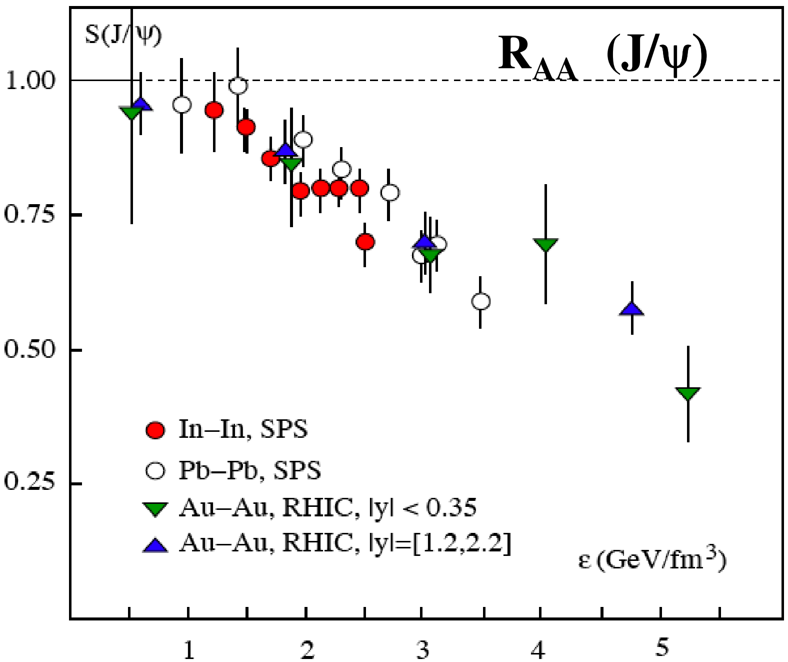
- **Theoretical expectation:**
  - Little energy loss for charm
  - No energy loss for bottom
- **Experimental observations:**
  - charm is quenched almost as much as light quarks/gluons!
  - Bottom most likely is also quenched!
  - Limited agreement with models
- **What is the energy loss mechanism?**
  - We do not know!
  - More than radiative energy loss
  - Non- perturbative interaction
  - Interactions with chromo-B fields

Matter is REALLY opaque to penetrating probes!

Hard Probes: Quarkonium

Clear signature for deconfinement?!

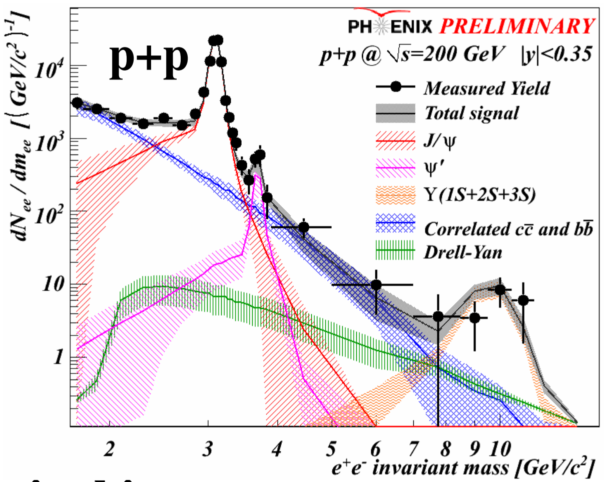




Much more progress needed in experiment and theory!

- **J/ψ production is suppressed**
  - Similar at RHIC and SPS
  - Consistent with consecutive melting of χ , ψ'
  - Consistent with melting J/ψ followed by regeneration
- **Upsilon production may also be suppressed!?**

$R_{AA}(\Upsilon) < 0.64$ at 90% CL



- **Many open theoretical issues:**
  - Quarkonium production mechanism
  - Cold nuclear matter effects (shadowing etc)
  - Recent Lattice QCD developments Quarkonium states do not melt at T_C
  - Can we really extract screening length from data?

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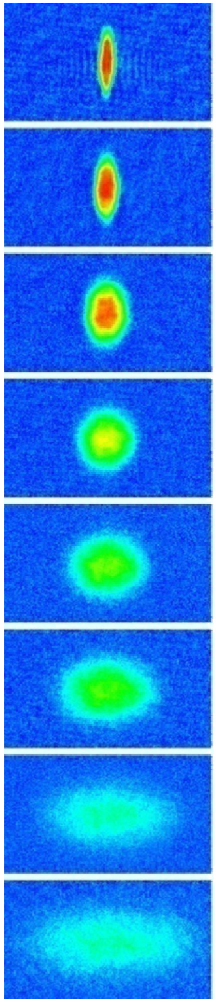
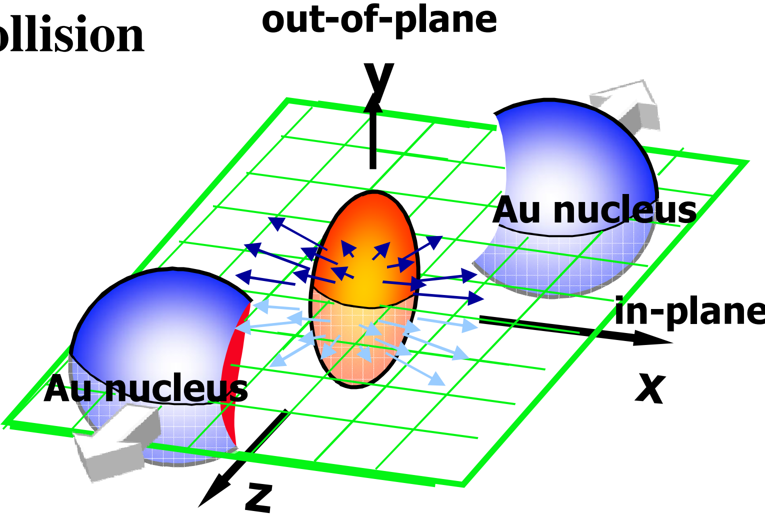
Collective Behavior: Elliptic Flow



Liquid Li Explodes into Vacuum

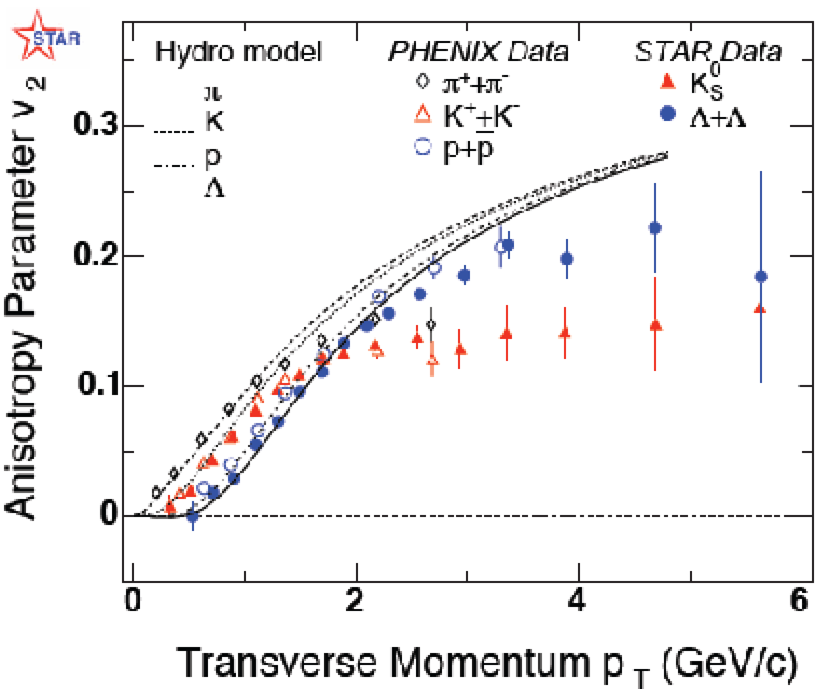
- **initial state of non-central Au+Au collision**
  - spatial asymmetry
  - asymmetric pressure gradients
  - momentum anisotropy in final state
  - expressed as elliptic flow "v_2"

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$



Non-central Collisions

- **elliptic flow is "self quenching"**
  - v_2 reflects early interactions and pressure gradients
- **observations at RHIC**
  - v_2 for low momentum hadrons agrees with ideal hydrodynamics



Early thermalization!

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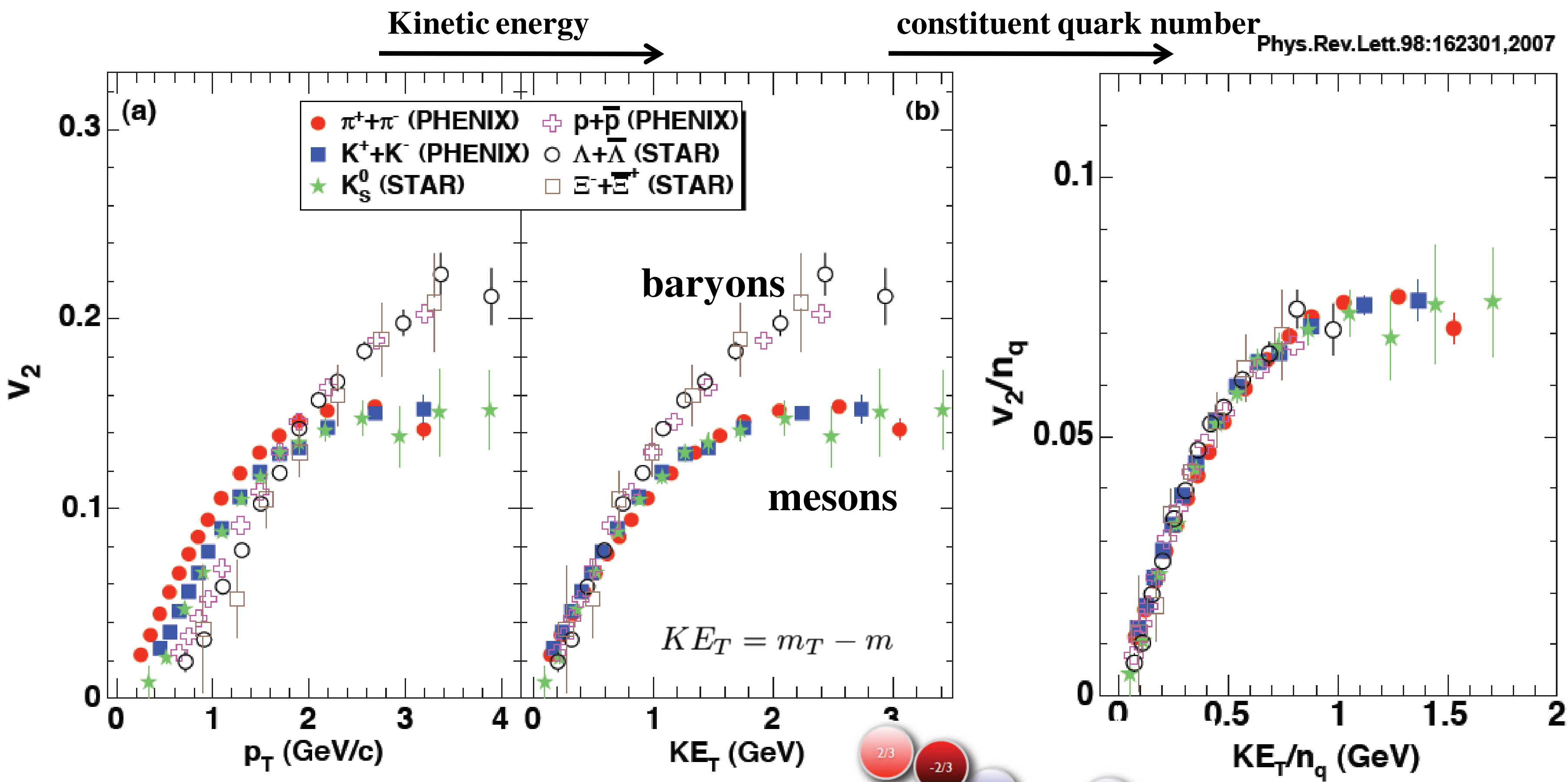
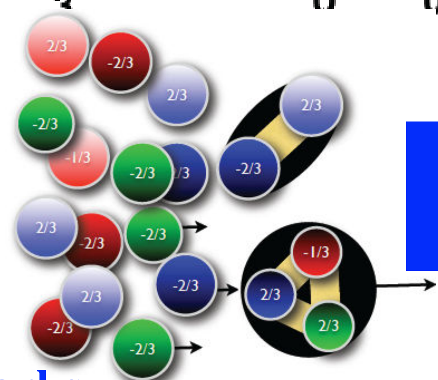
Quark Scaling Behavior of v_2



- All hadrons flow collectively
  - in common velocity field
  - works for ϕ and D mesons too
  - favors a pre-hadronic origin
  - Hadrons form from constituent quarks



quark degrees of freedom

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Deviations from Ideal Hydro: Shear Viscosity

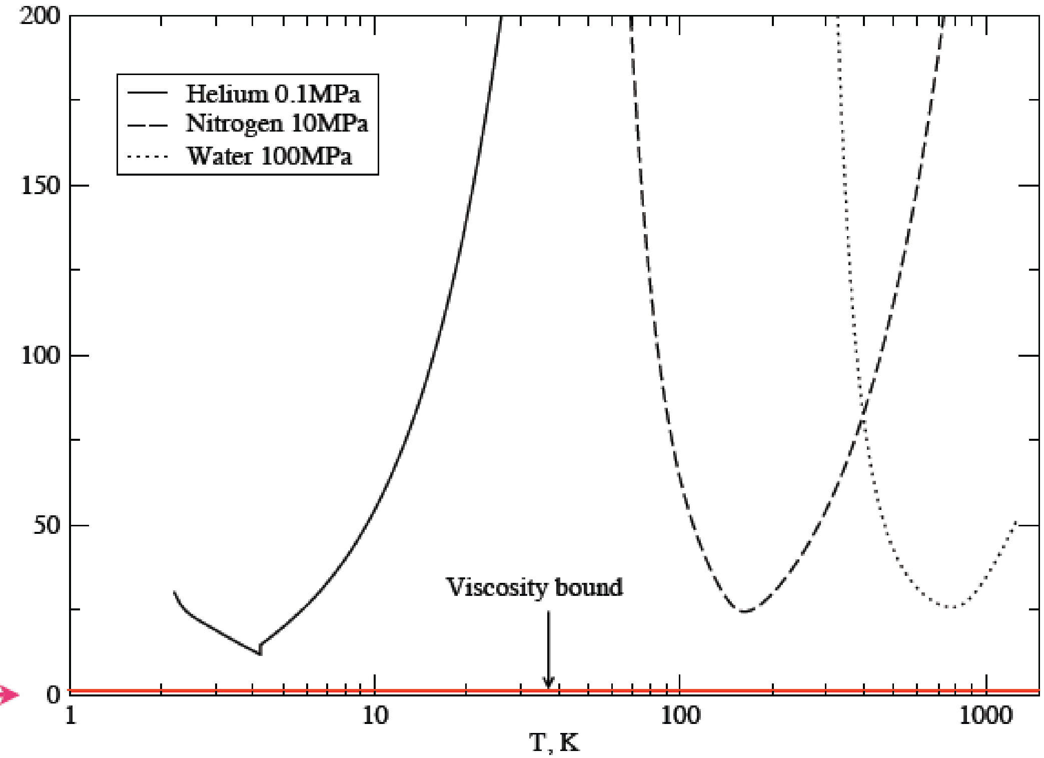
$\eta = \langle p \rangle / \sigma$ transport of momentum

- **Large cross section small viscosity**
- **Gas: η/s↑ for T↑ (because <p> ↑) divergent viscosity of ideal gas**
- **Liquid: η/s↓ for T↑ (lower T easier to transport p)**

→ η/s has a minimum at the critical point

H_2O (at normal conditions):
$\eta/s \sim 380\hbar/4\pi$

$$\frac{4\pi\eta}{\hbar s}$$



$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

viscosity bound
from AdS/CFT

Strongly coupled → low viscosity

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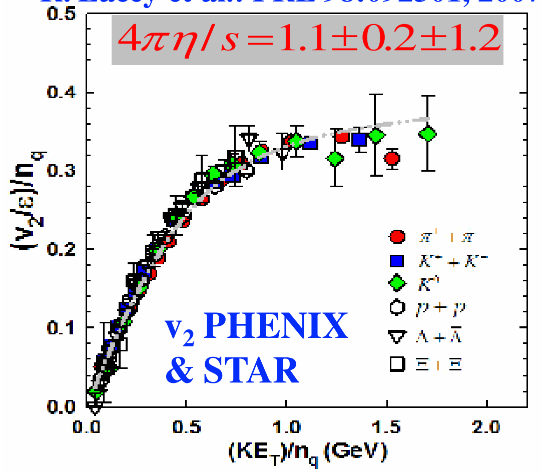
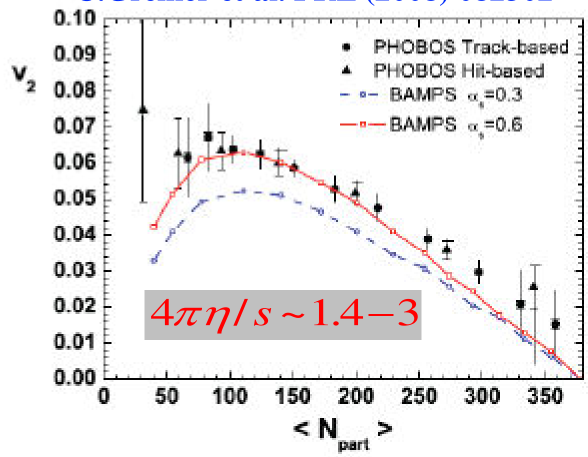
Viscosity Estimates: Model Comparison

- **Deviations from ideal hydrodynamics very sensitive to viscosity**

R. Lacey et al.: PRL 98:092301, 2007



C.Greiner et al. PRL (2008) 082302

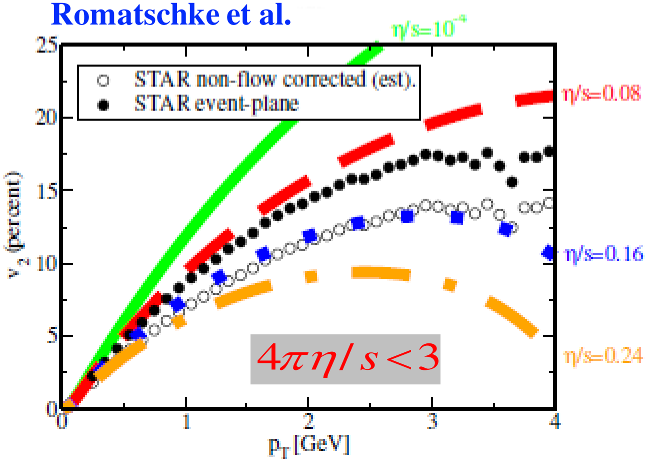


AdS/CFT

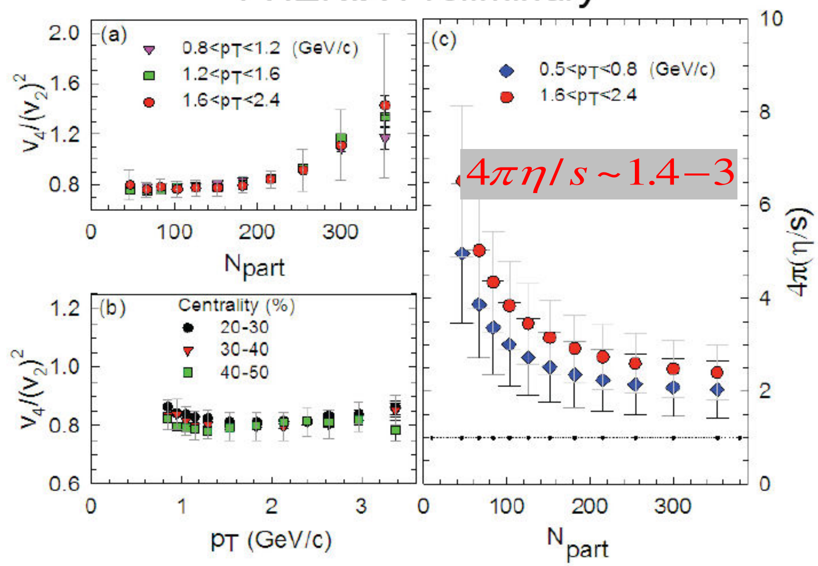
$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Low viscosity close to conjectured quantum limit

Romatschke et al.



PHENIX Preliminary



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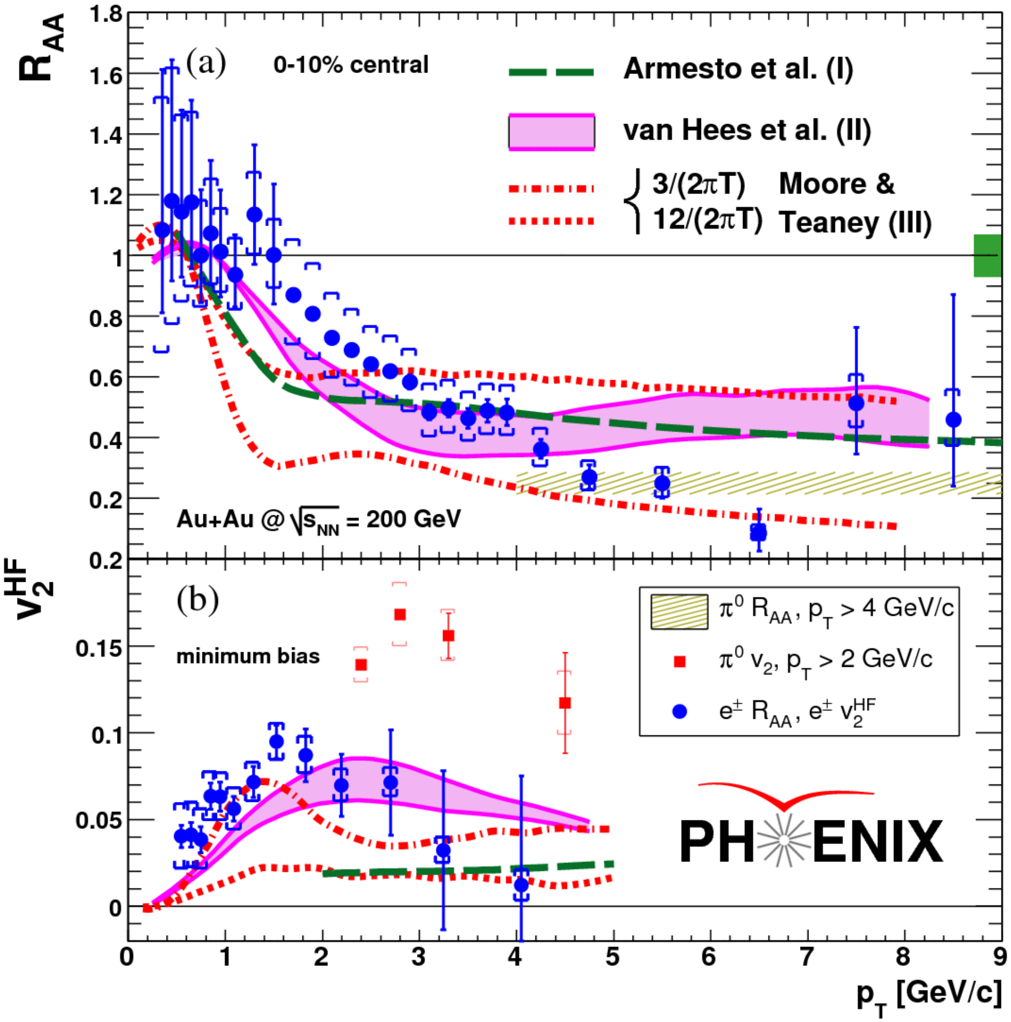
Viscosity Estimate: Heavy Quark Flow

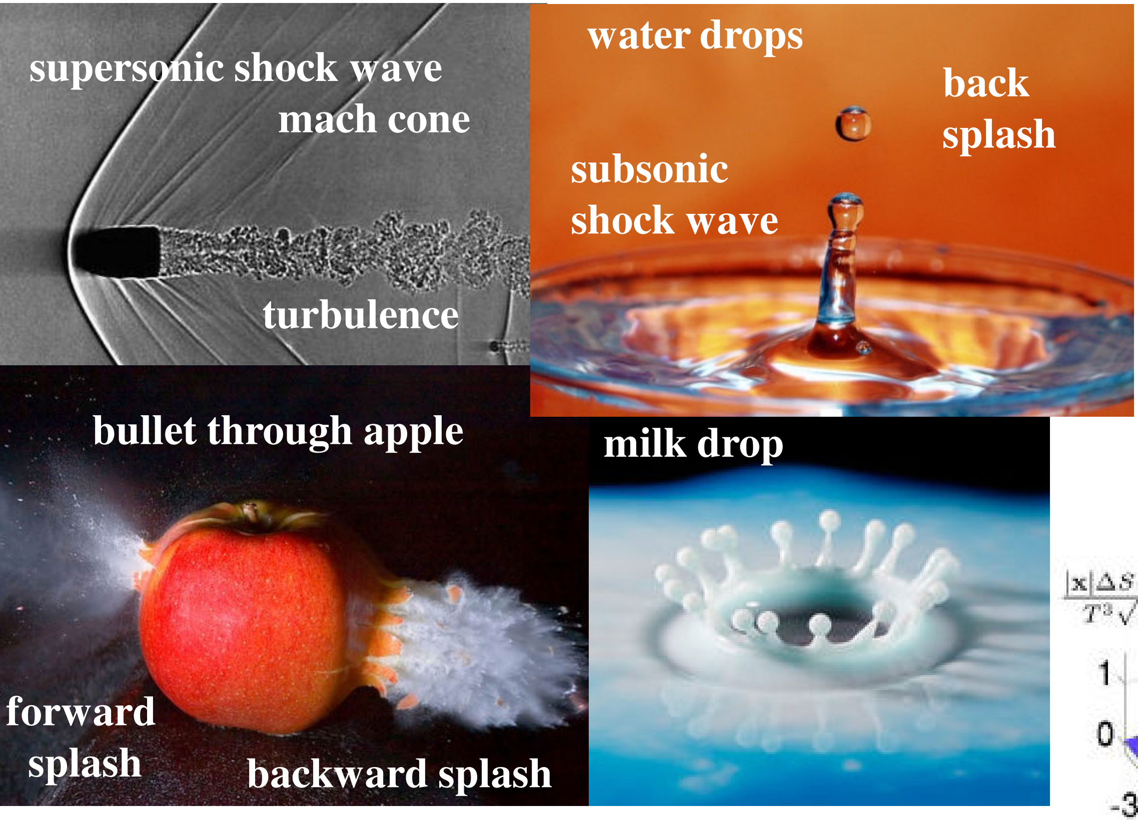


- **Experiment: heavy quark**
  - large momentum suppressed
  - significant elliptic flow
- **Models: non perturbative transport**
  - Simultaneous describes data
  - Diffusion coefficient range D ~ 4-6 /2πT
  - Estimate viscosity

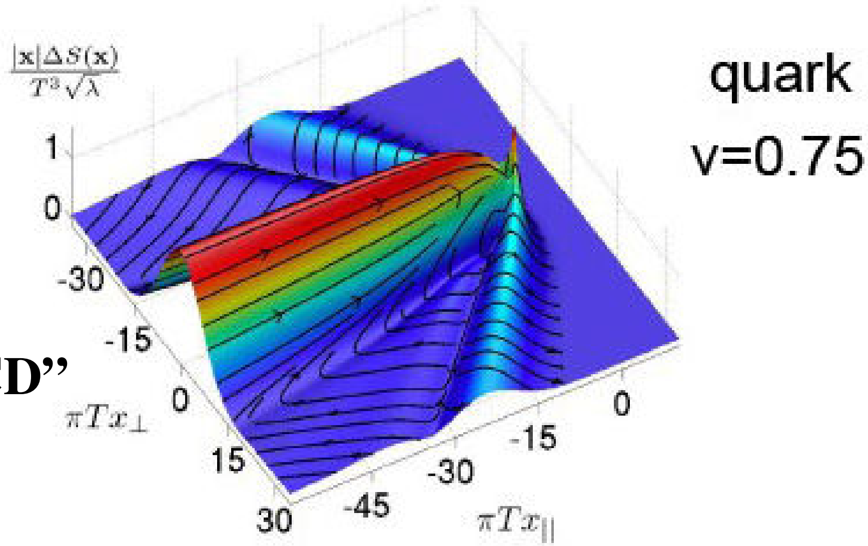
$$4\pi\eta/s \sim 1.33-2$$

Low viscosity ⇒ strongly coupled plasma or sQGP

"Hard Probes" and Fluids



- Expect local flow of medium
  - Hard probe losses energy
  - Absorbed by medium
  - E & p conservation
  - Local flow of medium



P. Chesler, L. Yaffe, 2008.
Similar results also by Gubser et al, 2008.

- Mach Cones and Shock Waves in "QCD"
  - Supported by various calculations
  - pQCD calculations
  - AdS/CFT correspondence

Relation to data mostly theoretical speculation

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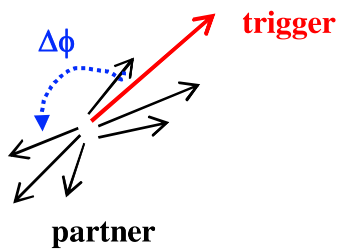
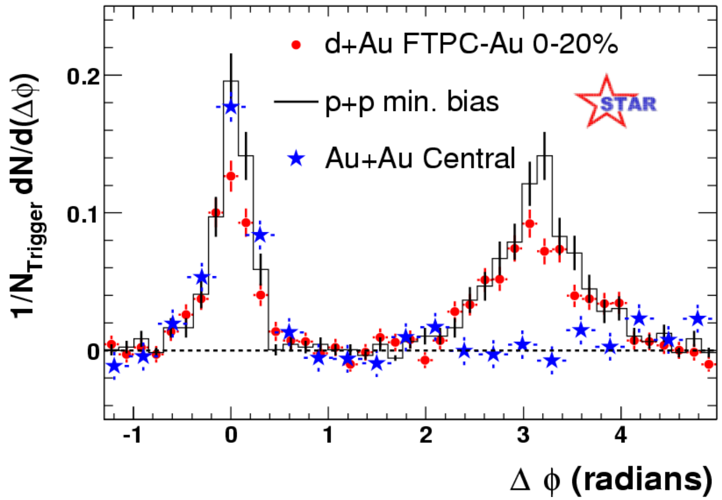
Local Flow Phenomena in Data?

- **2 particle correlations in azimuthal angle**

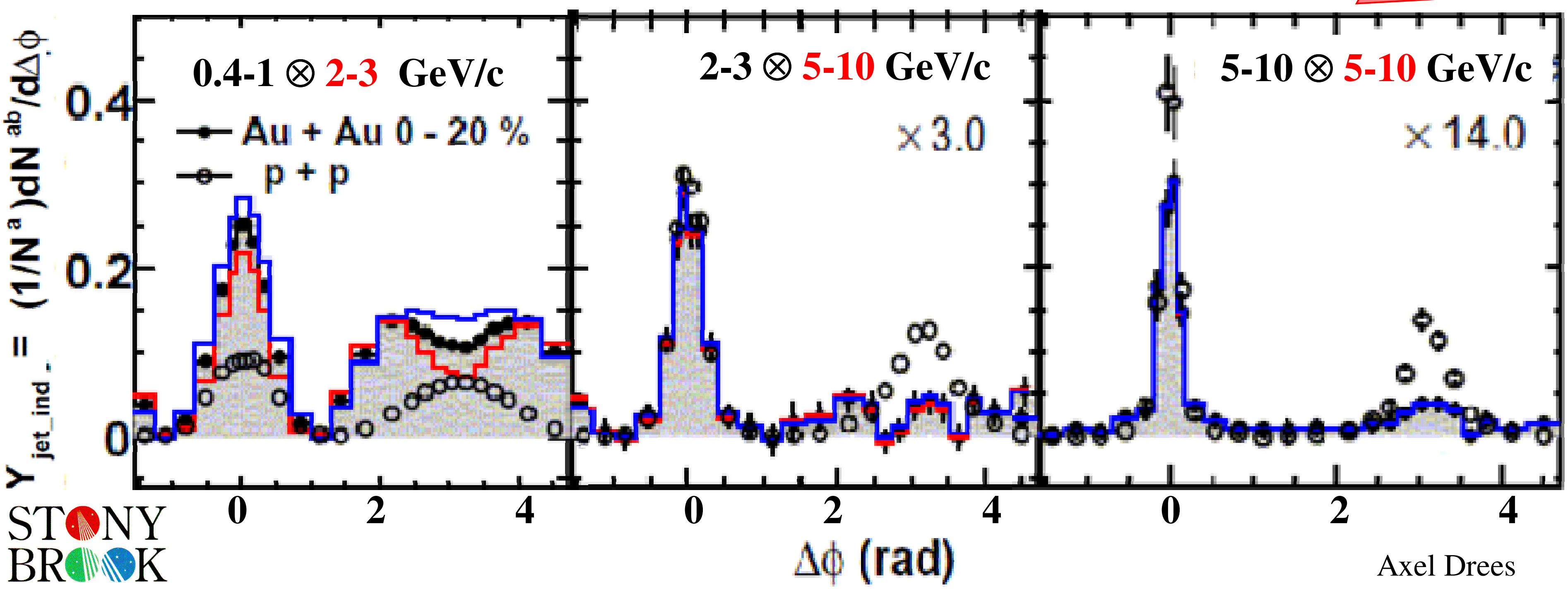




trigger 6 <pt< 8 GeV
partner 2 < pt < 6 GeV

lower p_T partner

higher p_T partner



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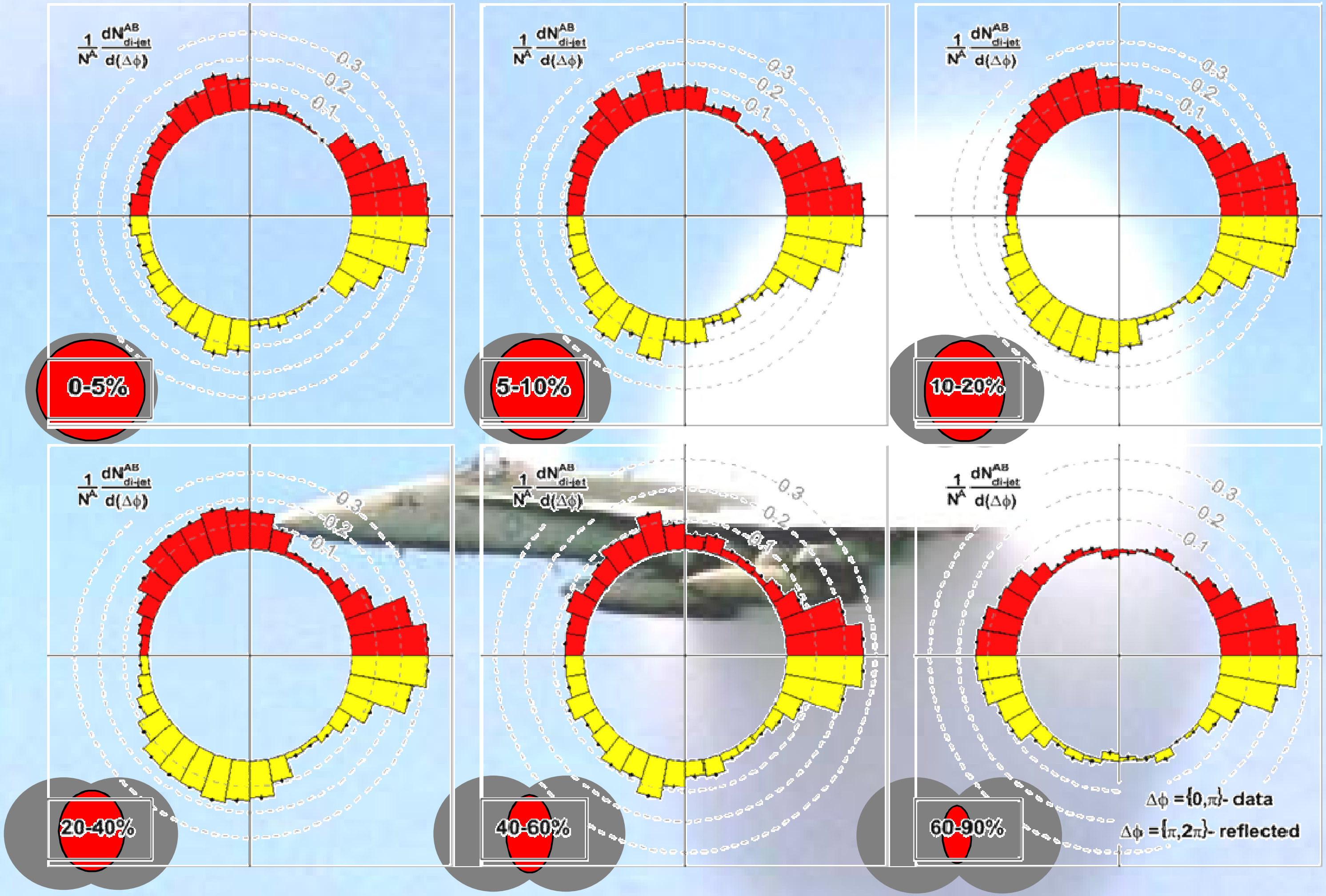
Away Side Structure in $\Delta\phi$



- Jet structure peripheral AuAu
- Away side: shock wave structure for all centraliy
- Angle of shock wave independent of centrality

Suggests Mach Cone

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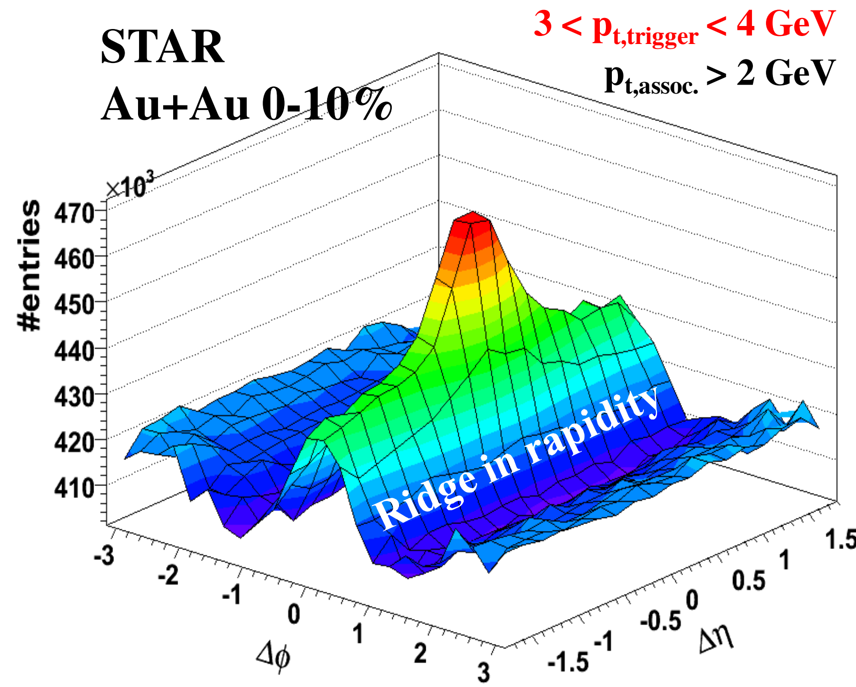
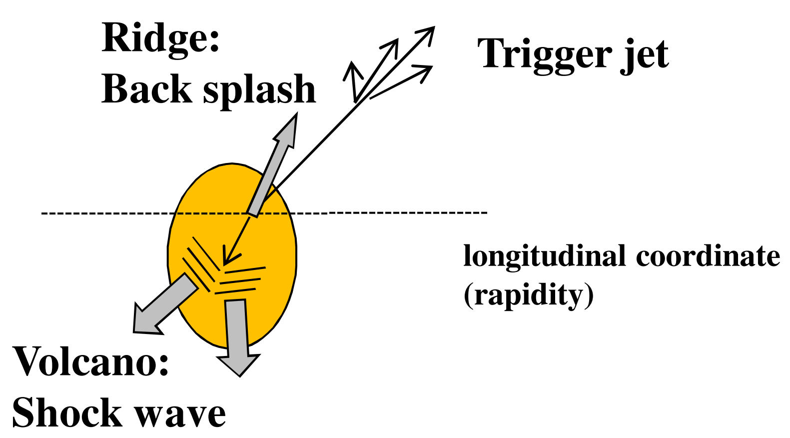
Near Side Structure in $\Delta\eta$

- **Jet structure in pp**
  - Near side: Correlation spherical in $\Delta\eta;\Delta\phi$
  - Away side: shifted in η
- **AuAu: Jet structure central AuAu**
  - Away side: Shock wave structure
  - Near side: Ridge like structure in η
- **Many models and ideas**



My favorite speculation:



RHIC Upgrades 2010 to 2014

On going effort with projects in different stages

- **Open heavy flavor**
  - **Vertex tracker**
- **Jet tomography (γ-jet)**
  - **Increased acceptance**
  - **High rate capability**

Luminosity upgrades

Stochastic cooling

- **At 200 GeV factor ~10**
- **Au+Au ~40 KHz event rate**

Electron cooling for low energy

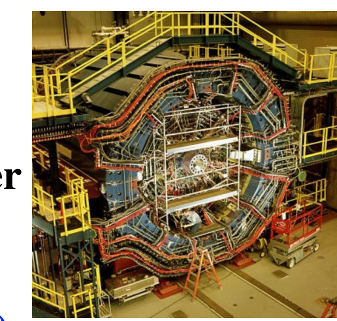
- **Au+Au 20 GeV ~15 KHz event rate**
- **Au+Au 2 GeV ~150 Hz event rate**

PHENIX

Detector upgrades

hadron blind detector
muon Trigger
silicon vertex barrel (VTX)
forward silicon (FVTX)
forward EM calorimeter (FOCAL)

forward meson spectrometer
DAQ & TPC electronics
full ToF barrel
heavy flavor tracker (HFT)
intermediate silicon tracker (IST)
forward GEM tracker (FGT)



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Completed, on going, in preparation

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Summary

- **Multitude of discoveries from 9 years of RHIC running**
- **New state of matter nothing like a parton gas:**
  - **Opaque to colored probes**
  - **Very strongly coupled**
  - **Behaves like a liquid**
  - **Low viscosity near quantum limit**
  - **Partonic degrees of freedom**

sQGP: strongly coupled quark gluon plasma

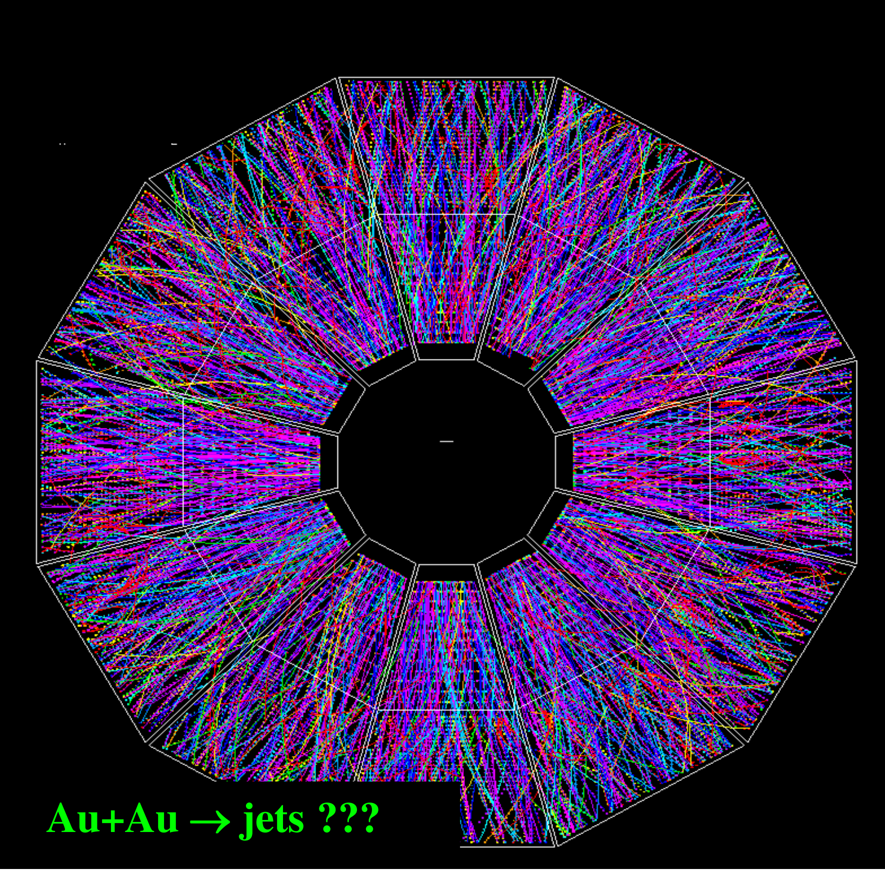
- **Many open questions:**
  - **What are the properties of sQGP?**

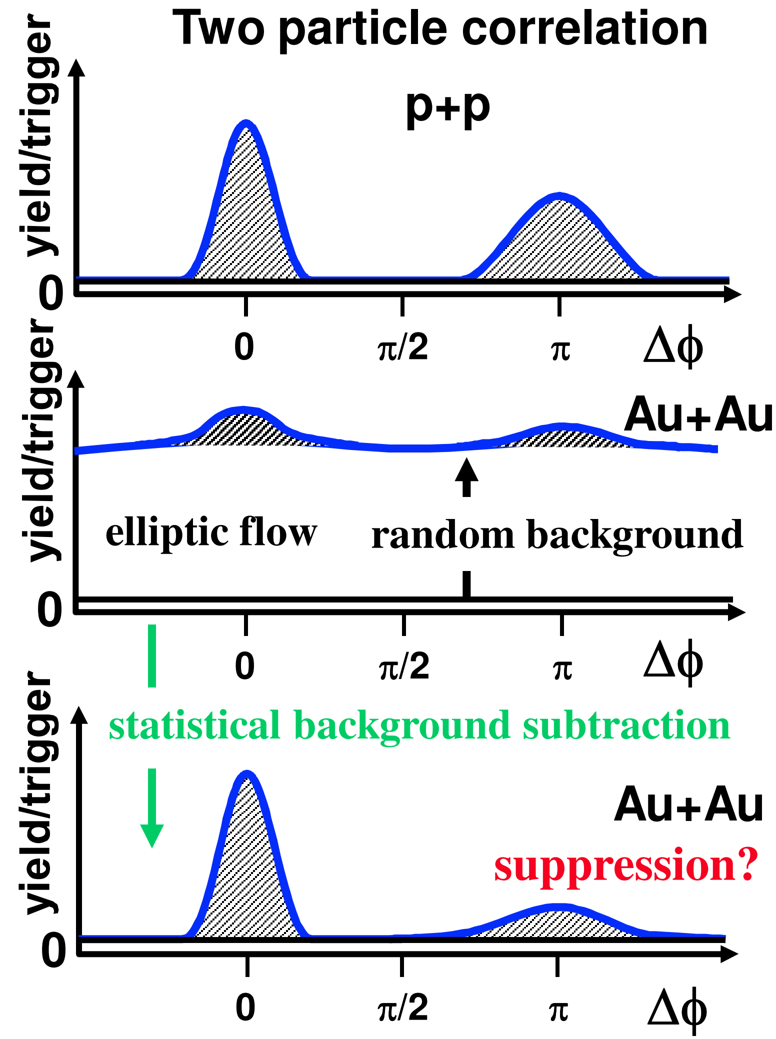
    Temperature, density, viscosity, speed of sound, diffusion coefficient, transport coefficients, color screening length
  - **Is chiral symmetry restored?**
  - **What is the mechanism of rapid thermalization?**
  - **How does the deconfined matter transform into hadrons?**
  - **What is the QCD energy loss mechanism?**
  - **Is there a critical point in the QCD phase diagram?**

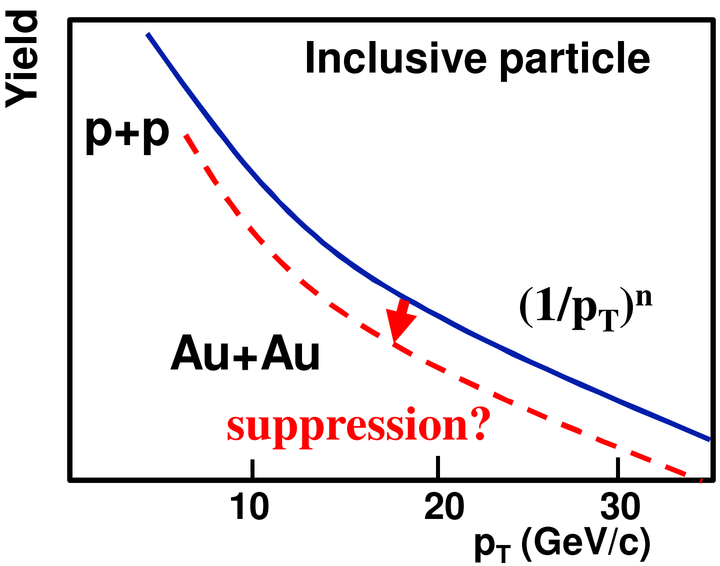
Expect more answers to come from RHIC and LHC

BACKUP

“Jets” with Heavy Ions







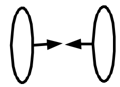
Nuclear Modification Factor

$$R_{AA} = \frac{Yield_{AA}}{N_{coll} Yield_{pp}}$$

Quark Matter Formation in Heavy Ion Collisions

system evolution | **expectations/observations**

collision hard scattering



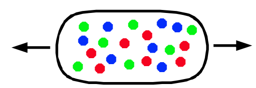
jets, heavy flavor, photons

↓

Strongly coupled plasma
"opaque black hole"

$\tau < 1$ fm

T_i~300 MeV at energy density 5-25 GeV/fm^3



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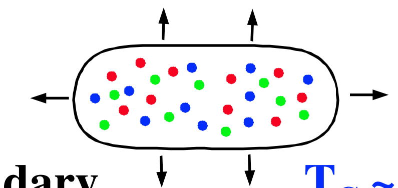
thermal radiation
jet quenching
J/ψ suppression

collective expansion of
fireball under pressure



memory effect in hadron spectra
elliptic flow

↓

confinement at phase boundary
in chemical equilibrium

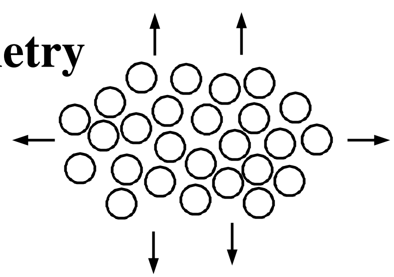
T_C ~ 170 MeV

relative hadron abundance

break down of chiral symmetry

modification of meson (ρ) properti

collective expansion of
fireball under pressure



memory effect in hadron spectra
transverse flow <v/c> ~ 0.5

↓

thermal freeze-out
end of strong interaction

$\tau > 10$ fm

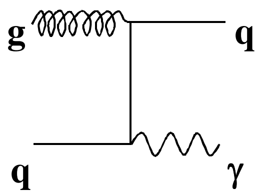
T_f = 100 MeV

two and one particle spectra

STONY BROOK

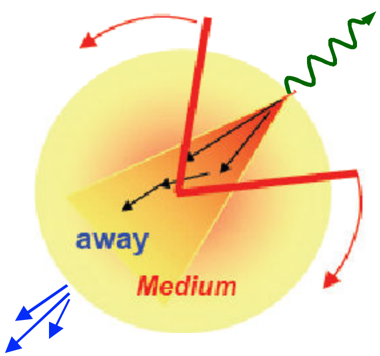
Axel Drees

Jet Tomography at RHIC II

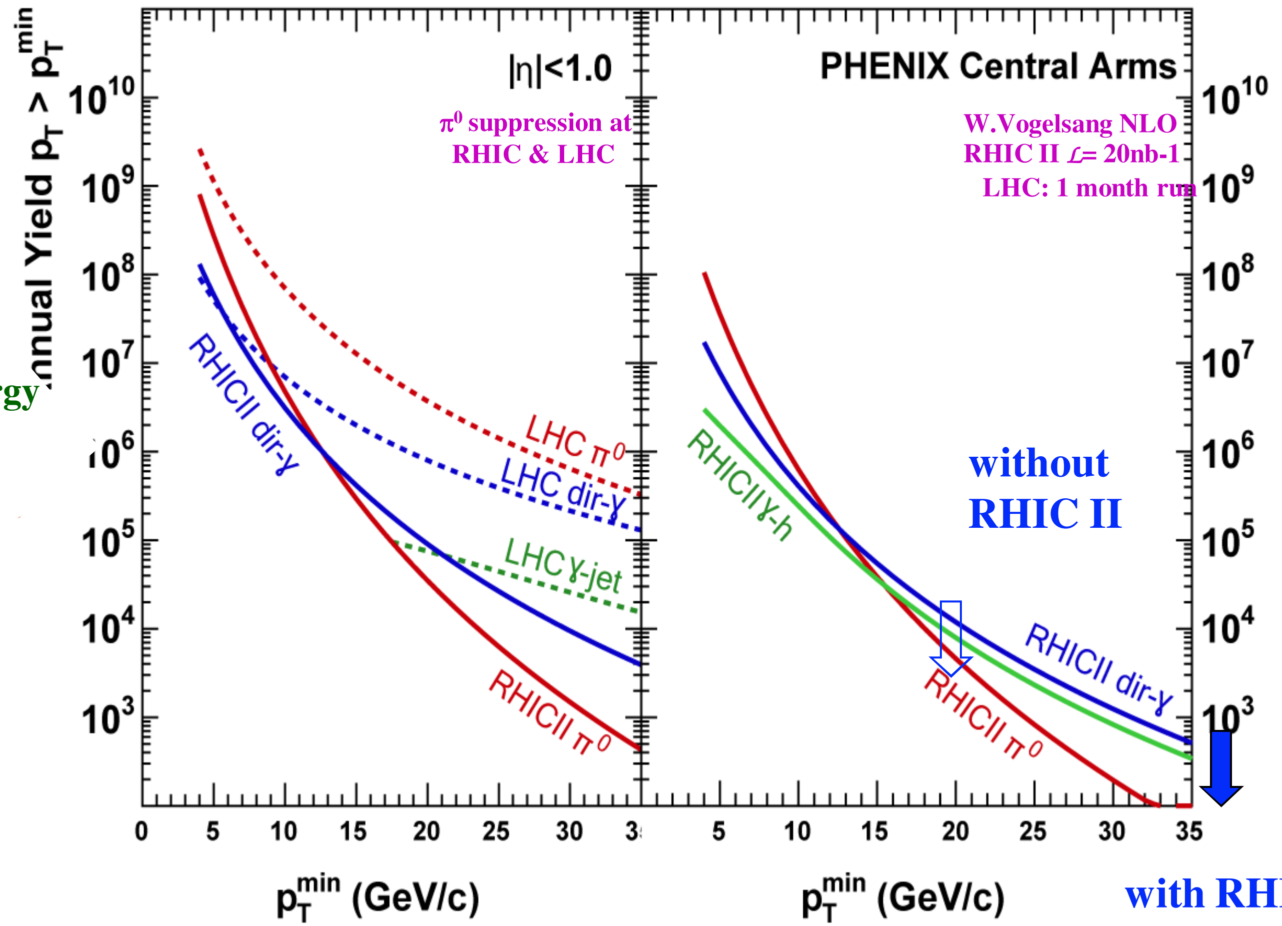


medium reacting
hadron < 4 GeV

γ: jet energy

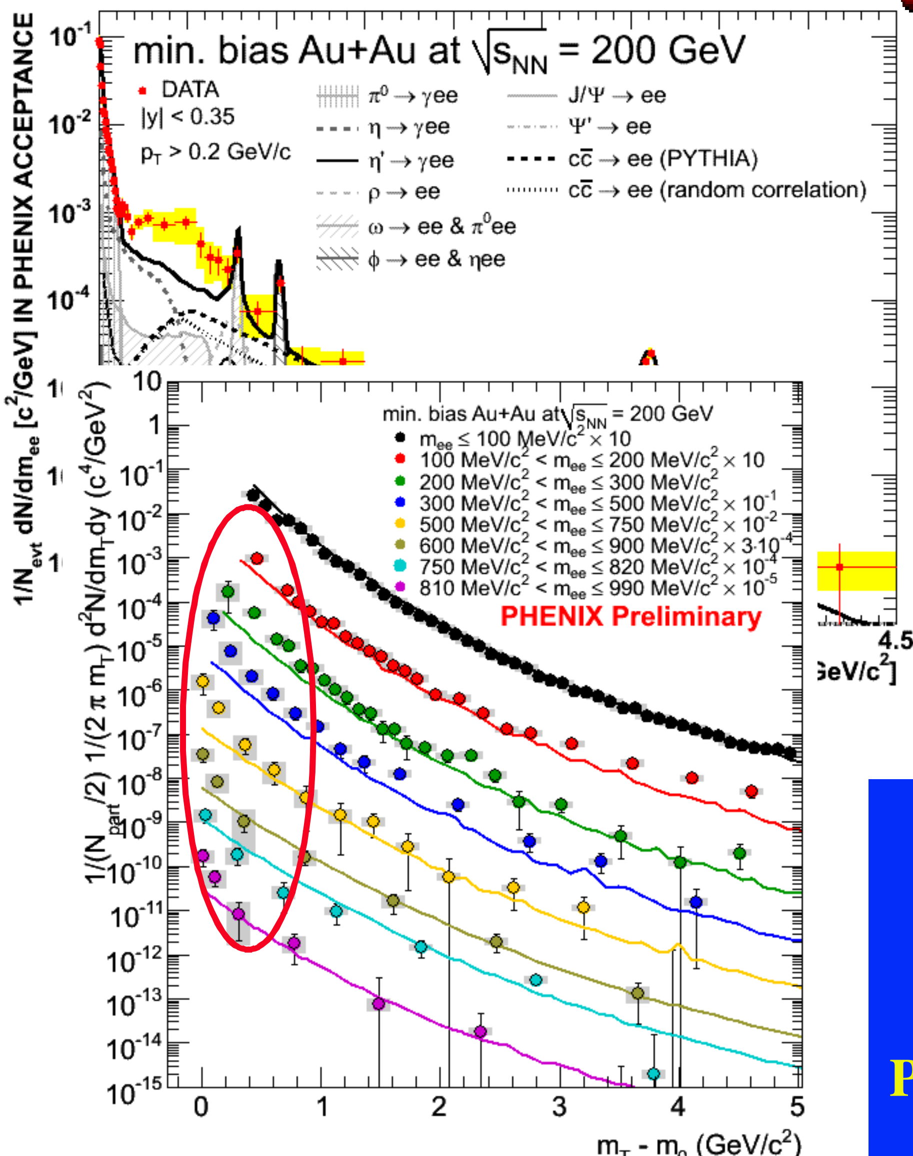


recoil jet: energy loss



RHIC II will give jets up to 50 GeV
- → separation of medium reaction and energy loss
- → sufficient statistics for 3 particle correlations p_T > 5 GeV
- → 2-3 particle correlations with identified particles

Dilepton Continuum at RHIC



- **Status**
  - Low mass enhancement (150-750 MeV)
    - Strong centrality dependence
    - Soft p_t component T_{eff} ~ 100 MeV
    - Both features qualitatively consistent with CERN experiments
    - No quantitative theoretical explanation
  - Open experimental issues:
    - Large combinatorial background prohibits precision measurements in low mass region!
    - Disentangle charm and thermal contribution in intermediate mass region!

Need tools to reject photon conversions and Dalitz decays and to identify open charm

PHENIX → hadron blind detector (HBD) vertex tracking (VTX)

Axel Drees