Heavy Ions Physics

From the Age of Discovery to the Age of Exploration: Determining the Properties of the Quark-Gluon-Plasma

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DIS 2008

University College, London

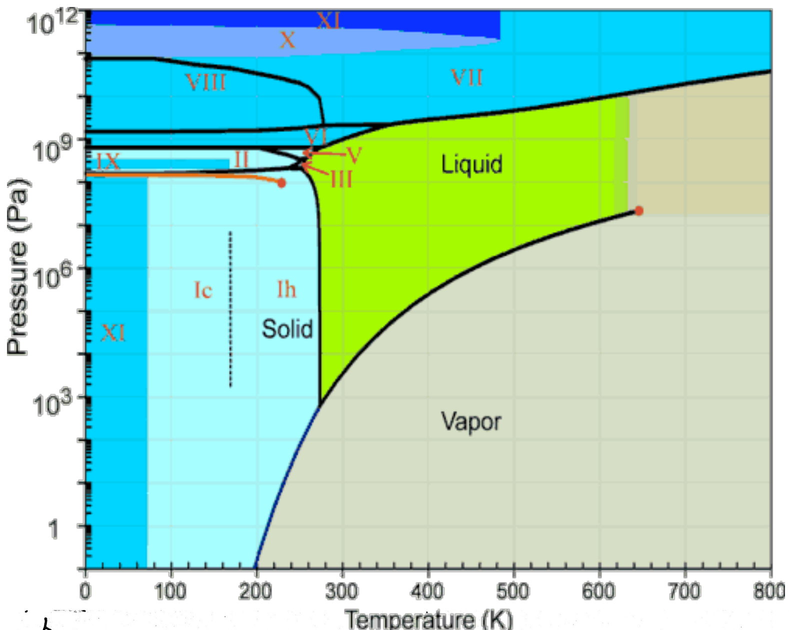
7-11 April 2008

RHIC
relativistic heavy ion collider

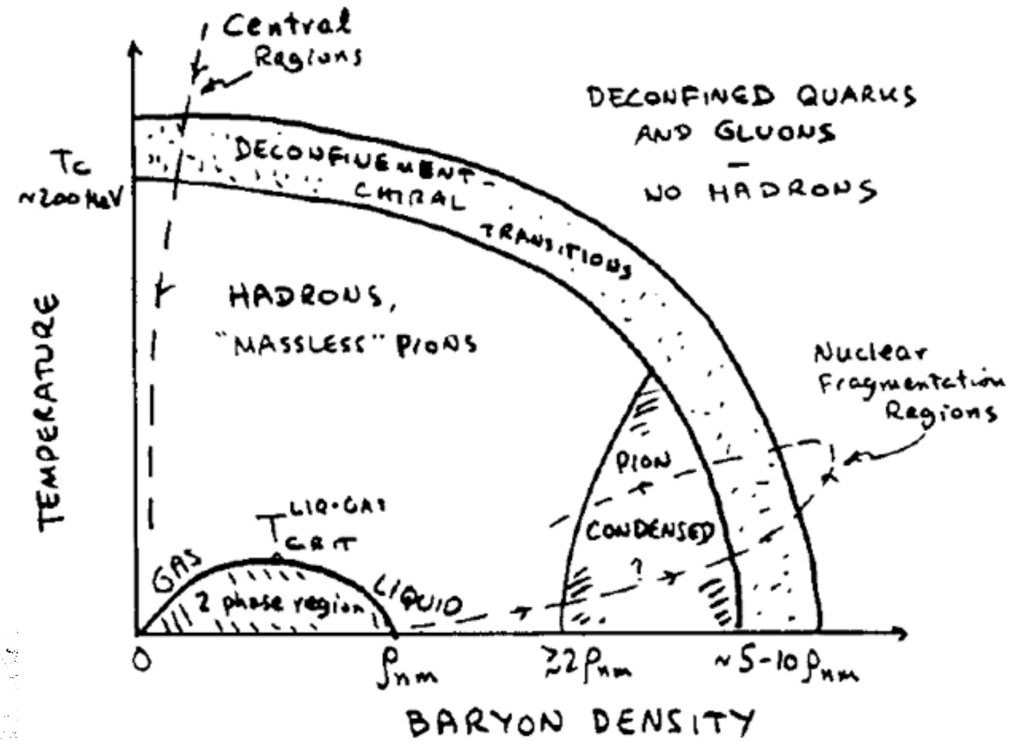
BROOKHAVEN
NATIONAL LABORATORY

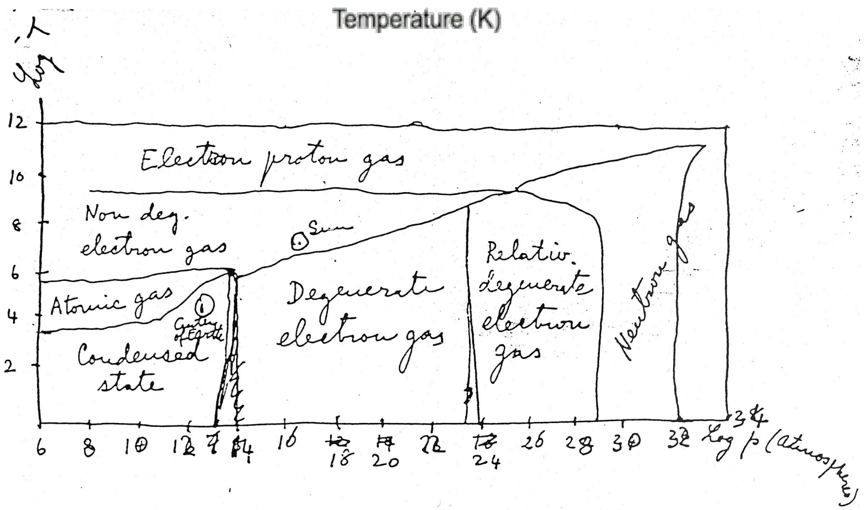
The Phases of Nuclear Matter

Phases of Water



PHASE DIAGRAM OF NUCLEAR MATTER



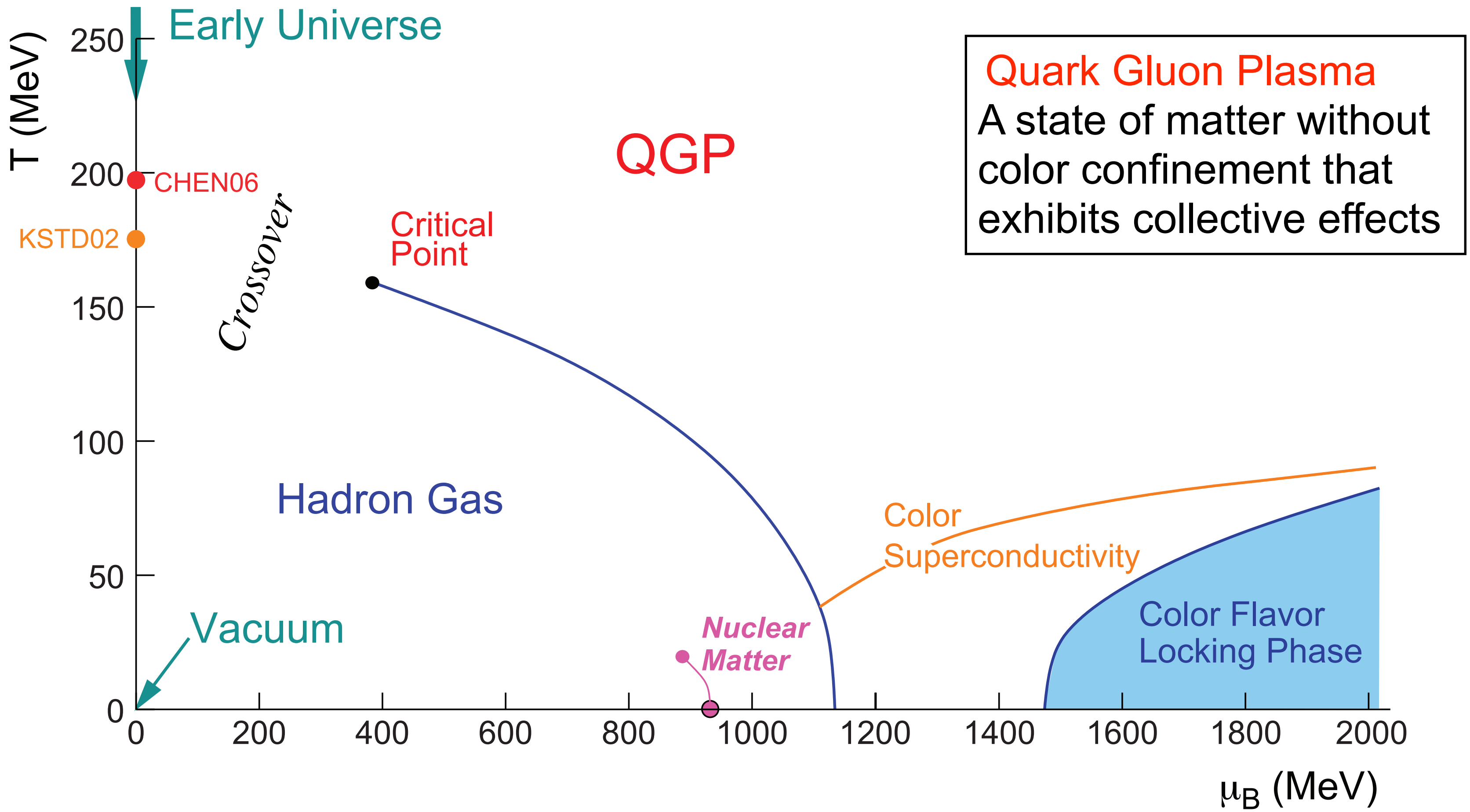


Matter in unusual conditions

Phase diagram of nuclear matter in equilibrium, and how it can be explored in ultrarelativistic heavy ion collisions, from the 1983 NSAC Long Range Plan.

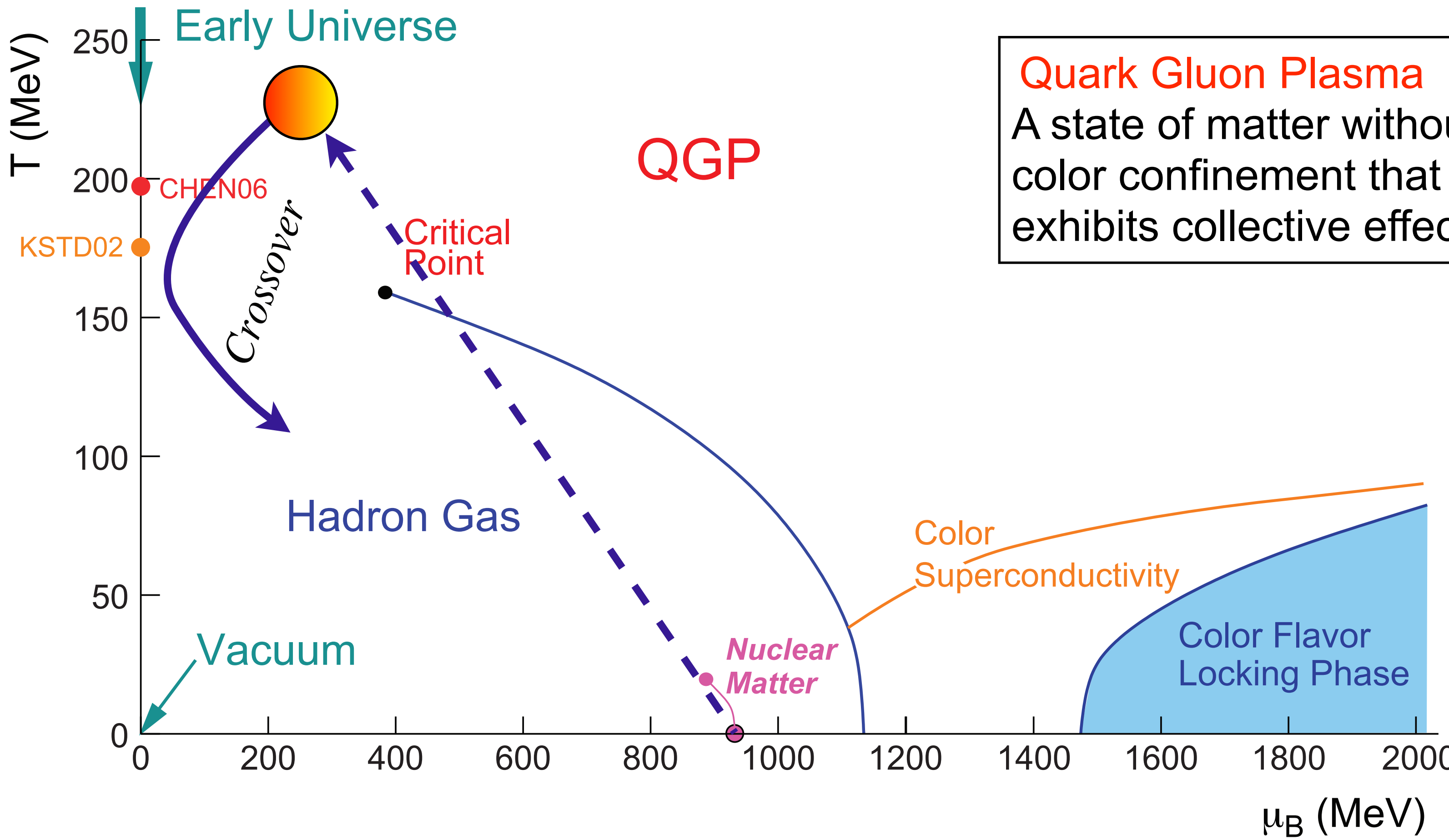
From Fermi's notes on thermodynamics

The Phases of QCD



- Lattice says crossover at $\mu_B = 0$
- Some discussion on methods to extract T_C ($175 \leq T_C/MeV \leq 191$)
- Lattice suggest the transition becomes 1st order at μ_B above the critical point (2nd order at the CP)

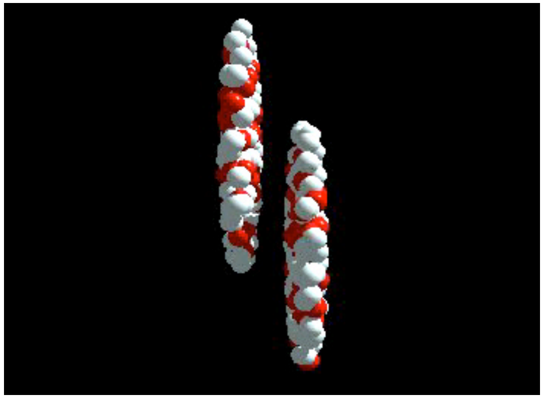
The Phases of QCD

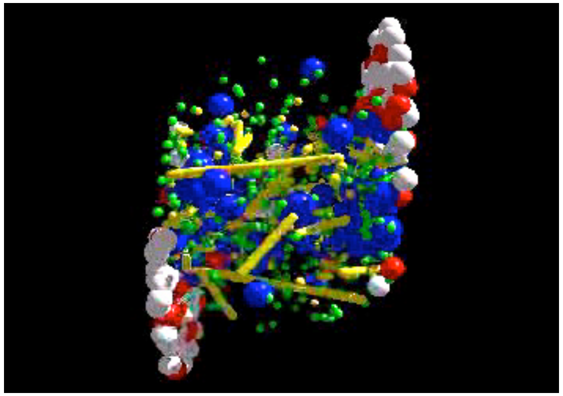


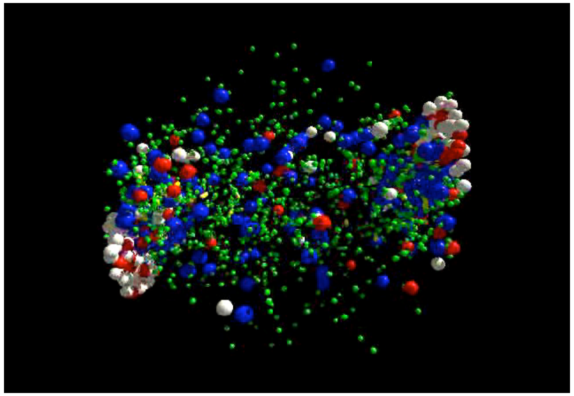
Quark Gluon Plasma A state of matter without color confinement that exhibits collective effects

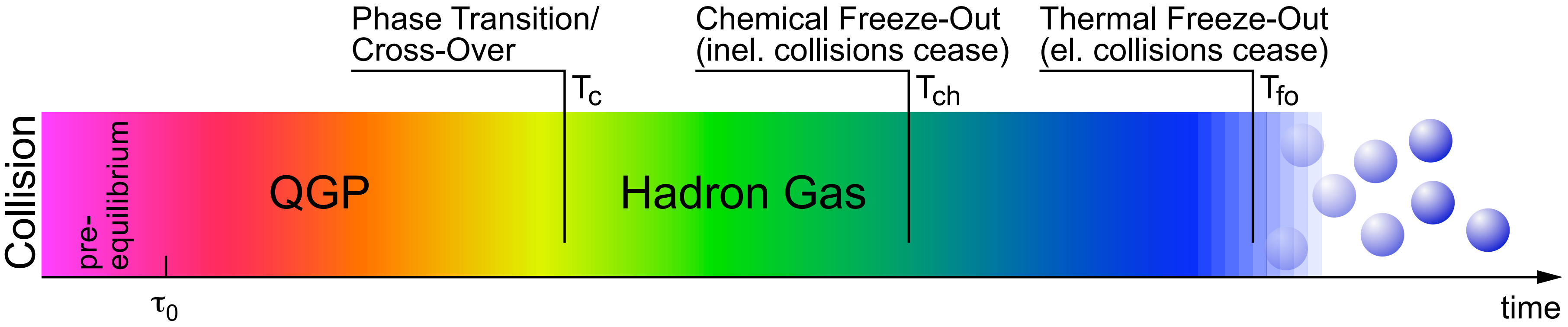
- Need experiments to explore the phase diagram of QCD
- Heavy Ion Collisions at RHIC create conditions sufficient to “melt” matter into a quark gluon plasma

The Phase Transition in the Laboratory









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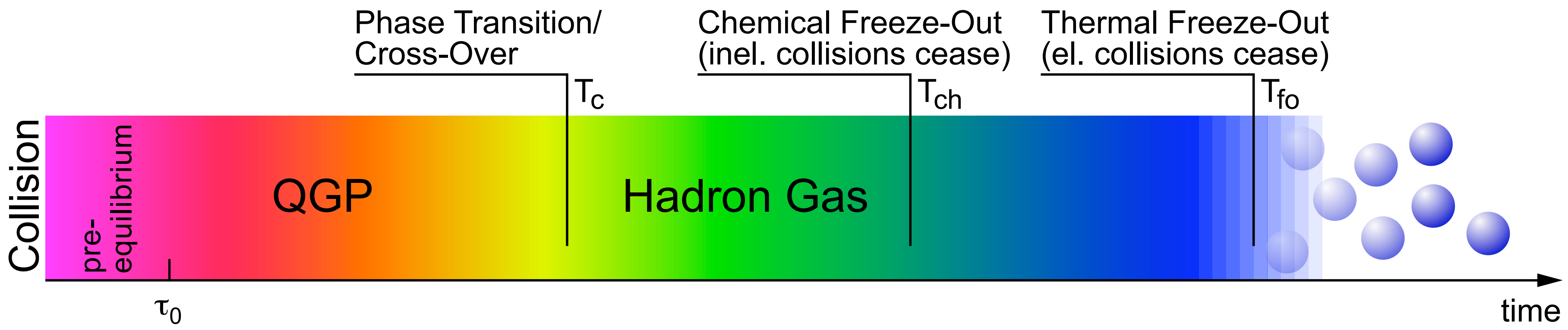
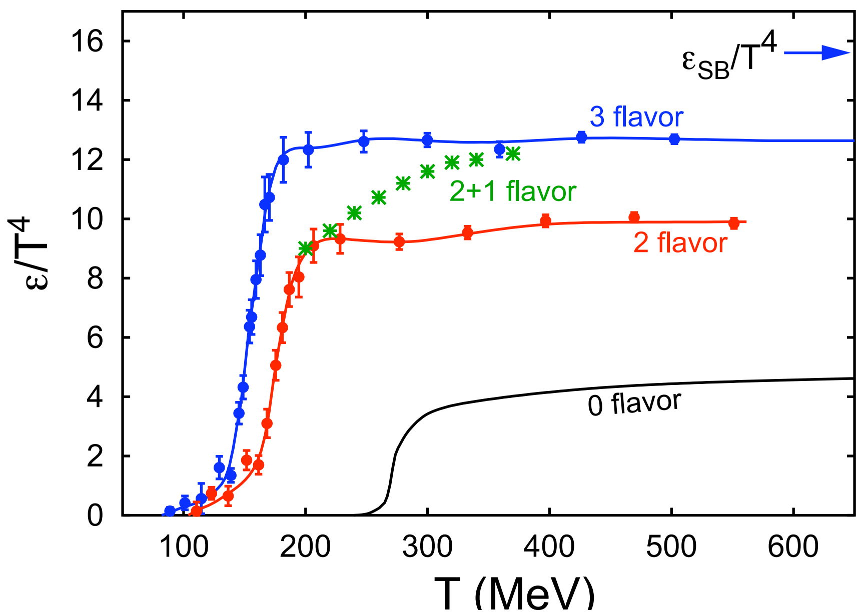


non-linear QCD, Color Glass Condensate	pQCD (LO, NLO)	Non-perturbative QCD, Hydrodynamics	Hadronic Models (RQMD, AMP)	Statistical thermal models, Fragmentation Functions
• Gluon density in initial state? • saturation phenomena • initial state effects (shadowing, EMC) • thermalization (how?)	Hard Processes • High-pt partons • Heavy Flavor • direct photons	• Collective Flow • Color screening • Jet quenching & medium response • Chiral Symmetry Restoration ⇒ mass shifts • thermal radiation	• Particle formation • Fragmentation • Recombination / Coalescense • Hadronic absorption	• Particle ratios • Particle yields • Hadrochemistry • High-p_T partons fragment ⇒ jets

Early Expectations - Freely Roaming ...

$T >> \Lambda_{QCD}$: weak coupling $\alpha_s(Q^2, T) \Rightarrow$ deconfined phase

Critical energy density: $\varepsilon_c = (6\pm2)T_c^4 \approx 1\ GeV/fm^3$ (at T_c~175 MeV)



QCD Lattice Calculations

Phase transformation with nearly an order of magnitude increase in thermodynamic degrees of freedom.

And it reaches 80% of the non-interacting gas limit.

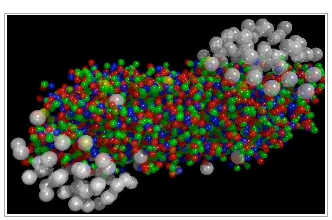
Press Release

New State of Matter created at CERN

PR01.00
10.02.00

At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

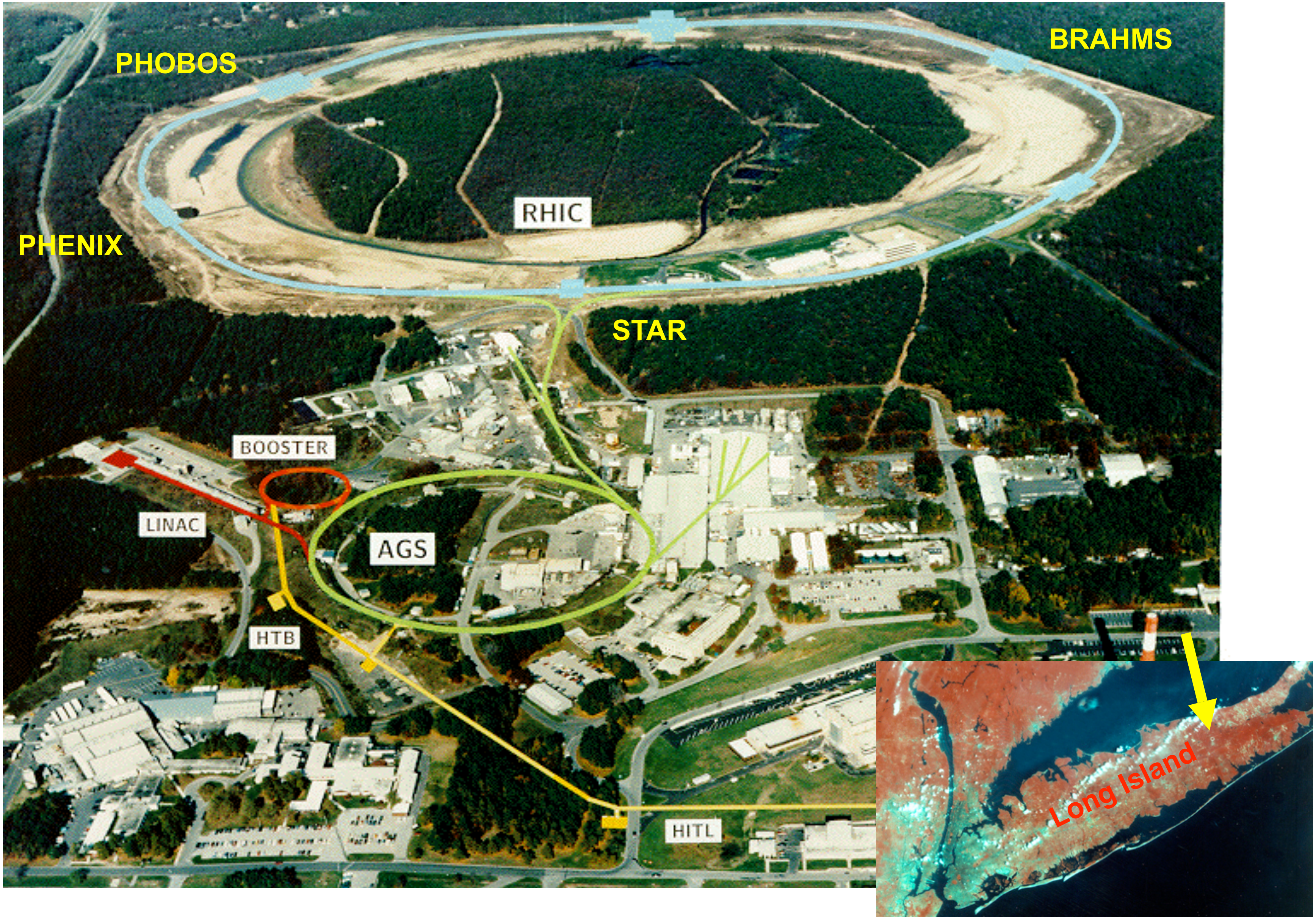
Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.



"Quarks and gluons freely roam within the volume of the fireball created by the collision."

CERN press release (2000)

Relativistic Heavy Ion Collider - RHIC



Relativistic Heavy Ion Collider - RHIC

~4 km circumference

Two independent rings

- 120 bunches/ring
- 106 ns crossing time

Capable of colliding

~any nuclear species

on

~any other species

Energy:

- 500 GeV for p-p
- 200 GeV for Au-Au
  (per N-N collision)

Design Luminosity

- Au-Au: 2×10^{26} cm^{-2} s^{-1}
- p-p : 4×10^{30} cm^{-2} s^{-1}
  (*polarized*)

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- Large $\sqrt{s}$
  - Access to reliable pQCD probes
  - Clear separation of valence baryon number and glue

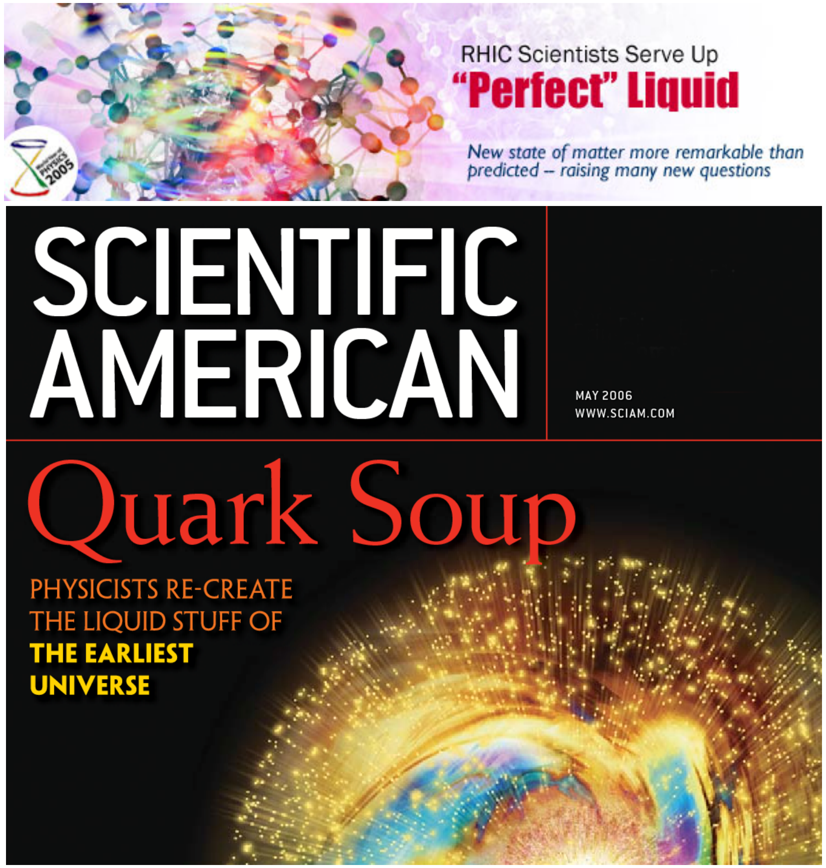
- Routine operation at 6x (5x) design luminosity in Au+Au (pp)

- Runs so far:
  - Species: Au+Au, d+Au, Cu+Cu, p↑+p↑
  - Energies $\sqrt{s}$:
    - 5 GeV (Au+Au)
    - 9 GeV (Au+Au)
    - 22 GeV (Au+Au, Cu+Cu, p↑)
    - 56 GeV (Au+Au)
    - 62 GeV (Au+Au,Cu+Cu, p↑+p↑)
    - 130 GeV (Au+Au),
    - 200 GeV (Au+Au, Cu+Cu, d+Au, p↑+p↑)
    - 410 GeV & 500 GeV (p↑)

Discoveries at RHIC

Major Findings at RHIC

- Strong Elliptic Flow
  - Efficient conversion of spatial anisotropy into momentum anisotropy consistent with collective flow
  - Constituent quark number degrees of freedom apparent in scaling laws of hadronic flow
- Jet Quenching
  - Energy loss of high-p_T partons traversing the hot and dense matter
  - Medium response: conical flow (?), ridge
- Particle Production through recombination/coalescence dominates over fragmentation at medium p_T



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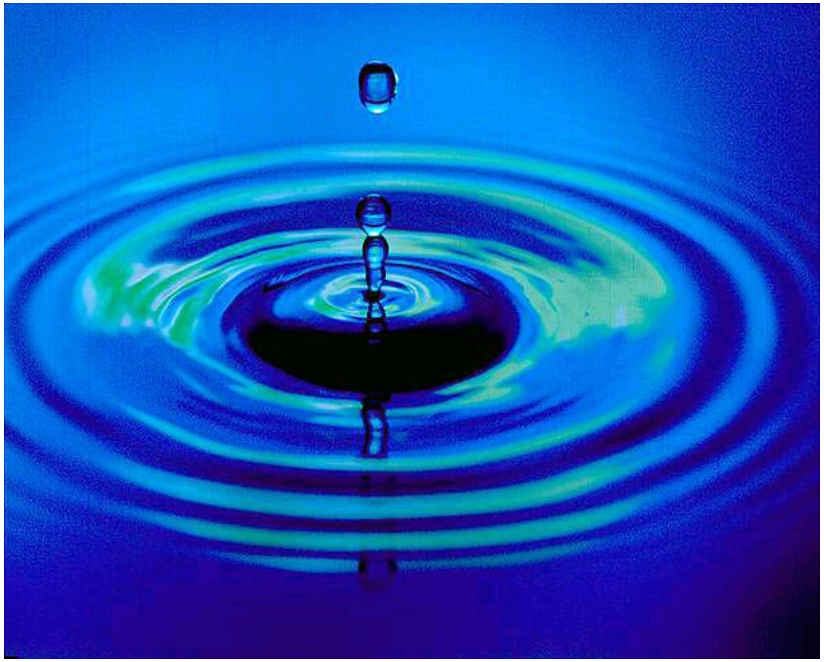
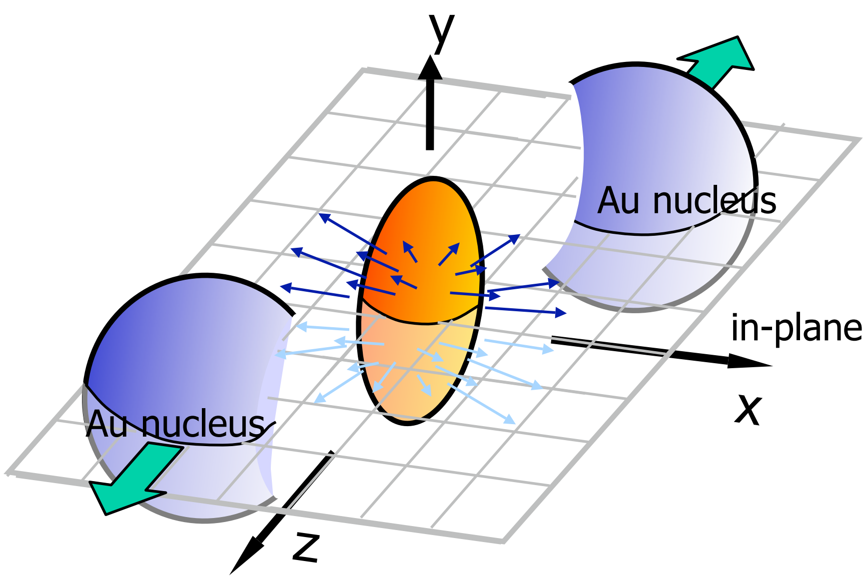


⇐ these and comparisons to models led to the “perfect fluid” hypothesis

Paradigm shift:

strongly coupled QGP = sQGP

Elliptic Flow – Indicator for Early Thermalization



Non-central Collisions

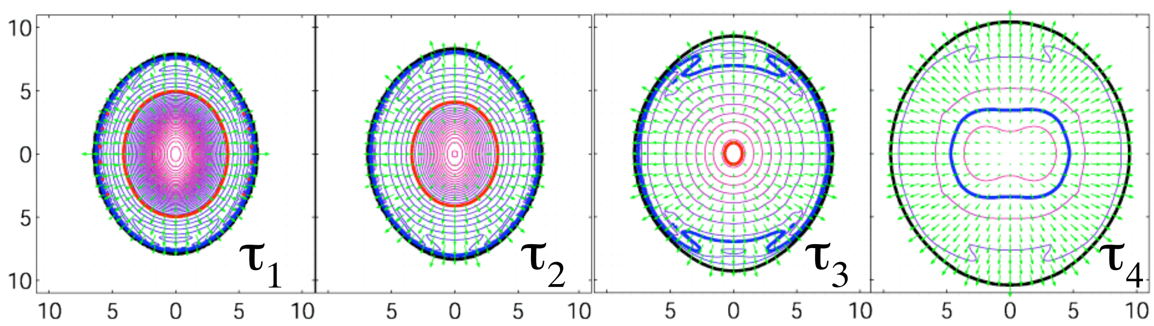
Use a Fourier expansion to describe the angular dependence of the particle density

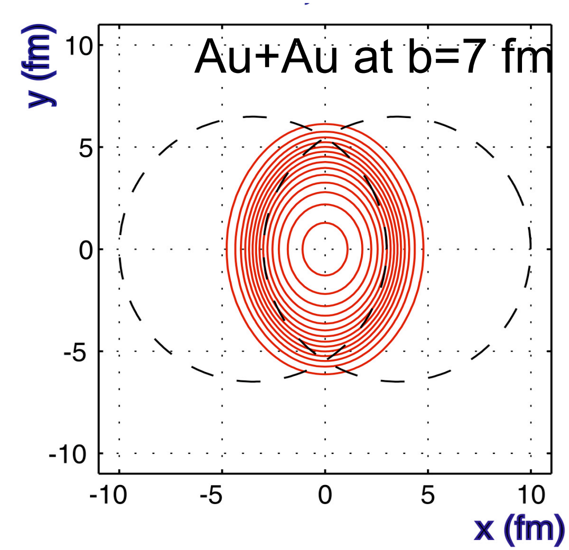
number of particles $\propto 1 + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \ldots$

- shape washes out as it expands
- $v_2 \rightarrow$ sensitive to early interactions and pressure gradients

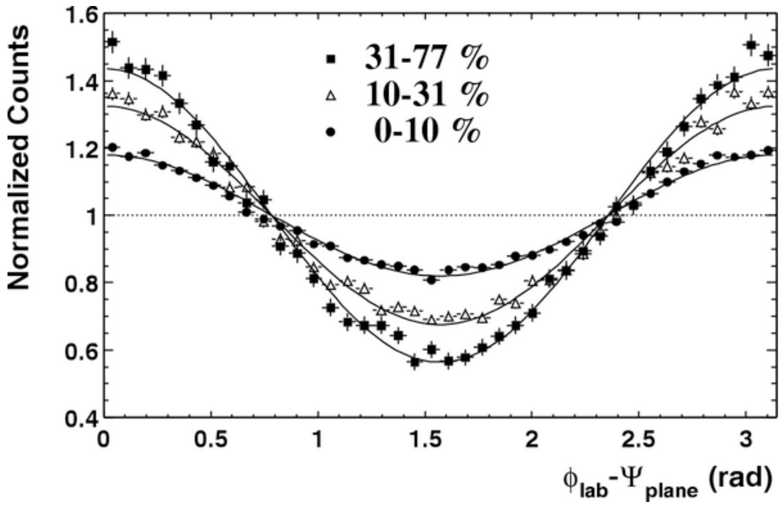
Au+Au at b=7 fm

P. Kolb, J. Sollfrank, and U. Heinz



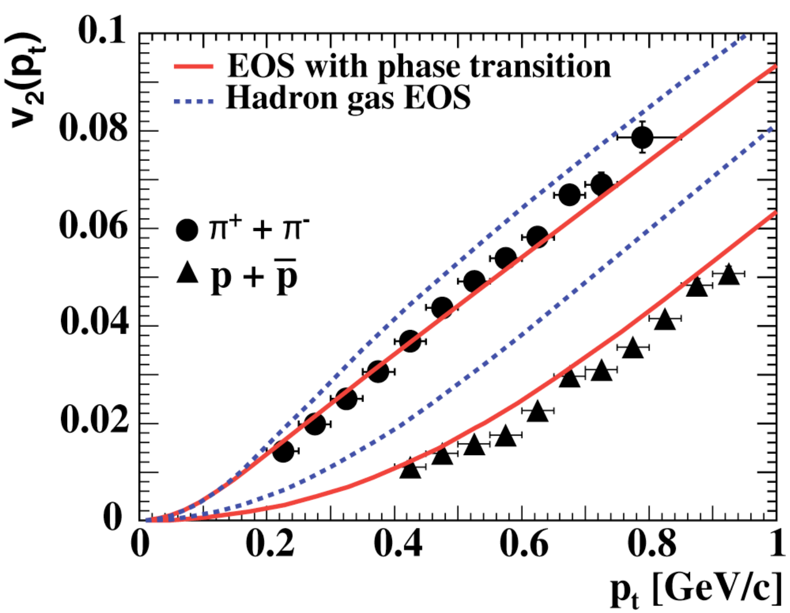


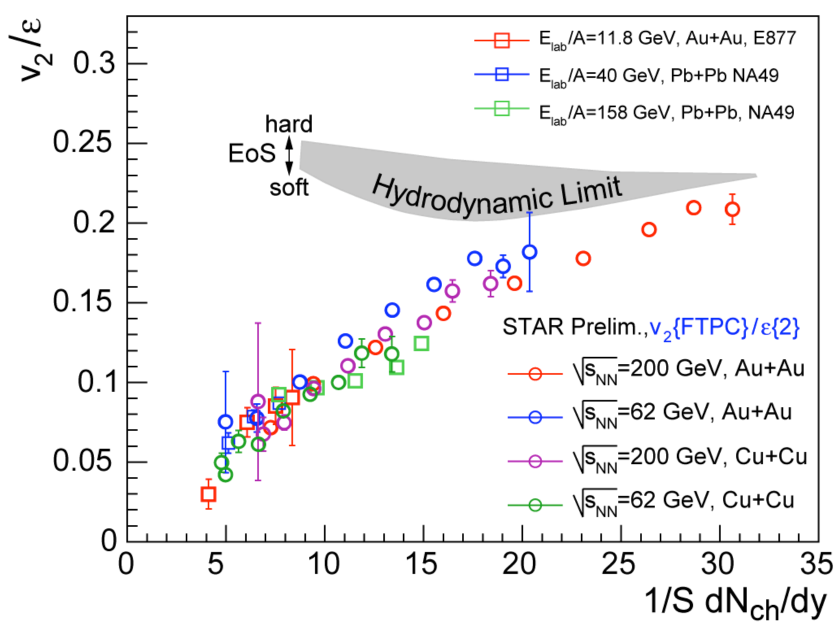
The "Flow" is ~Perfect



- Huge asymmetry found at RHIC
  - massive effect in azimuthal distribution w.r.t reaction plane
  - Factor 3:1 peak to valley from 25% v_2
- The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal (zero viscosity, λ=0) hydrodynamics

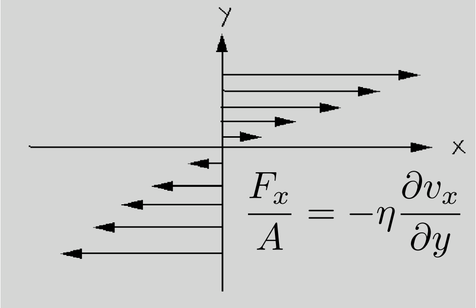
$\Rightarrow$ "perfect liquid"





How Perfect is “Perfect” ?

Viscous fluid



- supports a shear stress
- viscosity η:

$$\begin{aligned} \eta &\approx \text{momentum density} \times \text{mean free path} \\ &\approx n\bar{p}\lambda = n\bar{p}\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma} \end{aligned}$$

- small η ⇒ large σ ⇒ strong couplings

Hydrodynamic calculations for RHIC assumed zero viscosity

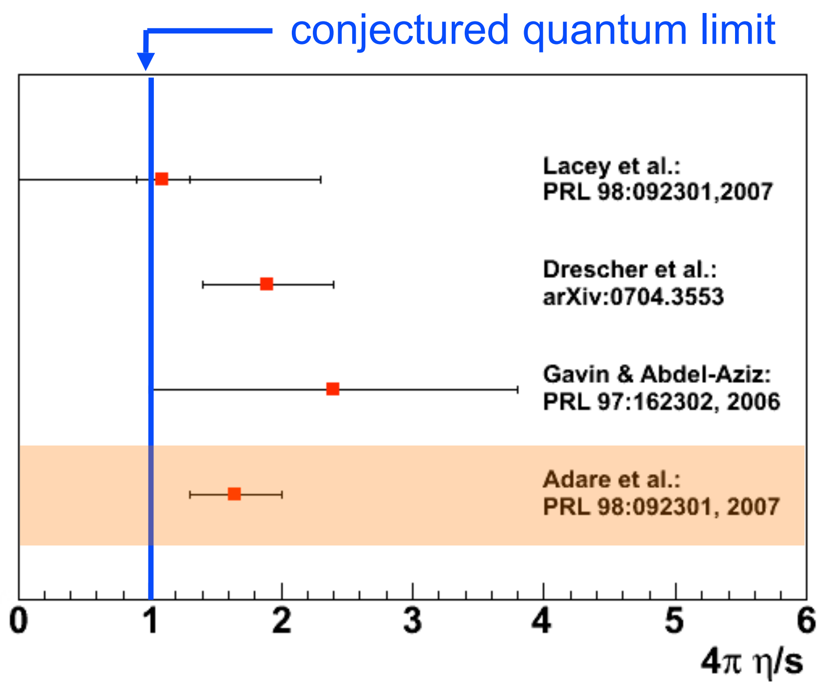
η = 0 ⇒ “perfect fluid”

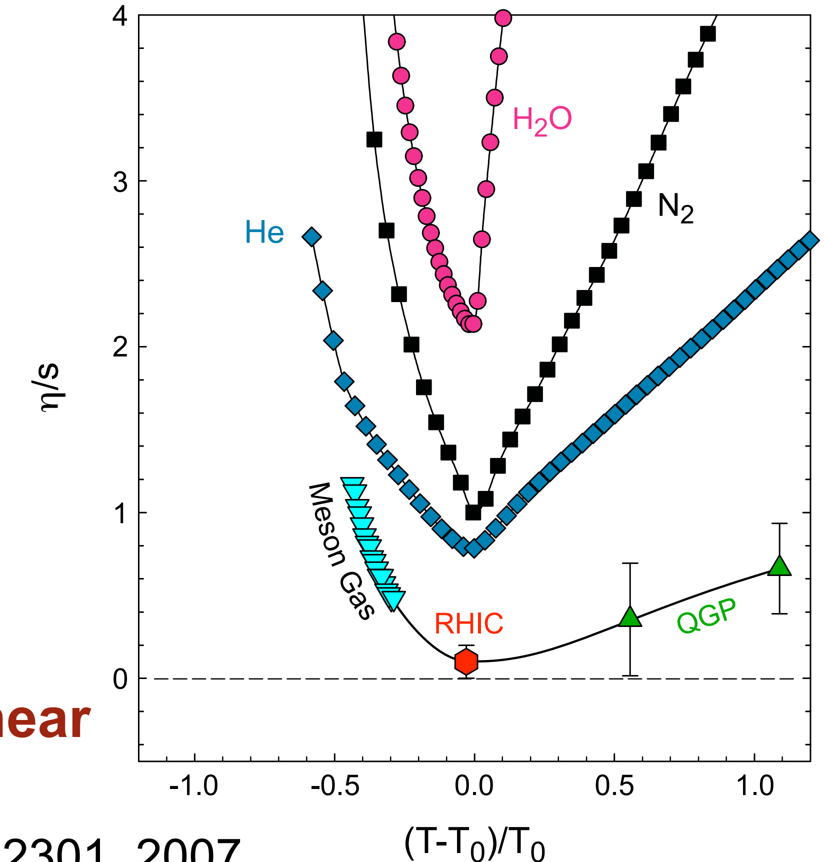
- But there is a (conjectured) quantum limit:
  - derived first in (P. Kovtun, D.T. Son, A.O. Starinets, PRL.94:111601, 2005) motivated by AdS/CFT correspondence

$$\eta \geq \frac{\hbar}{4\pi}(\mathit{Entropy\ Density}) \equiv \frac{\hbar}{4\pi}s$$

- N.B.: water (at normal conditions) η/s ~ 380 ħ/4π

What is η/s at RHIC ?





Observables that are sensitive to shear

- Elliptic Flow
  - R. Lacey et al.: Phys. Rev. Lett. 98:092301, 2007
  - H.-J. Drescher et al.: Phys. Rev. C76:024905, 2007
- p_T Fluctuations
  - S. Gavin and M. Abdel-Aziz: Phys. Rev. Lett. 97:162302, 2006
- Heavy quark motion (drag, flow)
  - A. Adare et al. : Phys. Rev. Lett. 98:092301, 2007

RHIC, Strings, and the Maldacena Conjecture

N=4 Supersymmetric Yang Mills at large coupling for T > 0 describes a strongly coupled plasma.

Under certain conditions ($N_c \rightarrow \infty$, $\lambda = g^2 N_c \rightarrow \infty$) this theory is equivalent to classical gravity

This is called the Maldacena Conjecture or AdS/CFT correspondence

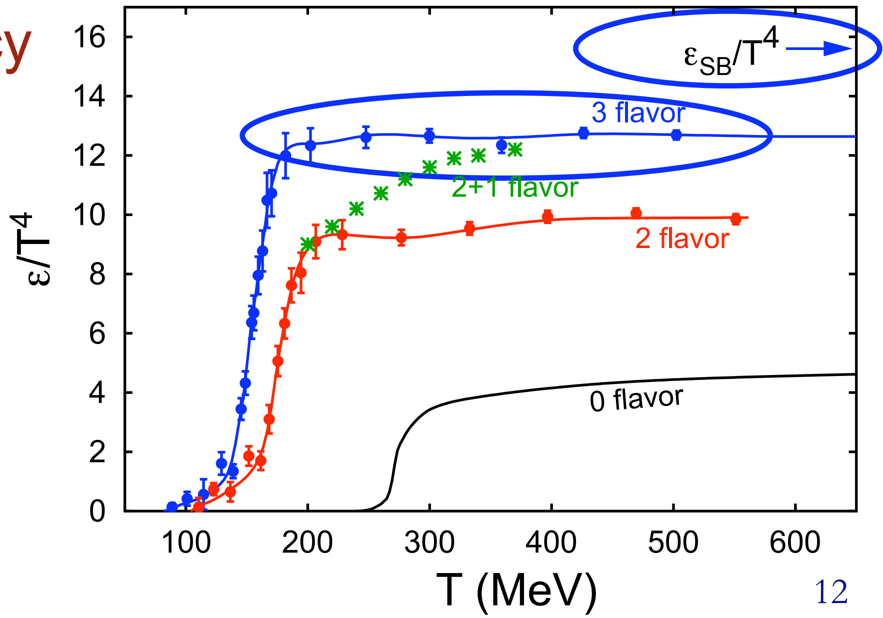
Impressive amount of work on AdS/CFT & sQGP:

$\hat{q}$, J/ψ suppression, heavy quark drag and diffusion, Mach cones, ...

Example: Understand the discrepancy between lattice results and Stefan-Boltzmann expectations:

Entropy and temperature of black 3-branes, Gubser, Klebanov, Peet, PRD54:3915

$$\frac{\varepsilon}{\varepsilon_{SB}} = \frac{3}{4}$$



RHIC, Strings, and the Maldacena Conjecture

There are certainly issues:
N=4 Super Yang-Mills ≠ QCD

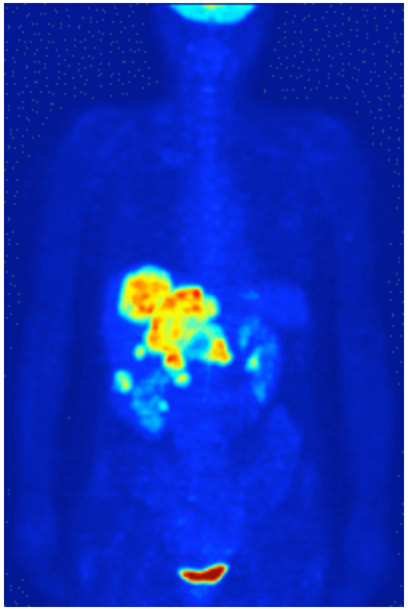
Some dislike the approach...
...but in the end the “right” approach will be validated by both ***qualitative*** concepts, and ***quantitative*** predictions

New Yorker, Jan 8, 2007

Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)



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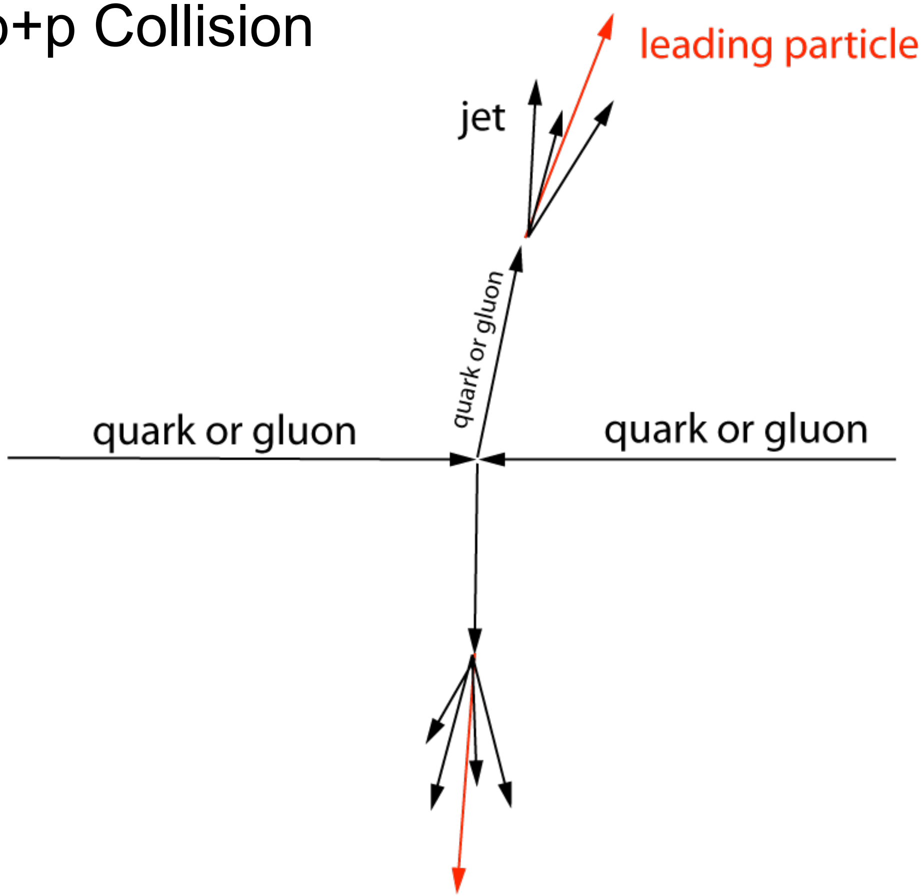
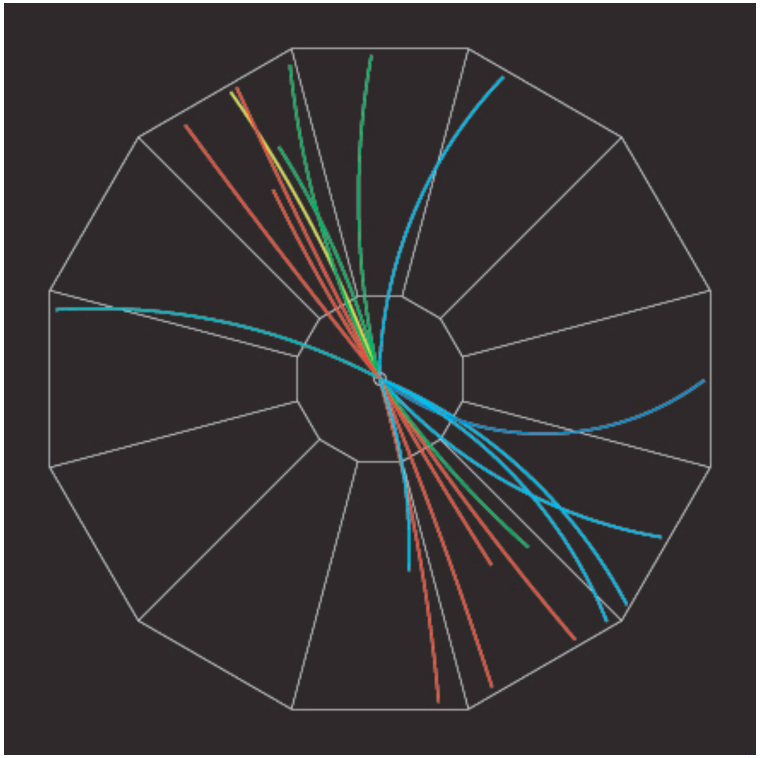
p+p Collision



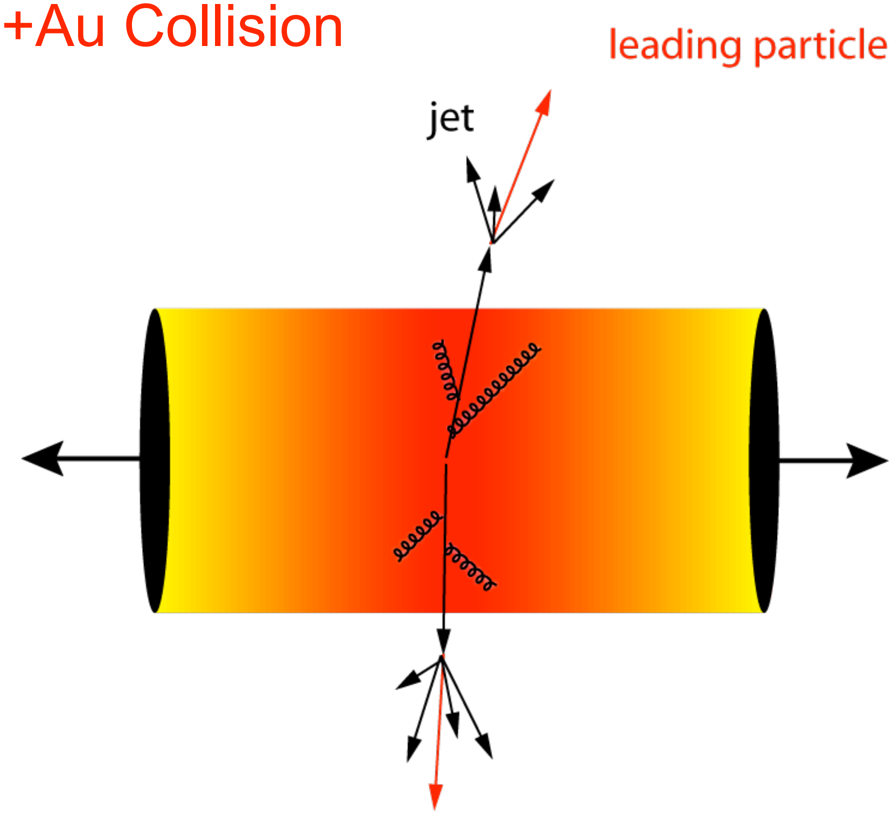


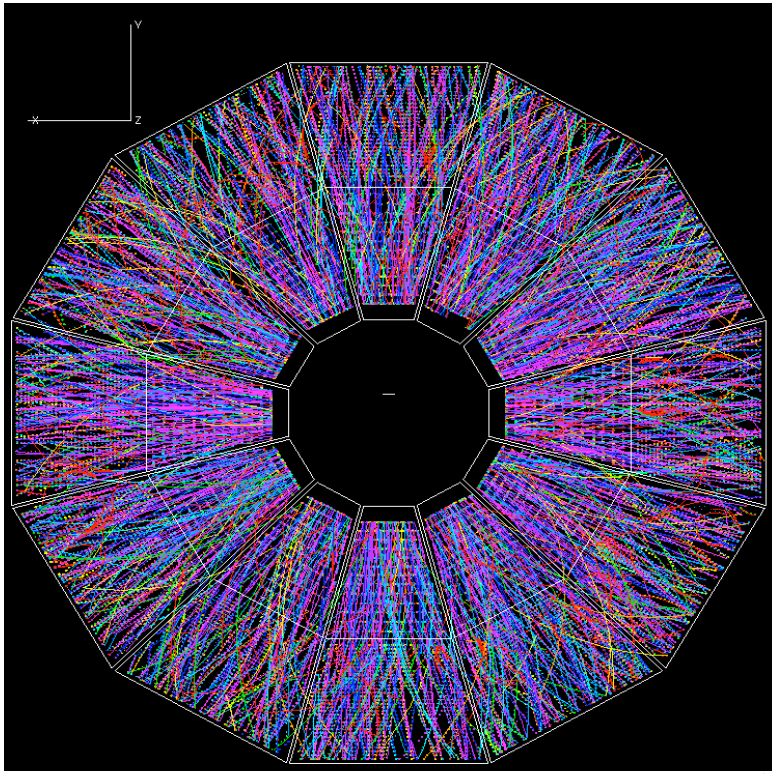
Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)
- Calibrated interaction (beam of known energy and direction)
- Suppression pattern tells about density profile

Au+Au Collision





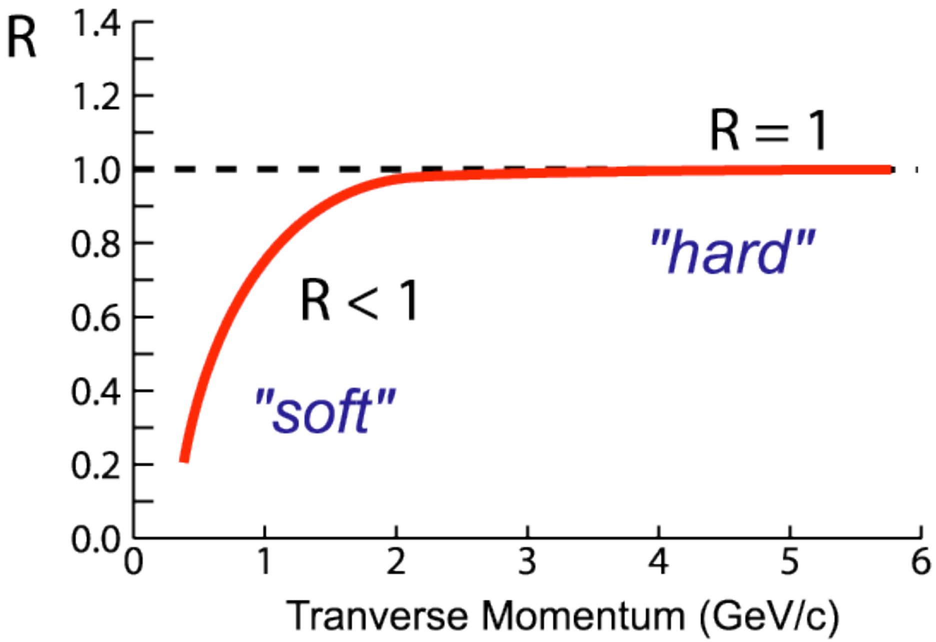
How to Measure ?

Compare Au+Au with p+p Collisions ⇒ R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

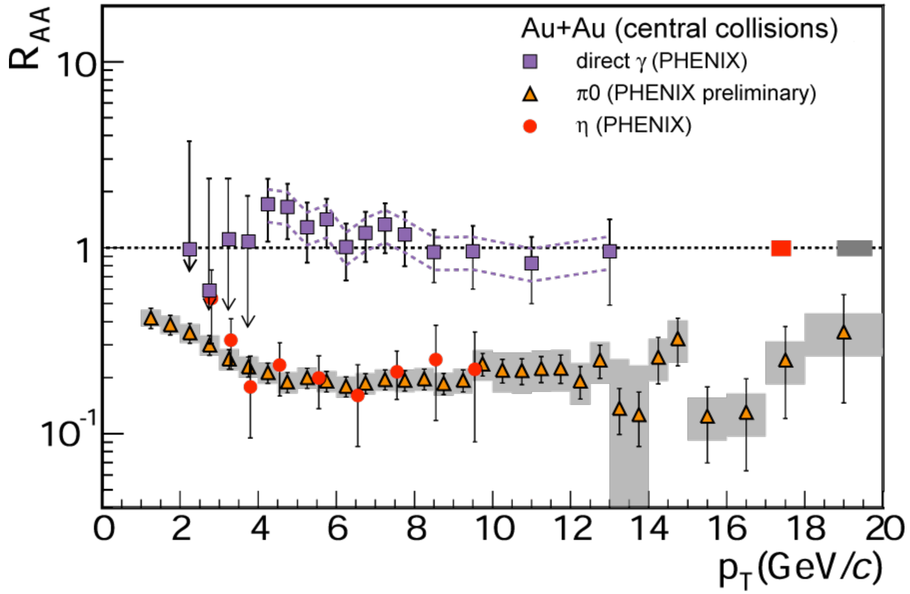
Average number of NN collision in an AA collision



No "Effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

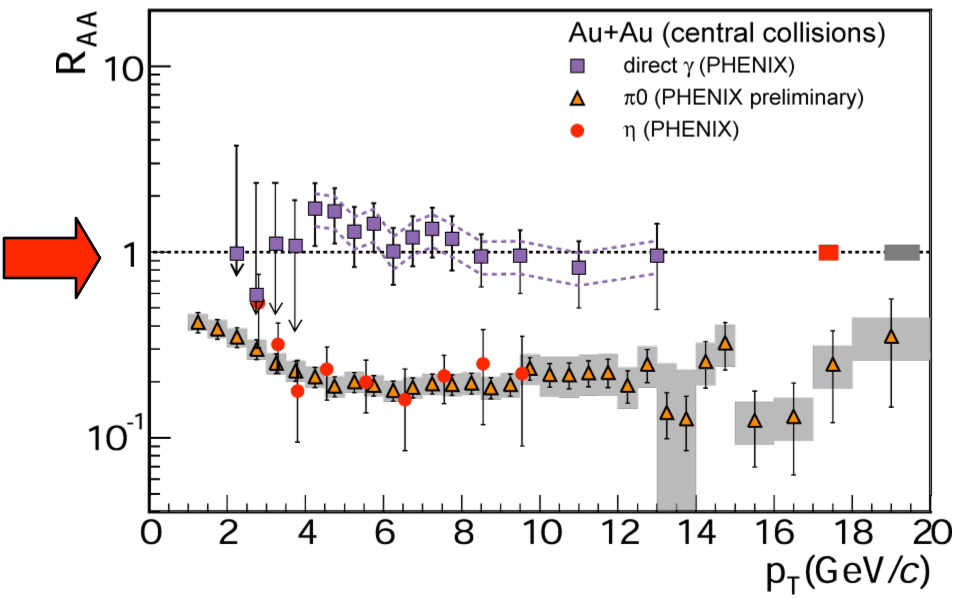
Suppression: R < 1

High-p_T Suppression – Matter is Opaque



Observations at RHIC:

High-p_T Suppression – Matter is Opaque



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   - Good! γ don't interact with medium
   - N_{coll} scaling works

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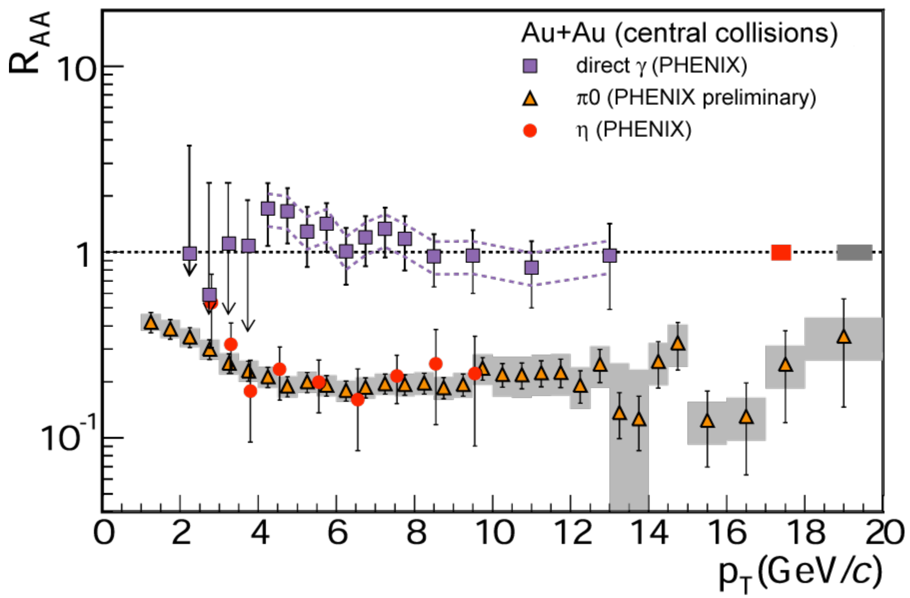

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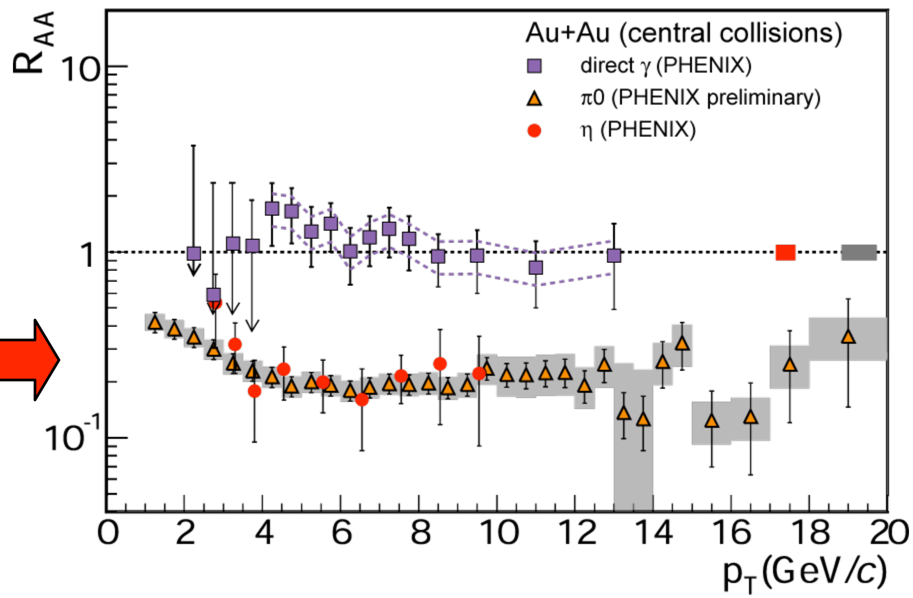

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   - Huge: factor 5

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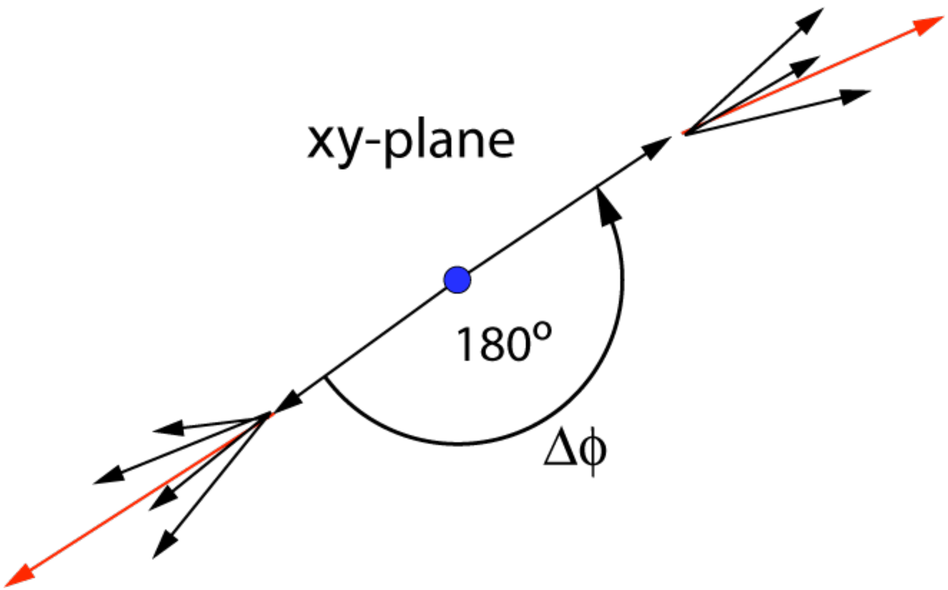

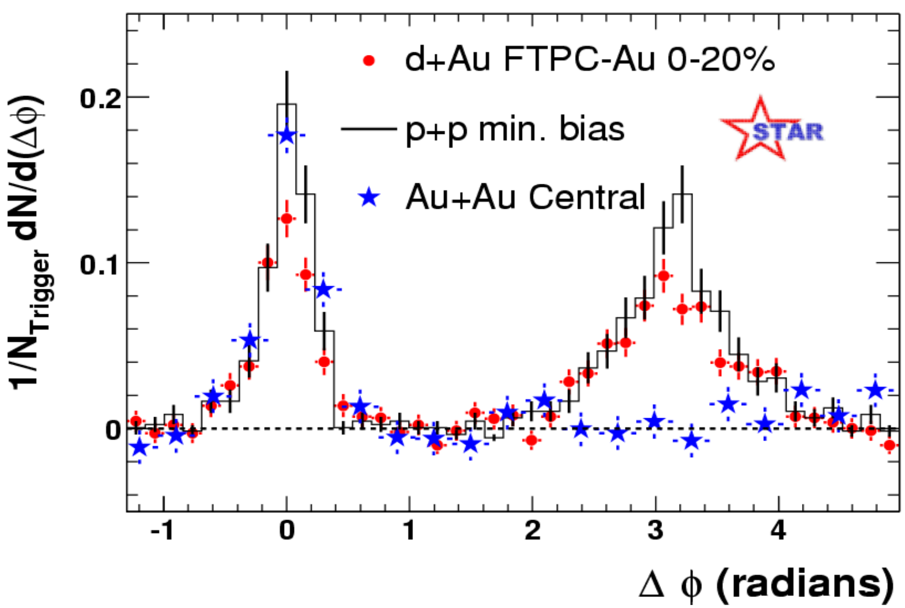

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   - Partner in hard scatter is absorbed in the dense medium

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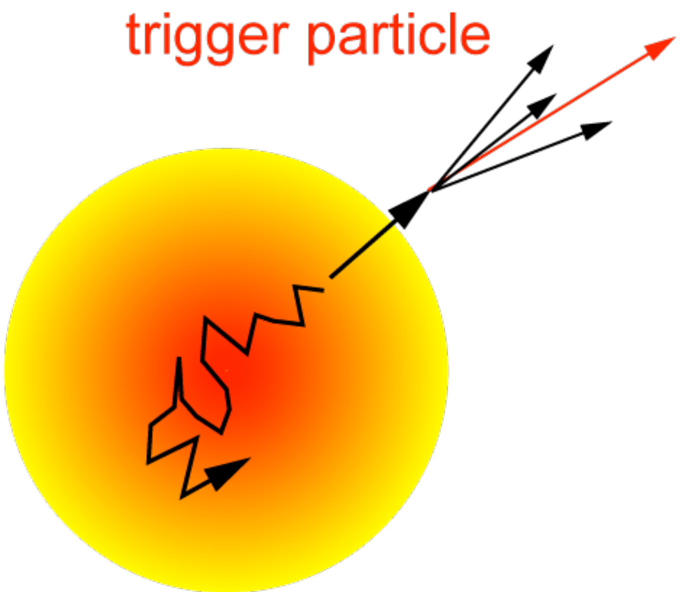

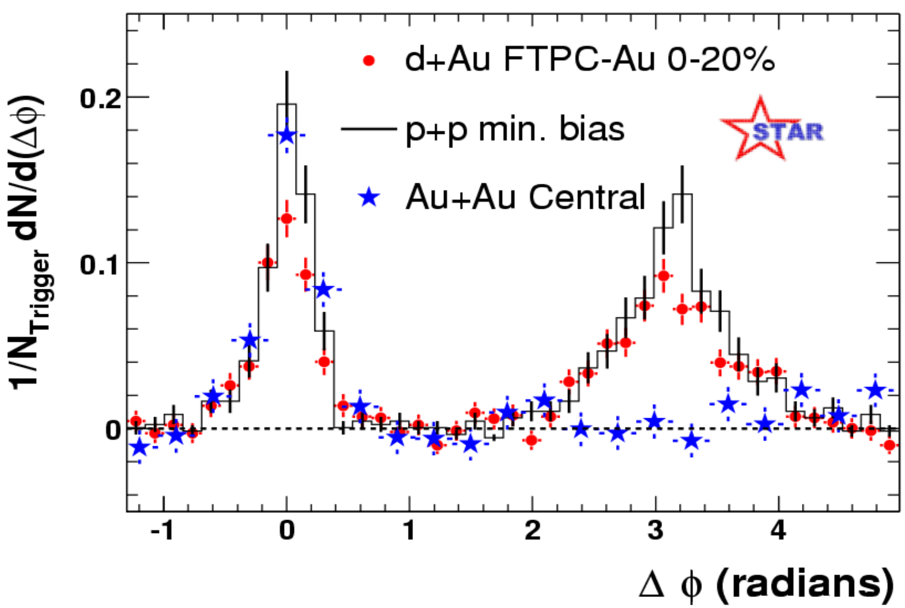

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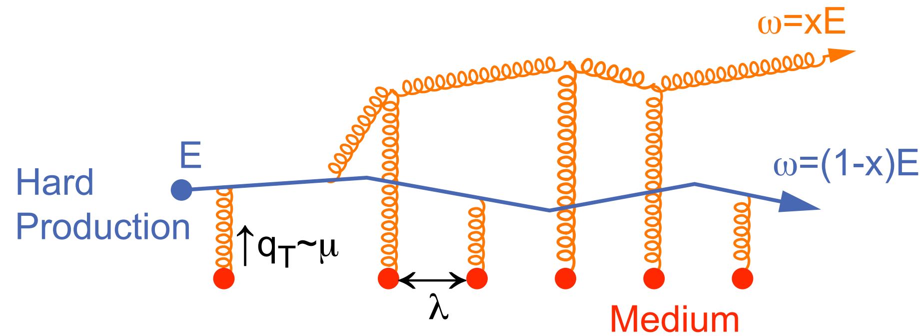
Interpretation

Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium



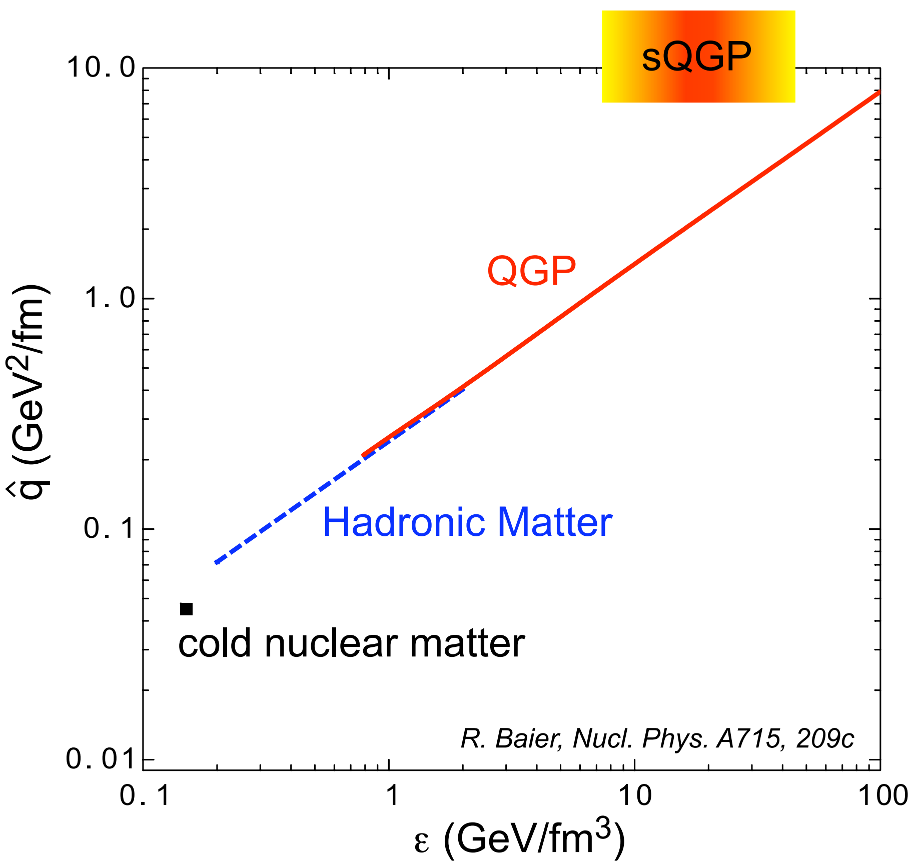
- Mean parton energy loss ∝ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim \Delta L^2$ (medium length)

    $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$

  is $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length

  - gluon density dN_g/dy
  - Note: expanding medium

$$\hat{q} = \hat{q}(\vec{r}, \tau)$$



Constraining $\hat{q}$

Model	Opacity Parameter
PQM	$\langle \overline{q} \rangle$ = 13.2 (+ 2.1 - 3.2)
GLV	dN_g/dy = 1400 (+270 -150)
WHDG	dN_g/dy = 1400 (+200 -375)
ZOWW	ε_0 = 1.9 (+0.2 - 0.5)

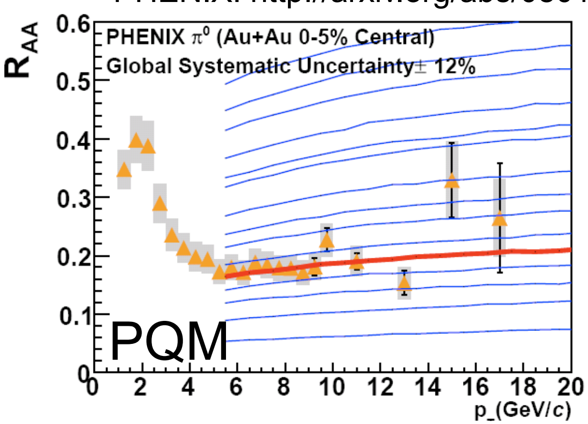
PHENIX: http://arxiv.org/abs/0801.1665

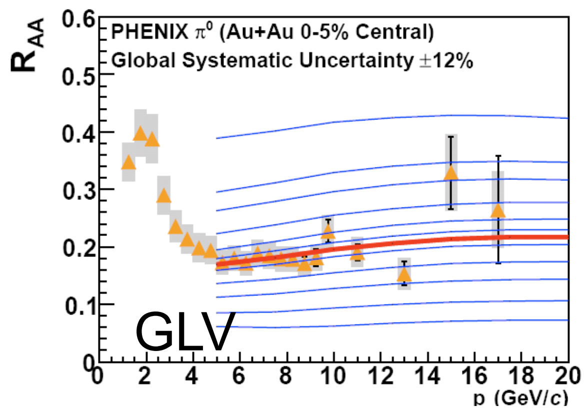
PQM: A. Dainese, C. Loizides, G. Paic, Eur. Phys. J C38: 461 (2005). C. Loizides, Eur. Phys. J.C49, 339 (2007).

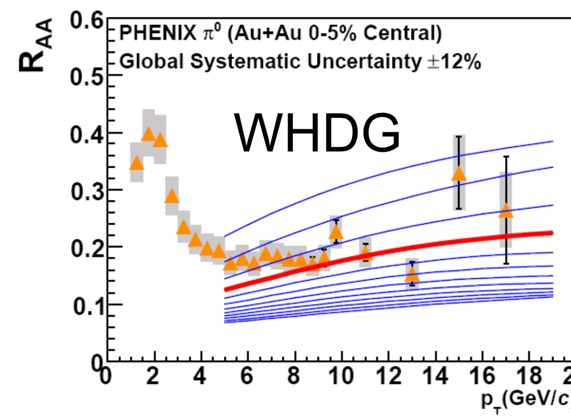
GLV: I. Vitev, Phys. Lett. B639, 38 (2006). M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B571, 197 (2000).

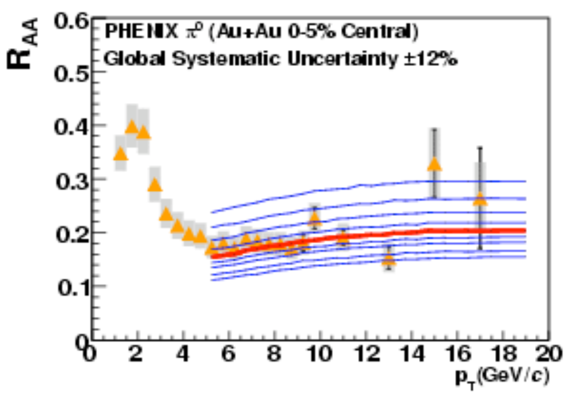
WHDG: W.A. Horowitz, S. Wicks, M. Djordjevic, M. Gyulassy,in preparation; S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A 783, 493 (2007); S. Wicks, W. Horowitz, M. Djordjevic,M. Gyulassy, Nucl. Phys. A 784, 426 (2007).

ZOWW: H. Zhang, J.F. Owens, E. Wang, X-N Wang, Phys Rev. Lett. 98: 212301 (2007).

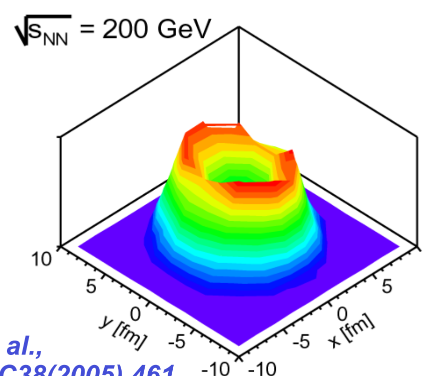








Problem:
Surface bias leads to saturation of R_{AA} with density



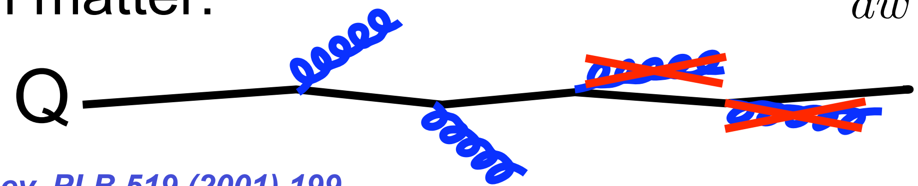
A. Dainese et al., Eur. Phys. J. C38(2005) 461

Distributions of parton production points in the transverse plane

High-p_T Heavy Quarks are Gray Probes

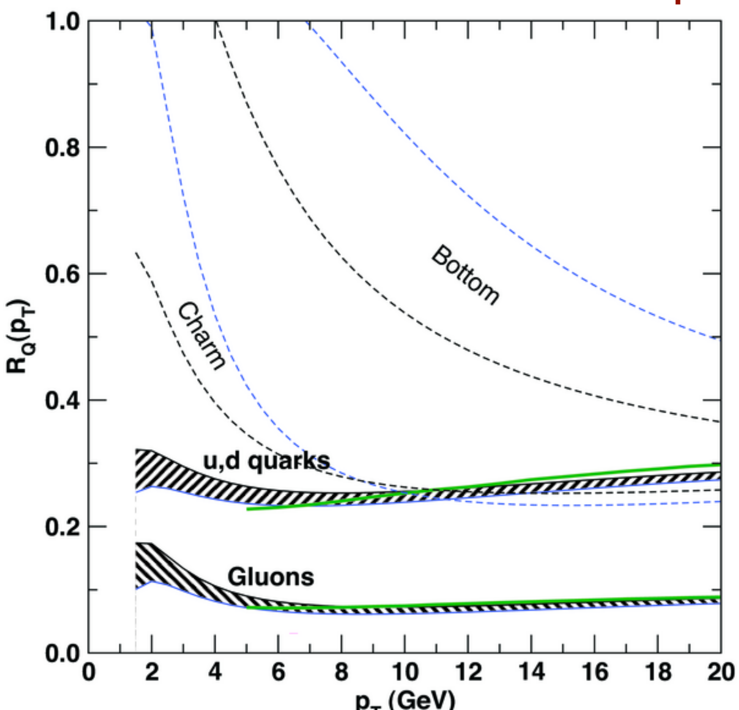
Dead cone effect implies lower heavy quark energy loss in matter:

$$\omega \left.\frac{dI}{dw}\right|_{\mathrm{HEAVY}} = \frac{\omega \left.\frac{dI}{dw}\right|_{\mathrm{LIGHT}}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

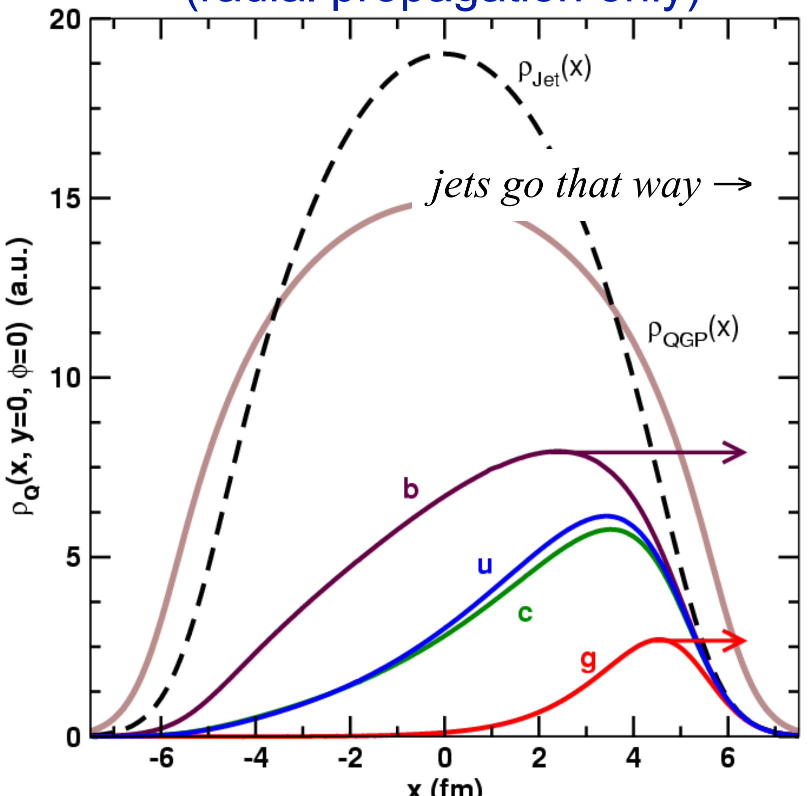


Dokshitzer and Kharzeev, PLB 519 (2001) 199.

- Problem: interaction with the medium so strong that information lost: “Black”⇒ use different probe



Origin of surviving jets p_T= 15 GeV (radial propagation only)



Wicks et al, Nucl. Phys. A784 (2007) 426

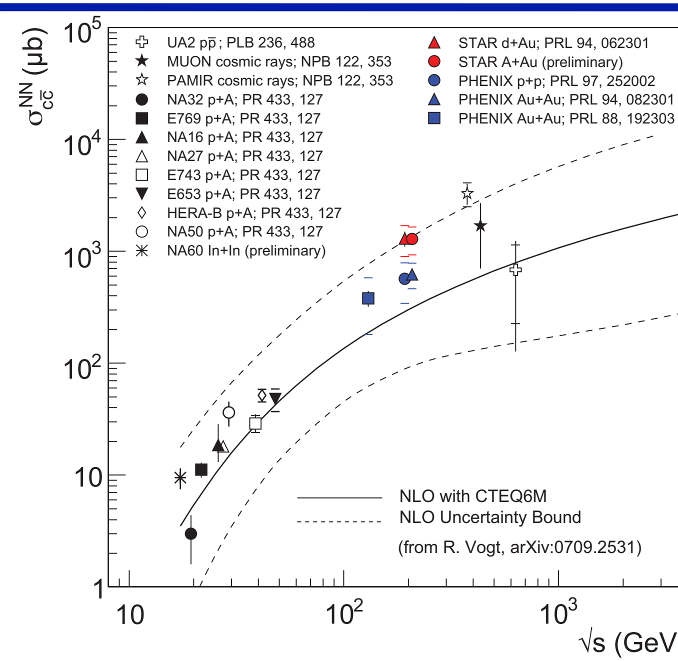
Open Heavy Flavor at RHIC

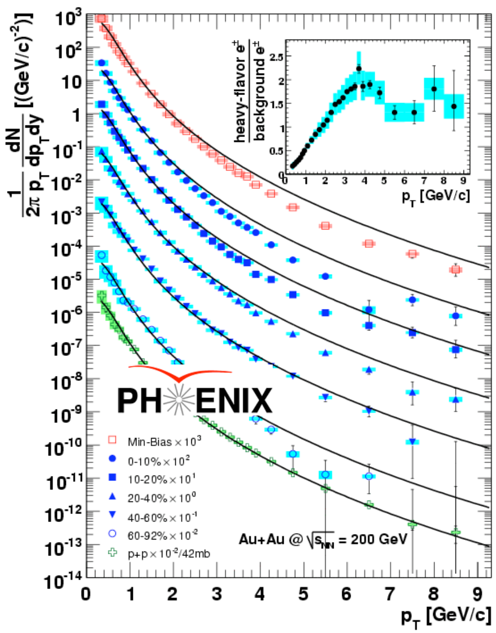
Hadronic Decay Channels

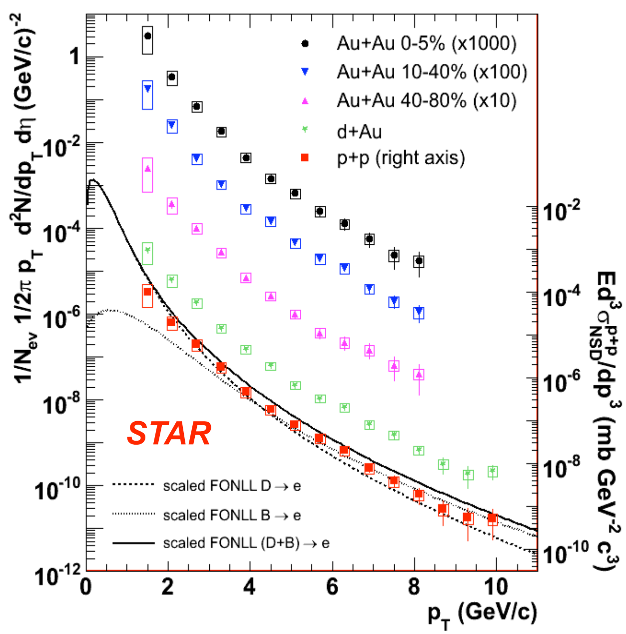
- e.g. $D^0 \rightarrow K\pi$ (B.R.: 3.8%)
- low S/B ratios
- no trigger capabilities
- low-p_T and $\sigma_{c\bar{c}}$
- need high-precision Si ($\Rightarrow$ detector upgrades)

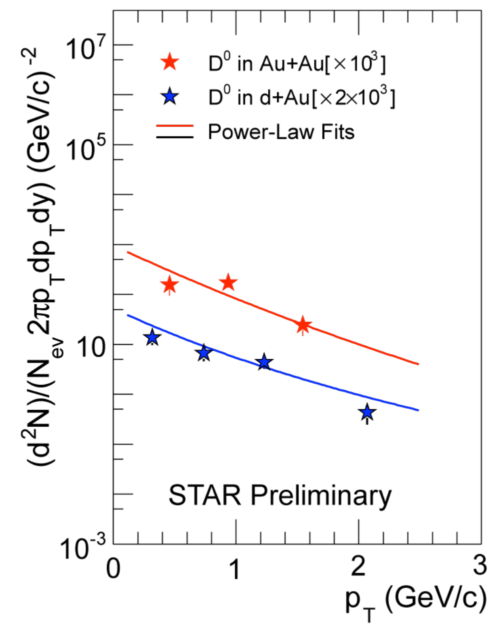
Semileptonic Decays

- e.g. $D^0 \rightarrow \ell^+ + \text{anything}$ (B.R.: 6.87%)
- photonic background
- bottom and charm intermix



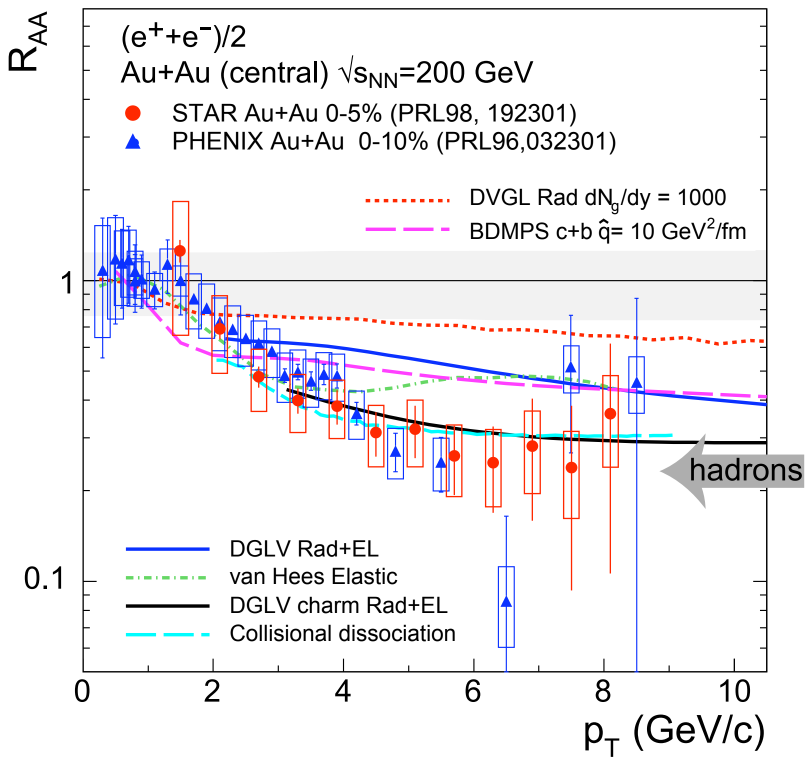






Big Surprise: Charm is Suppressed (is not Gray)

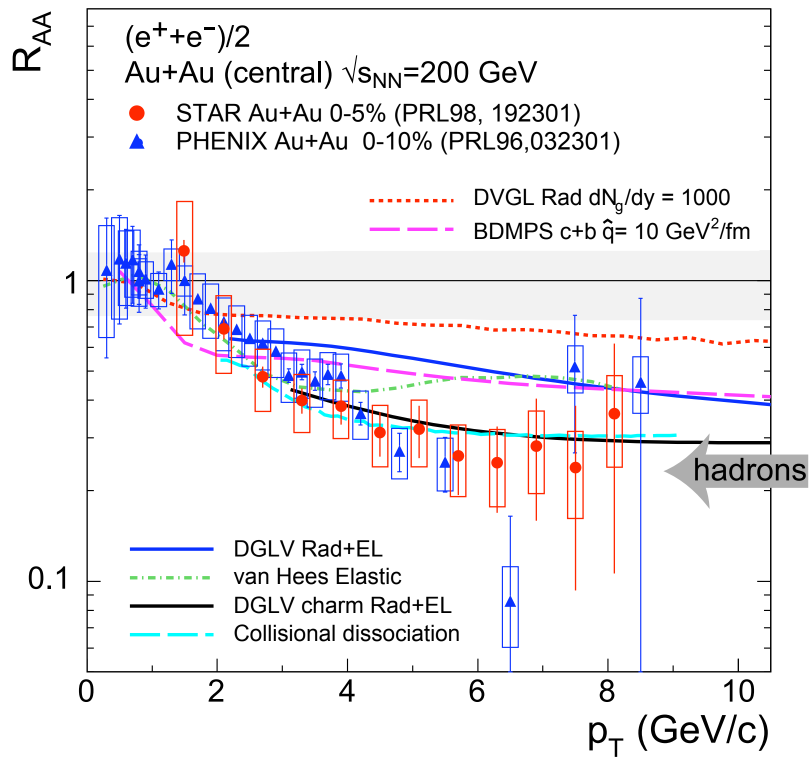
electrons from heavy flavor $c,b \rightarrow e\ K\ \nu$ NLO (FONLL): $c/b \rightarrow e\ X$



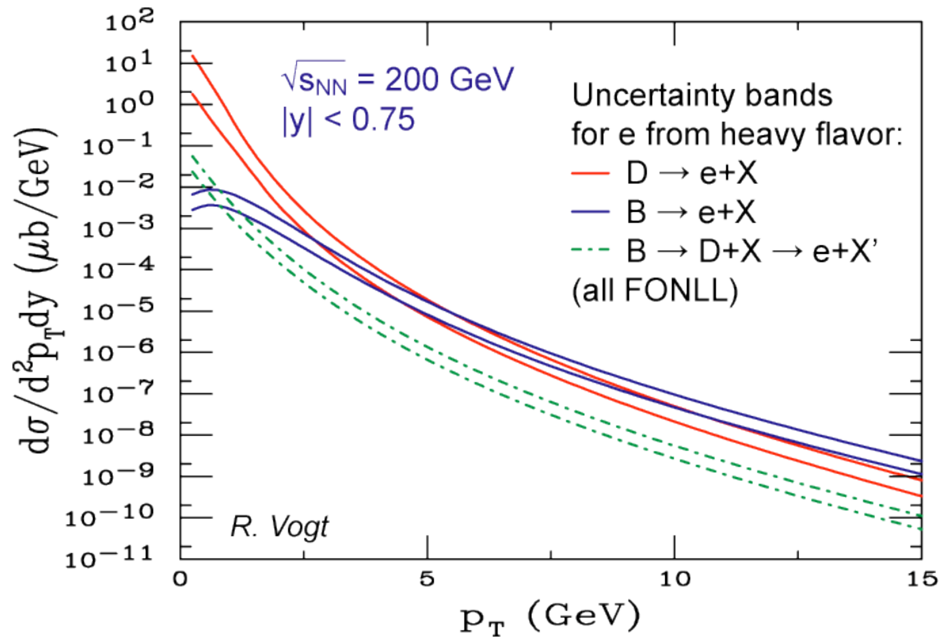
- Substantial suppression on same level to that of light mesons
- Describing the suppression is difficult for models
  - radiative energy loss | collisional E-loss | fragmentation and dissociation in medium
- What's about bottom?

Big Surprise: Charm is Suppressed (is not Gray)

electrons from heavy flavor c,b → e K ν

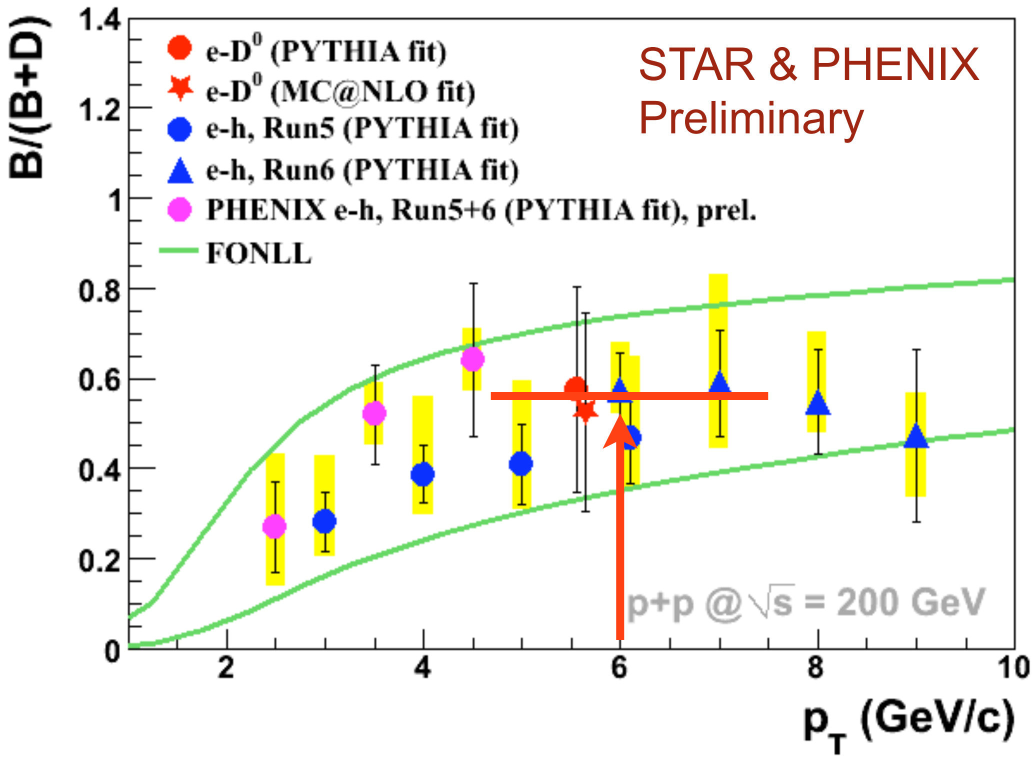


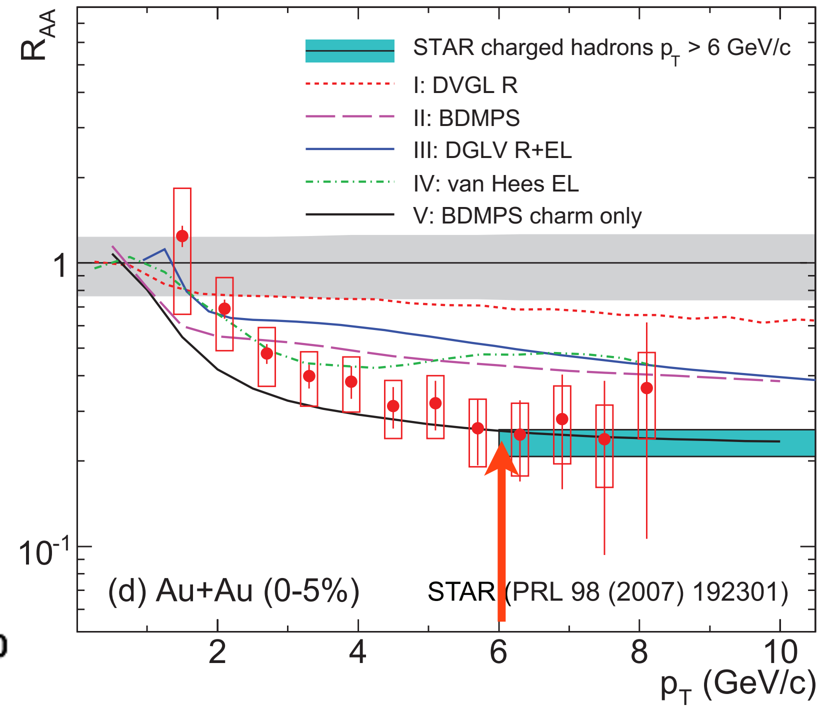
NLO (FONLL): c/b → e X



- Substantial suppression on same level to that of light mesons
- Describing the suppression is difficult for models
  - radiative energy loss | collisional E-loss | fragmentation and dissociation in medium
- What's about bottom?

It Gets Worse ... Bottom Not Gray Either





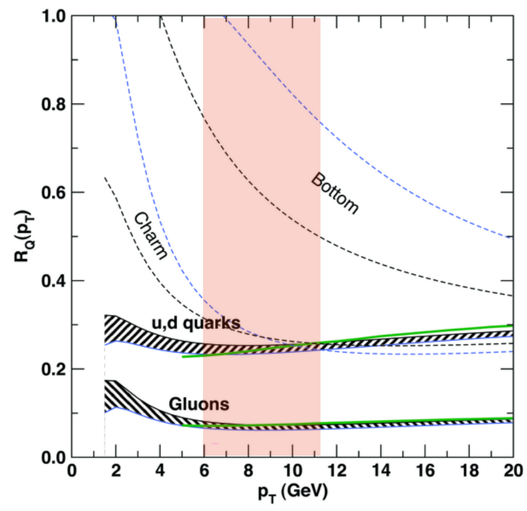
Correlation measurements in STAR and PHENIX constrain beauty contribution to non-photonic electrons in p+p collisions

⇒ ~55% at p_T^e = 6 GeV/c

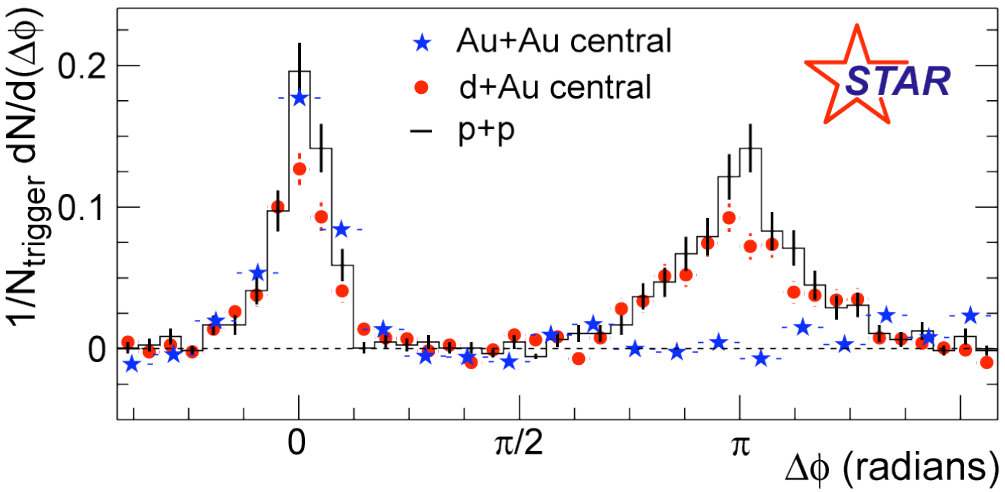
Beauty appears to be suppressed by more than predicted

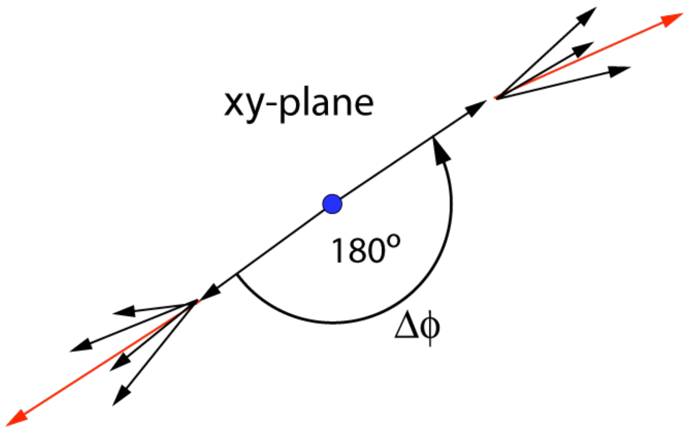
Do we really understand energy loss ?

Detector upgrades still sorely needed to measure b and c R_{AA} separately



Looking Closer: Dihadron Correlations

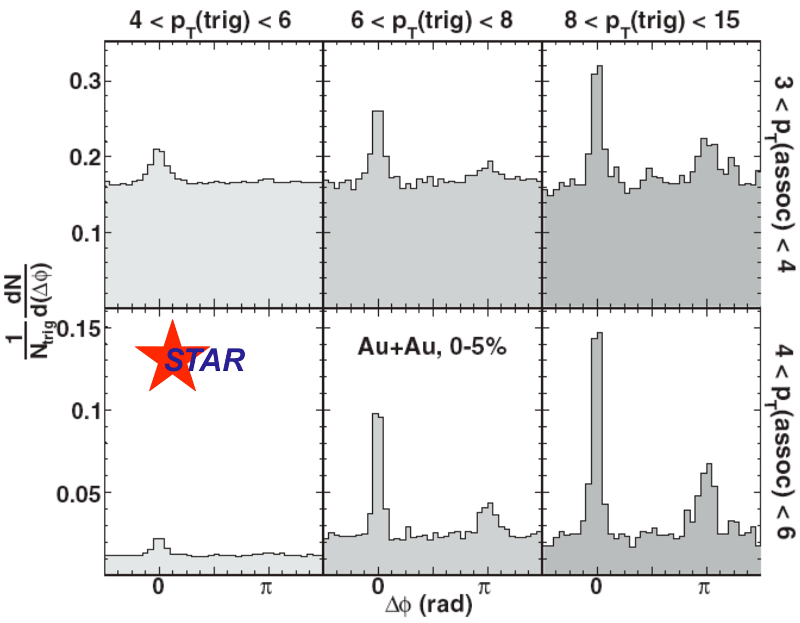




Per trigger correlated yield:

$$C(\Delta\phi) = \frac{1}{N_{trigger}} \frac{1}{\epsilon} \int d\Delta\eta N(\Delta\phi, \Delta\eta)$$

Looking Closer: Dihadron Correlations

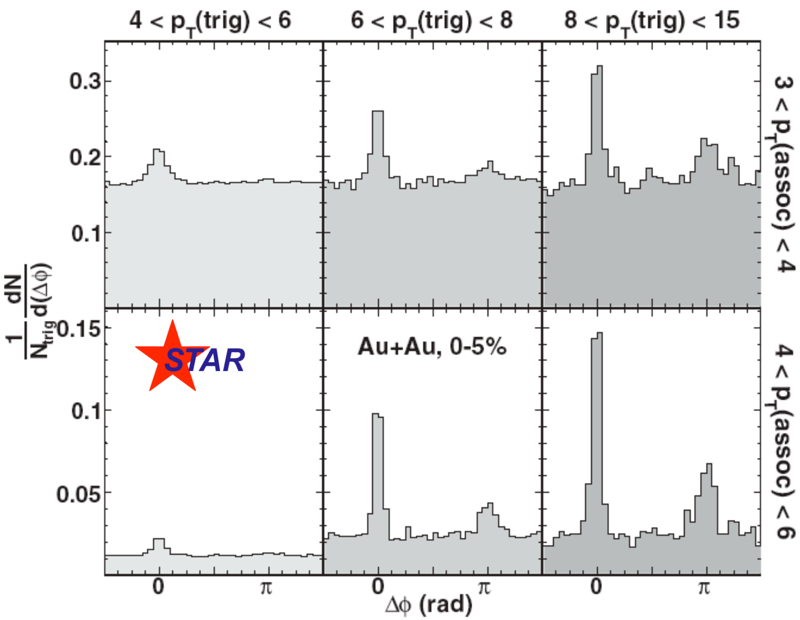


STAR (PRL 97, 162301):

At high p_T di-jets re-emerge in Au+Au

- punch through ?
- tangential jets ?

Looking Closer: Dihadron Correlations



STAR (PRL 97, 162301):

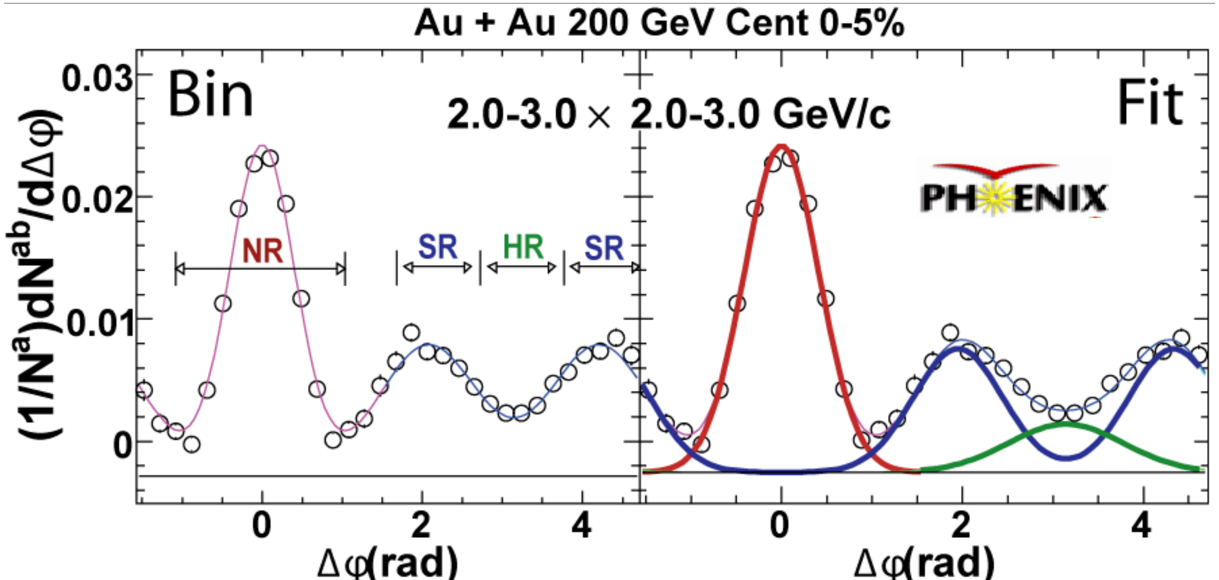
At high p_T di-jets re-emerge in Au+Au

- punch through ?
- tangential jets ?

PHENIX (PRC77, 011901):

Double hump structure on the away side for low p_T^{assoc}

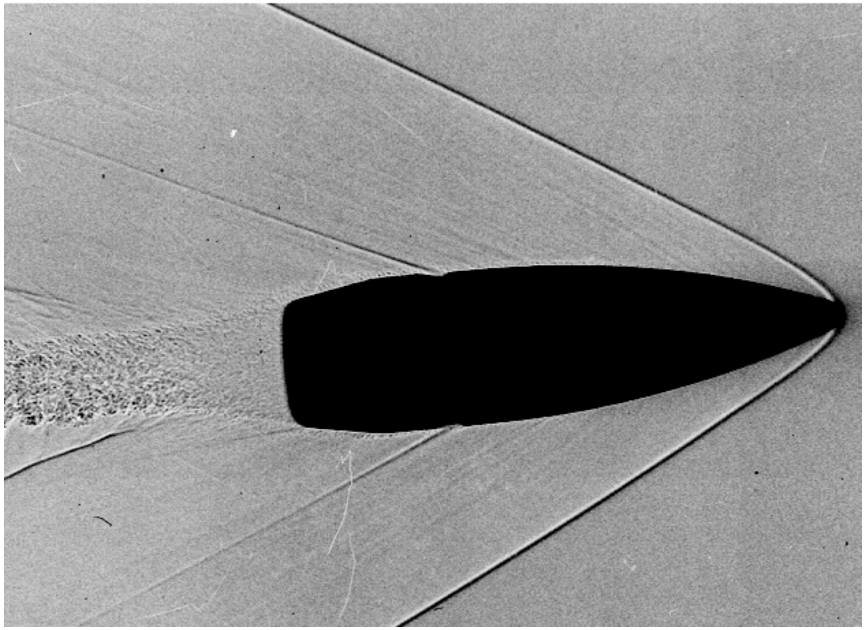
- medium response to jet
- conical emission ?
- mach cone ?
- deflected jets ?

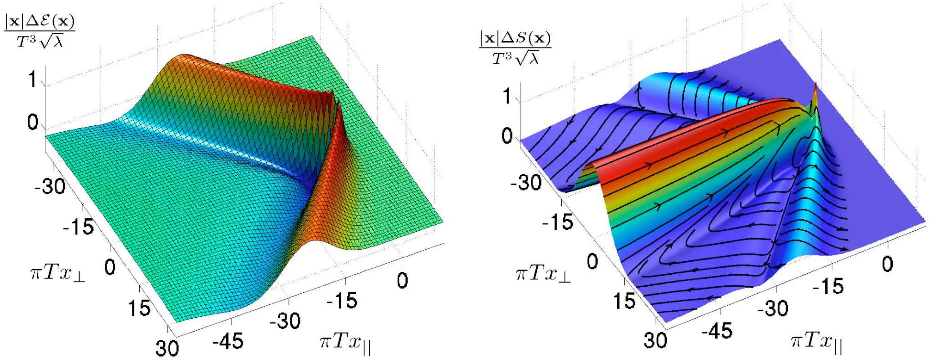


The (Mach) Cone

Possible Explanations:

- **Deflected jets**
- **Cherenkov cone**
  - I.M. Dremin (Nucl. Phys. A750: 233, 2006)
  - V. Koch et. al. (PRL 96, 172302, 2006)
- **Mach cone**
  - **Hydrodynamics**
    - H. Stöcker et al. (NPA750:121,2005)
    - J. Casalderra-Solana et. al. (Nucl.Phys.A774:577,2006)
    - T. Renk & J. Ruppert (PRC73:011901,(2006))
  - **Colored plasma**
    - J. Ruppert & B. Müller (PLB618:123,2005)
  - **AdS/CFT**
    - S. Gubser, S. Pufu, A. Yarom. (arXiv: 0706.4307v1, 2007)



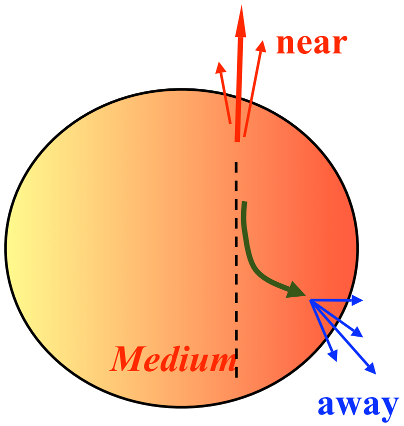


Chesler & Yaffe
arXiv:0712.0050

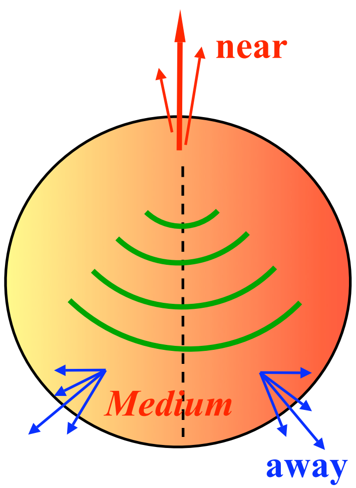
Is a Mach cone created when a supersonic parton propagates through the quark gluon plasma?

A Mach cone is formed when an object moves faster than the speed of sound in the medium.

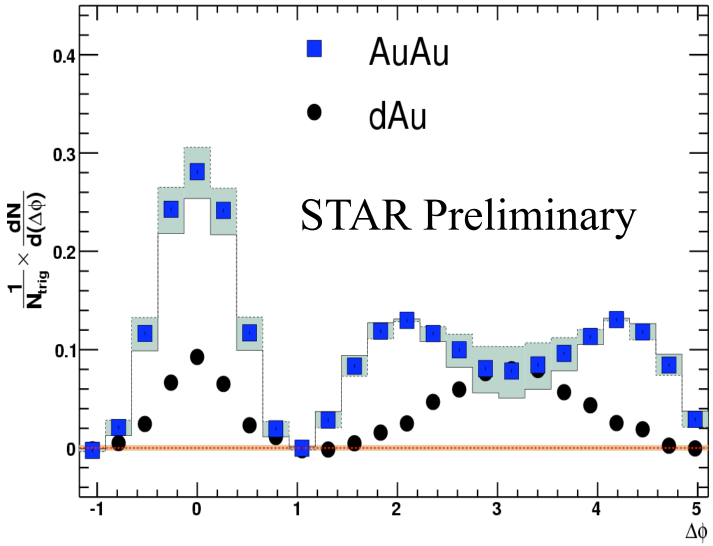
Deflected Jets or Conical Emission?



Deflected jets



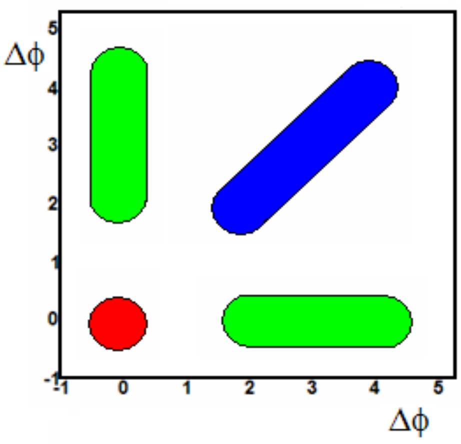
Conical Emission



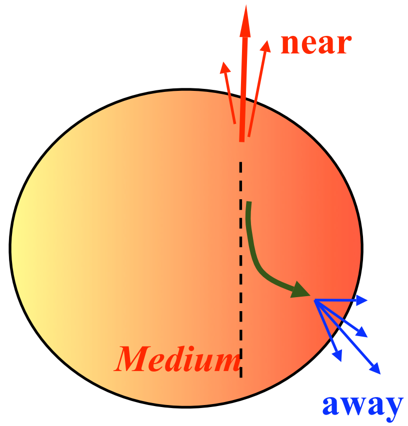
Conical emission or deflected jets?

Distinguish between models using 3-particle correlations

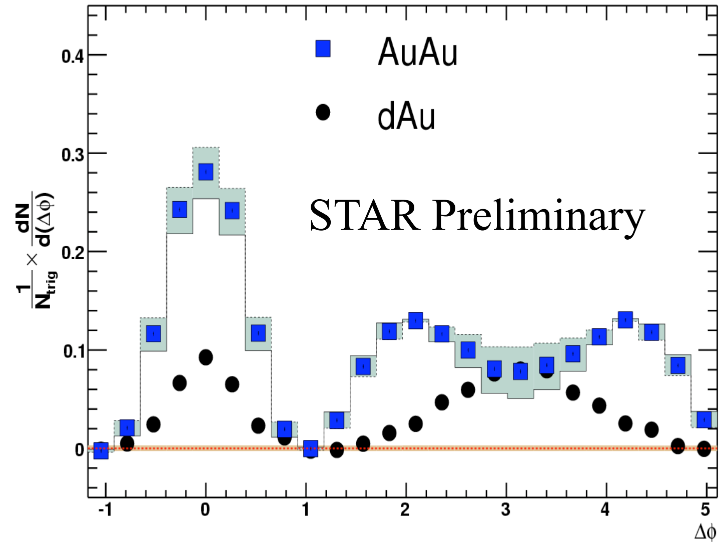
Deflected Jets or Conical Emission?



Deflected jets



Deflected jets



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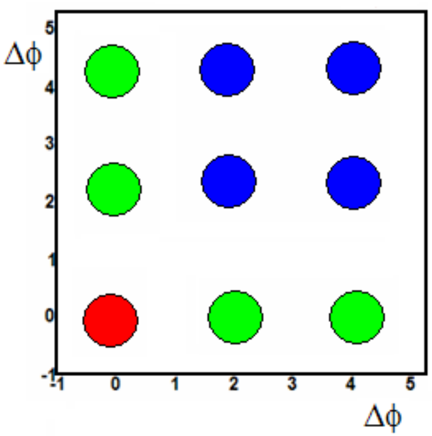
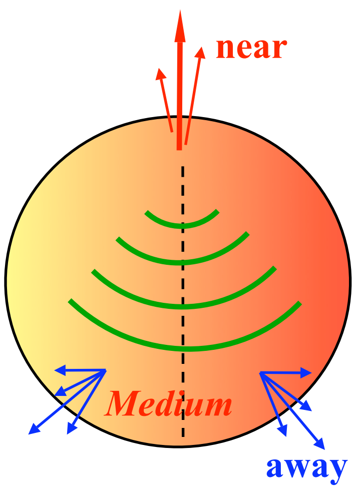


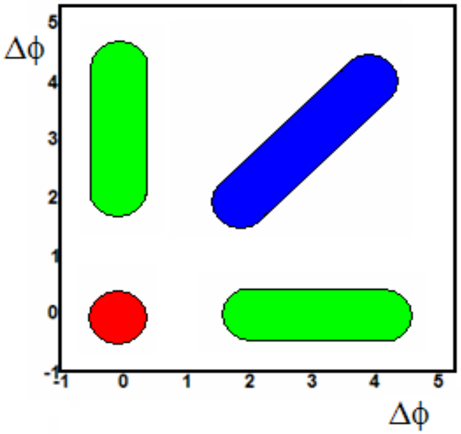
Conical Emission



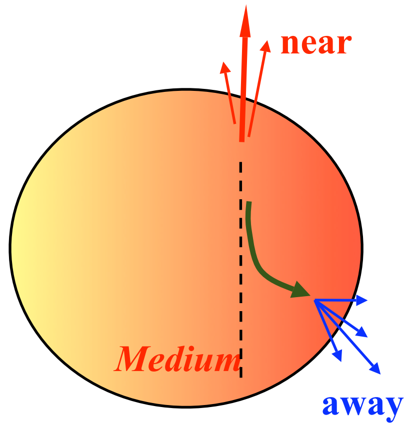
Conical Emission

Distinguish between models using 3-particle correlations

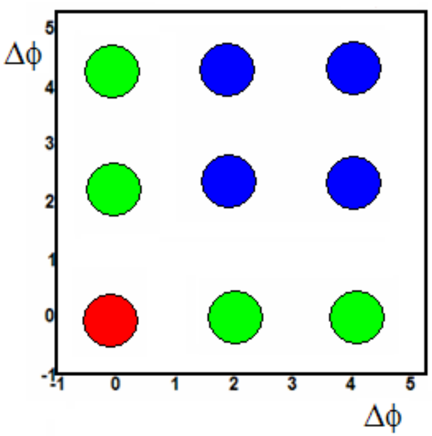
Deflected Jets or Conical Emission?



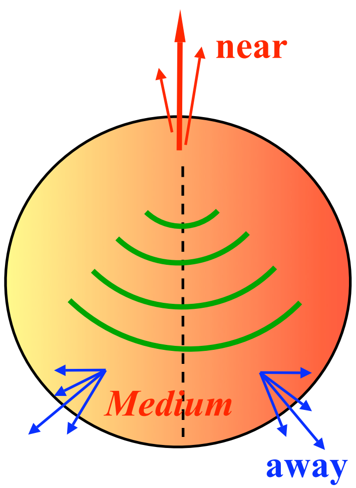
Deflected jets



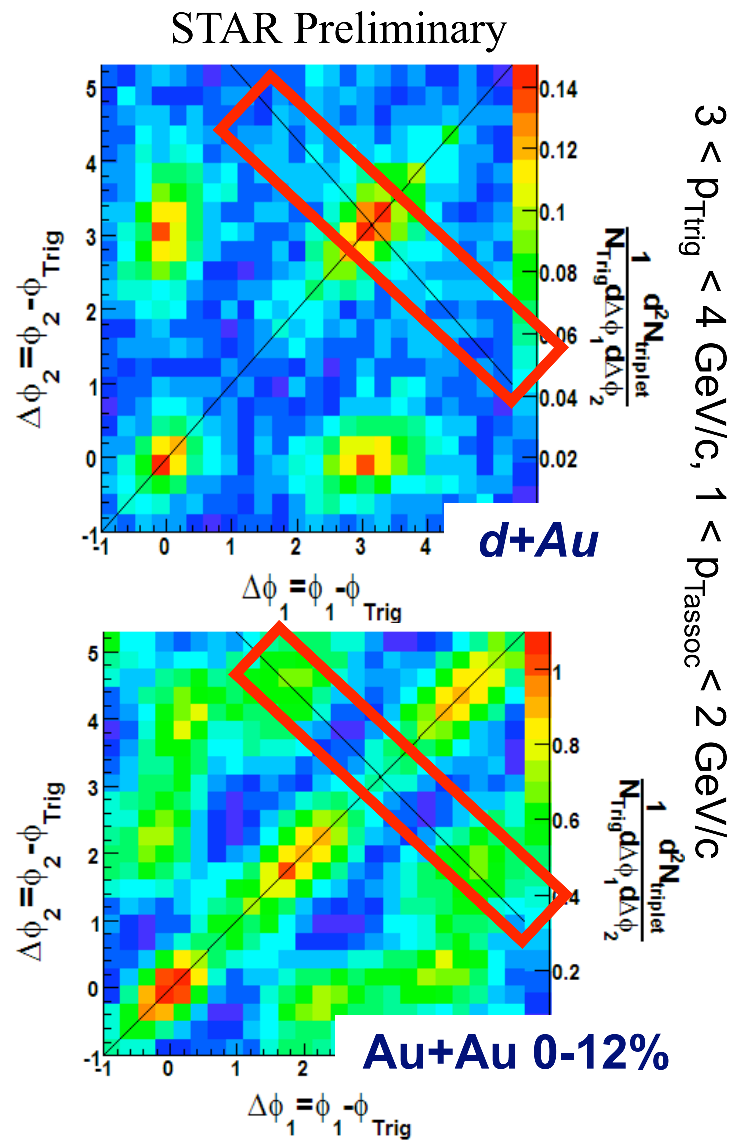
Deflected jets



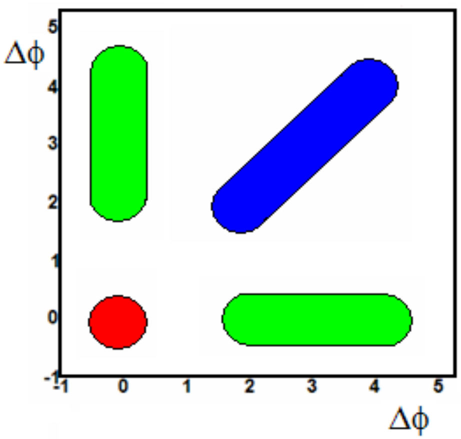
Conical Emission



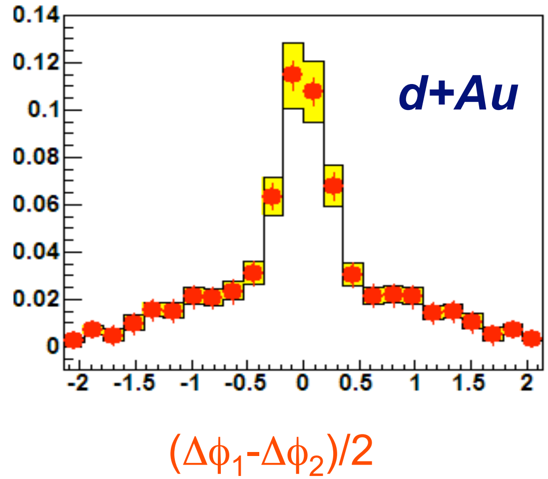
Conical Emission



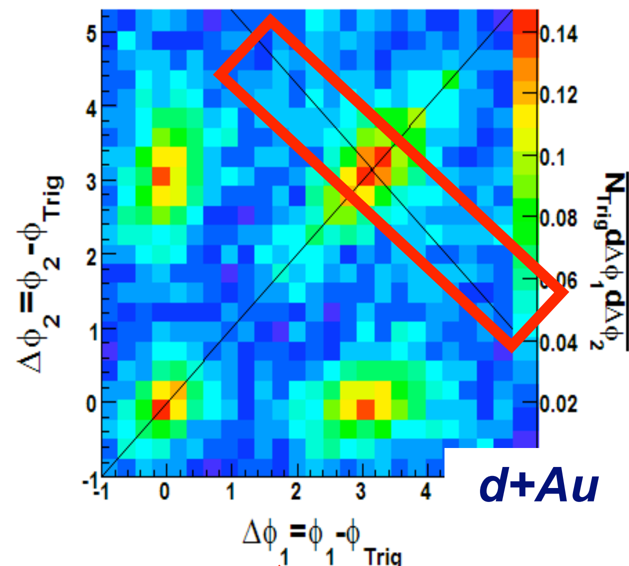
Deflected Jets or Conical Emission?

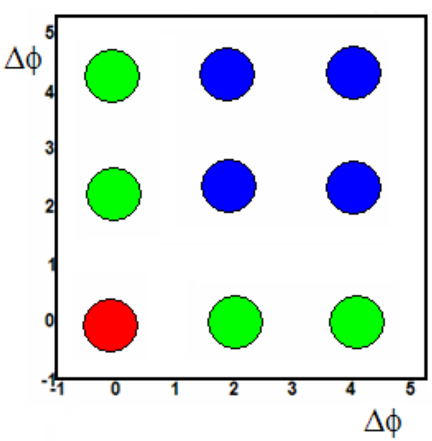


Deflected jets

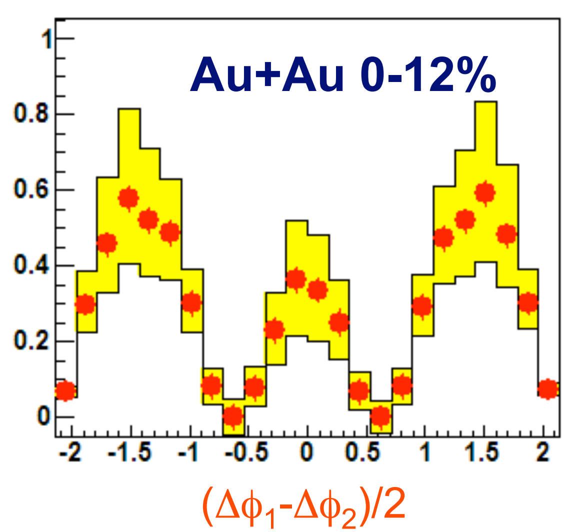


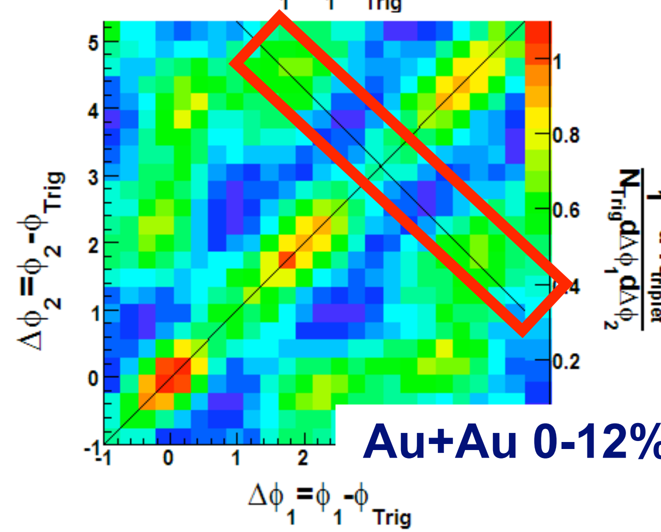
STAR Preliminary





Conical Emission





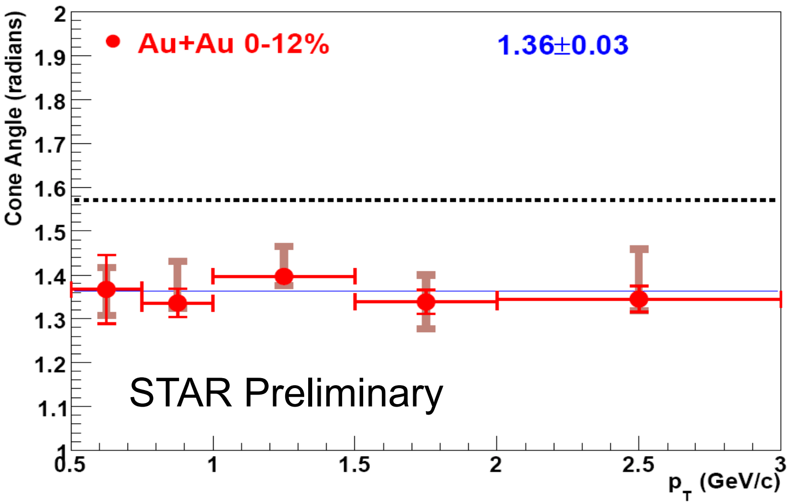
$3 < p_{Ttrig} < 4$ GeV/c, $1 < p_{Tassoc} < 2$ GeV/c

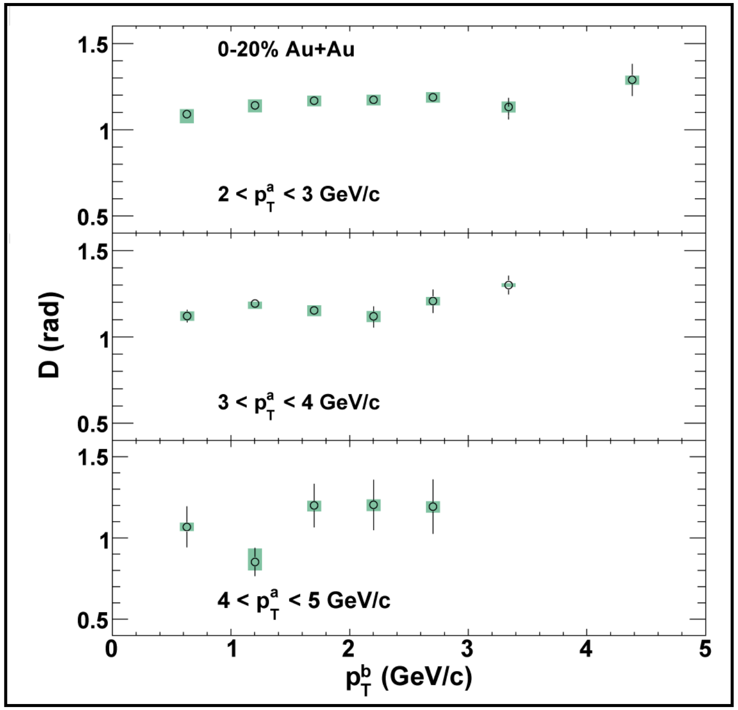
What if it's a Mach Cone ?

STAR and PHENIX find:

Cone angle does not change appreciably as a function of p_T of trigger or associated hadron ...

... or centrality, or angle wrt reaction plane





STAR from 3-particle correlations,
PHENIX from 2-particle correlations

Naive calculation of time averaged velocity of sound in medium:

$v_s = \cos(1.2 \ldots 1.4) \Rightarrow v_s = 0.2 \ldots 0.4c$ (QCD Lattice ~ 0.55c)

Proper treatment requires accounting for expansion & flow

(e.g. see Renk & Rupper PRC73, 01190; PRC 76, 014908)

RHIC "Summary"

Paradigm Shift

- We see the, *hottest*, *densest*, matter, ever studied in the laboratory that *flows* as a (nearly) perfect fluid with systematic patterns consistent with *quark degrees of freedom* and a *viscosity to entropy* density ratio lower than any other known fluid
- It appears to be a **s**trongly couple plasma ⇒ sQGP
- not the asymptotically plasma of "free" quarks and gluons as expected

We are past the discovery stage ⇒ towards the quantitative

- Recent examples: η/s, transport coefficients
- much remains to be done: EOS !
- New phenomena (conical flow, ridge, high-p_T, direct photon suppression ...) challenge our understanding

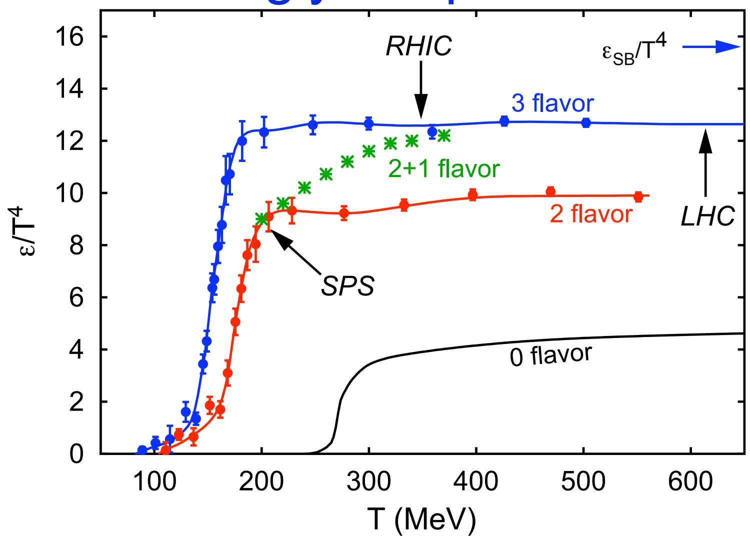
Next Steps:

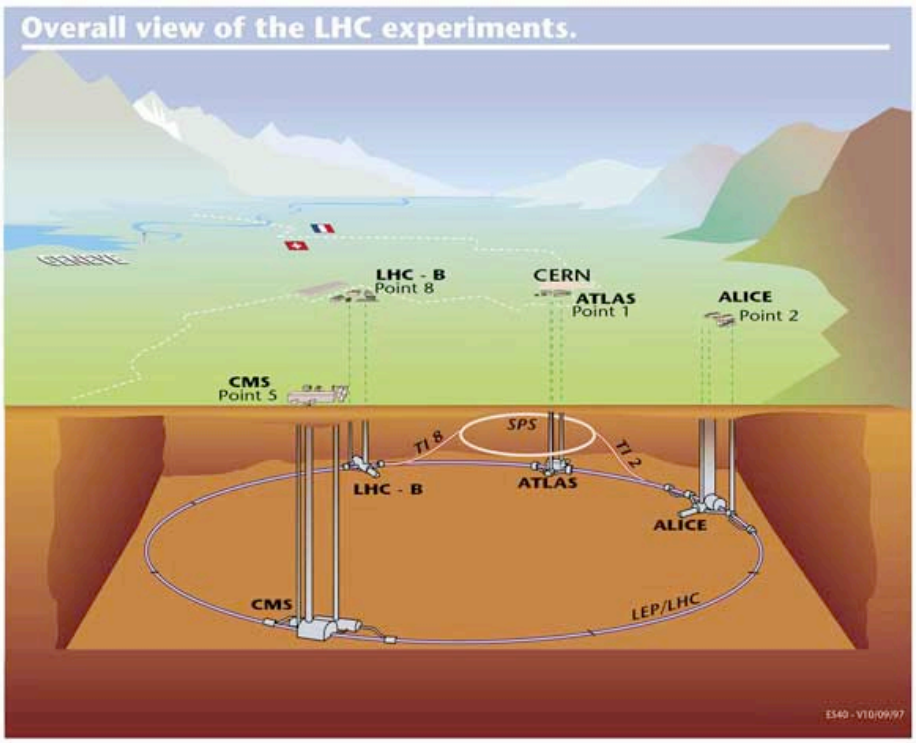
- Ongoing upgrades to STAR and PHENIX
  - Vertex detectors, increased coverage, improved triggering capabilities
- Electron Beam Ion Source (EBIS) to extend ranges of species (U+U)
- RHIC-II increase luminosity by factor 5 using stochastic cooling

The Next Energy Frontier: LHC

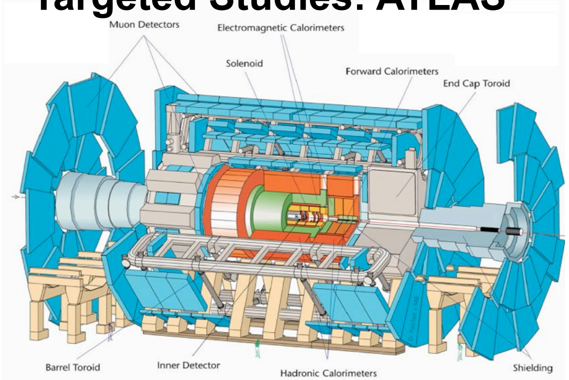
A unique opportunity to investigate "QGP" at unparalleled high √s

Will this too create a strongly-coupled fluid?

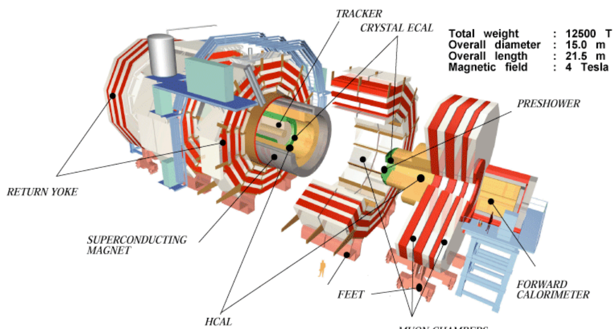




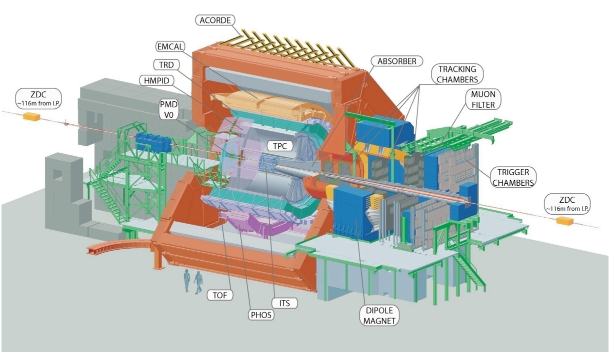
Targeted Studies: ATLAS



Targeted Studies: CMS



Dedicated Experiment: ALICE

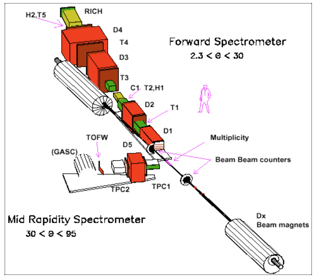


Additional Material

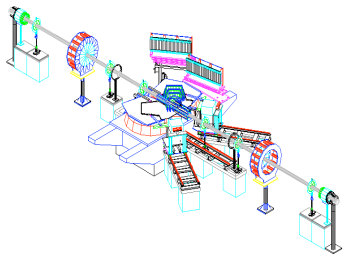
Energy Frontier History

	Bevalac-LBL and SIS-GSI fixed target max. **2.2 GeV**		Nuclear Fragmentation Resonance Production Strangeness Near Threshold
1992 Au-Au	AGS-BNL fixed target max. **4.8 GeV**	E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 …	Resonances Dominate Large Net Baryon Density Strangeness Important
1994 Pb-Pb	SPS-CERN fixed target max. **17.3 GeV**	NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, WA80/98, WA97, …	Charm Production Starts
	TEVATRON-FNAL (fixed target p-A) max. **38.7 GeV**		
2000 Au-Au	RHIC-BNL collider max. **200.0 GeV**	BRAHMS, PHENIX, PHOBOS, STAR	Low Net Baryon Density Hard Parton Scattering
2009? Pb-Pb	LHC-CERN collider max. **2760.0 GeV**	ALICE, ATLAS, CMS	Beauty Production

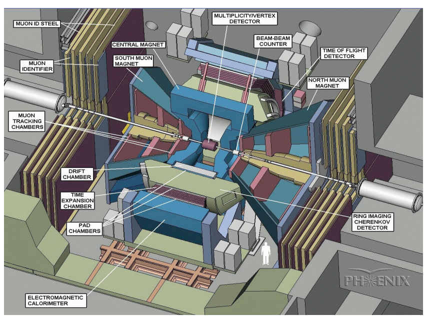
RHIC Experiments In a Nutshell



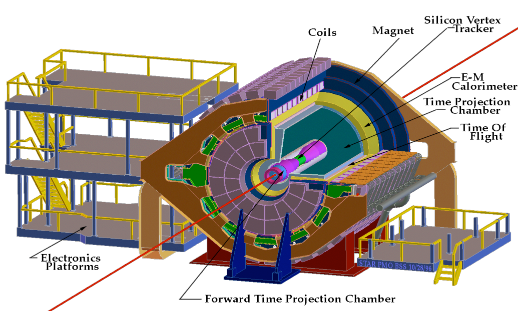
small experiment - 2 spectrometer arms
small acceptance $\Delta\phi$, $\Delta\eta$
movable arms $\Rightarrow$ large $\Delta\eta$ coverage



small experiment - “tabletop”
(i) 4π acceptance $\Delta\phi$, $\Delta\eta$, no p_T info, no PID
(ii) small acceptance $\Rightarrow$ very low - low p_T



large experiment - 2 central arms +
2 muon arms
central arms: $\Delta\phi = \pi$, $\Delta\eta = \pm\, 0.35$
leptons , photons, hadrons



large experiment
large acceptance: $\Delta\phi = 2\pi$, $\Delta\eta = \pm\, 1$
forward detectors
hadrons, jets, leptons, photons

PHENIX Present + Upgrades

<u>Charged Particle Tracking:</u>

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector
- Si Vertex Tracking Detector- Barrel
- Si Vertex Endcap (mini-strips)

<u>Particle ID:</u>

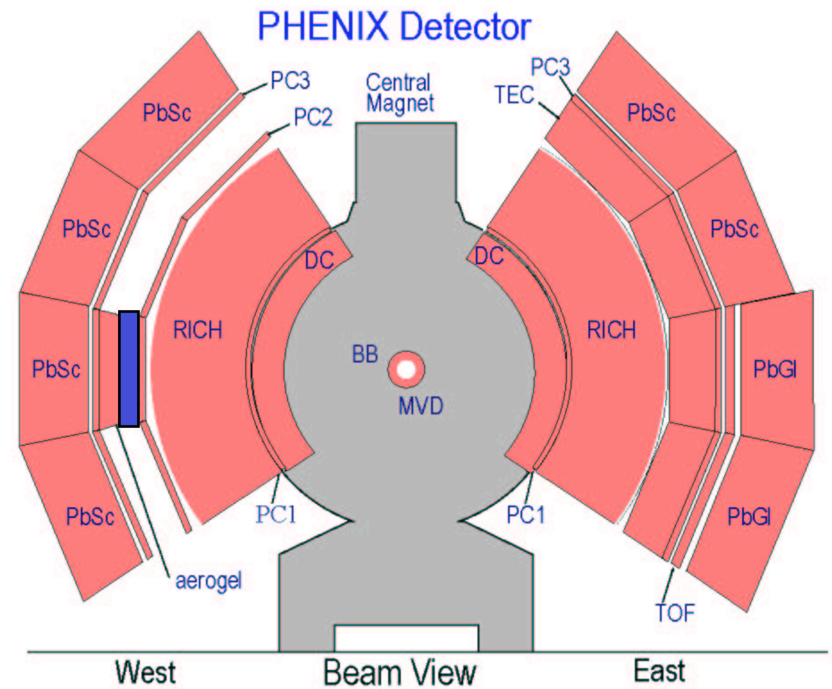
- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Gap Resistive Plate Chamber ToF
- Hadron Blind Detector

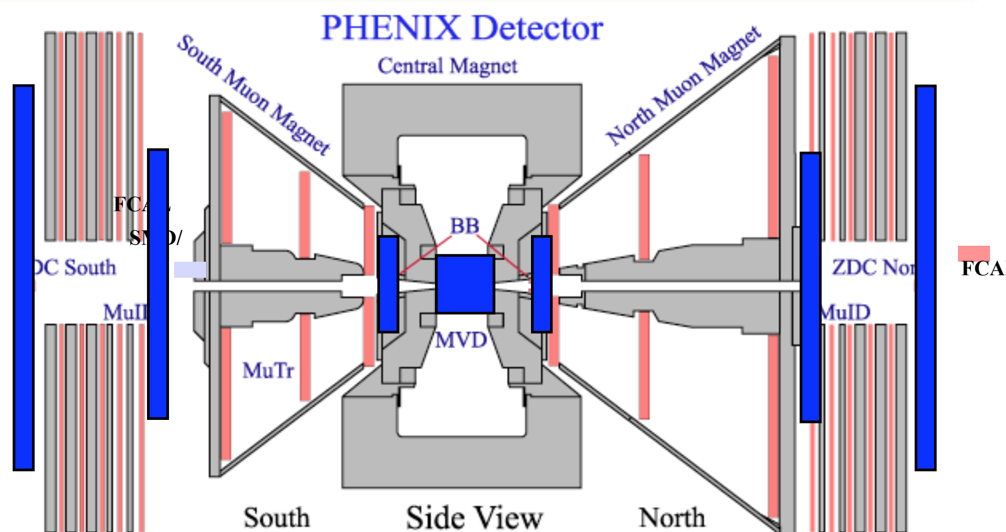
<u>Calorimetry:</u>

- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter
- Muon Piston Calorimeter

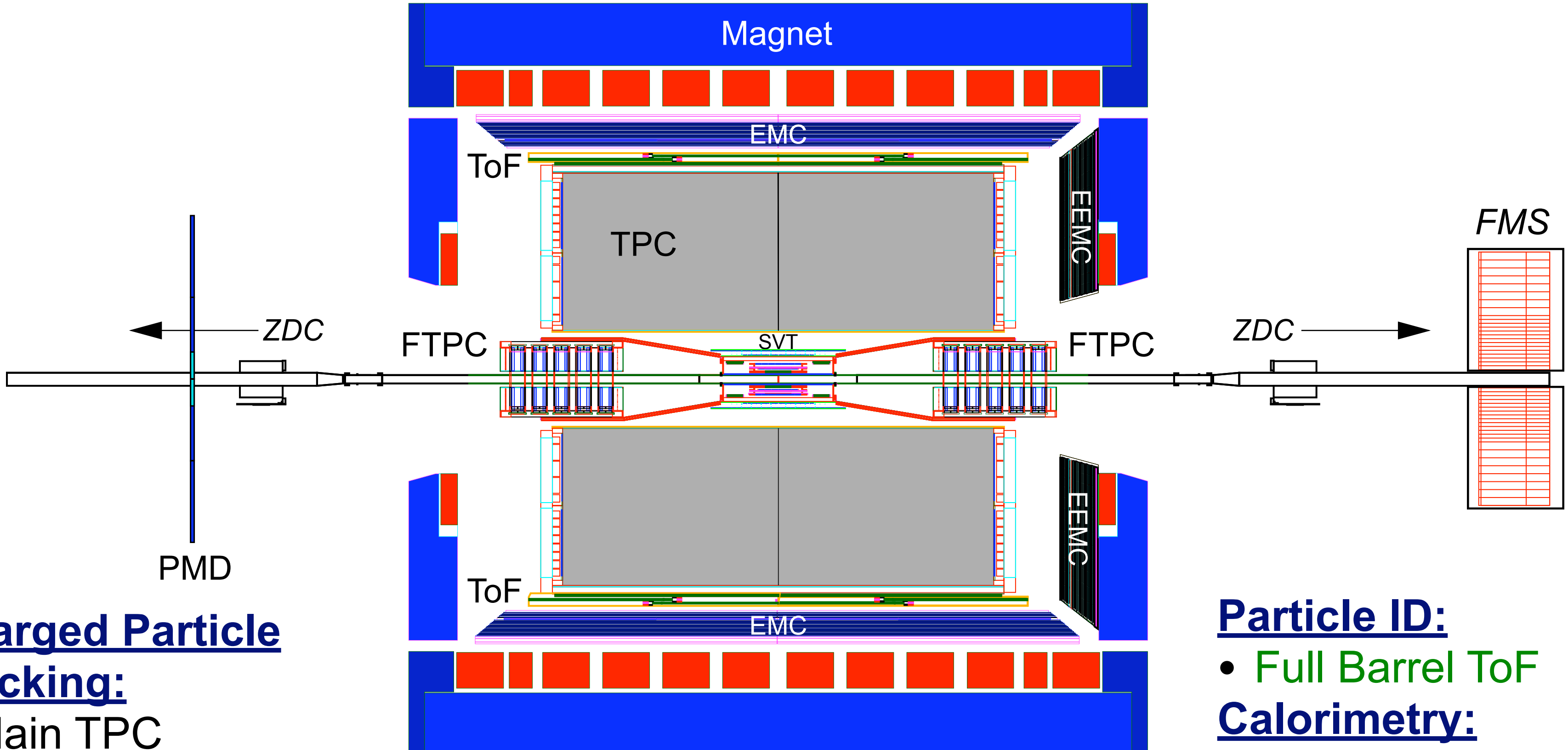
<u>Event Characterization:</u>

- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter
- Reaction Plane Detector





STAR Present + Upgrades



Charged Particle Tracking:

- Main TPC
- Forward TPC (FTPC)
- SSD + Intermediate Tracker + Active Pixel Detector = HFT(was SSD+SVT)
- Forward GEM Tracker

Event Characterization & Trigger:

- Beam-Beam Counter (BBC)
- Zero Degree Calorimeter (ZDC)
- Forward Pion Detectors (FPD)

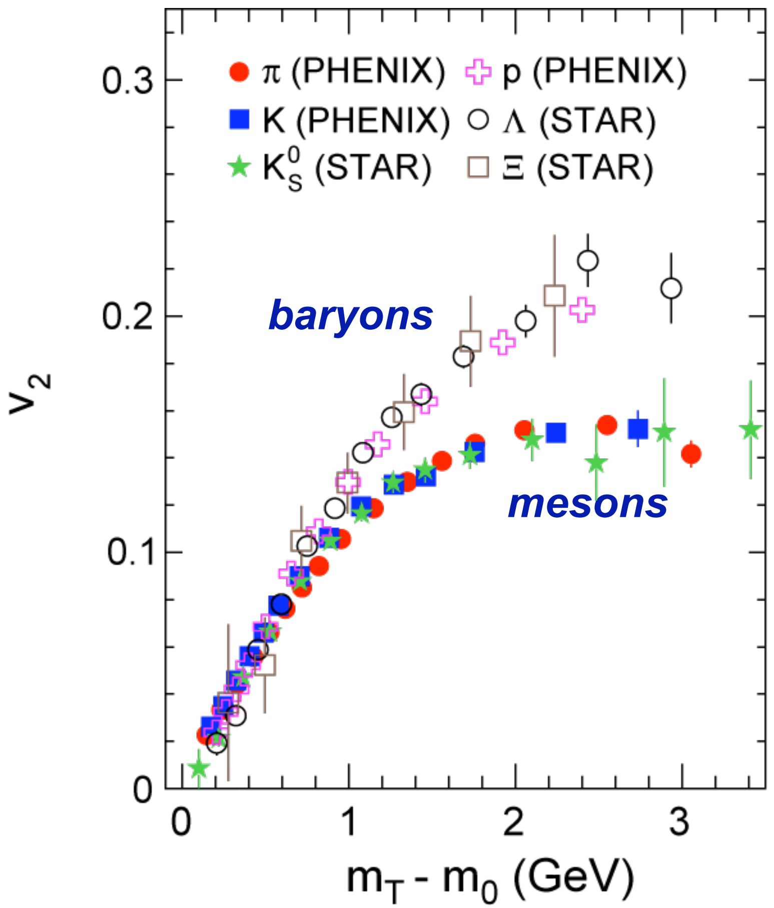
Particle ID:

- Full Barrel ToF

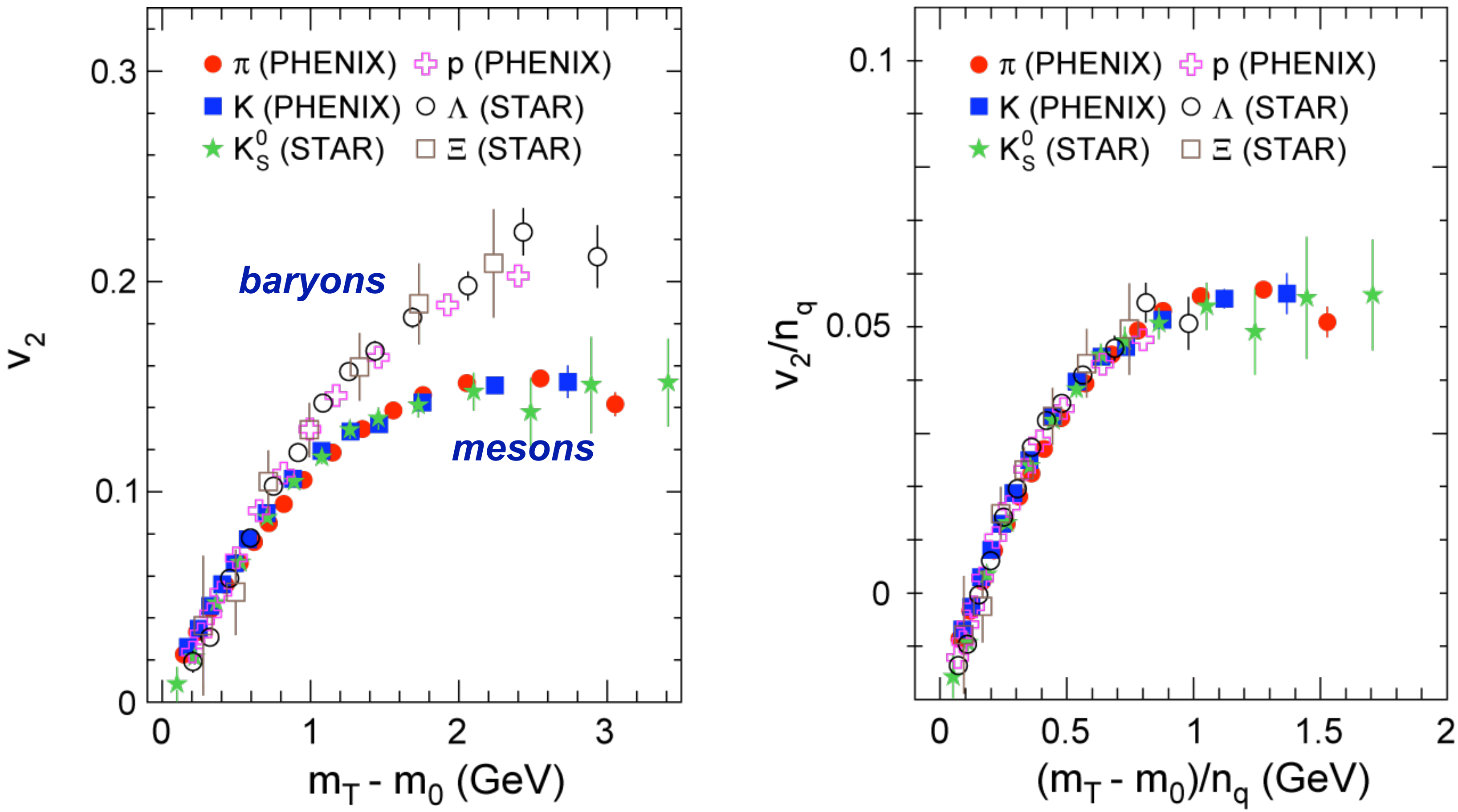
Calorimetry:

- Photon Multiplicity Detector (PMD)
- Barrel EMC
- Endcap EMC
- Forward Meson Spectrometer

The Constituents "Flow"



The Constituents "Flow"

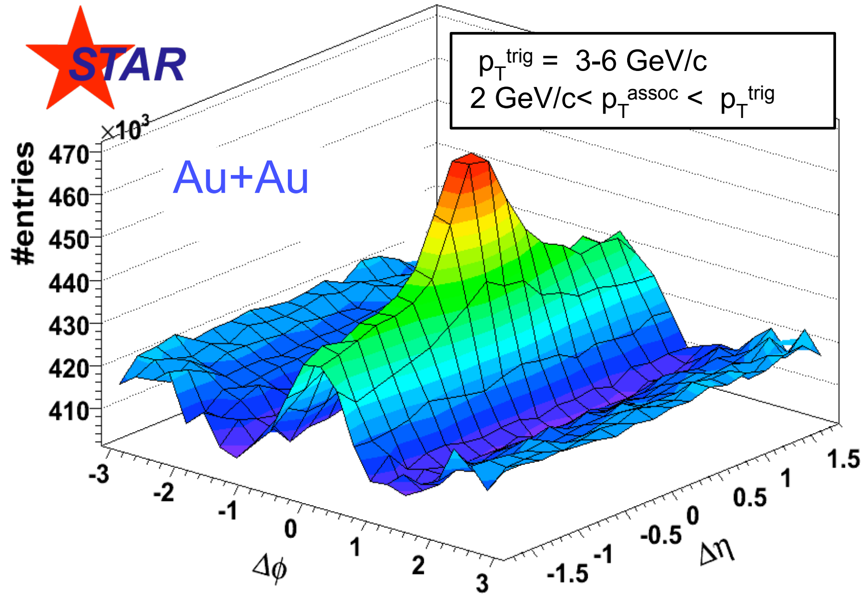


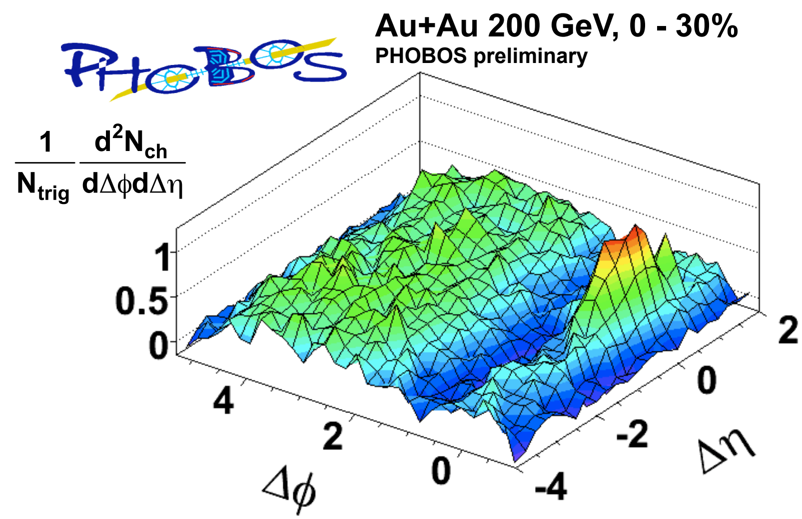
- Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

⇒ liquid of constituents (partons)

The Near-Side Response: The Ridge

Long range Δη correlations on the near-side

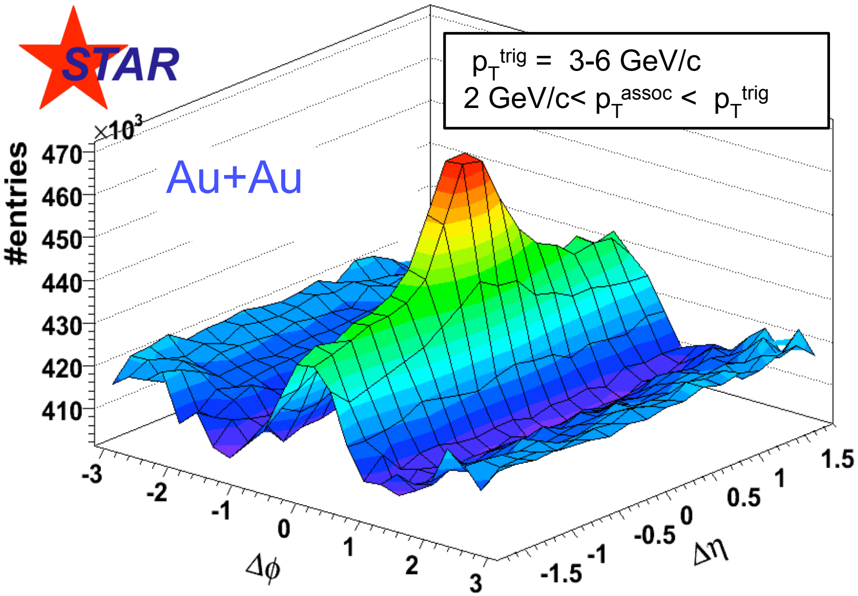


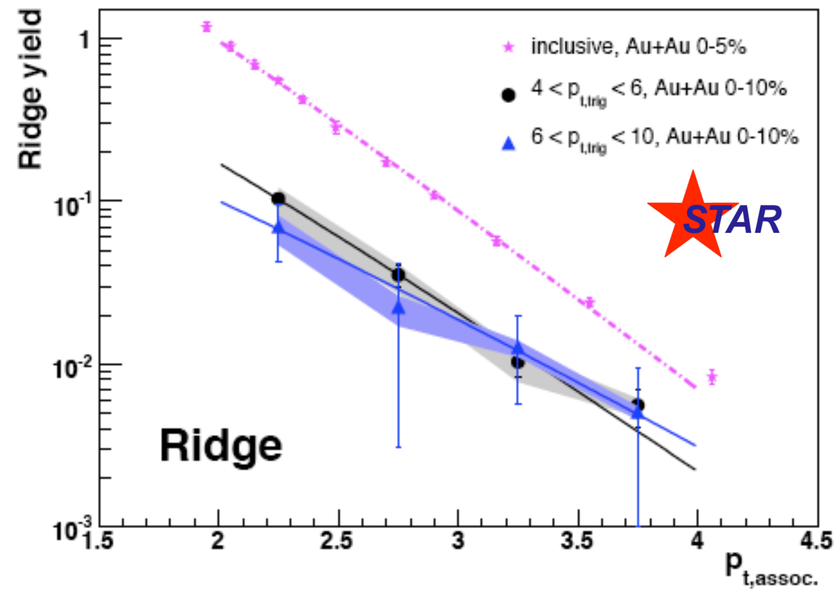


- medium response to jet ?
- the ridge extends to very high rapidity

The Near-Side Response: The Ridge

Long range Δη correlations on the near-side

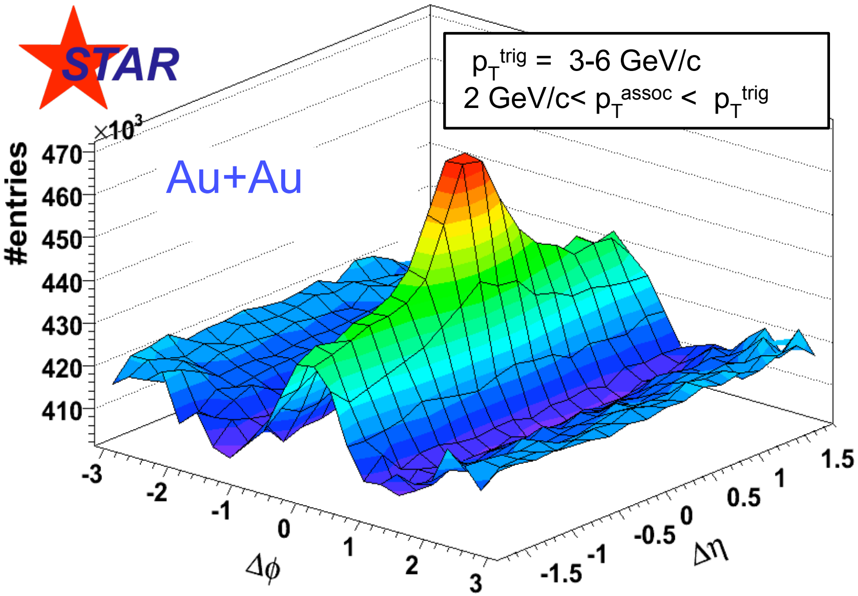


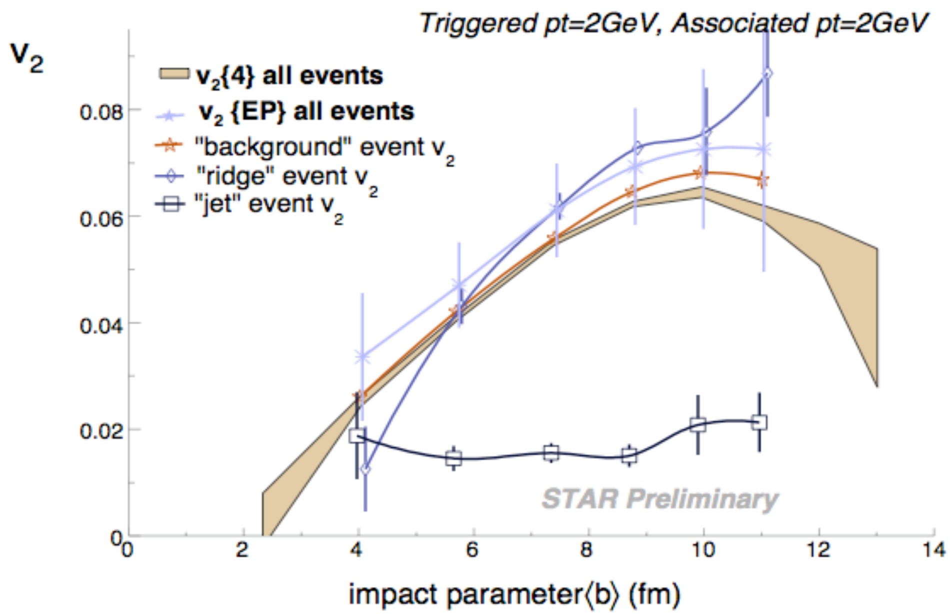


- medium response to jet ?
- the ridge extends to very high rapidity
- the p_T distribution is close to that of the underlying medium

The Near-Side Response: The Ridge

Long range $\Delta\eta$ correlations on the near-side





- medium response to jet ?
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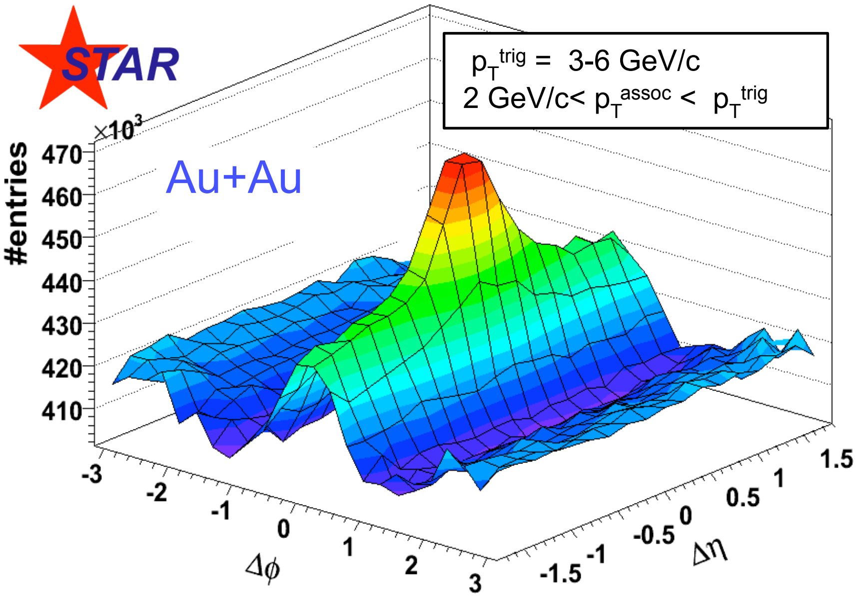
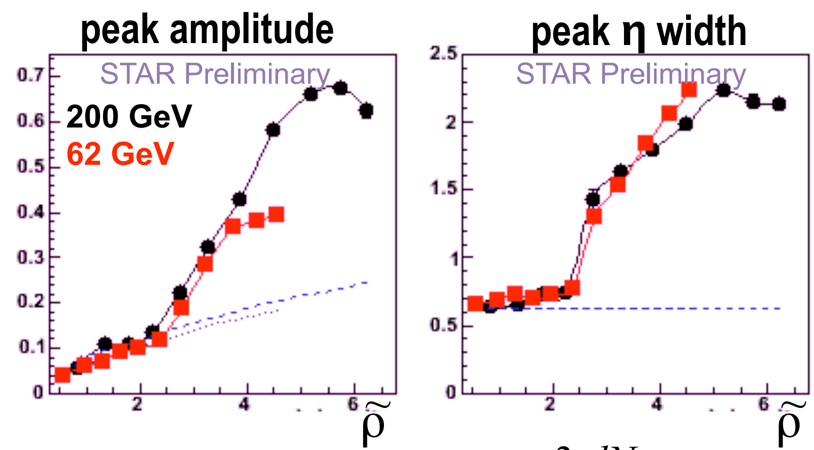
- v_2 of the ridge is close to that of the underlying medium

The Near-Side Response: The Ridge

Long range Δη correlations on the near-side

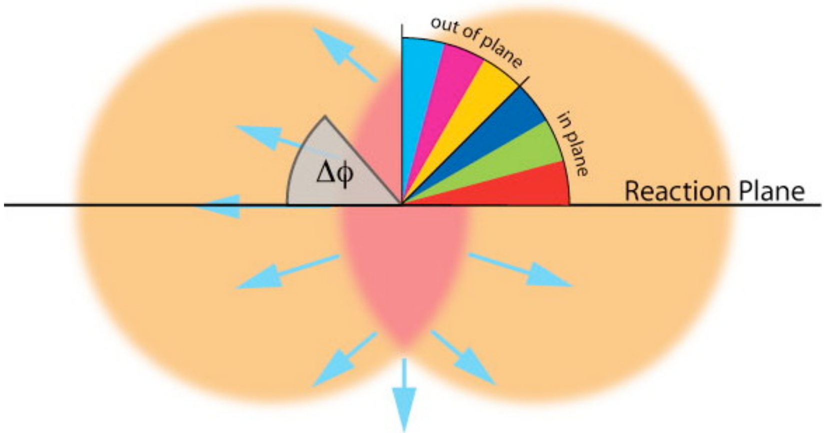




Transverse particle density $\tilde{\rho} = \frac{3}{2}\frac{dN_{ch}}{d\eta}/S$

- medium response to jet ?
- the ridge extends to very high rapidity
- the p_T distribution is close to that of the underlying medium
- v_2 of the ridge is close to that of the underlying medium
- At low p_T (untriggered), extension in $\Delta\eta$ turns on abruptly

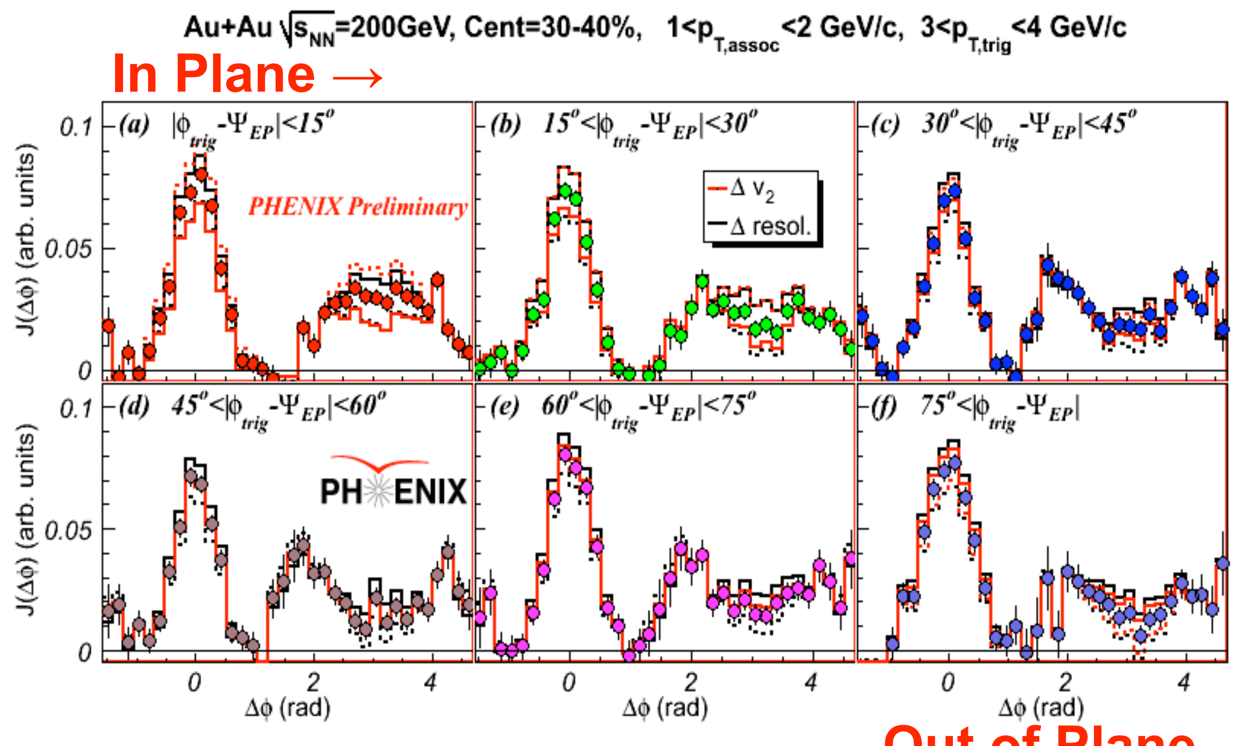
Dihadrons: L dependence of E-loss



- Study Reaction Plane dependence to gain more insights into the away-side modification and near-side ridge
- Non-central collision (20-60%):
- Select trigger particle direction relative to reaction plane.

Away side shape changes w/ angle of trigger with respect to reaction plane

The position of the cone (?) does not change with angle of trigger hadron *w.r.t* reaction plane.



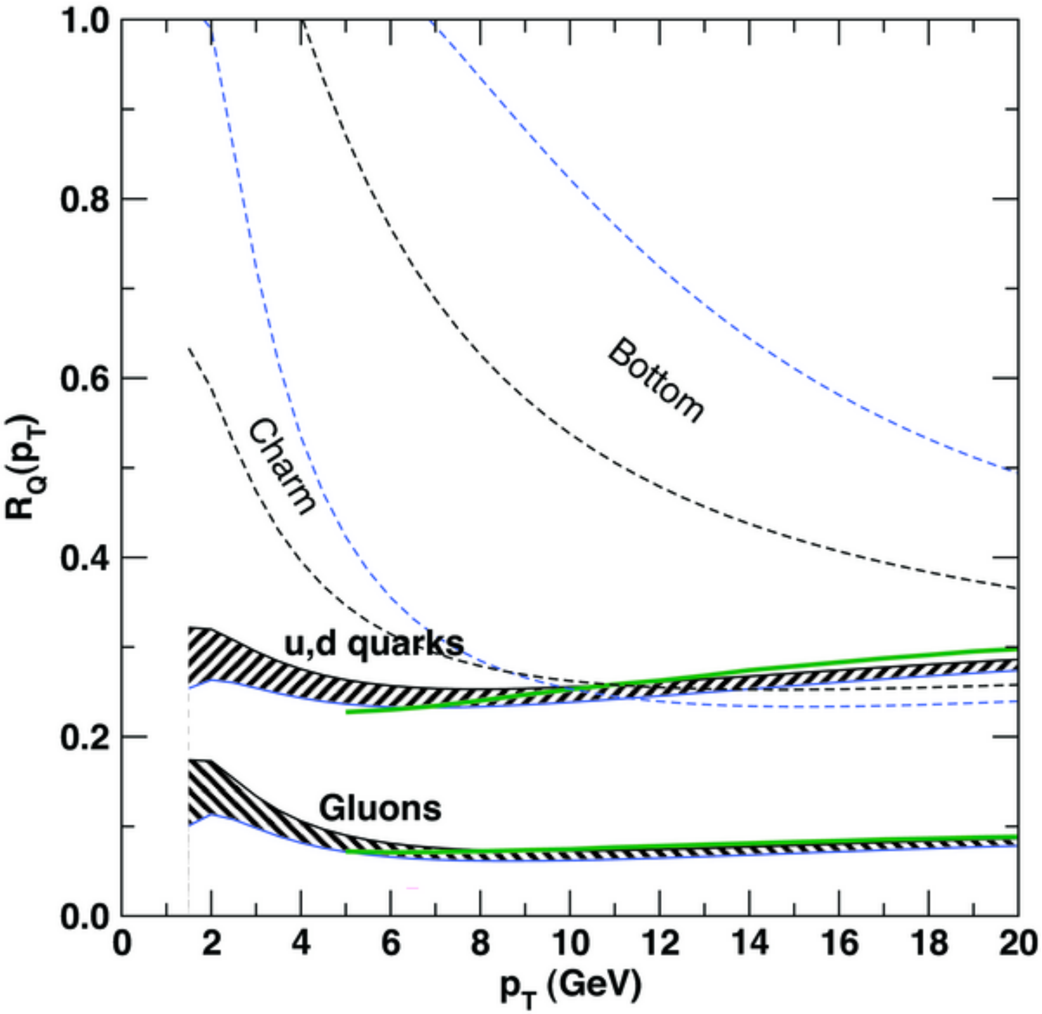
Calibrated Interaction? Gray Probes

- Problem: interaction with the medium so strong that information lost: "Black"
- Significant differences between predicted R_{AA}, depending on the probe

Experimental possibility:

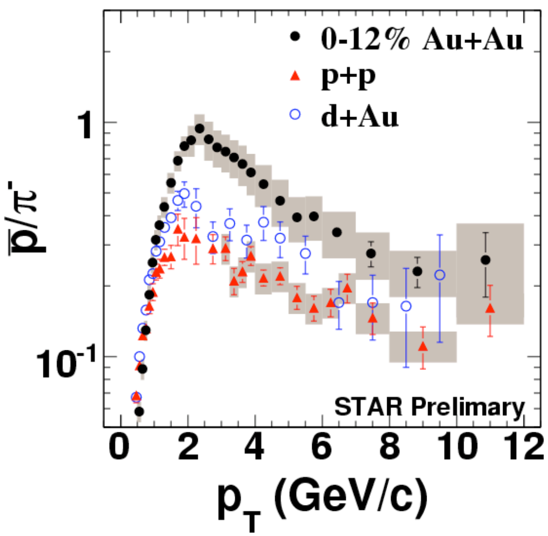
- recover sensitivity to the properties of the medium by varying the probe
- studying 2 or even 3 high-p_T particle correlations

Wicks et al, Nucl. Phys. A784 (2007) 426

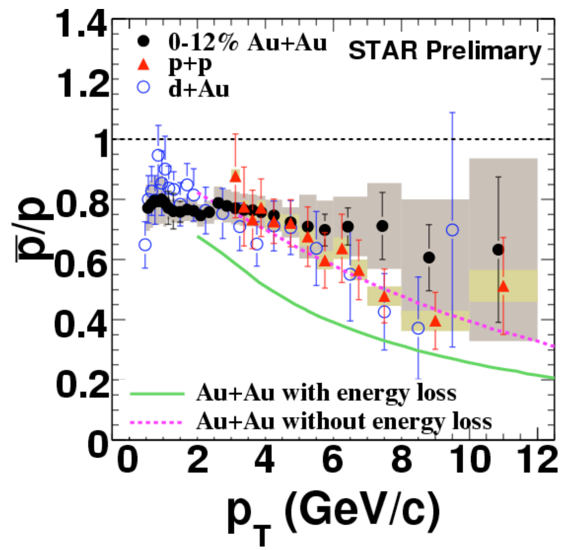


Color Factors: No shade of gray

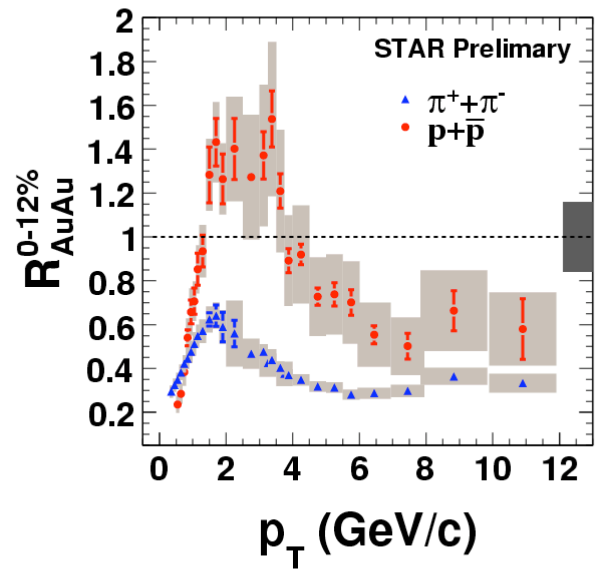
Anti-Baryon/meson



Anti-particle/particle

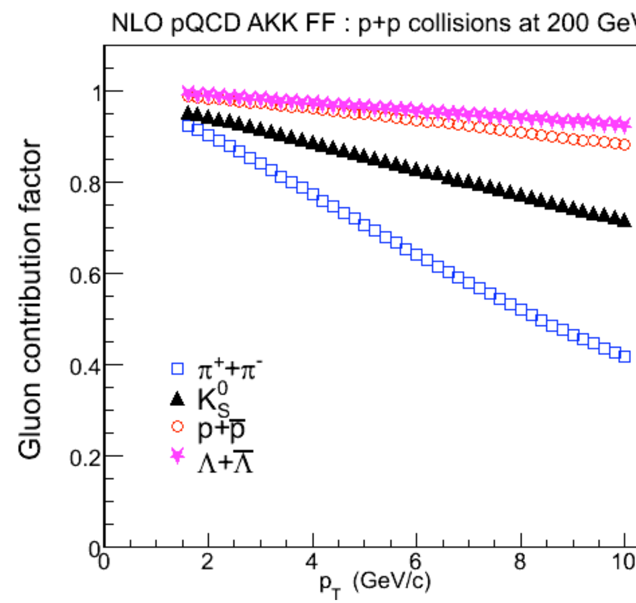


Baryon & meson NMF



$$\langle \Delta E \rangle \propto \alpha_s C \langle \hat{q} \rangle L^2$$

The Color Factor Effect $\dfrac{\Delta E_g}{\Delta E_q} = 9/4$

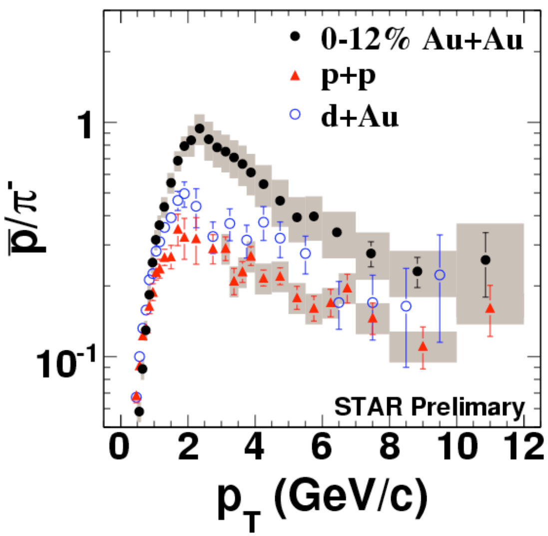


Higher precision p+p reference:

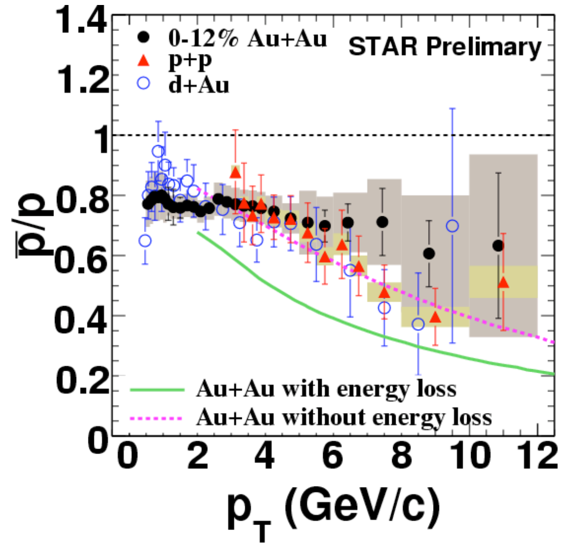
- Higher suppression of gluons than quarks should lead to higher suppression of protons and especially antiprotons
- **Still** no sign of this, in fact appears to go the wrong way

Color Factors: No shade of gray

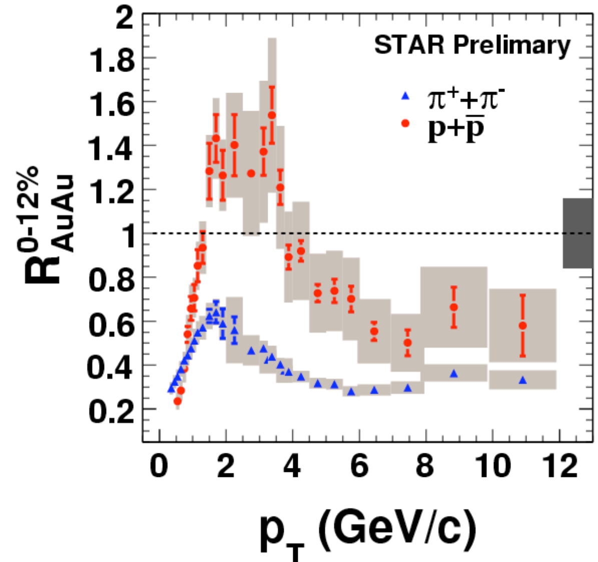
Anti-Baryon/meson



Anti-particle/particle

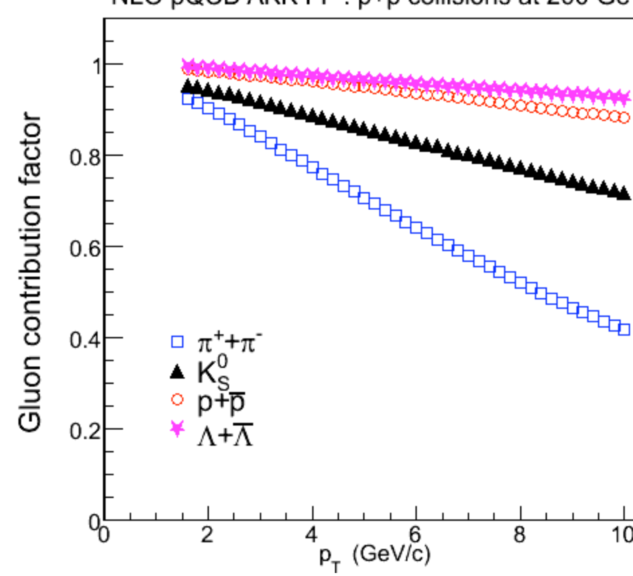


Baryon & meson NMF



STAR : PLB 637 (2006) 161, PRL 97 (2006) 152301, PLB 655 (2007) 104

NLO pQCD AKK FF : p+p collisions at 200 GeV



$$\langle \Delta E \rangle \propto \alpha_s C \langle \hat{q} \rangle L^2$$

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- Higher suppression of gluons than quarks should lead to higher suppression of protons and especially antiprotons
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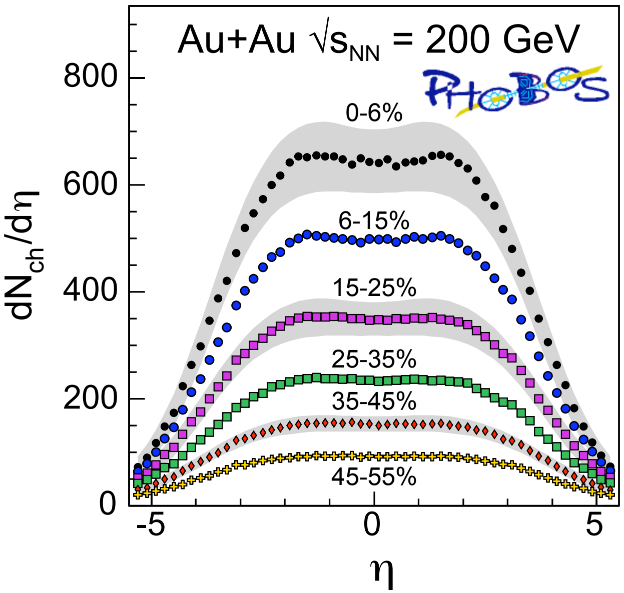
Initial Conditions at RHIC are Right



Charged Particle Multipicity:

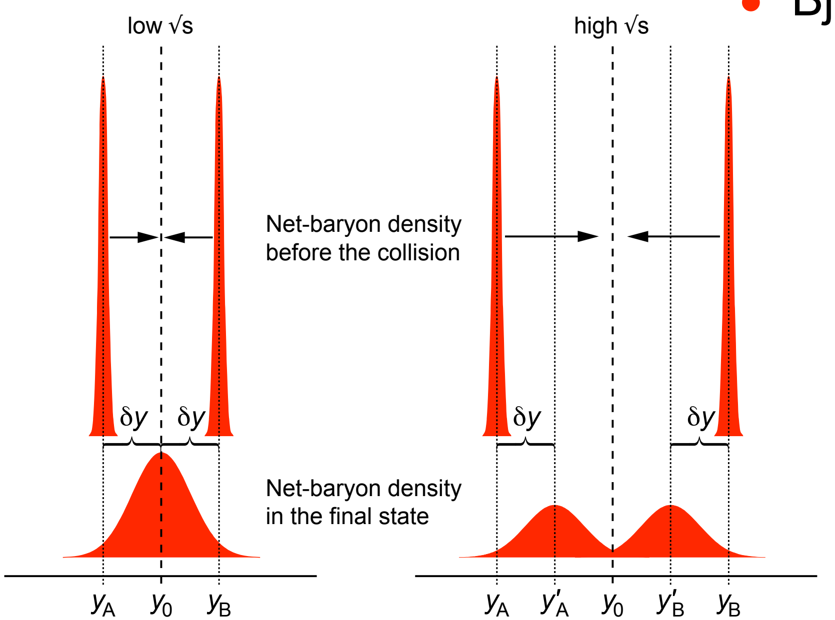
- 200 GeV Au+Au: N_{ch}~4800
- $dN_{ch}/dy|_{y=0}$ / N_{part} ~ 4 (~2.5 in p+p)

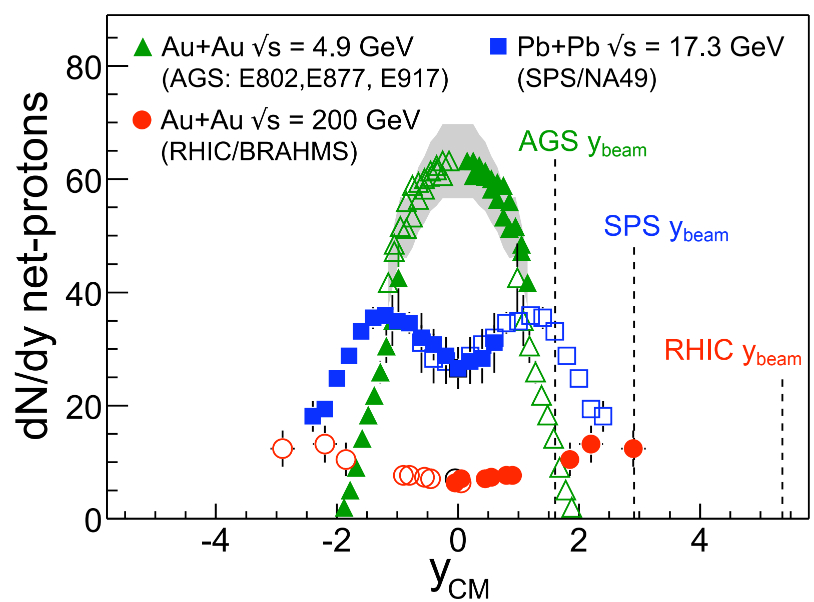
Stopping:

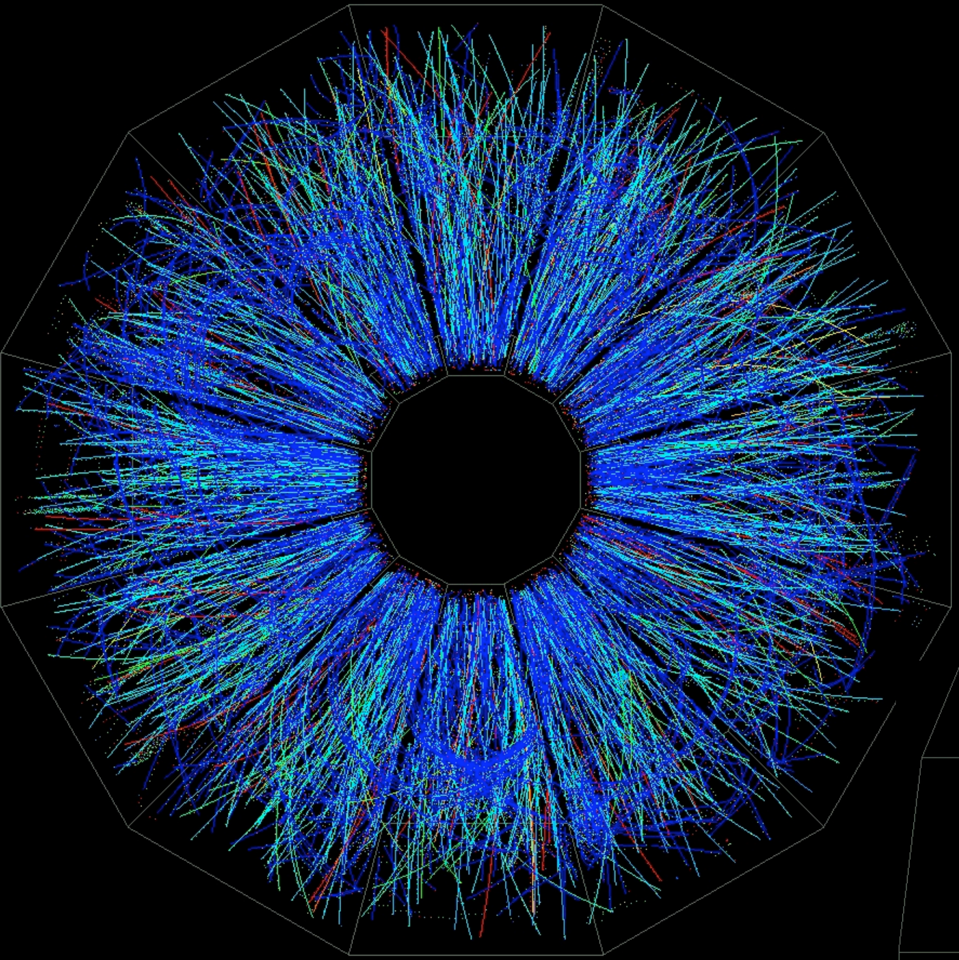
- Analysis of net-proton (~ net-baryon) spectra (p-$\bar{p}$)
  ⇒ Energy Loss of colliding nucleons
- Out of a maximum energy of 39.4 TeV in Au-Au reactions, 26 TeV is deposited in the "fireball"

E_T Spectra:

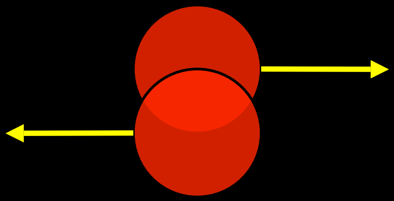
- Bjorken Energy-Density: $\varepsilon_{BJ} \geq 5.0$ GeV/fm^3

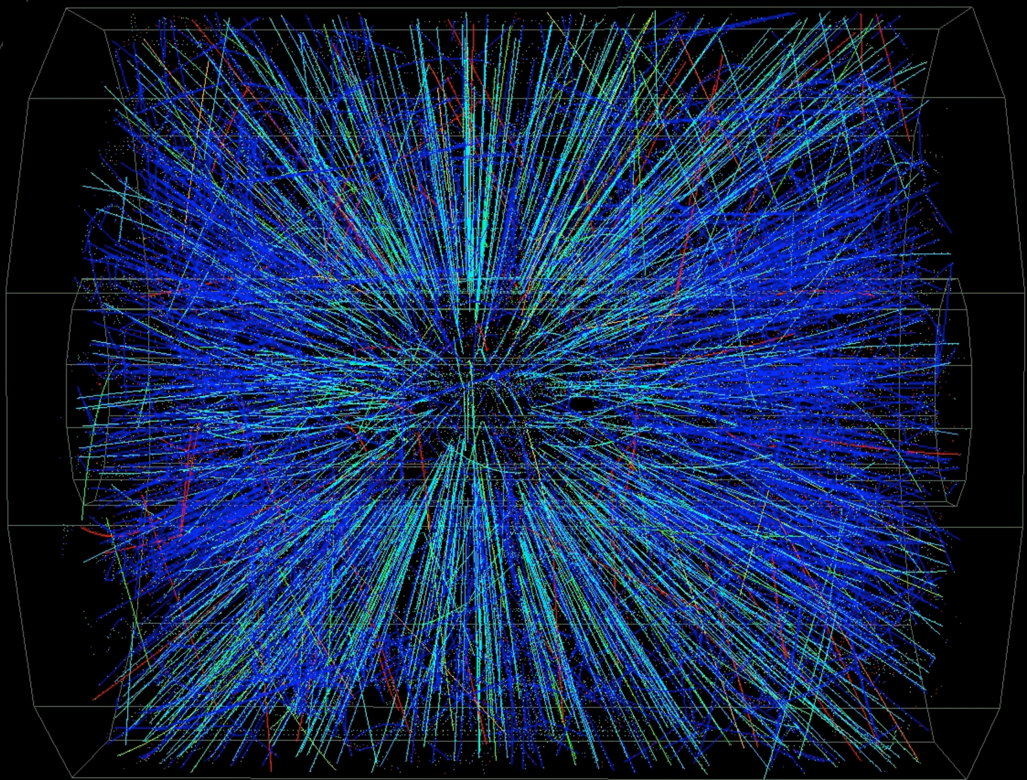


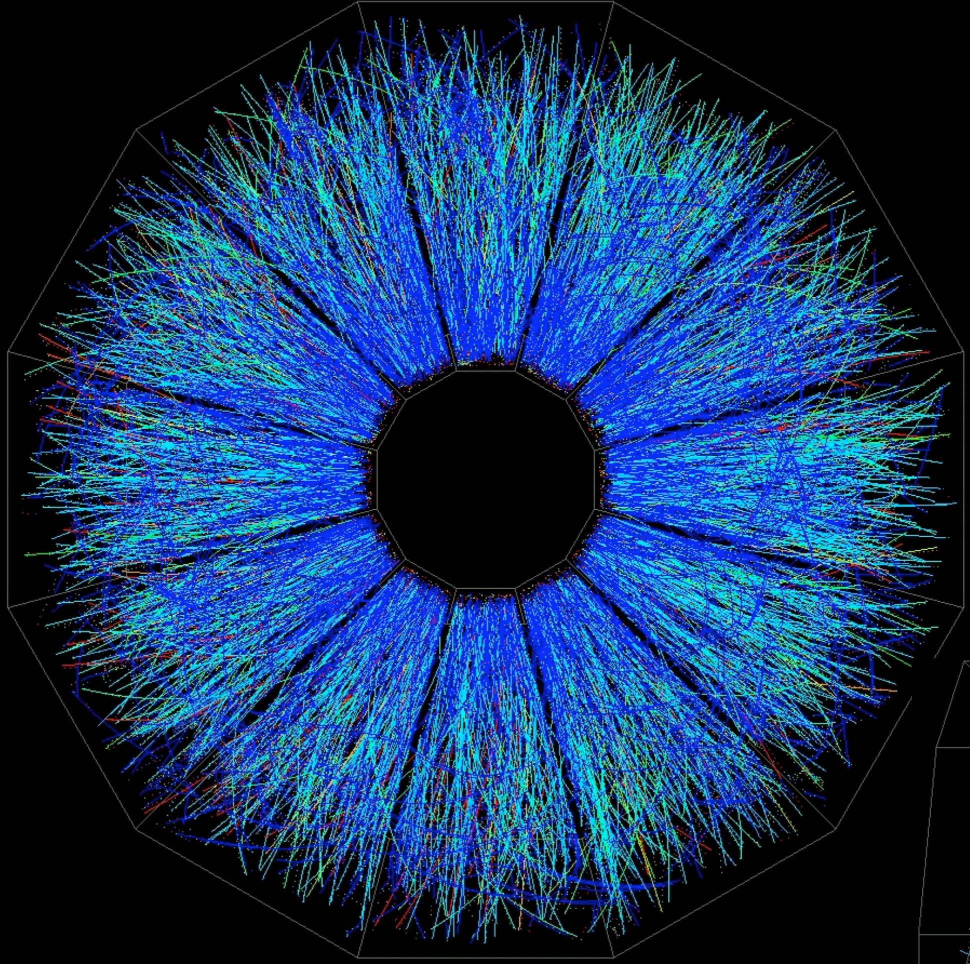




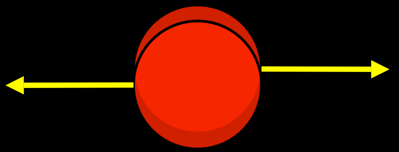
Mid-Central Event

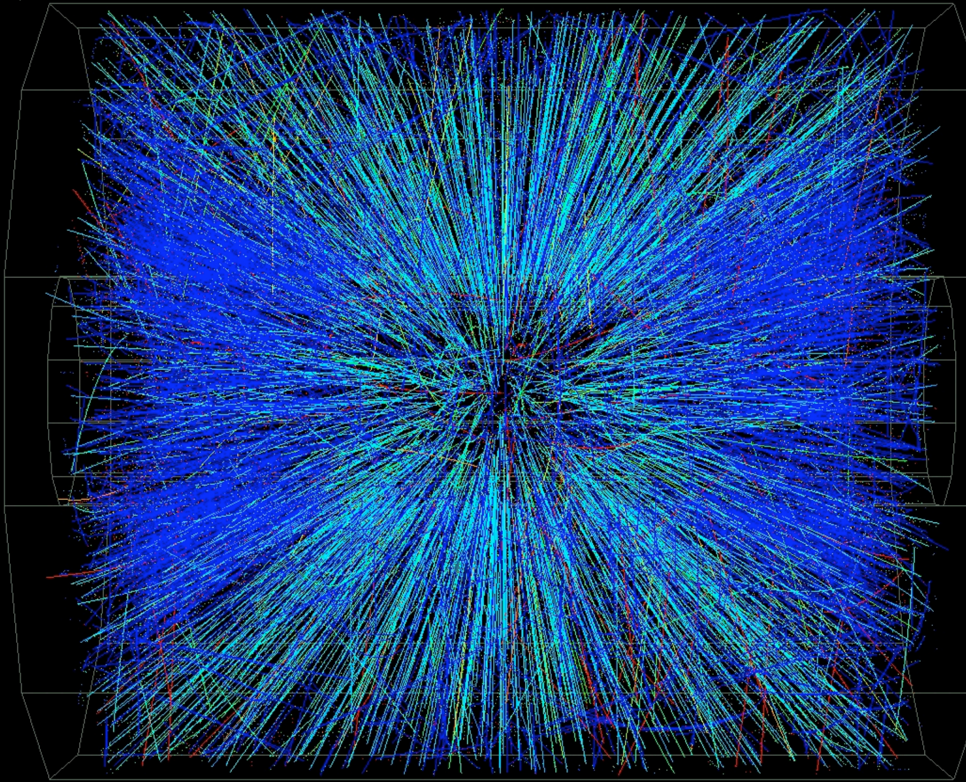






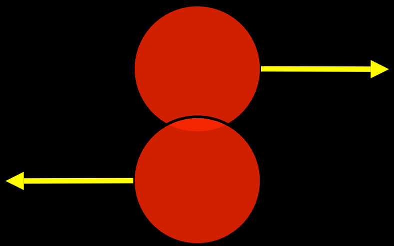
Central Event

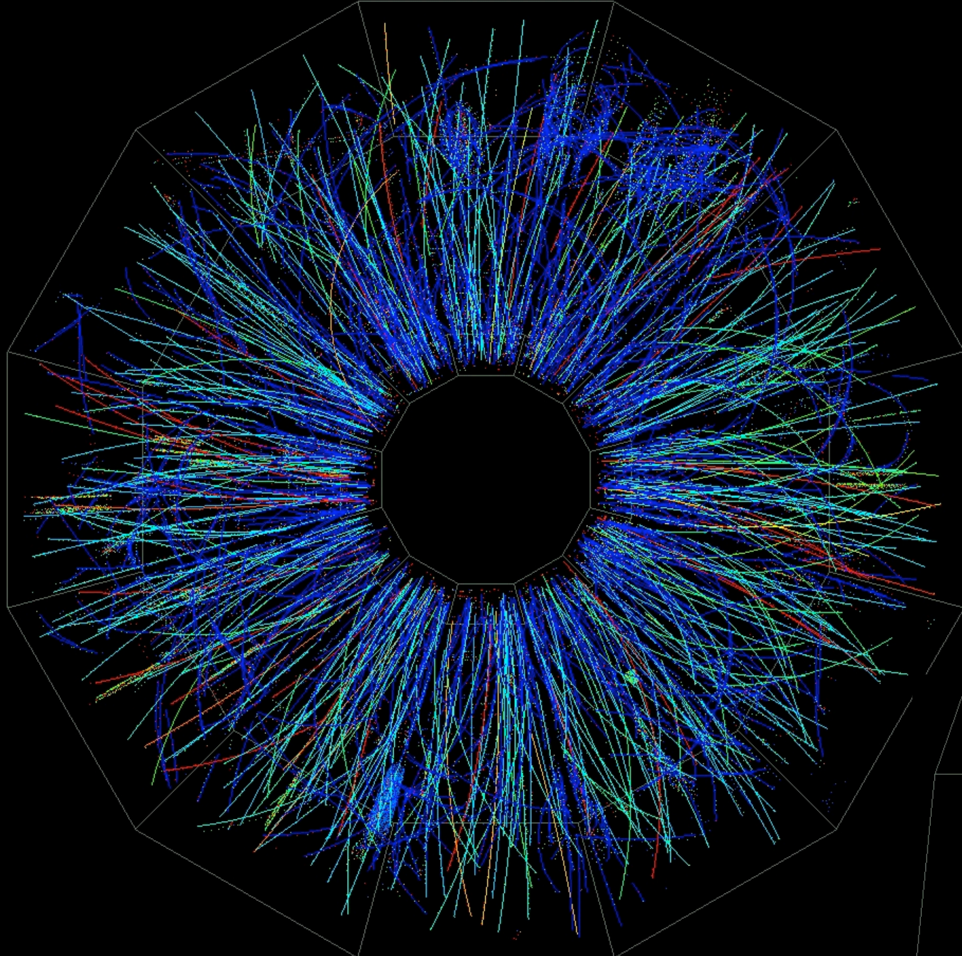


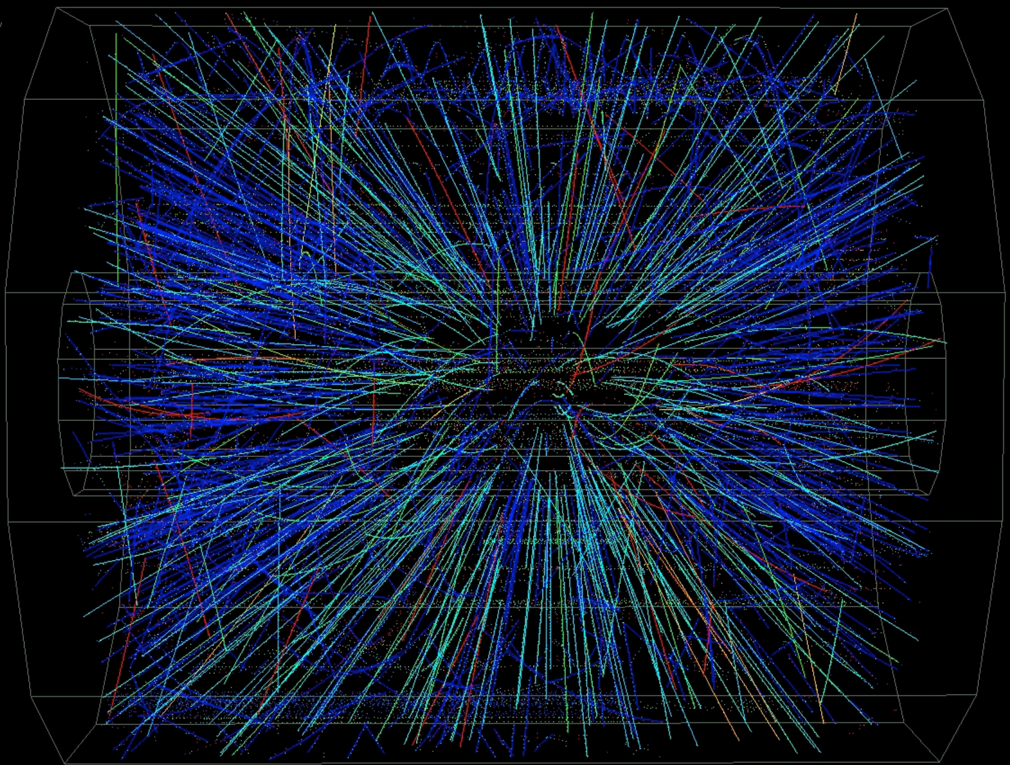


STAR

Peripheral Event







color code ⇒ energy loss

STAR

Looking Closer: Dihadron Correlations

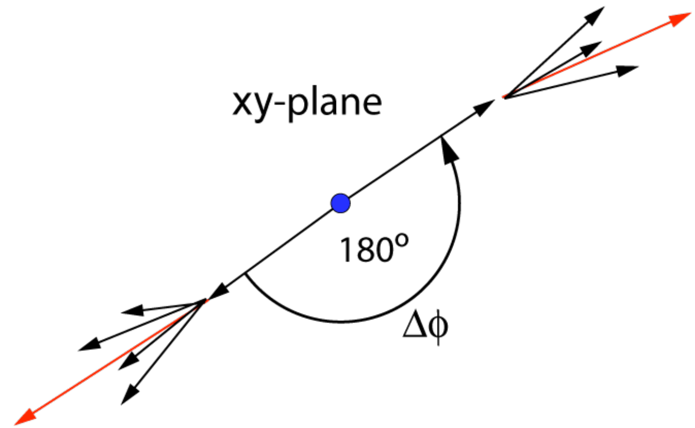
Terminology:

Trigger particle:

- Is the hadron that "triggered" the event
- typically the hadron with the highest p_T
- In most case that's the leading hadron of the jet
- It's p_T is labelled p_T^{trig}

Associated particle:

- Is the hadron that you correlate the trigger particle with
- Background from underlying event gets subtracted
- It's p_T is labelled p_T^{assoc}
- usually $p_T^{assoc} \leq p_T^{trig}$



Per trigger correlated yield:

$$C(\Delta\phi) = \frac{1}{N_{trigger}} \frac{1}{\epsilon} \int d\Delta\eta N(\Delta\phi, \Delta\eta)$$