Hot Nuclear Matter at RHIC

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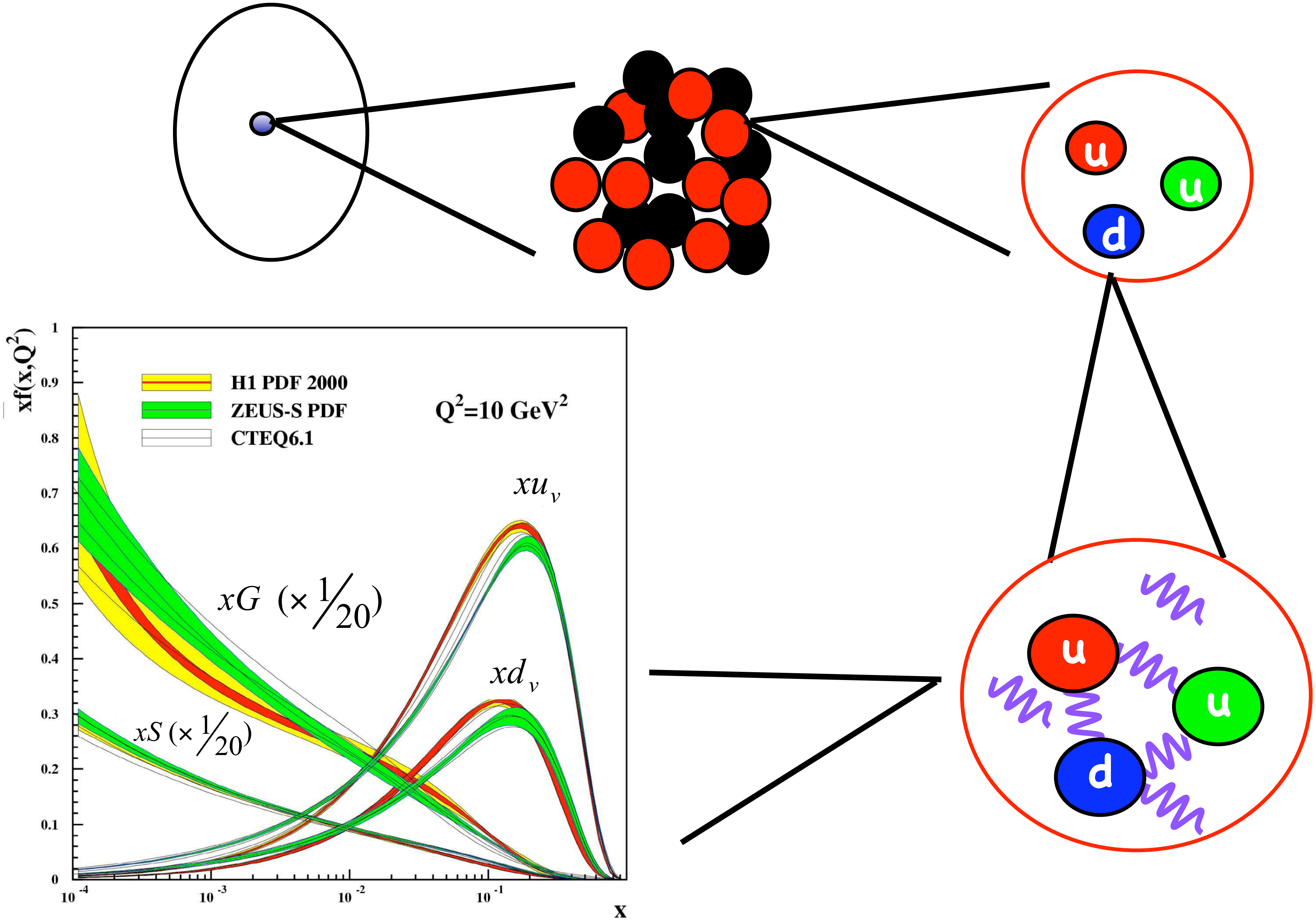
March 24, 2008

The Nucleus



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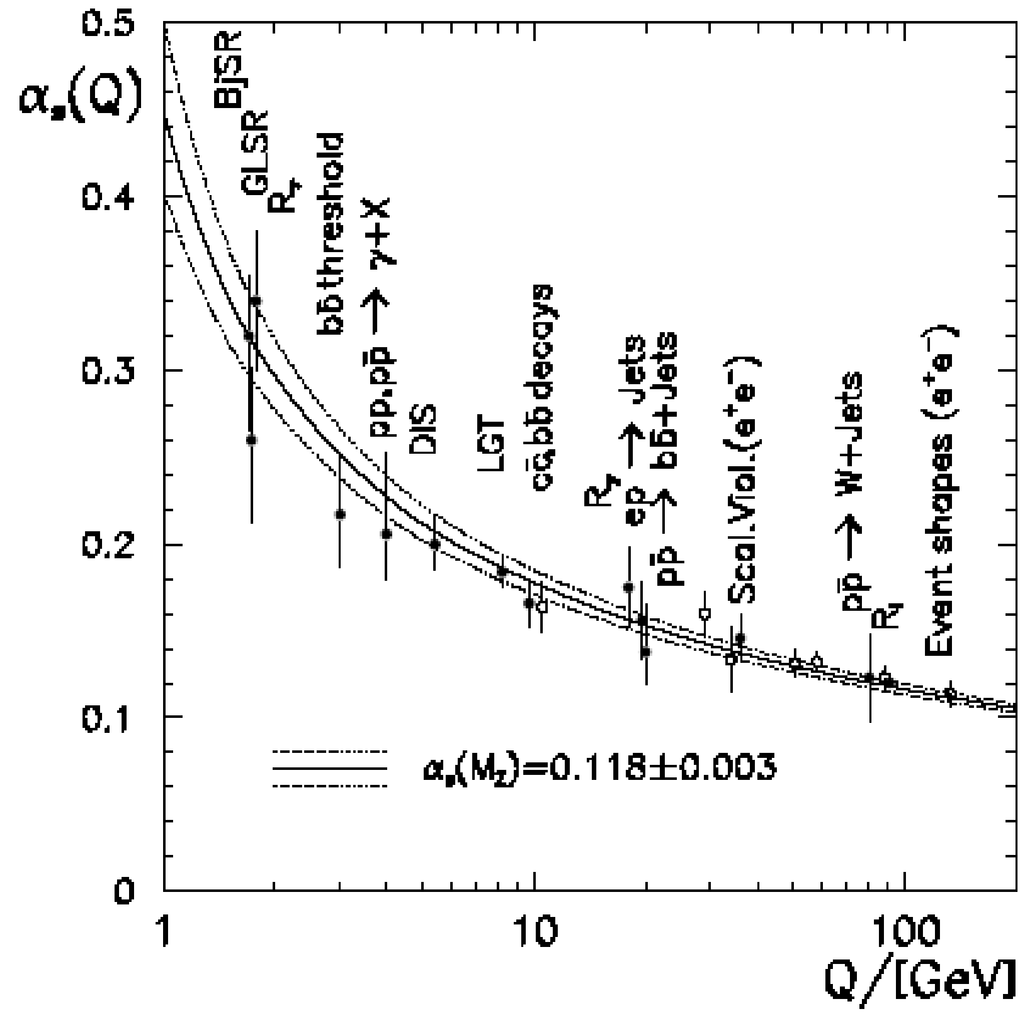
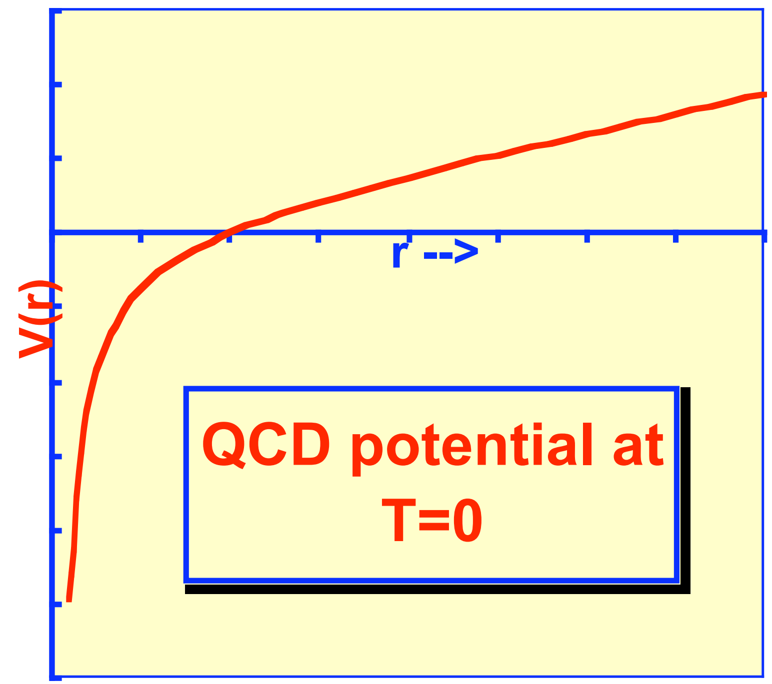
The Strong Force

- holds the nucleus together
- gluons are the force carriers
- quarks and gluons carry “color” charge
- α_S large at low energies decreases at large energies/small distances: asymptotic freedom



Confinement

- QCD force increases with distance
- energy required to separate quarks is greater than the energy required to create quark/anti-quark pair
- all normal matter is color neutral



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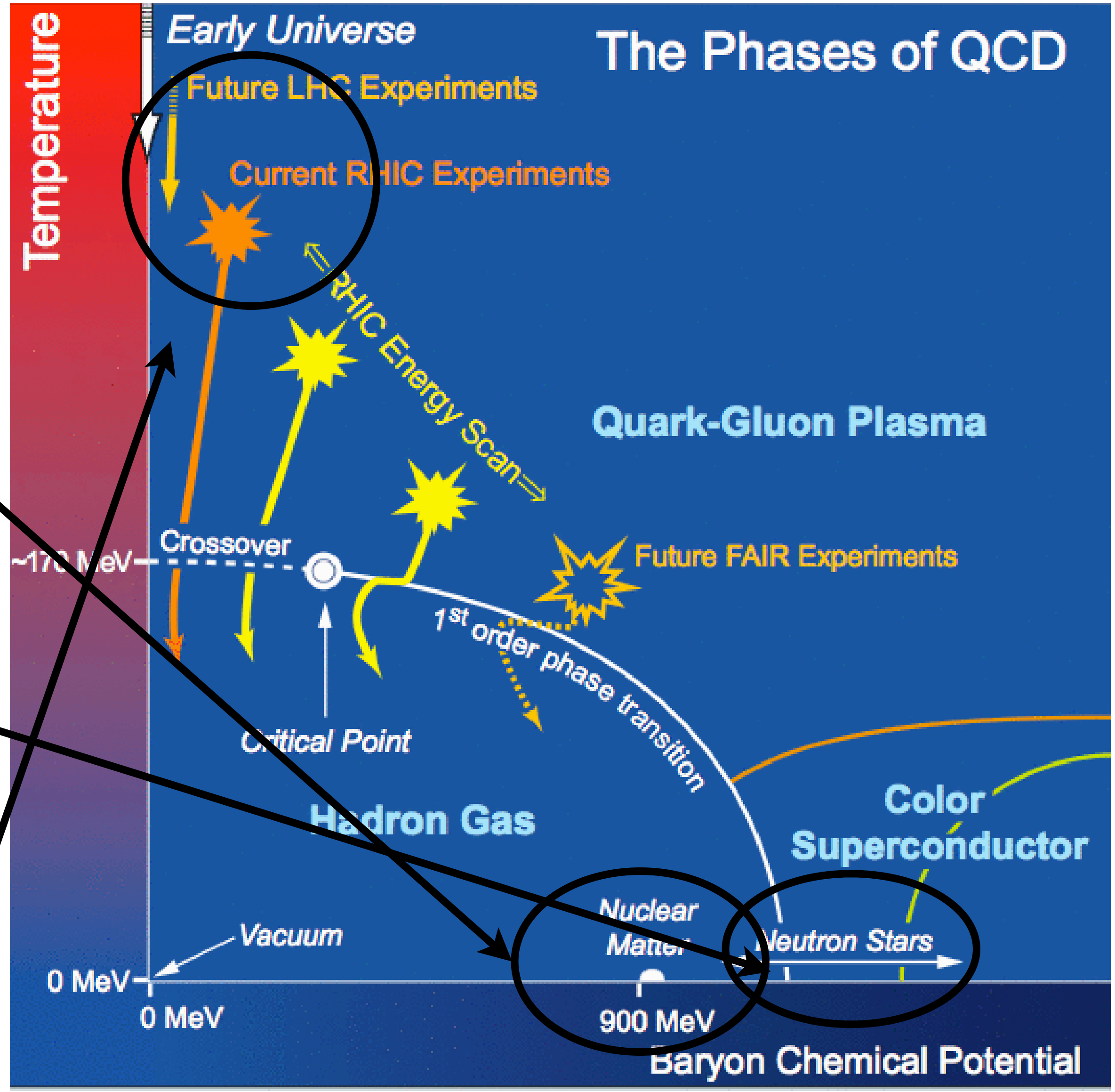
Moving Away from Normal Nuclei

Normal Nuclei

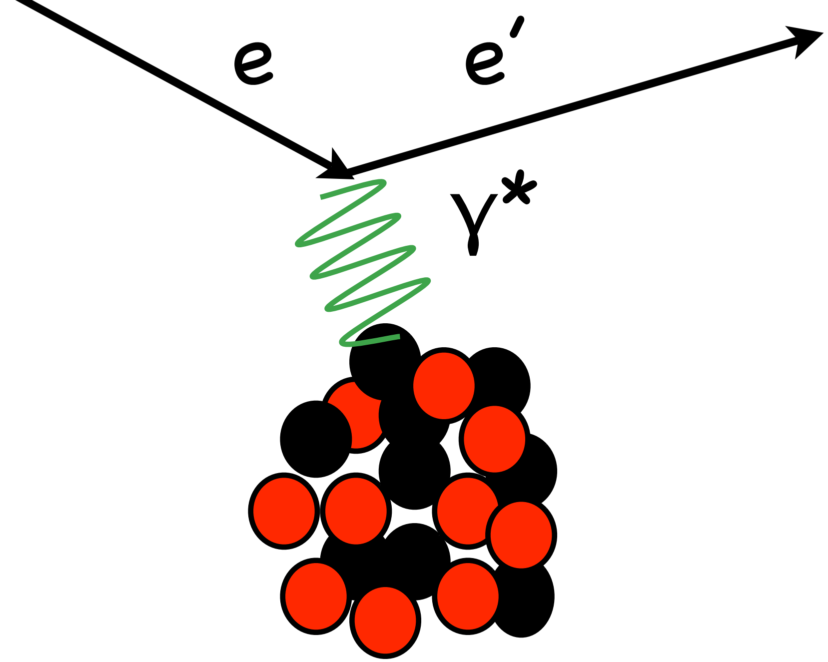
Increased Density: Neutron Stars

Increased Temperature: Quark Gluon Plasma



nuclear physics: interactions of partons

Electron Scattering



learn about the nucleus: calibrated probe

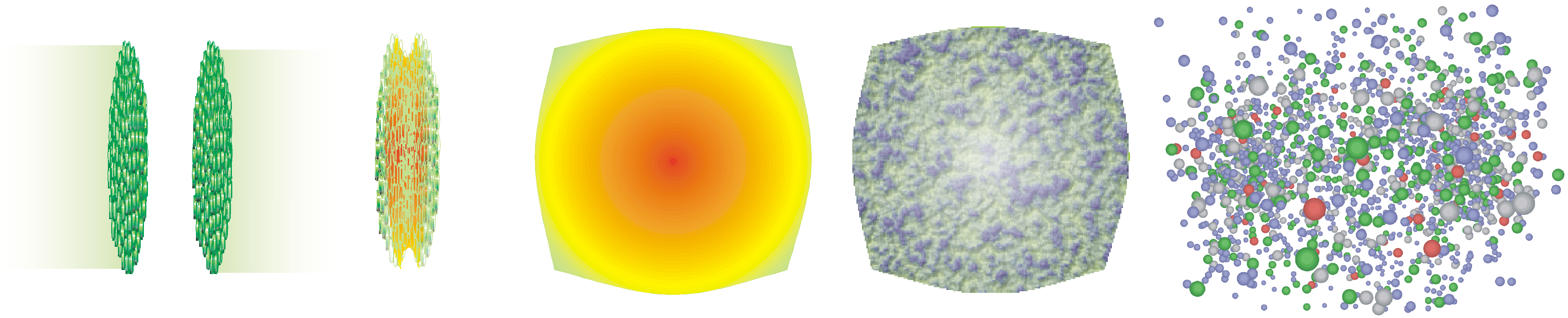
parton: quark, anti-quark or gluon

	Charge	Mass (GeV)
down	-1/3	0.006
up	+2/3	0.003
strange	-1/3	0.1
charm	+2/3	1.2
bottom	-1/3	4
top	+2/3	171

heavy ion collisions

- goal: hot partonic matter
- method: take large nuclei and collide them as fast as possible
  - details of the nuclear structure as mostly unimportant
- past: AGS at Brookhaven and SPS at CERN
- future: LHC at CERN
- present: RHIC at Brookhaven

Timeline of a Collision



incoming nuclei

hot matter

hadronic gas

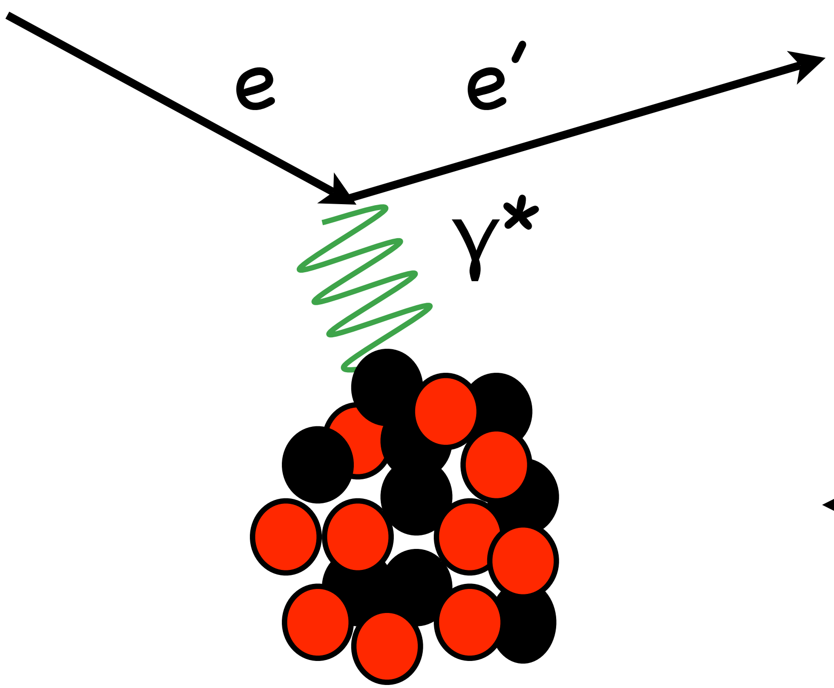
- radius of Au nuclei: ~7fm = 7×10^{-15}m
- time to traverse the nucleus: 7x10-15m/(3×10^{8}m/s)=20×10^{-23}s

illustration: S. Bass

Need a Calibrated Probe

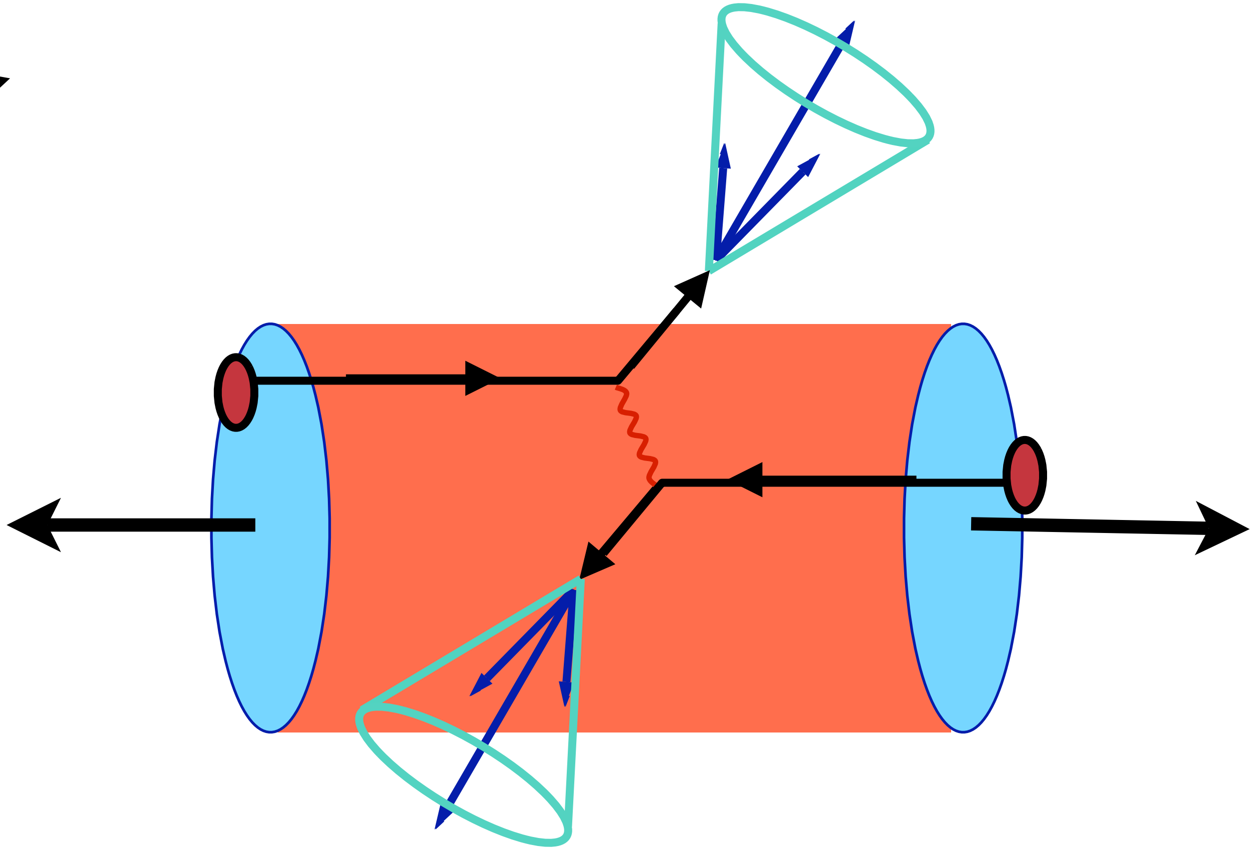
Cold Nuclear Matter

γ* as probe



Hot Nuclear Matter

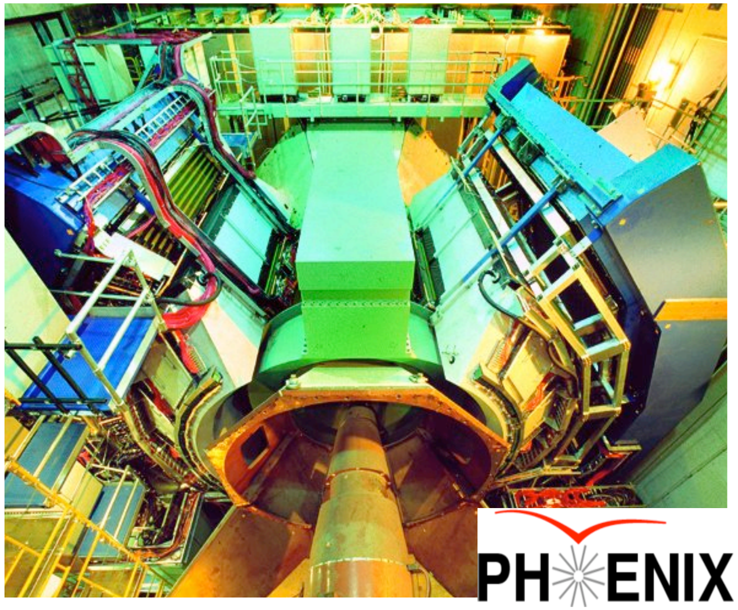
p+p Collision as Probe

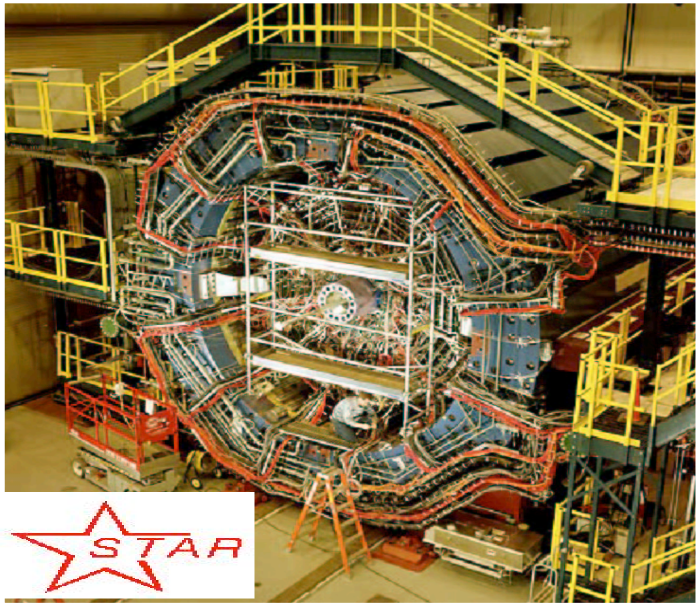


Relativistic Heavy Ion Collider

- 4km circumference
- up to 200GeV center of mass energy
- flexible: wide range of nuclei, asymmetric collisions

PHENIX & STAR





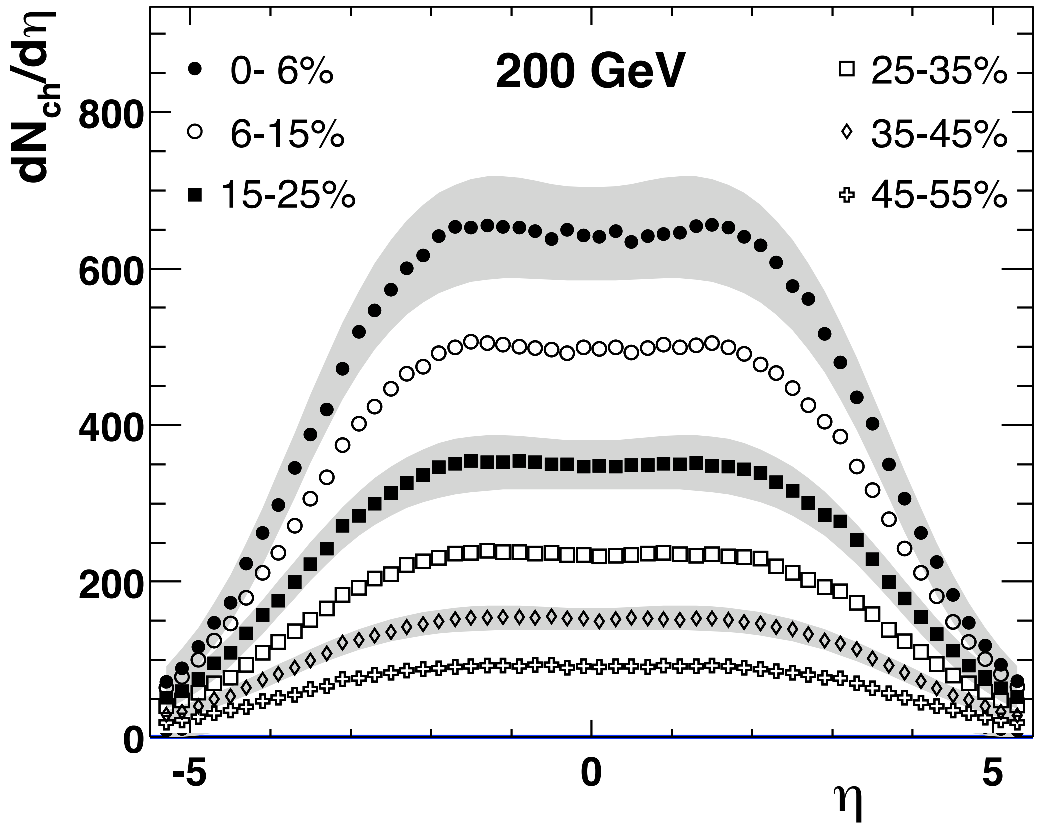
rare probes
high event rates
excellent
calorimeter

large acceptance
TPC for charged
particle tracking
and identification

detectors complementary

Counting Particles

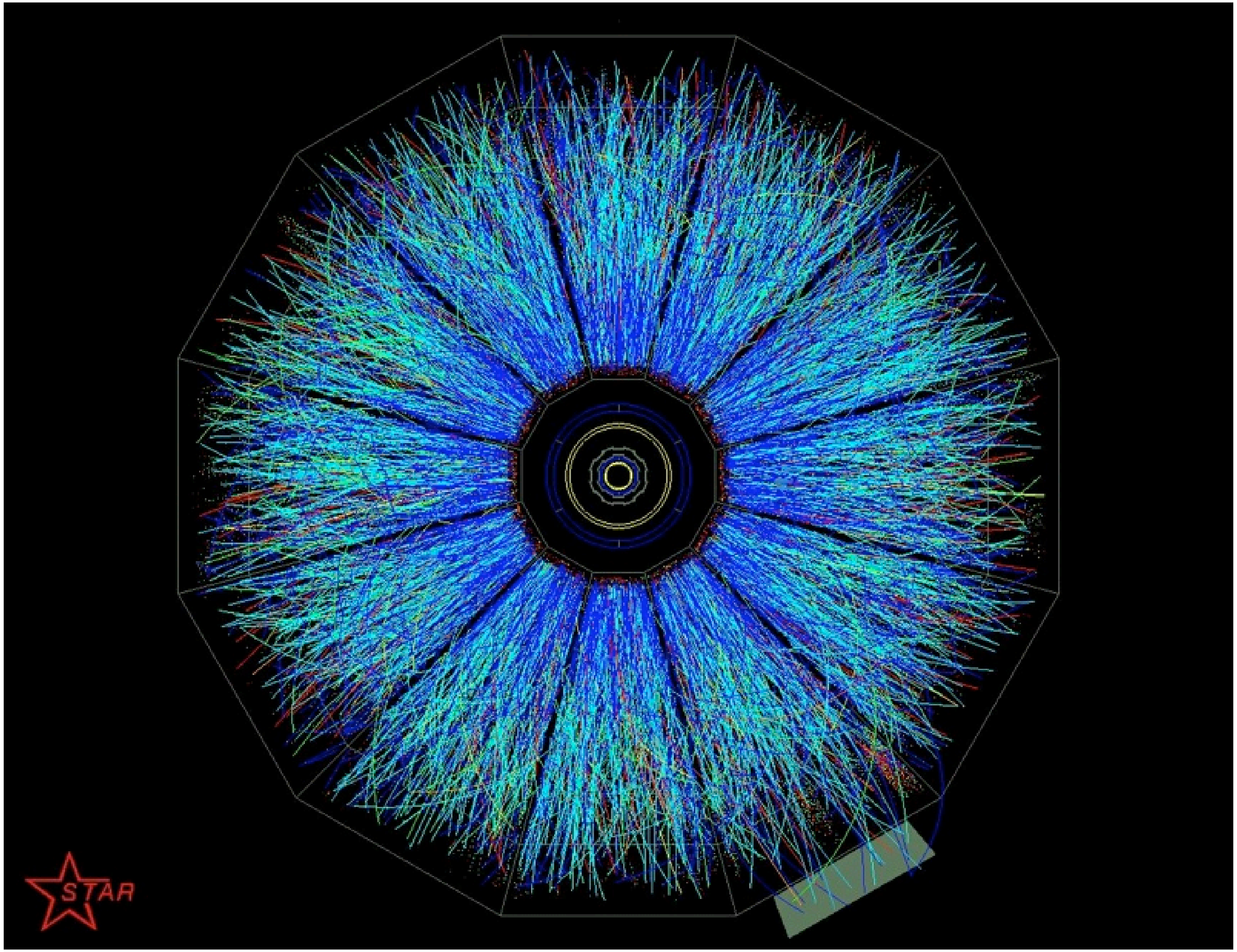
PHOBOS PRL 91 052303 (2003)



increasing system size
more produced particles

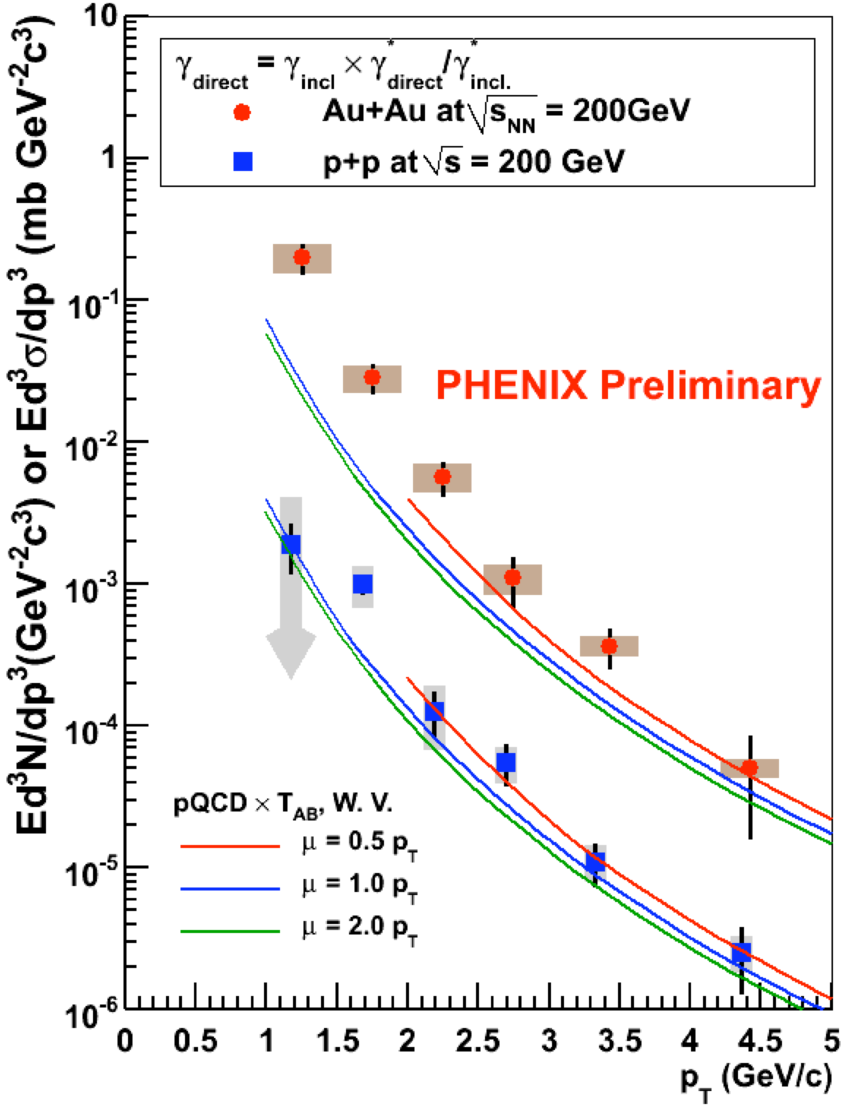
up to ~5000 charged particles produced in collisions

A Collision



Thermal Radiation

- excess photons observed in Au+Au collisions
  - possibly thermal radiation
- estimates of initial system temperature range from ~300-600MeV (see: J. Frantz J. Phys G34 S389 (2007))

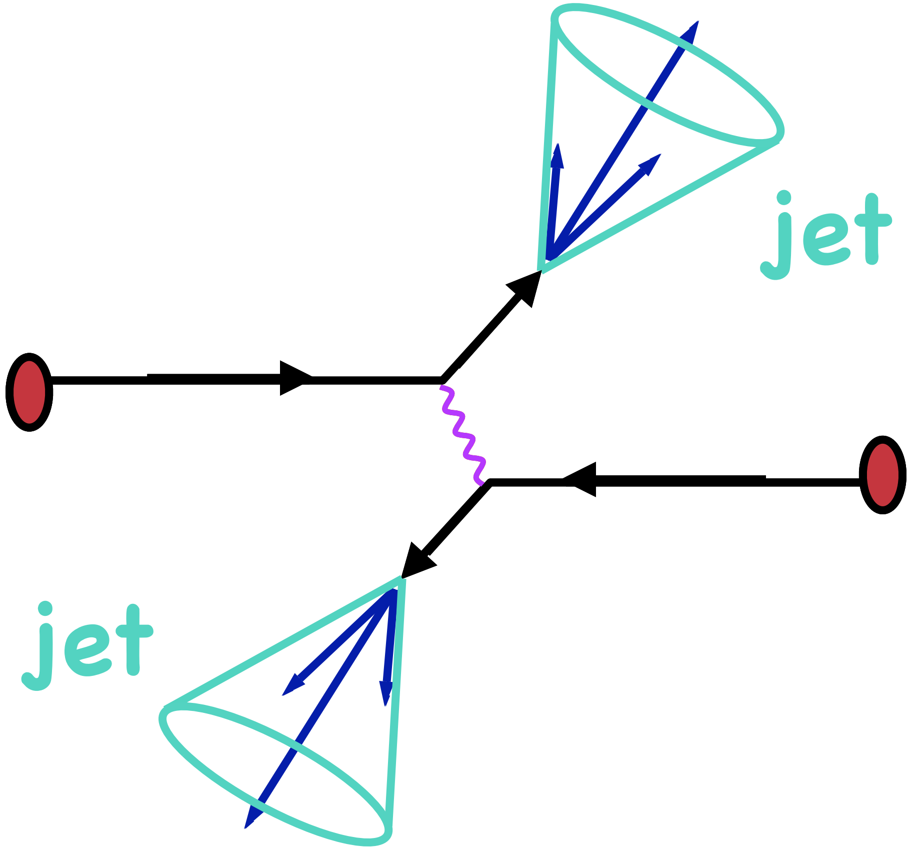


Jets in p+p Collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

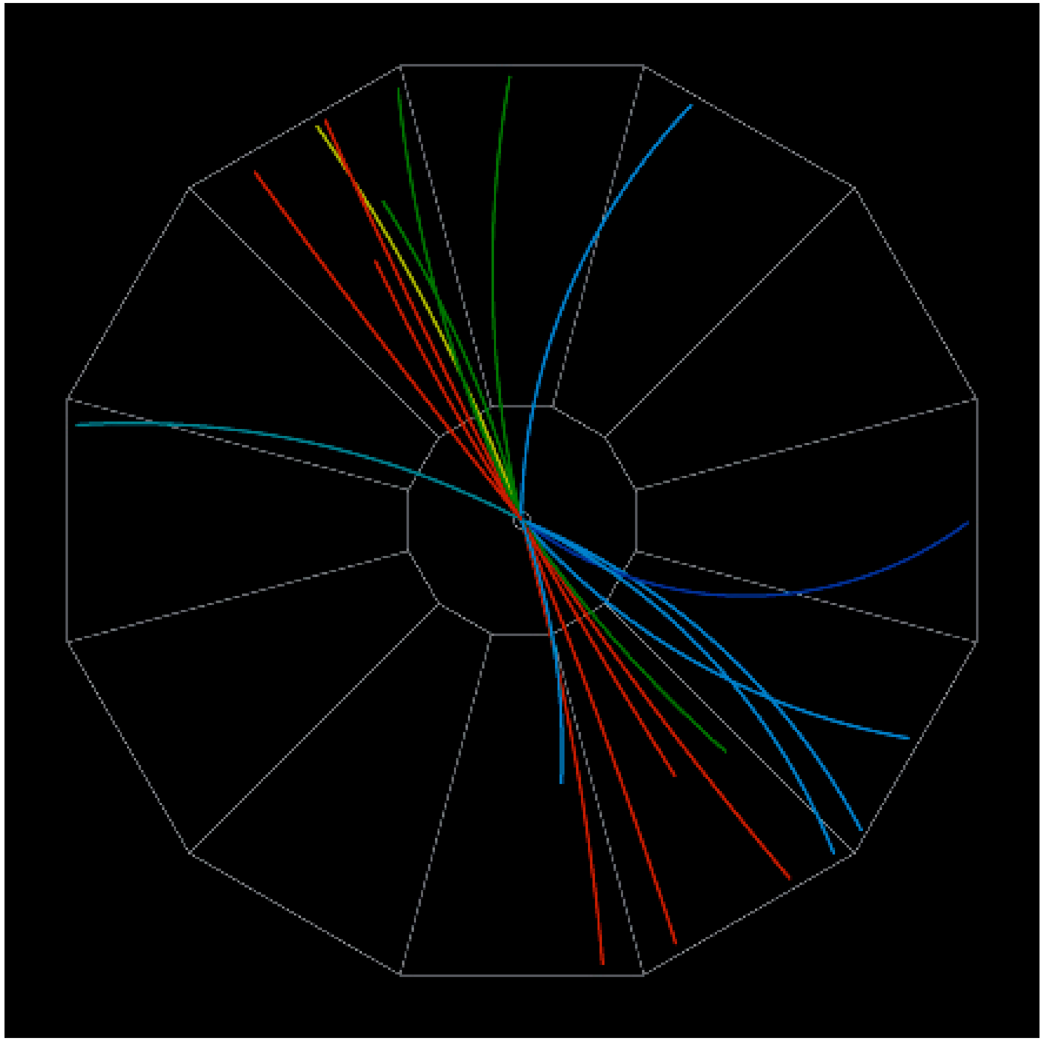
Hard Scattering Cross Section: Calculated with pQCD

Fragmentation into Hadrons: Measured in e+e- Collisions



$$\sigma^{pp->\pi^0 X} = \sum_{f_1,f_2,f} \int dx_1 dx_2 dz\, \underline{f_1^p(x_1)\, f_2^p(x_2)}\, \underline{\hat{\sigma}^{f_1 f_2 \rightarrow f+X}(x_1 p_1, x_2 p_2)}\, \underline{D_f^{\pi^0}(z)}$$

A Jet in STAR

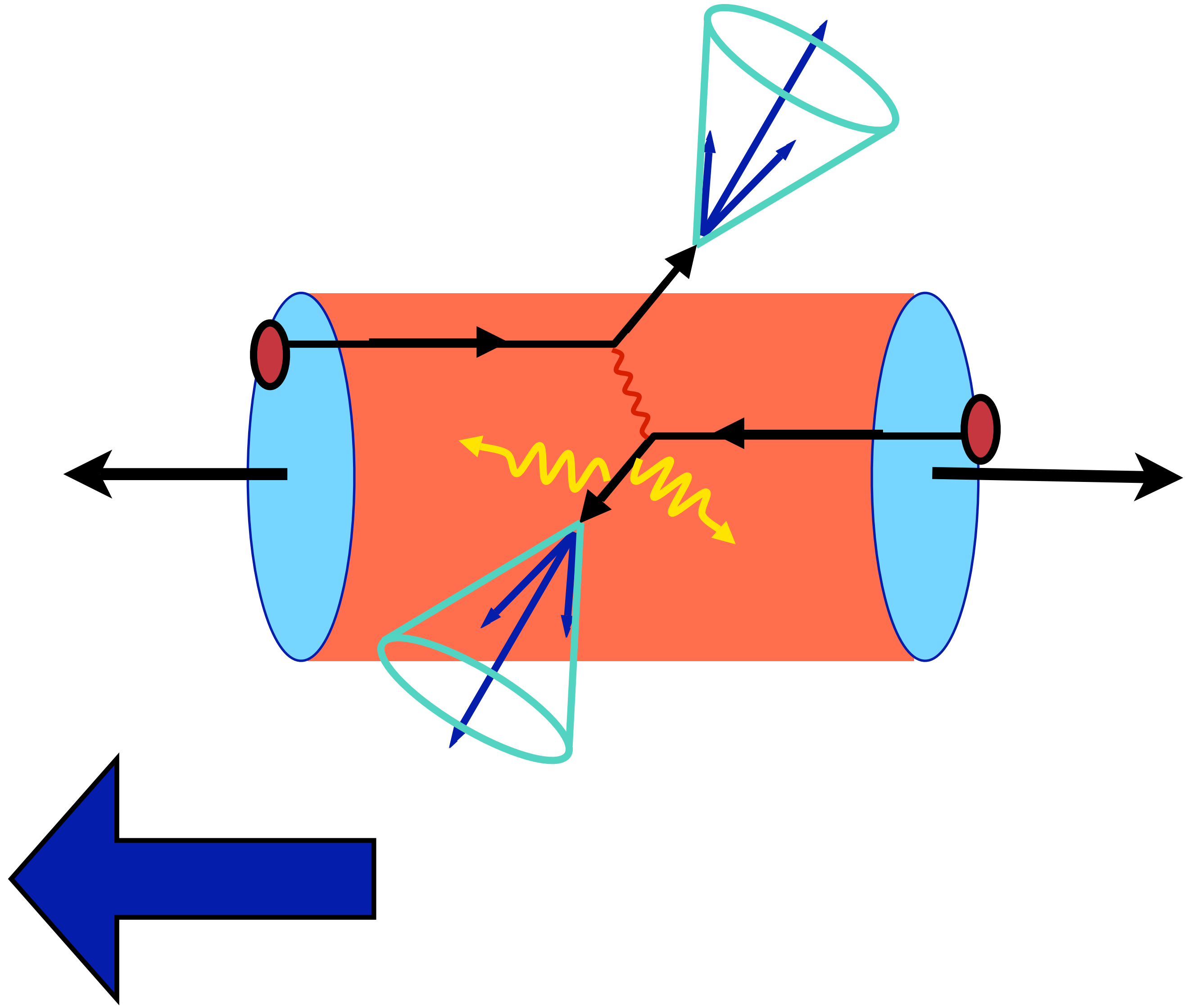


Heavy Ion Collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

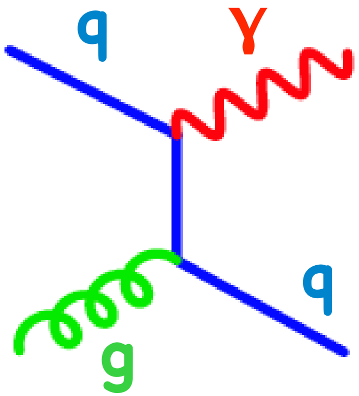
Hard Scattering Cross Section: Calculated with pQCD

Interactions Between the Hard Scattered Parton and the Produced Matter

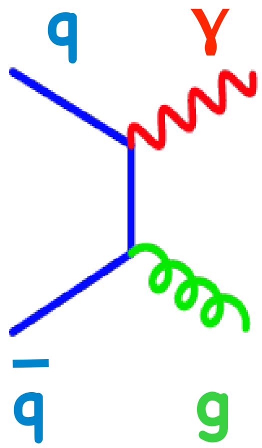


Testing Expectations

- QCD processes can produce photons:



Compton Scattering



Annihilation

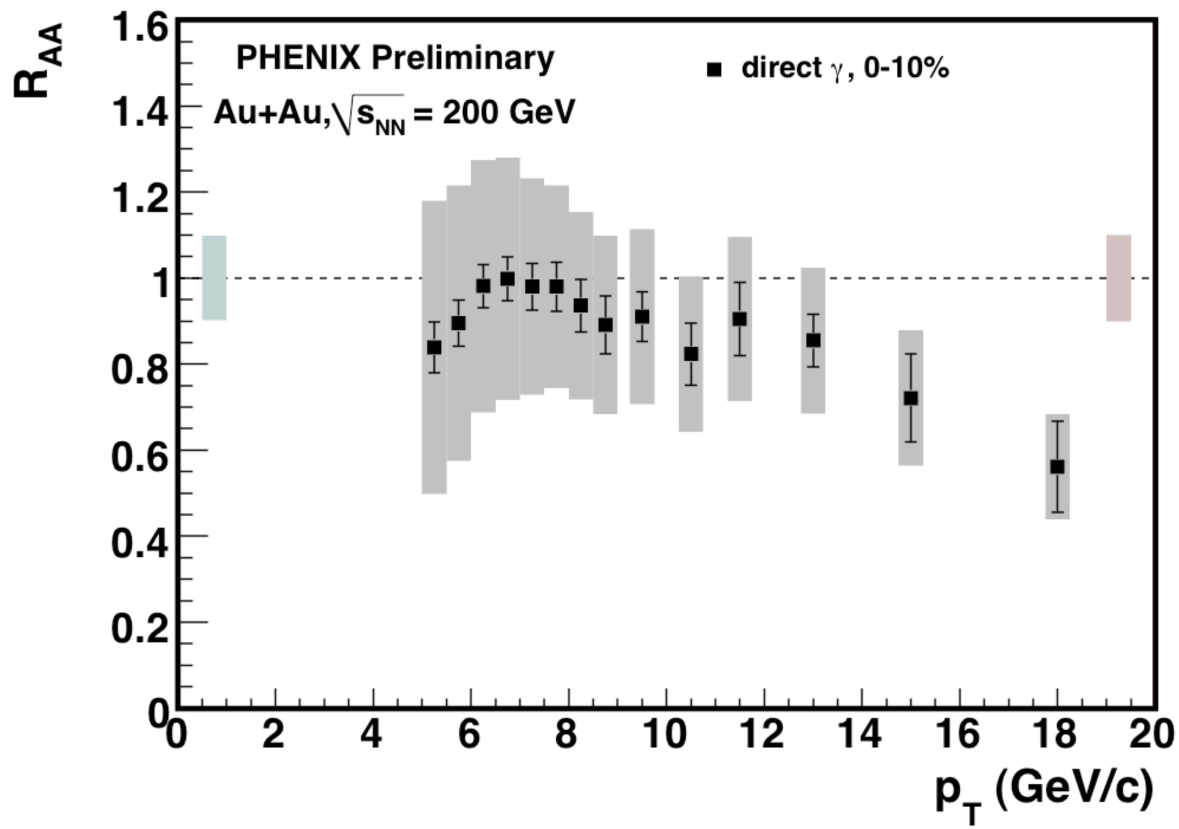
- Photons escape the colored final state without interacting
- If the initial state in heavy ion collisions is like a collection of p+p collisions, photon spectra should scale from p+p

Control Experiment

$$R_{AA} = \frac{yield_{AA}}{yield_{pp} * N_{coll}}$$

$R_{AA} = 1$

no nuclear effects

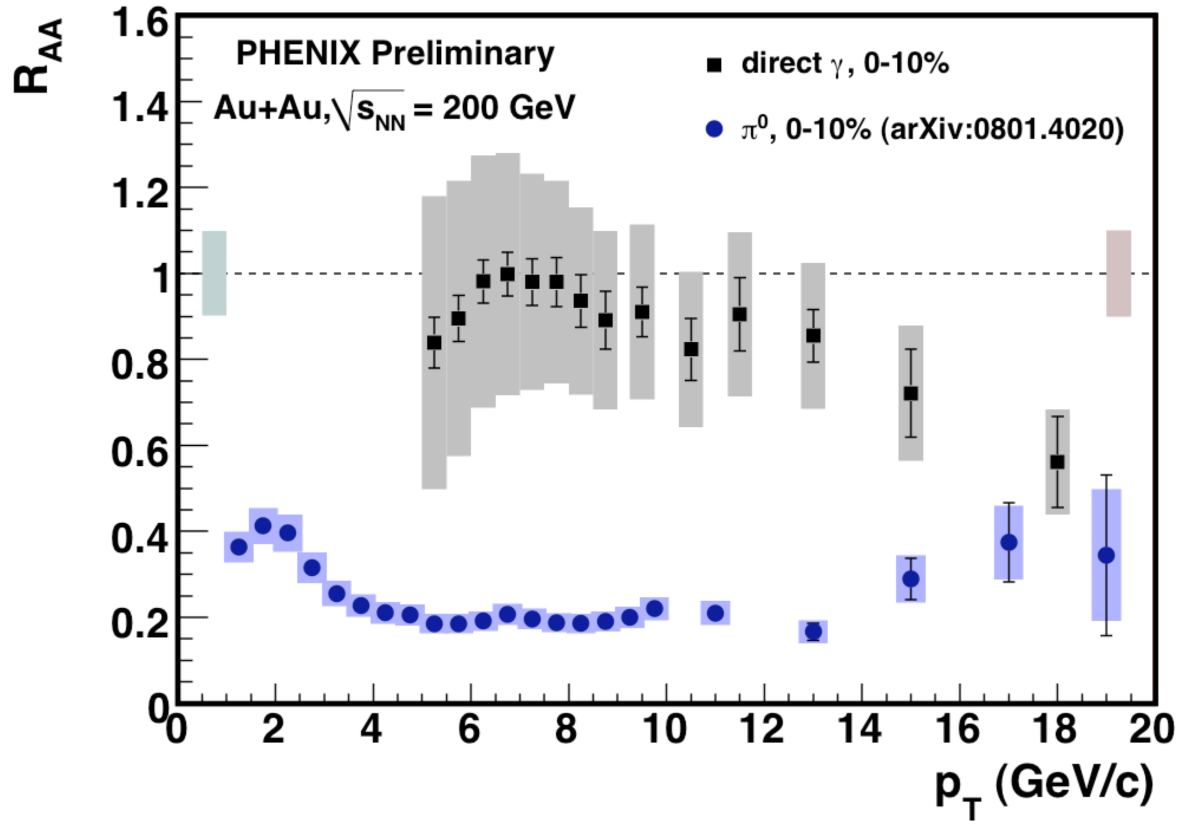


γ: no color charge → insensitive to produced matter
R_{AA} consistent with unity

What about Quarks & Gluons?

π^0: golden probe of energy loss lightest meson (contains quark & anti-quark)

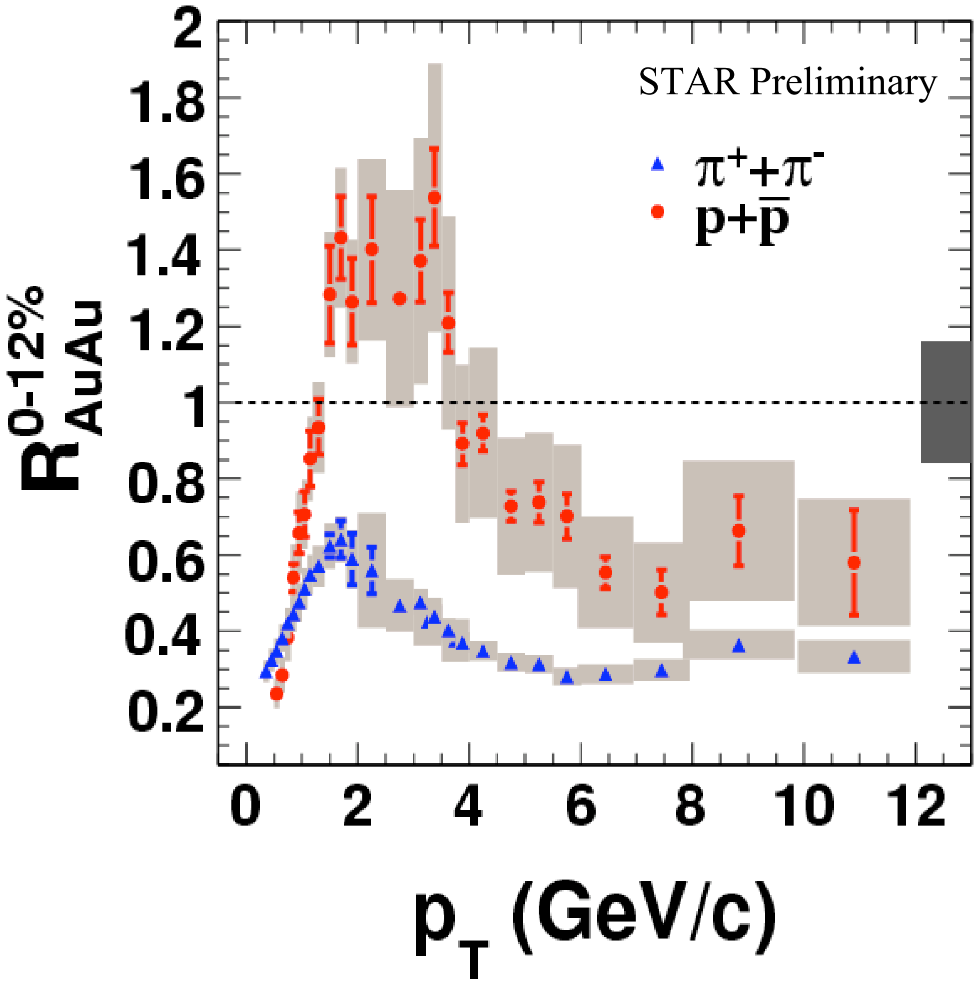
$$R_{AA} = \frac{yield_{AA}}{yield_{pp} * N_{coll}}$$



π^0: very large suppression → very opaque matter

where is the lost energy?

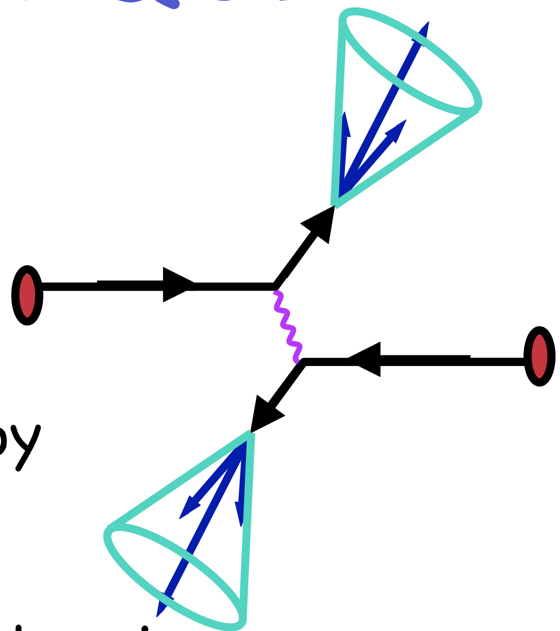
what happens with protons?



- proton R_{AA}~1 for $2<p_T<5$GeV/c
- similar to photon R_{AA}
    - but photons don't interact via the strong force

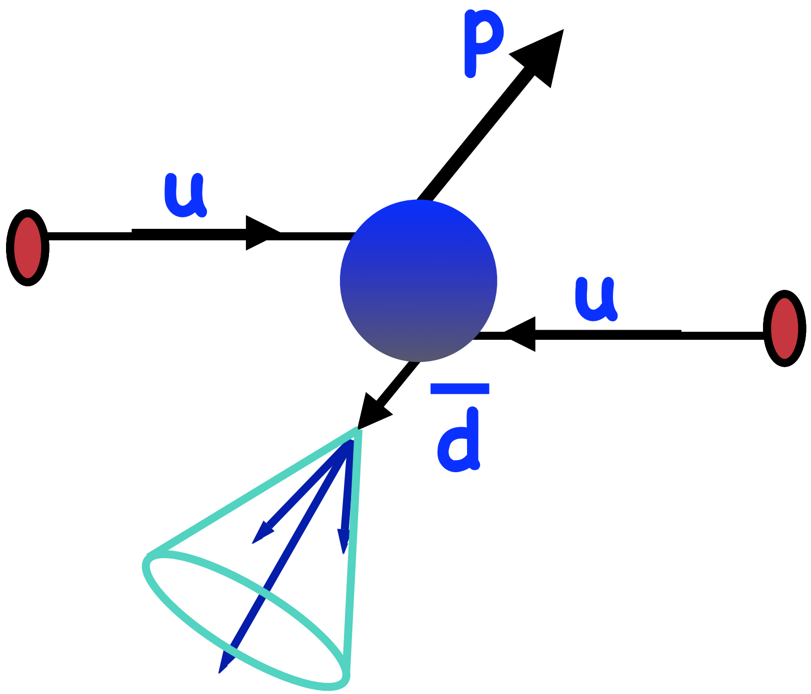
Is it possible protons aren't interacting with the matter?

Hadron Production in QCD



- 2→2 quark or gluon scattering followed by fragmentation
  - understood as creating quark/anti-quark pairs which combine forming hadrons
  - works well for mesons (e.g. pions)
- however proton production is suppressed
  - 3 quarks are needed
  - however, this suppression could increase sensitivity to novel QCD processes...

direct proton production



$uu \rightarrow p\bar{d}$

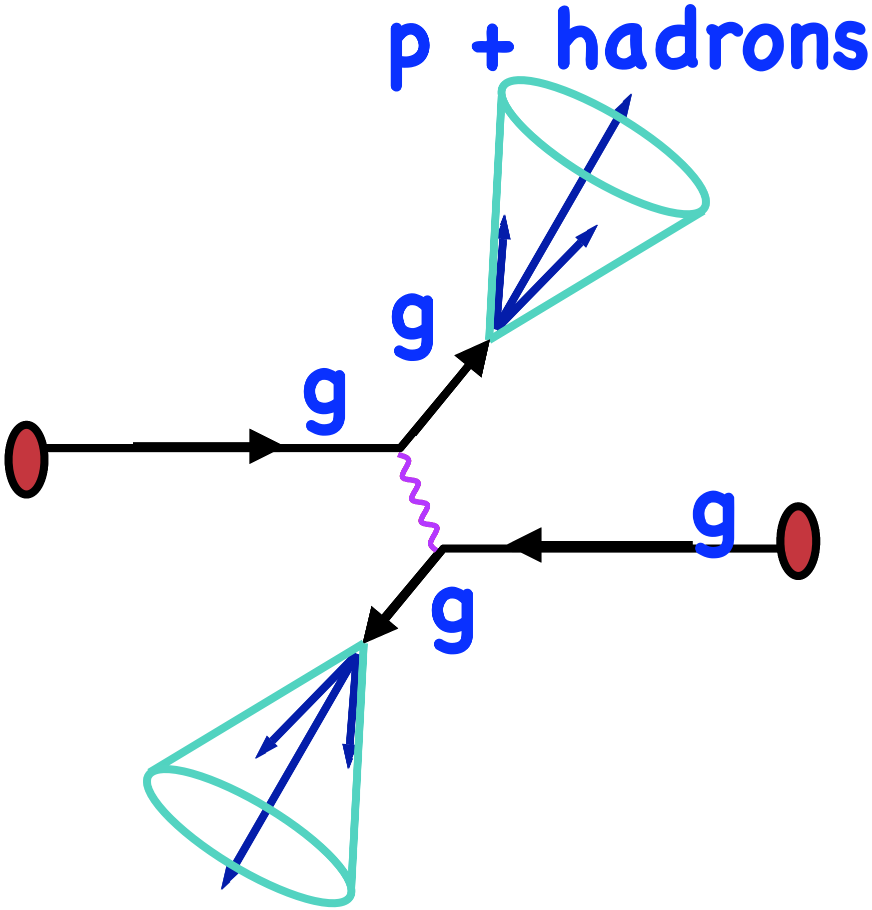
Brodsky SLAC-PUB-13082 Brodsky, AS in preparation

- color singlet proton directly produced within hard subprocess
- higher twist effect, but could be dominant within p_T range of interest
- size of proton decreases with increasing p_T: **color transparent**
  - proton exits collision region without interacting

Direct vs. Conventional Protons

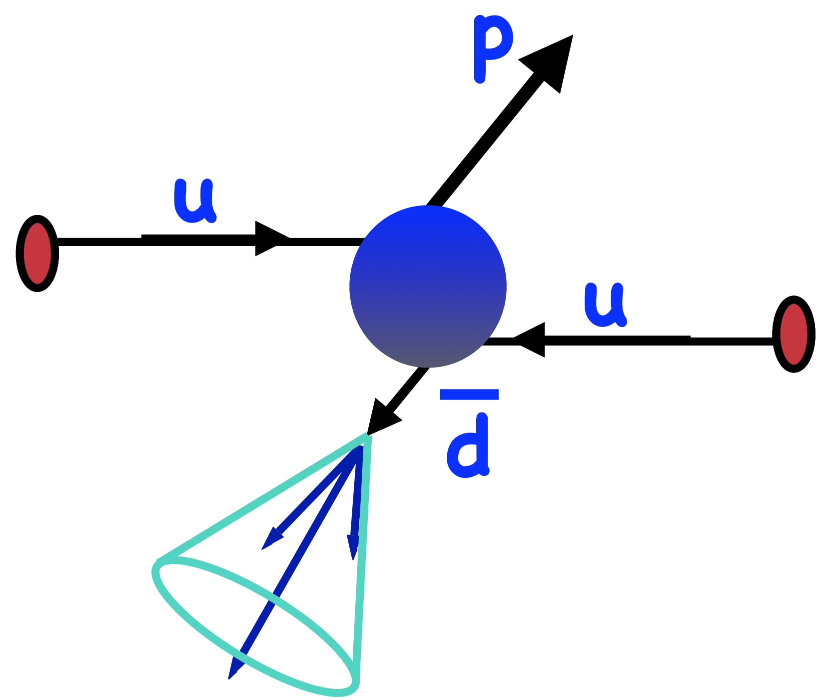
Conventional Production:

Proton with Other Jet Fragments

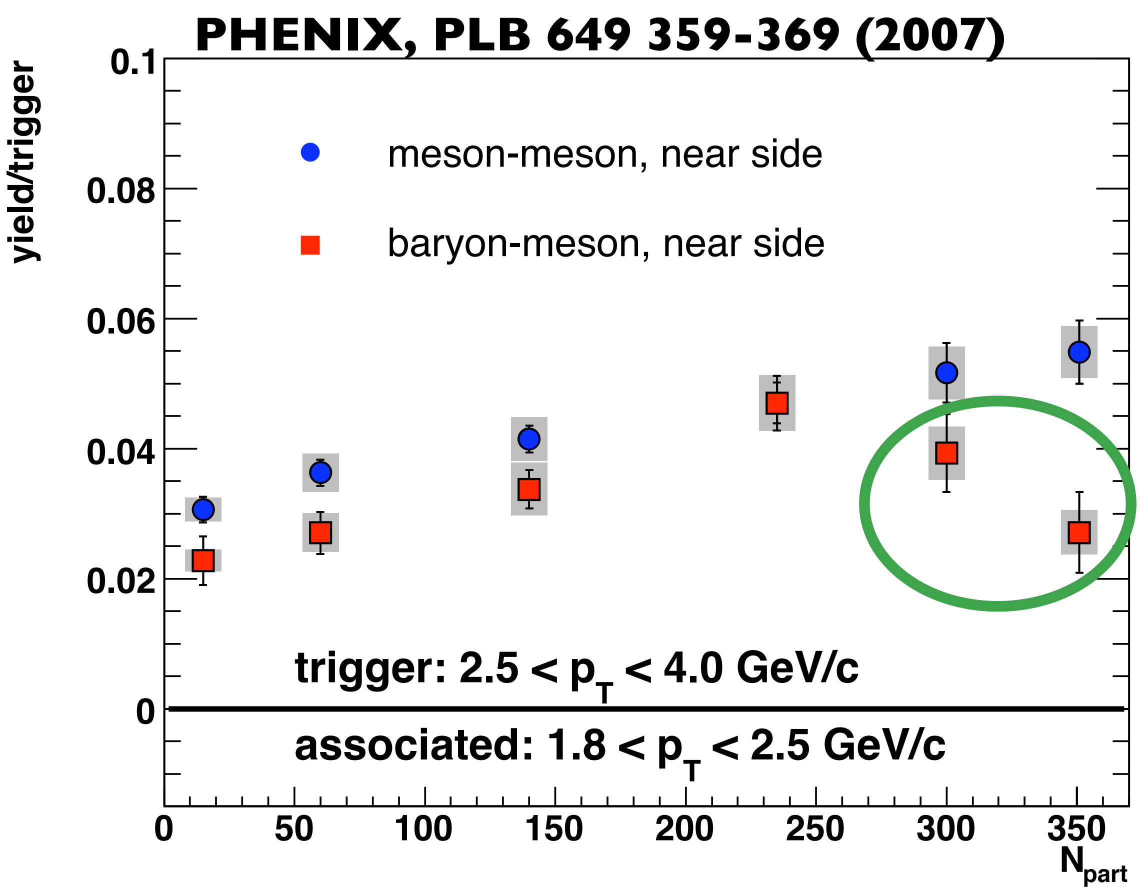


Direct Production:

Isolated Protons



where do protons come from?



system size →

increase → correlated lost energy

decrease only in the most central: large system allows through only color transparent protons (?)

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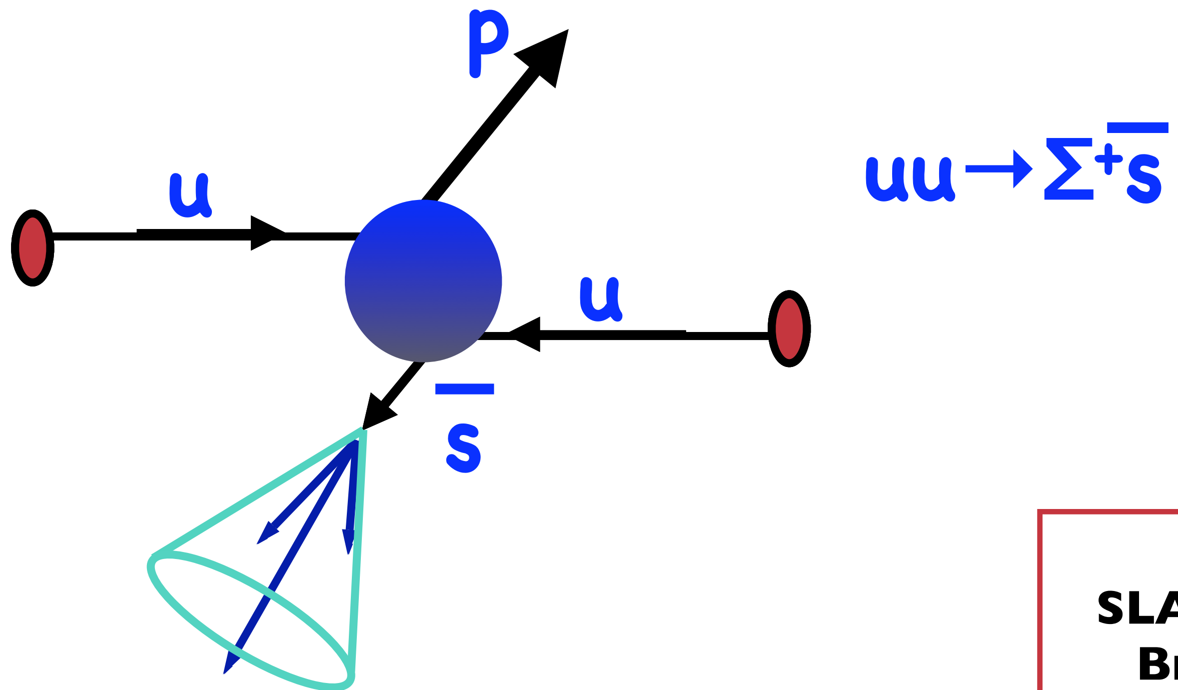
direct processes & strange baryons



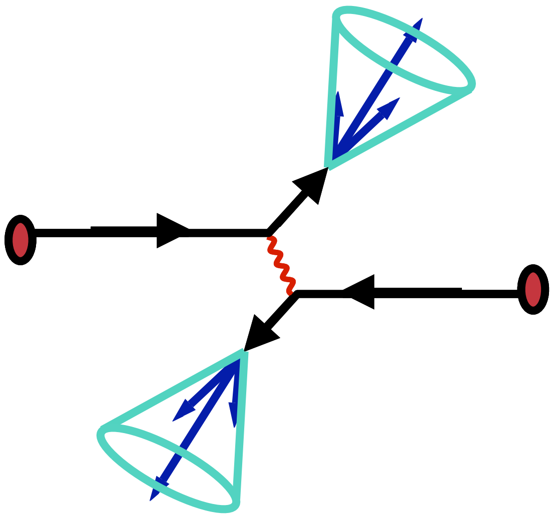
Brodsky
SLAC-PUB-13082
Brodsky, AS in preparation

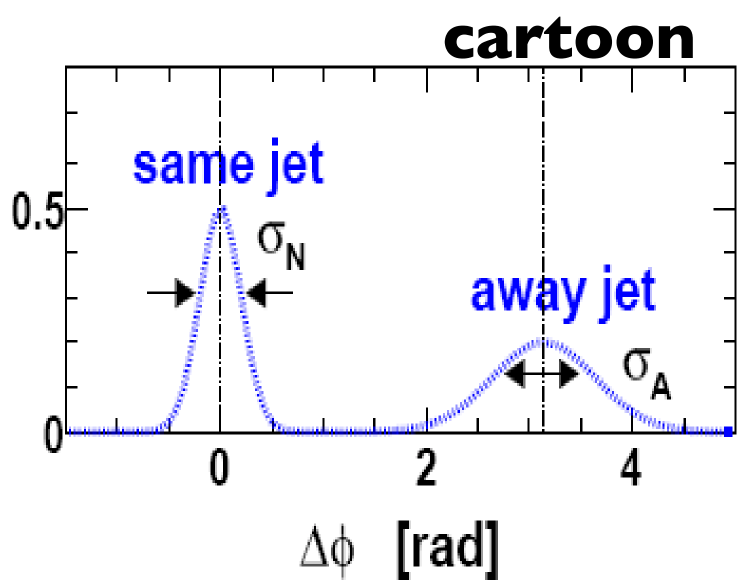
- can also make strange baryons: signature balancing strangeness will be on in recoil jet
- in contrast, in hard fragmentation picture: balancing strangeness will be close, in same jet

Back to the Matter @ Hand

what about those pions that lost so much energy?

2 particle correlations

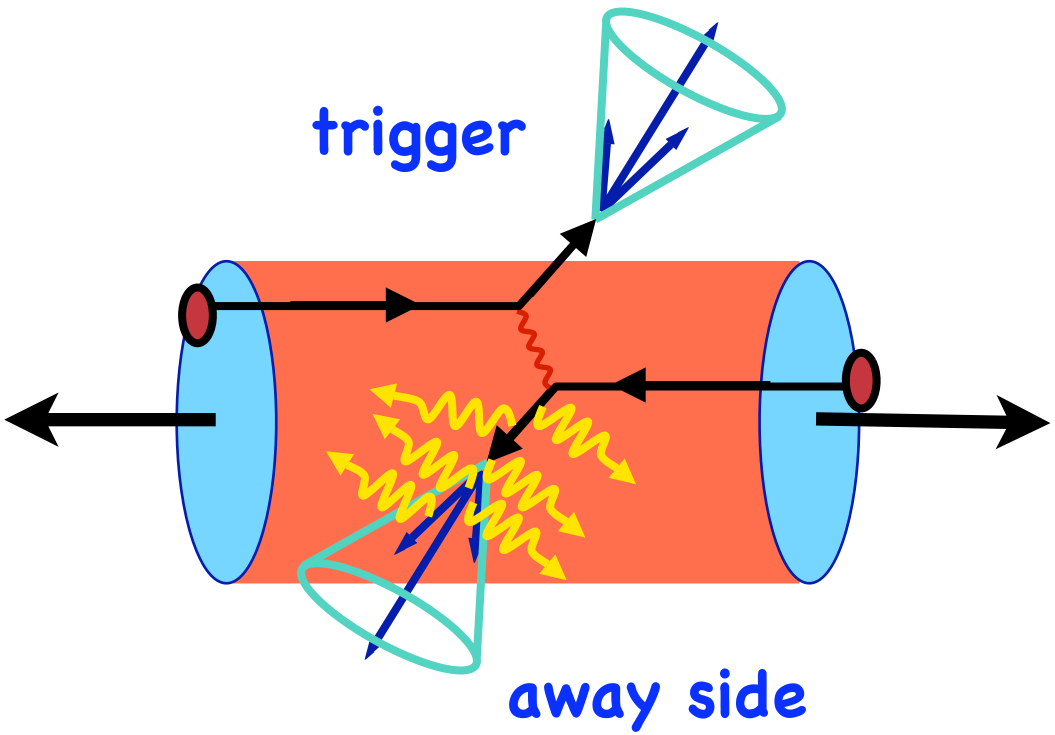




- "trigger" on high p_T particles to find a hard scattering
- count lower p_T particles to study medium interactions
- comparison of Au+Au and p+p allows measurements of matter's effect on jet properties

Δφ: azimuthal angle around beam direction

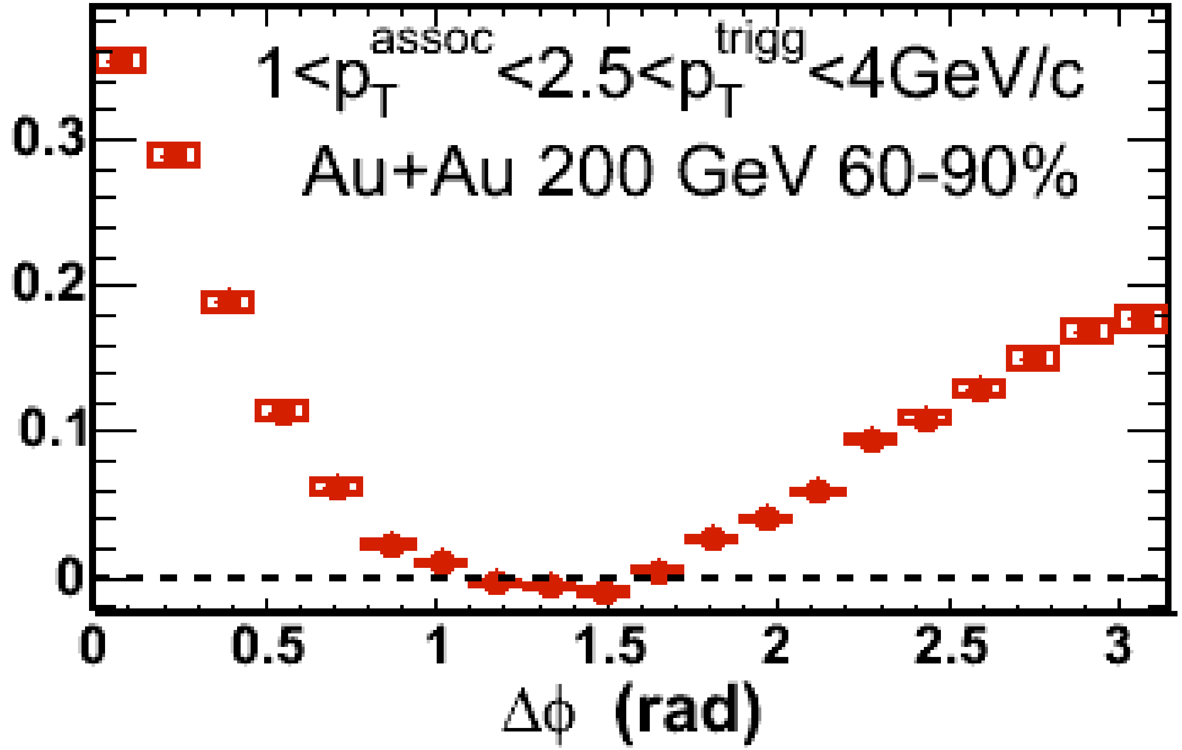
Surface Bias



- because of the large energy loss the trigger is biased toward small matter path lengths
- then the away side biased toward long path lengths in the matter
    - maximal interactions with the matter

Away Side

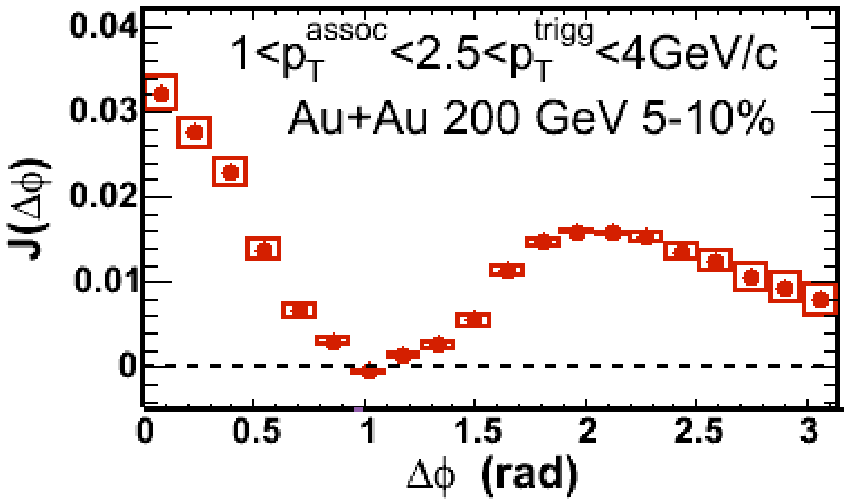
Glancing Au+Au: Peak ~ π



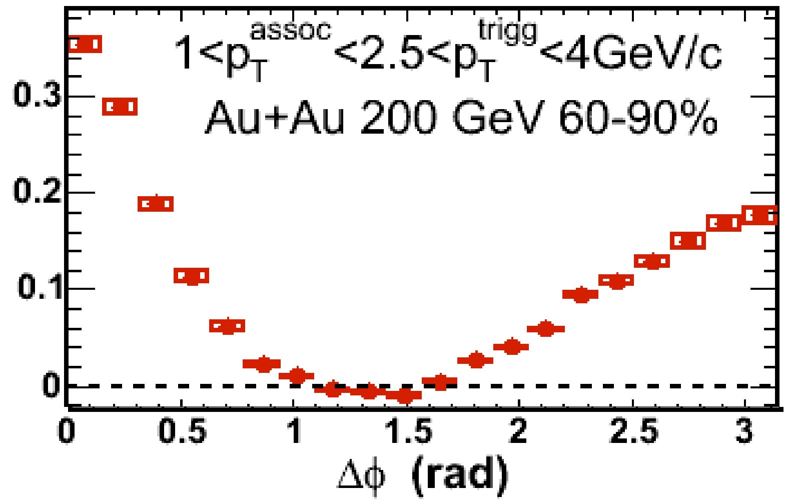
PHENIX, PRL 98 232302, 2007

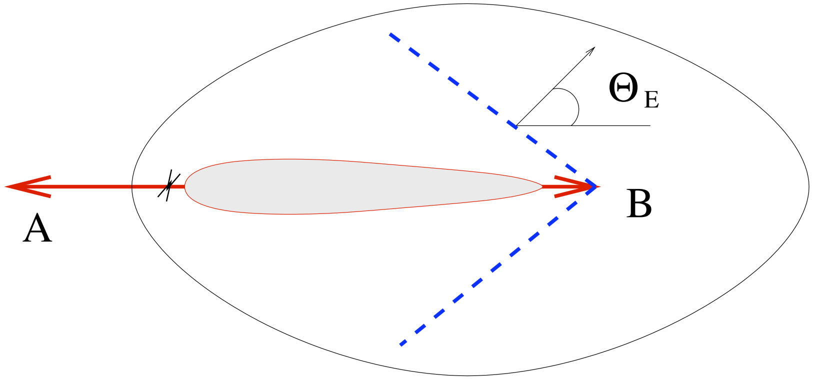
Away Side

Head On Au+Au: Peak ~ π-1



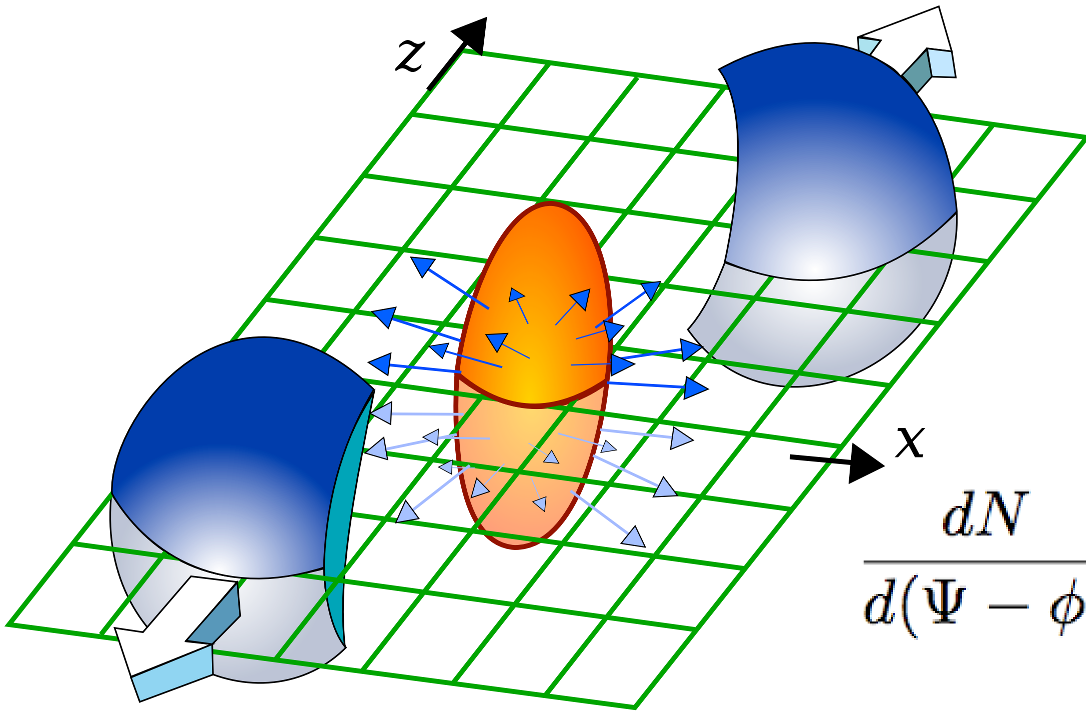
Glancing Au+Au: Peak ~ π





- observation of a Mach Cone?

how does the matter behave?



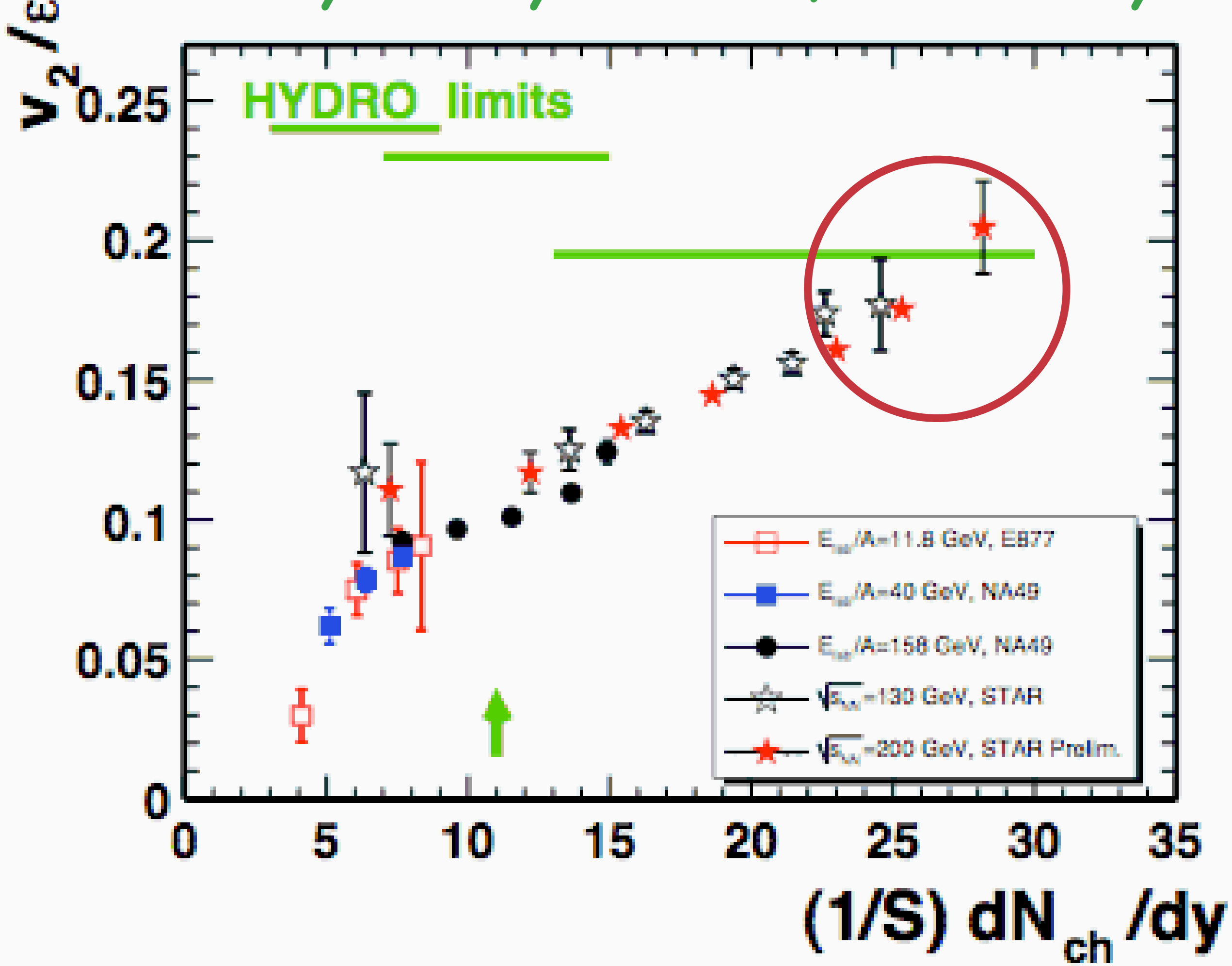
$$\frac{dN}{d(\Psi - \phi)} \propto 1 + 2v_2 \cos(\Psi - \phi) + \ldots$$

Weak Interactions
particles emitted
isotropically
small v_2

Strong Interactions
particles emitted
in reaction plane
large v_2

How Does the Matter Behave?

Ideal Hydrodynamics, viscosity = 0

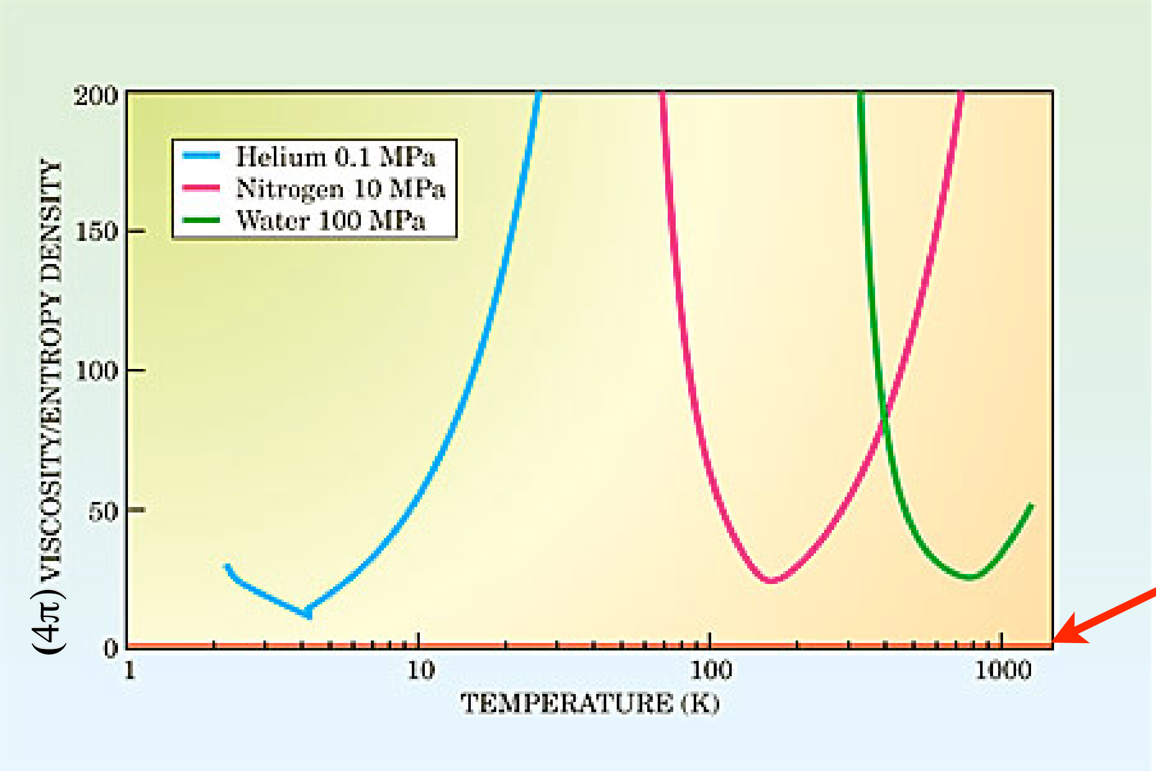


RHIC

energy density →

U. Heinz

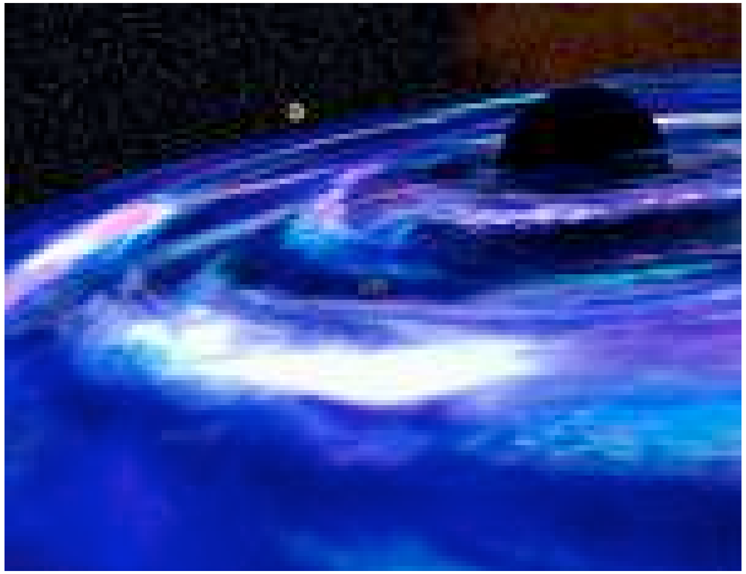
A Most Perfect Fluid?



conjectured lower bound

- conjectured lower bound to viscosity/entropy density (Kovtun, et al. PRL 94 111601 (2005))
  - initial estimates from RHIC data put ratio @ a few times the conjectured lower bound

An Exotic Connection?



- calculation done on 10 dimensional black holes
  - based on the insight from string theory of the duality between 4 dimensional strongly coupled gauge theories and higher dimensional gravity theories (Maldacena Adv. Theor. Math. Phys. 2, 231, 1998)

The Matter @ RHIC

- behaves as matter:
    - hydrodynamcially with very small viscosity
    - propagation of Mach Cones
- opaque:
    - energy loss in colored matter
- hot
    - estimated initial temperature 300-600MeV
- matter provides a unique way to study QCD itself
    - color transparent proton production

What's Ahead?

- Quantitative, Differential Measurements of the produced matter
  - heavy quarks are/will providing new constraints on matter properties & hadron production
  - vary the initial conditions: change collision energy & system size
- Explore whether we can use the matter to understand more about QCD, string theory, strong coupled systems, ...