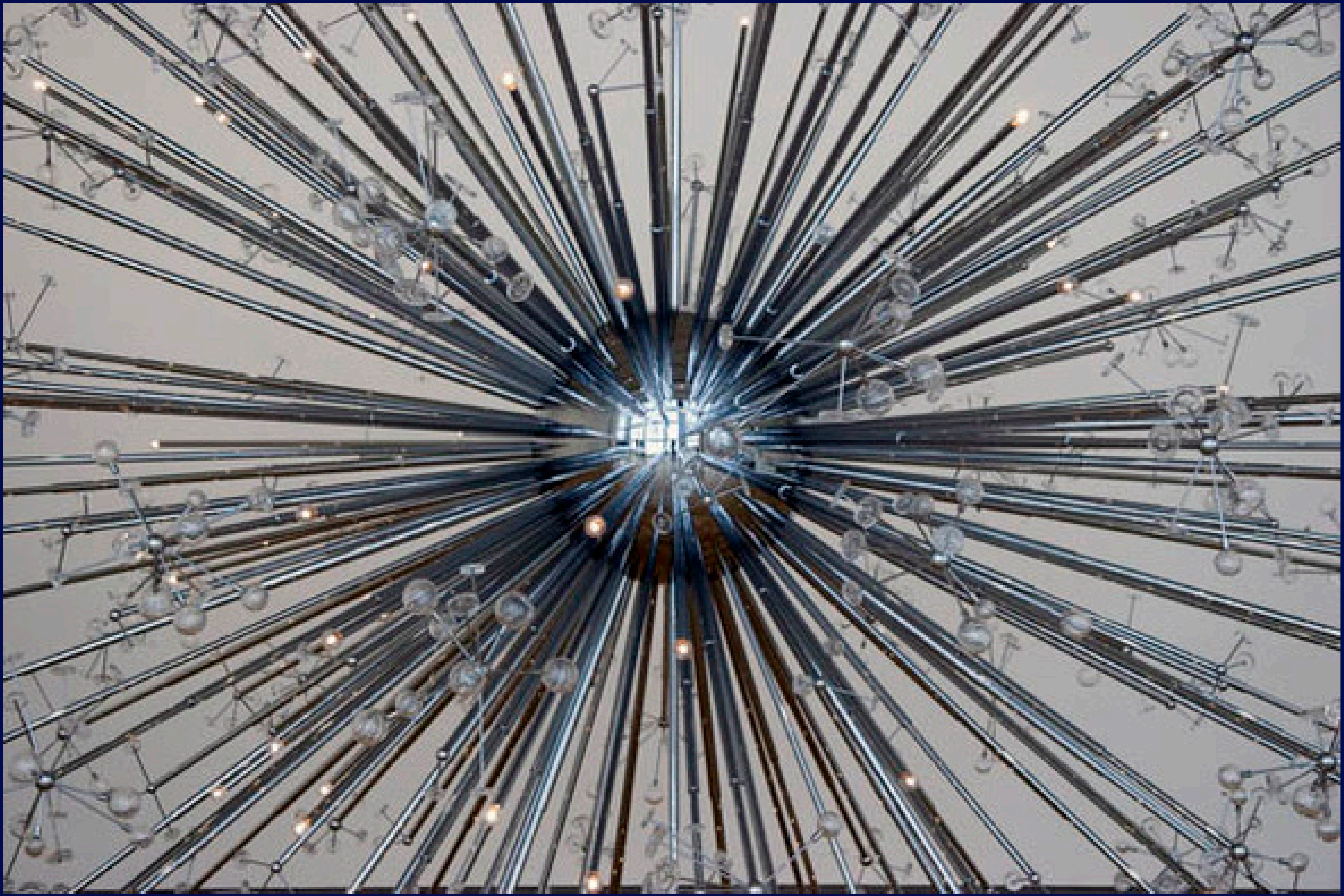


3 Lectures

- **Lecture 1**
  - Introduction to Heavy Ion Collisions
- **Lecture 2**
  - Hydrodynamics in Heavy Ion Collisions
- **Lecture 3**
  - Probing the Near-Perfect Fluid at RHIC

Lecture 3

Probing the Near-Perfect Fluid at RHIC

Peter Steinberg
Brookhaven National Laboratory
National Nuclear Physics Summer School, July 2007

Qualitative Assessment

Hotter (>10^{12} ^{o}K)
Denser (>30 GeV/fm^3)
Smaller (~6 fm)
Faster (τ_0<1 fm/c)

and "nearly" perfect

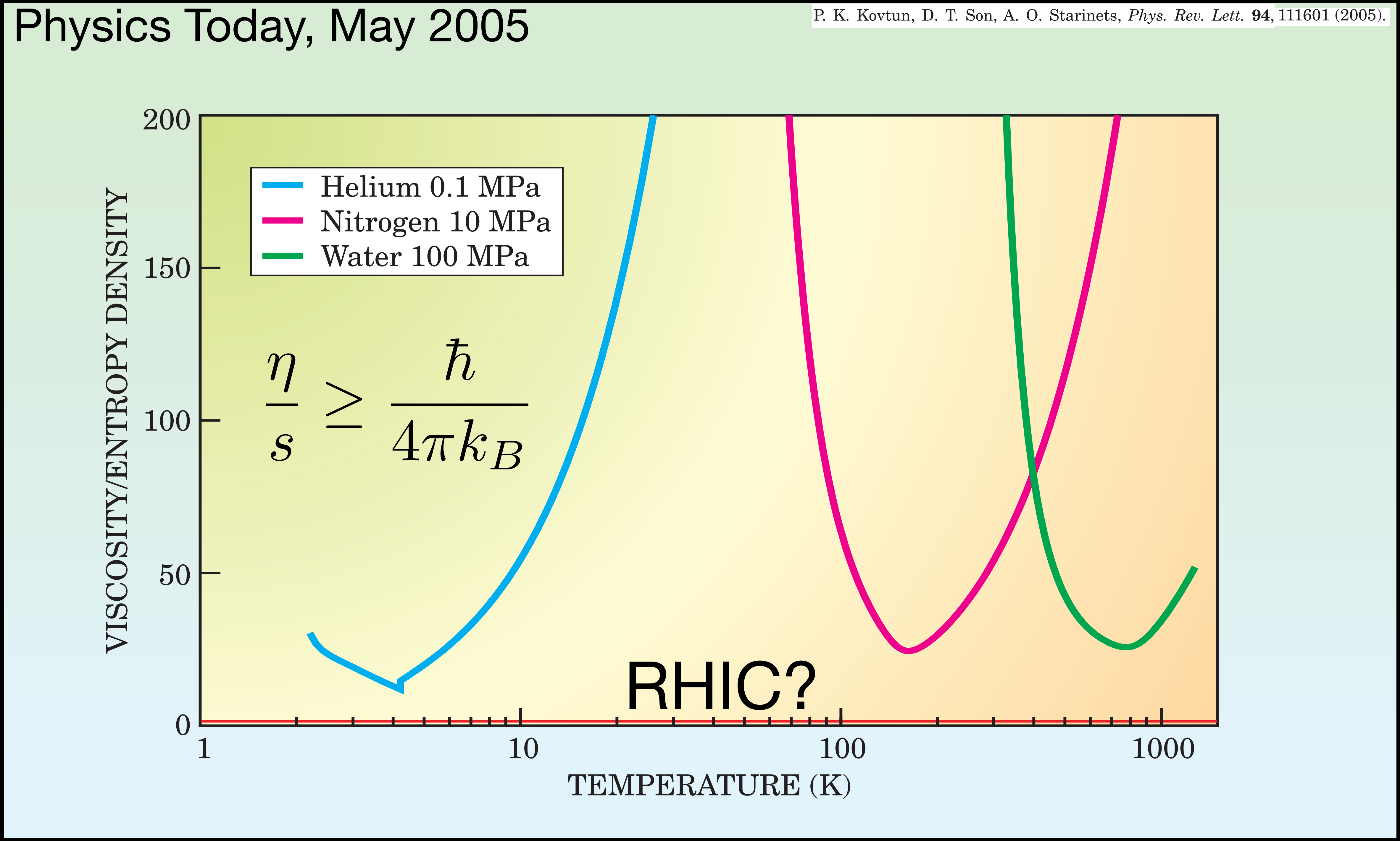
Quantitative Assessment

What is the

Thermalization time
Energy density
Stopping power
Viscosity

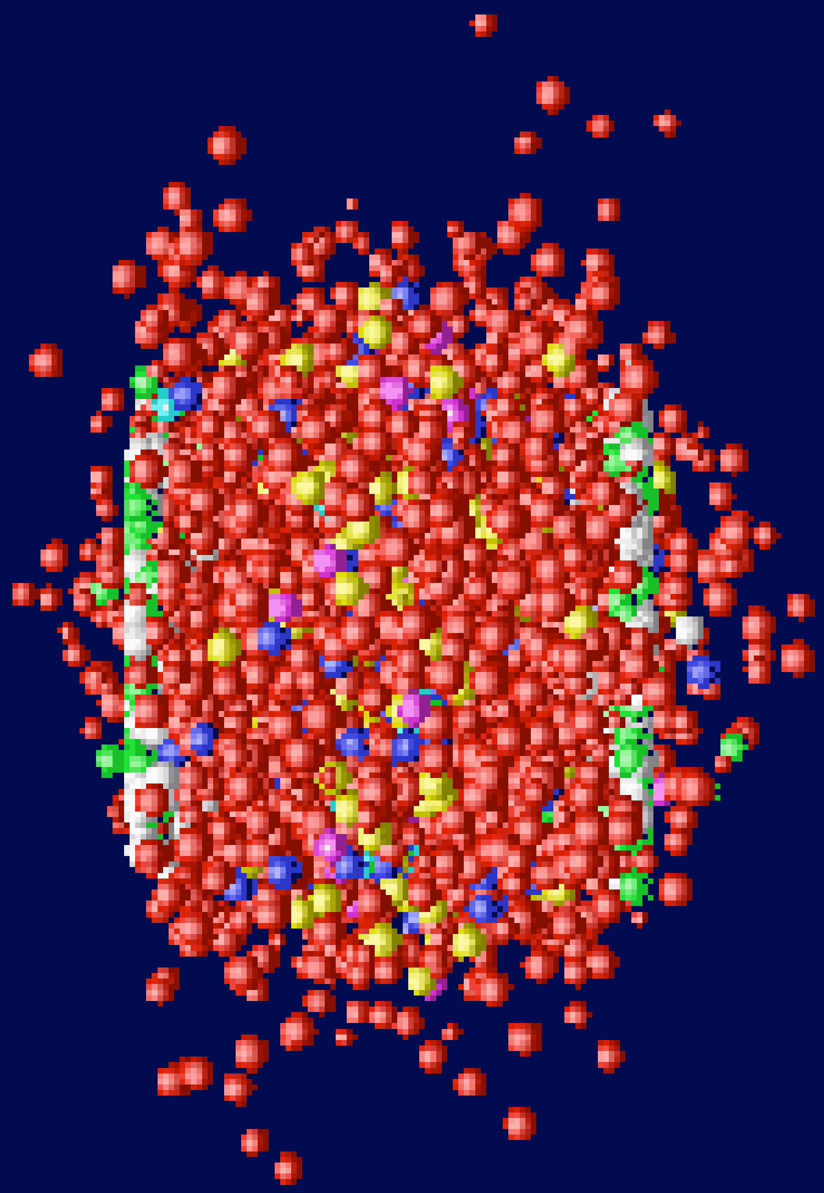
and with what
precision**?**

Lower Viscosity Bound



A perfect liquid is impossible - but is RHIC the most perfect?

What is the fluid made of?



<u>Rapidly</u> thermalized matter

$$\tau_0 \ll 1 fm/c$$

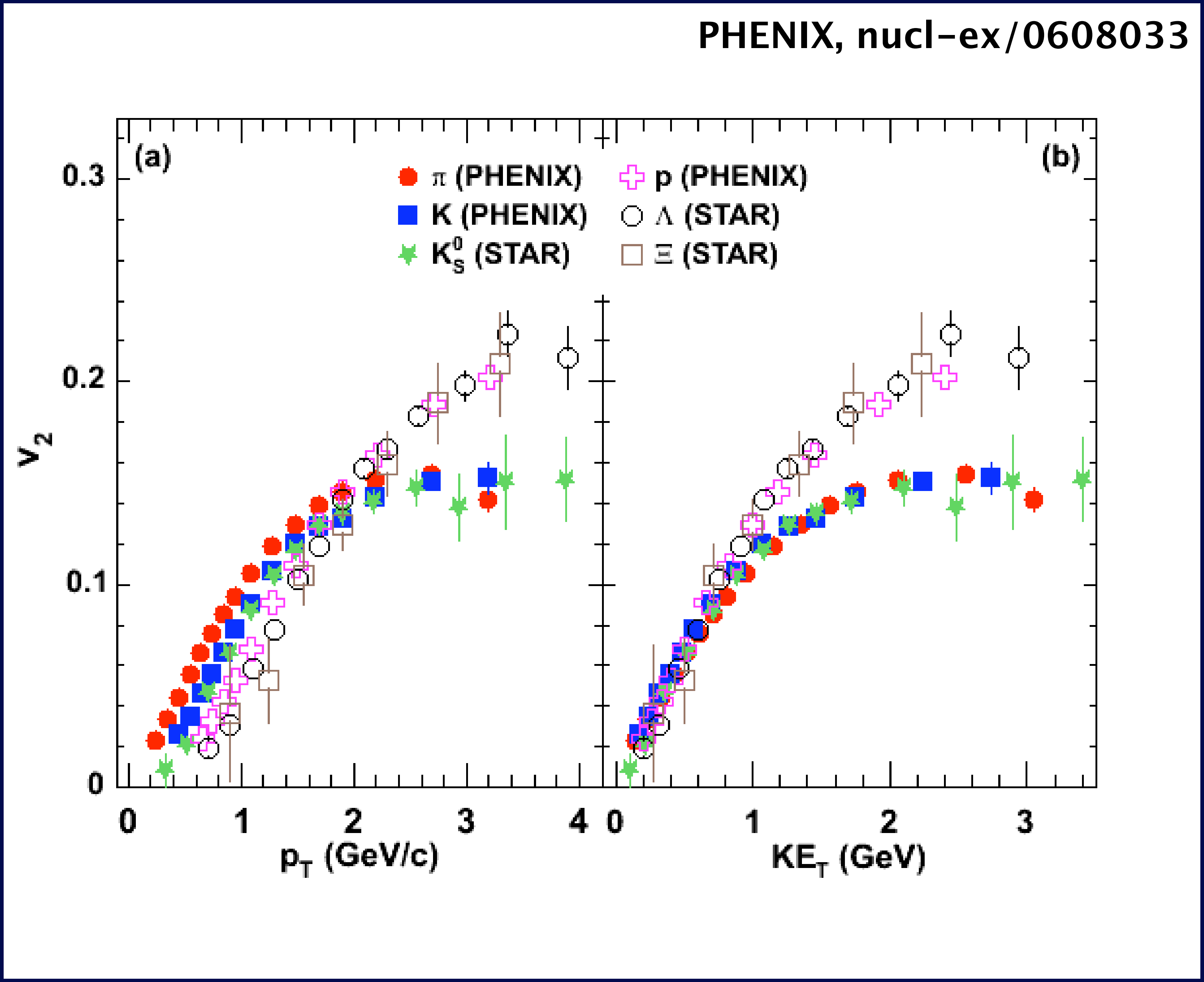
But of what? and how so fast?

Quarks & gluons?
Is it a real "quark-gluon plasma" (QGP)?

Constituents

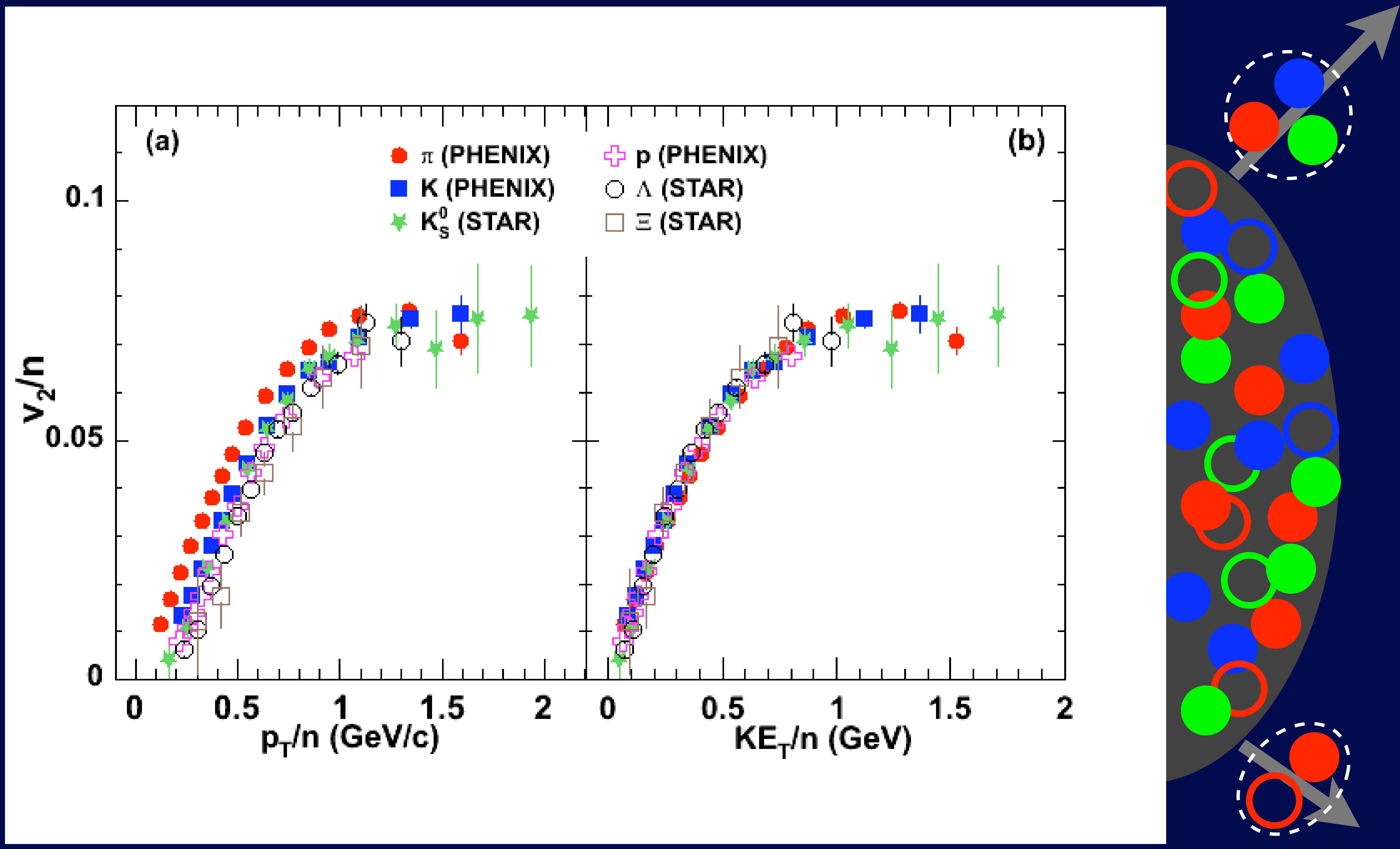
- **Perturbative quarks and gluons**
  - well-defined, but cross sections too small
- **Hadrons**
  - How can a hadron (R~1 fm) survive when the energy density is >10x the energy density of a proton?
- **"Constituent Quarks"**
  - What are these? Dressed quarks? Is there a theory for them?
- **"New" hadrons (Brown, Shuryak, etc.)**
  - Any experimental or lattice hint of new mass states in QCD plasma?

Identified Particle Flow



Complicated particle dependence of v_2 vs. p_T
is simpler when plotted vs. kinetic energy: $\boldsymbol{KE_T = m_T - m}$

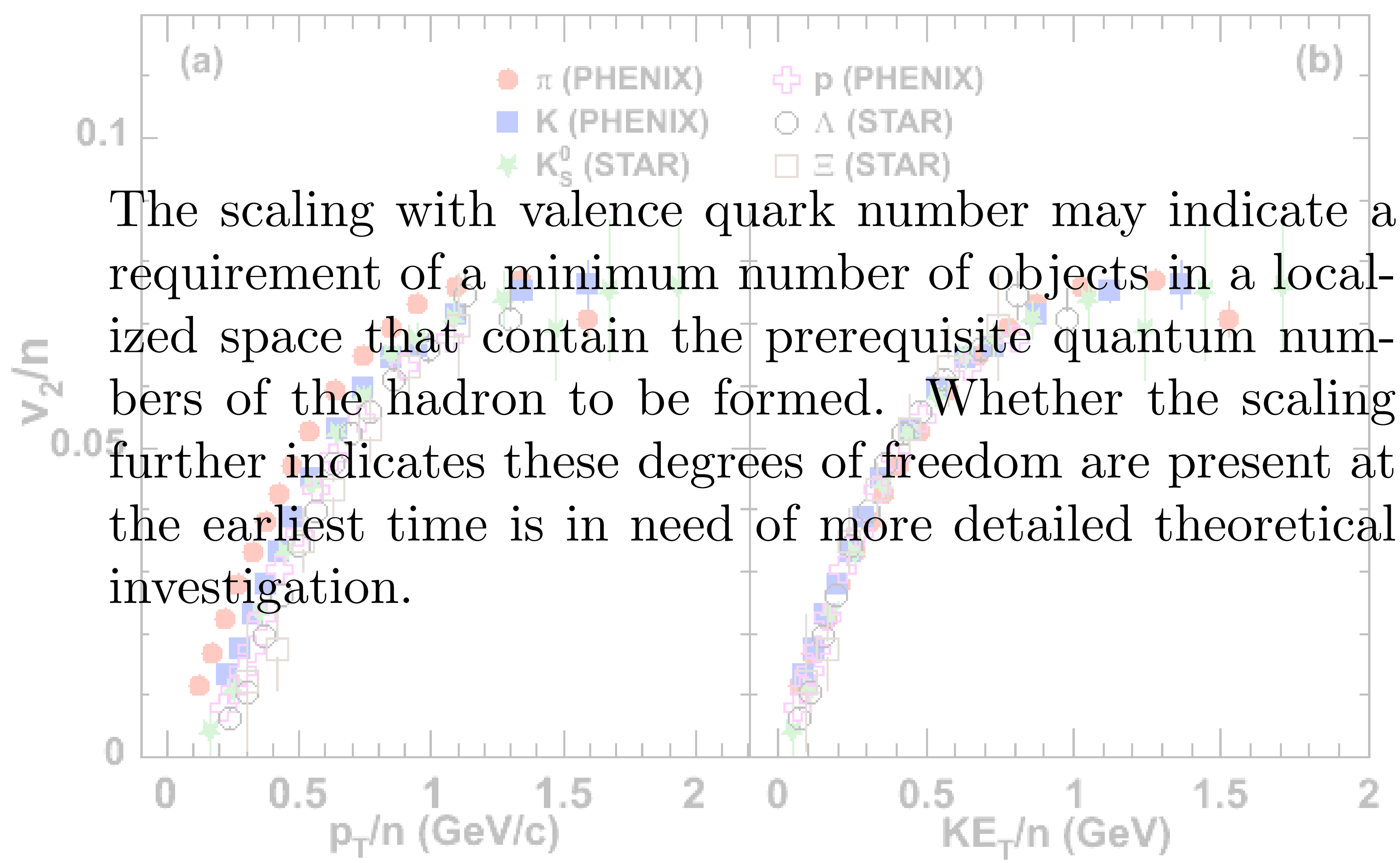
Constituent Quark QGP?



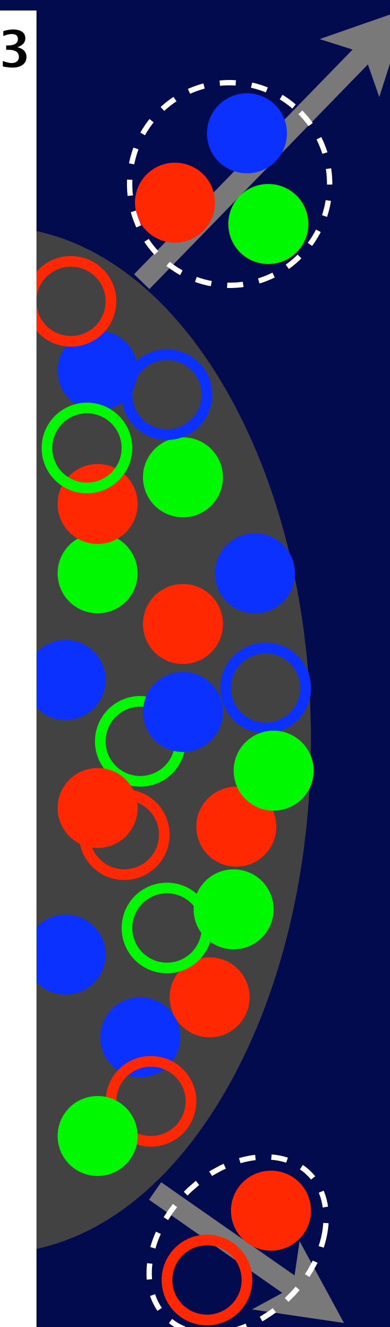
Even simpler when dividing by the number of constituent quarks (CQ): is the QGP a fluid of quarks?

Constituent Quark Scaling?

PHENIX, nucl-ex/0608033



The scaling with valence quark number may indicate a requirement of a minimum number of objects in a localized space that contain the prerequisite quantum numbers of the hadron to be formed. Whether the scaling further indicates these degrees of freedom are present at the earliest time is in need of more detailed theoretical investigation.



Degrees of Freedom

Parton distributions,
Nuclear Geometry,
Nuclear shadowing

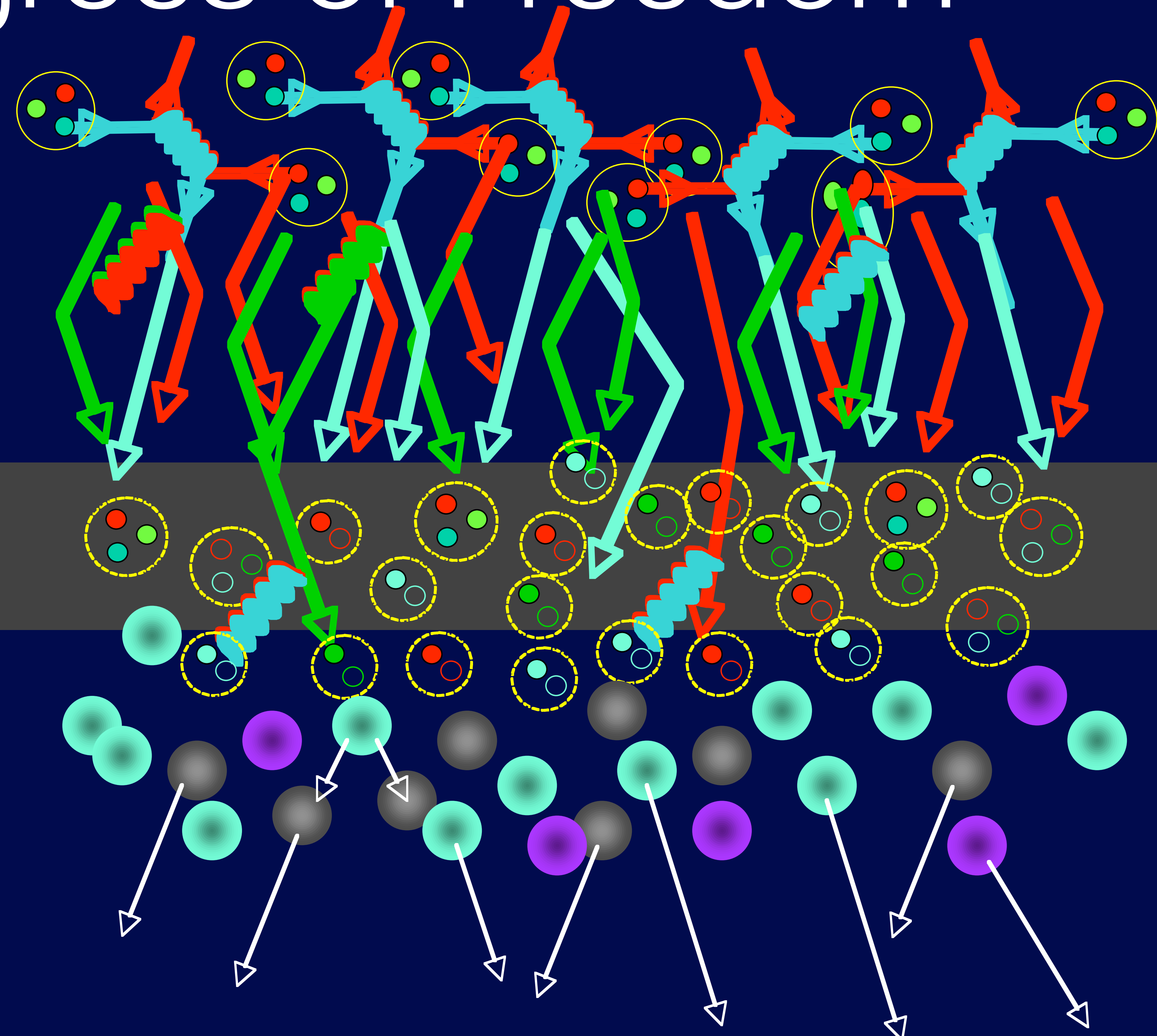
Parton production &
reinteraction
(or, sQGP!)

Chemical freezeout
(Quark recombination)

Jet fragmentation functions

Hadron rescattering

Thermal freezeout &
Hadron decays



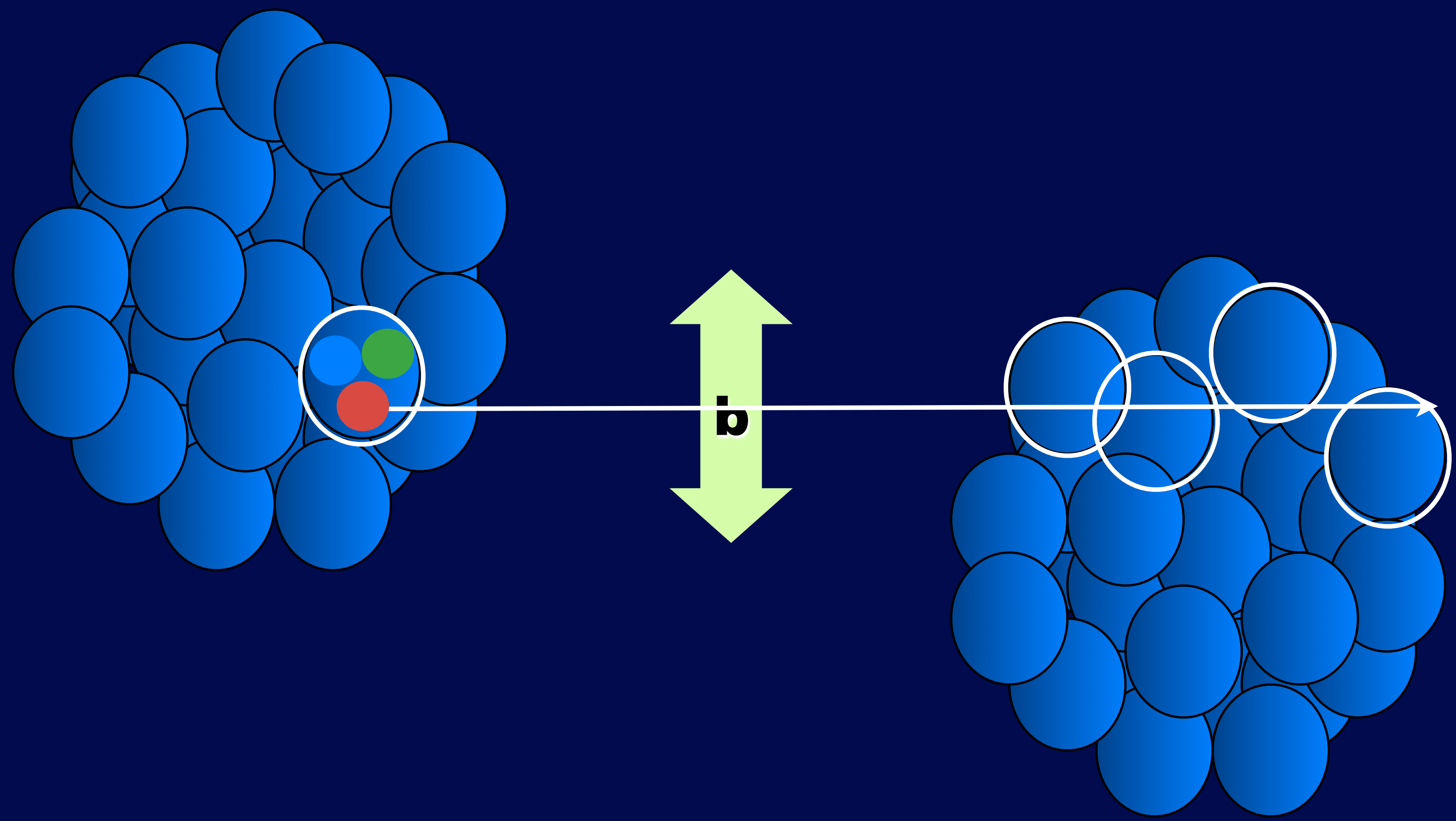
Probing the sQGP

- **Ideal fluid**
  - No particle states, no mean free path
  - Can only extract properties indirectly, via EOS
- **Non (near?)-ideal fluid**
  - Finite mean free path (MFP): a natural scale which is present during the evolution
  - Viscosity is directly related to MFP:

$$\lambda \sim \frac{1}{n\sigma} \sim \frac{\eta}{sT}$$

- **Need probes that couple to the system during evolution!**

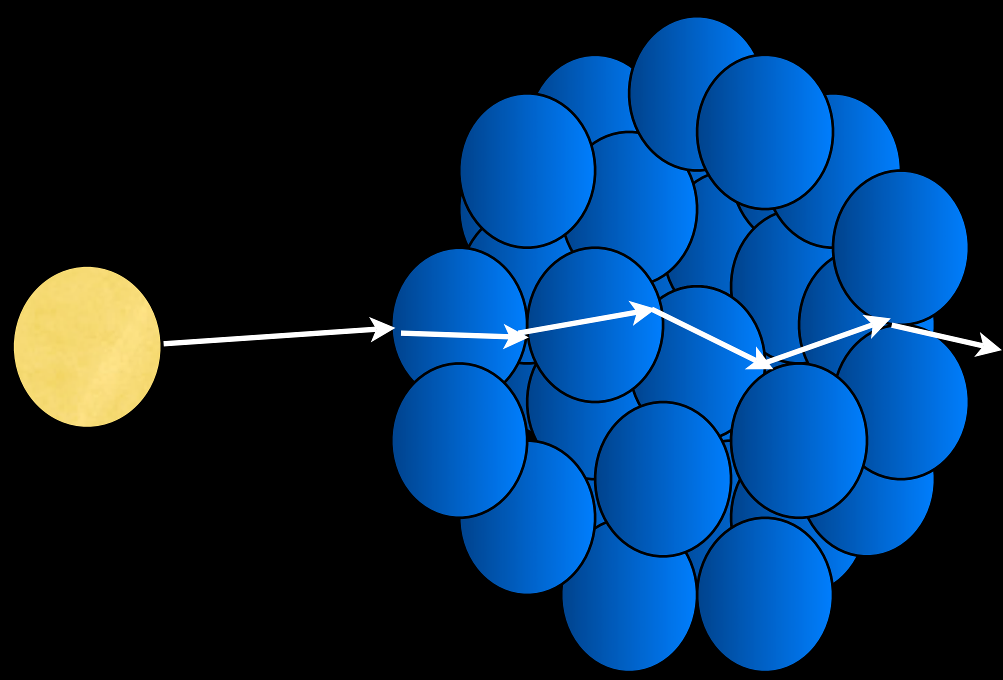
Perturbative Physics @ RHIC

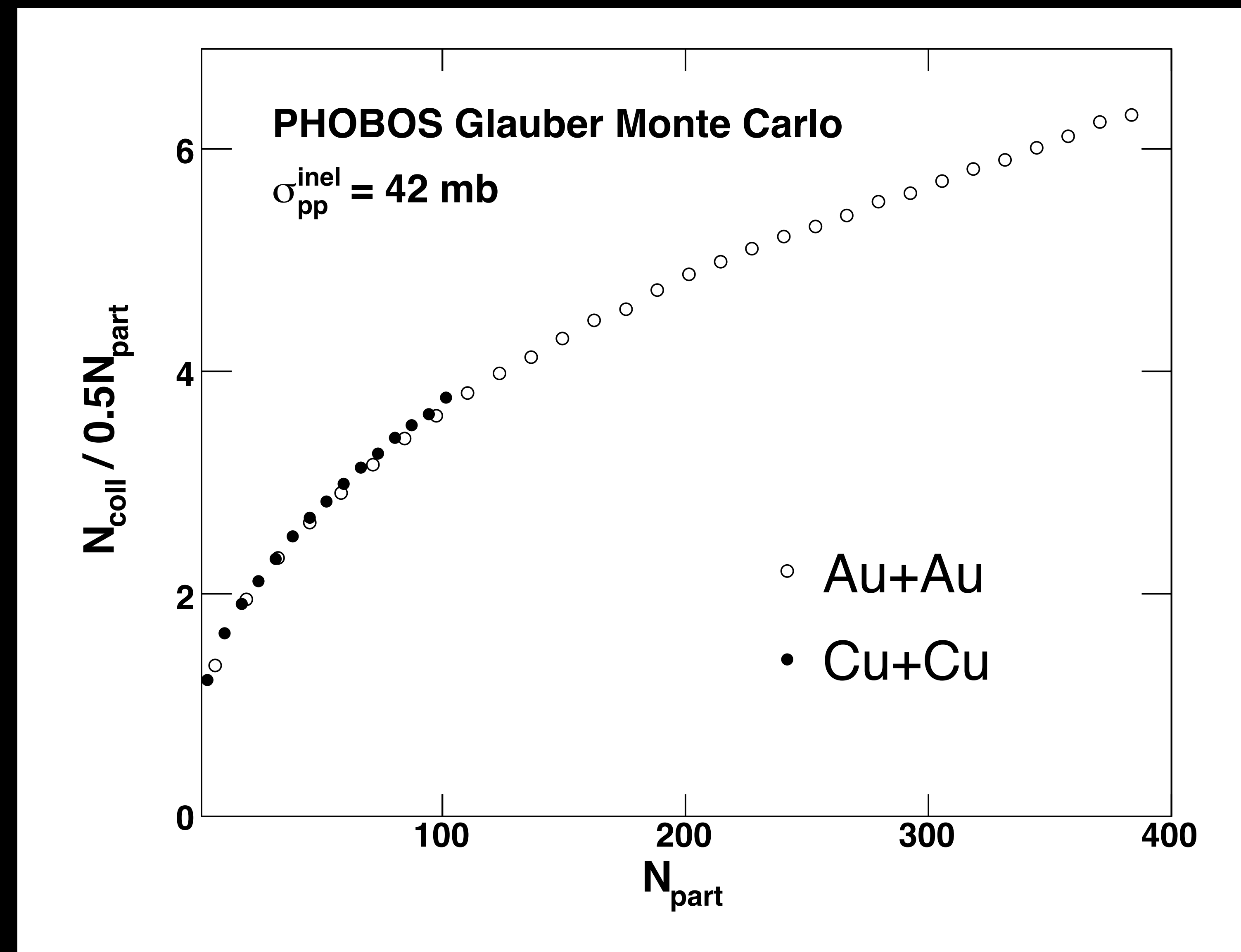


Bulk features controlled by macro “volume”: N_{part}
In principle, short distance physics should be sensitive to the “micro” structure, N_{coll}...

IF pQCD factorization holds true in hadron produciton in A+A
(vs. photon-mediated processes in p+p and e+p)

Participants vs. Collisions

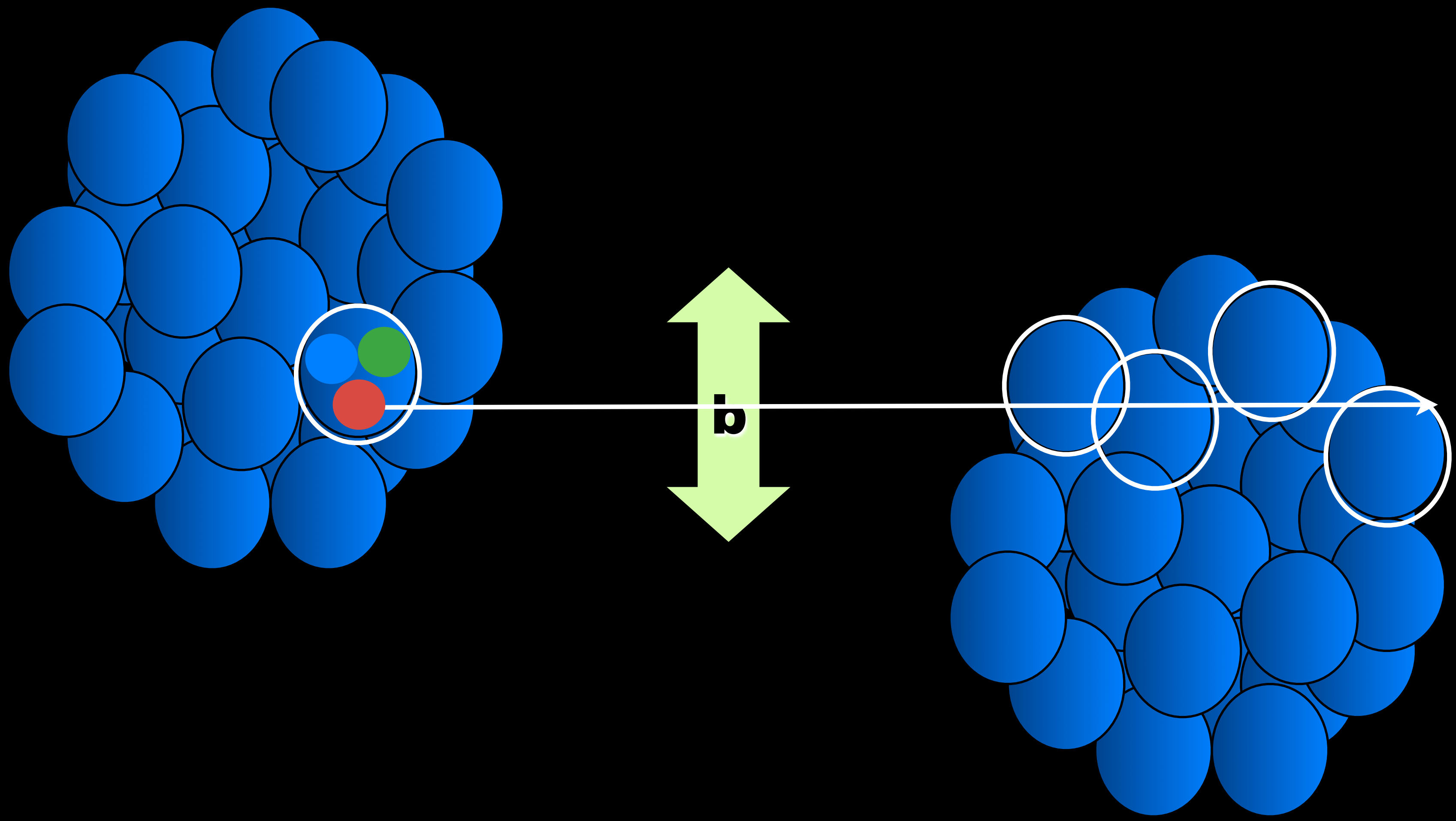




Collisions scale "like" AB, but more like $\sim N_{part}^{4/3}$.

Nuclear "thickness" (ν) scales like $N_{coll}/(N_{part}/2)$

Perturbative Physics @ RHIC

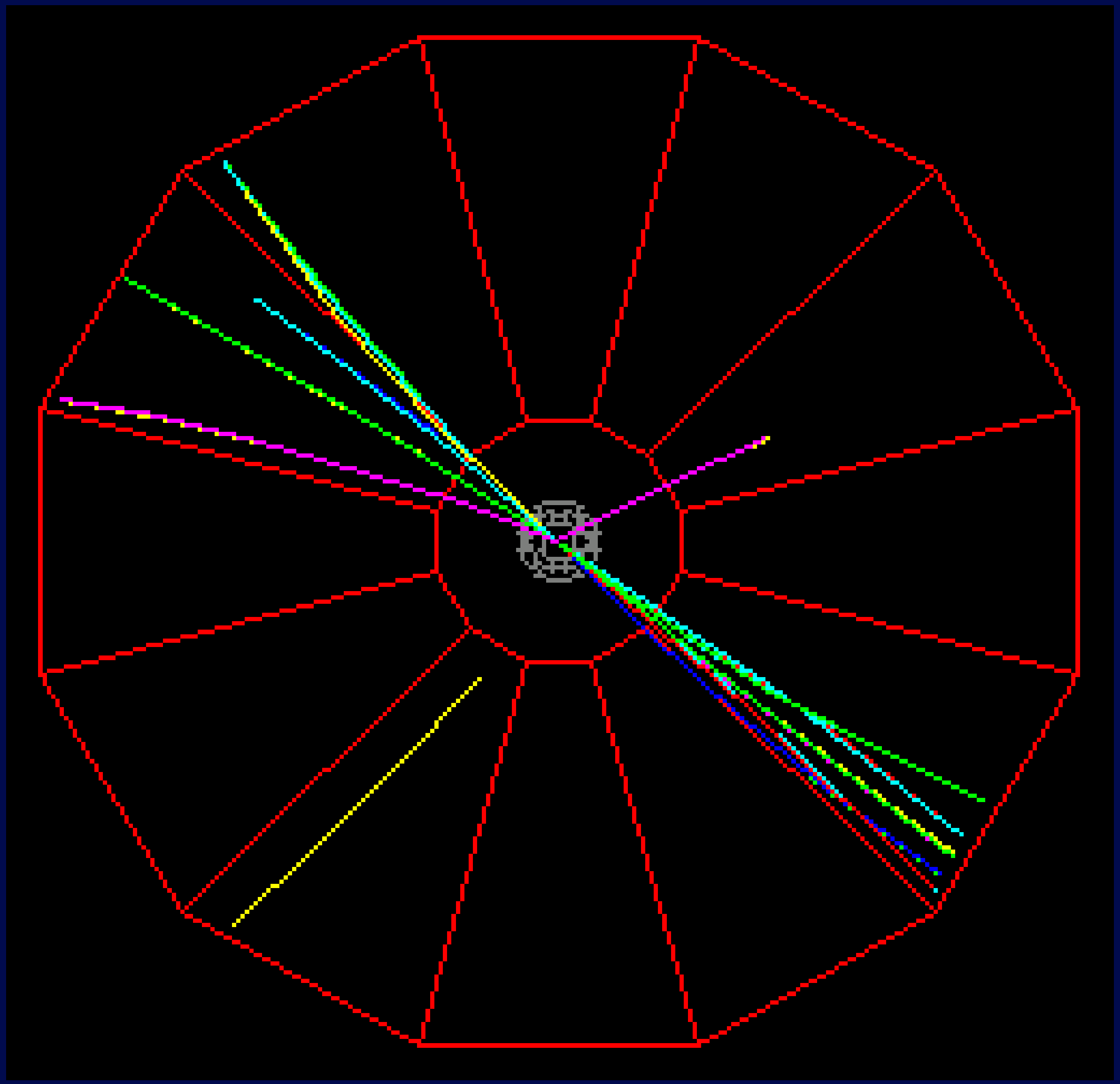


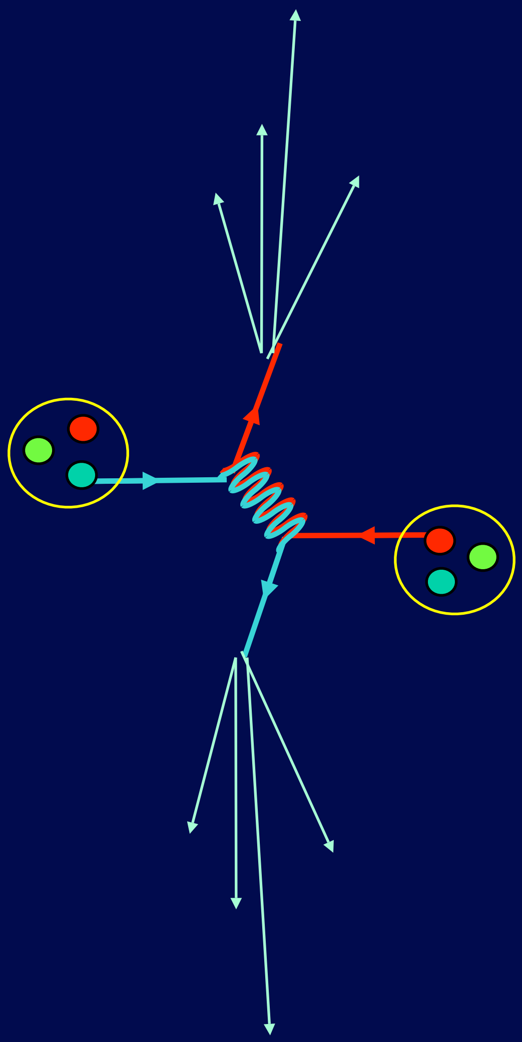
$$R_{AB} = \frac{1}{N_{coll}^{AB}} \frac{\frac{dN_{AB}}{dp_T}}{\frac{dN_{pp}}{dp_T}}$$

Yield per collision relative to p+p

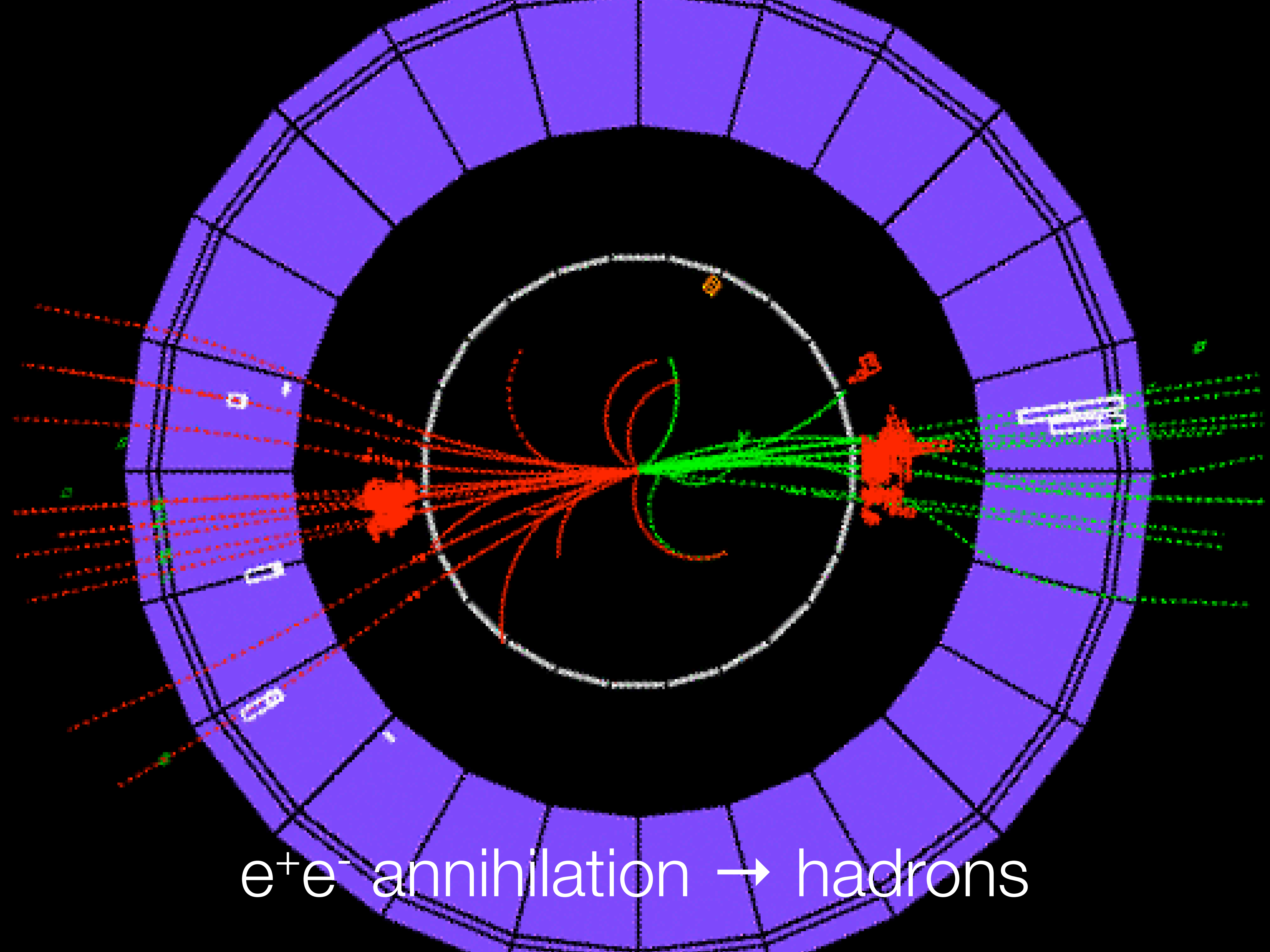
< 1 implies "nuclear effect" (or no factorization)

Jets





Jets are a “hard” phenomenon, characterized by large momentum transfer between partons
→ perturbative description



e^+e^- annihilation $\rightarrow$ hadrons

Fragmentation Functions

In simple reaction:

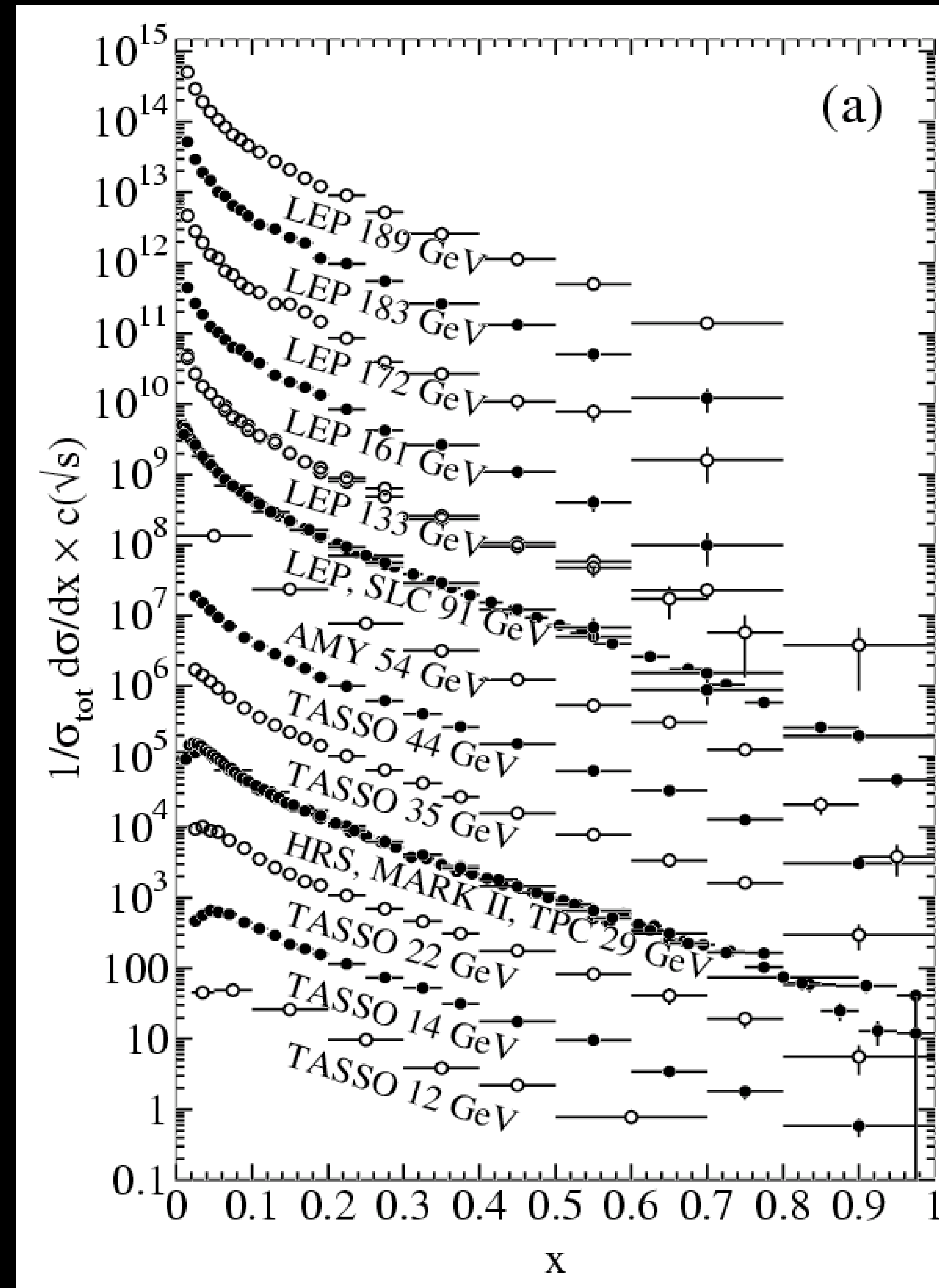
$$e^+ + e^- \to h + X$$

can define

"fragmentation function"

$$F^h_{(D(z))} = \frac{1}{\sigma_{tot}} \frac{d\sigma}{dx} \qquad x = \frac{2E_h}{\sqrt{s}}$$

$$t\frac{\partial}{\partial t} F_i^h(x,t) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s(s)}{2\pi} P_{ji}(z,\alpha_s) F_j^h(x/z,t)$$



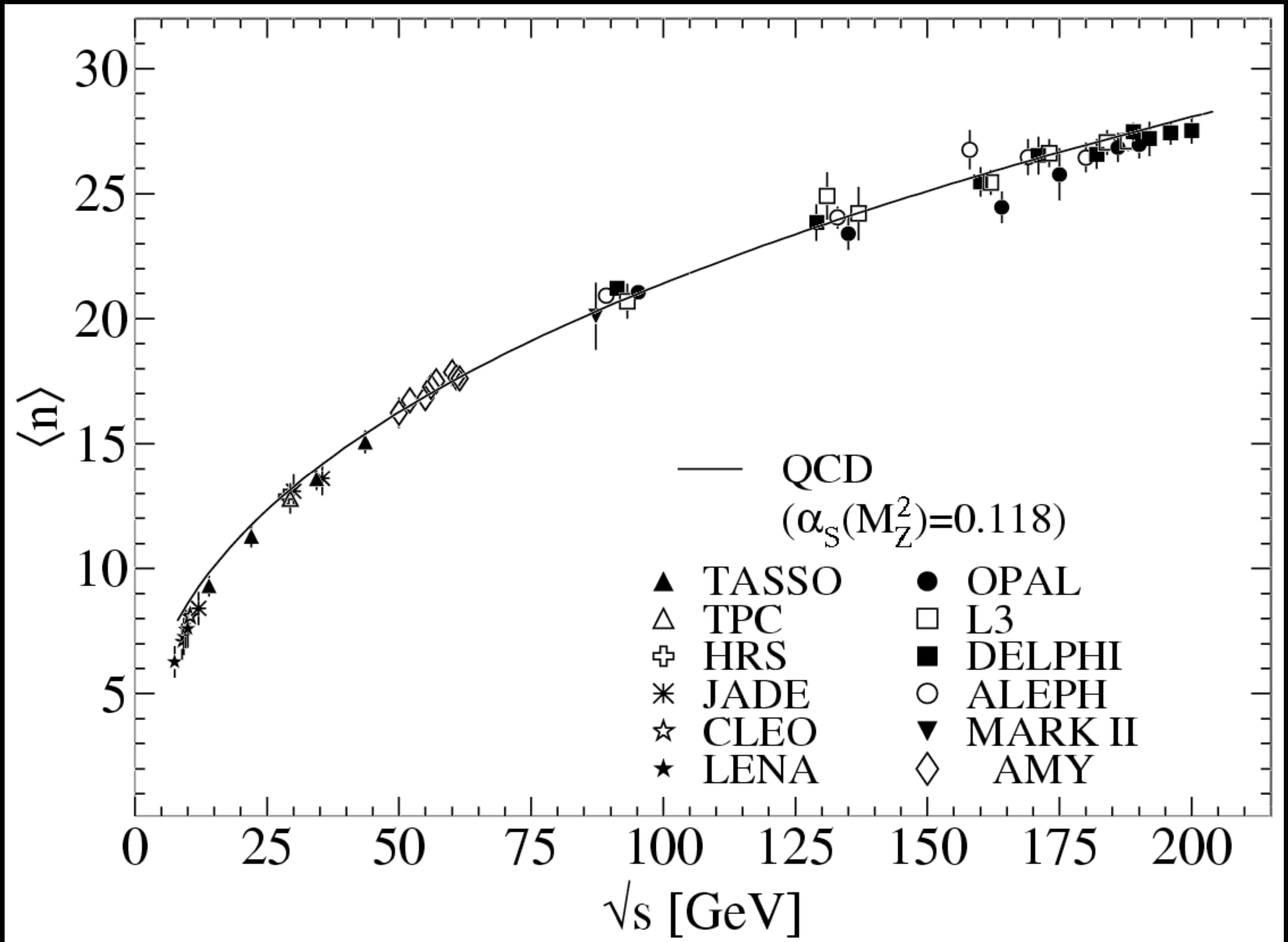
Review article in Review of Particle Properties

pQCD predicts N_{ch}

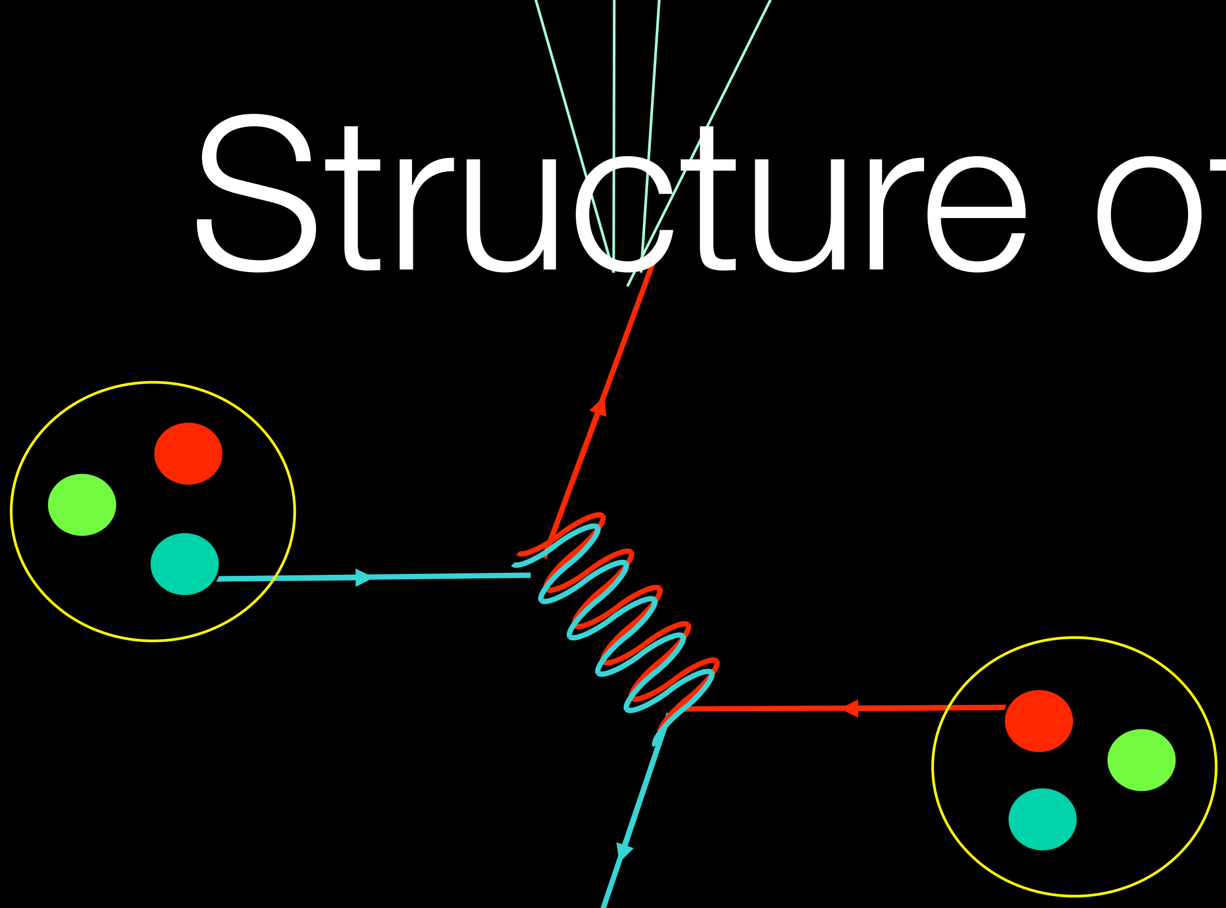
Total hadron yields are integrals of fragmentation function

$$n_h = \int F^h(x)dx$$

Evolution of multiplicity predictable in pQCD (not absolute scale!) in modified leading-log approximation



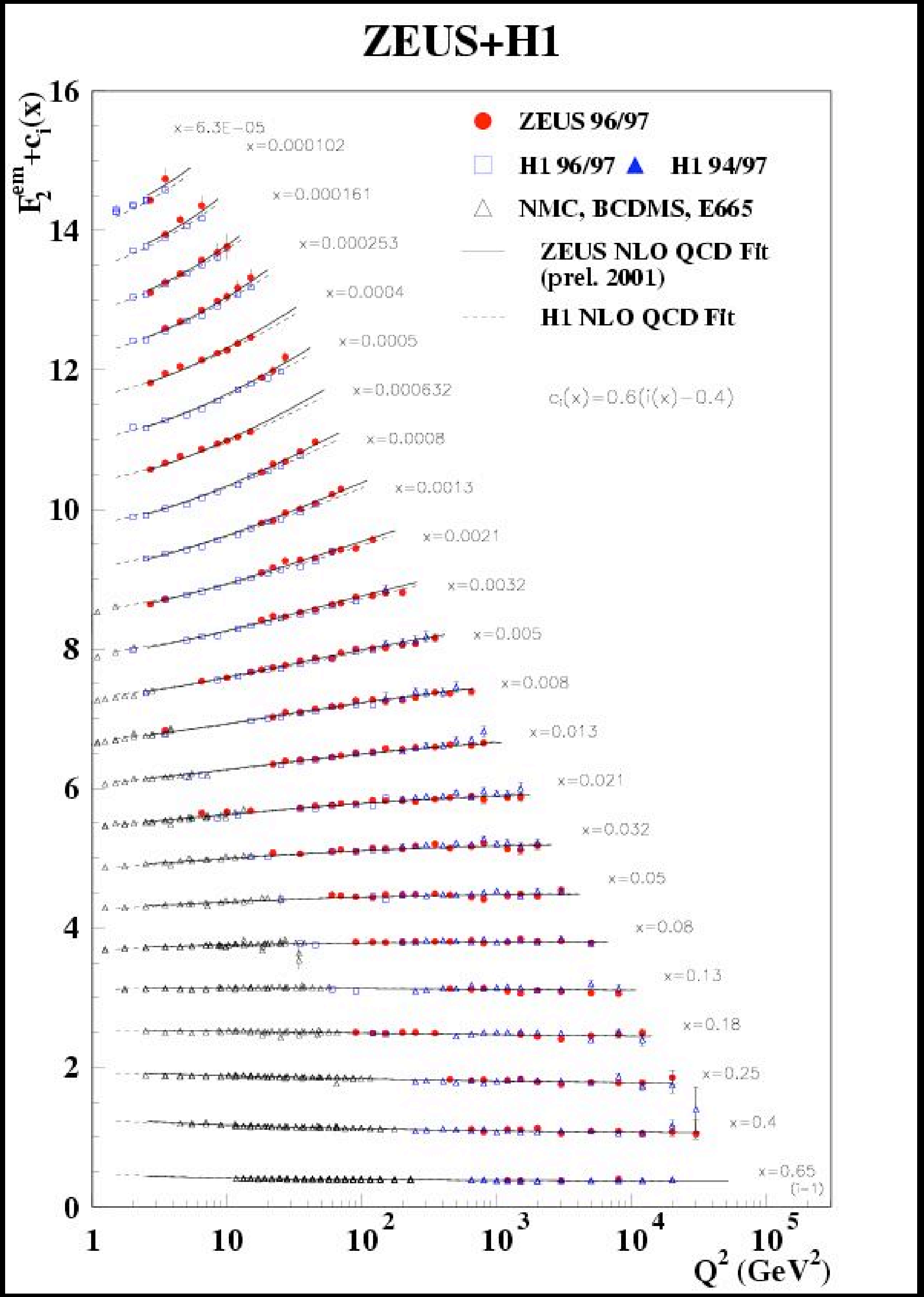
Structure of the Nucleon



Measuring structure functions (e.g. F_2 at HERA)

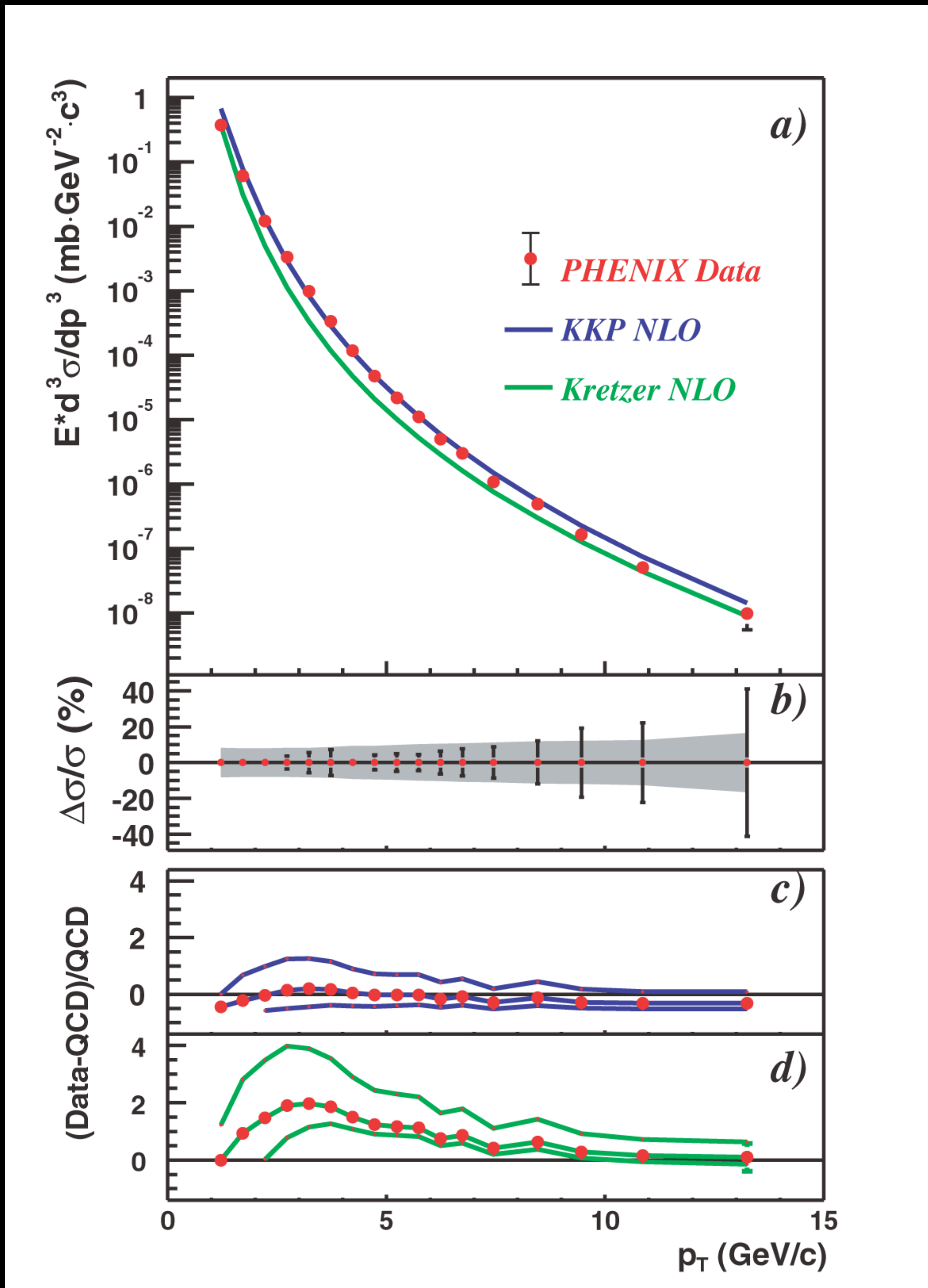
$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha_{em}^2}{Q^4}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

gives information about flux of incoming partons which can form jets. (Any reduction in flux would lead to reduction in jet rates)

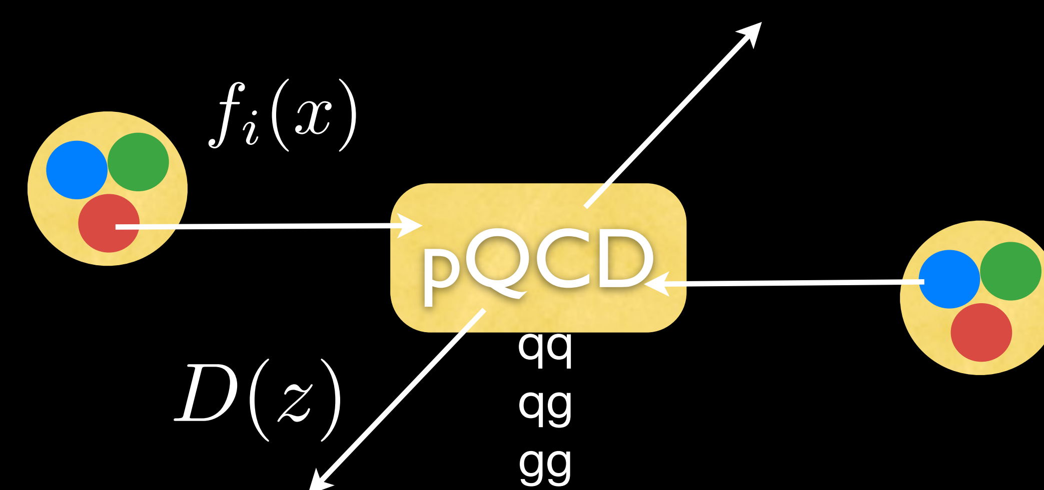


NLO pQCD describes evolution of F_2 in x and Q^2

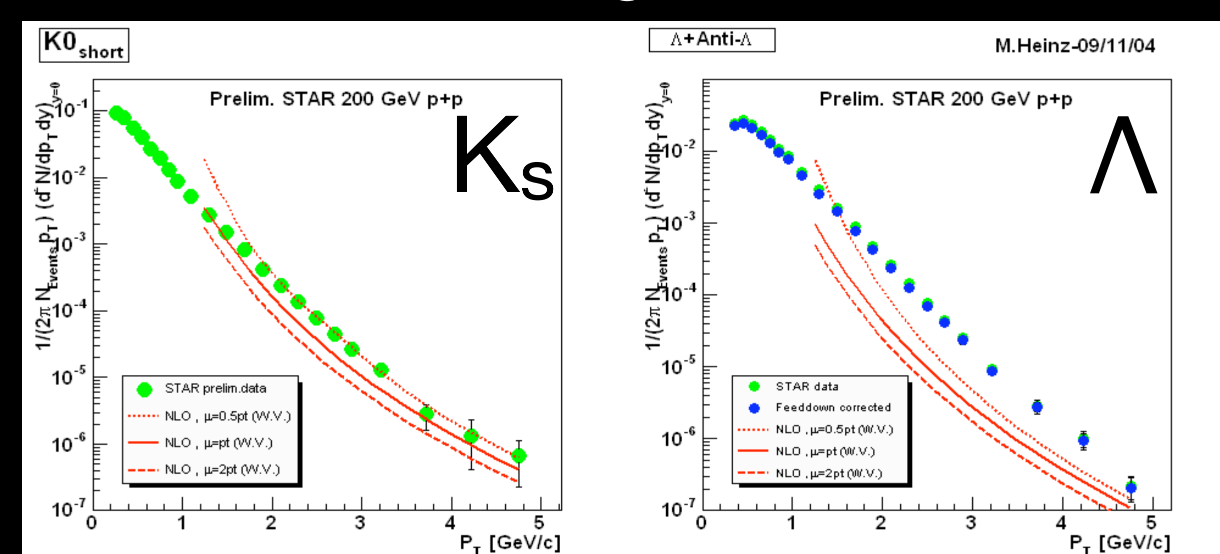
pQCD and p+p collisions



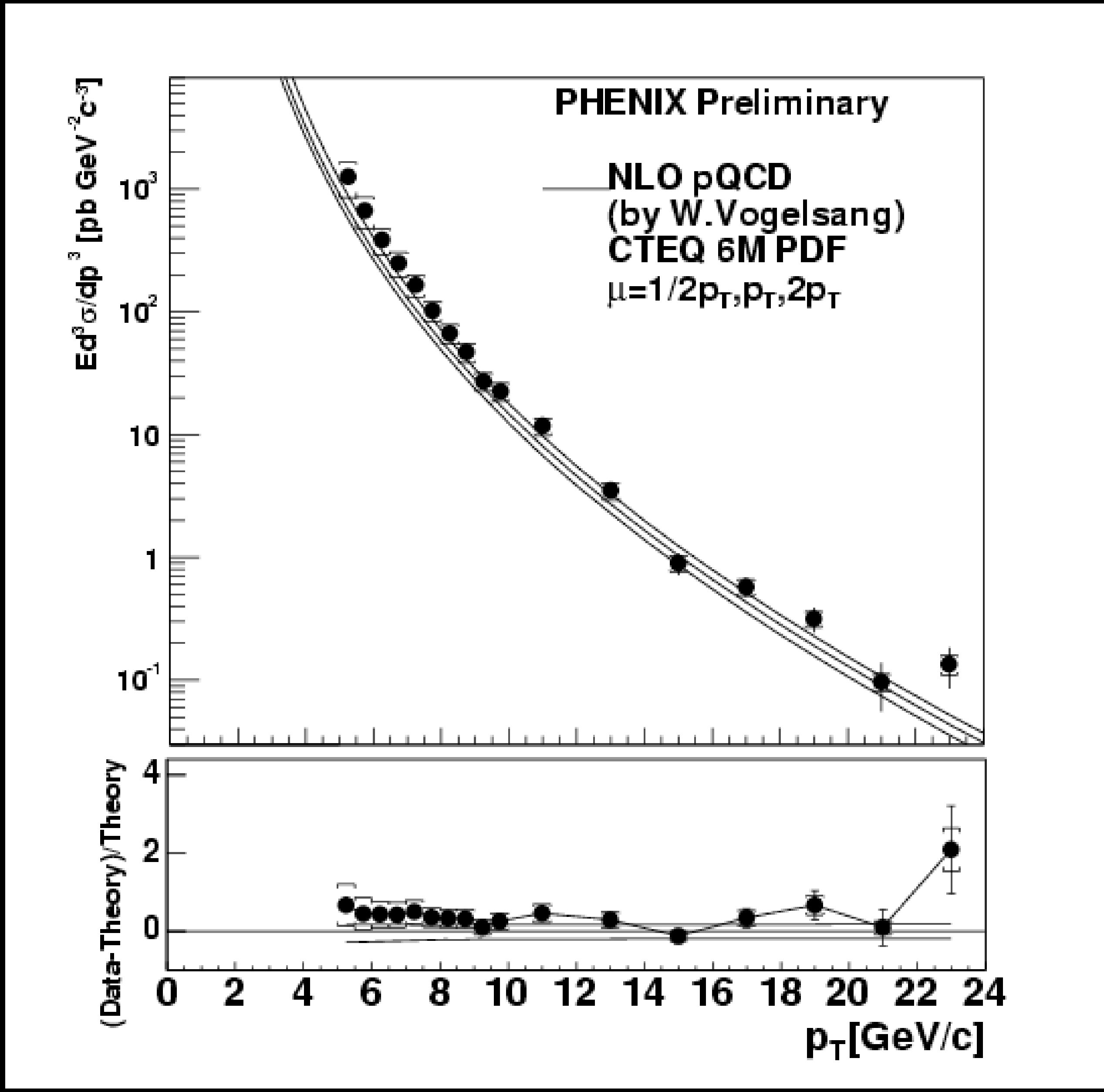
p+p data at 200 GeV is amenable to pQCD calculations for π^o & γ

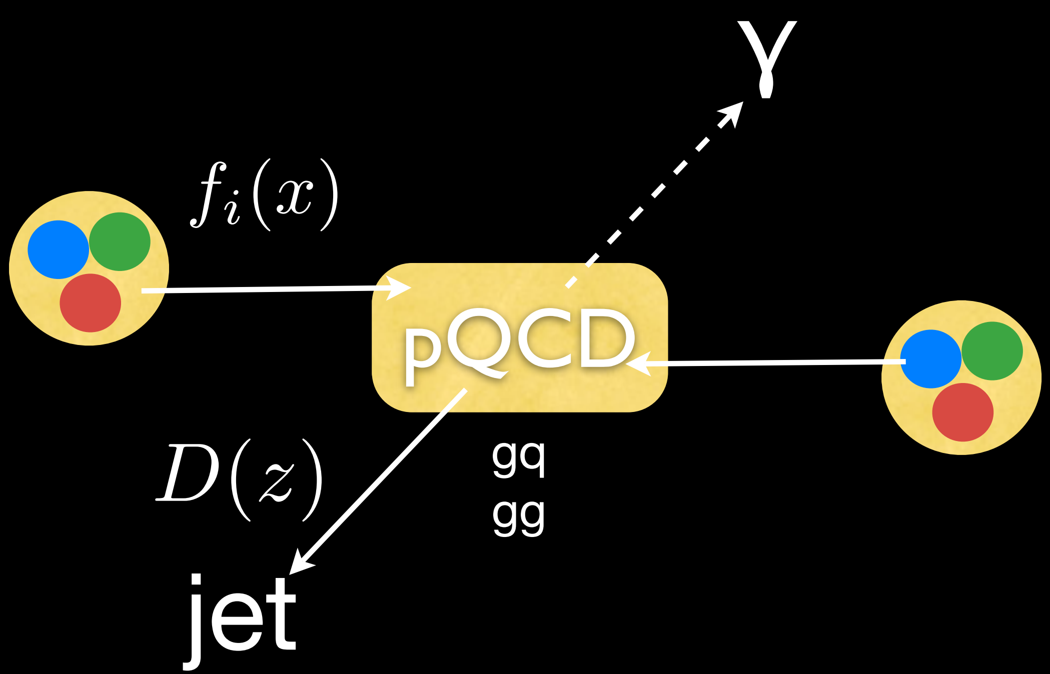


STAR preliminary p+p K_S and Λ shows issues with fragmentation functions...



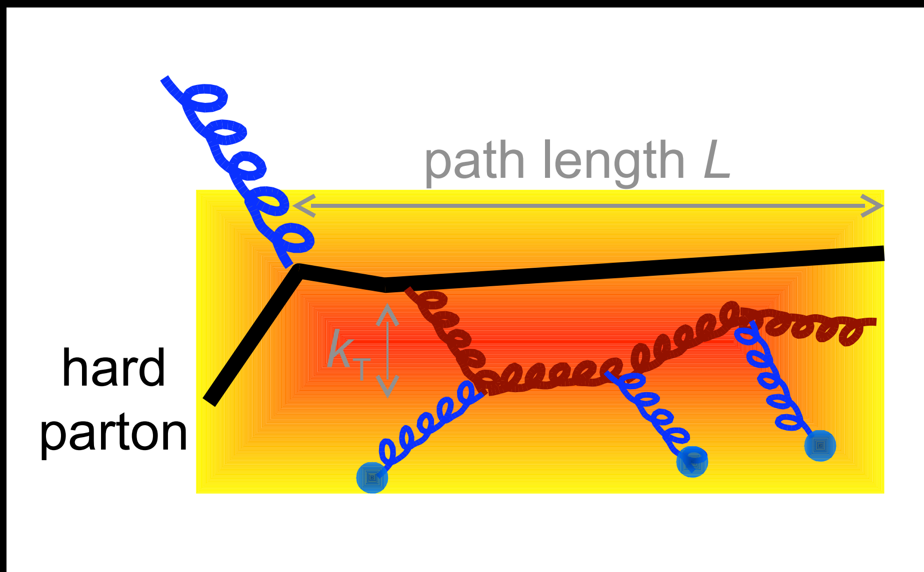
Direct Photons in p+p





Gamma + jet processes probe gluon structure of nucleon

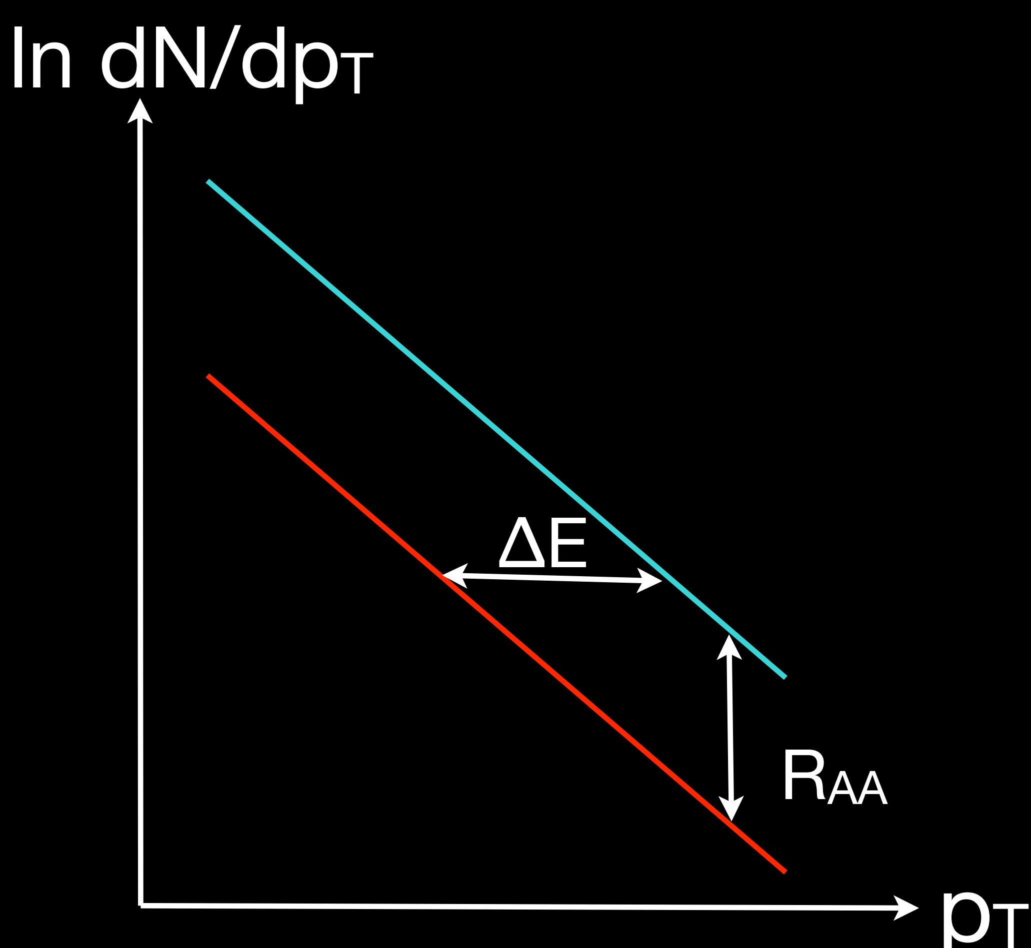
"Jet Quenching"

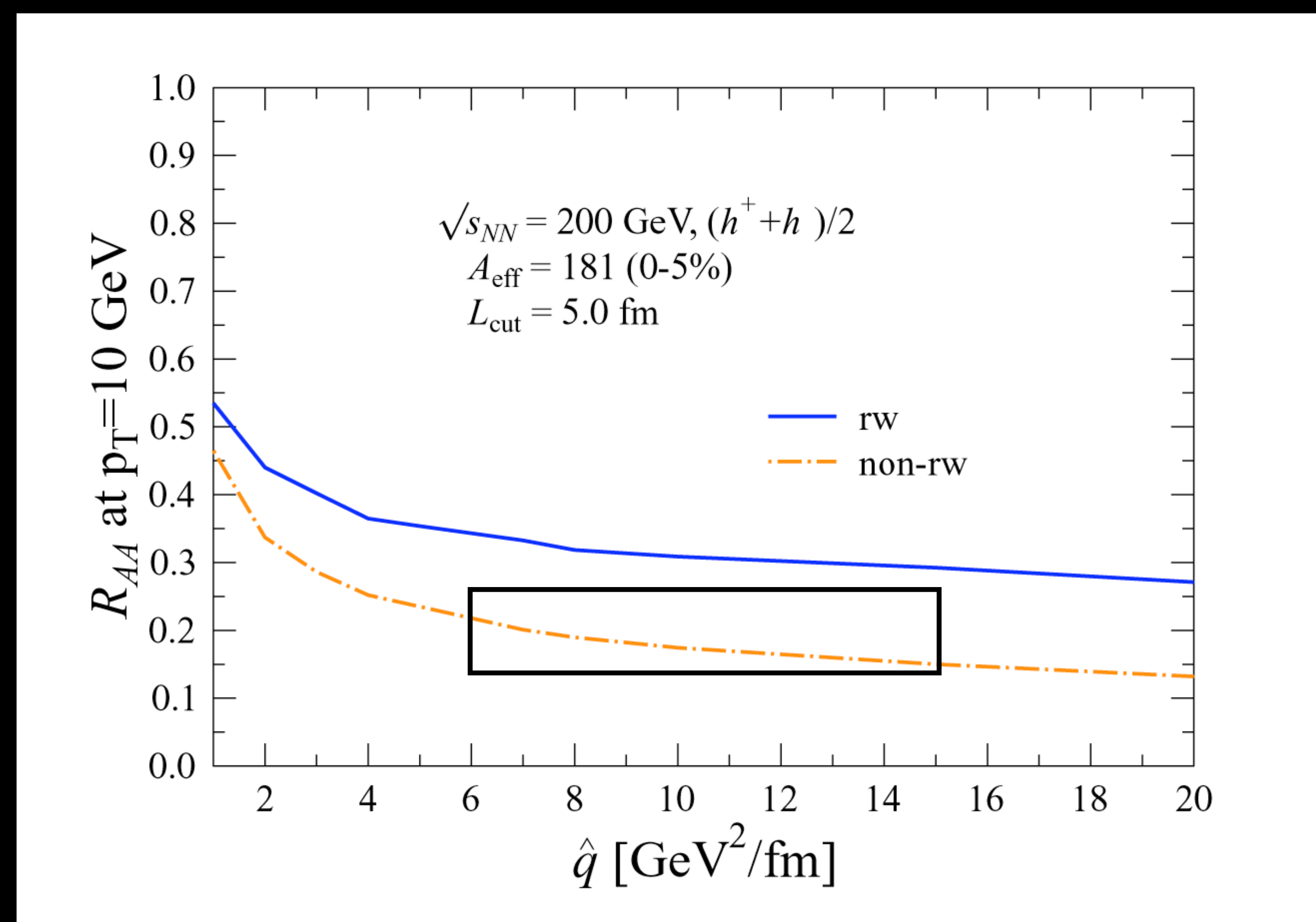


$$\langle \Delta E \rangle \approx \int_0^{\omega_c} d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_s\, C_R\, \omega_c \propto \alpha_s\, C_R\, \hat{q}\, L^2$$

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$

Transport coefficient sensitive to gluon density (not deconfinement!)

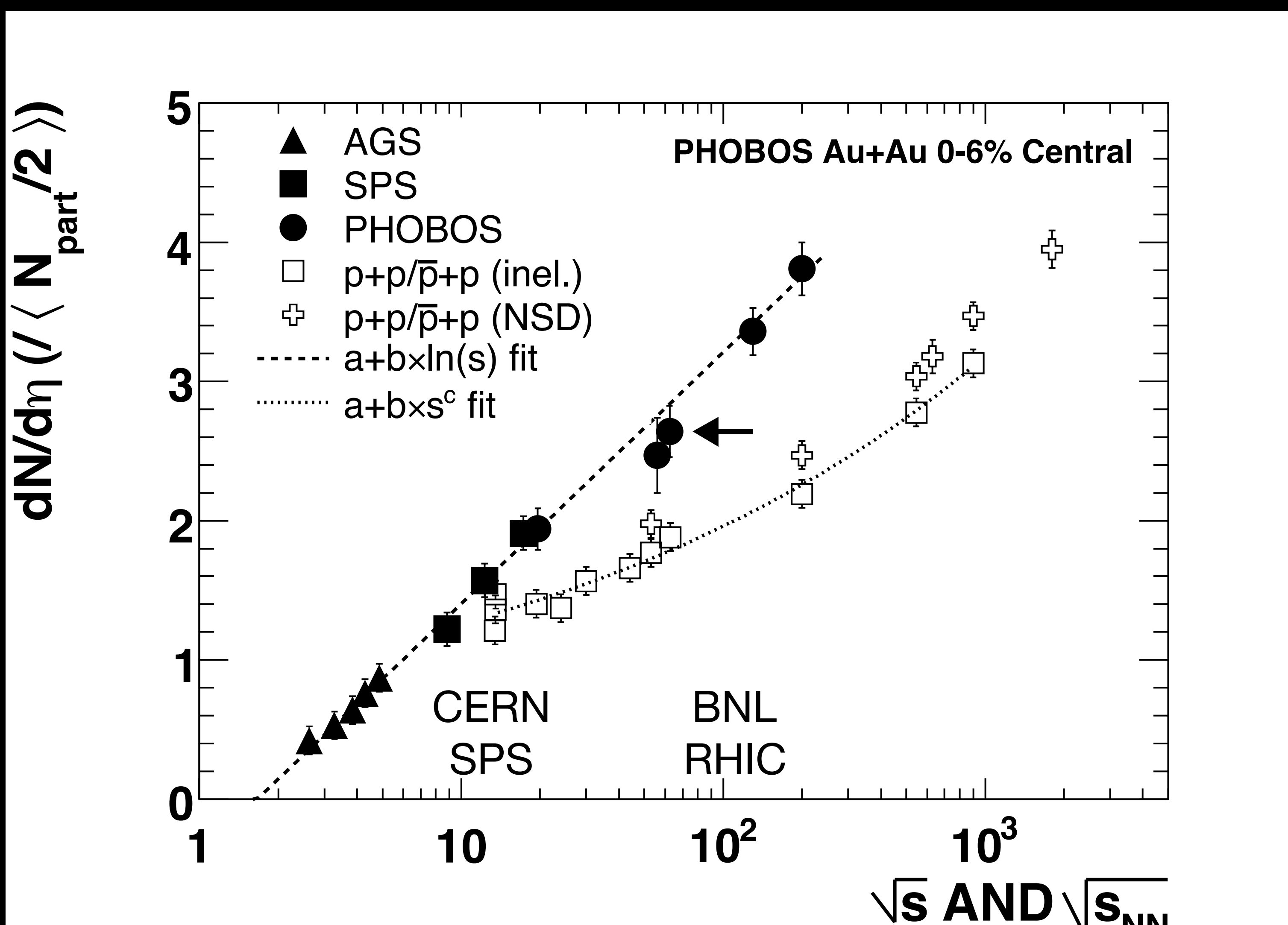




Gluon Density

- **Do we have another handle on the gluon density? Can't count confined partons...**
- **Assume hadronization doesn't change entropy**

$$N_{had} \propto N_g$$



Heavy ion experiments measure particle density vs. CM energy

CERN SPS experiments have ~1/2 particle density relative to RHIC...

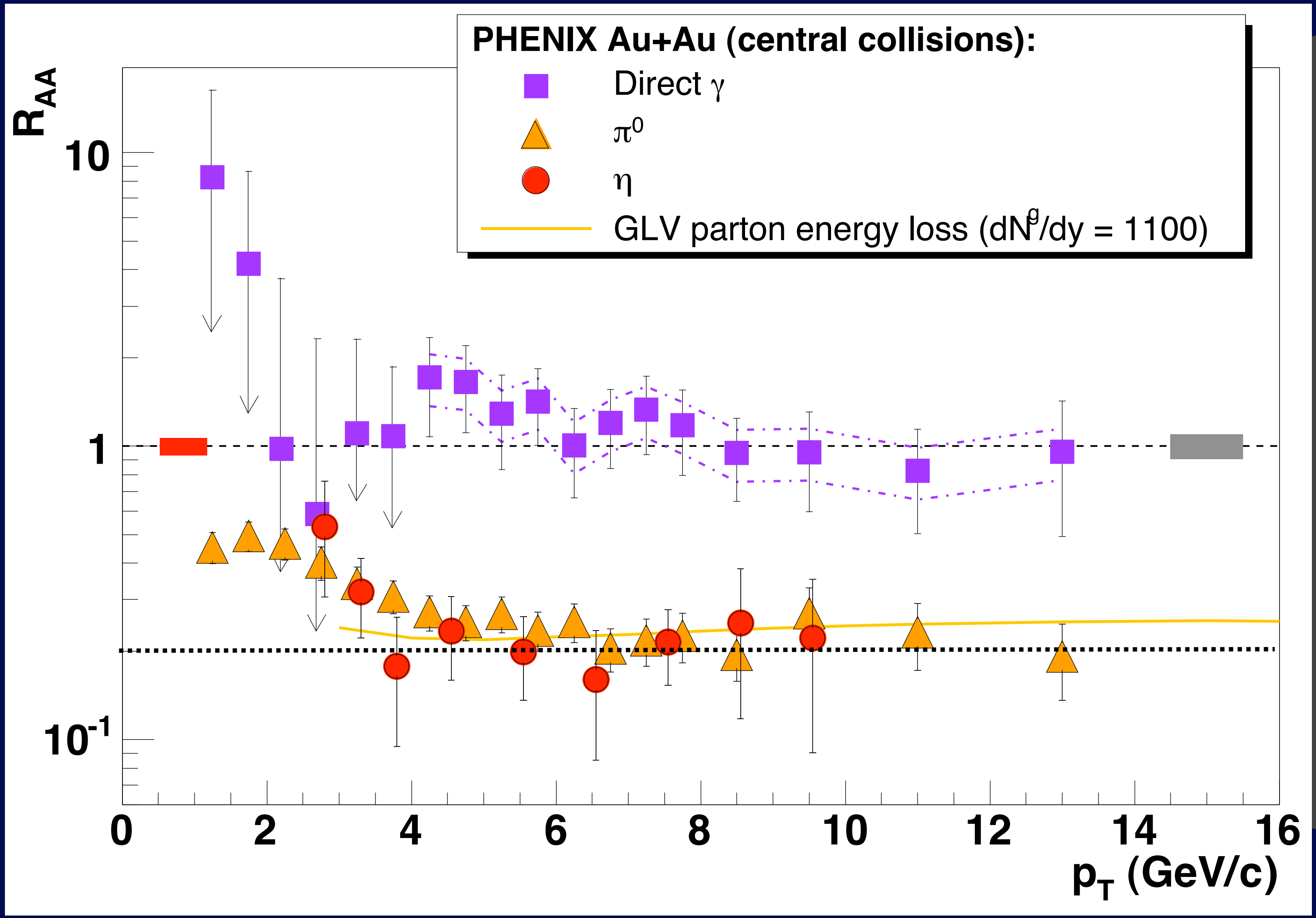
Quenching & Viscosity

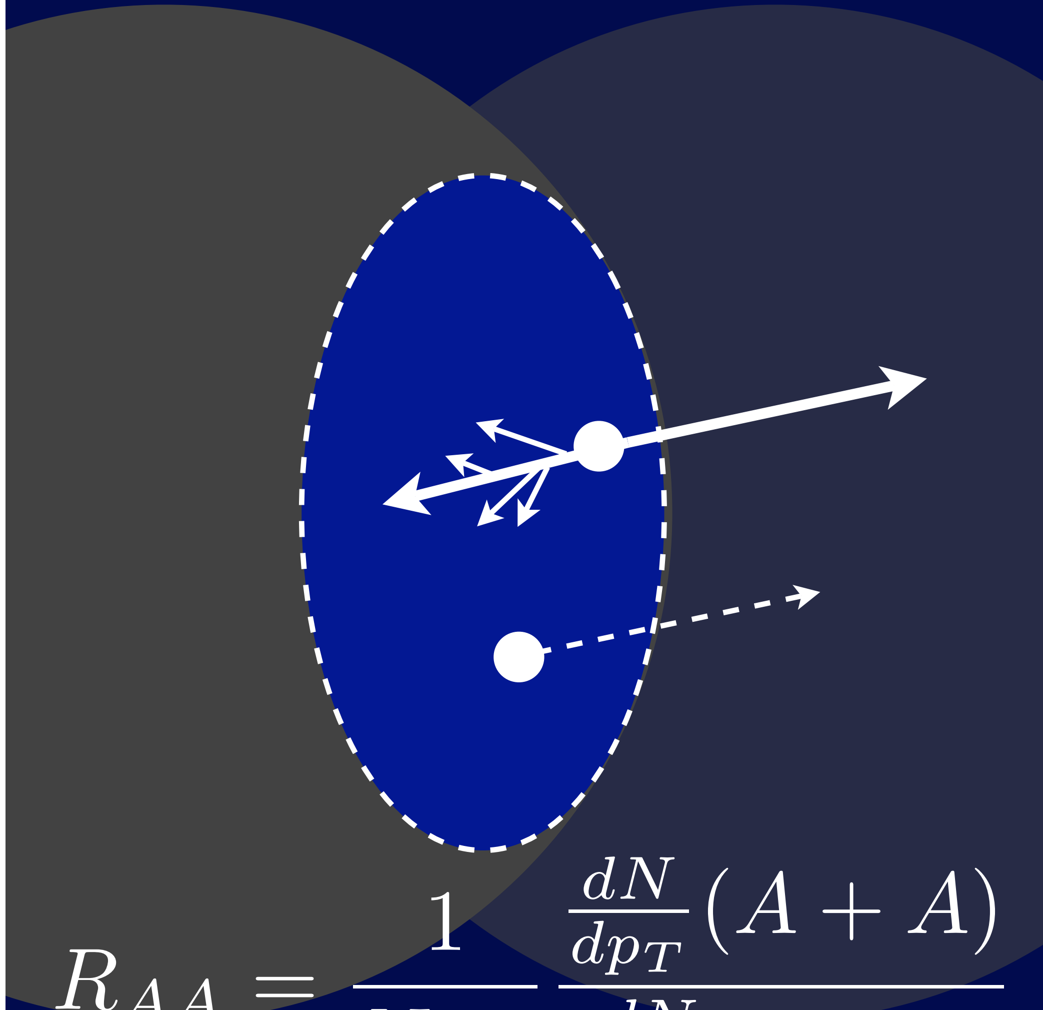
- **Probing the density with hard processes gives direct access to MFP: <u>gluon density</u> & <u>viscosity</u>**
- **Muller, Majumder & Wang estimated**

$$\frac{\eta}{s} \sim \frac{4}{3} \frac{T^3}{\hat{q}}$$

  - Large transport coefficient
    → large cross sections
    → low viscosity

High p_T Suppression



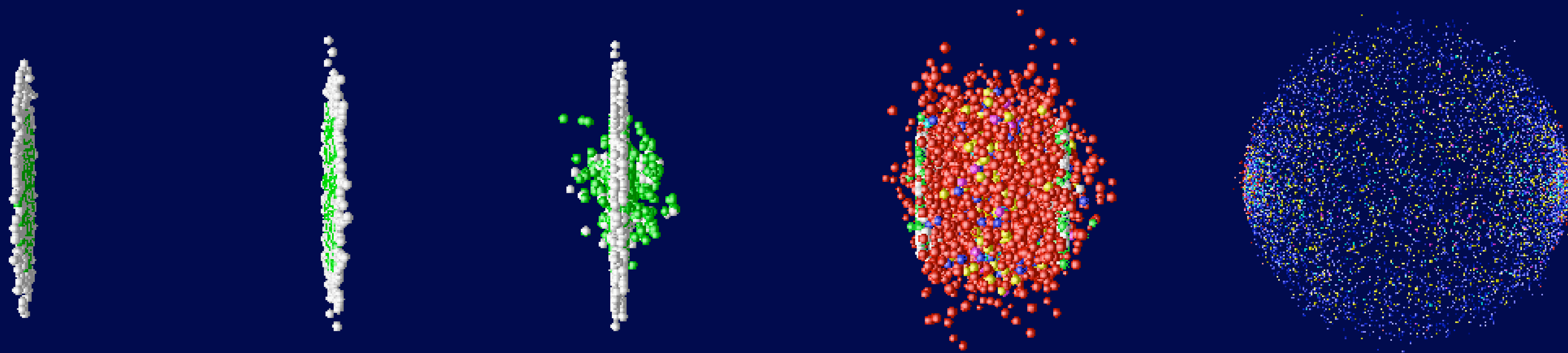


$$R_{AA} = \frac{1}{N_{coll}} \frac{\frac{dN}{dp_T}(A+A)}{\frac{dN}{dp_T}(p+p)}$$

High p_T particles are strongly suppressed relative to p+p spectrum × binary collisions (N_{coll}). Photons not.

pQCD energy loss calculations sufficient to describe light hadrons. Photons appear to be unaffected by medium.

When does Suppression Happen?



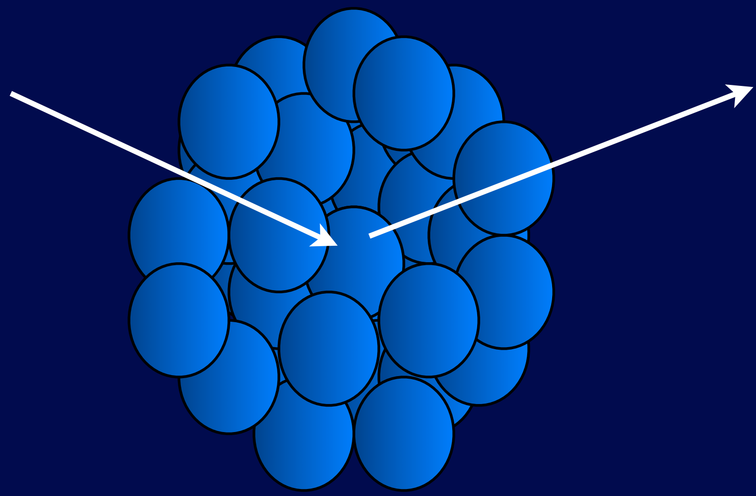
Some sort of strong "shadowing" phenomenon in the inital nuclear parton distributons...

...so there are simply fewer hard scatterings in the reaction?

Or does something occur in the strongly interacting partonic phase??

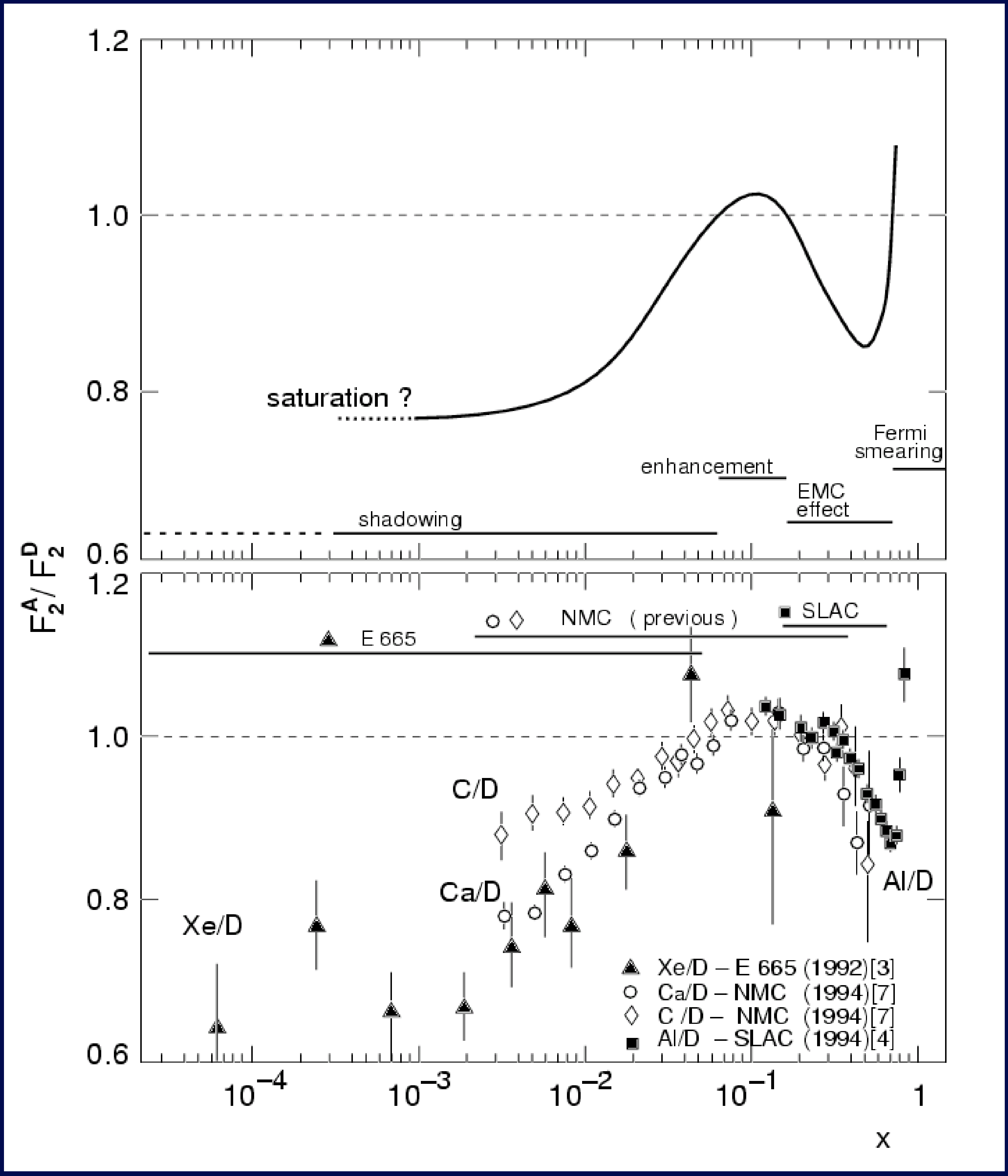
Collisions of the outgoing particles with the background of soft hadrons?

Is a Nucleon Always a Nucleon?

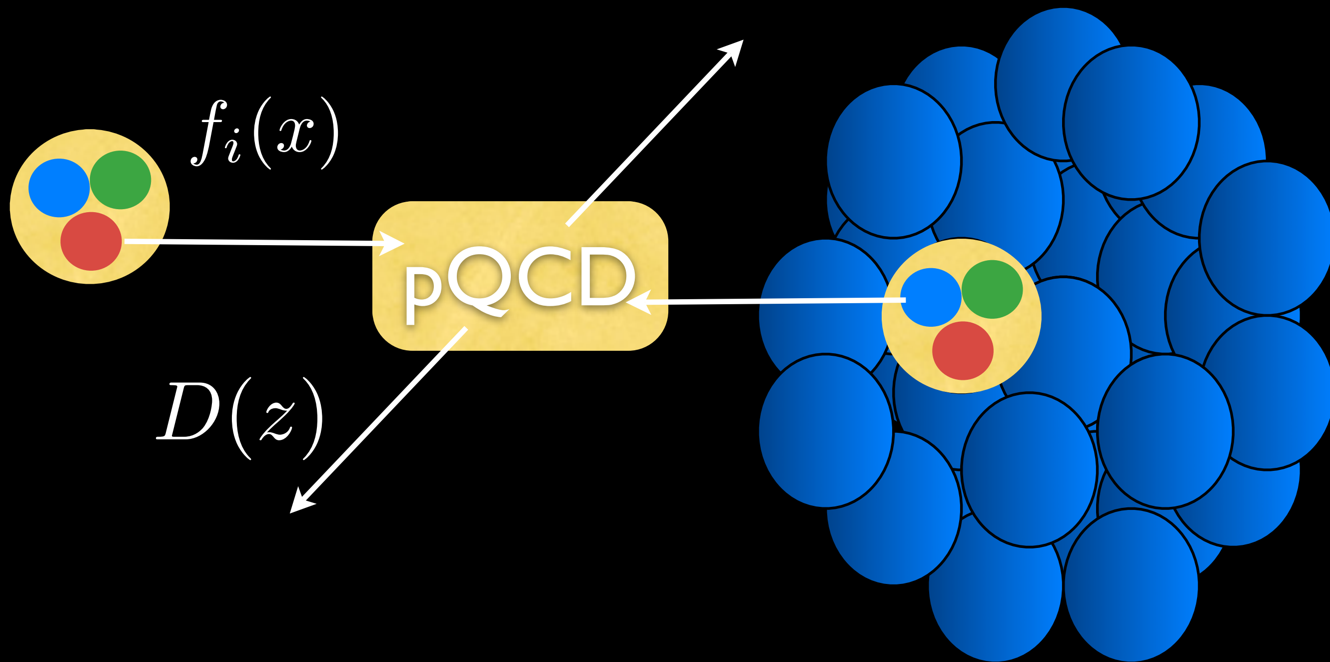


Ratio of cross sections of leptons on nuclei vs. deuterons show deviations from unity called “shadowing” (and “antishadowing”)

No generally-accepted explanation of these effects (many models!)

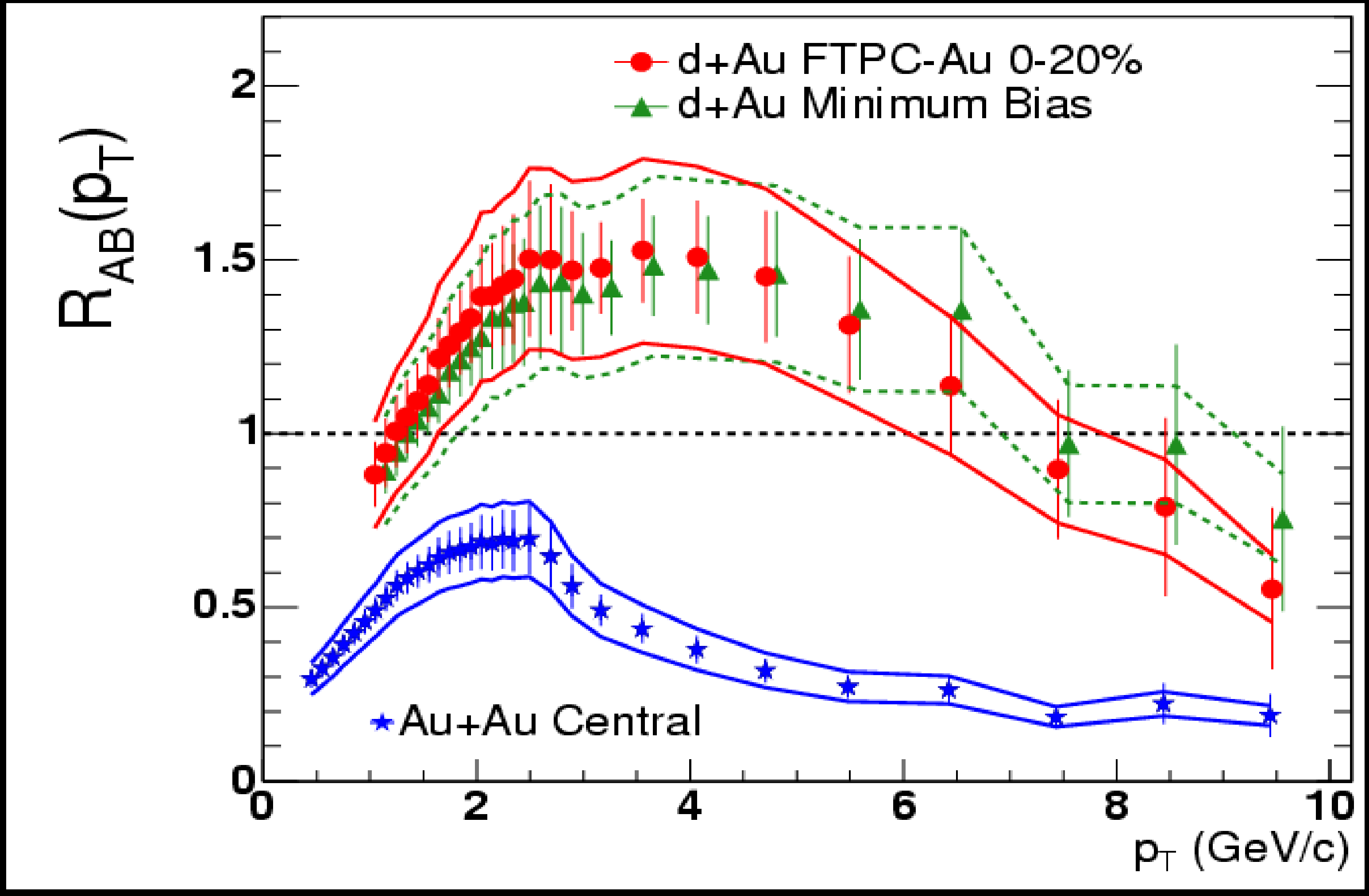


Initial vs. Final State

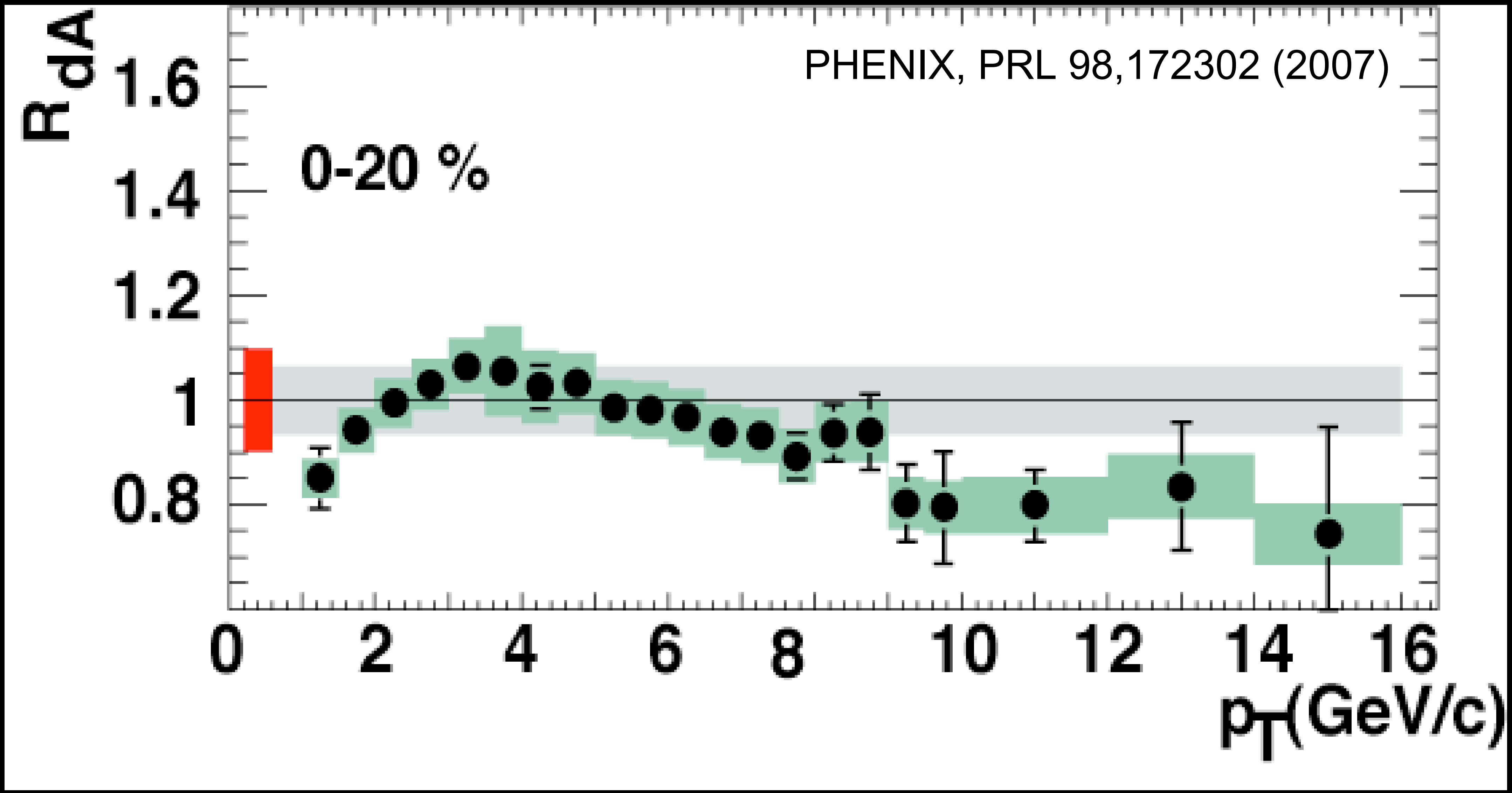


p+A collisions provide some access to the shadowing from the nuclear wave-function (reduction in initial flux)

d+Au is
not suppressed
(except at high p_T...)
while Au+Au shows
large effect at all p_T

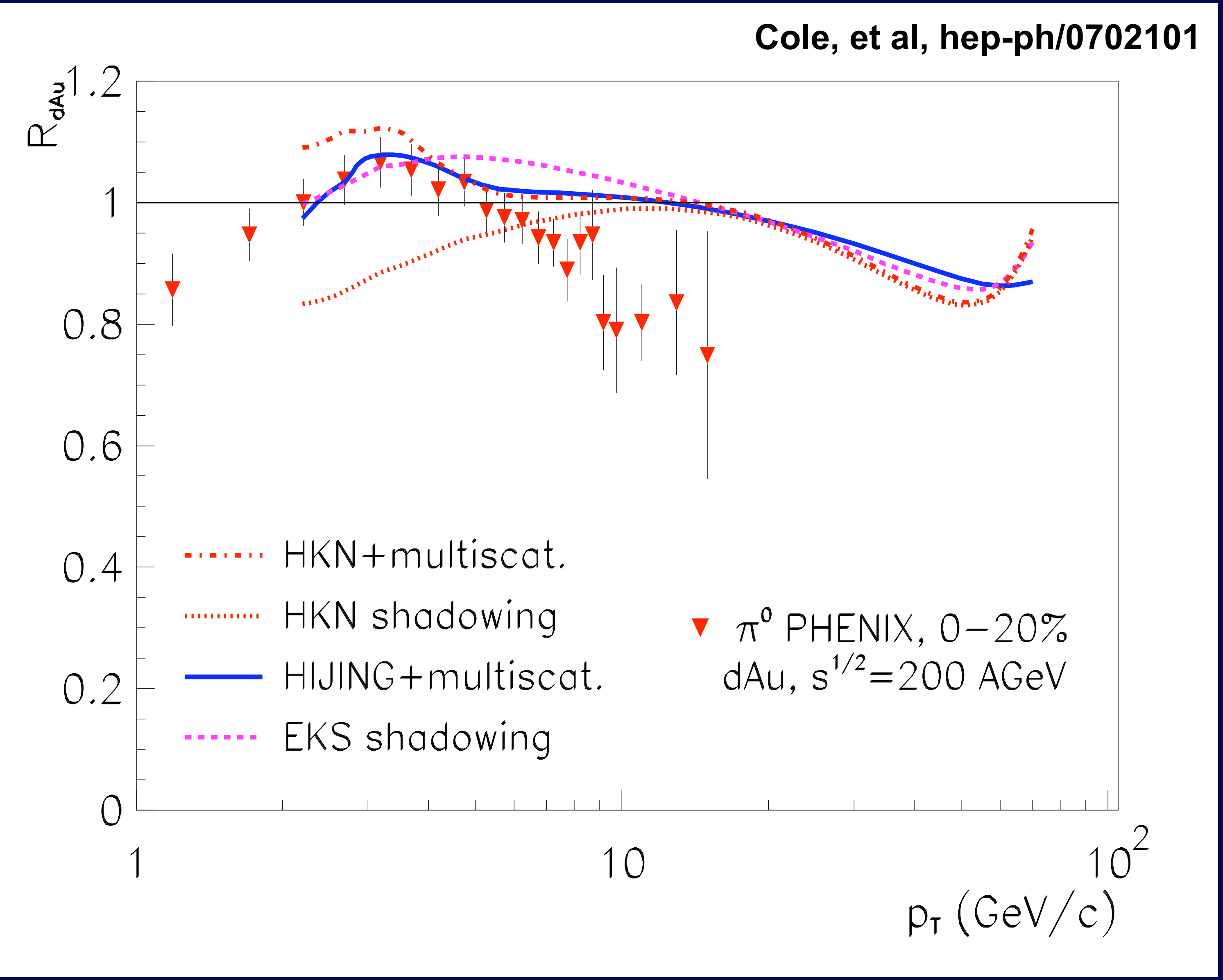


Return of Initial State?



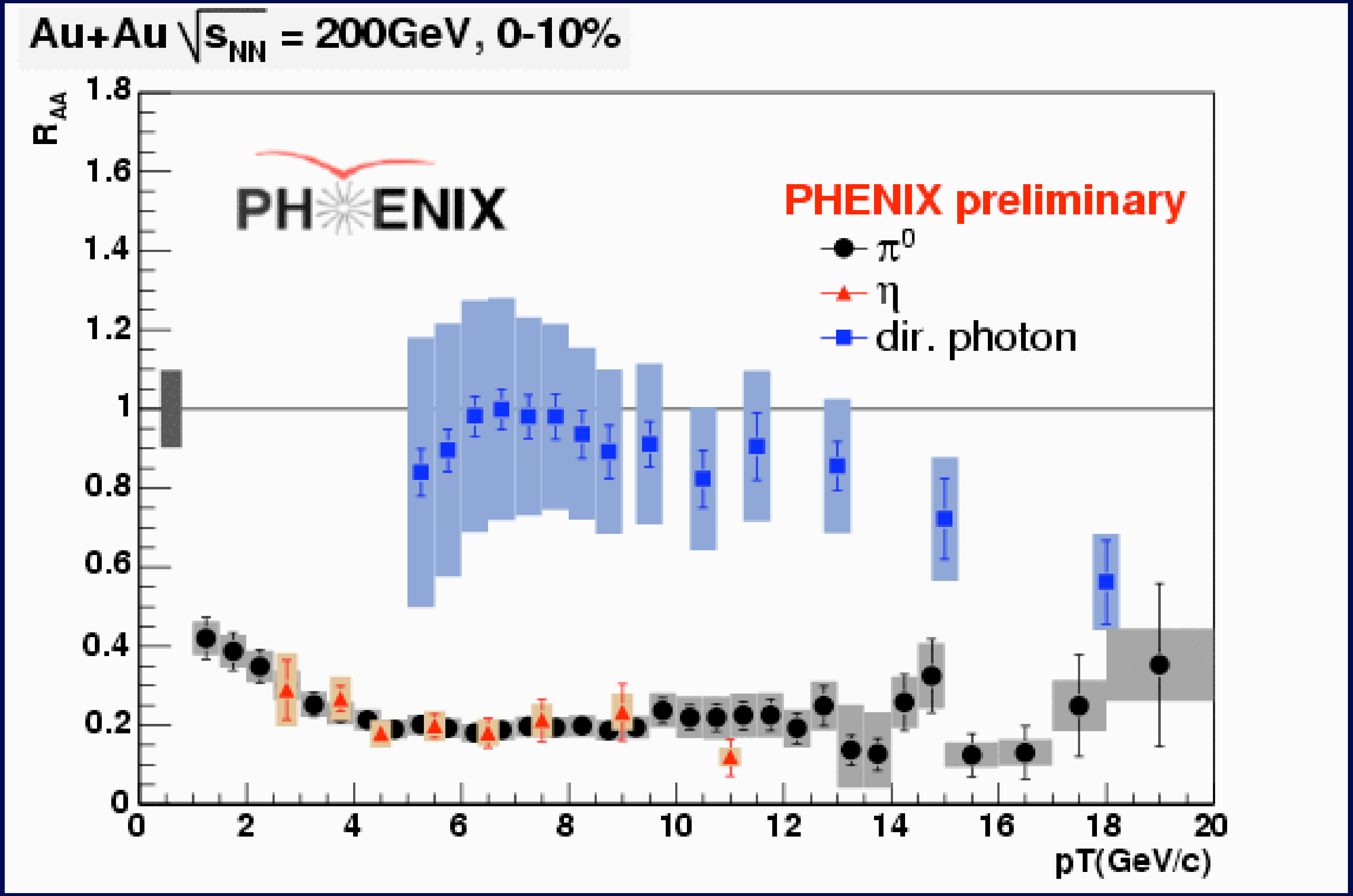
High pT π^0's show suppression even in d+Au!
Is this shadowing (not low x!)? EMC effect?...

EMC Effect?



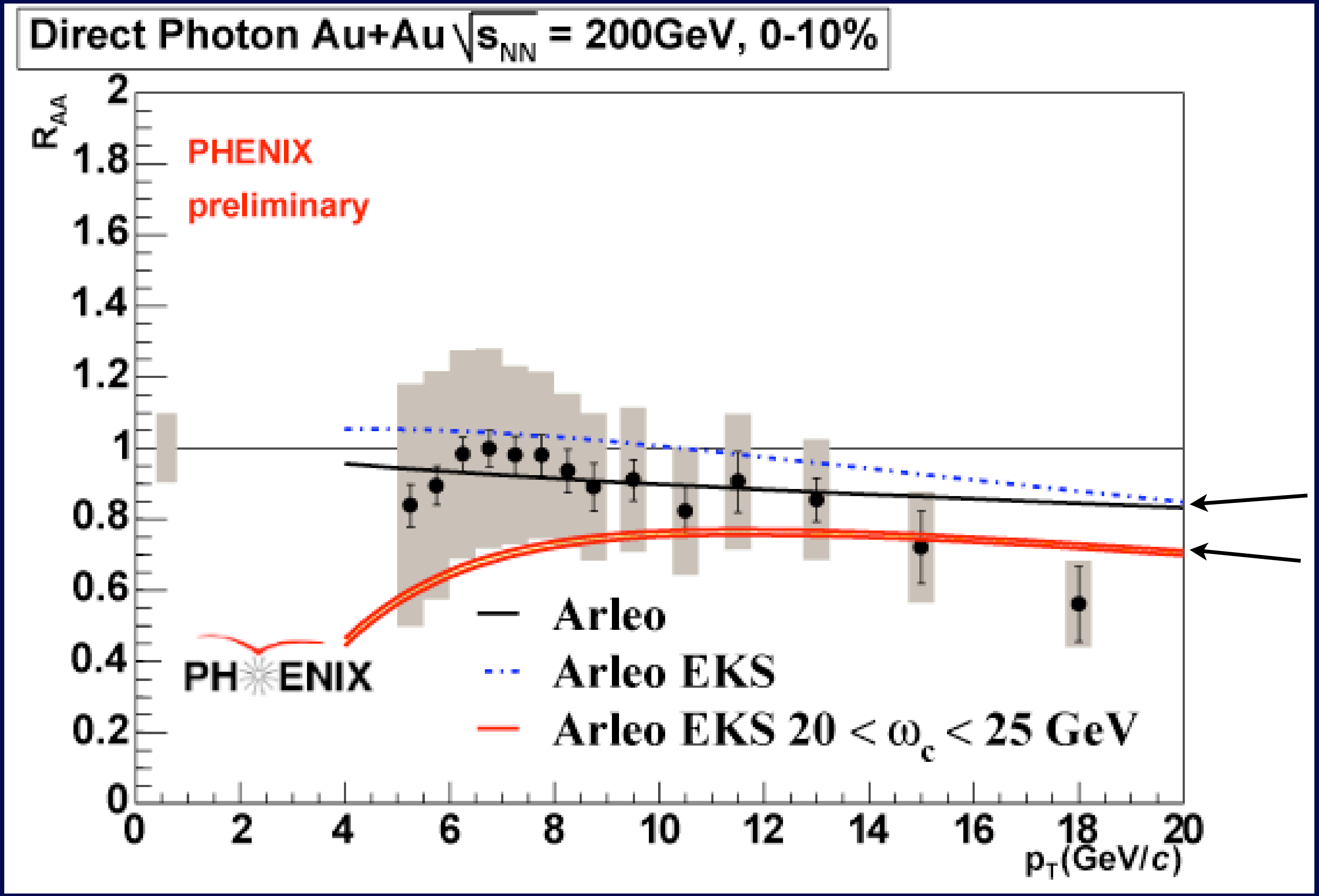
First attempts to model this find EMC matters at even higher p_T...

High Energy Photons



Similar surprises for very high p_T photons in Au+Au.
Is this initial or final state? Fragmentation of jets?

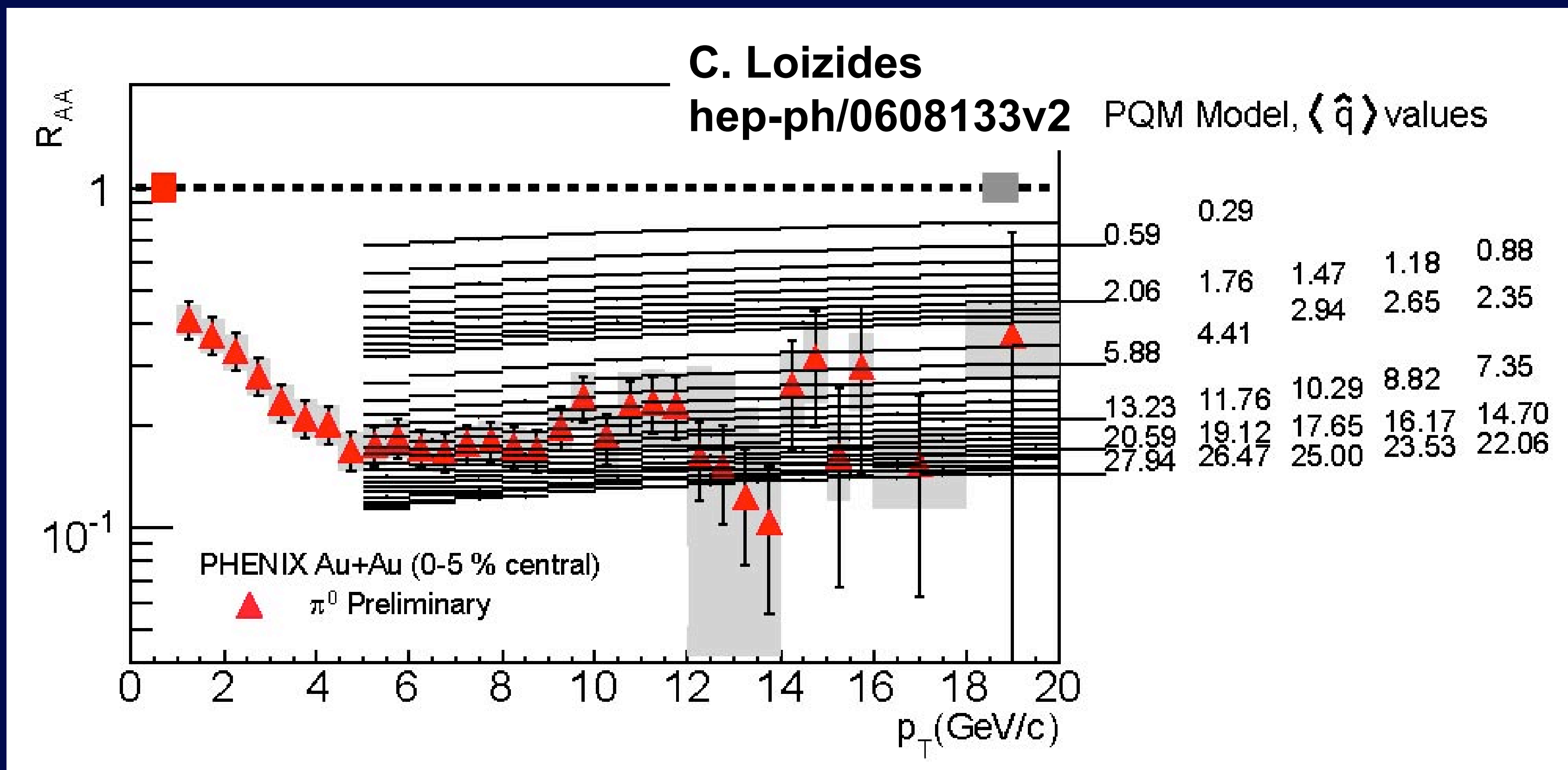
Theoretical Descriptions

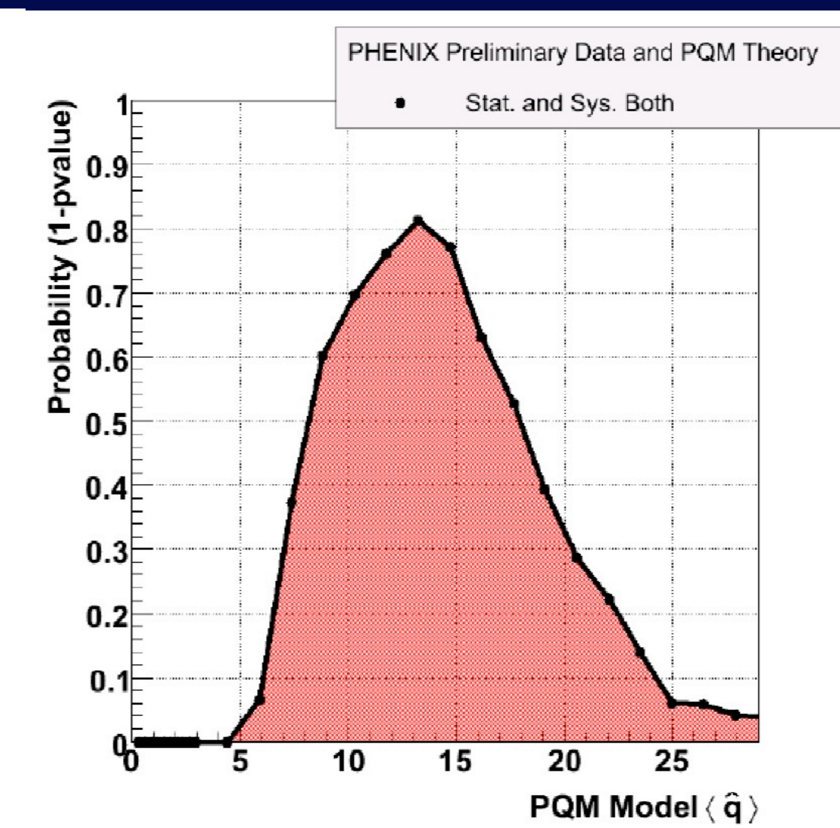


shadowing
& isospin effects
adding energy loss

Shadowing & isospin effects don't capture continual dropping of photon R_{AA}: need quenching?
(RHIC II will be essential to push even higher in p_T!)

Estimating Stopping Power



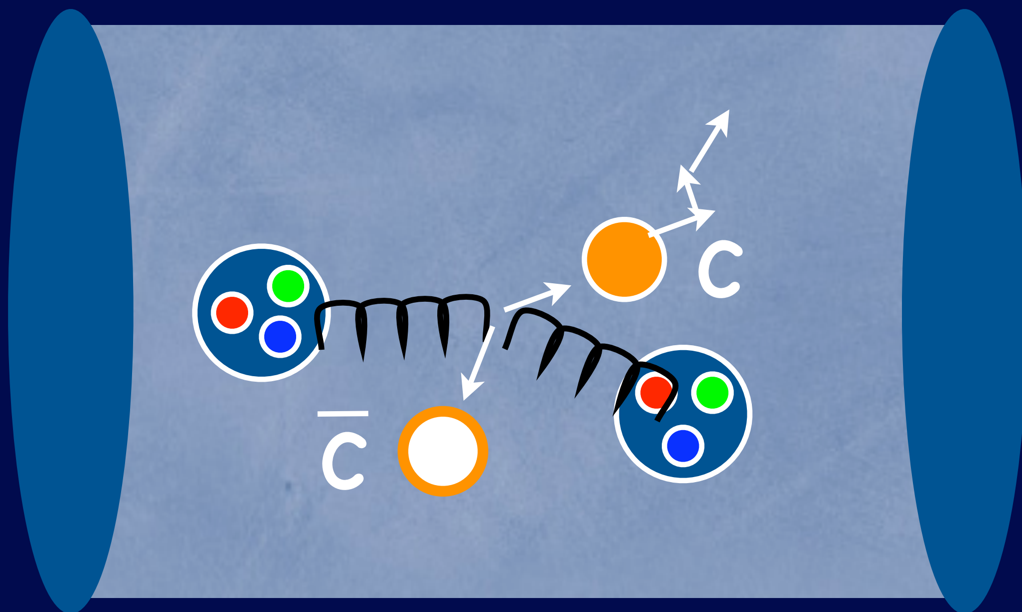


$$\Delta E \propto \hat{q} \propto \langle p_T^2 \rangle / \lambda$$

PHENIX χ^2 fits to PQM indicate $6 < \hat{q} < 24 \ \mathrm{GeV}^2/\mathrm{fm}$.
(model dependent: transverse flow, 2+1D, 3+1D)

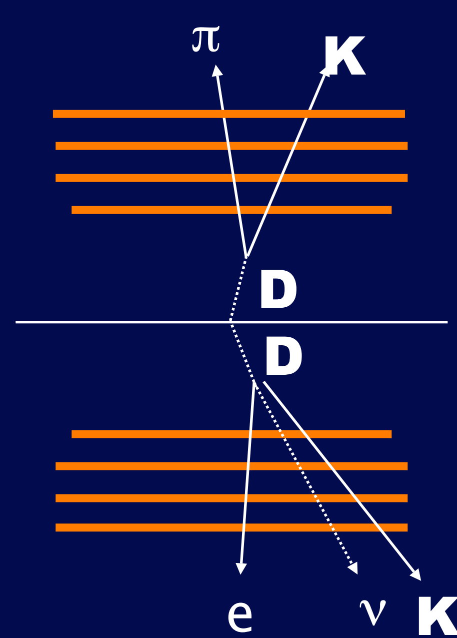
Comparisons with theory will require advances in experimental precision at high p_T: RHIC II luminosities

Heavy Flavor as a Probe

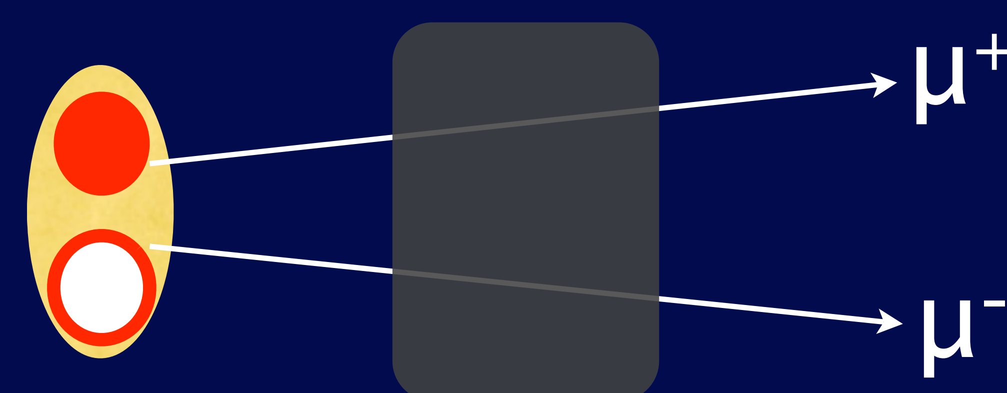


Heavy quarks (c and b) are not in the initial state (intrinsic charm?) so must be produced perturbatively and interact (or not!)

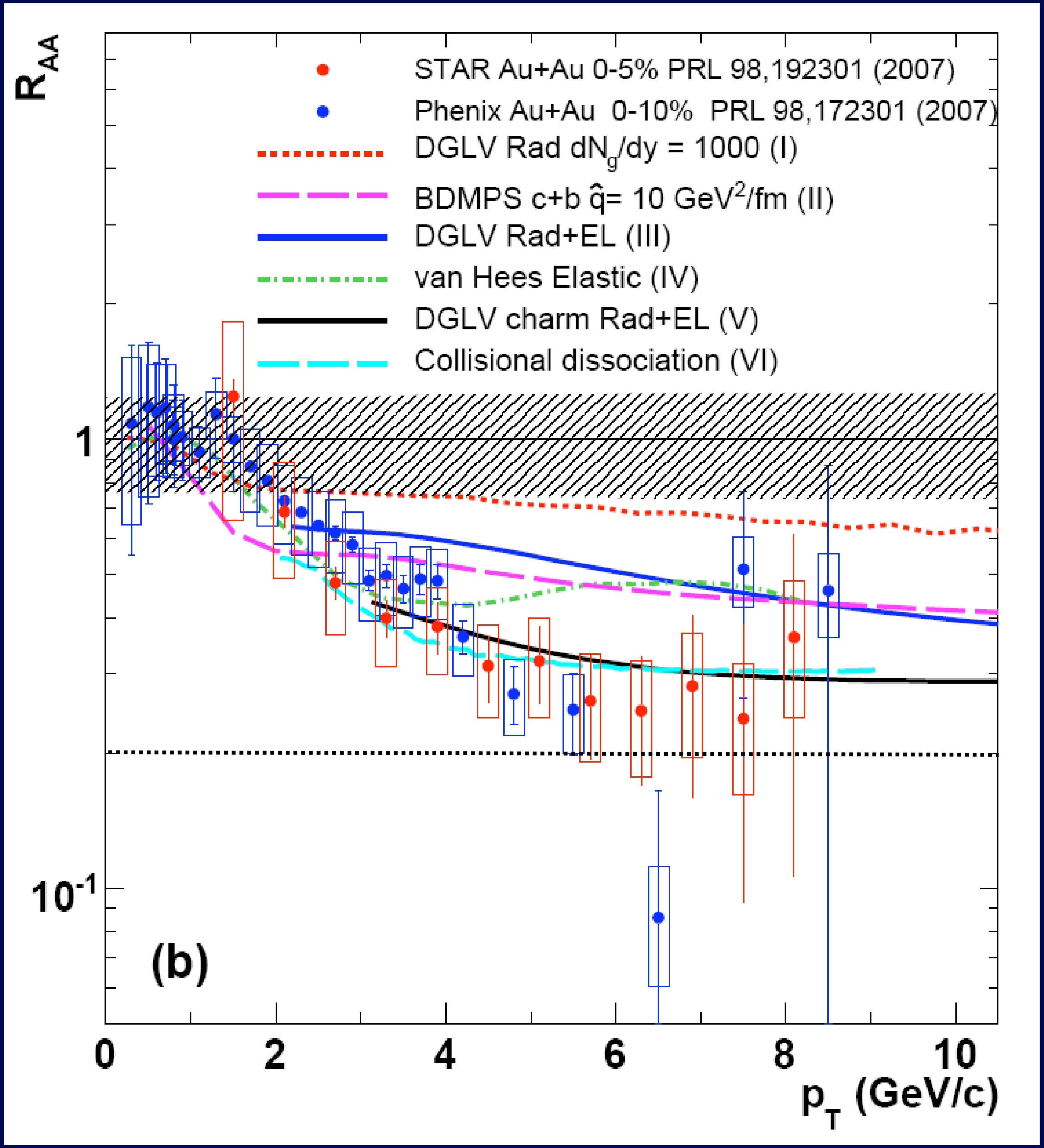
Open charm is the fragmentation of a single charm or anti-charm quark into a D, which decays hadronically, or semileptonically ($e^{\pm}$ or $\mu^{\pm}$: 14%)



Quarkonia are bound states of oppositely charged heavy quarks: clean dimuon channel



Single Electrons



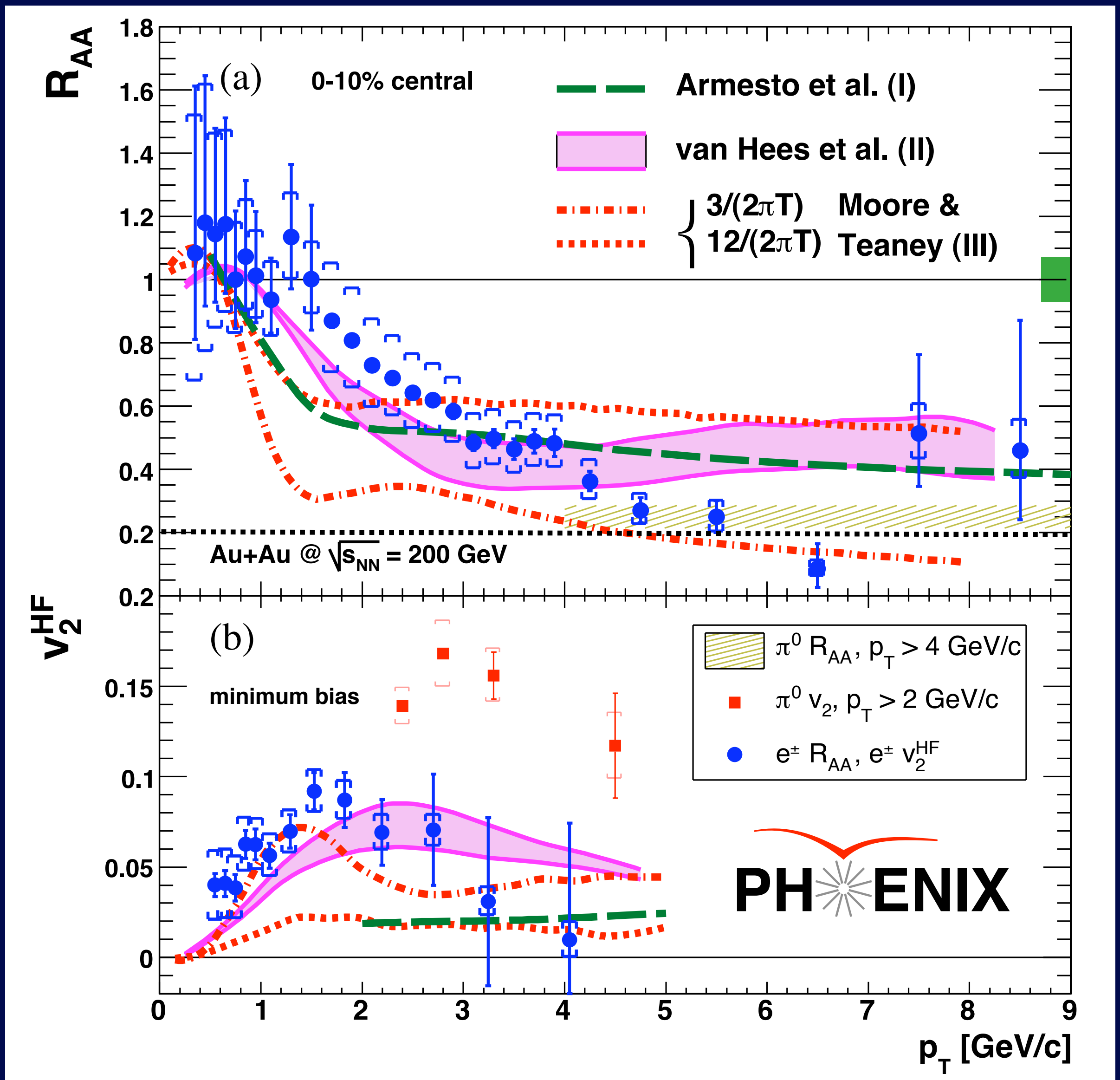
STAR and PHENIX have measured "non photonic" electrons (not from γ conversions, so treated as if from c)

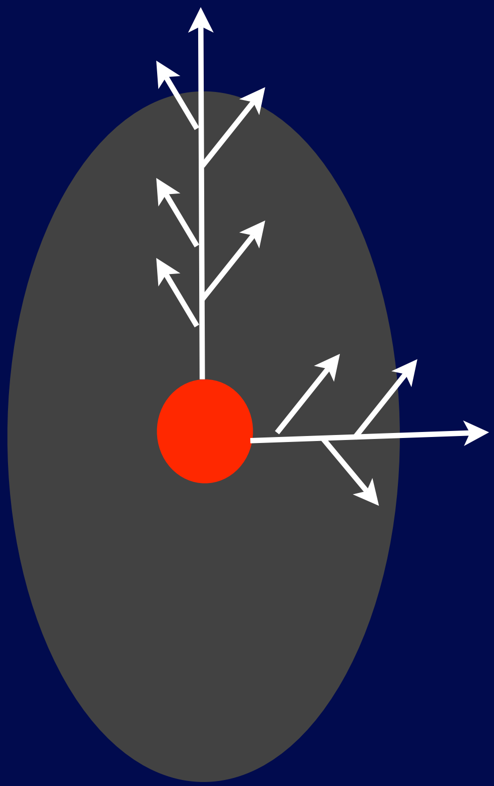
No suppression at lower pT (charm enhancement?)

Large suppression at higher p_T (similar to π)

Models which work for π (radiative energy loss) do not work for charm

Estimating η w/ Heavy Quarks





Charm R_{AA} is correlated with v_2:

comparisons with heavy quark rescattering models→ η/s

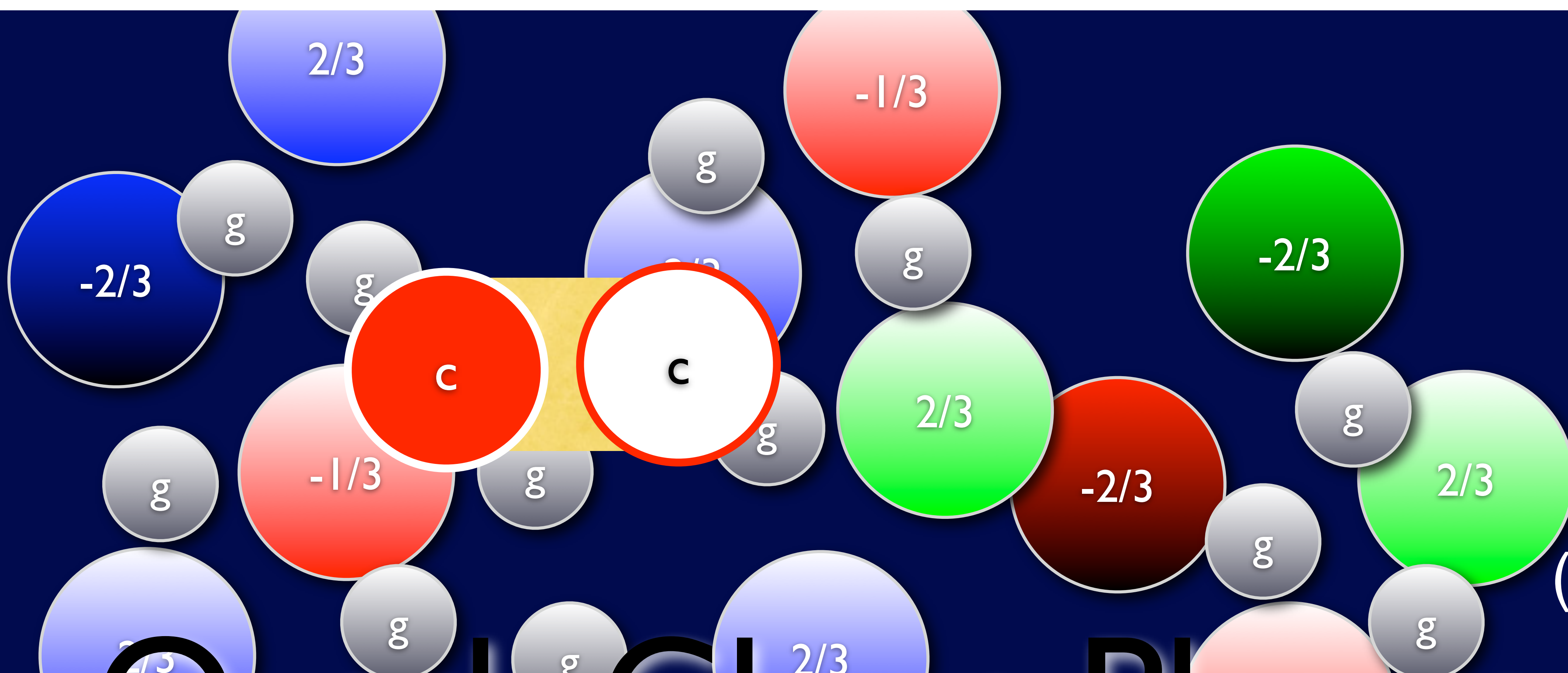
Comes close to quantum limit suggested by AdS/CFT

RHIC II detector upgrades will allow direct charm ID

Quarkonia

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
$E_s^i[GeV]$	0.64	0.20	0.005	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1-0.2	2.31	1.13	1.1	0.83	0.75
T_d/T_c	~ 1.42	~ 1.05	unbound	~ 3.3	~ 1.22	~ 1.18	-	-
T_d/T_c	1.78-1.92	1.14-1.15	1.11-1.12	$\gtrsim 4.4$	1.60-1.65	1.4-1.5	~ 1.2	~ 1.2

Table 1: Estimated dissociation temperatures T_d in units of T_c obtained from potential models using free energies [8] (green), a linear combination of F_1 and U_1 [10] (blue) and internal energies [9] (red) as effective T-dependent potentials.



Thermal medium breaks up J/Ψ & other onia states (including $\bar{b}b$)

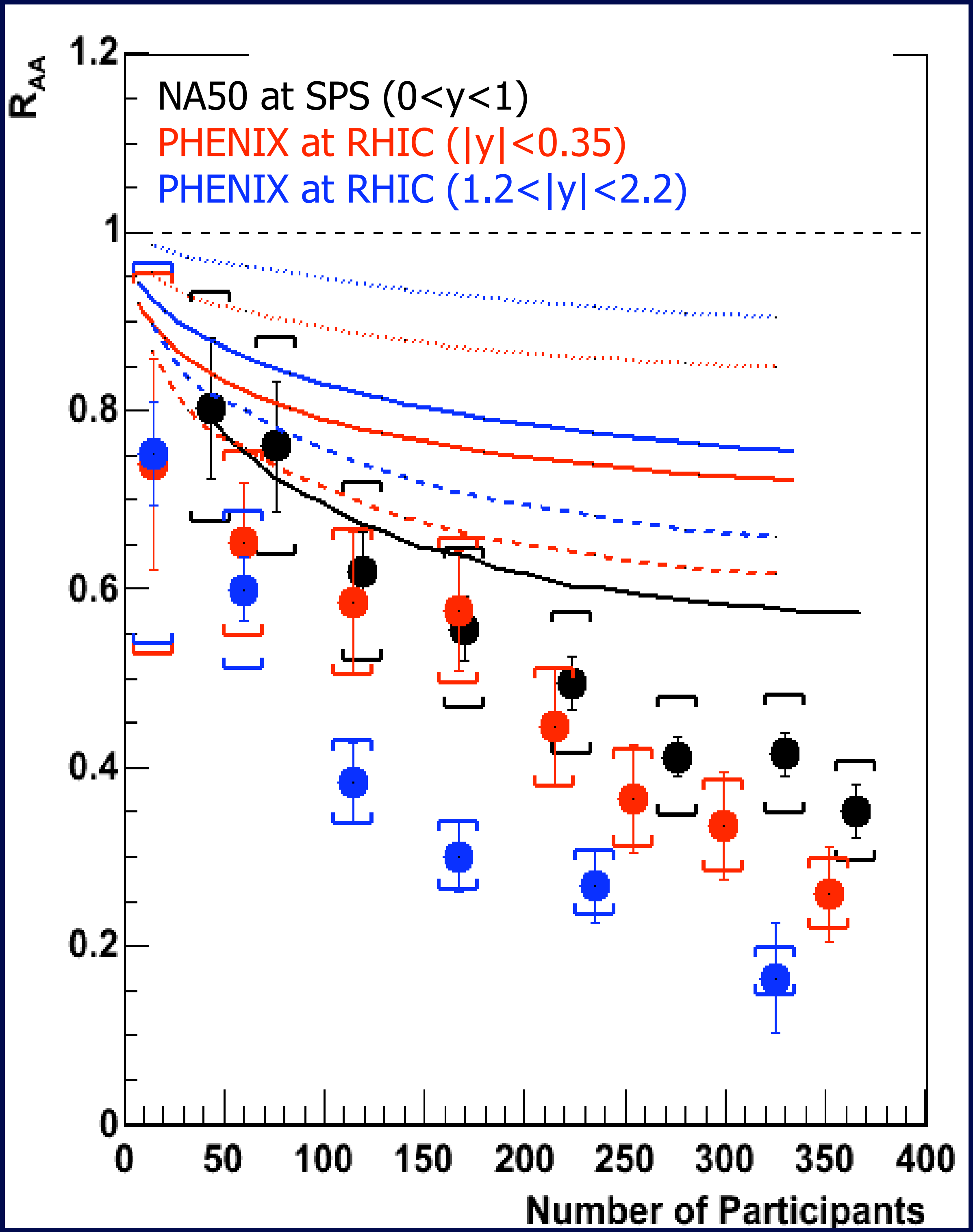
Quarkonium Puzzle

J. Nagle, WWND07

J/Ψ suppression
(represented as R_{AA})
is similar at
1) RHIC energies
2) Lower energies

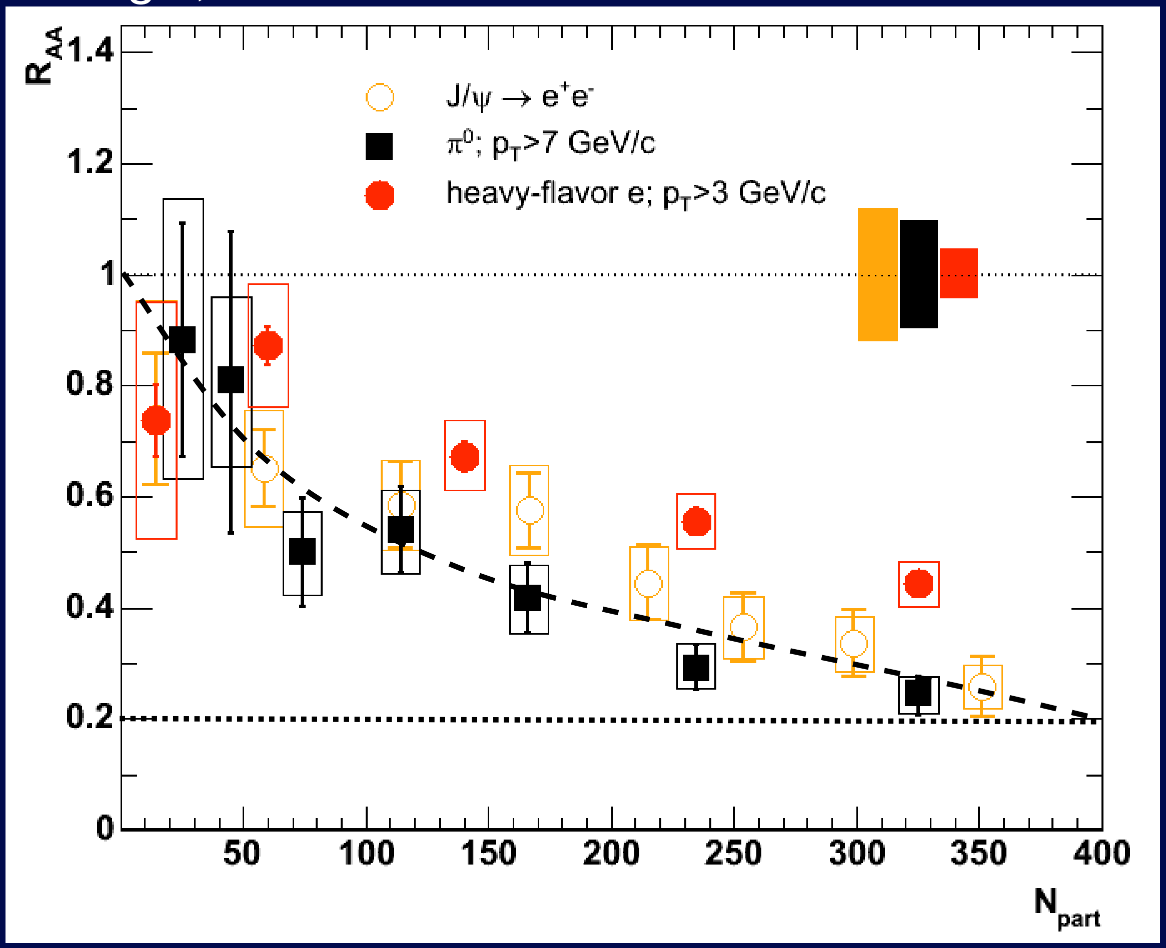
Surprising if suppression
depends on energy
or entropy density

Lots of new data to
assimilate!...



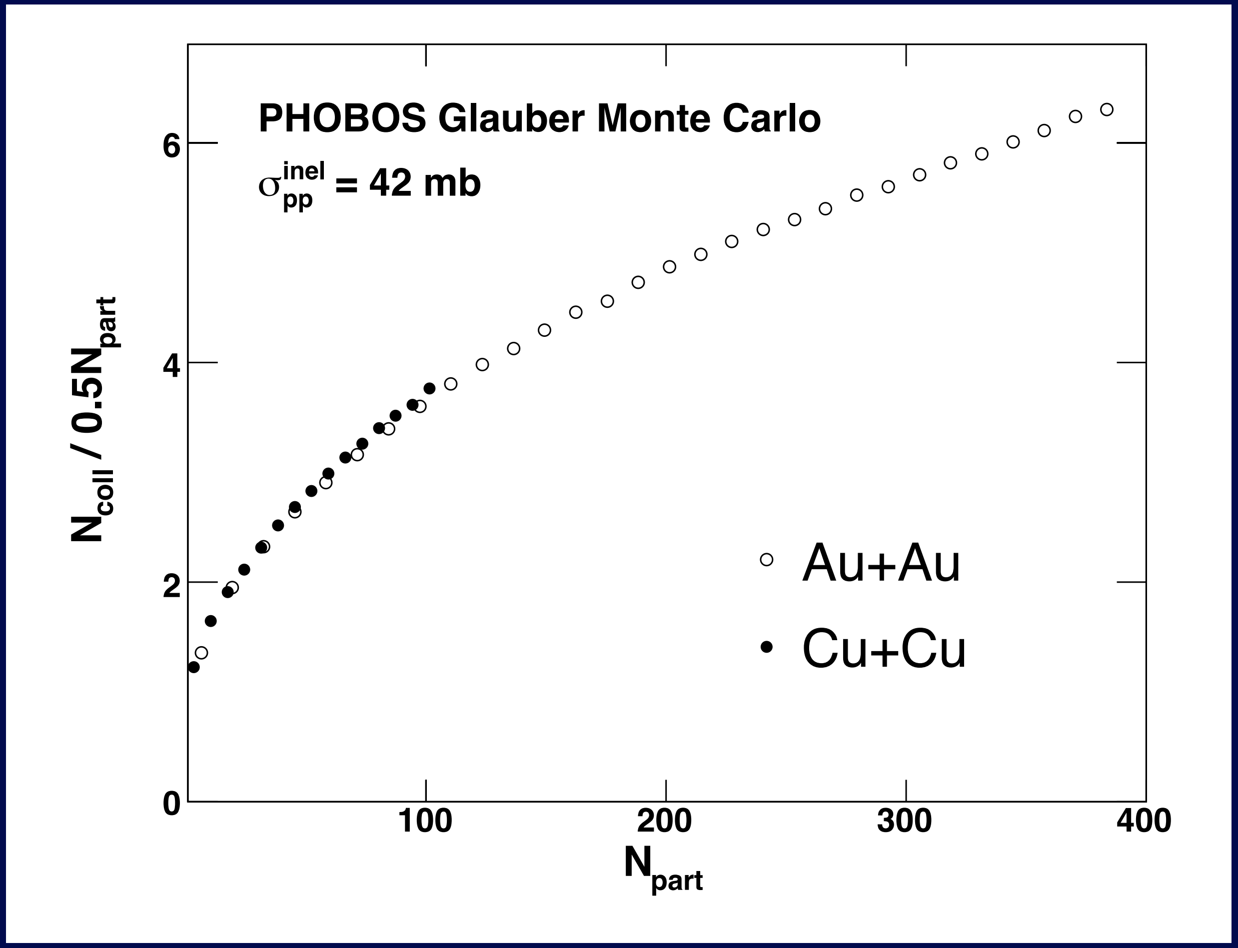
High p_T Puzzles

J. Nagle, WWND07



J/Ψ suppression similar to
1) high p_T hadrons
2) high p_T charm

Interesting to note that R_{AA} decreases ~ν, the nuclear thickness...



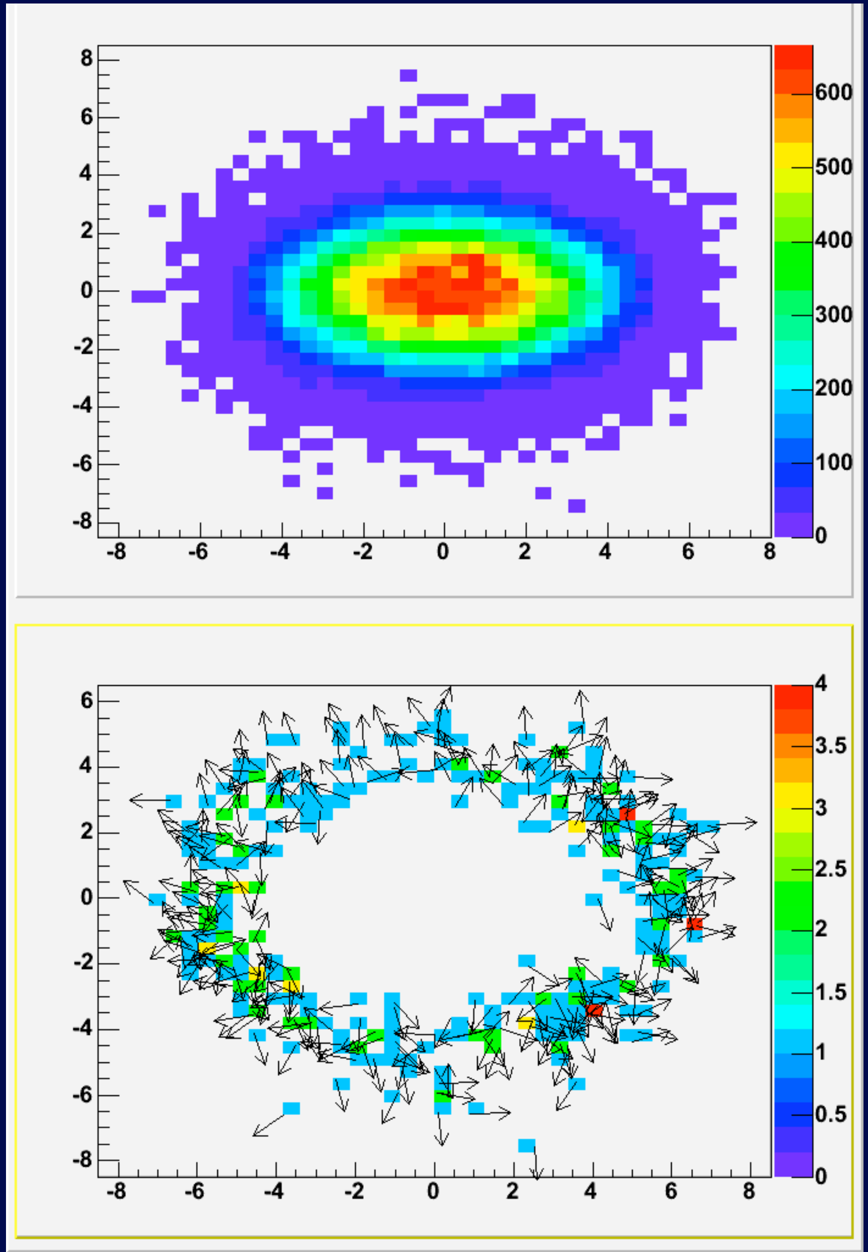
Single-particle suppression

Besides direct photons, other particles seem to end suppressed at same level $R_{AA} \rightarrow 0.2$

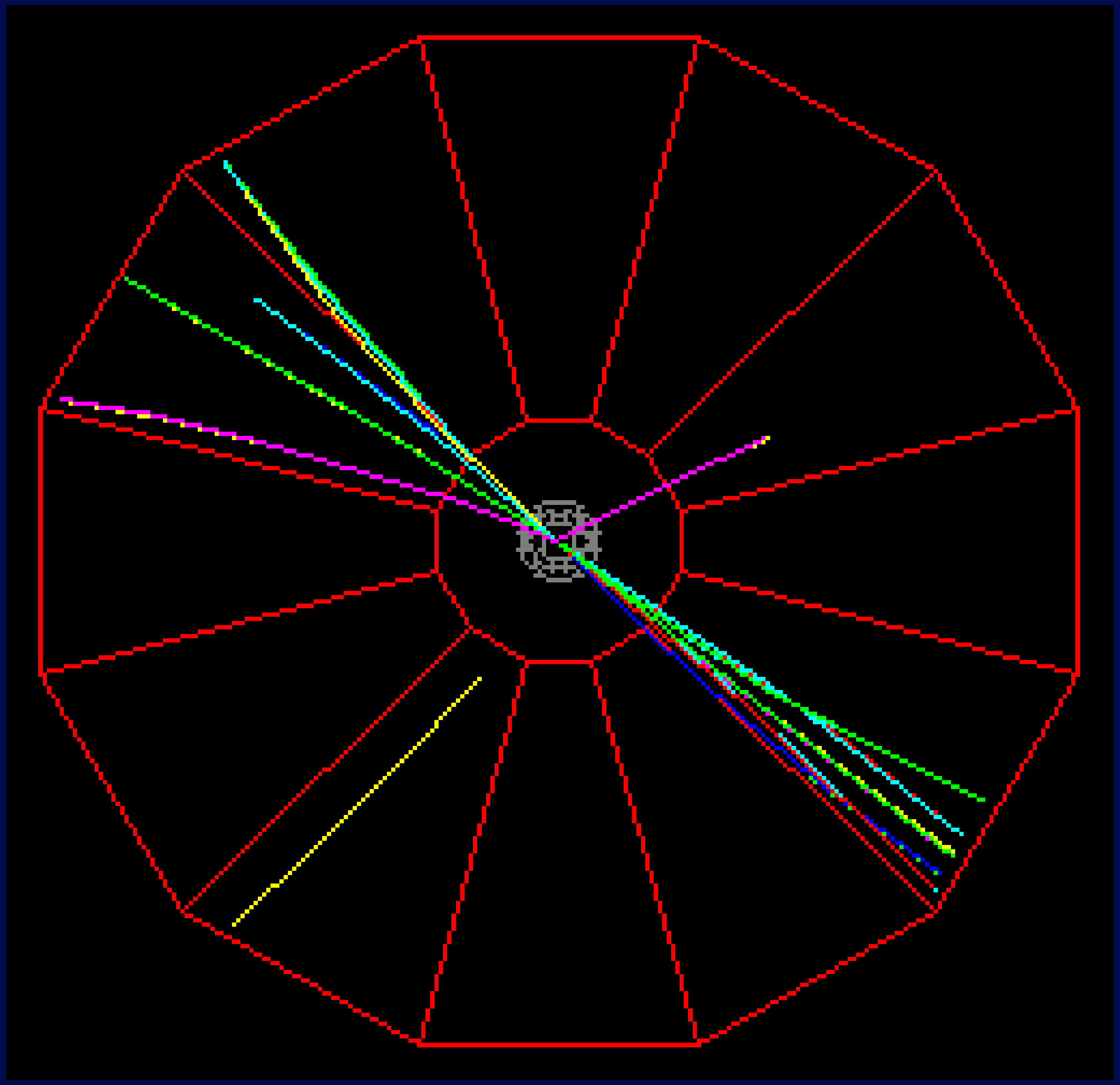
Put charm quarks into a model with rescattering partons...

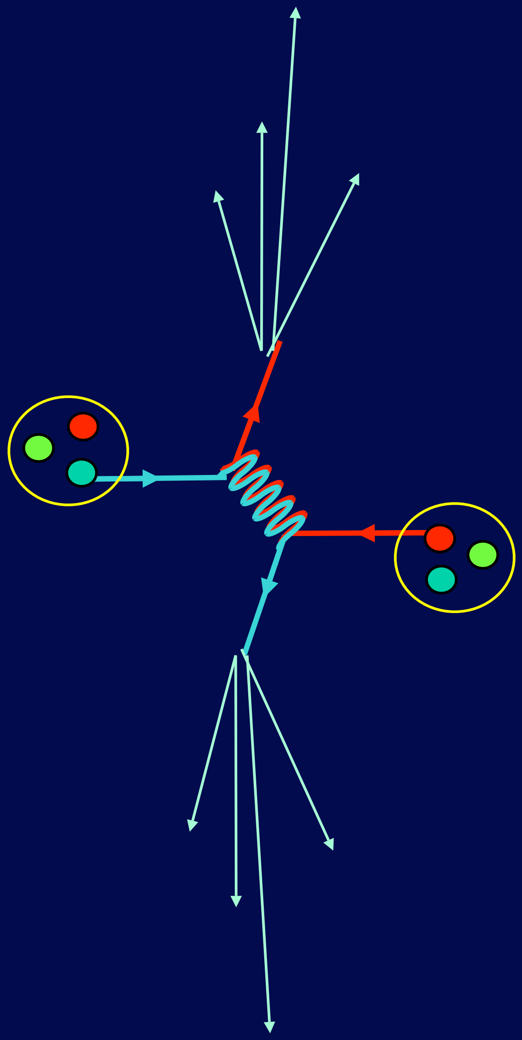
...and the only charm that survive started on the surface (similar explanation for jets!)

$$\frac{N_{coll}}{R} \propto \frac{A^{4/3}}{A^{1/3}} \propto A \propto N_{part}$$



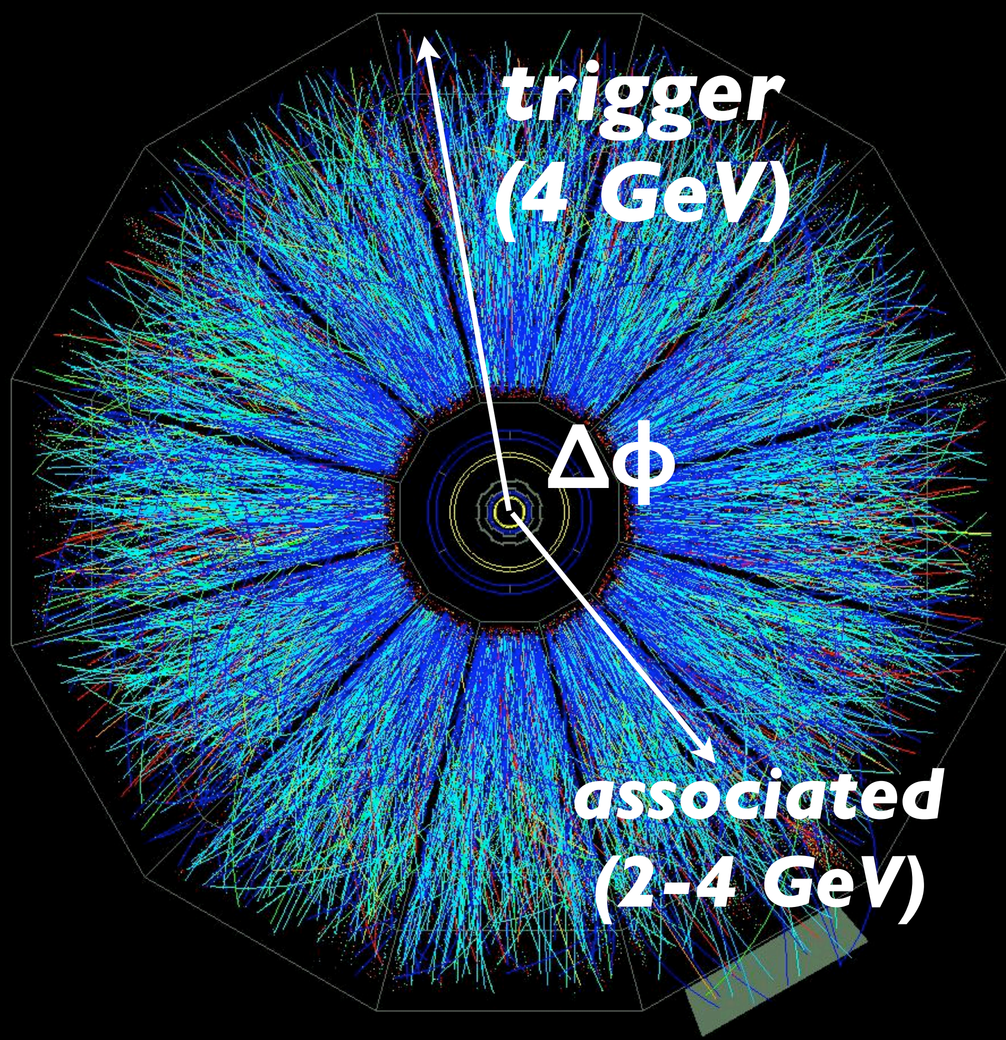
Correlations

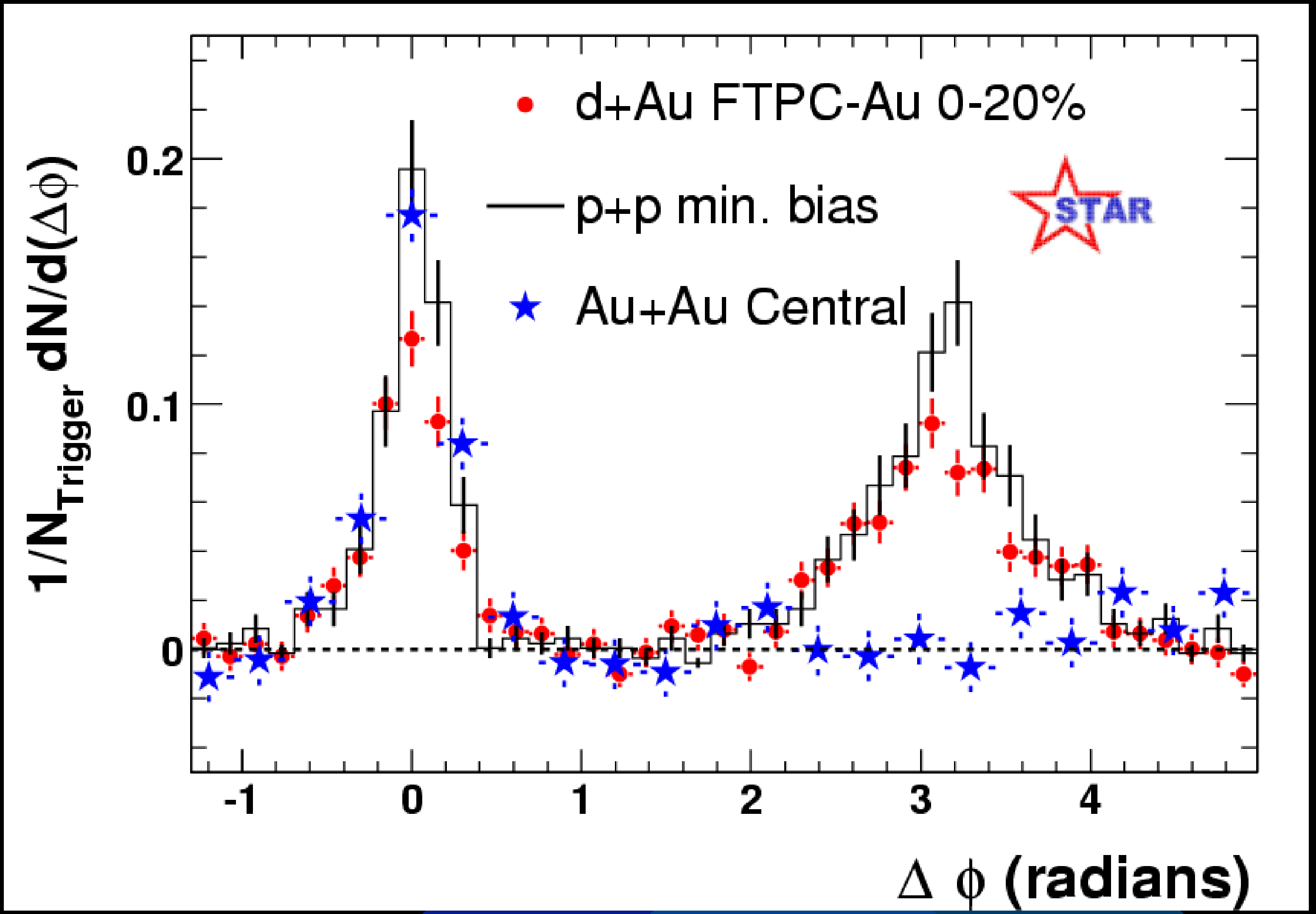




Jets are multi-particle phenomena:
2+ high p_T particles (quark and/or photon)
quarks fragment into multiple hadrons

Disappearance of Back-to-Back

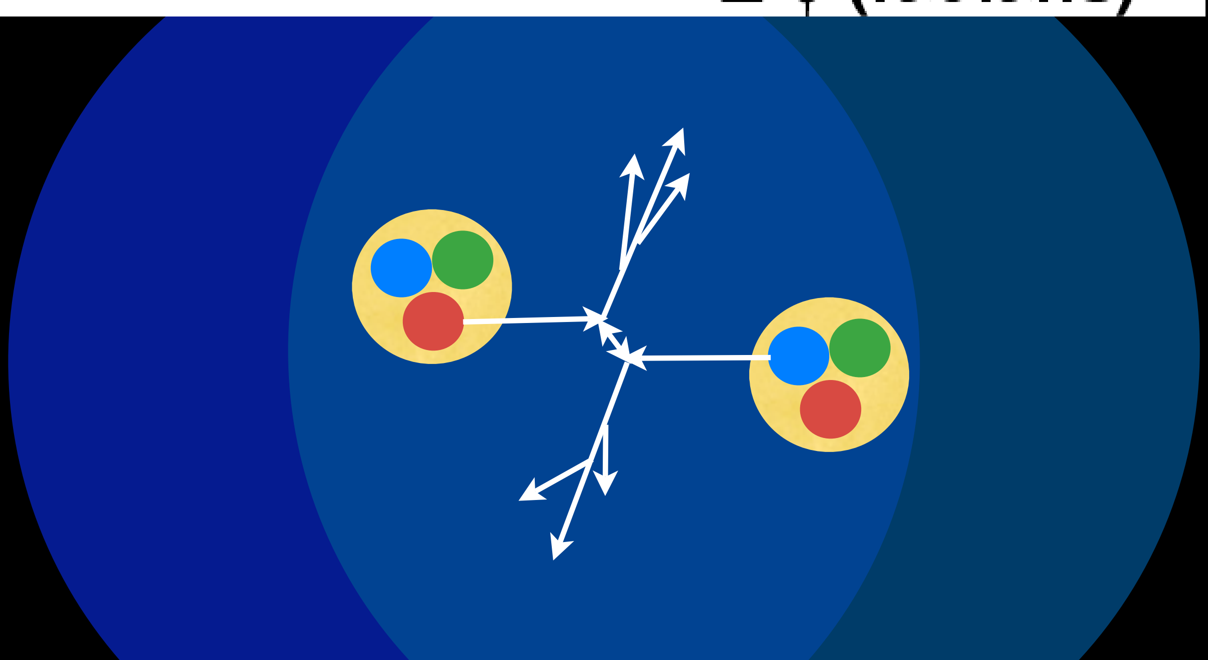




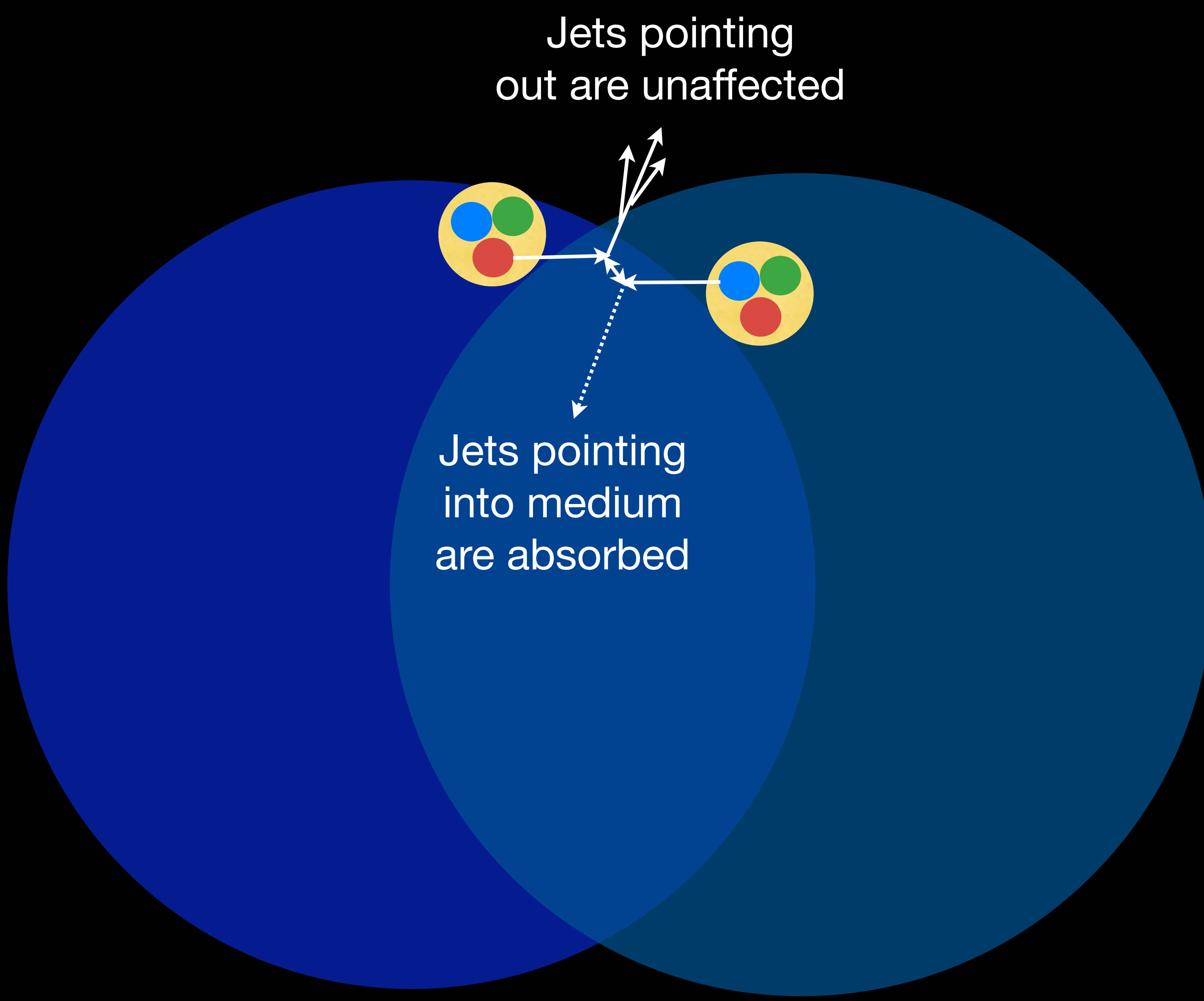
p+p shows "near" and "away" correlation

d+Au shows similar features

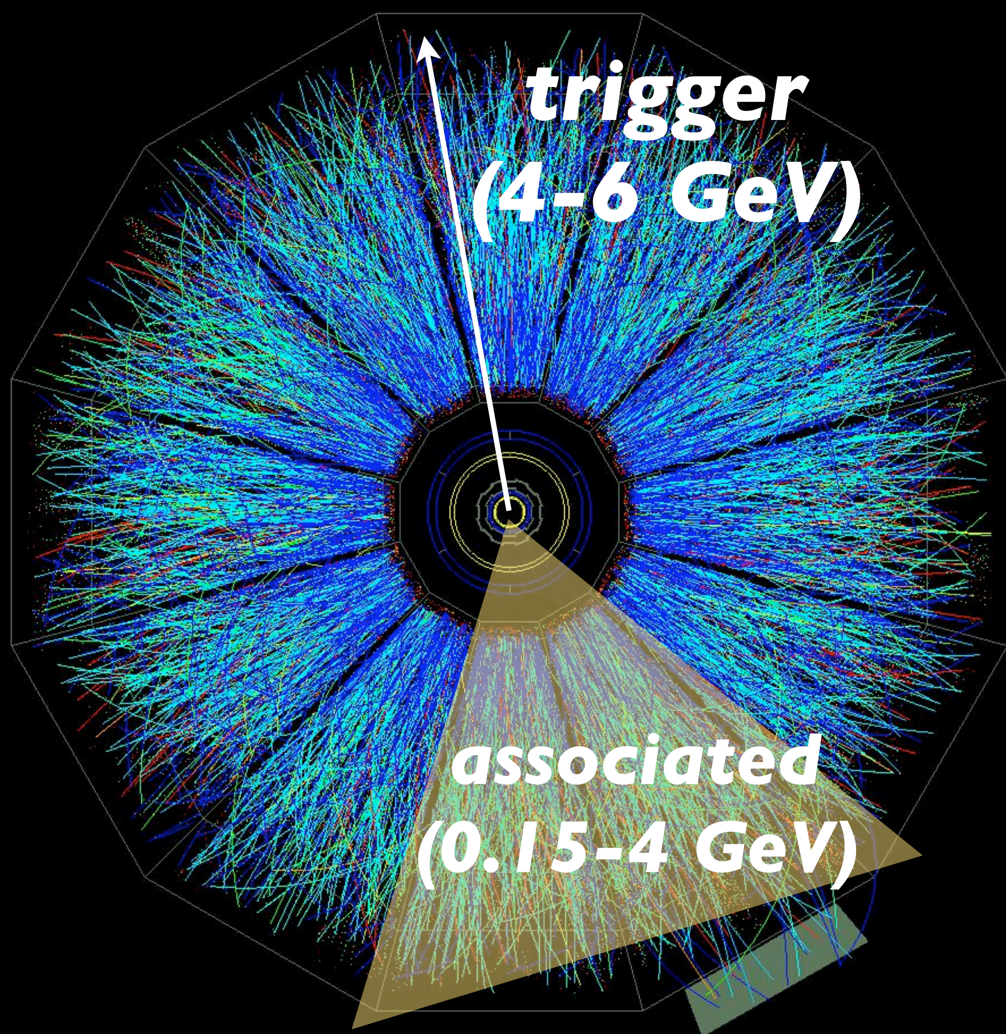
Au+Au shows a disappearance of the away side peak

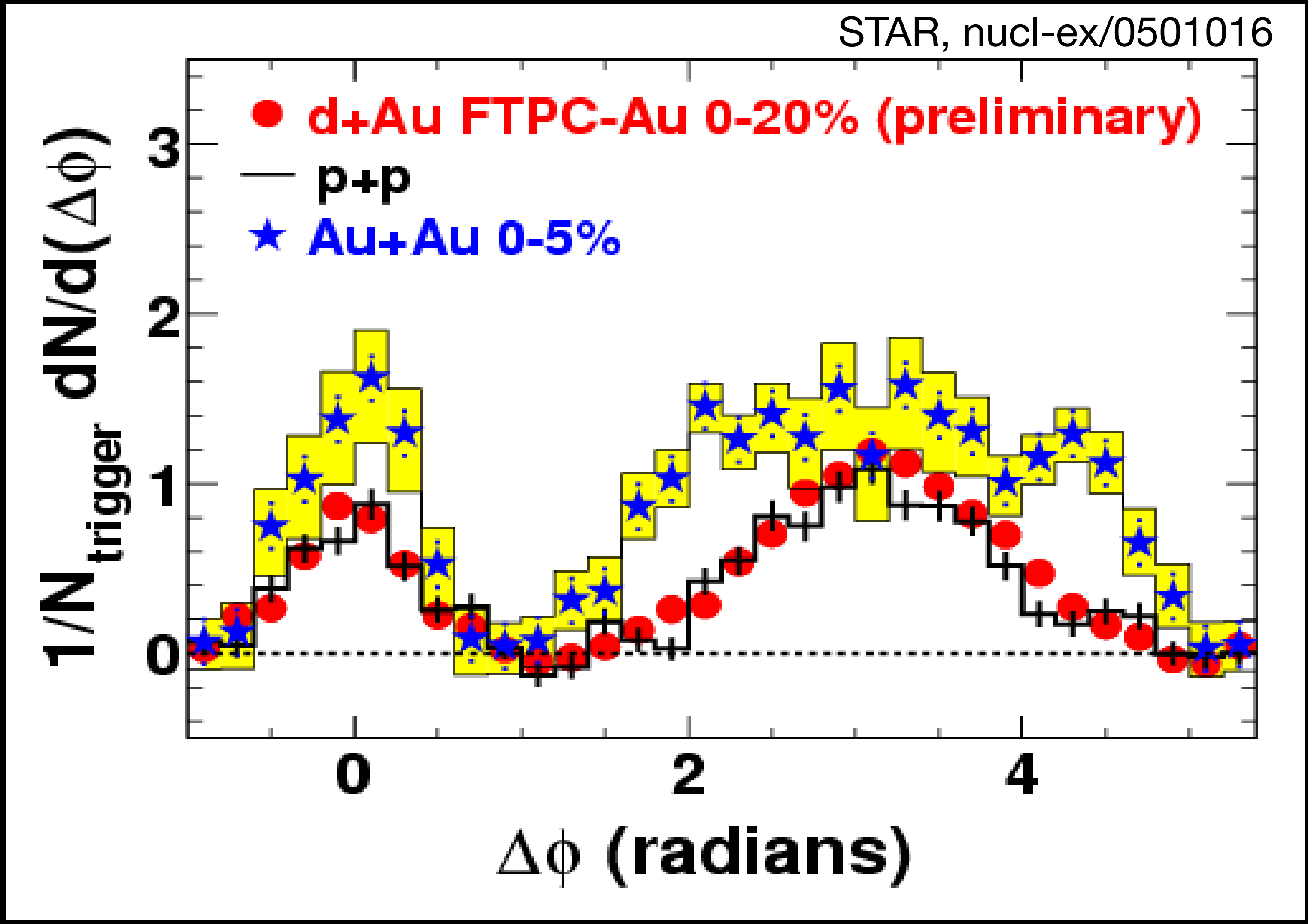


Surface bias



The Return of the “Away Side”

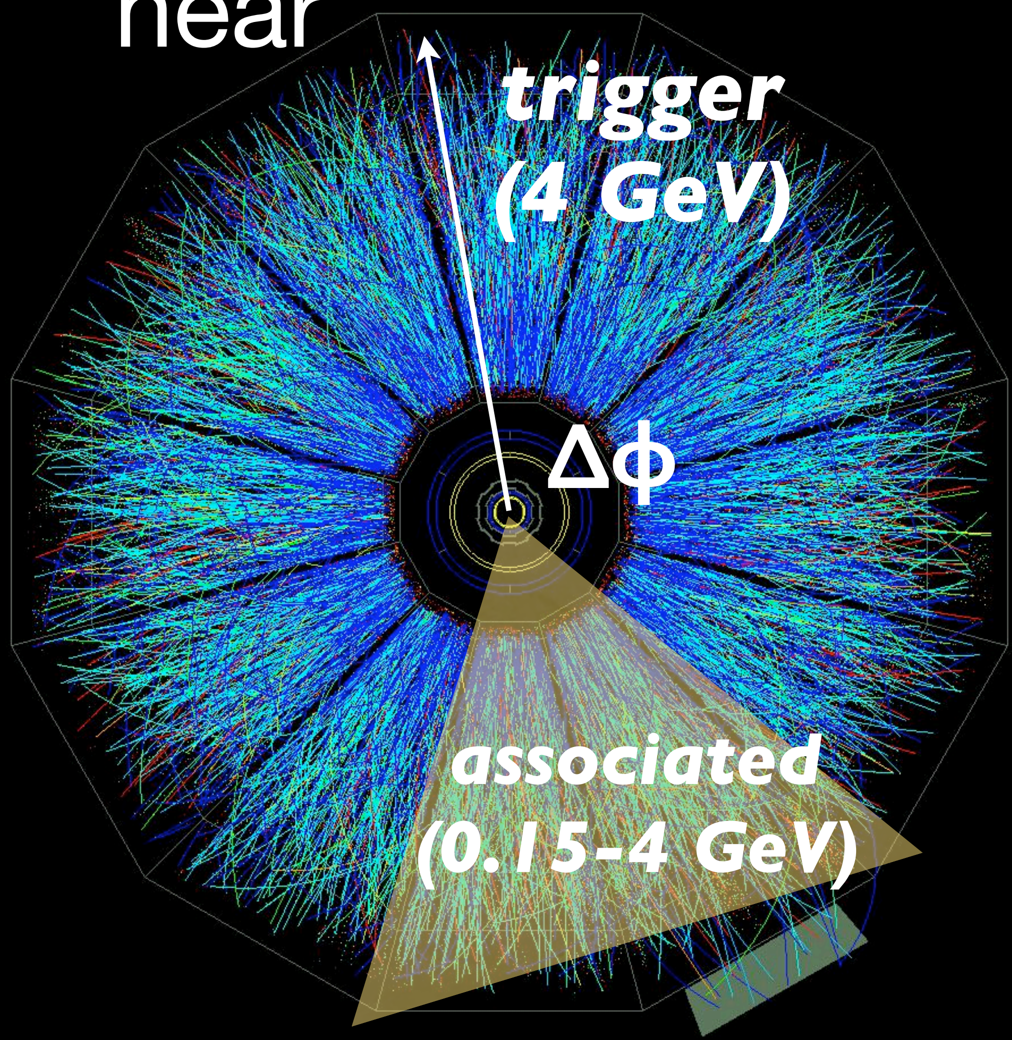


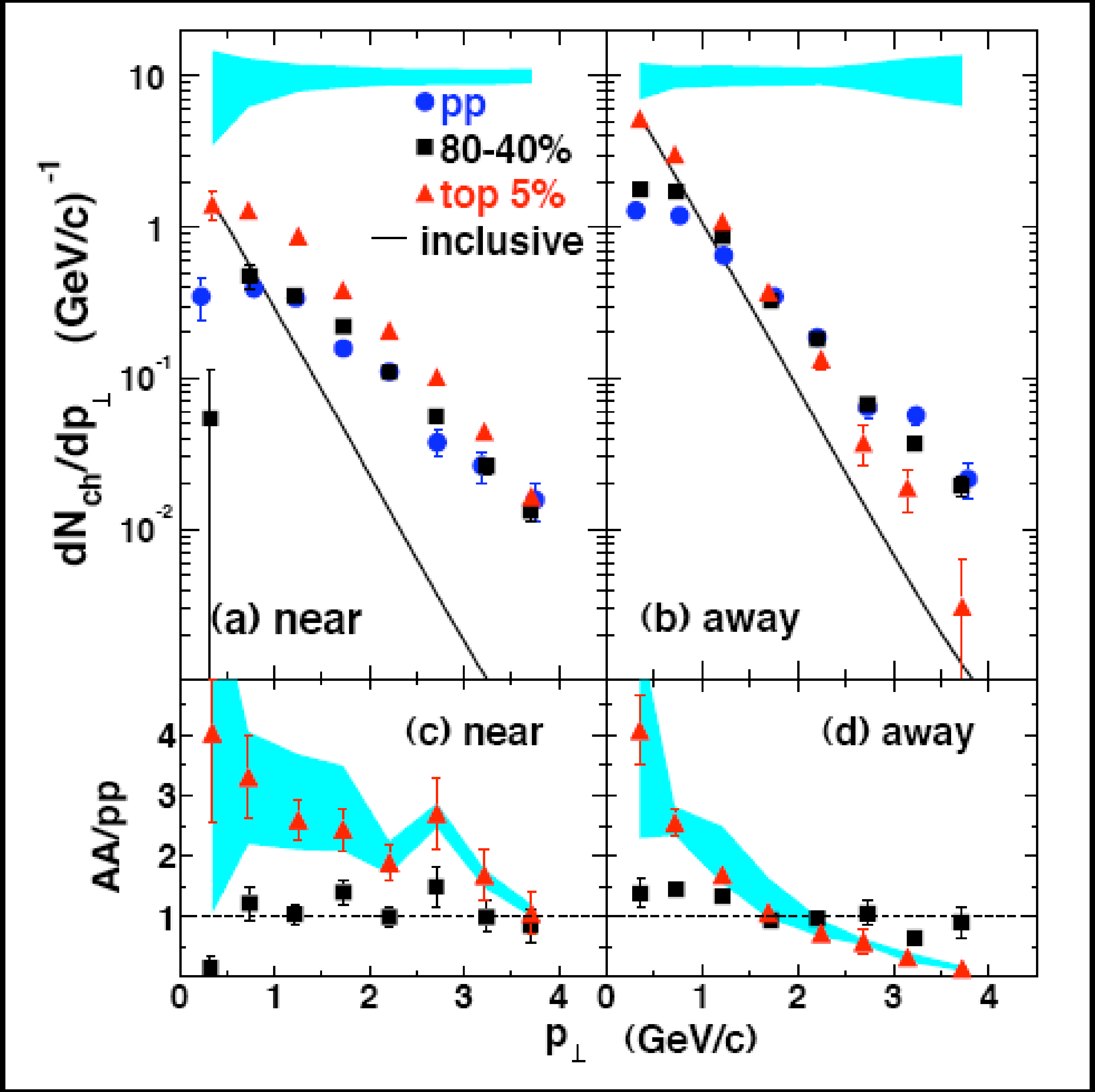


Including <u>all</u> particles (soft & hard) accounts for suppressed jet, but highly smeared-out in Φ .

Indicates non-trivial interaction with medium.

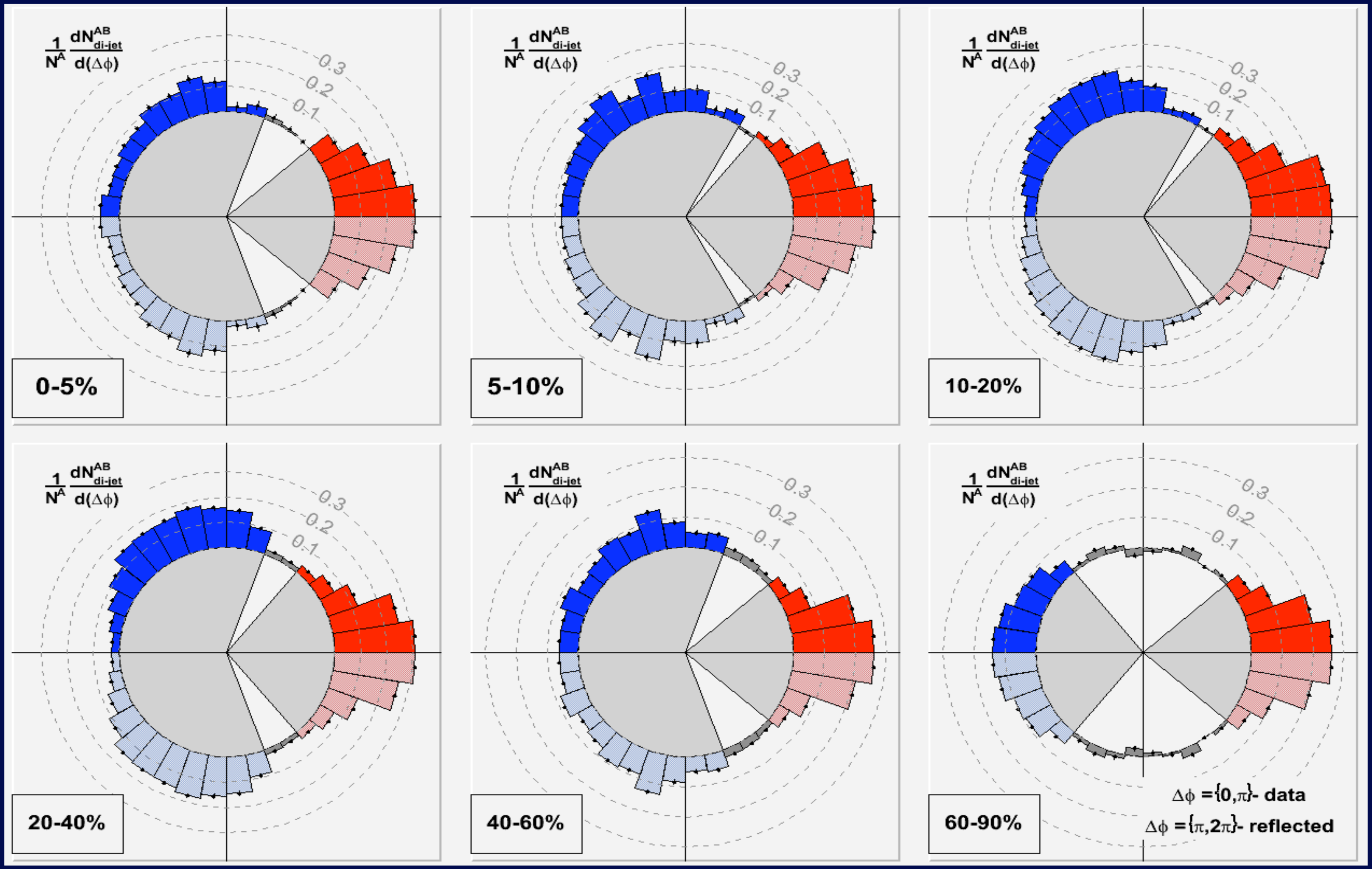
Spectral Modification

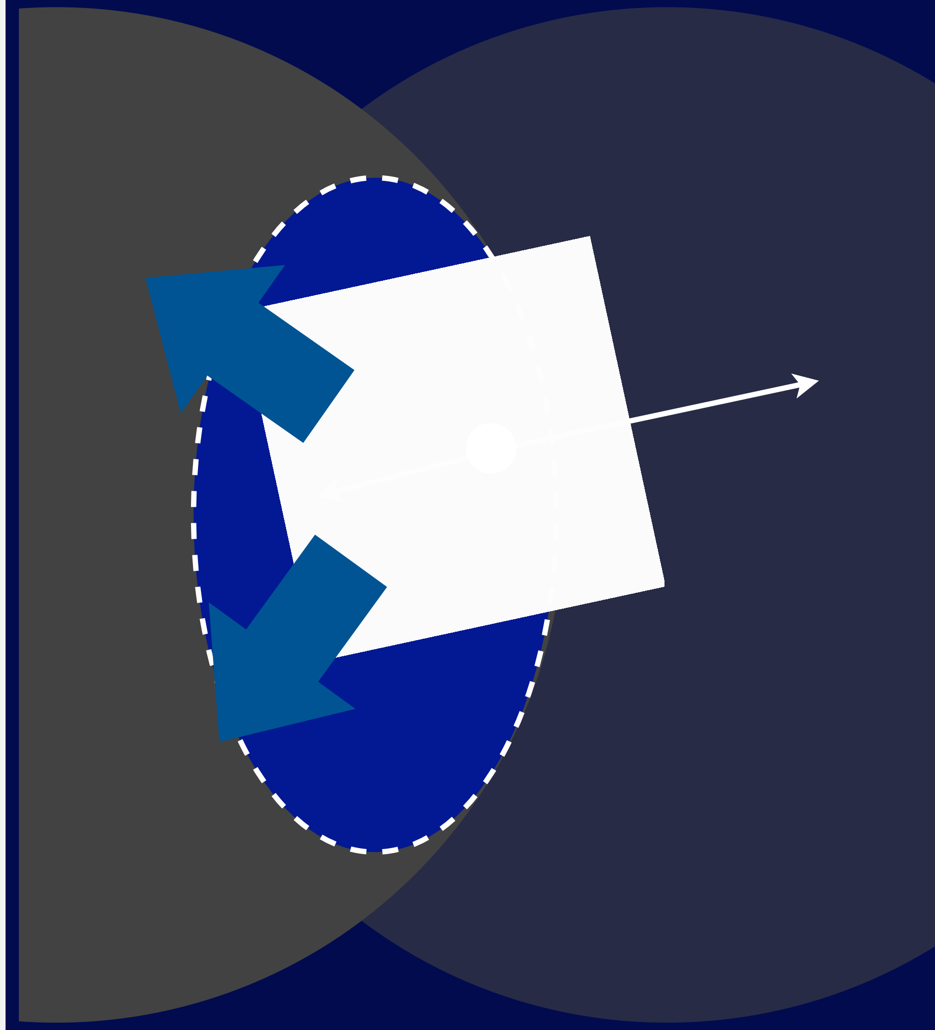




In more central events, away side disappears and spectrum starts to resemble inclusive “thermal” one

Medium Effects on Jets

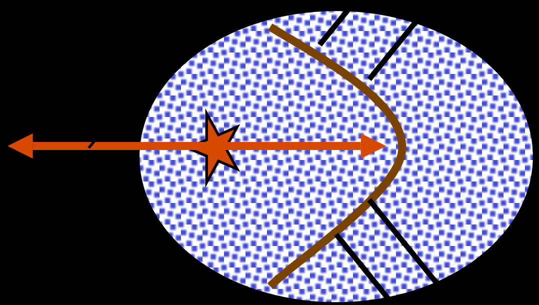




In central events, 2-particle correlations not back-to-back!

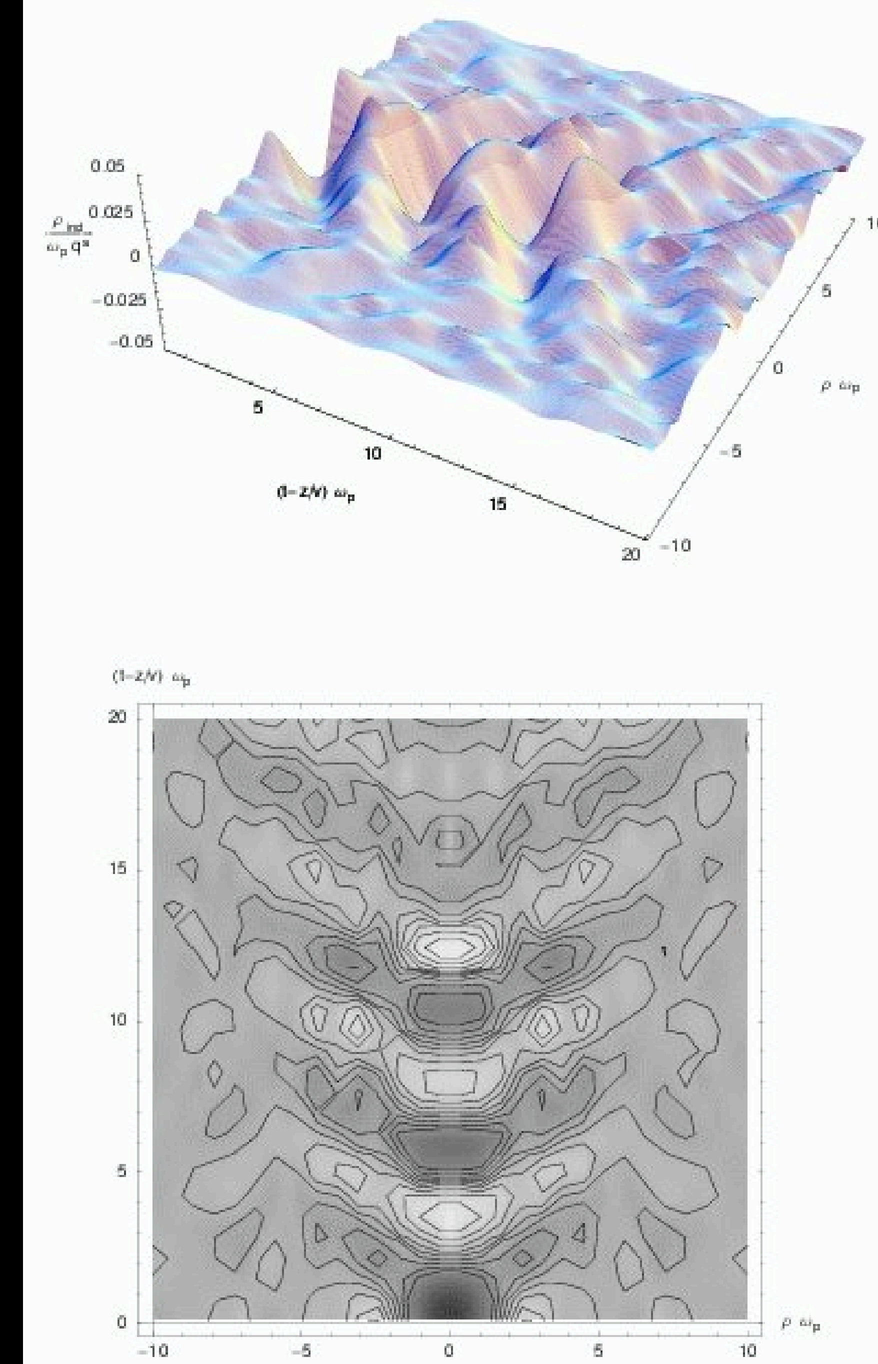
Suppression is a “redistribution” of energy/momentum. Excitations couple strongly to medium, rapidly thermalize

QCD Mach Cones?

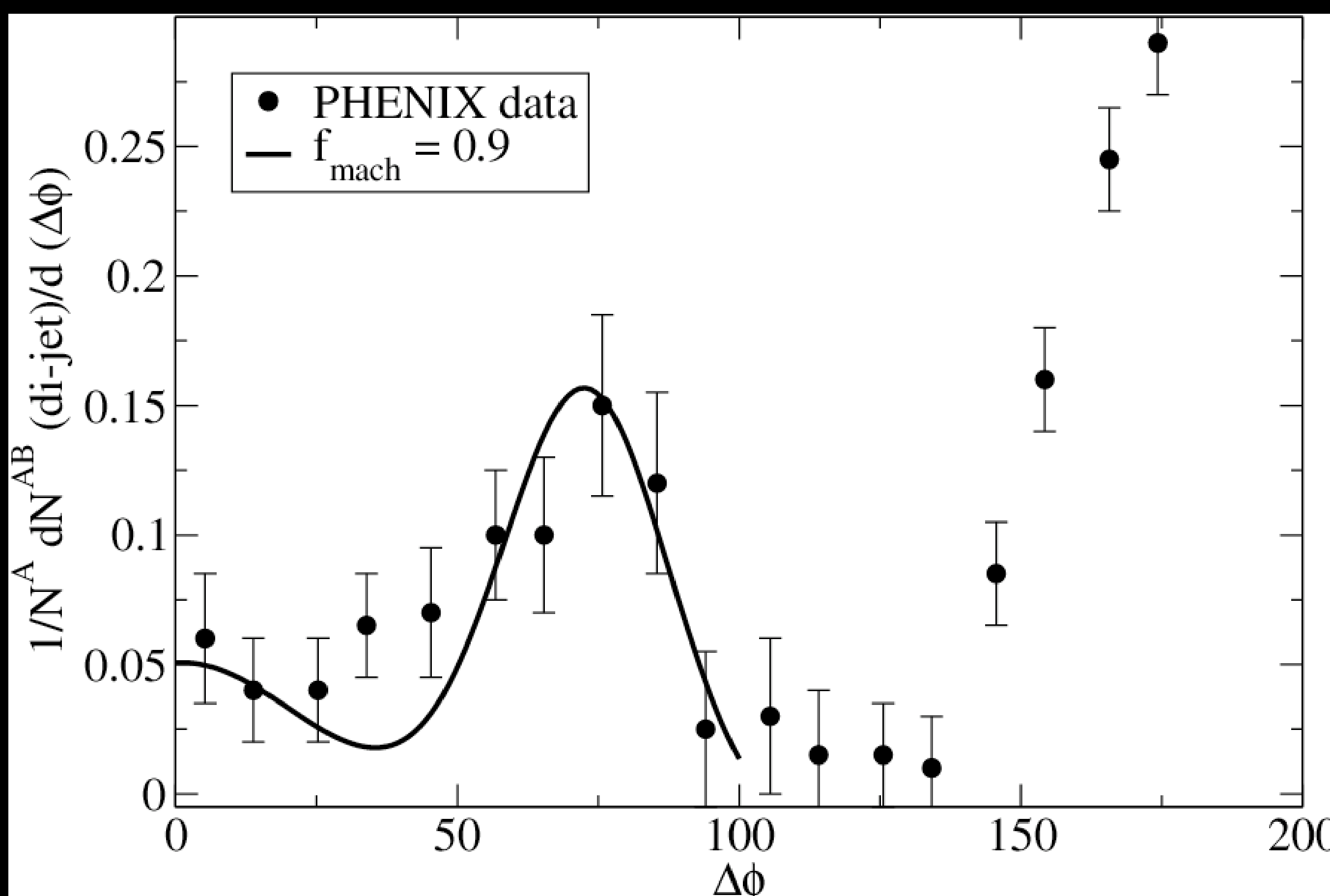


Does away-side jet, propagating at speed of light generate a Mach Cone?

$$\phi_M = \arccos(c_s/v)$$



Quantum Liquid, time-like branch in dispersion relation



J. Ruppert, QM2005

hep-th/0605182
PUPT-2198

Drag force in AdS/CFT

Mach cones from AdS/CFT, Gubser et al hep-th/0607022

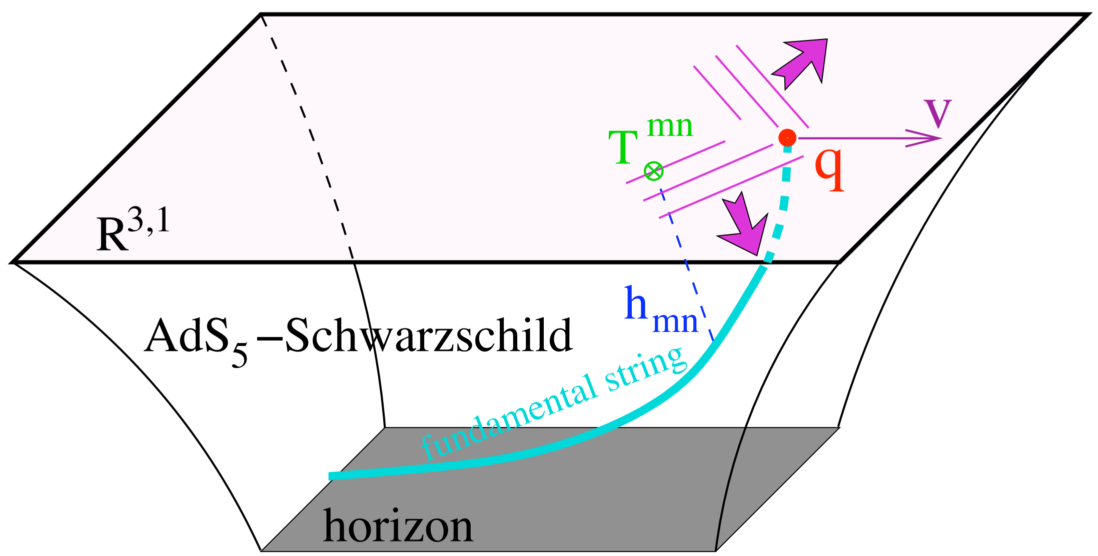
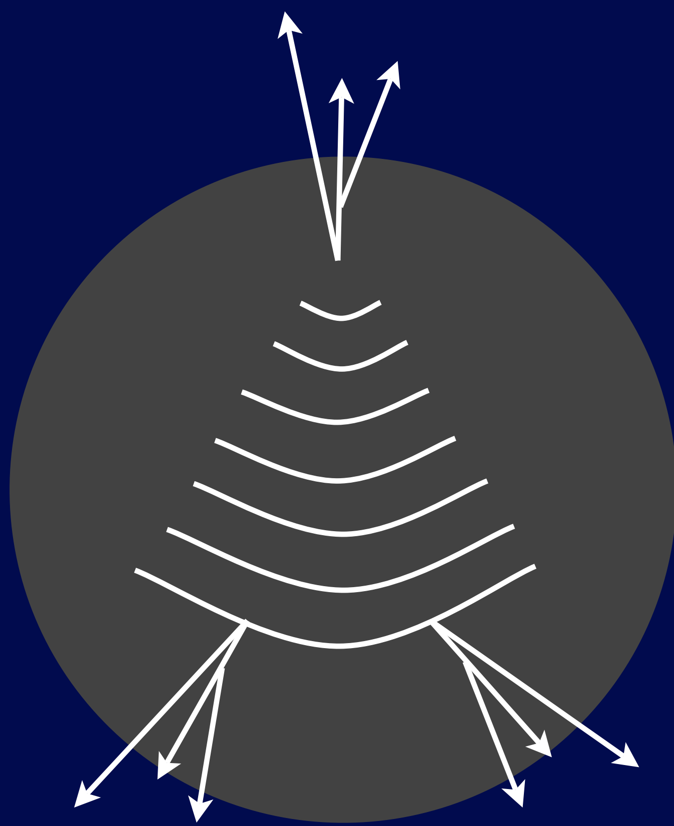


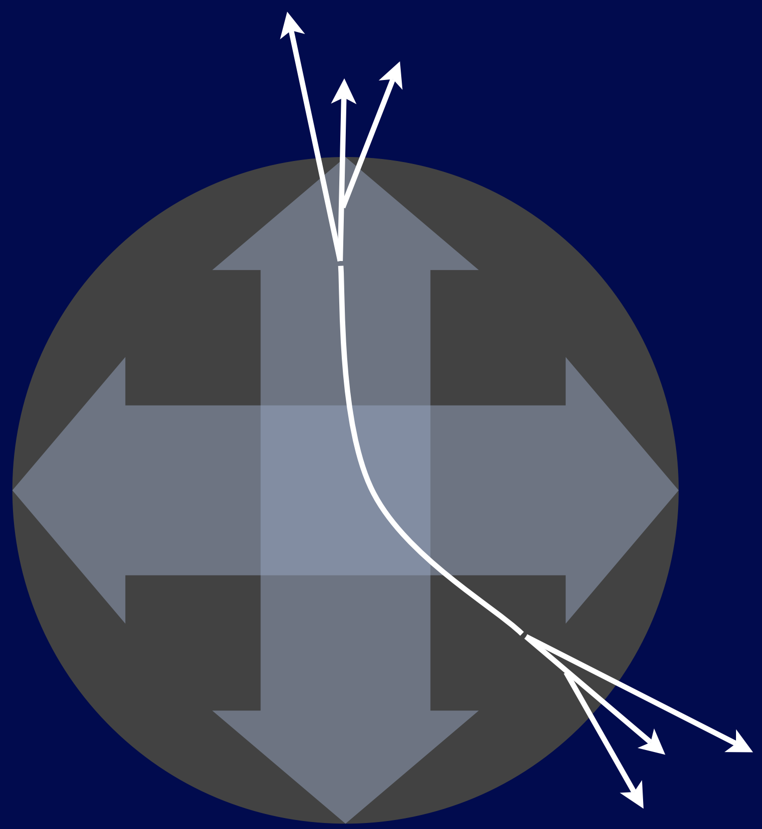
Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [24]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by its fundamental charge and interacting with the thermal medium.

May 2006

Alternative Explanations

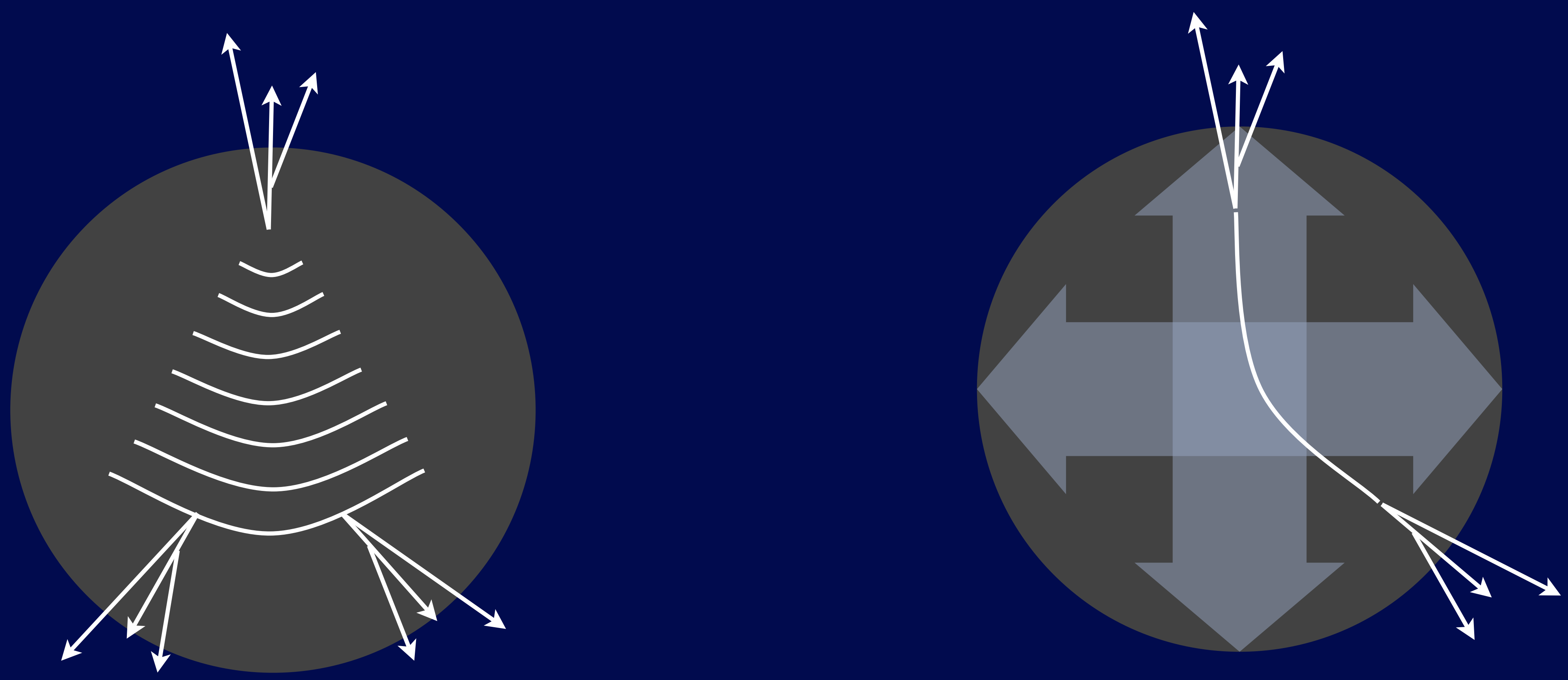


Mach Cone



Bent Jets
(radial flow)

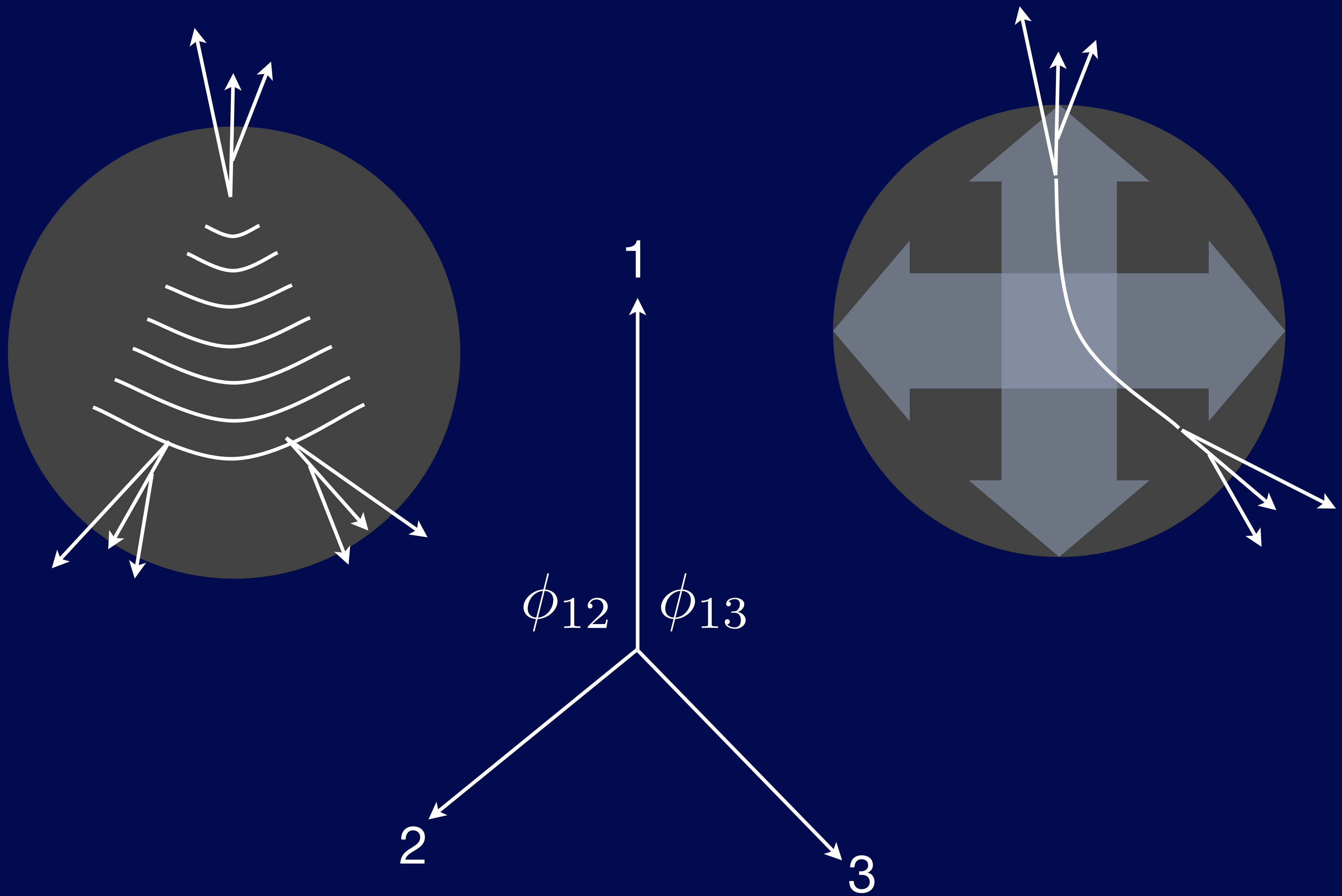
Alternative Explanations



Two particle correlations just see “acoplanarity” between trigger and associated particle.

Only three particle correlations can see “many body” aspects of different scenarios

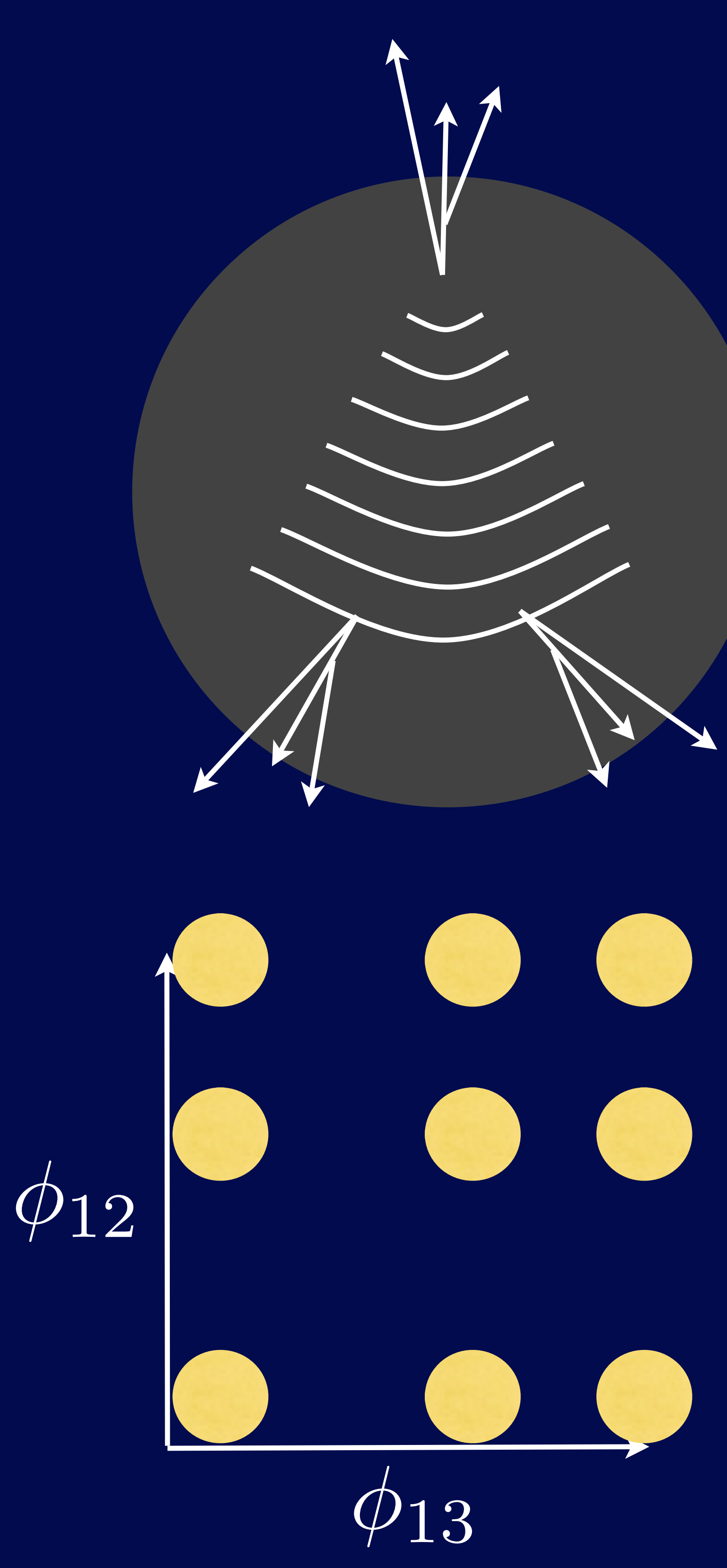
Three Particle Correlations

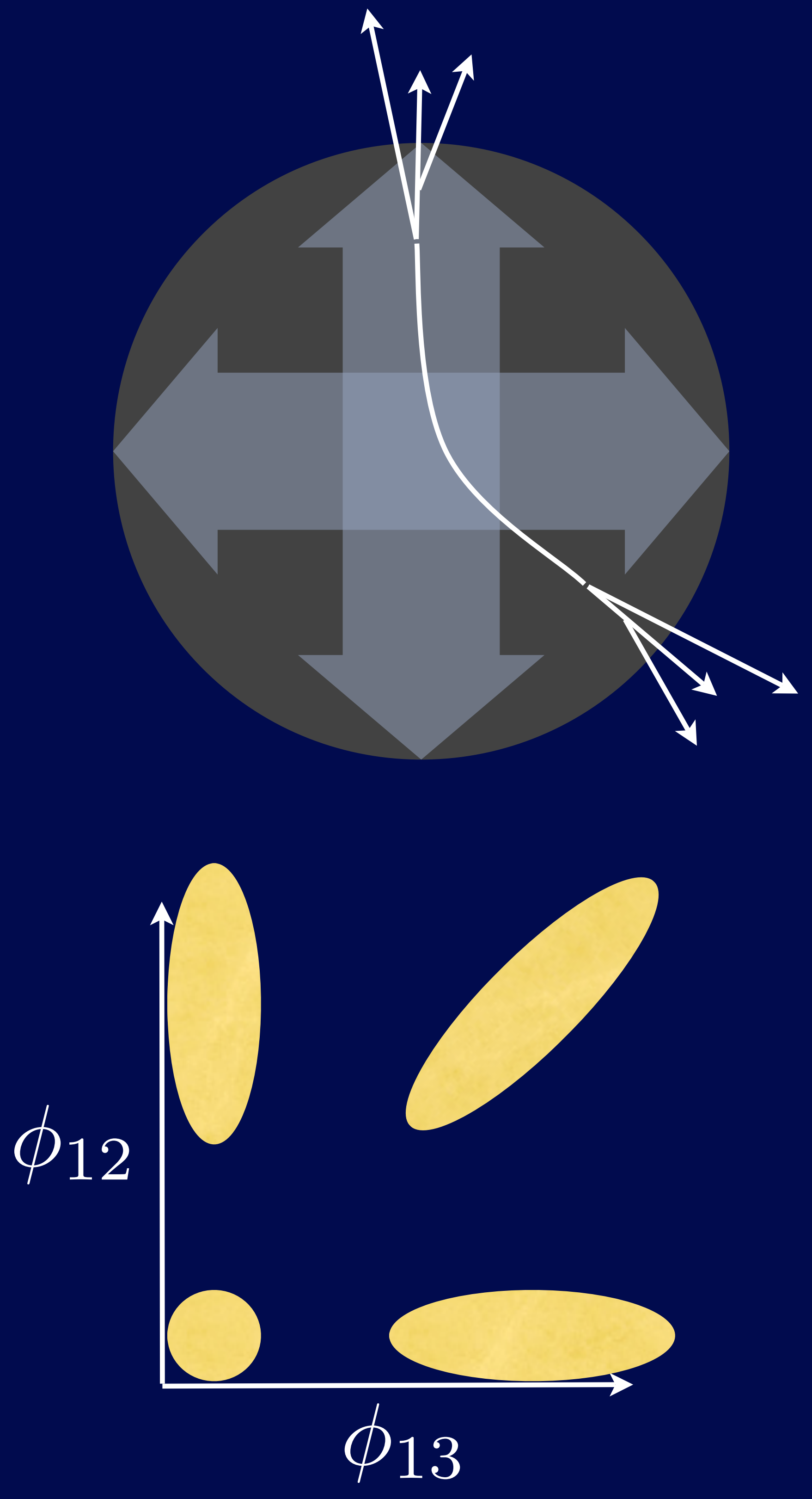


Correlate ϕ_{12} and ϕ_{13}

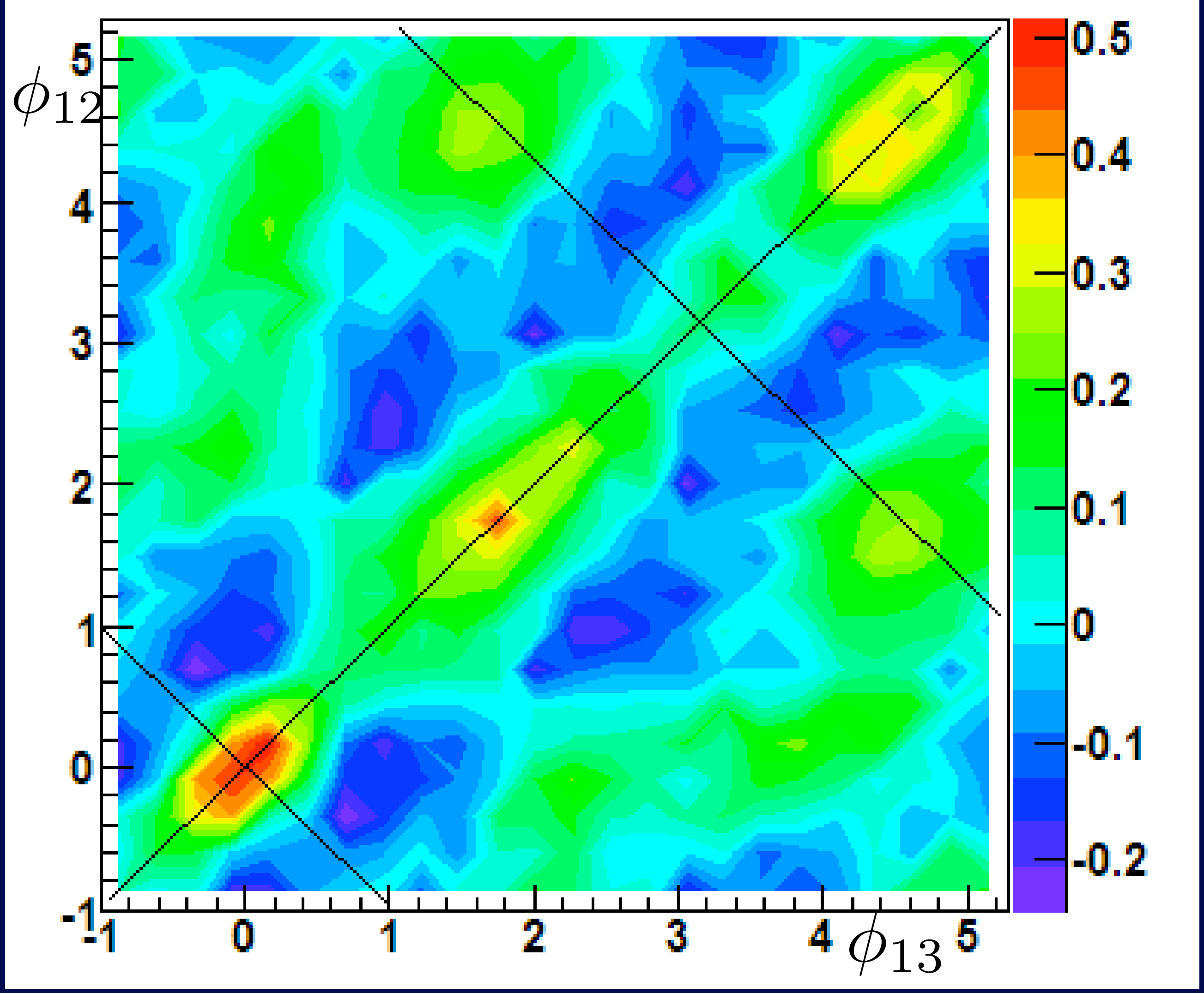
See if signatures are different for different scenarios

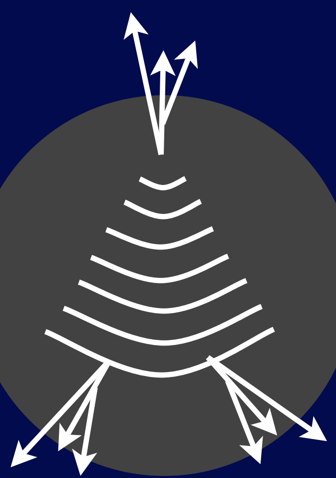
Correlation Patterns

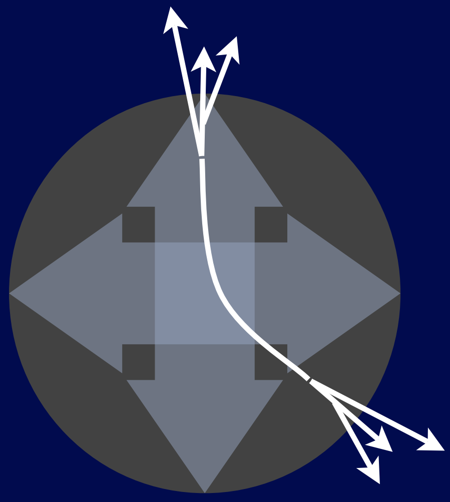


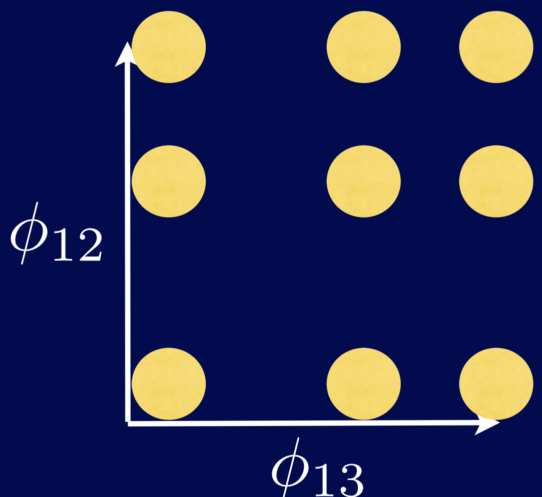


STAR Data

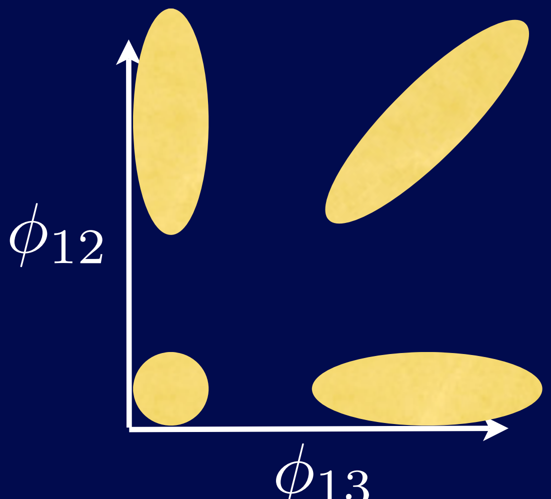






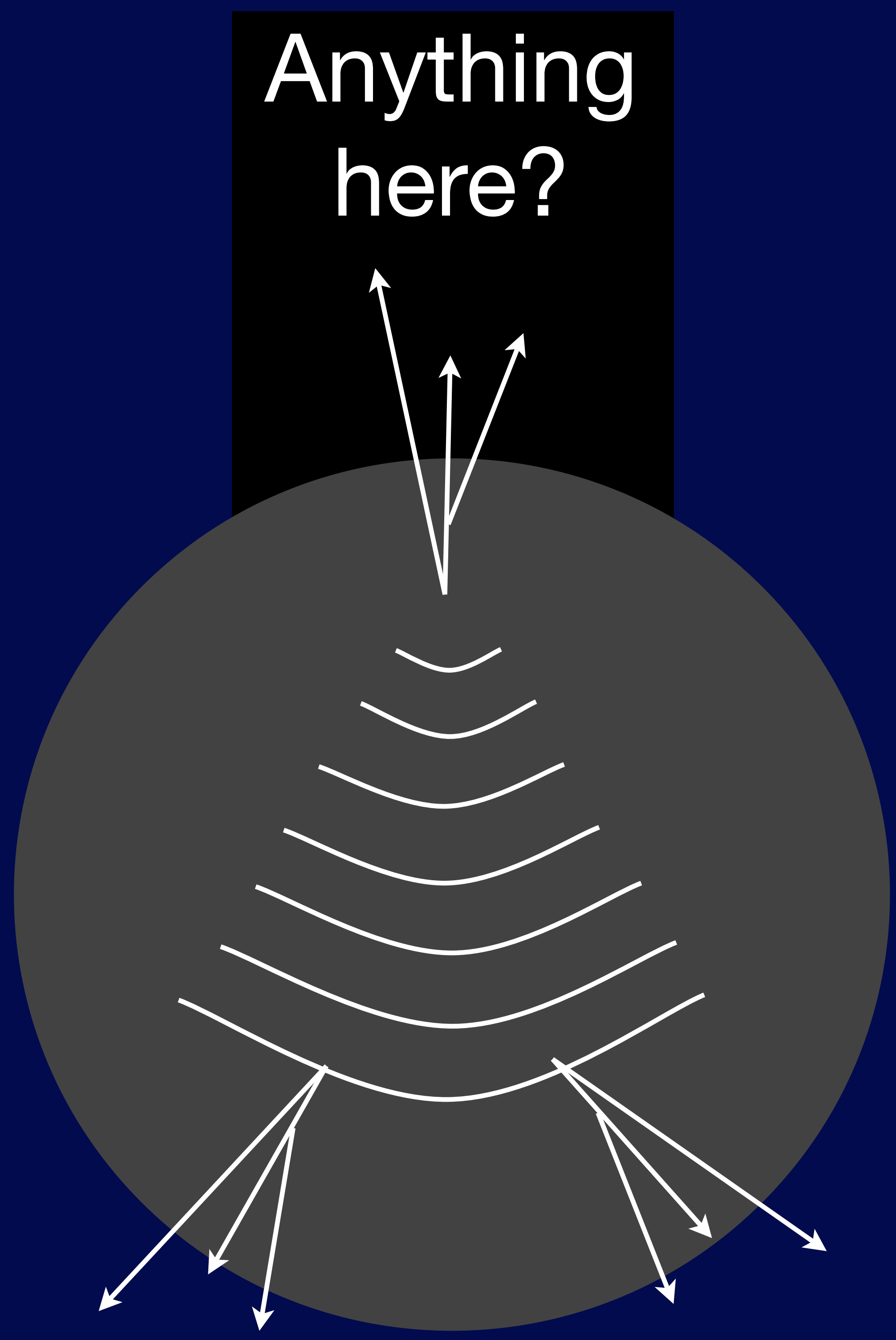


Generally thought
to support
Mach Cone vs. Bent Jets

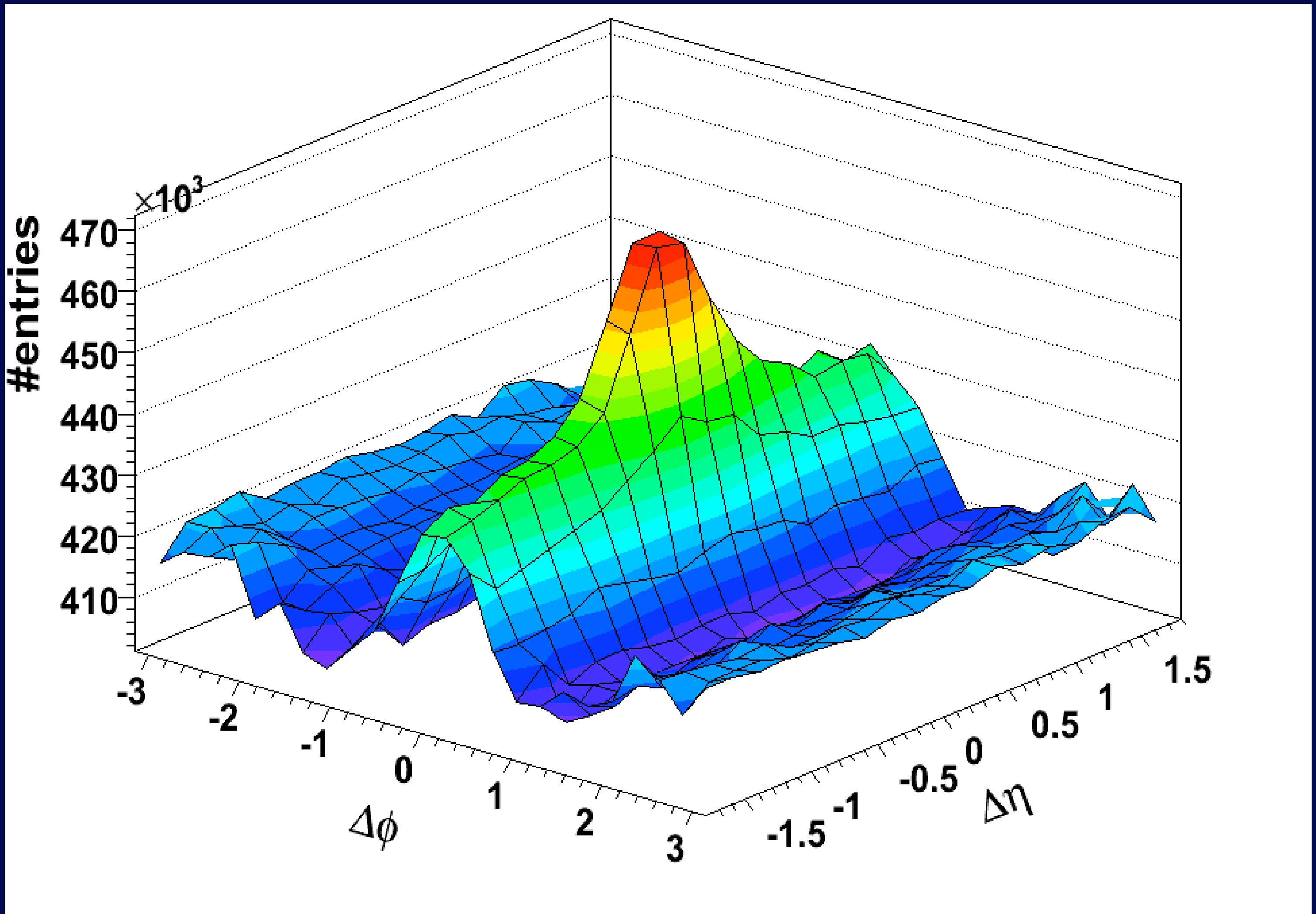


J. Ulery, conf. proceedings

Back to the Near Side

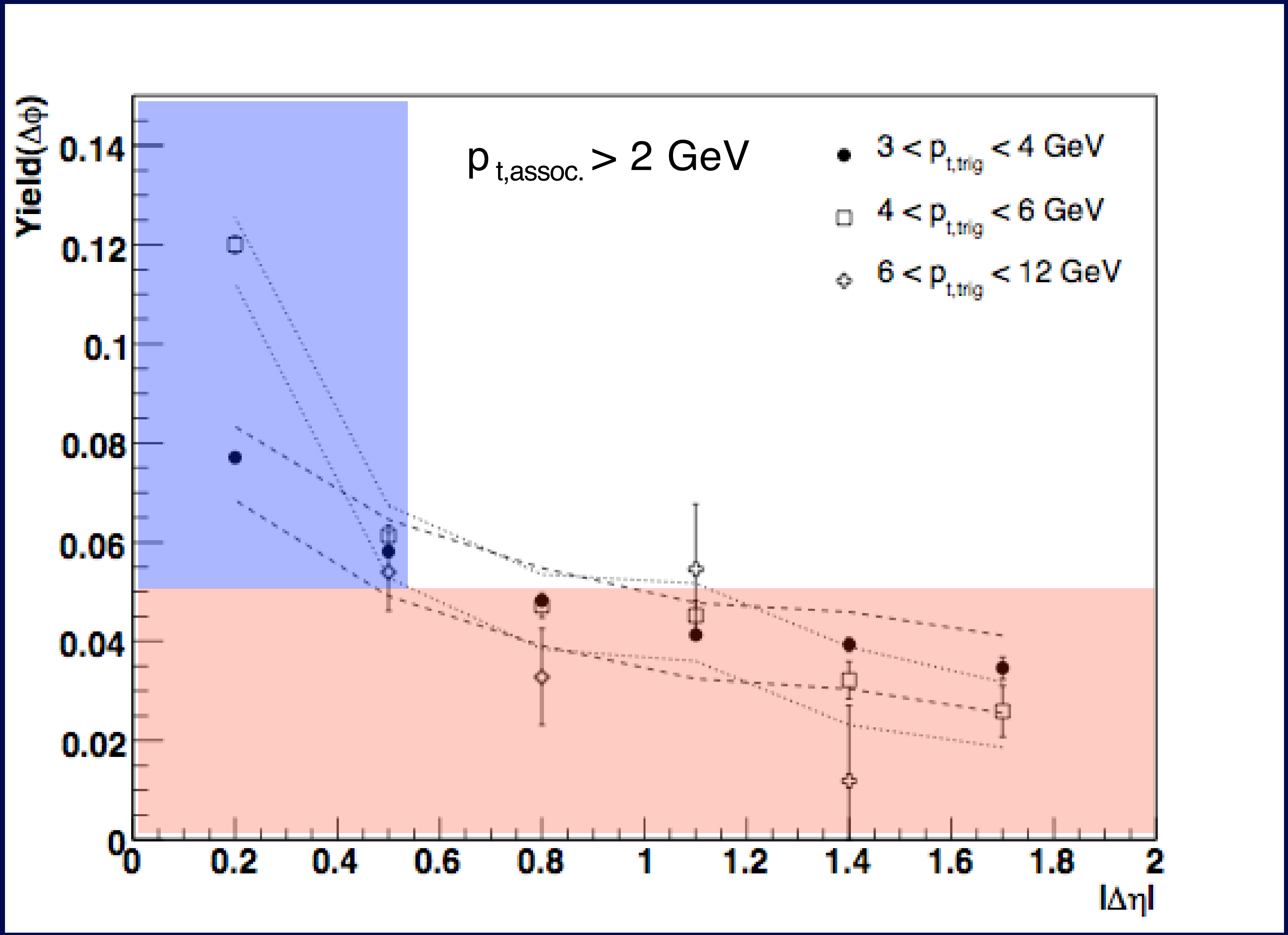


“The Ridge”

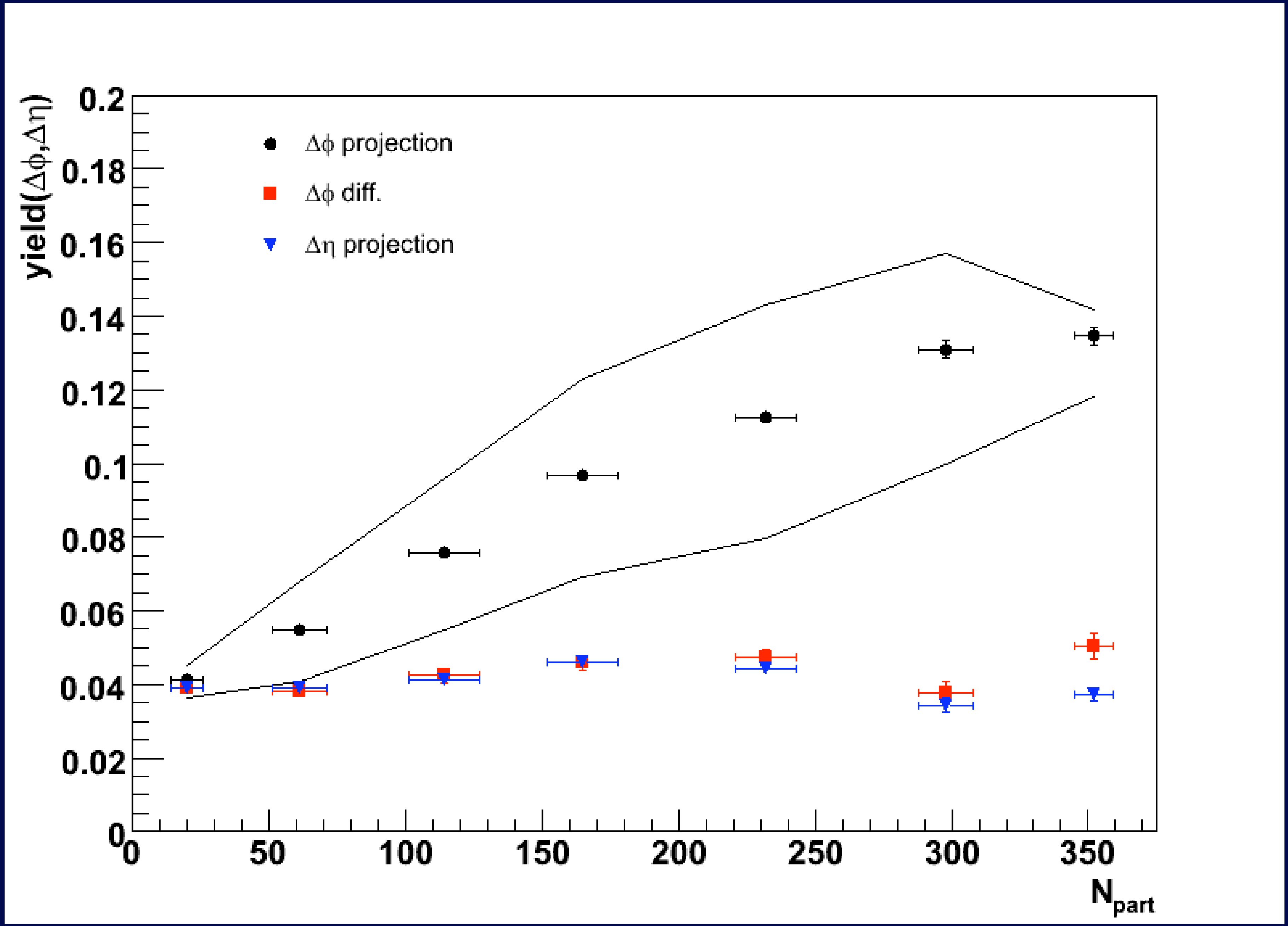


In central Au+Au, particles
tightly correlated in Δϕ, extended “ridge” in Δη

Subtracting Ridge

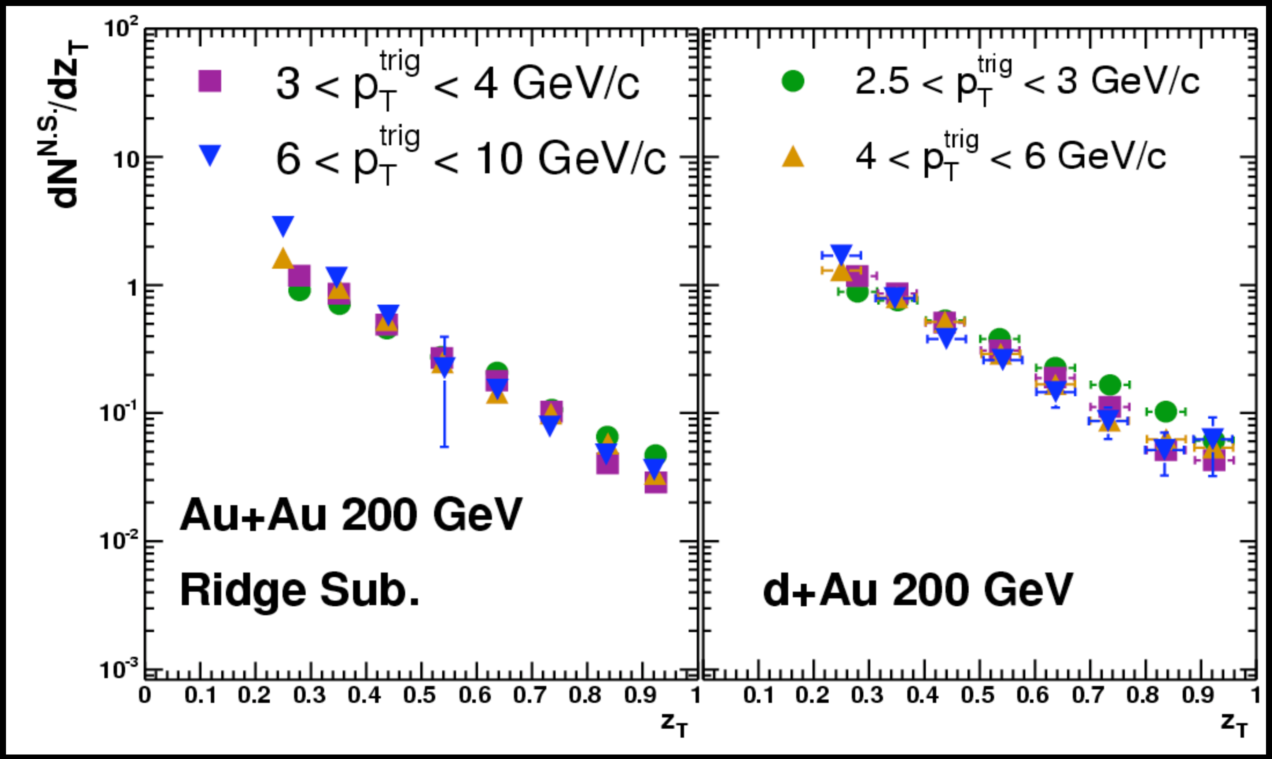


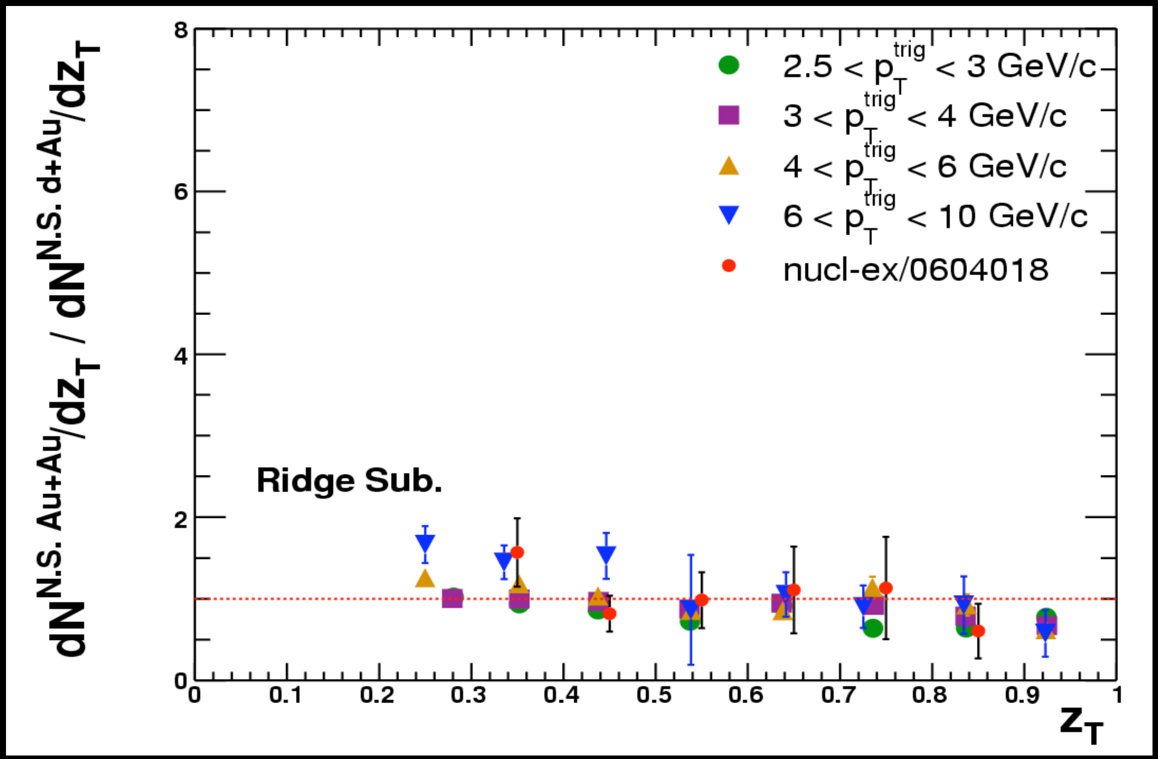
Jet vs. Ridge Yields



"Ridge" part of yield scales with N_{part}, while subtracted yield is constant

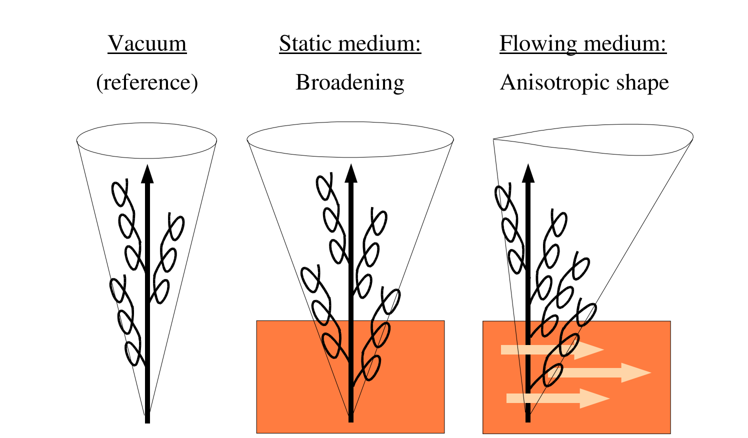
Jet Properties w/o Ridge





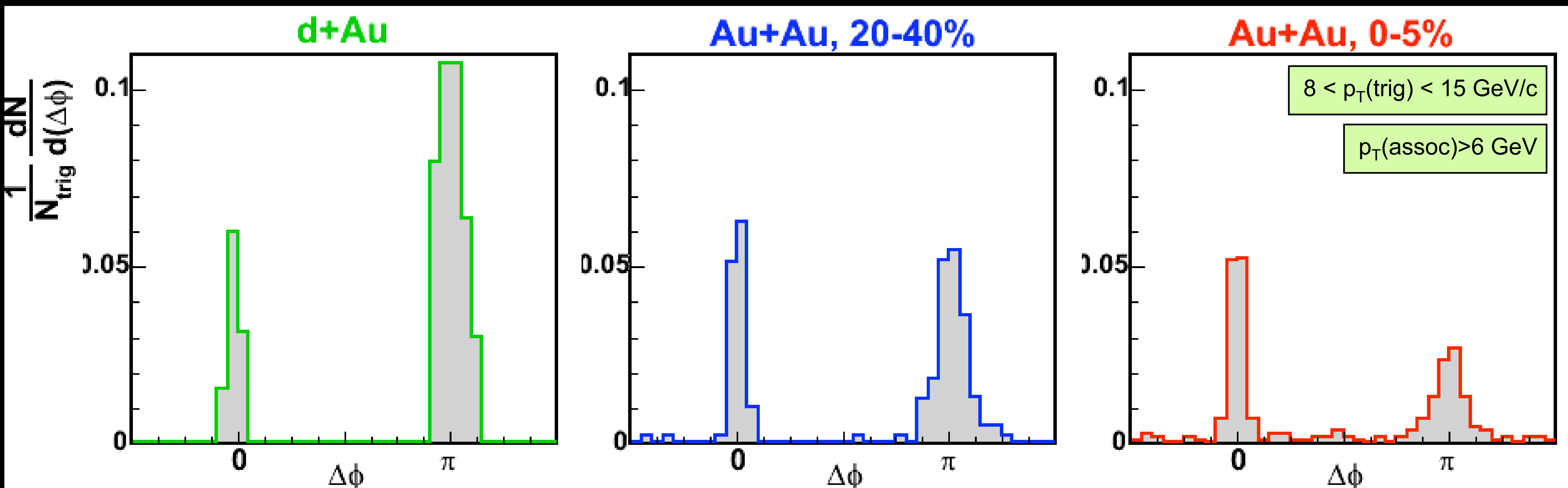
Fragmentation and yield of jets in Au+Au very similar to d+Au, after ridge removed.

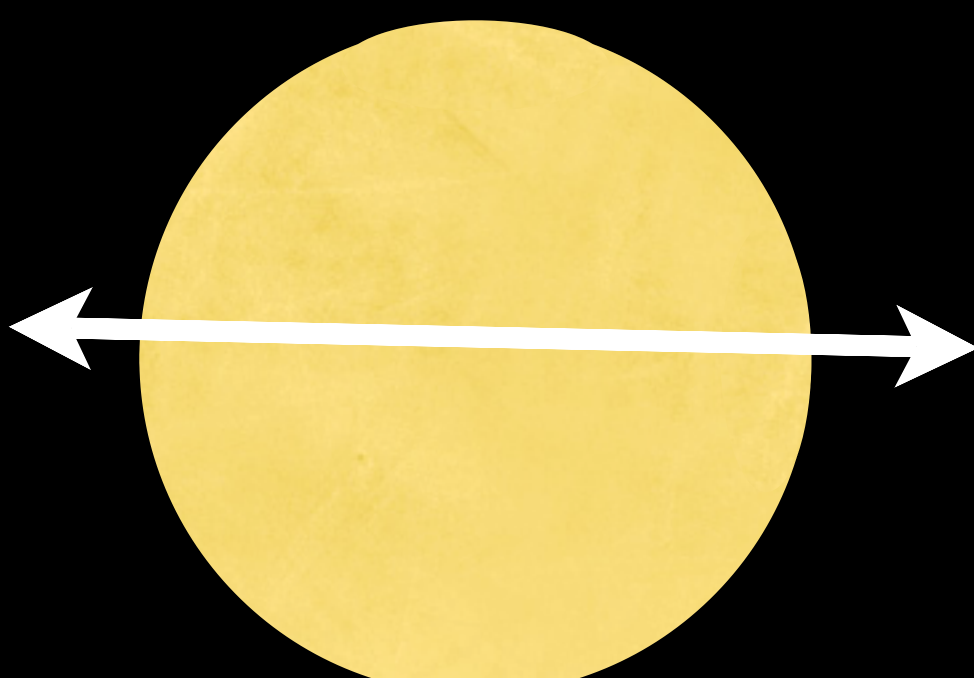
Is ridge from energy loss near surface, while the released gluons are "pulled" by longitudinal flow?...



Phys.Rev.Lett.93:242301,2004

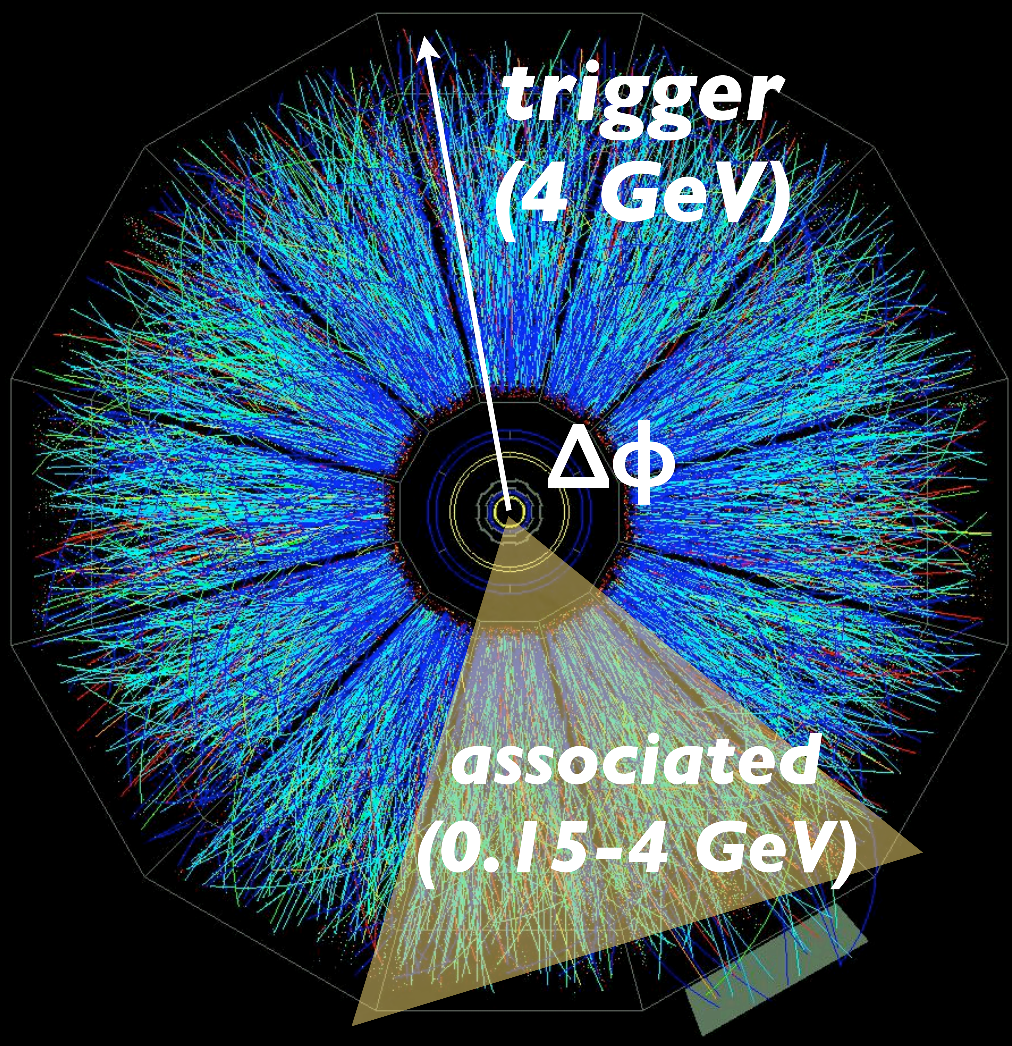
Return of “Back-to-Back” Jets

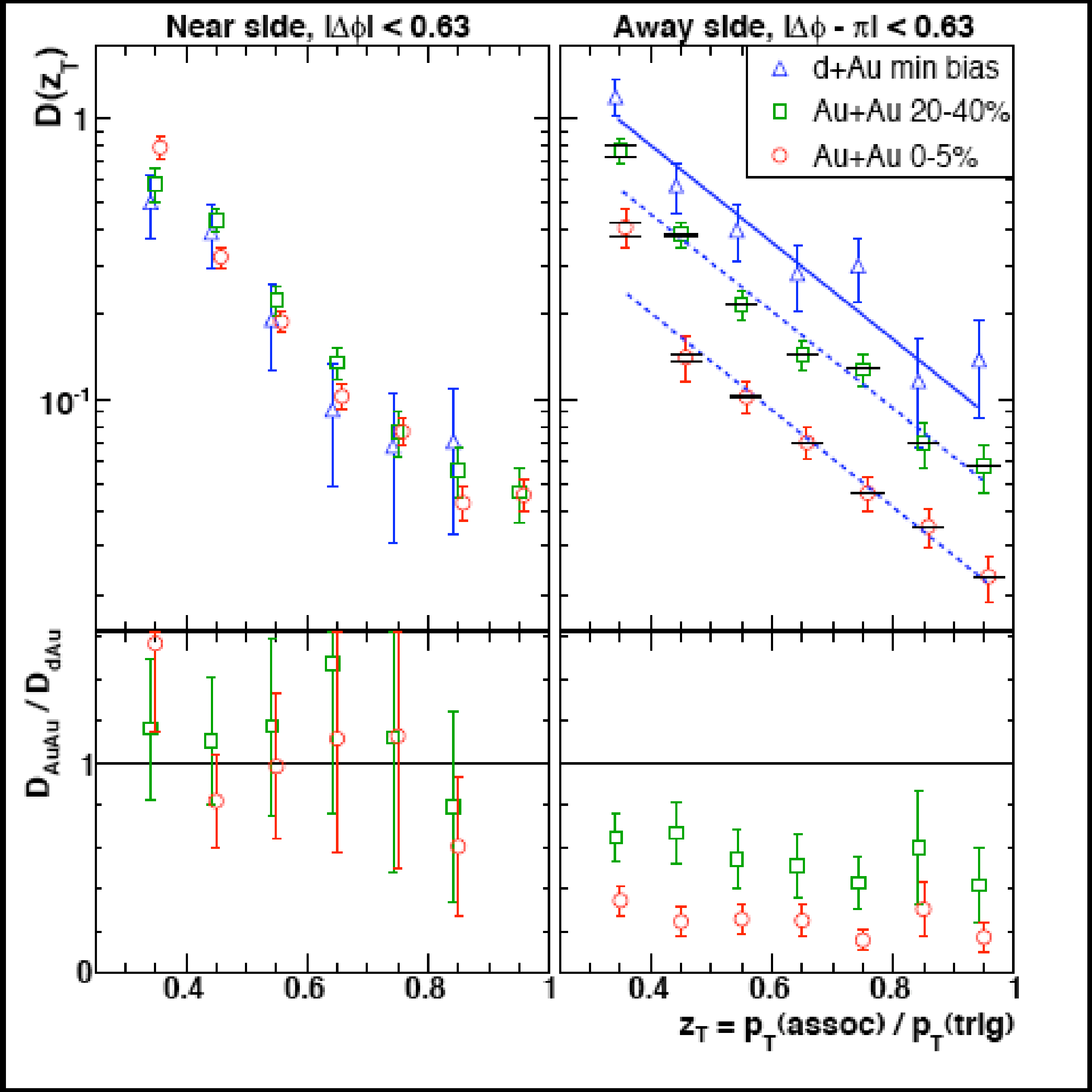




Is this really the “punch through” of high energy jets?

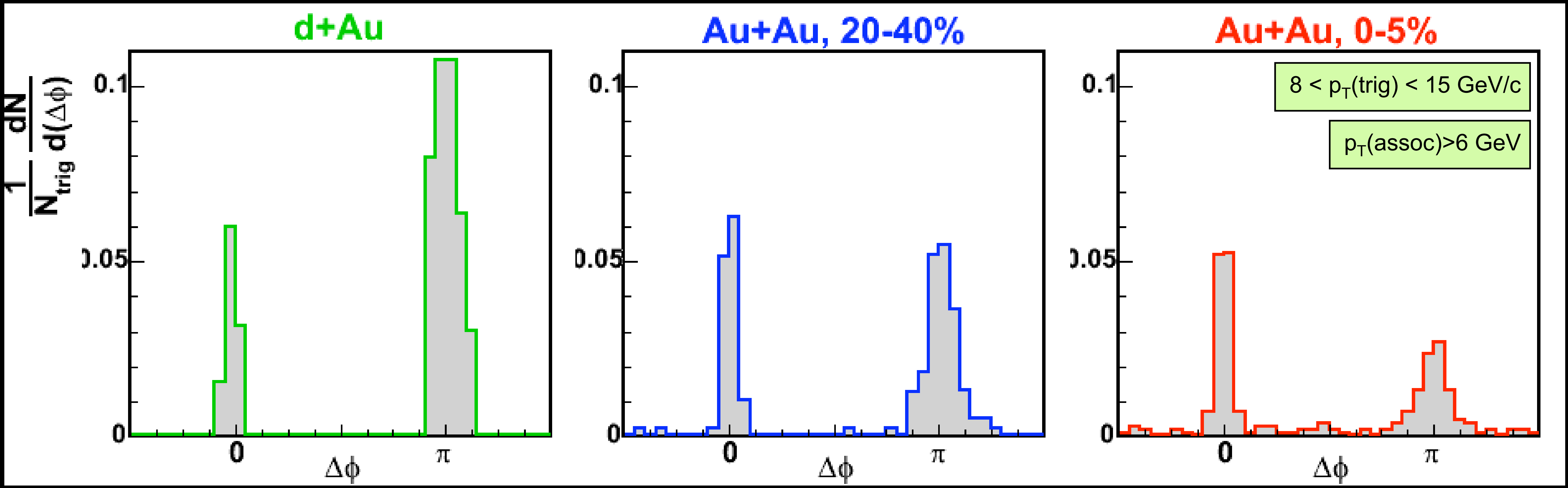
Spectral Modification

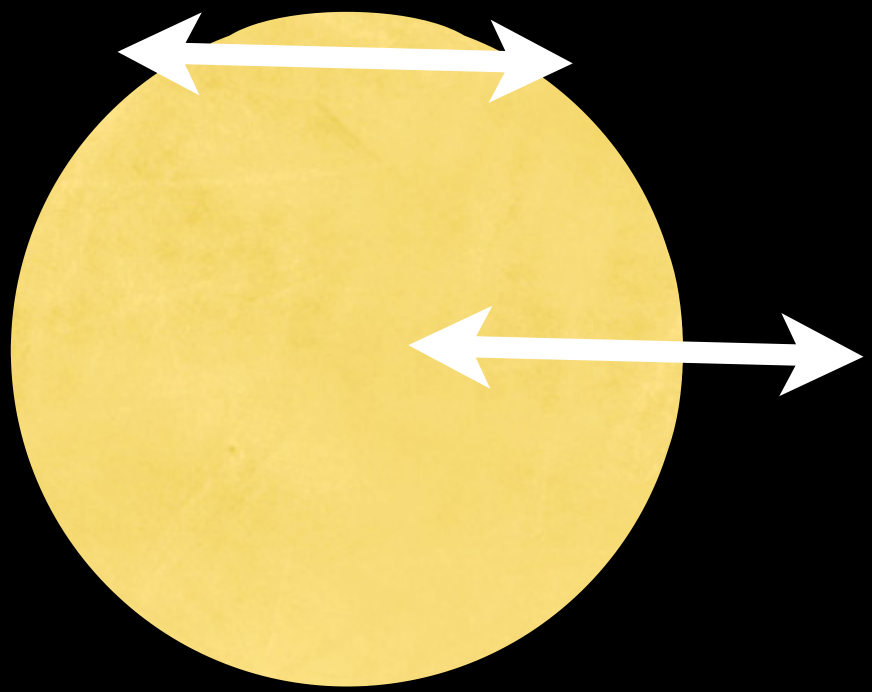




High "z_T" spectrum looks very similar in Au+Au & d+Au: jet fragmentation is similar when seen at all!

Return of "Back-to-Back" Jets

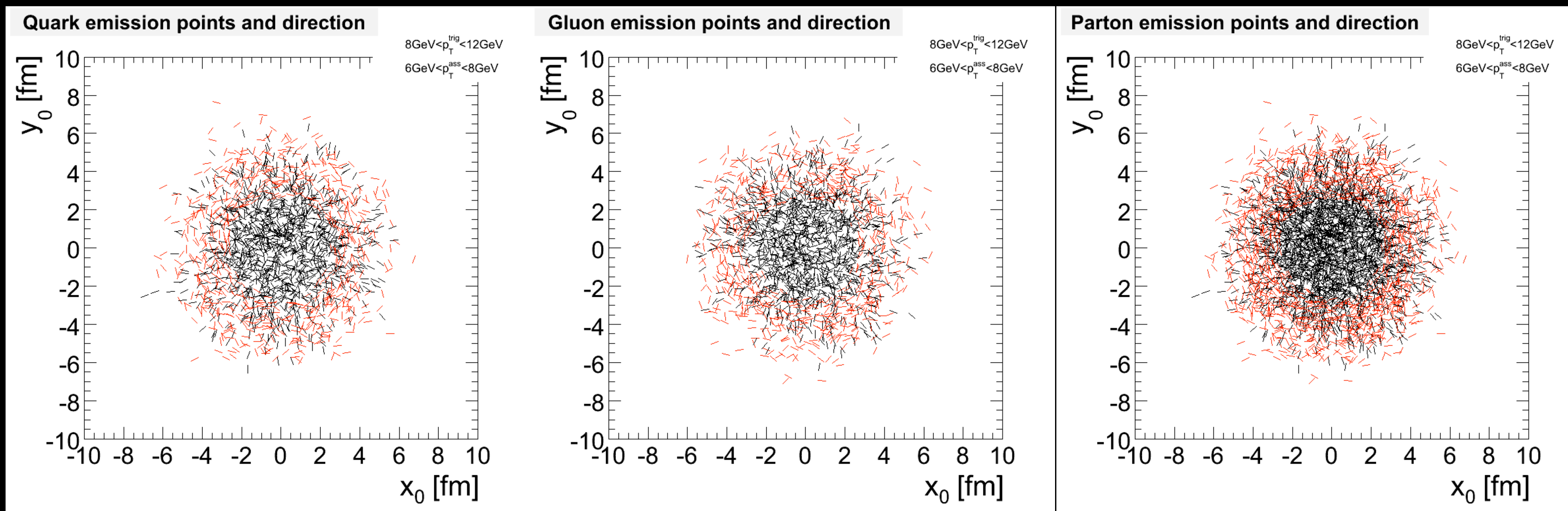


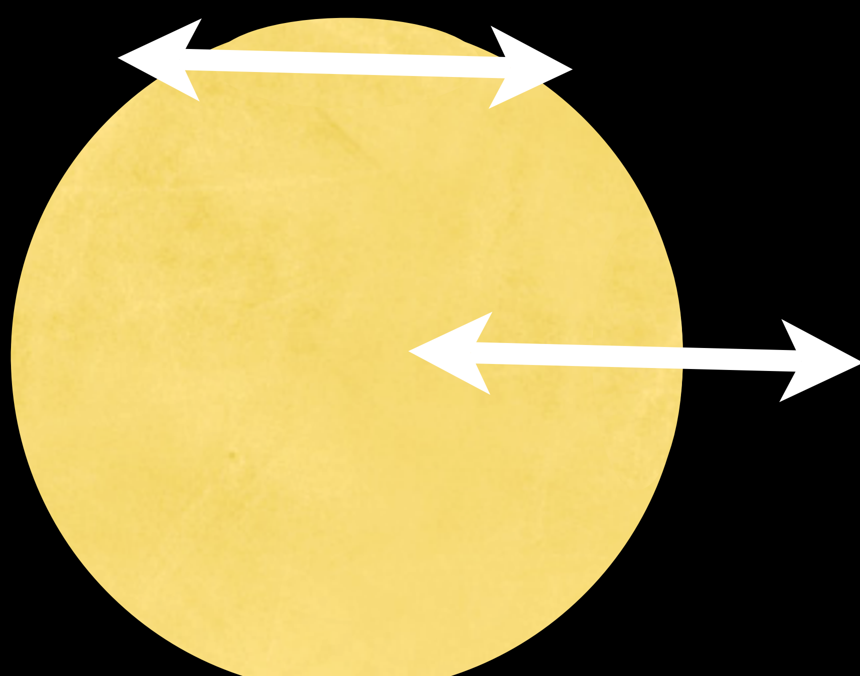


Might expect some fraction of jets where both escape, due to "halo" emission

Serious issue: under study!

Studies with PQM

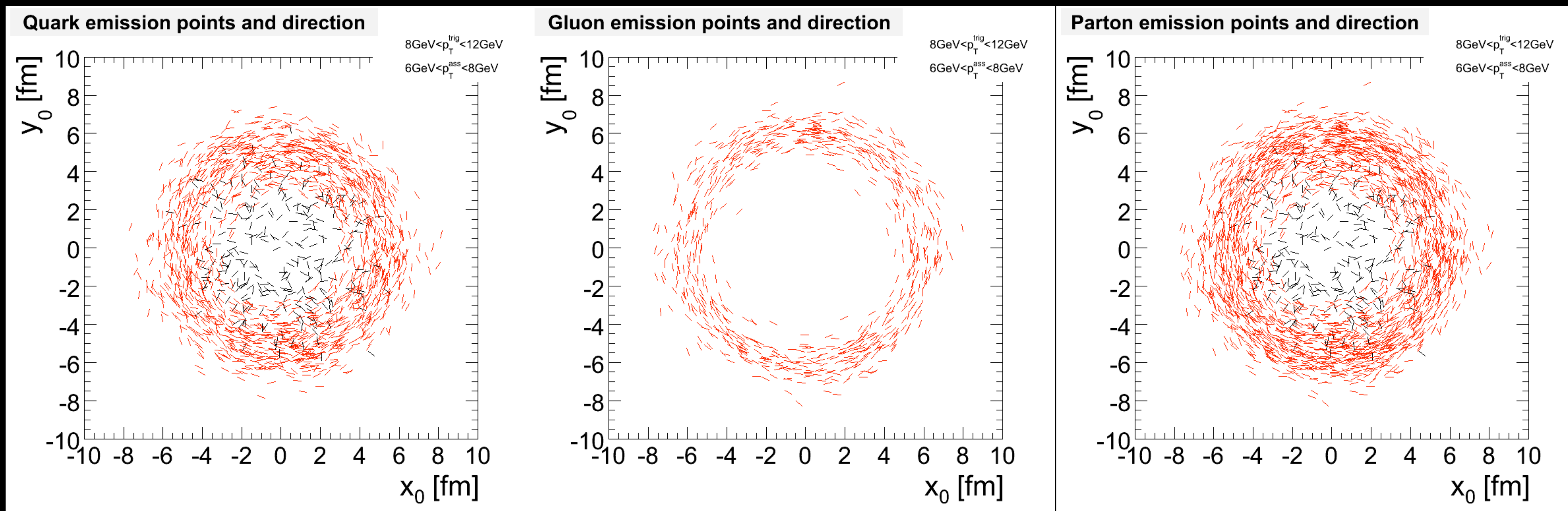


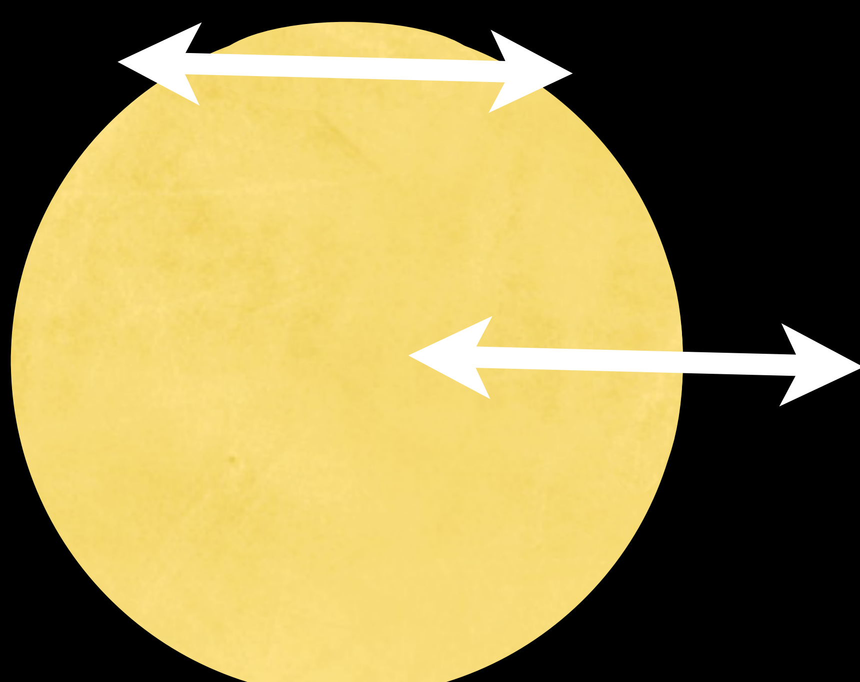


PQM uses standard jet-quenching formalism coupled to nuclear geometry in order to model density ($\hat{q}$)

PQM: Dainese, Loizides, Paic, nucl-ex/0406319

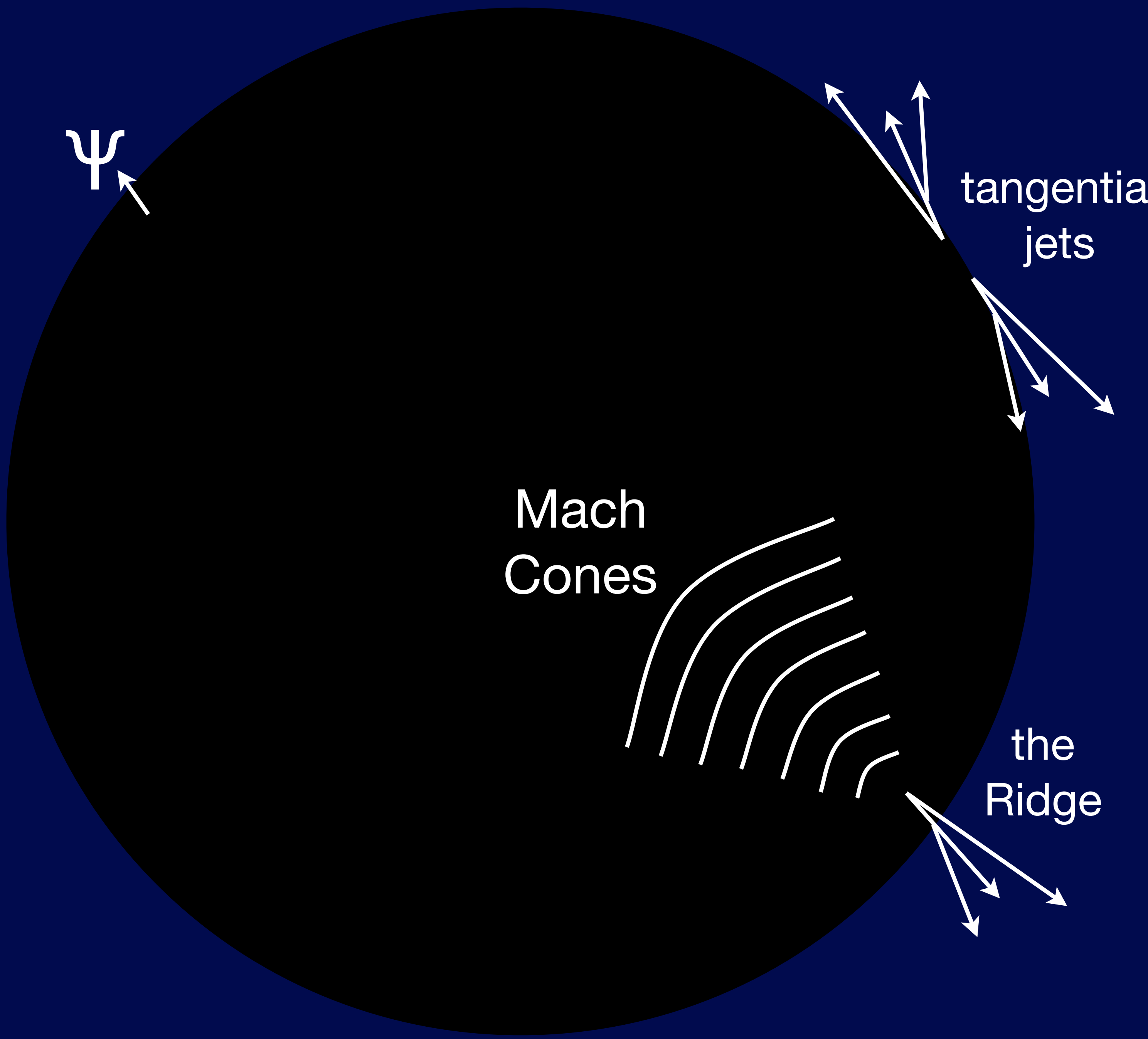
Studies with PQM





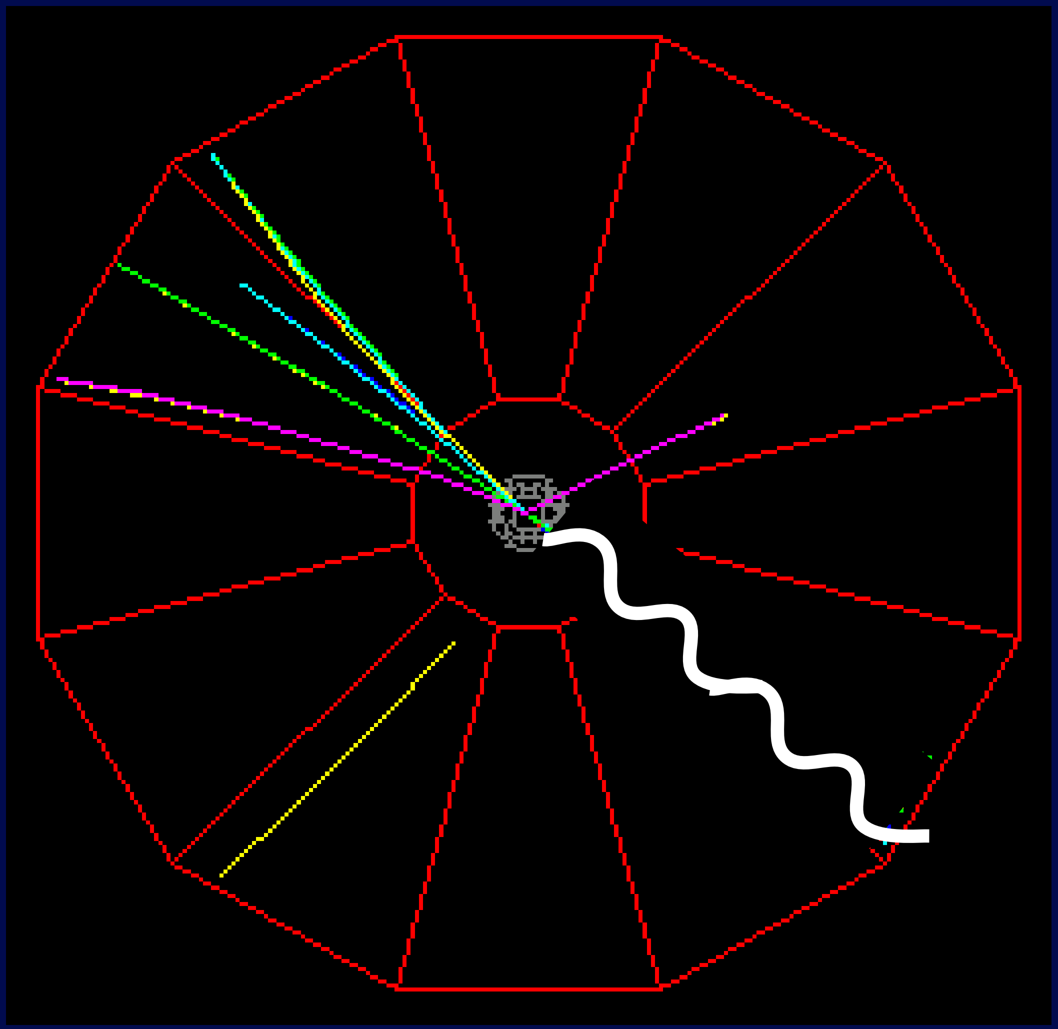
Adding quenching forces emission at the surface, with back-to-back jets emitted <u>tangentially</u>!

Outlook



At RHIC, hadrons come from the surface:
the interior seems to eat everything, like a black hole

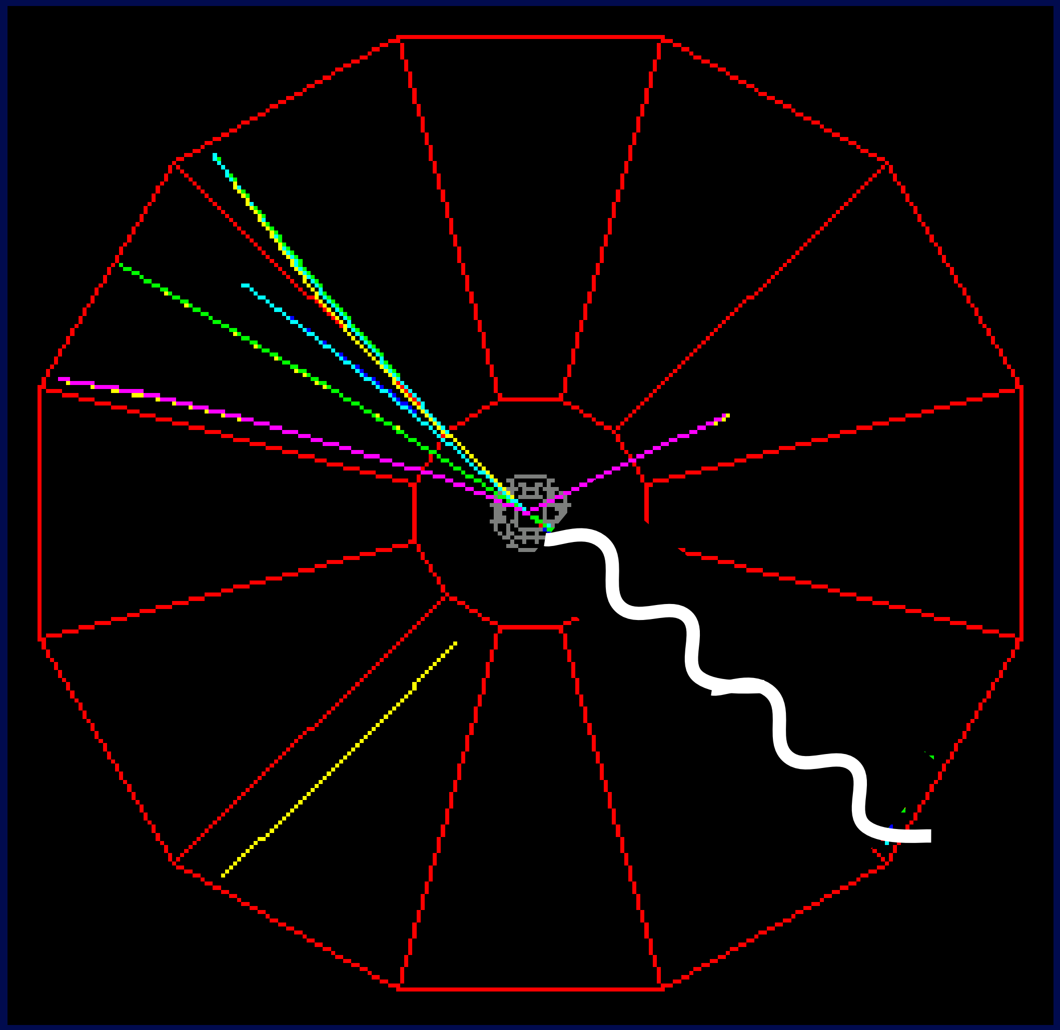
Photon-Hadron Correlations

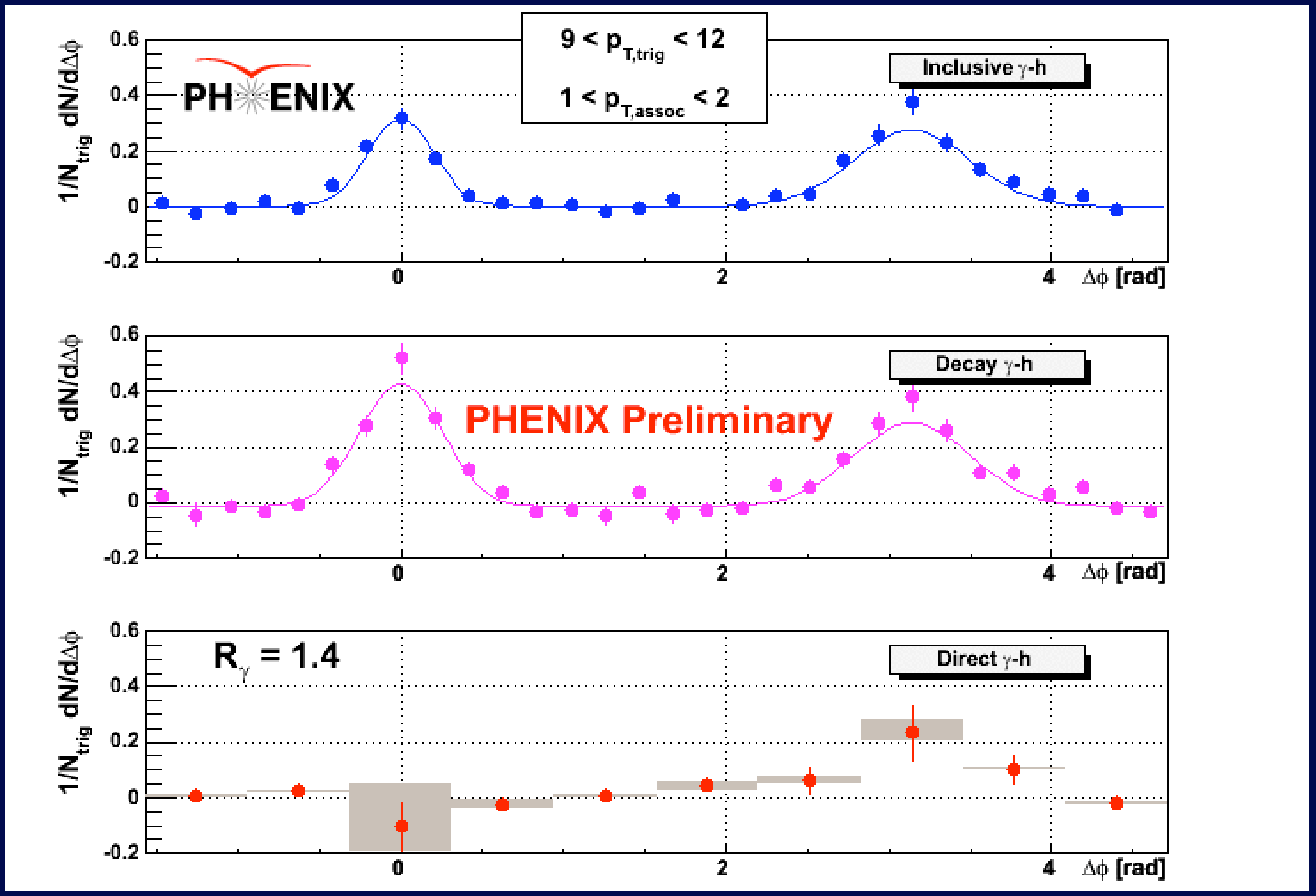


As we've seen before, photons are not suppressed like hadrons.

Thus, a photon produced by a hard process can constrain jet properties: measure energy loss

Photon-Hadron Correlations

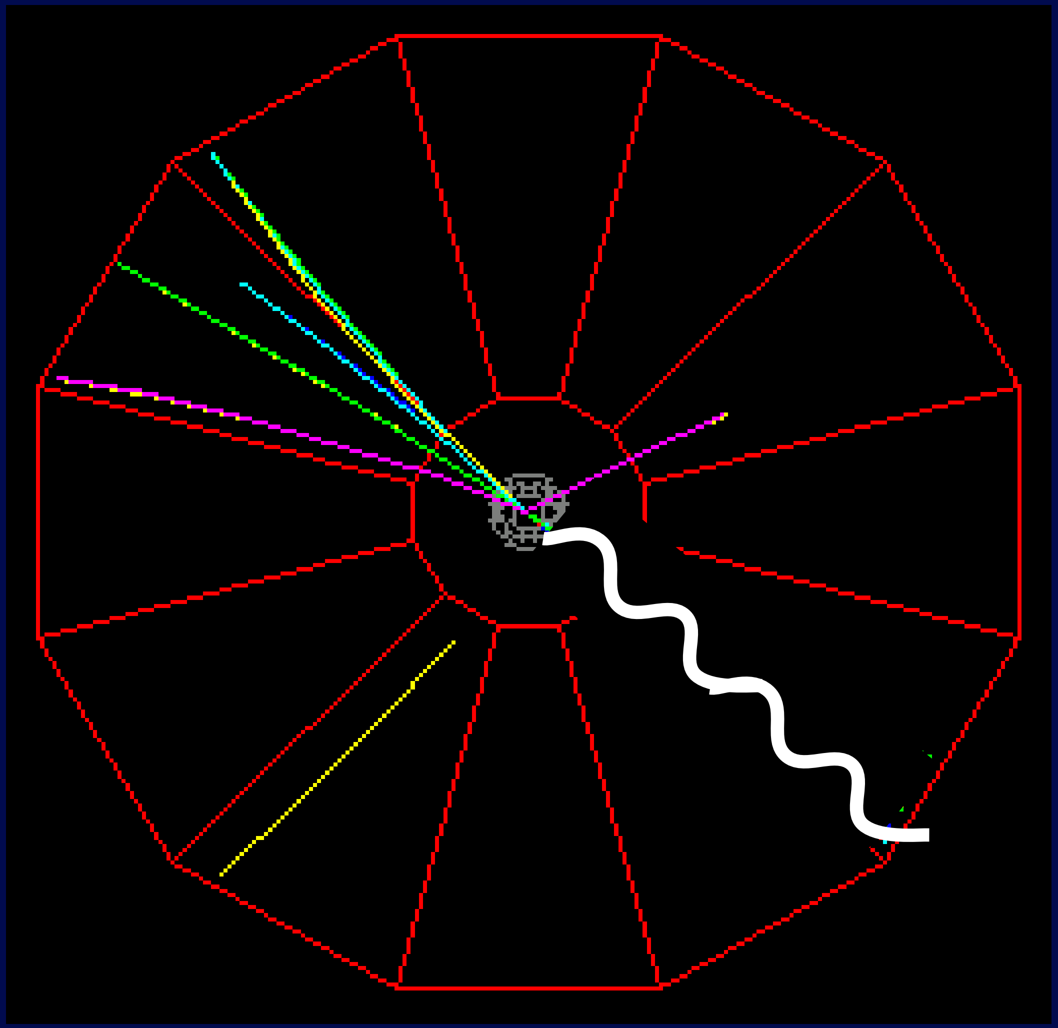


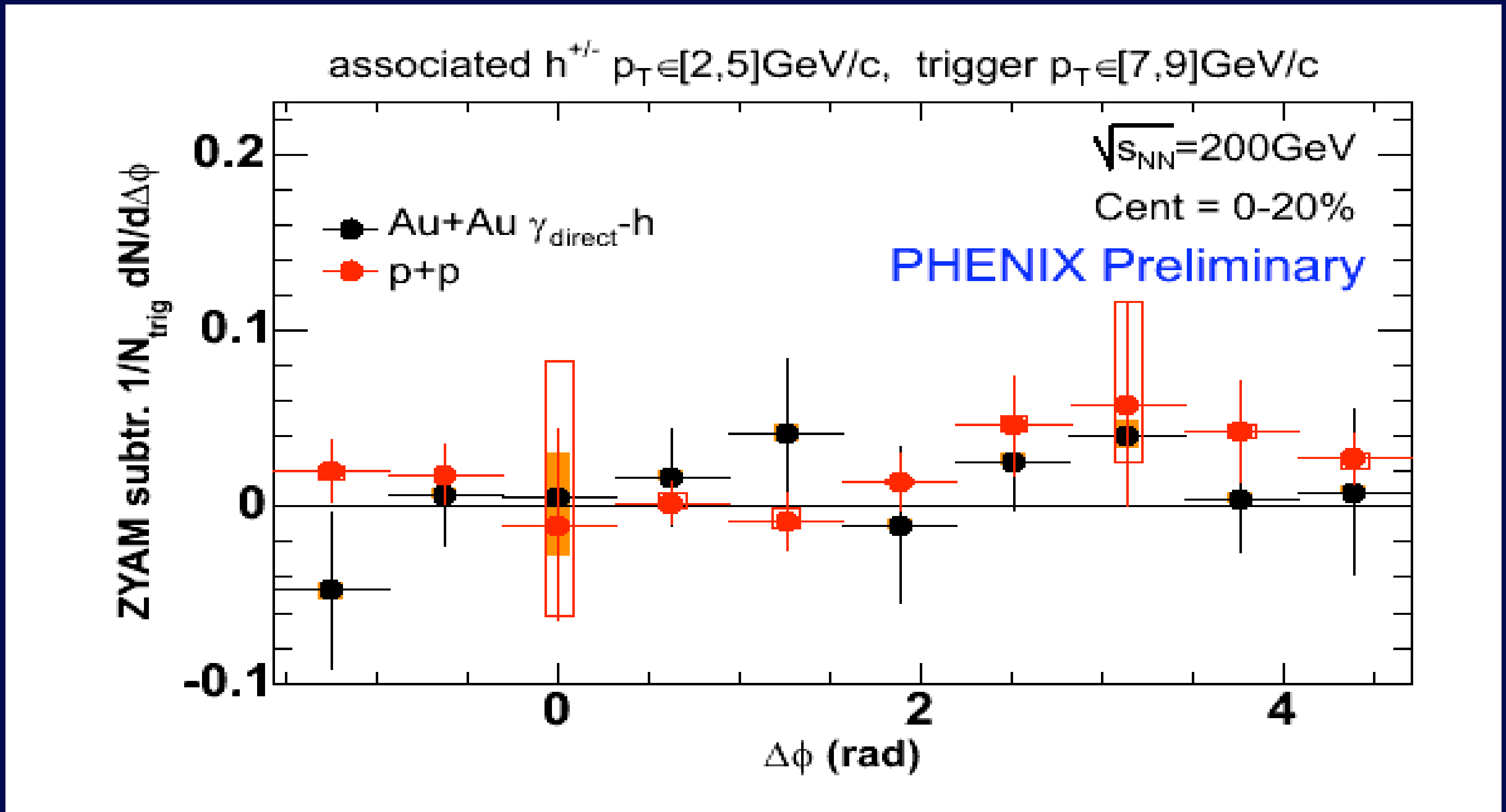


proton-proton collisions

Early RHIC p+p results find a significant (but small) correlation of photons with away-side hadrons

Photon-Hadron Correlations

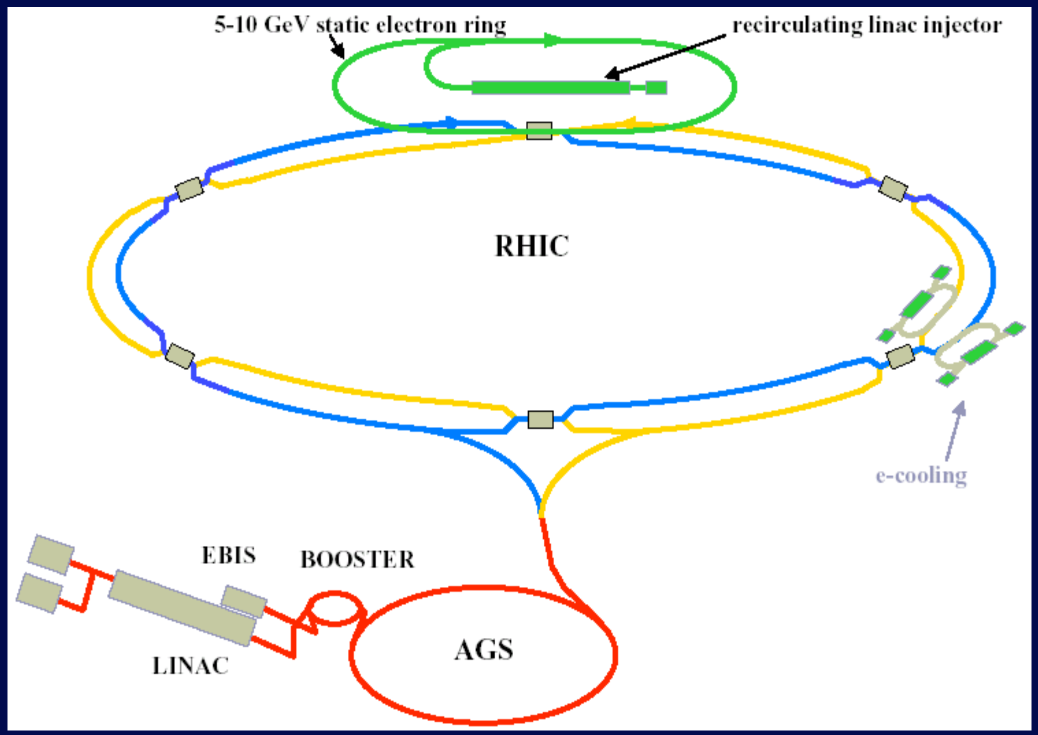


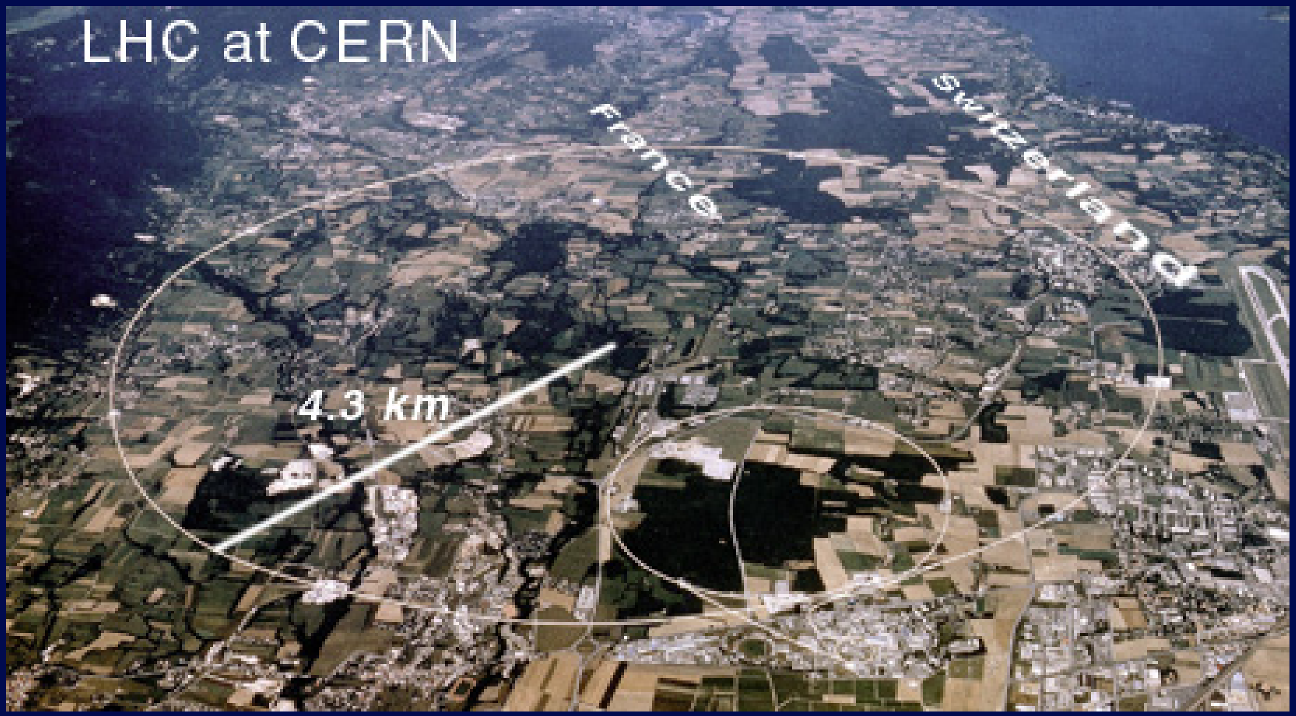


Au+Au collisions

Still marginal statistics at RHIC (need <u>luminosity</u>)
A clear goal for RHIC II and the LHC!

The Future

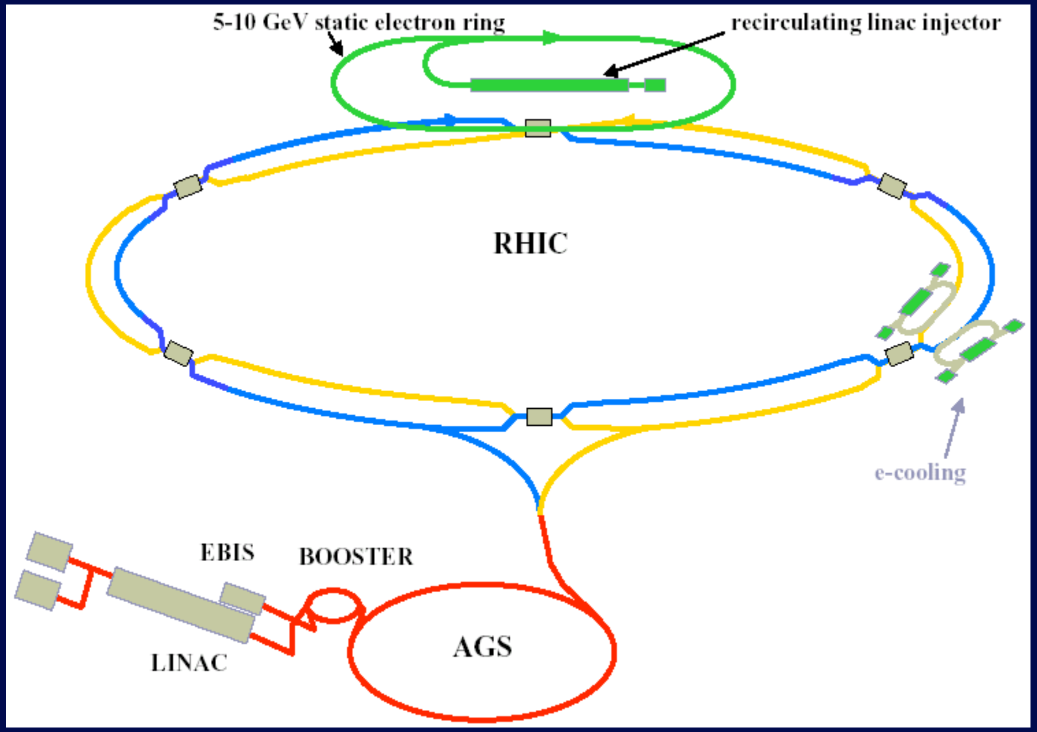


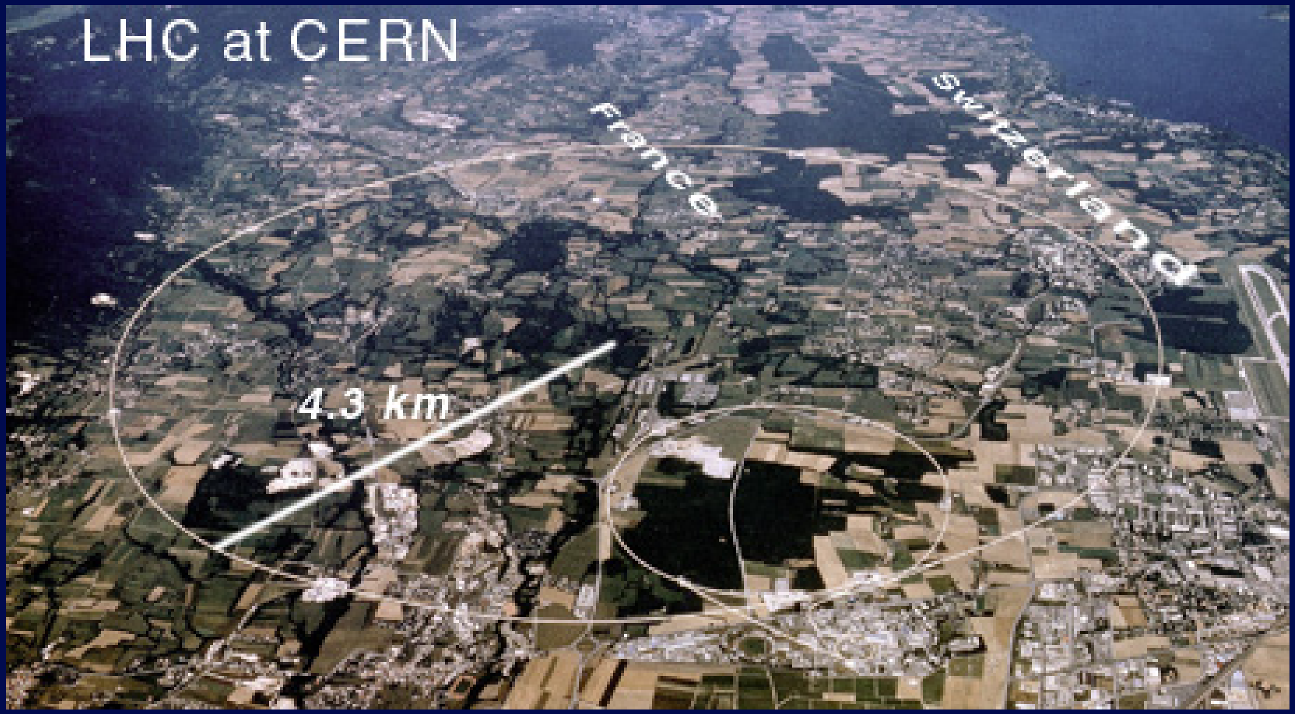


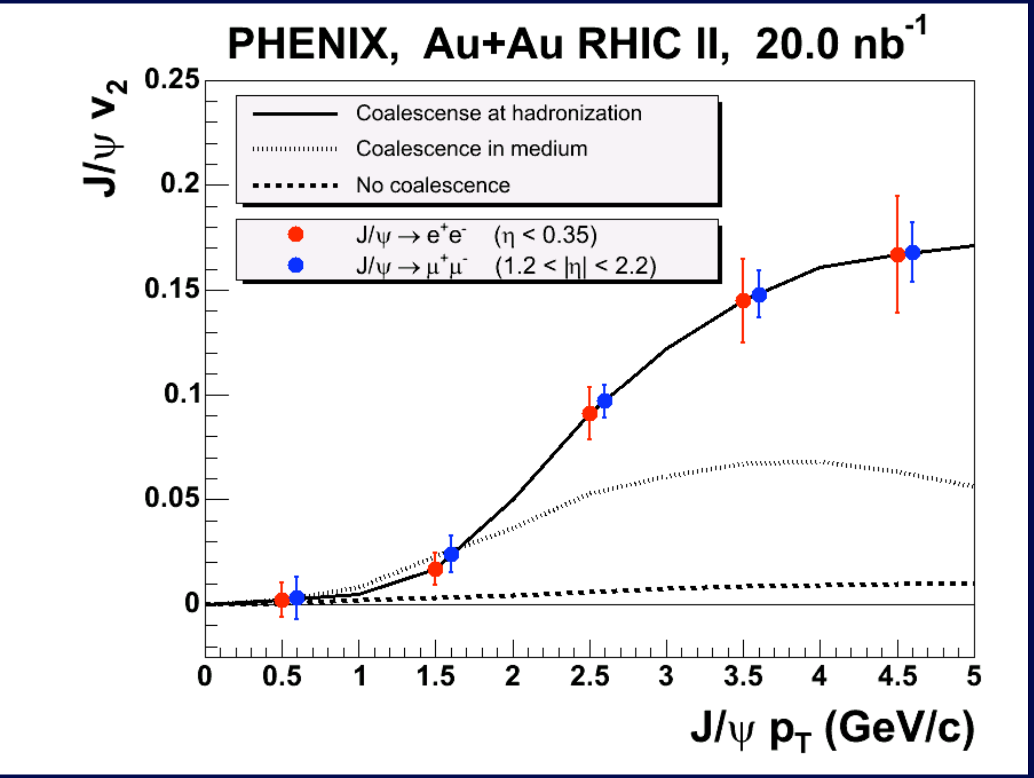
RHIC II:
dedicated facility
high luminosity (x10)
range of heavy beams
upgraded STAR/PHENIX

LHC:
1 month/year Pb+Pb
30x RHIC energy
Large jet, etc. rates
ATLAS/CMS/ALICE

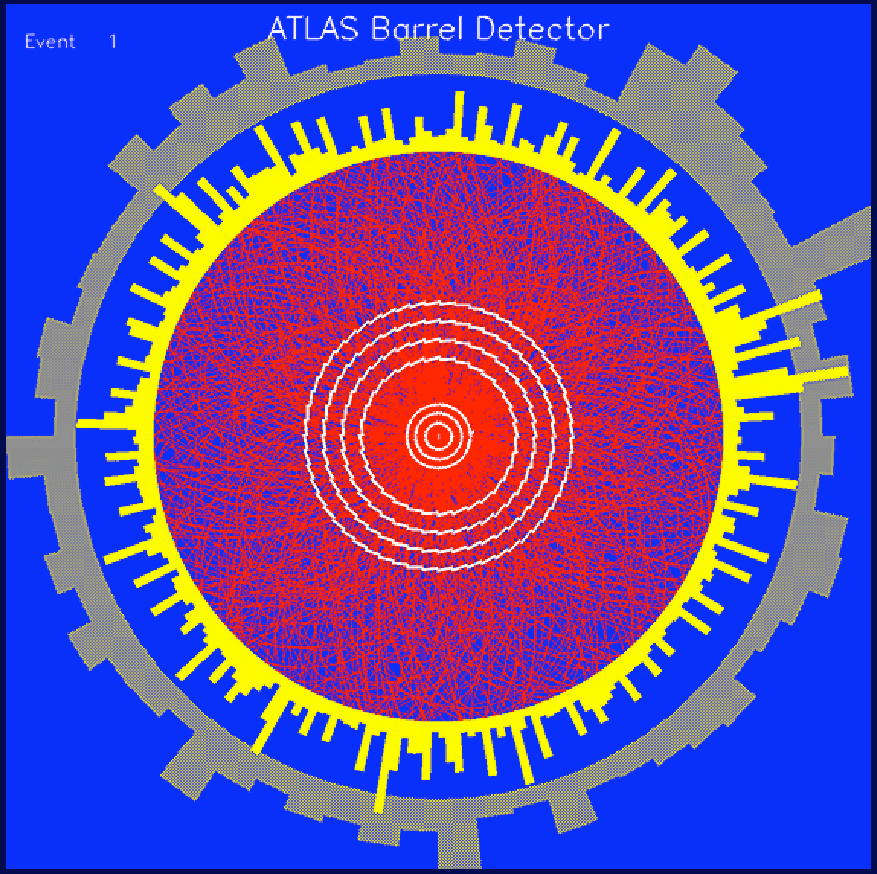
The Future







J/Psi v_2!



High densities

Huge rates at high p_T

Full jets

RHIC II vs. LHC

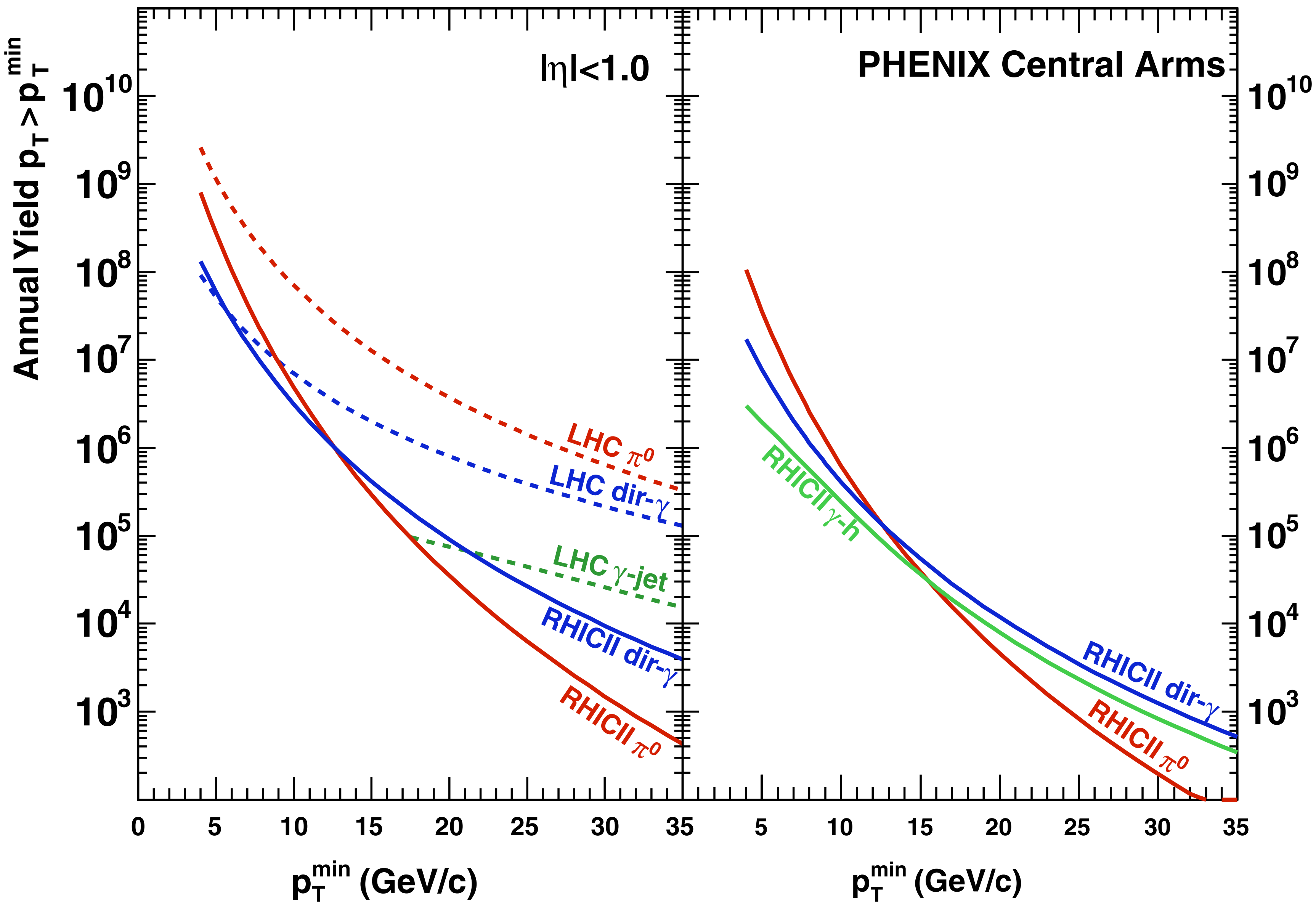
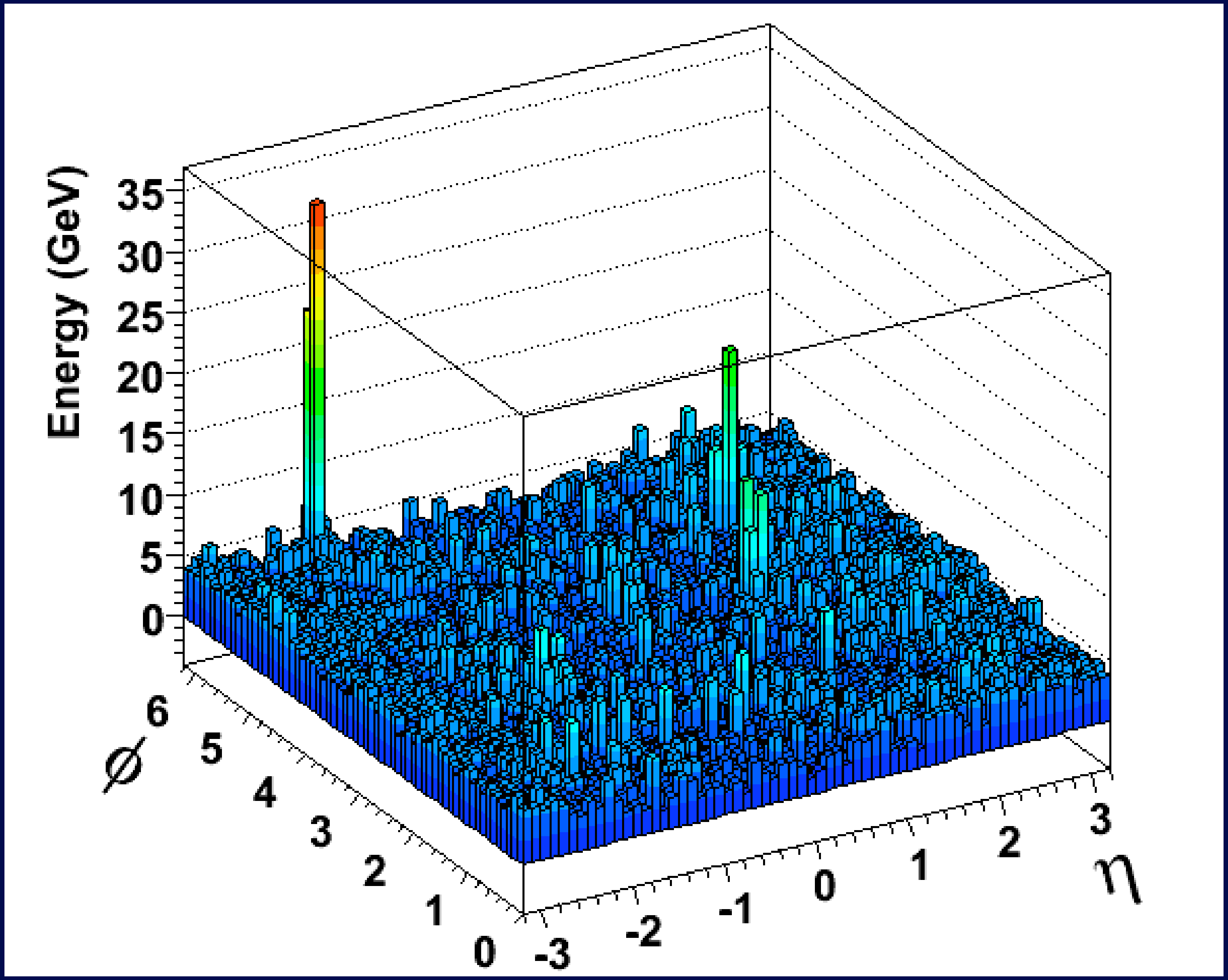


Figure 2. Annual recorded number of events of neutral pions, direct photons and photon-jet coincidences at RHIC II and LHC, based upon NLO pQCD from Vogelsang and scaled to minimum bias Au+Au or Pb+Pb collisions (see the text for details). The left panel shows yields into two units of rapidity centred at $y = 0$ and full azimuth, while the right panel shows yields into the PHENIX central arms.

Jets @ LHC

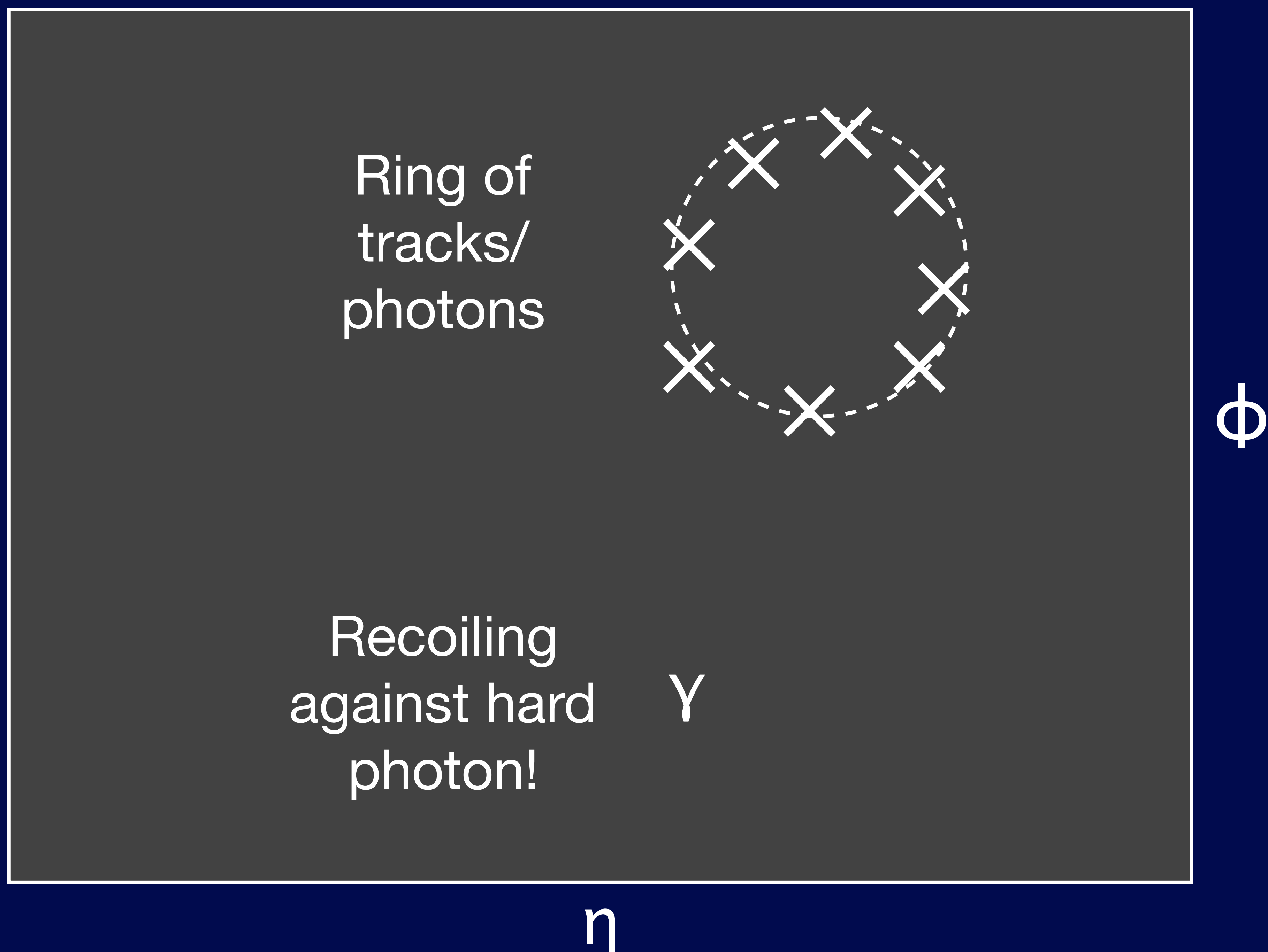


ATLAS & CMS have full acceptance in η & ϕ

Can see full jets: don’t need 2/3 particle correlations

Gamma-Mach Cone @ LHC?

a dream...



LHC may provide access to new phenomena

Summary

- **How can we look "into" the medium we create at RHIC?**
  - What is it made of? How dense is it?
- **Counting single particles**
  - High momentum hadrons
  - Heavy flavor
  - Direct Photons
- **Probing jet modifications with correlations**
  - Dihadron correlations:Mach cones & the ridge
  - Tangential jets
  - Gamma-hadron correlations
- **Future facilities**
  - RHIC II & Pb+Pb @ LHC

3 Lectures

- **Lecture 1**
  - Introduction to Heavy Ion Collisions
- **Lecture 2**
  - Hydrodynamics in Heavy Ion Collisions
- **Lecture 3**
  - Probing the Near-Perfect Fluid at RHIC