Two Lectures on Heavy Ion Physics

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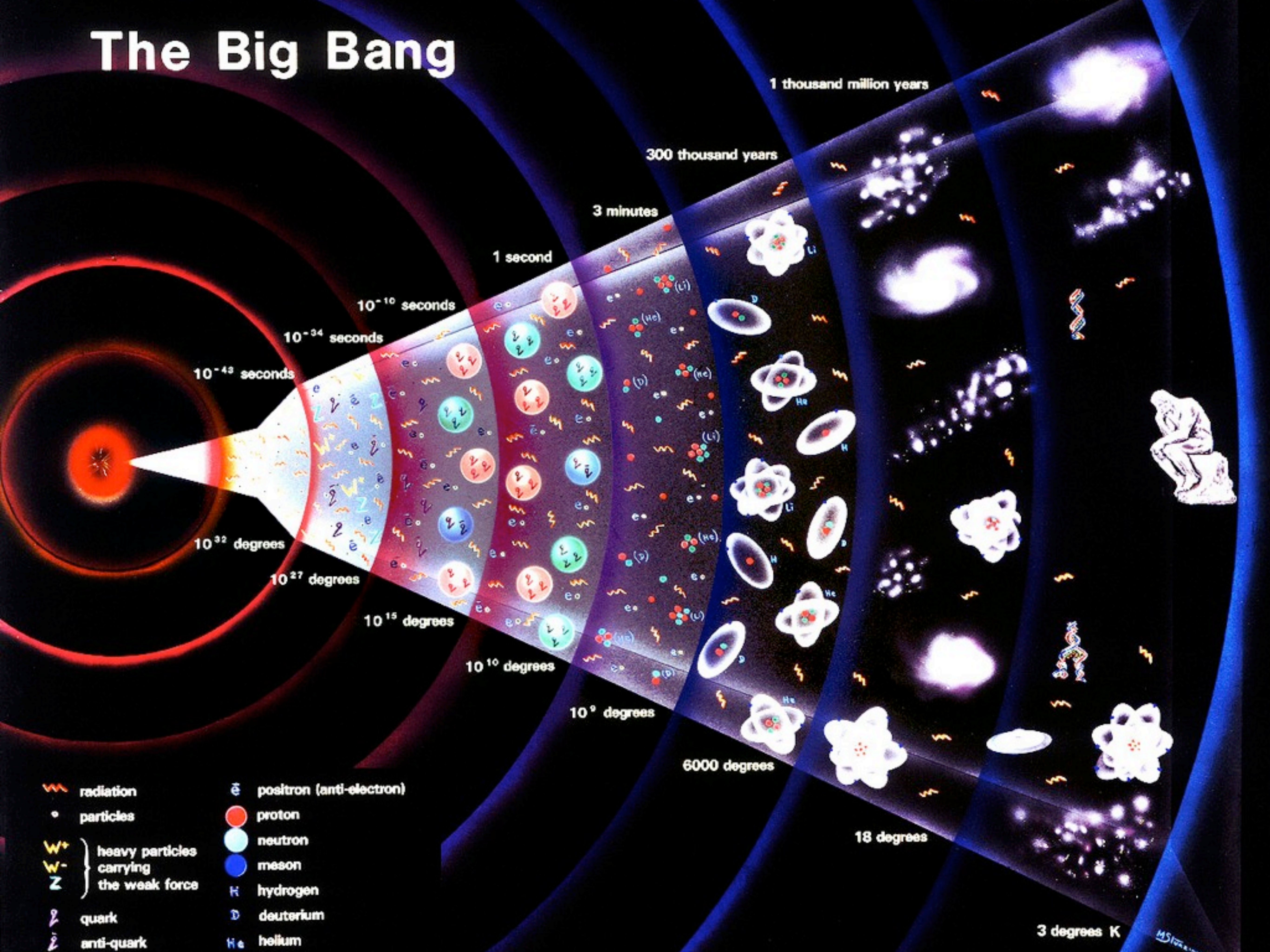
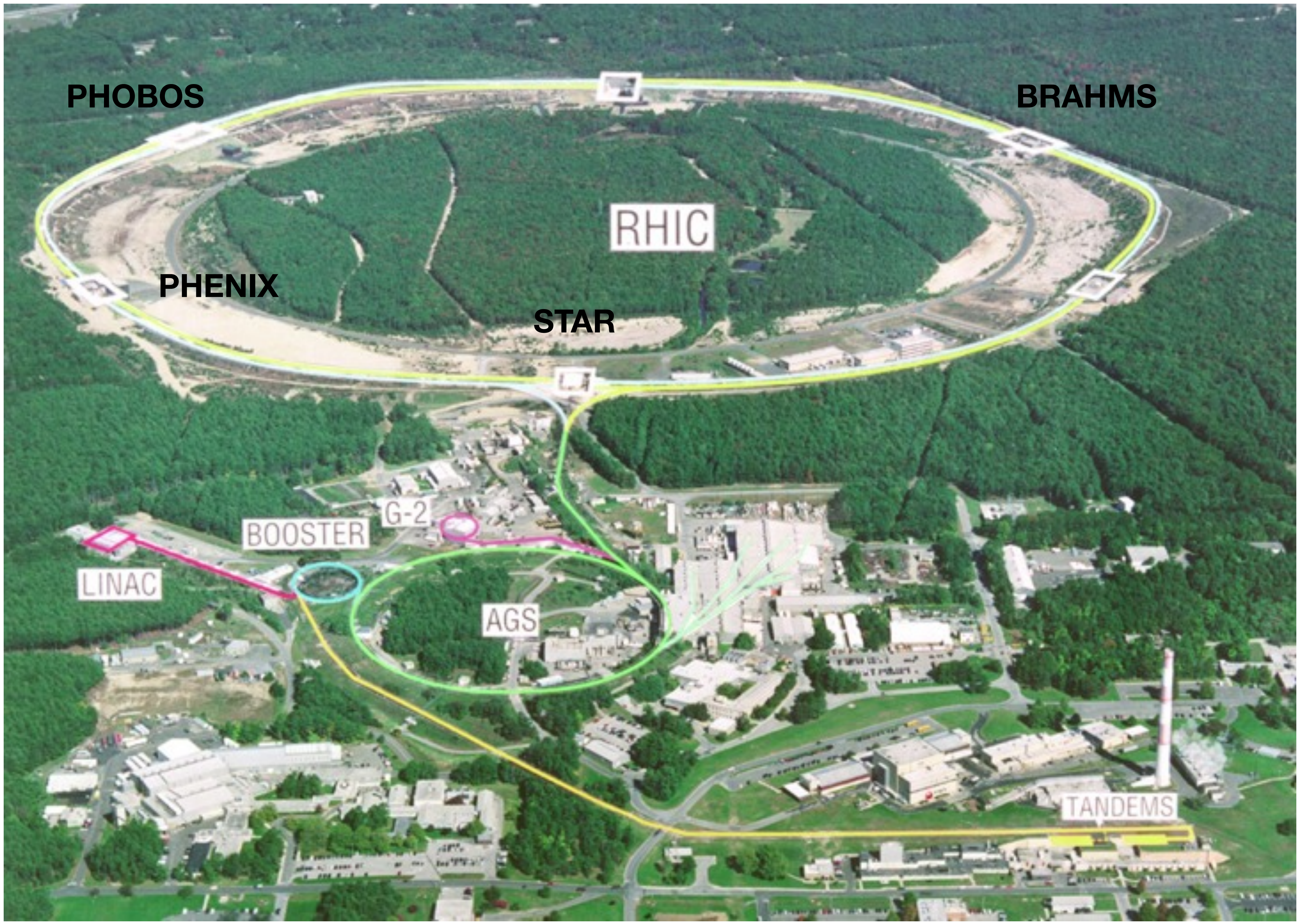
CTEQ Summer School
July 2, 2009
Madison, WI, USA

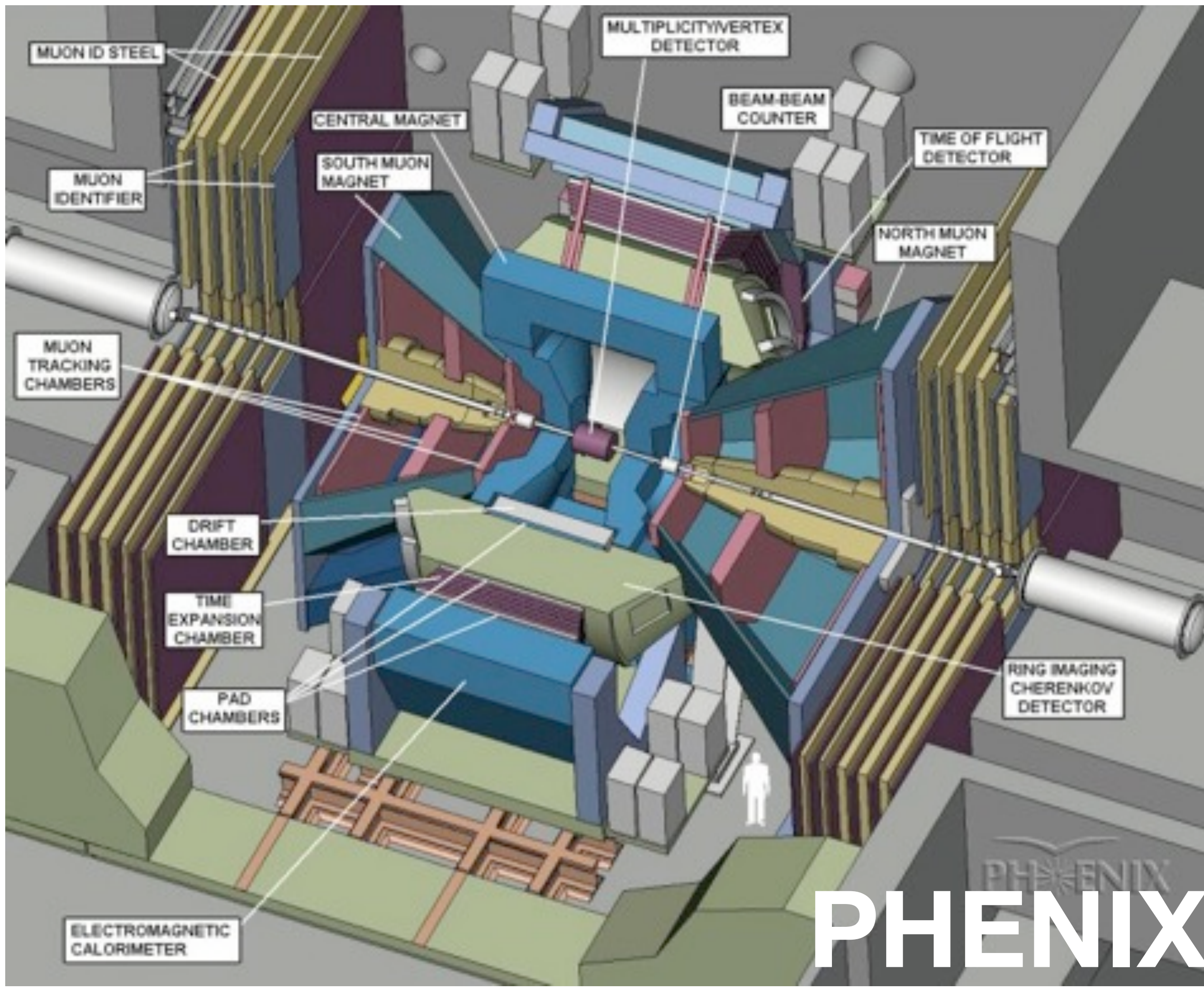


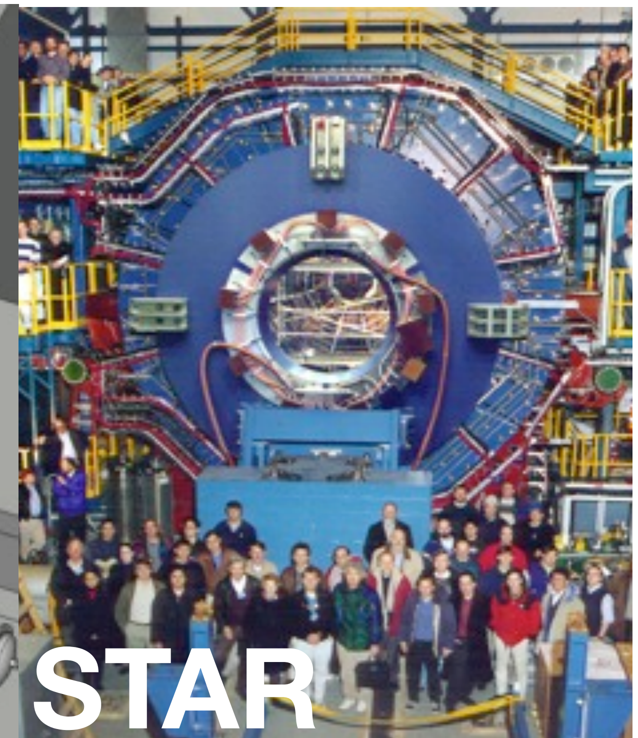
The Big Bang
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium

Relativistic Heavy Ion Collider (RHIC)

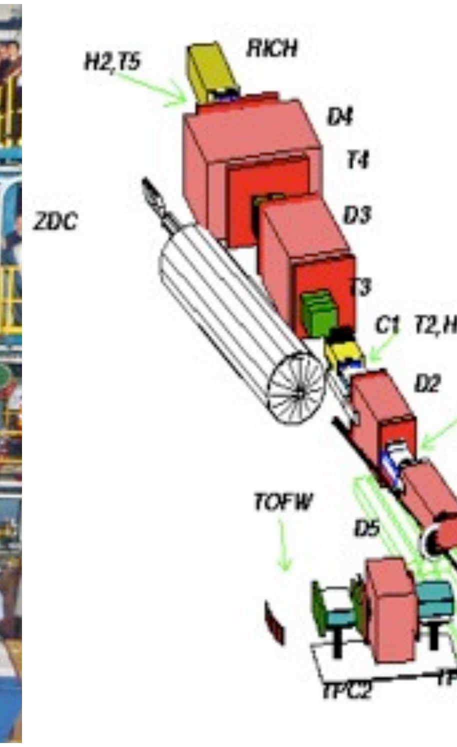


RHIC Experiments to Scale

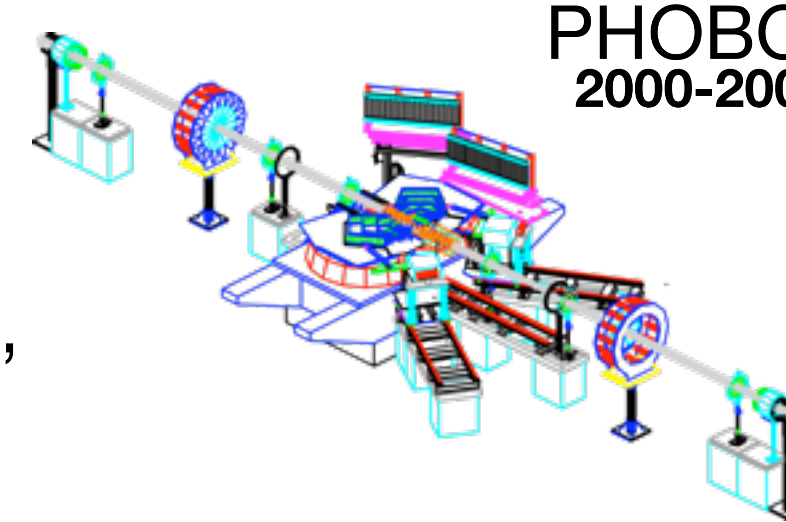




BRAHMS
2000-2006



PHOBOS
2000-2005



RHIC program has large <u>and</u> small detectors,
sufficient overlap to make cross-checks.
Billions of events since 2000:
p+p, d+Au, Cu+Cu, Au+Au, 19.6-200 GeV

Heavy Ion Collisions: Soft Physics

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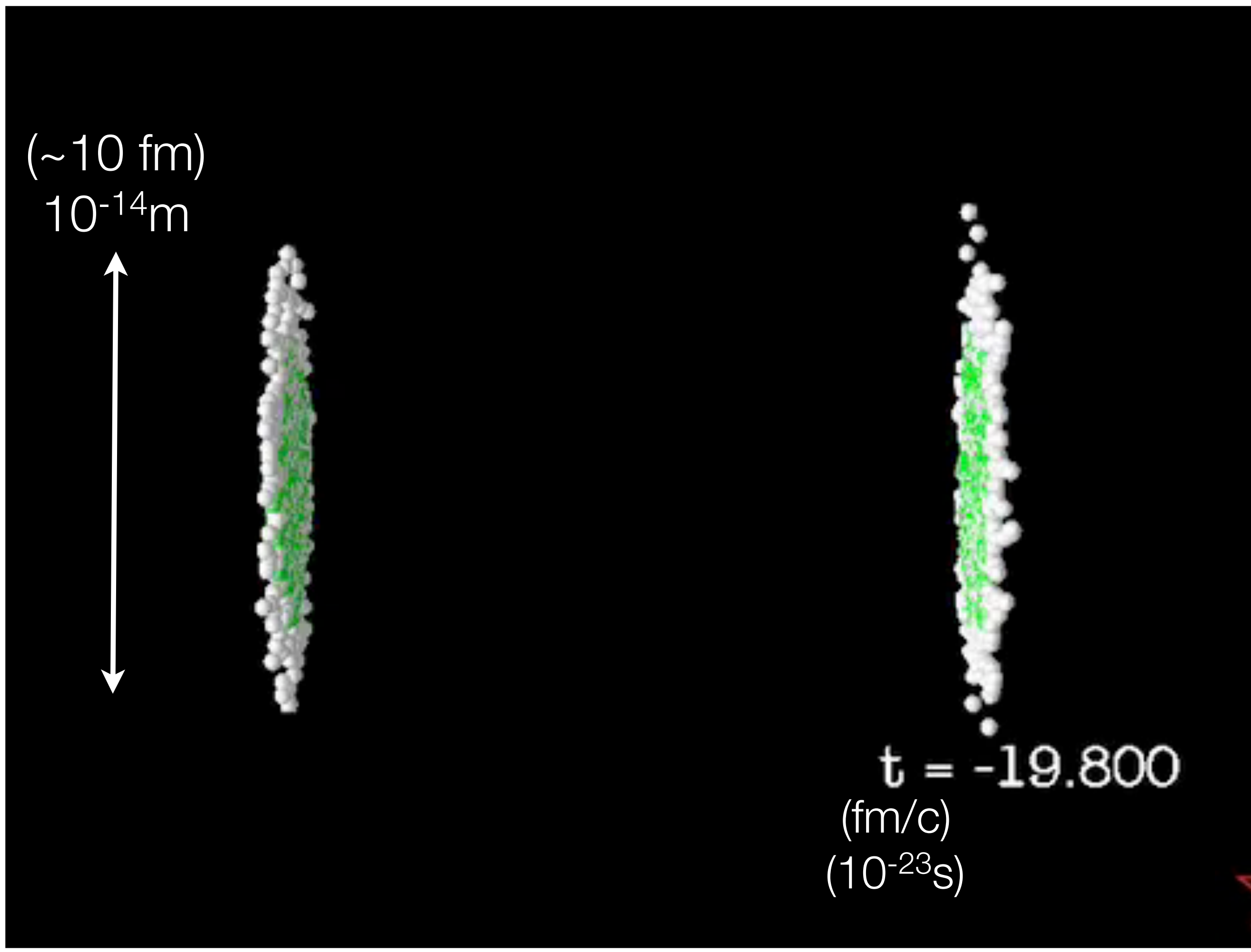
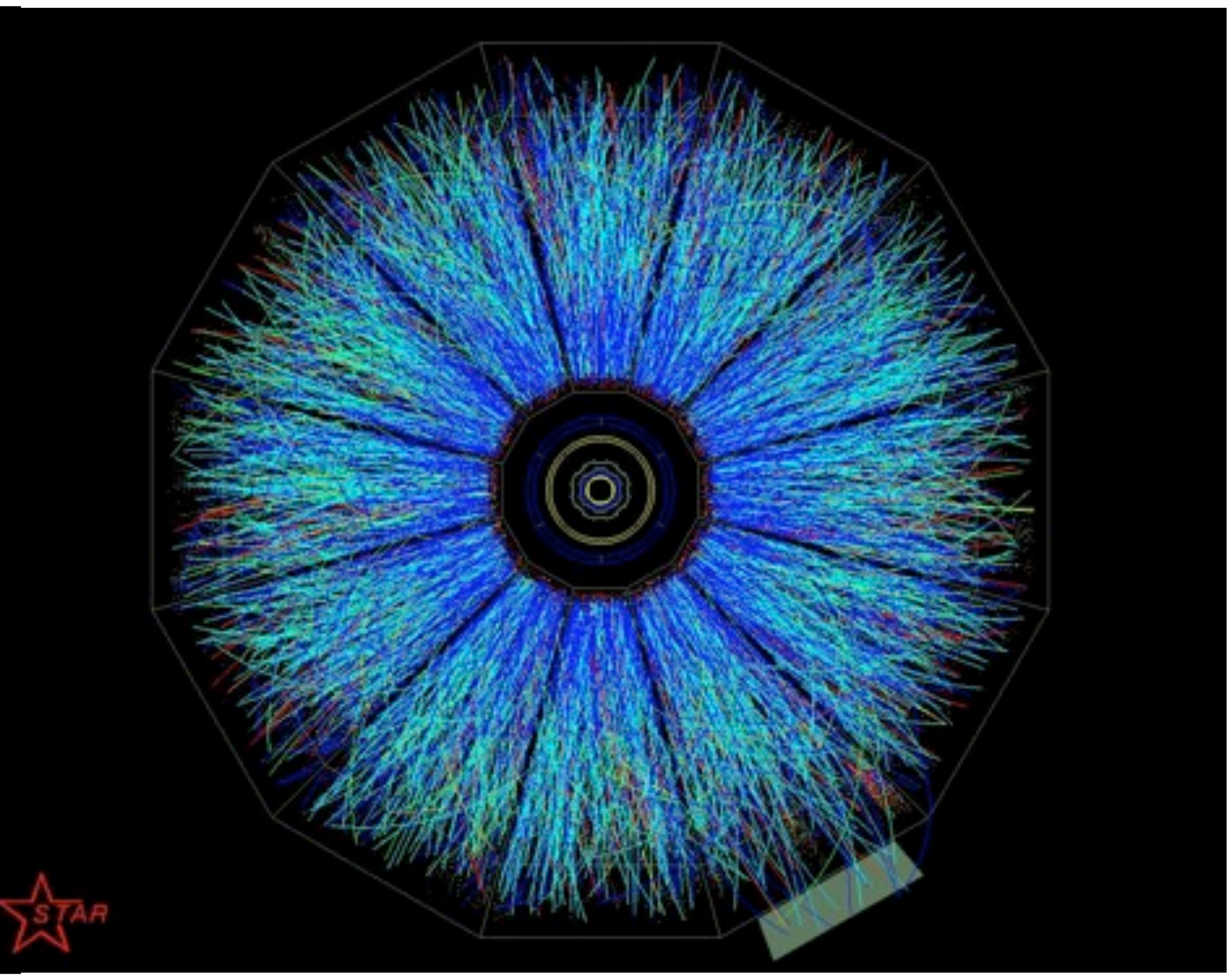
RHIC Physics in a Nutshell

Collisions of Ions



1000's of Particles



RHIC physics takes place in **space-time**

Need to "rewind" dynamical evolution to study QCD at high temperature and density

Bottom line: The most-perfect fluid?

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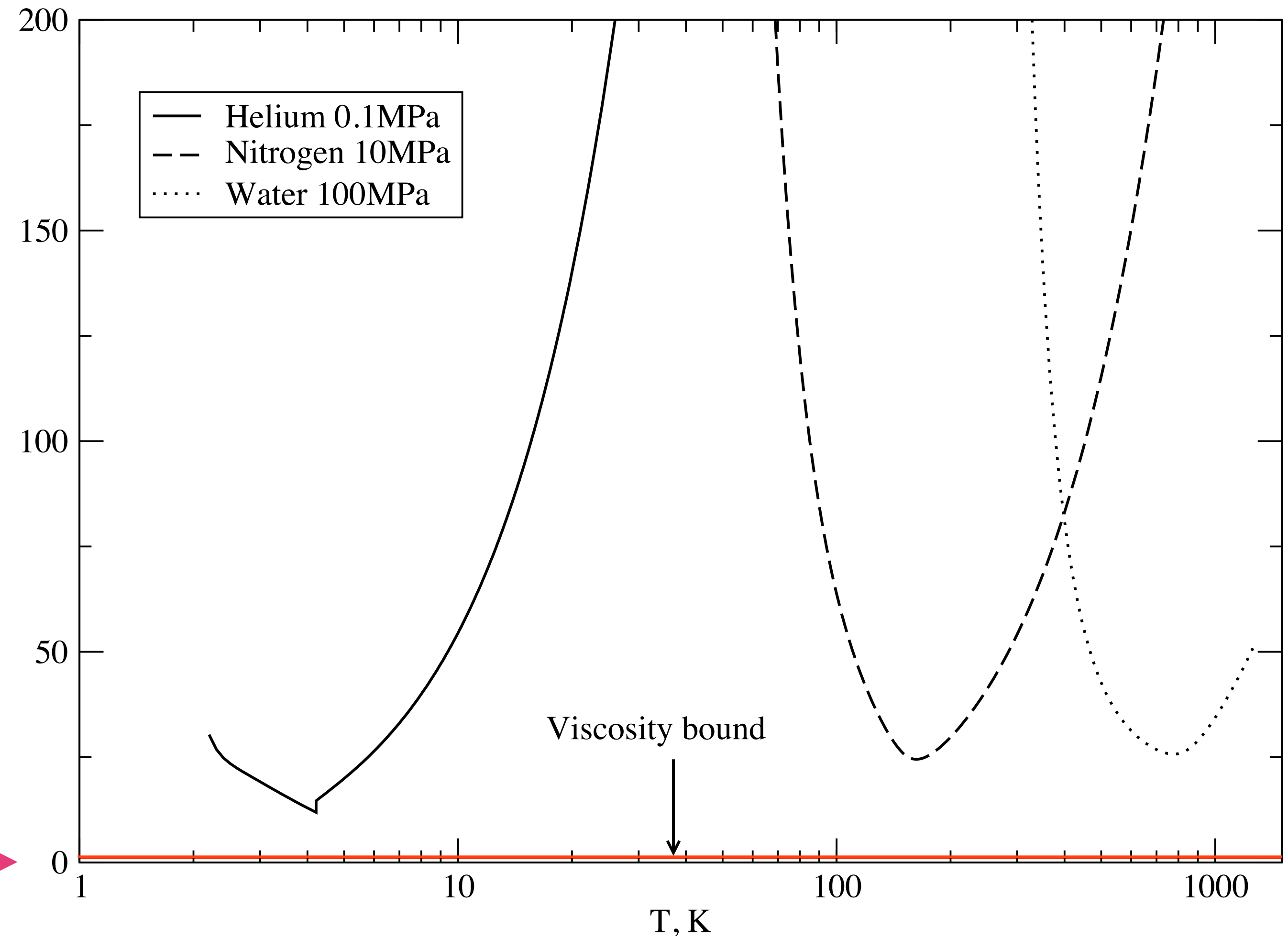
We say RHIC collisions behave like a “**perfect liquid**”
(or at least a “near perfect fluid”)

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



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

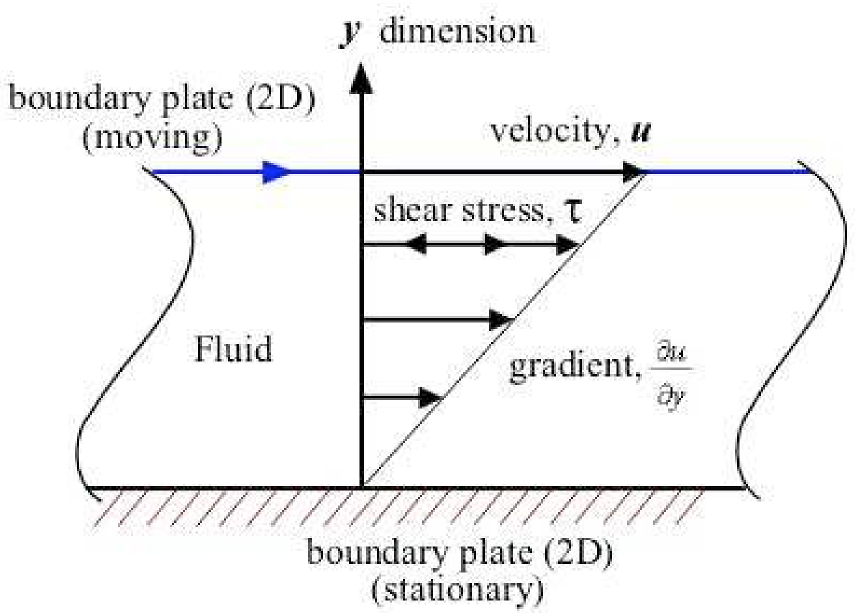
viscosity bound from AdS/CFT conjecture (D. Son, et al) →

local thermalization: **strong coupling** → low viscosity

These conclusions originally emerged from “soft” physics

What is viscosity?

- **From wikipedia (via Dam Son), shear viscosity is the flow of momentum between adjacent fluid layers**
  - Deviation from local equilibrium
  - Frictional (i.e. dissipative) force

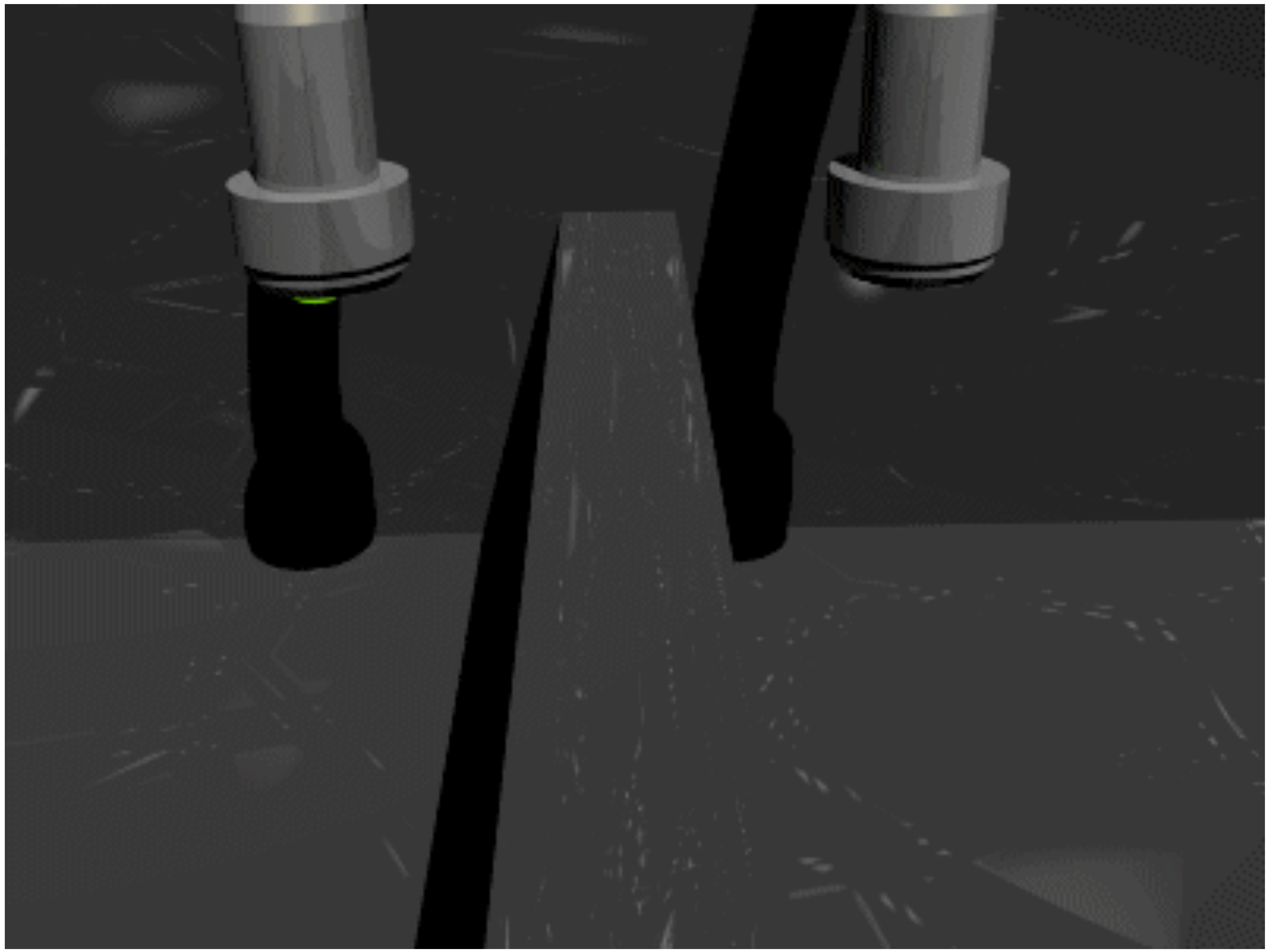


- **Simple way to think of it is as presence of a fundamental length scale in the dynamical evolution**
  - Scale over which energy/momentum can “escape” from a fluid cell
  - Ideal gas has infinite shear viscosity! $\eta = \rho v l \quad l = \frac{1}{n\sigma} \quad \eta \sim \frac{1}{\sigma}$

Viscosity Illustrated

en.wikipedia.org/Viscosity

low resistance to flow

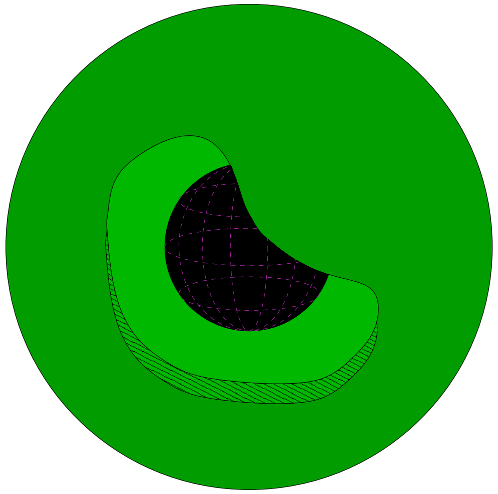


propagates ripples

high viscosity (e.g. honey) low viscosity (e.g. water)

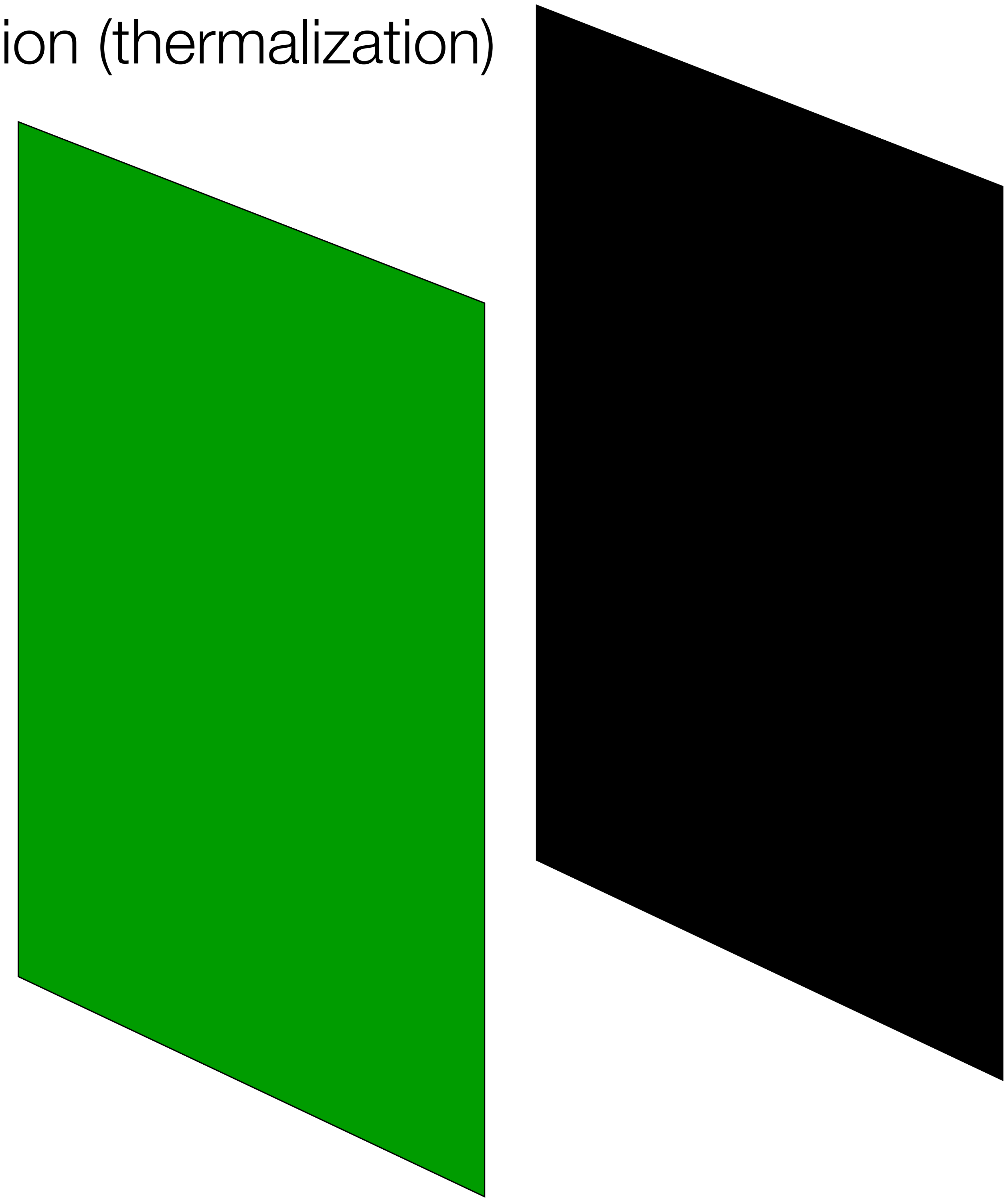
The least-perfect fluid

The Pitch Drop Experiment: http://www.physics.uq.edu.au/pitchdrop/pitchdrop.shtml



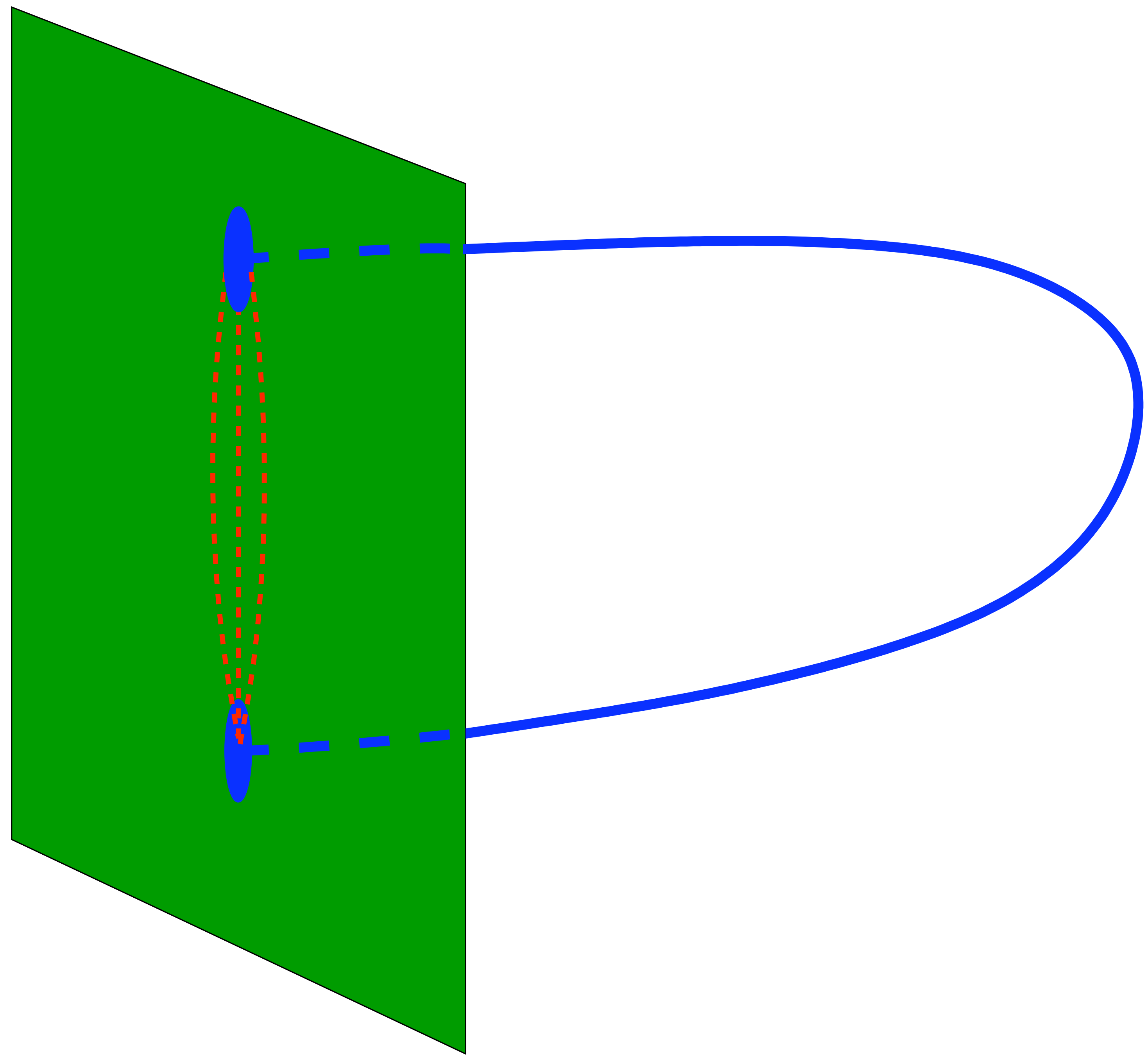
AdS/CFT calculations put a black hole in the 5th dimension (thermalization)

“unwrap” the spheres for clarity…

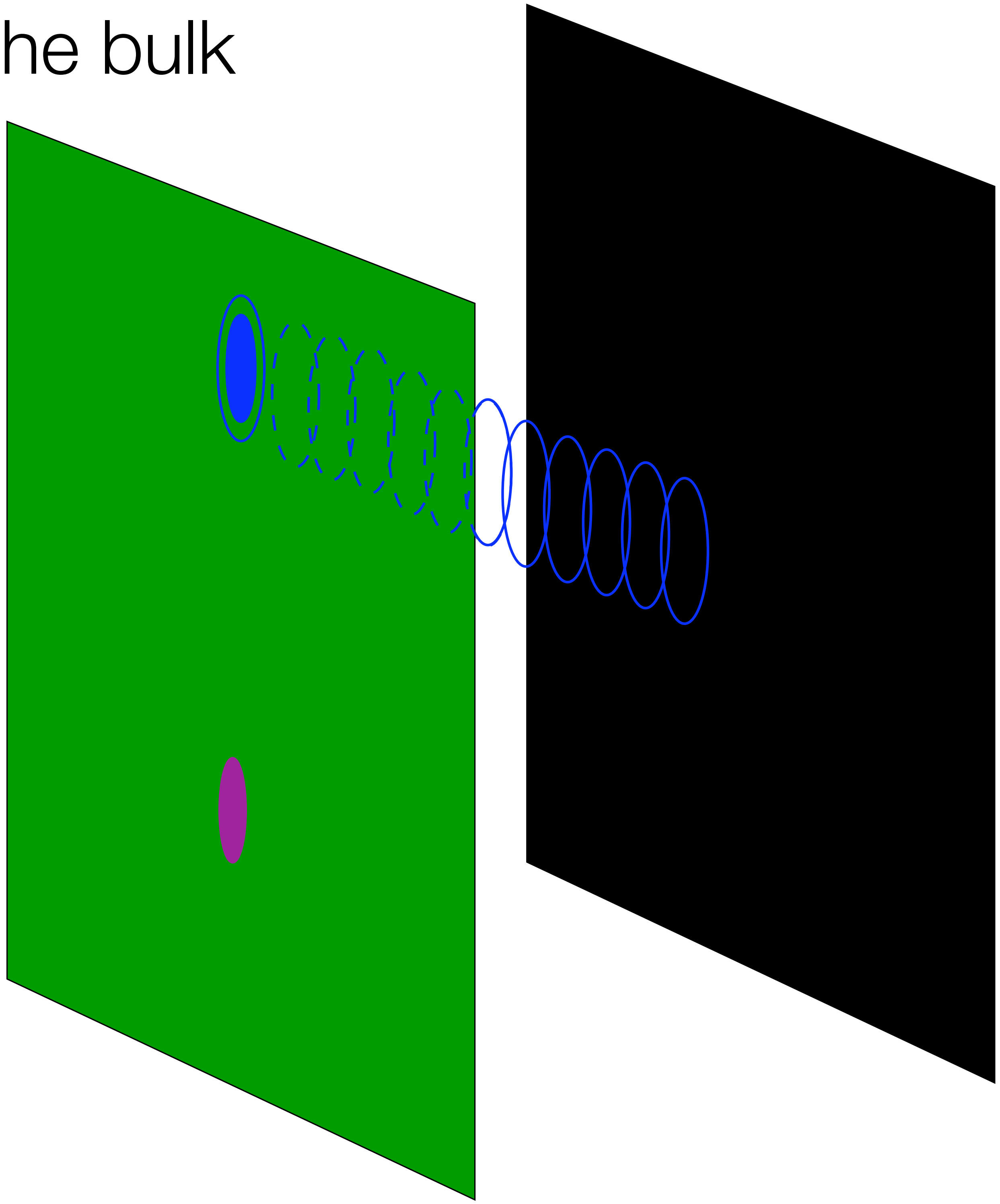


Explanation from Clifford Johnson, USC

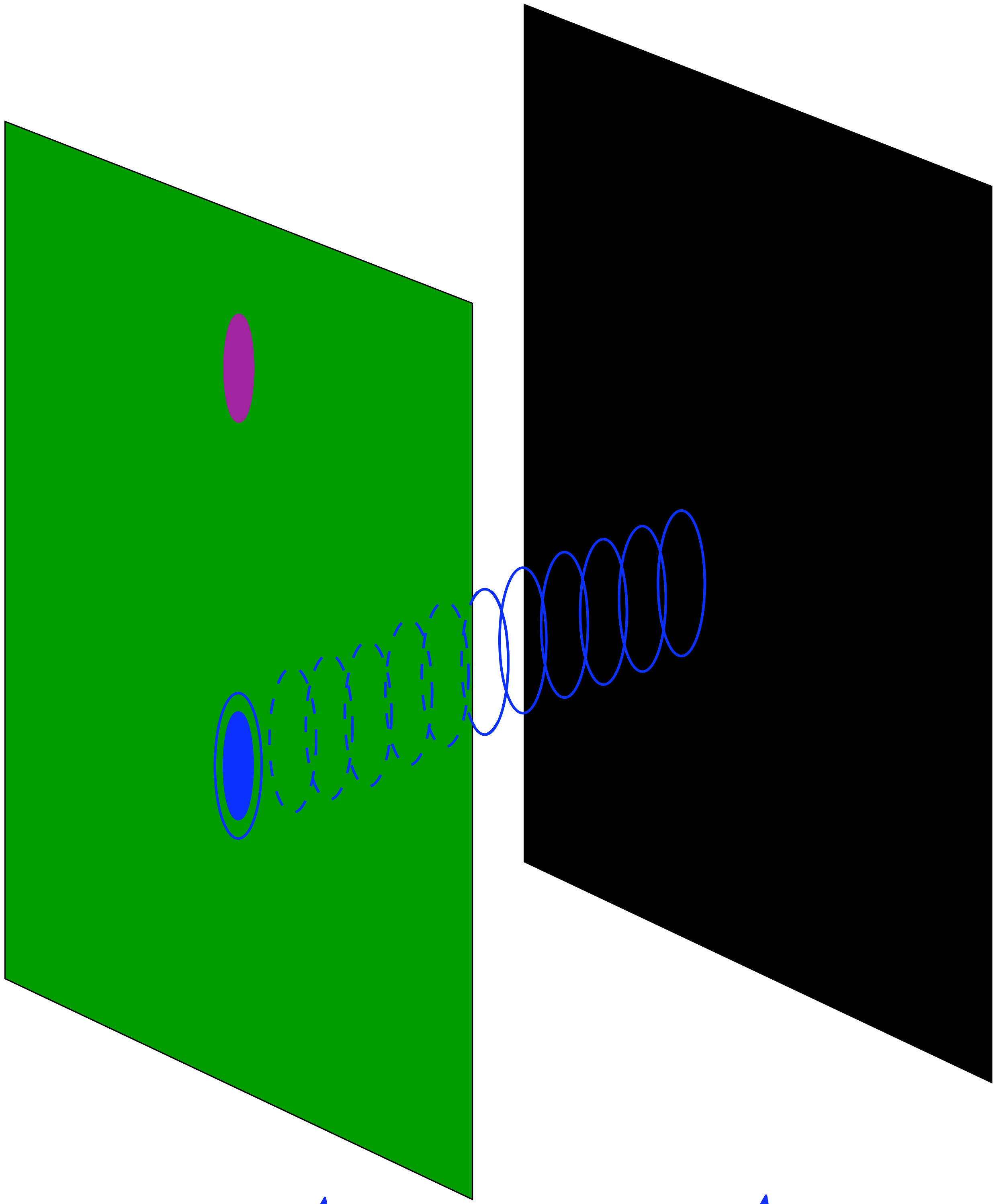
“QCD” in AdS/CFT is a string trailing into the bulk



A quark fires a graviton into the bulk



And scatters off
of the black hole



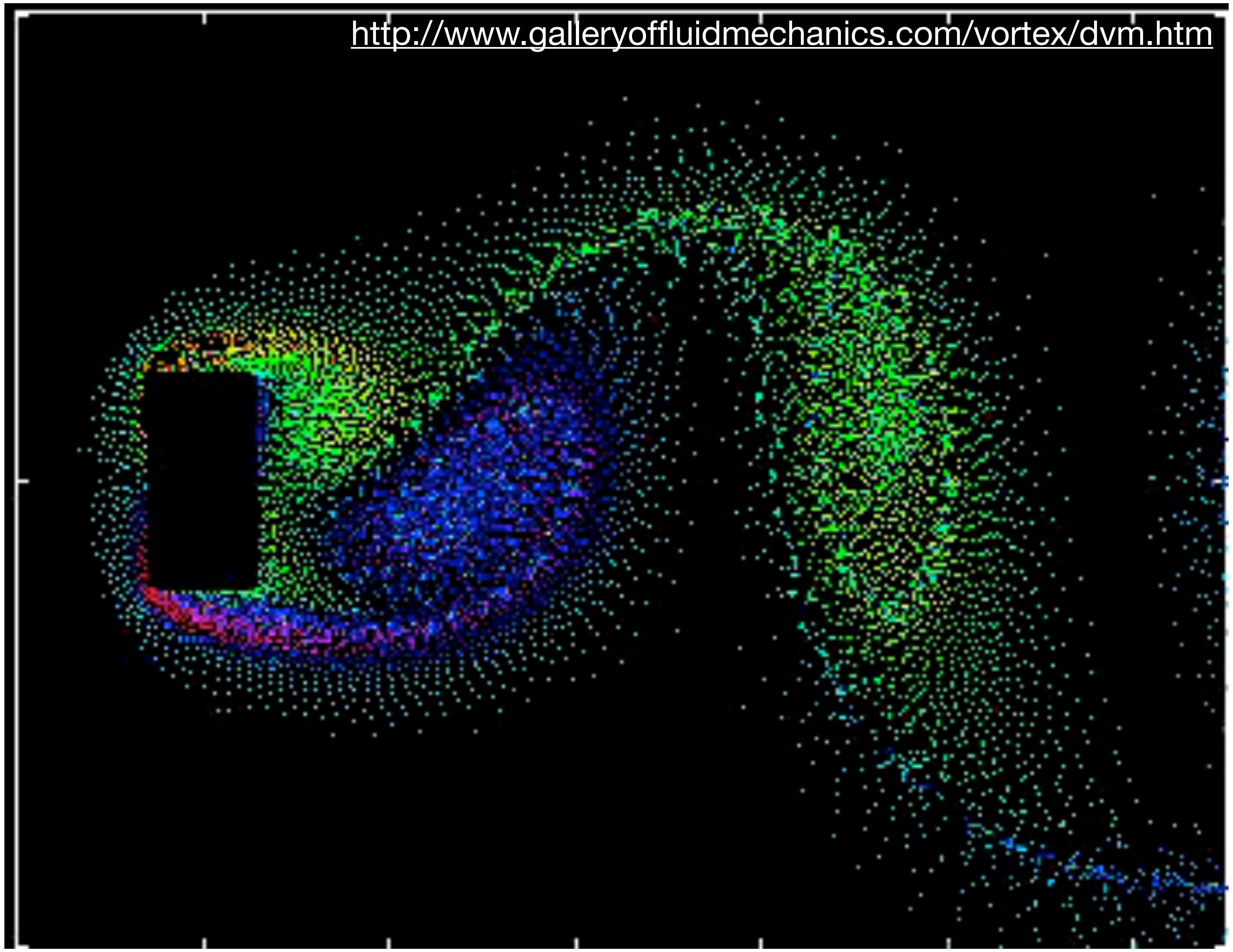
Black hole
absorption
is dissipative

$$\eta = \frac{A}{16\pi G}$$

$$S = \frac{A}{4G}$$

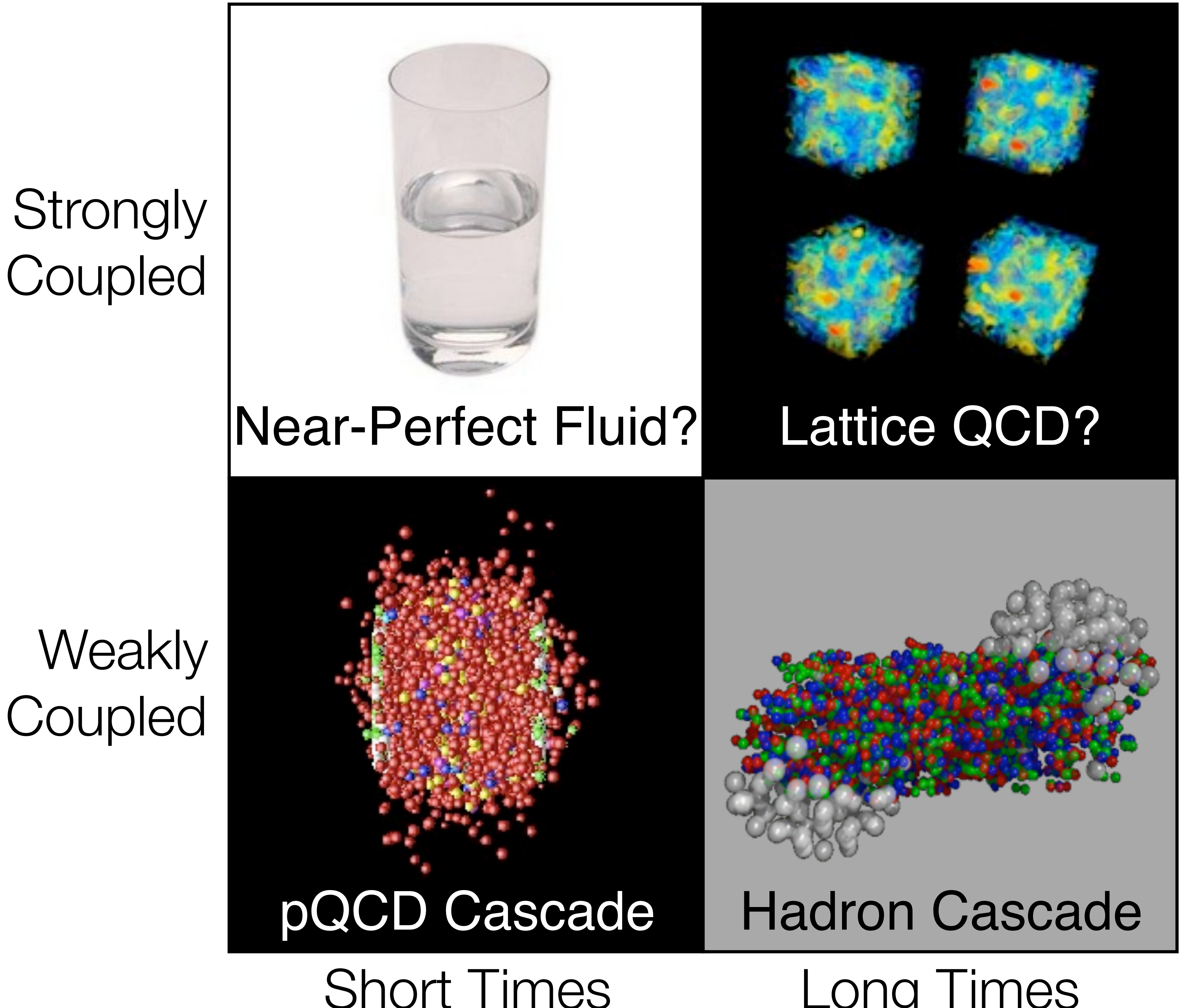
$$\frac{\eta}{S} = \frac{1}{4\pi}$$

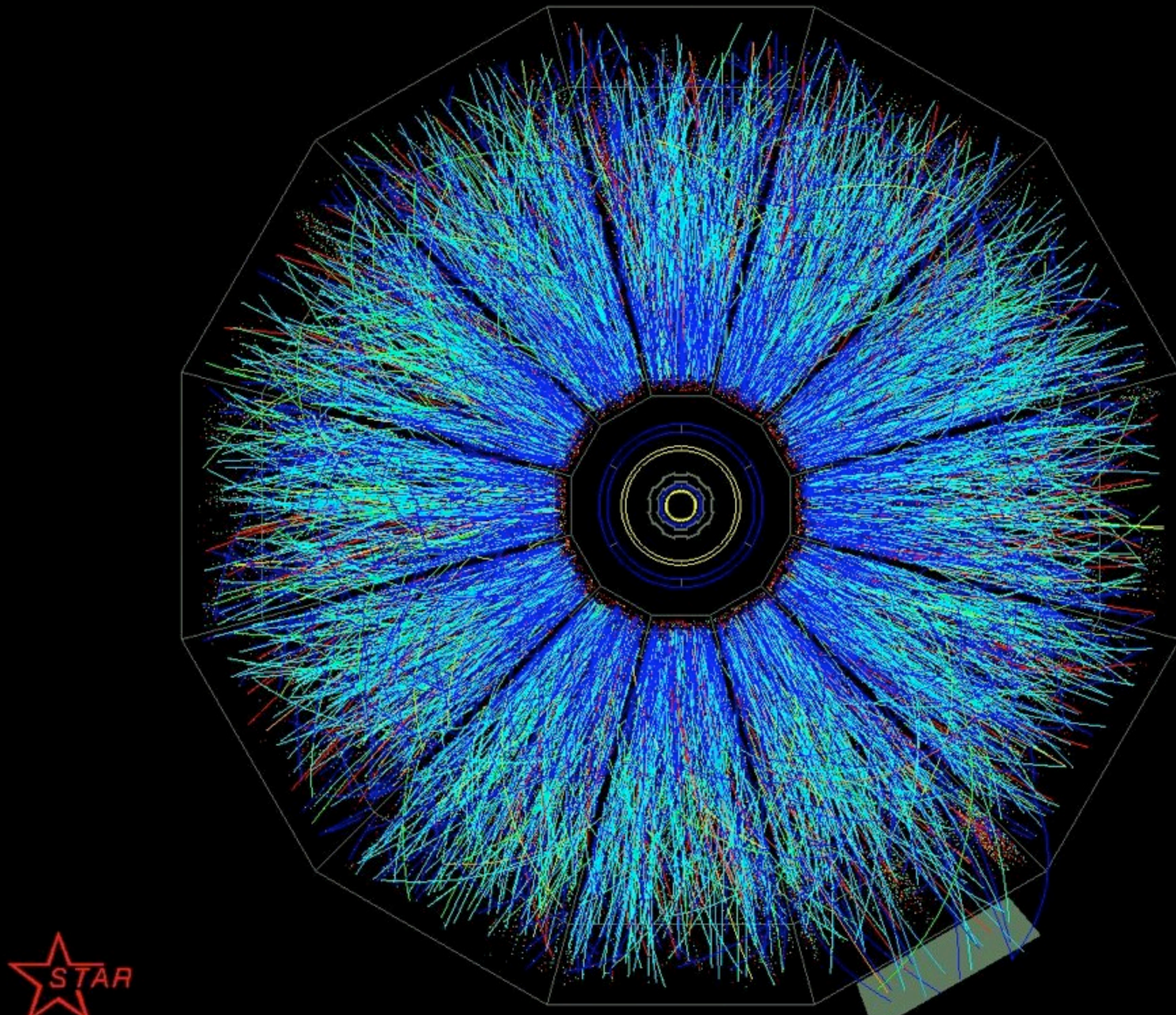
Viscous Hydrodynamics



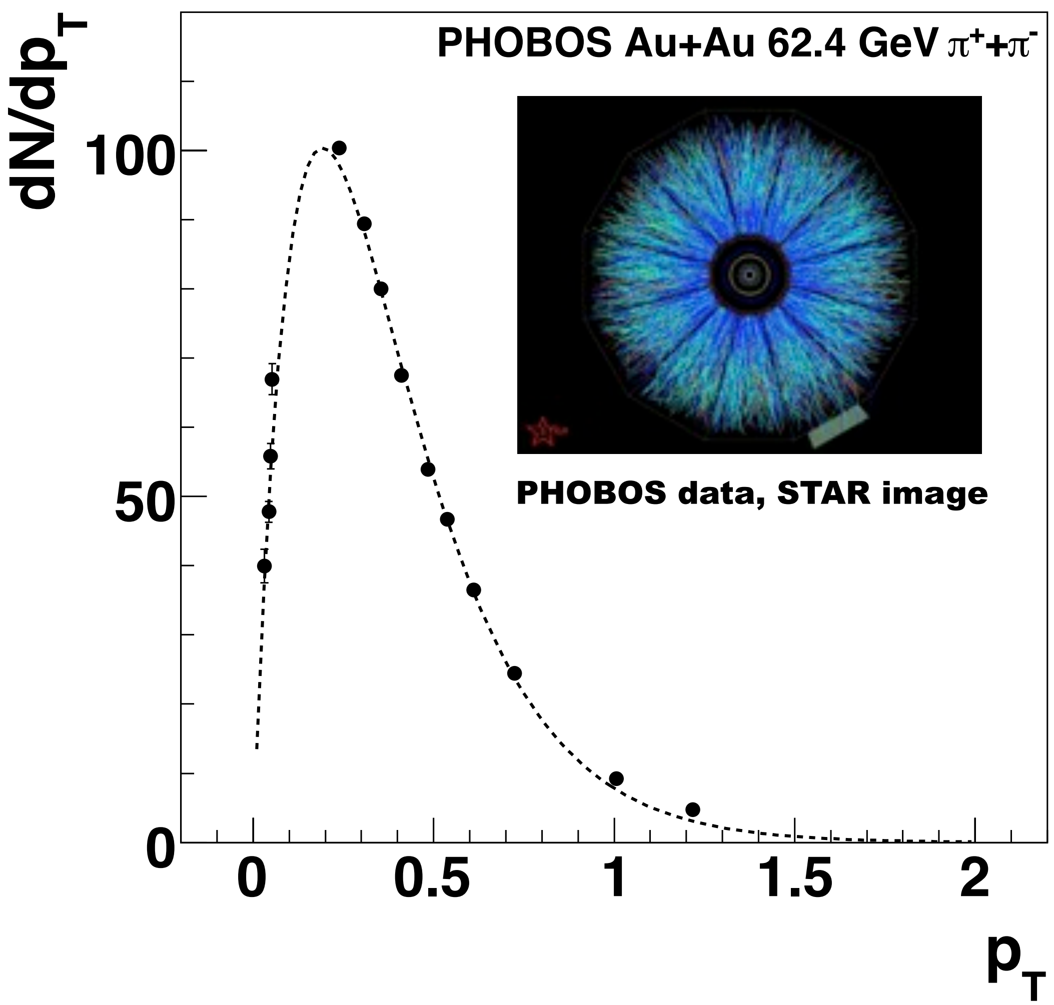
Viscosity introduces new dimensions to hydrodynamic phenomena

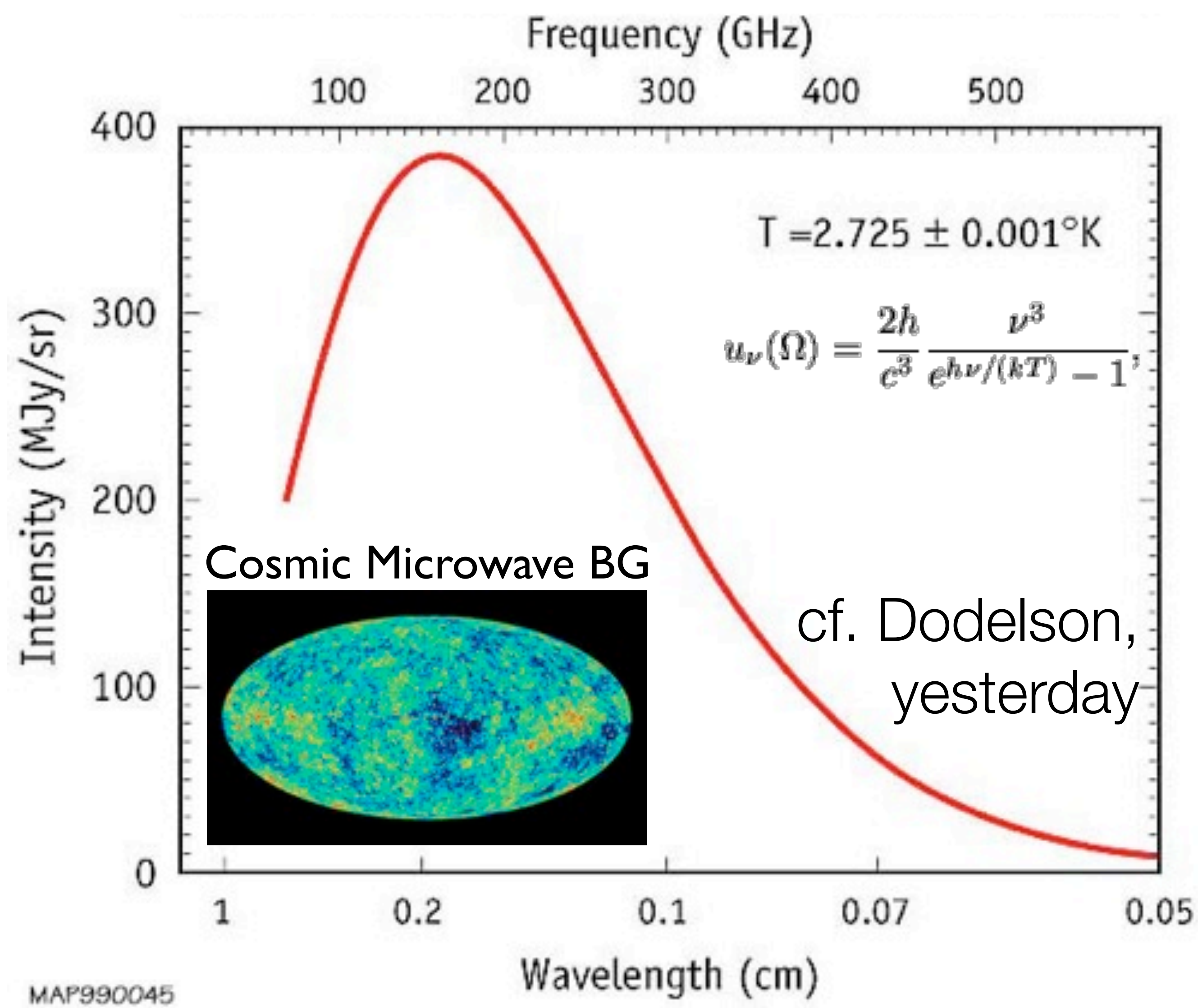
Dynamical Regimes of Hot QCD




STAR

Strong Blackbody Radiation





It is often overlooked that the spectra of particles emerging from a heavy ion collision is nearly blackbody but with <u>hadrons</u> instead of photons: **thermal system**

Hagedorn Tempera

1

Rolf Hagedorn predicted
bound state spectrum
rises indefinitely →
Singularity at
<u>limiting temperature</u>
T_H~170 MeV

$$\rho(m) \sim m^a e^{m/T_0}$$

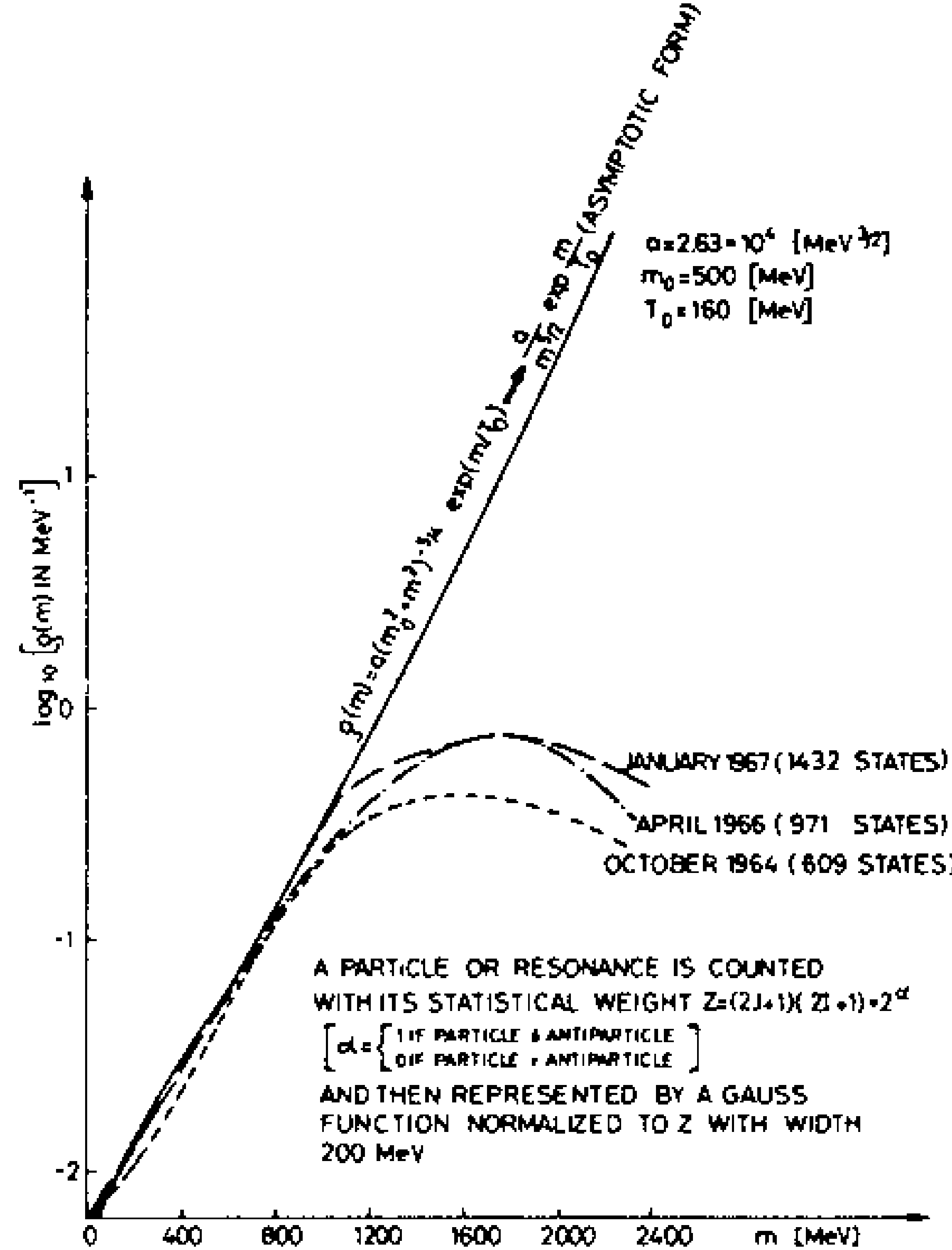
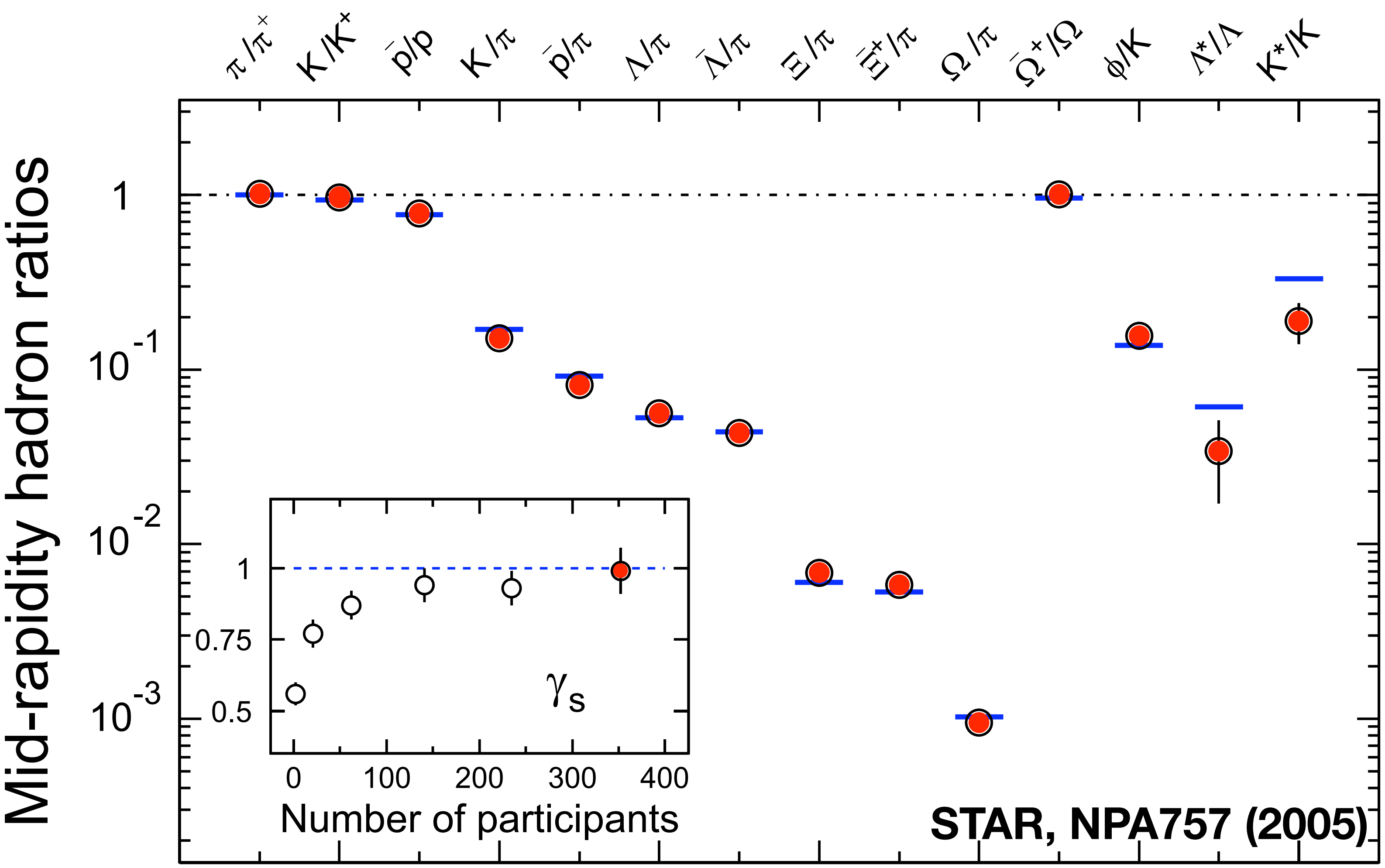


Fig. 3.1: The predicted and the experimental mass spectrum as it evolved from 1964 to 1967.

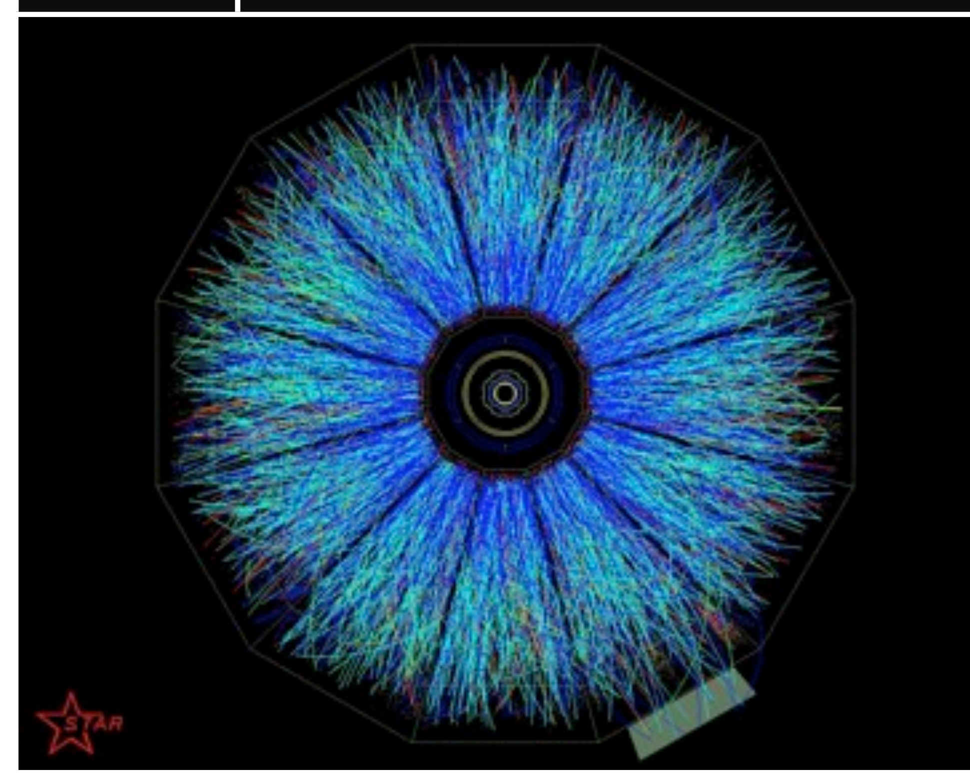
Strong Blackbody Radiation



200 GeV ^{197}Au + ^{197}Au central collision

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

T	Chemical freezeout temperature
μ_B	Baryochemical potential (more matter than antimatter)



All hadron species apparently emitted from a <u>thermal</u> source T_{ch} = 163±4, μ_B=24±4

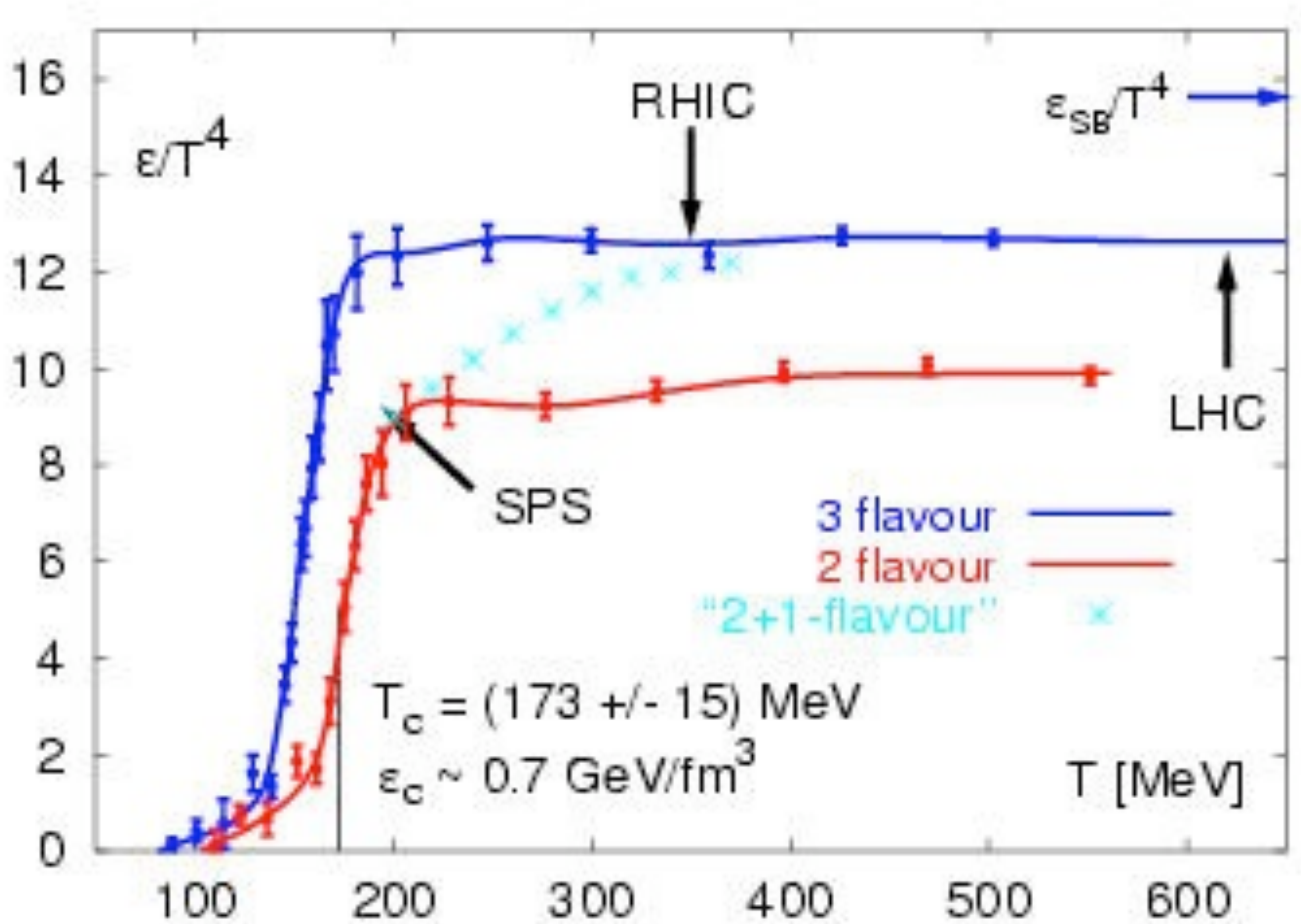
System decouples @ $T_{ch} \sim T_H$

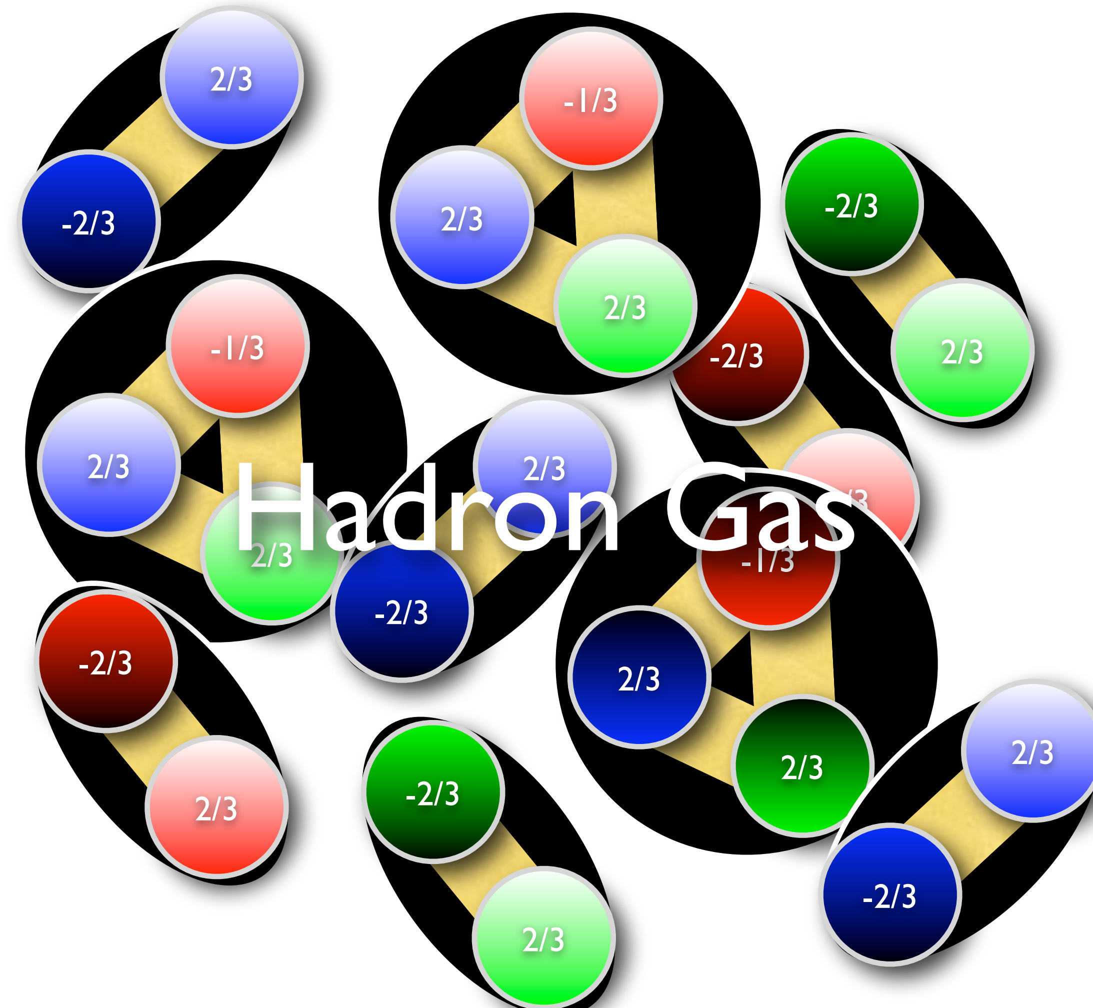
The Hagedorn Limit

Heating up a Hagedorn gas excites higher-mass resonances
→ T_H is the “limit” temperature

Nominally, no way to ever reach higher temperatures in a strongly-interacting system!

Quark Gluon Plasma





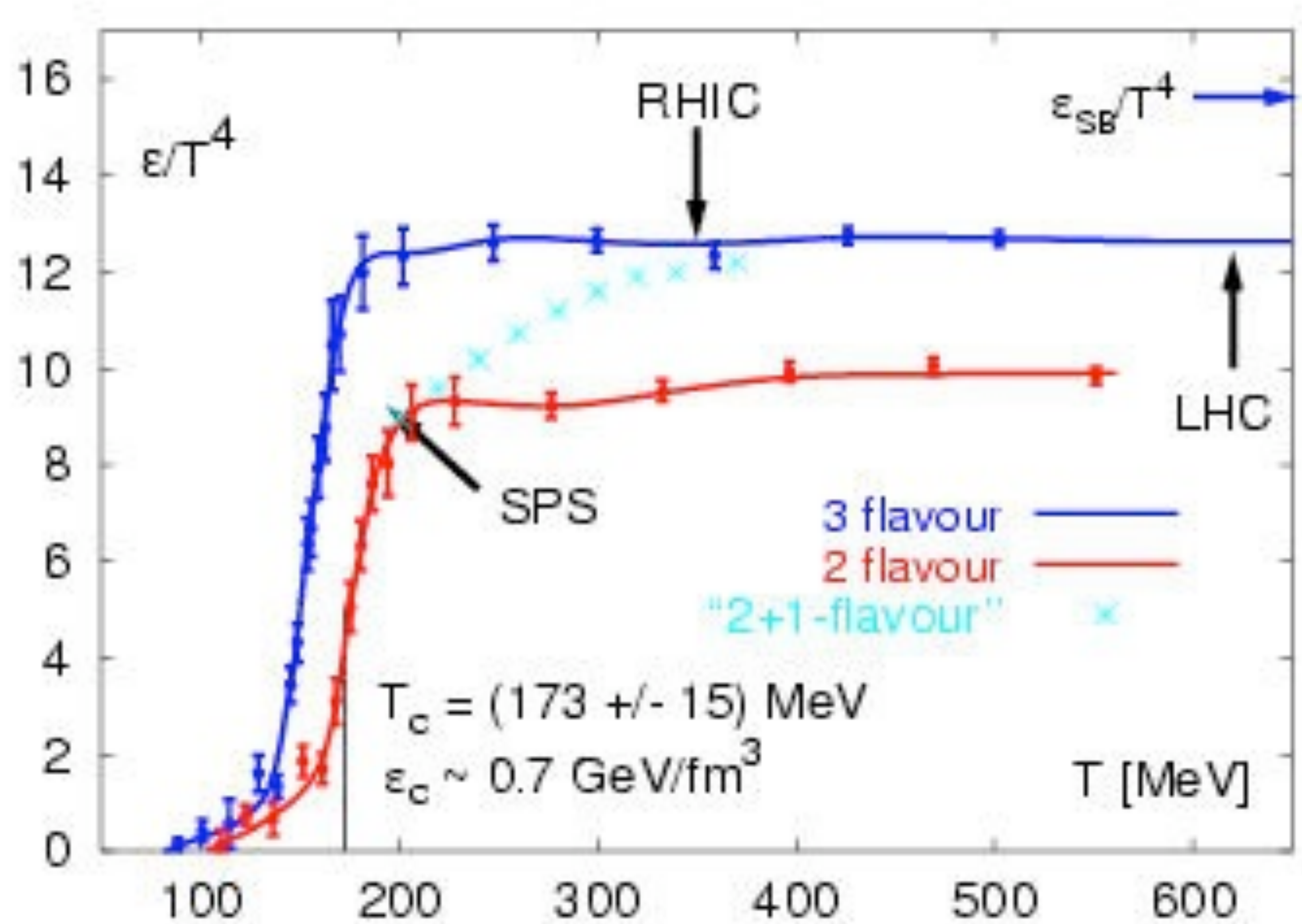
Lattice predicts a phase transition at T_C~170 MeV~T_H

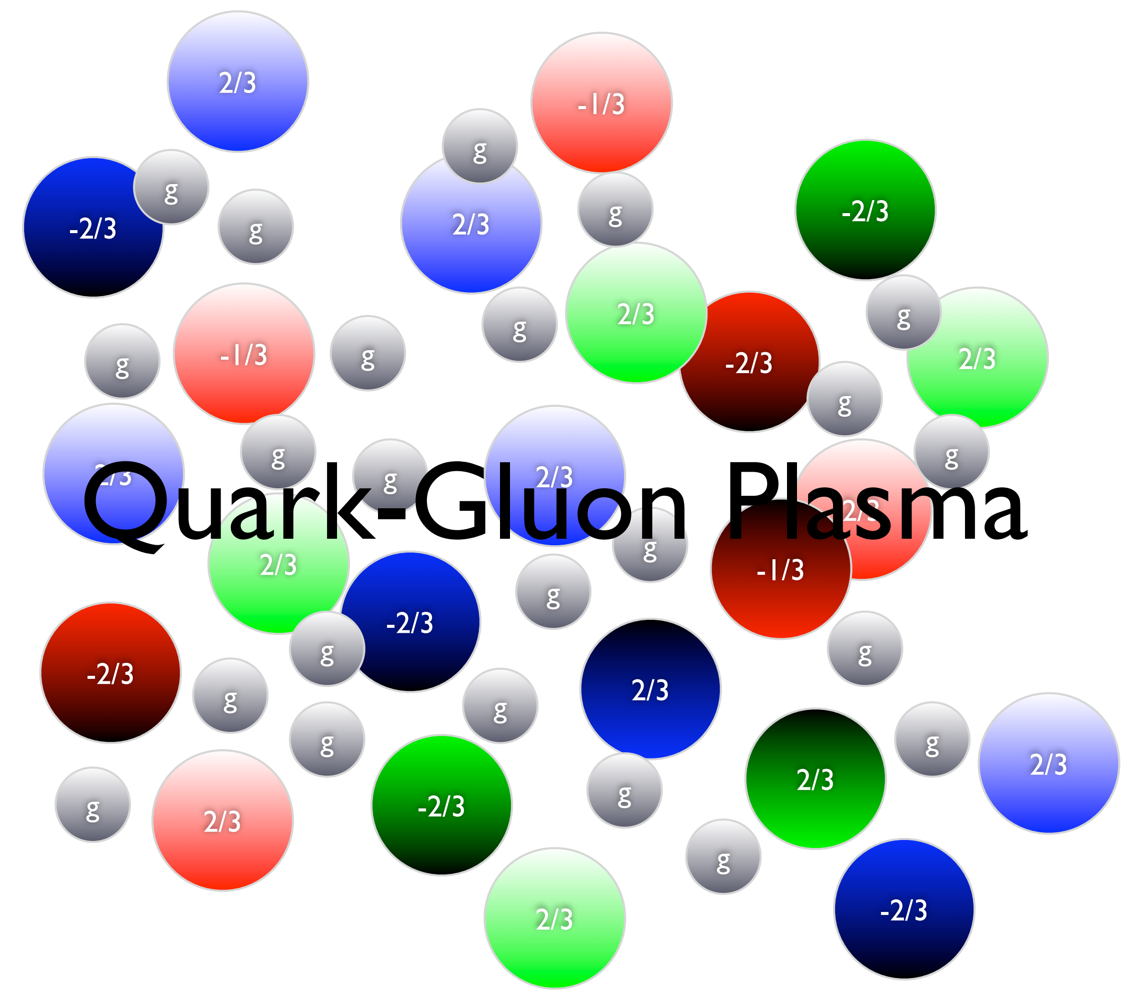
(ε_C~700 MeV/fm^3 > ε_N~500 MeV/fm^3)

from hadronic degrees of freedom to quark/gluon

Quark Gluon Plasma

#DOF





Lattice predicts a phase transition at T_C~170 MeV~T_H

(ε_C~700 MeV/fm^3 > ε_N~500 MeV/fm^3)

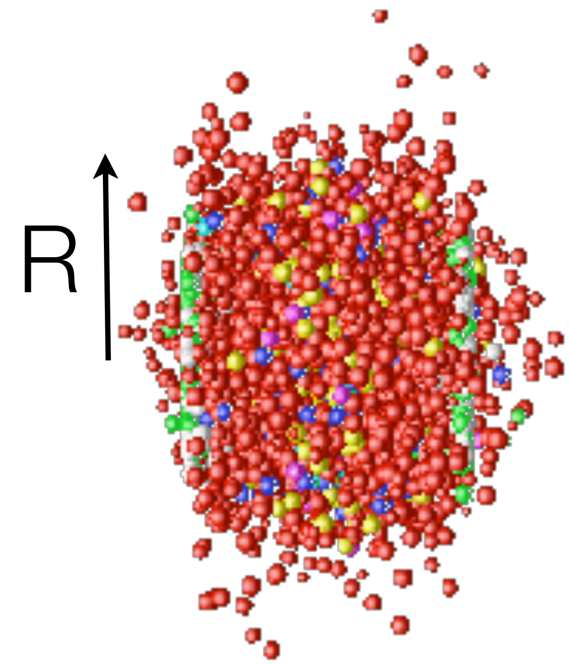
from hadronic degrees of freedom to quark/gluon

Probing Heavy Ion Dynamics with Soft Physics

Initial Collisions
(Nuclear geometry,
Baryon stopping)

Initial Boundary Conditions (Space-time)

Multiplicities

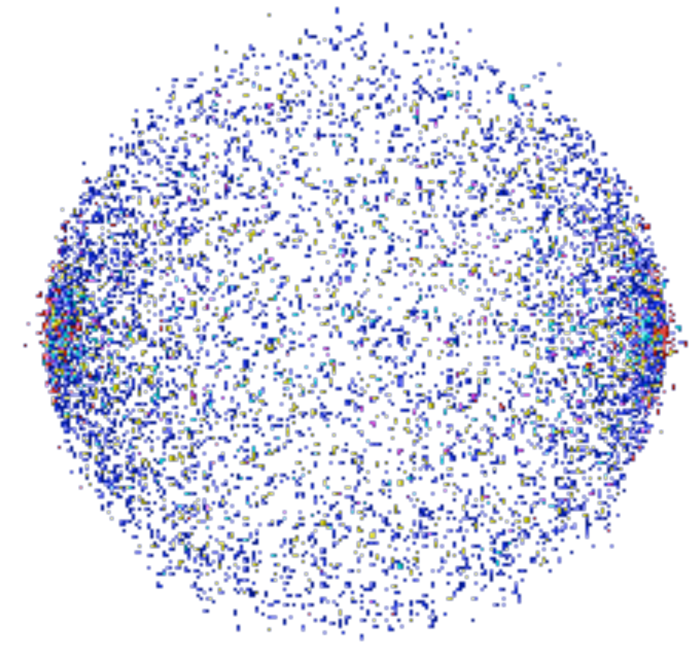


Dynamical evolution
$\tau \sim O(R)$

$$\partial_\mu T^{\mu\nu} = 0$$

$p(\epsilon)$ **(e.g. lattice)**

Spectra, Flow



Freezeout
(Hadronization)

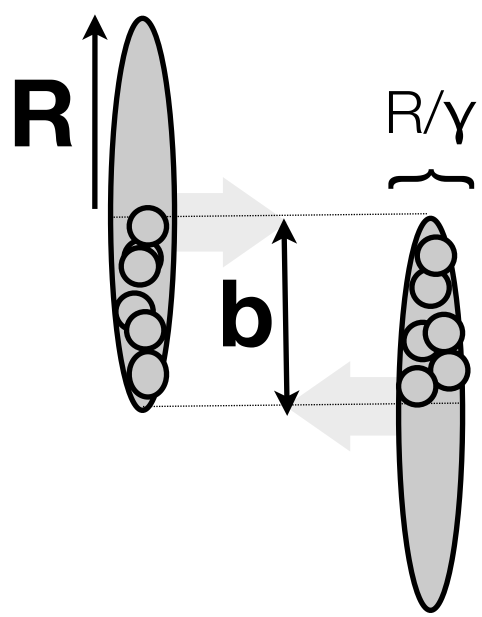
Final Boundary Conditions (Local)

$T = T_H$ or T_{th}

Yields, Correlations

Nuclear Geometry

Knowing collision geometry is essential for all heavy ion results

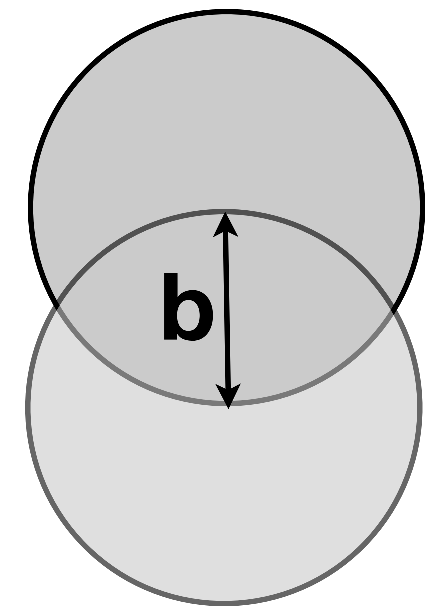


N_{part}, N_{coll},
participants
binary collisions
(~$N_{part}^{4/3}$)

N_{spec}:
spectators

$$\epsilon = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

"**eccentricity**"



x-z:
Longitudinal contraction (1/γ)

x-y:
Transverse overlap

Transverse and longitudinal scales are quite different:
spatial, temporal, momentum (via Δp=h/ΔR)

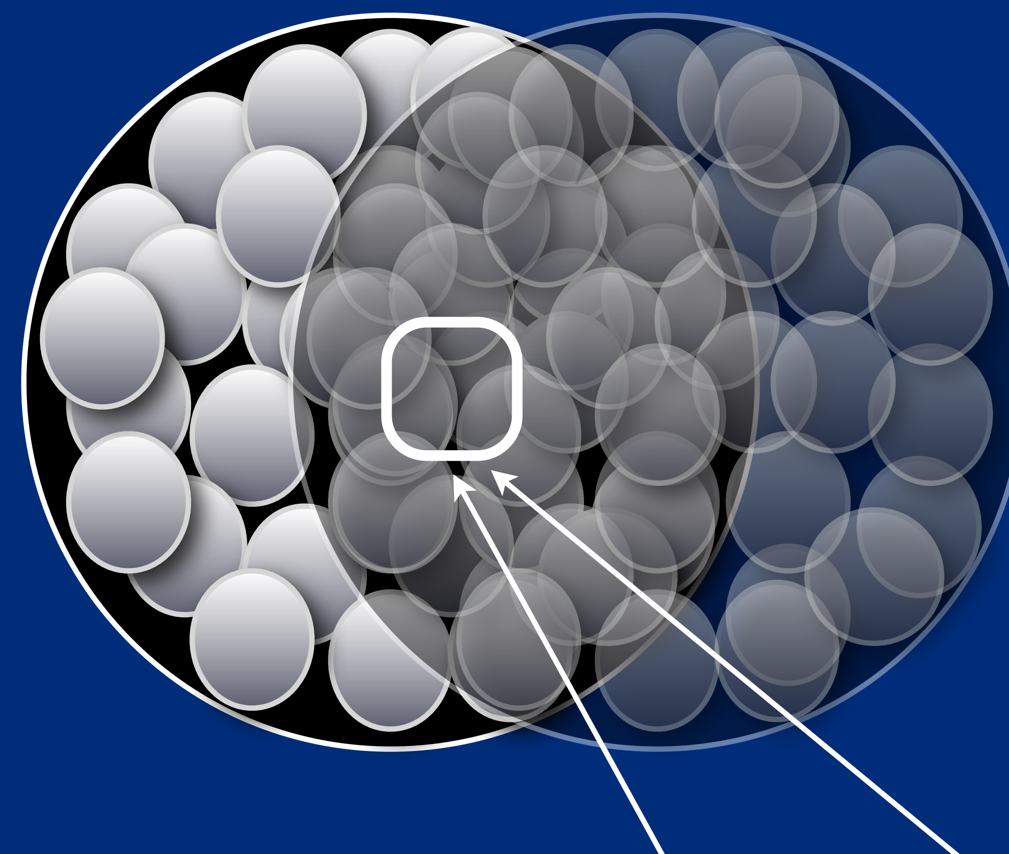
The Initial State

"Glauber model" is used to establish initial state (energy or entropy density) at one impact parameter, and evolve to other impact parameters

$$n_{part}(\vec{x}, b)$$

$$n_{coll}(\vec{x}, b)$$

more on this in the next lecture



$$\frac{d^3 s}{d\eta d^2\vec{x}} = n_{pp}\left\{(1-x)\frac{n_{part}(\vec{x})}{2} + x n_{coll}(\vec{x})\right\}$$

Participant density

Collision density

Hydrodynamic Expansion

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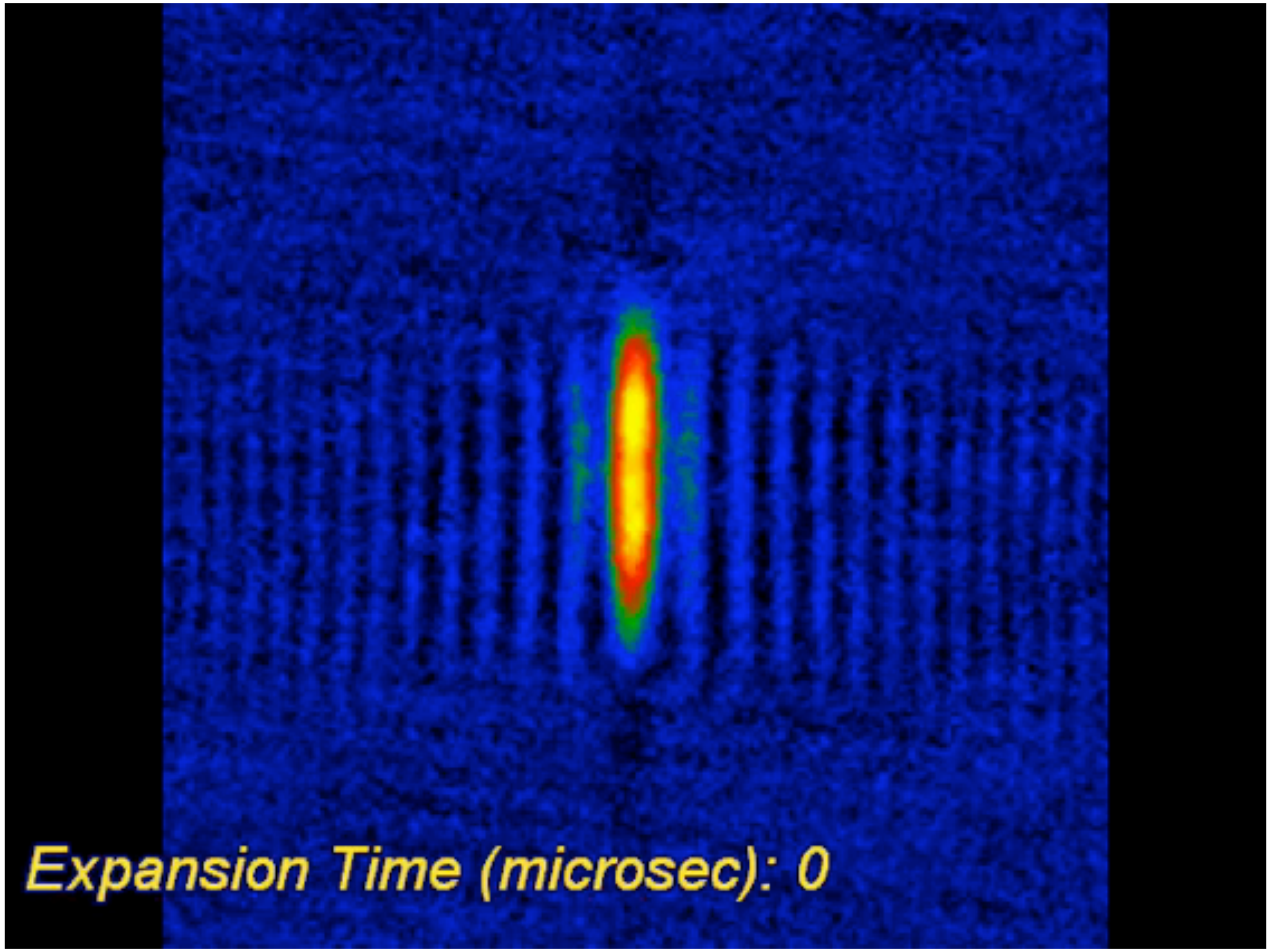
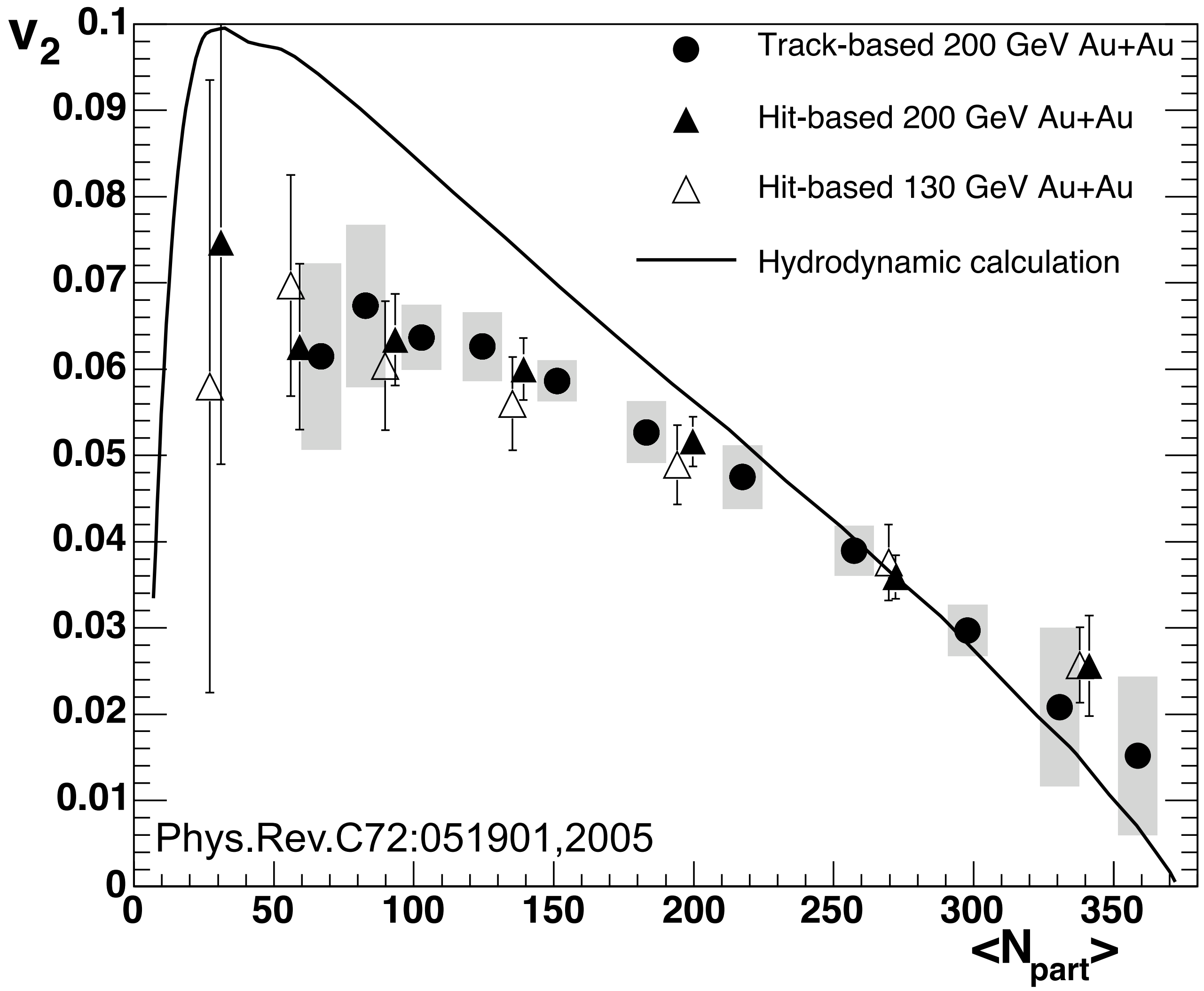
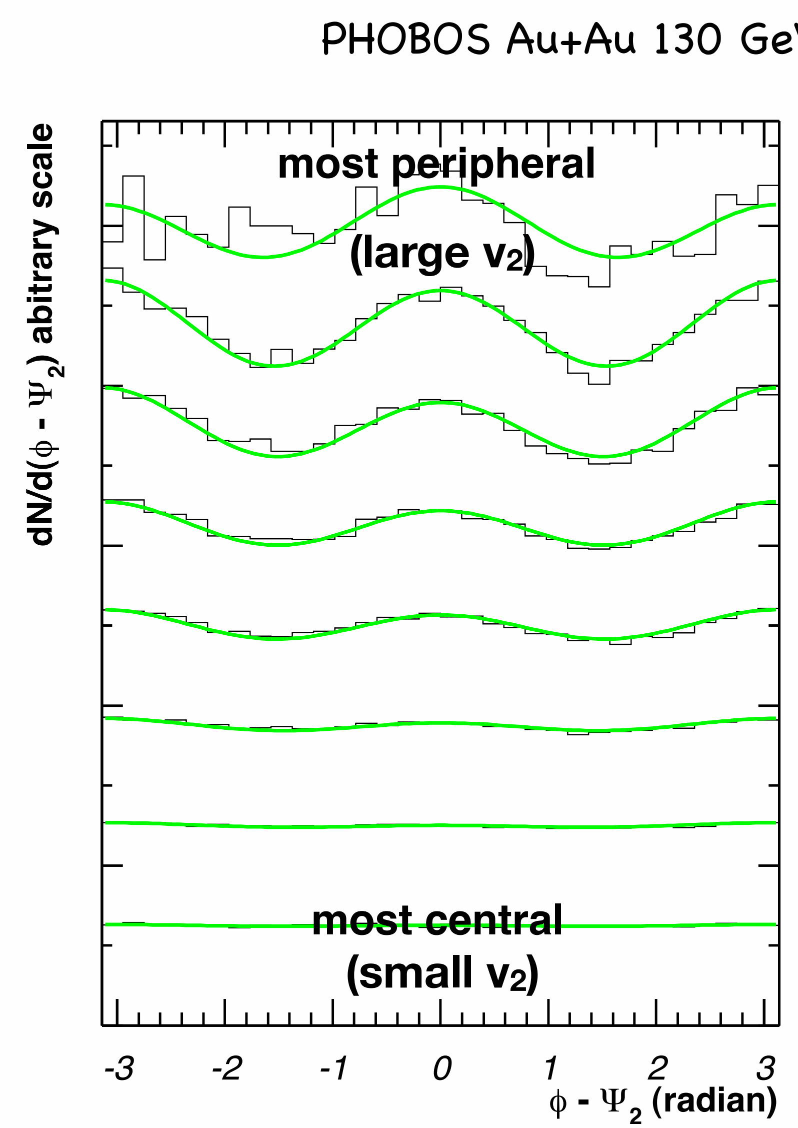
laser flash photography of trapped Li ions (J. Thomas, Duke)



Hydrodynamic evolution is very general:
initial spatial asymmetries → momentum asymmetries

Elliptic Flow (v_2)





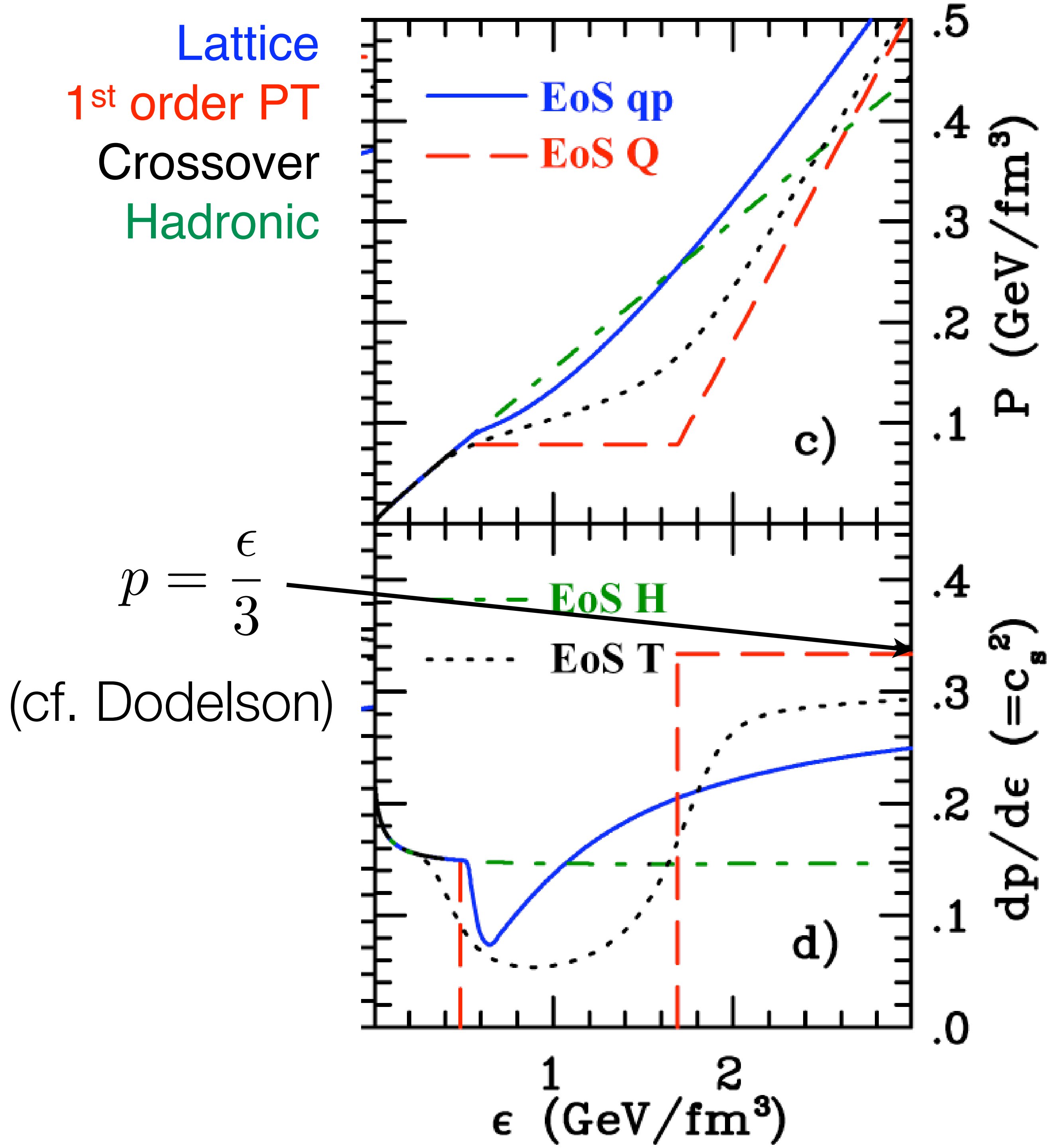
$$\frac{1}{N}\frac{dN}{d\phi} = 1 + 2v_1\cos(\phi - \Phi_R) + 2v_2\cos(2[\phi - \Phi_R]) + \ldots$$

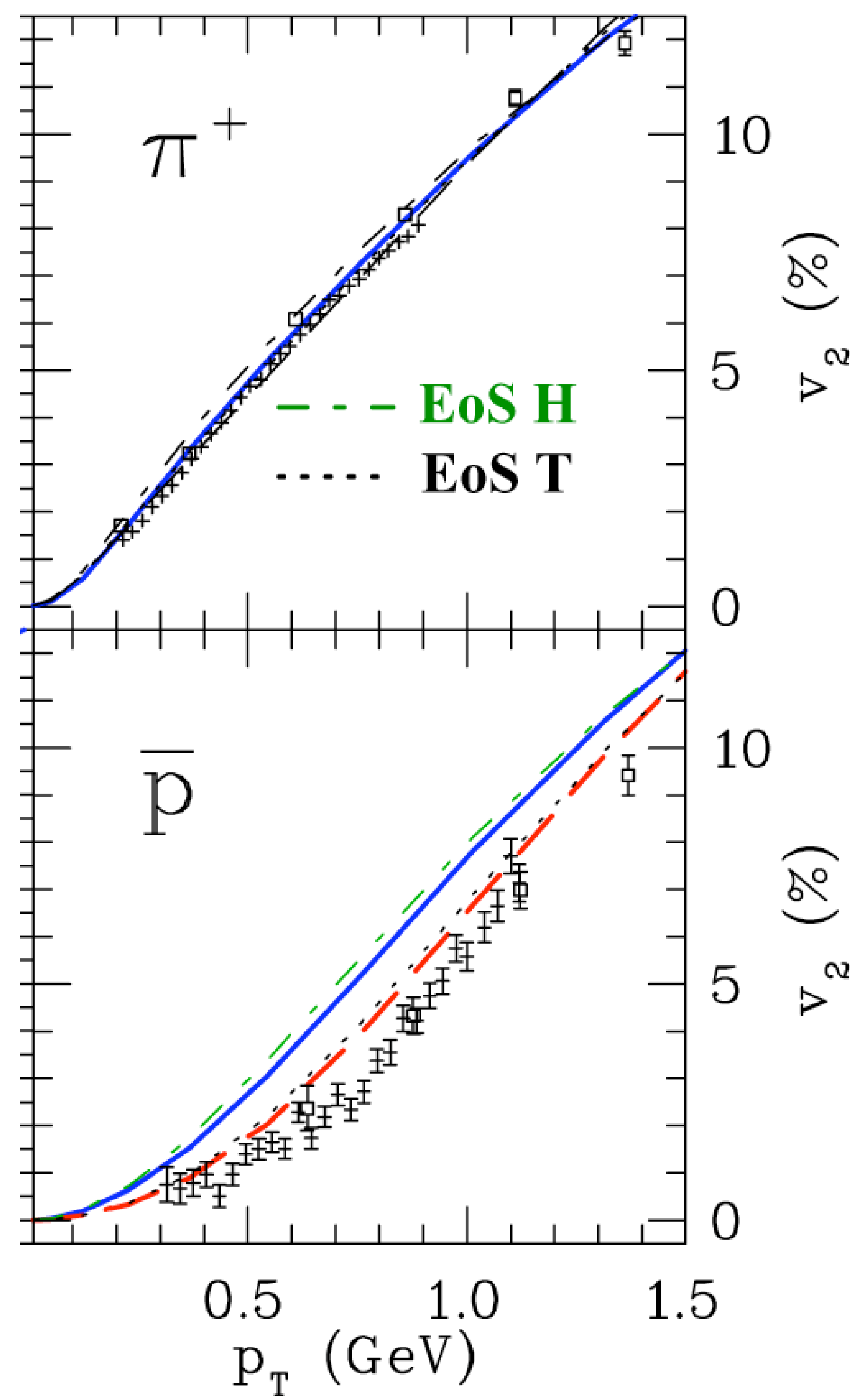
compared with Hydro (Huovinen)

Hydro (boost invariant) ε_0~30 GeV/fm^3 τ_0<0.6 fm^3 ε~0.5 GeV/fm^3 τ~1 fm^3 Hadronic scales

Equation of State ($v_2(p_T)$)

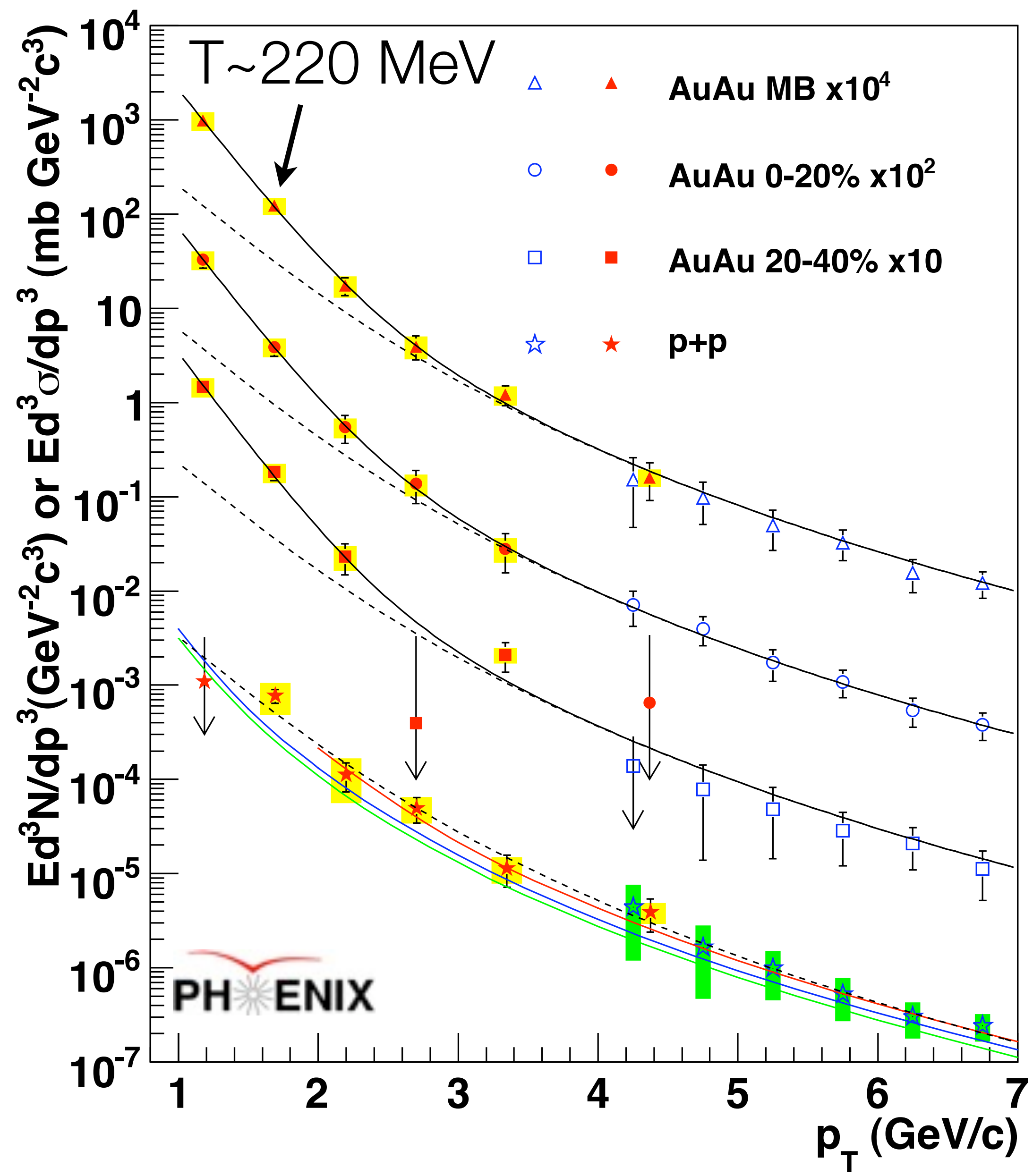
Nucl.Phys.A761:296-312,2005





Implications of Hydro

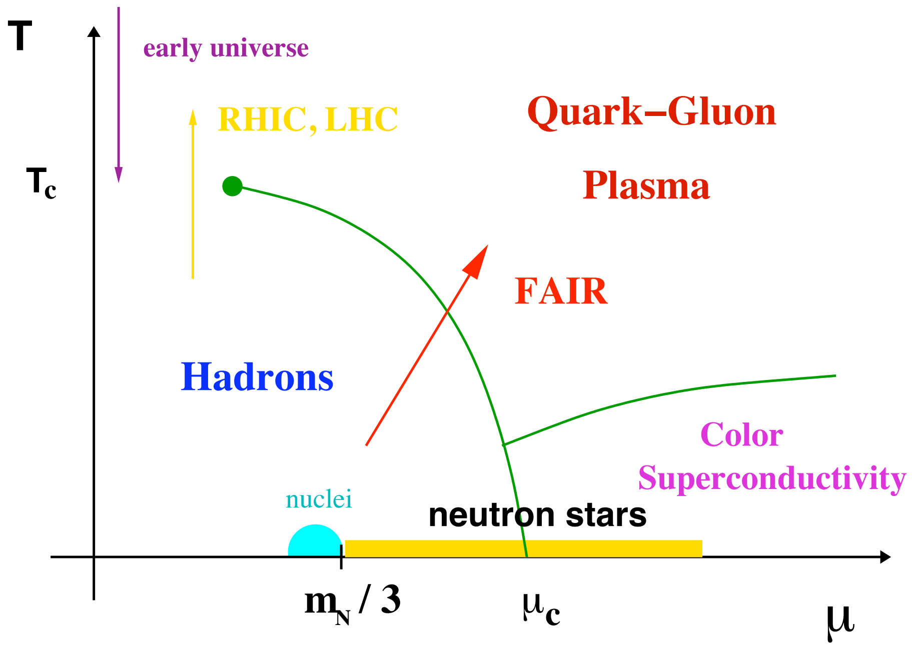
- **Hydro is not "just another" model**
- **The flowing medium is quite special**
  - Local thermalization (strong coupling)
  - "Lattice"-like equation of state (1st order PT)
- **Initial density so large (30xε_p) that can't justify a hadronic cascade**
- **Temperature exceeds T_H**
  - High temperature seen directly by direct thermal photons from PHENIX
- **This suggests that the medium <u>may well be</u> the "quark gluon plasma"**
  - What points to quark and gluon DOFs?



Studying Matter in Laboratory

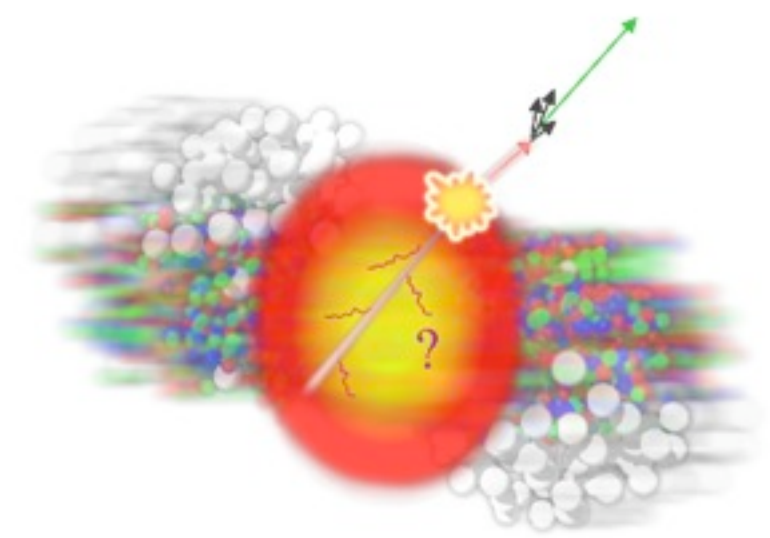
- **Changing initial conditions -- “soft” physics**

Ideal	Temperature	Matter	Density
Practical	Energy	Size	Shape



- **Probing it microscopically -- “hard” probes (next lecture)**

Ideal	Microscopy	Tomography	
Practical	Jets	Photons	Quarkonia



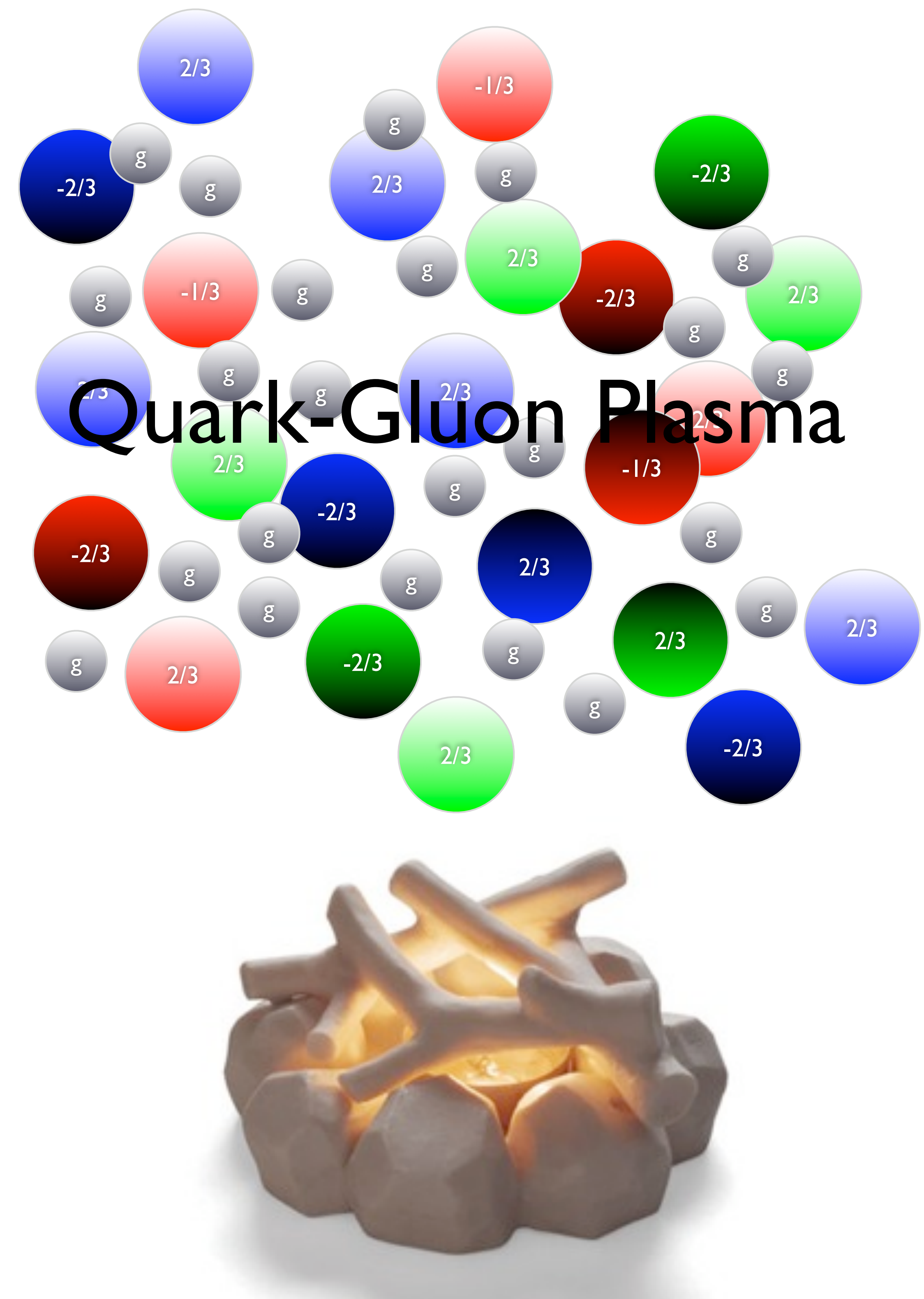
The Big Question: Thermalization at RHIC

Does the system truly thermalize? Everywhere?

What are the conditions (energy, density, size) for thermalization?

How fast does the system thermalize?

What thermalizes?



Degrees of Freedom: What Thermalizes?

Parton distributions
Nuclear Geometry
Nuclear shadowing

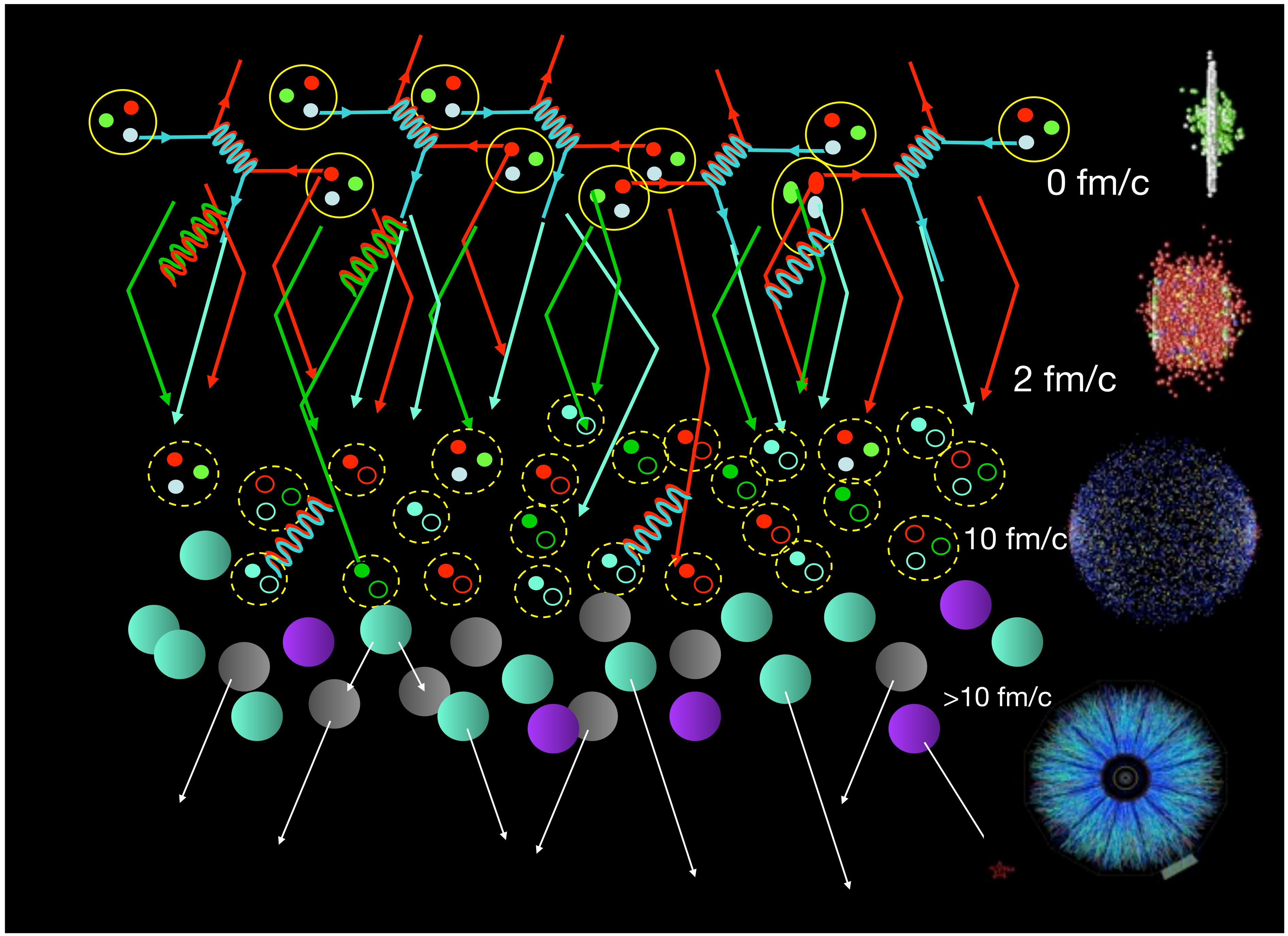
Parton production
& reinteraction

Chemical Freezeout &
Quark Recombination

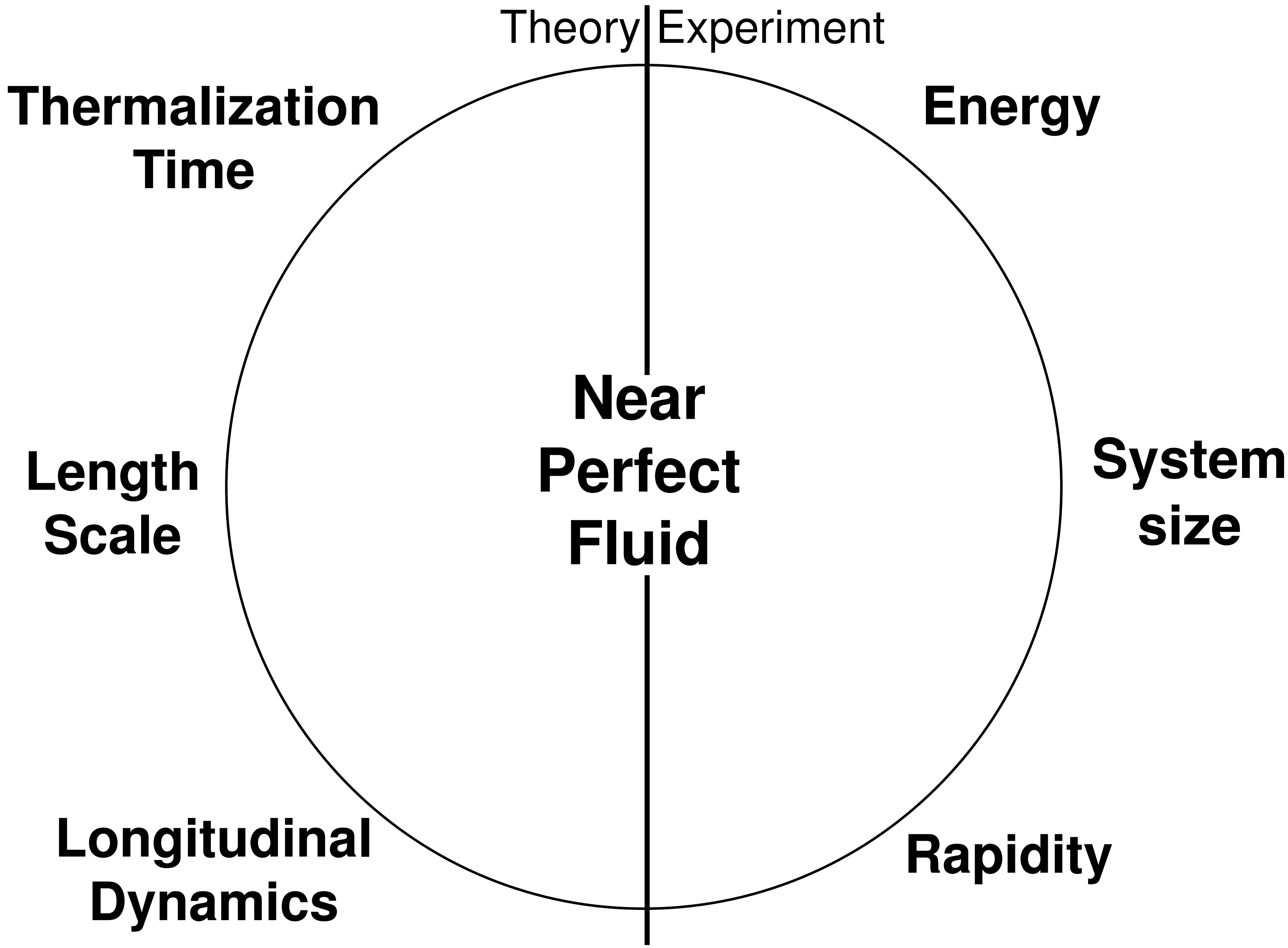
Jet Fragmentation
Functions

Hadron Rescattering

Thermal Freezeout &
Hadron decays



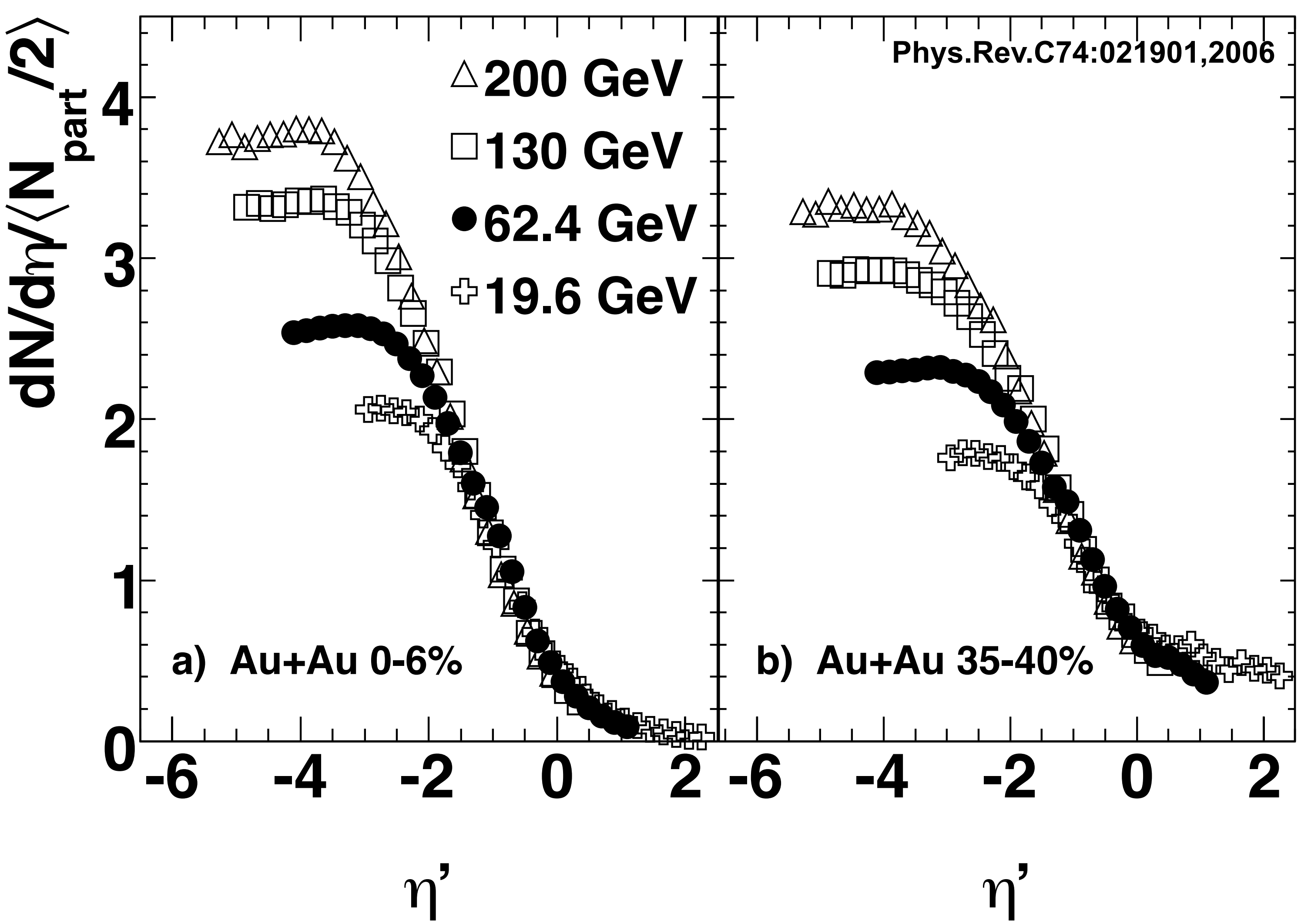
The Edge of Liquidity



Can we make what we see at RHIC “turn off”?

Extended Longitudinal Scaling (Limiting Fragmentation)

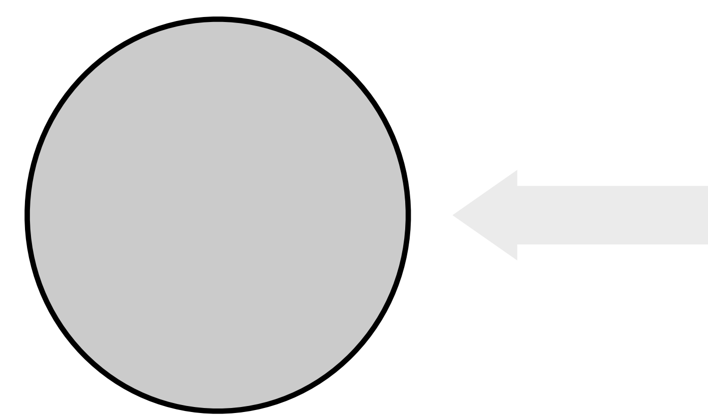
- **From rest frame of one projectile: yields invariant at fixed geometry (i.e. same b/2R or $N_{part}/2A$)**



$$y = \tanh^{-1}(\beta)$$

$$\sim -\log(\tan(\theta/2)) \equiv \eta$$

$$\eta' = \eta - y_b \sim \log(x_F)$$

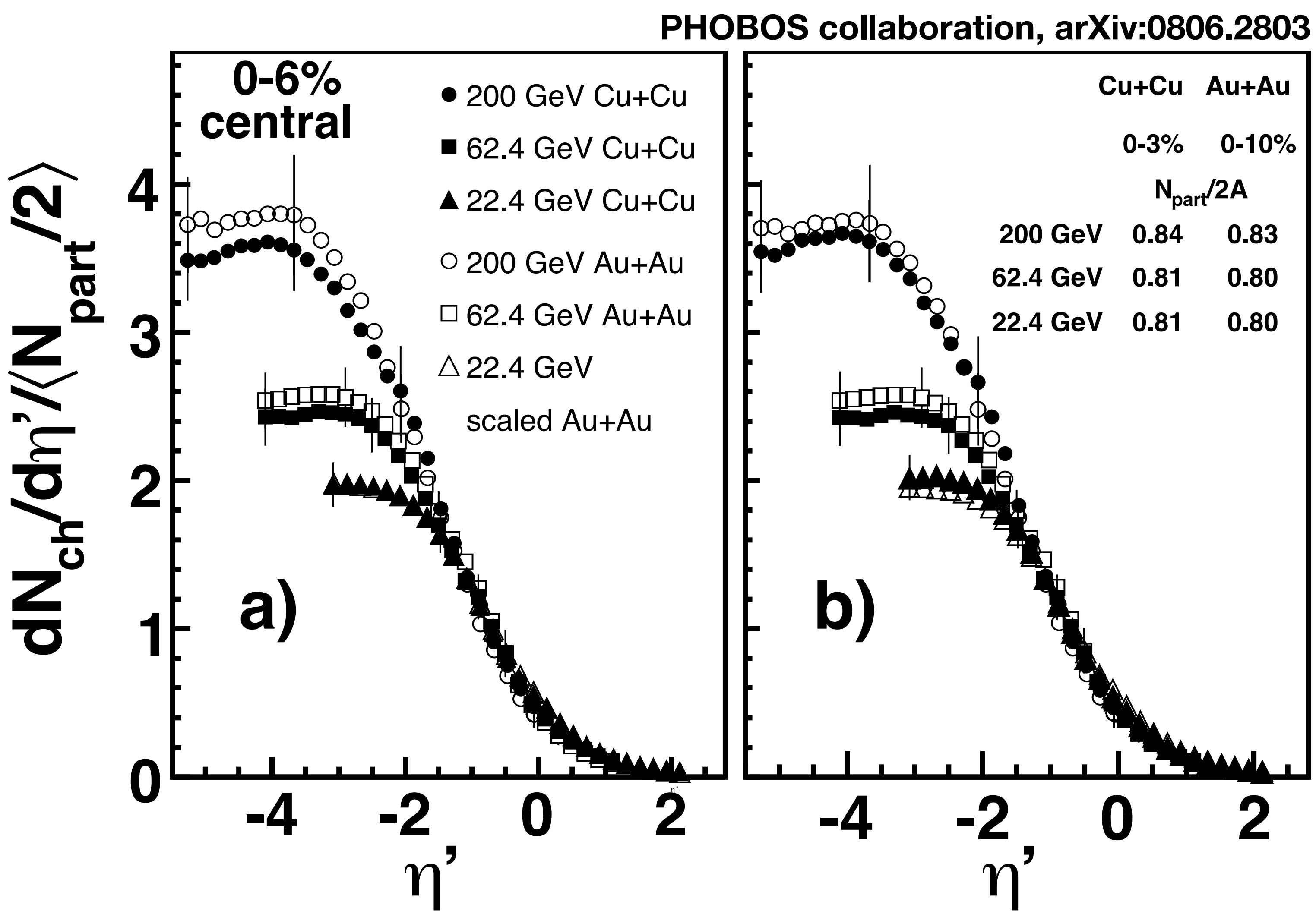


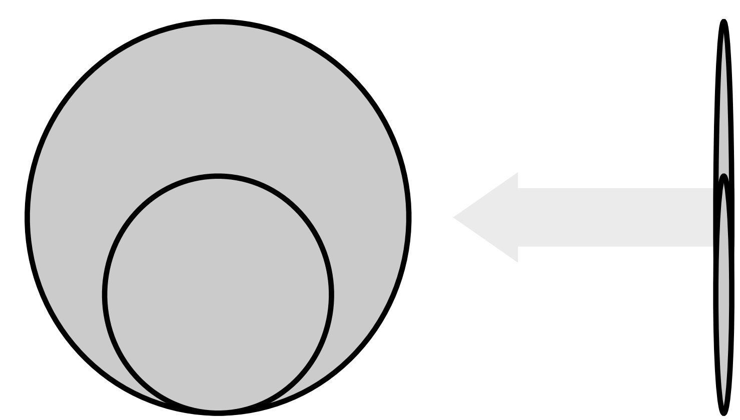
Midrapidity physics at lower energy = forward physics at higher energy

Energy and rapidity dependence is smooth

Extended Longitudinal Scaling (Limiting Fragmentation)

- **No change in shape moving from Au+Au → Cu+Cu**



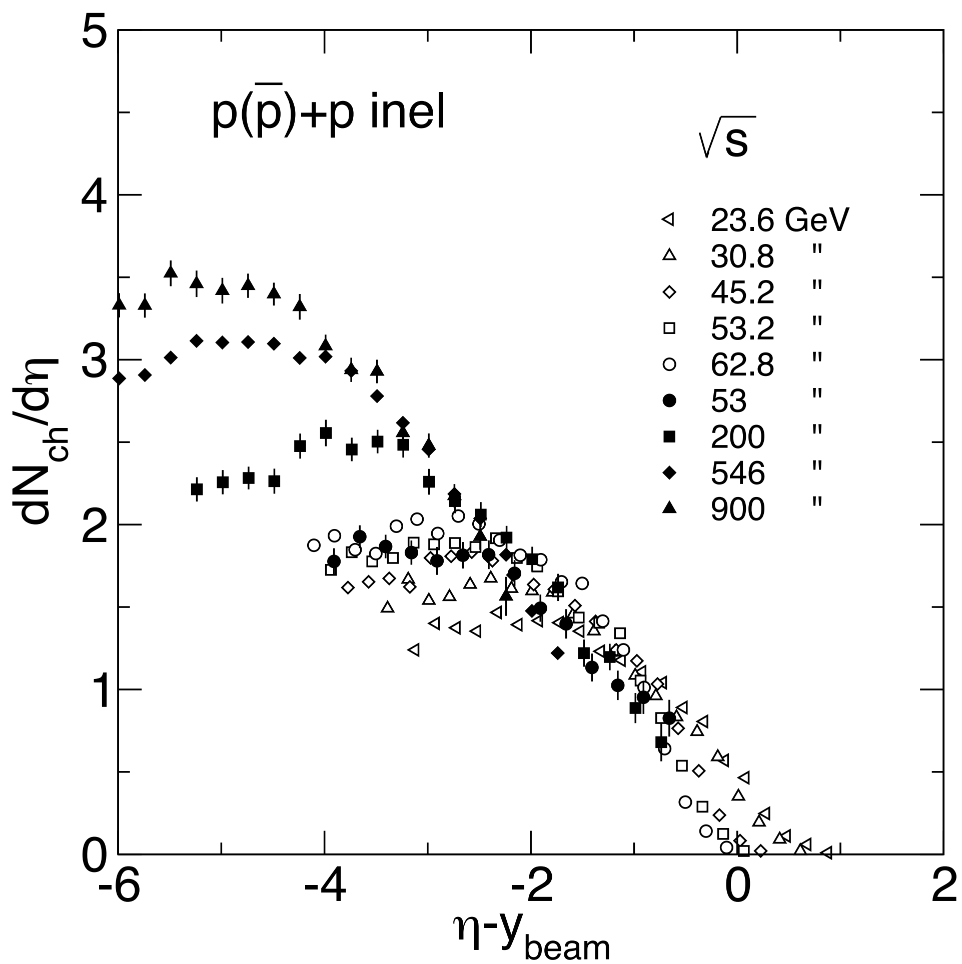


Change the nuclear size by x3: Au+Au→Cu+Cu

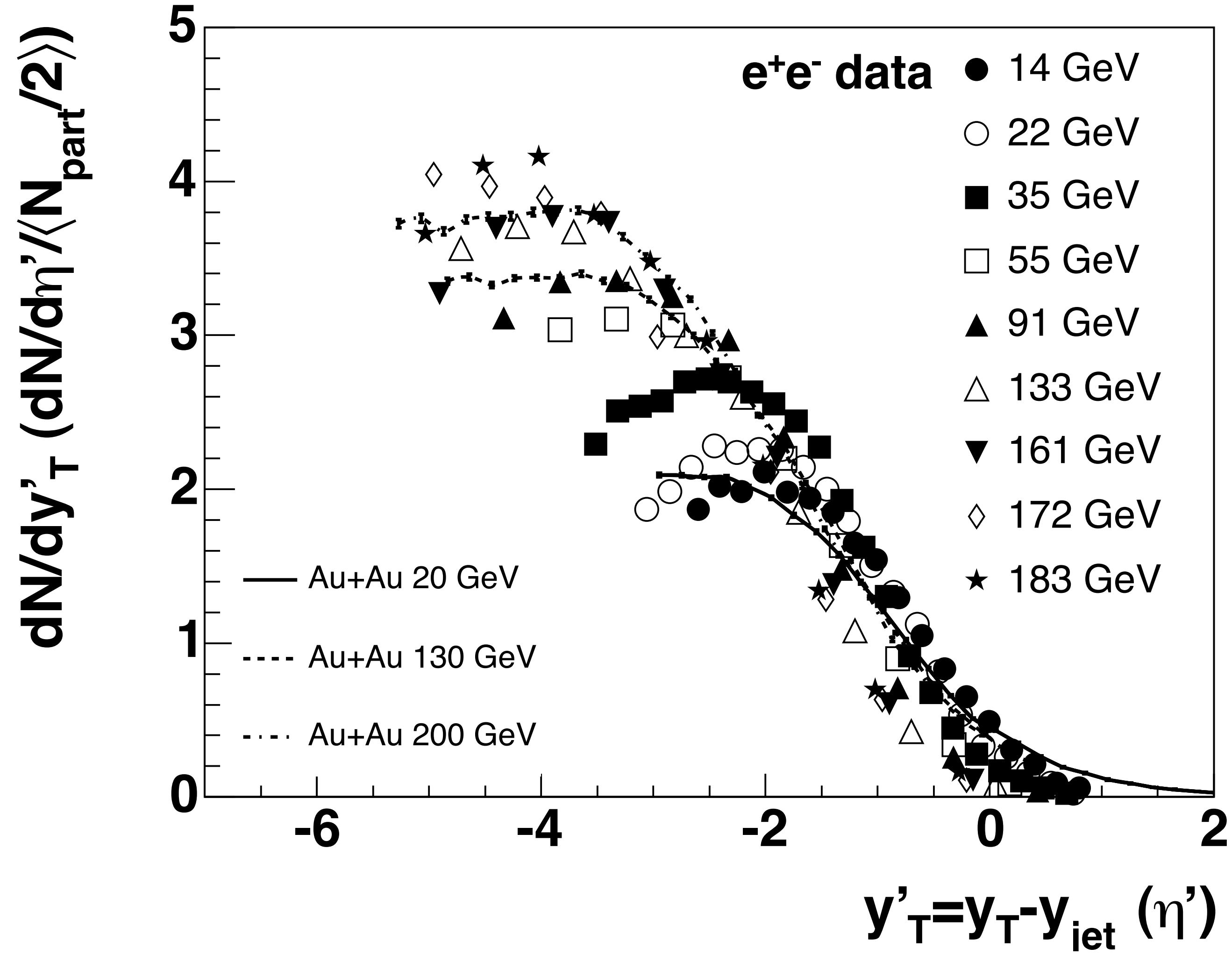
No change in shape for same centrality (b/2R)

Longitudinal Scaling in Elementary Systems (p+p, e^+e^-)

minbias $dN_{ch}/d\eta$



fragmentation functions!

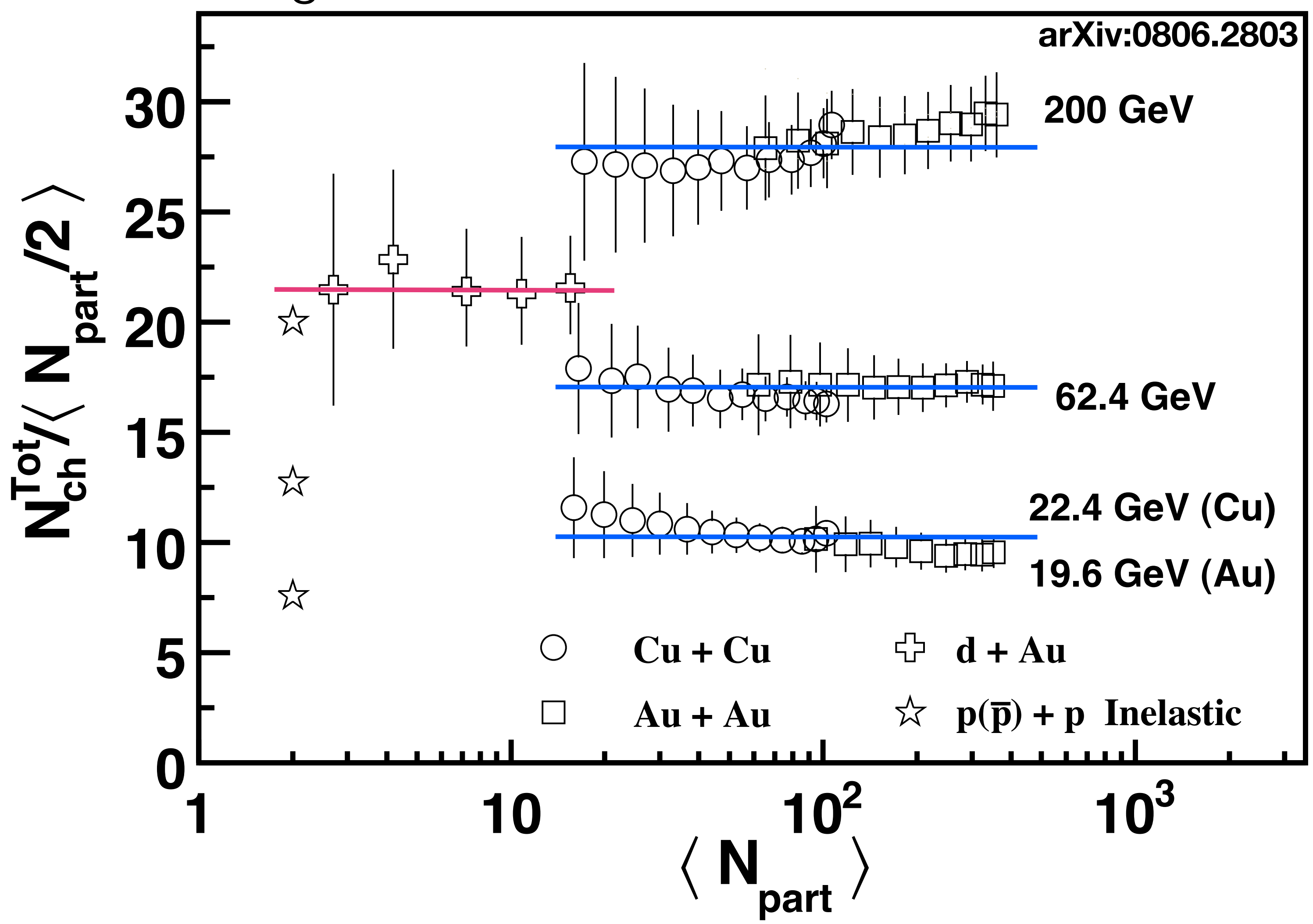


Even "small" systems (p+p and e^+e^-) show same feature, and magnitude for e^+e^-

Ubiquity → 1) **trivial** or 2) **deep**

When does the system get too small?

Integrated over 4π



$$S \propto sV \propto\propto N_{tot} \propto N_{part}$$

(Fermi-Landau model)

Cu+Cu & low energy data fit into systematics established by RHIC Au+Au: when is system "too small"?

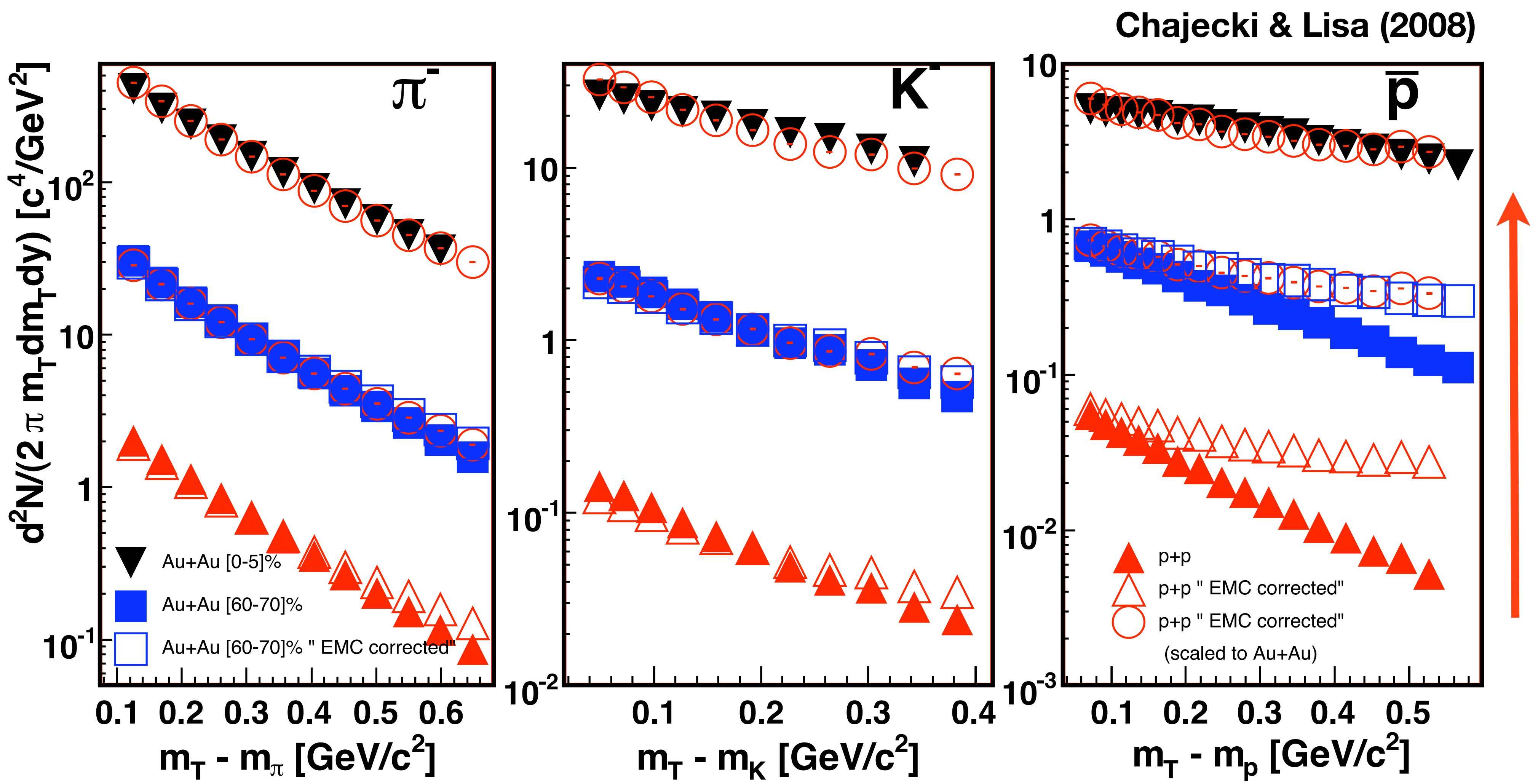
Total multiplicity (4π) shows "wounded nucleon" scaling to N_{part}=20

Suggests no change in overall degrees of freedom with **system size**

p+p/d+Au → A+A explained by "leading-particle" effects

Phys.Rev.C74:021902,2006

Small ~ Large?



"radial flow"

$T_{eff} = T_0 + m\beta^2$

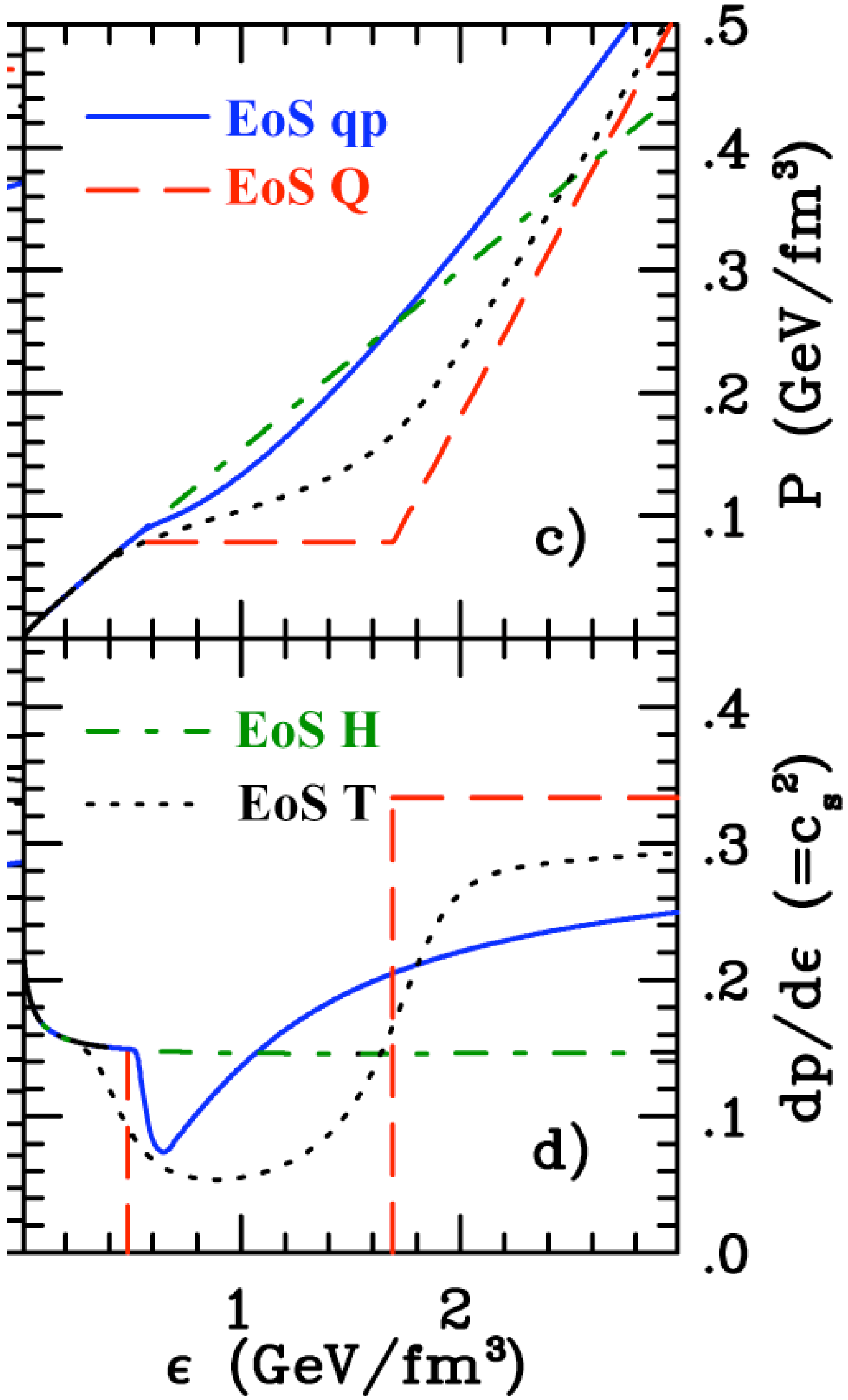
p+p spectrum, "undistorted" by energy-momentum conservation, compares well to A+A: radial expansion in p+p?

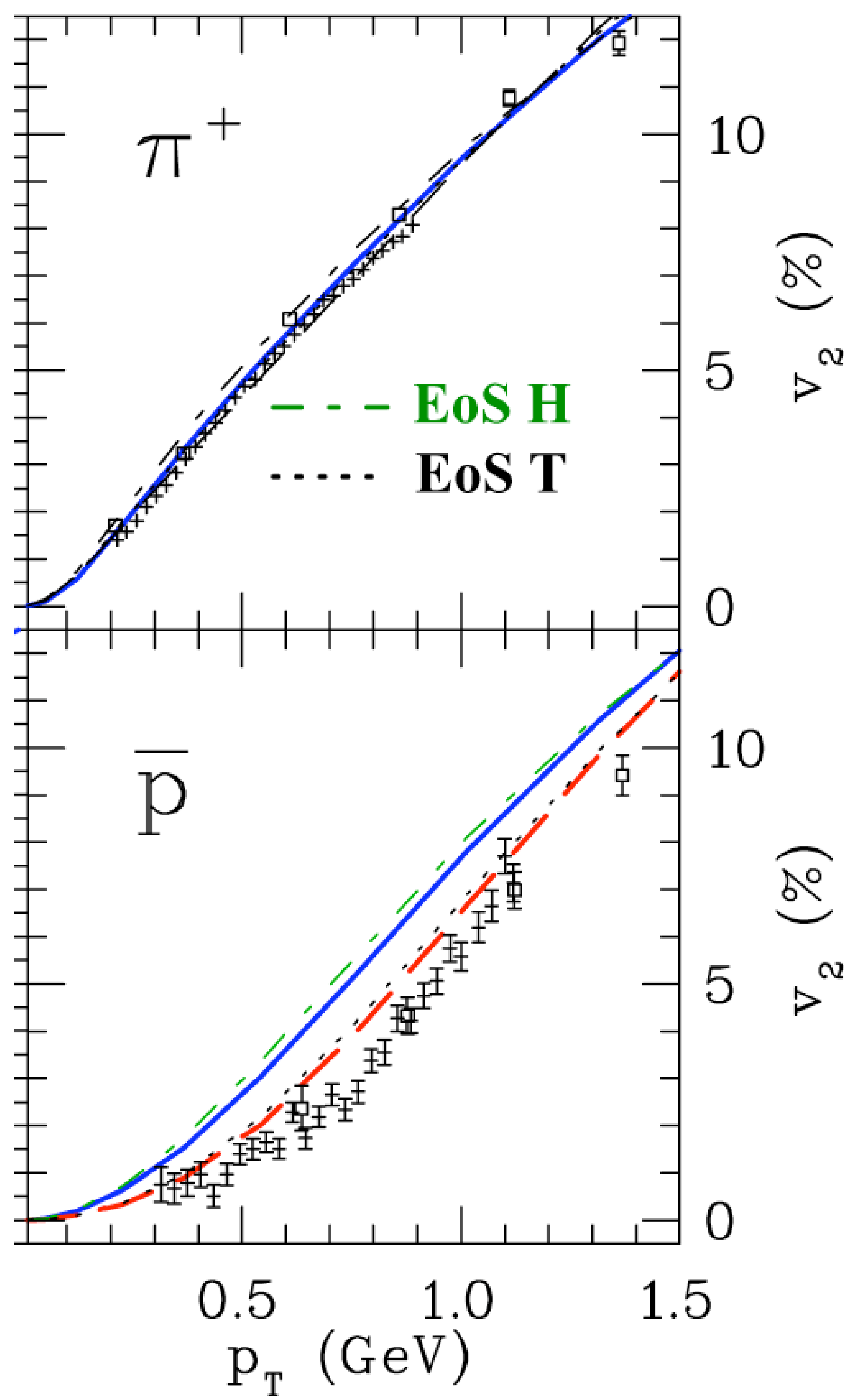
Does p+p behave like a thermalized, flowing system, like A+A?
(if so, what does this suggest about "underlying event"?)

Recap: EOS Degrees of Freedom

Nucl.Phys.A761:296-312,2005

Lattice
1st order PT
Crossover
Hadronic





Degrees of Freedom: What Flows?

Parton distributions
Nuclear Geometry
Nuclear shadowing

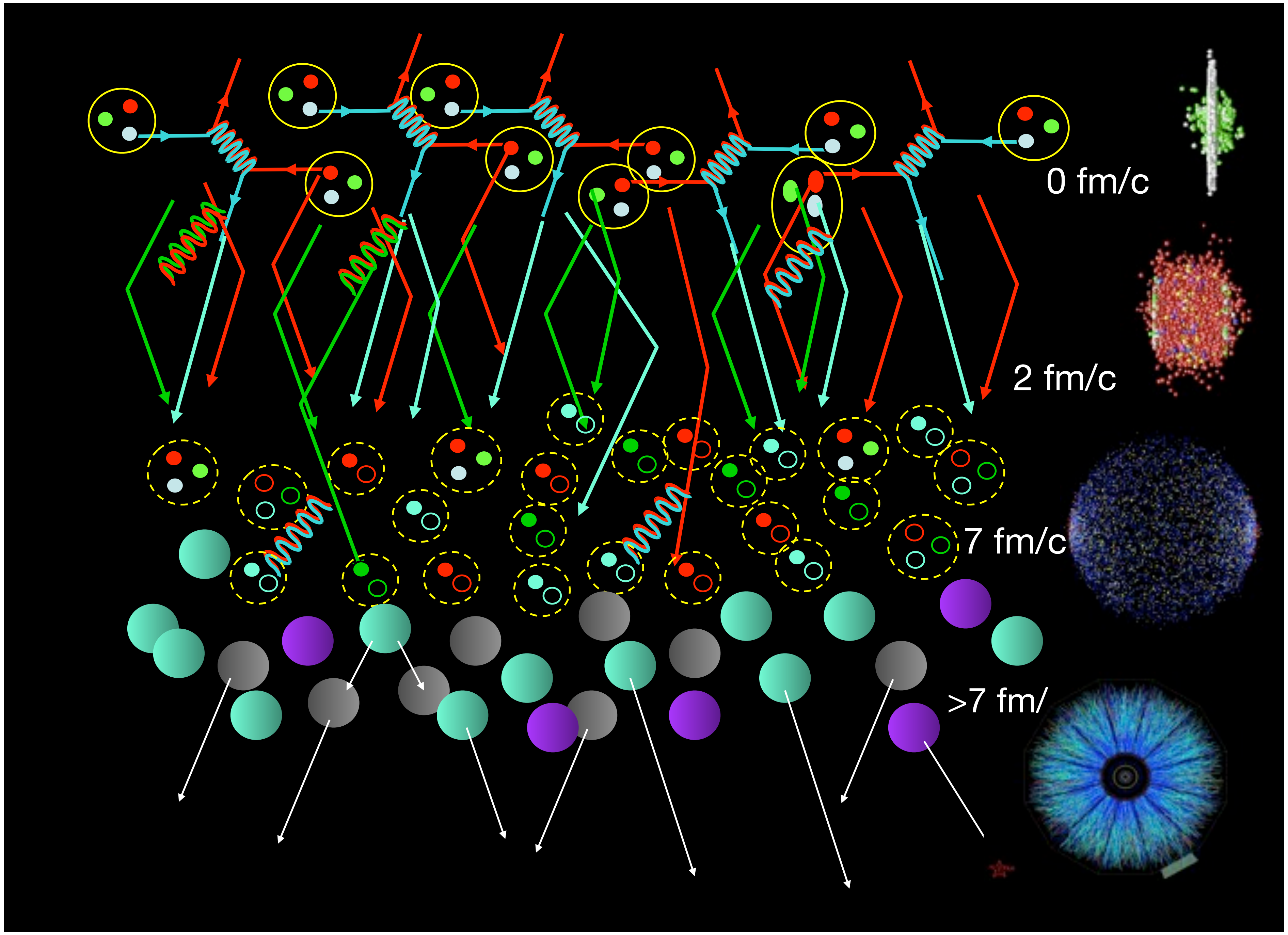
Parton production
& reinteraction

Chemical Freezeout &
Quark Recombination

Jet Fragmentation
Functions

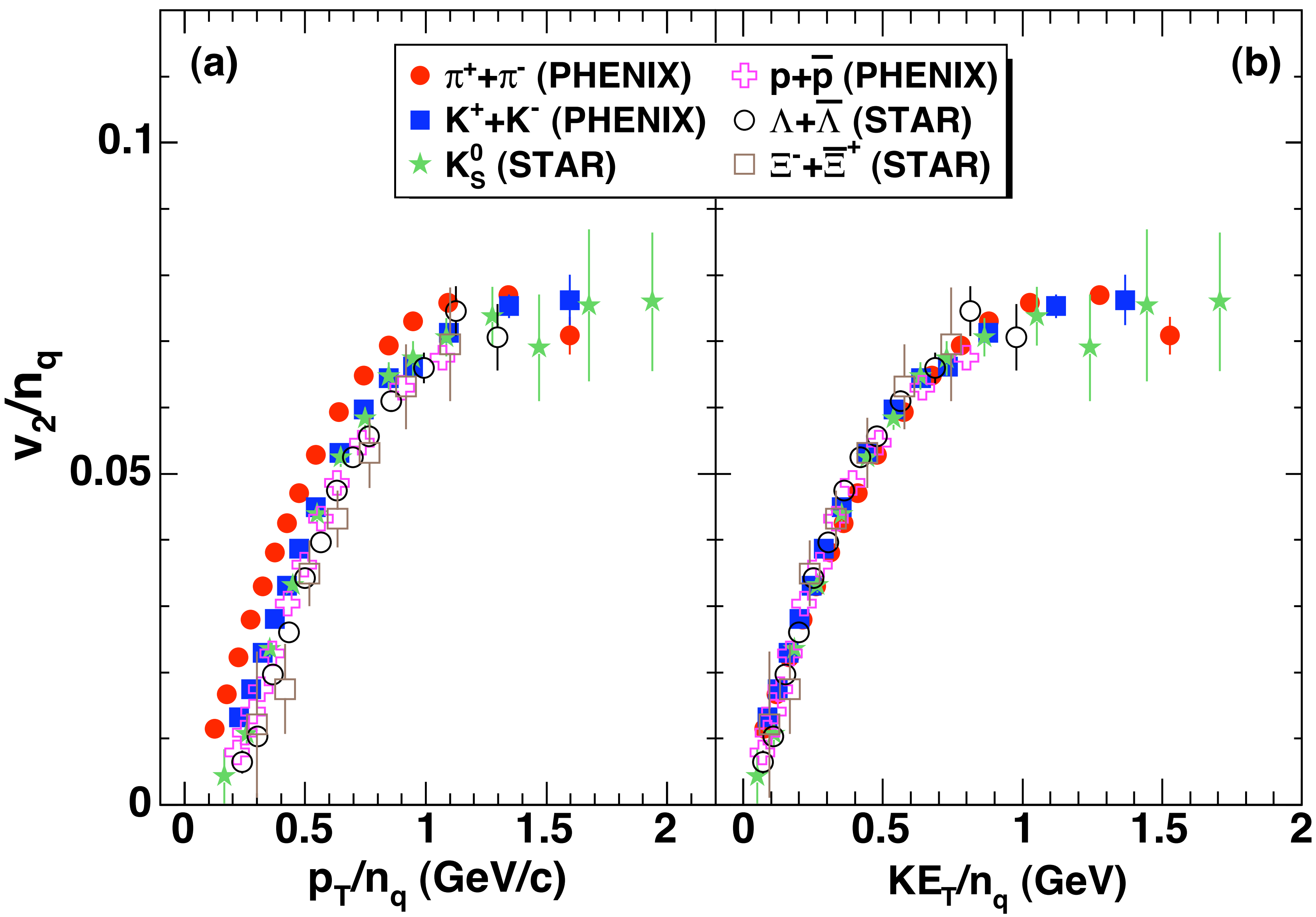
Hadron Rescattering

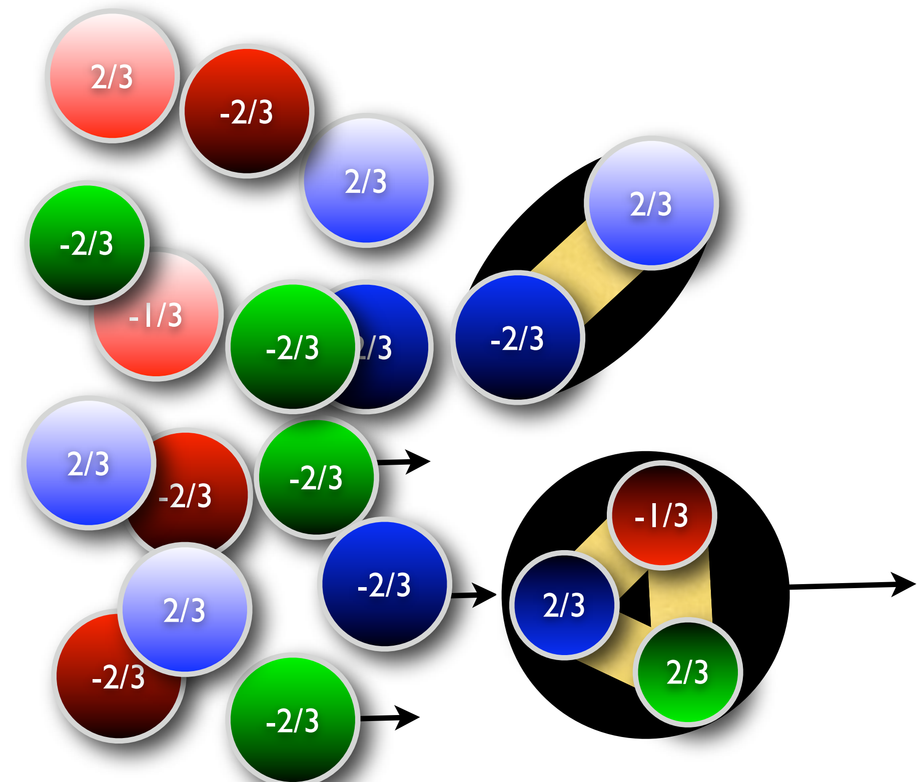
Thermal Freezeout &
Hadron decays



Constituent Quark Scaling

Phys.Rev.Lett.98:162301,2007



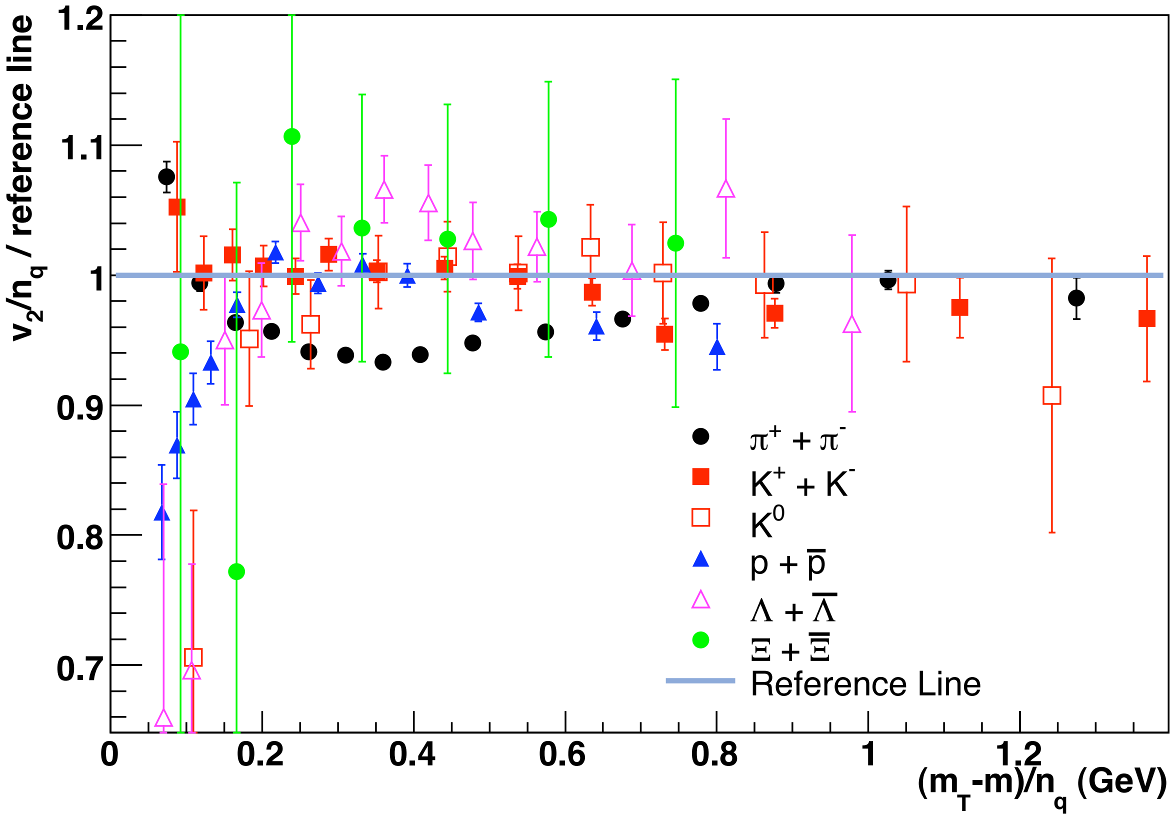


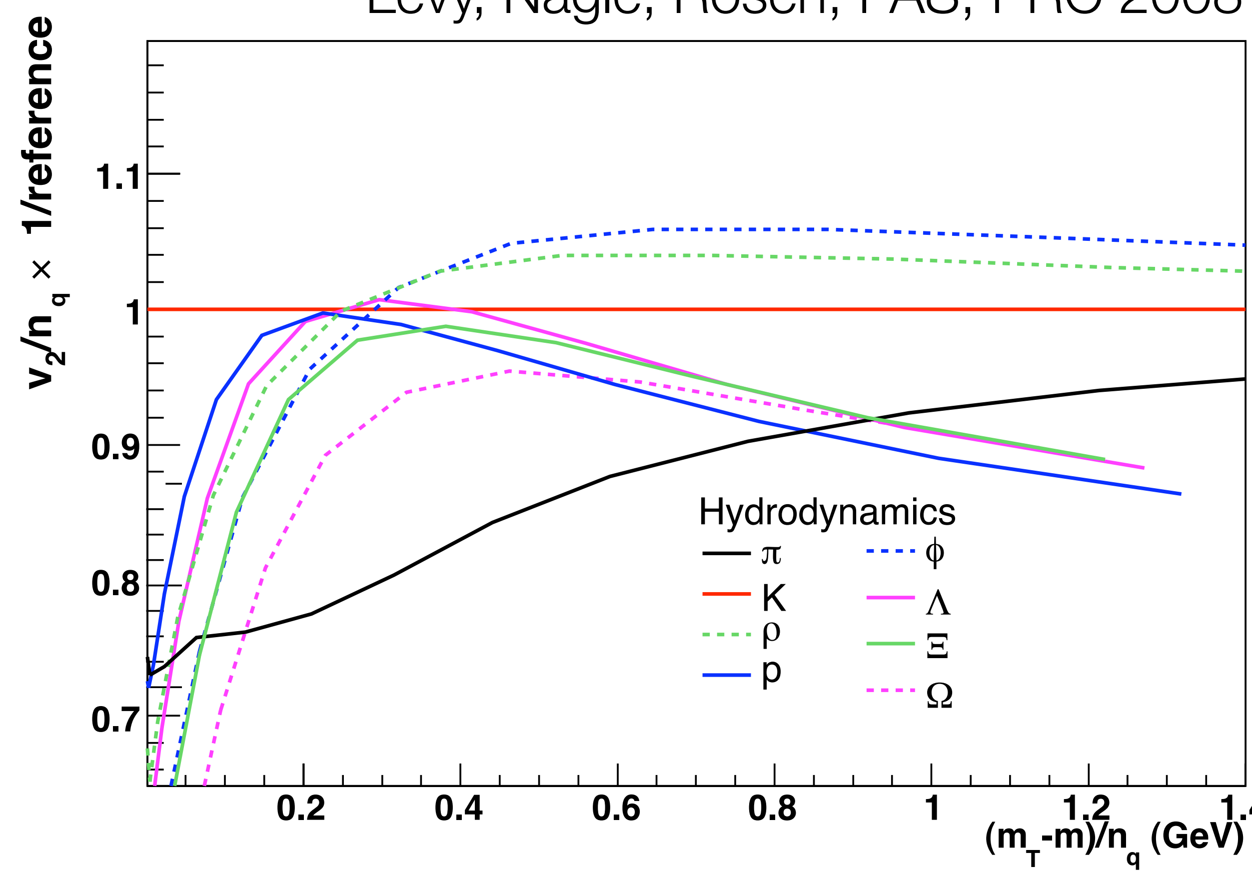
All particles flow as if frozen out from a flowing soup of constituent quarks

$$KE_T = m_T - m$$

Quasi-Particles in the sQGP

Levy, Nagle, Rosen, PAS, PRC 2008

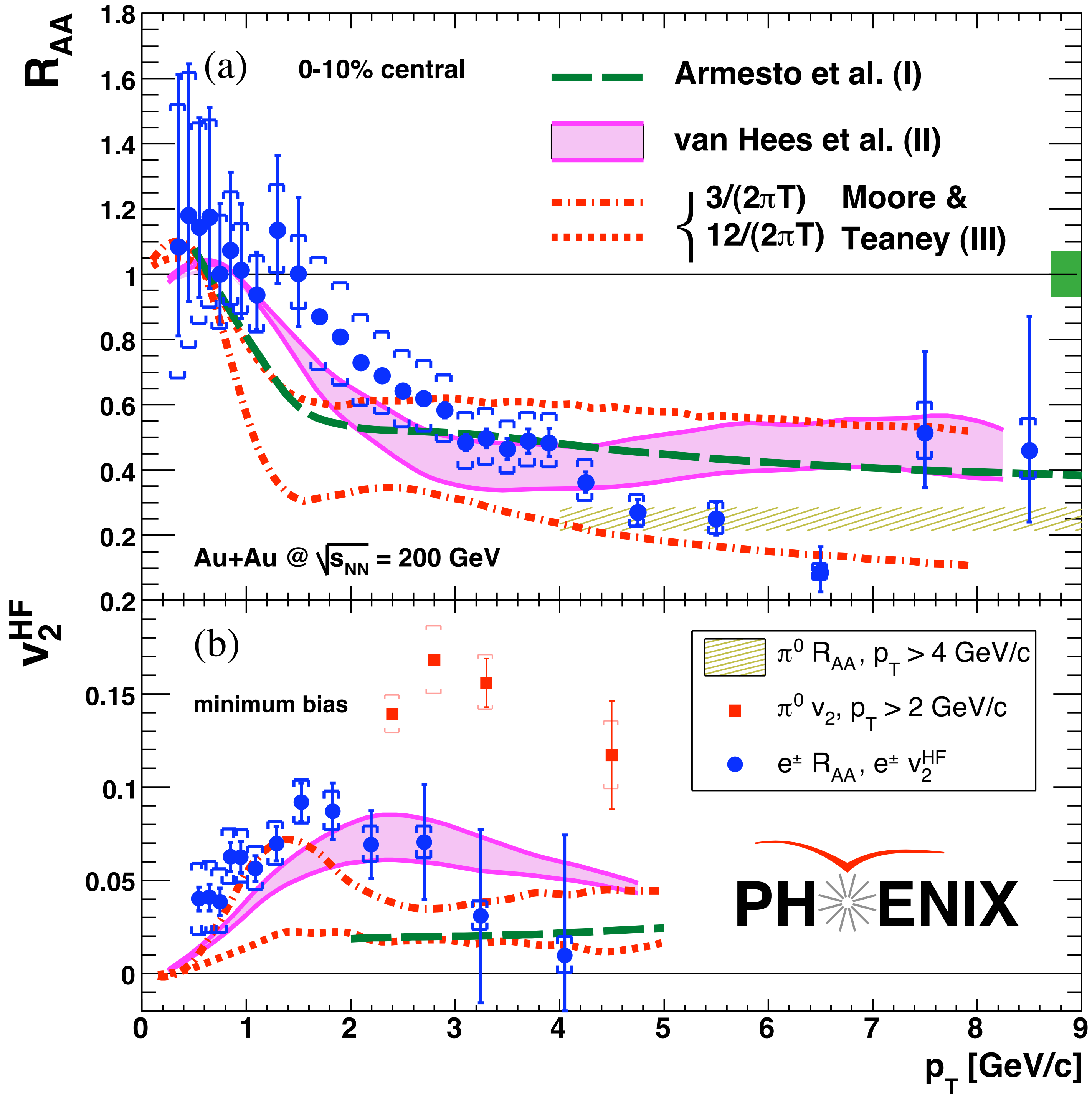




Data agree with n_q scaling substantially better than ideal hydro

"perfect fluid" ≠ good quasiparticles:
can we harmonize two scenarios?
(or give up on constituent quarks, or the perfect fluid...)

Direct Measurements of Viscosity: Heavy Flavor

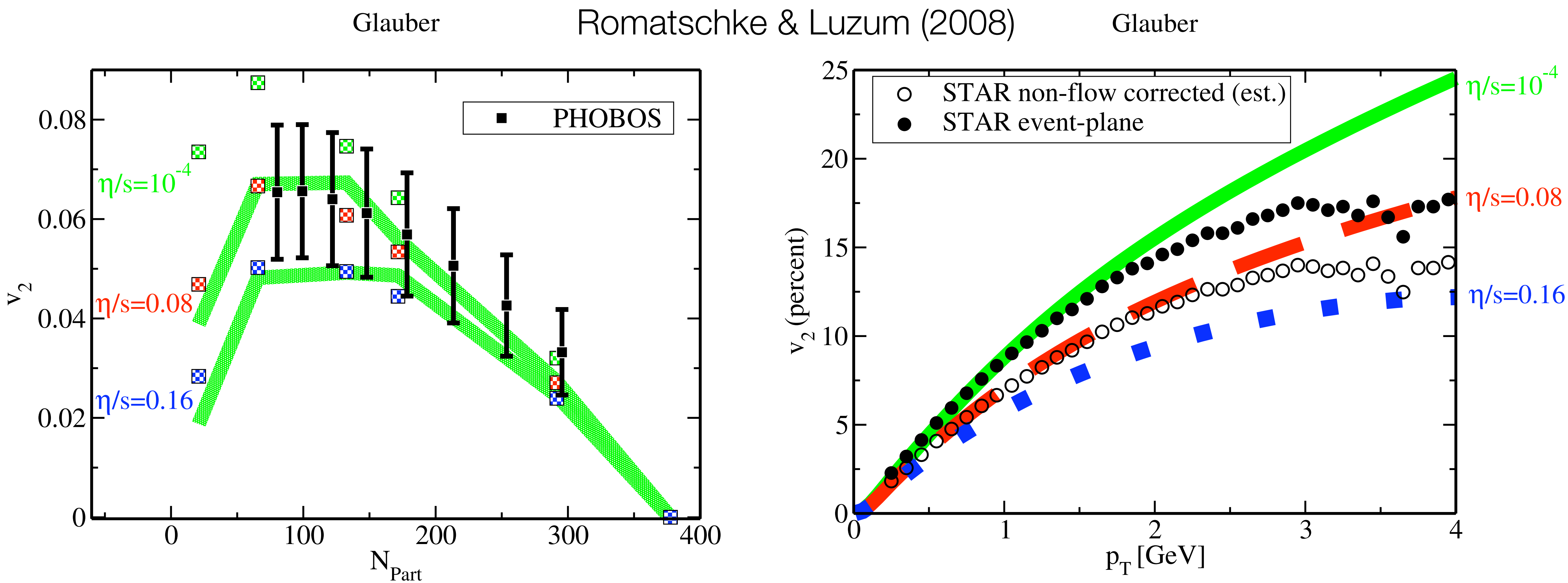


Charm suppression and flow (via non-photonic electrons) are correlated and reflect diffusion of heavy quark in medium (i.e. viscosity)

Models suggest non-zero viscosity, at or near AdS/CFT bound: challenge to quasi-particle interpretations of RHIC medium?

Viscous Hydrodynamics

Romatschke & Luzum (2008)



Recent advances in implementing viscous hydrodynamics

With Glauber initial conditions, RHIC data saturating viscosity bound (off by a factor of 2 in “Color Glass Condensate” approach)

Lessons from Soft Physics @ RHIC

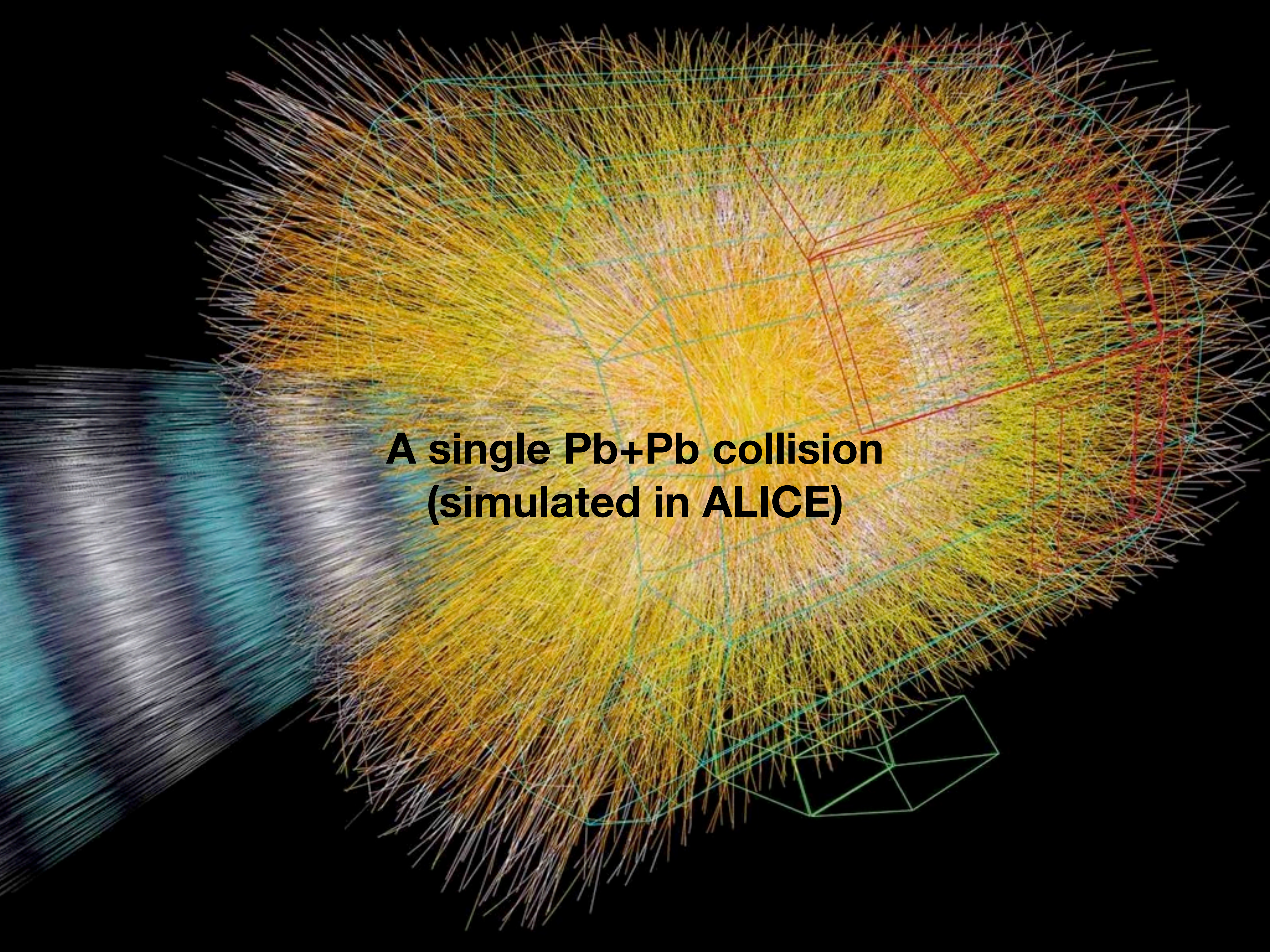
- **System is manifestly thermalized in final state**
  - Appears to freezeout at or near Hagedorn temperature
- **Hydro implies local thermalization in the initial state (and possibly presence of phase transition)**
  - System much hotter than T_H
- **No deviations in soft observables vs. rapidity, energy, size**
  - Extended longitudinal scaling ubiquitous in all systems
- **Viscosity appears to saturate bound from string theory**
  - How to harmonize with observation of constituent quark scaling, suggesting “quark” DOFs just before freezeout?

The Next Chapter: The LHC

CTEQ

Parameter	Units	Nominal	Early Beam
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	$cm^{-2}\ s^{-1}$	$1\ 10^{27}$	$5\ 10^{25}$
No. bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
β^*	m	0.5 (same as p)	1.0
Number of Pb ions/bunch		**$7\ 10^7$**	**$7\ 10^7$**
Transv. norm. RMS emittance	µm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	H	8, 4.5, 3	14, 7.5, 5.5

RHIC: 200 GeV/N Au+Au
LHC: 5500 GeV/N Pb+Pb
(14 TeV p+p)


A single Pb+Pb collision
(simulated in ALICE)

The Big Question: Thermalization at the LHC

CTEQ

<u>Does</u> the system still thermalize?

(or will running coupling increase viscous effects?)

What are the <u>conditions</u> (energy, density, size) for thermalization?

(Will p+p collisions clearly show it?)

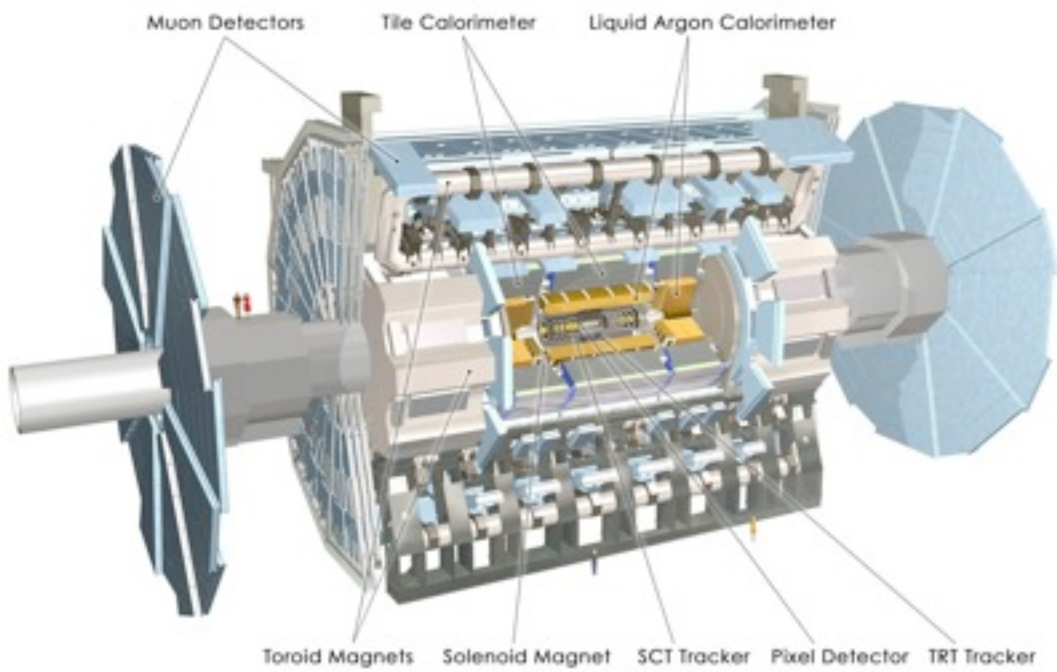
How <u>fast</u> does the system thermalize?

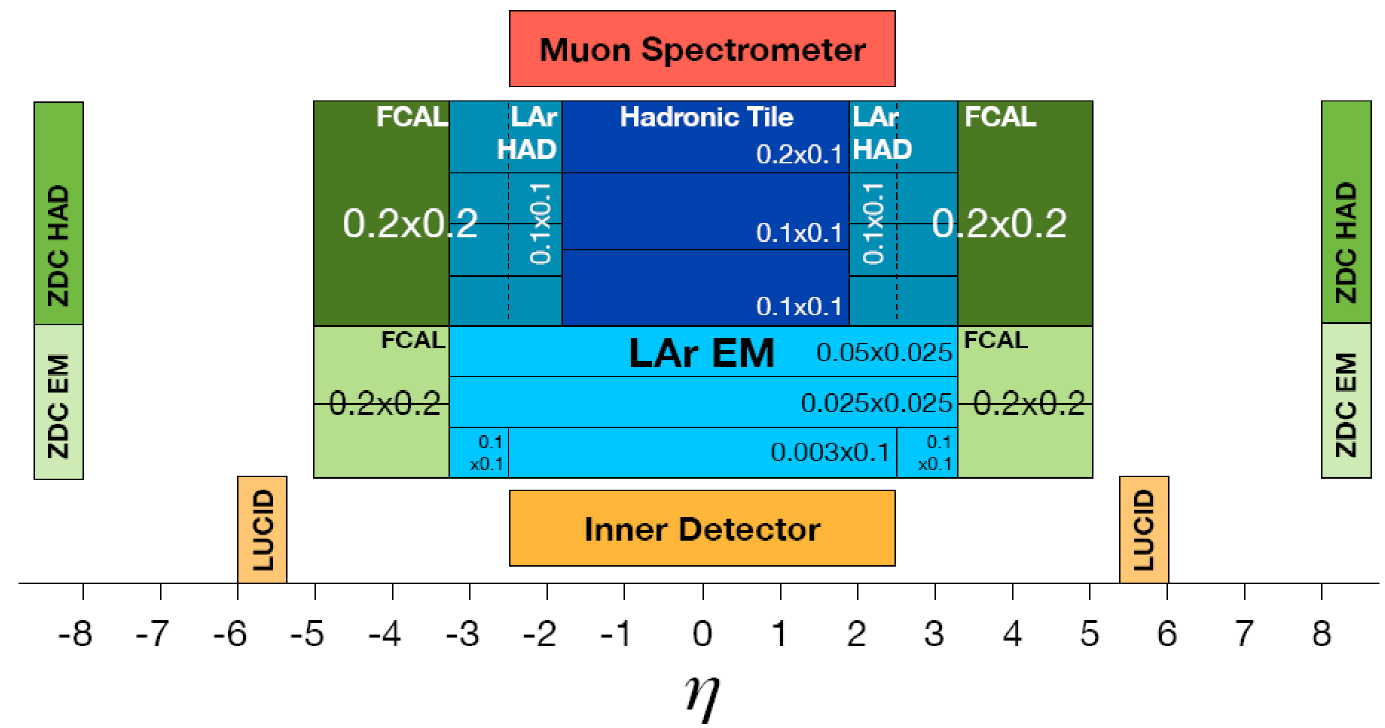
(initial longitudinal scale is 30x smaller!)

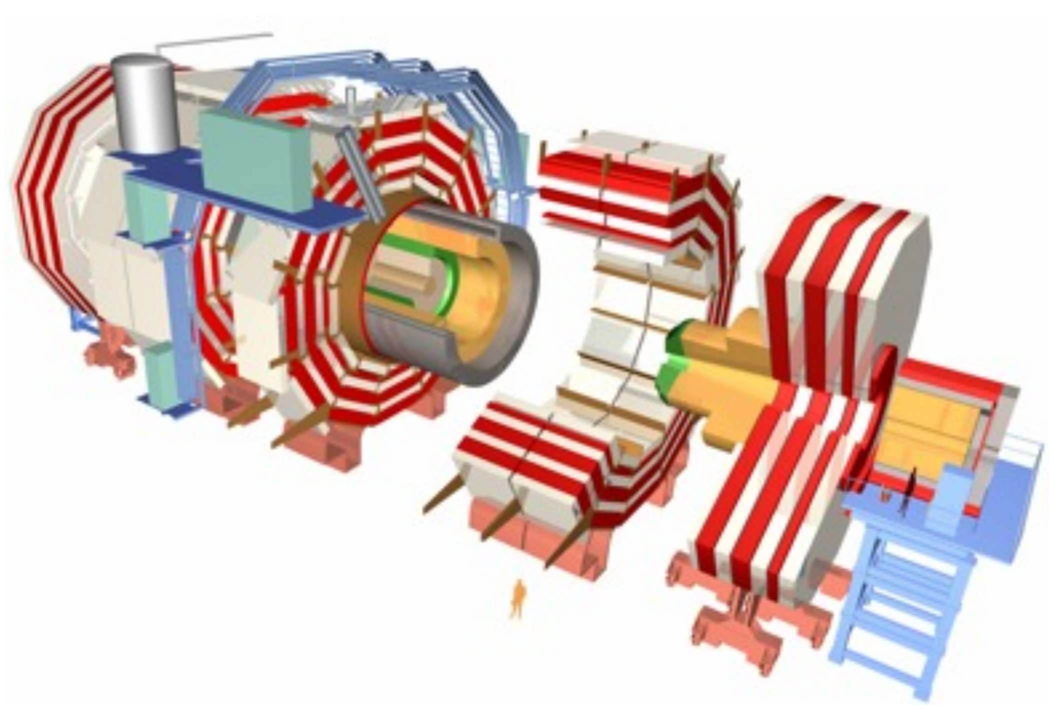
<u>What</u> thermalizes?

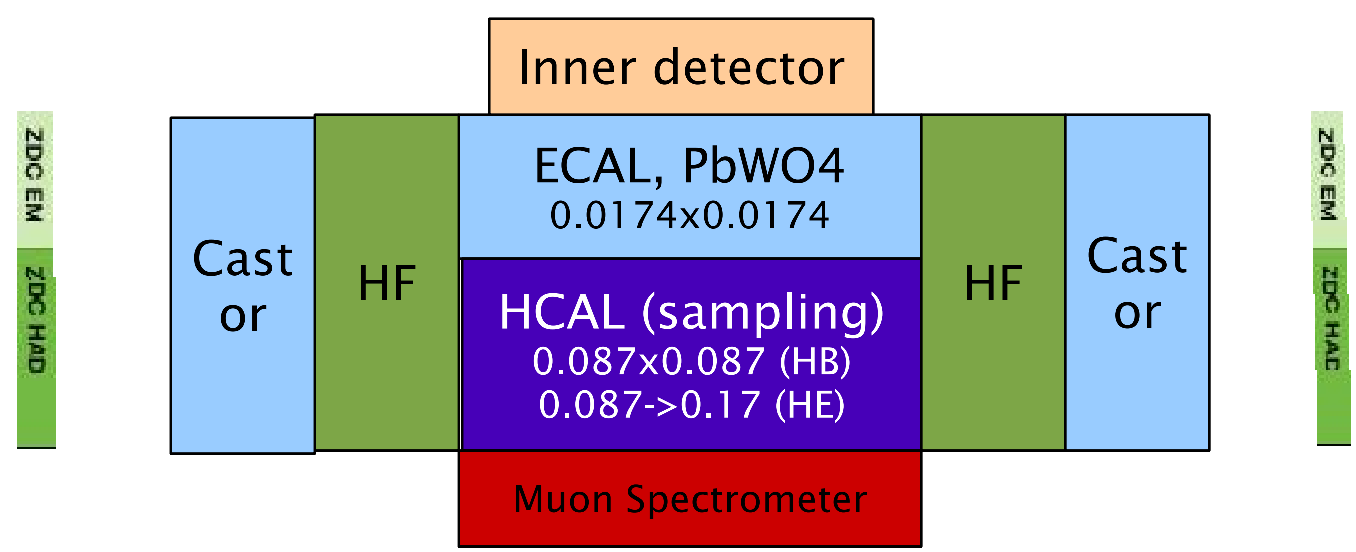
(Will degrees of freedom change?)

ATLAS & CMS @ LHC





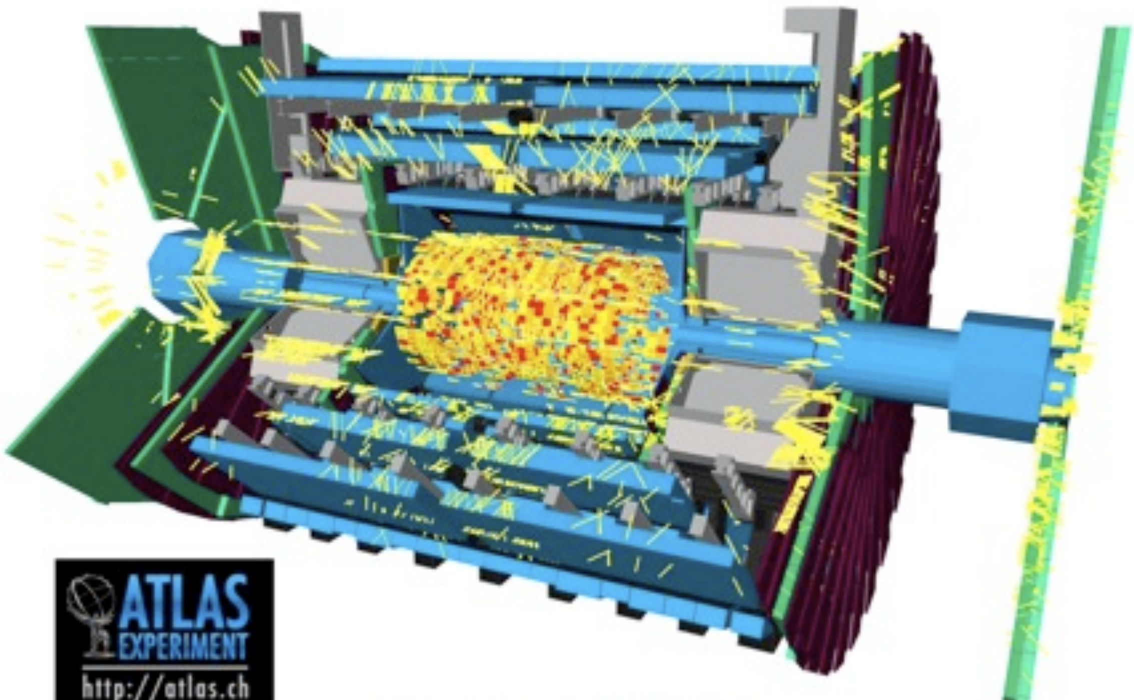




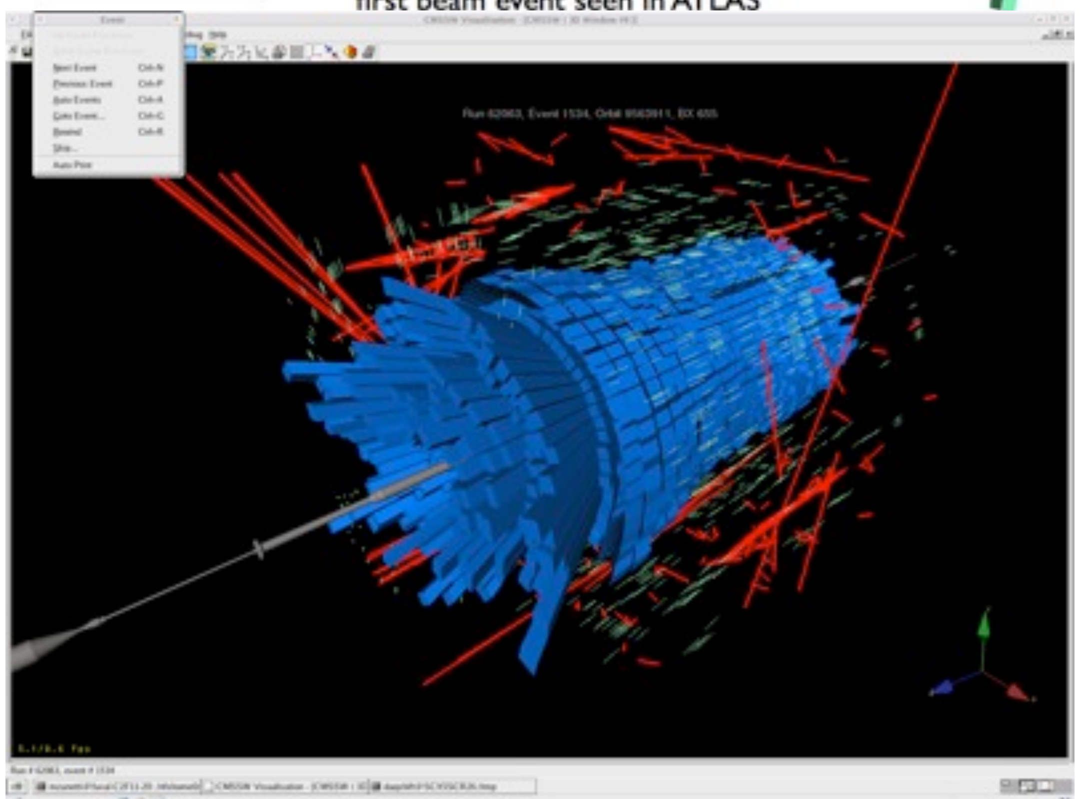
Enormous acceptance for soft physics

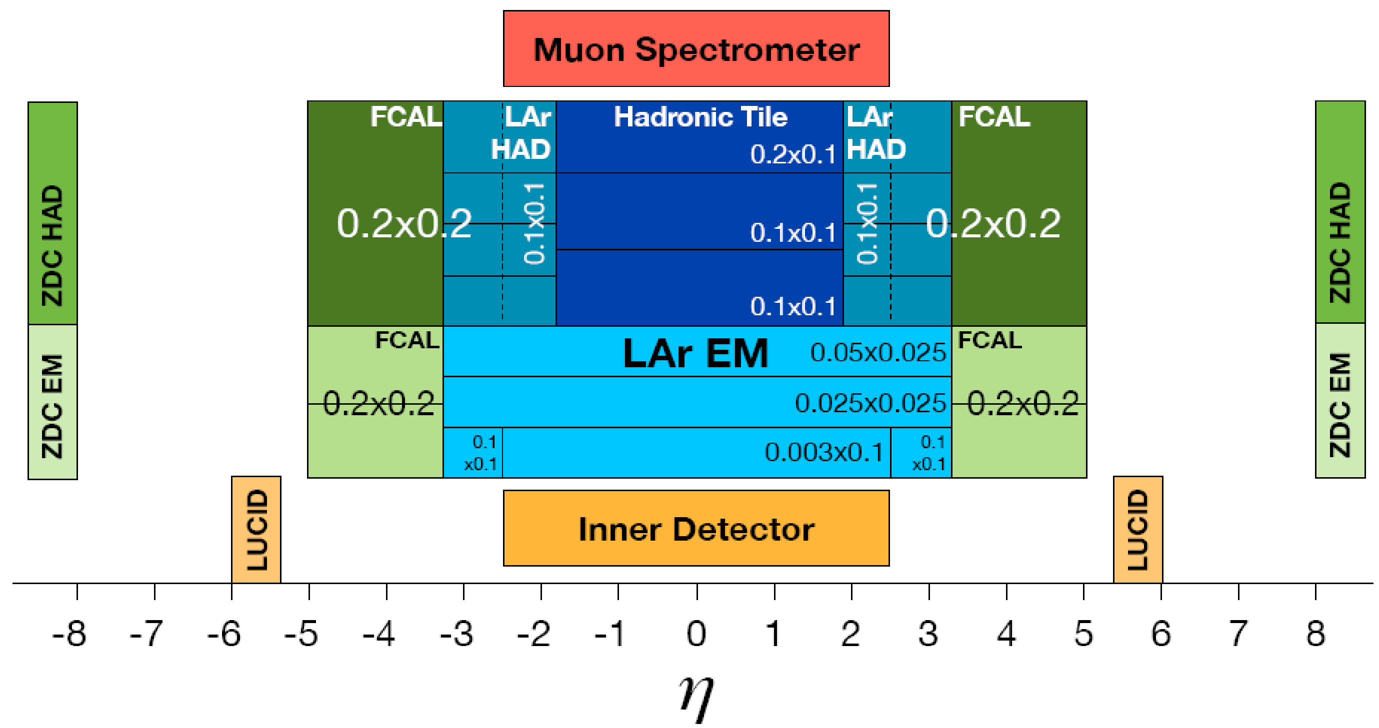
ATLAS & CMS @ LHC

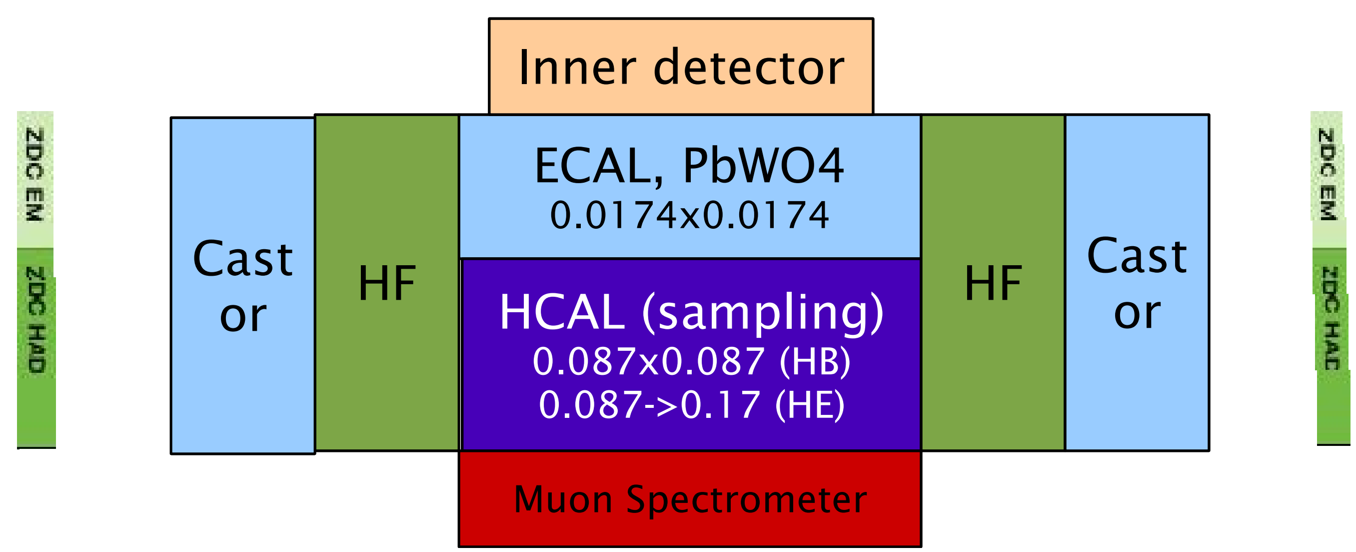
9/10/08!



first beam event seen in ATLAS



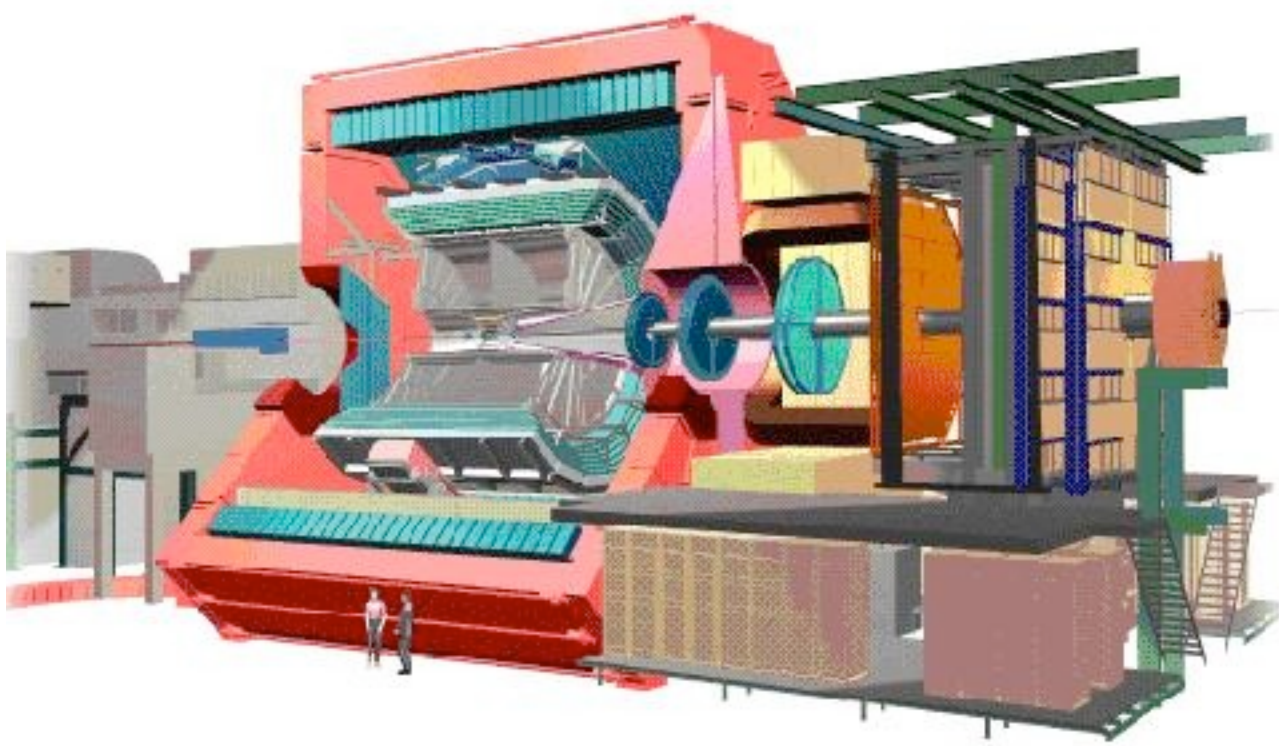


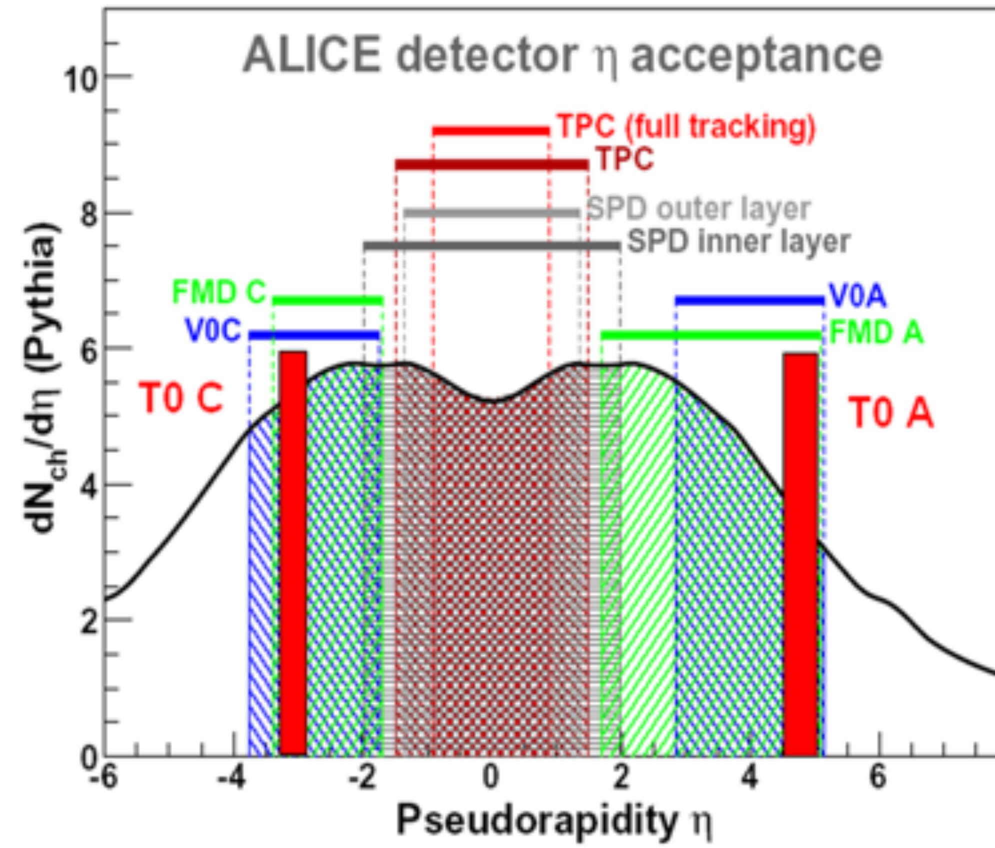


Enormous acceptance for soft physics

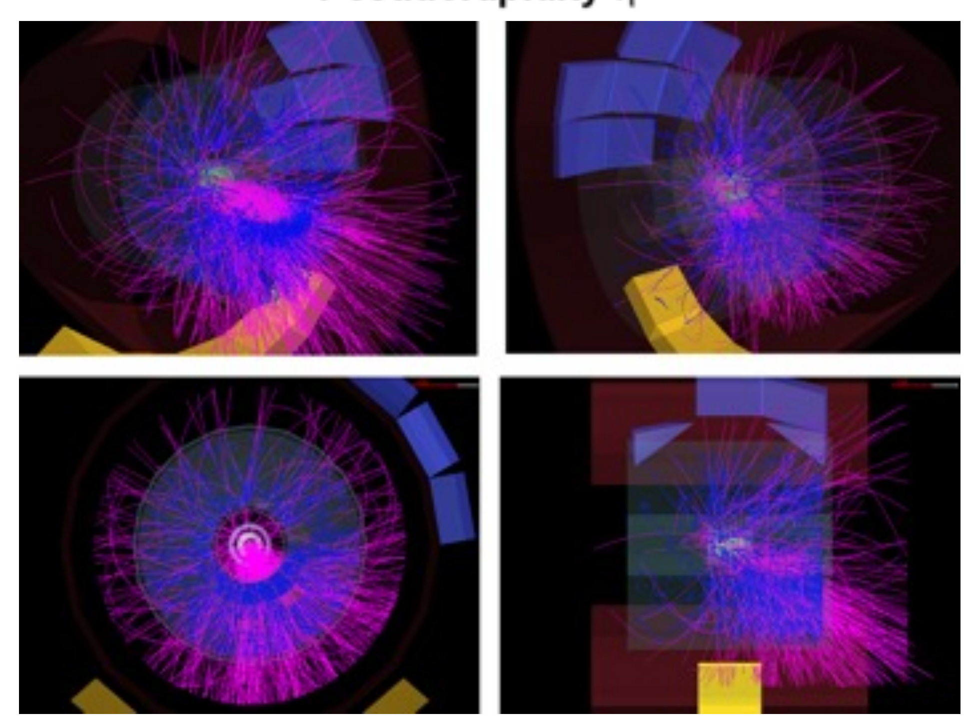
ALICE @ LHC

CTEQ

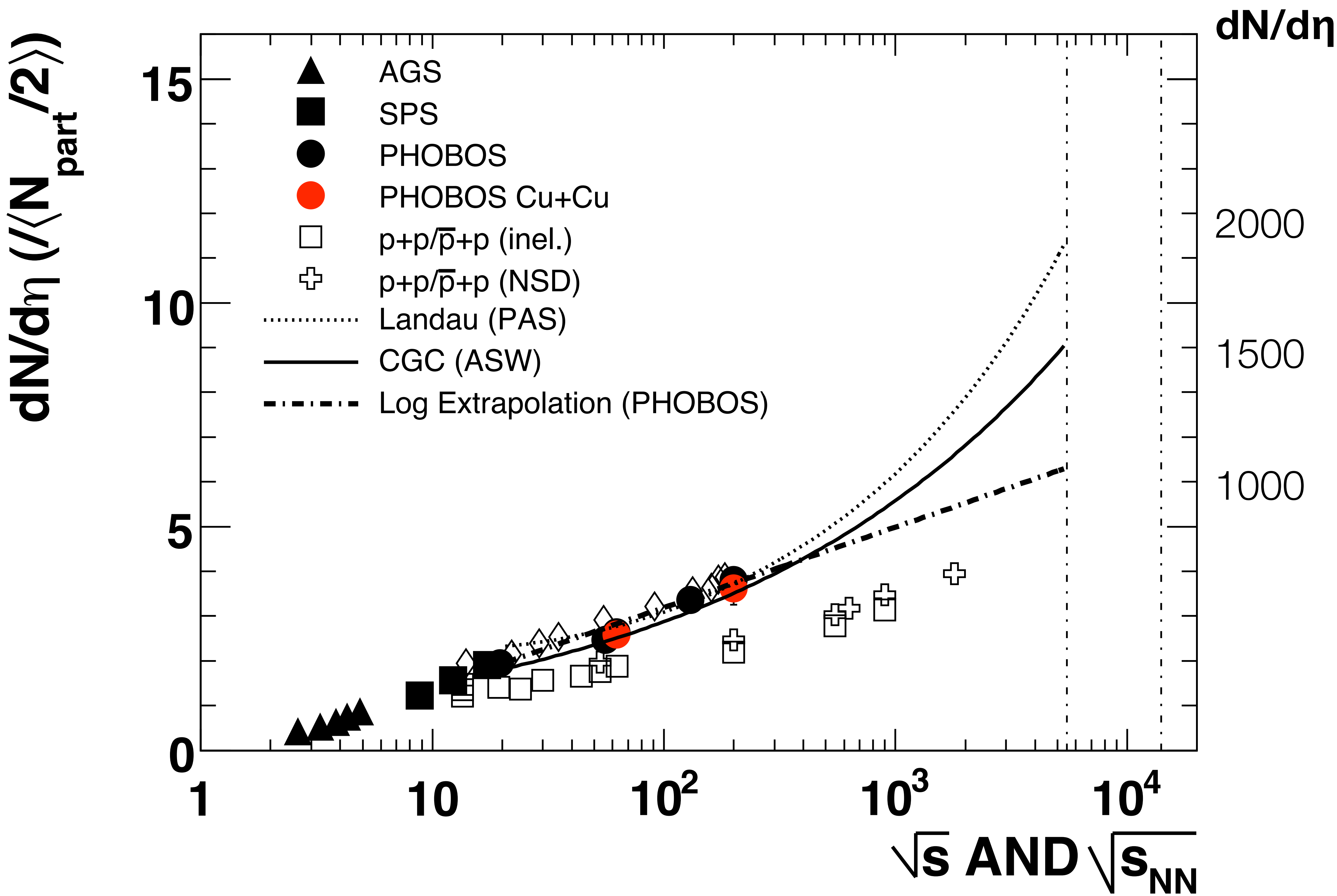




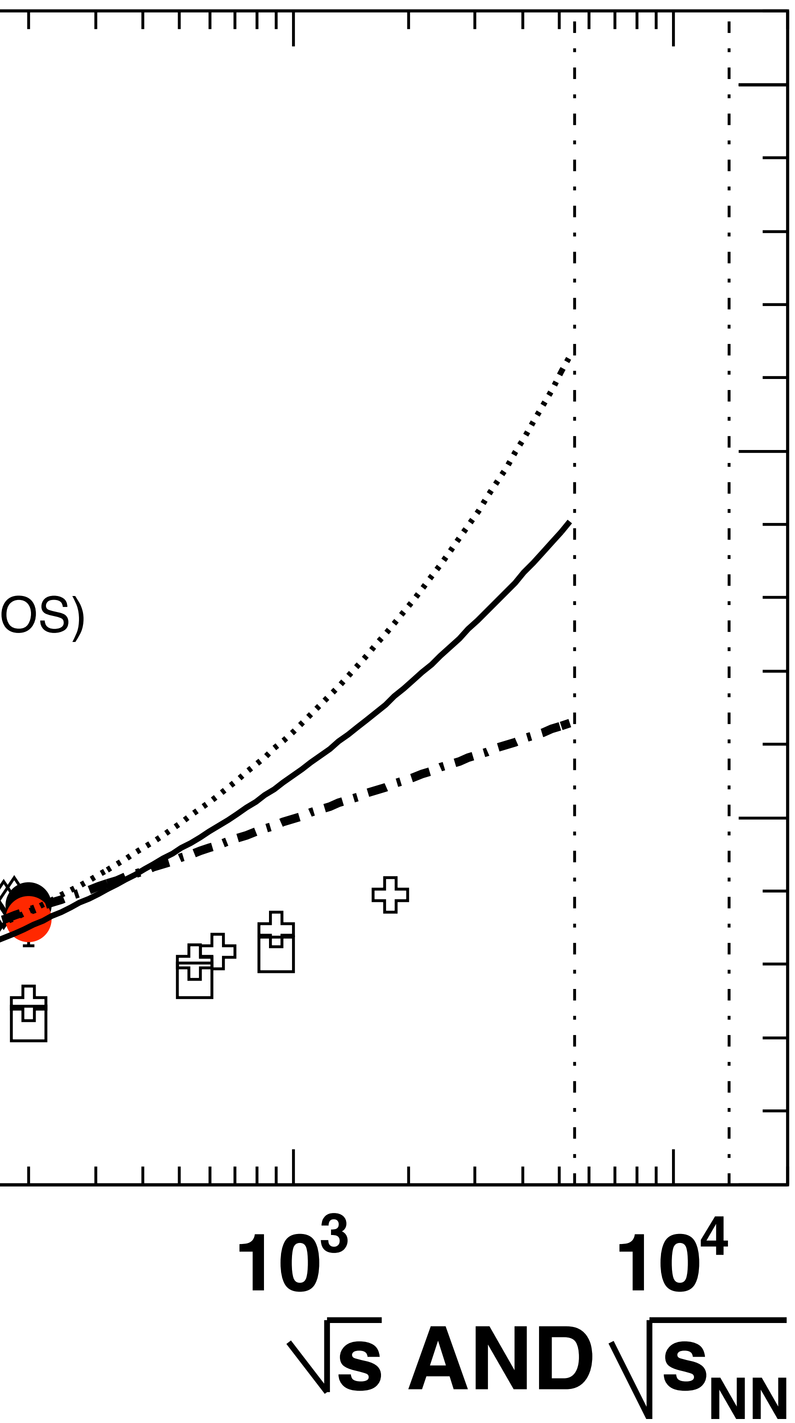
Optimized for tracking & PID
in high multiplicity
heavy ion events (TPC), with new
high p_T triggering abilities (EMCAL)



Predictions for the LHC: Multiplicity



Extrapolating to the LHC



Landau hydrodynamics: application of 1950's Fermi-Landau model & 1970's Carruther's approach

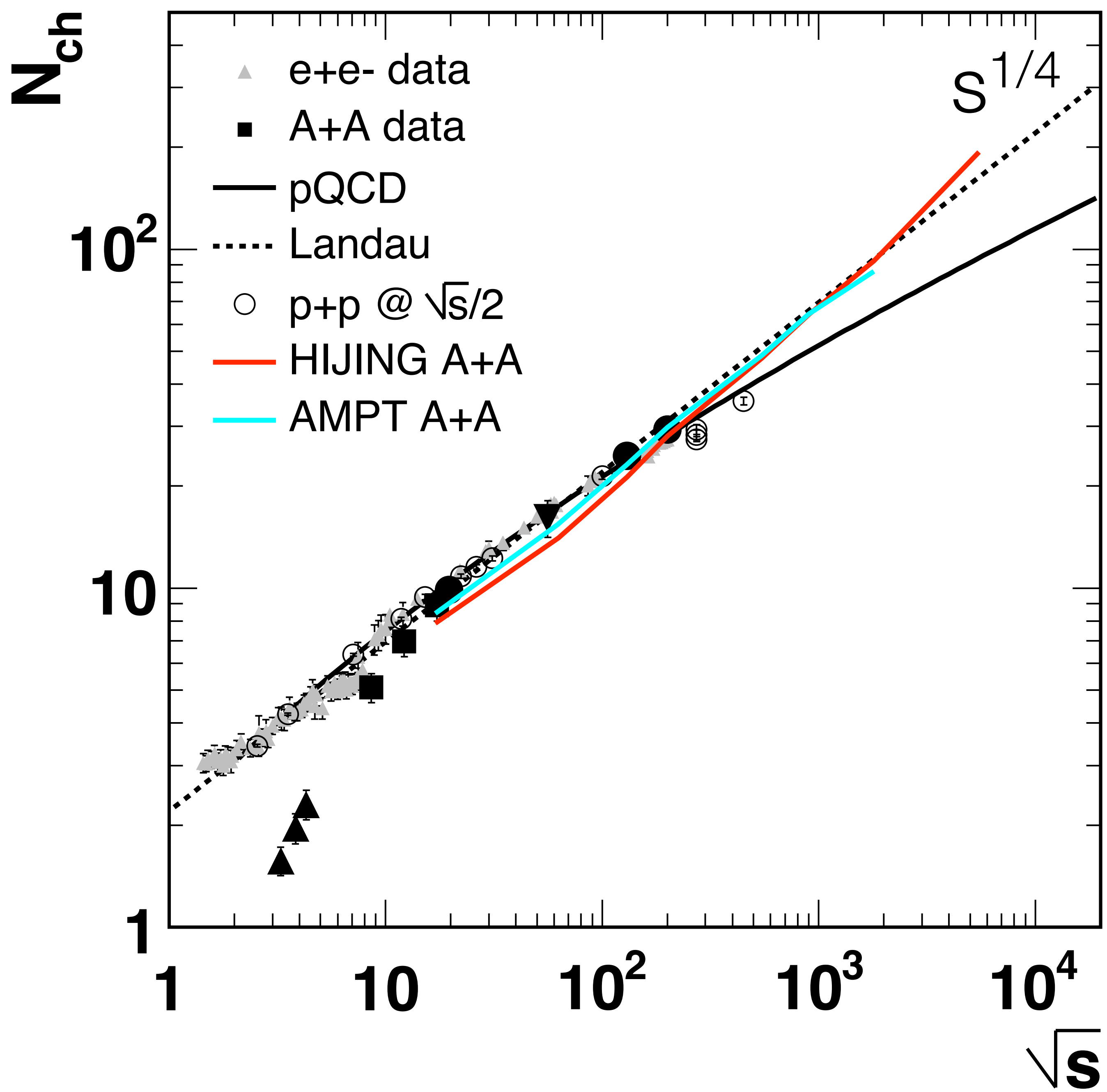
$$\frac{dN}{dy} = K s^{1/4} \frac{\exp(-y^2/2L)}{\sqrt{2\pi L}} \rightarrow \frac{s^{1/4}}{\sqrt{\ln(s)}} \qquad L = \ln\left[\frac{s}{4m_p^2}\right]$$

Color Glass Condensate:
QCD at *very* low x. involves parametrization of gluon PDF and simple hadronization model

$$\frac{dN}{d\eta} = K s^{\delta}$$

Logarithmic rise: assumption that current trends apply at larger energies

Total Multiplicity @ LHC using data & models



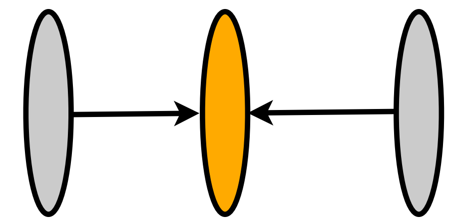
On a log-log plot, all data is approximately power-law

Where data exist, various models can approximate it: only the LHC provides test (unfortunately total yield is tough to measure!)

My favorite is Fermi-Landau (power law rise)

Fermi-Landau Model for Total Multiplicity

- **Assume complete thermalization in Lorentz-contracted volume**
  - Total energy scales as beam energy: $E = \sqrt{s}$
  - Total volume scales as $V = V_0/2m\sqrt{s}$
  - Energy density is *quadratic* in beam energy: $\varepsilon = E/V = (2m/V_0)s$



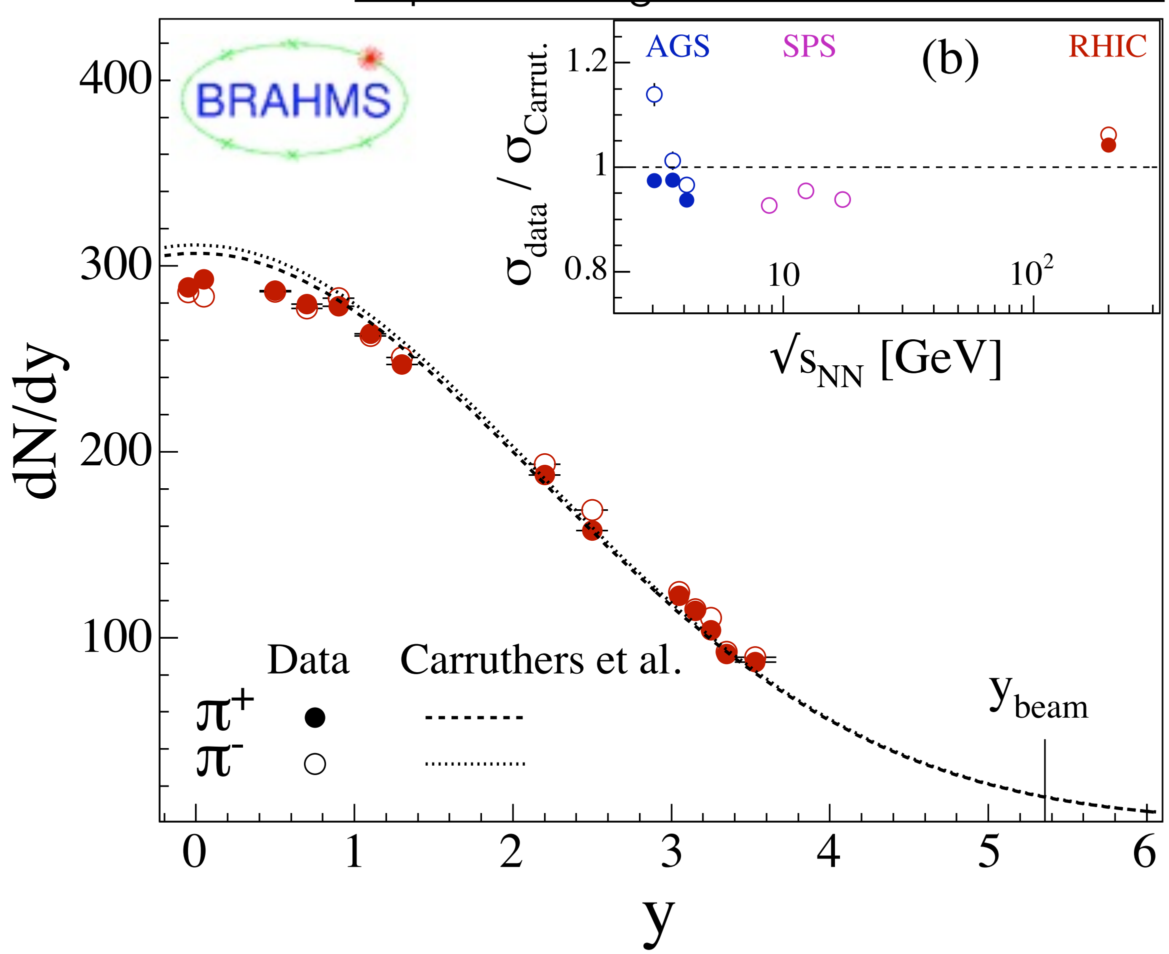
- **Blackbody radiation: $p = \varepsilon/d$ (d=# spatial dimensions, e.g. 3)**
  - Related to tracelessness of stress-energy tensor
  - When d=3, entropy density $\sigma \sim \varepsilon^{3/4}$ (or d/(d+1))

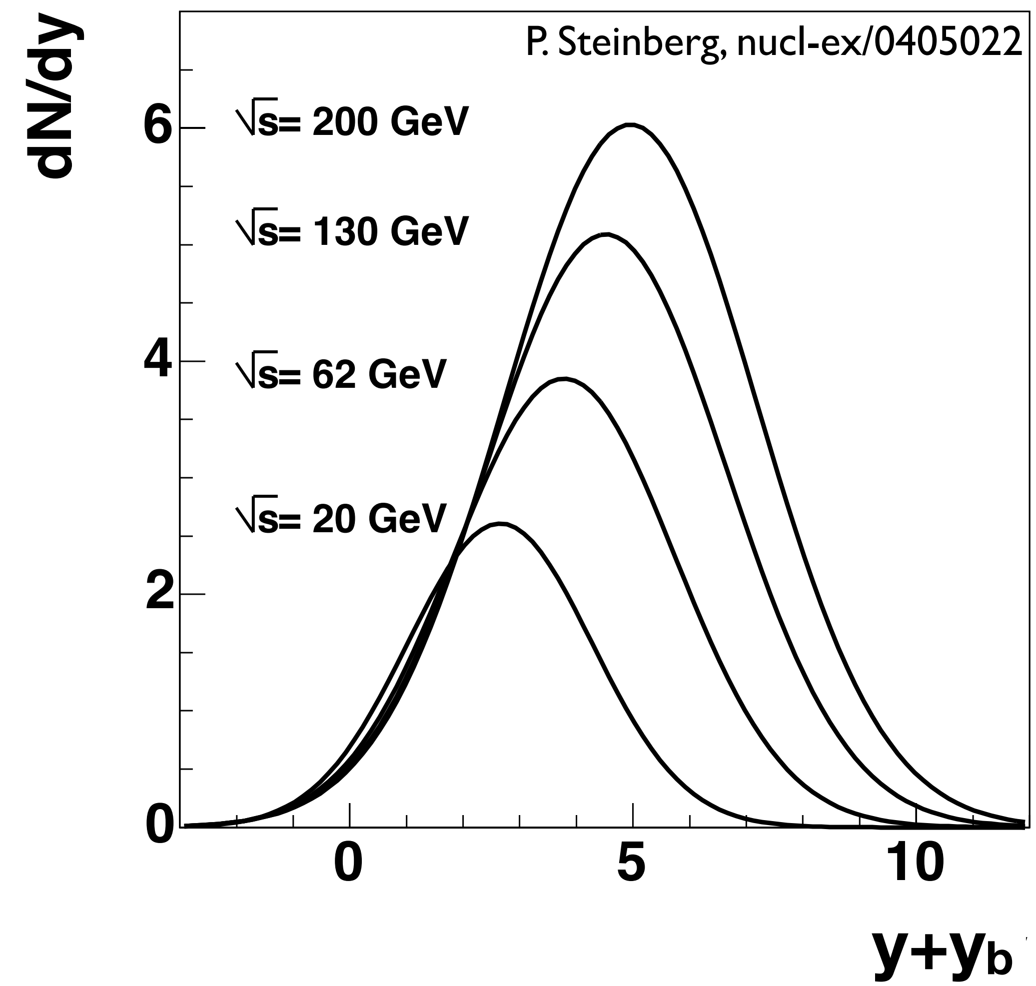
$$T_{\mu\nu} = \left\{ \begin{array}{cccc} \epsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{array} \right\}$$

- **Total entropy $S = \sigma V \sim s^{3/4}/s^{1/2} \sim s^{1/4} = \sqrt{E}$ (or $s^{0.5(d-1)/(d+1)}$)**
  - Total multiplicity assumed linear with N_{tot}
  - N_{tot} assumed linear with N_{ch}
- **Putting it all together: $N_{ch} \sim s^{1/4}$**

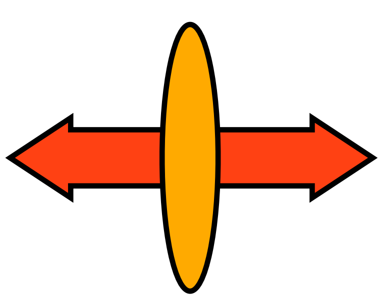
Gaussian Rapidity Distributions

http://arxiv.org/abs/nucl-ex/0403050v2



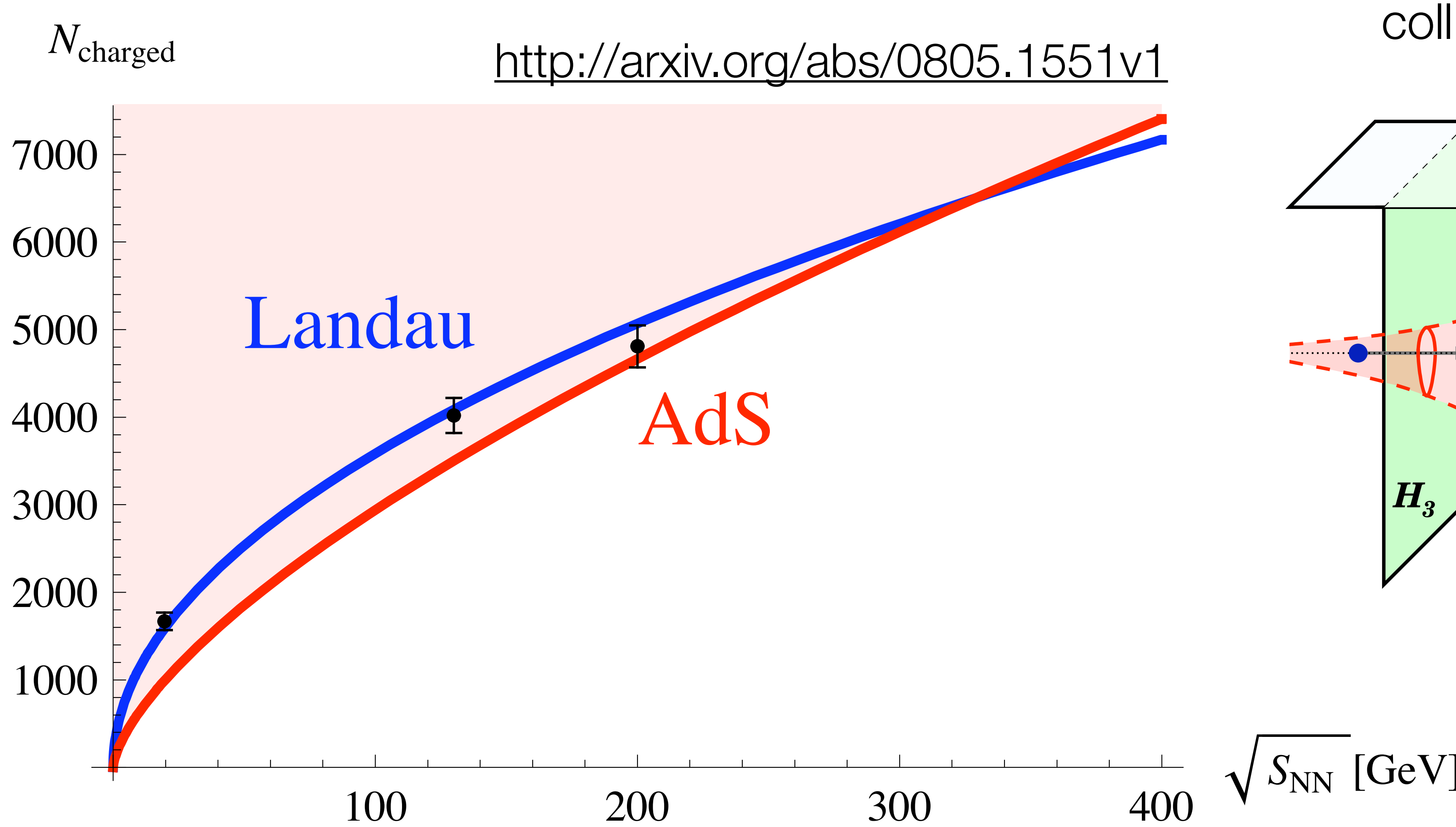


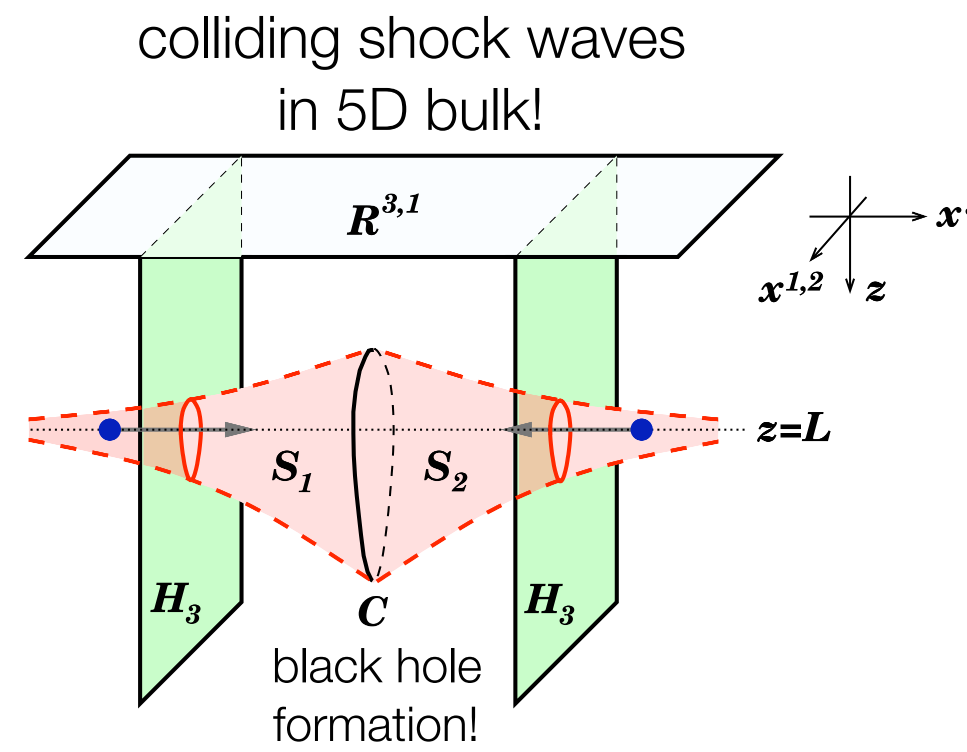
Hydrodynamics maps Lorentz contracted pancake into a Gaussian in rapidity with variance σ^2=ln(s/m$_P$). Agrees with data on dN/dy and naturally produces longitudinal scaling seen in data (all of it...)



Total Multiplicity from AdS/CFT

http://arxiv.org/abs/0805.1551v1





AdS/CFT now in the game: using colliding shock waves, and calculating area of trapped surface, Gubser et al predict $N_{ch} \sim s^{1/3}$

Substantially faster than measured rise of multiplicity,
1/3 implies d=5: true by construction?! Anyway, we'll test!

Soft Observables: From RHIC to LHC

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- **In the soft sector, RHIC has observed:**
  - **Elliptic flow** suggesting early thermalization (near perfect fluid)
  - **Extended longitudinal scaling** (trivial or deep?)
  - Intriguing **connections to elementary systems**
  - **Statistical** (& **constituent quark**) freezeout
- **Empirical and theoretical trends have emerged from the extensive data set, requiring testing at the LHC**
  - "**Day 1**" measurements in 2009 (p+p) and 2010 (A+A)
  - Lots will be learned very quickly -- stay tuned!
- **The collider era of heavy ion physics is upon us!**
  - We need all the help we can get to understand what we see

Help Wanted (Lattice? AdS/CFT?)

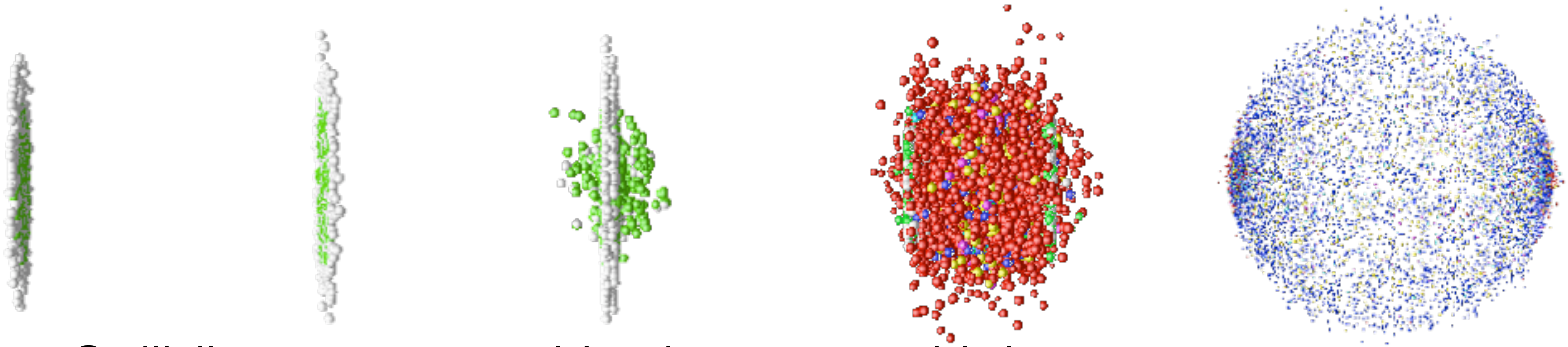
- **Even if prediction of η/s is "true": still lots to do**
- **Strongly-coupled sector of QCD is a real challenge**
  - Lattice is a powerful technique, but it requires analysis and interpretation
  - Data is simpler than expected, and thus more complicated to explain
- **Many basic properties of baryon still not understood: how do soft interactions proceed?**
  - Is there a fundamental (& simple) way to understand hadron structure?
  - pQCD works for jets, etc., but is inapplicable for small momentum transfers
  - What are colliding shock waves on gauge theory side, as interaction occurs?
- **How & when does thermalization occur?**
  - Again, describing system as a black hole doesn't explain the formation of the black hole
  - Attempts have been made (e.g. Shuryak, Kovchegov, Nastase), but have not yet led to novel predictions etc.

Heavy Ion Collisions: Hard Probes

Peter Steinberg
Brookhaven National Laboratory
Upton, NY

CTEQ Summer School
July 2, 2009
Madison, WI, USA

The promise of hard probes



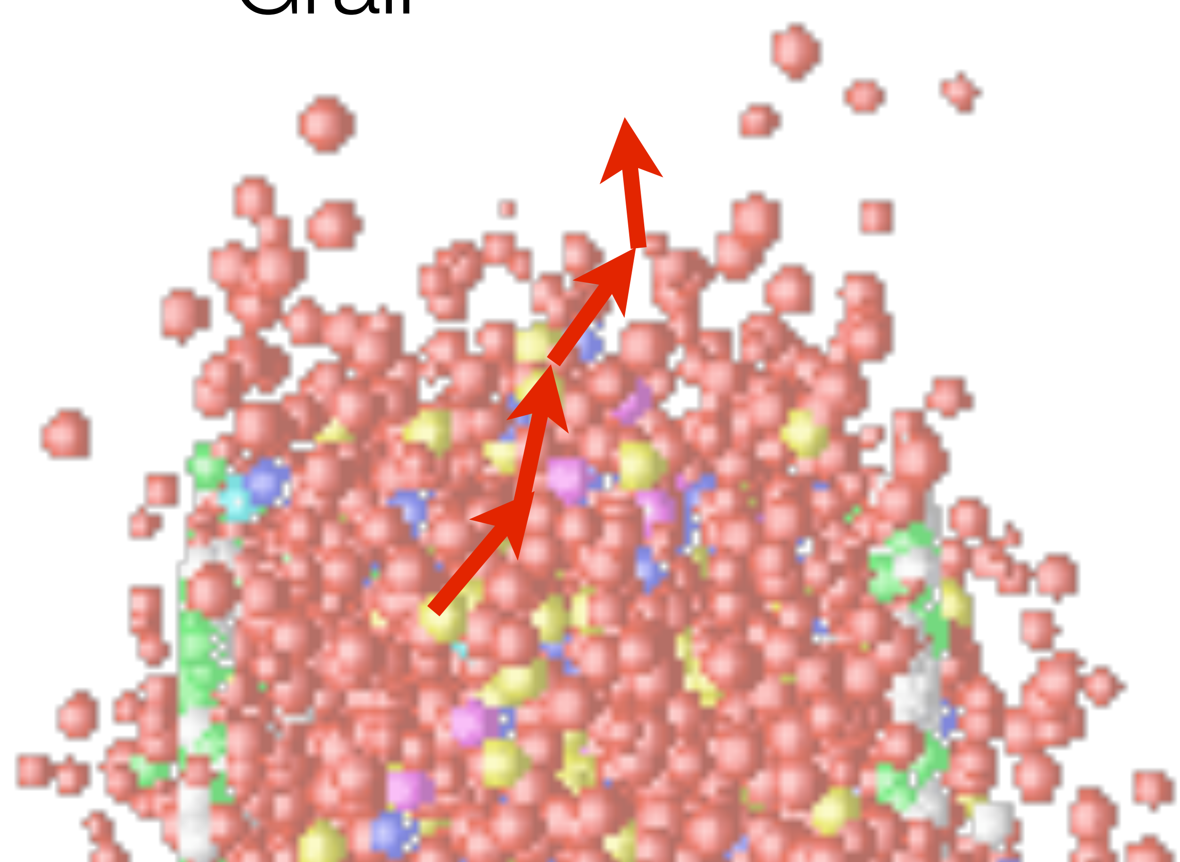
Colliding nuclei

Hard scattering

Holy Grail

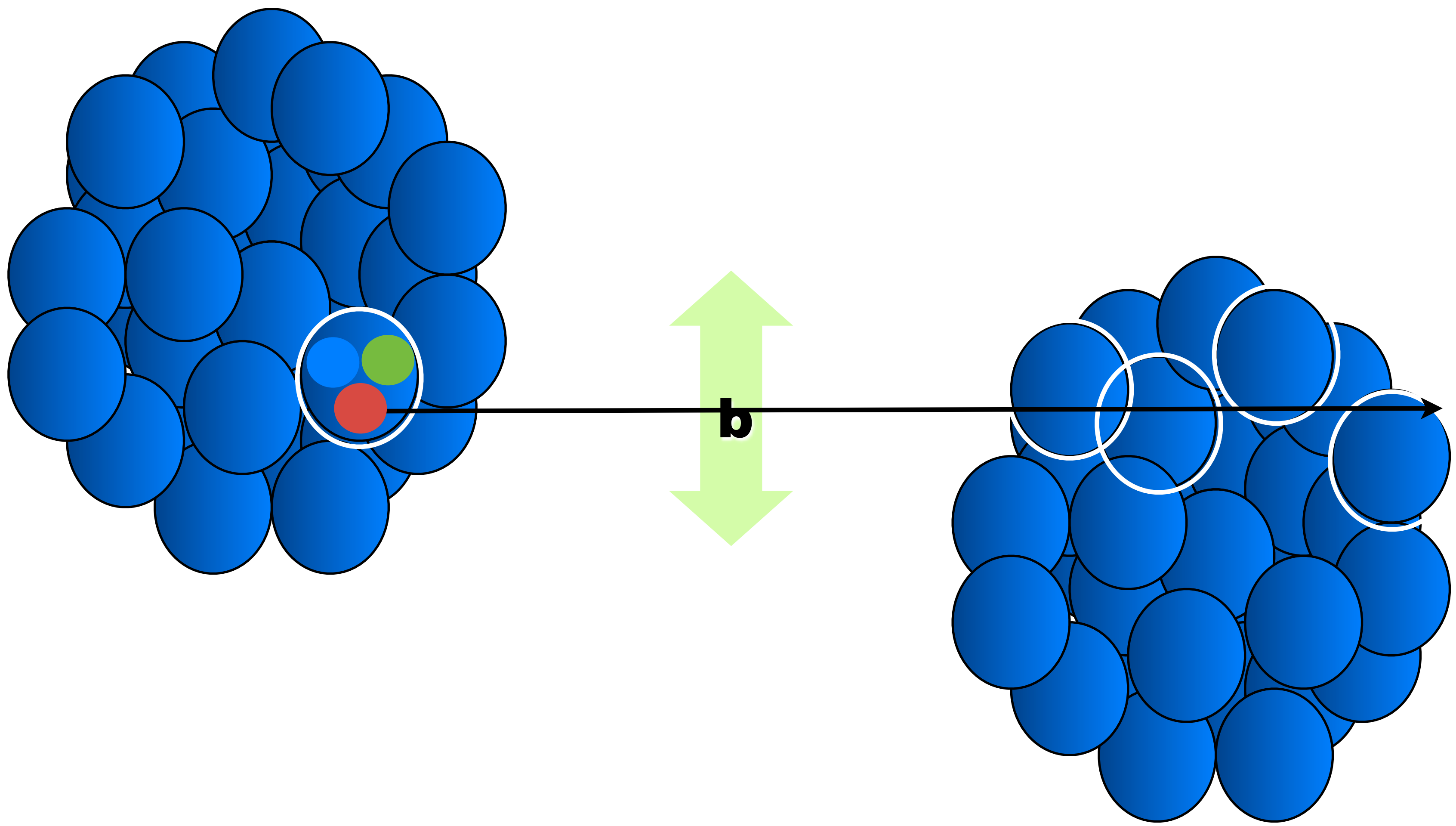
Final hadrons

To understand the microscopic properties of the sQGP, need a well-defined “probe” that can scatter off of its constituents



Participants vs. Collisions

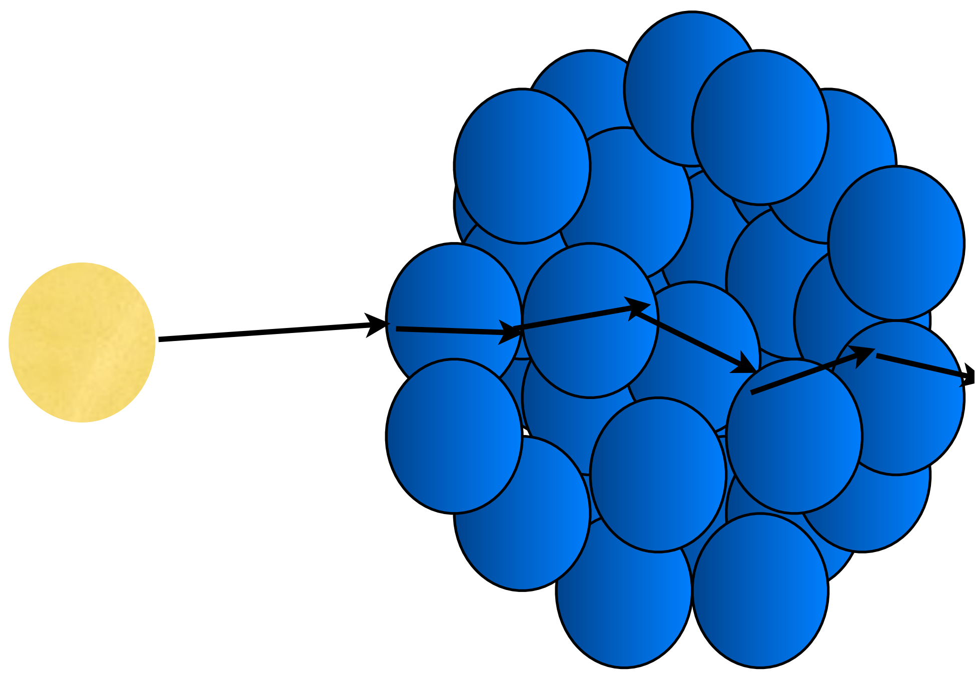
CTEQ

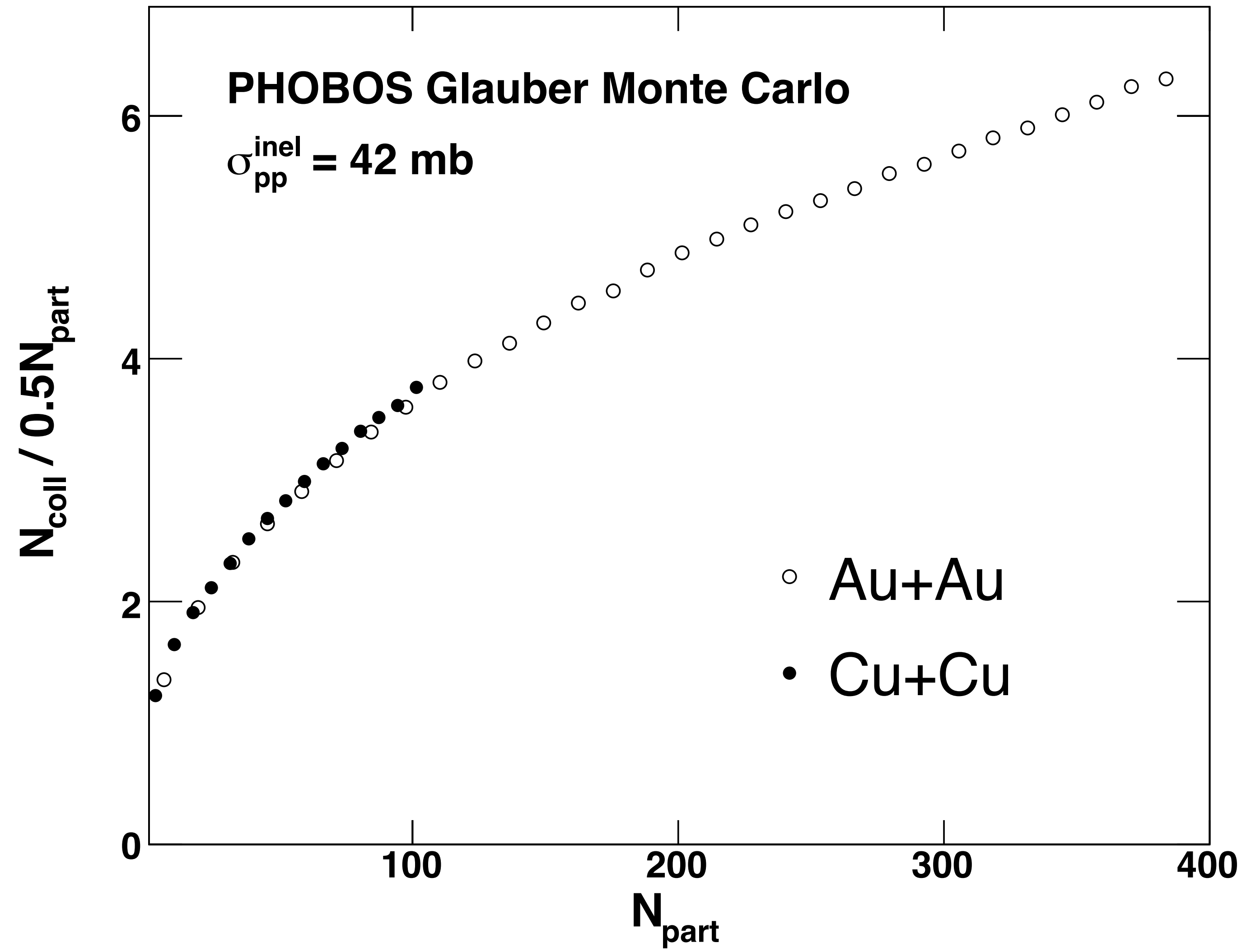


In principle, rates of hard processes should be sensitive to the "microscopic" structure, N_{coll}, iff pQCD factorization holds true in A+A

Participants vs. Collisions

CTEQ





The number of binary collisions scales as $\sim N_{part}^{4/3}$.

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

Extrapolating hard processes to A+A

CTEQ

A+A luminosity | HI total cross section | # of binary subcollisions (Glauber!) | yield in proton-proton

what you measure in Pb+Pb

$$N^X_{A+A} = \mathcal{L}\sigma_{A+A}\langle N_{coll}\rangle N_{p+p}$$

$$= \mathcal{L}\sigma_{A+A}\langle N_{coll}\rangle \frac{\sigma^X_{p+p}}{\sigma^{tot}_{p+p}}$$

ratio of subprocess to total

$$= \mathcal{L}\frac{\sigma_{A+A}}{\sigma^{tot}_{p+p}}\langle N_{coll}\rangle \sigma^X_{p+p}$$

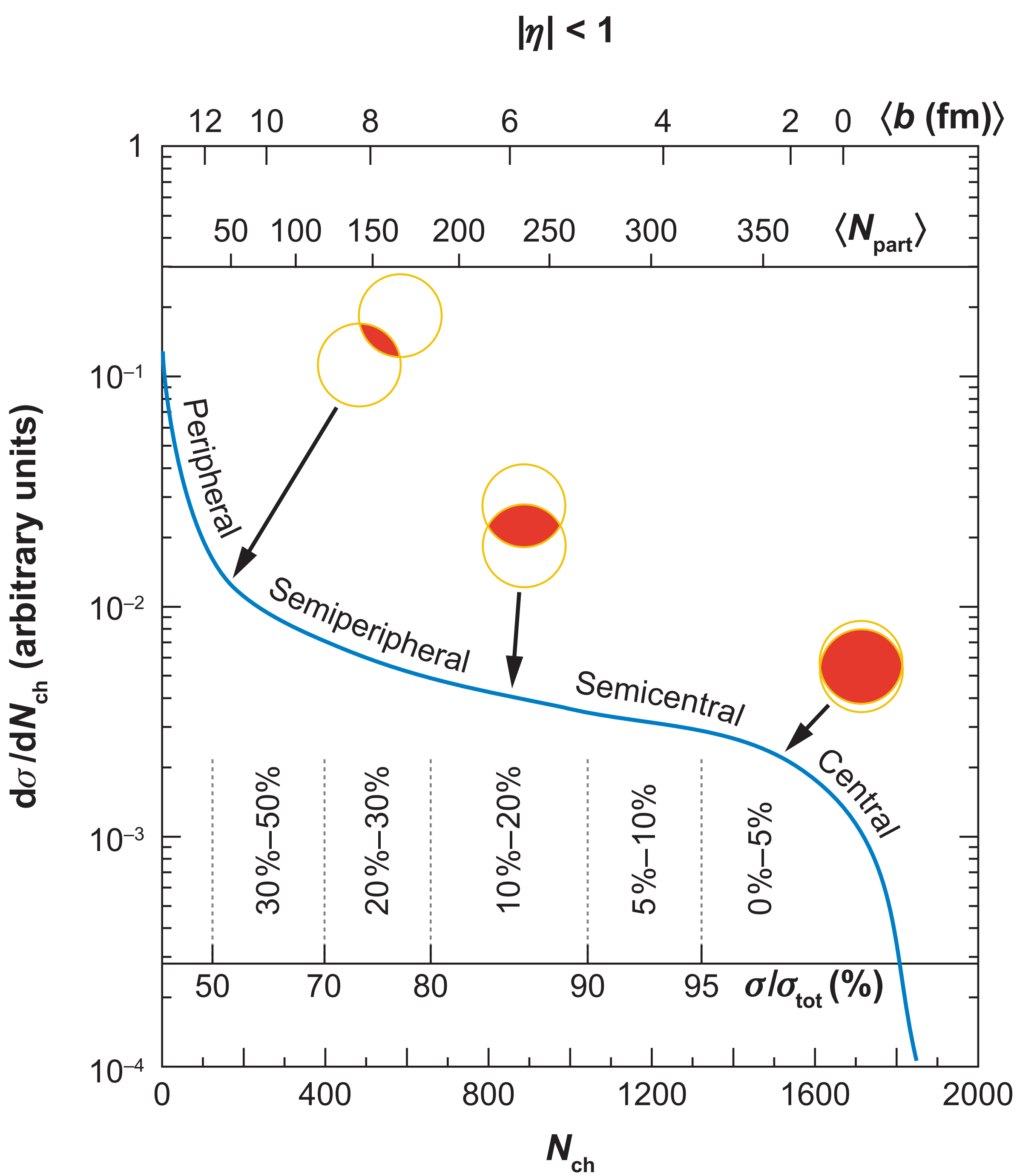
results from p+p reference

$$= \mathcal{L}(nb^{-1})A^2\sigma^X_{p+p}(nb)$$

pocket formula!

10^4 increase in "cross section" (but 10^7 decrease in $\mathcal{L}$)

Estimating Centrality



Any quantity which varies monotonically with impact parameter can be used to get a data-driven estimate of

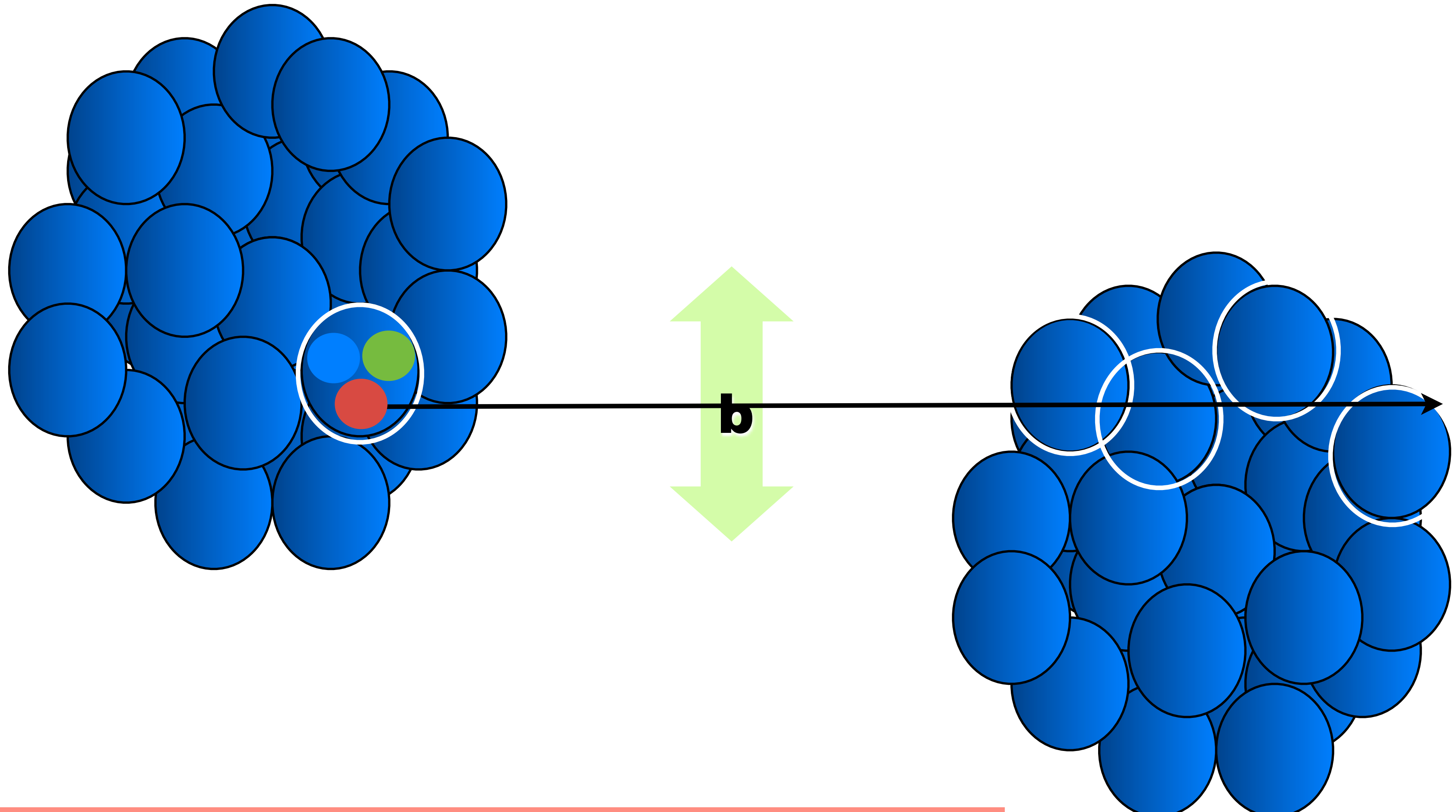
- Number of participants (***N_{part}***)
- Number of binary collisions (***N_{coll}***)
- Impact parameter (b)

by calculating a “percentile bin” in the variable, and the similar percentile in the geometric quantity.

For this, we use the “Glauber model”

Annu. Rev. Nucl. Part. Sci. 2007. 57:205–43

Nuclear Modification Factor

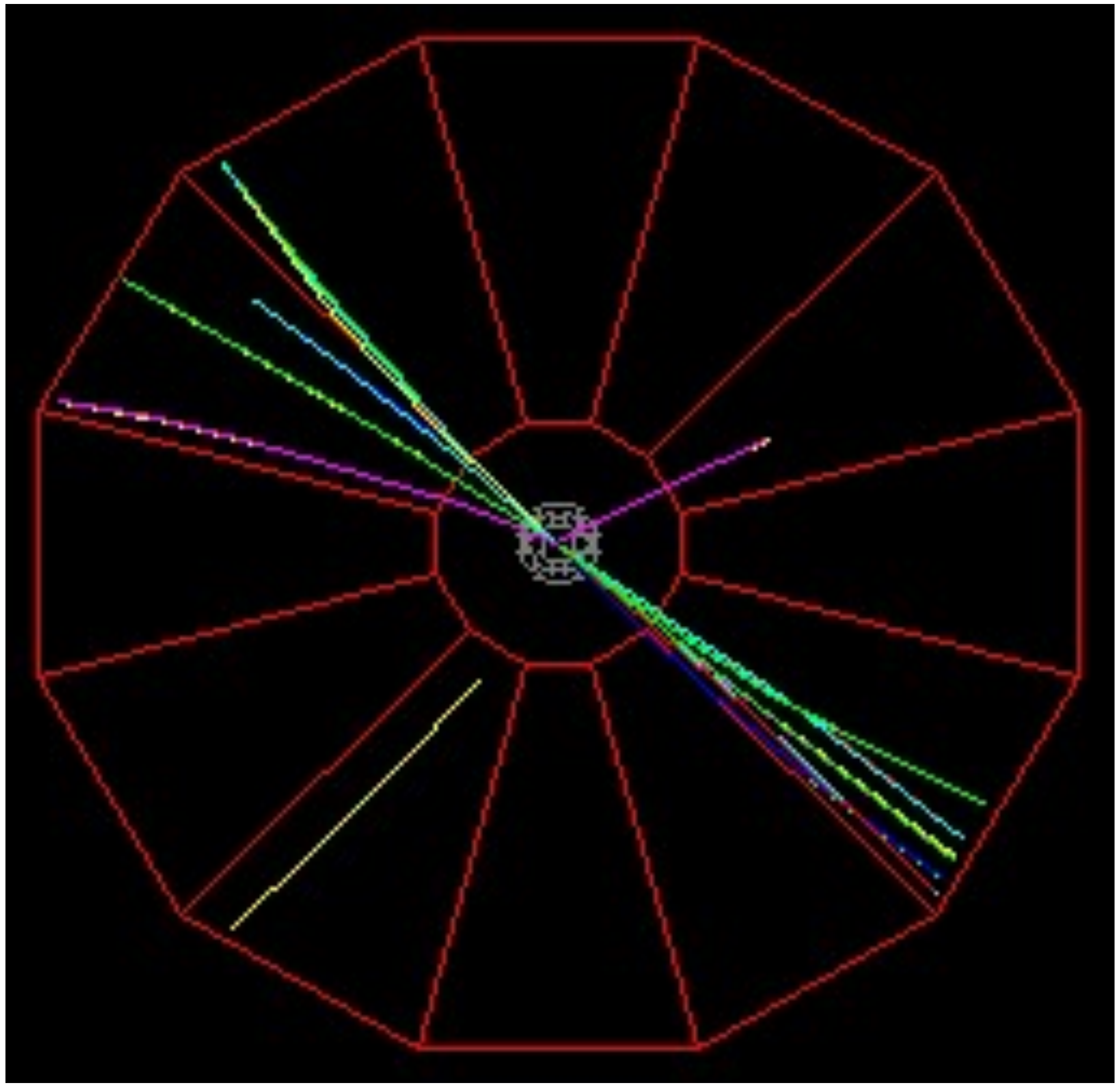


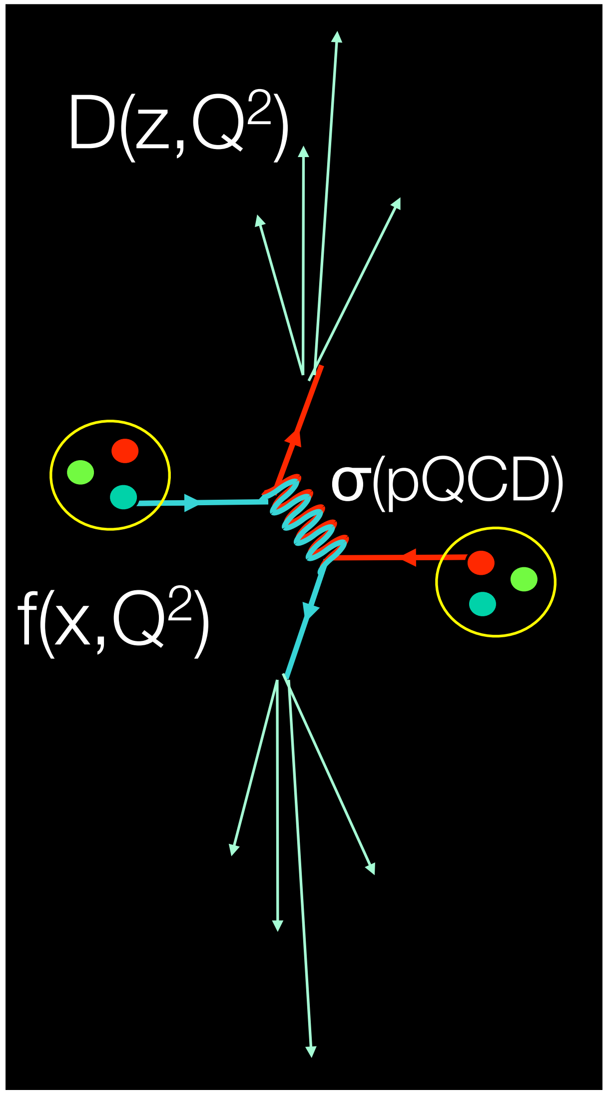
$$R_{AB} = \frac{1}{N_{coll}^{AB}} \frac{\frac{dN_{AB}}{dp_T}}{\frac{dN_{pp}}{dp_T}}$$

Yield per collision relative to p+p

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

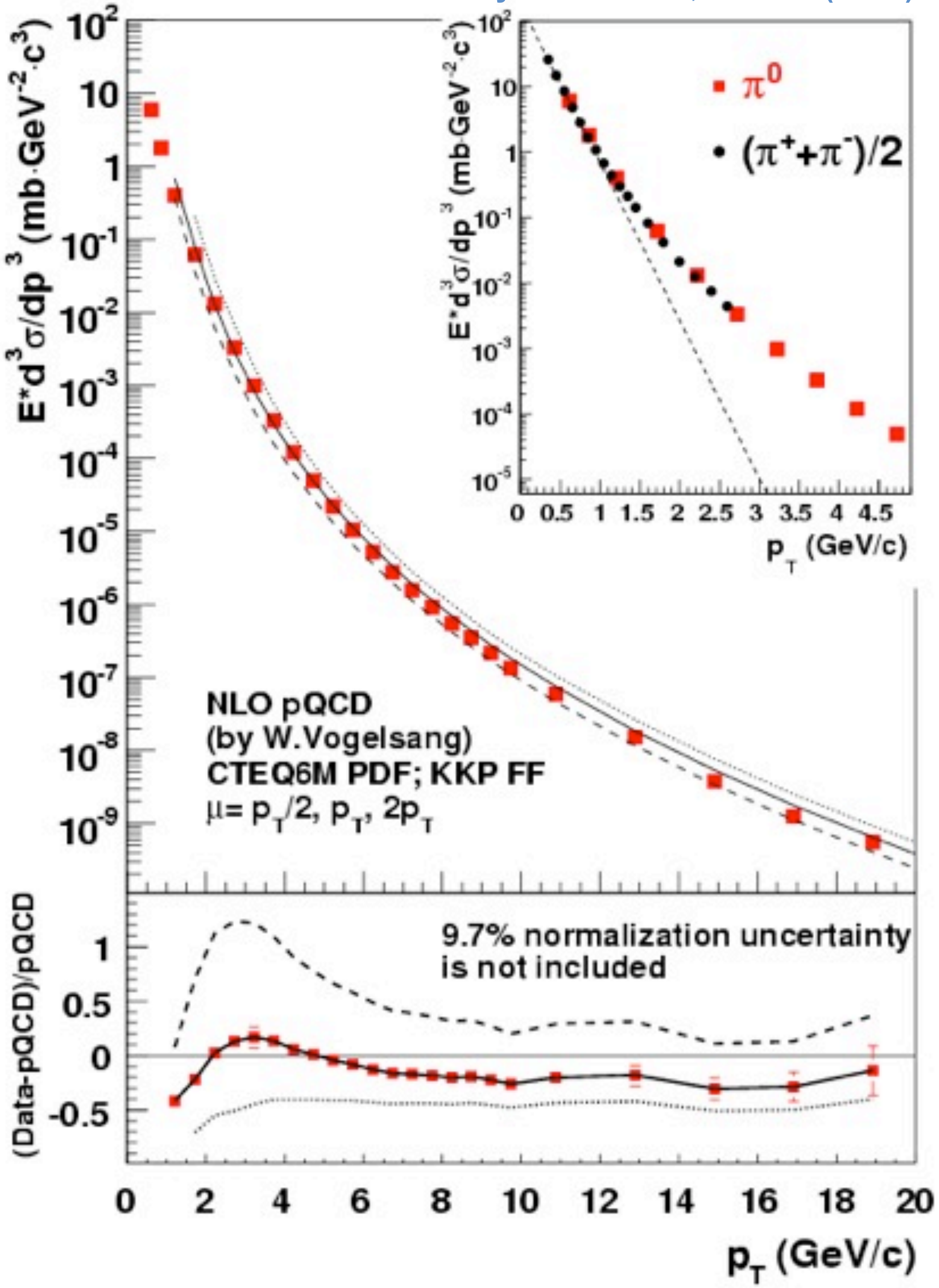
Jets in p+p





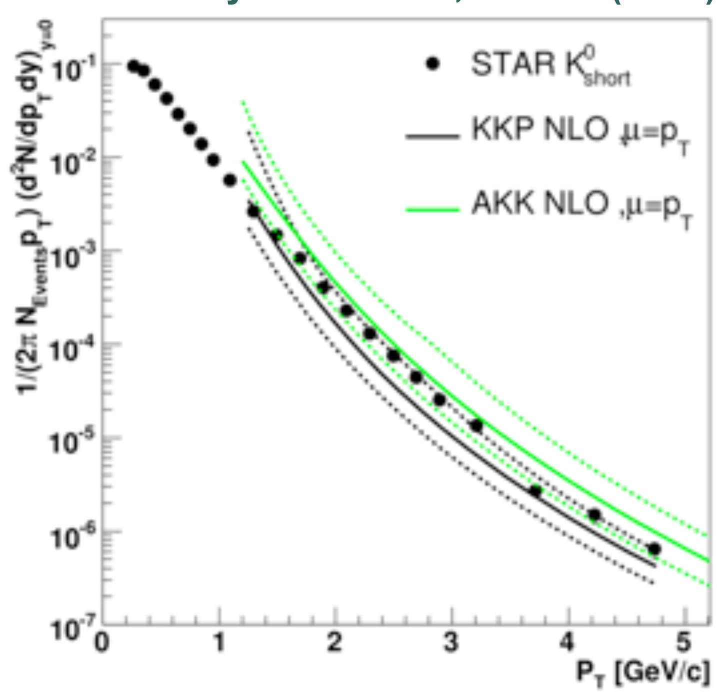
Jets are a “hard” phenomenon, allow pQCD description

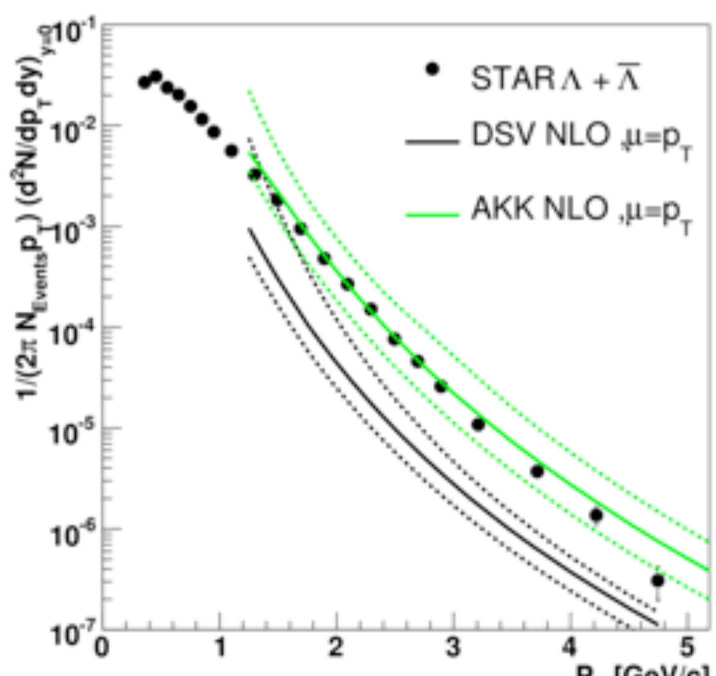
pQCD @ RHIC



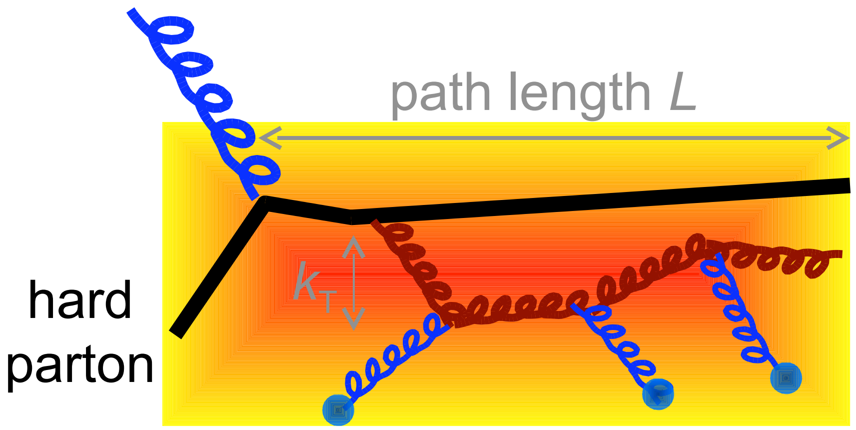
←Great for pions

Less so for K & Λ →





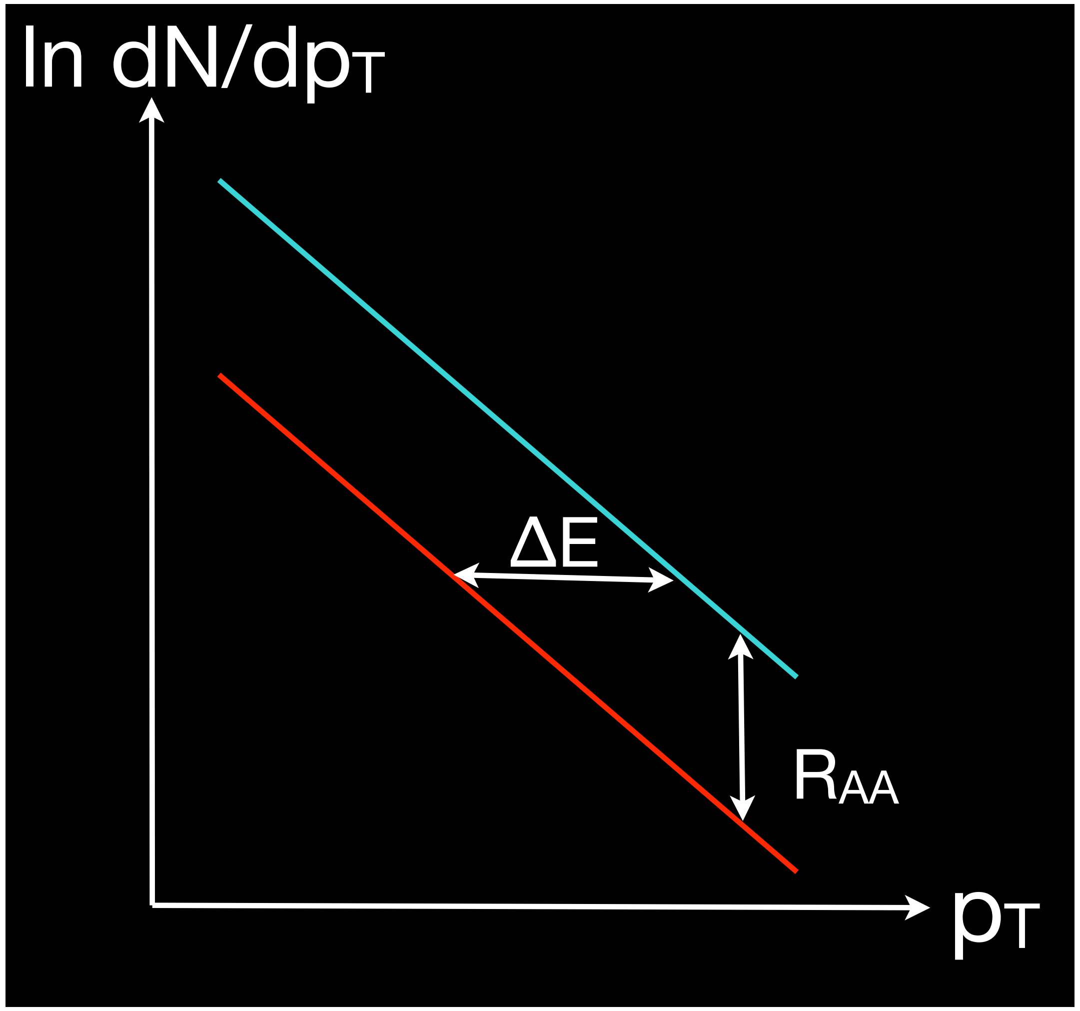
"Jet Quenching"

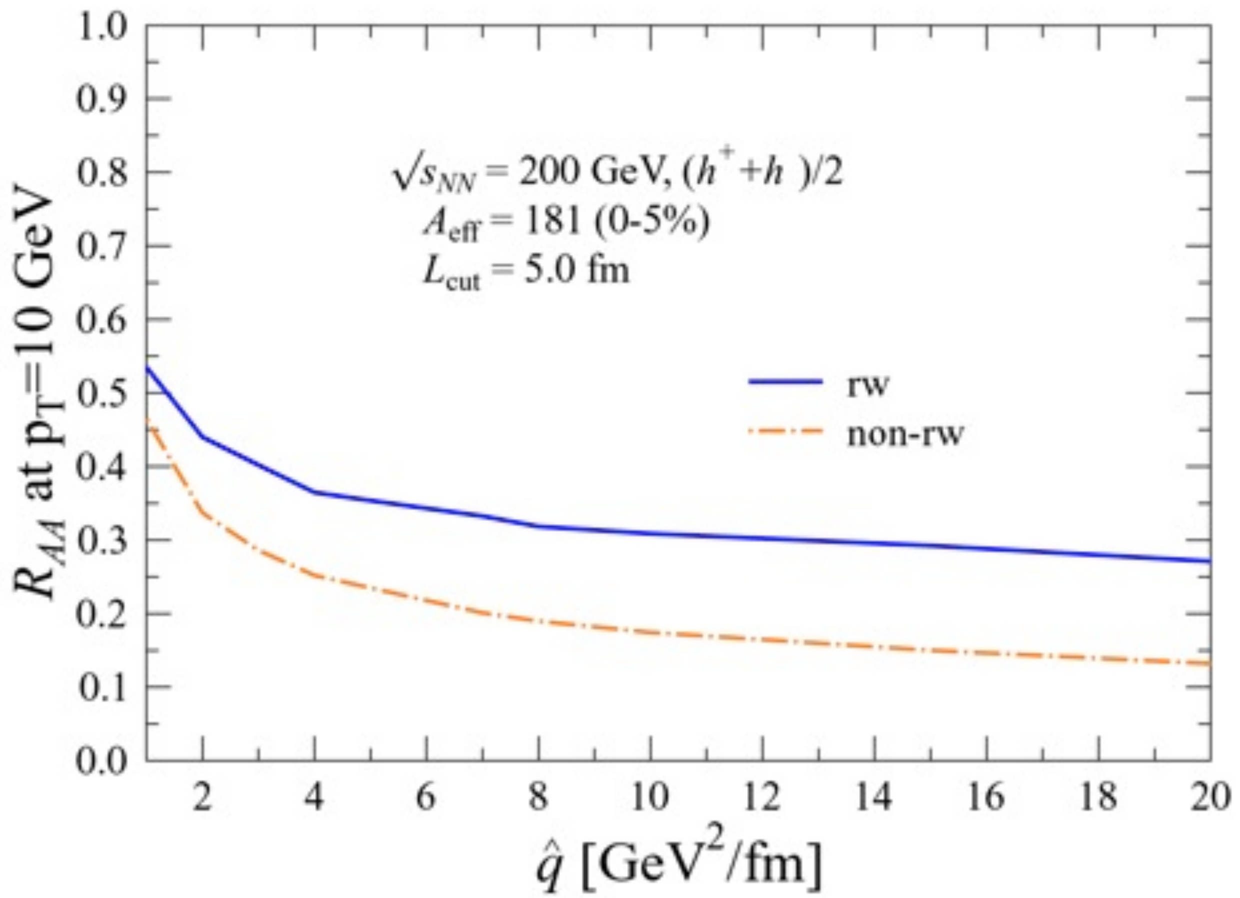


$$\langle \Delta E \rangle \approx \int_0^{\omega_c} d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_s C_R \omega_c \propto \alpha_s C_R \hat{q} L^2$$

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

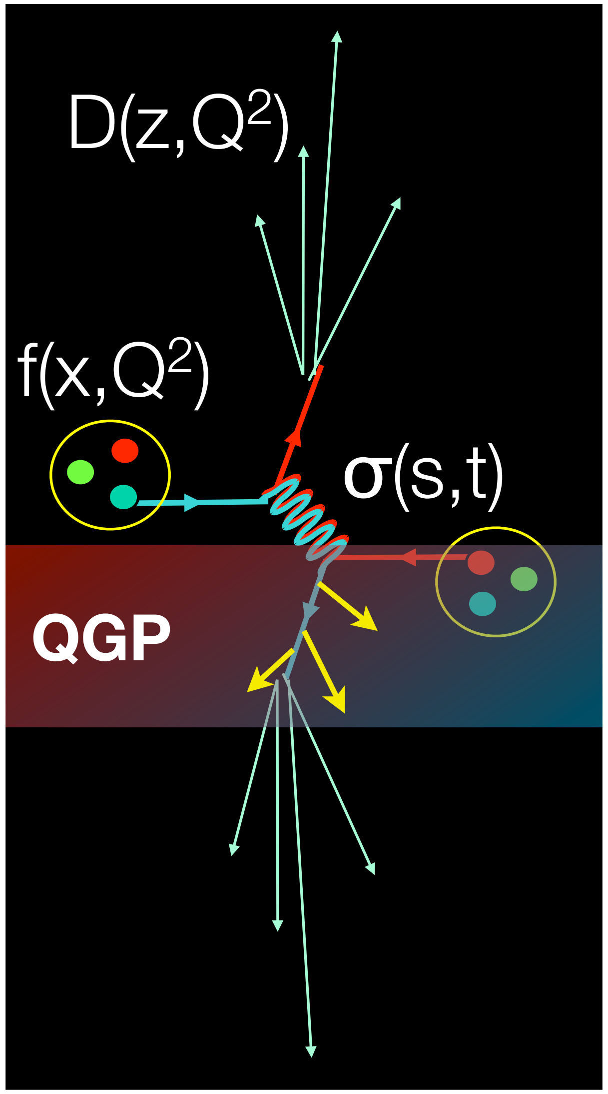
Transport coefficient (GeV^2/fm)
sensitive to gluon density
(not deconfinement!)





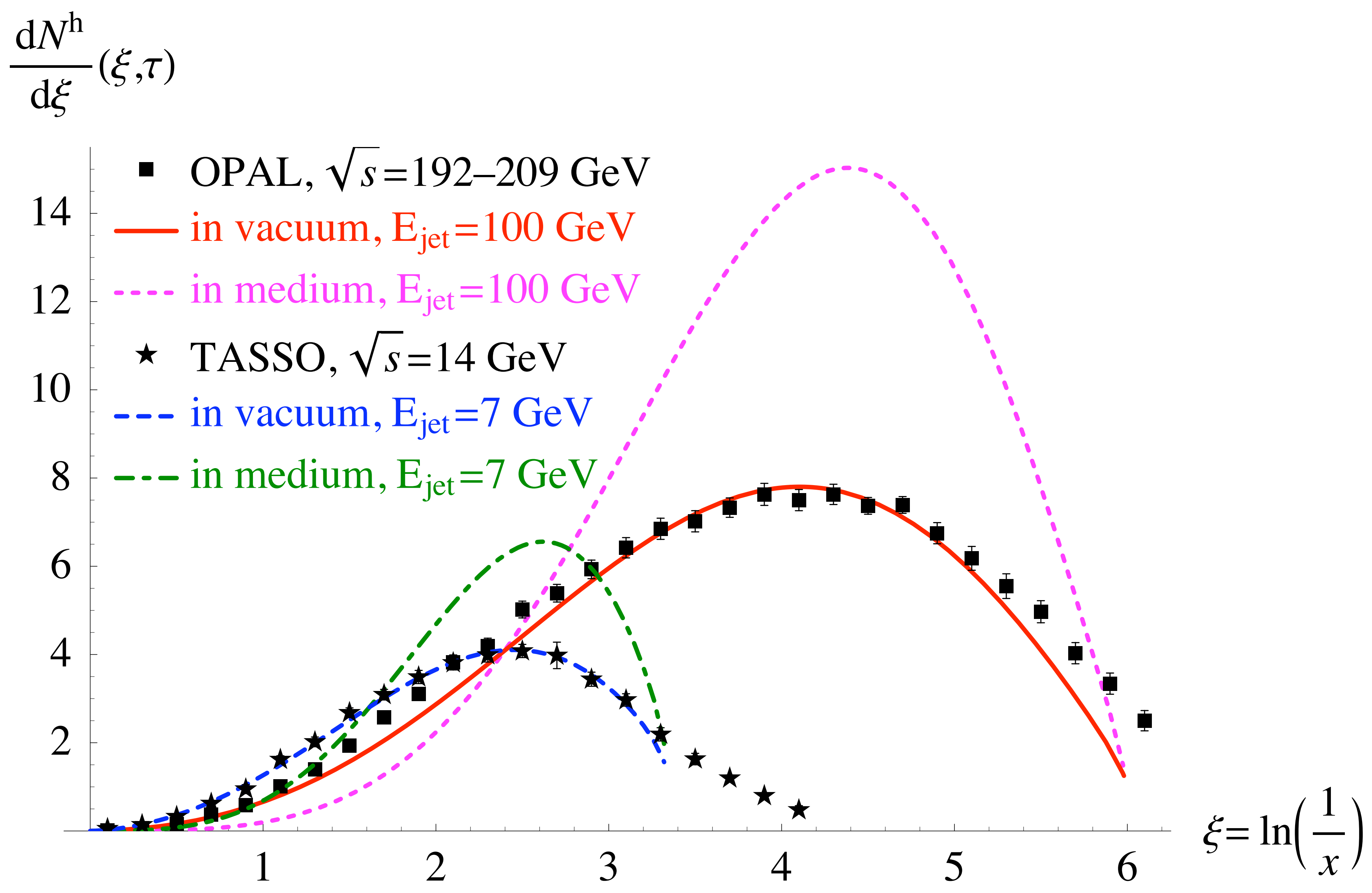
Modified Fragmentation

- **The typical scenario**
  - Hard parton produced in medium according to pQCD cross sections
  - Energy loss: generation of additional radiation, elastic scattering
  - Vacuum fragmentation of attenuated parton
- **"Modified fragmentation"**
- **Variety of implementations**
  - Many soft gluons (ASW/BDMPS)
  - Few hard gluon (DGLV)
  - Higher twist (HT)
  - Thermal field theory (AMY)
  - Even AdS/CFT (LRW)

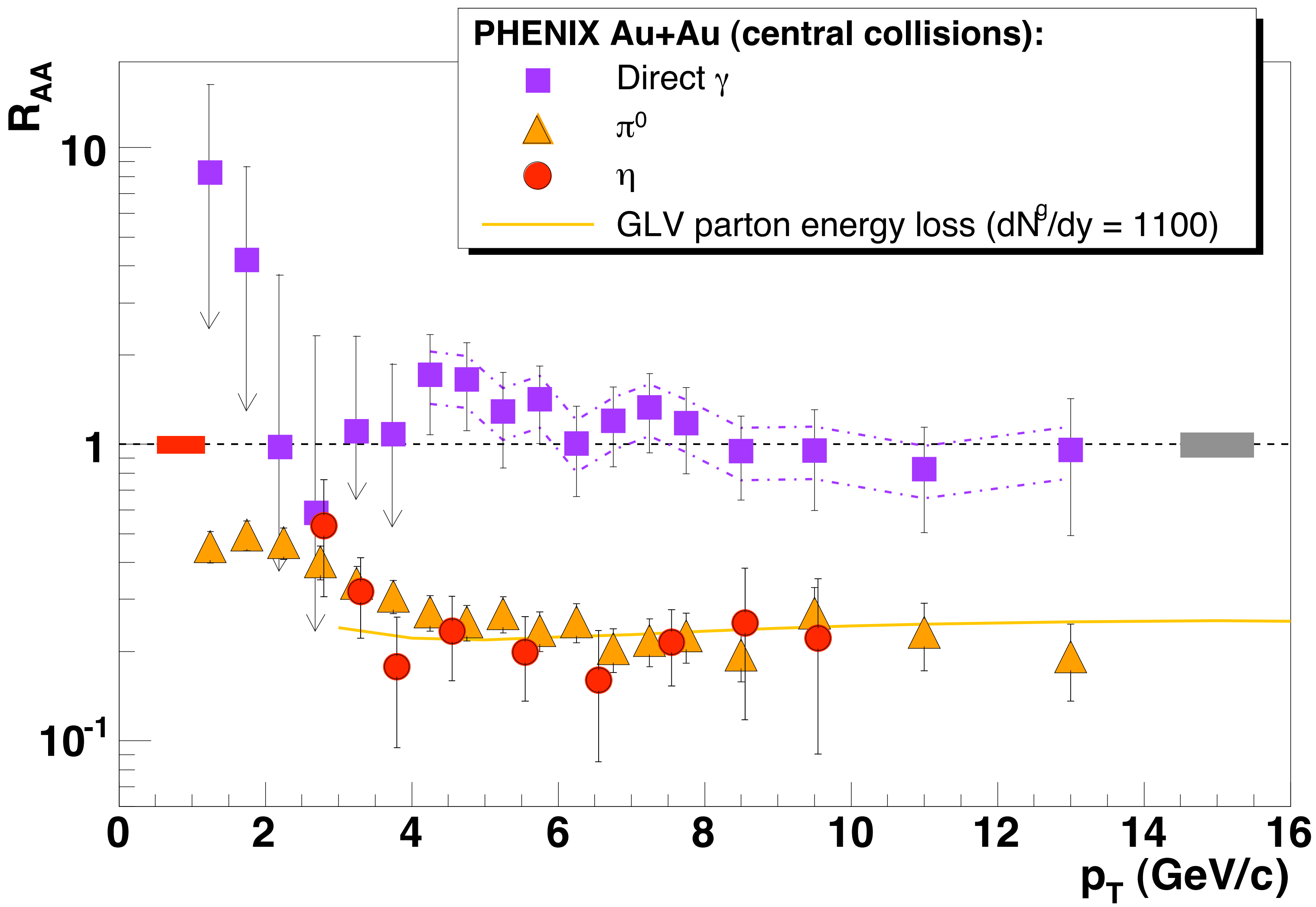


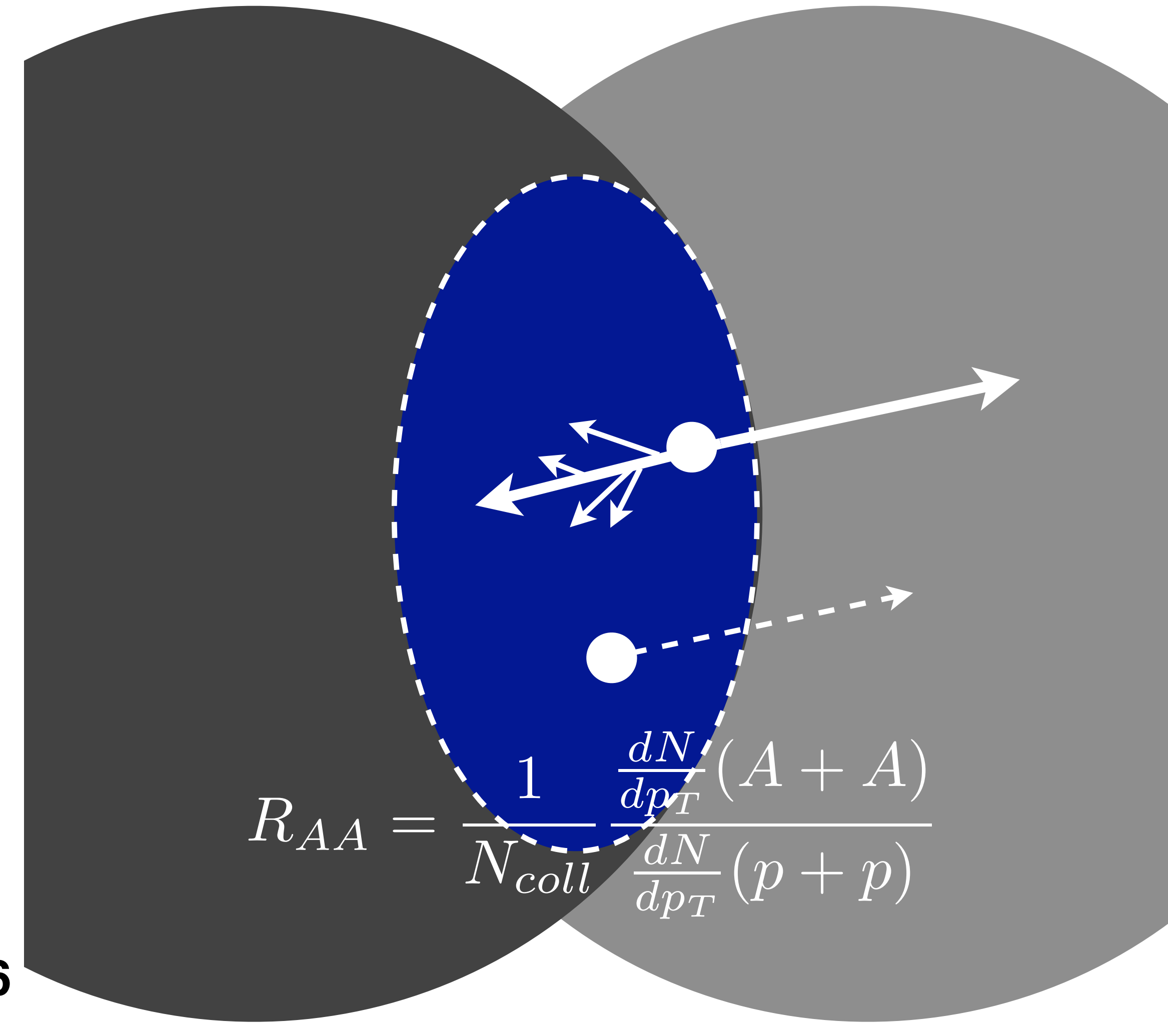
$\hat{D}(z,Q^2)$

Modified Fragmentation



High p_T Suppression



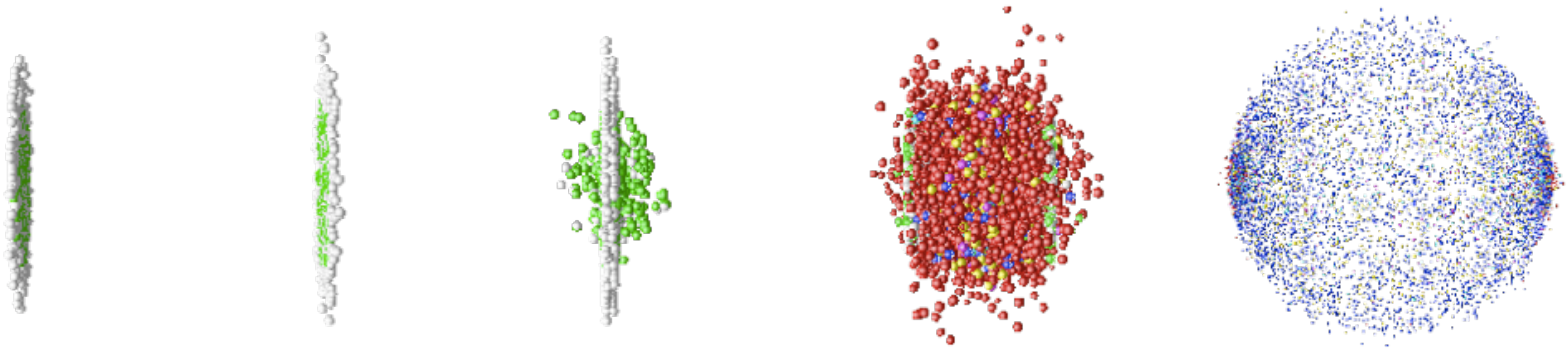


$$R_{AA} = \frac{1}{N_{coll}} \frac{\frac{dN}{dp_T}(A+A)}{\frac{dN}{dp_T}(p+p)}$$

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

pQCD energy loss calculations describe light hadrons. Photons appear to be <u>unaffected</u> by medium.

When does suppression occur?



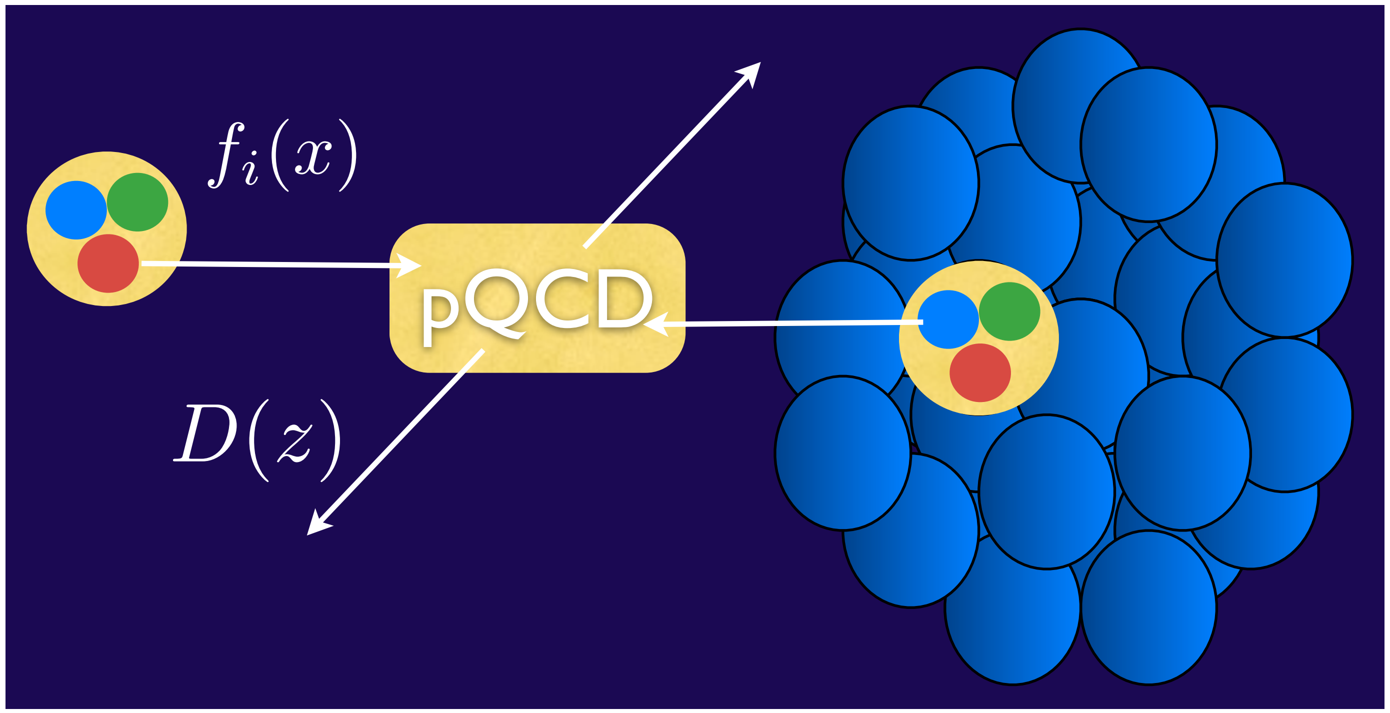
Some sort of strong "shadowing" phenomenon in the inital nuclear parton distributons...

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

Or does something occur in the strongly interacting stage??

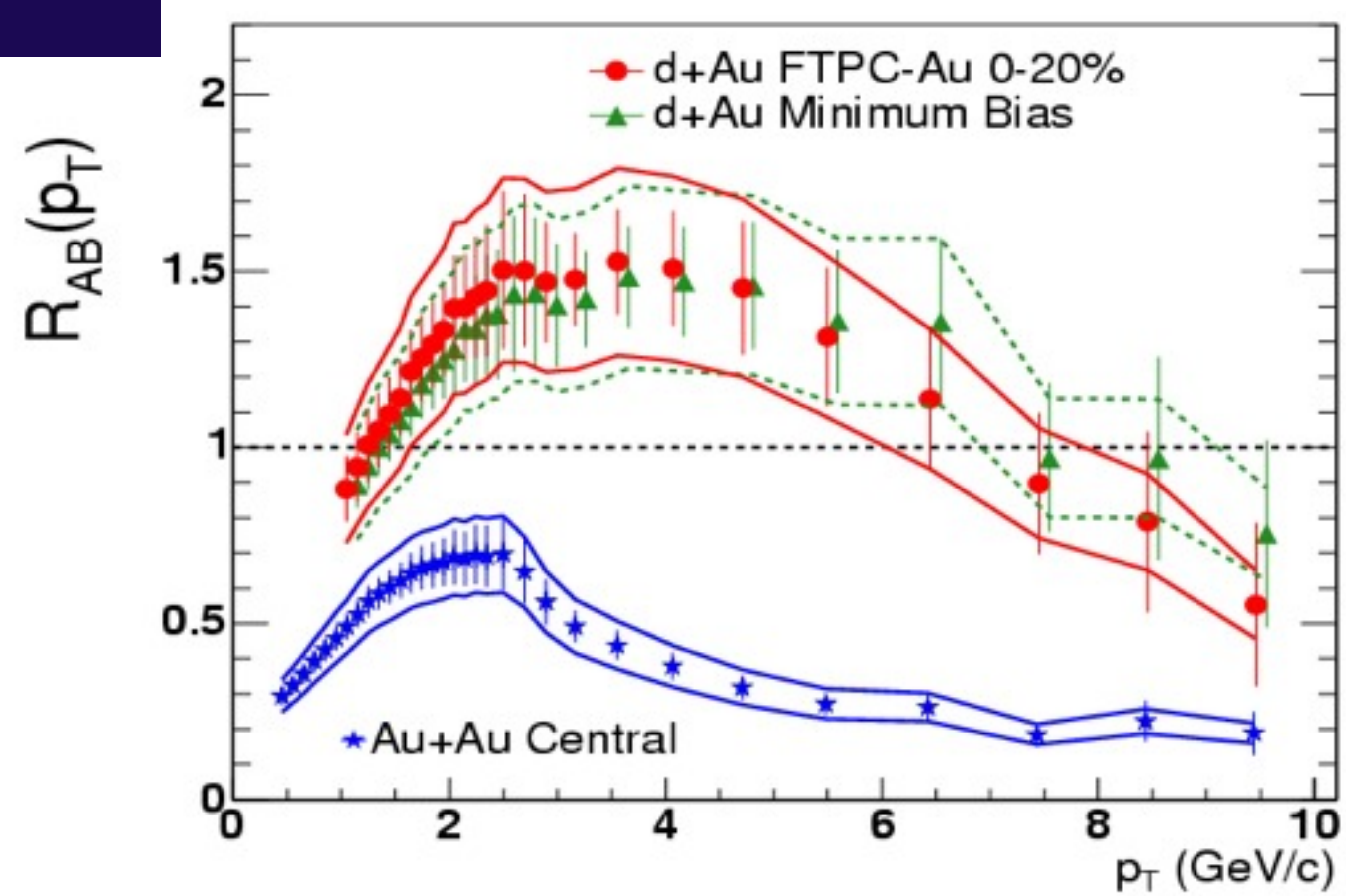
Collisions of the outgoing particles with the background of soft hadrons?

Initial vs. Final State

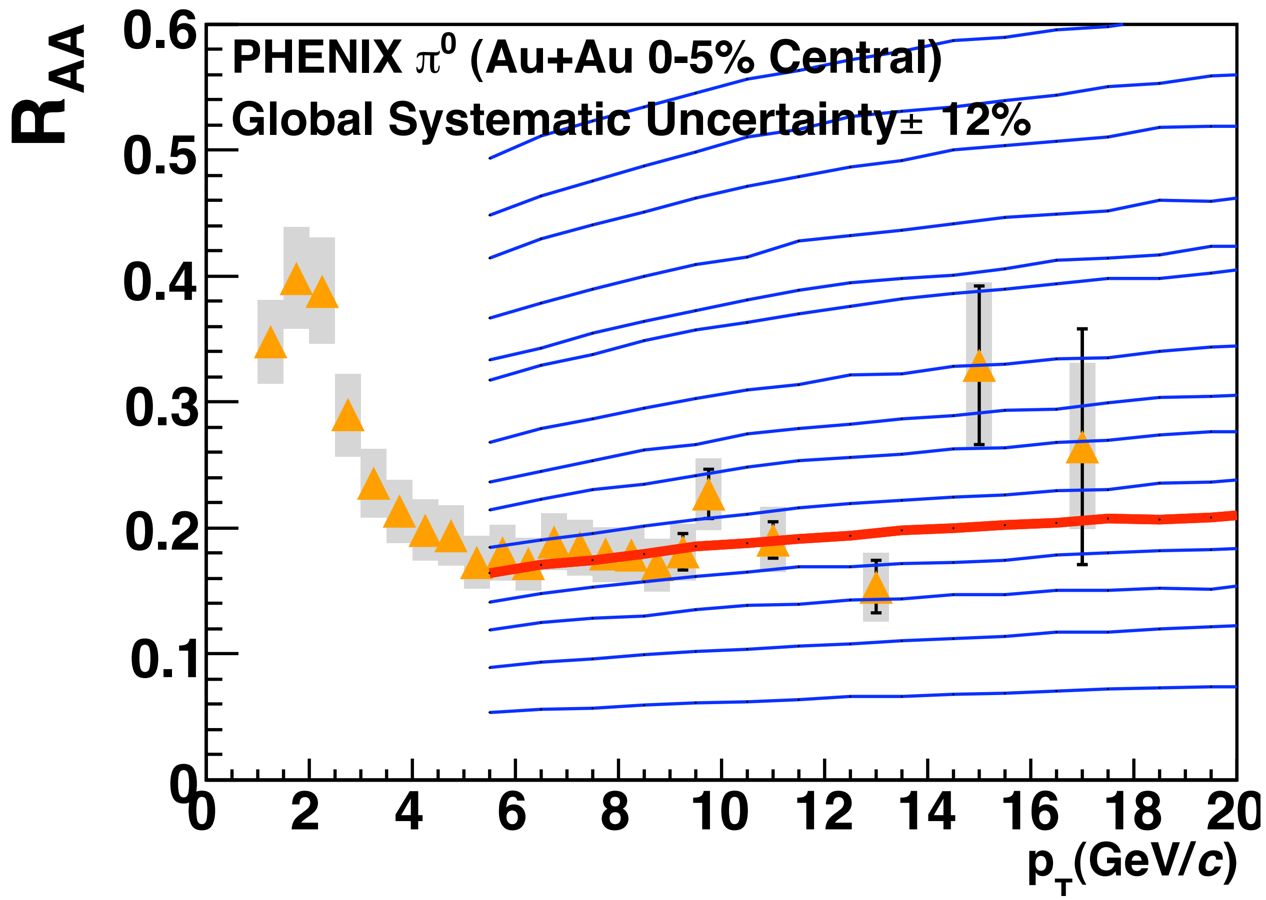


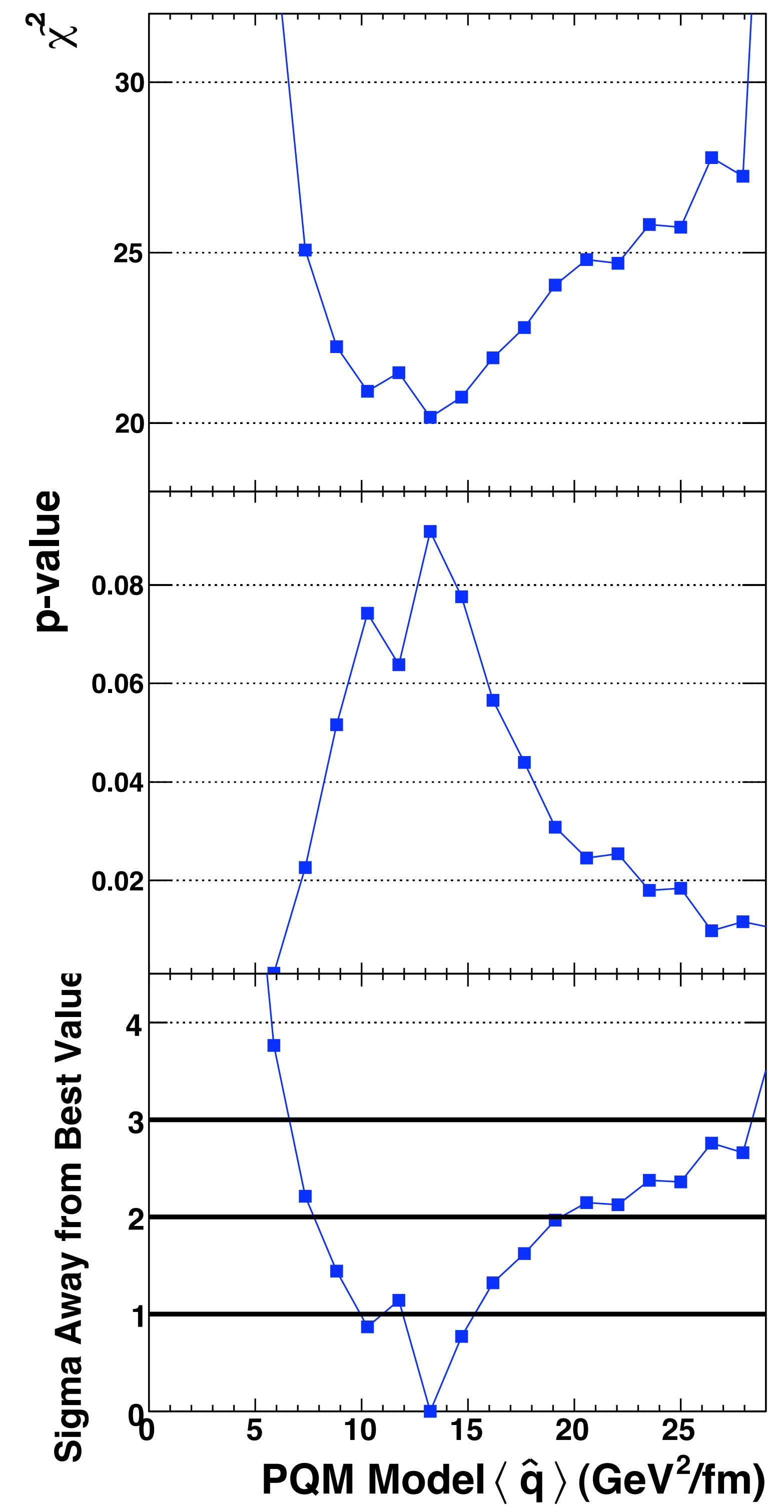
p+A collisions provide some access to the shadowing from the nuclear wave-function (reduction in initial flux)

d+Au not suppressed (except at high p_T...) while Au+Au shows large effect at all p_T: evidence for final state



Estimating Stopping Power (PHENIX)





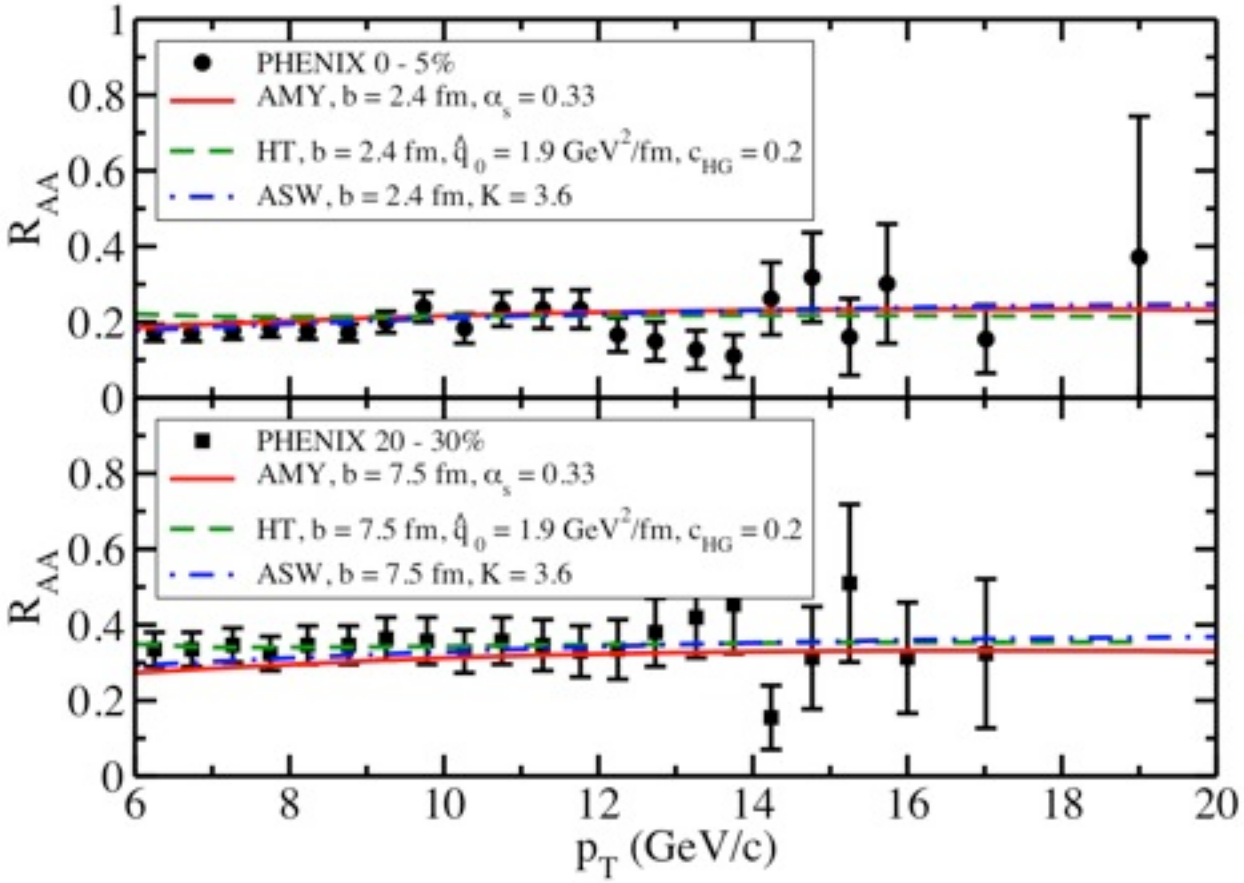
$$\Delta E \propto \hat{q} \propto \langle p_T^2 \rangle / \lambda$$

PHENIX χ^2 fits to PQM indicate $6 < \hat{q} < 24\,\mathrm{GeV}^2/\mathrm{fm}$.

First “real” quantitative constraints!

Comparison of approaches - singles

Bass, et al, arXiv:0808.0908v3



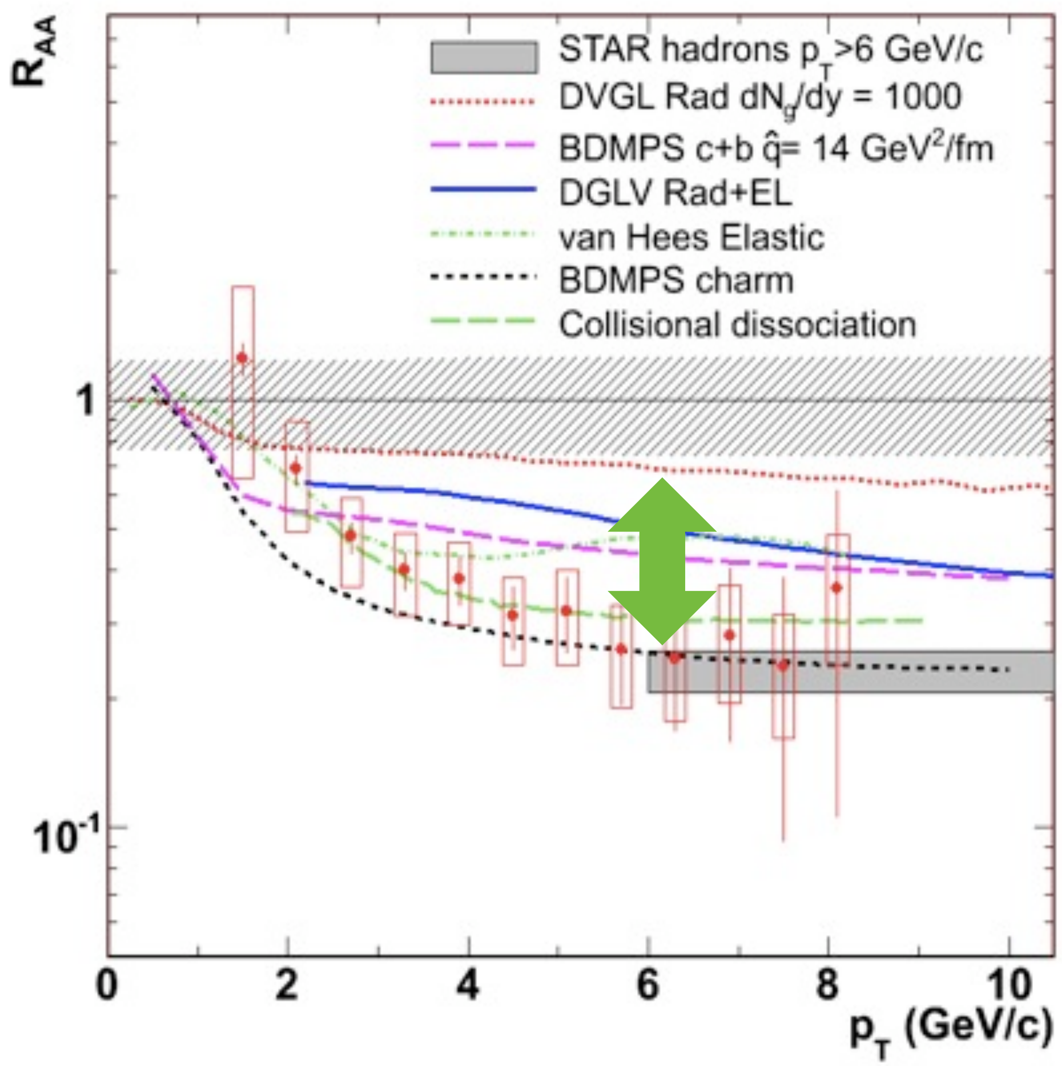
$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

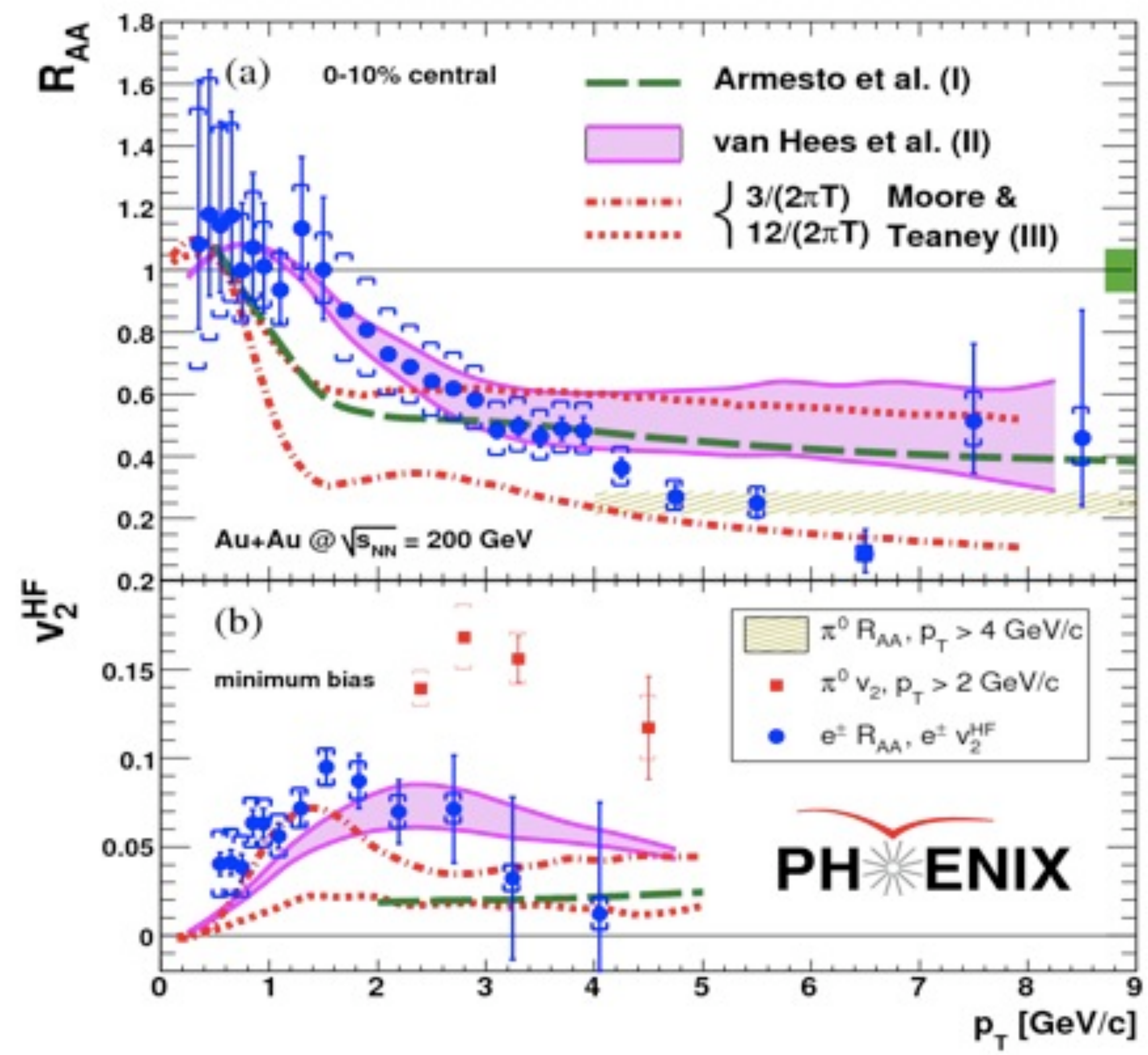
Very different values
for transport coefficient…

Variety of jet quenching implementations all give the “same” result for high p_T suppression - dominated by geometry

Heavy Flavor: a fly in the ointment

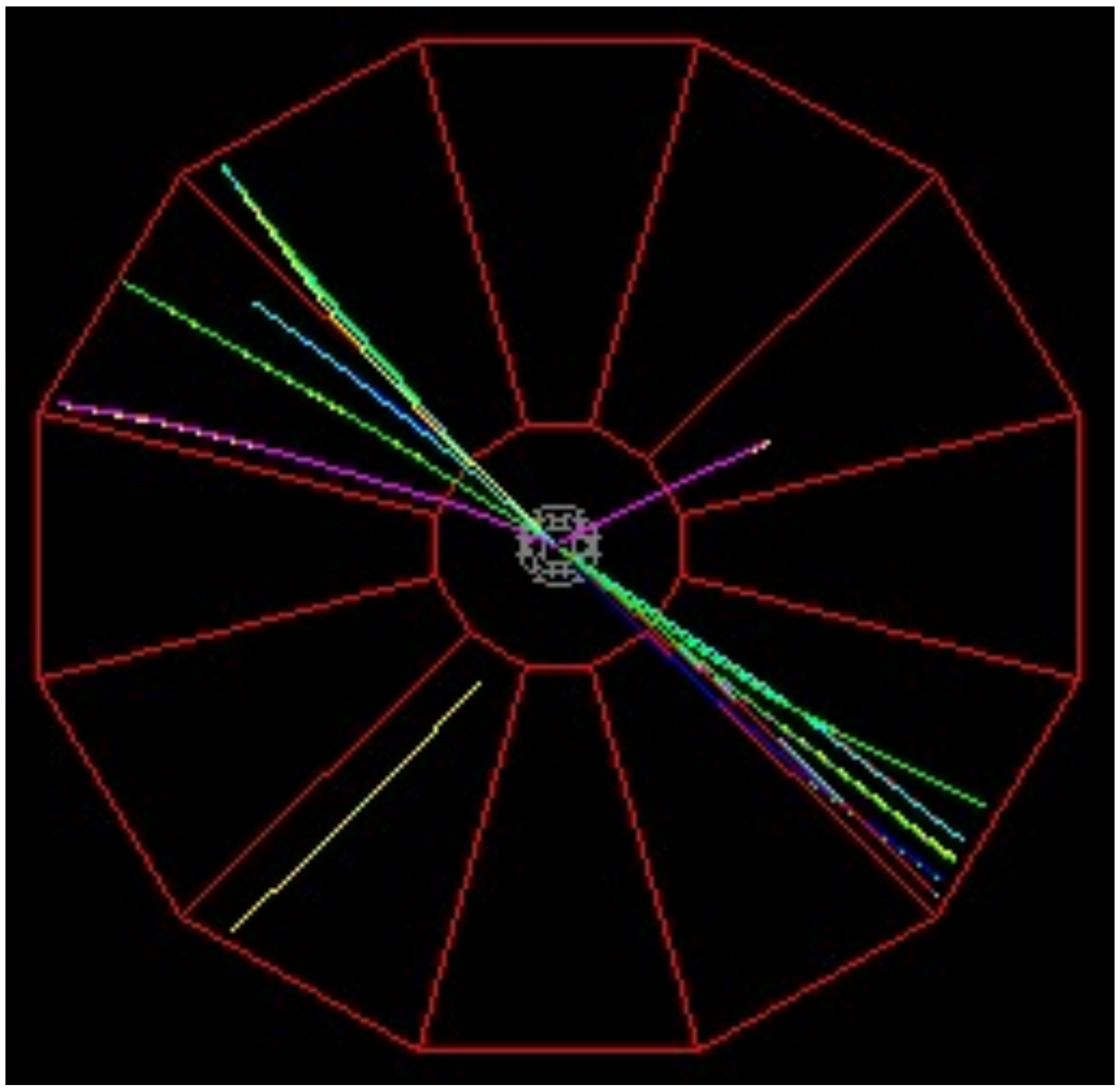
CTEQ

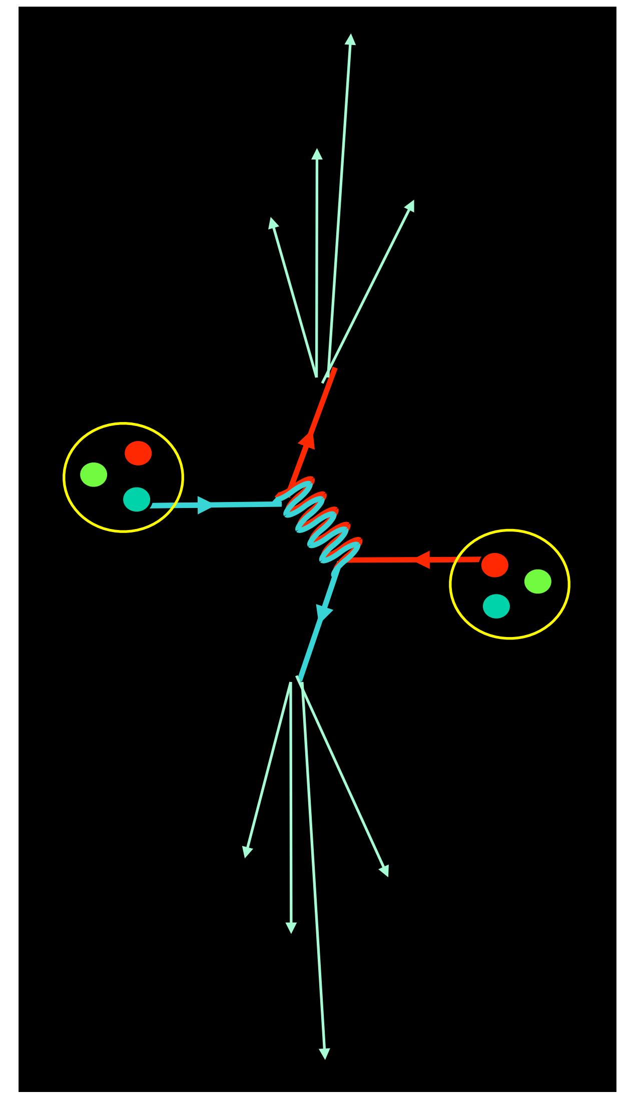




Heavy flavor (c,b) measured via semi-leptonic mode.
Suppression at high pT is very similar to other hadrons:
surprising since mass should reduce radiation ("dead-cone")

Correlations (jet-medium interactions)



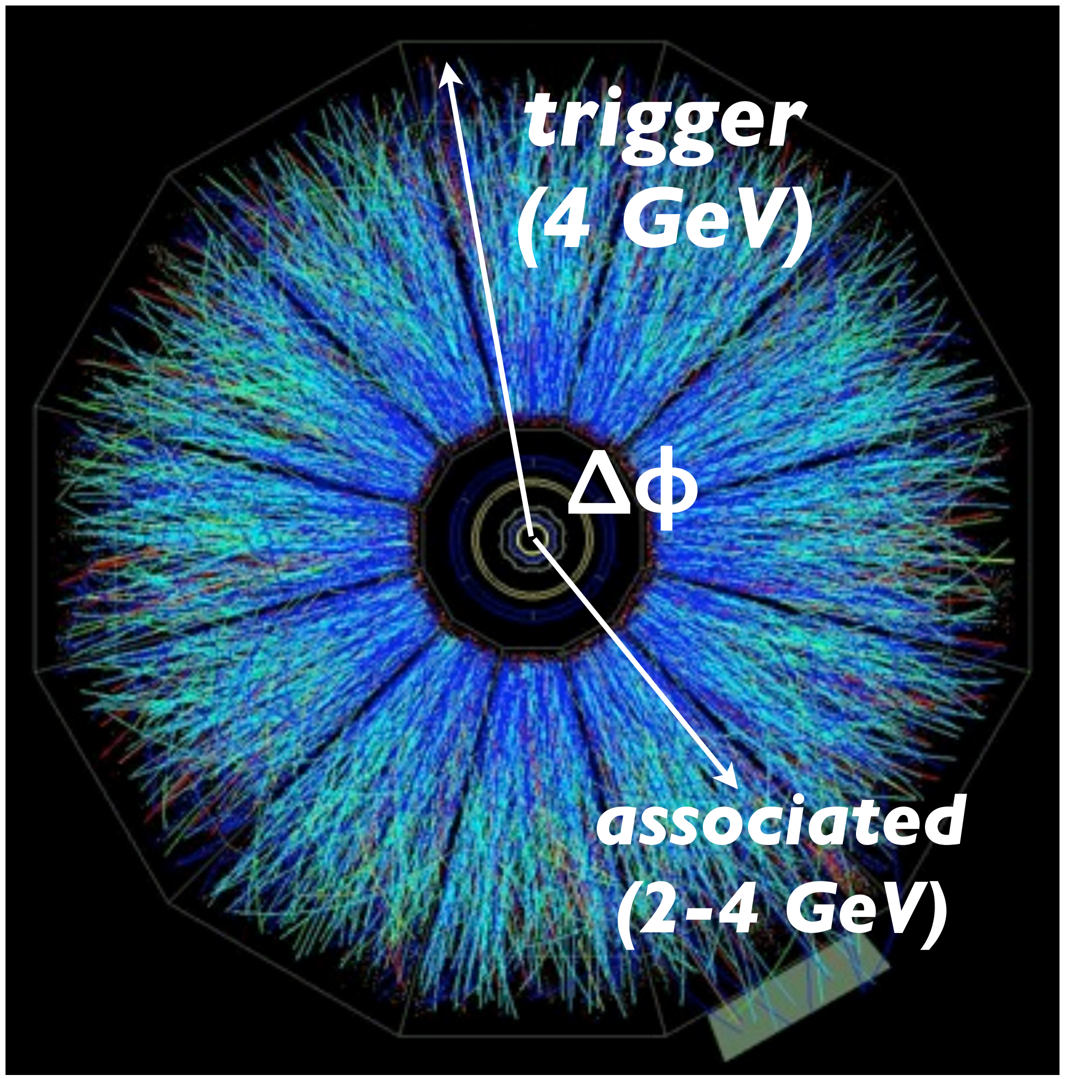


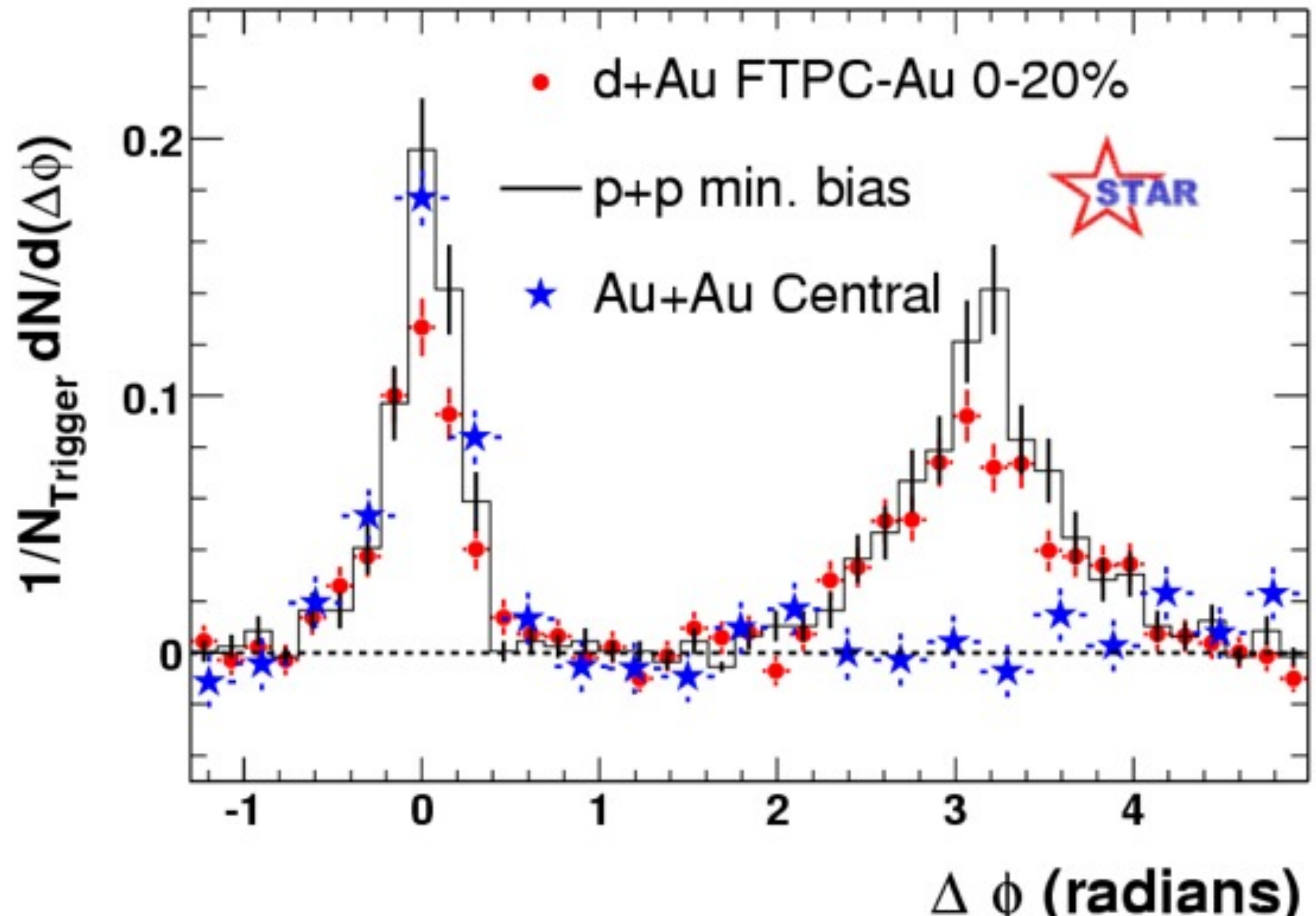
Jets are multi-particle phenomena:

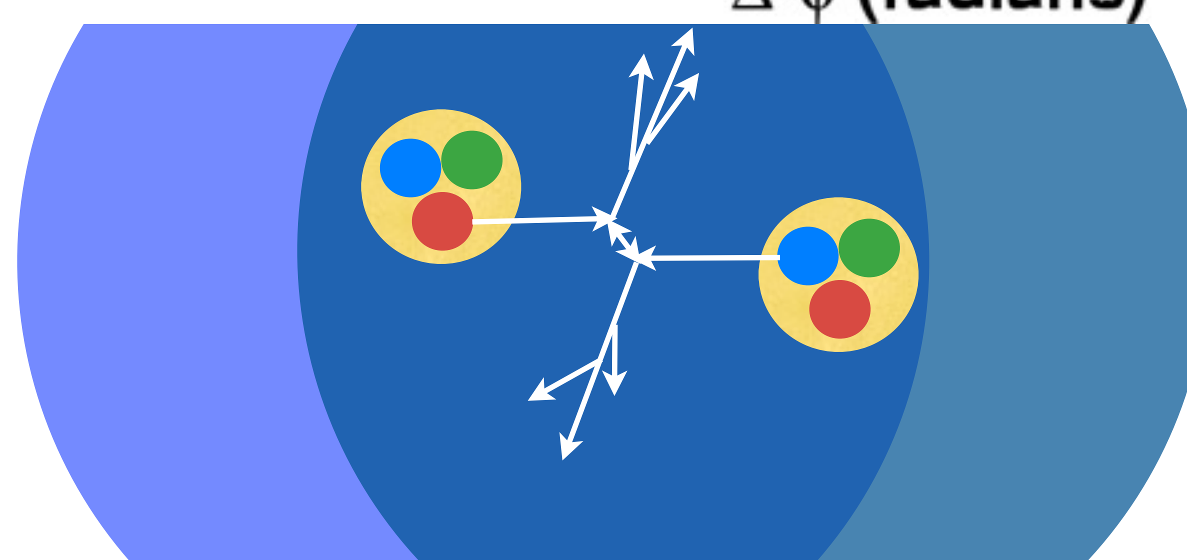
2+ high p_T particles (quark and/or photon)

quarks fragment into multiple hadrons

“Back-to-Back” Disappearance (b2bd)



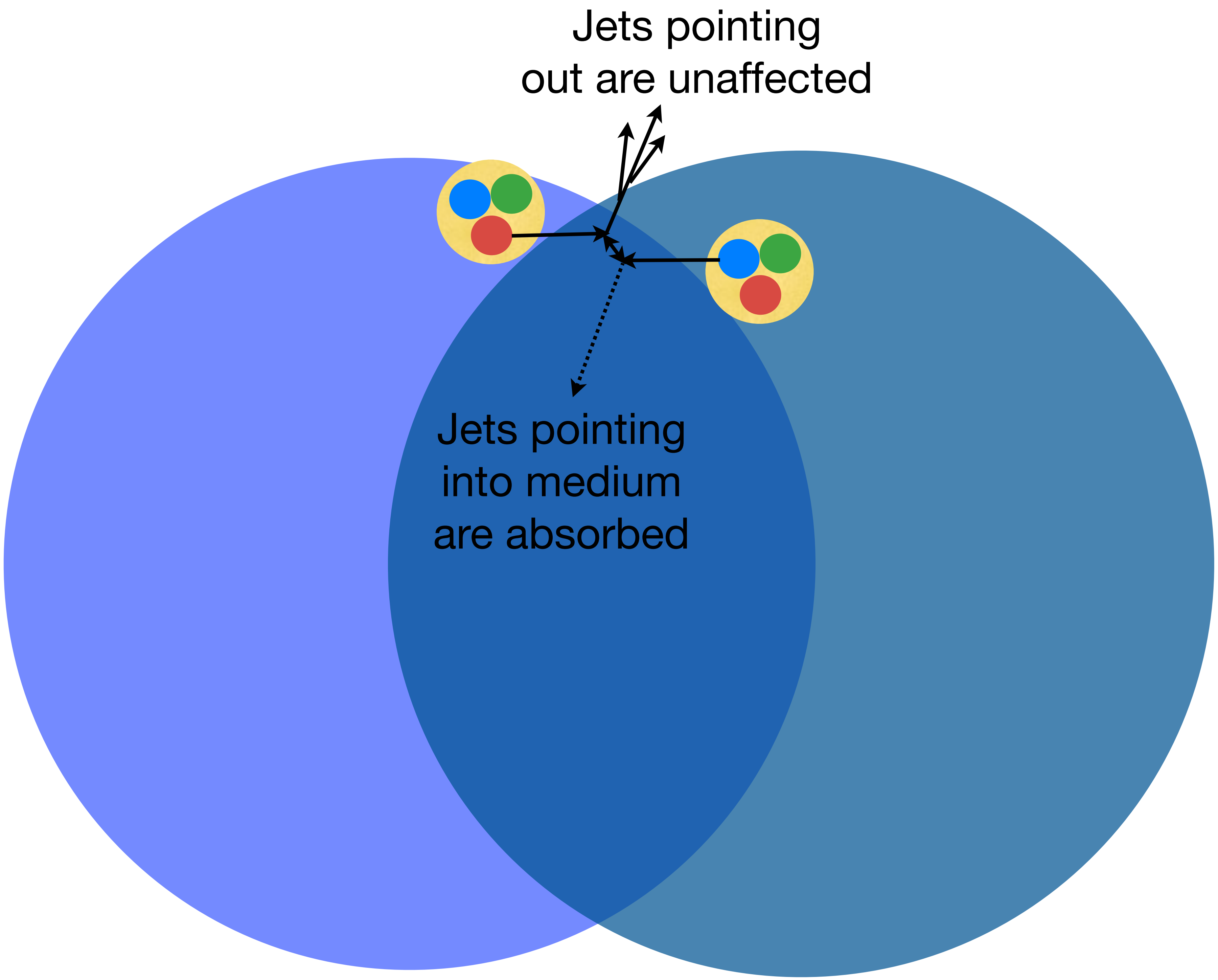




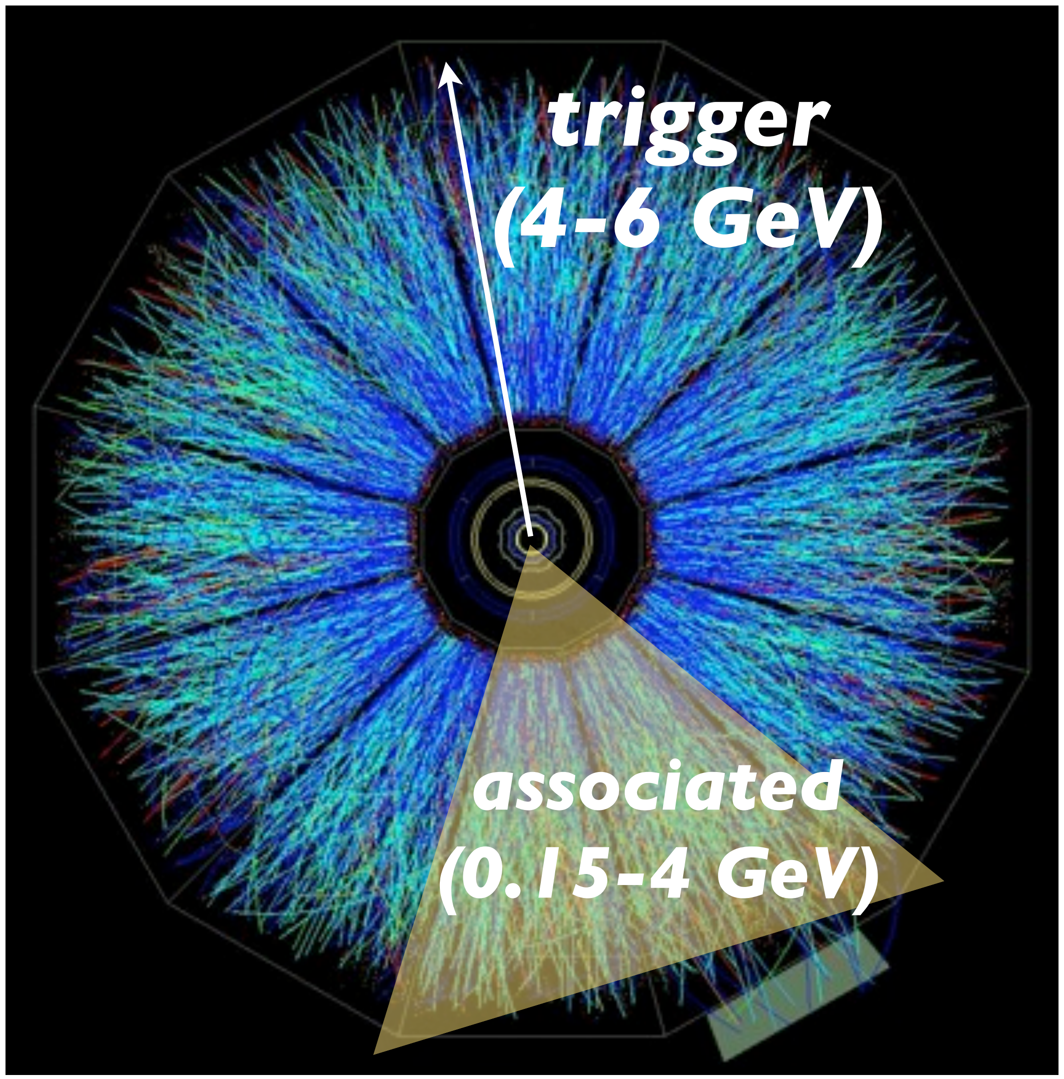
d+Au similar to p+p

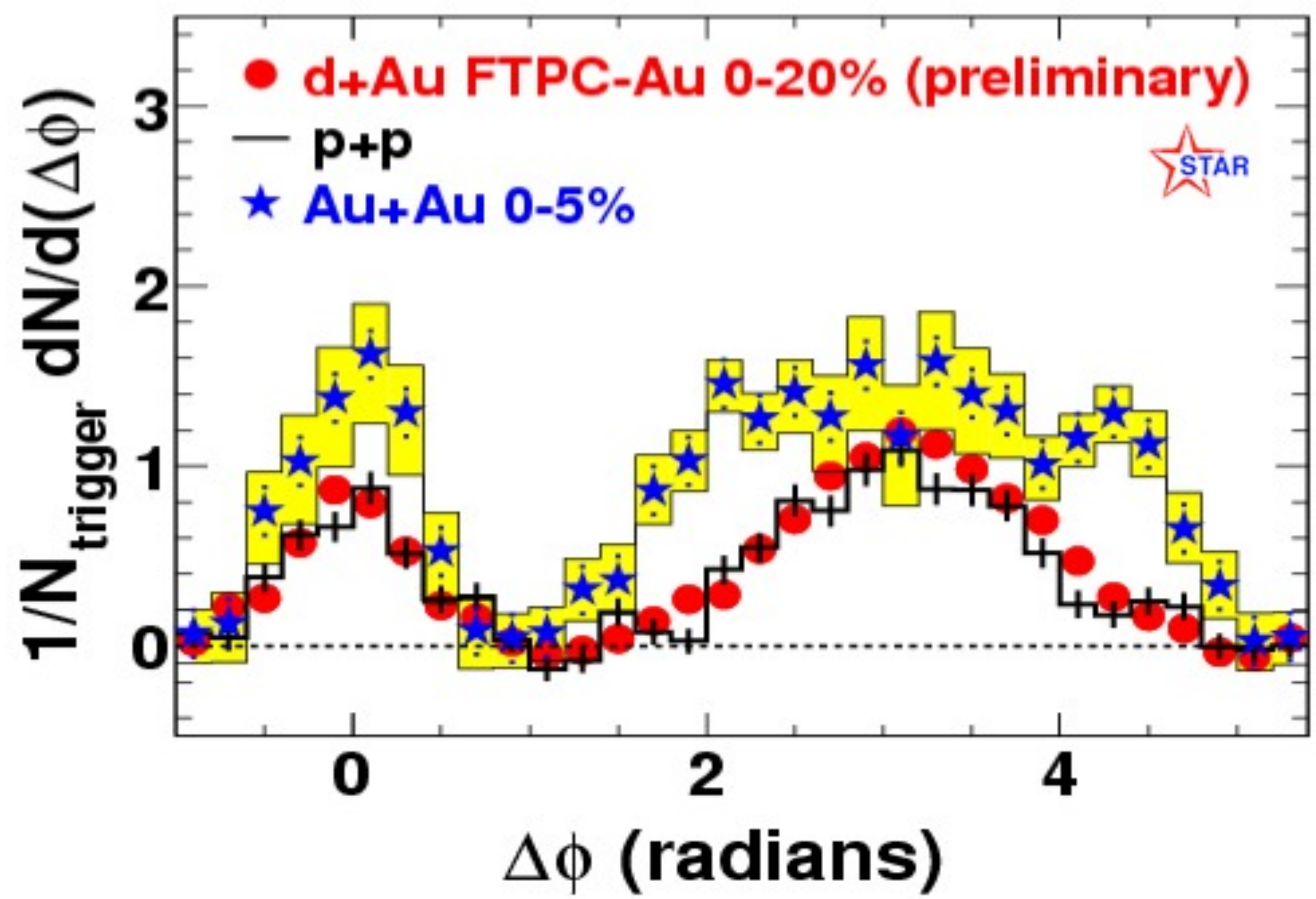
Au+Au shows a disappearance of the away side peak

Surface Bias



Return of the "Away Side"

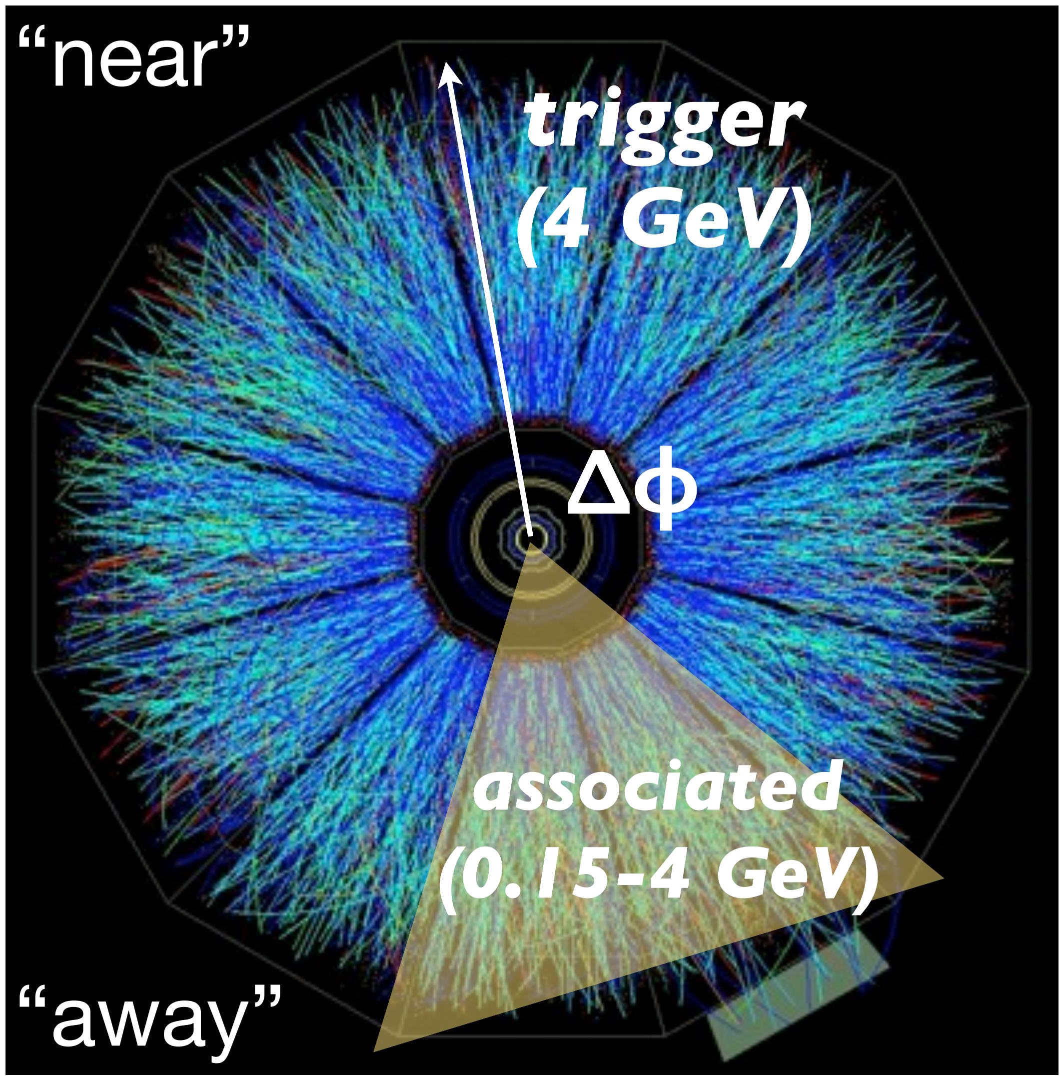


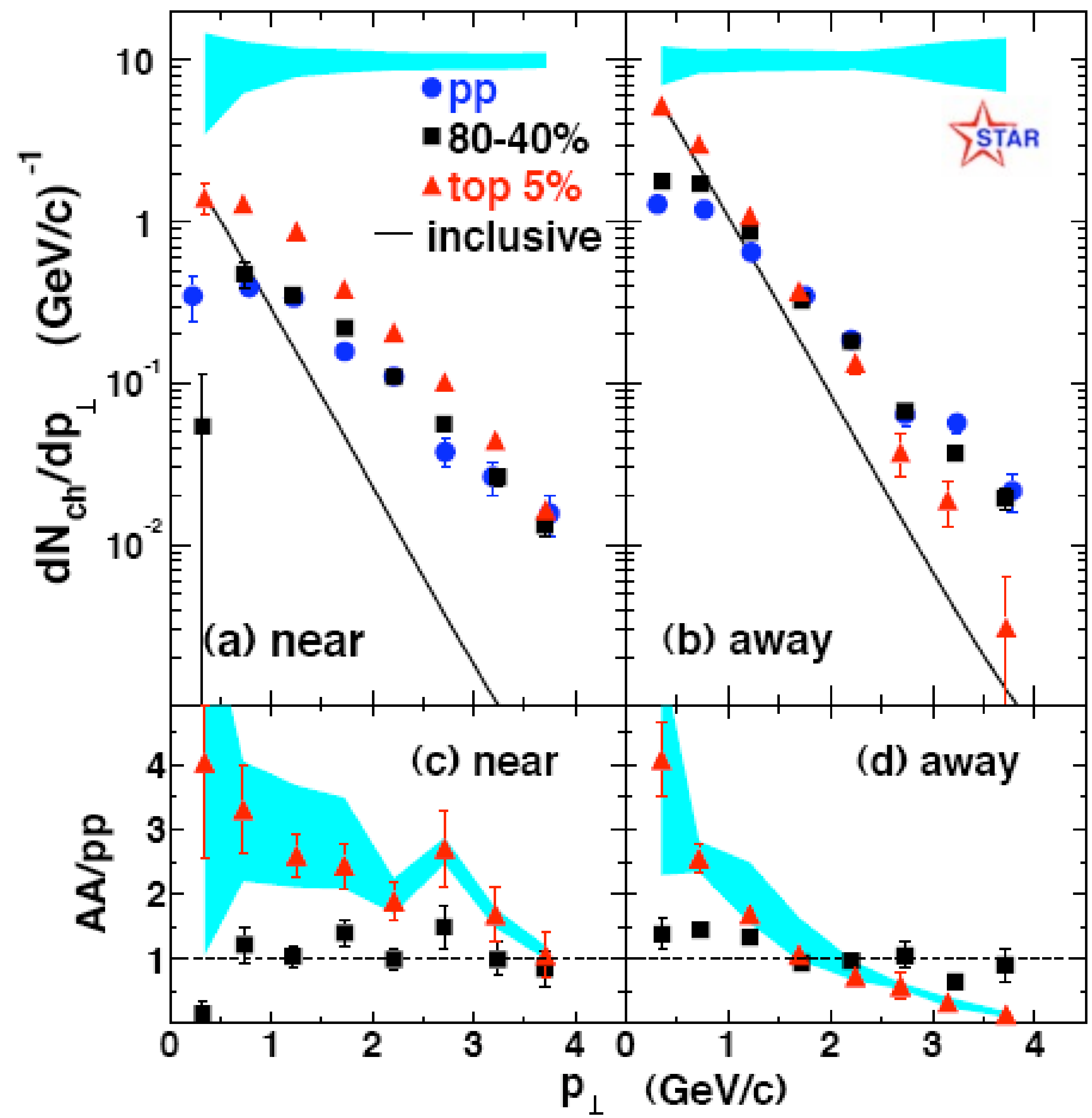


Including <u>all</u> particles (soft & hard) accounts for suppressed jet, but highly smeared-out in **Φ**

Indicates non-trivial interaction with medium.

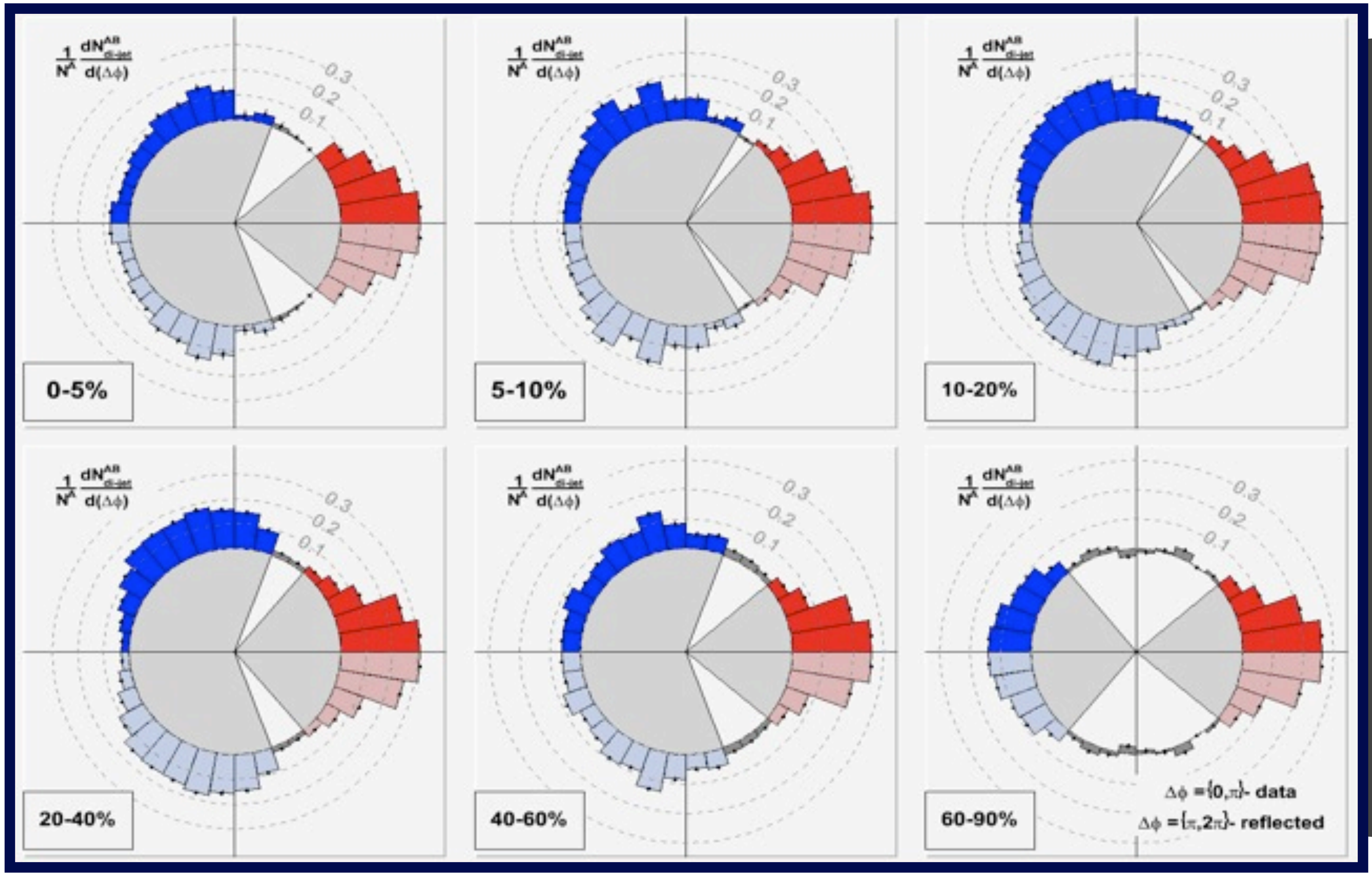
Spectral Modification (thermalization)

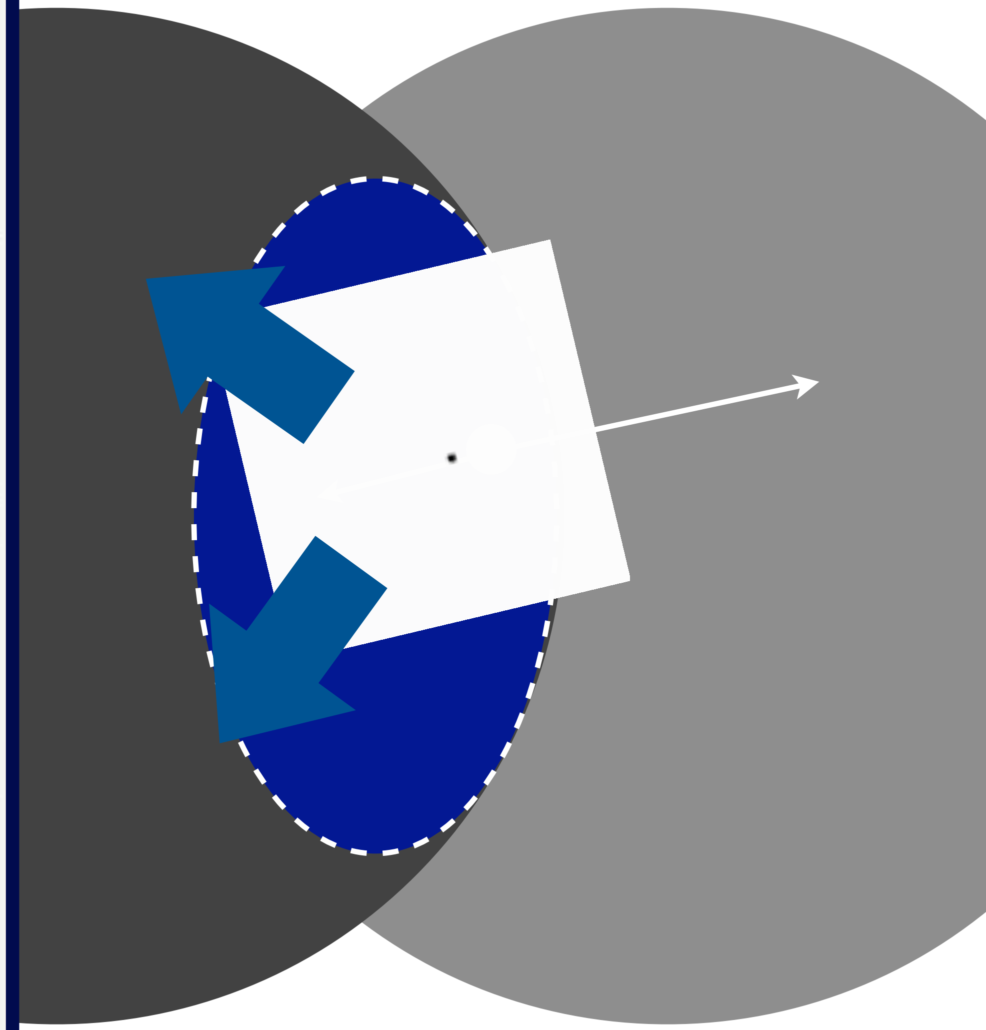




Away-side spectrum starts to resemble inclusive "thermal" one

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

hep-th/0605182
PUPT-2198

Drag force in AdS/CFT

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

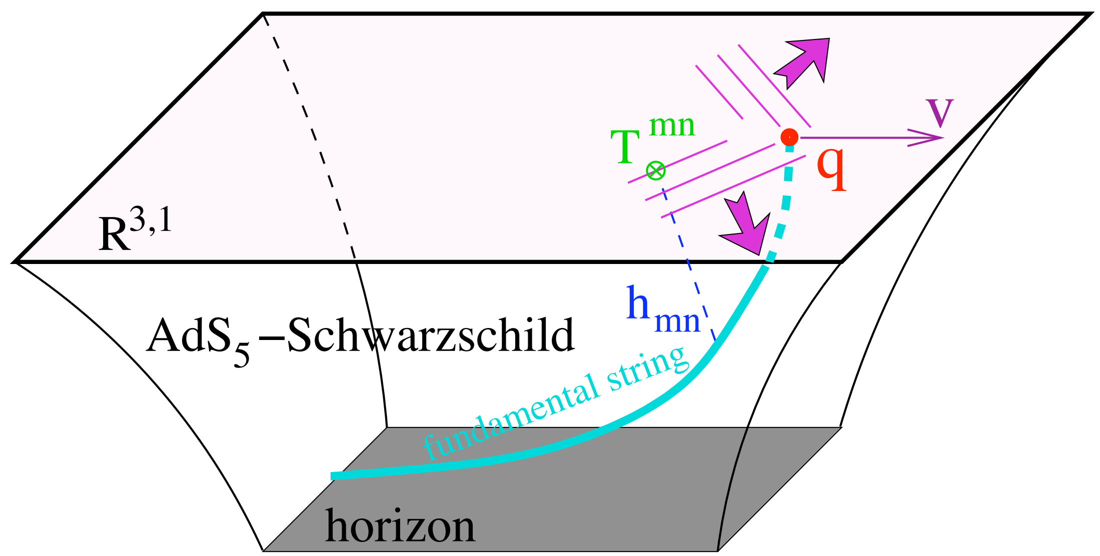
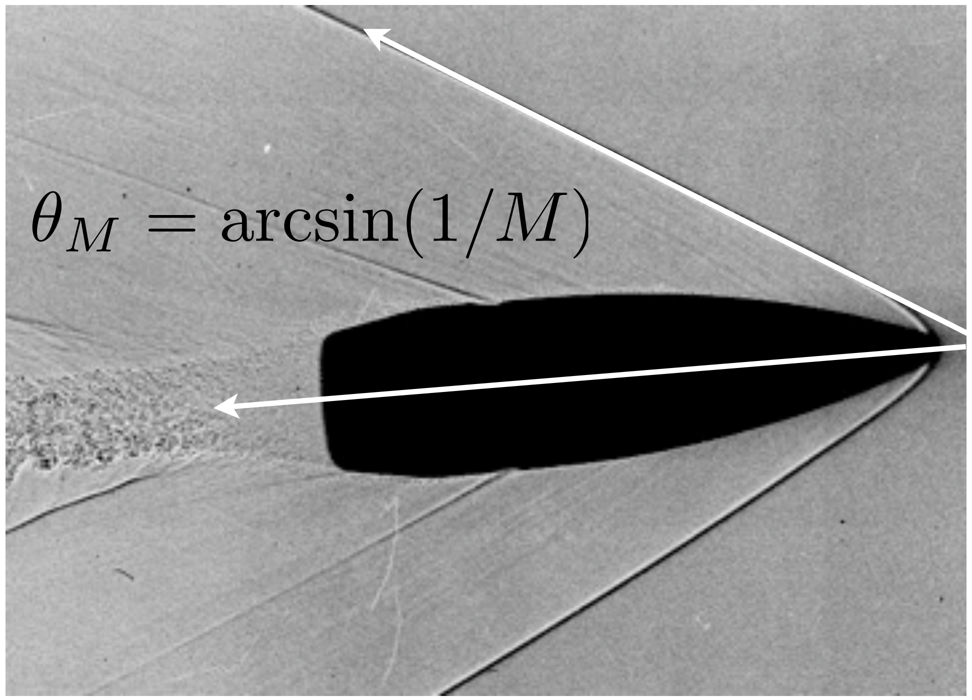


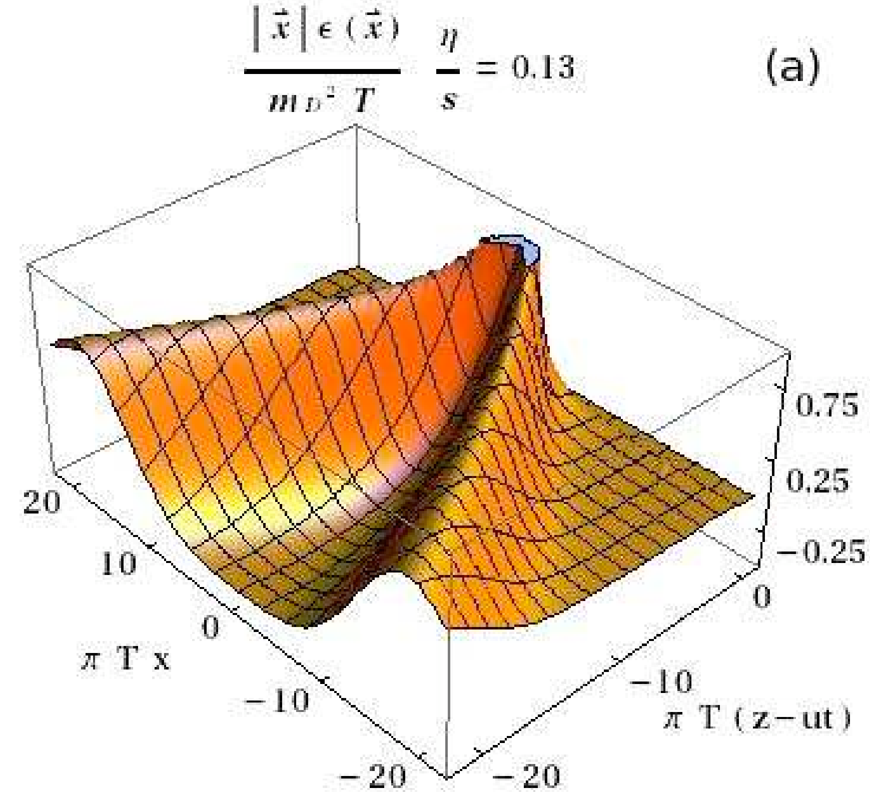
Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [24]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by its fundamental charge and interacting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

May 2006

QCD Mach Cones?



wQGP: Neufeld, Ruppert, Mueller (2008)

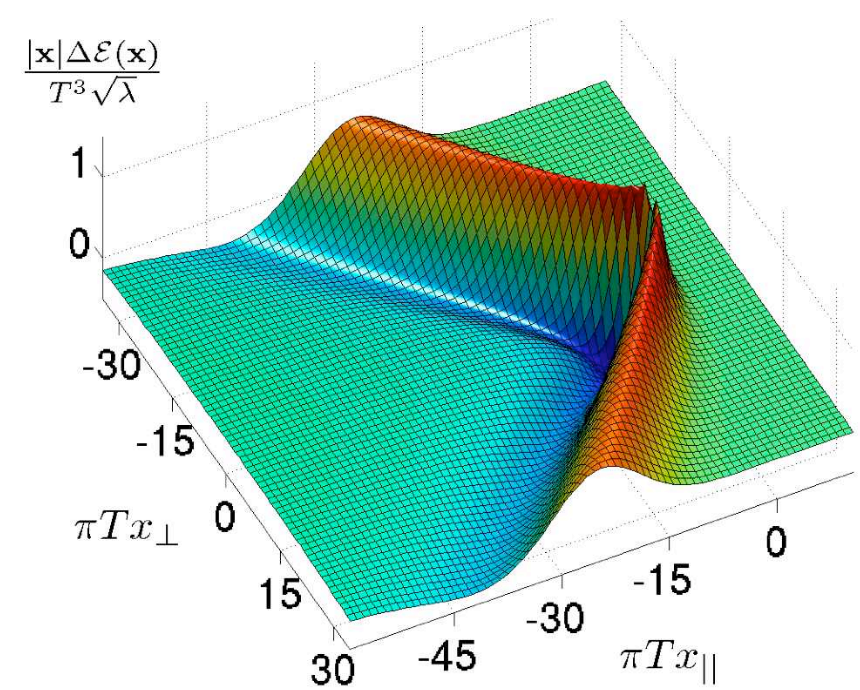


Speed of light: c
Speed of sound: c/√3

Expect shock wave ~1 radian from jet axis

Hot debate: 3p correlations

sQGP: Chesler Yaffe (2007)

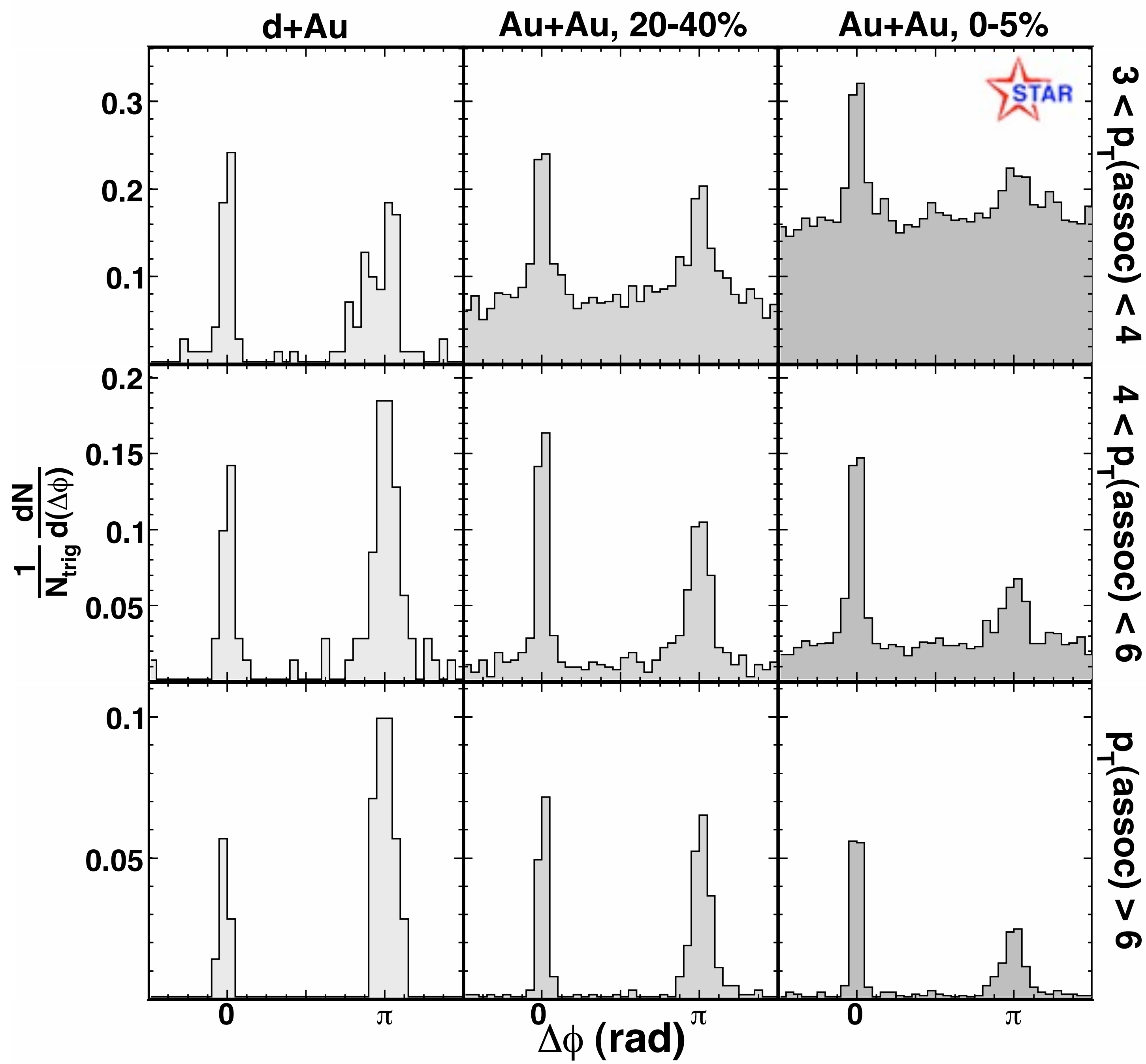


Back to Back comes back (STAR)

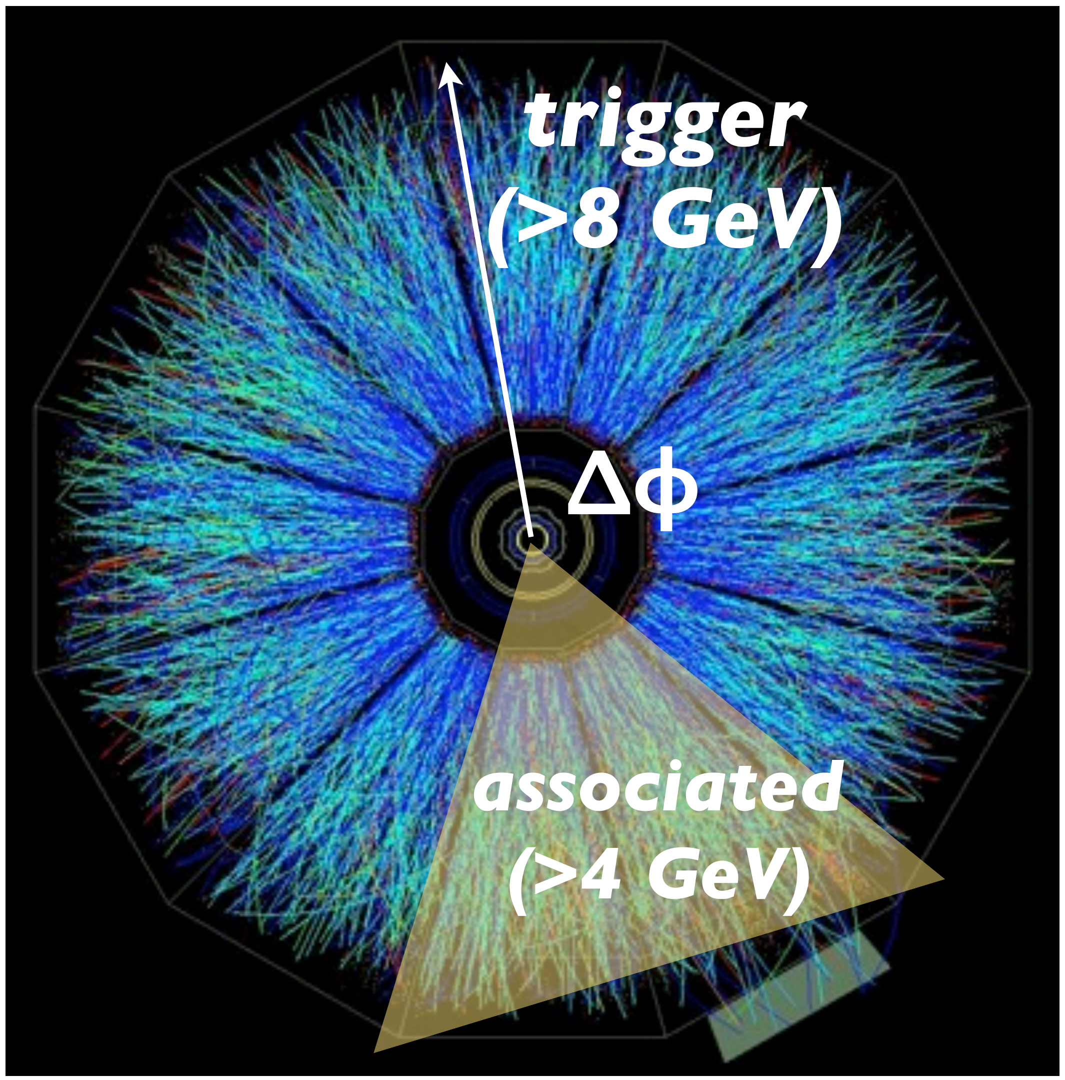
Previous results:
near-complete quenching in strongly-coupled plasma.

Raising momentum of trigger & associated particles show back-to-back jets

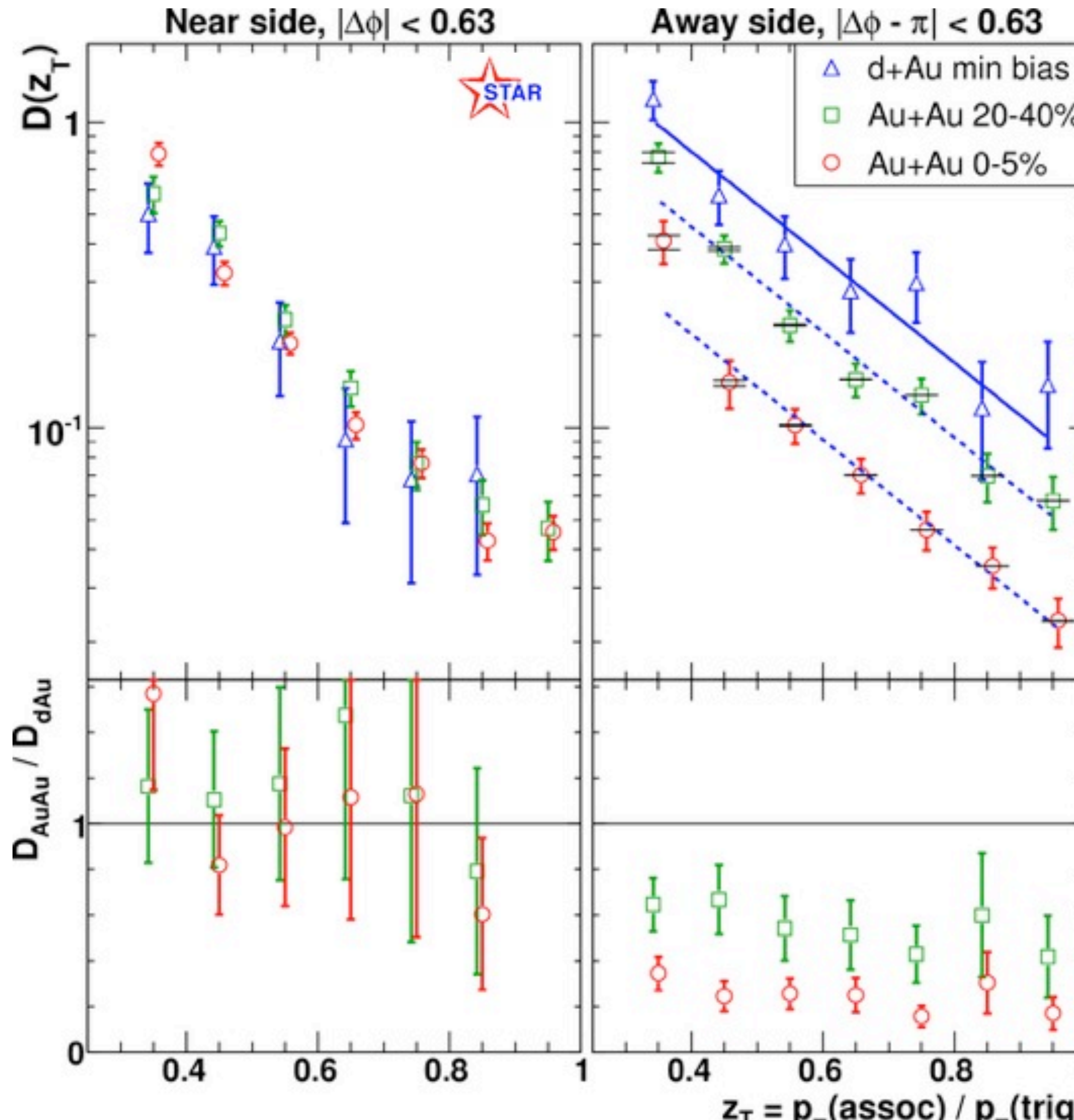
Observation of dijets in heavy ion collisions



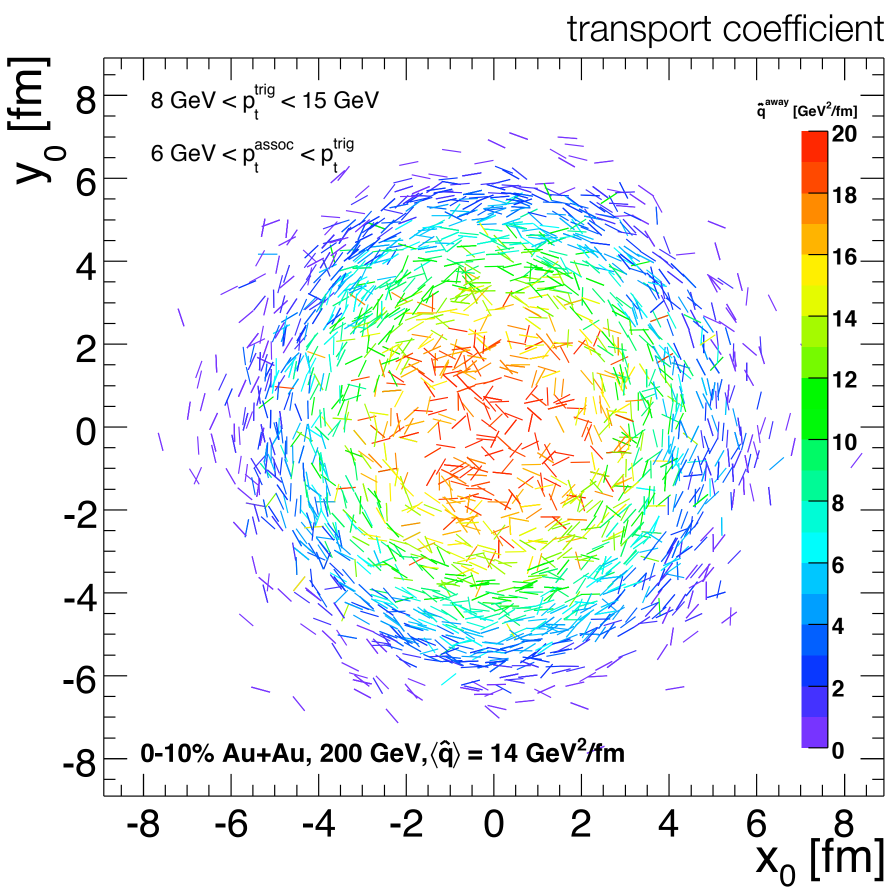
Spectral non-modification

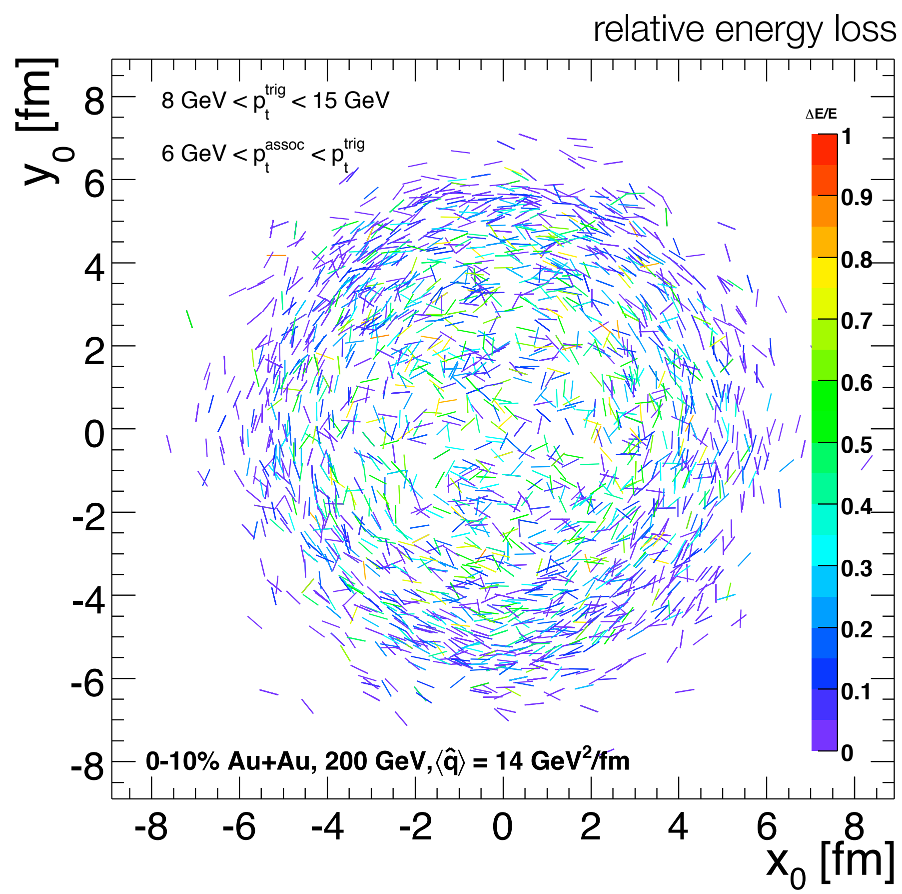


Dijet fragmentation on away side appears unmodified relative to d+Au



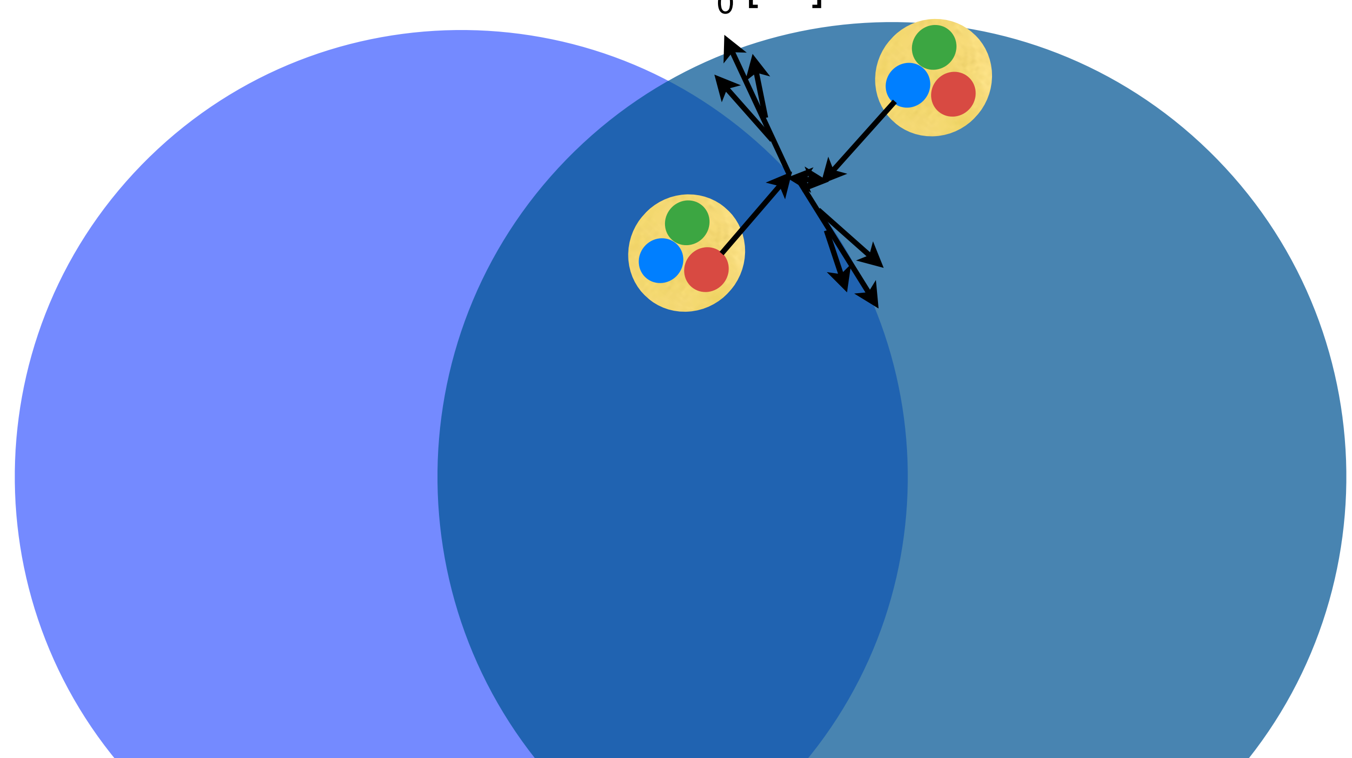
Tangential emission



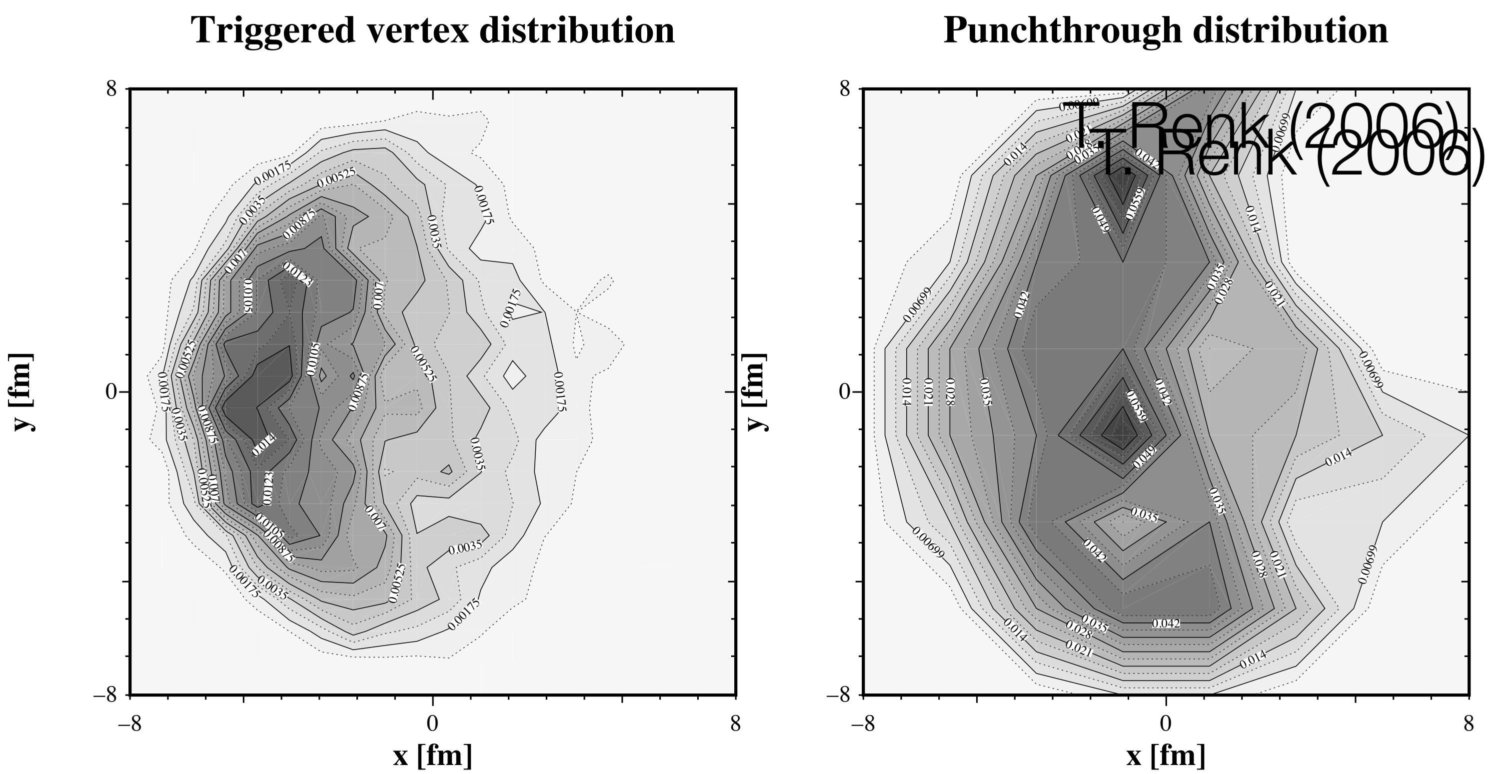


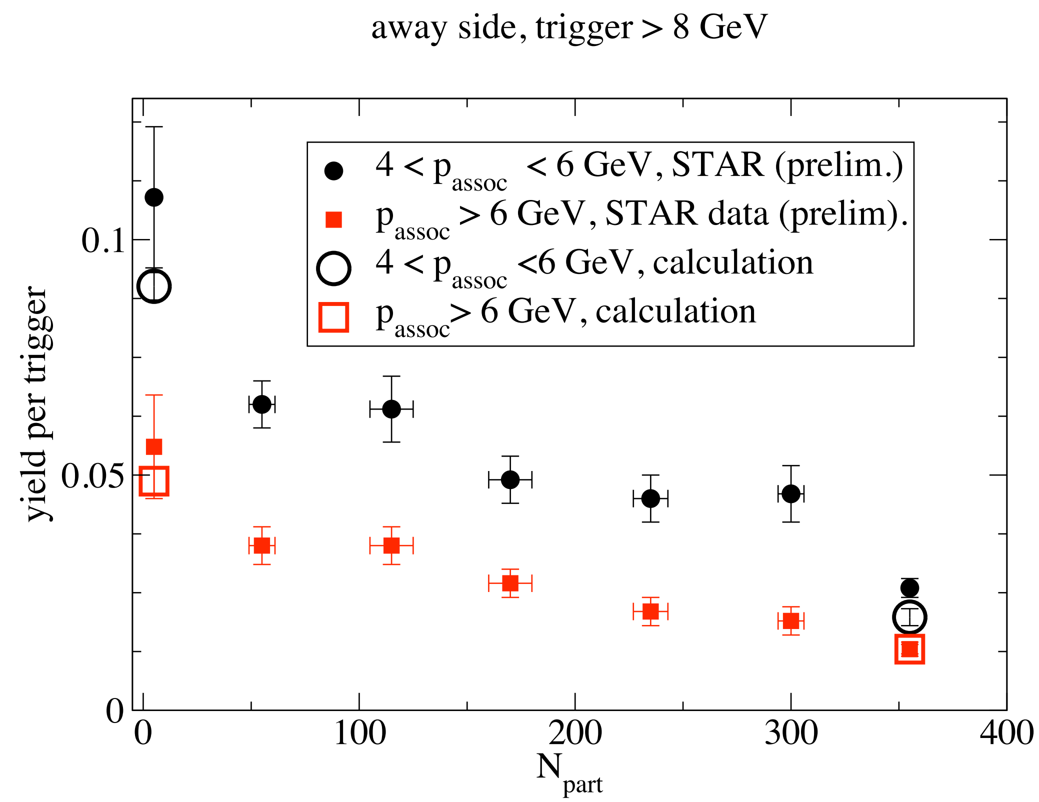
Loizides HQ06(2006)

Jet rates and no observable modification suggests that these jets “escaped”: “tangential emission”

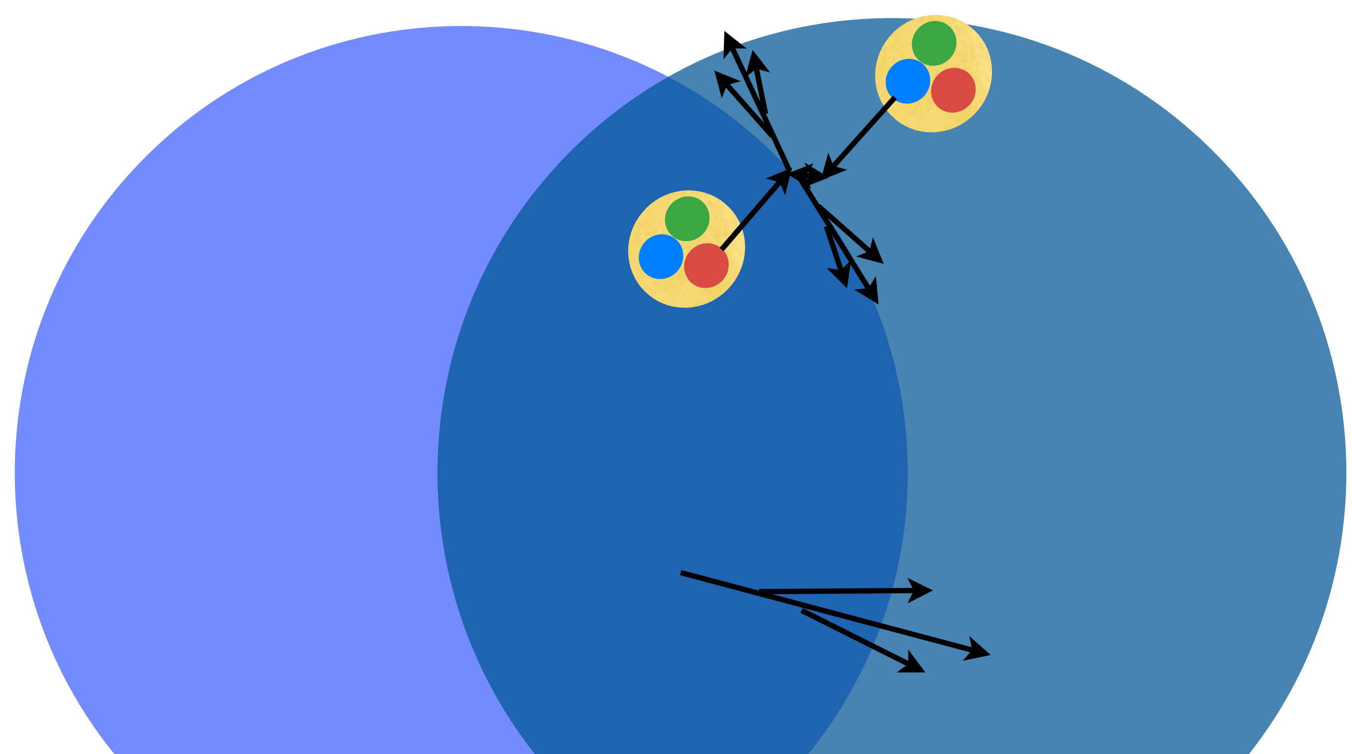


“Punch through”



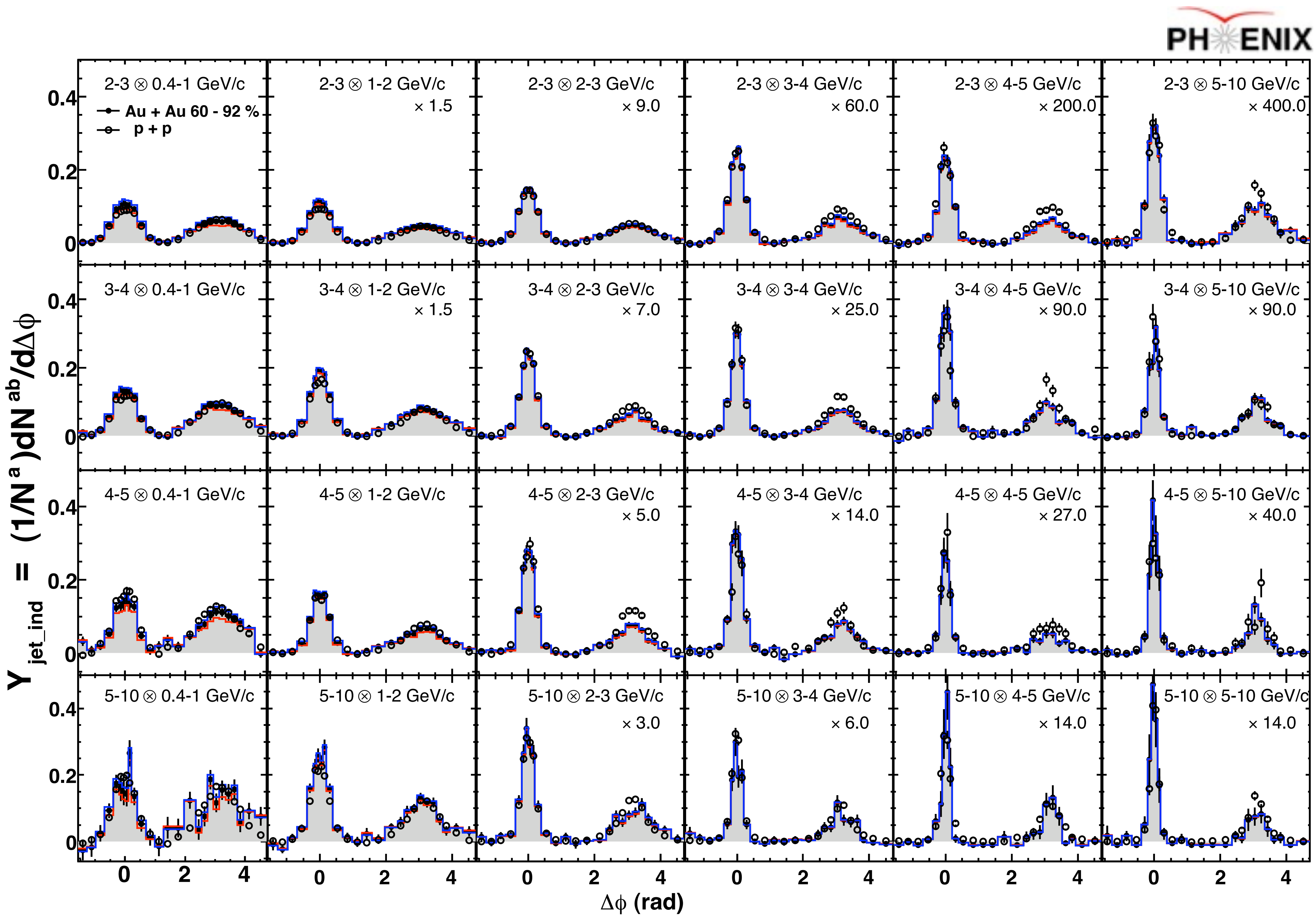


some jets will lose little energy even when passing through medium: “punch through” (25% in this case)



The Landscape of 2-particle ΔΦ correlations

CTEQ

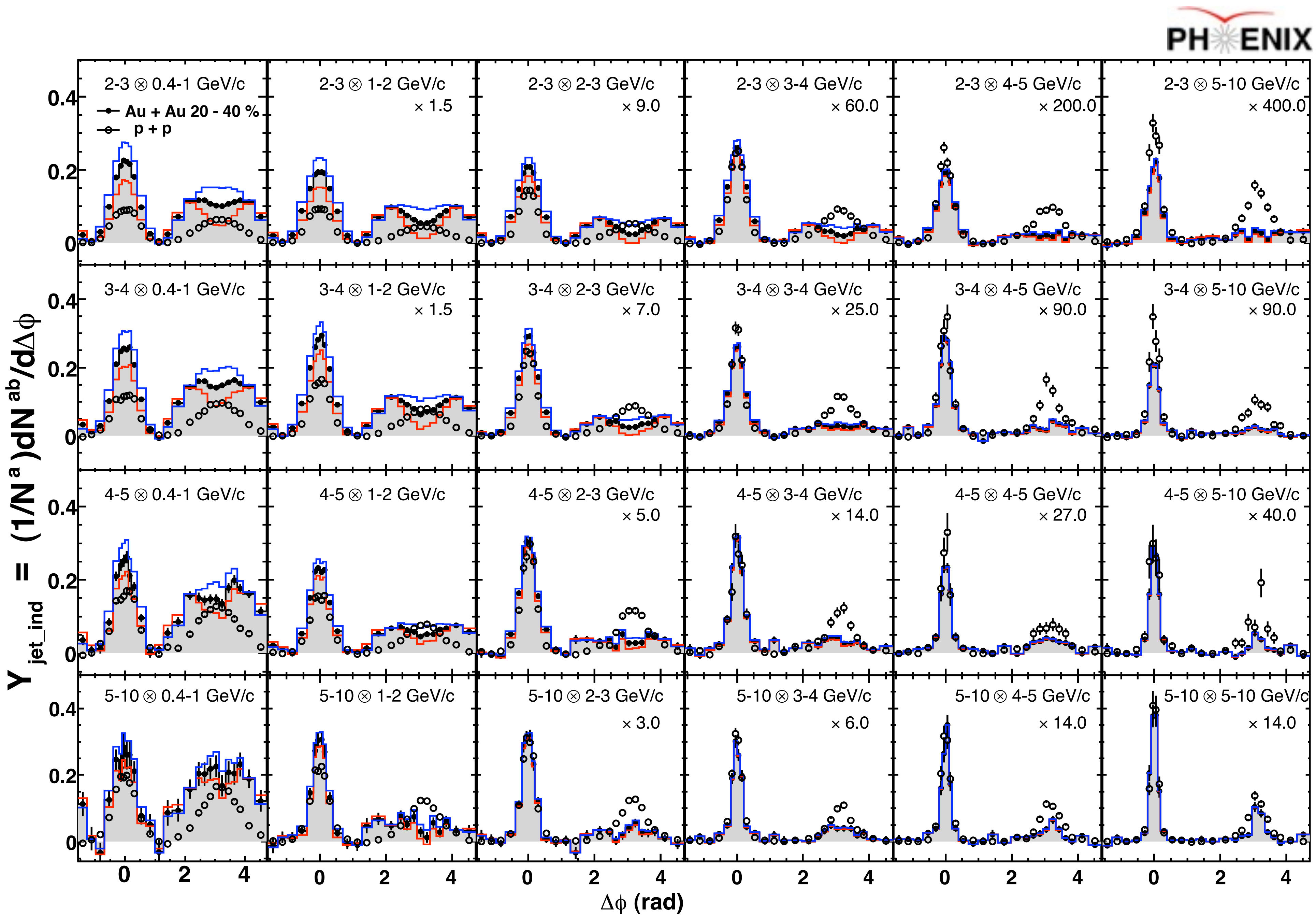


p+p

FIG. 38: (Color online) Per-trigger yield versus $\Delta\phi$ for successively increasing trigger and partner p_T ($p_T^a \otimes p_T^b$) in $p+p$ (open circles) and 60-92 % Au+Au (filled circles) collisions. Data are scaled to the vertical axes of the three left panels. Histograms indicate elliptic flow uncertainties for Au+Au collisions.

The Landscape of 2-particle ΔΦ correlations

CTEQ



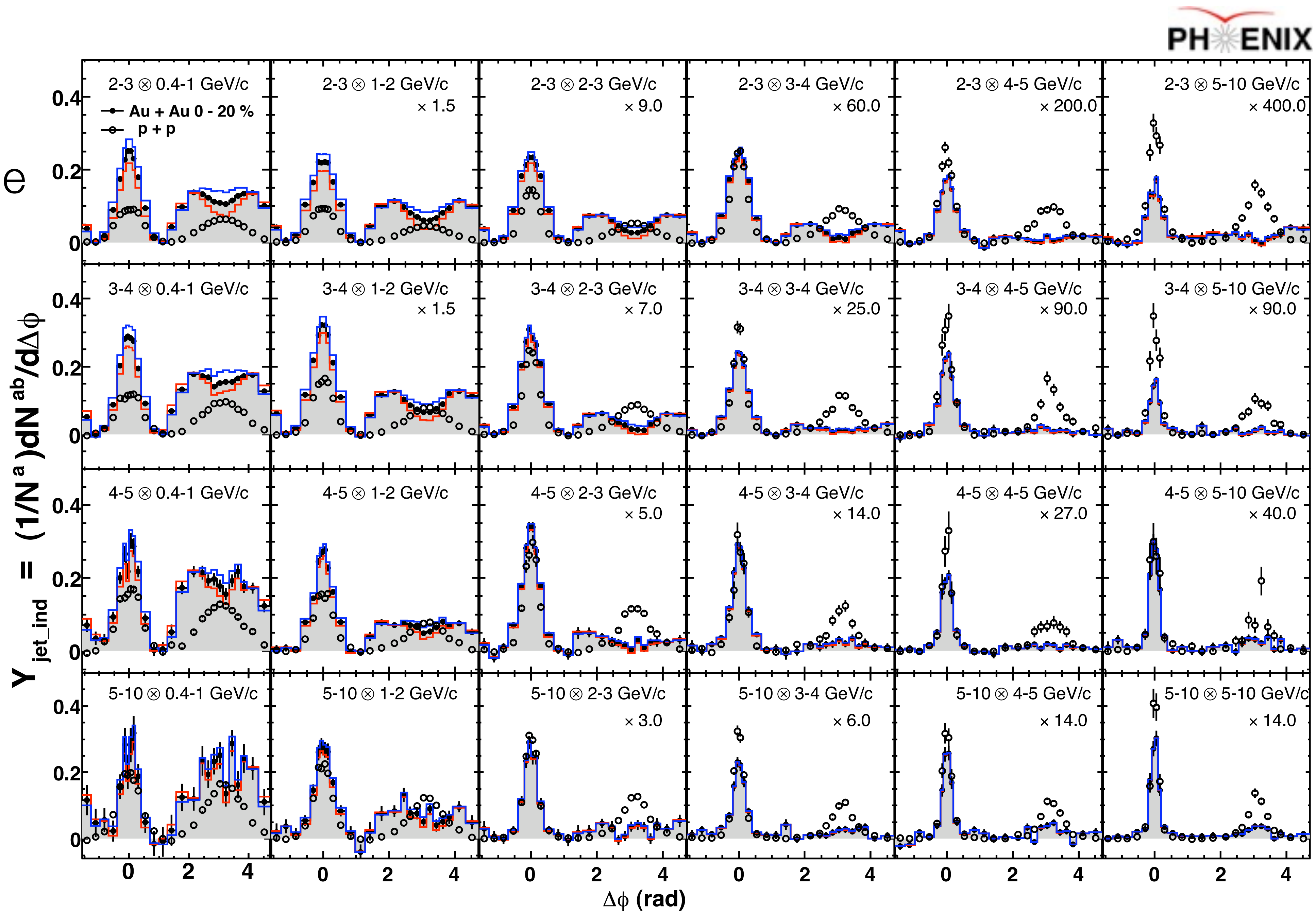
Au+Au (peripheral)

FIG. 37: (Color online) Per-trigger yield versus $\Delta\phi$ for successively increasing trigger and partner p_T ($p_T^a \otimes p_T^b$) in $p+p$ (open circles) and 20-40 % Au+Au (filled circles) collisions. Data are scaled to the vertical axes of the three left panels. Histograms indicate elliptic flow uncertainties for Au+Au collisions.

31

The Landscape of 2-particle ΔΦ correlations

mach cone + “extra”



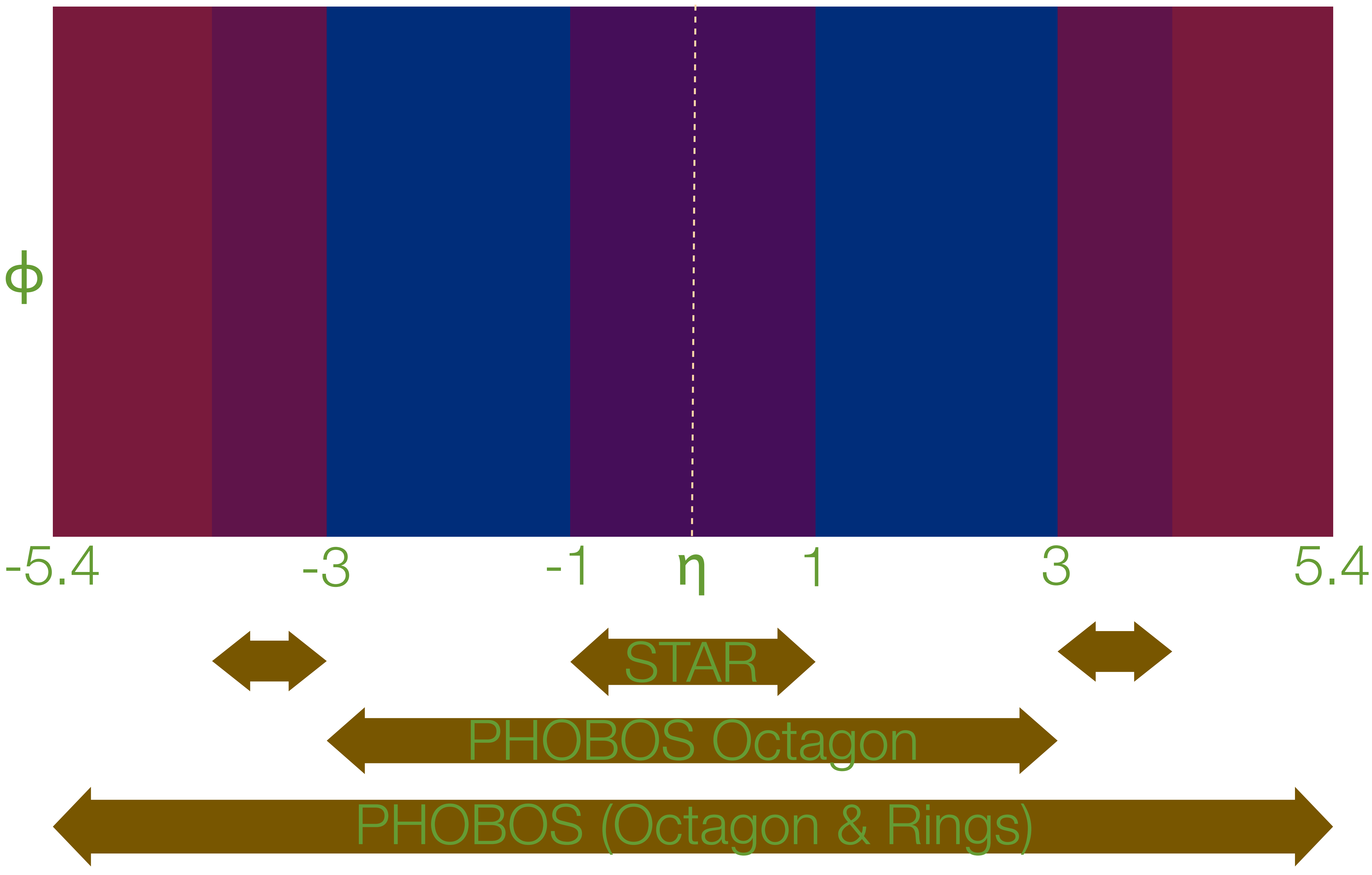
back-to-back disappearance

Au+Au (central)

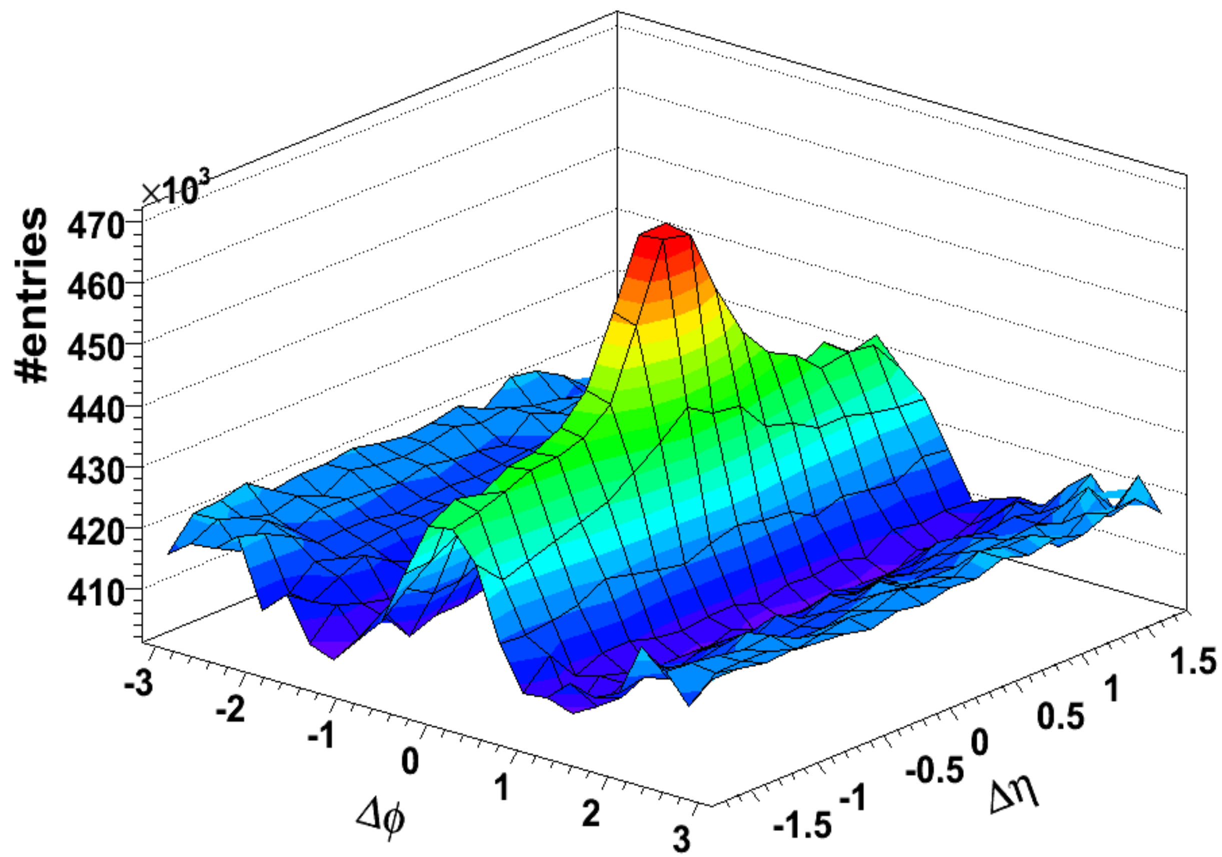
dijets

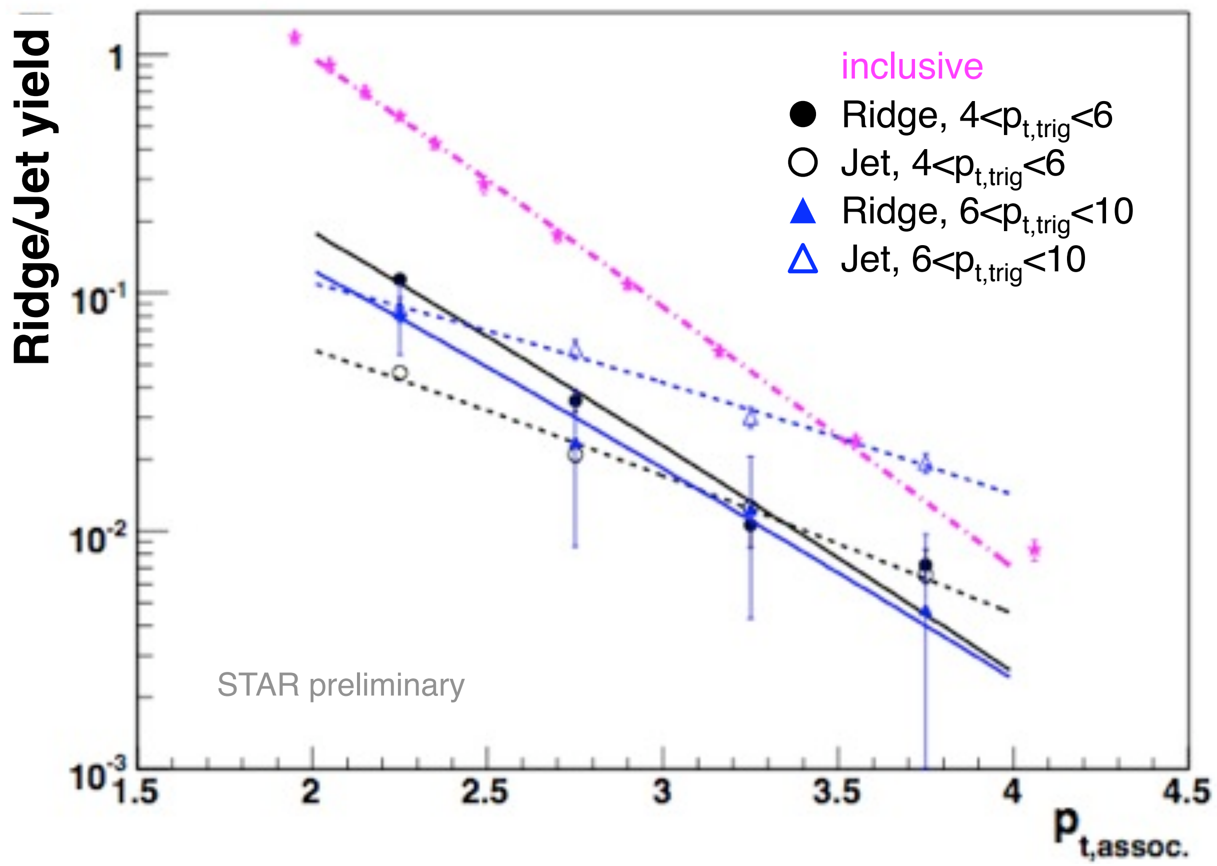
FIG. 36: (Color online) Per-trigger yield versus $\Delta\phi$ for successively increasing trigger and partner p_T ($p_T^a \otimes p_T^b$) in $p+p$ (open circles) and 0-20 % Au+Au (filled circles) collisions. Data are scaled to the vertical axes of the four left panels. Histograms indicate elliptic flow uncertainties for Au+Au collisions.

What about Δη?



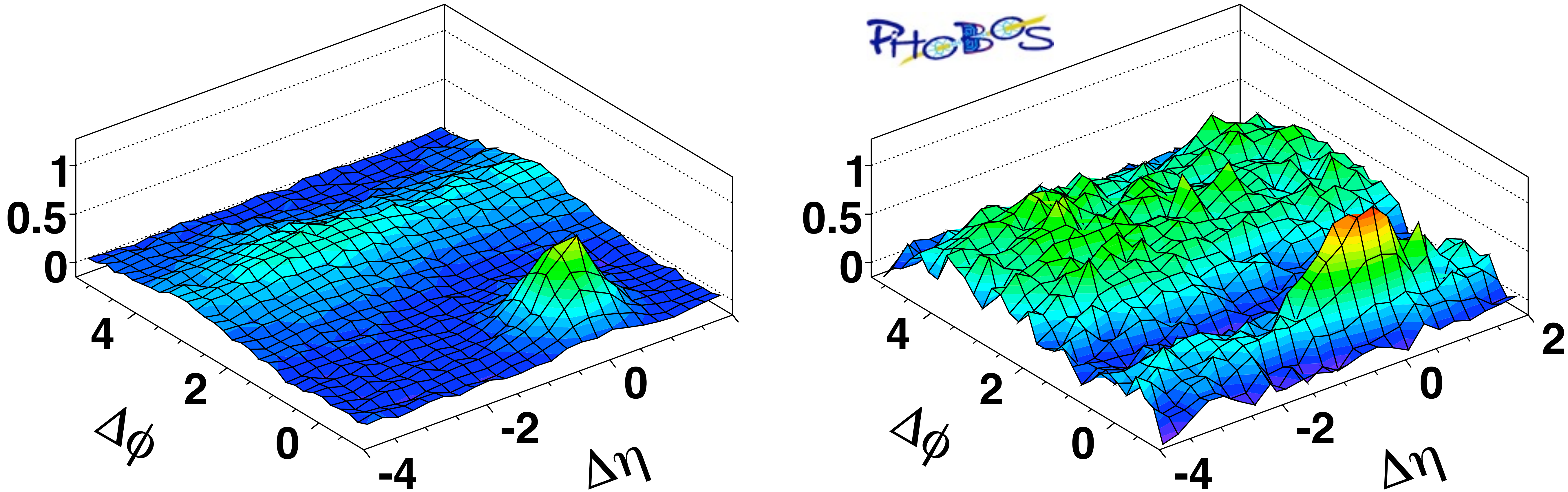
The STAR "ridge"





A surprising feature not predicted by anyone: extended longitudinal correlations, with excess reflecting properties of the "thermal" bulk

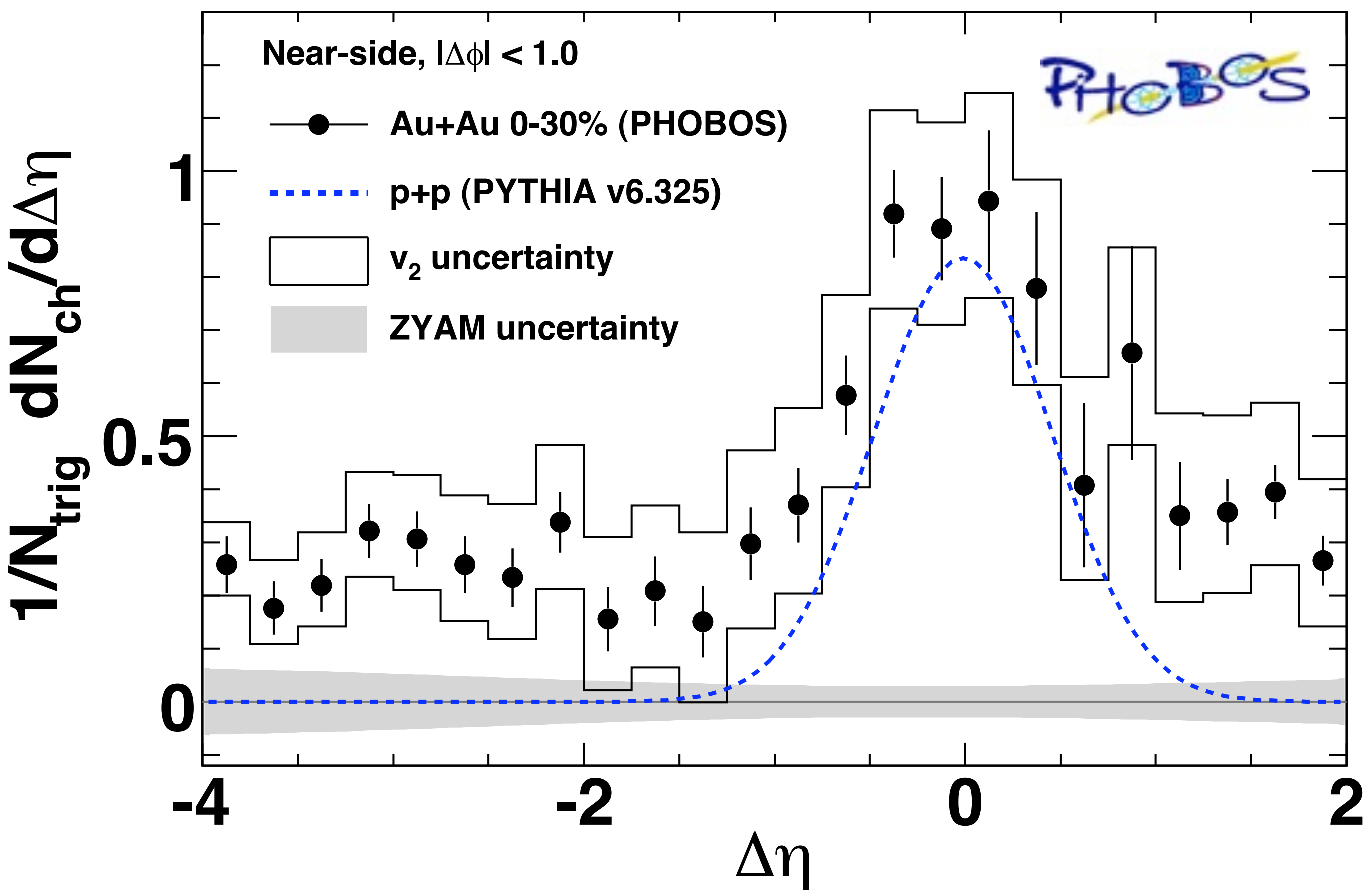
Long-range modifications

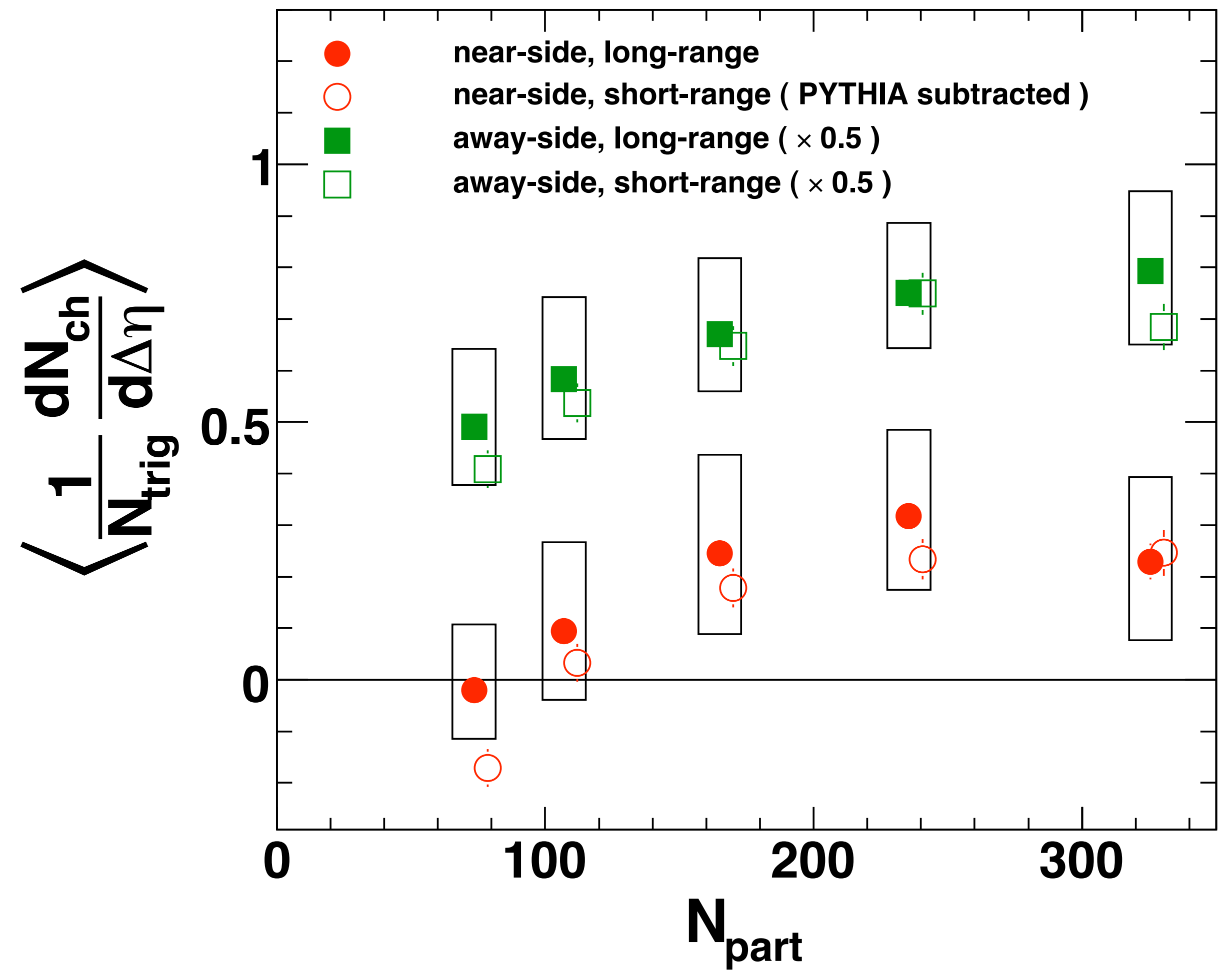


PHOBOS has measured a large-acceptance correlation function for p_T(trigger) > 2.5 GeV
(PYTHIA used for p+p reference, confirmed by STAR data)

http://arxiv.org/abs/0903.2811

“The Ridge”





Substantial correlated yield out to **Δη**=4
Jet yield on near side seems to sit “on top” of the “ridge”

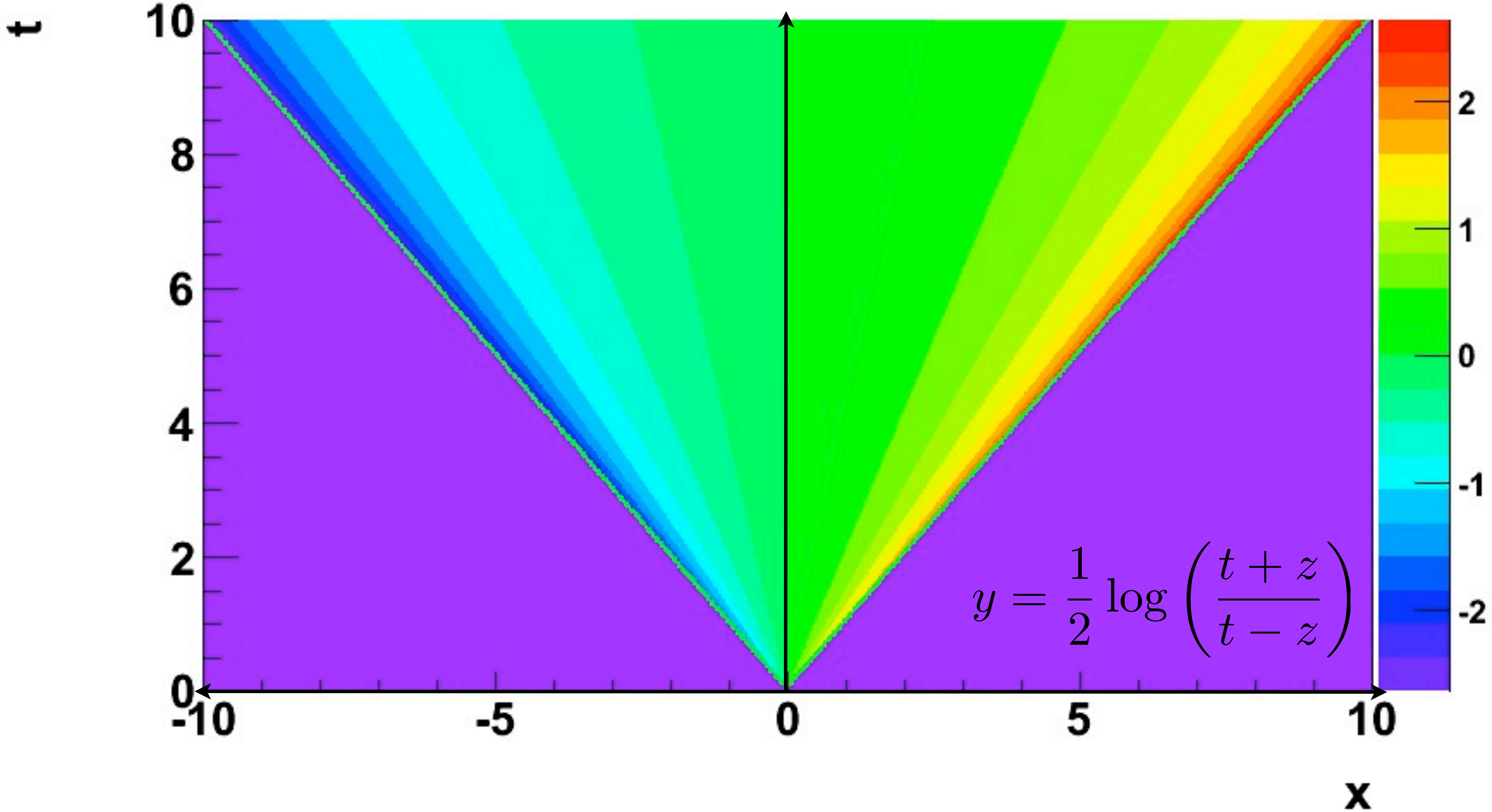
http://arxiv.org/abs/0903.2811

The Problem of the Ridge

- **Coupling of induced radiation to longitudinal flow**
  Armesto et al., PRL 93, 242301
- **Recombination of shower + thermal partons**
  Hwa, arXiv:nucl-th/0609017v1
- **Anisotropic plasma**
  Romatschke, PRC 75, 014901
- **Turbulent color fields**
  Shuryak, arXiv:0706.3531v1
- **Bremsstrahlung + transverse flow + jet-quenching**
  Majumder, Muller, Bass, arXiv:hep-ph/0611135v2
- **Splashback from away-side shock**
  Pantuev, arXiv:0710.1882v1
- **Momentum kick imparted on medium partons**
  Wong, arXiv:0707.2385v2
- **Glasma Flux Tubes**
  Dumitru, Gelis, McLerran, Venugopalan, arXiv:0804.3858; Gavin, McLerran, Moscelli, arXiv:0806.4718

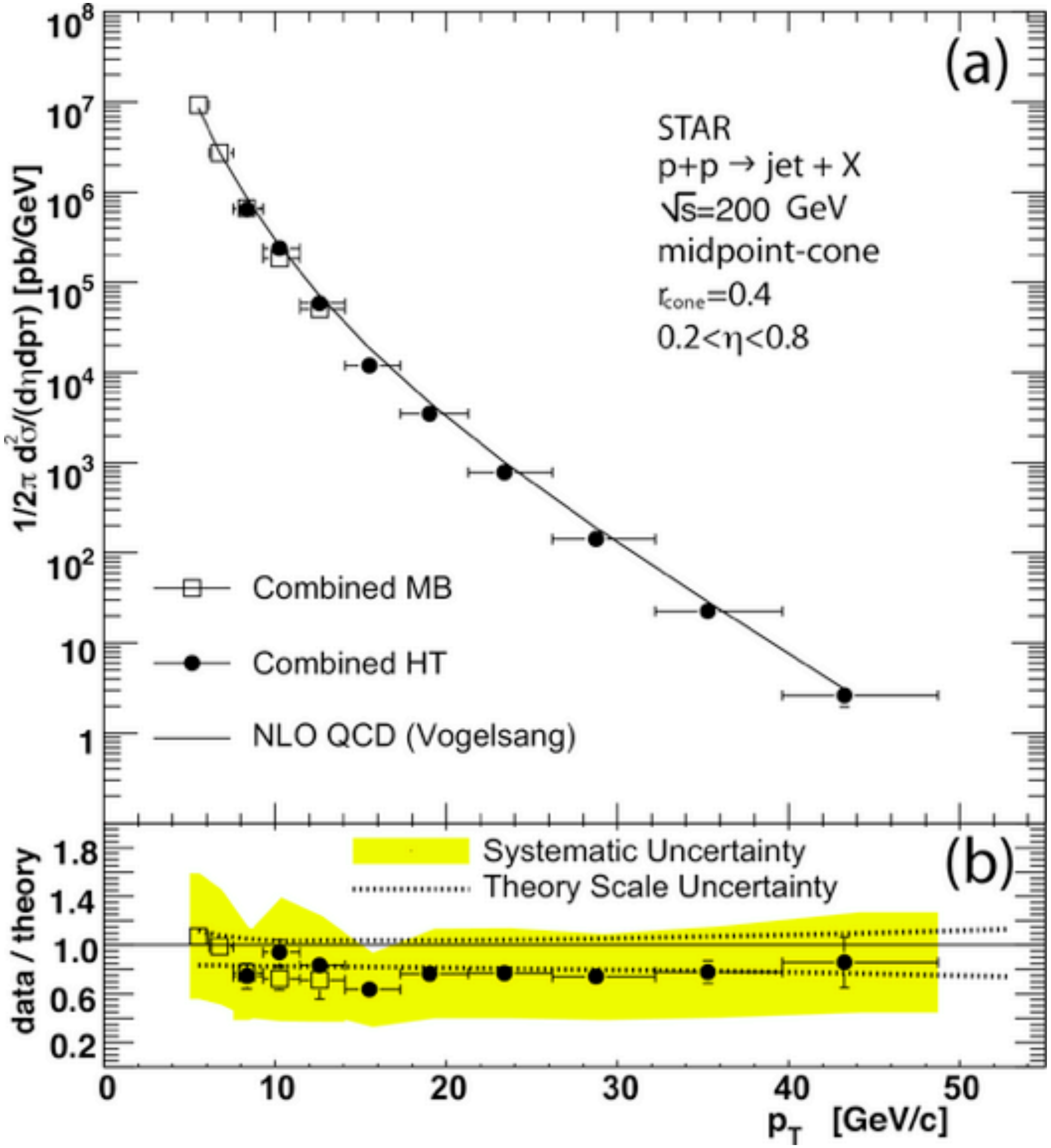
E. Wenger (QM2008)

The Problem of the Ridge



Jumping rapidity bins requires large spatial correlation, unless takes place at early time

Jets @ RHIC



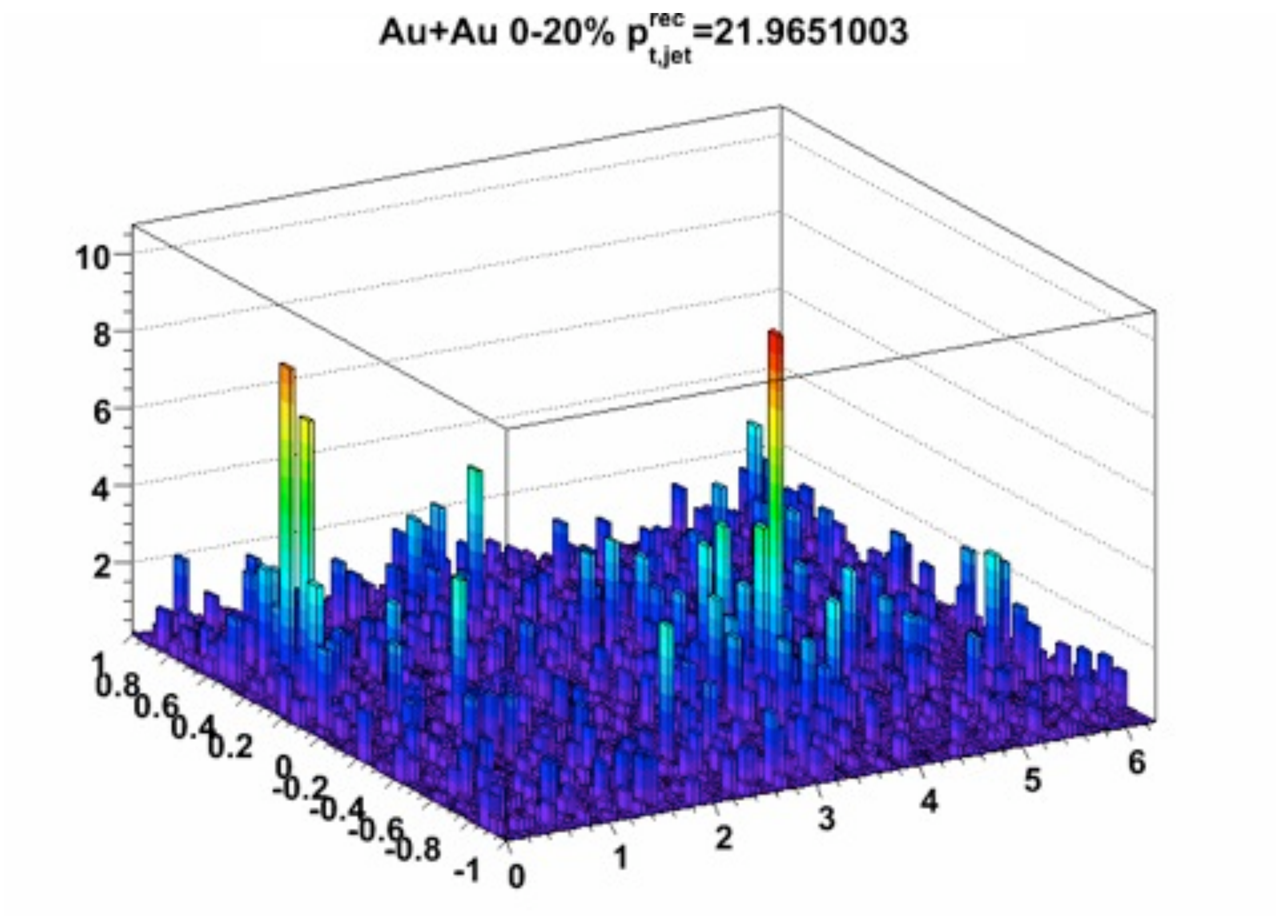
Midpoint cone R=0.4

- neutral energy from EMC
- charged particles from TPC

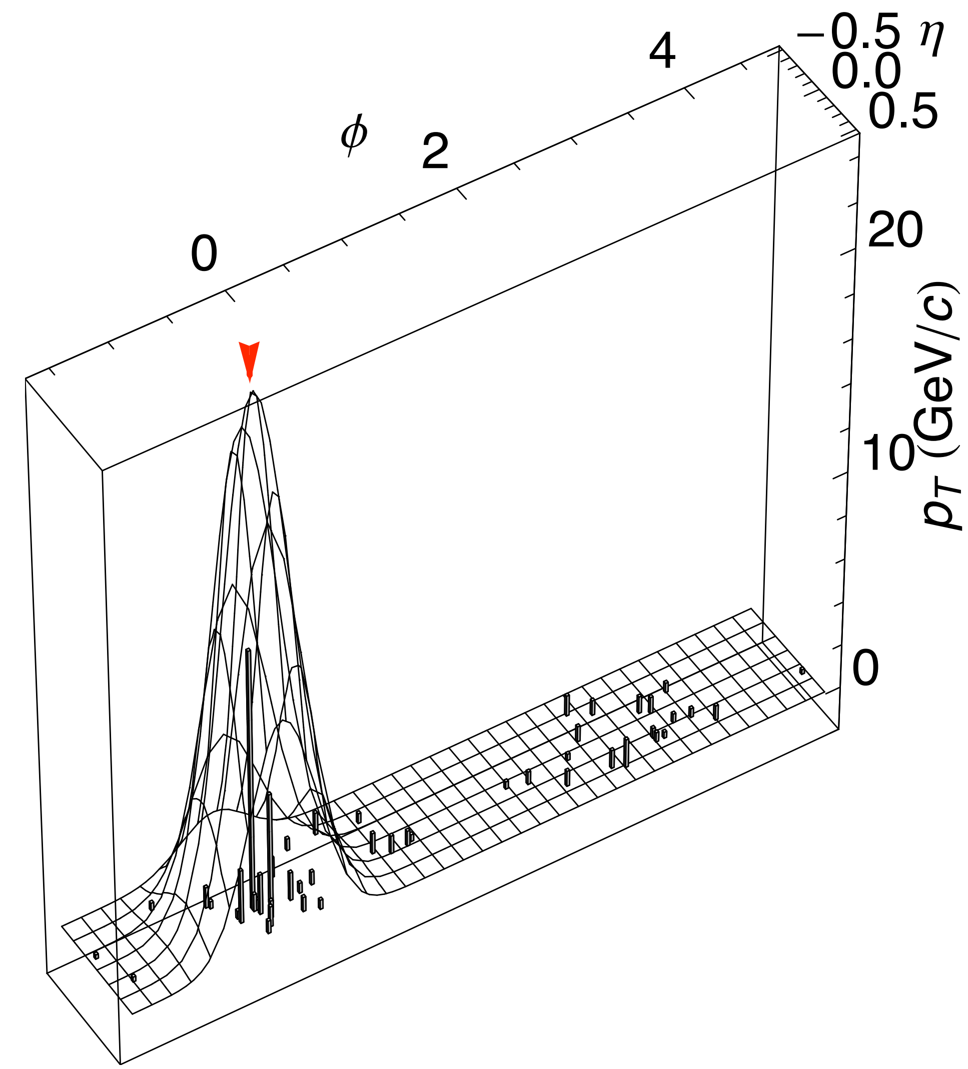
Good agreement with NLO pQCD

Experimental uncertainties are large (50%)

Jets in Heavy Ions



STAR



PHENIX

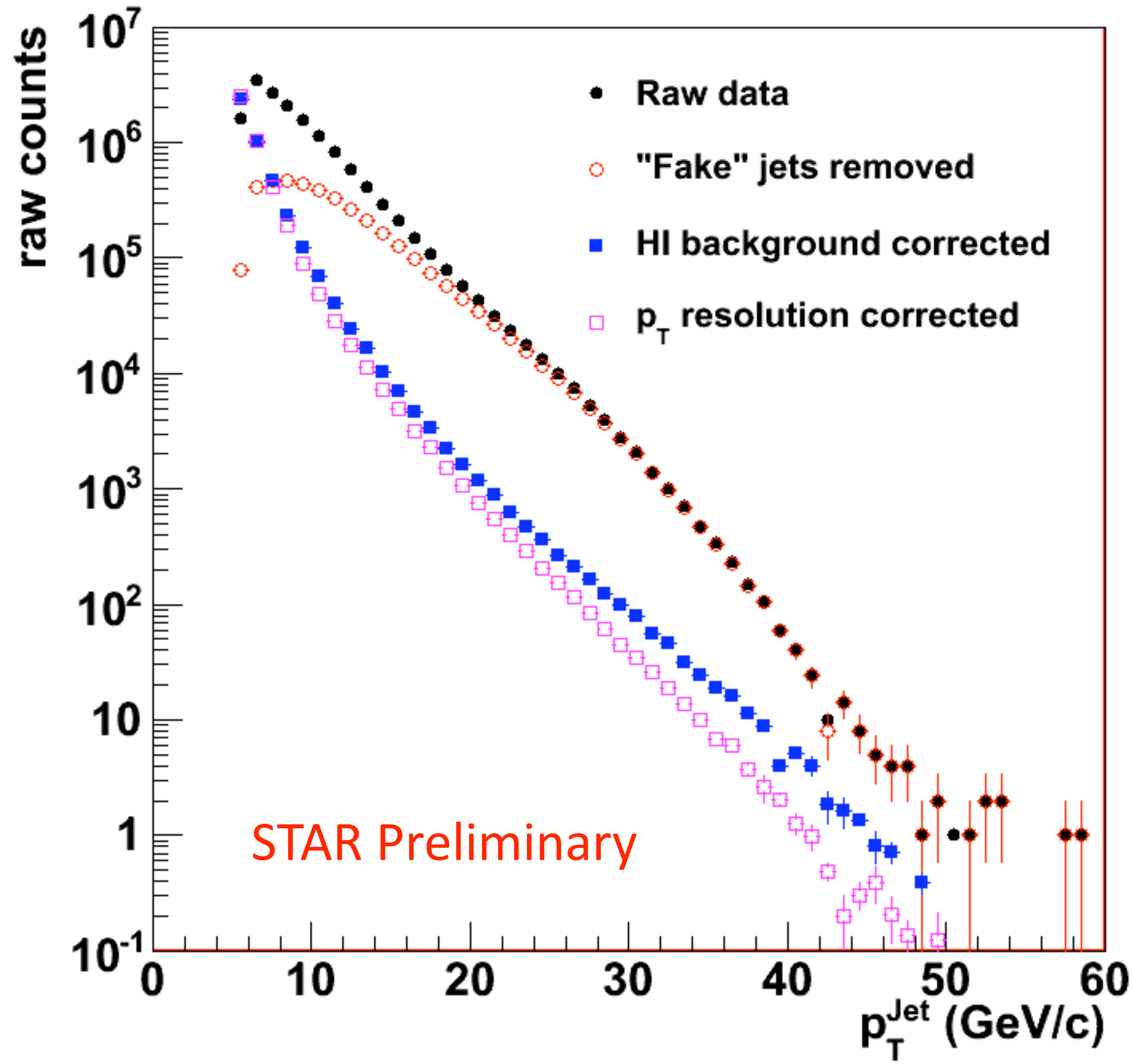
Despite enormous multiplicities, experiments @ RHIC are starting to reconstruct jets even in nuclear collisions

STAR jet spectrum extraction

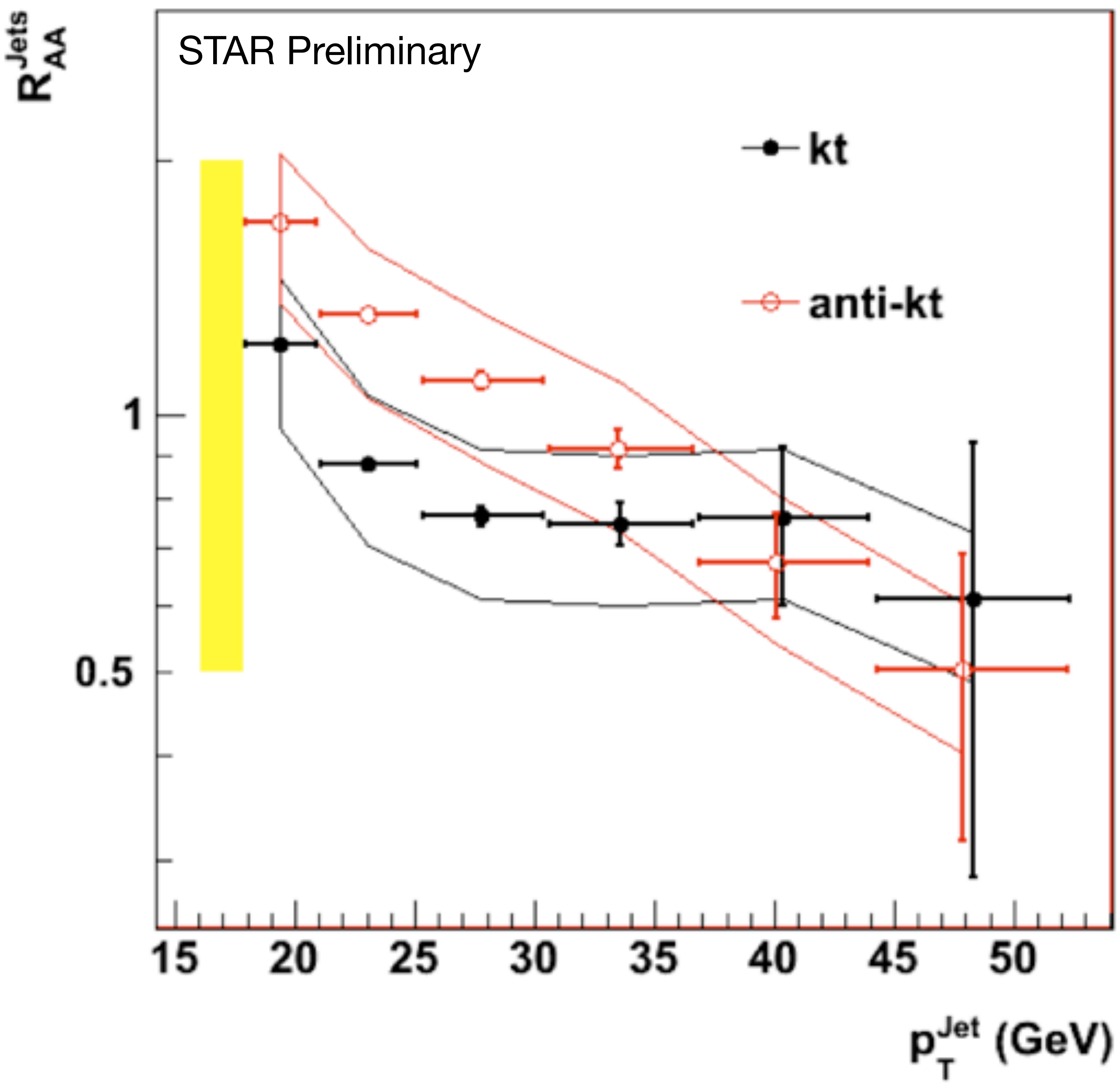
CTEQ

Running k_T and anti-k_T algorithms, but with small cone sizes of R=0.2, 0.4

Need to reject fakes (look at "jets" at 90°), remove background (pedestal subtract) and unfold spectrum (correct for resolution)



Jet suppression at RHIC

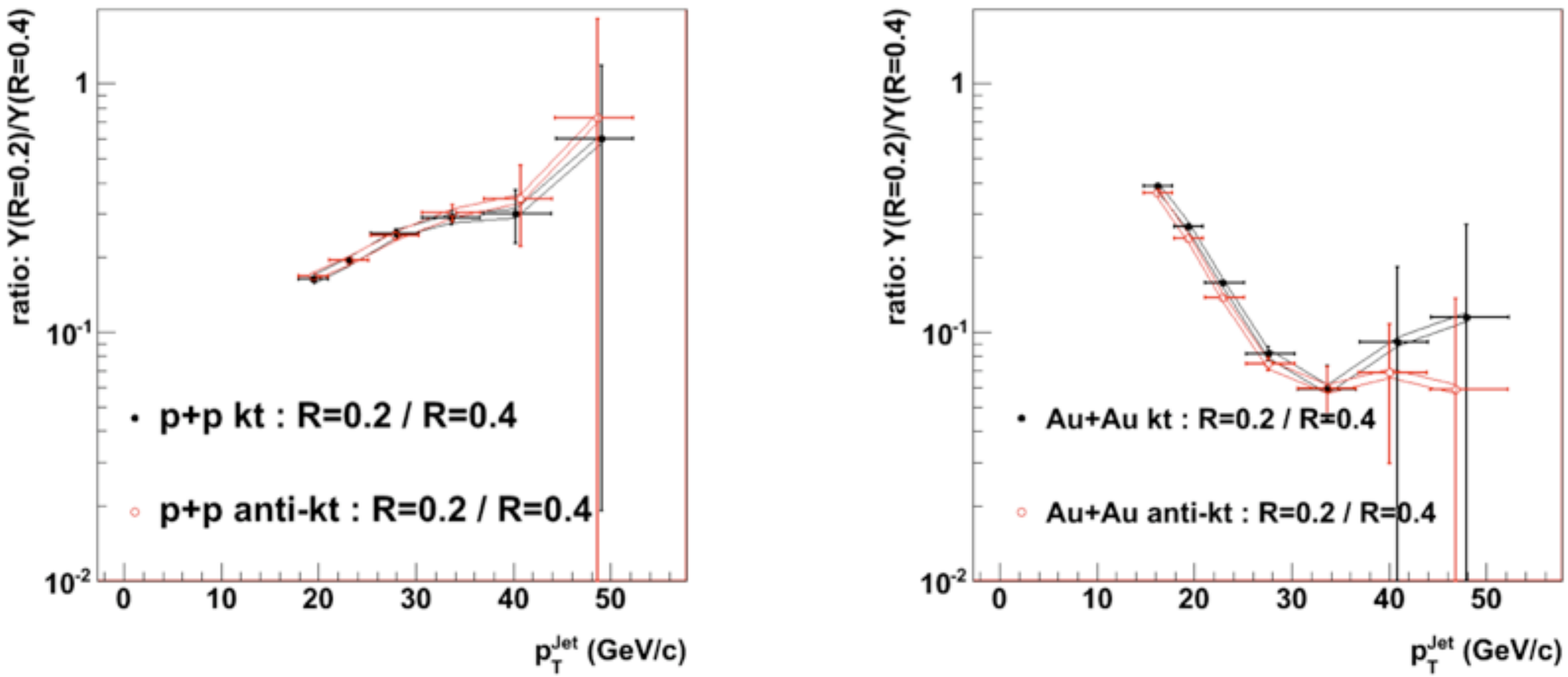


Strong algorithm dependence

No substantial suppression of jets themselves

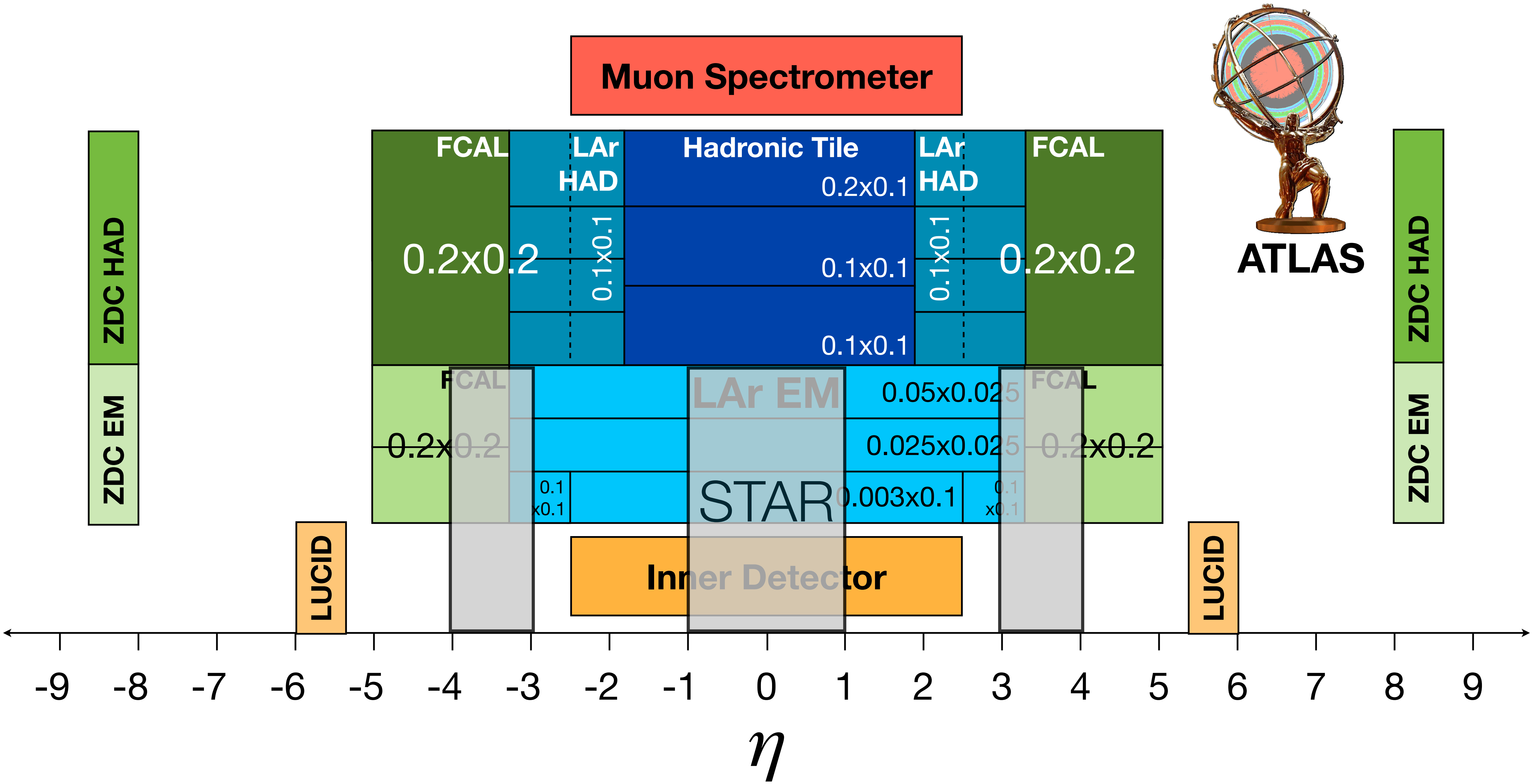
Suggestive that it is mainly the fragmentation that is modified

First measurements of jet shape



Comparison of jets with R=0.2 & 0.4
suggest that jets in Au+Au get broader with p_T
(cf. p+p, where they apparently narrow)

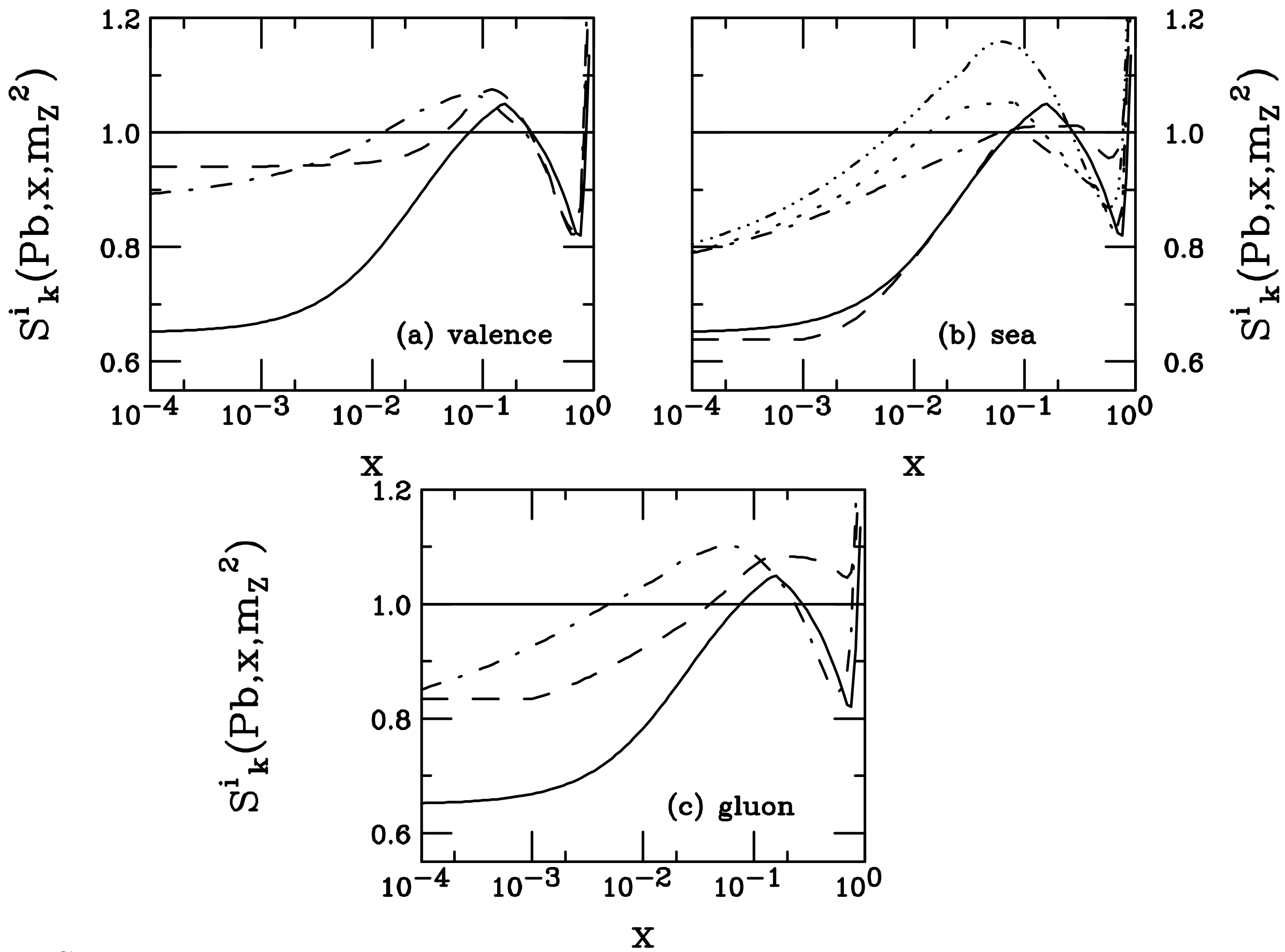
The Future of Jets in HI (ATLAS case)



The LHC detectors provide unprecedented capability for high p_T

Z as a probe of nuclear PDFs

PDFs show “shadowing” at low-x



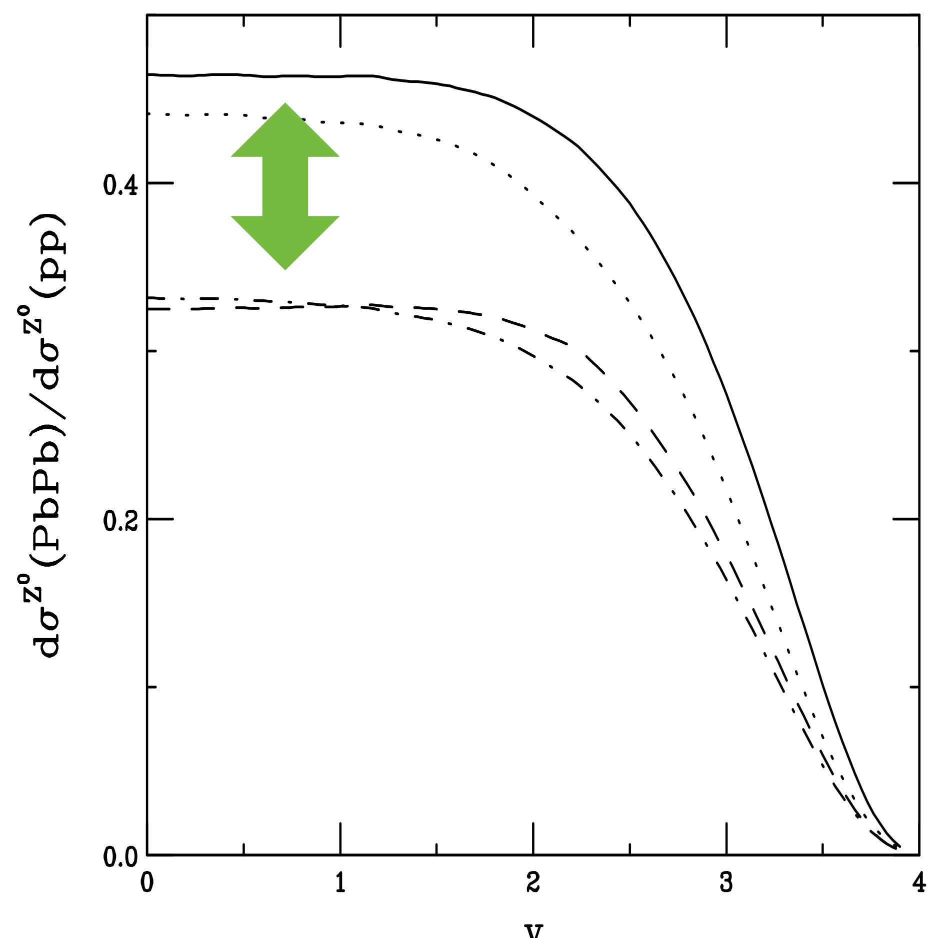
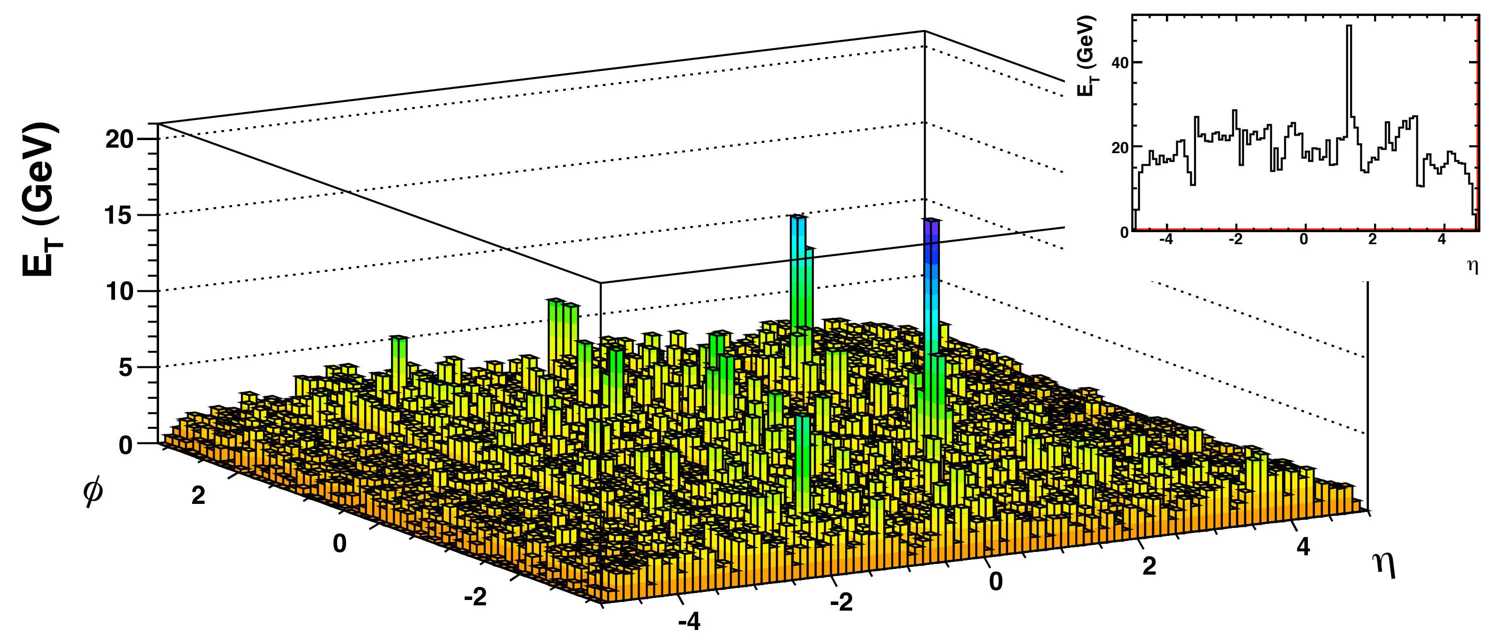


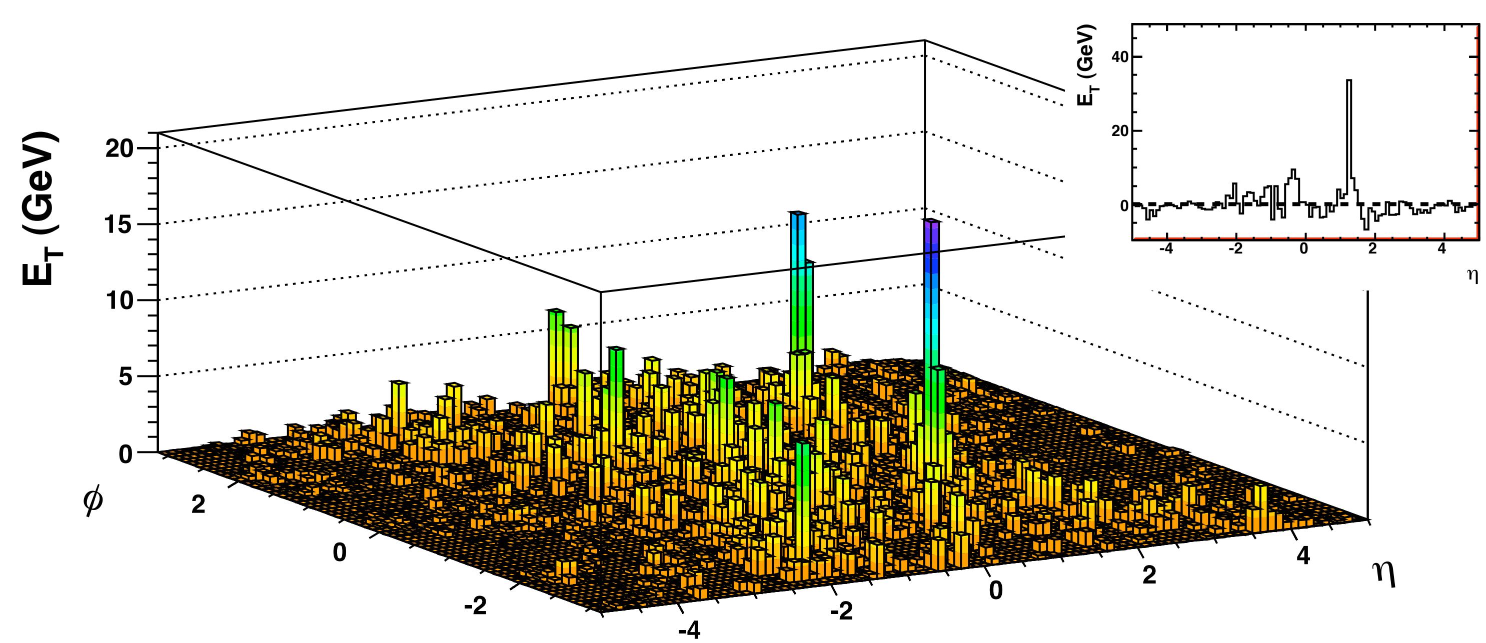
FIG. 10. The ratios of the Z^0 rapidity distributions in Pb+Pb collisions relative to pp collisions, calculated with the MRST HO distributions. The solid curve is the ratio without shadowing. The homogeneous shadowing results are given in the dashed, S_1, dot-dashed, S_2, and dotted, S_3, lines.

At the LHC, can use the production of Z bosons as a background-free probe of the very initial PDFs.
Expect 1000’s of Z’s each LHC year

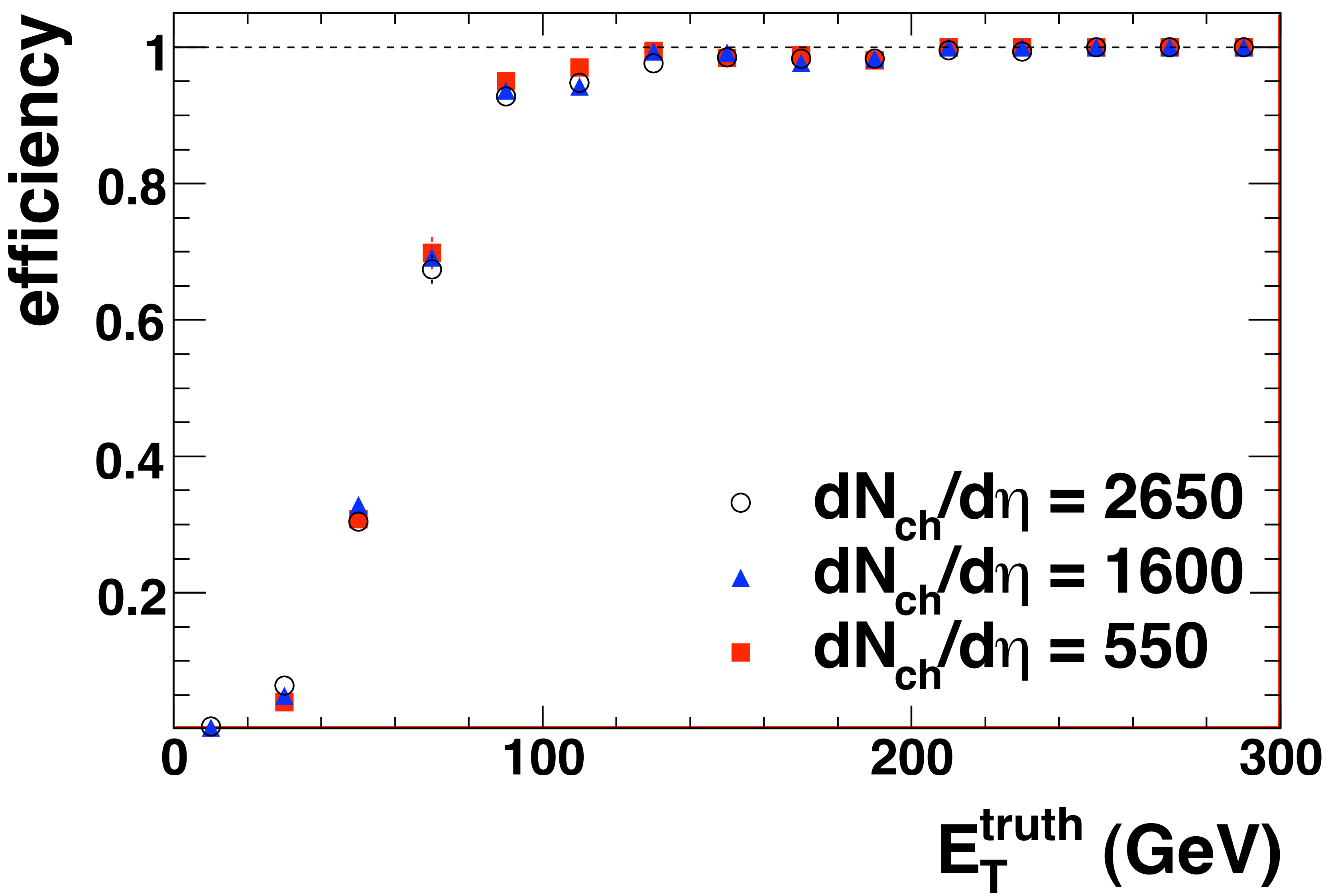
Jet Finding in HI

- Cells collected in to 0.1x0.1 Towers
- Seed finding used to exclude candidate jets
- Background calculated in Eta bins, subtracted layer by layer
- Seeded midpoint cone algorithm to find jets
- Calibrations applied after jet finding





Jet Efficiency

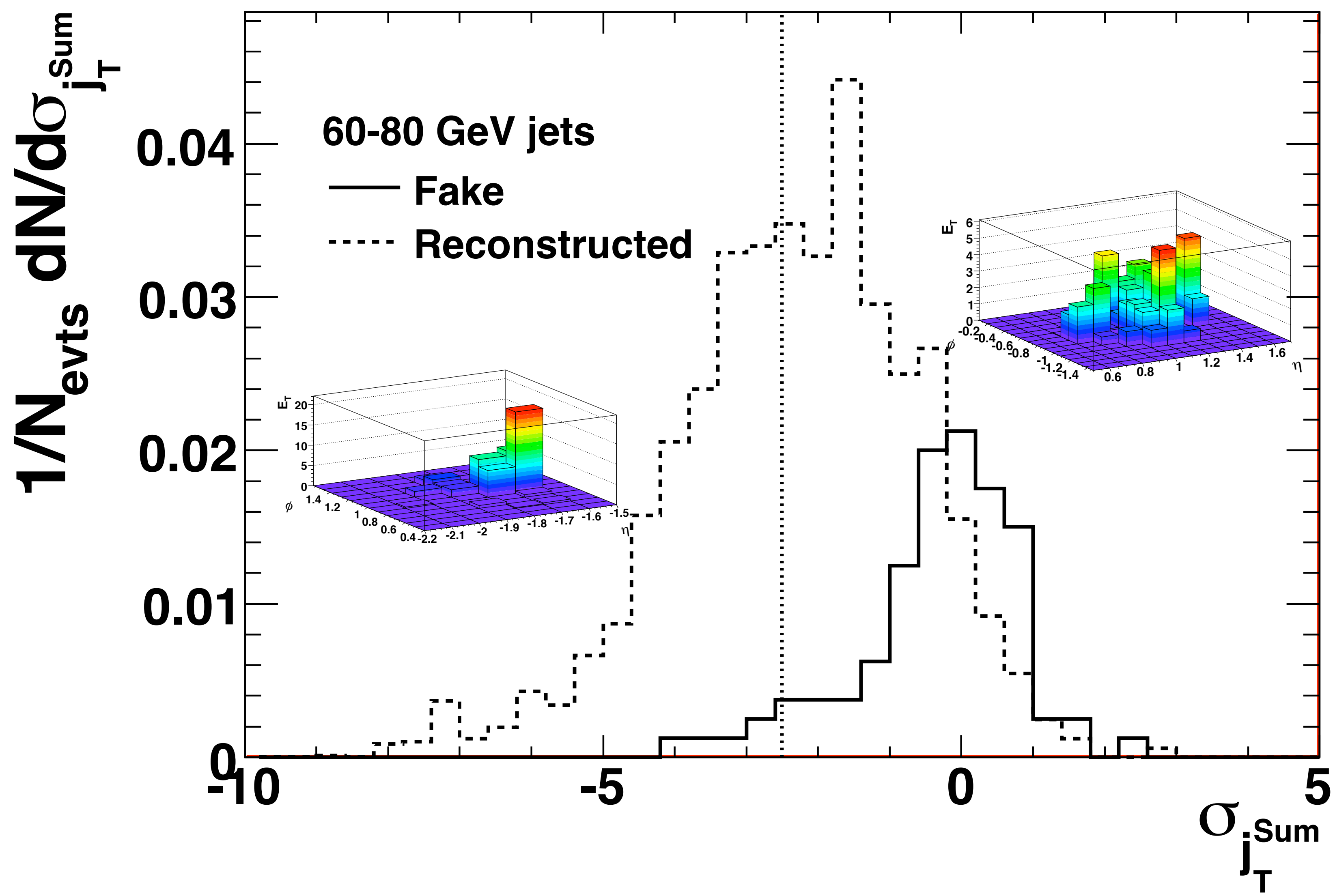


Efficiency turn-on curve reaches 100% at ~100 GeV
(it's "easy" above that energy)

Fake Jets

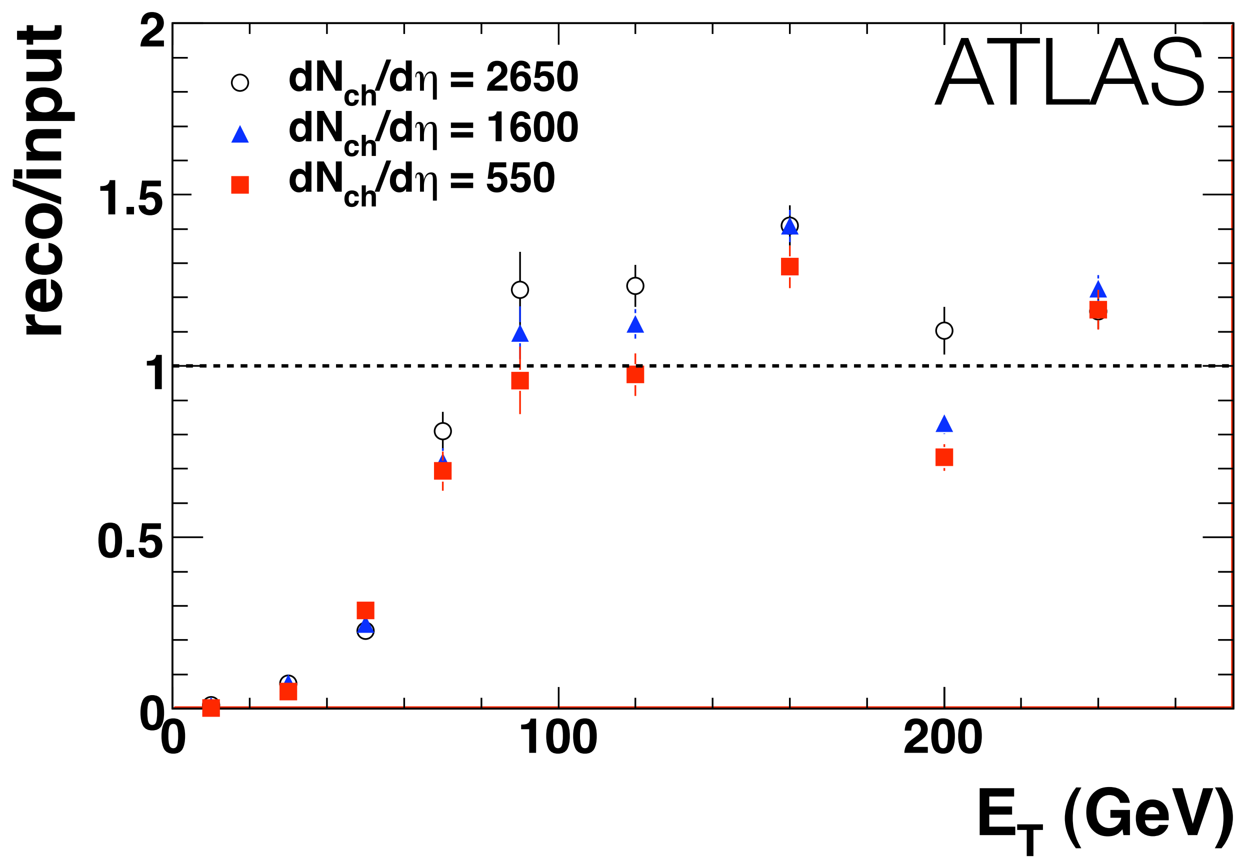
"Jets" triggered by a seed and supported by background have a different shape than normal jets

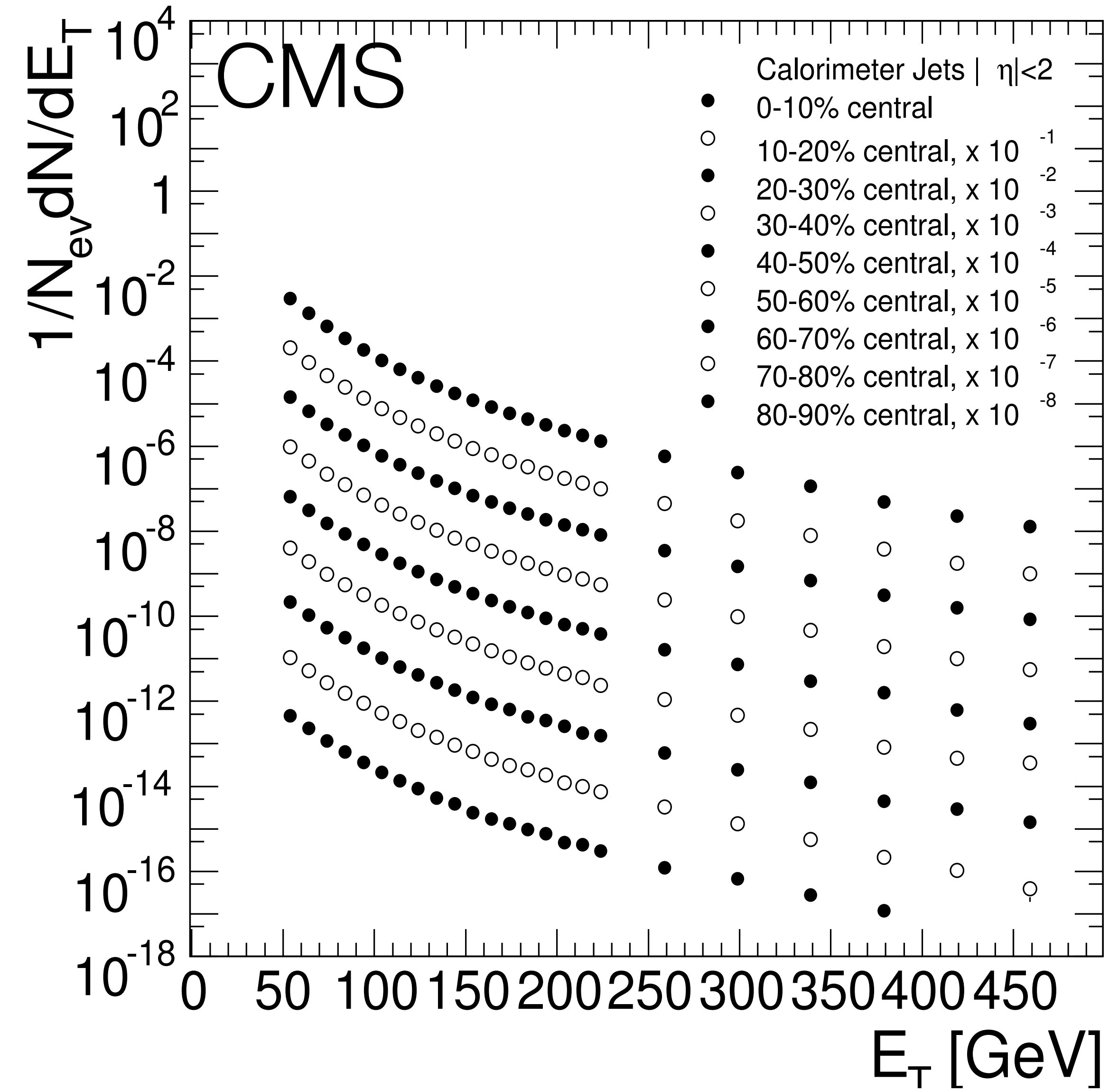
Experimented with a variety of estimators to cut against fakes, "SumJt" most effective



$$j_T^{Sum} = \sum_{cell} E_T^{cell} \sin R_{cell} \qquad \sigma_{j_T^{Sum}} = \frac{j_T^{Sum}(E_T) - \langle j_T^{Sum} \rangle (E_T)}{\sigma(E_T)}$$

Jet reconstruction & expected rates

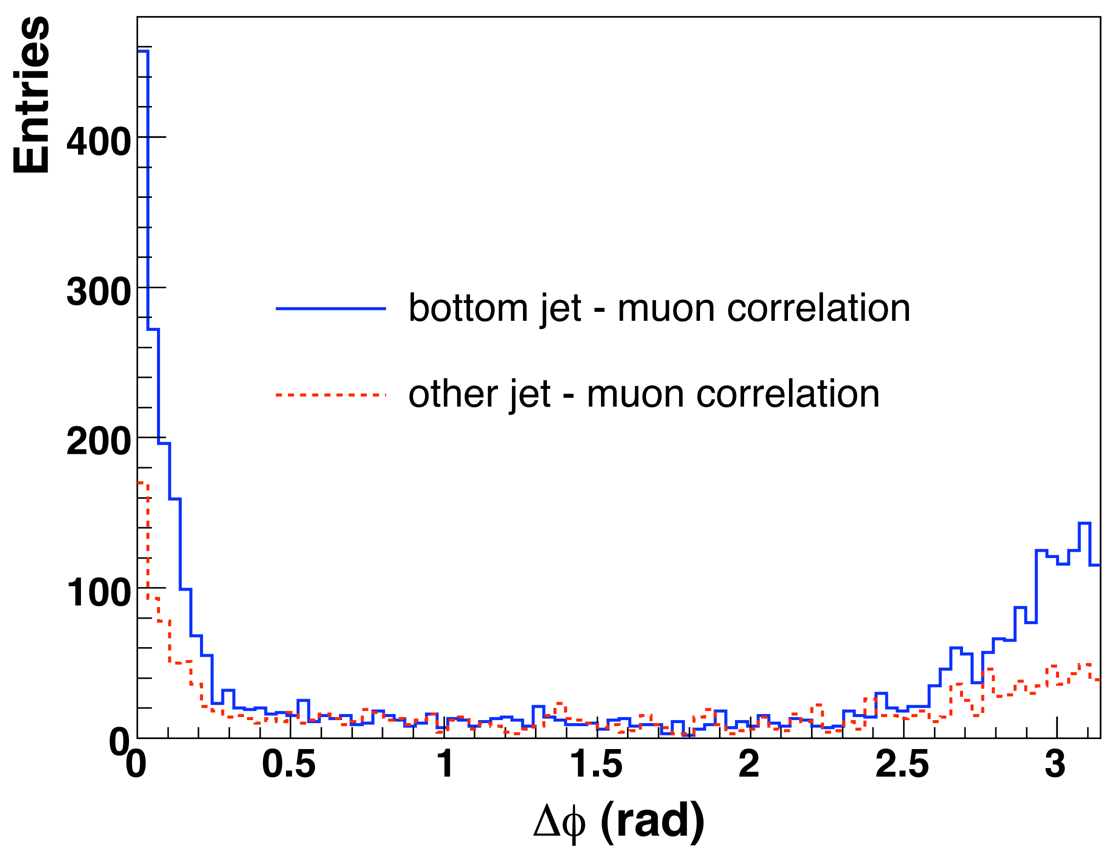


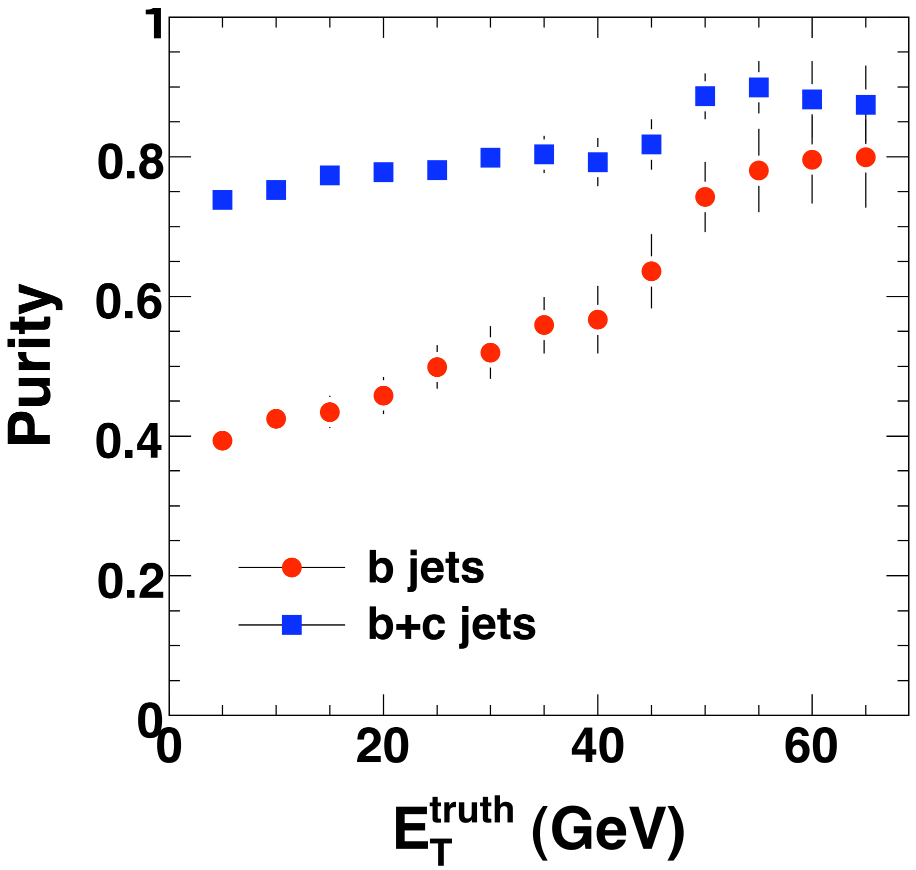


Straightforward to achieve 20% reconstruction of jet spectrum.

LHC Luminosity should provide out to 400 GeV (2xRHIC $\sqrt{s}$!)

Heavy Flavor Jets

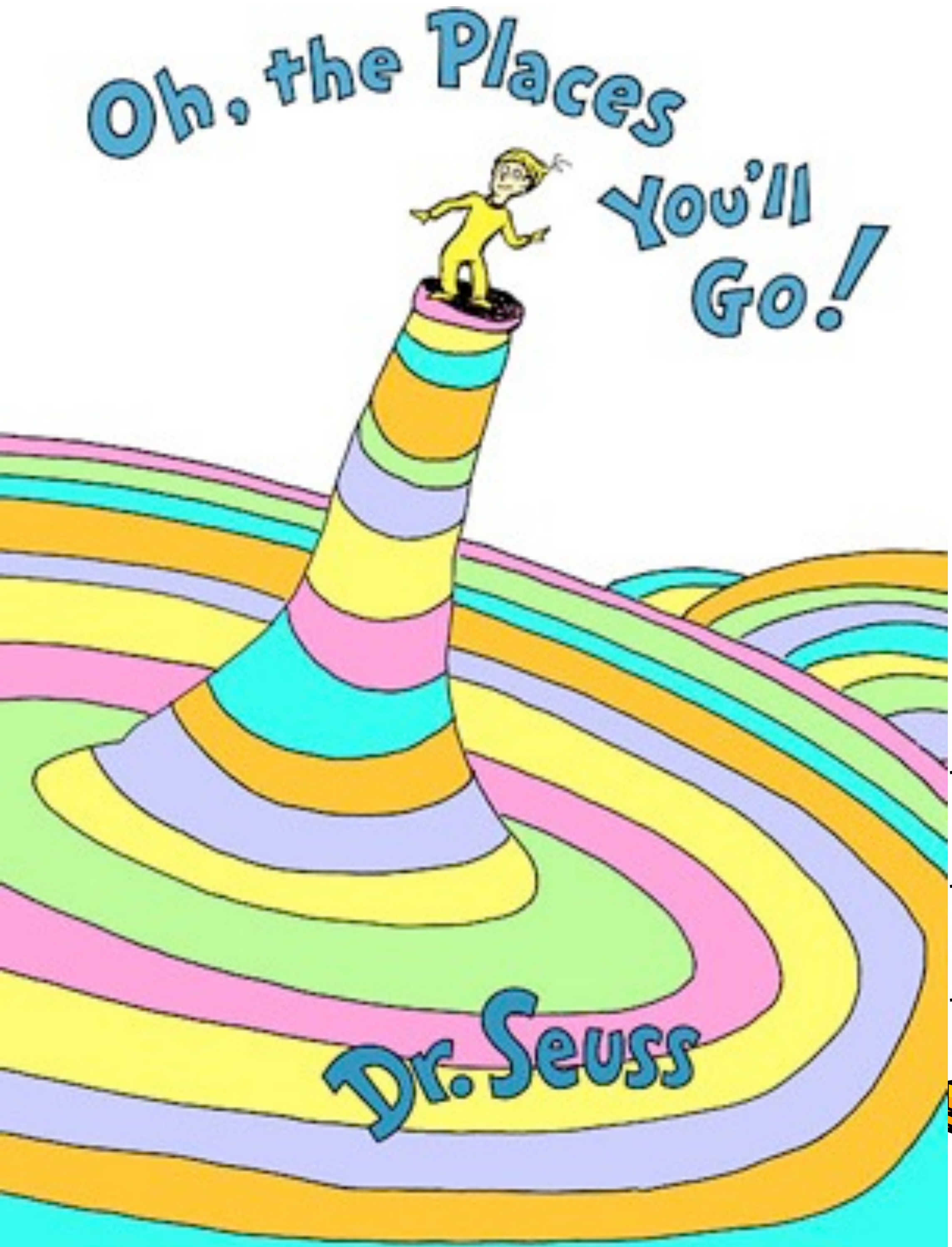




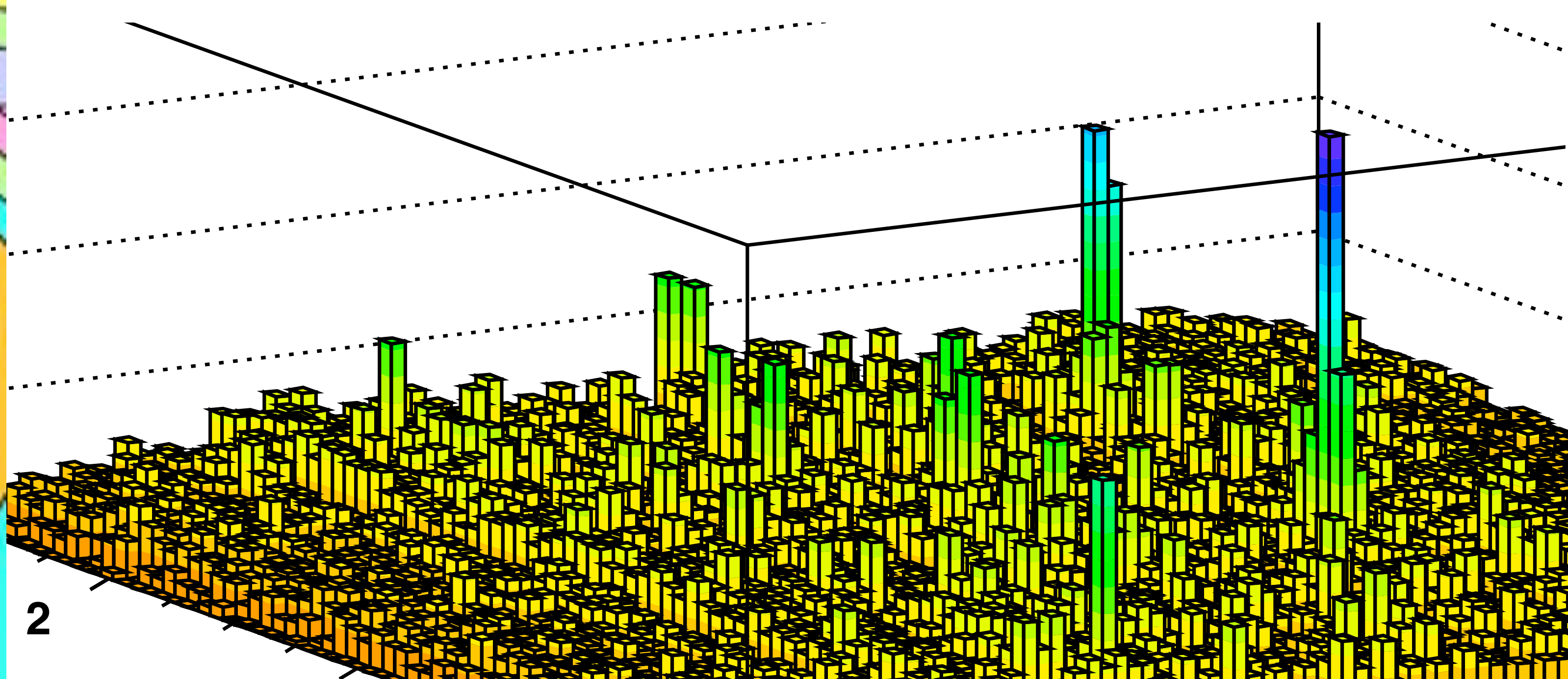
Requiring a muon to be correlated with a jet enhances the contribution from b-quarks: can look for HQ modifications to jet energy loss!

Oh, the places we'll go with jets @ LHC

CTEQ



- **Jet rates**
  - Singles (RAA
  - Correlations (dijet broadening)
- **Fragmentation functions**
  - Direct measurement of modified FF's
- **Flavor tagging**
  - s,c,b can be tagged via leading hadrons
- **γ+Jet, Z+jet**



“Conclusions” (or, a new beginning!)

CTEQ

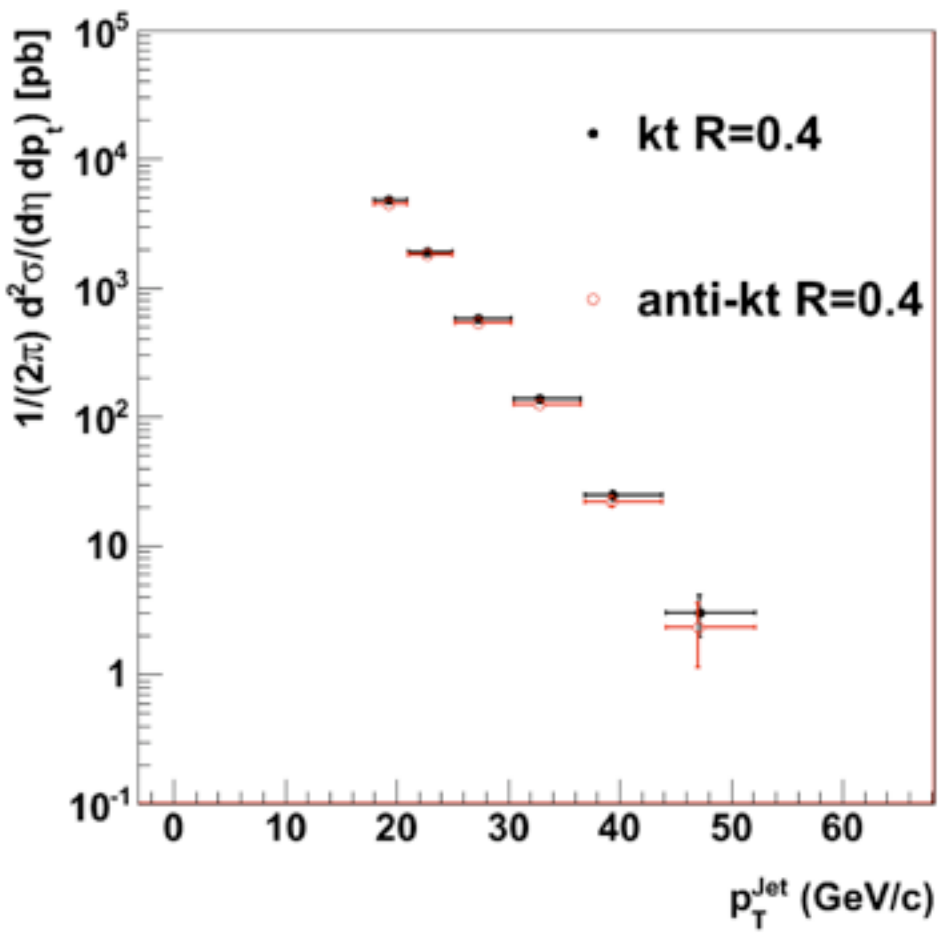
- **RHIC program has been incredibly productive**
  - Discovery of what seems to be a new strongly-coupled state of matter!
- **The future is particularly bright, especially for high p_T**
  - RHIC II is on the way: increased luminosity
  - LHC is on the way: increased energy of hard probes
  - pQCD technology will be essential for progress her
- **Opportunities in “soft” QCD**
  - Interesting phenomena not necessarily treatable by pQCD
  - Entropy production, cone, ridge, etc. require understanding of both soft sector and hard sector
  - Even jet quenching requires detailed knowledge of initial conditions etc. & viscous hydro evolution...

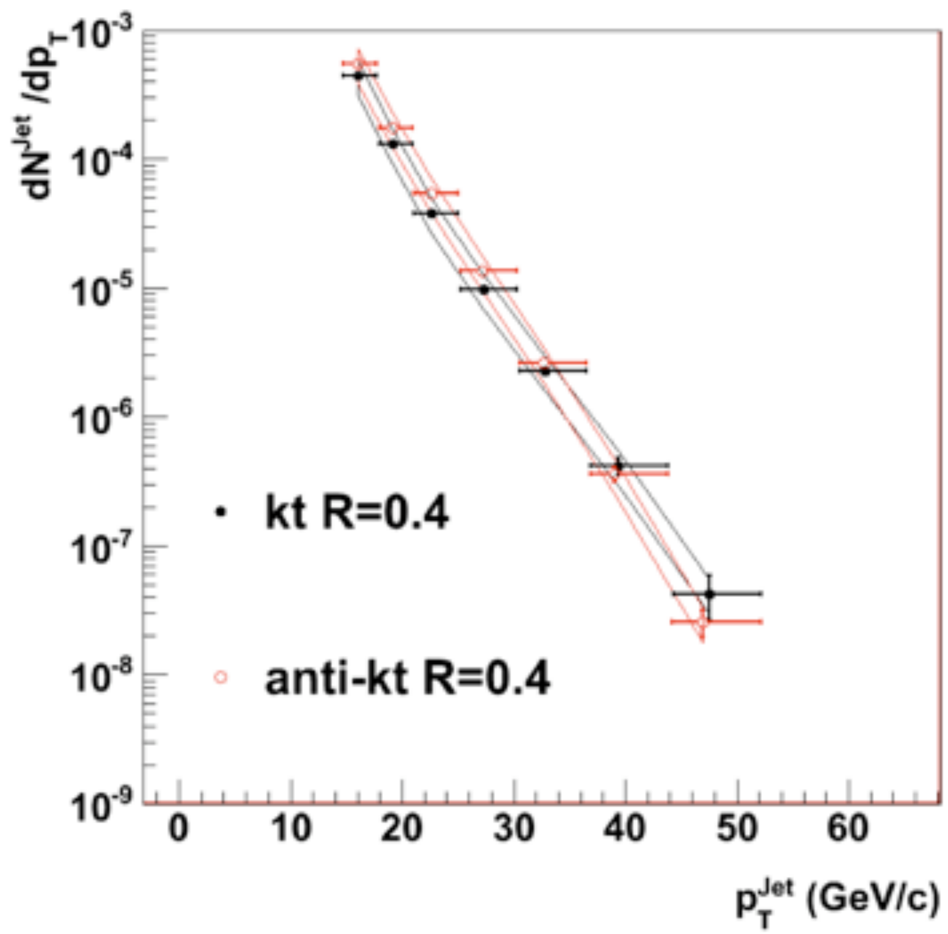
Nuclear modification factor

CTEQ

$$
\begin{aligned}
R_{A+A} &= \frac{N_{A+A}}{\langle T_{A+A}\rangle \sigma_{p+p}} \\
&= \frac{d^2N_{A+A}/dp_T dy}{\langle T_{A+A}\rangle d^2\sigma_{p+p}/dp_T dy} \\
&= \frac{1}{\langle T_{A+A}\rangle \sigma_{p+p}} \frac{d^2N_{A+A}/dp_T dy}{d^2N_{p+p}/dp_T dy} \\
&= \frac{1}{N_{coll}} \frac{d^2N_{A+A}/dp_T dy}{d^2N_{p+p}/dp_T dy}
\end{aligned}
$$

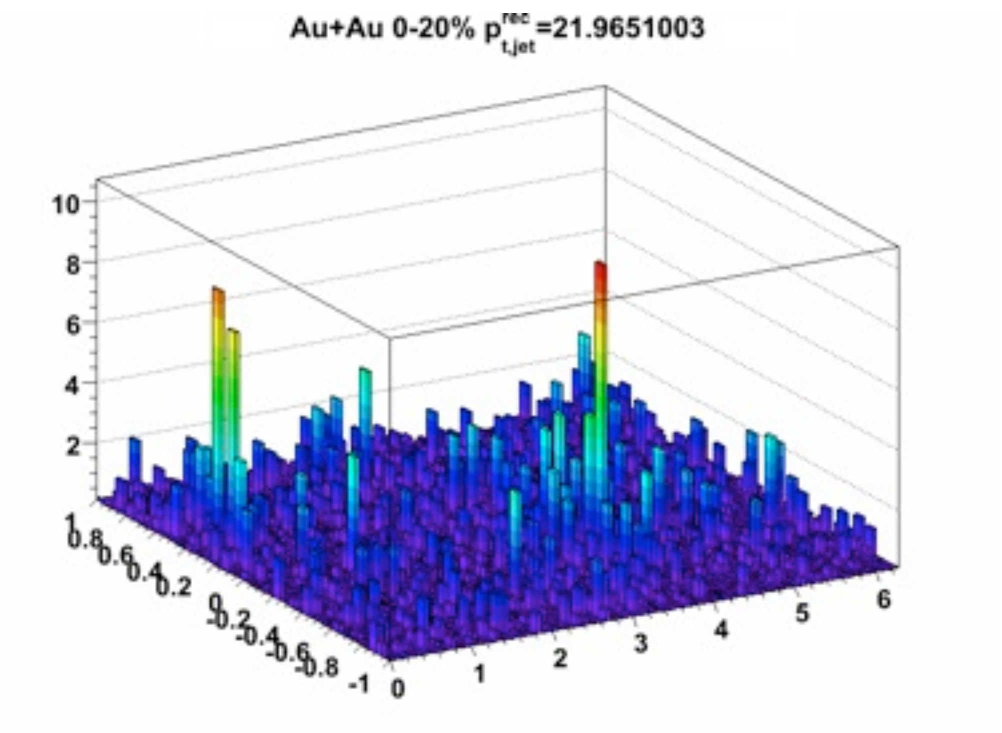
Results for p+p & Au+Au



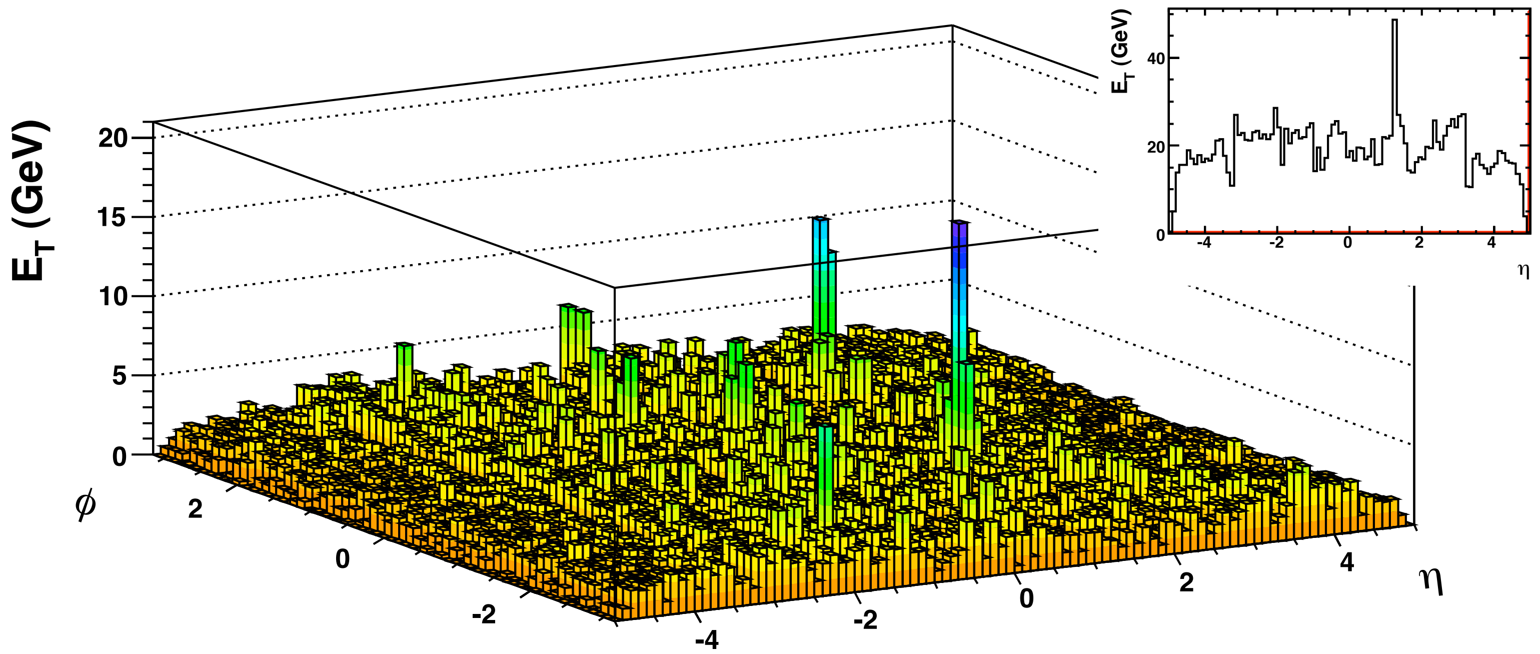


Spectral shape apparently quite similar between p+p & Au+Au for k_T and anti-k_T

Increased acceptance at the LHC



$|\eta|<1$



$|\eta|<5$