Soft Physics: From RHIC to the LHC

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Upton, NY

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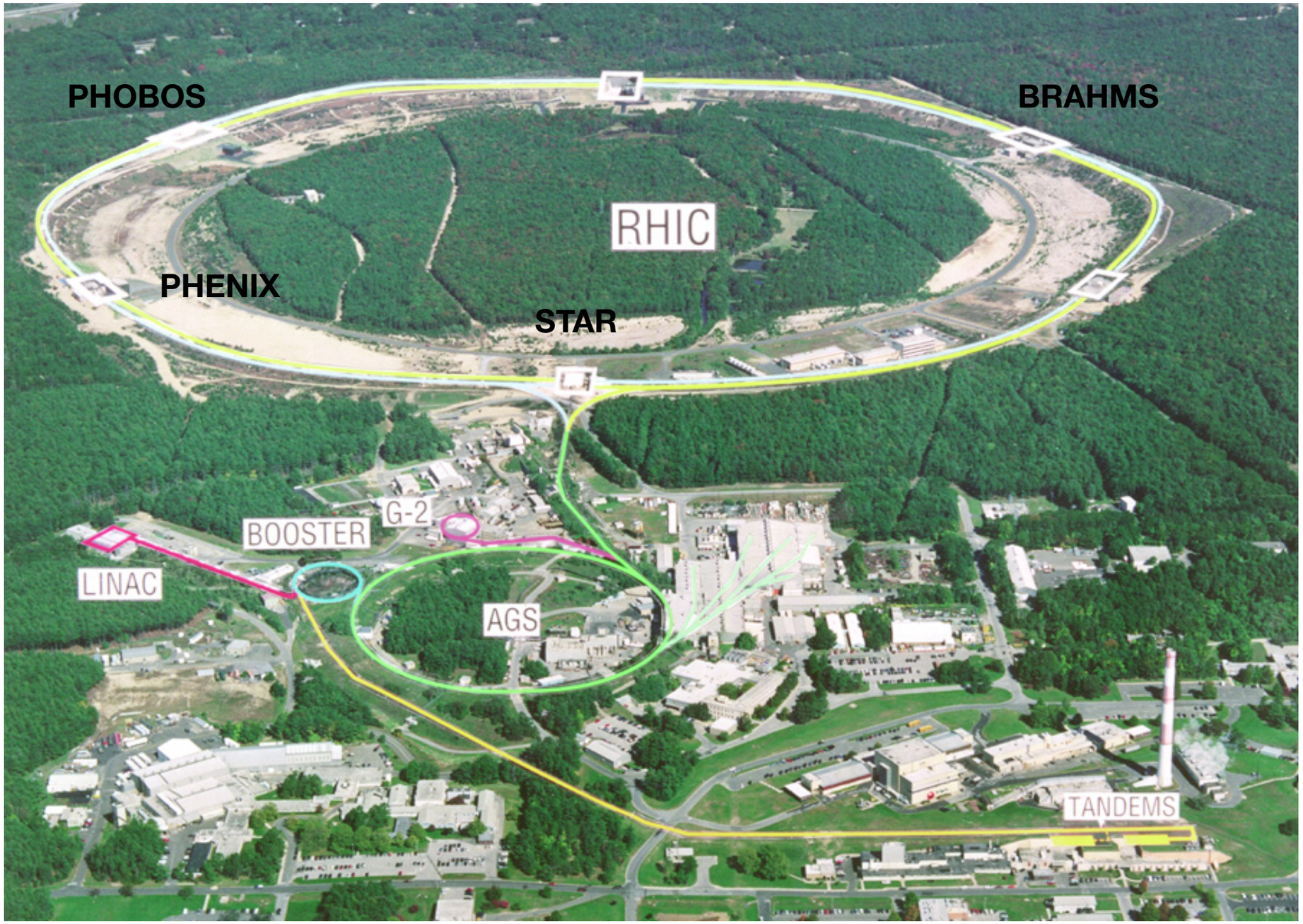
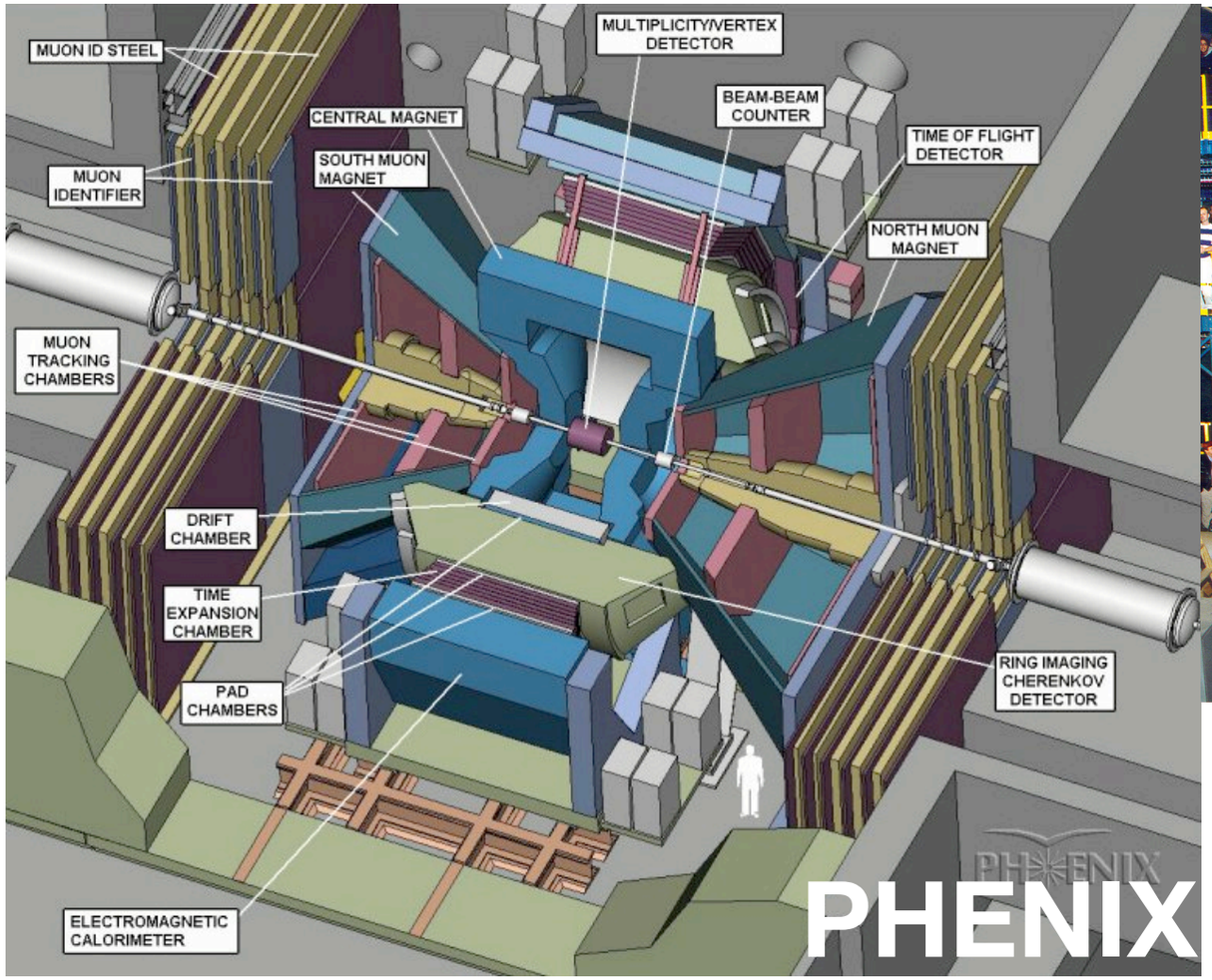
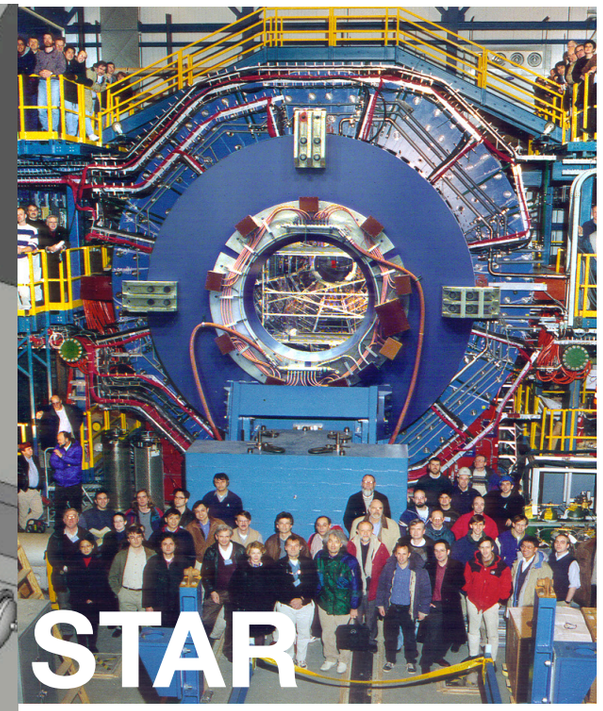
Eilat, Israel
13 November 2008

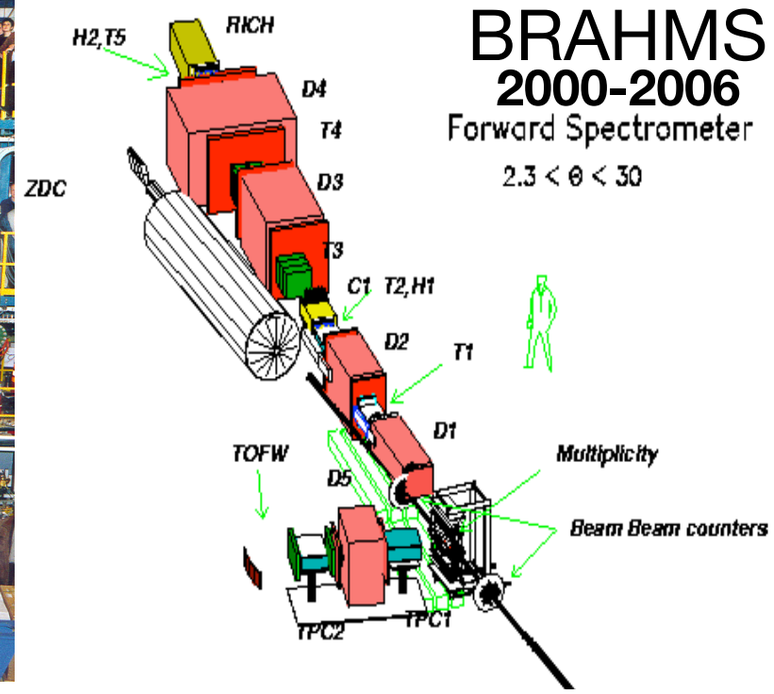
Relativistic Heavy Ion Collider (RHIC)

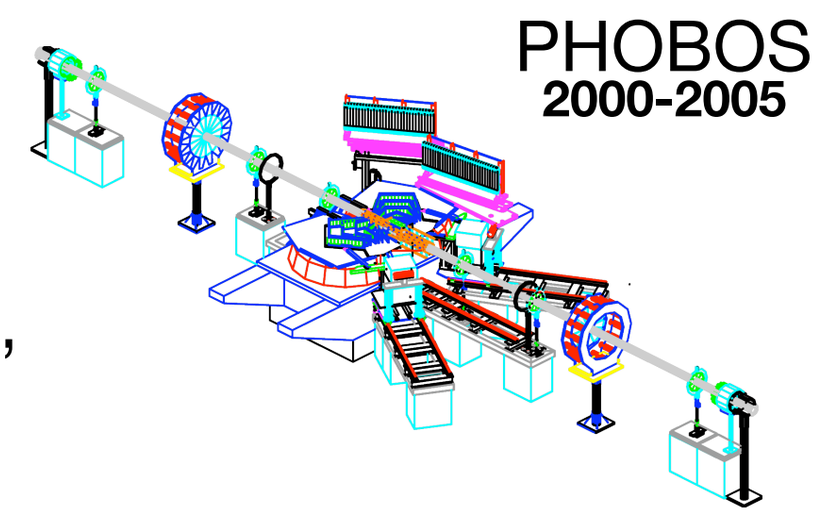


RHIC Experiments to Scale





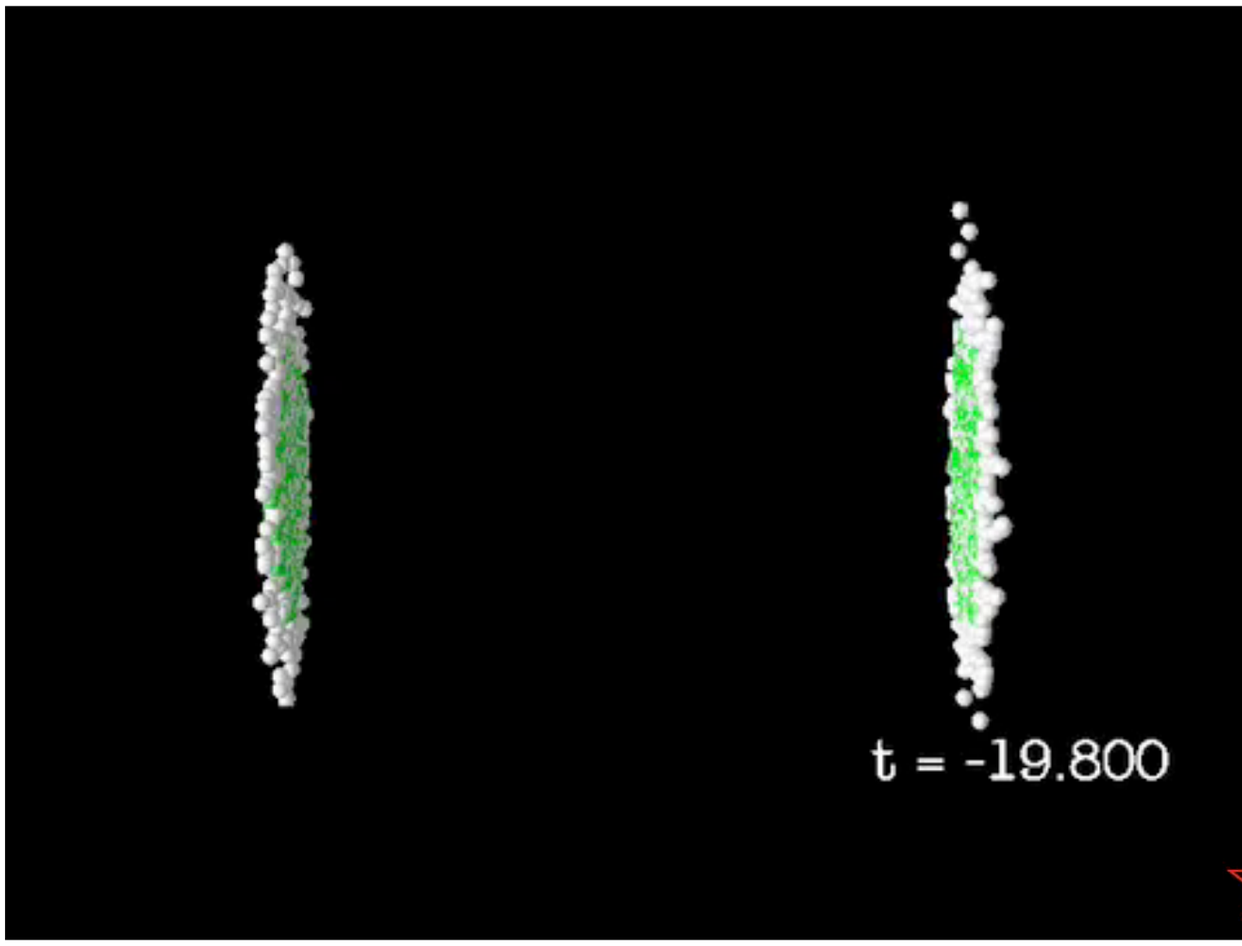




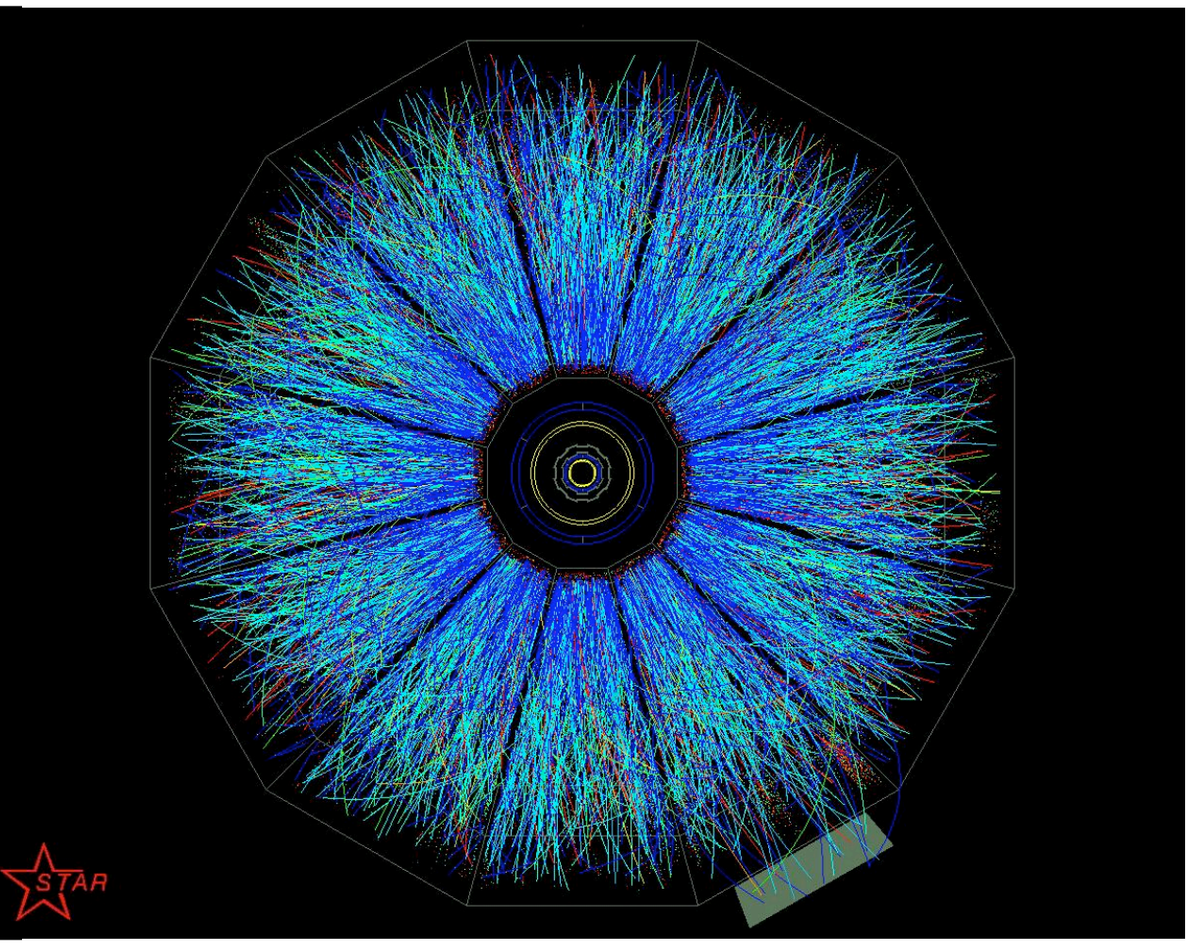
RHIC program has large <u>and</u> small detectors,
sufficient overlap to make cross-checks.
Billions of events since 2000:
p+p, d+Au, Cu+Cu, Au+Au, 19.6-200 GeV

RHIC Physics in a Nutshell

Collisions of Ions



1000's of Particles



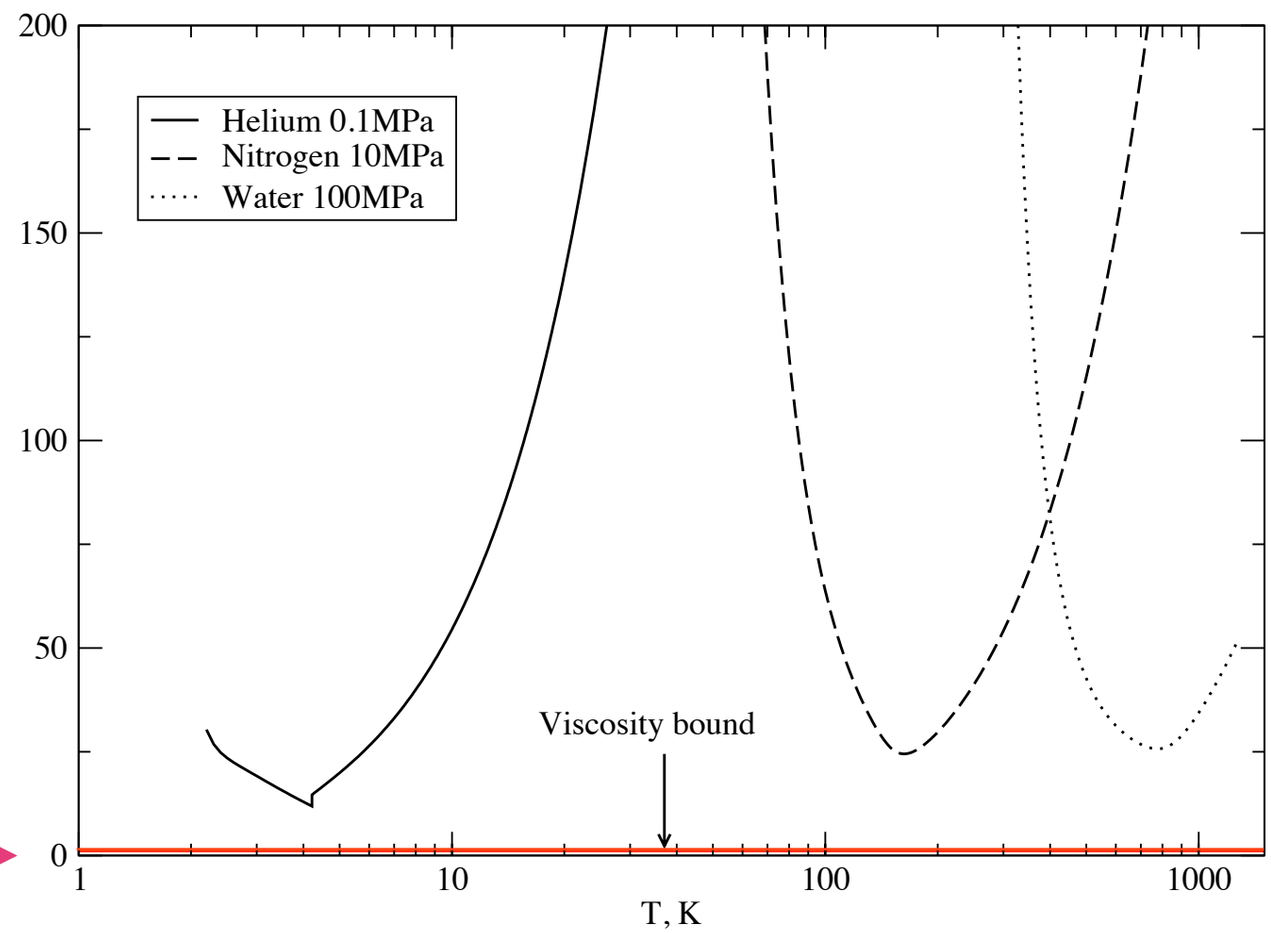
RHIC physics takes place in **space-time**

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

The most-perfect fluid

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
(D. Son, Tues)

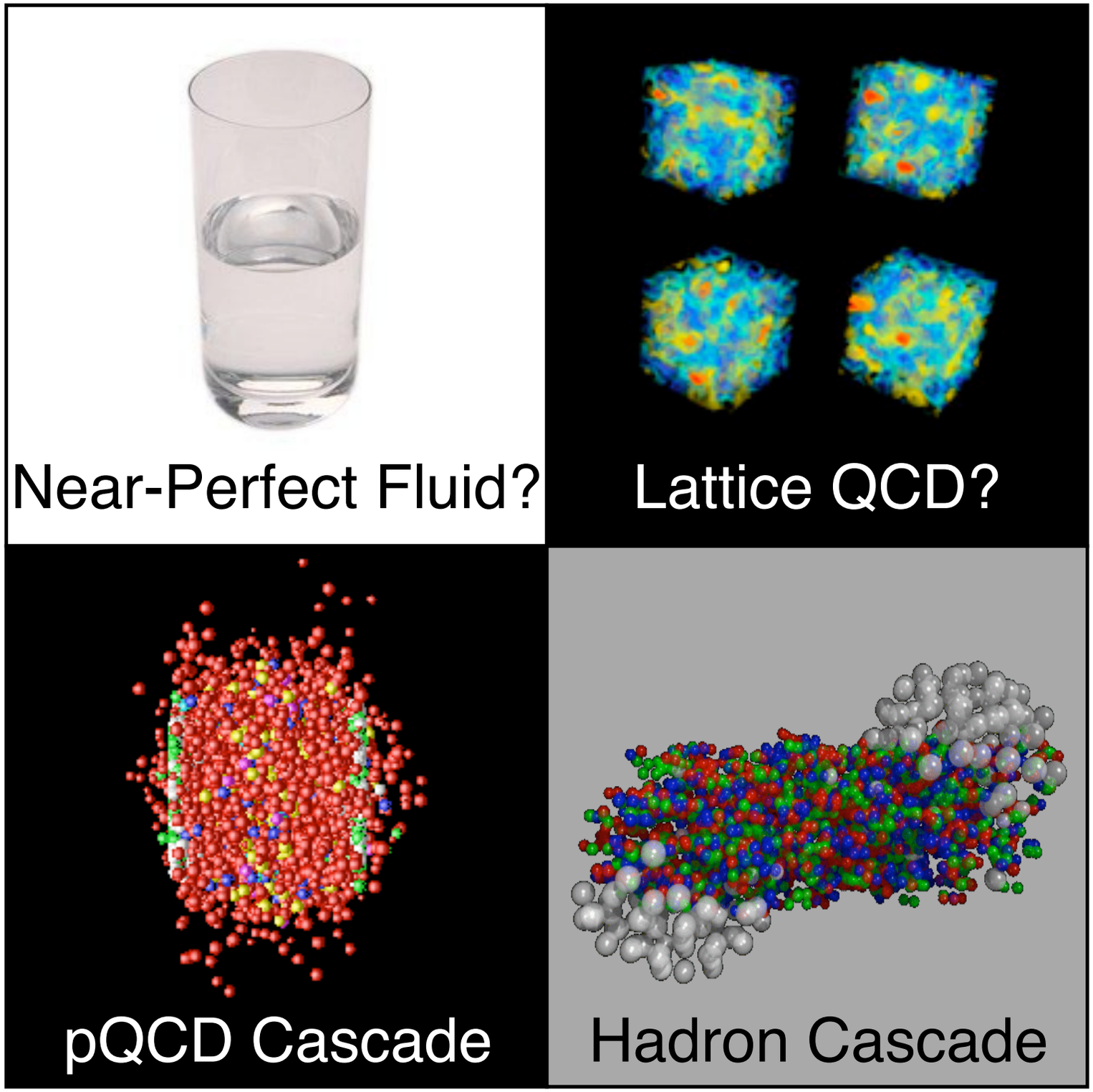
local thermalization: **strong coupling** → low viscosity

These conclusions originally emerged from "soft" physics

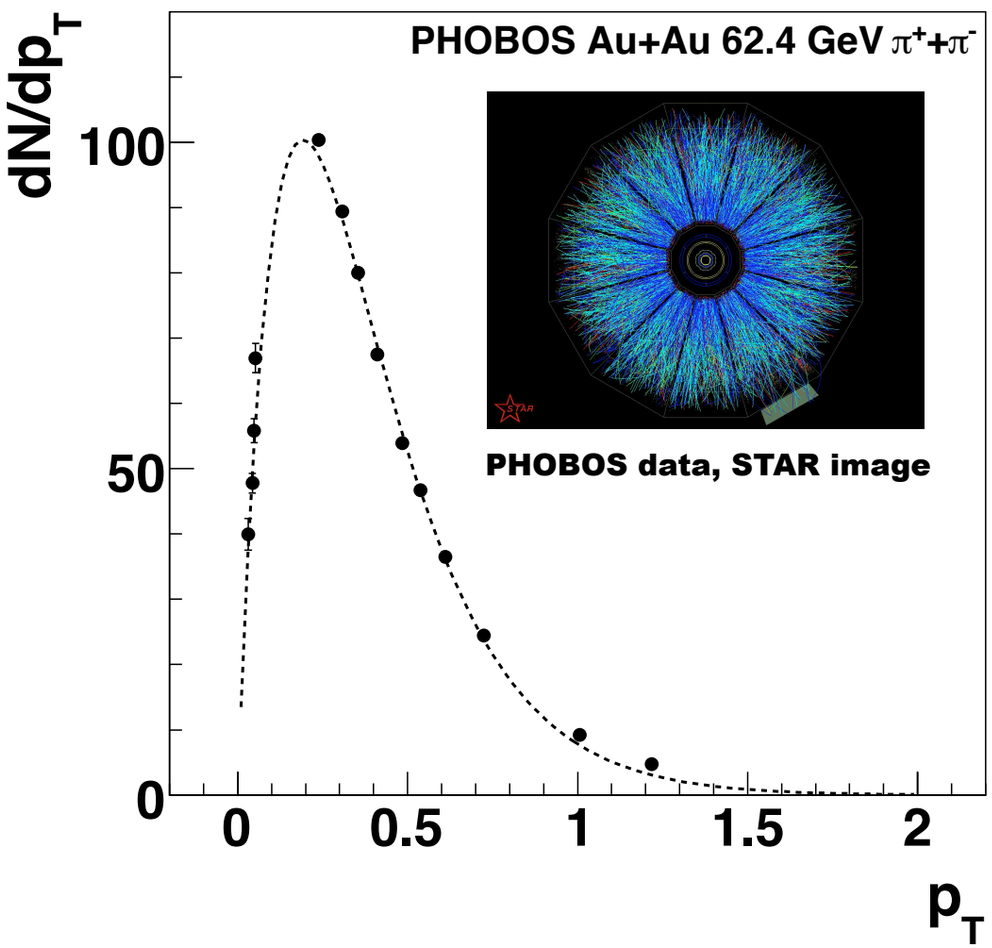
The least-perfect fluid

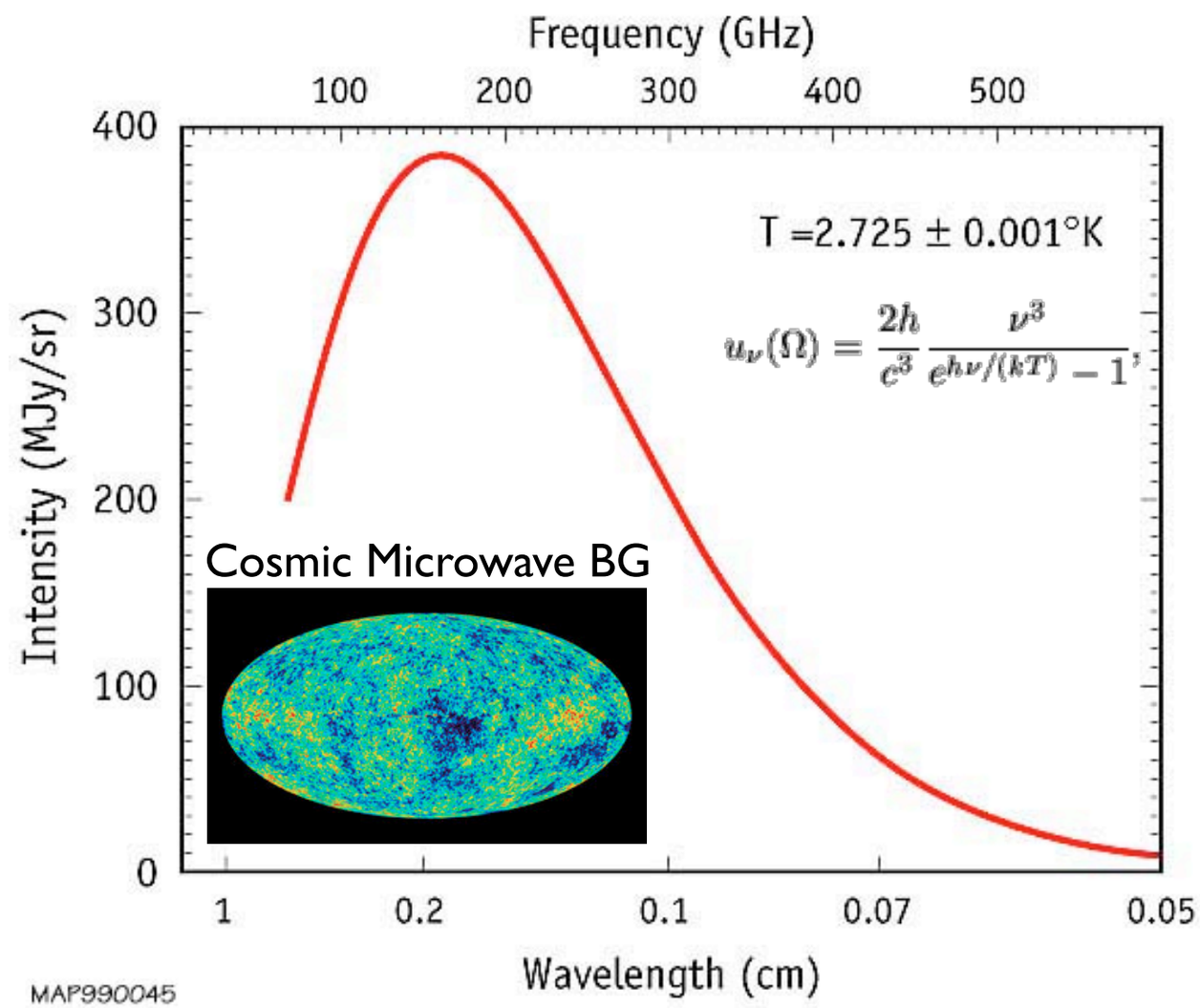
The Pitch Drop Experiment: http://www.physics.uq.edu.au/pitchdrop/pitchdrop.shtml

Dynamical Regimes of Hot QCD



Strong Blackbody Radiation

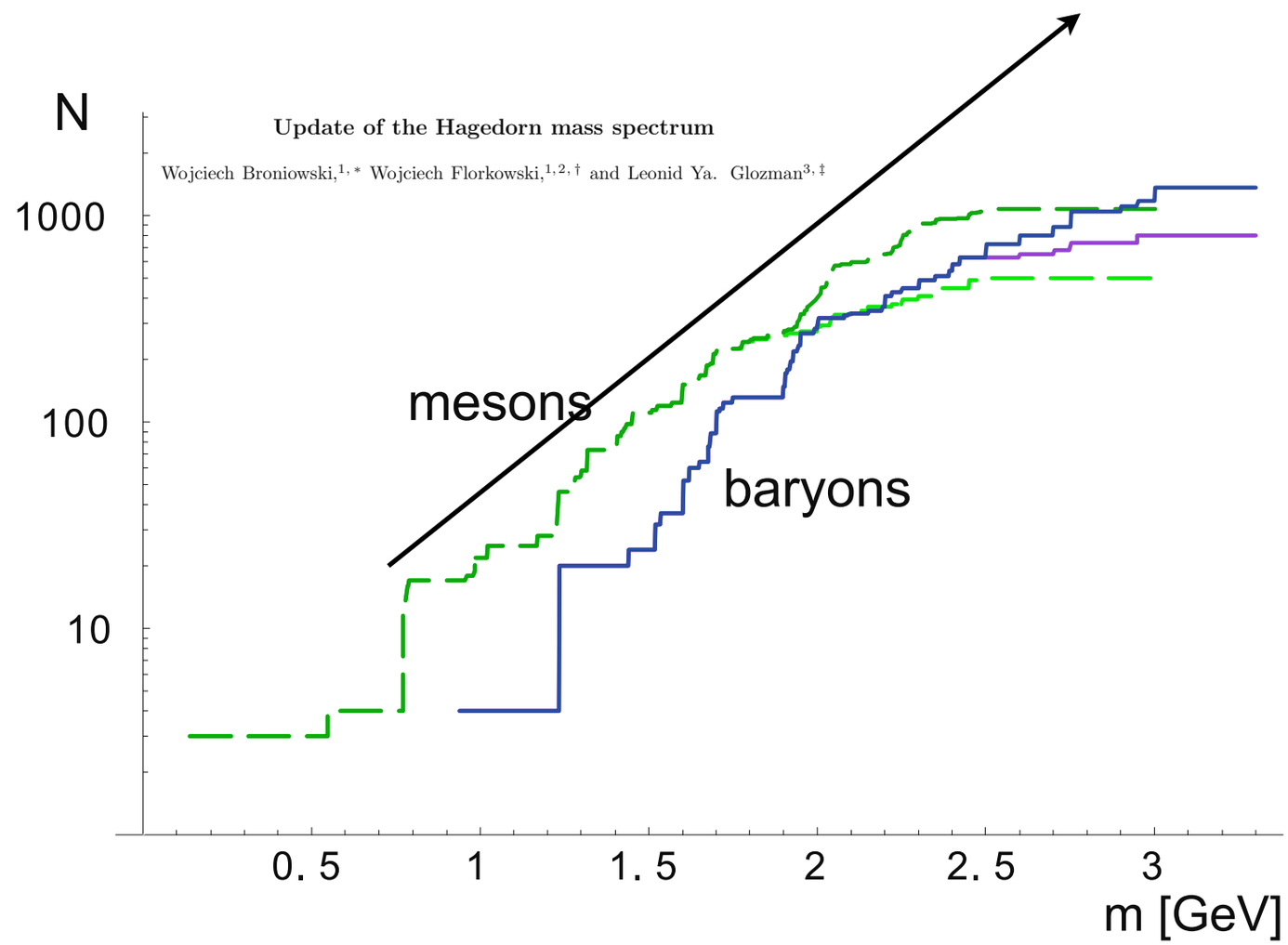




It is often overlooked that the spectra of particles emerging from a heavy ion collision is nearly blackbody but with <u>hadrons</u> instead of photons: **thermal system**

Hagedorn Temperature

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



$$\rho(m) \sim m^a e^{m/T_0} \rightarrow Z = \int \rho(m) e^{-m/T} \rightarrow \infty (T \geq T_0)$$

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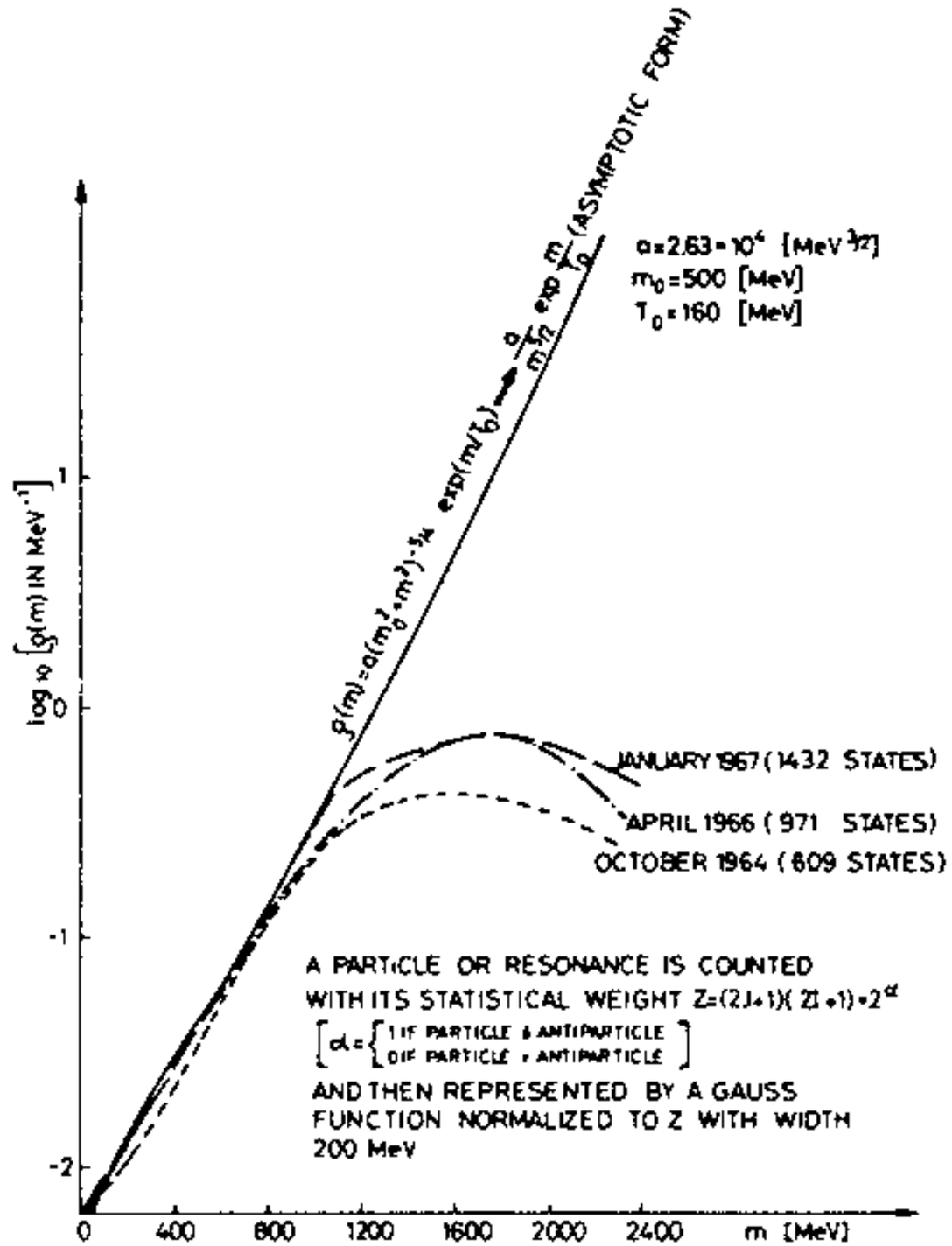

Fig. 3.1: The predicted and the experimental mass spectrum as it evolved from 1964 to 1967.

Hagedorn Temperature

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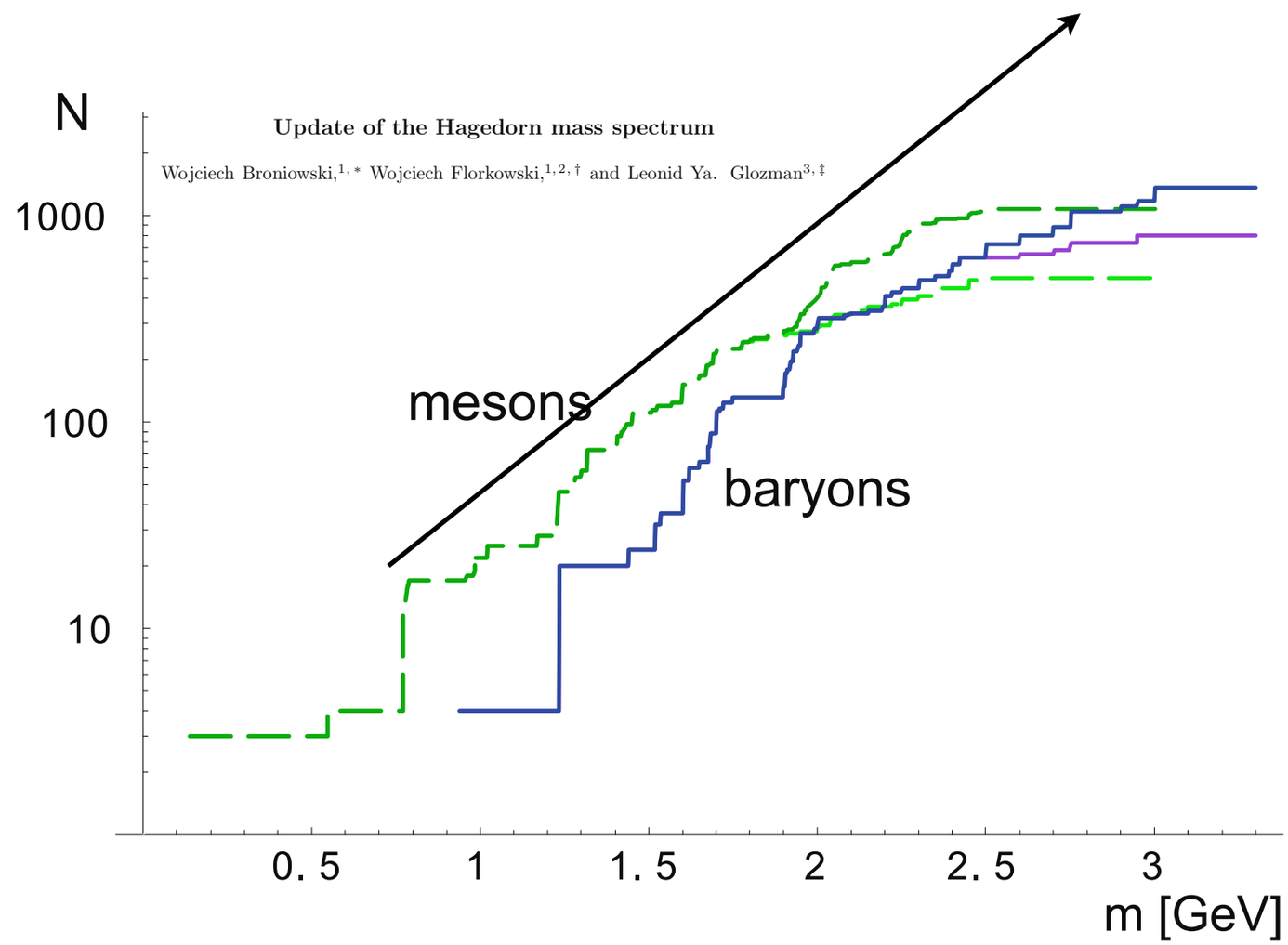

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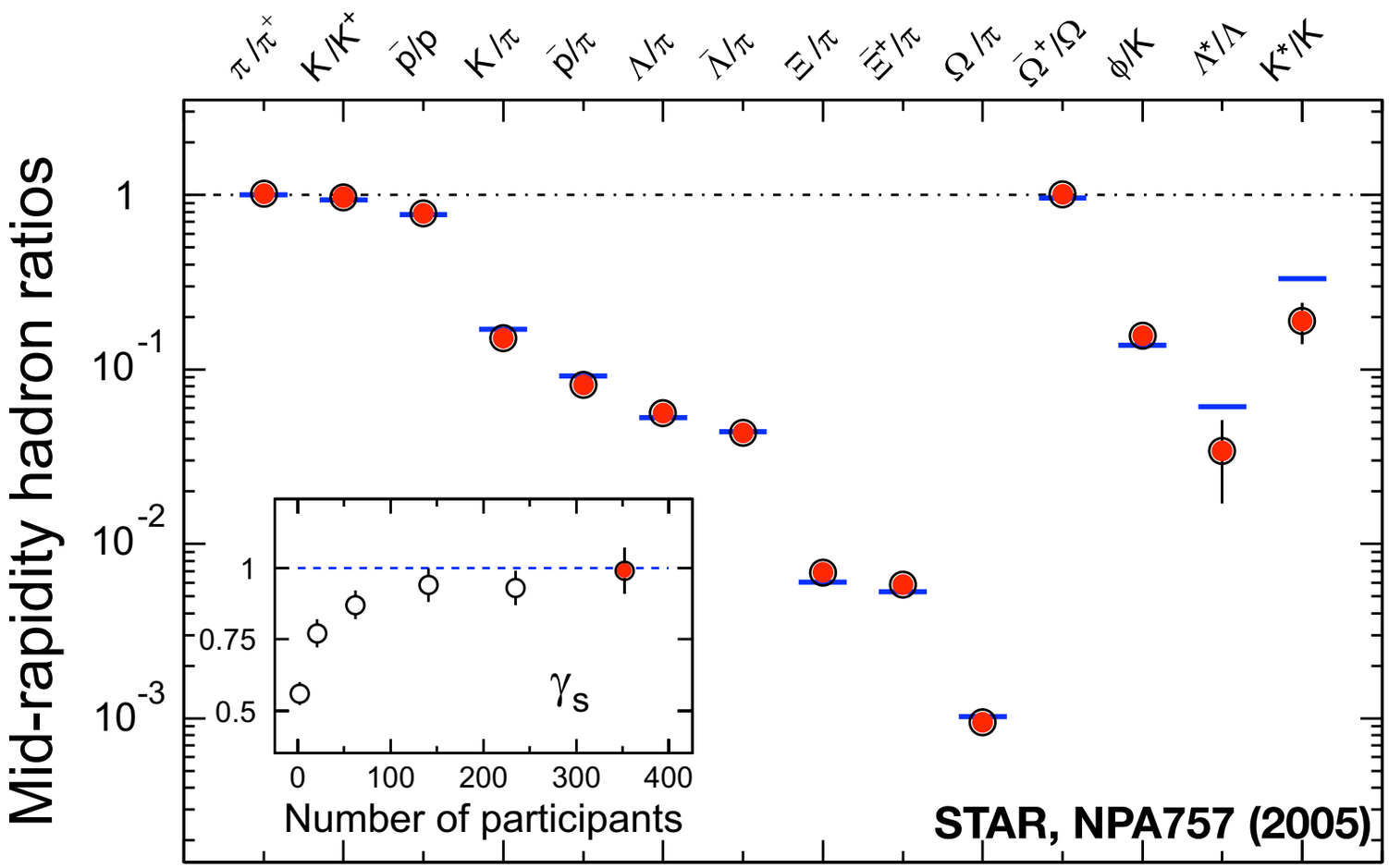
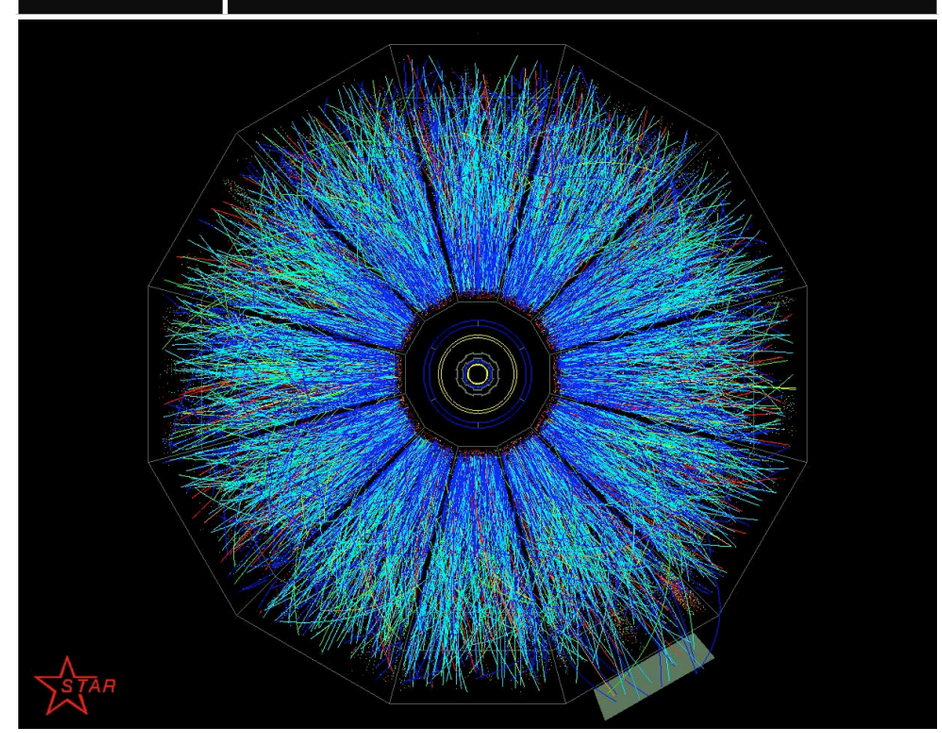
Strong Blackbody Radiation



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)



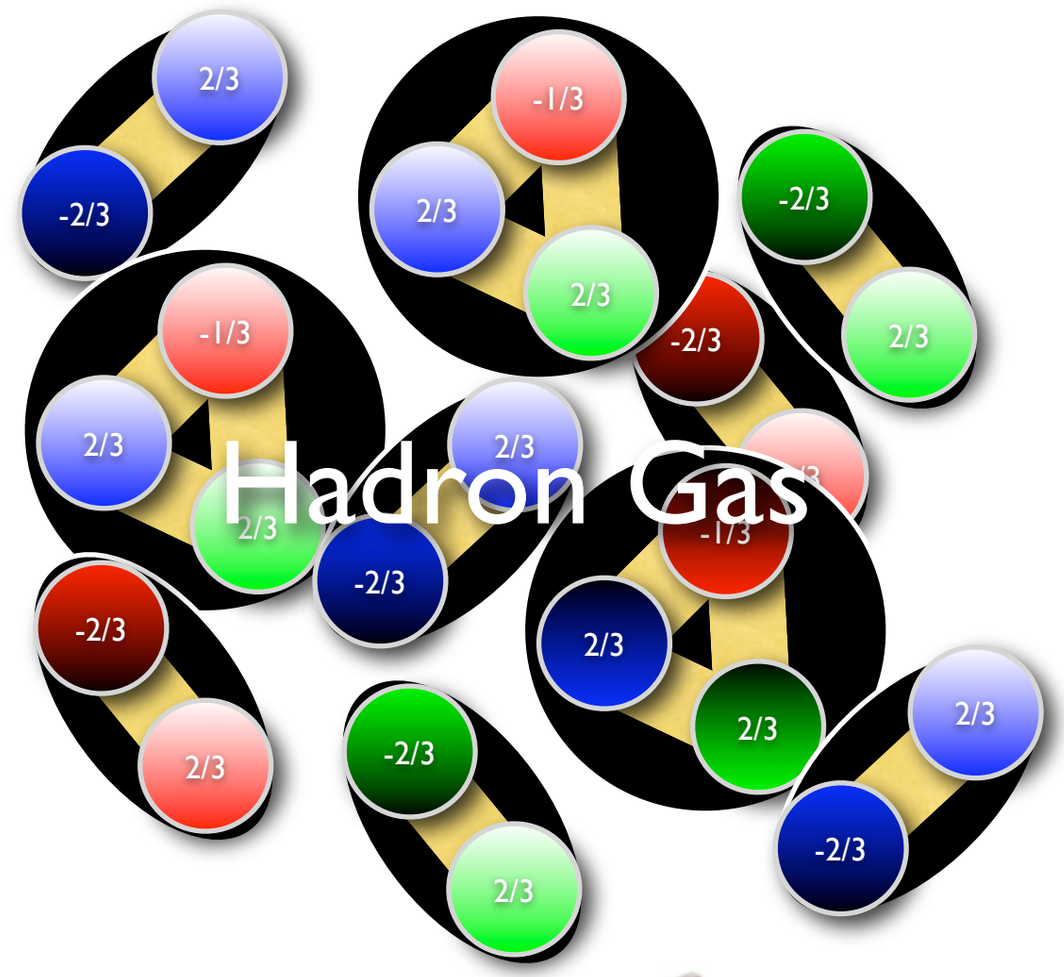
All hadron species apparently emitted from a <u>thermal</u> source $T_{ch} = 163 \pm 4$, $\mu_B = 24 \pm 4$

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

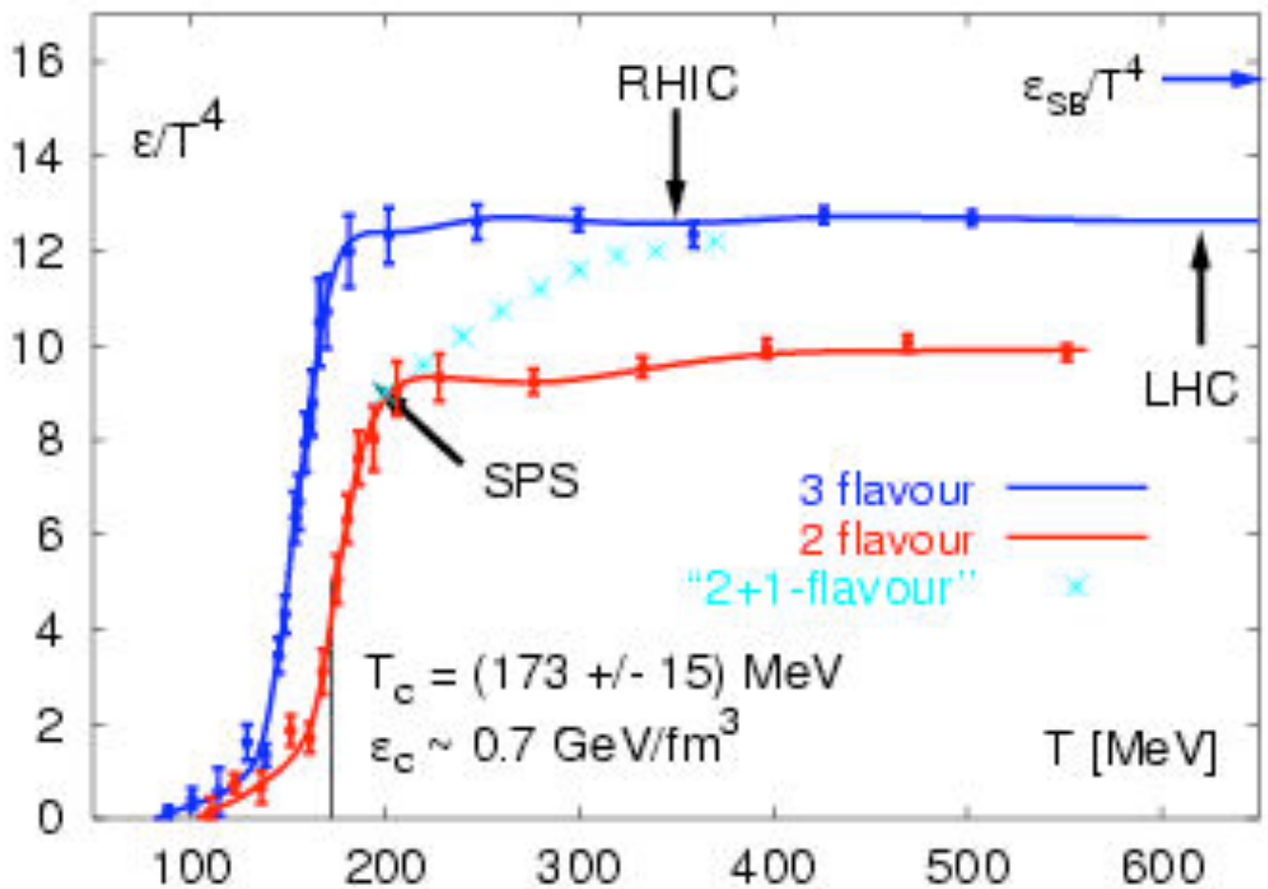
The Hagedorn Limit

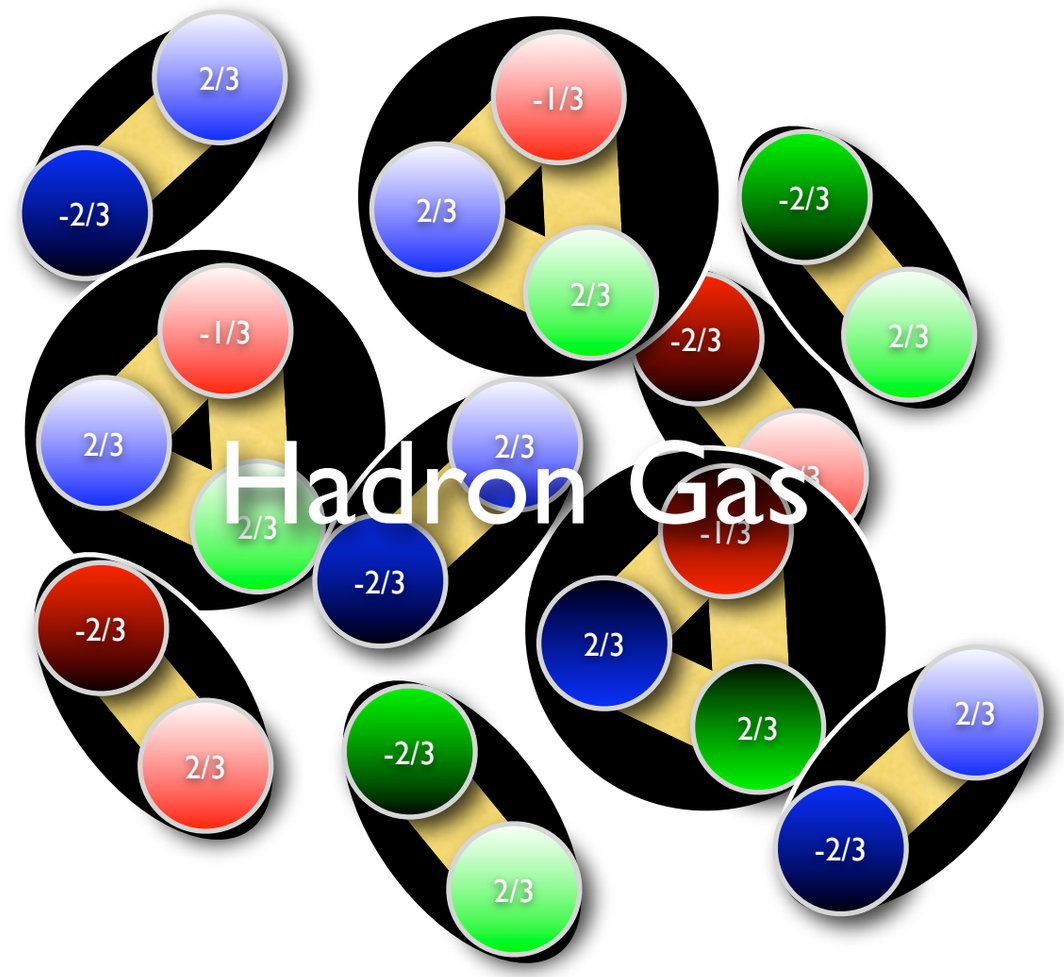
Heating up a Hagedorn gas excites higher-mass resonances
→ T_H is the "limit" temperature

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



Quark Gluon Plasma

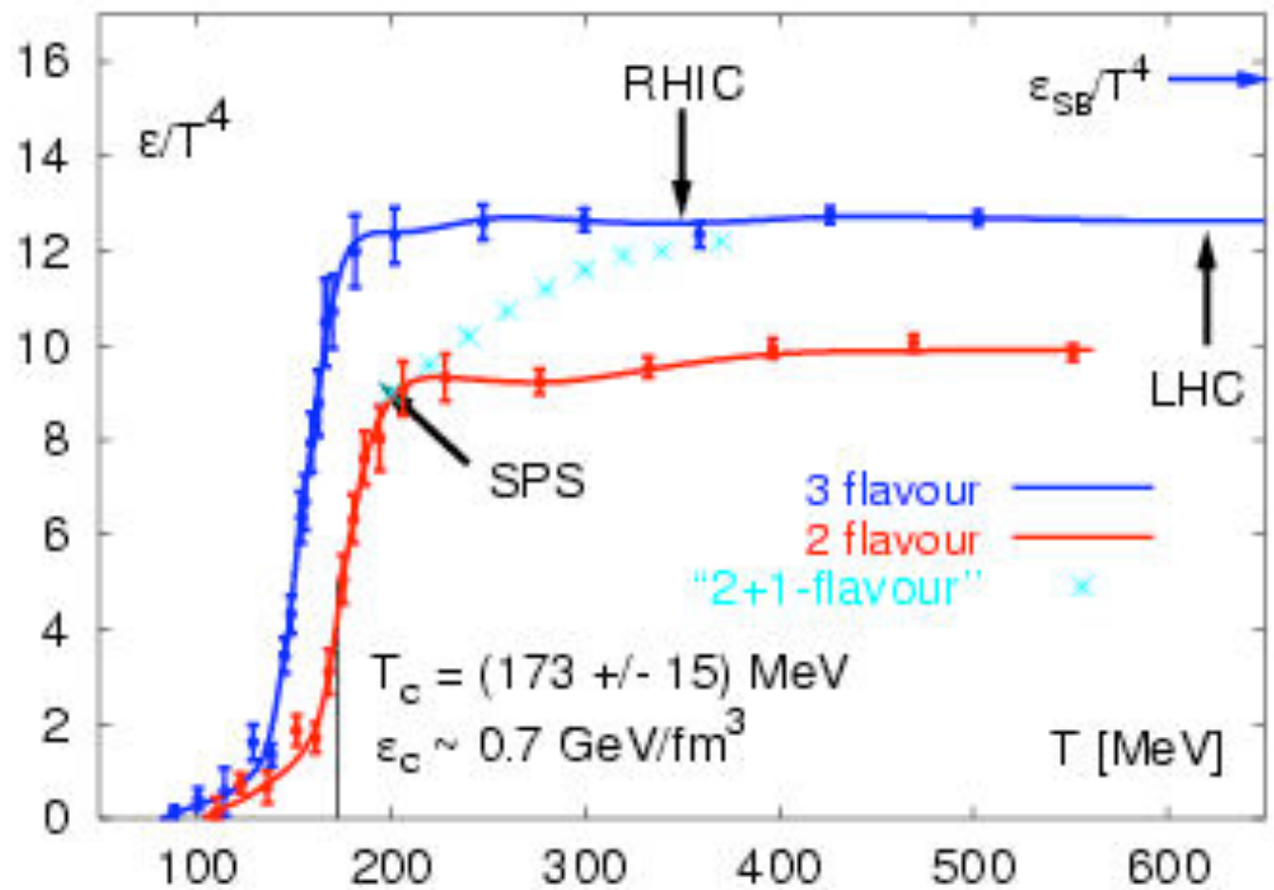


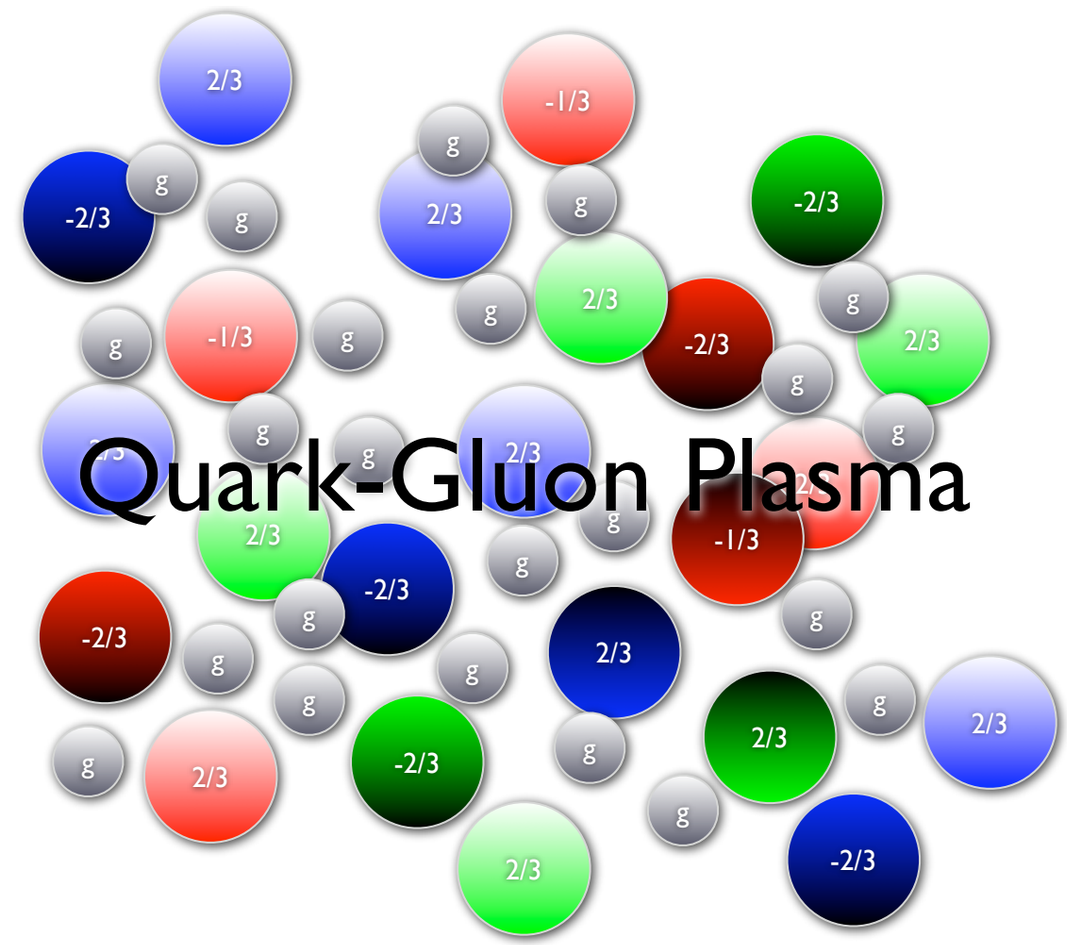


Lattice predicts a phase transition at T_c~170 MeV~T_H
($\boldsymbol{\varepsilon}_c$~700 MeV/fm^3 > $\boldsymbol{\varepsilon}_N$~500 MeV/fm^3)
from hadronic degrees of freedom to quark/gluon

Quark Gluon Plasma

#DOF





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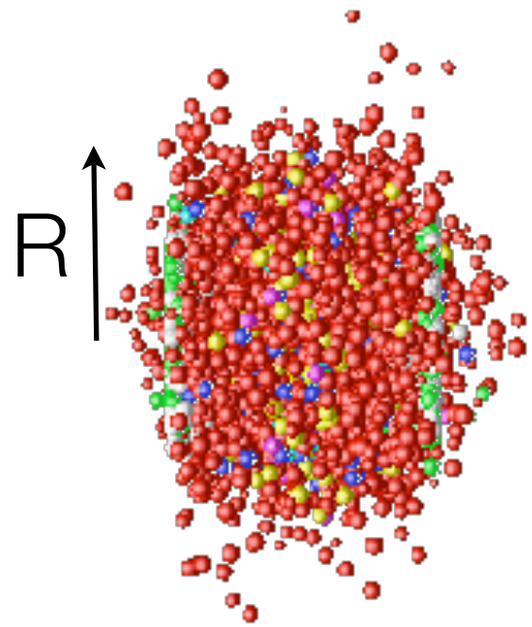
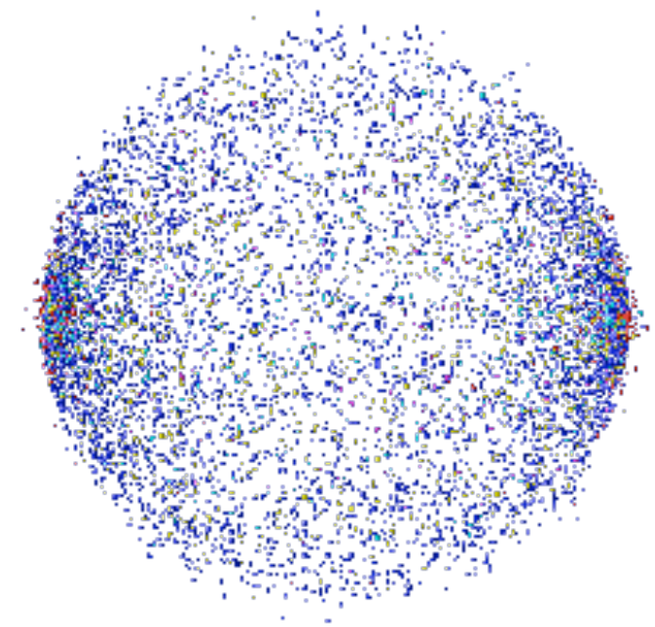
Probing Heavy Ion Dynamics with Soft Physics

Initial Collisions
(Nuclear geometry,
Baryon stopping)



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



Freezeout
(Hadronization)

Initial Boundary Conditions (Space-time)

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

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

Final Boundary Conditions (Local)

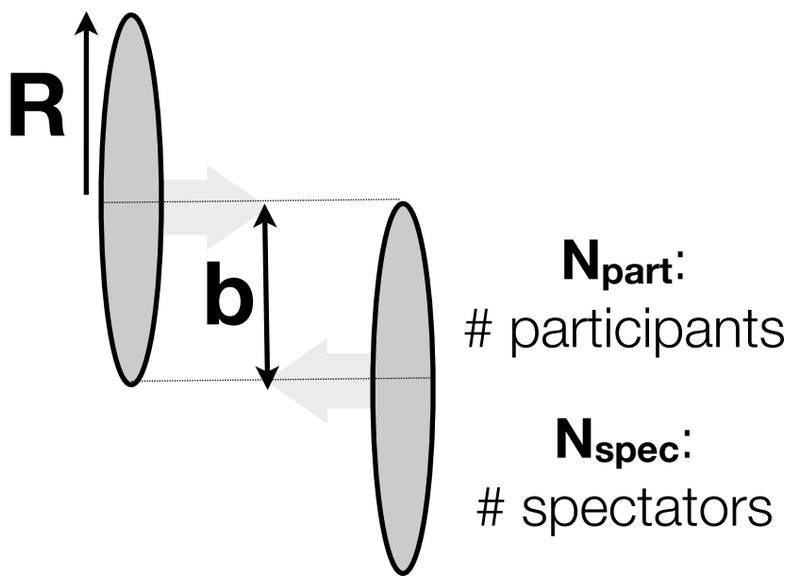
Multiplicities

Spectra, Flow

Yields, Correlations

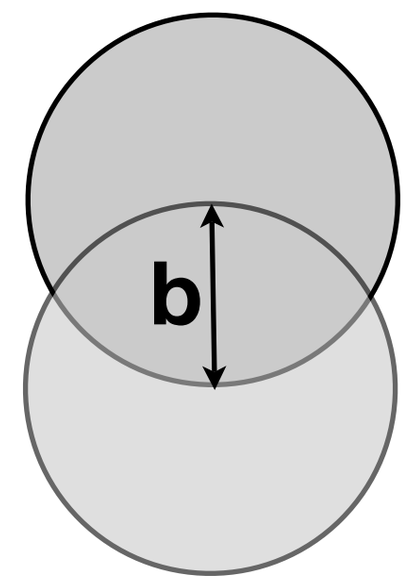
Nuclear Geometry

Knowing collision geometry is essential for all heavy ion results



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

"**eccentricity**"

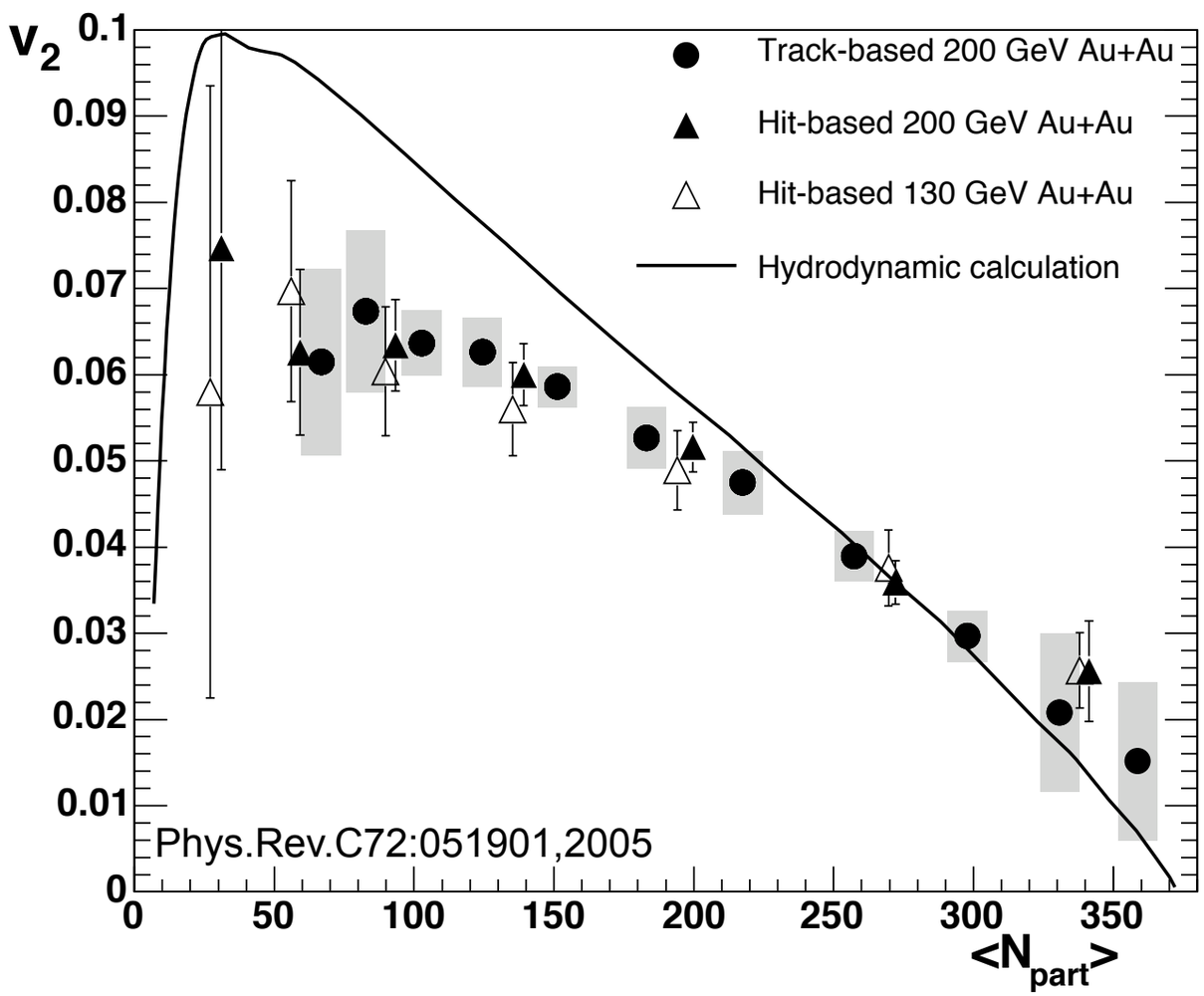


x-z:
Longitudinal contraction (1/γ)

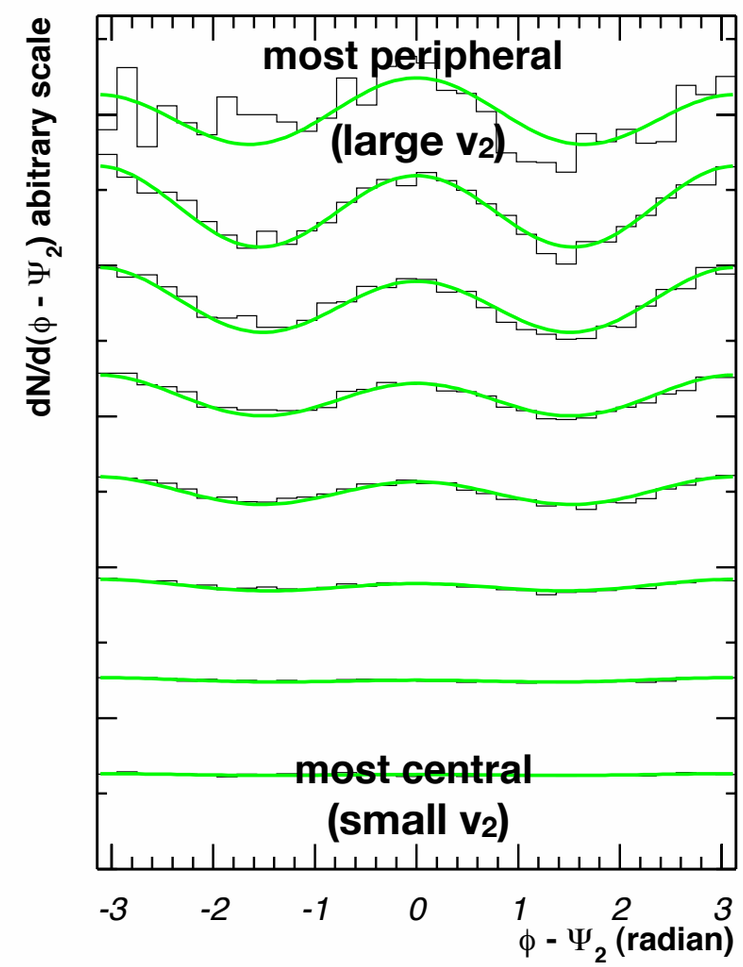
x-y:
Transverse overlap

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

Elliptic Flow



PHOBOS Au+Au 130 GeV



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

compared with Hydro (Huovinen)

Hydro scales

ε_0~30 GeV/fm^3 ε~0.5 GeV/fm^3

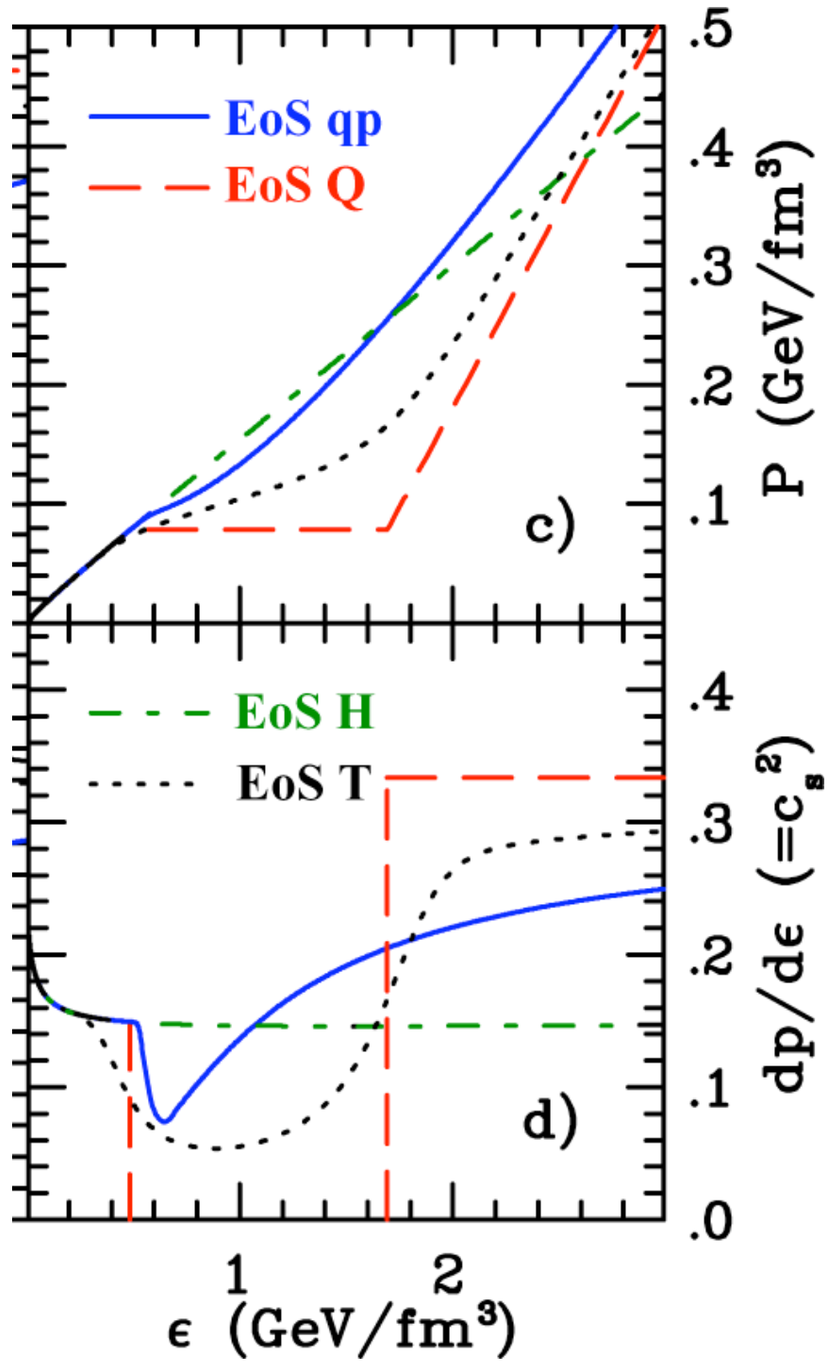
τ_0<0.6 fm^3 τ~1 fm^3

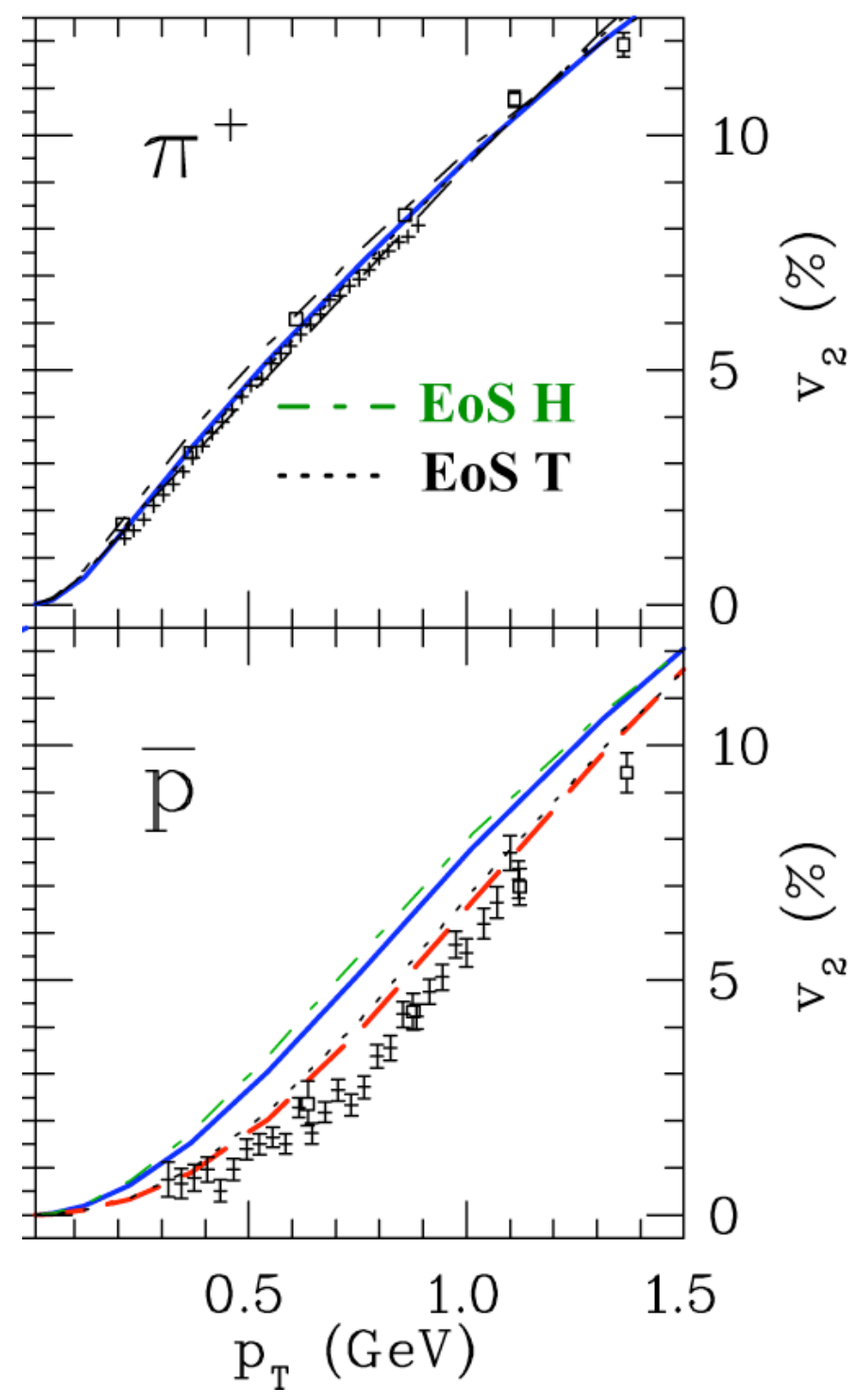
Hadronic scales

Equation of State

Nucl.Phys.A761:296-312,2005

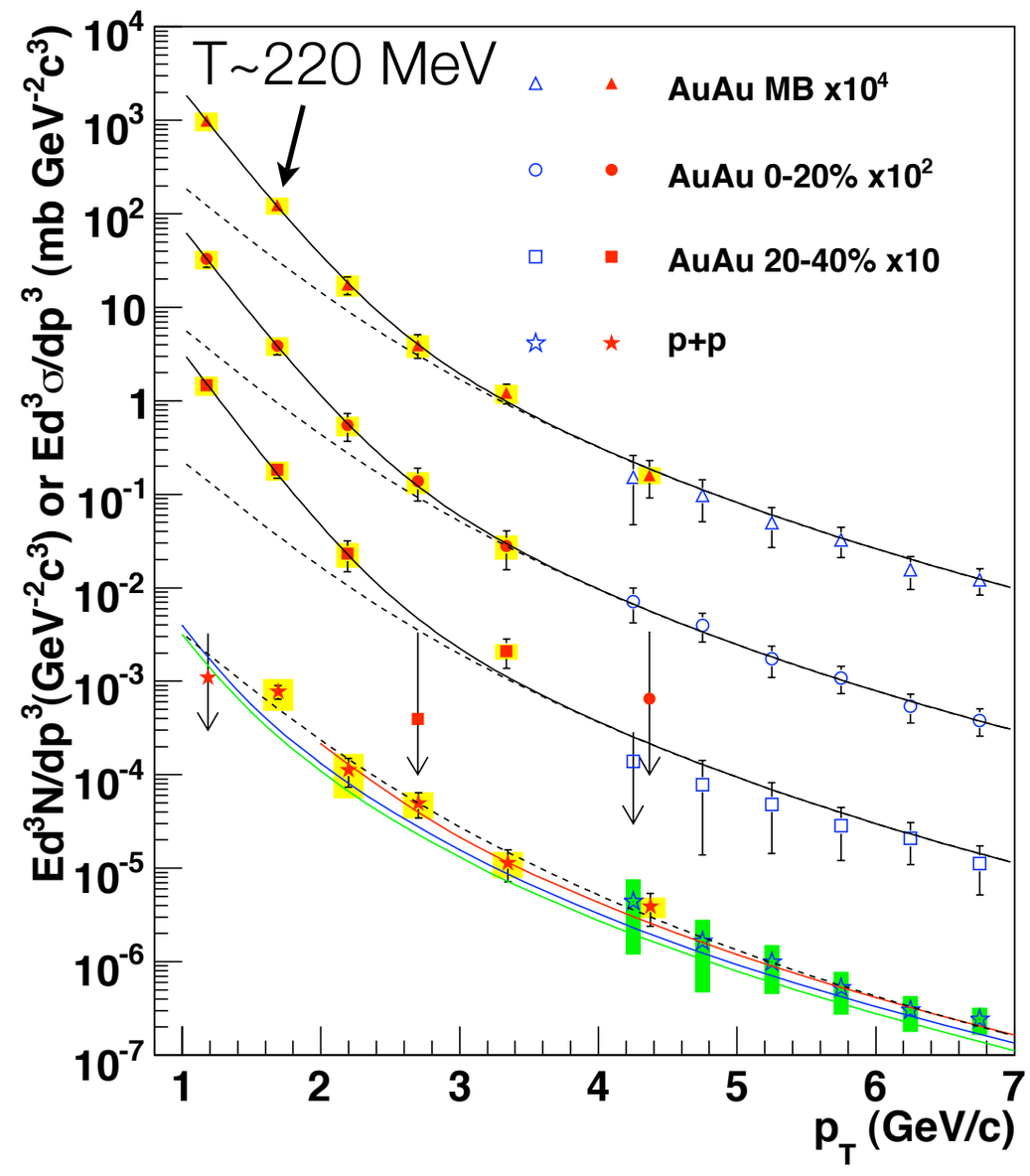
Lattice
1st order PT
Crossover
Hadronic





Implications of Hydro

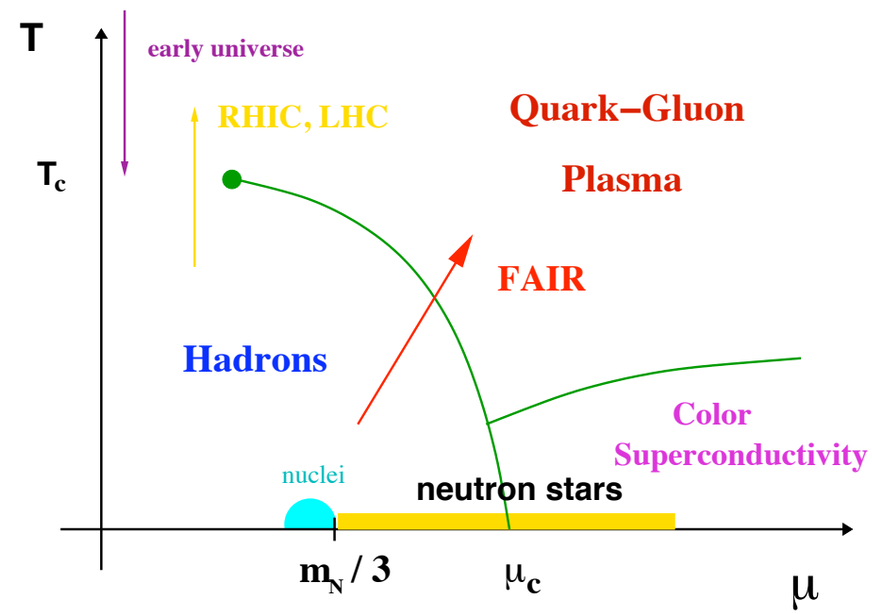
- **Hydro is not "just another" model**
- **The flowing medium is quite special**
  - Local thermalization (strong coupling)
  - "Lattice"-like equation of state (1st order PT)
- **Initial density so large (30xε_p) that can't justify a hadronic cascade**
- **Temperature exceeds T_H**
  - High temperature seen directly by 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

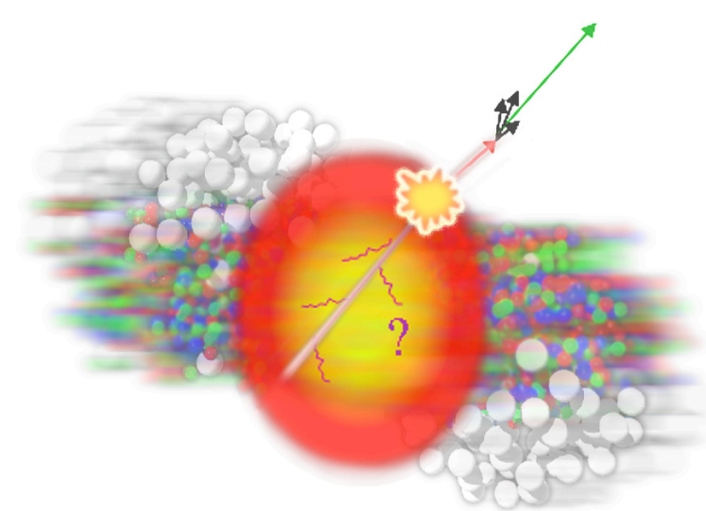
- **Changing initial conditions -- “soft” physics**

Ideal	Temperature	Matter	Density
Practical	Energy	Size	Shape



- **Probing it microscopically -- “hard” probes (van Leeuwen, next)**

Ideal	Microscopy	Tomography	
Practical	Jets	Photons	Quarkonia



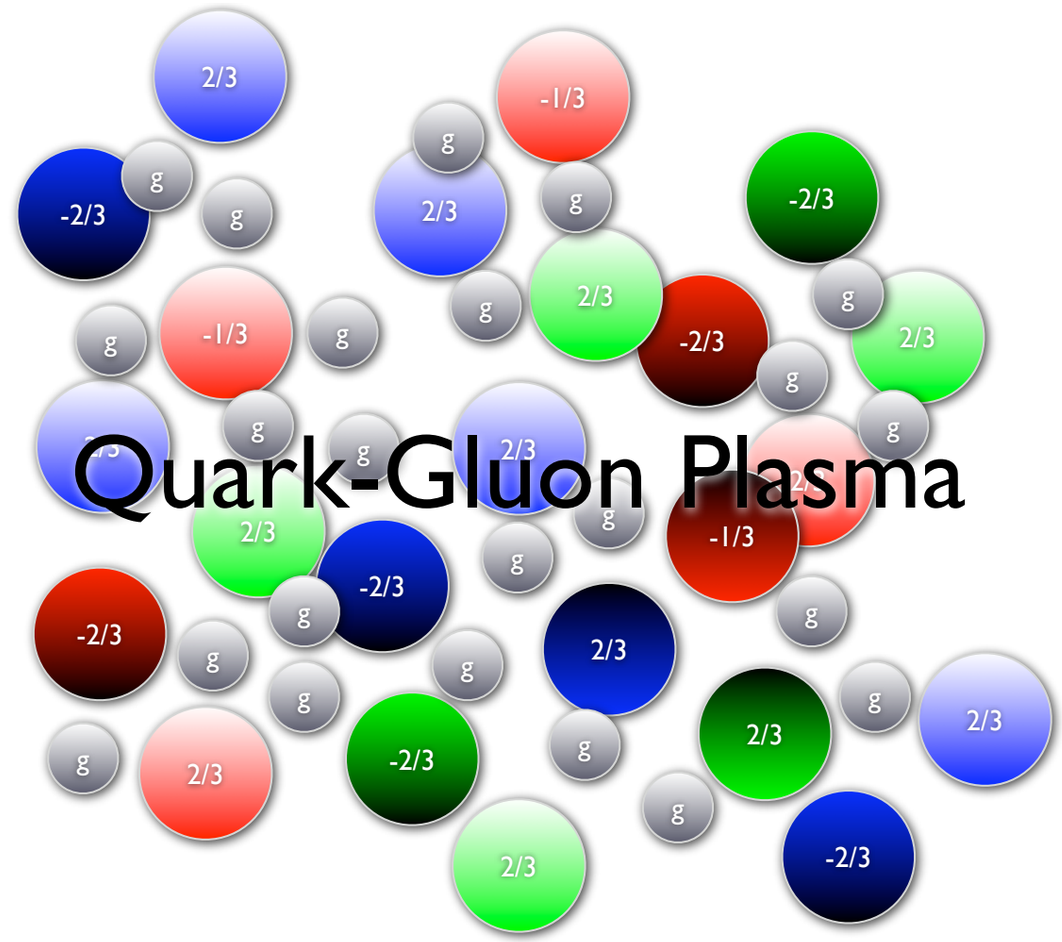
The Big Question: Thermalization at RHIC

Does the system truly thermalize? Everywhere?

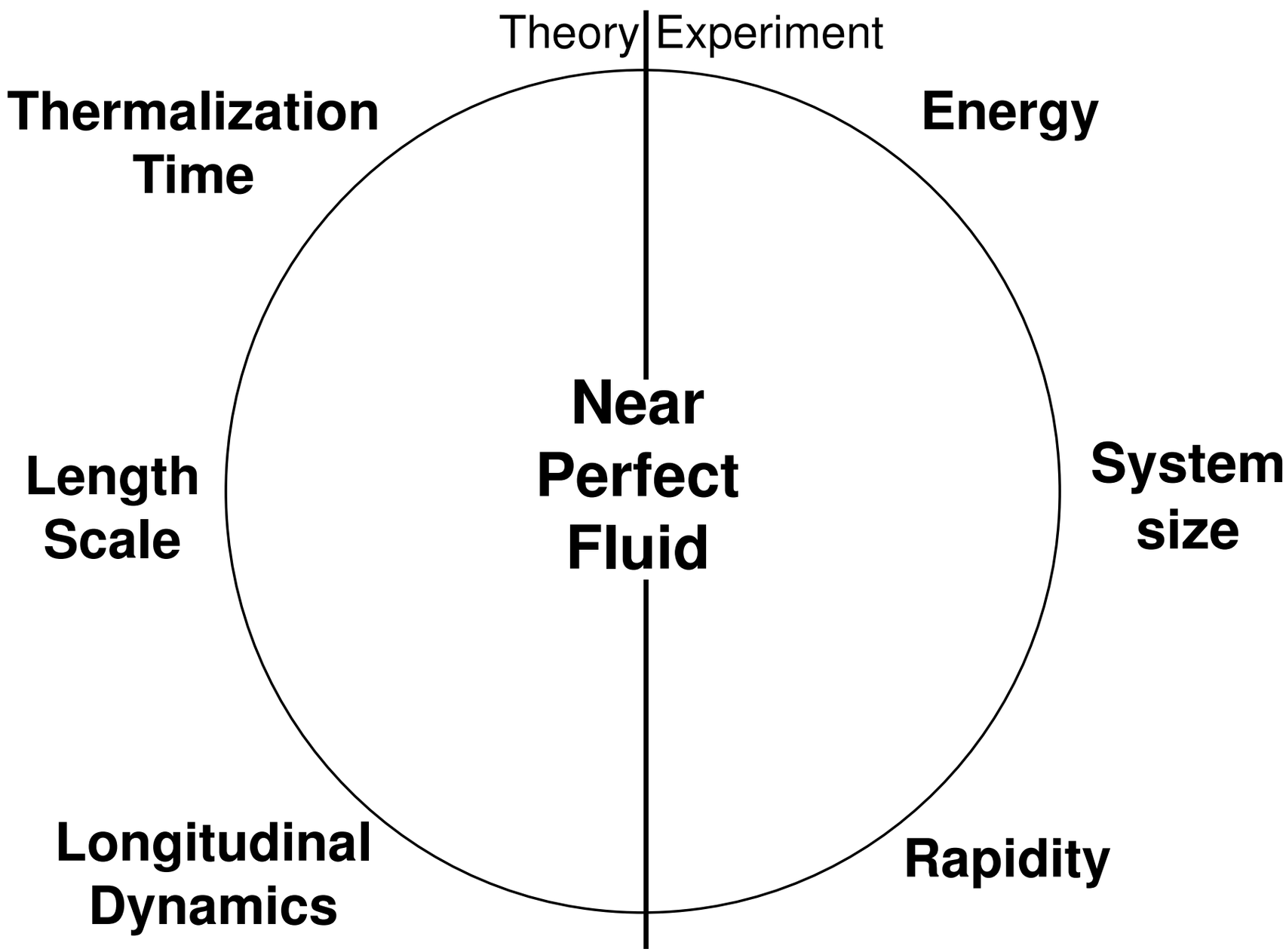
What are the conditions (energy, density, size) for thermalization?

How fast does the system thermalize?

What thermalizes?



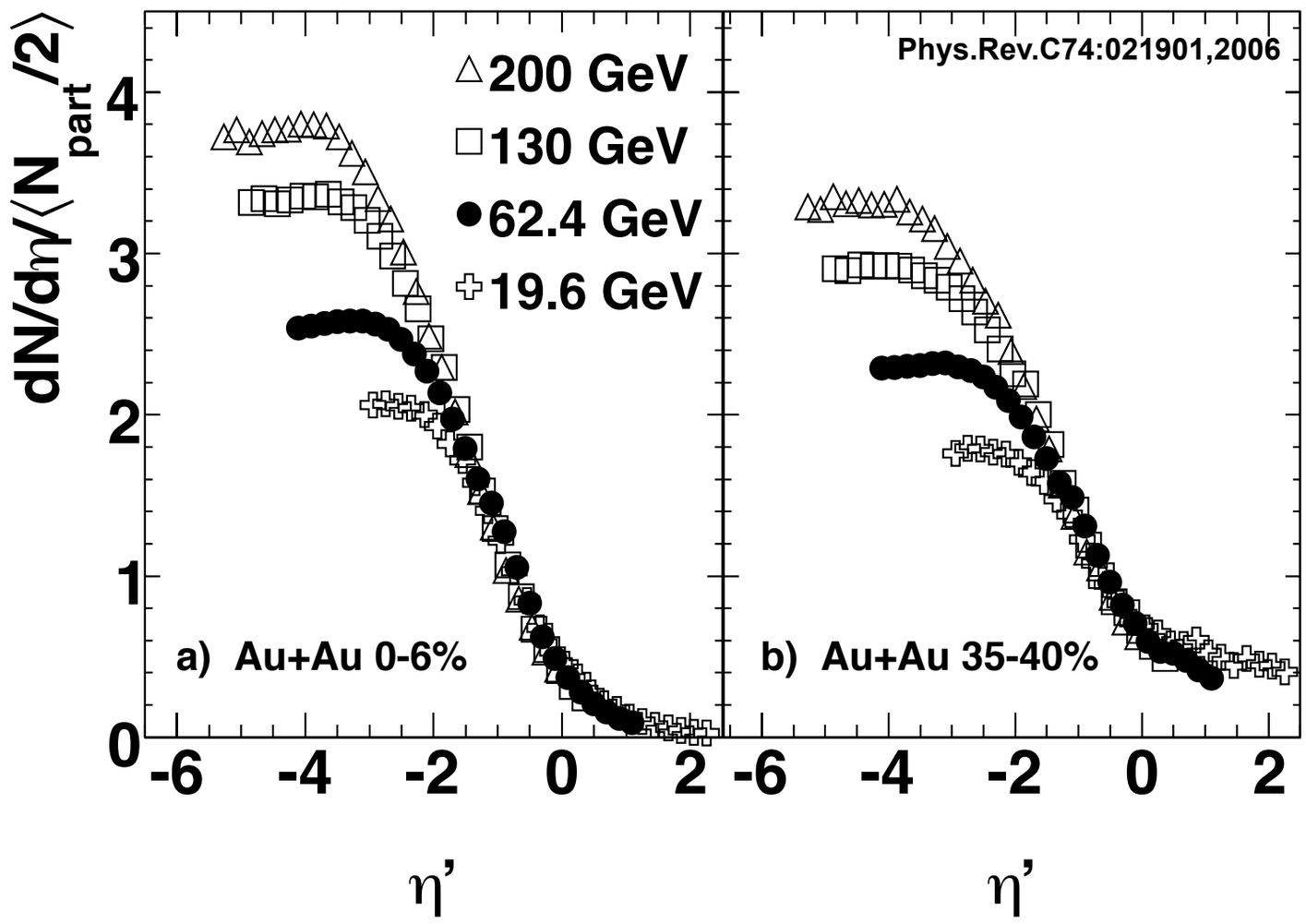
The Edge of Liquidity

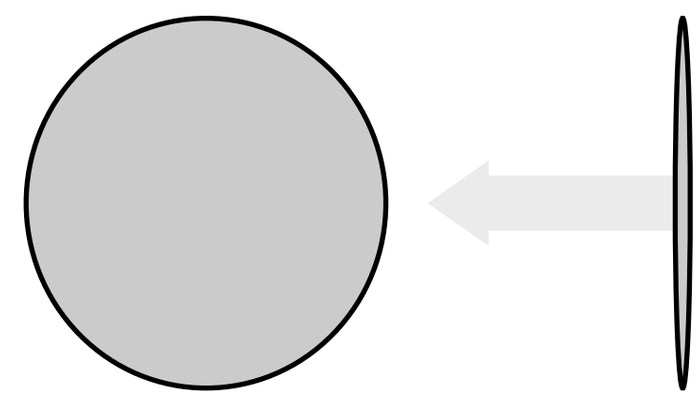


Can we make what we see at RHIC “turn off”?

Extended Longitudinal Scaling (Limiting Fragmentation)

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





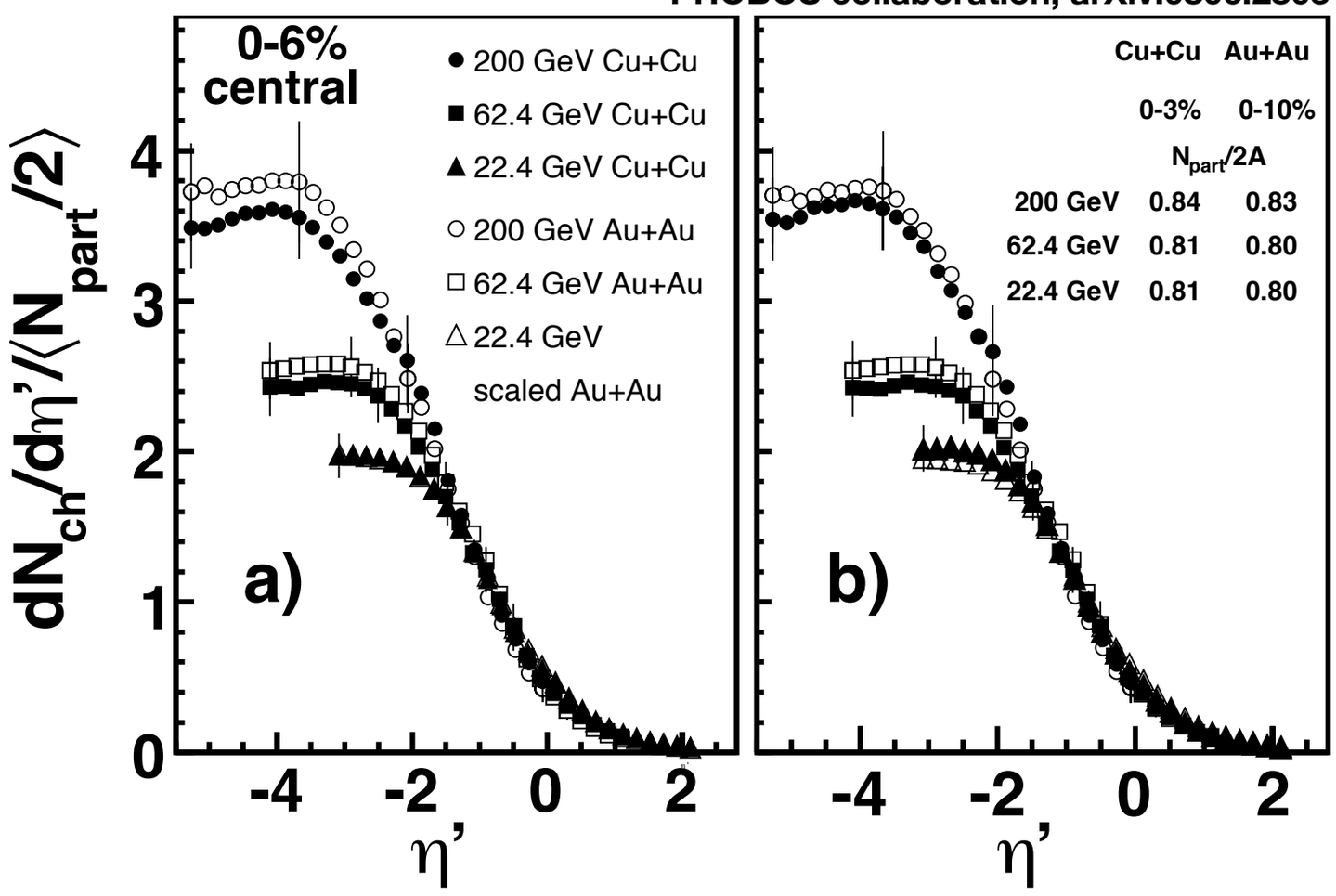
Midrapidity physics at lower energy = forward physics at higher energy

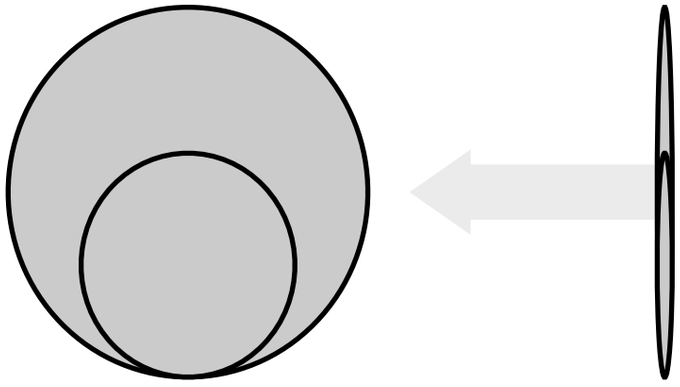
<u>Energy</u> and <u>rapidity</u> dependence is <u>smooth</u>

Extended Longitudinal Scaling (Limiting Fragmentation)

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

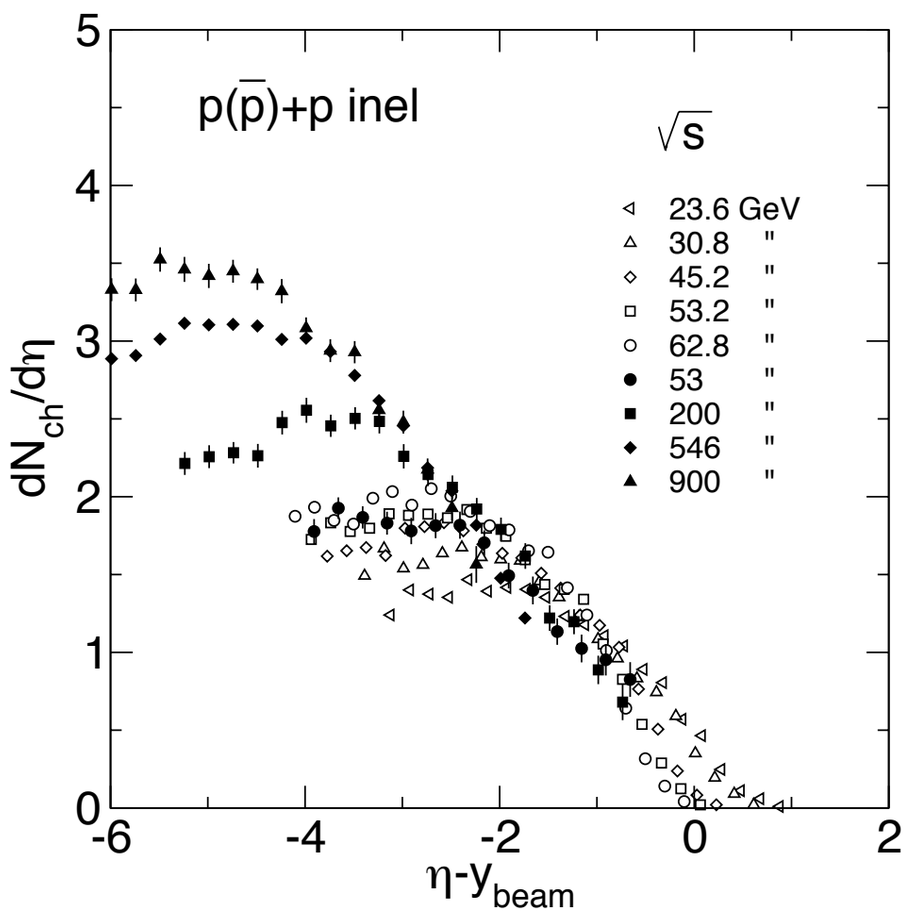
PHOBOS collaboration, arXiv:0806.2803

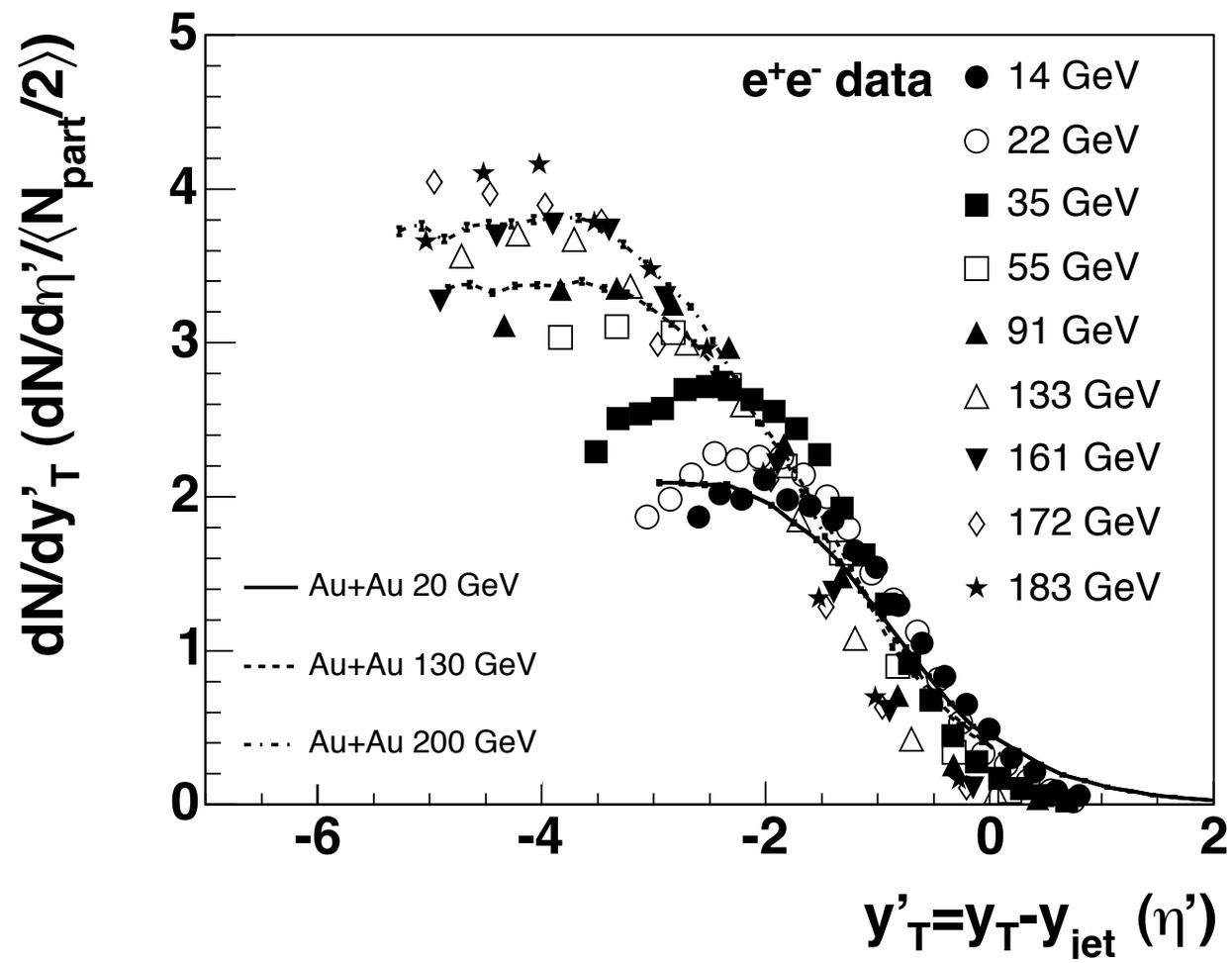




Change the nuclear size by x3: Au+Au→Cu+Cu
No change in shape for same centrality (b/2R)

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



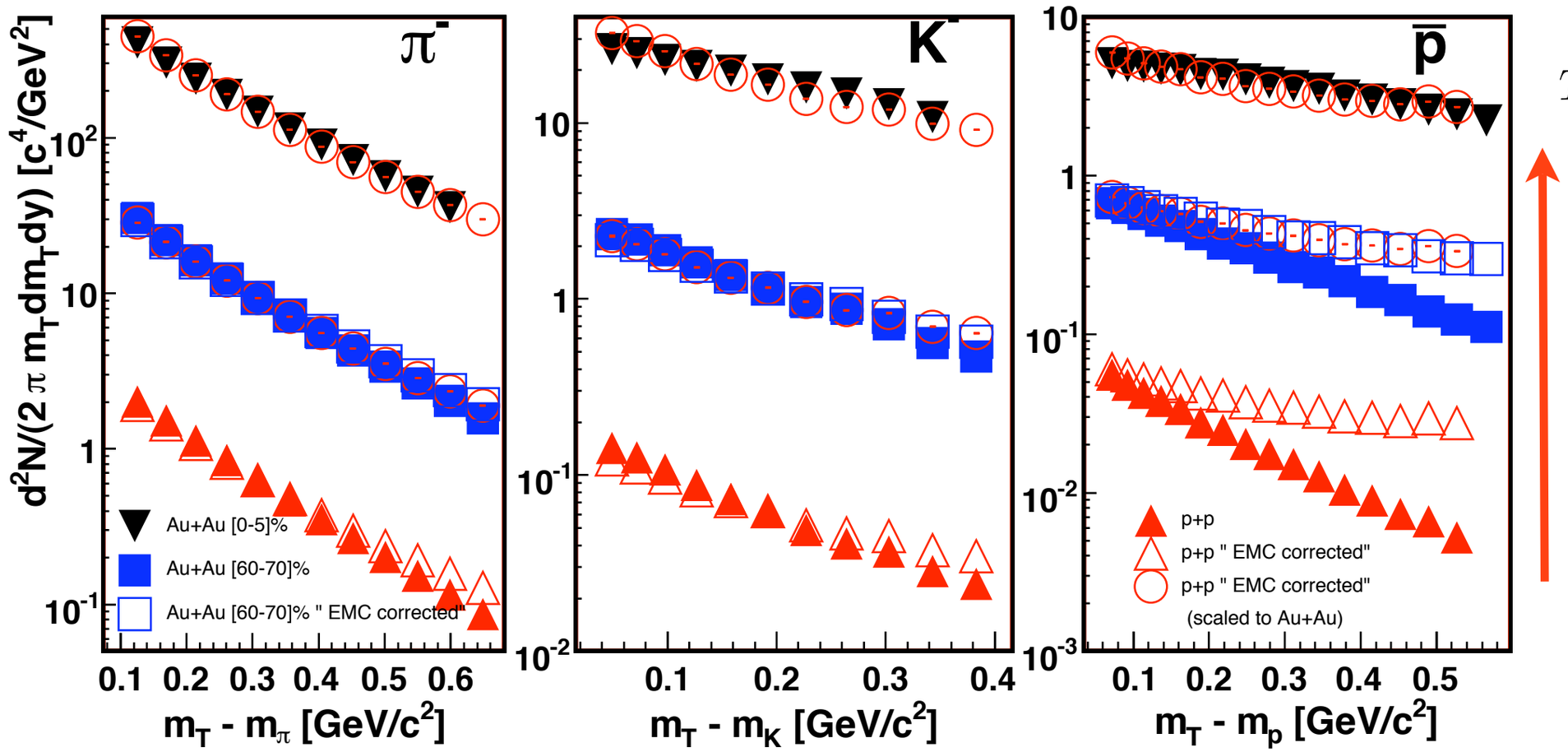


Even "small" systems (p+p and e^+e^-) show same feature, and magnitude for e^+e^-

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

Small ≠ Large?

M. Lisa, Tuesday, arXiv: 0805.3569

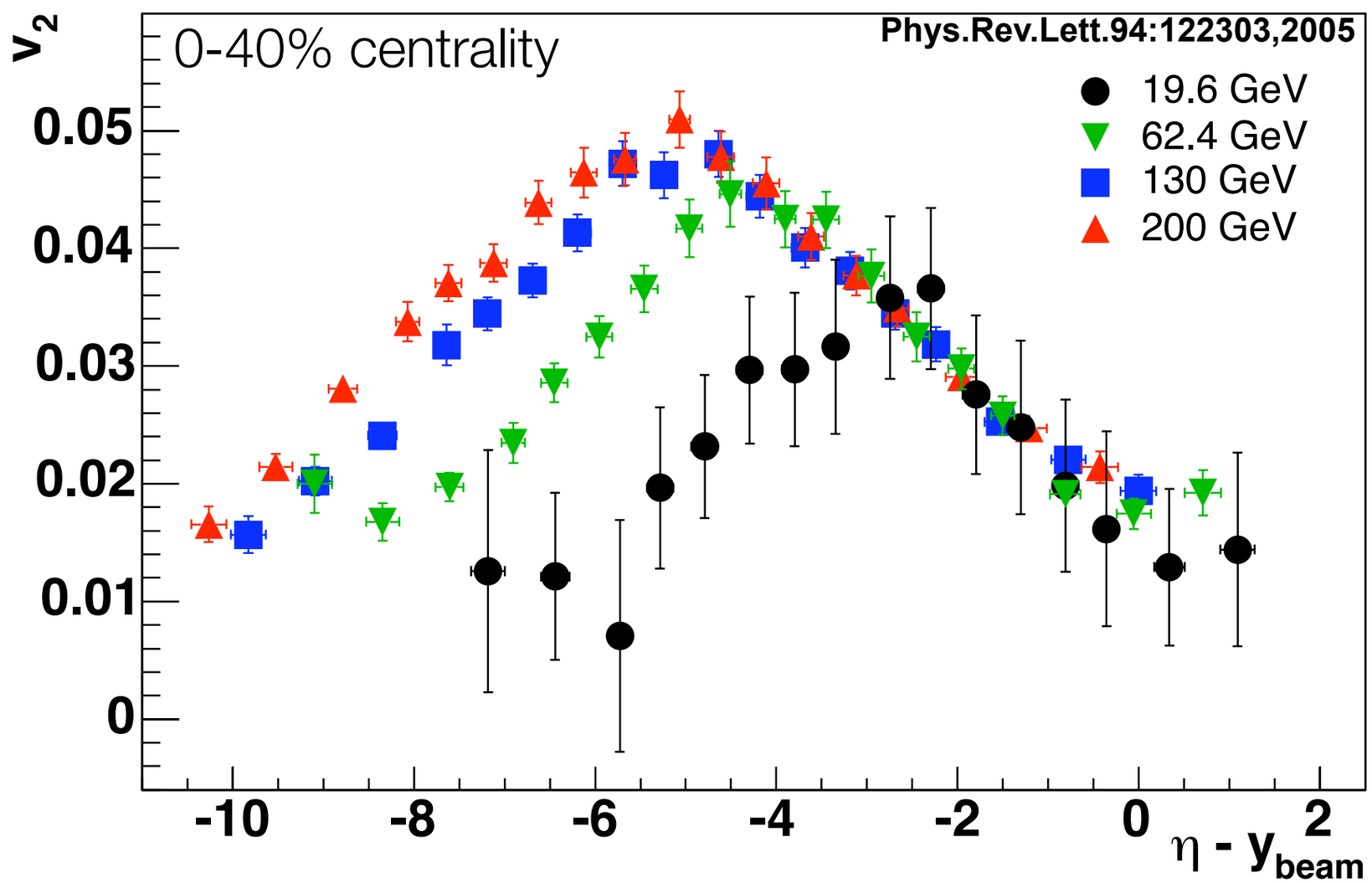


$T_{eff} = T_0 + m\beta^2$

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?

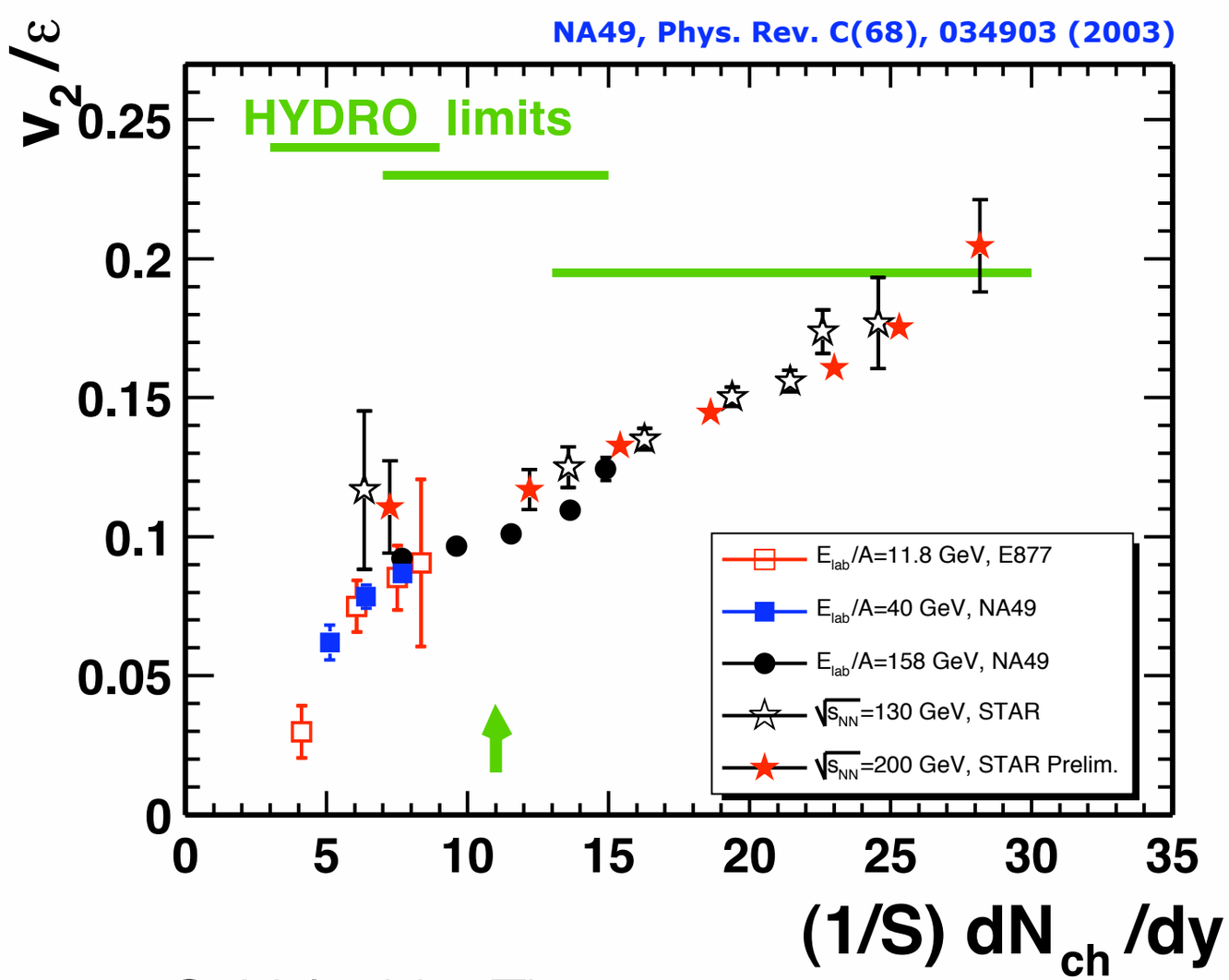
Longitudinal Scaling of Elliptic Flow



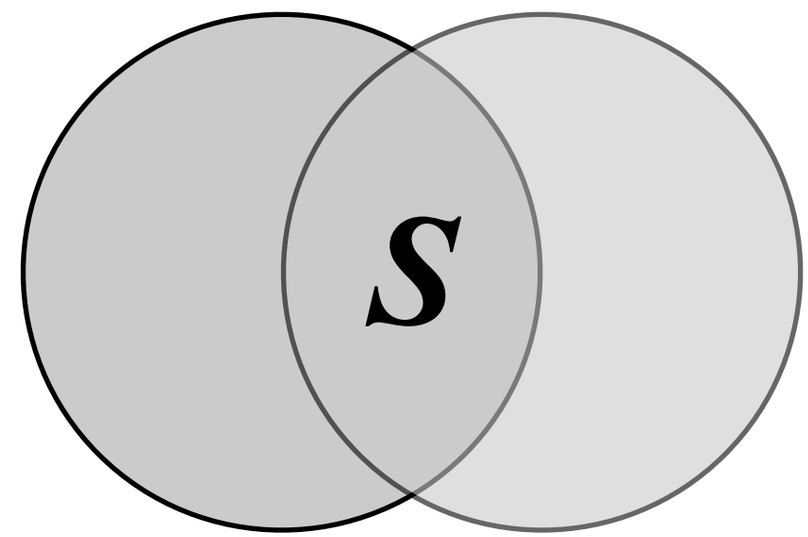
Scaling also observed for $v_2(\eta)$: related to $dN/d\eta$?

Elliptic flow “scales” across beam energies

The ratio v_2/ε found to be a good scaling variable for Au+Au between different energies when plotted vs. dN/dy / S



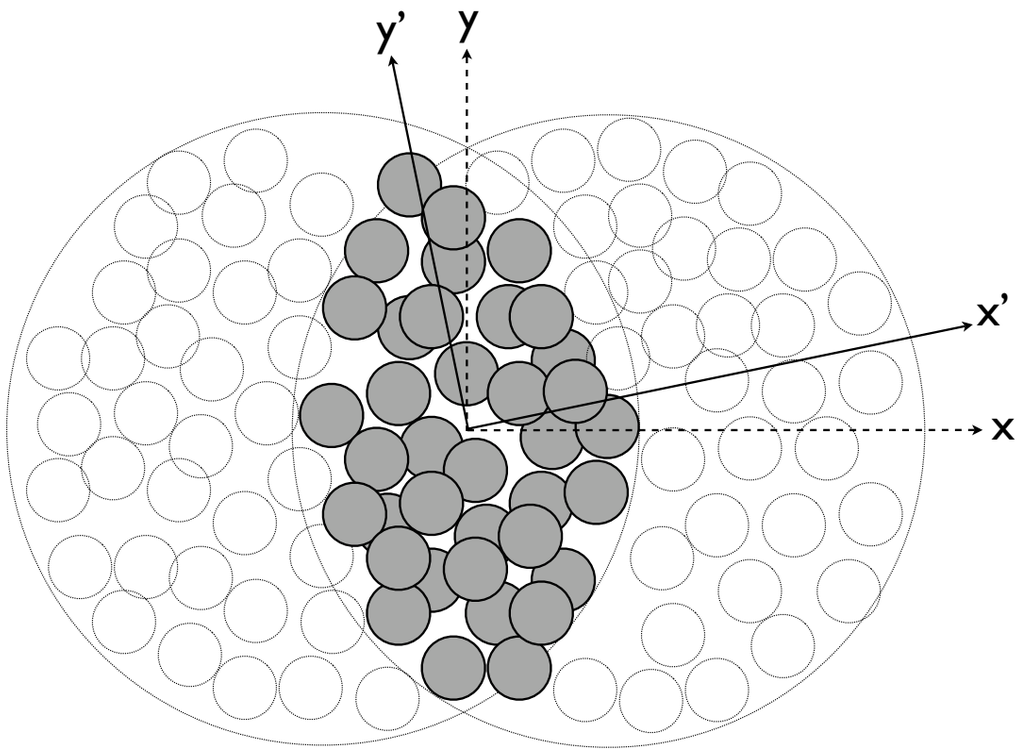
S. Voloshin, Thurs.

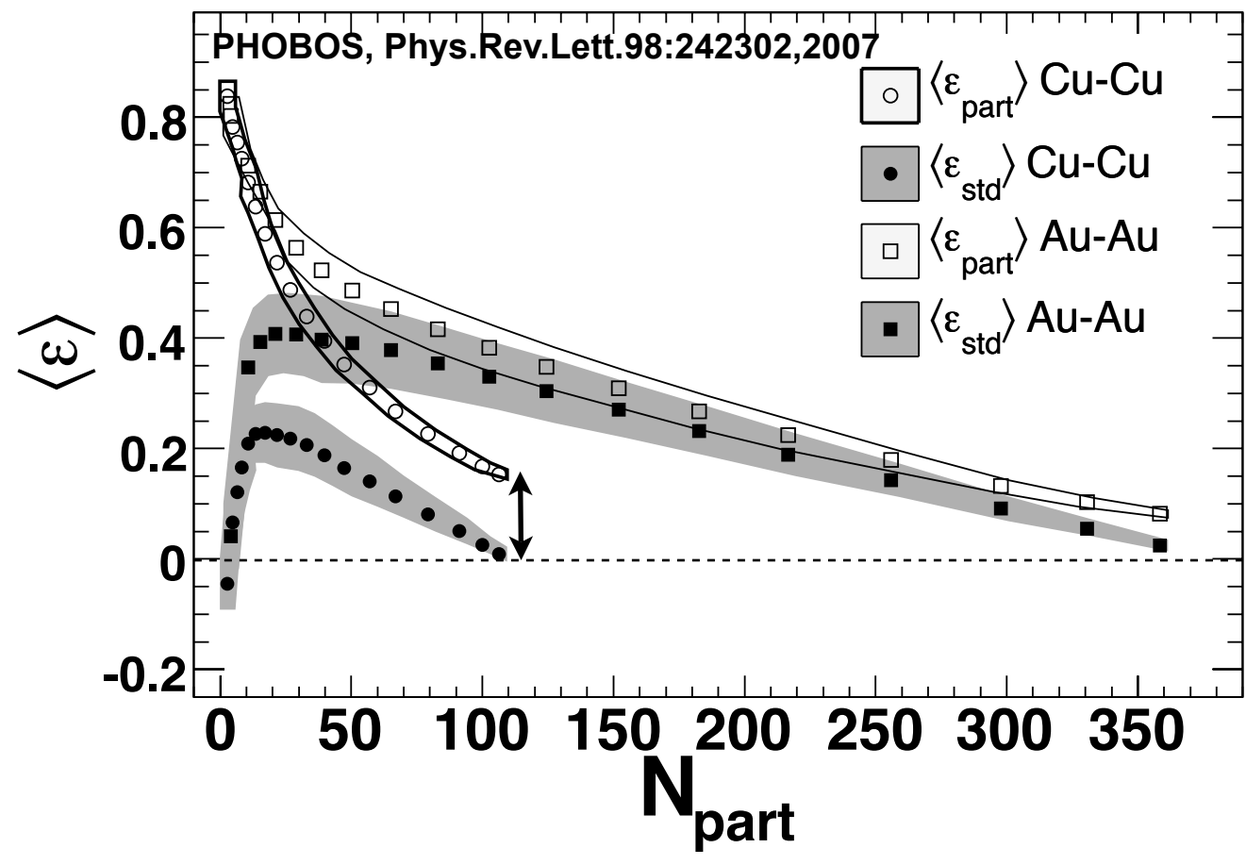


$$v_2 \propto \epsilon \frac{dN/dy}{S}$$

Flow depends only on <u>shape</u> and <u>area density</u> and not on beam energy

What is a Nucleus?: Participant Eccentricity





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

Eccentricity usually defined relative to impact parameter

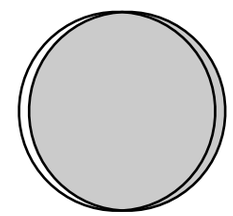
$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

Can also define relative to participants themselves, assuming thermalization is <u>fast</u> & <u>local</u>

Participant Eccentricity in Au+Au and Cu+Cu

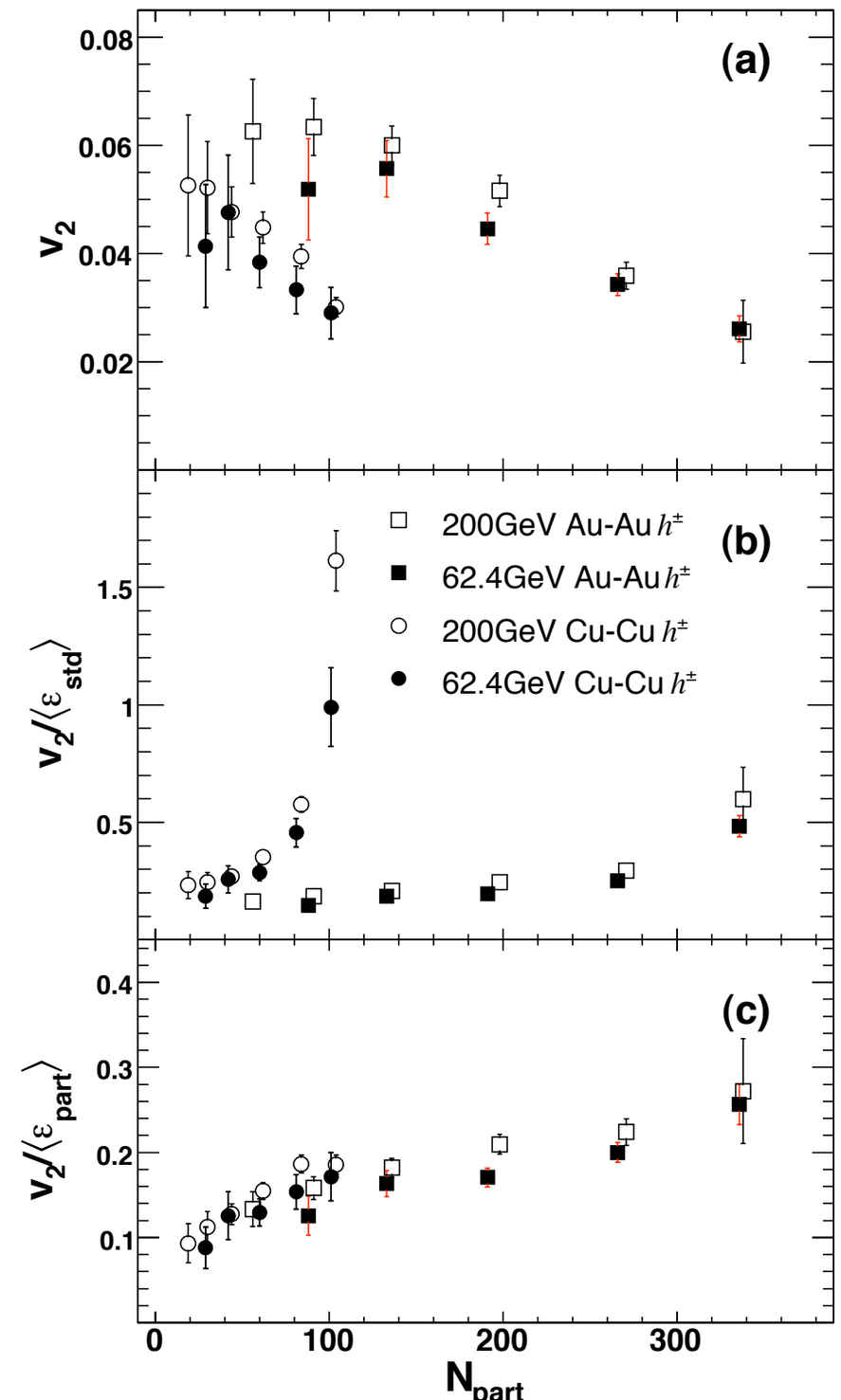
PHOBOS, Phys.Rev.Lett.98:242302,2007

$v_2 \not\to 0$ even when $b \to 0$



Since $\varepsilon_{std} \to 0$, v_2/ε_{std} <u>diverges</u> for central Cu+Cu events

v_2/ε_{part} <u>scales</u> for Au+Au and Cu+Cu: Nucleon configuration "**frozen-in**" very early (**small τ_0**)



Degrees of Freedom: What Flows?

Parton distributions
Nuclear Geometry
Nuclear shadowing

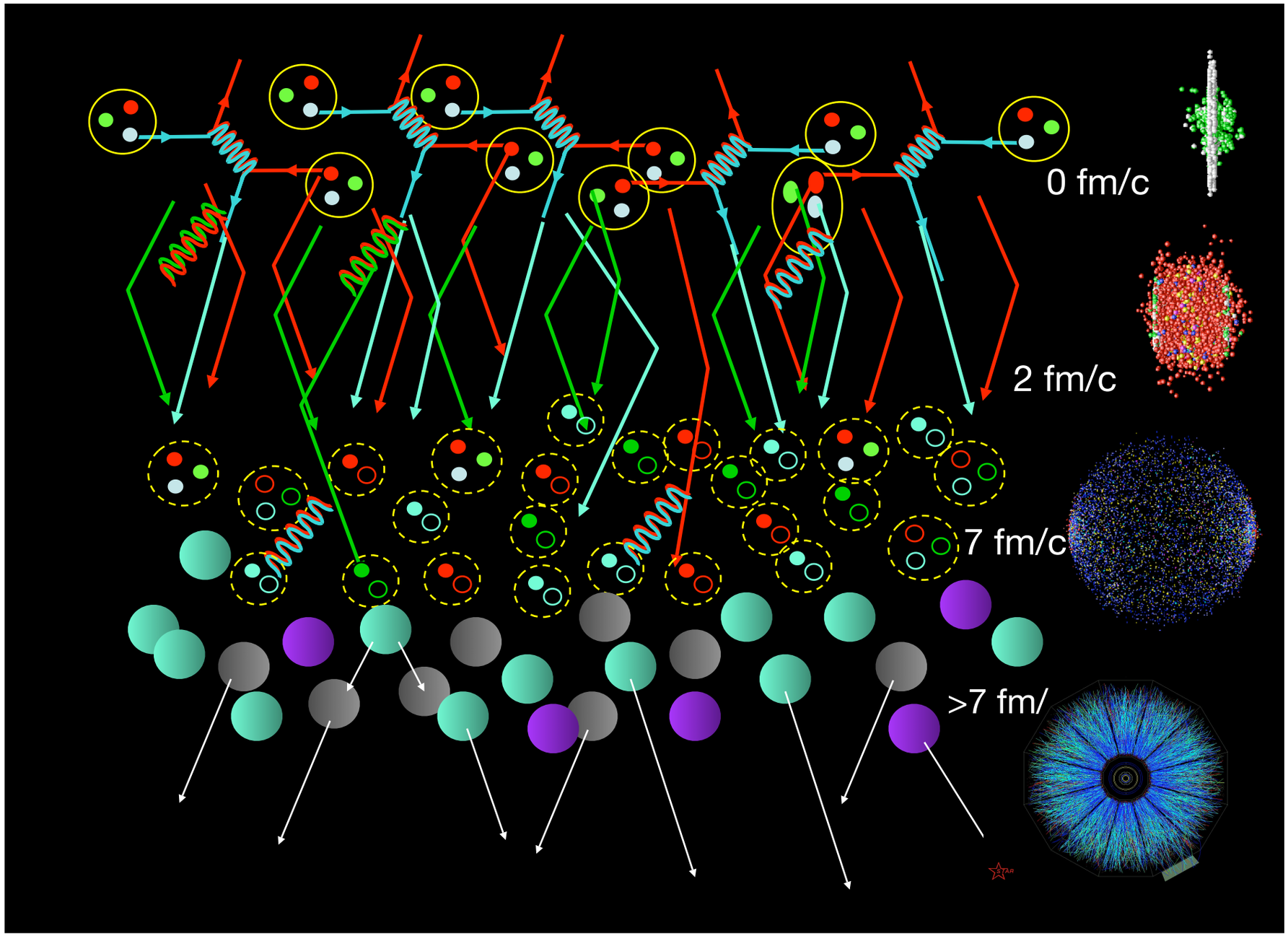
Parton production
& reinteraction

Chemical Freezeout &
Quark Recombination

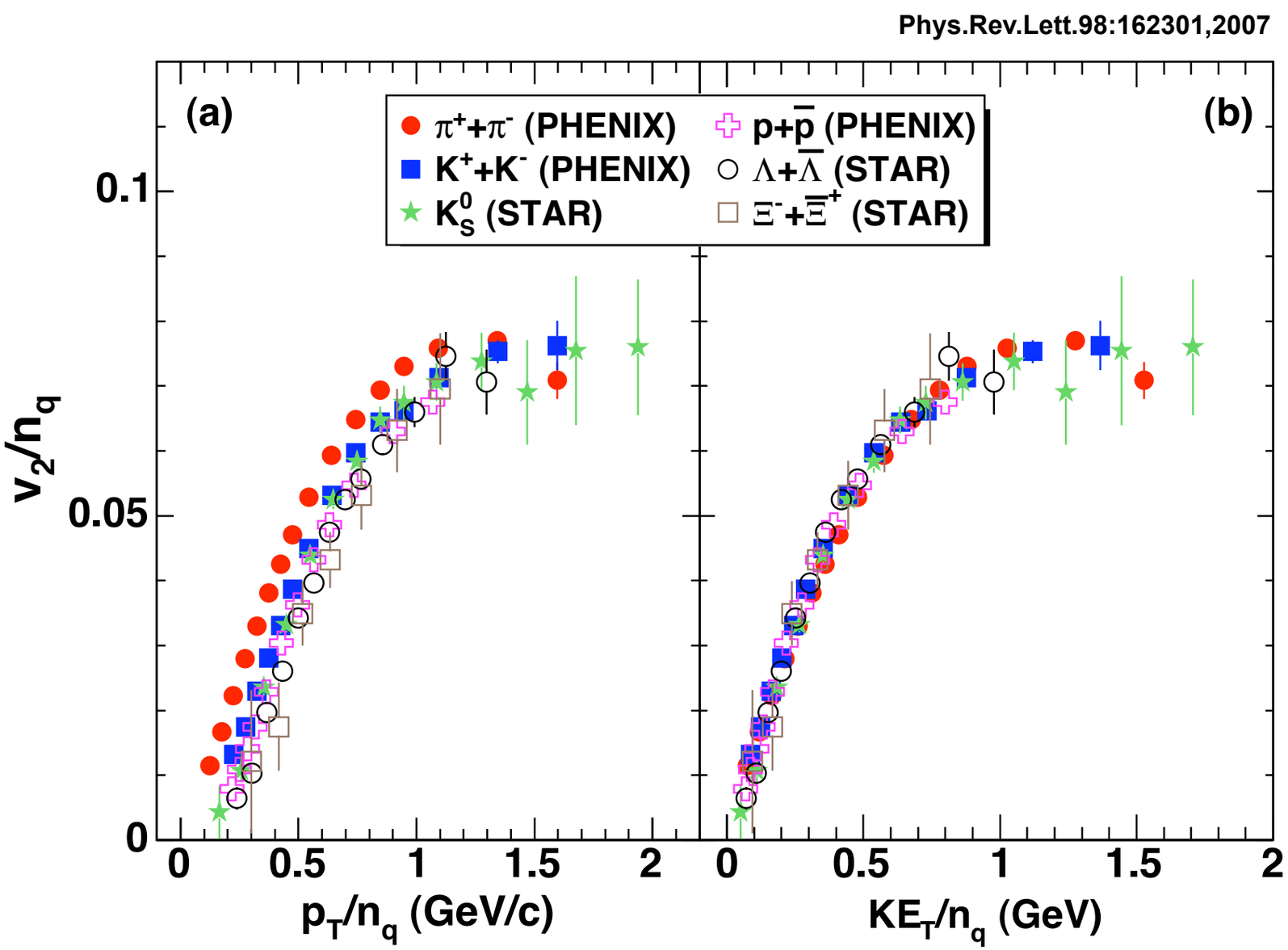
Jet Fragmentation
Functions

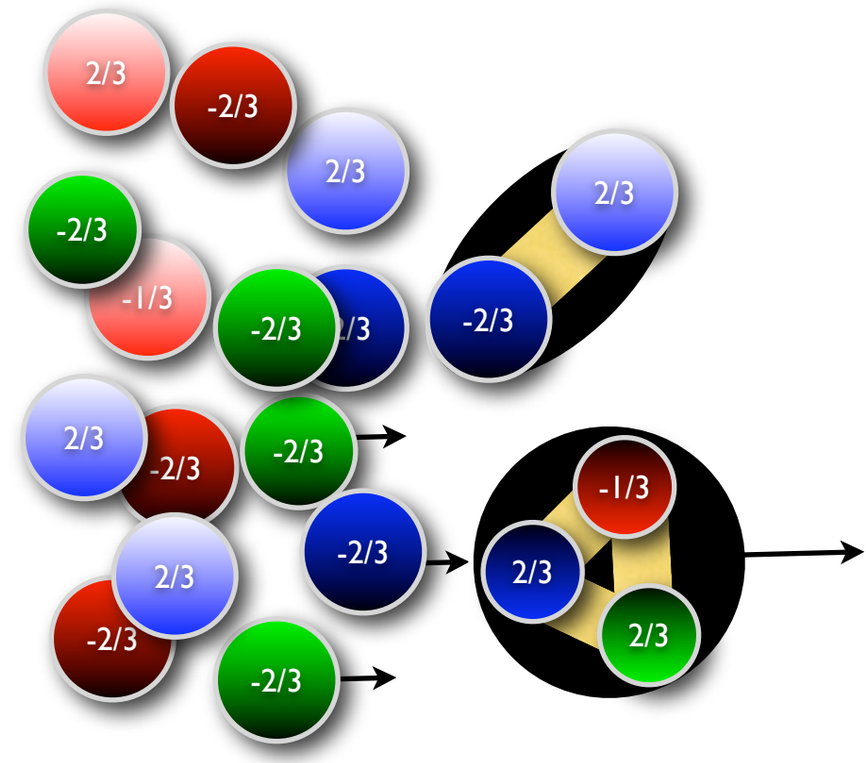
Hadron Rescattering

Thermal Freezeout &
Hadron decays



Constituent Quark Scaling

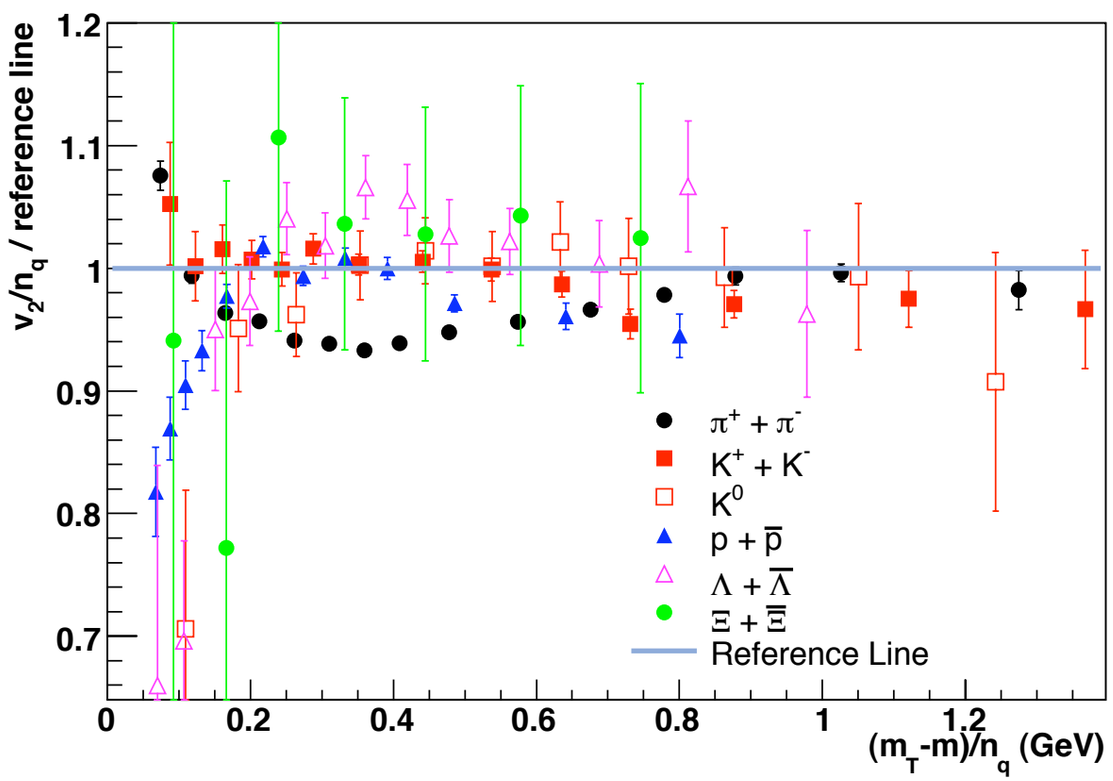




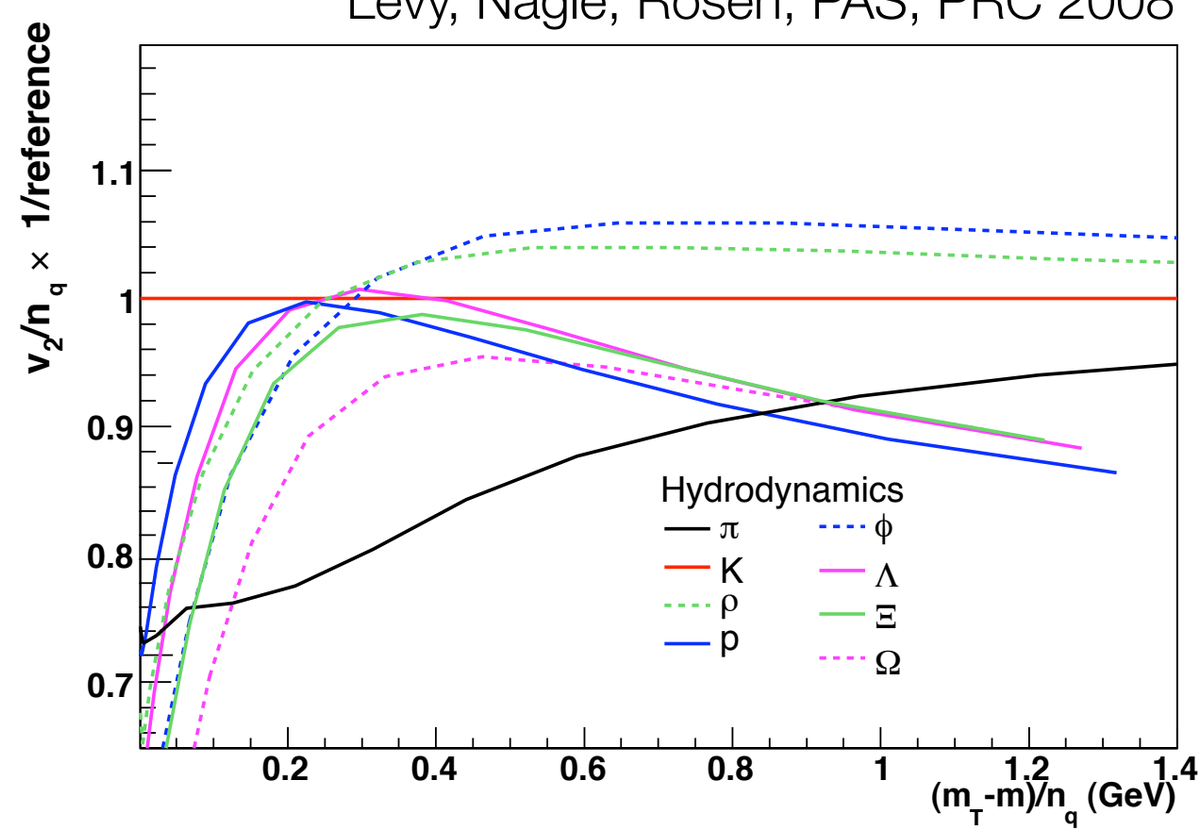
All particles flow as if frozen out from a flowing soup of constituent quarks

$$KE_T = m_T - m$$

Quasi-Particles in the sQGP



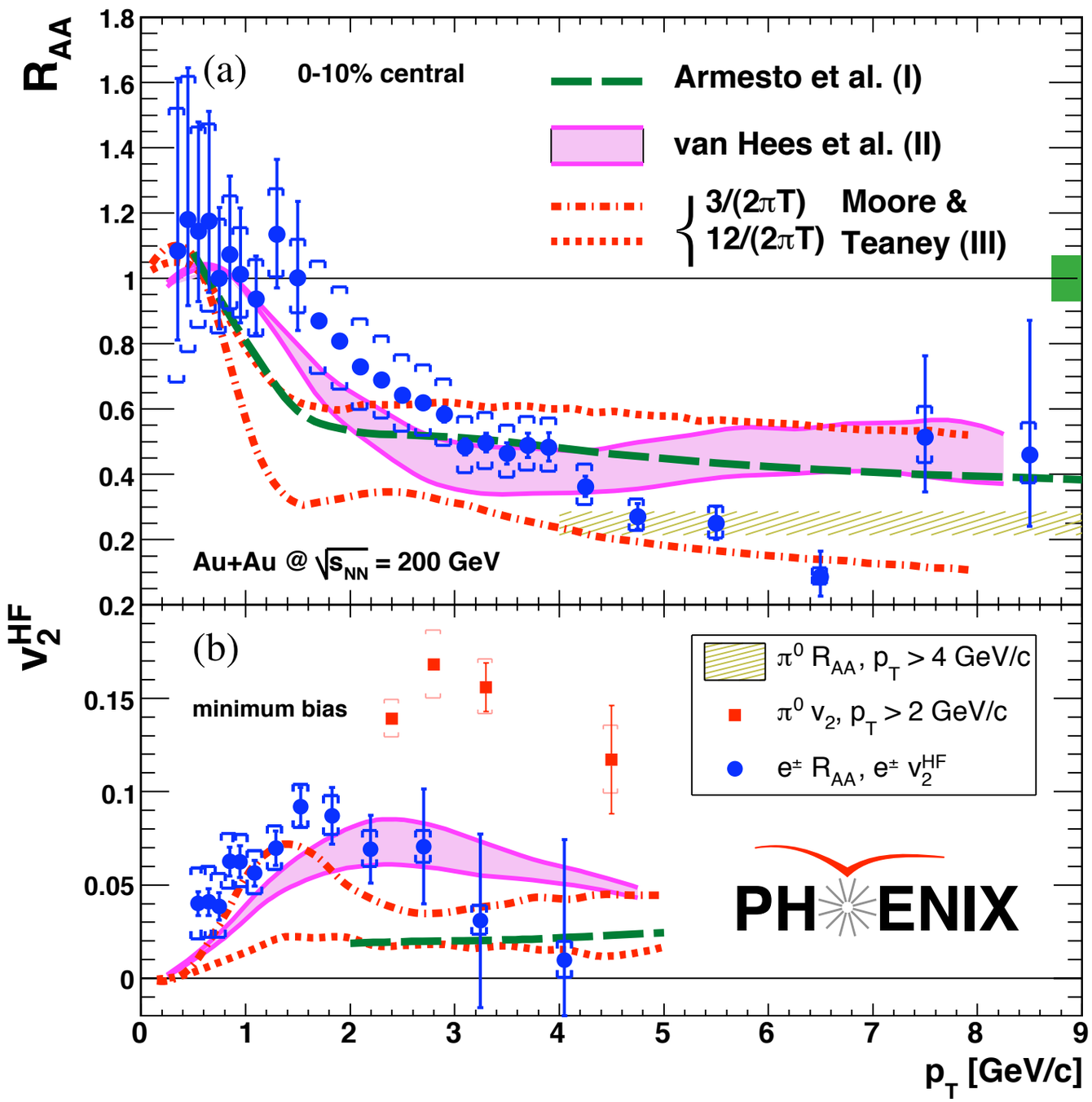
Levy, Nagle, Rosen, PAS, PRC 2008



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...)

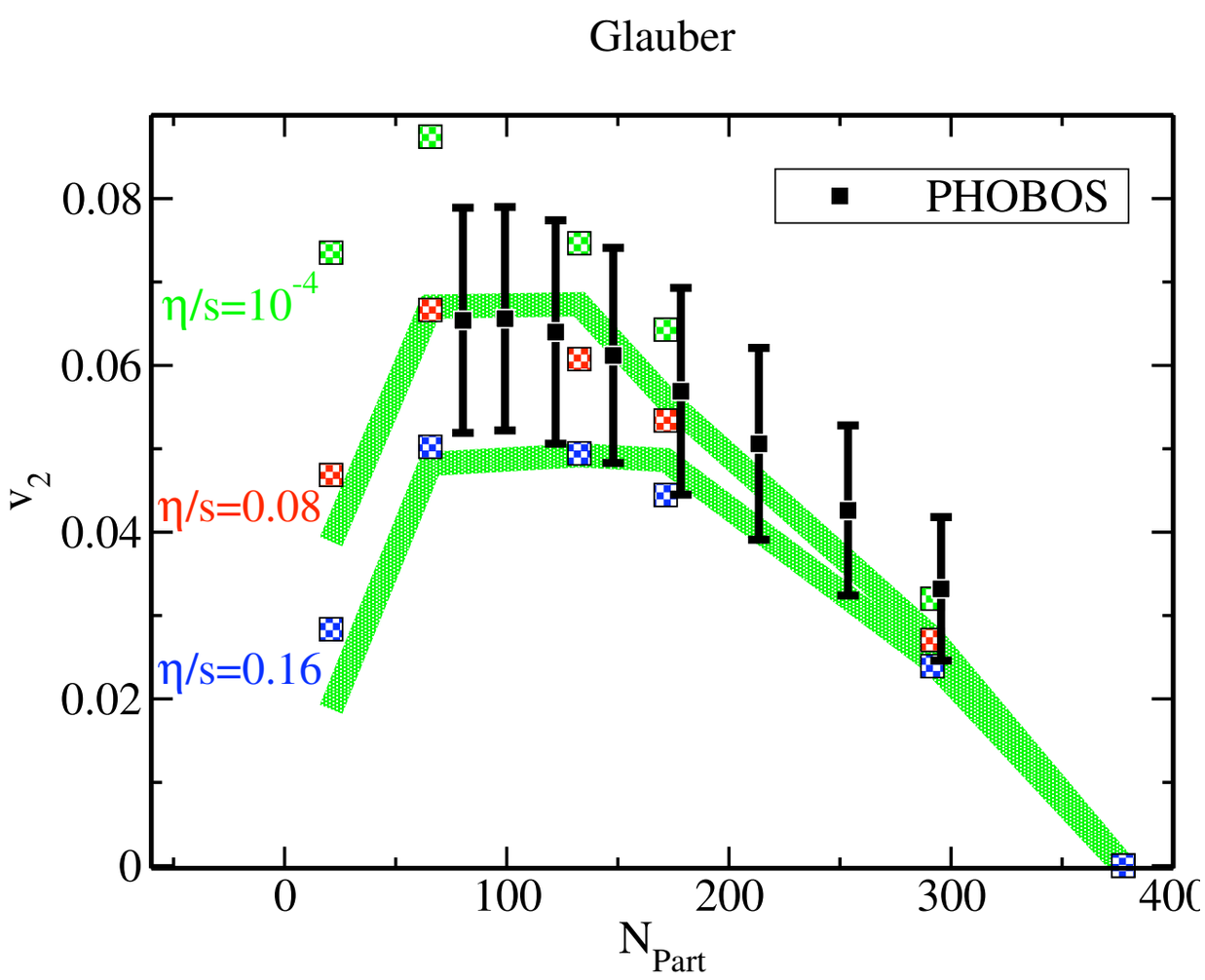
Direct Measurements of Viscosity

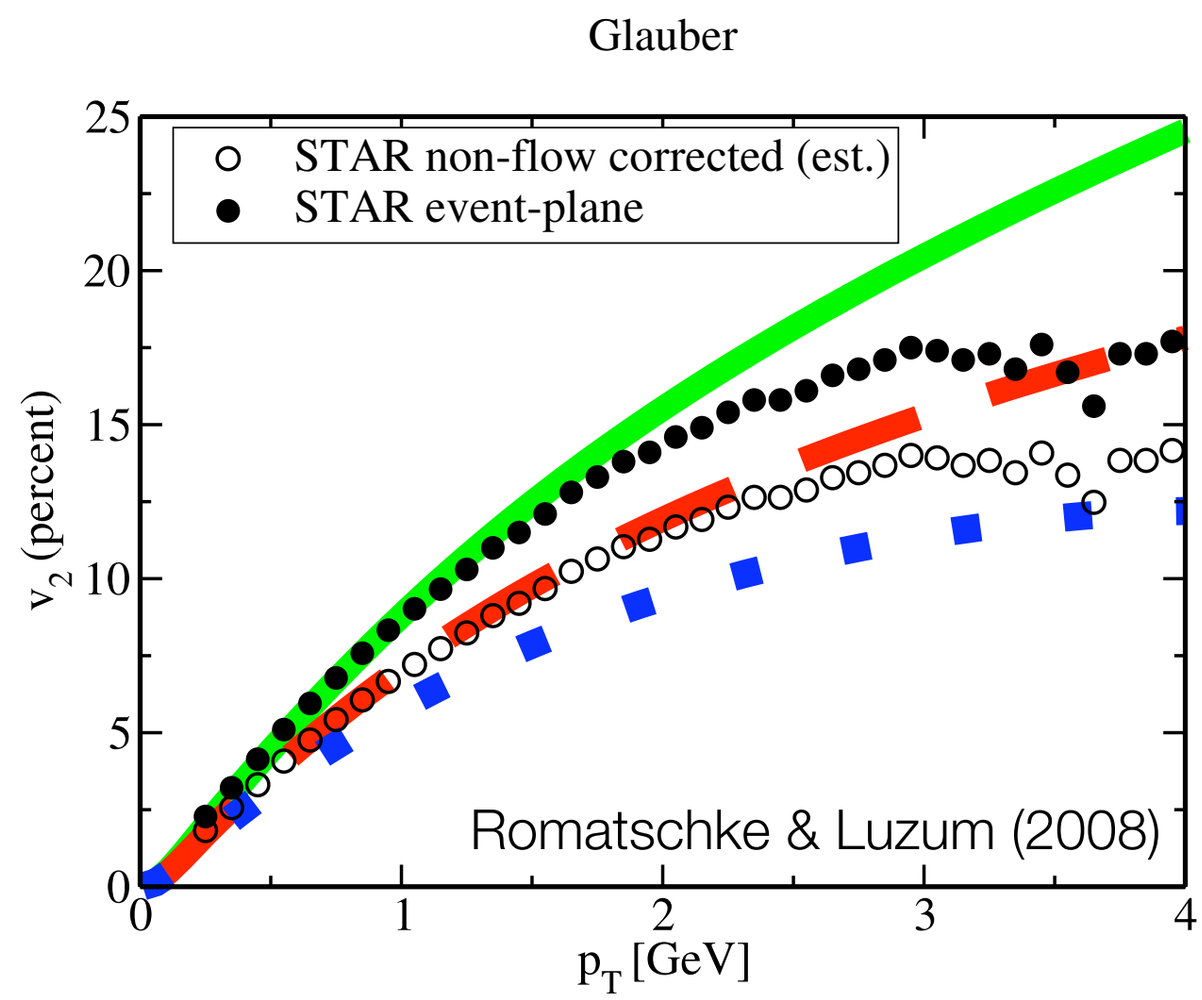


Suppression and flow of charm (via electron) are correlated and reflect diffusion of heavy quark in medium (i.e. viscosity)

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

Viscous Hydrodynamics





Recent advances in implementing viscous hydrodynamics

With Glauber initial conditions, RHIC data saturating viscosity bound!

Lessons from Soft Physics @ RHIC

- **System is manifestly thermalized in final state**
  - Hagedorn freezeout temperature

- **Hydro implies local thermalization in the initial state (and possibly presence of phase transition)**
  - System much hotter than T_H

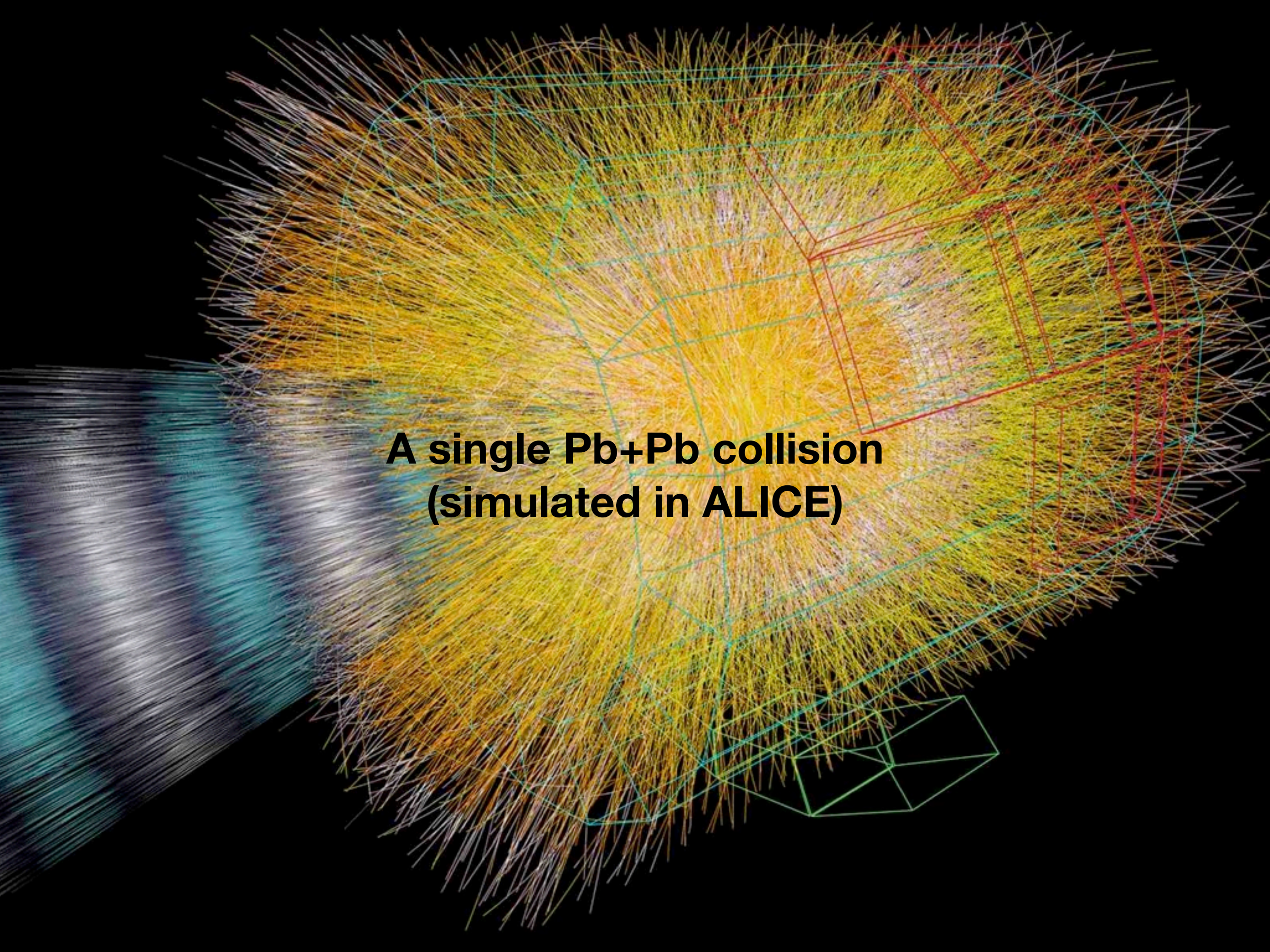
- **No deviations in soft observables vs. rapidity, energy, size**
  - Extended longitudinal scaling ubiquitous in all systems

- **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

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

<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?)

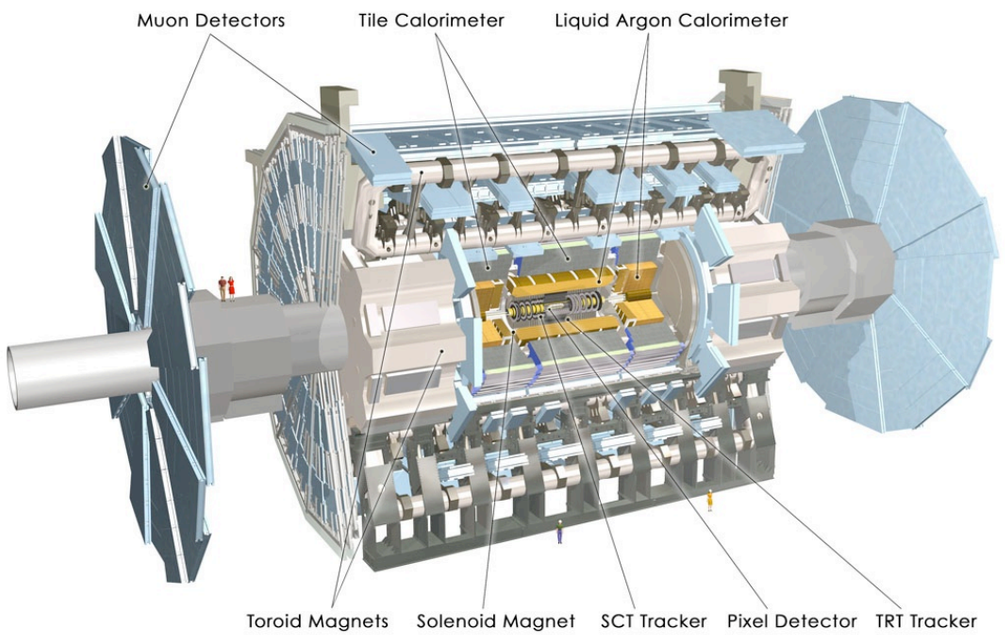
How <u>fast</u> does the system thermalize?

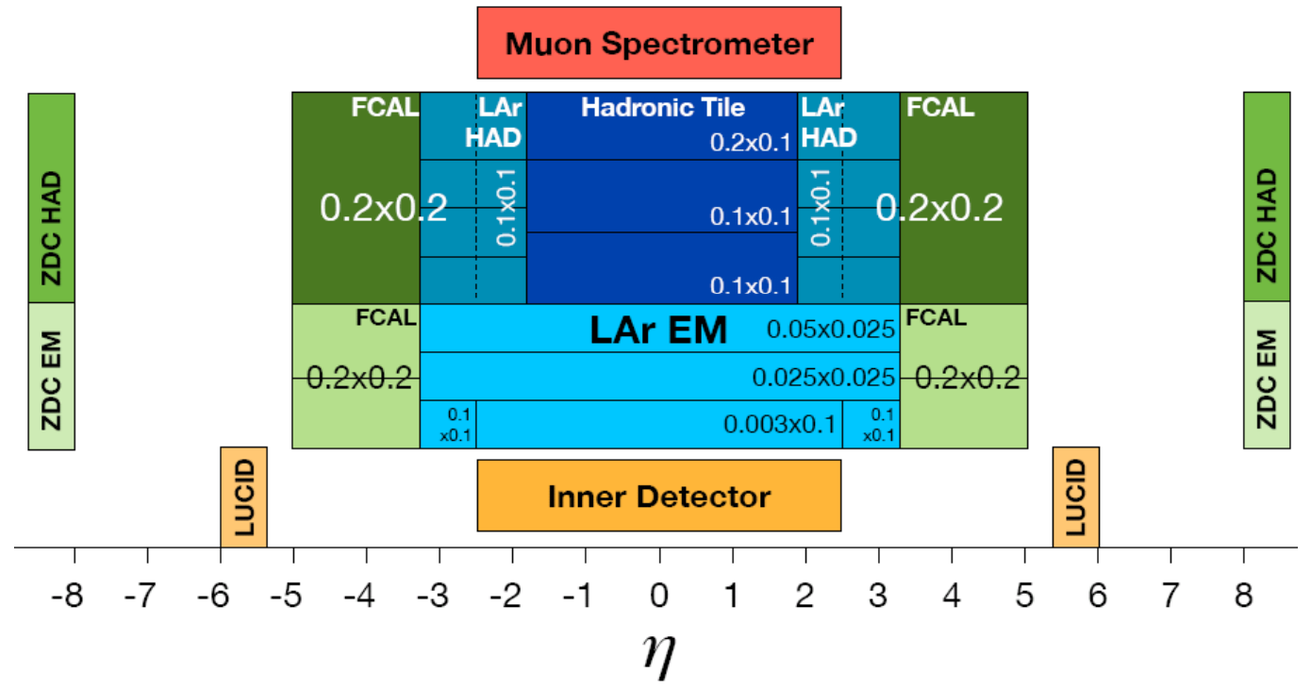
(initial longitudinal scale is 30x smaller!)

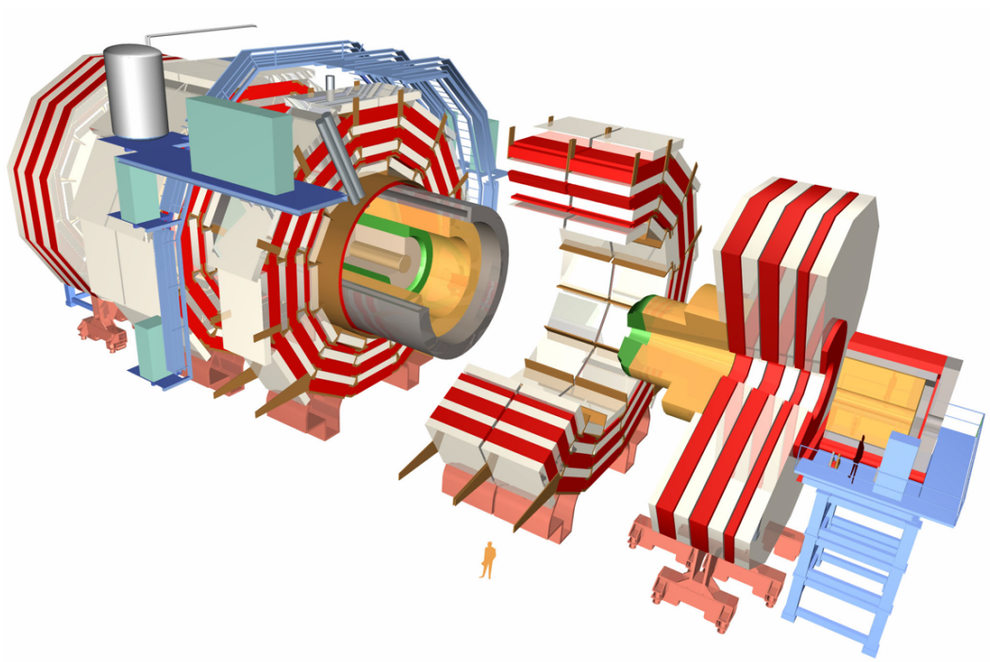
<u>What</u> thermalizes?

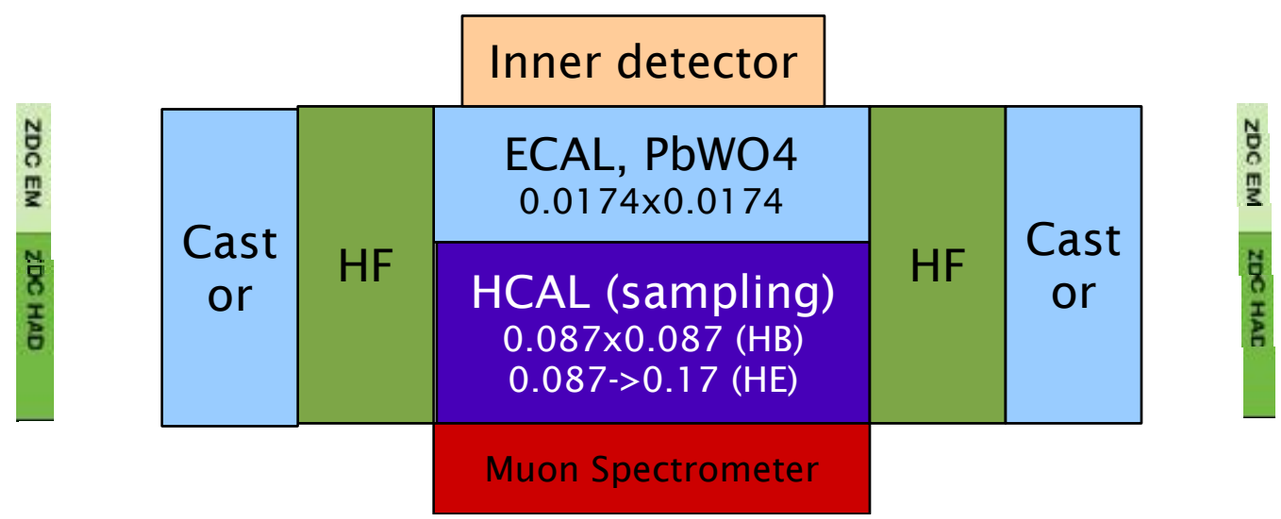
(Will degrees of freedom change?)

ATLAS & CMS @ LHC





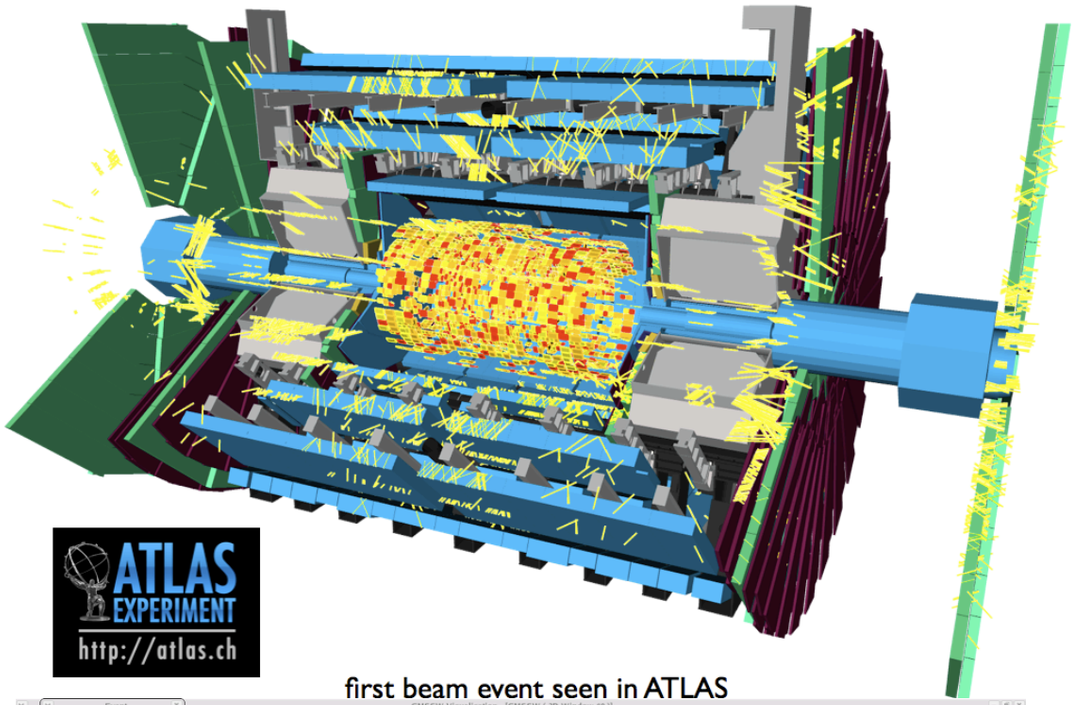




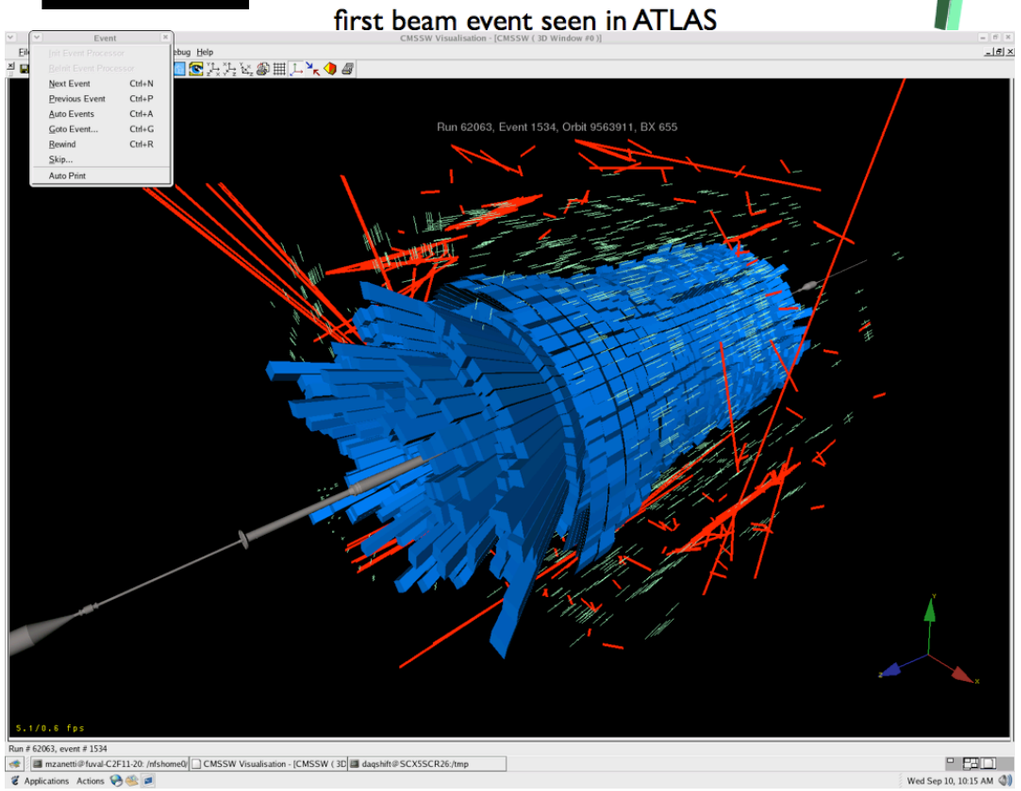
Enormous acceptance for soft physics

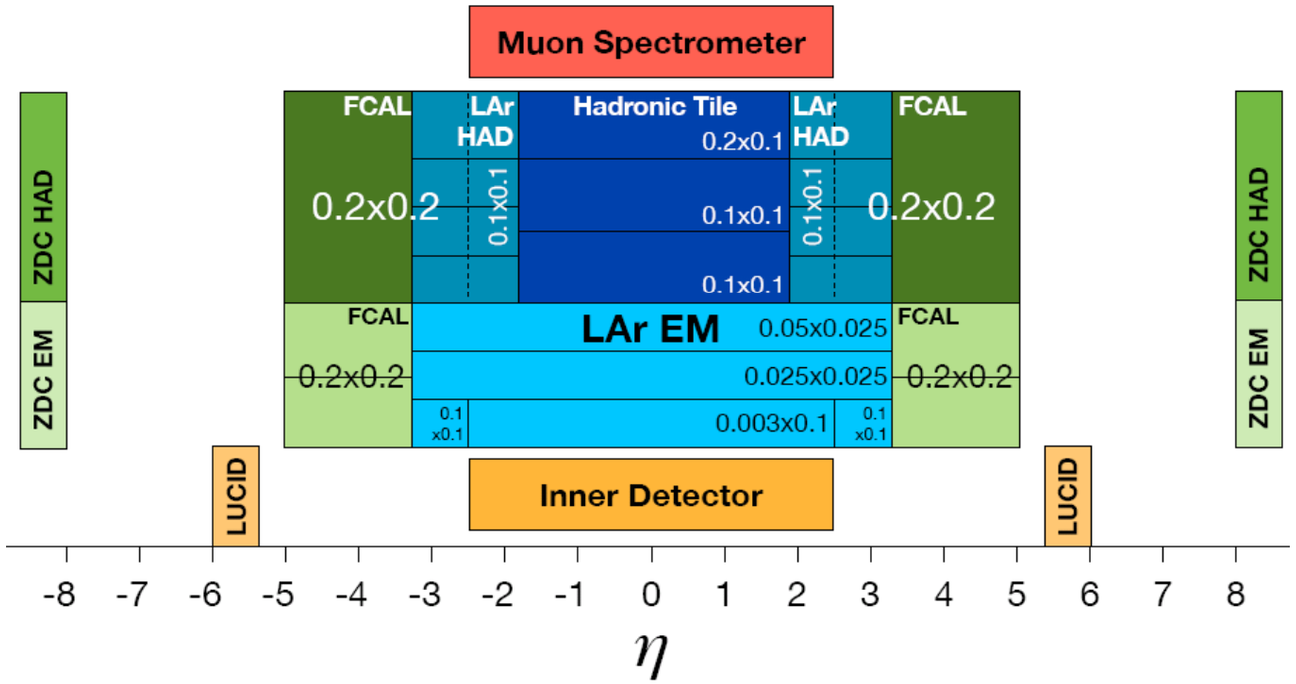
ATLAS & CMS @ LHC

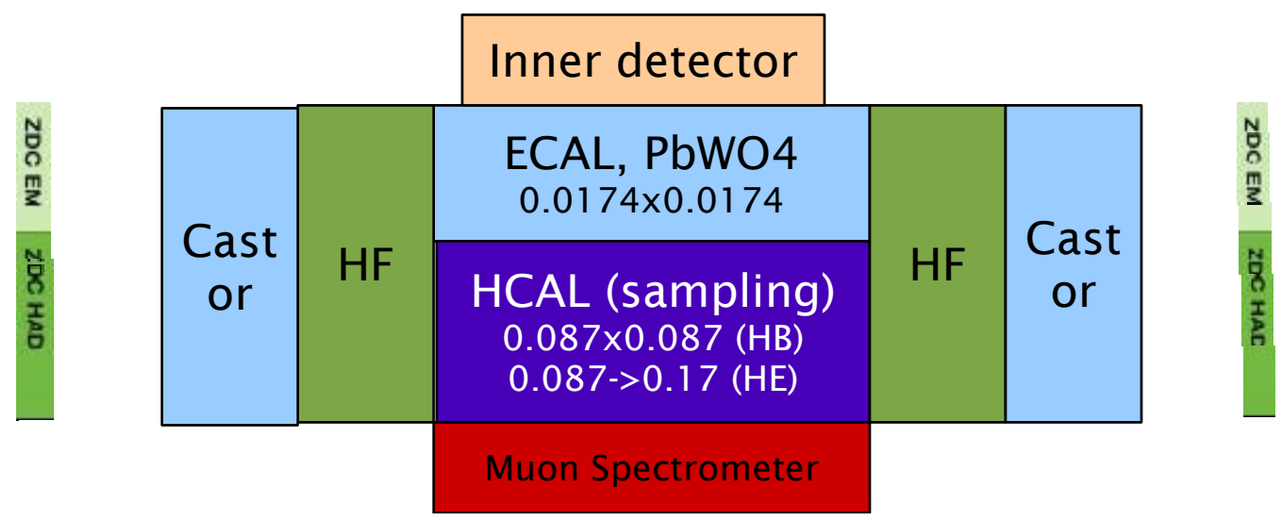
9/10/08!



first beam event seen in ATLAS

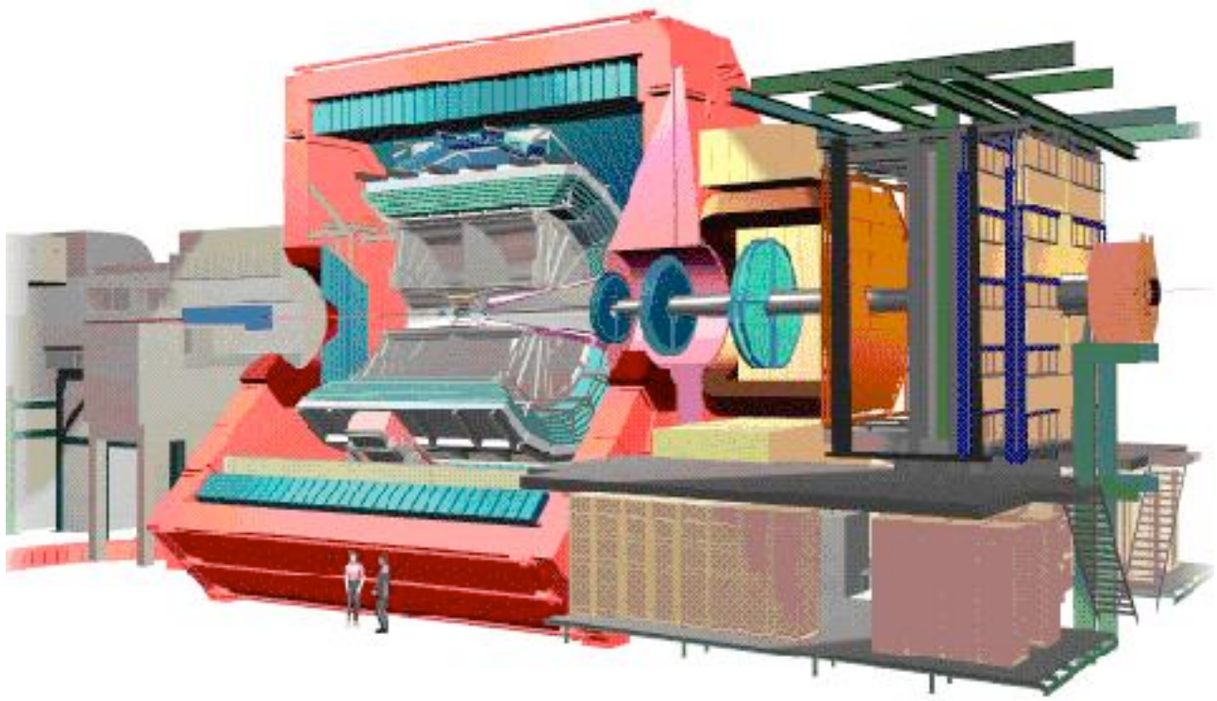


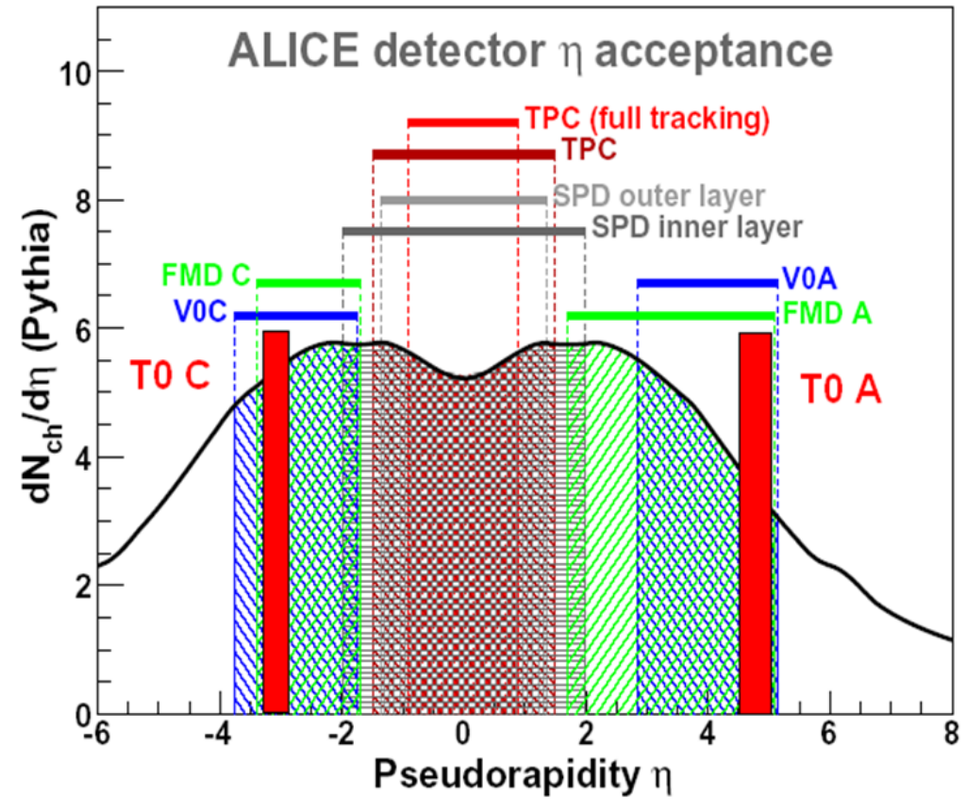




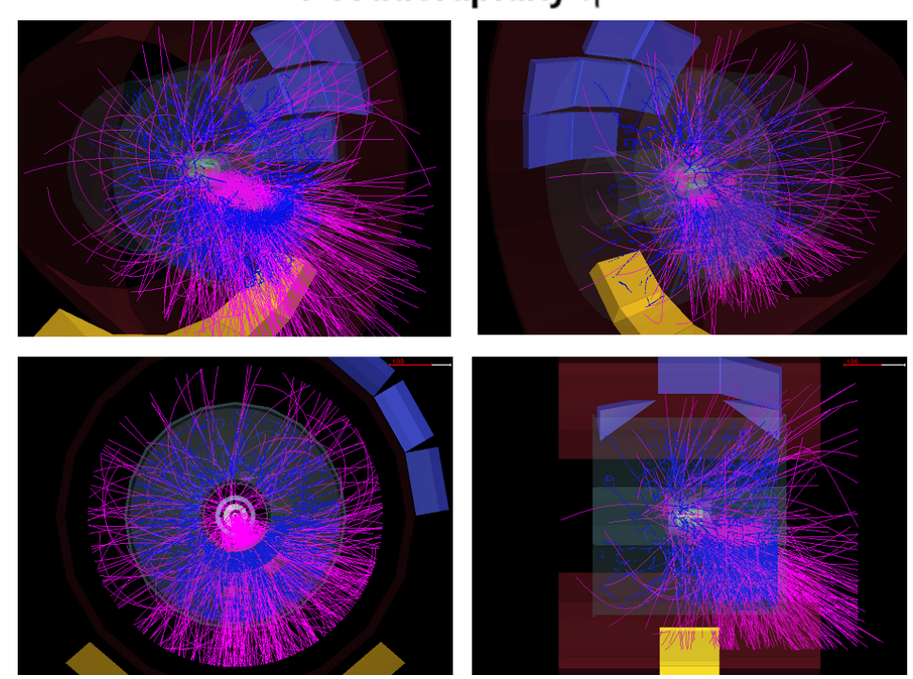
Enormous acceptance for soft physics

ALICE @ LHC



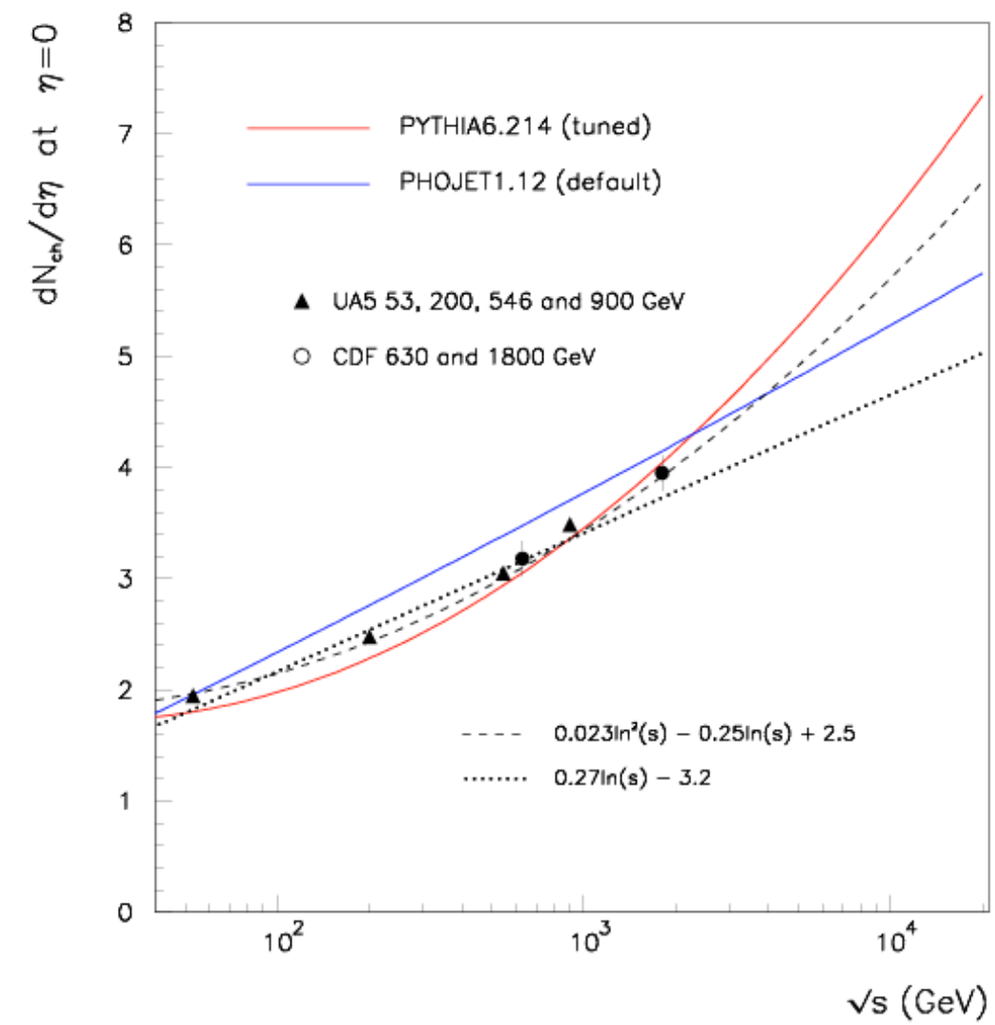


Optimized for tracking & PID
in high multiplicity
heavy ion events (TPC), with new
high p_T triggering abilities (EMCAL)



Two “Day 1”’s at the LHC

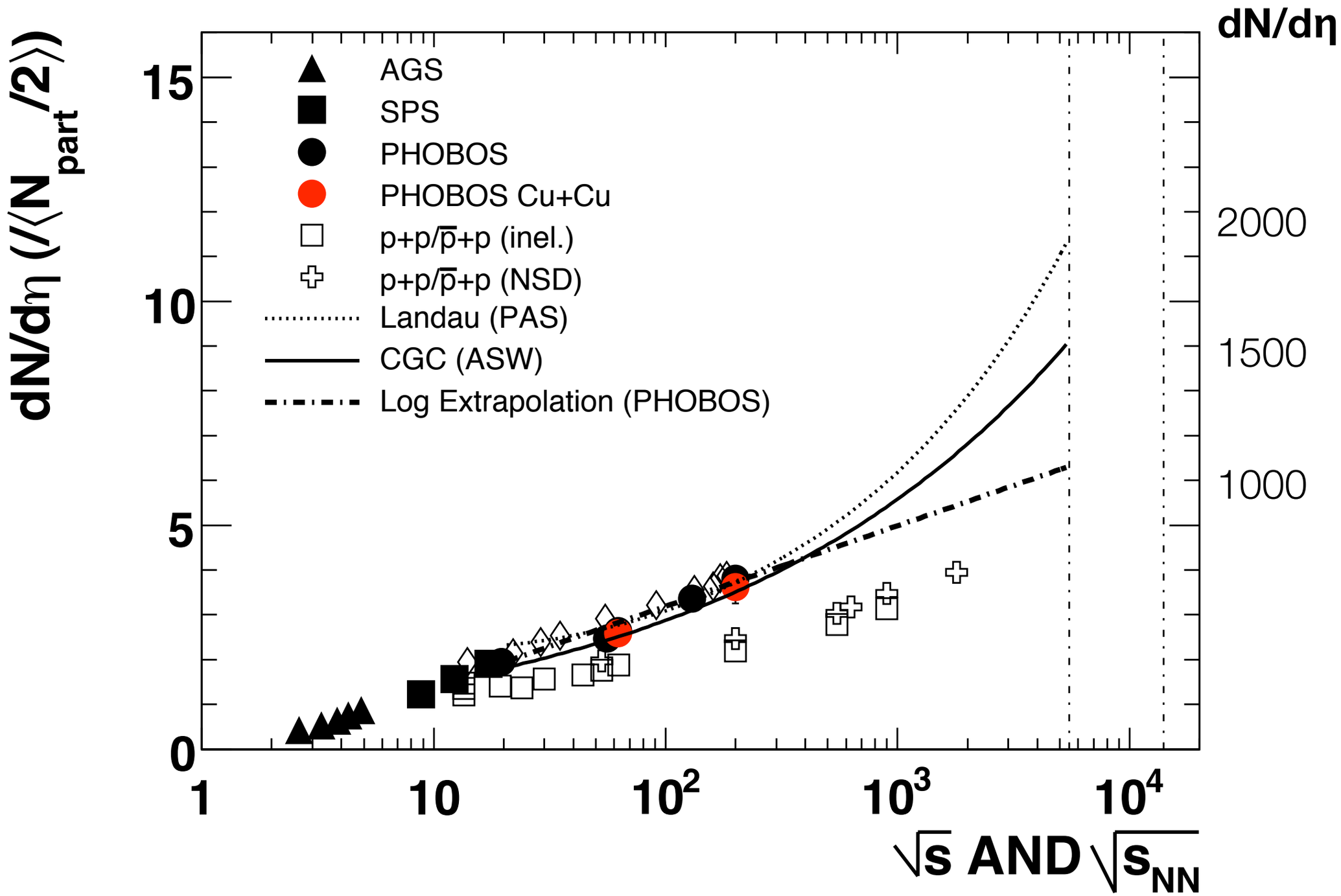
- **Day 1: Fall 2009 p+p run(s)**
  - dN/dη, E_T p+p at 900 GeV, 10 TeV, 14 TeV
  - Testing of models (PYTHIA, PHOJET, etc.)
  - Diffractive events (background & signal)



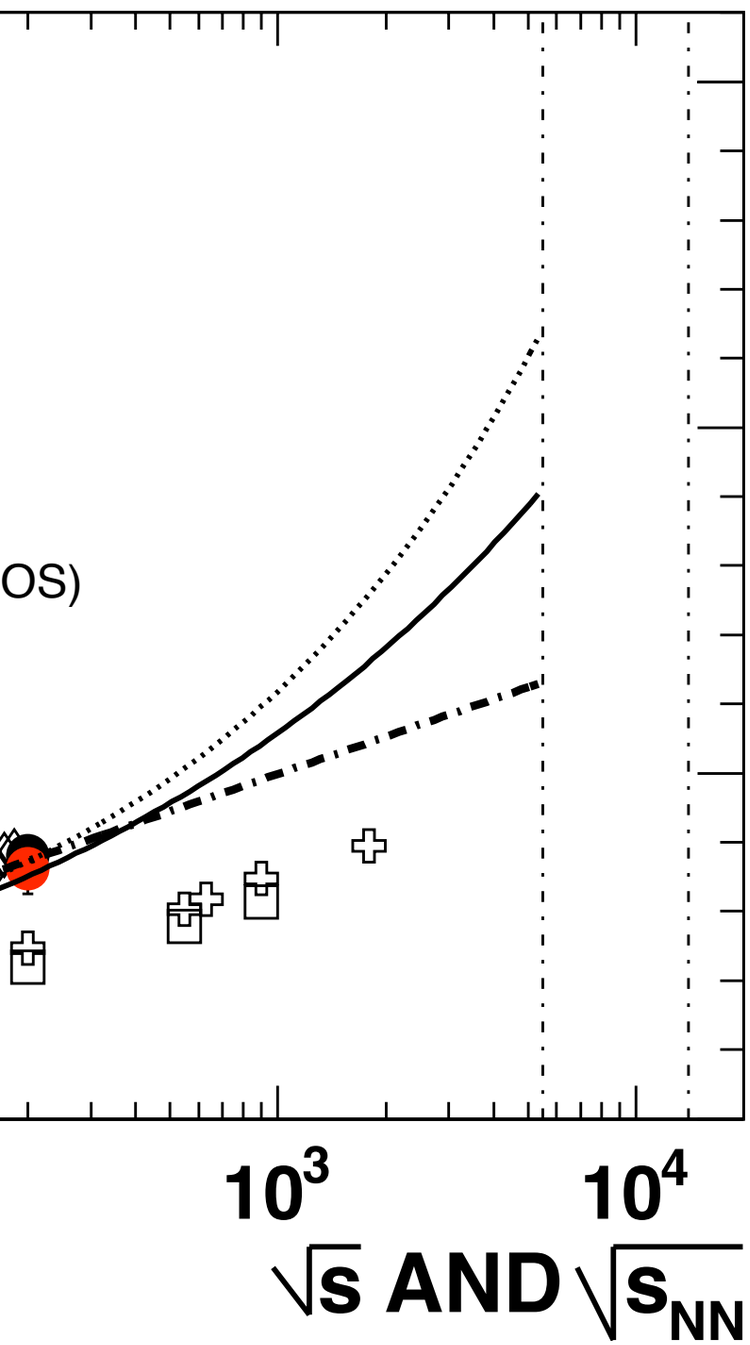
- **Day 1: Fall 2010(?) Pb+Pb run**
  - Measurements of dN/dη, E_T , $v_2(\eta)$ (w/ PID for n_q scaling)
  - Most models and extrapolations will be tested in days

Will trends seen at RHIC break, or not?
How will this affect our understanding of early thermalization?

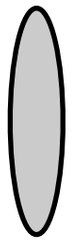
Predictions for the LHC: Multiplicity



Extrapolating to the LHC



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



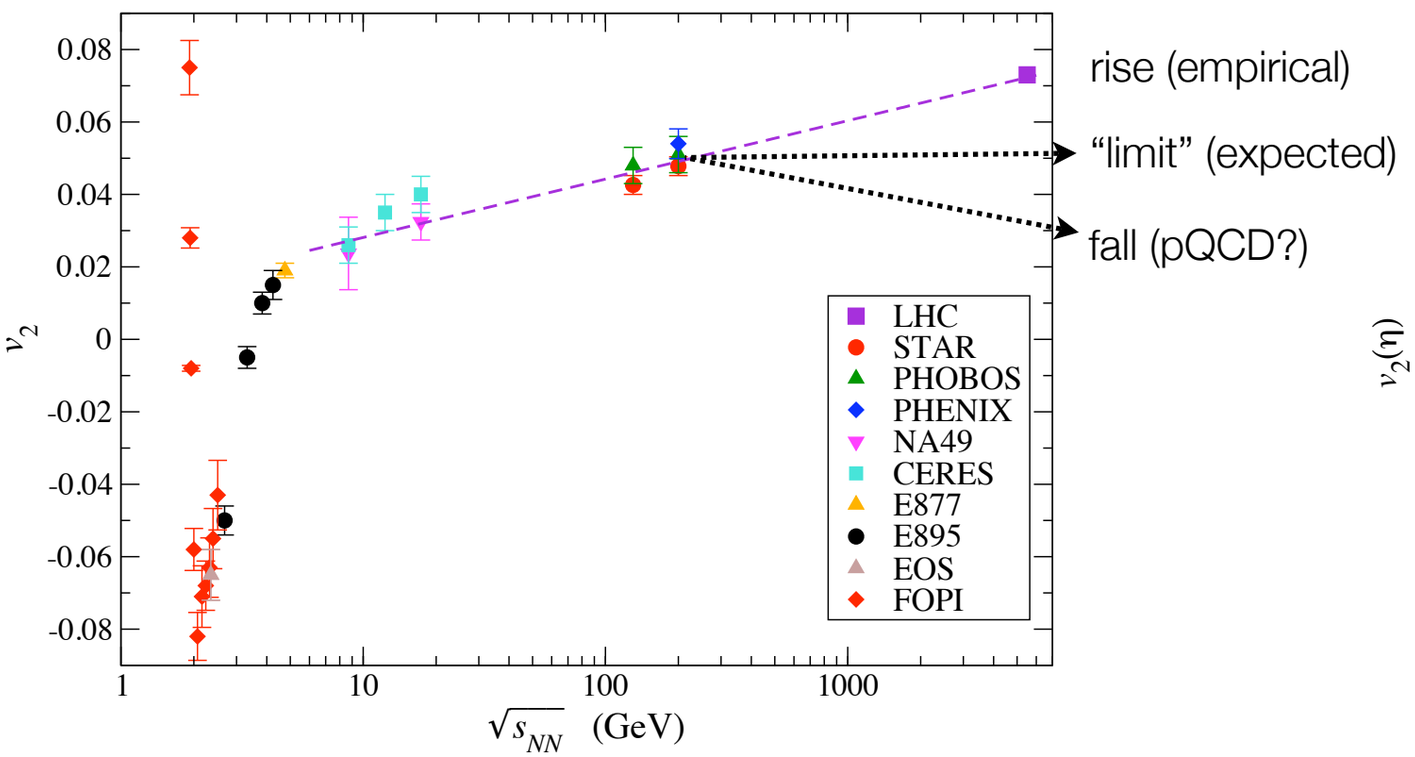
$$\frac{dN}{dy} = K s^{1/4} \frac{\exp(-y^2/2L)}{\sqrt{2\pi L}} \rightarrow \frac{s^{1/4}}{\sqrt{\ln(s)}} \quad L = \ln\left[\frac{s}{4m_p^2}\right]$$

Color Glass Condensate: parametrization including rise of gluon PDF and simple hadronization model

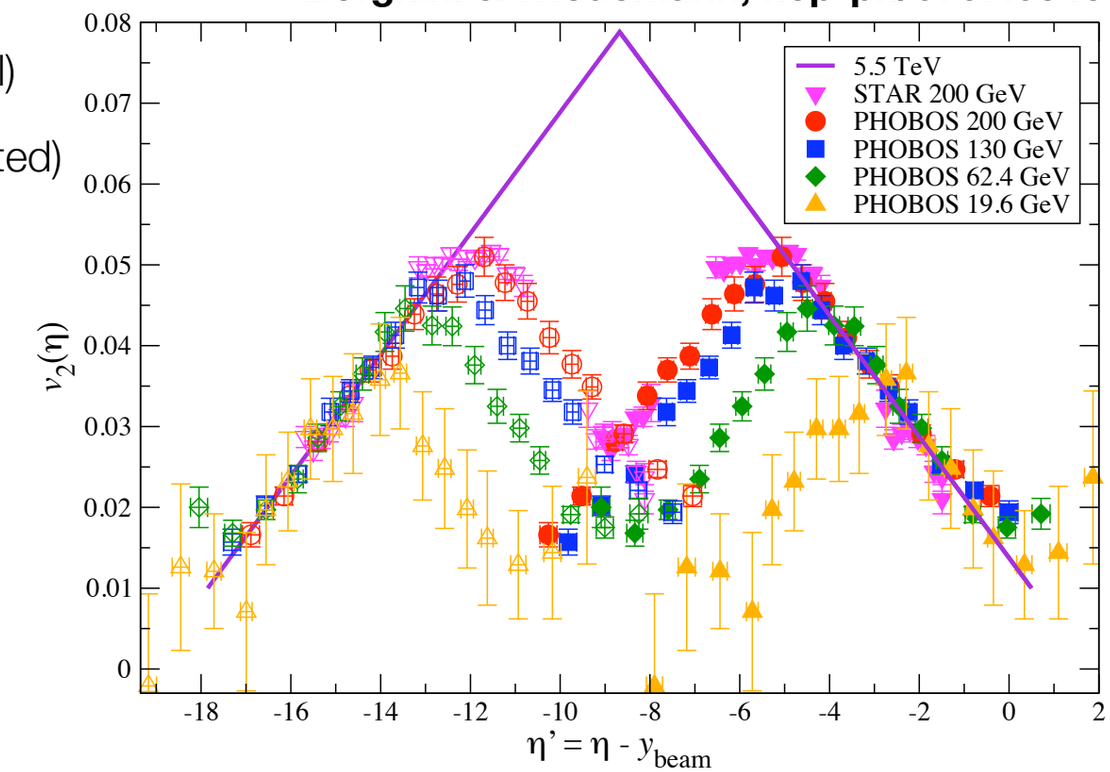
$$\frac{dN}{d\eta} = K s^{\delta}$$

Logarithmic rise: assumption that current trends apply at larger energies

Energy Dependence of Elliptic Flow



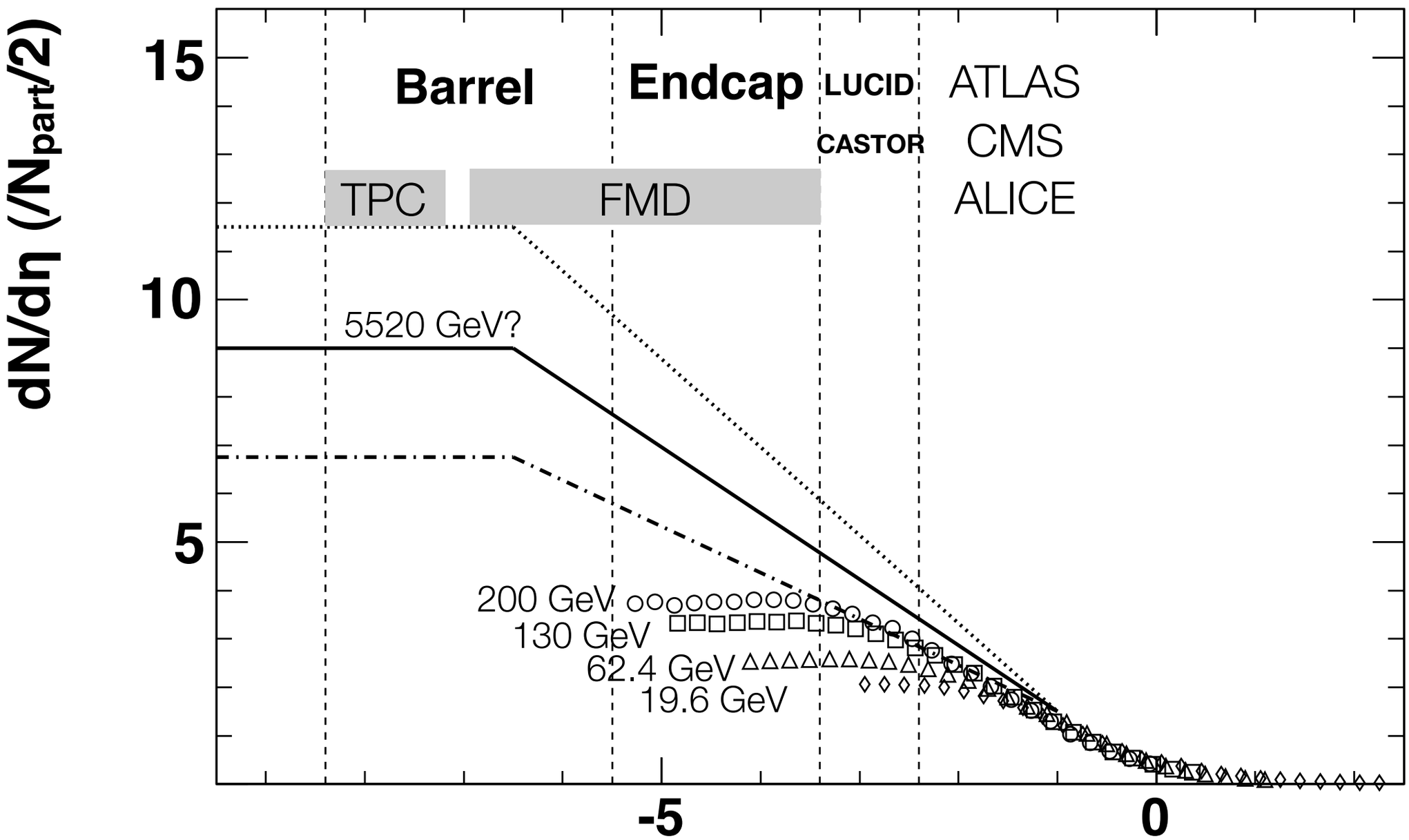
Borghini & Wiedemann, hep-ph/0707.0546



Controversy about fate of v_2 at the LHC:
wide range of predictions: theoretical and empirical

Will be resolved within O(1 day) of first data:
all experiments have full azimuthal acceptance (N_{ch} & E_T)

Longitudinal Scaling at the LHC



LHC can make direct connection with RHIC

$\eta' = \eta - y_b$

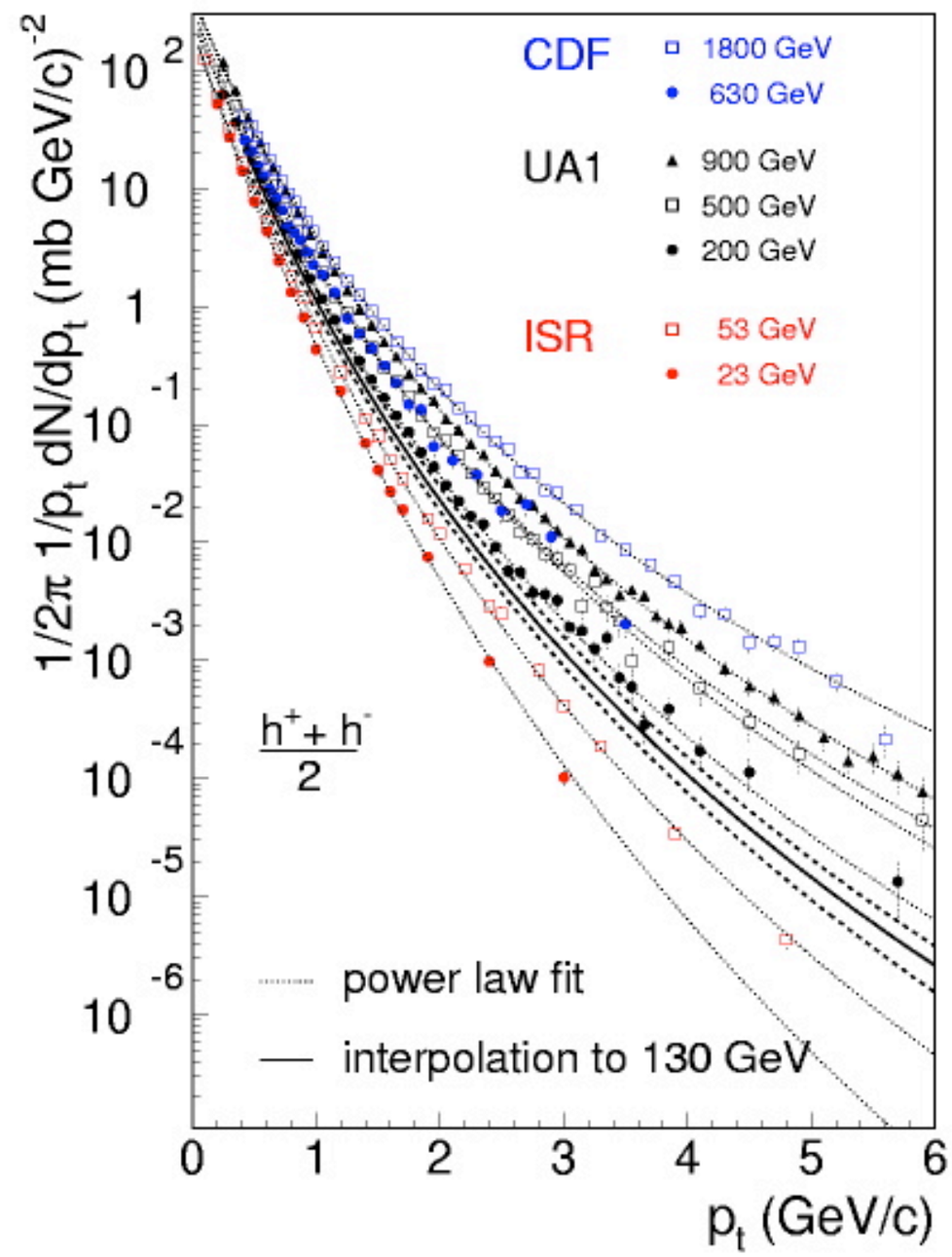
The Question of Minijets

At RHIC, many expect particle production and energy from hard & semi-hard processes that scale with $N_{coll} \sim N_{part}^{4/3}$.

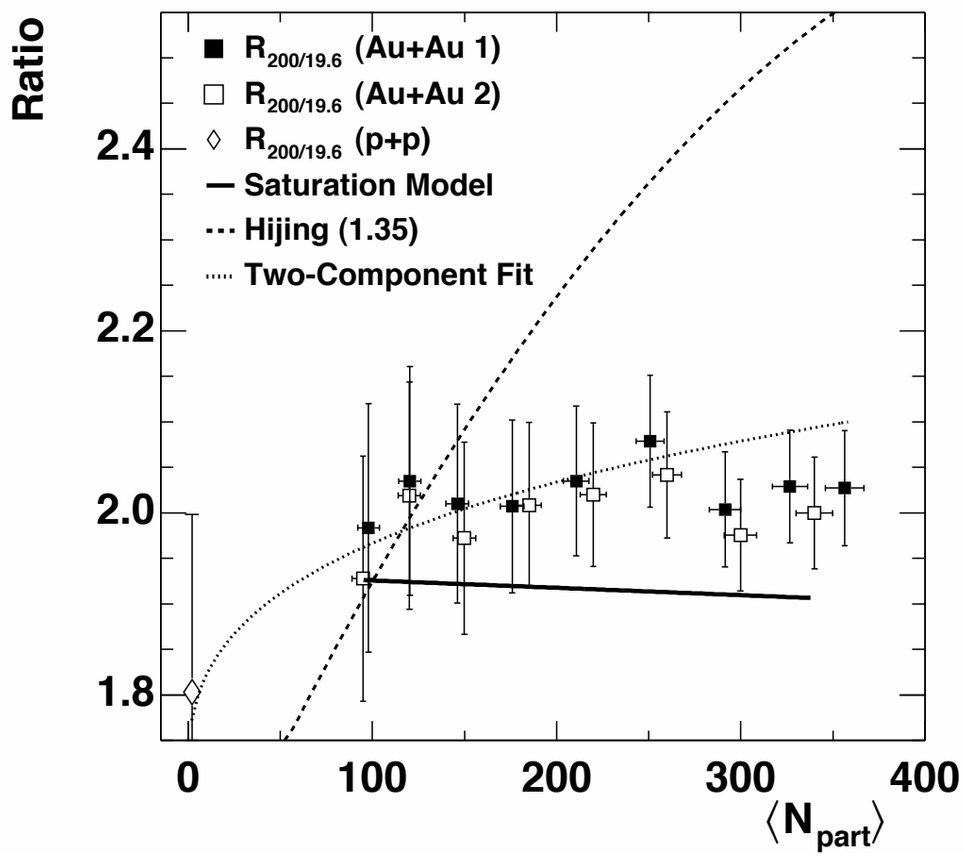
$$\frac{dN_{ch}}{d\eta} = n_{pp}\left[(1-x)\frac{N_{part}}{2} + xN_{coll}\right]$$

Should be extreme at LHC (cf. HIJING)

If so, the centrality dependence of N_{ch} and E_T will definitively test this "two-component model"



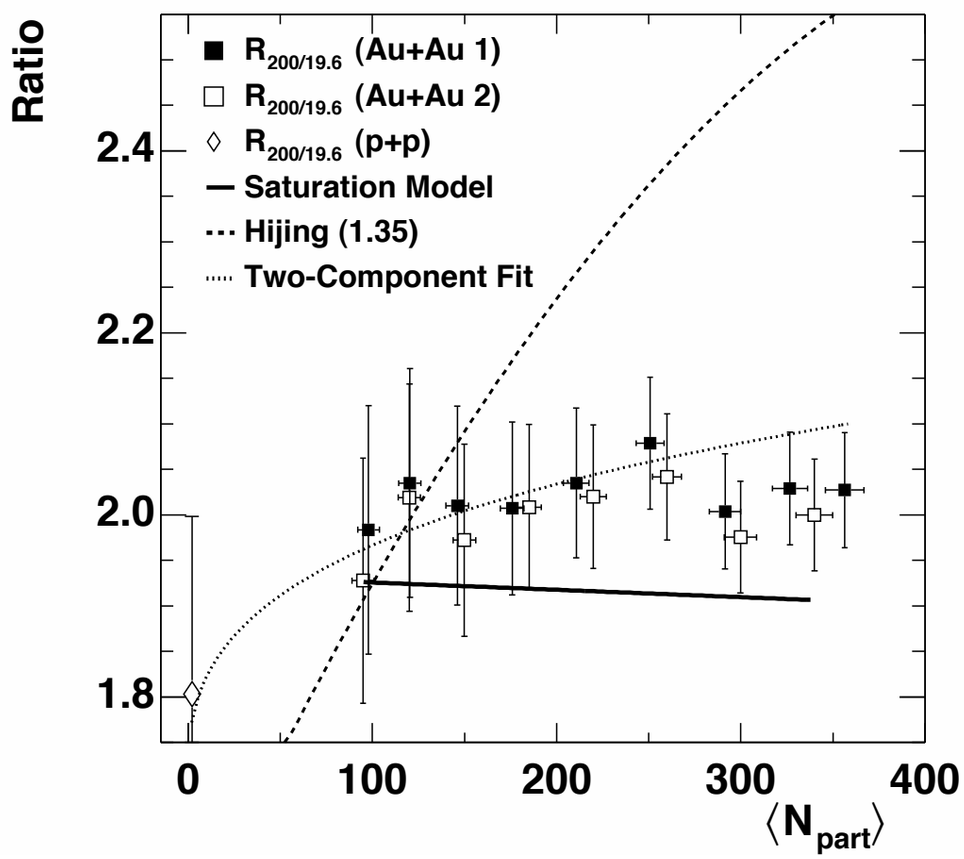
Centrality Evolution of Multiplicity and E_T



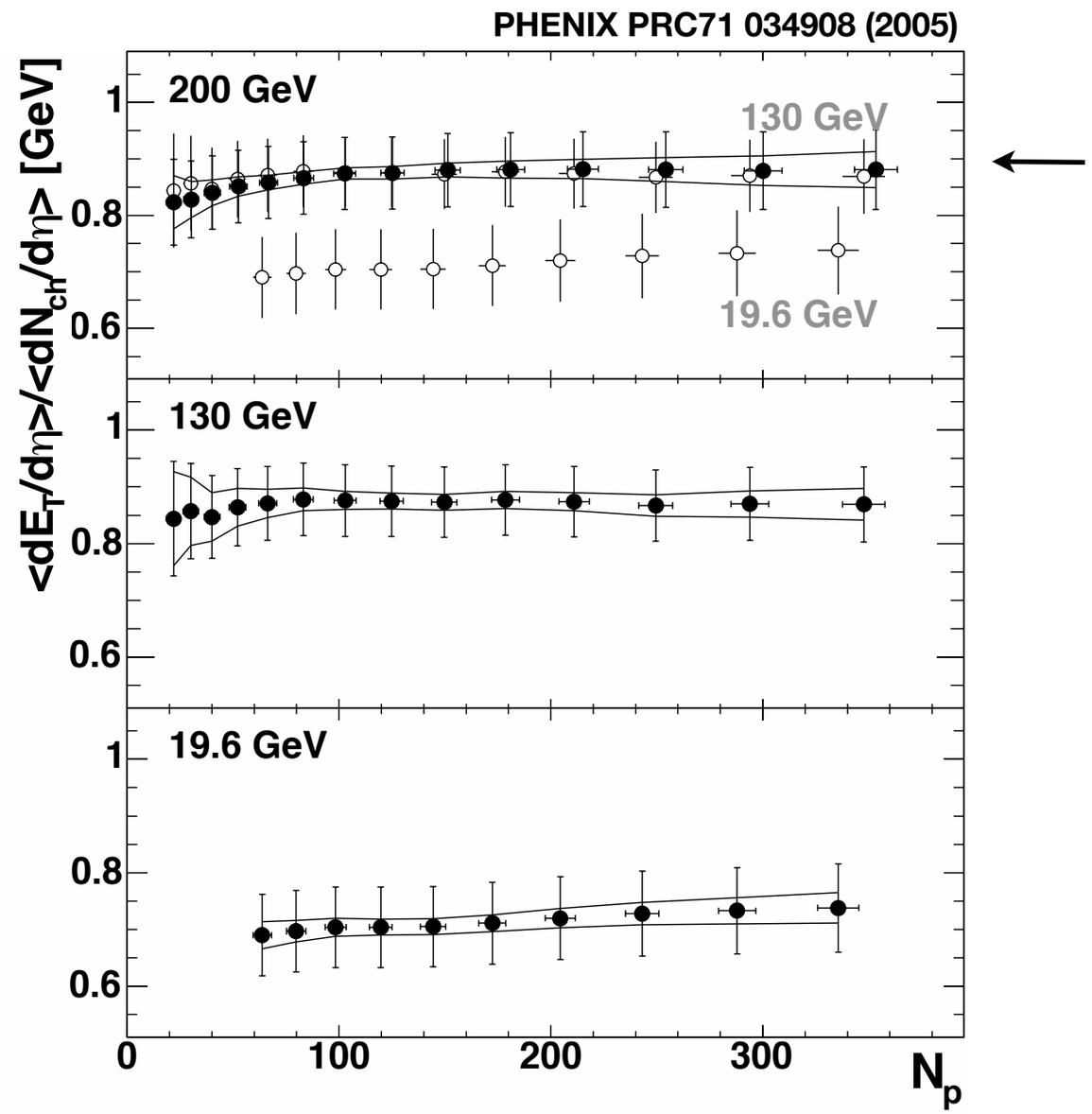
$$R(N_{part}) = \frac{\rho_{200}(N_{part})}{\rho_{19.6}(N_{part})}$$

Centrality evolution of $\rho = dN/d\eta/N_{part}$
is same at 20 and 200 GeV

Centrality Evolution of Multiplicity and E_T



$$R(N_{part}) = \frac{\rho_{200}(N_{part})}{\rho_{19.6}(N_{part})}$$



Centrality evolution of $\rho = dN/d\eta/N_{part}$ is same at 20 and 200 GeV

E_T per charged particle essentially constant

Soft Observables: From RHIC to LHC

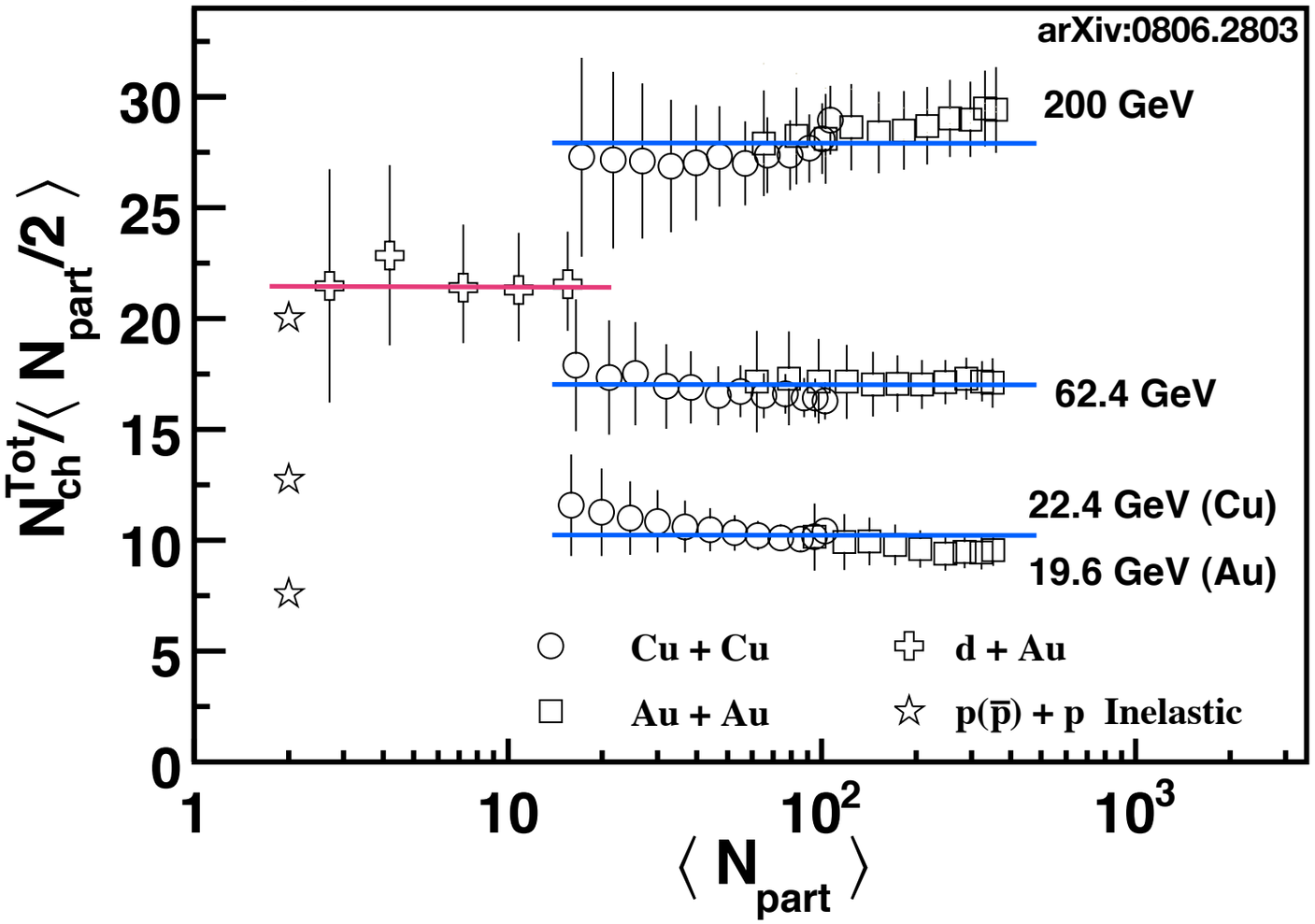
- **In the soft sector, RHIC has observed:**
  - **Elliptic flow** suggesting early thermalization (near perfect fluid)
  - **Extended longitudinal scaling** (trivial or deep?)
  - Intriguing **connections to elementary systems**
  - **Statistical** (& **constituent quark**) freezeout
- **Empirical and 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)
  - High impact on the theoretical underpinnings of the field
  - Soft physics will be sensitive to increased role of minijets, if relevant
- **The collider era of heavy ion physics is upon us!**
  - High baryon density physics (FAIR) is also essential to disentangle role of matter in the QGP (& prove existence of QCD critical point)

Thank You to PANIC 2008 Organizers

"The Last Scattering Surface": Josiah McElheny

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

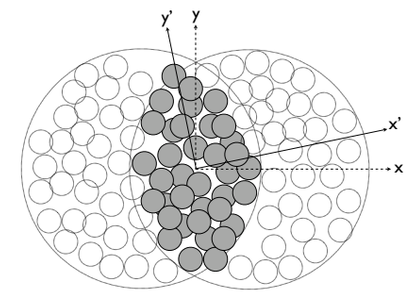
Suggests no change in overall degrees of freedom with **system size**

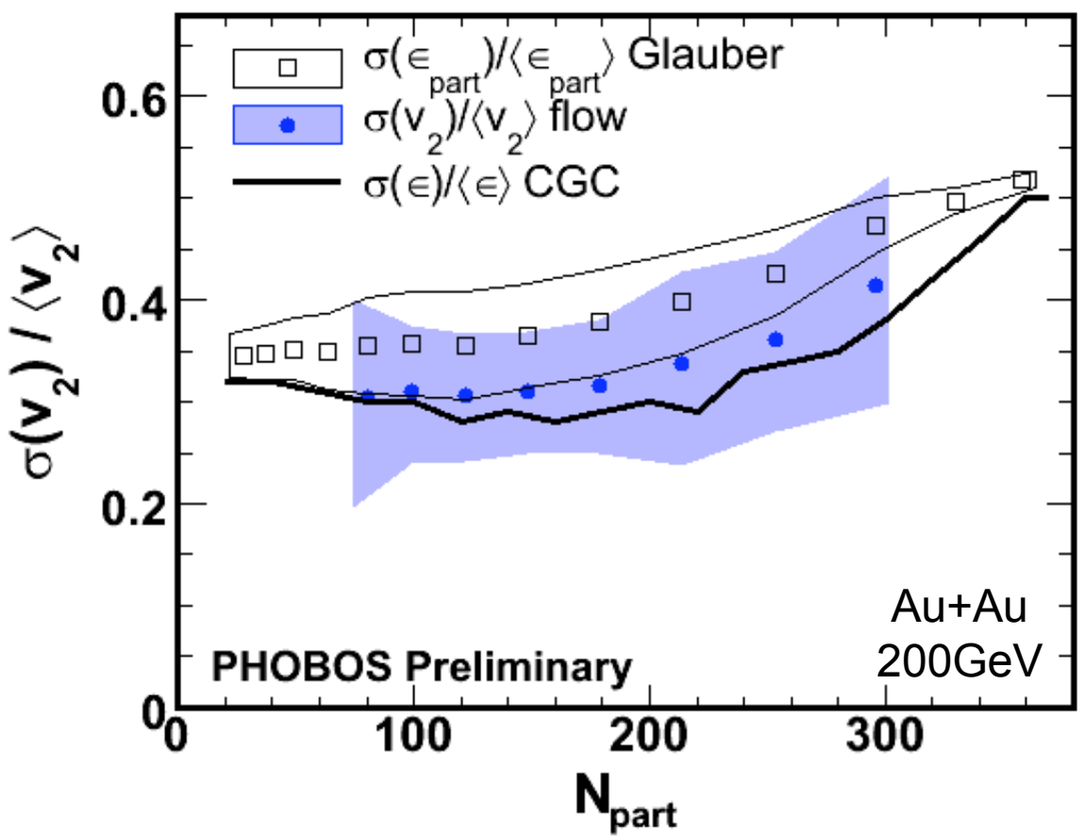
p+p/d+Au → A+A explained by "leading-particle" effects

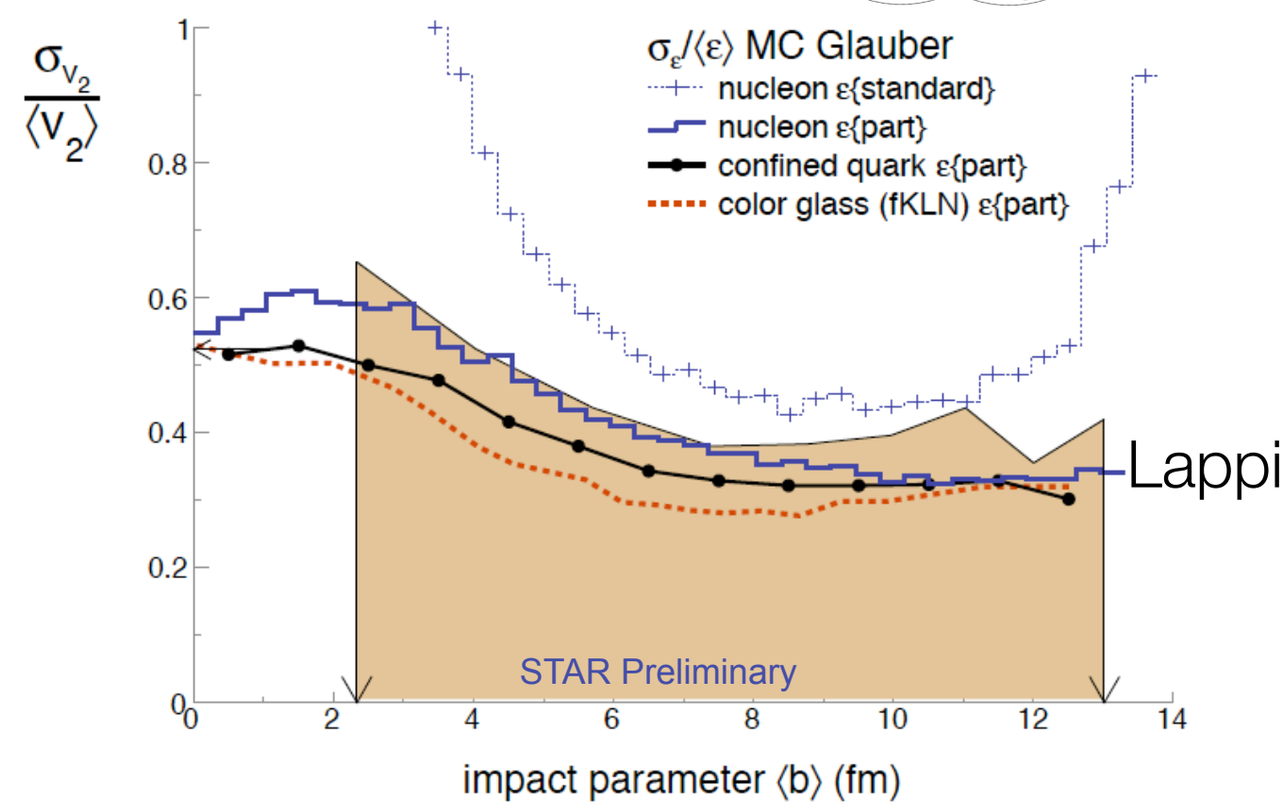
Phys.Rev.C74:021902,2006

Does v_2 Fluctuate Event-by-Event

- **If nucleon positions fluctuate, then v_2 itself will fluctuate event by event! seen by PHOBOS & STAR**

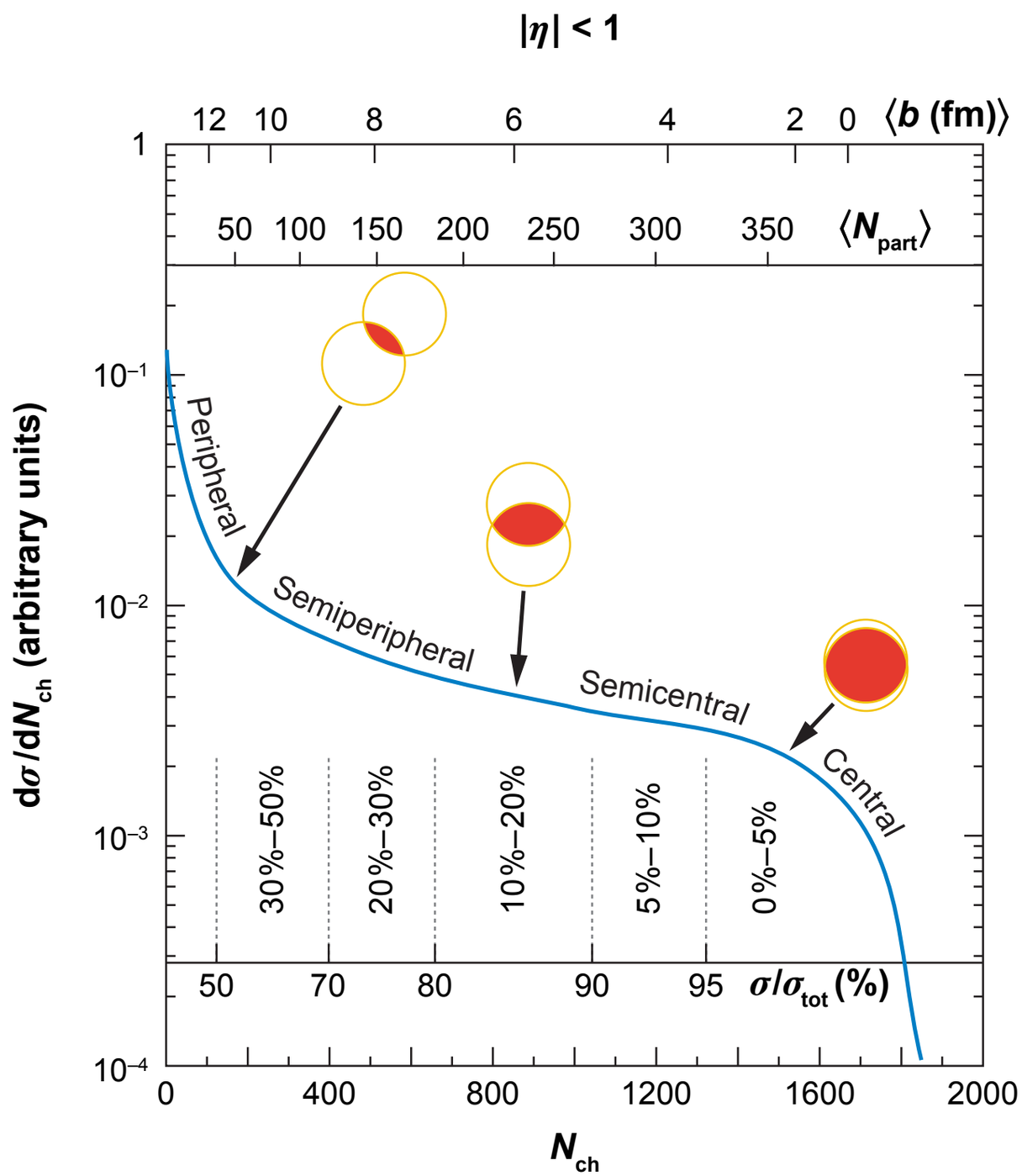






- **Decays and other correlations ("non flow") magnify the v_2 value.**
  - STAR only quotes upper limit, PHOBOS applies correction

“Centrality”



Miller et al, Ann.Rev.Nucl.Part.Sci.57:205-243,2007

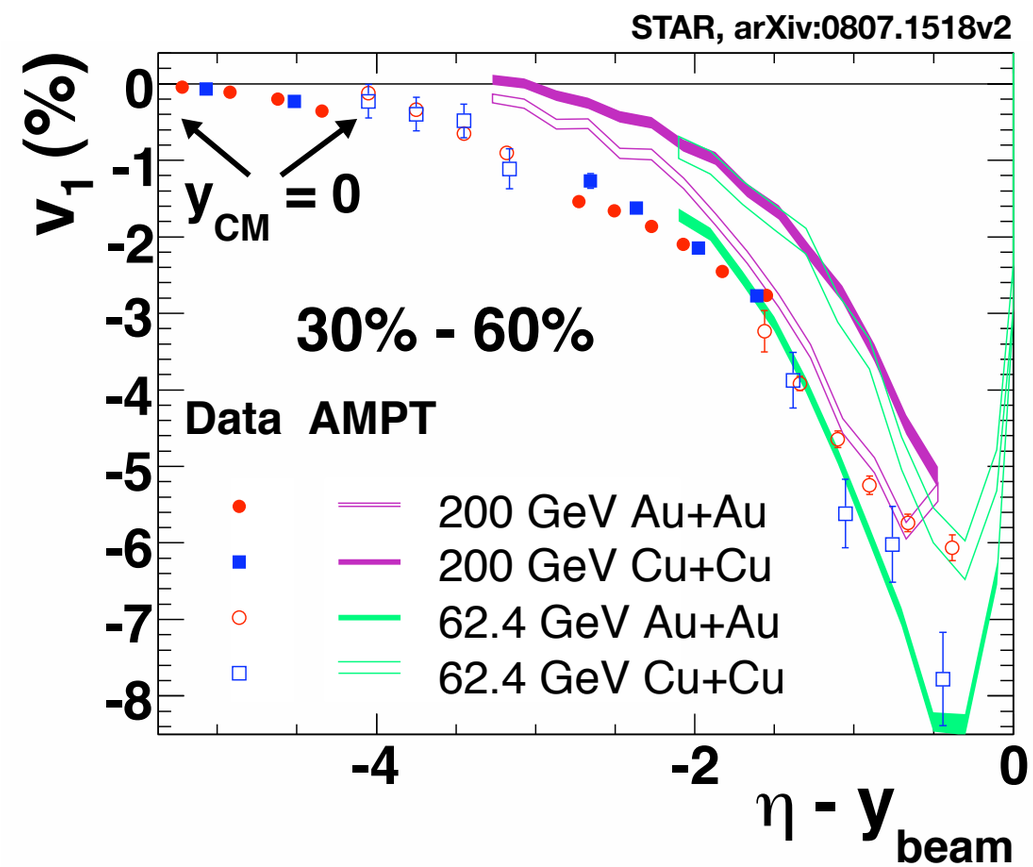
Cannot directly measure N_{part}, N_{spec}, b, **ε**, etc.

Measure distributions and assume they are <u>monotonic</u> with variable of interest

Bin data in “fractions of total inelastic cross section” (requires estimation of σ_{inel}) and relate to same bin in geometric distribution

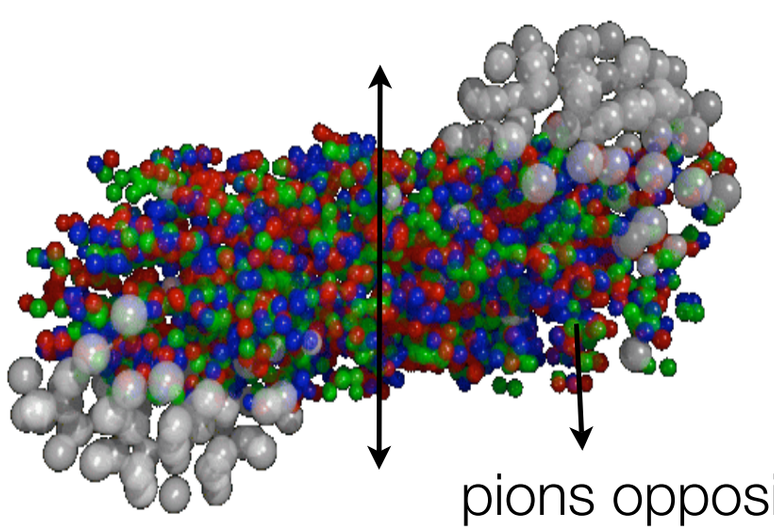
Thank You to PANIC 2008 Organizers

“Geometric Scaling”



“Directed” flow (v_1) also scales with the fraction of cross section (b/2R) and <u>not</u> rapidity density, and shows longitudinal scaling

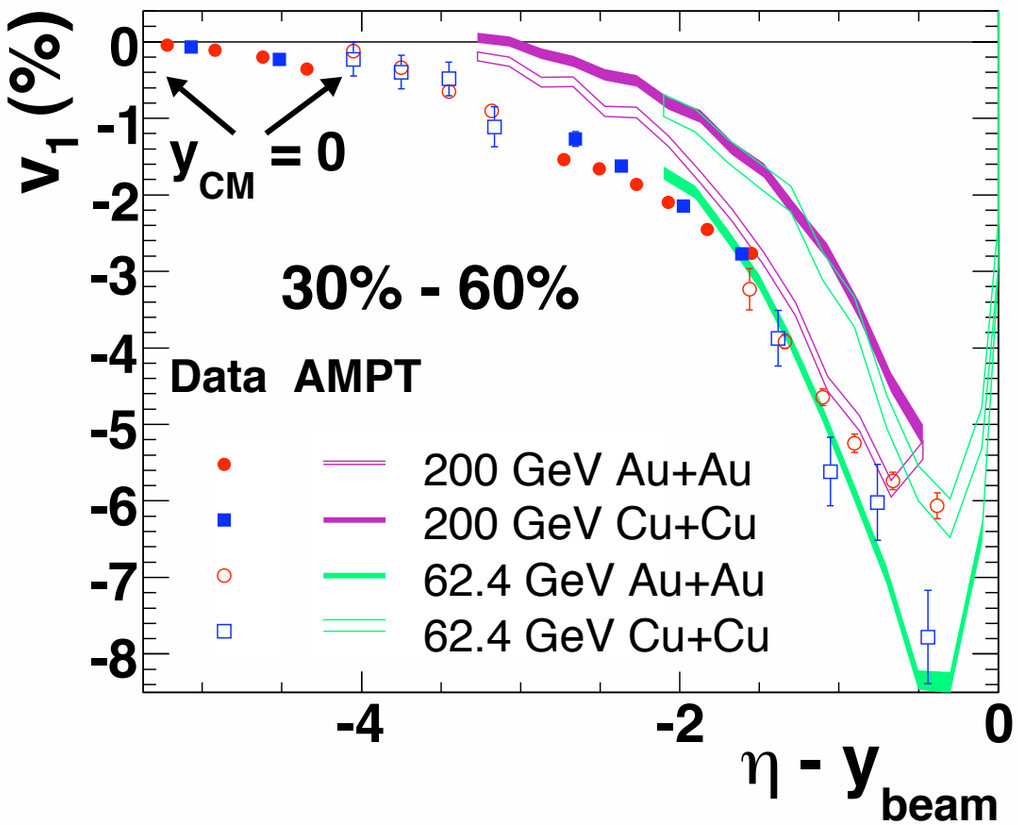
Change energy & size by x3 and all data collapses



pions opposite to nucleons

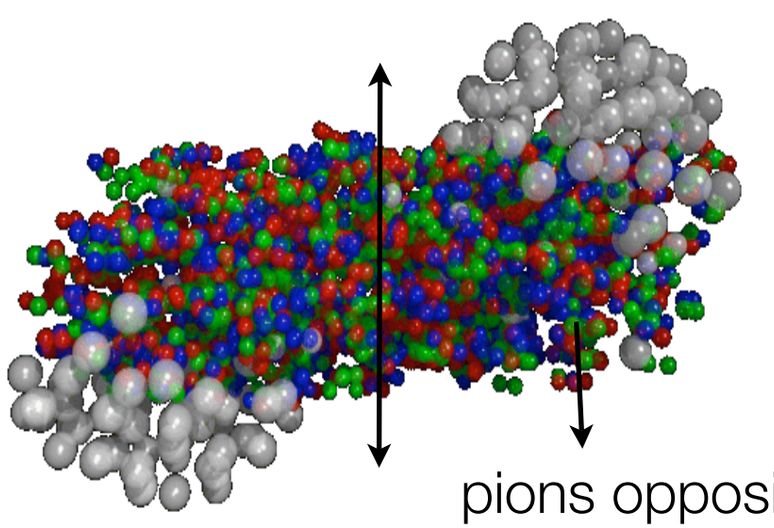
Rule of thumb: physics of involving large rapidities seems to see the small longitudinal scale ($1/\sqrt{s}$), not transverse (R_A)

“Geometric Scaling”



“Directed” flow (v_1) also scales with the fraction of cross section (b/2R) and <u>not</u> rapidity density, and shows longitudinal scaling

Change energy & size by x3 and all data collapses



pions opposite to nucleons

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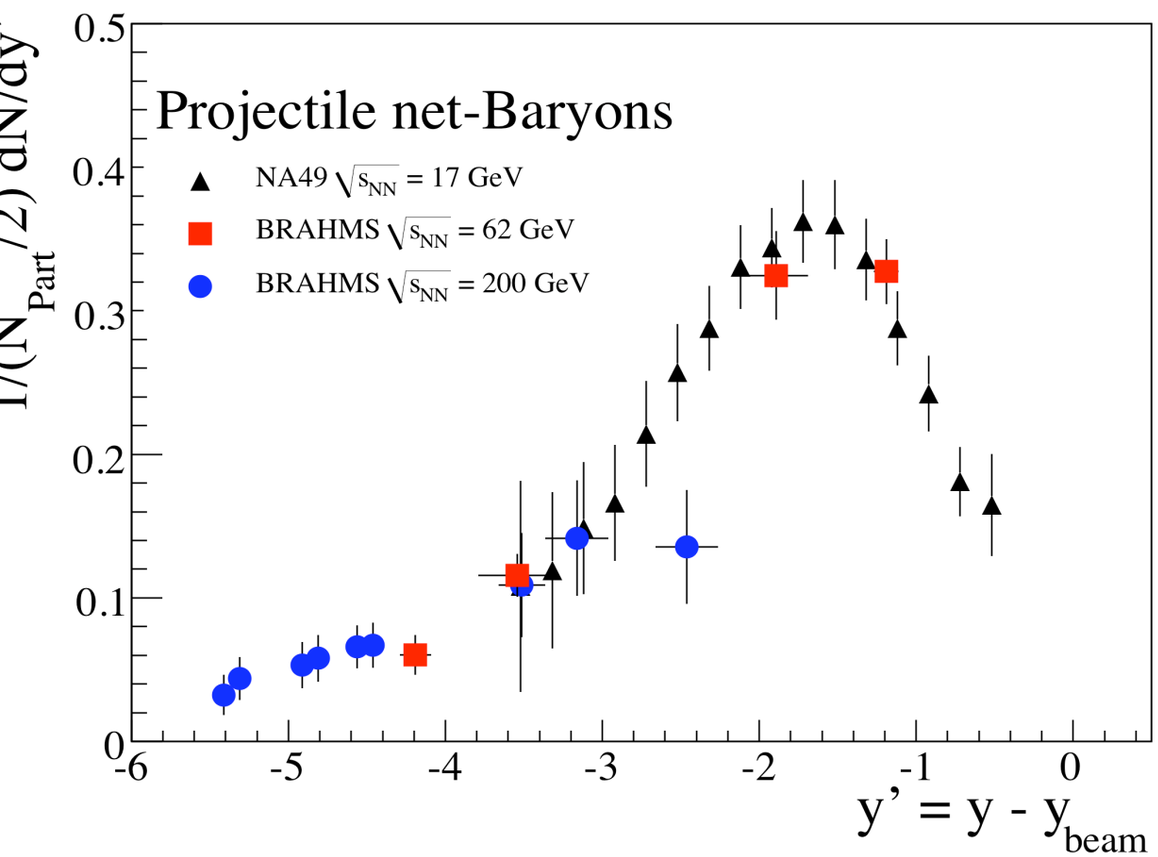

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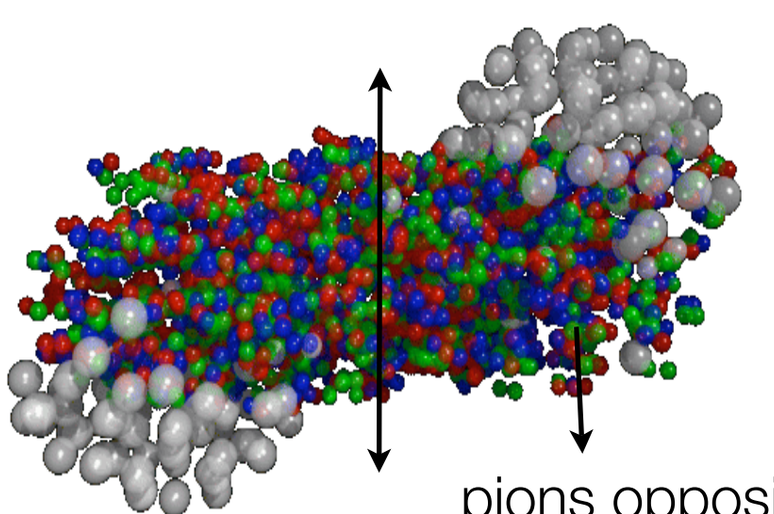

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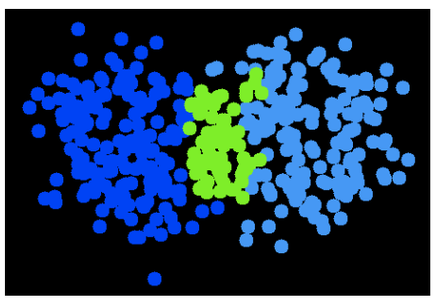
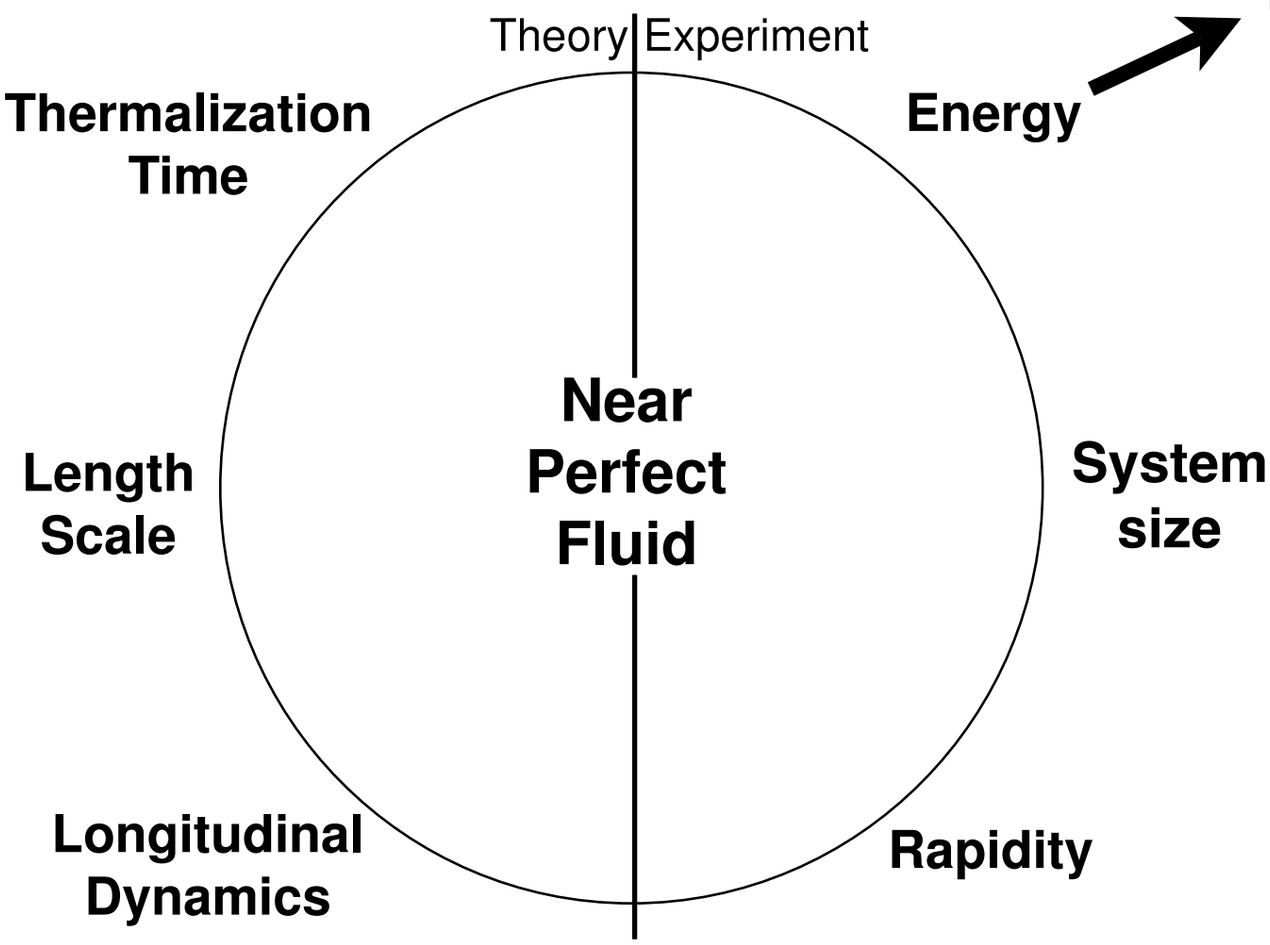
Soft Physics @ RHIC



Small η/s
n_q scaling

Longitudinal scaling?



LHC!

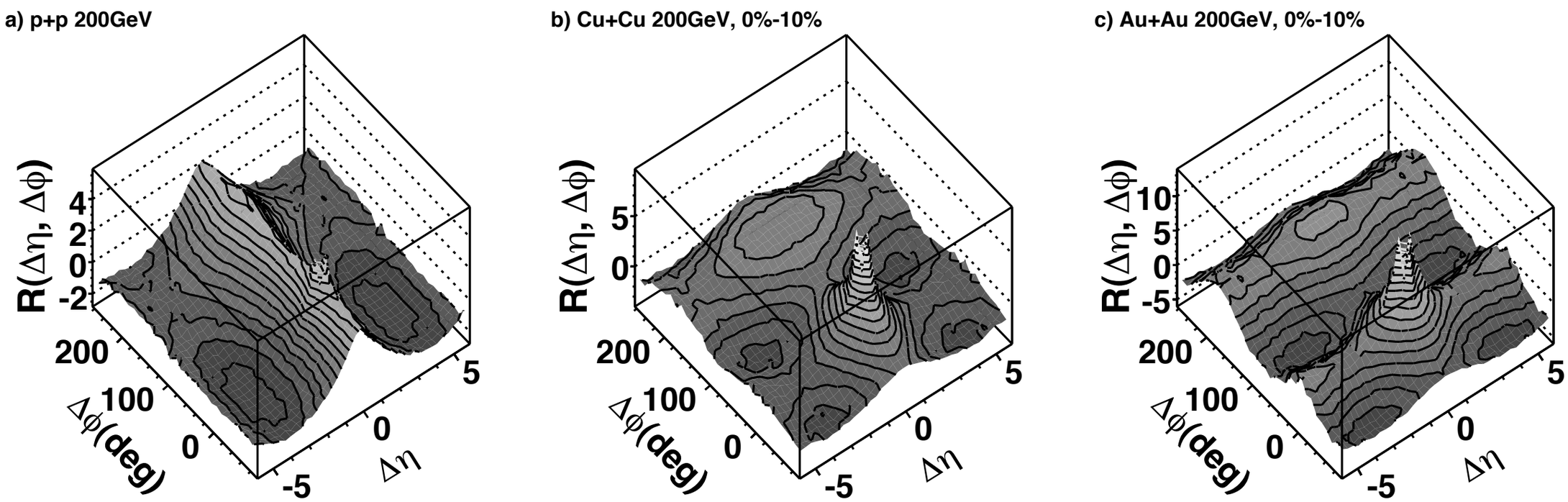
Multiplicities

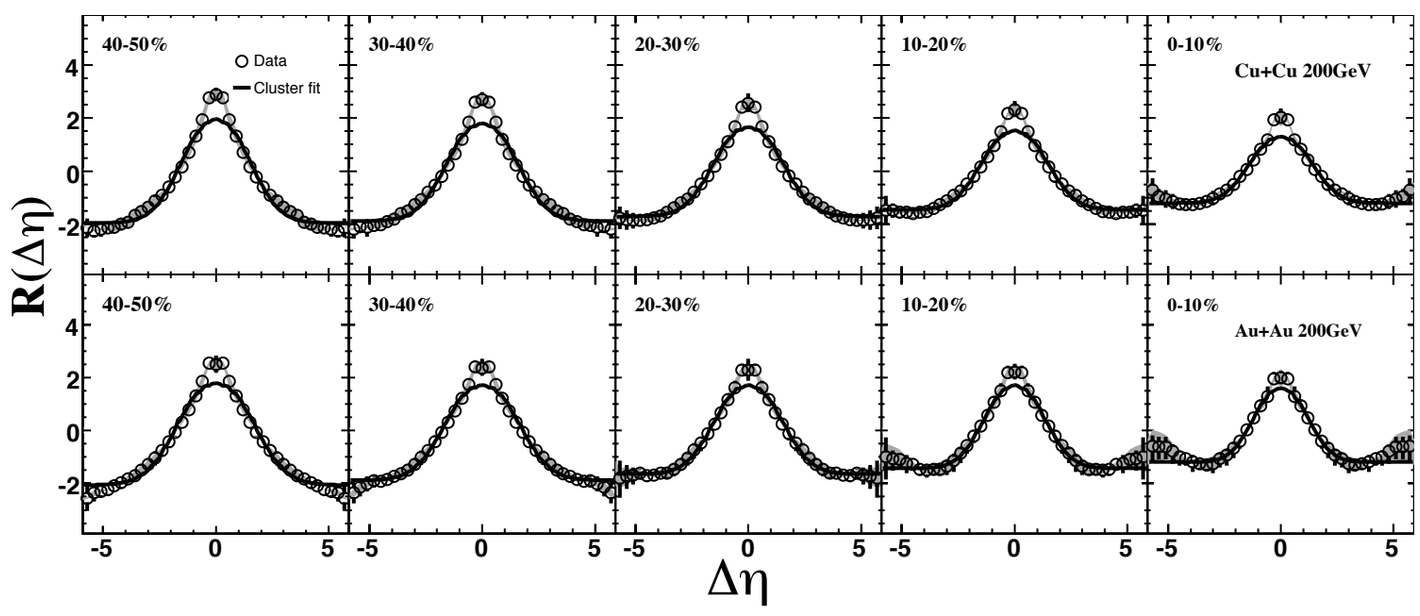
Spectra

Flow

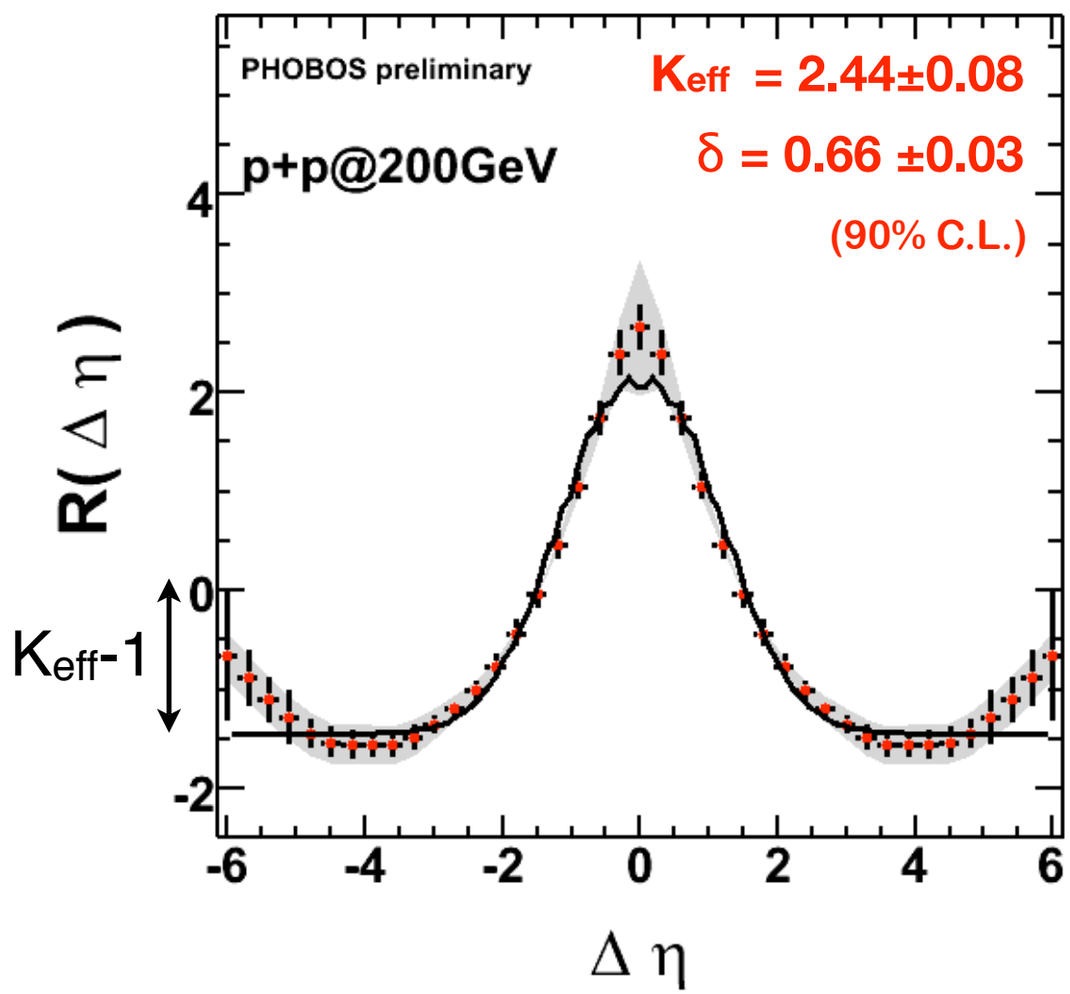
Trends in data are surprisingly smooth,
and persist as we vary energy, size, rapidity

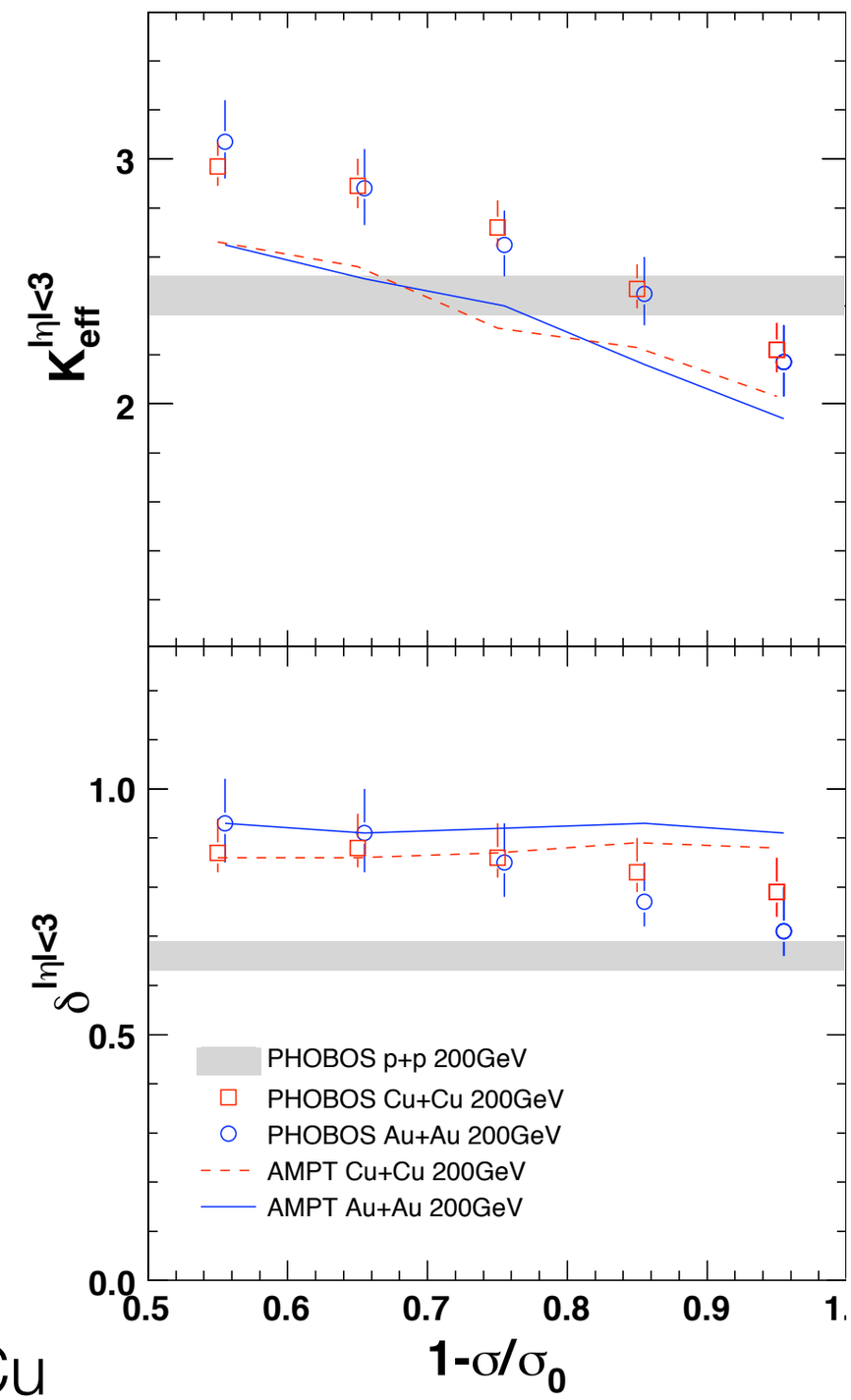
Two Particle Correlations





“Clusters”



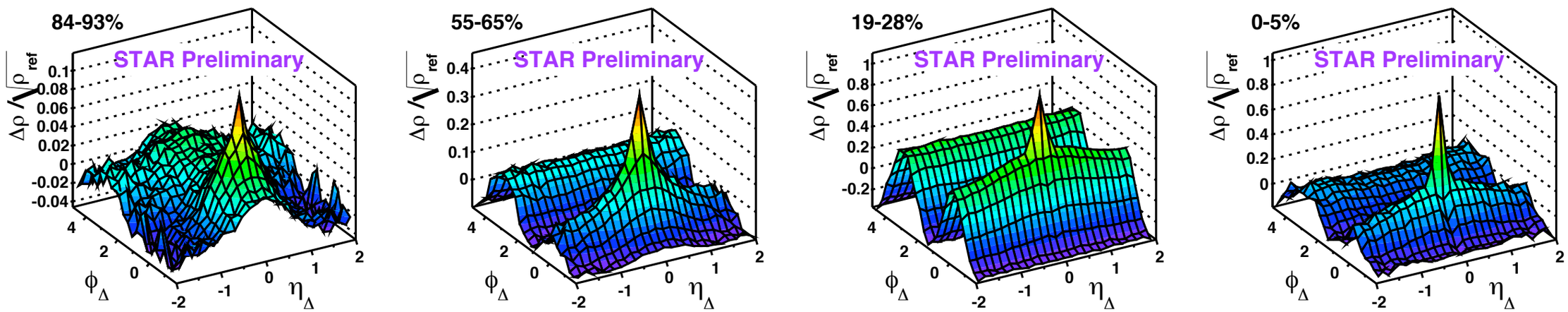


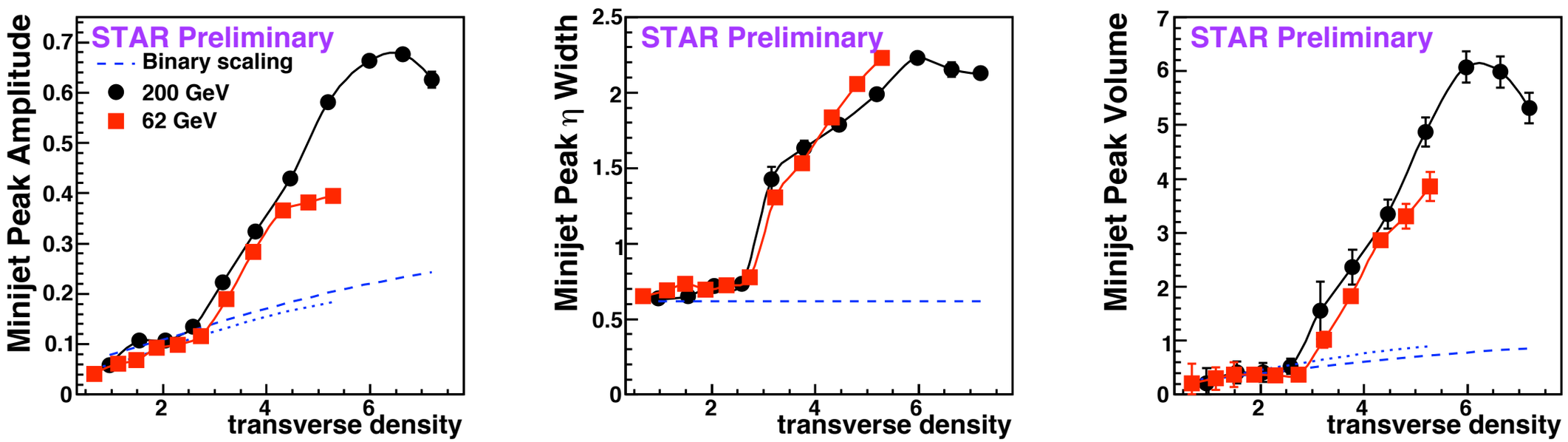
2-particle correlations in p+p & A+A can be fit by a “cluster model” with size K_{eff} and range **δ**.

Every particle has at least 1.5 other “friends”!

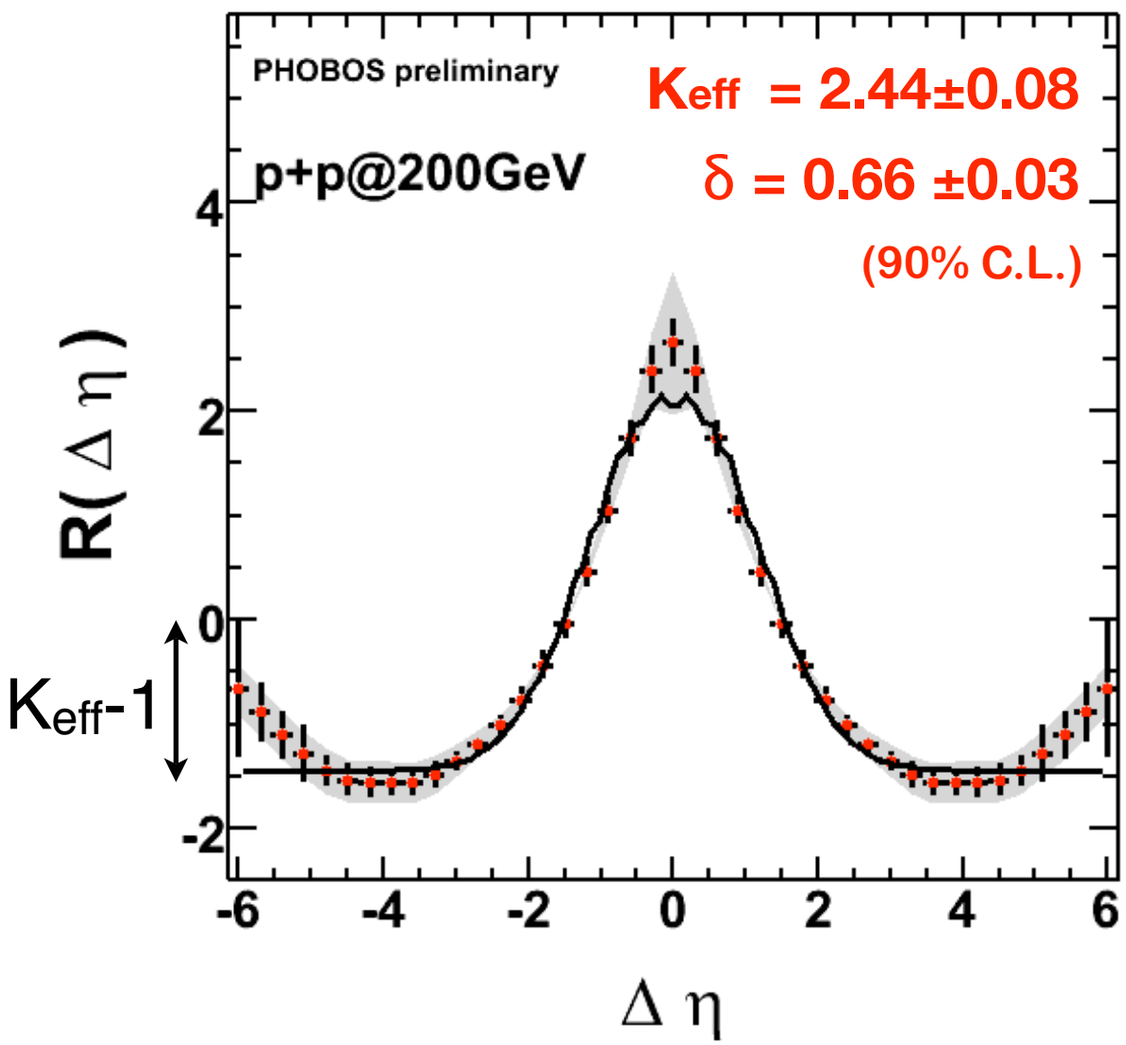
Surprising scaling with <u>geometry</u> in Au+Au & Cu+Cu

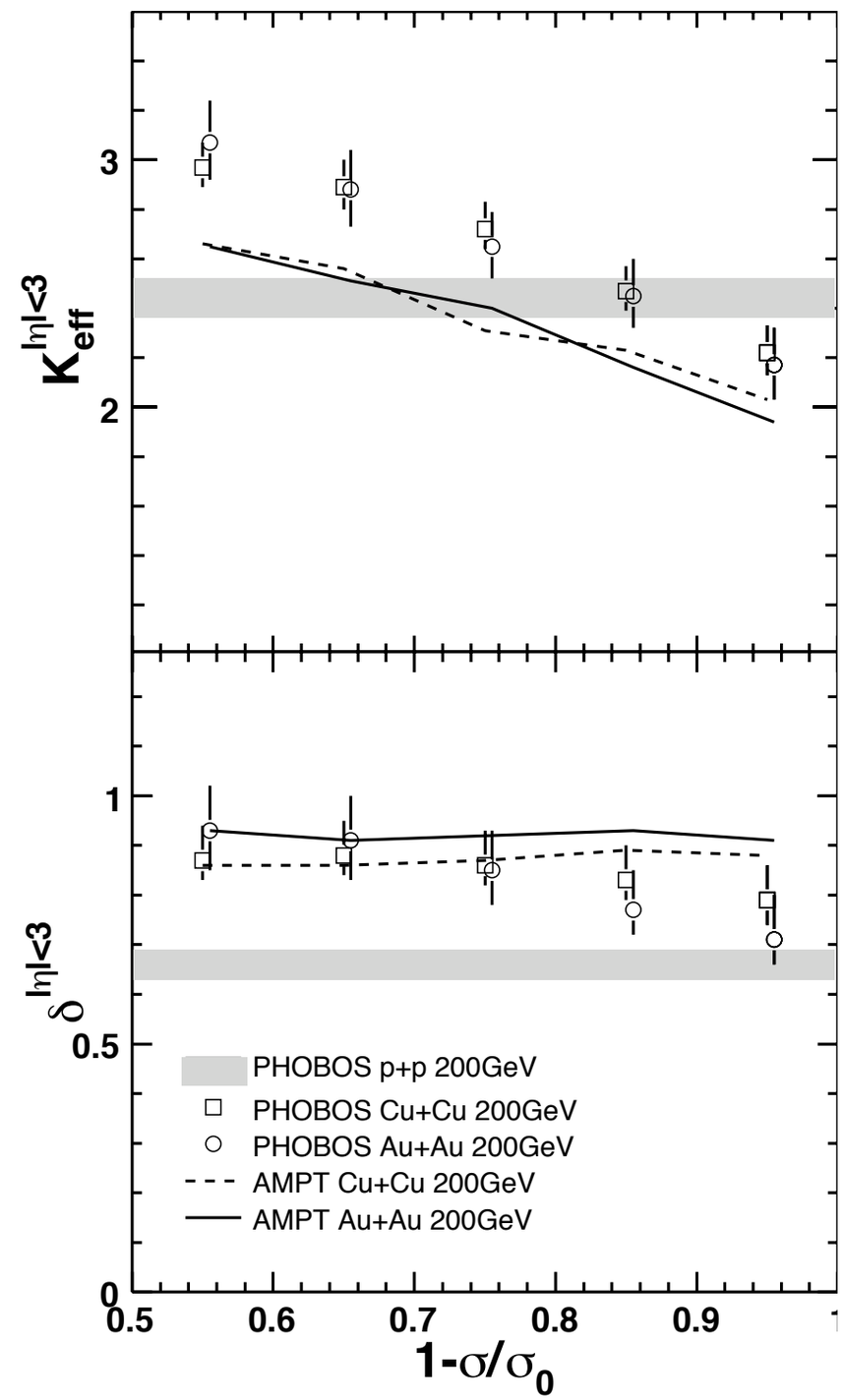
Minijets from Two Particle Correlations?



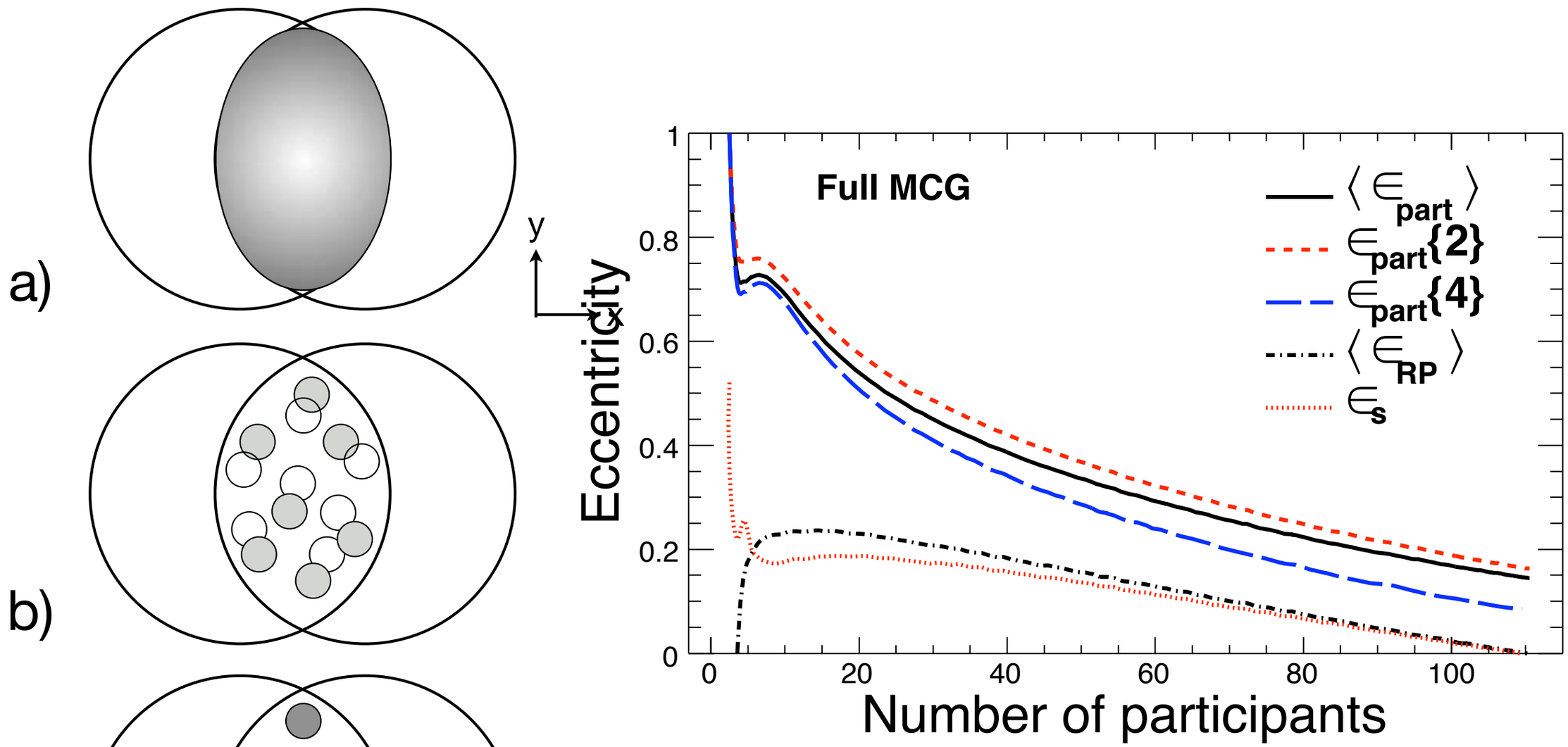


Two Particle Correlations from PHOBOS: Minijets?

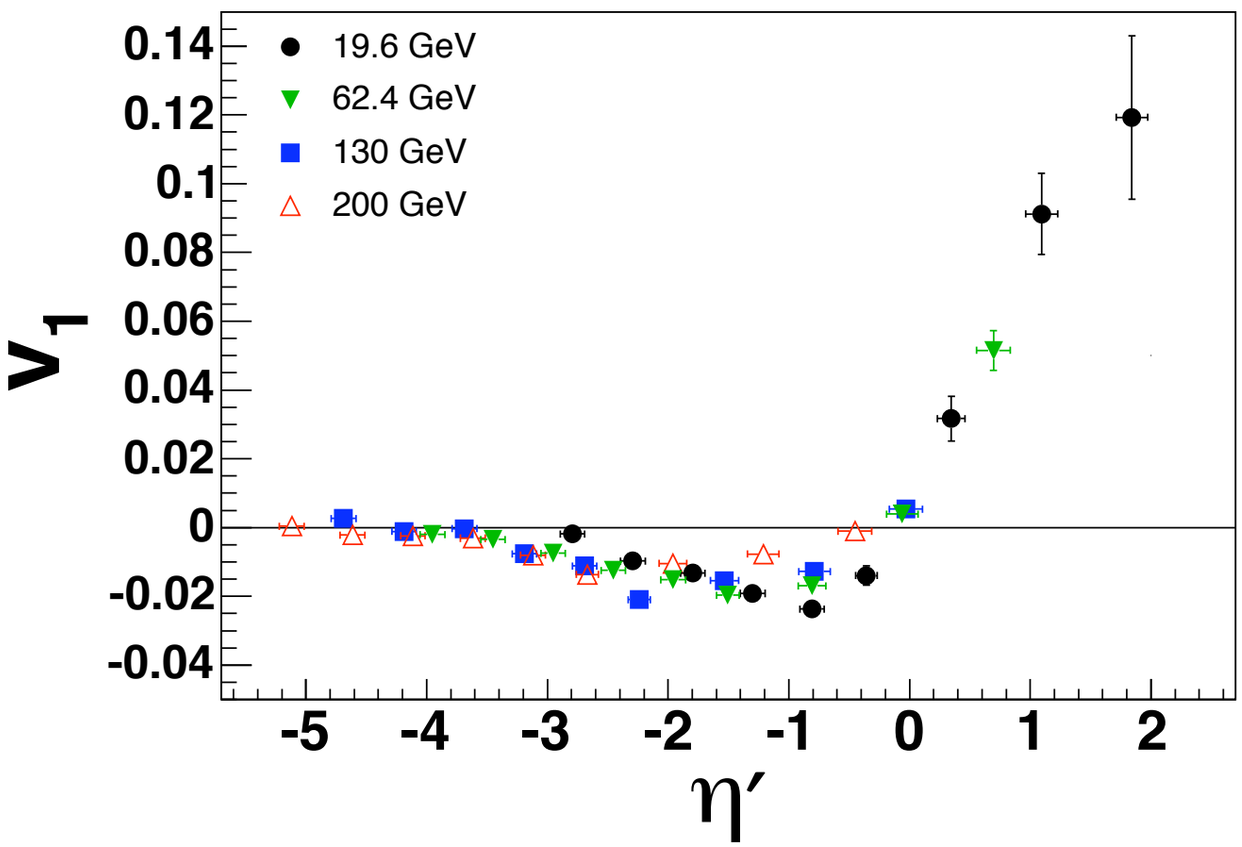




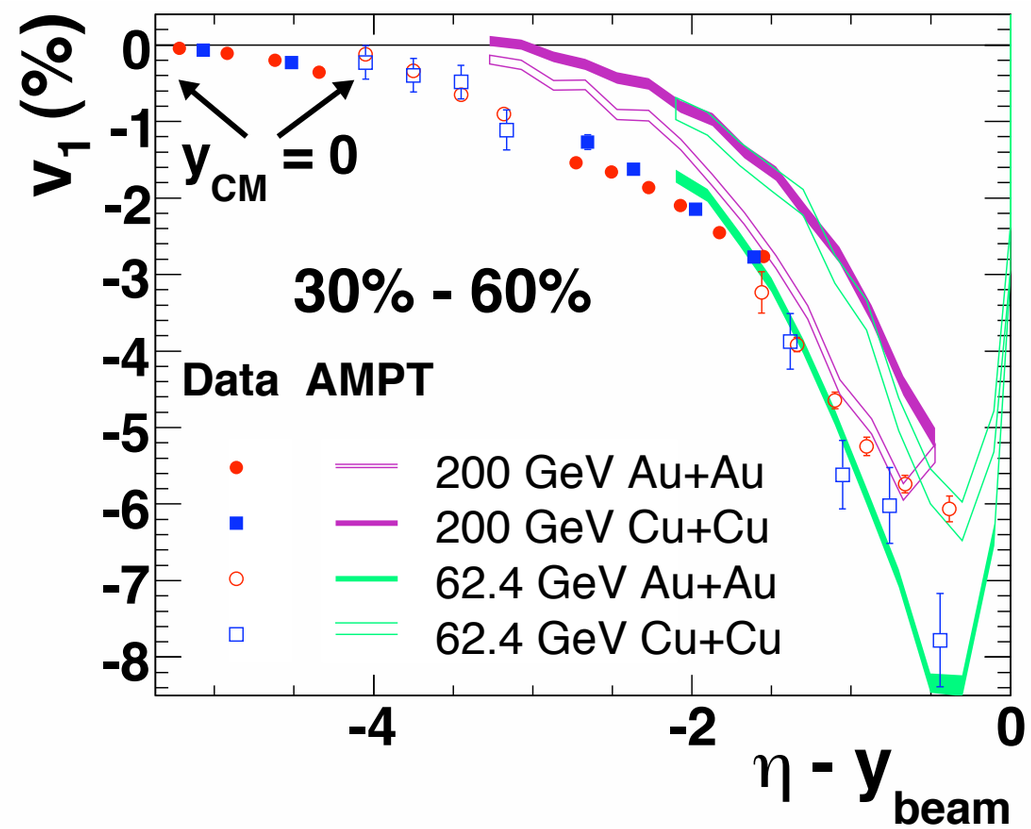
Fluctuations in Initial Geometry



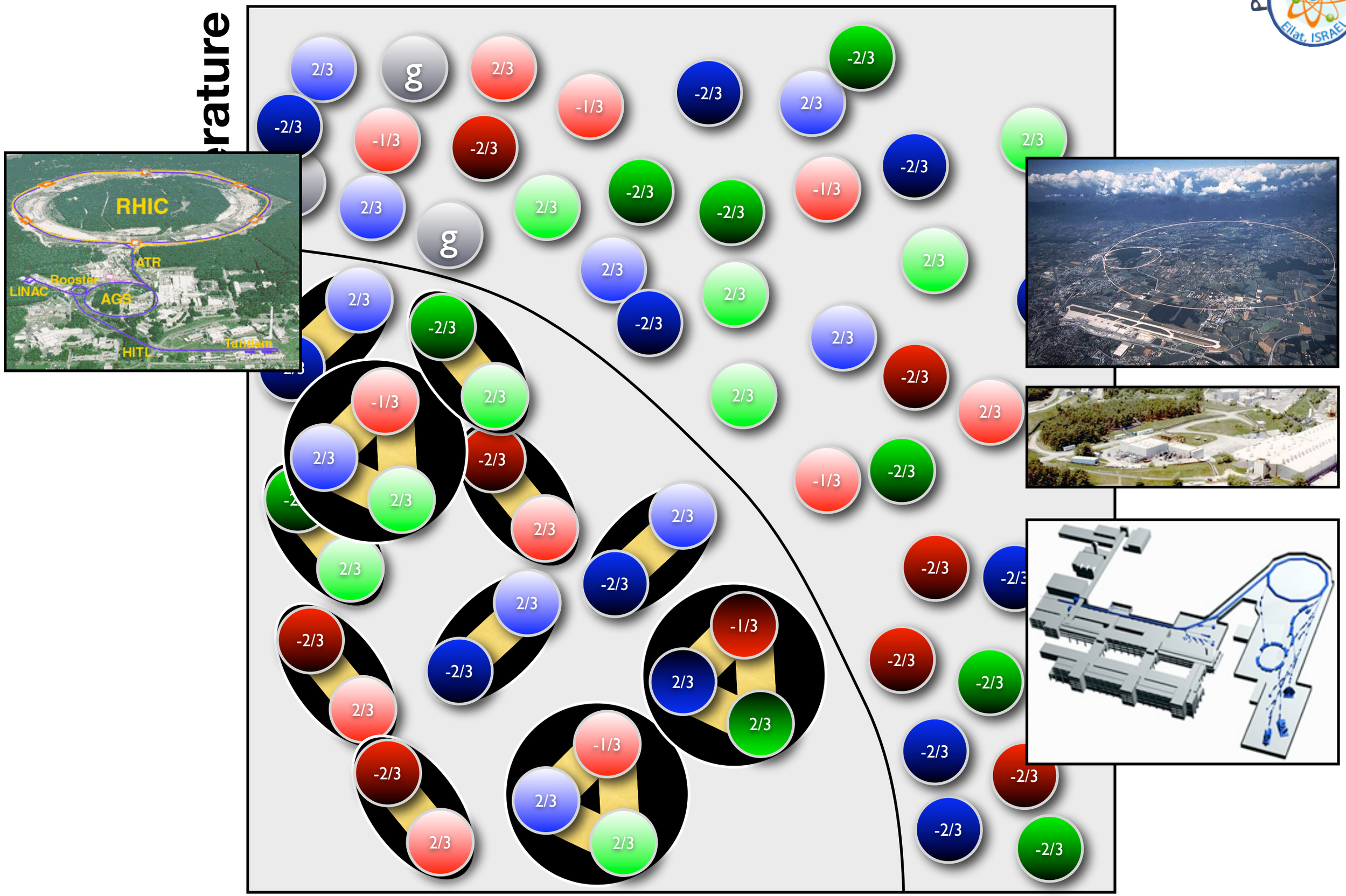
Directed Flow

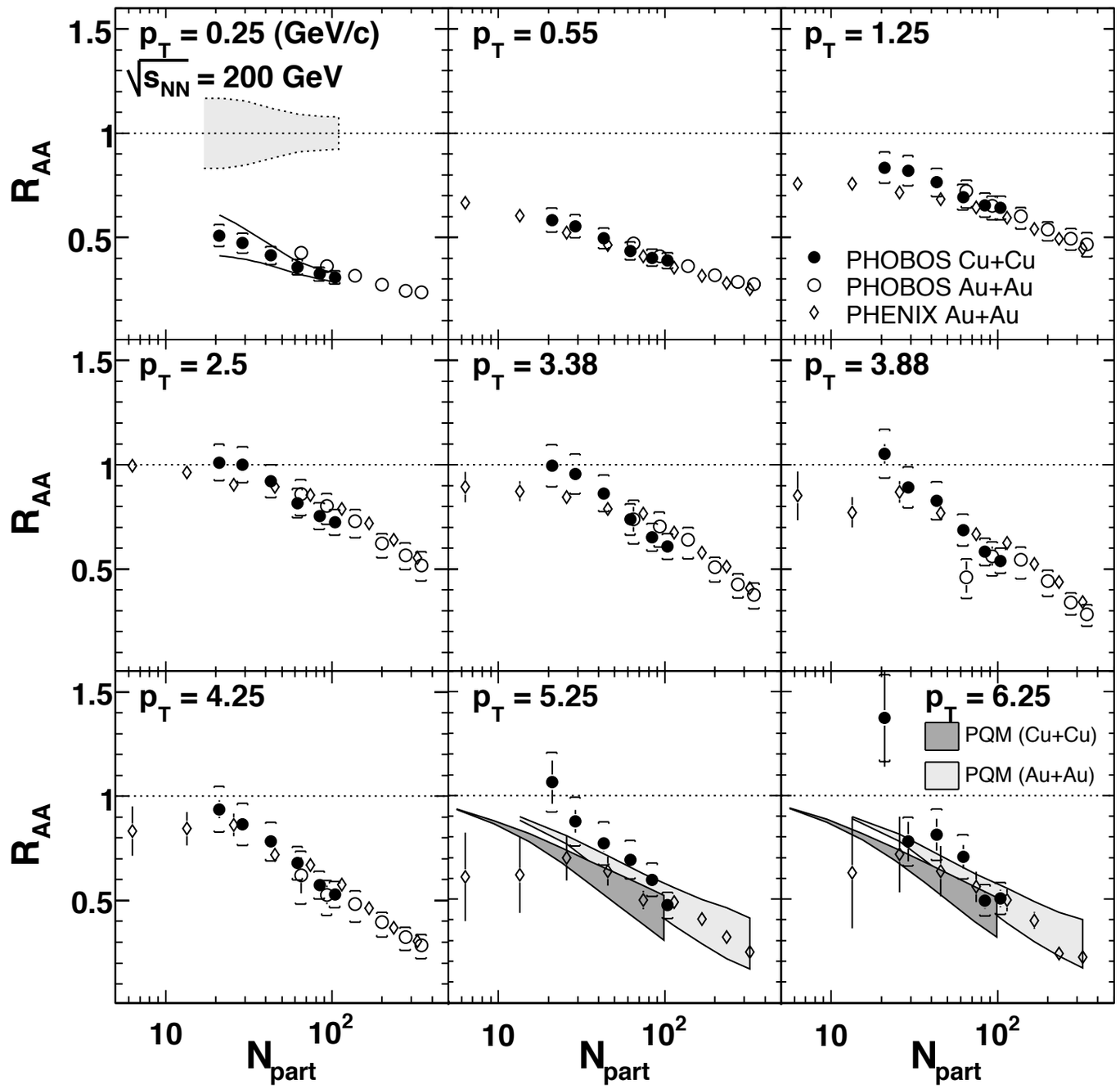


Directed flow also shows limiting fragmentation

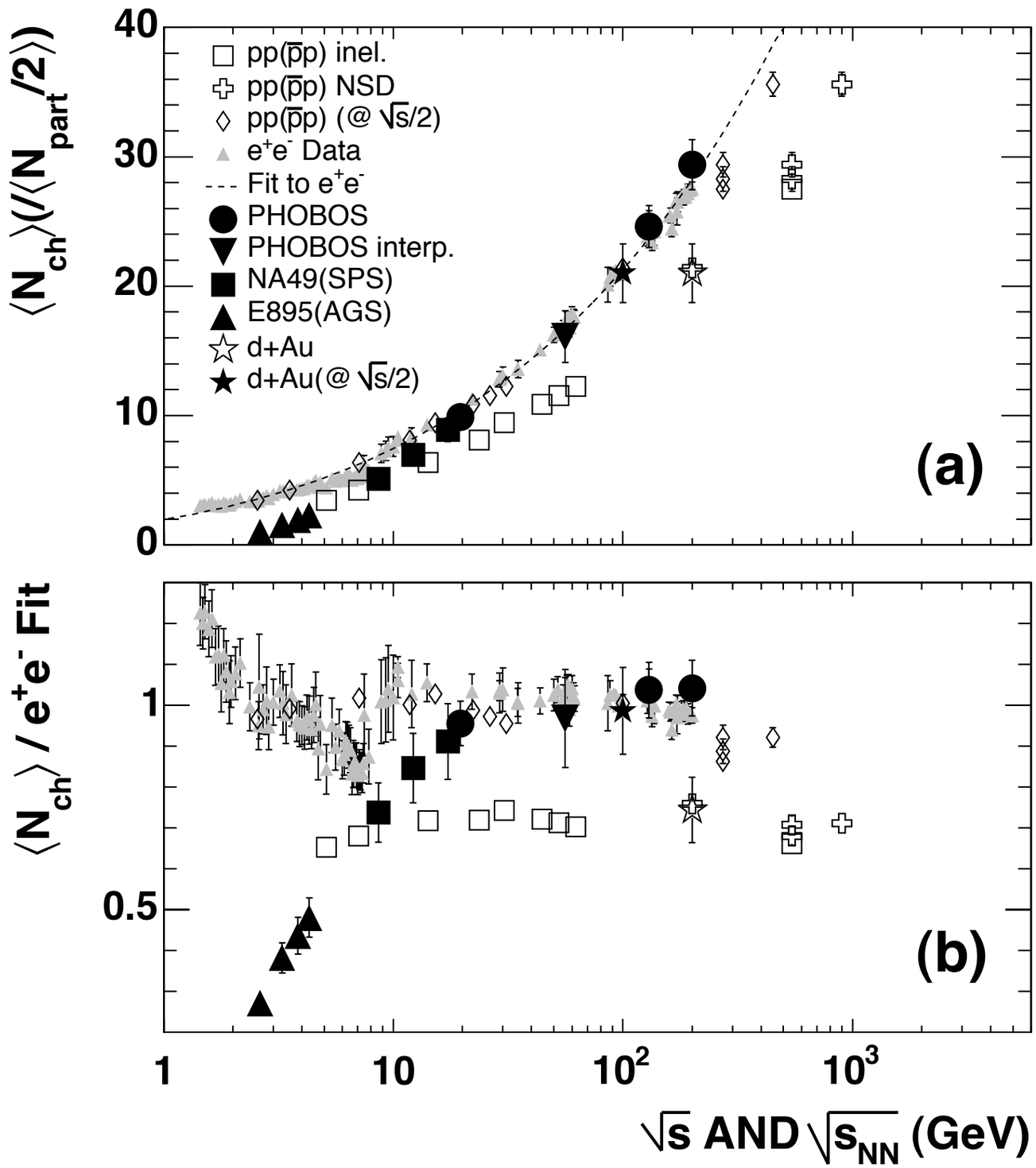


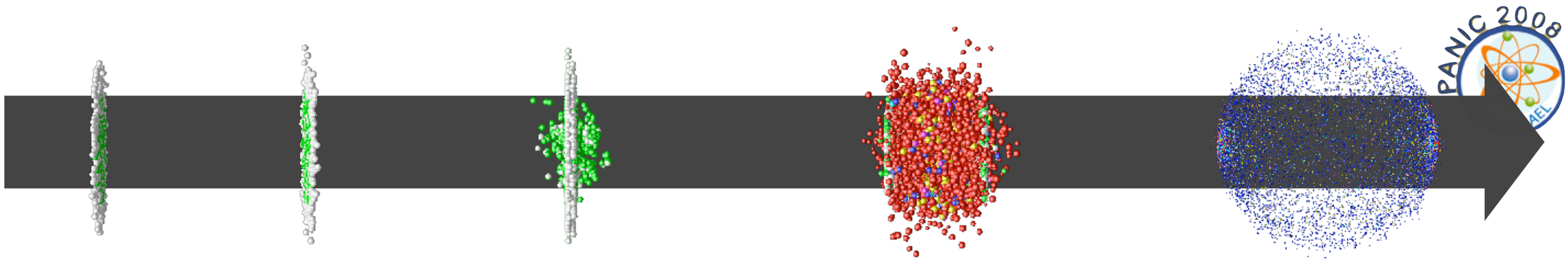
Scales with fraction of cross section (b/2R)


rature
RHIC
ATR
Booster
LINAC
AGS
HITL
Tandem
Baryochemical Potential


p_T = 0.25 (GeV/c)
$\sqrt{s_{NN}}$ = 200 GeV
p_T = 0.55
p_T = 1.25
p_T = 2.5
p_T = 3.38
p_T = 3.88
p_T = 4.25
p_T = 5.25
p_T = 6.25
PHOBOS Cu+Cu
PHOBOS Au+Au
PHENIX Au+Au
PQM (Cu+Cu)
PQM (Au+Au)
R_{AA}
N_{part}
1.5
1
0.5
10
10^2

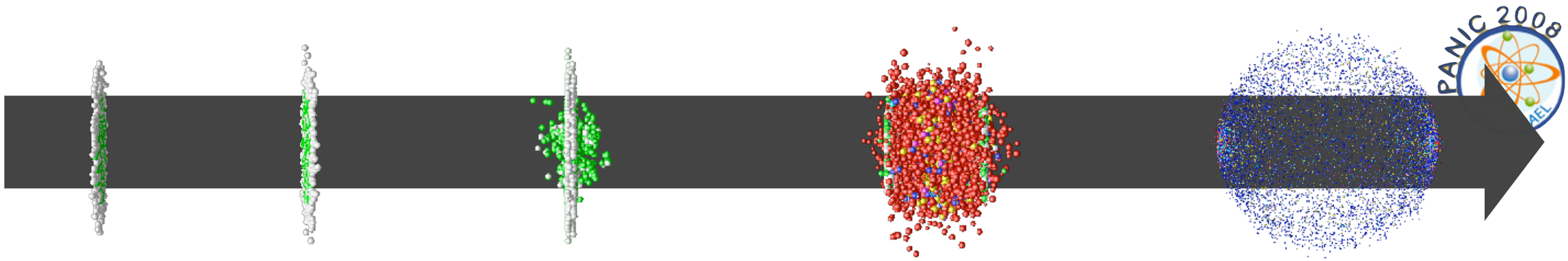
Total Multiplicity Systematics





	Experimental Observable	Theoretical Tools	Physics
Nuclear PDFs	**Particle multiplicities, monojets**	Color Glass Condensate (Parton Saturation)	**High-density pQCD**
Hard Processes	Jets, Photons, Heavy Quarks & Onia, Z&W	pQCD	**QCD in medium**
(non-) Ideal Hydrodynamics	$\frac{d^3N}{d\eta d\phi dp_T}$	3+1D Hydro Initial conditions	**Equation of State (Degrees of Freedom)**
Hadron Freezeout	**Particle yields, correlations, fluctuations**	Statistical models, Cluster models	**Hadronization**

Global variables provide access to full range of evolution history



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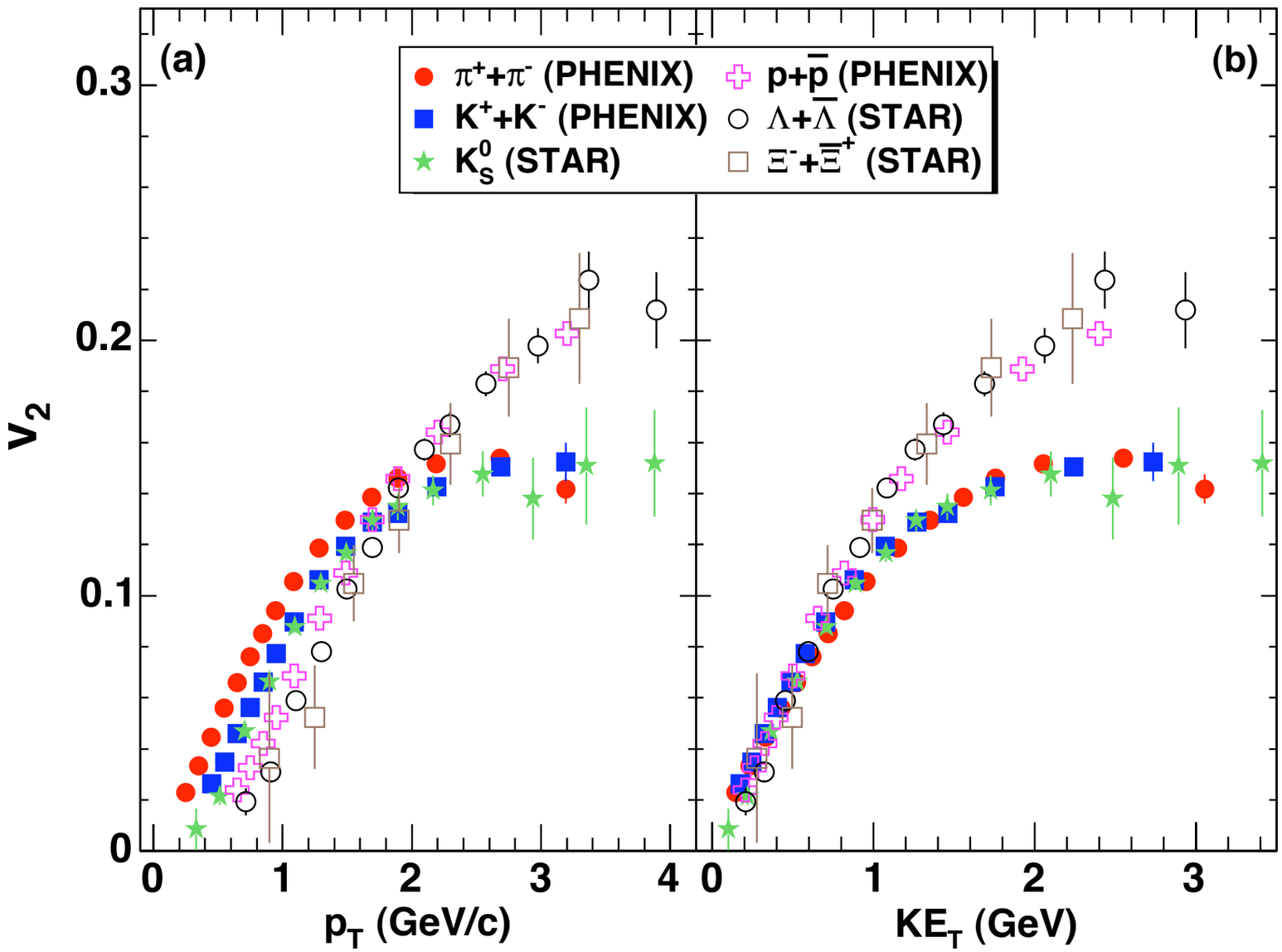
Elliptic Flow for Identified Particles

Phys.Rev.Lett.98:162301,2007



$$KE_T = m_T - m$$