Bulk Observables in Heavy Ion Collisions

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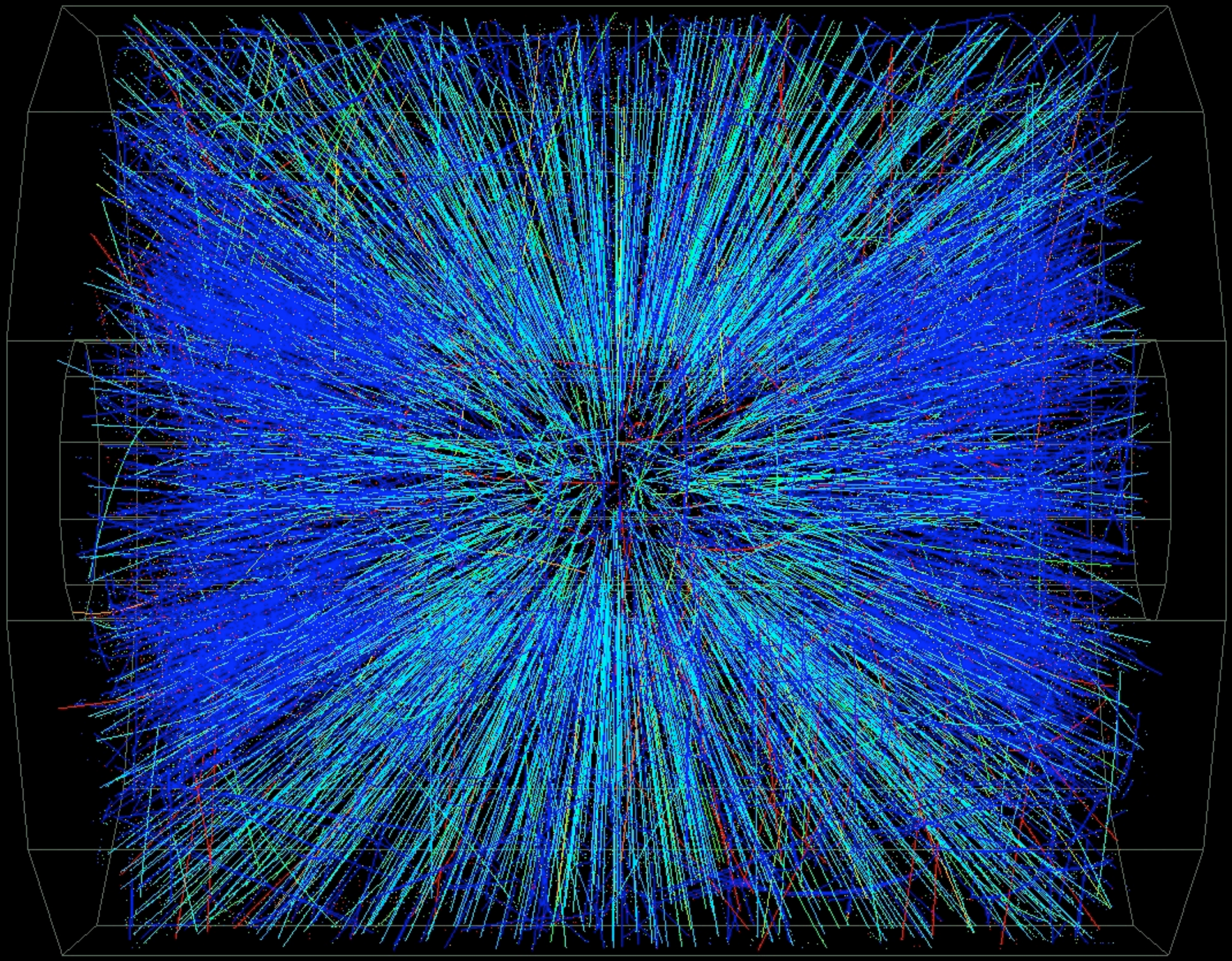
Heavy Ion Physics with ATLAS
12 May 2008
JINR, Dubna, Russia

ATLAS, ROCKEFELLER CENTER, NEW YORK CITY



The Particle Zoo

Baryon
(3 q or $\bar{q}$)

Σ
Λ Ω
p Δ Ξ
n

Meson
(1 q & $\bar{q}$)

ω ρ
K π
φ
ρ

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

$\phi(1680)$ $I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1680 \pm 20$ MeV [n]
Full width $\Gamma = 150 \pm 50$ MeV [n]

$\phi(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}^*(892)+$ c.c.	dominant	462
$K^0_S K\pi$	seen	621
$K\overline{K}$	seen	680
e^+e^-	seen	840
$\omega\pi\pi$	not seen	623

$\rho_3(1690)$ $I^G(J^{PC}) = 1^+(3^{--})$

Mass $m = 1688.8 \pm 2.1$ MeV [n]
Full width $\Gamma = 161 \pm 10$ MeV [n] (S = 1.5)

$\rho_3(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
4π	(71.1 ± 1.9) %		790
$\pi^\pm\pi^+\pi^-\pi^0$	(67 ±22) %		787
$\omega\pi$	(16 ± 6) %		655
$\pi\pi$	(23.6 ± 1.3) %		834
$K\overline{K}\pi$	(3.8 ± 1.2) %		629
$K\overline{K}$	(1.58± 0.26) %	1.2	685
$\eta\pi^+\pi^-$	seen		727
$\rho(770)\eta$	seen		520
$\pi\pi\rho$ Excluding 2ρ and $a_2(1320)\pi$.	seen		633
$a_2(1320)\pi$	seen		307
$\rho\rho$	seen		333

$\rho(1700)$ [s] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1720 \pm 20$ MeV [n] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)
Full width $\Gamma = 250 \pm 100$ MeV [n] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

$\rho(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$2(\pi^+\pi^-)$	large	803
$\rho\pi\pi$	dominant	653
$\rho^0\pi^+\pi^-$	large	650

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1000's of "hadronic states" (particles & anti-particles) have been observed: more all the time

The Particle Zoo

Σ
Λ Ω
p Δ Ξ
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(3 q or $\bar{q}$)

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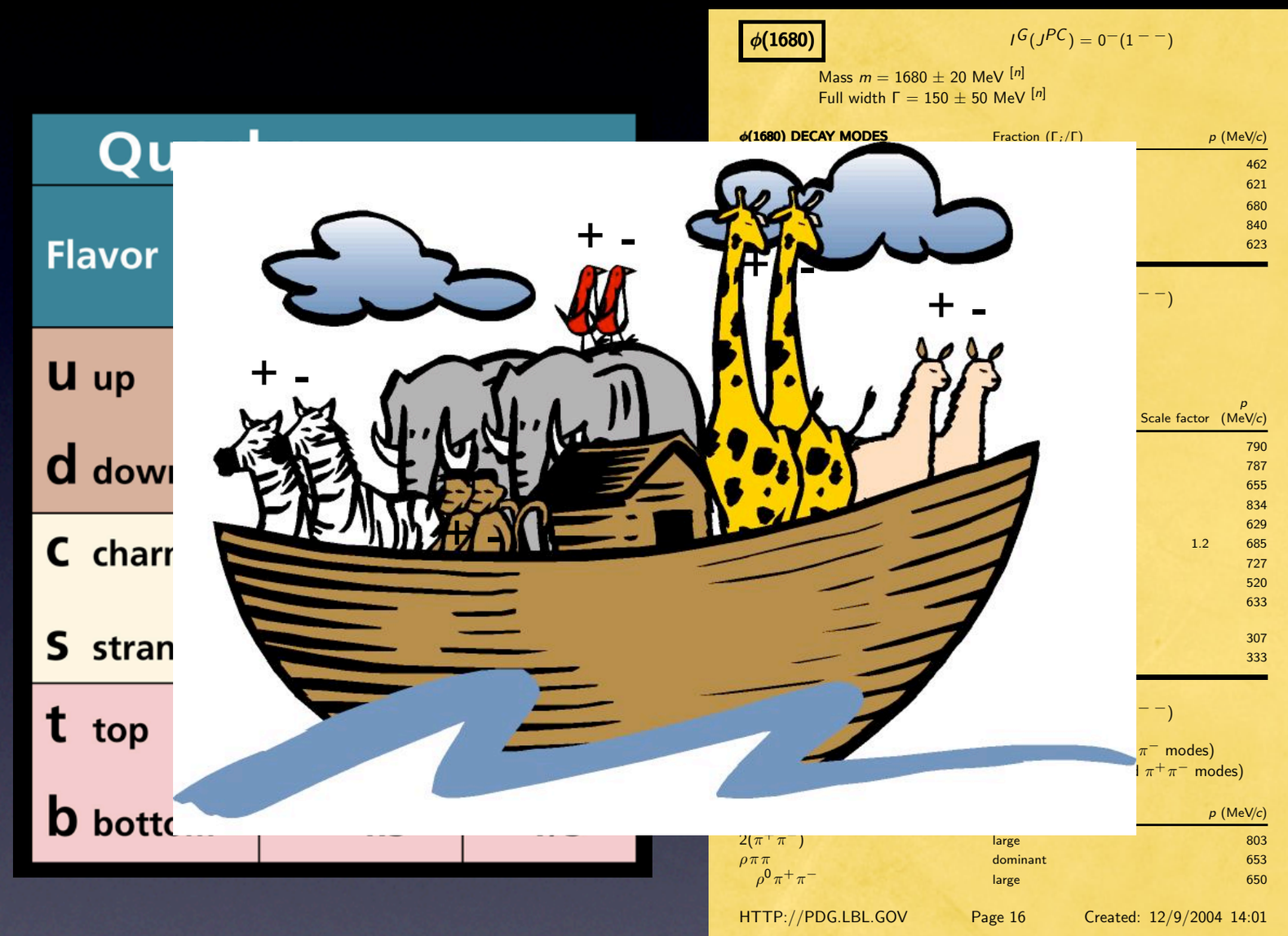
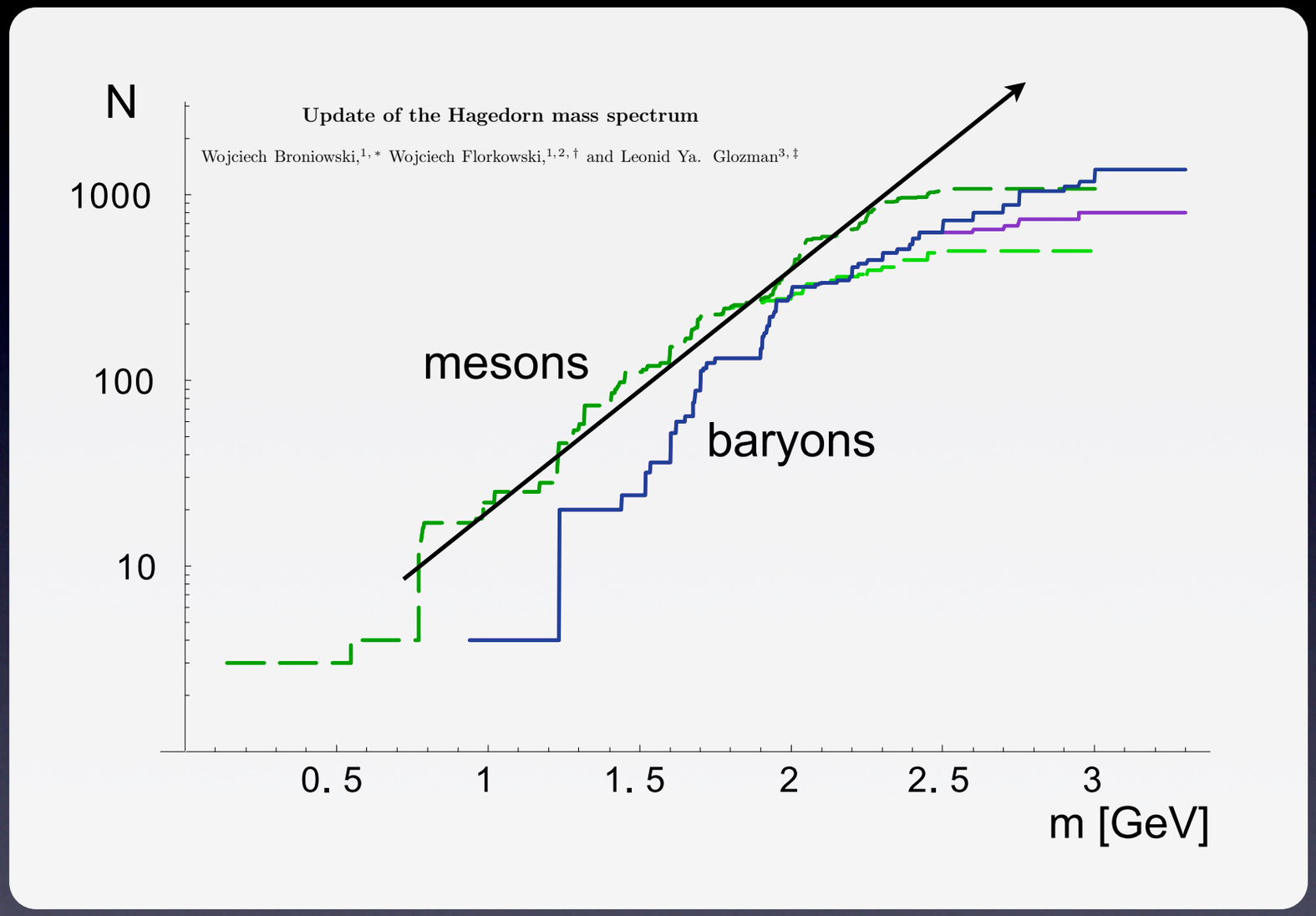


1000's of "hadronic states" (particles & anti-particles) have been observed: more all the time

Heating up Hadrons

In the early 1960's Rolf Hagedorn predicted that the bound state spectrum would rise indefinitely → Singularity at <u>limiting temperature</u> T_H~170 MeV



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

Heating

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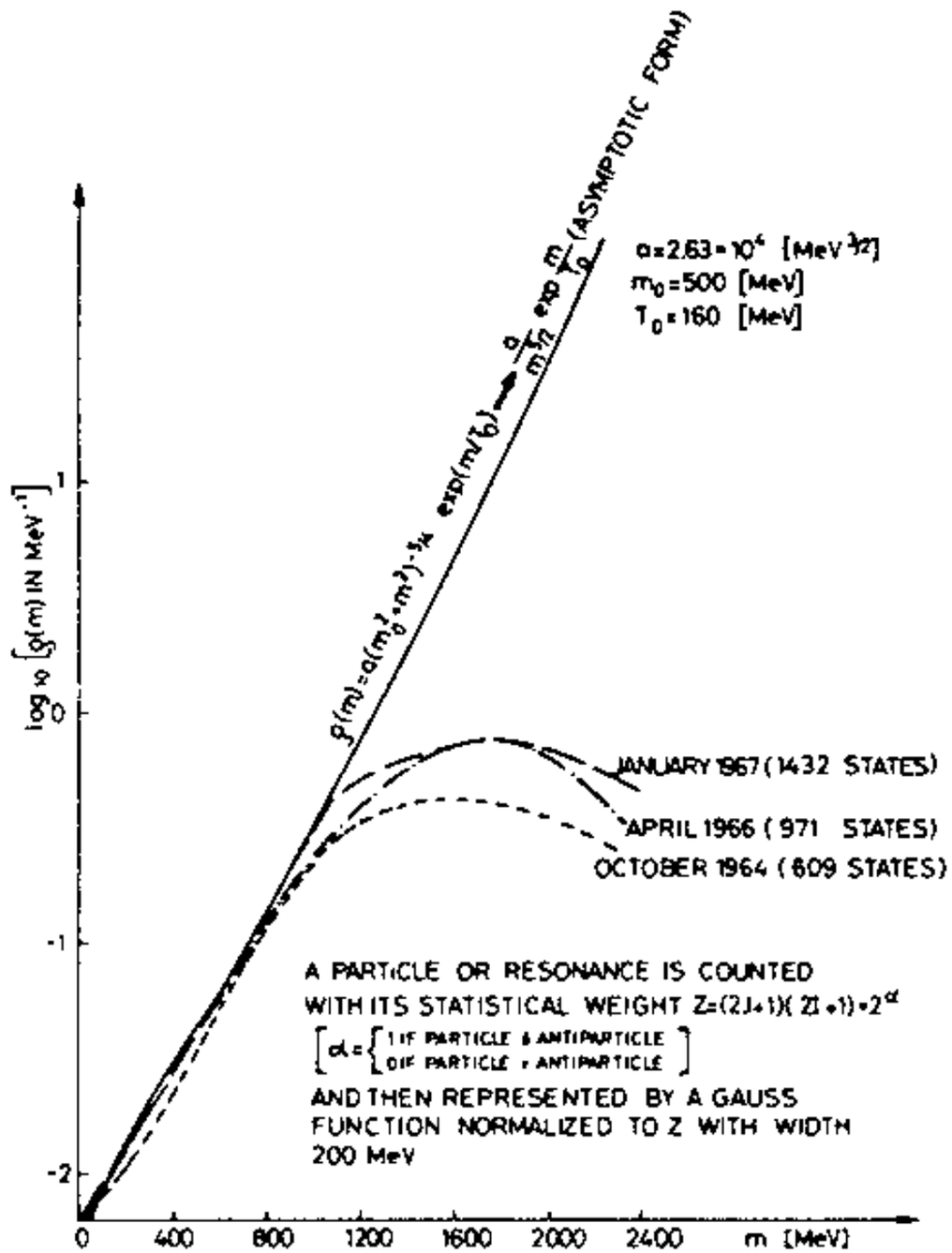

Fig. 3.1: The predicted and the experimental mass spectrum as it evolved from 1964 to 1967.

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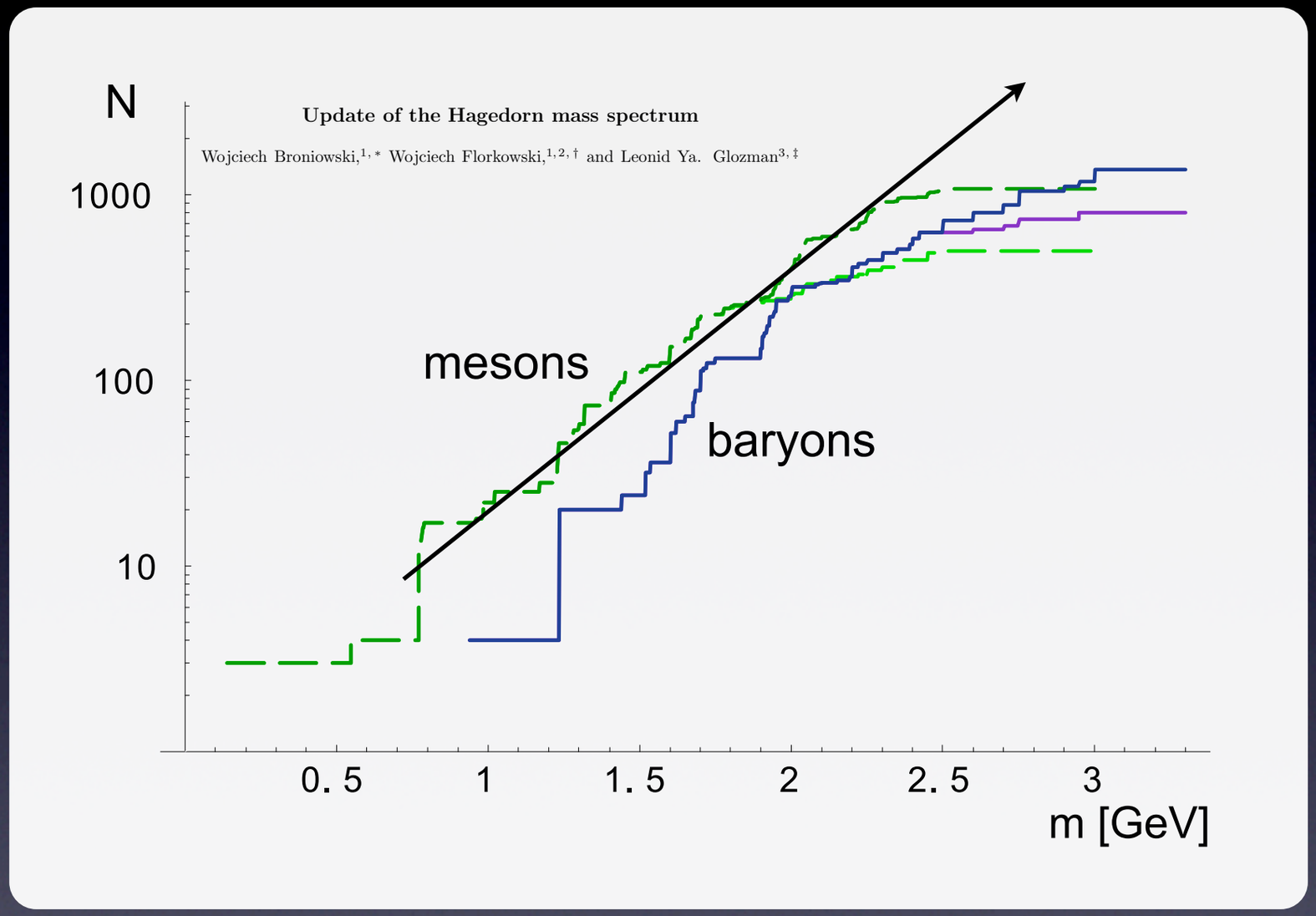

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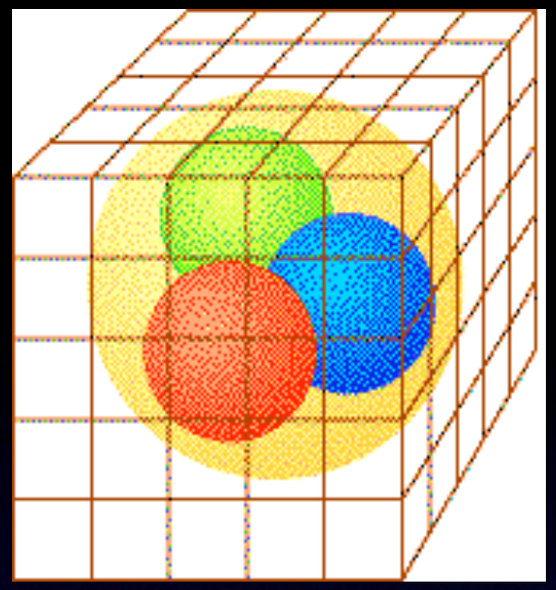
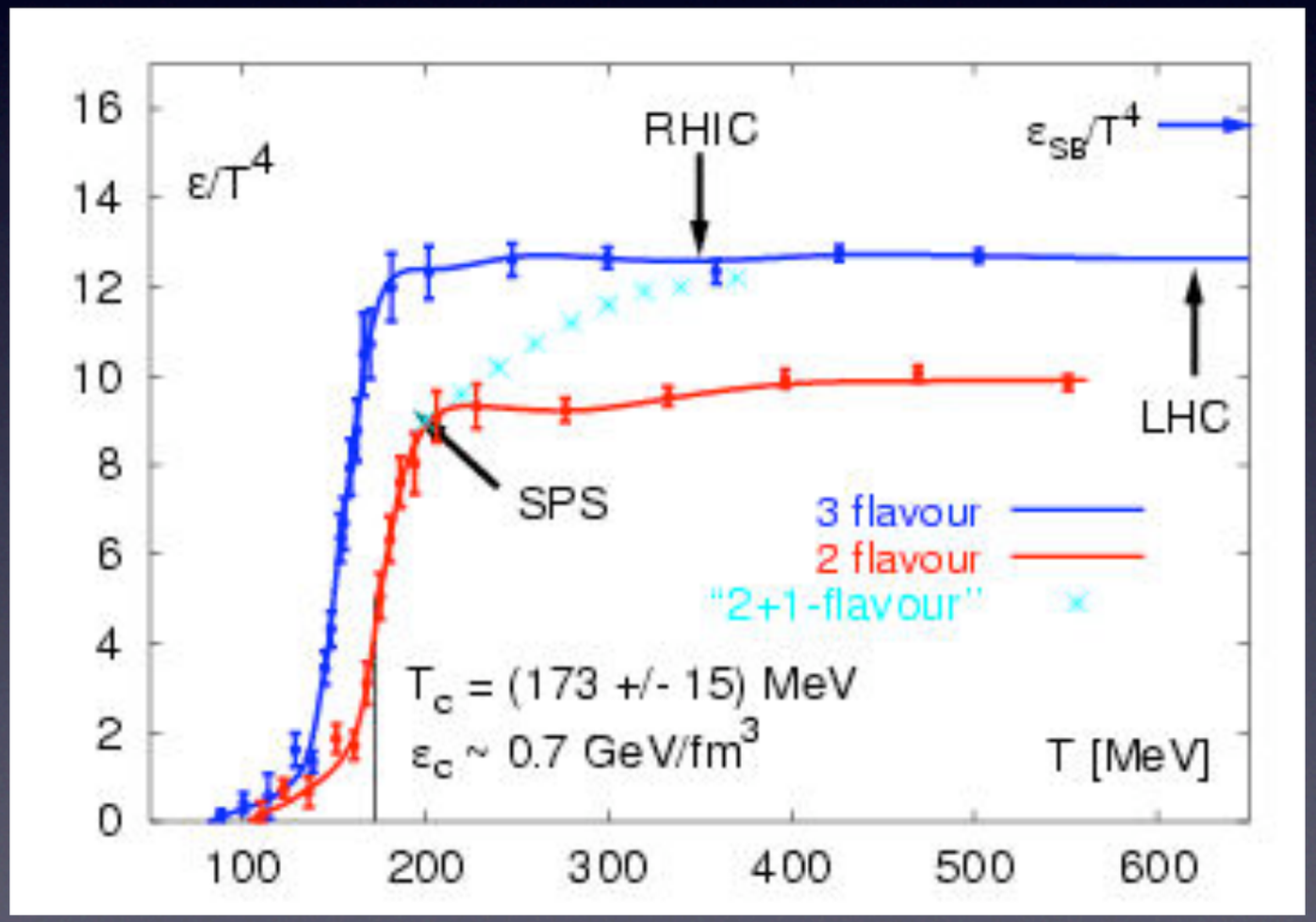
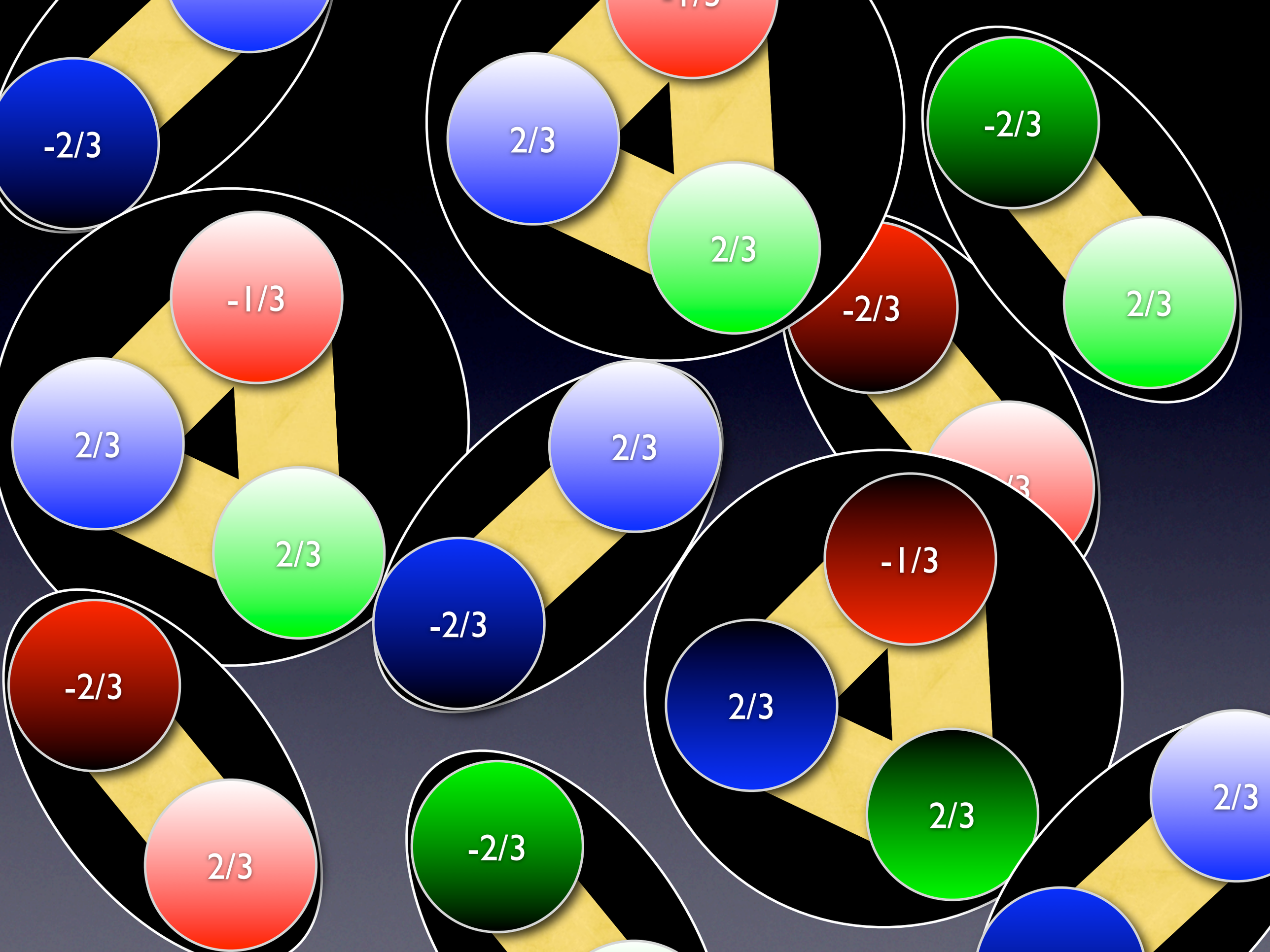


QCD is notoriously hard to solve for high temperature, so solved numerically on powerful machines!



Years ago, it was discovered that there is a “jump” in the number of “degrees of freedom” at the Hagedorn temperature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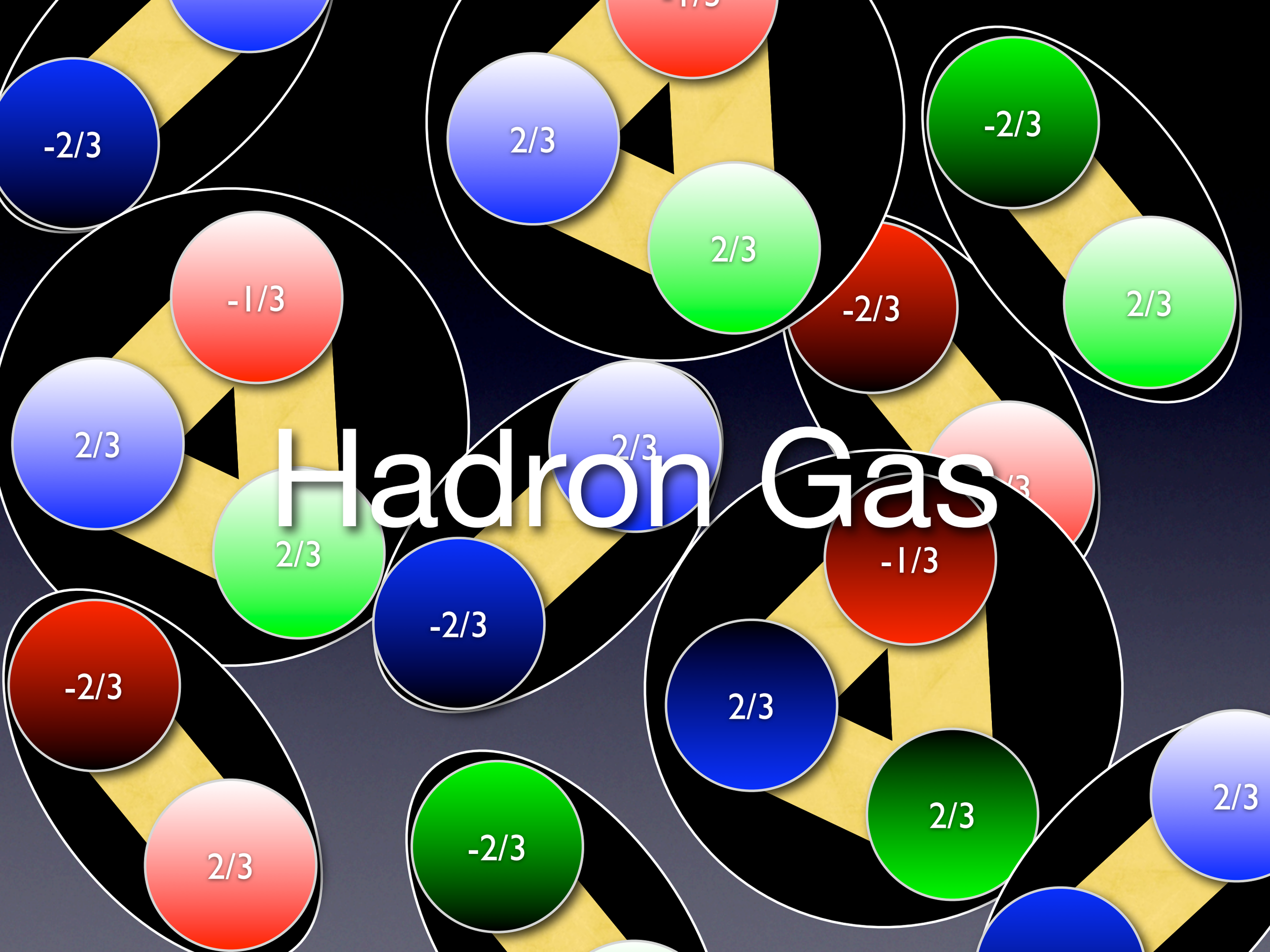
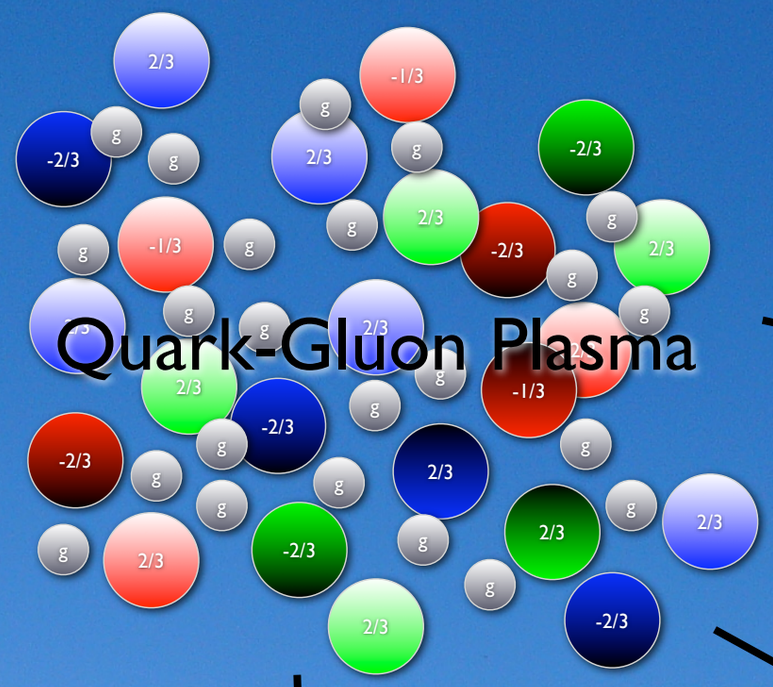
Hadron Gas



Quark-Gluon Plasma

QGP is a new state of matter



?

Gas

?

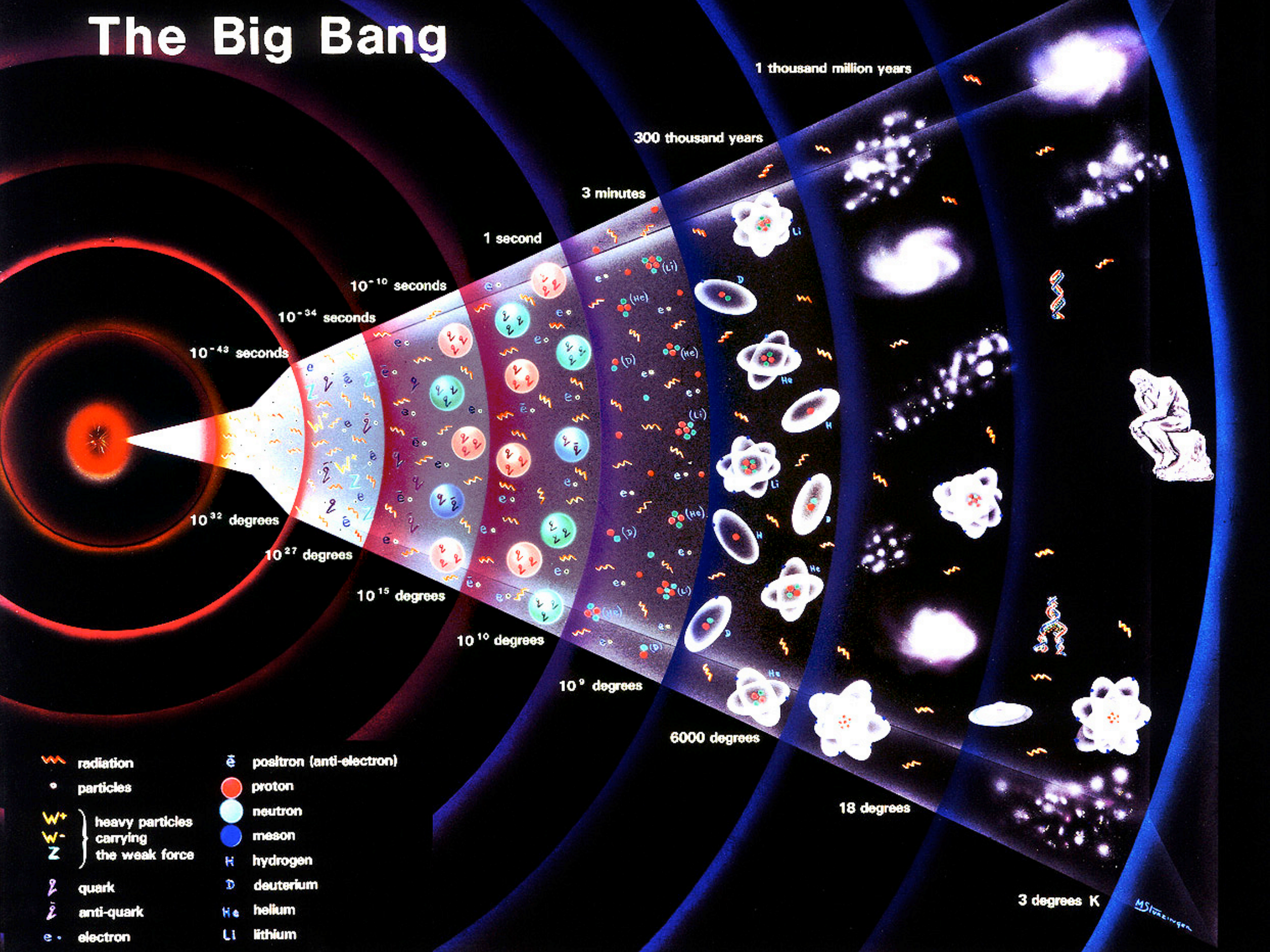
Plasma

?

Liquid

Solid

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
e
electron
positron (anti-electron)
proton
neutron
meson
H
hydrogen
D
deuterium
He
helium
Li
lithium

What State of Matter?

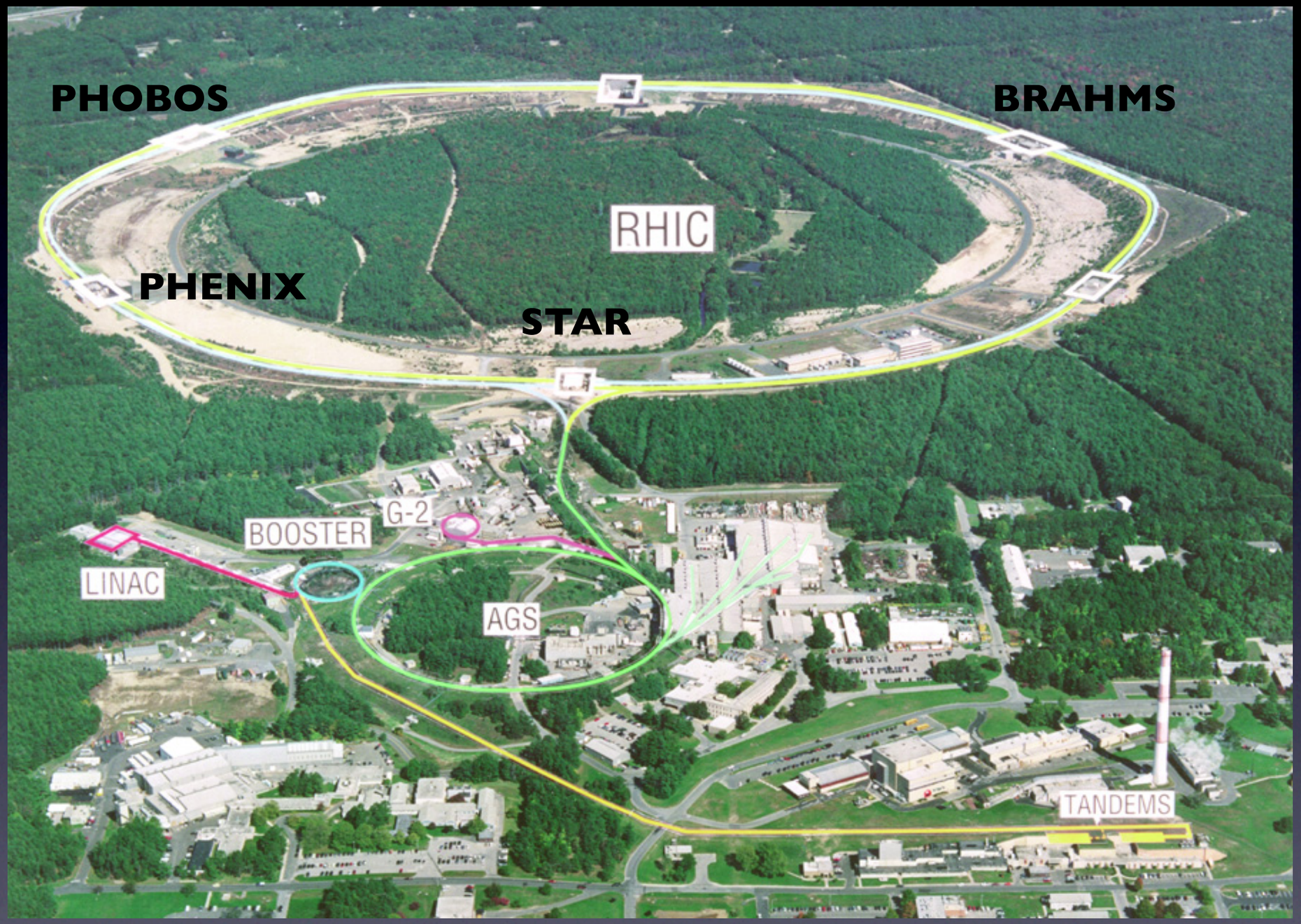
Does it act
like an ideal gas?

Does it flow,
like a (compressible) liquid?

RHIC

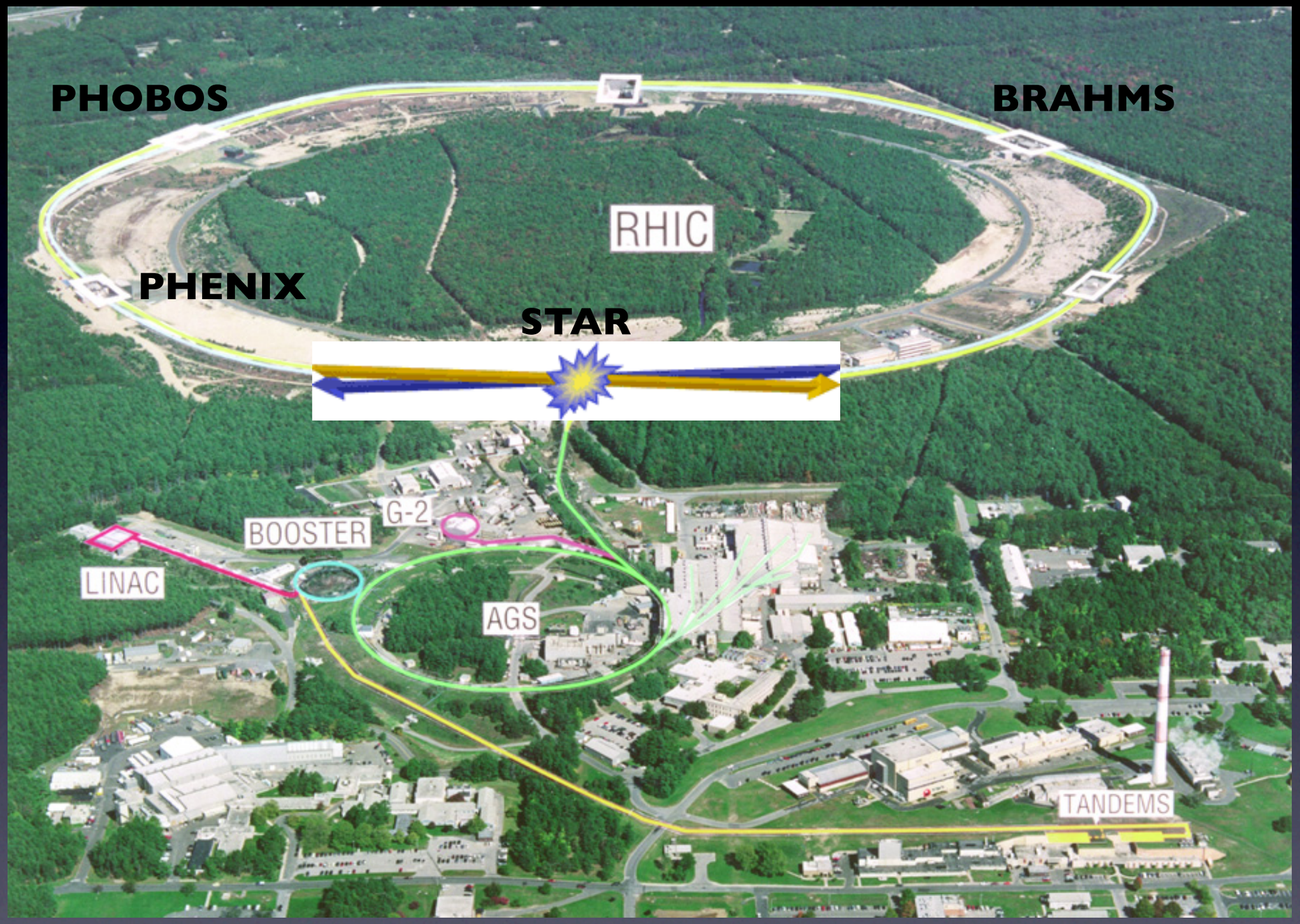
Relativistic Heavy Ion Collider

RHIC



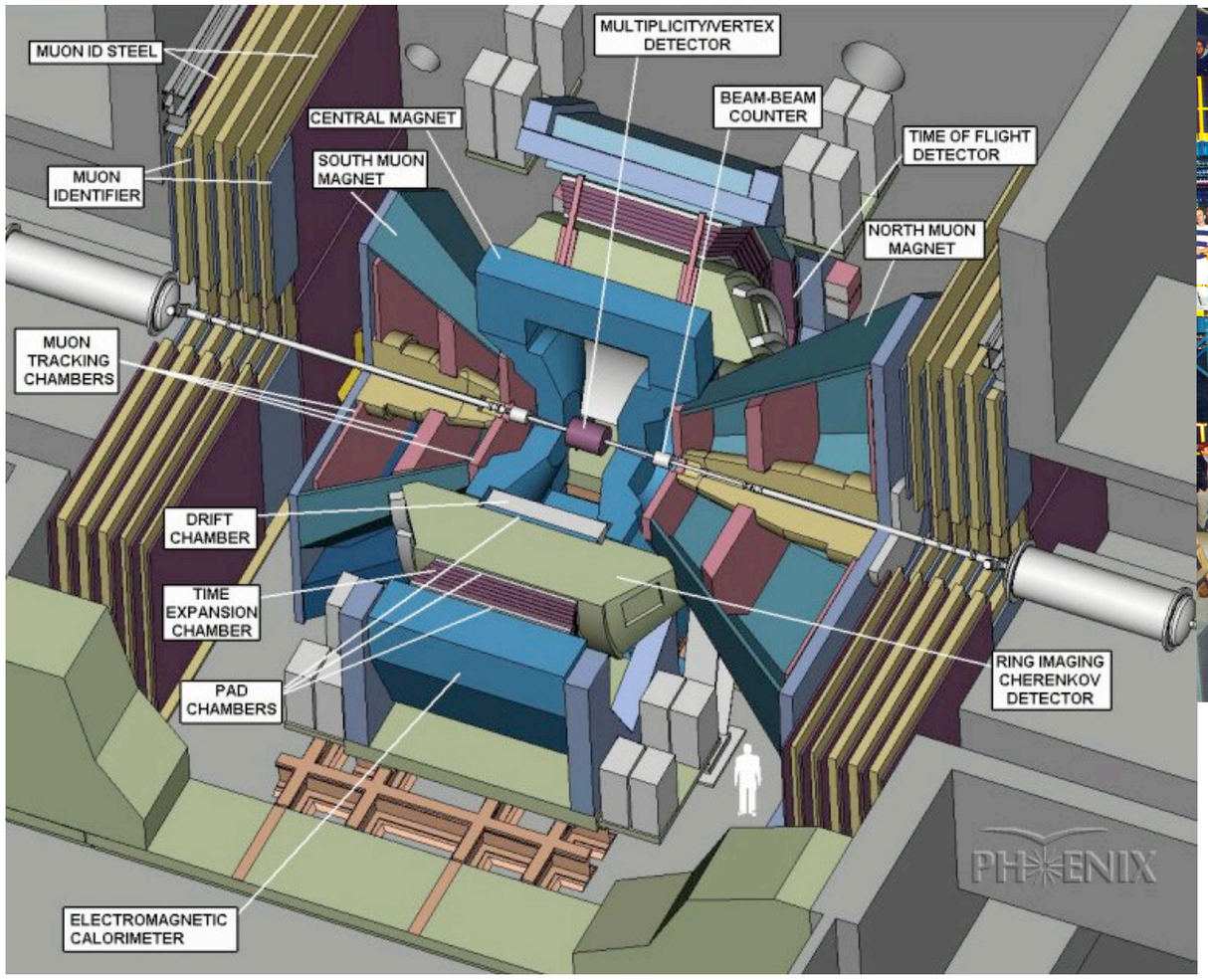
Relativistic Heavy Ion Collider

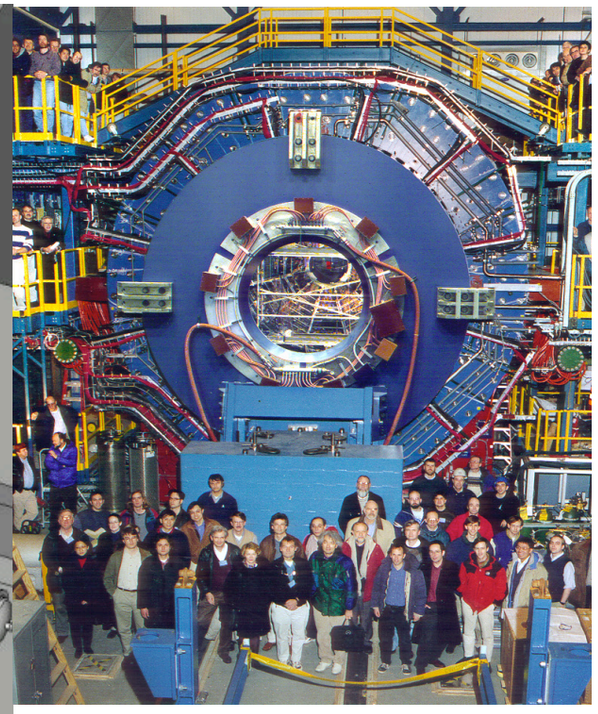
RHIC

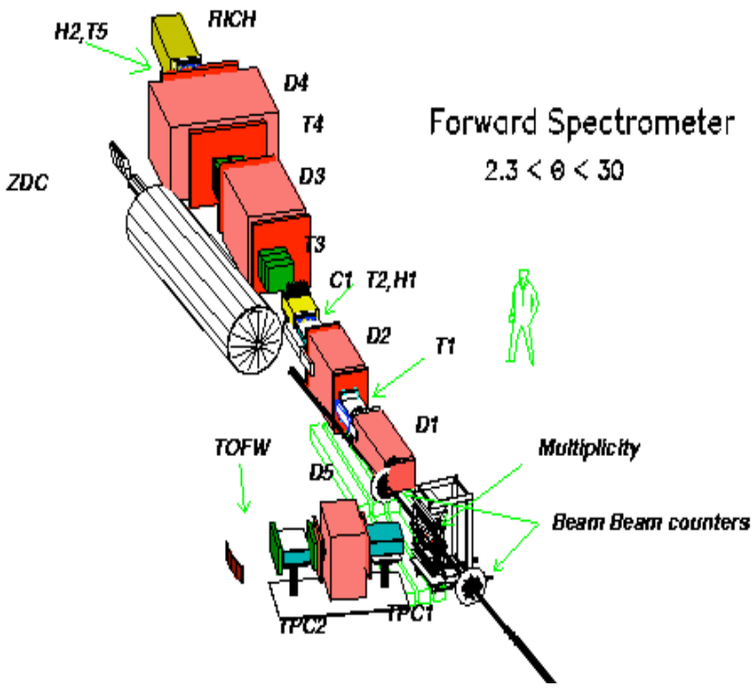


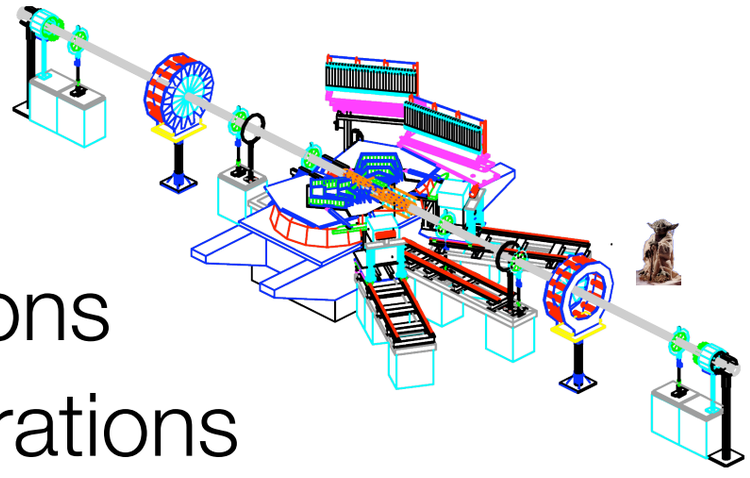
Relativistic Heavy Ion Collider

RHIC Experiments to Scale





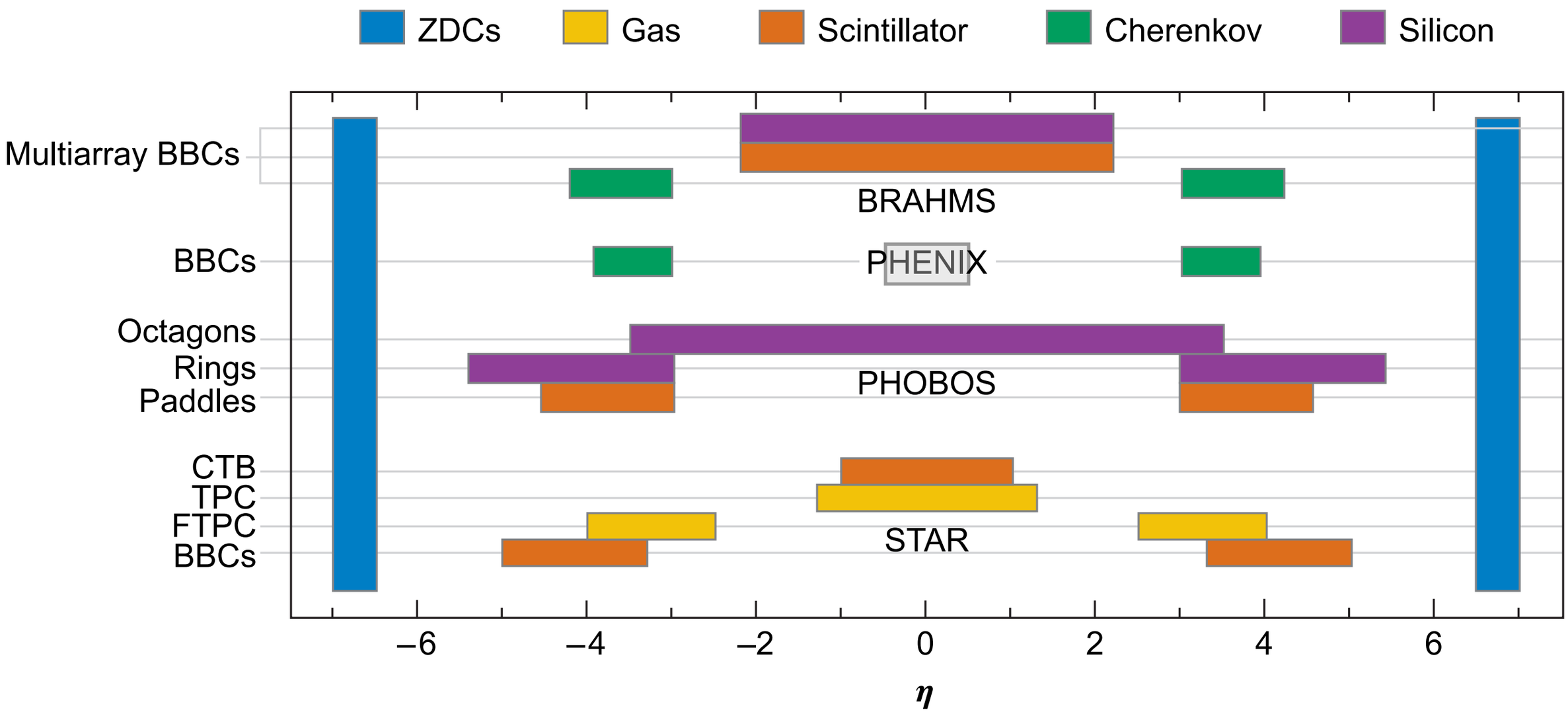




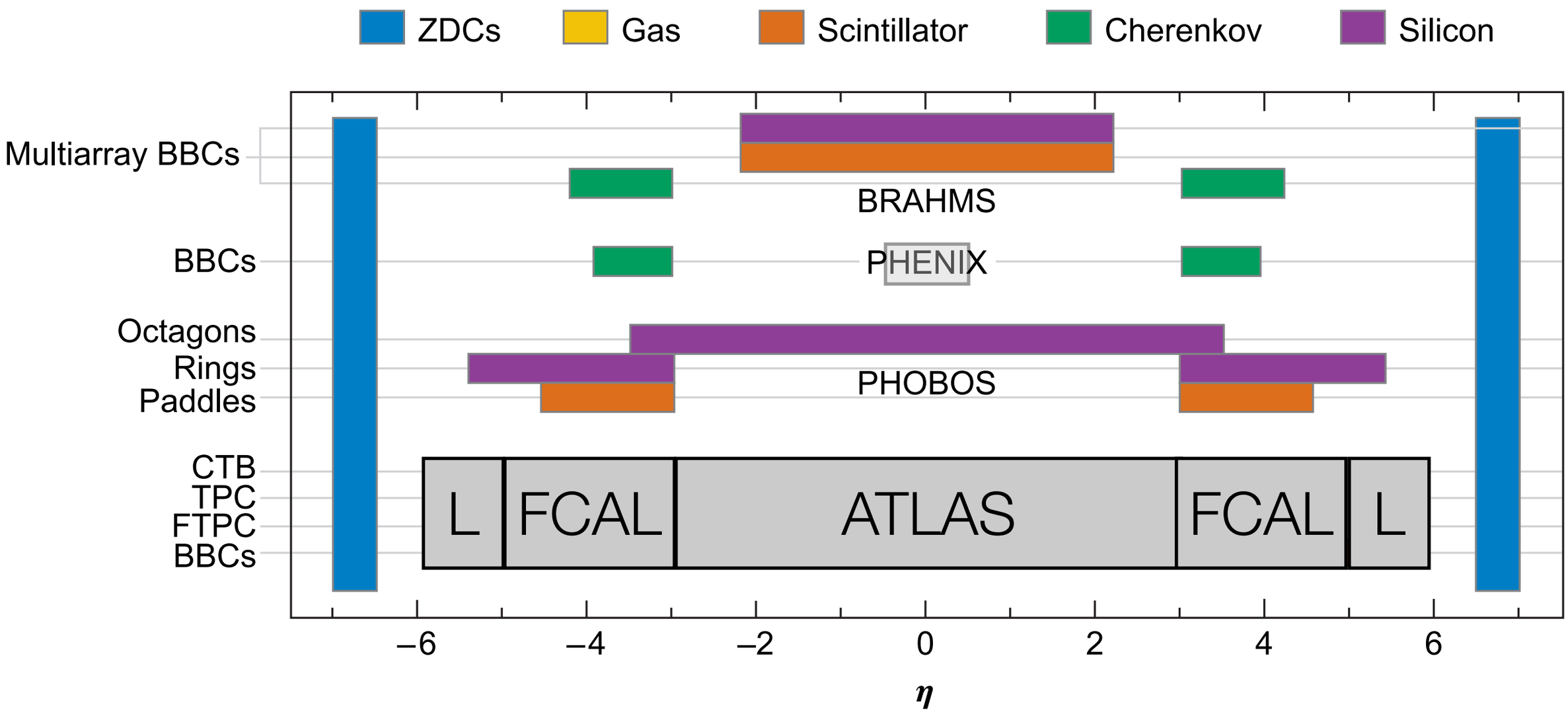
STAR & PHENIX - ~500 member collaborations

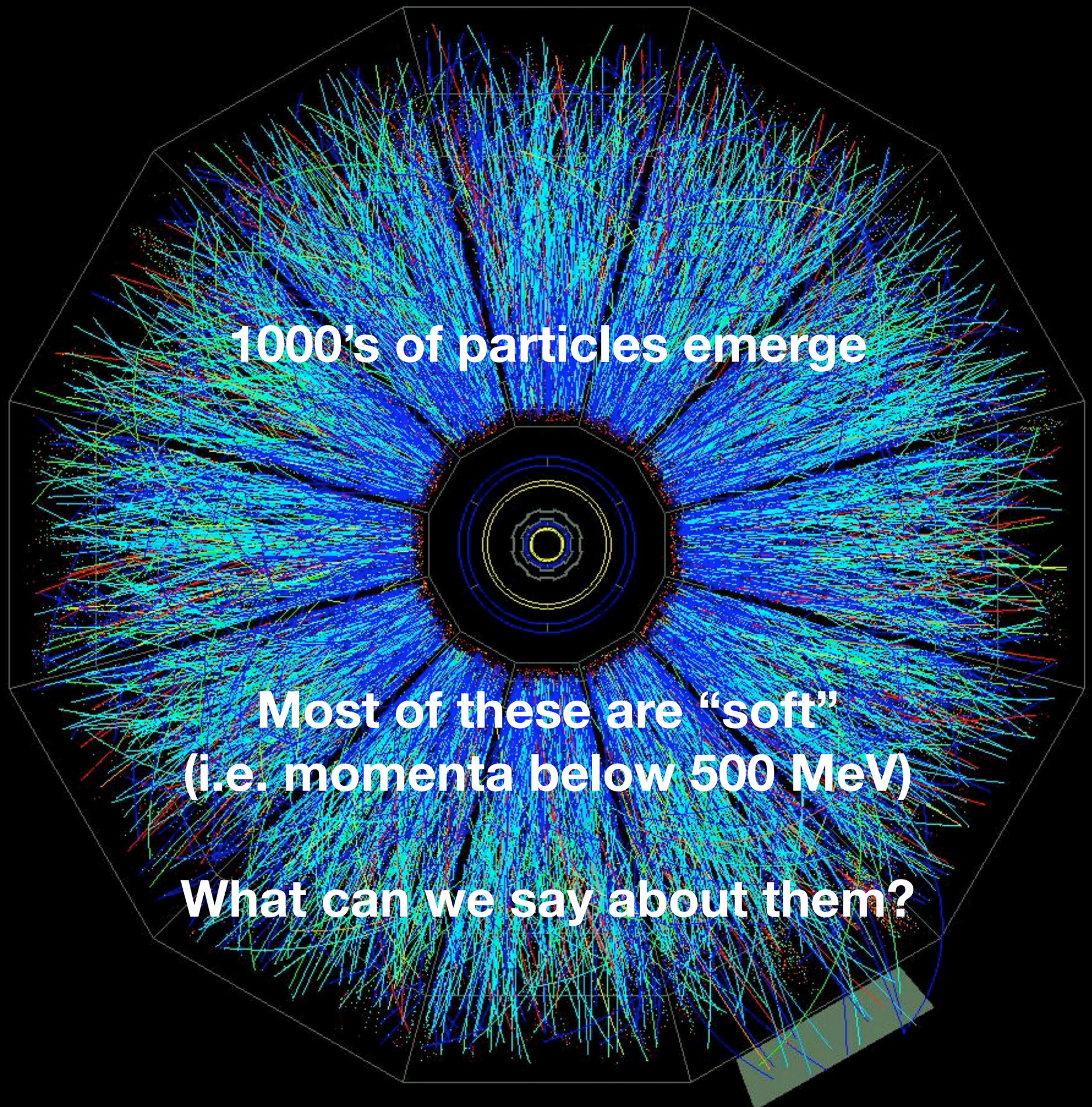
PHENIX & PHOBOS - ~50 member collaborations

RHIC Experiments



RHIC Experiments





1000's of particles emerge

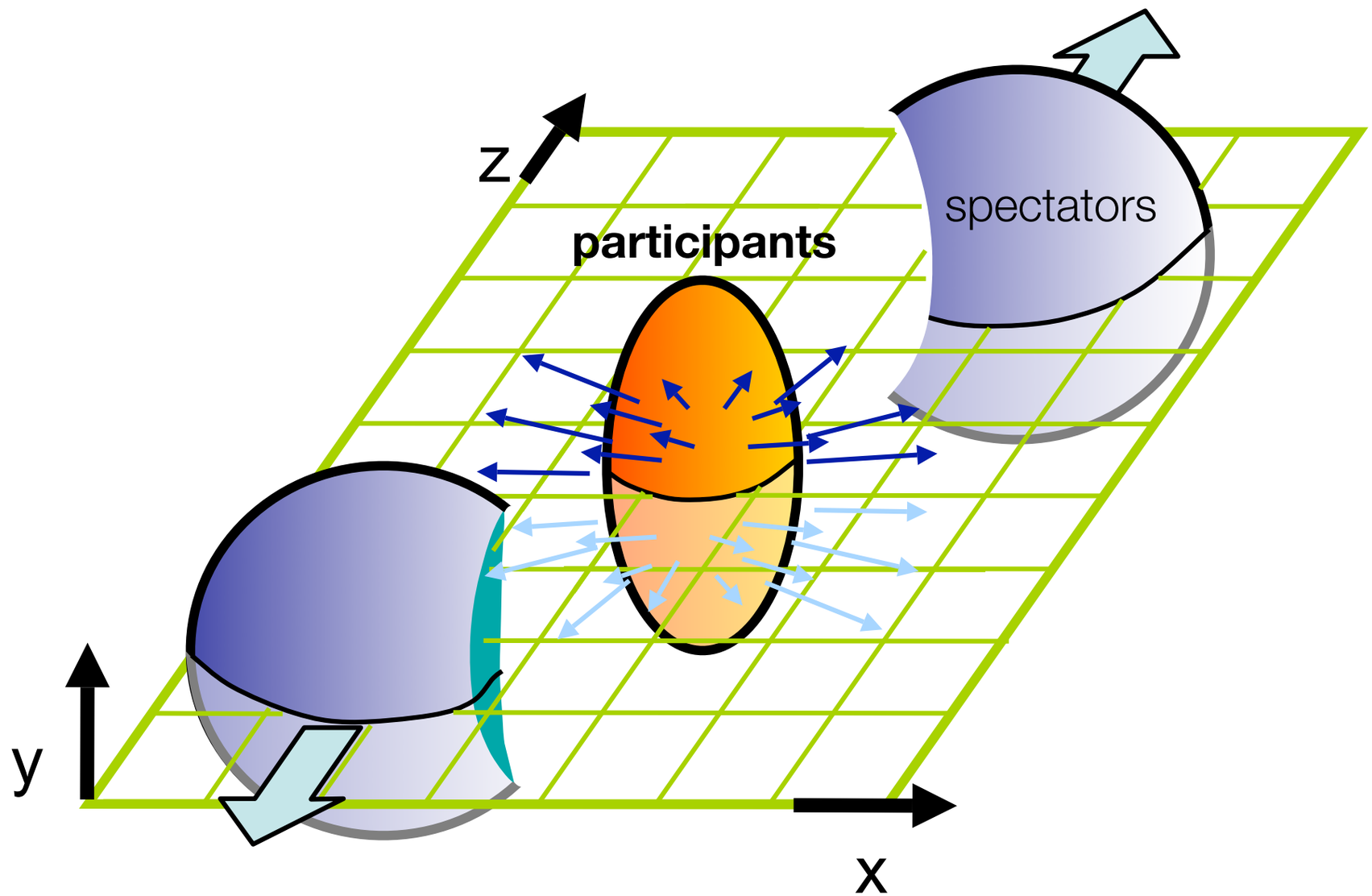
Most of these are "soft"
(i.e. momenta below 500 MeV)

What can we say about them?

A Brief Review of Soft RHIC Physics

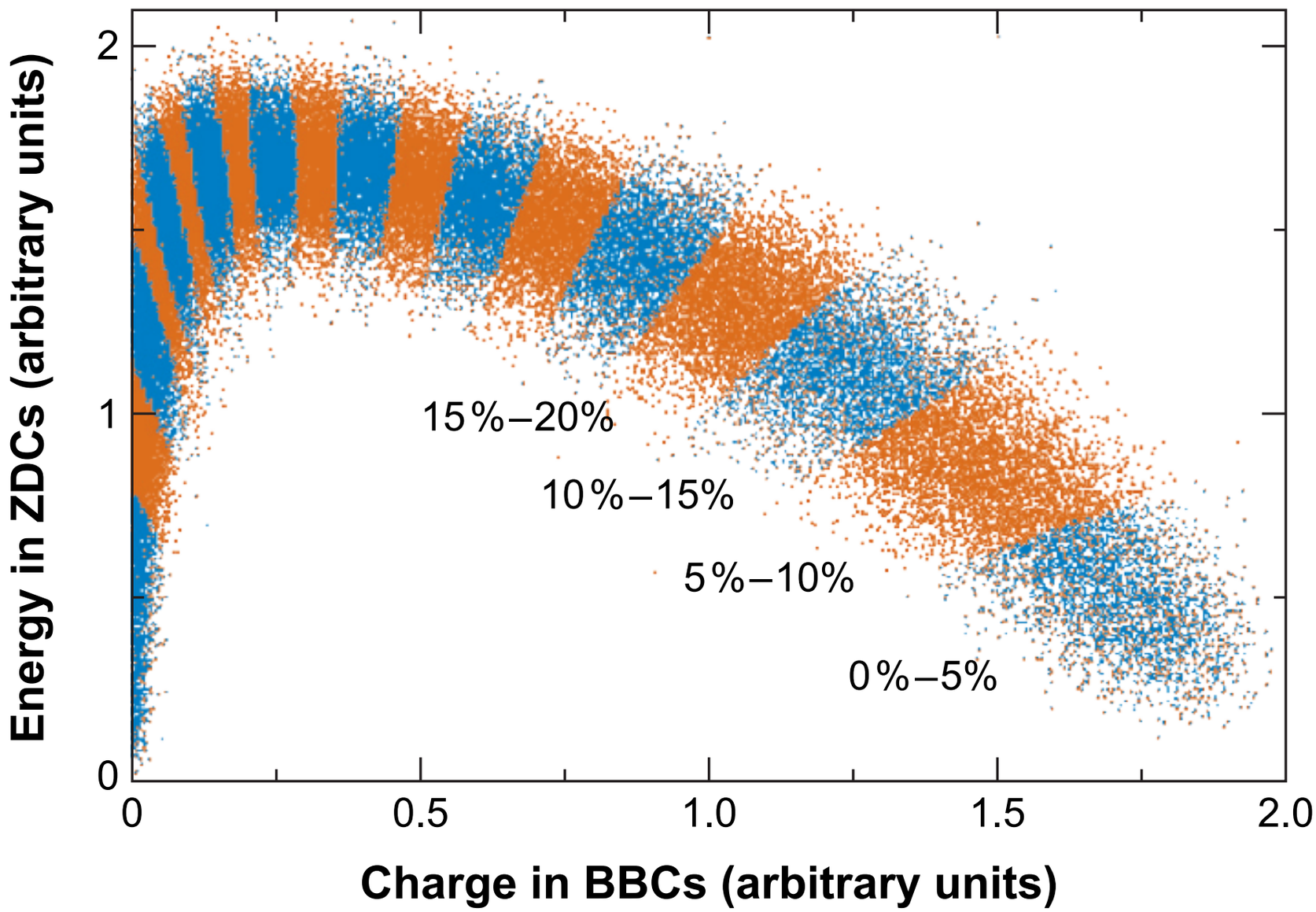
- **Centrality Measurements**
- **Particle Multiplicities**
- **Particle Spectra / Radial Flow**
- **Elliptic Flow**

Centrality



Classical impact parameter between nucleons controls
1) size & shape of overlap region, 2) number of spectators

ZDC vs. BBC



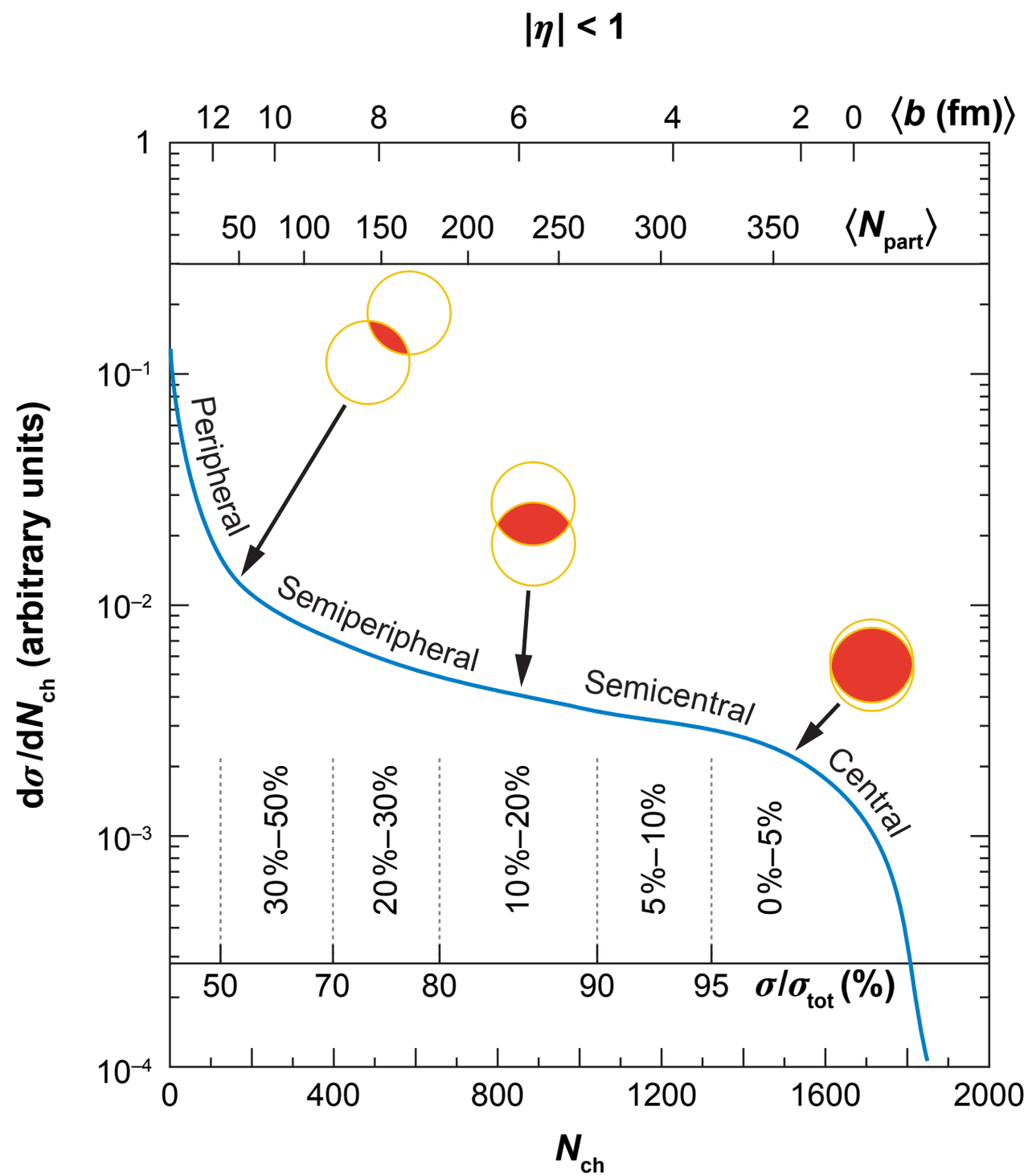
Prove that ZDC and BBC are monotonic in a large region

Centrality Measurements

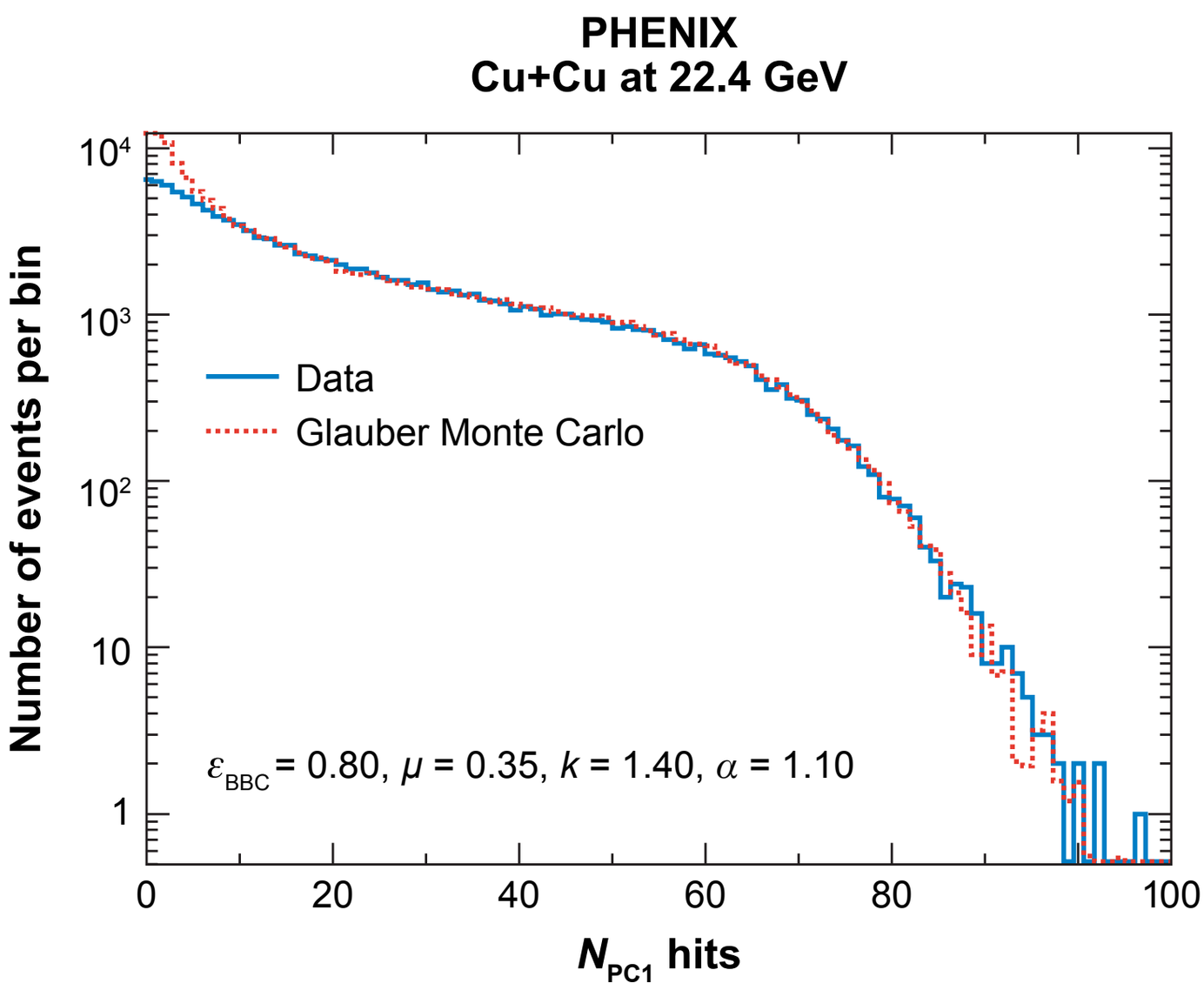
Centrality is generally a “fraction” of the total inelastic cross section

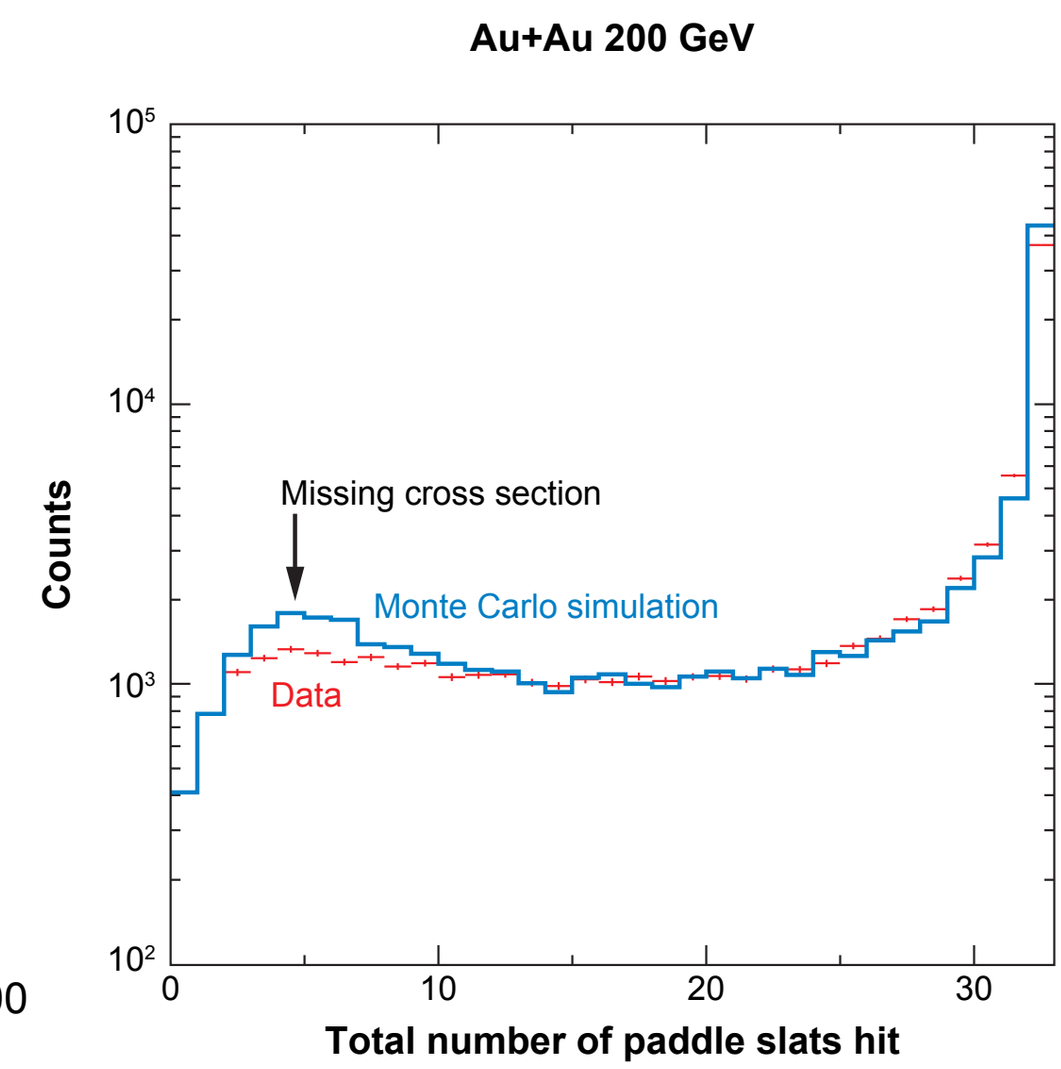
We <u>assume</u> that the events with the top 10% of the N_{ch} distribution are top 10% in b, N_{part}, etc.

Let’s us extract b, N_{part}, etc.



Fraction of Total Cross Section

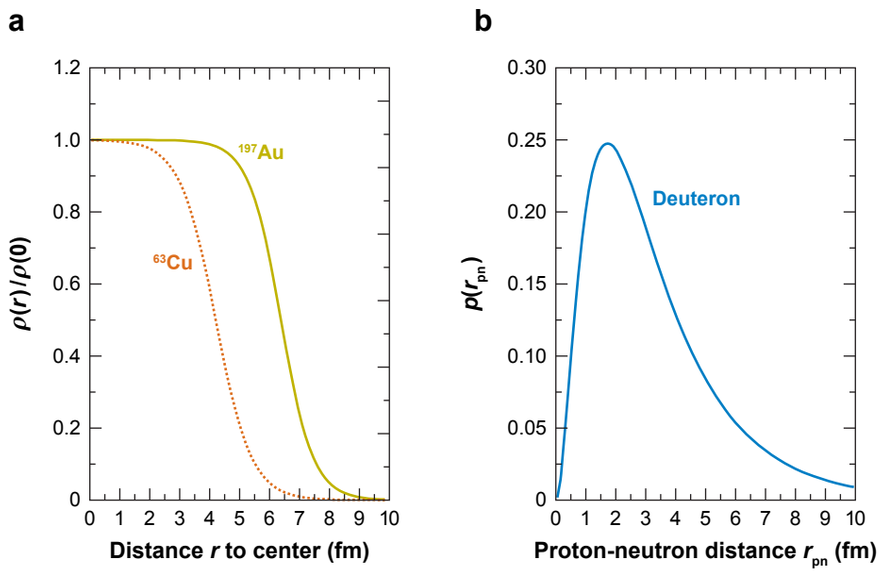




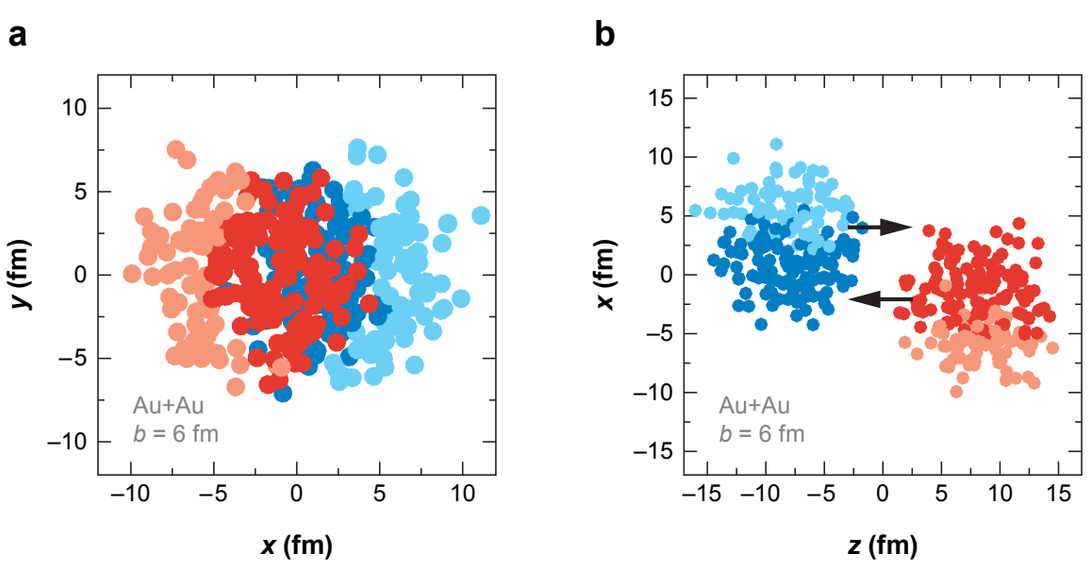
How much of 100% do we have?

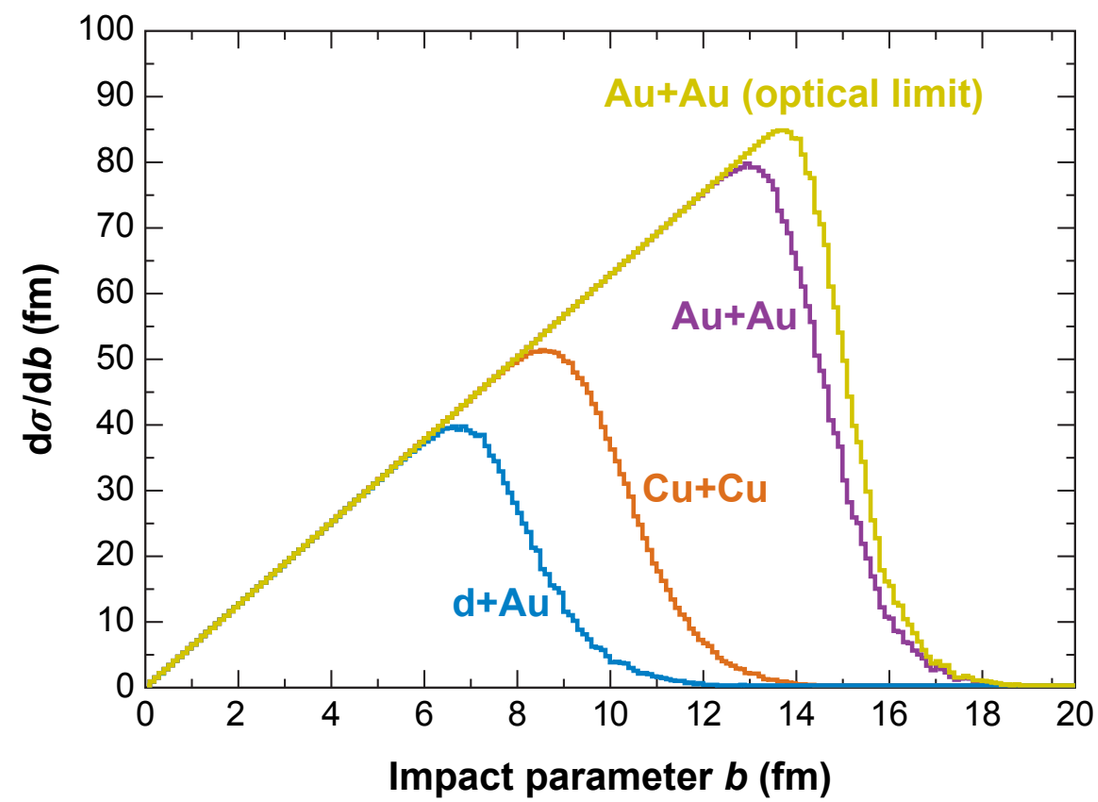
Major contributor to systematic errors!

Optical vs. Monte Carlo Glauber Models



Treat nuclei as smooth densities or nucleon configurations?

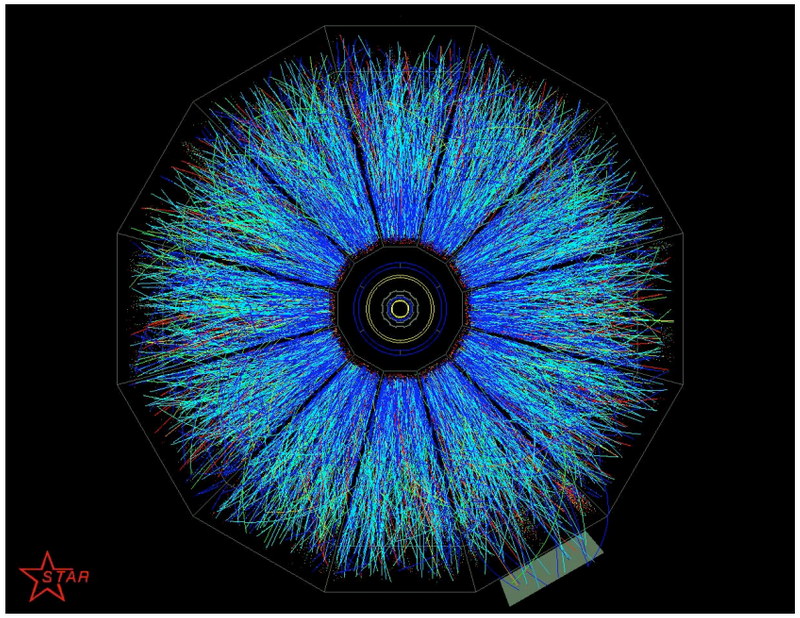




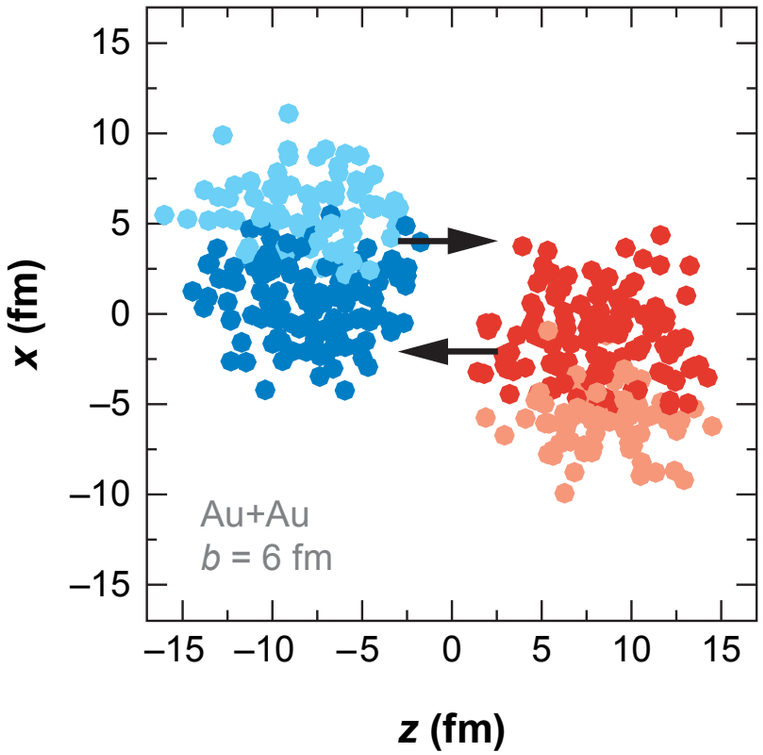
A non-trivial effect on knowledge of total cross section!

Multiplicity per “Participant Pair”

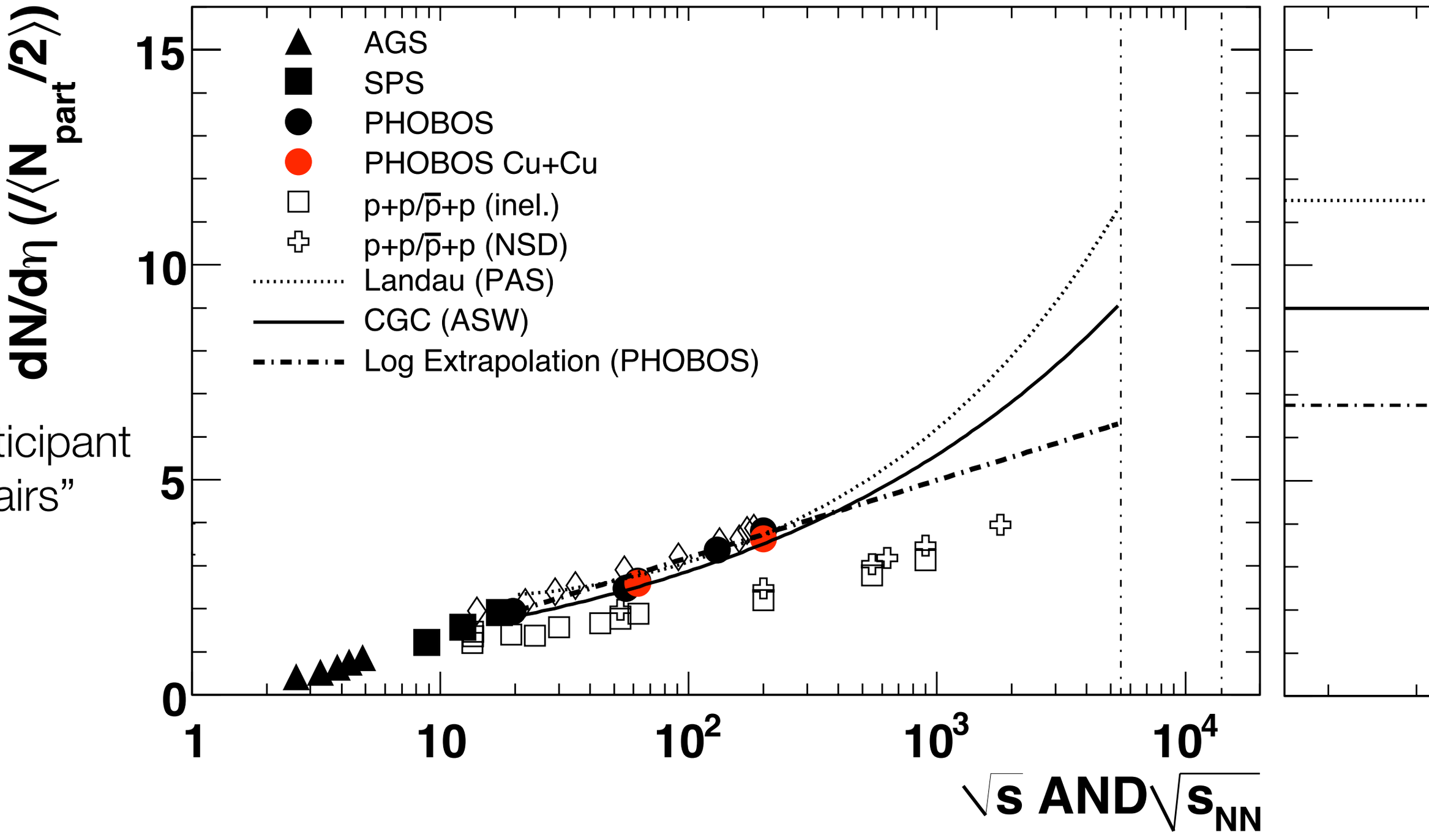
Particle Multiplicity



Number of Participants

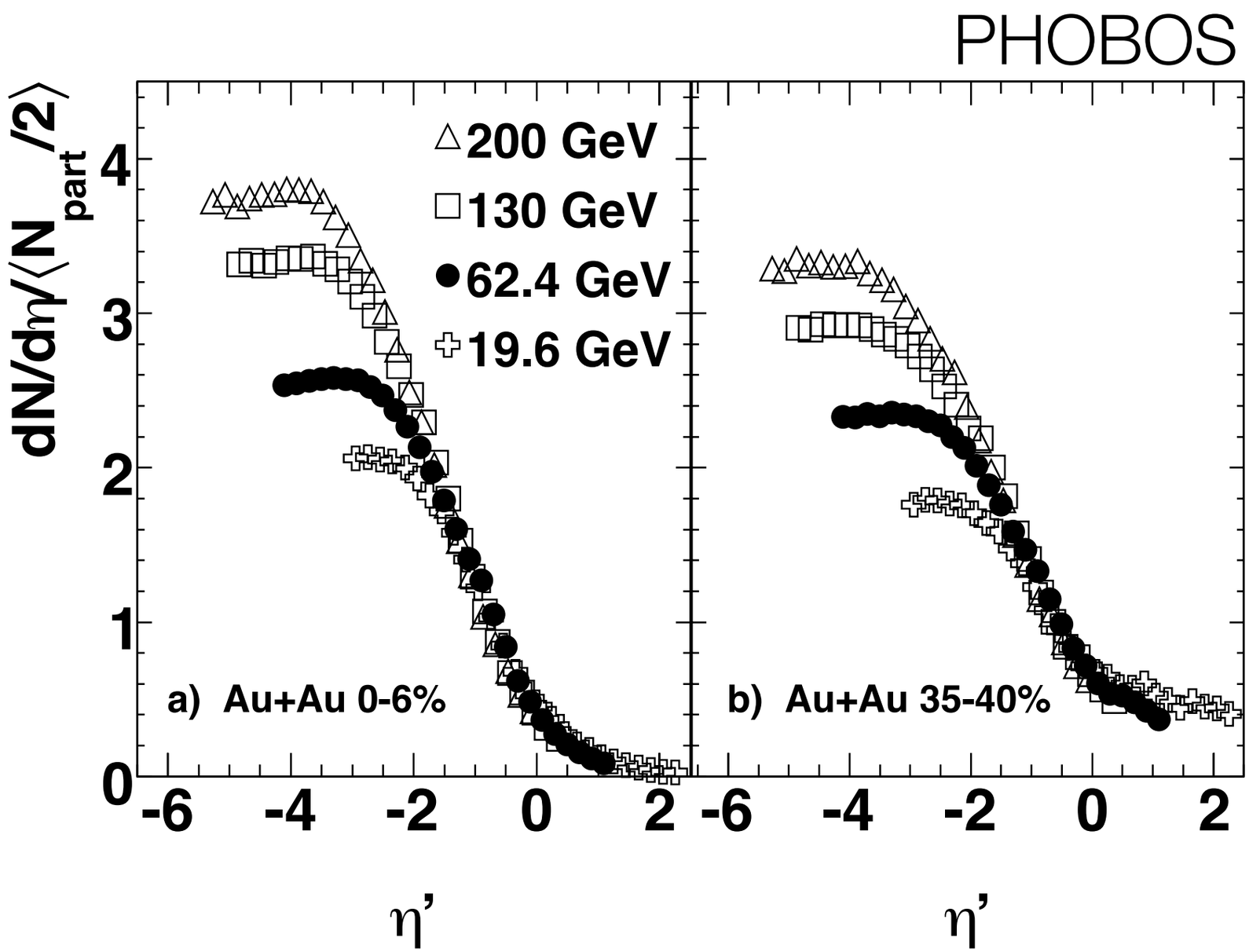


Energy Dependence of Multiplicity



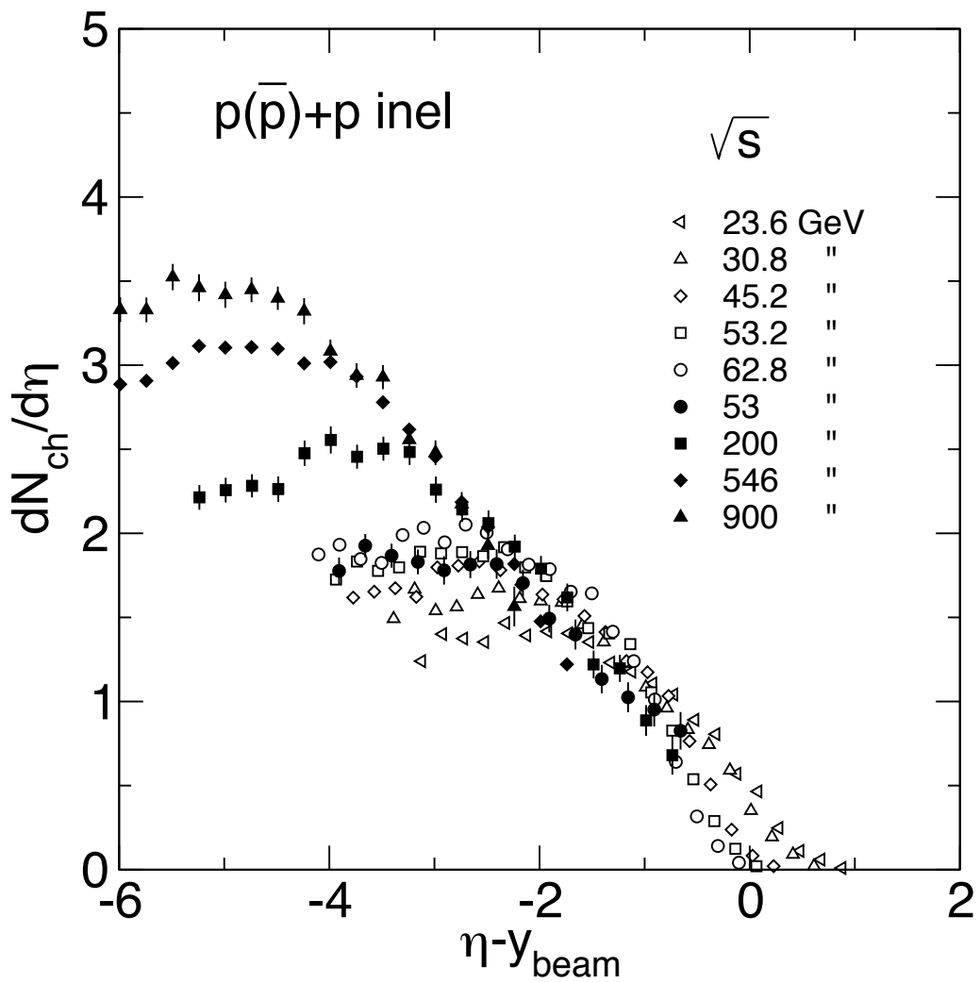
"Participant pairs"

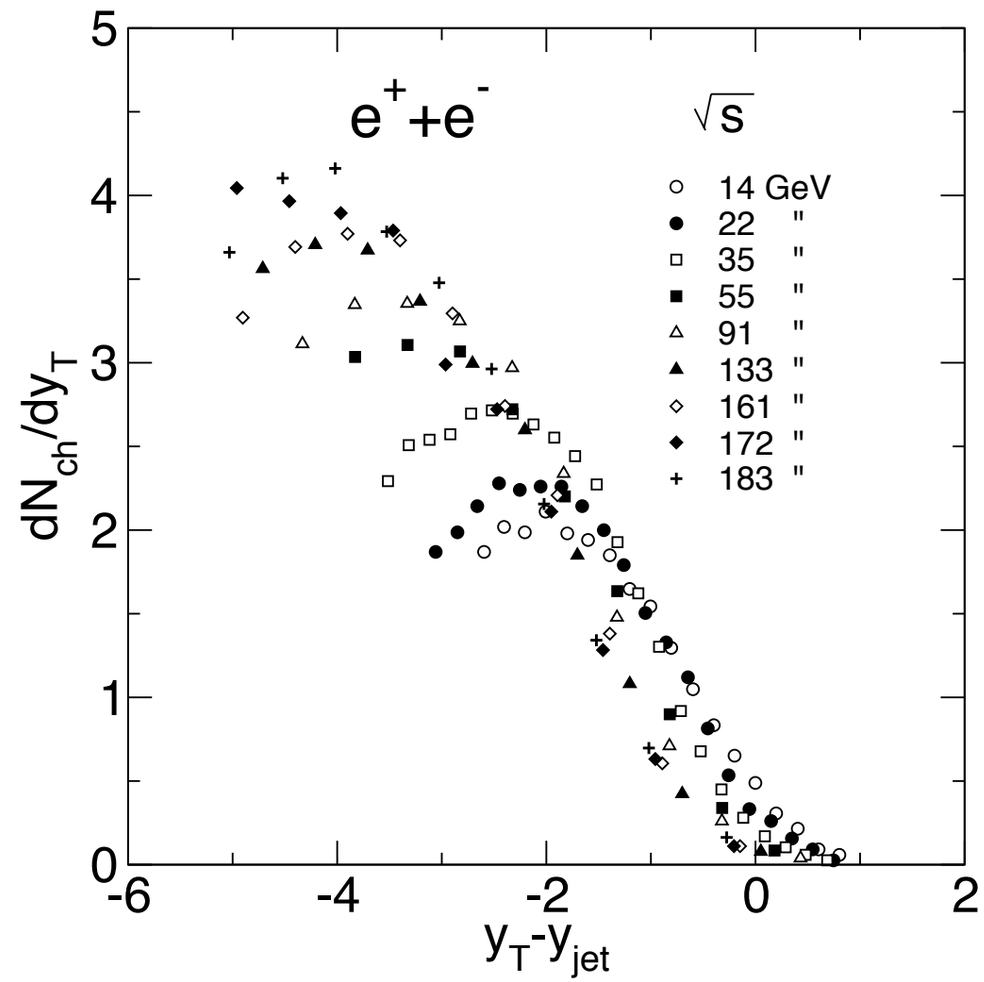
“Extended Longitudinal Scaling”



Invariance of yields viewed from rest frame of one projectile

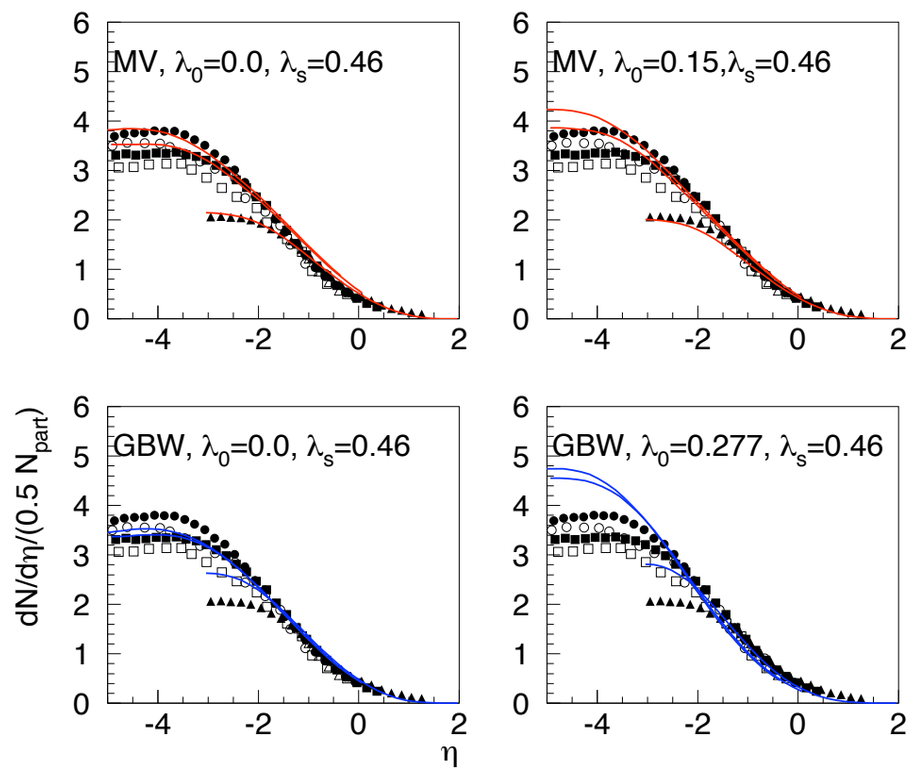
“Extended Longitudinal Scaling”



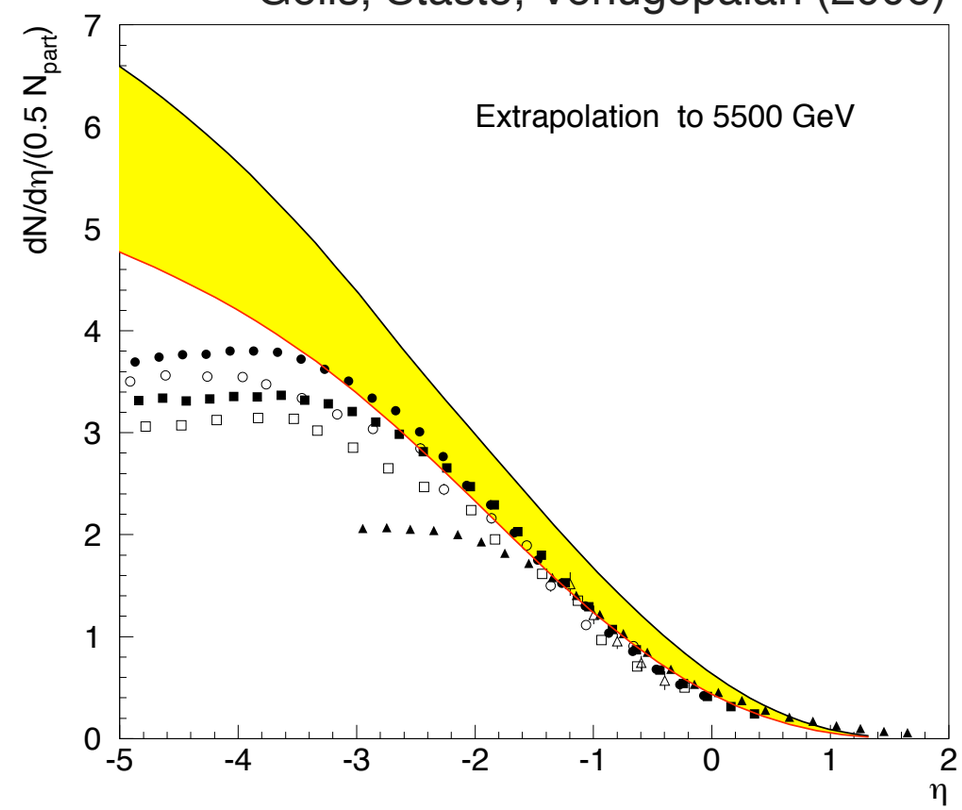


Scaling also observed in elementary collision processes (hasn’t broken yet in p+p!)

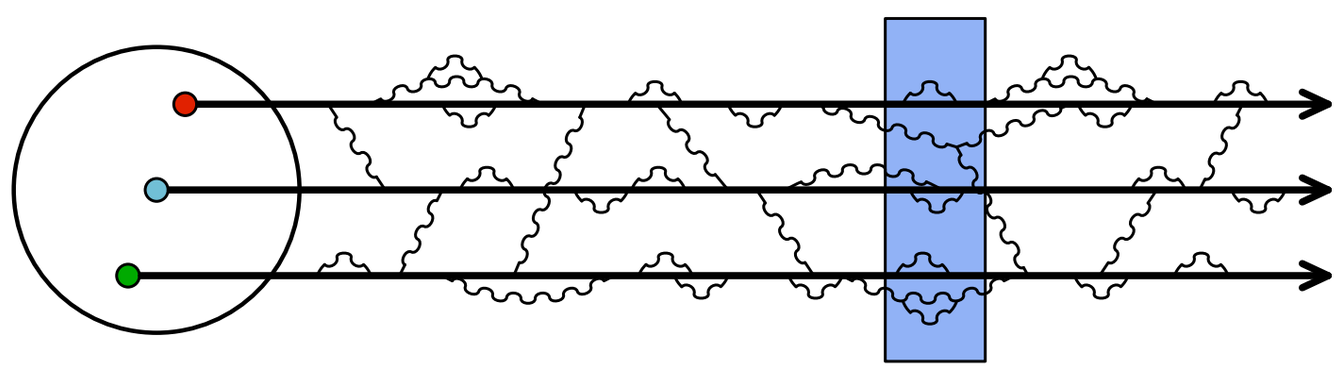
Color Glass Condensate



Gelis, Stasto, Venugopalan (2006)



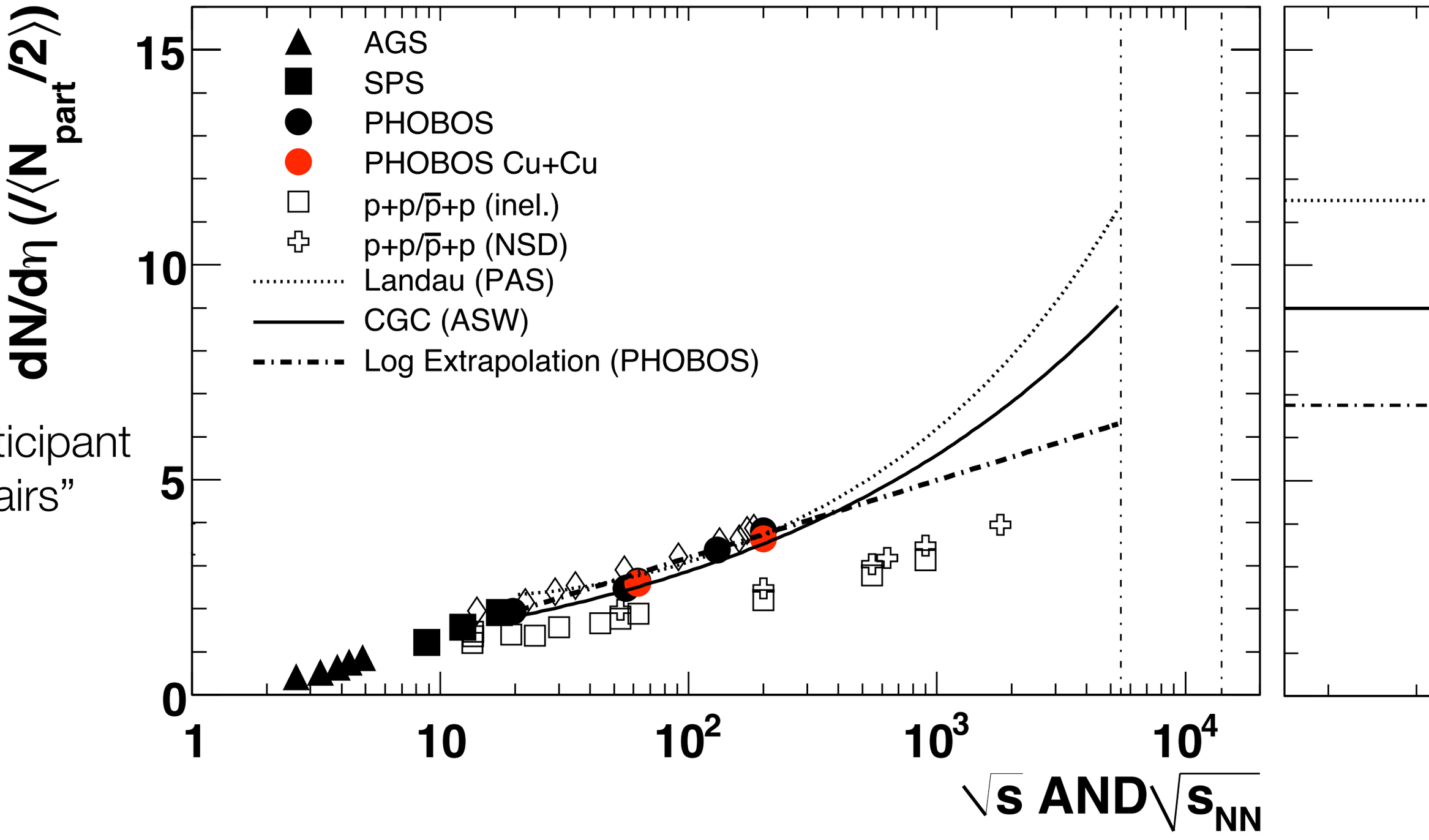
Gelis QM2006



Nucleon and nuclear wave function in an essential feature of initial state → physics @ RHIC II (y), EIC, LHC

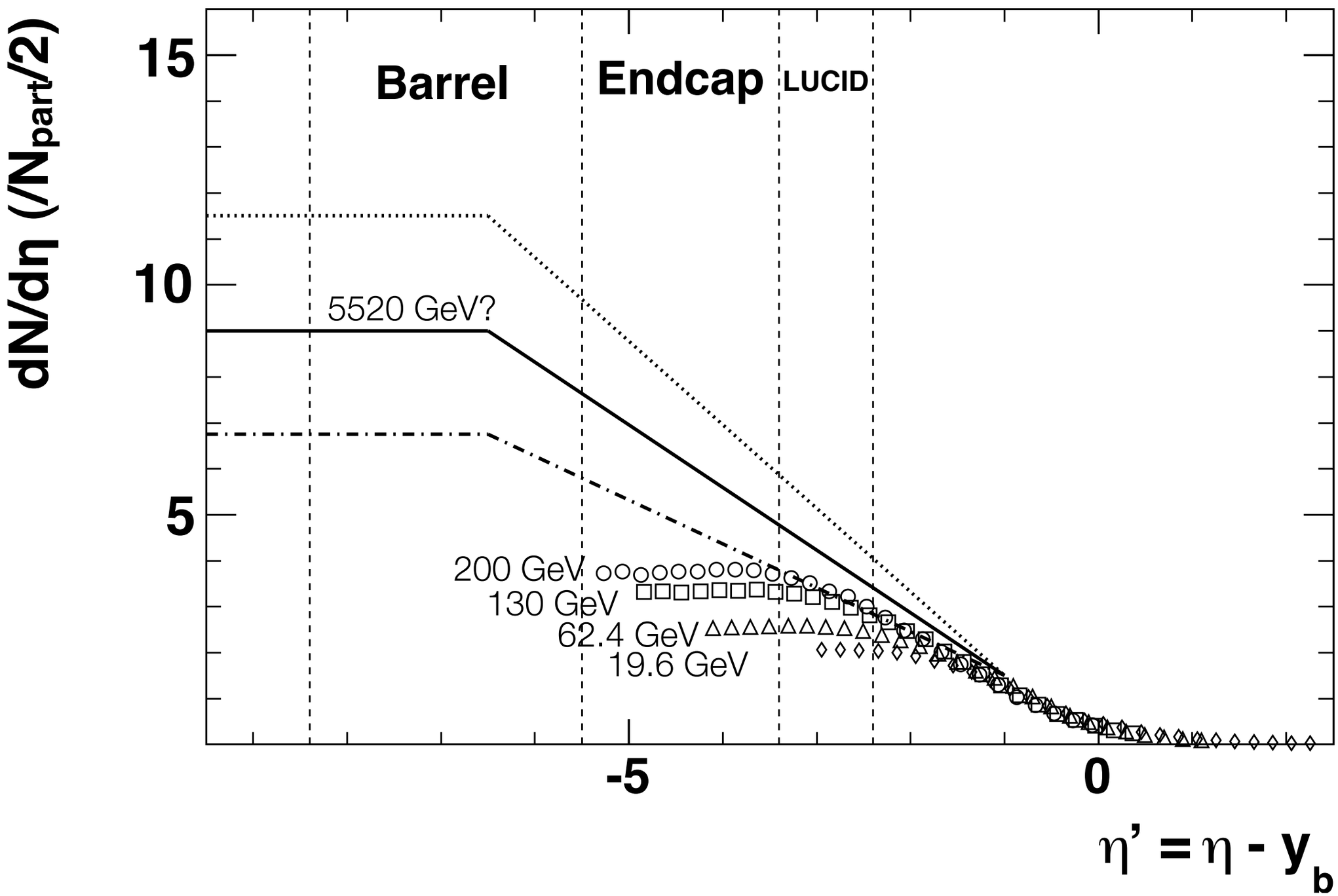
Is there a deep connection w/ hydro?

Energy Dependence of Multiplicity

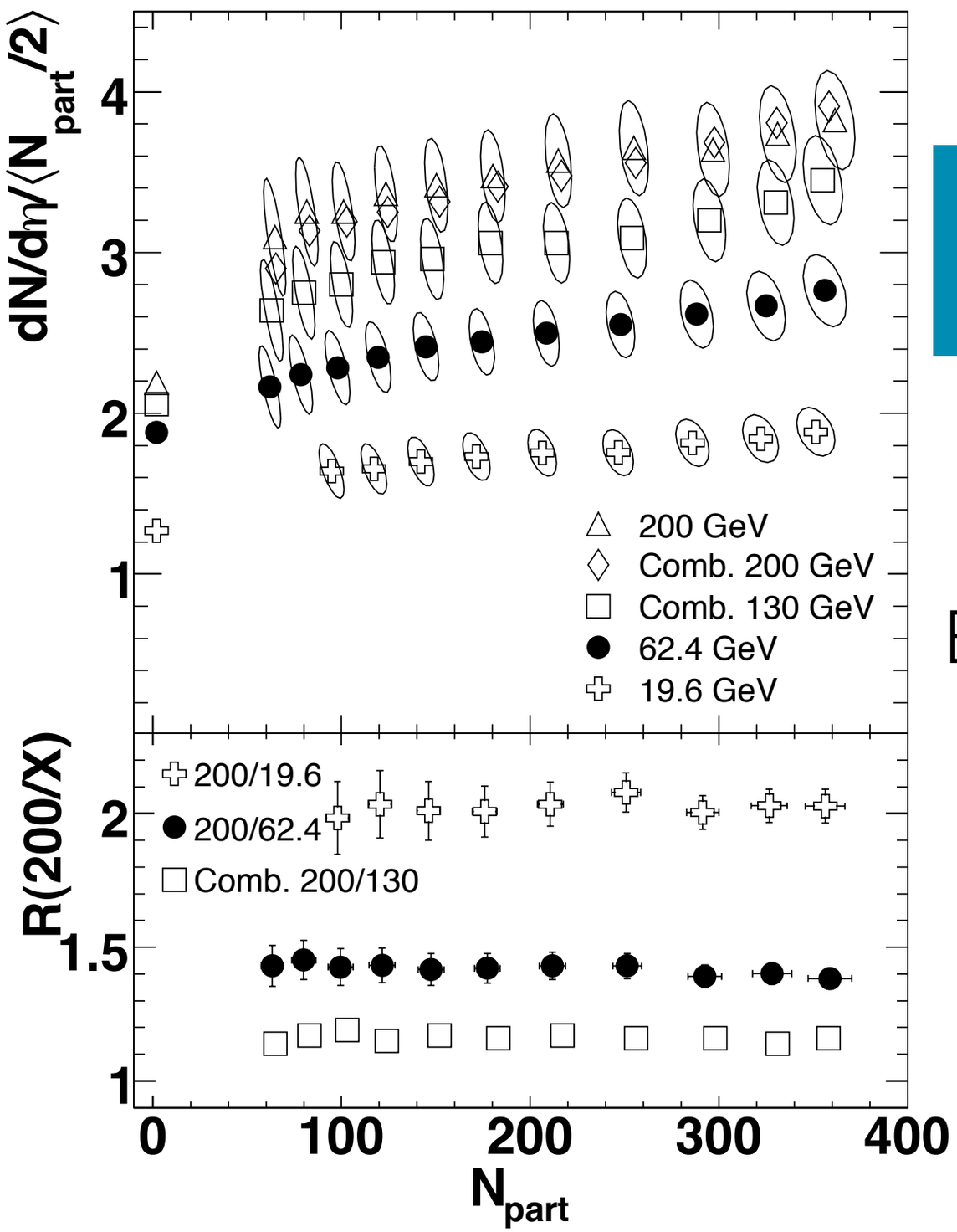


"Participant pairs"

Extended Longitudinal Scaling



Centrality Dependence?



Two component model?

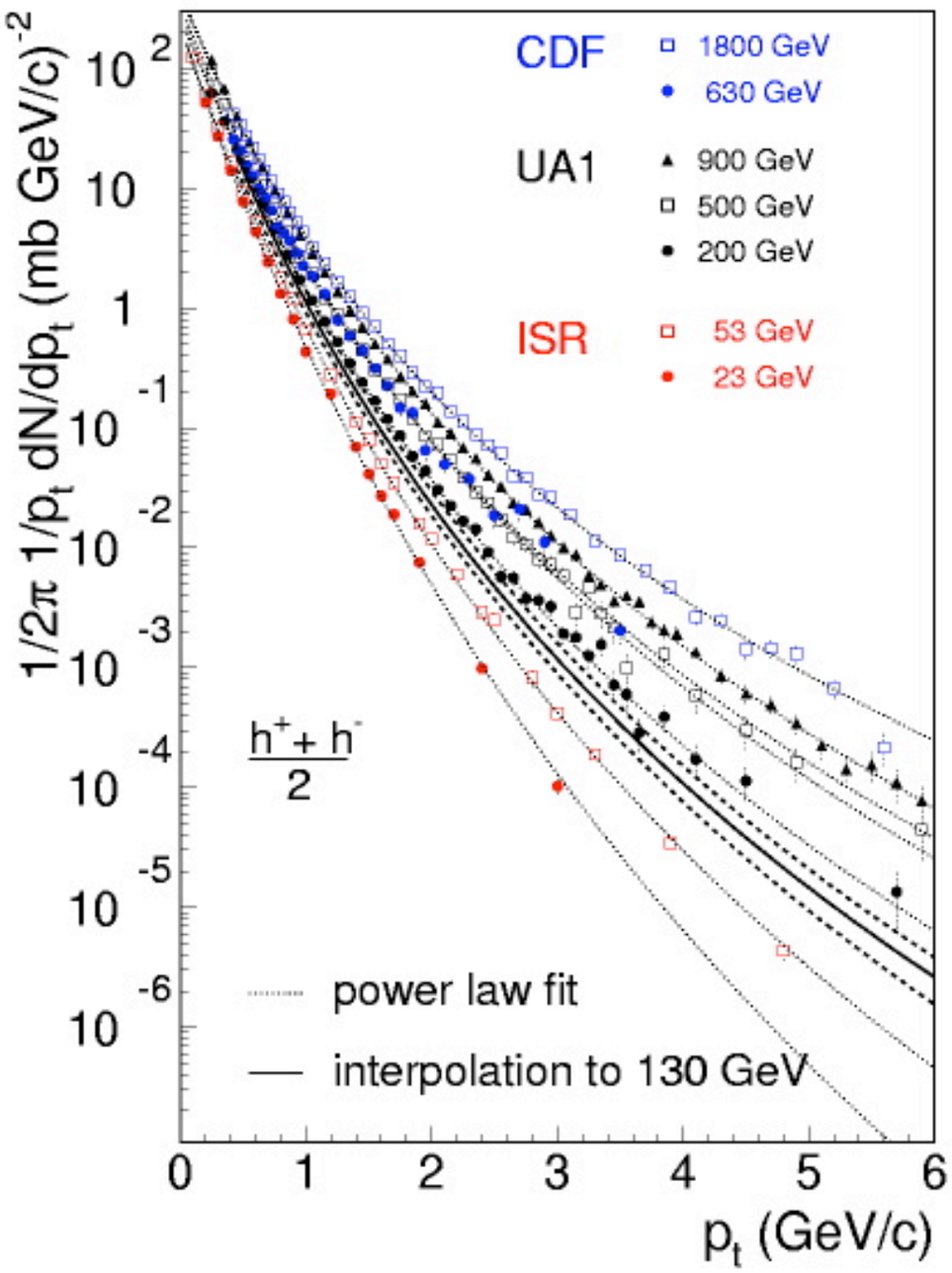
$$\frac{dN}{d\eta} = n_{pp}\left\{(1-x)\frac{N_{part}}{2} + xN_{coll}\right\}$$

Divide each set by 200 GeV data

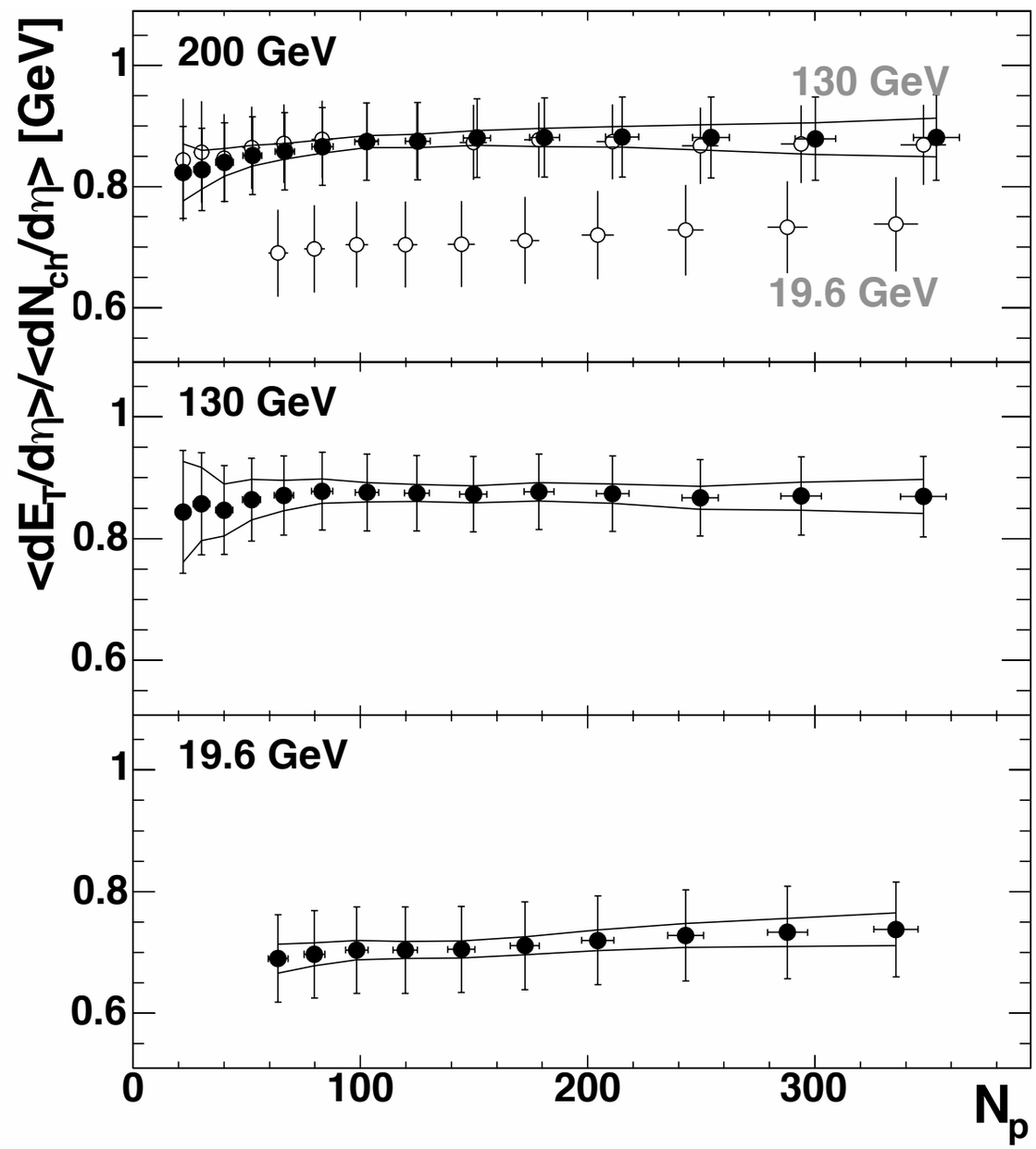
Energy and centrality dependence "factorize"

No additional multiplicity increase with higher energies, thus more "minijets"

The Question of Minijets



Spectra in p+p



Transverse energy per particle constant!

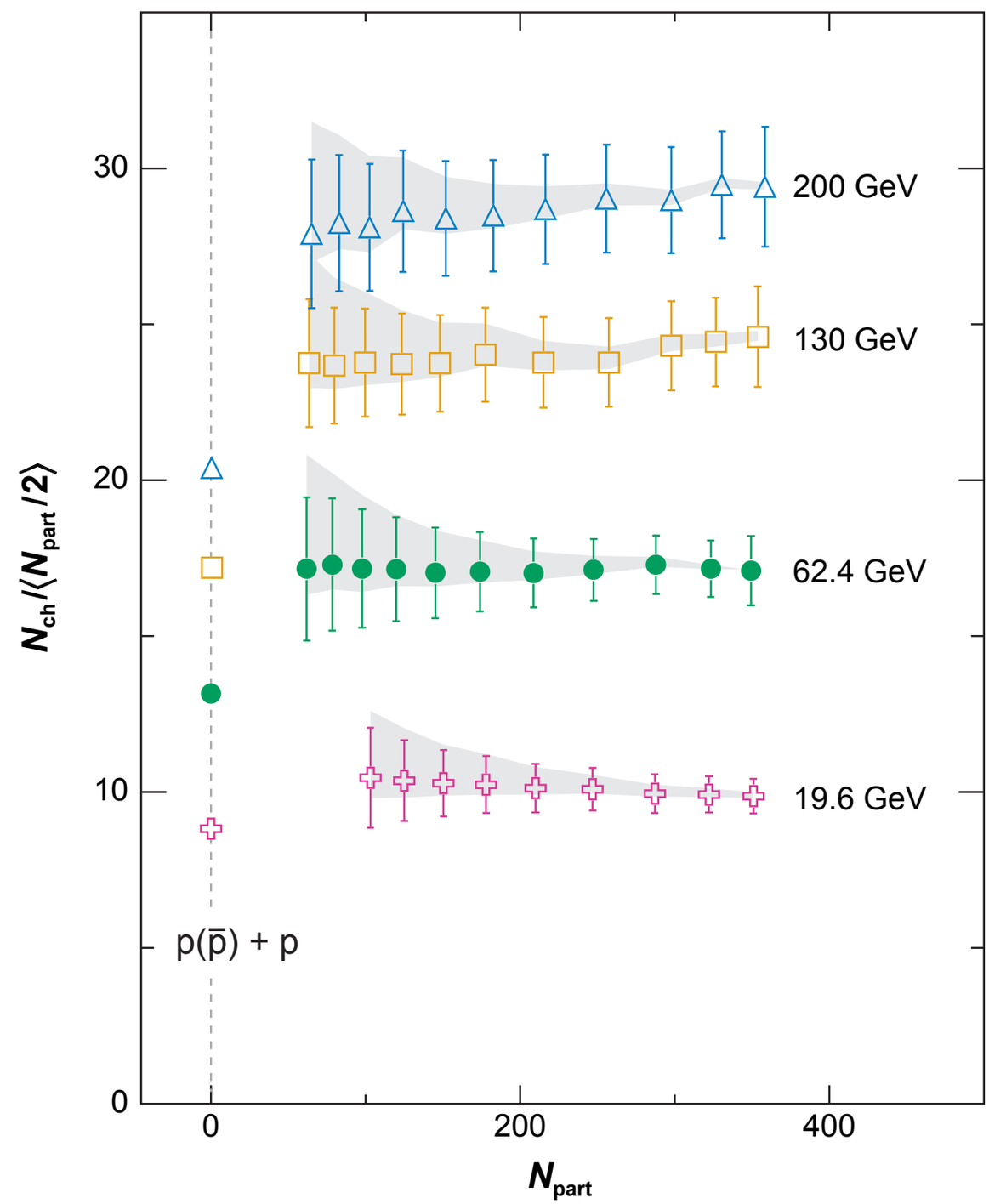
Total Multiplicity

When we integrate over all pseudorapidity find very simple result:

$$N_{ch} \propto N_{part}$$

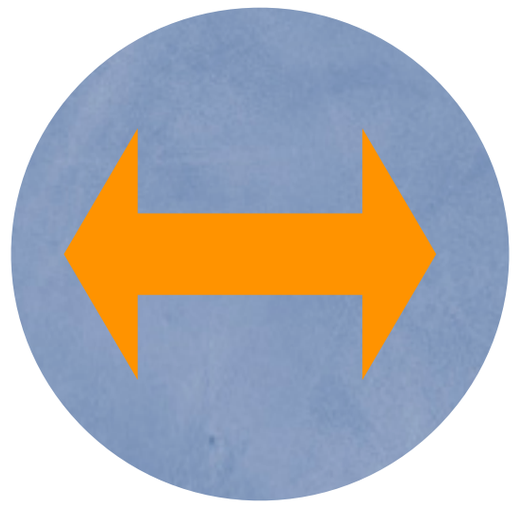
"one" component model

suggests a simple statistical scenario (N scales with V) not naturally predicted from QCD



Hydrodynamics

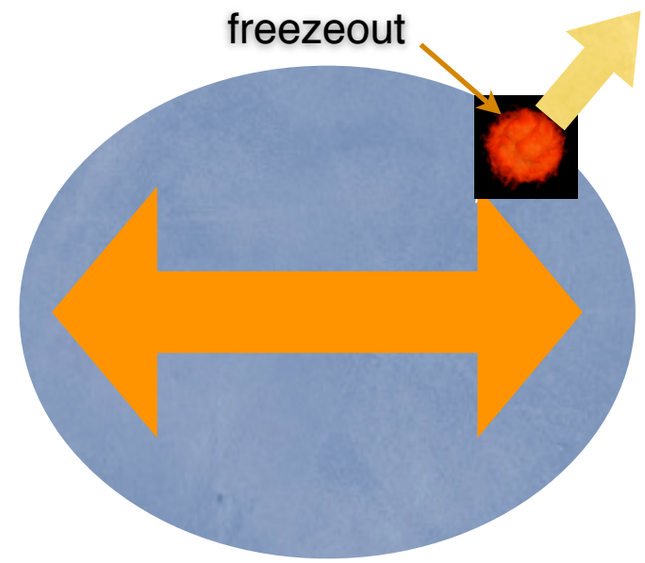
Energy **locally** equilibrated in a volume, adjacent cells are in causal contact



Pressure gradients develop via **ideal** (inviscid) **scale-invariant** expansion into vacuum

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

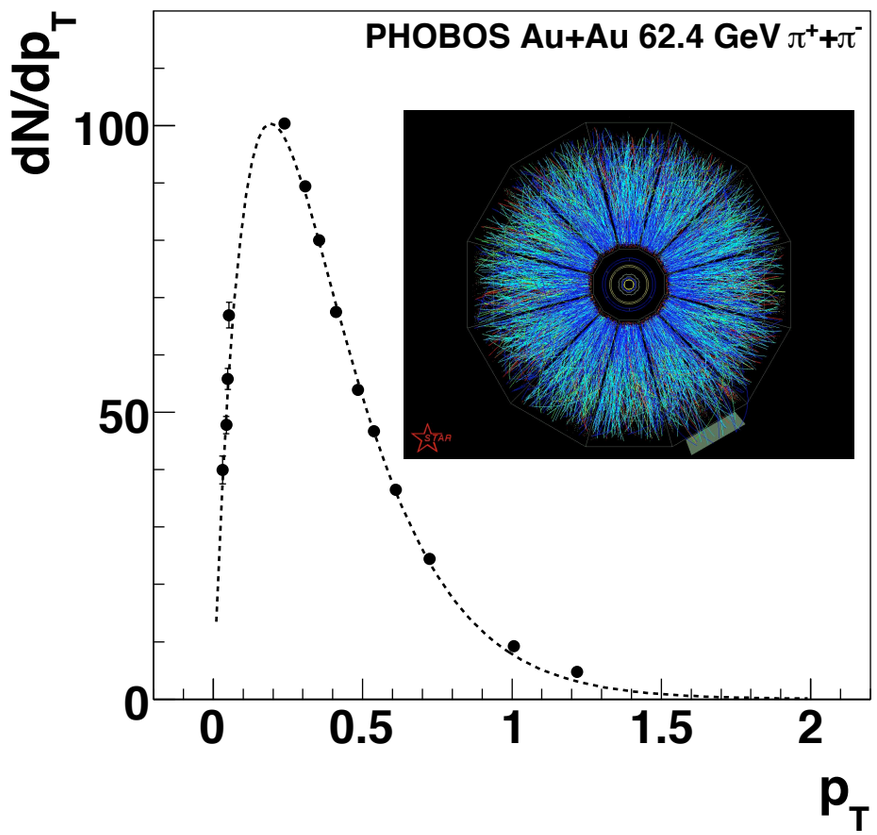
$$c_s^2 = dp/d\epsilon$$

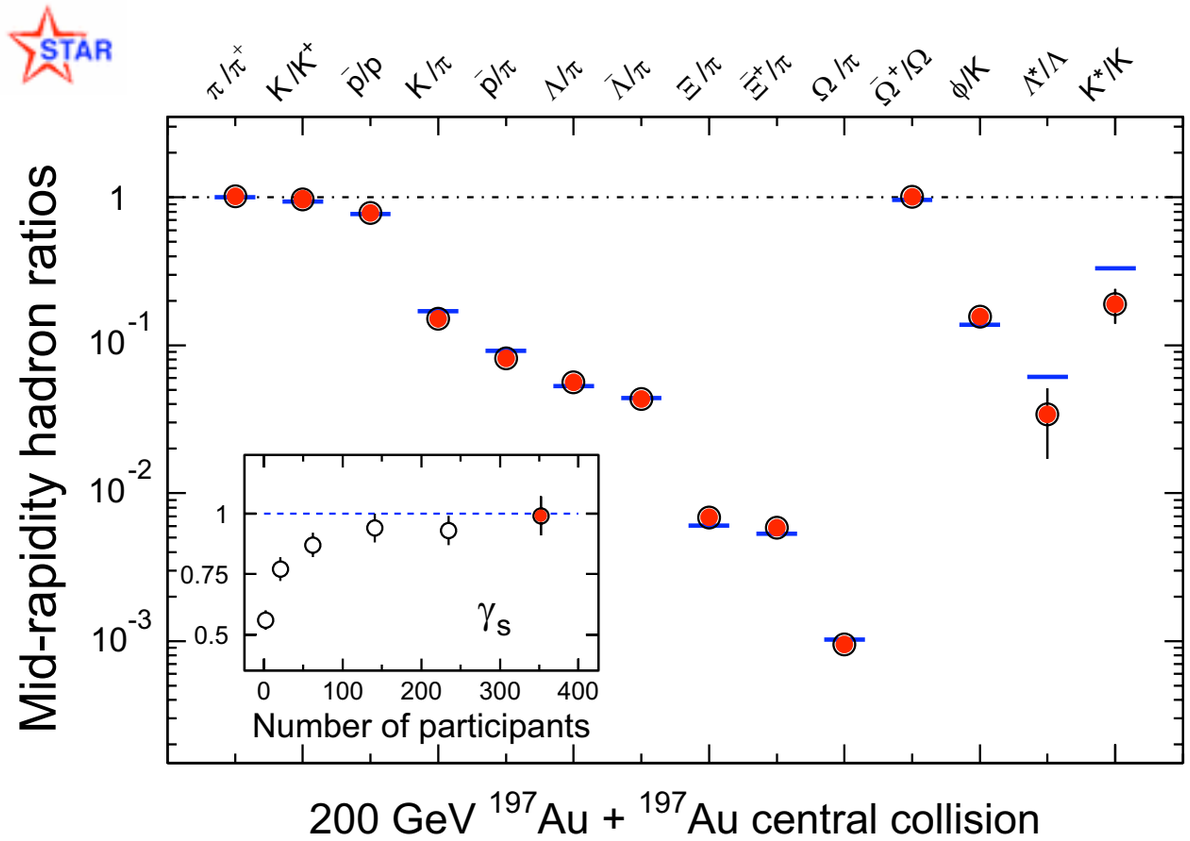


Fluid elements freezeout isotropically in local rest frame into hadron states when

$T < T_{ch}$

Thermal “Blackbody” Rates





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

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

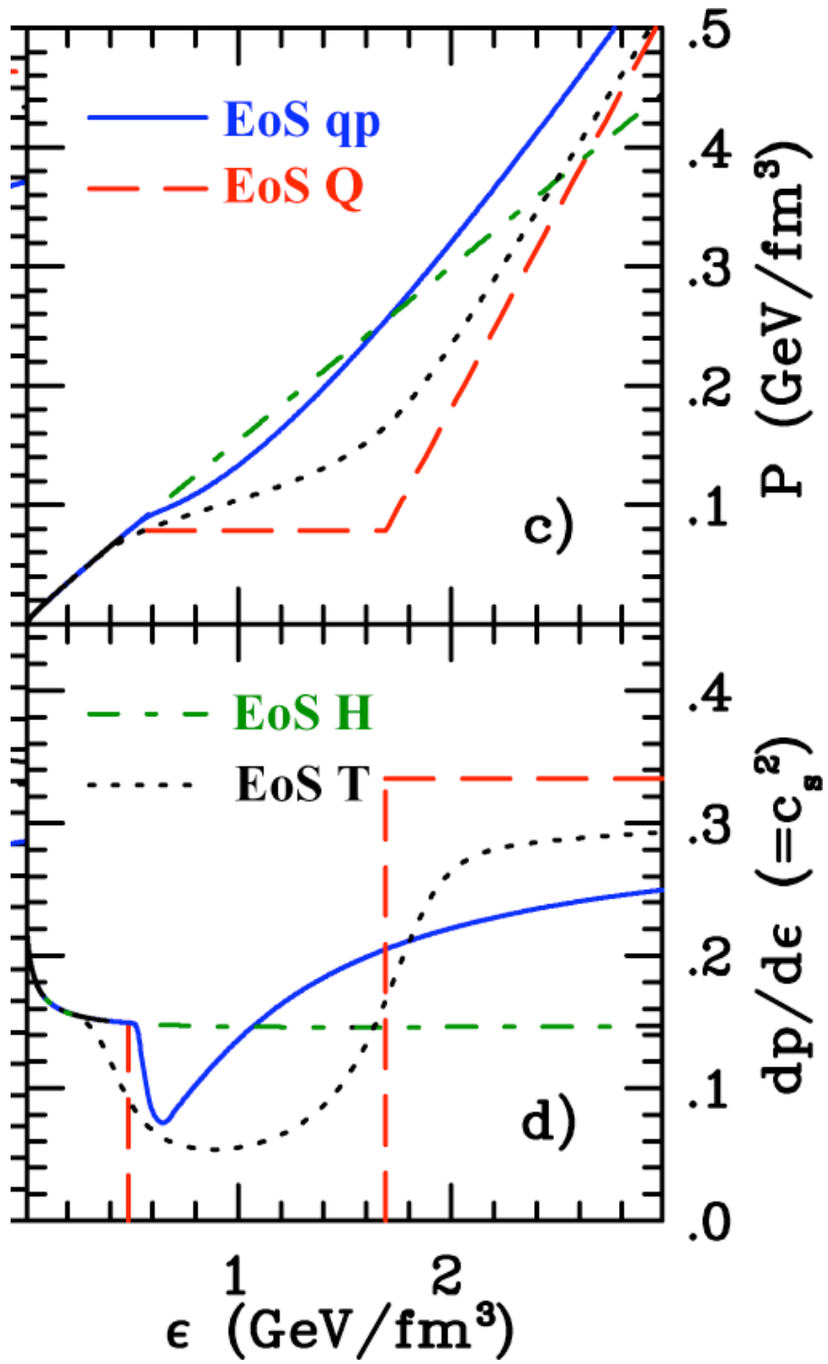
$k_B T$=177 MeV~2x10^{12} ^{o}K

All hadrons are available with thermal abundances @ freezeout

Equation(s) of State

Nucl.Phys.A761:296-312,2005

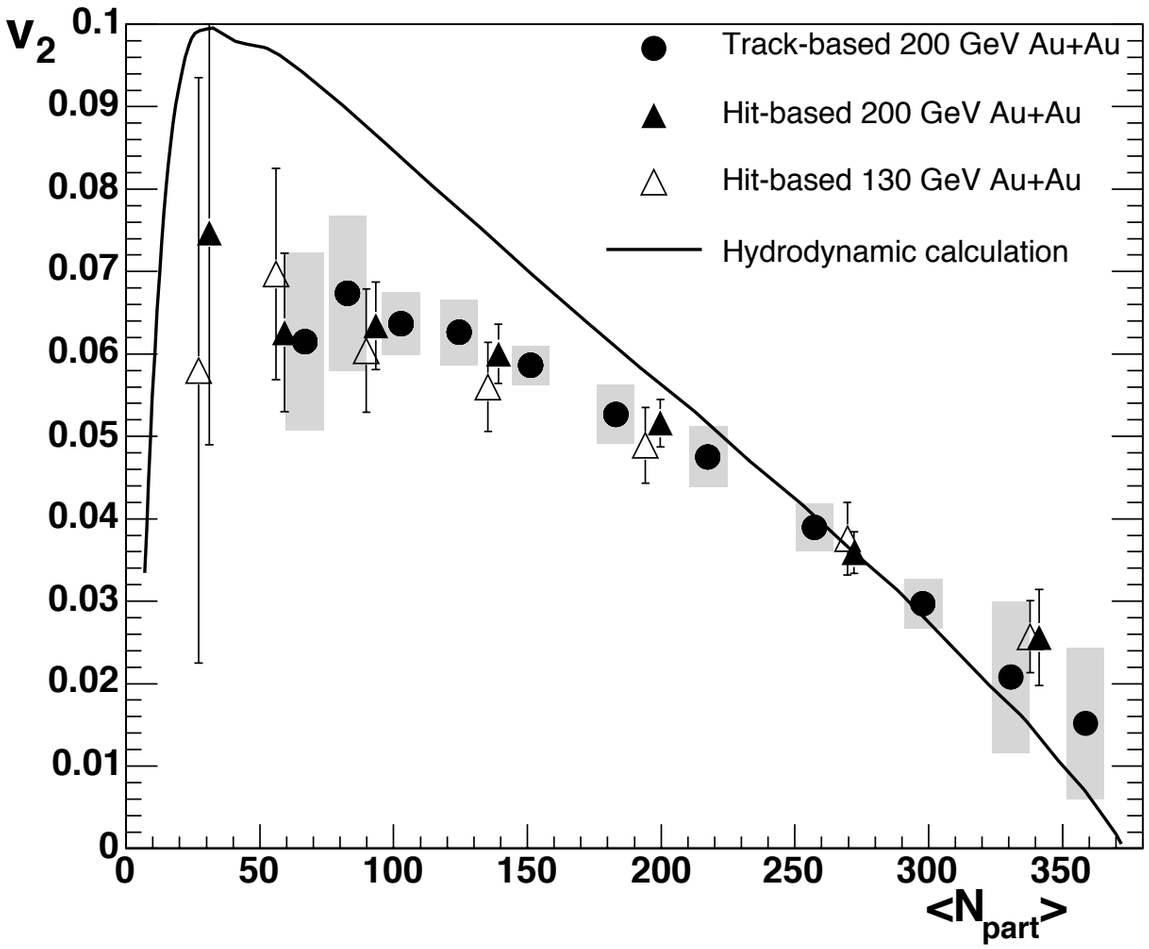
Lattice
1st order PT
Crossover
Hadronic

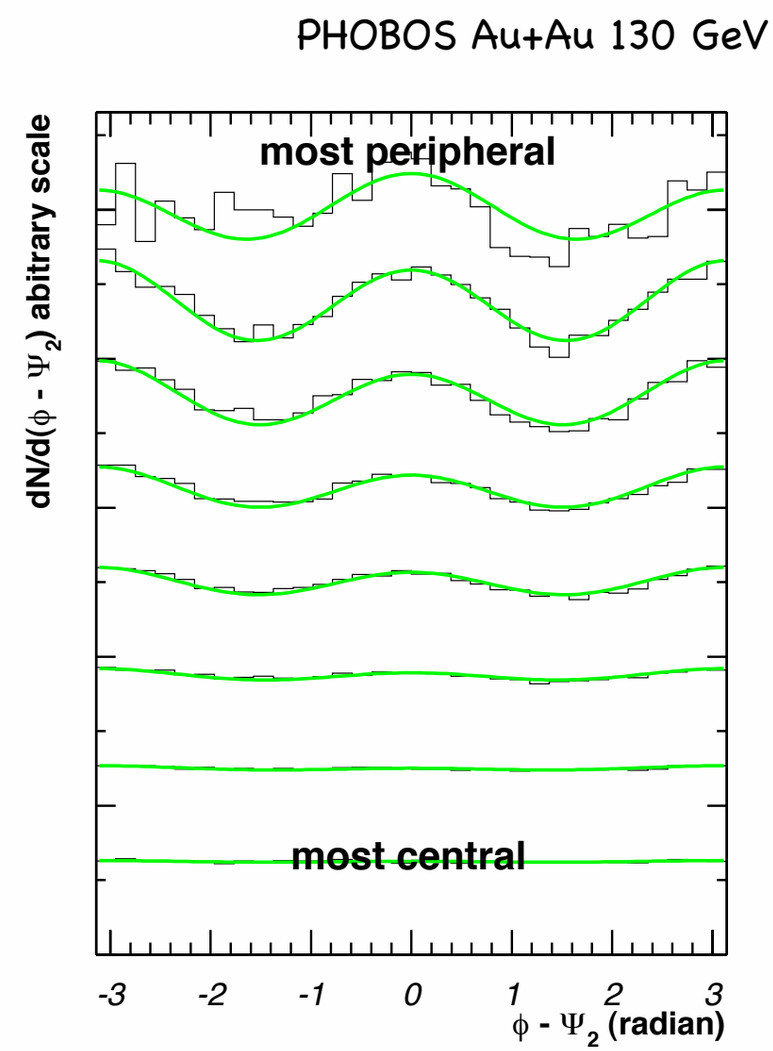


Equation of state gives some information on microscopic degrees of freedom

Shows how speed of sound varies with energy density

Hydrodynamics in RHIC Data





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

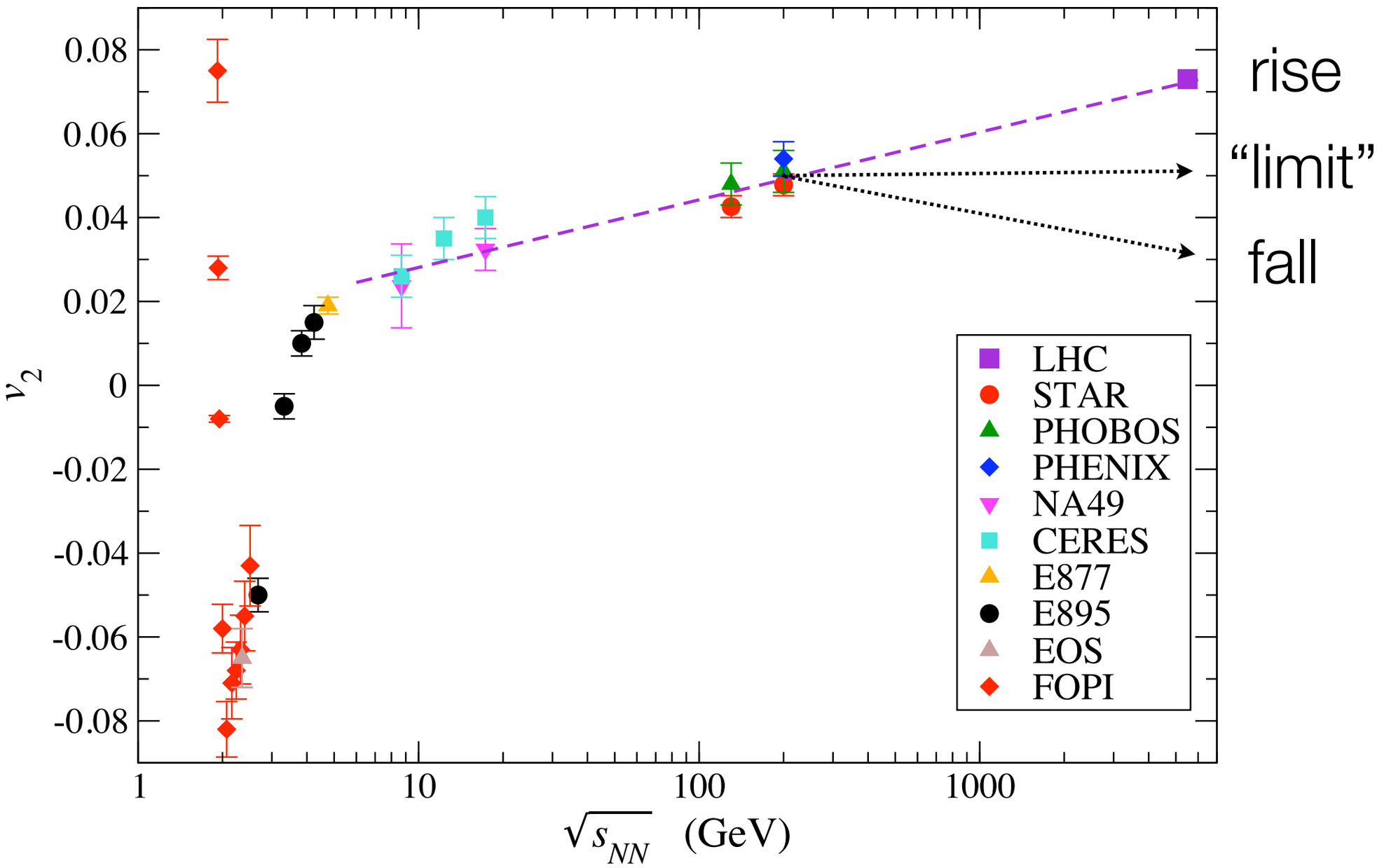
Hydro scales

ε_0~30 GeV/fm^3 τ_0<0.6 fm^3

ε_0~0.5 GeV/fm^3 τ_0~1 fm^3

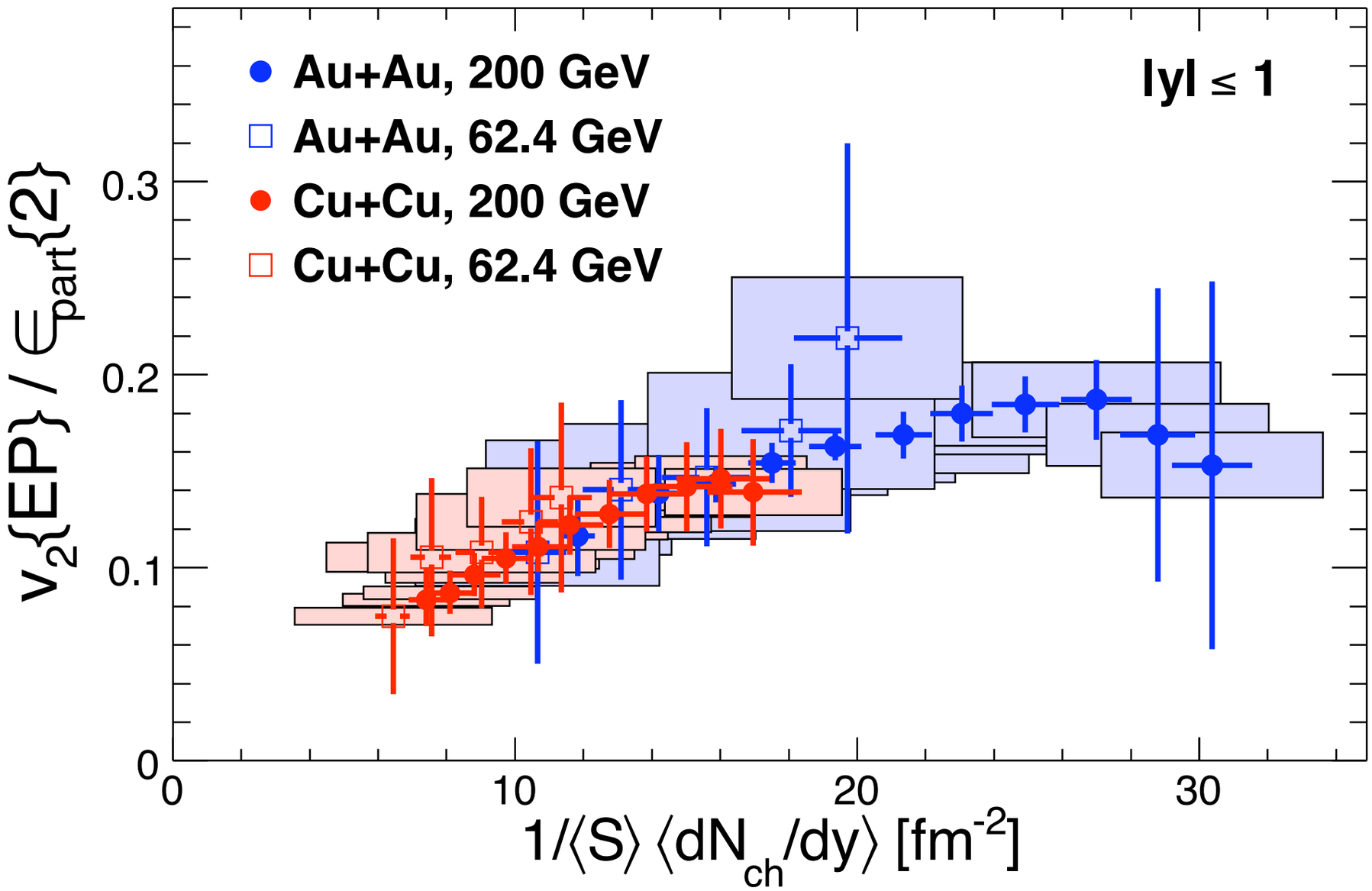
Hadronic scales

Energy Dependence of Elliptic Flow



Controversy about fate of v_2 at the LHC

Scaling with “Area Density”

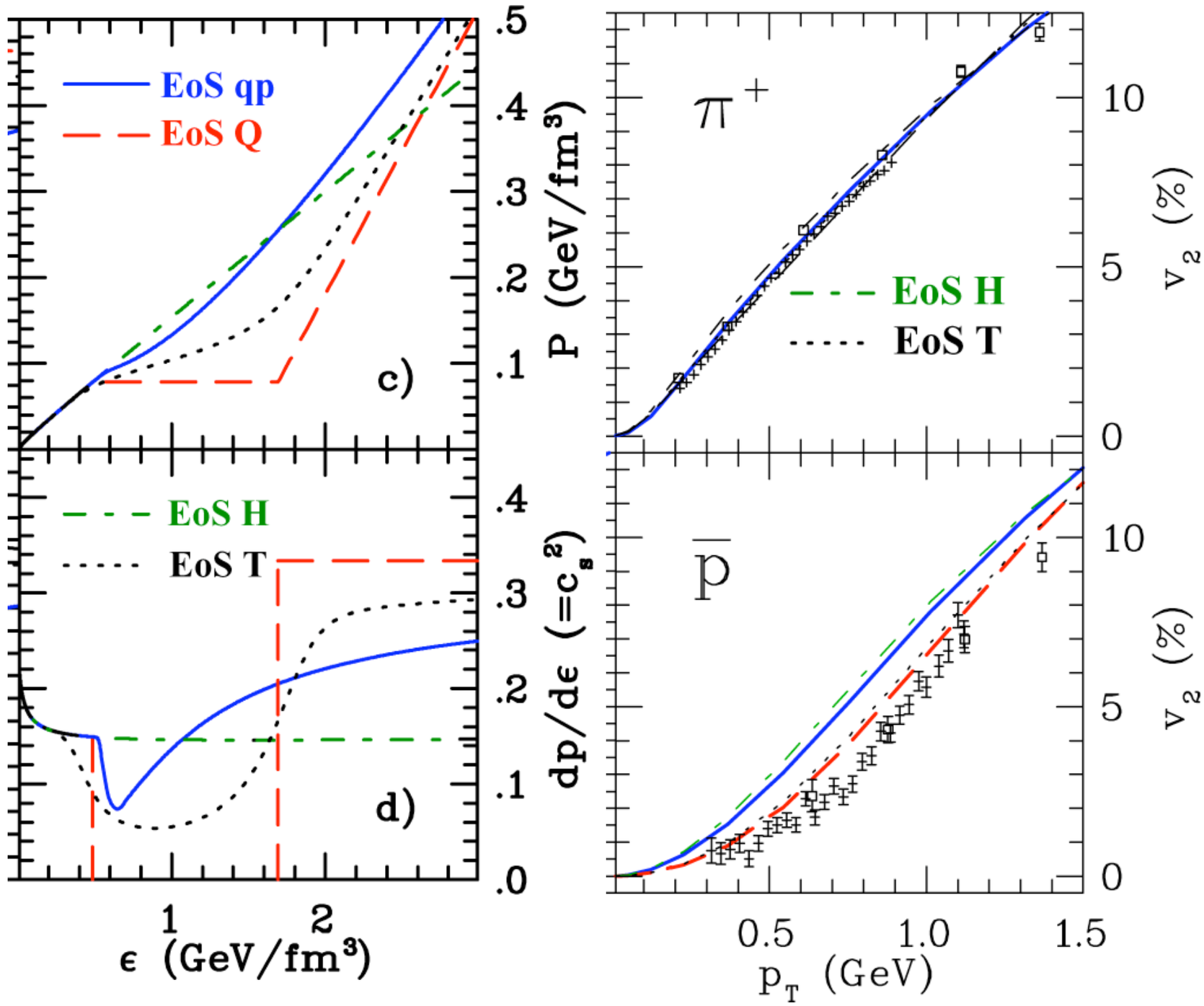


(particle density / overlap area)

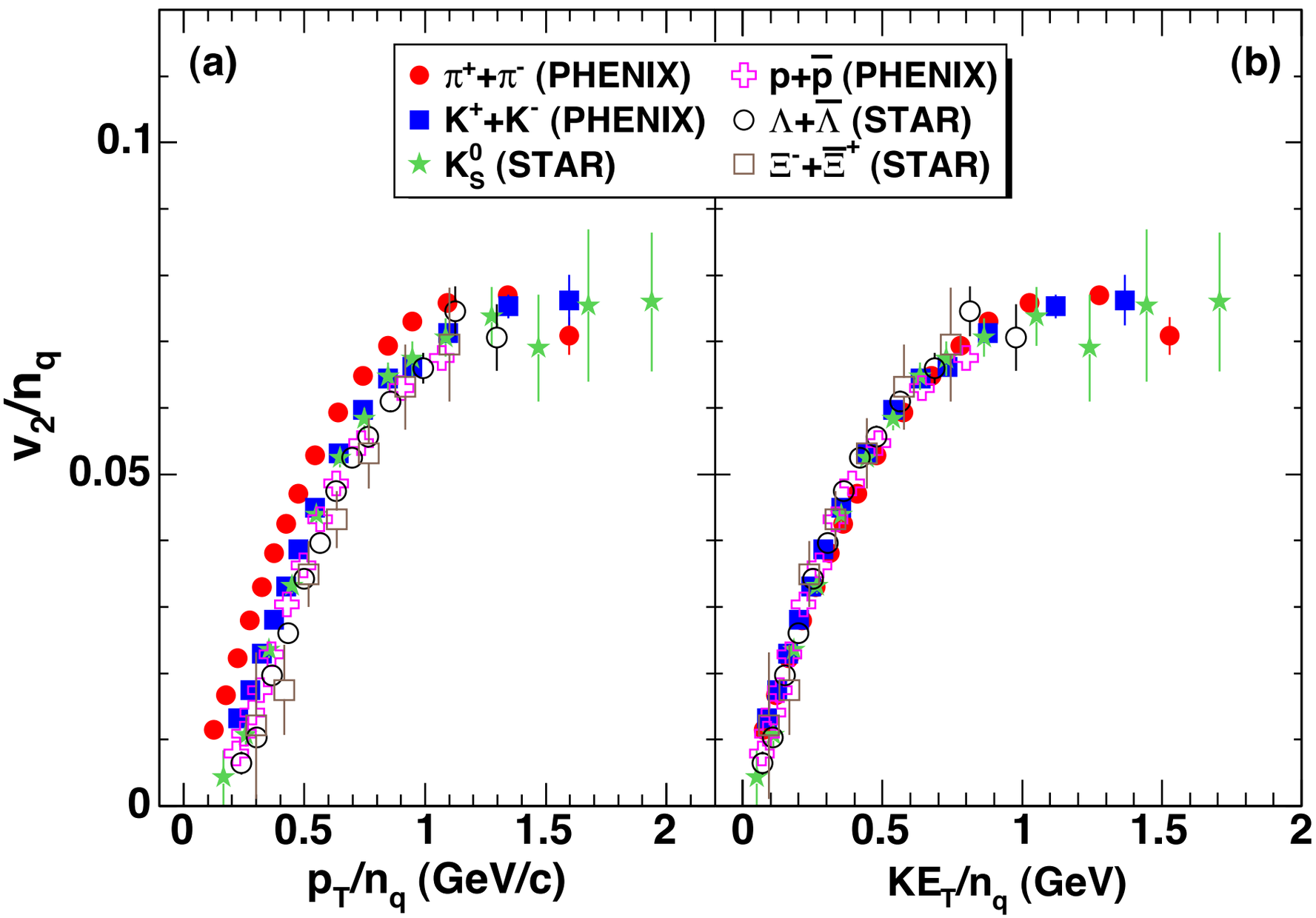
Degrees of Freedom (Equation of State)

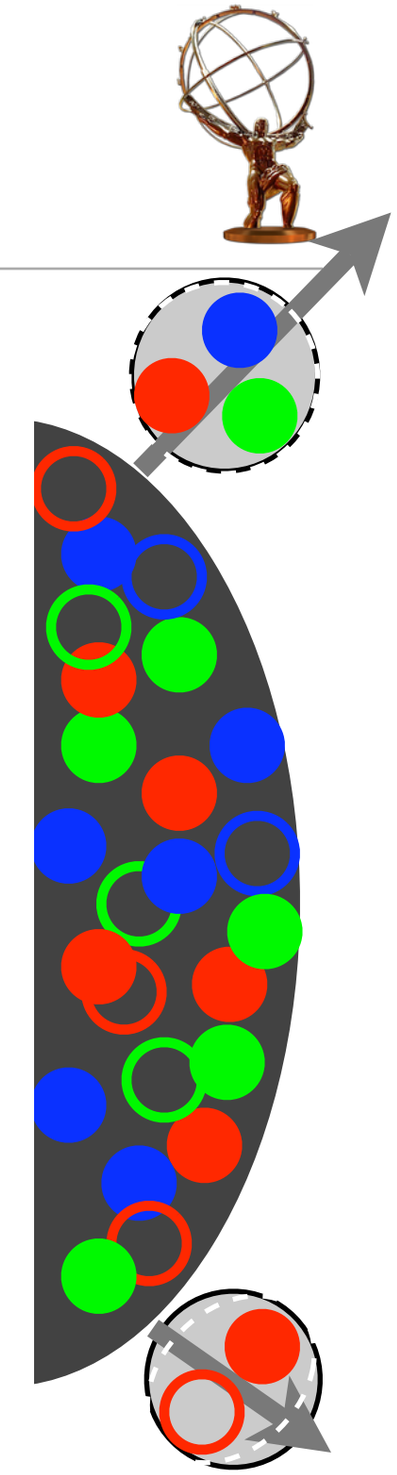
Nucl.Phys.A761:296-312,2005

Lattice
1st order PT
Crossover
Hadronic



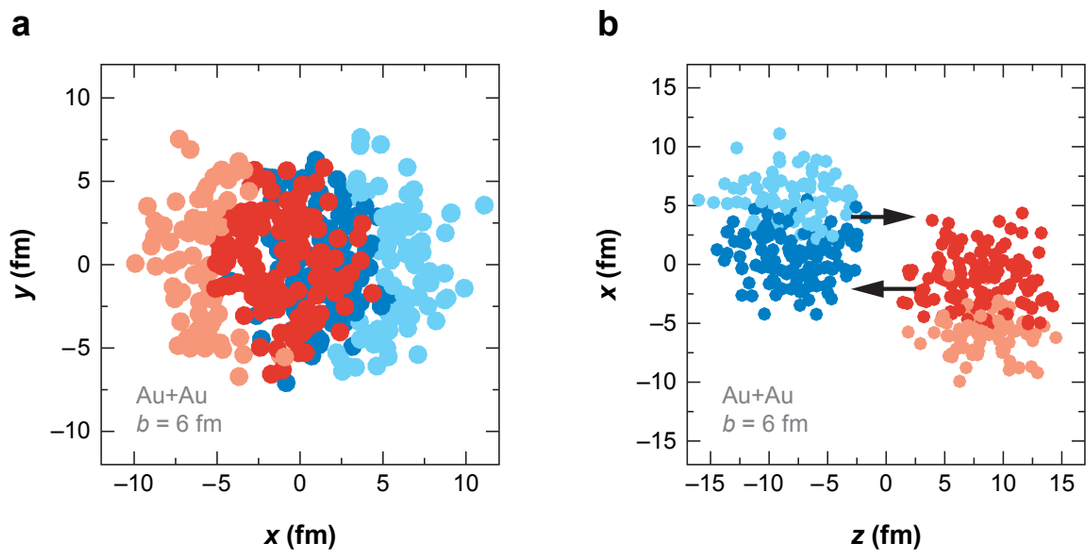
Degrees of Freedom (Constituent Quarks)





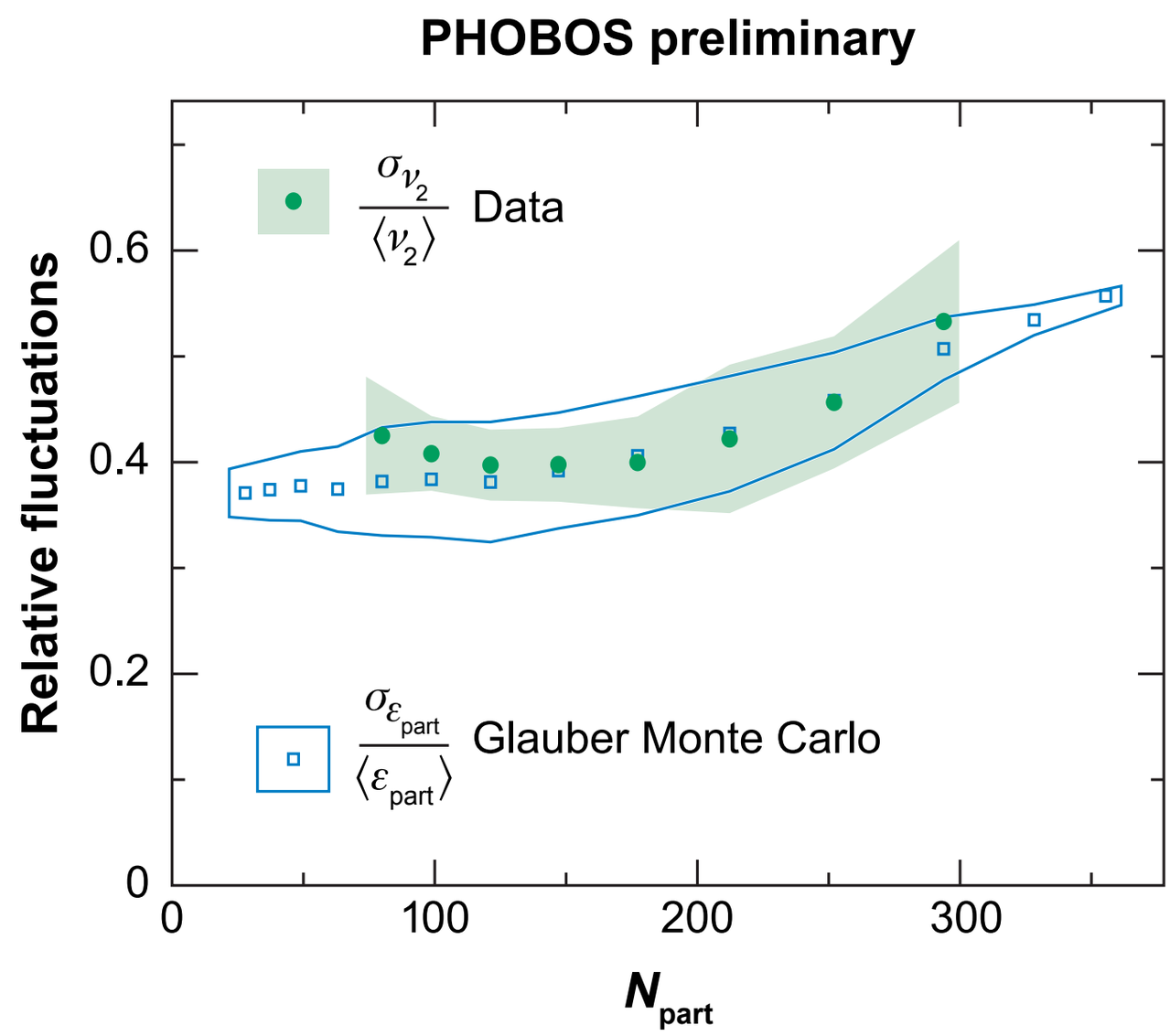
Does the system freeze into hadrons, or quarks?

Flow Fluctuations (2006)



If initial state fluctuates from nucleon positions, does v_2 fluctuate?

Does the reaction really "freeze-in" these fluctuations?



Difficult to control effect of 2-particle correlations!

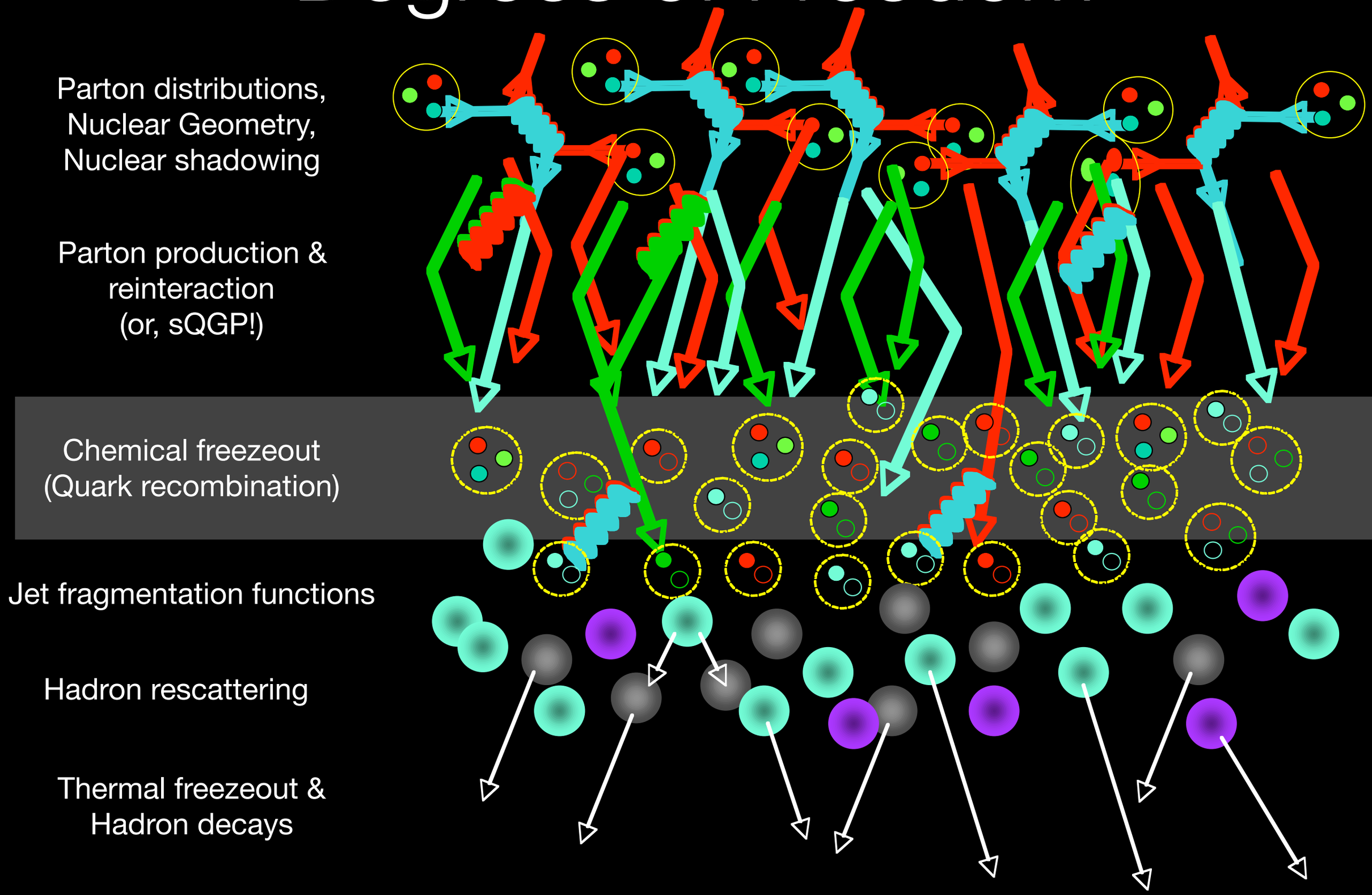
The Big Questions

Is the system evolution really consistent with being locally thermalized?

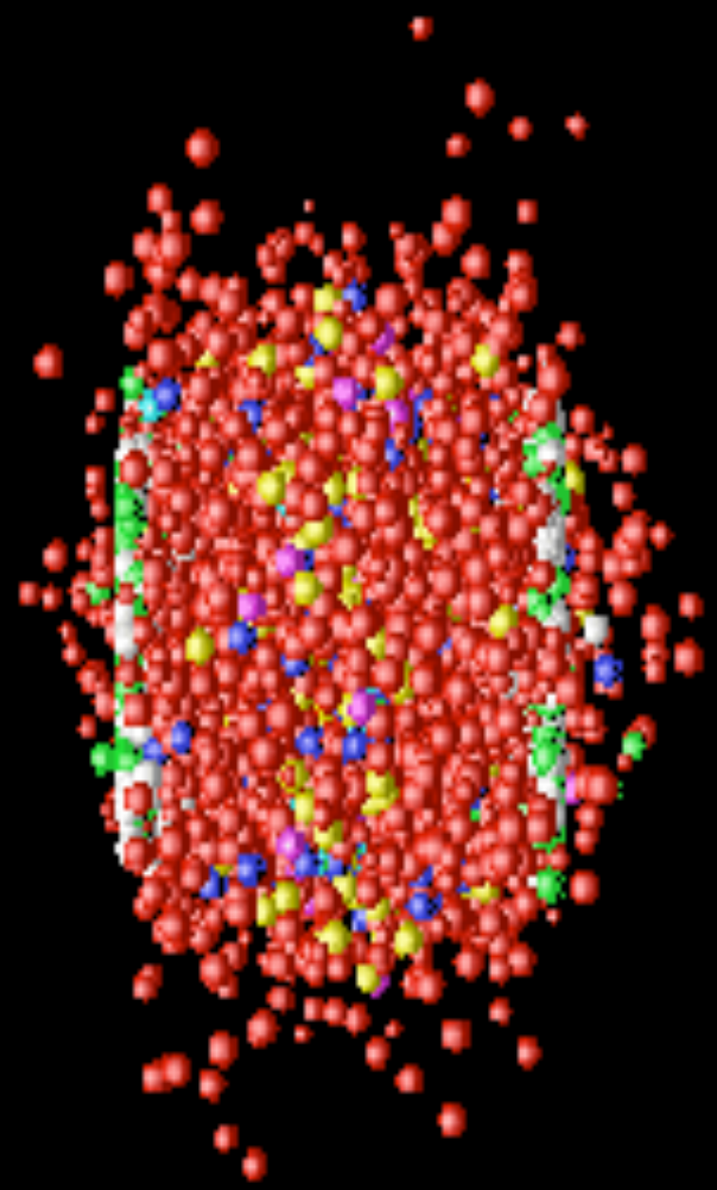
How is this equilibrium established so fast (<1 fm/c)?

What degrees of freedom are active as it thermalizes, as it evolves, and as it freezes out?

Degrees of Freedom

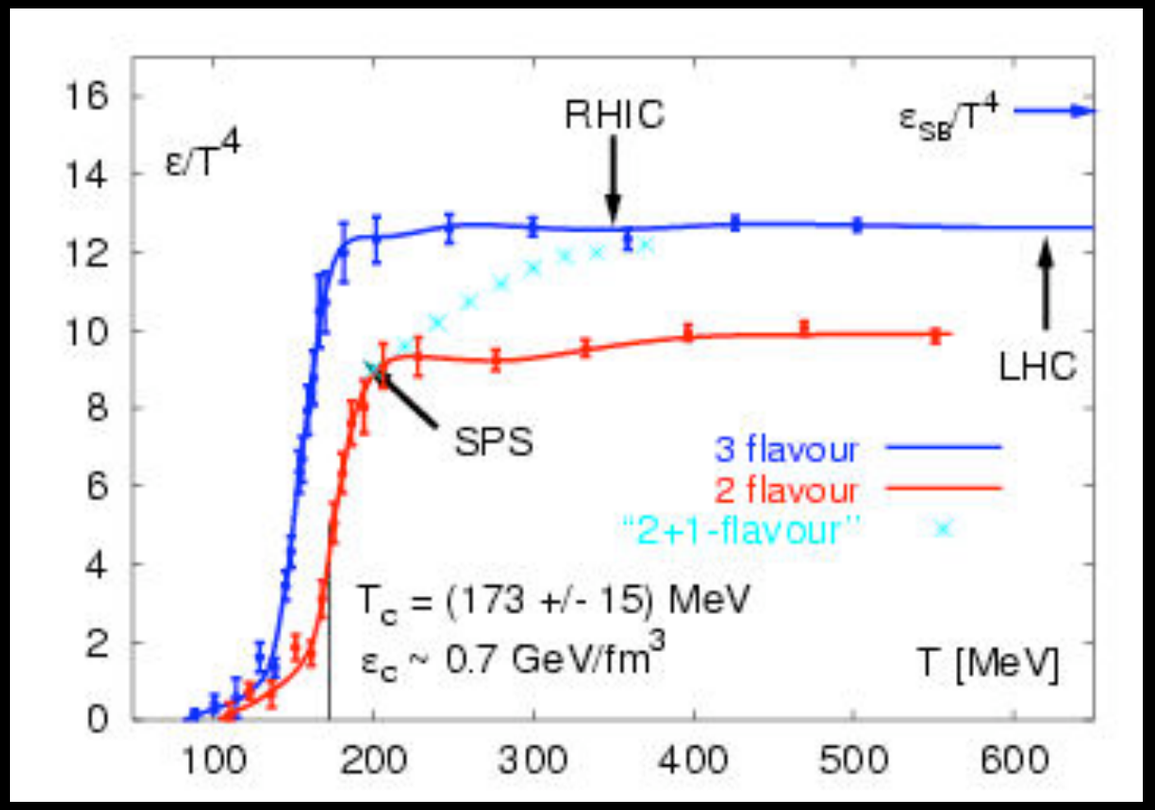


What is the fluid made of?



$$\epsilon = \frac{E}{V} \propto n_{d.o.f.} T^4$$

energy density



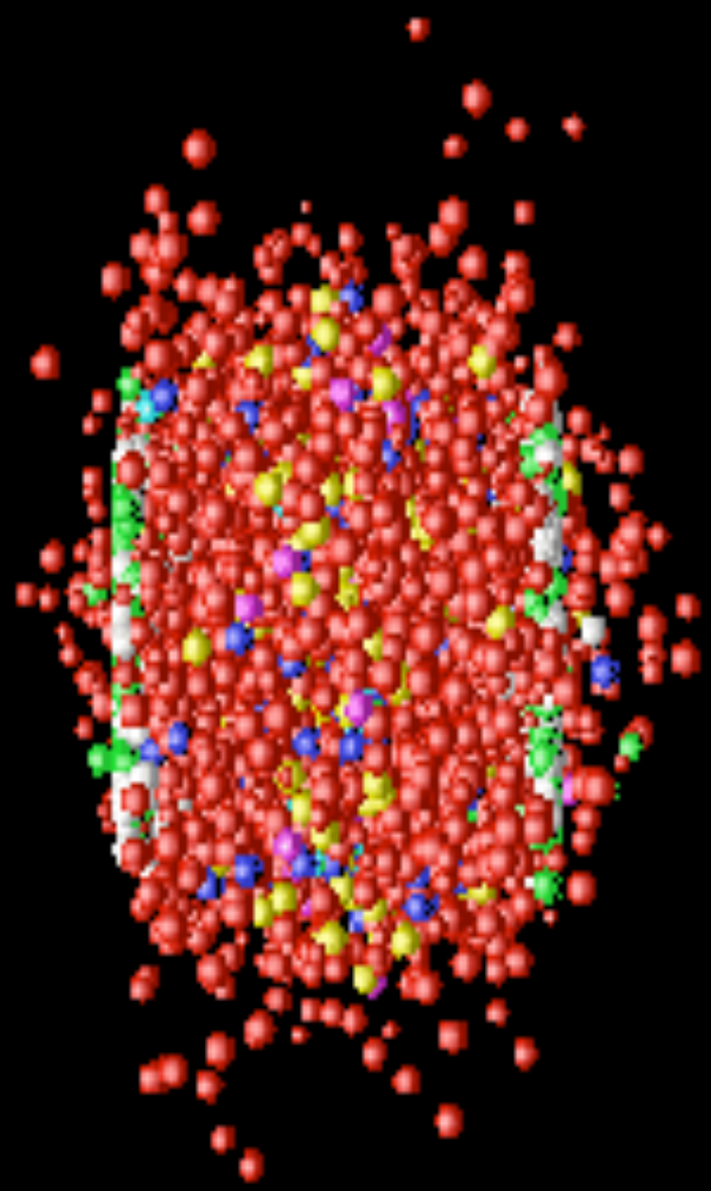
← ?

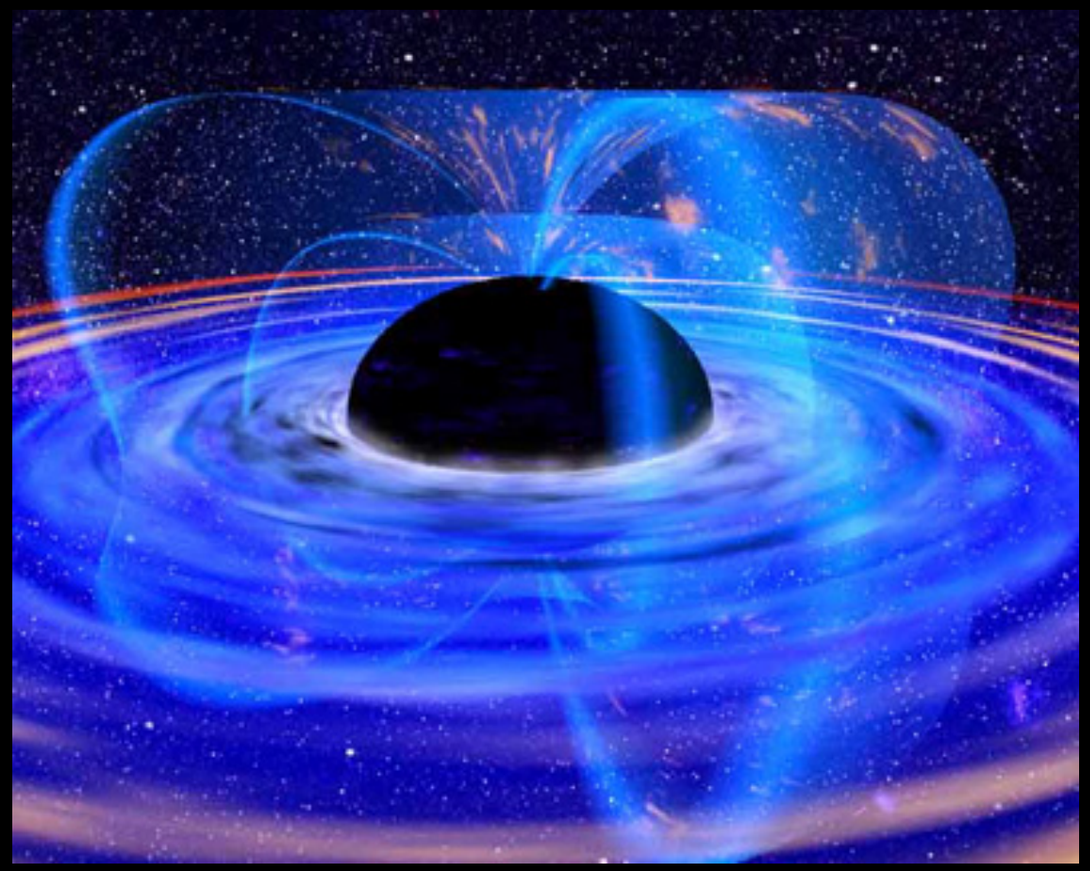
Karsch et al, 2001

↑

"deconfinement" @ T_c

What is the fluid made of?

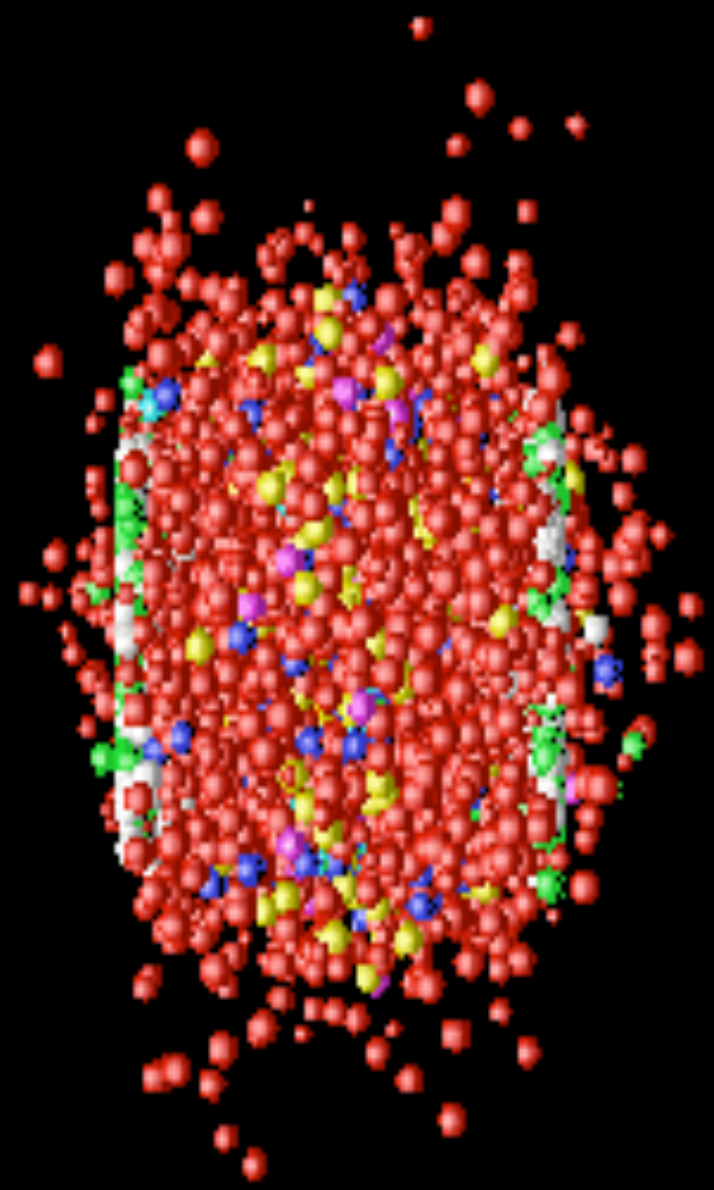


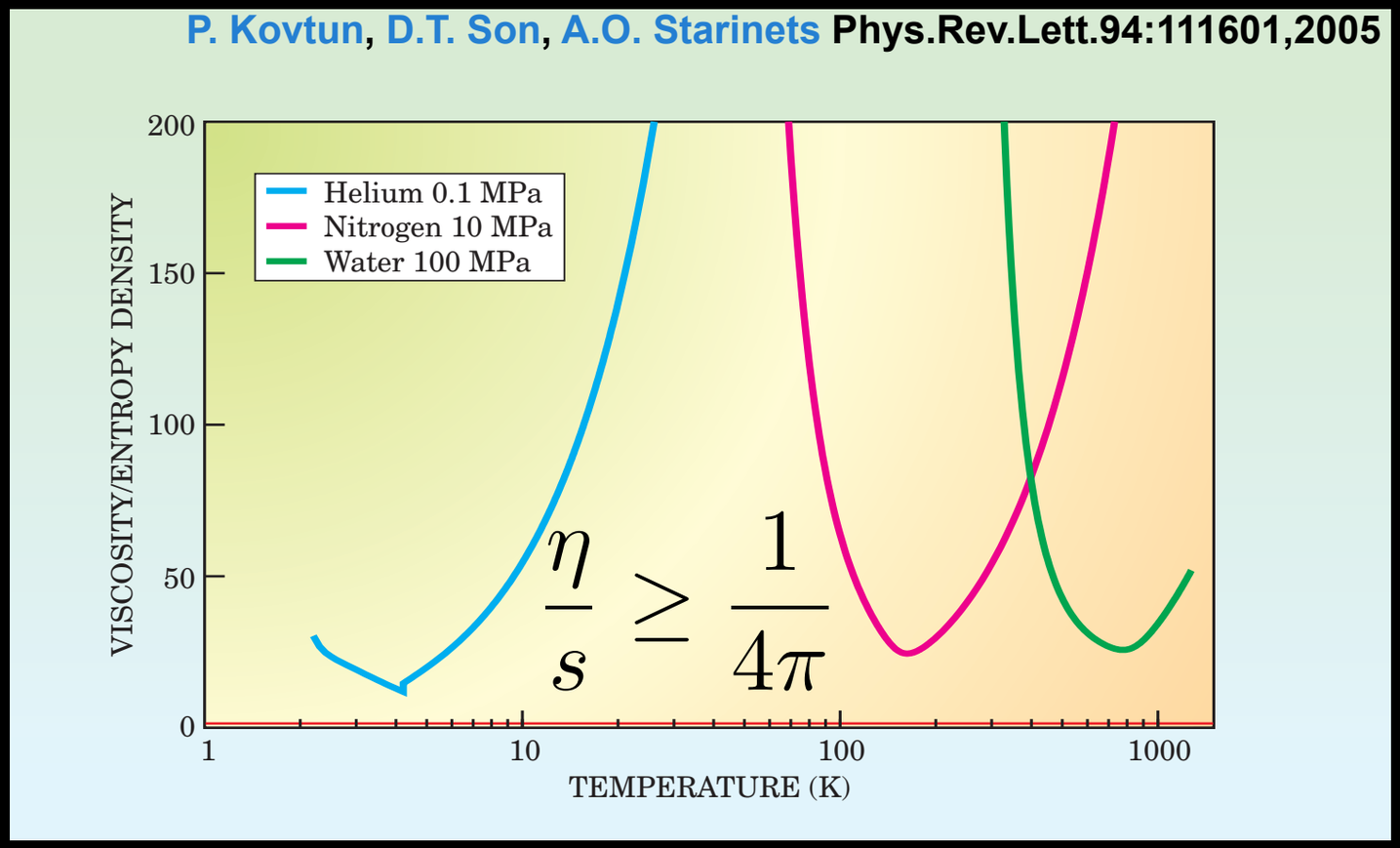


AdS/CFT arguments suggest that a QGP should be "strongly coupled"

$$n_{d.o.f.}^{sQGP} = \frac{3}{4} n_{d.o.f.}^{SB}$$

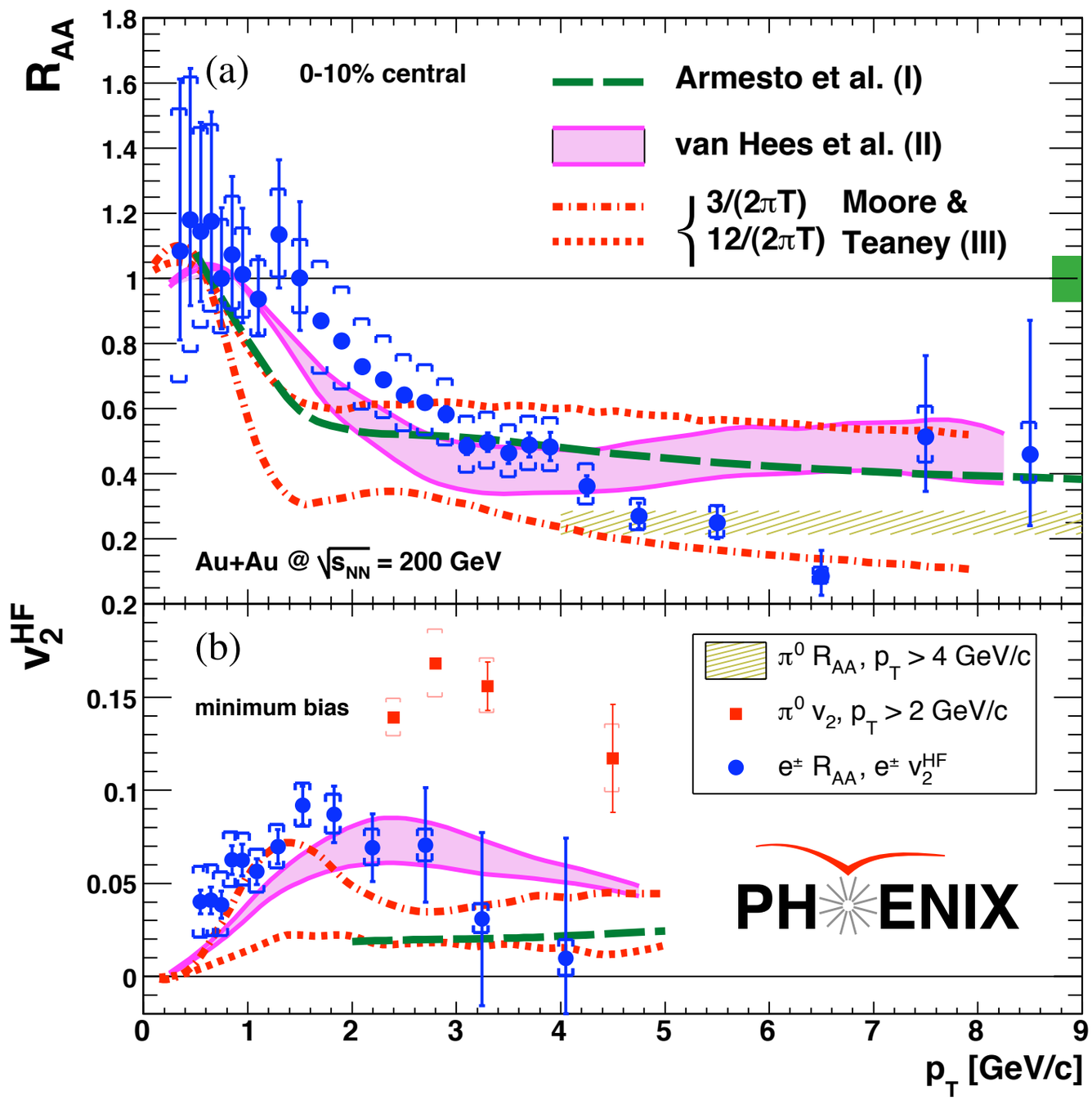
What is the fluid made of?





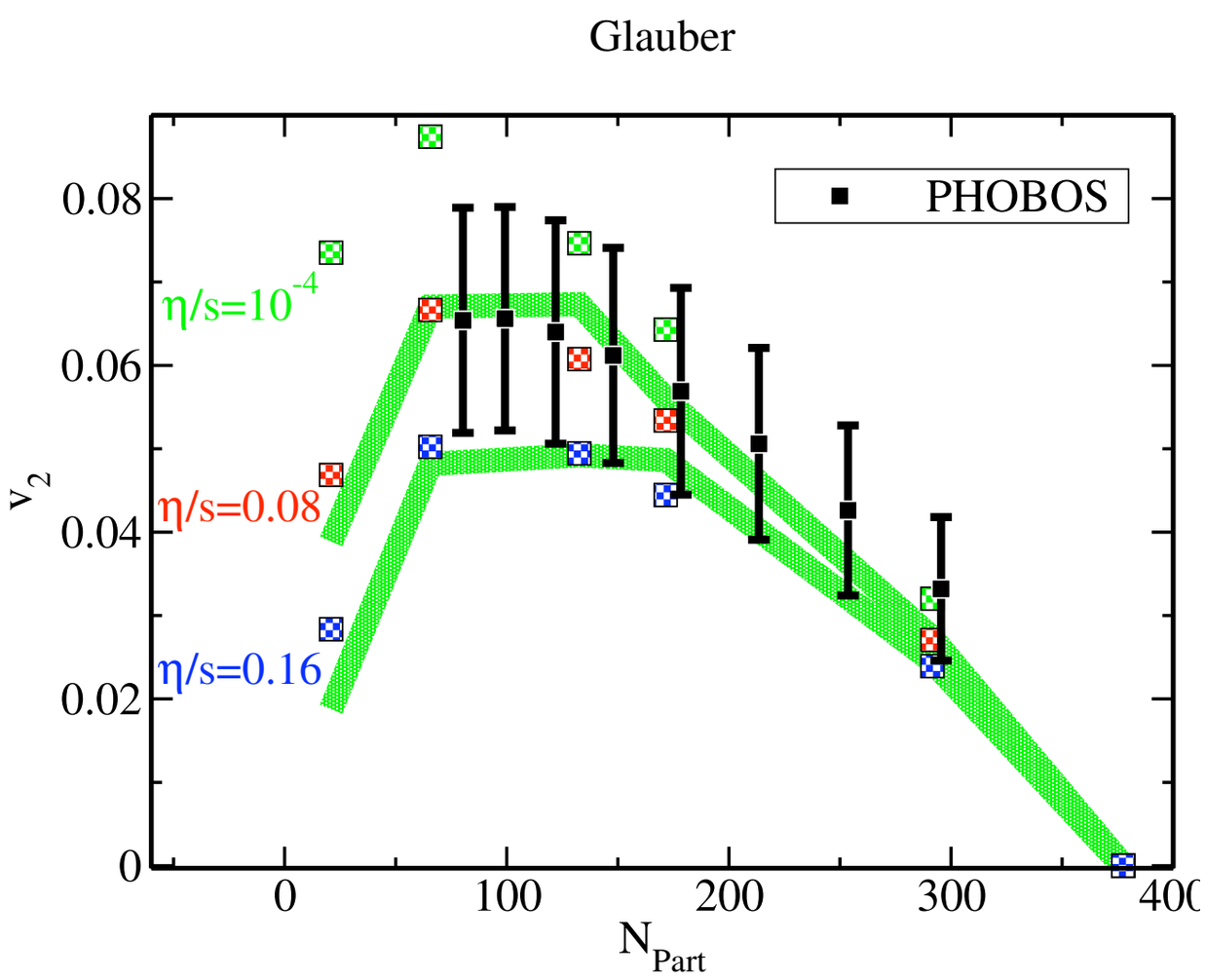
Data suggests that A+A produces a strongly-coupled system with subhadronic degrees of freedom ("sQGP") → perhaps saturating "viscosity bound" from AdS/CFT

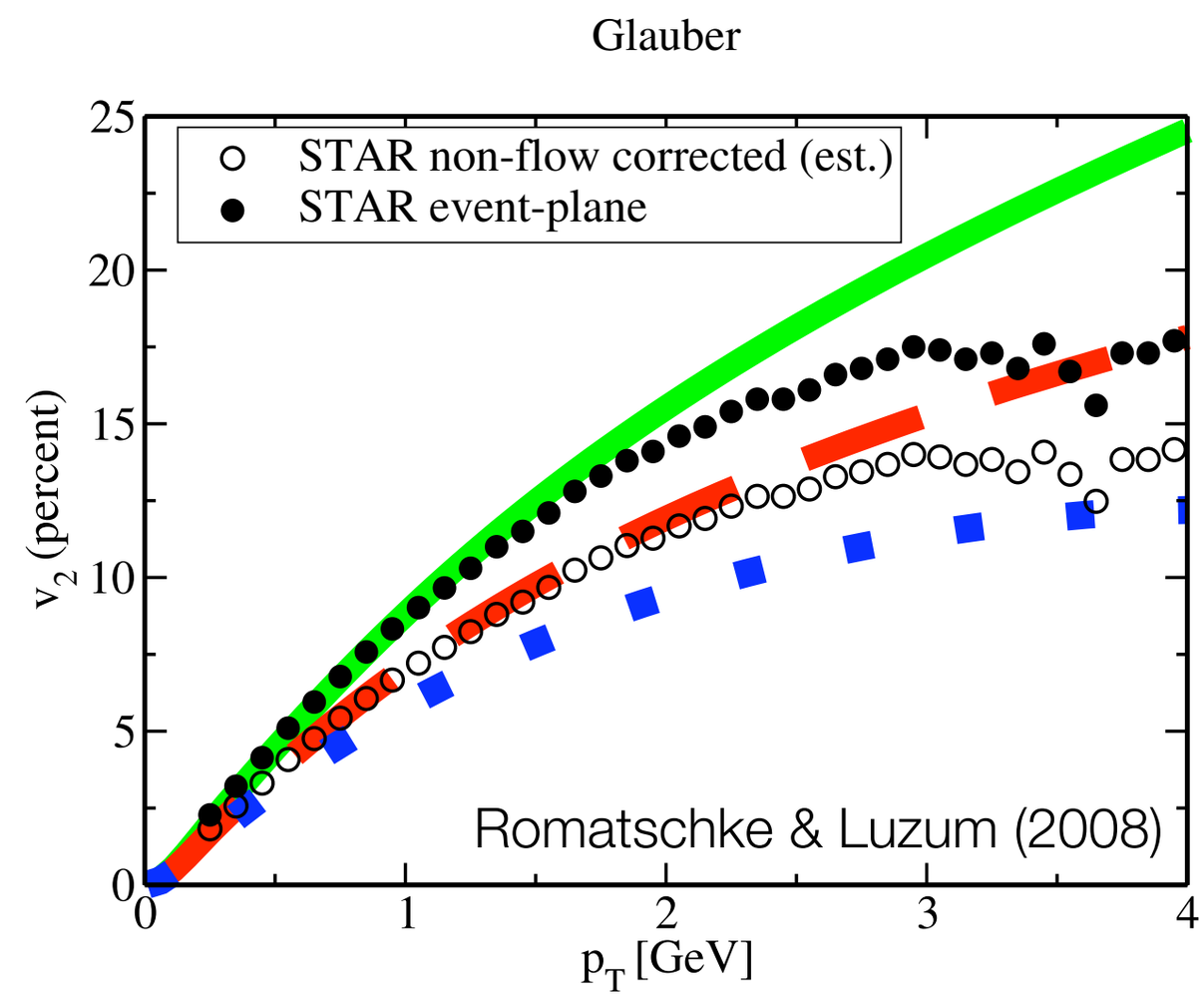
Measuring Viscosity @ RHIC



Models predict correlation of v_2 and R_{AA} (later!)

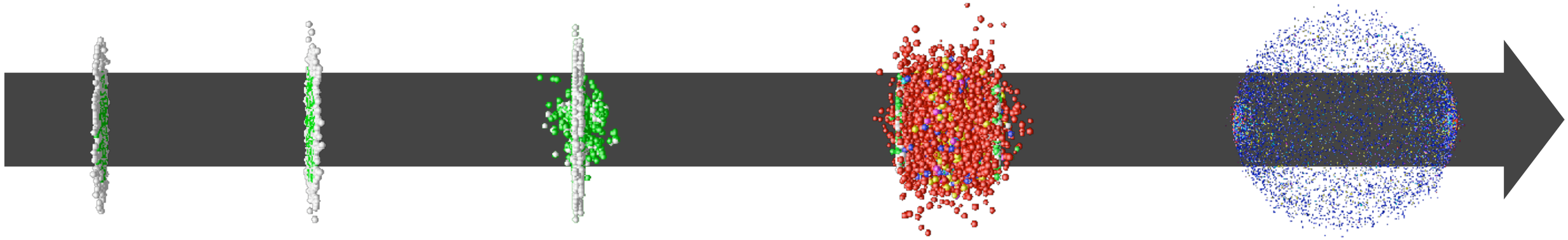
Viscous Hydrodynamics (under construction!)





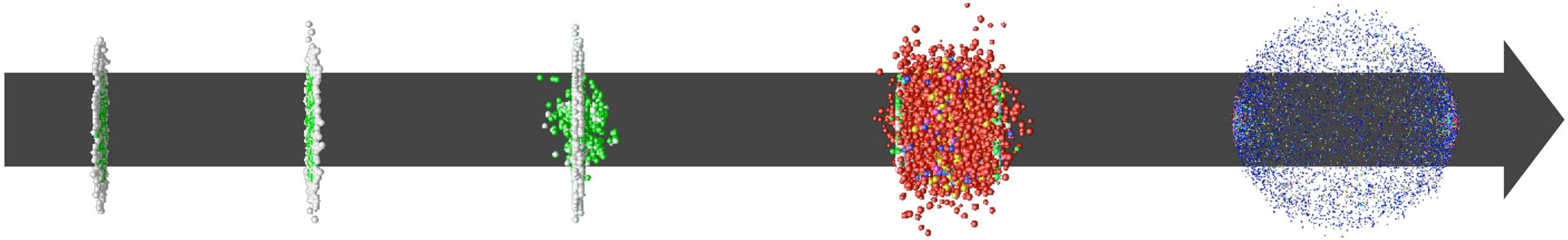
Viscous terms quite complicated, but dramatic theoretical progress recently (and connections with transport!)

Large uncertainties in modeling, but surprising success



	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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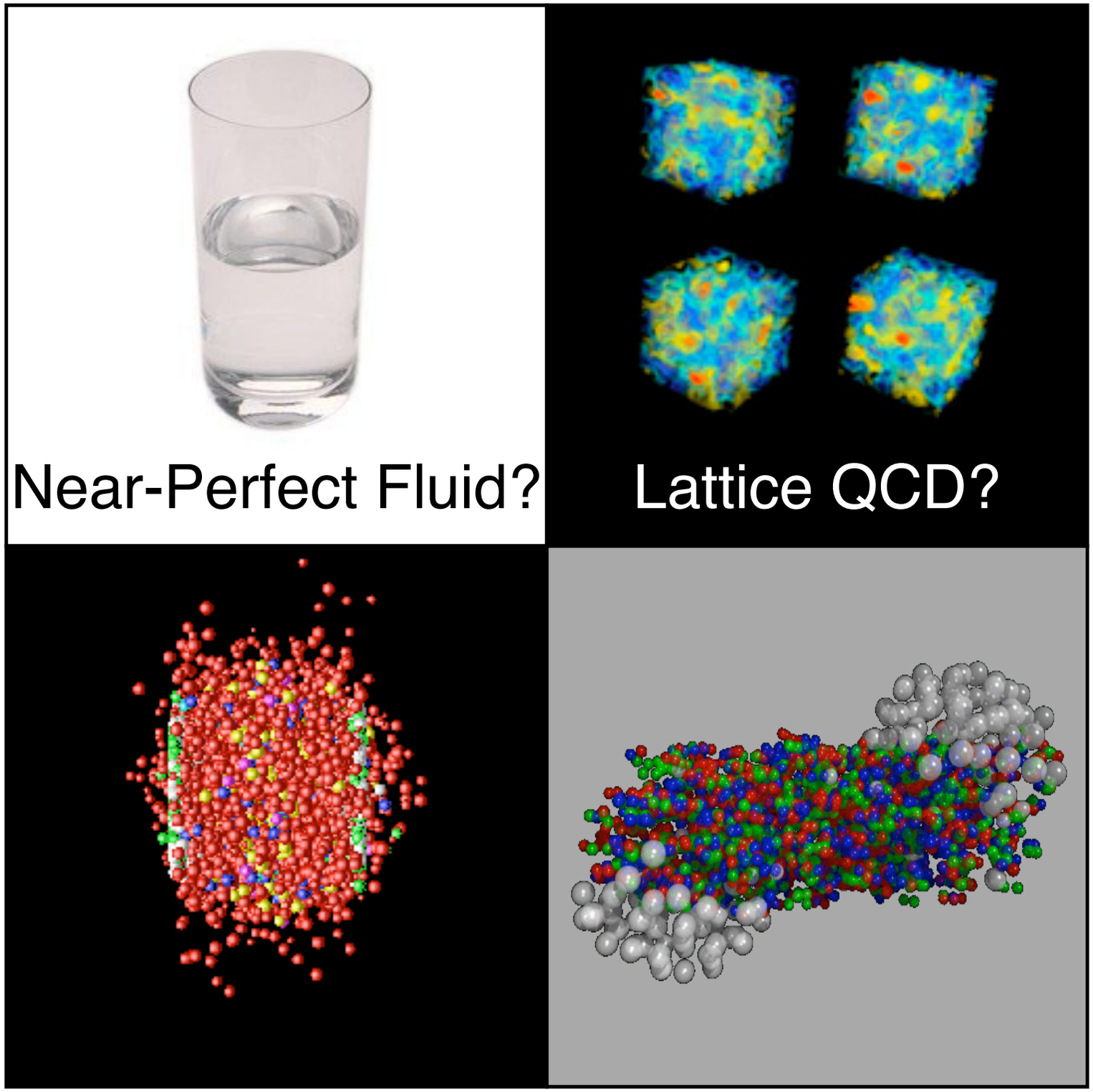
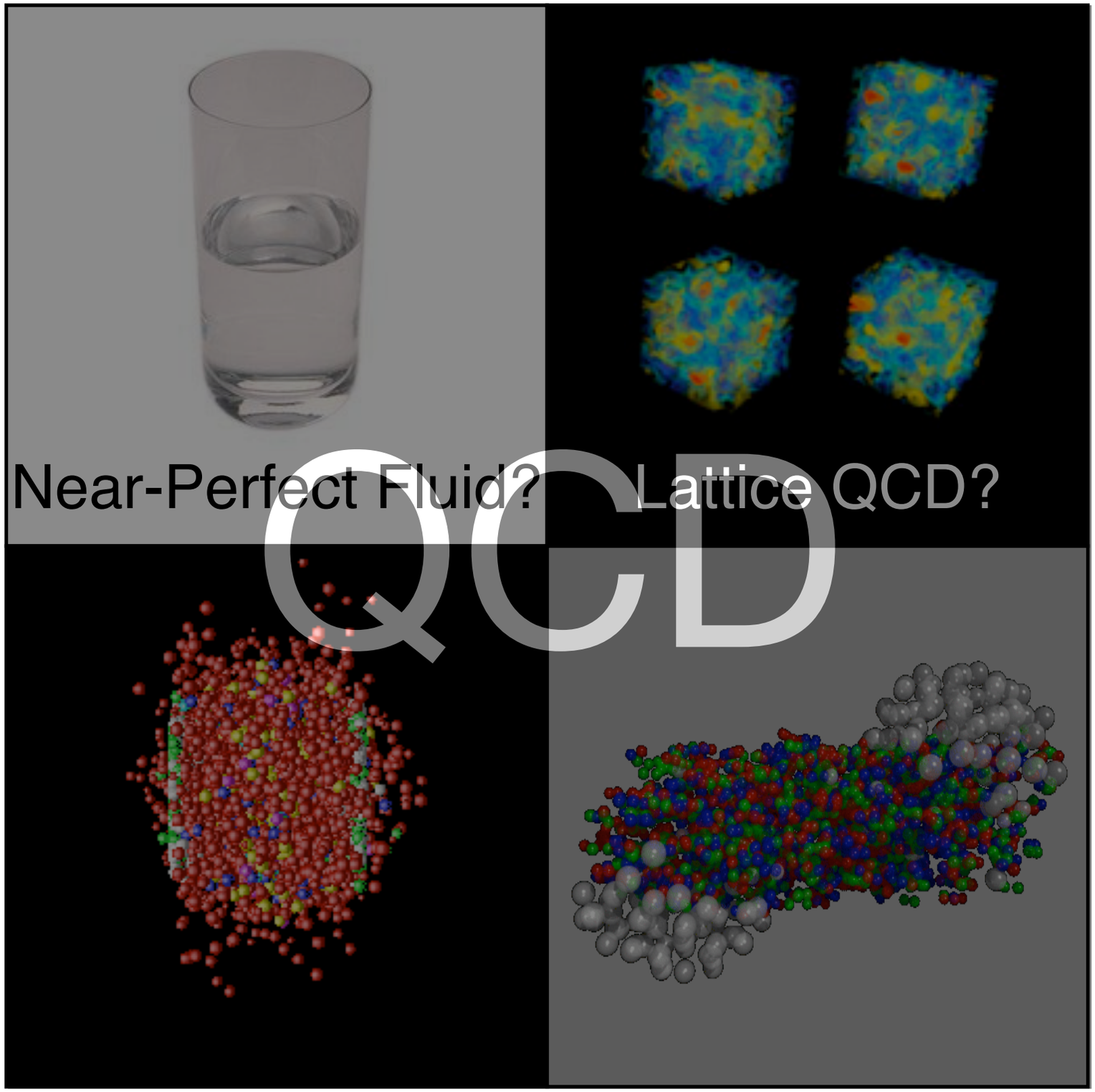
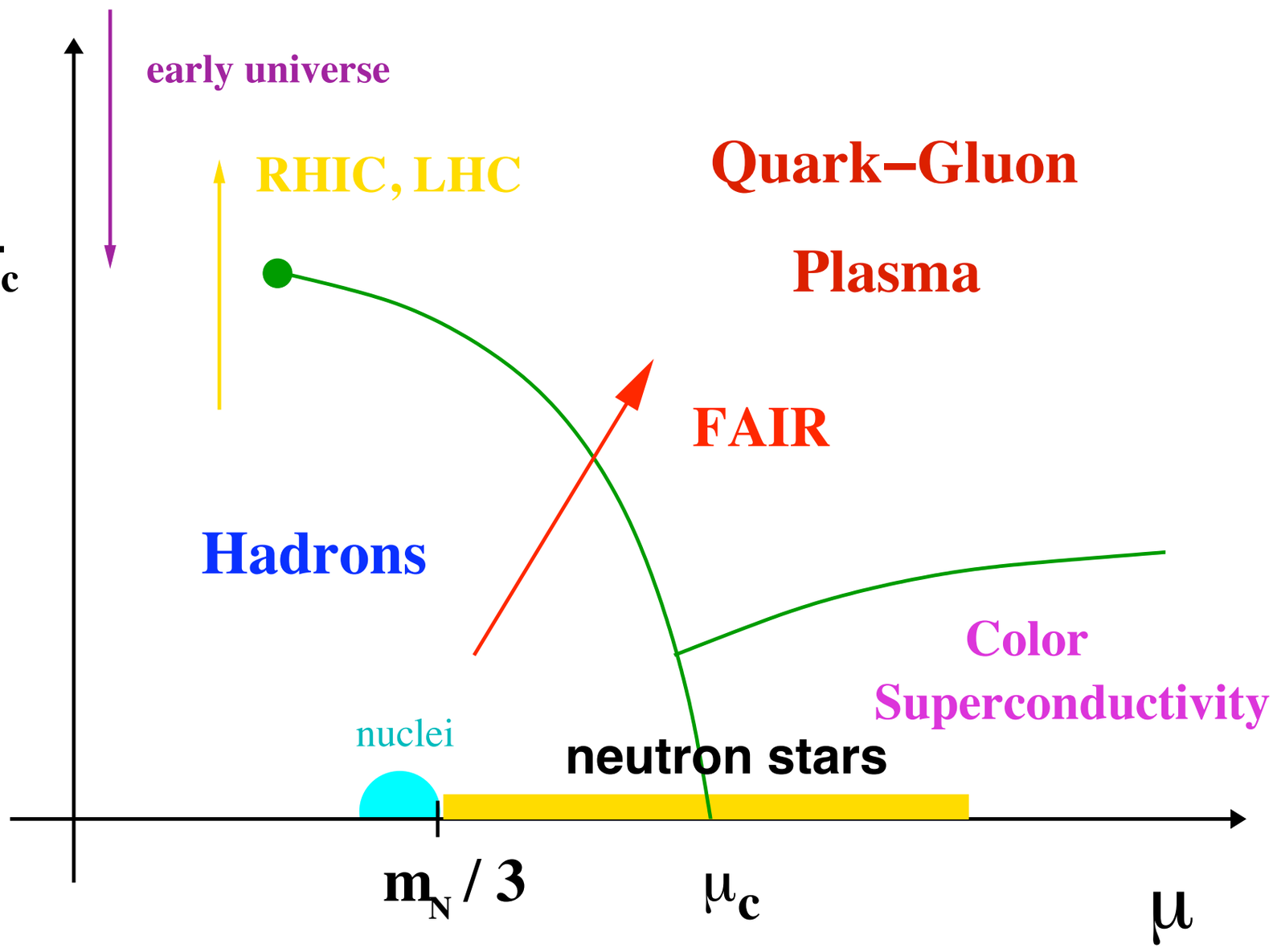
Global variables provide access to full range of evolution history

Dynamical Regimes of QCD



Dynamical Regimes of QCD



The QCD Phase Diagram