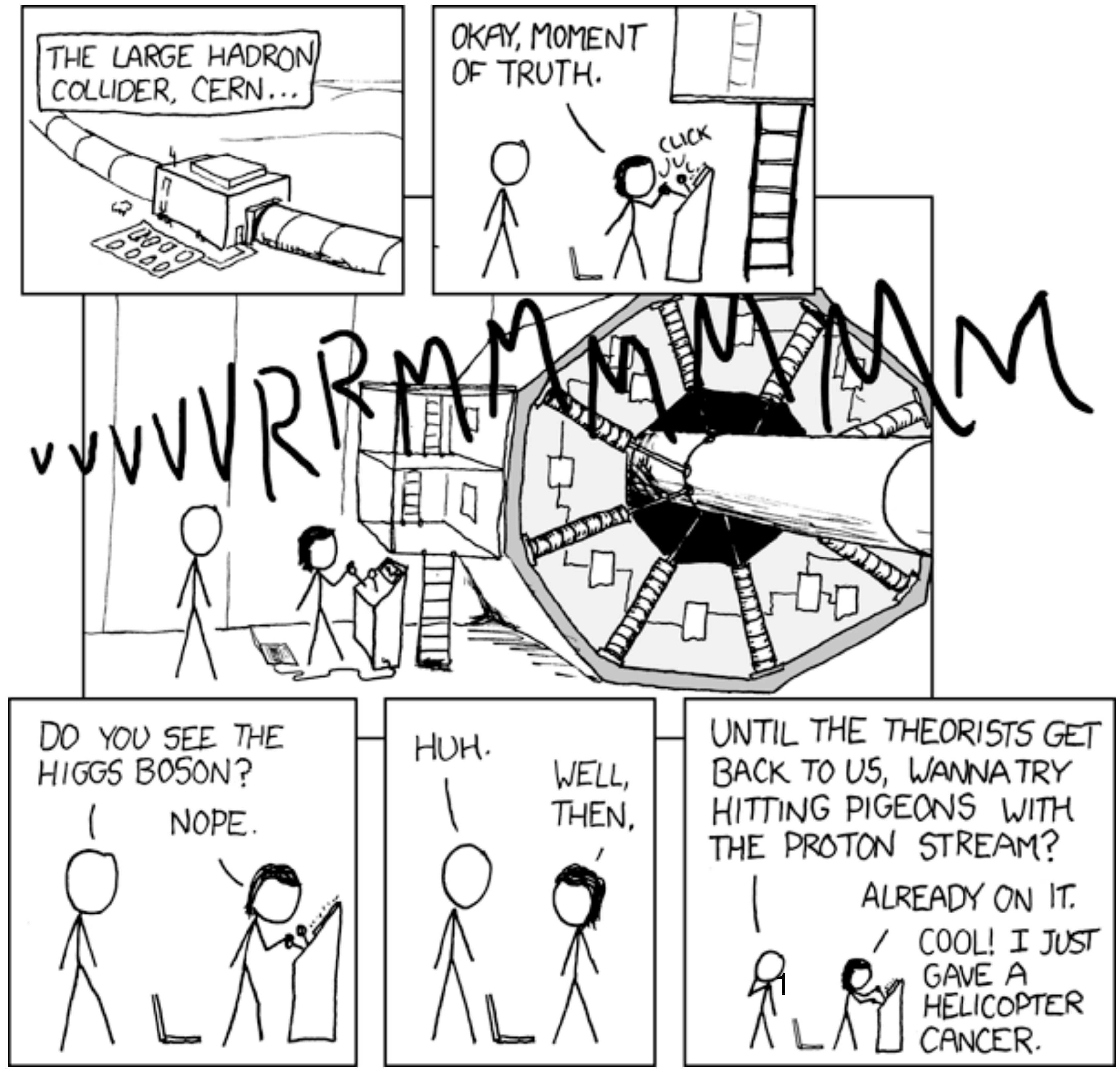
Studying a New Phase of Matter - An Introduction to the Quark Gluon Plasma and Relativistic Heavy Ion Physics

2016 Hadron Collider Physics Summer School

Fermi Lab

Helen Caines - Yale University



Lecture 1: Creating the QGP

Lecture 2: Studying the QGP

Relativistic Heavy Ions I - The What, Why, Where, and How of It All

Outline :

QCD and Asymptotic Freedom

Necessary Conditions to Make the QGP

The Accelerators & Experiments

Evidence for the QGP

Color confinement - QCD

Quarks seem to be confined within colorless hadrons

- Nobody ever succeeded in detecting an isolated quark or gluon

One half of the fundamental fermions are not directly observable.

- Why?

Frequently listed as one of the top unresolved problems in physics

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Why?

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To understand the strong force and confinement: Create and study a system of deconfined colored quarks and gluons

Asymptotic freedom

Coupling constant is not a "constant"

Runs with Q^2 (mtm transfer)
accounts for vacuum polarisation

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{[1 + (\alpha_s(\mu^2)\frac{(33-2n_f)}{12\pi})ln(Q^2/\mu^2)]}$$

$\alpha_s(\mu^2) \sim 1$!!
μ^2 : renormalization scale
33 : gluon contribution
n_f : # quark flavors = 6

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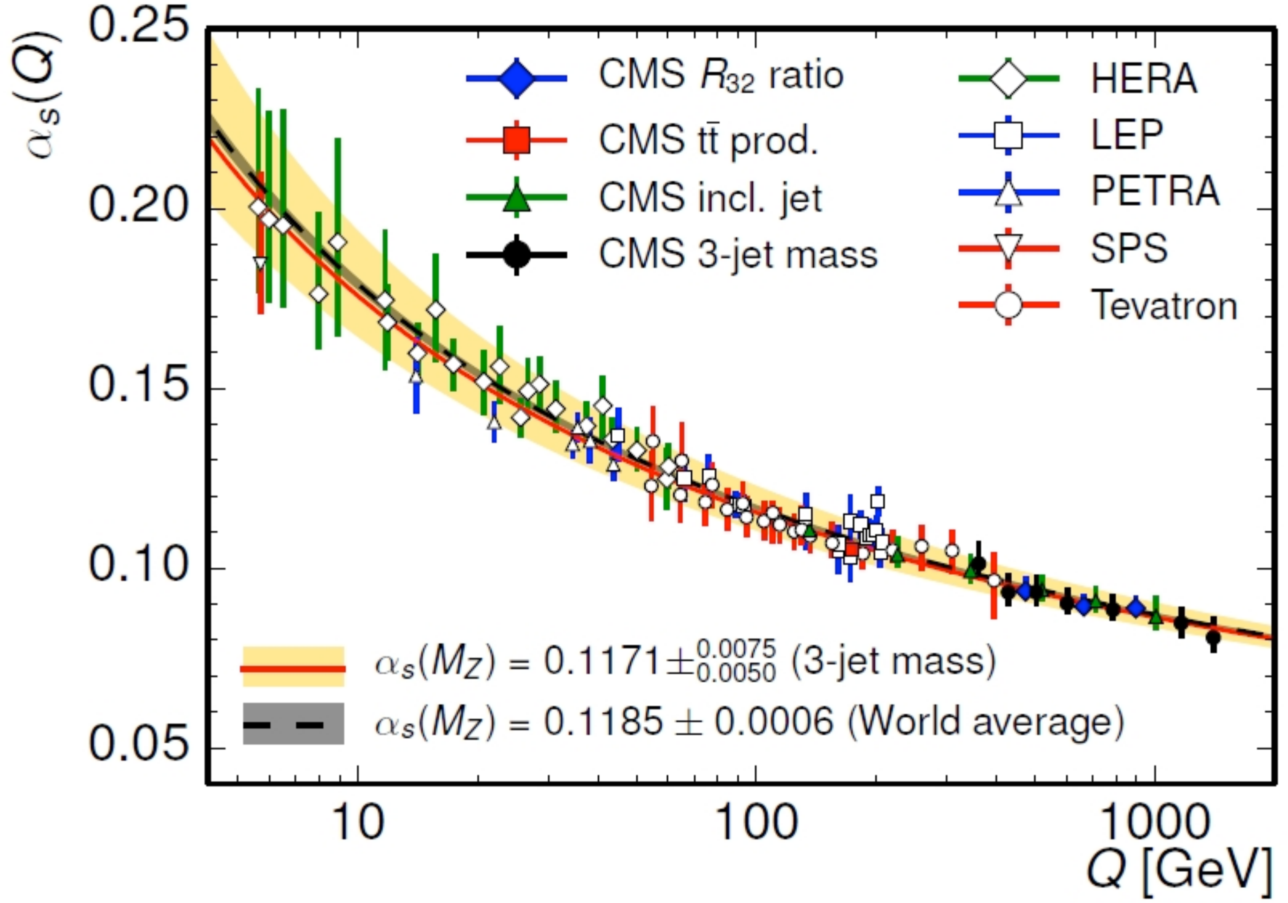
(33-12)/(12π) is positive

$\alpha_s(Q^2) \rightarrow 0$, as $Q \rightarrow \infty$, $r \rightarrow 0$
Coupling very weak
→ partons are essentially free

Asymptotic Freedom

Measured experimentally



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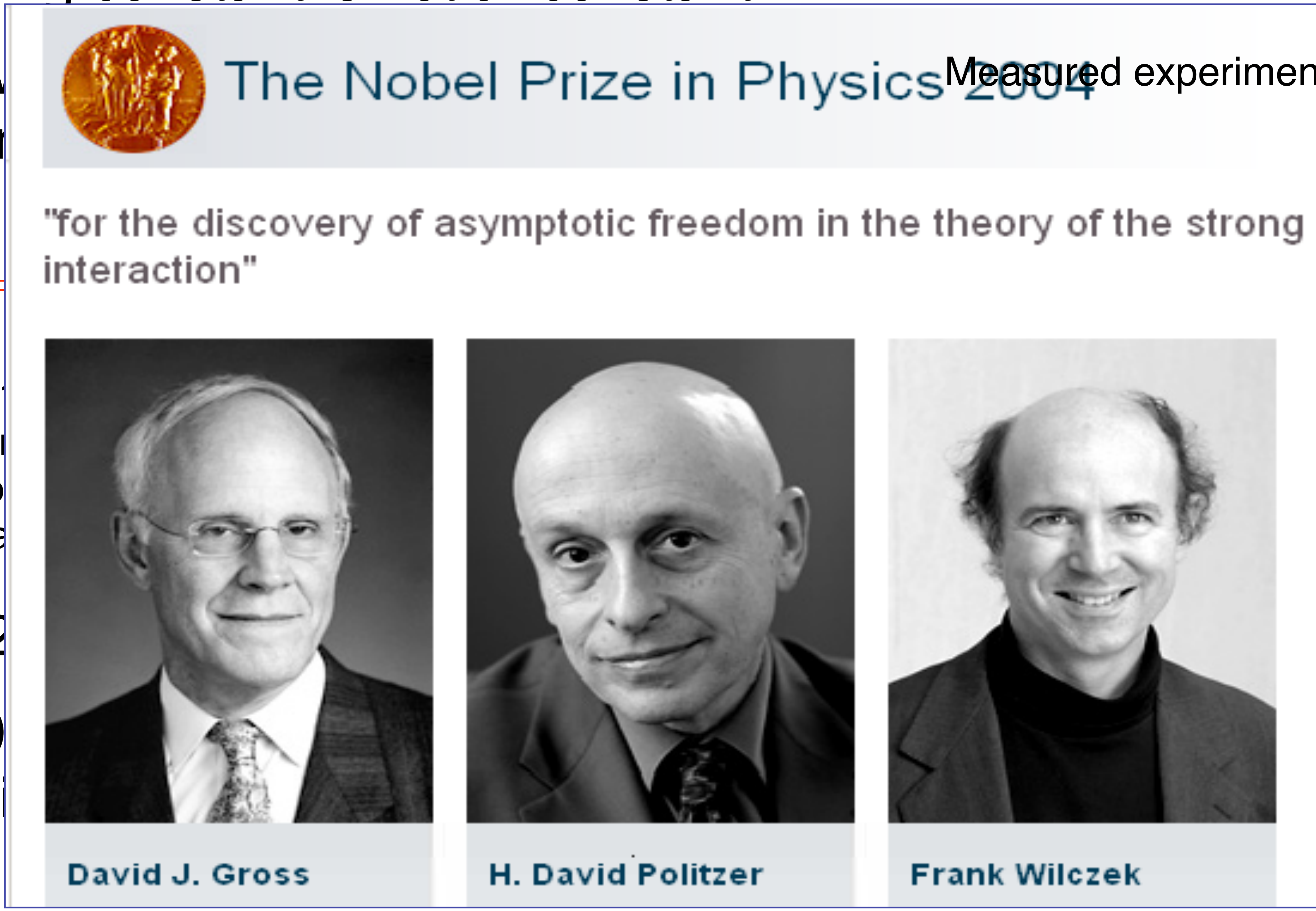

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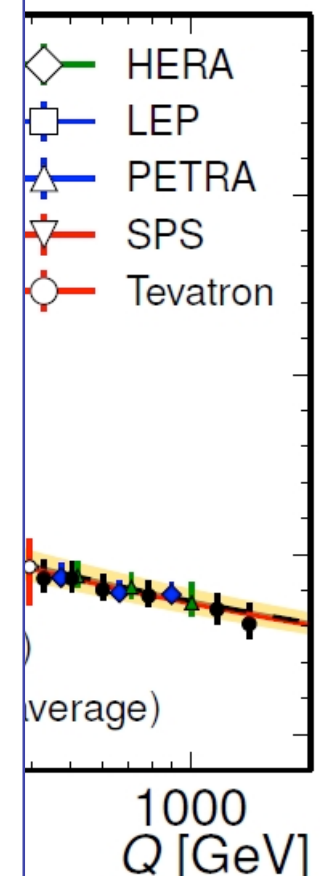


Asymptotic Freedom

Asymptotic freedom vs Debye screening

Asymptotic freedom occurs at very high Q^2
Problem: Q^2 much higher than available in the lab.

So how to create and study this new phase of matter?
Solution: Use effects of Debye screening

In the presence of many color charges (charge density n), the short range term of the strong potential is modified:

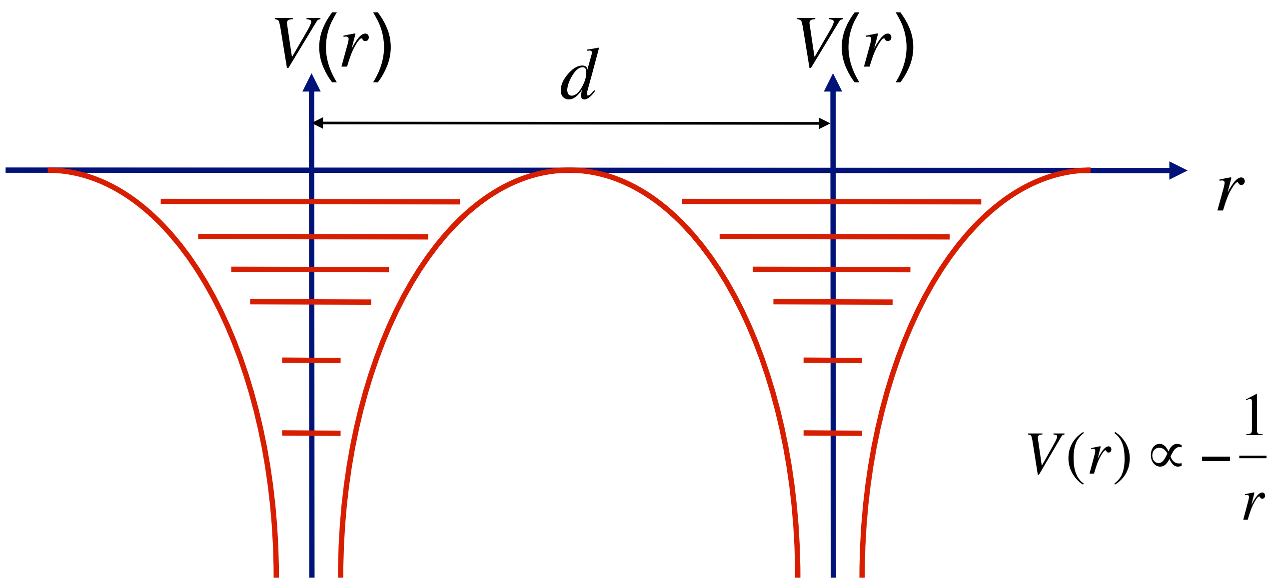
$$V_s(r) \propto \frac{1}{r} \Longrightarrow \frac{1}{r} exp[\frac{-r}{r_D}]$$

where $r_D = \frac{1}{\sqrt[3]{n}}$ is the Debye radius

Charges at long range ($r > r_D$) are screened

QED and Debye screening

$r > r_D$



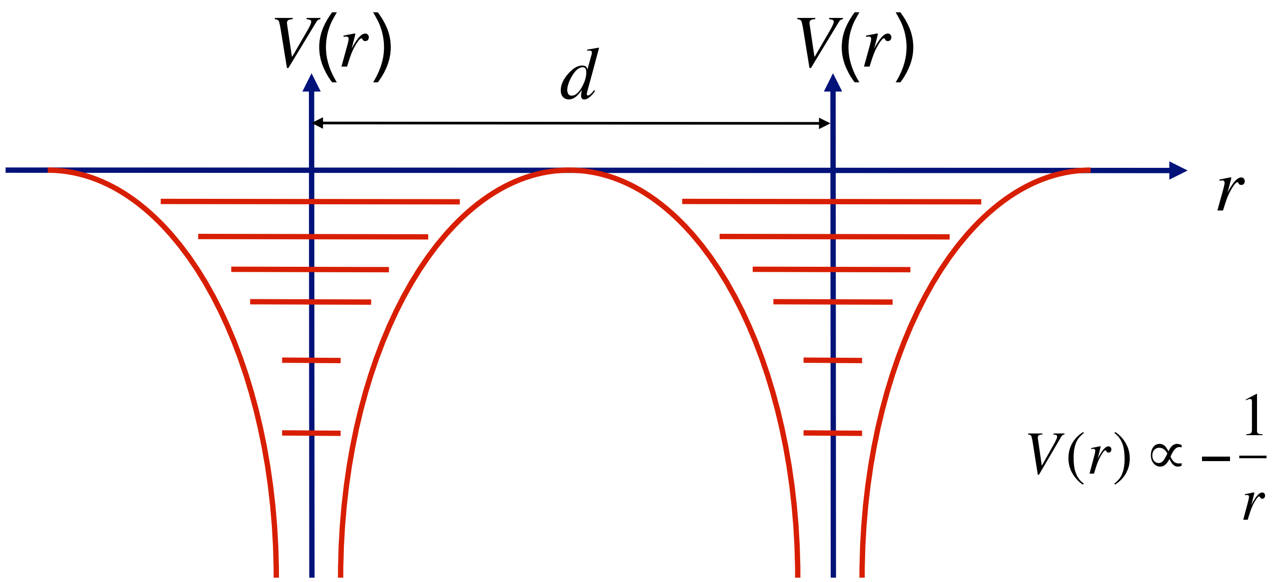
$$V(r) \propto -\frac{1}{r}$$

In condensed matter this leads to an interesting transition

e^- separation > e^- binding radius
→ insulator

QED and Debye screening

$r > r_D$



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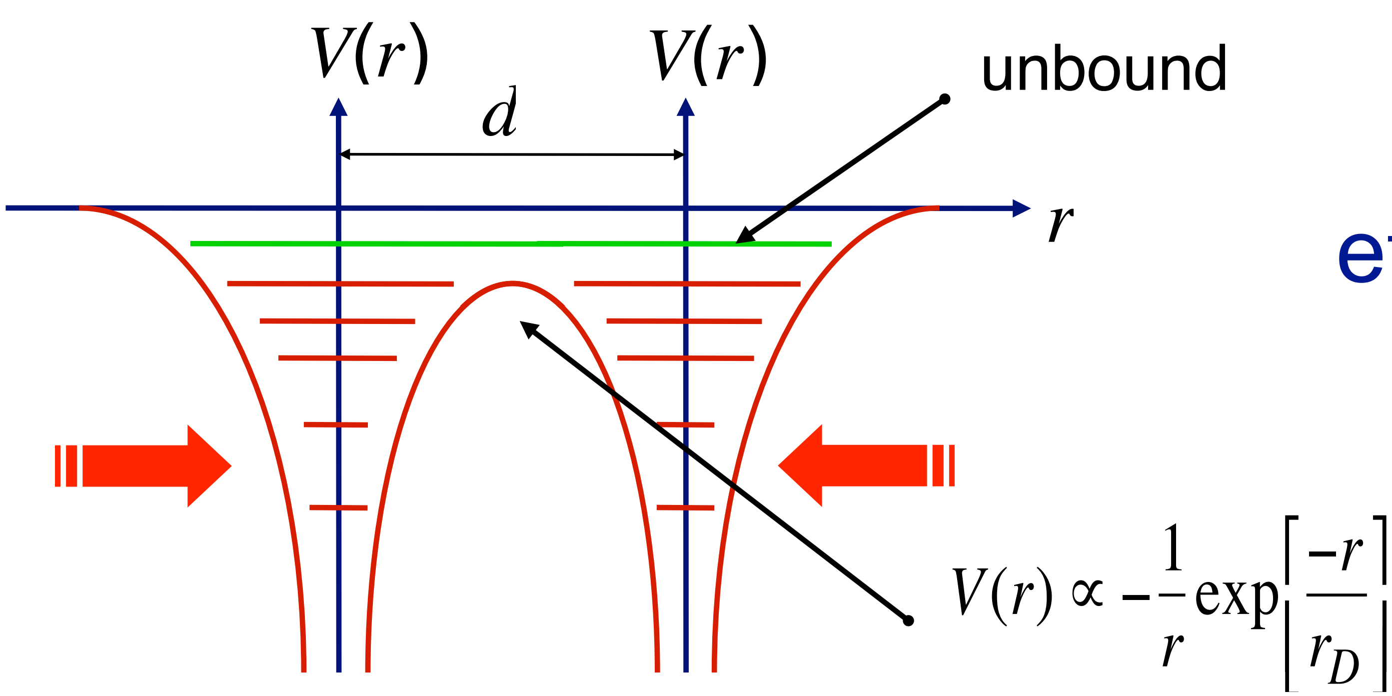


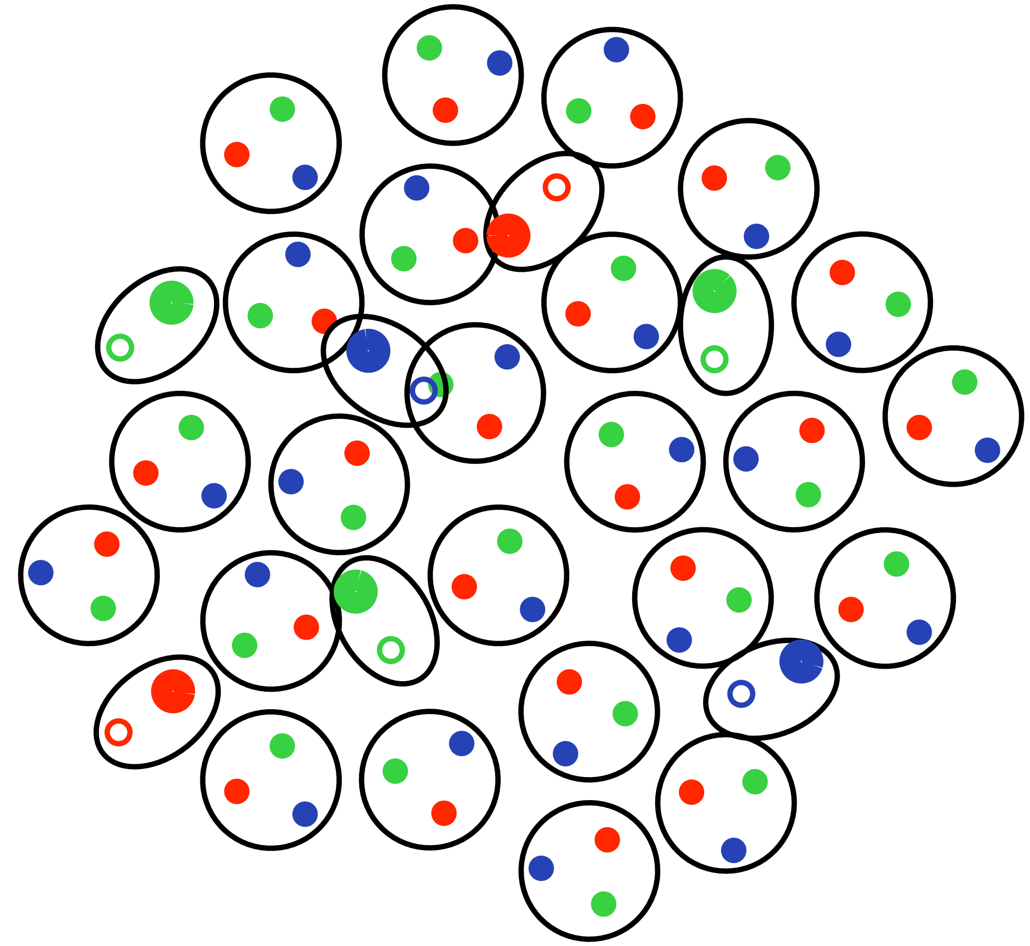
e^- separation < e^- binding radius
→ conductor

This is the Mott Transition

QCD and Debye screening

At low color densities:

quarks and gluons confined into color singlets
→ hadrons (baryons and mesons)



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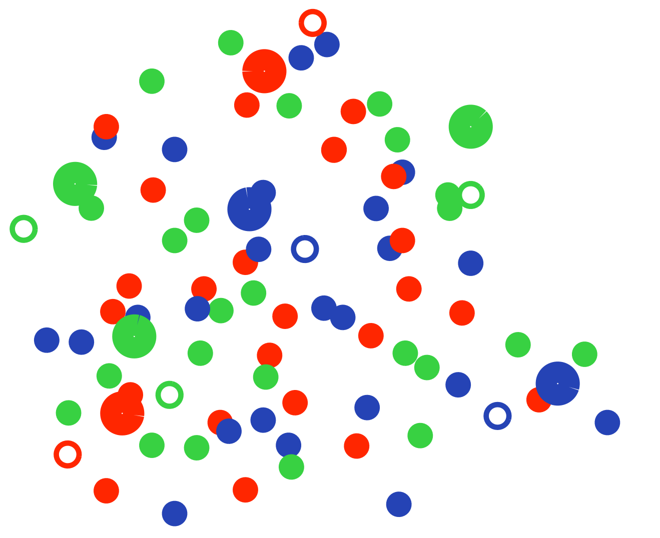

At high color densities:

quarks and gluons unbound
Debye screening of color charge

→ QGP - color conductor

QCD and Debye screening

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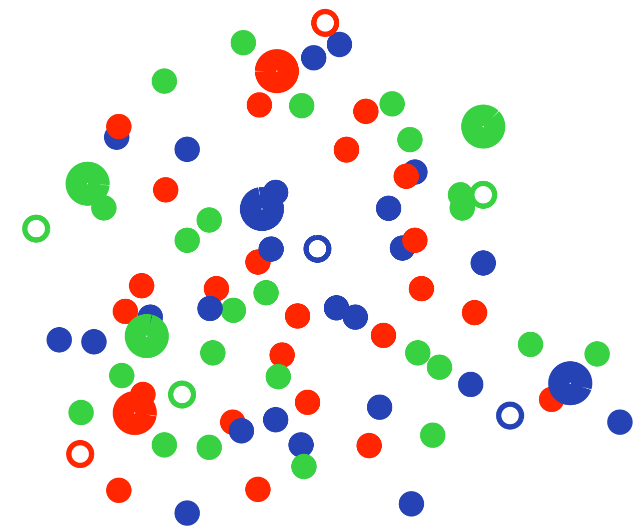

At high color densities:

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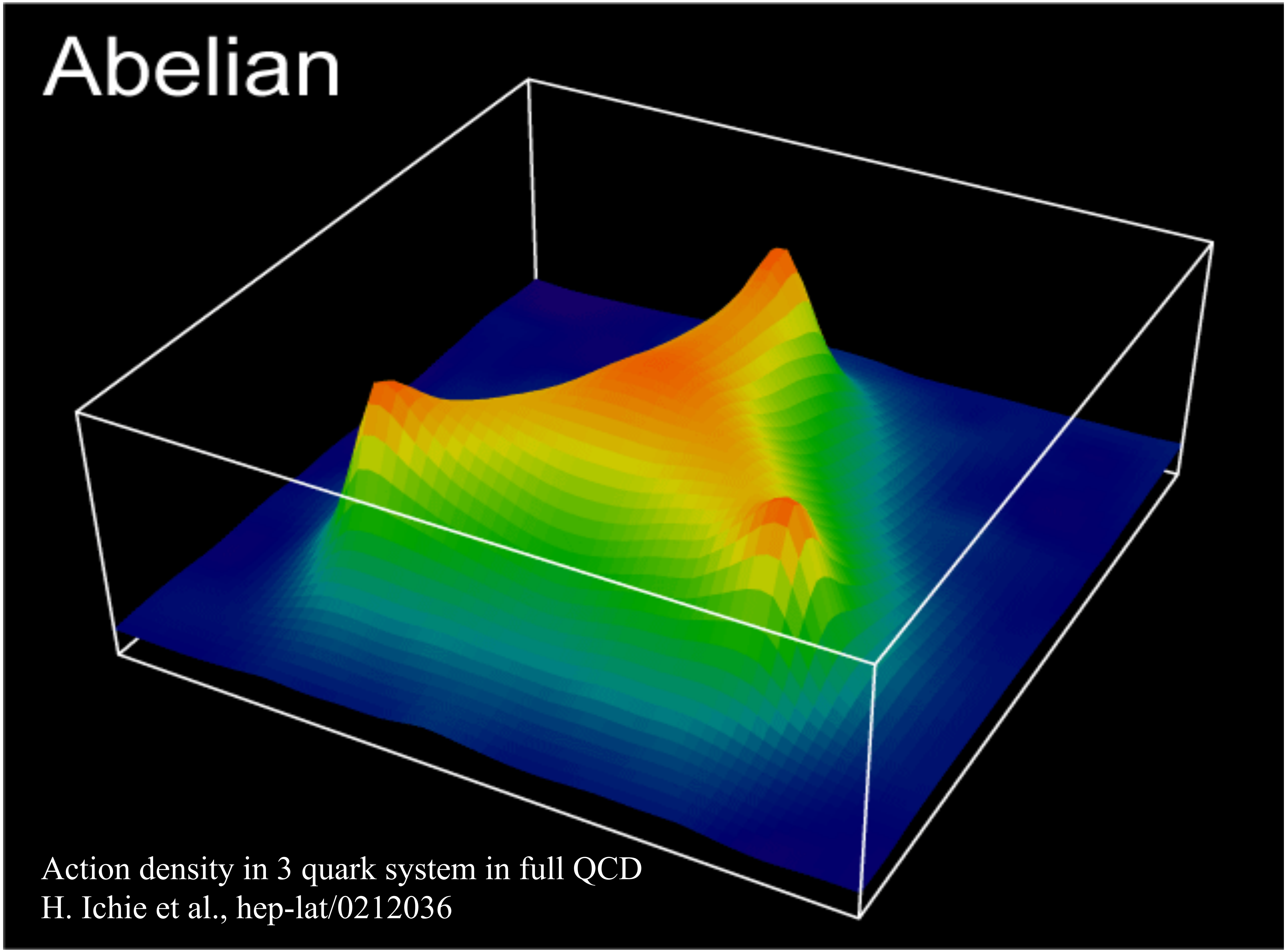
→ QGP - color conductor

Can create high color density by heating or compressing

→ QGP creation via accelerators or in neutron stars

What is T_c ? - Lattice QCD



Action density in 3 quark system in full QCD
H. Ichie et al., hep-lat/0212036

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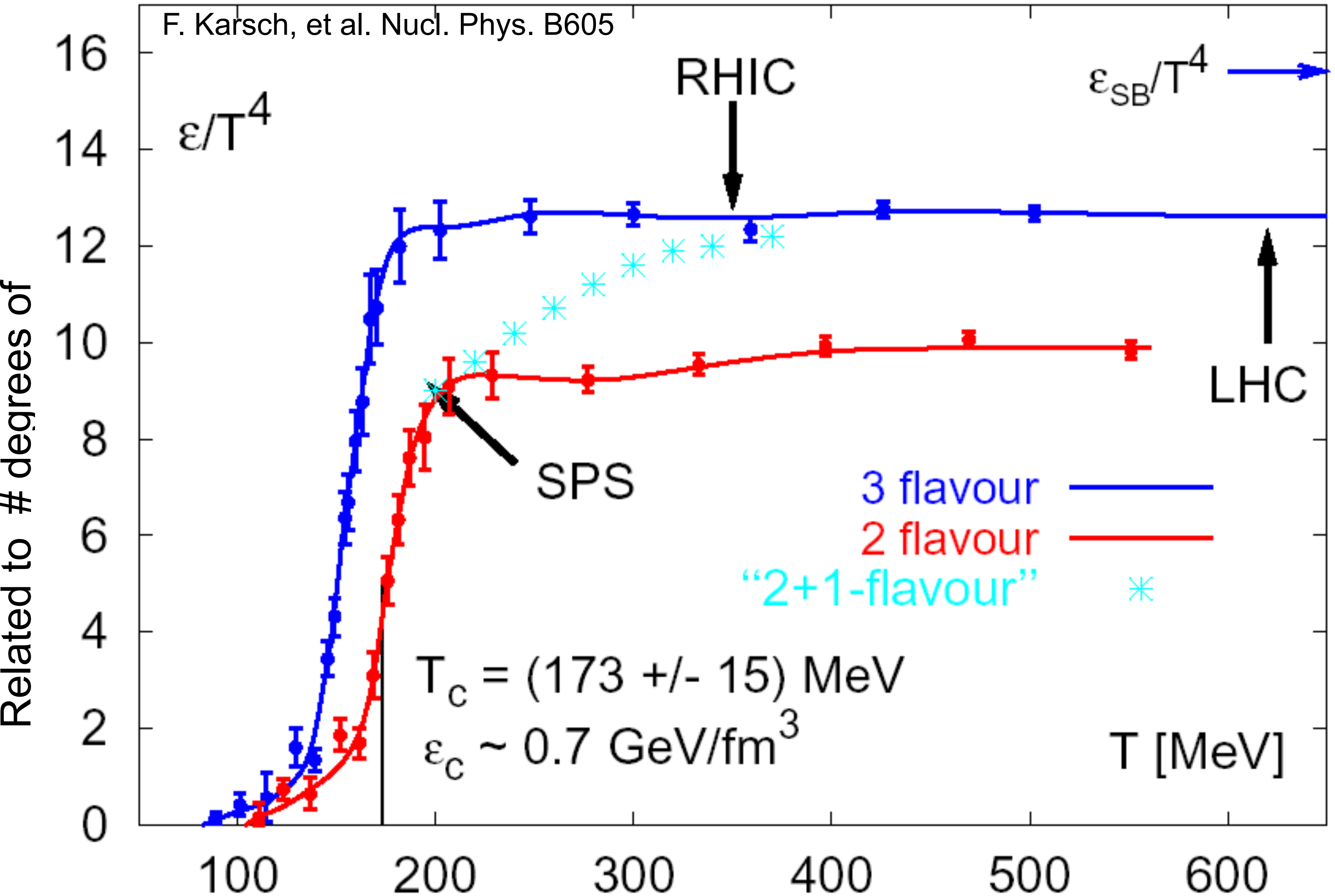
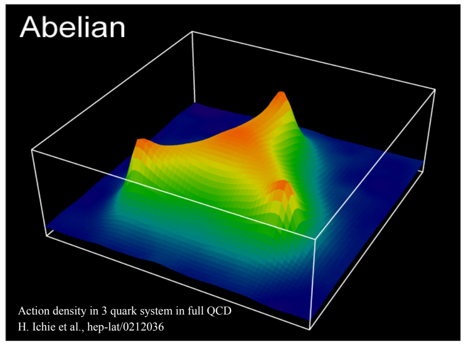


Number of degrees of freedom increases by factor 10 → quarks and gluons

Quark Gluon Plasma created in Heavy Ion collisions at RHIC and LHC



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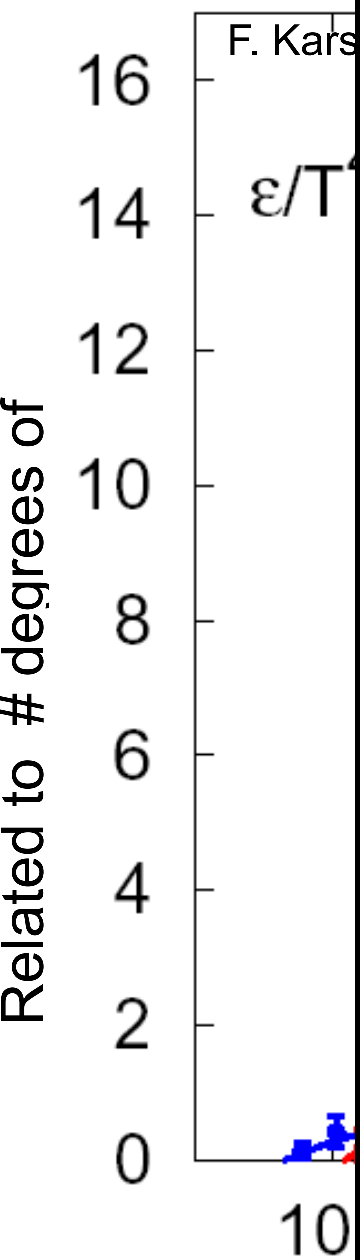

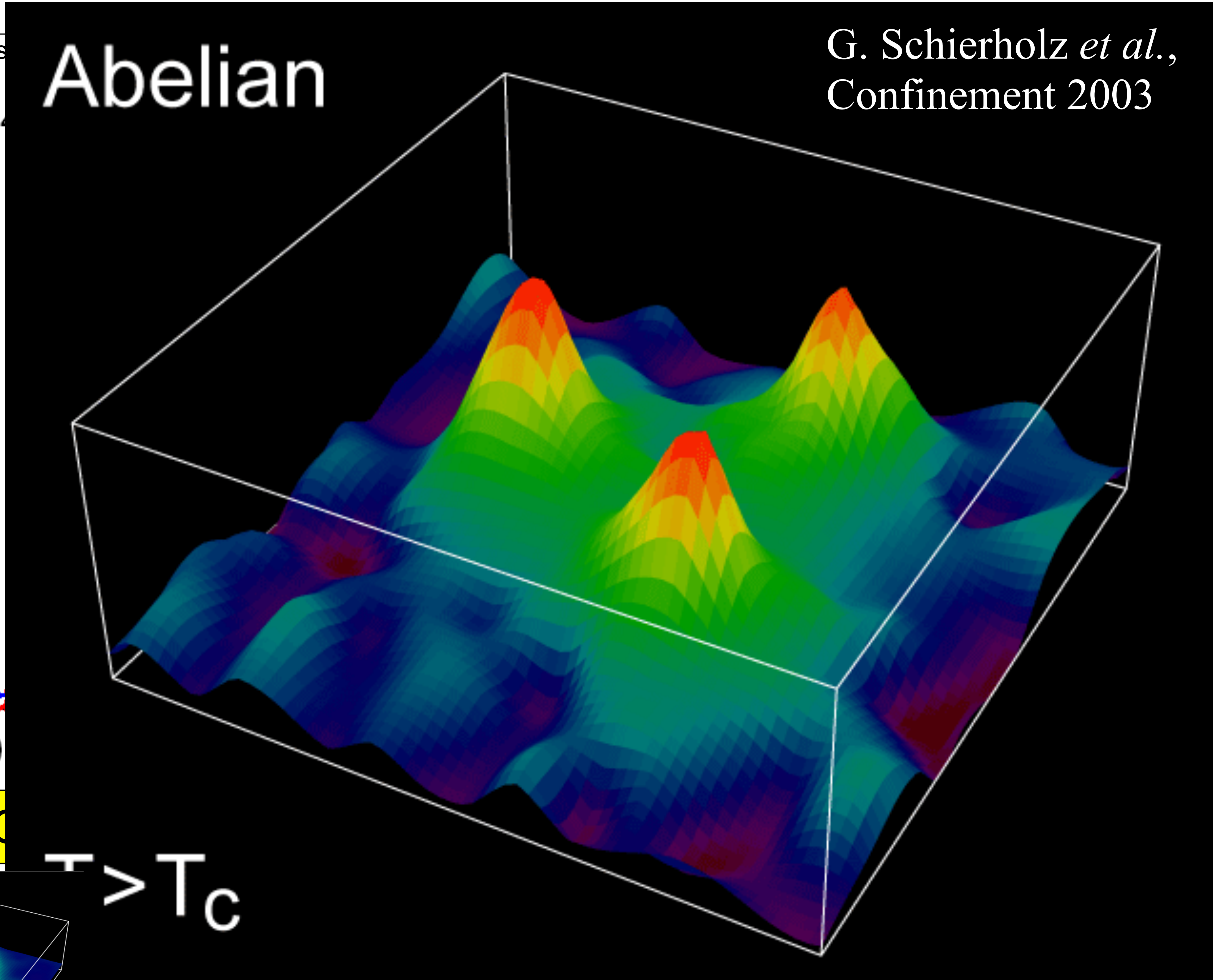

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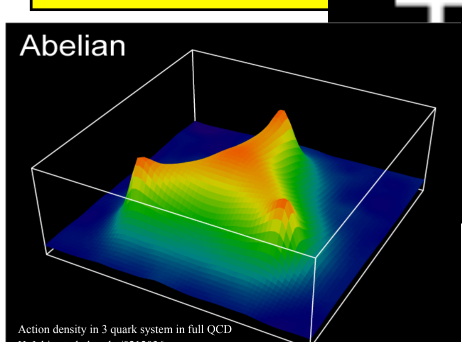
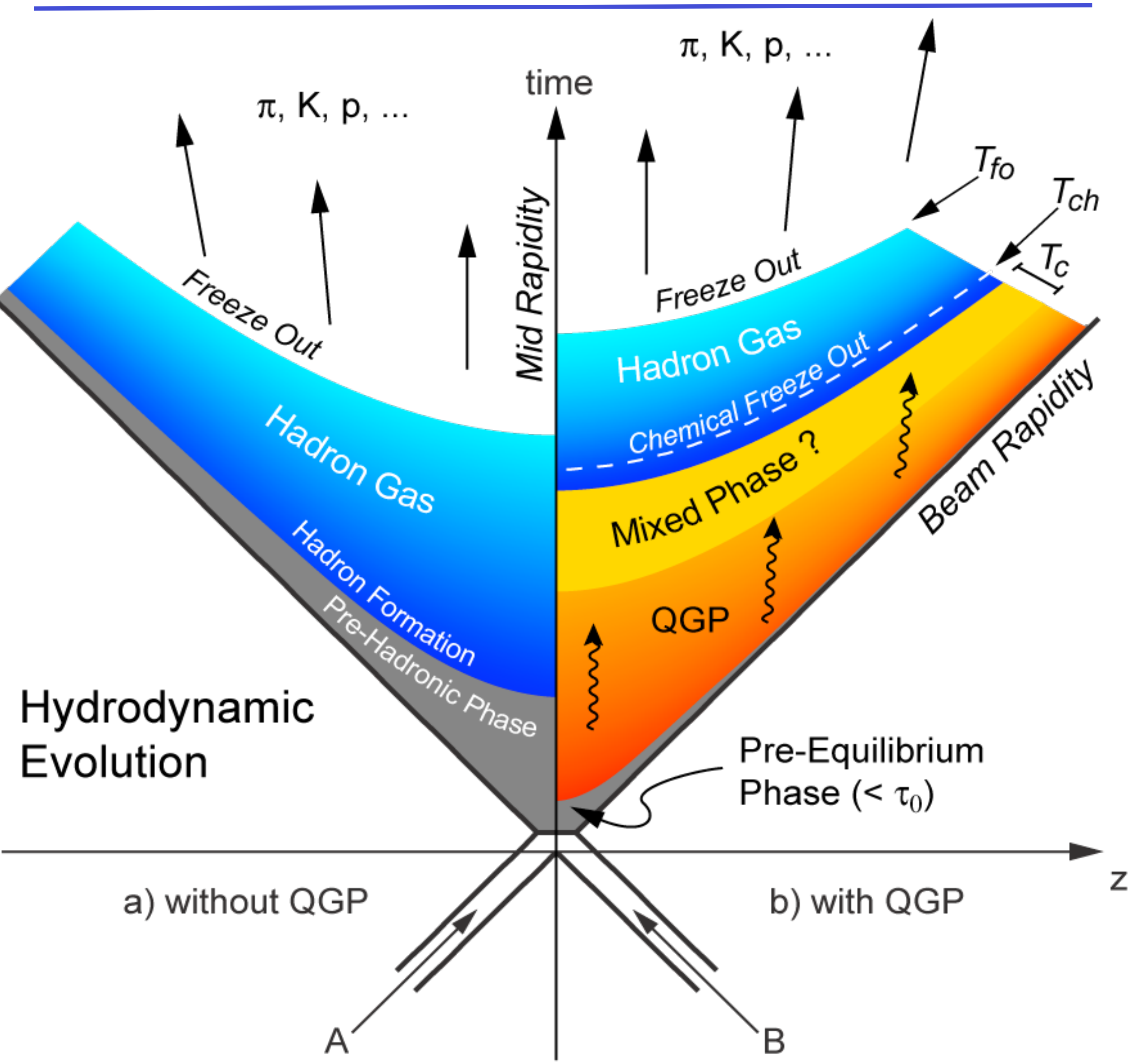
Quark G … LHC



The phase transition in the laboratory



Cold nuclear matter

$\varepsilon_{cold} \approx u \,/\, {}^4/_3\pi r_0^3 \approx 0.13$ GeV/fm^3

Lattice (2-flavor):

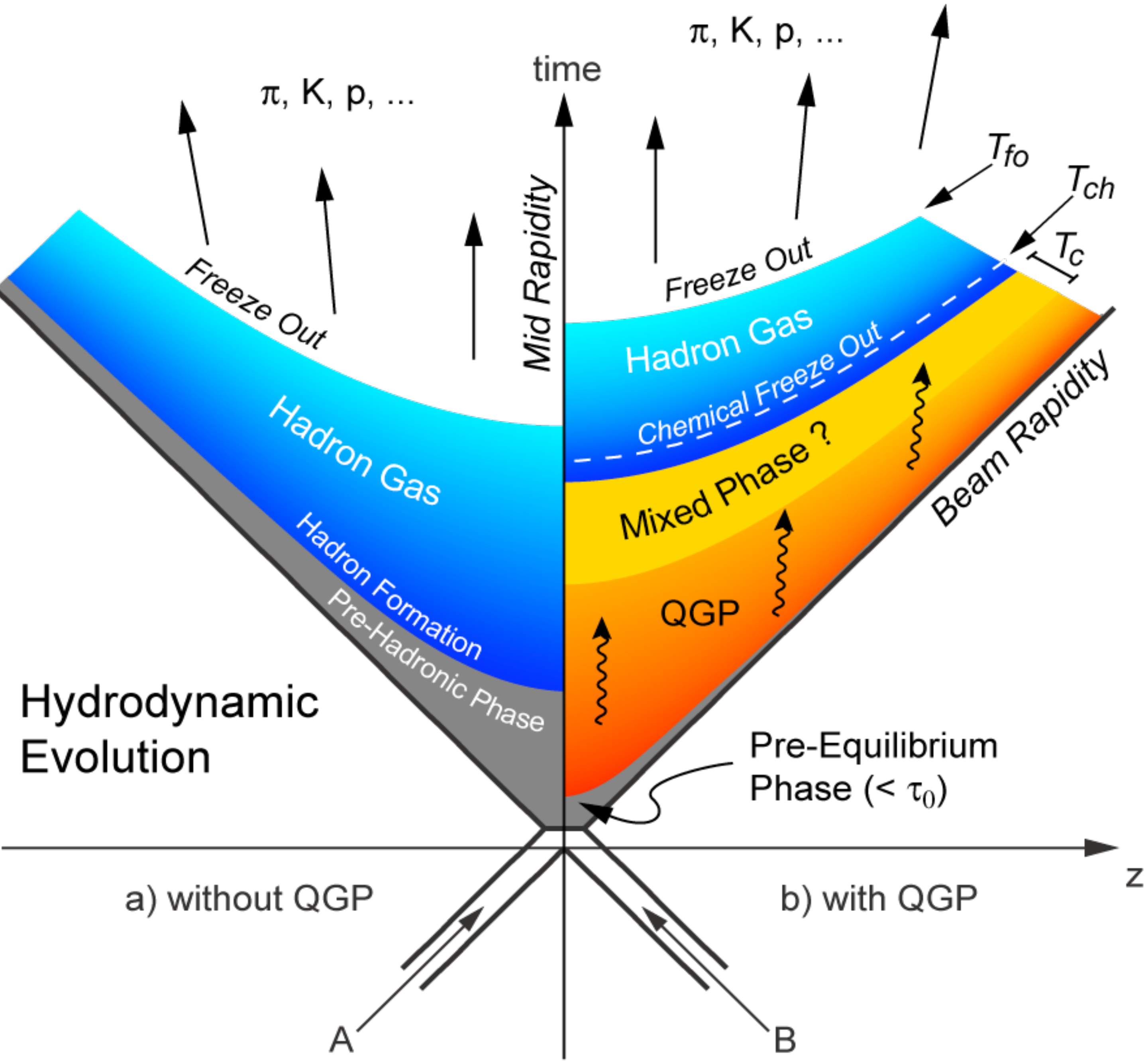
$T_C \approx 173\pm8$ MeV

$\varepsilon_C \approx (6\pm2)\ T^4 \approx 0.70$ GeV/fm^3

Chemical freeze-out:
($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out:
($T_{fo} \leq T_{ch}$): elastic scattering ceases

The phase transition in the laboratory



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Necessary but **not** sufficient condition

$\varepsilon(\sqrt{s}$ =7 TeV pp LHC) >>

$\varepsilon(\sqrt{s}$ =200 GeV Au+Au RHIC)

Chemical freeze-out:

($T_{ch} \le T_c$): inelastic scattering ceases

Kinetic freeze-out:

($T_{fo} \le T_{ch}$): elastic scattering ceases

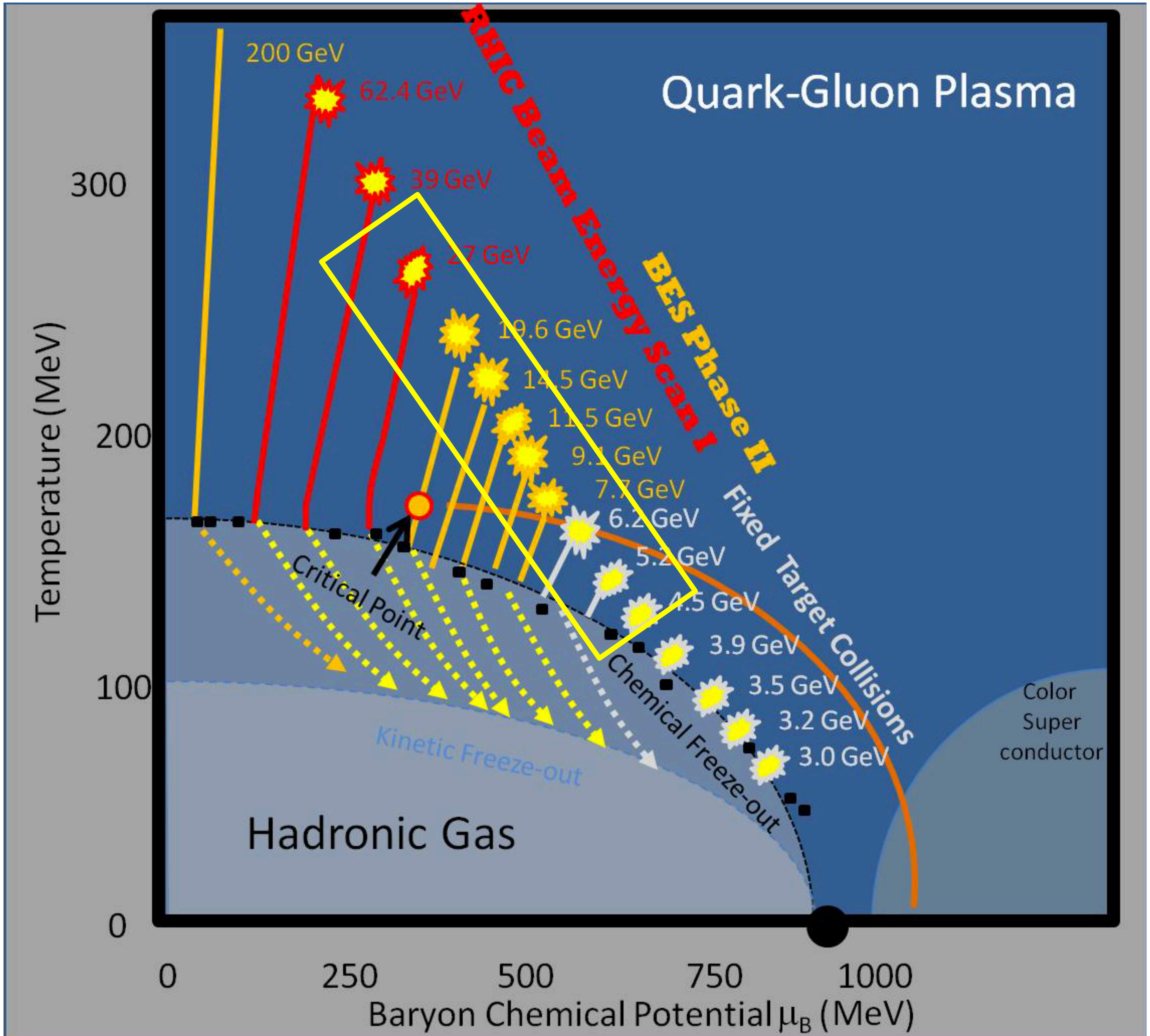
Thermal Equilibrium ⇒

many constituents

RHIC and the LHC

	RHIC	LHC
Start date	2001	2009
Ion	Au-Au & p-p	Pb-Pb & p-p
$\sqrt{s_{NN}}$	5-200 GeV	2.76 & 5 TeV
Circumference	2.4 miles	17 miles
Depth	On surface	175 m below ground
HI Exp.	BRAHMS,PHENIX, PHOBOS, STAR	ALICE, ATLAS, CMS, LHCb
Located	BNL, New York, USA	CERN, Geneva, Switzerland
HI Running	~12 weeks/year	~4 weeks/year

Phase diagram of nuclear matter



Explore phase diagram by changing beam energy and/or nuclei collided

Versatility of RHIC being fully exploited

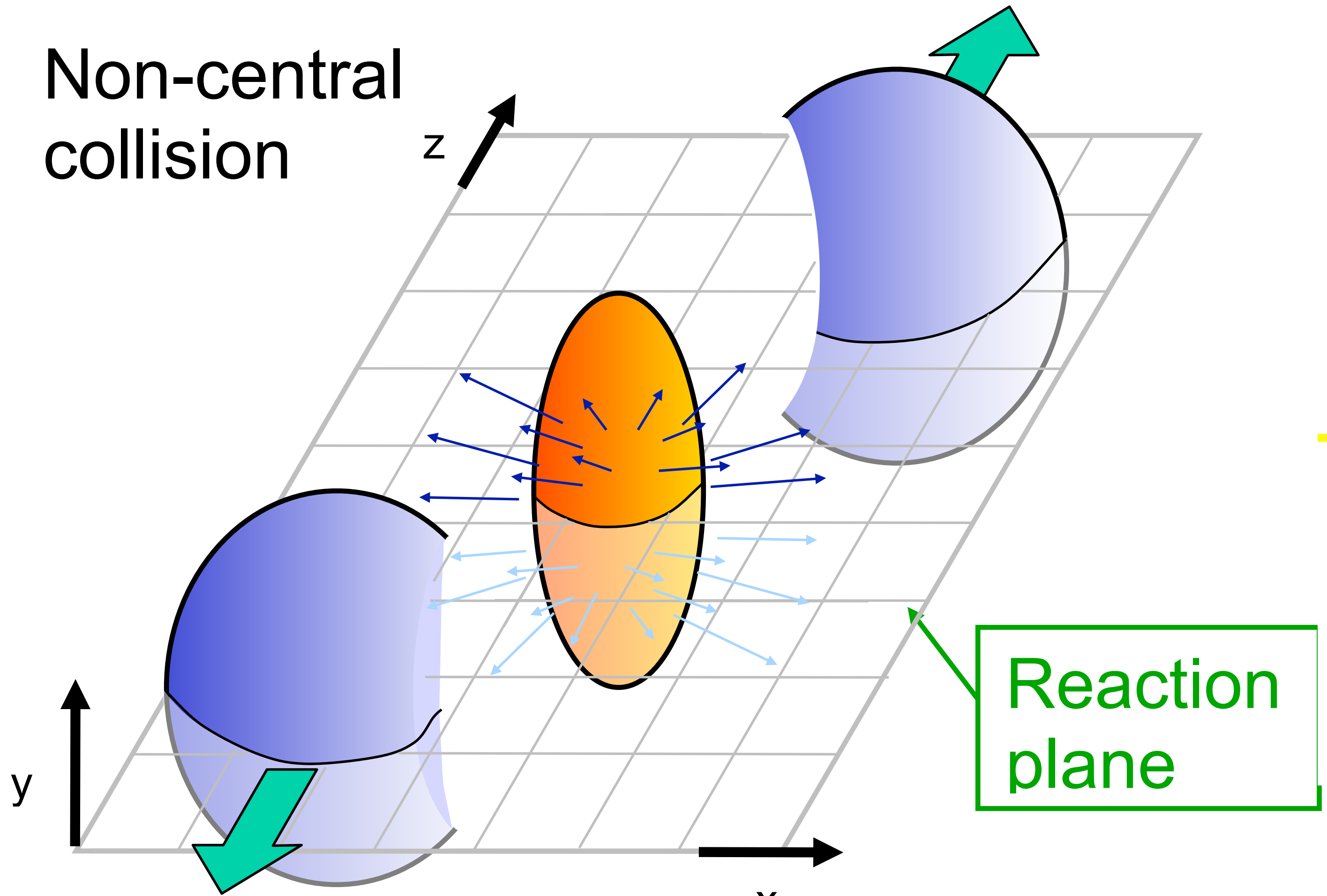
Beam Energy Scan underway

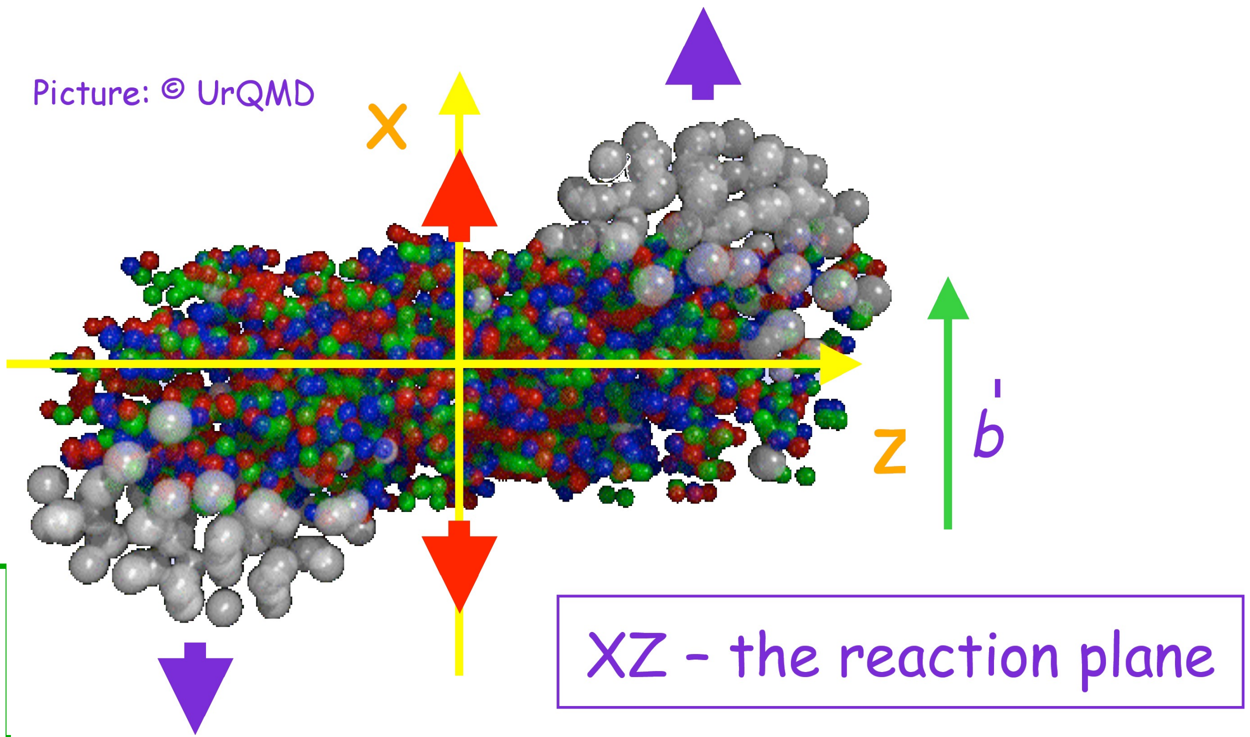
Phase-I completed
Phase-II 2019-2020

Seeking evidence:
- of turn-off of QGP
- location of the Critical Point
- 1st order phase transition

QCD creates a rich landscape to explore

Geometry of a heavy-ion collision





“<u>peripheral</u>” collision ($b \sim b_{max}$)

“<u>central</u>” collision ($b \sim 0$)

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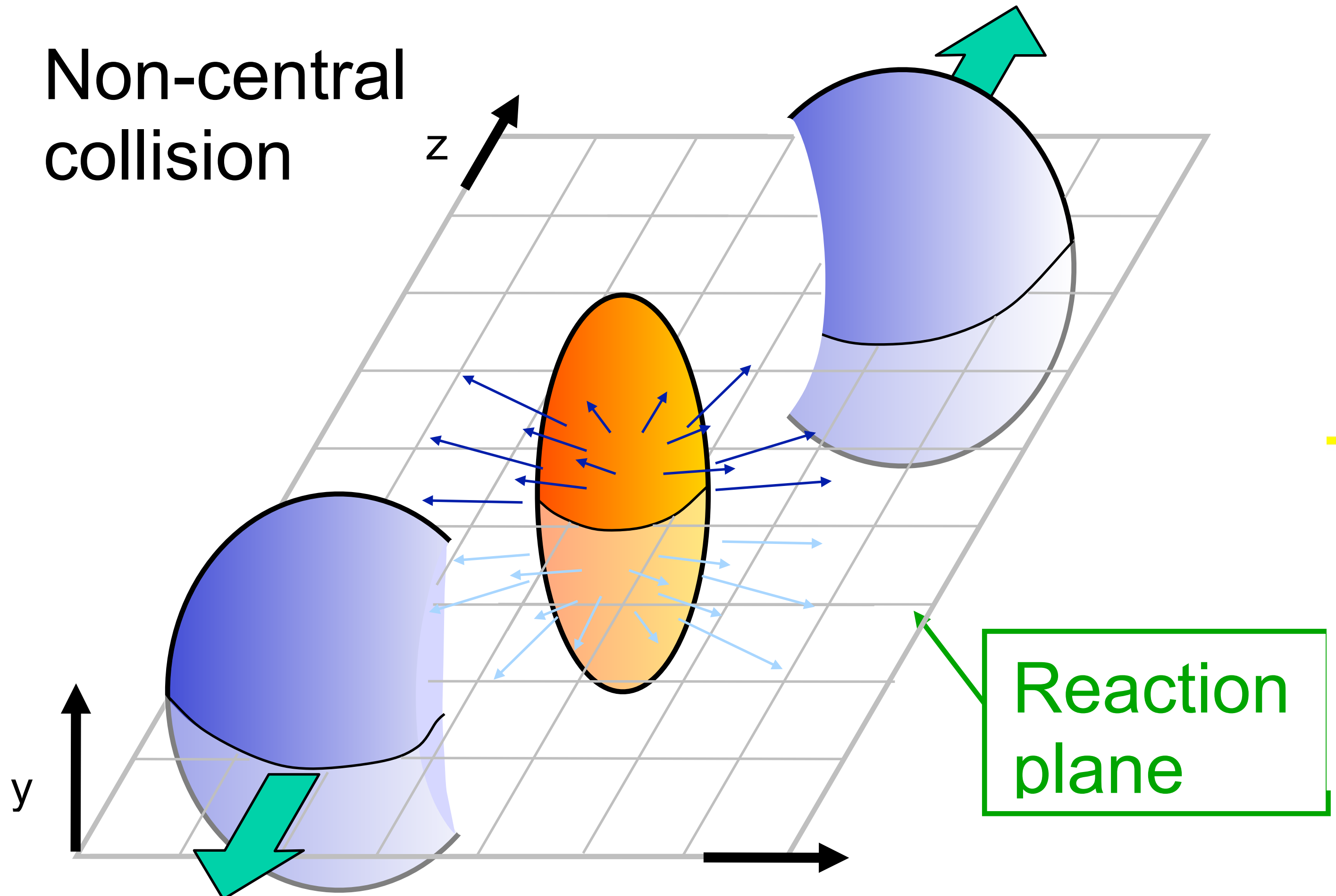
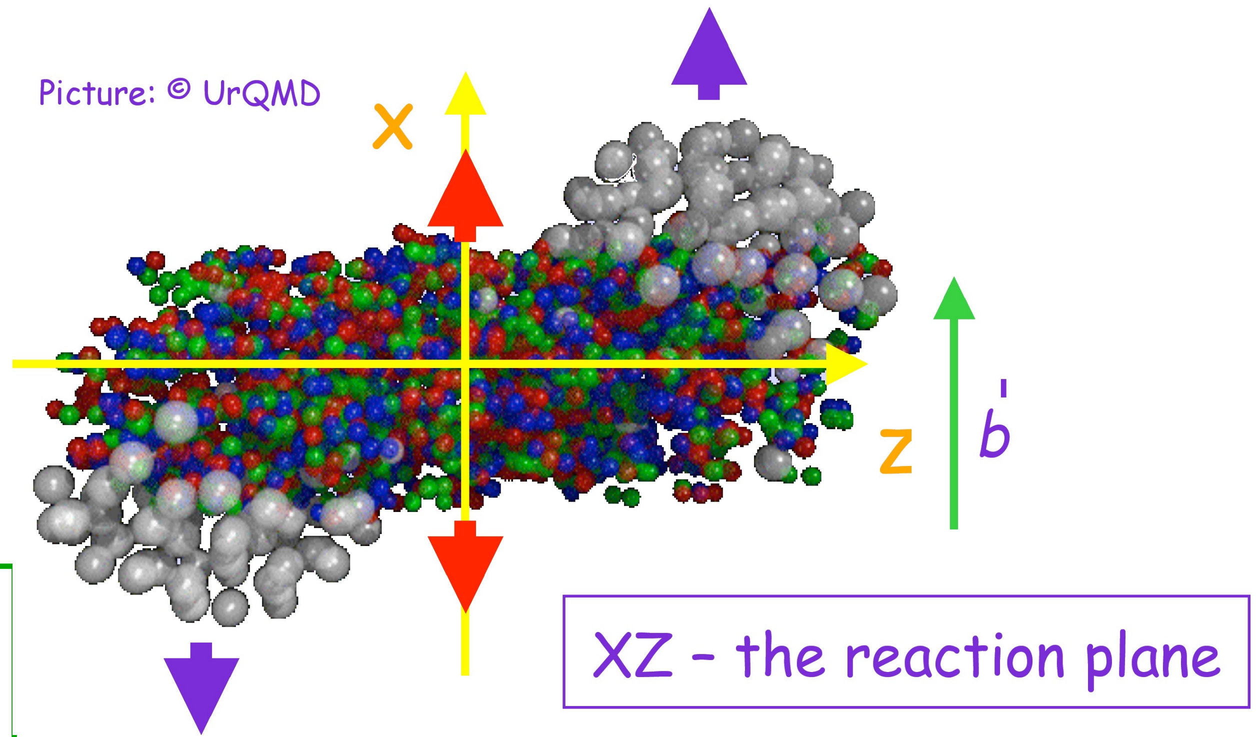




"peripheral" collision ($b \sim b_{max}$)

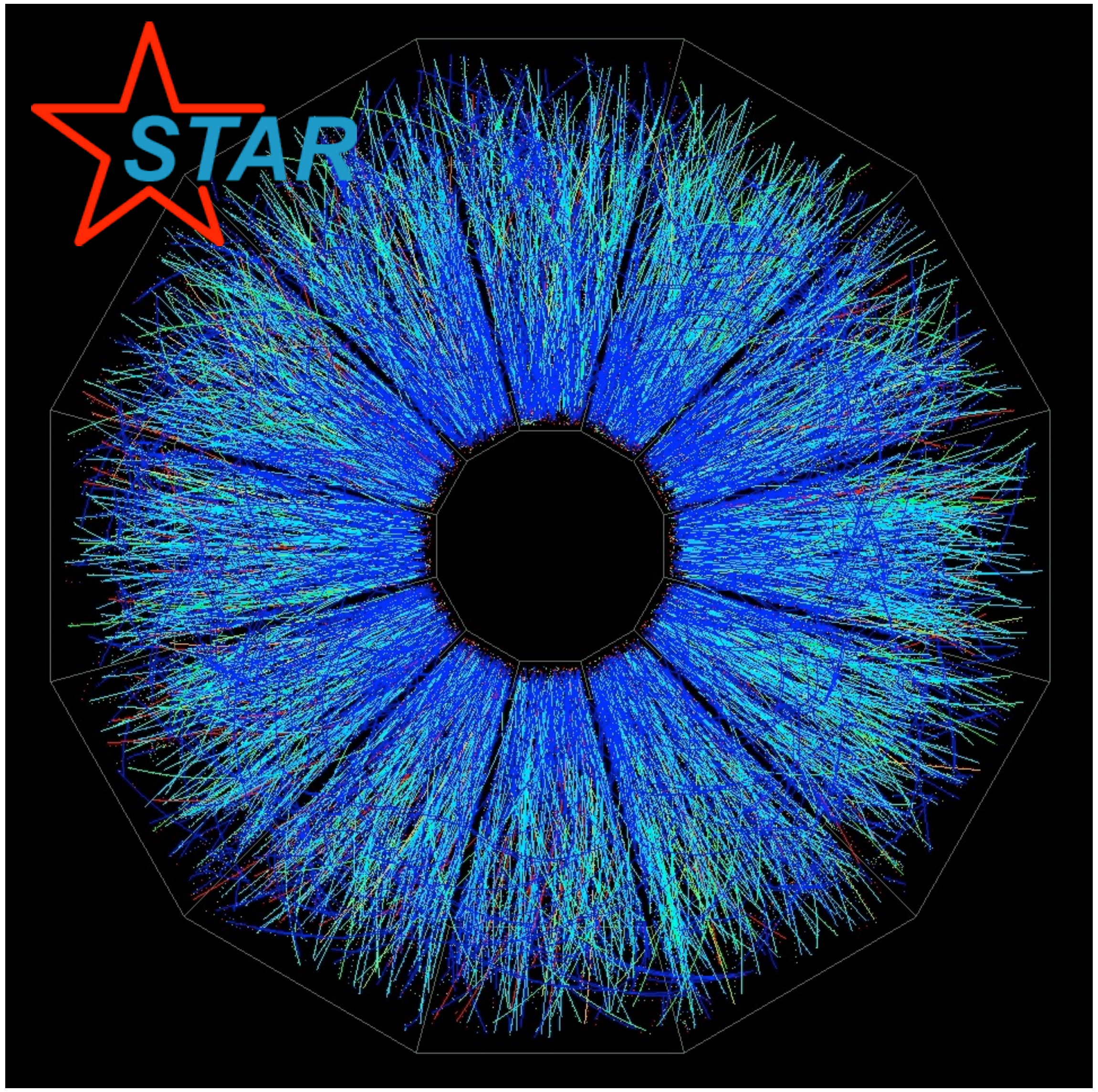
"central" collision ($b \sim 0$)

Number of participants (N_{part}): number of incoming nucleons (participants) in the overlap region

Number of binary collisions (N_{bin}): number of equivalent inelastic nucleon-nucleon collisions

$N_{bin} \geq N_{part}/2$

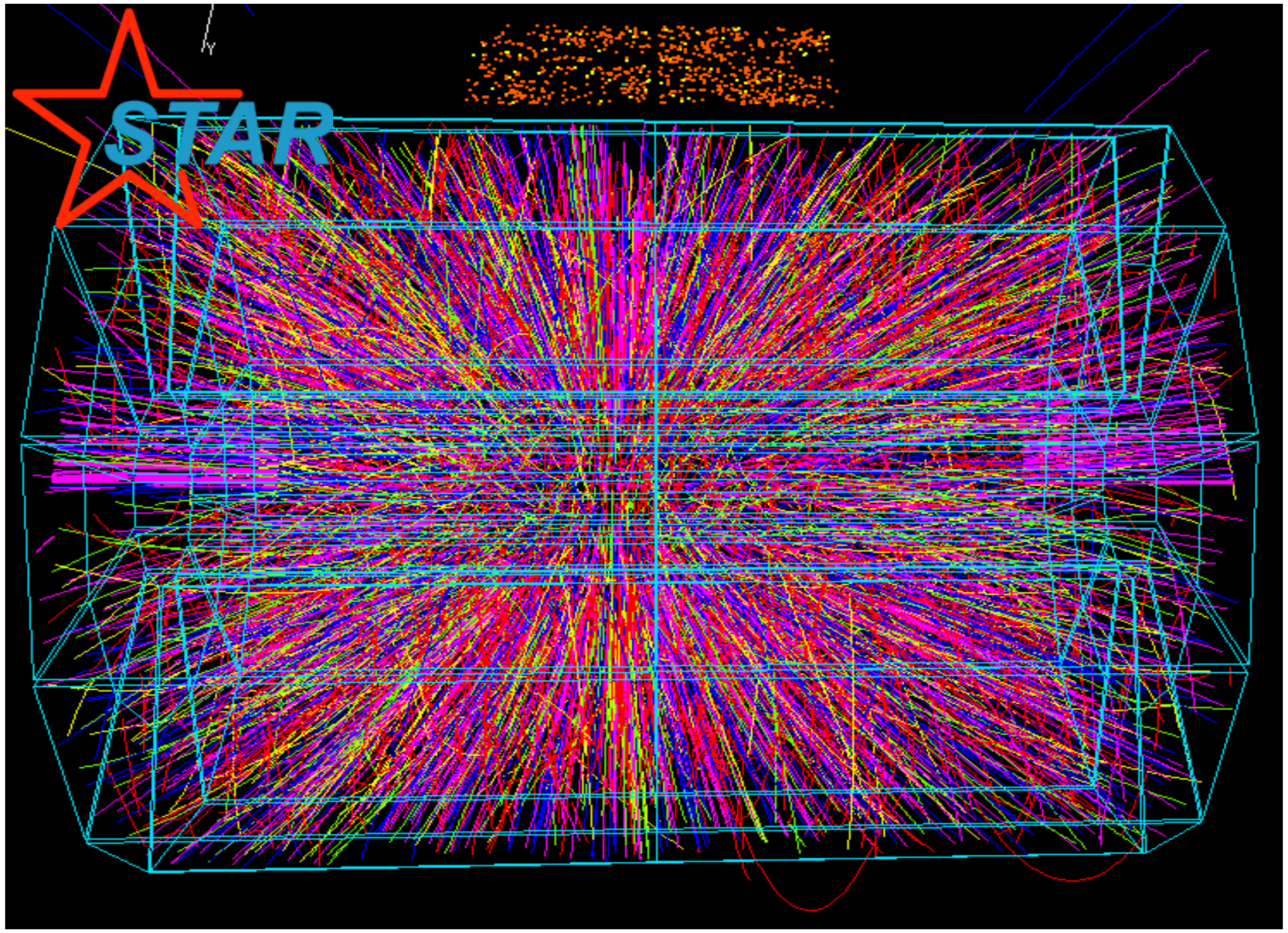
39.4 TeV in central Au-Au collision



>5000 hadrons and leptons

- Only charged particles shown

- Neutrals don't ionise the TPC's gas so are not "seen" by this detector.



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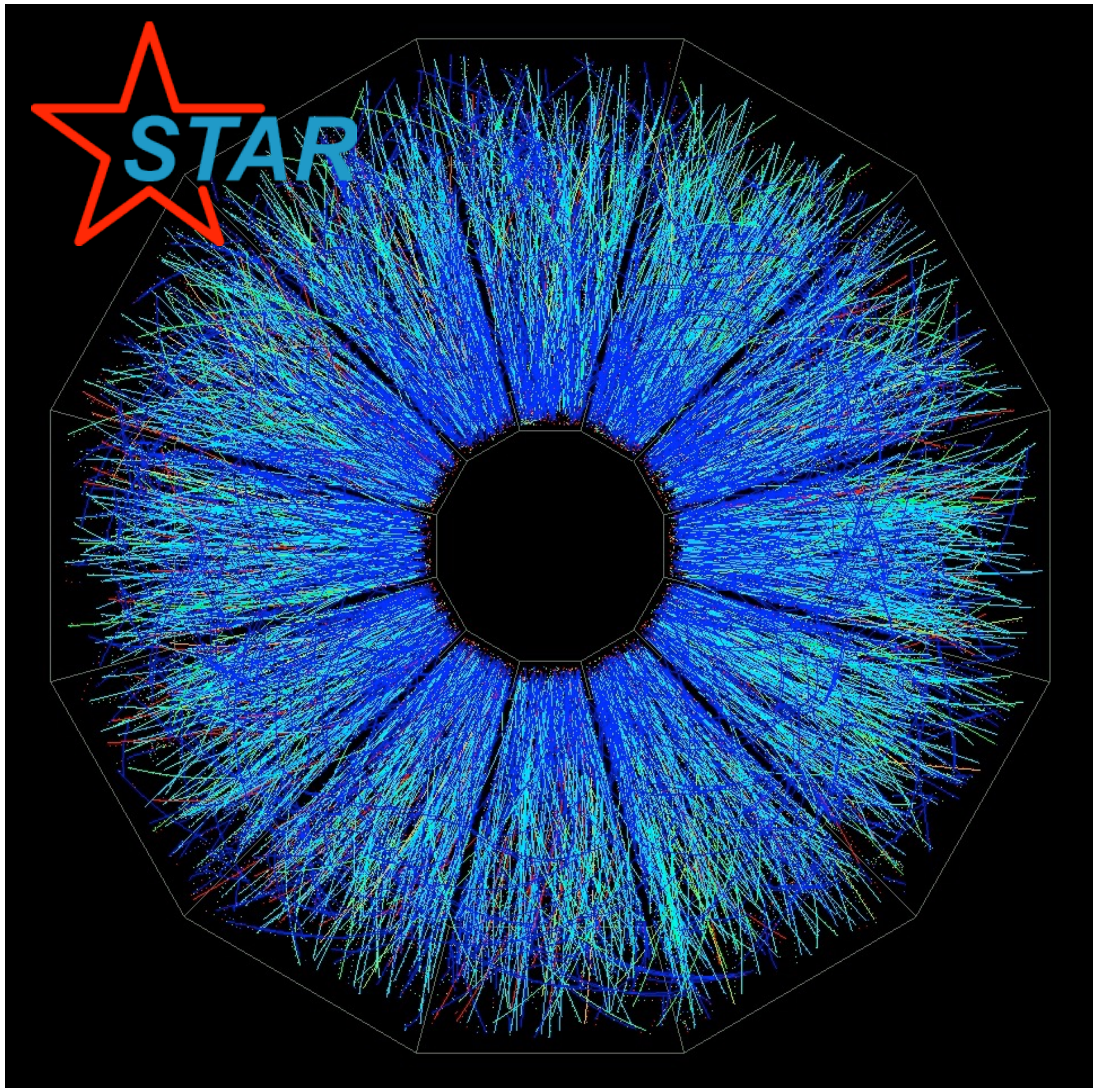

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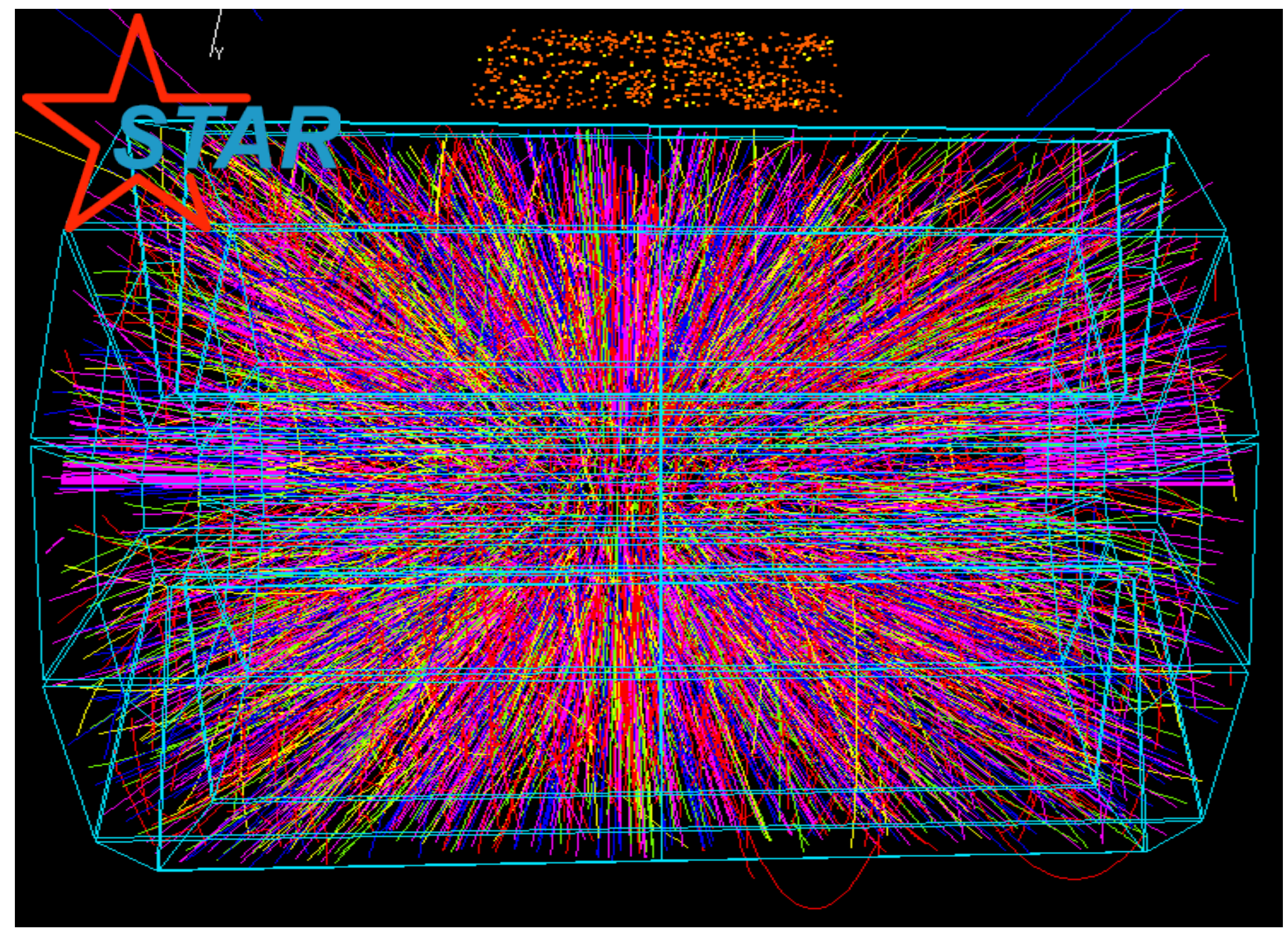


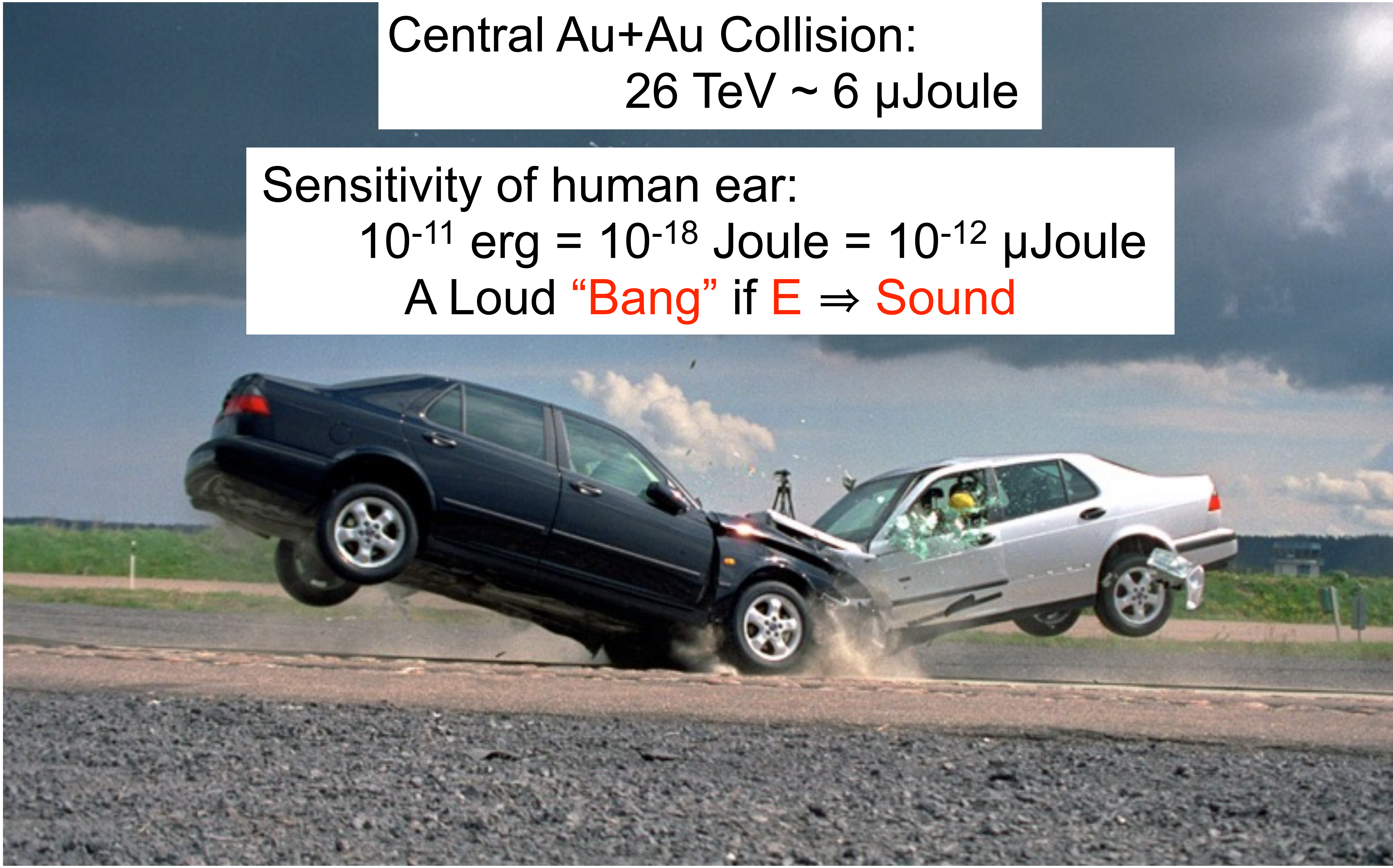
>5000 hadrons and leptons

26 TeV is removed from colliding beams.

The energy is contained in one collision

Central Au+Au Collision:
26 TeV ~ 6 μJoule

The energy is contained in one collision



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Sensitivity of human ear:
10^{-11} erg = 10^{-18} Joule = 10^{-12} μJoule
A Loud "Bang" if E ⇒ Sound

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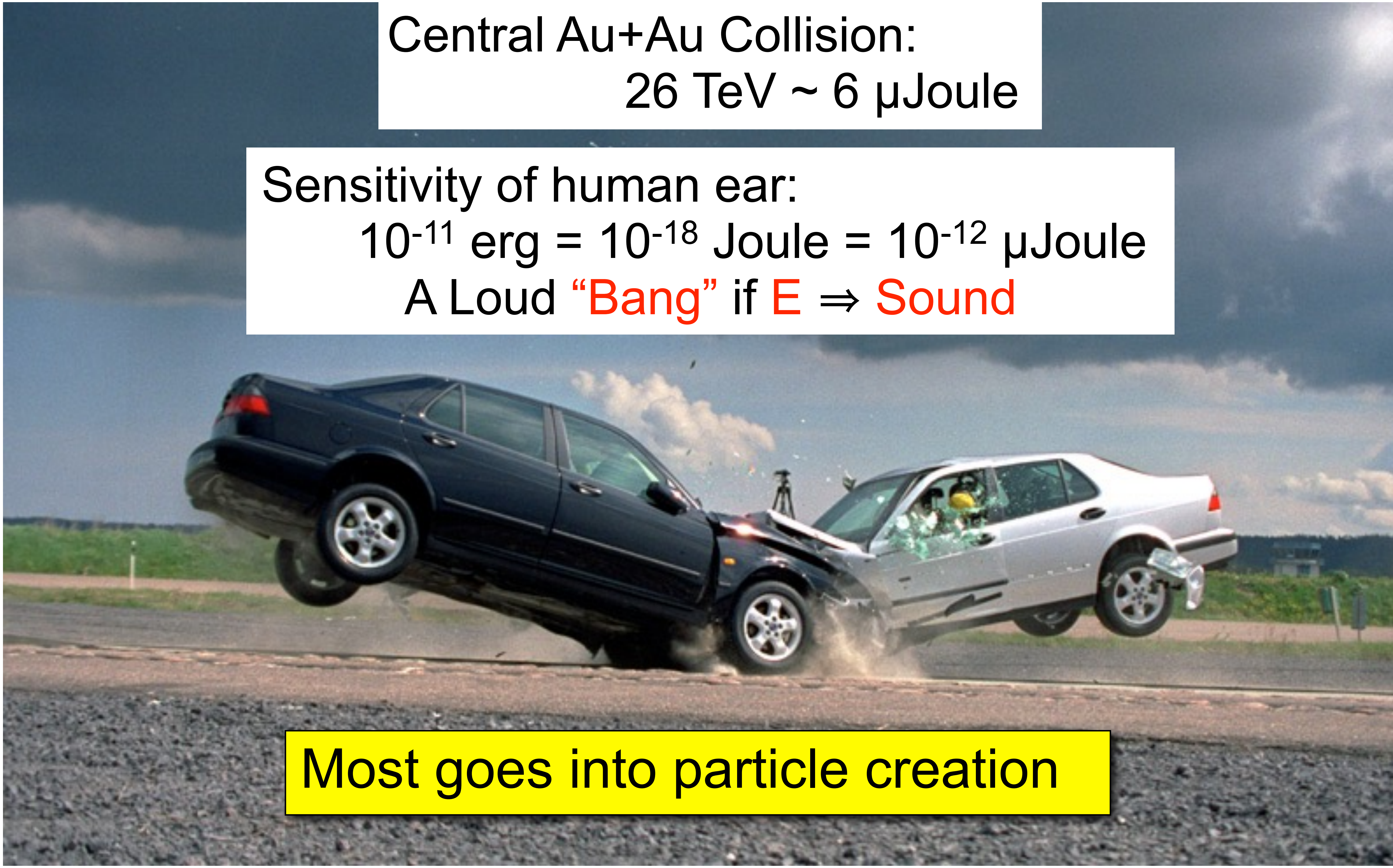
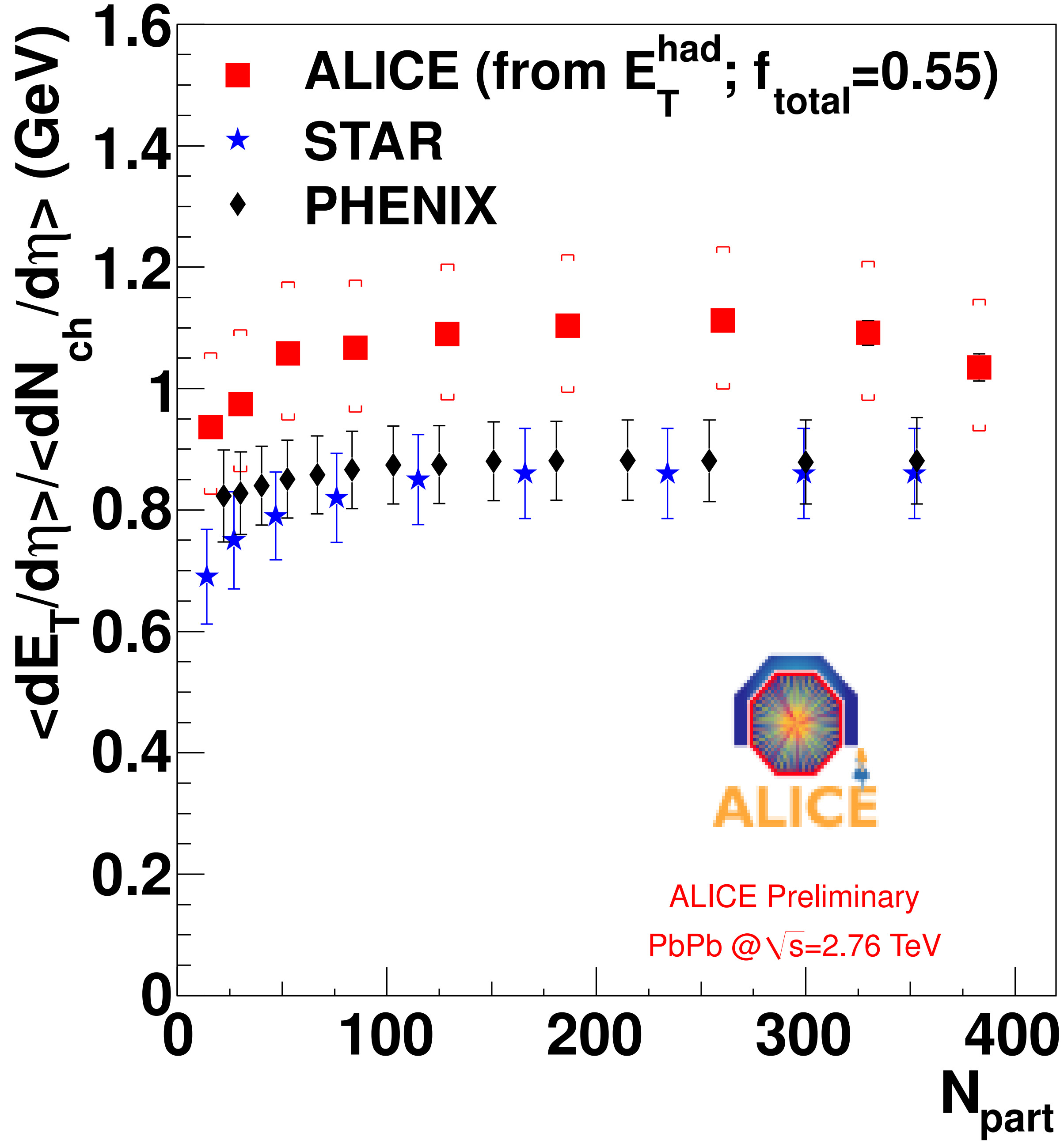


Most goes into particle creation

Early conditions: Energy density

- use calorimeters to measure total energy



LHC: $dN_{ch}/d\eta$ = 1584±4(stat)±76 (sys)

Early conditions: Energy density

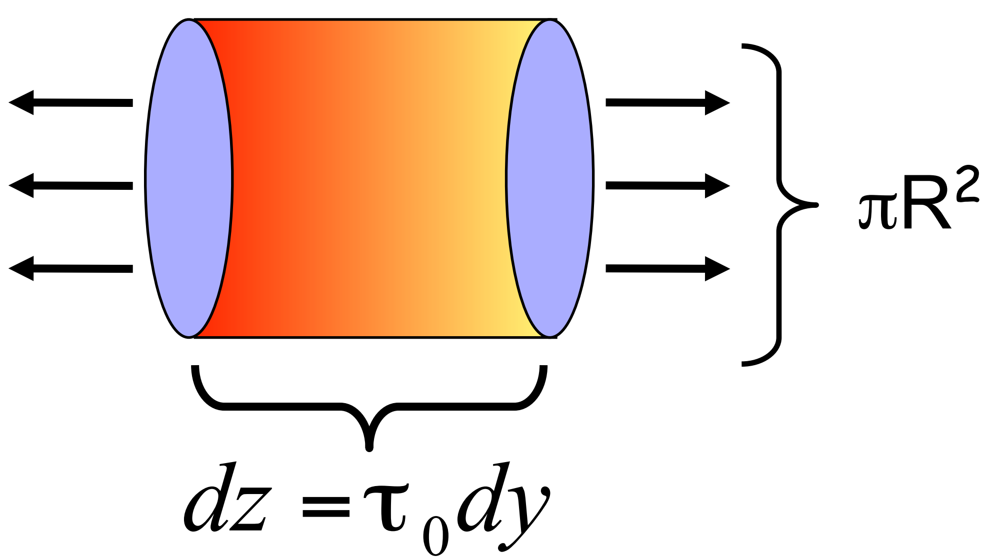
- use calorimeters to measure total energy
- estimate volume of collision

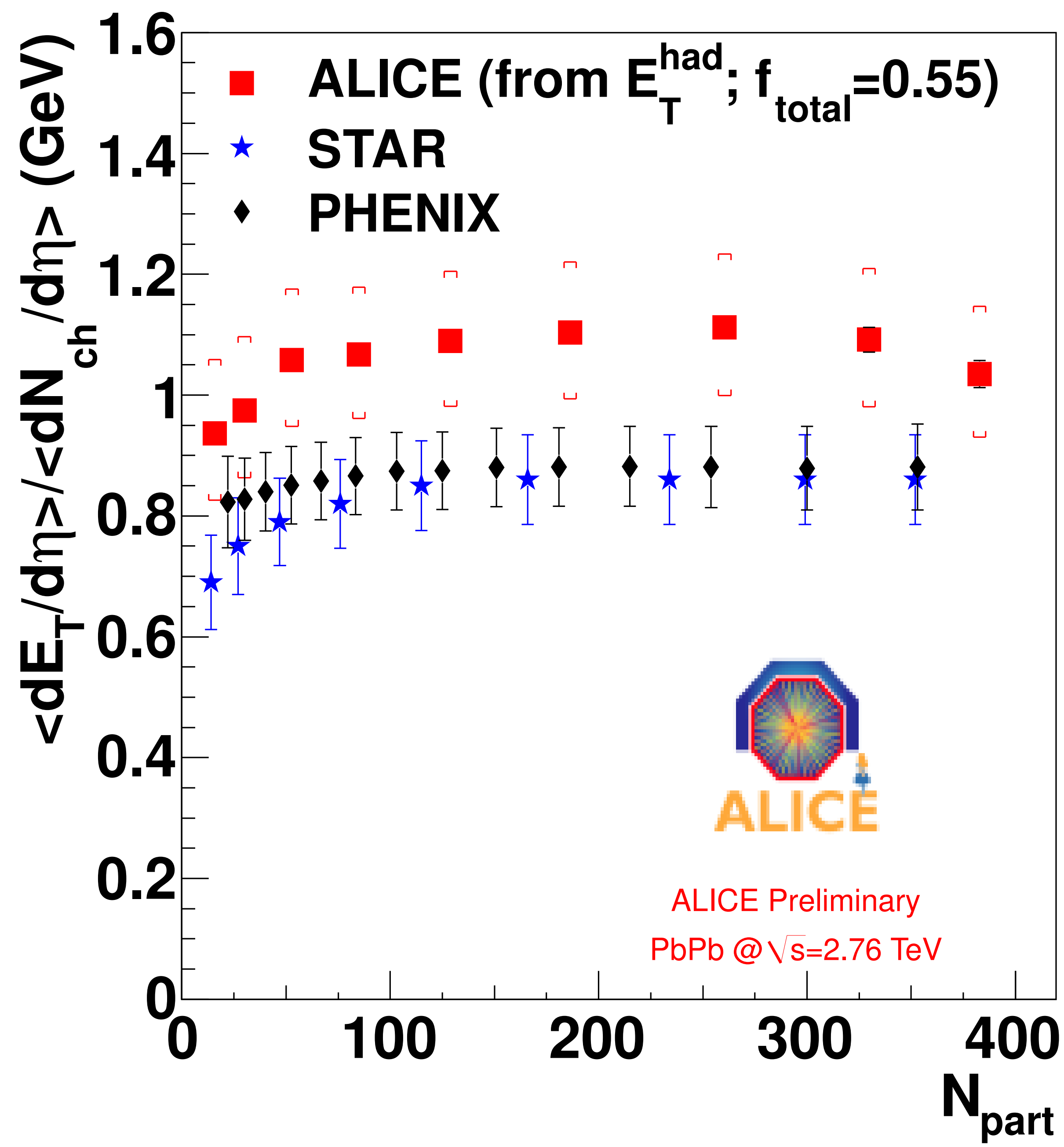
Bjorken-Formula for Energy Density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system (t_0 ~ 1 fm/c)





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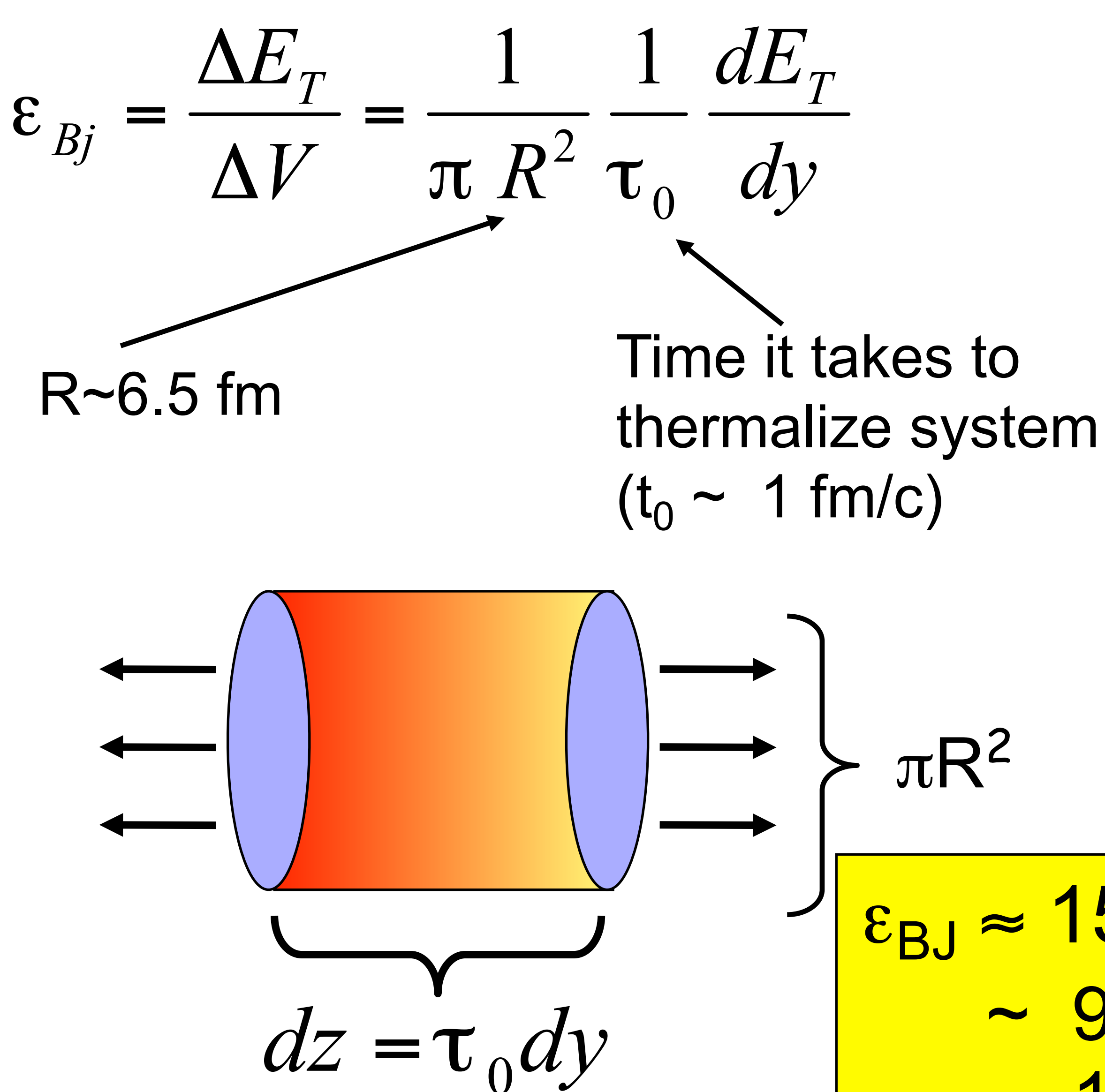

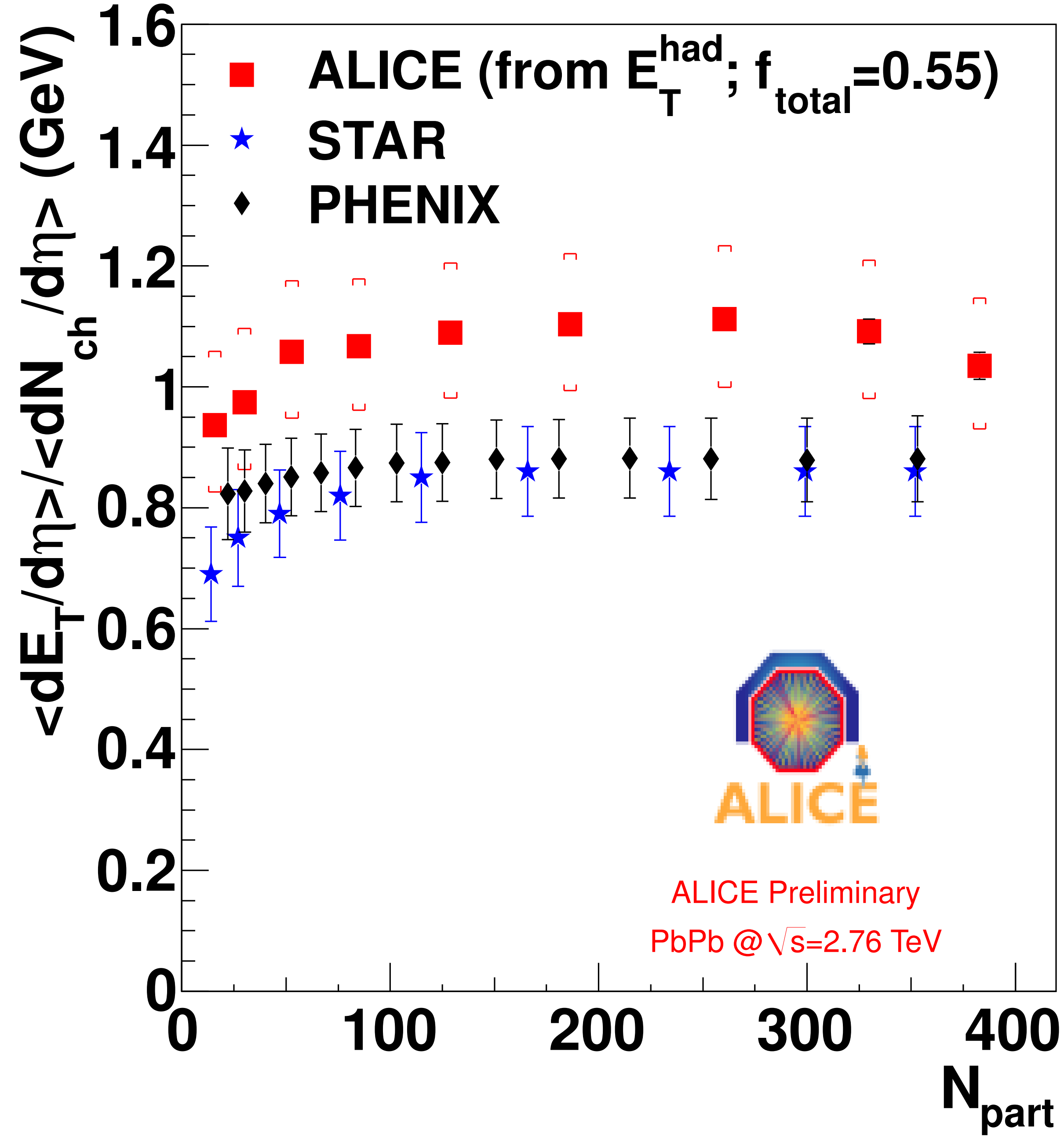

LHC: $dN_{ch}/d\eta$ = 1584±4(stat)±76 (sys)

$\varepsilon_{BJ} \approx$ 15 GeV/fm^3 (RHIC: ~5 GeV/fm^3)
~ 90 (30) times normal nuclear density
~ 15 (5) times > $\varepsilon_{critical}$ (lattice QCD)

5 GeV/fm^3. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy
(1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060 J}{BTU} \times \frac{1 eV}{1.6 \times 10^{-19} J} = 6.6 \times 10^{38} eV$$

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At 5 GeV/fm^3, this would fit in a volume of:

$$6.6 \times 10^{38} eV \div \frac{5 \times 10^{9} eV}{fm^3} = 1.3 \times 10^{29} fm^3$$

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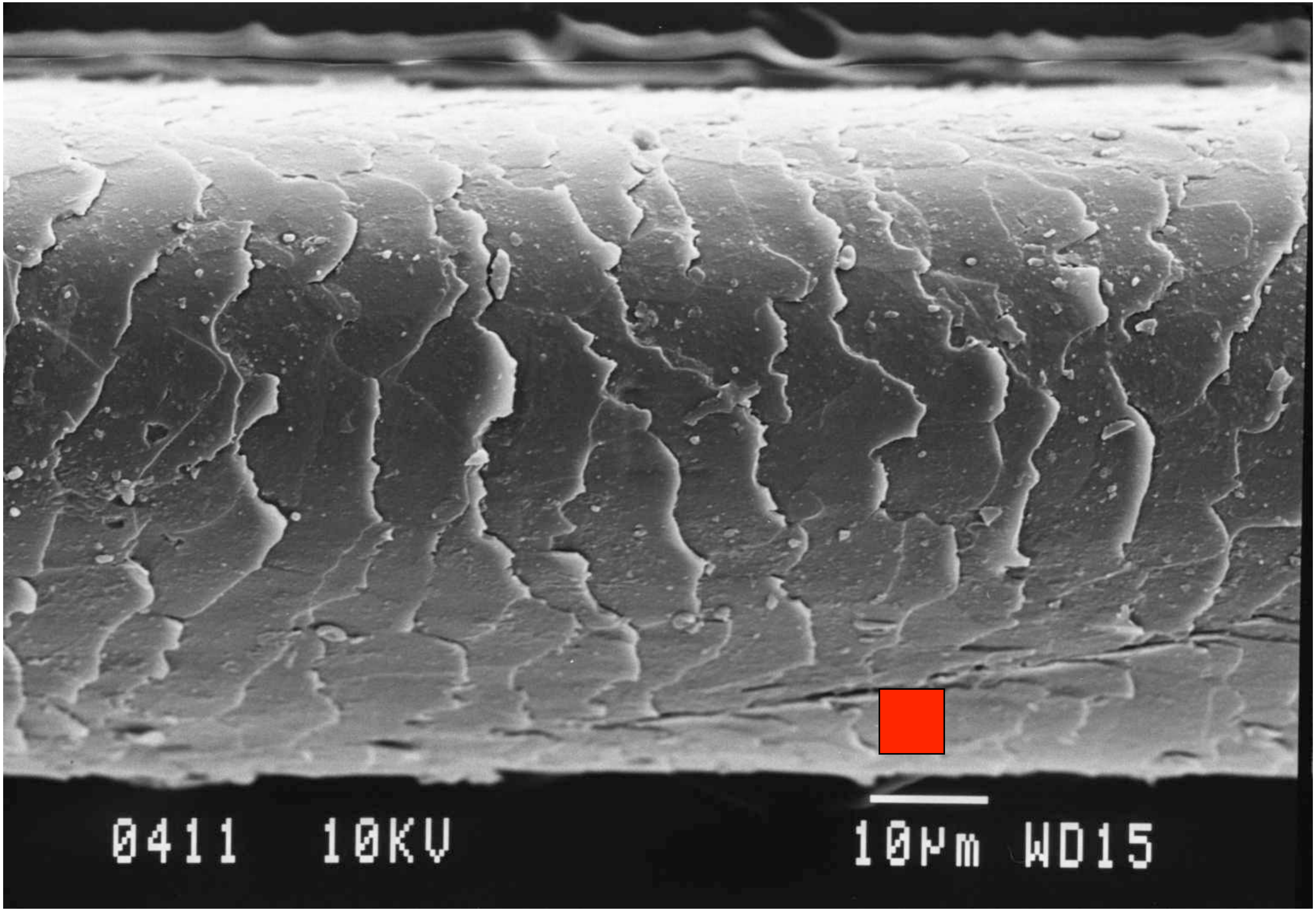
Or, in other words, in a box of the following dimensions:

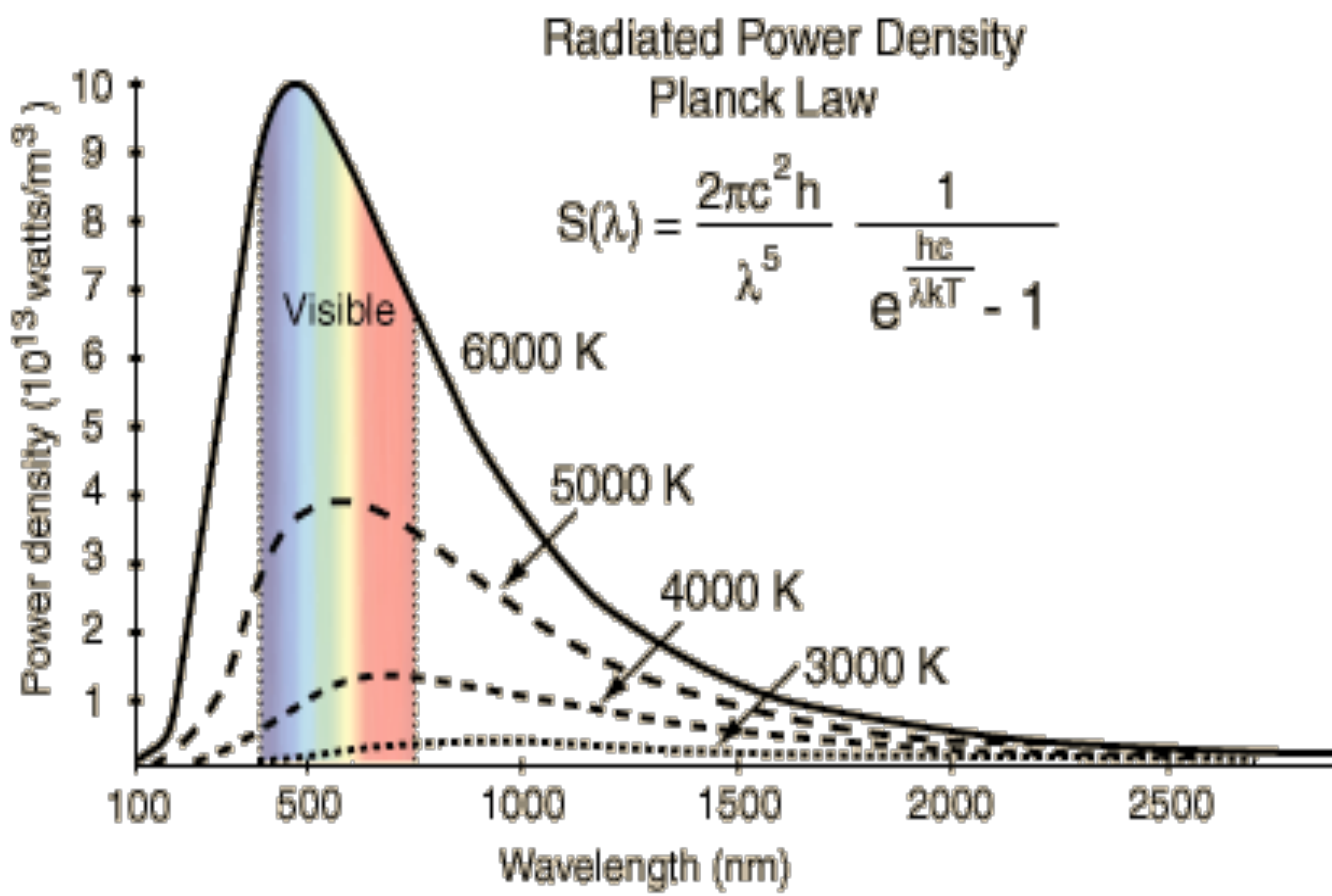
$$\sqrt[3]{1.3 \times 10^{29}\, fm^3} = 5 \times 10^{9}\, fm = 5 \mu m$$

A human hair



Measuring the initial temperature

Planck distribution describes intensity as a function of the wavelength of the emitted radiation



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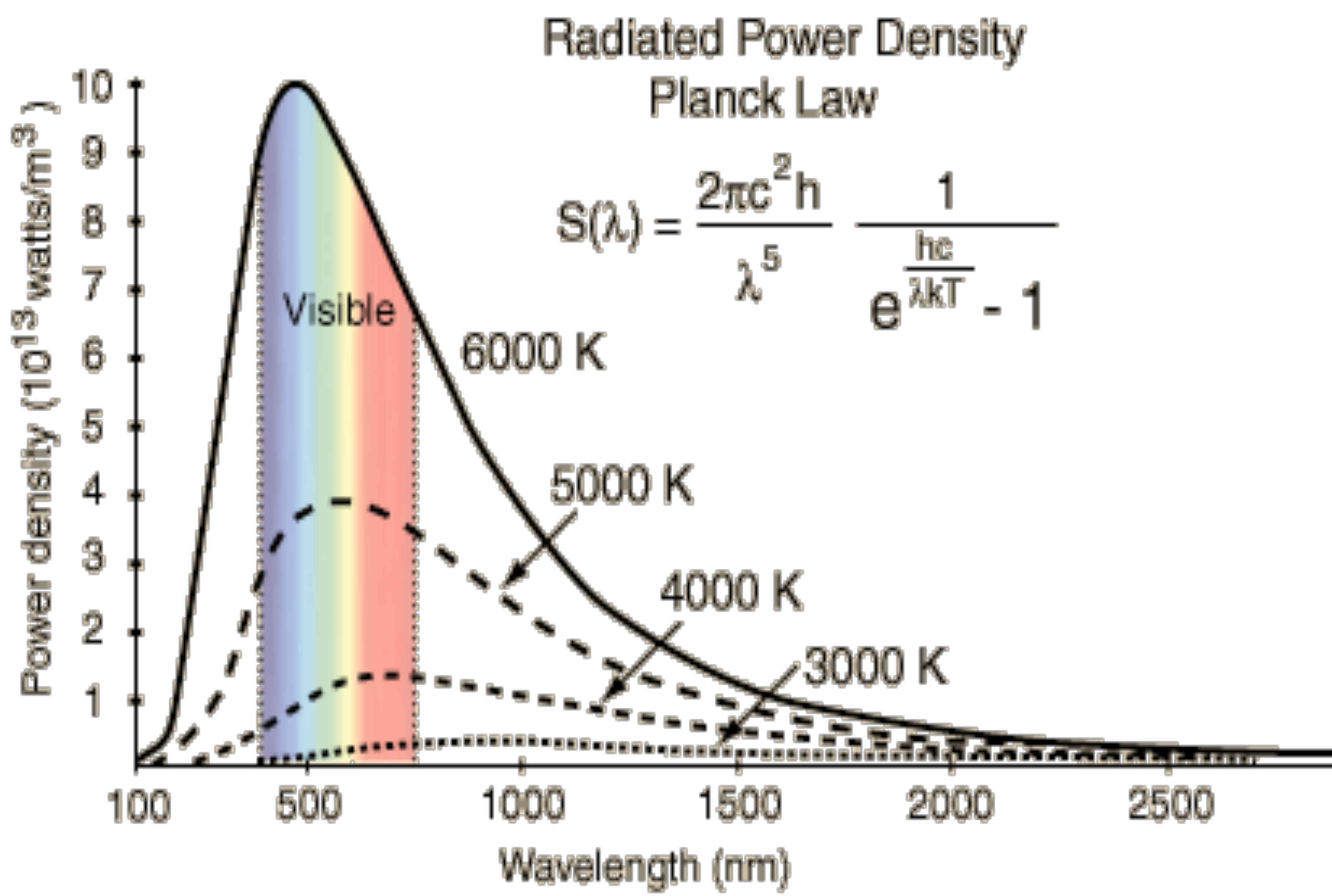
"Blackbody" radiation is the spectrum of radiation emitted by an object at temperature T



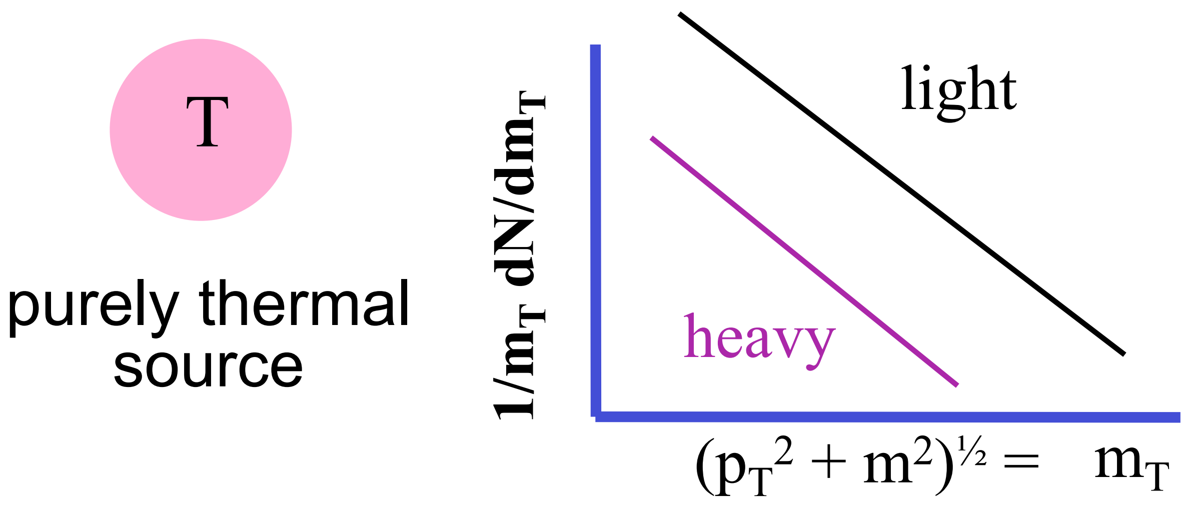
As T increases curve changes

Use momentum spectra to reveal temperature of QGP

Initial conditions: Temperature

Thermal source emits "Blackbody" radiation

→ p_T spectra reveal temperature of QGP



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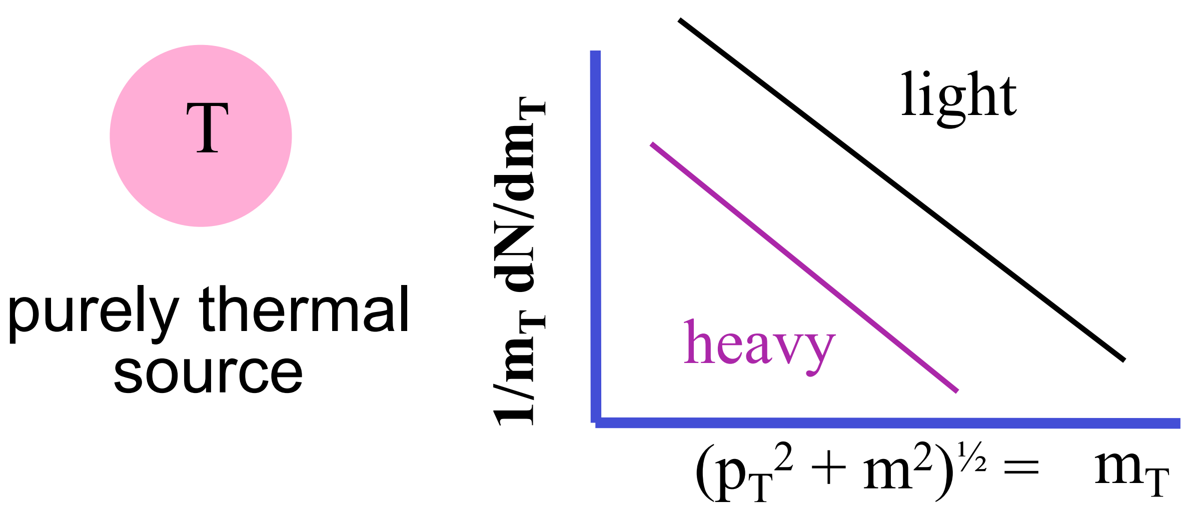

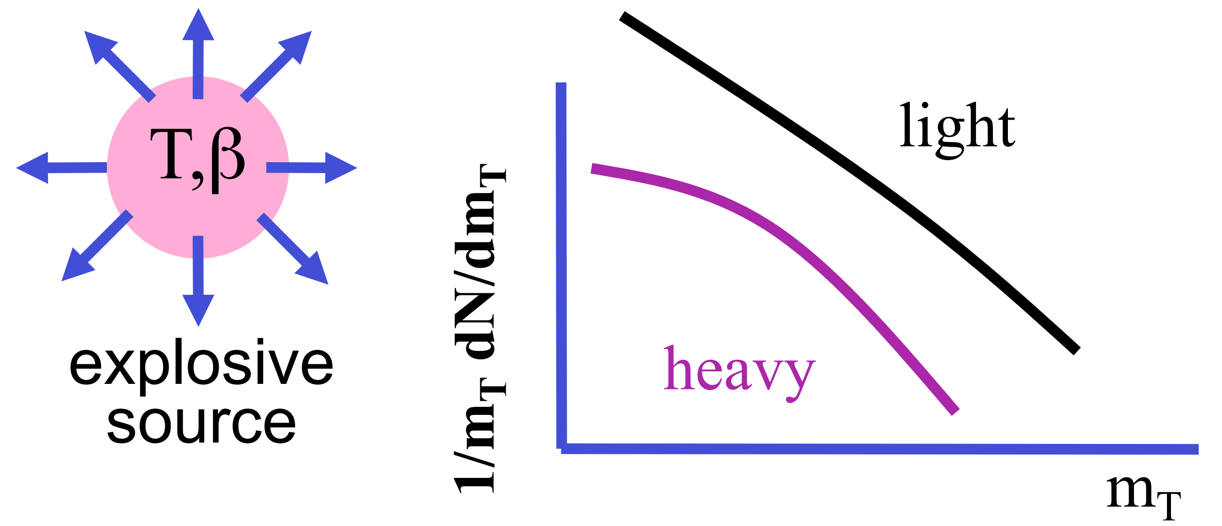

Different spectral shapes for particles of differing mass
→ strong collective radial flow

π light so not/hardly affected by flow

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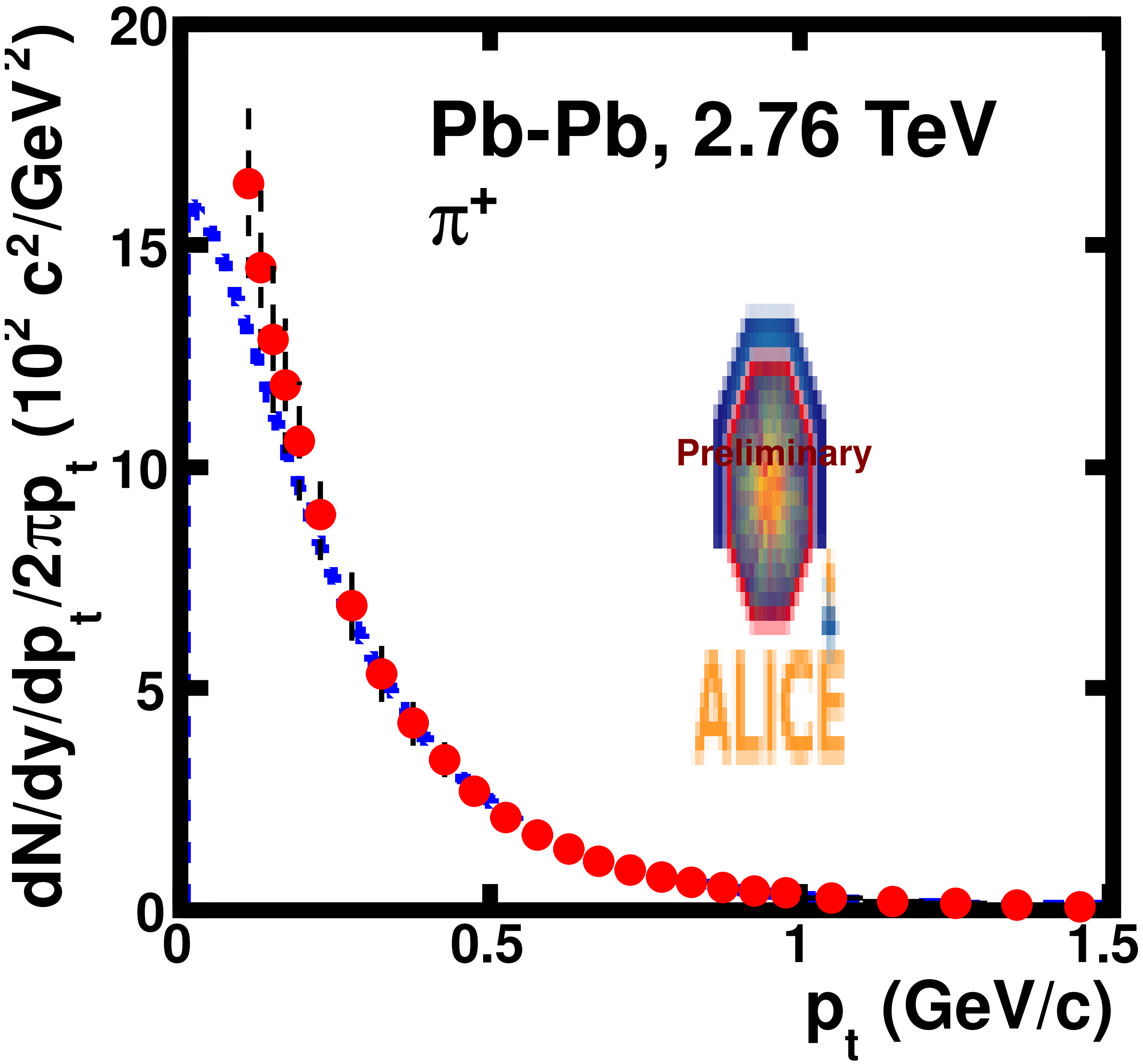

Fit to central data T ~80 MeV

$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k}$$

$$= \frac{2 \times 80 \times 10^6}{3 \times 1.4 \times 10^{-23}} \times 1.6 \times 10^{-19}$$

$$\sim 9 \times 10^{11} K$$

Source is explosive

See mass dependence as expected

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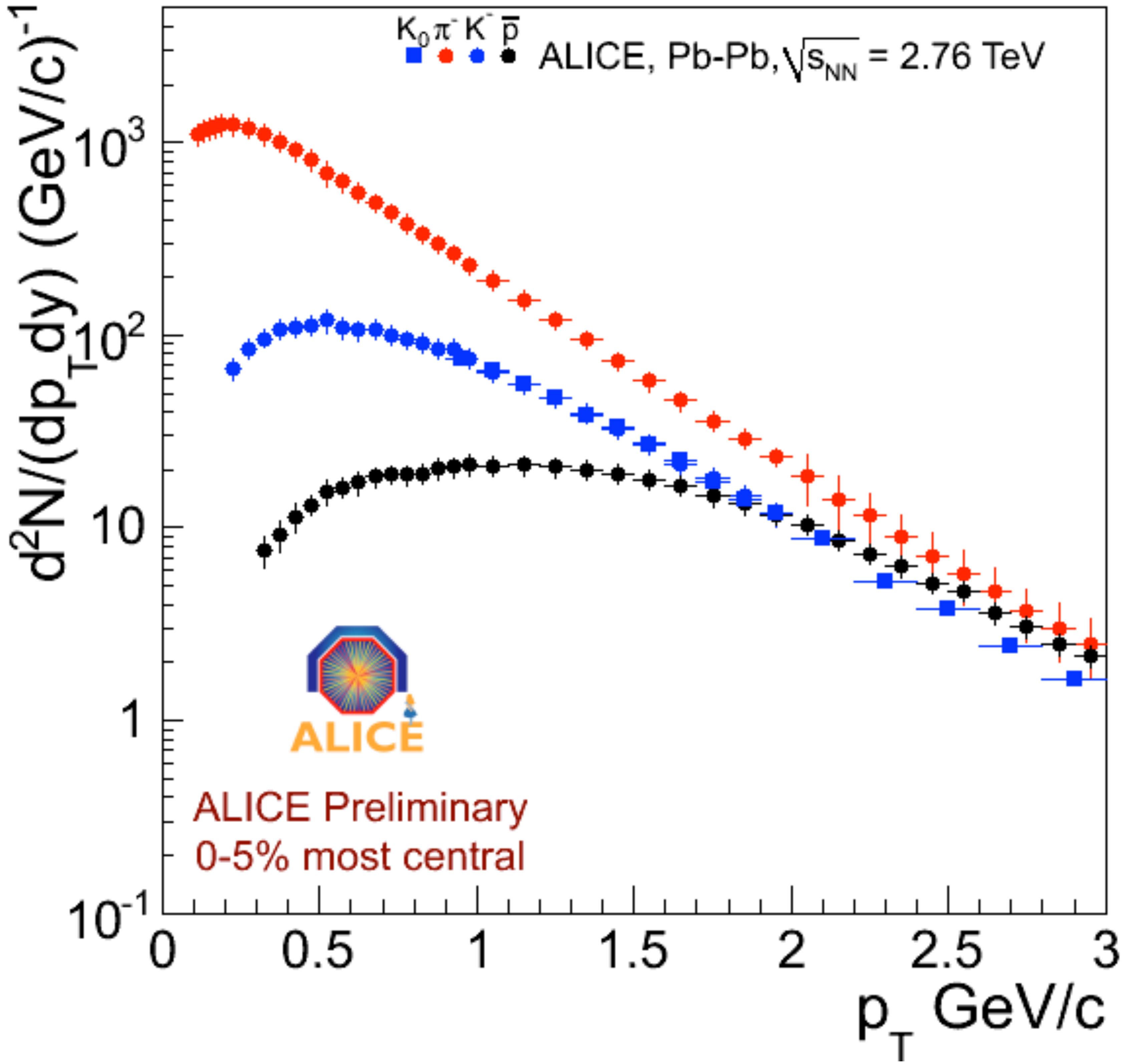

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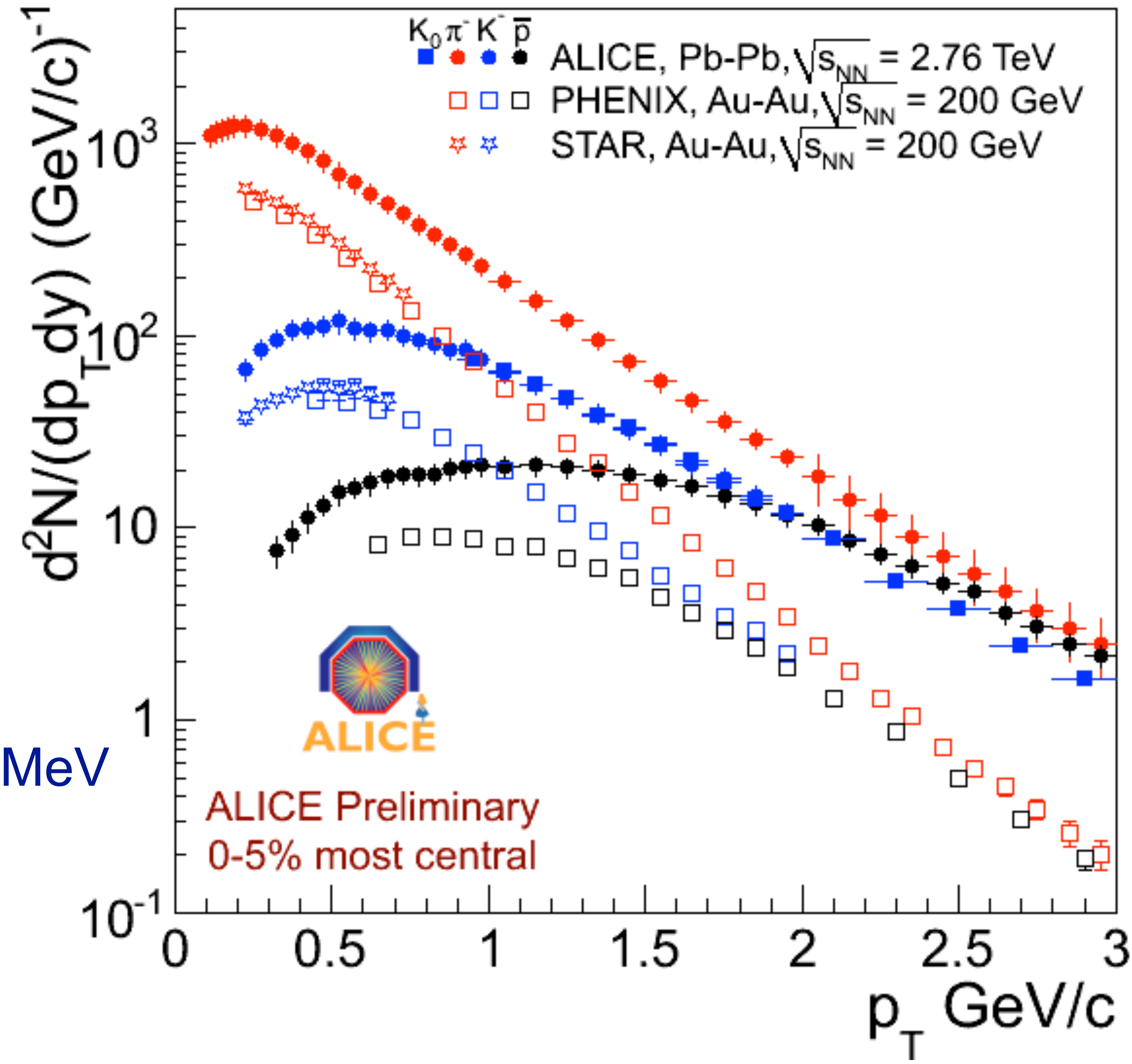
See mass dependence as expected

Spectra much harder and yield higher than at RHIC

Very strong radial flow

$\beta_{LHC} \approx 0.65c \sim 1.1\ \beta_{RHIC}$

$T_{kin,LHC} = T_{kin,RHIC} \sim$ 80-95 MeV



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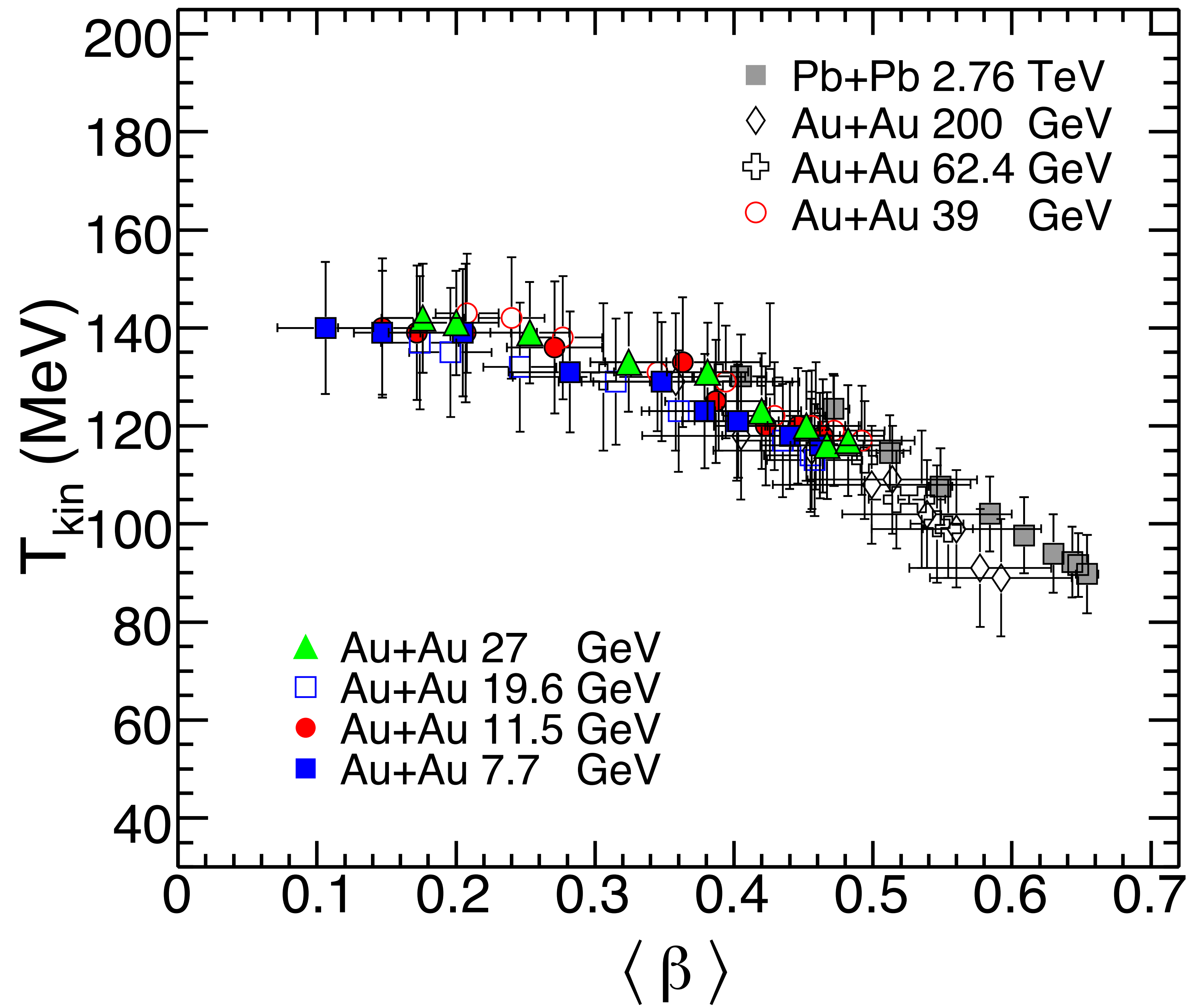
$T_{kin,LHC} = T_{kin,RHIC} \sim$ 80-95 Me

QGP expands explosively

Only gives access to temp at kinetic freeze-out

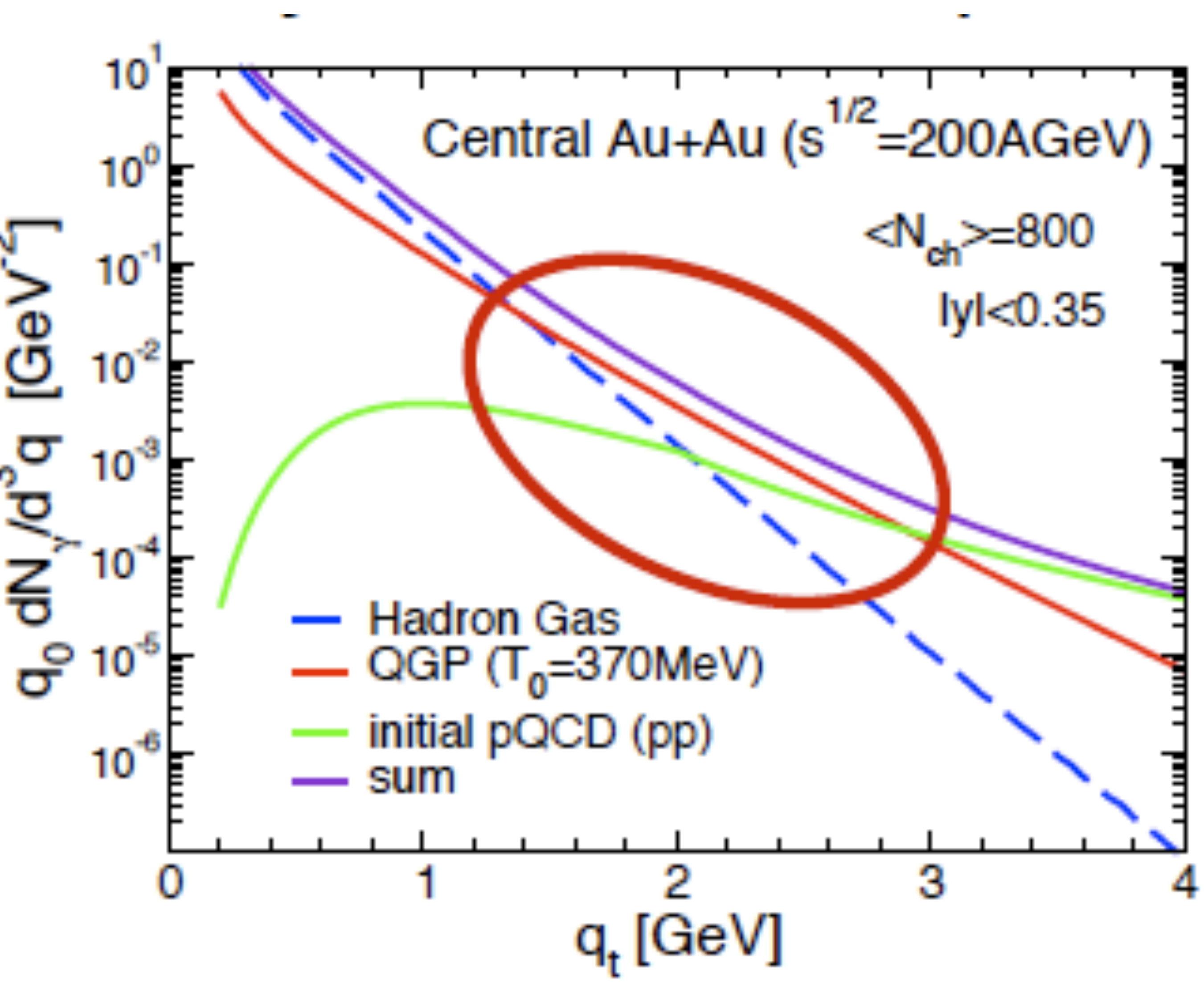


Early conditions: Temperature

Direct Photons:

- no charge or color → don't interact with medium
- emitted over all lifetime → convolution of all T

Theory well developed



QGP dominates:1< p_T < 3 GeV/c

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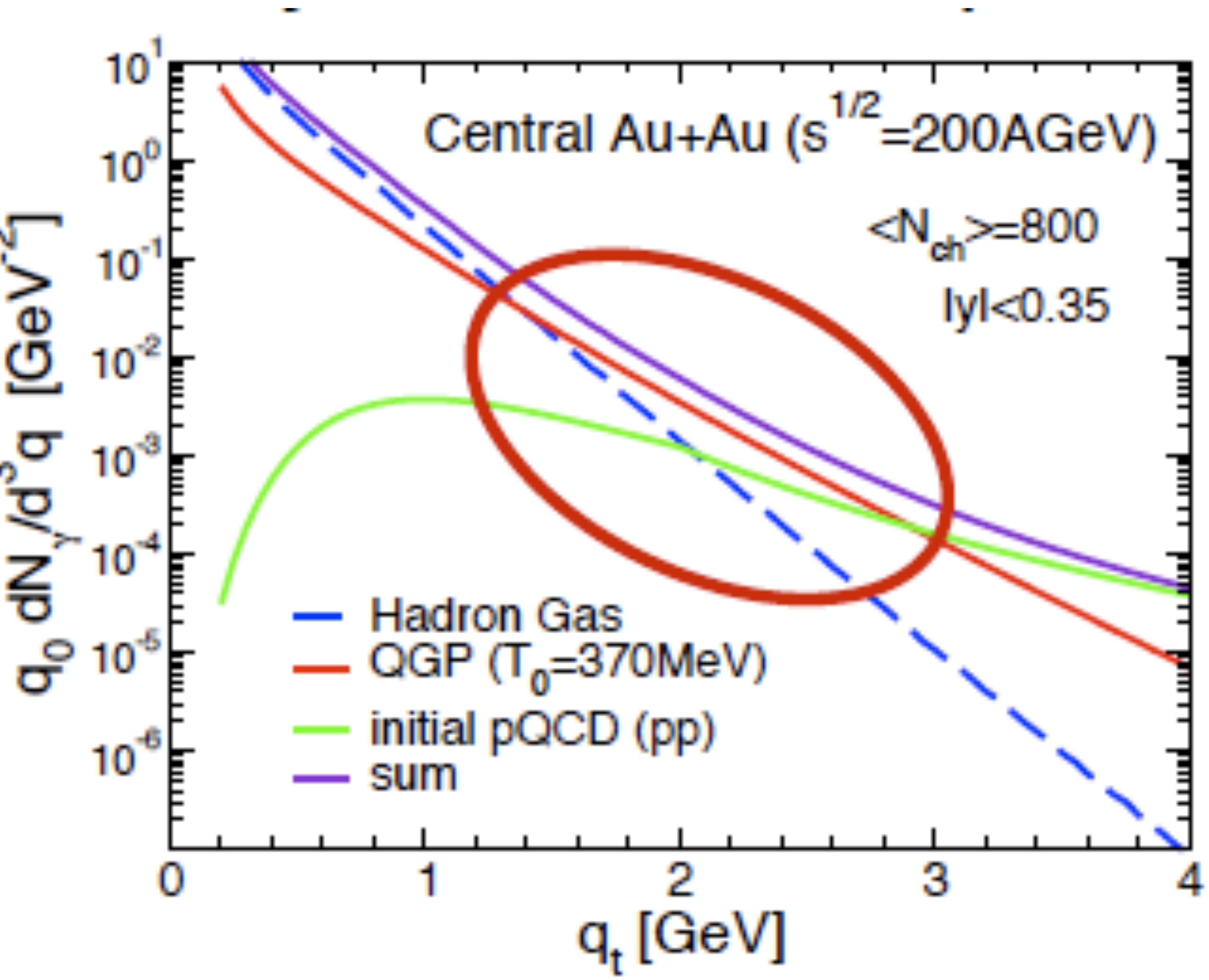
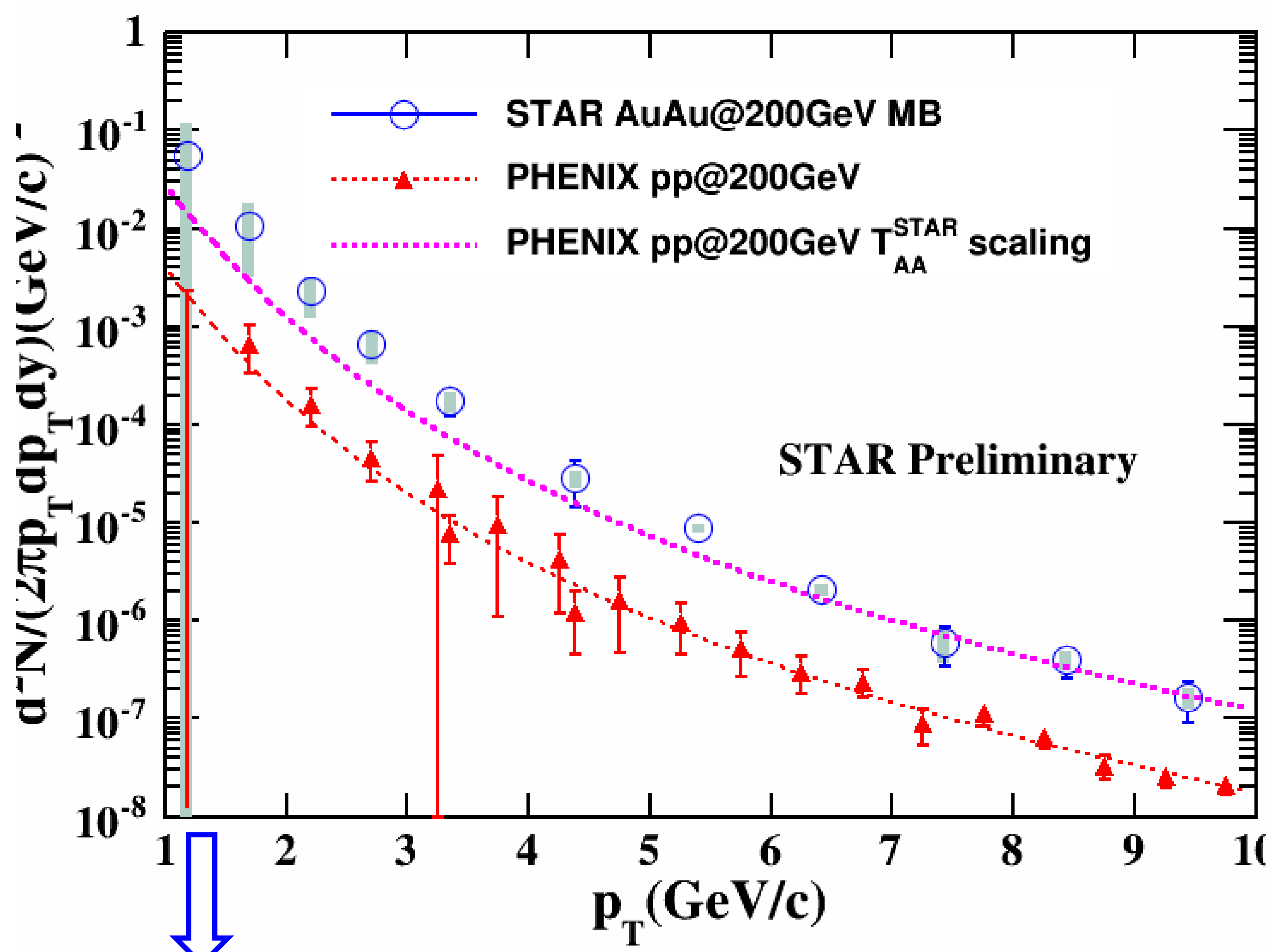


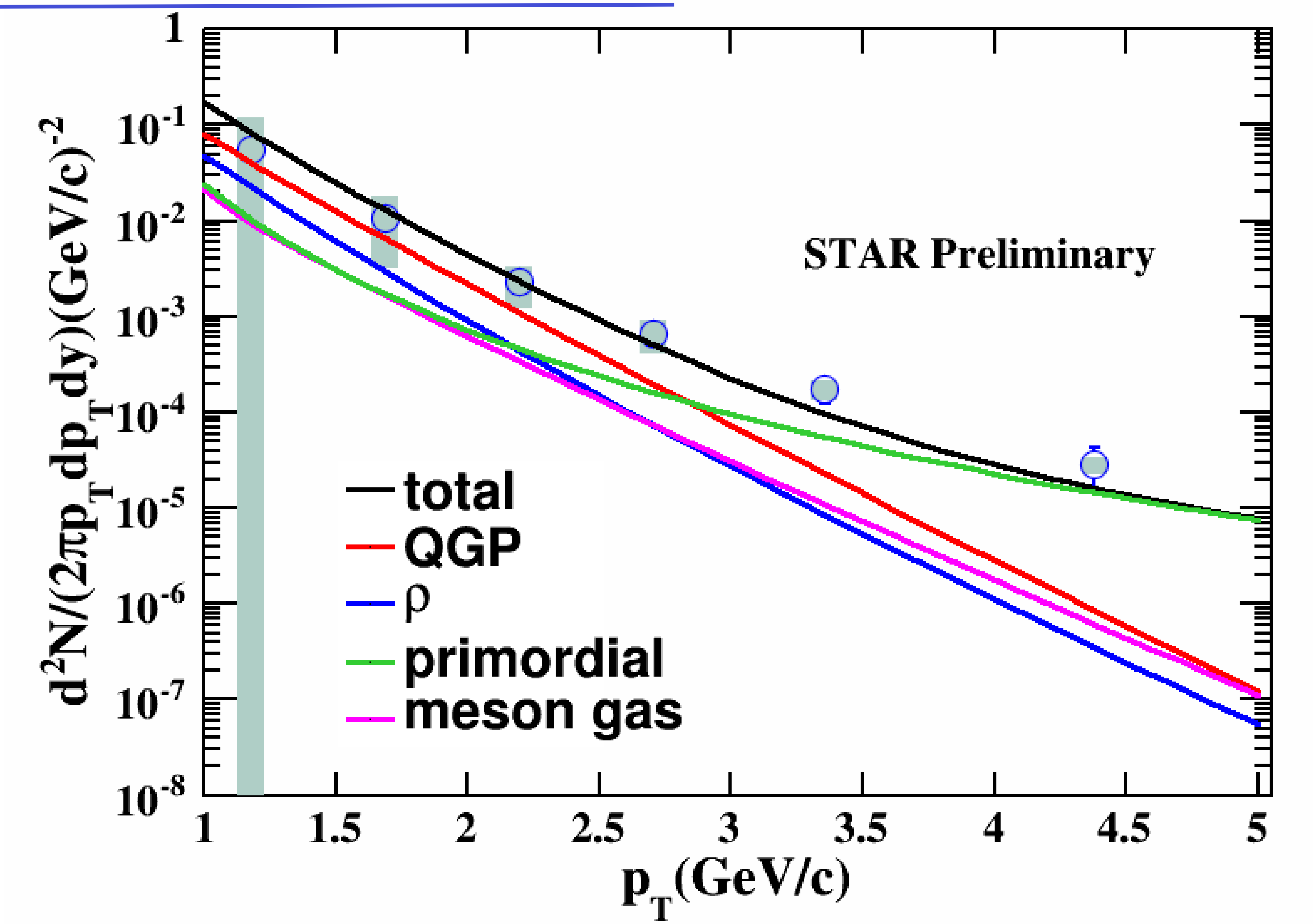


no η measurement in $p_T < 2$ GeV/c

QGP dominates: $1 < p_T < 3$ GeV/c

Vogelsang Private comm.

Early conditions: Temperature



Consistent with T_{init}= 320 MeV

Even higher at the LHC

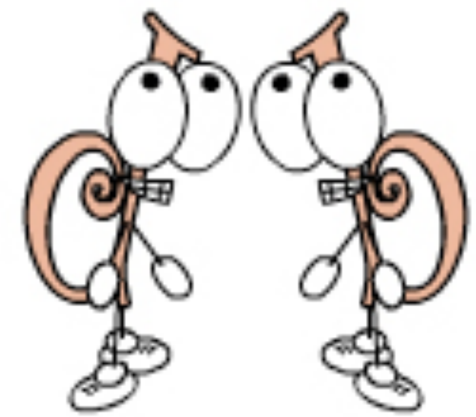
(T_c ~ 170 MeV)

[*Van Hees, Gale, and Rapp, Phys. Rev. C 84, 054906*]

Melting quarkonia

Quarkonia - bound states of heavy quark-anti-quark pairs

$c + \bar{c} = J/\psi$

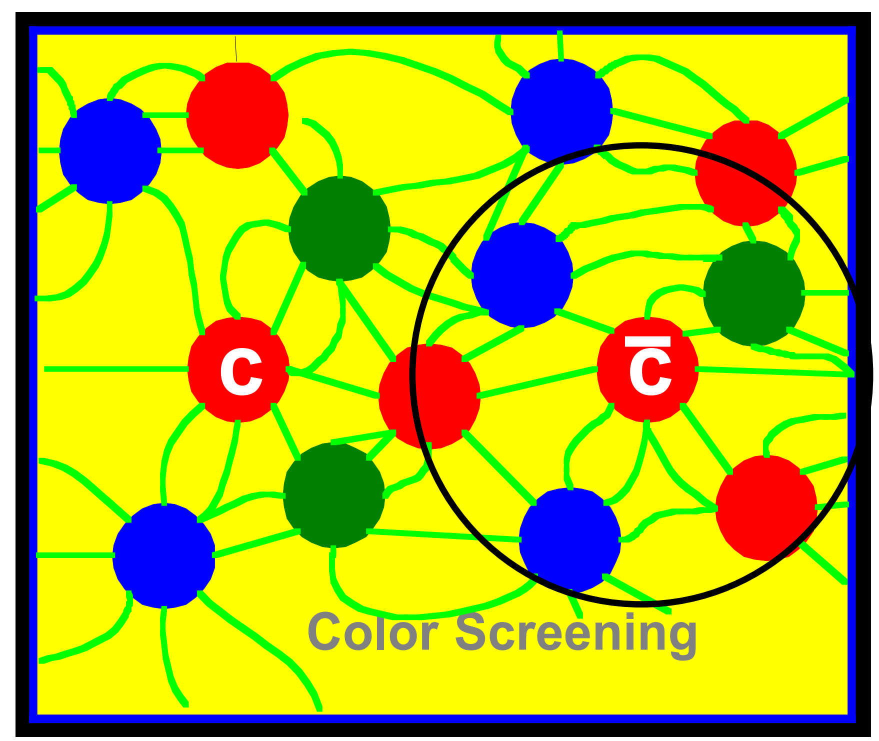


$b + \bar{b} = \Upsilon$

Formed only in the very early stages of the collision due to their high masses

Only loosely bound

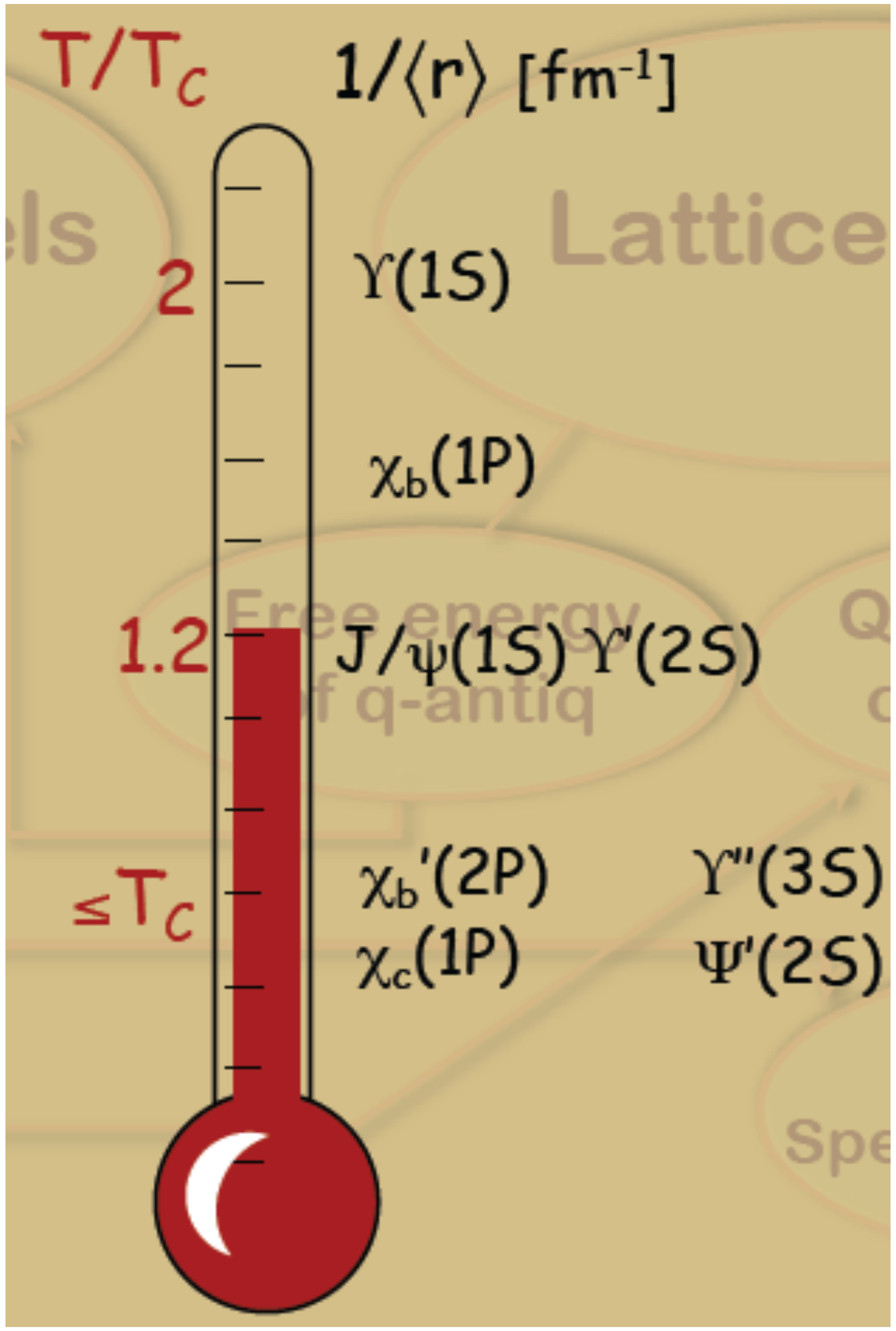
Melt in the QGP



Quarkonia - QGP thermometers

Color screening of static potential between heavy quarks

(Matsui and Satz, *Phys. Lett. B* **178** (1986) 416)



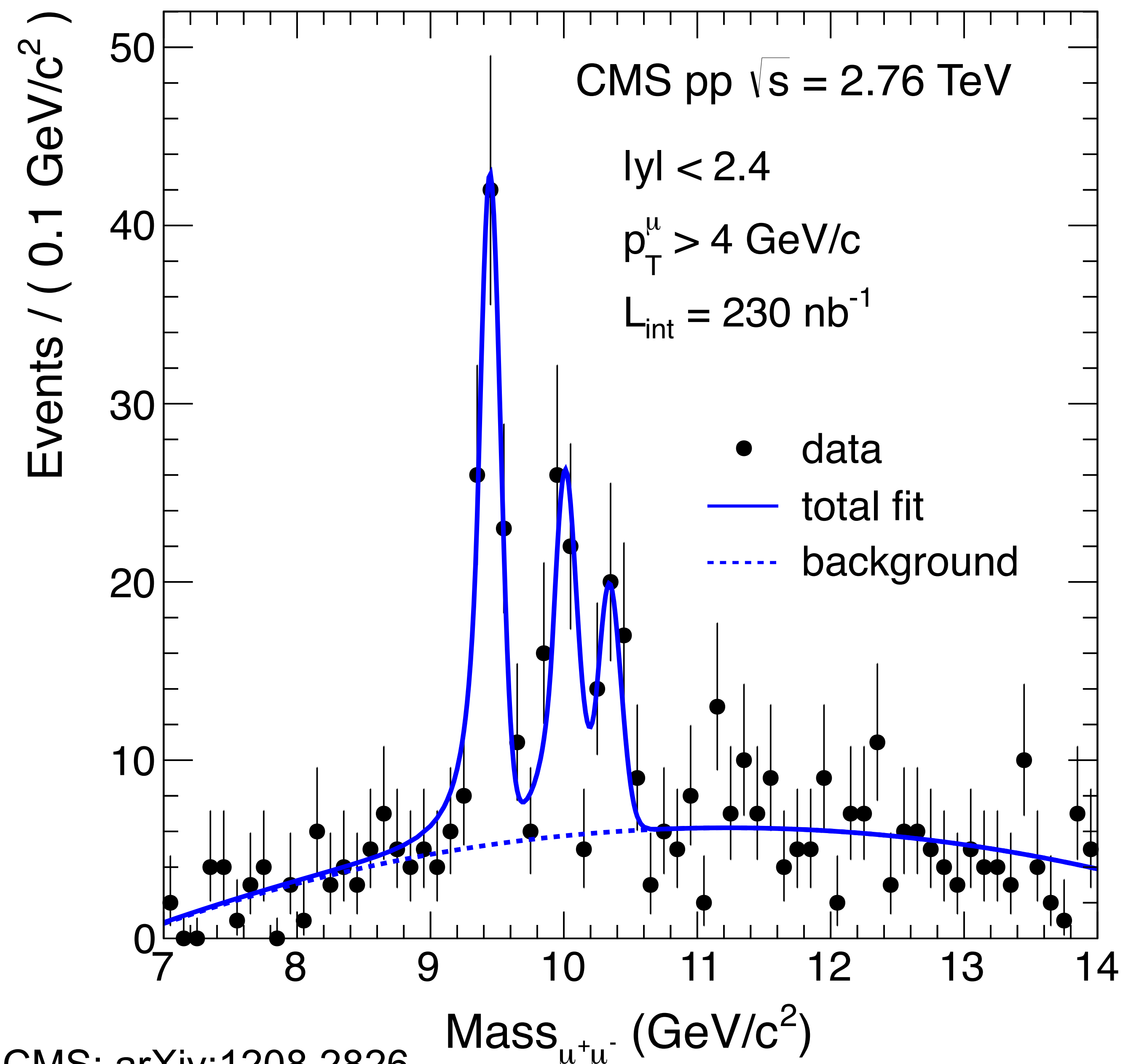
Charmonia: J/ψ, Ψ', χ_c

Bottomonia: ϒ(1S), ϒ(2S), ϒ(3S)

	$E_{binding}$ (GeV)
J/ψ	0.64
ψ'	0.05
χ_c	0.2
ϒ(1S)	1.1
ϒ(2S)	0.54
ϒ(3S)	0.31

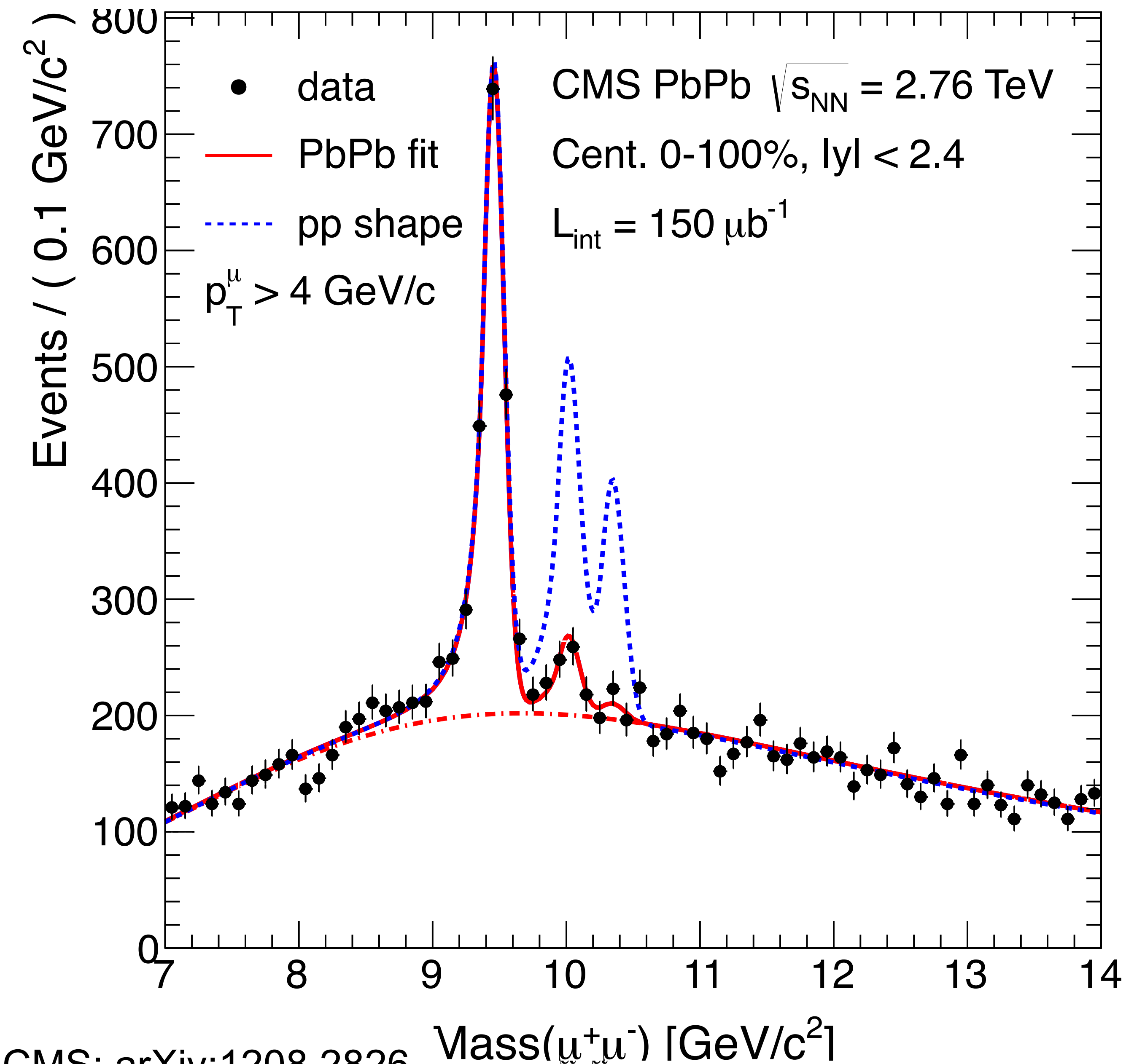
Suppression determined by T and binding energy

Sequential melting of the Quarkonia



CMS: arXiv:1208.2826

Sequential melting of the Quarkonia



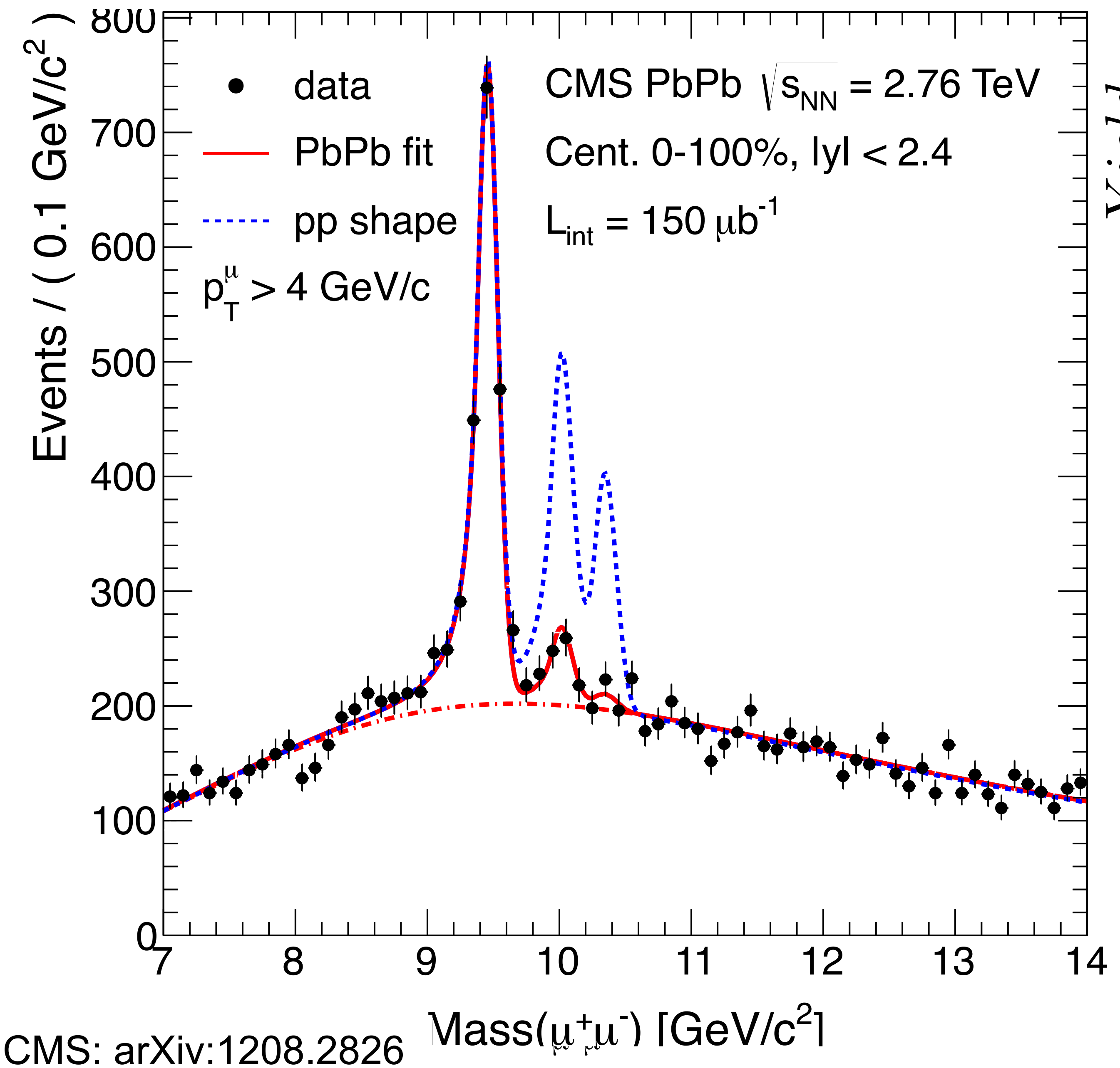
CMS: arXiv:1208.2826

$$\frac{\Upsilon(1S)_{AA}}{N_{bin}\Upsilon(1S)_{pp}} = 0.56 \pm 0.08 \pm 0.07$$

$$\frac{\Upsilon(2S)_{AA}}{N_{bin}\Upsilon(2S)_{pp}} = 0.12 \pm 0.04 \pm 0.02$$

$$\frac{\Upsilon(3S)_{AA}}{N_{bin}\Upsilon(3S)_{pp}} = 0.03 \pm 0.04 \pm 0.01$$

Sequential melting of the Quarkonia



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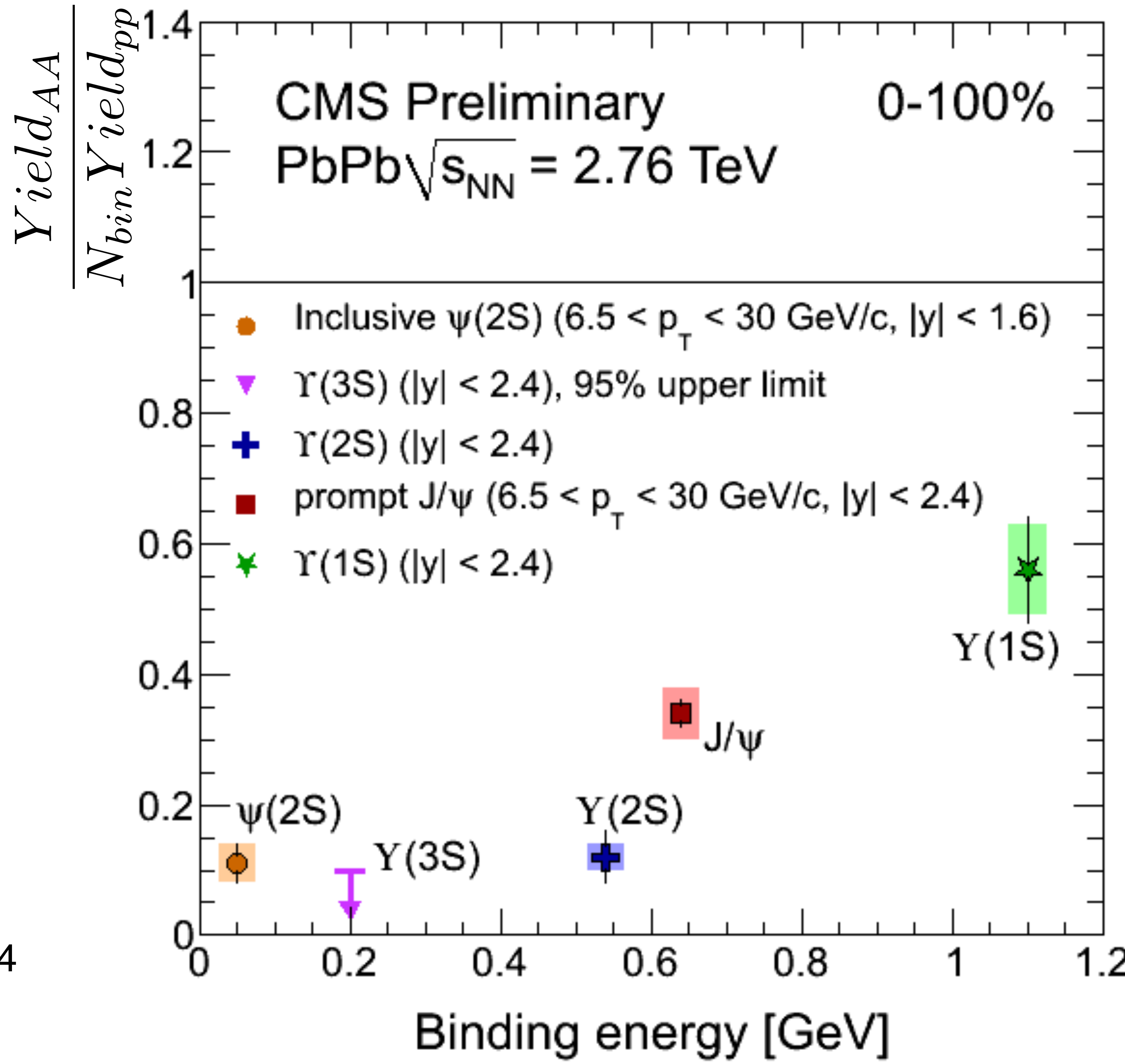
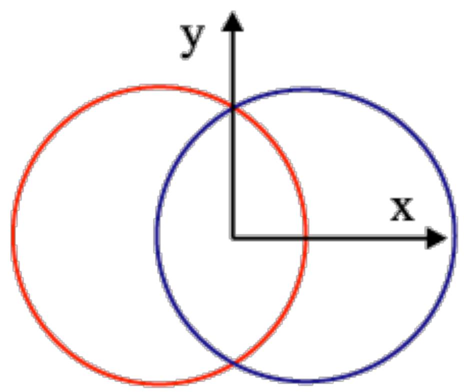
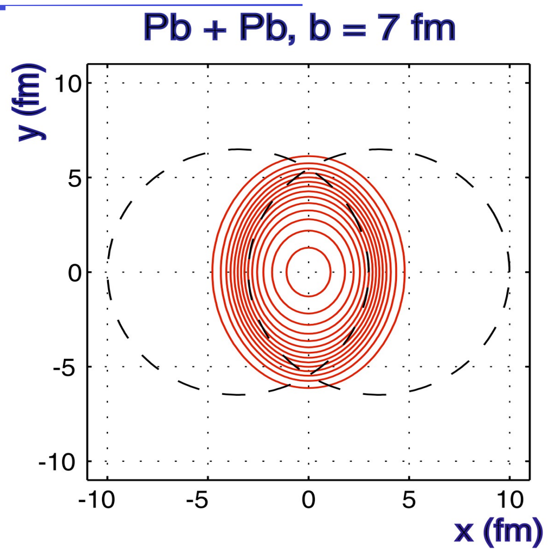


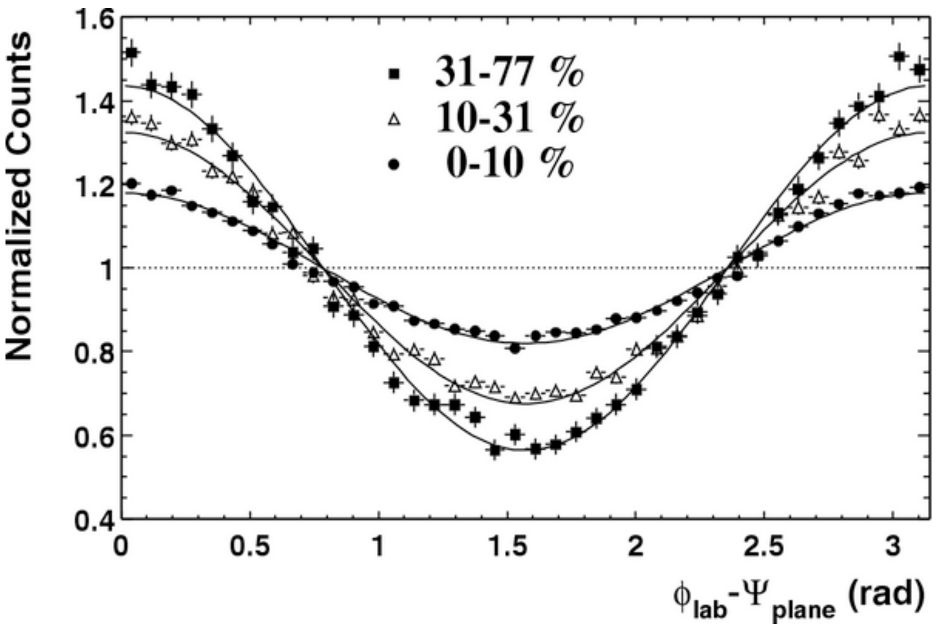
Most lightly bound states have melted

T > 1.5 T_c ~ 300 MeV

Initial conditions: Thermalization





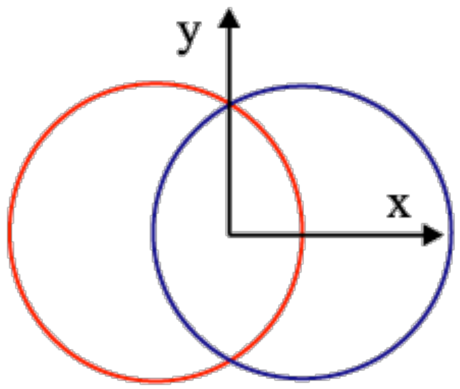


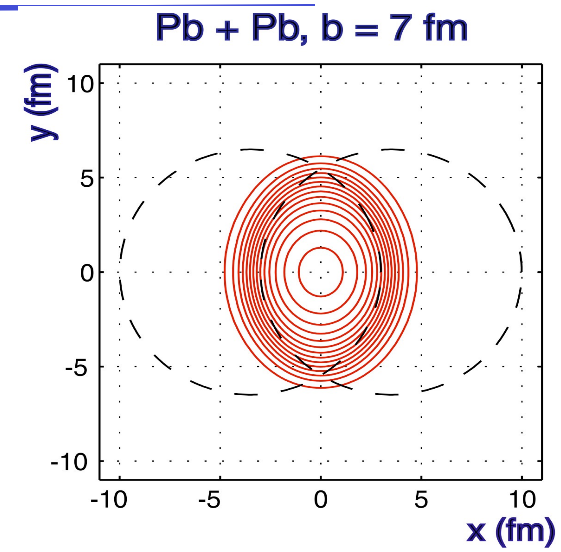
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

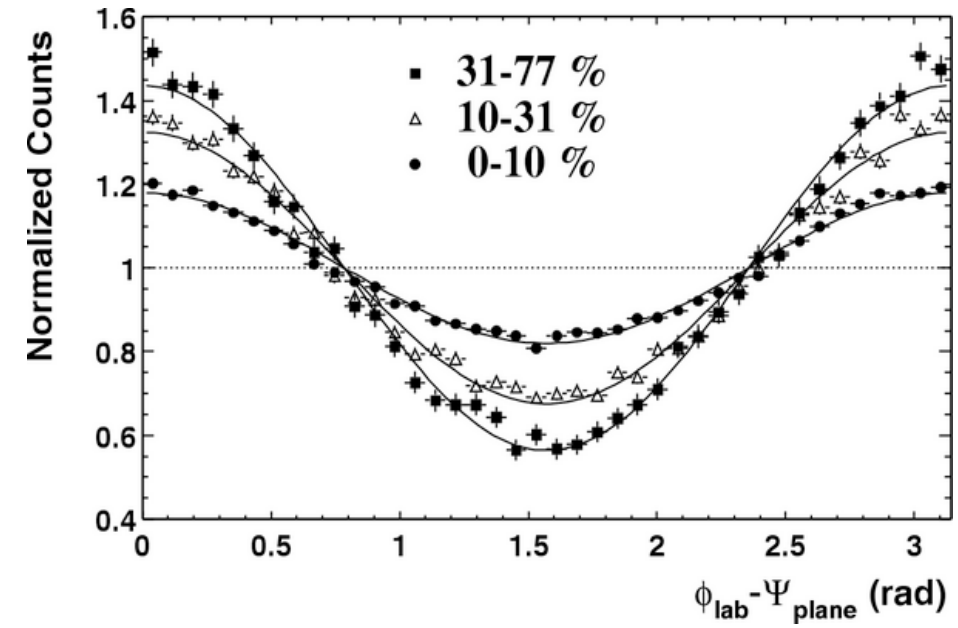
$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots.$ $\phi=\mathrm{atan}(p_y/p_x)$ $v_2 = \langle\cos 2\phi\rangle$

v_2: 2nd harmonic Fourier coefficient in $dN/d\phi$ with respect to the reaction plane

Initial conditions: Thermalization







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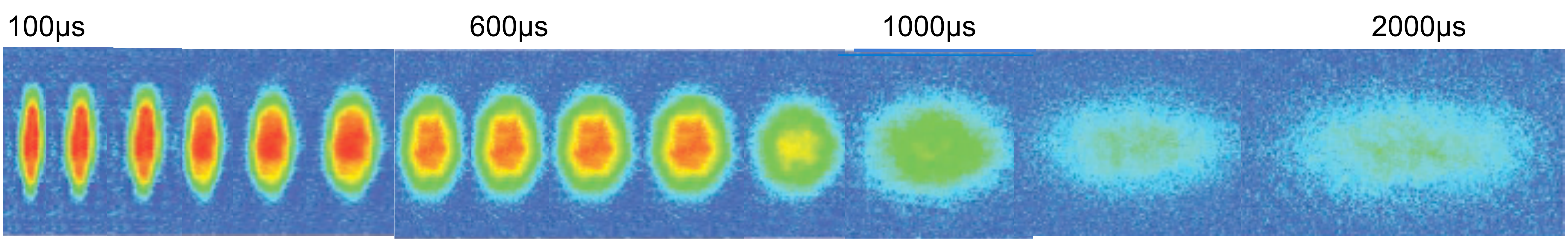
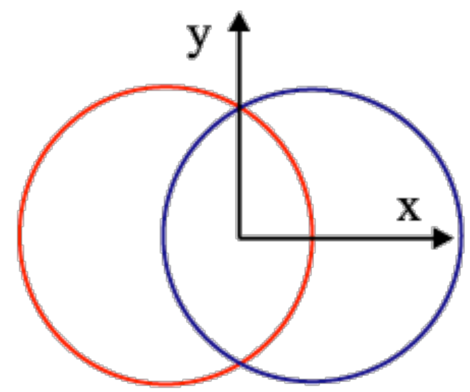
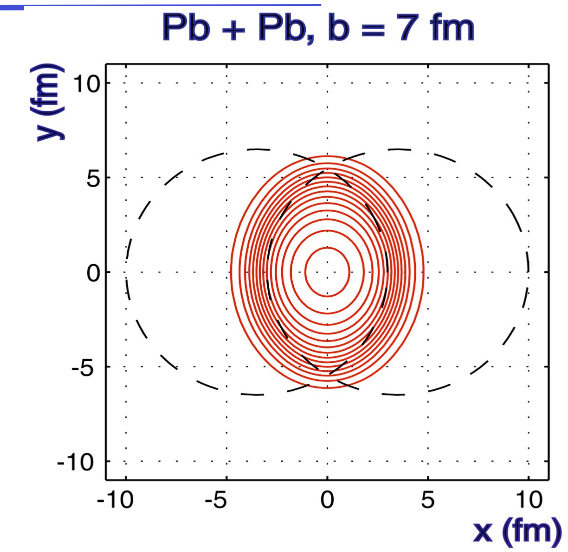


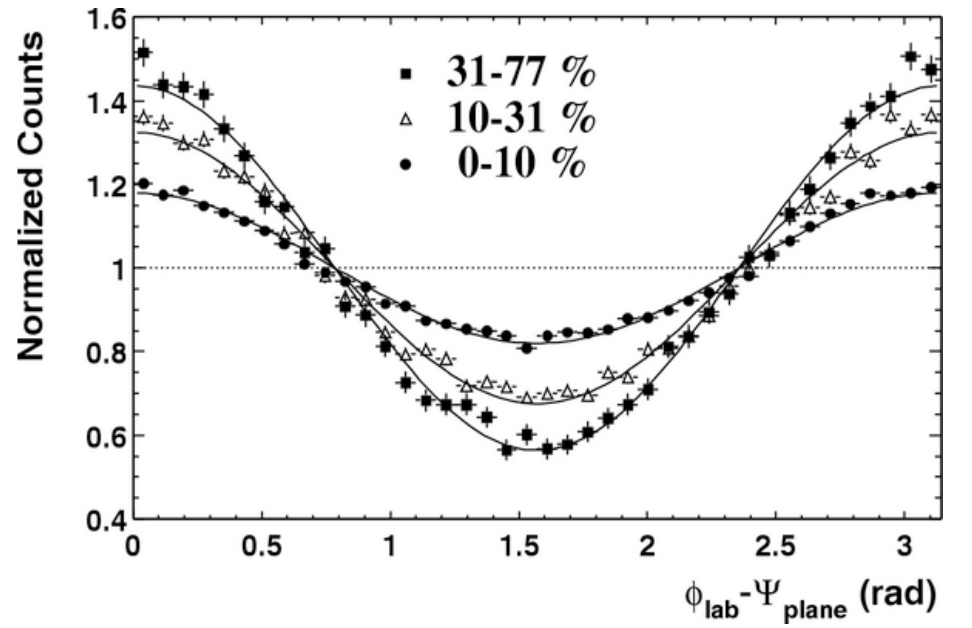
Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Initial conditions: Thermalization







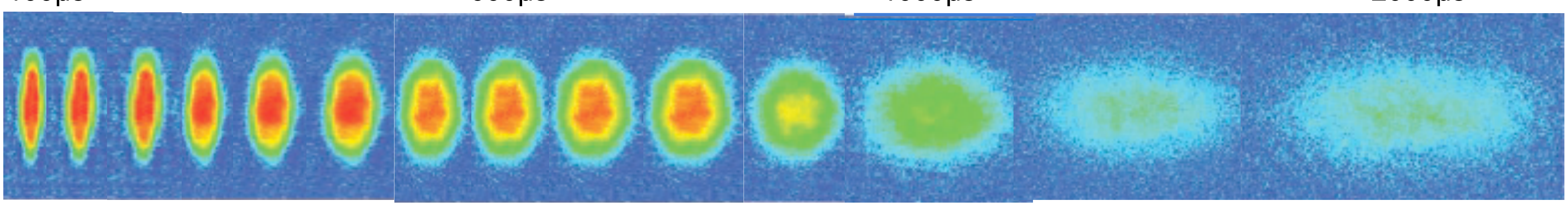
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum

Elliptic flow observable sensitive to early evolution of system

Mechanism is self-quenching

Large v_2 is an indication of ***early*** thermalization

100μs 600μs 1000μs 2000μs



→ Time

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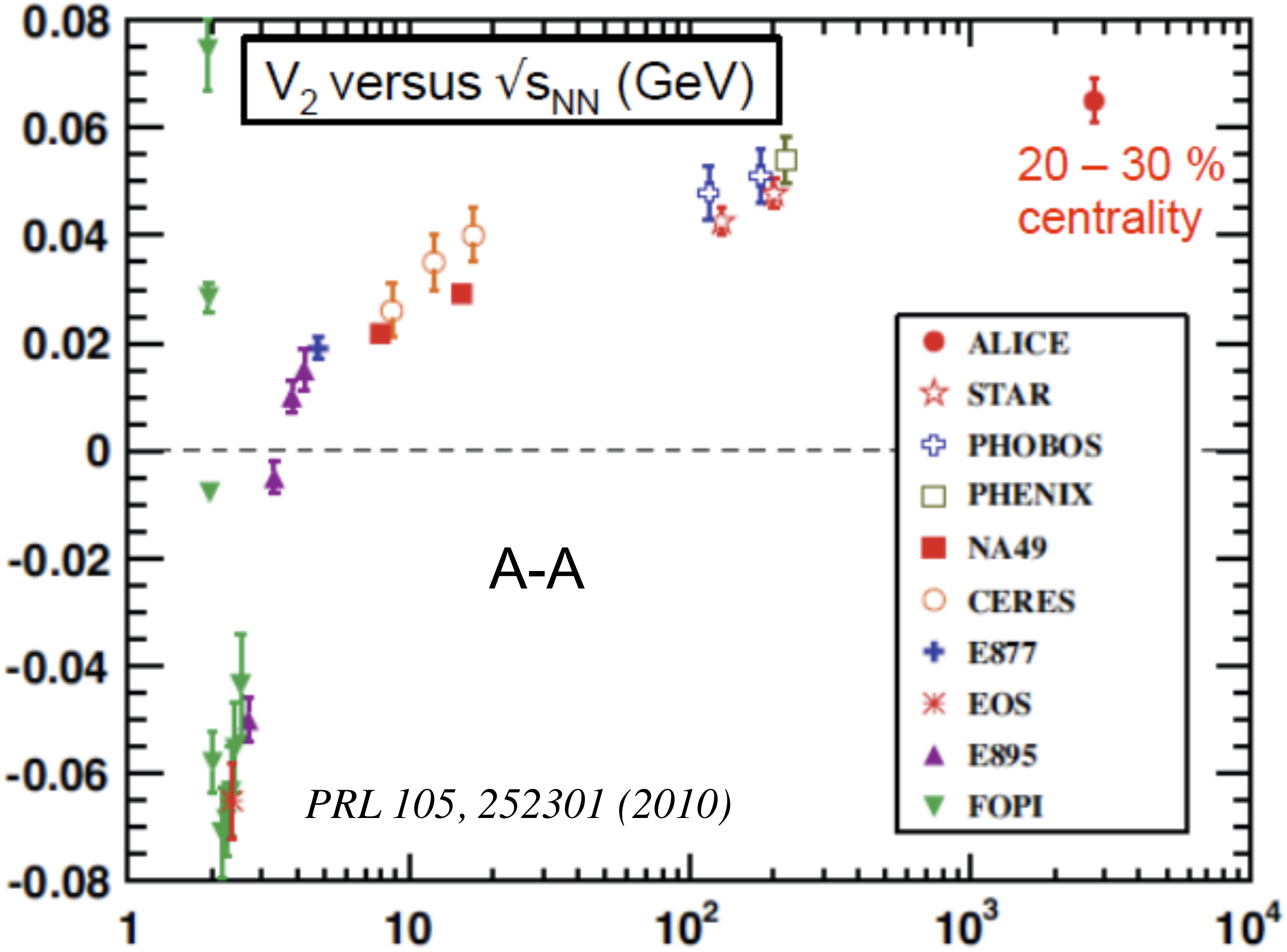
Early thermalization - elliptic flow



v_2 (p_T int.) LHC ~1.3x (p_T int.) RHIC

The overall increase is consistent with the increased radial expansion leading to a higher mean p_T

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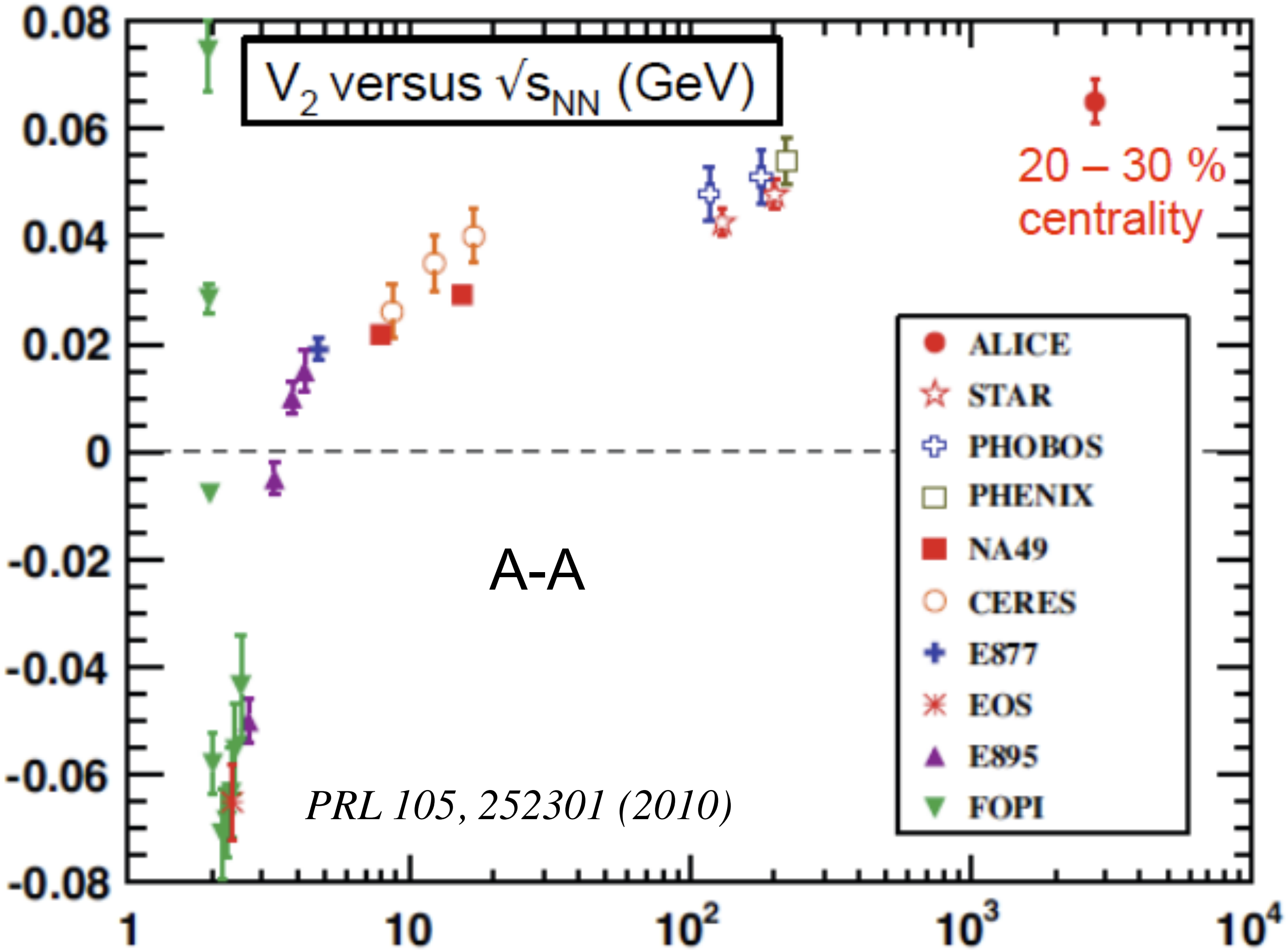
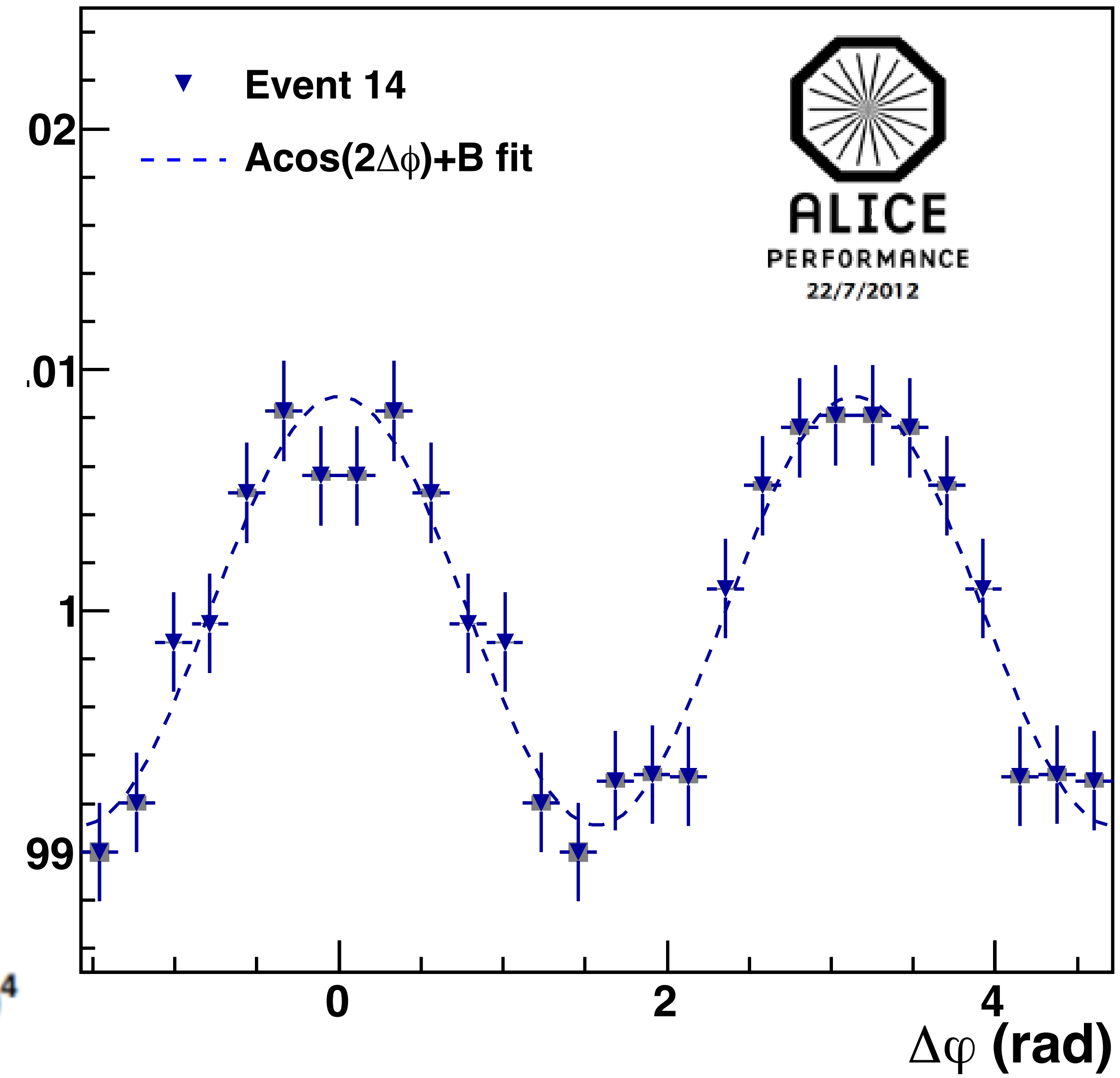




v_2 (p_T int.) LHC ~1.3x (p_T int.) RHIC

The overall increase is consistent with the increased radial expansion leading to a higher mean p_T

Such high event multiplicity flow measured event-by-event

Strong evidence for thermalization

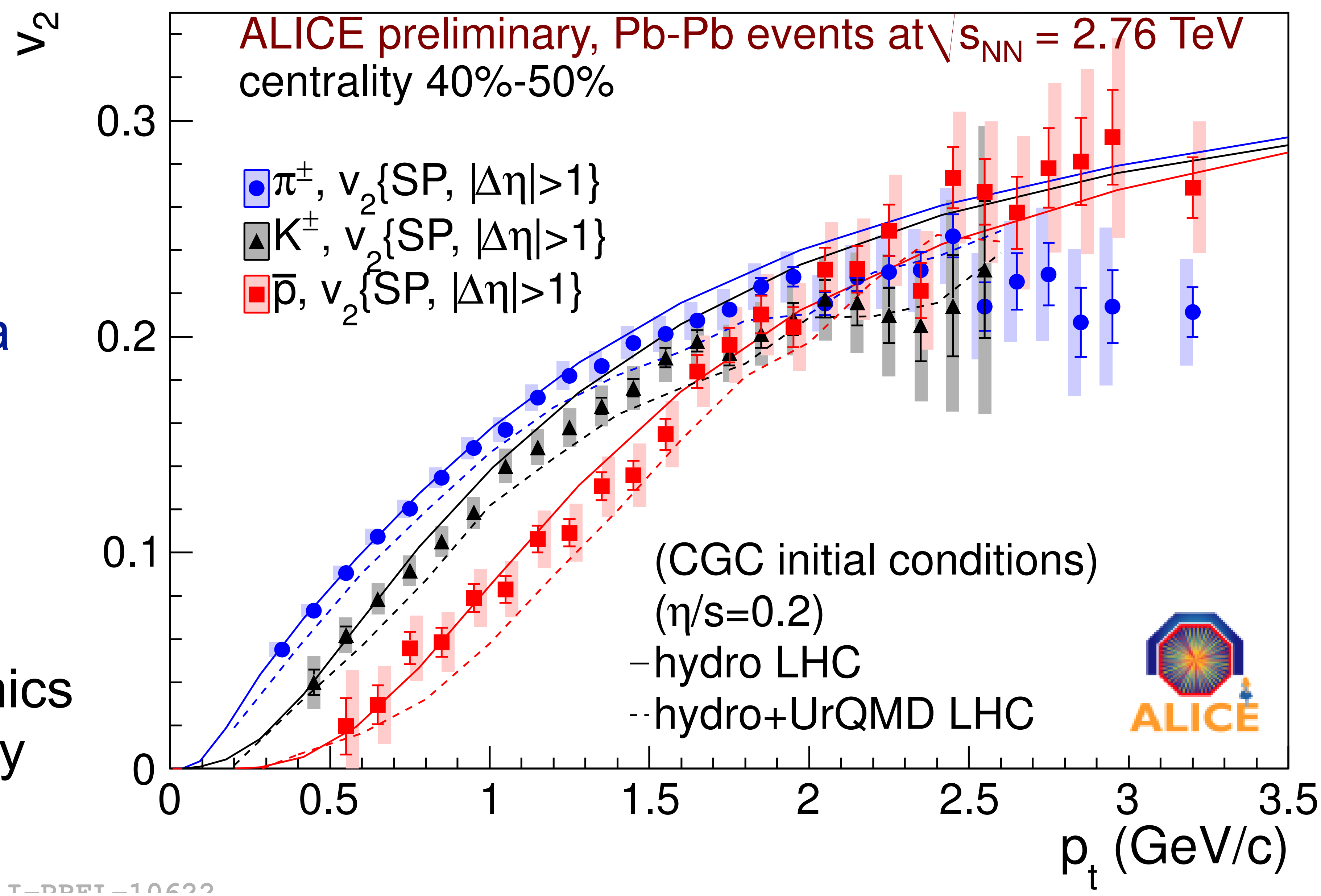
Elliptic flow and the “Perfect fluid”

Confirmation of RHIC discovery that a QGP is almost a perfect fluid

CERN Press release
Nov26, 2010

‘confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)...’

Description of medium’s evolution via fluid dynamics with almost zero viscosity very successful



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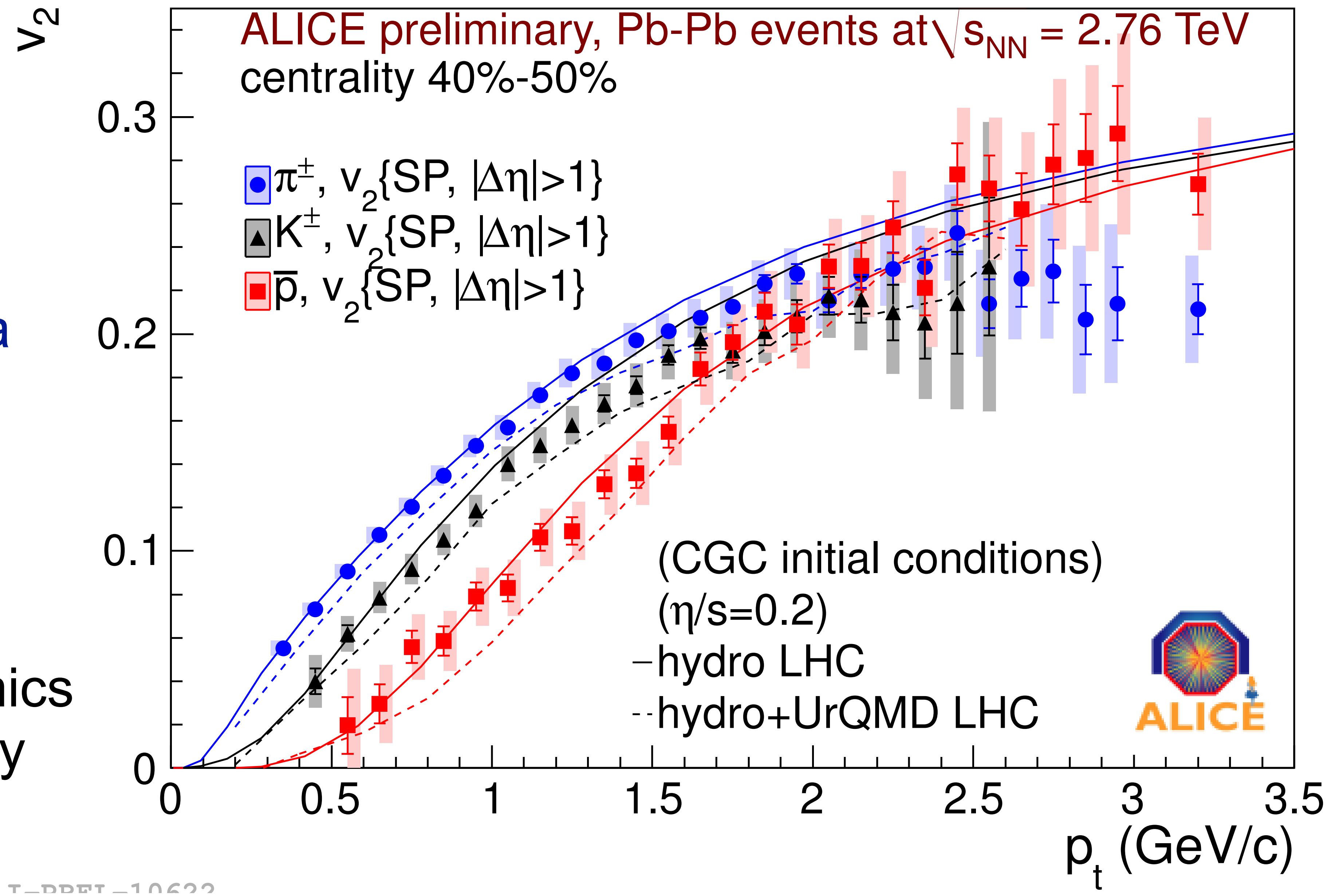
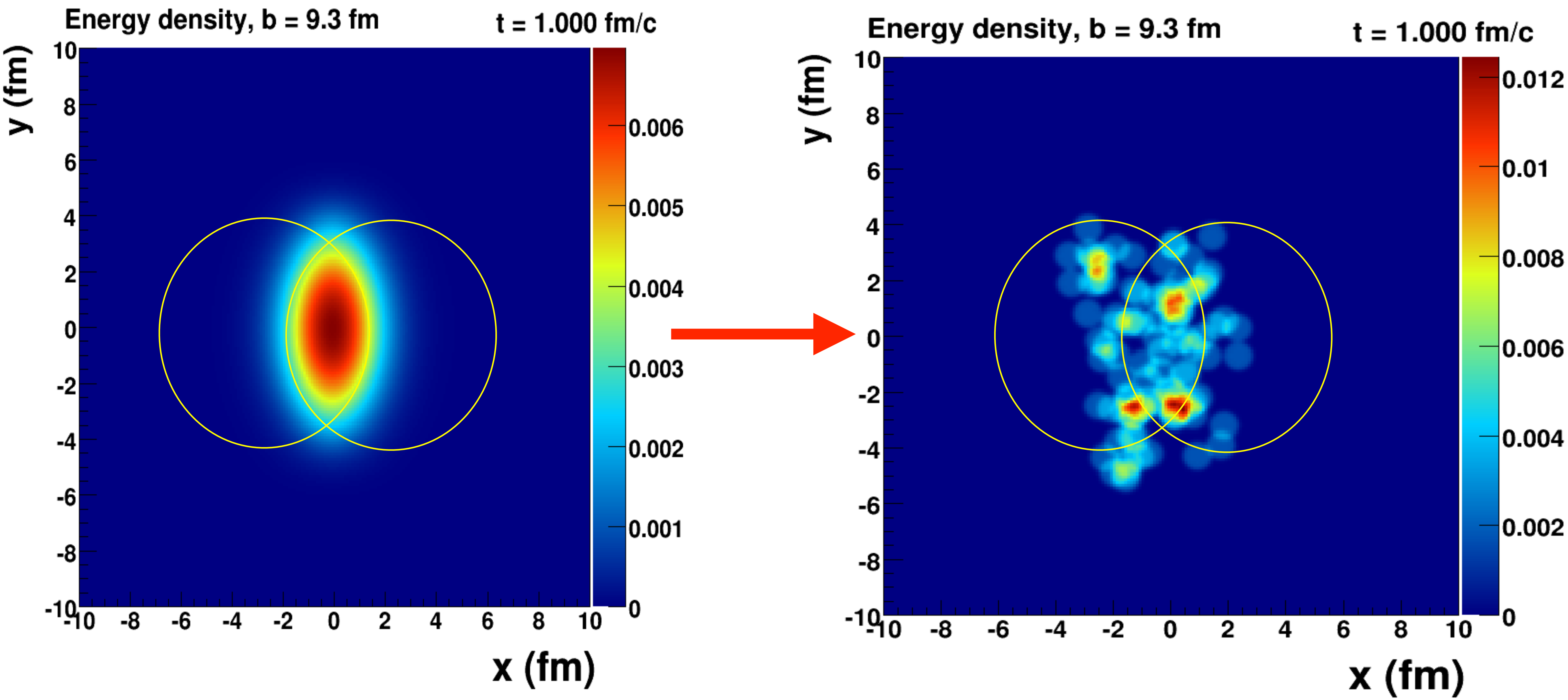


Better description with
non-zero η/s
+ realistic initial conditions
+ hadronic rescattering afterburner

High precision data bringing the picture into sharp focus

Initial conditions are complex



Event-by-event fluctuations in the initial conditions are important

- induce angular correlations

Pressure gradients convert all spatial anisotropies into momentum anisotropies

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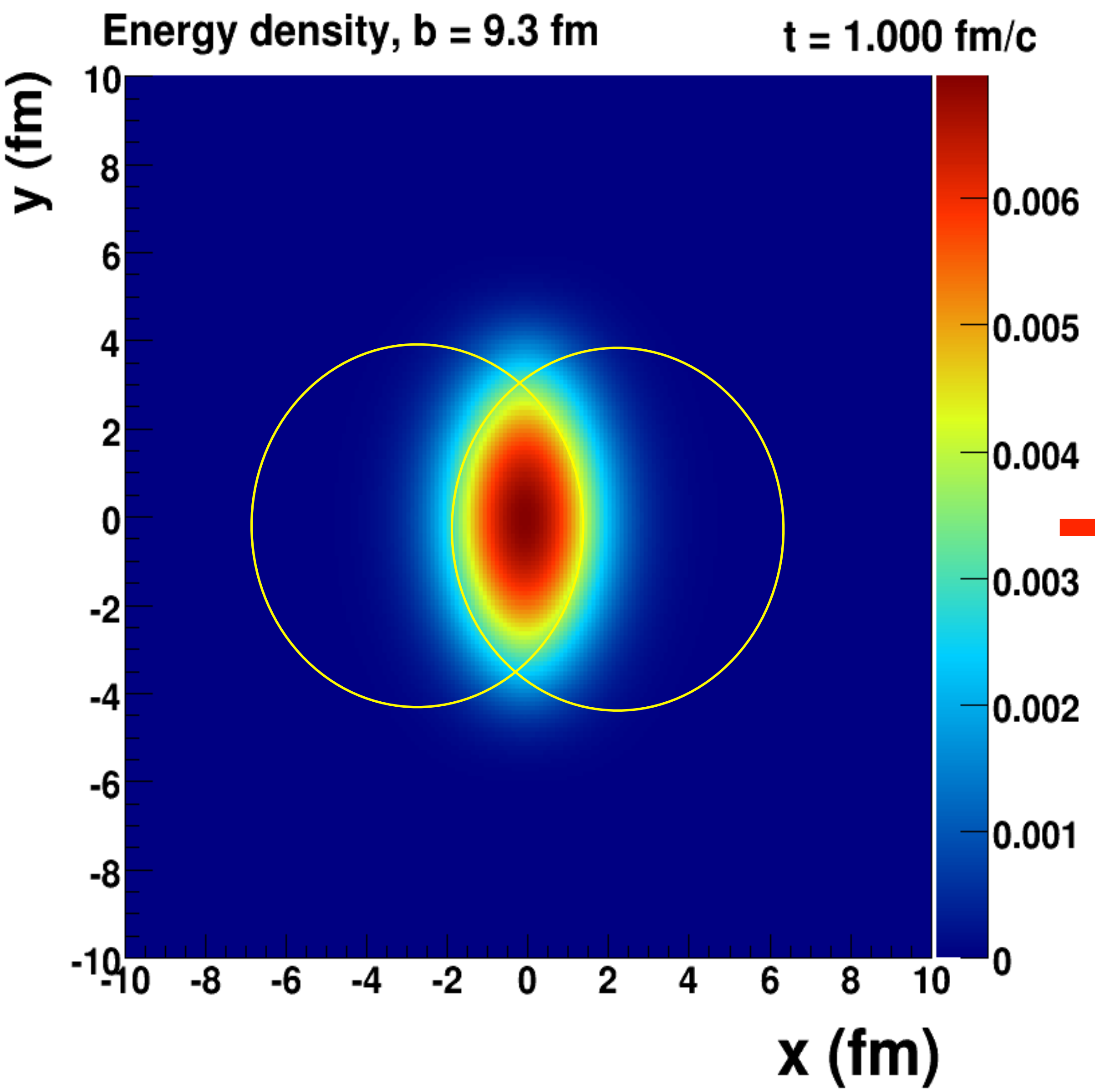

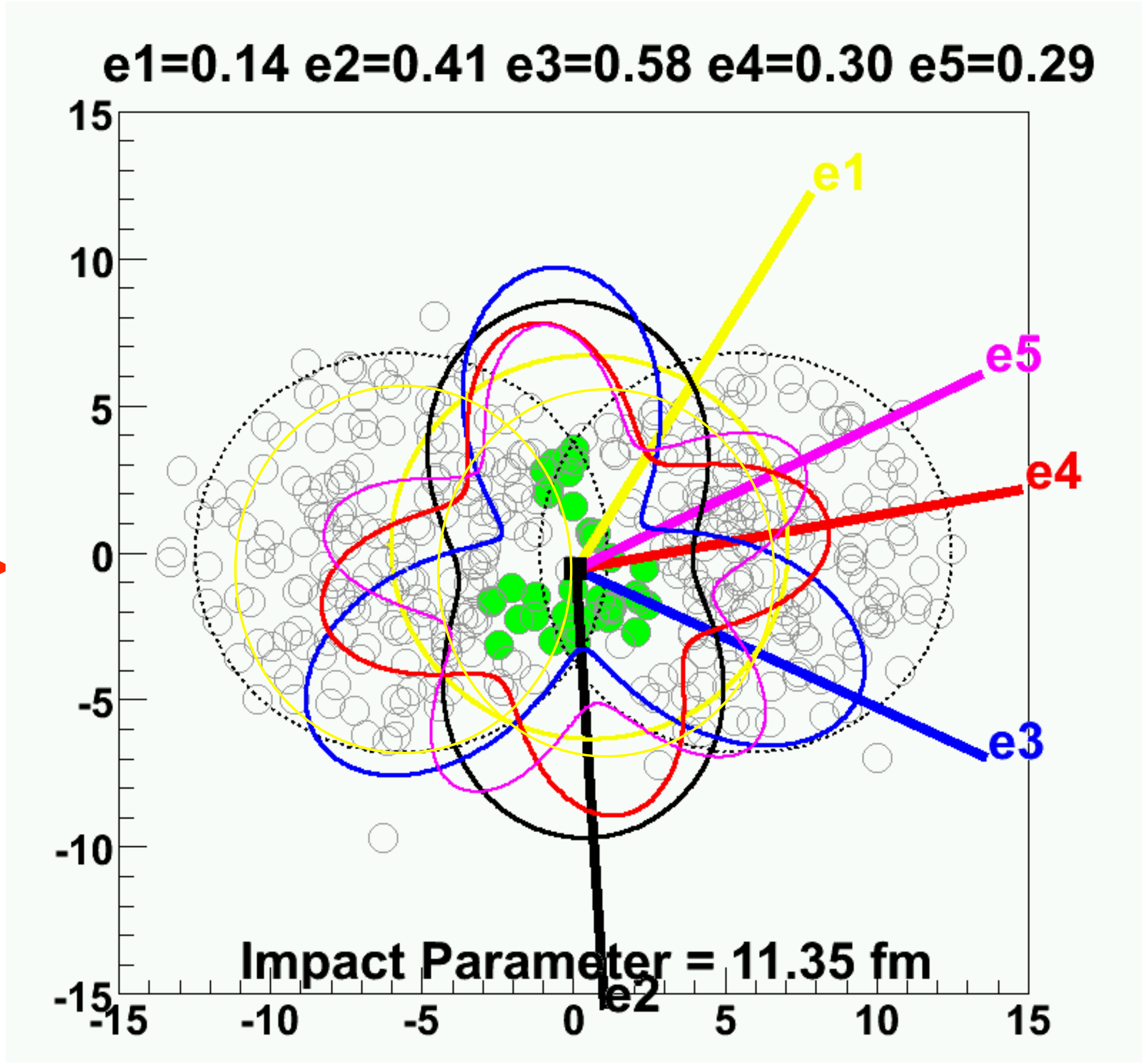

Event-by-event fluctuations in the initial conditions are important

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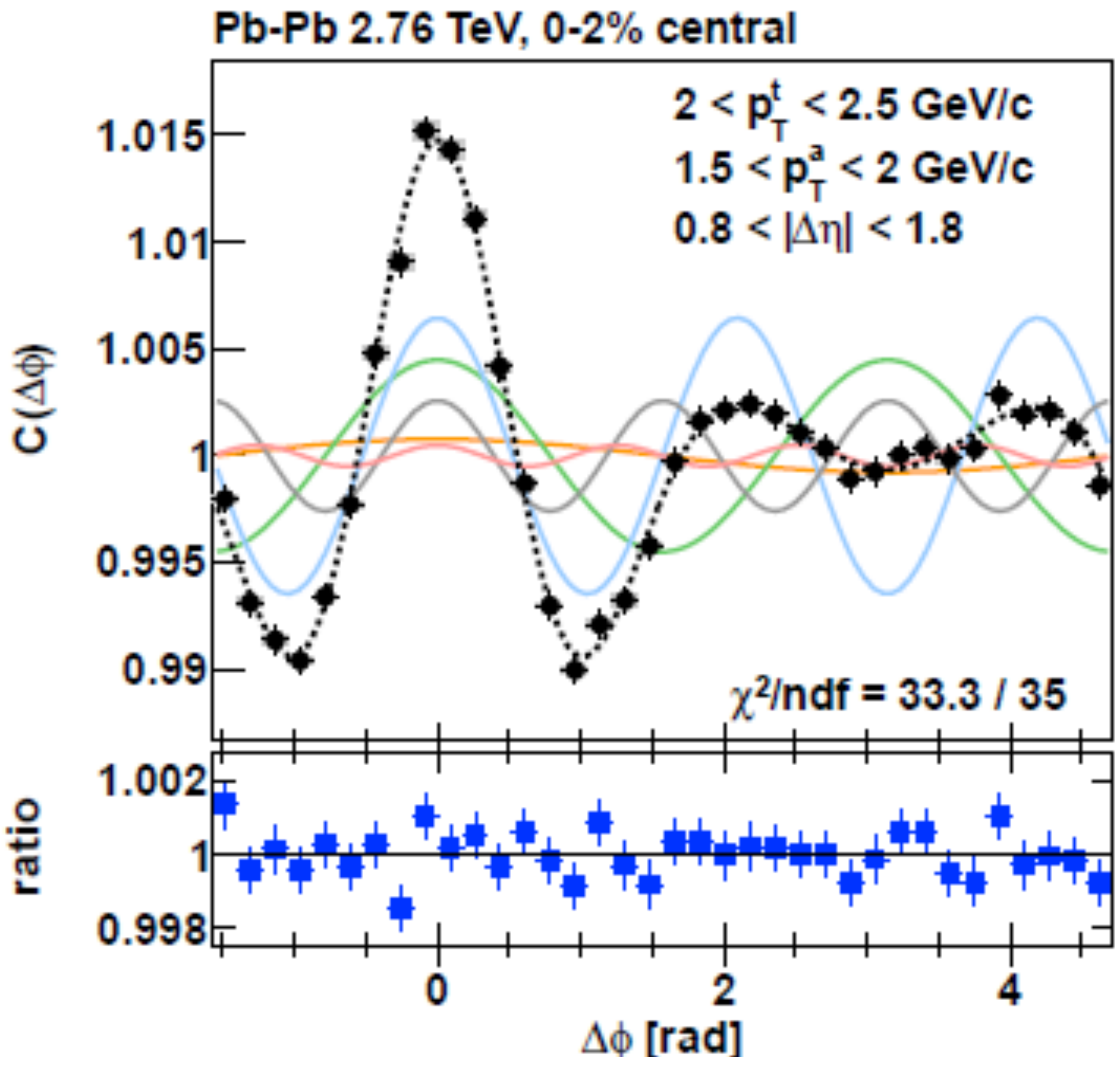
Pressure gradients convert all spatial anisotropies into momentum anisotropies

More than just elliptic flow

v_n - magnitude of the flow w.r.t n^{th} plane

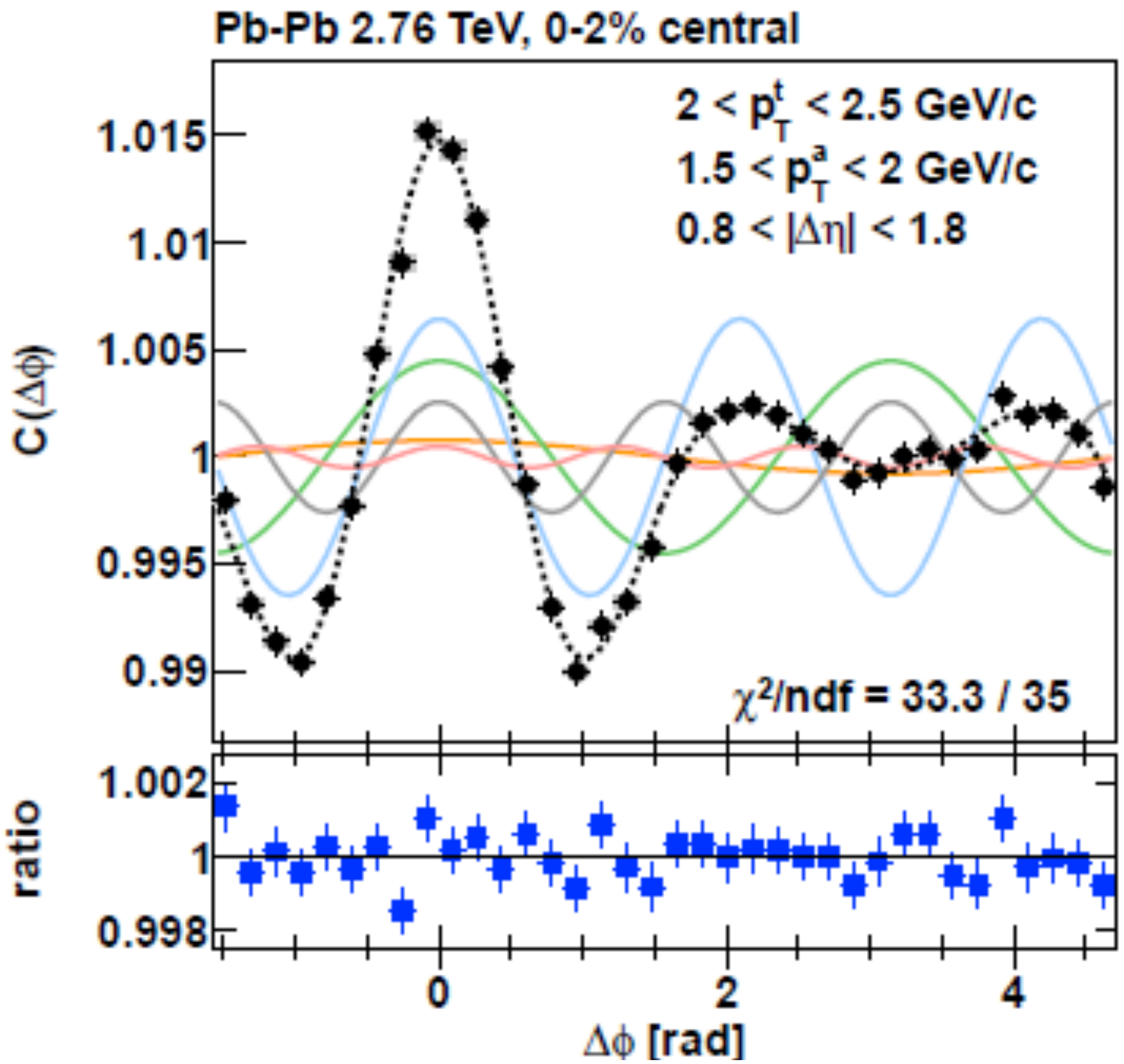
Higher harmonics



First 5 v_n components seem to be all that's needed to describe correlations

PRL 107:032301 (2011)

Higher harmonics



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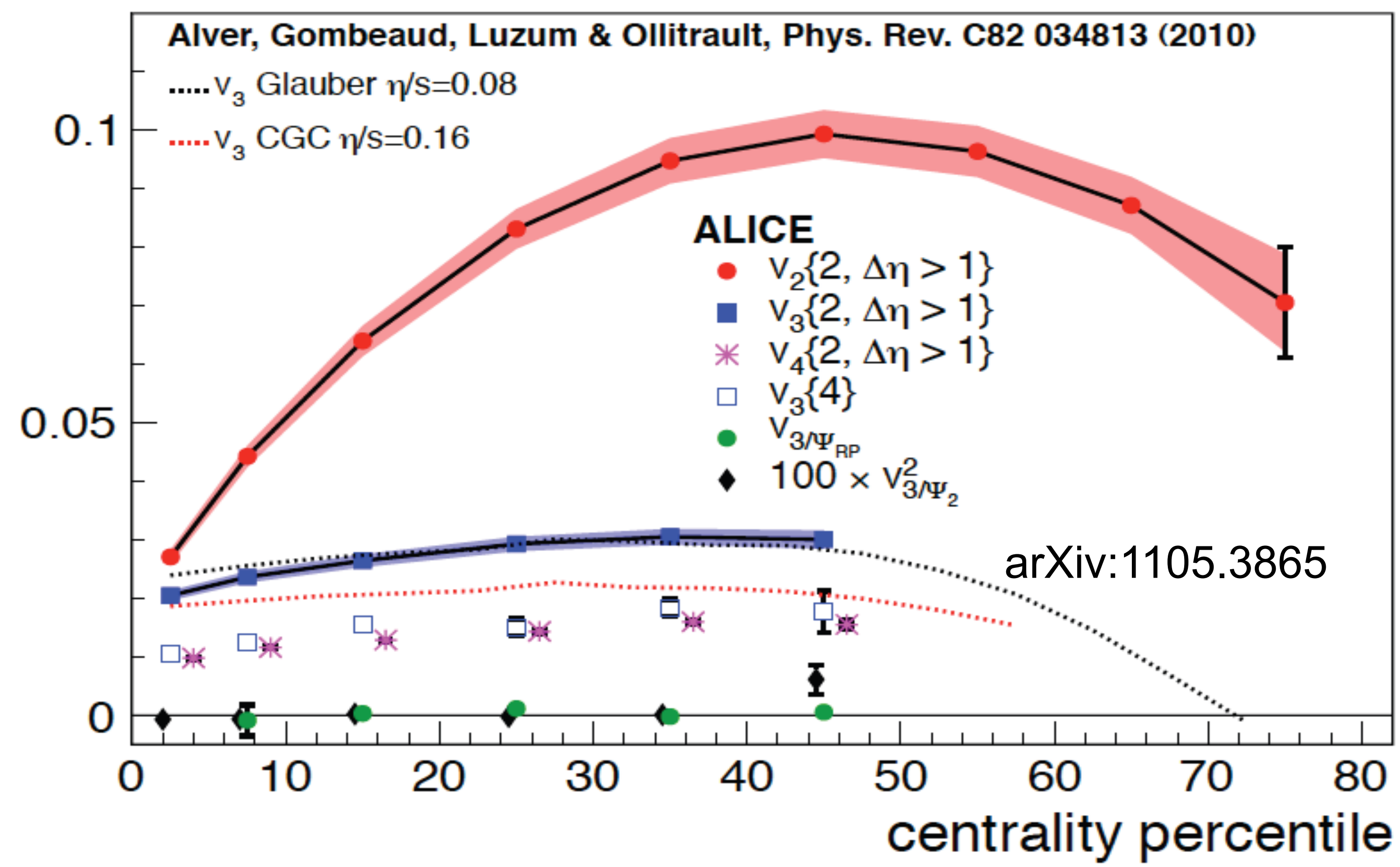


Data indicate fluctuating initial conditions with $0.07 < \eta/s < 0.43$

The constituents "flow"

- Elliptic flow is additive.
- If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2\, v_2(p_T)\cos(2\phi)$$

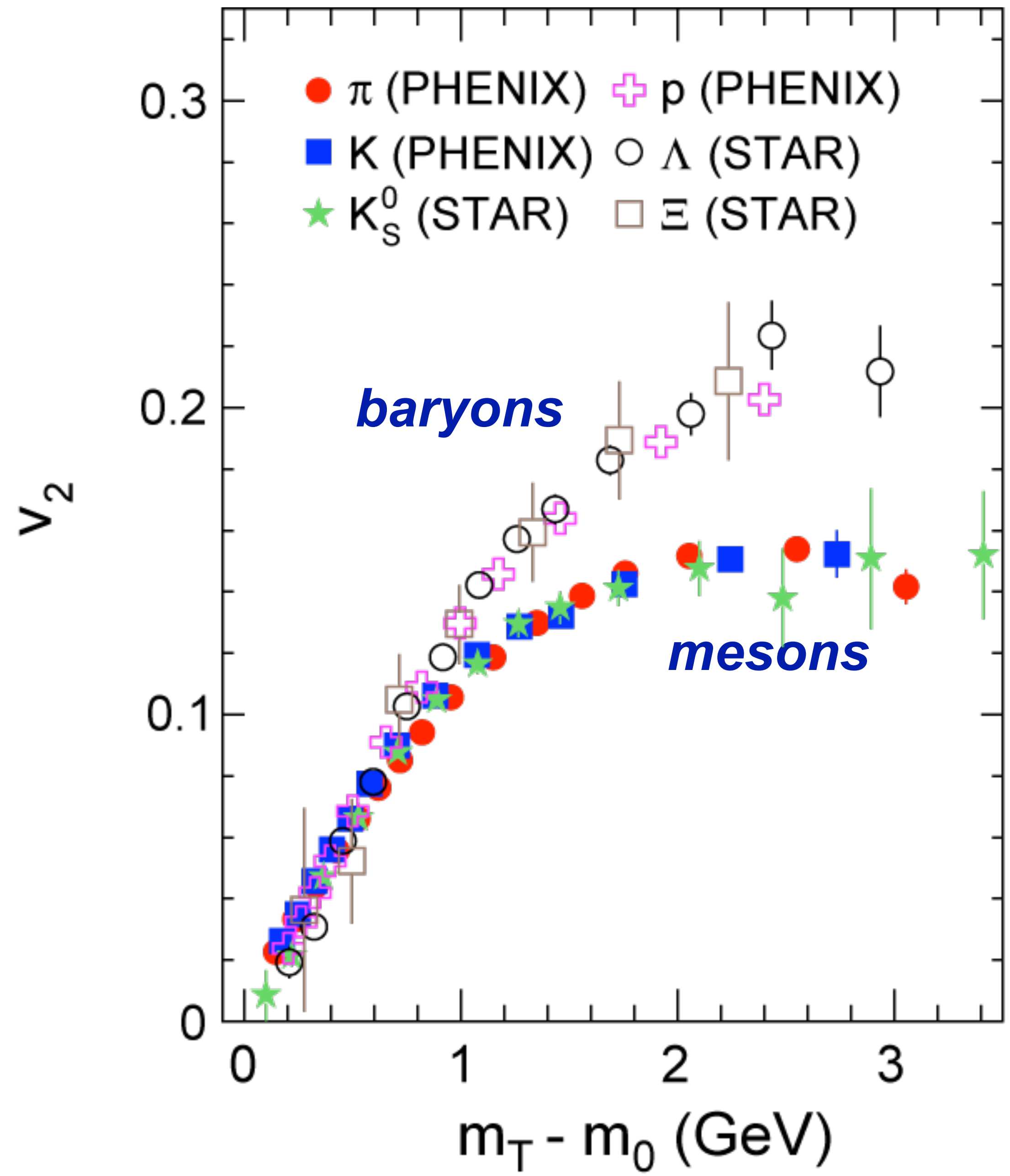
should become *simple* at the quark level

$p_T \rightarrow p_T/n$

$v_2 \rightarrow v_2/n$,

n = (2, 3) for (meson, baryon)

$$m_T = \sqrt{p_T^2 + m_0^2}$$



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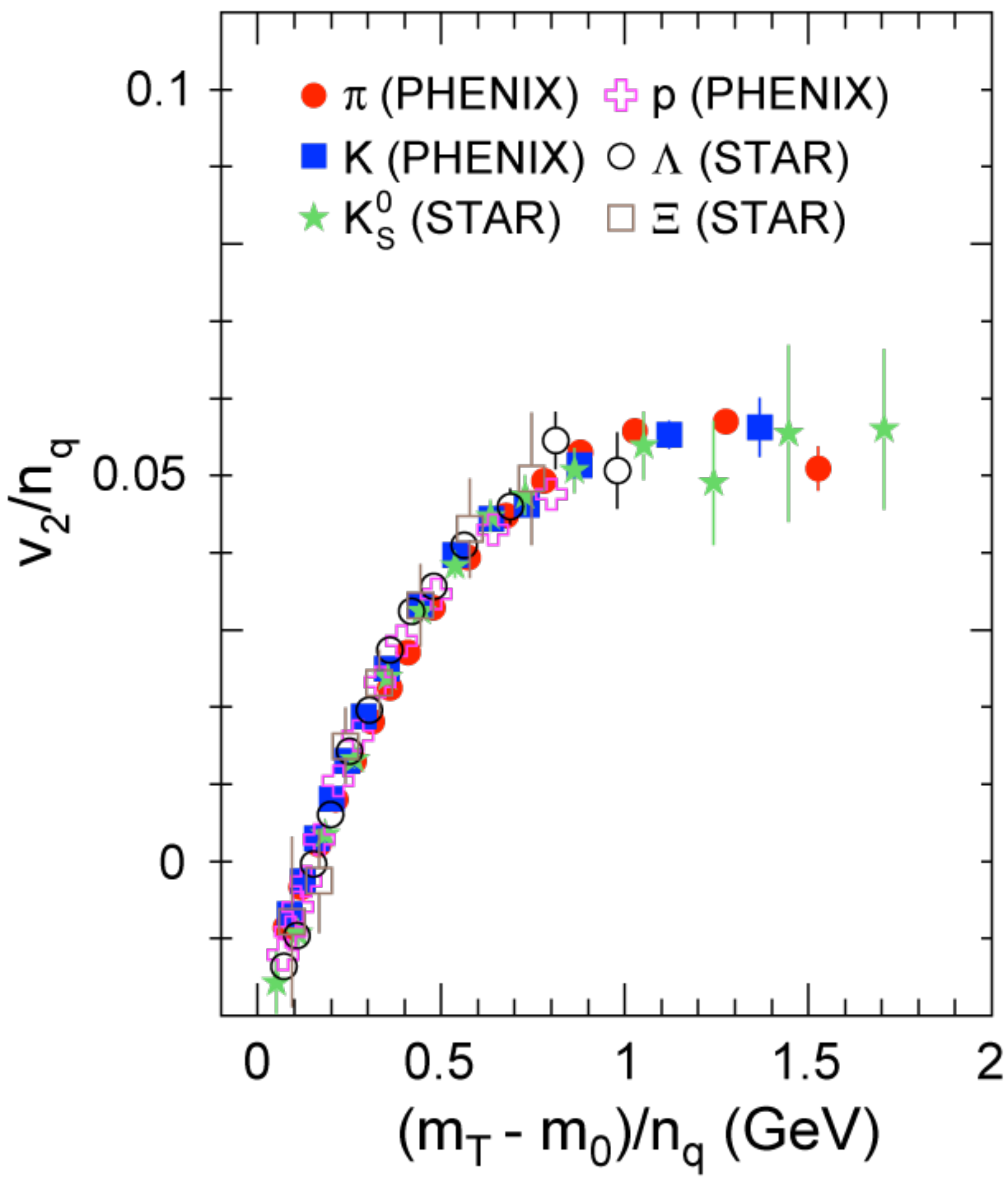
n = (2, 3) for (meson, baryon)

Works for p, π, K^0_s, Λ, Ξ..

$v_2^s \sim v_2^{u,d} \sim 7\%$

$$m_T = \sqrt{p_T^2 + m_0^2}$$

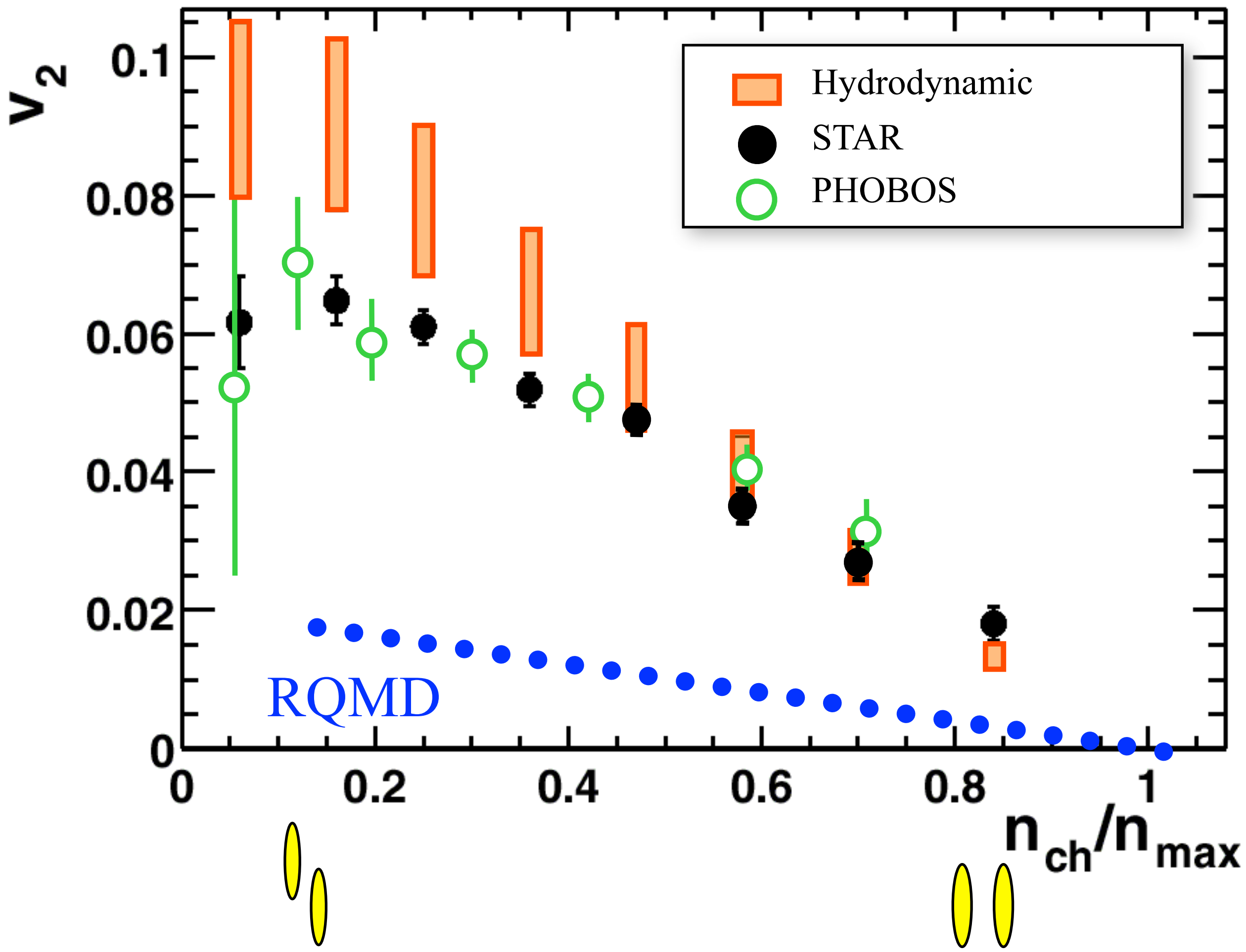


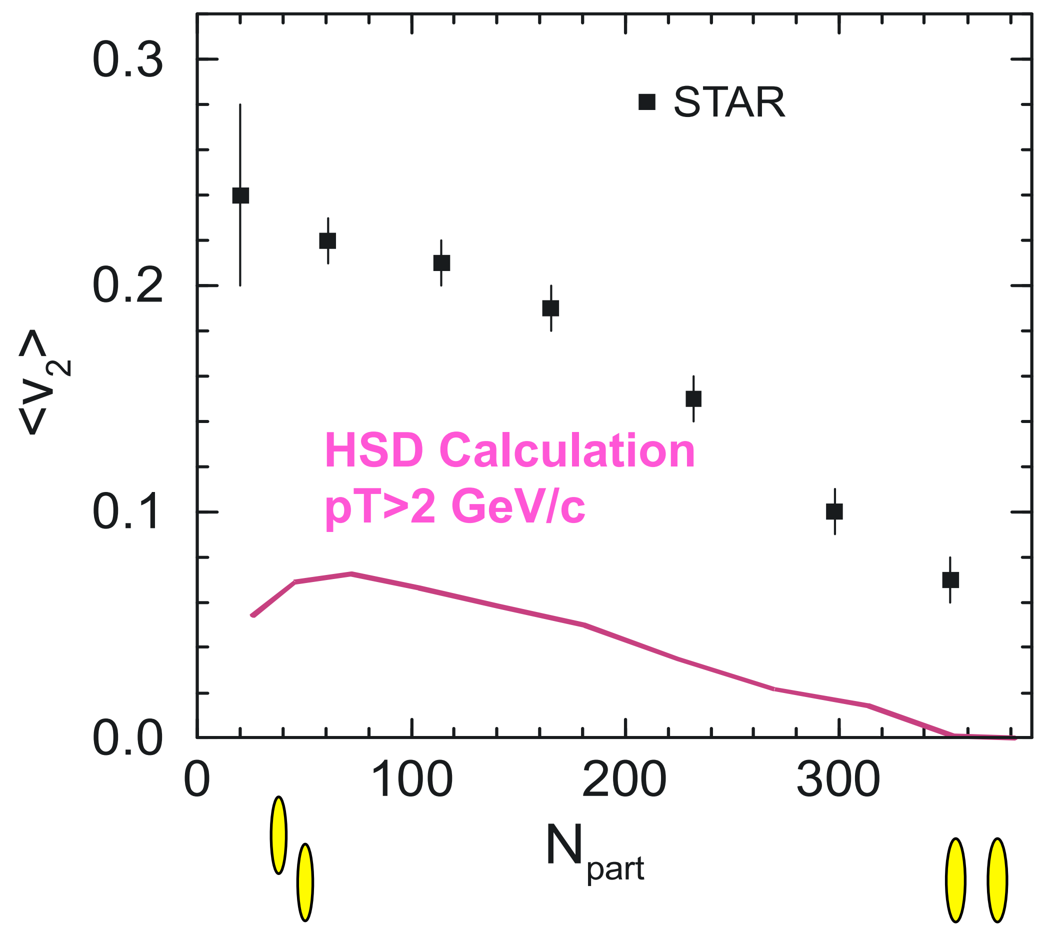
Constituents of QGP are partons

Just a gas of hadrons?

Just a gas of hadrons?

Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe data.





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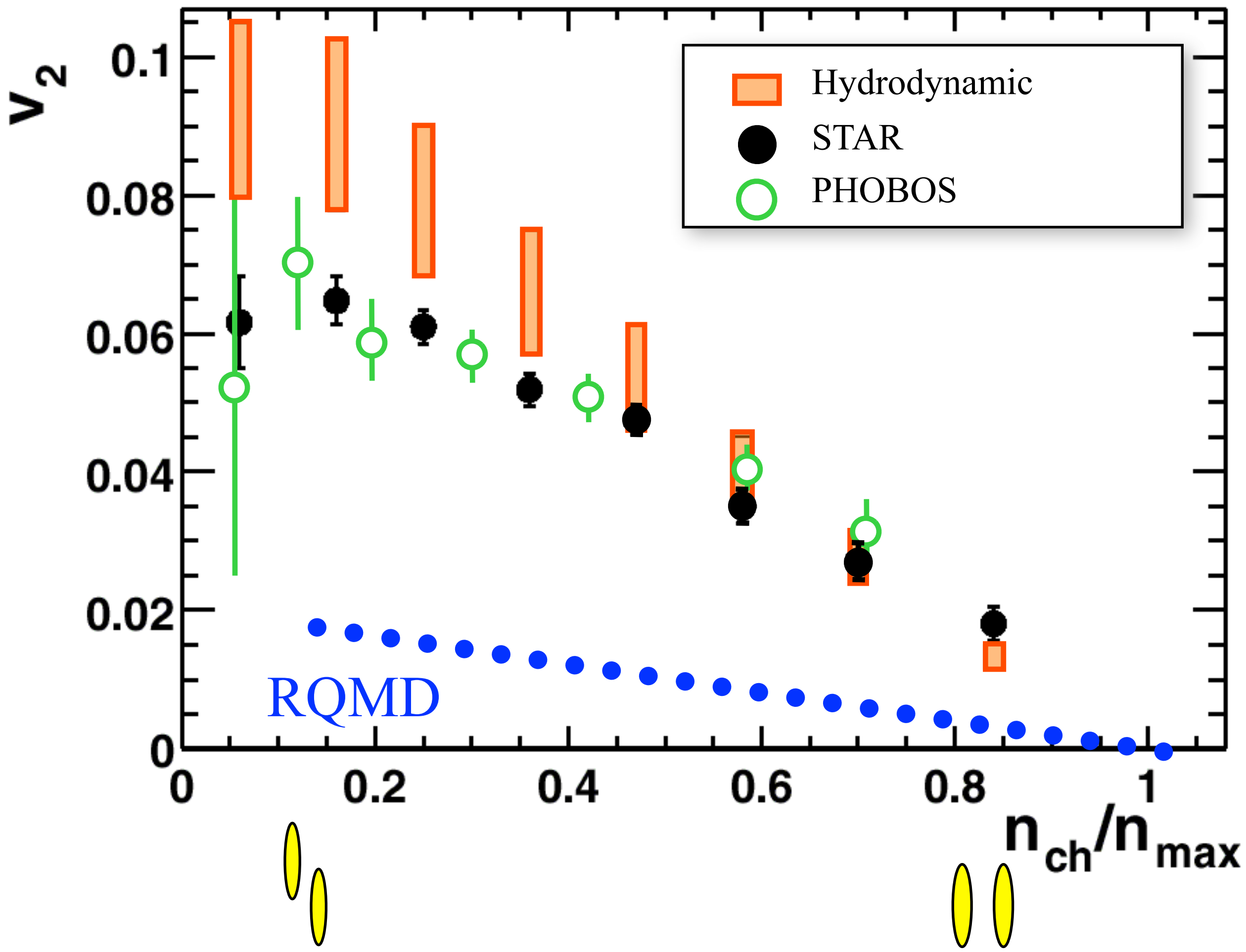

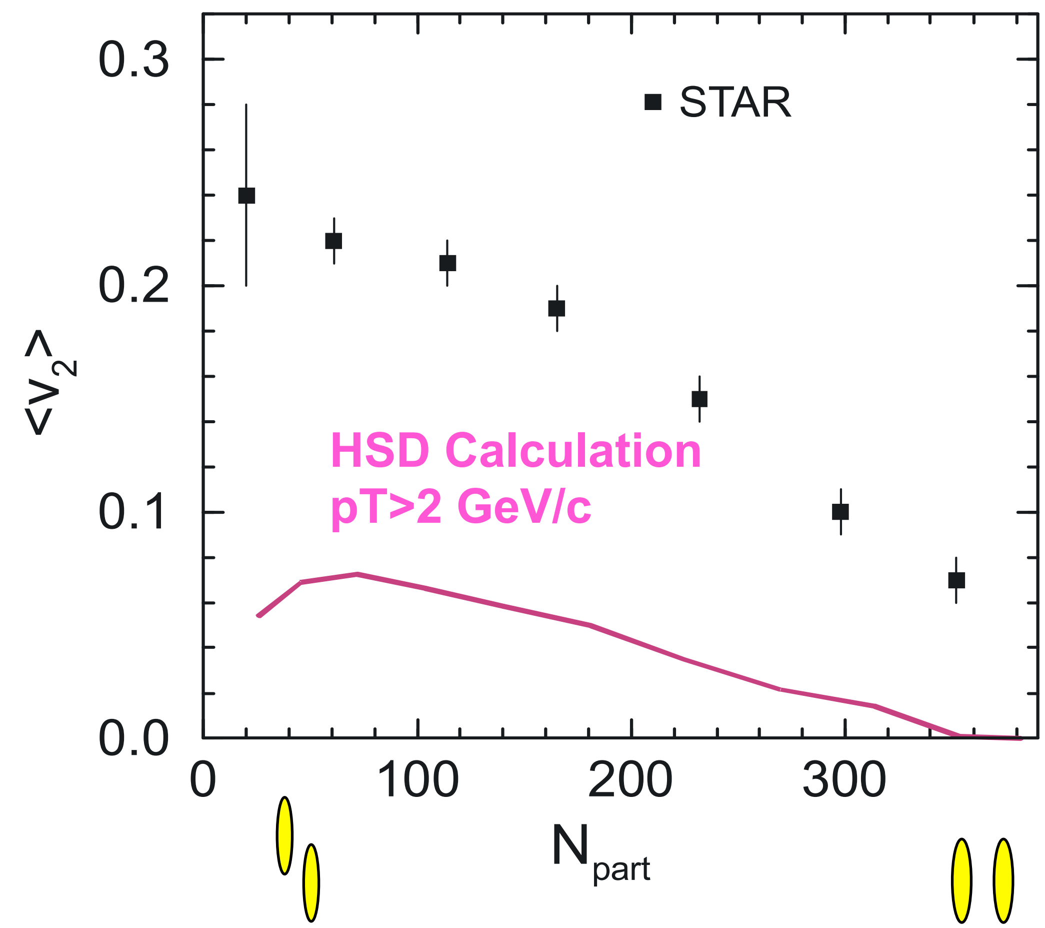

Clearly the system is not a hadron gas. Not surprising.

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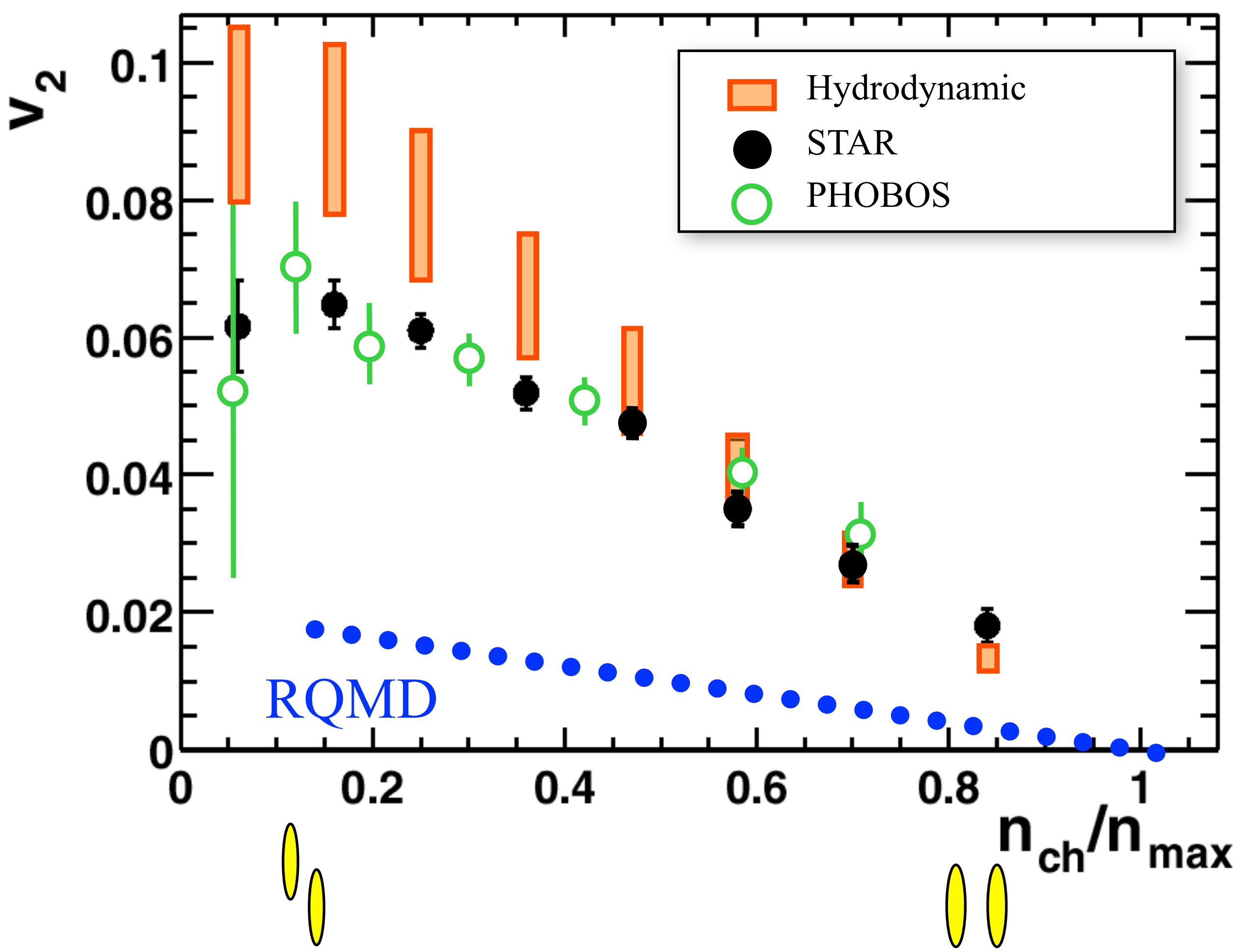
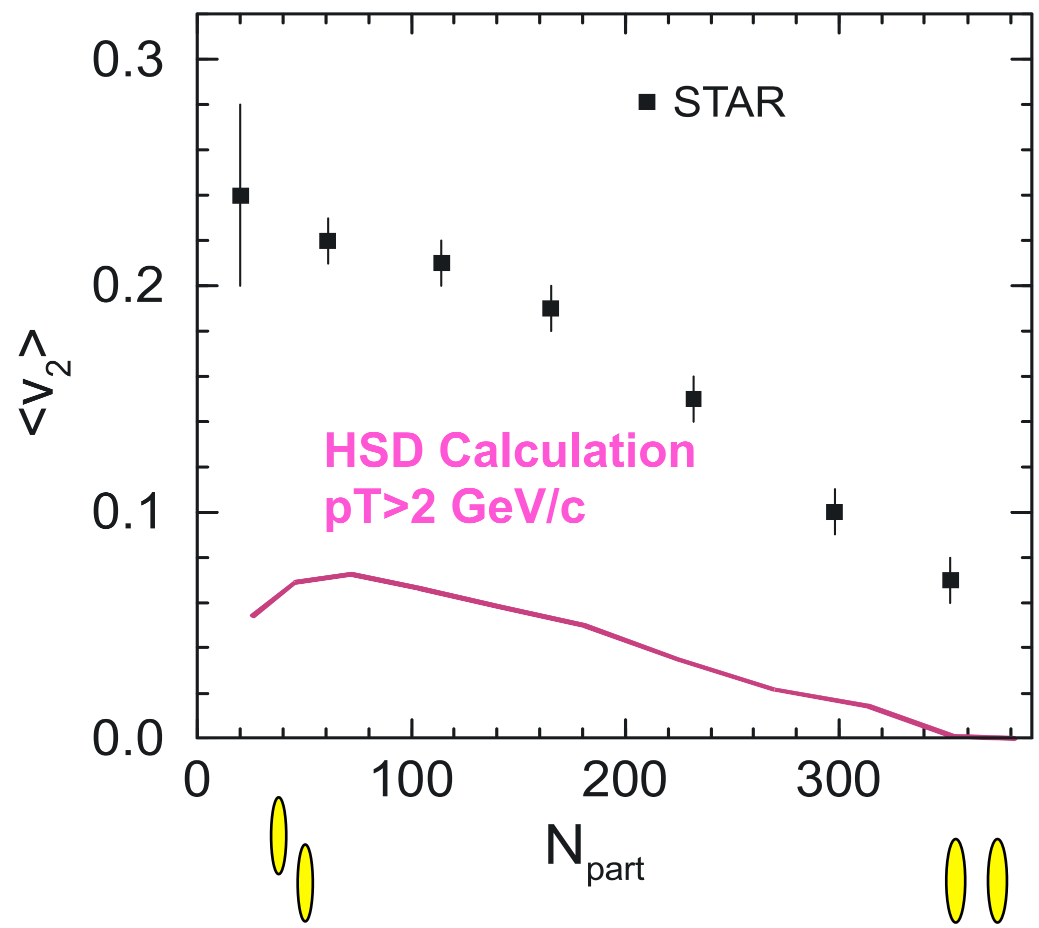


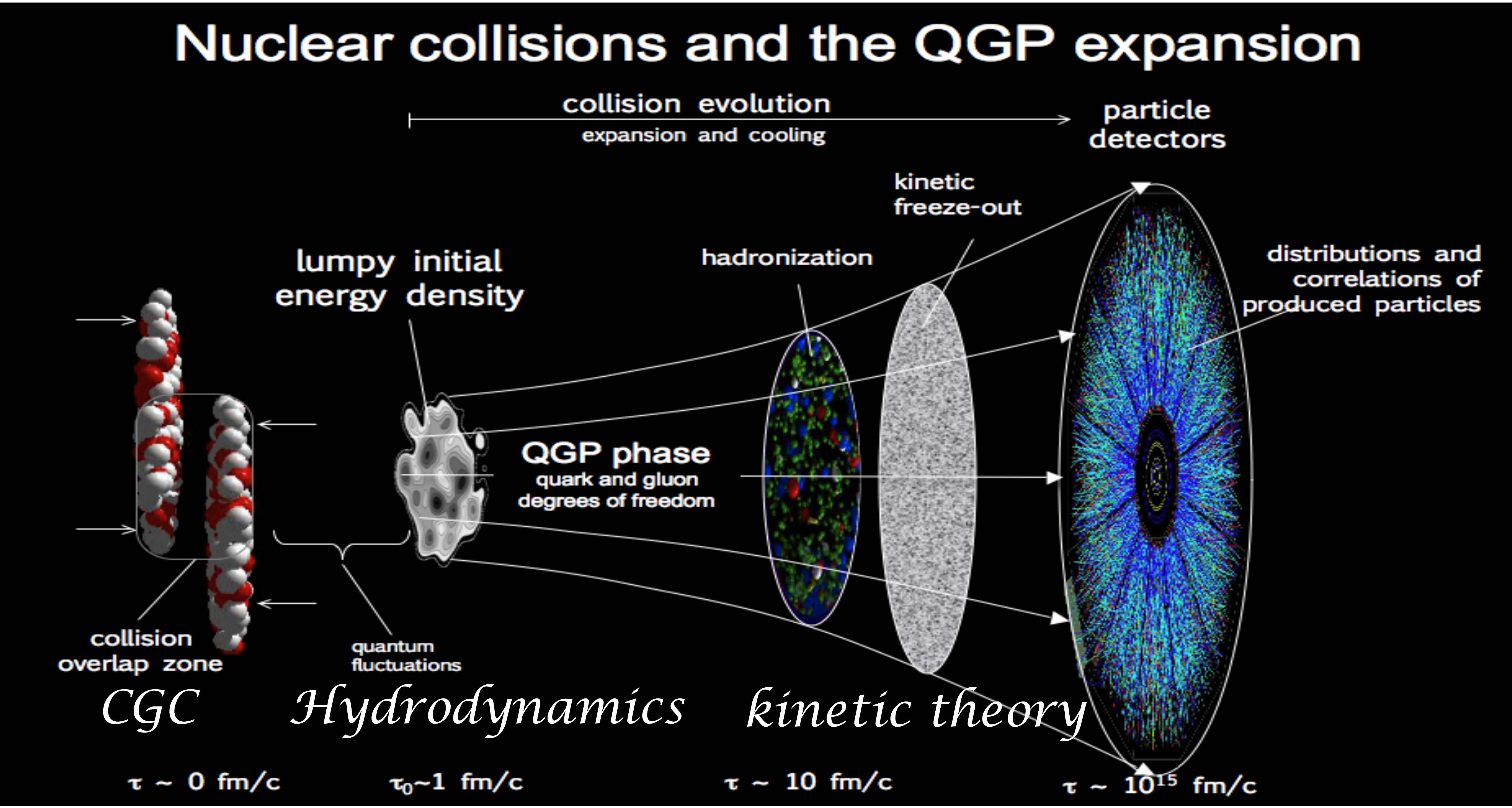


Clearly the system is not a hadron gas. Not surprising.

Hydrodynamical calculations:thermalization time t=0.6 fm/c

What interactions can lead to equilibration in < 1 fm/c?

Evolution of a HI collision



Executive summary of Soft Physics

- Energy density in the collision region is way above that where hadrons can exist

- The initial temperature of collision region is way above that where hadrons can exist

We create a new state of matter in HI collisions - the QGP. Smooth transition from RHIC to LHC

- Quark and gluon degrees of freedom in initial stages

- It flows like an almost "perfect" liquid and interacts strongly with partons passing through it

What can we now learn about the QGP properties and evolution?

Glauber calculations

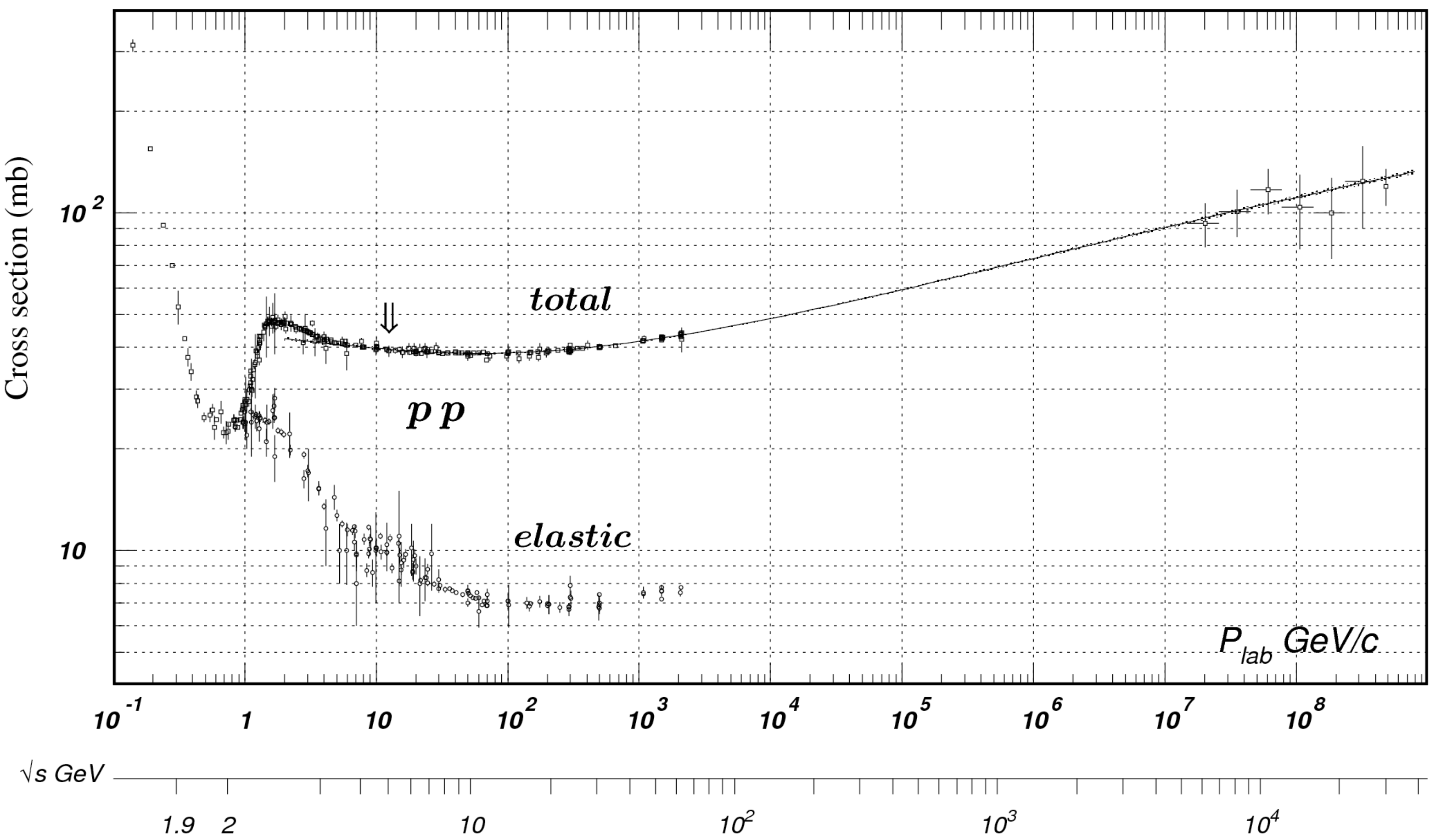
Use a Glauber calculation to estimate N_{bin} and N_{part}

- Roy Glauber: Nobel prize in physics 2005 for "his contribution to the quantum theory of optical coherence"

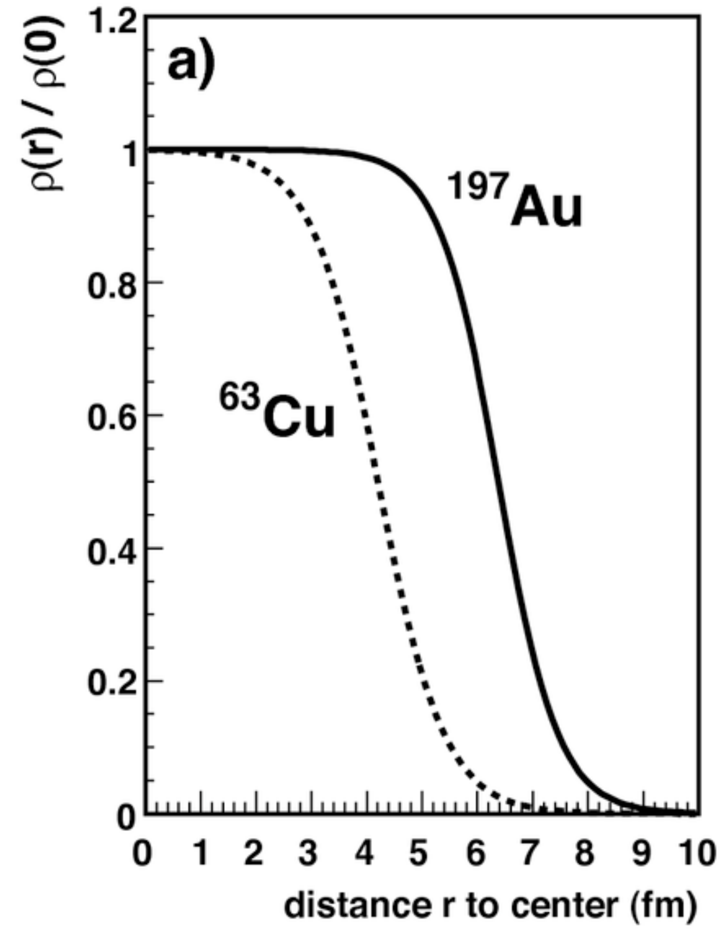
- Application of Glauber theory to heavy ion collisions does not use the full sophistication of these methods. Two simple assumptions:
  - Eikonal: constituents of nuclei proceed in straight-line trajectories
  - Interactions determined by initial-state shape of overlapping nuclei

Ingredients for Glauber calculations

Particle Data Book: W.-M. Yao et al., J. Phys. G 33,1 (2006) Fig 40.11



M. Miller et al, nucl-ex/0701025



- Assumptions: superposition of straight-line interactions of colliding nucleons
- Need nucleon-nucleon interaction cross section

  Most use inelastic: 42 mb at √s=200 GeV

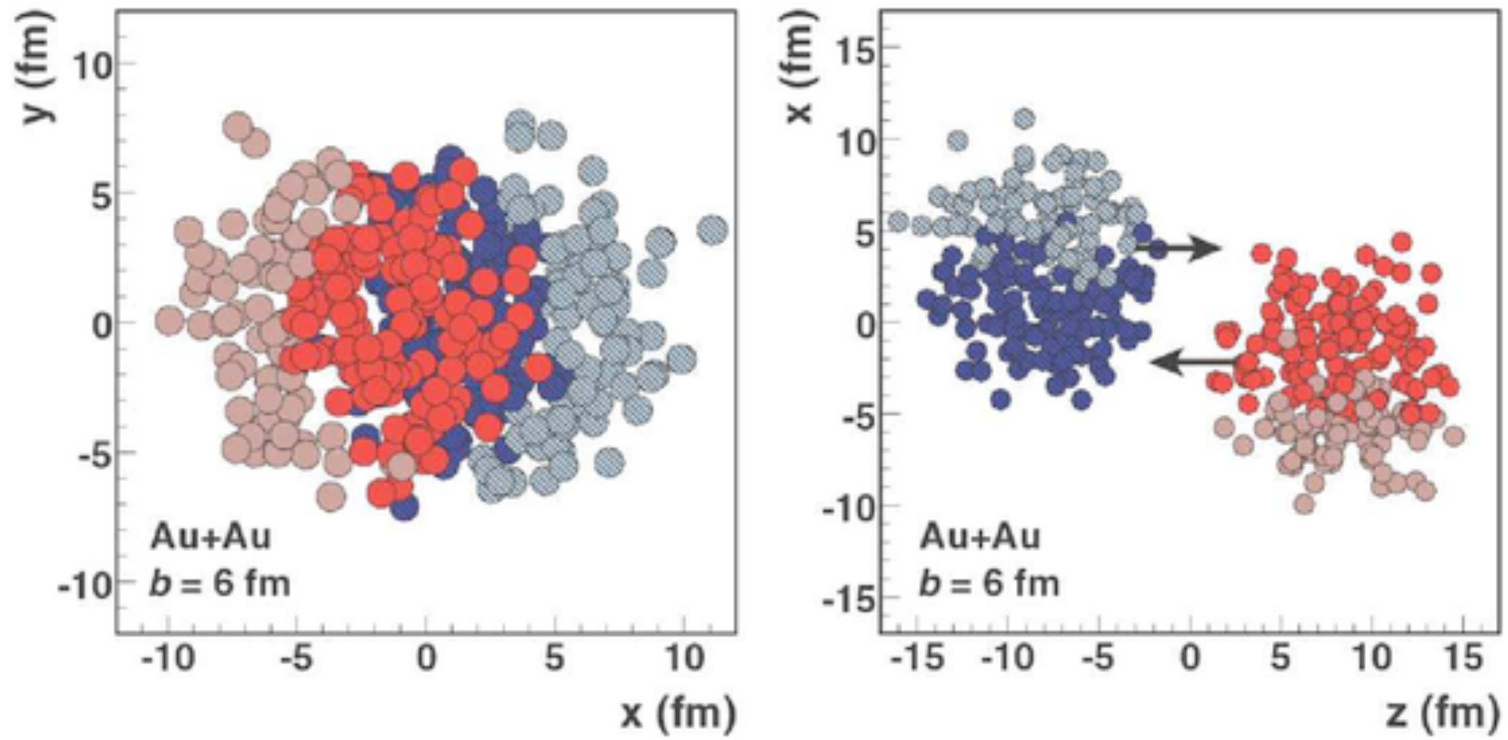
  Other choices: Non-singly-diffractive, 30 mb at √s = 200 GeV
- Need probability density for nucleons:

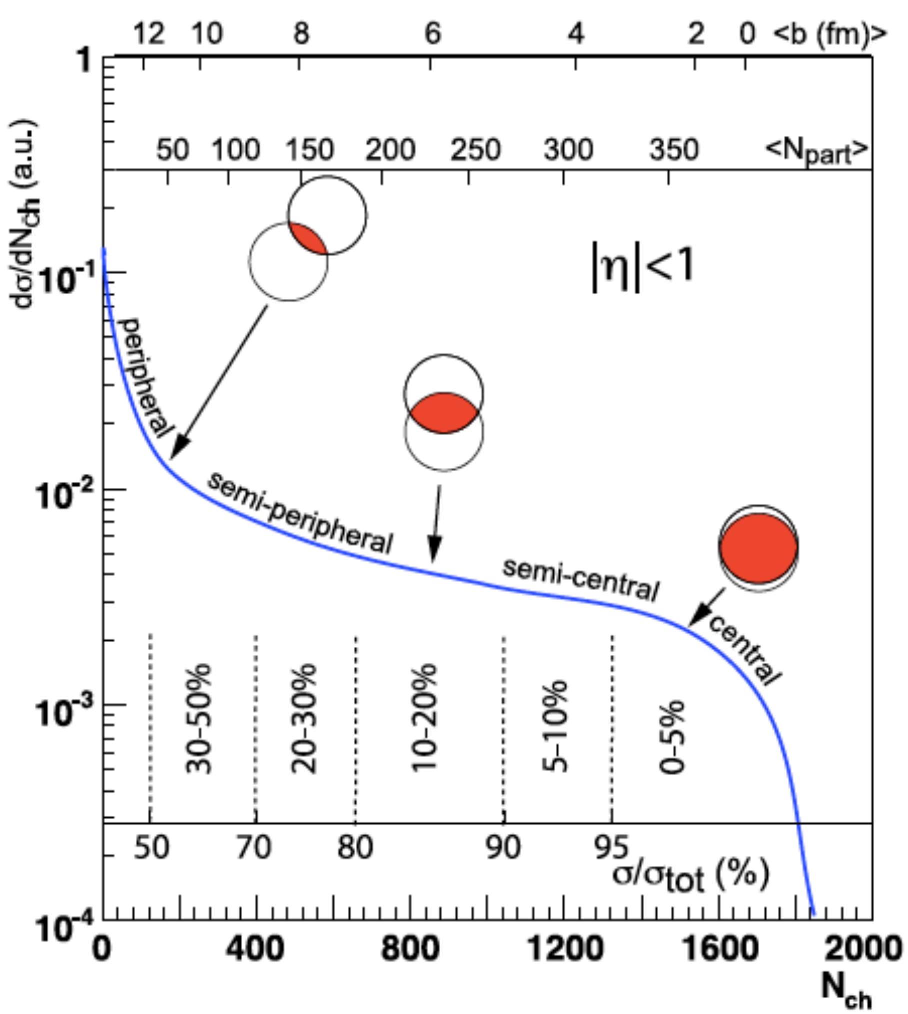
  \`Wood-Saxon' from electron scattering experiments

Glauber modeling

M. Miller et al, nucl-ex/0701025

- Monte Carlo Glauber
  - Randomly initialize nucleons sampling nuclear shape
  - At randomly selected impact parameter, allow nuclei to interact
  - Randomly sample probability of nucleons to interact from interaction cross-section
    - e.g. if distance d between nucleons is < $\sqrt{\sigma_{int}/\pi}$



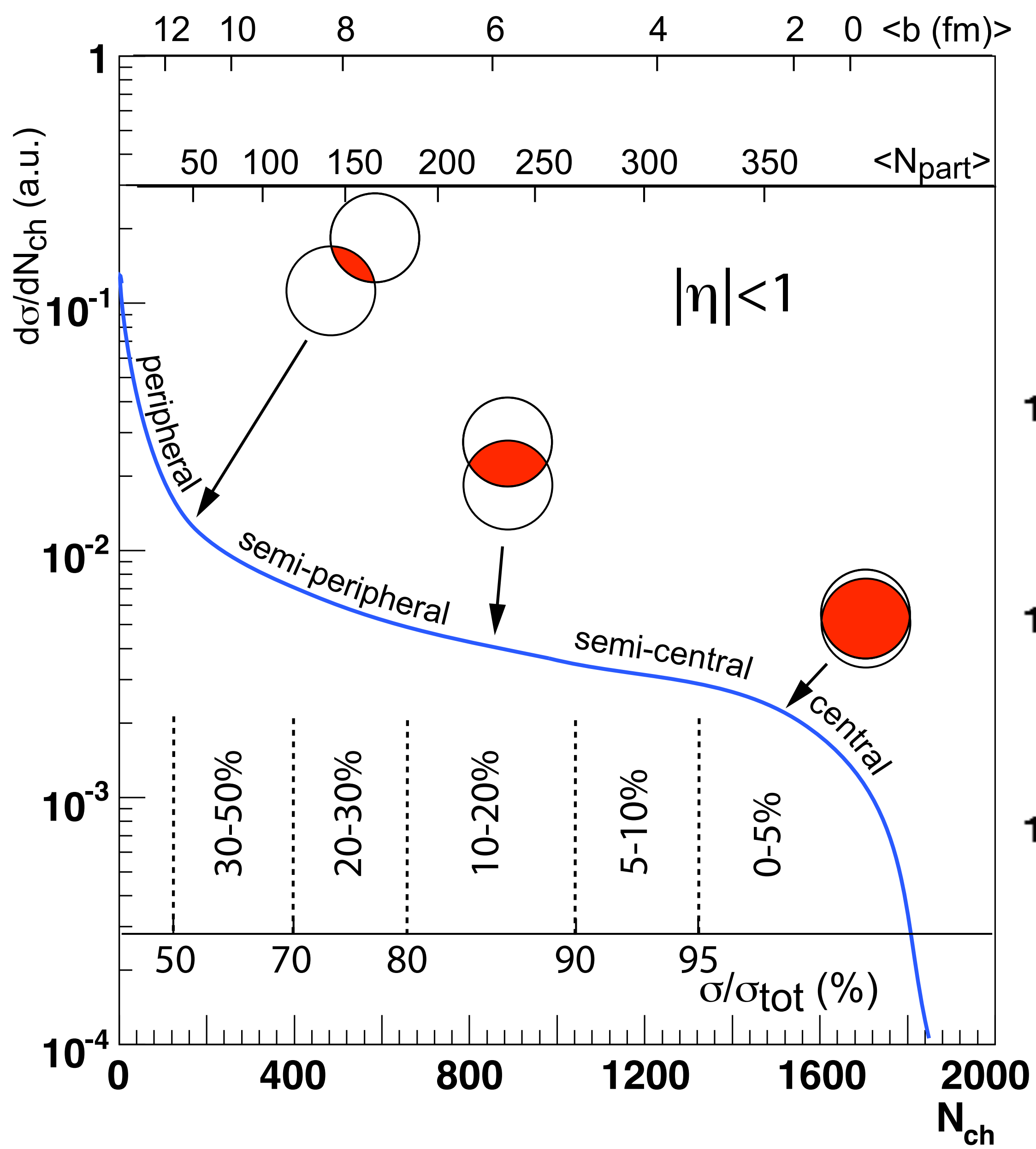


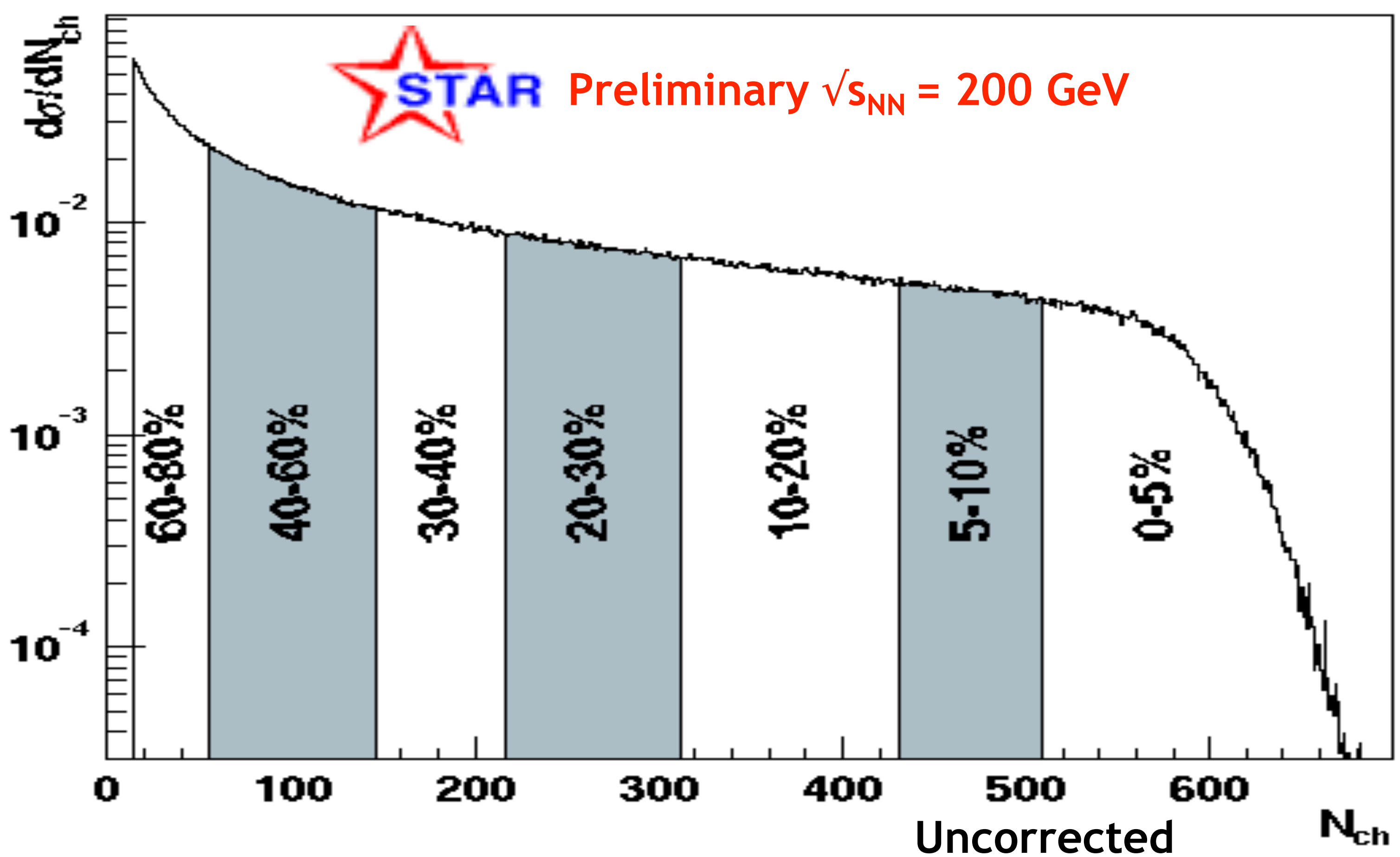
Calculate probability that N_{part} or N_{bin} occurs per event

Map onto an experimentally measurable variable expected to scale with centrality

i.e. particle multiplicity

Comparing to data heavy-ion collision





Good agreement between data and calculation

Measured mid-rapidity particle yield can be related to size of overlap region

What are the necessary conditions?

First Estimation: Phenomenological calculation

The MIT bag model (Bogolioubov (1967)) :

- Hadrons are non-interacting quarks confined within a bag
- Quarks are massless inside “bag”, infinite mass outside
- Quarks confined within the “bag” but free to move outside
- Confinement modeled by Dirac equation.

(m_{inside}~0, $M_{outside}$~infinity, θ_V = 1 inside the bag and zero outside the bag)

$$i\gamma^\mu \partial_\mu \psi - M\psi + (M - m)\theta_V \psi = 0$$

Wave function vanishes outside of bag, satisfying boundary conditions at bag surface

With bag radius = R

$$E_i = \omega_i \frac{\hbar c}{R}$$

MIT bag model

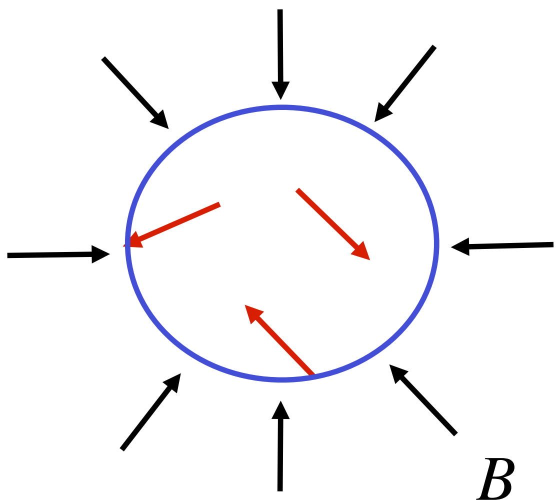
MIT group realized E-p conservation violated

Included an external "bag pressure" balances internal pressure from quarks.

e.g. nucleon ground state is
3 quarks in $1s_{1/2}$ level

To create this pressure the vacuum attributed with energy density B

$$E_i = \omega_i \frac{\hbar c}{R} + \frac{4\pi}{3} R^3 B$$



Boundary condition now:
Energy minimized with respect to R

$$B^{\frac{1}{4}} = (\Sigma_i \omega_i \frac{\hbar c}{4\pi})^{\frac{1}{4}} \frac{1}{R}$$

R=0.8 fm, 3 quarks

$B^{1/4}$ = 206 MeV/fm^3

Critical temperature from MIT bag

If μ (chemical potential) = 0 (true for massless quarks):

degeneracy factor

$$E_q = \frac{\overbrace{g_q}^{\text{degeneracy factor}} V}{2\pi^2} \int_0^\infty \underbrace{\frac{p^3 dp}{1 + e^{p/T}}}_{\text{Fermi-Dirac distribution}}$$

$$E_g = \frac{g_g V}{2\pi^2} \int_0^\infty p^3 dp \{ \frac{1}{\underbrace{e^{p/T} - 1}_{\text{Bose-Einstein distribution}}} \}$$

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P = 1/3 ε, $T_c = (\frac{90}{37\pi^2})^{\frac{1}{4}} B^{\frac{1}{4}}$,$B^{1/4}$ = 206 MeV/fm^3

i.e. T > T_c, the pressure in the bag overcomes the bag pressure

$T>T_c$=144 MeV → de-confinement and QGP

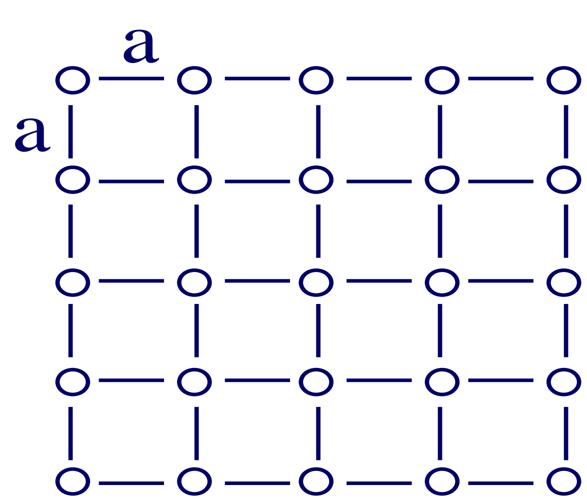
What are the necessary conditions? - II

Second estimation: Lattice QCD

At large Q^2: coupling small, perturbation theory applicable

At low Q^2 : coupling large, analytic solutions not possible, solve numerically → Lattice QCD

$$N_s^3 \times N_t$$



quarks and gluons can only be placed on lattice sites

Can only travel along connectors

Better solutions:

- higher number sites
- smaller lattice spacing

Cost:

- CPU time

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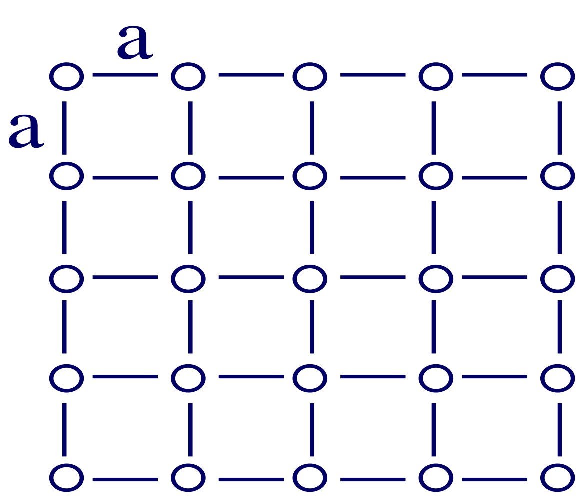

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Lattice QCD making contact with experiments:

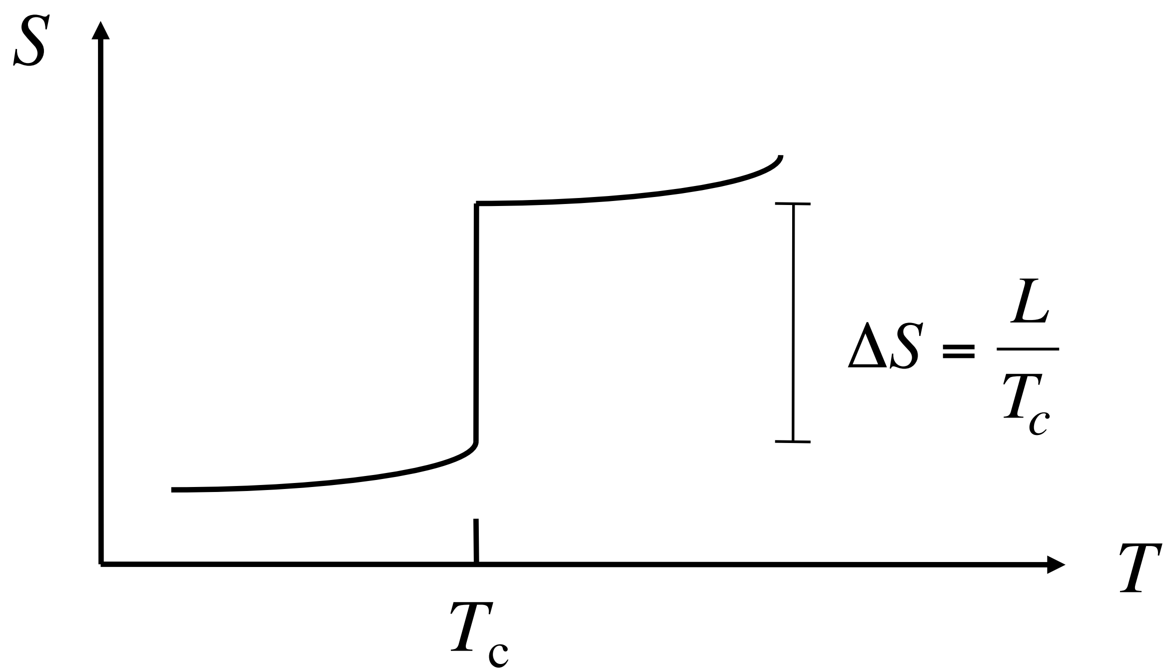
Proton mass calculated to within 2%

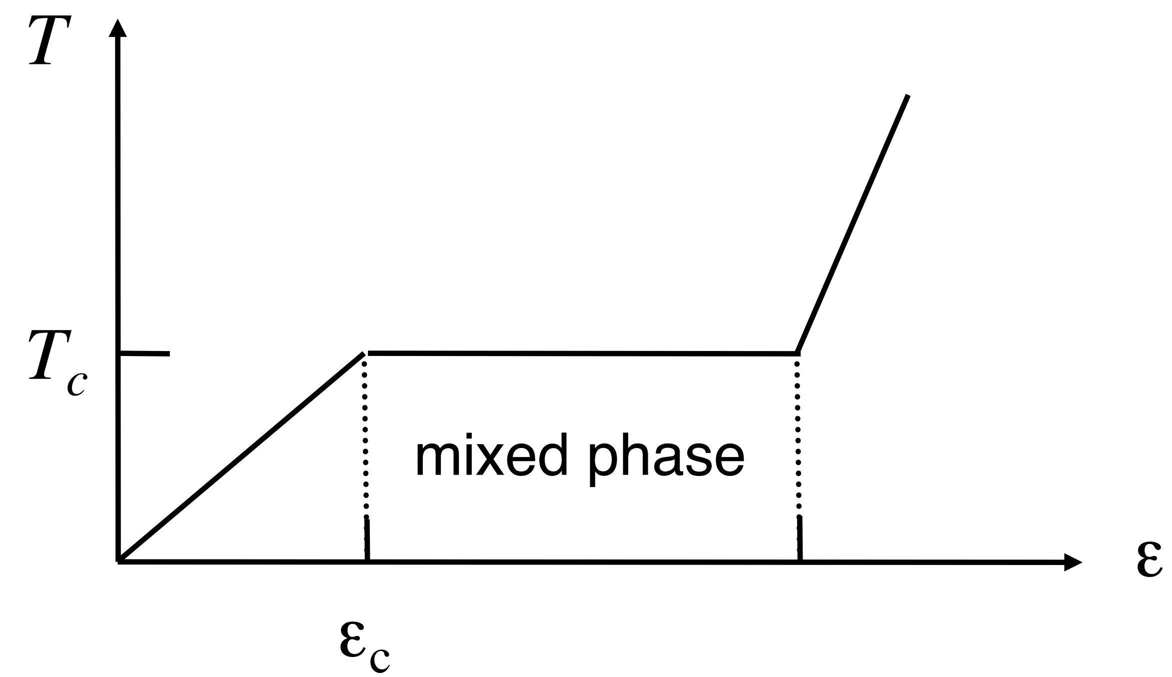
Thermodynamics - phase transitions

Phase transition or a crossover?

Signs of a phase transition:

1st order: discontinuous in entropy at T_c → Latent heat, a mixed phase





Higher order: discontinuous in higher derivatives of $\delta^n S/\delta T^n$ → no mixed phase - system passed smoothly and uniformly into new state (ferromagnet)

Temperature ⇔ transverse momentum

Energy density ⇔ transverse energy

Entropy ⇔ multiplicity

$$T \propto \langle p_T \rangle$$

$$e \propto dE_T/dy \cong \langle m_T \rangle dN/dy$$

$$S \propto dN/dy$$

What is the temperature of the medium?

- Statistical Thermal Models:
  - Assume a system that is thermally (constant T_{ch}) and chemically (constant n_i) equilibrated
  - System composed of non-interacting hadrons and resonances
  - Obey conservation laws: Baryon Number, Strangeness, Isospin
- Given T_{ch} and μ 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

Fitting the particle ratios

Number of particles of a given species related to temperature

$$dn_i \sim e^{-(E-\mu_B)/T} d^3p$$

- Assume all particles described by same temperature T and μ_B
- one ratio (e.g., $\bar{p}$ / p) determines μ / T :

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-2\mu_B/T}$$

- A second ratio (e.g., K / π) provides T $\rightarrow$ μ

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K - E\pi)/T}$$

- Then all other hadronic ratios (and yields) defined

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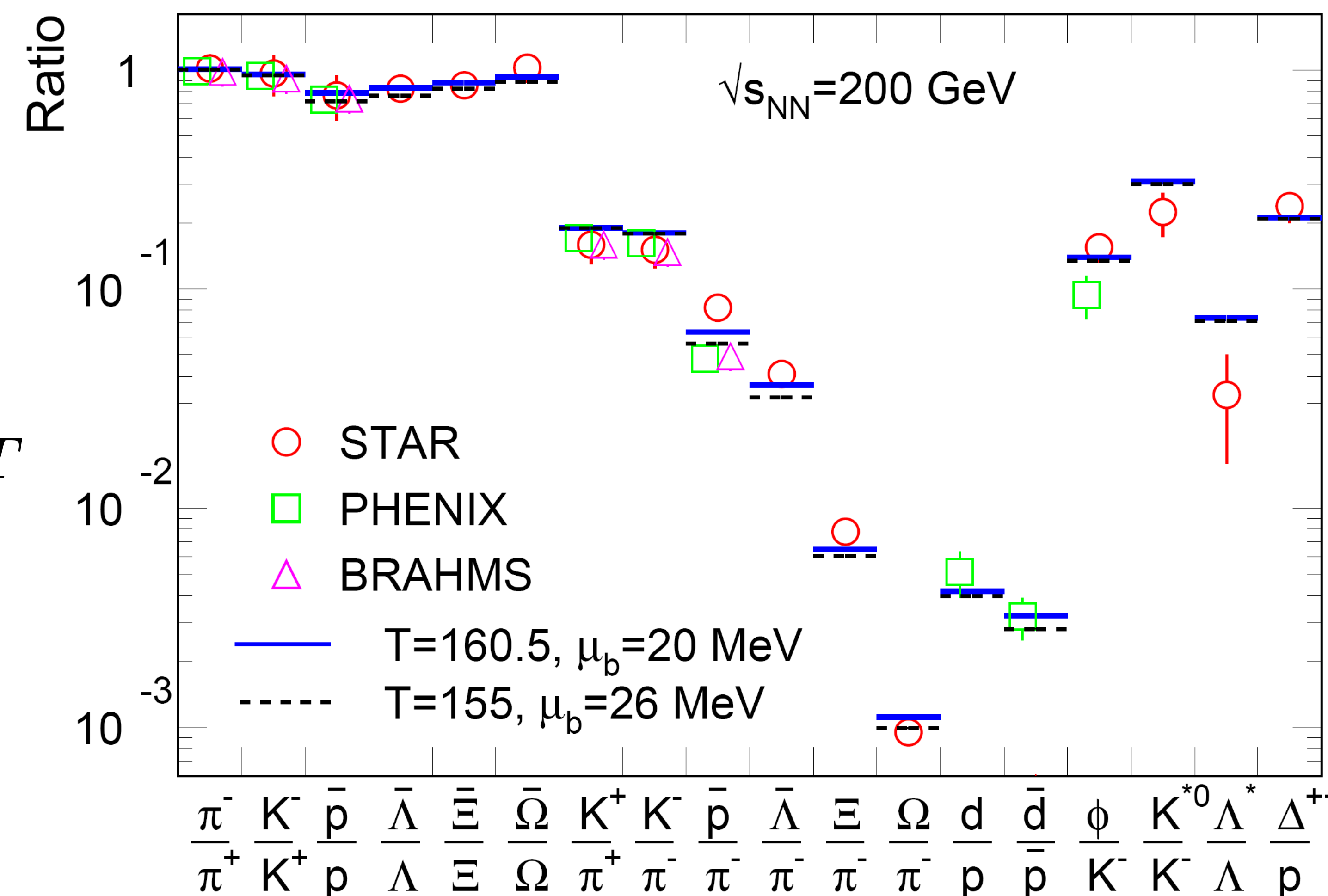
A. Adronic *et al.*, NPA772:167



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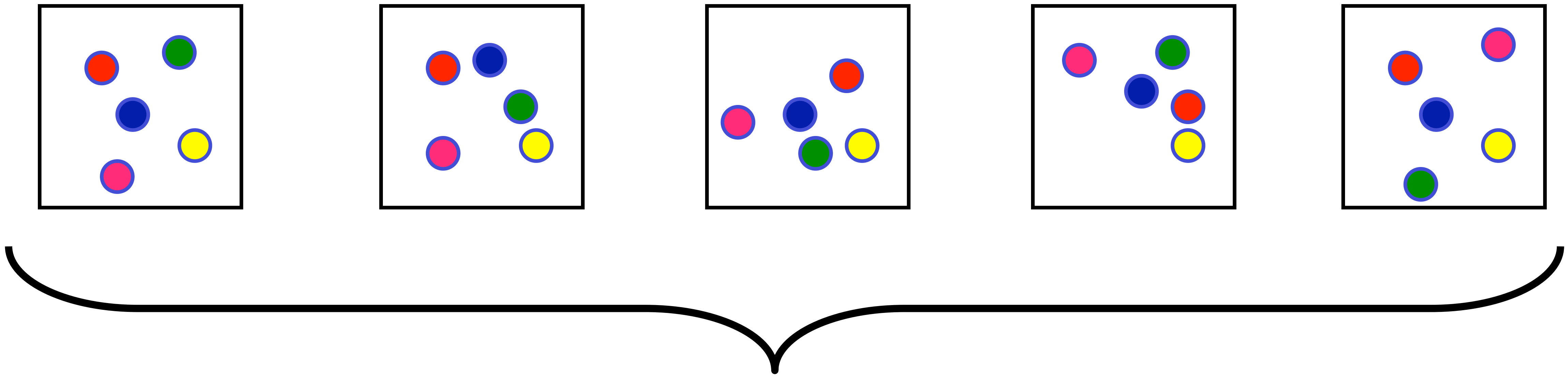
T ~ 160 MeV, μ_b ~ 20 MeV

Initial Temperature probably much higher

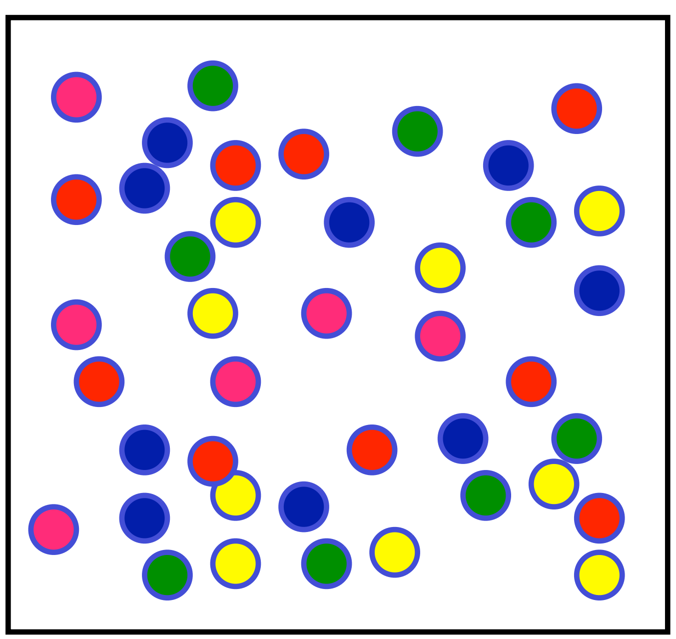
Statistics ≠ thermodynamics

p+p



Ensemble of events constitutes a statistical ensemble
T and μ are simply Lagrange multipliers
"Phase Space Dominance"

A+A



One (1) system is already statistical !

- We can talk about pressure
- T and μ are more than Lagrange multipliers

Evidence for thermalization?

- Not all processes which lead to multi-particle production are thermal - elementary collisions

- *Any* mechanism for producing hadrons which evenly populates the free particle phase space will mimic a microcanonical ensemble.

- Relative probability to find n particles is the ratio of the phase-space volumes $P_n/P_{n'} = \varphi_n(E)/\varphi_{n'}(E)$ $\Rightarrow$ given by statistics only.

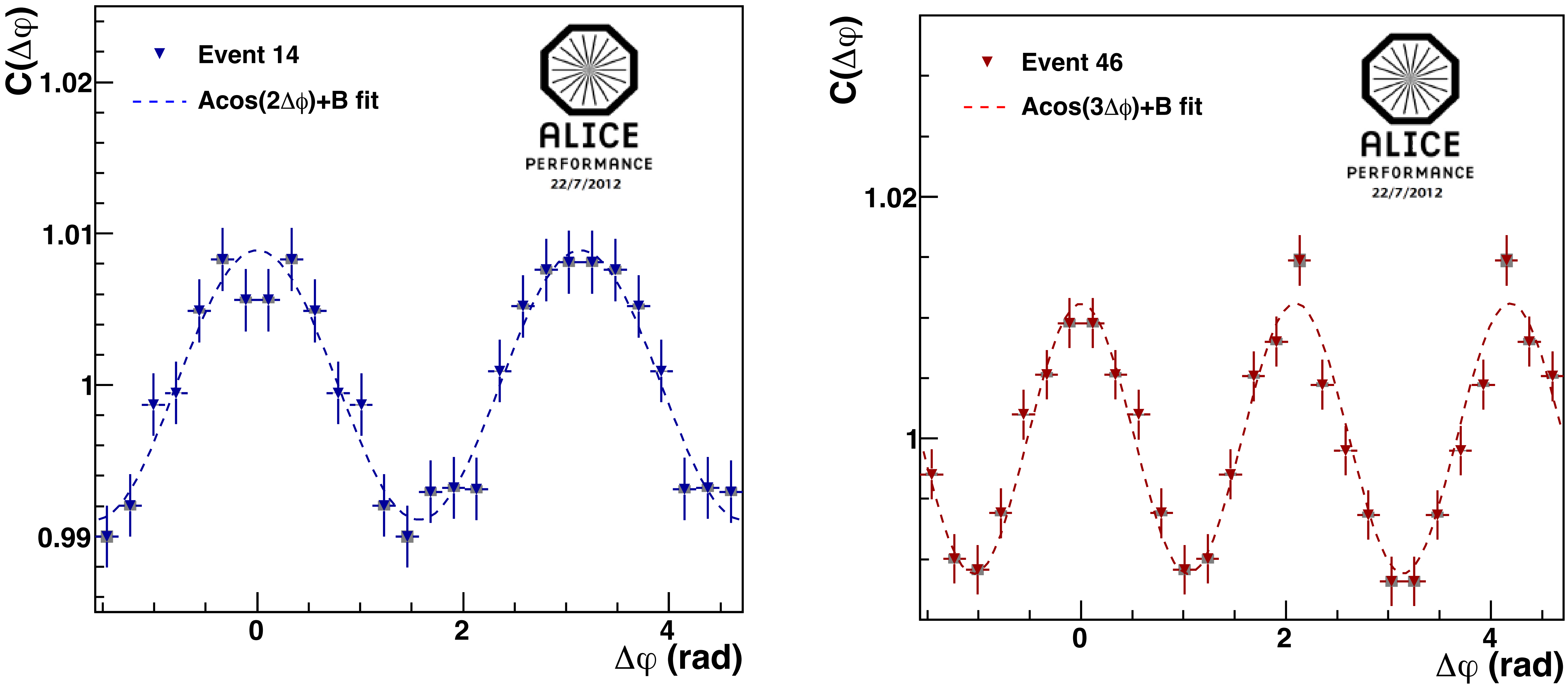
- Difference between MCE and CE vanishes as the size of the system N increases.

- Such a system is NOT in thermal equilibrium - to thermalize need interactions/re-scattering

Need to look for other evidence of collective motion

Event-by-event flow

Pb-Pb 4-5% central events at 2.76 TeV



Some events are dominated by elliptic flow, some by triangular..

Run averaged data hiding some information - more to left learn