Benjamin Audurier - Aussois classes - Jan. 2023

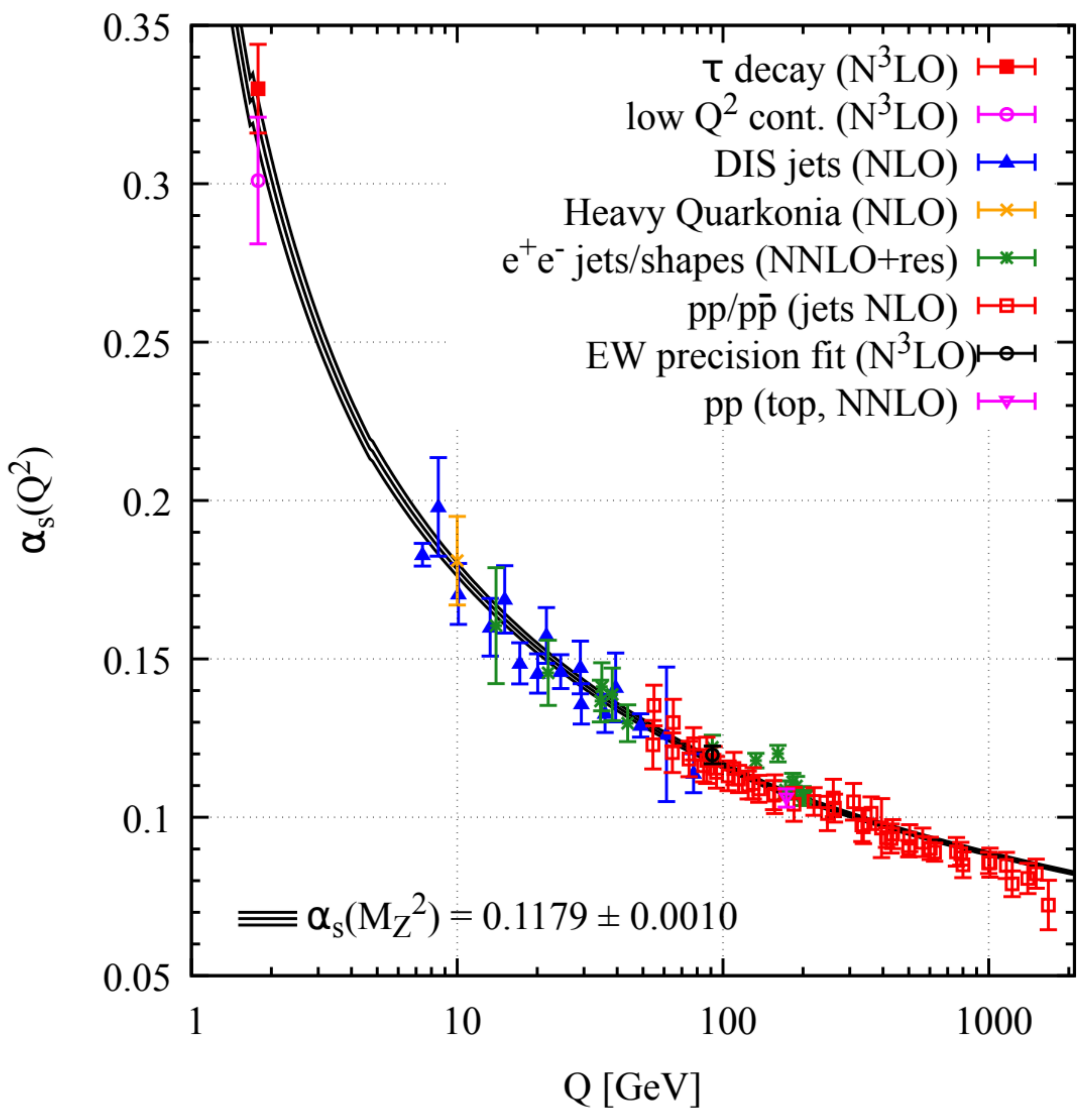
GENERAL INTRODUCTION TO HEAVY-ION PHYSICS

« Heavy-ion talks always start with someone doing a weird clap with flat hands »

-A physicist from Strasbourg that I know.

The best of two worlds

Quantum Chromodynamics



- Non-renormalizable.
- Headache to solve numerically.

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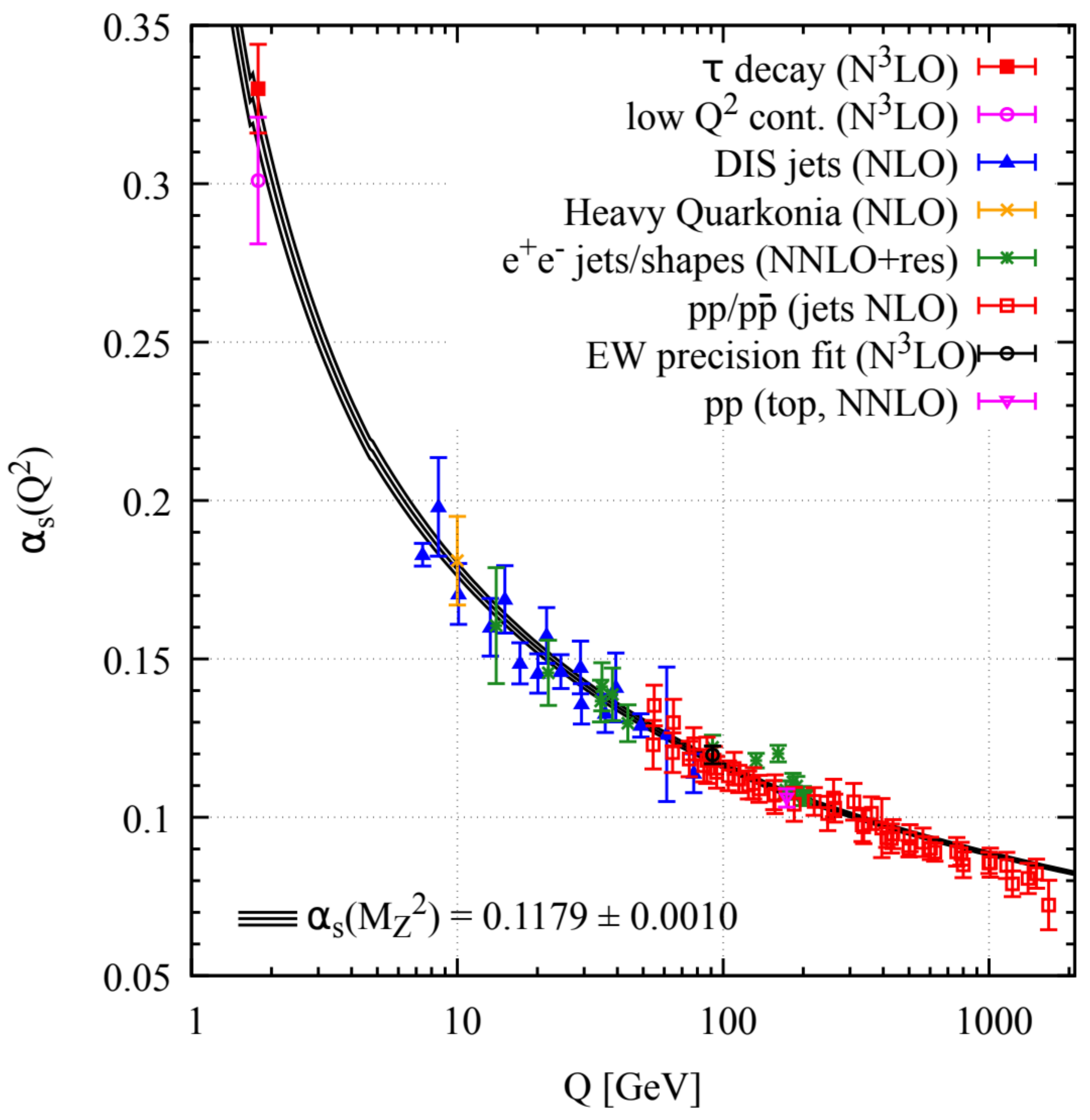

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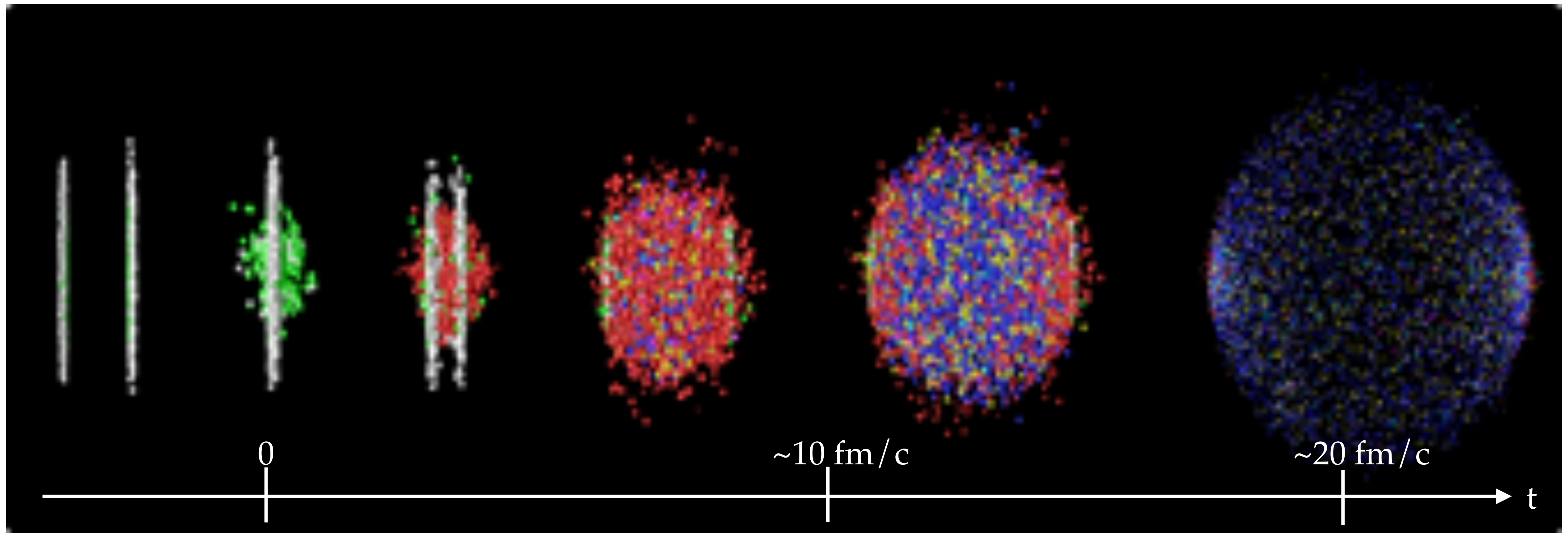
Dynamic colliding nuclear medium



- Initial conditions are different from proton-proton collisions.
- Expending medium in the collision.

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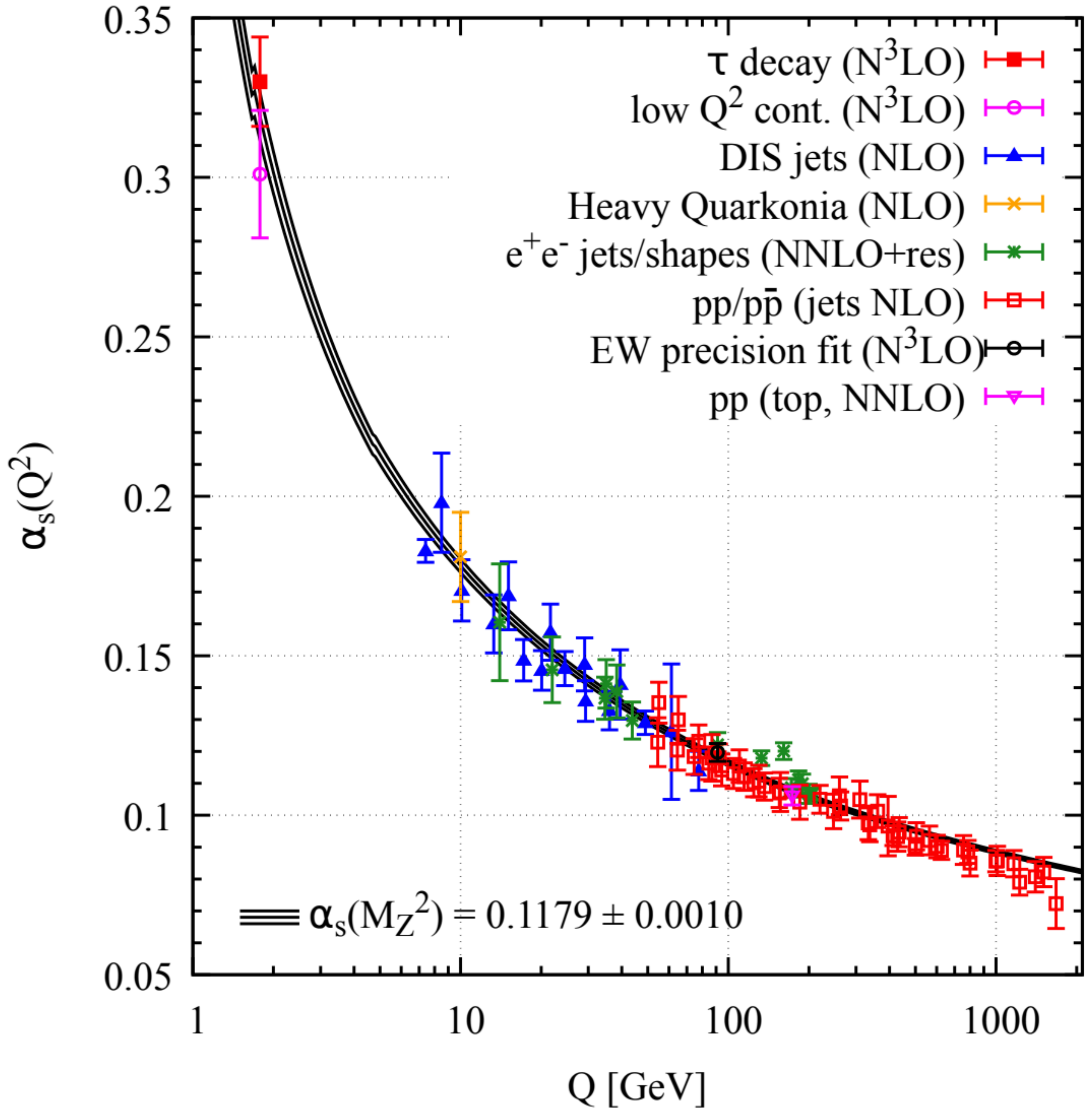

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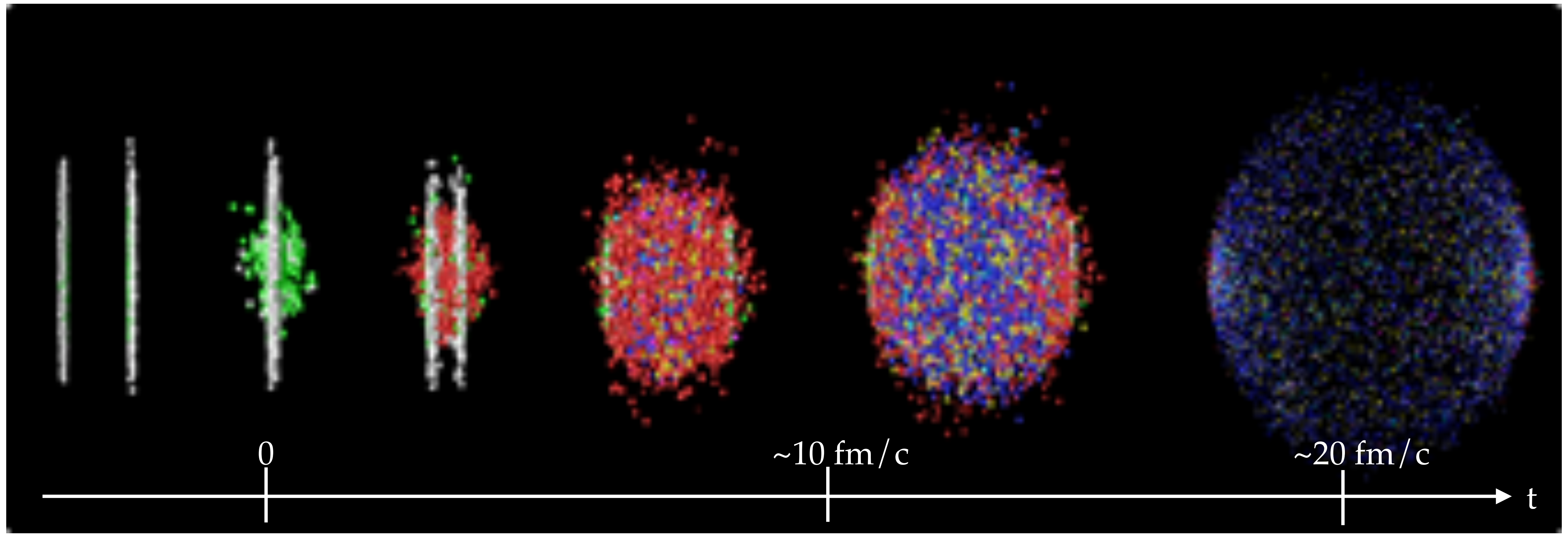

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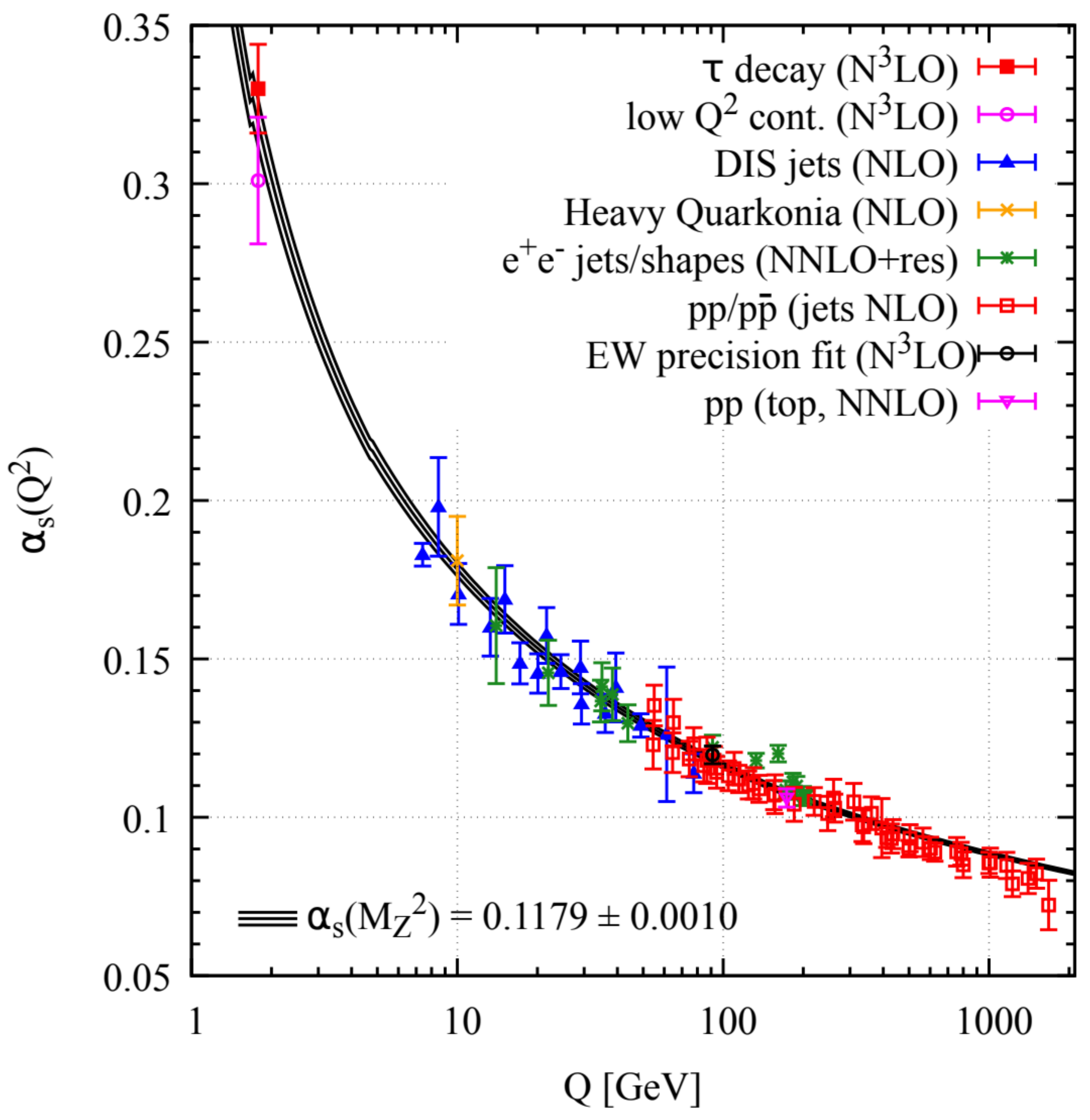
Heavy-ion physics: interface between effective theory, modeling and phenomenology

One medium to rule them all

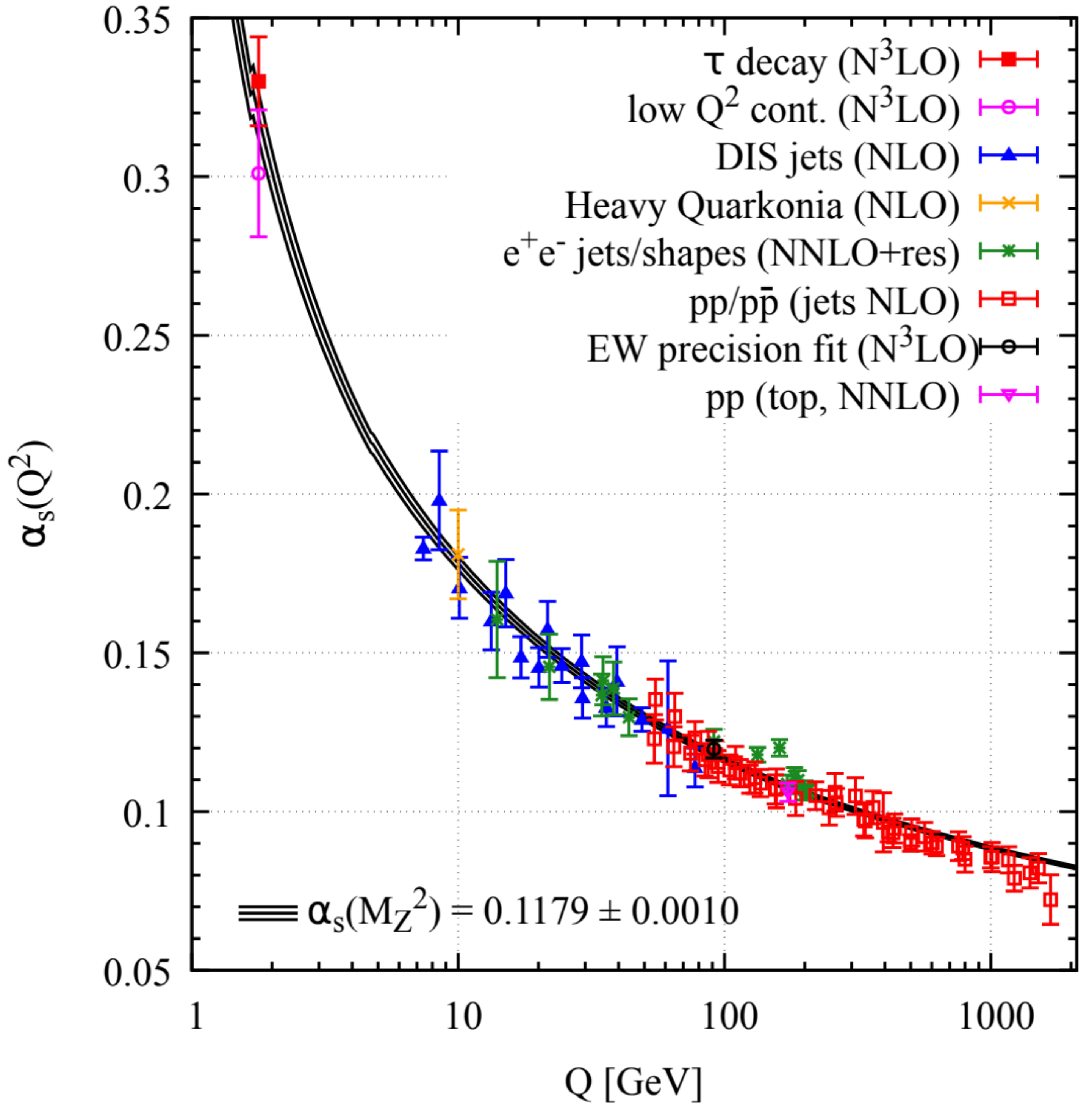
Quantum Chromodynamics



One medium to rule them all

Quantum Chromodynamics

Confinement



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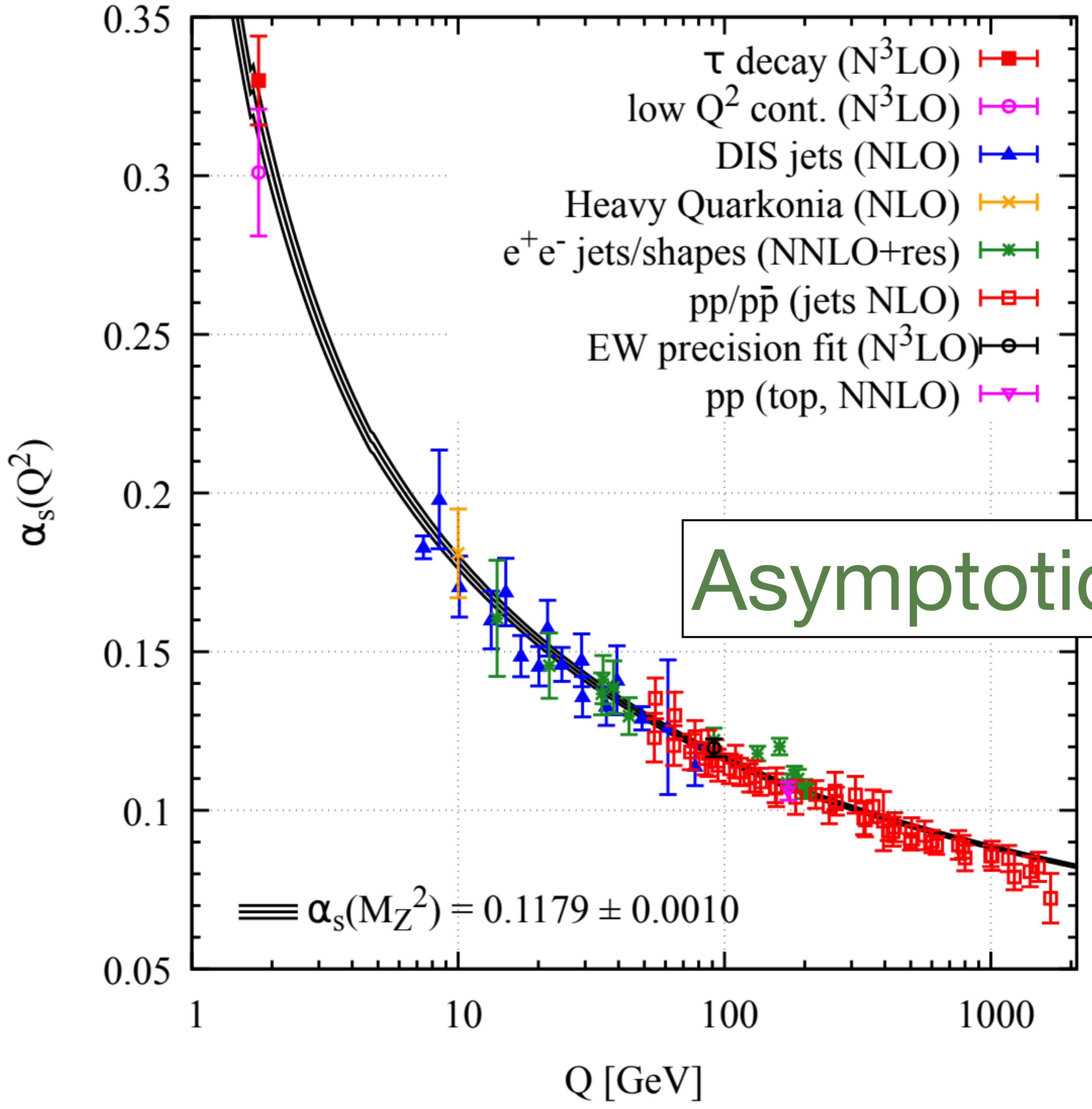

Asymptotic freedom

One medium to rule them all

Quantum Chromodynamics

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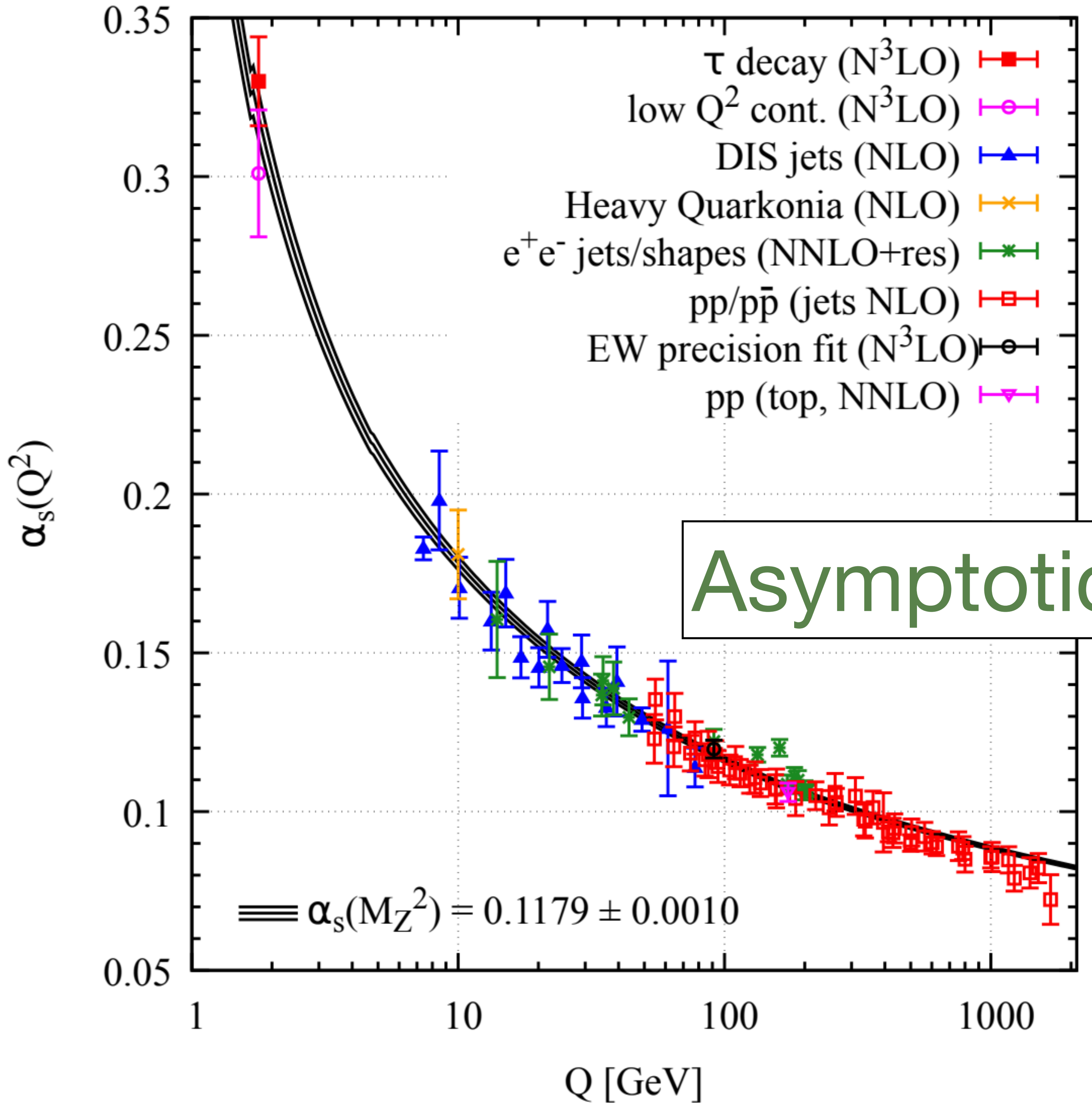
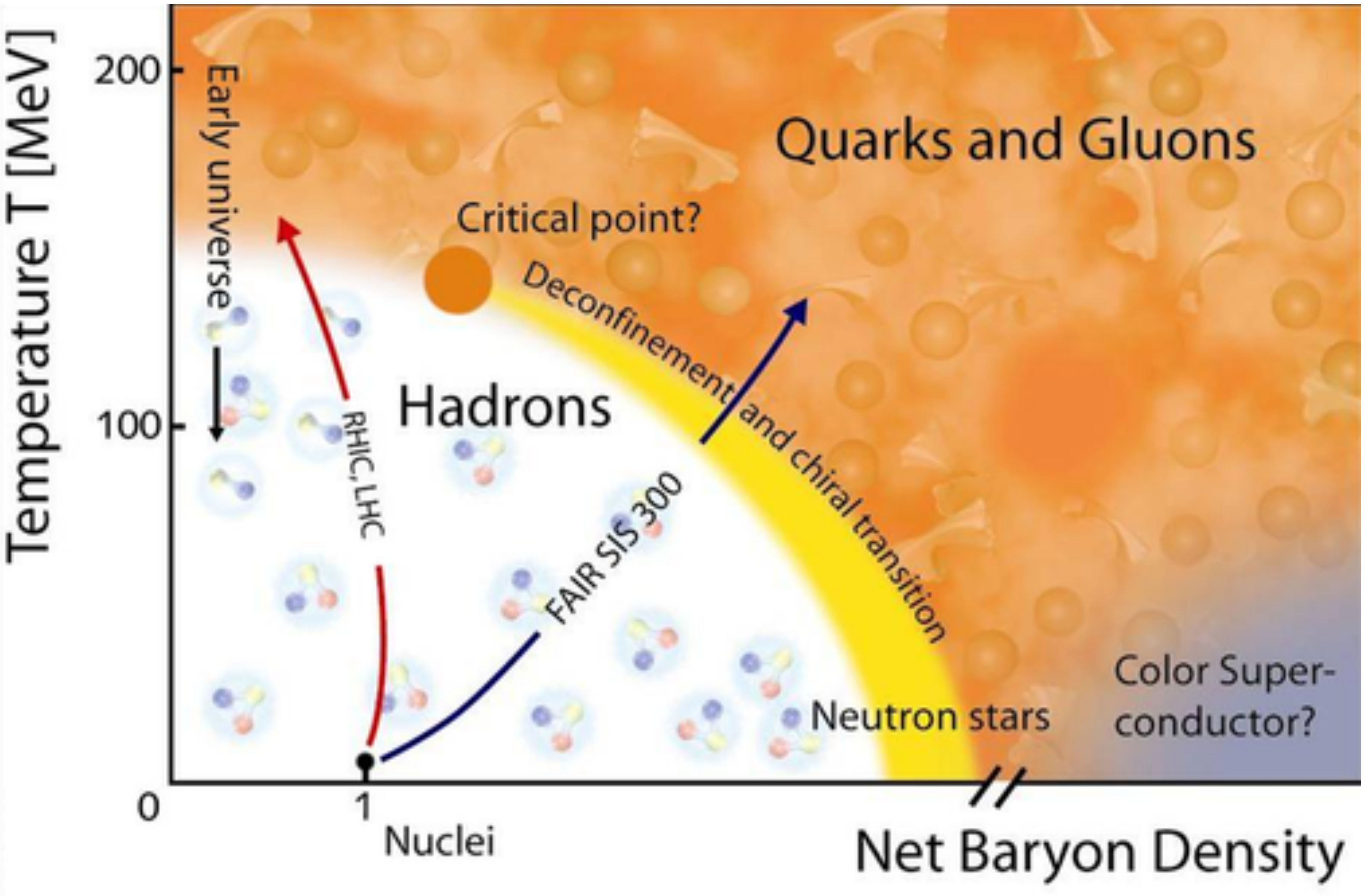


Asymptotic freedom

Phase diagram of hadronic matter



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Quantum Chromodynamics

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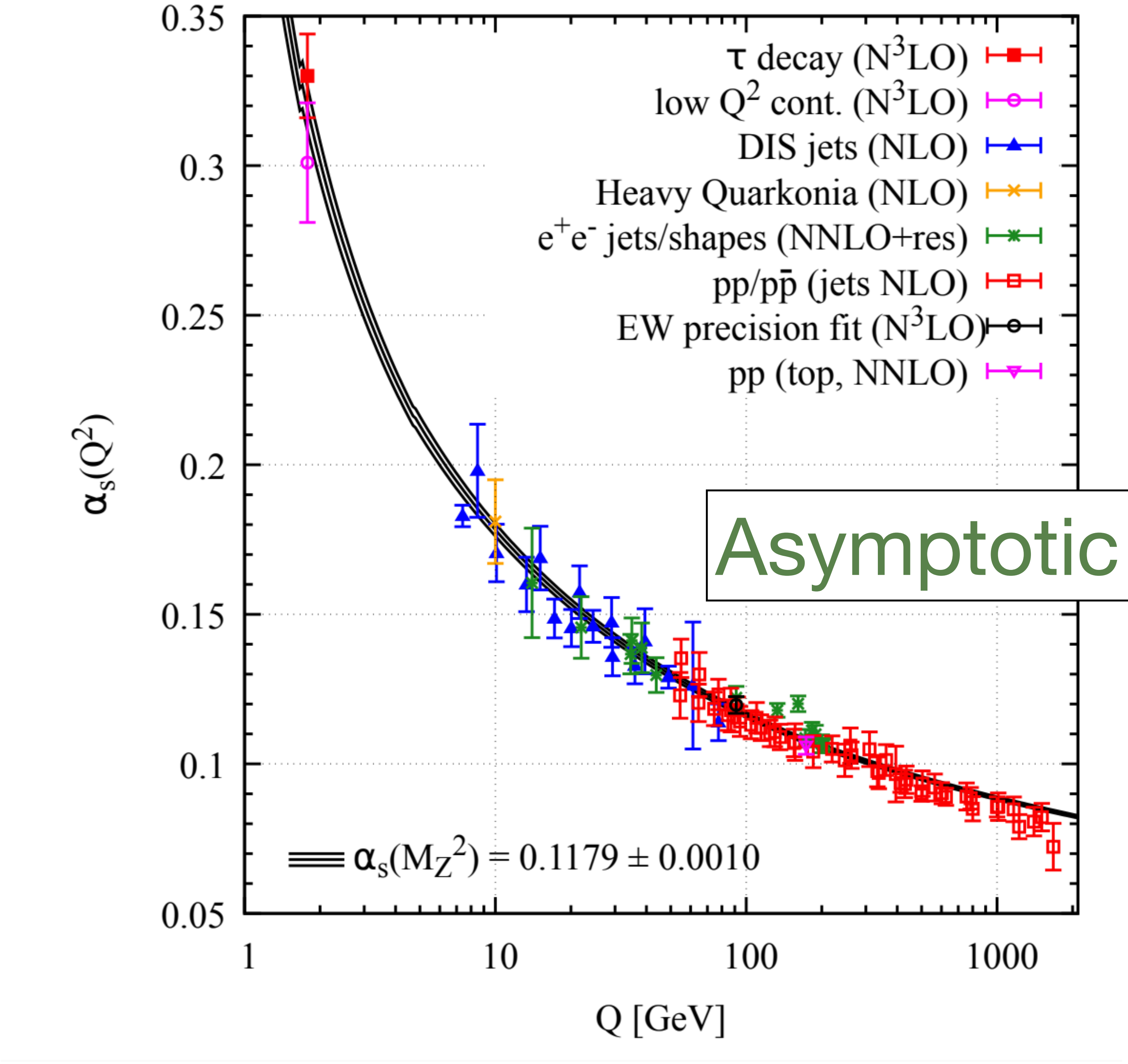

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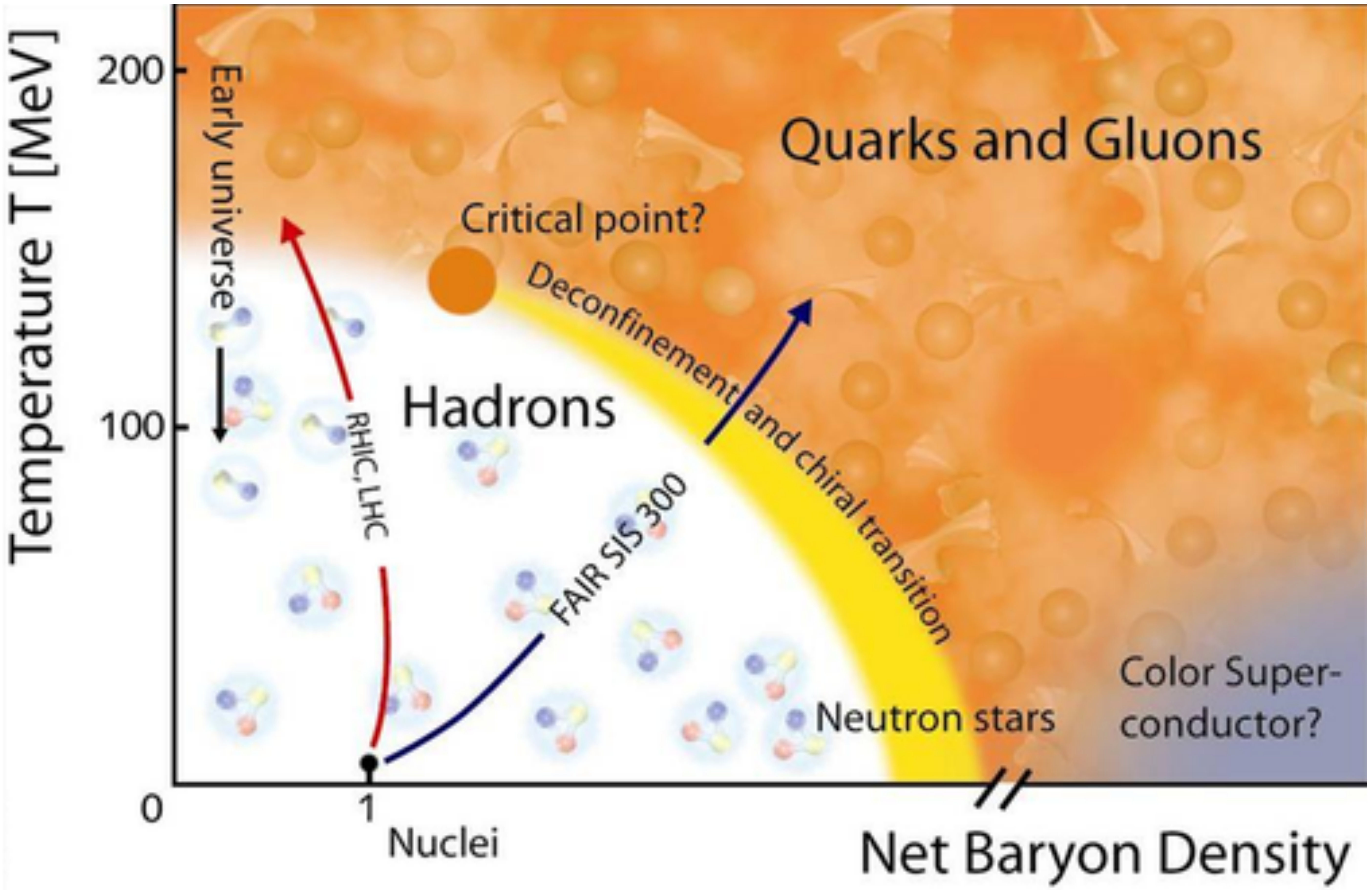
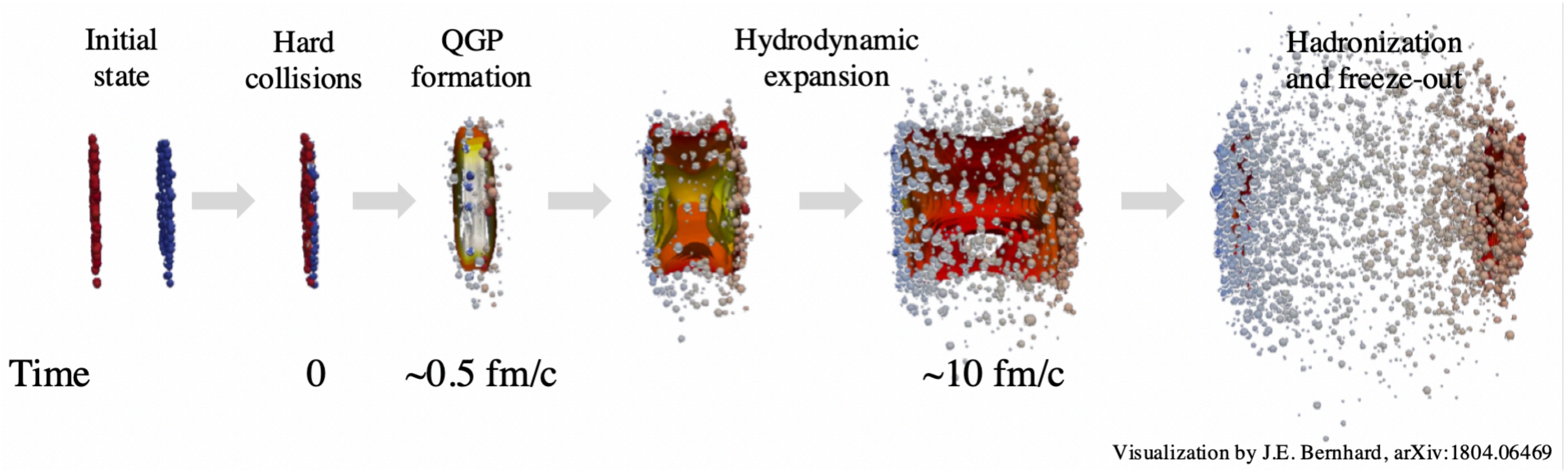


High temperature/density: formation of the Quark-Gluon Plasma

Why study the QGP?



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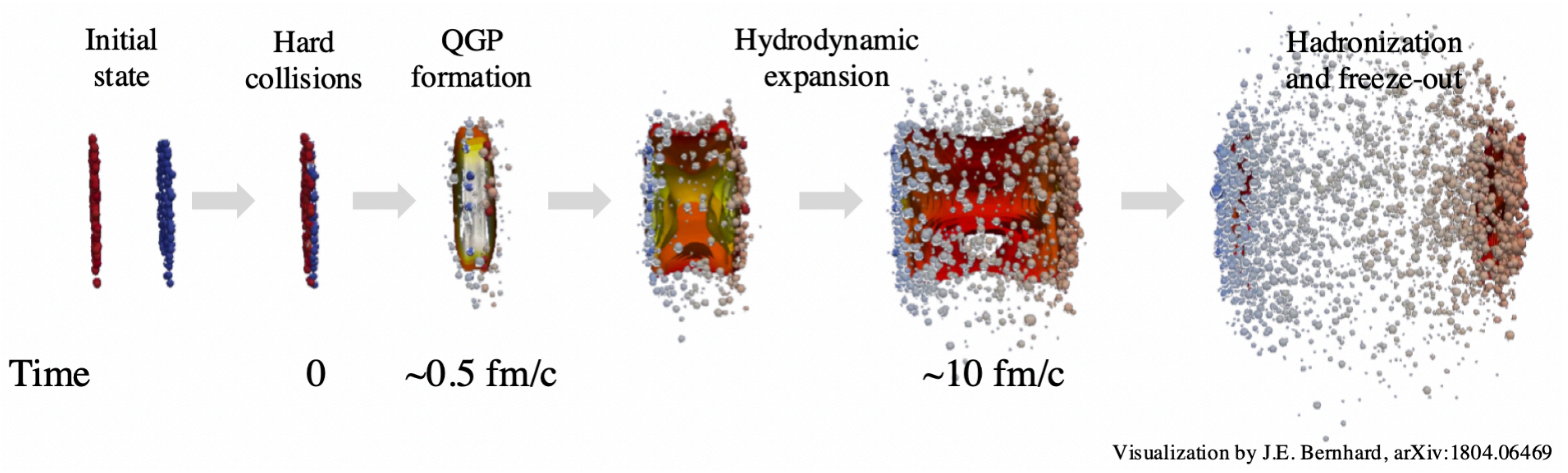

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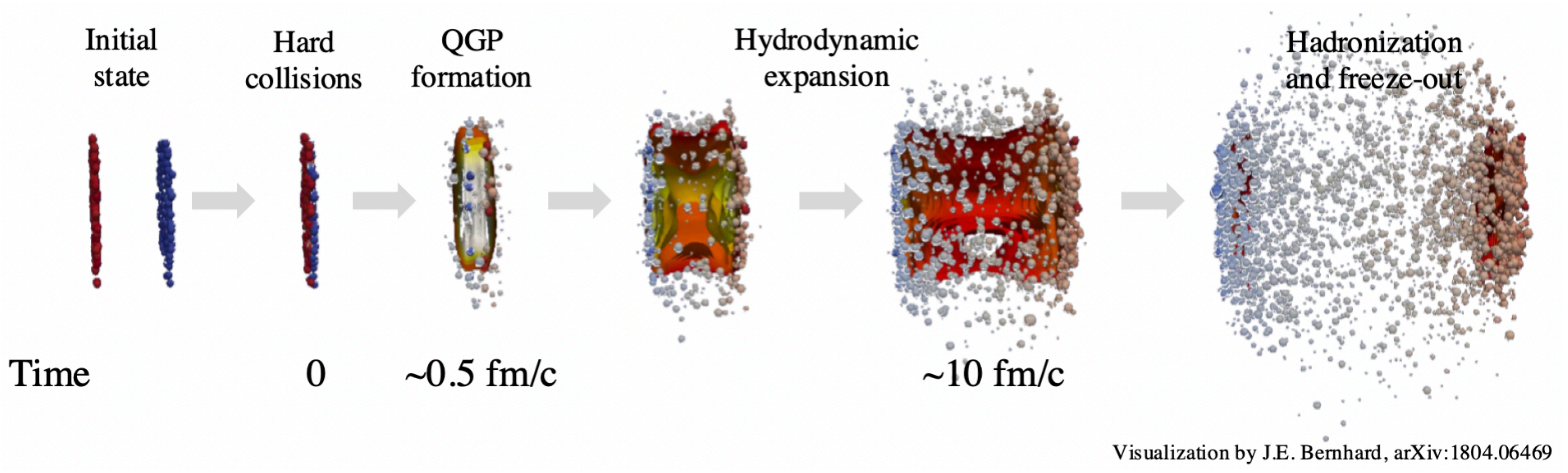

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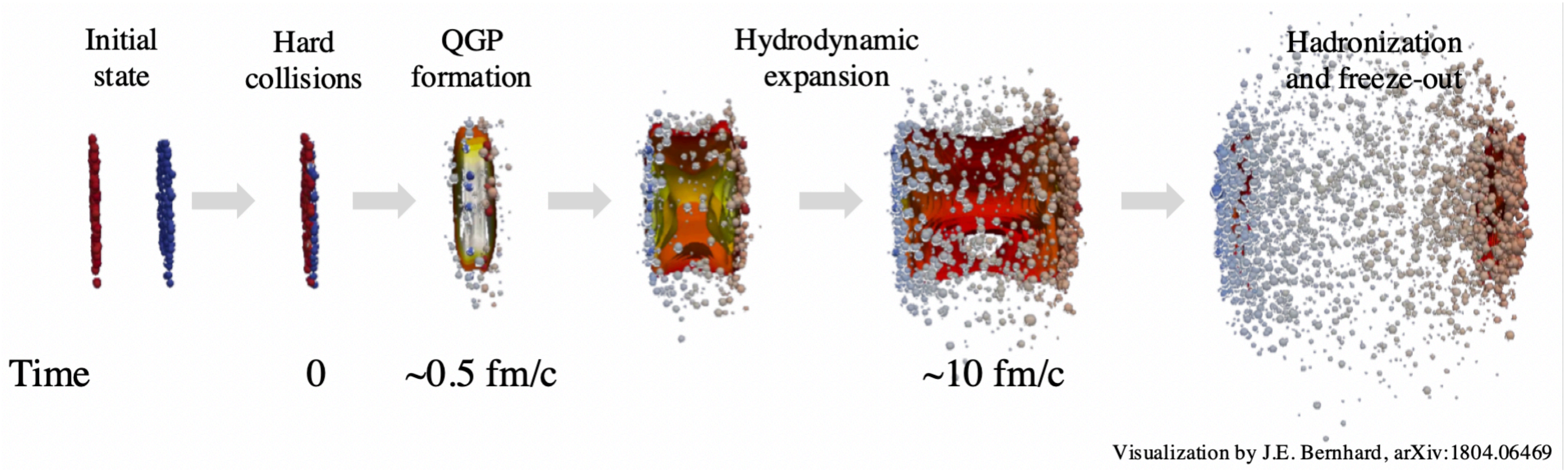

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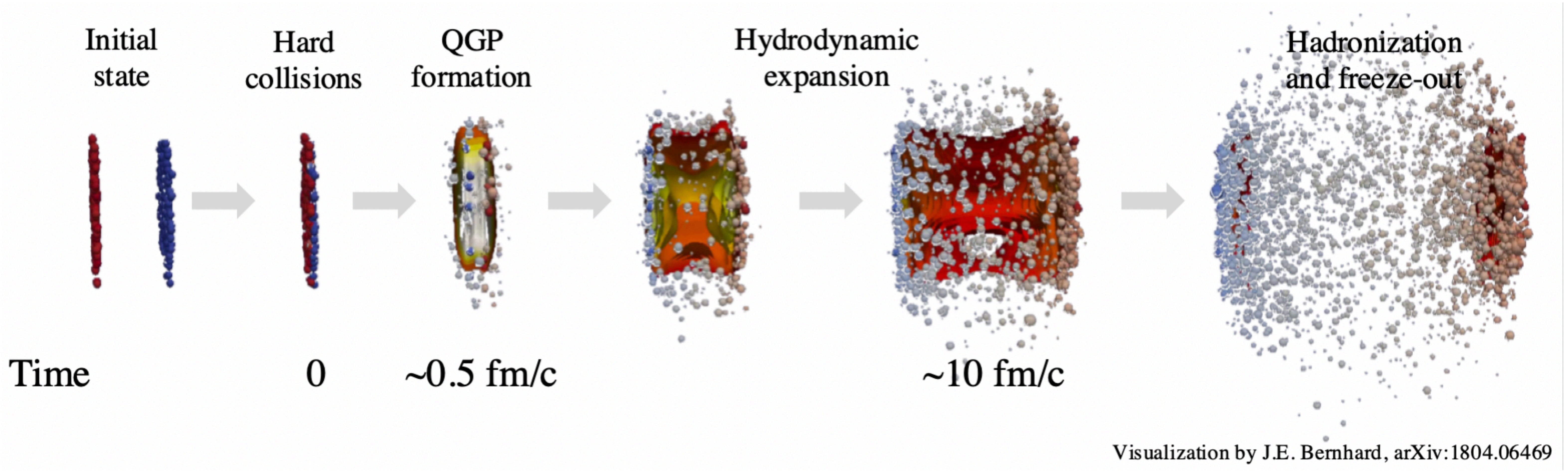

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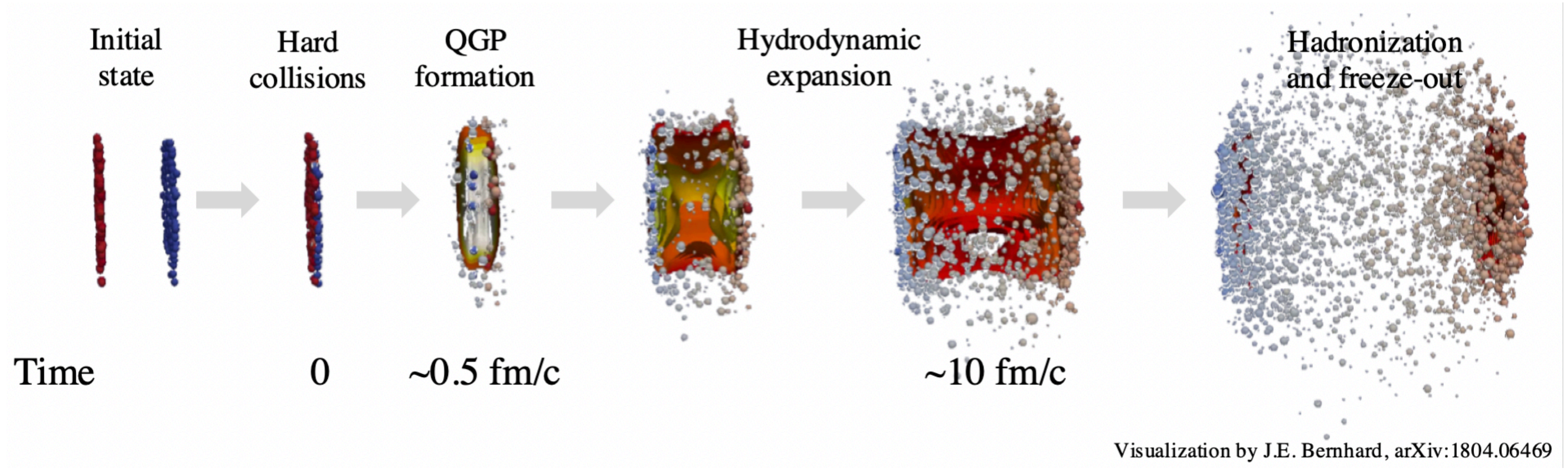

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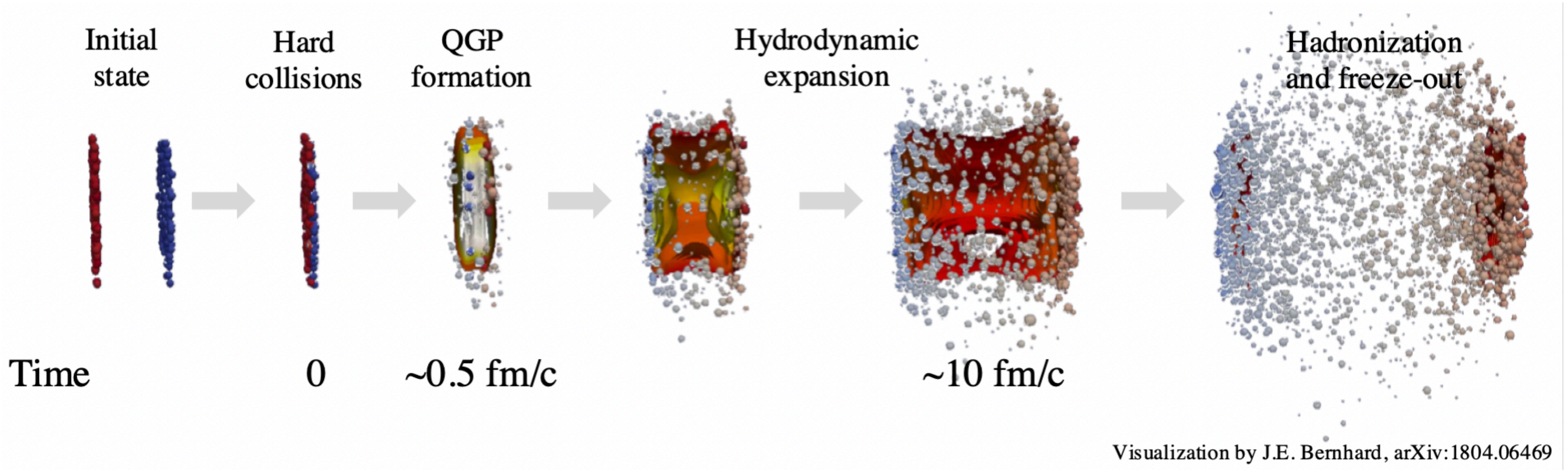
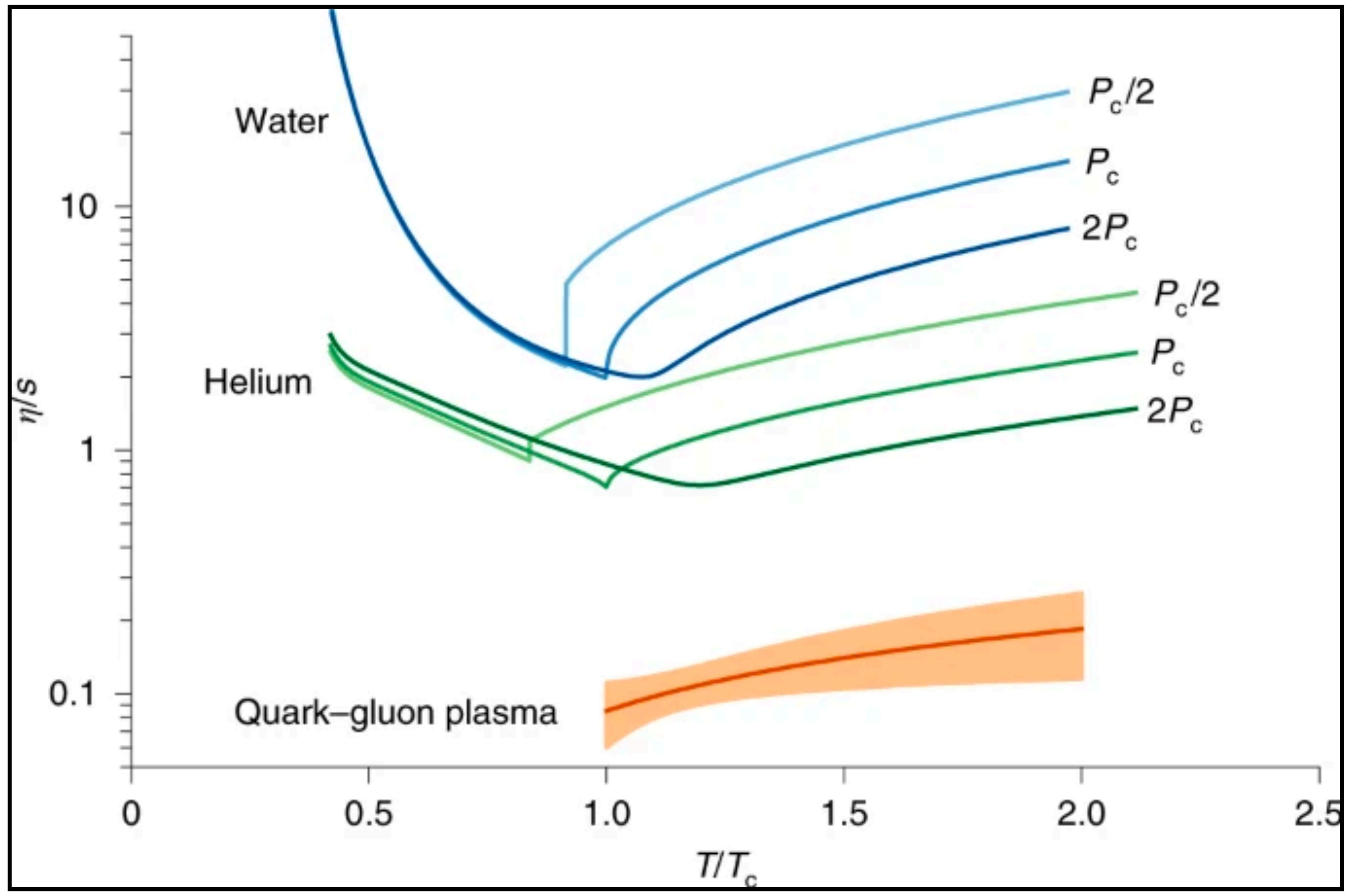


Nature Physics, volume 15, pages 1113–1117 (2019)



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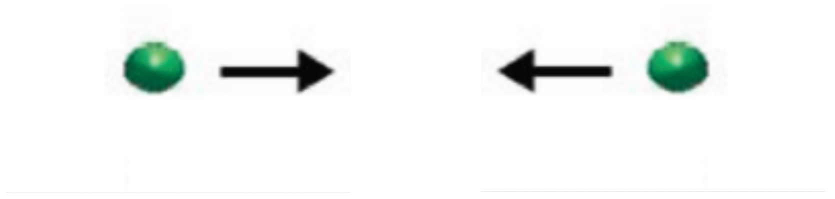
QGP = perfect build

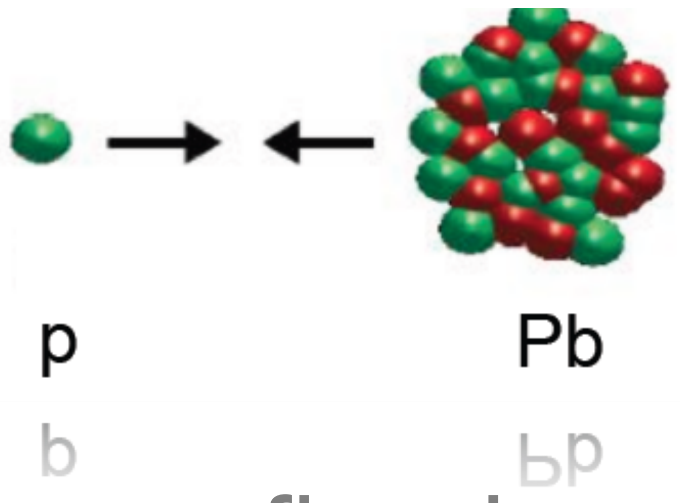
Where it gets ‘messy’

Where it gets 'messy'

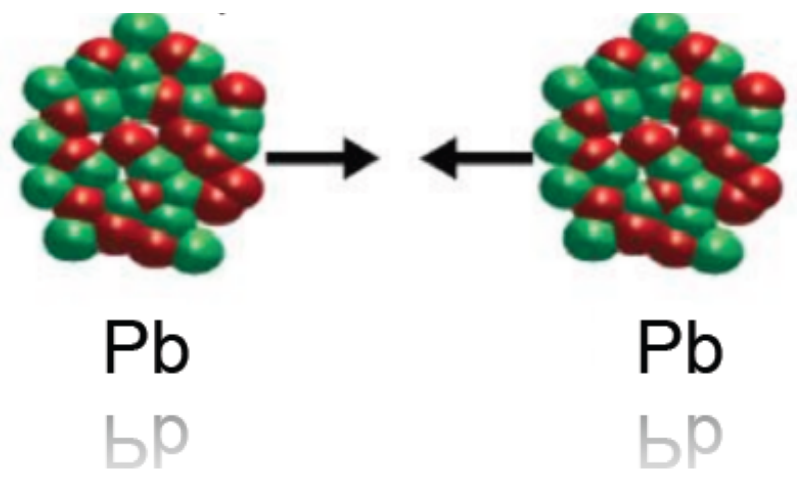
The orthodoxe approach



- The QCD 'vacuum'.



- The confined matter.



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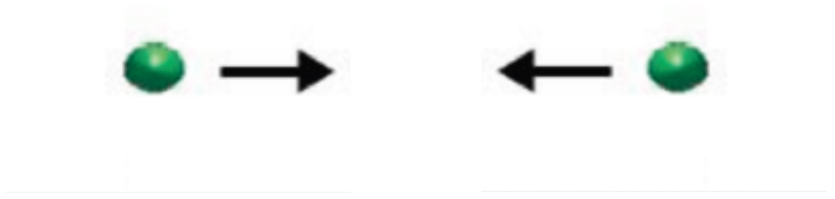

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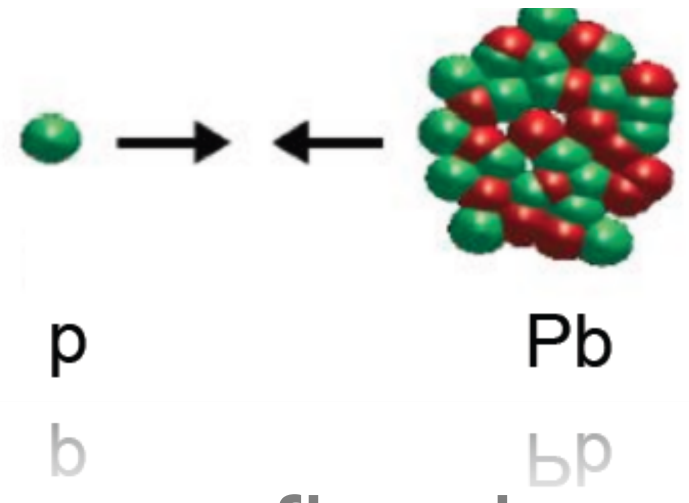

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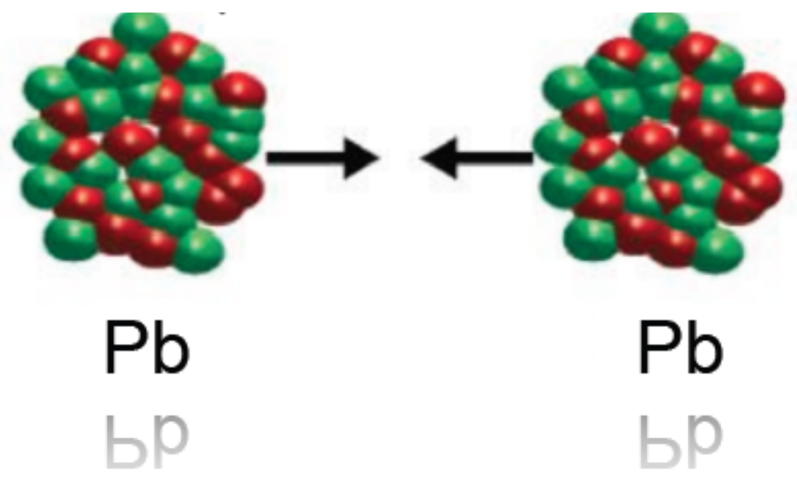

- The QGP

The probes

Hard probes

- Heavy-quark mesons, quarkonia, jets…

Soft probes

- Charged particles, light hadrons, low-mass hadrons …

Electromagnetic probes

- Drell-Yan, photons, weak bosons …

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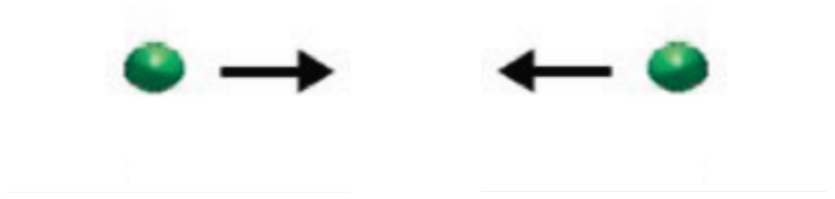

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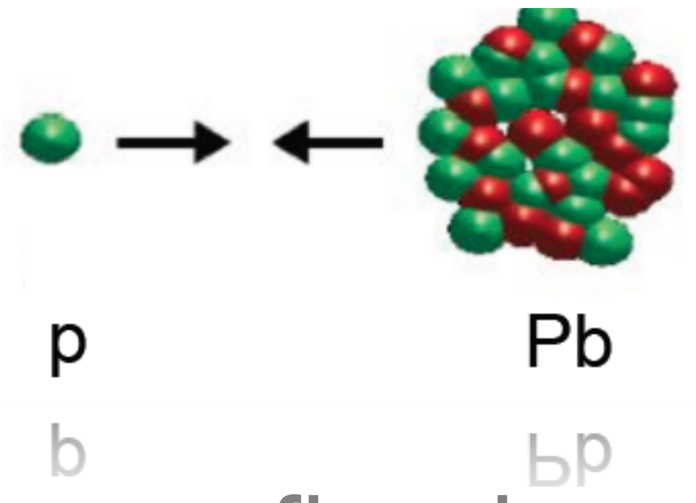

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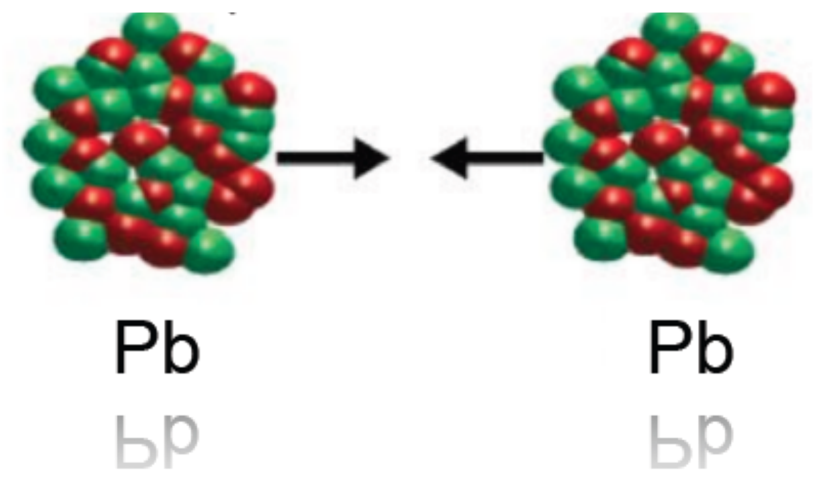

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The observables

Production

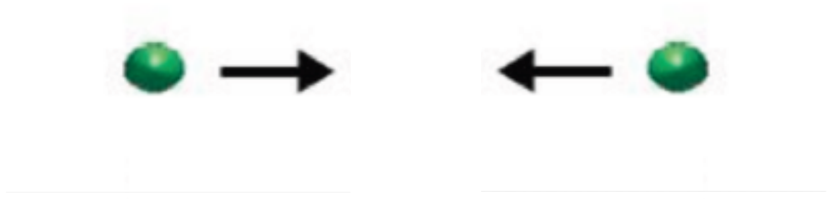
- Cross-sections, Nuclear modification factor, Relative ratios …

Correlations

- Multiplicity dependance, flow measurements…

Where it gets 'messy'

The orthodoxe approach



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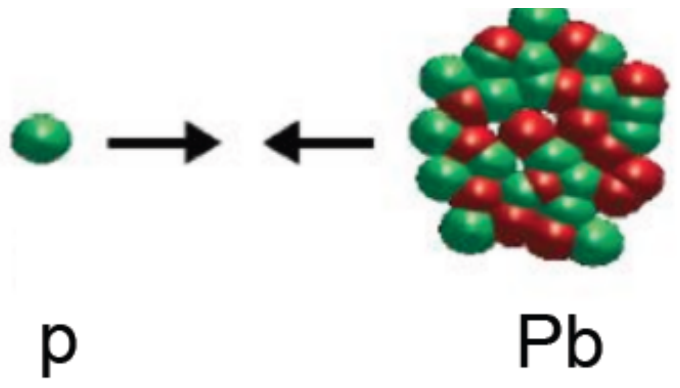

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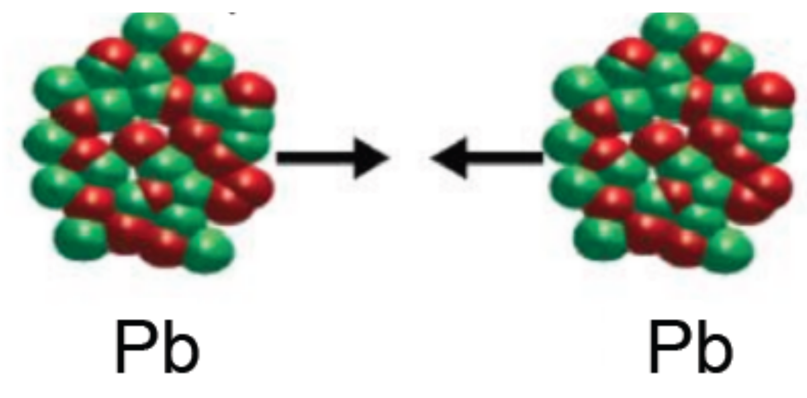

- The QGP

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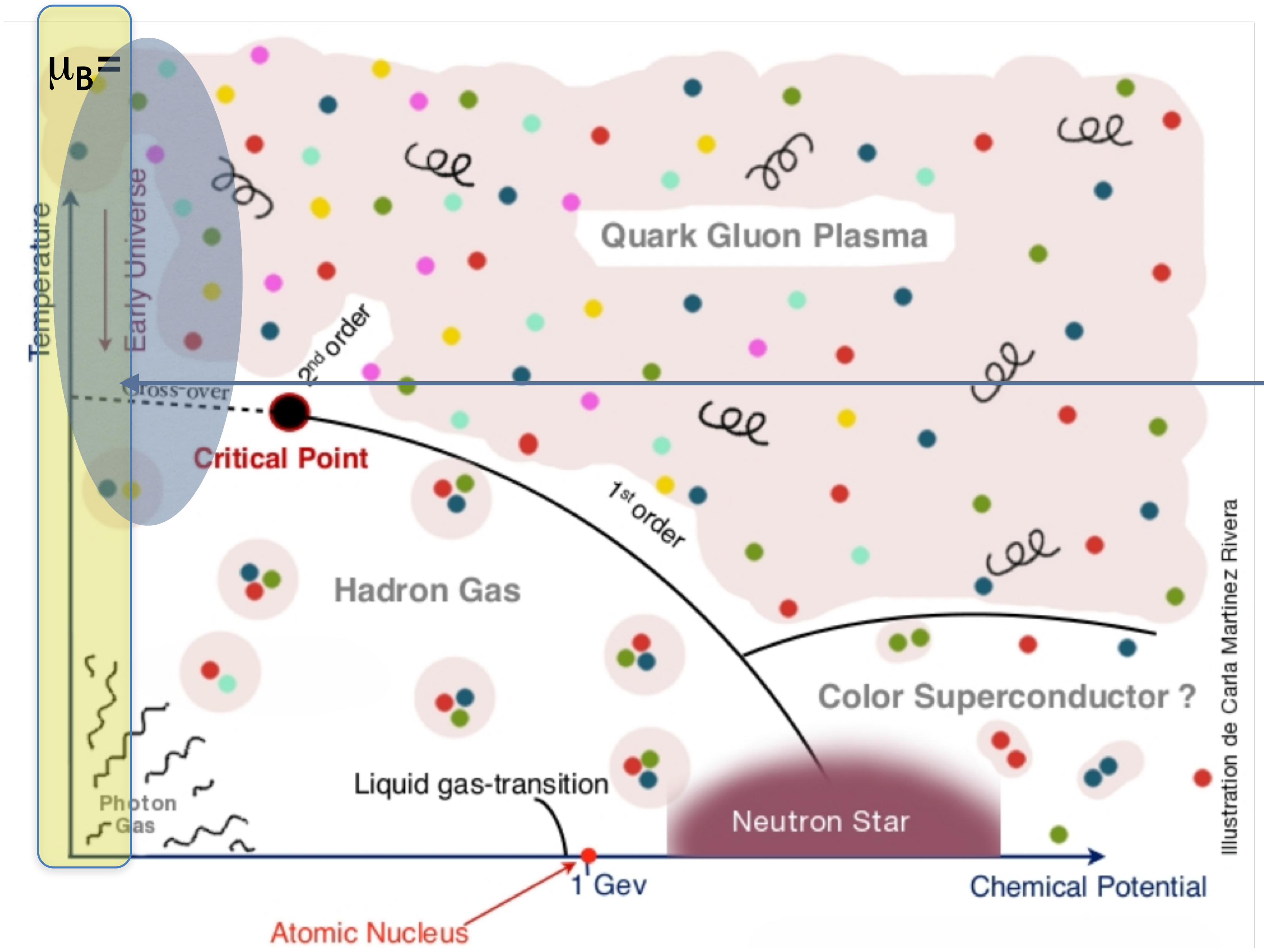
A QGP physicist should know everything about his/her favorite probs !

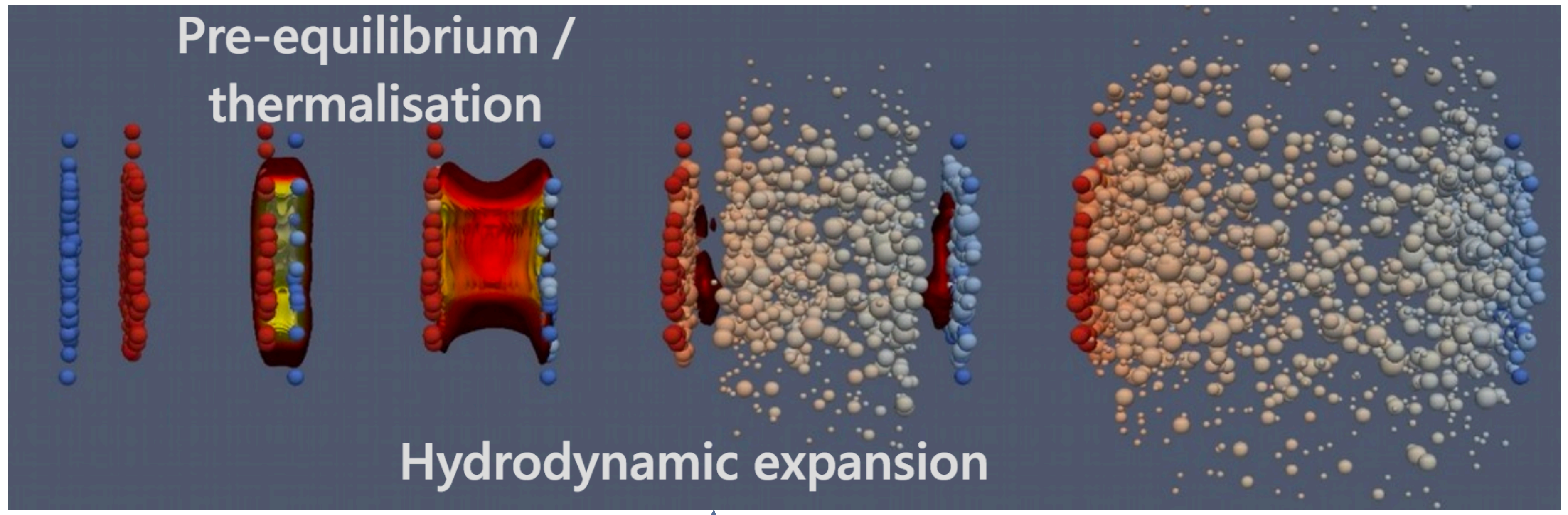
MODELING A HIC : HYDRODYNAMICS

- Eur. J. Phys. 29 (2008) 275-302

From the phase diagram to the collision



We now want to study this area

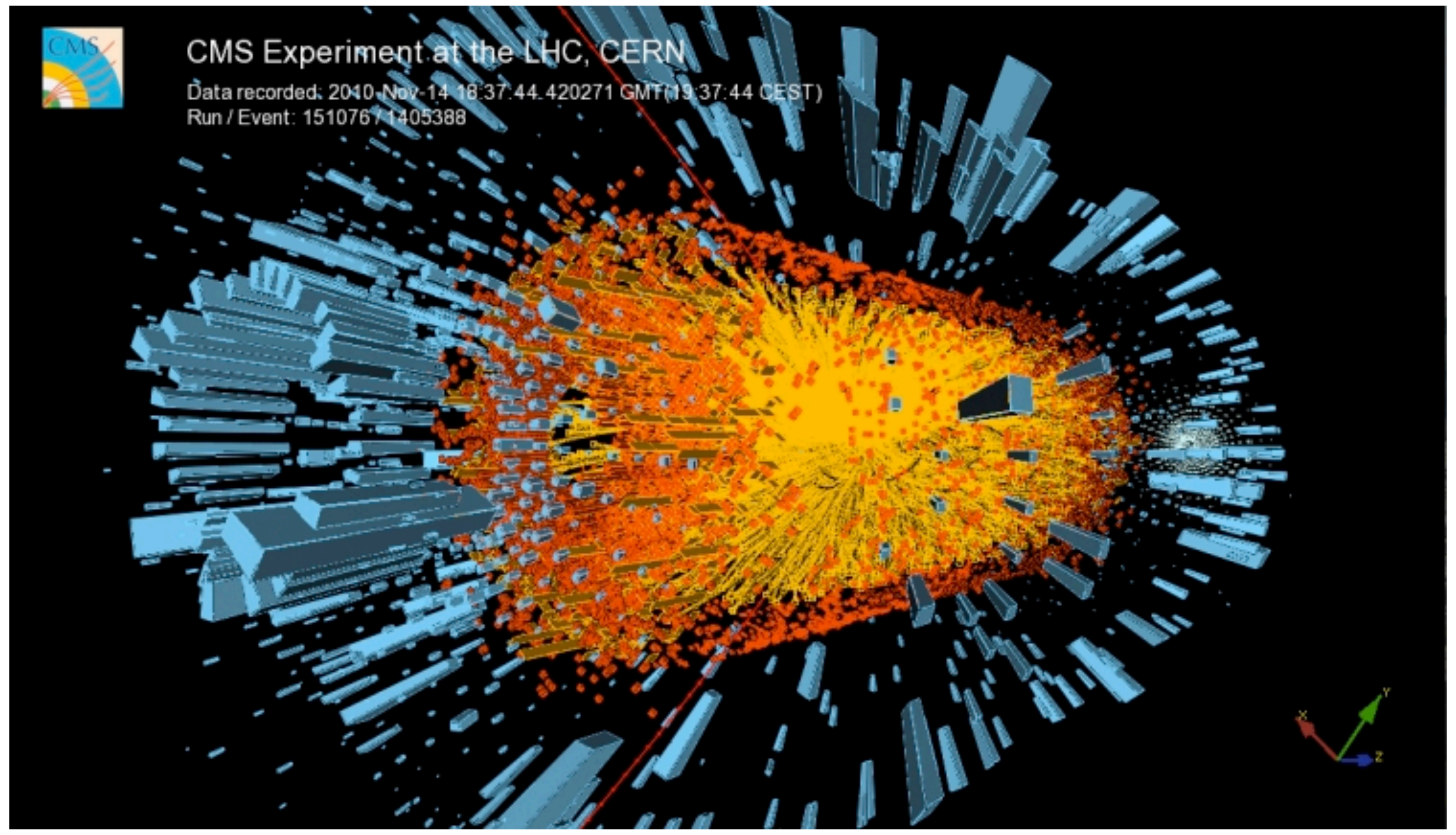


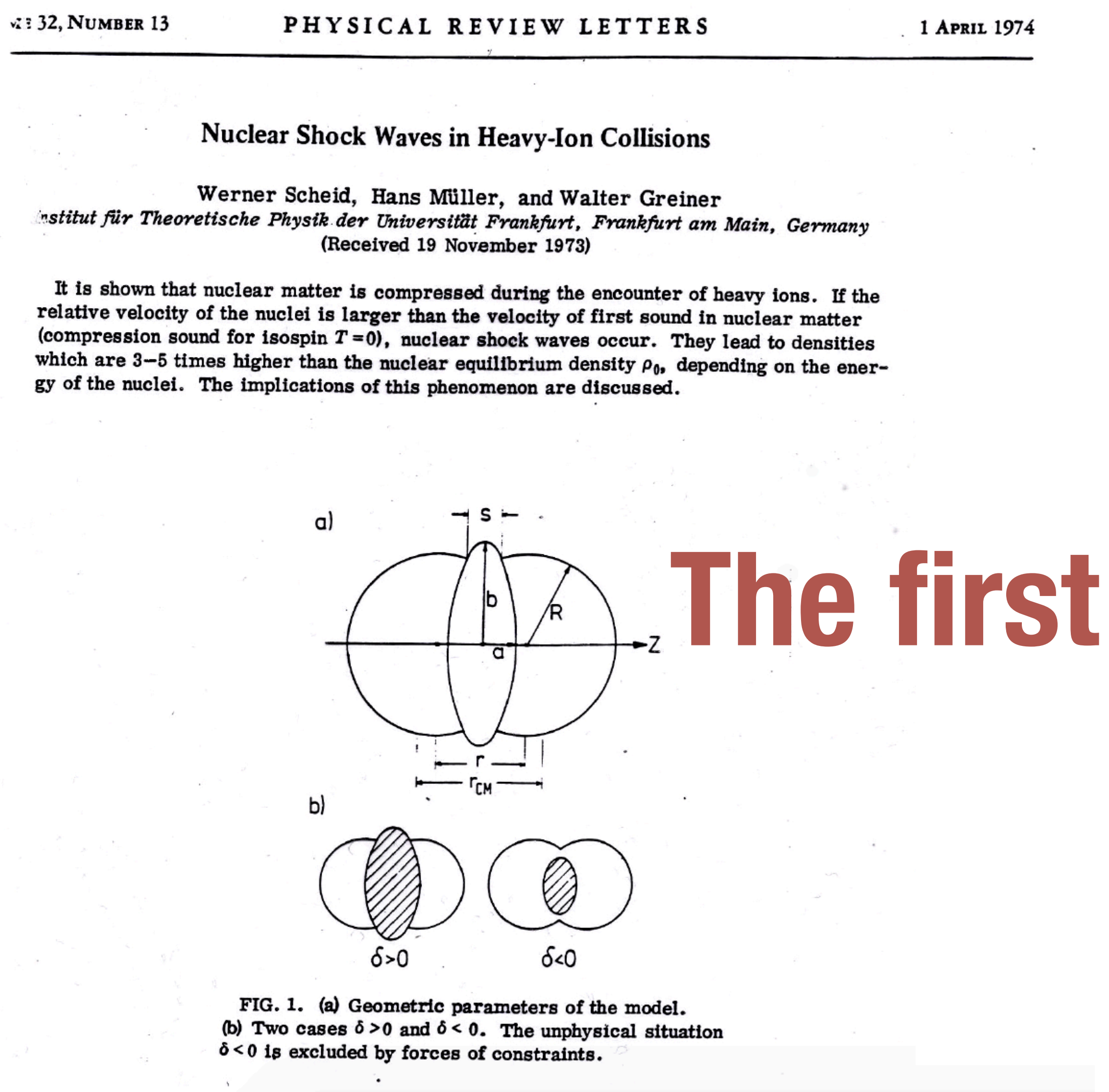
- The basic approach strategy :
  - « Hey, let's take two big nuclei and smash them as hard as we can ! »
- The immediate answer :
  - « Oh cool ! … but how does it look like, a heavy-ion collisions ?»

Goal for today : get to this representation !

Hydro : a good approach

- Why Hydrodynamics :
  - Heavy-ion collisions (HIC) : a bunch of quarks and gluons happily colliding together.
  - Ideal tool to study **bulk properties** and **dynamical evolution.**
- Assumptions : $\langle\lambda\rangle$ << L where :
  - $\langle\lambda\rangle$: the mean free path of particles between two interactions.
  - L : the size of the system.
- Hydro's pros :
  - Simple : all the informations encoded in thermo. properties.
  - General : only assume **thermal equilibrium.**
- **This talk : we go through basic hydro. model and derive basic hydro. features !**




32, NUMBER 13 PHYSICAL REVIEW LETTERS 1 APRIL 1974

Nuclear Shock Waves in Heavy-Ion Collisions

Werner Scheid, Hans Müller, and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 19 November 1973)

It is shown that nuclear matter is compressed during the encounter of heavy ions. If the relative velocity of the nuclei is larger than the velocity of first sound in nuclear matter (compression sound for isospin $T=0$), nuclear shock waves occur. They lead to densities which are 3–5 times higher than the nuclear equilibrium density ρ_0, depending on the energy of the nuclei. The implications of this phenomenon are discussed.

FIG. 1. (a) Geometric parameters of the model. (b) Two cases $\delta>0$ and $\delta<0$. The unphysical situation $\delta<0$ is excluded by forces of constraints.

The first paper

Relativistic thermodynamics

- Standard thermodynamics : assume a global equilibrium of the system.
- This is clearly **not the case** in HIC collisions !
- But at first we can assume ***local*** thermodynamic equilibrium :
  - For any point, P and T vary slowly in some neighborhoods around it (fluid element)
- In the ideal (inviscid) case, one must derives the following equations :

Local conservation of energy-momentum

$$\partial_\mu T^{\mu\nu}_{\mathrm{id}} = 0 \,, \quad \partial_\mu J^\mu_B = 0$$

Conservation of baryon flux

$T^{\mu\nu}_{\mathrm{id}}$: Energy-momentum tensor

J^μ_B: Net Baryon current

Let's derive those equations in the fluid element rest frame!

The Energy-Momentum tensor

Tensor in the fluid rest frame

$$T_{(0)} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

Lorentz transformation for any moving fluid cells

Tensor in the first order in velocity

Density of the j^th component of momentum

$$T^{\mu\nu}_{\mathrm{id}} = T = \begin{pmatrix} \epsilon & (\epsilon+P)v_x & (\epsilon+P)v_y & (\epsilon+P)v_z \\ (\epsilon+P)v_x & P & 0 & 0 \\ (\epsilon+P)v_y & 0 & P & 0 \\ (\epsilon+P)v_z & 0 & 0 & P \end{pmatrix}$$

Energy flux along axis i

Reduce formula

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

$$g^{\mu\nu} \equiv \mathrm{diag}(1, -1, -1, -1)$$

$$u^\mu = \left(\frac{1}{\sqrt{1-|v|^2}}, \frac{\vec{v}}{\sqrt{1-|v|^2}}\right) \equiv \text{4velocity of the fluid cell}$$

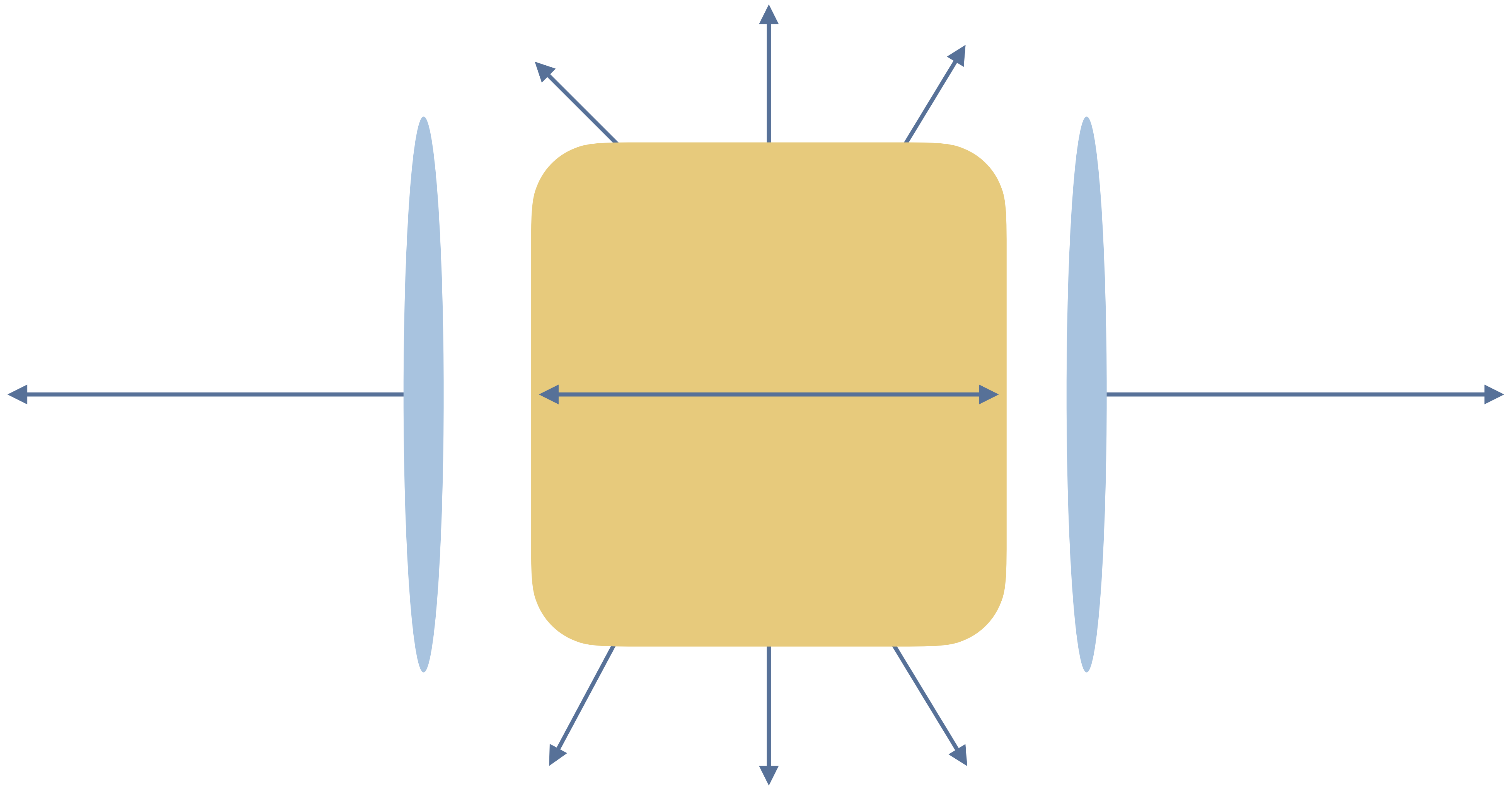
- By definition vx = vy = vz = 0 in the fluid rest frame
- **Thanks captain obvious**, but not really useful…
  - To go to non-relativistic limits :
    - (ε + P).**v** ~ ε.**v** ≃ ρ**v**
  - **The tensor is symmetric** in all rest frame.
    - ***momentum density = energy flux***

Baryon number conservation

- The equation $\partial_\mu J^\mu_B = 0$ can also be written as $\boxed{\partial_\mu (n u^\mu) = 0}$
- There are similar equations for any conserved charges.
- To close the equations system, one must add the *equation of state* : $P = P(\epsilon, n_i)$
- For the sake of arguments :
  - 3 comp. of u + ε + P + n_i(i=1,…M) = 4 + M + 1 equations
- **Let's now try to get a model out of all these eq. !**

THE BJORKEN SCENARIO

Simple picture : the Bjorken scenario



- **Initial conditions** :
  - Highly boosted « pancakes » in the centre-of-mass system, that cross within $\tau_{cross} \sim 2R/\gamma$.
  - Note that $\gamma_{SPS} \sim 10 < \gamma_{RHIC} \sim 100 < \gamma_{LHC} \sim 2500\text{-}7000$, thus $\tau_{cross} < \tau_{QCD} \sim 1 / \Lambda_{QDC} \sim 1$ fm/c.
  - We assume fast thermalization.
  - We assume $\langle p_x \rangle = \langle p_y \rangle = 0 \rightarrow$ **Flow (see later) only comes from Hydro. phase.**
- Bjorken's prescriptions : **the fluid rapidity = the space-time rapidity**

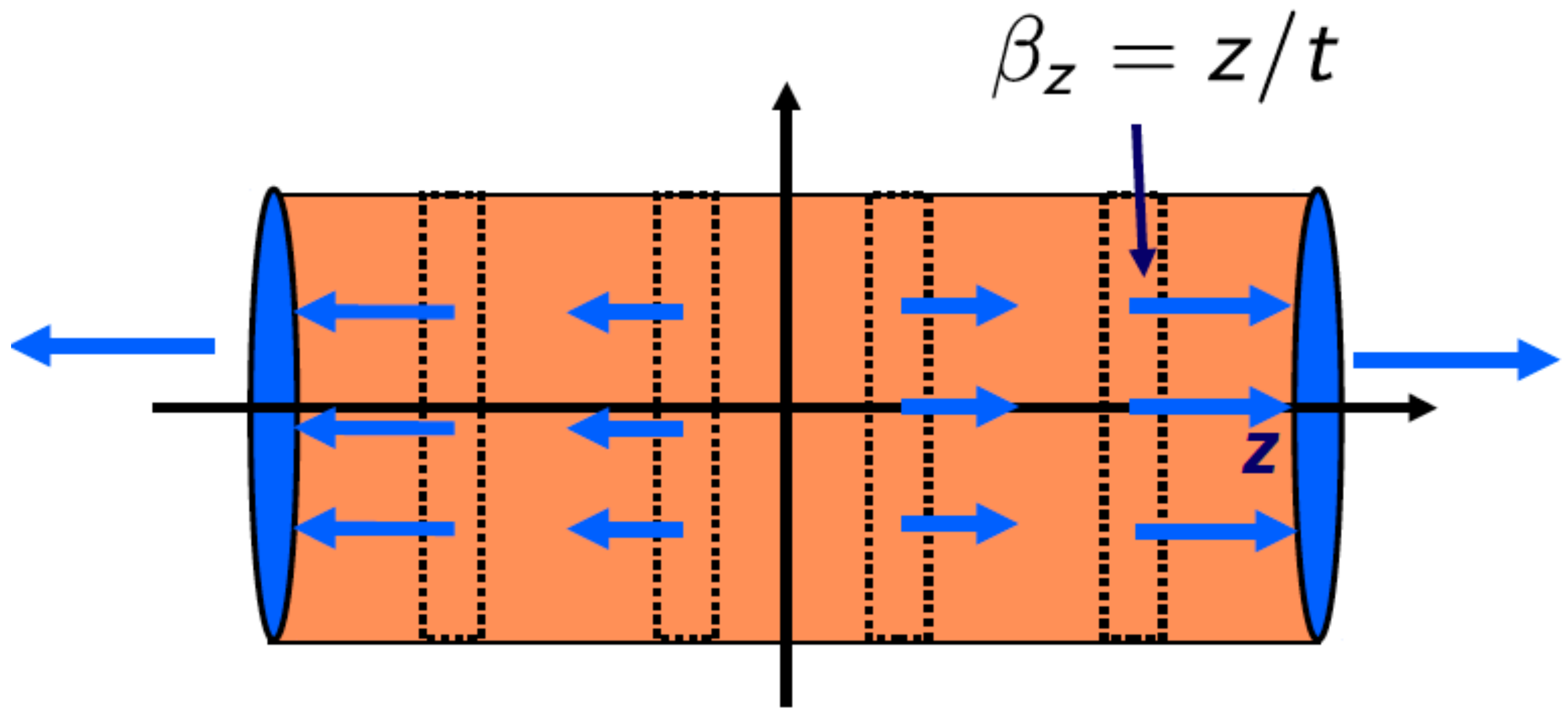
New variables

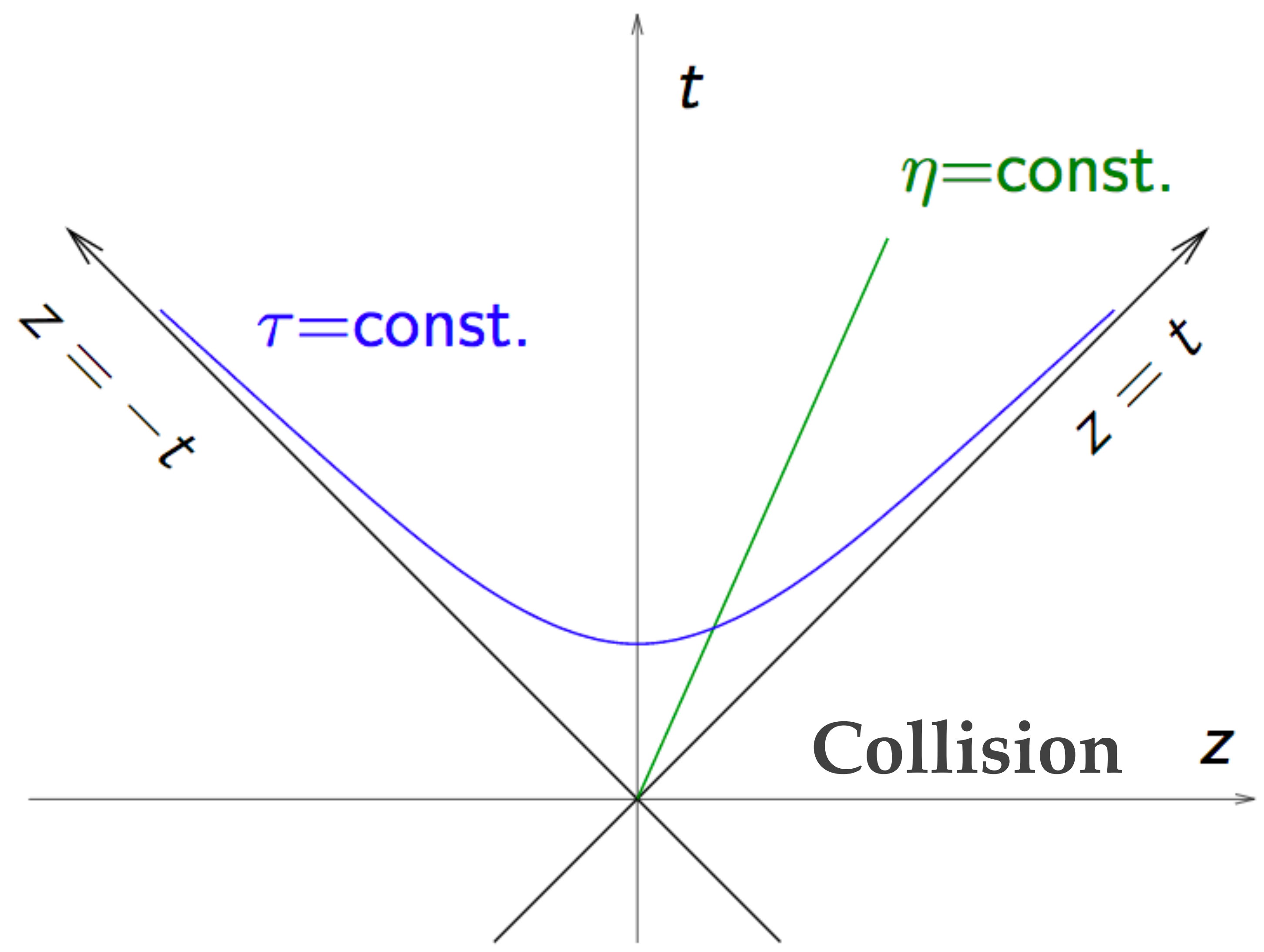
Bjorken's prescriptions

$$t = \tau \cosh \eta_s \qquad z = \tau \sinh \eta_s \qquad v_z = \tanh Y$$

$$\tau = \sqrt{t^2 - z^2} \qquad \eta_s = \frac{1}{2} \log \frac{t+z}{t-z} \quad = \quad Y = \frac{1}{2} \log \frac{1+v_z}{1-v_z}$$

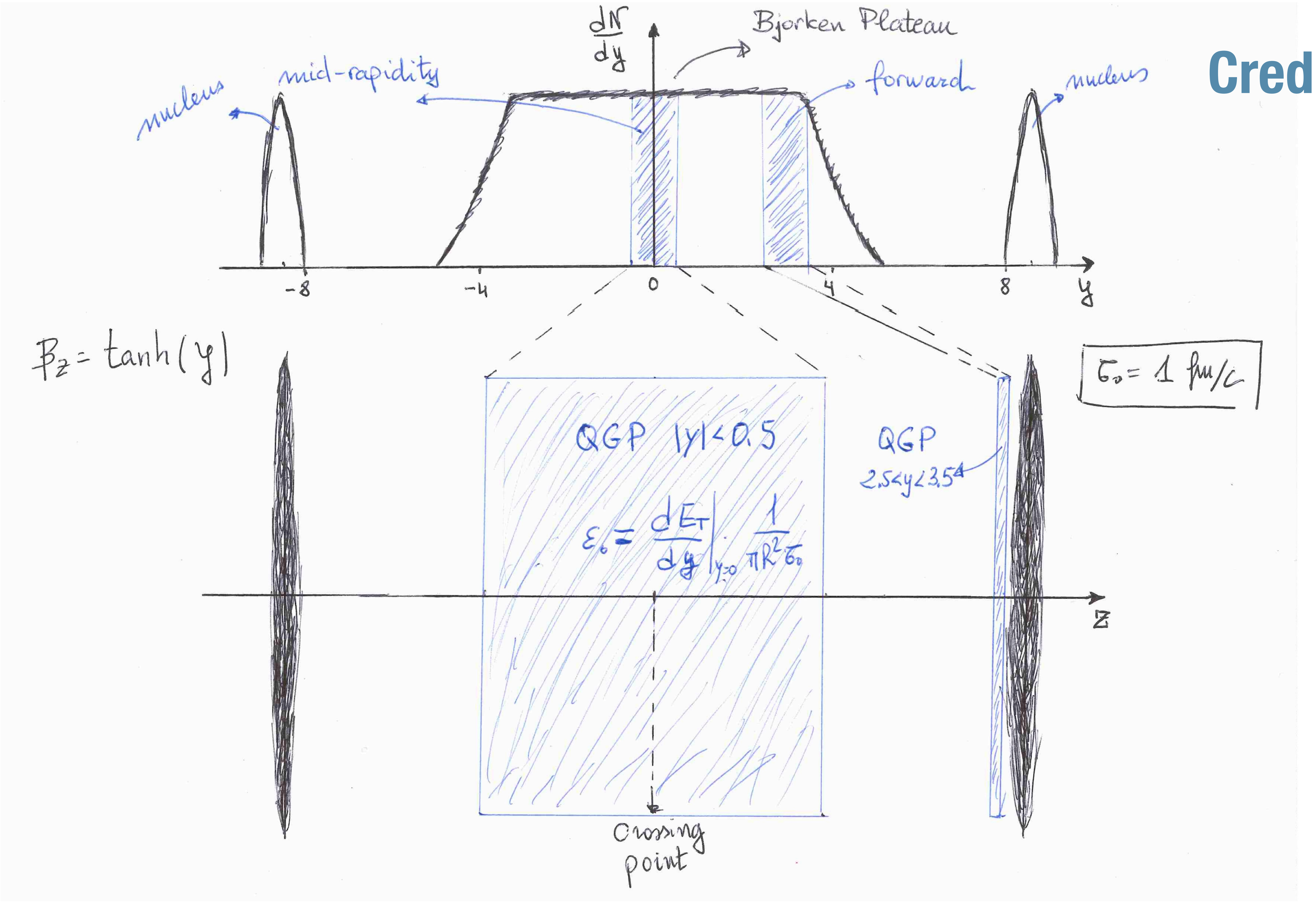
Proper time | **Space-time rapidity** | **Fluid rapidity**





Space -time representation of a collision

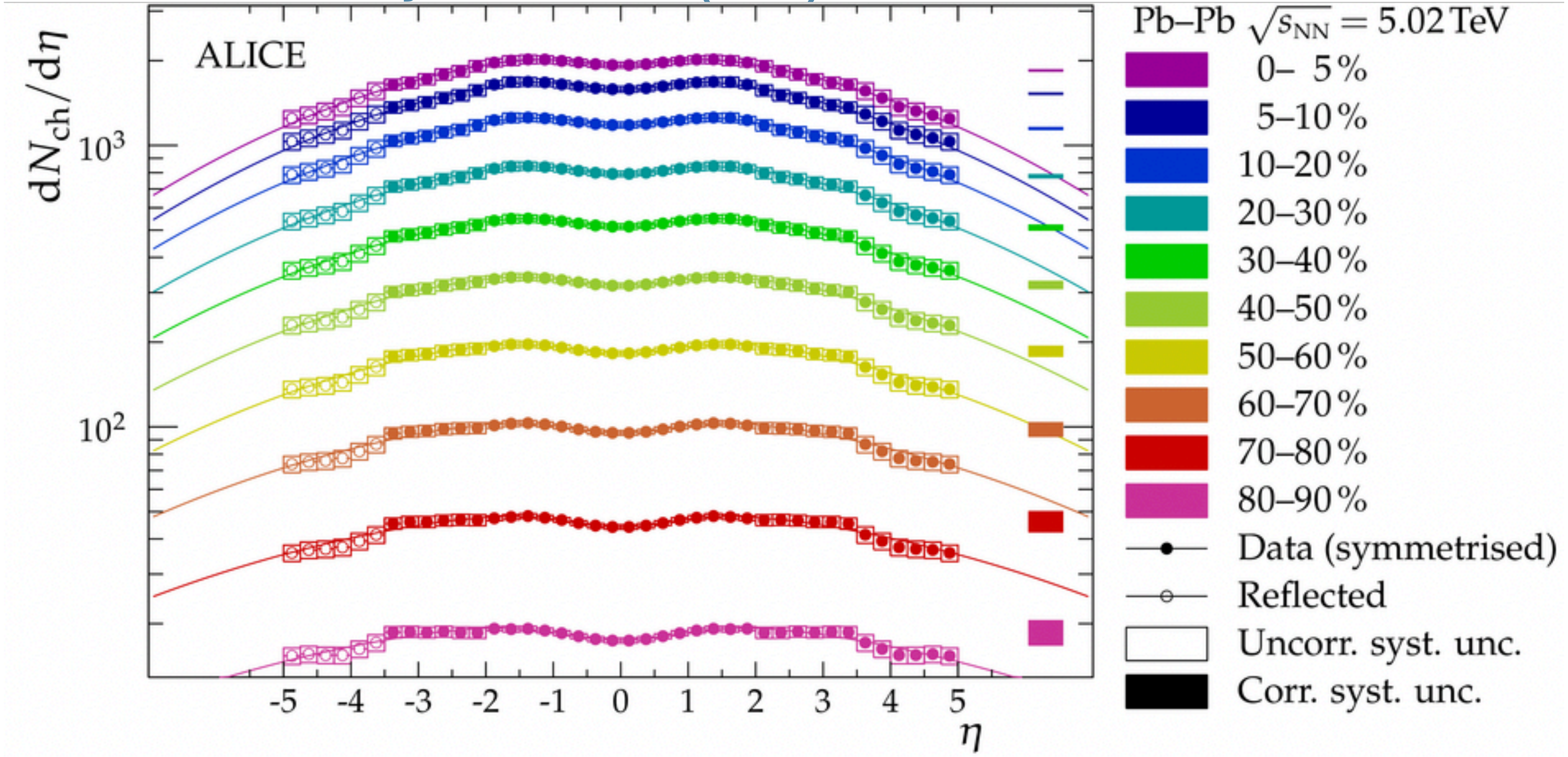
The famous Bjorken's plateau



Credit : Ginés Martinez

The famous Bjorken's plateau?

Phys. Lett. B 772 (2017)



Back to hydro with Bjorken's prescription

$$\partial_\mu T^{\mu\nu}_{\rm id} = 0$$

Versus z

$$\frac{\partial \epsilon}{\partial t} + \vec{\nabla}\cdot((\epsilon+P)\vec{v}) = 0$$
$$\frac{\partial}{\partial t}((\epsilon+P)\vec{v}) + \vec{\nabla}P = \vec{0}.$$

$$\frac{\partial}{\partial t}((\epsilon+P)v_z) + \frac{\partial}{\partial z}P = 0$$

$v_z = 0$

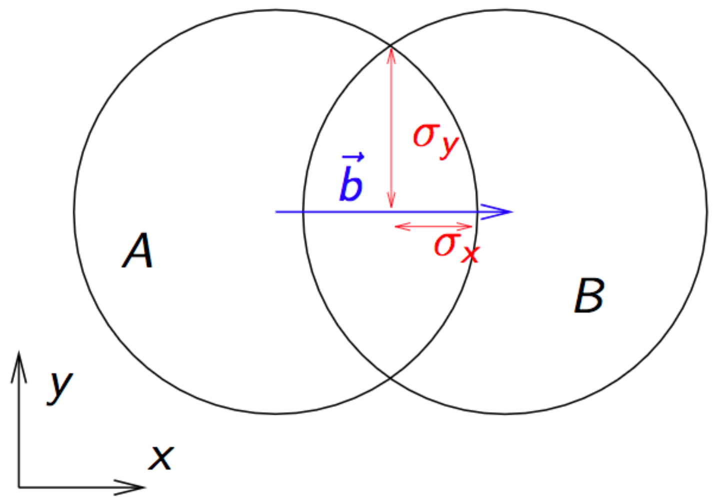
$$\frac{d\epsilon}{\epsilon+P} = \frac{ds}{s}$$

$$c_s = \left(\frac{\partial P}{\partial \epsilon}\right)^{1/2}$$

$$\frac{\partial v_z}{\partial t} = -\frac{1}{\epsilon+P}\frac{\partial P}{\partial z} = -c_s^2\frac{\partial \ln s}{\partial z}$$

Near z = 0 …

$$\frac{\partial Y}{\partial \tau} = \frac{c_s^2}{\tau}\frac{\eta_s}{\sigma_\eta^2}$$



Toy model for initial density (entropy)

$$s(x,y,\eta_s) \propto \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{\eta_s^2}{2\sigma_\eta^2}\right)$$

fluid cell rapidity →

$$Y(\tau) = \left(1 + \frac{c_s^2\ln(\tau/\tau_0)}{\sigma_\eta^2}\right)\eta_s$$

← **Space-time rapidity**

To which extend Bjorken is valid ?

- c_s = speed of sound
- Y **proportional** to η_s
- **Bjorken : $Y = \eta_s$**
- **Good approximation** as long as t << σ_x/c_s, σ_y/c_s → **before longitudinal expansion !**
- We will see later that transverse expansion acts like a cut-off for the longitudinal expansion.

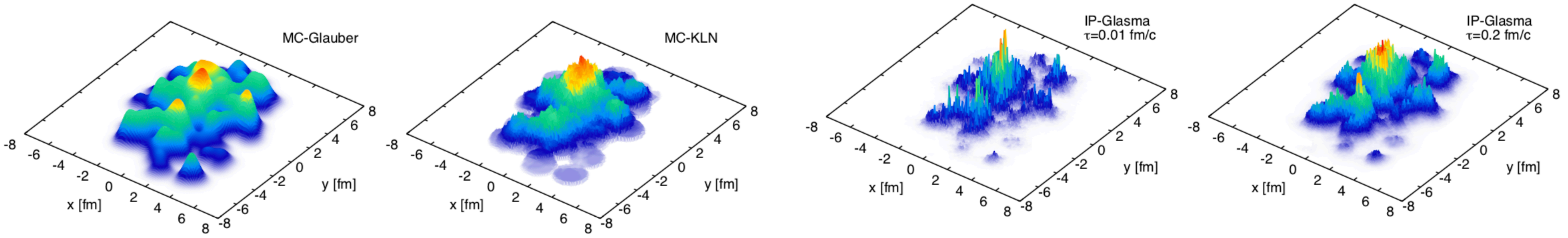
$$Y(\tau) = \left(1 + \frac{c_s^2 \ln(\tau/\tau_0)}{\sigma_\eta^2}\right)\eta_s$$

Initial conditions

- For our toy model, we assumes

$$s(x, y, \eta_s) \propto \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{\eta_s^2}{2\sigma_\eta^2}\right)$$

- In reality, many prescriptions can be used :



Longitudinal expansion

- Similarly with the baryon density around z=0 :

$$\frac{\partial n}{\partial t} + \frac{n}{t} = 0 \quad \Longrightarrow \quad nt = \text{const.}$$

Conserved

- The energy density :

$$\boxed{\begin{array}{l} \frac{\partial \epsilon}{\partial t} + \vec{\nabla}\cdot((\epsilon + P)\vec{v}) = 0 \\ \frac{\partial}{\partial t}((\epsilon+P)\vec{v}) + \vec{\nabla}P = \vec{0}. \end{array}} \longrightarrow \frac{\partial \epsilon}{\partial t} + \frac{\epsilon + P}{t} = 0 \quad \Longrightarrow$$

A bit of shuffling that you can do yourself…

$$\Longrightarrow \quad \mathrm{d}(\epsilon t) = -P\mathrm{d}t$$

Not Conserved

$$\boxed{\frac{\partial V_z}{\partial z} = \frac{1}{t}}$$

- Comments
  - Longitudinal cooling → $\varepsilon_{init} > \varepsilon_{fin}$
  - No experimental evidence of longitudinal cooling (we measure final state particles), but we can still probe the initial stage with electromagnetic probes (thermal photons …).
  - Comoving energy decreases due to negative work of pressure forces → only appear as a result of a thermalization process.

- However, entropy density is conserved :

$$\boxed{d\epsilon = Tds + \mu dn} \longrightarrow \frac{\partial s}{\partial t} + \frac{s}{t} = 0 \quad \Longrightarrow \quad st = \text{const.}$$

From thermodynamics

= No heat diffusion between fluid cells

Transverse momentum expansion

- The initial transverse velocity is usually zero, but acceleration is not :

$$\frac{\partial v_x}{\partial t} = -\frac{1}{\epsilon + P}\frac{\partial P}{\partial x} = -c_s^2 \frac{\partial \ln s}{\partial x}$$

- Assuming c_s constant :

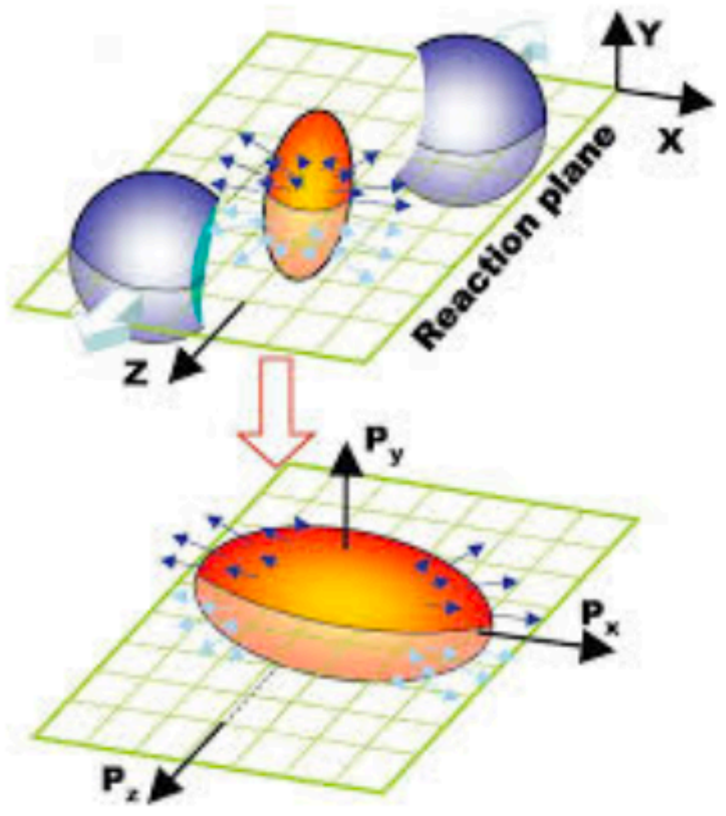
$$v_x = \frac{c_s^2 x}{\sigma_x^2} t, \qquad v_y = \frac{c_s^2 y}{\sigma_y^2} t.$$

- Comments :
  - Very smooth process.
  - Typical time-scale σ_x/c_s . For t << σ_x/c_s ~R/c_s, longitudinal expansion dominates.

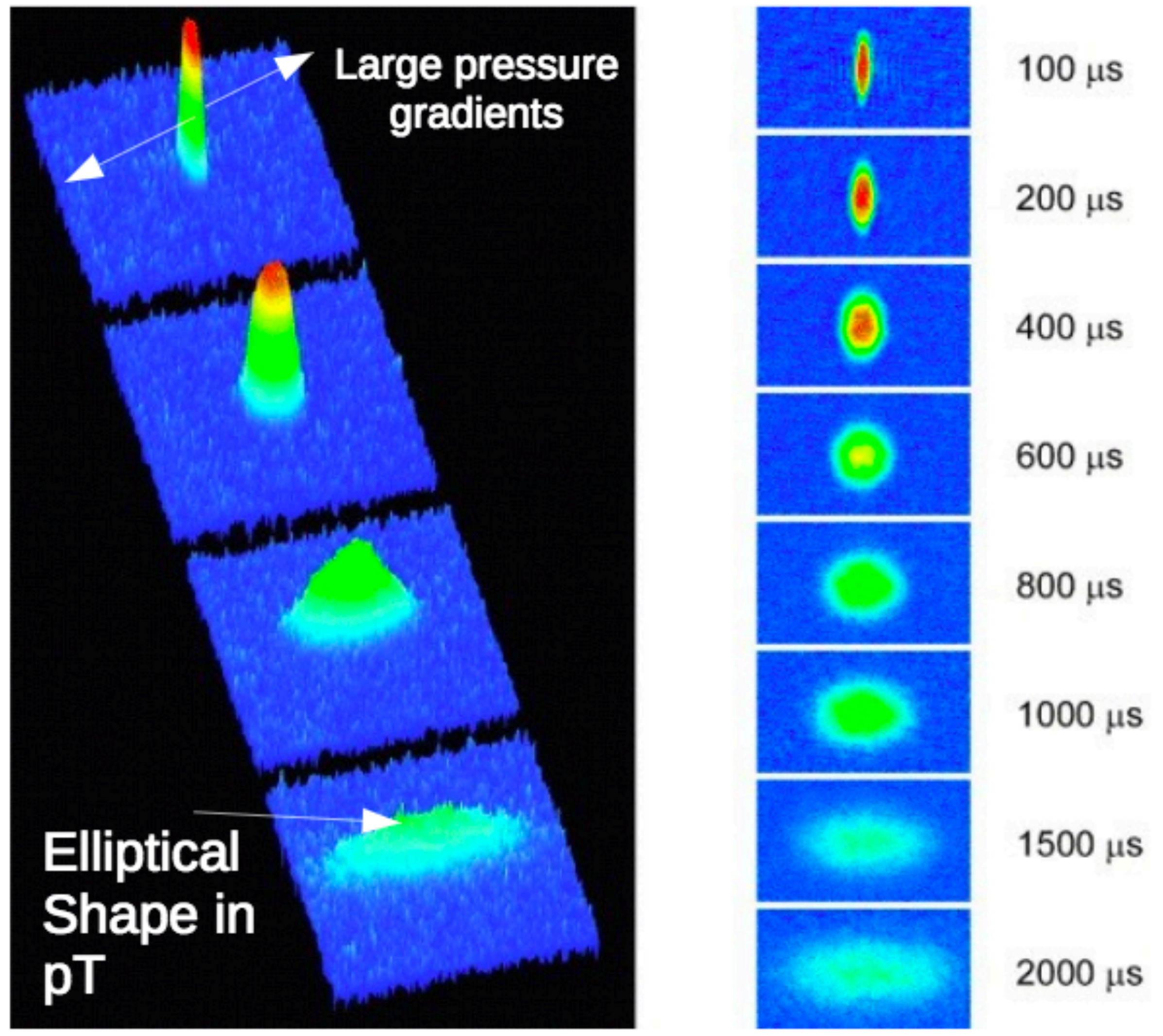
Predictions from Hydro - angular correlation

- In non-central collisions : $\sigma_x < \sigma_y$
- This leads to a *elliptical flow v2*: $\langle v_x^2 \rangle > \langle v_y^2 \rangle$
- Typical time scale:

Assuming Gold ions are spheres...



Cold Atoms



Transverse expansion starts

Longitudinal cooling | **Energy density of the medium is constant**

$t = 0$ $\quad$ $t_{v2} = R/c_s = \sqrt{(1/\sigma^2_x + 1/\sigma^2_y)}/c_s$ $\quad$ t

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

A puzzle : high-multiplicity events in small system

- Striking similarities between all the colliding system.
- Many questions and possible origin :
    - Momentum space correlation
    - Position space correlation
    - Other ?

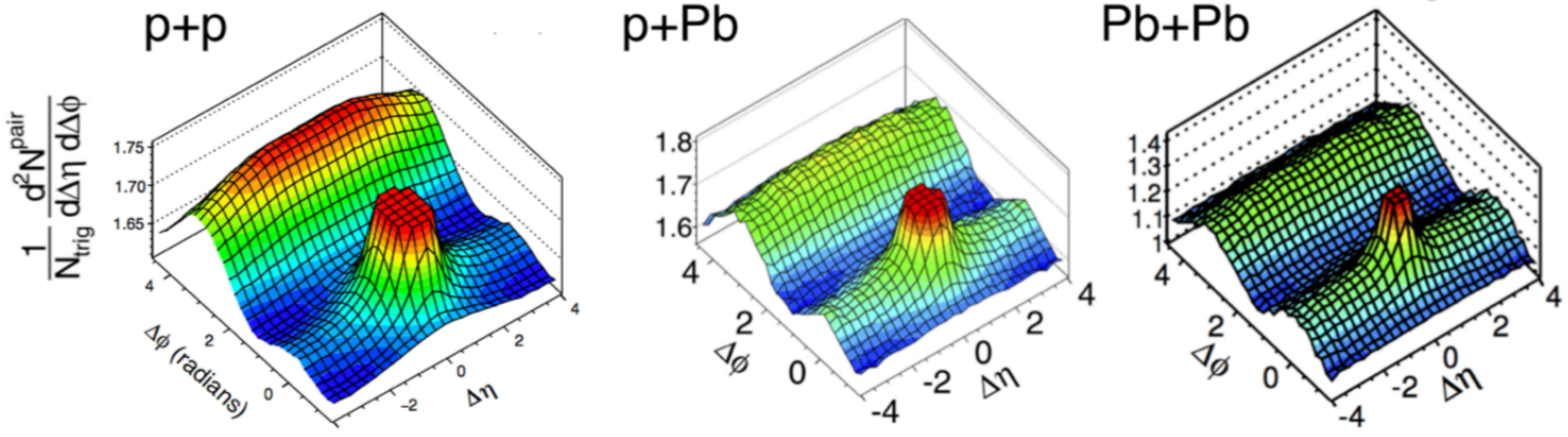
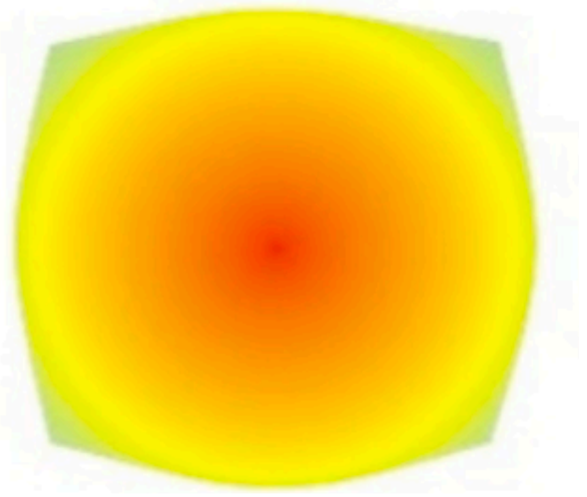


fig: CMS collb.

Last step : particle spectra

Cooper-Frye formula

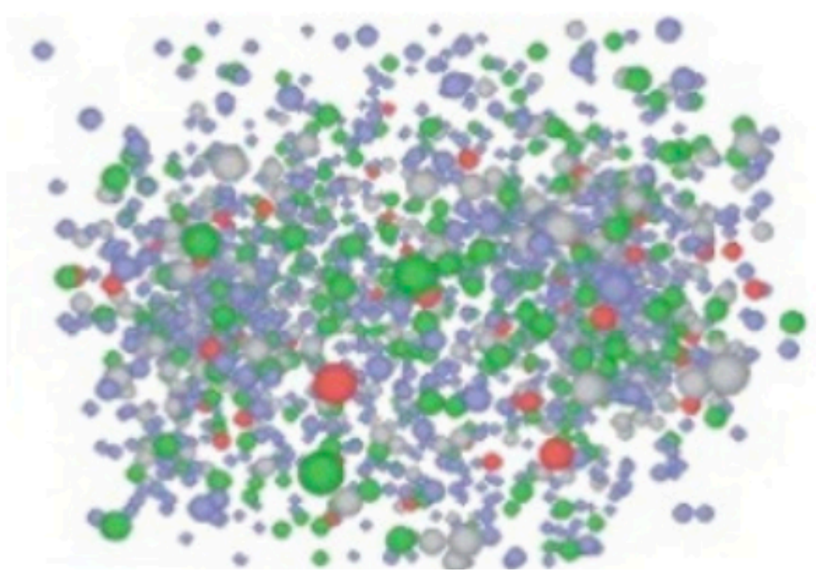


$$E\frac{dN}{d^3p} = \int_\Sigma d\Sigma_\mu p^\mu f(T, p_\mu u^\mu, \pi^{\mu\nu})$$

The Freeze-out surface

Particle distribution function

Forget this beast for the moment



- Basic assumptions :
  - $p^\mu_{\text{fluid}} = p^\mu_{\text{freeze-out}}$ for all the particles.
  - The fluid = ideal gaz.
- If we ask momentum distributions to follow Boltzmann statistics :

Spin degrees

Energy of the particle in the fluid rest frame = $p_\mu u^\mu$

$$\frac{dN}{d^3x d^3p} = \frac{2S+1}{(2\pi\hbar)^3}\exp\left(\frac{E^*}{T}\right)$$

Freeze-out temperature

Last step : particle spectra

- What does this formula tell us : $$\frac{dN}{d^3x d^3p} = \frac{2S+1}{(2\pi\hbar)^3} \exp\left(-\frac{E^*}{T}\right)$$
  - More particles when E^* is minimum → particles ***move*** with the fluid.
  - For fast particles (E^*>m), E^* is minimum when particle momentum ***is parallel*** to the fluid momentum.
  - For simplicity, we assume p_z=0 and that the fluid velocity is parallel to the particle velocity to write down :

$$E^* = p^\mu u_\mu = m_t u^0 - p_t u,$$

$$m_t = \sqrt{p_T^2 + m^2}$$

Particle spectra

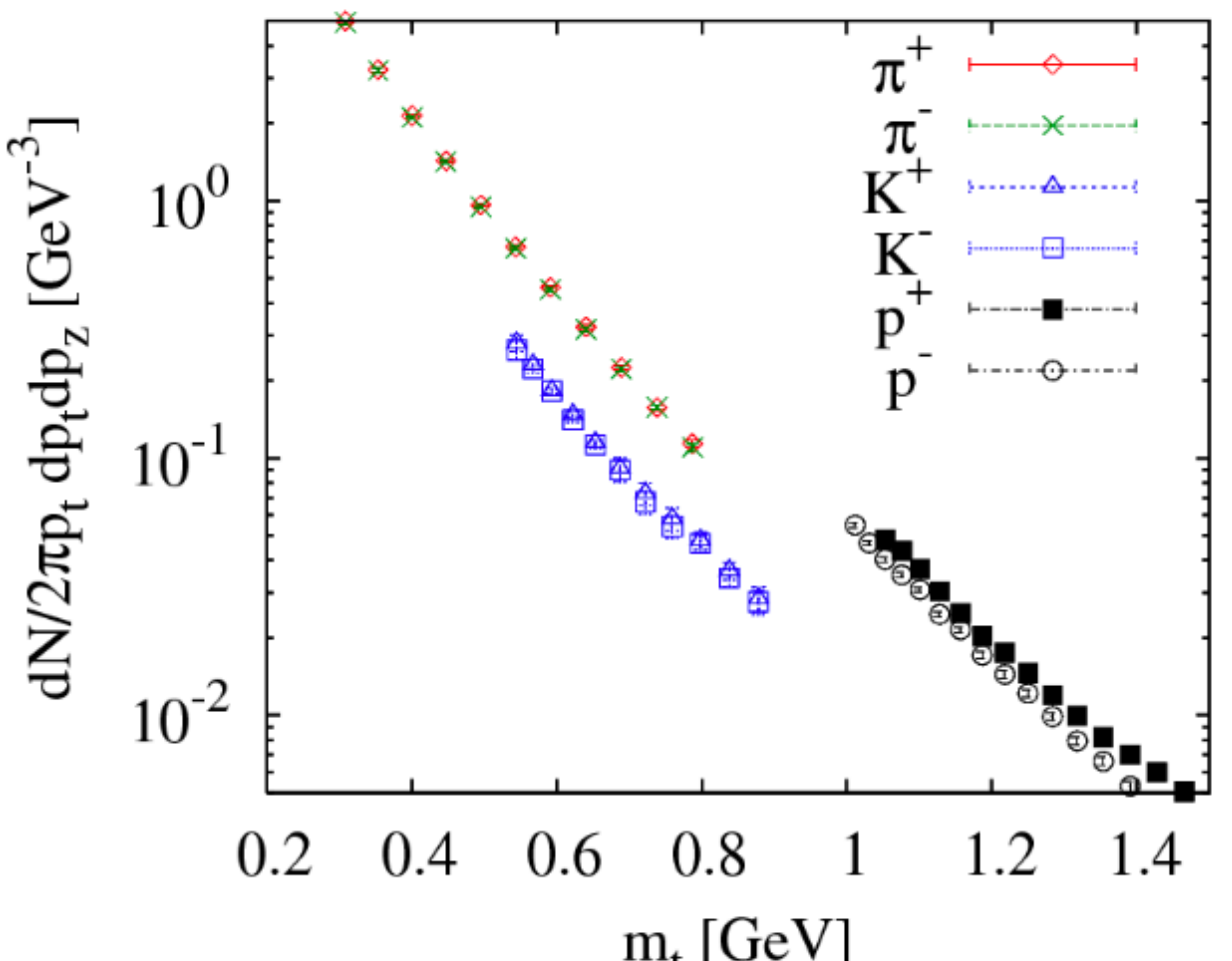
$$\frac{dN}{d^3x d^3p} = \frac{2S+1}{(2\pi\hbar)^3} \exp\left(-\frac{E^*}{T}\right)$$

$$E^* = p^\mu u_\mu = m_t u^0 - p_t u,$$

$$\frac{dN}{2\pi p_t dp_t dp_z} \propto \exp\left(\frac{-m_t u_0 + p_t u}{T}\right)$$

Adams J et al. [STAR Collaboration] 2004 Phys. Rev. Lett. 92 112301

- *pp* collisions at $\sqrt{s}$ = 200 GeV near $p_z = 0$.
- Clear scaling with transverse mass.
- What about Au-Au ?



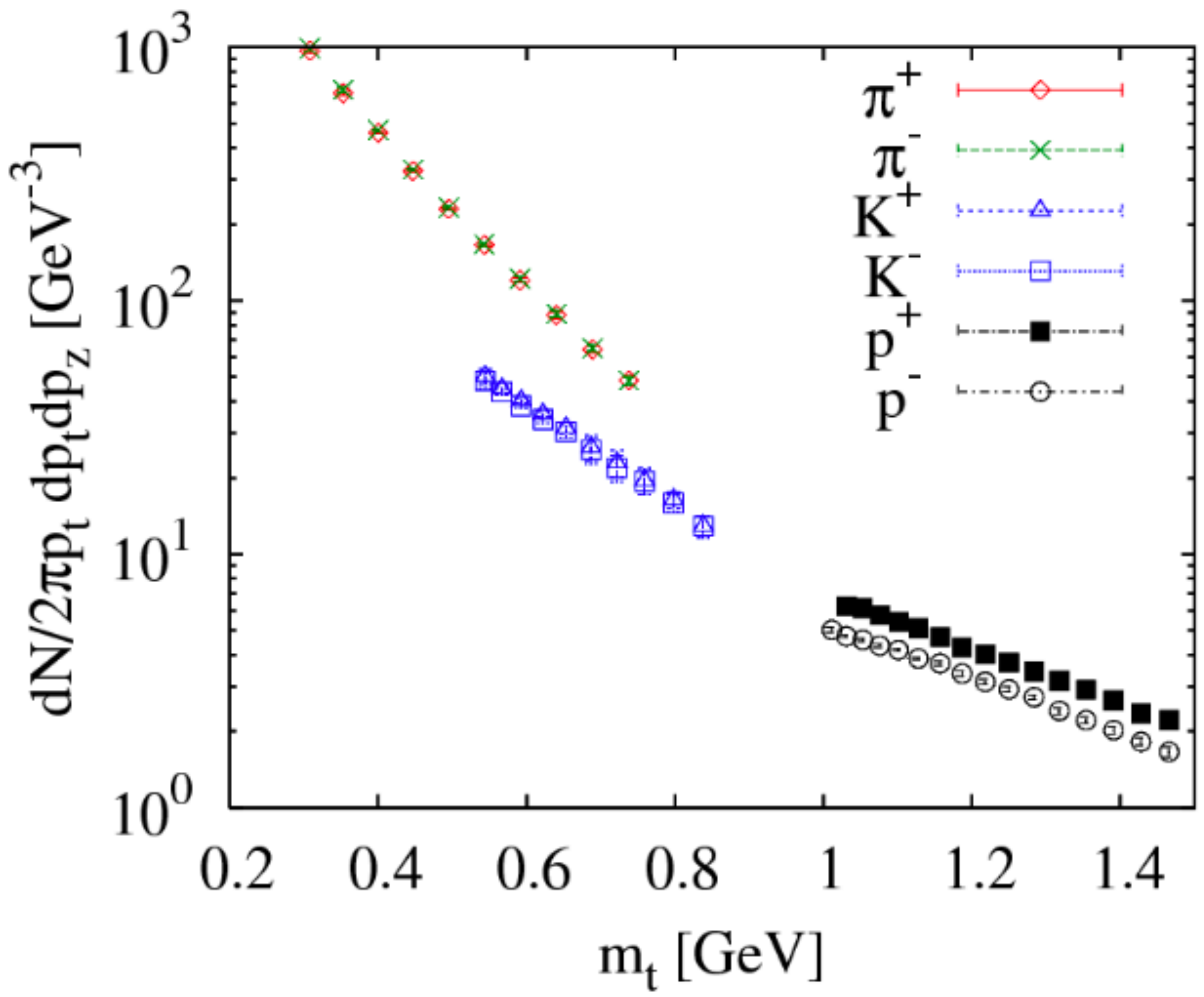
Particle spectra

- Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV near $p_z = 0$
- m_t scaling is broken → **collective velocity.**
- To convince you :

$$\frac{d}{dm_t}\log\left(\frac{dN}{2\pi p_t dp_t dp_z}\right) = \frac{-u_0 + u m_t/p_t}{T}$$

- Those results show evidence of **transverse flow.**

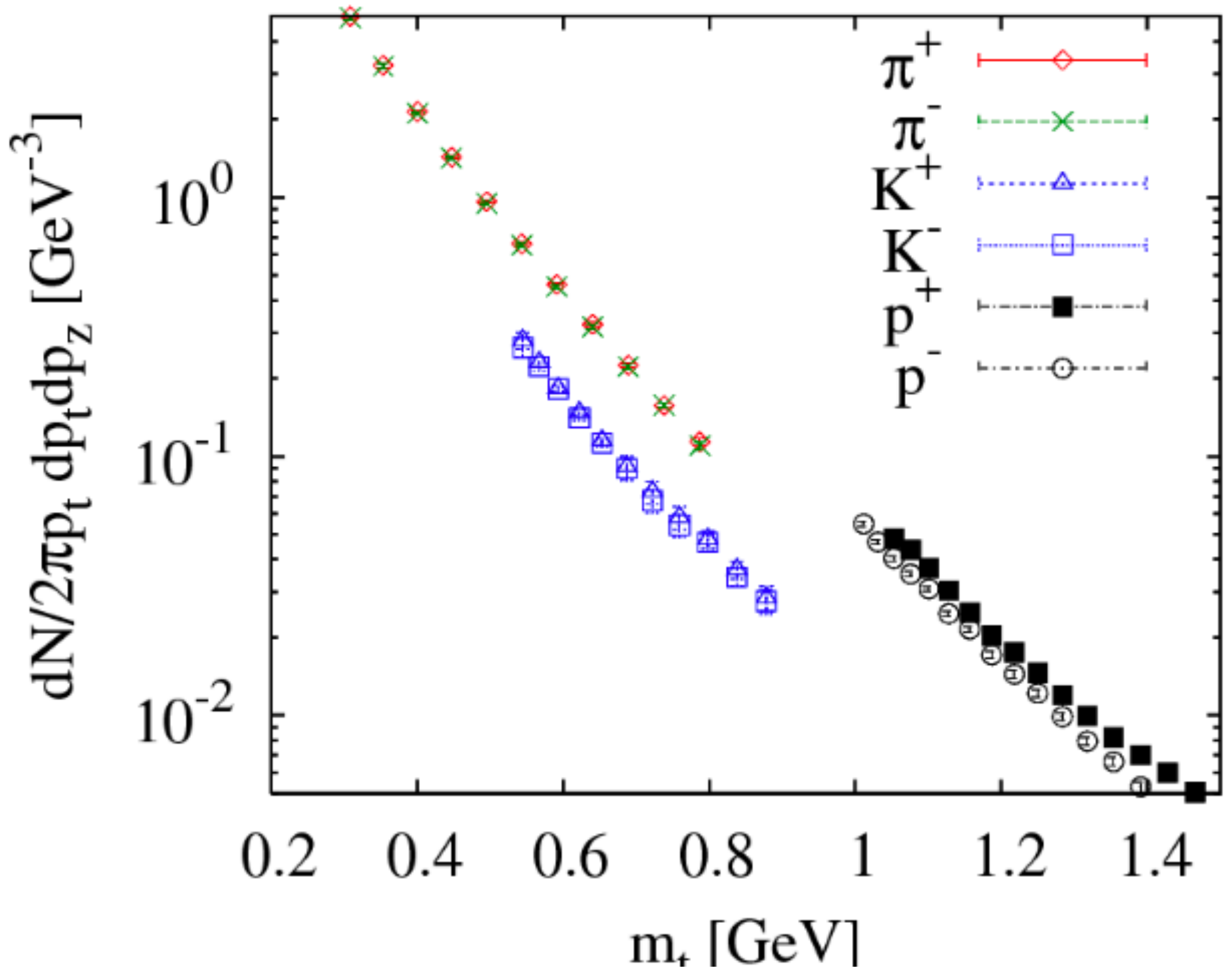
Adams J et al. [STAR Collaboration] 2004 Phys. Rev. Lett. 92 112301

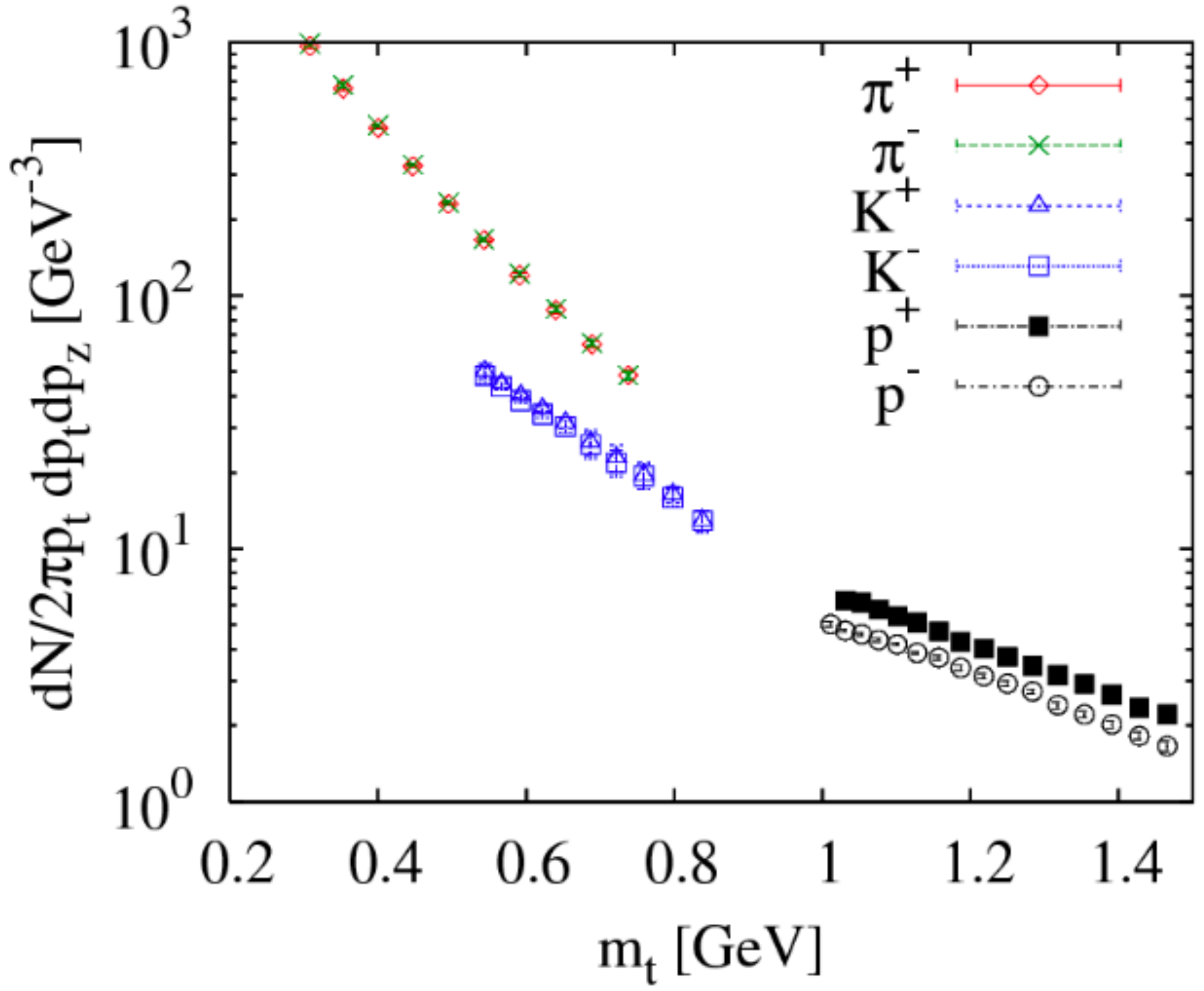


On the freeze-out temperature

$$\frac{dN}{2\pi p_t dp_t dp_z} \propto \exp\left(\frac{-m_t u_0 + p_t u}{T}\right)$$

- Same relative abundances of pions, kaons, and (anti)protons in *pp* and Au-Au.
- Particle ratios only depends on *T*:
  - « **Chemical Freeze-out** » $T_C \simeq 170$ MeV
- But in Au-Au due to radial flow, *T* **must be lower:**
  - « **Kinetic Freeze-out** » $T_f \simeq 100$ MeV





Consequences on v_2

- We can rewrite :

$$\frac{dN}{2\pi p_t dp_t dp_z} \propto \exp\left(\frac{-m_t u_0 + p_t u}{T}\right) \longrightarrow \frac{dN}{p_t dp_t dp_z d\phi} \propto \exp\left(\frac{-m_t u_0(\phi) + p_t u(\phi)}{T}\right)$$

- Since the fluid velocity is larger on the *x*-axis than the *y*-axis, $u(\phi)$ can be parameterized as :

$$u(\phi) = u + 2\alpha \cos 2\phi,$$

- Finally, experiment suggests $\alpha \sim 4\%$. Using $u^0 = \sqrt{(u^2+1)}$ and expanding to first order in α :

$$u^0(\phi) = u^0 + 2v\alpha \cos 2\phi$$

$v = u/u_0$

Consequences on v_2

$$\frac{dN}{p_t dp_t dp_z d\phi} \propto \exp\left(\frac{-m_t u_0(\phi) + p_t u(\phi)}{T}\right)$$

$$u(\phi) = u + 2\alpha \cos 2\phi,$$

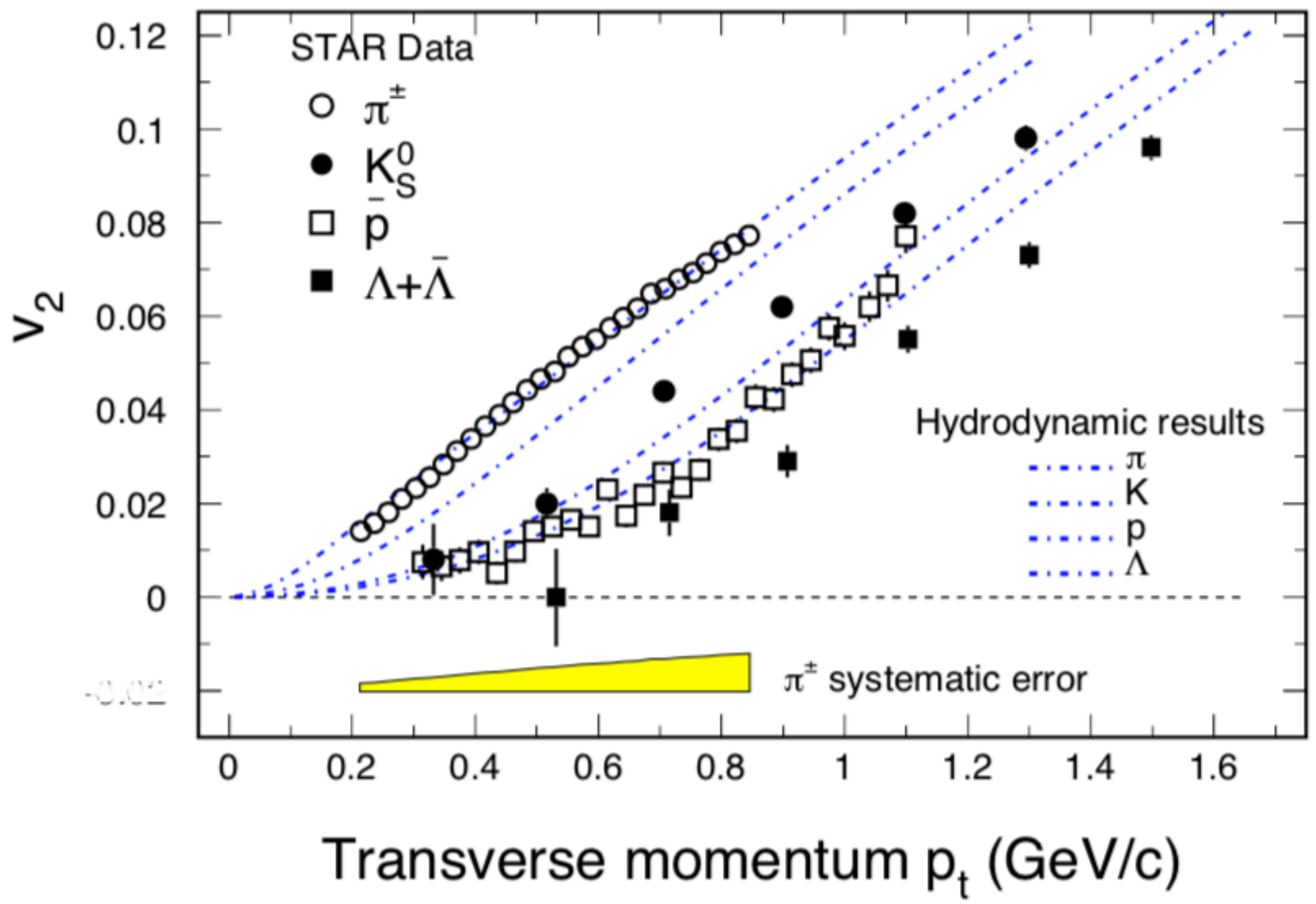
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

$$u^0(\phi) = u^0 + 2v\alpha \cos 2\phi$$

Take all the formula at fist order in α …

$$v_2 = \frac{\alpha}{T}\left(p_t - v m_t\right)$$

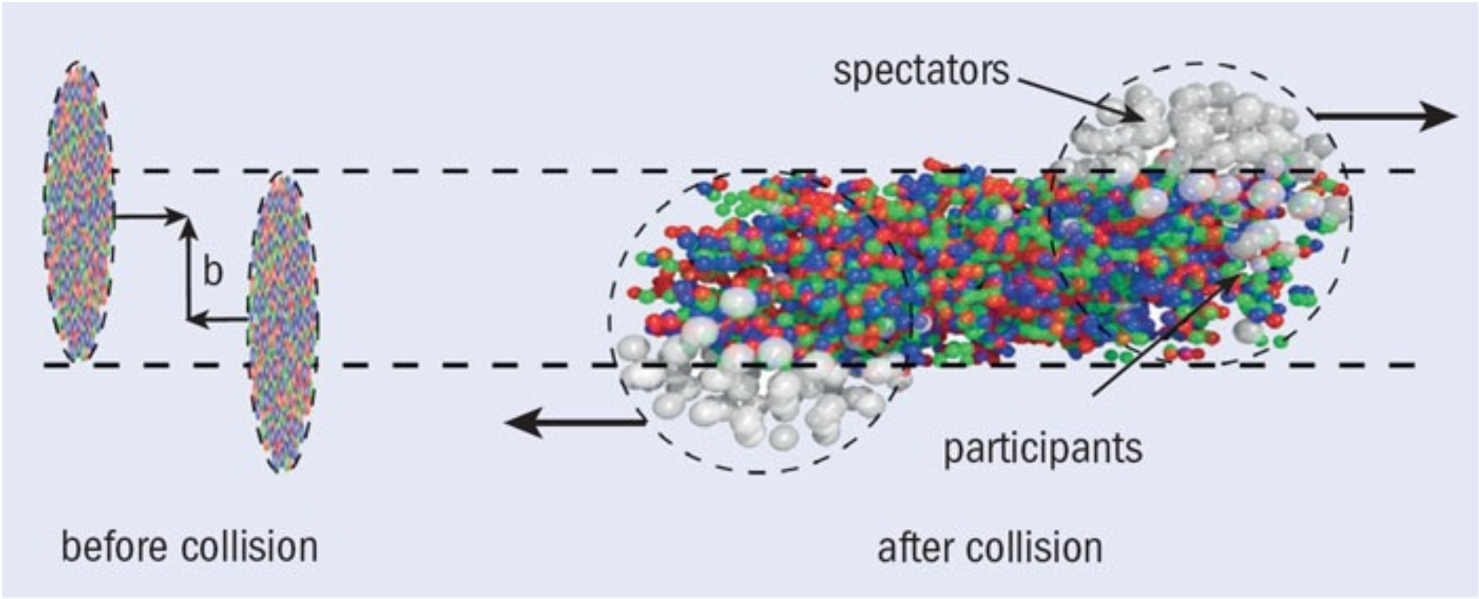
- Mass ordering for the v_2.
- Good agreement data/theory up to p_t ~ 2 GeV
- At higher p_t : v_2 saturates (viscous effect ?).



THE GLAUBER MODEL

Centrality and Glauber Model

- The quantity that relate if a (A-A) collision is head-on or more peripheral is called *centrality.*



- **Question** : How do we determine this quantity ?

$$\frac{dN_{ch}}{d\eta} \propto (N_{part} \leftrightarrow N_{coll}) \propto b \rightarrow \text{Centrality}$$

Experimental Observable

Glauber Model

What we want

History of Glauber Model

- **Roy Glauber :**
  - 1950's: Used quantum mechanical scattering techniques to analytically describe multi-body scattering of composite systems.
  - 1970's: Beams of protons and ions are scattered off nuclear targets and Glauber's work was found useful for computing total cross-sections.
  - 2005 : Nobel prize in physics for his contributions to quantum optics
  - Present: Glauber Monte Carlo models are used to determine centrality in HIC (among other things).
- **Glauber model assumptions :**
  - Nucleons travel on straight trajectories
  - Nucleon-nucleon cross-section is independent of the number of collisions a nucleon underwent before
  - Assume « optical limit » : particles have momenta such that they are deflected very little as they pass through each other
- Complete review : https://arxiv.org/pdf/nucl-ex/0701025.pdf

Analytical model

- Thickness function :

$$\hat{T}_A(\mathbf{s}) = \int \hat{\rho}_A(\mathbf{s}, z_A)dz_A$$

$$\int T_{\rm A}(\vec{s})\, {\rm d}^2 s = A$$

- Overlap Function:

$$\hat{T}_{AB}(\mathbf{b}) = \int \hat{T}_A(\mathbf{s})\, \hat{T}_B(\mathbf{s}-\mathbf{b})d^2 s.$$

- Probability of having n such NN Collisions:

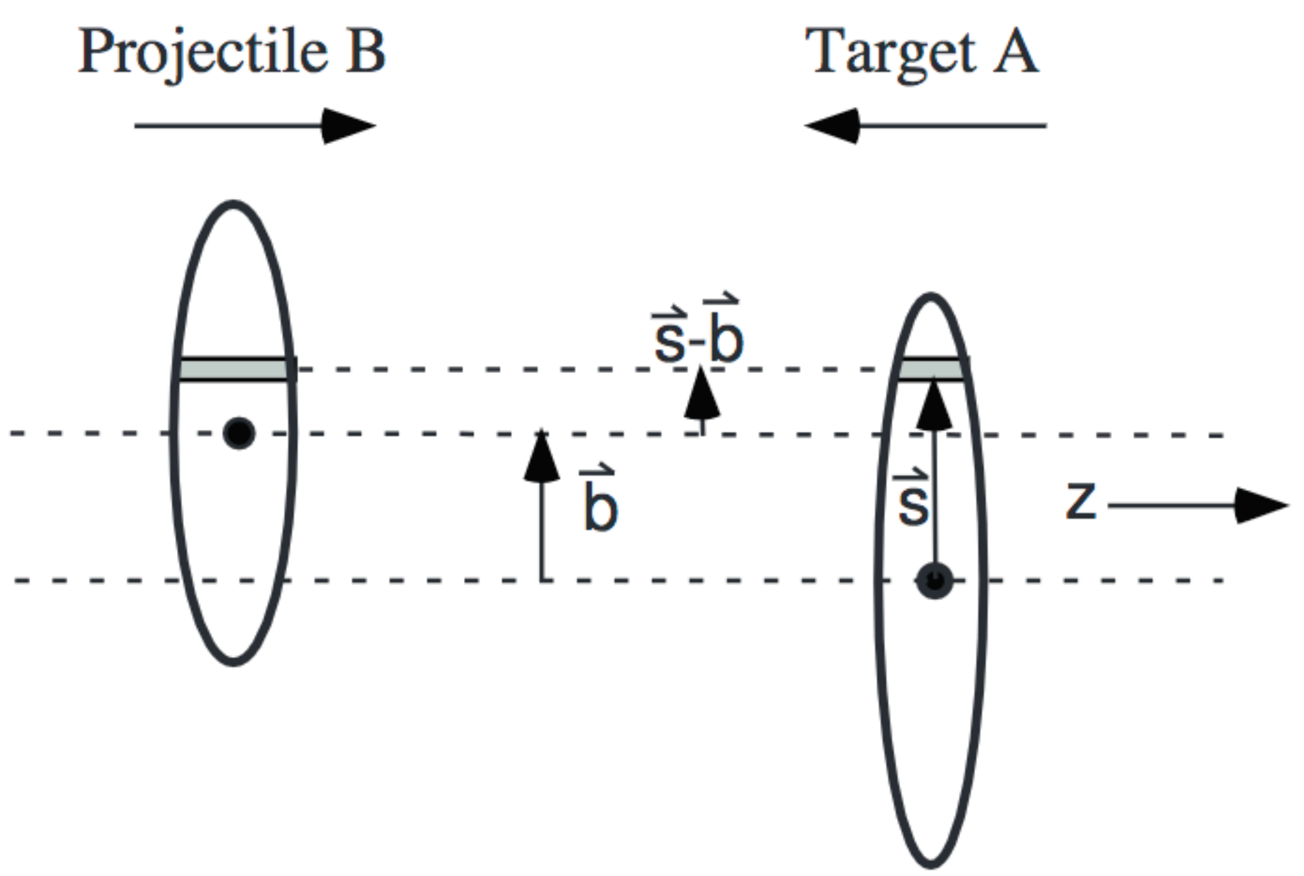
$$P(n, \mathbf{b}) = \binom{AB}{n} \left[\hat{T}_{AB}(\mathbf{b})\, \sigma_{\rm inel}^{\rm NN}\right]^n \left[1 - \hat{T}_{AB}(\mathbf{b})\, \sigma_{\rm inel}^{\rm NN}\right]^{AB-n}$$

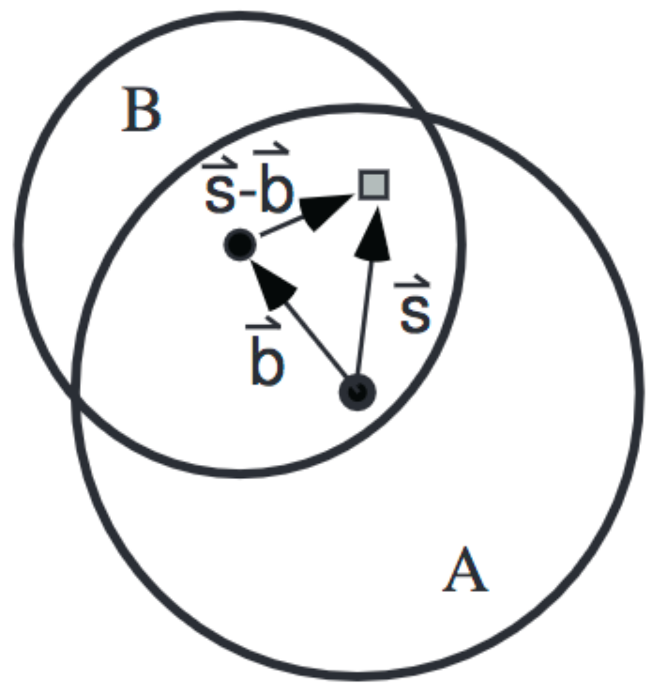
$$\binom{AB}{n} = \frac{(AB)!}{n!(AB-n)!}$$

Probability of n hits

Probability of AB-n miss

Side view





Beam-line view

Small definition

$$\hat{T}_{\rm B}(\vec{x}) := T_{\rm B}(\vec{x})/B$$

Analytical model

- Total inelastic cross-section :

$$\sigma_{\text{inel}}^{\text{A+B}} = \int_0^\infty 2\pi b db \left\{1 - \left[1 - \hat{T}_{AB}(b)\, \sigma_{\text{inel}}^{\text{NN}}\right]^{AB}\right\}$$

- Number of Binary collisions :

$$N_{\text{coll}}(b) = \sum_{n=1}^{AB} nP(n,b) = AB\hat{T}_{AB}(b)\, \sigma_{\text{inel}}^{\text{NN}}$$

- Number of participant (wounded) nucleons :

$$\begin{aligned} N_{\text{part}}(\mathbf{b}) \quad = \quad & A\int \hat{T}_A(\mathbf{s}) \left\{1 - \left[1 - \hat{T}_B(\mathbf{s}-\mathbf{b})\, \sigma_{\text{inel}}^{\text{NN}}\right]^{B}\right\} d^2s + \\ & B\int \hat{T}_B(\mathbf{s}-\mathbf{b}) \left\{1 - \left[1 - \hat{T}_A(\mathbf{s})\, \sigma_{\text{inel}}^{\text{NN}}\right]^{A}\right\} d^2s, \end{aligned}$$

MC Glauber

- In practice, solving analytically Glauber requires a 2x(A+B+1) dimensional integral … No thanks !

- Receipt for a MC Glauber model :
  - <u>Step 1 : Create nuclei</u>
    - For each nucleon specify a position vector by drawing random p= (x,y,z) location from Woods-Saxon
  - <u>Step 2 : Define Orientations of Nuclei</u>
    - Generate 3 random numbers in range [0,1] to uniformly sample phase space transform thusly...
    - Draw Random Impact Parameter from $d\sigma/db = 2\pi b$
    - Rotate Nucleon position vectors and translate by b
  - <u>Step 3 : Compute Ncoll and Npart</u>

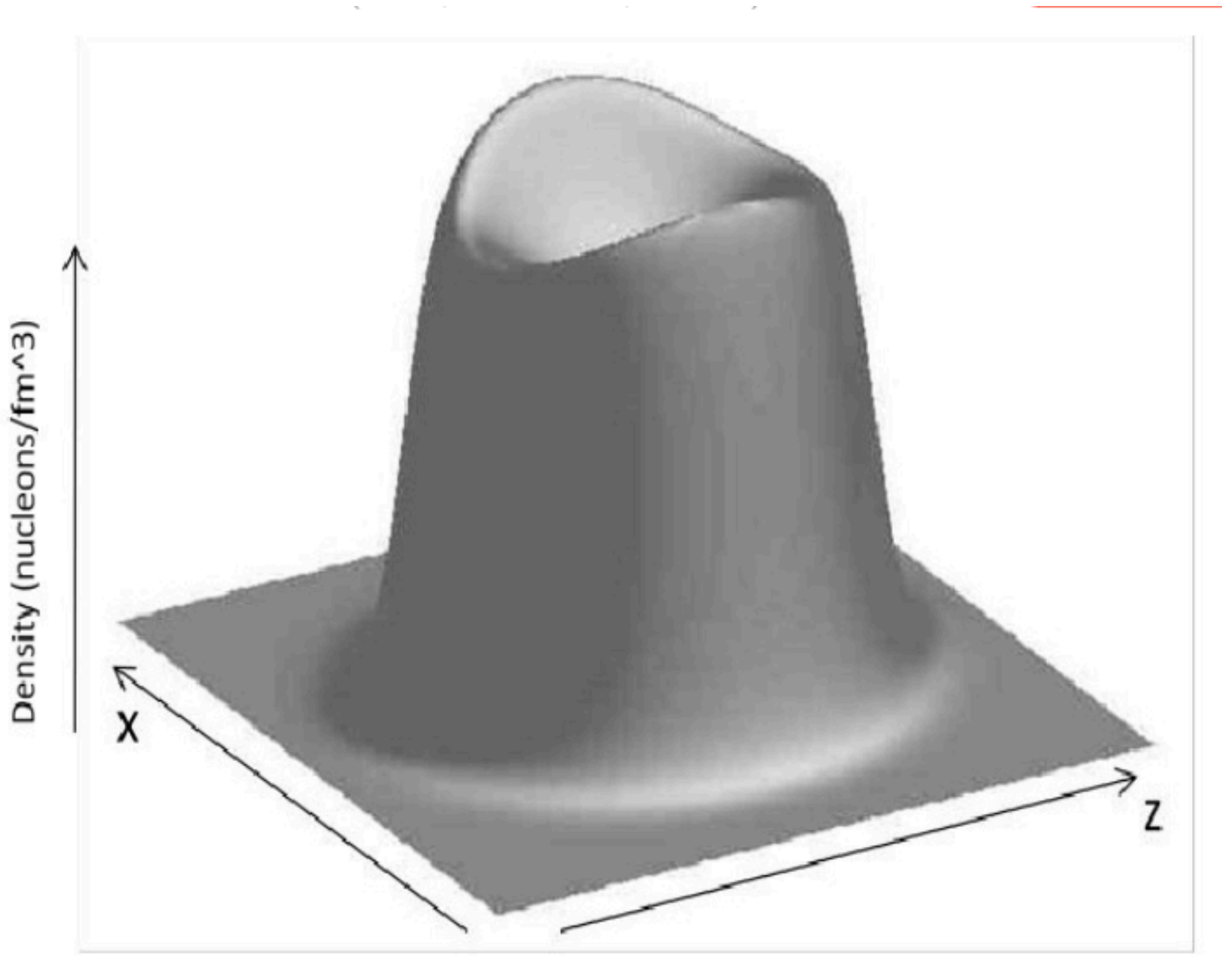
Step 1 – Creating Nuclei

- Woods-Saxon nuclear density profile :

$$\rho(r) = \frac{\rho_0\left(1 + wr^2/R^2\right)}{1 + \exp((r-R)/a)}$$

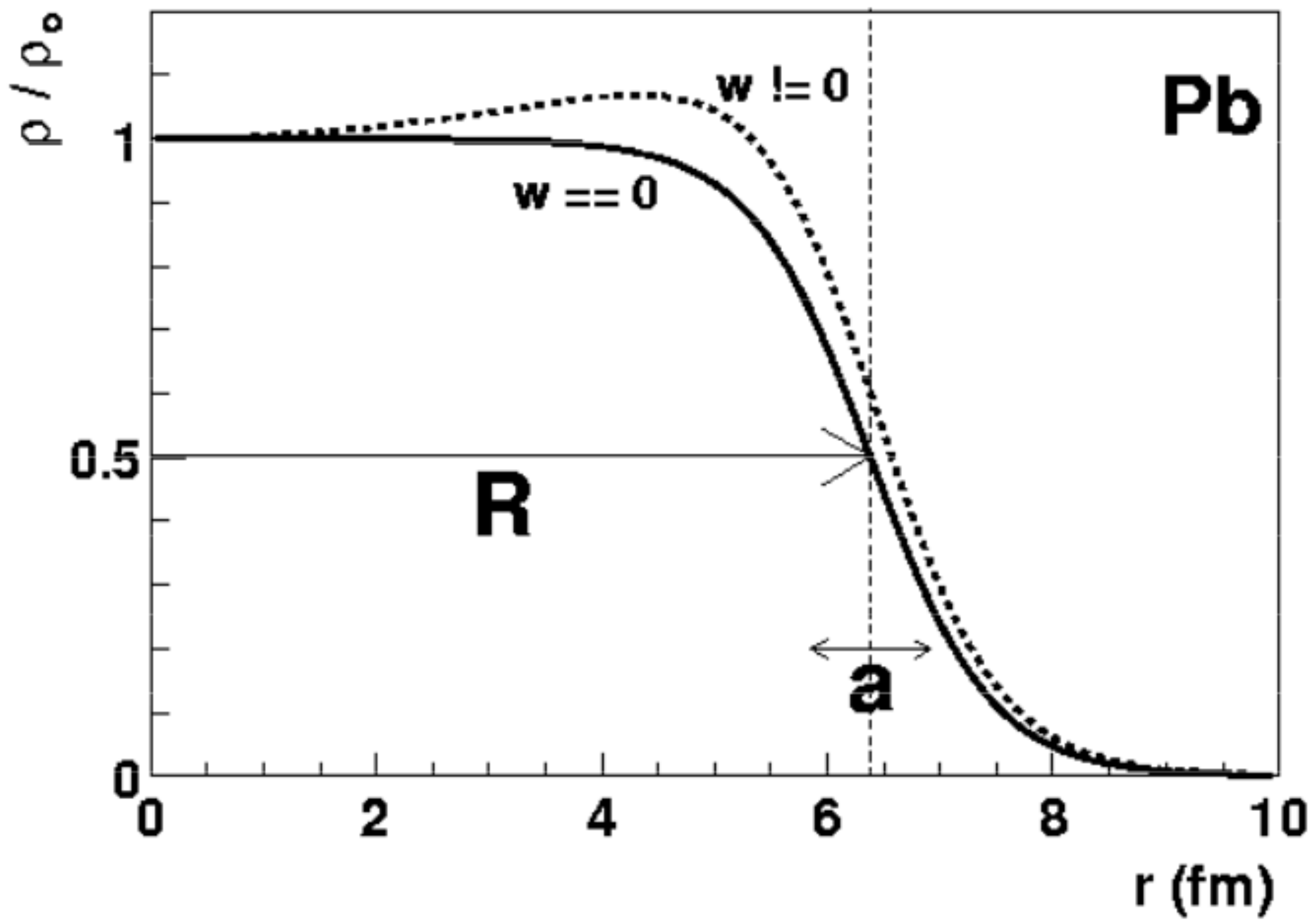
- Woods-Saxon parameters typically determined by electron scattering.

- Differences between neutron and proton distributions are small and typically neglected.

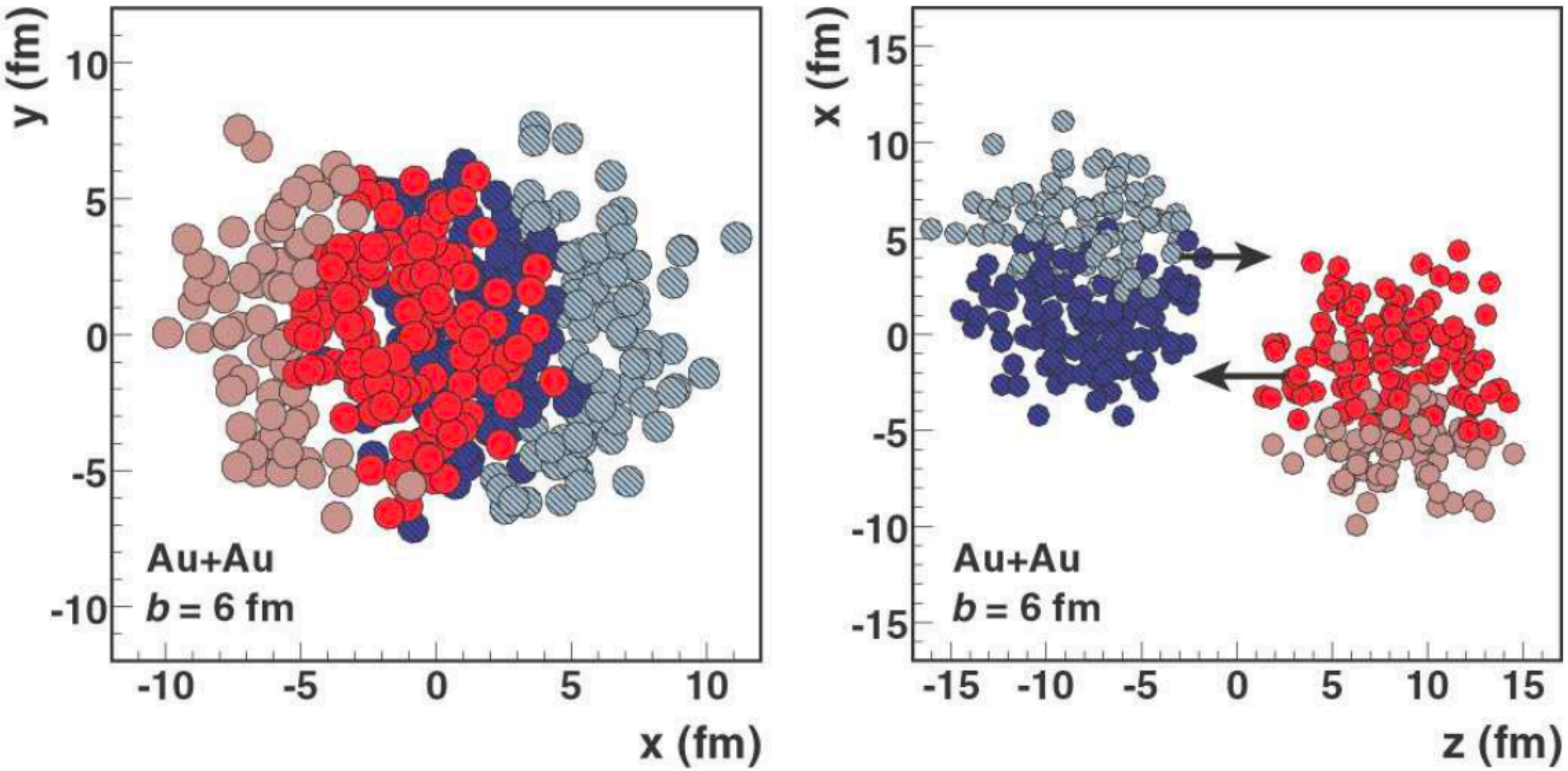


Nucleus	A	R (fm)	a (fm)	w
C	12	2.47	0	0
O	16	2.608	0.513	-0.051
Al	27	3.07	0.519	0
S	32	3.458	0.61	0
Ca	40	3.76	0.586	-0.161
Ni	58	4.309	0.516	-0.1308
Cu	63	4.2	0.596	0
W	186	6.51	0.535	0
Au	**197**	**6.38**	**0.535**	**0**
Pb	208	6.68	0.546	0
U	238	6.68	0.6	0

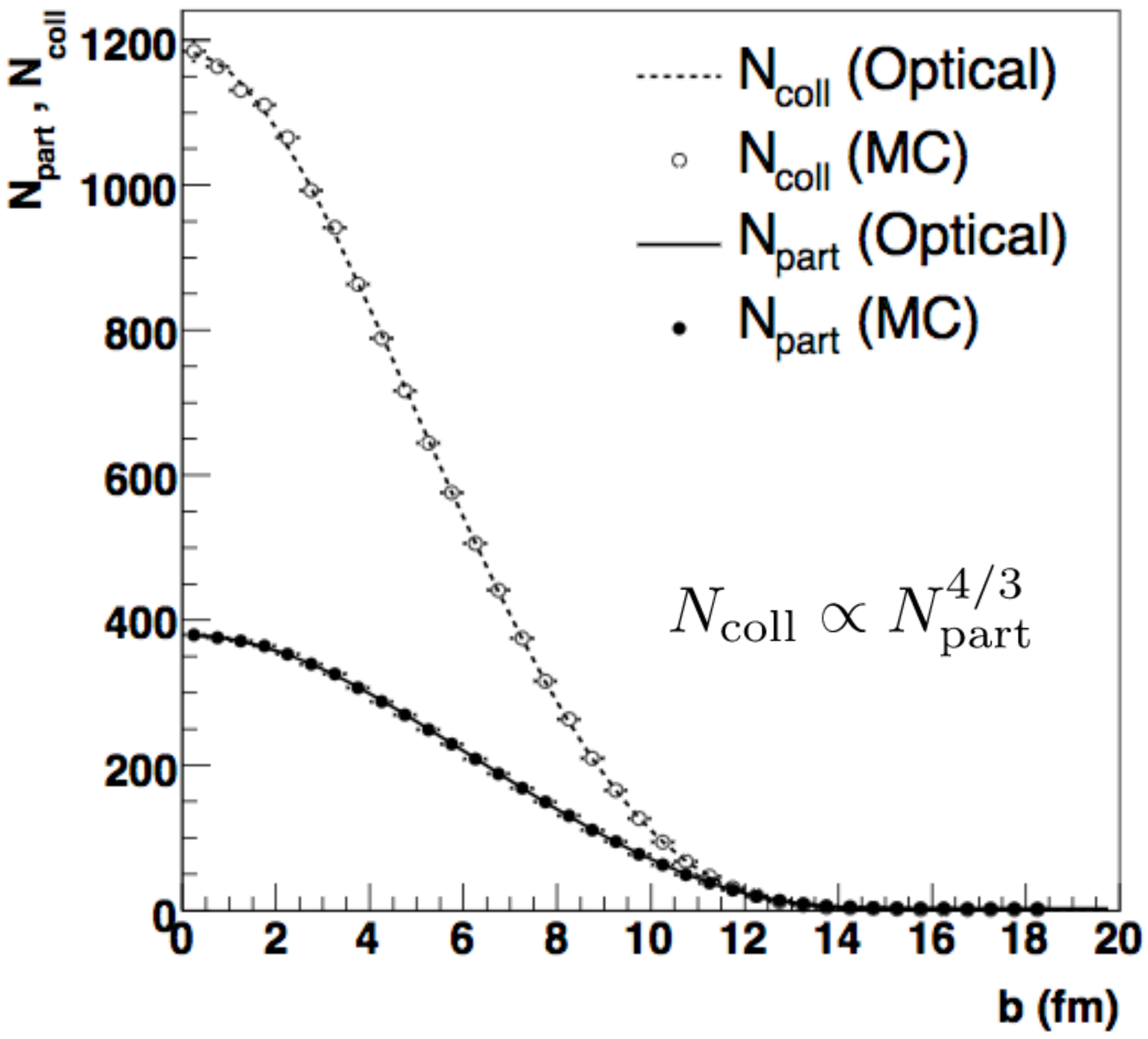
H. DeVries, C.W. De Jager, C. DeVries, 1987

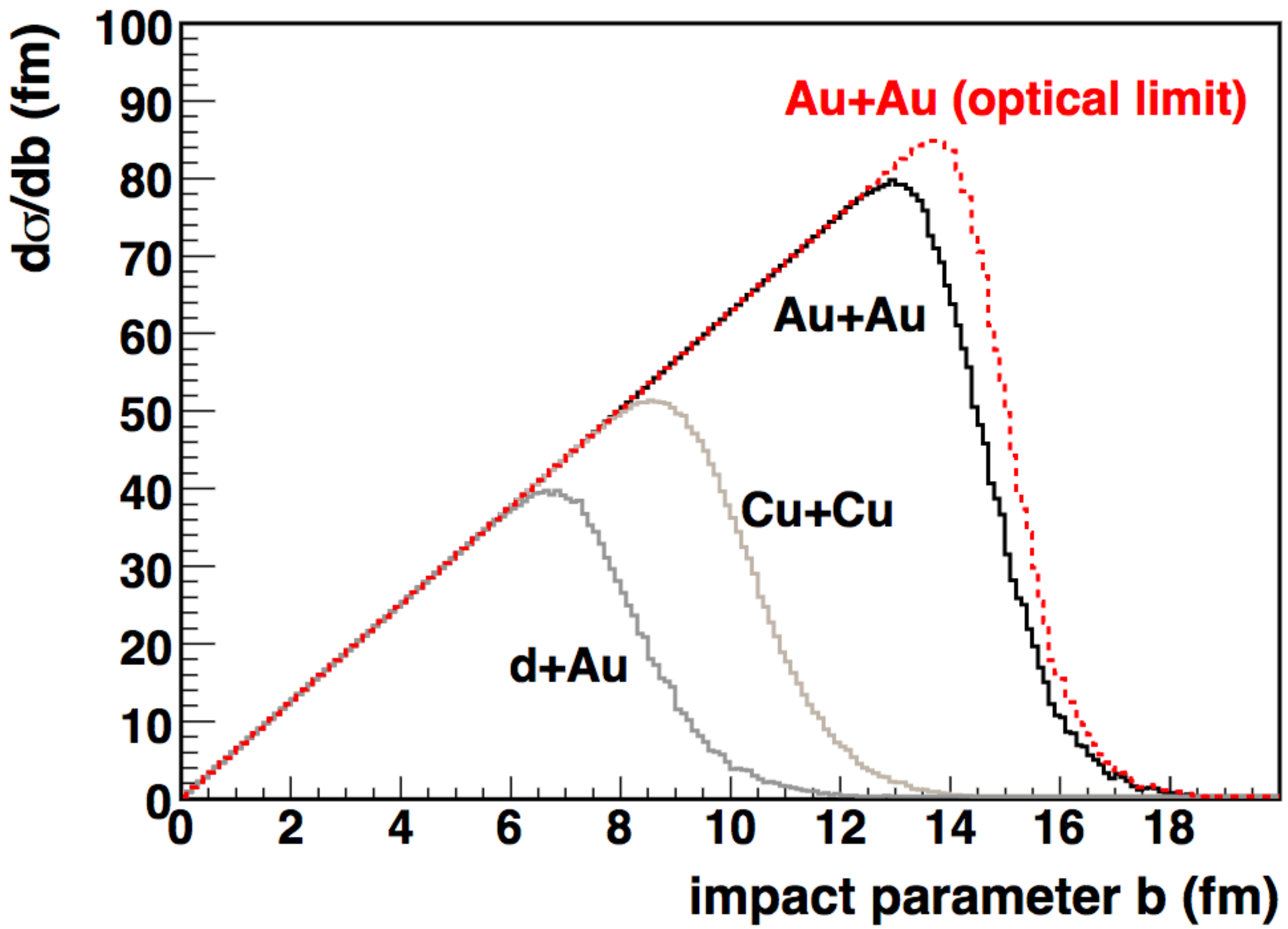


MC Glauber illustrated



MC Glauber illustrated

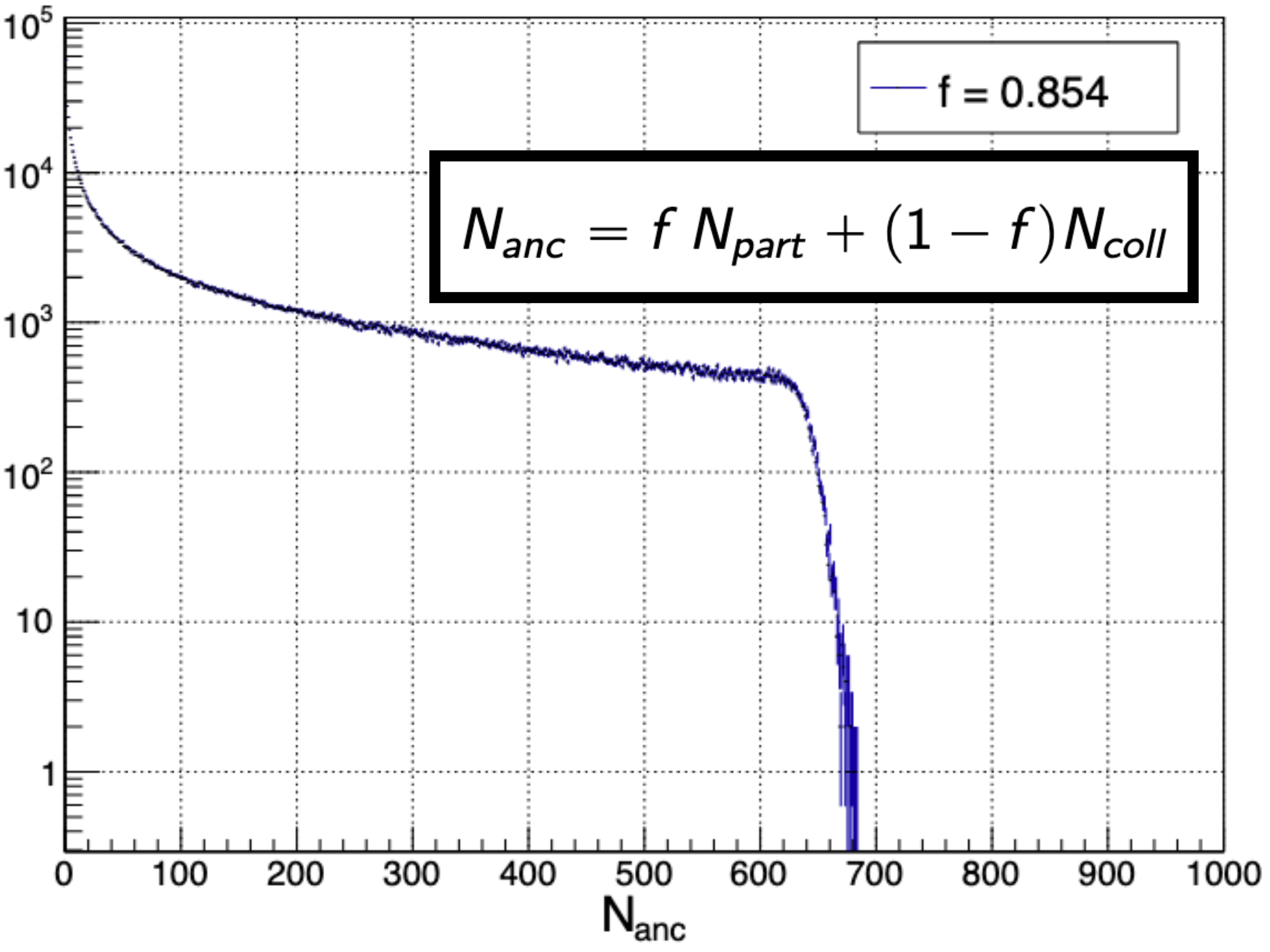




Connecting MC Glauber to Centrality : LHCb case

***Step one* : translate <Ncoll> into an equivalent number of charged particles.**

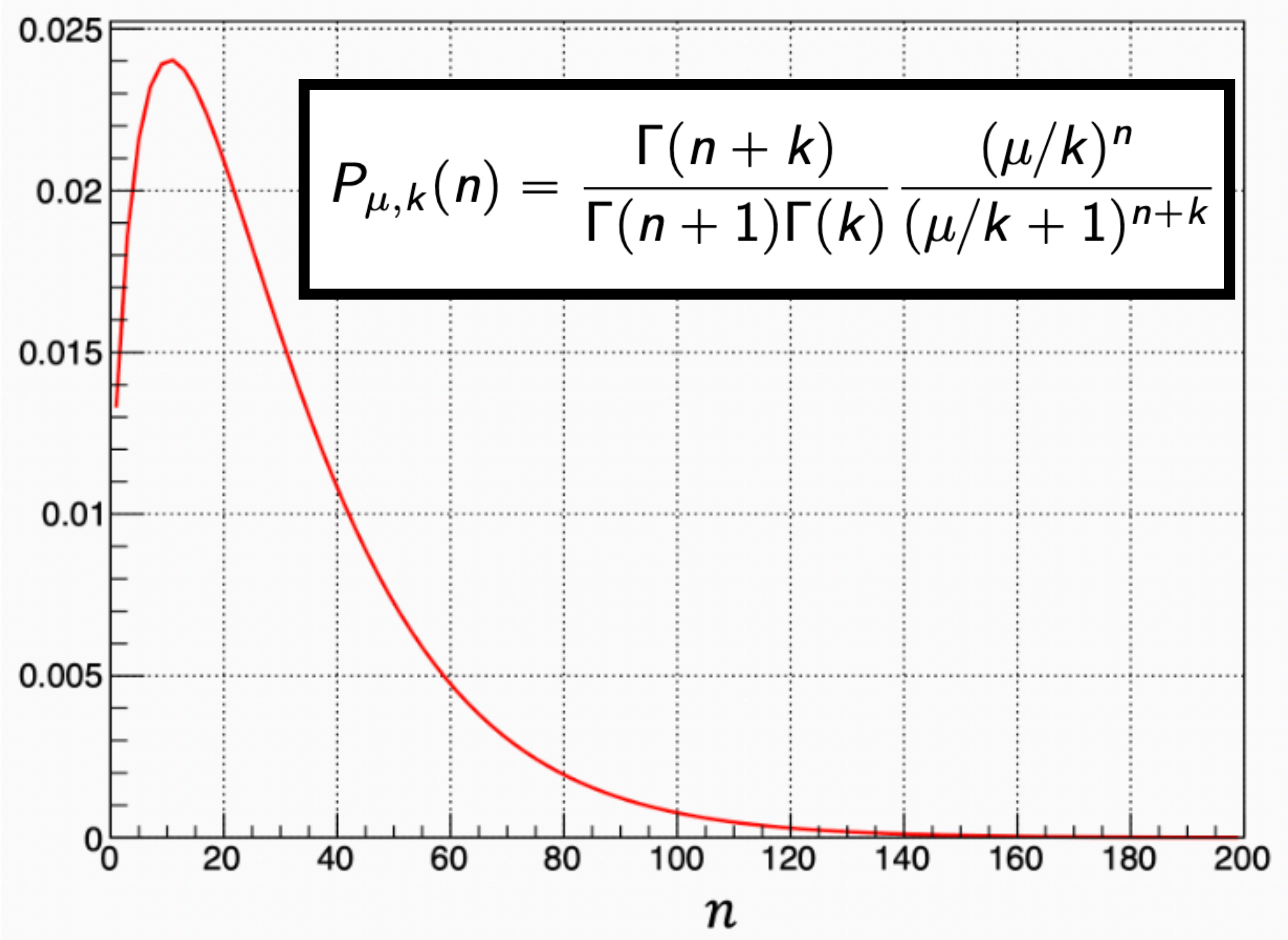
From Glauber



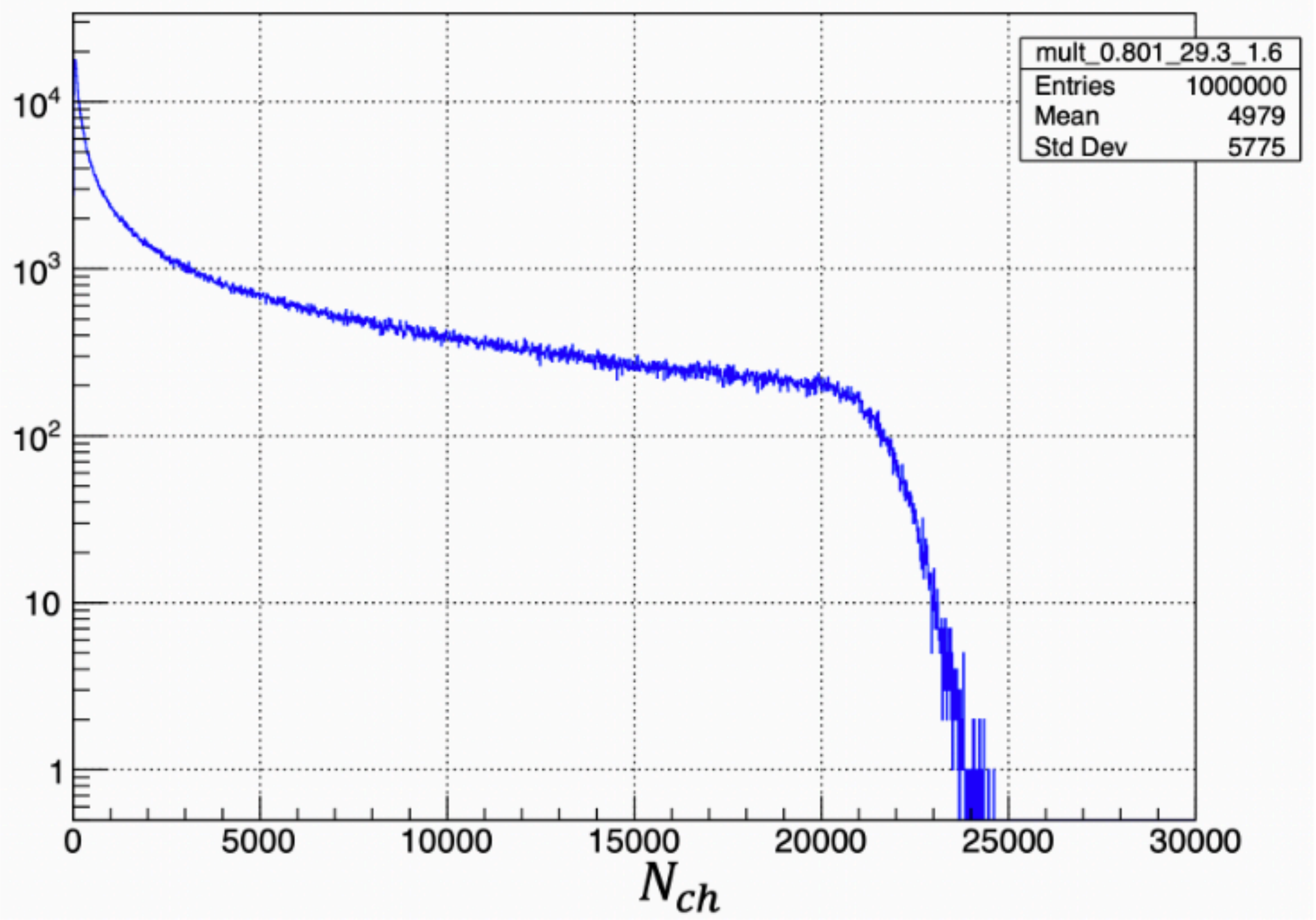
Source to sample …

P := negative binomial distributions

:= charged particles distribution per ancestor



Equivalent number of charged particles

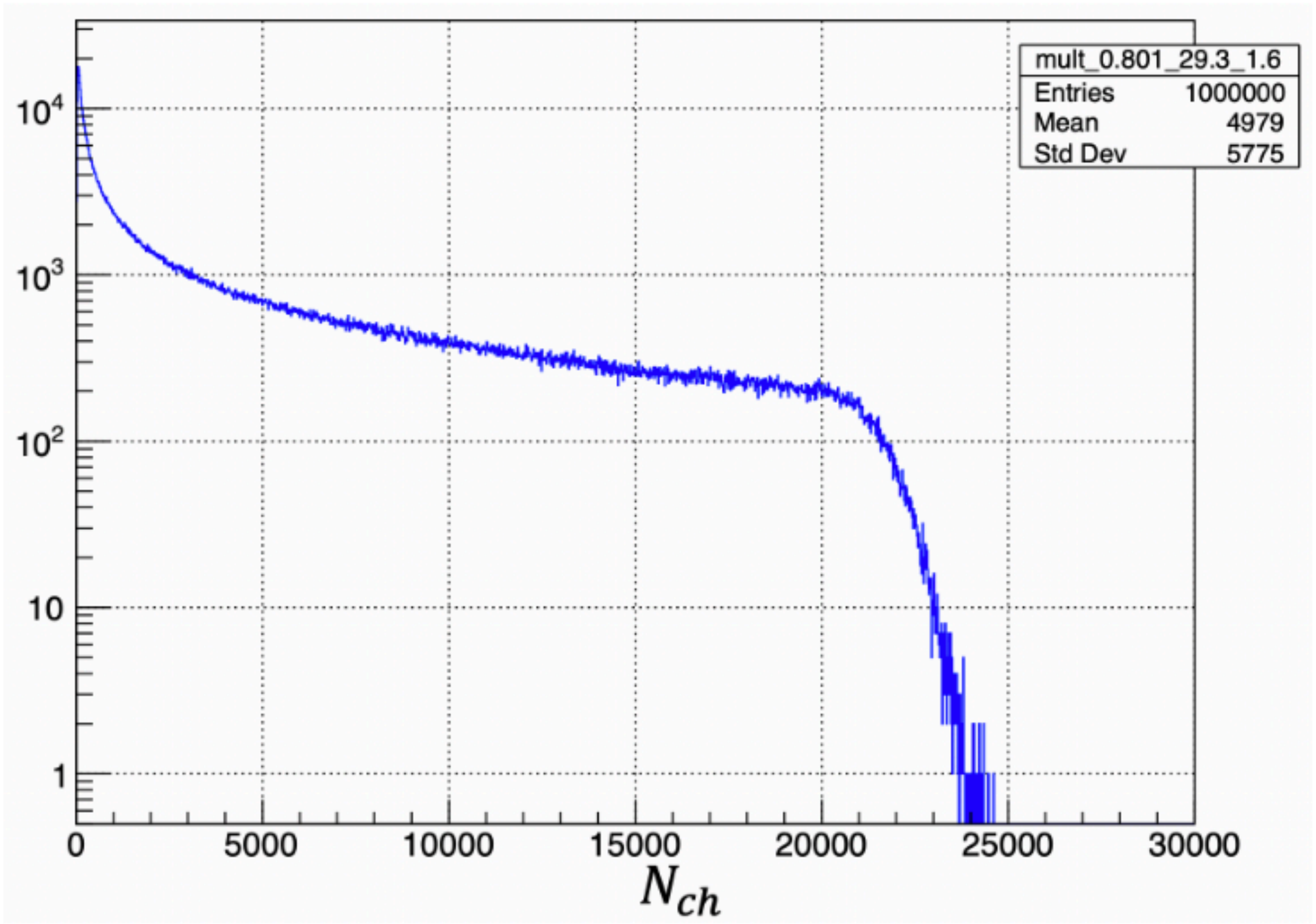


Sampled for every event N_{anc} times…

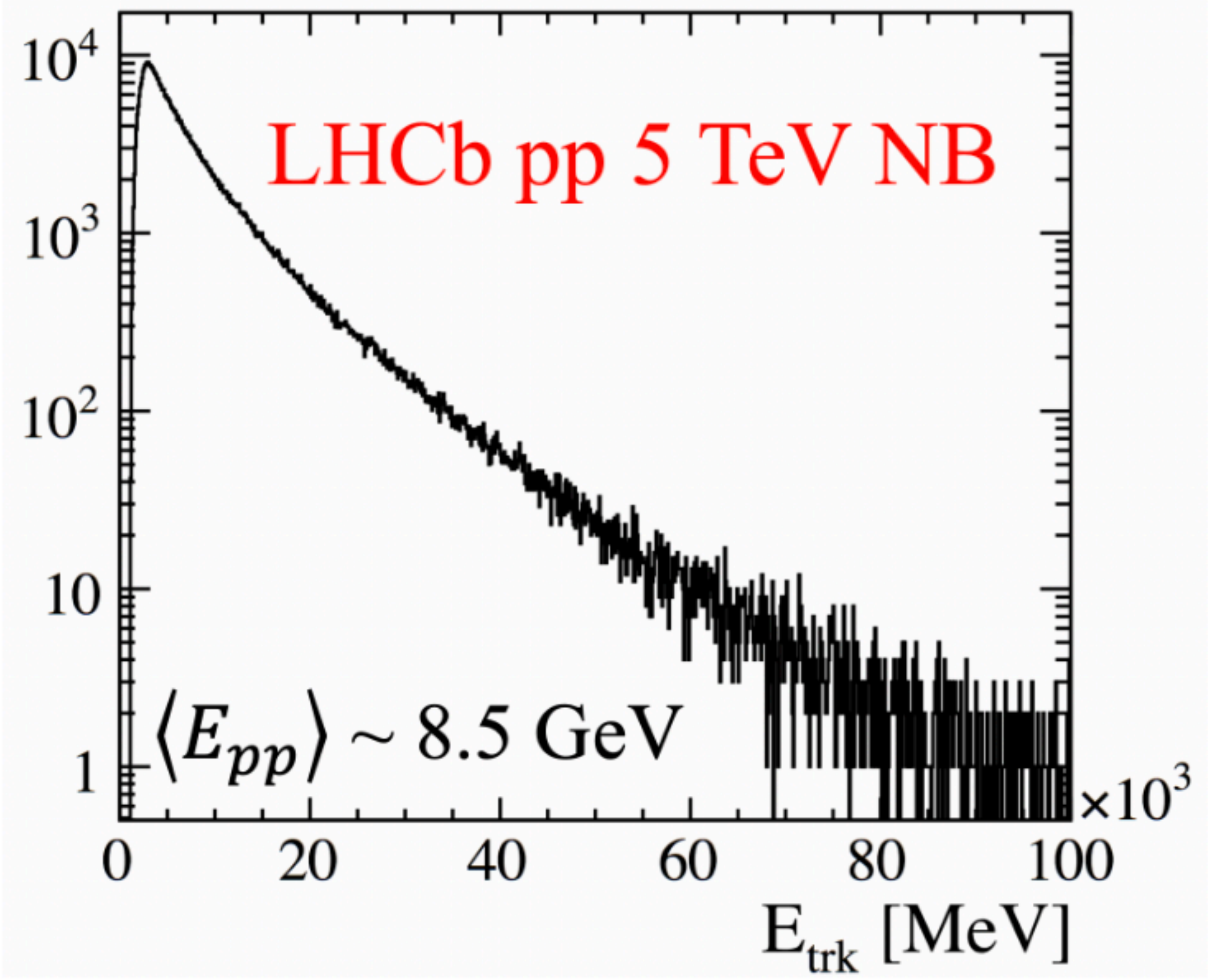
Connecting MC Glauber to Centrality : LHCb case

Step two : translating to energy deposit.

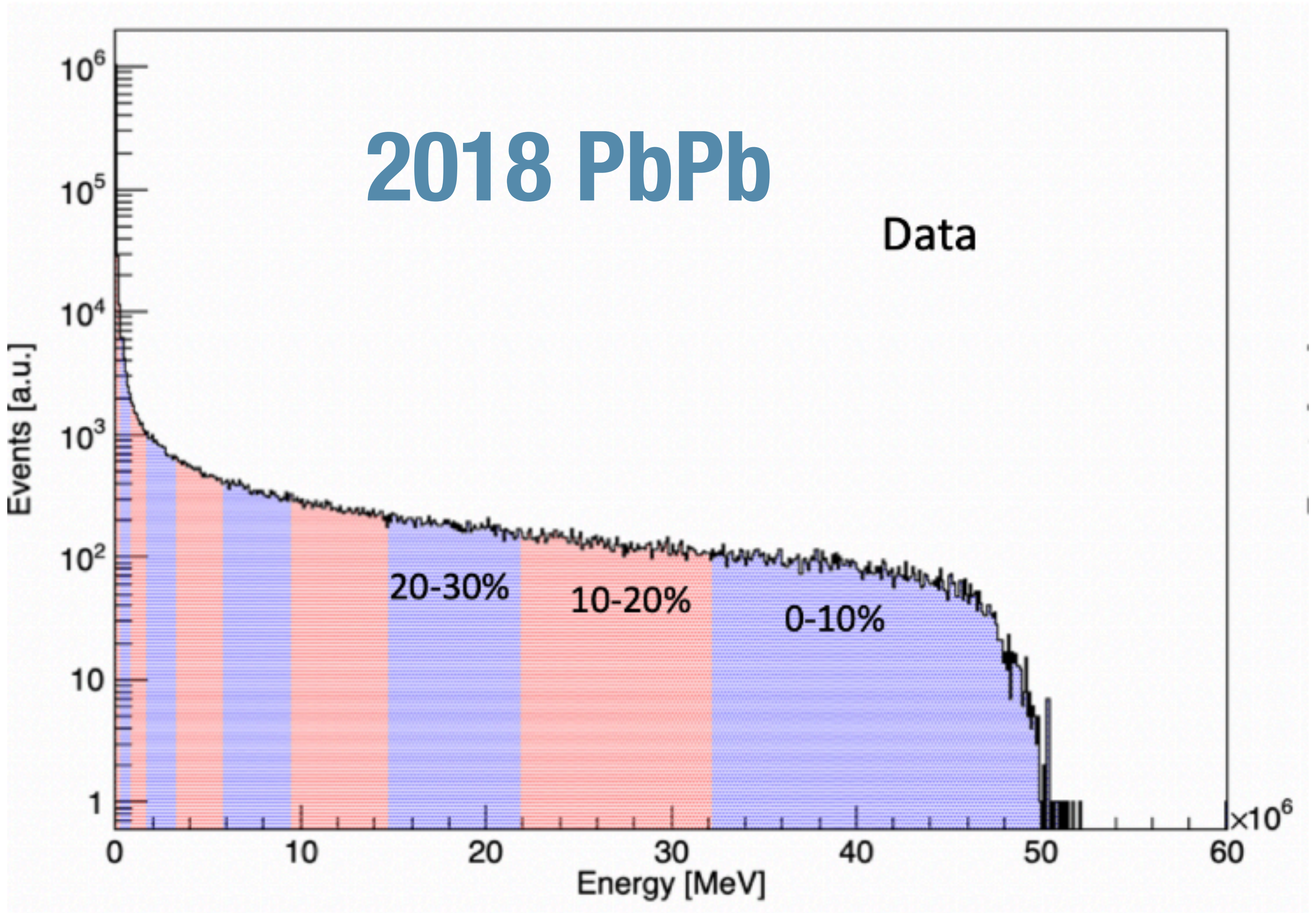
Equivalent number of charged particles



Source to sample …



Centrality class



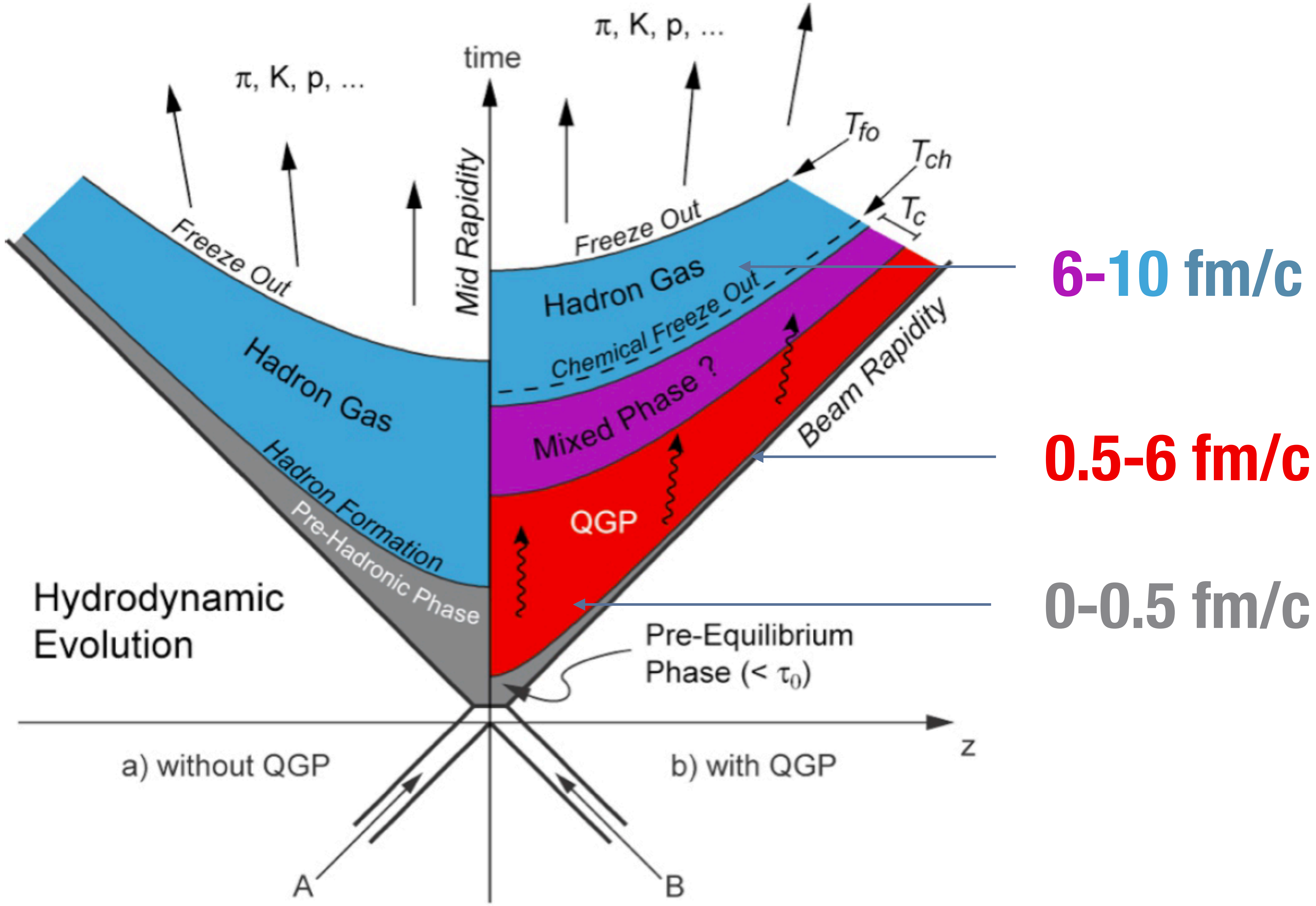
Use <E_{pp}> and fit eCal distribution…

Small detour: centrality

$E_{tot}^{cal} \otimes$ Glauber fit = centrality

Points to take home: Evolution of a nucleus-nucleus collisions

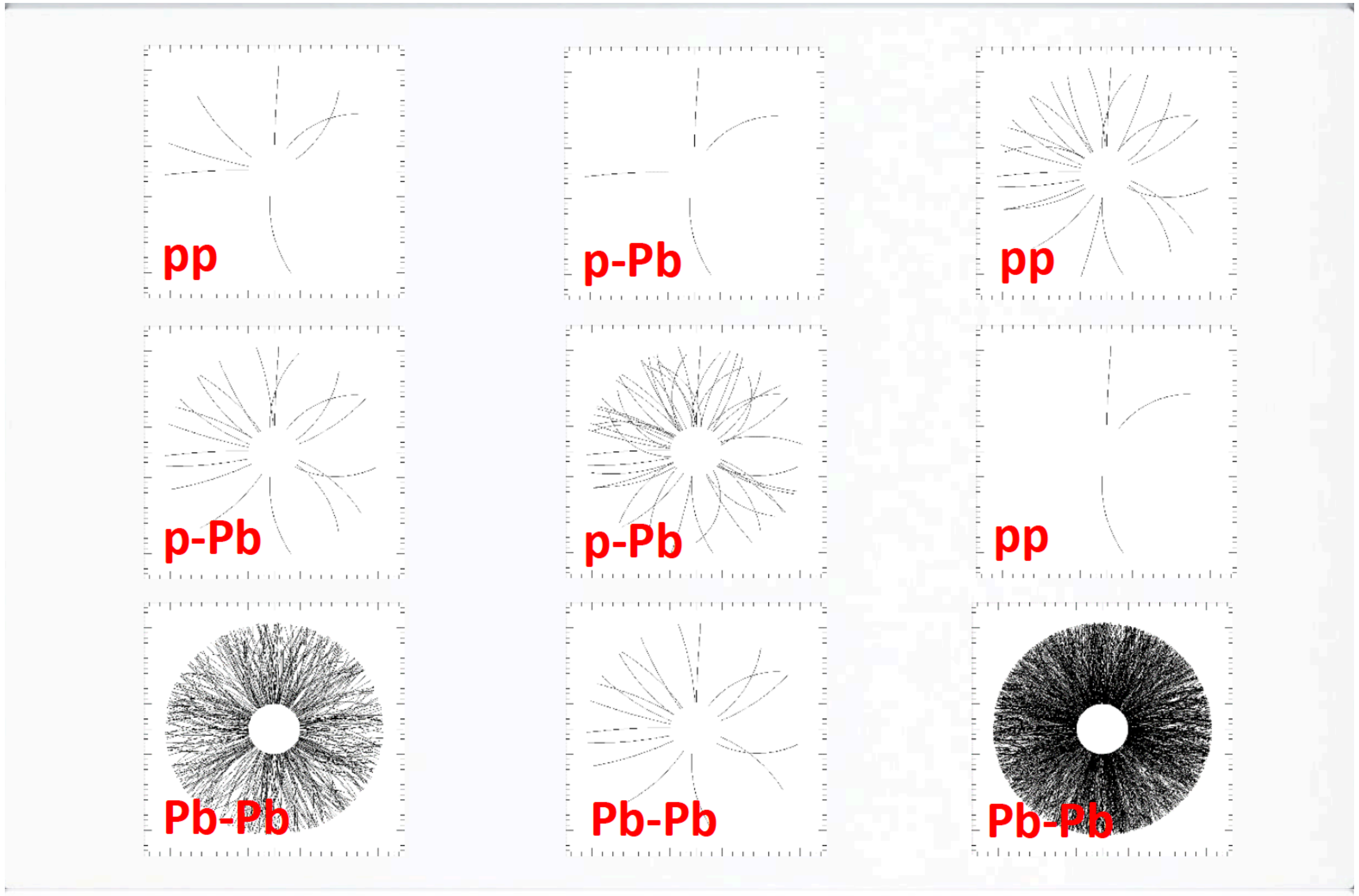
- Hydro : very nice approach to descibe the evolution of the bulk :
  - Predicts particle correlations and mass ordering of the v_2.
- From fitting the current data with hydro models from LHC@2.76TeV:
  - Initial energy density : 12–14 GeV/fm^3
  - Effective temperature of the early QGP ≈ 297 MeV
  - Chemical freeze-out : $T_{ch} \approx$ 156 MeV
  - Kinetic freeze-out : $T_{kin} \approx$ 96 MeV
  - Size of the QGP in 0-5% centrality ~5000 fm^3



OUTRO: HYDRO IN SMALL SYSTEMS ??

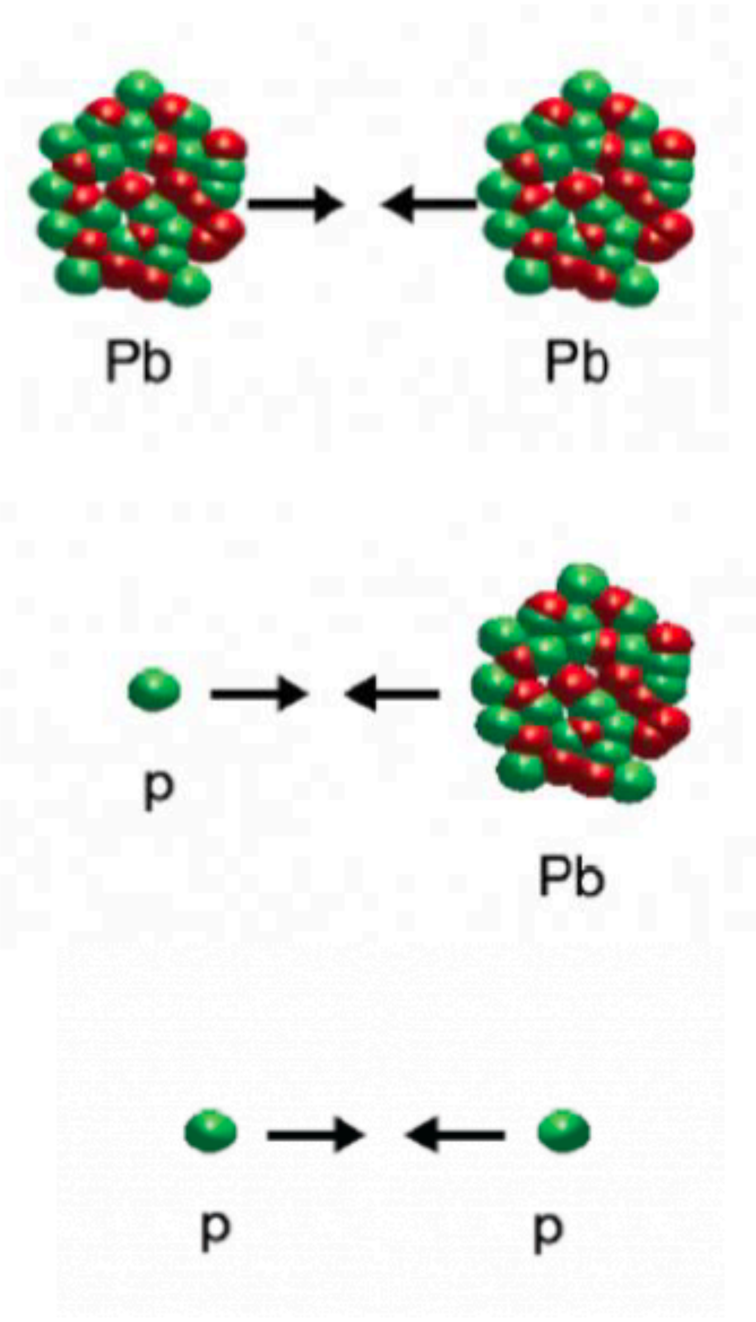
What are « small systems » ?

- Small refers to :
  - Size of colliding objects.
    - ee < pp < pA < AA
  - Size of created medium.
    - Ncoll, Npart
    - Multiplicity



What do we search for in small system ?

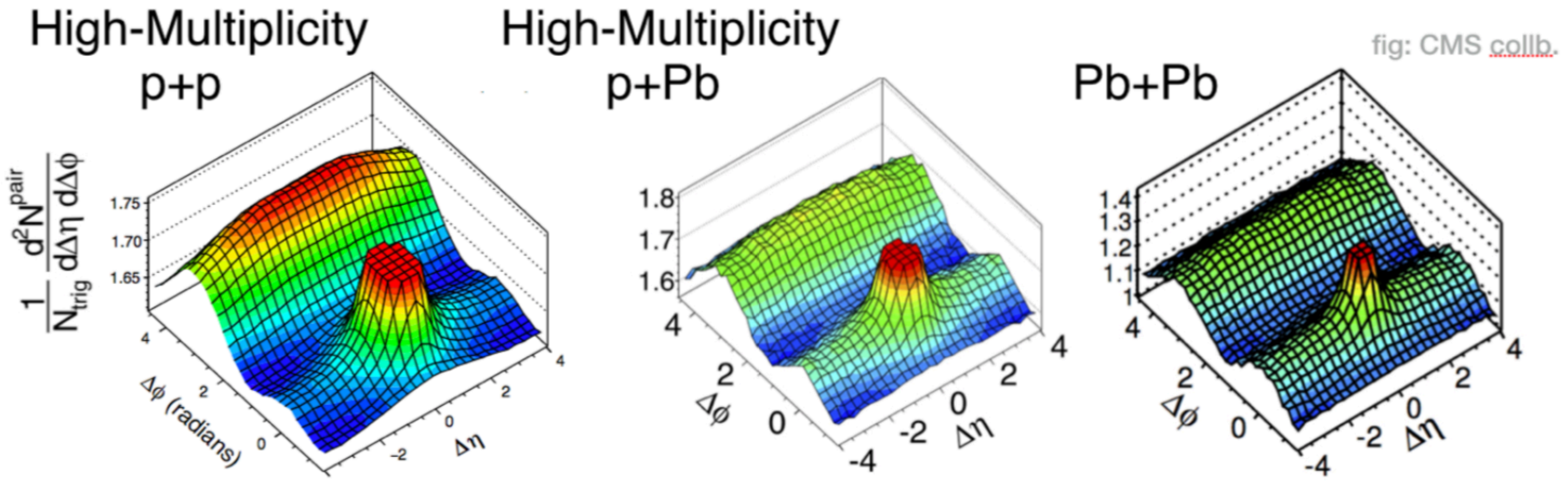
- Small systems are traditionally considered « control systems » for HIC.



QGP

Cold nuclear matter effect

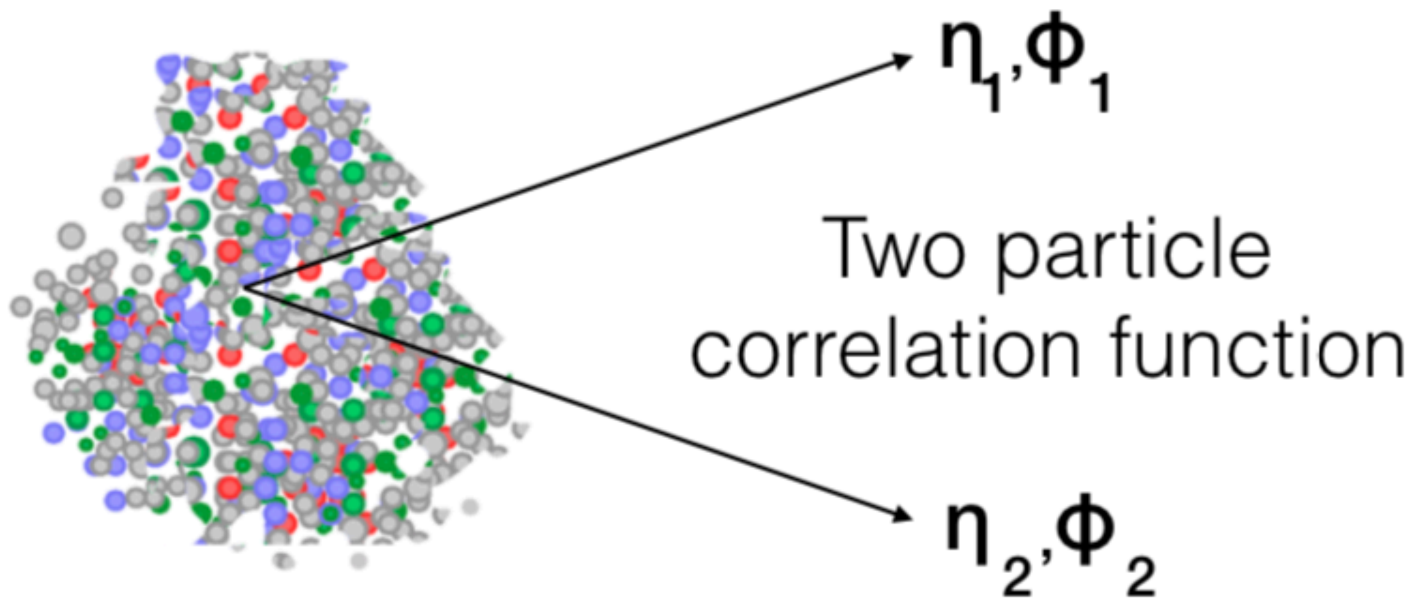
Baseline

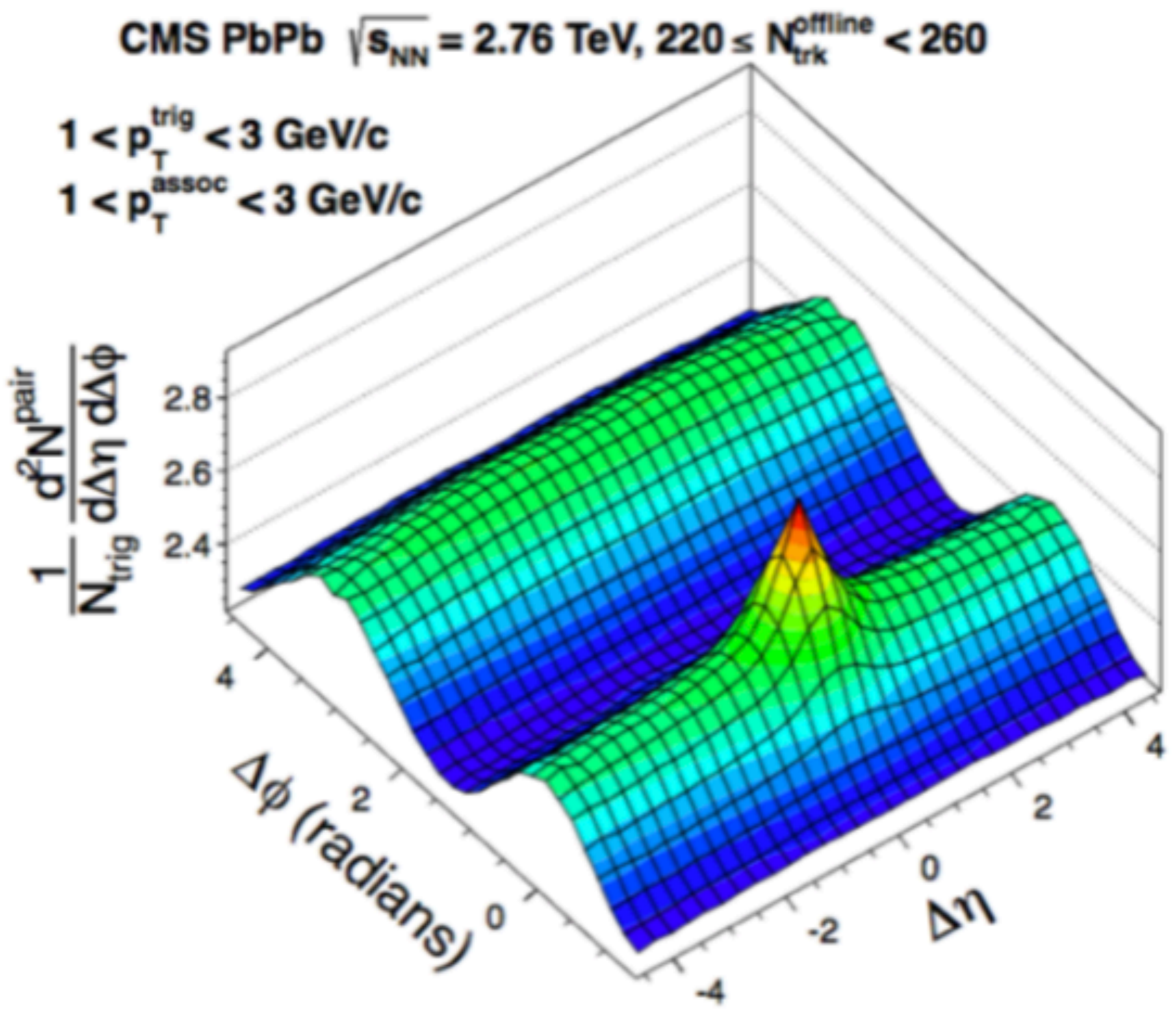


QGP in small system ?

We need to change our perspectives and look closely at small systems

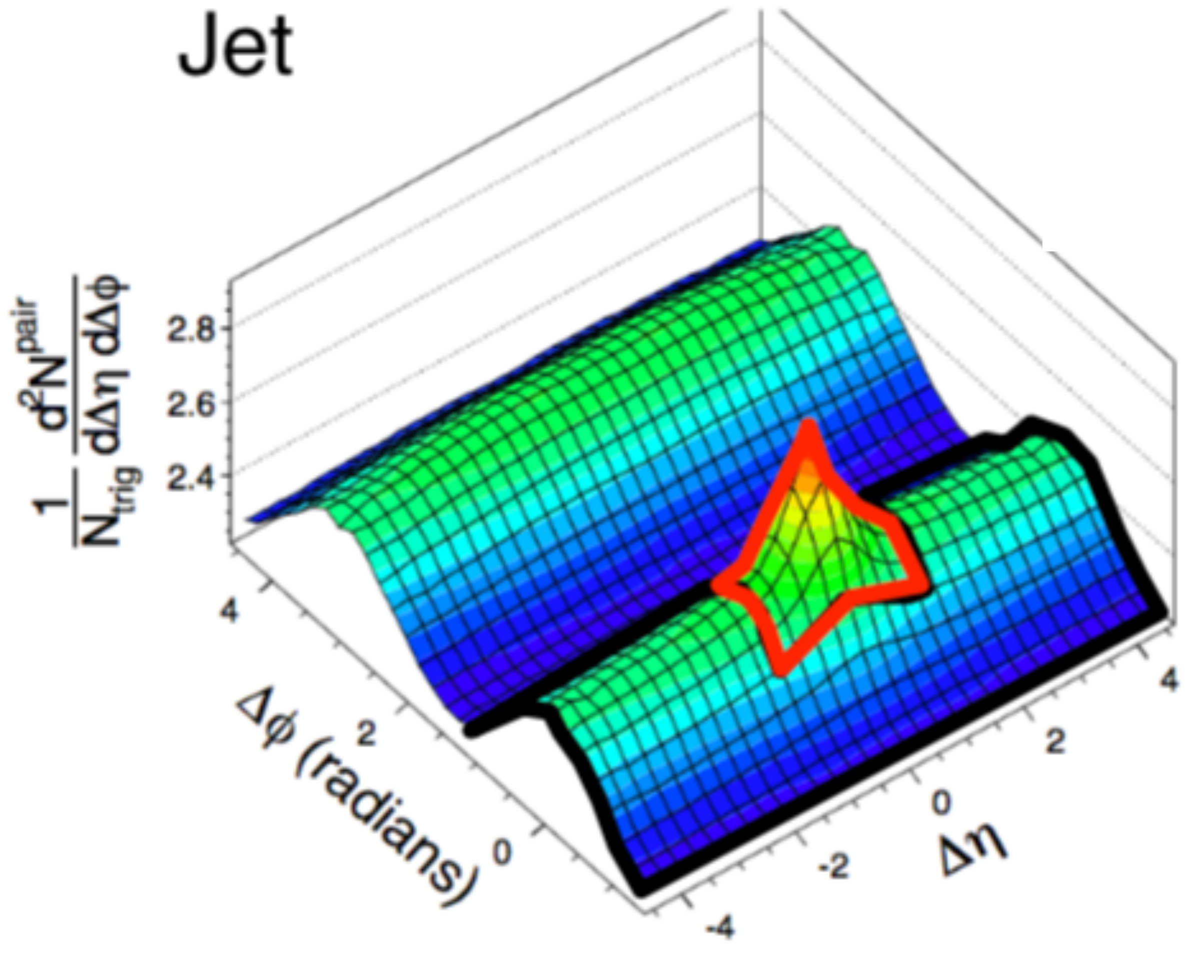
Angular correlation : two-particles correlations

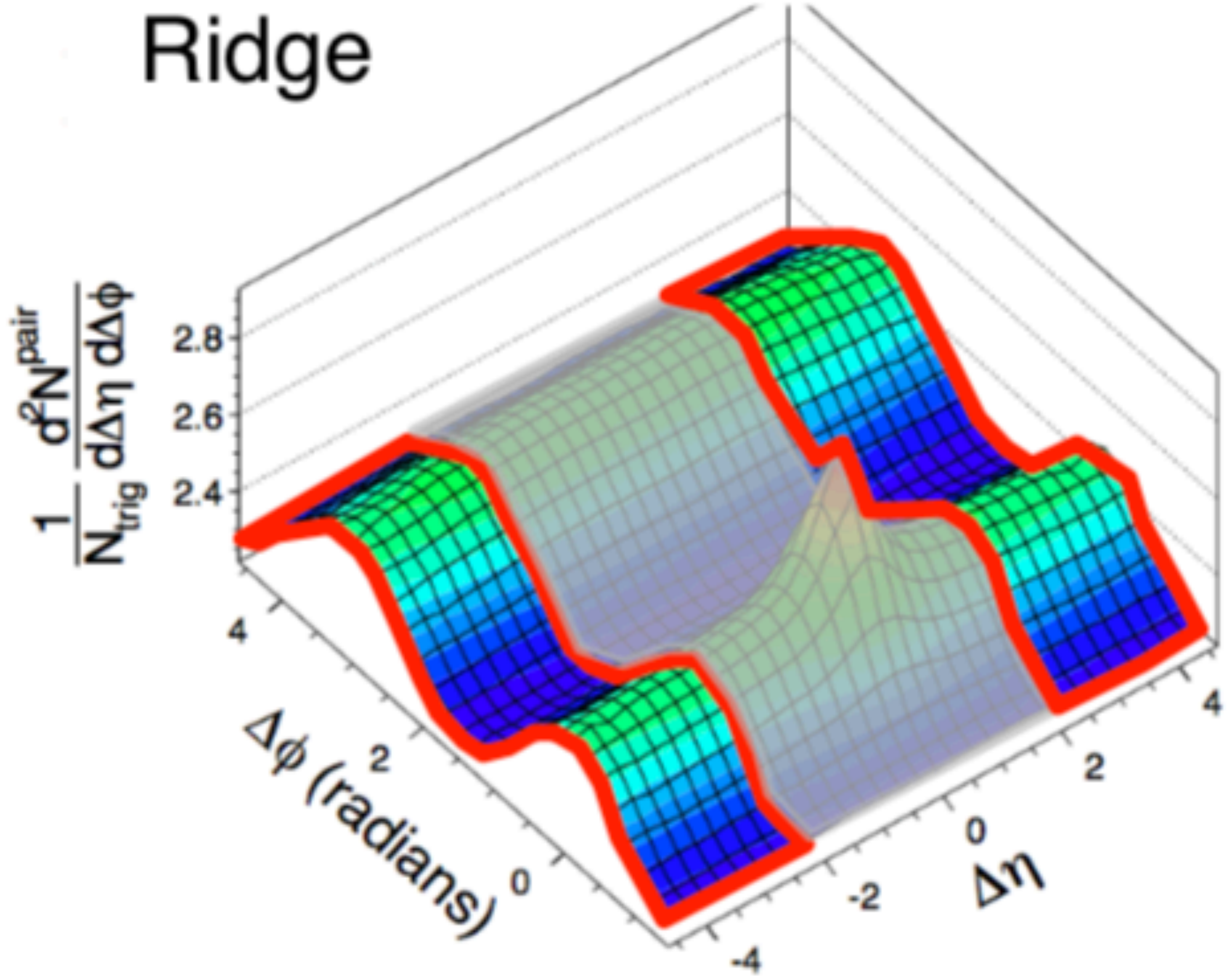




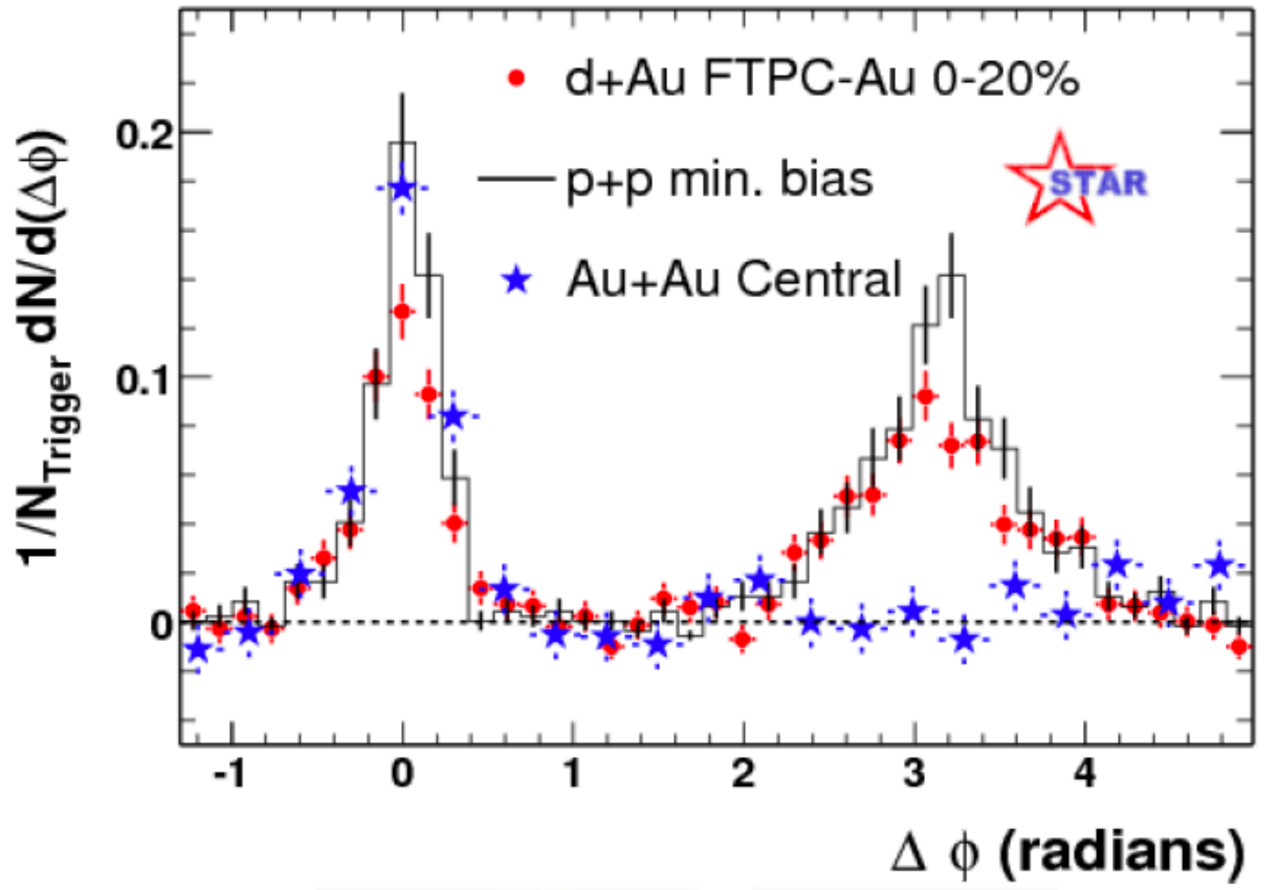
- What are those structures on the correlation matrice ?

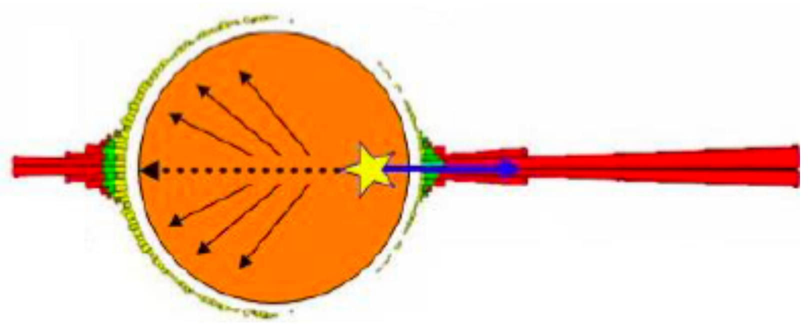
Angular correlation : two-particles correlations



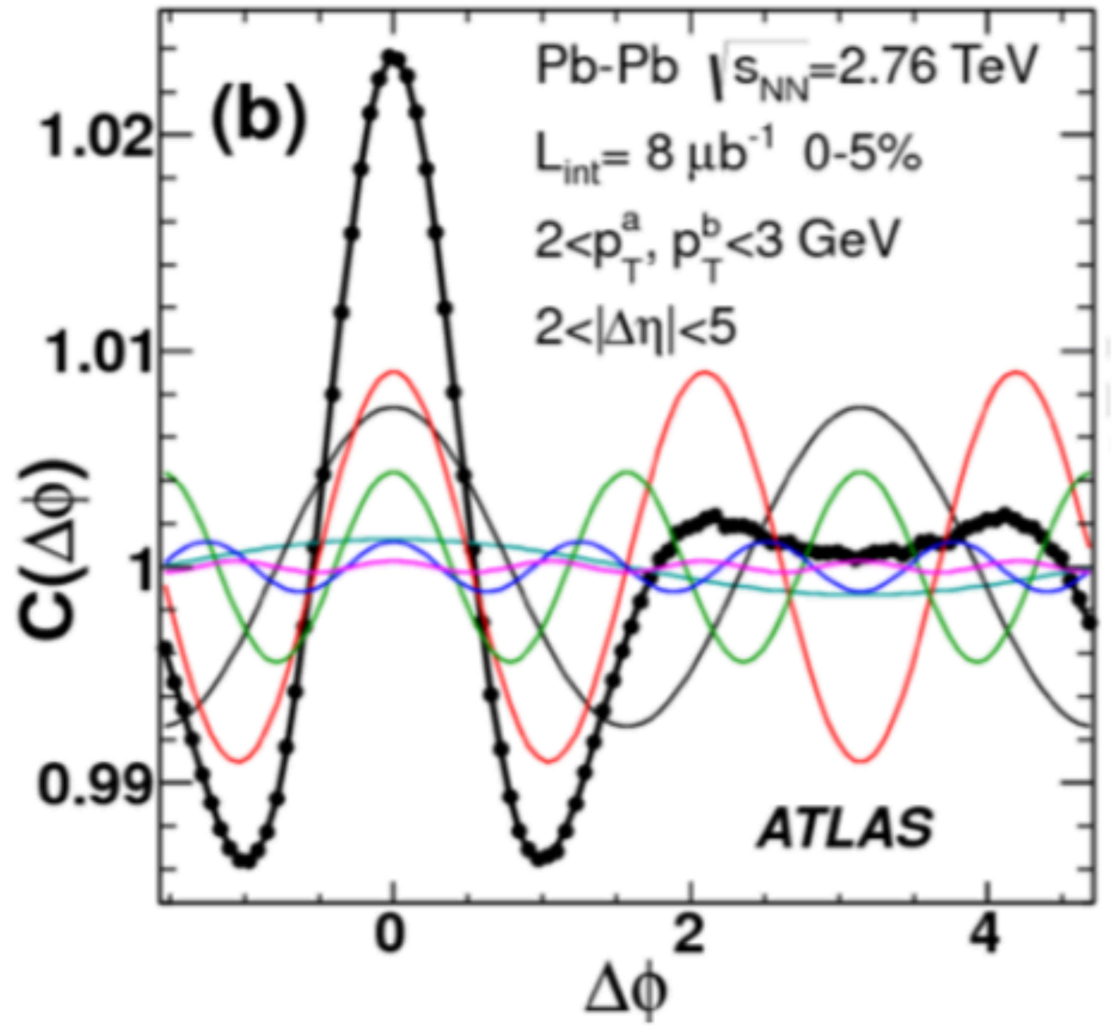


Jet Quenching



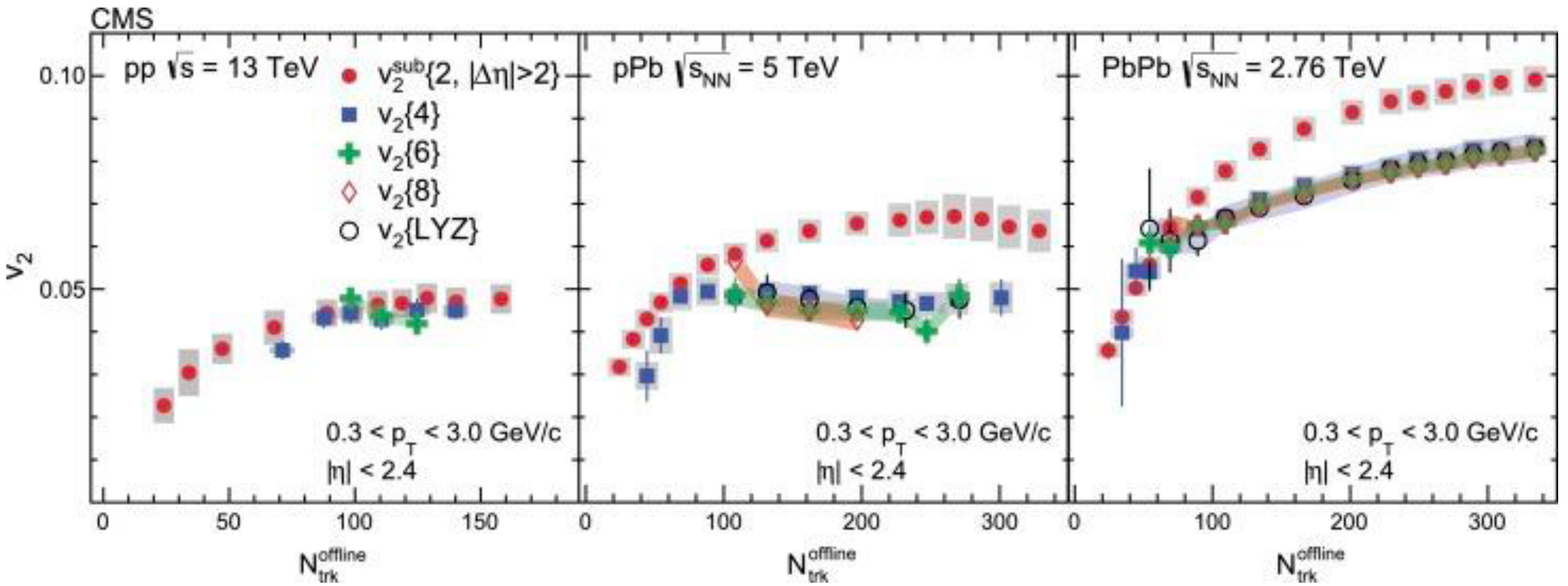


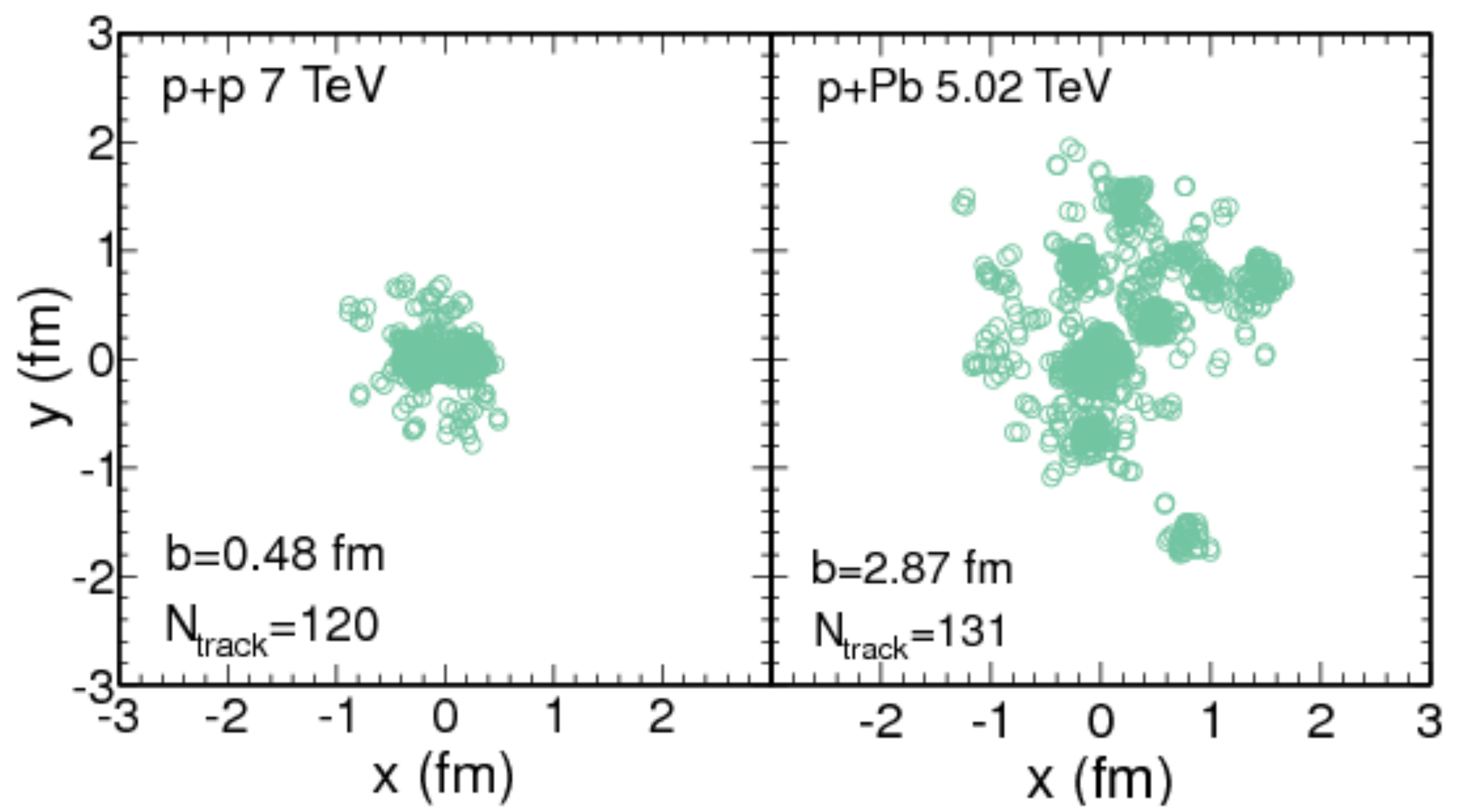
Anisotropic flow



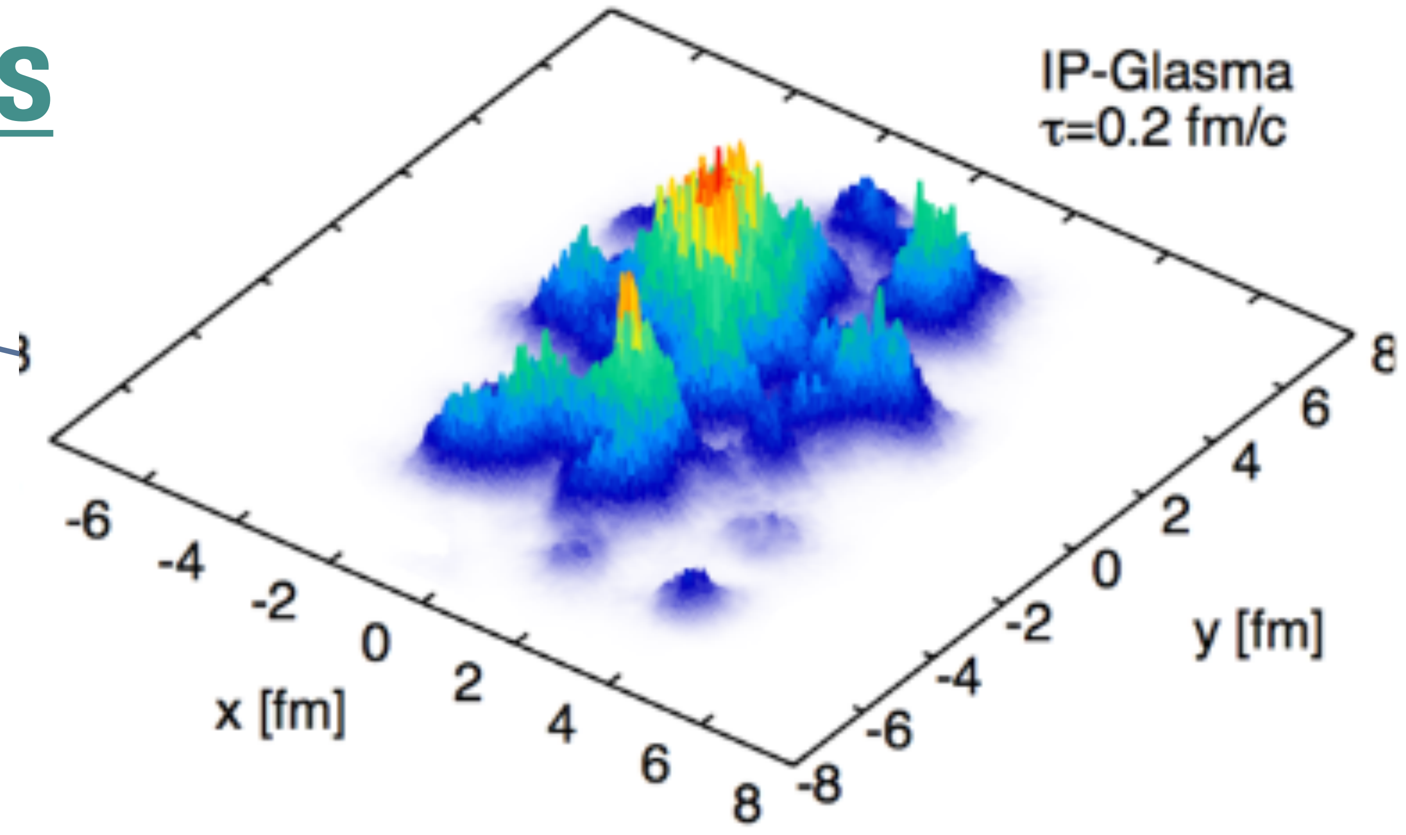
Elliptic flow in small systems

- $v_2 > 0$ for all systems !
- Is it really hydro ?
  - **If hydro → flow**
  - **If flow ↛ hydro**
- **Flow = correlation!**





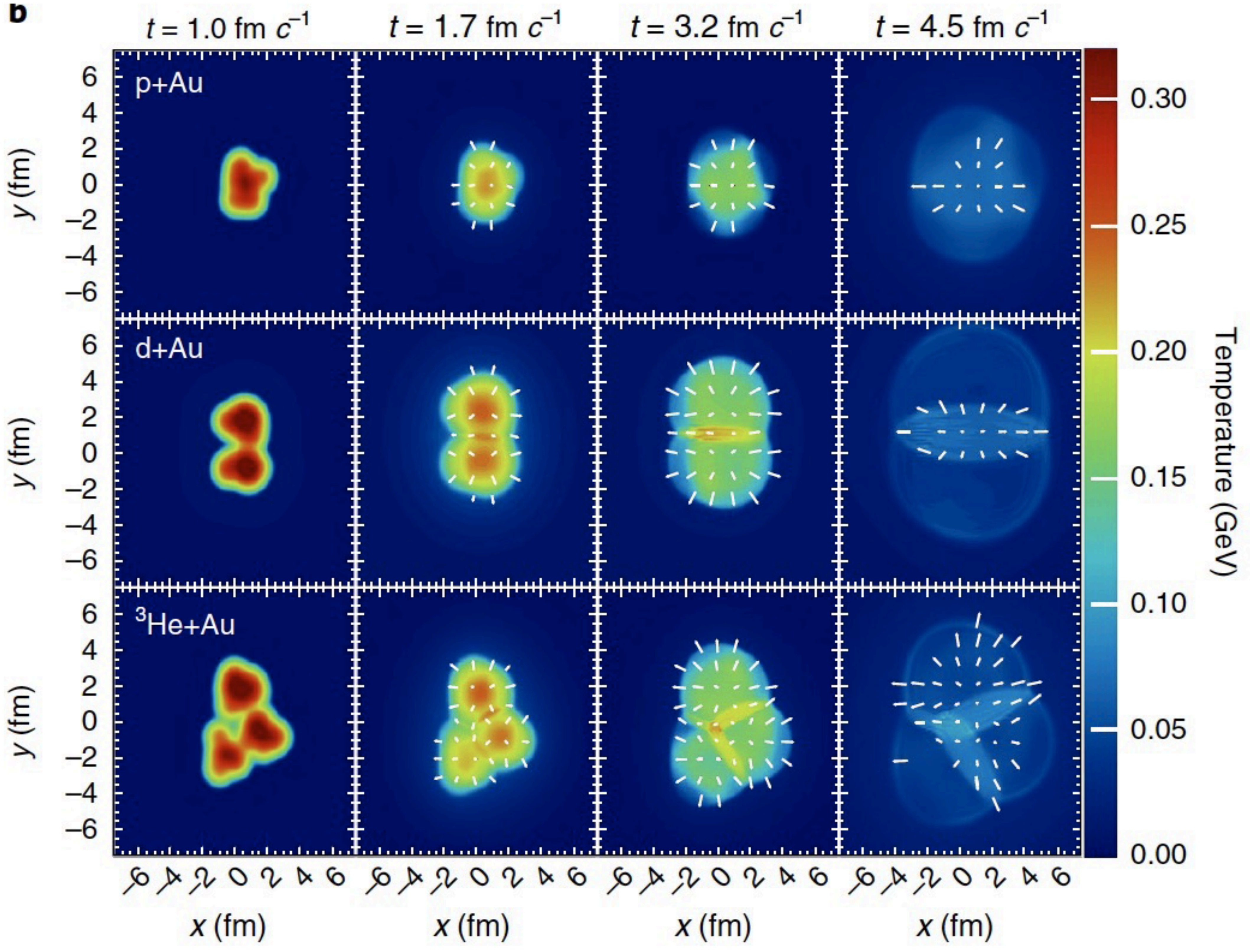
Initial density distributions



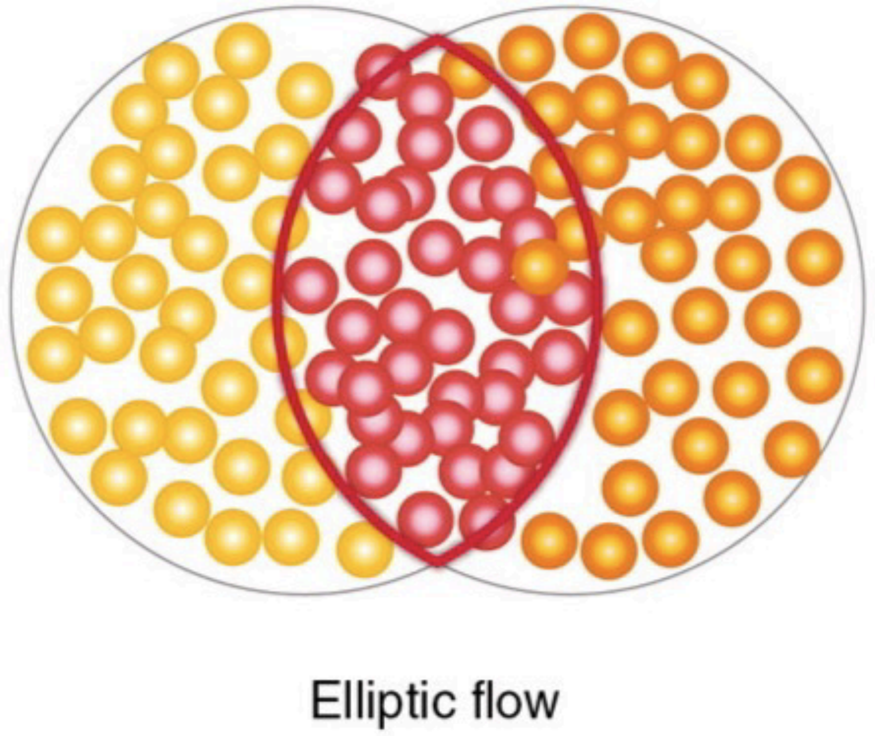
Angular flow: latest result from PHENIX

PHENIX, Nature Physics 15 214–220 (2019)

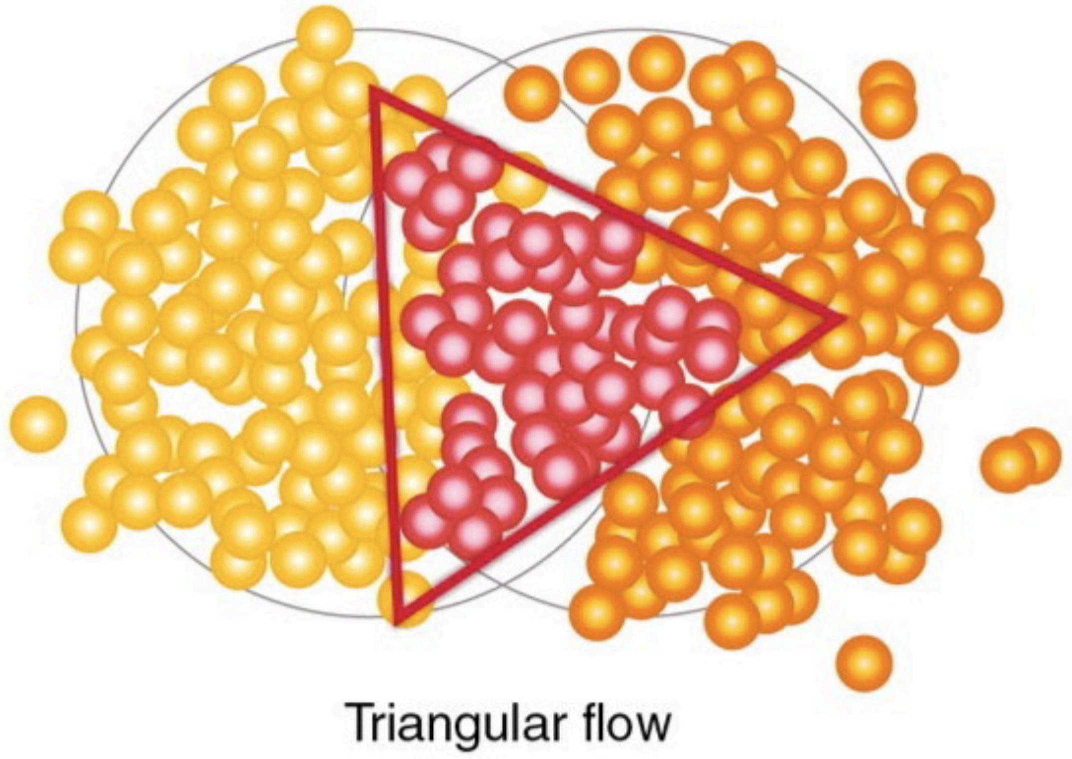
Creation of quark–gluon plasma droplets with three distinct geometries



Hydro simulation



d+A collisions have intrinsic ellipticity: enhanced $v2$

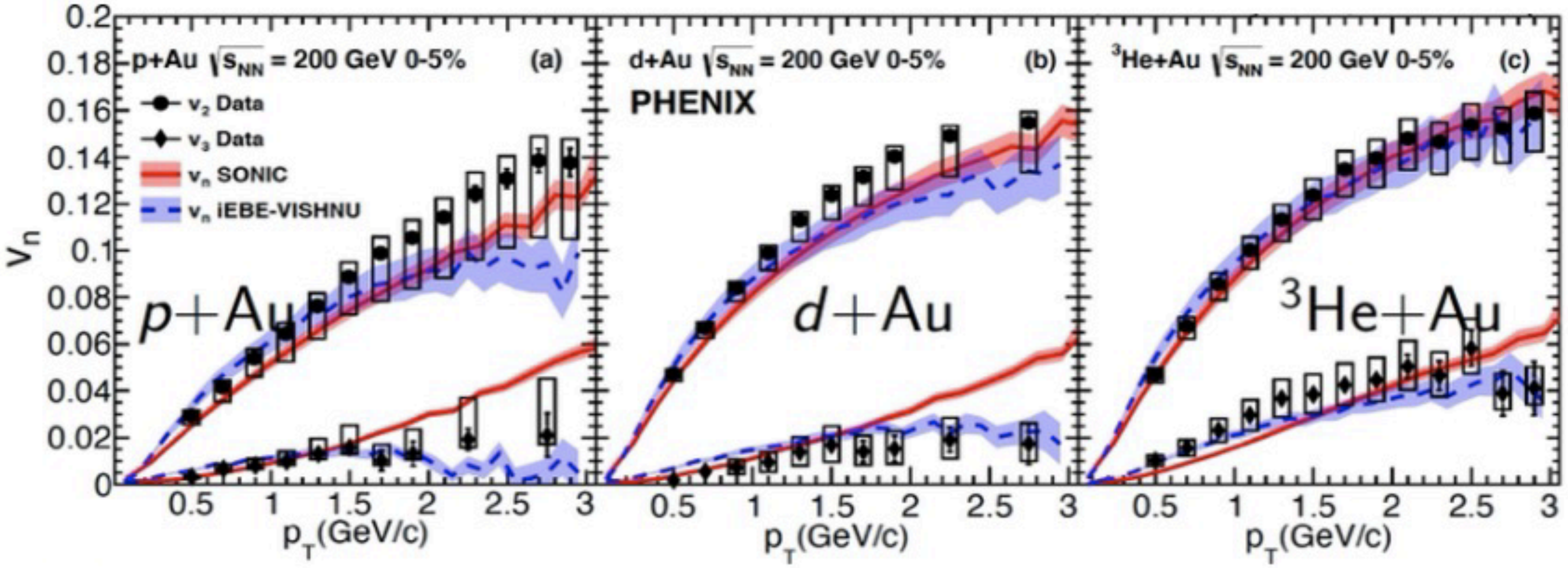


^{3}He+A collisions have intrinsic triangularity: enhanced $v3$

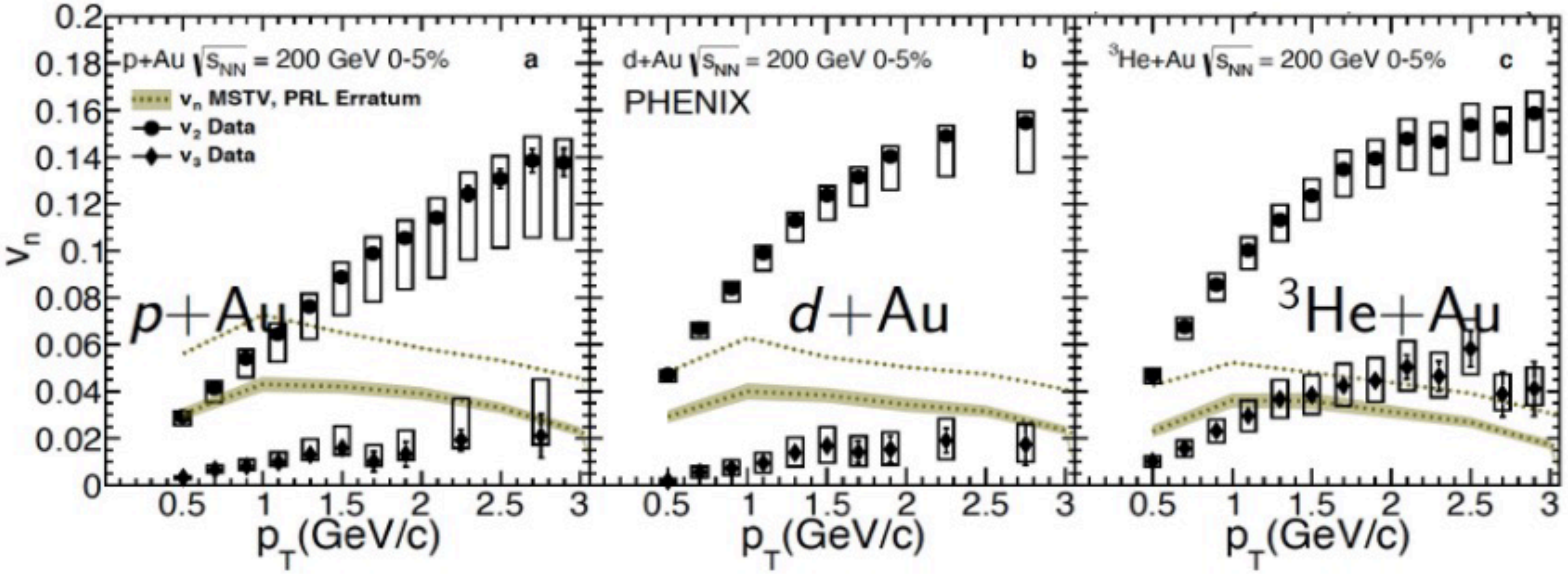
$$v_2^{\mathrm{p+Au}} < v_2^{\mathrm{d+Au}} \approx v_2^{^3\mathrm{He+Au}}$$

$$v_3^{\mathrm{p+Au}} \approx v_3^{\mathrm{d+Au}} < v_3^{^3\mathrm{He+Au}}$$

The results ....



SONIC and iEBE-VISHNU: hydrodynamics predictions



MSTV: initial state calculation, does not match data

Small system flow depends on intial geometry, just like large systems. Points to similar origin.