Heavy-ion physics primer

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Disclaimer

Heavy ion physics is a large and very diverse universe

➡ From measurements of τ lepton anomalous magnetic dipole moment to the measurement of binding energies of hypernuclei, passing through the characterisation of the densest matter humankind can create

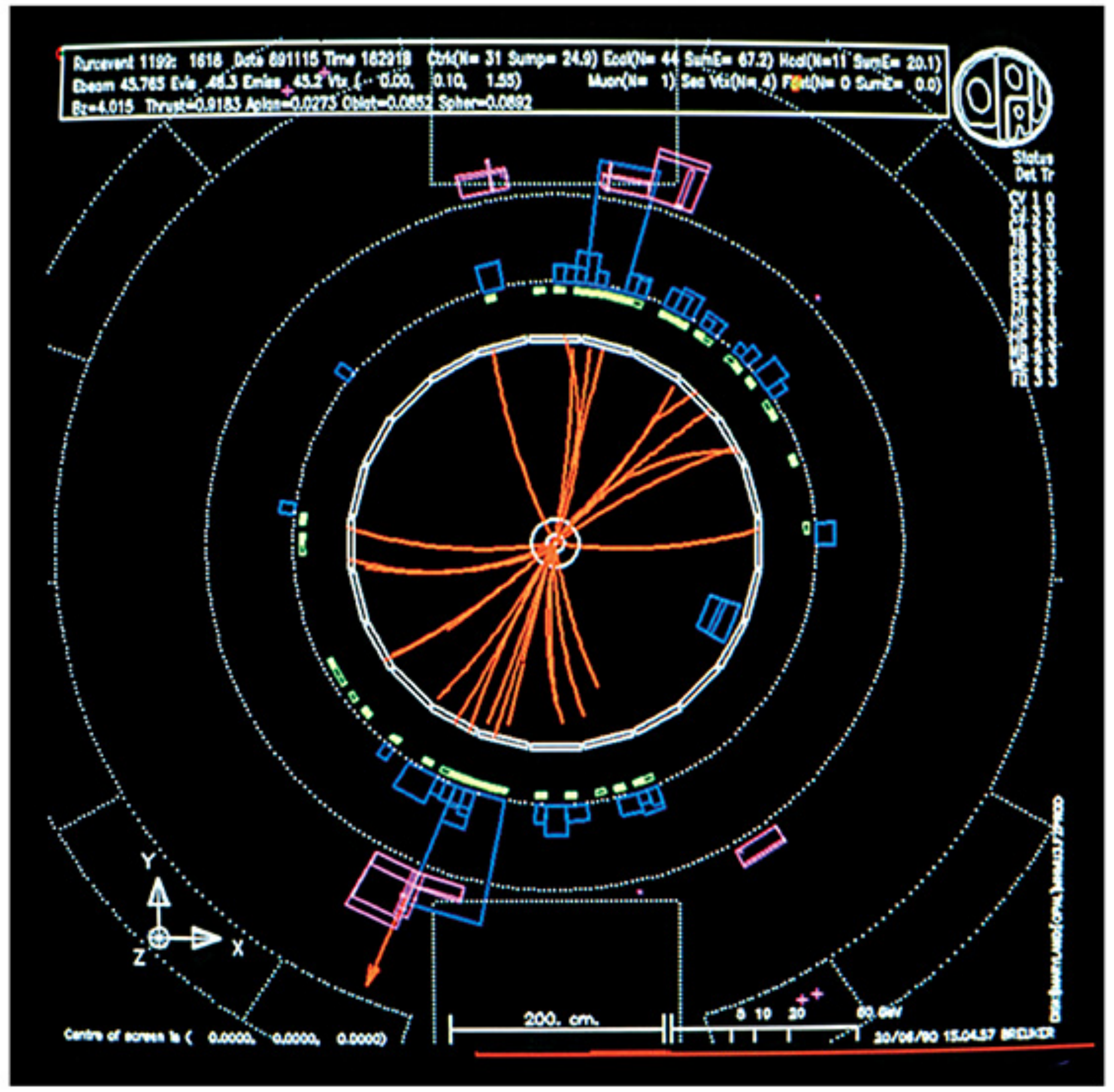
In 1.5h I will try to give you a taste of it

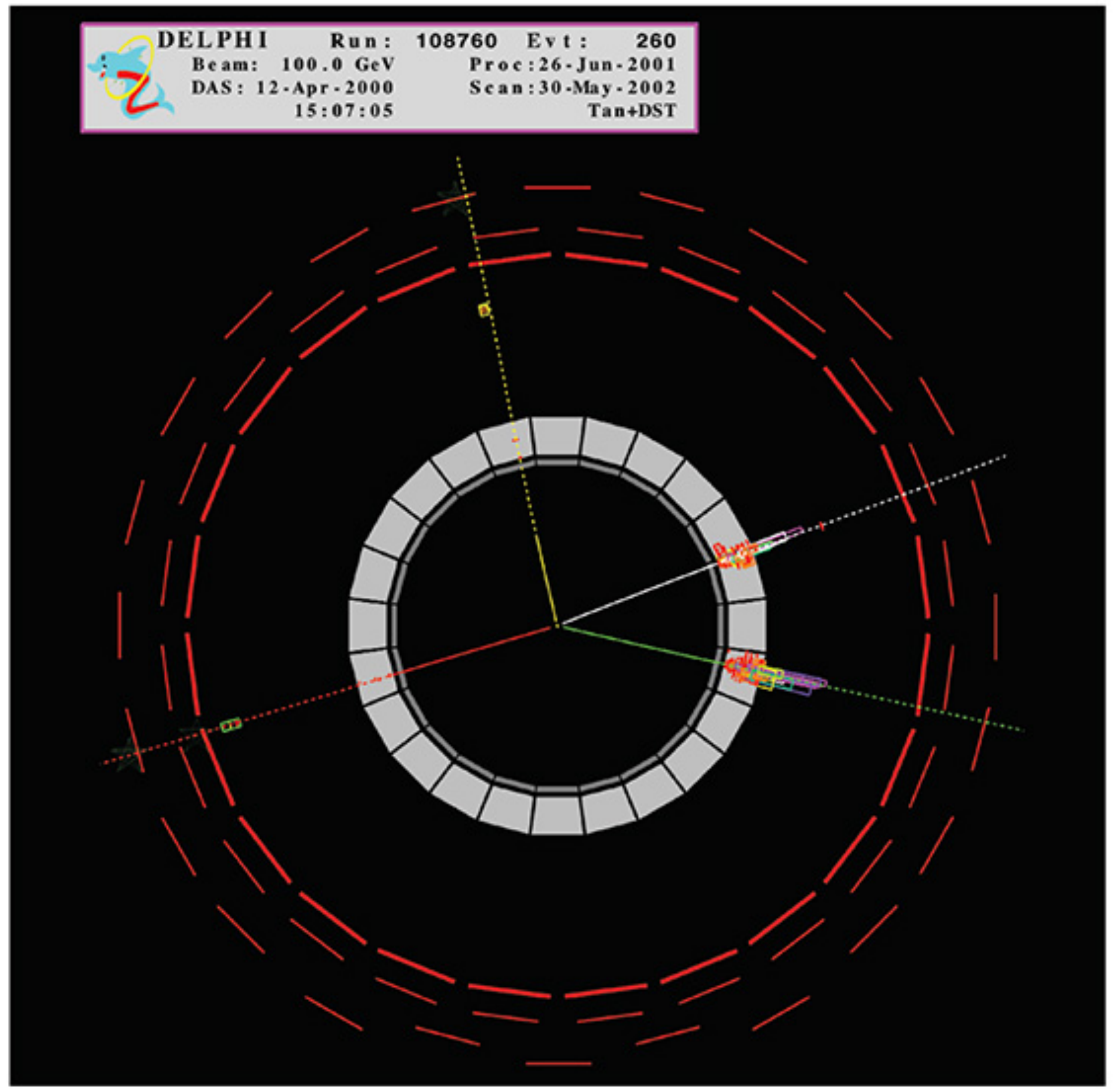
- Focusing mostly on the basic concepts of heavy-ion and mainly measurements at the LHC
- … but of course much more is out there! Feel free to ask me during the lecture, during the break or send an email (mpuccio@cern.ch)

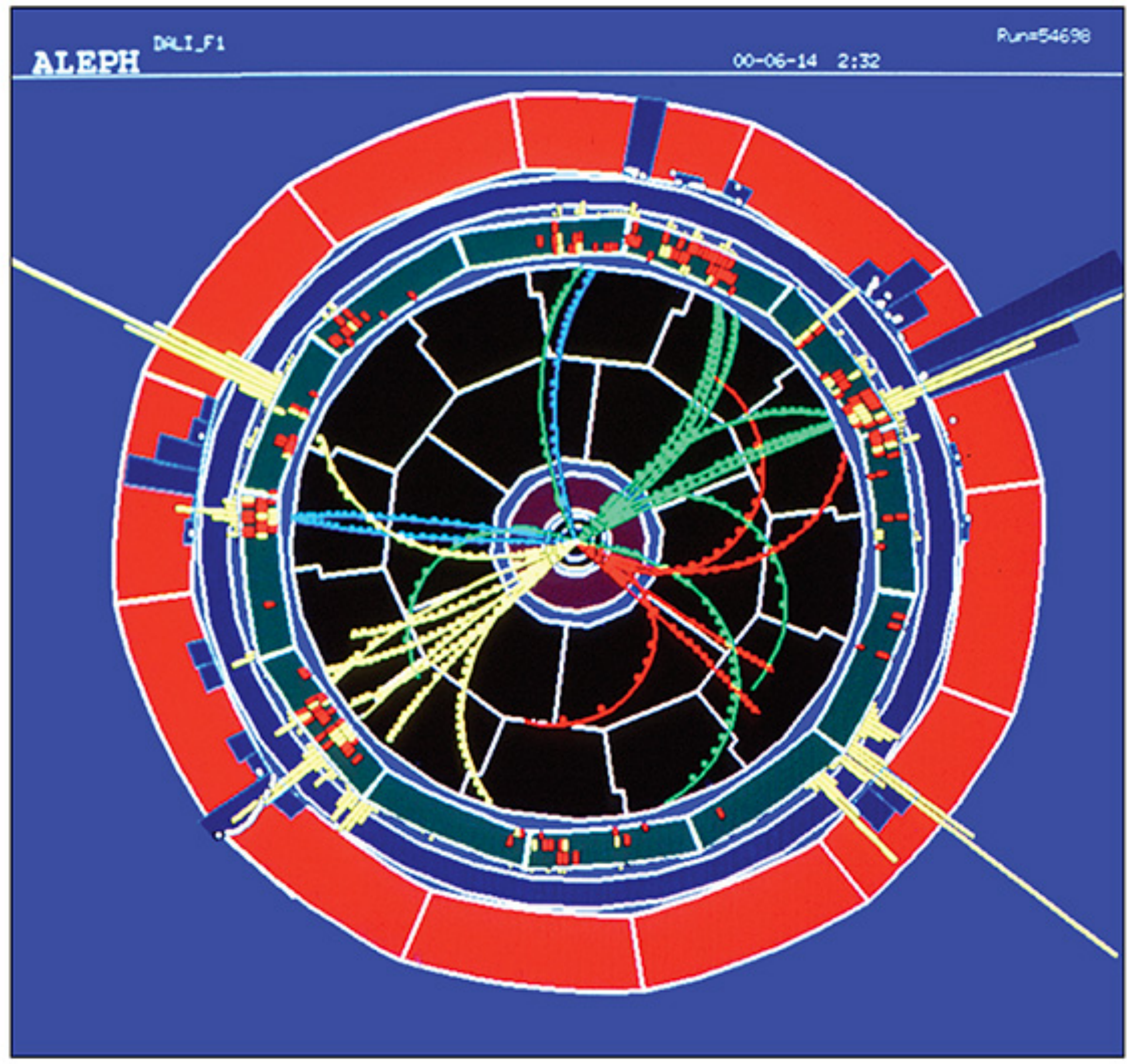
The content of this lecture is partially derived from lectures given by some of my mentors and teachers, to whom I am grateful:

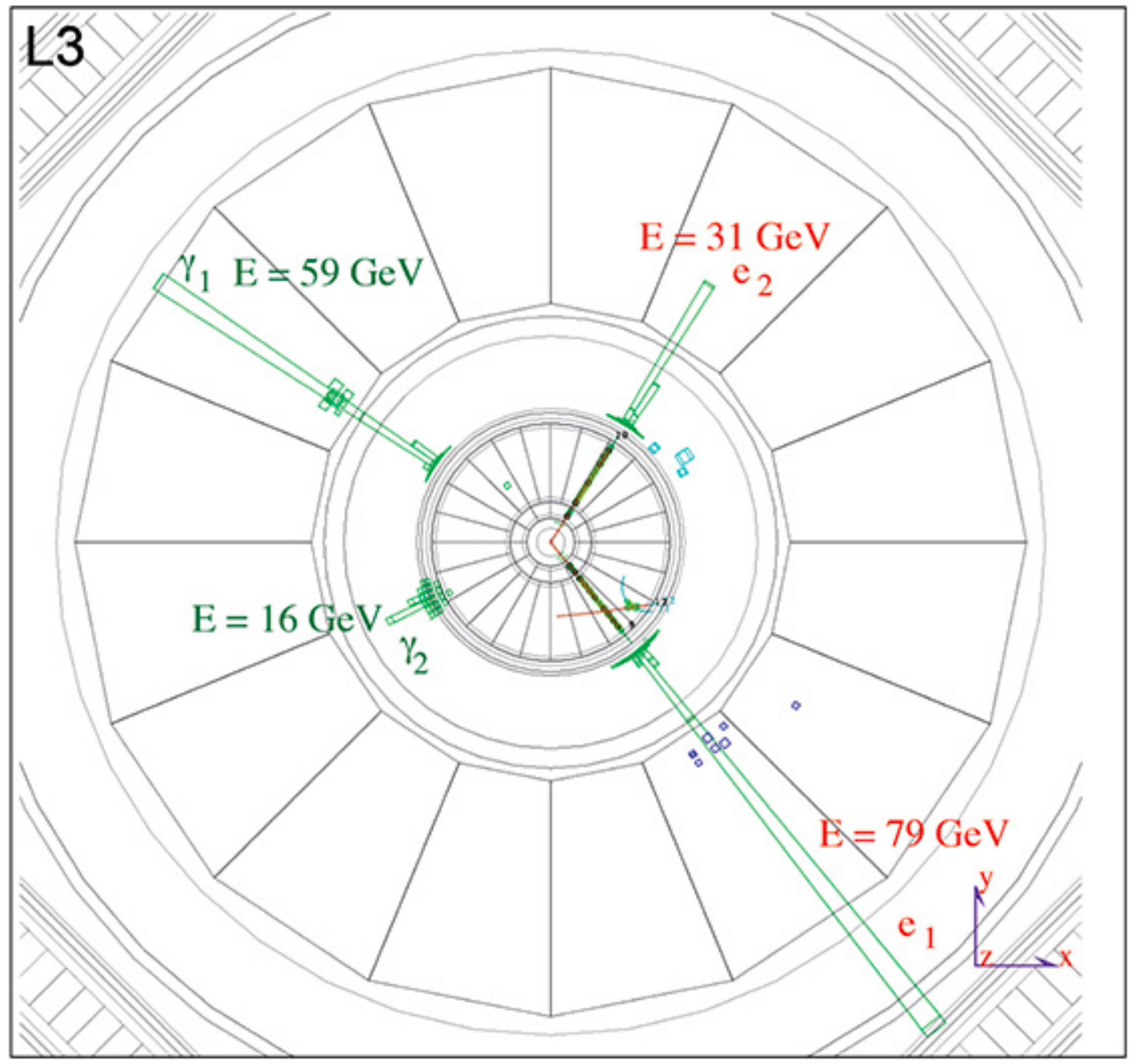
- Alexander Kalweit, Johanna Stachel, Francesco Prino, Enrico Scomparin

Particle collisions: e^+e^-



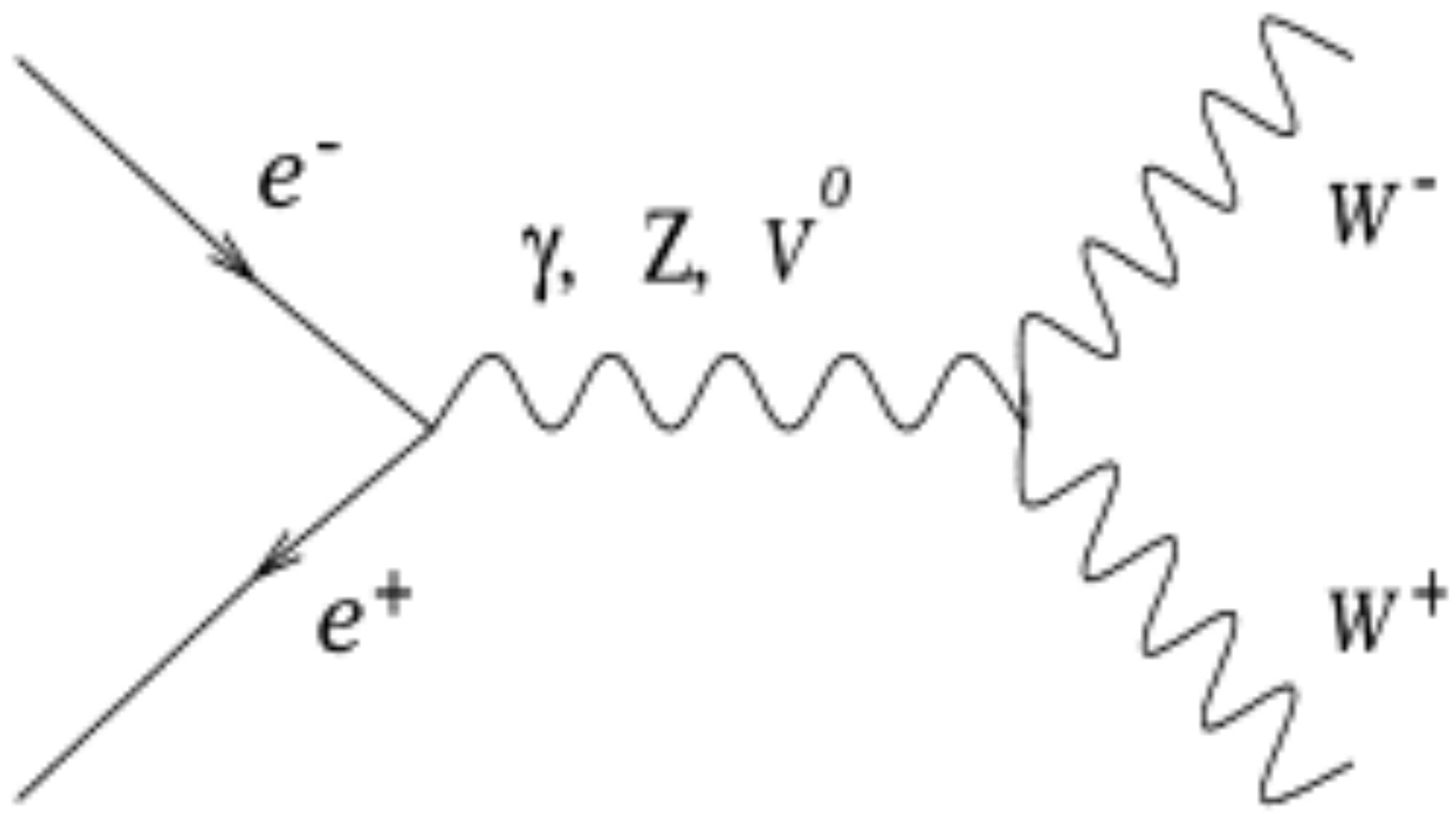




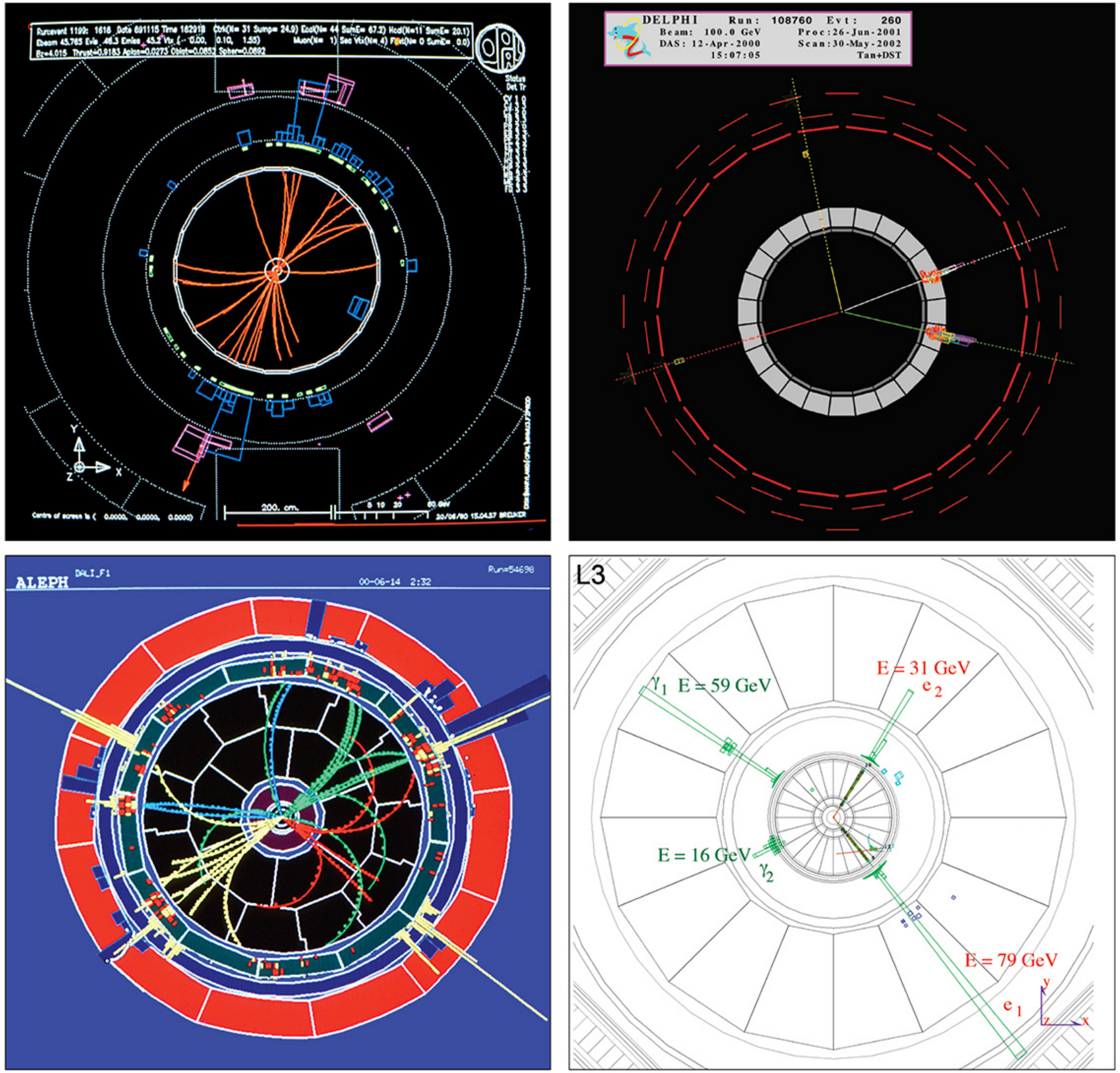


Particle collisions: e+e-

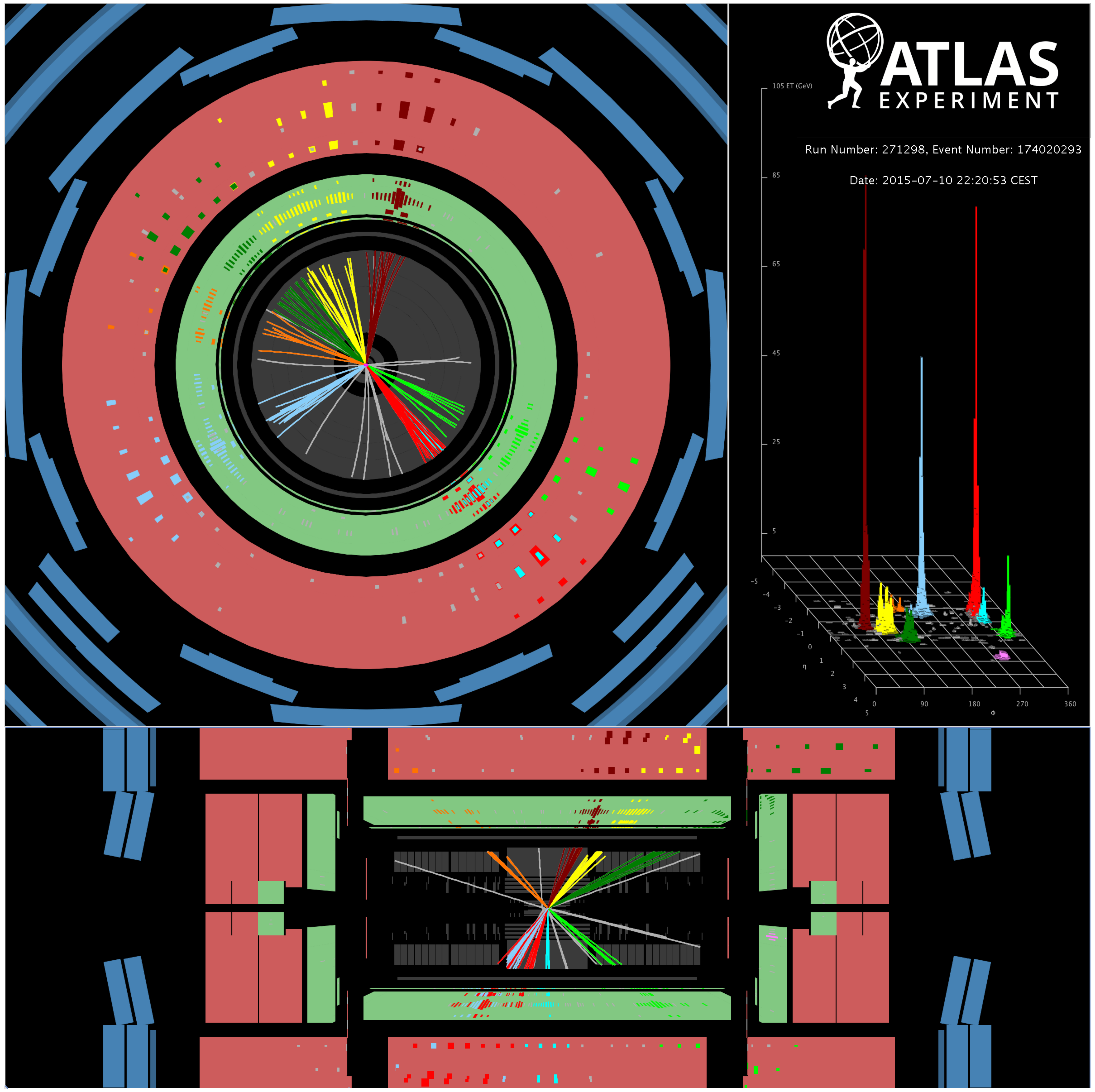
Elementary collisions:



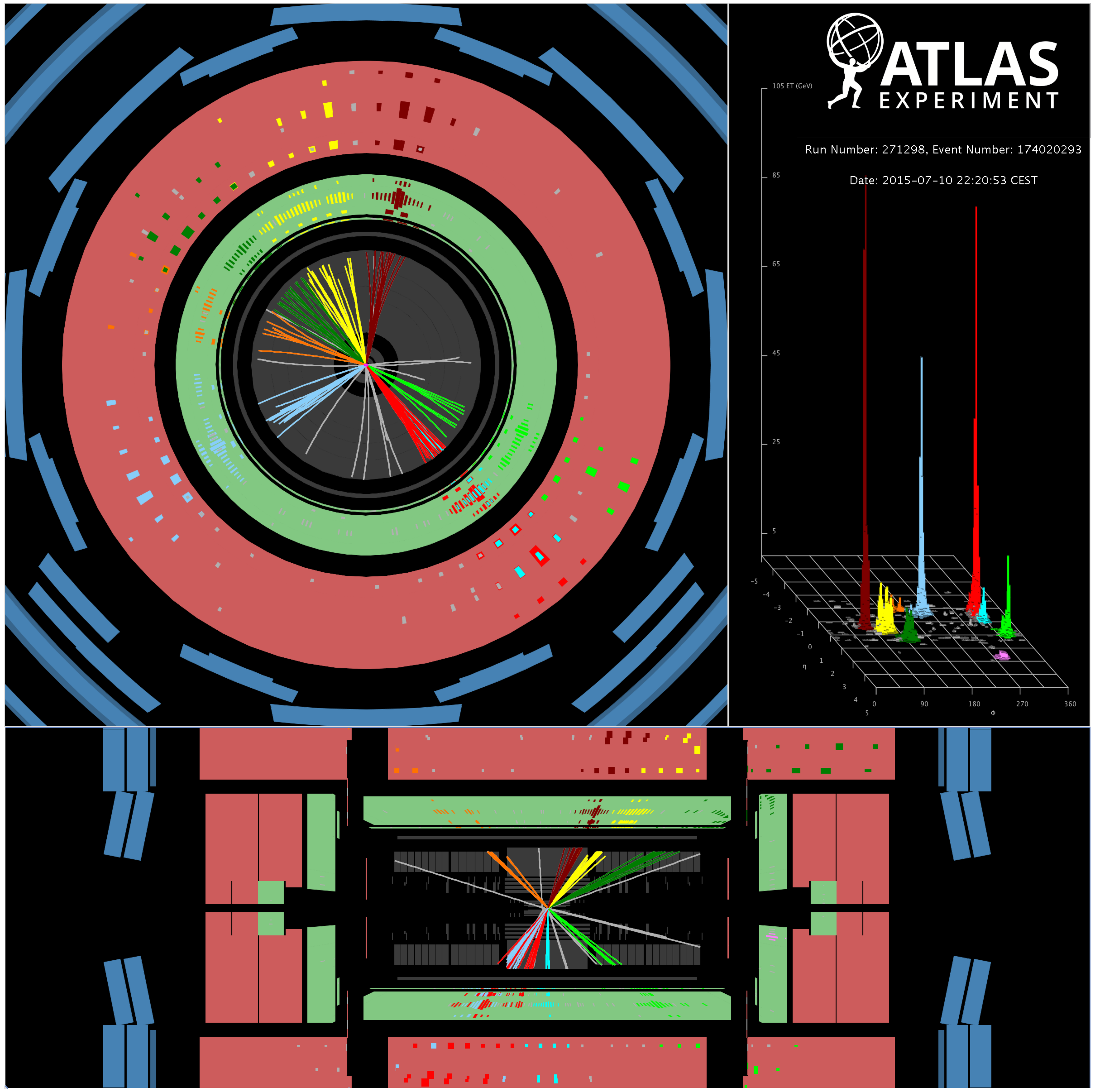
- Simplest theoretical modelling
- Small experimental backgrounds
- Energy reach of collider limited by synchrotron $\propto (p/m)^4$



Particle collisions: pp

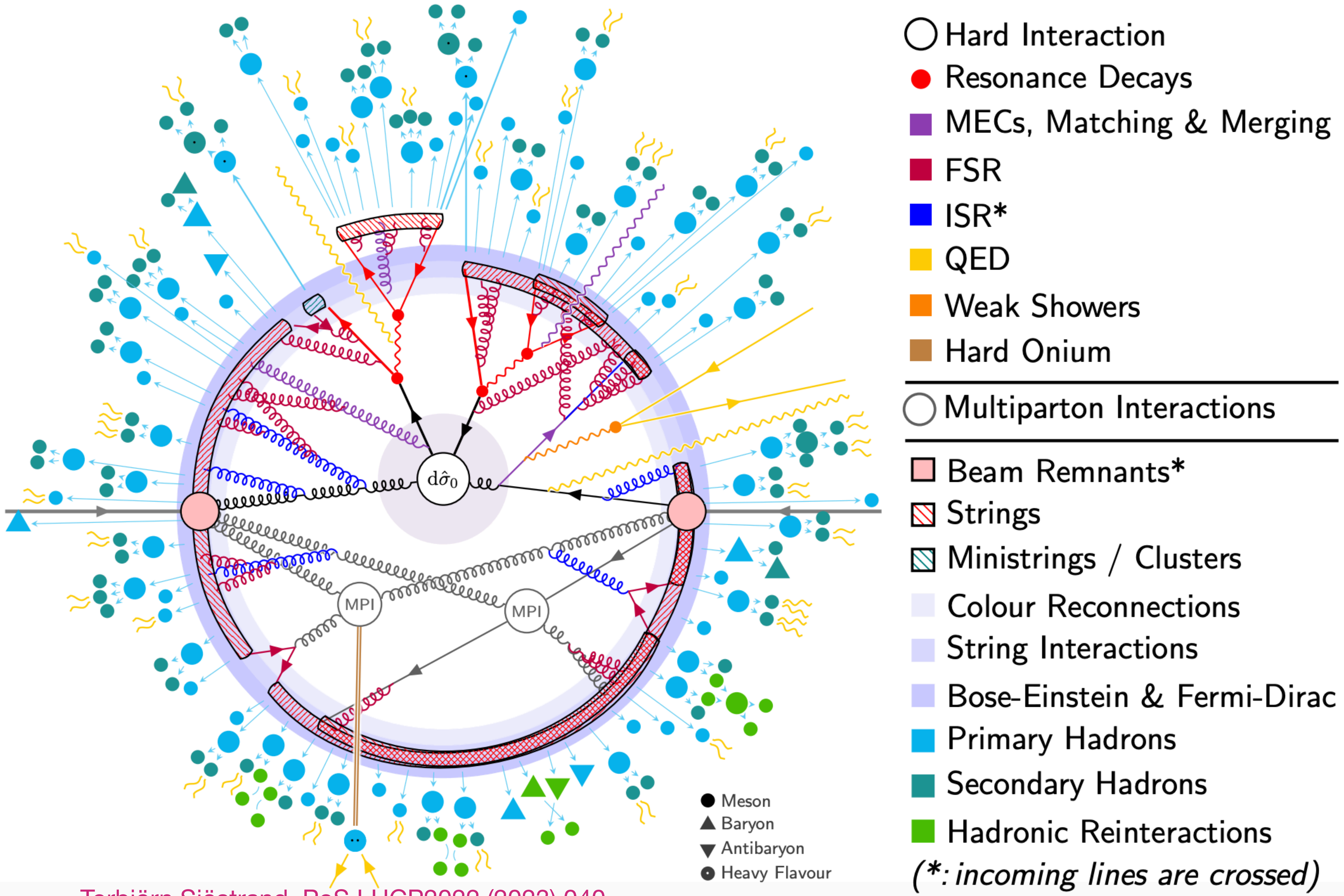


Particle collisions: pp



Overlap of many elementary collisions

- Hard and soft scatterings among partons
- Huge QCD background
- Complex MC modelling of what's happening

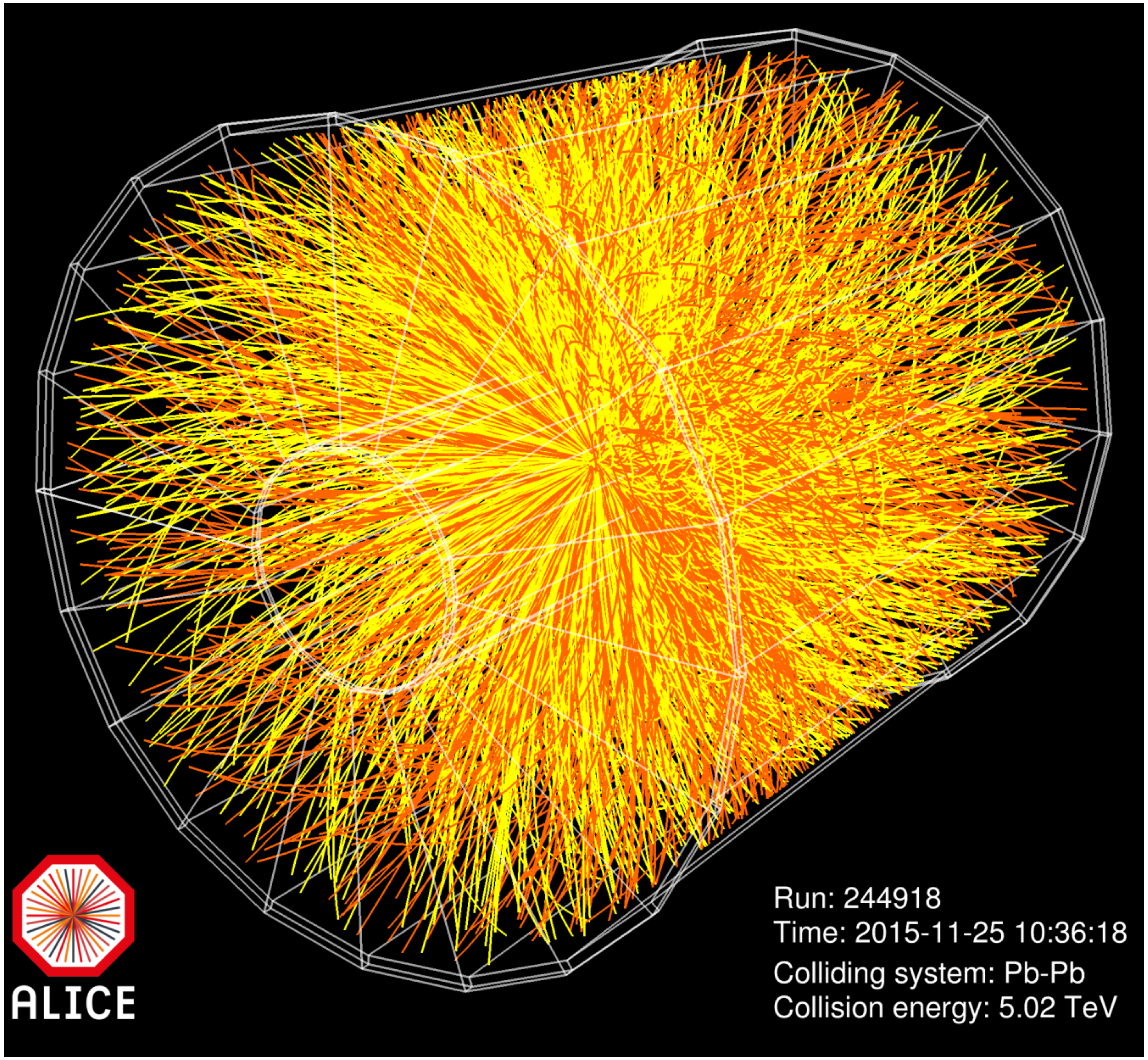


Torbjörn Sjöstrand, PoS LHCP2022 (2023) 040

Particle collisions: heavy-ion

Overlap of many nucleon-nucleon collisions

- That are overlap of many partonic collisions
- Different possible collisions:
  - “Head-on” interactions of the nuclei with up to thousands particles being produced
  - “Grazing collisions” where ɣ ɣ and ɣPb interactions can be investigated



Particle collisions: heavy-ion

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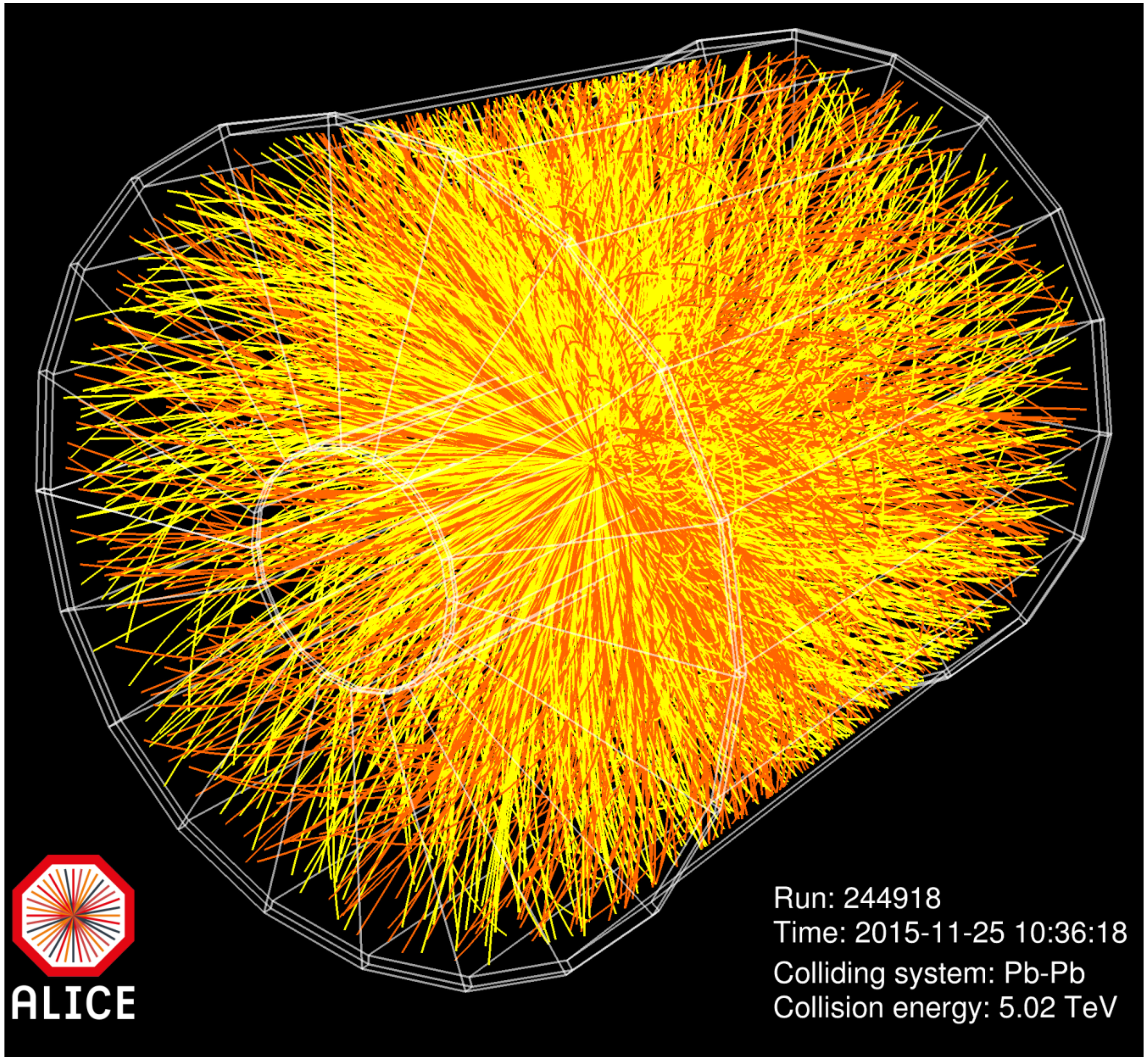
Why do we investigate this complex environment?

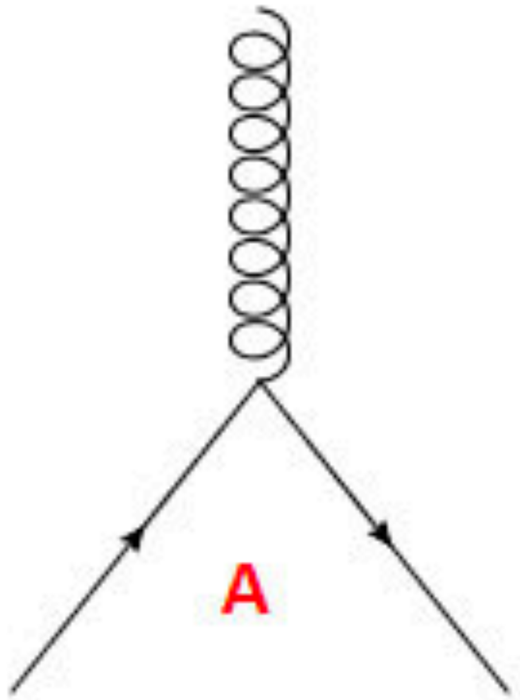


Quick prelude: quantum chromodynamics (I)

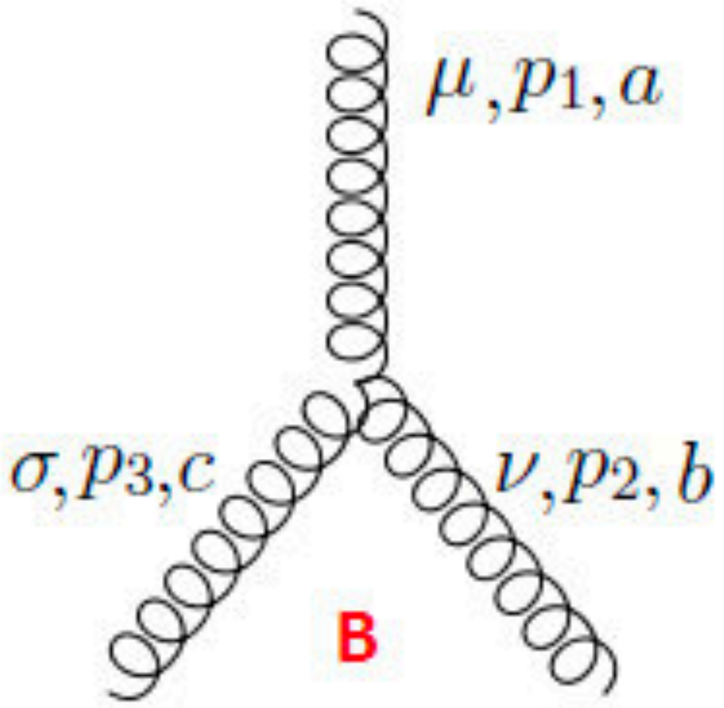
$$\mathscr{L} = \sum_q \overline{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - \frac{1}{2} g_s \gamma^\mu \lambda^C_{ab} \mathscr{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

With the gluon field tensor:

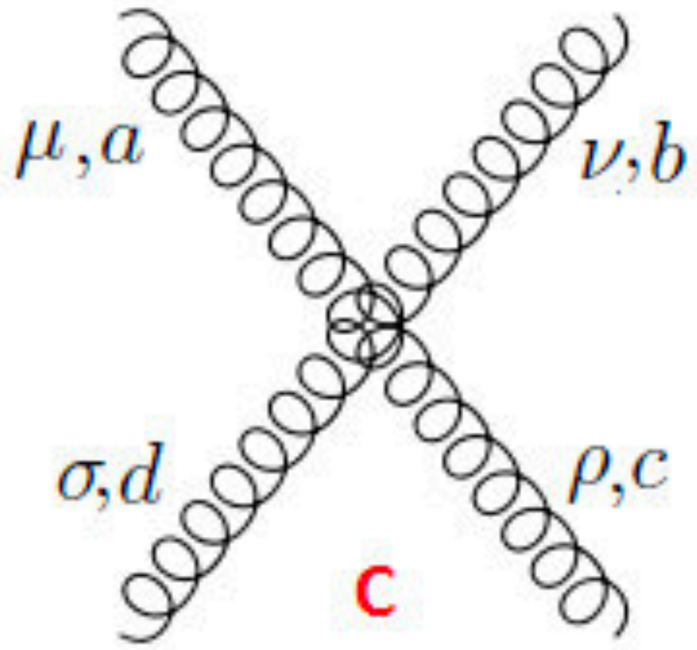
$$F^A_{\mu\nu} = \partial_\mu \mathscr{A}^A_\nu - \partial_\nu \mathscr{A}^A_\mu - g_s f_{ABC} \mathscr{A}^B_\mu \mathscr{A}^C_\nu$$



$$-\imath g_s T^a \hat{\gamma}^\mu$$



$$-g_s f_{abc} V_{3g}^{\mathrm{Cin}}(p_1, p_2, p_3, \mu_1, \nu_1, \sigma_1)$$
$$\eta^{4D}_{\mu_1\mu}\eta^{4D}_{\nu_1\nu}\eta^{4D}_{\sigma_1\sigma}$$



$$-\imath g_s^2 V_{4g}(p_1^{\mu_1}, p_2^{\nu_1}, p_3^{\rho_1}, p_4^{\sigma_1}, a, b, c, d)$$
$$\eta^{4D}_{\mu_1\mu}\eta^{4D}_{\nu_1\nu}\eta^{4D}_{\rho_1\rho}\eta^{4D}_{\sigma_1\sigma}$$

Quick prelude: quantum chromodynamics (I)

Colour — Gluon field — Colour

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Quark fields

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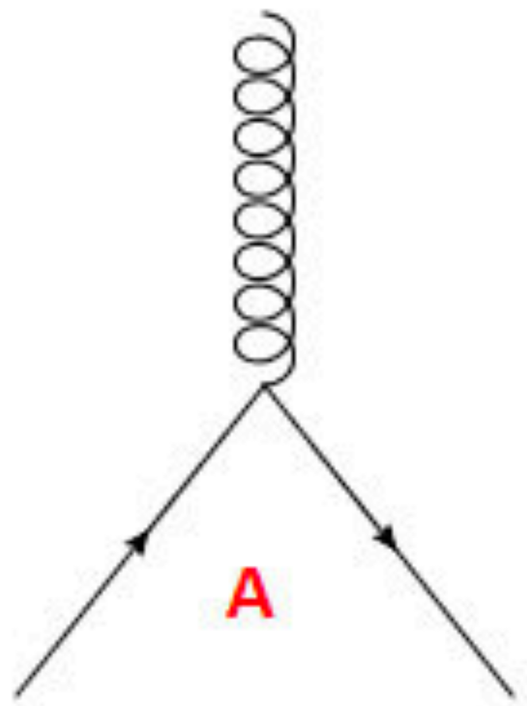

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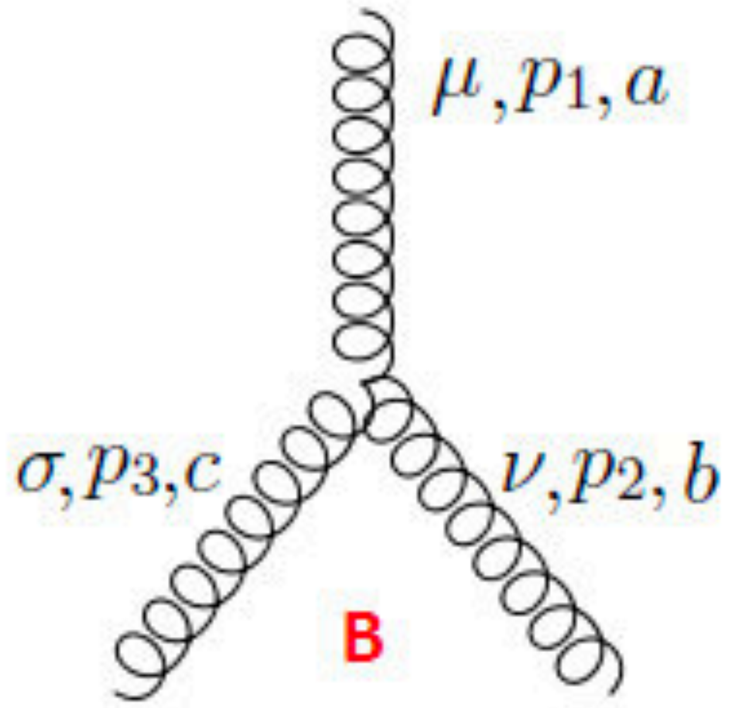

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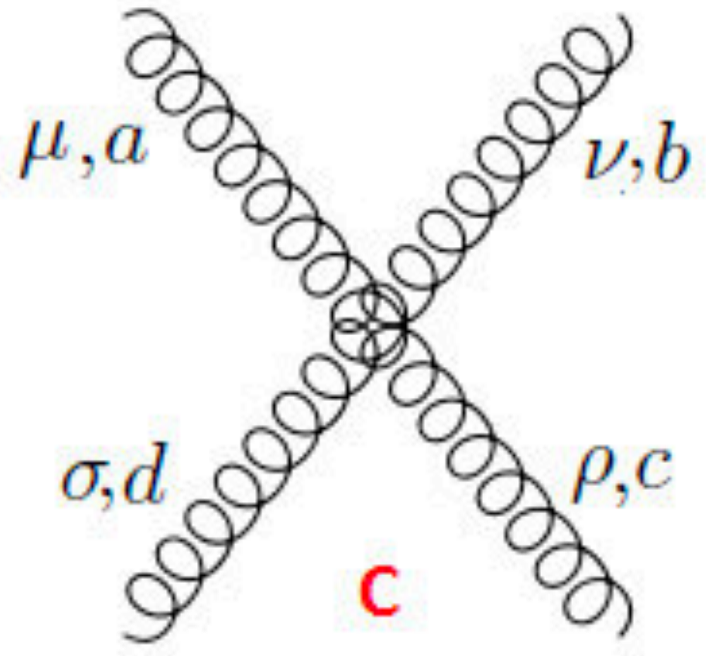

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Quick prelude: quantum chromodynamics (II)

Gluon field

$$\mathscr{L} = \sum_q \overline{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - \frac{1}{2} g_s \gamma^\mu \lambda^C_{ab} \mathscr{A}^C_\mu - m_q \delta_{ab}) \psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

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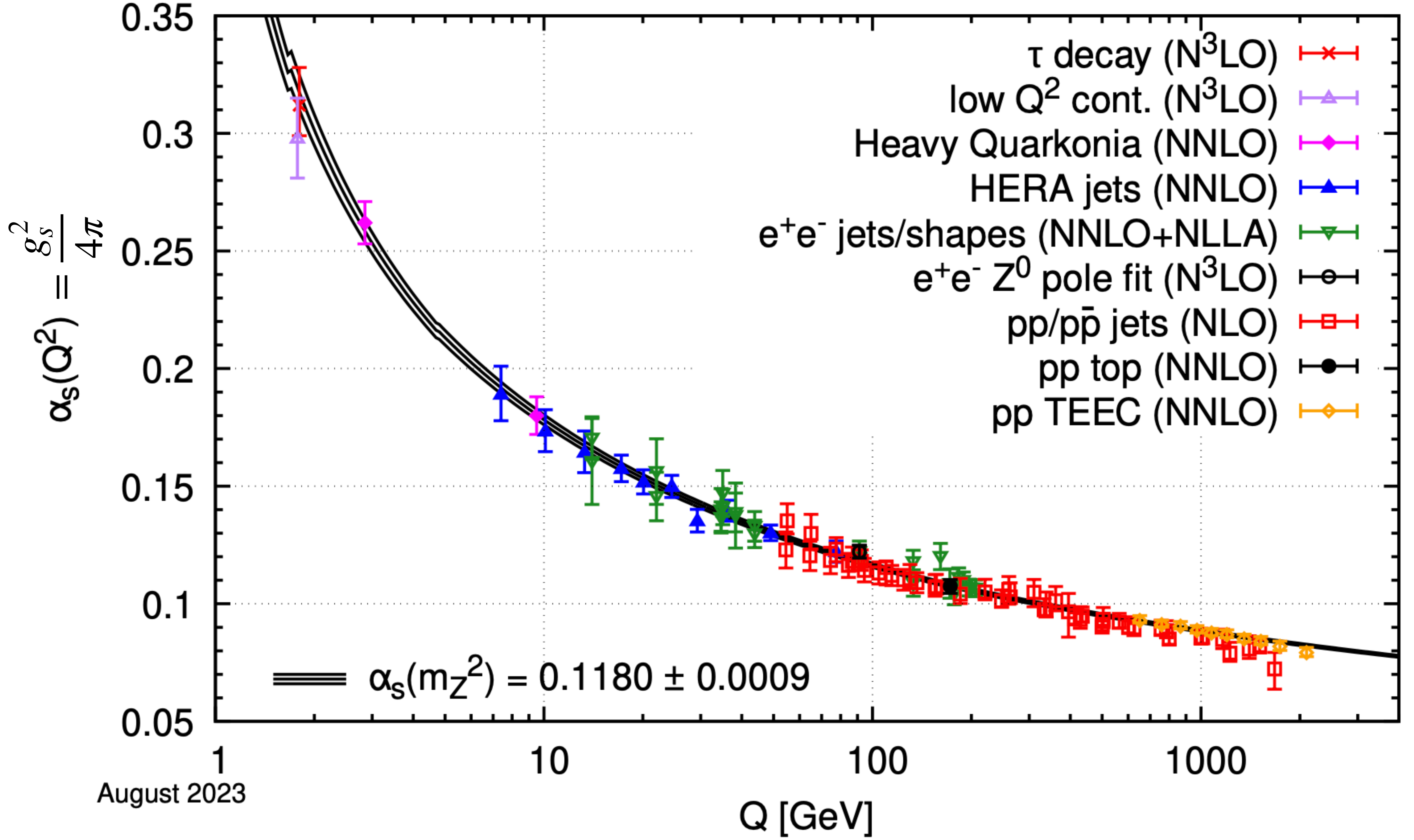
Properties of QCD relevant for heavy-ions:

1. *Confinement*: quarks and gluons are bound in color neutral mesons ($q\overline{q}$) or baryons (qqq).
2. *Chiral symmetry*: Interaction between left- and right handed quarks disappears for massless quarks.
3. *Asymptotic freedom*: Interaction strength decreases with increasing momentum transfer ($\alpha_S \rightarrow 0$ for $Q^2 \rightarrow \infty$).



Color confinement

No free quarks and gluons have been observed in nature

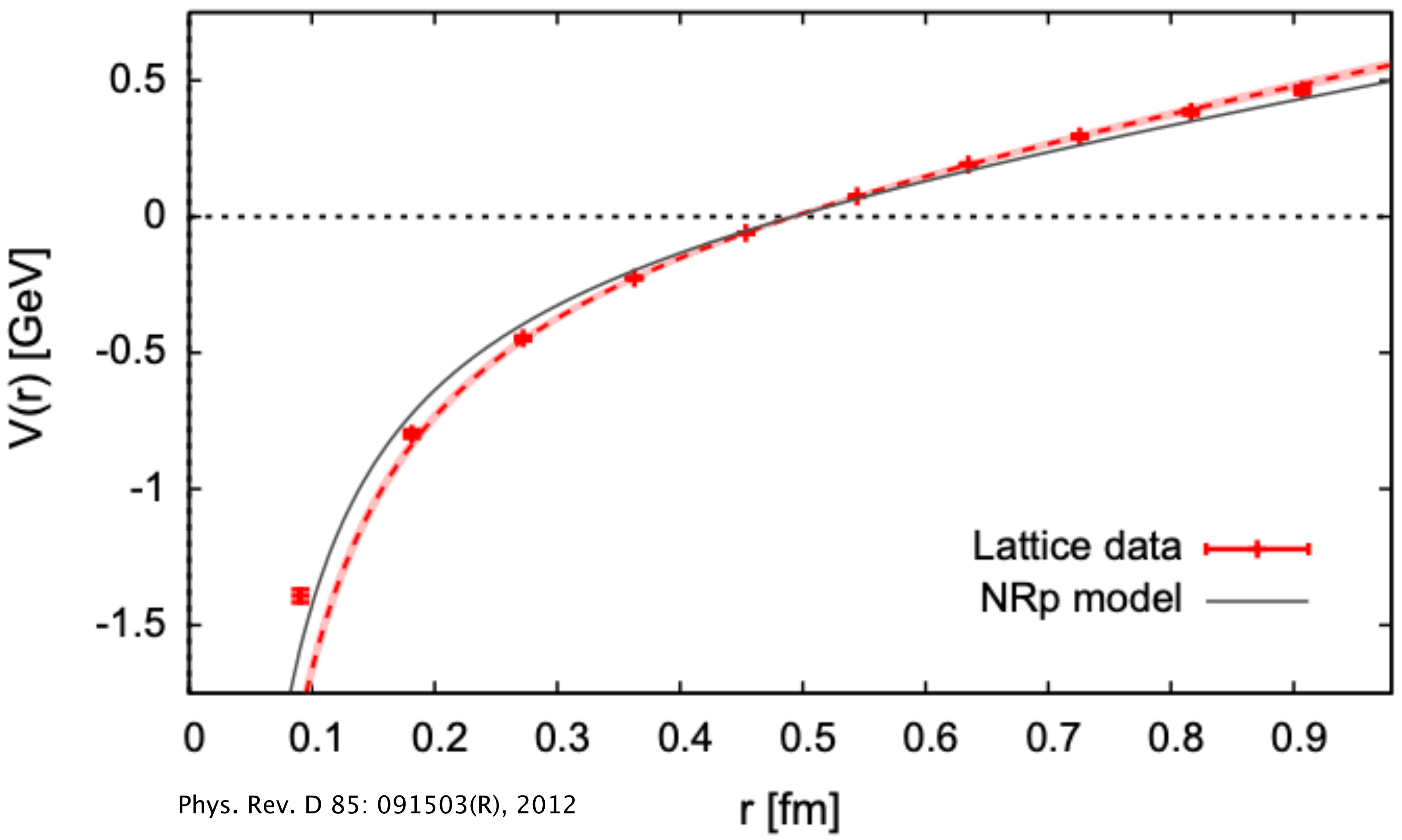
- In QCD this is understood by the large coupling constant and the non-abelian nature of the QCD symmetry group

This creates an “anti-screening” effect among quark pairs that is effectively modelled by the Cornel potential:

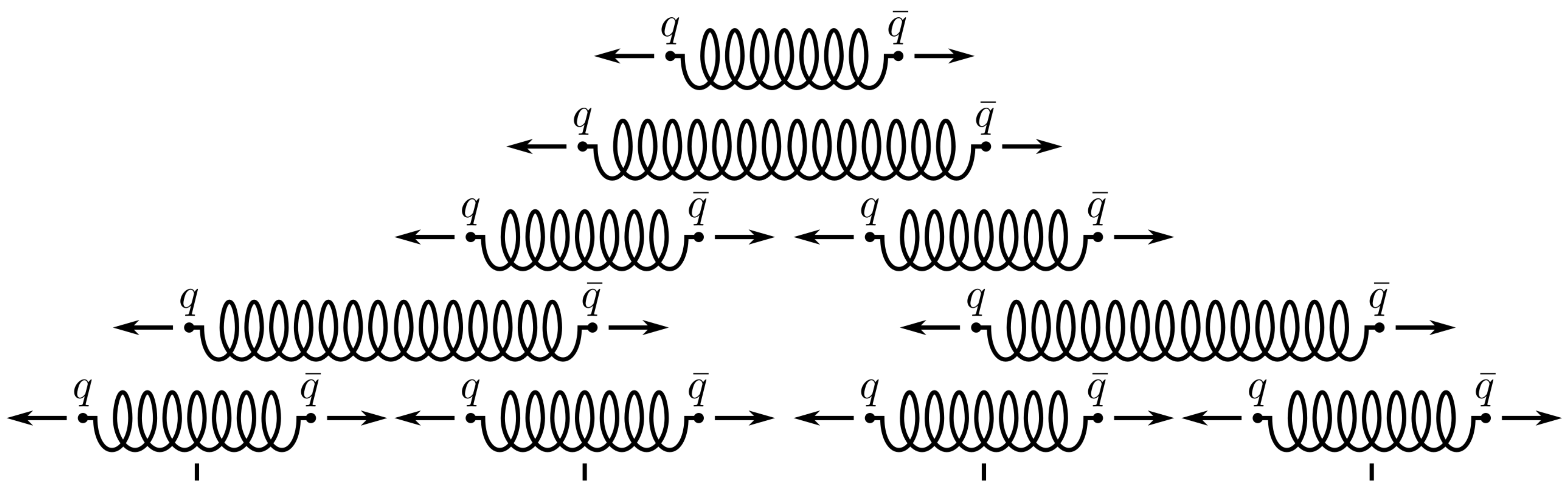
$$V(r) = -\frac{\alpha}{r} + Kr$$

Coulomb (QED like) component

Elastic string potential K~O(800) MeV/fm



Phys. Rev. D 85: 091503(R), 2012

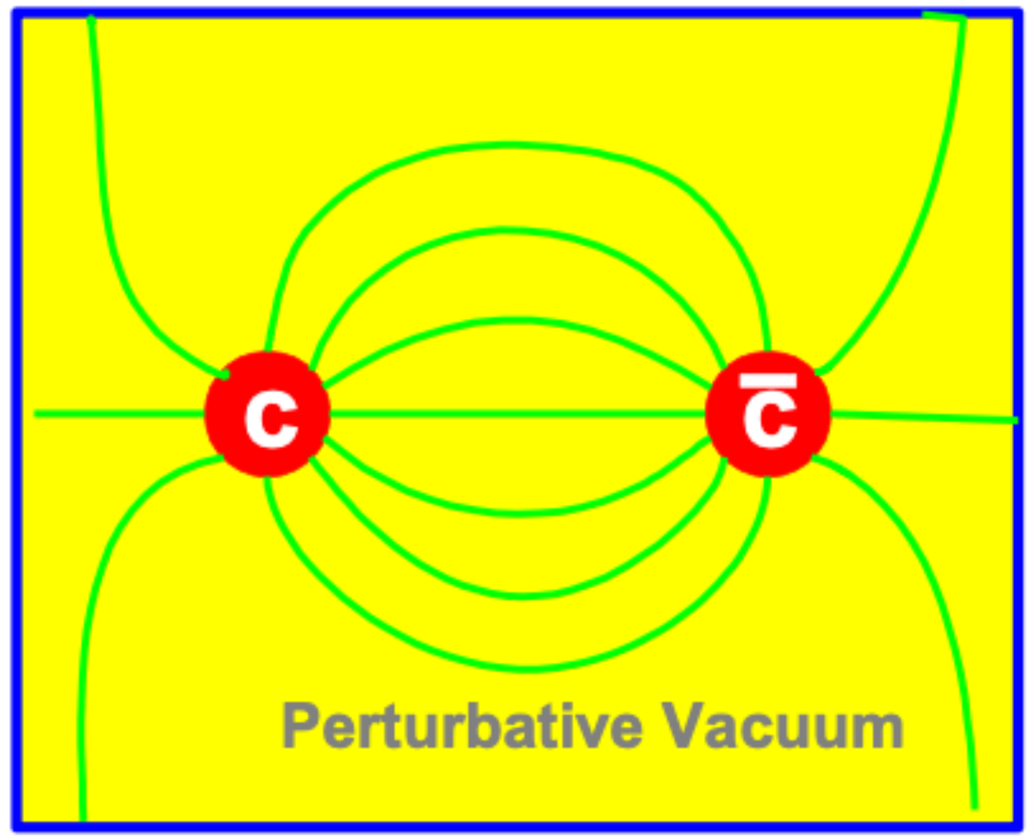


Pulling a $q\bar{q}$ pair apart, makes enough energy to create another $q\bar{q}$

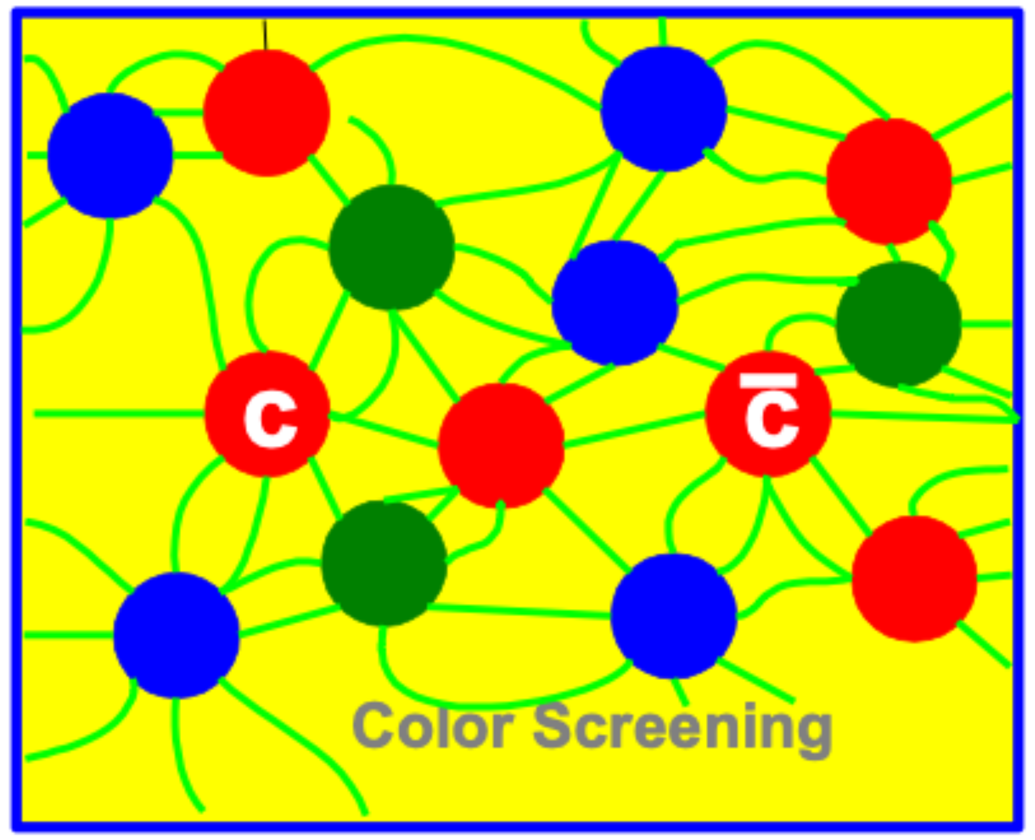
Color de-confinement and Debye screening

At very high transferred momenta, the quark are asymptotically free

- Is there another way?



$$V(r) = -\frac{\alpha}{r} + Kr$$

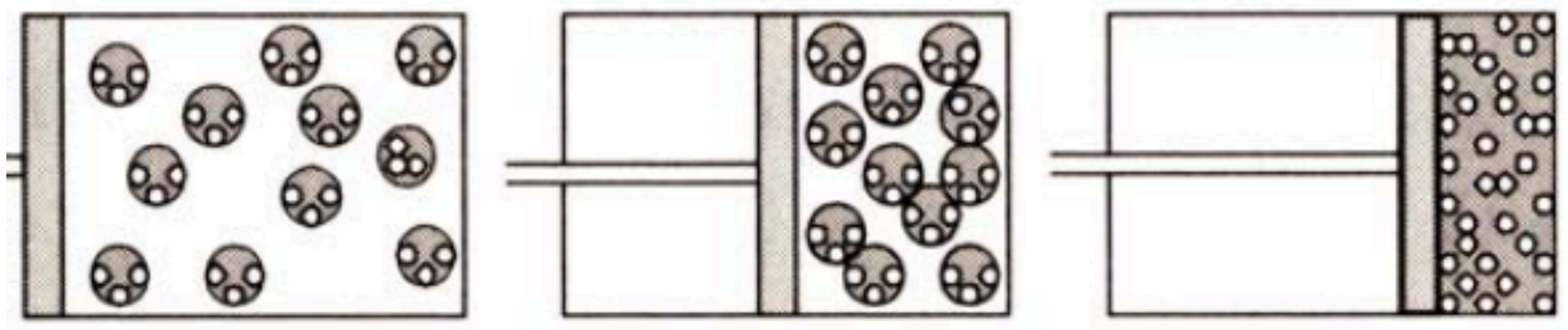


$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

Let's consider a quark pair surrounded by colour charges

- The interaction among the two quark is screened
- The effective $q\bar{q}$ potential becomes Yukawa like
  - Hadrons with constituents quarks at distances larger than λ_D cannot be bound

$T < T_c$ $T \sim T_c$ $T > T_c$



$\rho < \rho_c$ $\rho \sim \rho_c$ $\rho > \rho_c$

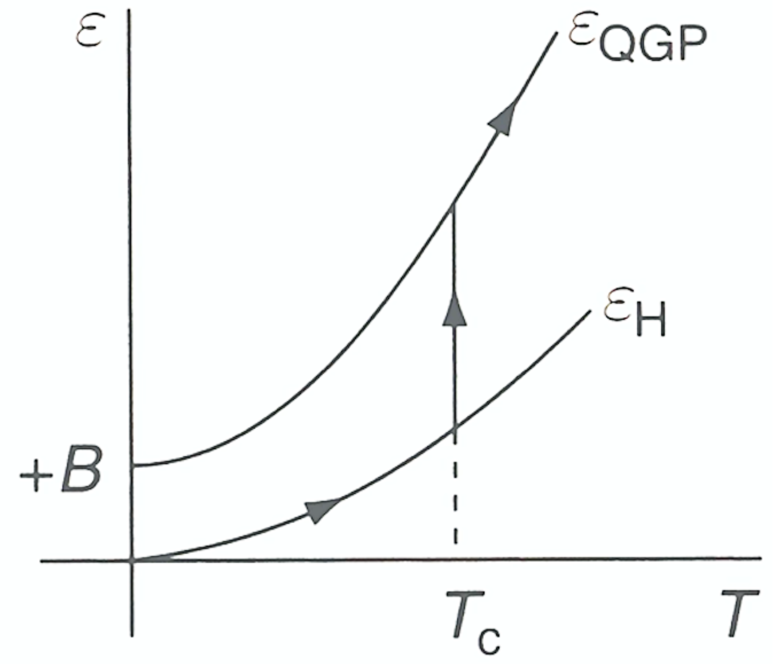
Anatomy of the QCD phase transition

Let's take a spoon of the Sun core matter ($T=1.5 \cdot 10^7$ K ~ 1.3 keV)

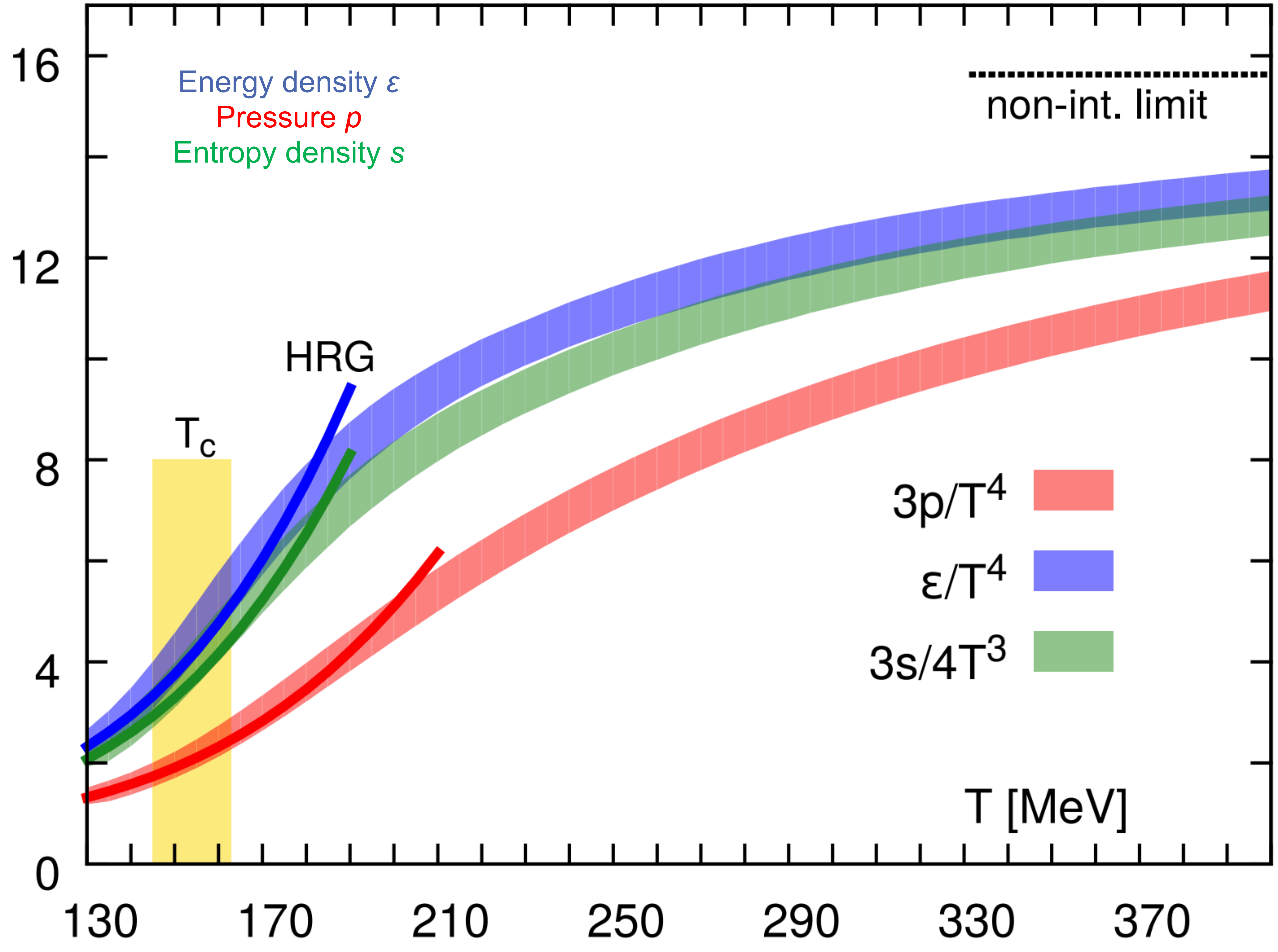
- ~70% of free protons, ~30% of helium

Assume to turn up the temperature

- The rate and intensity of the interactions among the particle will increase
- With increasing temperature the hadronic gas starts populating with different particles (pions, kaons, …)
- At some point, it becomes more favourable to have free quarks

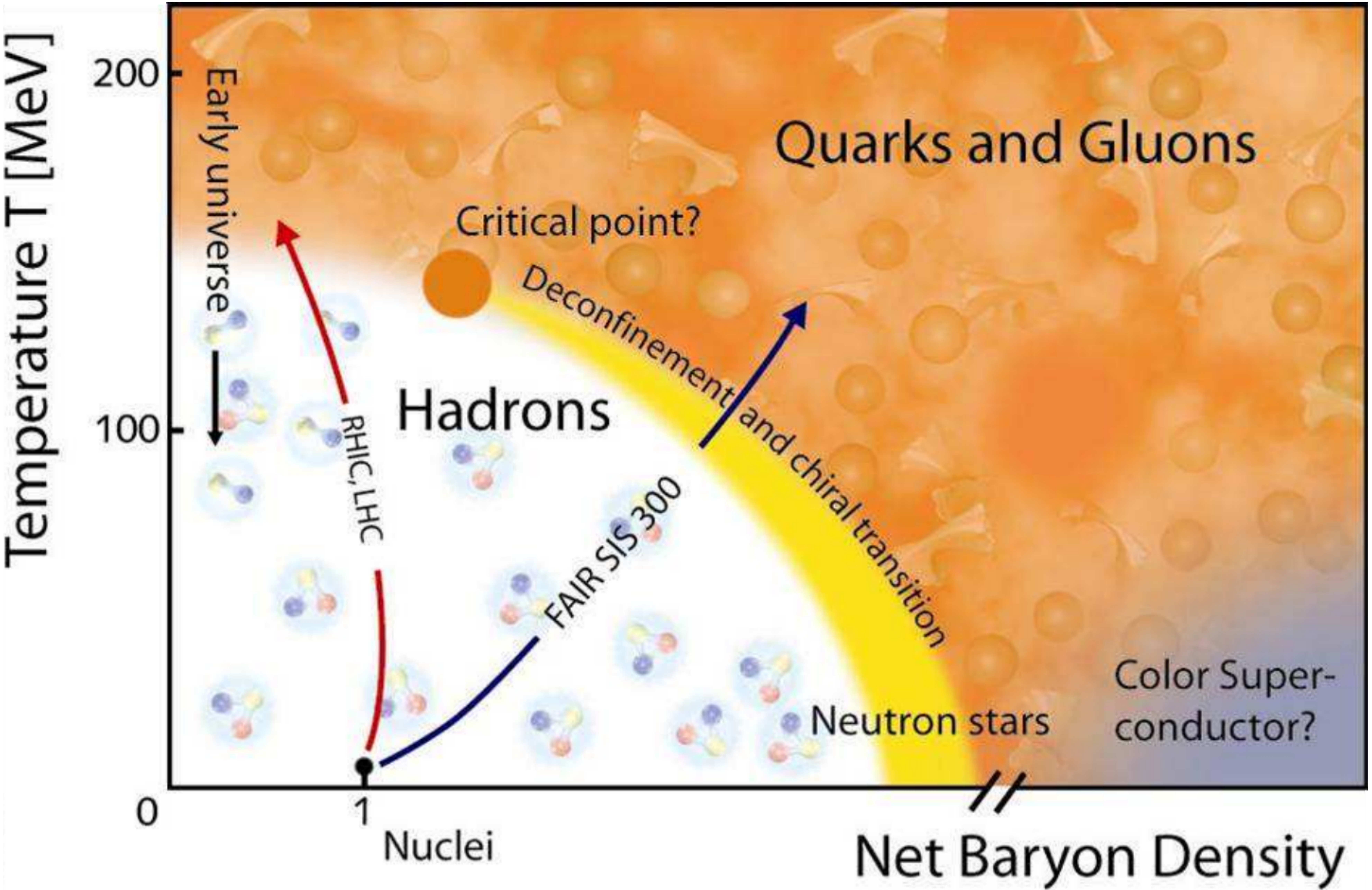


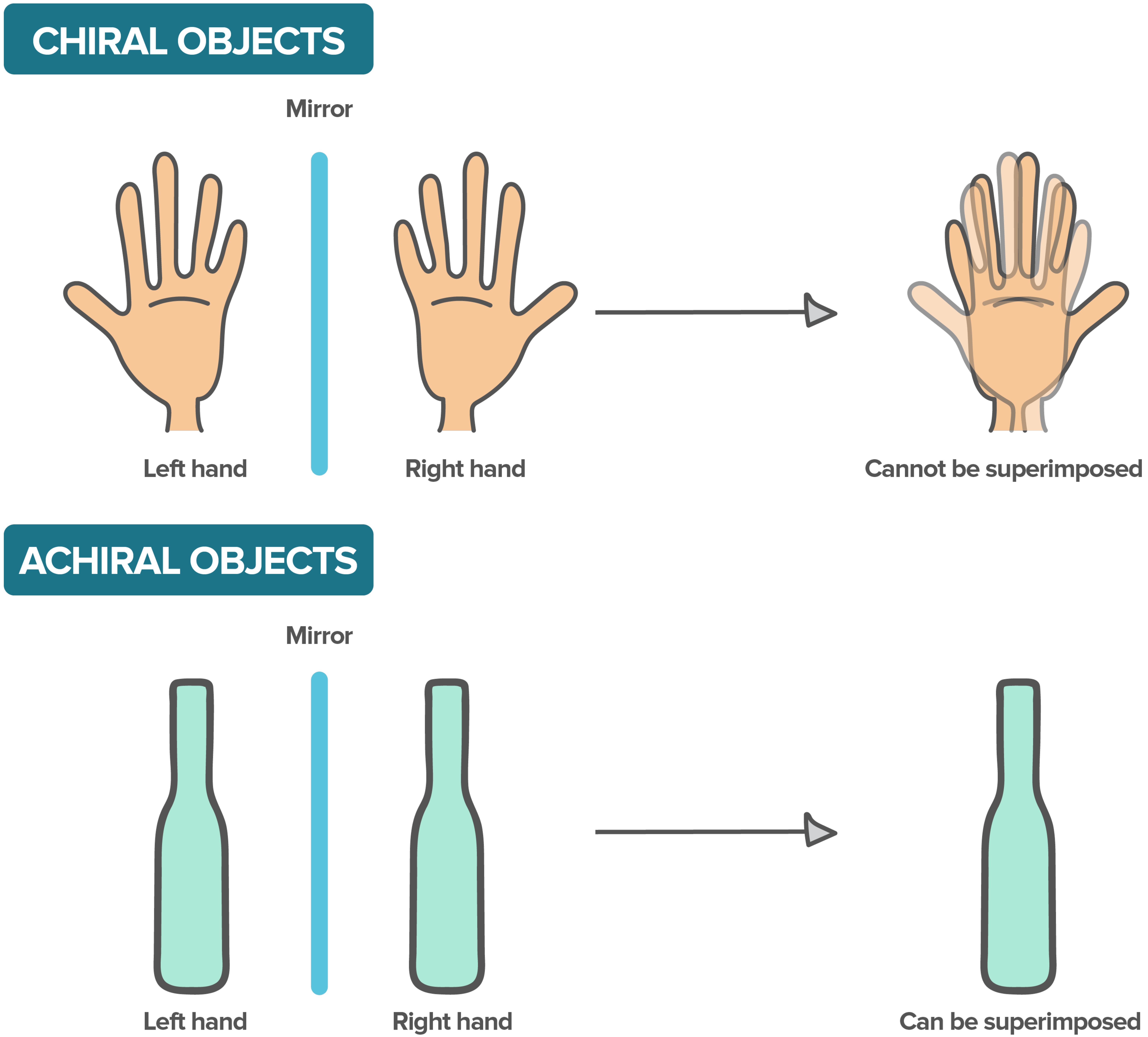
- Smooth transition, not a sudden (first order) change!

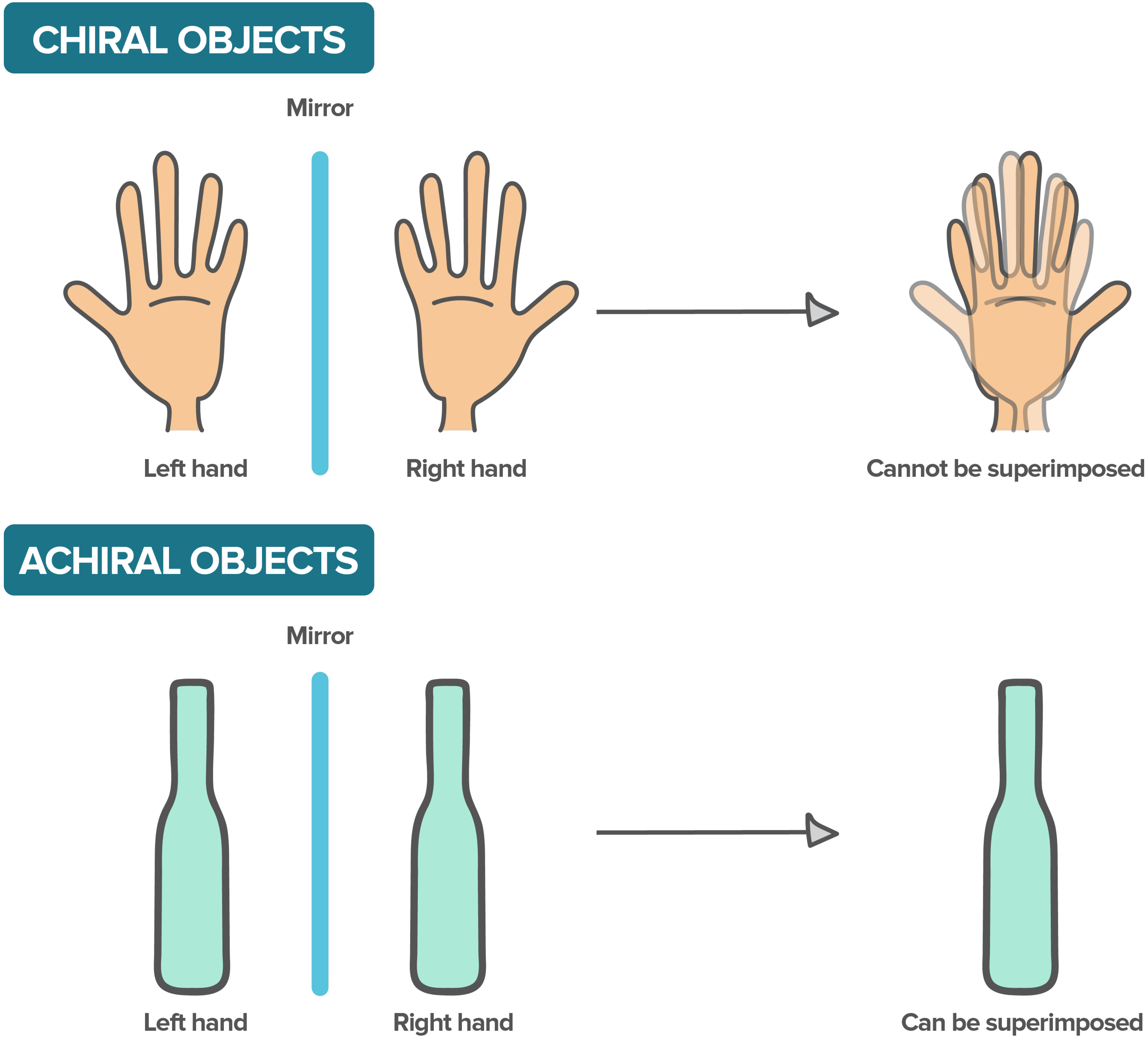


For comparison:
$T=156$ MeV ≙ $1.8 \cdot 10^{12}$ K
Sun core: $1.5 \cdot 10^7$ K
Sun surface: 5778 K

The phase diagram of QCD

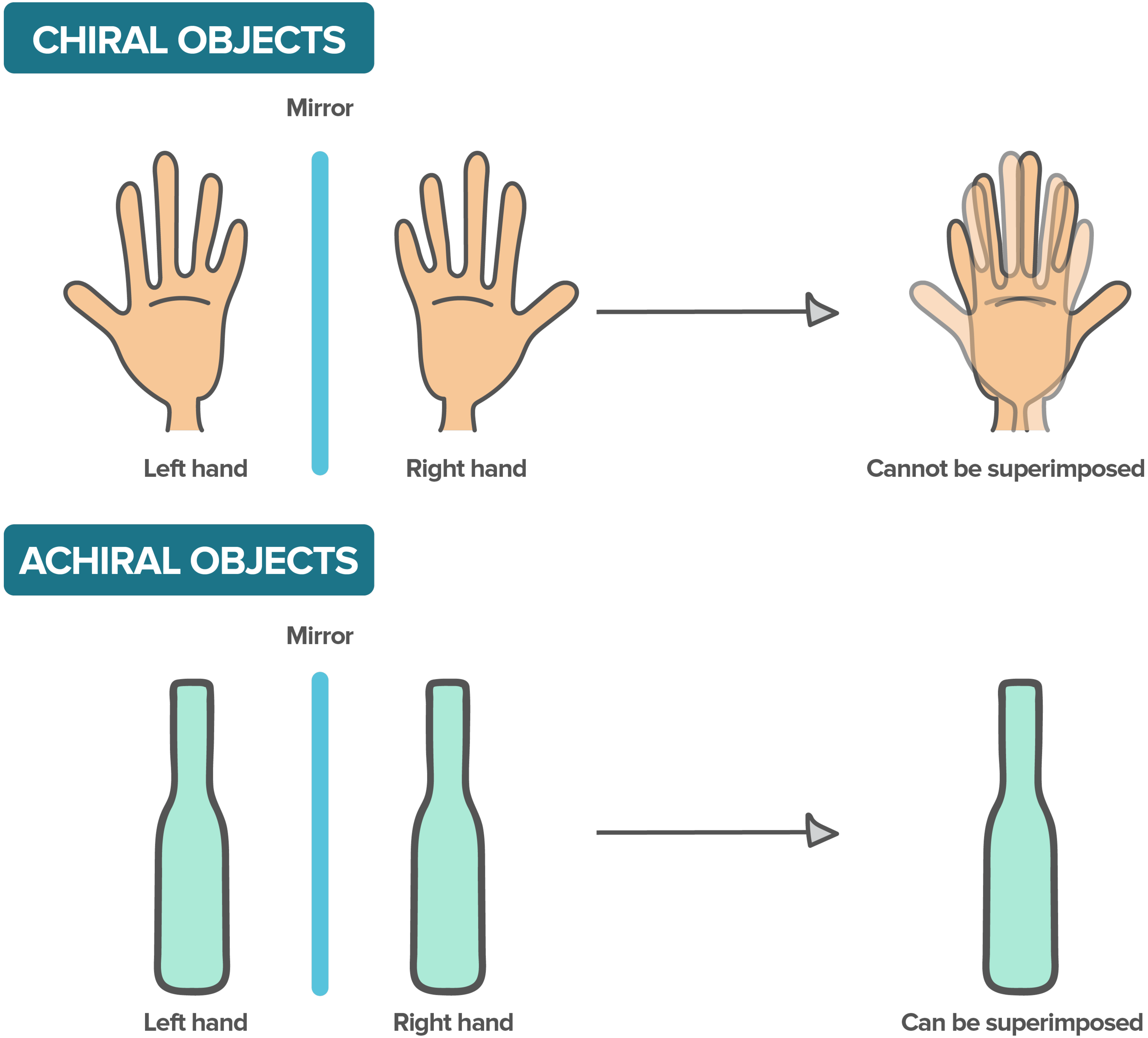



CHIRAL OBJECTS
Mirror
Left hand
Right hand
Cannot be superimposed
ACHIRAL OBJECTS
Mirror
Left hand
Right hand
Can be superimposed



In science:

- In biology the compound with the wrong chirality can kill you
- In particle physics



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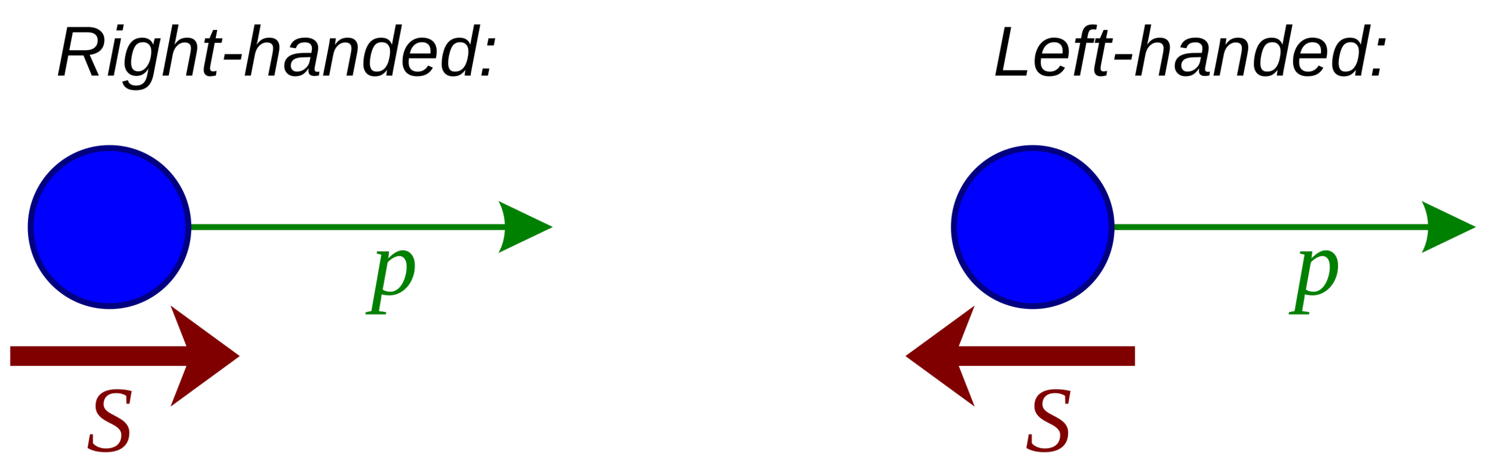
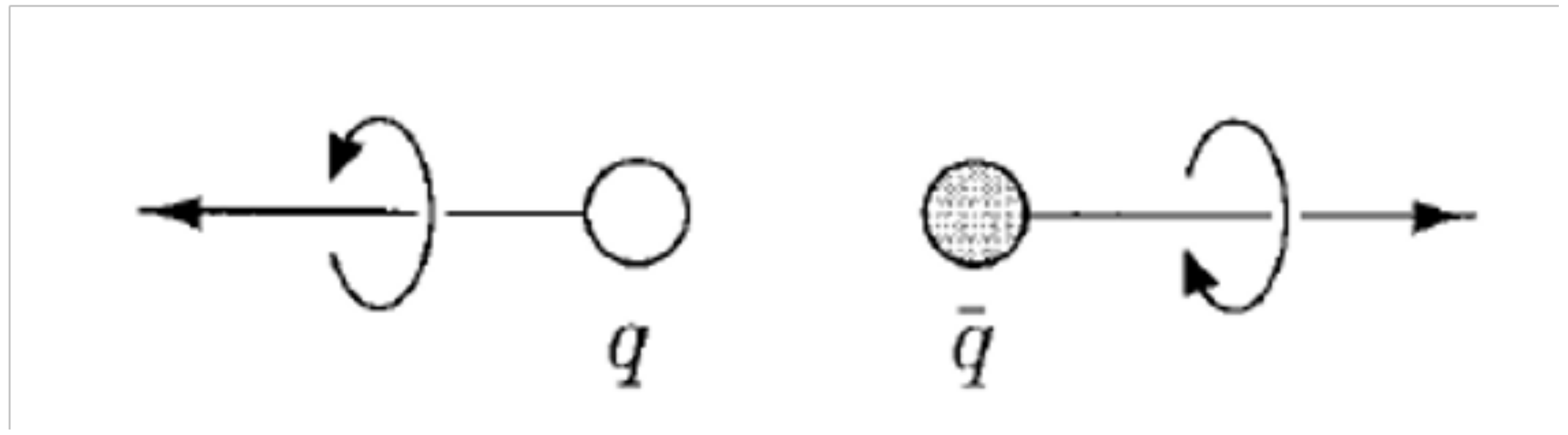


Chiral symmetry breaking in QCD

$$\mathscr{L}_{QCD}^{m=0} = i\bar{q}_R\gamma_\mu D^\mu q_R + i\bar{q}_L\gamma_\mu D^\mu q_L - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}$$

Massless QCD Lagrangian does not mix different chiral states → Chiral symmetry

However, one can create out of the vacuum only pairs with the same chirality for momentum and helicity conservation.



$$\langle q\bar{q}\rangle = \langle q_R\bar{q}_R\rangle + \langle q_L\bar{q}_R\rangle + \langle q_R\bar{q}_L\rangle + \langle q_L\bar{q}_L\rangle = \langle q_L\bar{q}_R\rangle + \langle q_R\bar{q}_L\rangle \neq 0$$

The vacuum mixes chiral states → chiral symmetry is spontaneosly broken

- Same dynamics behind the Higgs mechanism

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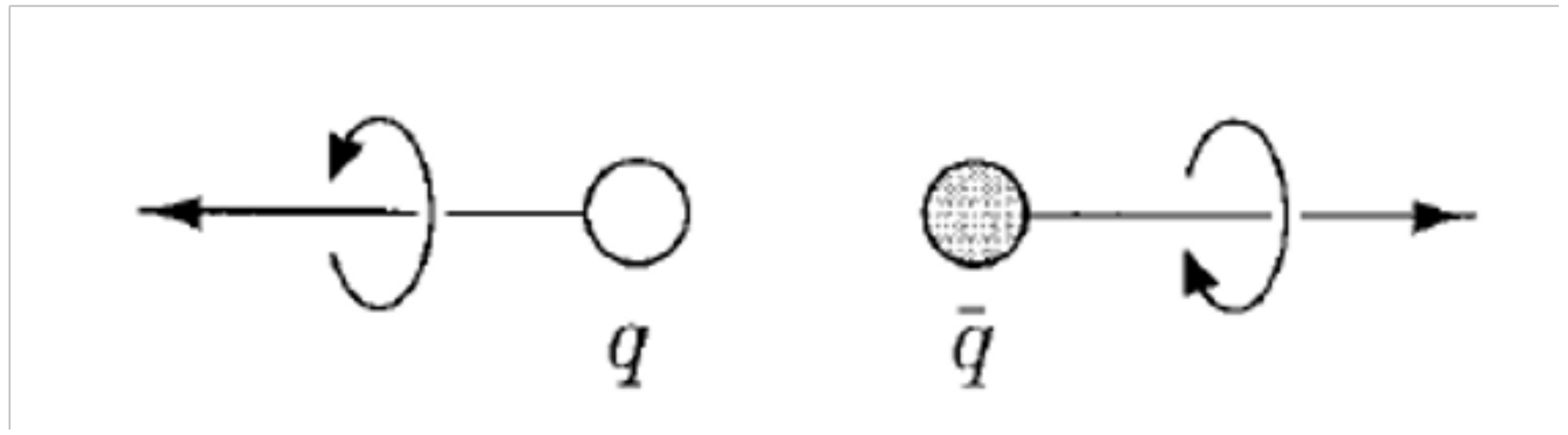

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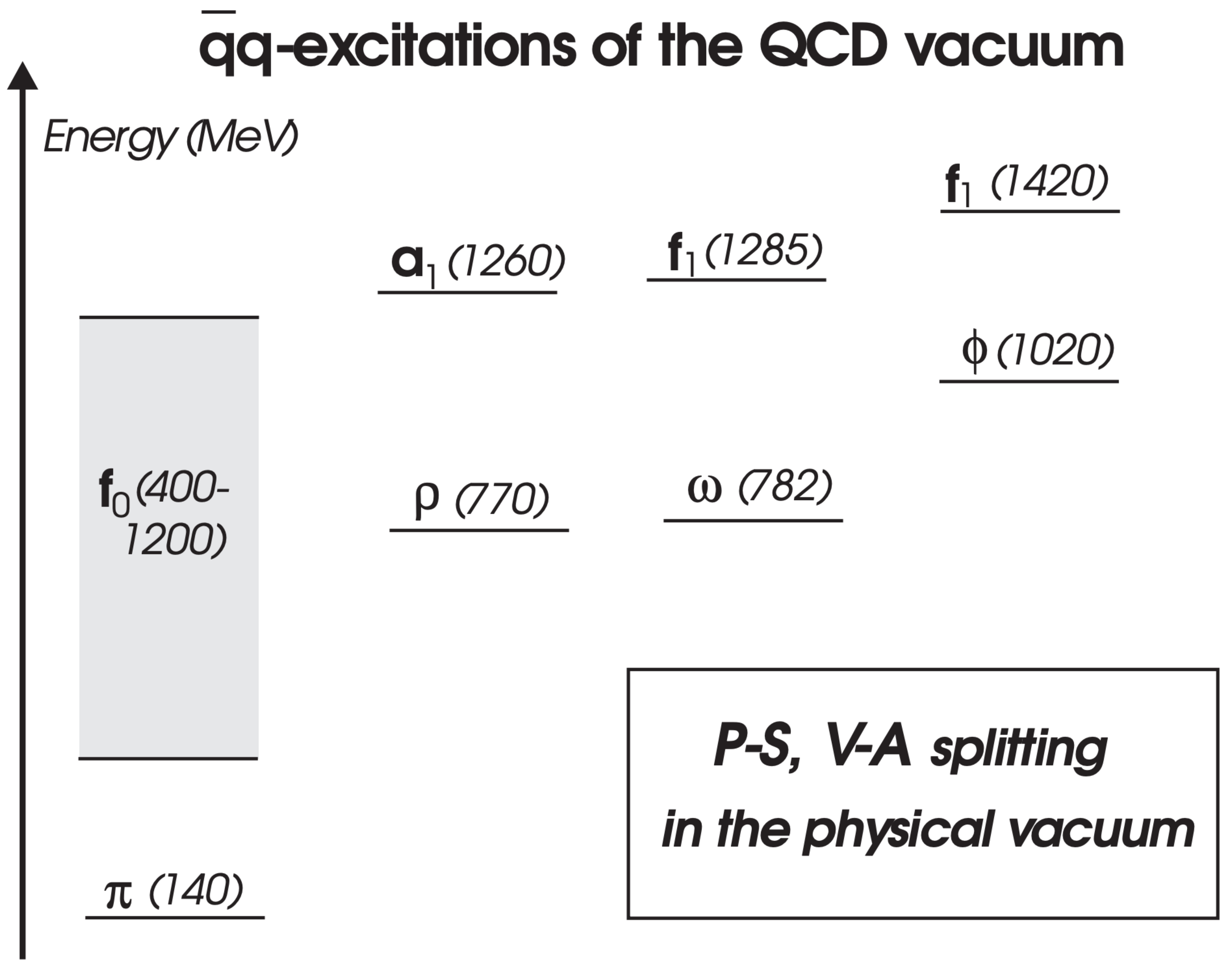
The vacuum mixes chiral states → chiral symmetry is spontaneosly broken

- Same dynamics behind the Higgs mechanism

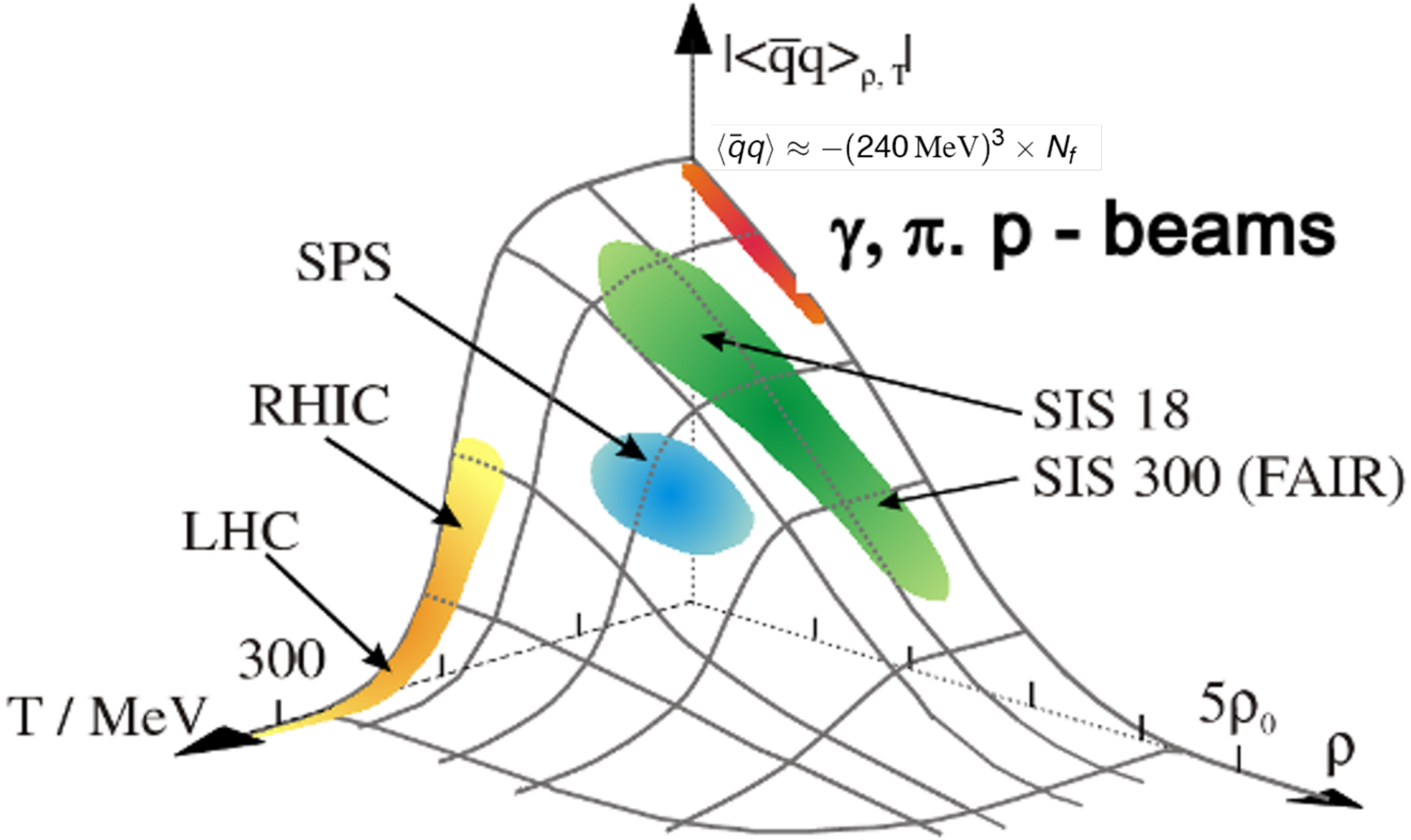
Not the only thing in common with the Higgs:

- Higgs mechanism gives mass to elementary particles
  - Only 1% of ordinary matter mass
- **Much more of the ordinary matter mass is due to the CSB in QCD**



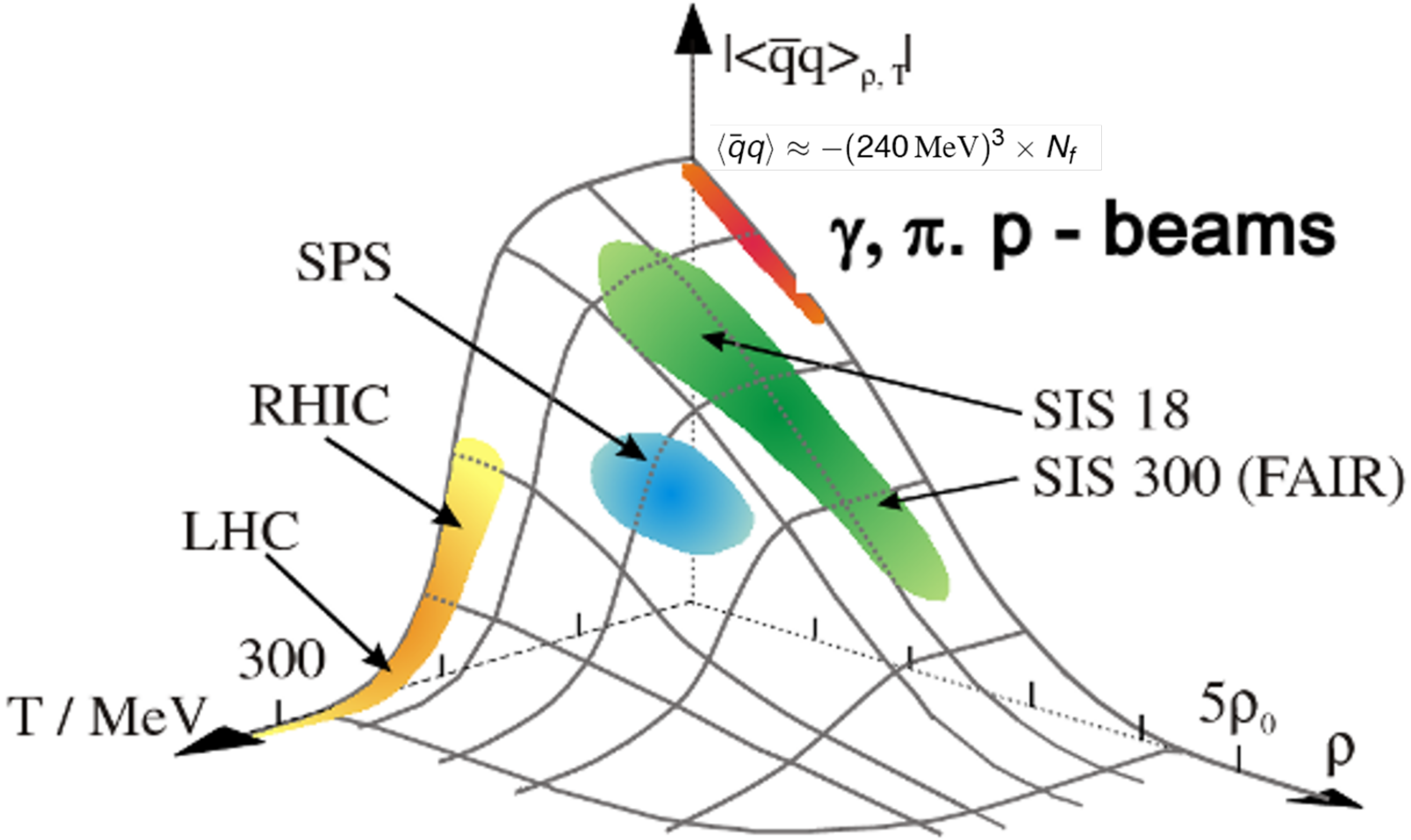
R. Rapp and J. Wambach, Adv.Nucl.Phys 25 (2000)

Chiral symmetry restoration in QCD

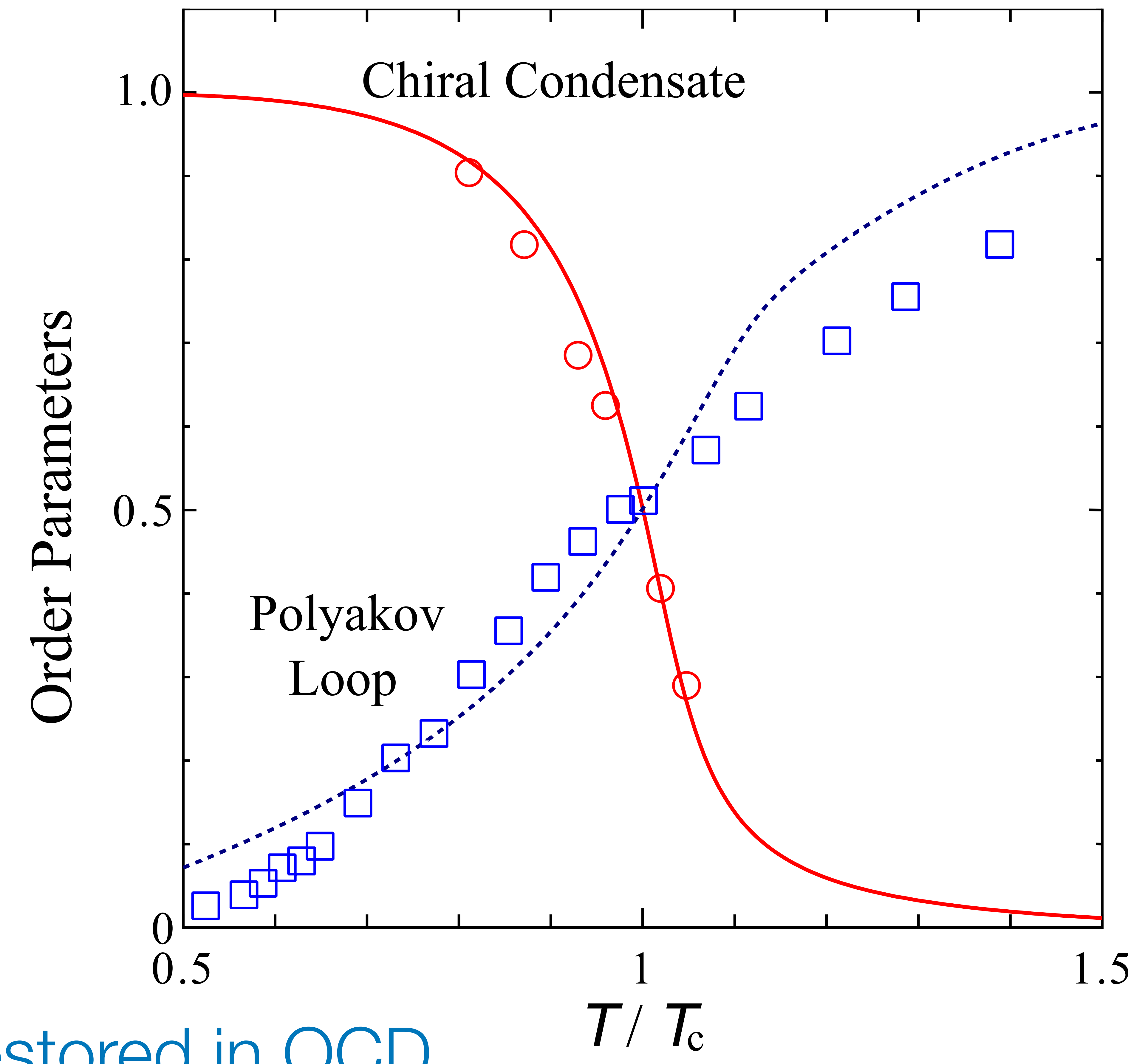


Key prediction: at high temperatures chiral symmetry is restored in QCD

Chiral symmetry restoration in QCD



Lattice QCD calculation



Key prediction: at high temperatures chiral symmetry is restored in QCD

According to LQCD, the chiral symmetry restoration is also an unambiguous signature of a deconfined state of matter and a true fundamental phenomenon in the Standard Model

➡ Measure the chiral symmetry restoration in QCD -> get the Nobel

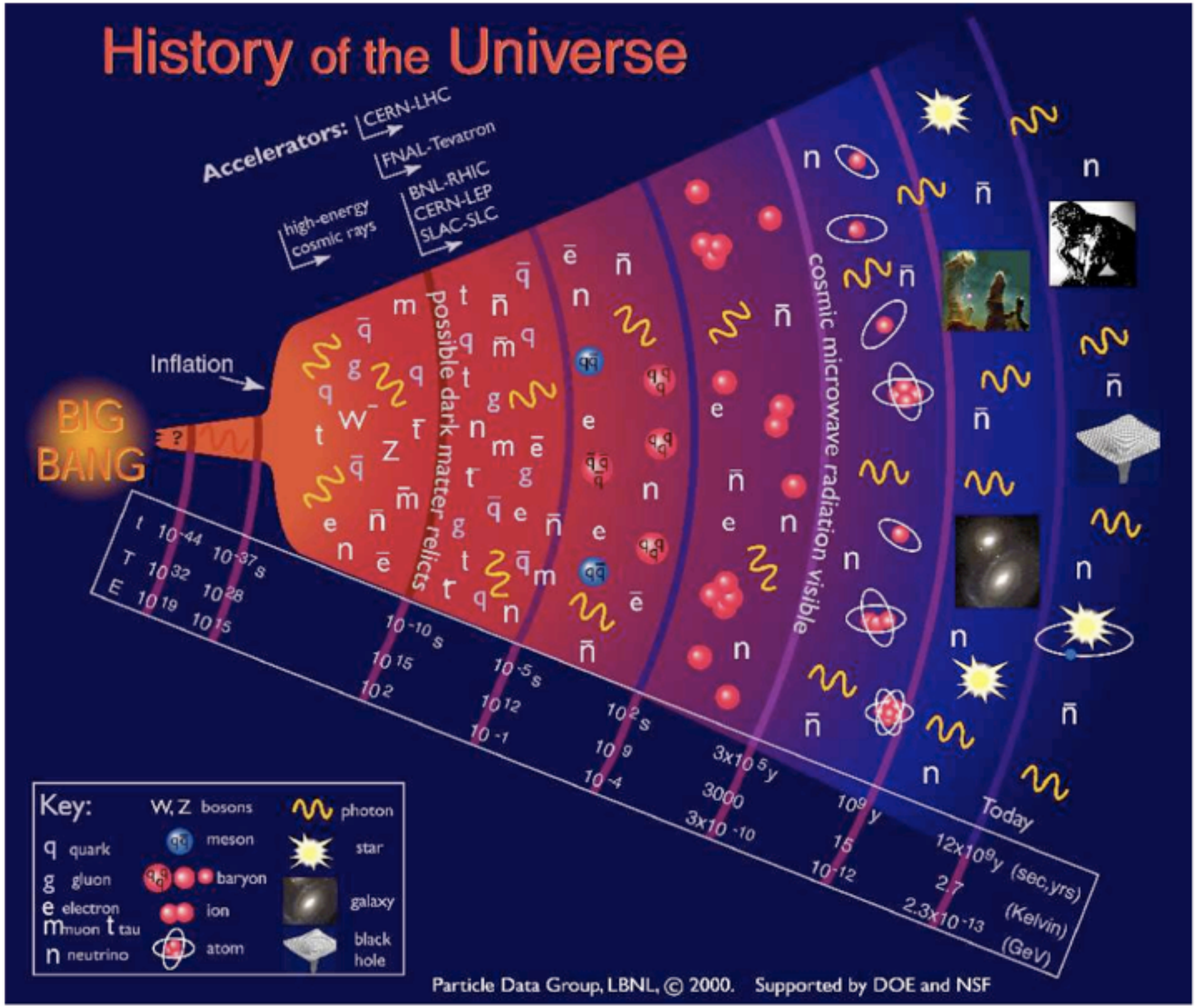
QGP and where to find it

Heavy ions and the early universe (I)

- Big bang in the early universe and little bang in the laboratory.

- The Universe went through a QGP phase about 10ps after its creation and froze out into hadrons after about 10μs which later formed nuclei.

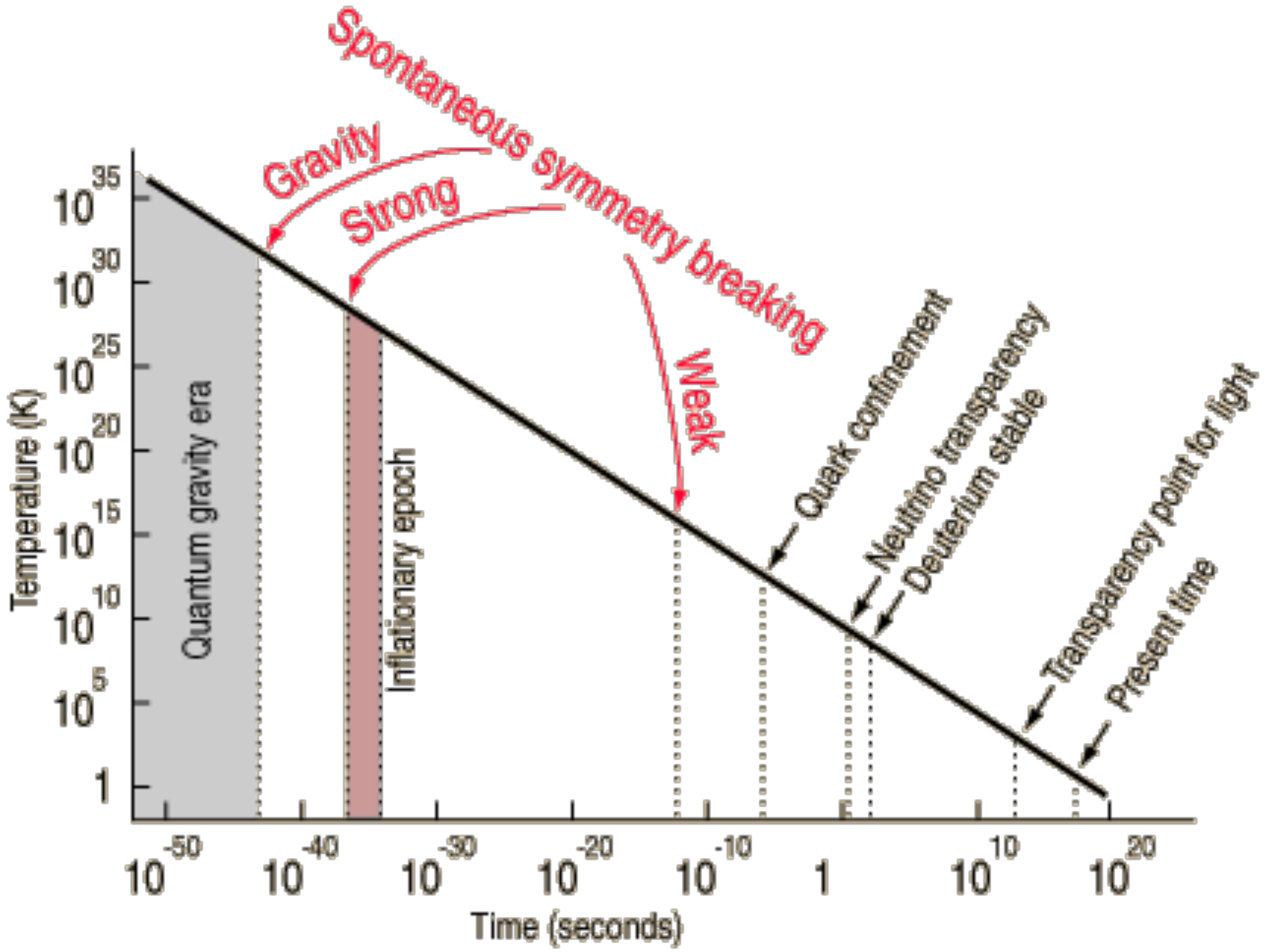
- In addition, there are similarities between the big bang (universe QGP) and the little bang (heavy-ions) concerning the **decoupling**.

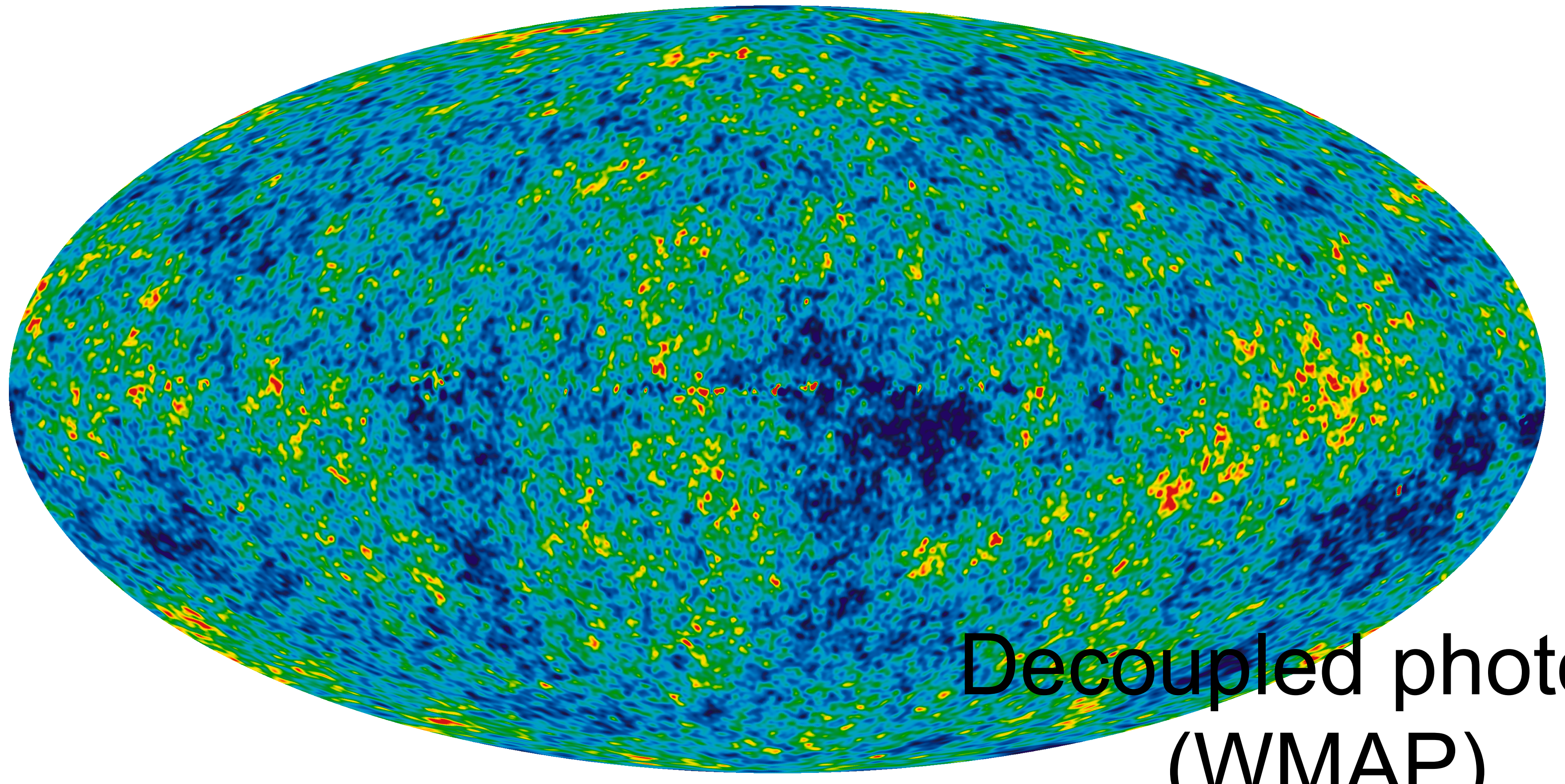


Heavy ions and the early universe (II)

- Decoupling: different type of particles fall out of thermal equilibrium with each other and *freeze out* when the mean free path for interaction is comparable to the size of the expanding system.

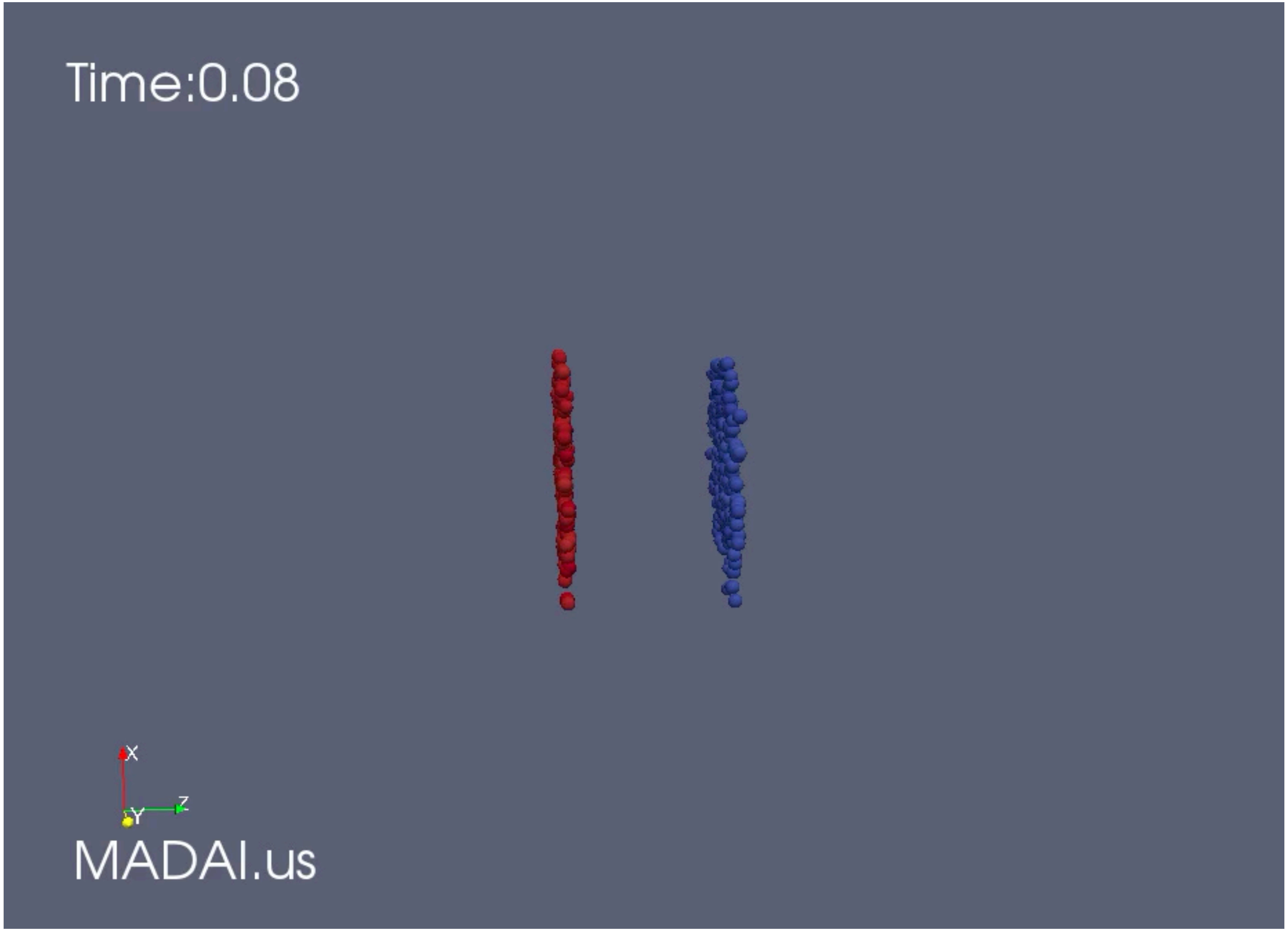
- Examples of this analogy:
  – Early Universe: neutrinos decouple early as their interaction is weak.
  – Heavy-ions:
    - chemical freeze-out (inelastic interactions changing particle type) happens before kinetic freeze-out (elastic interactions changing only momenta)
    - Kinetic freeze-out of strange particles might happen before the kinetic freeze-out of non-strange particles





Decoupled photons (WMAP)

Timelapse of the collision



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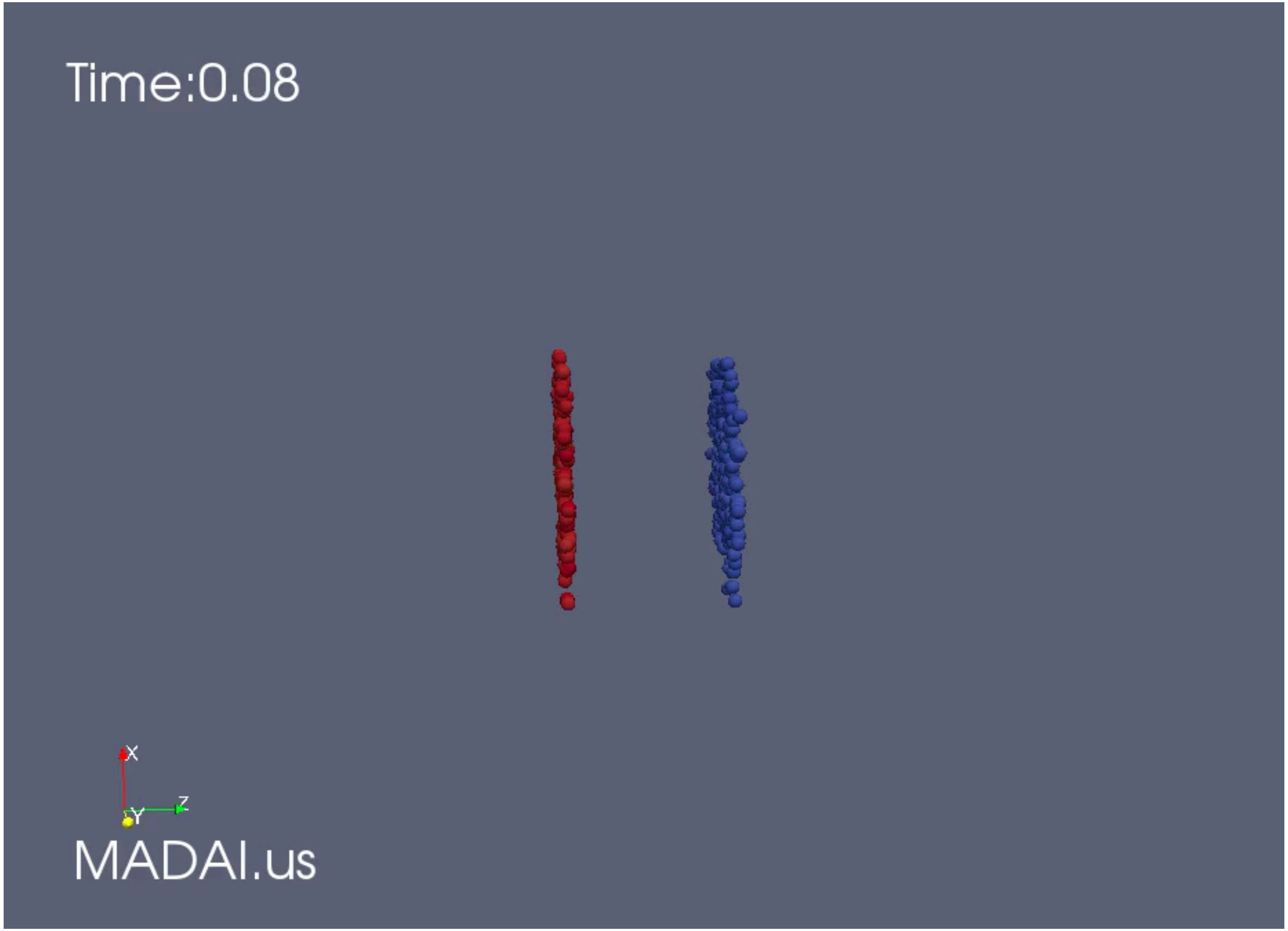
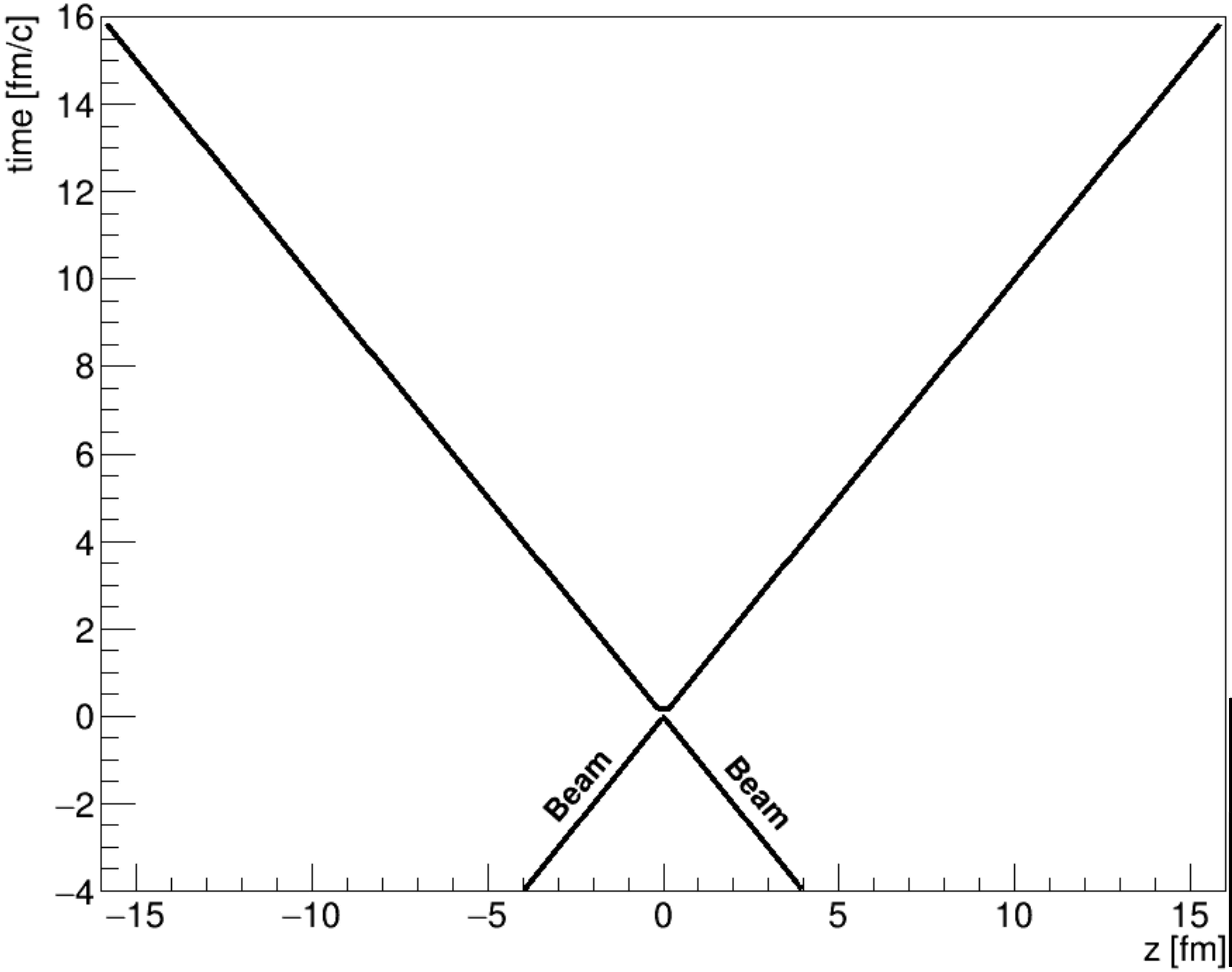
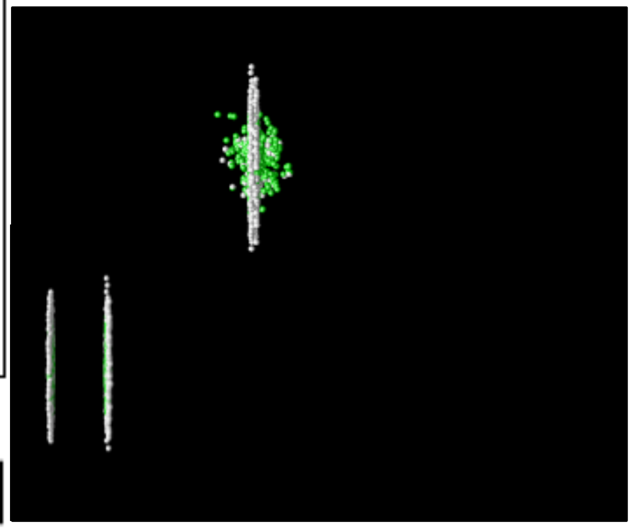


Heavy ion collision





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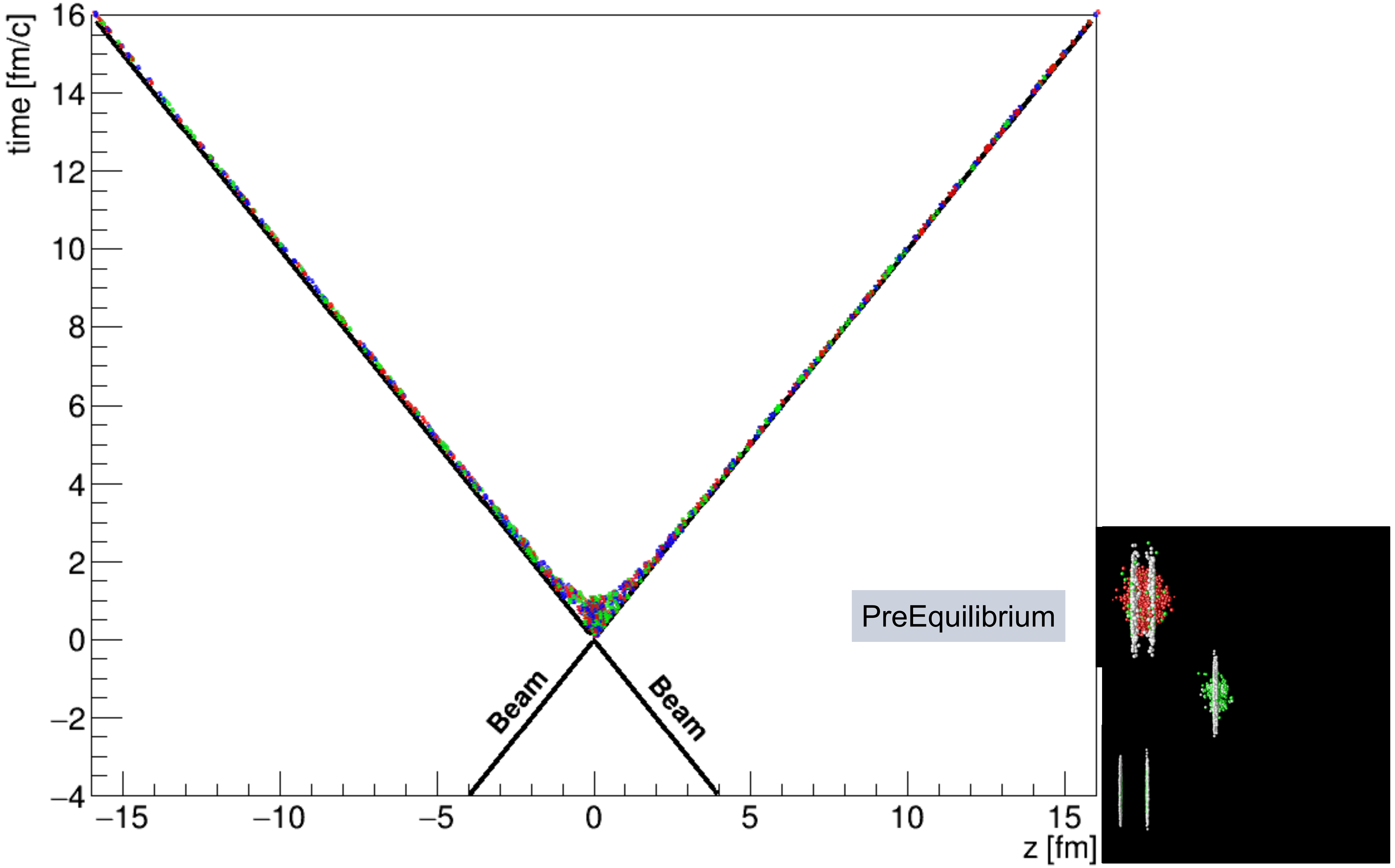

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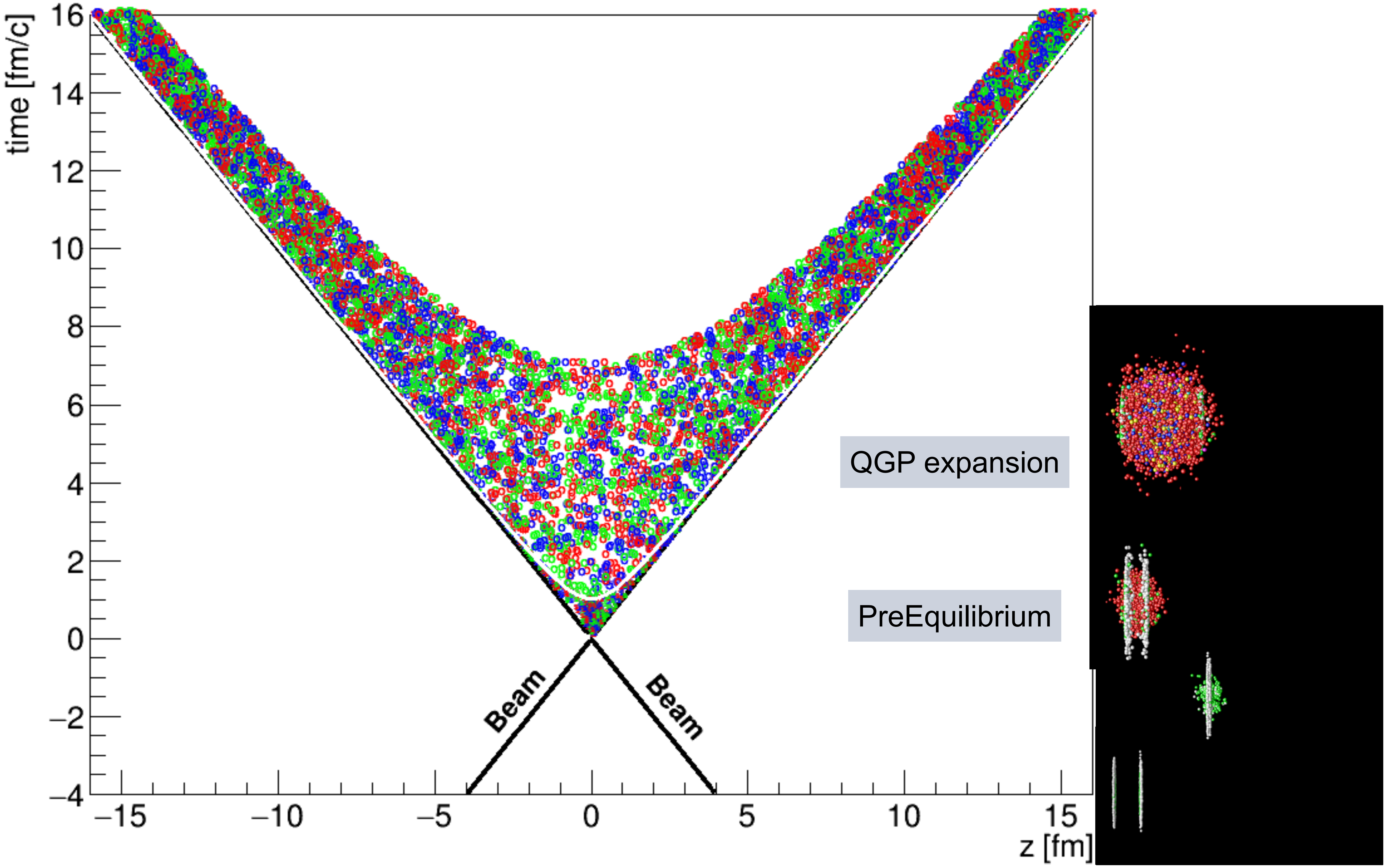

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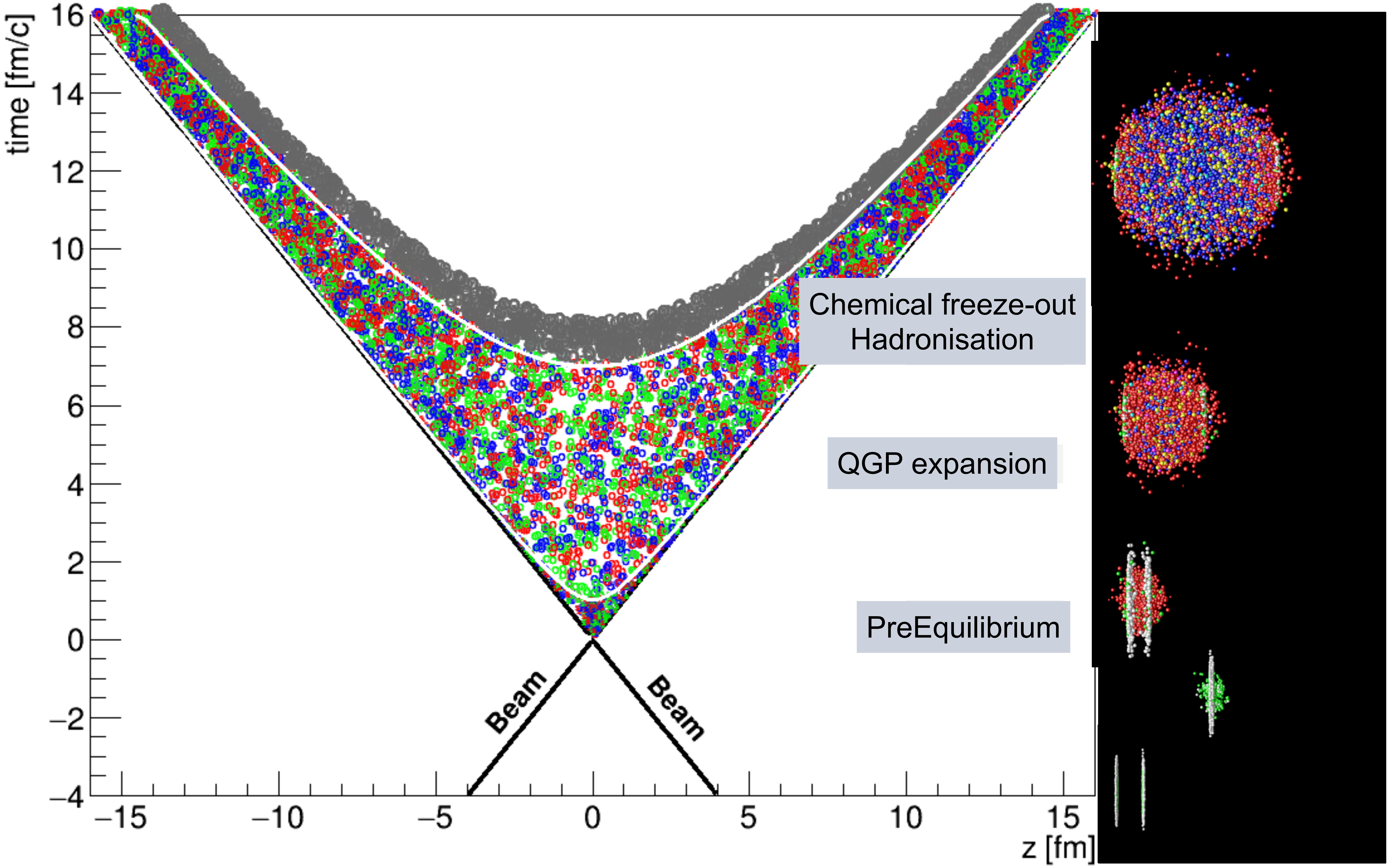


Heavy ion collision

Particle detection
($t \approx 10^{15}$fm/c)

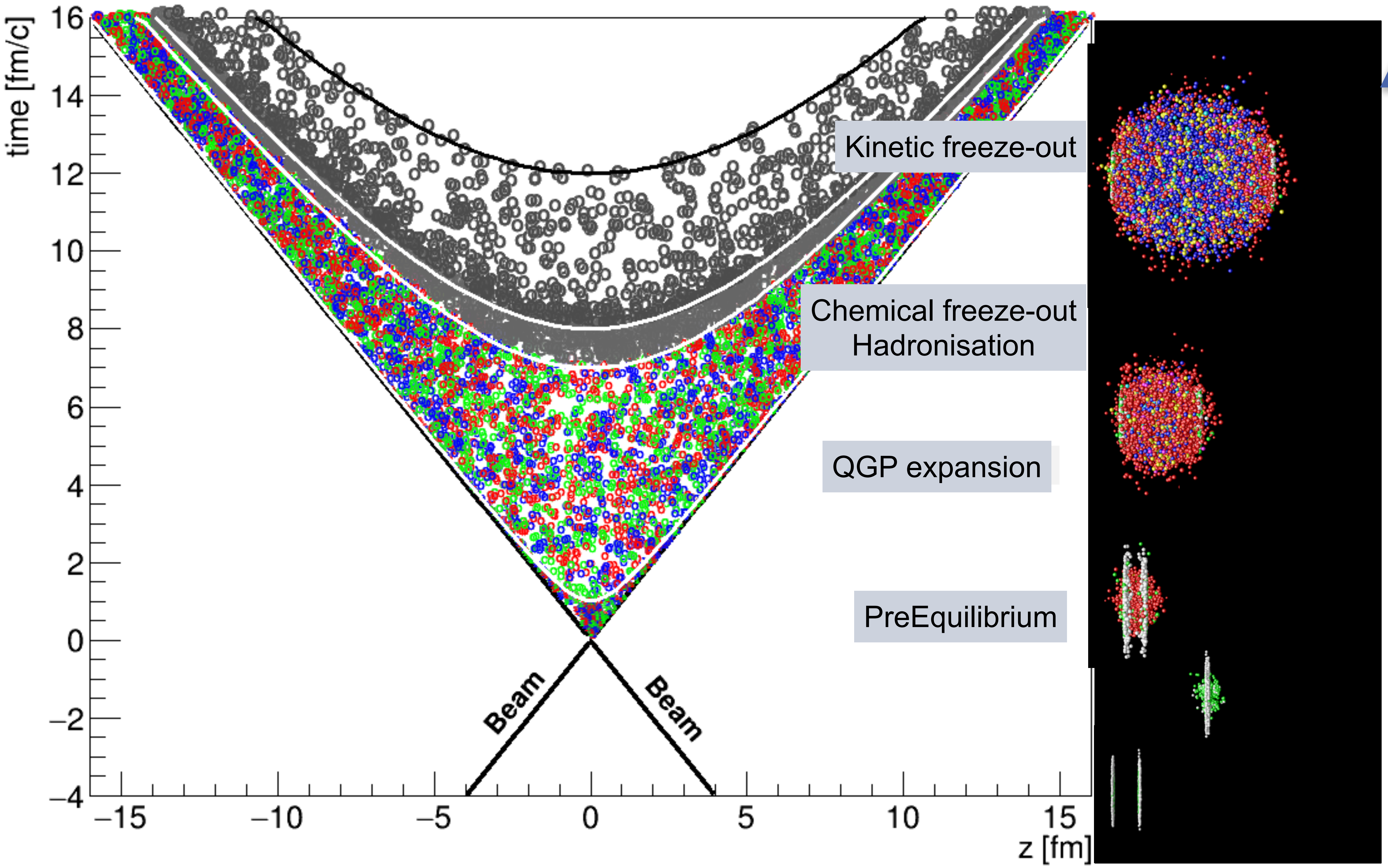
Kinetic freeze-out
(t=10fm/c)

Chemical freeze-out

Hydrodynamic
evolution (t~0.5fm/c)

Pre-equilibrium

Collision (t=0fm/c)



T ~ 90 MeV

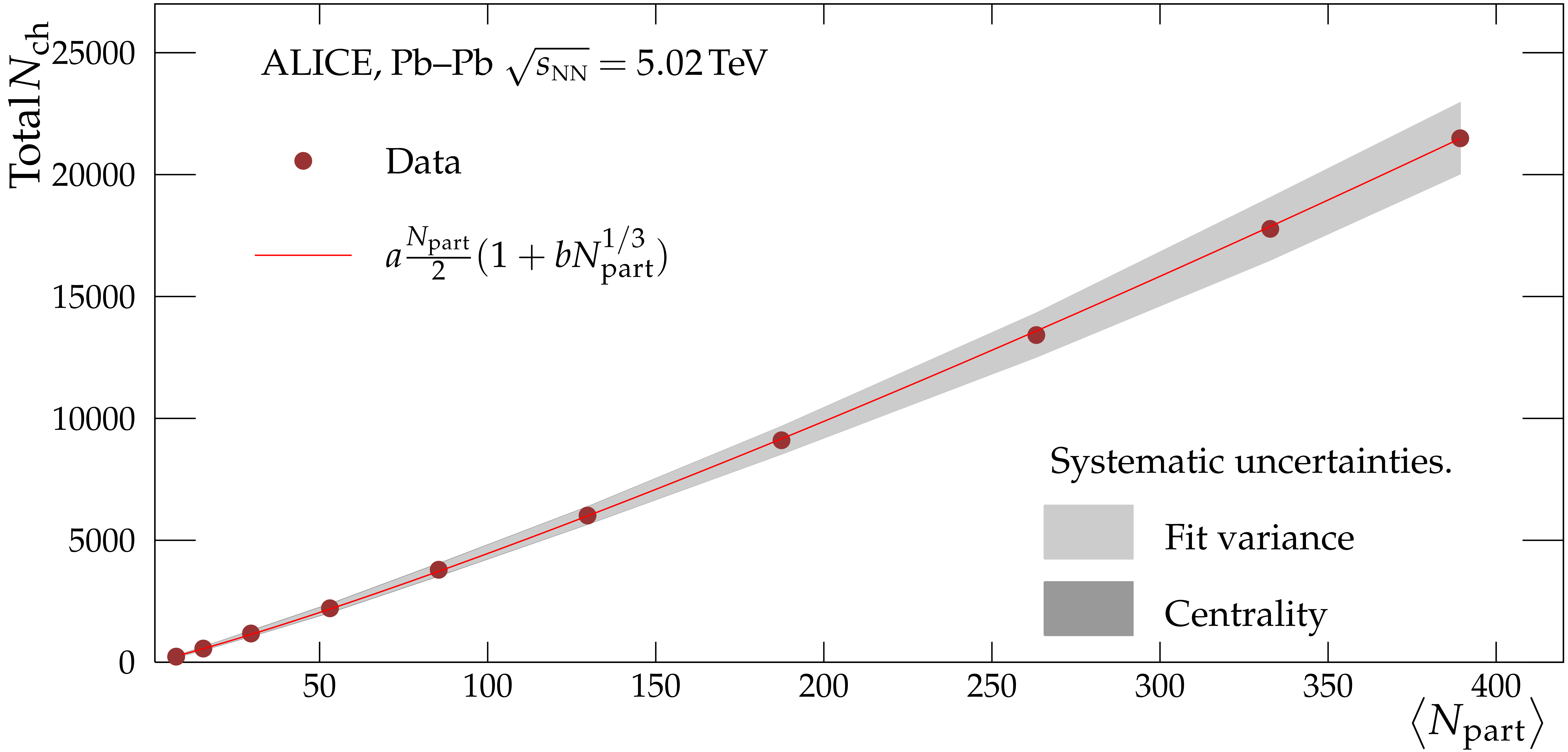
System cools down by (isentropic) expansion

T > 300 MeV

How to study heavy-ions collisions

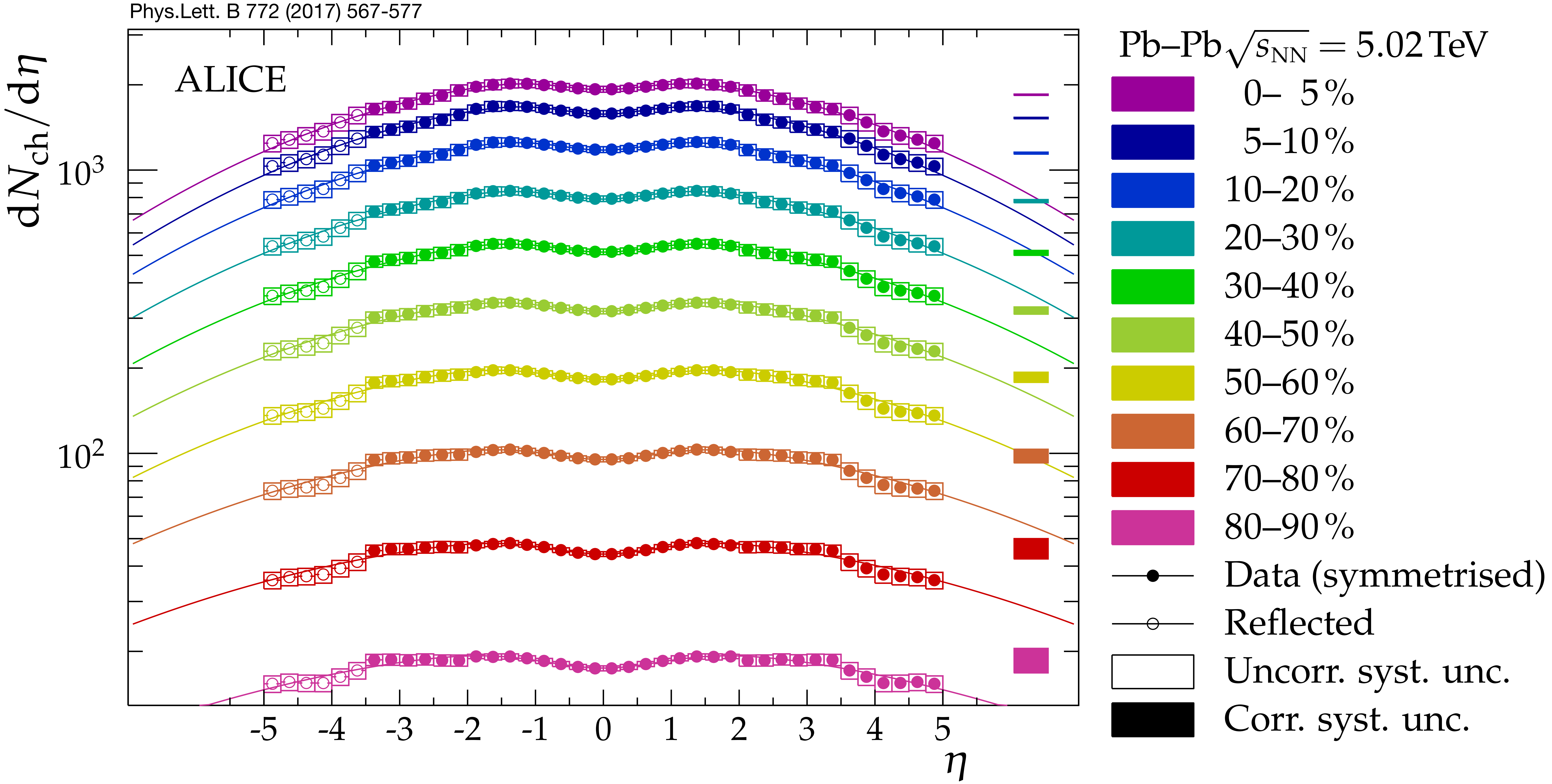

ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV
6th Nov 2024
13:16:46 CET
CMS Experiment at the LHC, CERN
Data recorded: 2024-Nov-06 10:55:06.459264 GMT
Run / Event / LS: 387854 / 23097014 / 33
ATLAS
EXPERIMENT
LHCb Experiment at CERN
Run / Event: 310067 / 3591585364
Data recorded: 2024-11-06 12:08:15 GMT

Thousands of particles of particles

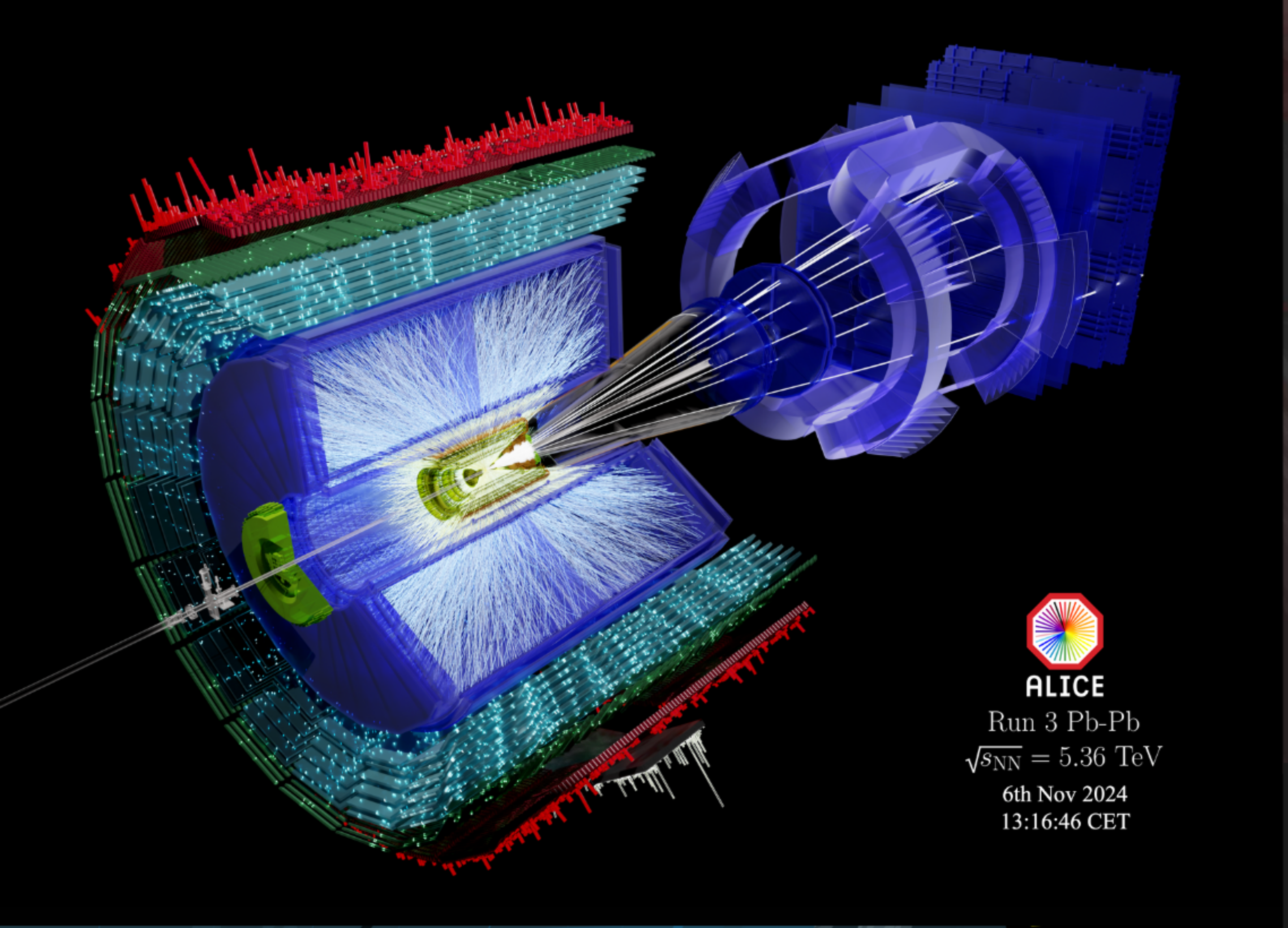


More than 20k charged particles crossing your detector!

High particle density environment



- Even at the LHC, 95% of all particles are produced with p_T < 2 GeV/c in pp and Pb-Pb collisions.
- Bulk particle production and the study of collective phenomena are associated with **"*soft*" *physics*** in the non-perturbative regime of QCD.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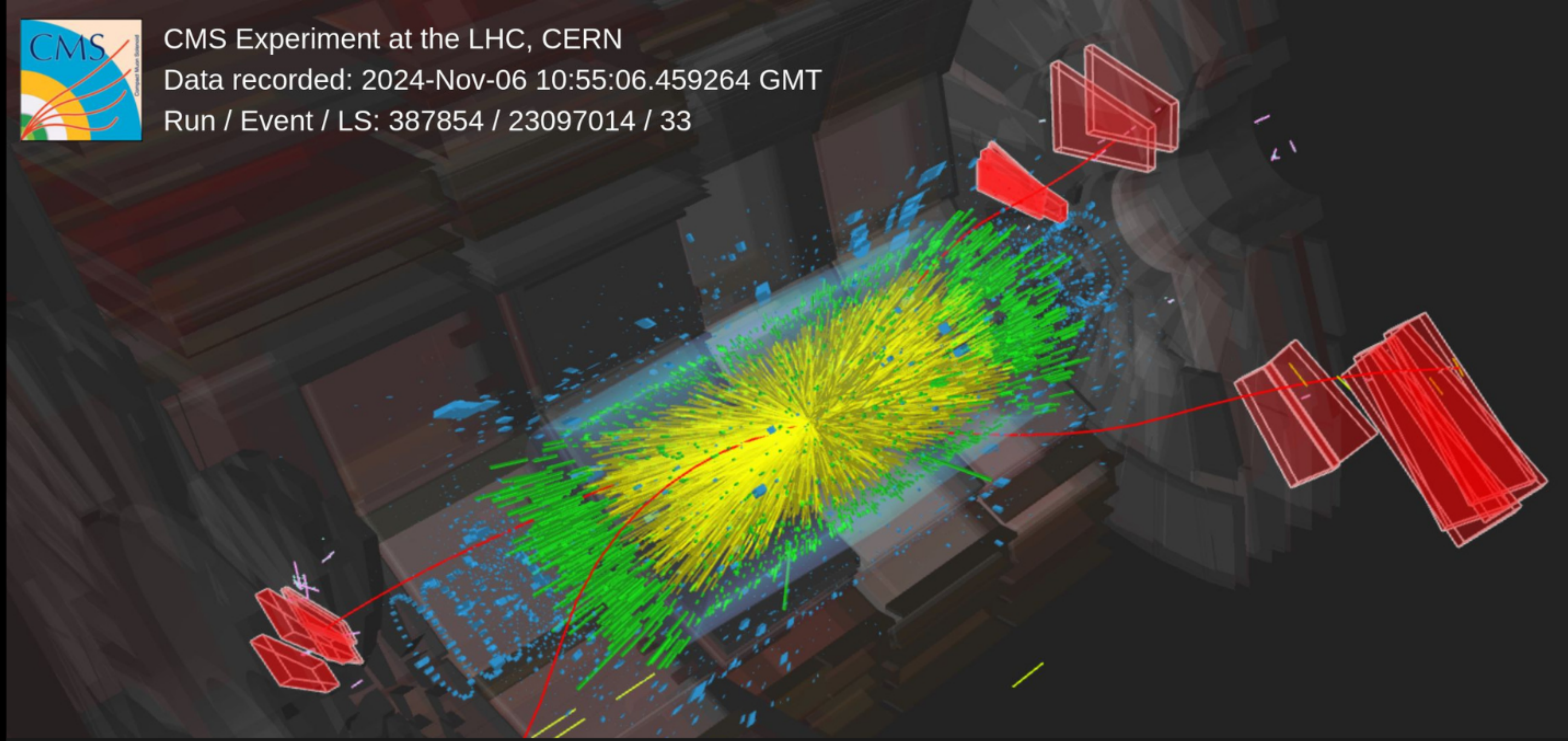
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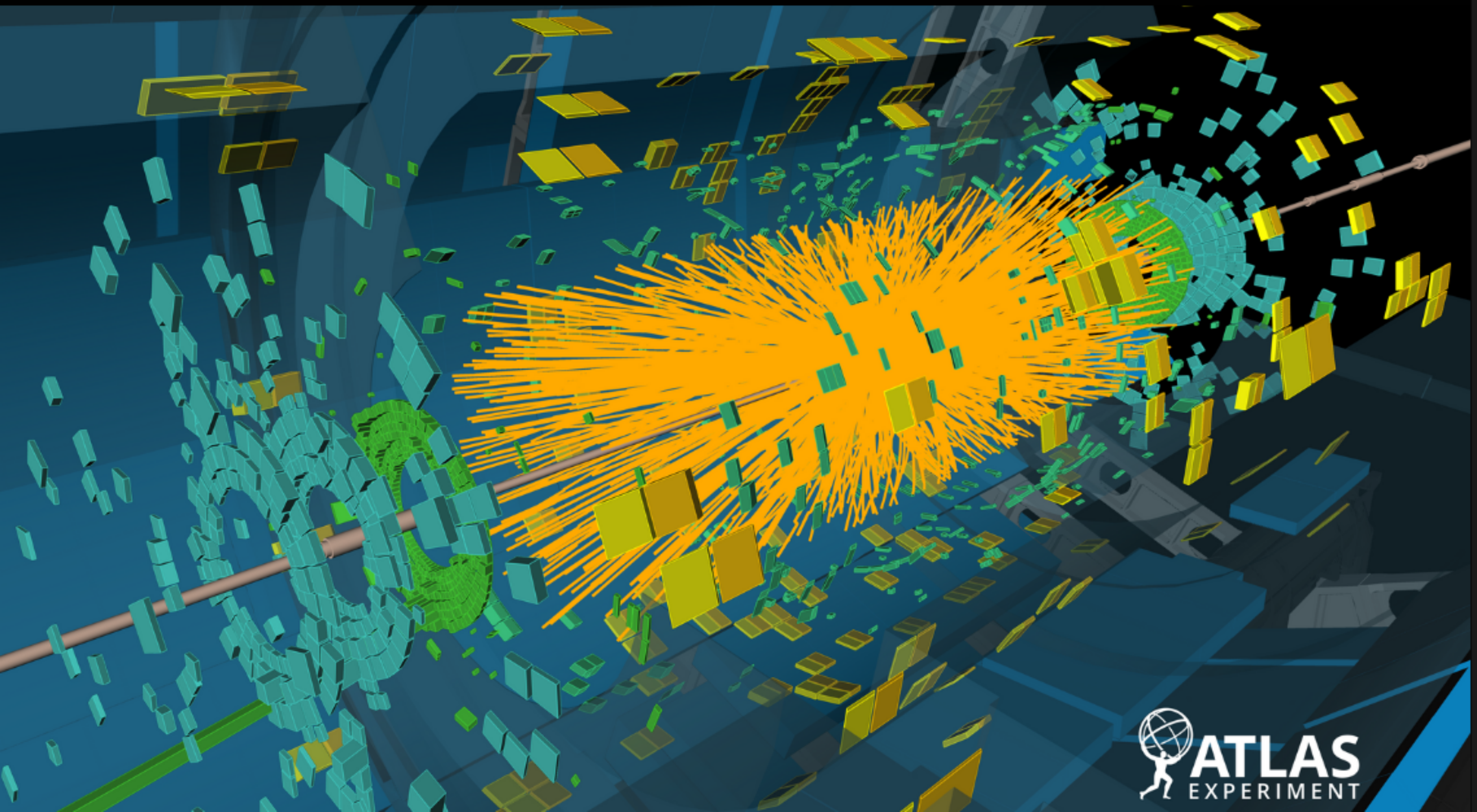
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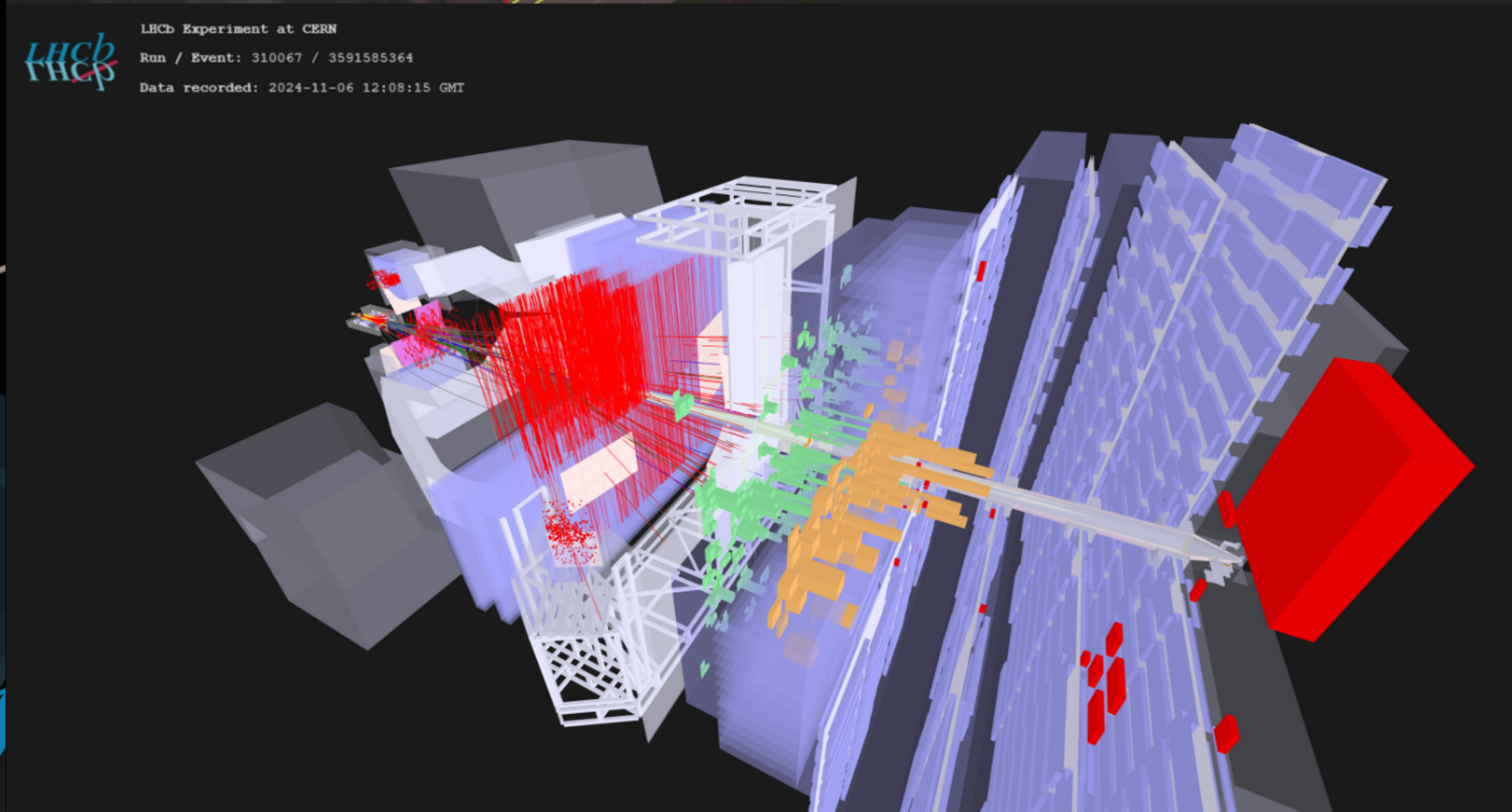
LHCb Experiment at CERN
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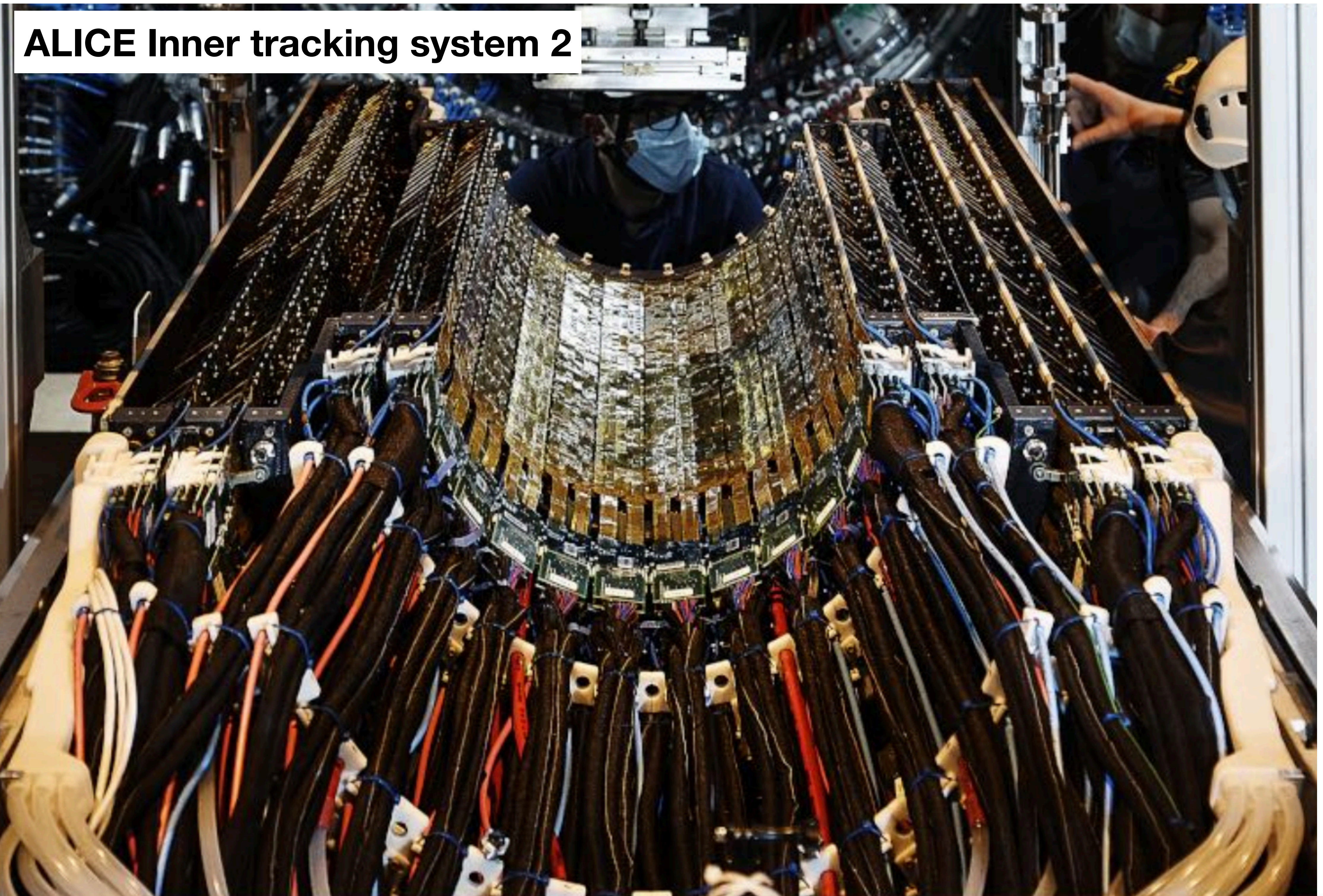
Detector granularity is key

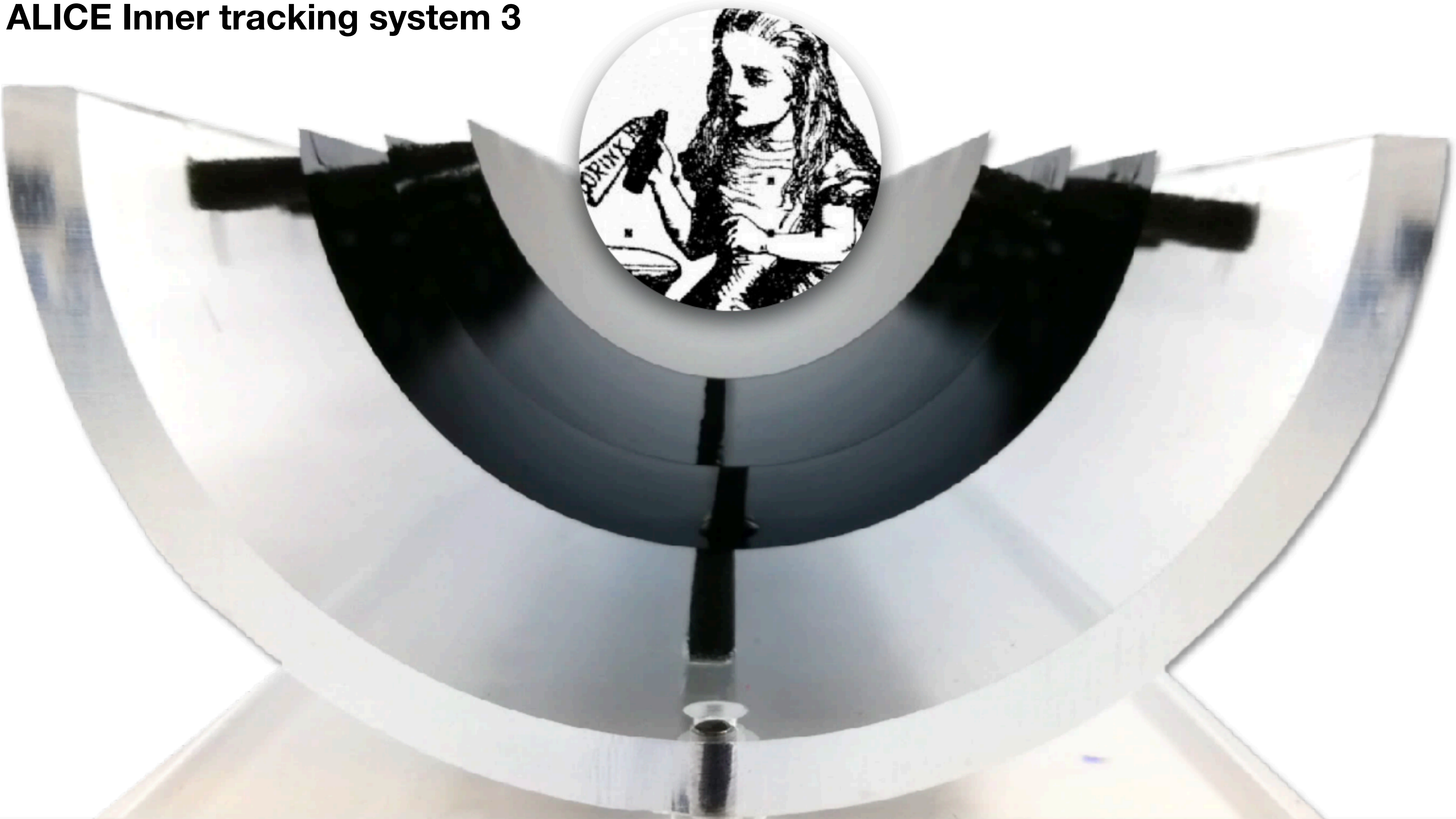
We need highly granular detectors to reconstruct the trajectories of particles

- up to o(100k) channels per cm^2 when we are 1-2 cm far away from the interaction region
  - Fabulous evolution of the silicon detector technologies
- Farther away we can start using other technologies like gaseus detector
  - Most prominent examples: STAR and ALICE Time Projection Chambers

ALICE Inner tracking system 2



ALICE Inner tracking system 3



Hadron identification

Different particles are sensitive to different stages of the collisions

- Stable particles: identification through dE/dx, Cherenkov, time of flight
- Weakly decaying particle (e.g. Λ, Ξ, Ω): topological identification

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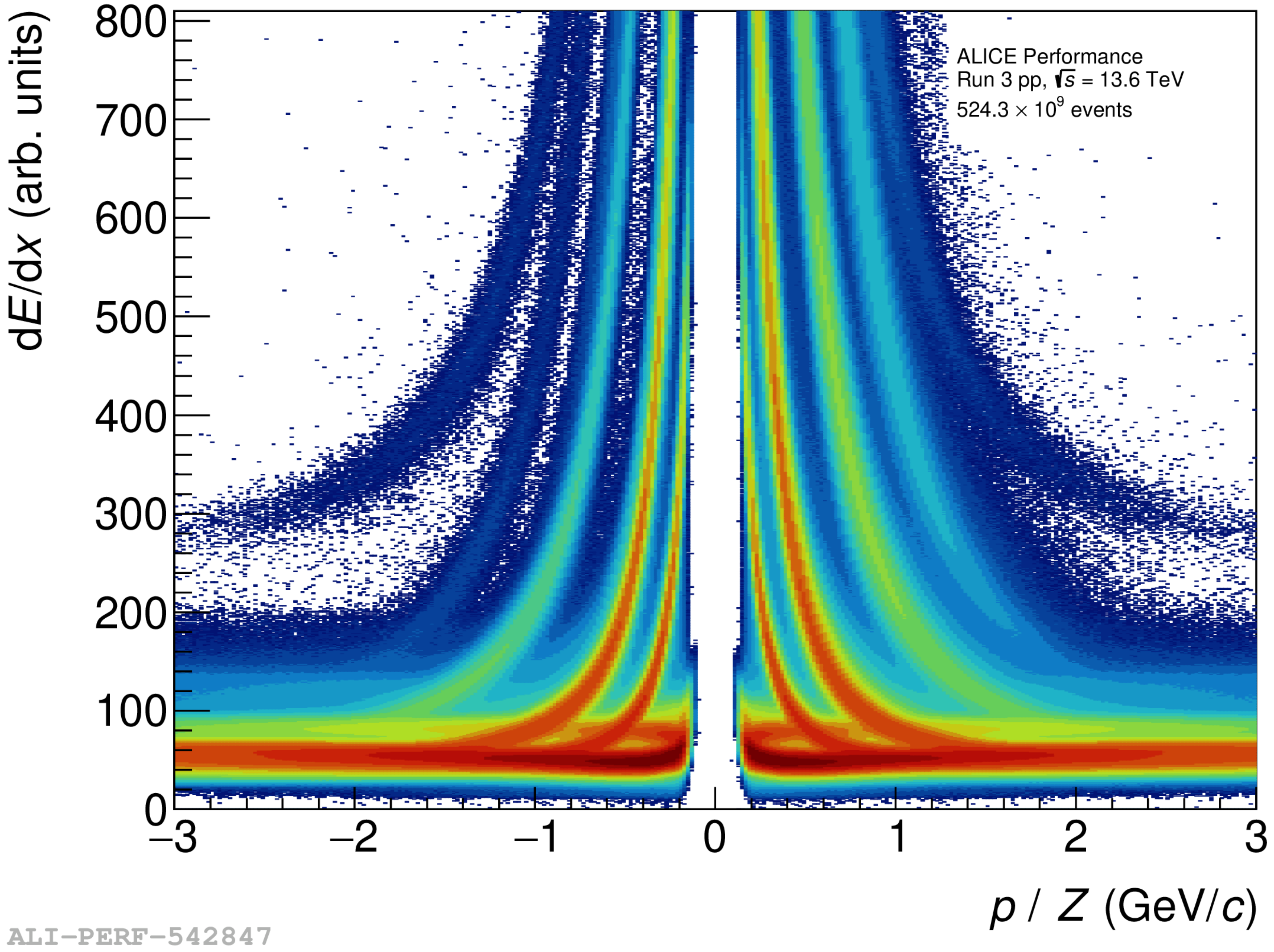

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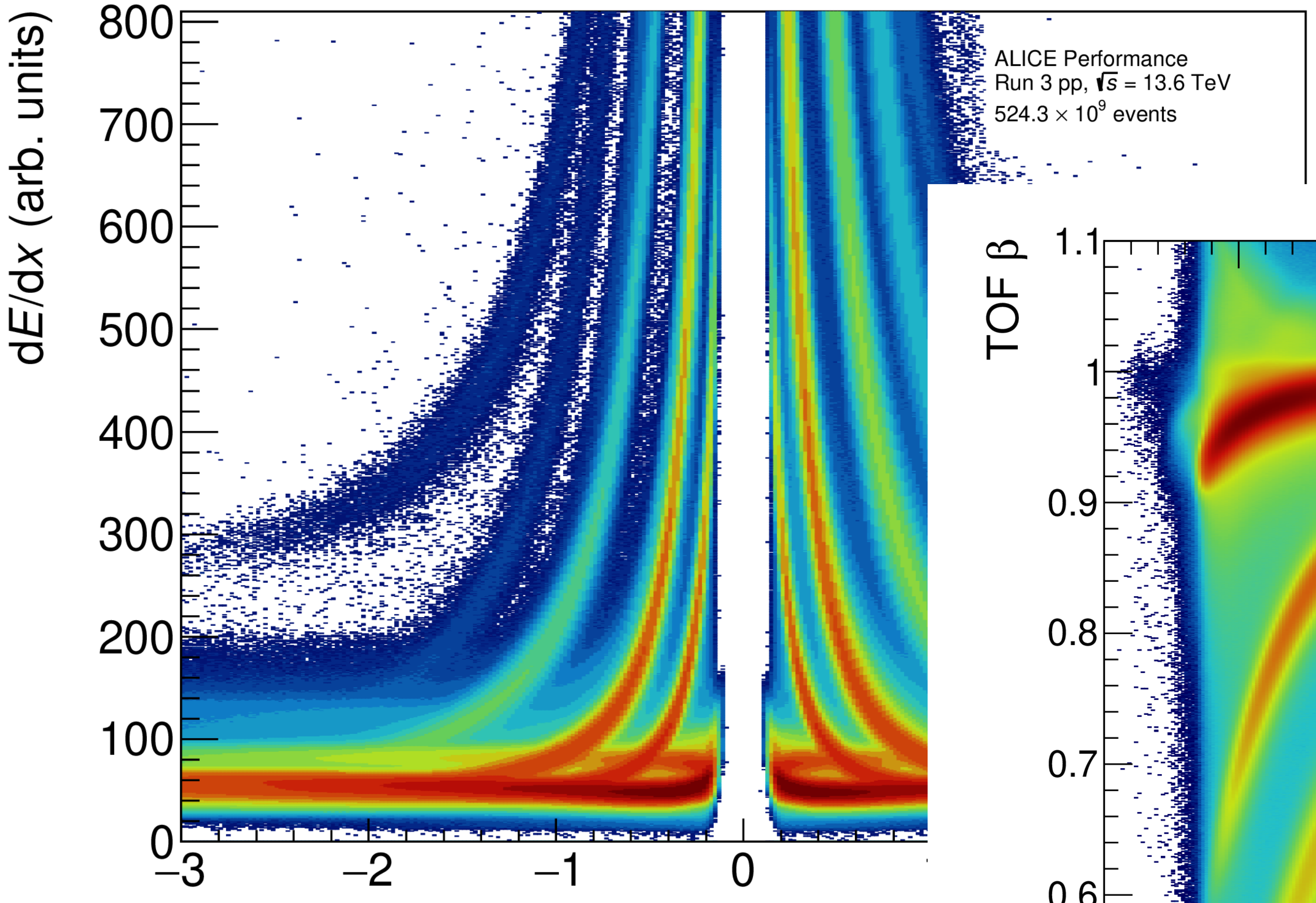
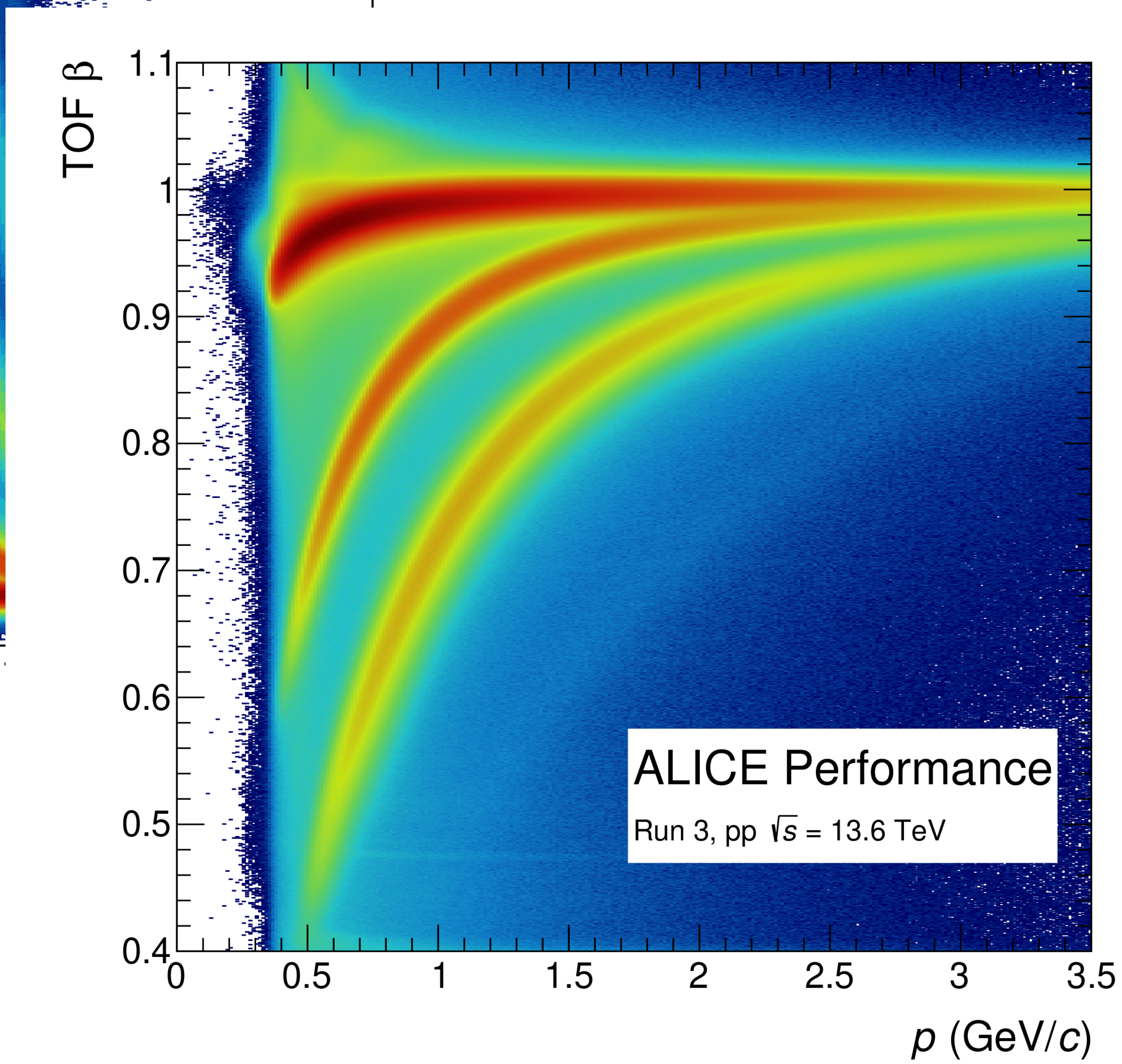


ALI−PERF−542847



ALI−PERF−537607

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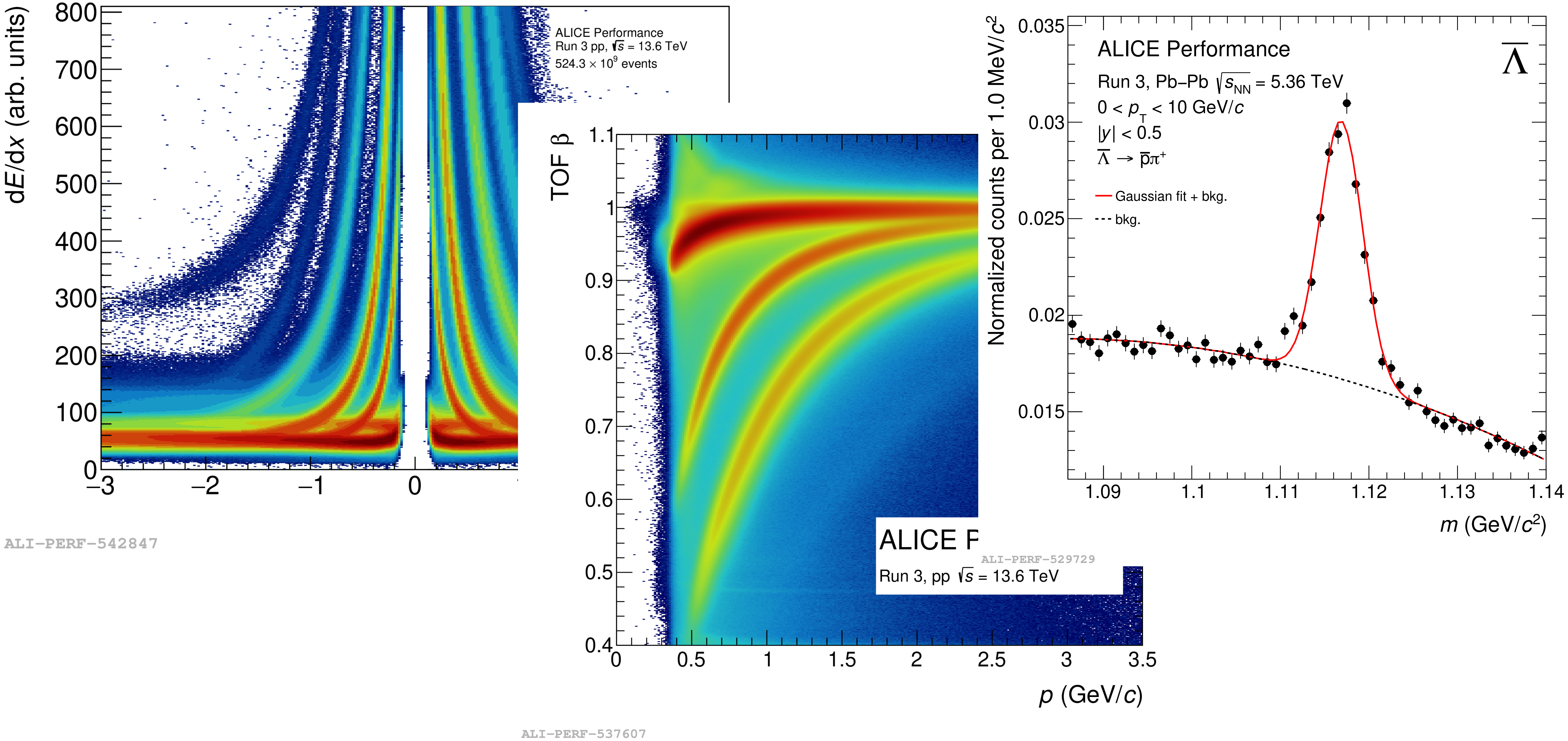

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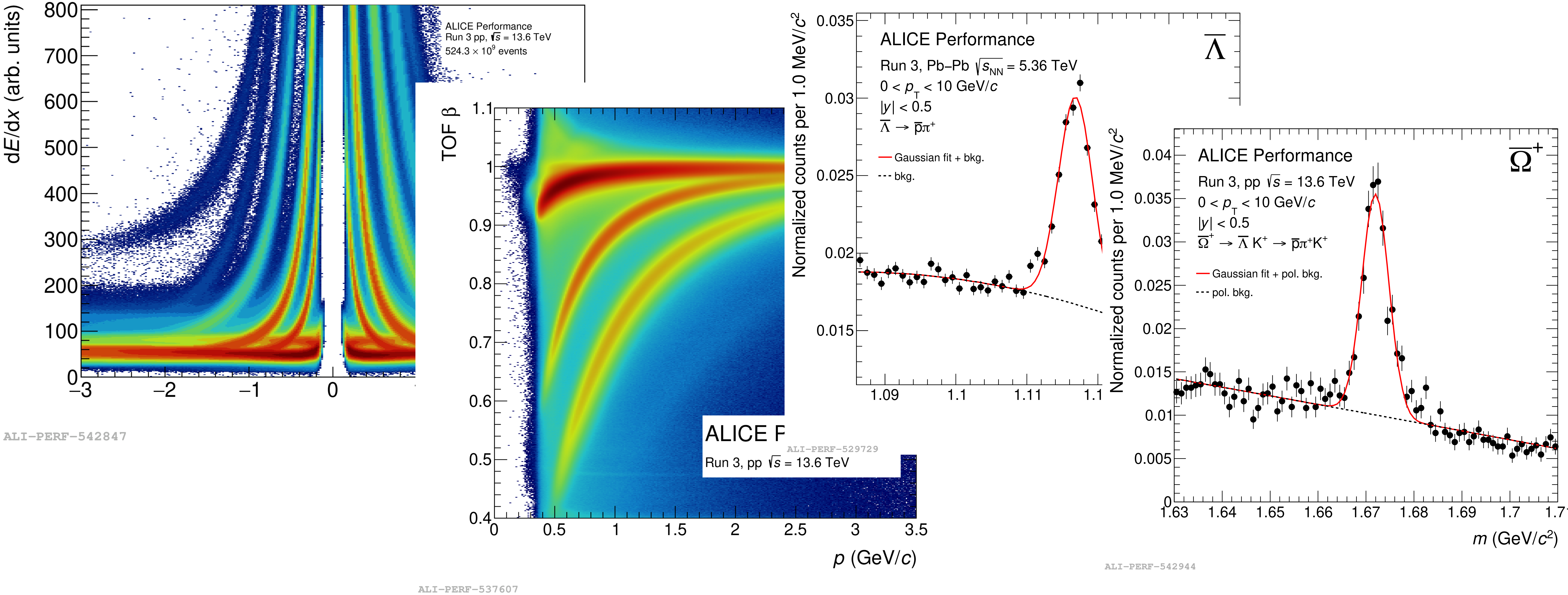
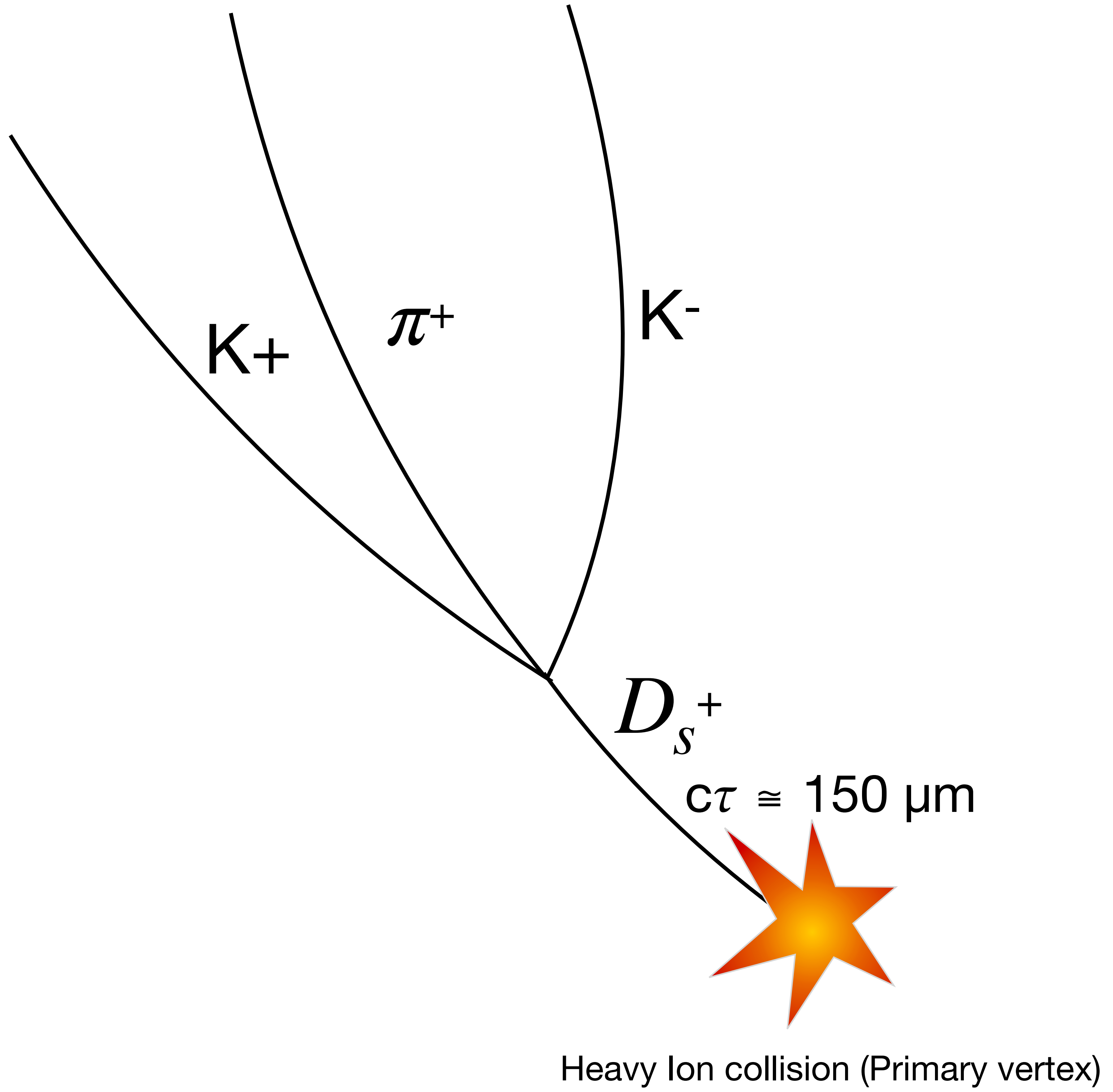
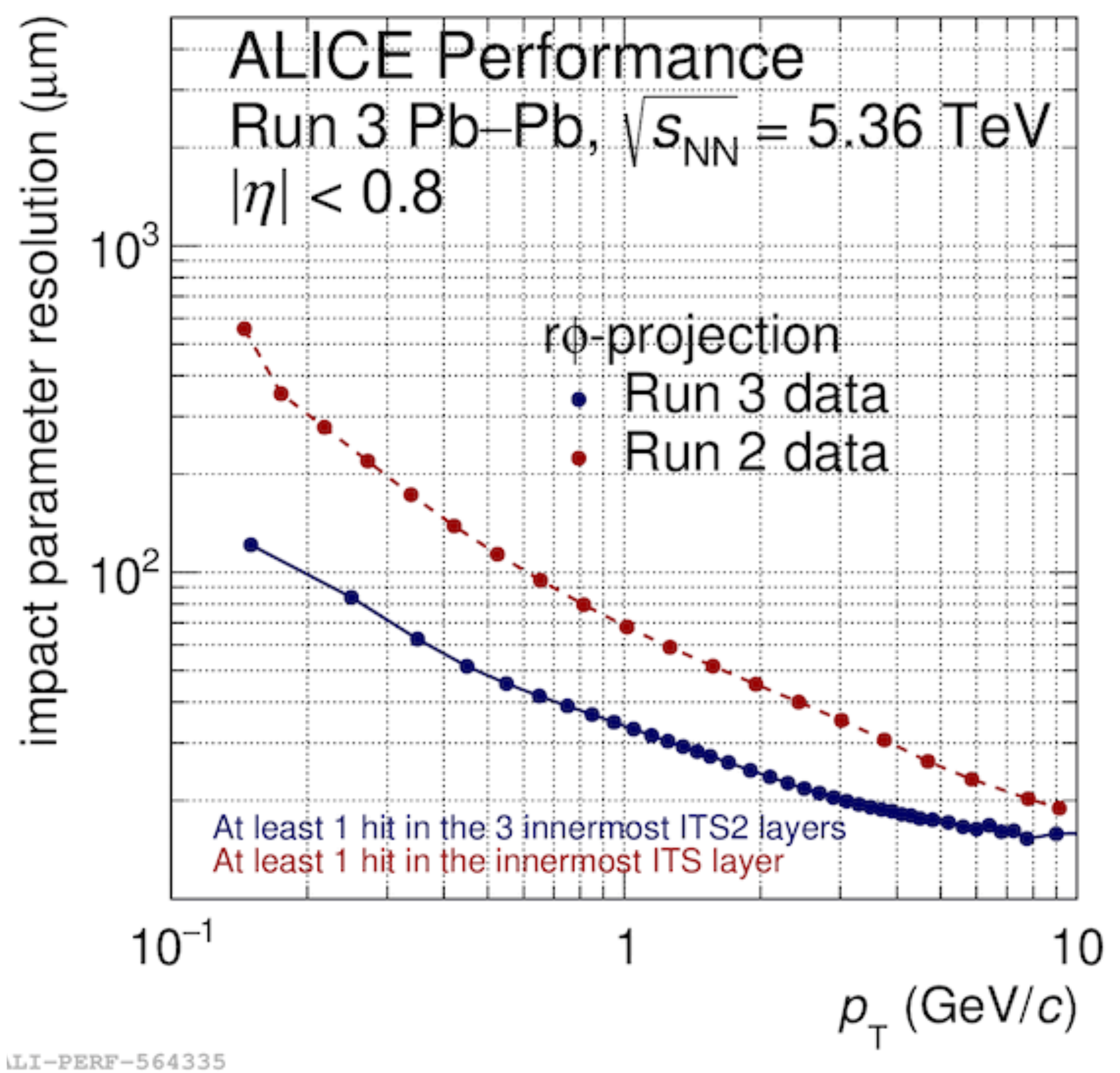


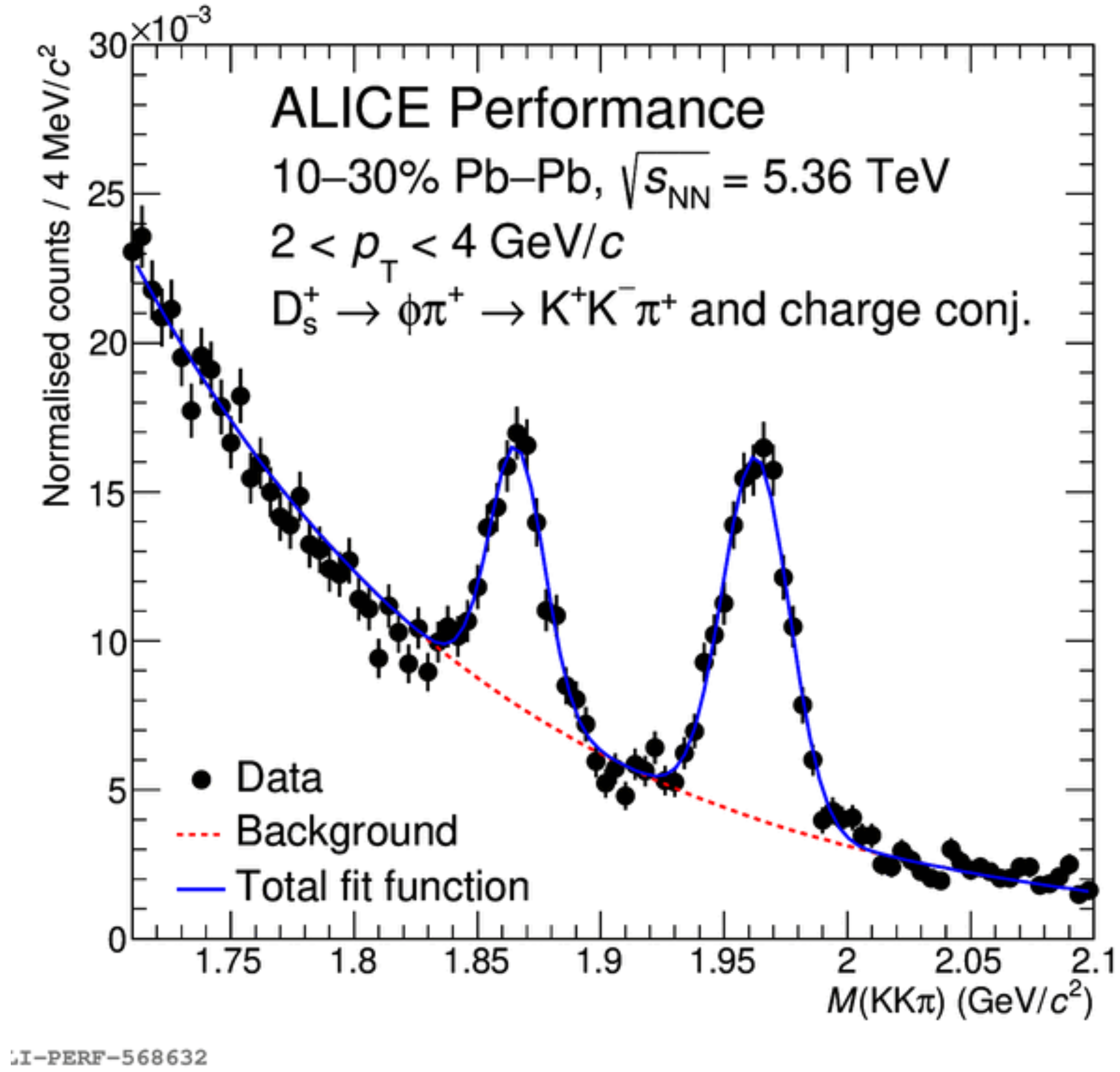
Topological identification of particles

Not all the particles fly through our detectors

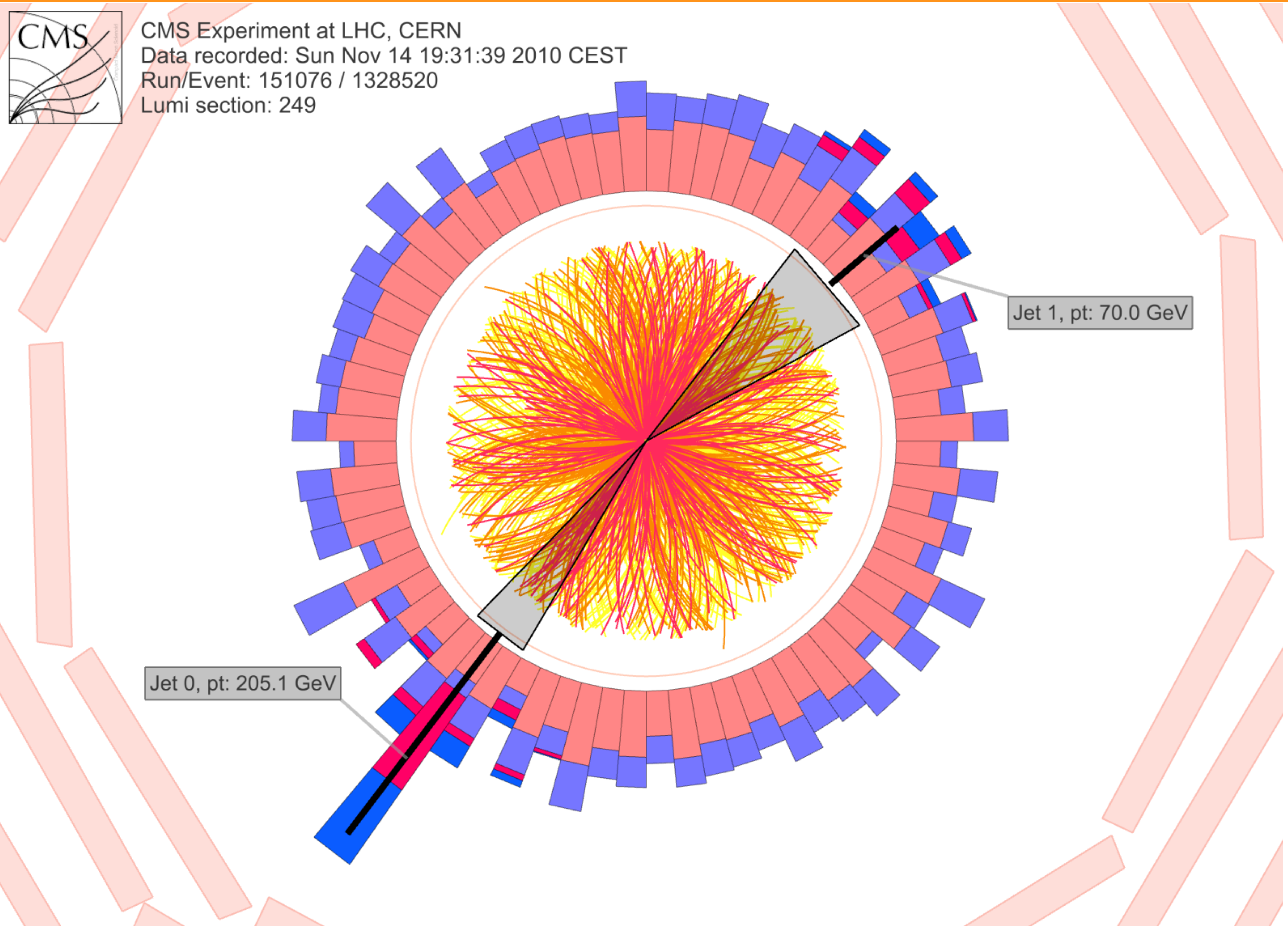
- Many actually decay within few hundreds um from the collisions
- Using silicon vertex detectors we can reconstruct the decay point (vertices)
- Secondary vertex + momentum information of the daughter tracks = topological selections







Calorimetry



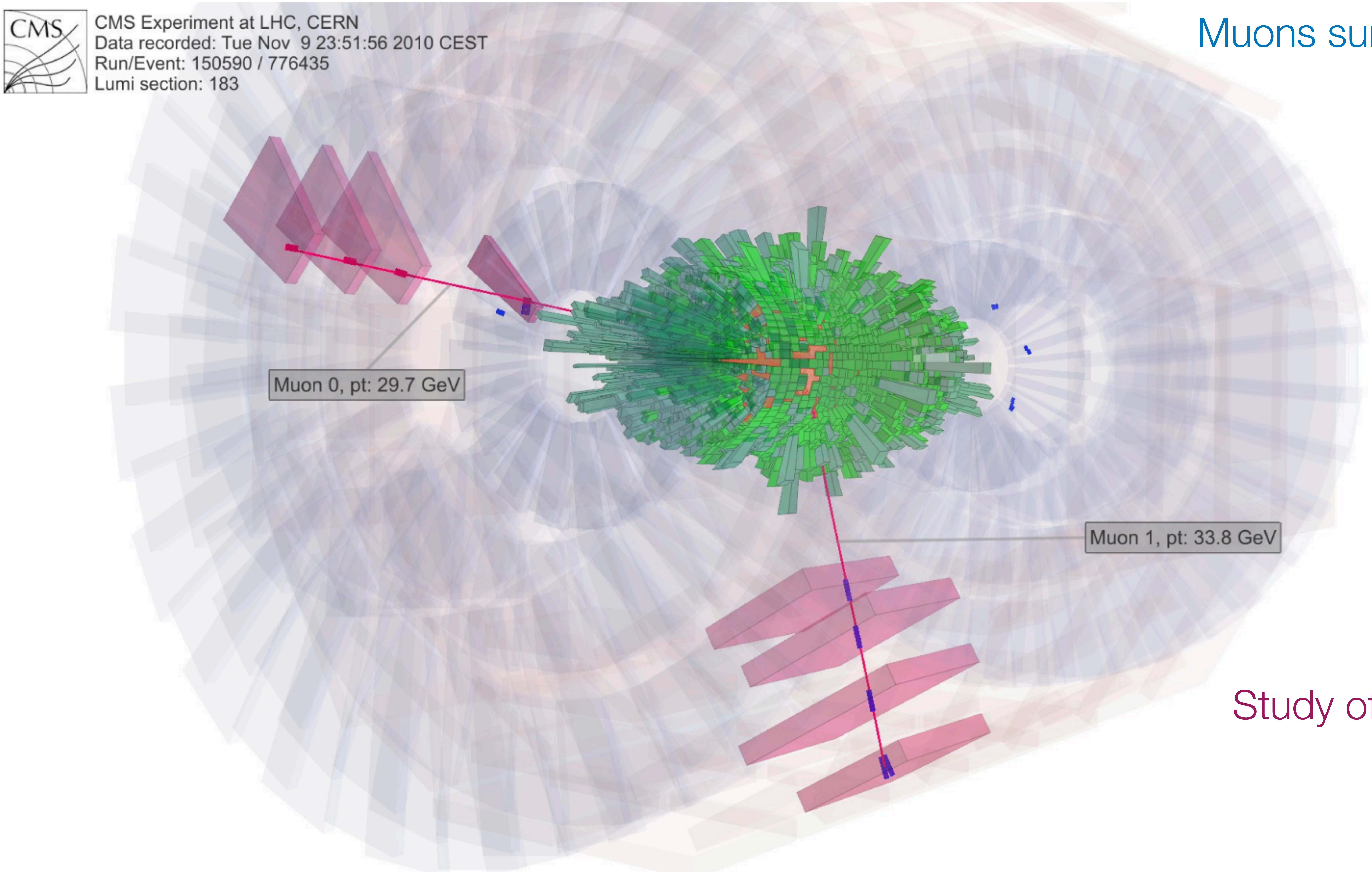
Photon and high energy electrons can be identified by EM calorimeters

- Positioned after the trackers
  - Electron/gamma separation
  - Smaller granularity allowed

The energy of the rest of the hadron can be measured in hadronic calorimeters

- They enable to measure the energy of the collision going to neutral particles

Muon identification



Muons survive all calorimeters

Clean identification

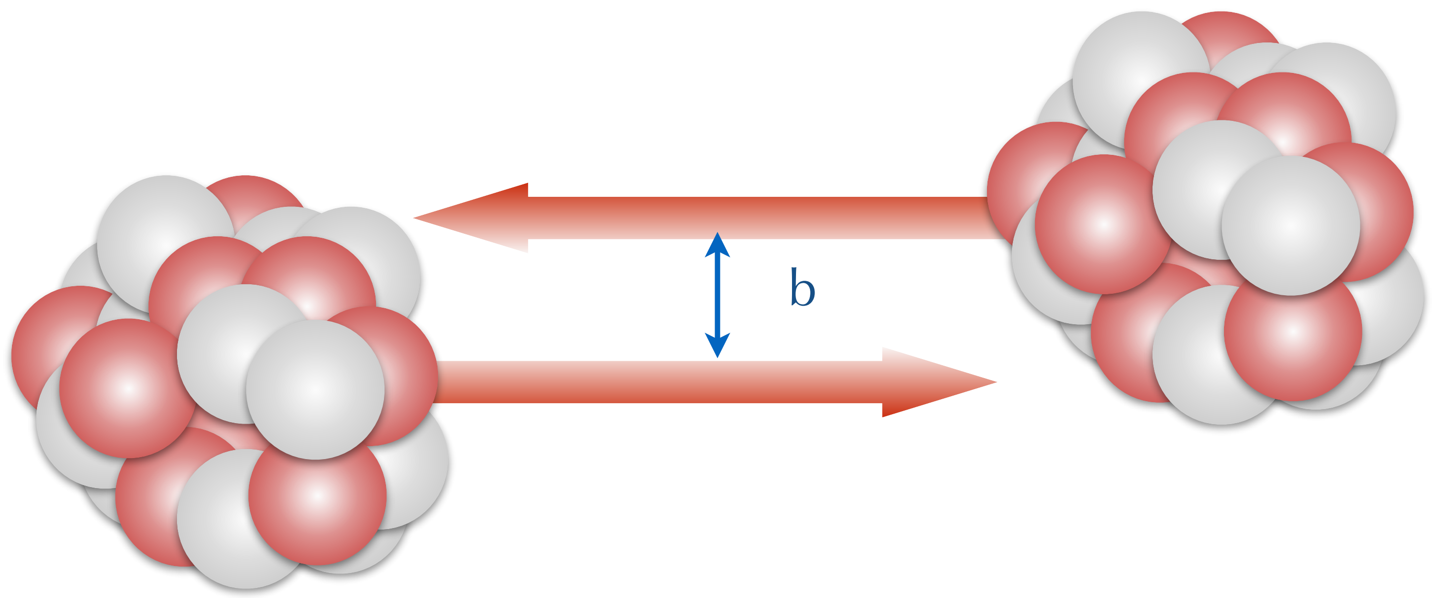
Study of quarkonia, Z, W, H

What do we measure?

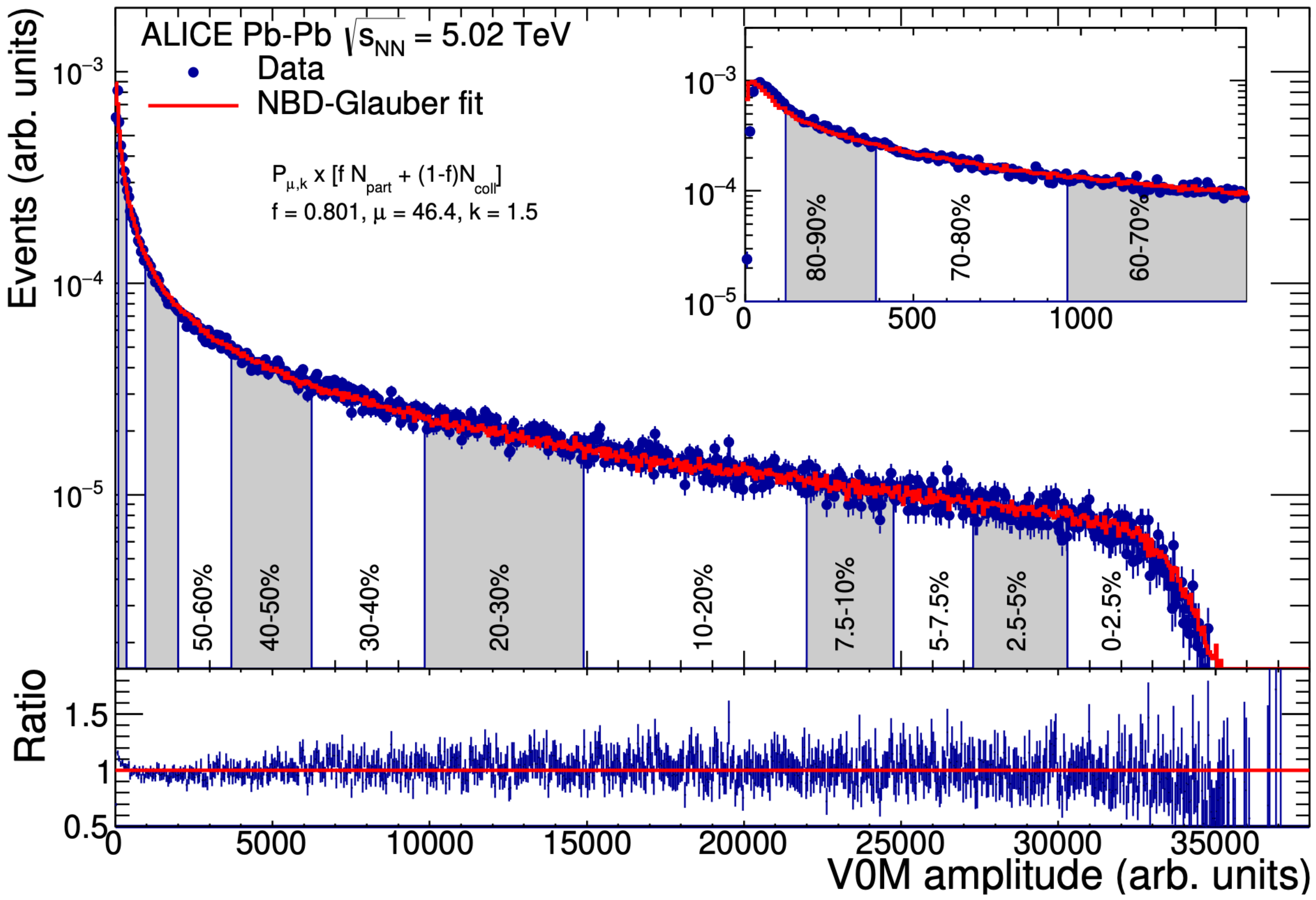
Different kind of collisions: centrality

The centrality of a collision is defined by the impact parameter *b*:

Most central collision ⇔ Smallest b



Experimentally it is possible to correlate the charged particle multiplicity to *b* by fitting data with the function shape predicted by the Glauber model.

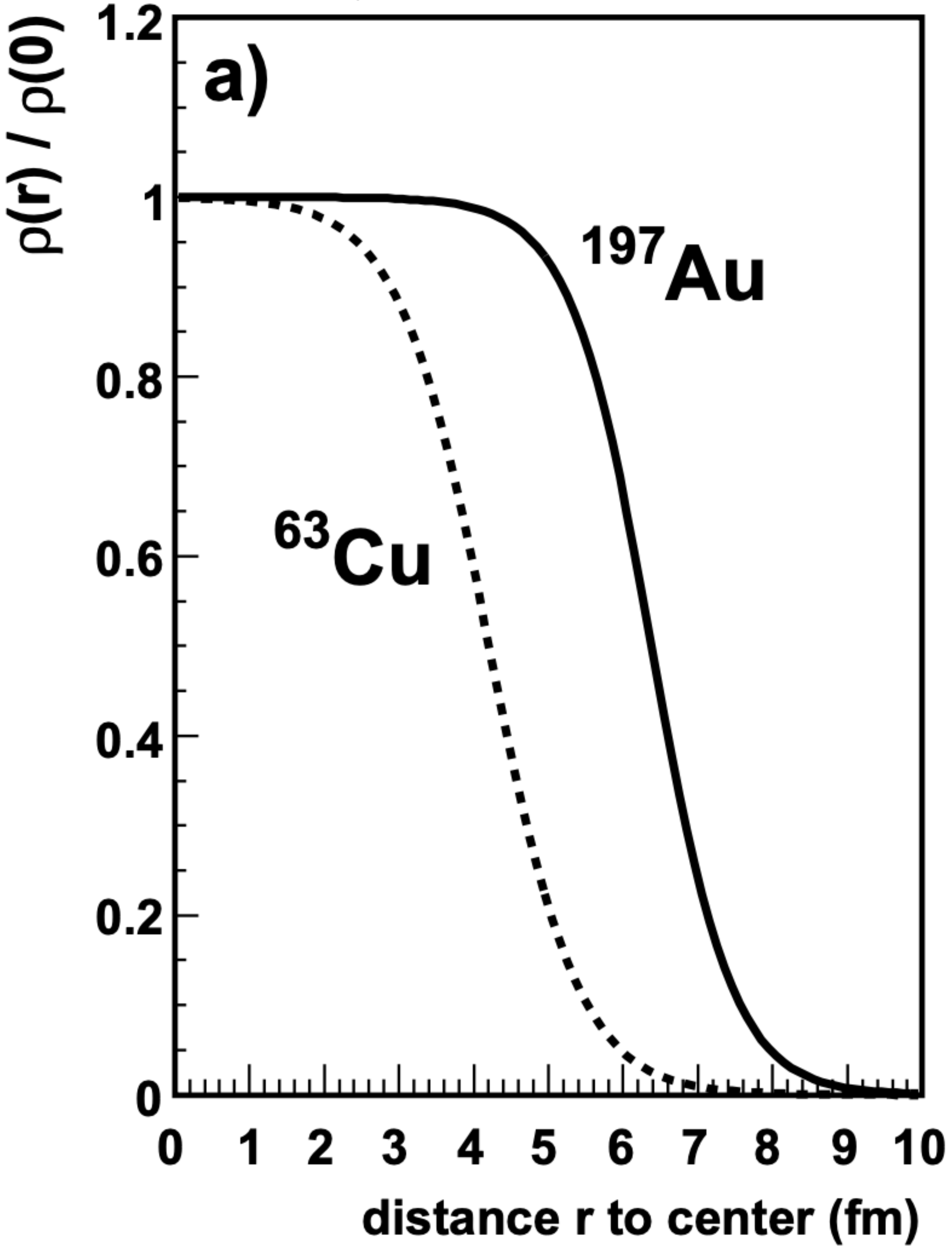


Assumptions of the Glauber model:

- Nucleons travel on straight lines
- Collisions do not alter their trajectory and remain intact
- No quantum-mechanical interference
- Interaction probability for two nucleons is given by the nucleon-nucleon (pp) cross-section.

Glauber Monte Carlo simulation (I)

https://arxiv.org/pdf/nucl-ex/0701025.pdf



Nucleons are distributed in space sampling from the Woods-Saxon distribution:

$$\rho(r) = \frac{\rho_0}{1 + e^{r-R/a}}$$

ρ_0 is the density in the center, *R* is the radius of the nucleus and *a* the skin depth (*R* and *a* are measured in electron-nucleus scatterings)

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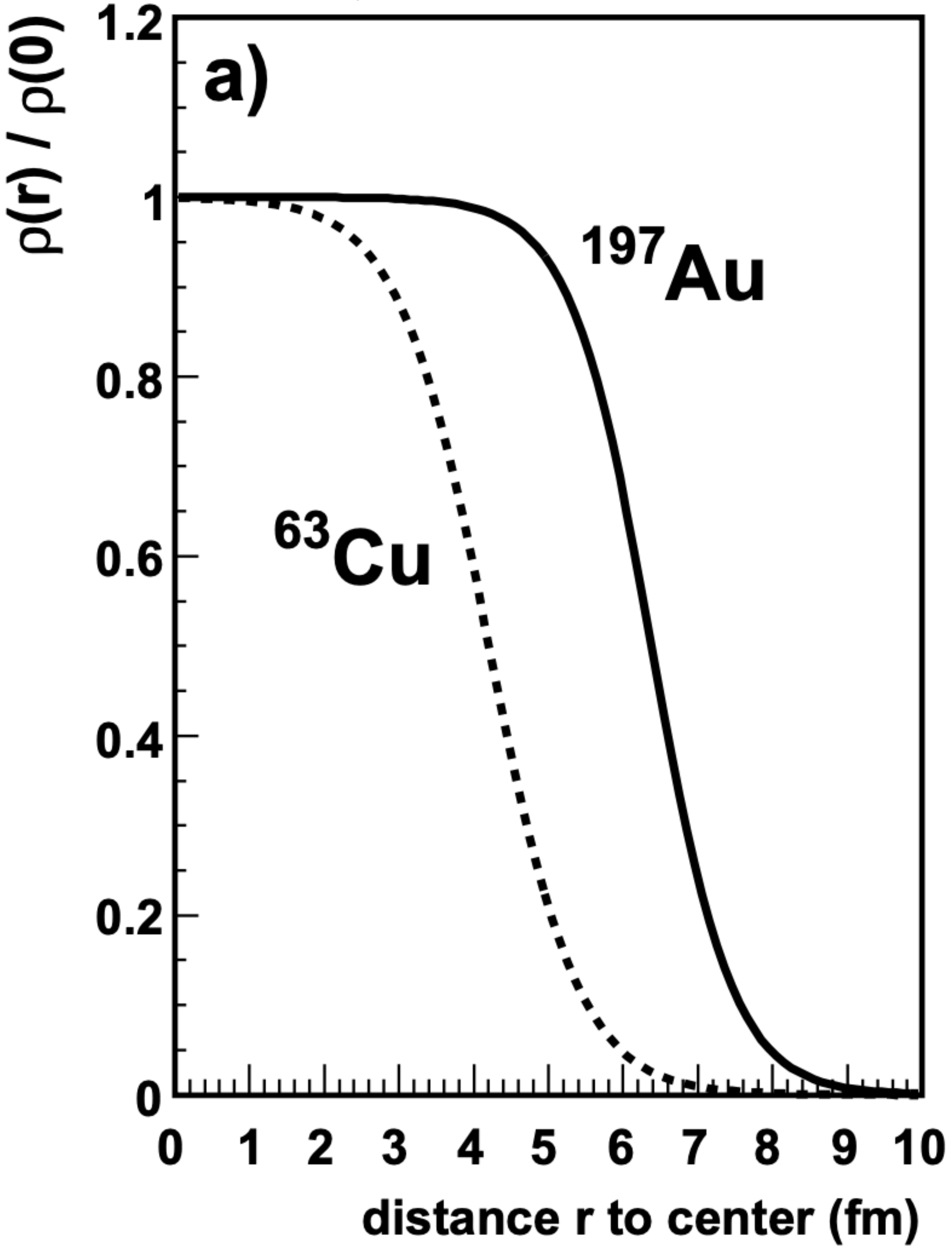

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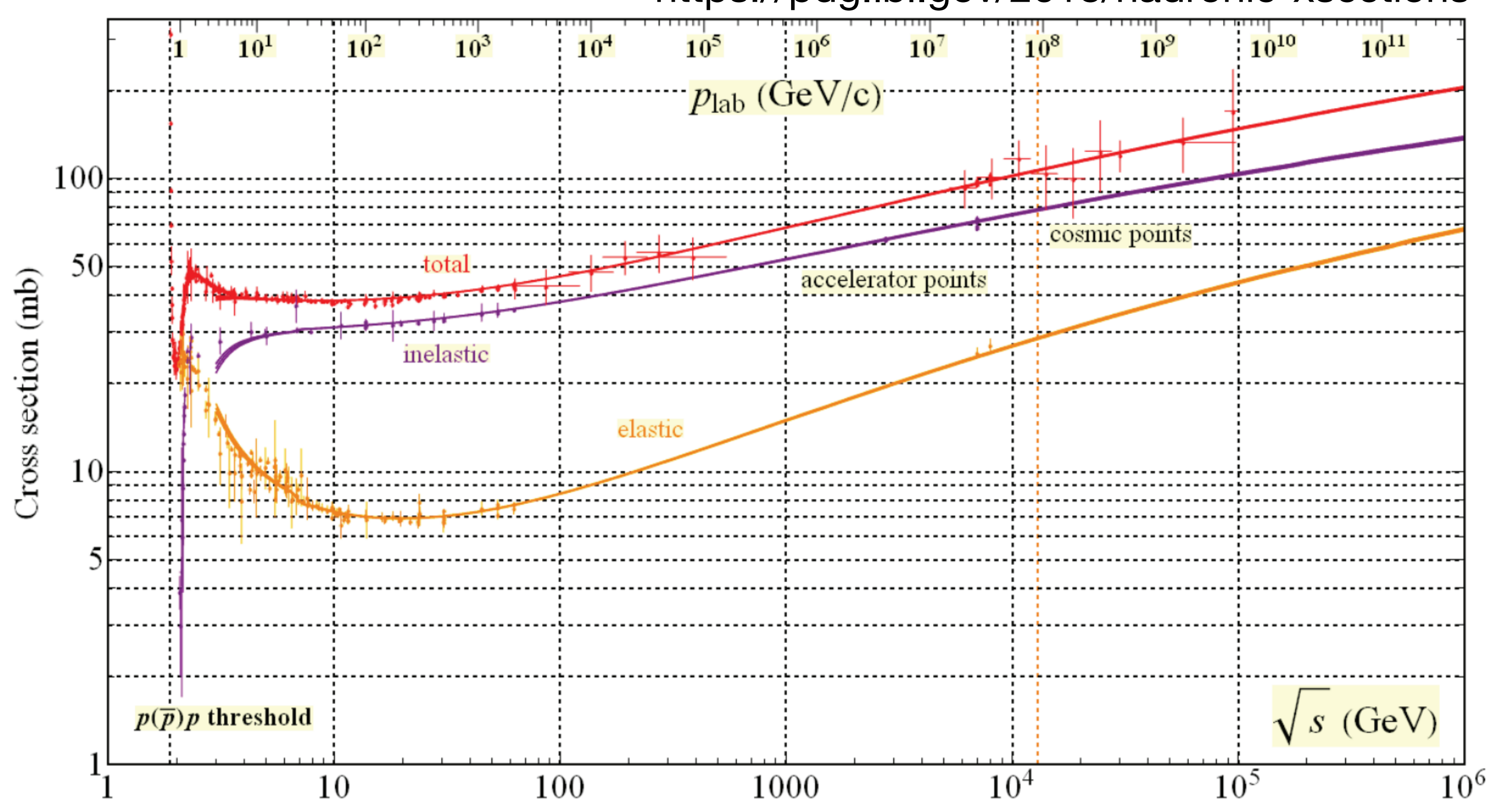
The interaction probability is taken from measurements and their interpolations

https://pdg.lbl.gov/2018/hadronic-xsections

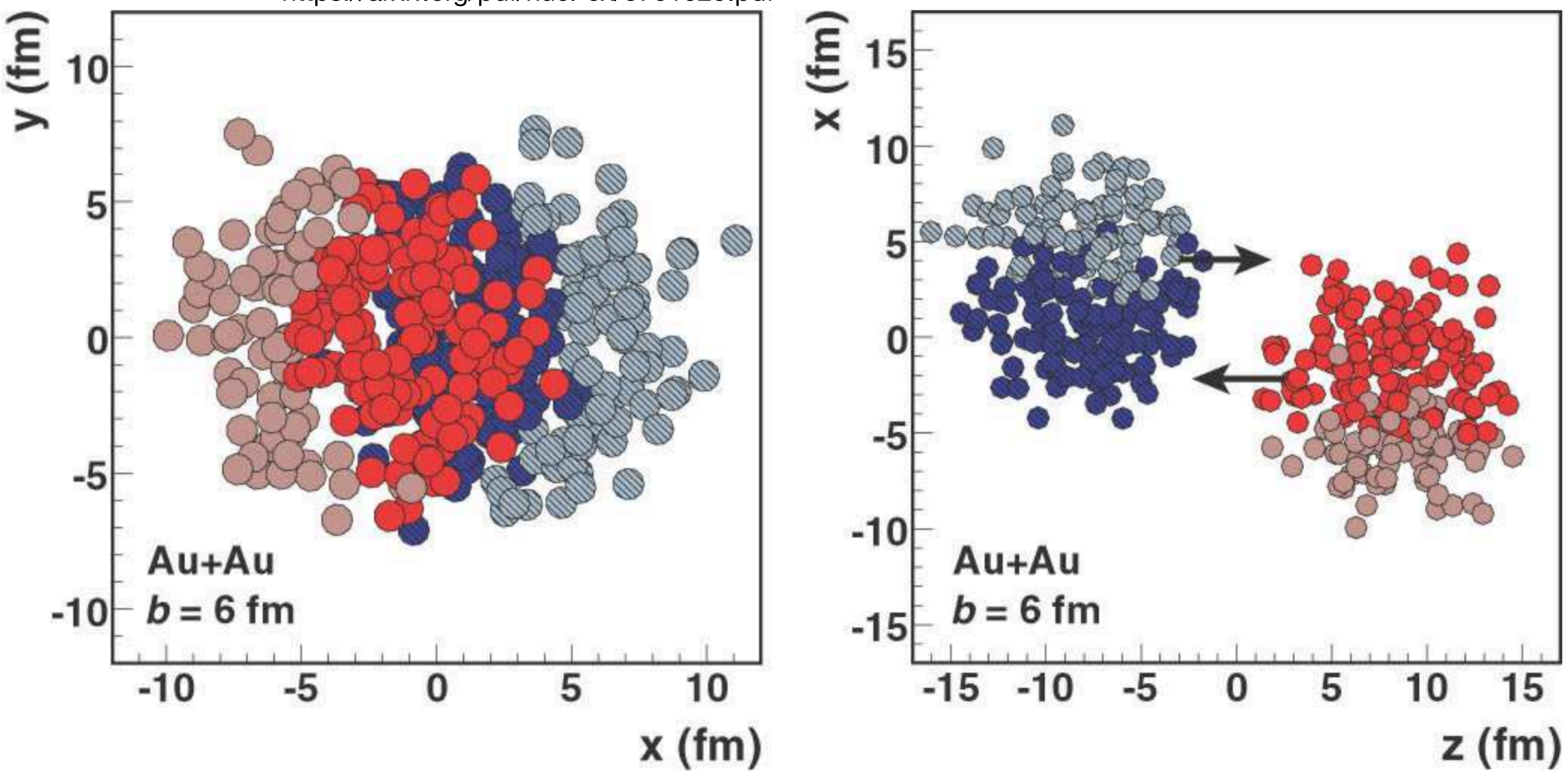


2 nucleons from the colliding nuclei are considered as interacting if their distance on the transverse plane satisfies:

$$d \leq \sqrt{\sigma_{\mathrm{inel}}^{\mathrm{NN}}}$$

Glauber Monte Carlo simulation (II)

https://arxiv.org/pdf/nucl-ex/0701025.pdf



Once distributed in space, the nucleons travel on straight paths along the z axis. One can compute:

- Number of nucleons participating in at least one interaction (N_{part})
- Number of binary collisions (N_{coll})

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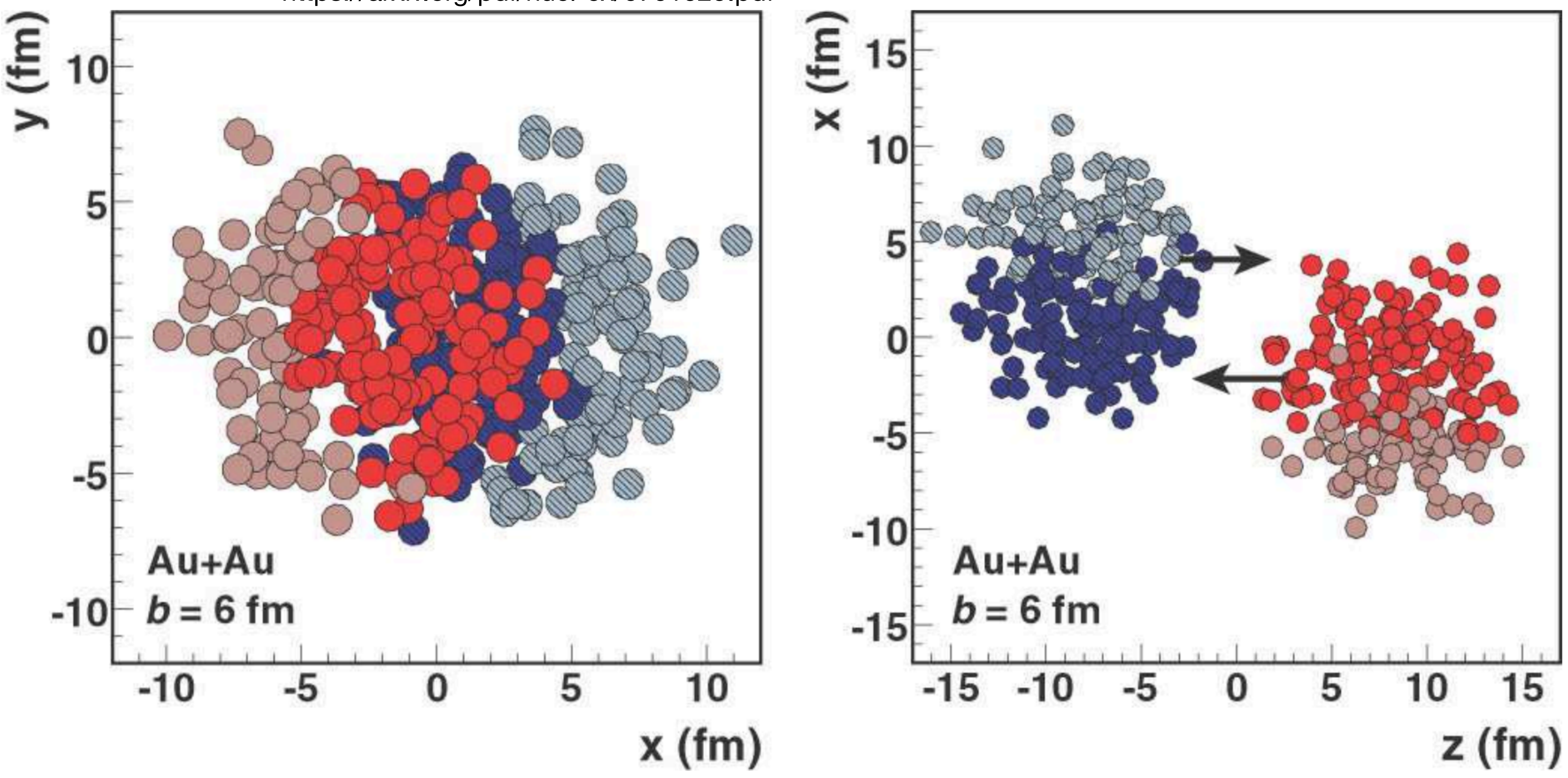

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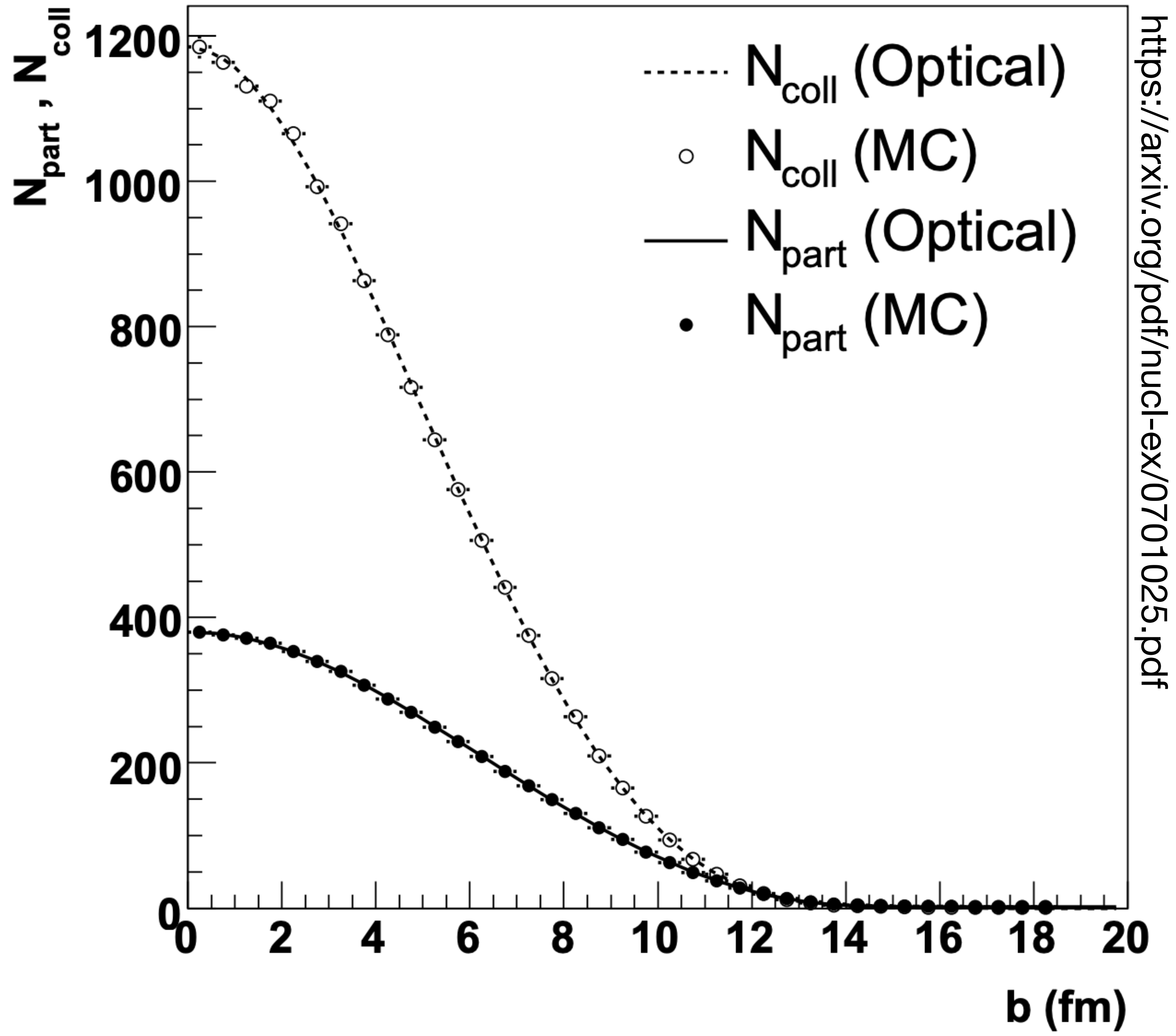

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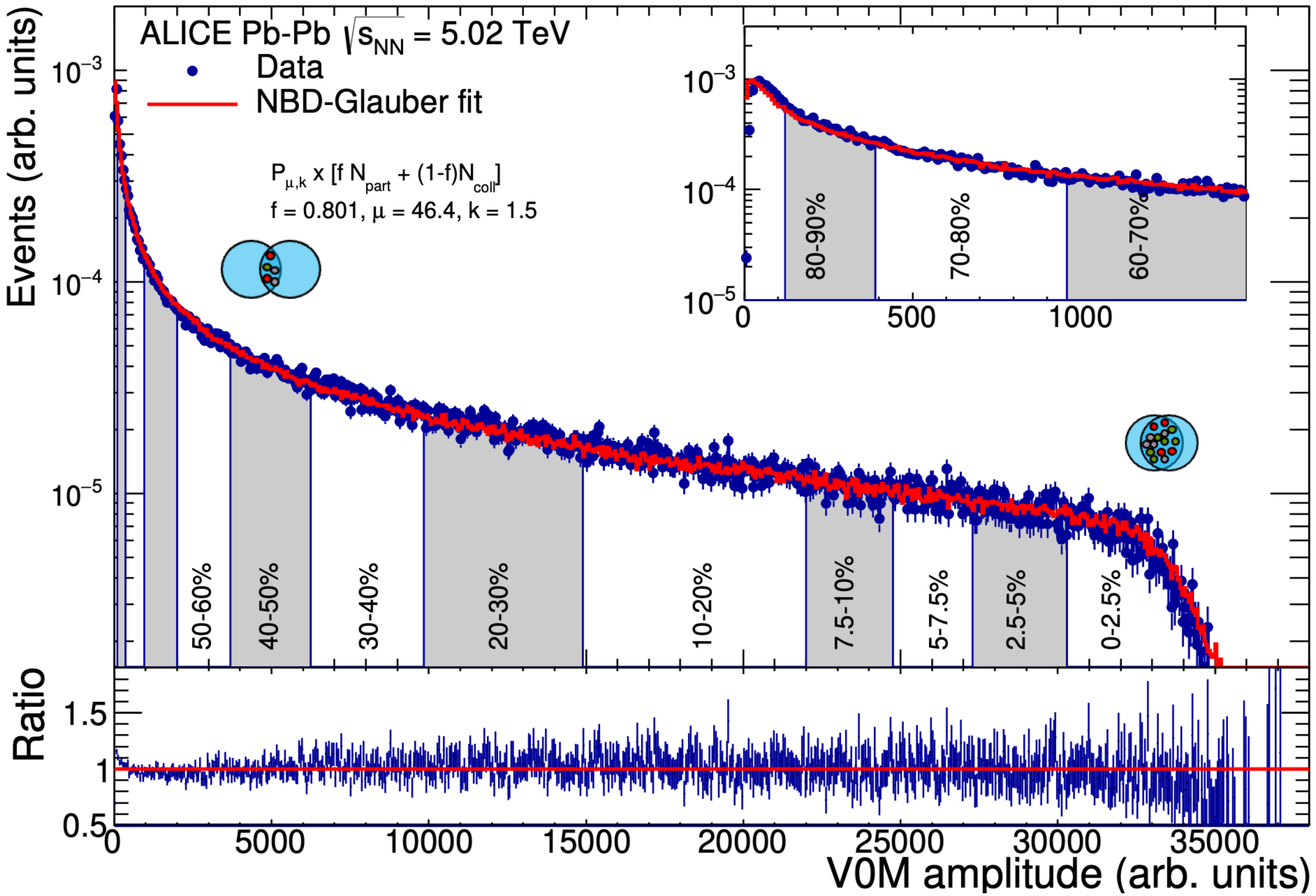
Examples:

- 10% most central collisions at RHIC (Au-Au, 200 GeV): N_{coll} ~1200, N_{part} ~380
- 5% most central collisions at LHC (Pb-Pb 2.76 TeV): N_{coll} ~1680, N_{part} ~382

The Glauber Model fit

In pp collisions at high energy, the charged particle multiplicity $d\sigma/dN_{ch}$ has been measured over a wide range of rapidity and is well described by a Negative Binomial Distribution



$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{(\mu/k)^n}{(\mu/k+1)^{n+k}}$$

The parameters of the NBD, as well as N_{part} and N_{coll} are fitted to the measured multiplicity distribution

- Percentiles of hadronic cross-section are defined, e.g.
  - 0-5%: central (“many particles”)
  - 80-90%: peripheral (“few particles”)

Nuclear modification factor R_{AA}

- Hard process occur in initial nucleon-nucleon (NN) collisions. The momentum transfers in the later evolution of the system are smaller.
- Heavy-ion collision: many NN collisions
- Without nuclear effects (interaction with the QCD medium), a heavy-ion collision would just be a superposition of independent NN collisions with incoherent fragmentation.
- The number of independent NN collisions $\langle N_{coll} \rangle$ can be calculated for a given impact parameter/centrality in the Glauber model.

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

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From the Glauber model

$$\langle T_{\mathrm{AA}} \rangle = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{pp}}^{\mathrm{inel}}$$

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Question: how much is the RAA if Pb-Pb collisions are a mere superposition of pp collisions?

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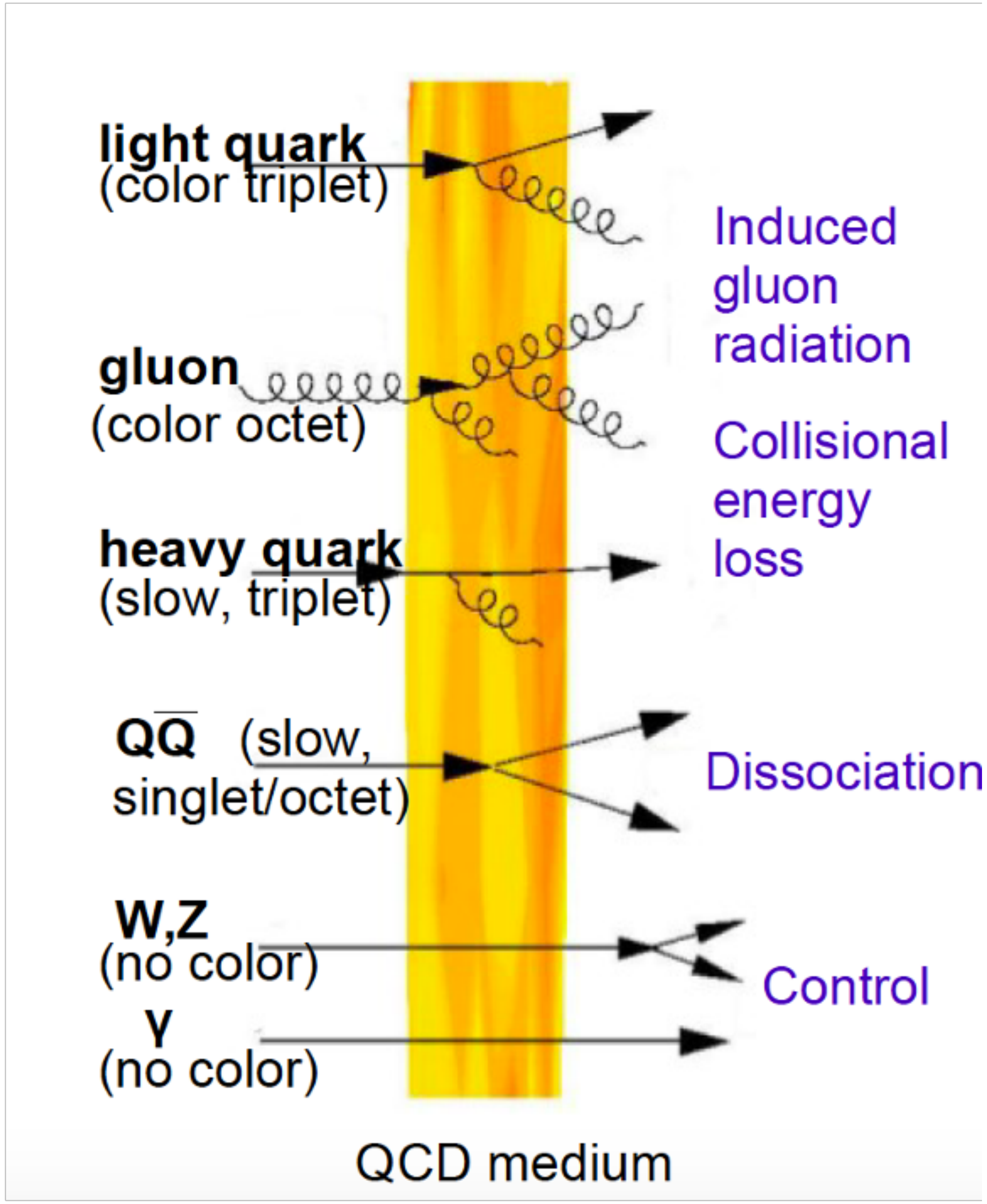
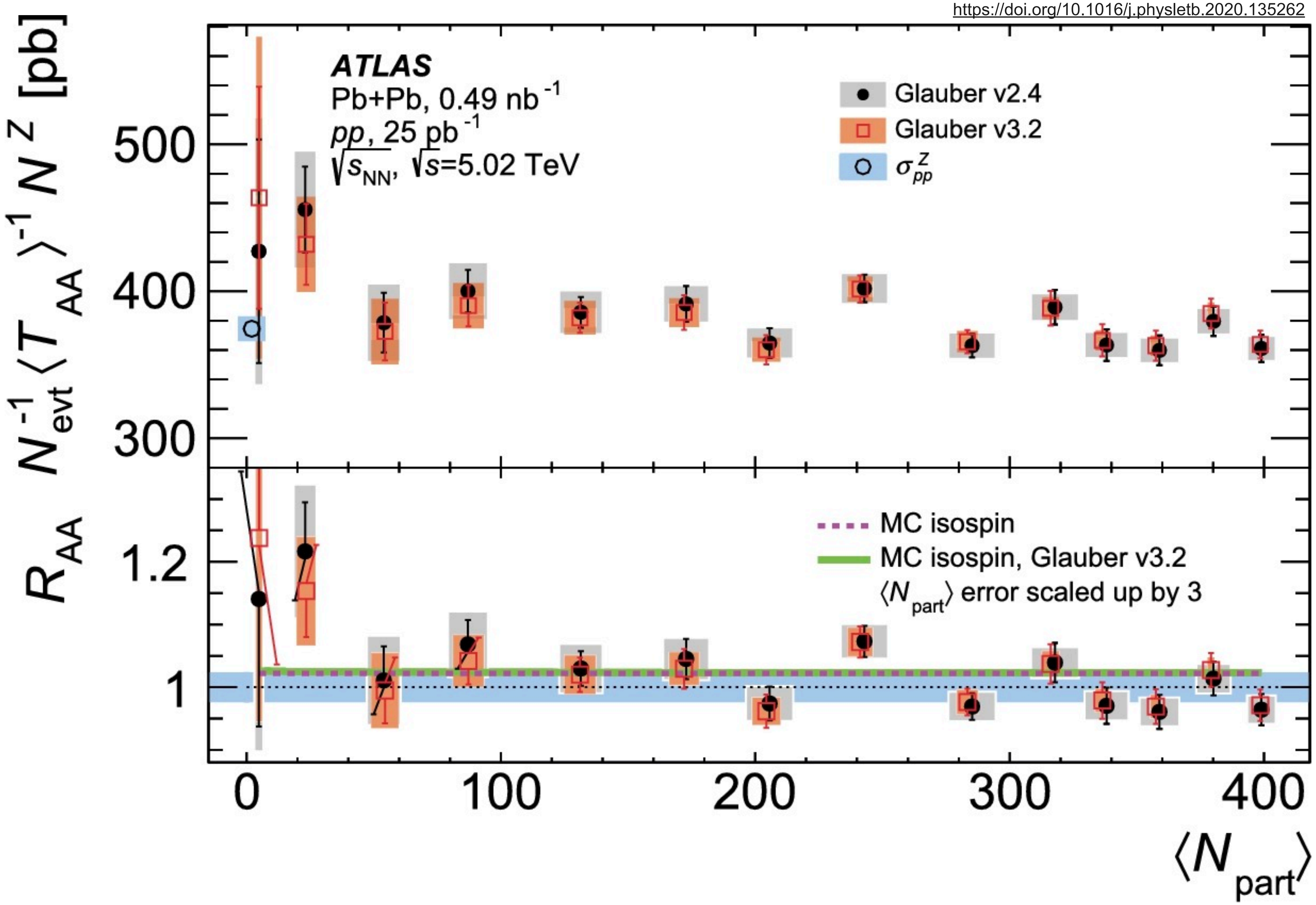
Answer: 1

Control experiment: R_{AA} of electroweak probes



https://doi.org/10.1016/j.physletb.2020.135262



Electroweak bosons allow us to test our understanding of the collision centrality with the Glauber model: R_{AA}=1

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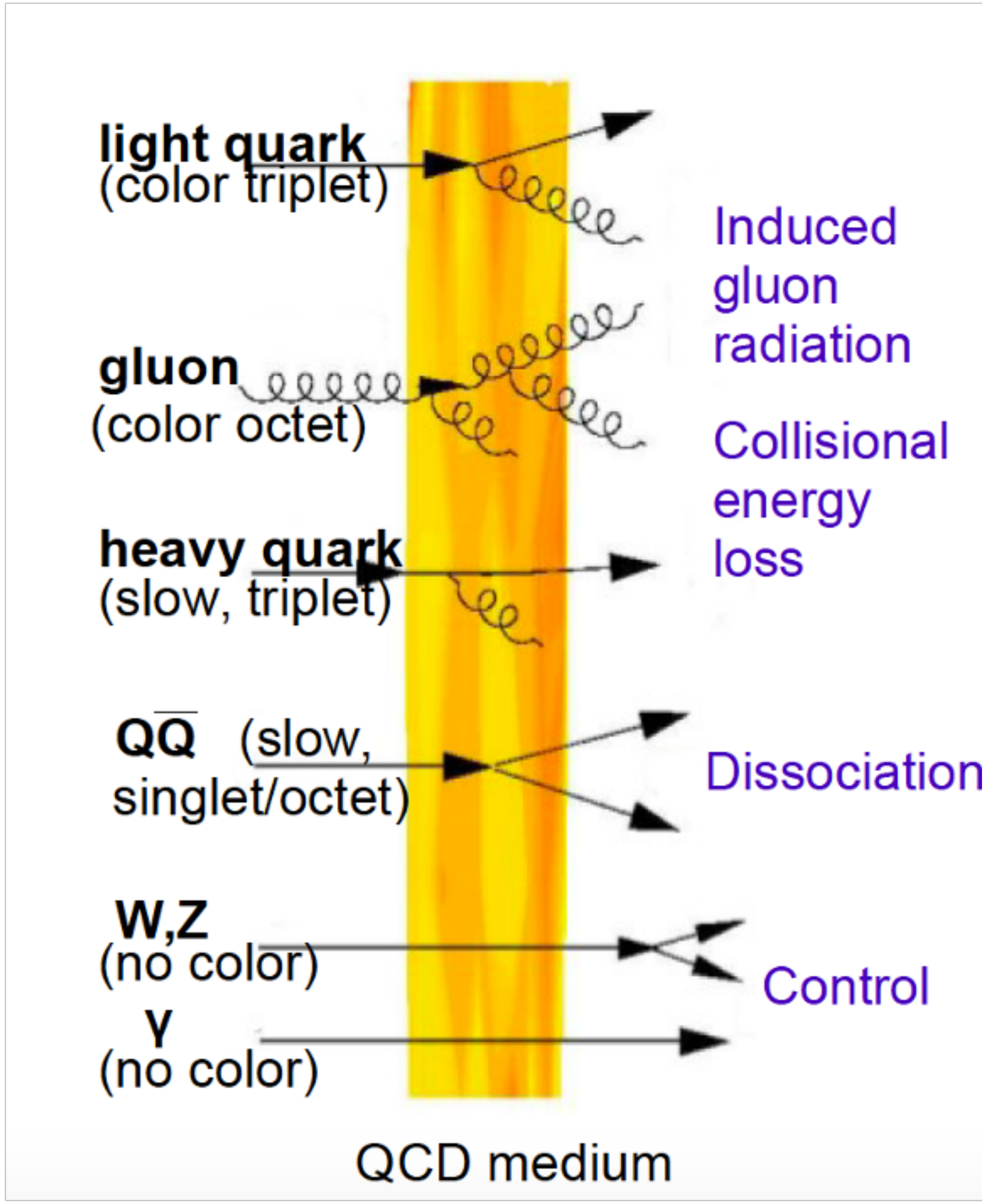

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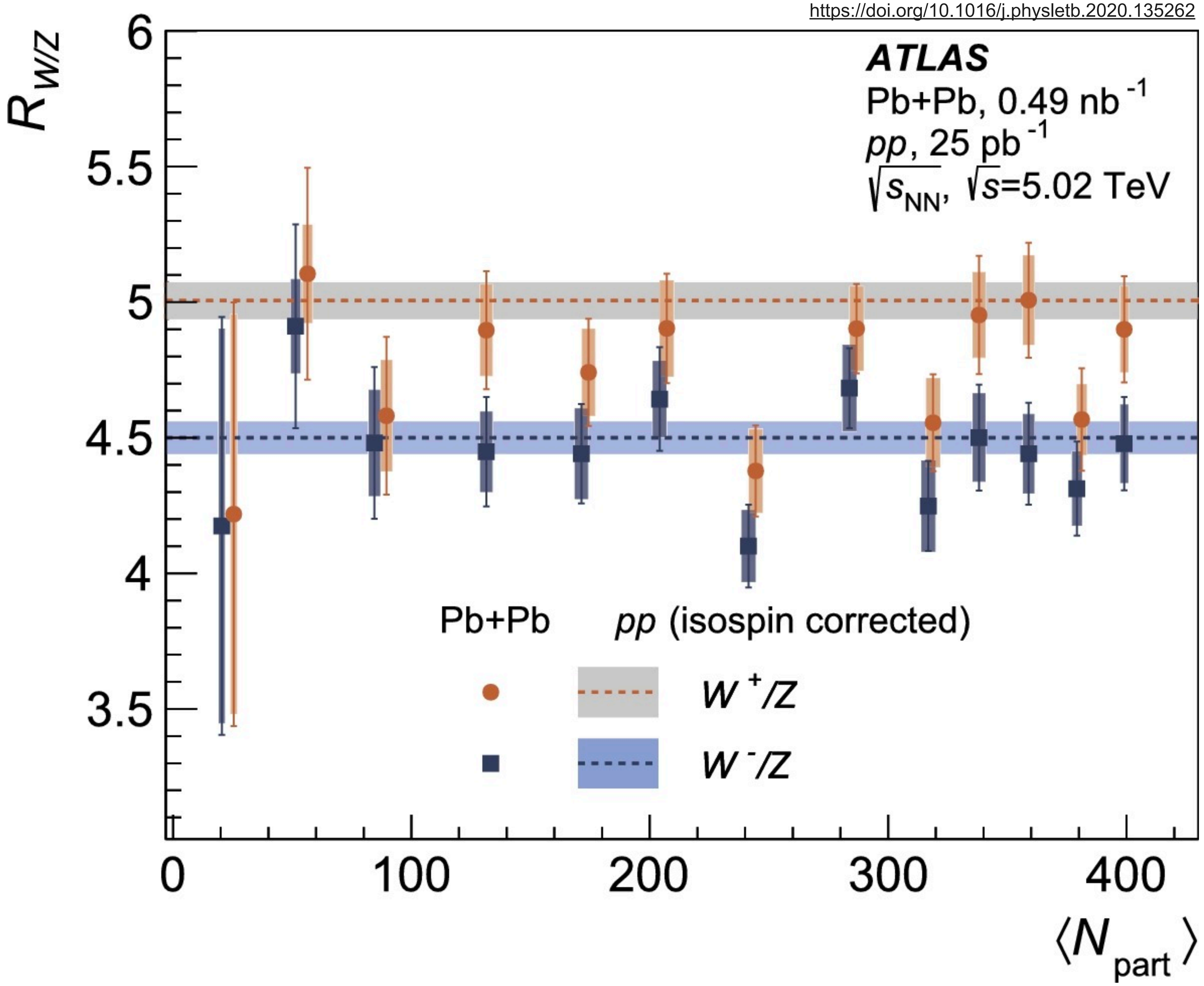
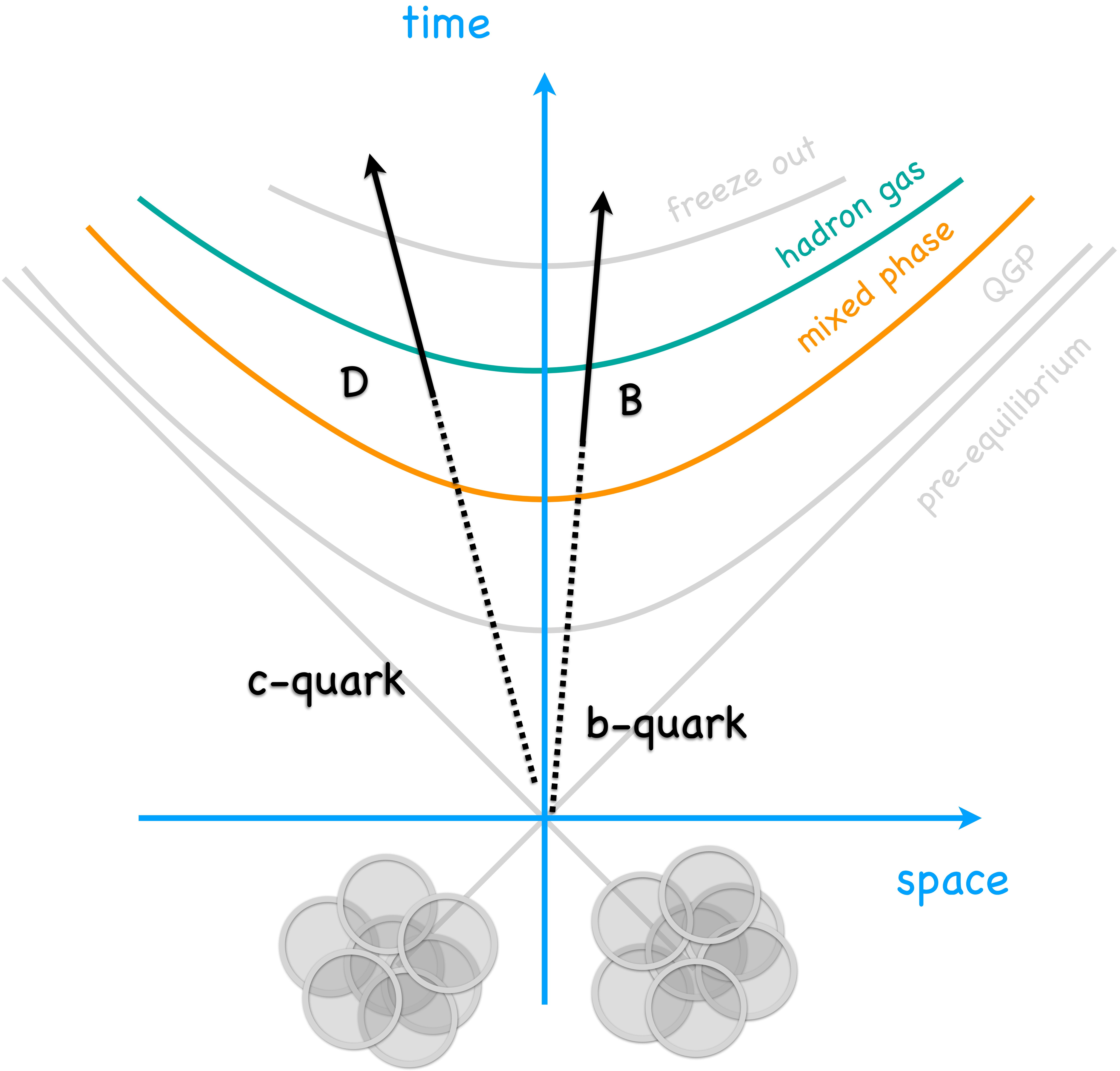
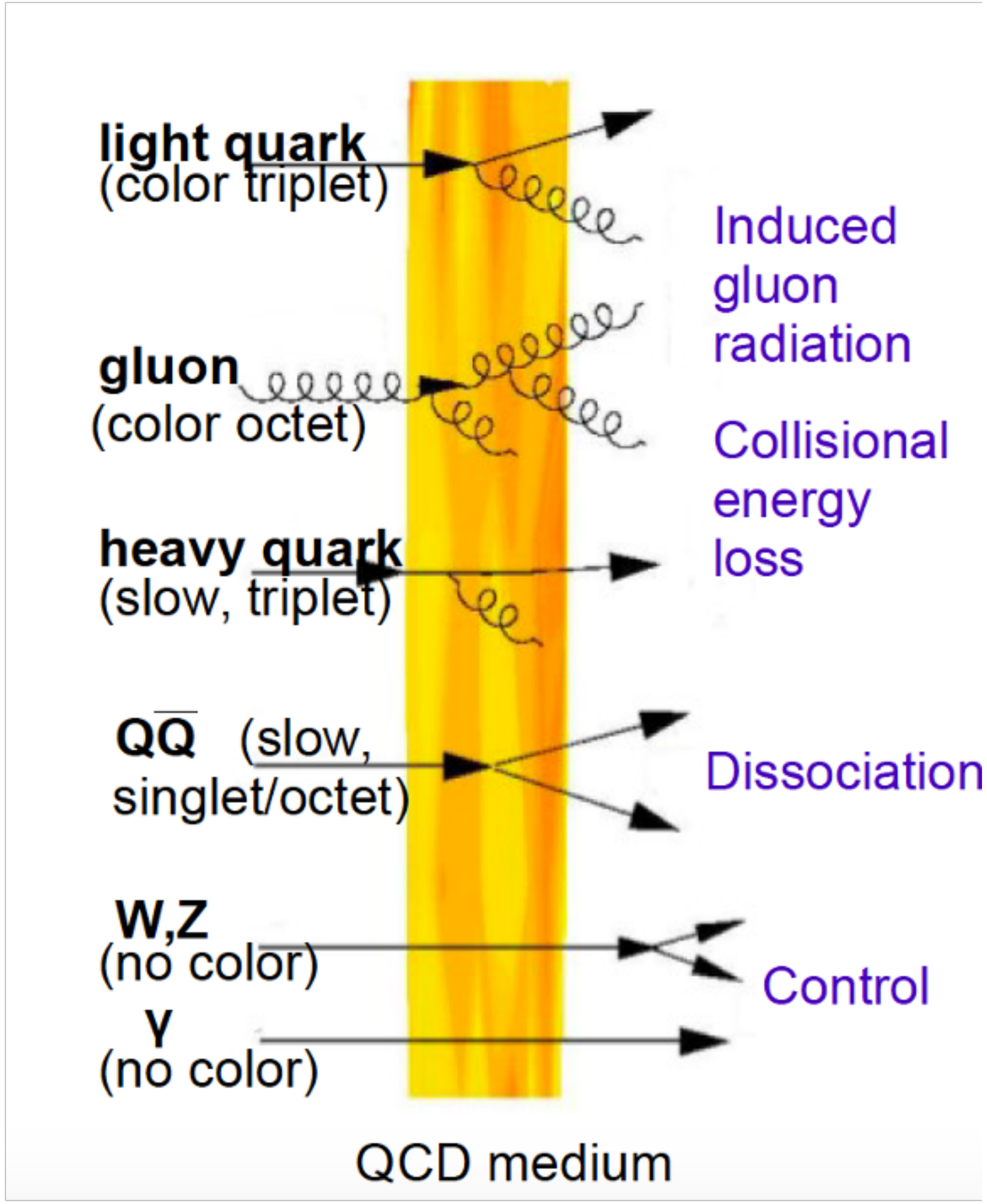


Electroweak bosons allow us to test our understanding of the collision centrality with the Glauber model: R_{AA}=1

- Or is it? Initial isospin is different for pp and Pb-Pb but we can correct for this effect

Not all particles are unaffected by the QGP





Pictures by F. Grosa

Disappearing jets

Phys. Rev. Lett. **105**, 252303

Peripheral Pb-Pb collision

Central Pb-Pb collision

Disappearing jets

Phys. Rev. Lett. **105**, 252303

Peripheral Pb-Pb collision

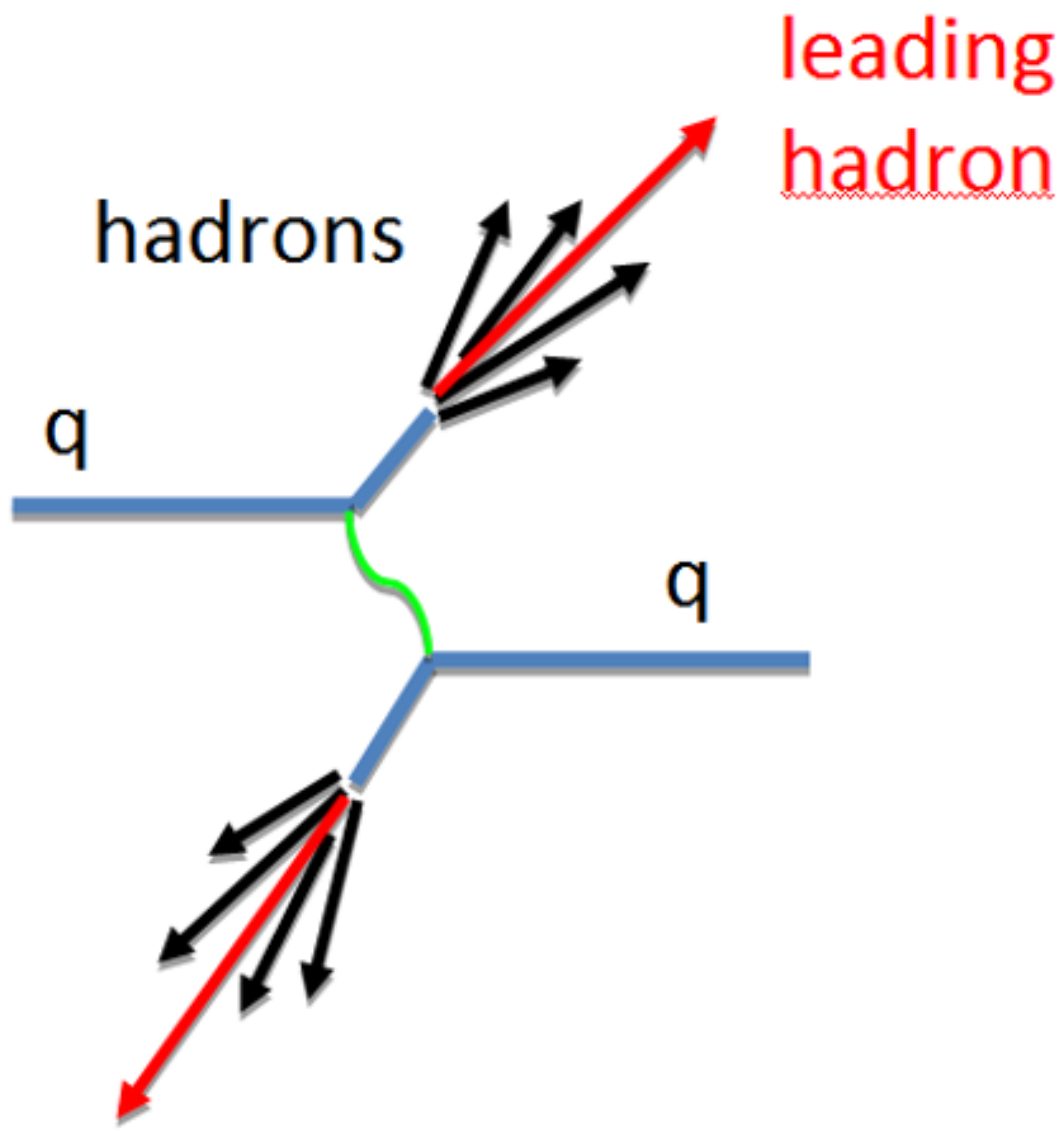
Central Pb-Pb collision

One of the two jets disappears (is quenched) in central collisions

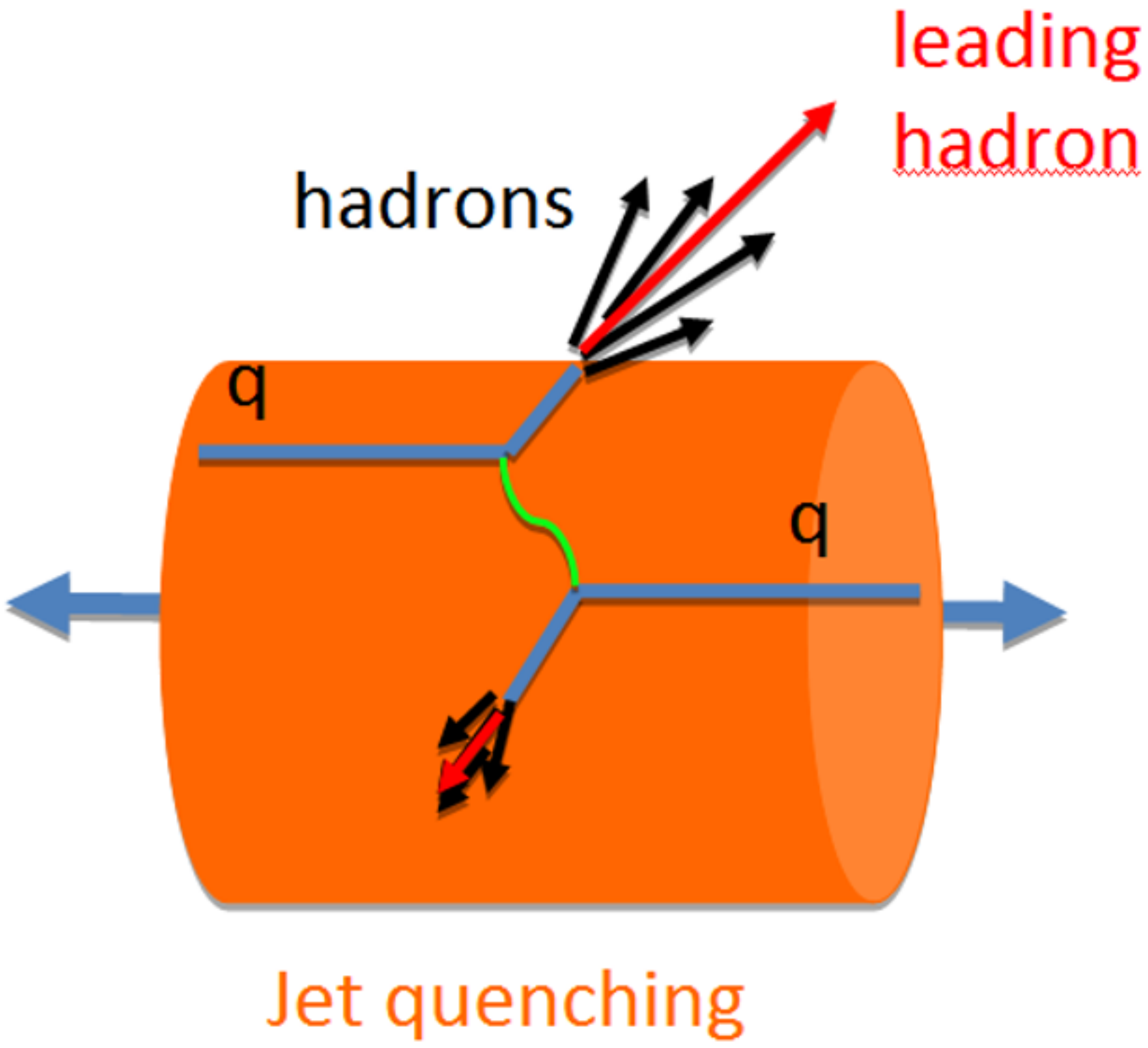
The most dense material mankind creates

How this happens?

- High momenta partons generating the jet are created at the early stages of the collisions
- They travel through the QGP: the position at which they are created matters!

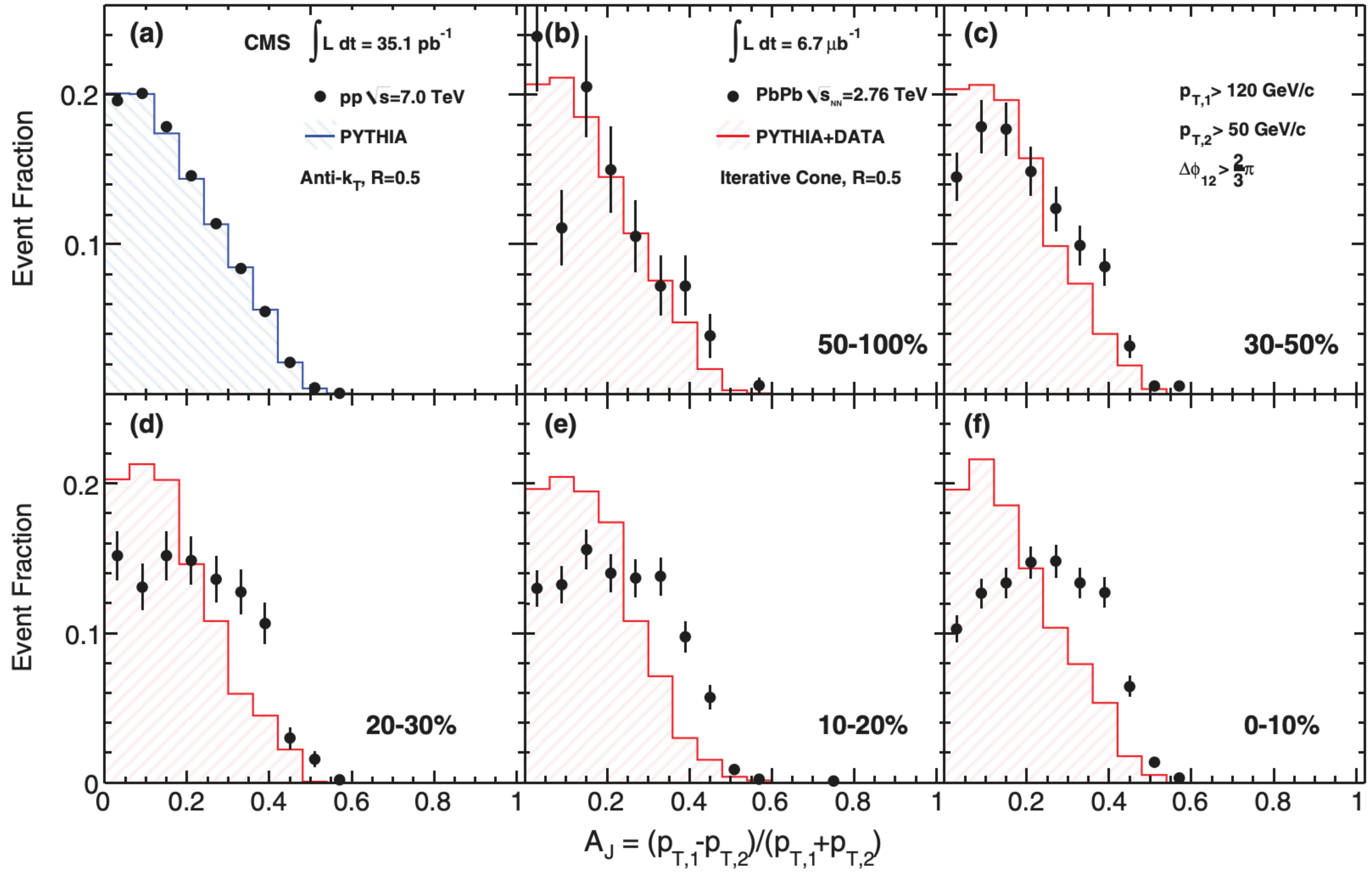


Drawing: M. Knichel



To stop a highly energetic jet (e.g. 100 GeV), it needs a 10fm droplet of QGP or ~1.5m of hadronic calorimeter

Dijet imbalance



PRC 84 (2011) 024906

$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

$p_{T1} = p_{T2} \rightarrow A_J = 0$

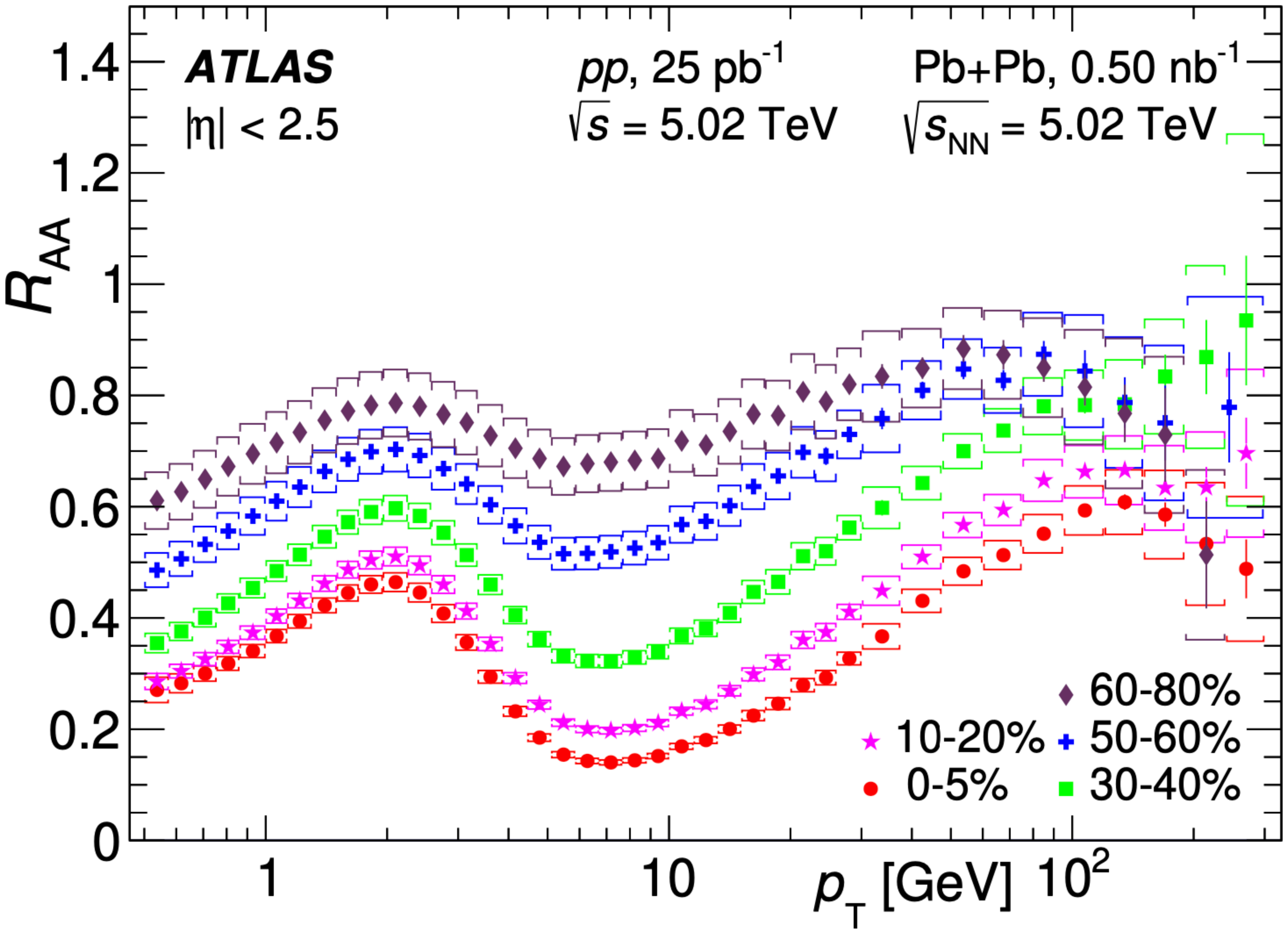
1/3 $p_{T1} = p_{T2} \rightarrow A_J = 0.5$

- Peripheral collisions: distribution as in Pythia (as in pp)
- Central collisions:
  - Symmetric configuration is significantly depleted
  - Enhancement of asymmetric configurations

Suppression of high-p_T hadrons

There is a significant suppression of high p_T-particles observed in AA collisions which is a true medium effect

- High p_T particle production in AA collision is not a simple superposition of incoherent nucleon-nucleon collisions.

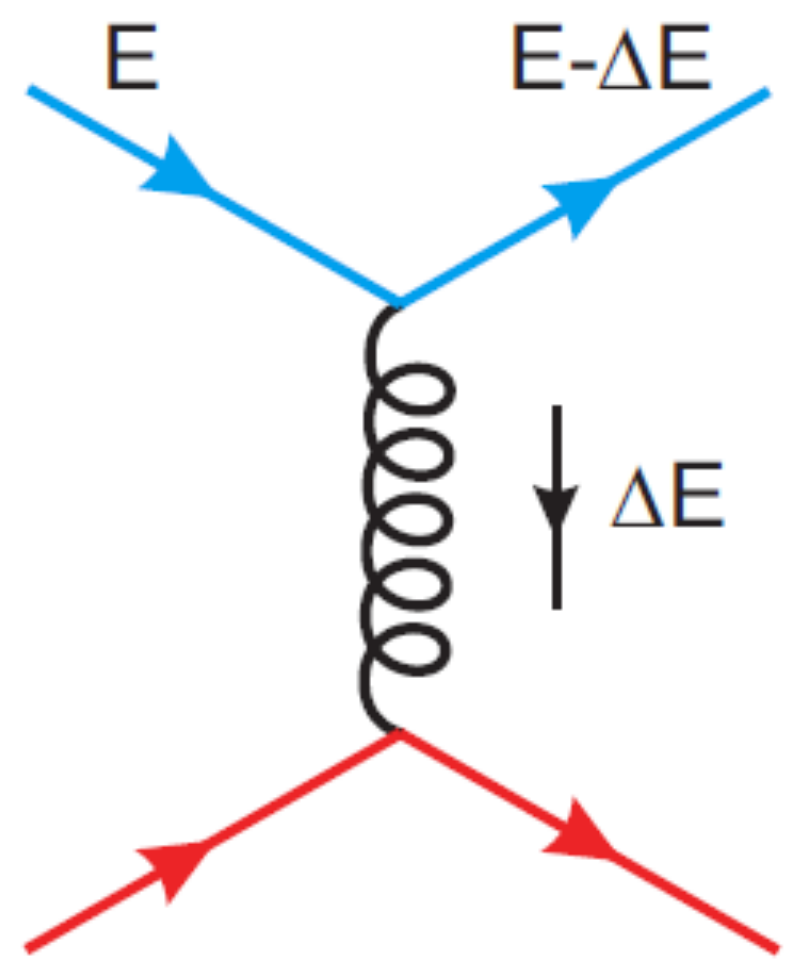


- Suppression more important in central collisions
- At momenta above 100 GeV/c the suppression subdues
- How do high energetic partons lose energy in the medium?

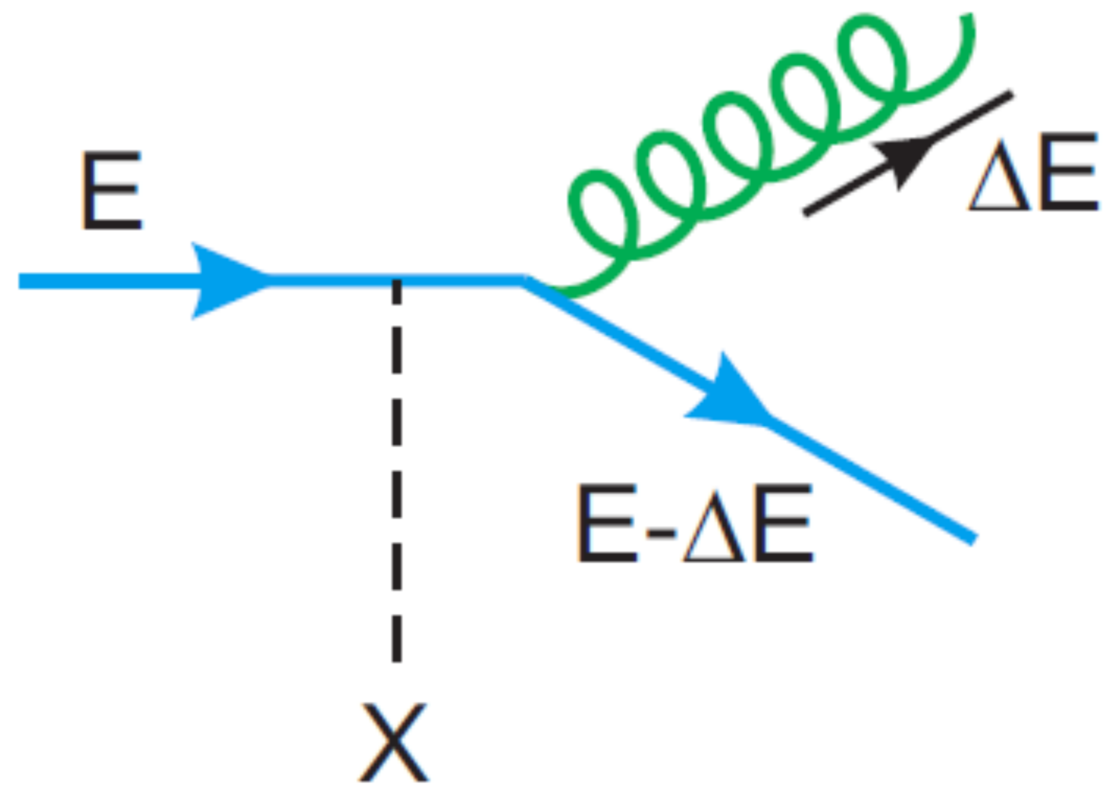
Energy loss mechanism in the QGP

Energy loss in QED: Bethe Bloch formula. What about in QCD?

- The QGP is a high density source of color sources (quarks and gluons) which are felt by the traversing quark or gluon.
- It experiences
  - Collisional energy loss: elastic scatterings, dominant at low momentum
  - Radiative energy loss: inelastic scatterings, gluon bremsstrahlung, dominates at high momentum
- Total energy loss is a sum of the two processes.



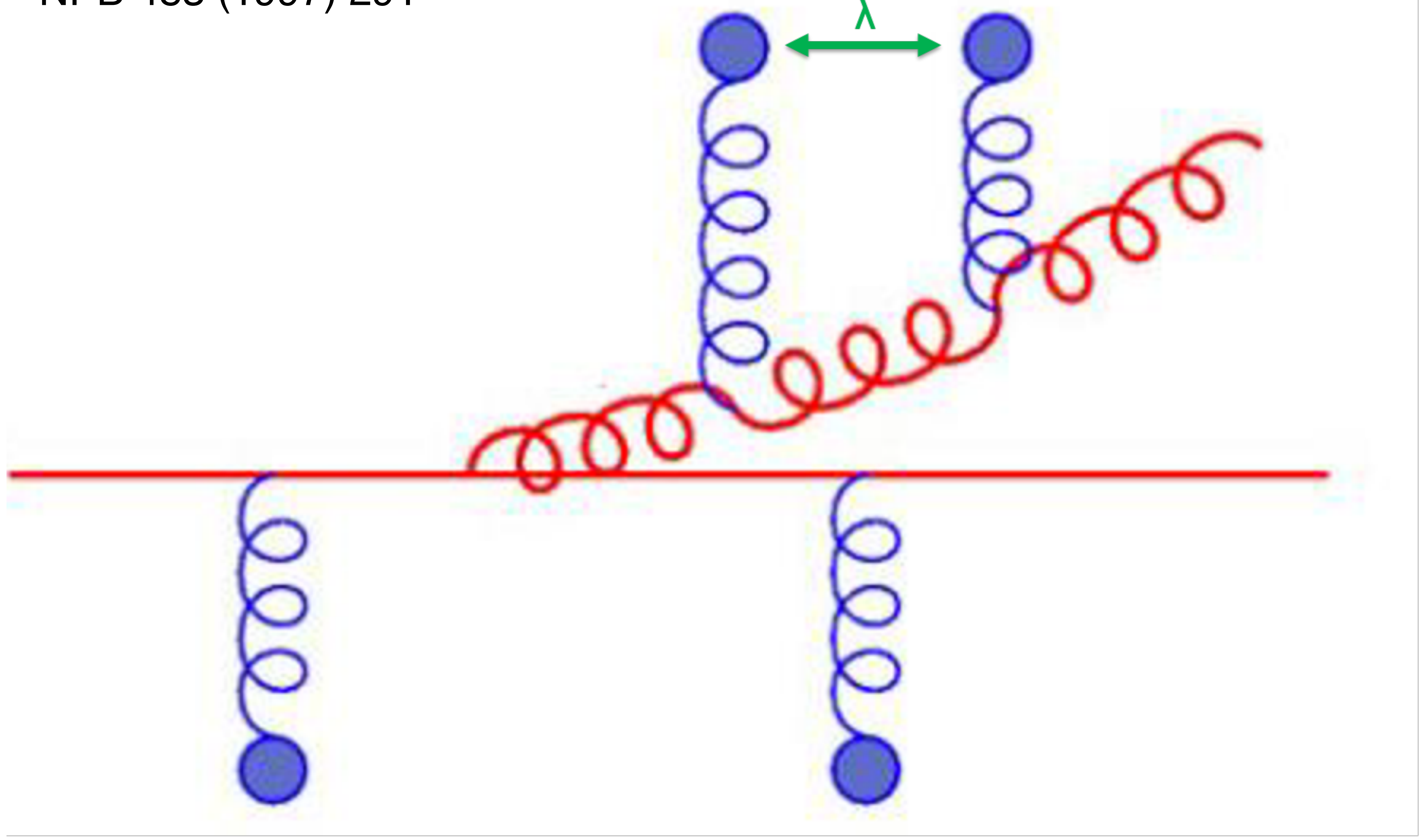
Collisional energy loss



Radiative energy loss

Radiative energy loss

NPB 483 (1997) 291



Average momentum transfer

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

Free mean path

BDPMS (Baier, Dokshitzer, Mueller, Peigne, Schiff) formalism

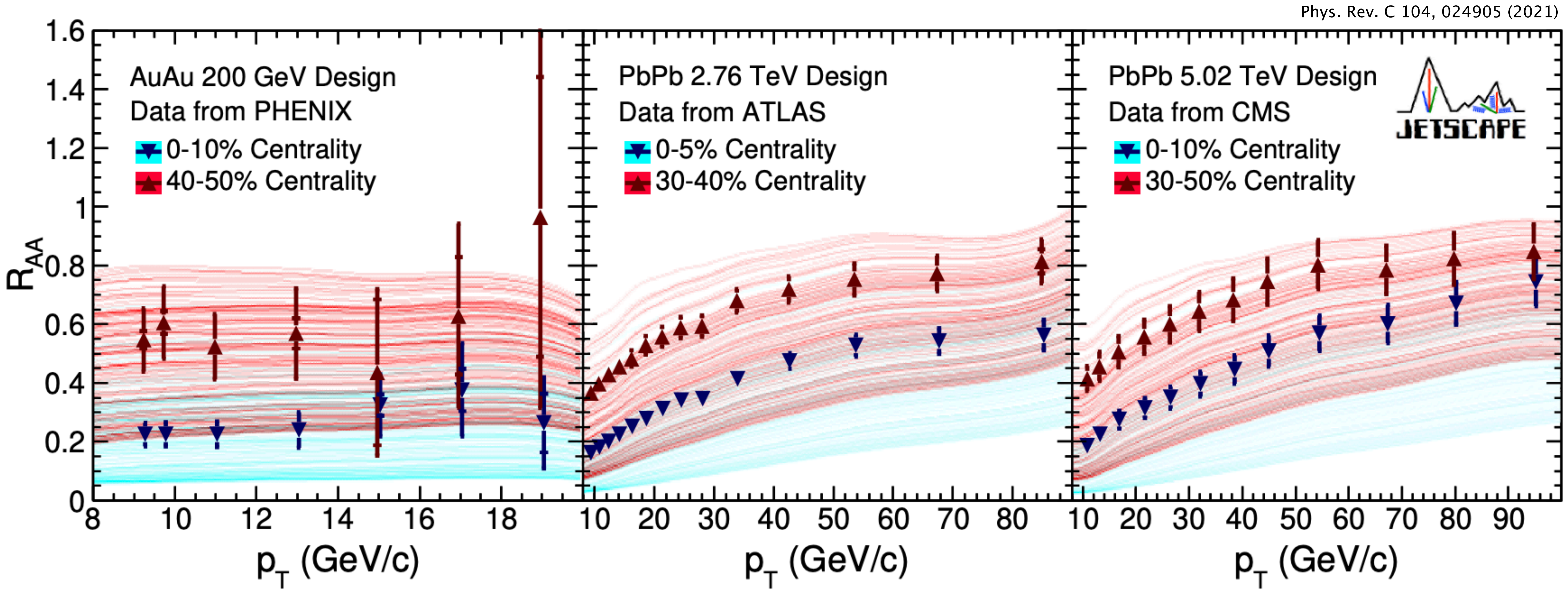
- Infinte energy limit
- Static medium

$$\Delta E \propto \alpha_S \cdot C_R \cdot \hat{q} \cdot L^2$$

Energy loss proportional to:

- Path length through medium **squared**
- Casimir factor
  - CR = 4/3 (quarks)
  - CR = 3 (gluons)
- Medium properties are encoded in the parameter “q-hat” which corresponds to the average squared transverse momentum transfer per mean free path.

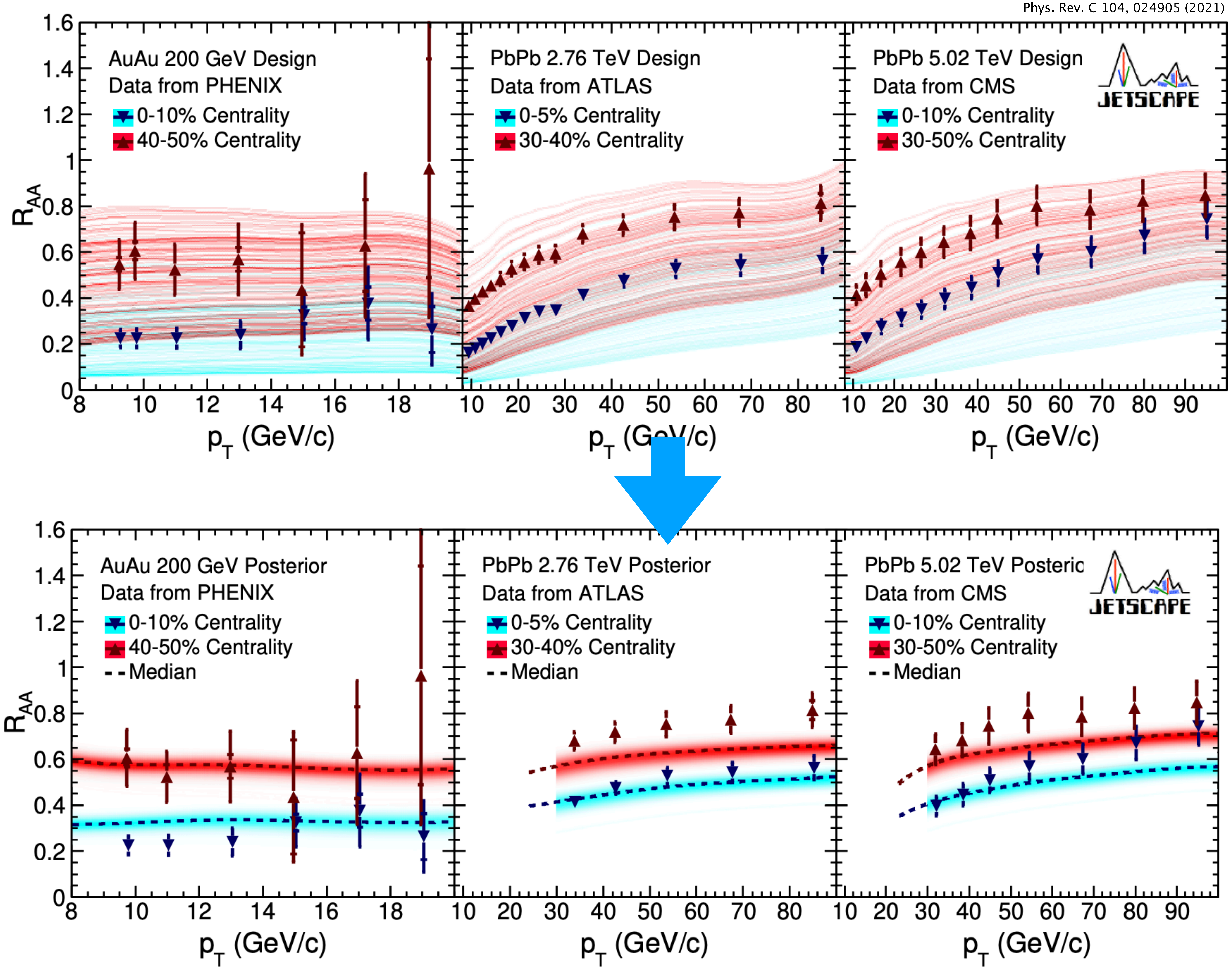
Bayesian analysis to extract q-hat



Oversimplifying:

- Step 1: establishing the prior distributions

Bayesian analysis to extract q-hat

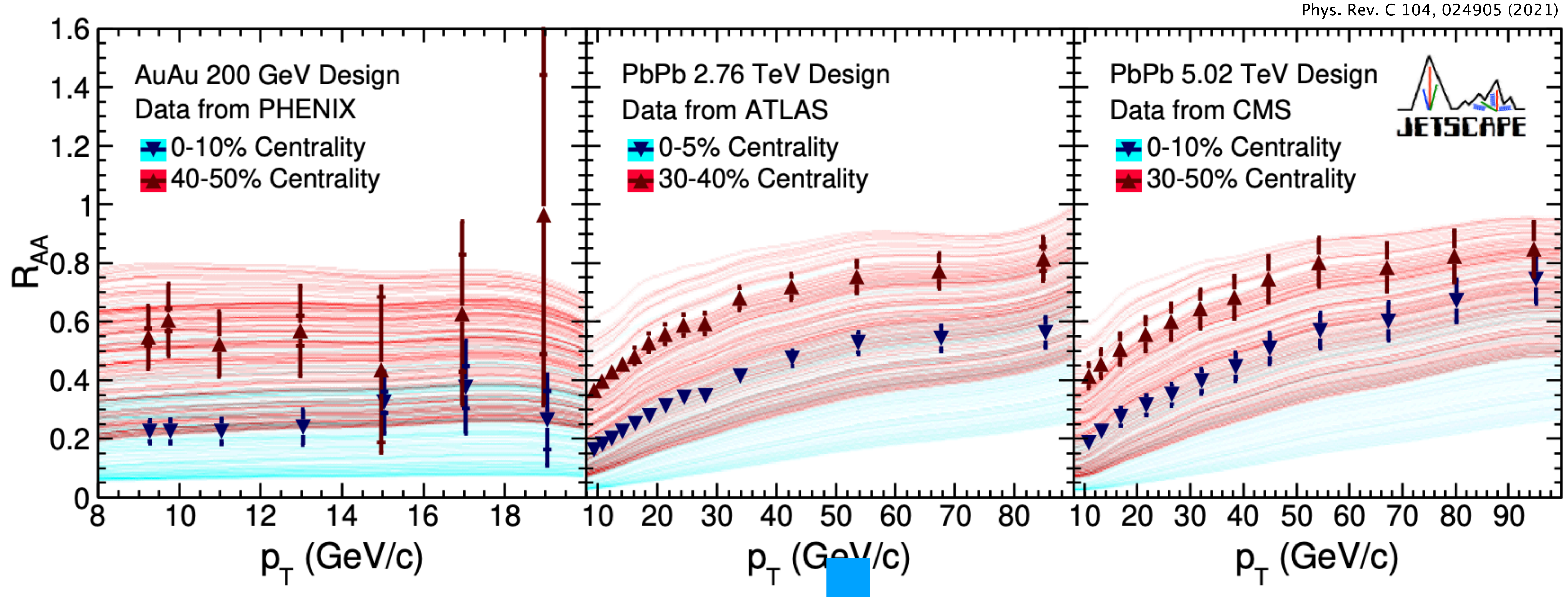


Oversimplifying:

- Step 1: establishing the prior distributions
- Step 2: bayesian optimisation of the model parameters, obtain the posterior distributions

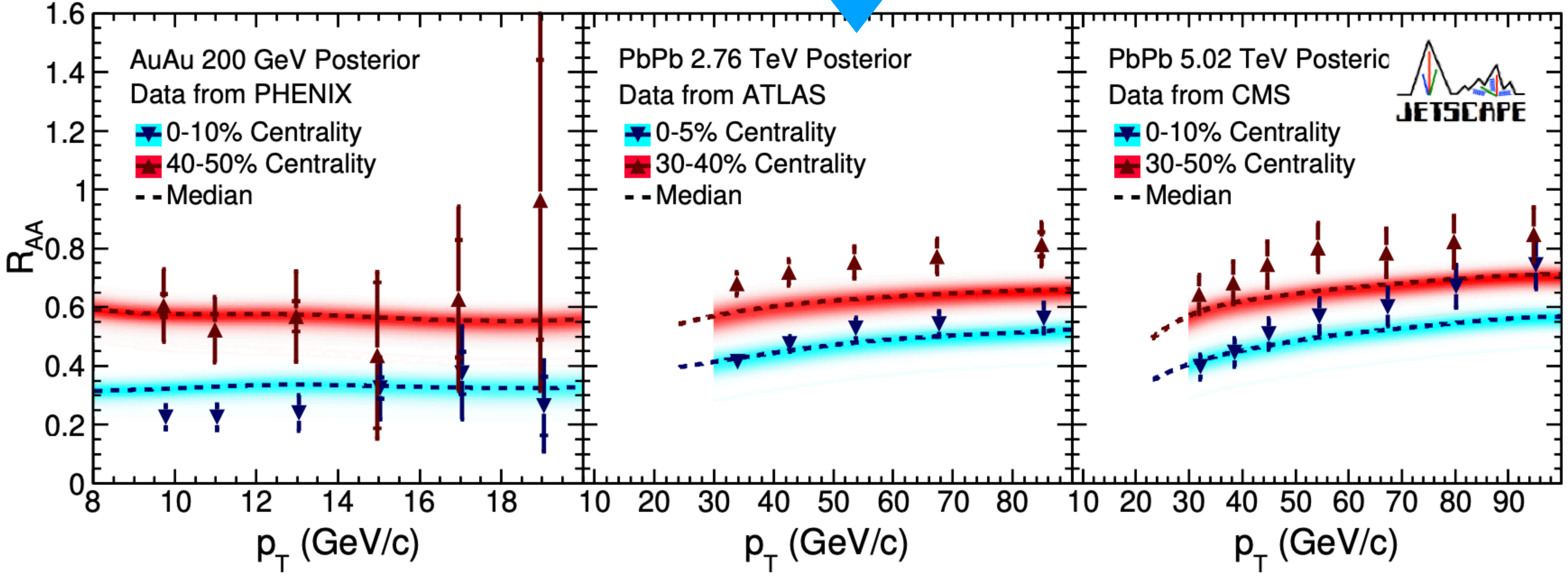
Bayesian analysis to extract q-hat

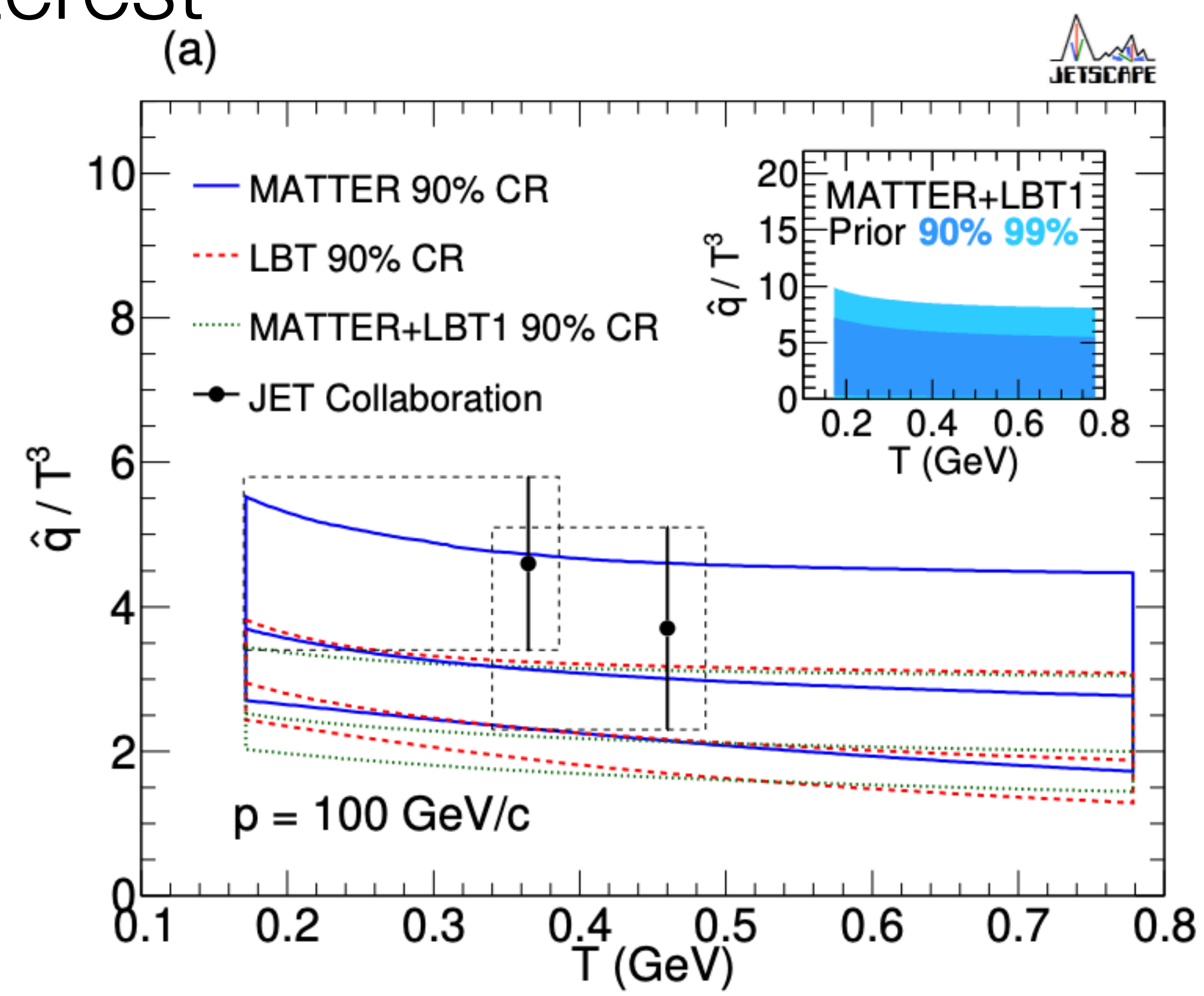
Phys. Rev. C 104, 024905 (2021)



Oversimplifying:

- Step 1: establishing the prior distributions
- Step 2: bayesian optimisation of the model parameters, obtain the posterior distributions
- Step 3: extract the parameters of interest



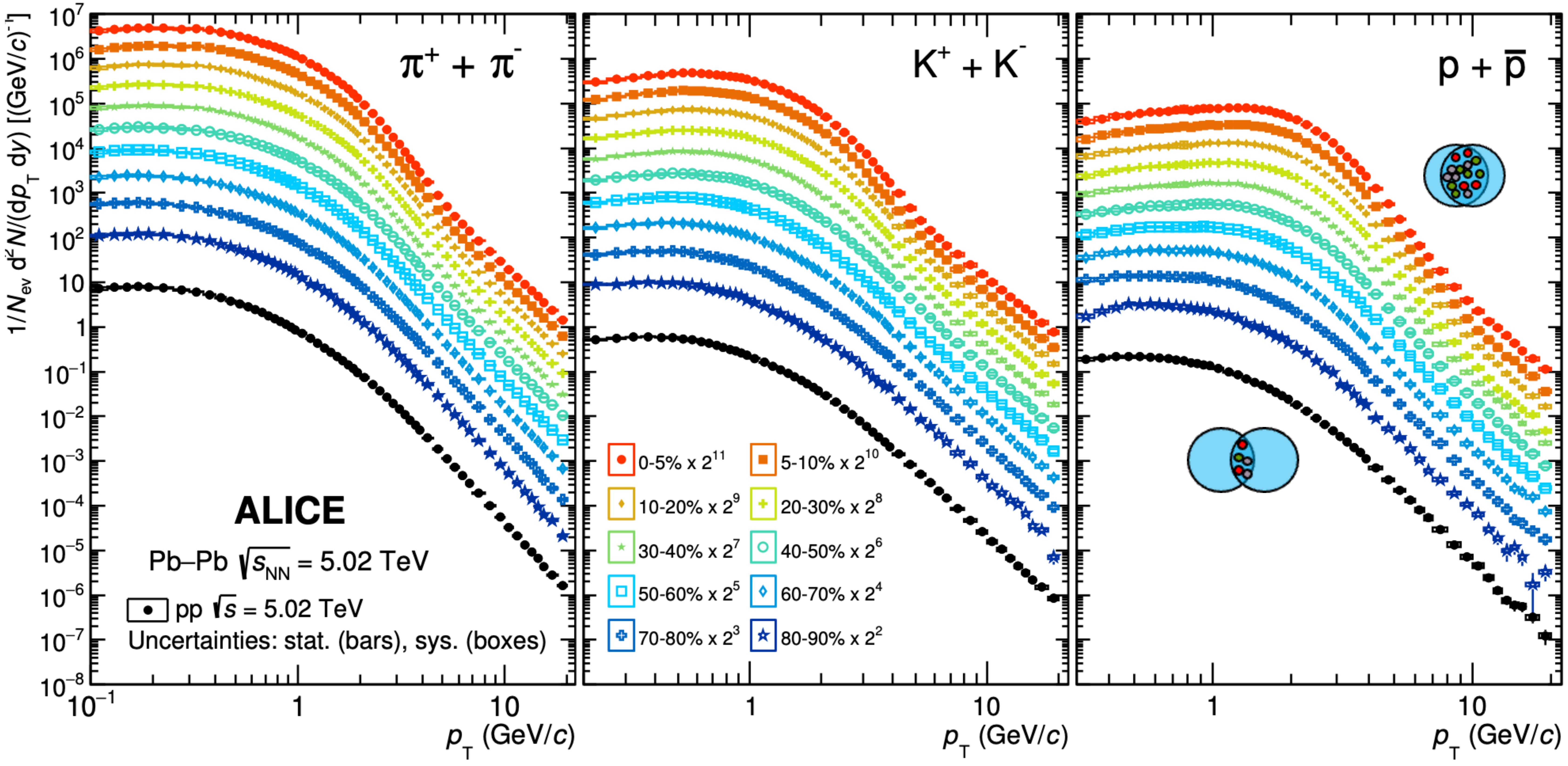


- Unique way to extract QGP properties keeping into account data and model systematics

What else is produced in Heavy Ion?

Particle spectra

Phys. Rev. C 101, 044907 (2020)



1. Identify particle in the detector (pion, kaon, proton, Λ, Ξ, Ω, antideuteron…)
2. Fill p_T-spectrum
3. Interpolate unmeasured region at low p_T (at high p_T negligible)
4. Integrate:

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\varphi} d\varphi dp_T$$

Chemical equilibrium and freeze-out temperature

Production
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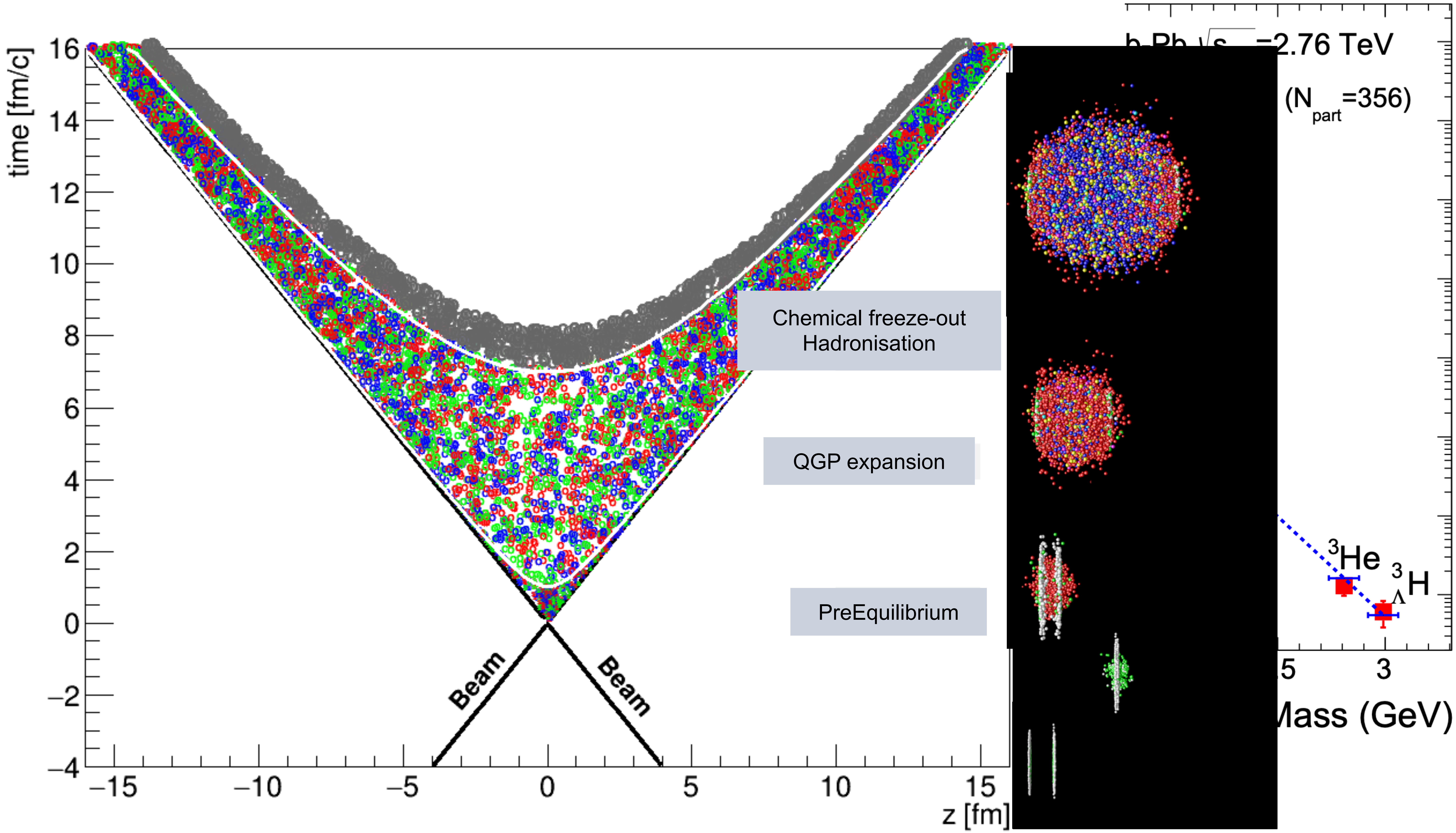


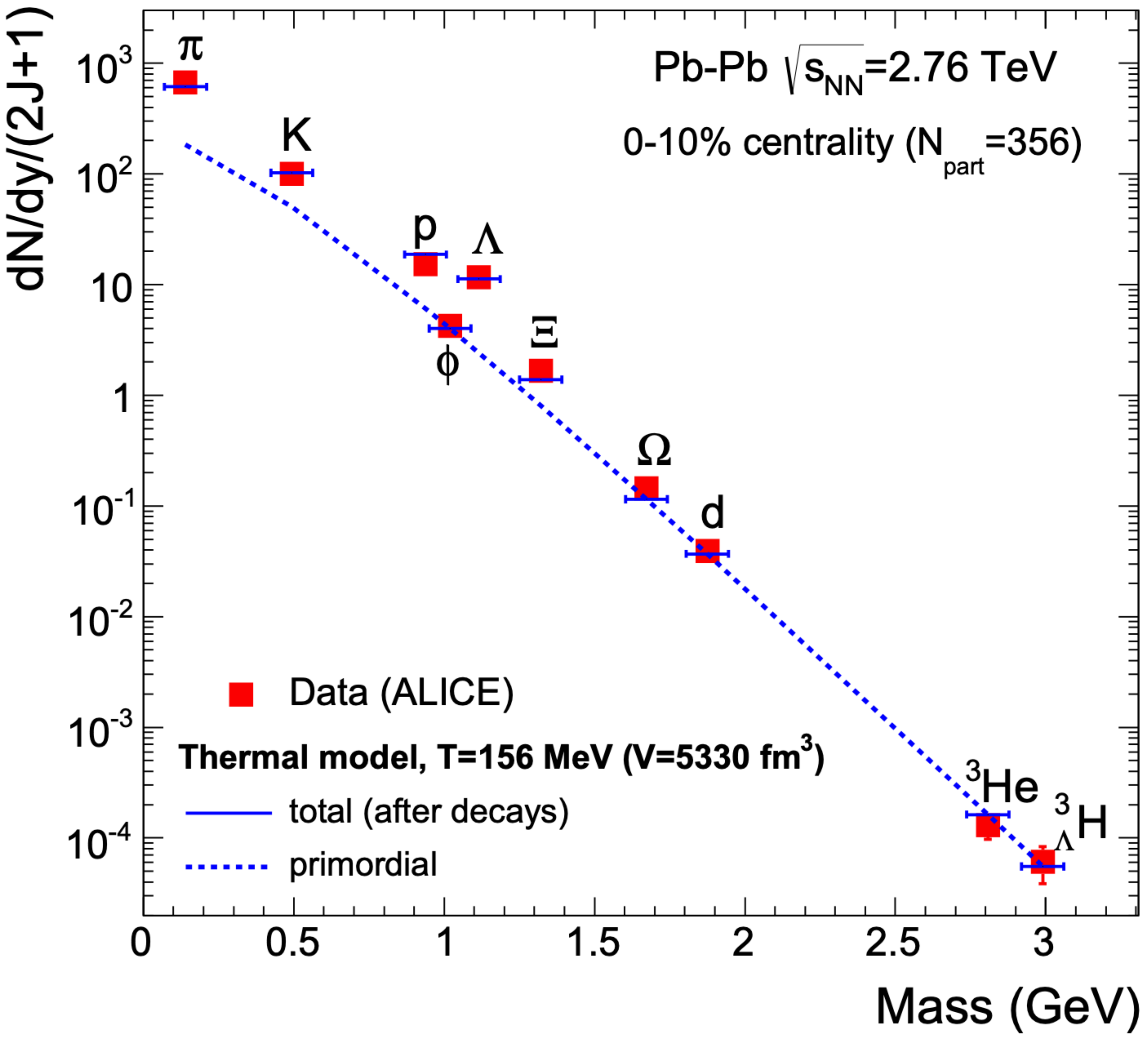
Chemical equilibrium and freeze-out temperature

Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by Statistical Hadronisation Model (roughly $dN/dy \sim e^{-m/T_{ch}}$)

- In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a **common** chemical freeze-out temperature of $\boldsymbol{T_{ch} \approx 156}$ **MeV**.

- This includes **strange hadrons** which are rarer than u,d quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

- Light (anti)nuclei fit also in this picture despite their low binding energy ($E_b << T_{ch}$).

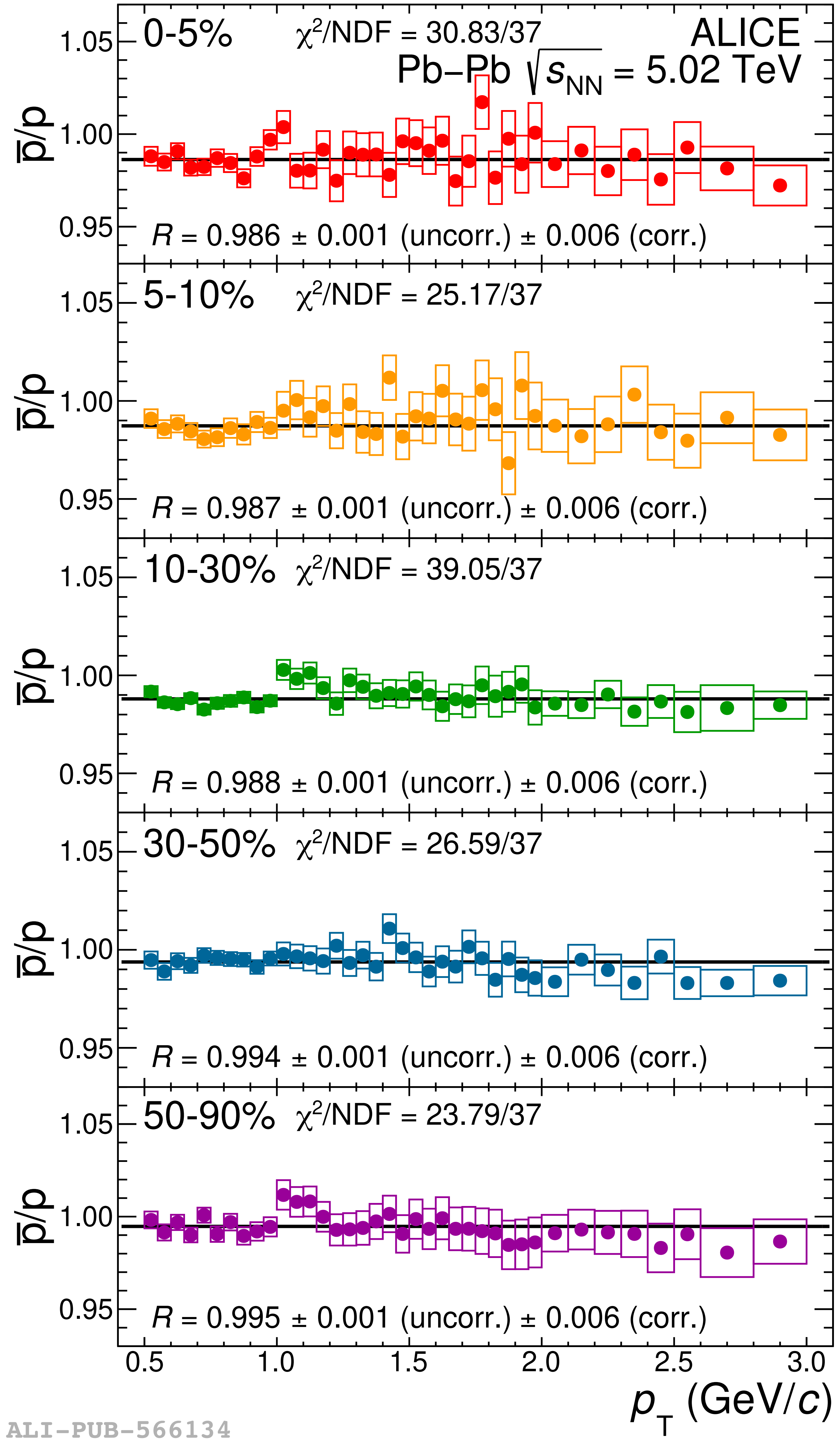


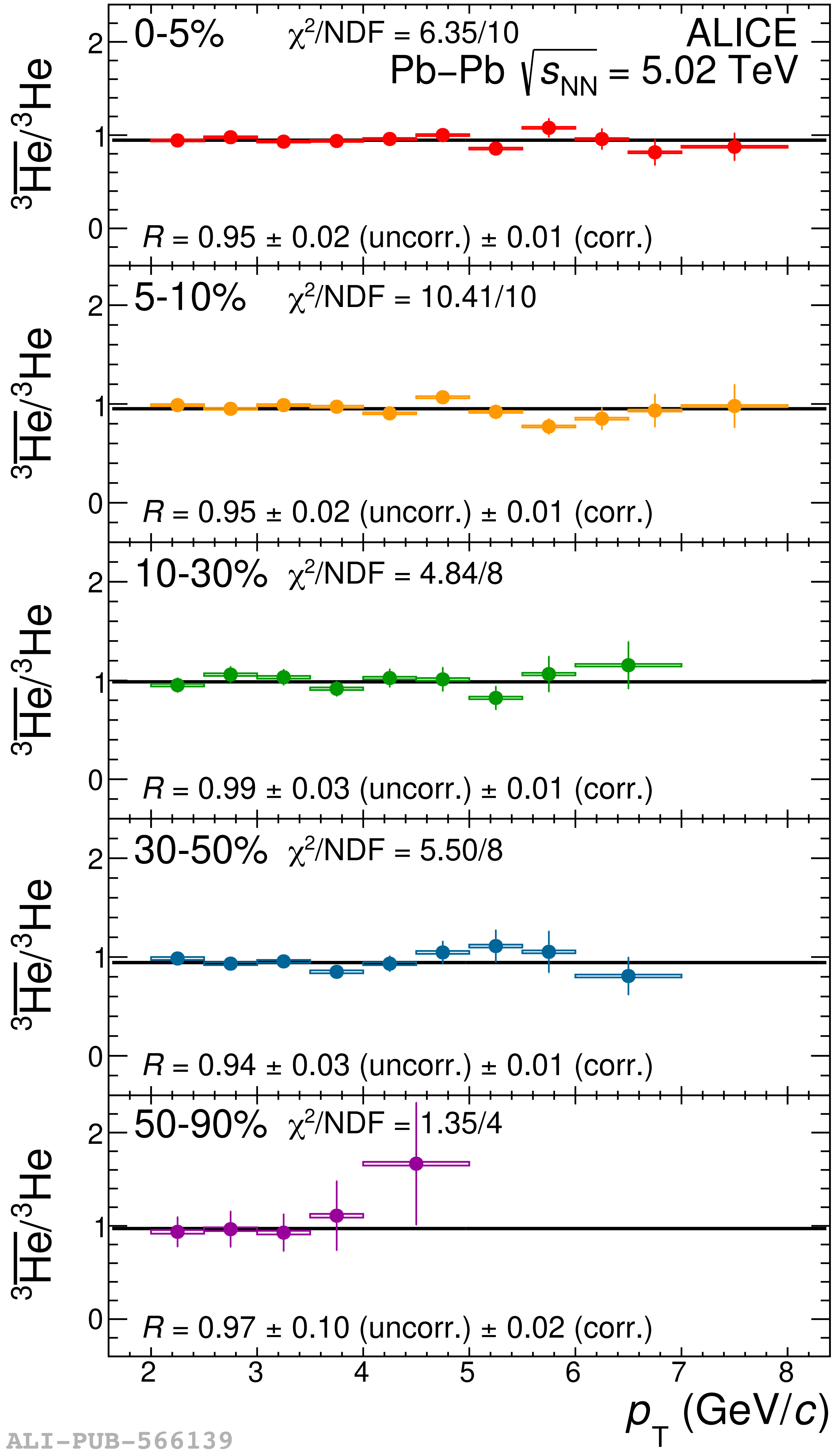
Chemical potential determination (I)

From the ratio between particles and antiparticles it is possible to determine the chemical potentials according to the SHM:

$$\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T_{ch}} - 2Q\frac{\mu_Q}{T_{ch}}\right]$$

arxiv:2311.13332





Chemical potential determination (II)

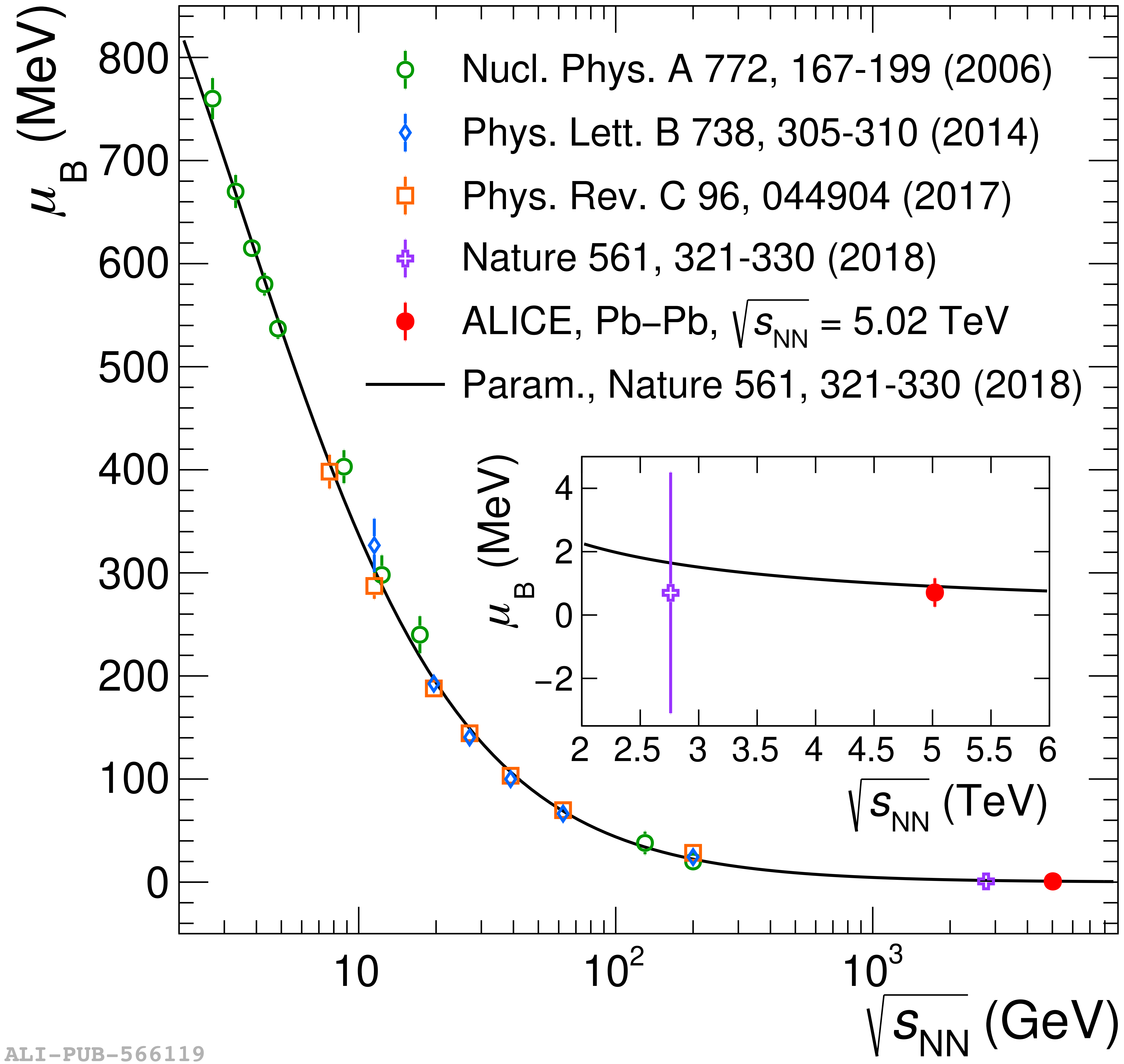
From the ratio between particles and antiparticles it is possible to determine the chemical potentials according to the SHM:

$$\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T_{ch}} - 2Q\frac{\mu_Q}{T_{ch}}\right]$$

From the fits new determination of the baryochemical potential at hadronisation

- Far smaller uncertainties thanks to the direct cancellation of uncertainties in the ratios
- Nearly baryon free system at the LHC for |y|<0.5

arxiv:2311.13332



ALI-PUB-566119

Chemical equilibrium vs collision energy

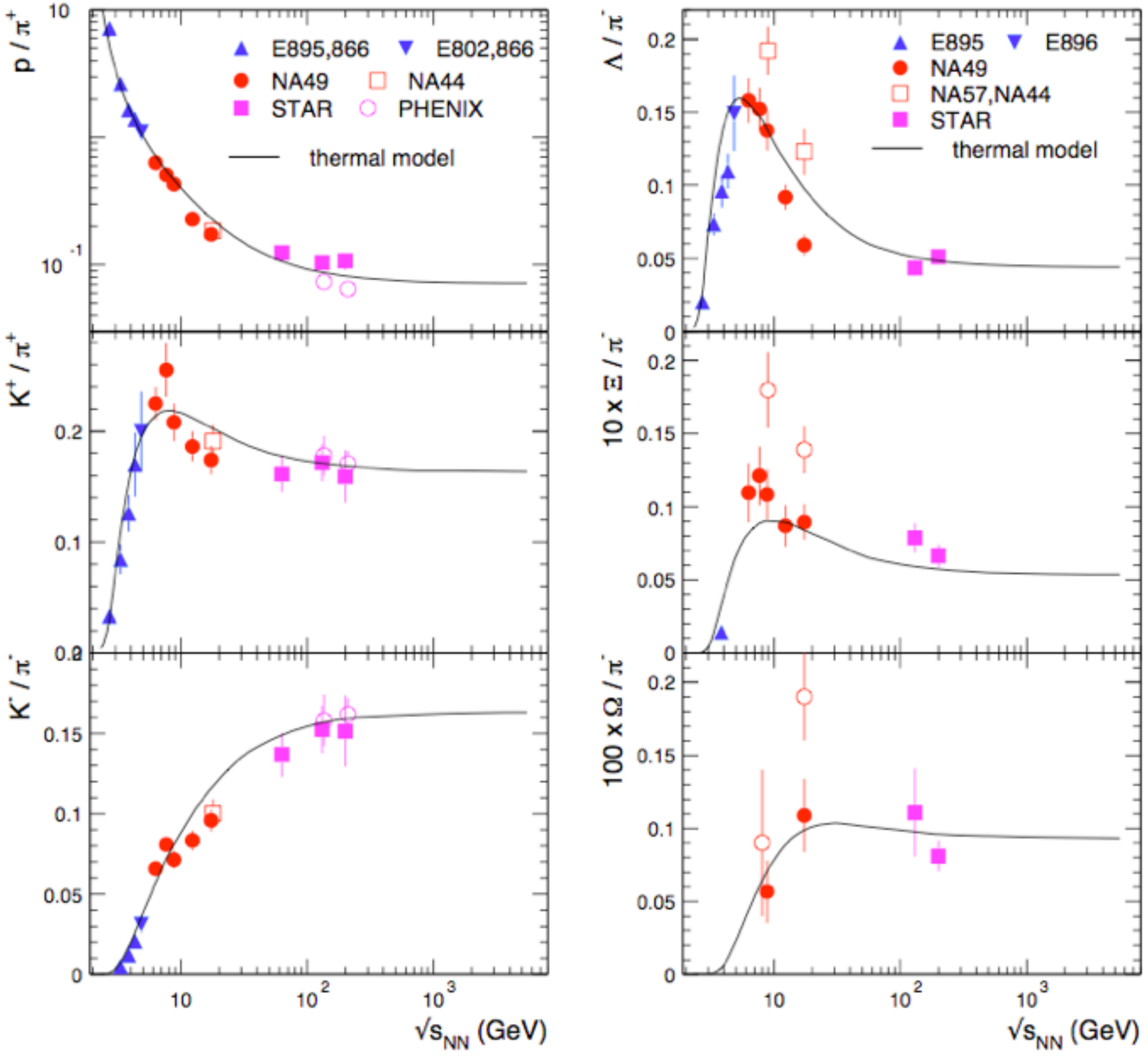
- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.
- Effective parameterization of (T, μ_B) as a function of collision energy:

$$T[\mathrm{MeV}] = T_{lim}\left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\mathrm{GeV})) - 2.9)/1.5}\right)$$

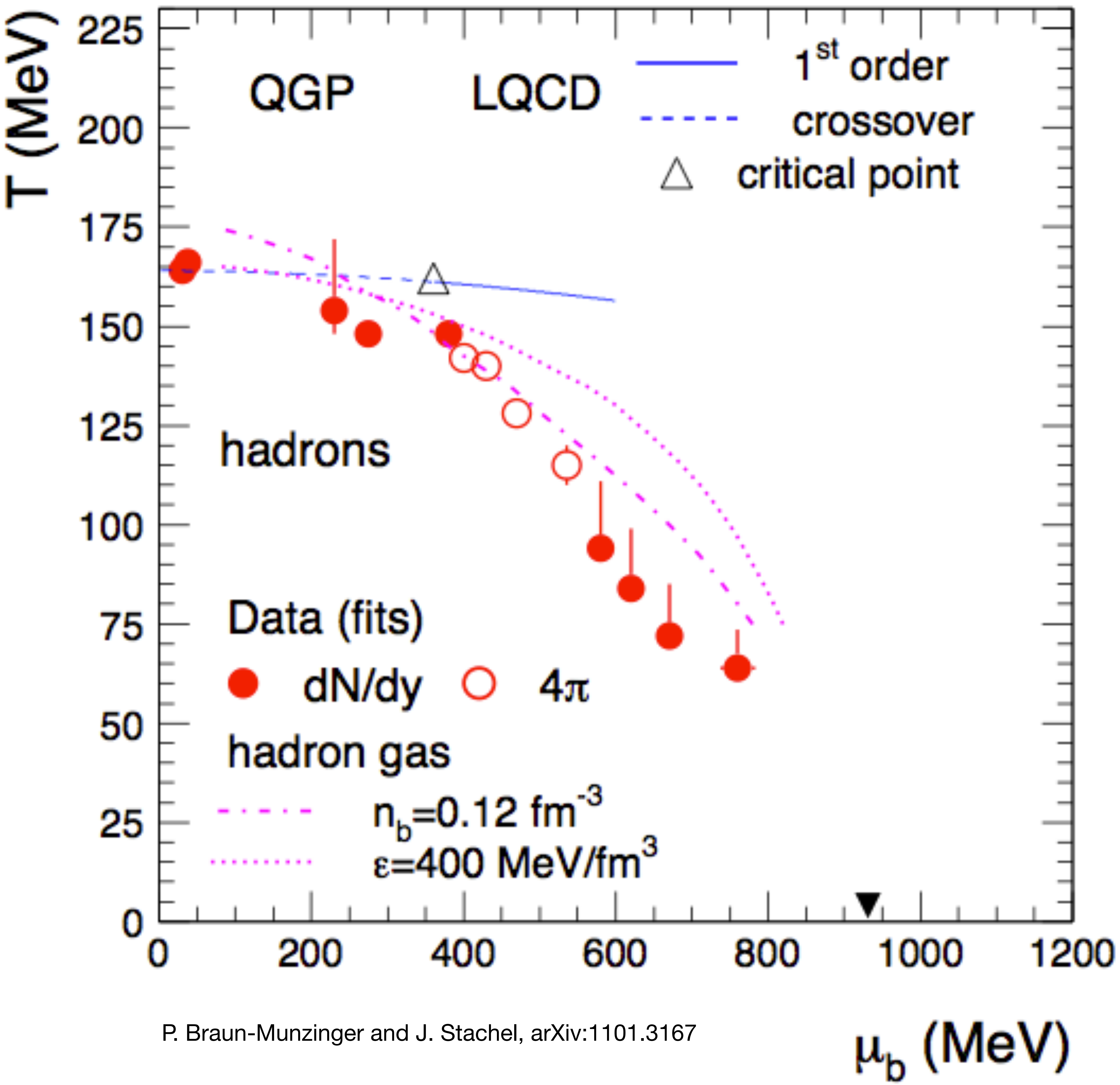
$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})},$$

- Particle ratios can be calculated at any collision energy

→ One observes a *limiting temperature of hadron production* around T≈160MeV.



Where are we in the phase diagram



P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

- By colliding nuclei with different center of mass energies, different regions of the phase diagram are explored.
- Thermal model fits to the experimental data define the chemical freeze-out line in the QCD phase diagram.
- The previously schematic phase diagram becomes one which is actually measured.

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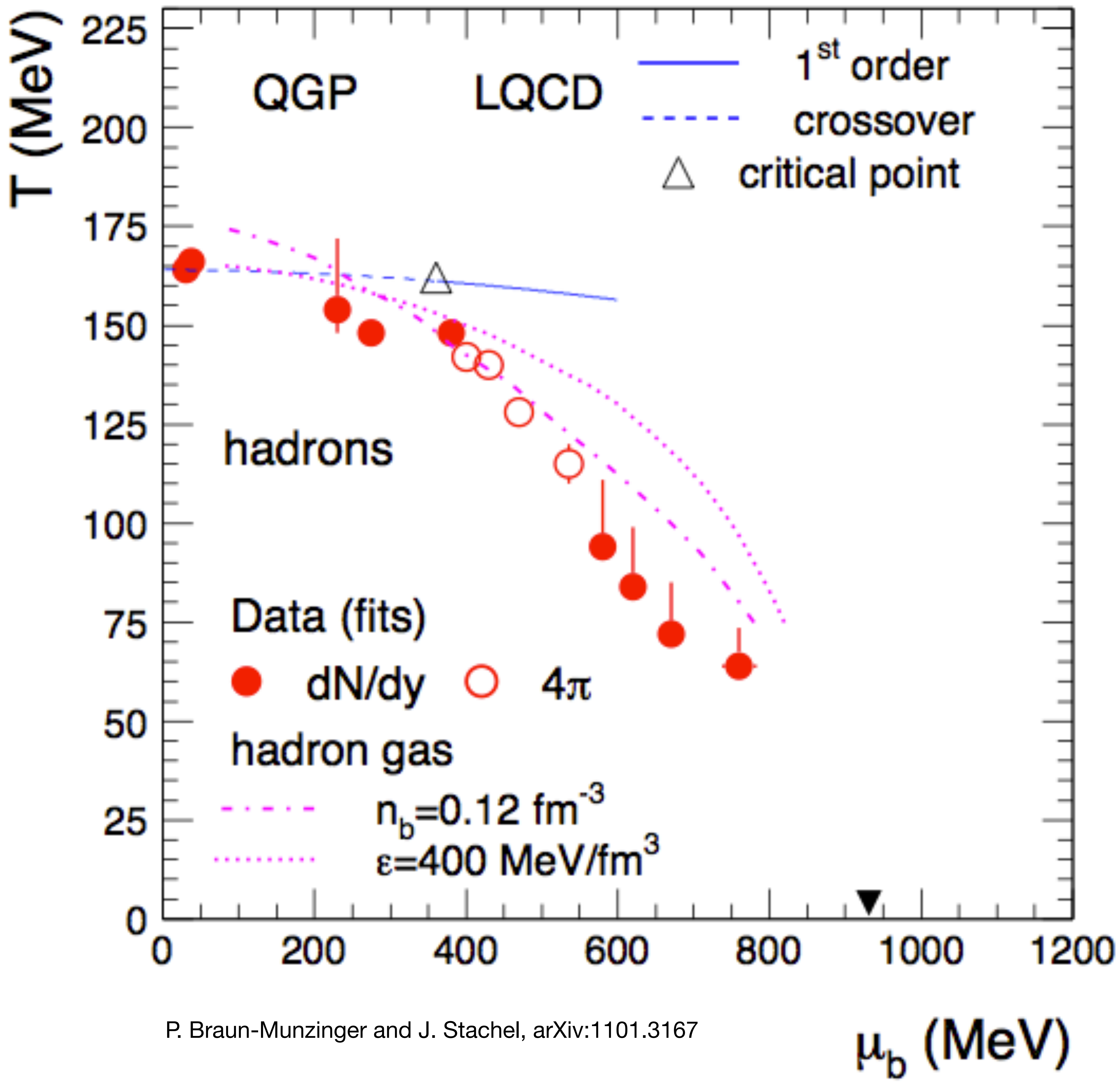
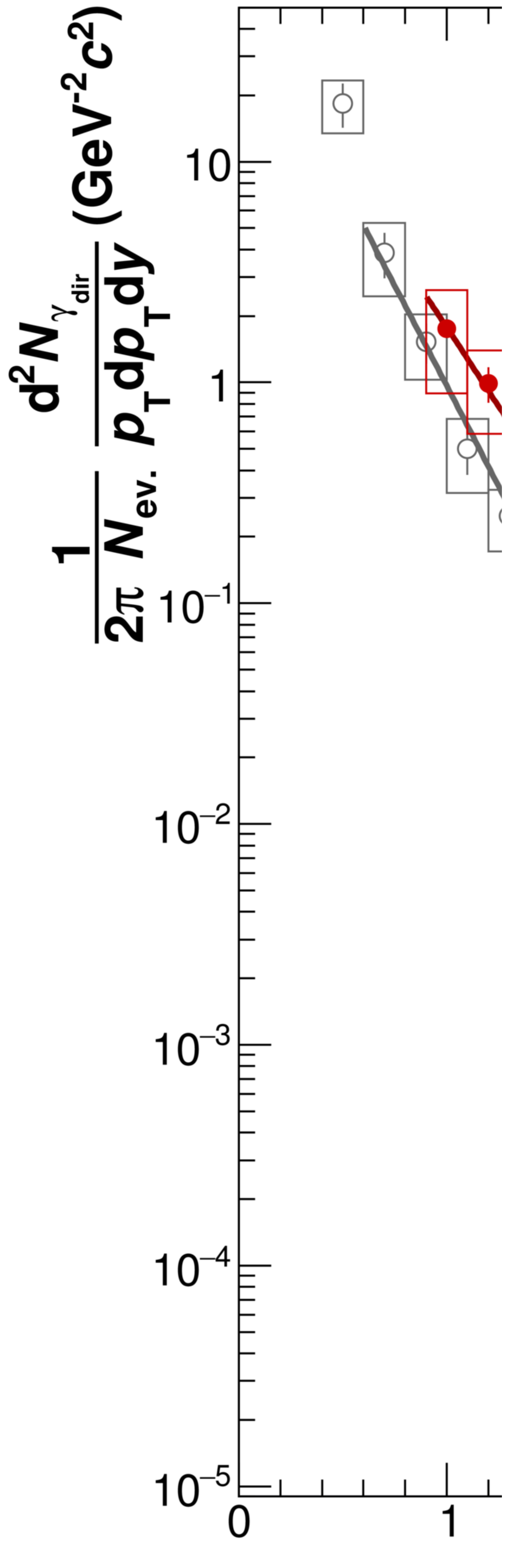


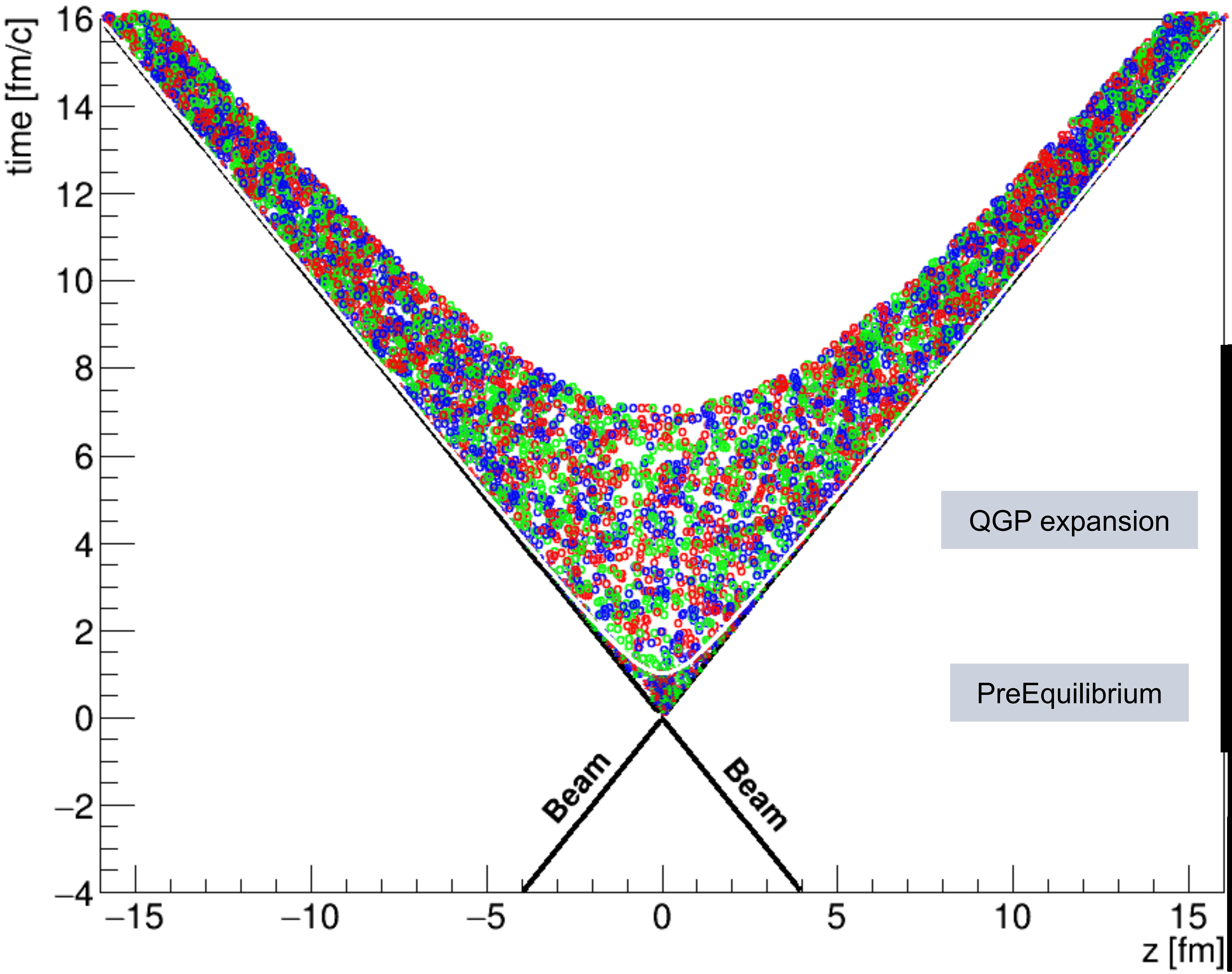
P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

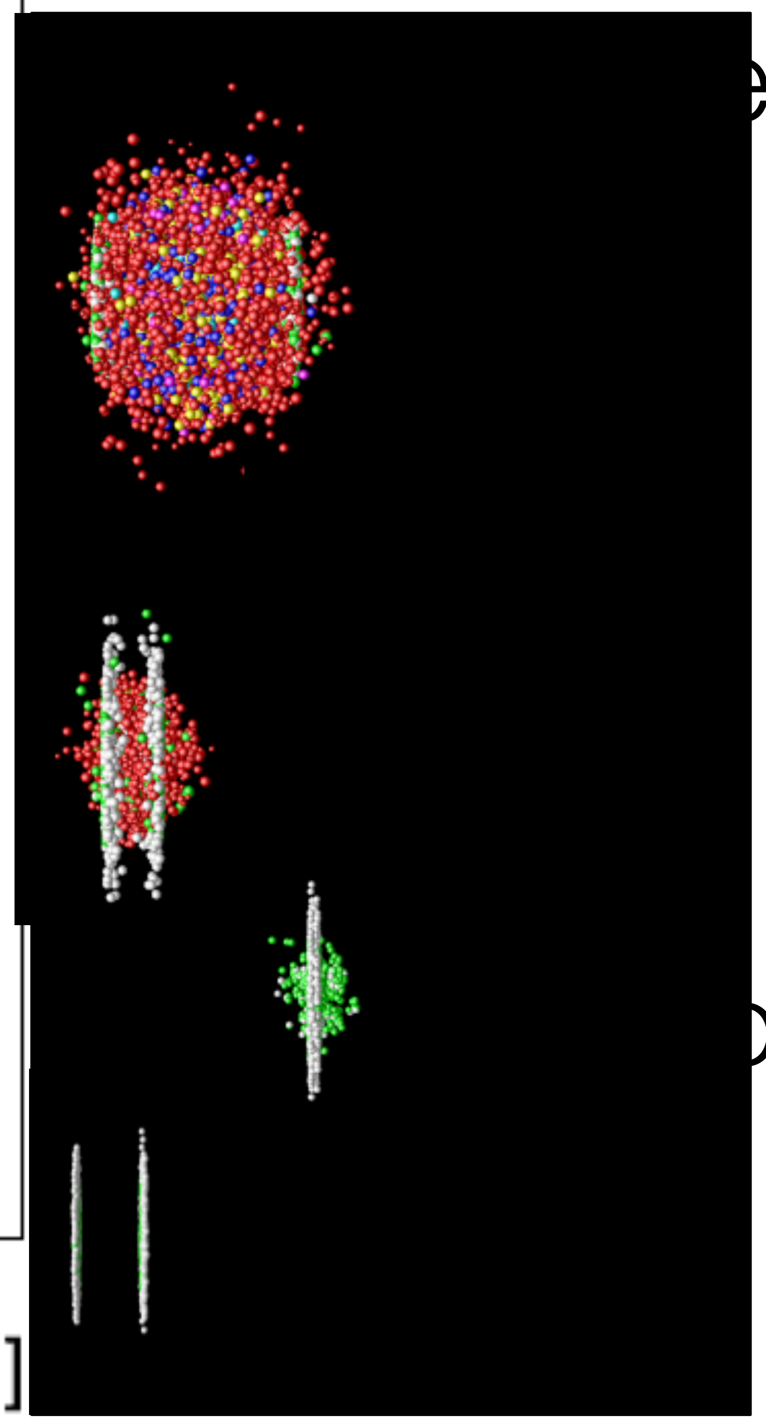
- By colliding nuclei with different center of mass energies, different regions of the phase diagram are explored.
- Thermal model fits to the experimental data define the chemical freeze-out line in the QCD phase diagram.
- The previously schematic phase diagram becomes one which is actually measured.
- SHM is not QGP: it's a Hadron Resonance Gas
  - However, the chemical freeze-out line determined by thermal fits coincides with the phase boundary calculated by lattice QCD above top SPS energies
  - Do multi-particle collisions near TC equilibrate the system? A rapid change in density near the phase transition can explain this.

How about the initial temperature of the QGP?



ALI-PUB-97914





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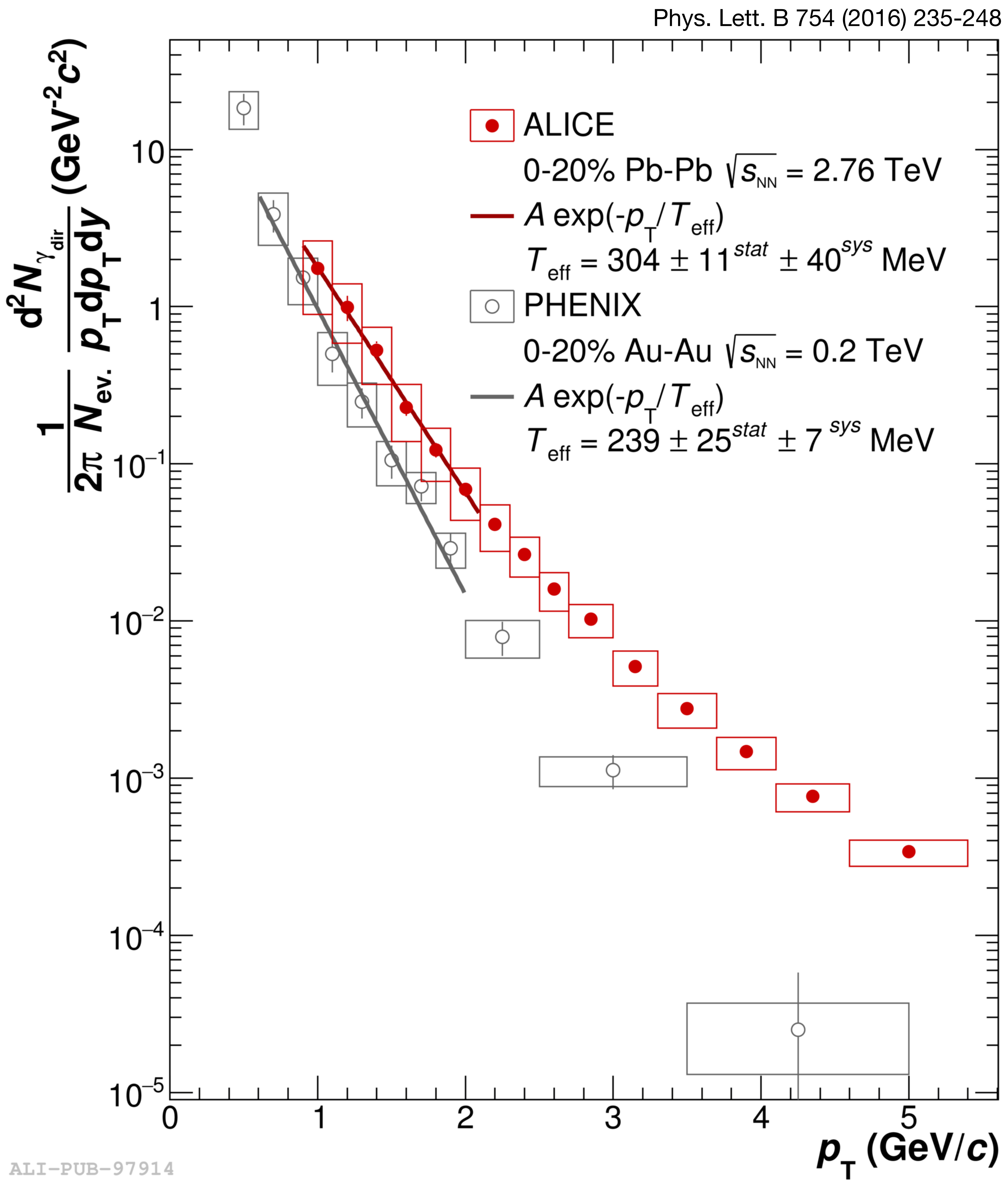


We can study the photon directly produced by the QGP

- challenging subtraction of the decay photons (e.g. $\pi^0 \rightarrow \gamma\gamma$)
- model comparisons are needed as direct photons are also emitted at later stages of the collision.

T_{eff} = 304 ± 11 ± 40 MeV

➡ Effective temperature of approx. 300 MeV is observed as a result of a high initial temperature and the blue-shift due to the radial expansion of the system.

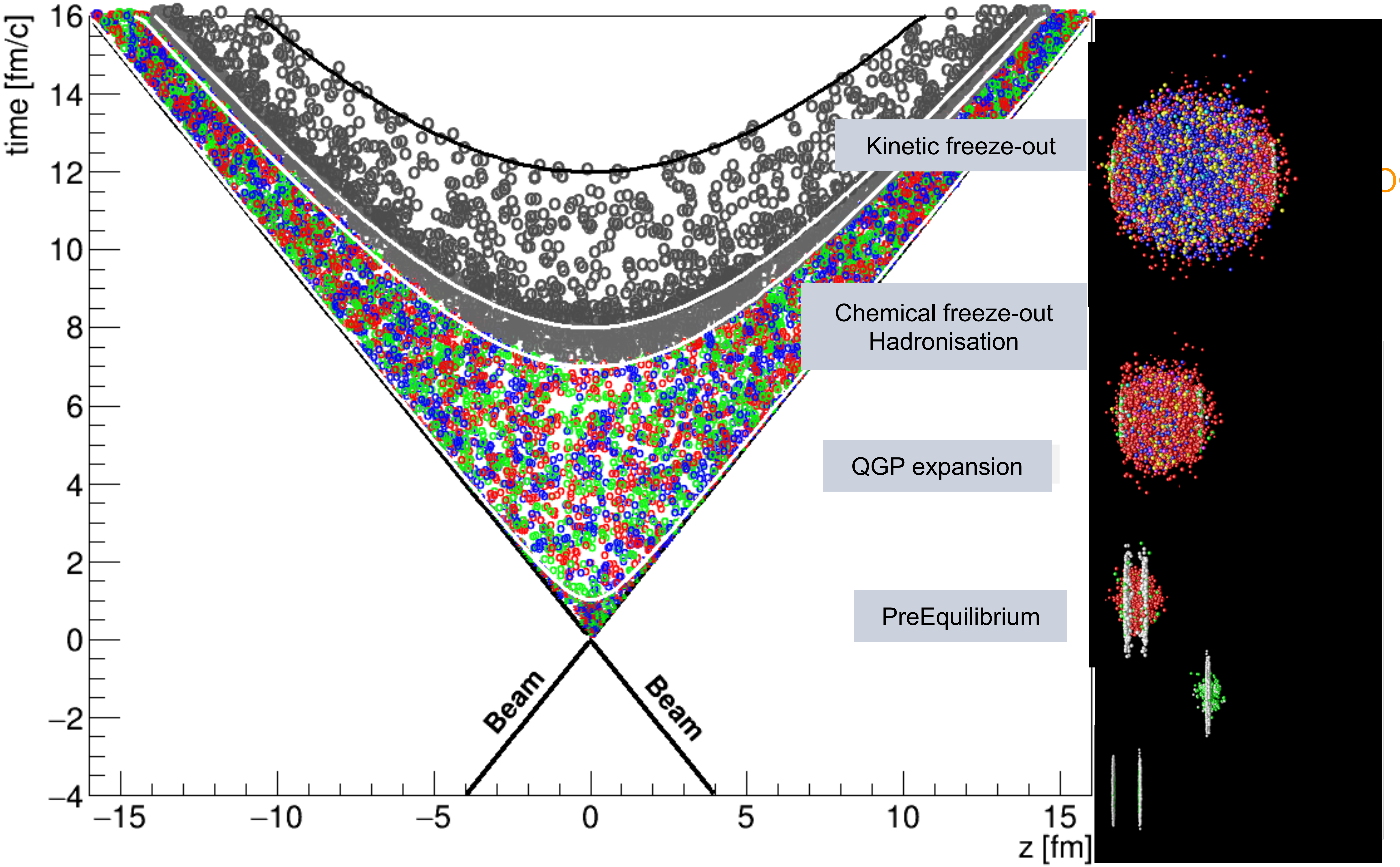
Kinetic equilibrium of soft particles

As seen in th   foresees the

creation of a

What makes

- The partic   odel
- The partic



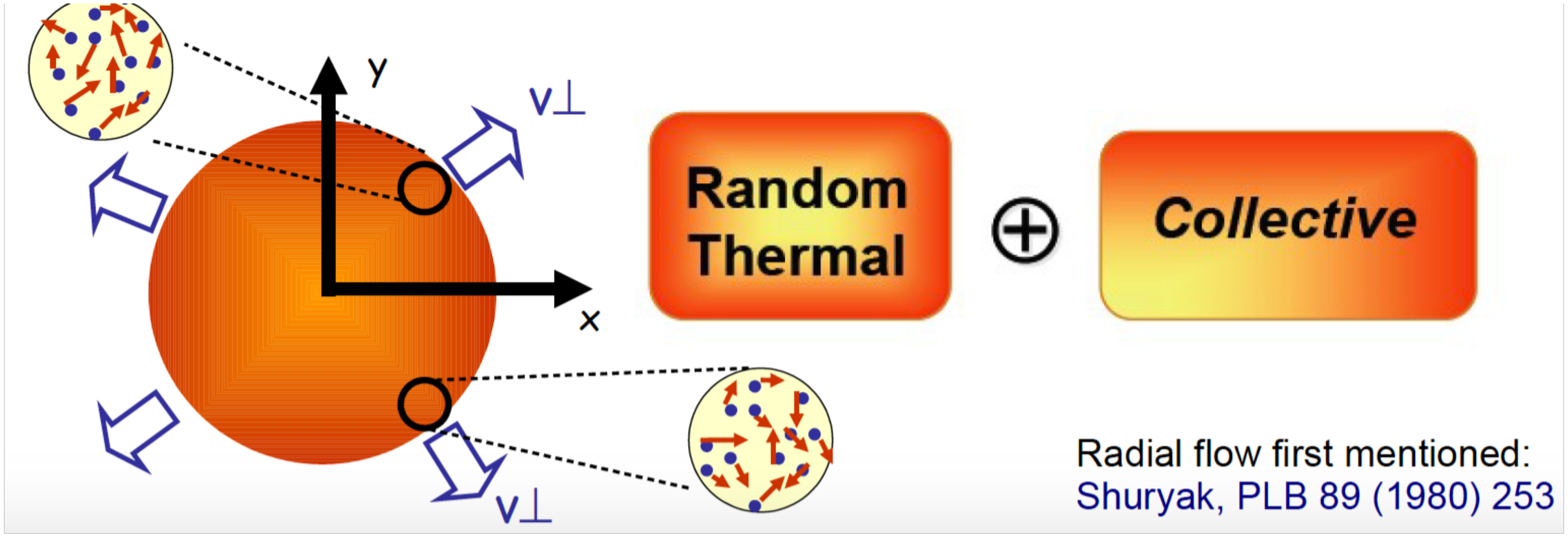
From:

Kinetic equilibrium of soft particles

As seen in the collision simulation, the current *standard heavy ion description* foresees the creation of a rapidly expanding fireball containing *u,d,* and *s* quarks.

What makes us think that:

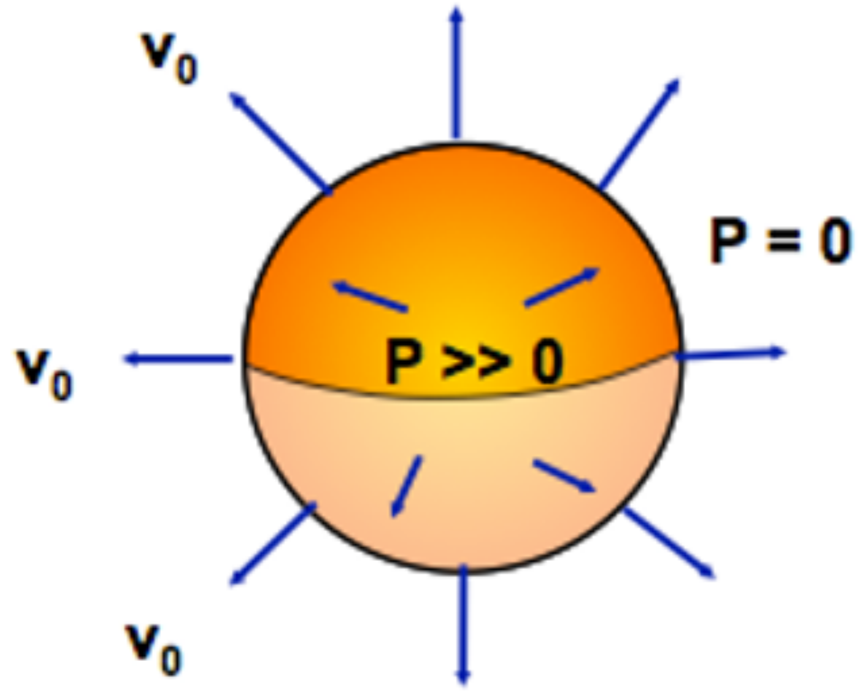
- The particle chemistry agrees with the calculation of the Statistical Hadronisation Model
- The particle momenta distribution agree with the expectation of hydrodynamics



From: C. Loizides

Collective motion: radial flow (I)

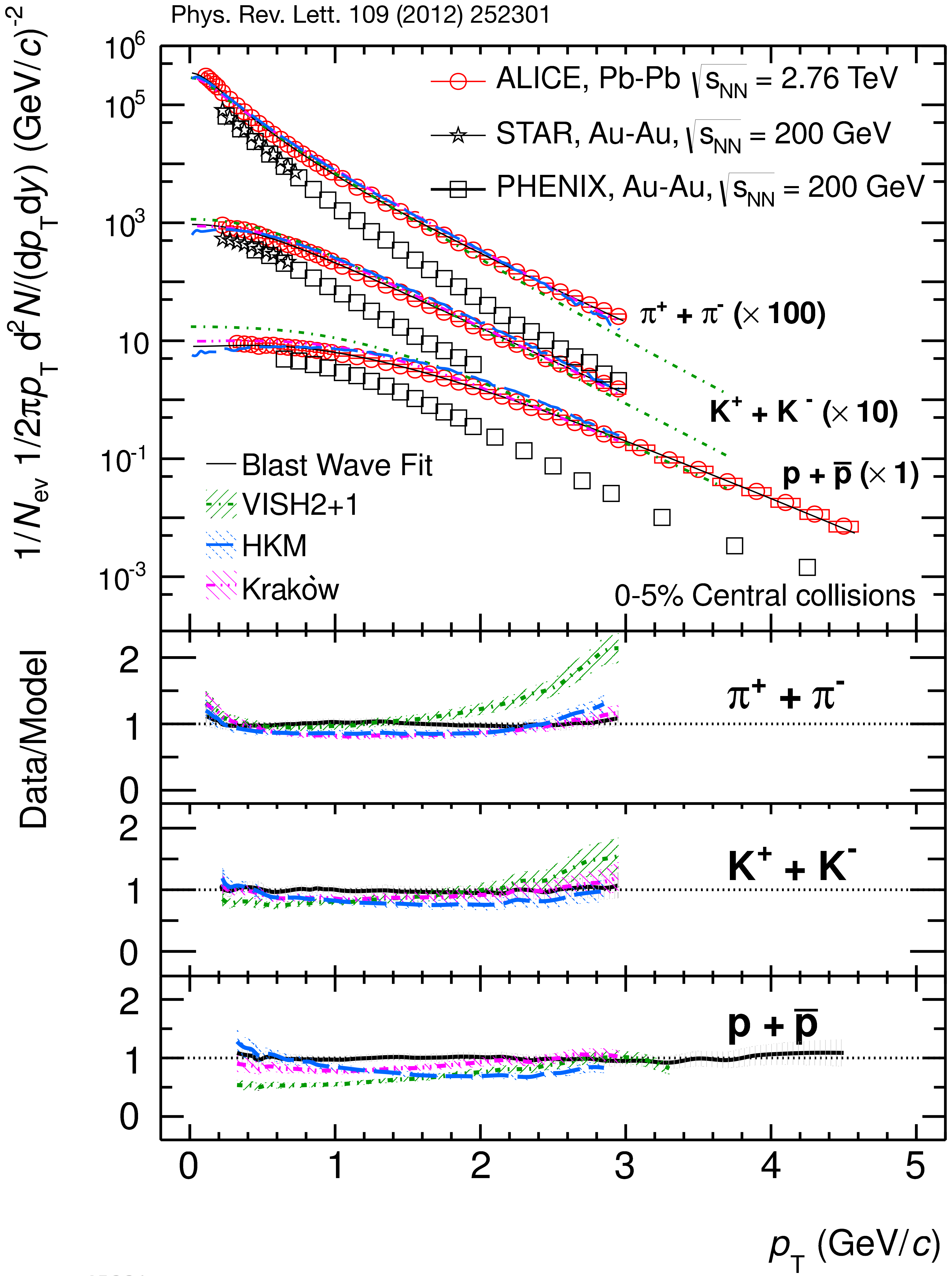
Isotropic radial flow



$$p = \gamma\beta m$$

Common radial hydrodynamic expansion: all particles are pushed at the same velocity:

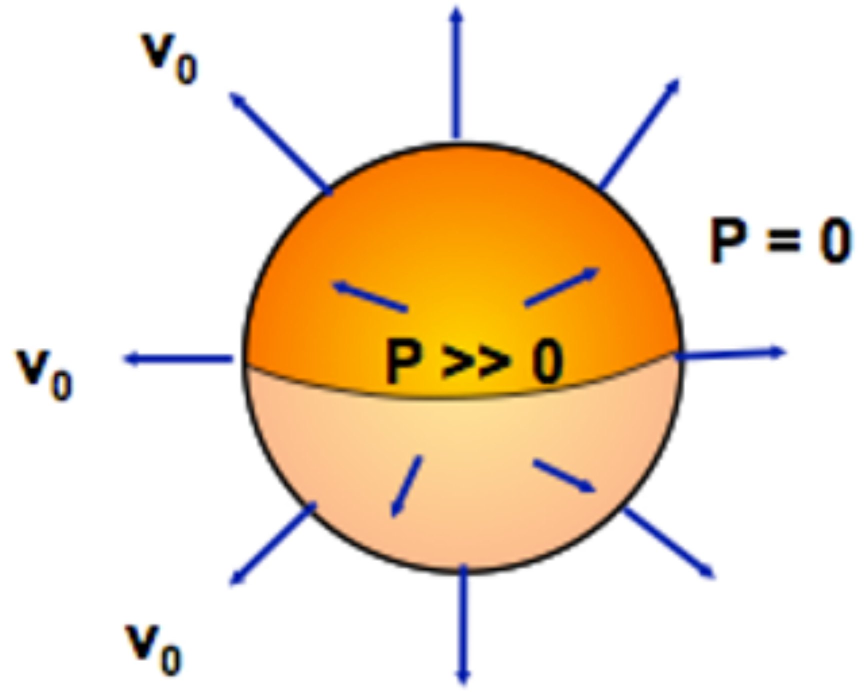
- Higher mass = harder spectra
- Higher collision energy = harder spectra



ALI-PUB-45331

Collective motion: radial flow (II)

Isotropic radial flow



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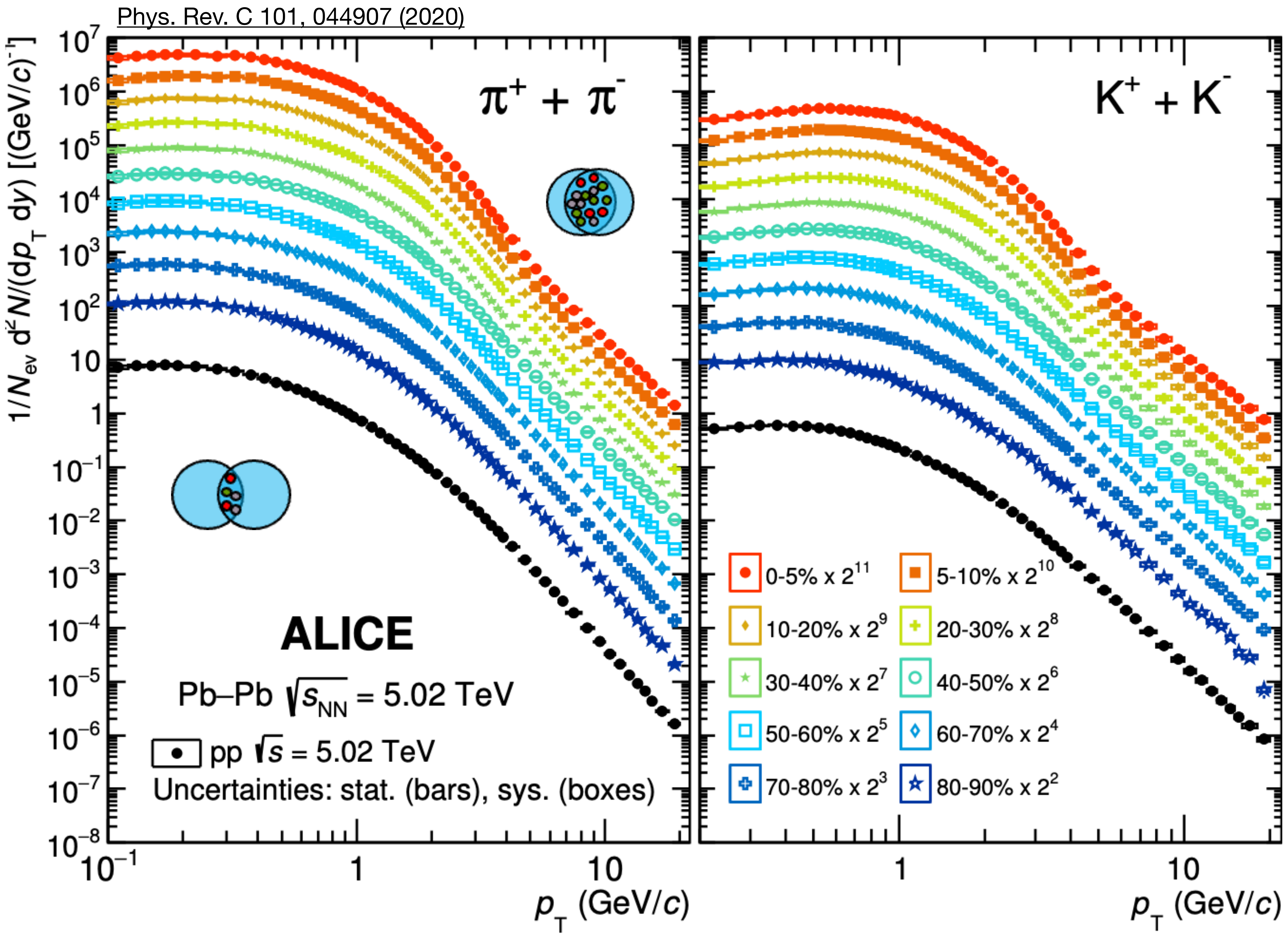

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- More central collision = harder spectra

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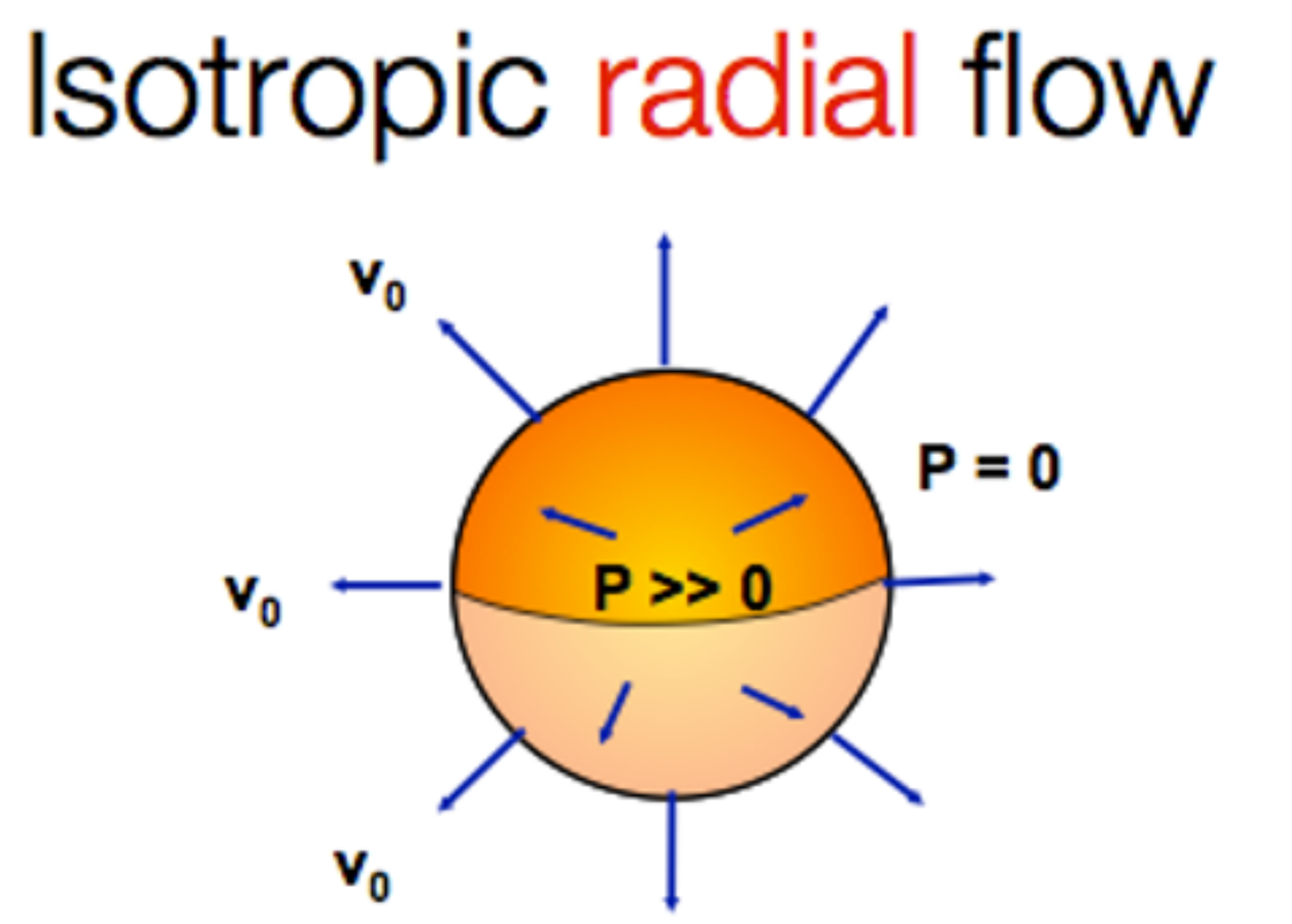

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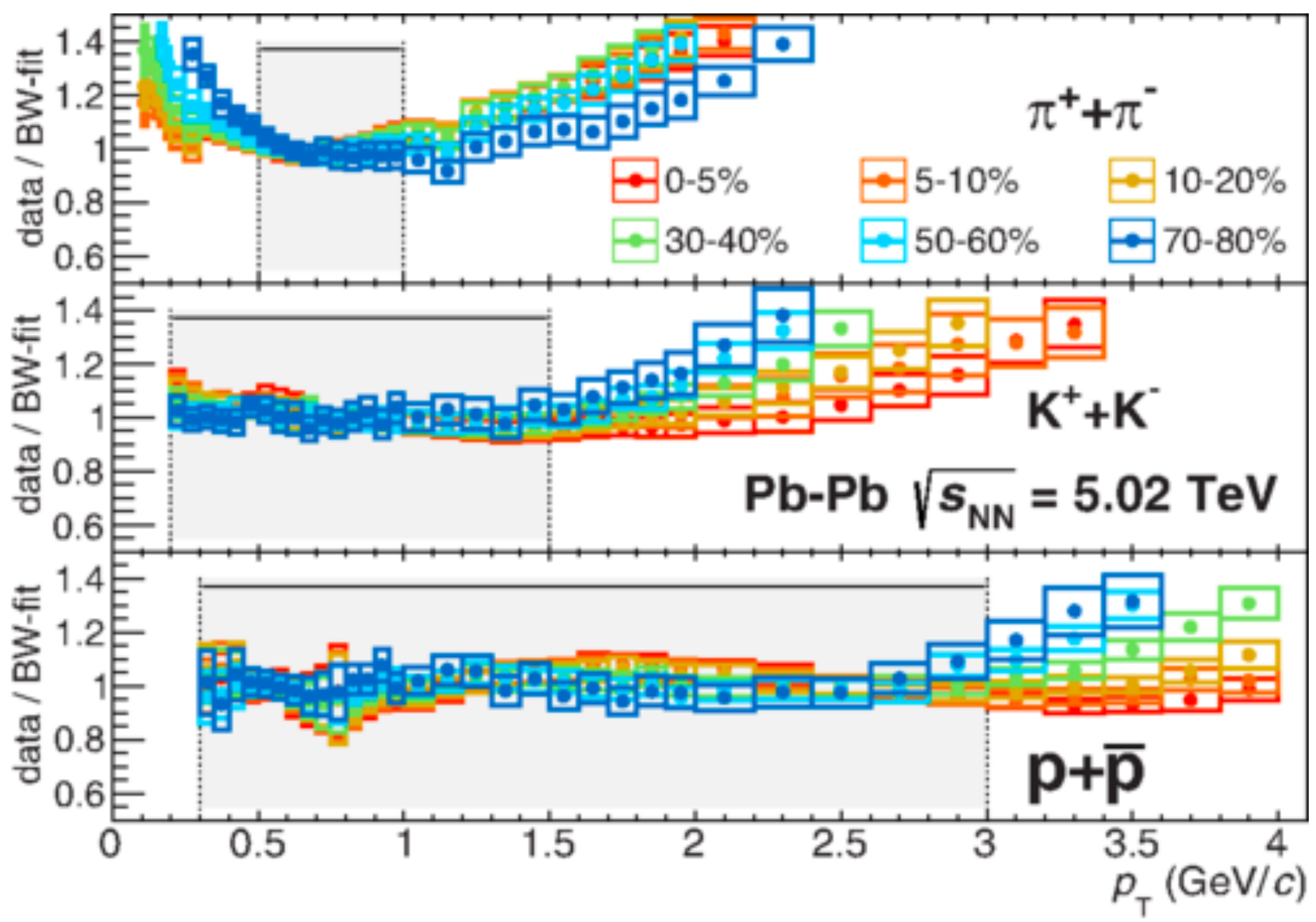
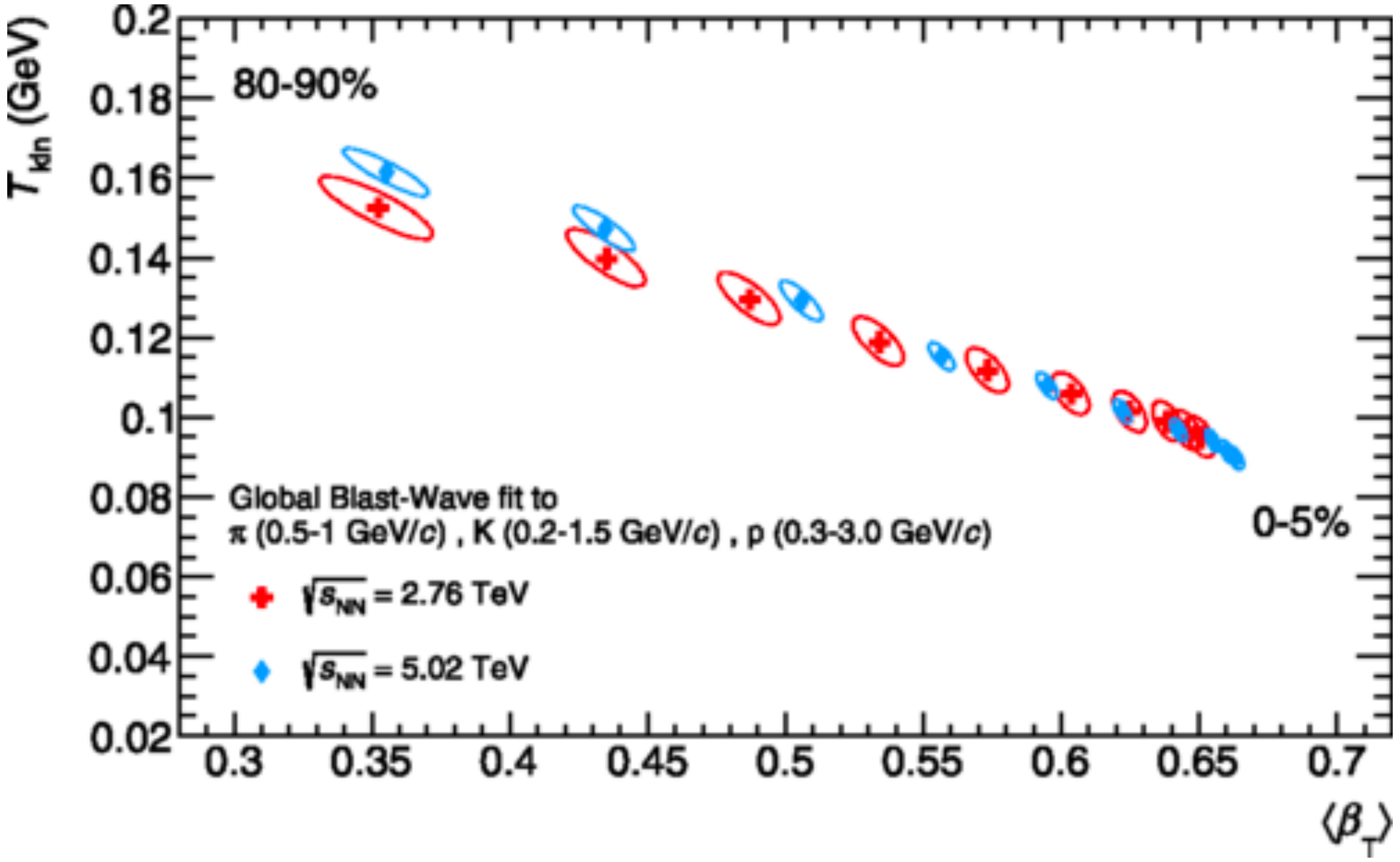
Common radial hydrodynamic expansion: all particles are pushed at the same velocity:

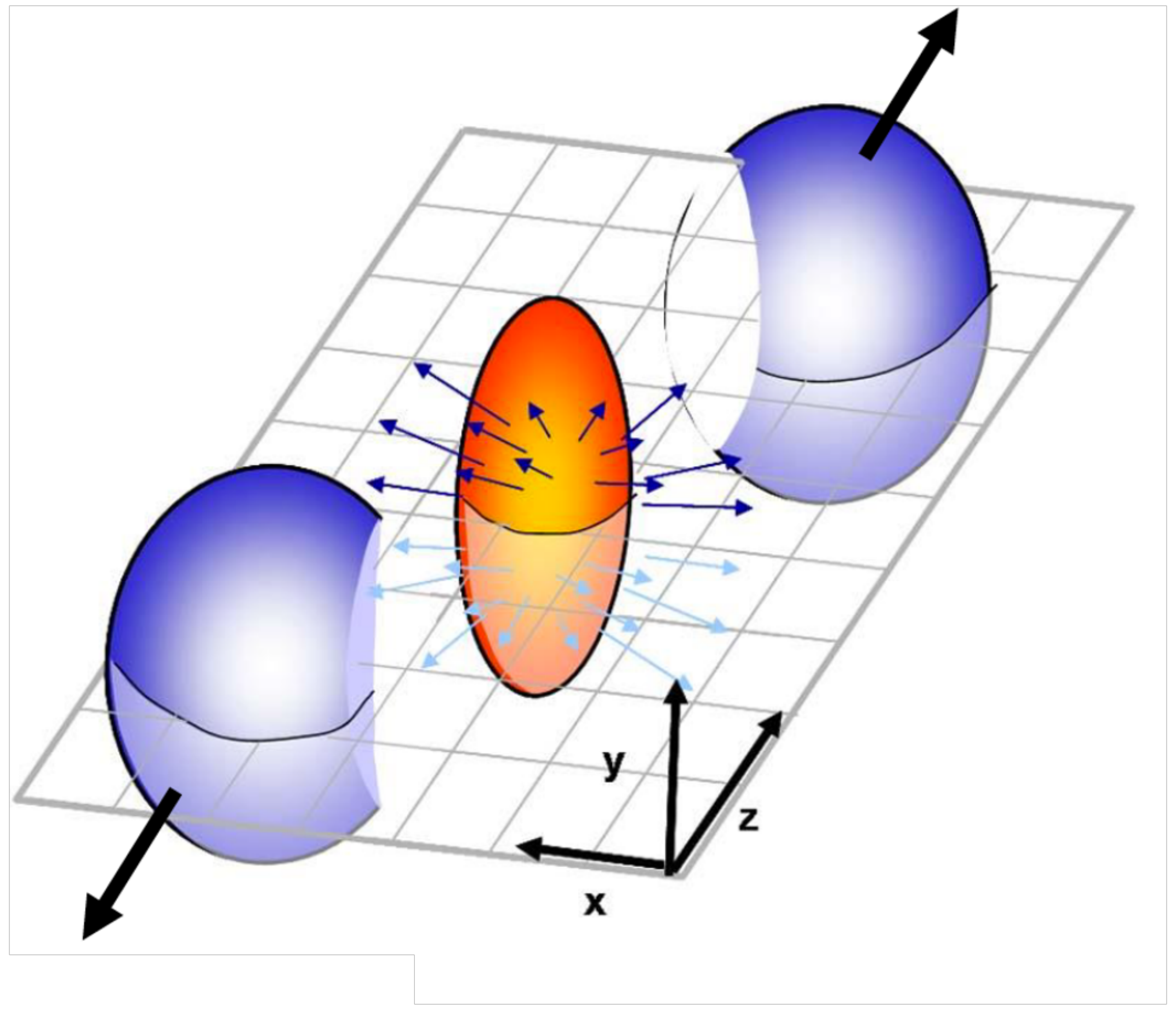
- Higher mass = harder spectra
- Higher collision energy = harder spectra
- More central collision = harder spectra
- Hydro model describe the spectra and define a kinetic freeze-out surface

Phys. Rev. C 101, 044907 (2020)





Collective motion: elliptic flow (I)



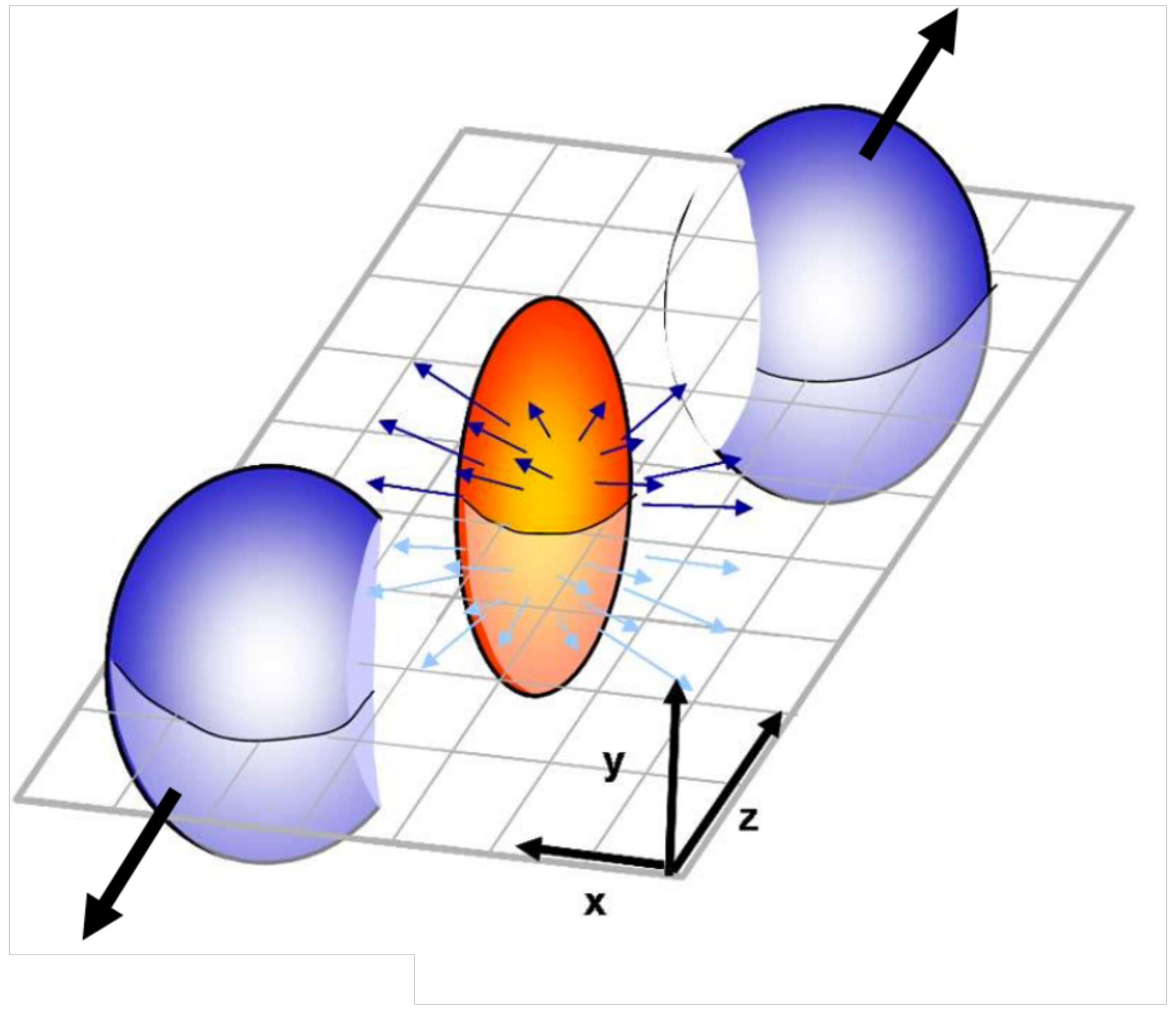
Initial spatial anisotropy can translate in a momentum anisotropy

- How efficiently this process can happen depends on the properties of the QGP created in the collisions

$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\varphi - \psi_n)]\right\}$$

Radial flow $\quad$ v_1 – direct flow, $\quad$ v_2- **elliptic flow**

Collective motion: elliptic flow (I)



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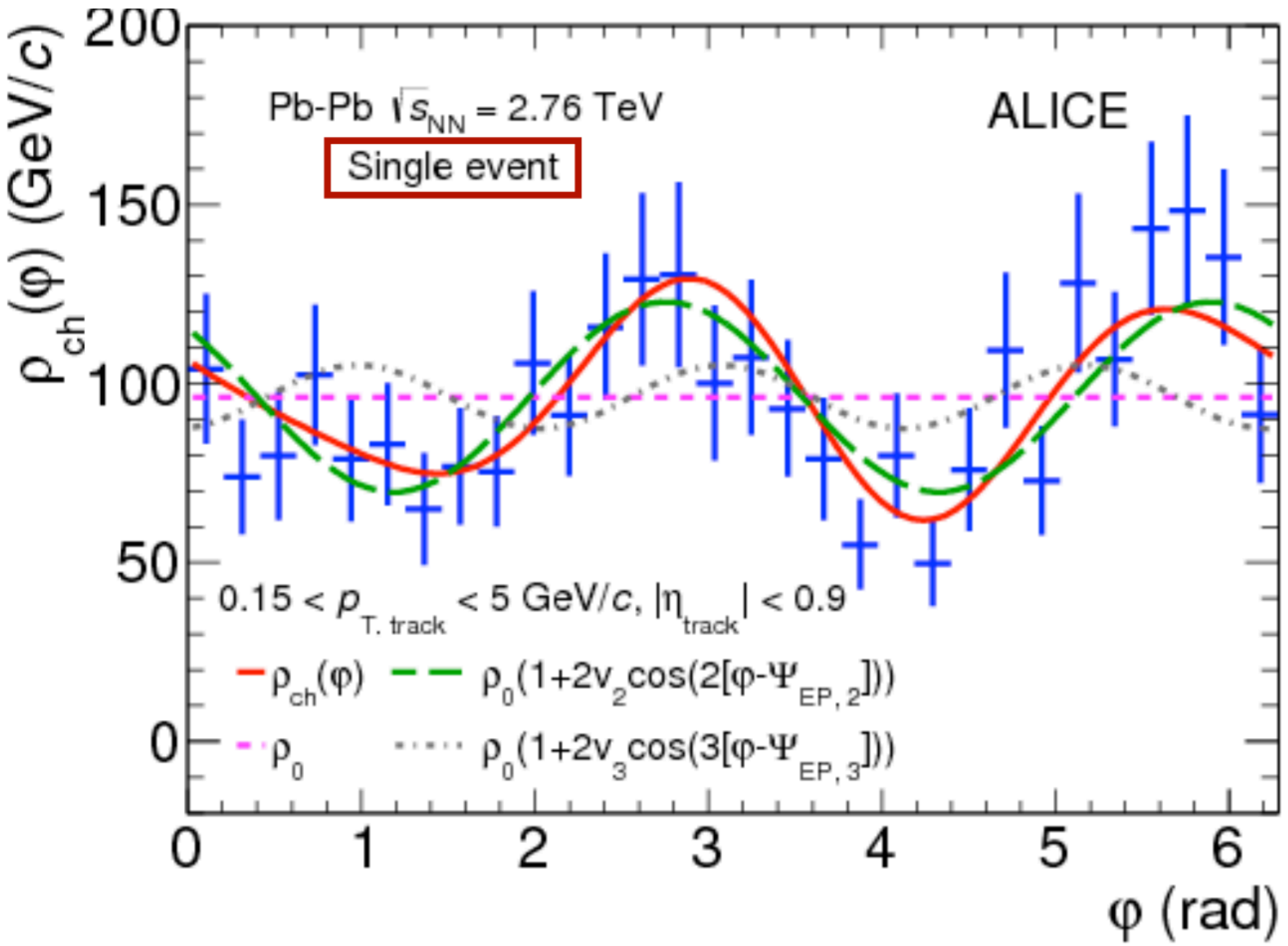
Radial flow v_1 – direct flow, $\boldsymbol{v_2}$**- elliptic flow**

Even in single event we can se a modulation in the azimuthal distribution of particle production

- One could just do the Fourier transformation of the distribution to get the v_n coefficients
  - However: other non-collective effect influence this distribution (e.g. jets, decays of resonances)
- A awful lot of work to correct for these effects (multi particle correlations, large pseudo rapidity gaps)



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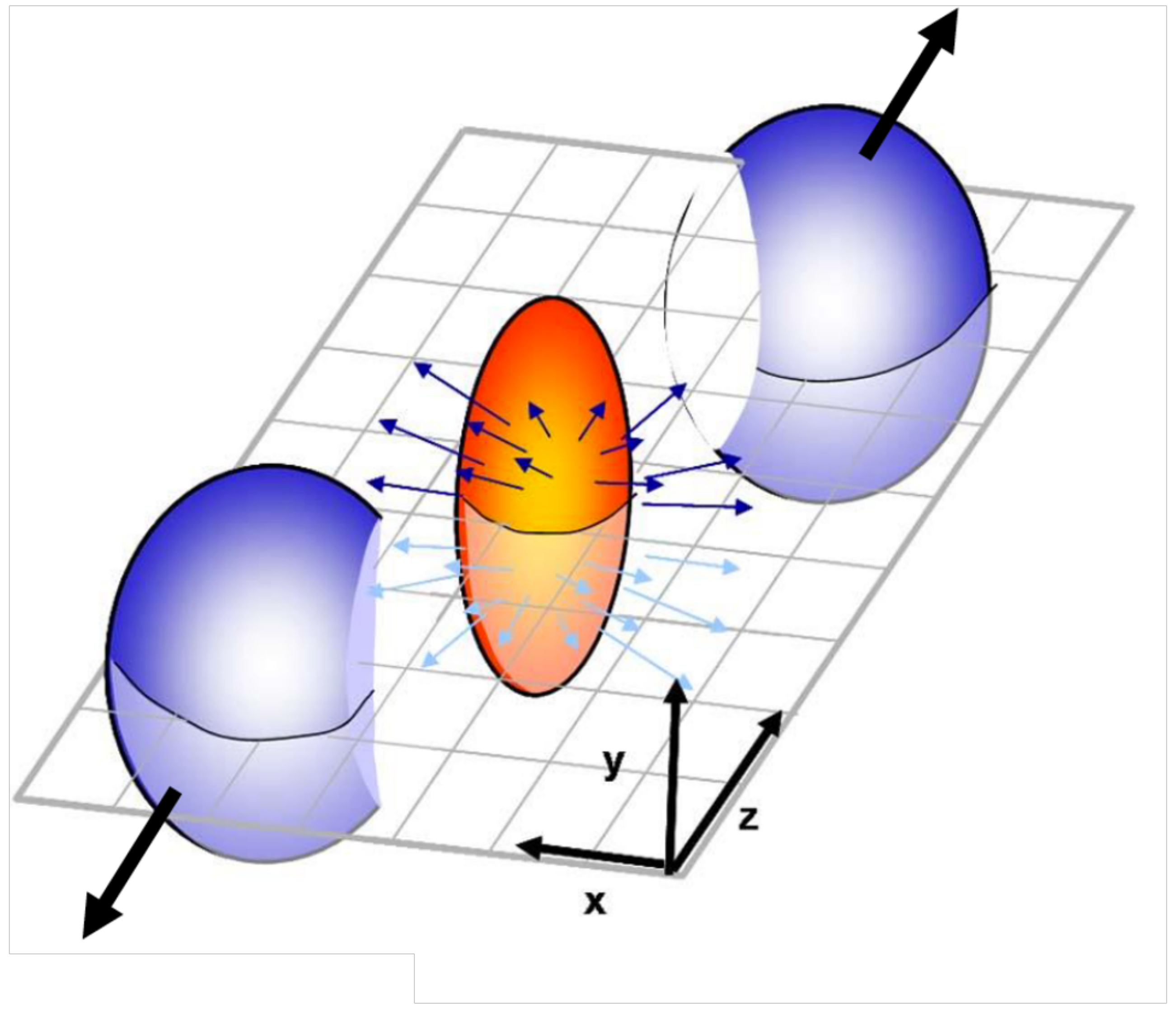
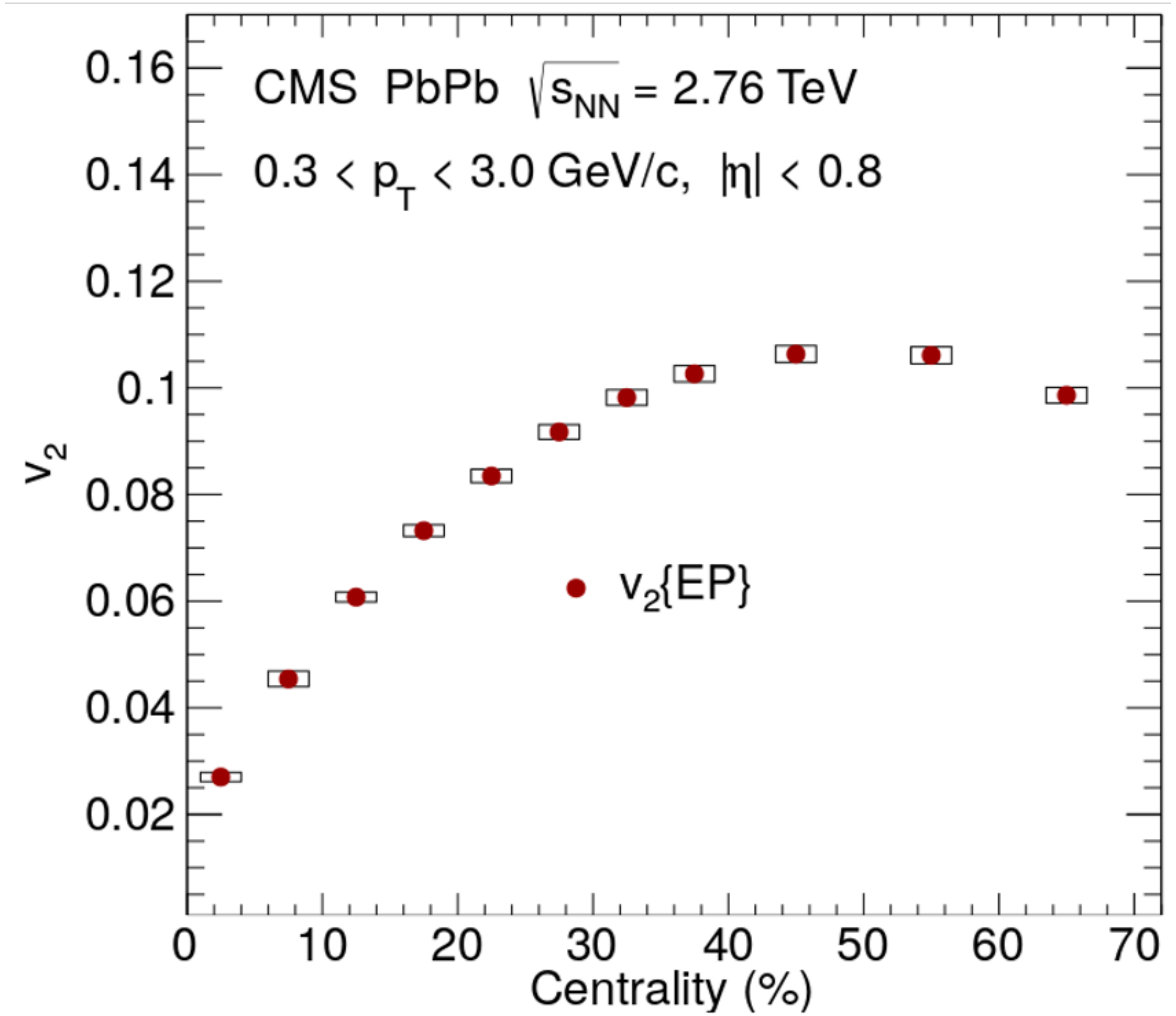
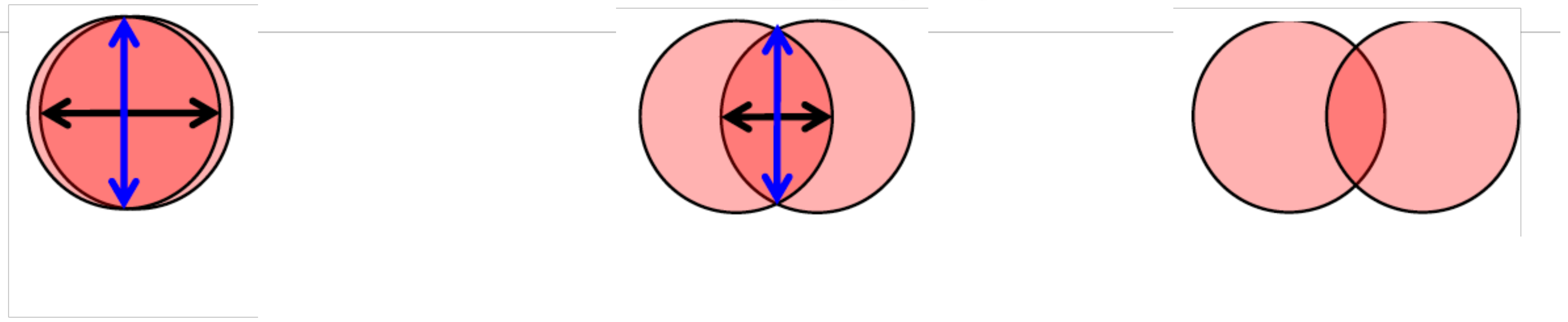
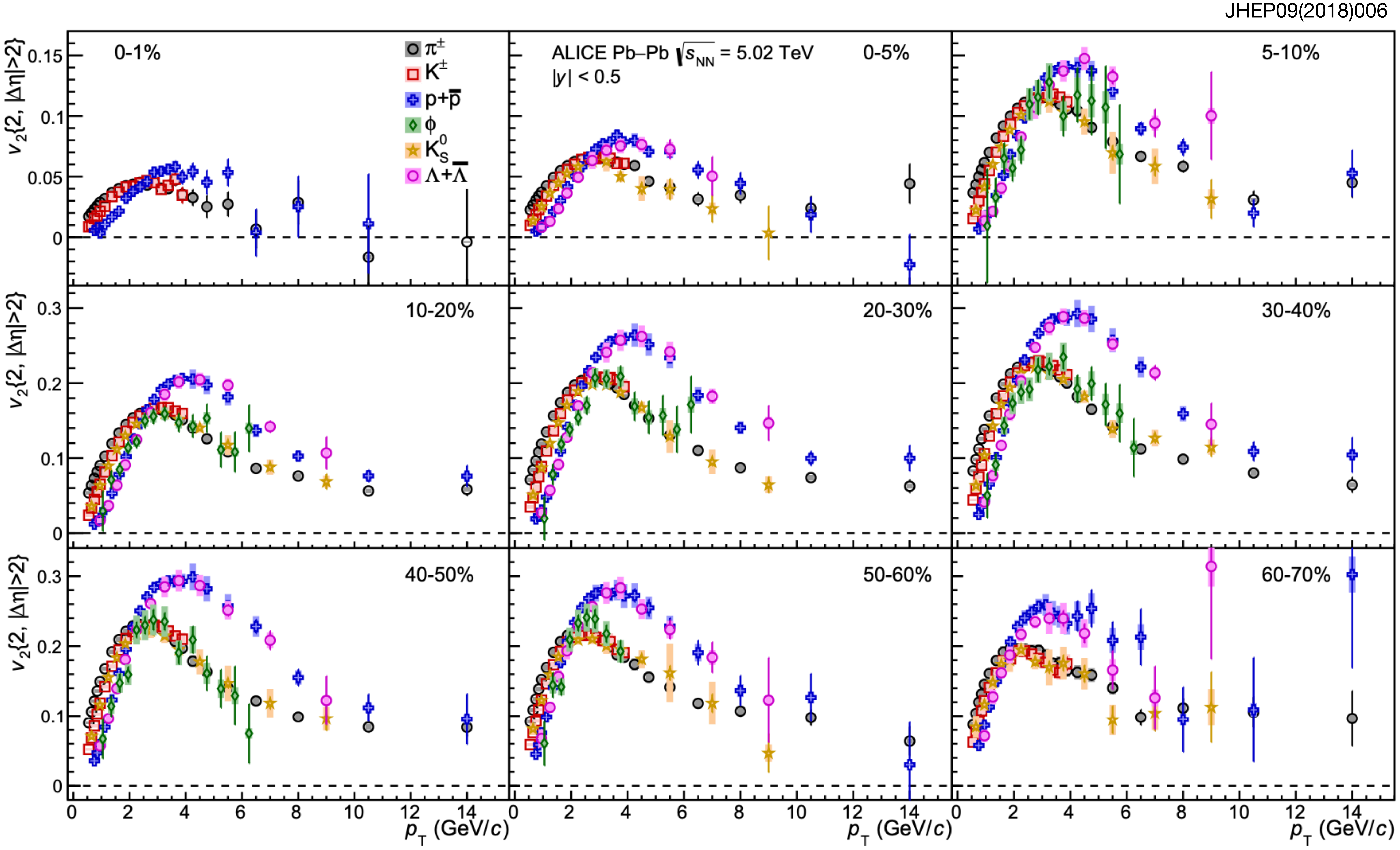


- v_2 exhibits a strong centrality dependence
- v_2 largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions





Mass ordering of v_2



At p_T< 2 GeV/c, the elliptic flow shows the same mass ordering (p = βγ·m) as radial flow

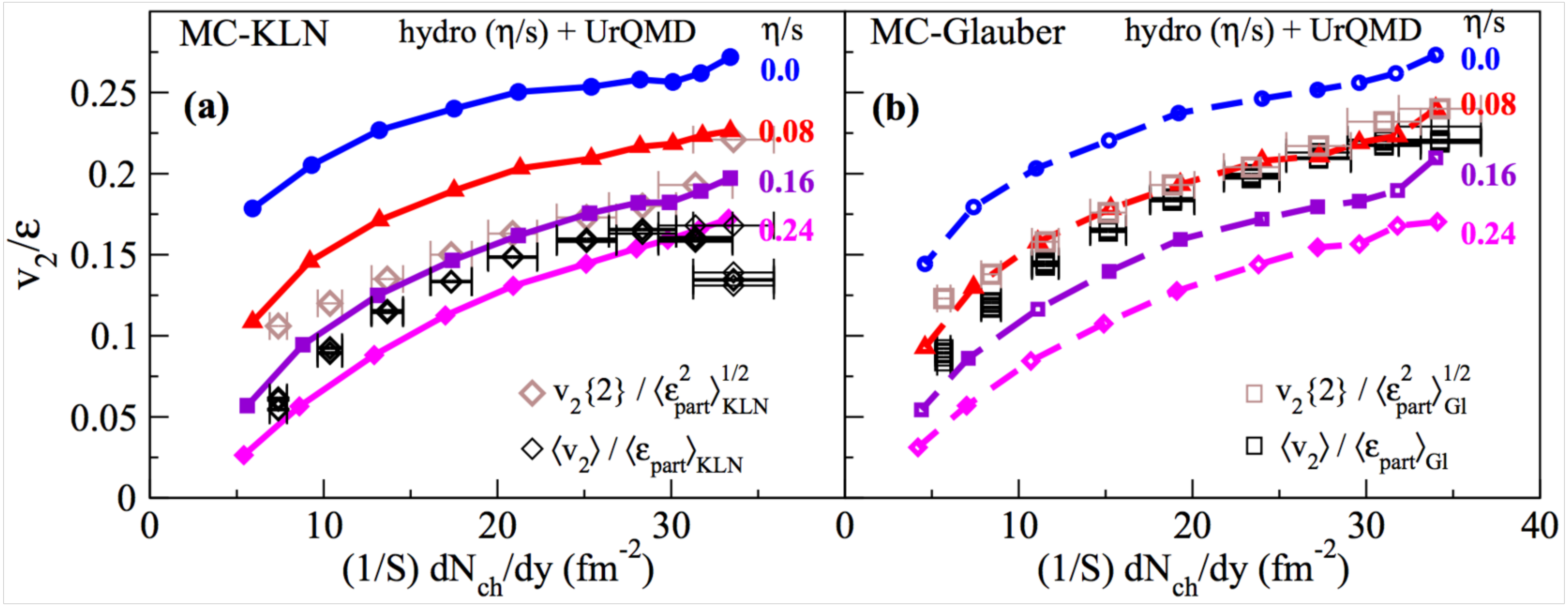
- Interplay between radial flow and elliptic flow, as expected by hydrodynamics

At intermediate transverse momentum: baryon-meson grouping

- Direct effect of the modification of the hadronisation in the medium due to quark recombination

Sensitivity of v_2 to shear viscosity

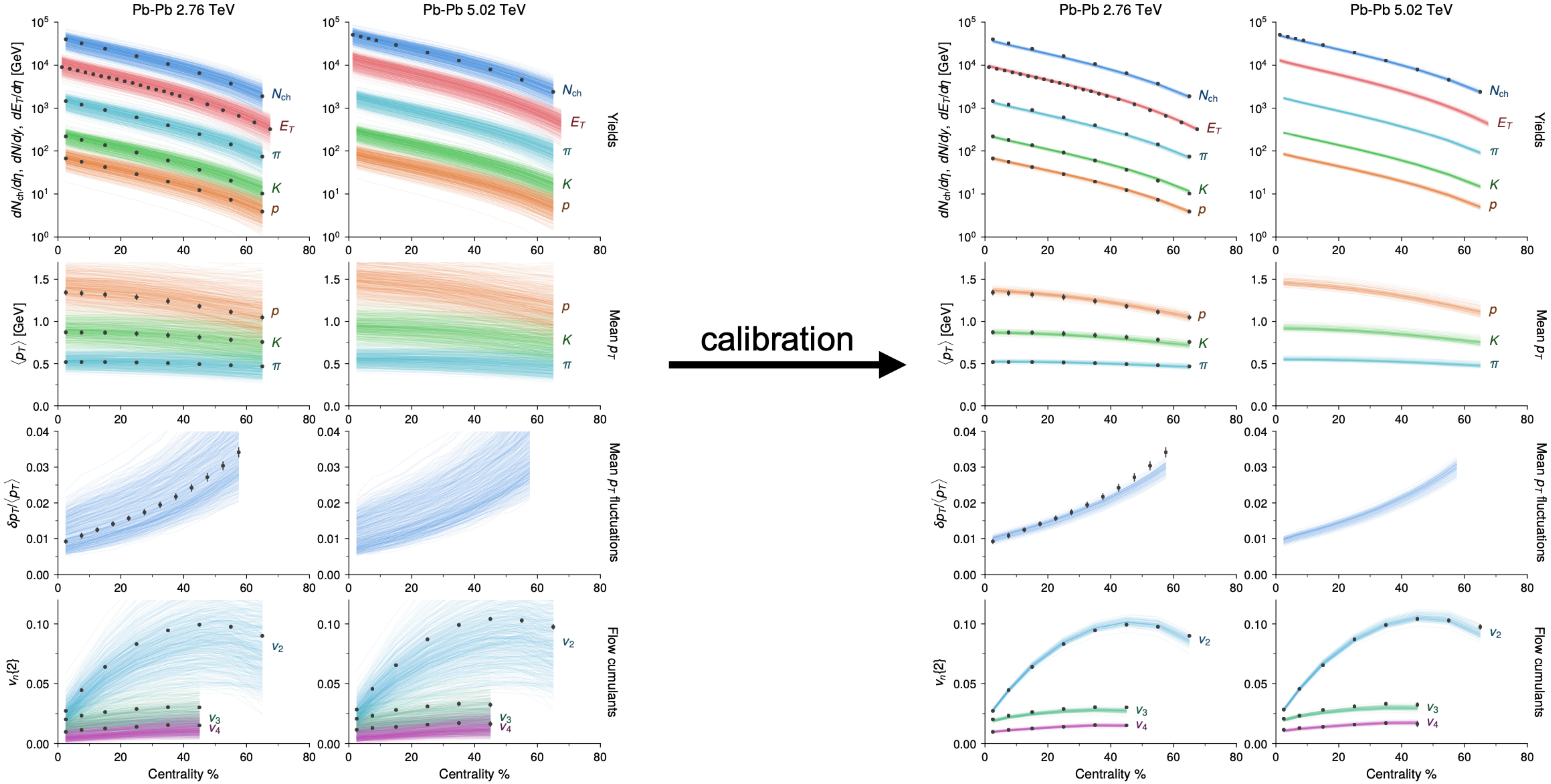
[Phys.Rev.Lett. 106 (2011) 192301]



- The larger the shear viscosity per entropy density ratio *η/s* of the QGP, the more v_2 is reduced.
- Dissipative losses hamper the buildup of flow => measuring the magnitude of v_2 and comparing it to models, we can determine how *ideal* the QGP liquid is.

QGP properties and bayesian analyses

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

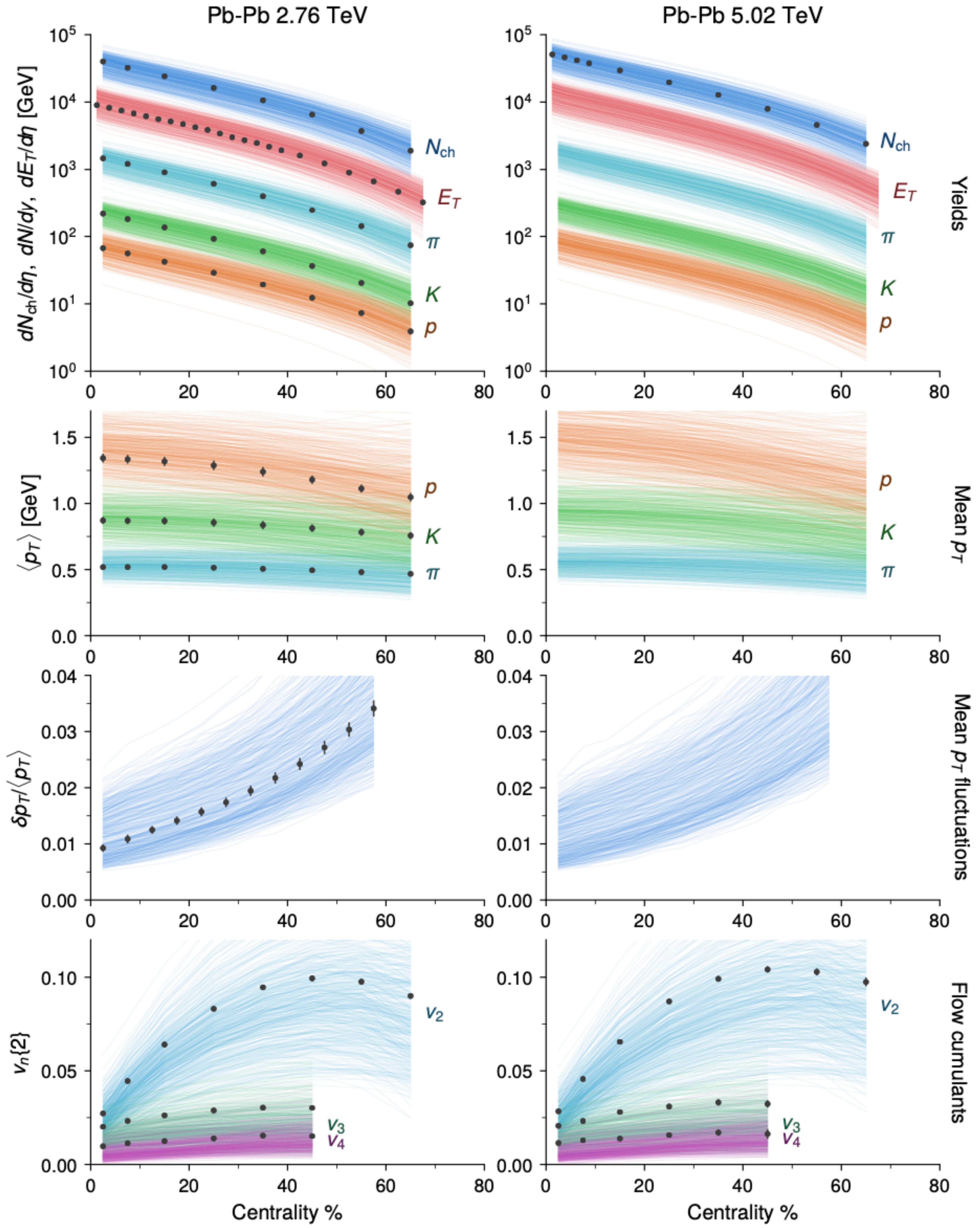


Bayesian analysis: a new way of interpreting the large amount of data from Heavy Ion collisions

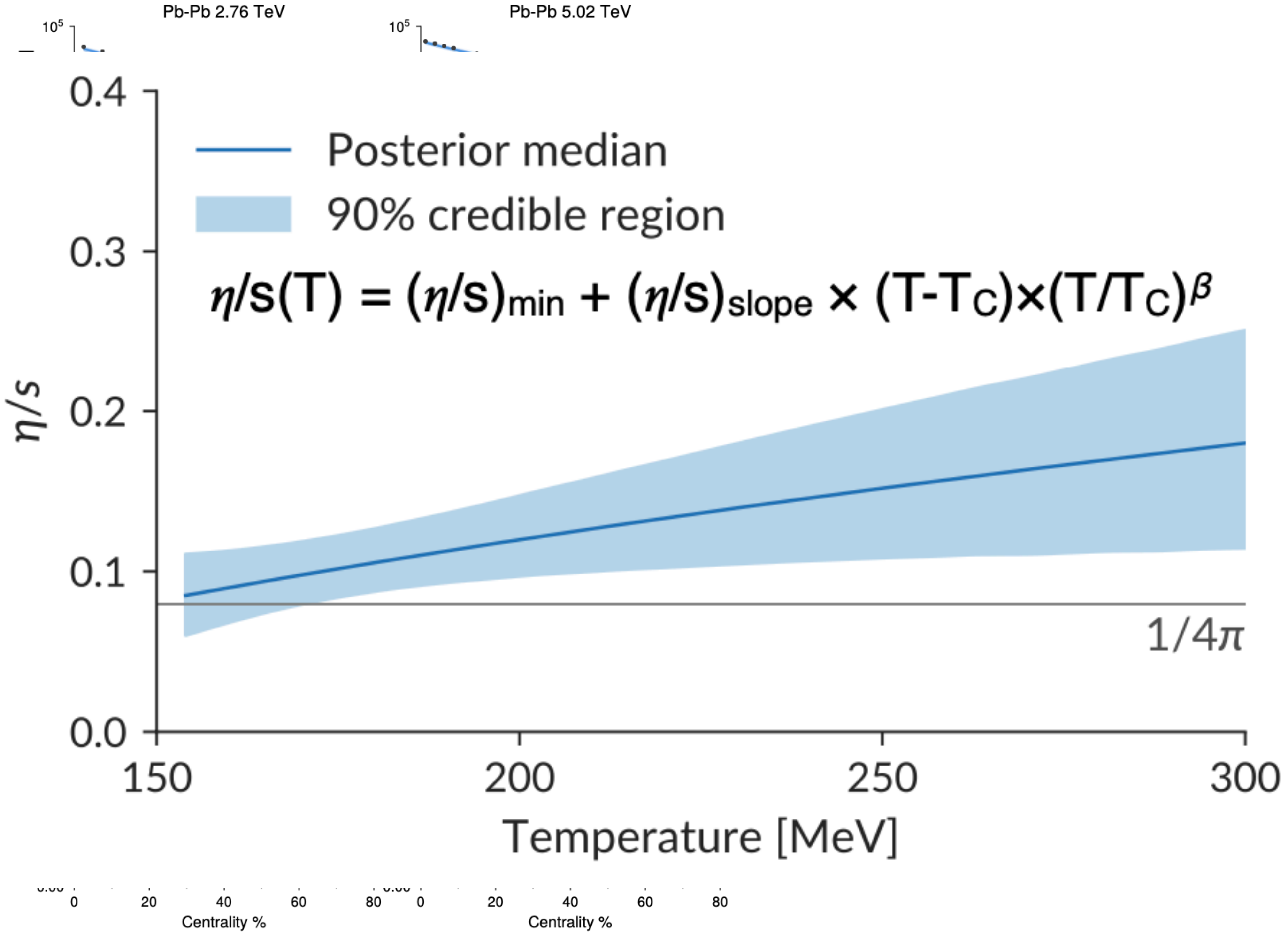
- Parameter estimation taking into account several different measurements and models

QGP properties and bayesian analyses

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



calibration



Bayesian analysis: a new way of interpreting the large amount of data from Heavy Ion collisions

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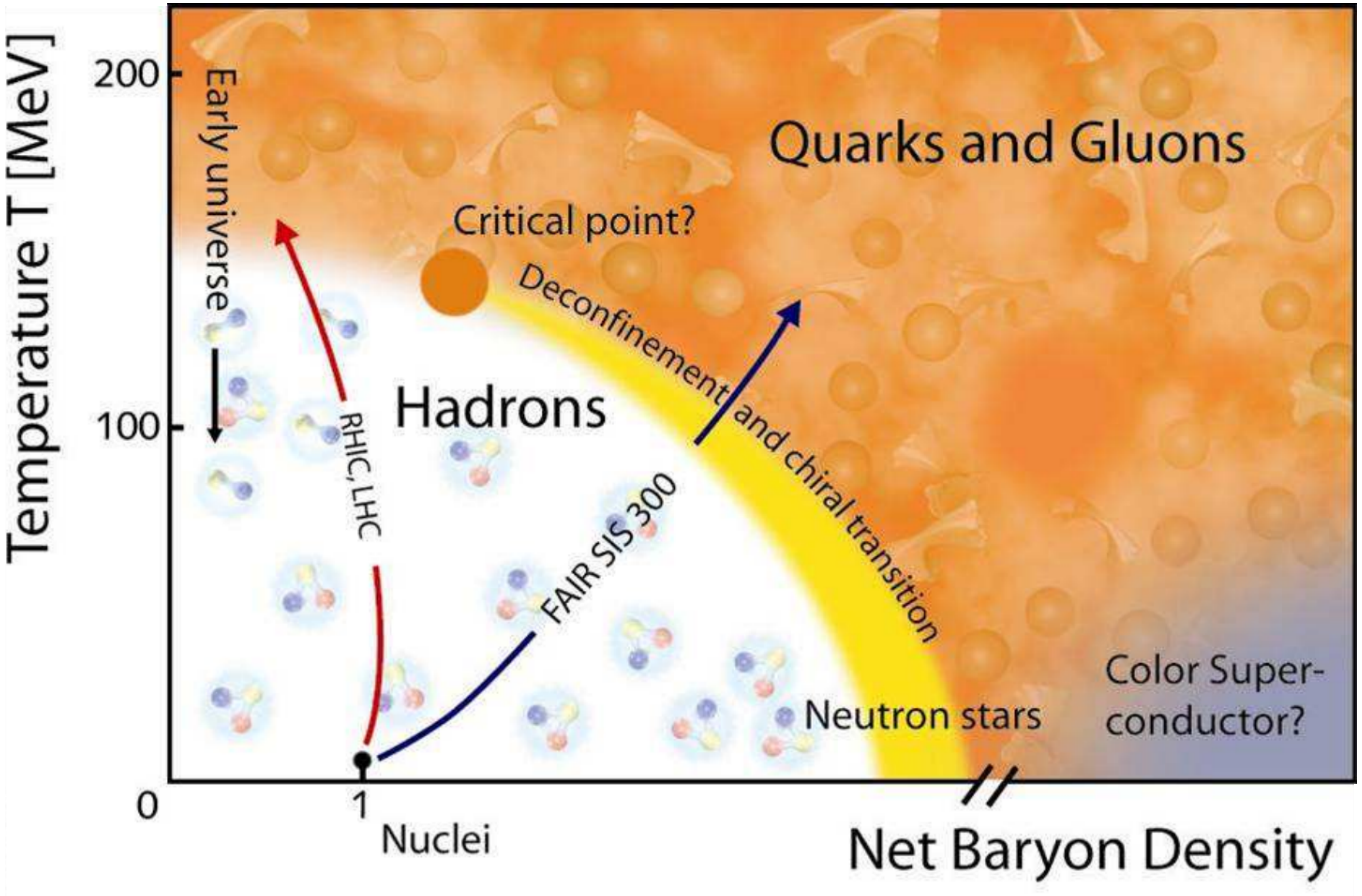
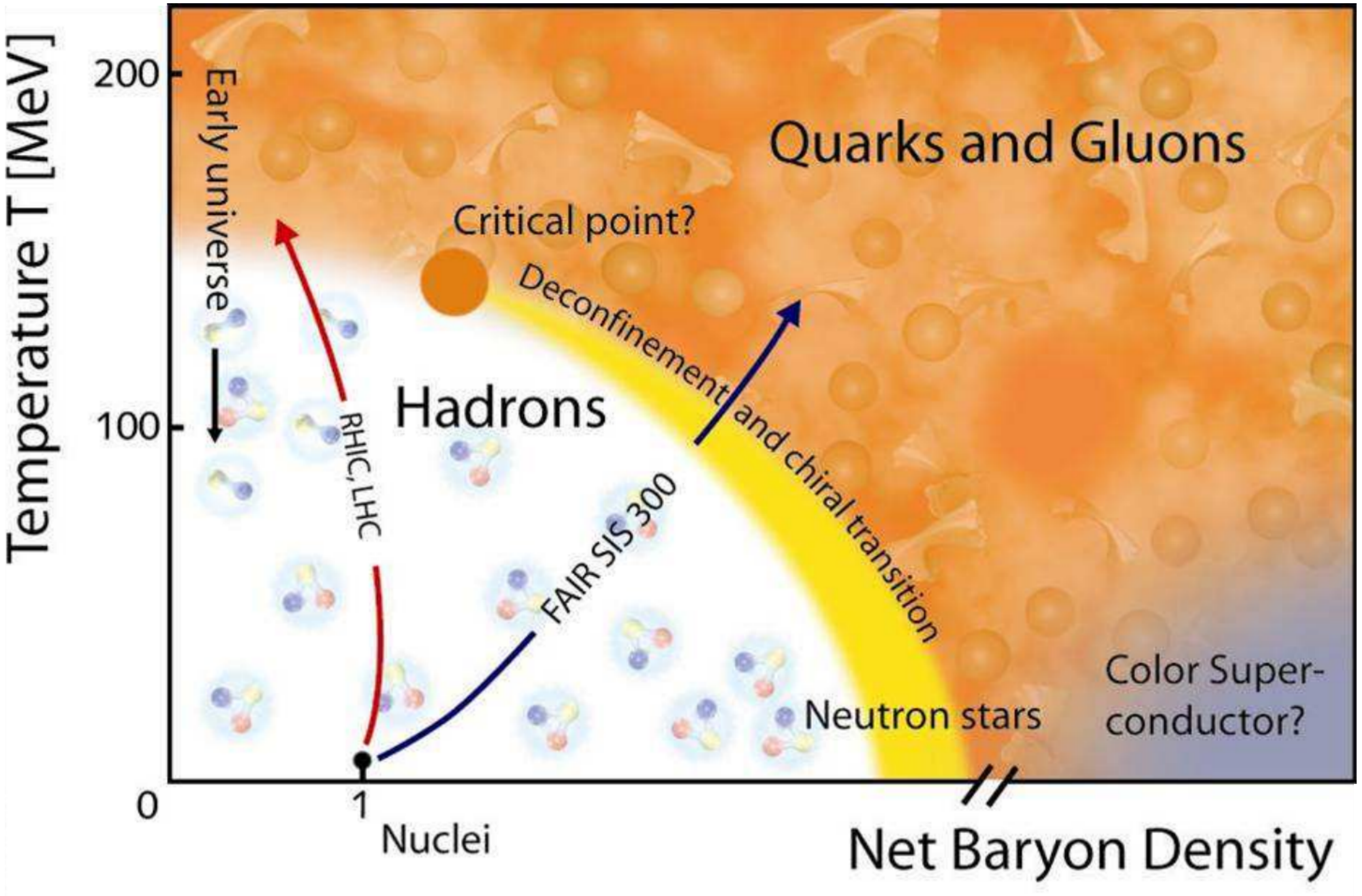
Searching the QCD critical point



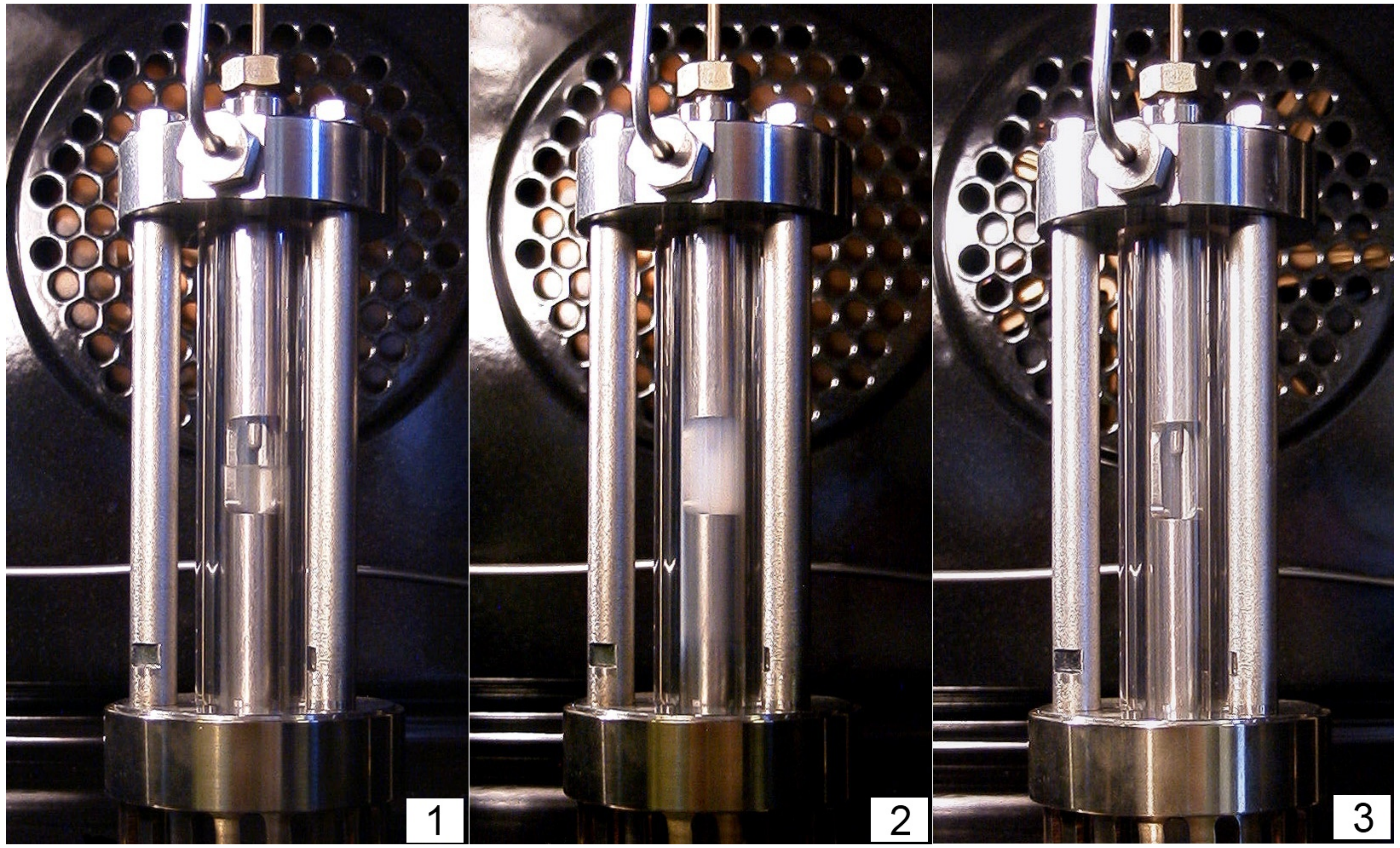
Expected to be at lower energies: RHIC beam energy scan program

- Looking for critical phenomena in the production of soft particles

Searching the QCD critical point



S. Horstmann, Ph.D. Thesis University Oldenburg



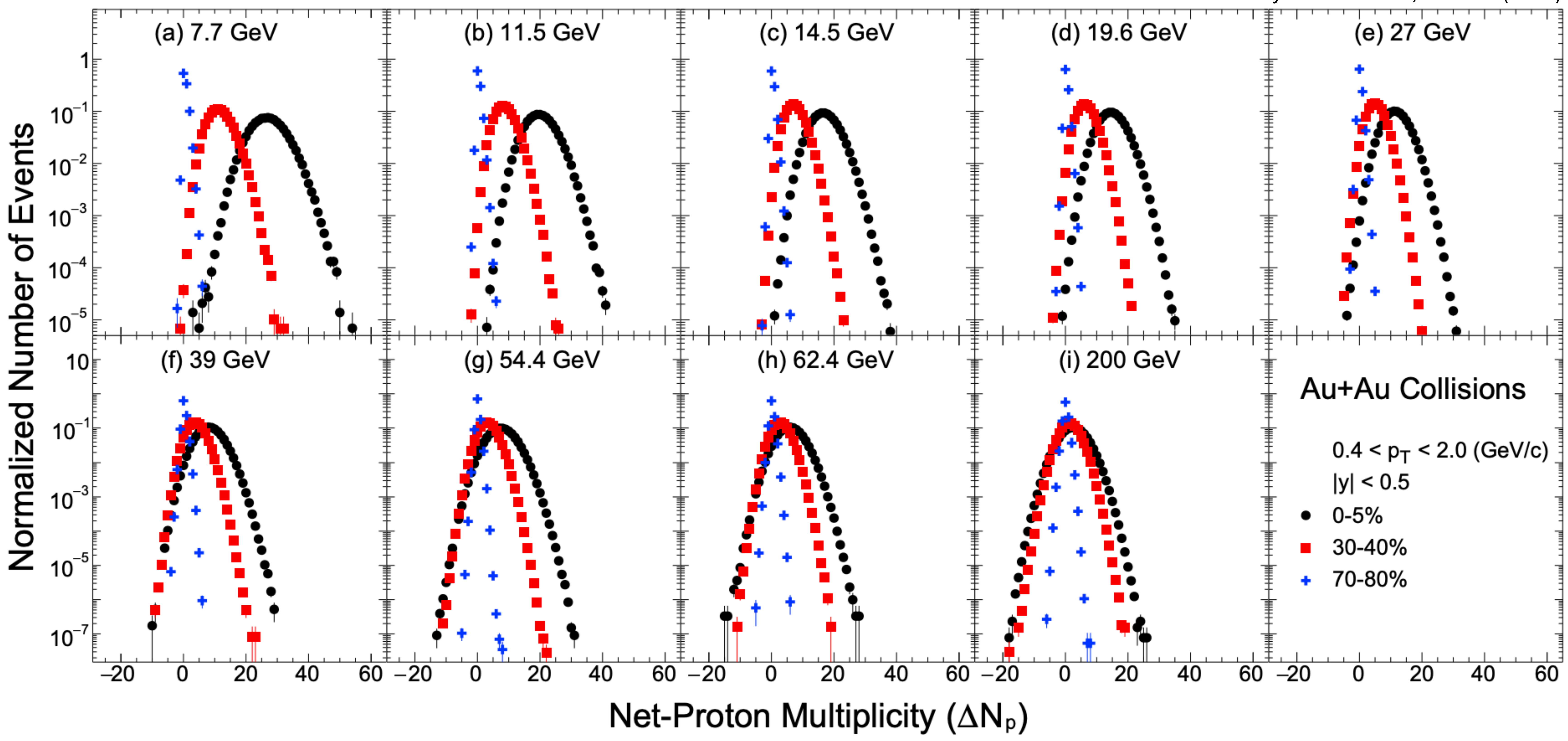
Expected to be at lower energies: RHIC beam energy scan program

- Looking for critical phenomena in the production of soft particles
  - Example in ordinary matter: ethylene opalescence at the critical point, collective fluctuations in the gas at long enough wavelengths to scatter visible light.

Search of the critical point in QCD matter (I)

- We look at collective fluctuations of the quantum numbers conserved by QCD (**B**aryon number, **C**harge, **S**trangeness)
- Fluctuations: we need to go beyond the measurement of average production per event
  - e.g. we measure the number of protons - the number of antiprotons in every event (net-proton distribution)

Phys. Rev. C 104, 024902 (2021)



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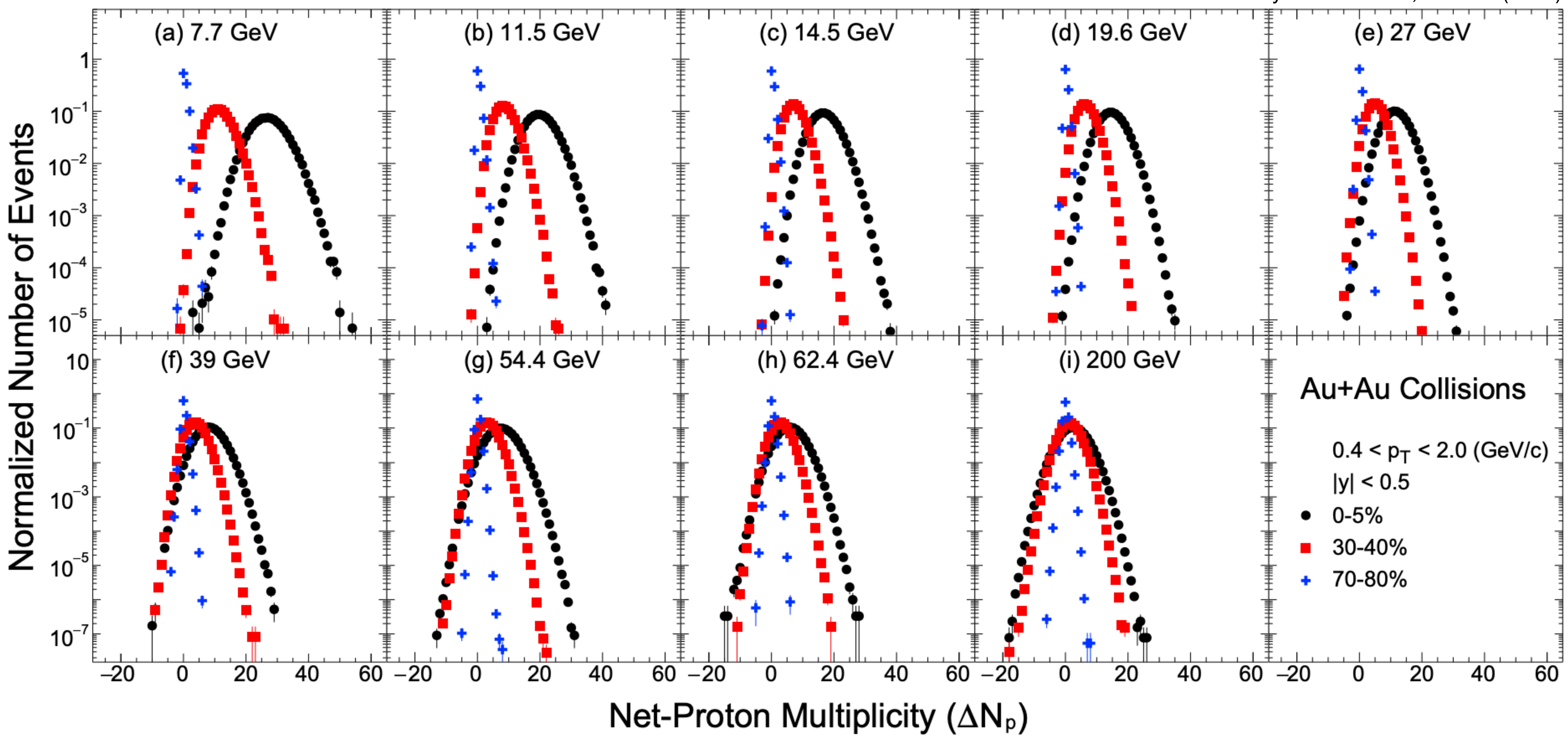

Question: if we baryon number is conserved, why don't we see a Dirac delta?

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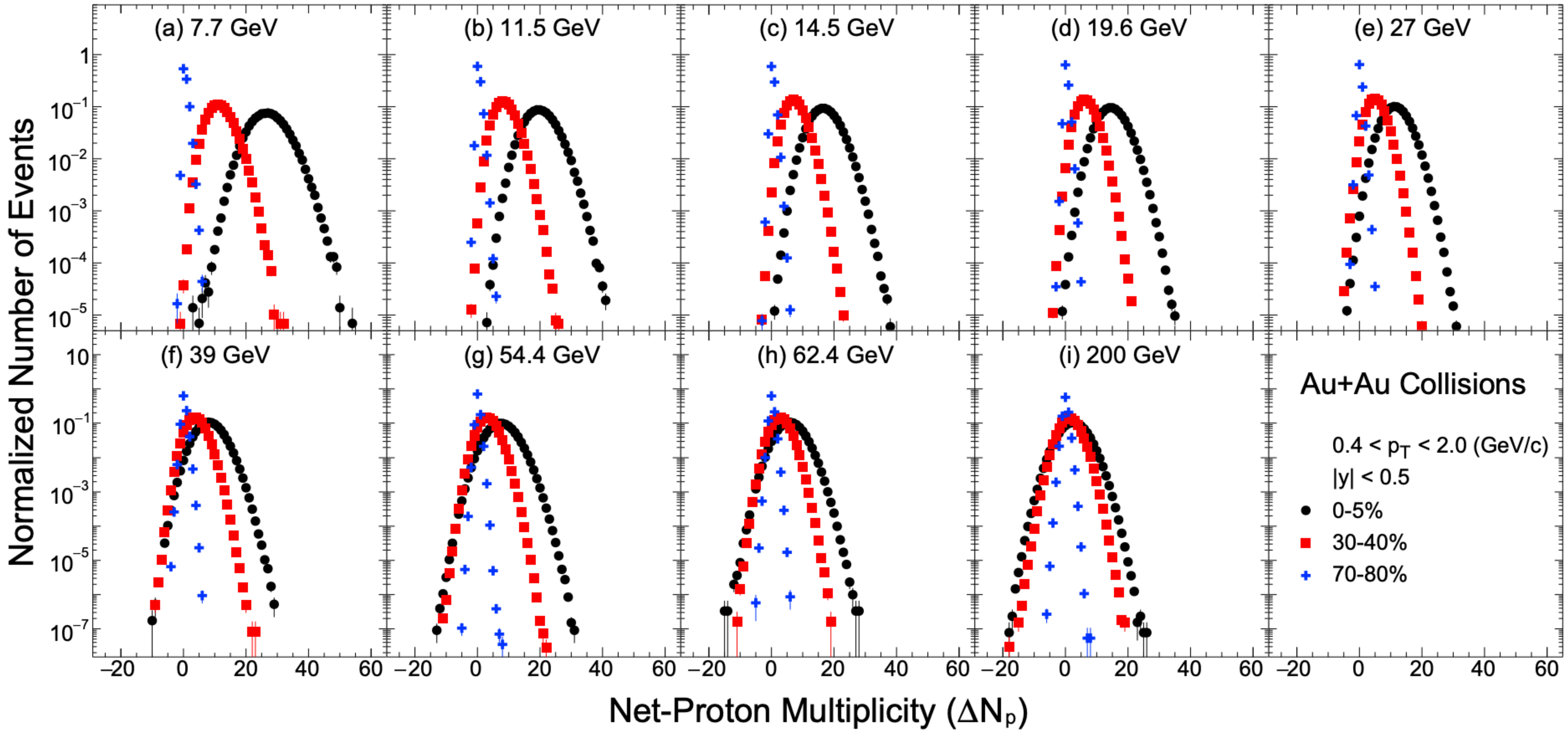
Phys. Rev. C 104, 024902 (2021)

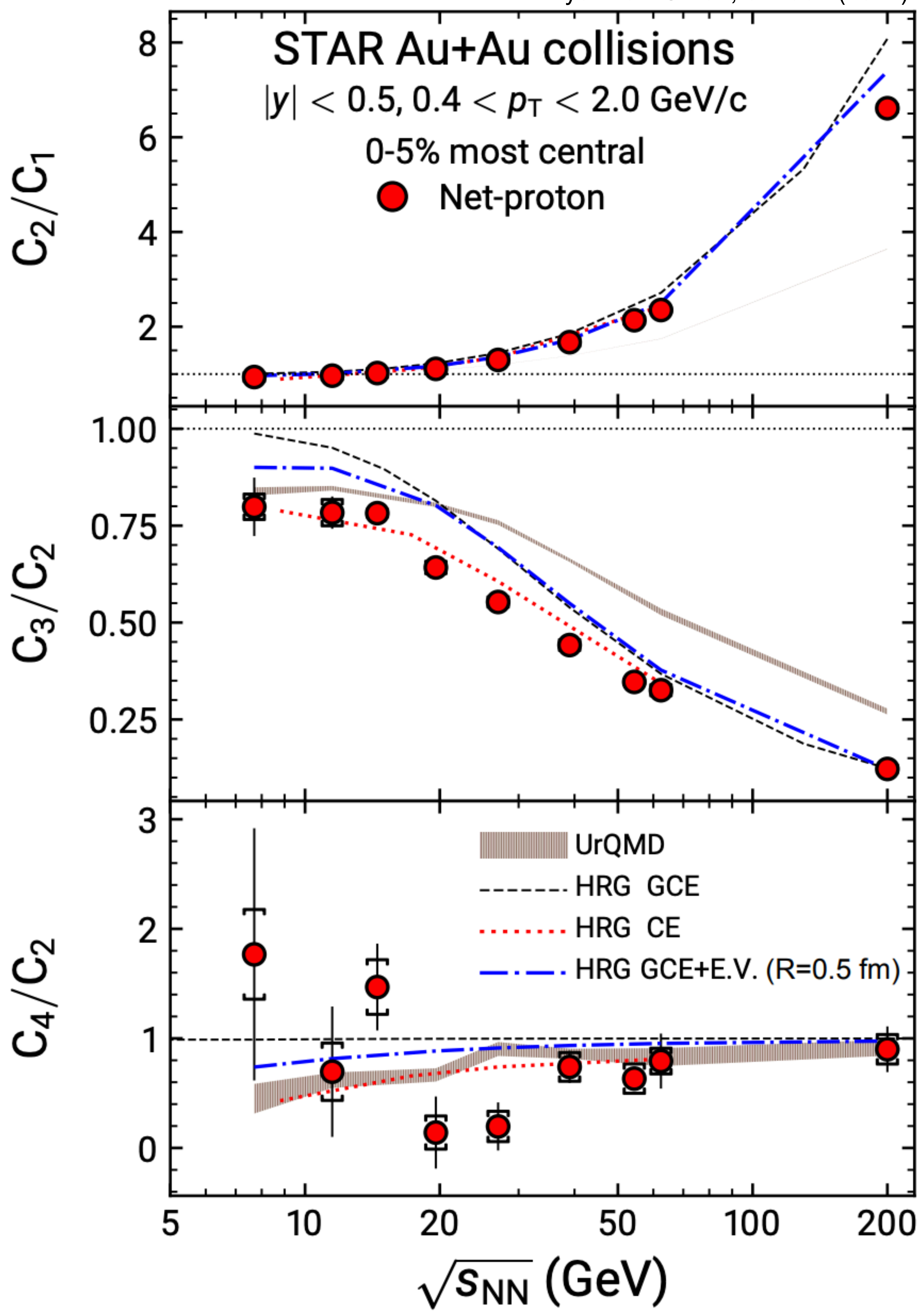


Question: if we baryon number is conserved, why don't we see a Dirac delta?

Answers: one can balance the baryon number and charge of the proton with e.g. an antineutron and a pion, and our detectors have a limited acceptance

Search of the critical point in QCD matter (II)

Phys. Rev. C 104, 024902 (2021)



In principle, the moment of the distributions of the net-charges can be compared directly with the susceptibilities χ computed with the Lattice QCD:

$$\chi^{BSQ}_{lmn} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l\,\partial(\mu_S/T)^m\,\partial(\mu_S/T)^n}$$

Net charges distribution moments and their relation to the susceptibilities:

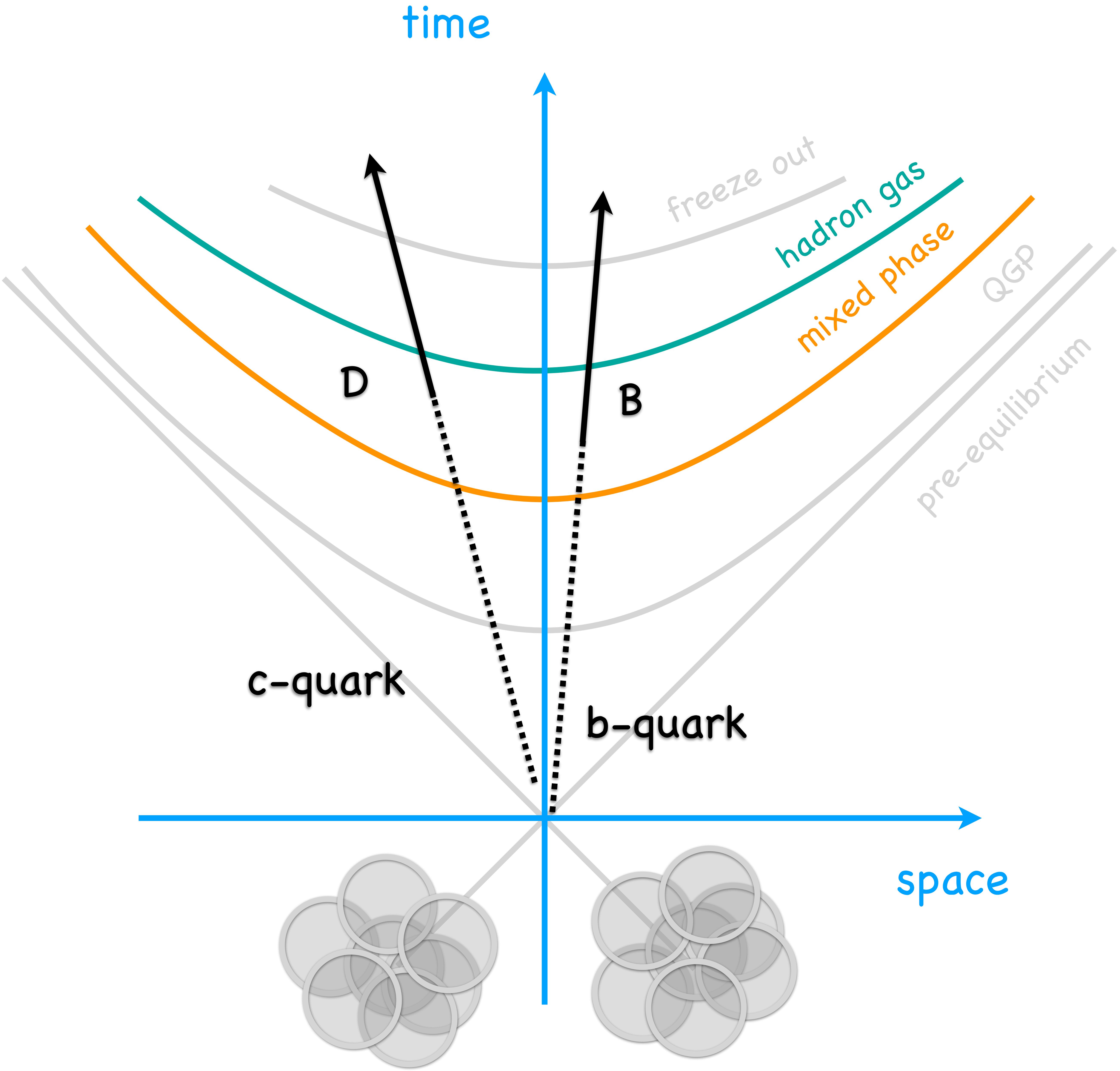
$$\begin{array}{lllllllll} M & = & K_1 & = & \mu & = & \langle N\rangle & = & VT^3\cdot\chi_1 \\ \sigma^2 & = & K_2 & = & \mu_2 & = & \langle(\delta N)^2\rangle & = & VT^3\cdot\chi_2 \\ S & = & K_3/\sigma^3 & = & \mu_3/\sigma^3 & = & \langle(\delta N)^3\rangle/\sigma^3 & = & VT^3\cdot\chi_3/(VT^3\cdot\chi_2)^{3/2} \\ \kappa & = & K_4/\sigma^4 & = & (\mu_4-3\mu_2^2)/\mu_2^2 & = & \langle(\delta N)^4\rangle/\sigma^4-3 & = & (VT^3\cdot\chi_4)/(VT^3\cdot\chi_2)^2 \end{array}$$

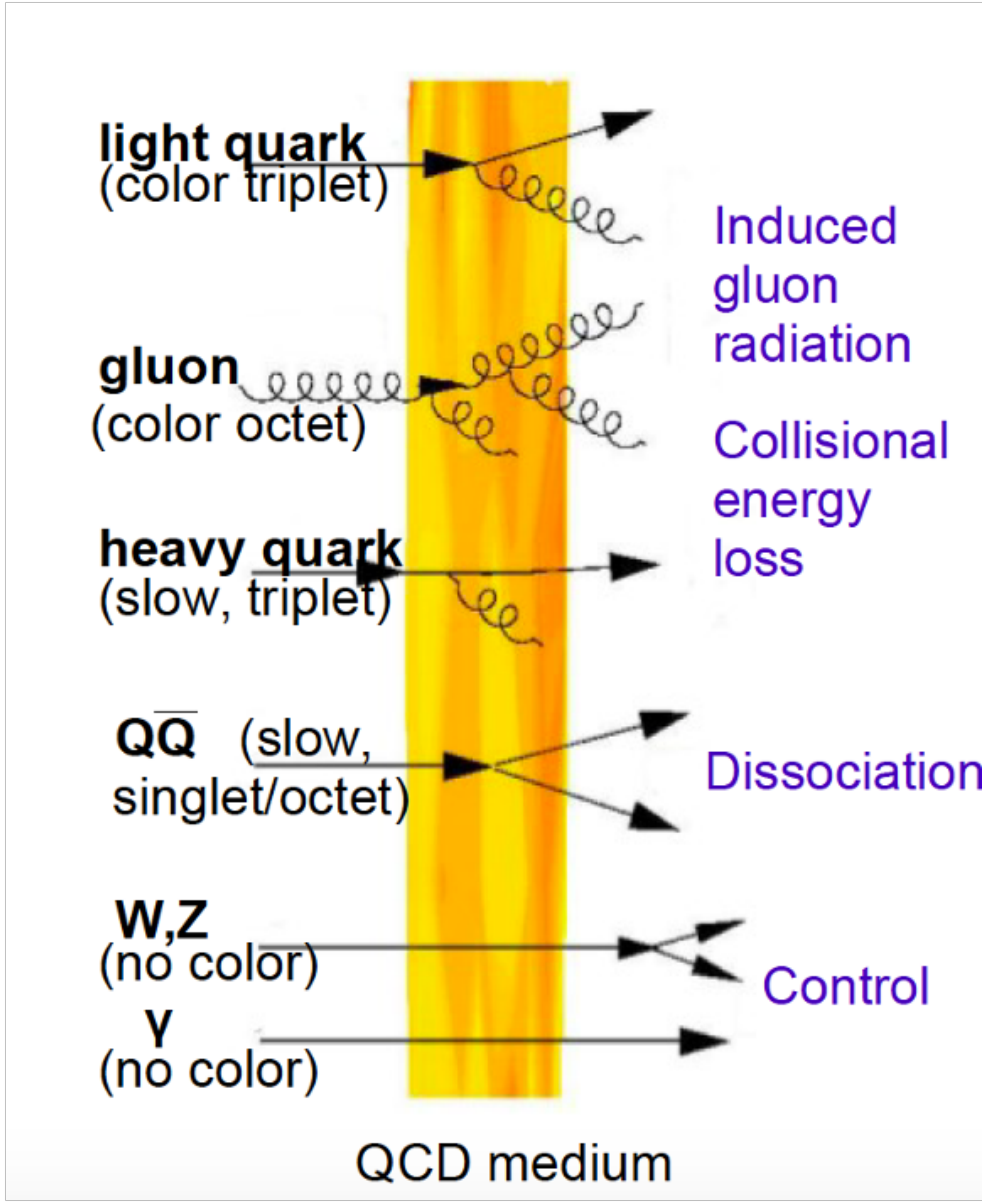
Issue: we cannot compare directly with LQCD at low energy (sign problem), then we compare with non-critical models

- Models are monotonic with energy, but C_4/C_2 measurement show an hint of non-monotonic behaviour around 20 GeV

Heavy quarks

Where are heavy quarks in the evolution of the fireball?

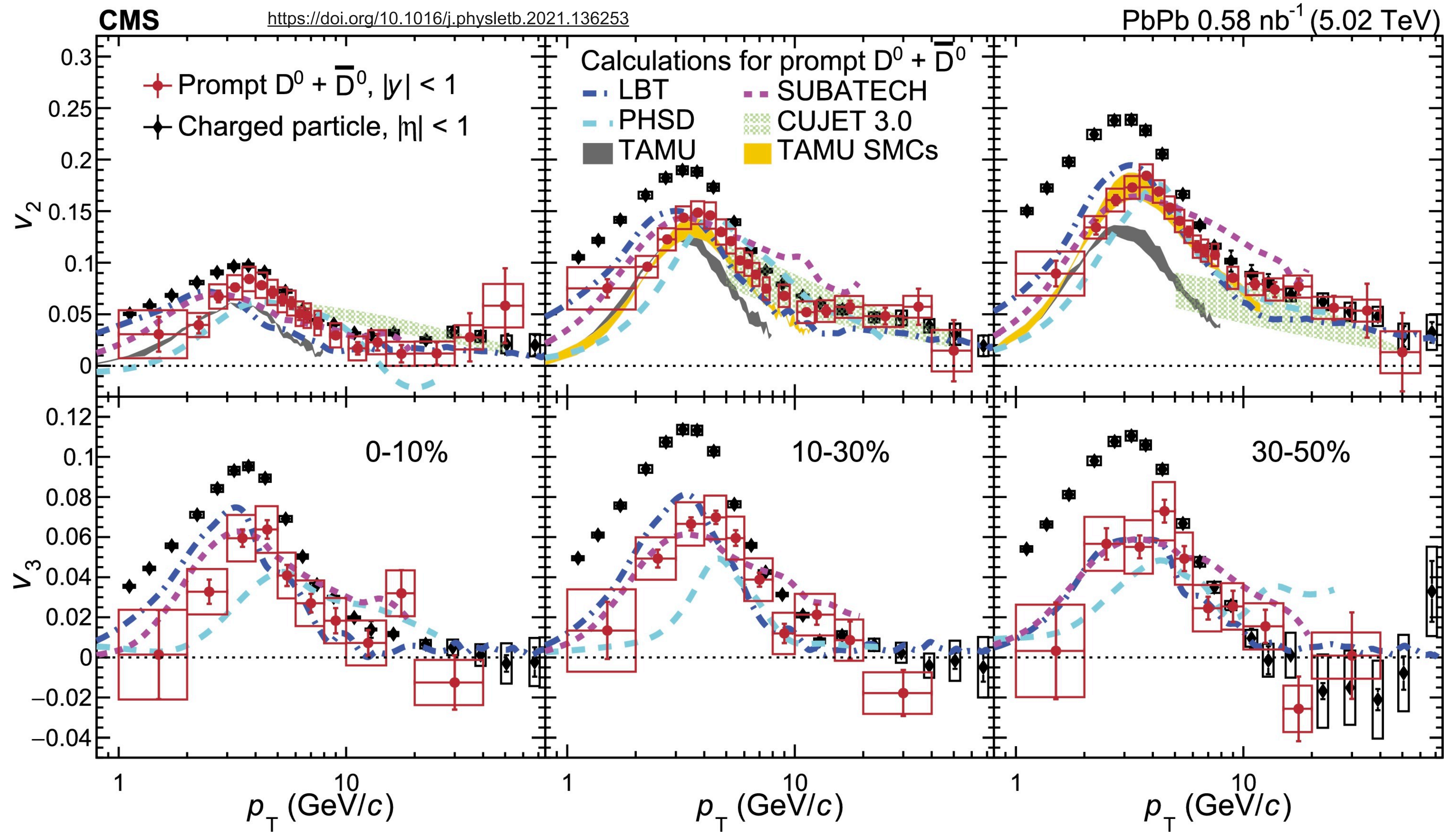


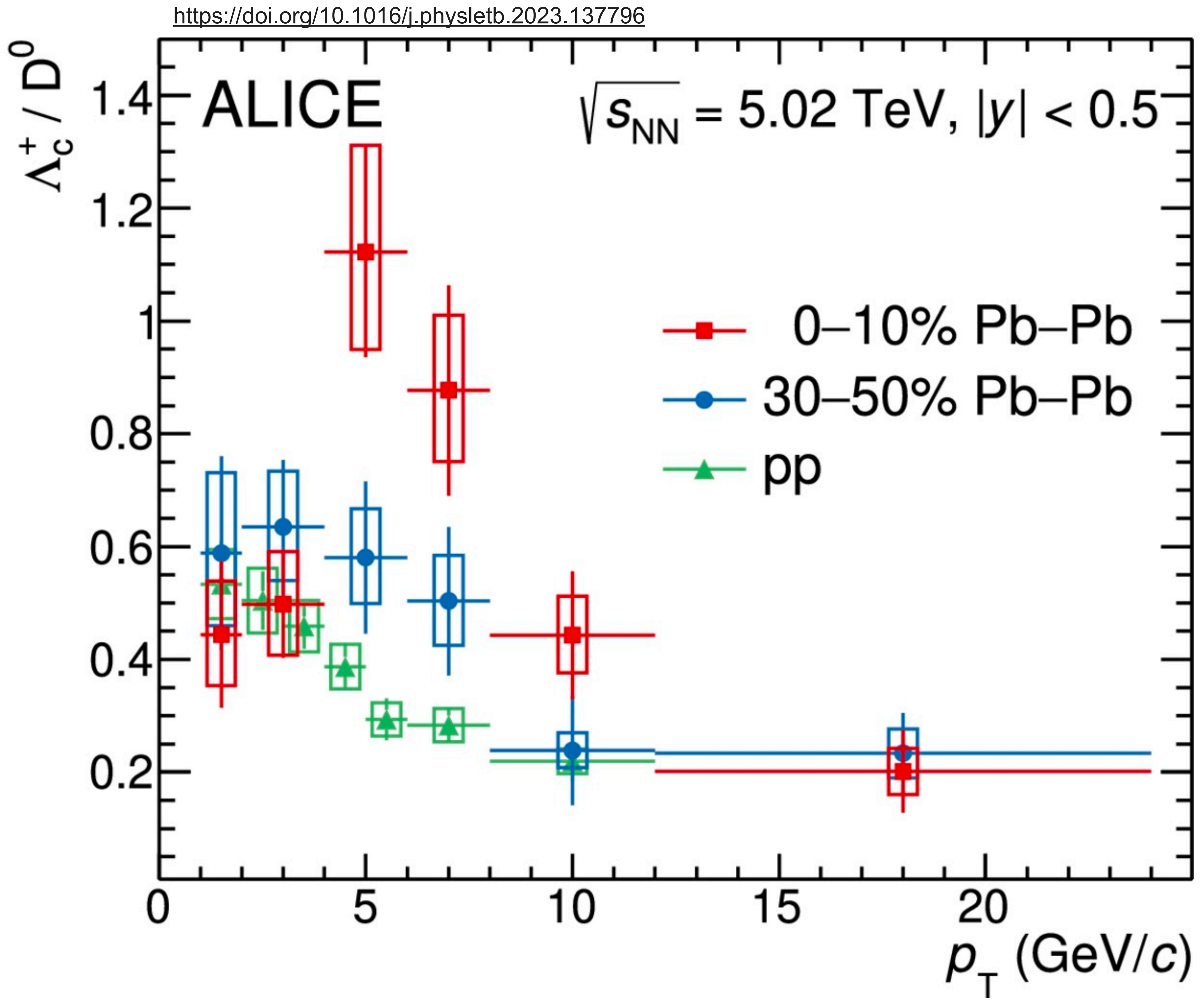


Pictures by F. Grosa

Heavy quark dynamics

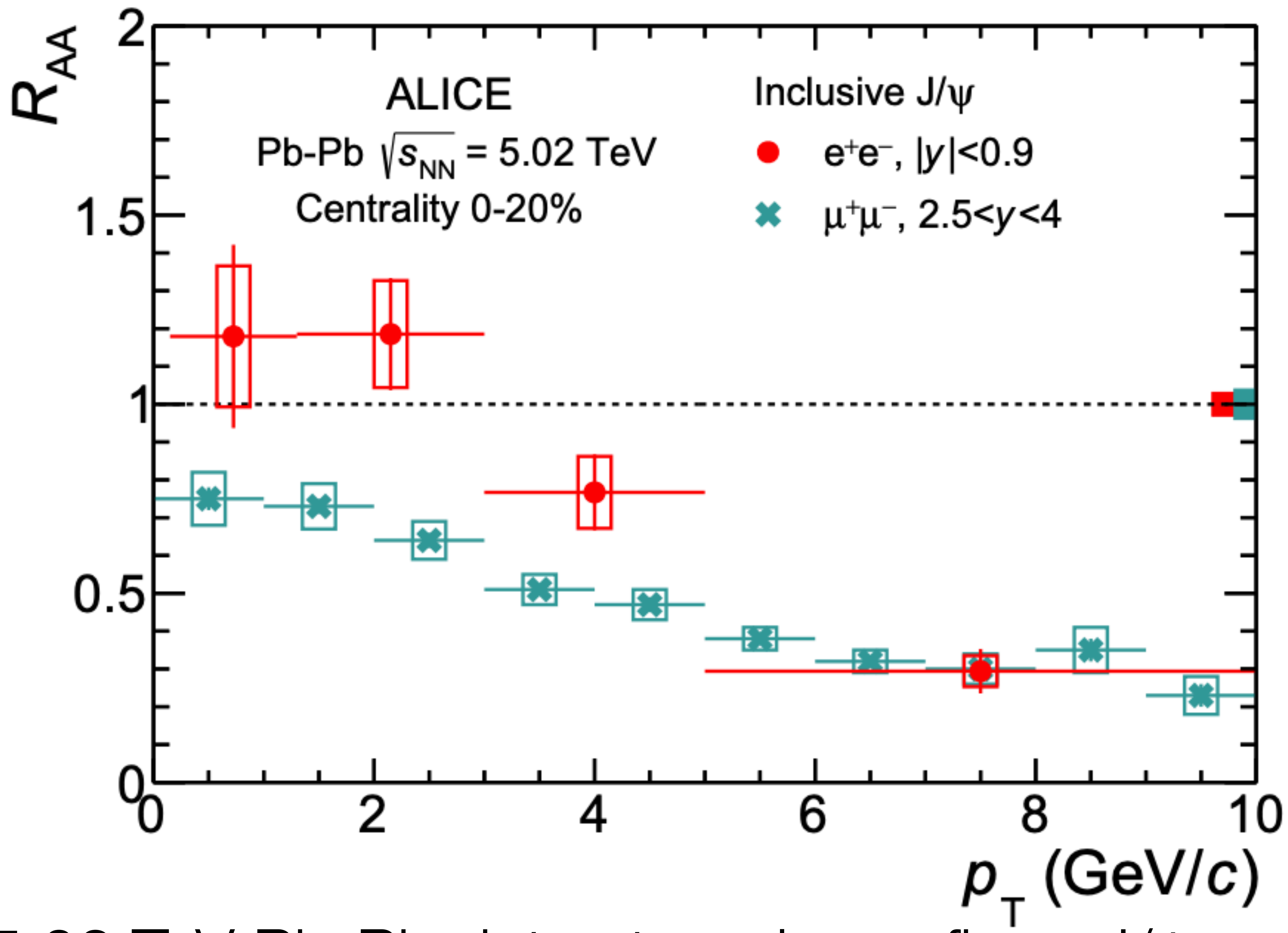
- Heavy quark flavors (*c*,*b*) are dominantly produced in initial hard scatterings (calculable in pQCD) and then interact with the medium.
- There is strong evidence that **charm quarks *thermalize*** in the medium.

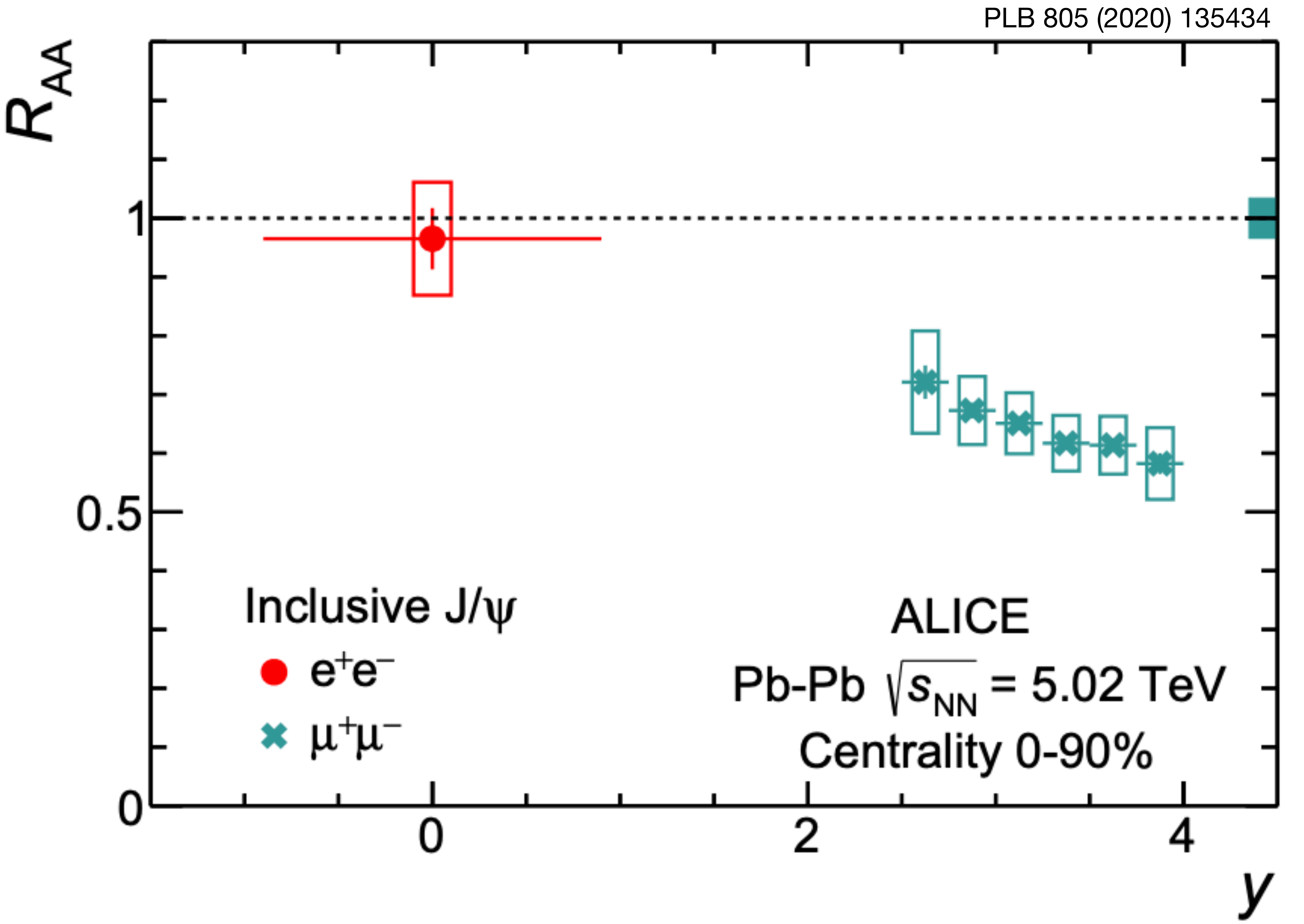




Charmonia suppression and recombination

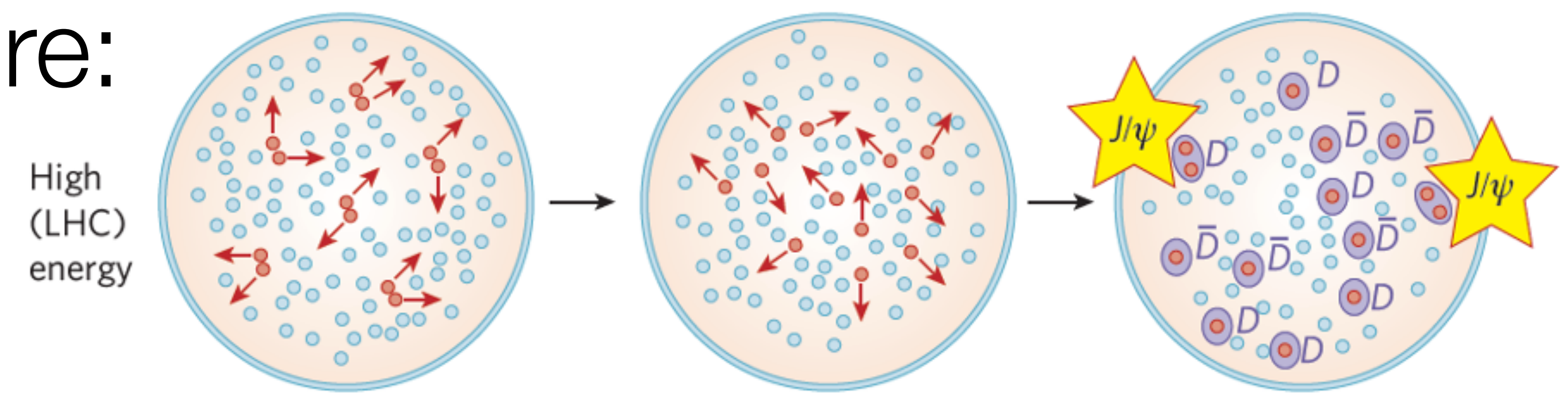
The J/ψ is expected not to be bound in the QGP phase (*Matsui/Satz*, 1986), but it can regenerate at the phase boundary.





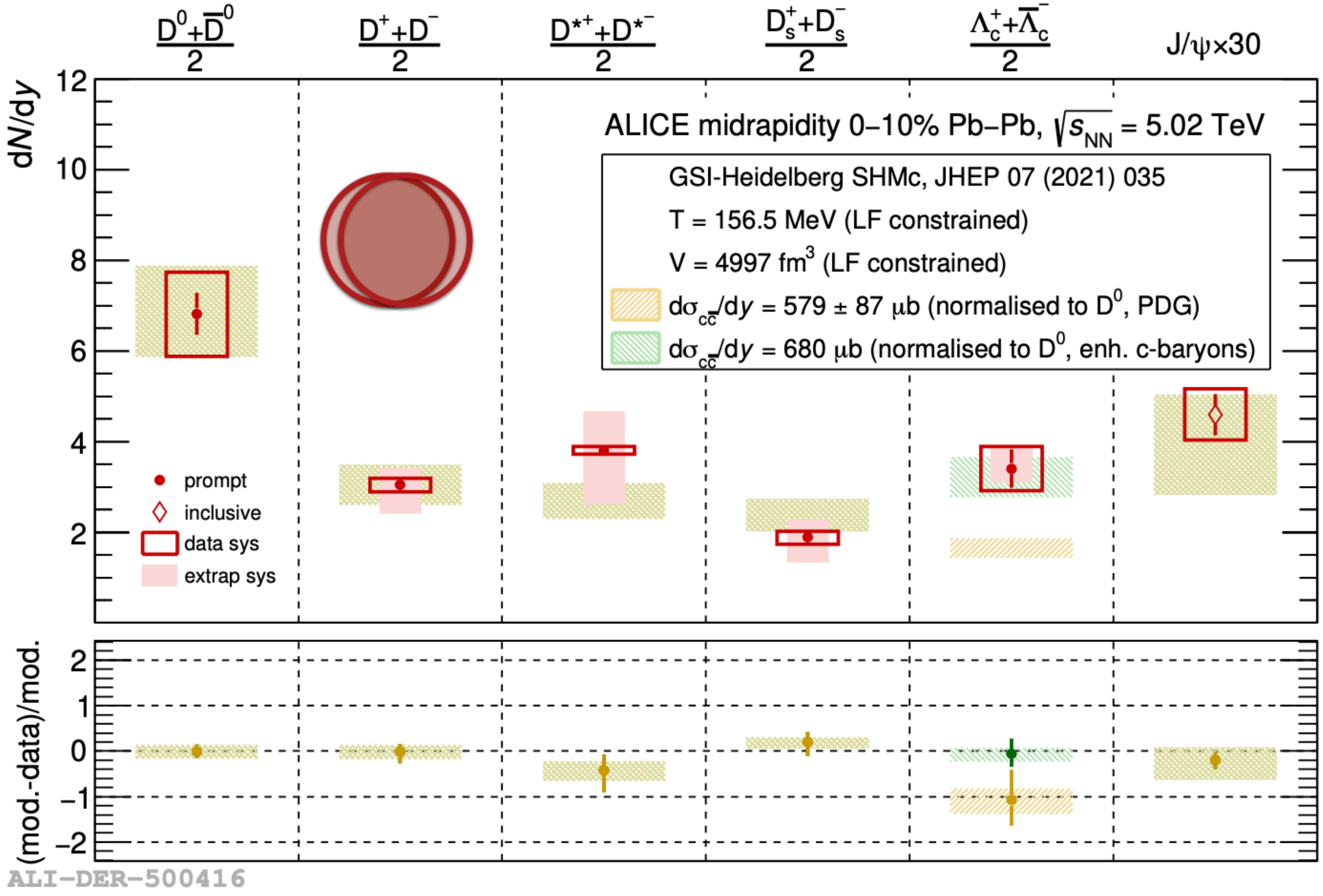
In 5.02 TeV Pb-Pb data strongly confirms J/ψ recombination picture:

- R_{AA}(LHC) > R_{AA}(RHIC)
- R_{AA} midrapidity > R_{AA} forward rap.



doi:10.1038/nature06080

The case for charm statistical hadronisation



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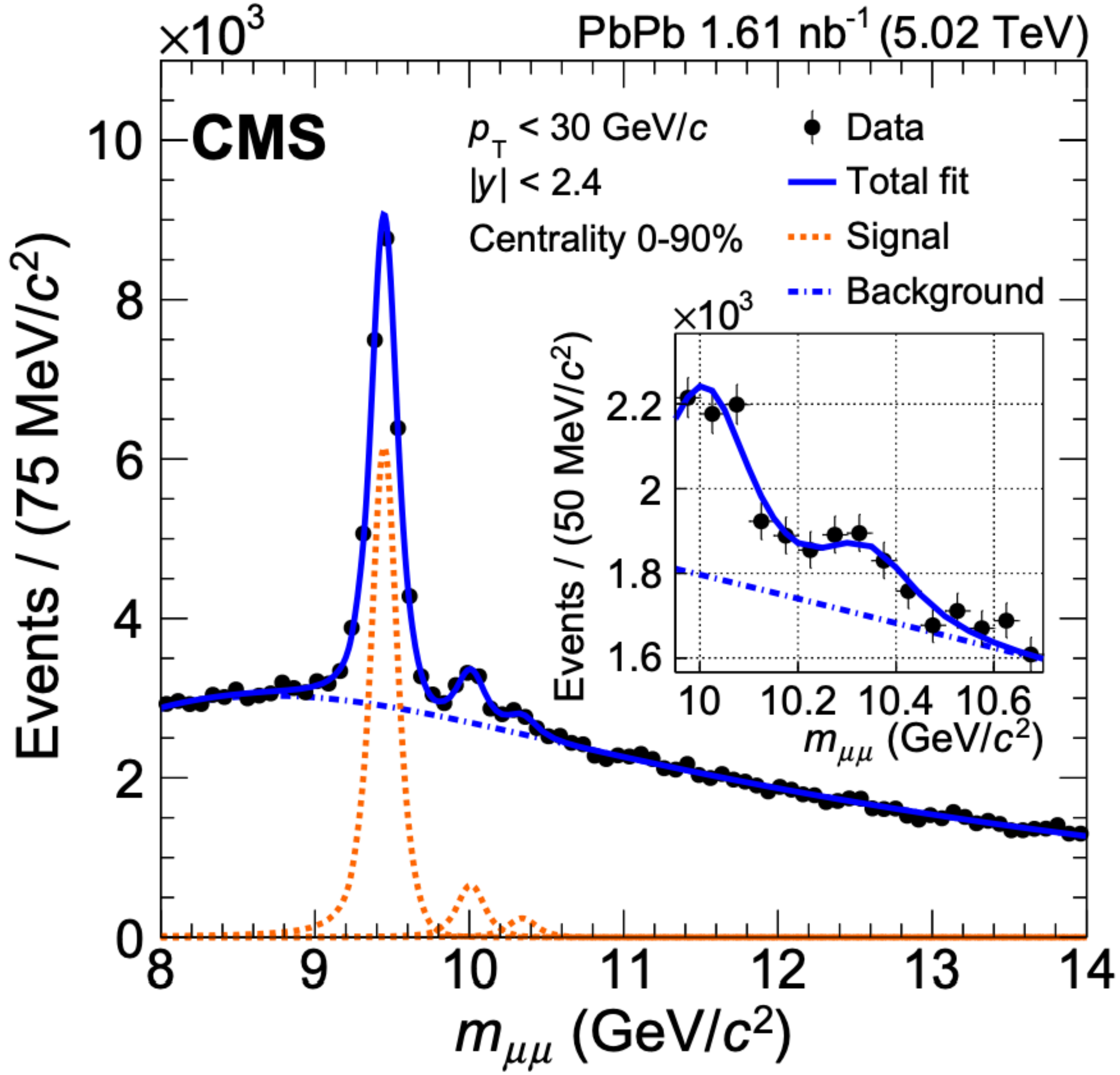
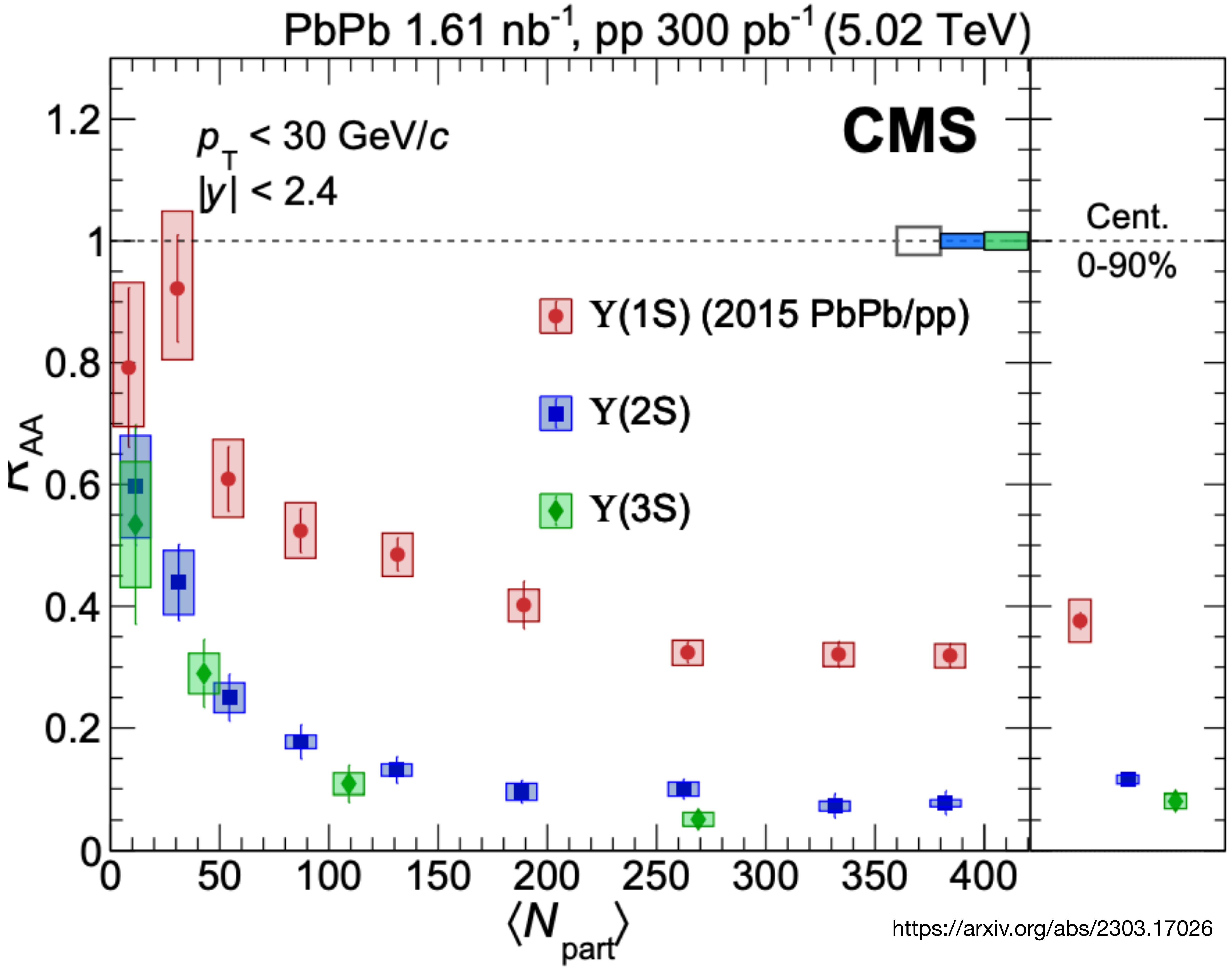
The recombination effect is such that you can even explain the yield of charm hadrons using the SHM!

- Only additional input: number of c-cbar pairs in the system
- One more hint in the direction of the presence of a deconfined medium

The same description only partially work for beauty quark (not enough of them in the system)

The counter-example: bottomonia





https://arxiv.org/abs/2303.17026

- No re-generation for the much more rare b-quarks!
- Suppression of Y(1S) ground, and excited Y(2S) and Y(3S) states.
- Ordering of R(3S)<R(2S)<R(1S) consistent with sequential melting

Conclusions

Conclusions

What I could not cover:

- Ultra peripheral collisions
- Nuclei and exotic hadron formation (most of my research, sigh)
- Dilepton measurements for temperature and chiral symmetry restoration measurements
- Femtoscopy
- … and more

If you are interested in some of these topics, drop me an email and I will provide some pointers or have a look at the Hadron Collider Physics School Heavy Ions lectures

New physics does necessarily mean beyond the standard model: the study of multi-particle systems can lead to the discovery of new phenomena that can surprise us

Backup

Statistical hadronisation model

Starting point: grand-canonical partition function for a *relativistic ideal quantum gas of hadrons* of particle type i (i = pion, proton,… → full PDG!):

$$\mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S$$

$$\ln Z_{GK_i} = \pm\, g_i \frac{V}{2\pi^2\hbar^3}\int_0^\infty \mathrm{d}p^2 \ln\left(1 \pm e^{-\frac{\sqrt{m_i^2+p^2}-\mu_i}{kT}}\right)$$

Once Z is known, we can calculate all other thermodynamic quantities:

$$\boxed{n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu}} \quad P = \frac{\partial(T\ln Z)}{\partial V} \quad s = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial T}$$

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Only two free parameters are needed: **(T,μ_B)**. Volume cancels if particle ratios n_i/n_j are calculated. If yields are fitted, it acts as the third free parameter.

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Partition function shown here is only valid in the resonance gas limit (HRG), i.e. relevant interactions are mediated via resonances, and thus the non-interacting hadron resonance gas can be used as a good approximation for an interacting hadron gas.