

Fundação
para a Ciência
e a Tecnologia

This work was financially supported by 2024.00227.CERN

Heavy ions and QGP tomography

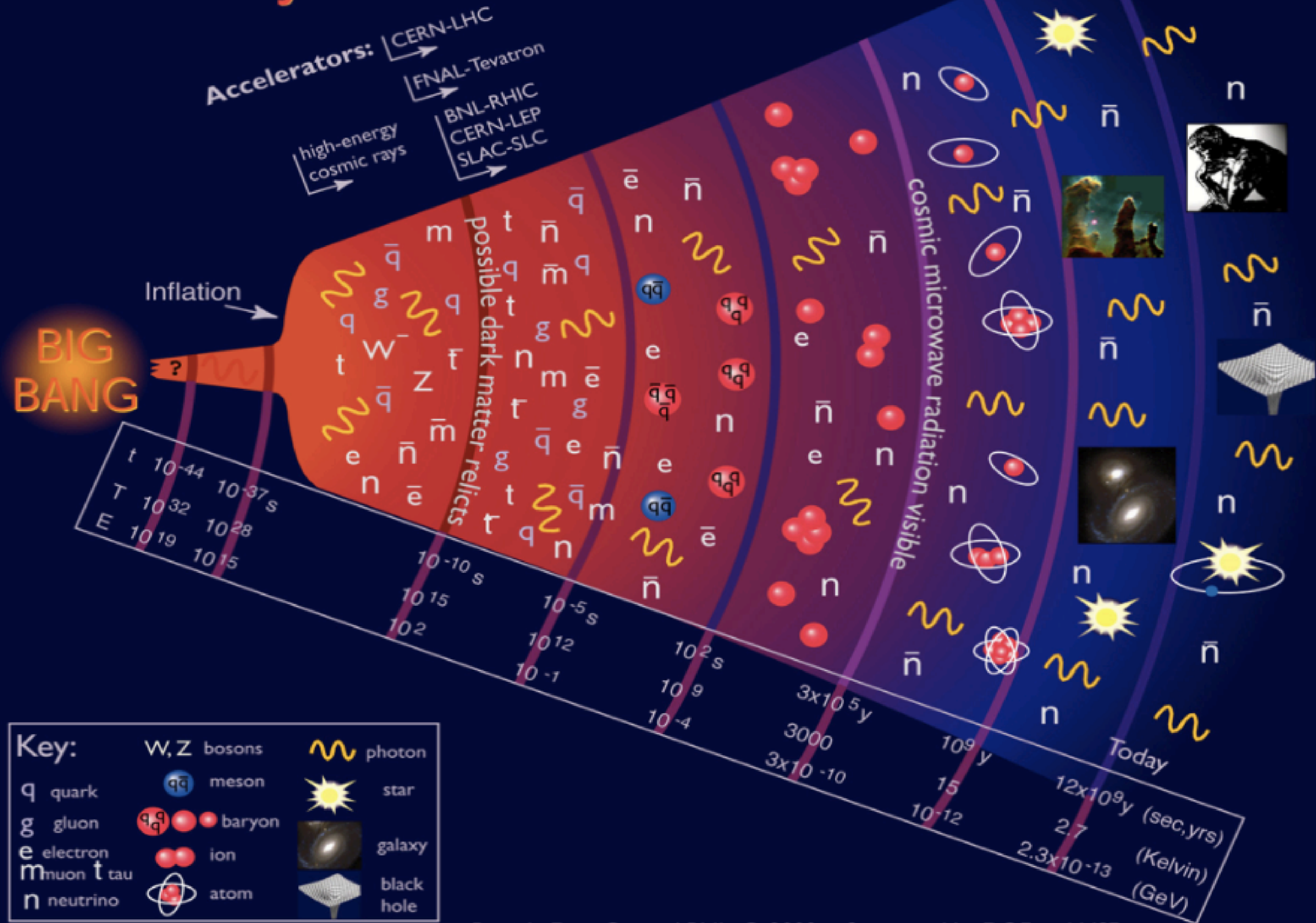
Helena Santos

LIP

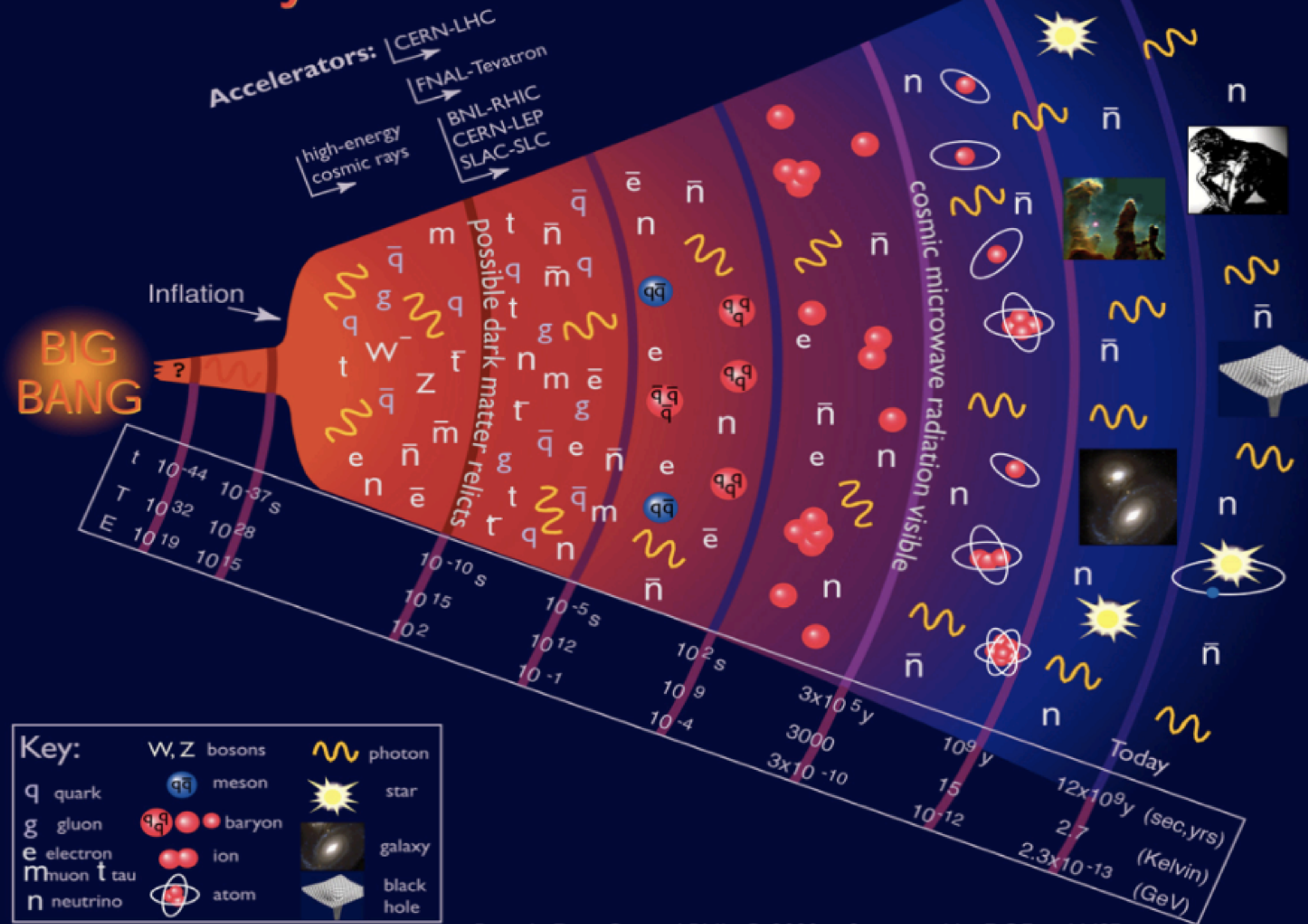
Physics at LHC, IST, 7 May 2025

History of the Universe

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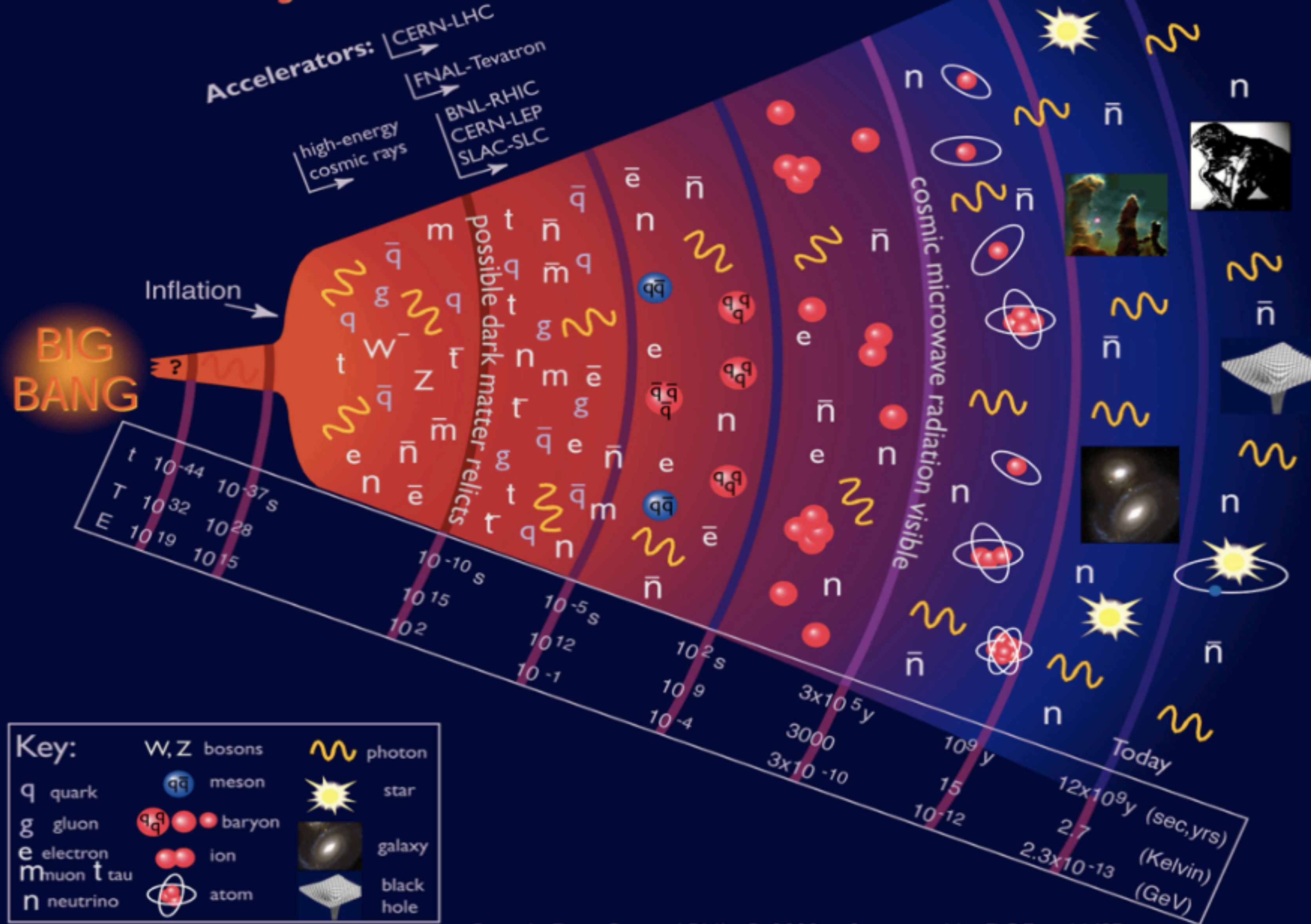


History of the Universe



James Webb Space Telescope looks back over 13.4 billion years, about 300–400 million years after the Big Bang.

History of the Universe

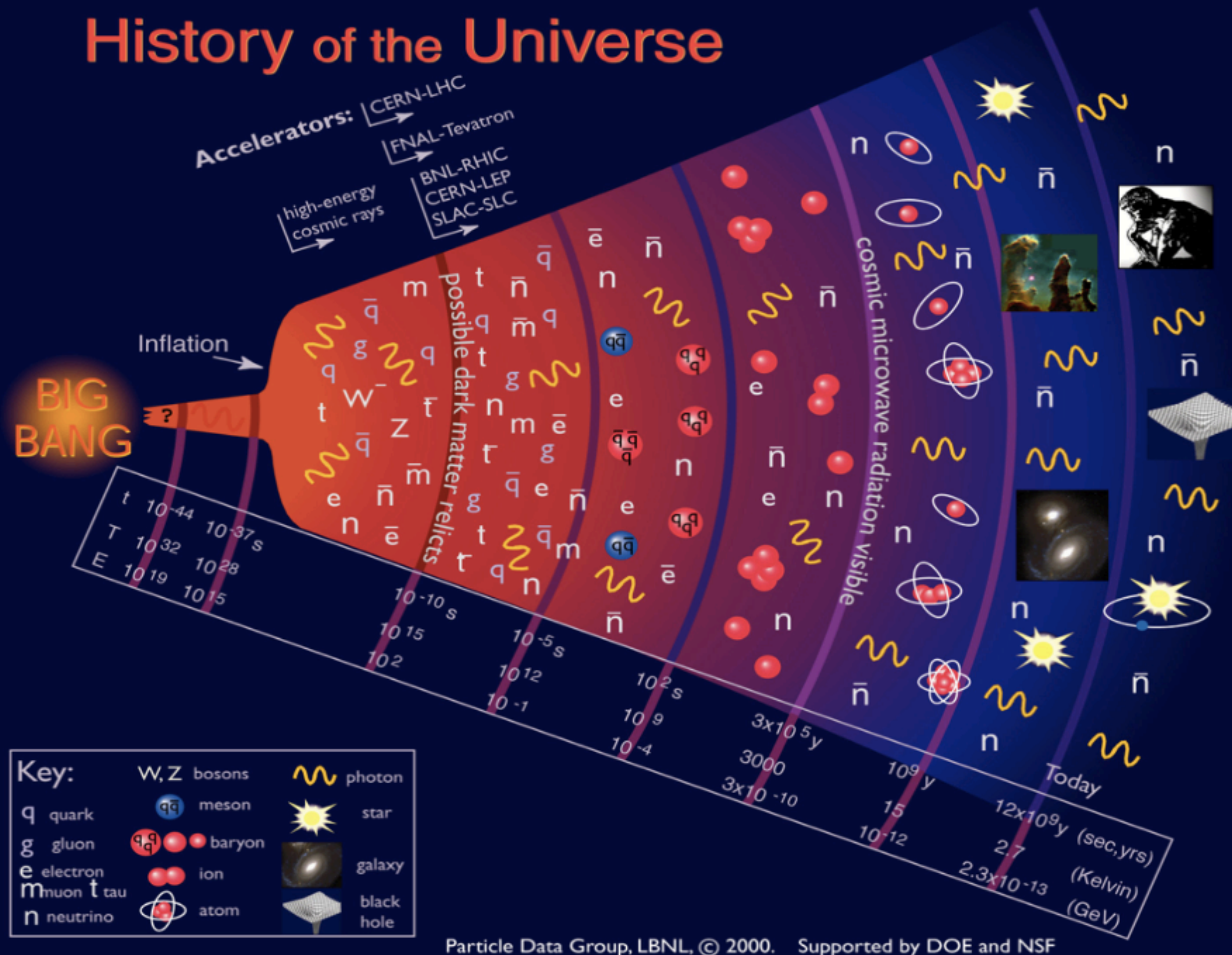


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

At ~380,000 years after the Big Bang, the universe cooled enough for electrons to combine with protons, to form neutral hydrogen.

The CMB is the oldest light we can observe directly.

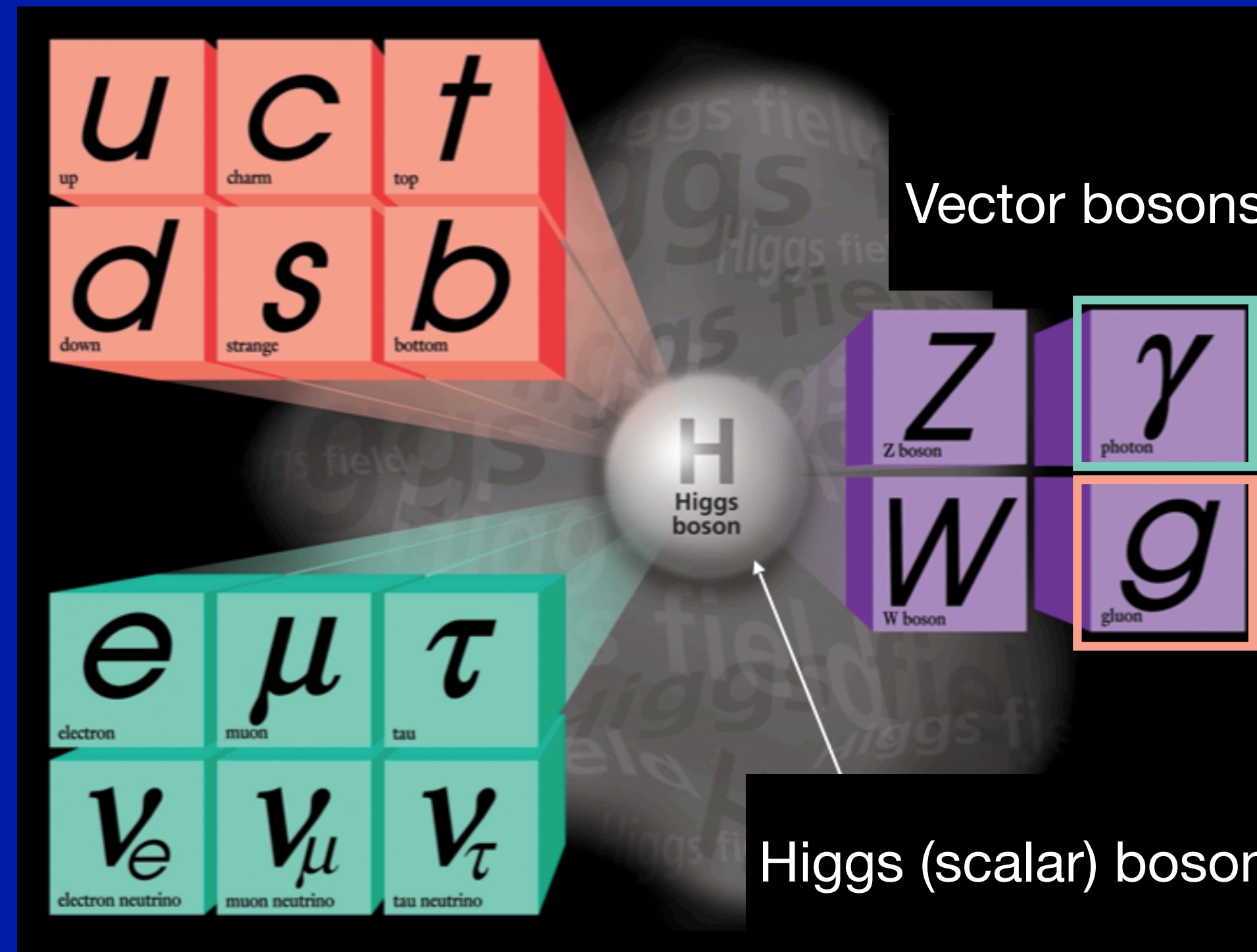
History of the Universe



What do we really know about the 5% of the universe we can see? 6

Quarks: fractional electric charged, colour charged, mediated by the gluon

Leptons: electric charge ± 1 , mediated by the photon



Vector bosons: responsible for mediating the fundamental forces

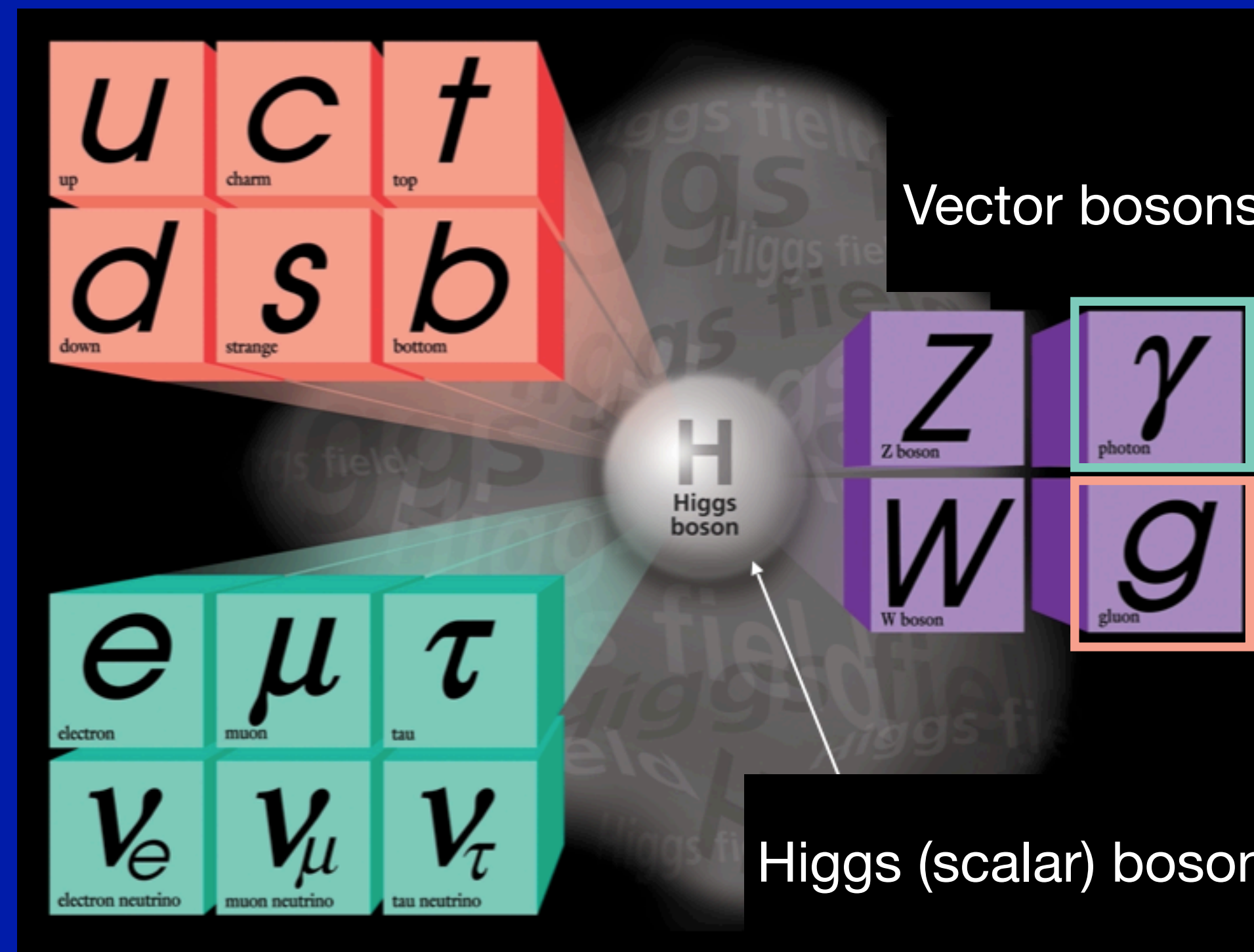
Higgs (scalar) boson : responsible for the mechanism of the mass acquisition of the elementary particles.

Three generations of matter. They combine to form mesons (quark-antiquark pairs) or barions (3, 4, 5, ... quarks).

What do we really know about the 5% of the universe we can see? 7

Quarks: fractional electric charged, colour charged, mediated by the gluon

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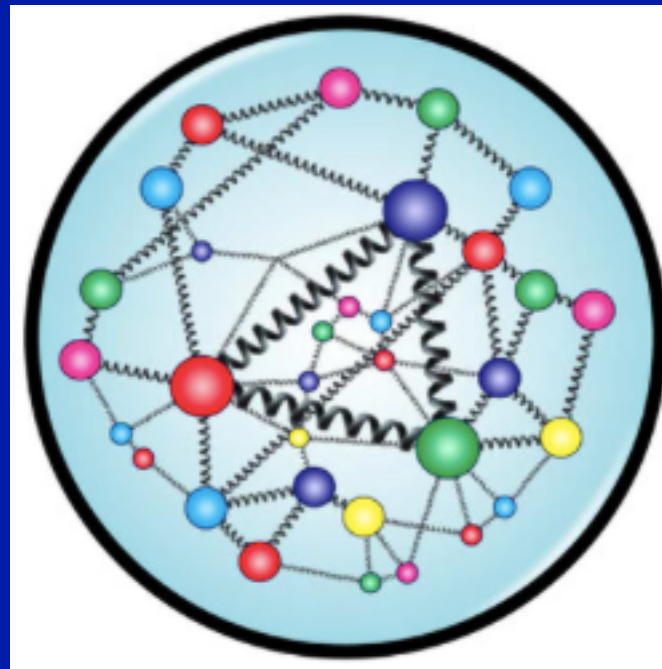


Vector bosons: responsible for mediating the fundamental forces

Higgs (scalar) boson : responsible for the mechanism of the mass acquisition of the elementary particles.

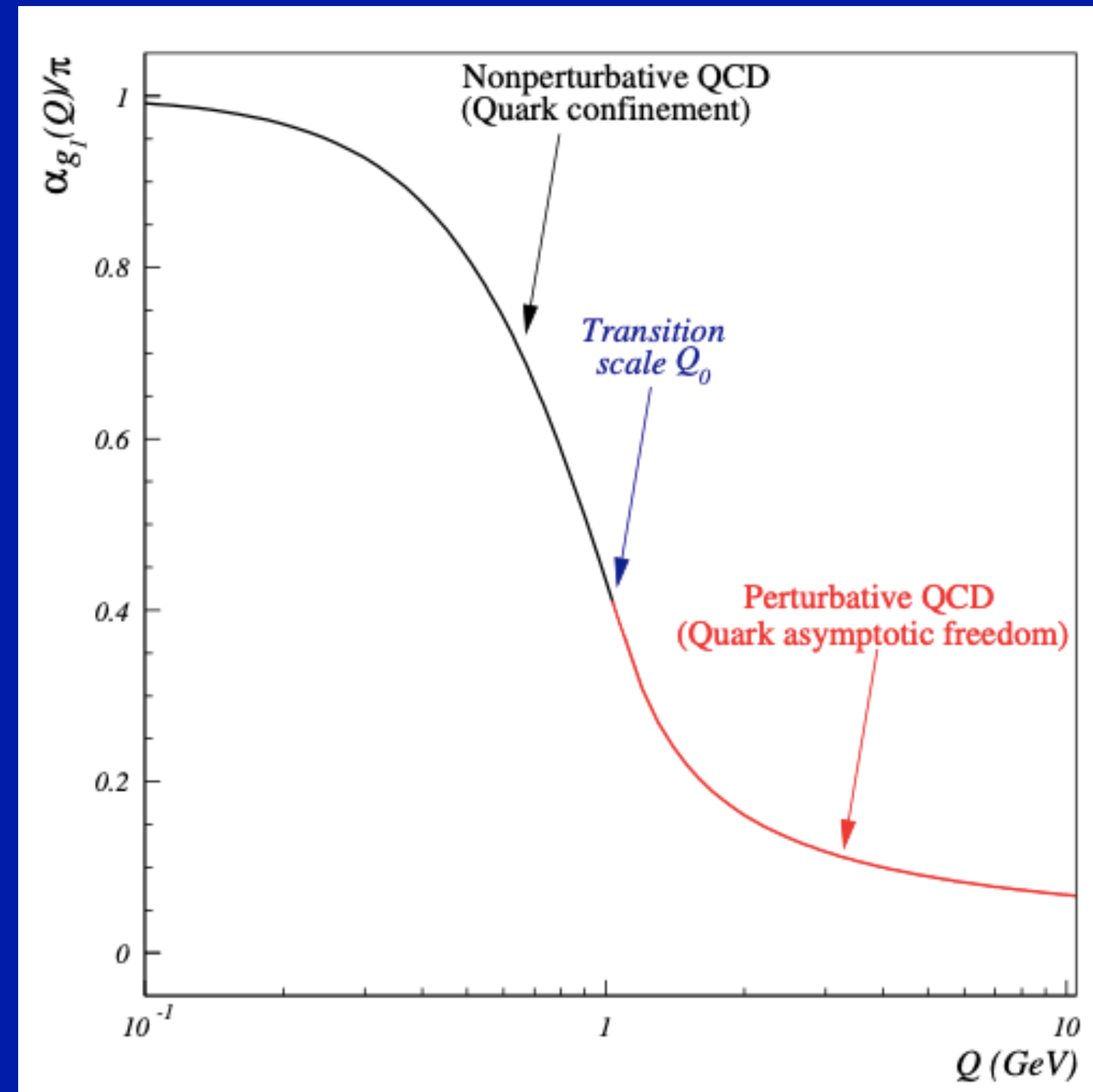
Three generations of matter. They combine to form mesons (quark-antiquark pairs) or barions (3, 4, 5, ... quarks).

The LHC is deeply committed to the Heavy Ion Program —> exploring **QCD** at its ultimate frontier:
matter under extreme temperature and density

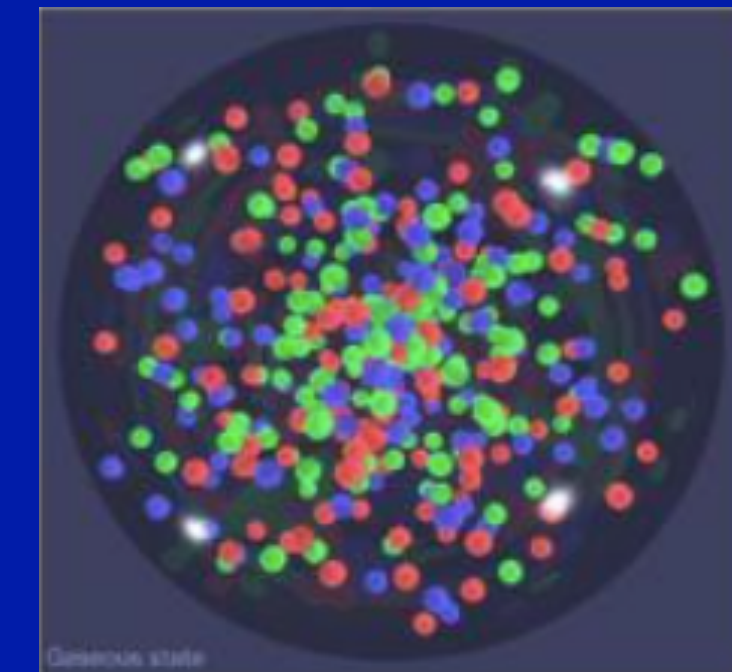


At “observable” distances

- At long distances (1fm) quarks are confined
- Strong coupling
- Perturbation theory fails



Phys. Lett. B 750, 528 (2015)



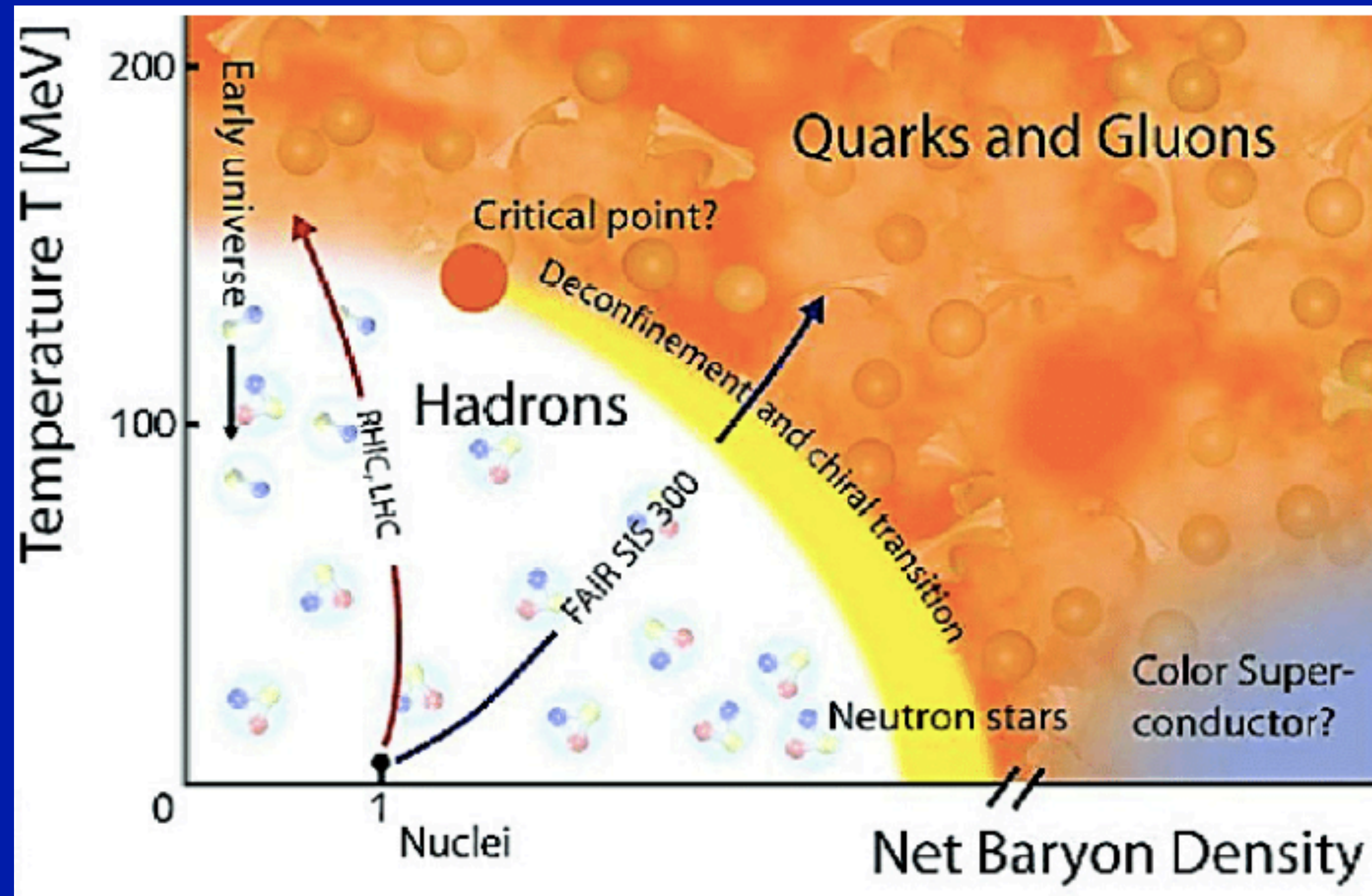
Deep inside the proton

- At short distances quarks behave as free particles
- Weak coupling
- Perturbation theory applies

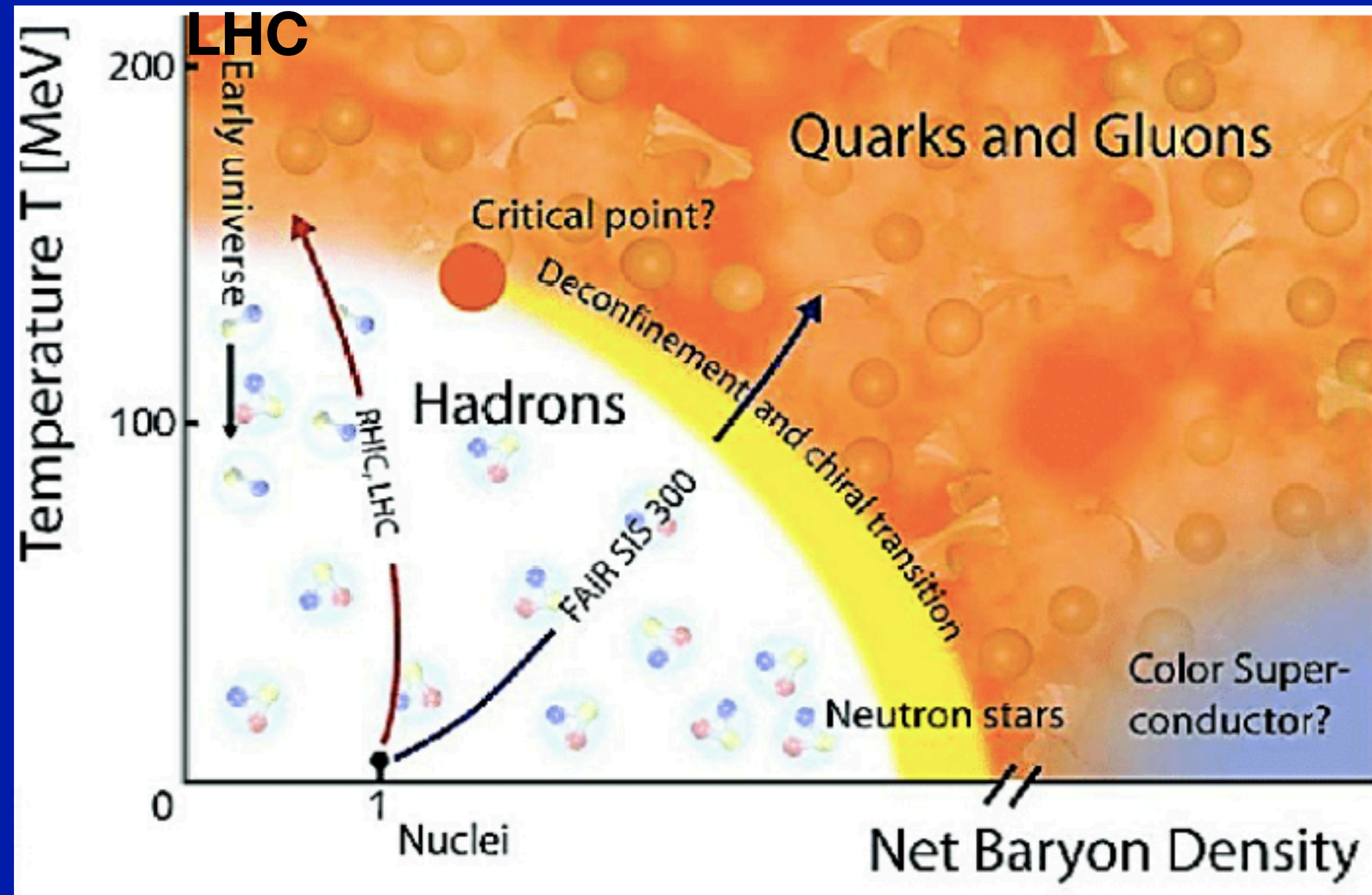
The QCD phase diagram

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The QCD phase diagram maps the different states of strongly interacting matter



How can heavy-ion collisions be used to experimentally probe the different territories of the QCD phase diagram?

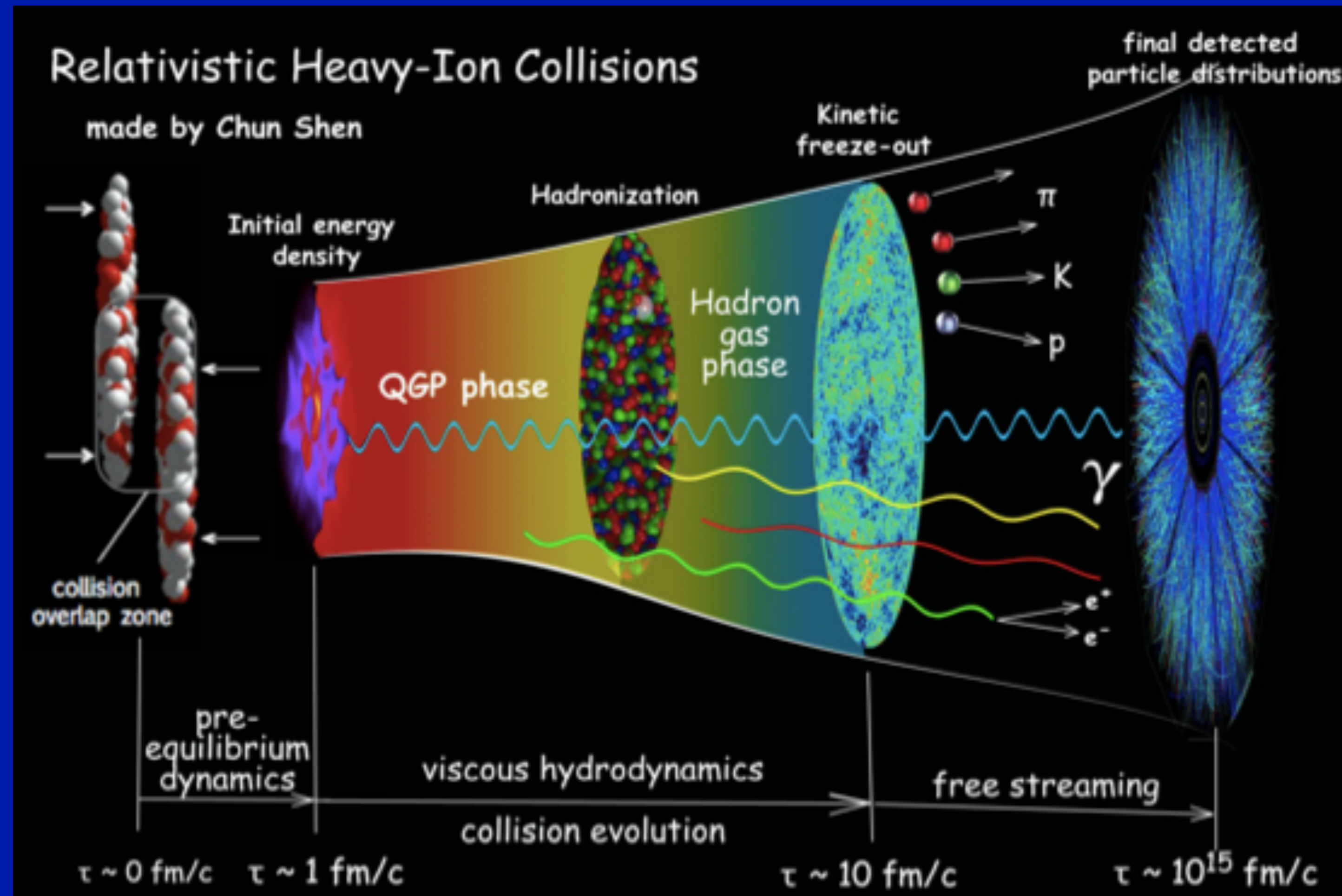


create the two distinct phases of matter: the hadronic and the QGP

Initial state

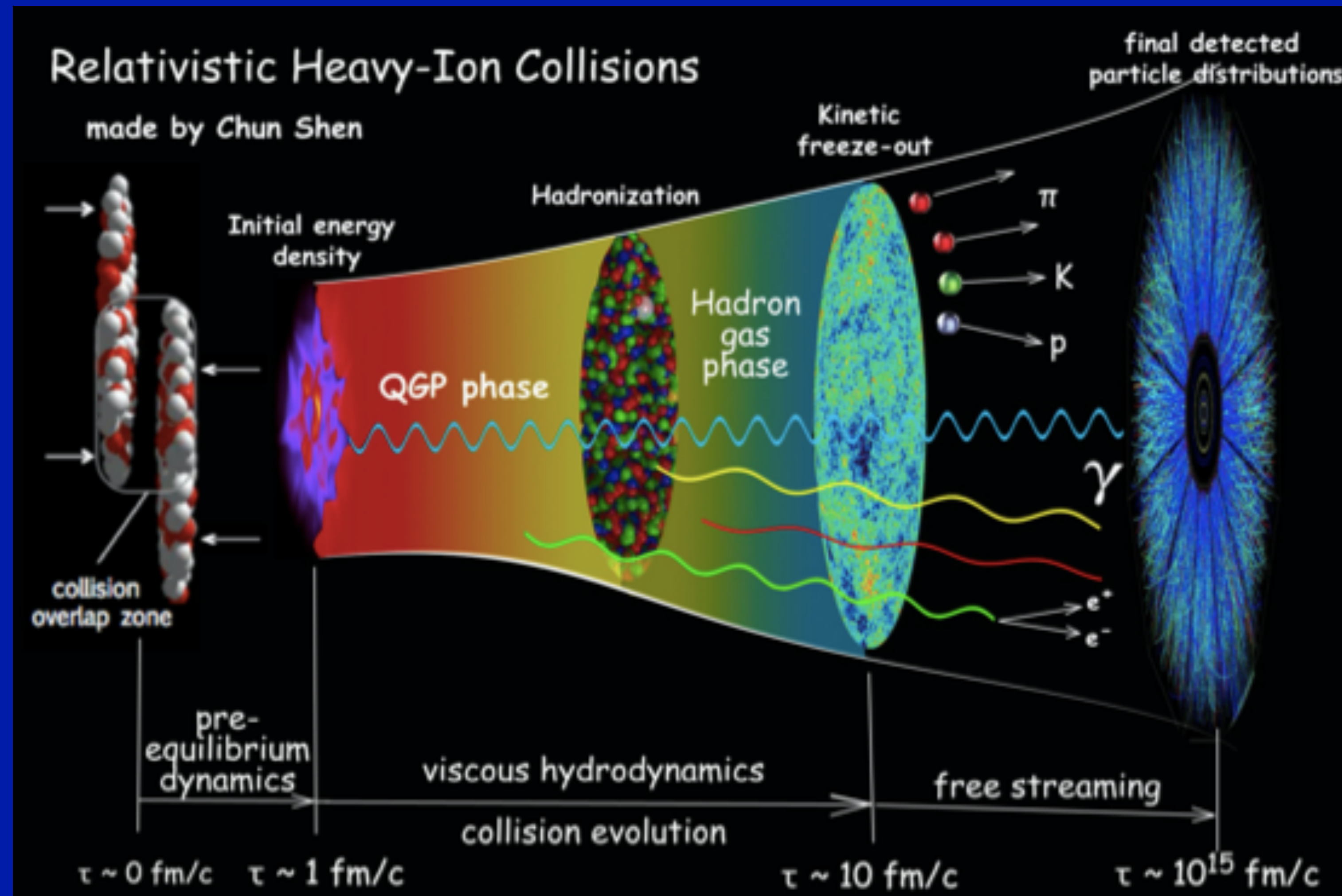
Time evolution of HI collisions: QGP state

Hadronic state



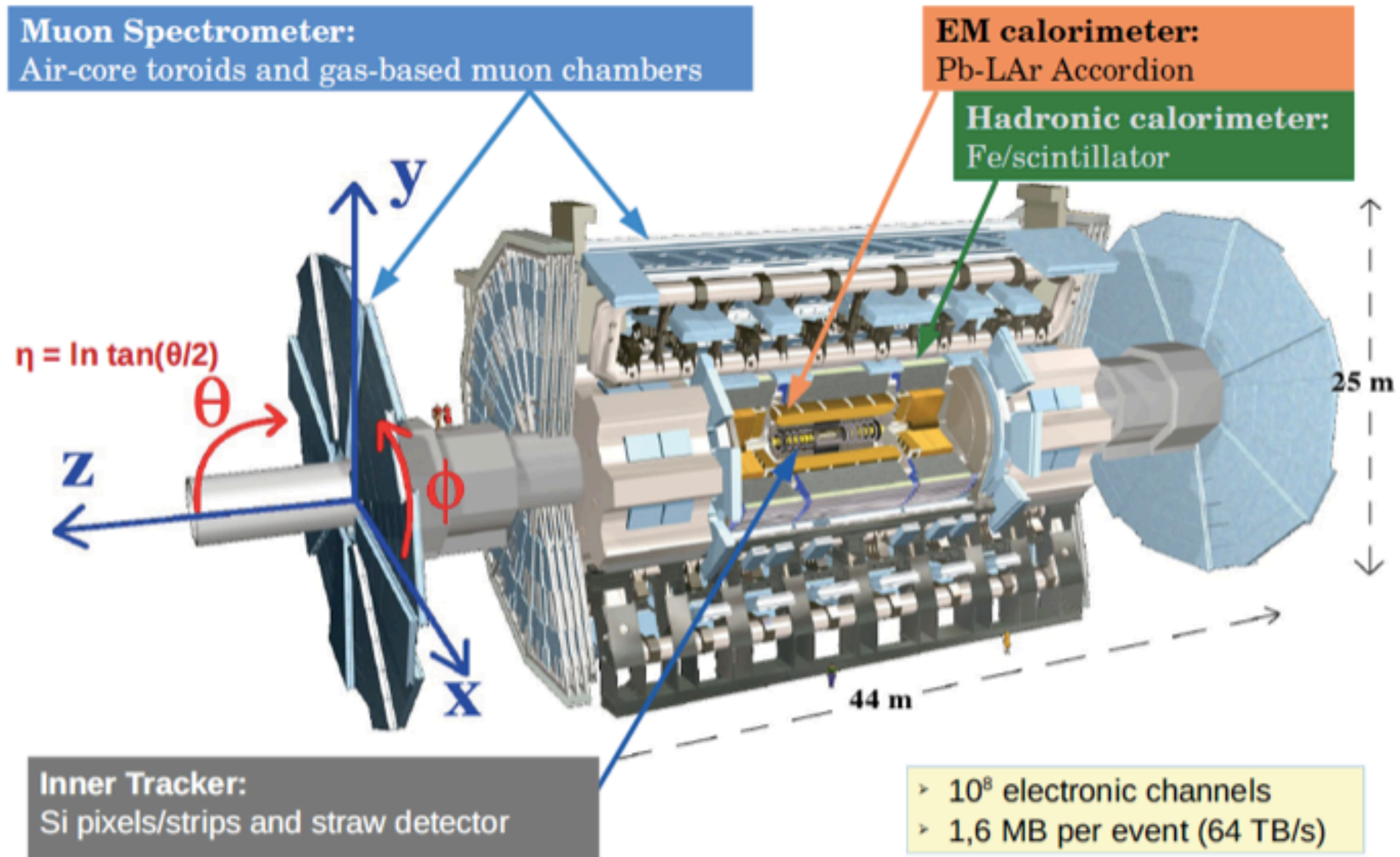
QGP exists for $\sim 10^{-23}$ s. It is impossible to study it using external probes.

How to understand the different stages?

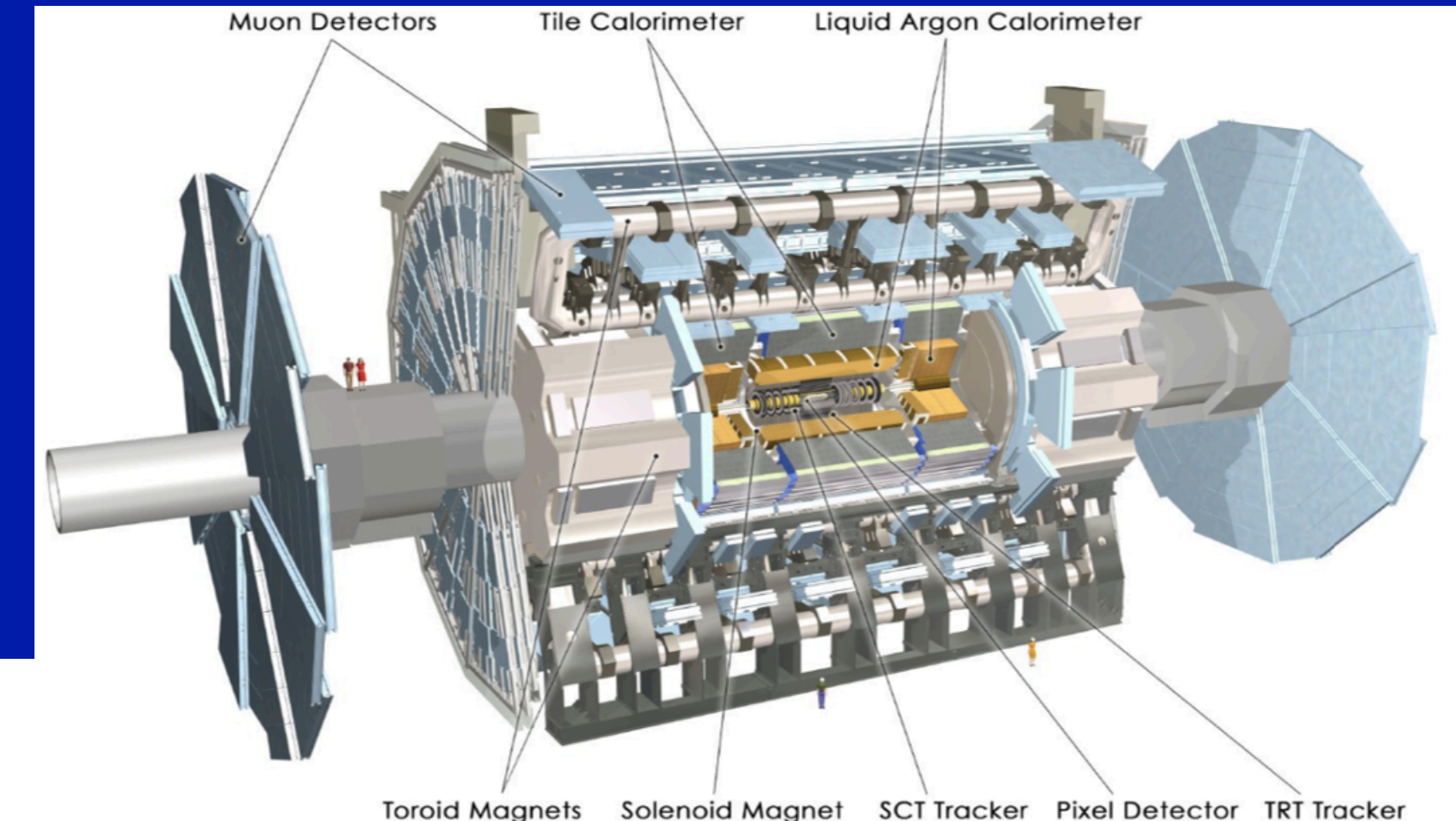


Use probes emitted during these stages:

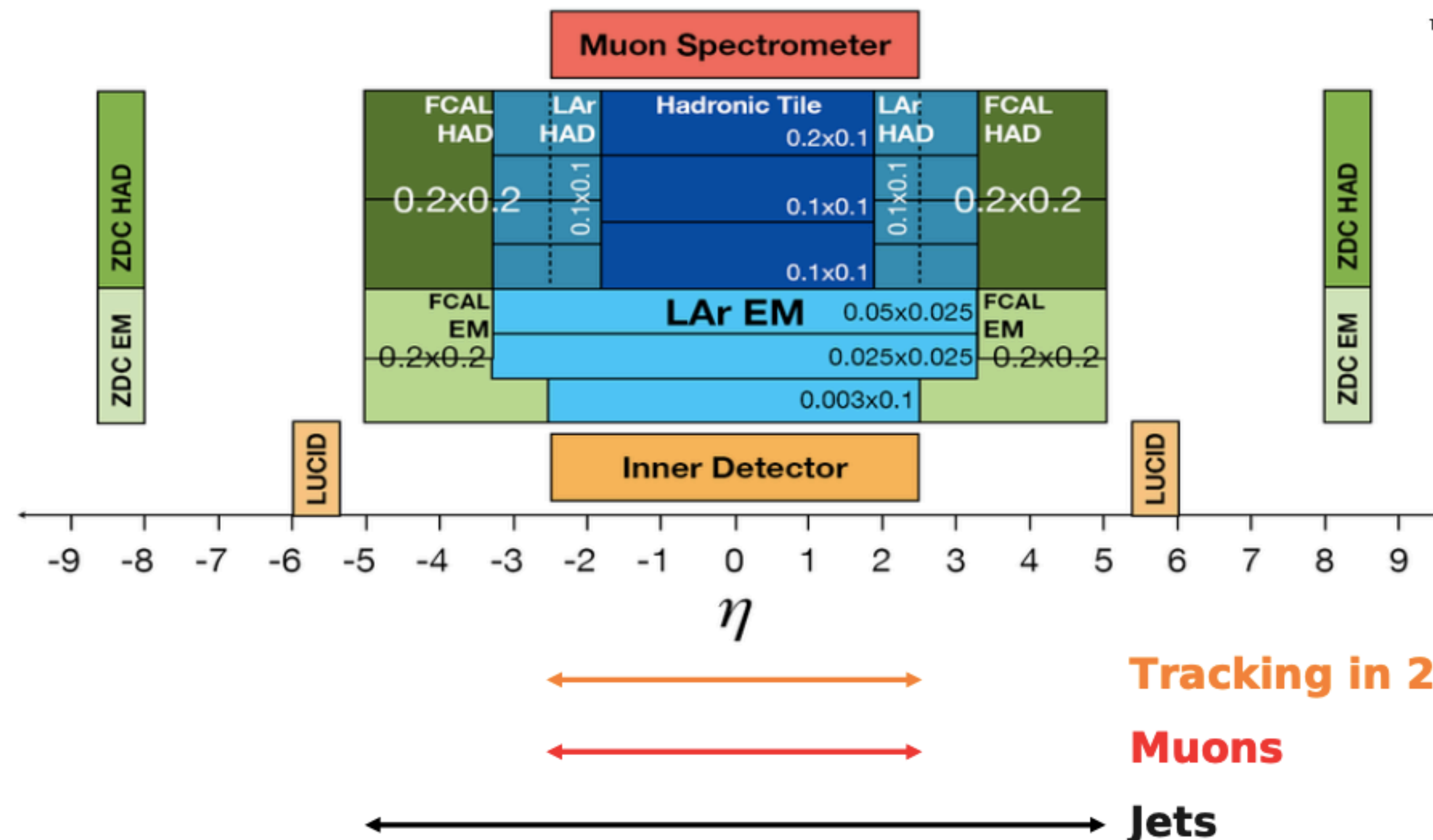
- Initial conditions, collisions geometry: electroweak bosons, particle correlations
- QGP and hadronic state: hadrons, jets, quarkonia

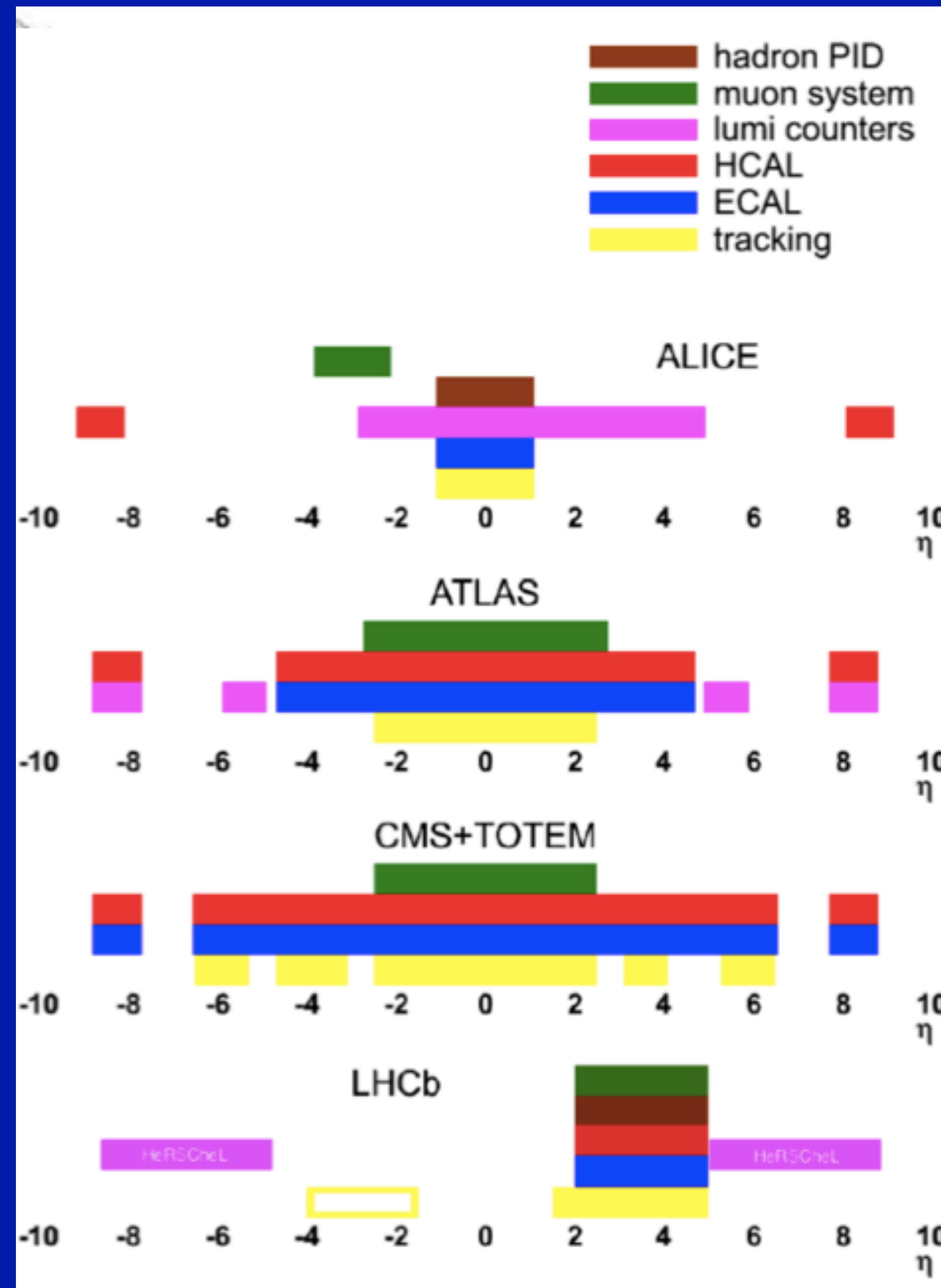
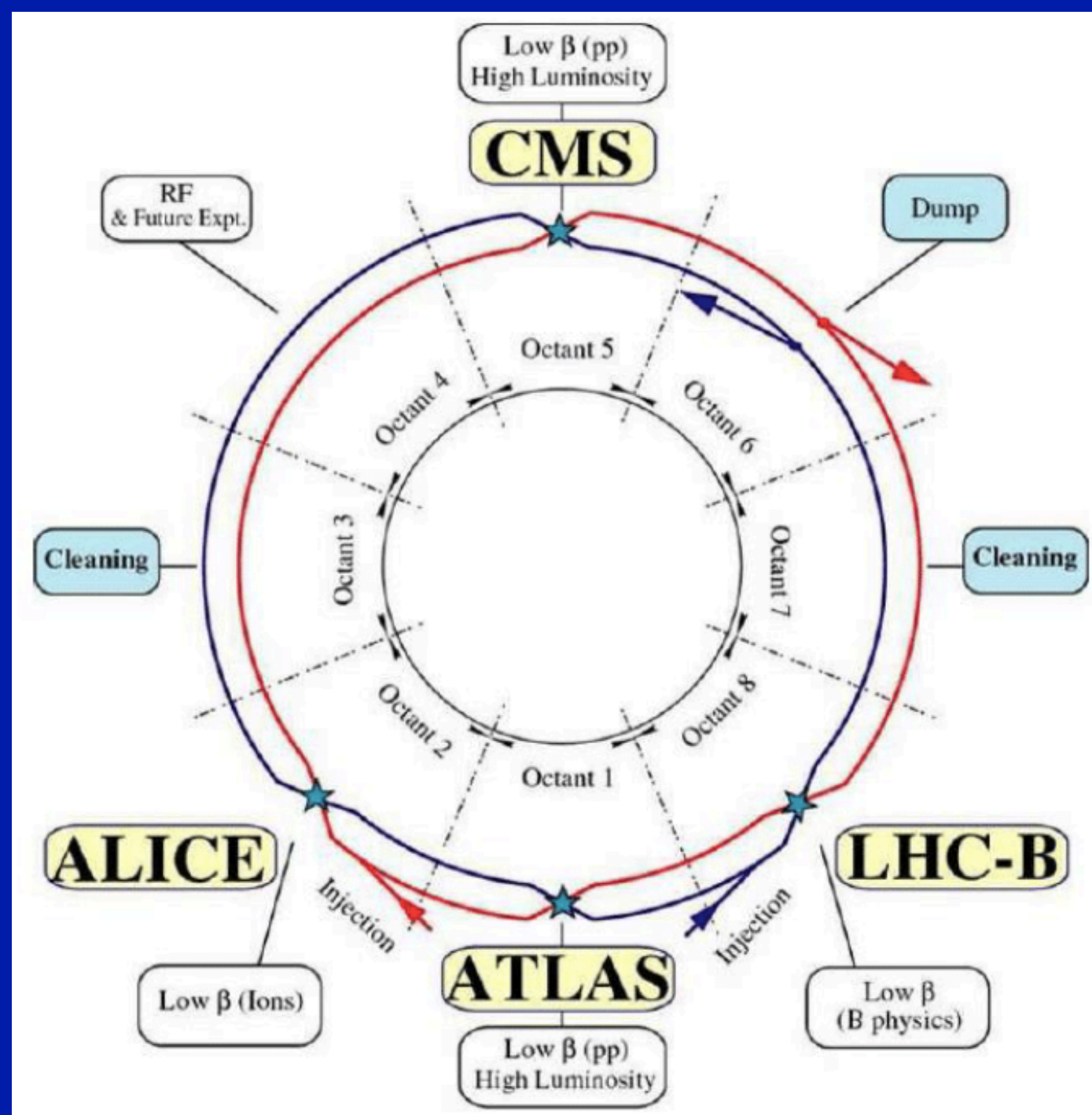


An excellent detector for the LHC Heavy-Ion program,
with enormous trigger capabilities



Full azimuthal coverage



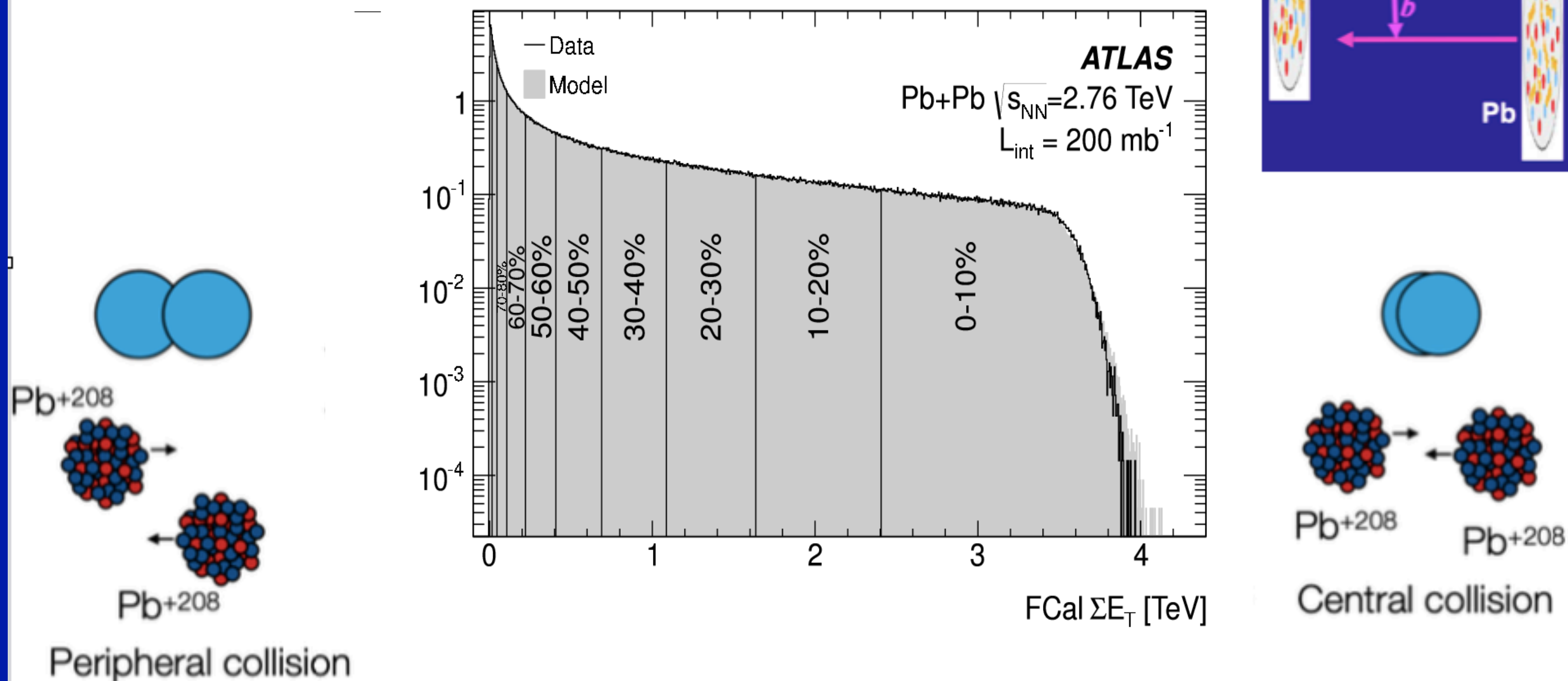


Detector being smaller or asymmetric is not necessarily worse.

ATLAS and CMS are multipurpose detectors that work greatly during the LHC Heavy Ion Program.

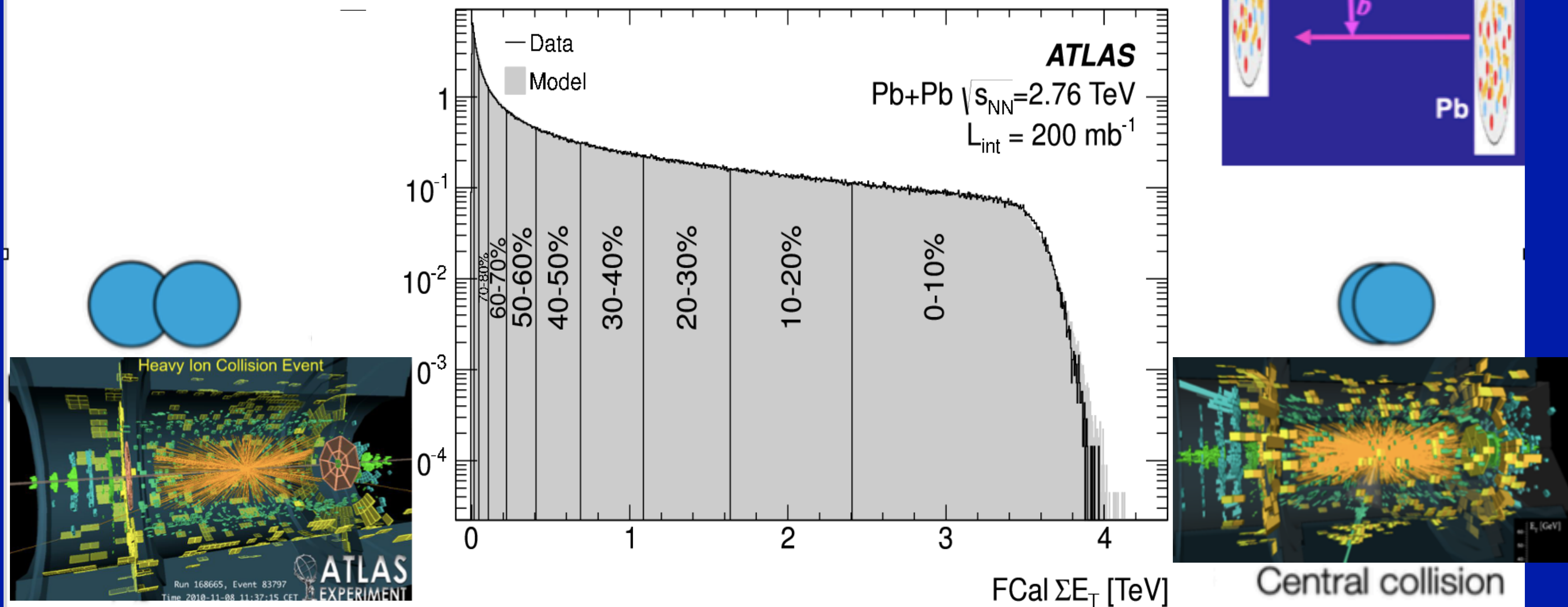
However, ALICE has excellent tracking and particle identification capabilities. It is a detector specially designed for the LHC Heavy Ion Program.

HI collision's dynamics controlled by impact parameter “ b ”



Each heavy-ion event is characterised by “centrality”, the geometrical overlap between the two nuclei. The higher the centrality, the higher the transverse energy deposited in the forward (FCal) calorimeter.

HI collision's dynamics controlled by impact parameter “ b ”



Peripheral collision

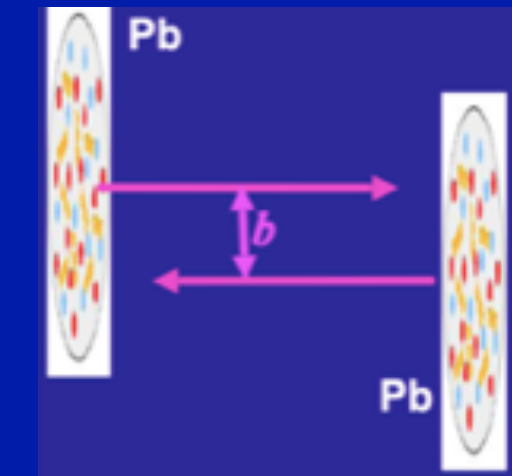
Each heavy-ion event is characterised by “centrality”, the geometrical overlap between the two nuclei. The higher the centrality, the higher the transverse energy deposited in the forward (FCal) calorimeter. Assessing that is fundamental because the QGP is formed mostly when they overlap.

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

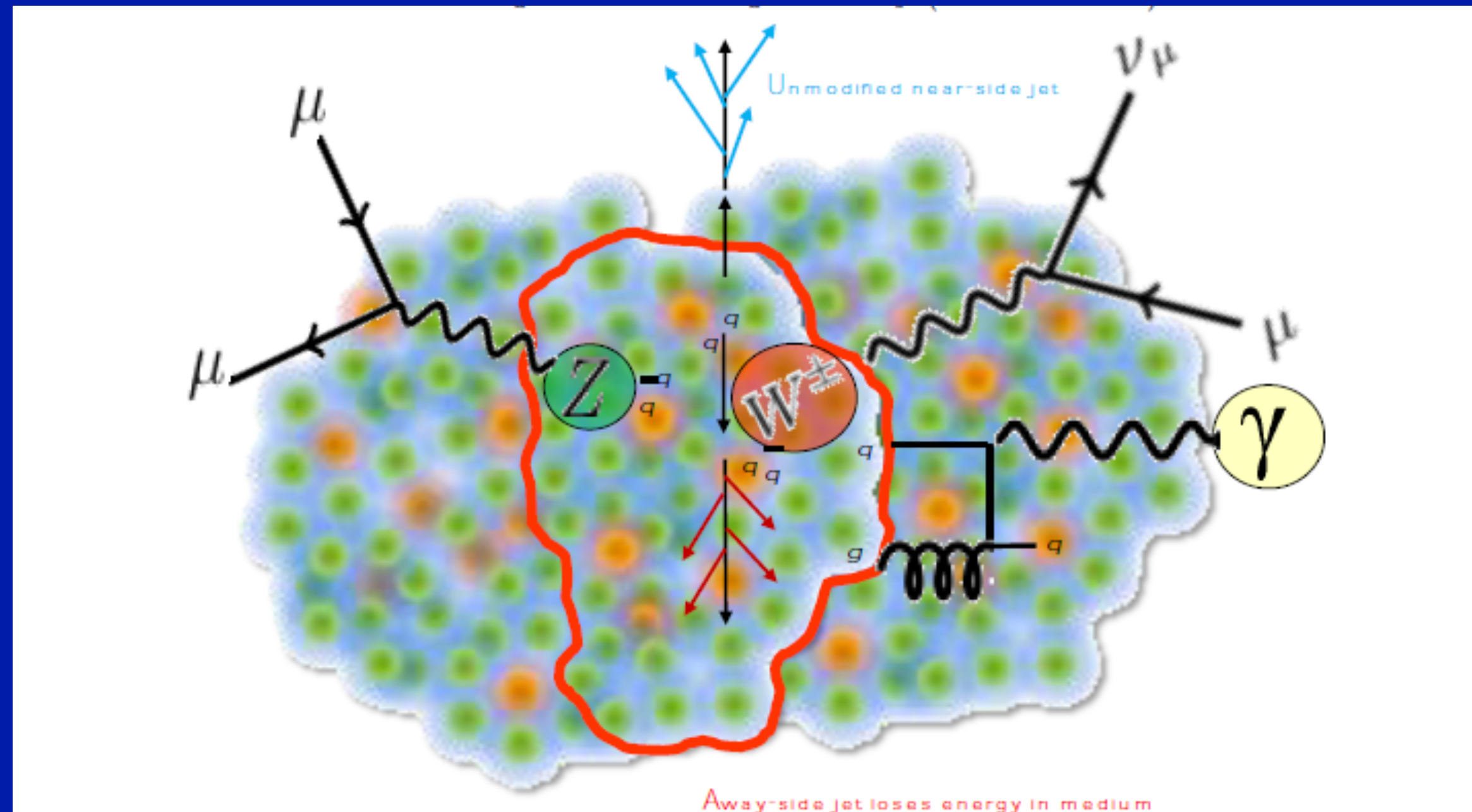
Nuclear thickness function
 $\langle N_{coll} \rangle / \sigma_{NN}$

Cross section in pp collisions (in vacuum)



- $\langle T_{AA} \rangle$ quantifies the transverse overlap of two nuclei at impact parameter b , and is proportional to the number of binary nucleon-nucleon collisions in a heavy ion collision.
- Nuclear modification factor quantifies the **change of yields in the medium**, relatively to the **production in vacuum**.
- Any deviation from unity points to suppression or enhancement of the **yields in Pb+Pb**.

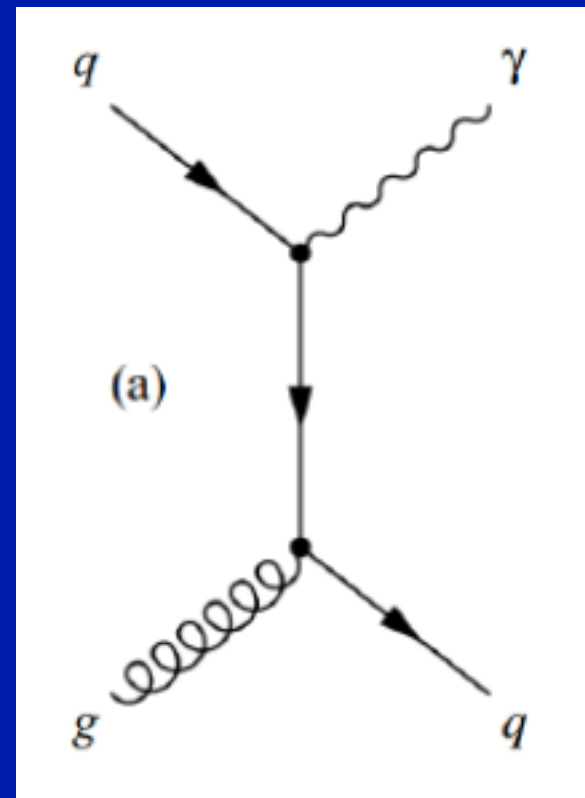
W/Z, photons, are not supposed to interact with the QGP



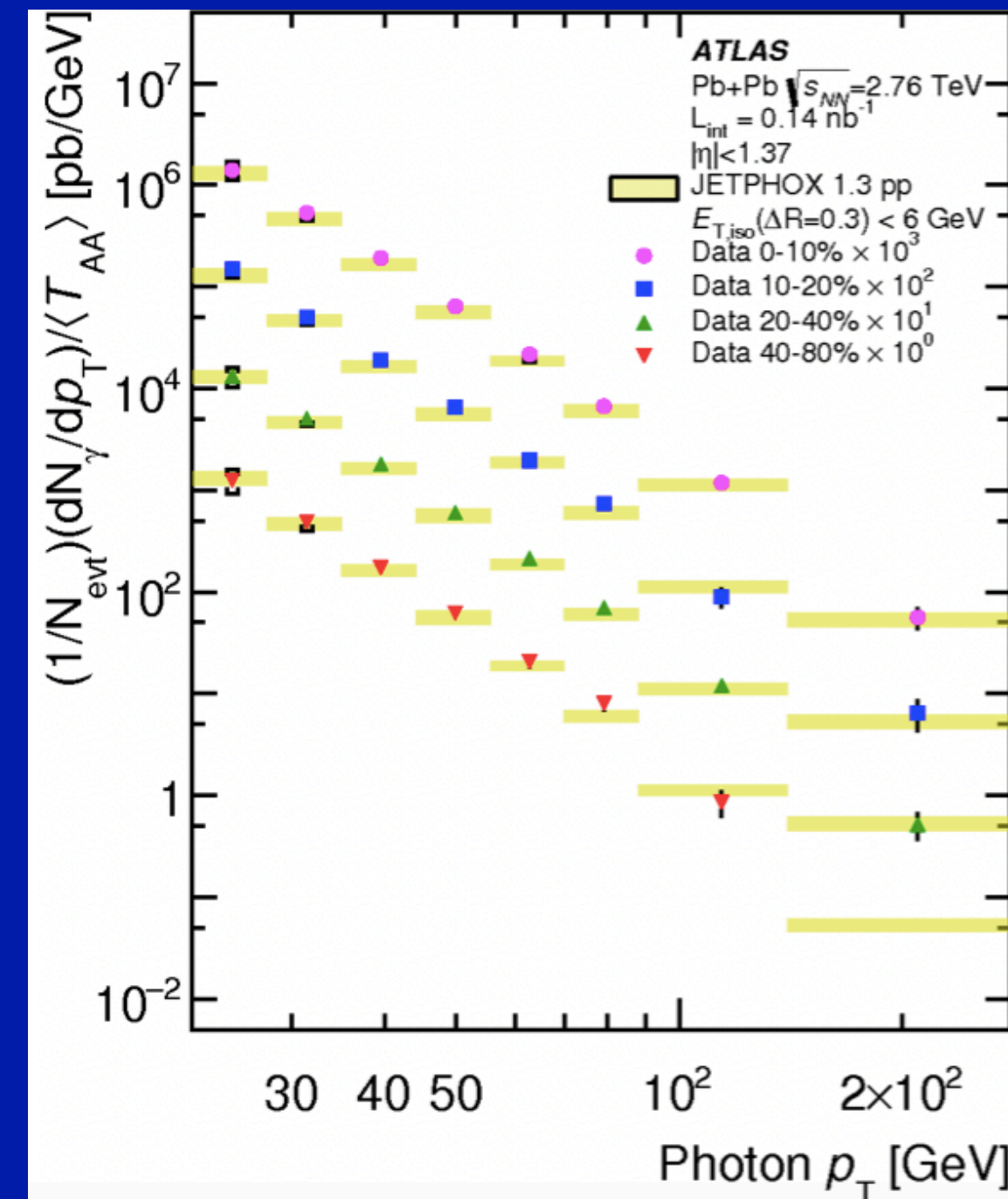
They are produced in HI collisions before QGP is formed:

- Production mechanisms sensitive to nuclear PDFs \rightarrow the cross sections depend on the momentum distributions of quarks and antiquarks inside bound nucleons
- Can be used to check models of collision geometry. Their production is expected to be proportional to the nuclear overlap.
- Provide calibration for jet energy loss in the QGP (photon-jet, Z-jet).

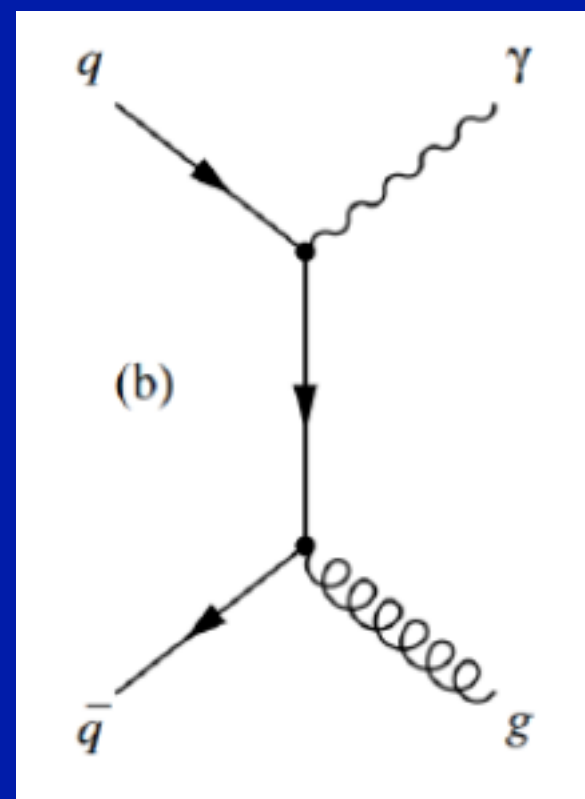
QCD Compton scattering



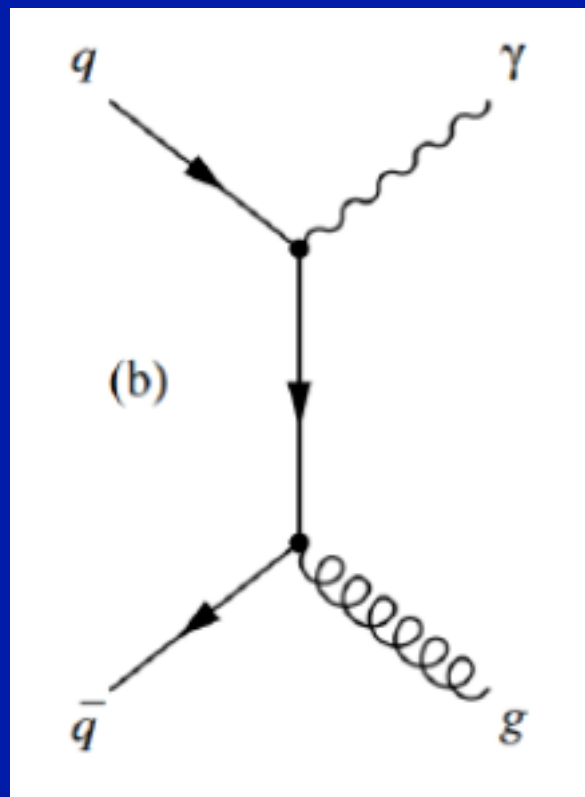
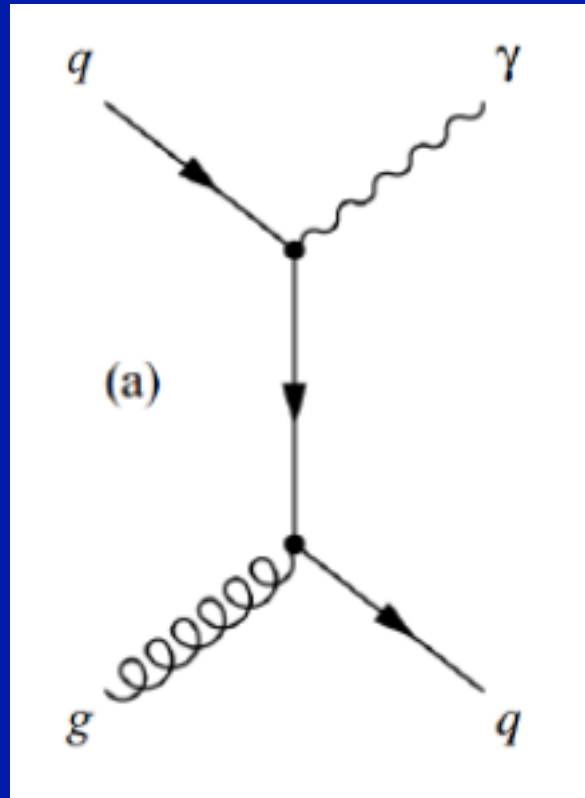
Prompt photons as a function of p_T



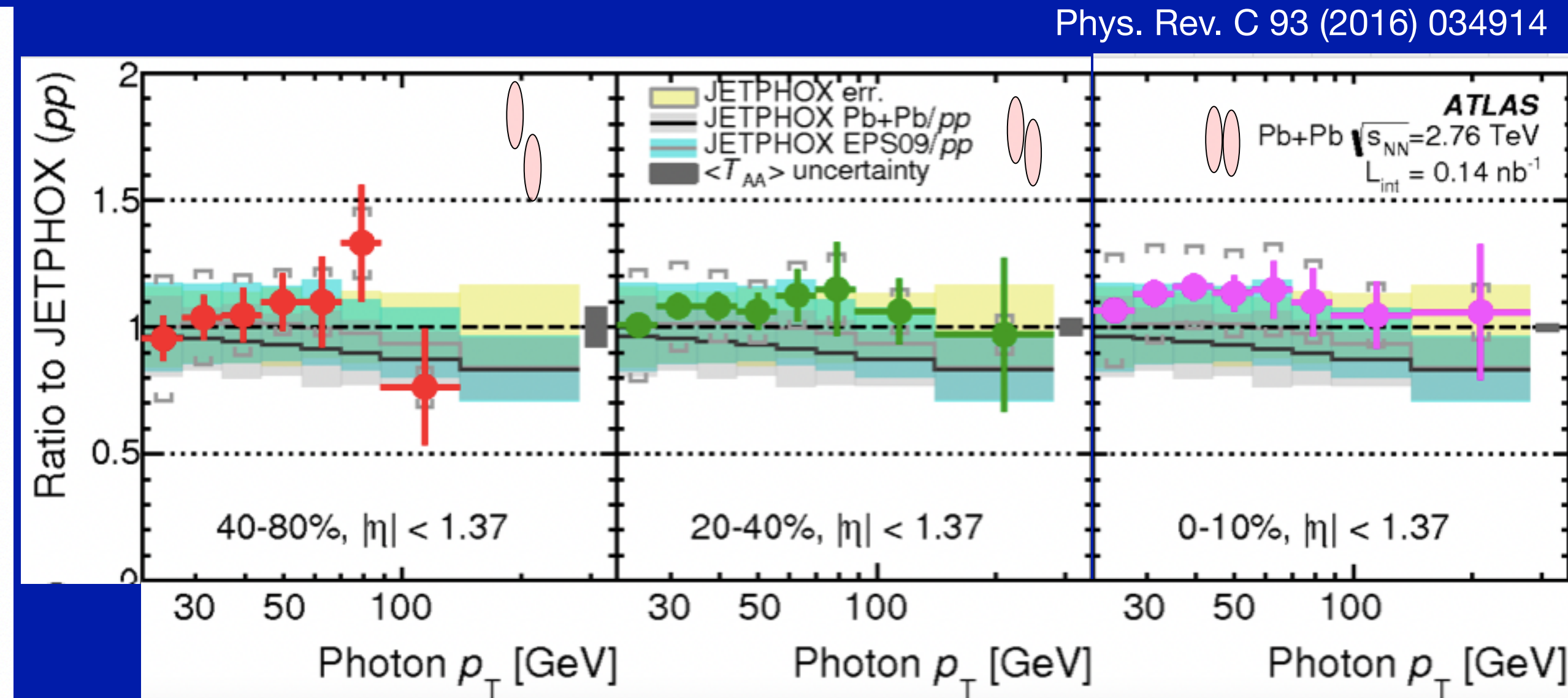
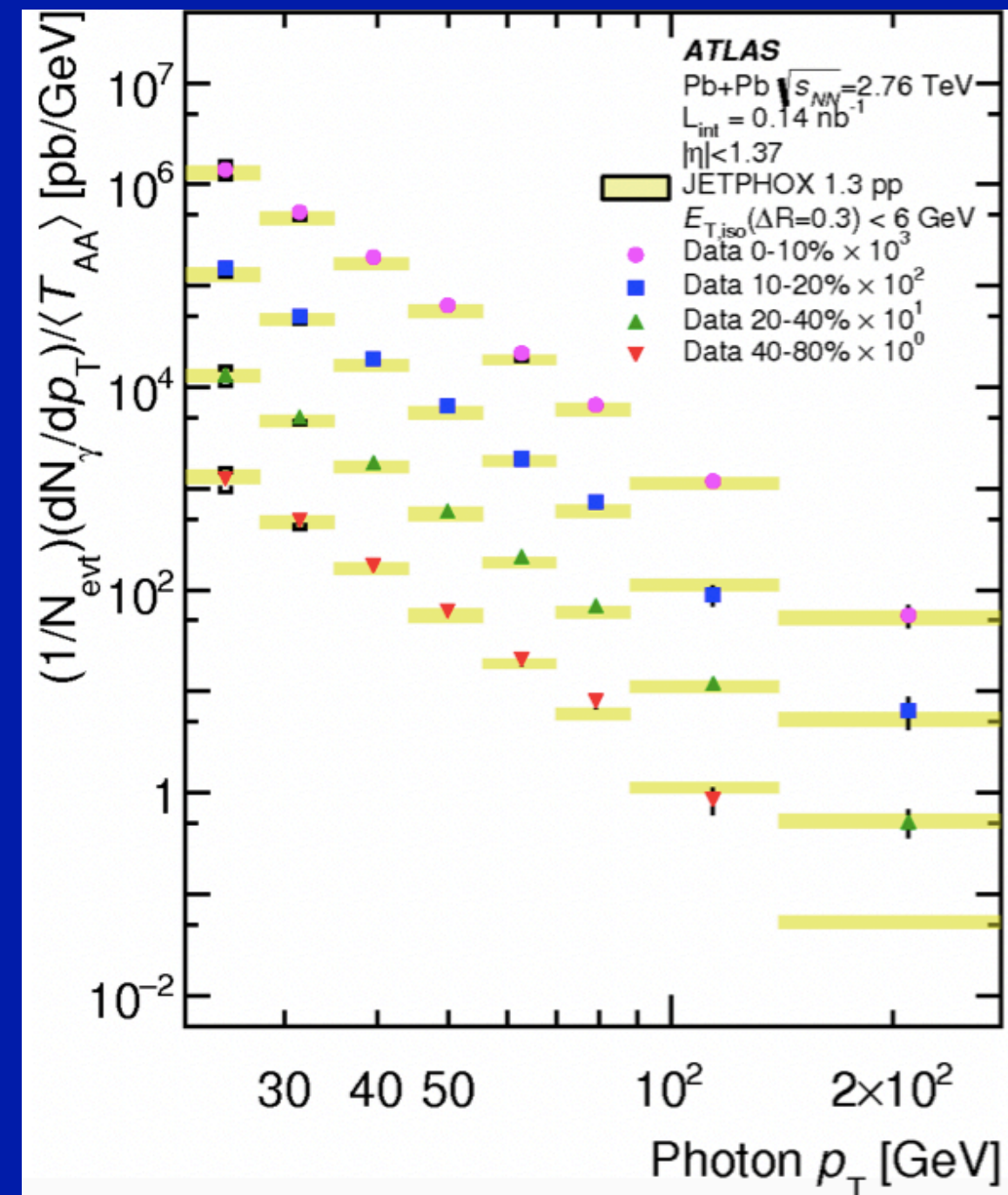
quark-antiquark annihilation



QCD Compton scattering



Prompt photons as a function of p_T

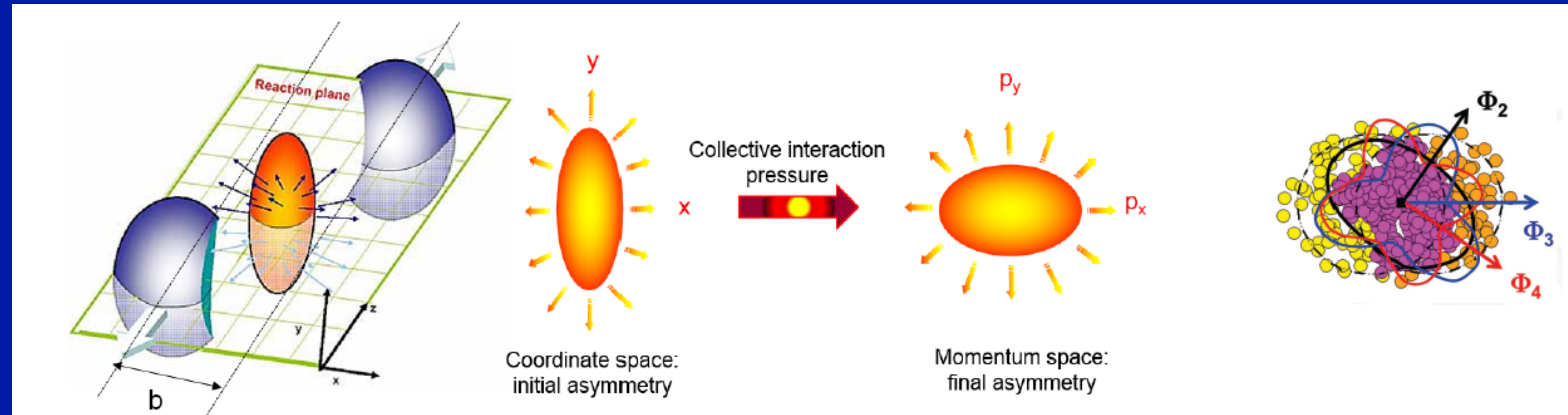
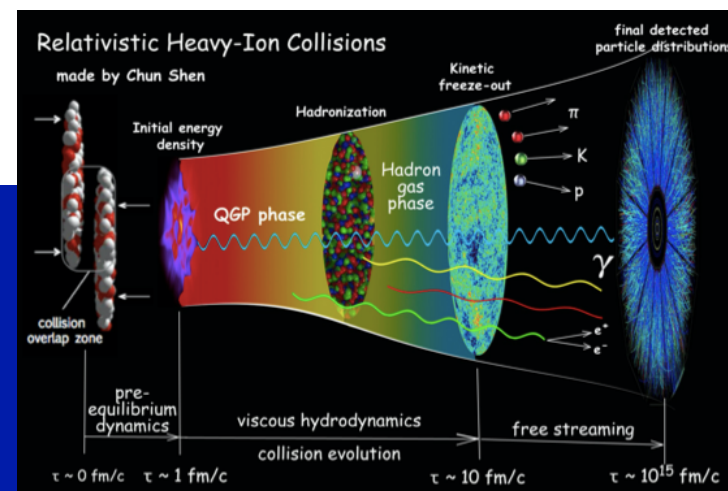


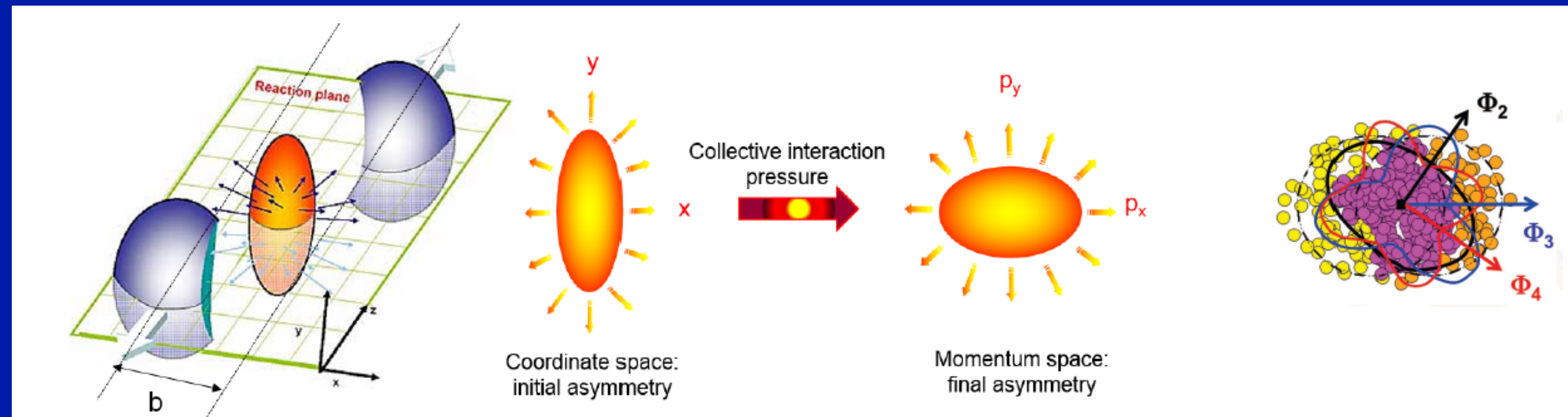
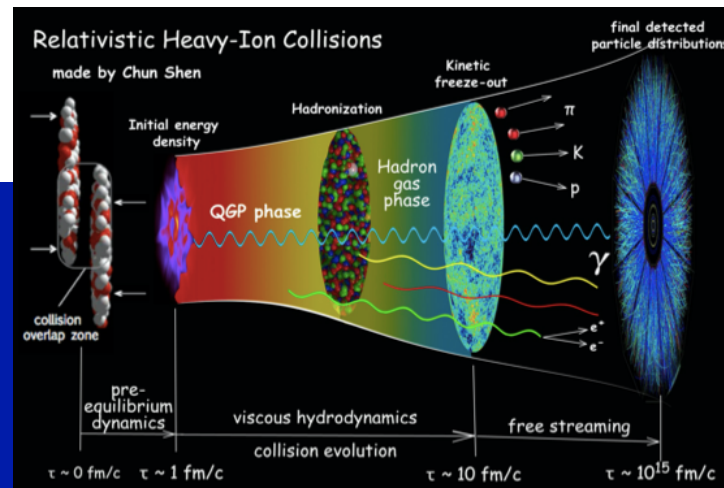
Ratio to JETPHOX (equivalent to an R_{AA}) is 1.

Photons are not suppressed in the QGP

Probing the initial stages and QGP - Flow

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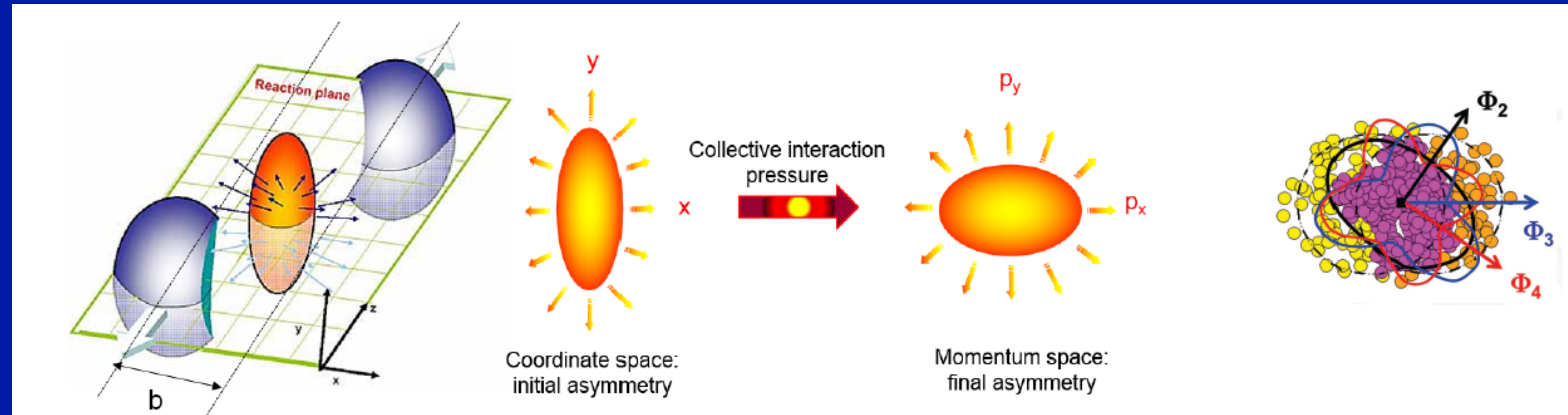
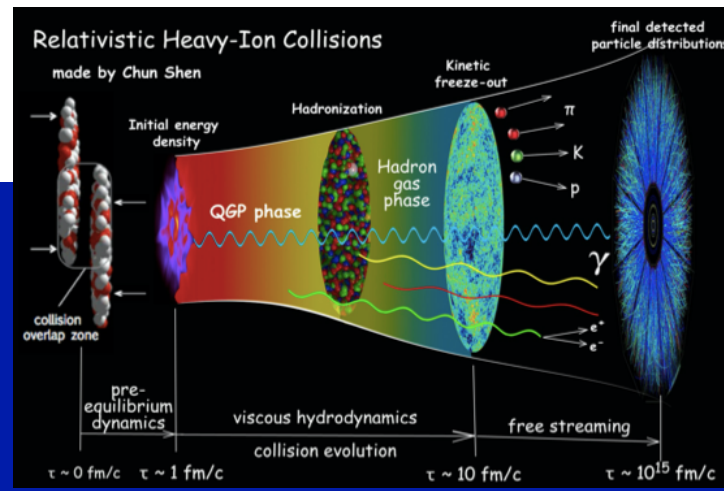




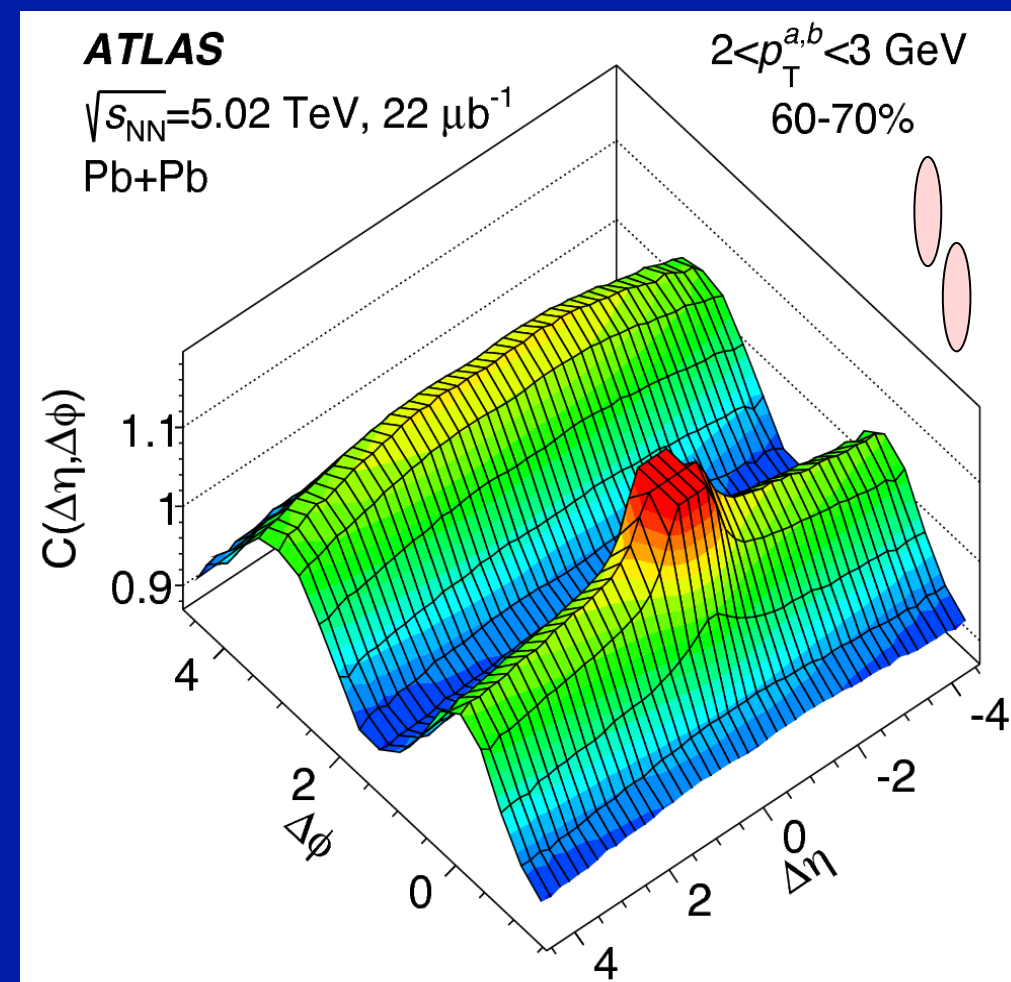
Anisotropic collective motion is described by a Fourier expansion of particle distribution in azimuthal angle ϕ

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

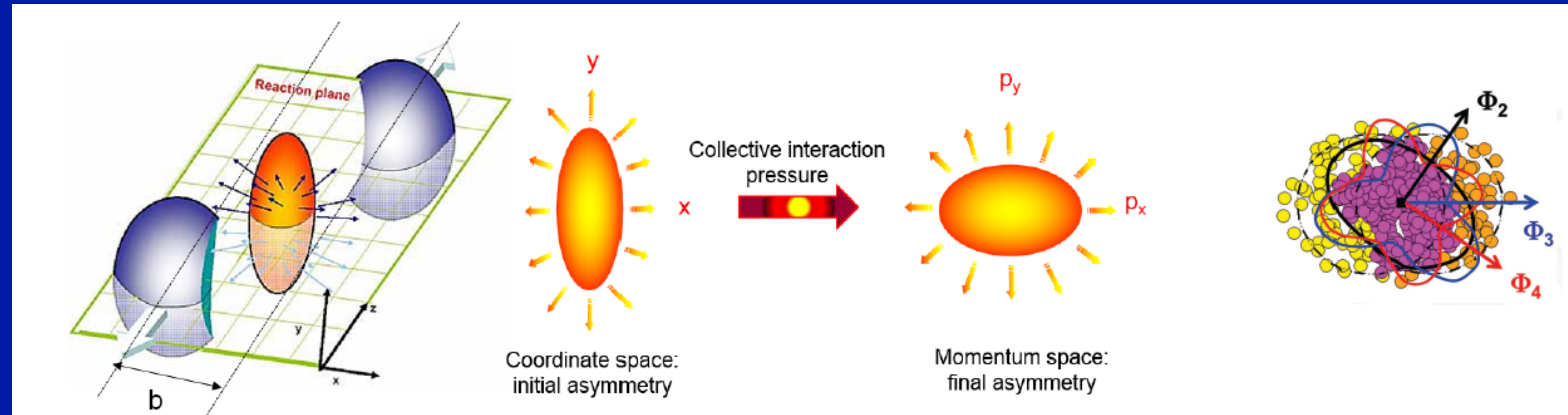
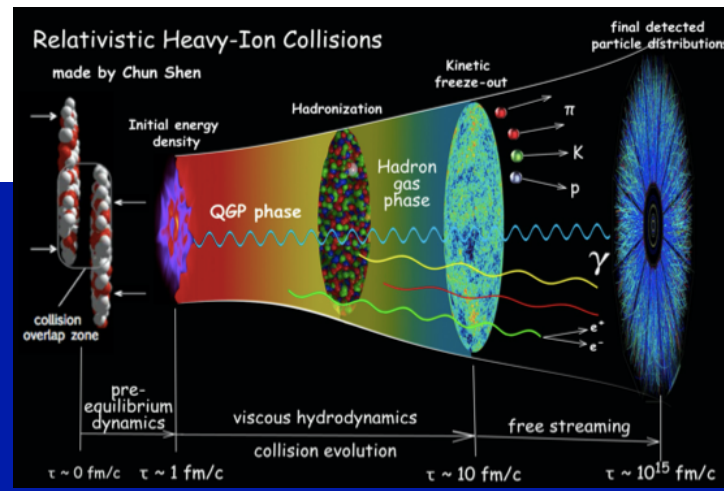
Probing the initial stages and QGP- Flow



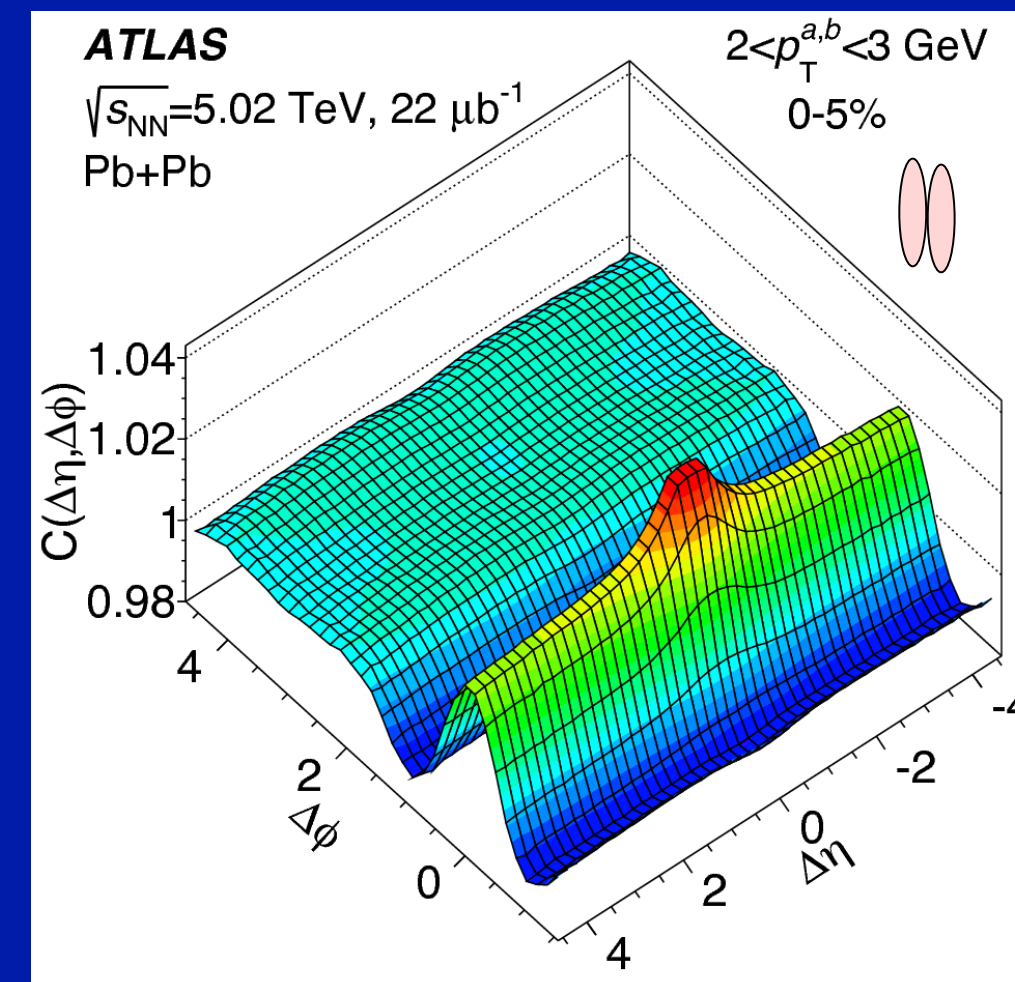
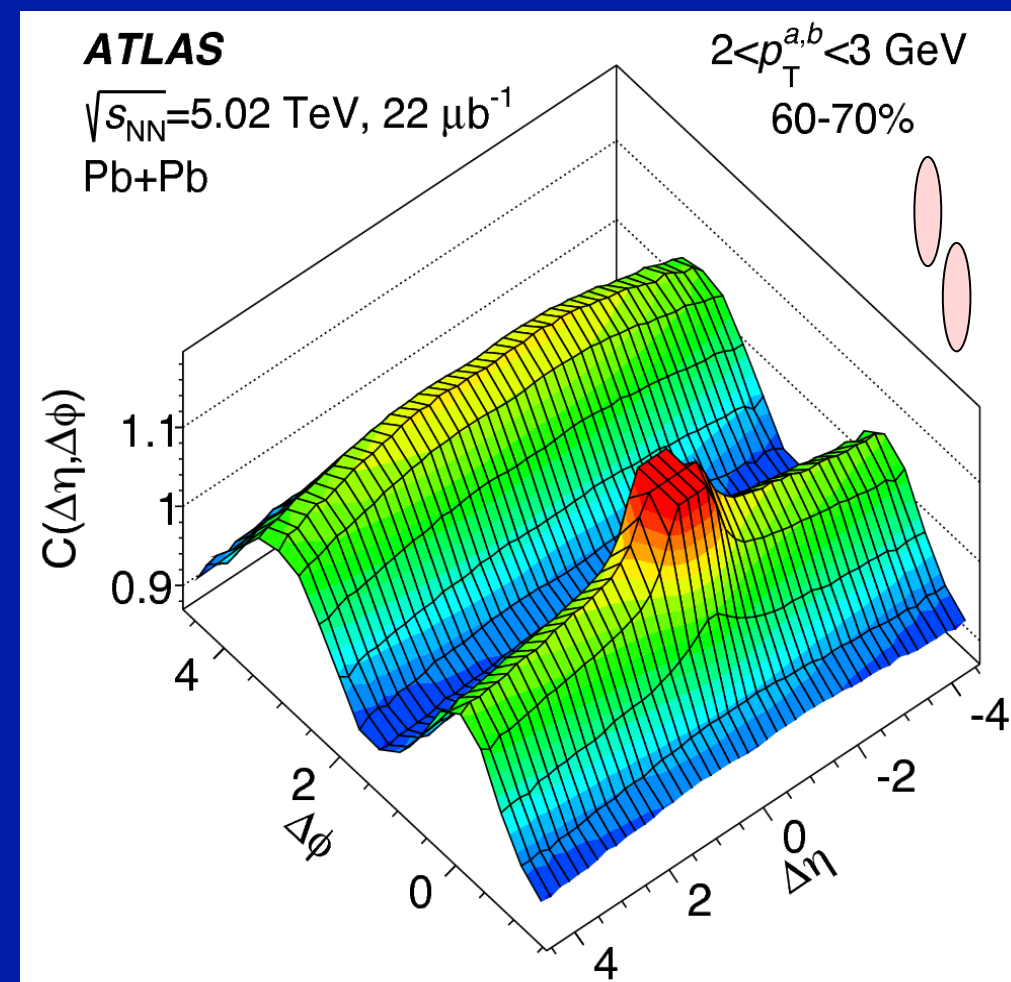
correlation between pairs of particles formed in high-multiplicity collisions



Probing the initial stages and QGP - Flow



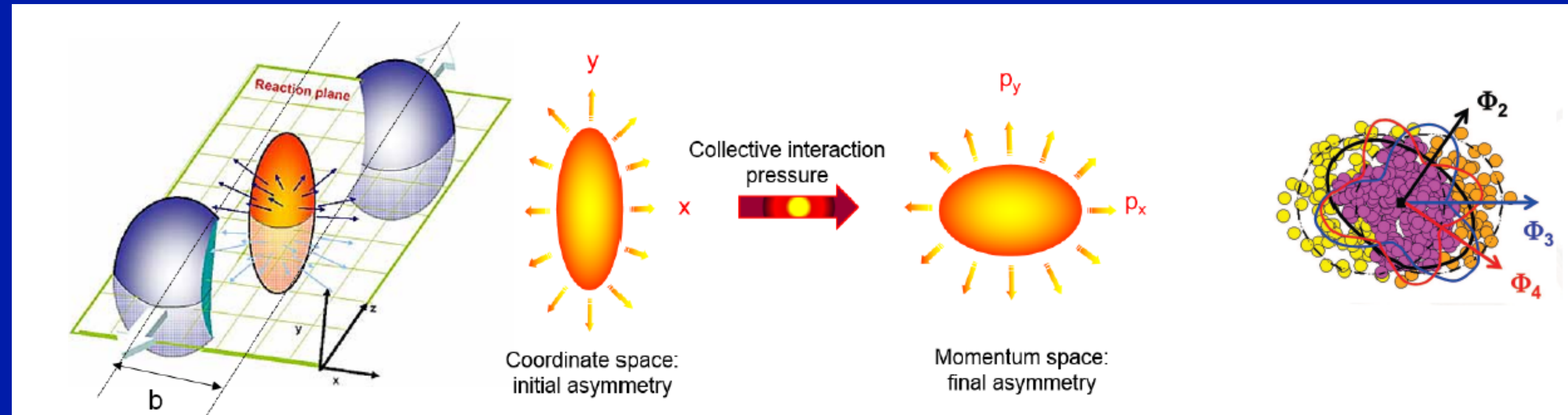
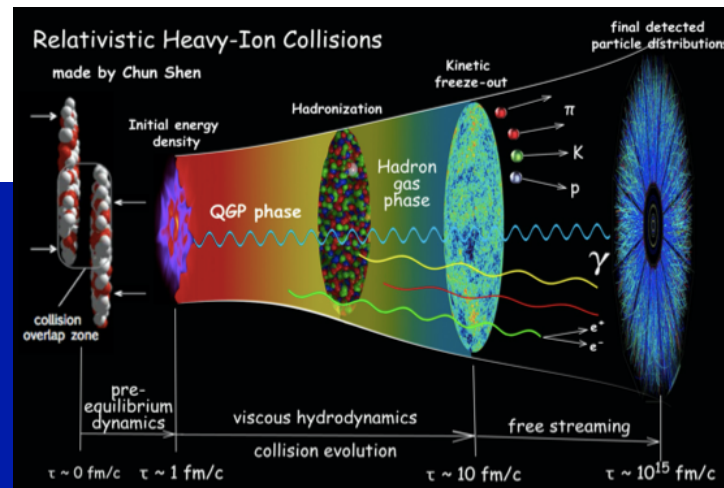
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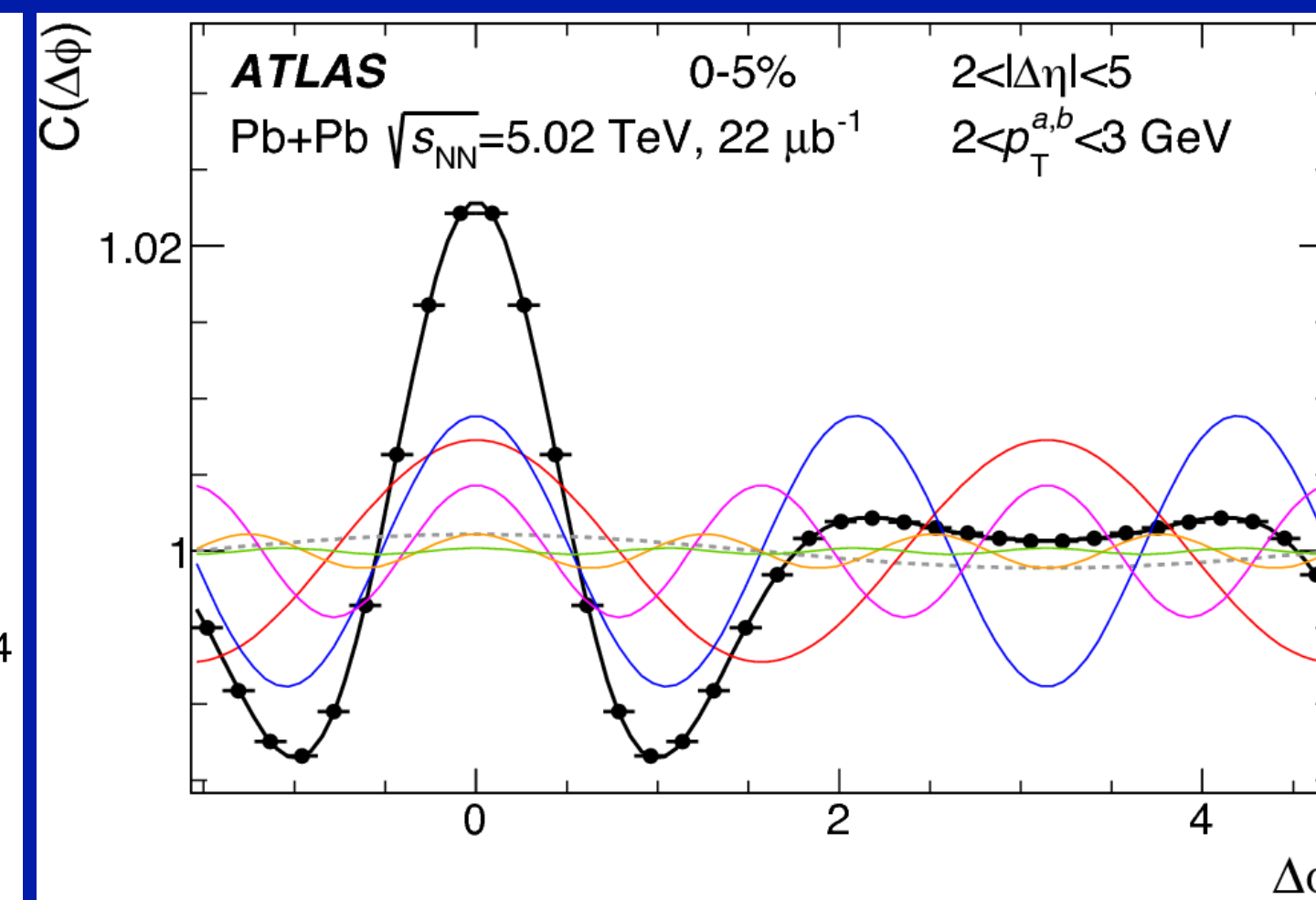
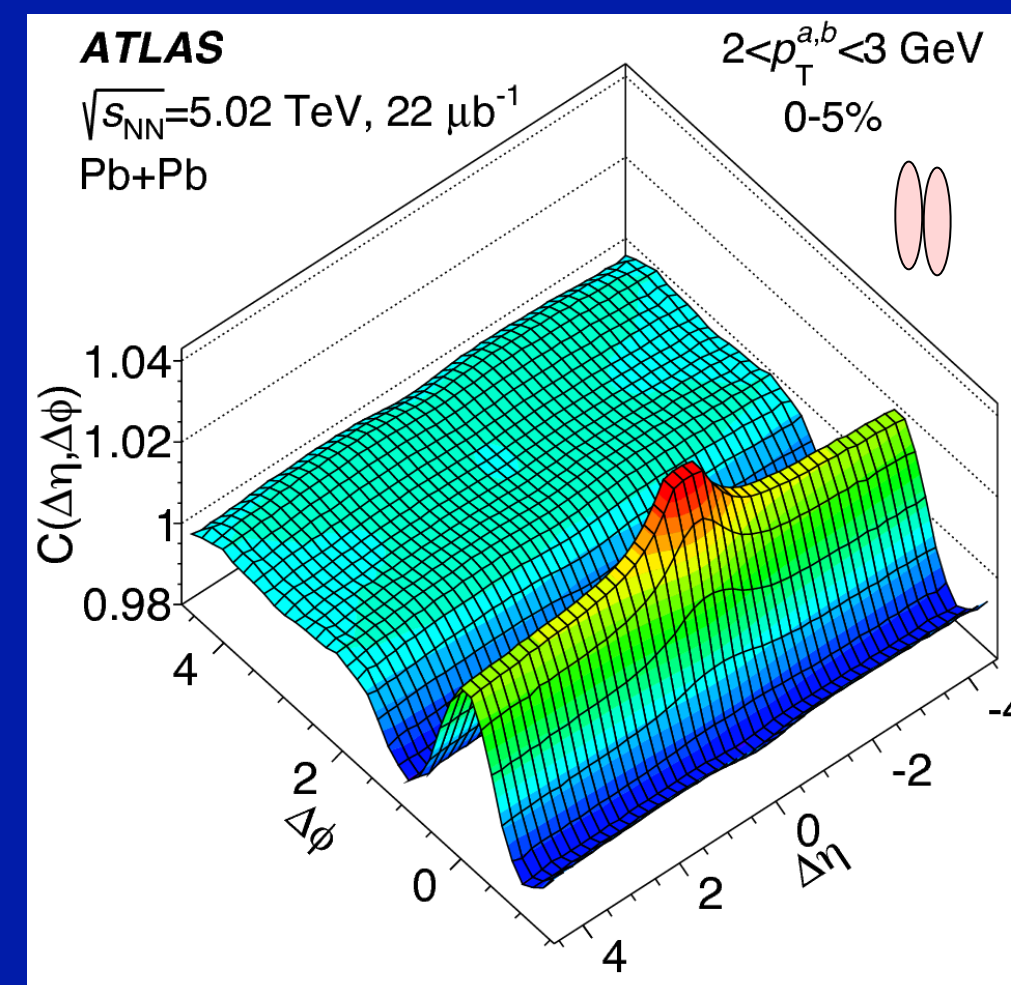
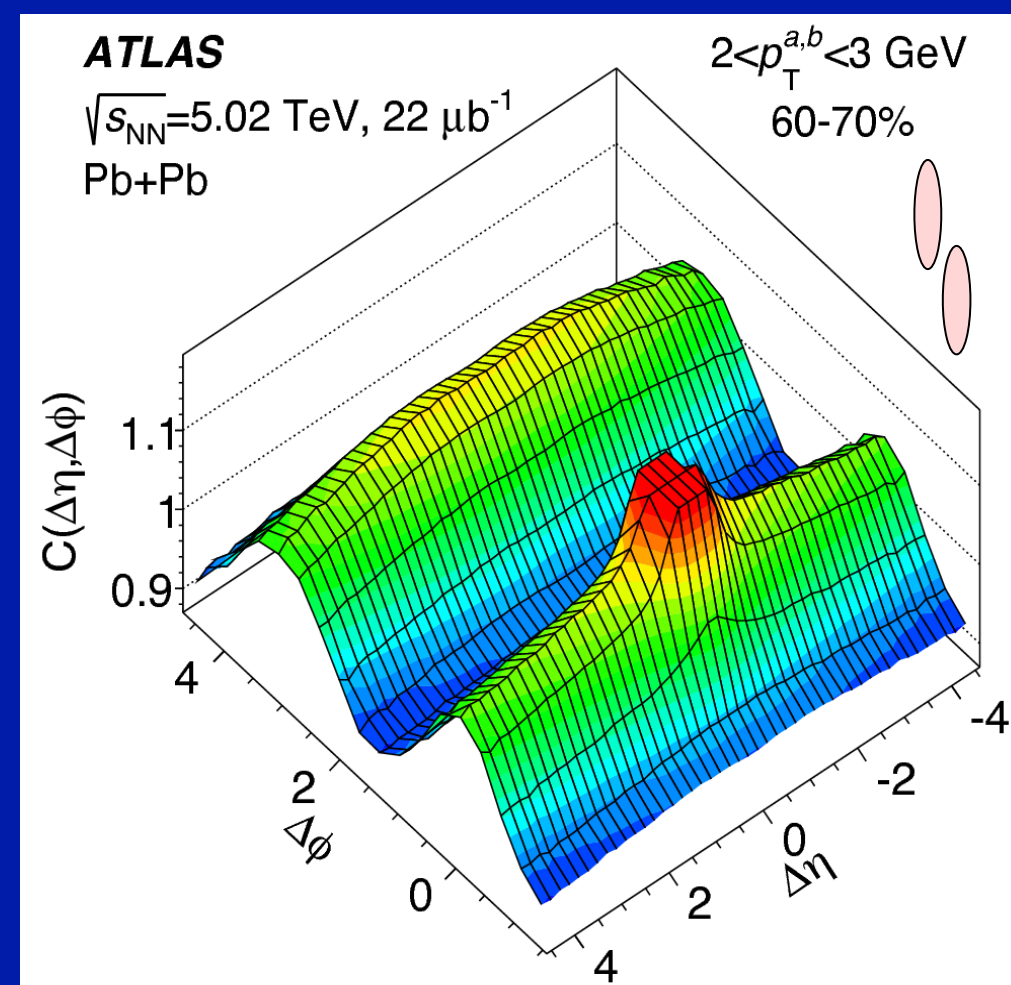
Probing the initial stages and QGP - Flow

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arXiv:1808.03951v2 [nucl-ex]



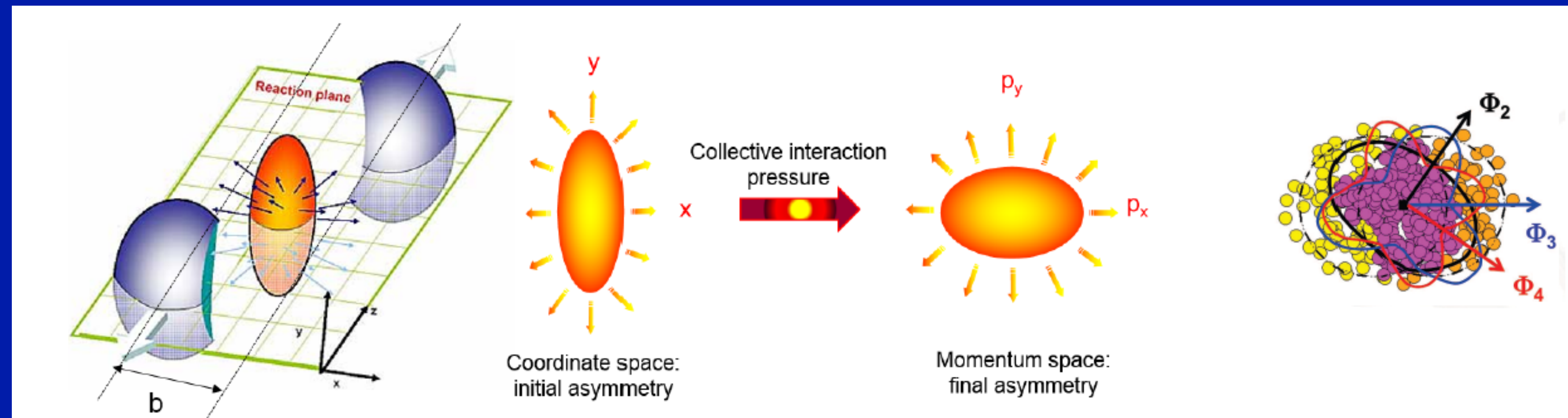
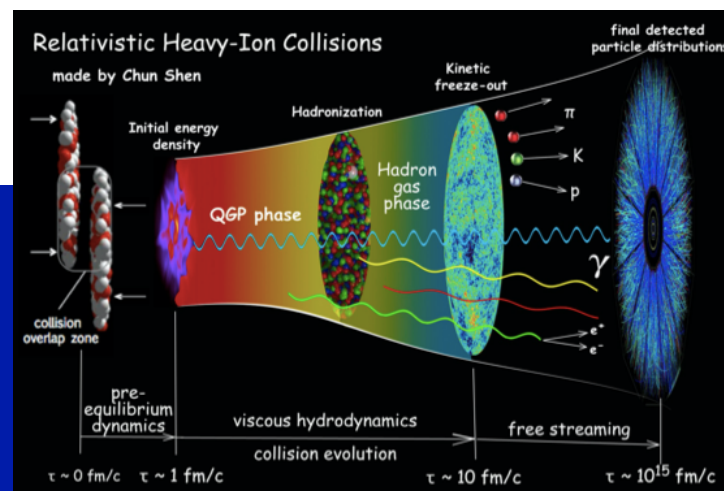
Anisotropic collective motion is described by a Fourier expansion of particle distribution in azimuthal angle ϕ



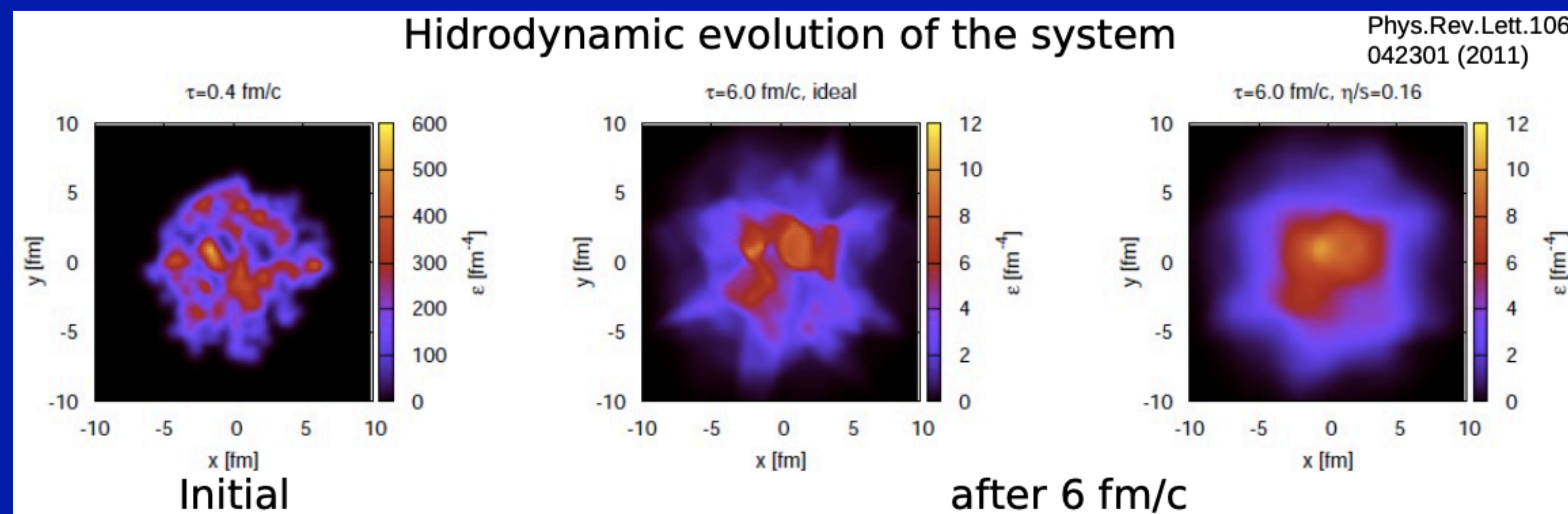
High order coefficients ($n > 2$) are associated with fluctuations of nucleon positions in the overlap

Probing the initial stages and QGP - Flow

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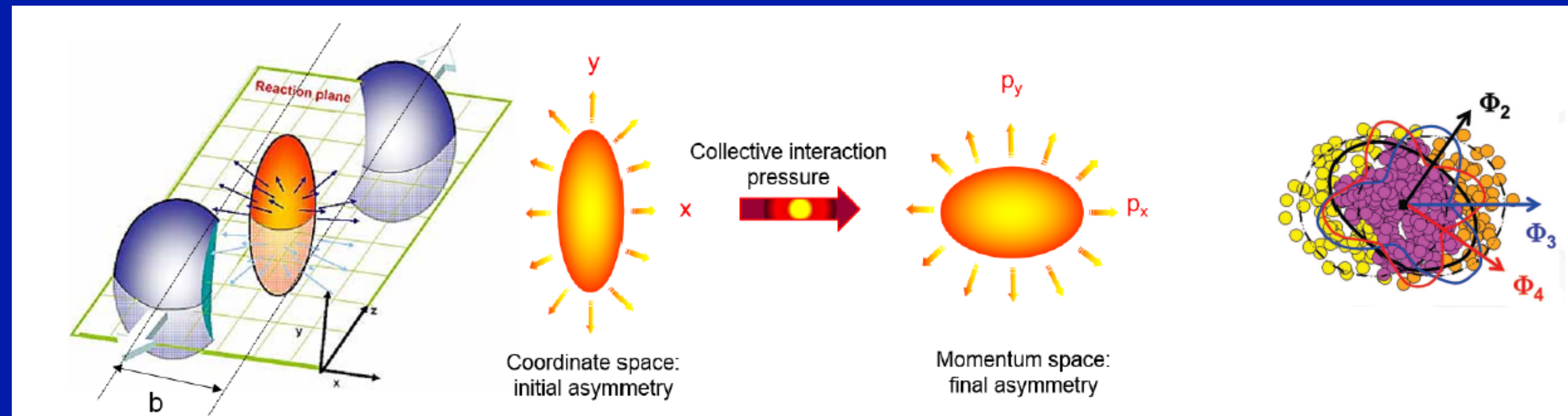
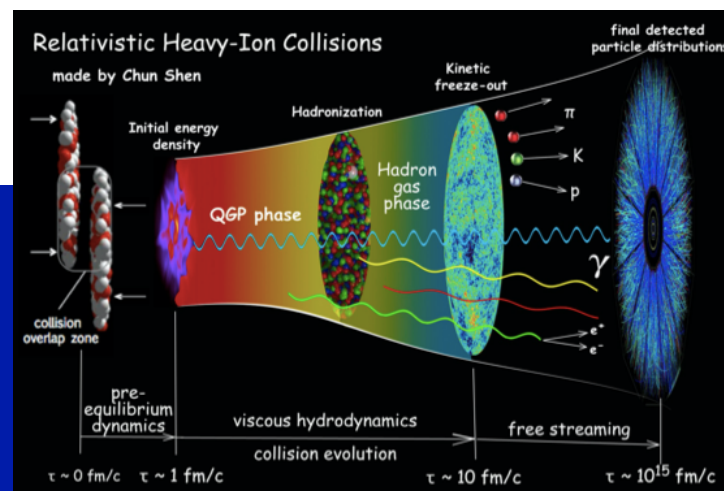


The long-range correlations observed in Pb+Pb collisions are interpreted as evidence of hydrodynamic expansion in the medium, providing insights into its fluid properties. Strikingly, this matter exhibits flow with minimal frictional resistance, resulting in an exceptionally low viscosity. (see Nature Physics 1113 (2019))

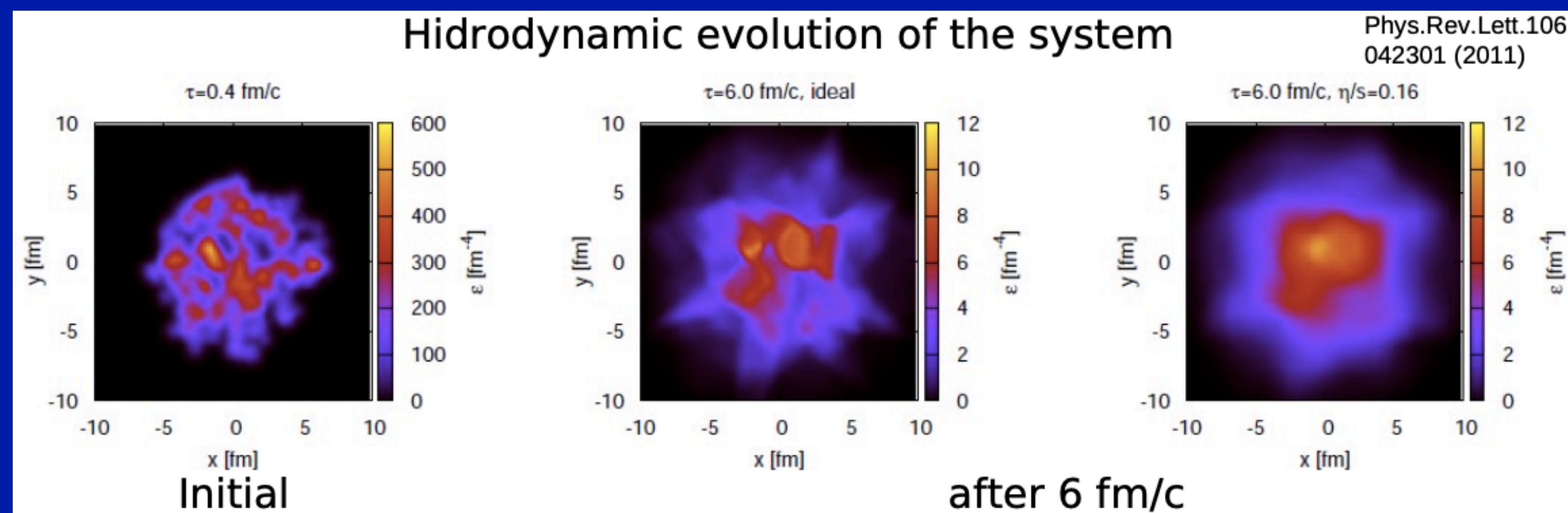


Probing the initial stages and QGP - Flow

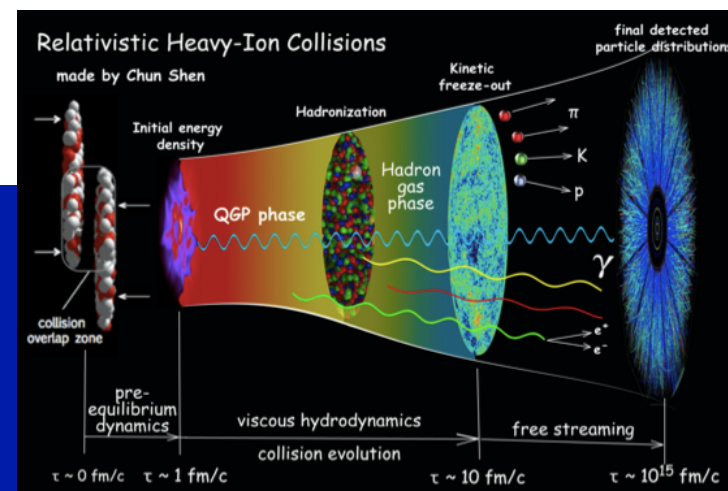
28



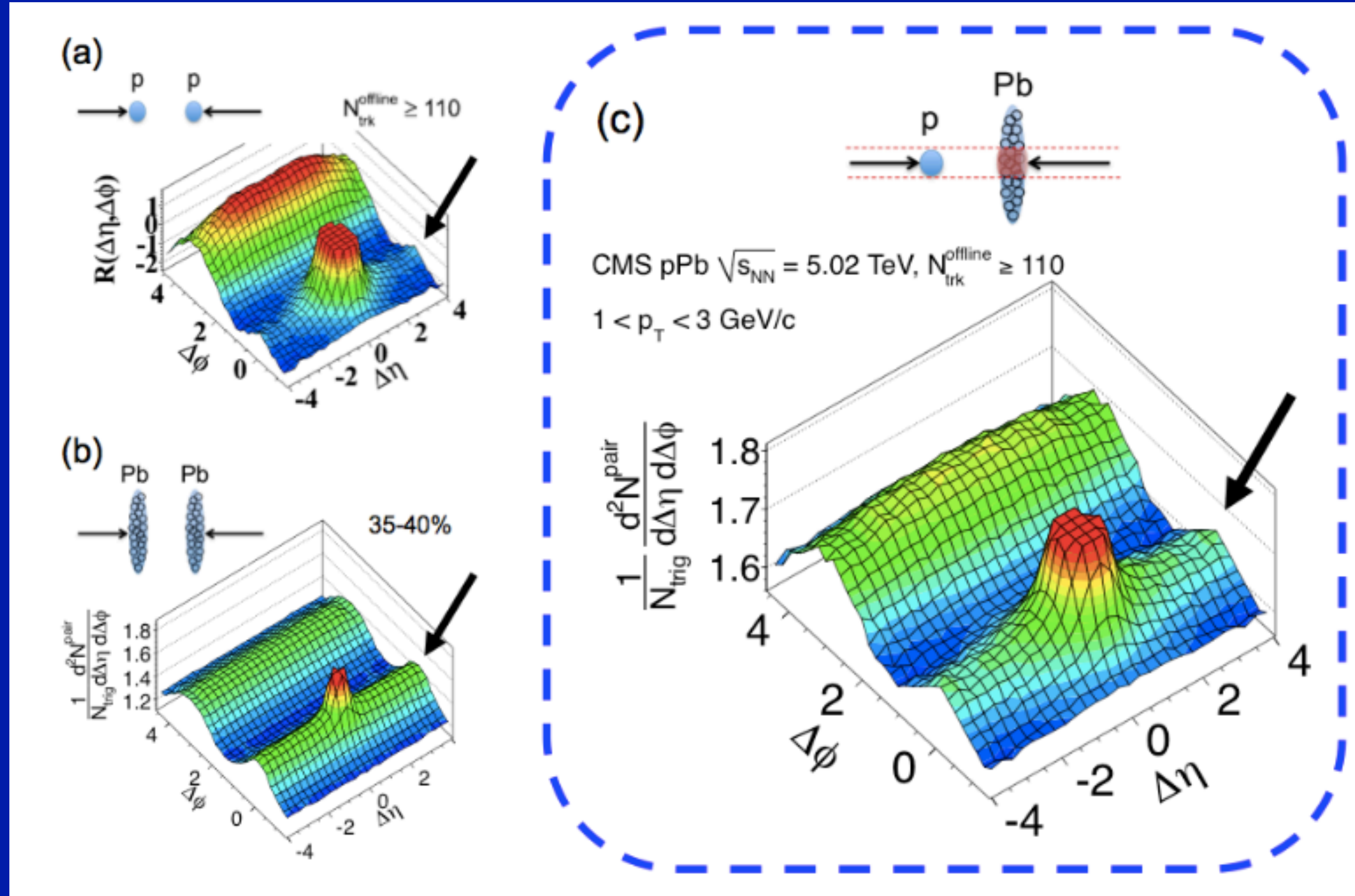
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Low η/s (shear viscosity) means strong coupling
—> QGP is not a hot gas composed of partons moving freely (as initially thought)



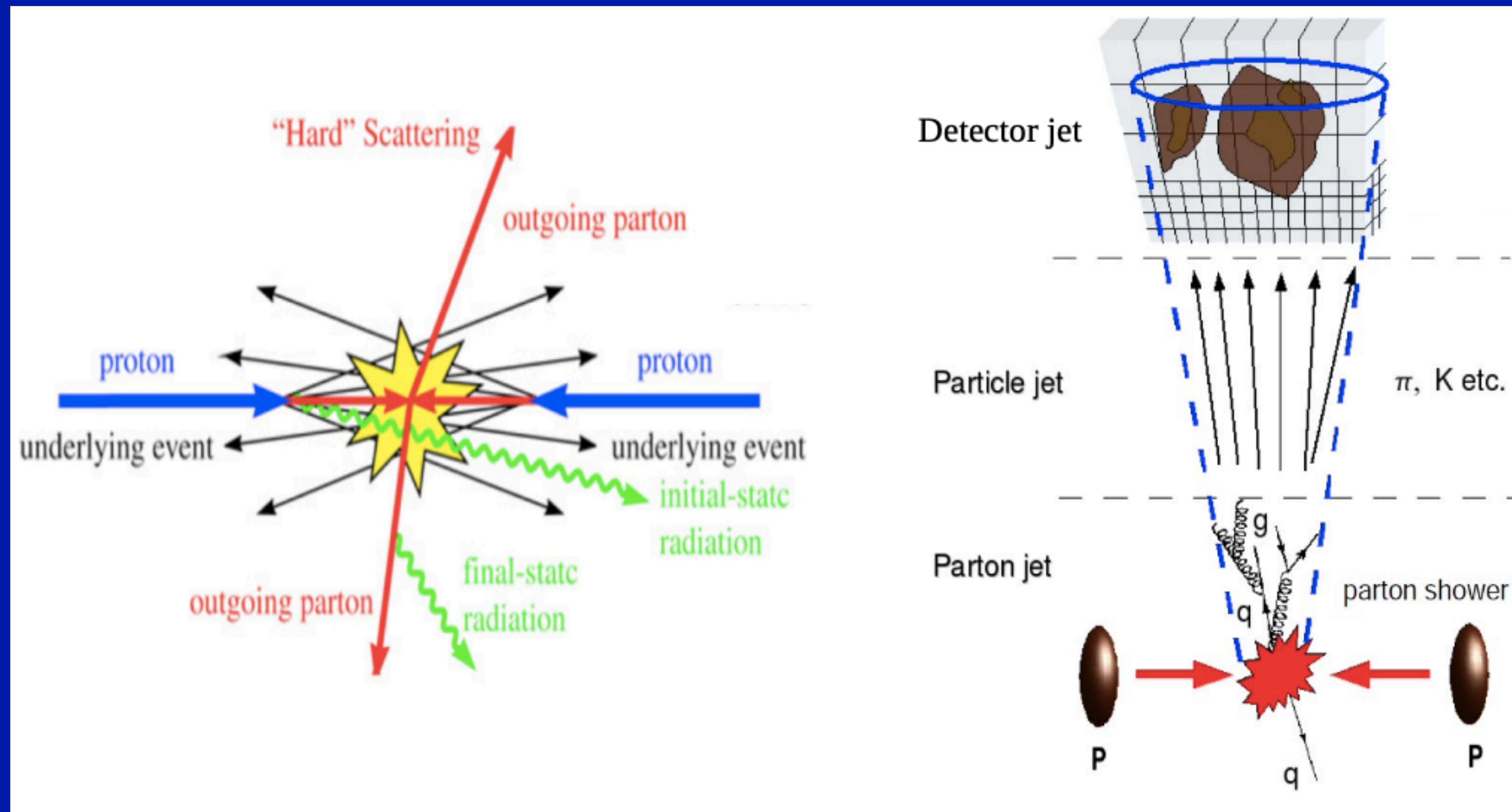
In pp data, these correlations are observed only in extremely rare events—those where a single proton-proton collision produces an unusually high particle density.



The effect in pPb collisions is much stronger than in pp collisions.

The ridge remains in small collision systems: pp and pPb
Not fully understood

Jets are among the most powerful tools for studying QCD. They result from hard scattering processes involving large momentum transfers between two partons



Tracks in the Inner Detector and clusters in the calorimeters

Non-Perturbative Regime

calculable using perturbative QCD

Jets are among the most powerful tools for studying QCD. They result from hard scattering processes involving large momentum transfers between two partons

Need to define the jet, i.e., decide which particles should be part of the jet

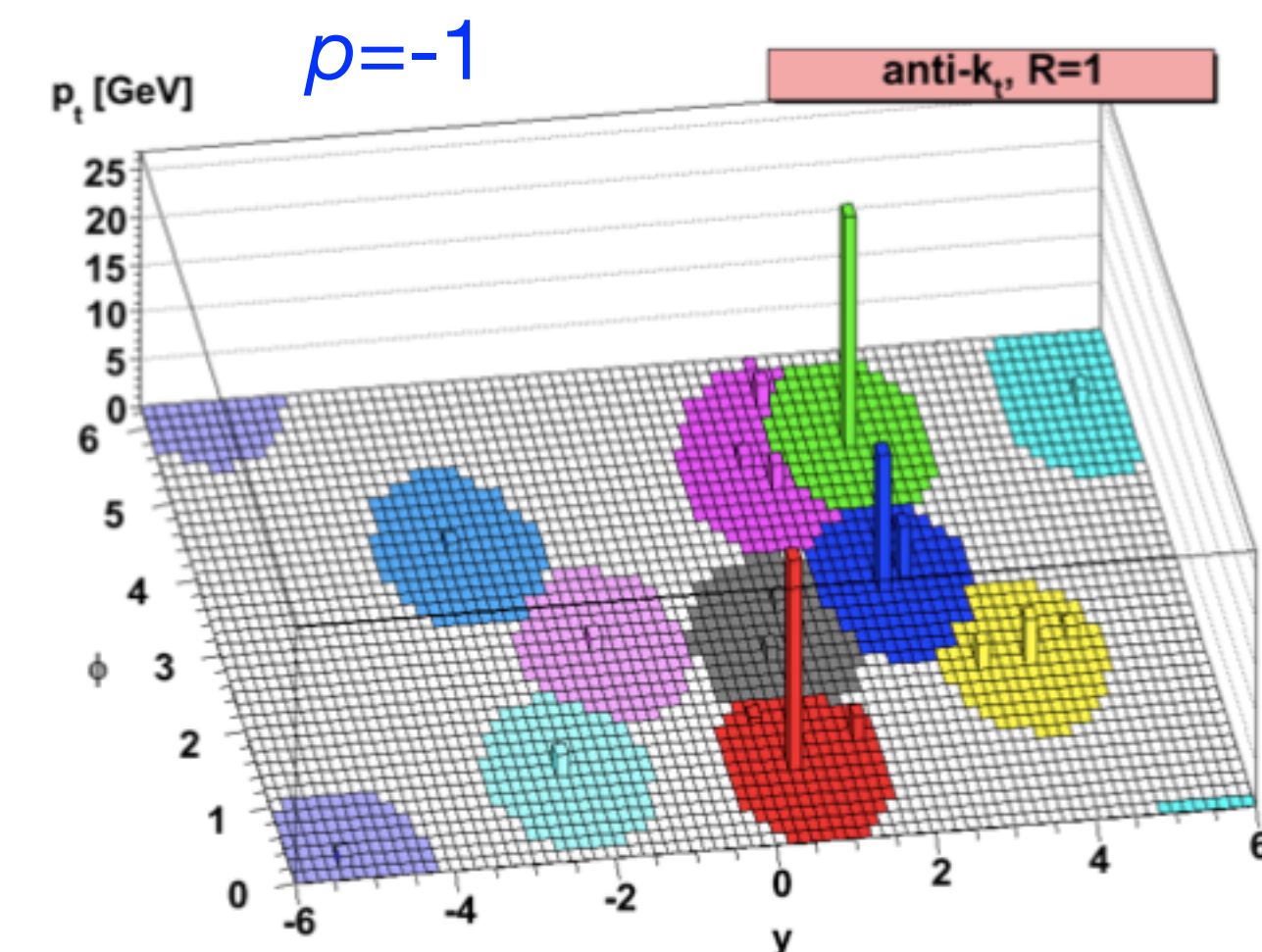
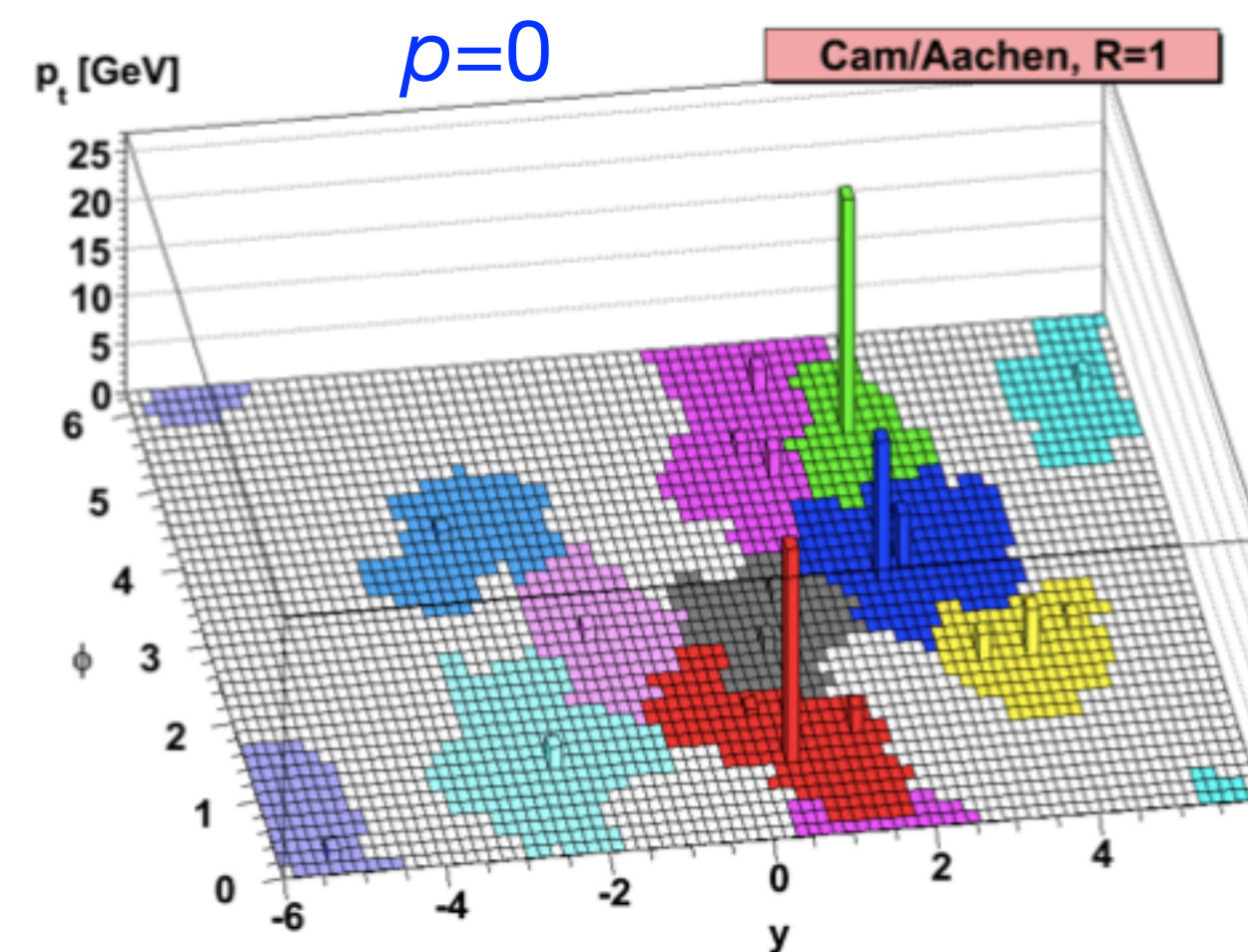
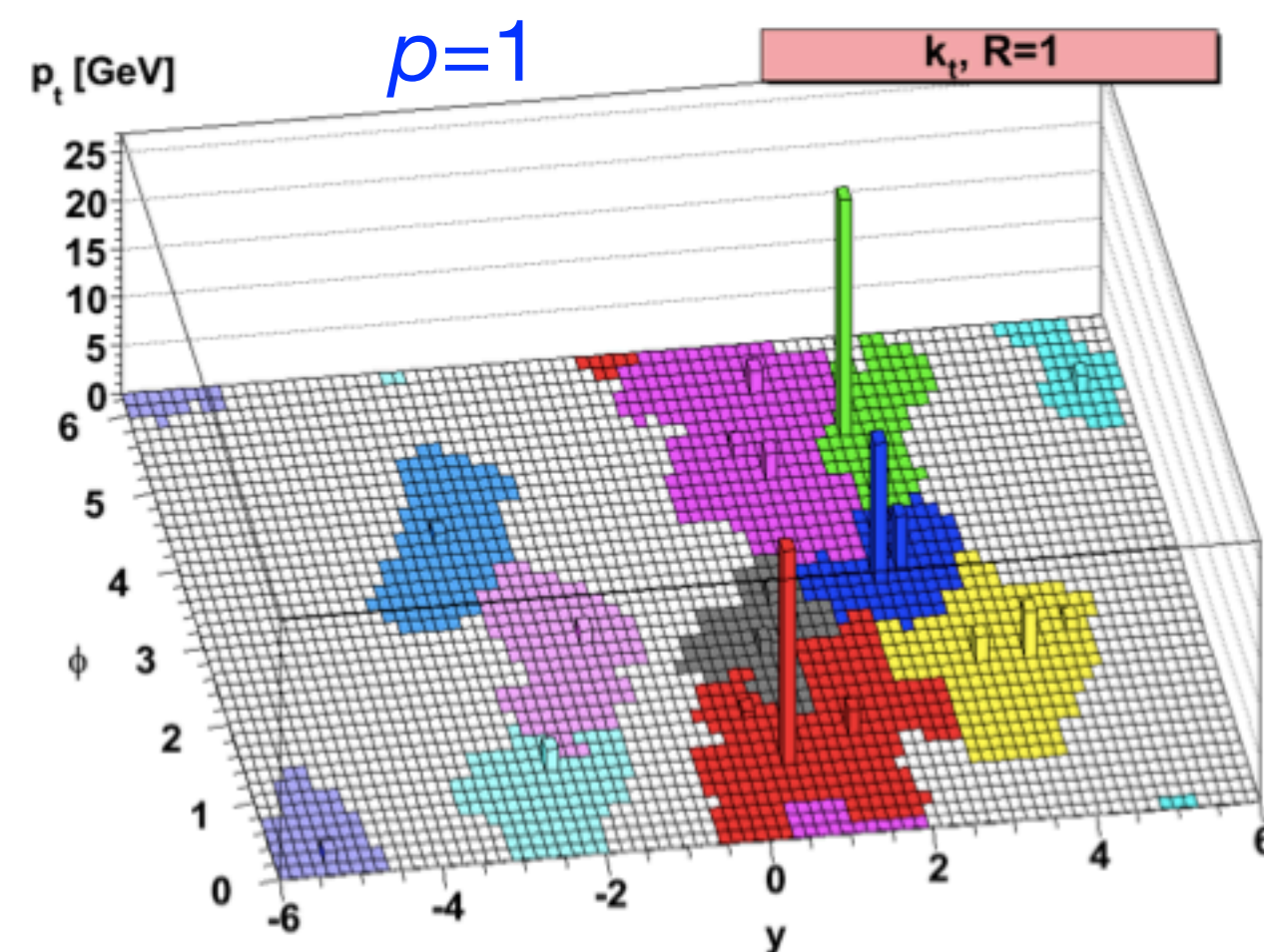
JHEP 0804:063,2008

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

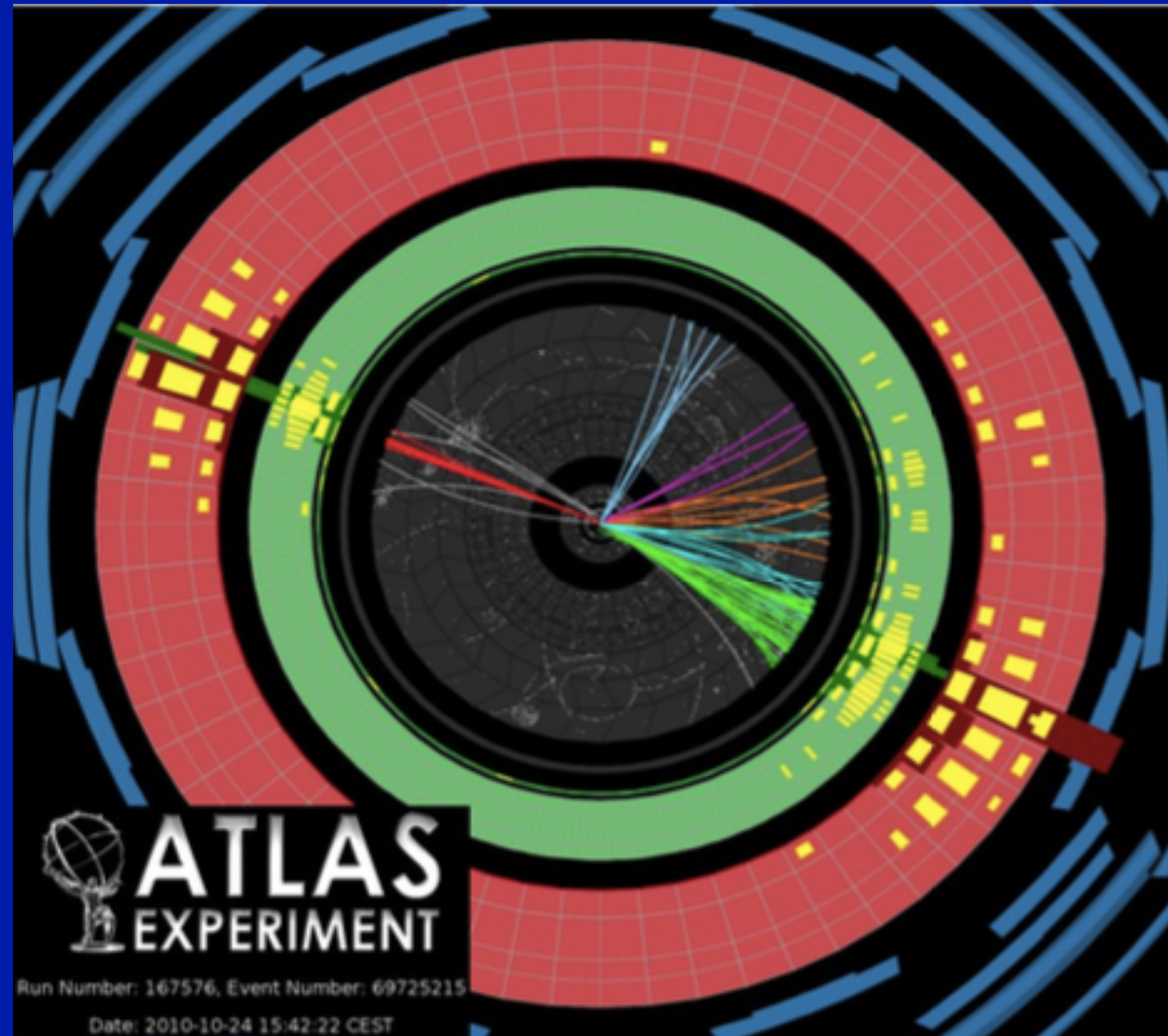
$$d_{iB} = k_{ti}^{2p}, \quad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Jet size runs from $R = 0.2 \dots 1.0$ (R defines how close in the η, ϕ plane particles need to be to get clustered into the same jet)

Depending on the value of the parameter p , a different jet is reconstructed. For most of the analyses in LHC experiments, $p=-1$ is chosen \rightarrow the so called anti- k_t jet clustering algorithm.



At leading order of QCD, two jets are produced back-to-back in the azimuthal plane ($\Delta\phi=\pi$), with equal transverse momenta.

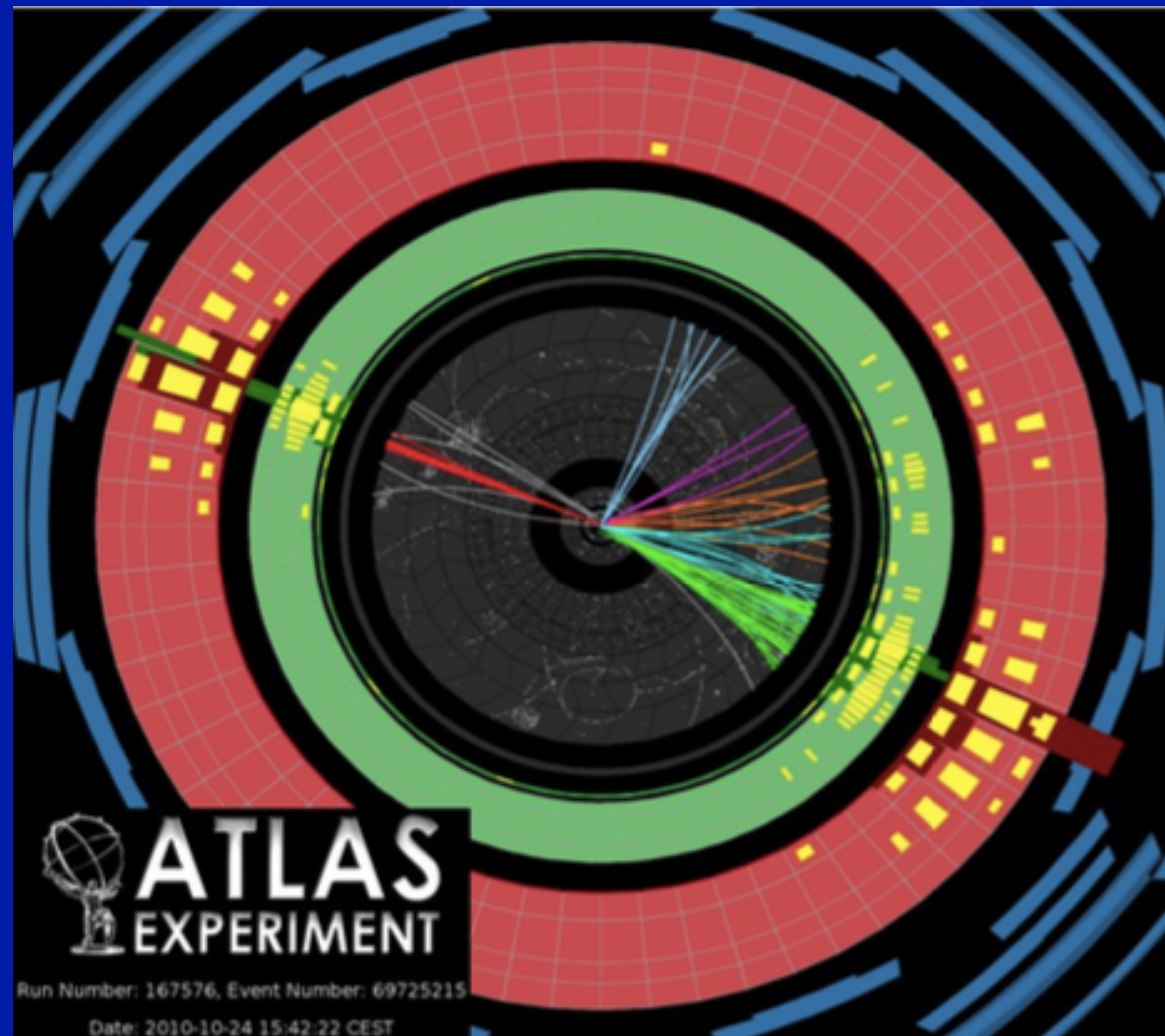


The event displays shows two well balanced jets produced in pp collisions at LHC

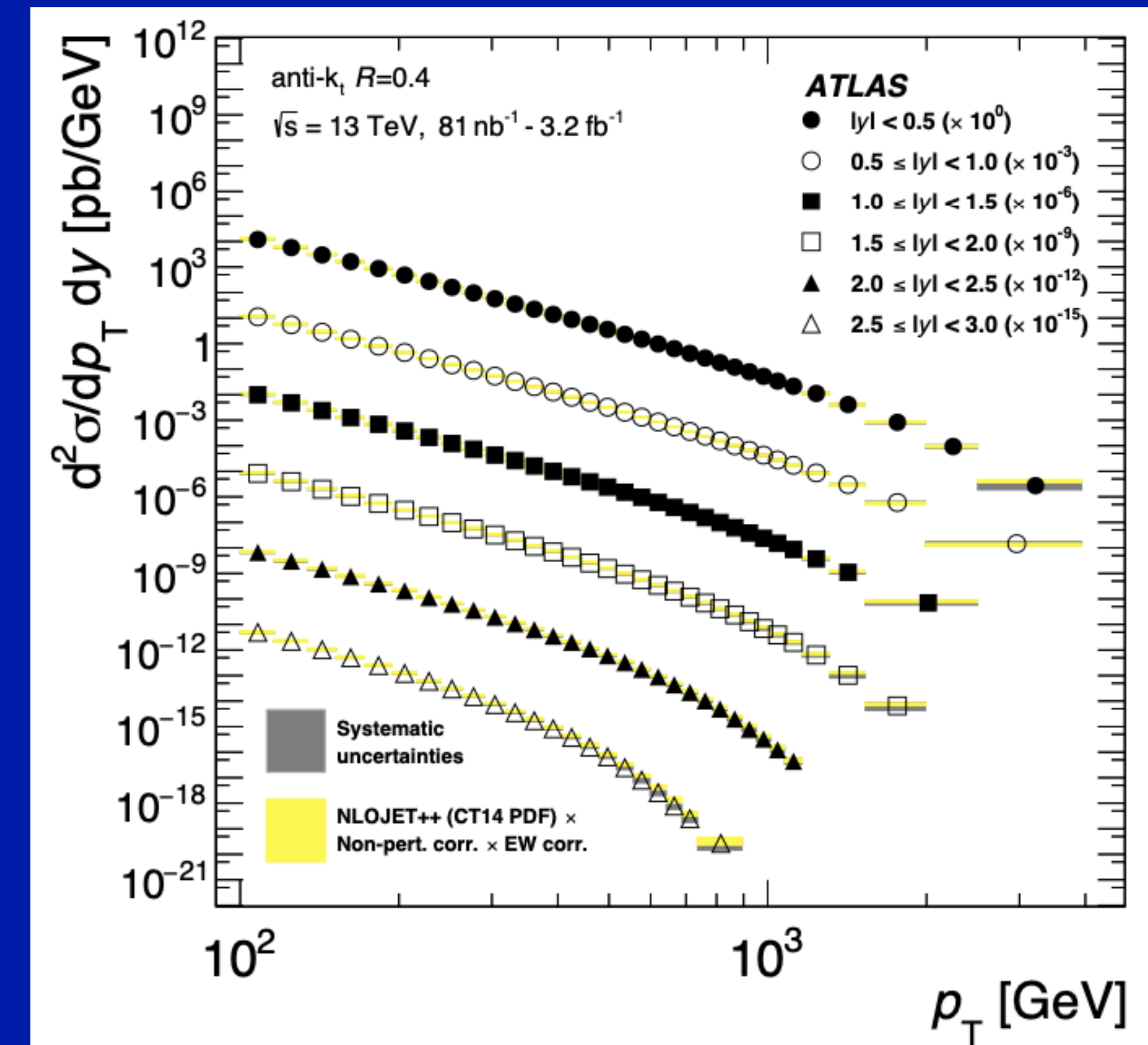
Leading jet : $p_T = 1.3$ TeV, $\eta = 0.2$, $\phi = -0.5$

Sub-leading jet: $p_T = 1.2$ TeV, $\eta = 0.0$, $\phi = 2.8$

At leading order of QCD, two jets are produced back-to-back in the azimuthal plane ($\Delta\phi=\pi$), with equal transverse momenta.

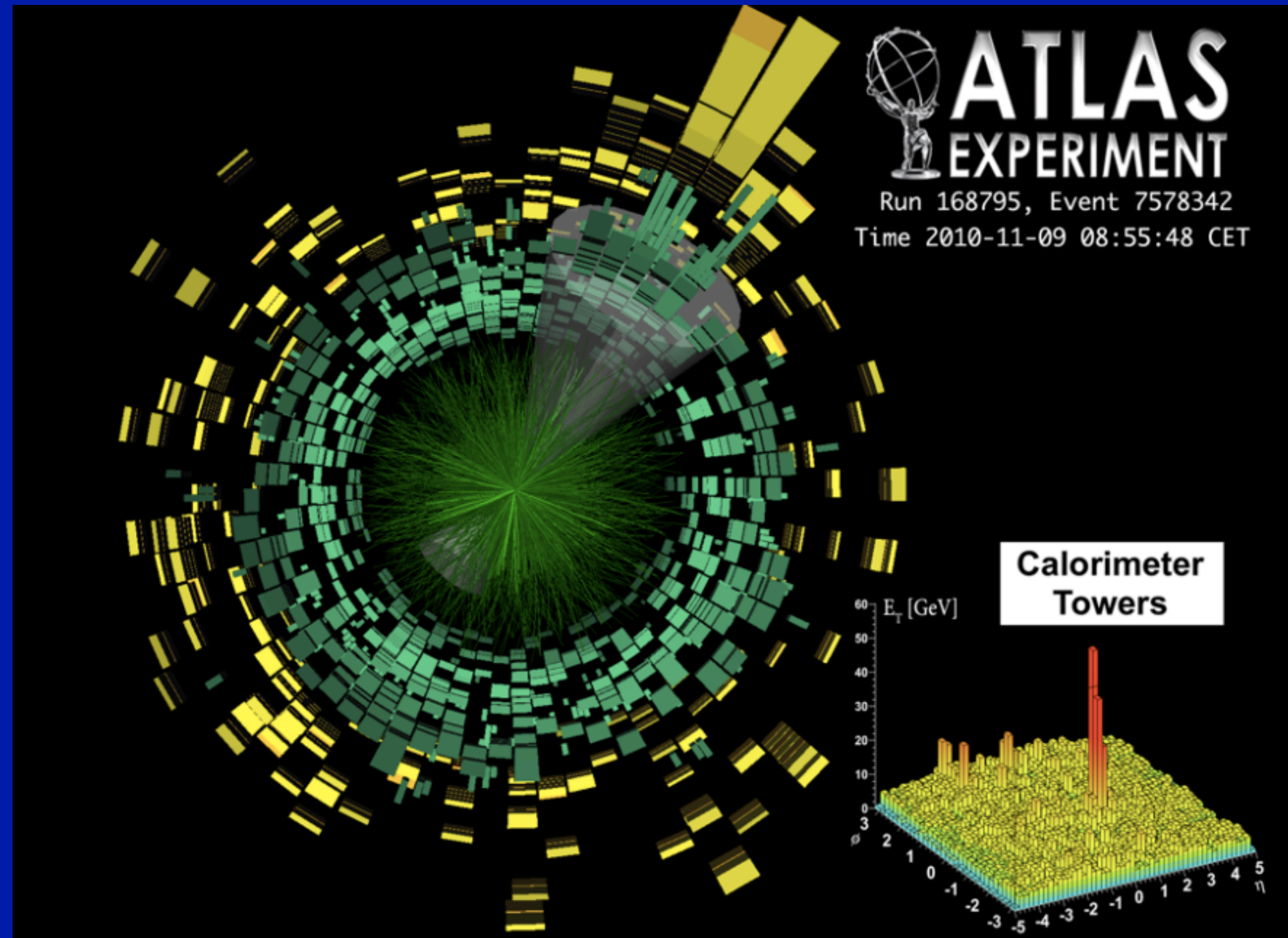


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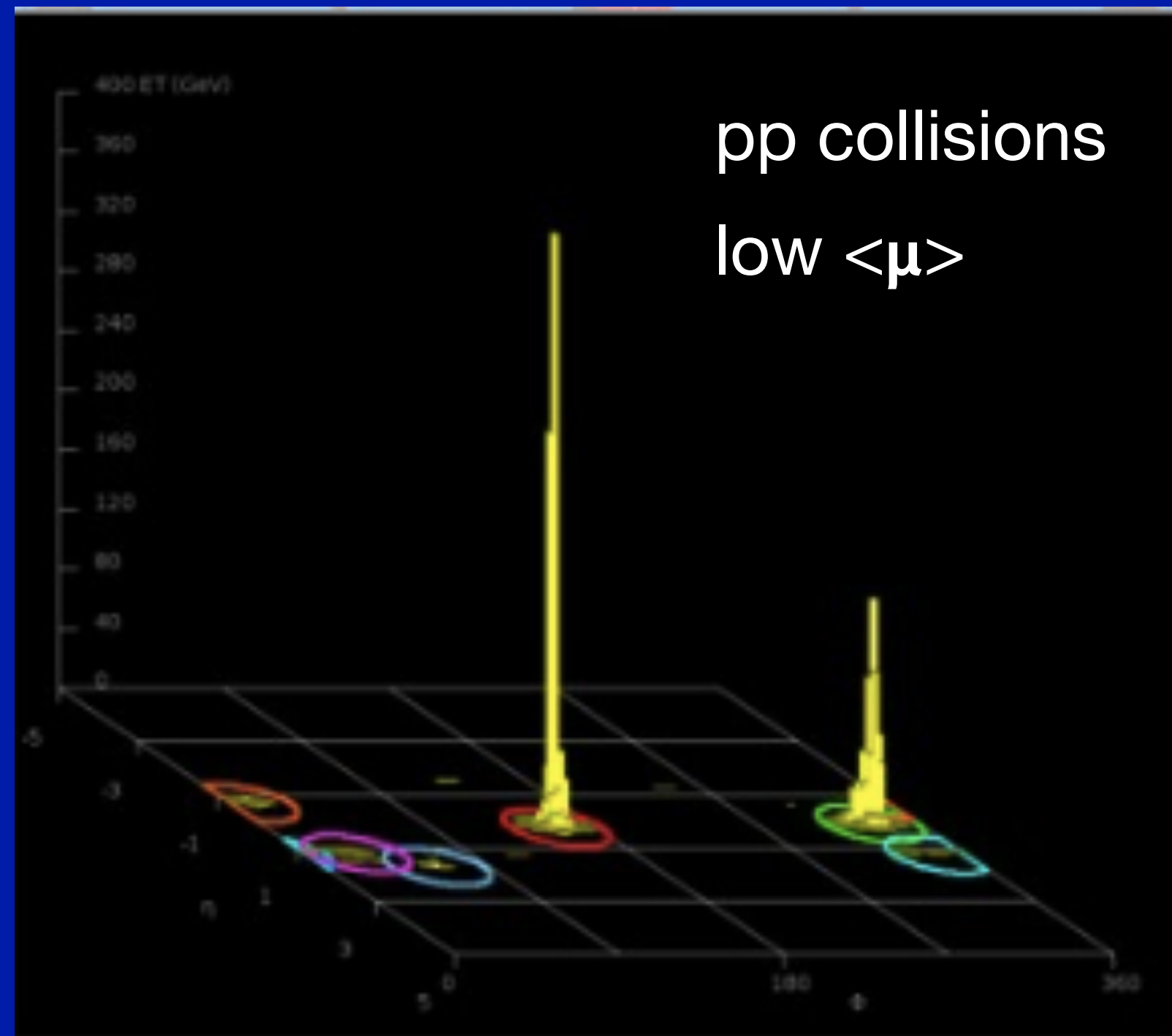
Jet production at LHC pp collisions is well understood over 9 orders of magnitude and up to 3 TeV

But dijets at Pb+Pb collisions are largely asymmetric \rightarrow “Jet Quenching”

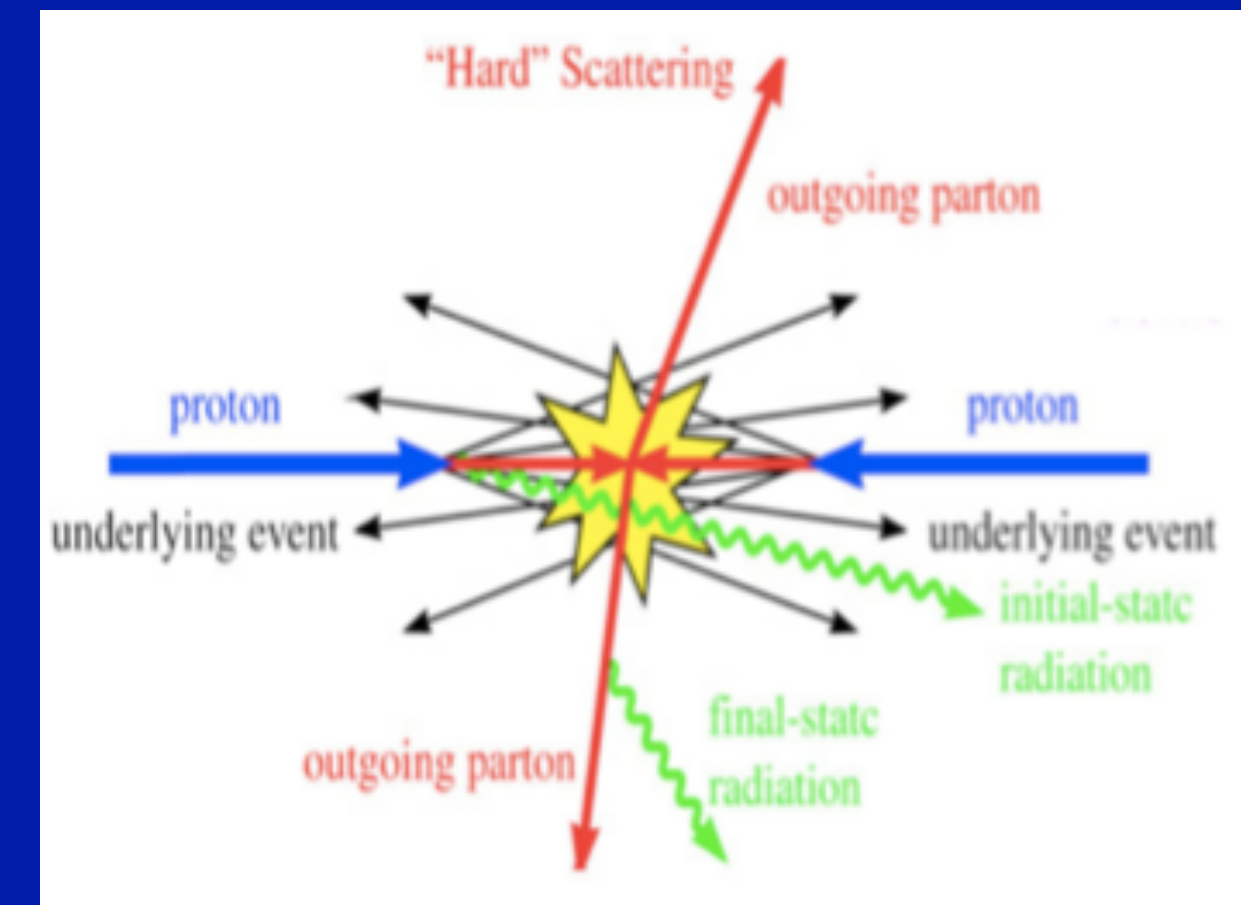


Jet quenching is the modification of the parton showers in the QGP. The partons lose energy while traversing it.

Event seen by the Calorimeters

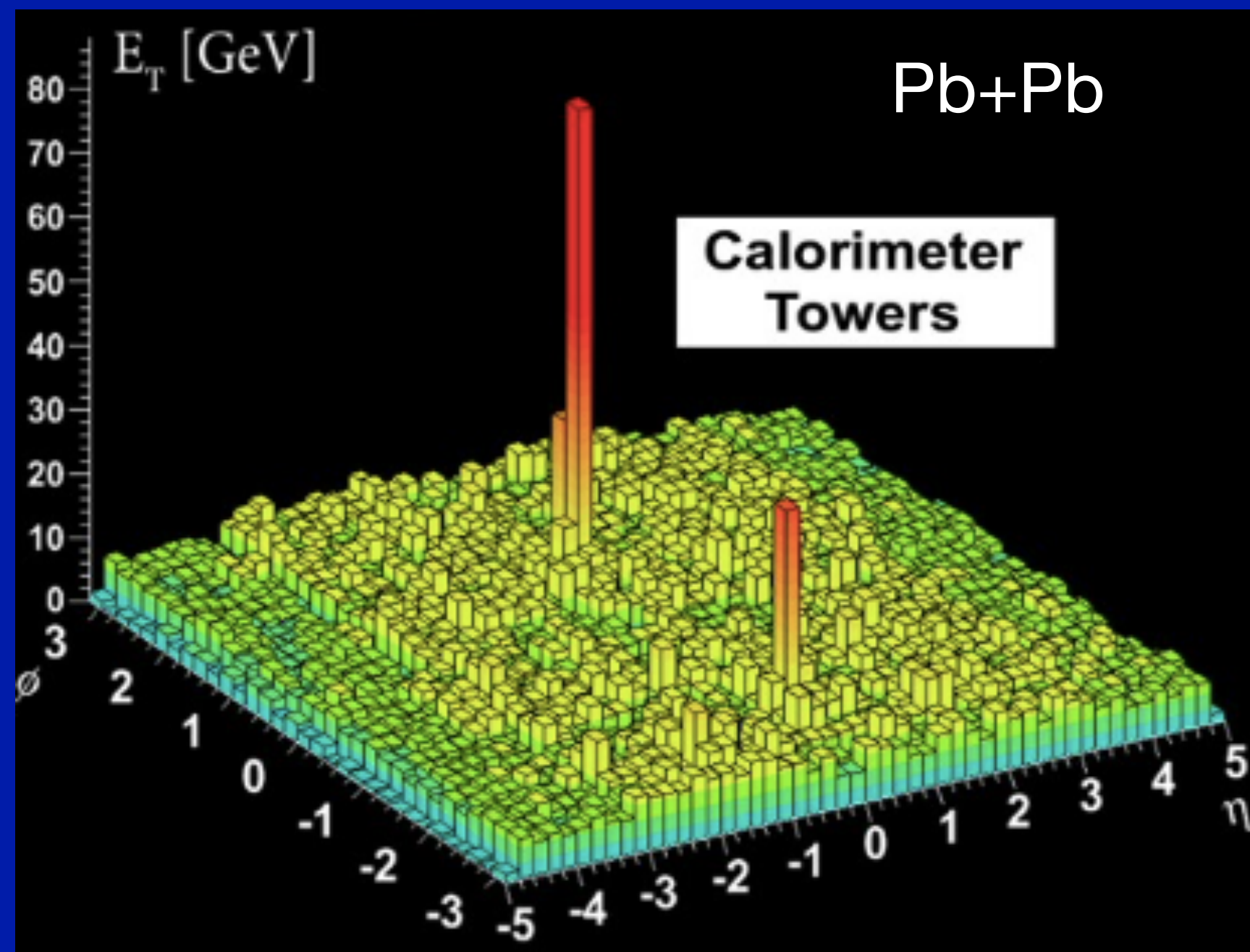


Granularity of the ATLAS calorimeters:
 $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ “towers” (piled calorimeter cells)

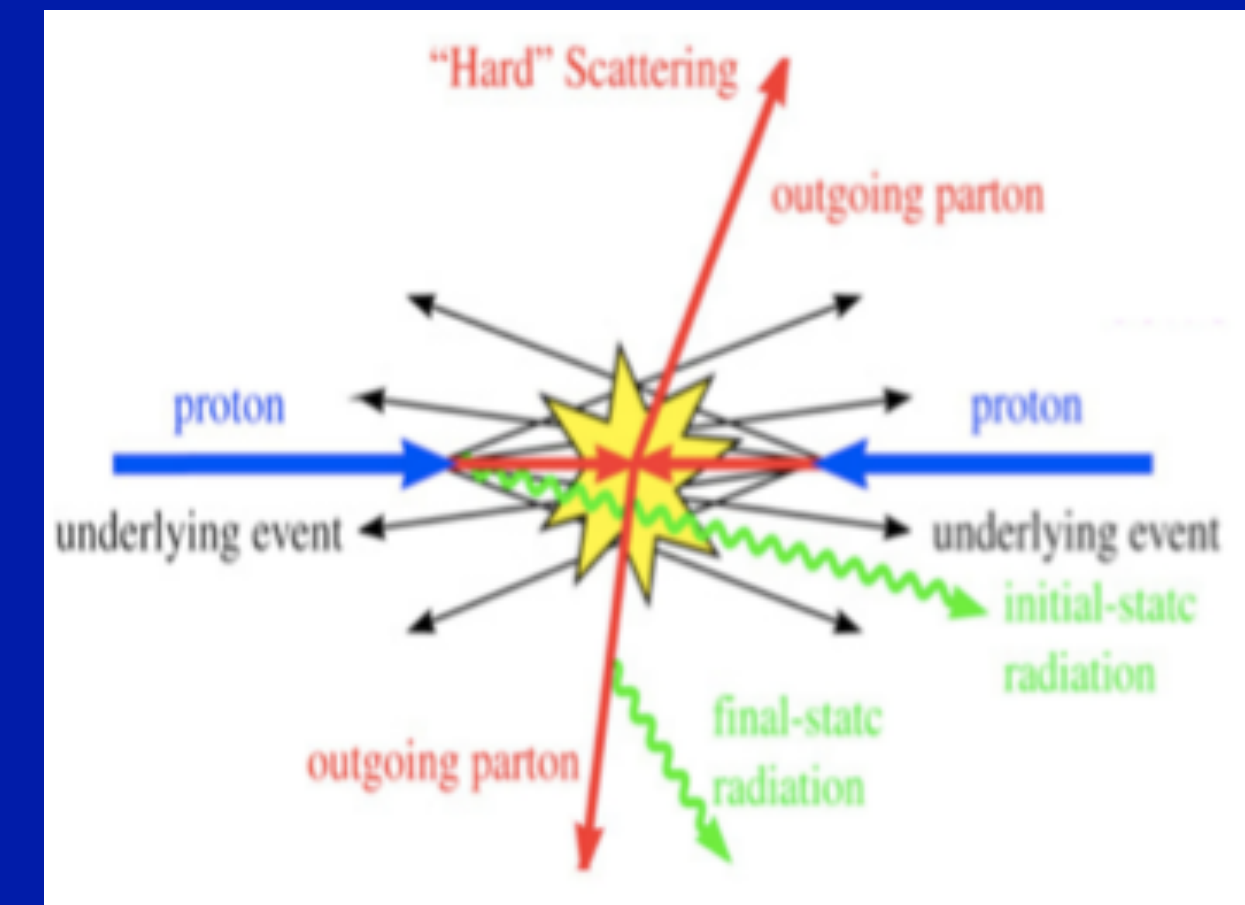


- 1 - The jets are initiated by the two outgoing partons (“the signal”), but the other partons also interact and radiate gluons.
- 2 - They form the “Underlying Event” (the “background”)

Event seen by the Calorimeters



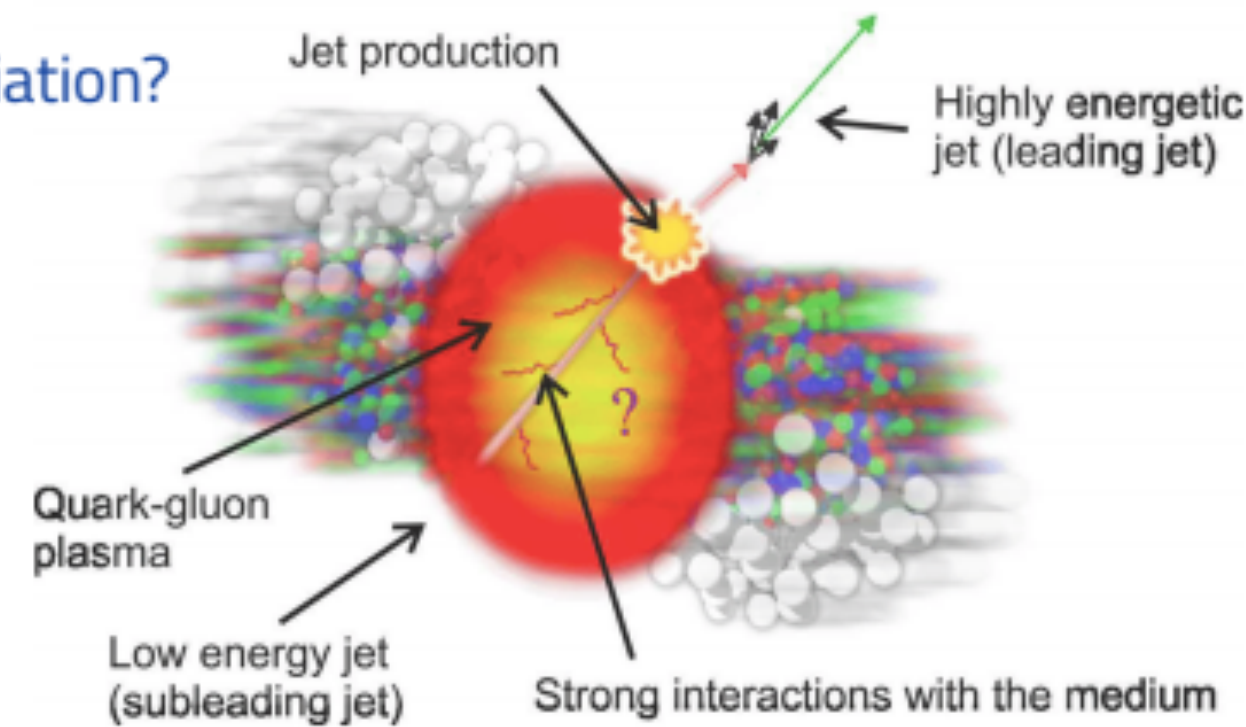
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- 1 - The jets are initiated by the two outgoing partons (“the signal”), but the other partons also interact and radiate gluons.
- 2 - They form the “Underlying Event” (the “background”)
- 3 - In Pb+Pb central collisions this process is huge, and the whole calorimeter gets uniformly populated.
- 4 – This “pedestal” must be subtracted in order for the jets to be correctly reconstructed.

- Distinguish the nature of the energy loss

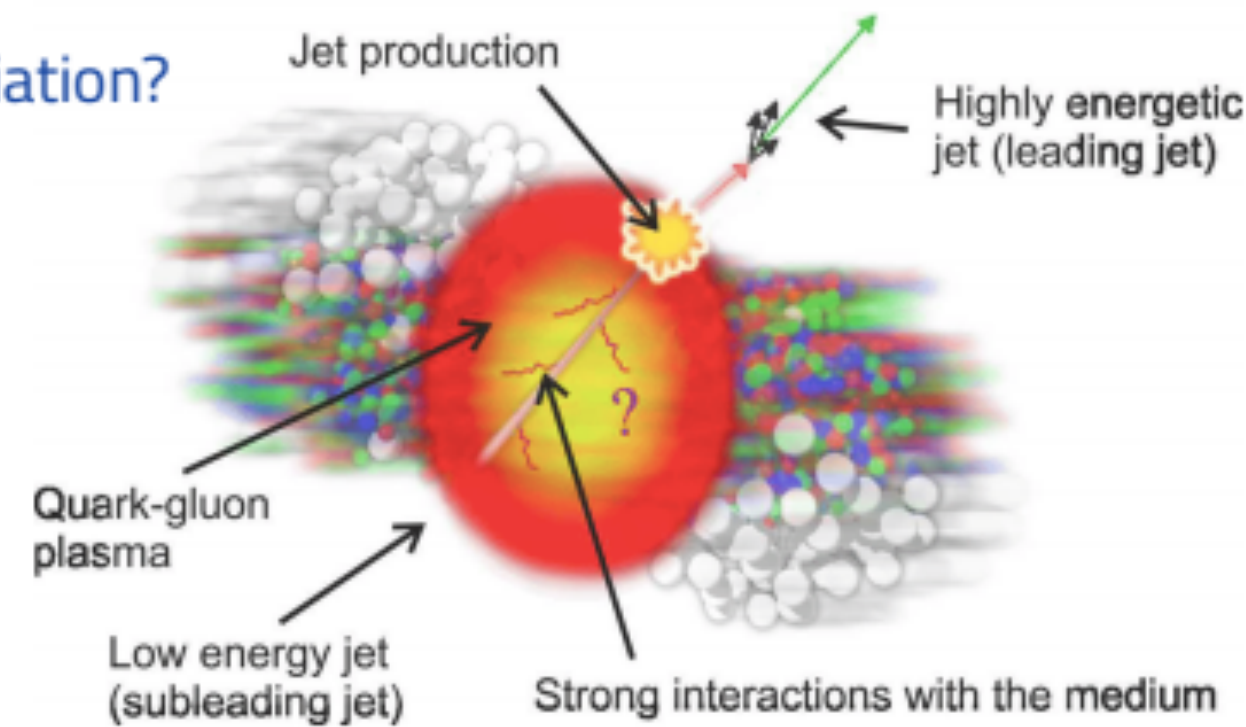
- Collisional?
- Radiation?



In head-on Pb+Pb collisions, the QGP forms. The figure shows an extreme dijet production scenario at the periphery of the fireball: one jet escapes untouched (like jets in pp collisions), while the other traverses the QGP, losing energy and having its substructure modified.

- Distinguish the nature of the energy loss

- Collisional?
- Radiation?

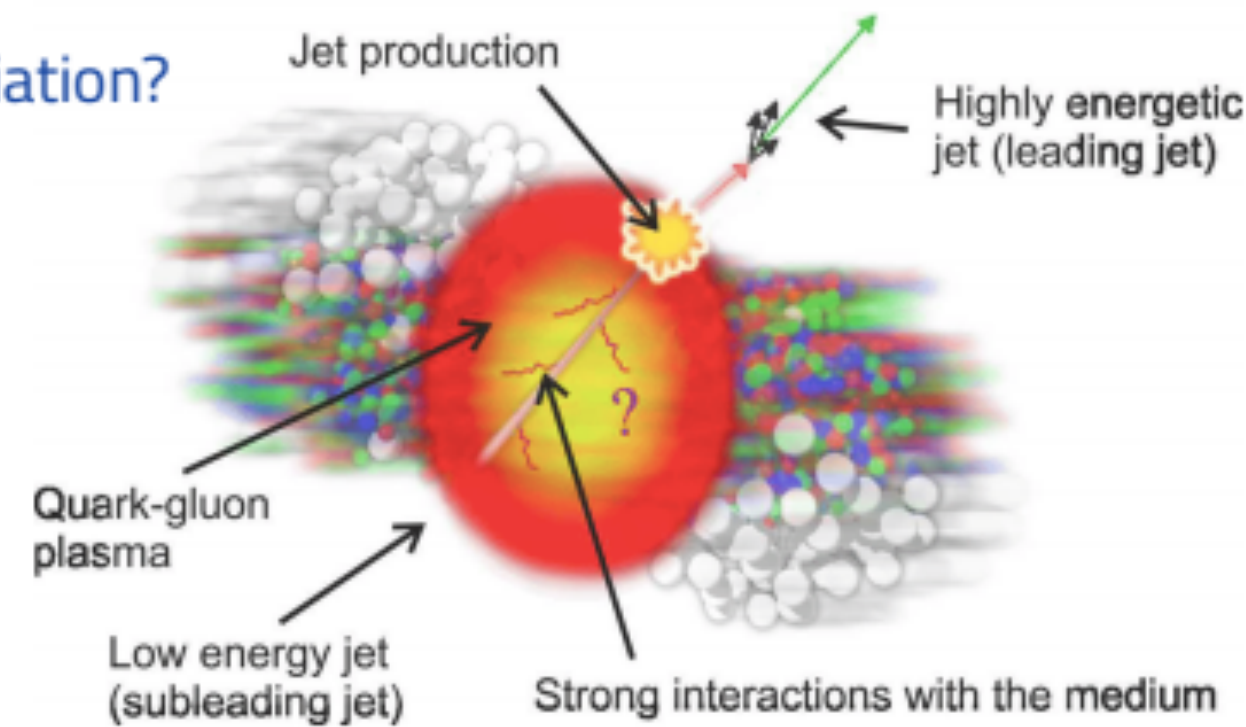


In head-on Pb+Pb collisions, the QGP forms. The figure shows an extreme dijet production scenario at the periphery of the fireball: one jet escapes untouched (like jets in pp collisions), while the other traverses the QGP, losing energy and having its substructure modified.

By studying how jets lose energy—whether through collisions or radiation—as they pass through the quark-gluon plasma, we can probe the properties of this extreme state of matter.

- Distinguish the nature of the energy loss

- Collisional?
- Radiation?



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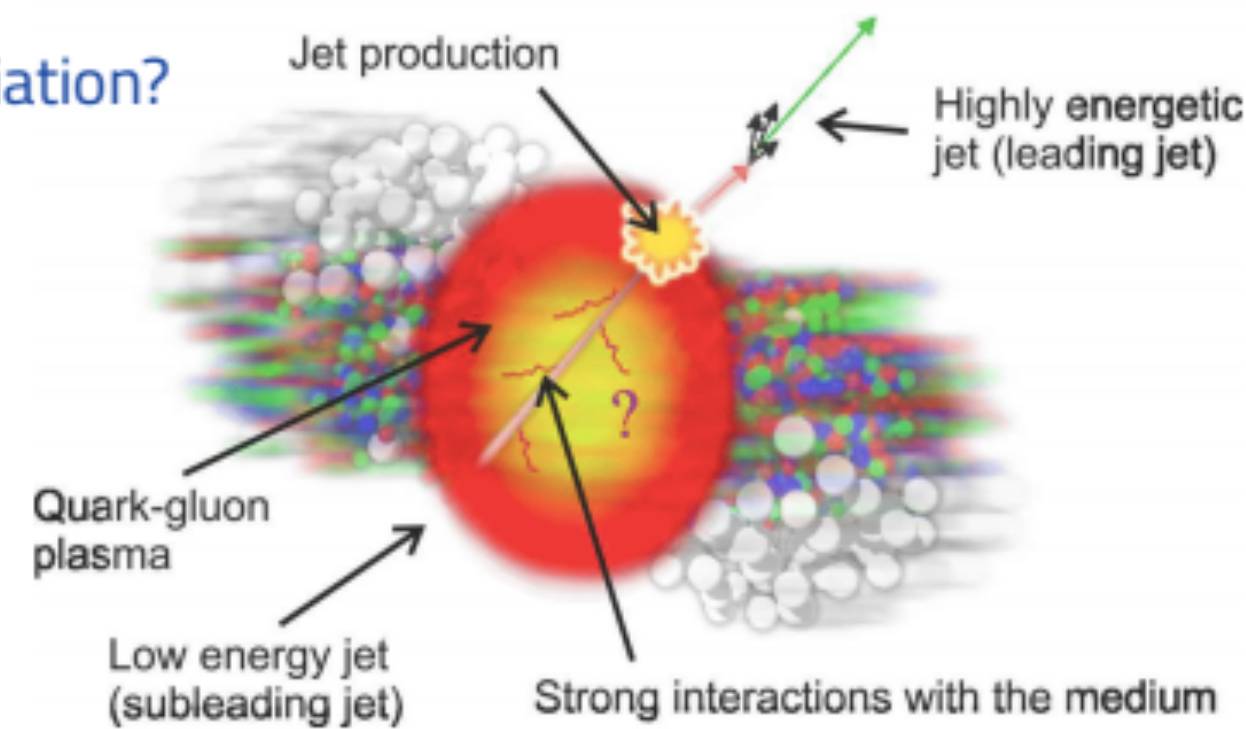
Collisional energy loss depends on the temperature and density of the QGP - how often the jet partons scatter with the medium's quarks and gluons. Studying it will tell us about :

- medium's momentum transport properties (related to viscosity)
- density of particles in the QGP

- Distinguish the nature of the energy loss

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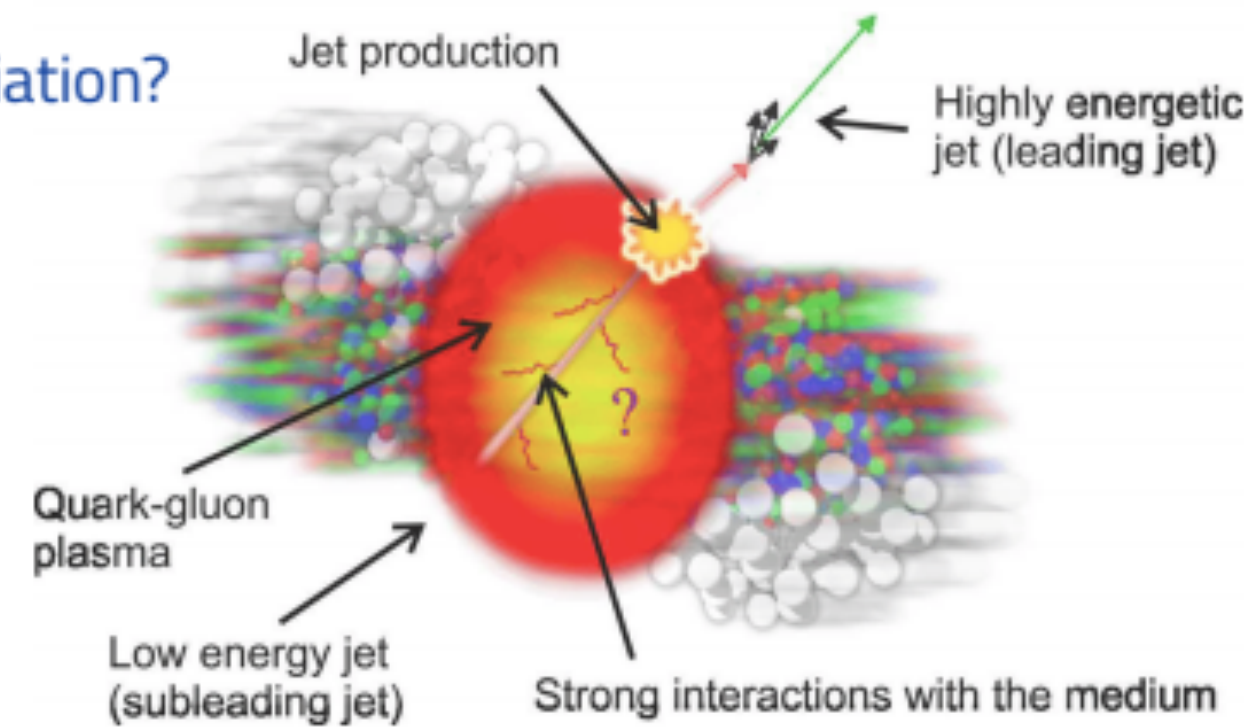
- medium's momentum transport properties (related to viscosity)
- density of particles in the QGP

Radiative energy loss depends on the the medium's colour field strength and the coherence length over which gluons can be radiated. It will tell us about:

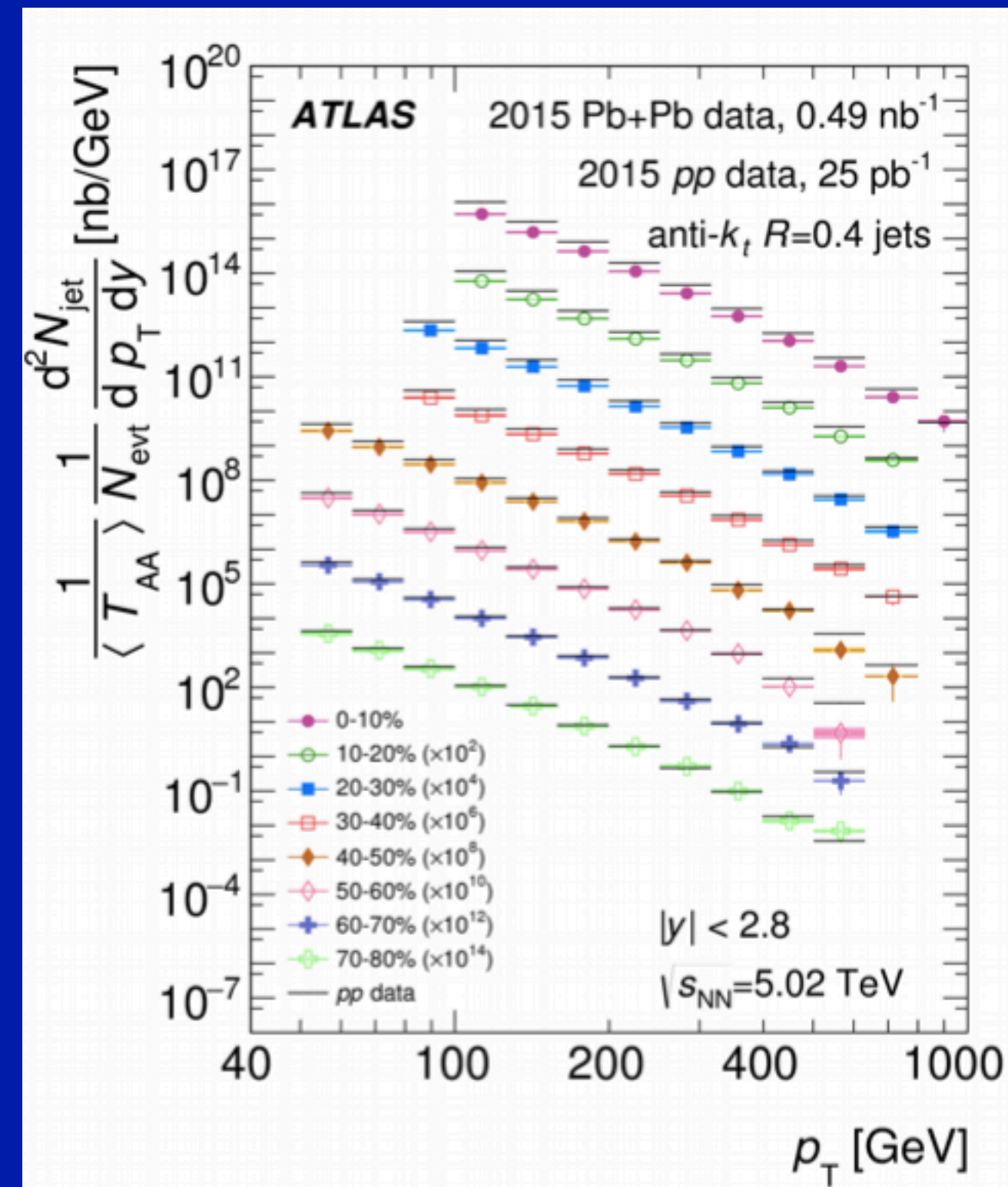
- The colour charge density
- The jet quenching parameter \hat{q} , which characterizes how much momentum the medium transfers to a fast parton per unit length

- Distinguish the nature of the energy loss

- Collisional?
- Radiation?



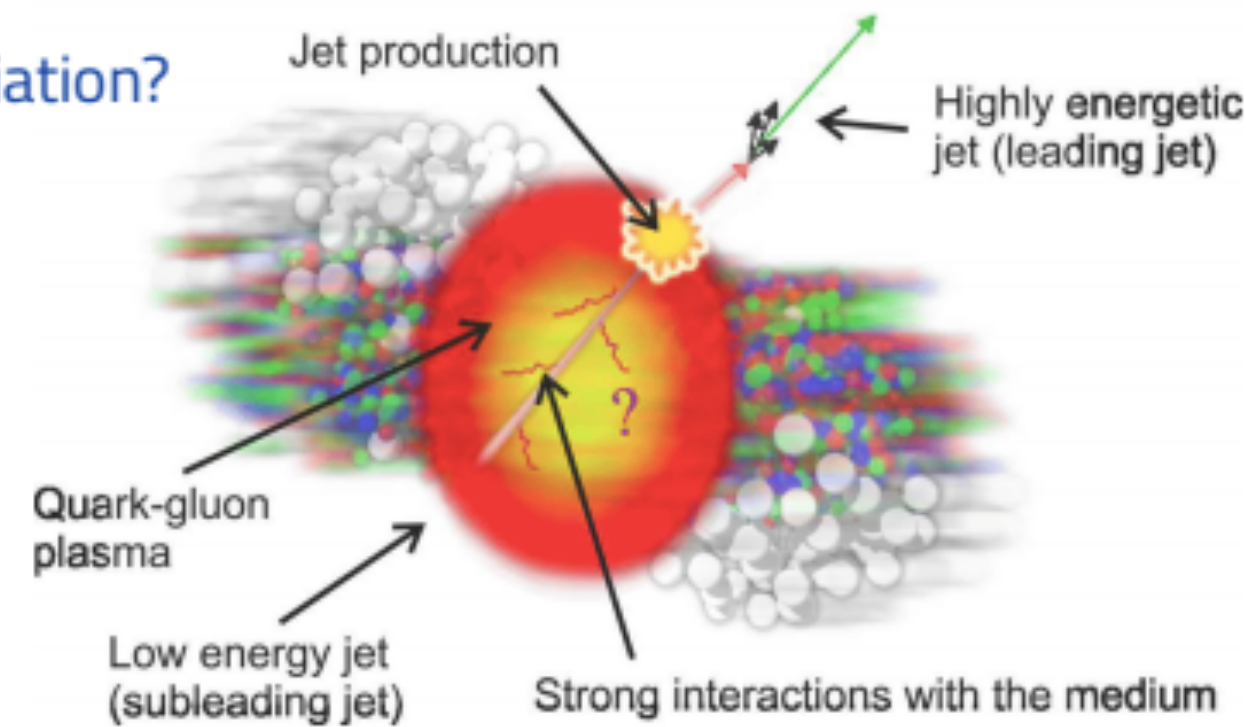
Inclusive jet production in Pb+Pb and pp



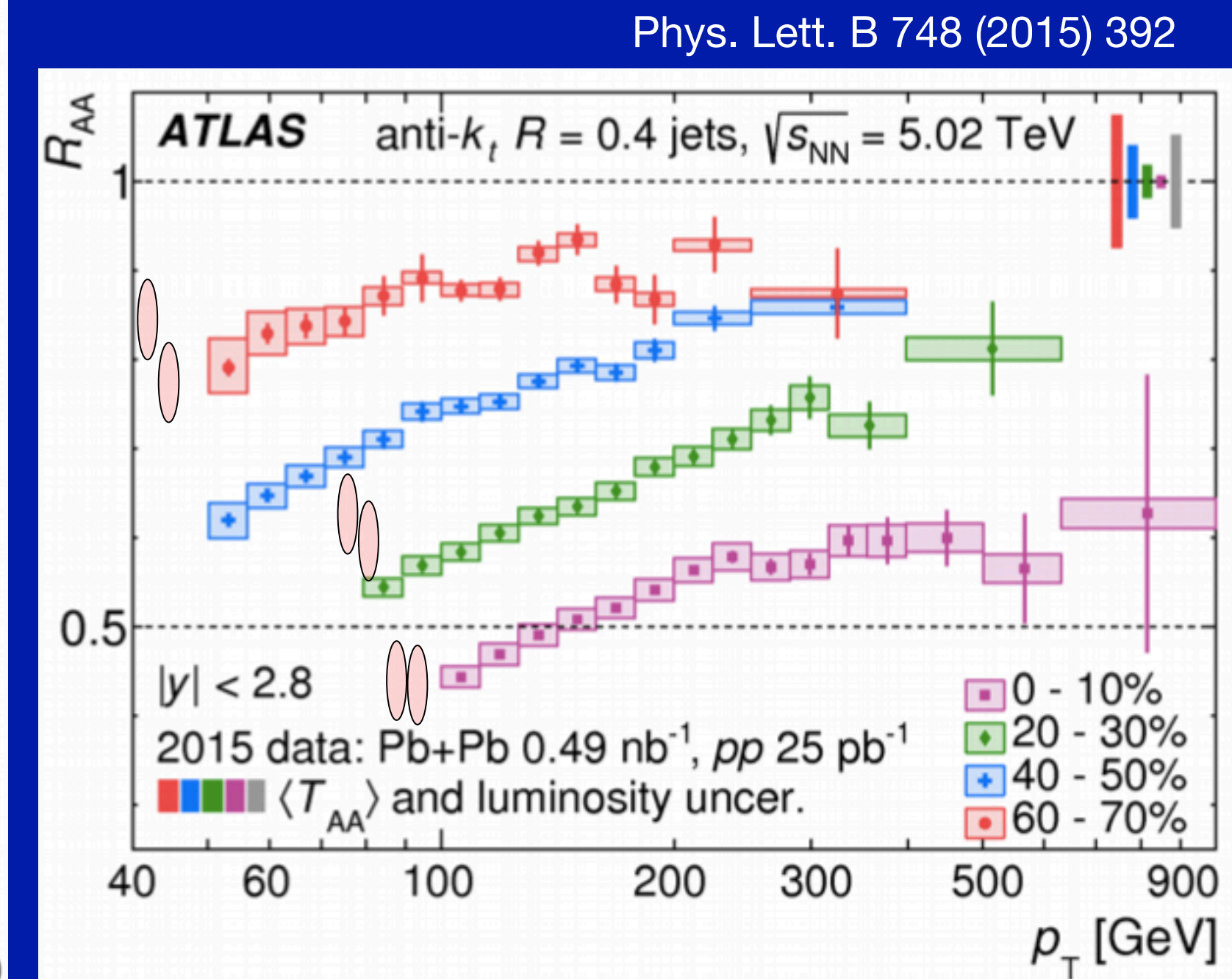
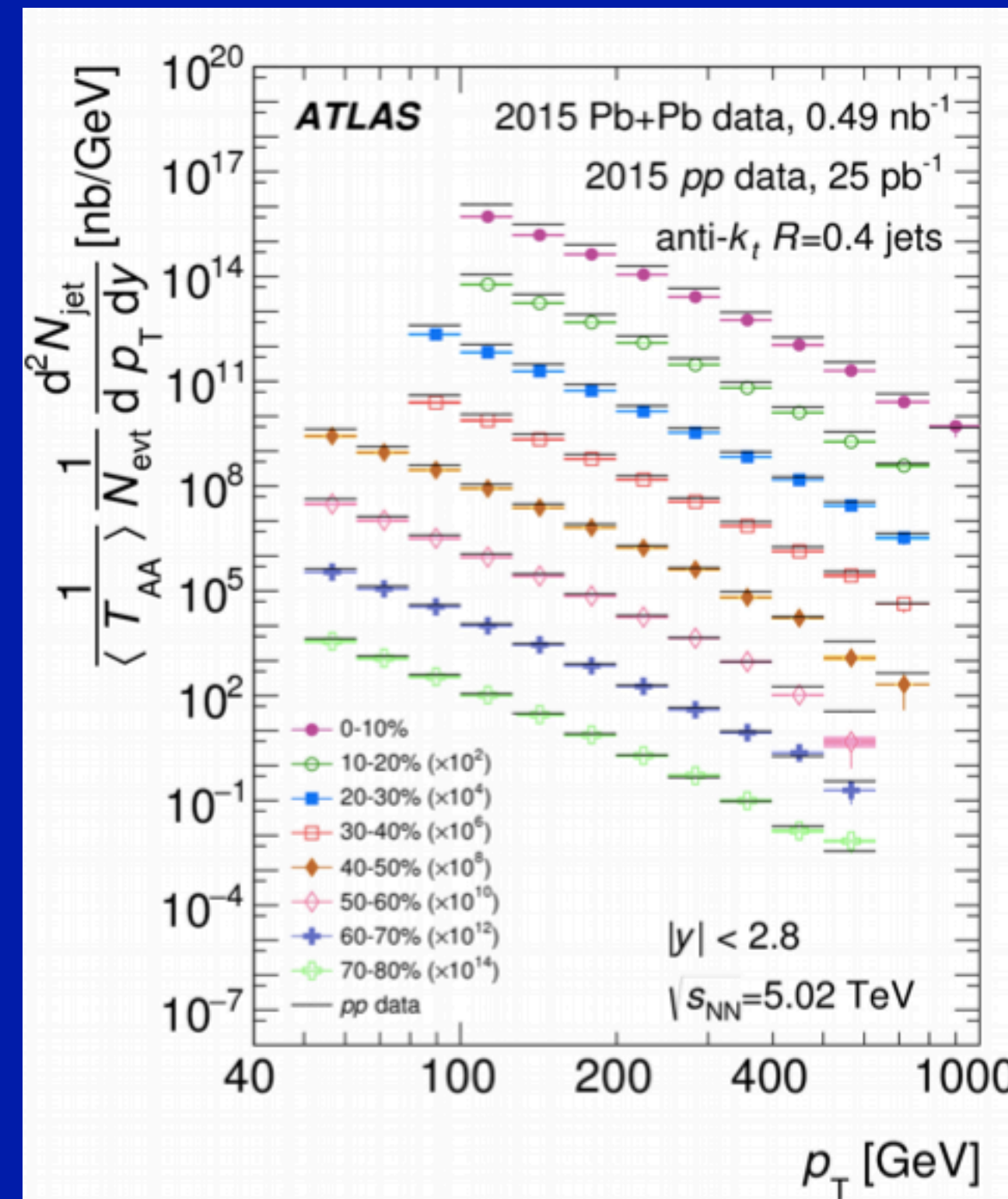
- Distinguish the nature of the energy loss

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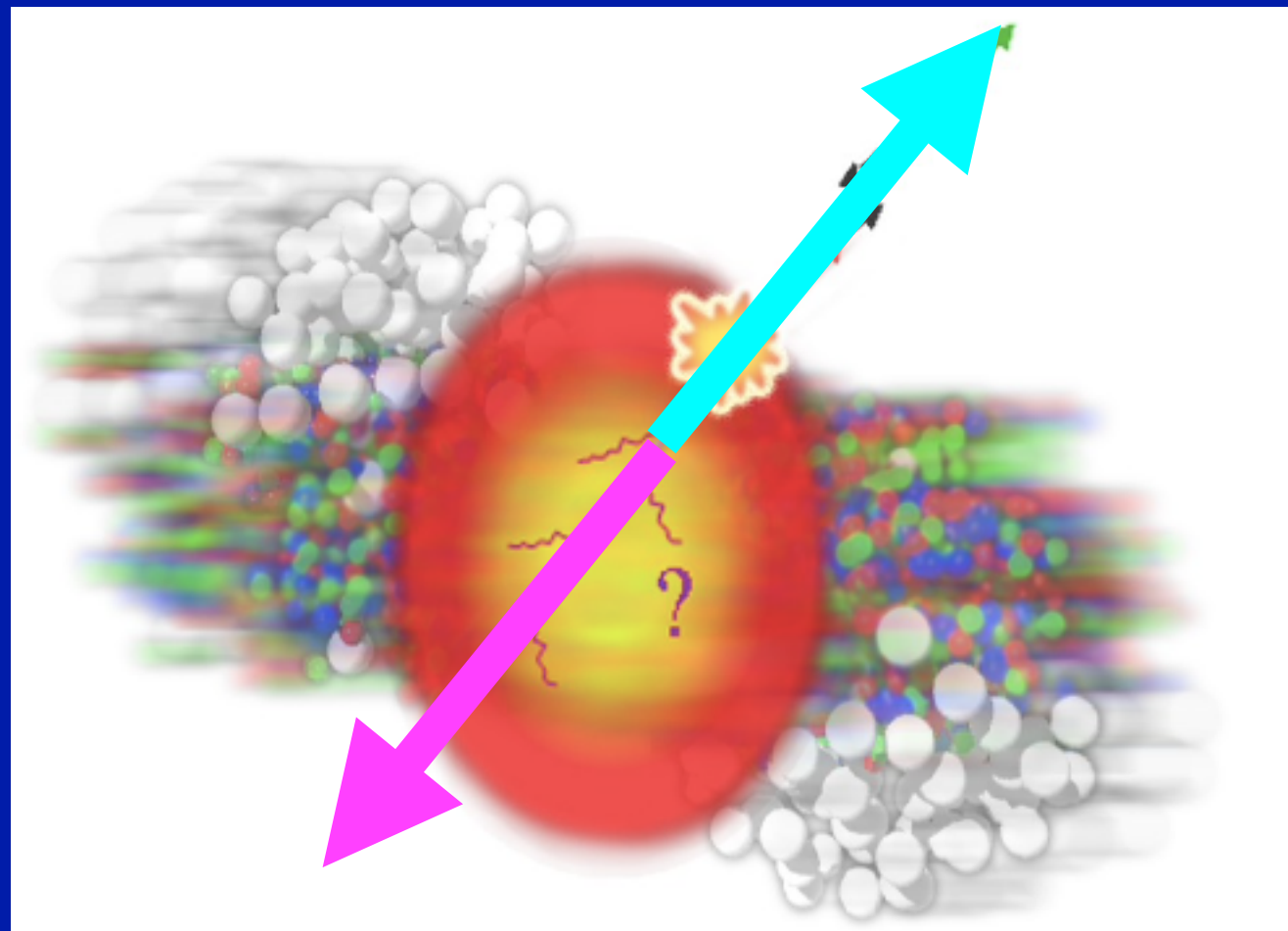


Inclusive jet production in Pb+Pb and pp



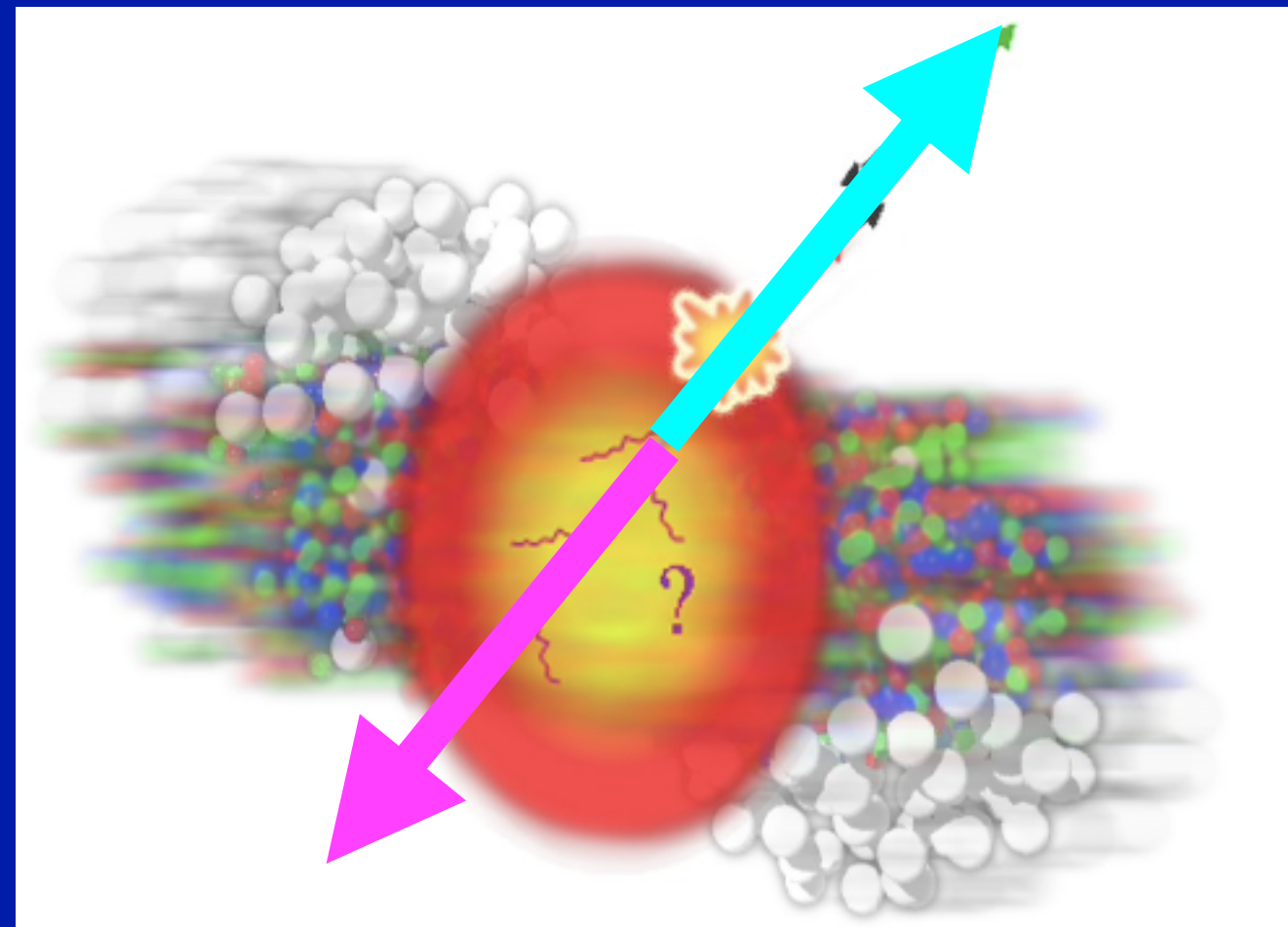
- Jets are suppressed by a factor of two in central (0-10%) Pb+Pb collisions with clear dependence on transverse momentum, p_T .
- Peripheral collisions (60 – 70%) show also significant suppression.

How to calibrate jet energy loss?

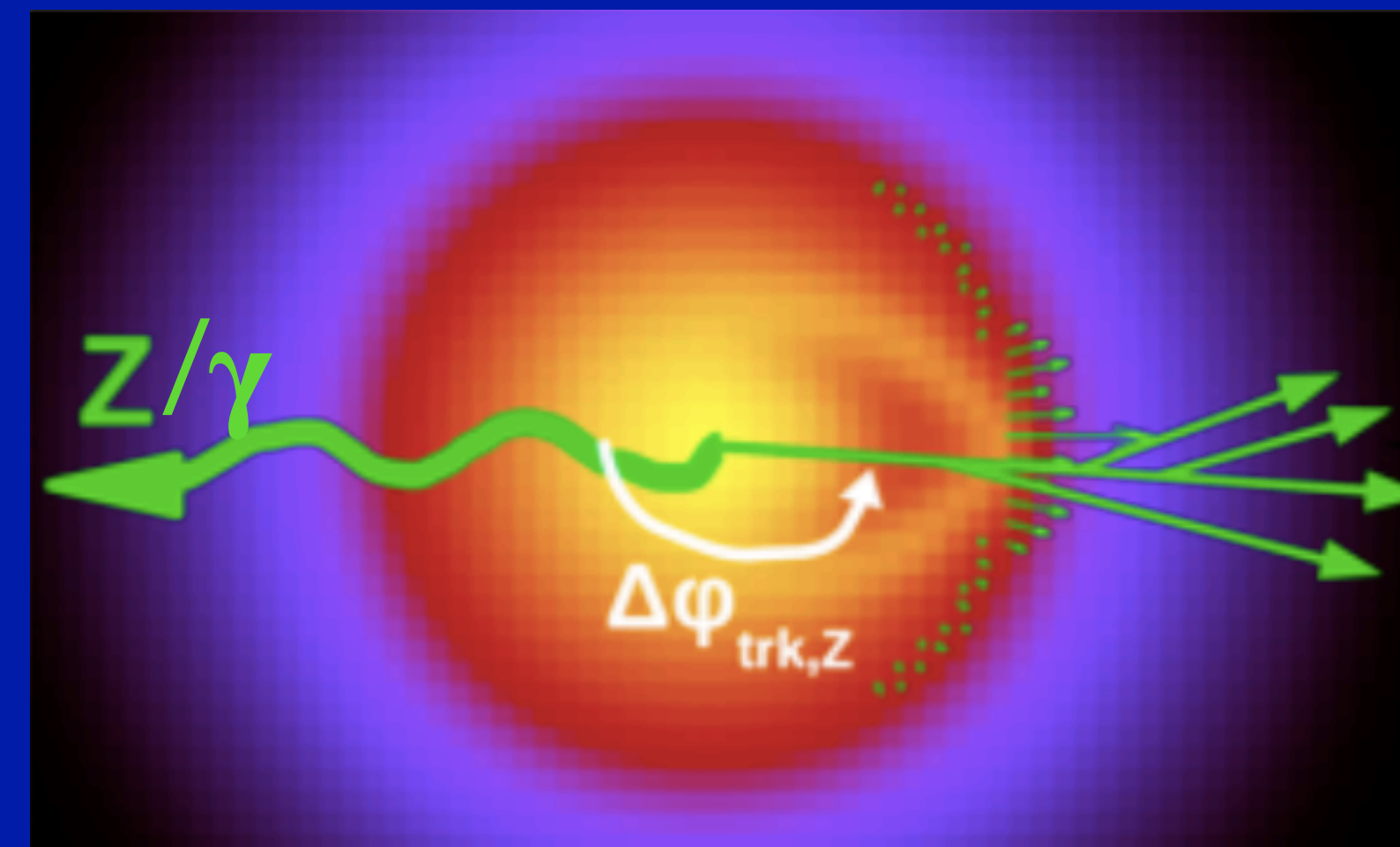


Jet 1 and **Jet 2** travel different path lengths in the QGP, losing different amounts of energy. There is no way to measure how much energy each one has lost.

How to calibrate jet energy loss?

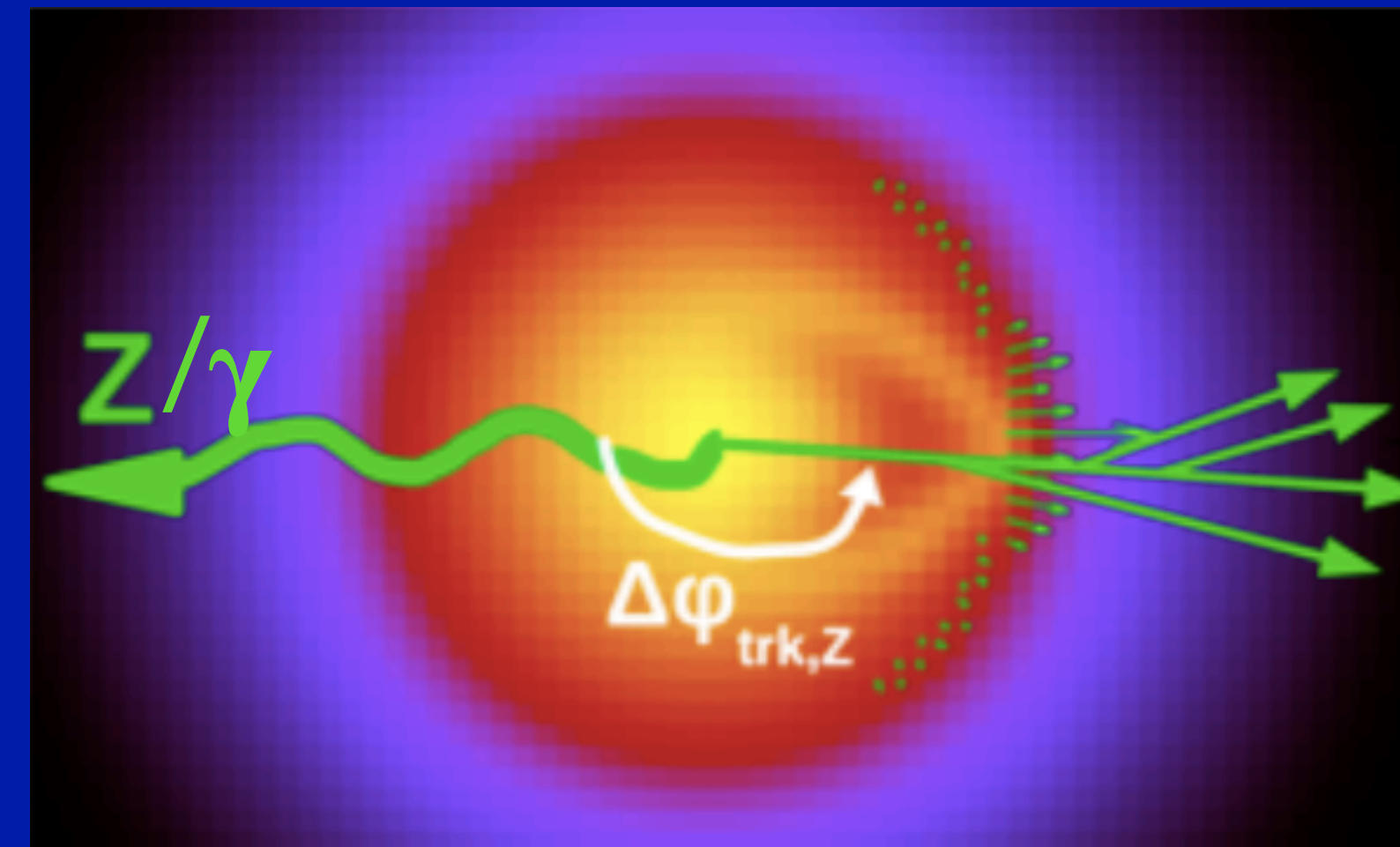
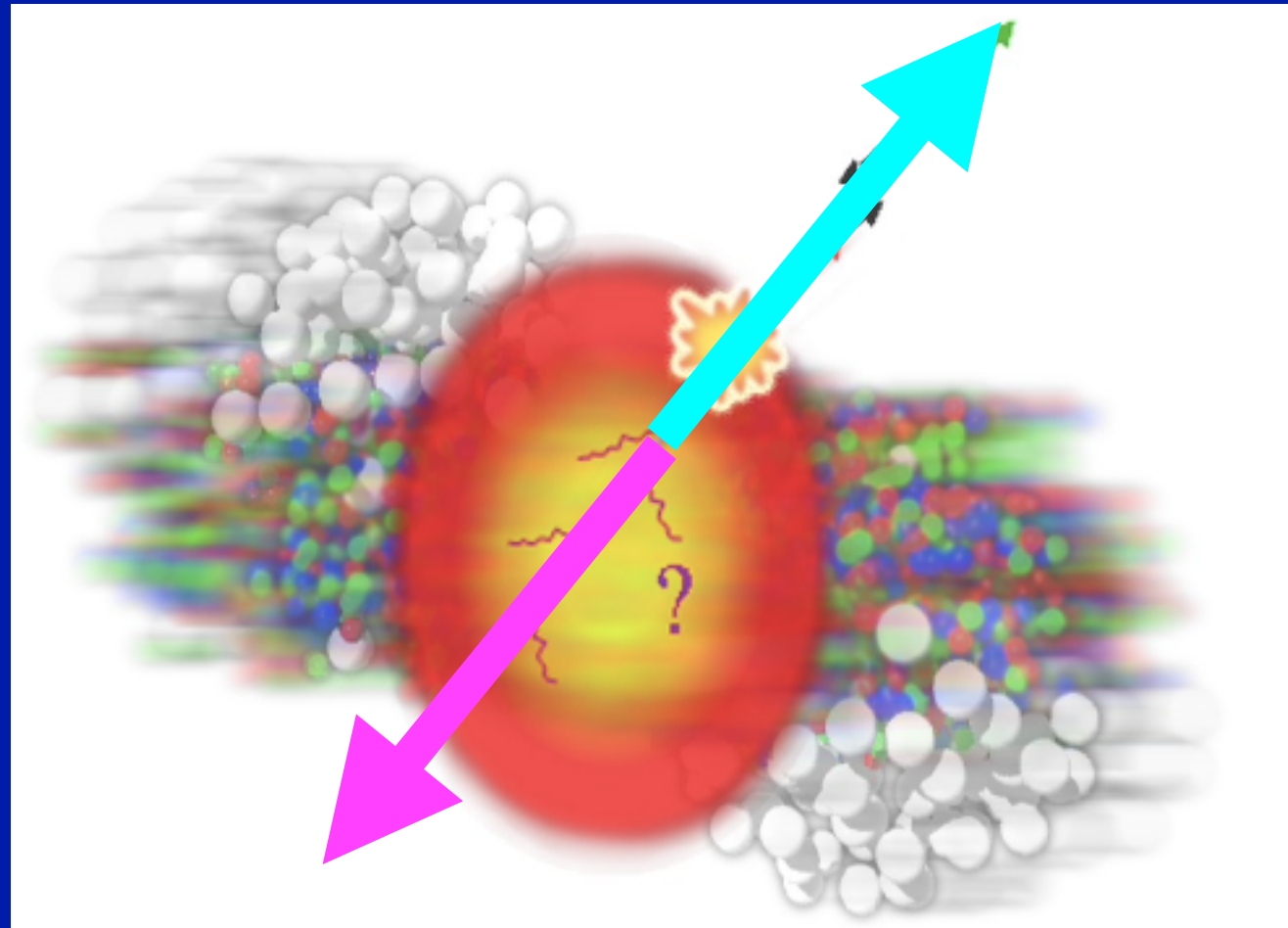


Jet 1 and **Jet 2** travel different path lengths in the QGP, losing different amounts of energy. There is no way to measure how much energy each one has lost.



However, for **a jet** recoiling against **a boson**, its energy loss can be measured because the boson's energy is unaffected.

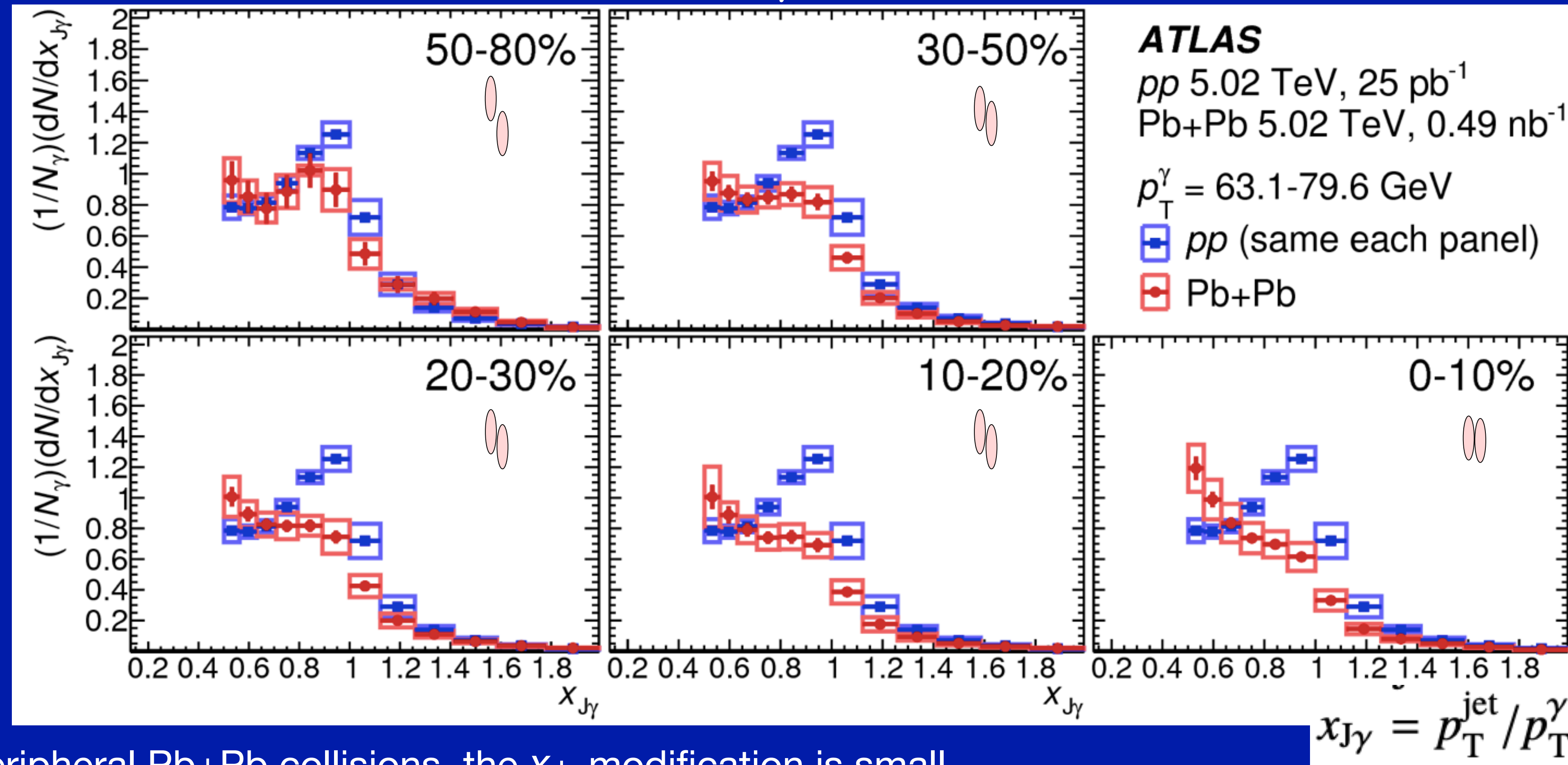
Jets created in association with a photon or a Z boson can be used as a calibrated probe to study energy loss in the medium created in nuclear collisions.



The simplest observable: jet-to-photon transverse momentum ratio

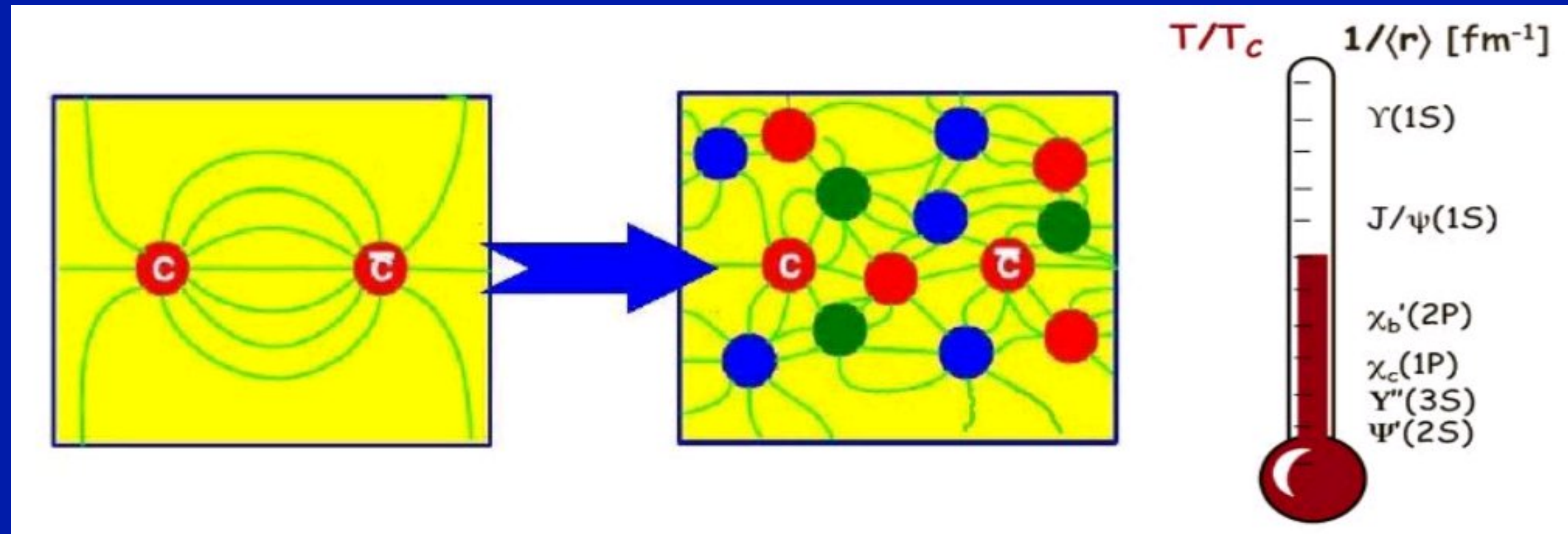
$$x_{J\gamma} = p_T^{\text{jet}} / p_T^{\gamma}$$

photon-jet pairs distribution as a function of $x_{J\gamma}$ in pp collisions and Pb+Pb different centralities



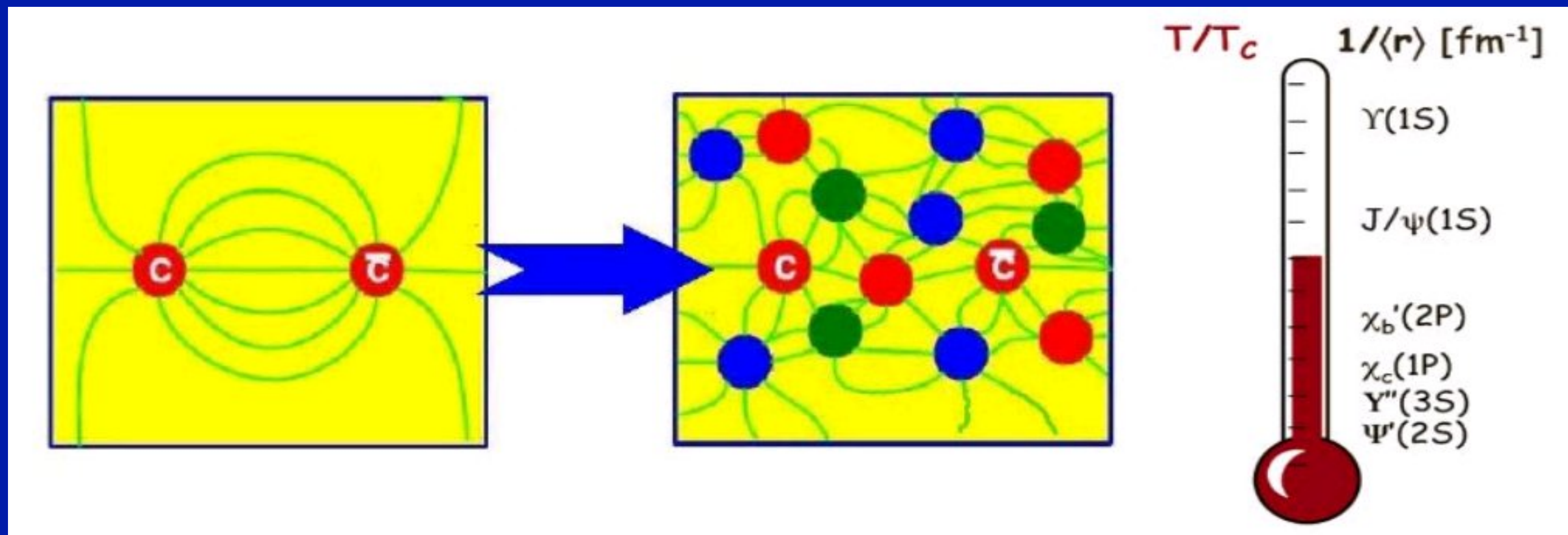
- In peripheral Pb+Pb collisions, the $x_{J\gamma}$ modification is small
- The photon-jet momentum asymmetry increases with increasing collisions centrality
- In 0-10% the number of p_T balanced photon-jets drops by a factor of two. The number of asymmetric pairs is maximal.

Quarkonia suppression in HI collisions is predicted by lattice QCD calculations



temperature-dependent
screening lengths

Quarkonia suppression in HI collisions is predicted by lattice QCD calculations



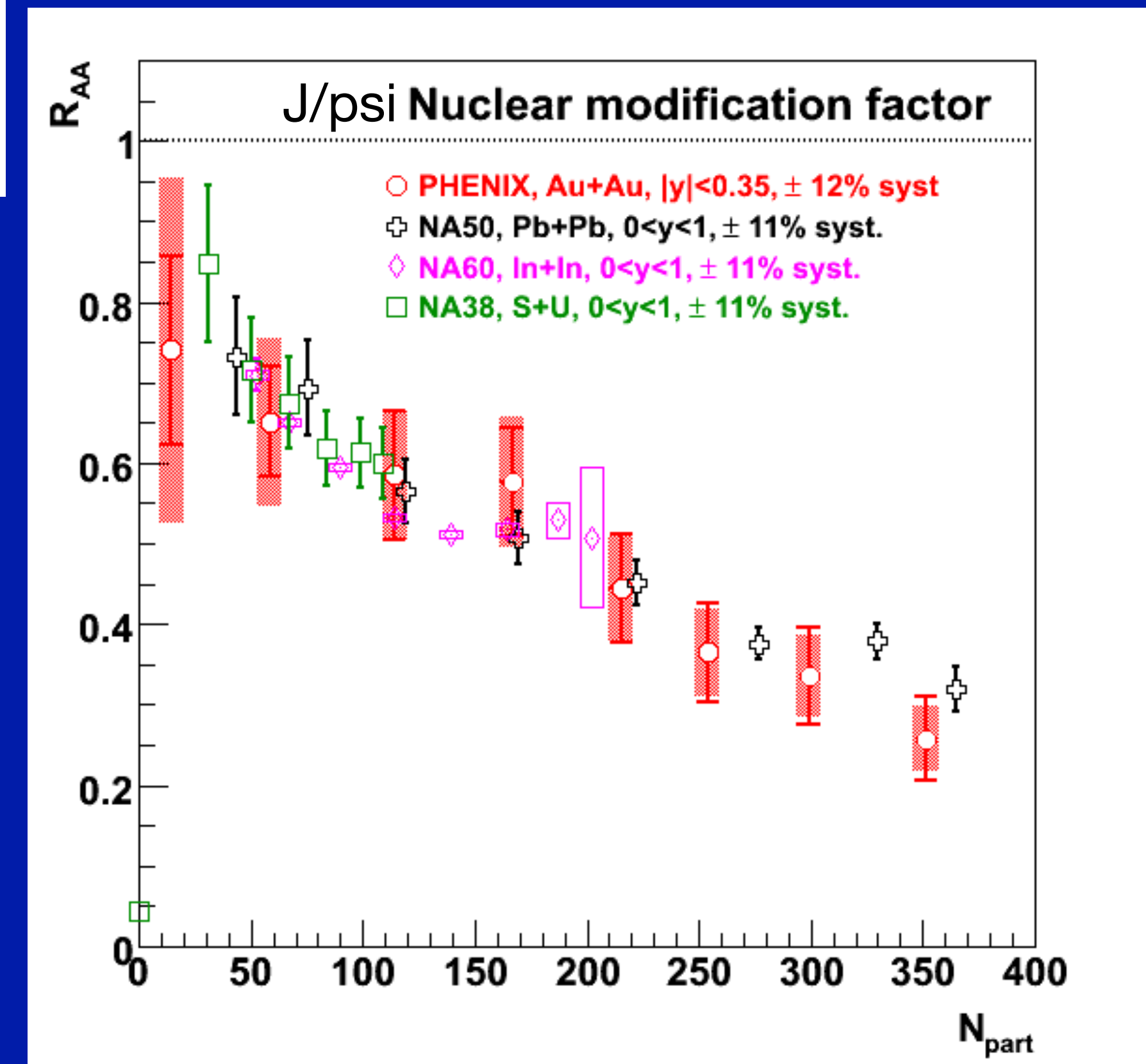
$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

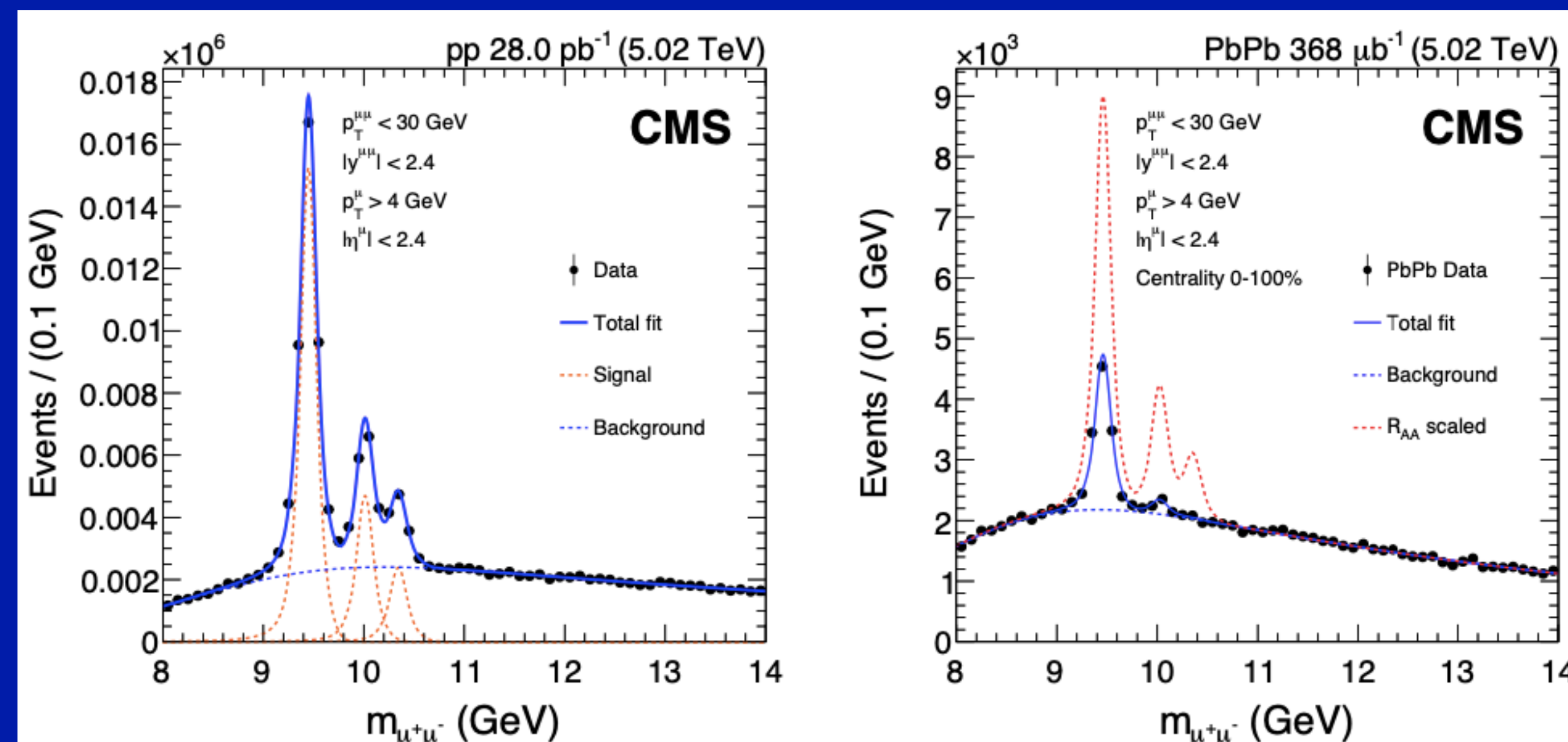
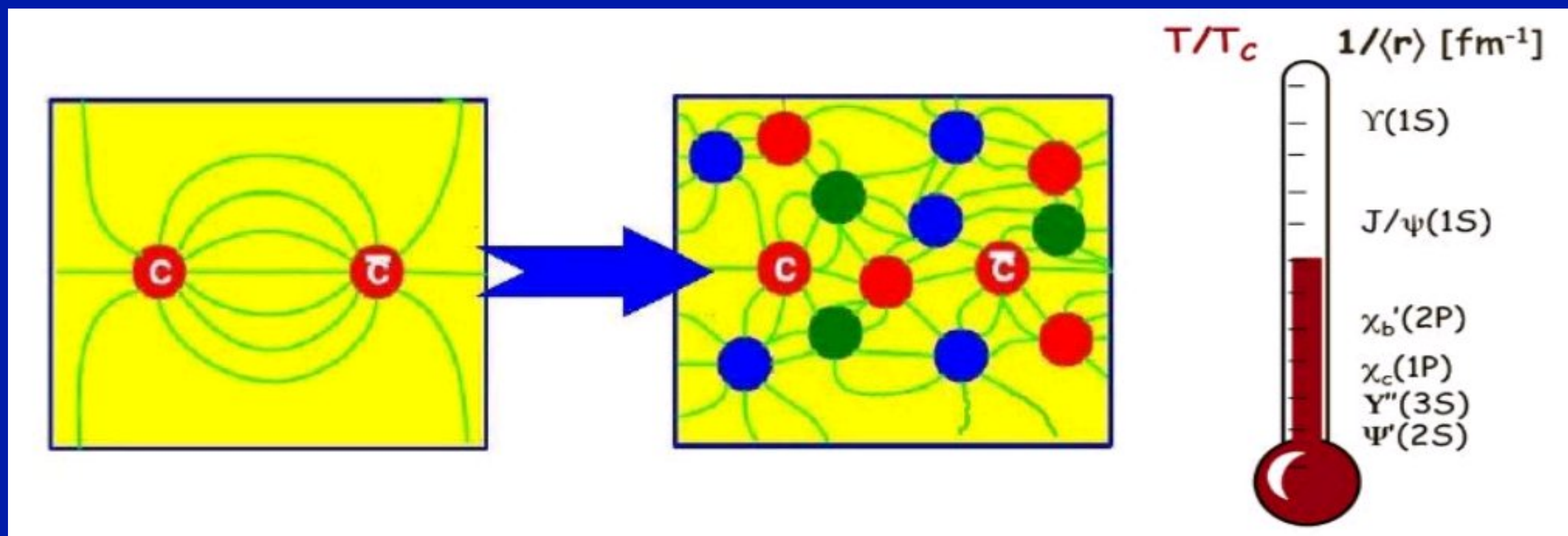
Nuclear thickness function $\langle N_{coll} \rangle / \sigma_{NN}$ Cross section in pp collisions (in vacuum)

J/psi anomalous suppression by Debye colour screening (Matsui and Satz, 1986)

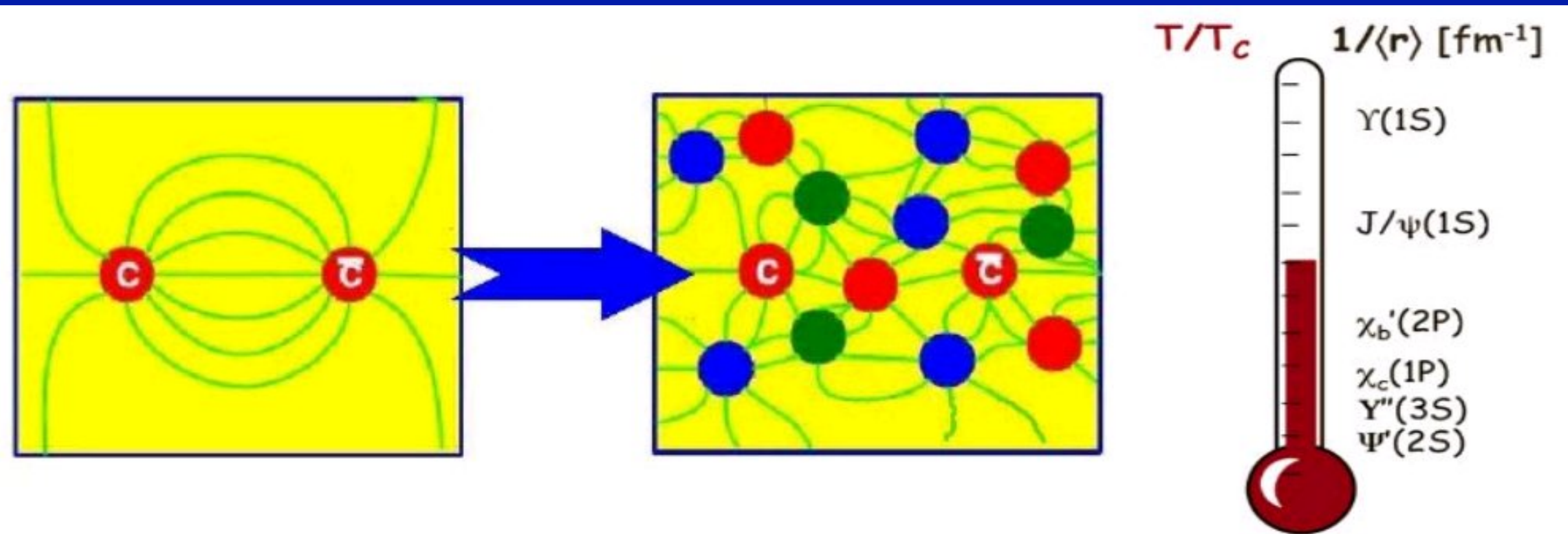
- One of the most striking signatures for the QGP
- A major contribution from LIP



Quarkonia suppression in HI collisions is predicted by lattice QCD calculations



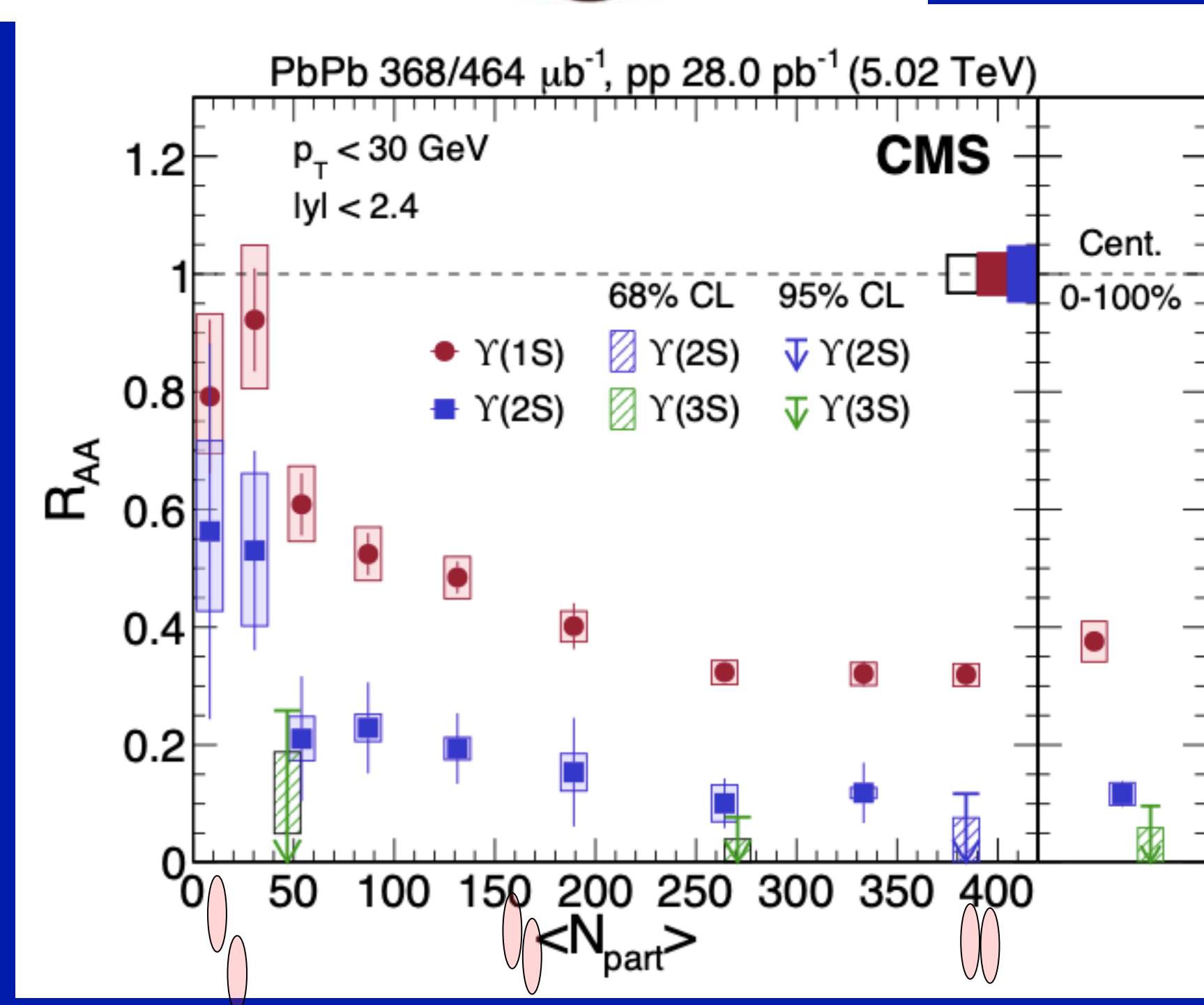
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$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

Nuclear thickness function $\langle N_{coll} \rangle / \sigma_{NN}$ Cross section in pp collisions (in vacuum)



N_{part} = number of nucleon participants in the collision, a proxy to collisions centrality.

- Global observables (multiplicity, correlations, and flow) are integrals over final-state particles, but they reflect properties like entropy and energy density established much earlier in the system's evolution. These early conditions give rise to a **system that flows collectively**, with extremely low viscosity - a **Quark–Gluon Plasma** behaving as a **nearly perfect fluid**.
- Photons, being unaffected by the strong interaction, are not suppressed in the QGP.
- The way jets lose energy in the QGP carries information about how hot, dense, and strongly interacting the medium is... In this talk, we saw that jets are **suppressed by about a factor of two in central (0–10%) Pb+Pb collisions**, a clear signature of jet quenching. *Many other striking features are involved, which go beyond this overview.*
- Quarkonia are strongly suppressed in the QGP, naively due to Debye screening (*more phenomena, competing with Debye screening, are involved. Not addressed in this talk, though*).

Results shown are just a tiny fraction of an amazing set. See Heavy Ion public results at:
[ALICE](#), [ATLAS](#), [CMS](#), [LHCb](#)

