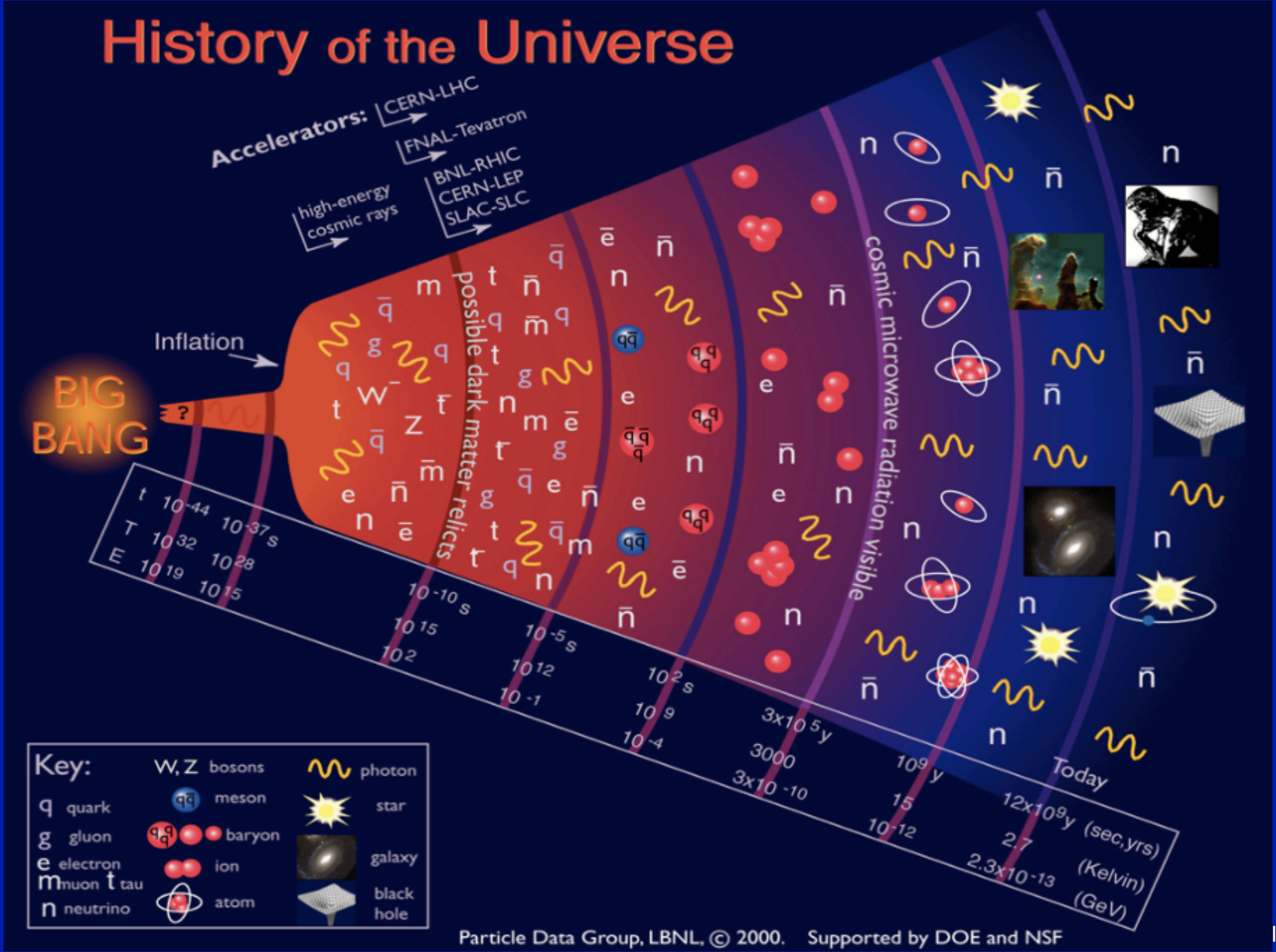
This work was financially supported by 2024.00227.CERN

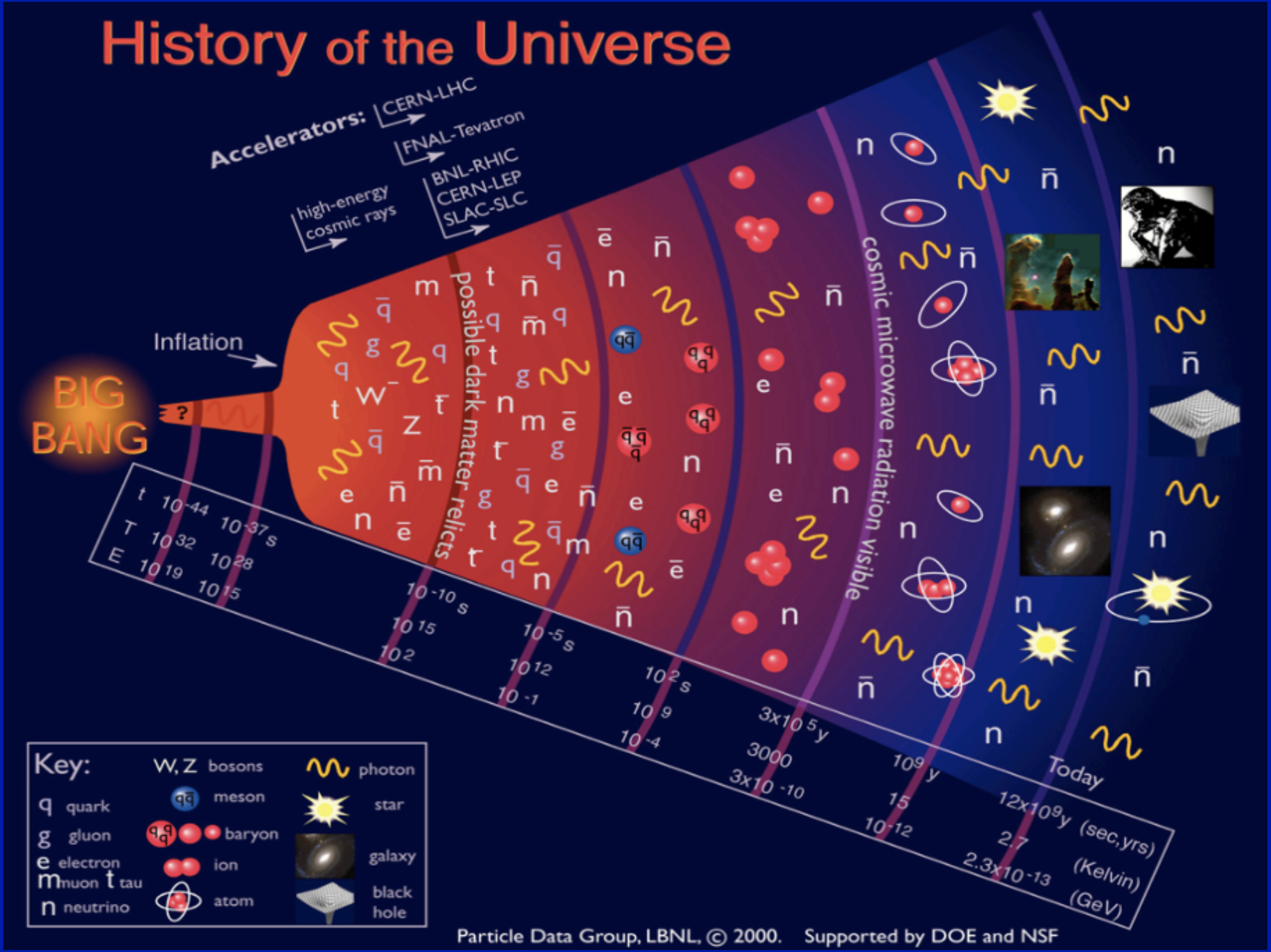
Heavy Ions and QGP tomography

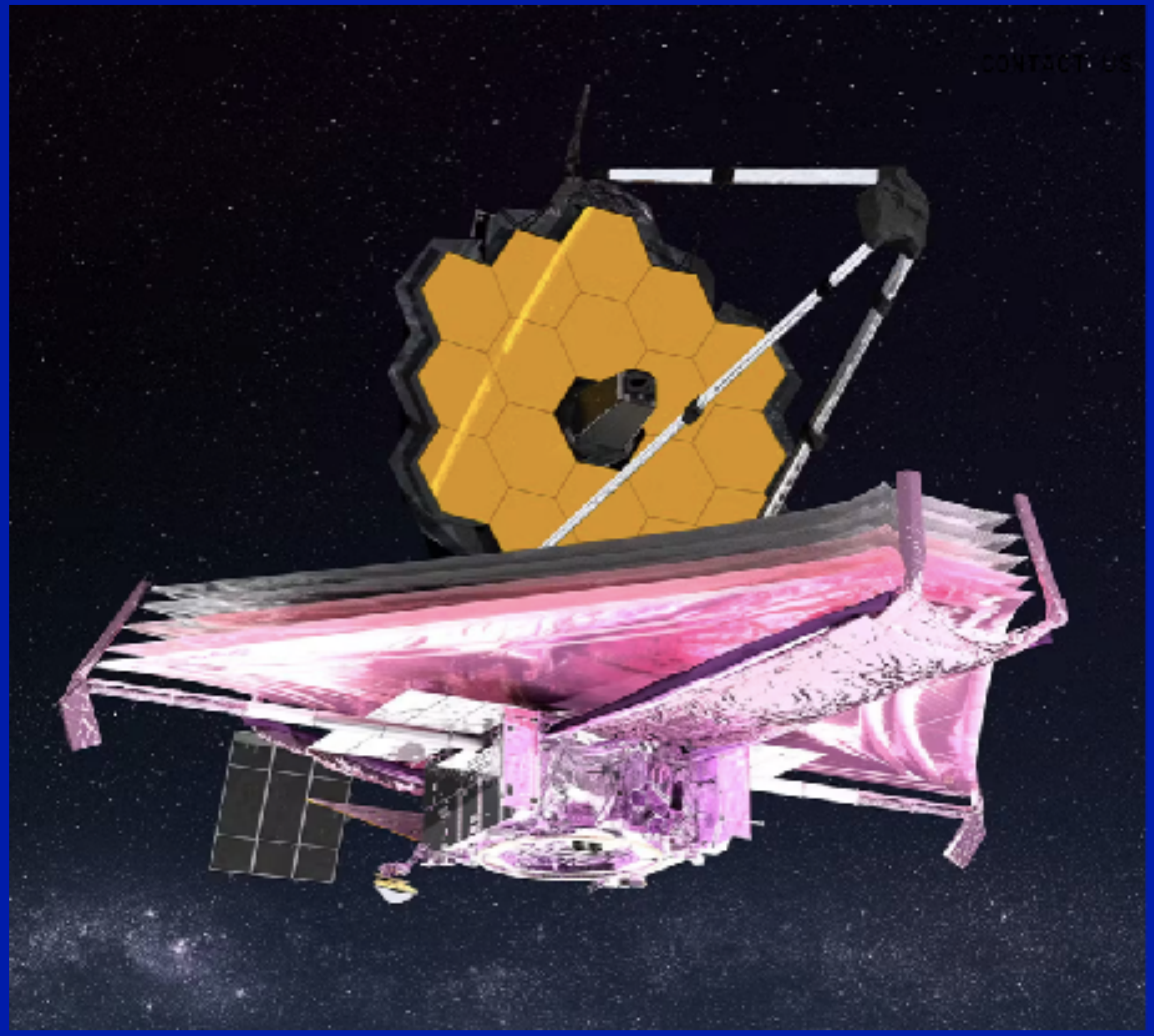
Helena Santos

LIP

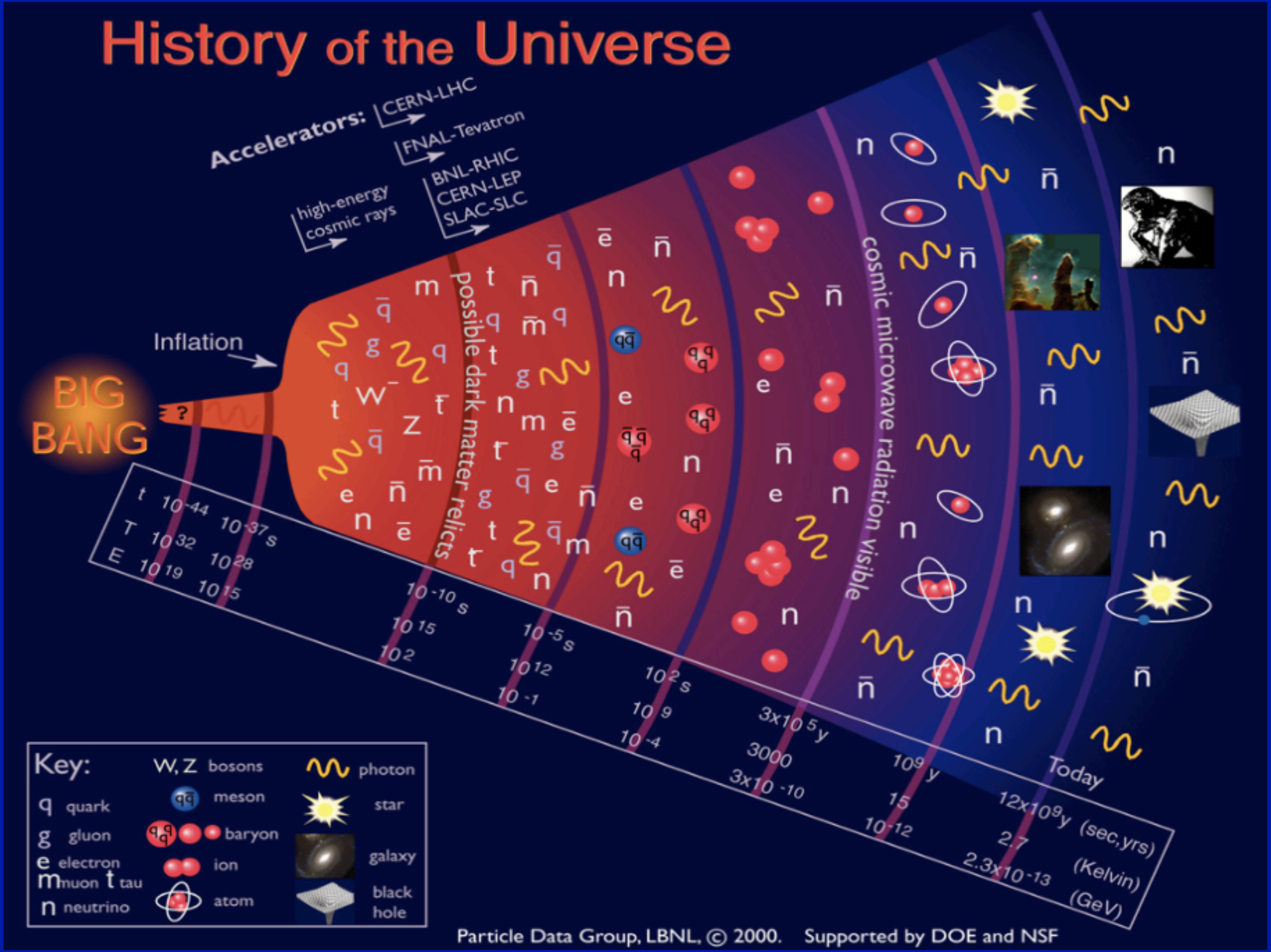
Physics at LHC, IST, 28 April 2026


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



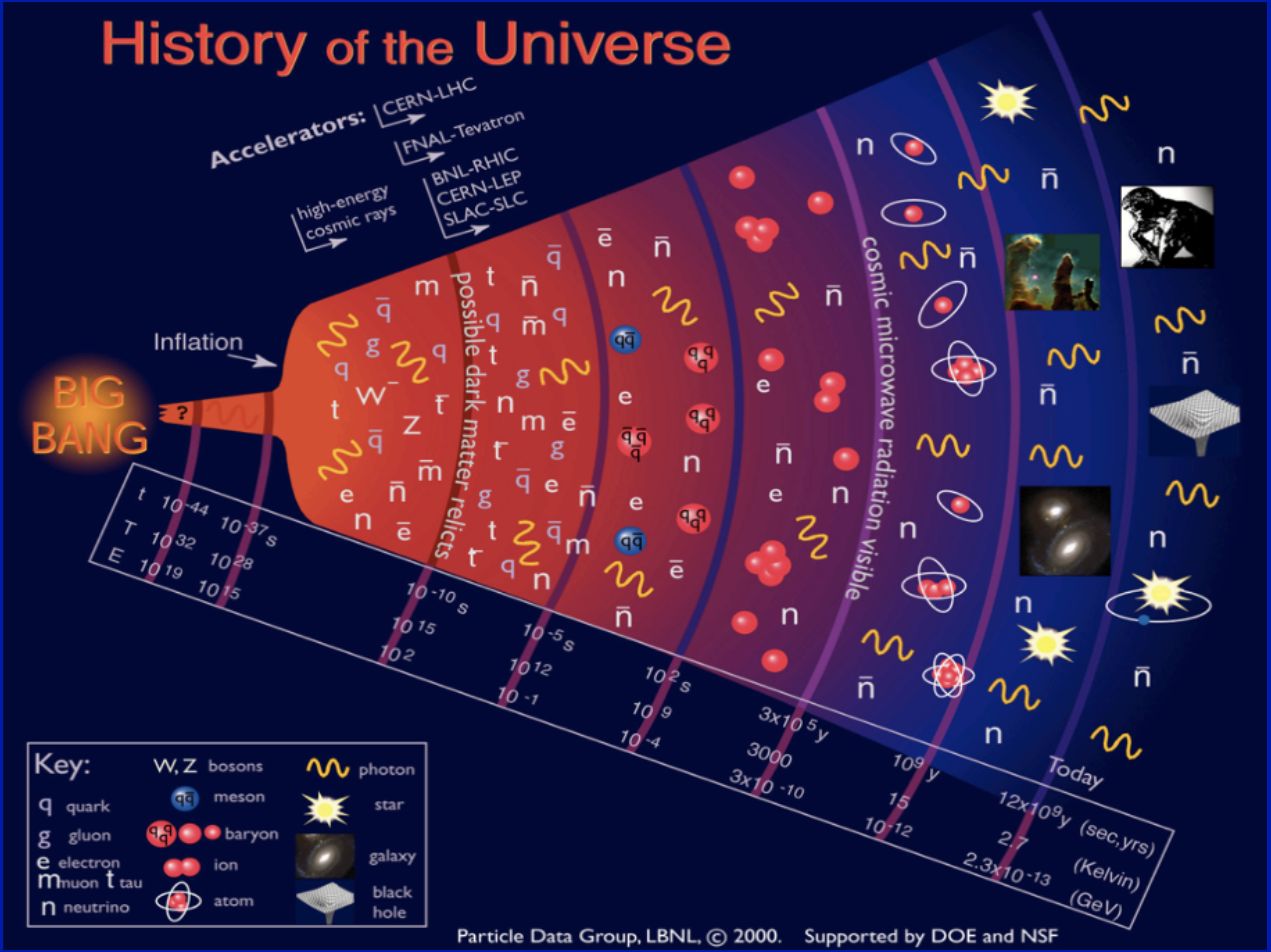


James Webb Space Telescope looks back over 13.4 billion years, about 300–400 million years after the Big Bang.



At ~380 kyr 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.



At ~380 kyr 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.

To probe earlier than the CMB we need non-photonic menssagers like:

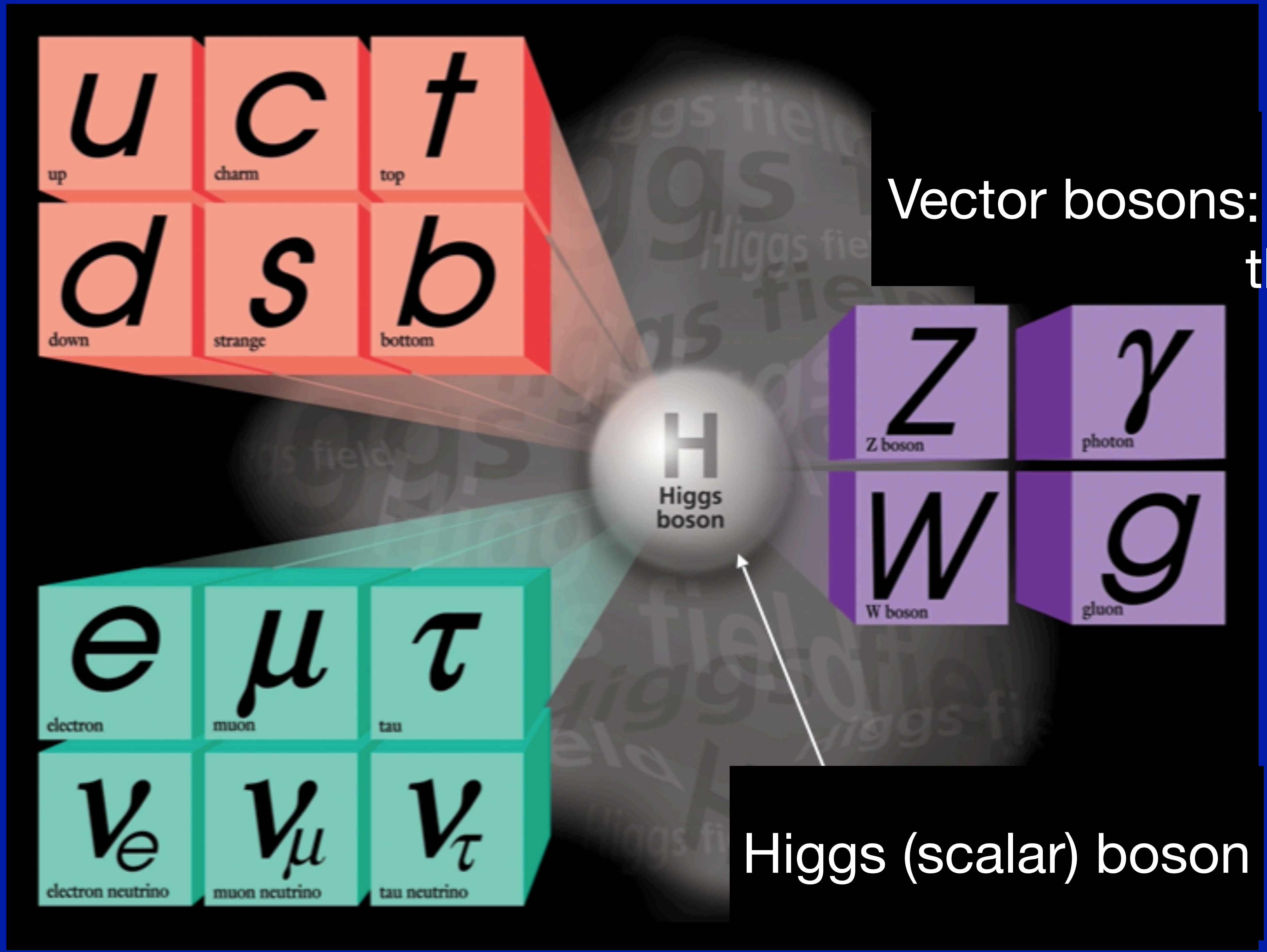
- Neutrinos probe the thermal history (CνB ~1 s to ~380 kyr)
- Primordial gravitational waves probe the inflationary era (~10^{-32} s)

Both are extremely difficult to detect

Or reproduce conditions at accelerators as CERN-LHC

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

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



Vector bosons: responsibles for mediating the fundamental forces

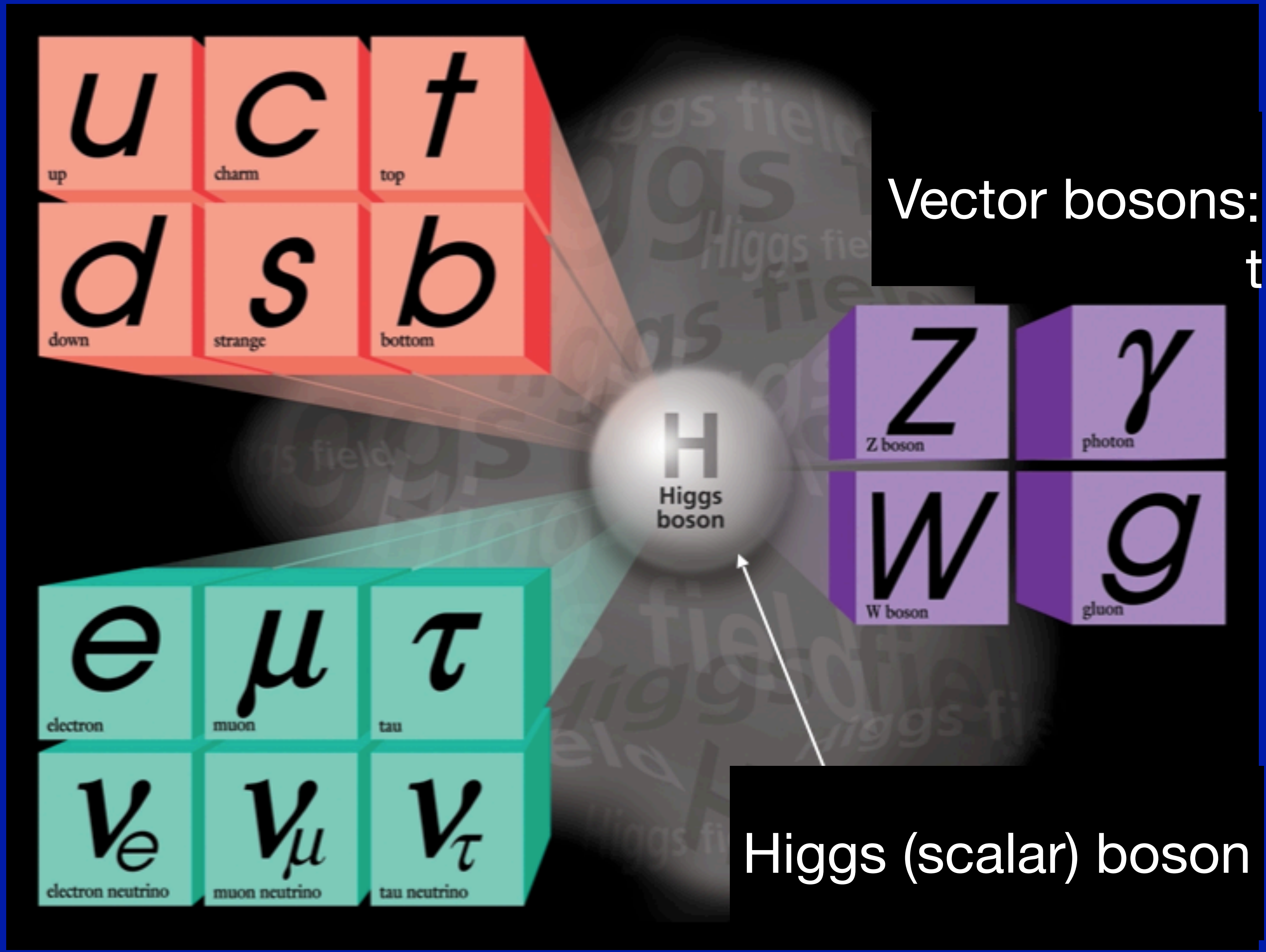
Leptons: electric charge ± 1, mediated by the photon

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?

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



Vector bosons: responsibles for mediating the fundamental forces

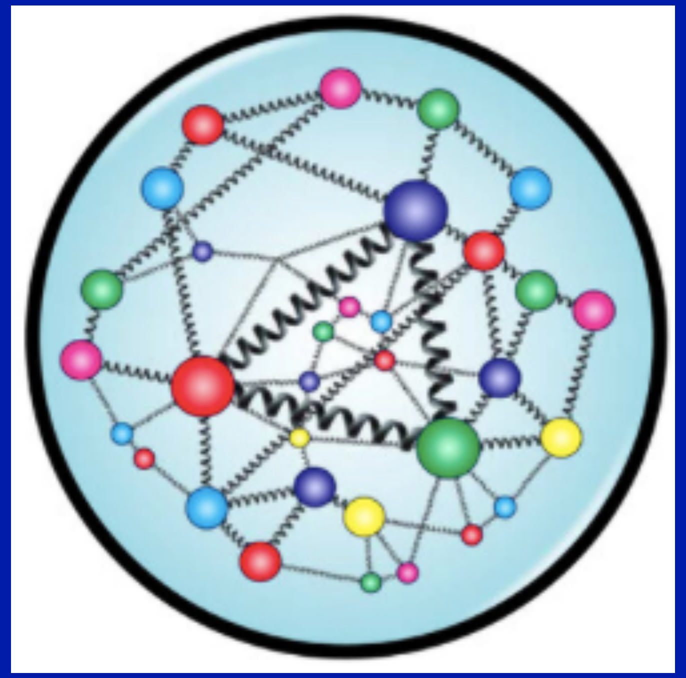
Leptons: electric charge ± 1, mediated by the photon

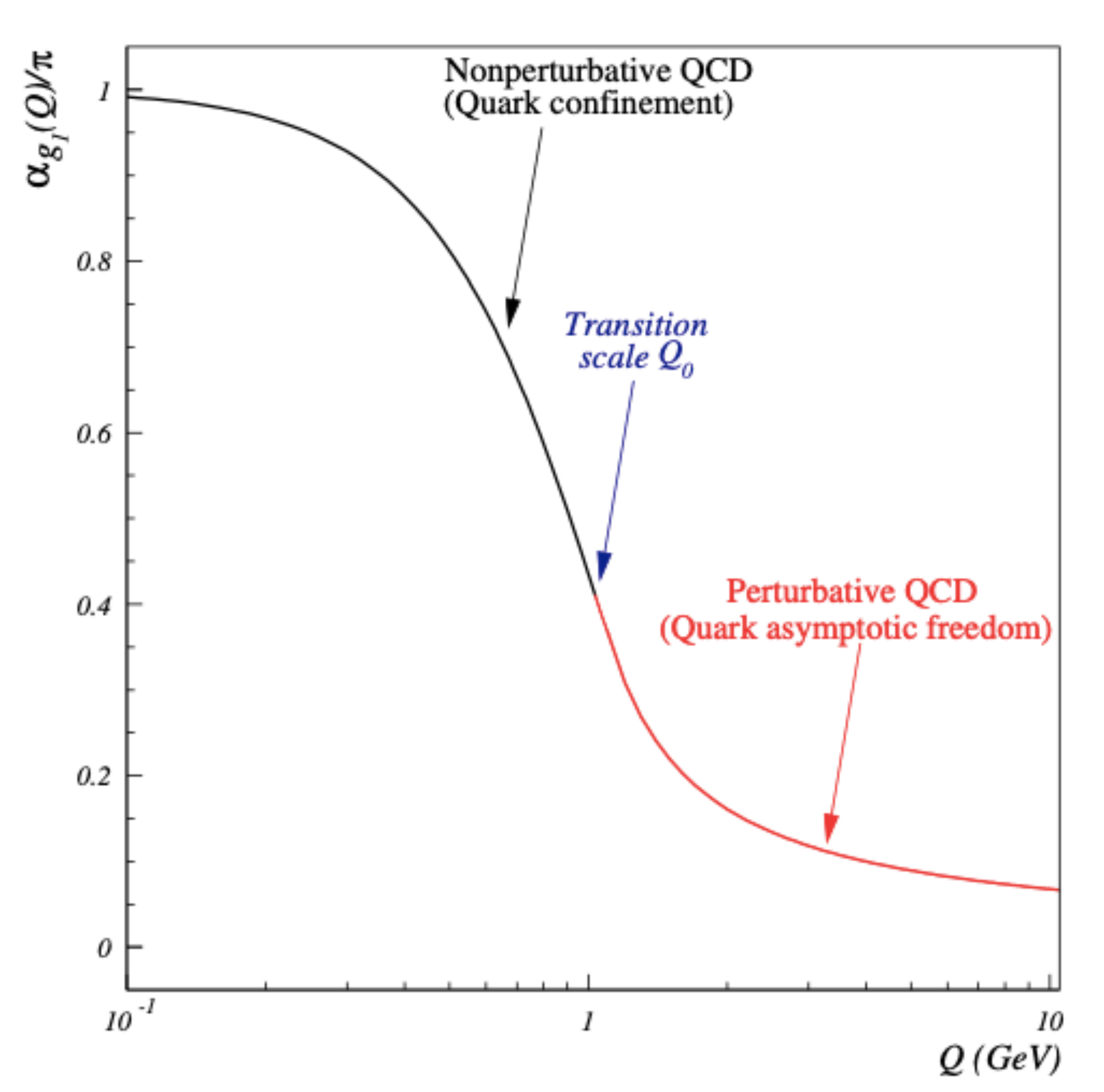
Higgs (scalar) boson : responsible for the mechanism of the mass acquisition of the elementary particles.

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

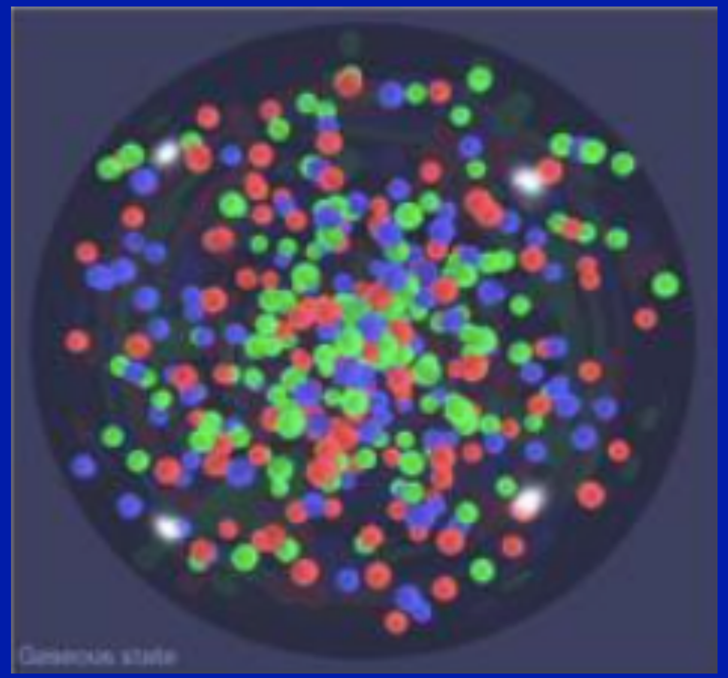
The LHC is deeply committed to the Heavy Ion Program —> exploring **QCD** at its ultimate frontier: matter under extreme temperature and density

Running of the Strong Coupling α_s





Phys. Lett. B 750, 528 (2015)



At "observable" distances

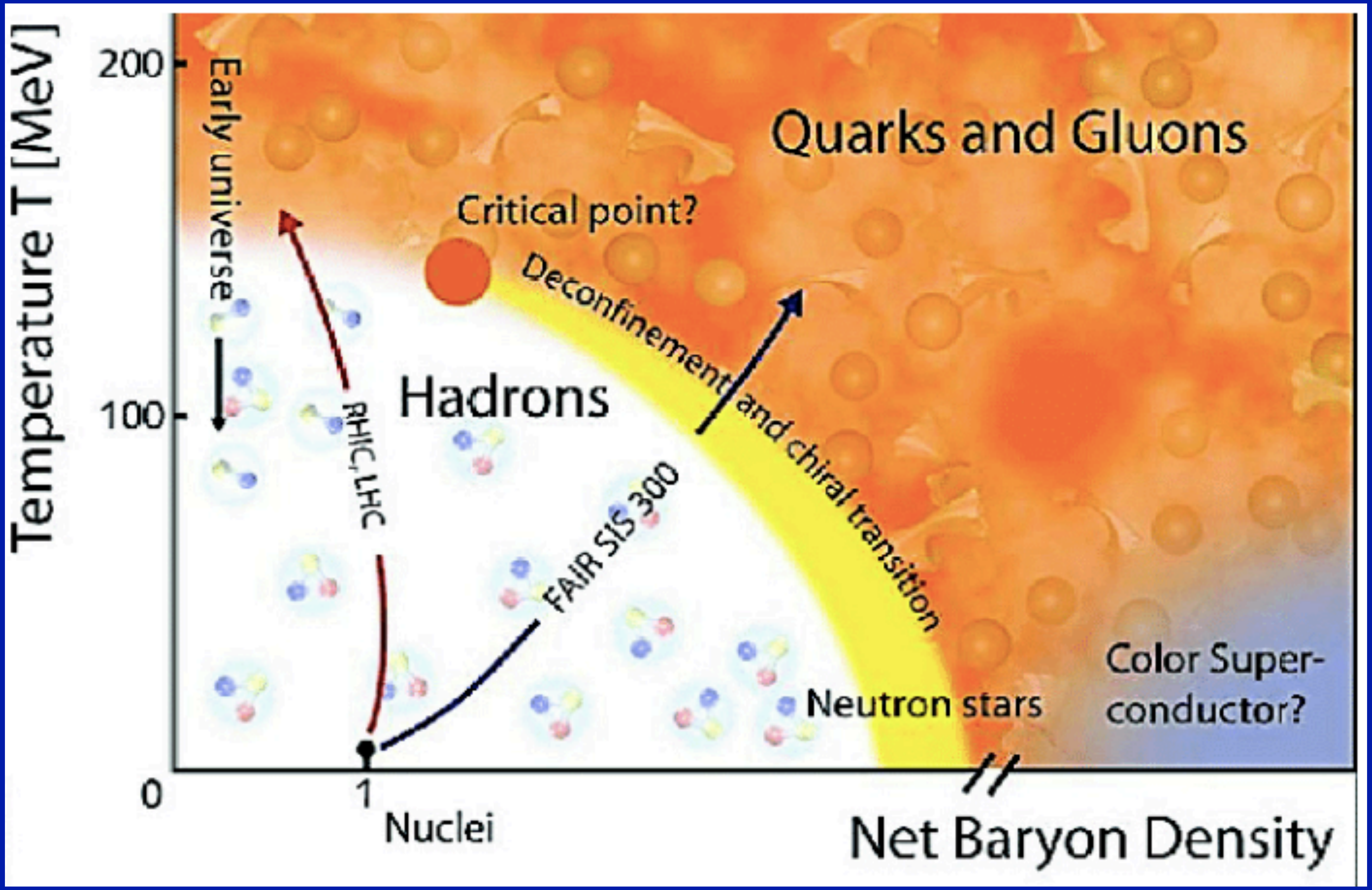
- At long distances (1fm) quarks are confined
- Strong coupling
- Perturbation theory fails

Deep inside the proton

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

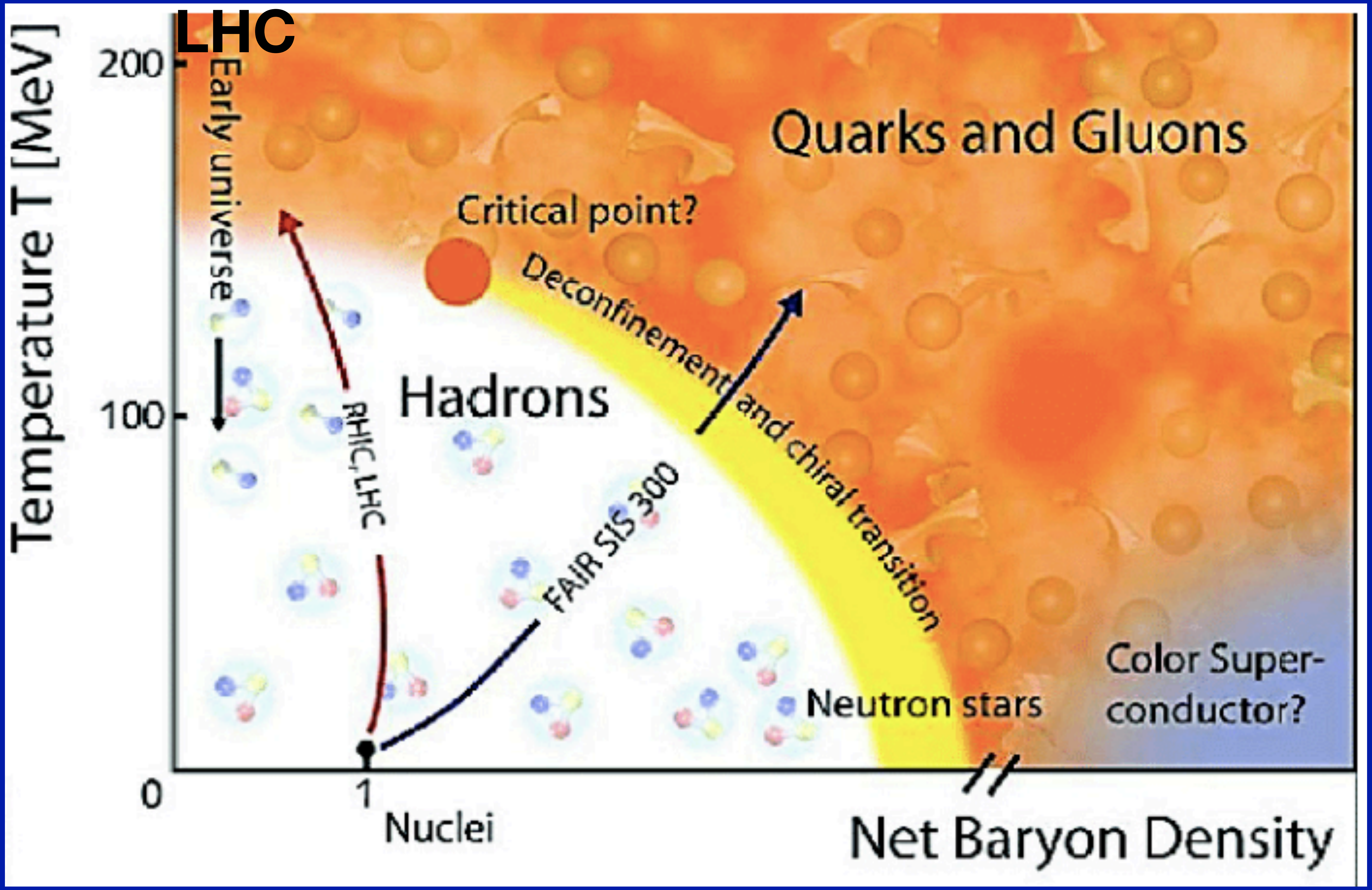
The QCD phase diagram

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



The QCD phase diagram

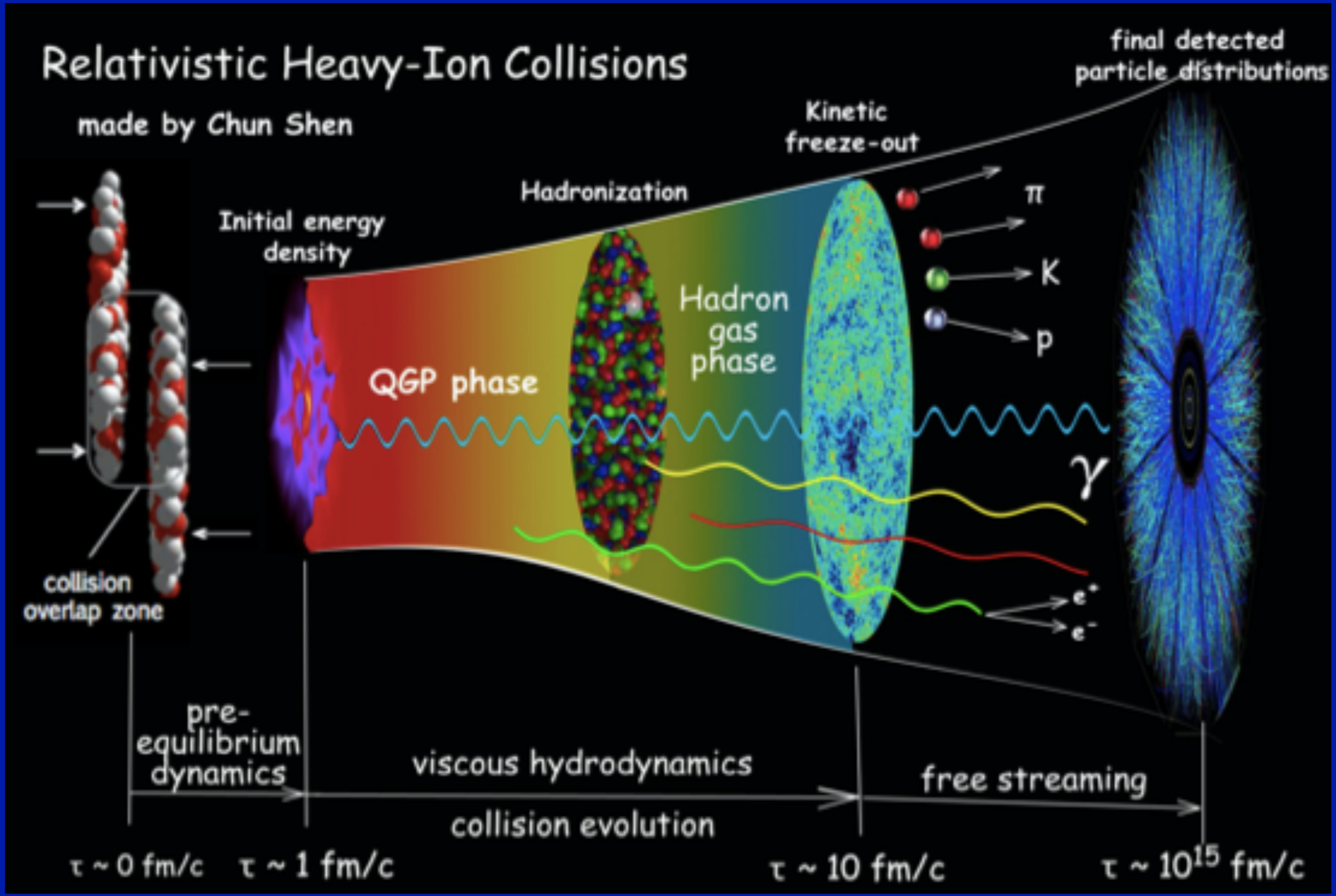
How can heavy-ion collisions be used to experimentally probe the different territories of the QCD phase diagram?



goal: create the two distinct phases of matter: the hadronic and the QGP (quark-gluon plasma)

Heavy Ion Physics

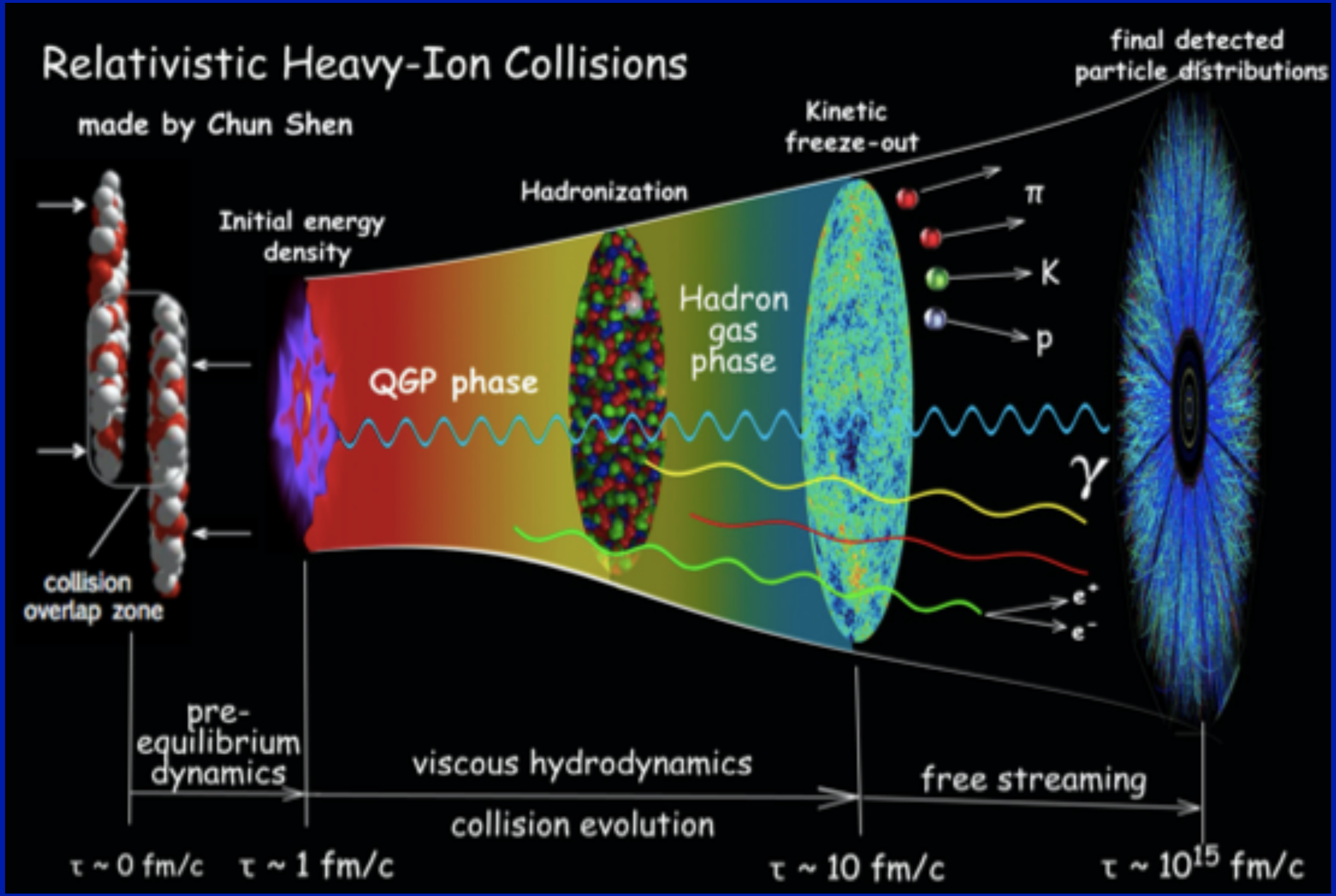
Time evolution of HI collisions:
- Initial state
- QGP state
- Hadronic state



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

Heavy Ion Physics

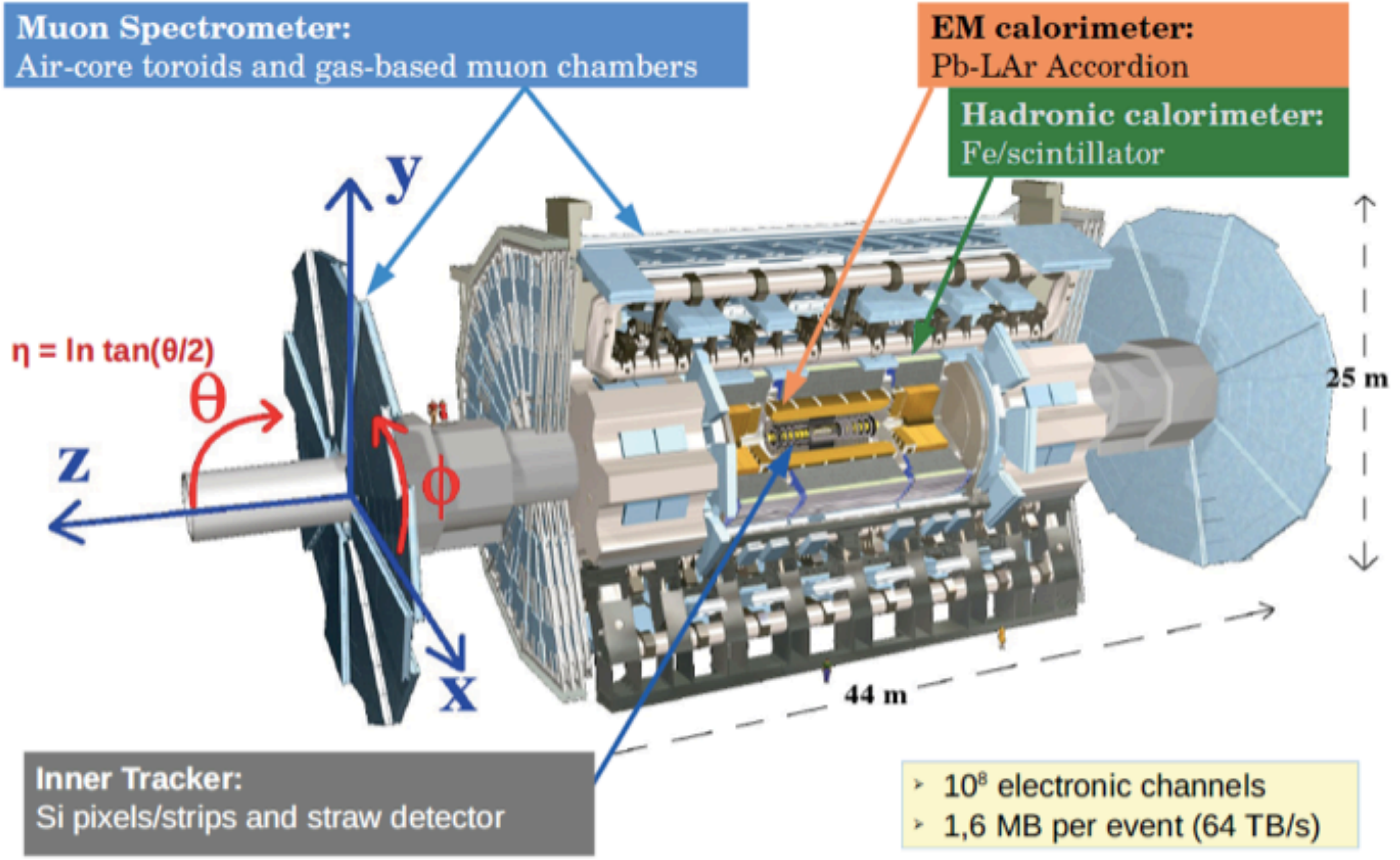
How to understand the different stages?



Use probes emitted during these stages:

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

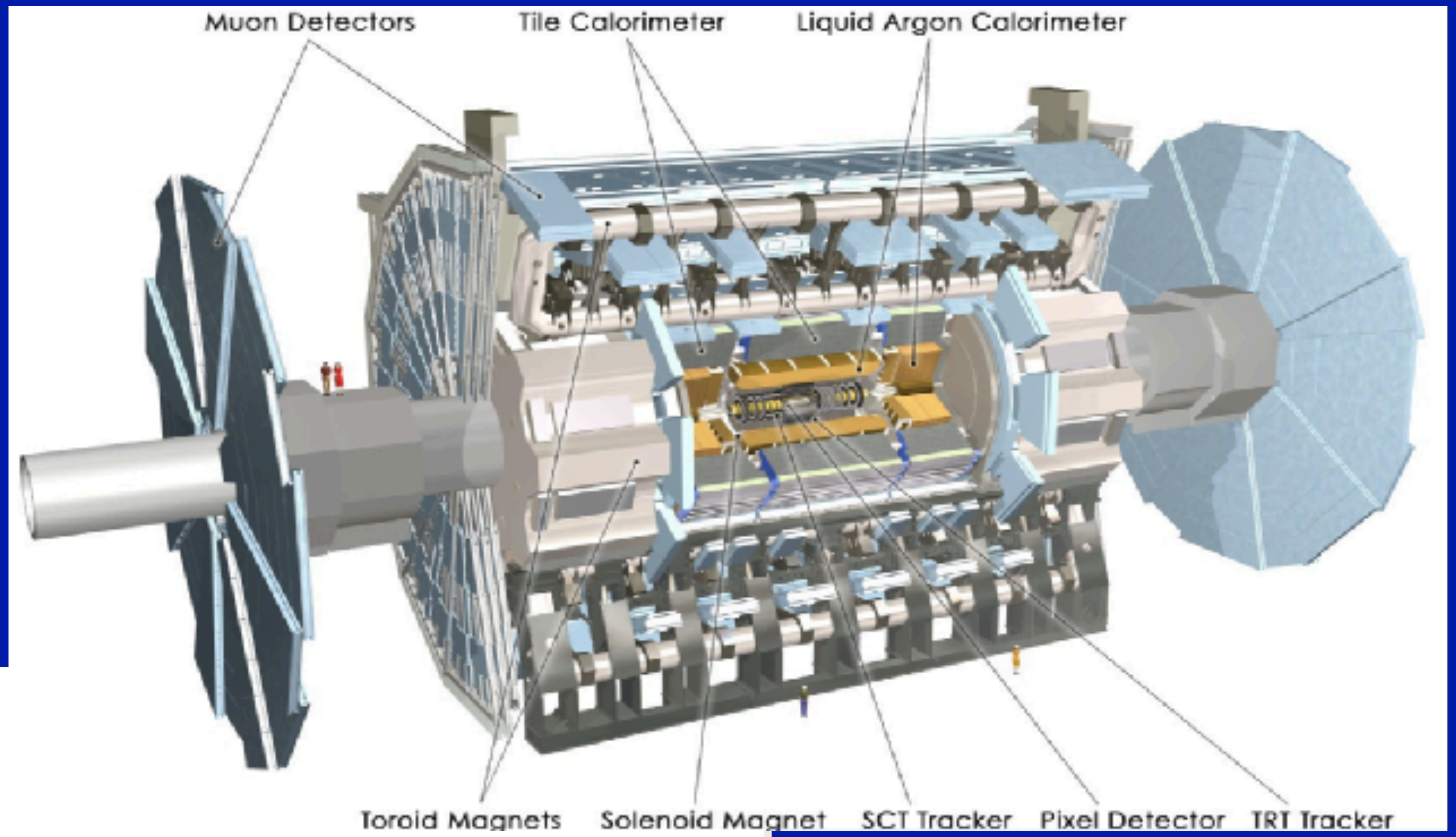
The ATLAS Detector

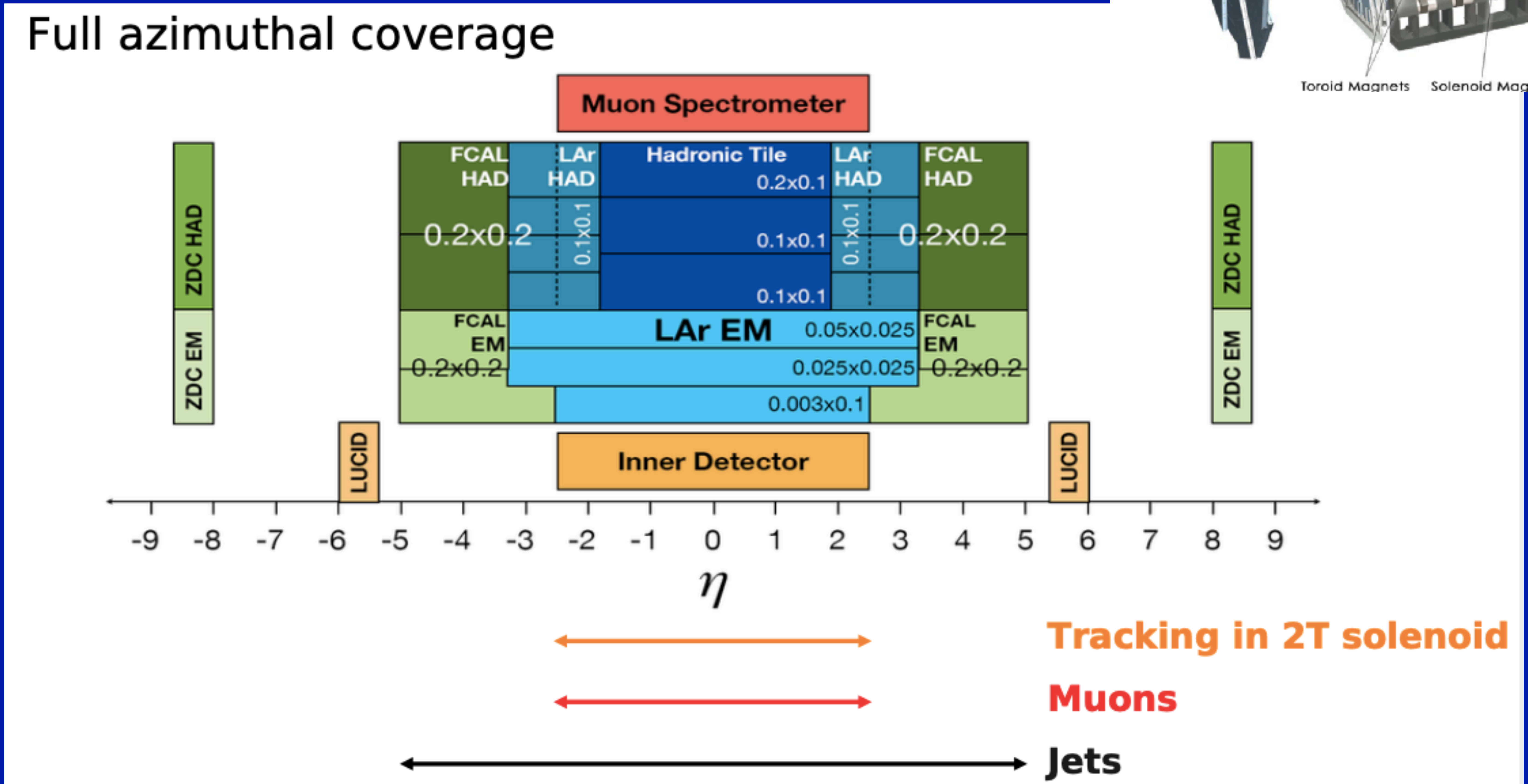


- 10^8 electronic channels
- 1,6 MB per event (64 TB/s)

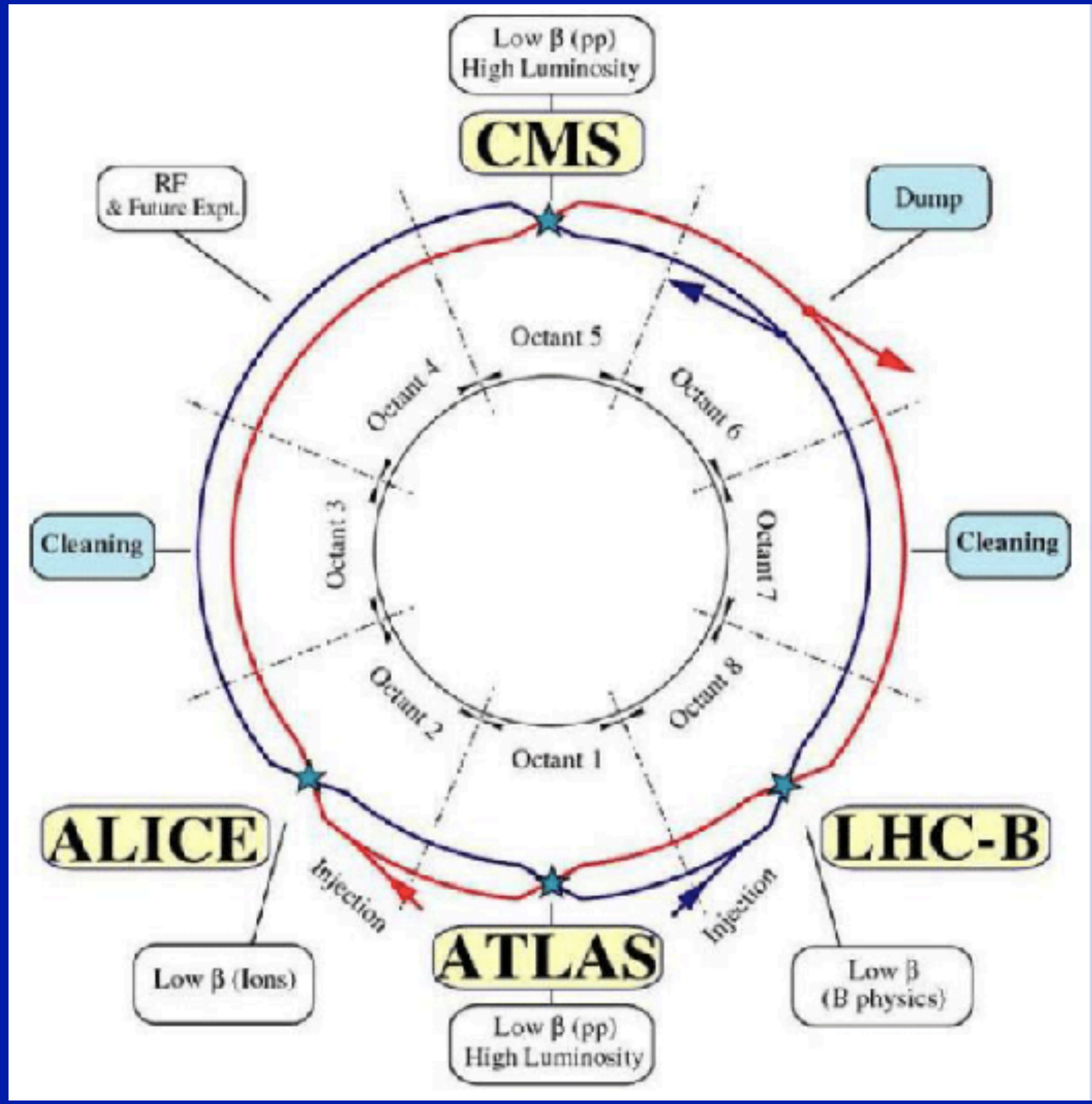
The ATLAS Detector

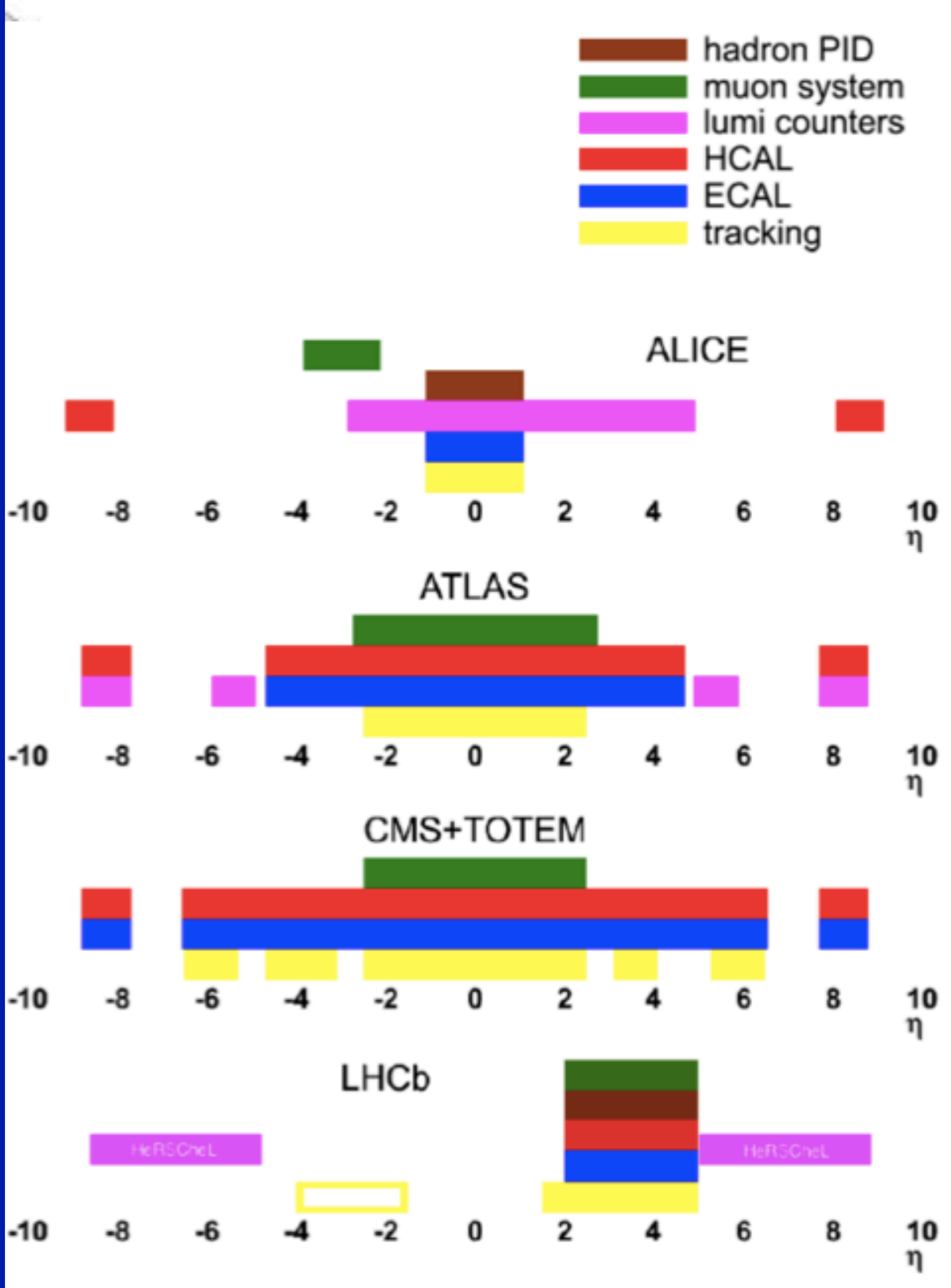
An excellent detector for the LHC Heavy-Ion program, with enourmous trigger capabilities





The acceptance of the LHC detectors



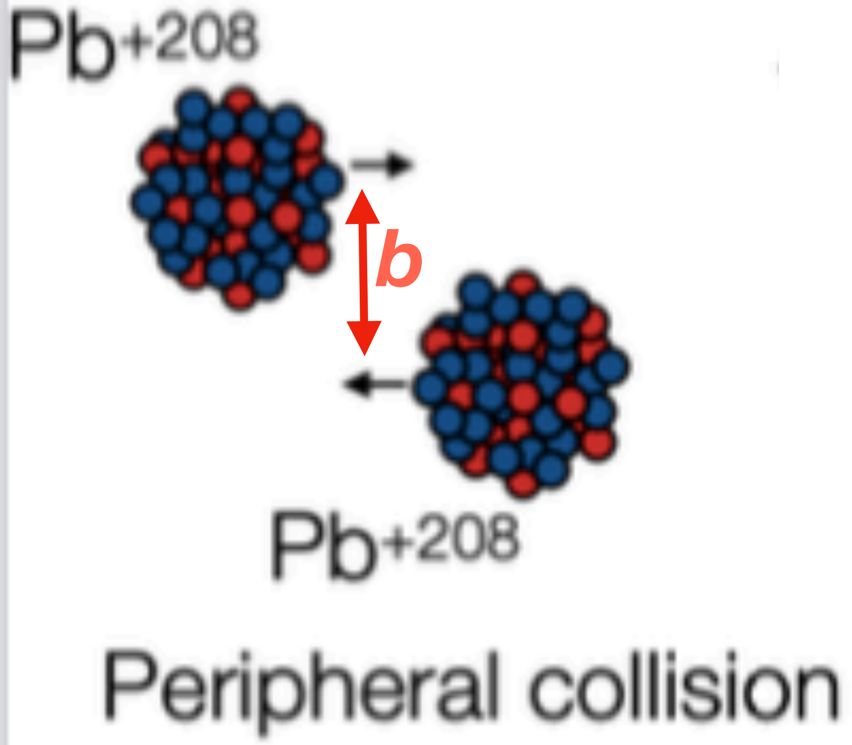


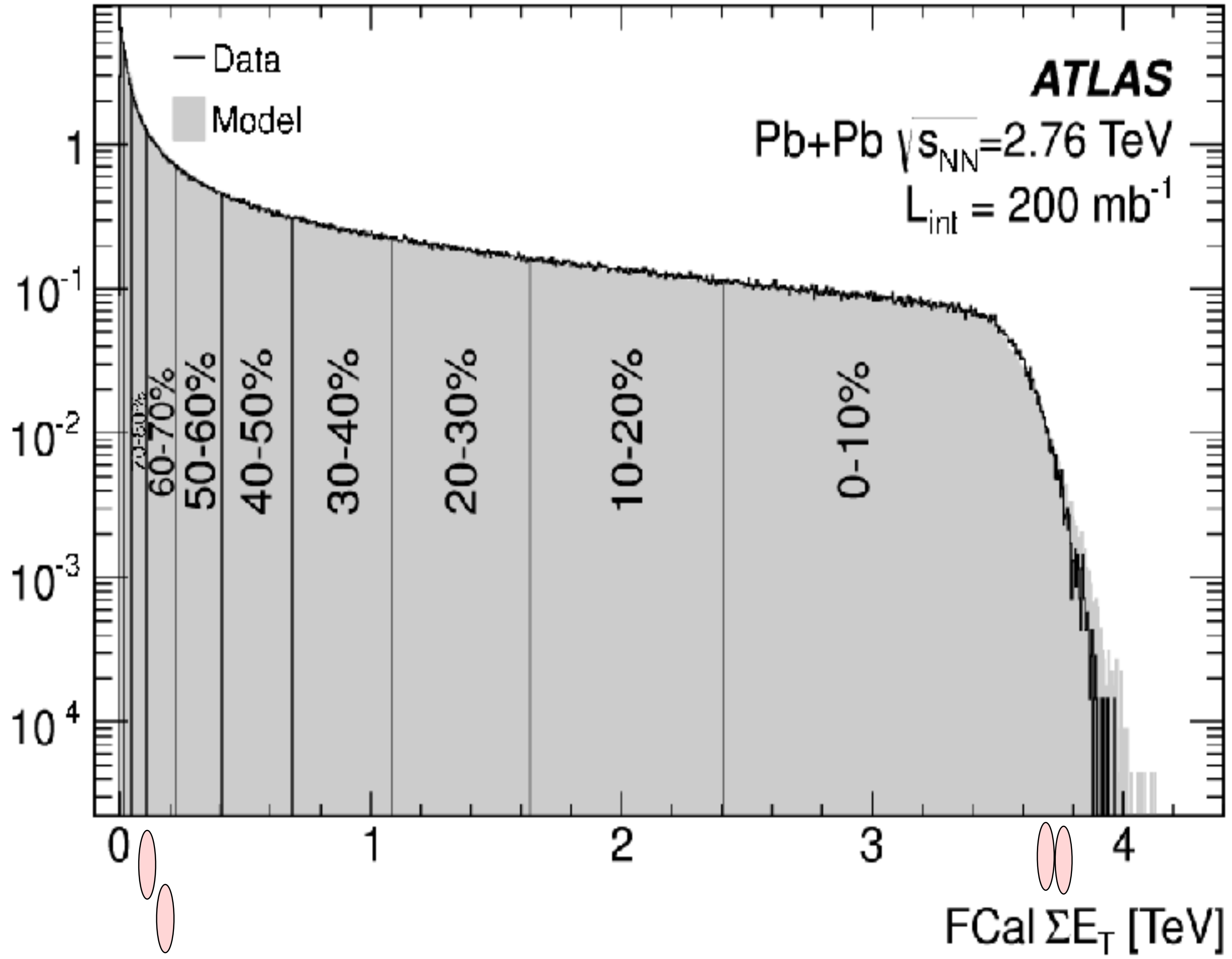
ATLAS and CMS are multipurpose detectors that work greatly during the LHC Heavy Ion Program.

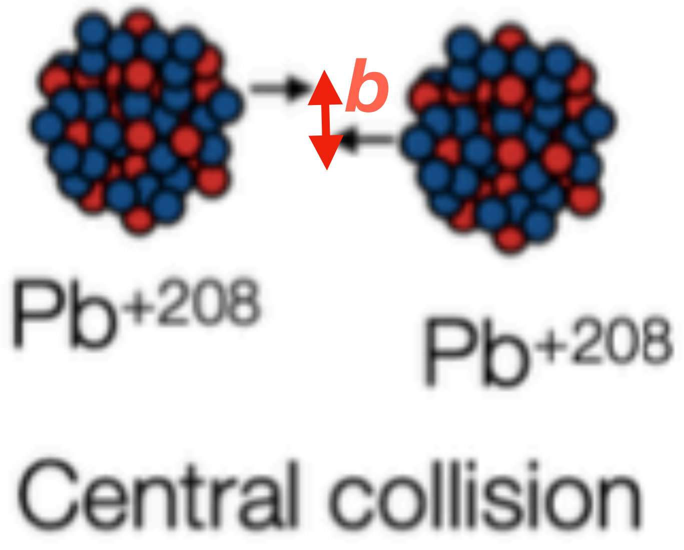
Detector being smaller or asymmetric is not necessarily worse - ALICE has excellent tracking and particle identification capabilities. It is a detector specially designed for the LHC Heavy Ion Program.

Intermezzo - HI collisions centrality

HI collision's dynamics is controlled by the impact parameter "*b*"





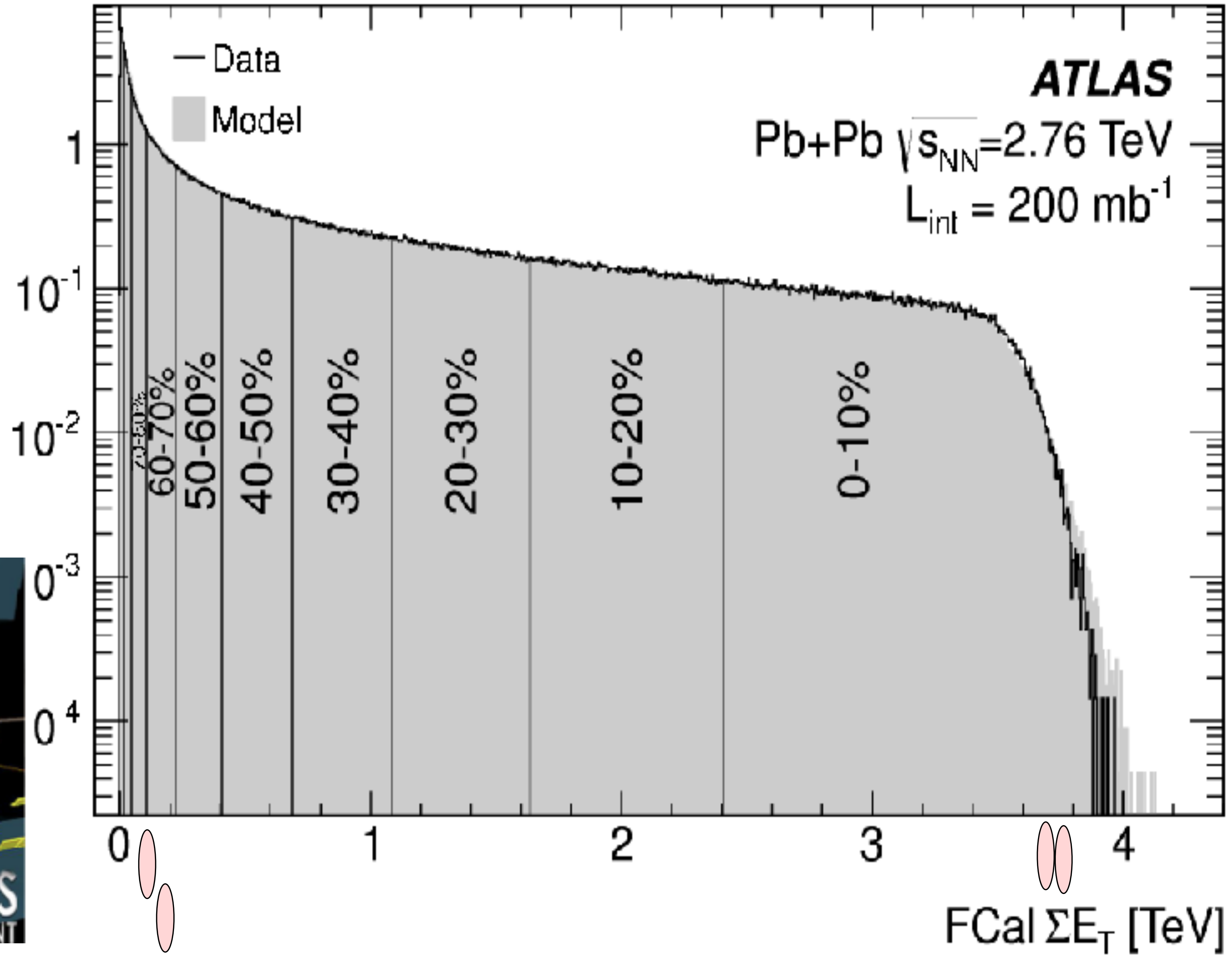


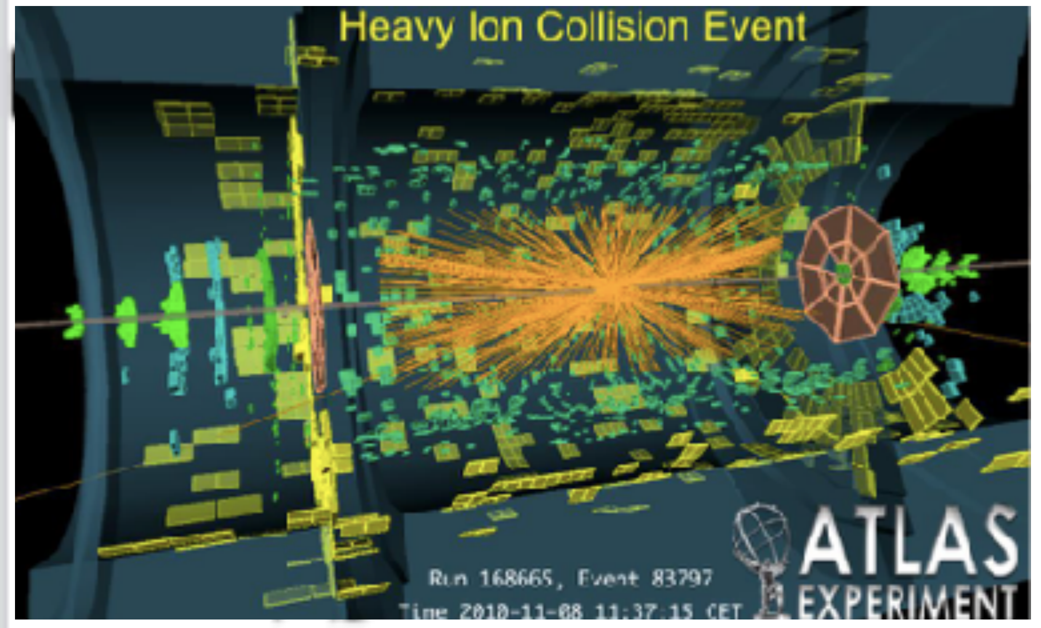
Each heavy-ion event is characterised by "centrality", the geometrical overlap between the two nuclei.

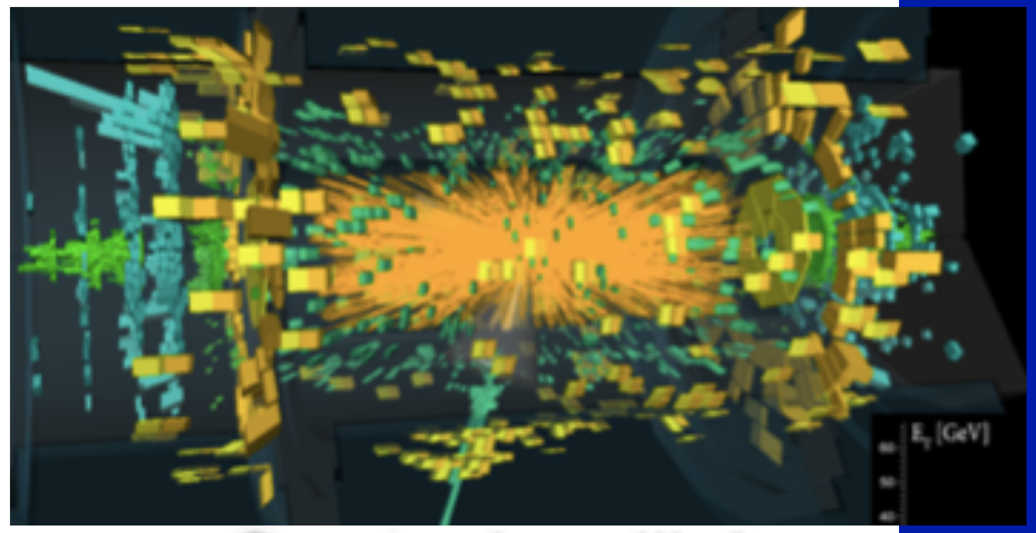
The higher the centrality, the higher the transverse energy deposited in the forward (FCal) calorimeter.

Intermezzo - HI collisions centrality

HI collision's dynamics is controlled by the impact parameter "*b*"







Central collision

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 nuclei overlap.

Intermezzo - Nuclear Modification Factor (R_{AA})

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

Yields in Pb+Pb collisions, (in medium)

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

Cross section in pp collisions (in vacuum)

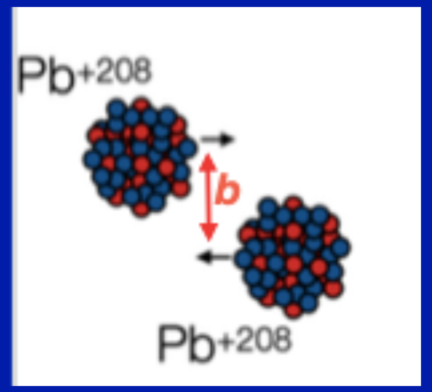
Intermezzo - Nuclear Modification Factor (R_{AA})

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

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*

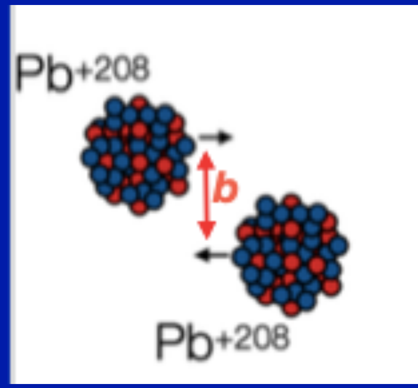
Intermezzo - Nuclear Modification Factor (R_{AA})

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

Yields in Pb+Pb collisions, (in medium)

Nuclear thickness function $<N_{coll}>/\sigma_{NN}$

Cross section in pp collisions (in vacuum)



- $<T_{AA}>$ quantifies the transverse overlap of two nuclei at impact parameter *b*

- Nuclear modification factor quantifies the change of yields in the medium, relatively to the production in vacuum.

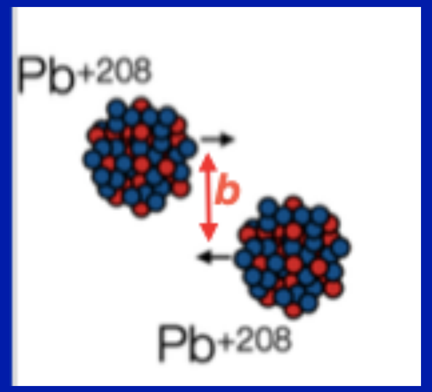
Intermezzo - Nuclear Modification Factor (R_{AA})

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

Yields in Pb+Pb collisions, (in medium)

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

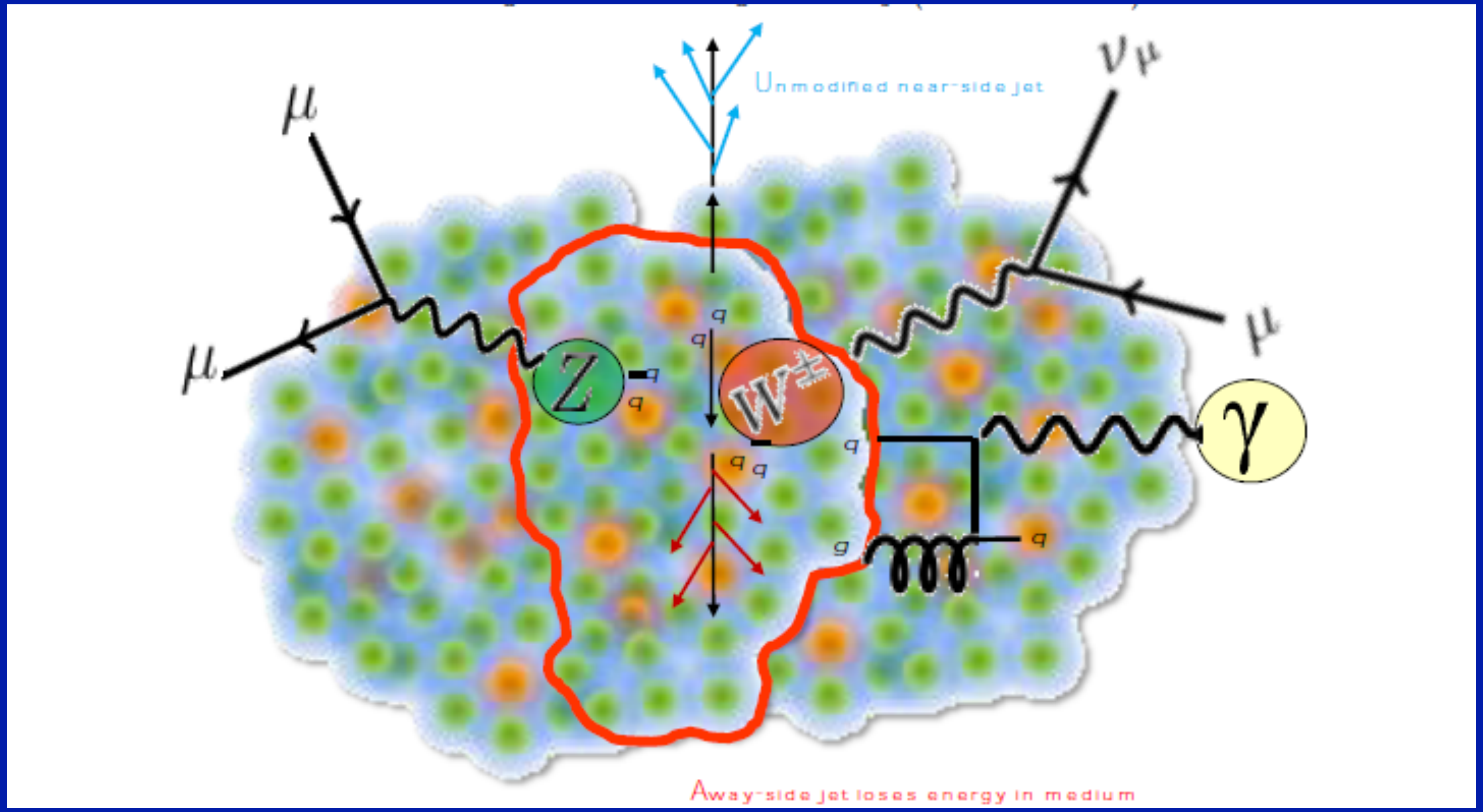
Cross section in pp collisions (in vacuum)



- $\langle T_{AA} \rangle$ quantifies the transverse overlap of two nuclei at impact parameter *b*
- 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.

Probing the initial stages - electroweak bosons

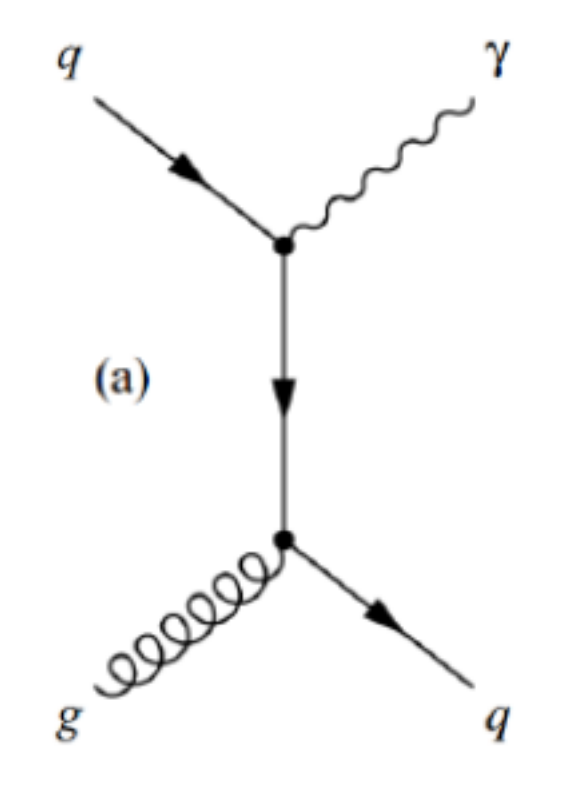
W/Z, photons are produced at the initial stages of HI collisions but they are insensitive to QGP



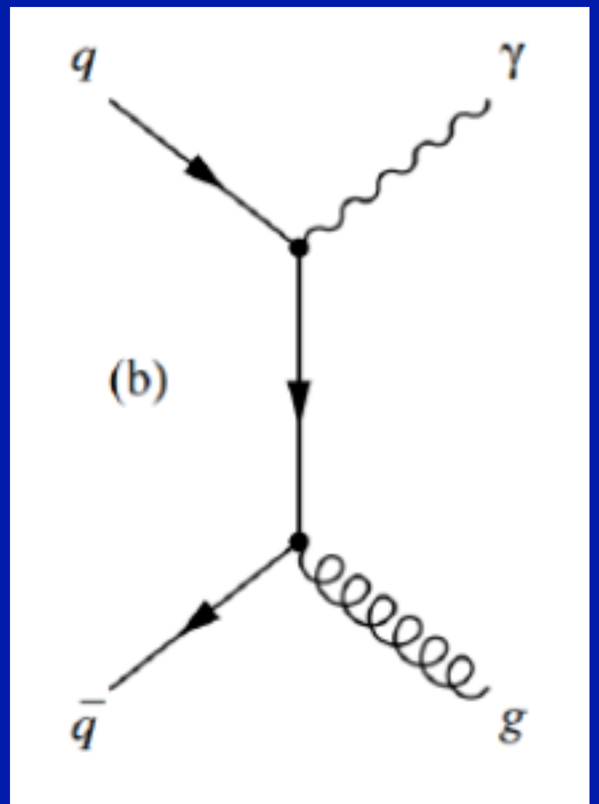
- They probe nuclear PDFs, since their cross sections are determined by the quark and antiquark momentum distributions inside bound nucleons.
- They an be used to check models of collision geometry because their production is expected to be proportional to the nuclear overlap.
- Provide calibration for jet energy loss in the QGP (photon-jet, Z-jet).

Probing the initial stages - prompt photons

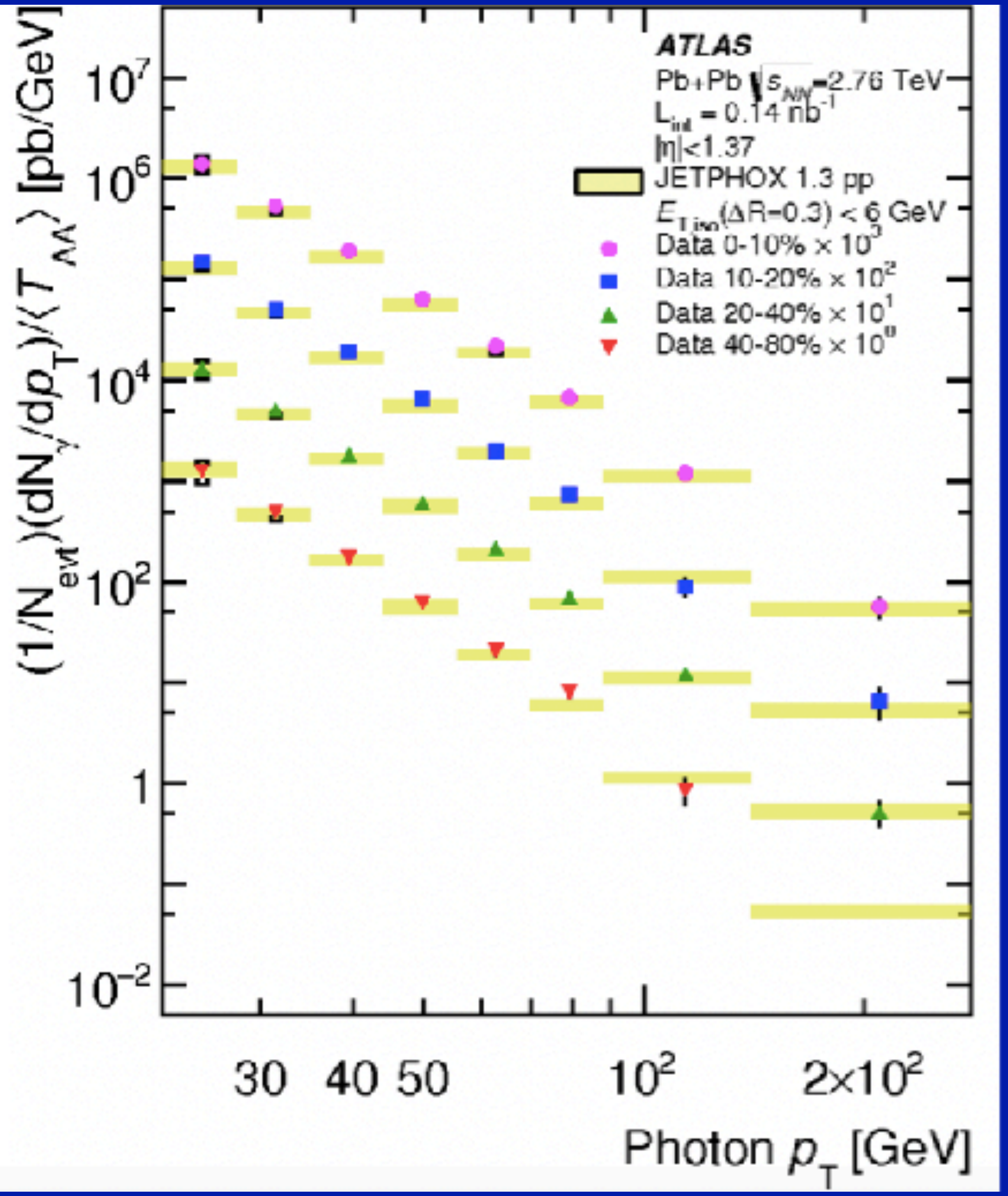
QCD Compton scattering



quark-antiquark annilhilation

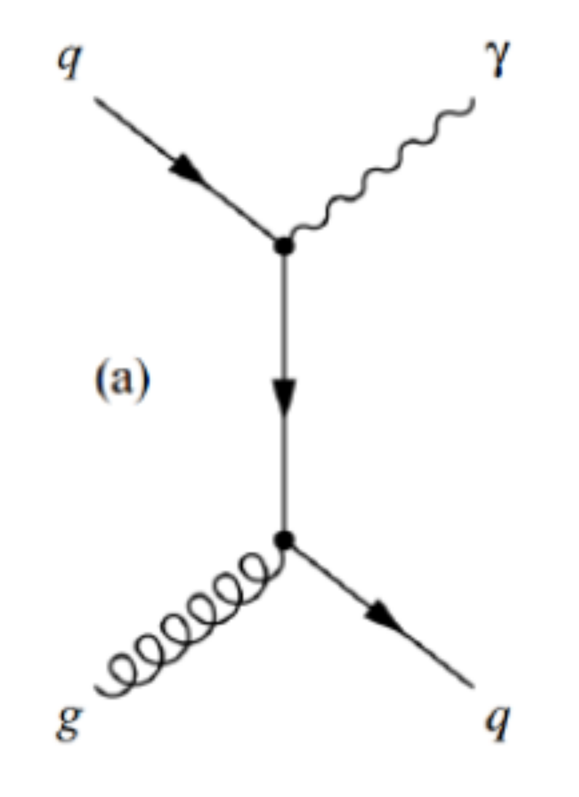


Prompt photons as a function of p_T

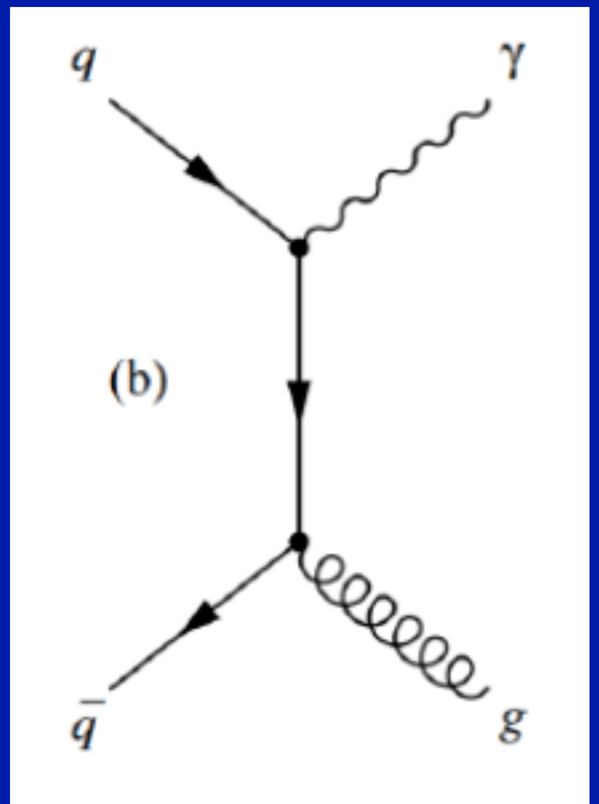


Probing the initial stages - prompt photons

QCD Compton scattering

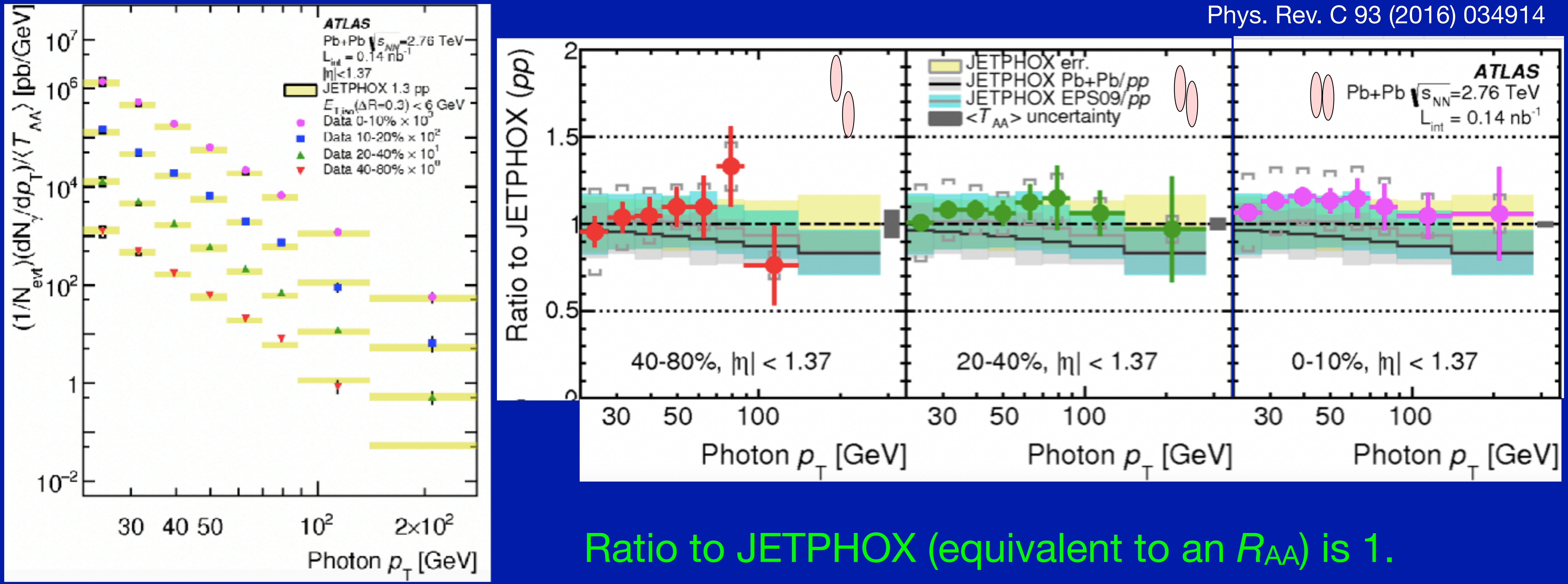


quark-antiquark annilhilation



Prompt photons as a function of p_T

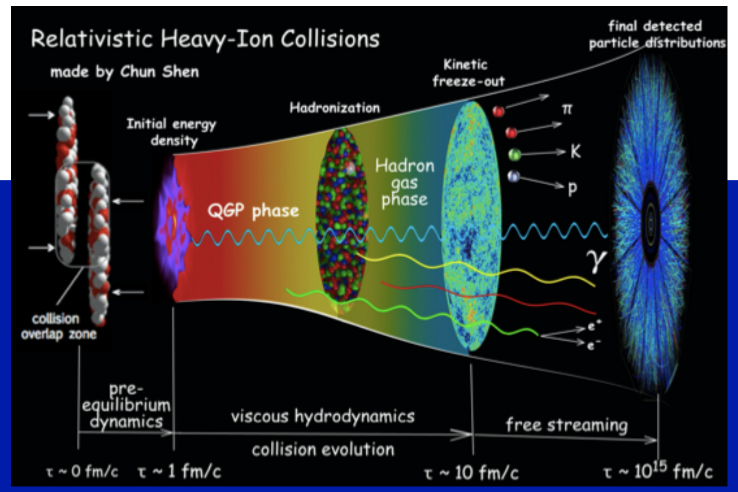
Phys. Rev. C 93 (2016) 034914



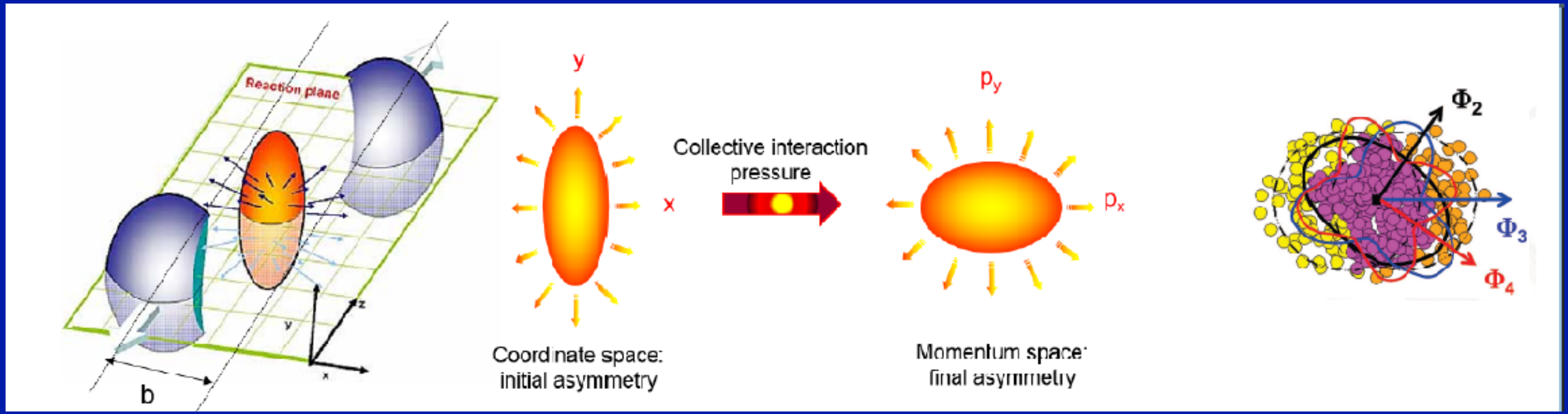
Ratio to JETPHOX (equivalent to an R_{AA}) is 1.

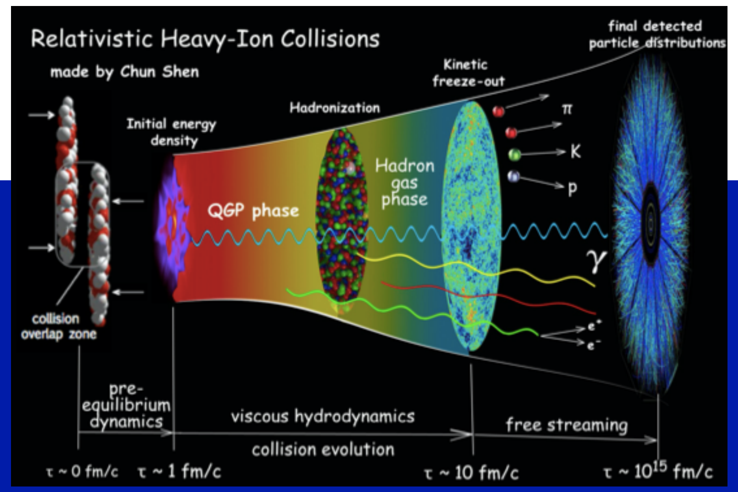
Photon production is not modiefied in the QGP.

Probing the initial stages and QGP - Flow

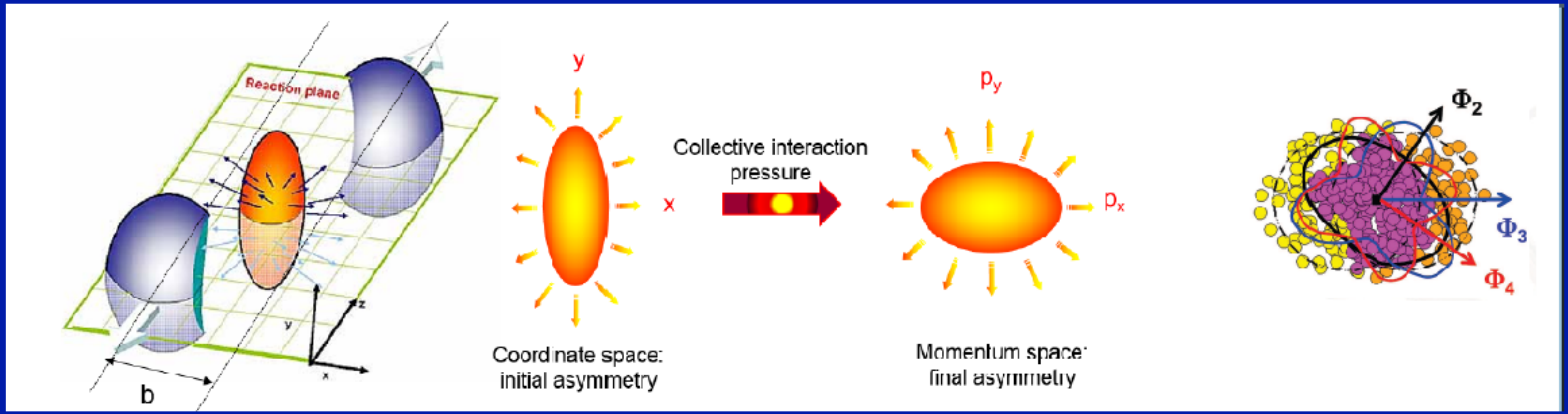


Probing the initial stages and QGP - Flow





Probing the initial stages and QGP - Flow

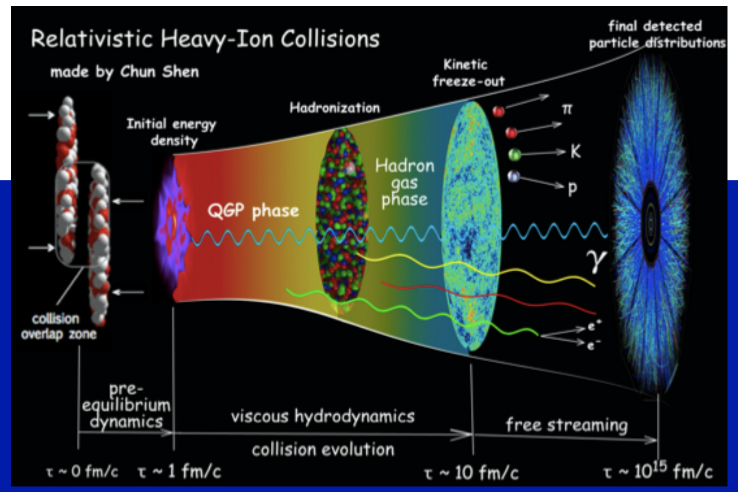


Anisotropic collective motion is described by a Fourier expansion of particle distribution in azimuthal angle ϕ

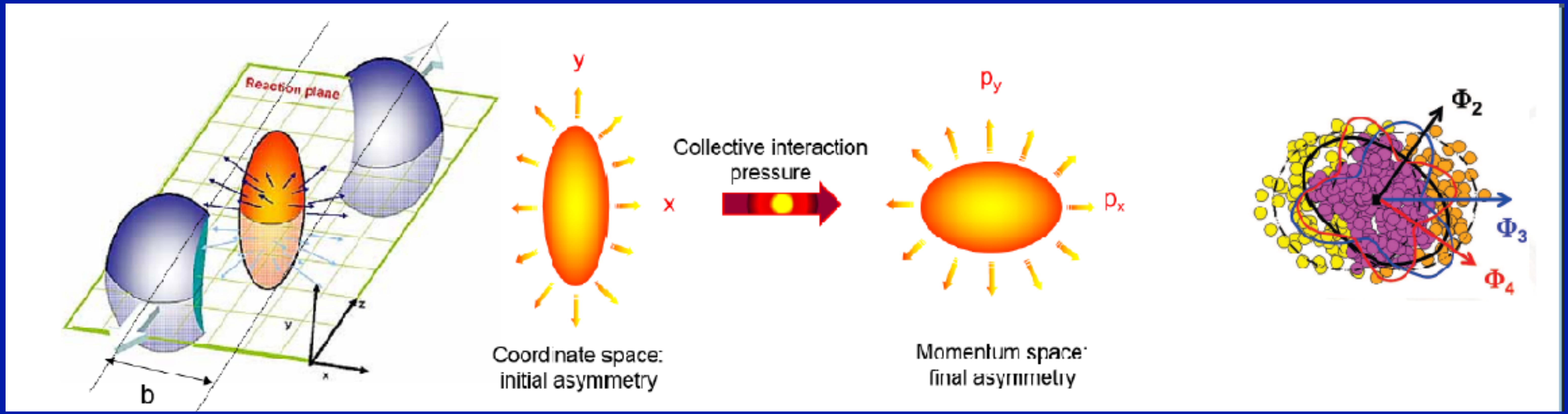
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

Coefficients *n* are associated with different eccentricities $\varepsilon_n e^{in\Phi n}$ and hydrodynamics maps these spatial anisotropies into the corresponding azimuthal anisotropy coefficients $v_n \approx \kappa_n \varepsilon_n$, where κ_n depends on viscosity, system size, lifetime, equation of state.

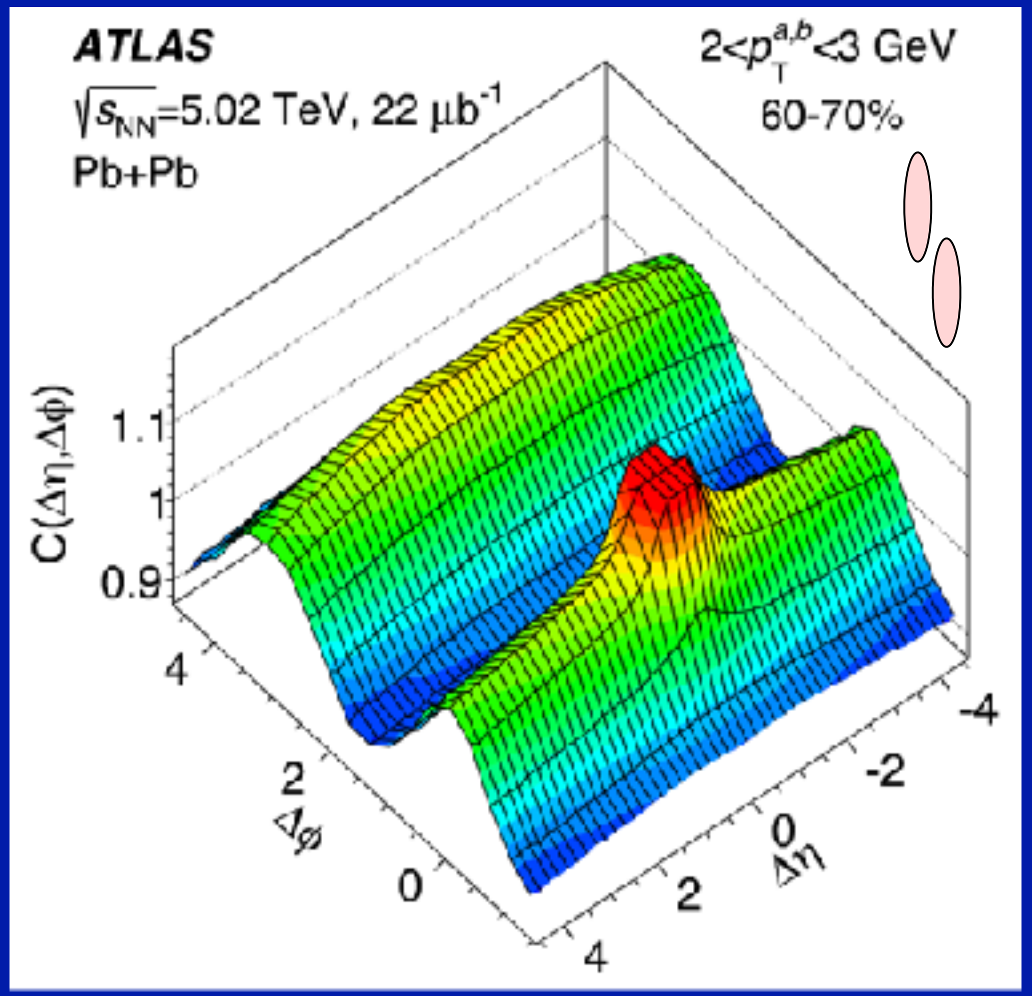
- ε_2 gives elliptic flow v_2
- ε_3 gives triangular flow v_3
- ε_4 gives quadrangular flow v_4

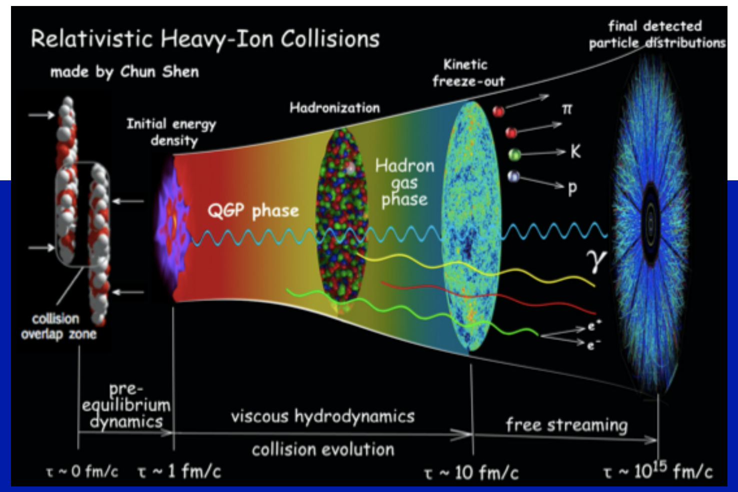


Probing the initial stages and QGP- Flow

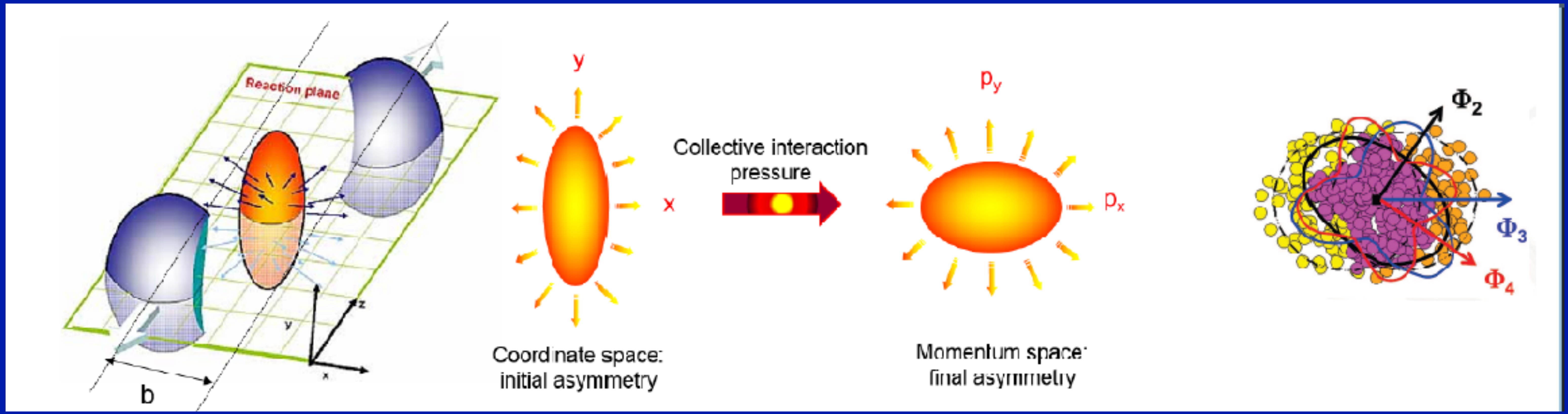


correlation between pairs of particles formed in high-multiplicity collisions

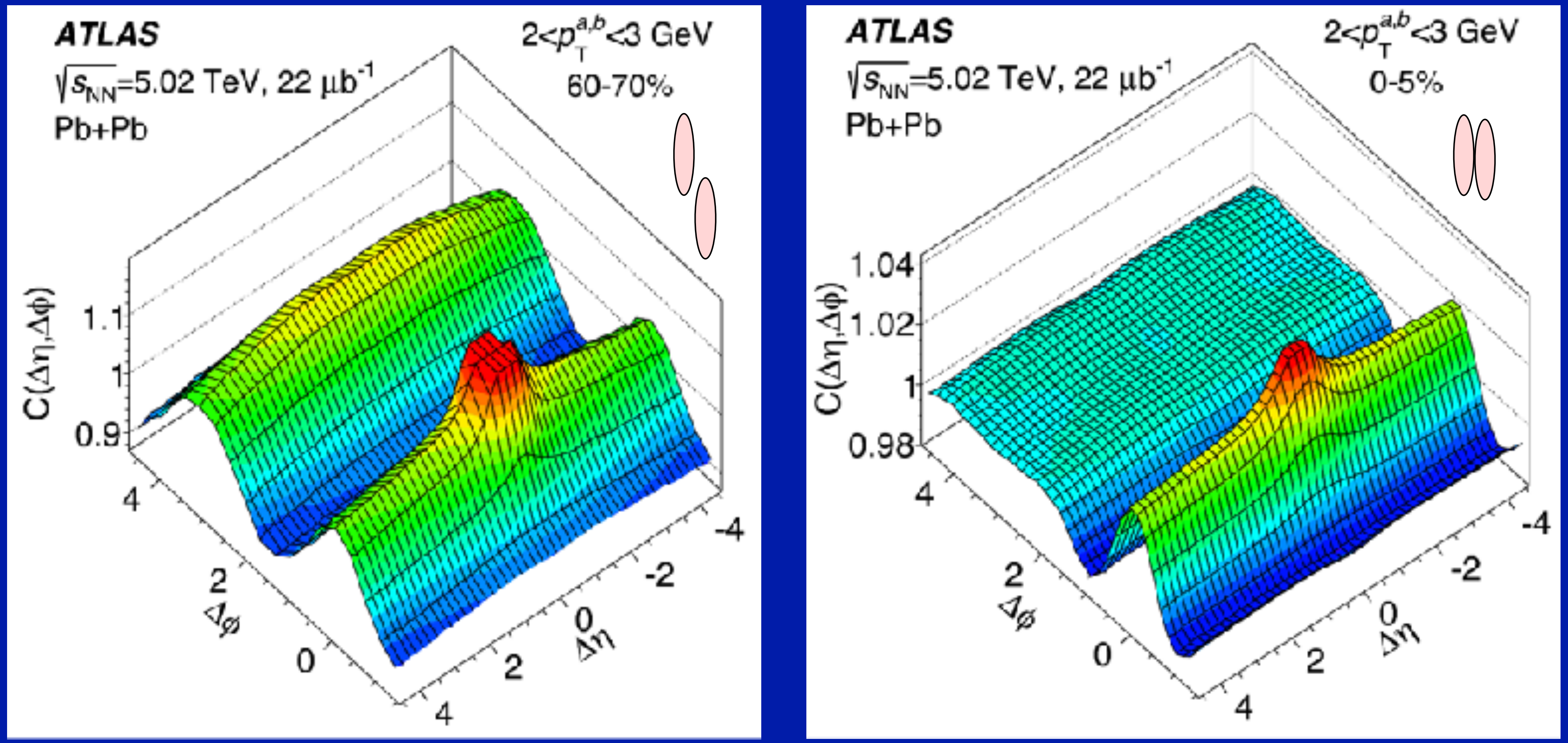


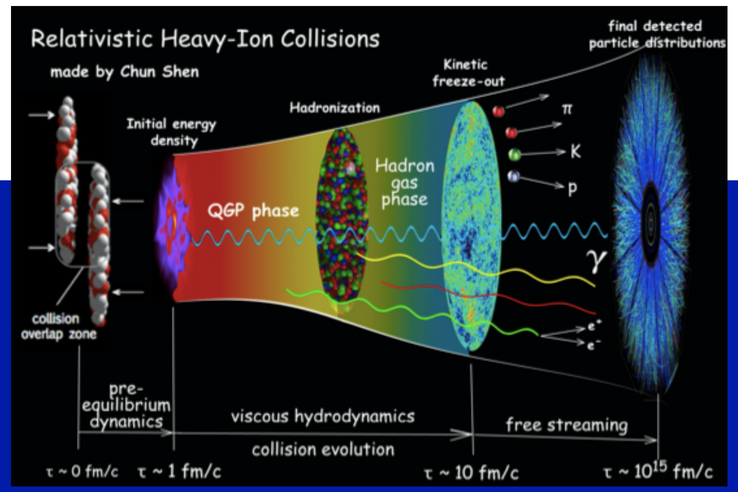


Probing the initial stages and QGP - Flow



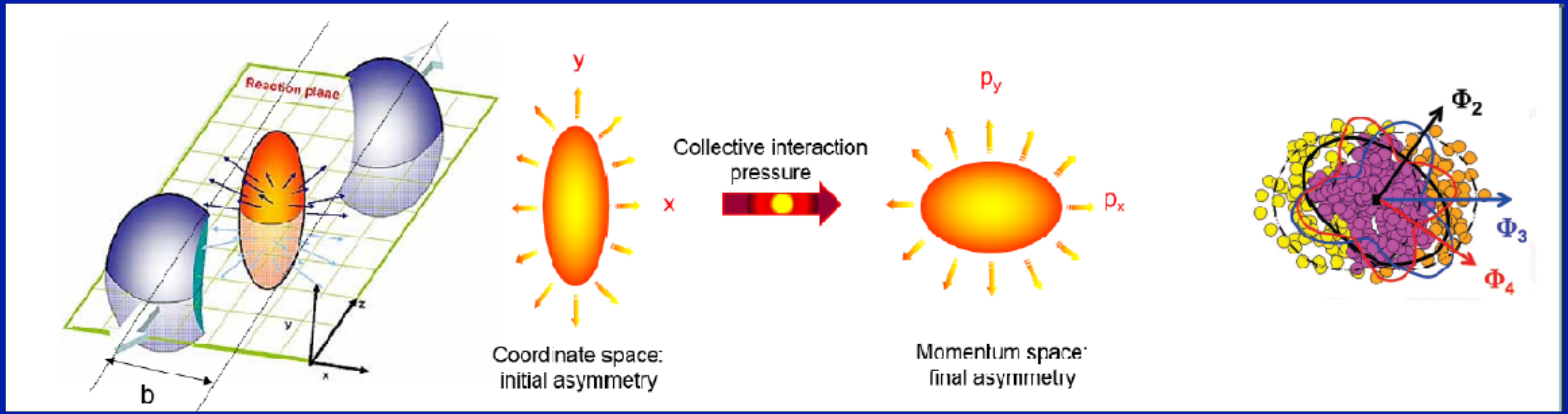
correlation between pairs of particles formed in high-multiplicity collisions



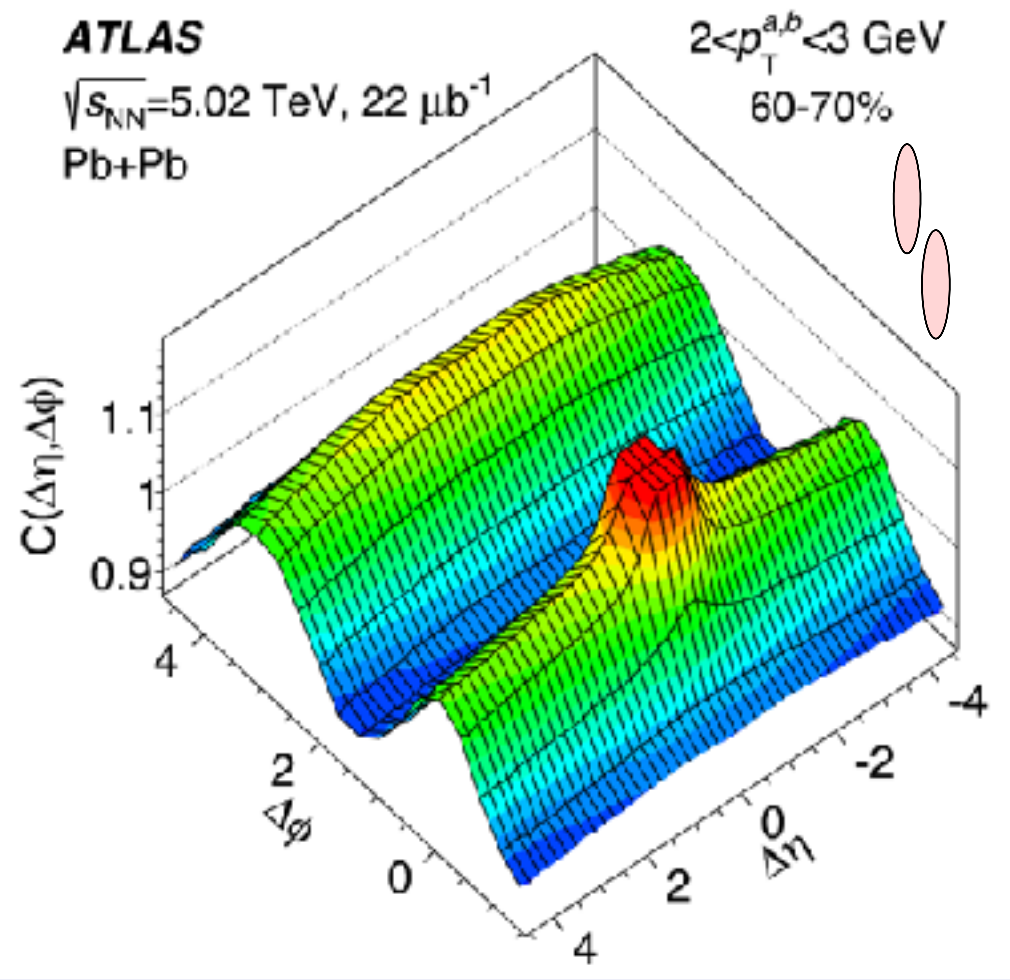


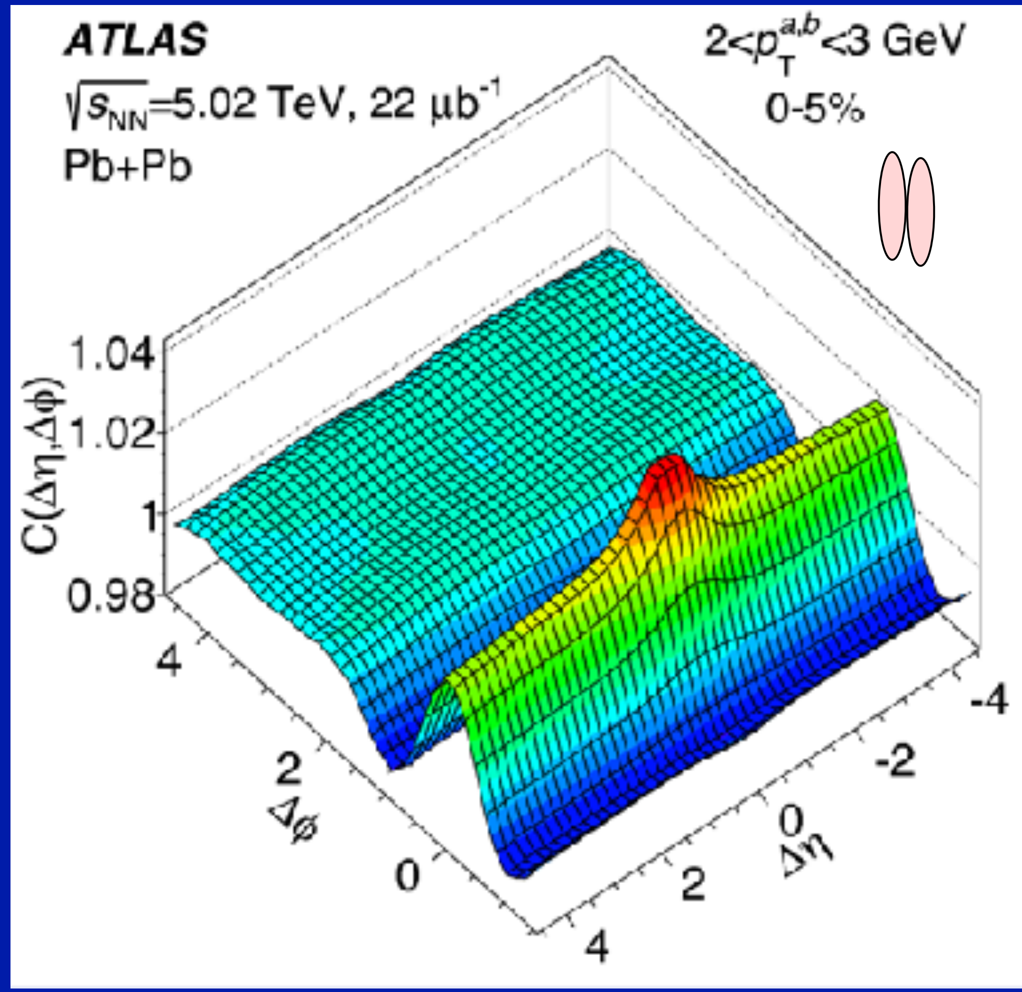
Probing the initial stages and QGP - Flow

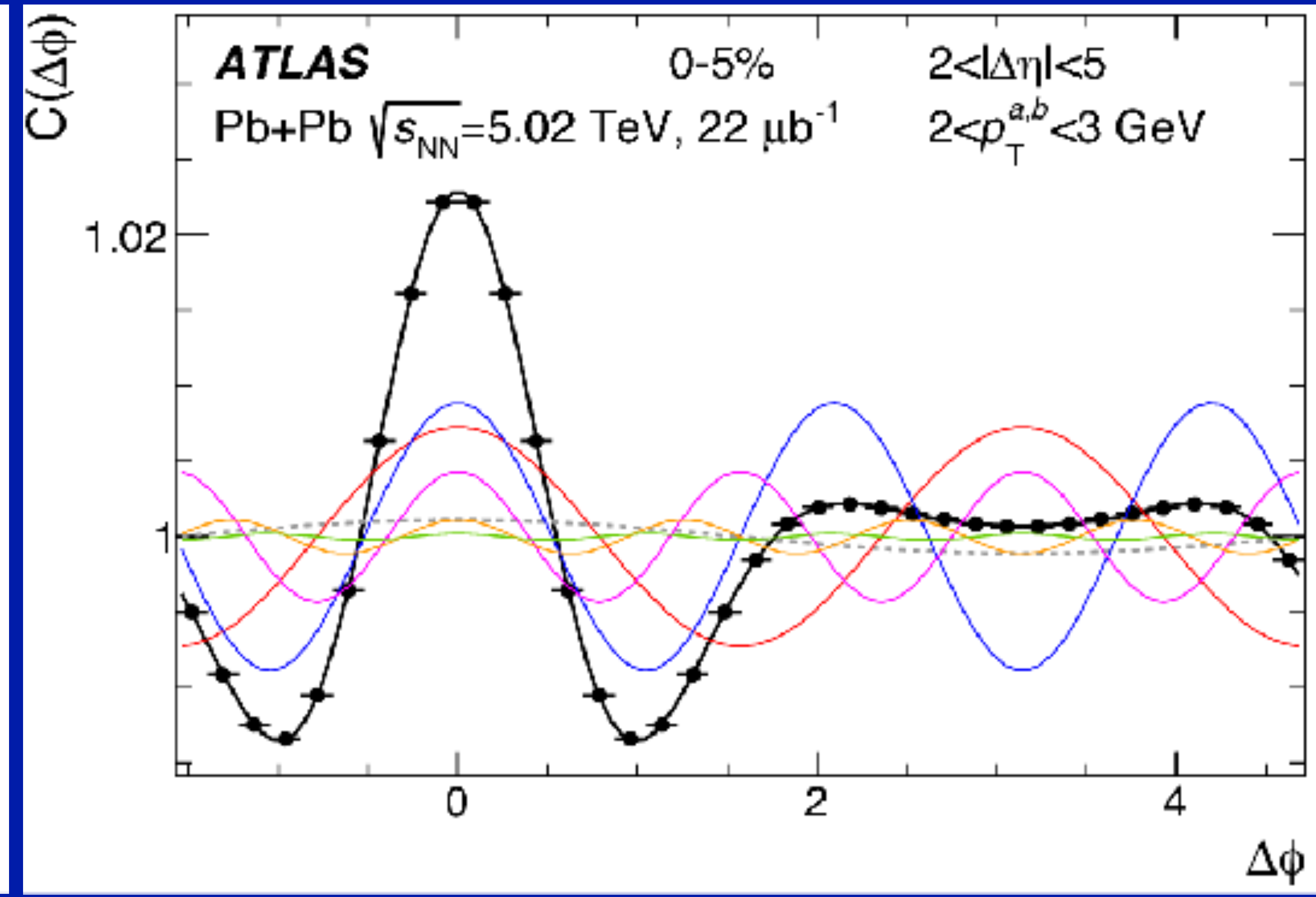
arXiv:1808.03951v2 [nucl-ex]



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

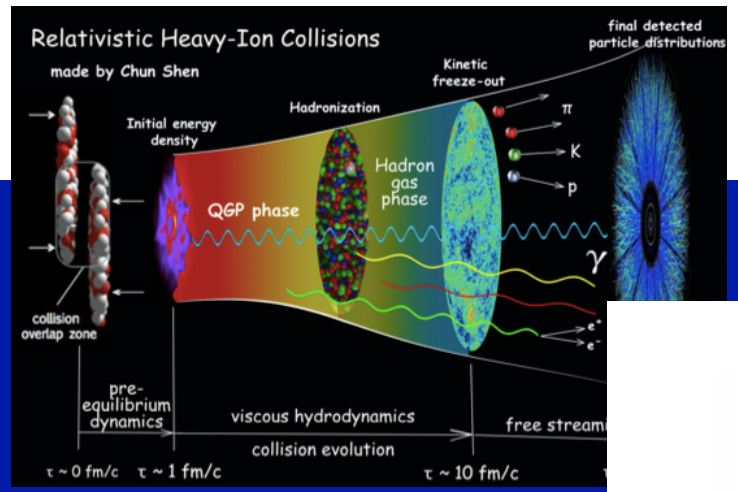


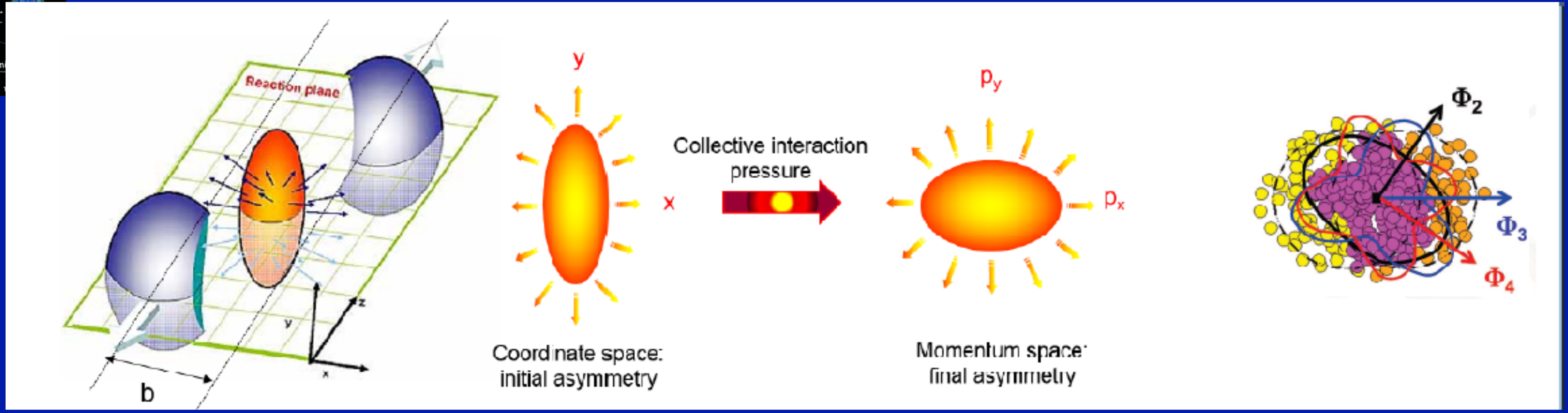


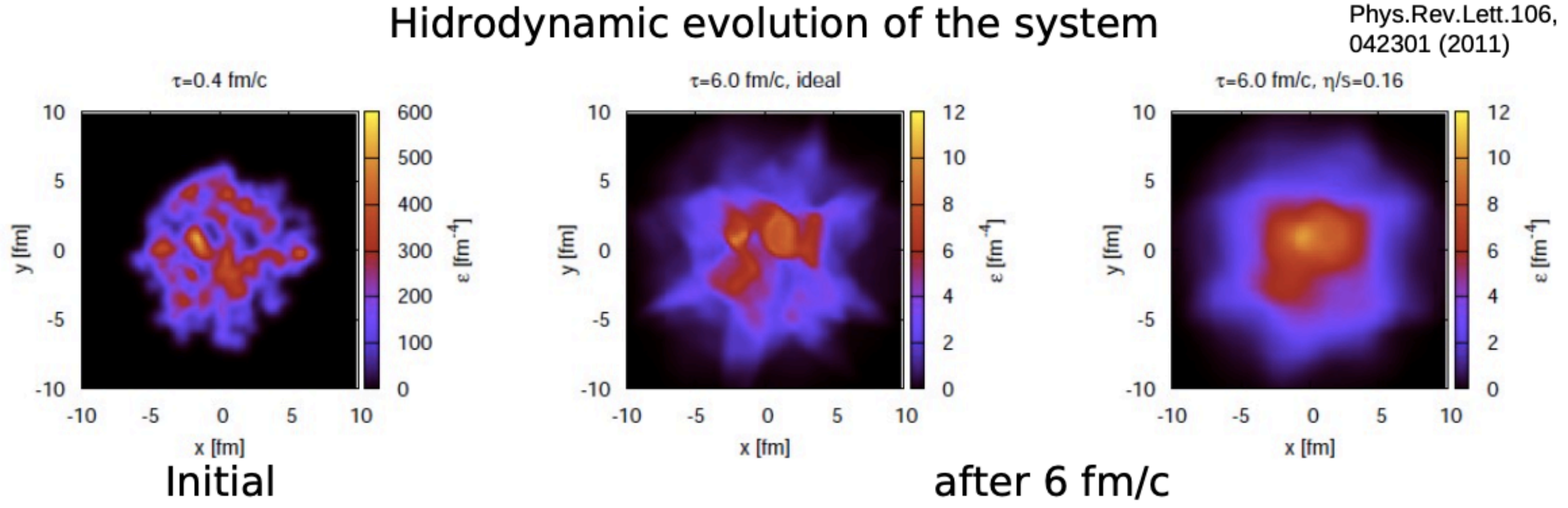


Visible ridge along $\Delta\eta$
Strong suppression at the away-side ($\Delta\varphi\approx\pi$) in central collisions

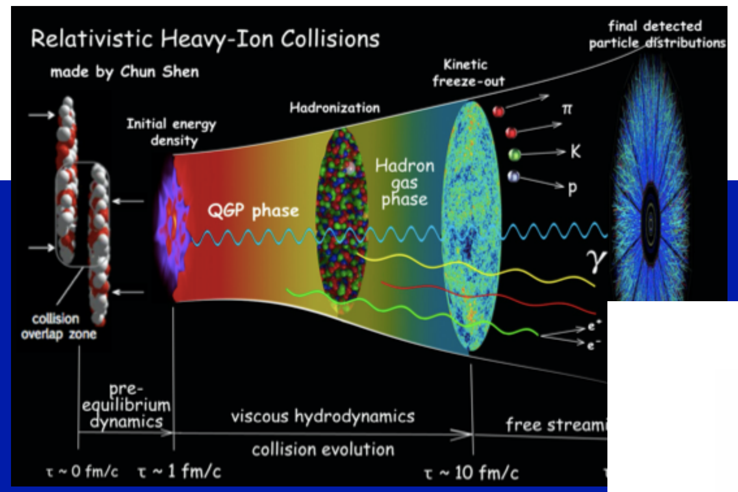
Probing the initial stages and QGP - Flow



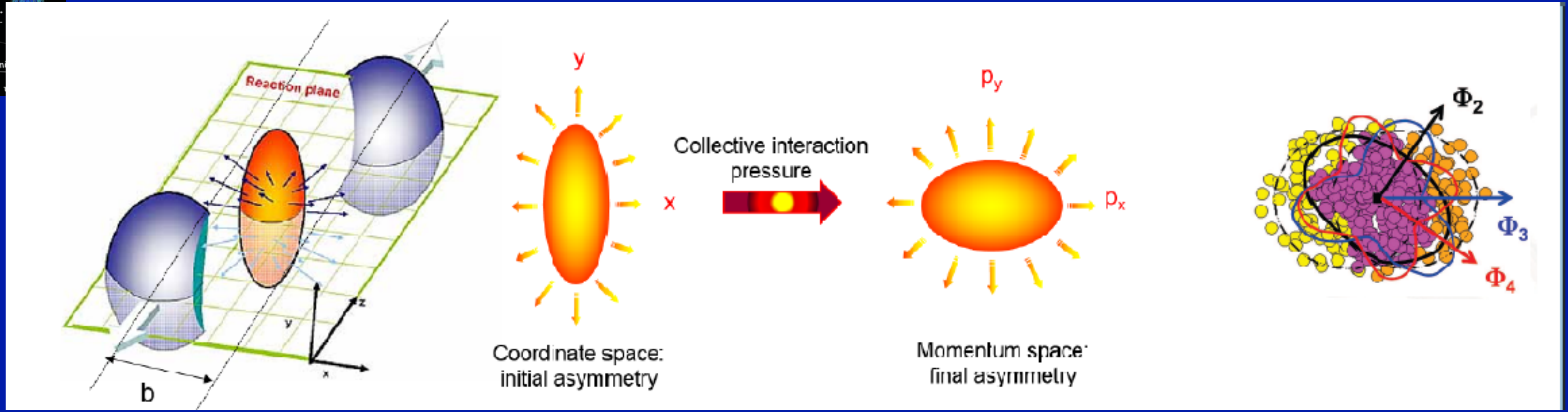


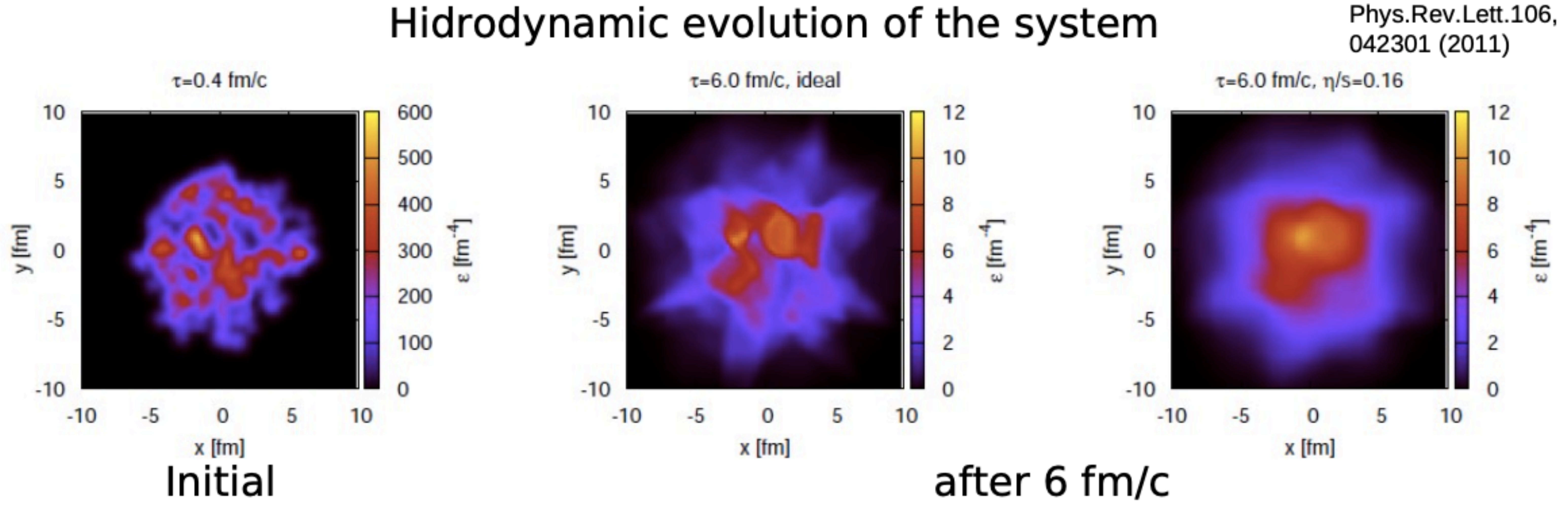


Viscosity over entropy density, η/s, measures how strongly velocity gradients are dissipated. In a weakly coupled system, particles travel farther before interacting, so momentum is transported over larger distances and the viscosity is high. In a strongly coupled medium, the mean free path is short, momentum is redistributed over short distances, and η/s is low.



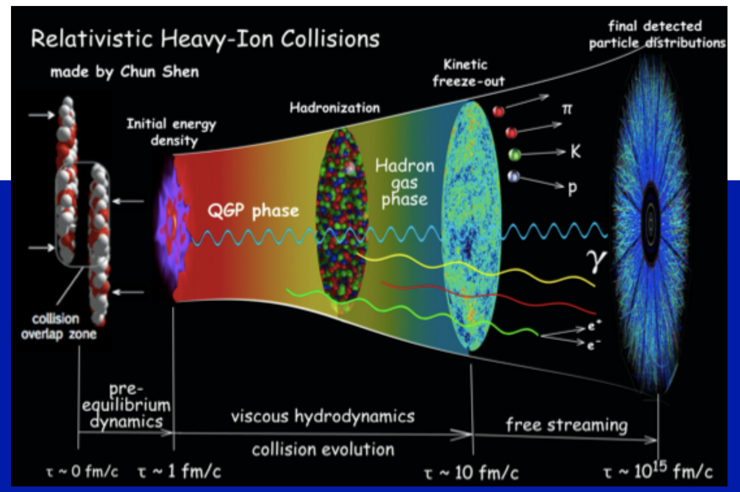
Probing the initial stages and QGP - Flow





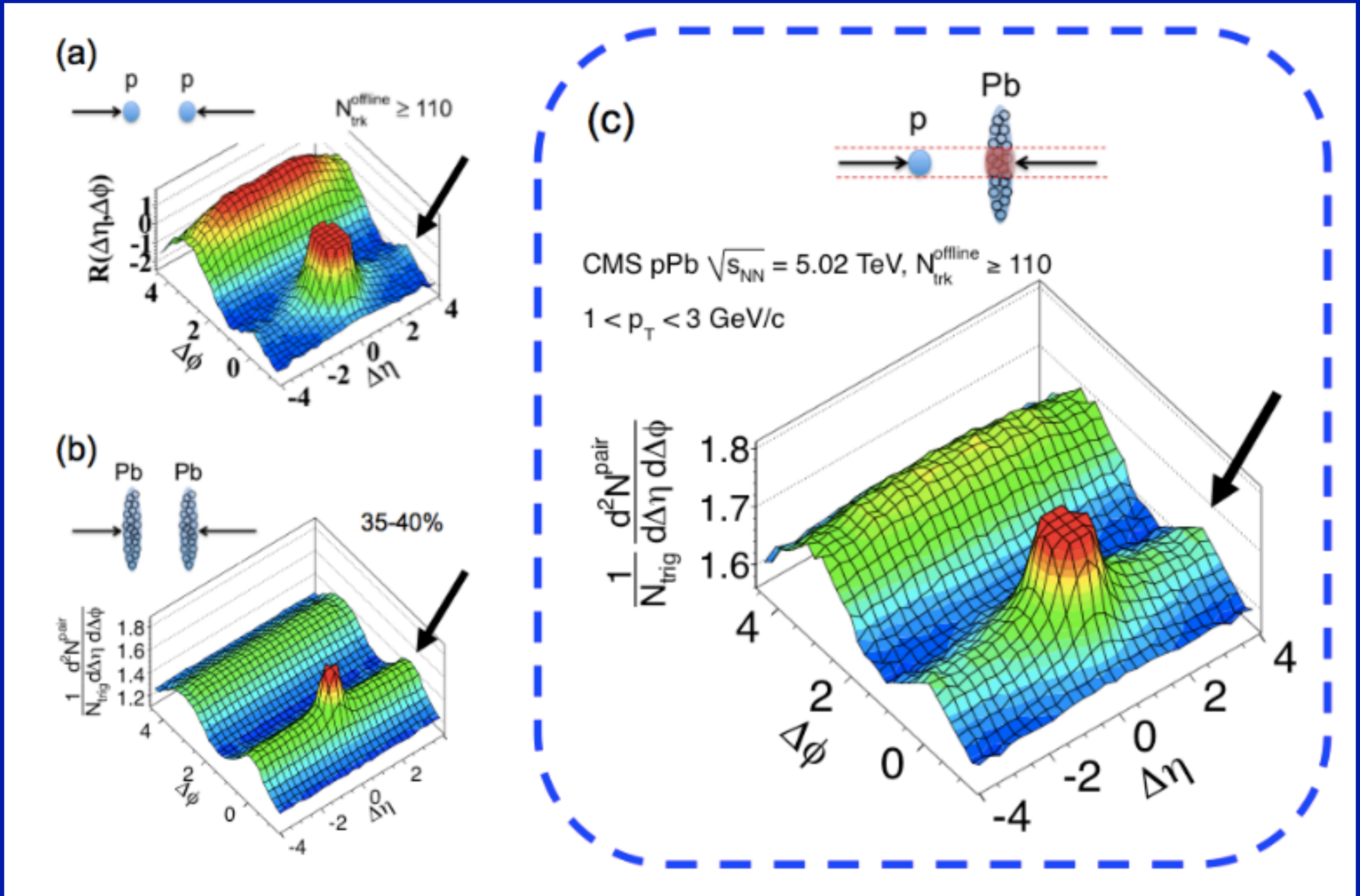
Viscosity over entropy density, η/s, measures how strongly velocity gradients are dissipated. In a weakly coupled system, particles travel farther before interacting, so momentum is transported over larger distances and the viscosity is high. In a strongly coupled medium, the mean free path is short, momentum is redistributed over short distances, and η/s is low.

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

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.



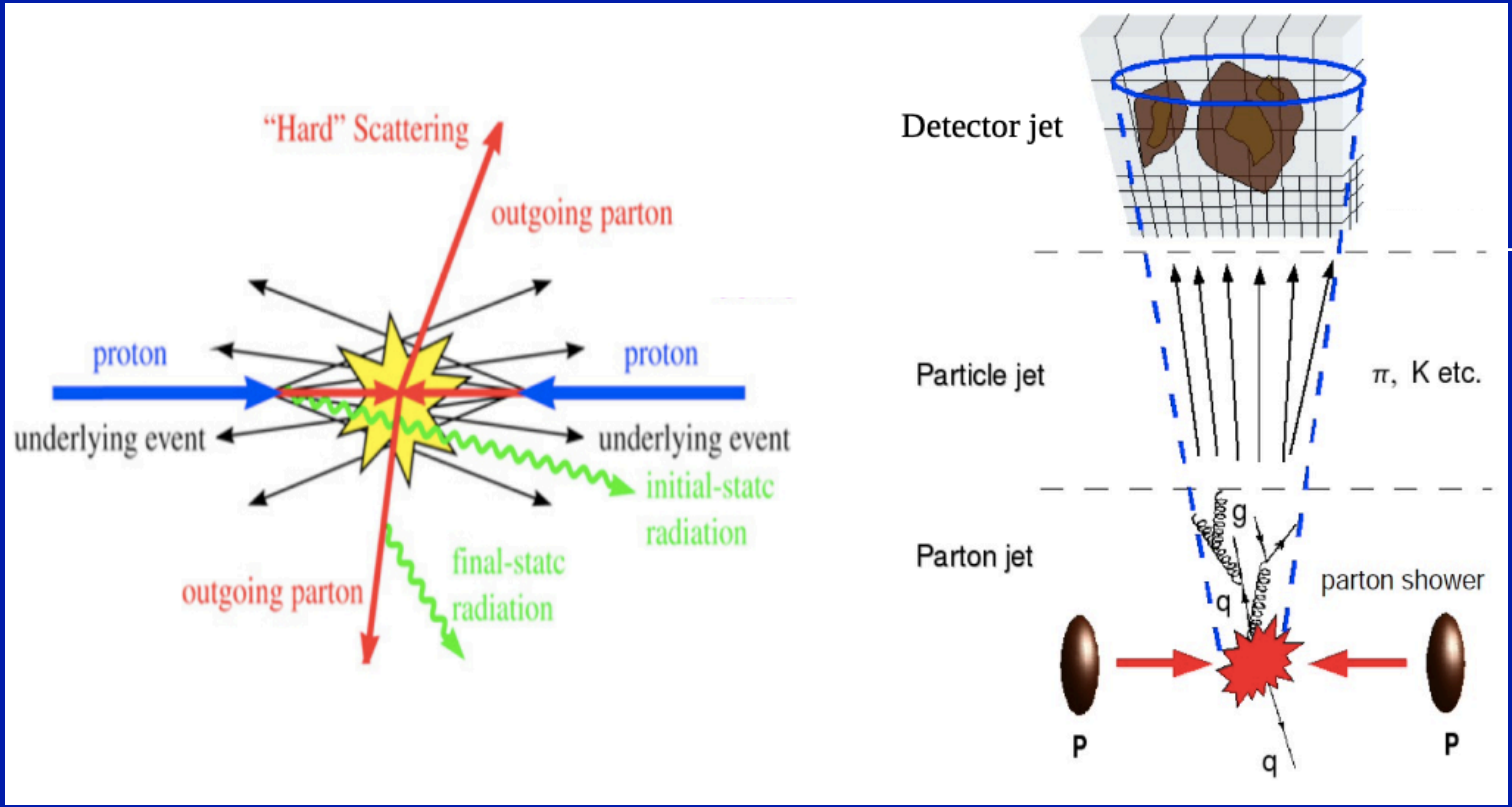
The effect in pPb collisions is much stronger than in pp collisions.

The ridge remains in small collisions systems. In pPb there is substantial evidence for genuine collectivity, while in pp the origin remains actively debated, with both initial-state and final-state mechanisms likely playing a role.

Probing the QGP and hadronic states - Jets

Probing the QGP and hadronic states - Jets

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

Probing the QGP and hadronic states - Jets

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

JHEP 0804:063,2008

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

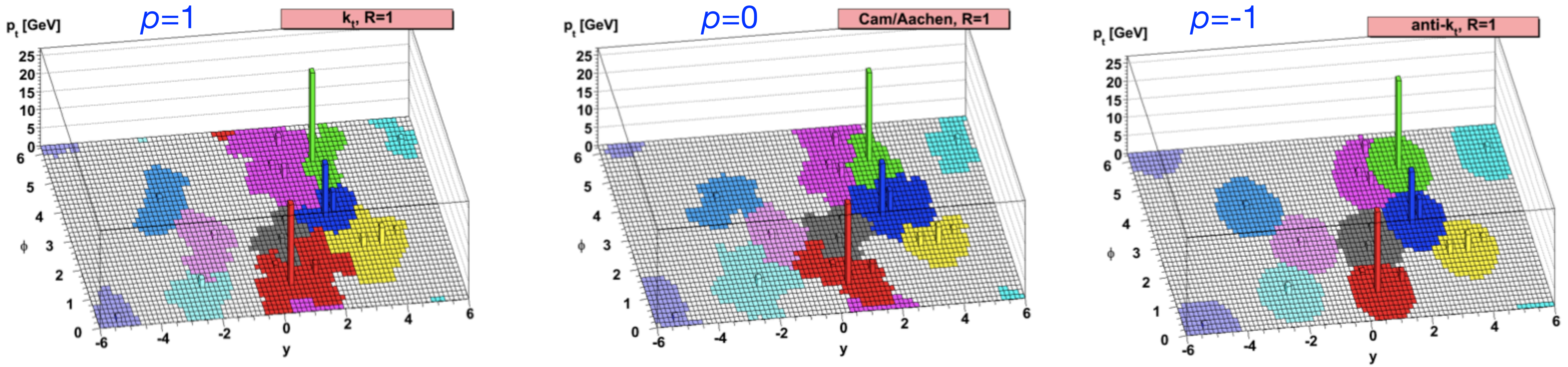
$$d_{iB} = k_{ti}^{2p}, \qquad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

A sequential algorithm builds a jet step by step:

- start from many inputs (calo clusters, towers, tracks, particle-flow objects)
- merge the closest pair into a pseudojet
- keep updating the pseudojet momentum by four-vector addition
- stop when that object is better interpreted as a completed jet than as something that should merge further

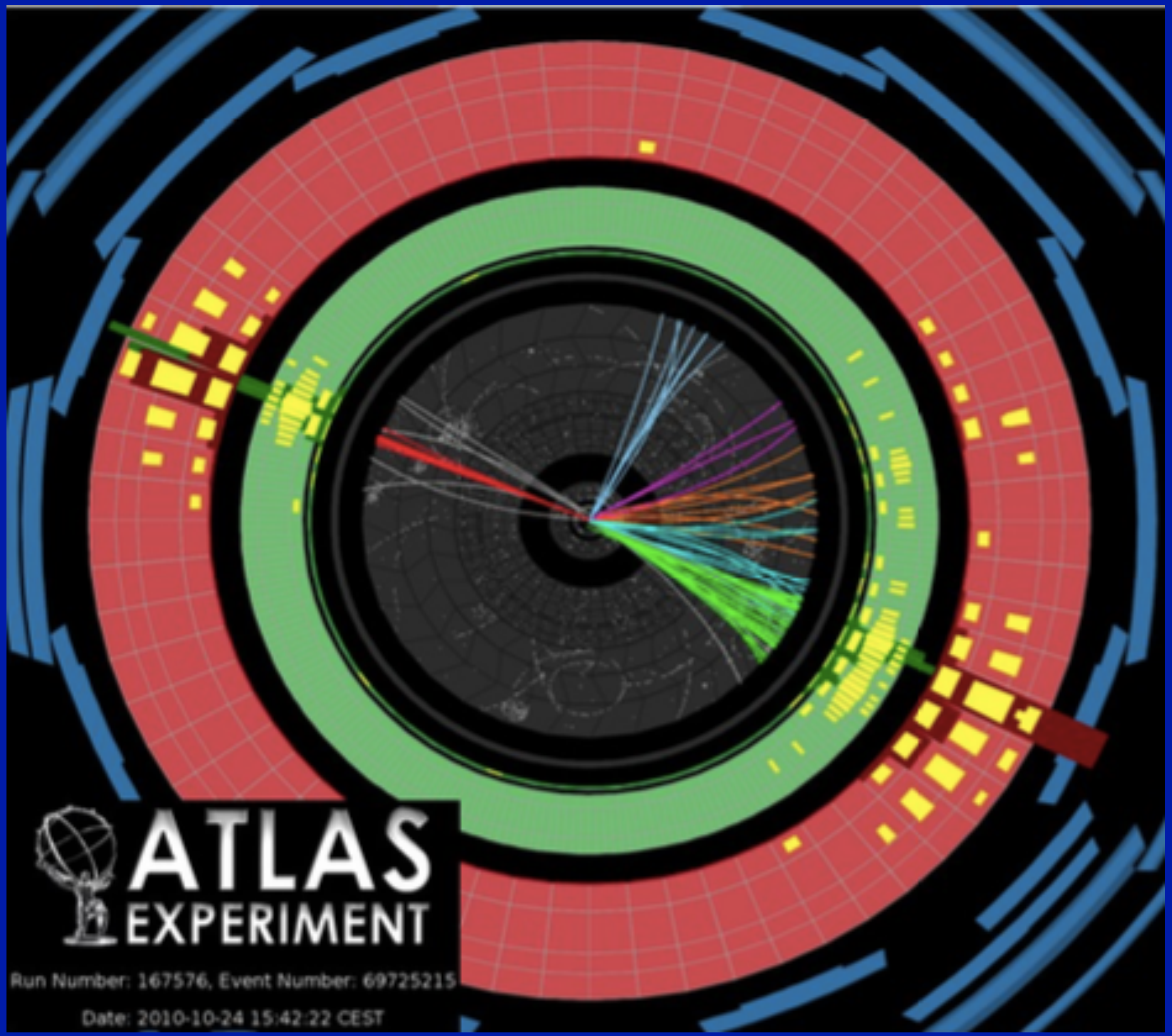
Jet size runs from R = 0.2 … 1.0 (R sets how close particles must be in η–ϕ space to be grouped into one jet)

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 → the so called anti-k_t jet clustering algorithm.



Probing the QGP and hadronic states - Jets

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



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

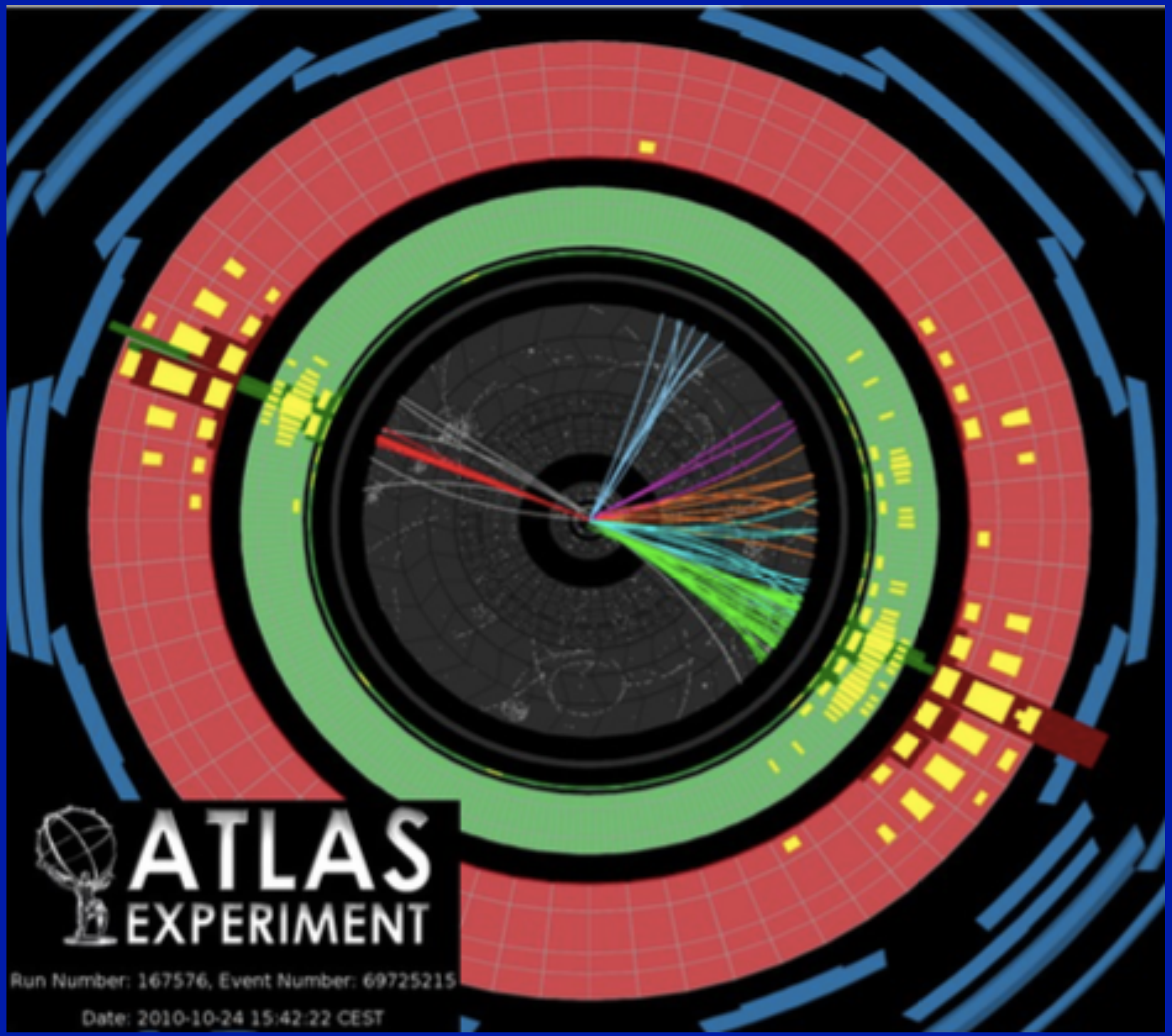
Leading jet : p_T = 1.3 TeV, η = 0.2, ϕ = -0.5

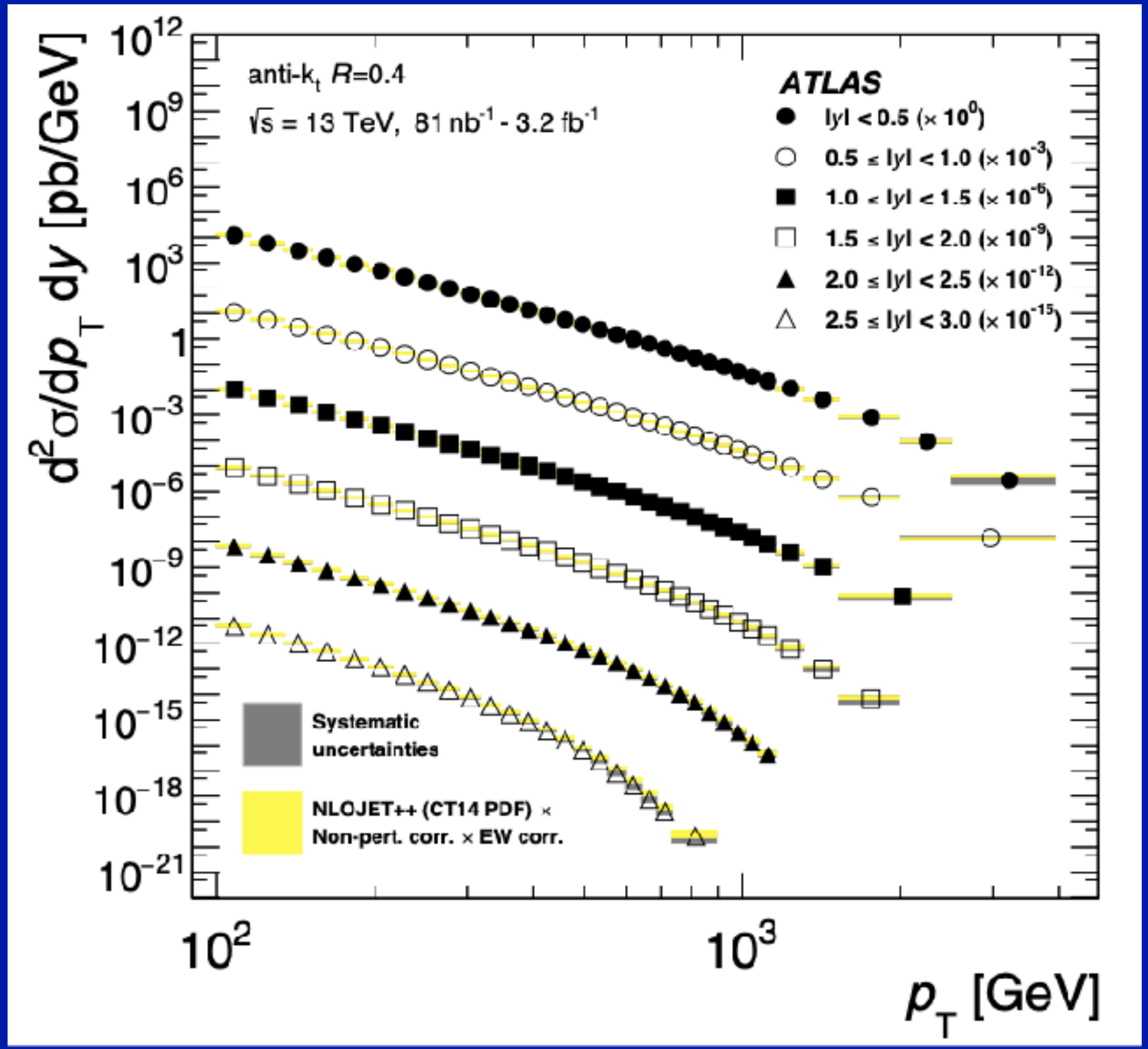
Sub-leading jet: p_T = 1.2 TeV, η = 0.0, ϕ = 2.8

Probing the QGP and hadronic states - Jets

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

JHEP 05 (2018) 195

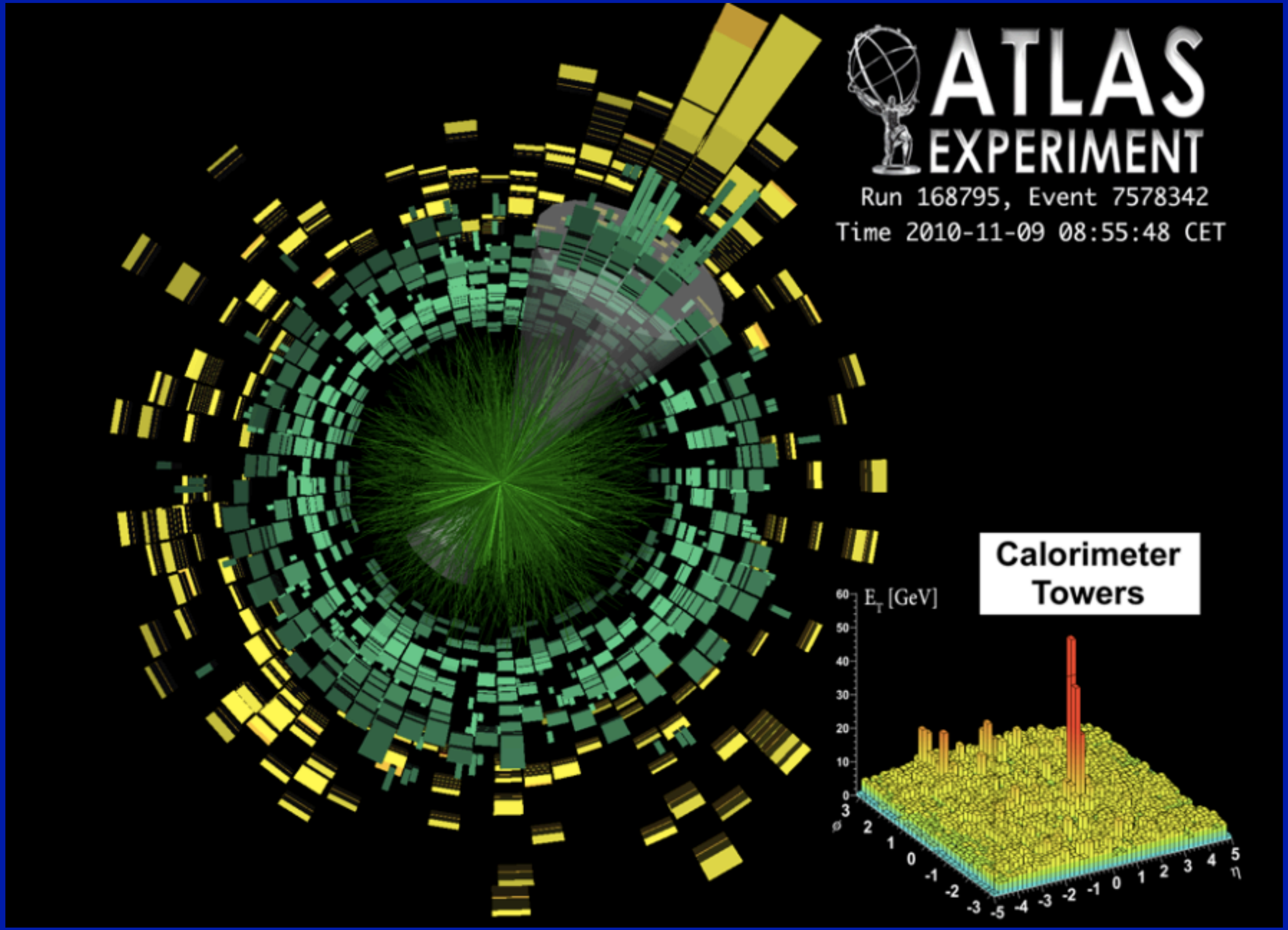




Jet production at LHC *pp* collisions is well understood over 9 orders of magnitude and up to 3 TeV

Probing the QGP and hadronic states - Jets

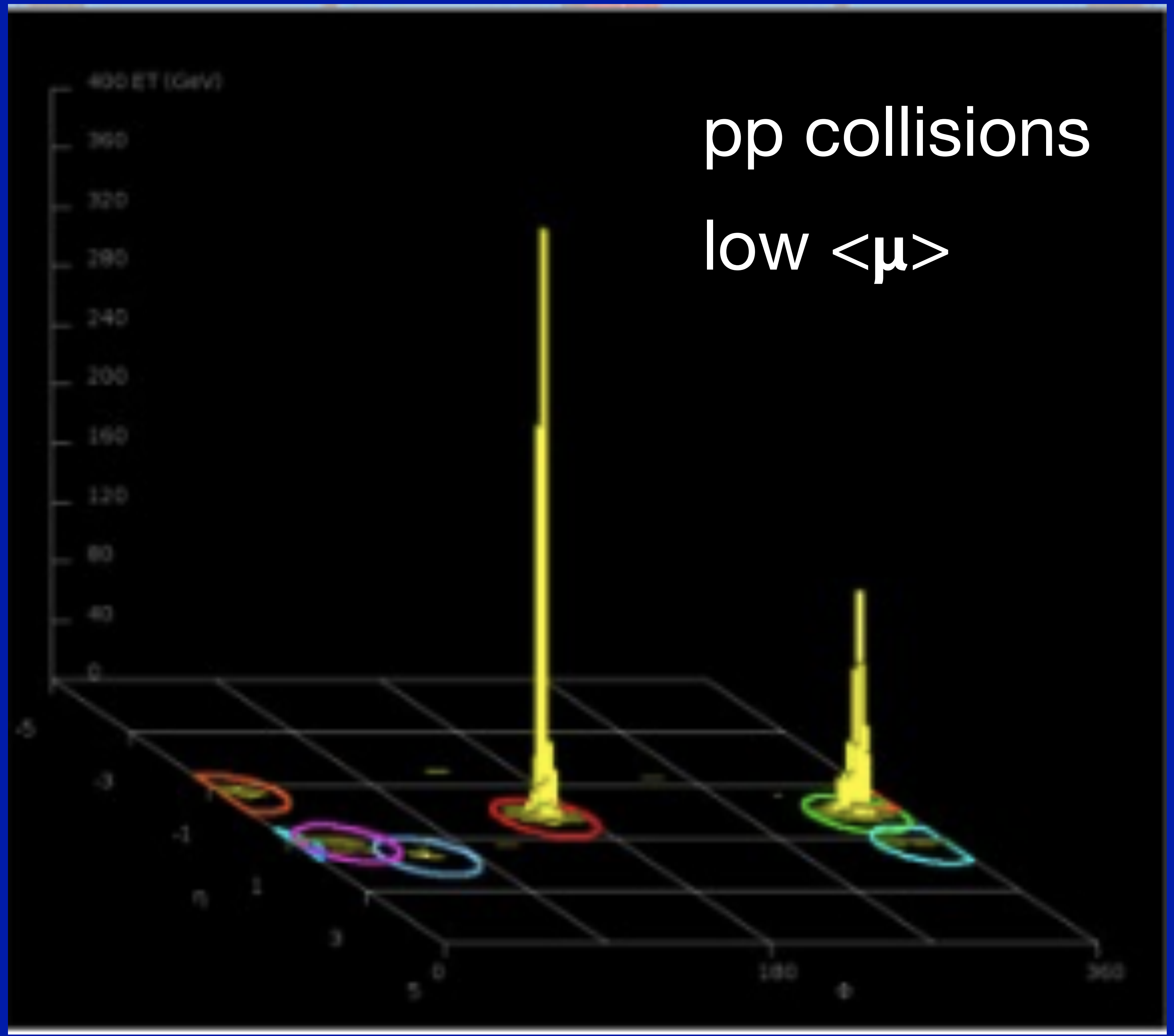
But dijets at Pb+Pb collisions are largely asymmetric —> “Jet Quenching”



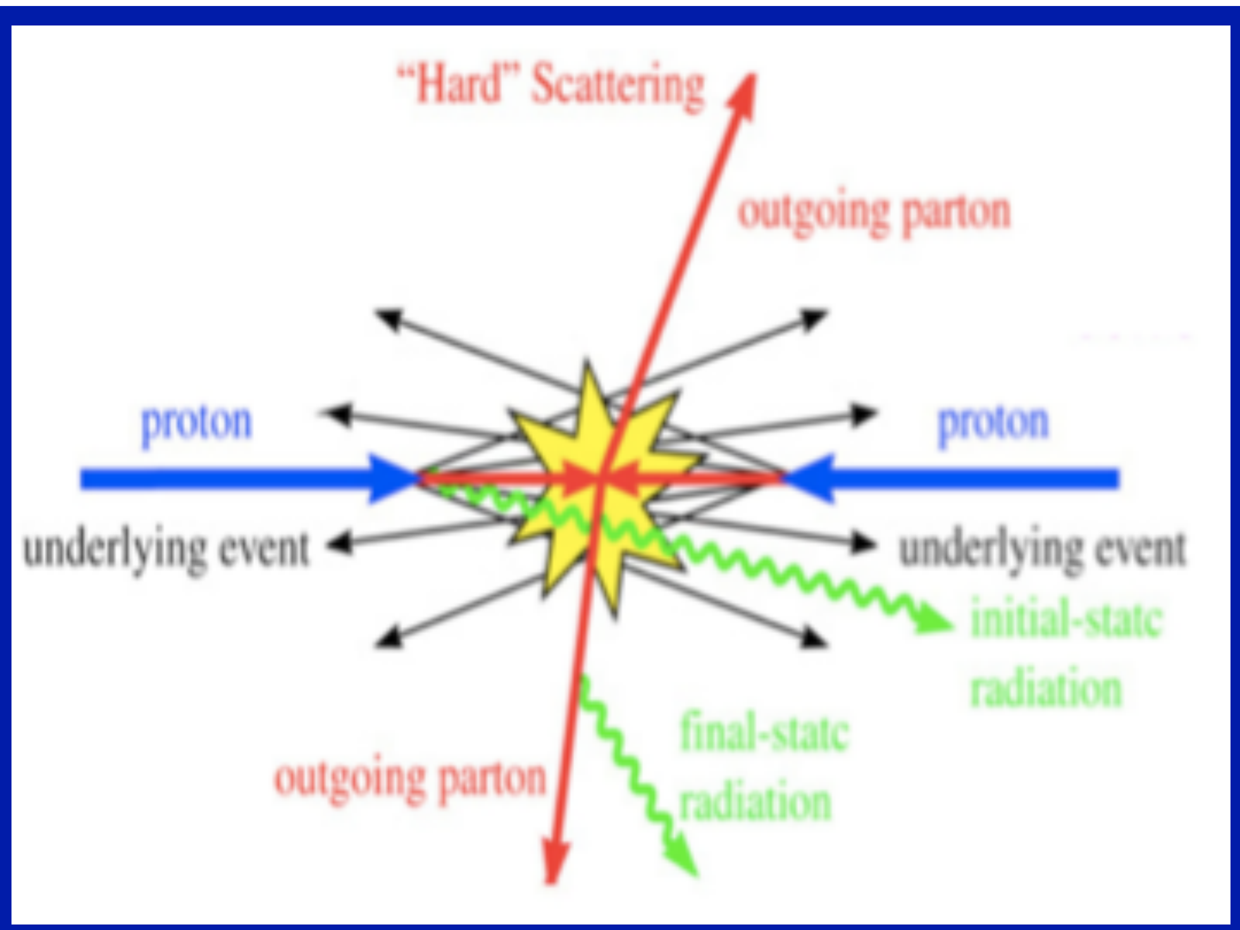
Jet quenching is the modification of the parton showers in the QGP. The partons loose energy while traversing it.

Probing the QGP and hadronic states - Jets

Event seen by the calorimeters



Granularity of the ATLAS calorimeters: $\Delta\eta \times \Delta\phi$ = 0.1x0.1 "towers" (piled calorimeter cells)

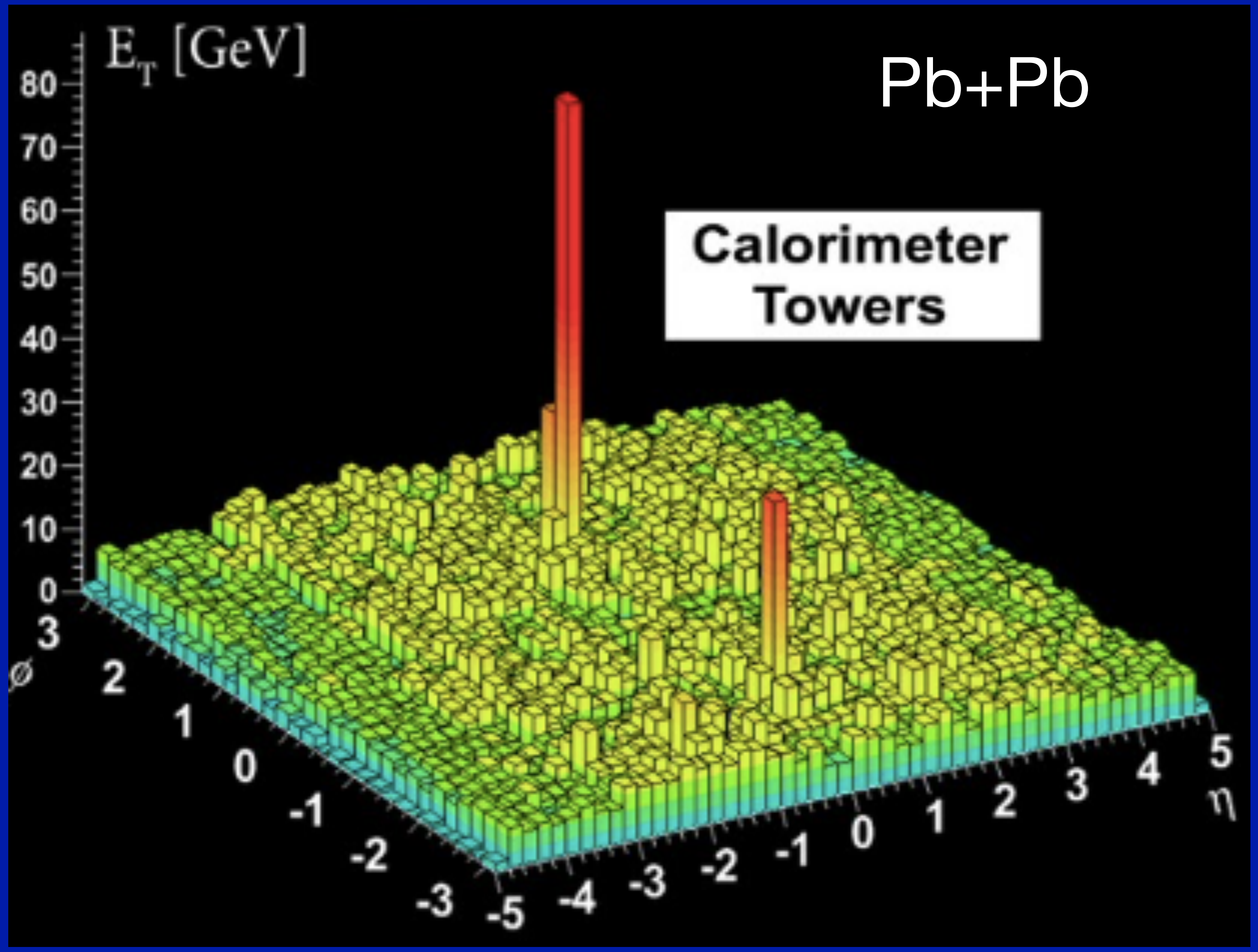


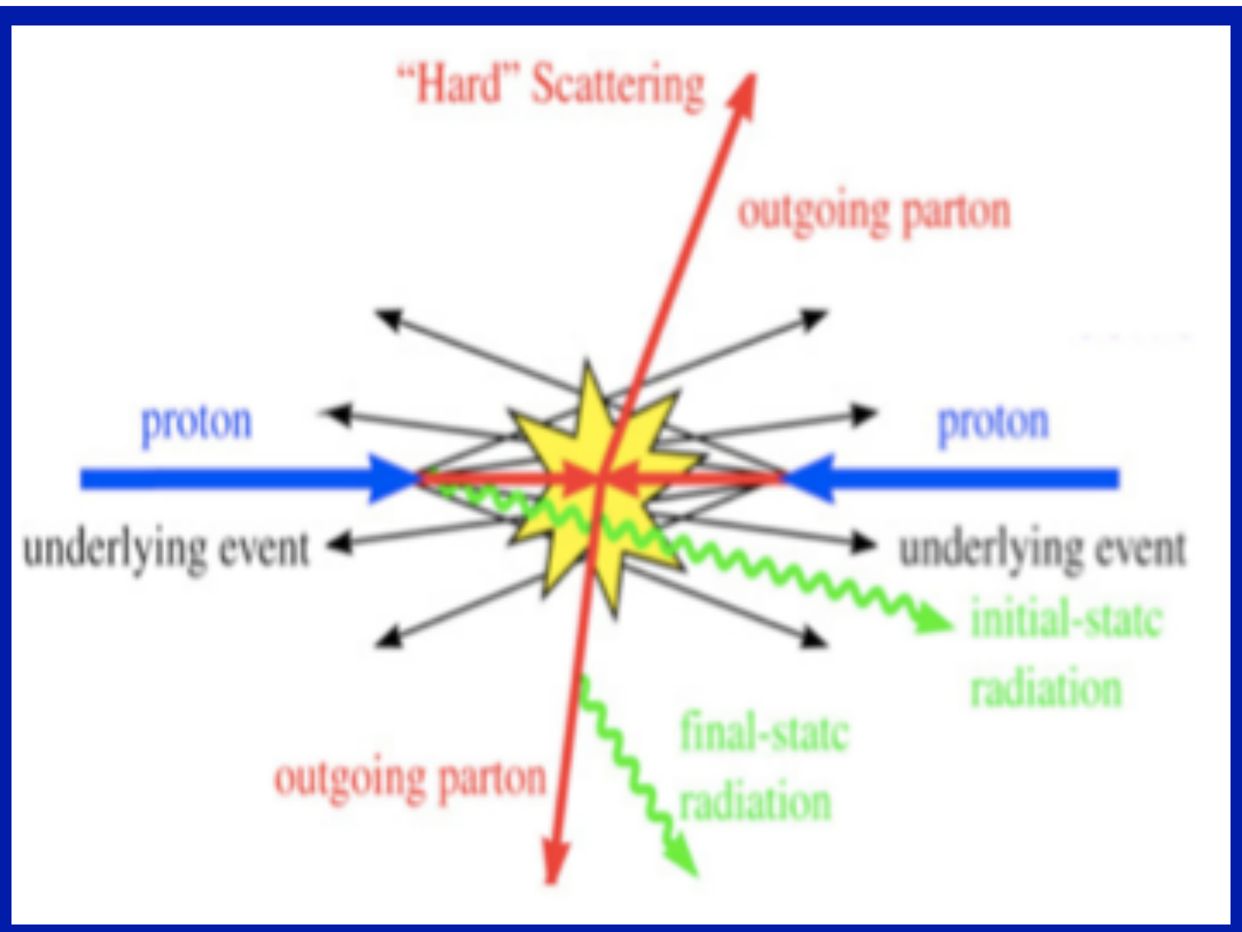
1 - The jets are initiated by the two outgoing partons ("the signal"), but the other partons also interact and radiate gluons.

2 - They form the "Underlying Event" (the "background")

Probing the QGP and hadronic states - Jets

Event seen by the calorimeters





Granularity of the ATLAS calorimeters: ΔηxΔϕ = 0.1x0.1 "towers" (piled calorimeter cells)

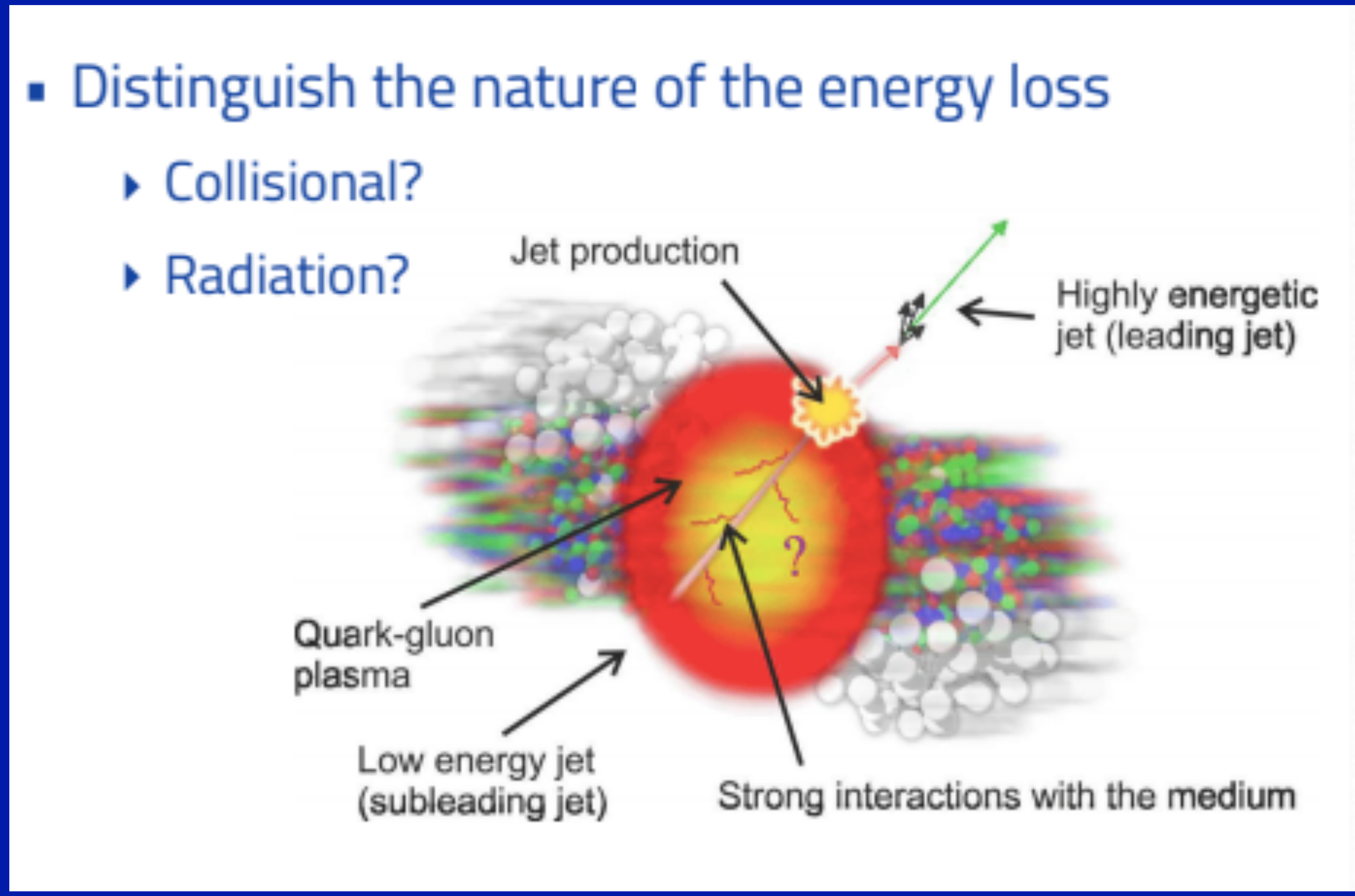
1 - The jets are initiated by the two outgoing partons ("the signal"), but the other partons also interact and radiate gluons.

2 - They form the "Underlying Event" (the "background")

3 - In Pb+Pb central collisions this process is huge, and the whole calorimeter gets uniformly populated.

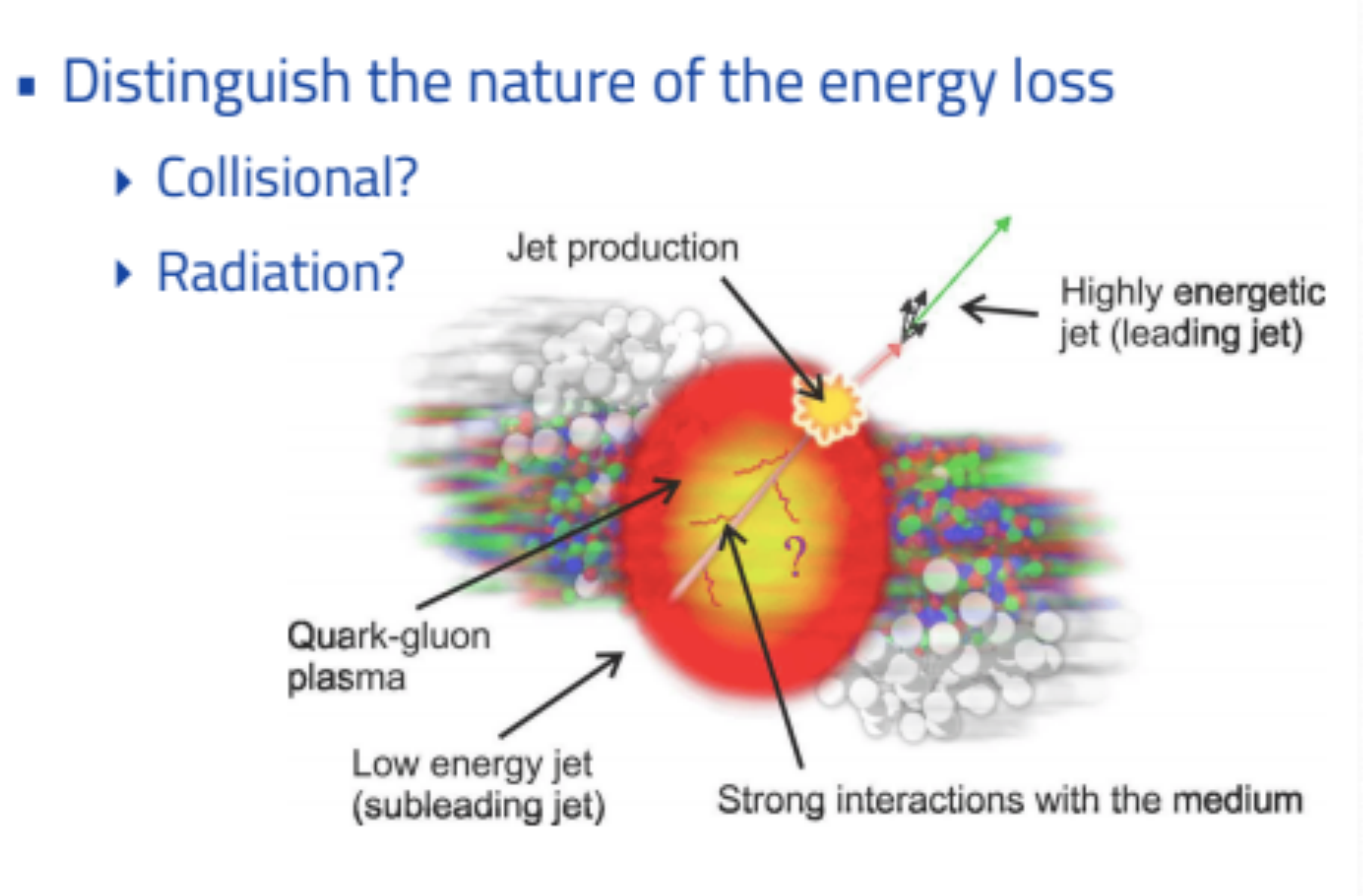
4 – This "pedestal" must be subtracted in order for the jets to be correctly reconstructed.

Probing the QGP and hadronic states - Jets



In head-on Pb+Pb collisions, the QGP forms. The cartoon 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.

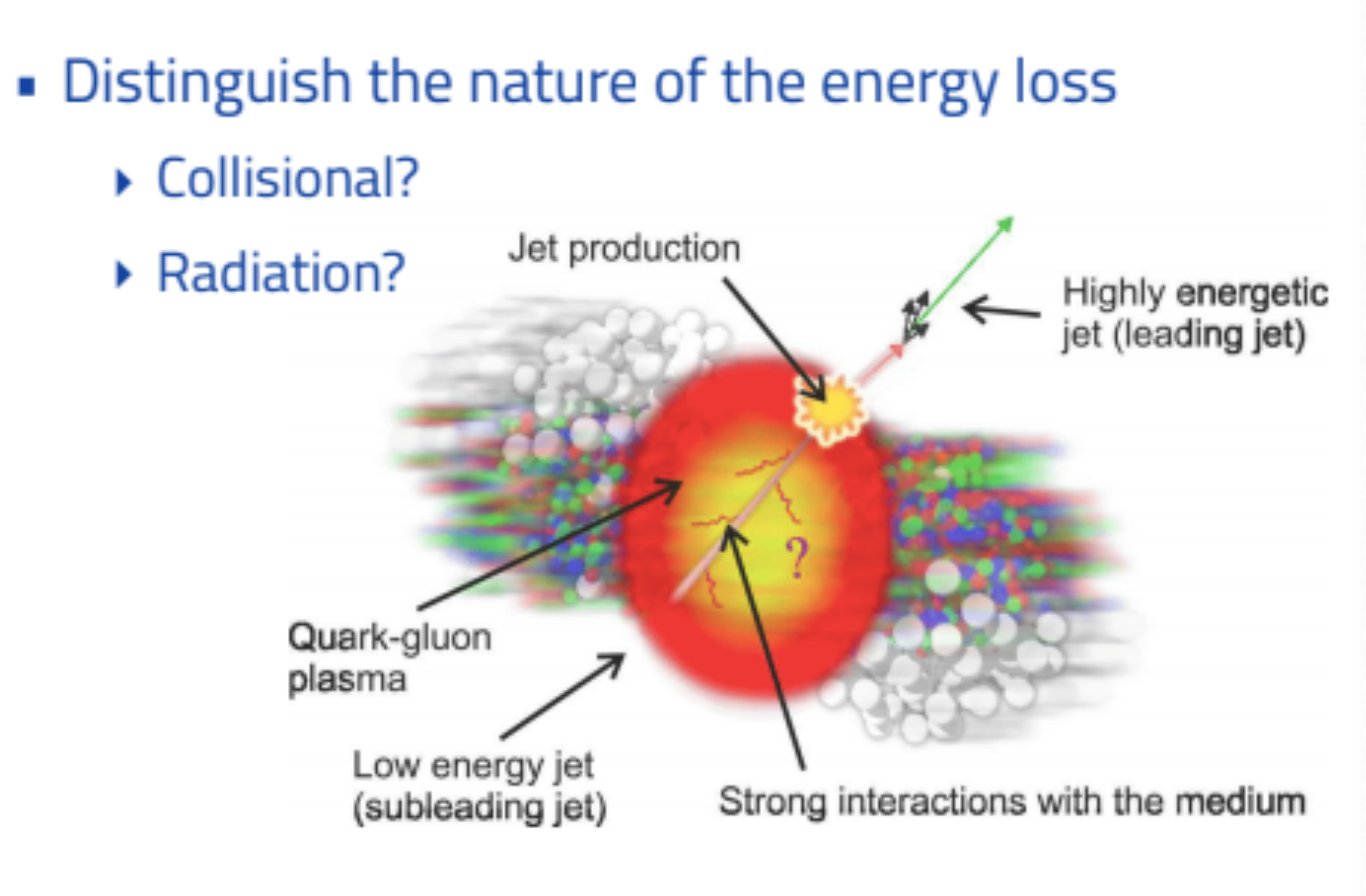
Probing the QGP and hadronic states - Jets



In head-on Pb+Pb collisions, the QGP forms. The cartoon 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.

Probing the QGP and hadronic states - Jets



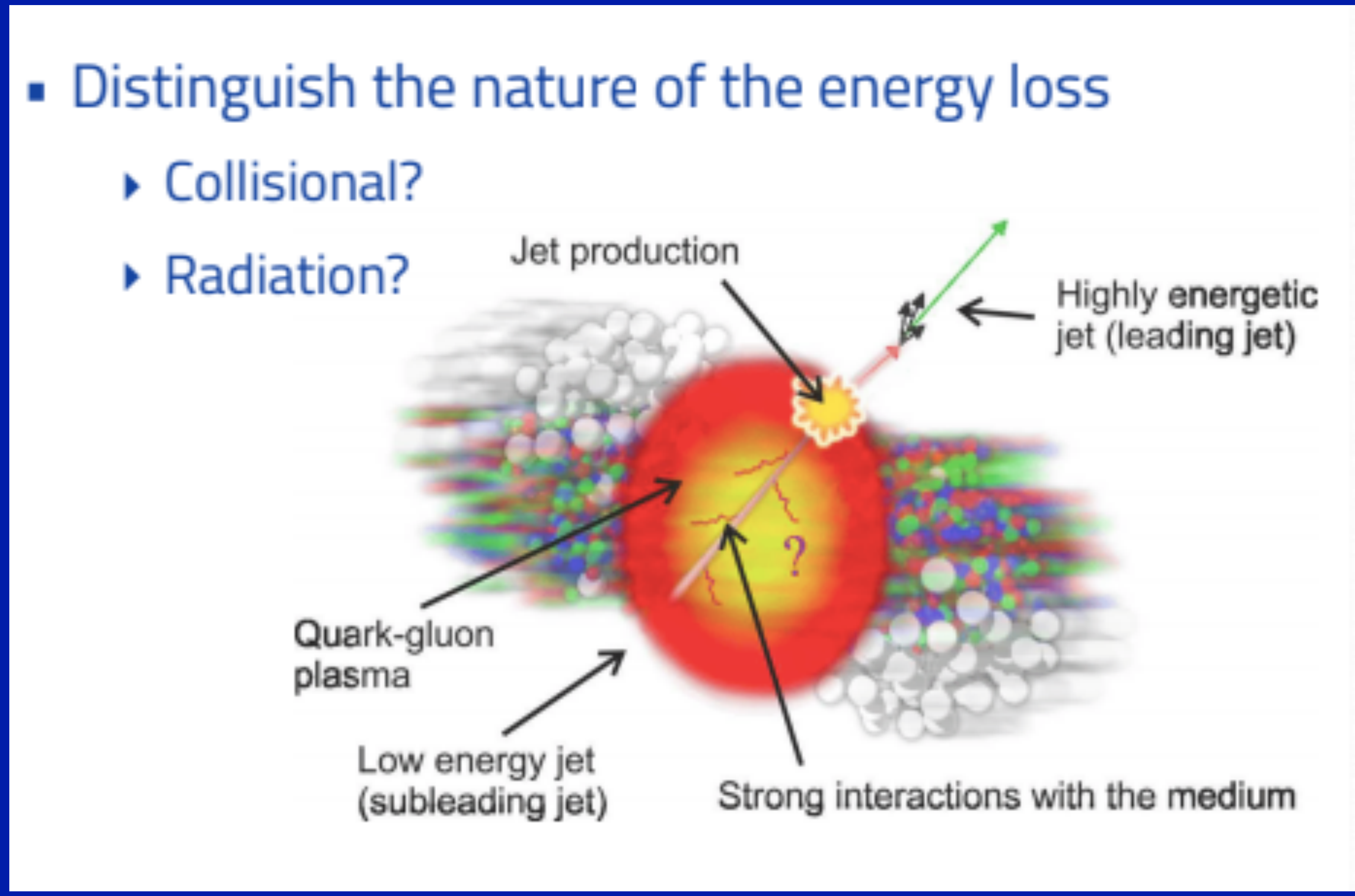
In head-on Pb+Pb collisions, the QGP forms. The cartoon shows an extreme dijet production scenario at the periphery of the fireball: one jet escapes untouched (like jets in pp collisions), while the other traverses the QGP, losing energy and having its substructure modified.

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.

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

Probing the QGP and hadronic states - Jets



In head-on Pb+Pb collisions, the QGP forms. The cartoon 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.

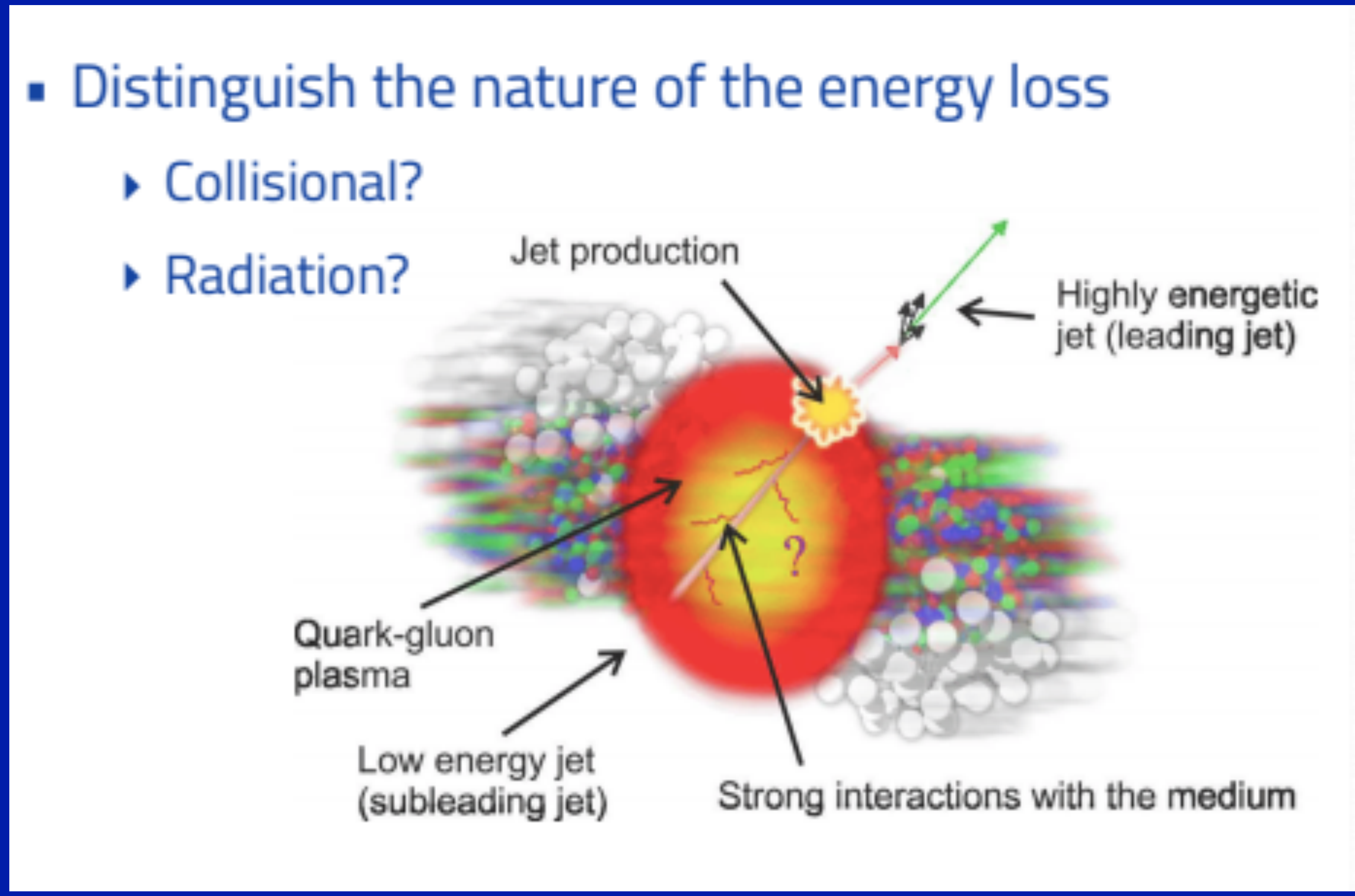
Collisional energy loss depends on the temperature and density of the QGP - how often the jet partons scatter with the medium's quarks and gluons. Studying it will tell us about :

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

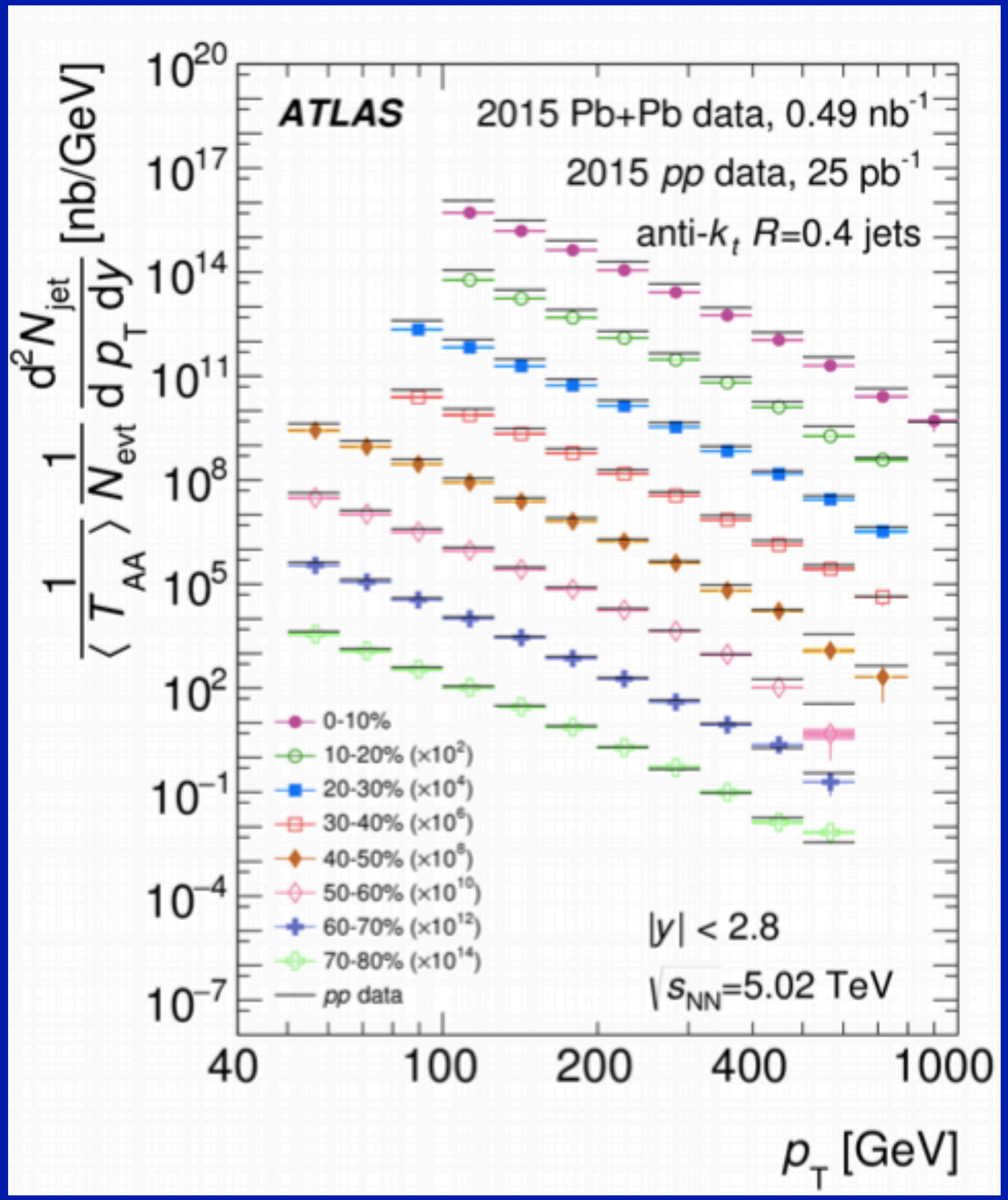
Radiative energy loss depends on the the medium's colour field strength and the coherence length over which gluons can be radiated. It will tell us about:

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

Probing the QGP and hadronic states - Jets

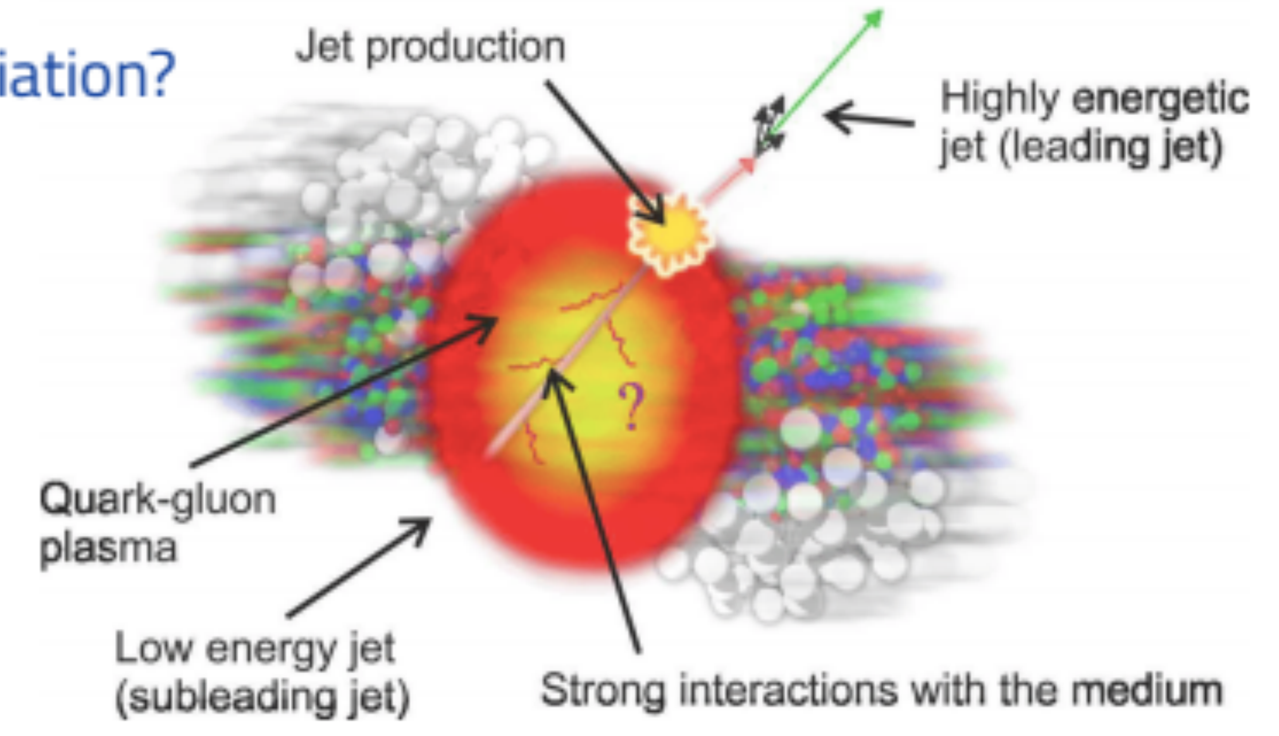


Inclusive jet production in Pb+Pb and pp



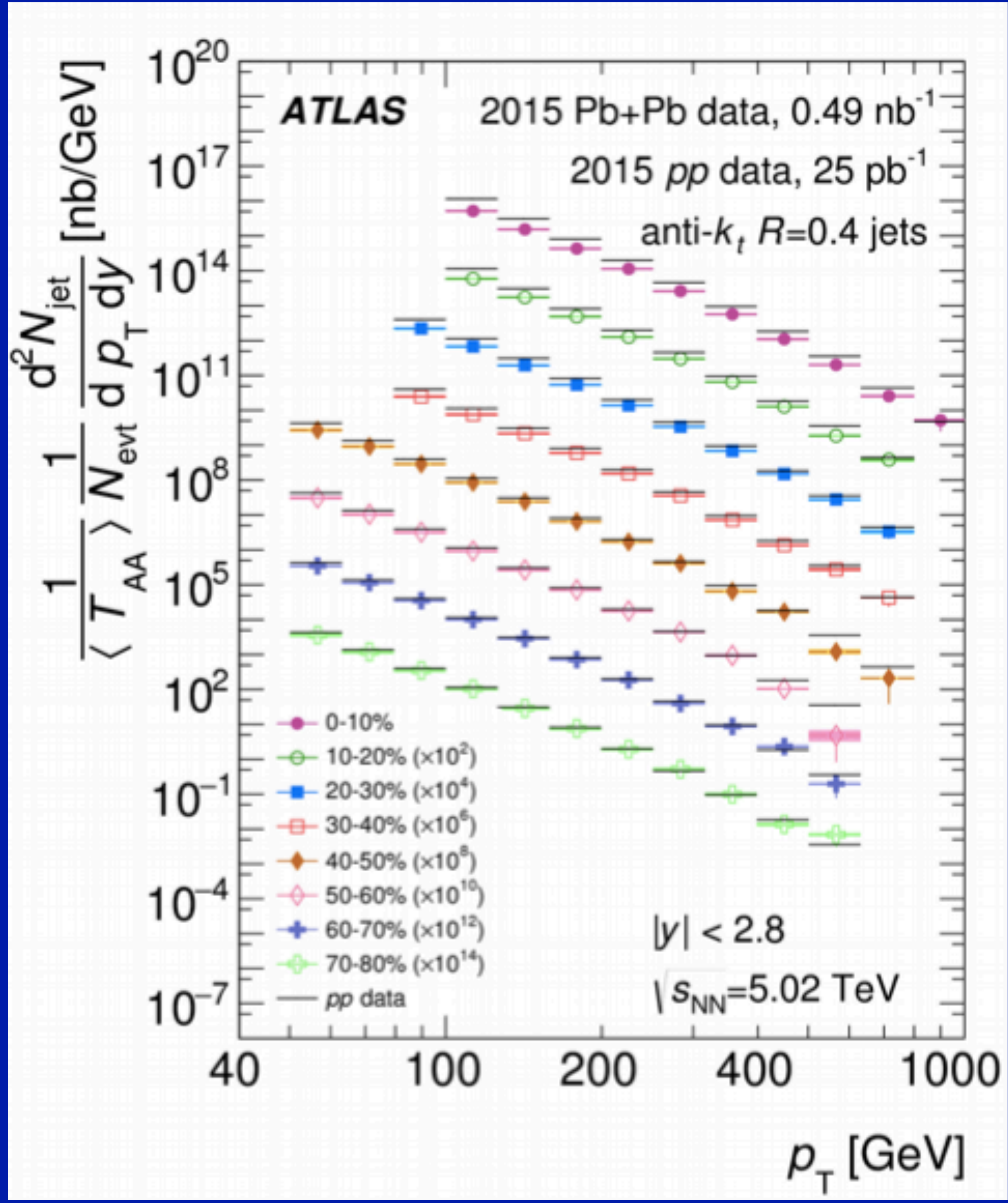
Probing the QGP and hadronic states - Jets

- Distinguish the nature of the energy loss
  - Collisional?
  - Radiation?

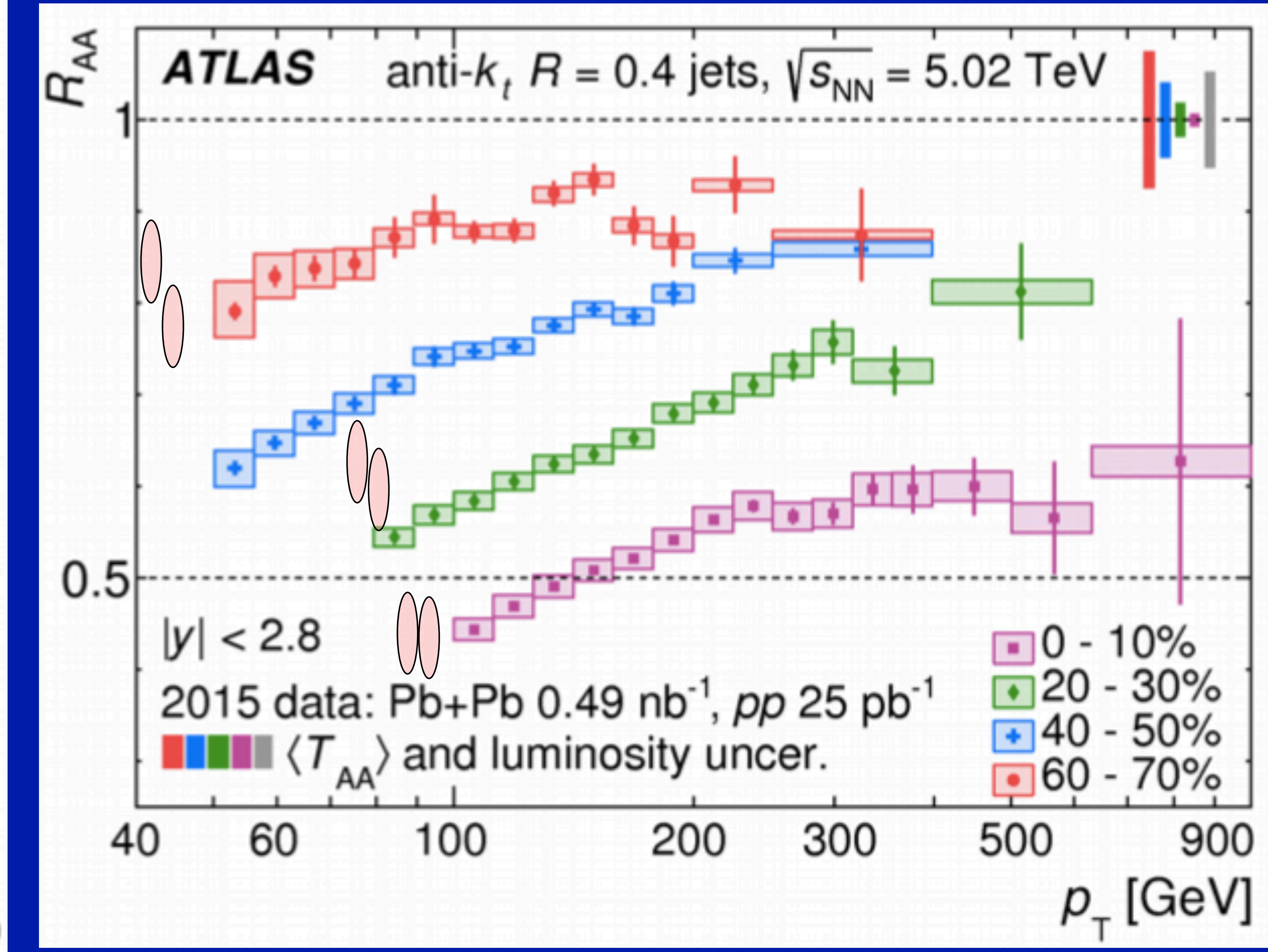


$$R_{AA} = \frac{N_{AA}}{\langle T_{AA}\rangle \times \sigma_{pp}}$$

Inclusive jet production in Pb+Pb and pp



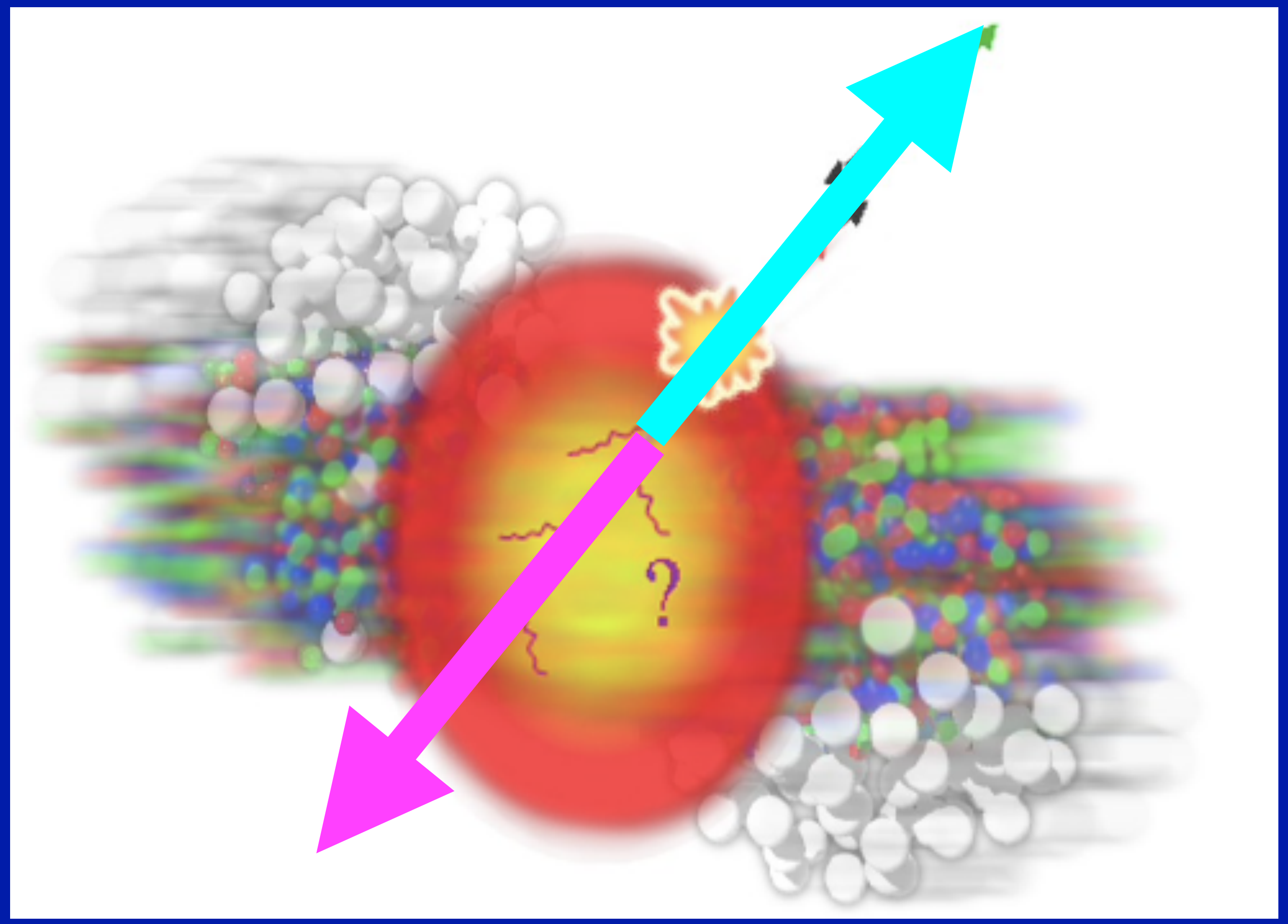
Phys. Lett. B 748 (2015) 392



- 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.

Probing the QGP and hadronic states - Jets

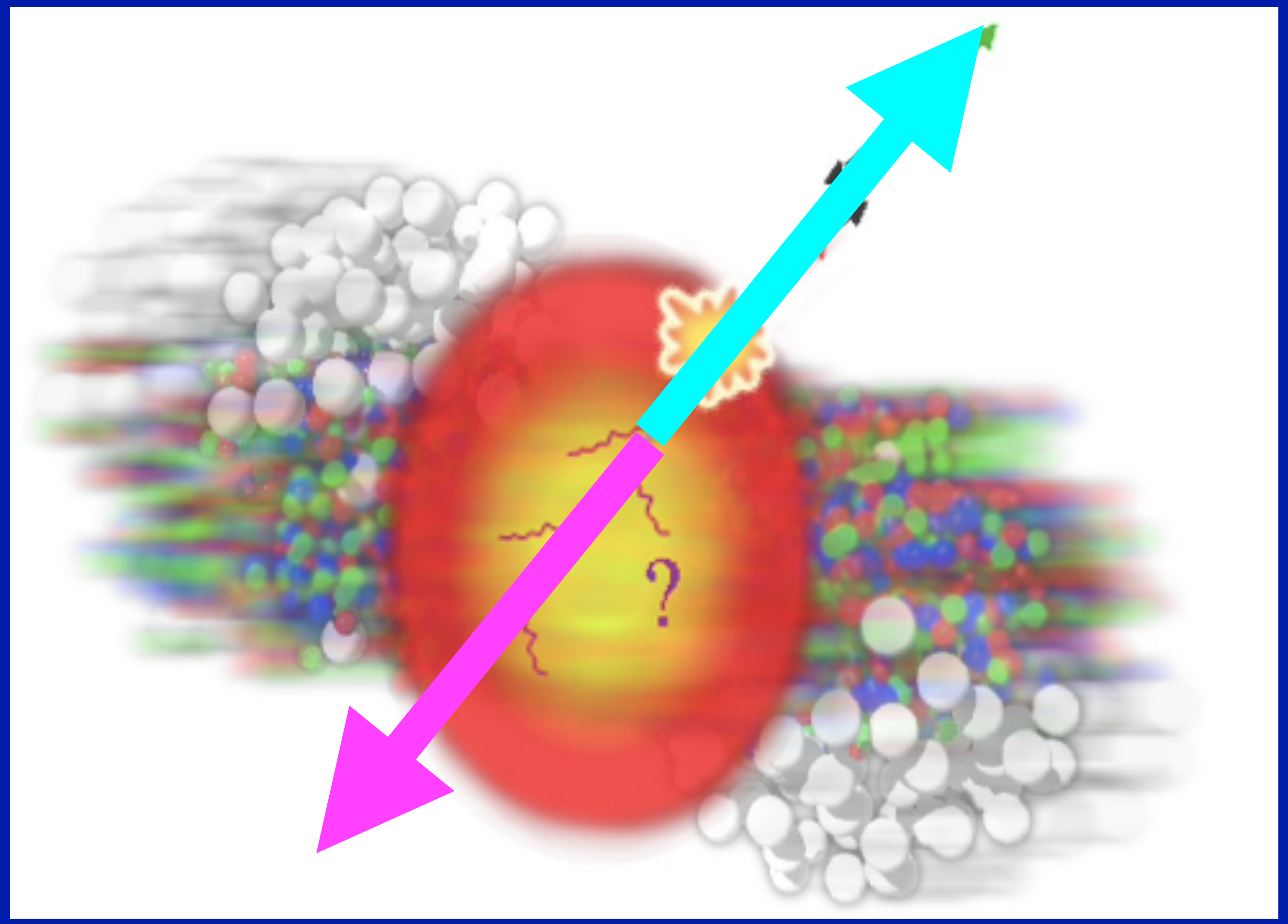
How to calibrate jet energy loss?

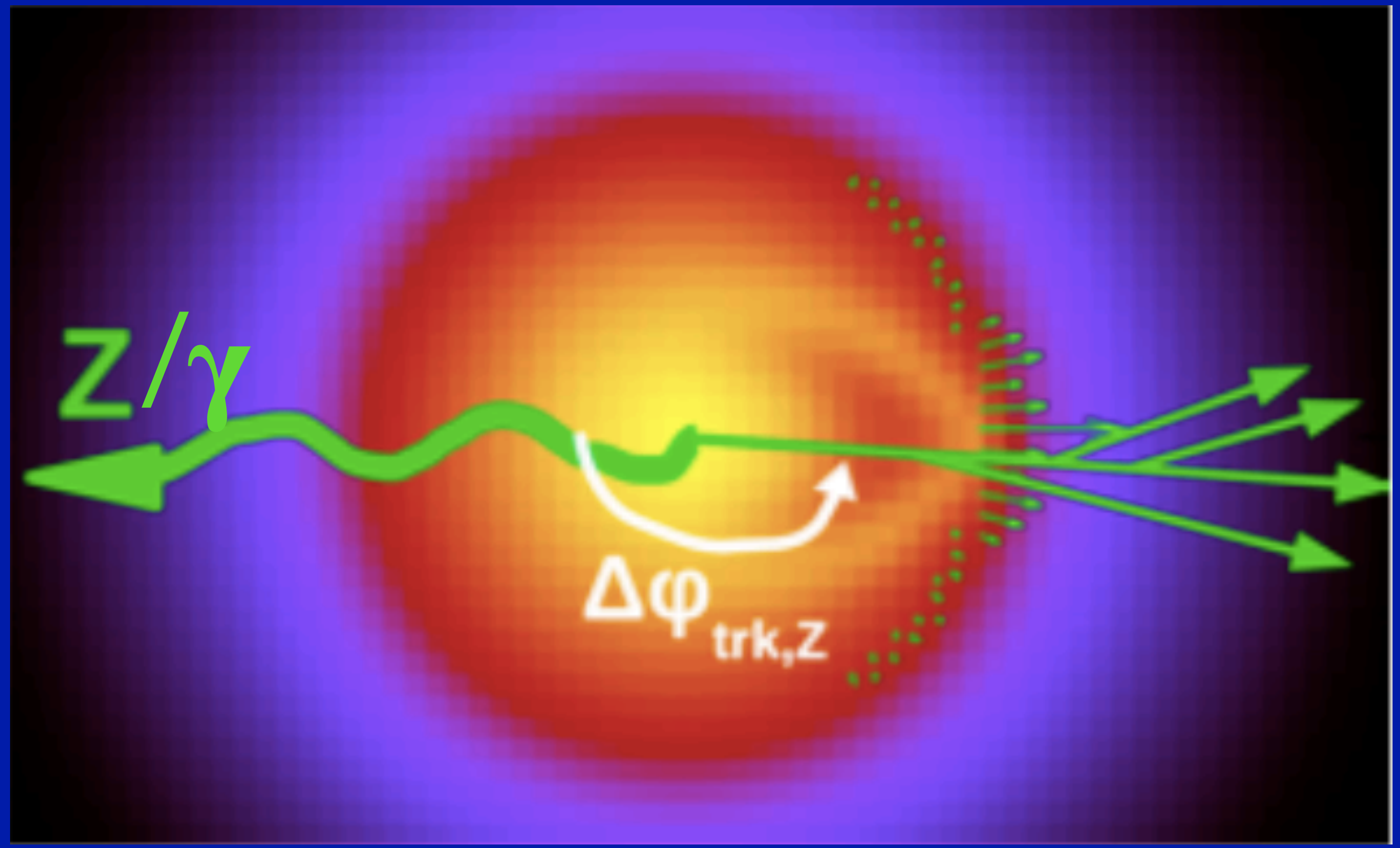


Jet 1 and Jet 2 travel different path lengths in the QGP, loosing different amounts of energy. There is no way to measure how much energy each one has lost.

Probing the QGP and hadronic states - Jets

How to calibrate jet energy loss?



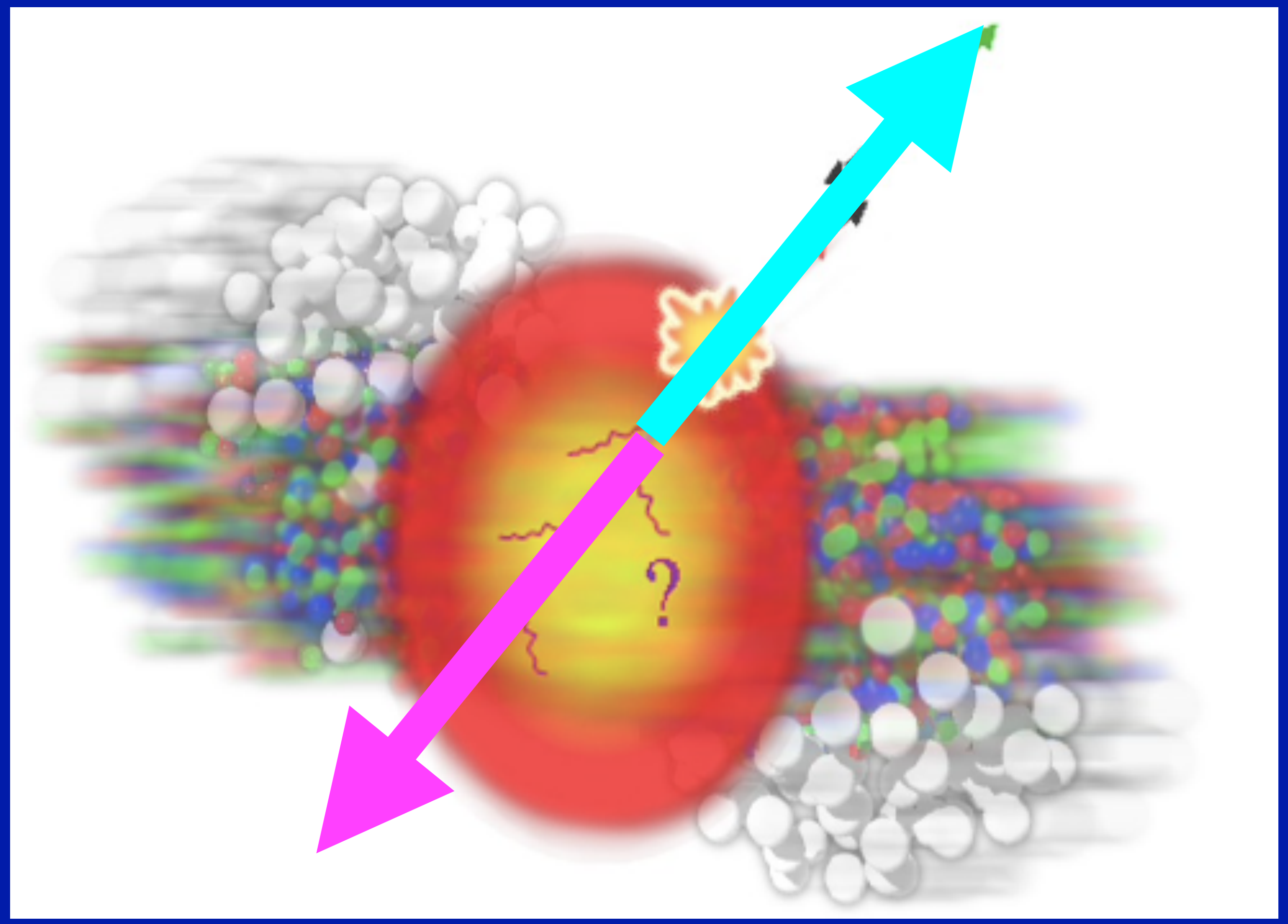


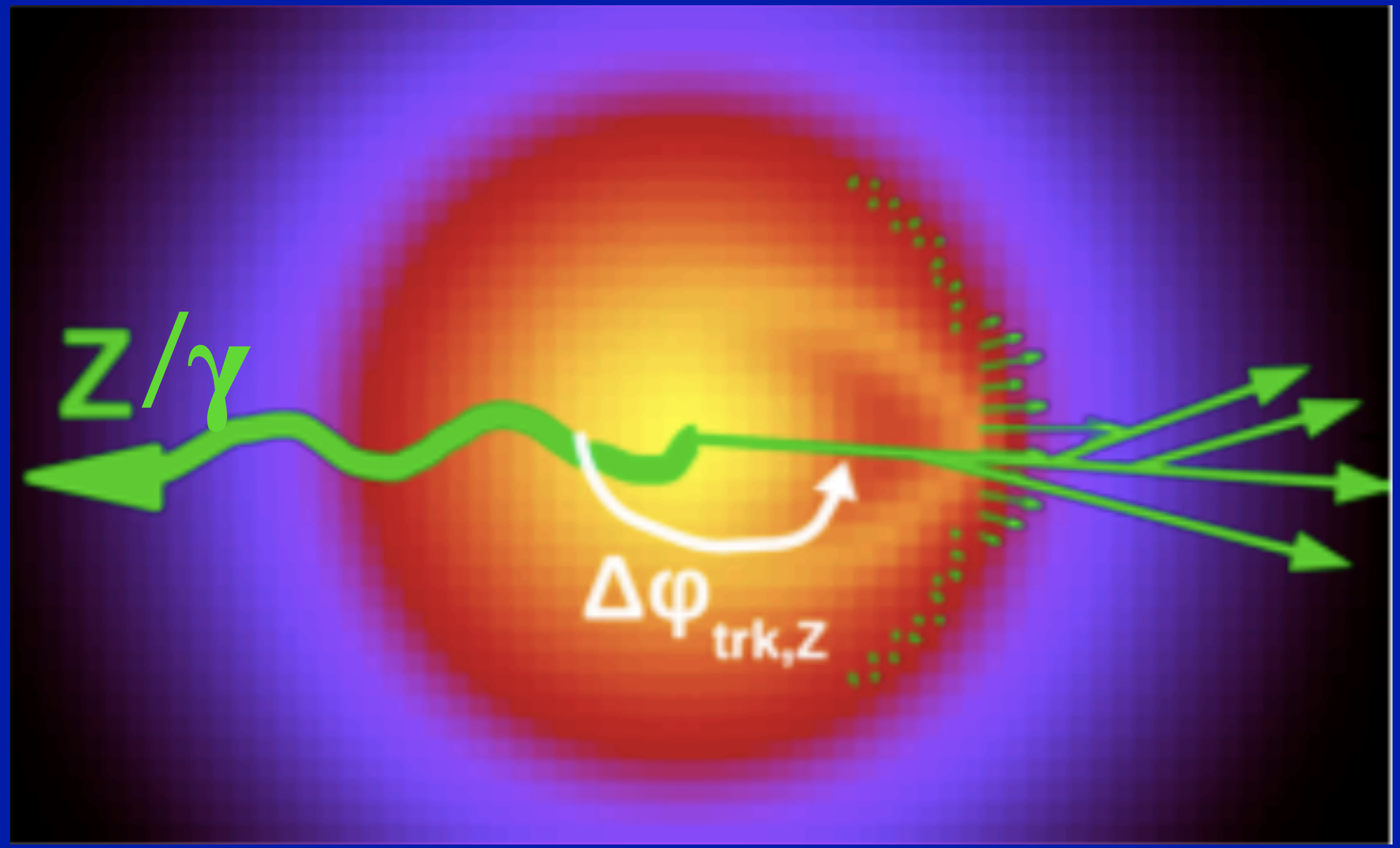
Jet 1 and Jet 2 travel different path lengths in the QGP, loosing different amounts of energy. There is no way to measure how much energy each one has lost.

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

Probing the QGP and hadronic states - Jets

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.

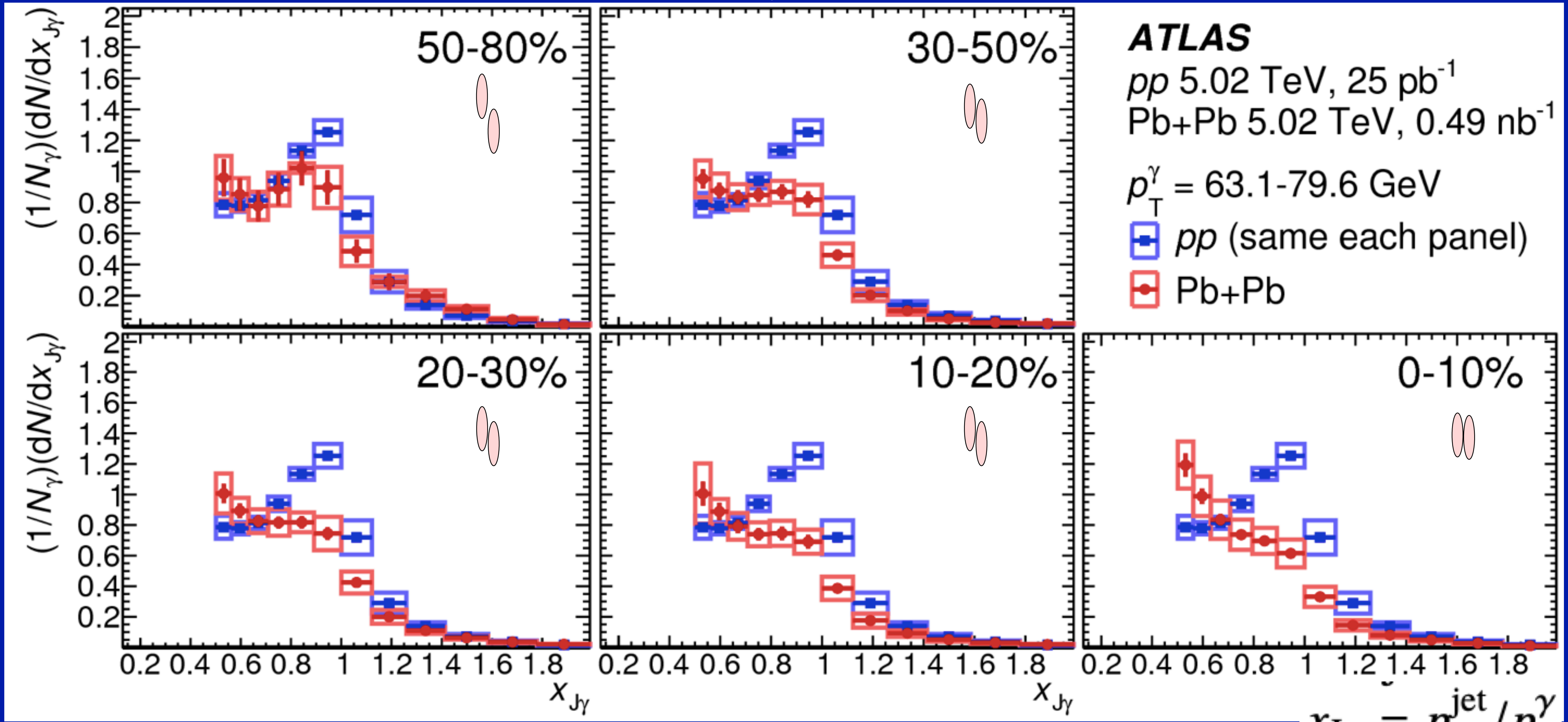




The simplest observable: jet-to-photon transverse momentum ratio $x_{J\gamma} = p_{T}^{jet}/p_{T}^{\gamma}$

Probing the QGP and hadronic states - Jets

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



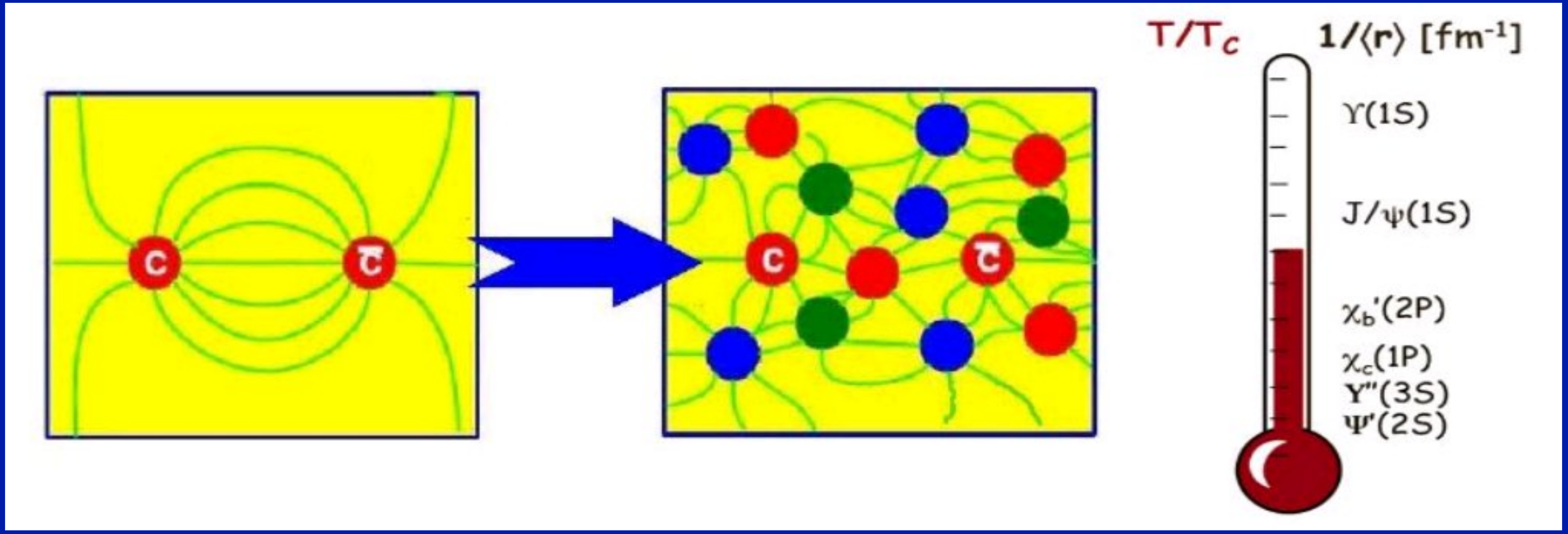
$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$

- 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 asymetric pairs is maximal.

Probing the QGP and hadronic states - Quarkonia

Probing the QGP and hadronic states - Quarkonia

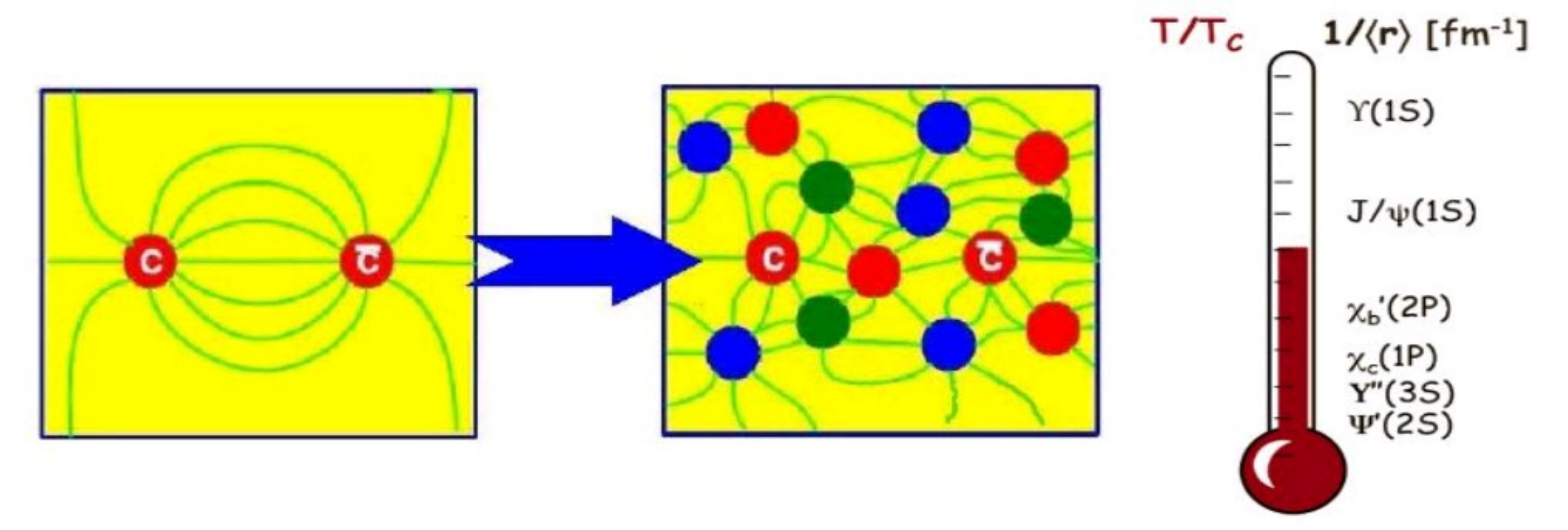
Quarkonia suppression in HI collisions is predicted by lattice QCD calculations



temperature-dependent screening lengths

Probing the QGP and hadronic states - Quarkonia

Quarkonia suppression in HI collisions is predicted by lattice QCD calculations

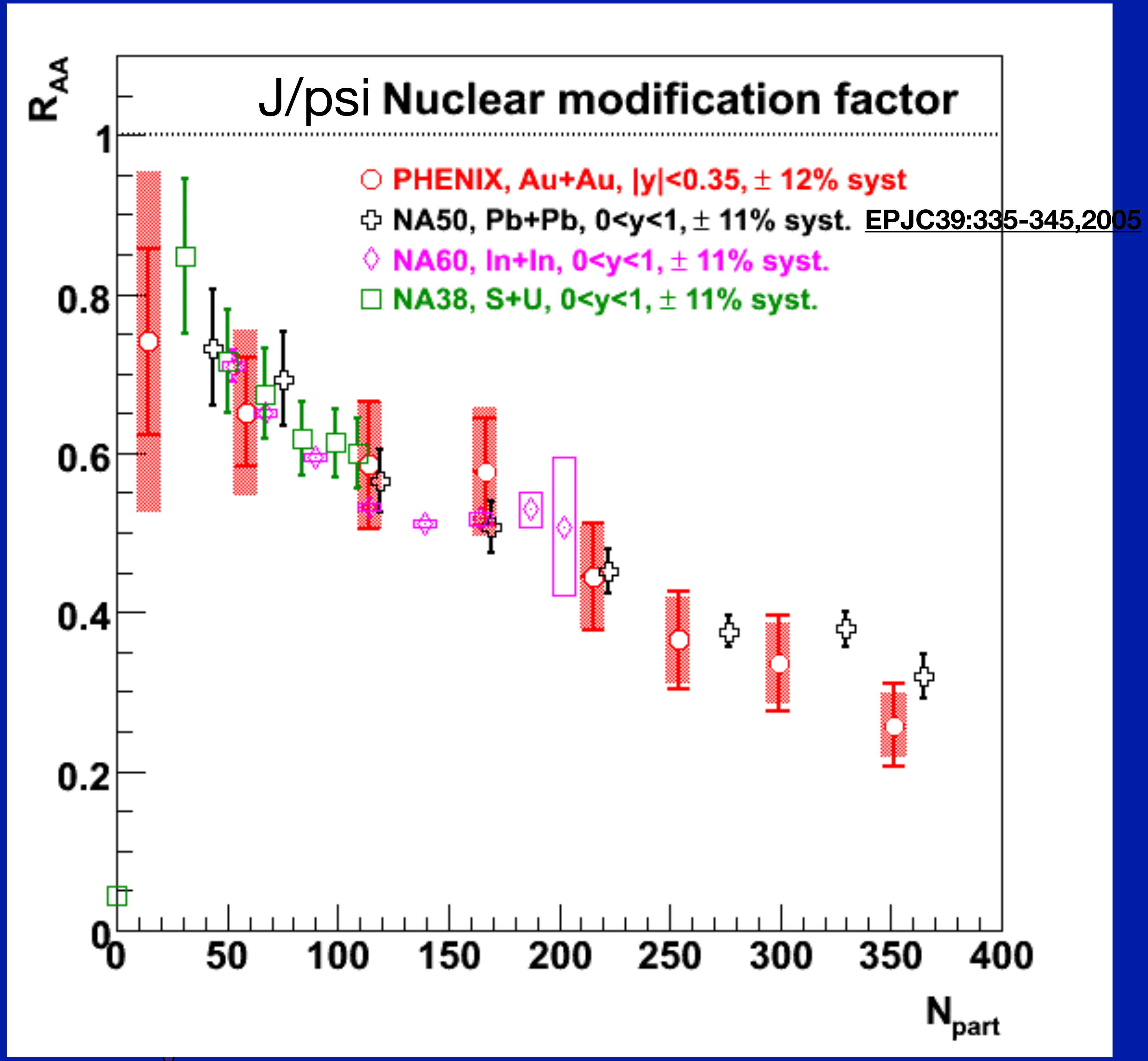


$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

Nuclear thickness function $<N_{coll}>/\sigma_{NN}$

Cross section in pp collisions (in vacuum)



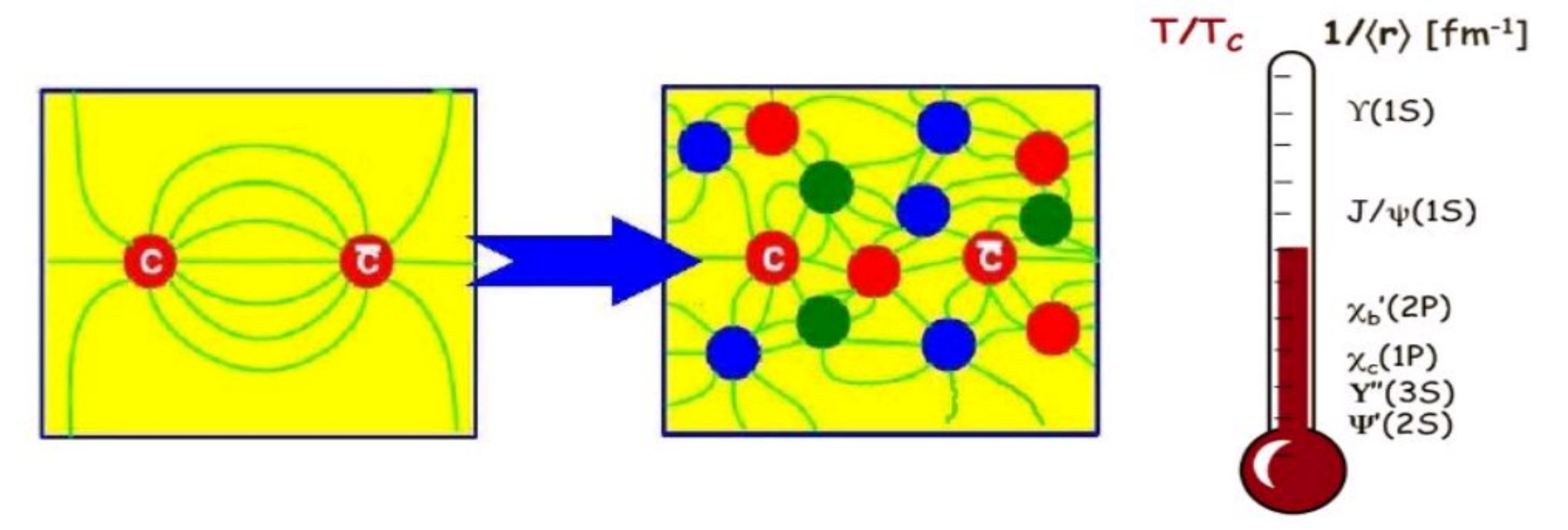
J/psi anomalous suppression by Debye colour screening (Matsui and Satz, 1986)

→ One of the most striking signatures for the QGP

→ A major contribution from LIP

Probing the QGP and hadronic states - Quarkonia

Quarkonia suppression in HI collisions is predicted by lattice QCD calculations

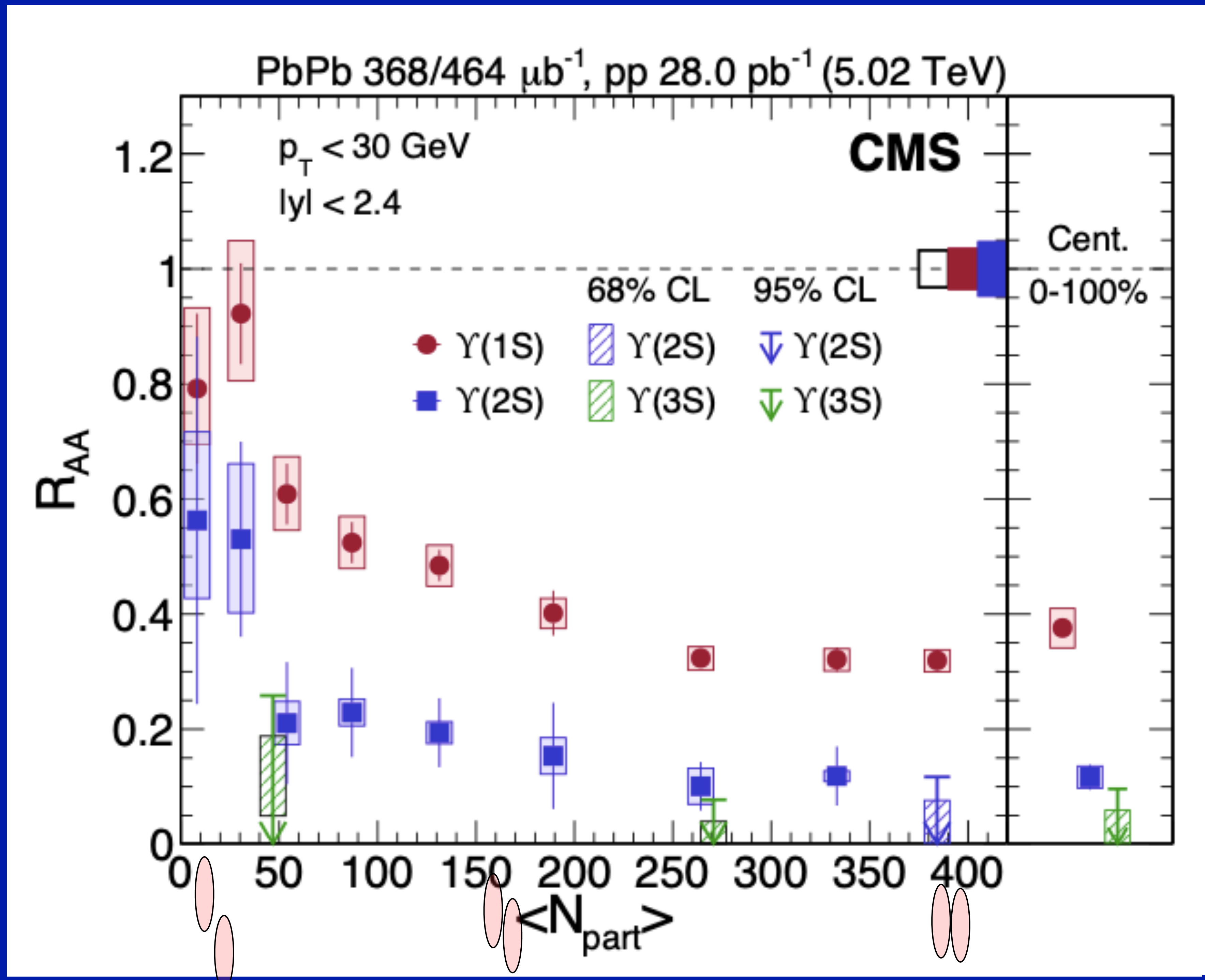


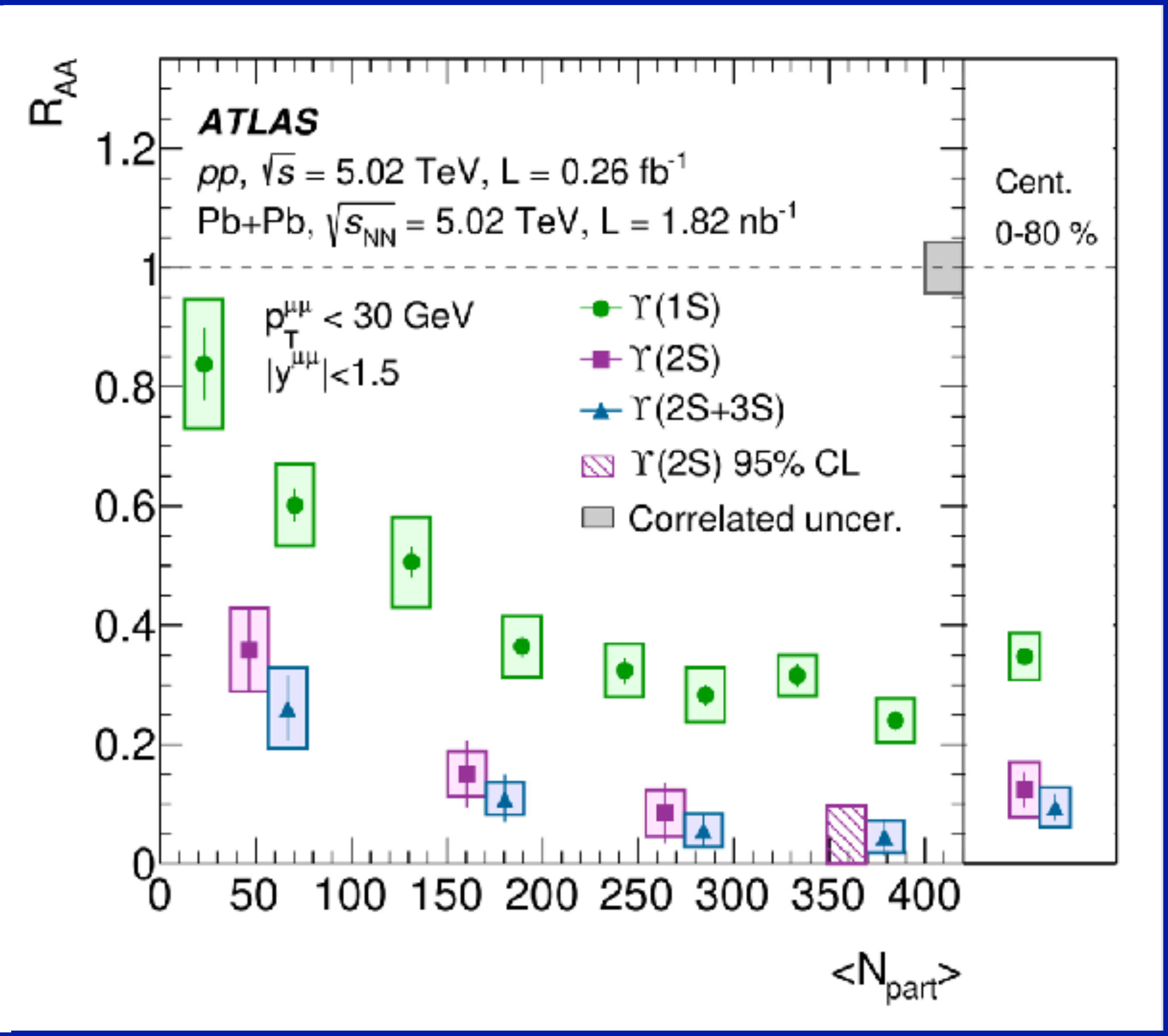
$$R_{AA} = \frac{N_{AA}}{\langle T_{AA}\rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

Nuclear thickness function $<N_{coll}>/\sigma_{NN}$

Cross section in pp collisions (in vacuum)

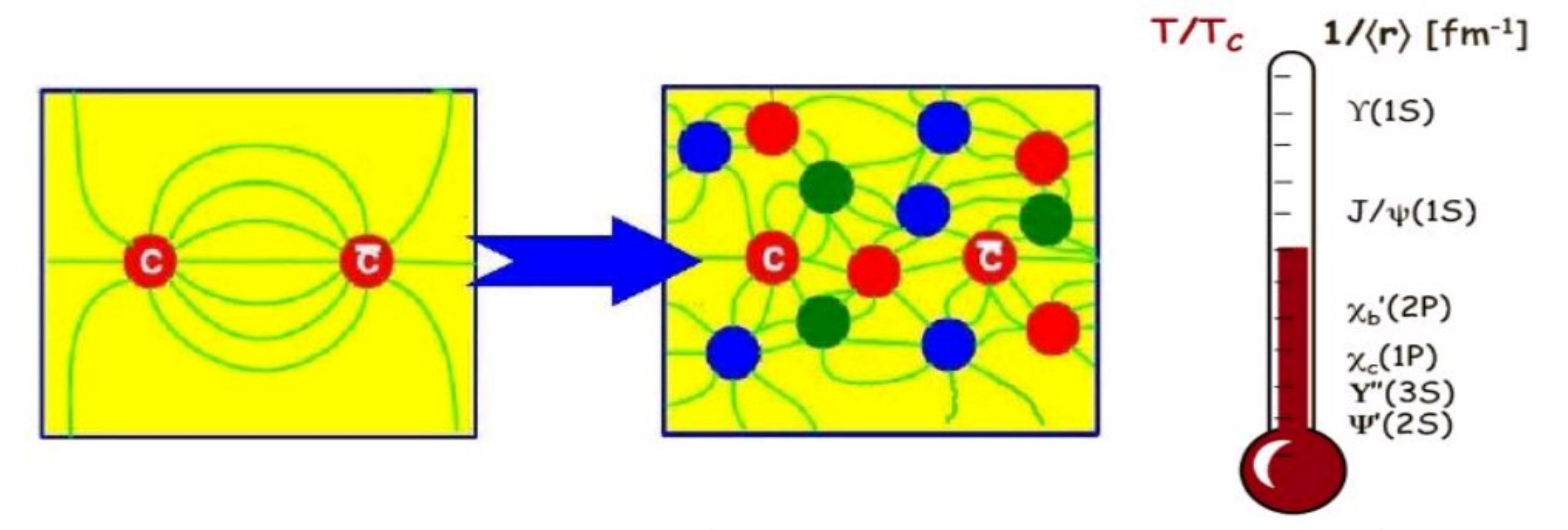


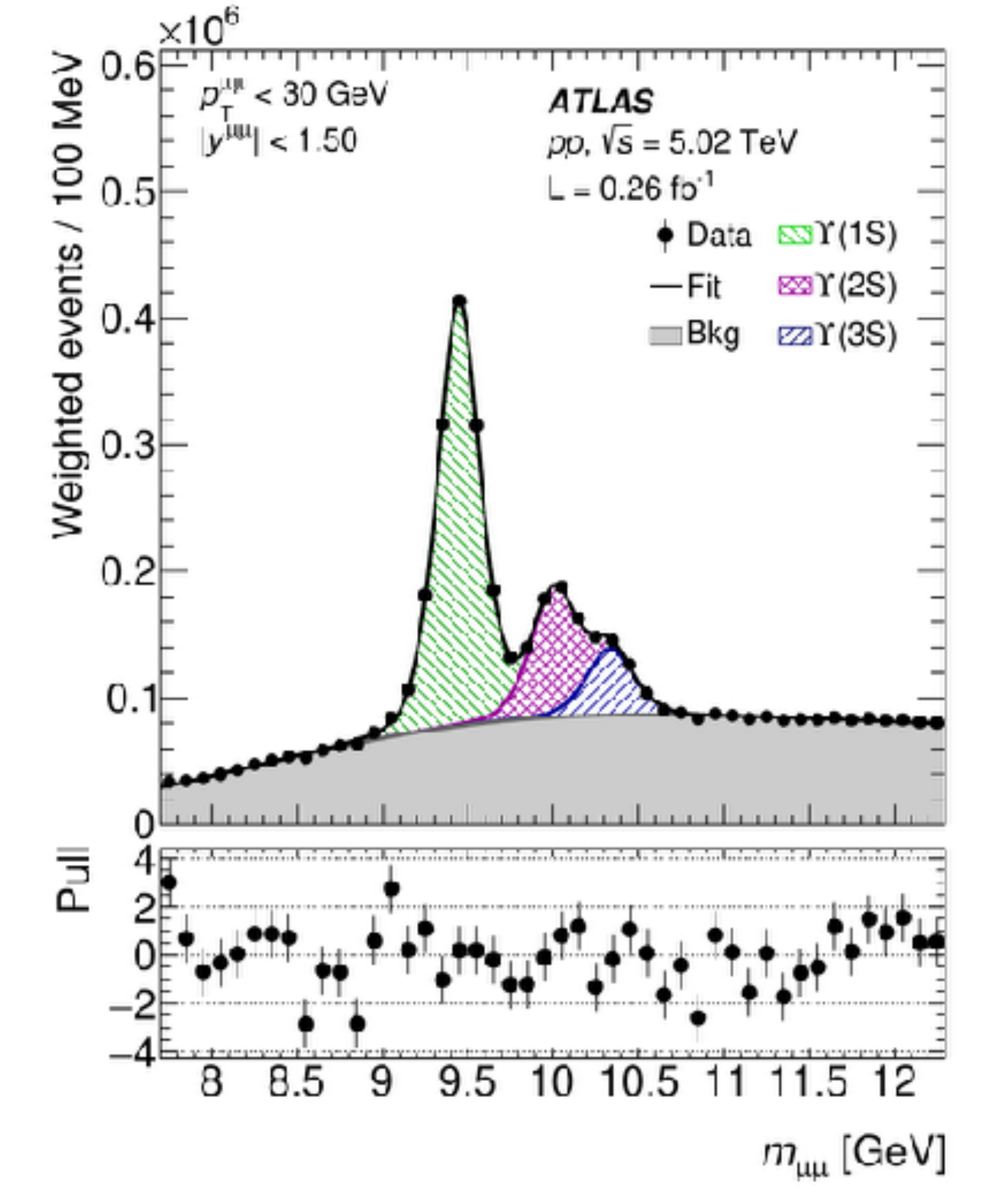


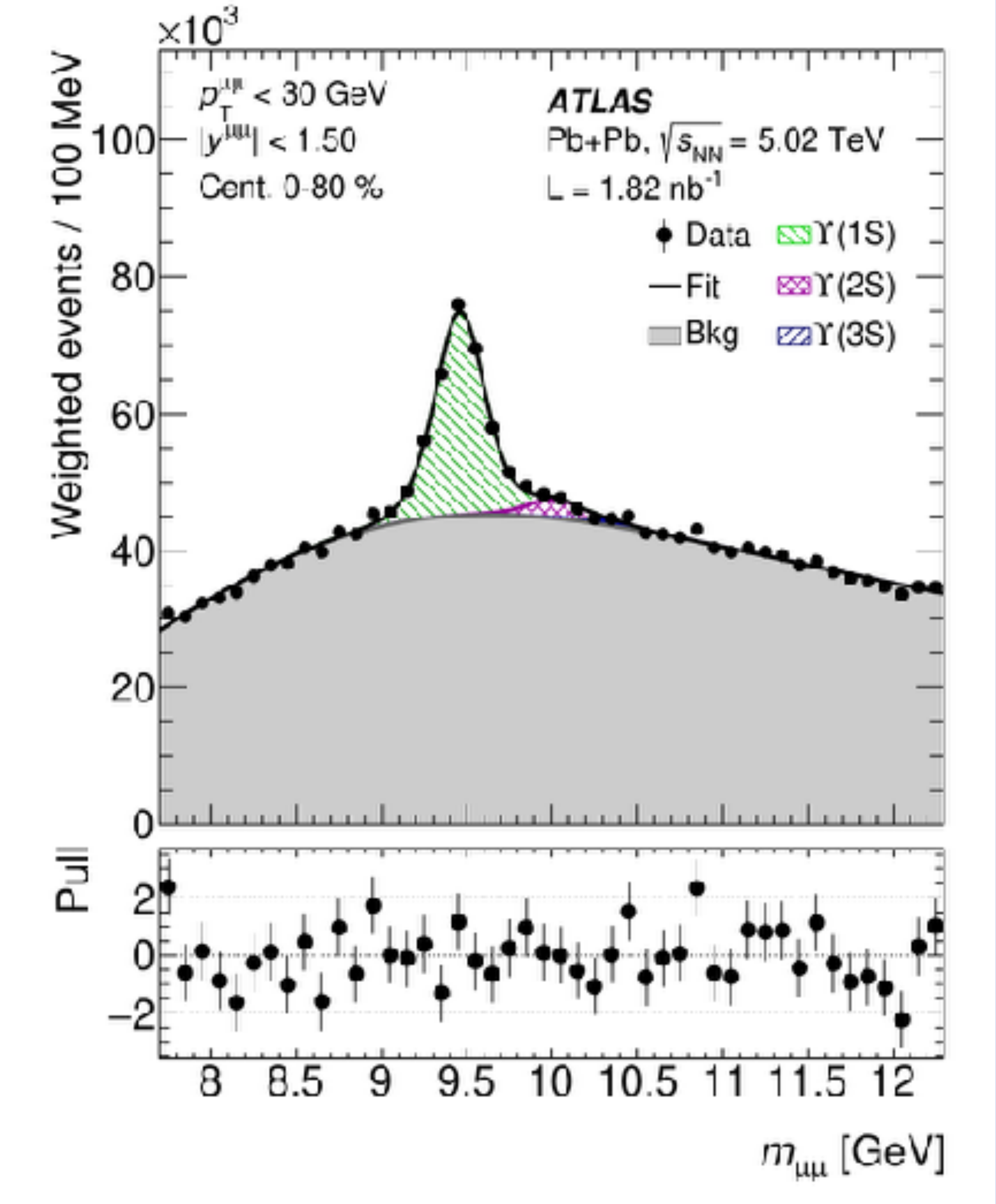
N_{part} = number of nucleon participants in the collision, a proxy to collisions centrality.

Probing the QGP and hadronic states - Quarkonia

Quarkonia suppression in HI collisions is predicted by lattice QCD calculations

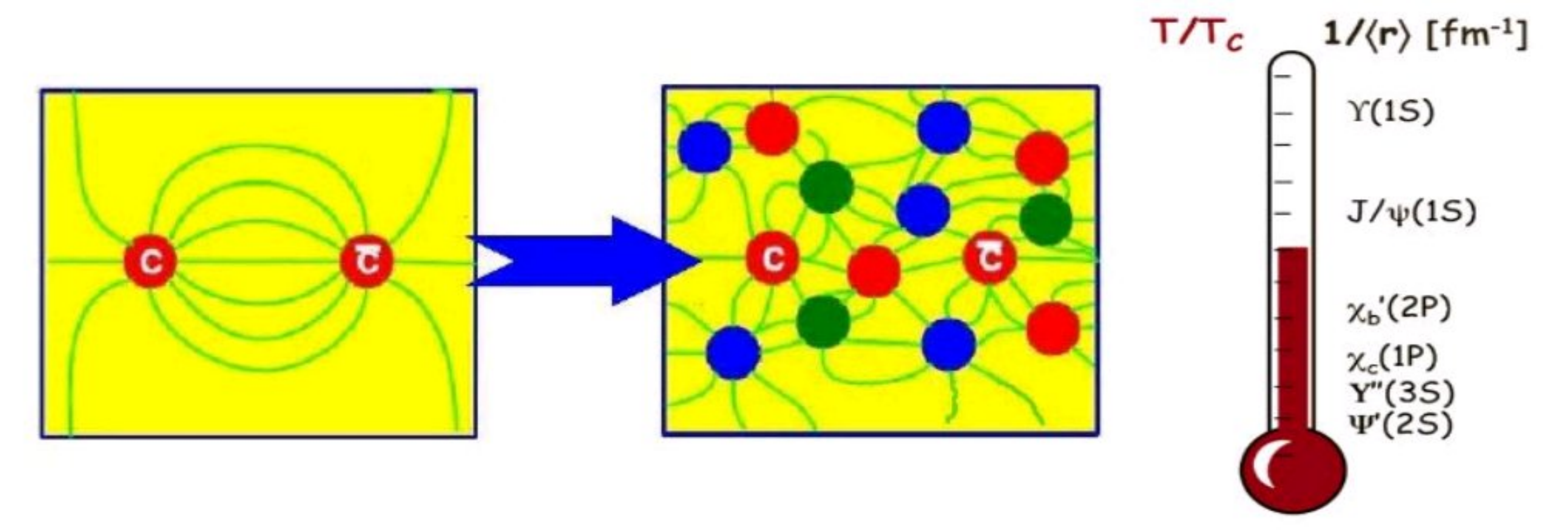


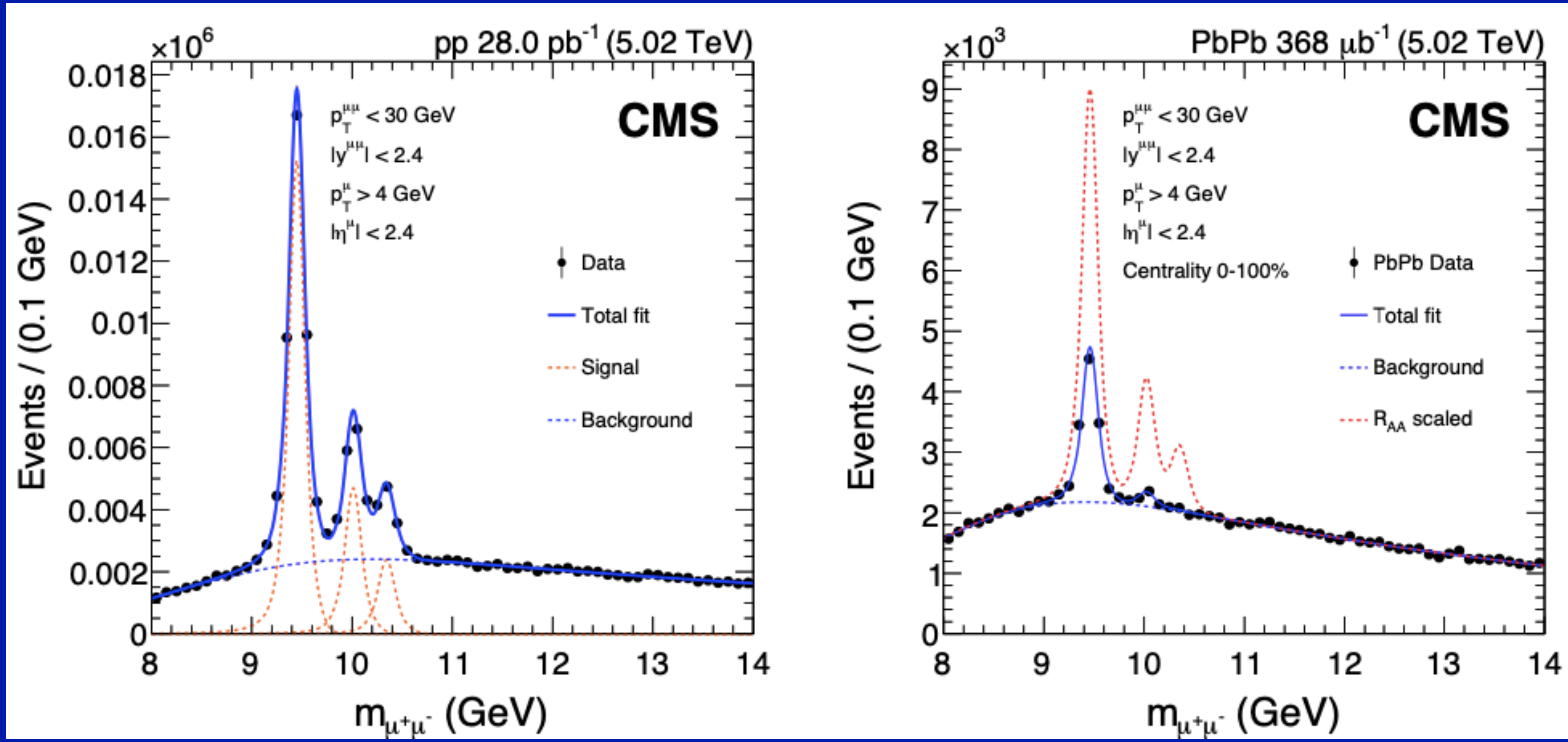




Probing the QGP and hadronic states - Quarkonia

Quarkonia suppression in HI collisions is predicted by lattice QCD calculations





Messages from QGP probes

- 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 (and the other electroweak bosons), being insensitive to 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 lecture.*

- Quarkonia are strongly suppressed in the QGP, naively due to Debye screening (*more phenomena, competing with Debye screening, are involved*).

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

Backup

Jet reconstruction in Pb+Pb collisions