Heavy Ion Physics

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The International summer School on TeV Experimental Physics (iSTEP2018)

What is Heavy-Ion Physics

- A way to study QCD

  … without confinement

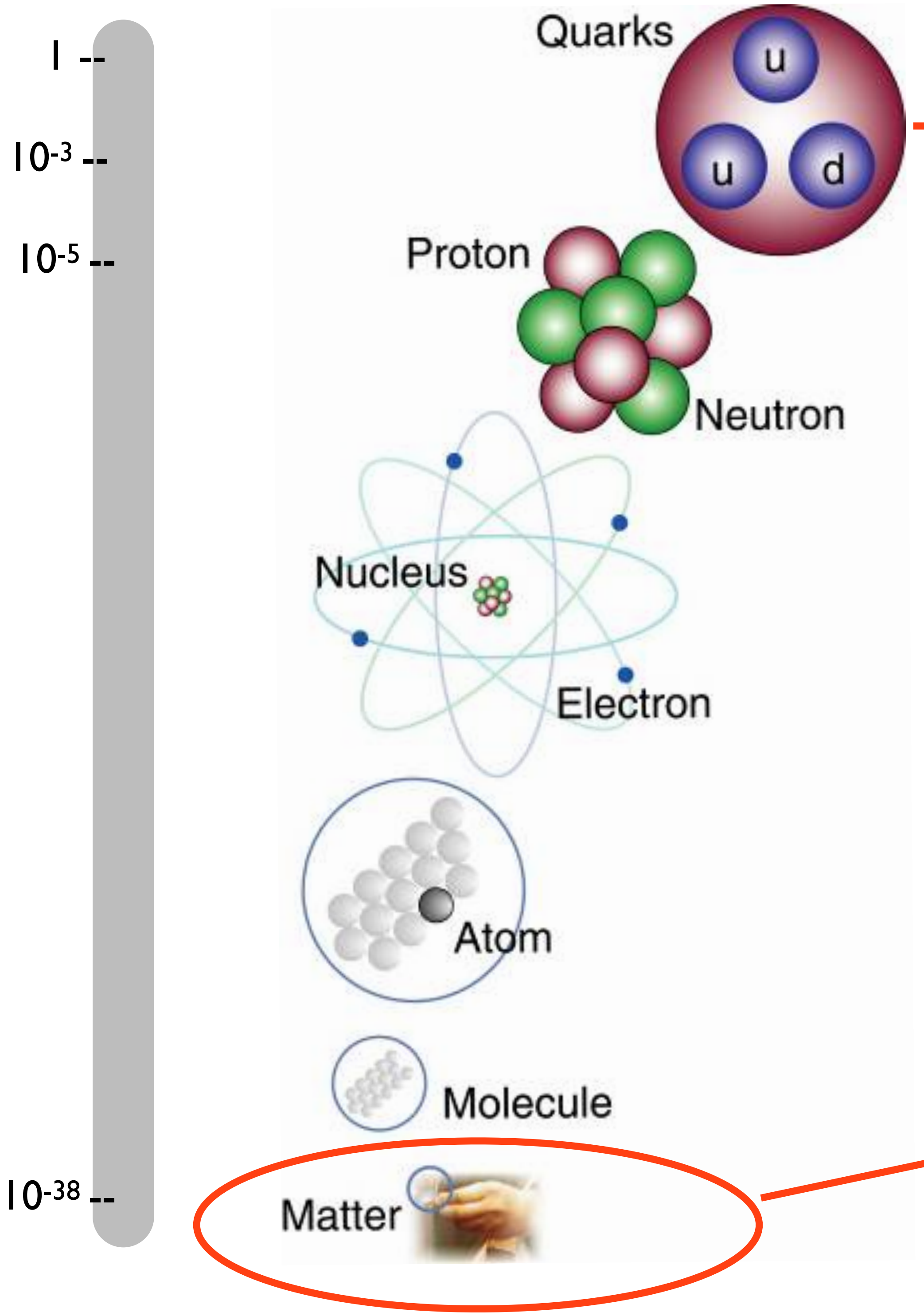
  … with quarks at their bare masses

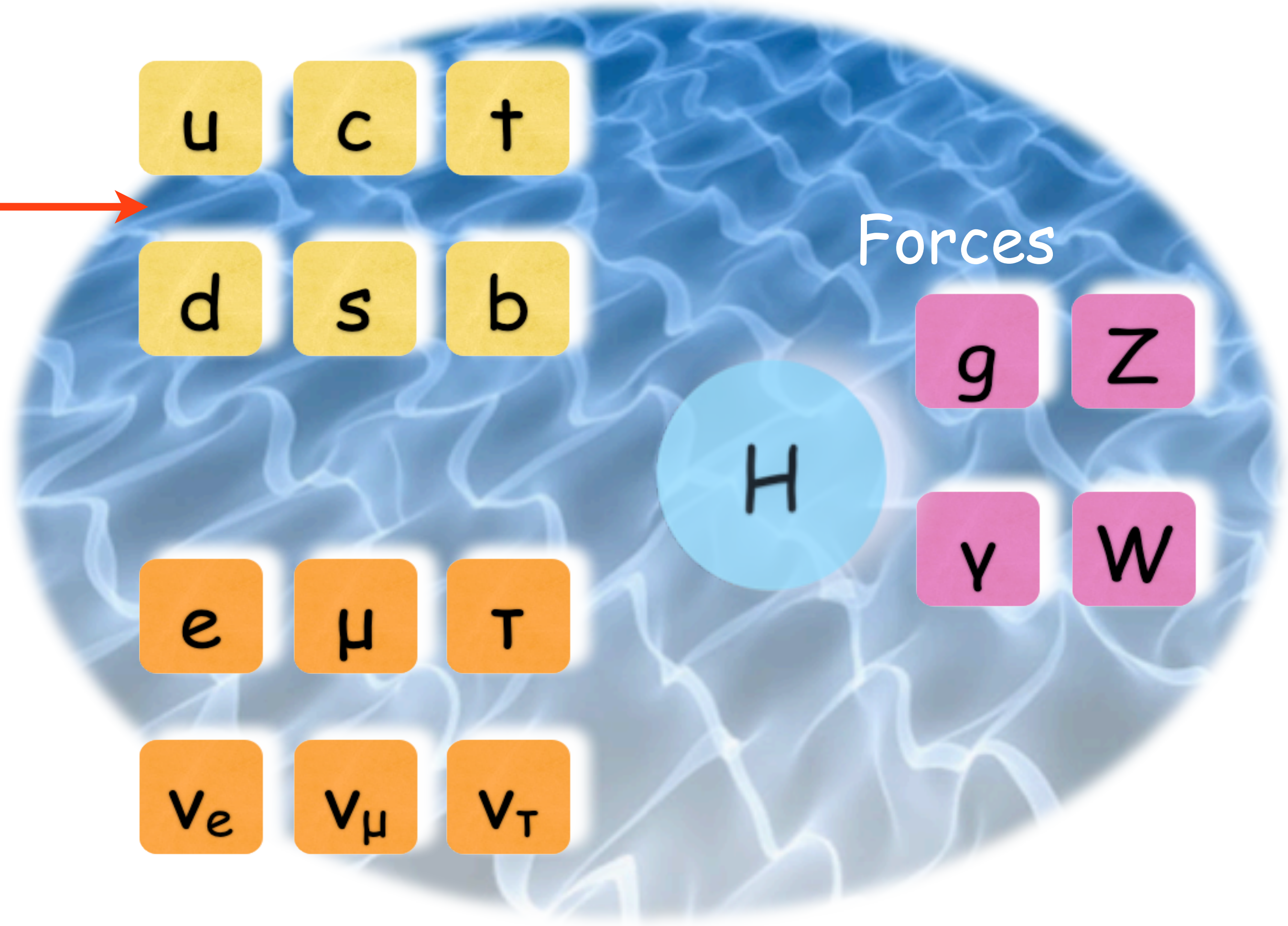
- A way to study matter

  … at energy densities like 10 μs after the Big Bang

  … at temperatures 10^5 times larger than in the sun core

Particles : building blocks of matter!



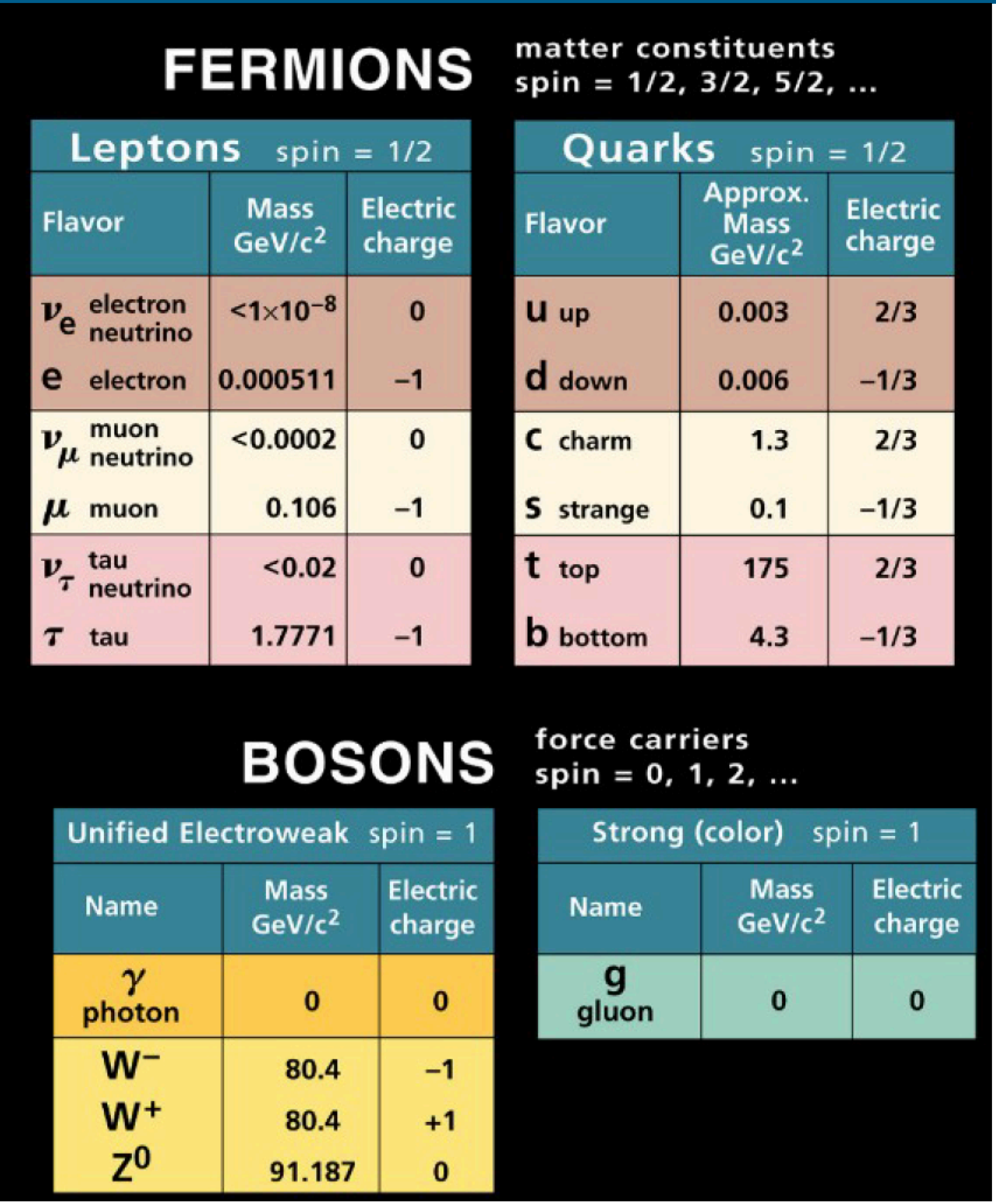


You!

but also the air you breath, the water you drink, the Sun, galaxies...

all visible objects in the Universe

The standard model and QCD



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Strong interactions
  - Binds quarks into hadrons
  - Binds nucleons into nuclei
- Described by QCD
  - Interaction between quarks and gluons carrying color charge
  - Mediated by gluons, the strong force carries

Hadrons = particles composed of quarks bound by gluons

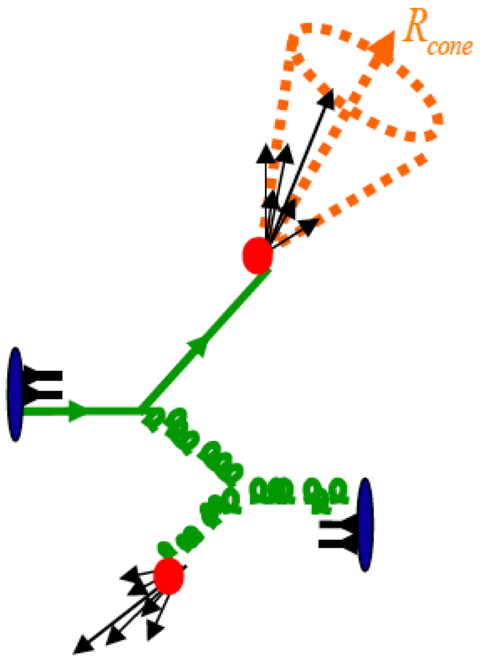
baryons: protons, neutrons, Λ, etc : 3 quarks

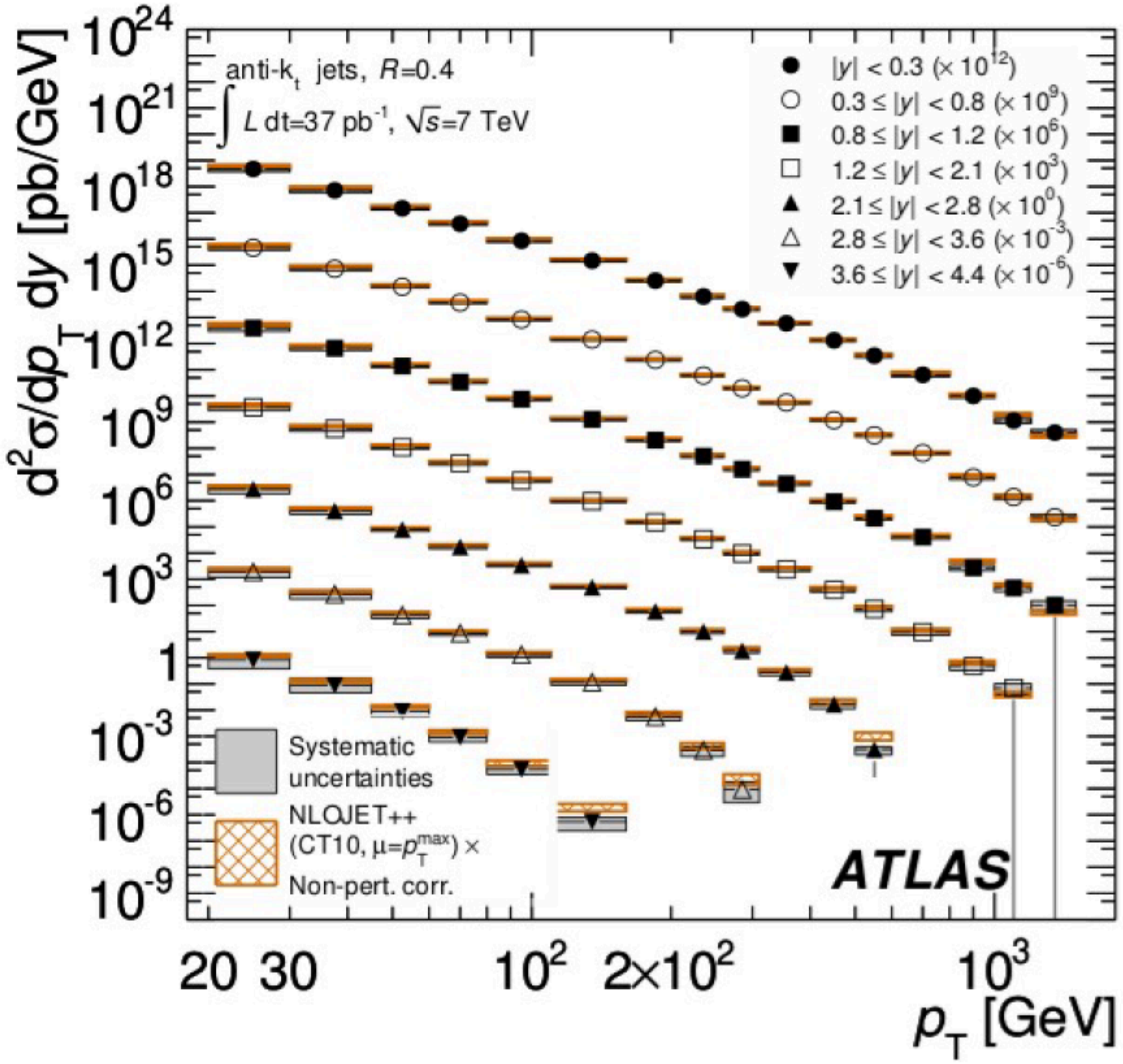
mesons: pions, kaons, J/ψ, etc : 1 quark + 1 antiquark

Strong-Interaction Physics

- QCD is a very successful theory …

  e.g. pQCD vs. production of high energy jets





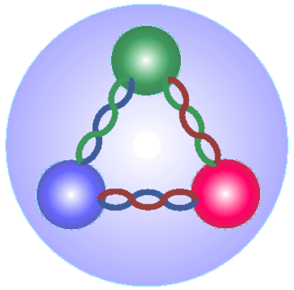
ATLAS, Phys.Rev. D86 (2012) 014022

- But, with outstanding puzzles…

Hadron Masses

Proton consists of 2 u and 1 d quark
m_p = 938 MeV != ~10 MeV = m_{uud}

Where is the extra mass generated?



Confinement

Impossible to find an isolated quark or gluon

Why?

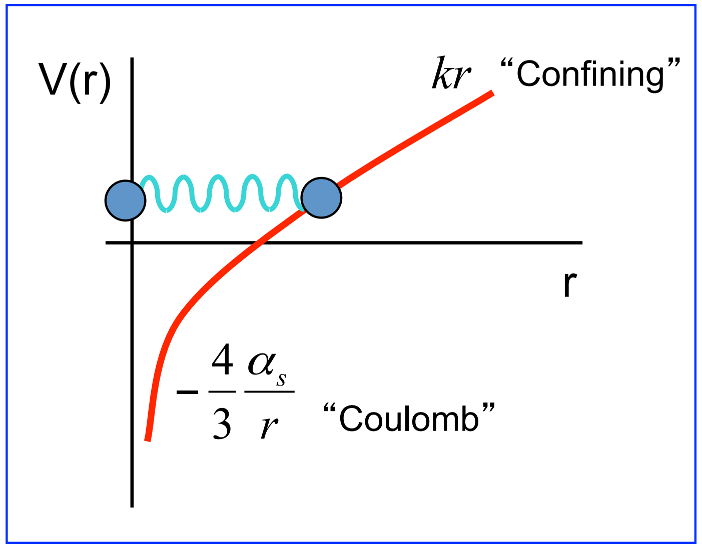
in a regime where perturbative methods are not applicable …unfortunately

Confinement

- The increase of the interaction strength (for a $q\bar{q}$ pair) can be approximated by Cornell potential

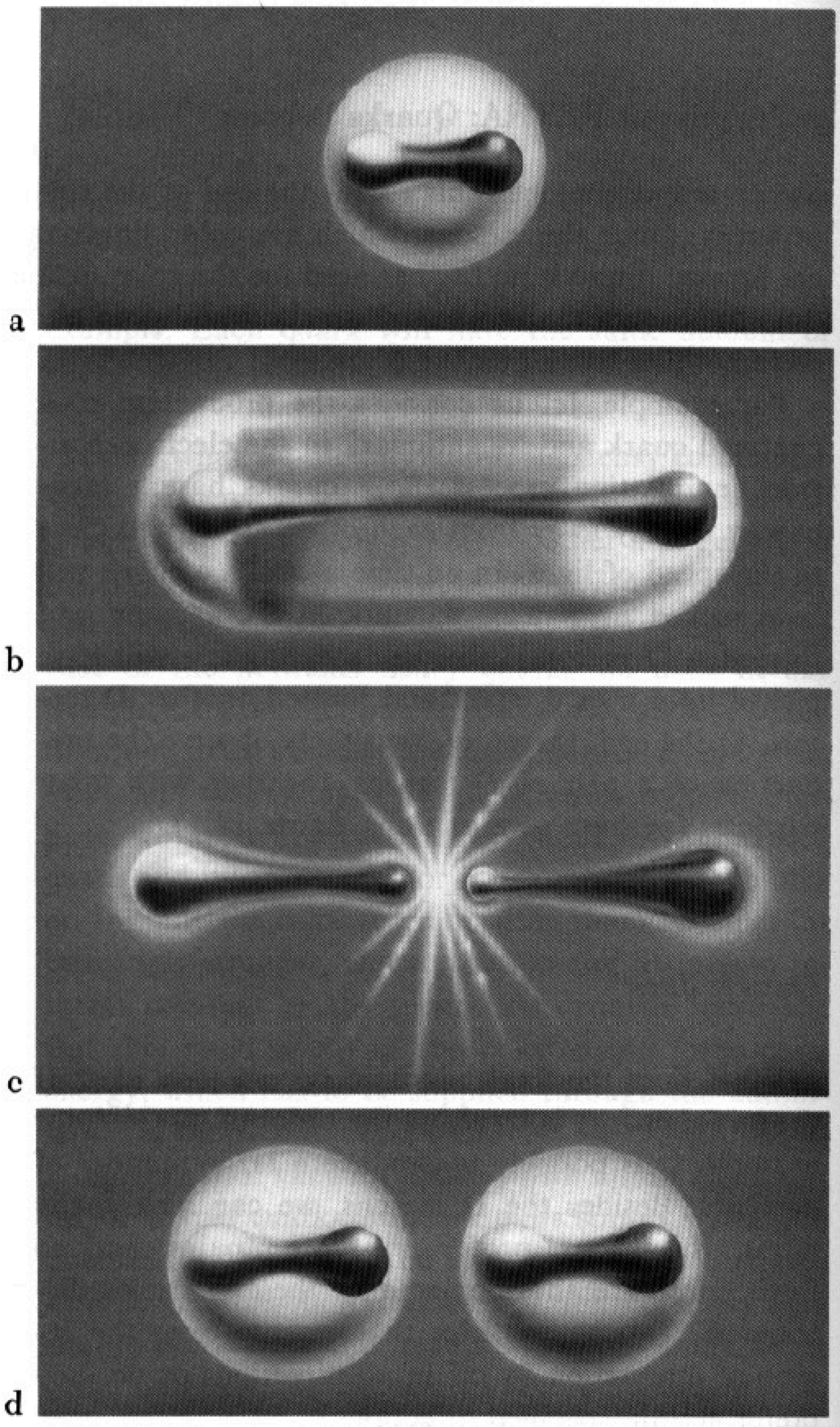
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + K\,r$$

Kr parametrizes the effects of confinement



- When r increases, the color field can be seen as a tube
- At large r, energy in string increases
- New $q\bar{q}$ pair is created once energy is above production threshold

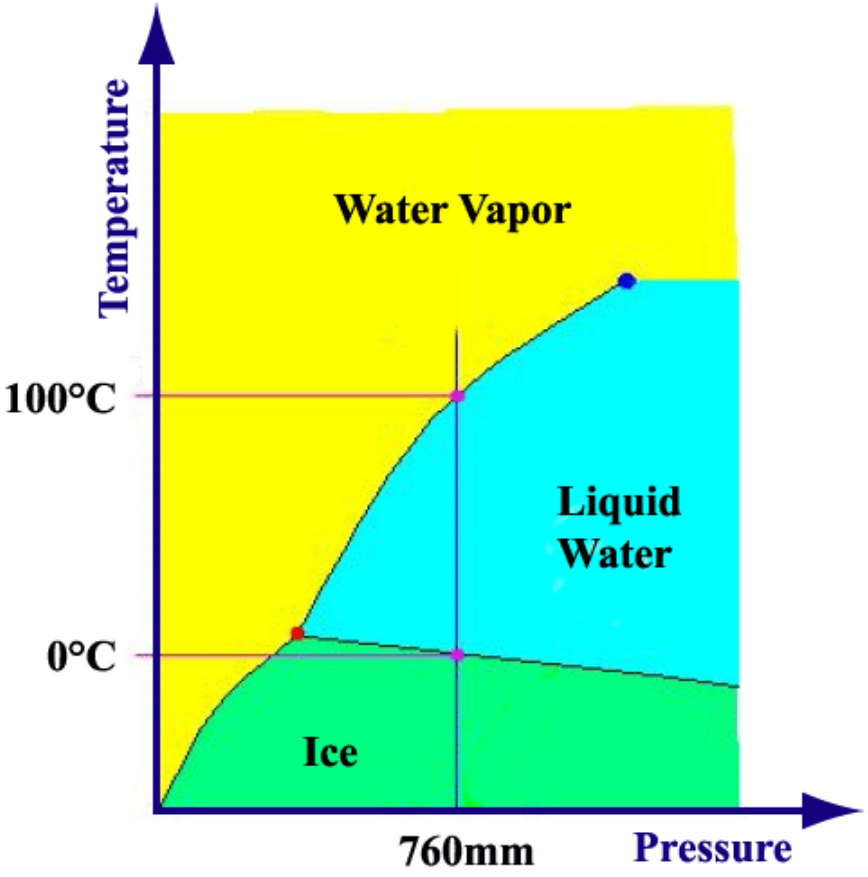
No free quark can be obtained → confinement

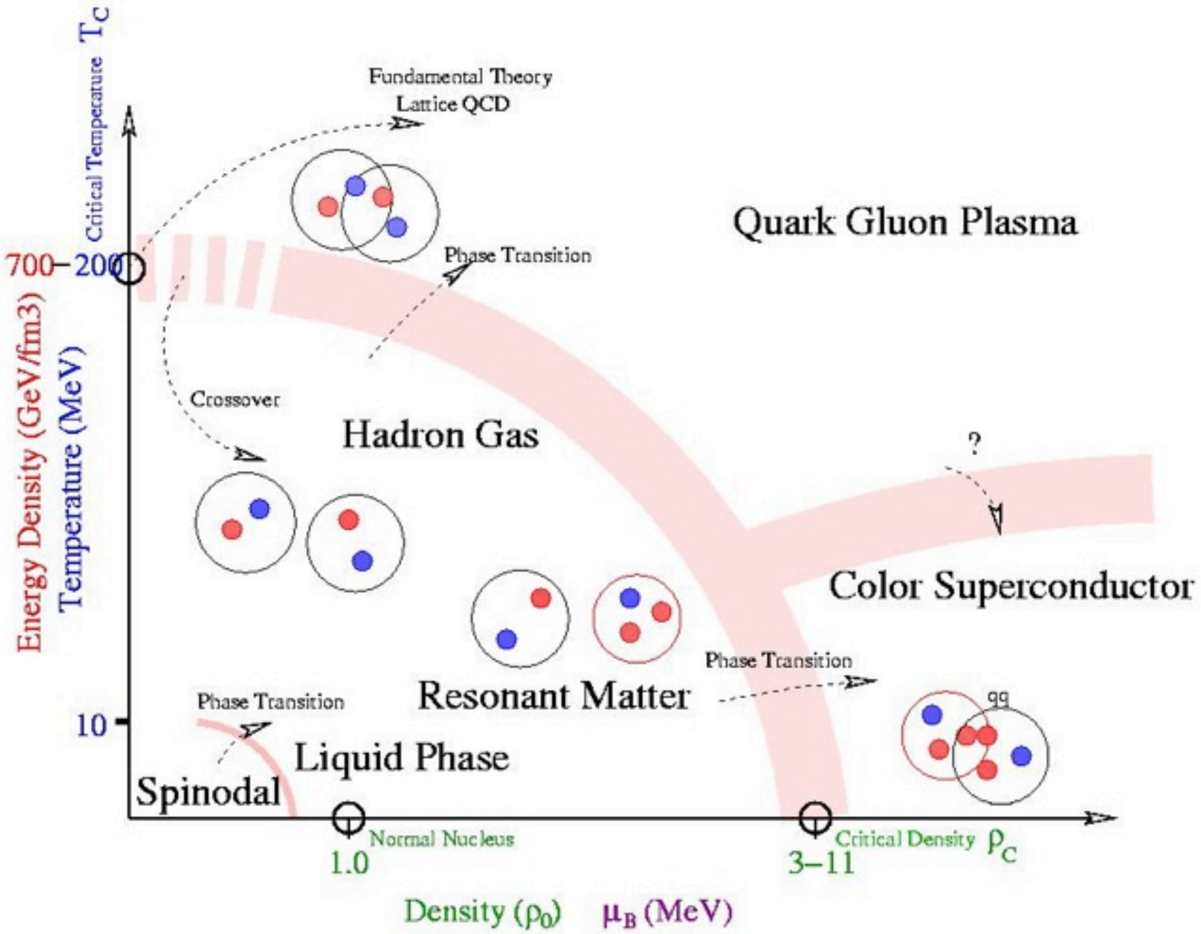


(Illustration from Fritzsch)

How can one recreate primordial matter of free quarks and gluons ?

Phase transitions in nature





QCD (the strong interaction sector of the Standard Model of particles and forces) predicts:
“at sufficient high energy density (provided by HIC) nuclear matter undergoes a transition from ordinary matter to a new state of matter called the Quark Gluon Plasma (**QGP**)”

The MIT Bag Model

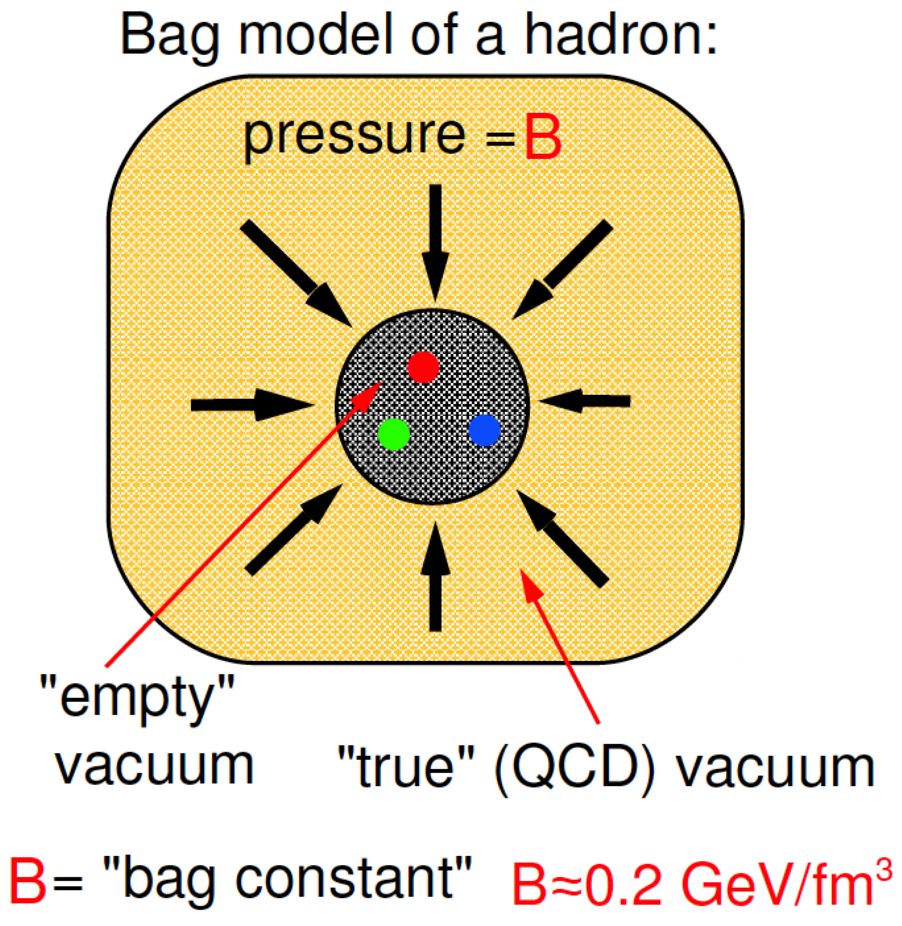
- The MIT bag model assumes that quarks are confined within bags of perturbative (empty) vacuum of radius R, in which they are free to move
- The QCD (true) vacuum creates a confining bag pressure B
- The bag constant is obtained by balancing the vacuum with the kinetic pressure of the quarks
- Massless fermions in spherical cavity

$$E = \frac{2.04N}{R} + \frac{4\pi}{3}R^3 B$$

N quarks
R radius
B bag pressure

- Equilibrium defines bag radius
- Proton radius (~0.8 fm) → $B^{1/4}$ ~206 MeV

If kinetic pressure exceeds bag pressure → deconfinement



Chodos et al., PRD 10 (1974) 2599

Deconfinement phase transition

- If kinetic pressure exceeds bag pressure → deconfinement

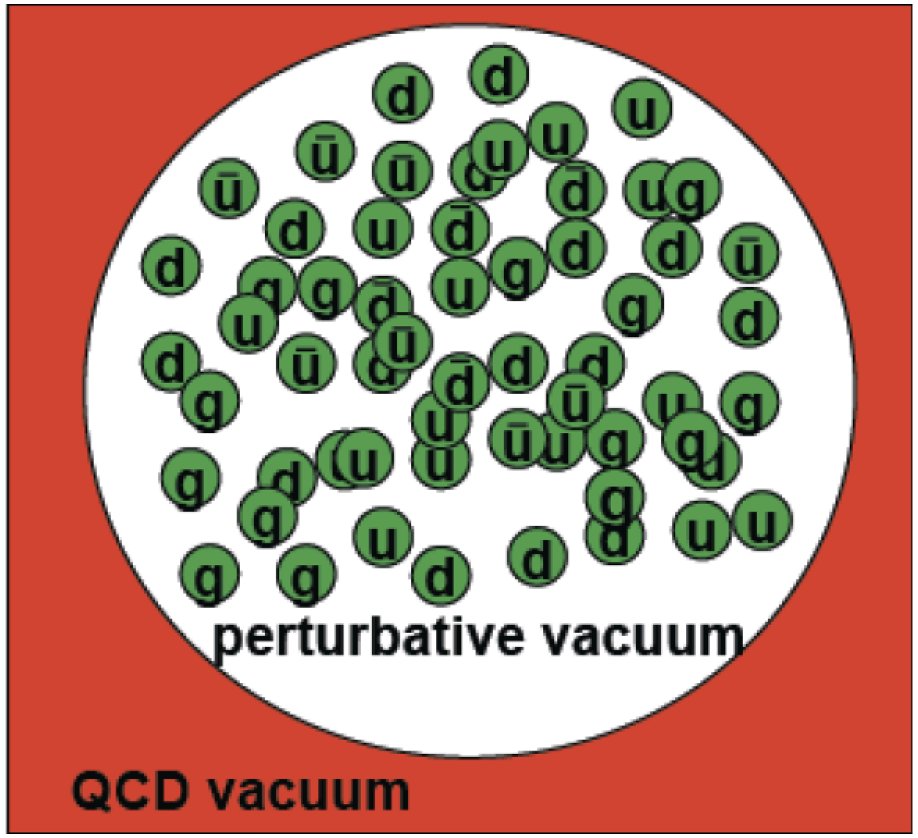
- Relativistic massless quark gas

$$p = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$$g_B = 16 \quad g_F = 24$$

8 gluons x 2 spins

2 quarks x 2 spins x 3 colors + antiquarks



- Pressure exceeds bag pressure (p > B) at T_c ~ 144 MeV
  - quark-gluon plasma above T_c

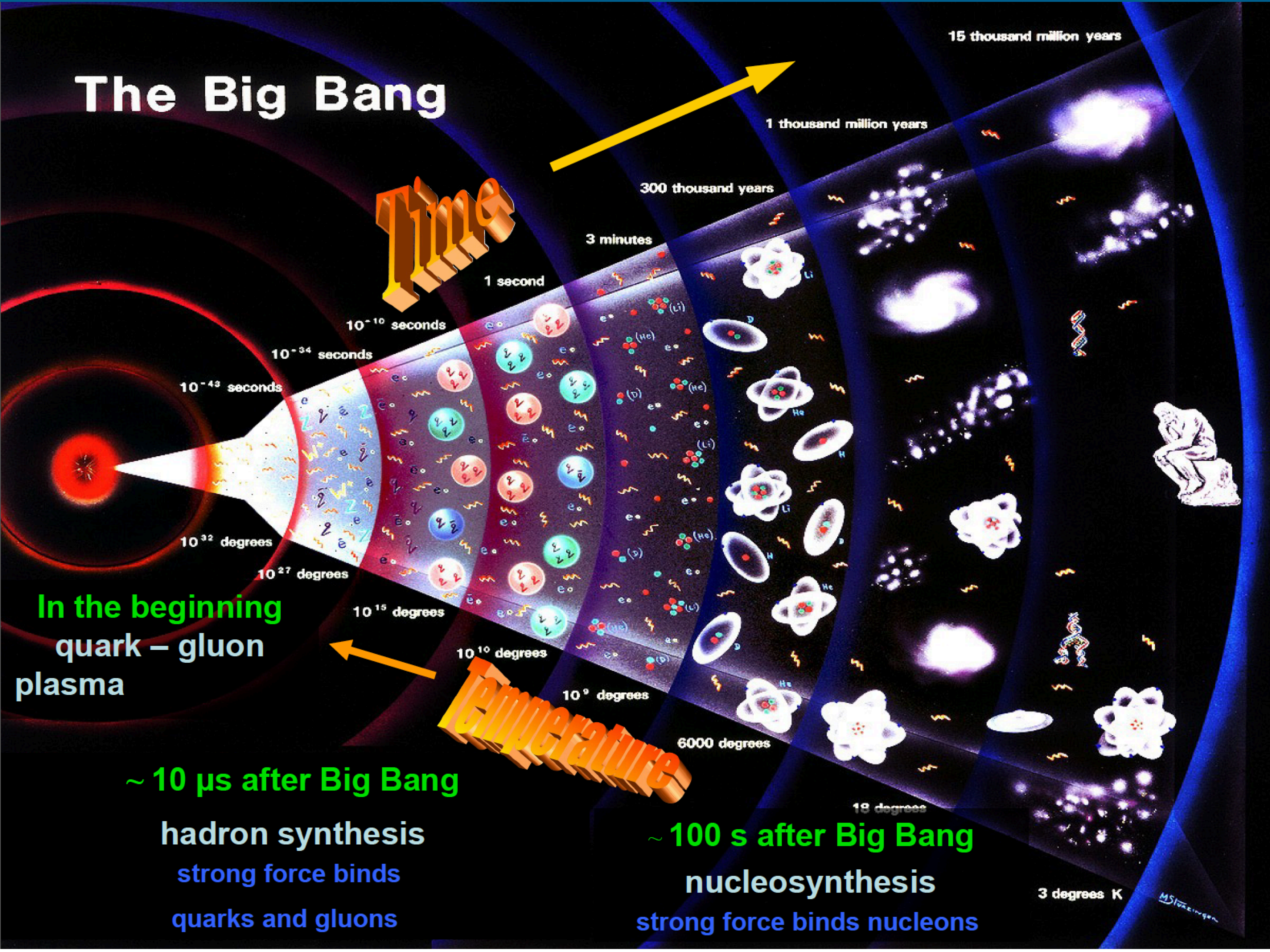
More thorough estimate of the phase transition temperature can be done with lattice QCD → T_c ~ 156 MeV

Fundamental Questions

- How do “free” quarks and gluons behave?
- How do quarks and gluons behave when chiral symmetry is restored?
- What generates the constituent masses?

- In the early universe a phase with free quarks and gluons and restored chiral symmetry has existed
  - Quark-Gluon Plasma (QGP)
  - Recreate in the laboratory with heavy-ion collisions

- How does matter behave at very large densities and temperatures?



In the beginning

quark – gluon plasma

~ 10 µs after Big Bang

hadron synthesis

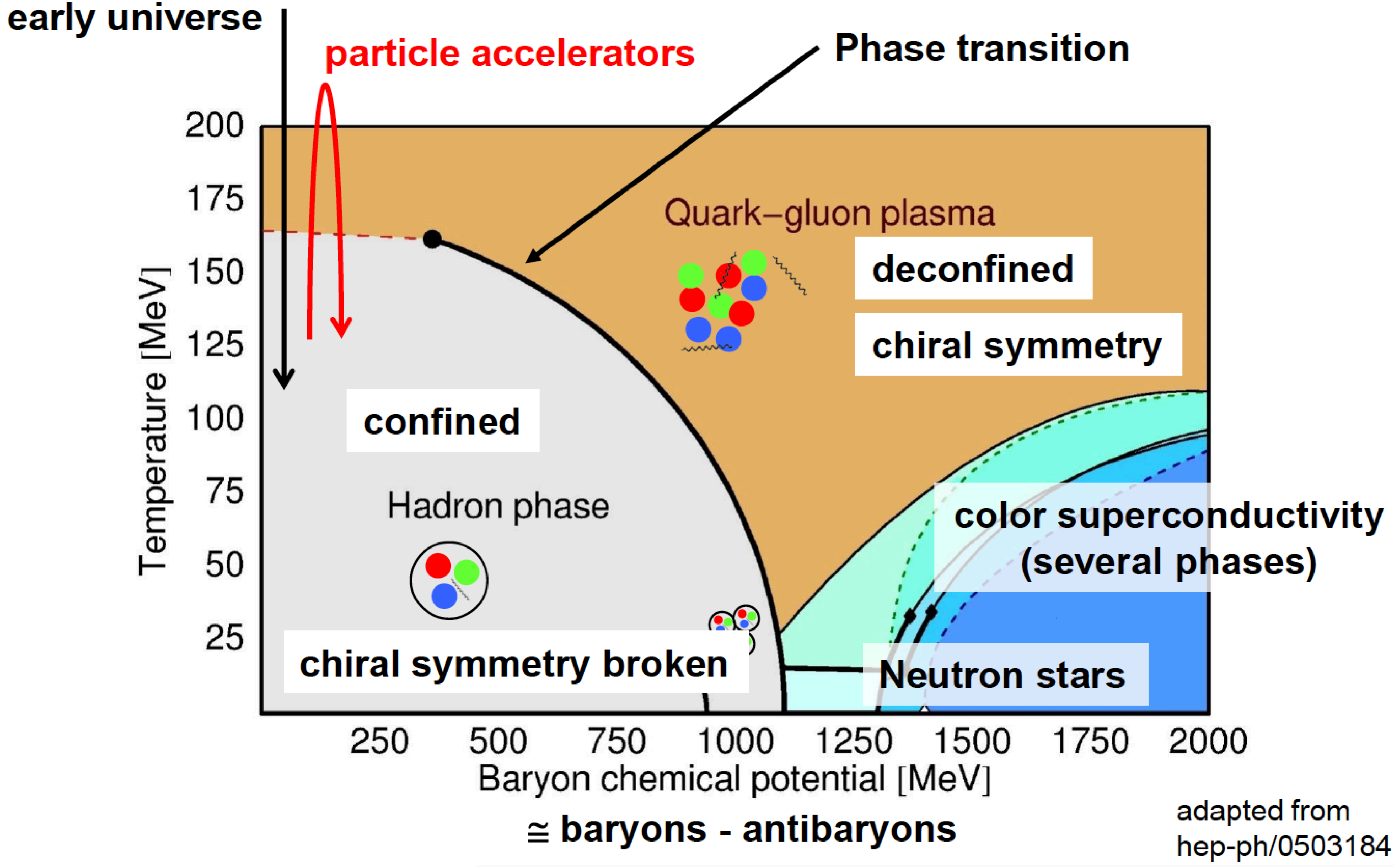
strong force binds quarks and gluons

~ 100 s after Big Bang

nucleosynthesis

strong force binds nucleons

QCD Phase Diagram

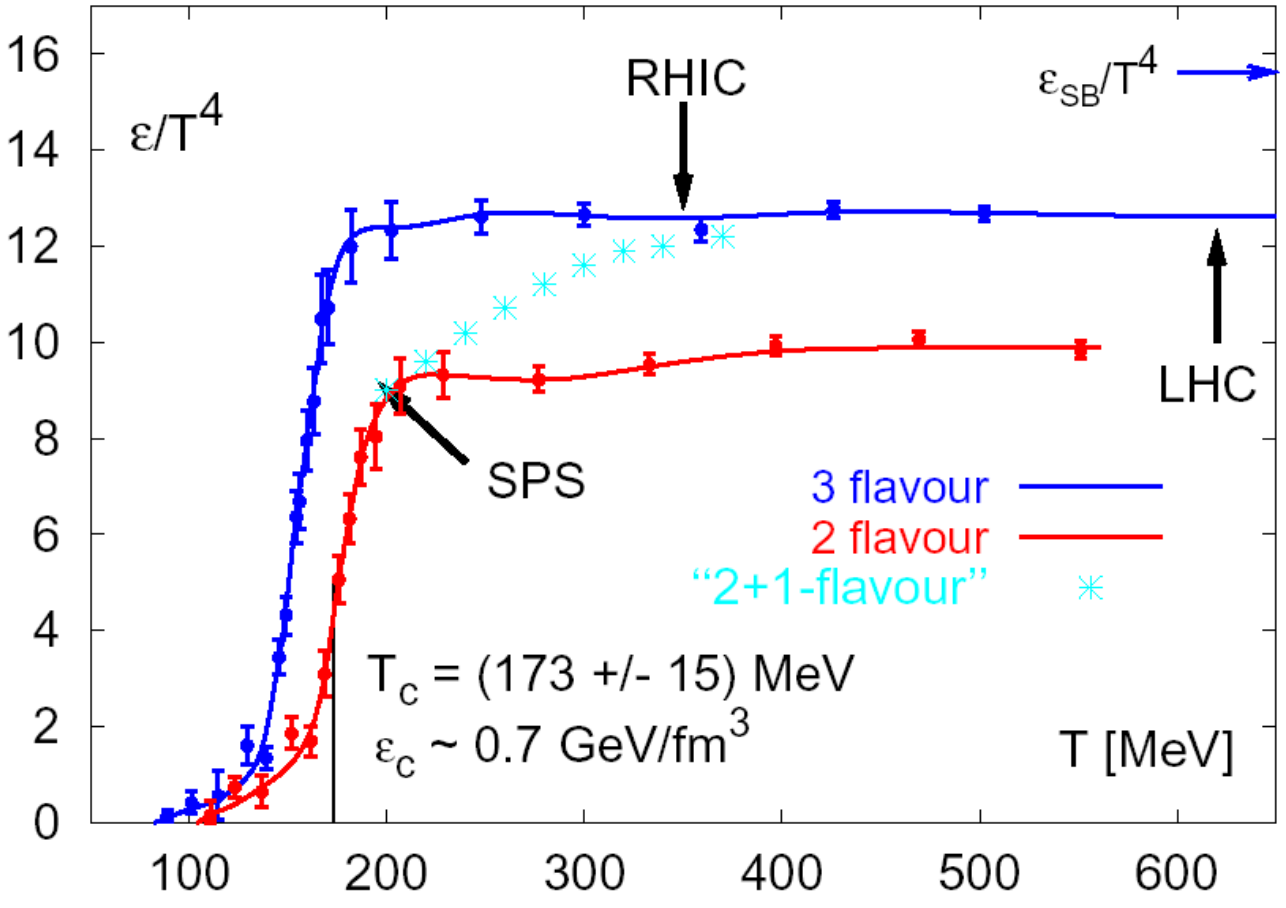


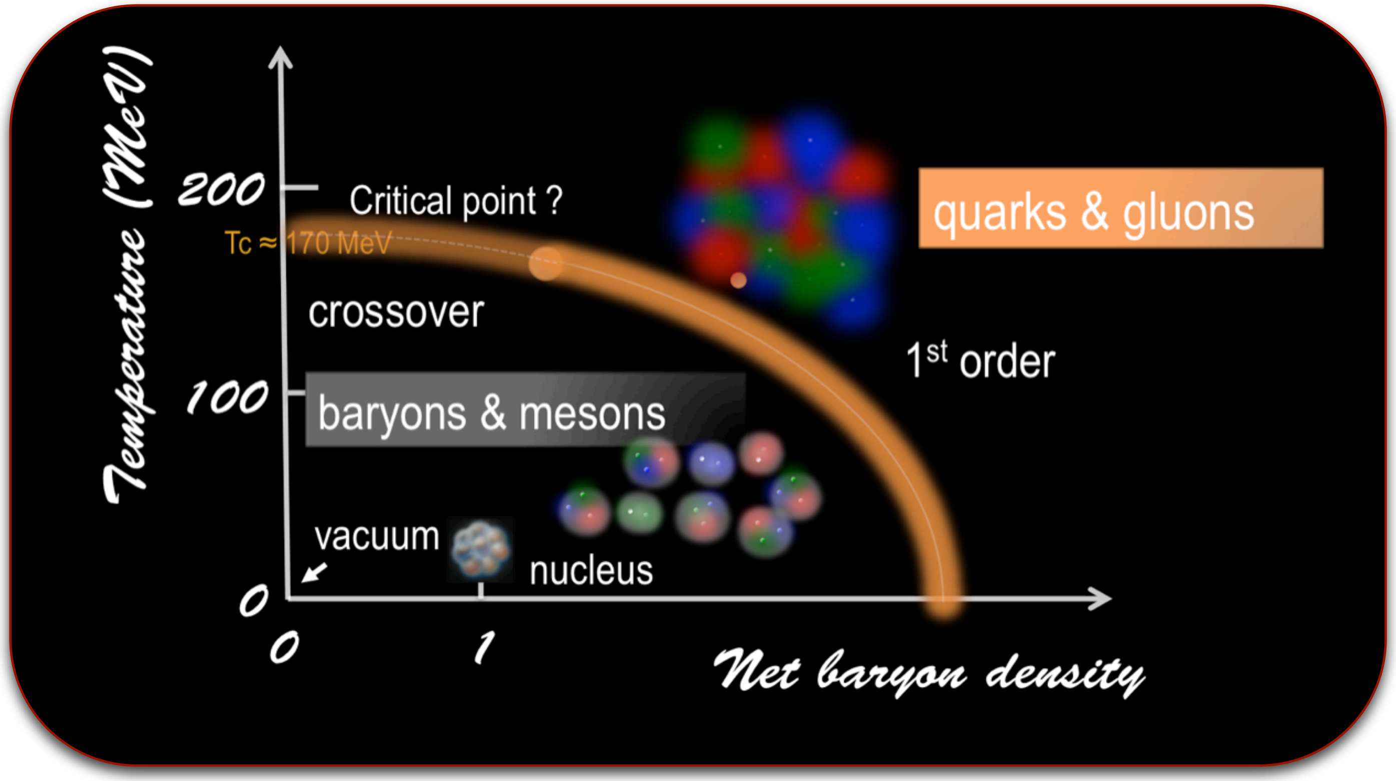
adapted from hep-ph/0503184

The QCD phase transition

- QCD calculations (on the lattice) indicate that the phase transition occurs at a critical energy density

We can thus create a system of deconfined quarks and gluons
➡ by heating (T)
➡ by compression (matter density)

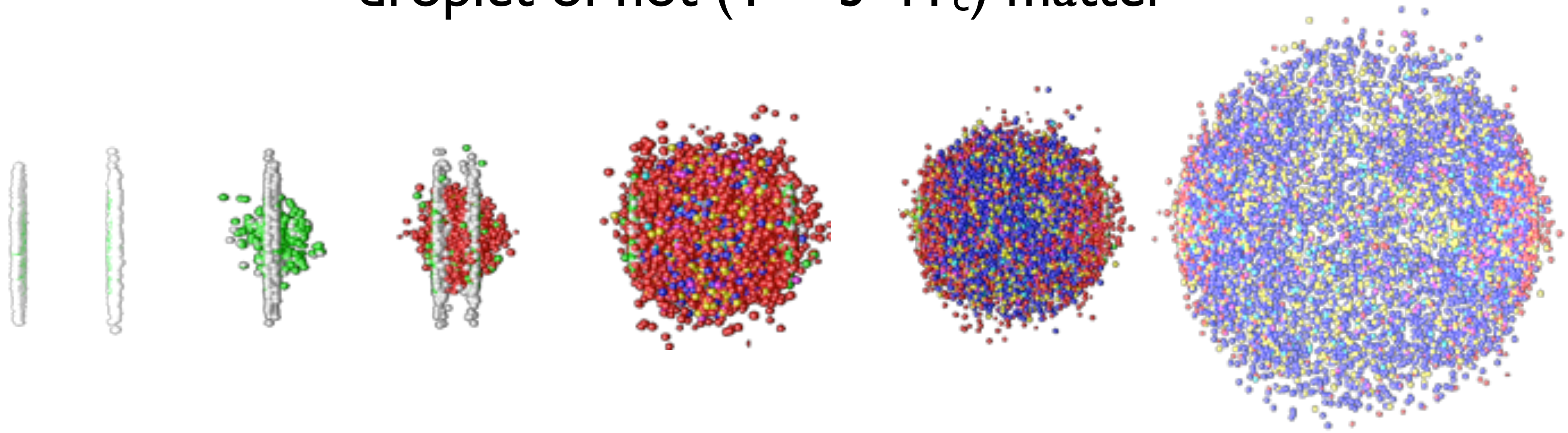




QGP factory: Heavy ion collisions

--suggesed by T. D. Lee

We collide heavy nuclei at ultra-realistic energies ($E \gg mc^2$) to produce a droplet of hot ($T \sim 3\text{-}4T_c$) matter



Heavy nuclei accelerated at speed of light collide

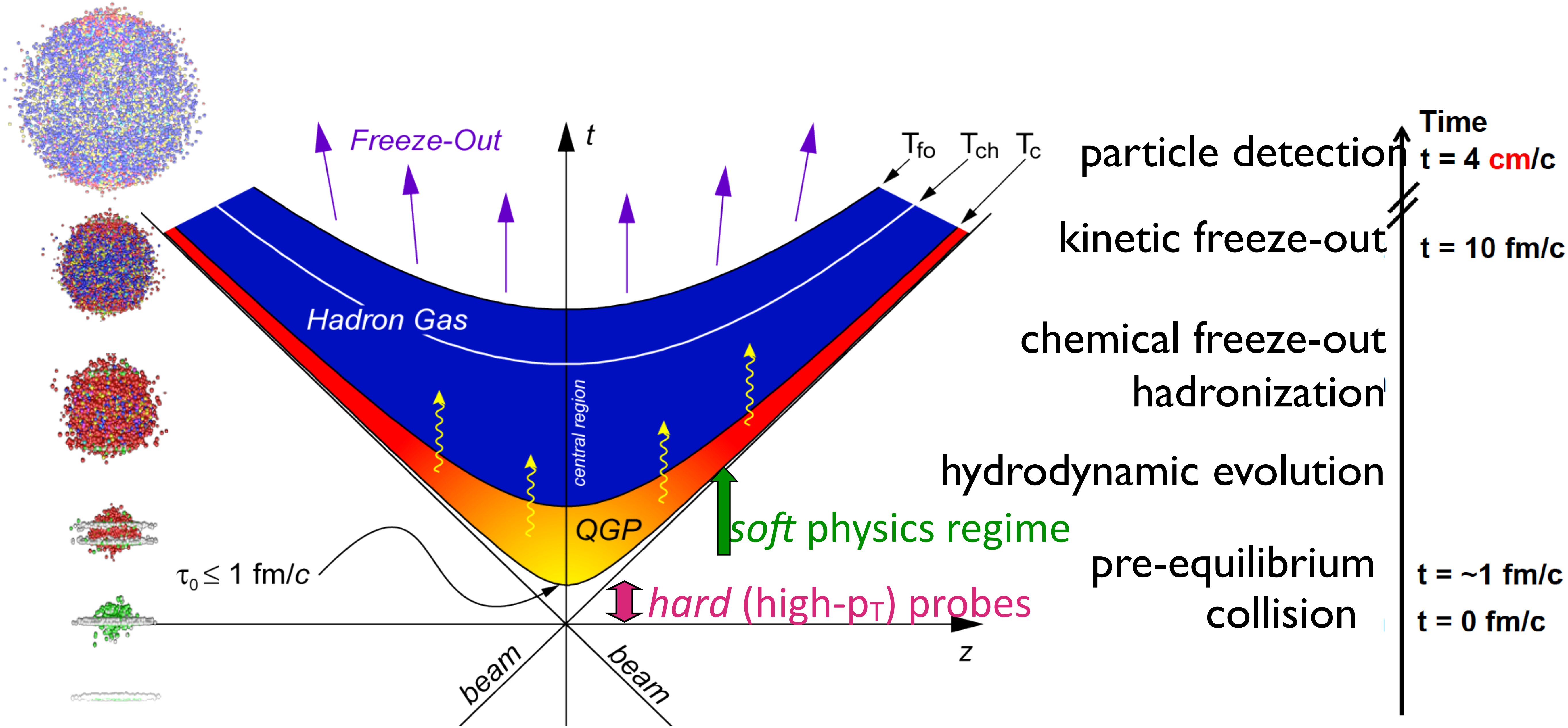
Quarks and gluons are created out of the vacuum ($E=mc^2$)

They interact to form a drop of thermalized matter

Matter cools down while expanding

Quarks and gluons condense into observable hadrons

System evolution in heavy-ion collisions



particle detection

kinetic freeze-out

chemical freeze-out

hadronization

hydrodynamic evolution

soft physics regime

pre-equilibrium

collision

hard (high-p_T) probes

1 fm/c = 3 x 10^{-24}s

In reality, strong dynamical evolution of the system …

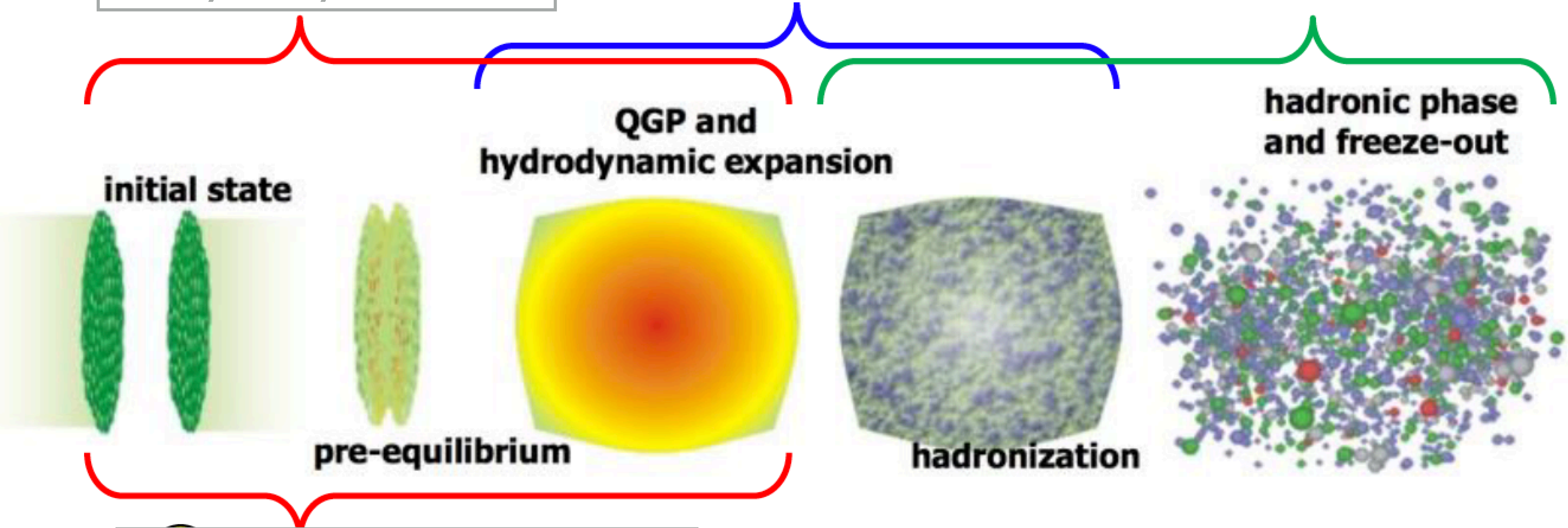
Outline of the Lecture

- How to use detector to learn about the QGP?
- This lecture will focus on the main topic

Collective flow & hydrodynamics

Jet quenching, energy loss & quarkonia

Particle yields & Statistical model



Collectivity in small systems

Outline of the Lecture (what I have no time to cover …)

Nuclear Parton Distribution Functions

Direct Photons

Femtoscopy

Collective flow & hydrodynamics

Jet quenching, energy loss & quarkonia

Particle yields & Statistical model

Global Event Properties

Jet Reconstruction

Higher Moments

Fragmentation Functions

Dileptons

Jet Structure

Creating Heavy-Ion Beams

Ultra-peripheral collisions

Diffraction

Collectivity in small systems

Heavy-Ion Experiments

Literature

- Lectures
  - J. Stachel, K. Reygers (2011)
    http://www.physi.uni-heidelberg.de/~reygers/lectures/2011/qgp/qgp_lecture_ss2011.html
  - P. Braun-Munzinger, A. Andronic, T. Galatyuk (2012)
    http://web-docs.gsi.de/~andronic/intro_rhic2012/
  - Quark Matter Student Day (2014)
    https://indico.cern.ch/event/219436/timetable/#20140518.detailed
  - Quark Matter Student Day (2017)
    https://indico.cern.ch/event/433345/timetable/#20170205.detailed
- Books
  - C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994
    http://books.google.de/books?id=Fnxvrdj2NOQC&printsec=frontcover
  - L. P. Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994 (**free as pdf**)
    http://www.csernai.no/Csernai-textbook.pdf
  - E. Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004
    http://books.google.de/books?id=rbcQMK6a6ekC&printsec=frontcover
  - Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005
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  - R. Vogt, Ultrarelativistic Heavy-ion Collisions, Elsevier, 2007
    http://books.google.de/books?id=F1P8WMESgkMC&printsec=frontcover
  - W. Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010
    http://books.google.de/books?id=4gIp05n9lz4C&printsec=frontcover
  - S. Sarkar, H. Satz and B. Sinha, The physics of the quark-gluon plasma, Lecture notes in physics, Volume 785, 2010 (**free within CERN/university network**)
    https://link.springer.com/book/10.1007%2F978-3-642-02286-9

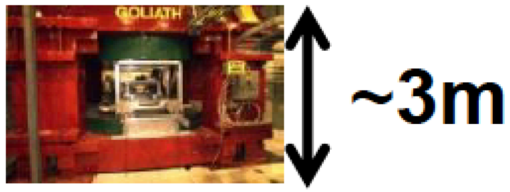
Accelerators

	SPS	RHIC	LHC
top $\sqrt{s_{NN}}$ (GeV)	17	200	5020 (5500)
Volume at freeze-out (fm^3)	1200	2300	5000
Energy density (GeV/fm^3)	3-4	4-7	10
Life time (fm/c)	4	7	10

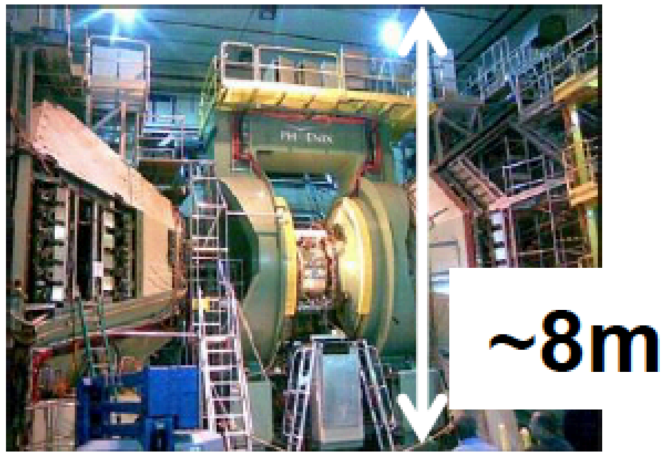
Heavy-ion collisions:

$\sqrt{s}$ given per nucleon pair ($\sqrt{s_{NN}}$)

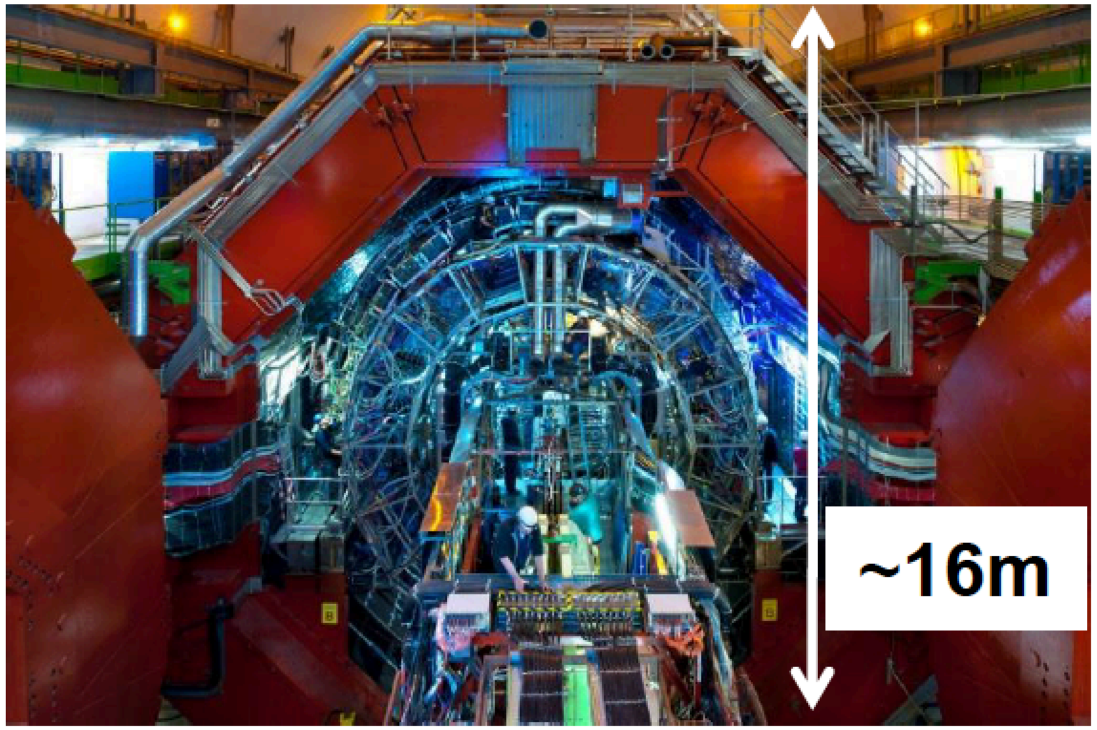
$\sqrt{s_{NN}} = 5$ TeV → $\sqrt{s_{Pb\text{-}Pb}} = 1040$ TeV



NA57 (SPS)



PHENIX (RHIC)



ALICE (LHC)

Two main laboratories for heavy-ion collisions

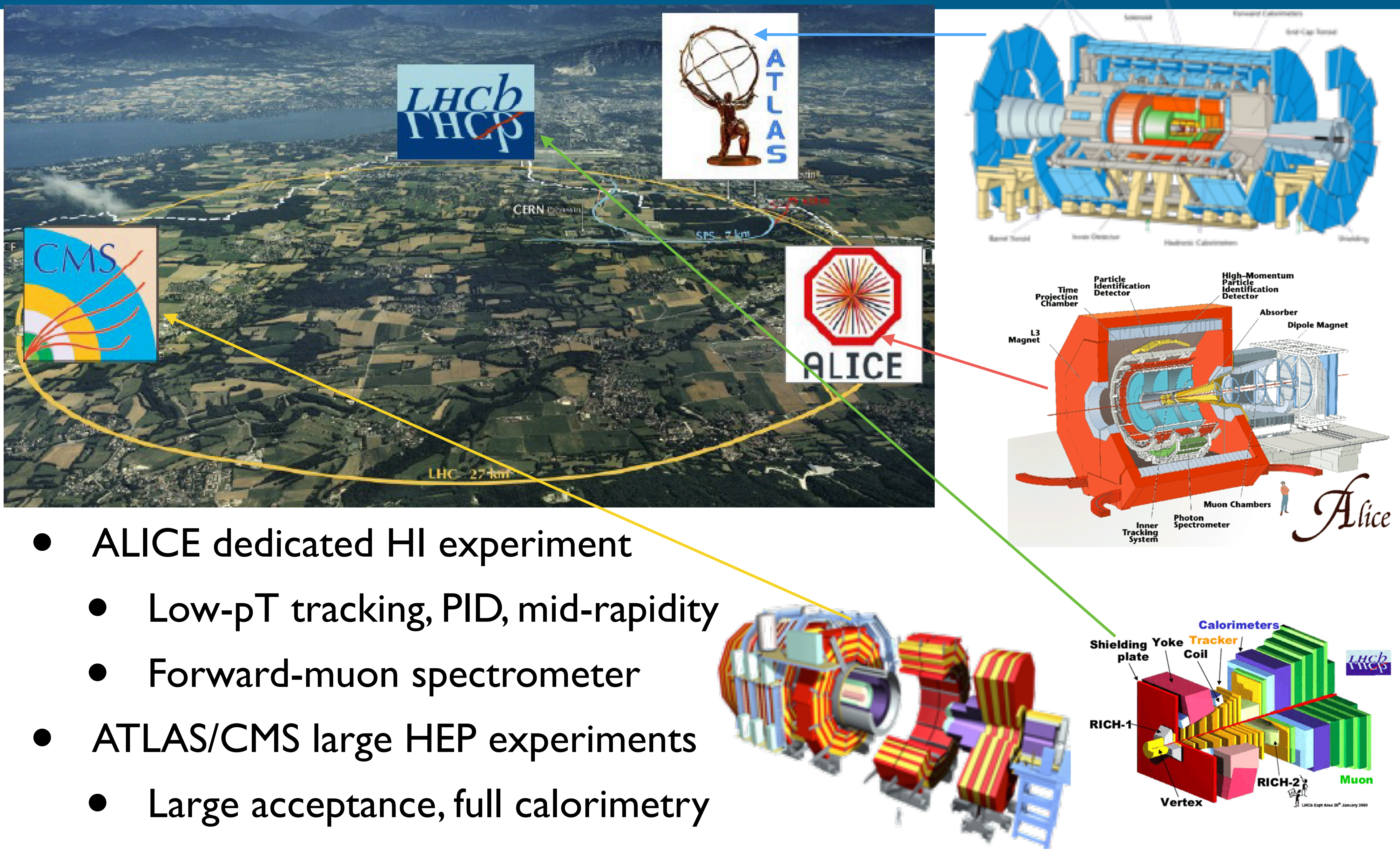
AGS : 1986 – 2000
- Si and Au beams ; $\sqrt{s} \sim 5$ GeV
- only hadronic variables

RHIC : 2000 – ?
- He^3, Cu, Au beams ; up to $\sqrt{s} = 200$ GeV
- 4 experiments (only two remain)

SPS : 1986 – 2003 + 2009 — ?
- O, S, In, Pb beams ; $\sqrt{s} \sim 20$ GeV
- Various experiments in North Area

LHC : 2009 – ?
- Pb beams ; up to $\sqrt{s} = 5500$ GeV
- ALICE, CMS, ATLAS and LHCb

LHC: the Large Hadron Collider



- ALICE dedicated HI experiment
    - Low-pT tracking, PID, mid-rapidity
    - Forward-muon spectrometer
- ATLAS/CMS large HEP experiments
    - Large acceptance, full calorimetry
- LHCb (pPb in 2013, PbPb since 2015)
    - Forward tracking, PID, calorimetry

Heavy-Ion Environment

- Measurements in an environment with $dN_{ch}/d\eta$ up to 1600 ($\sqrt{s_{NN}}$ = 2.76 TeV)

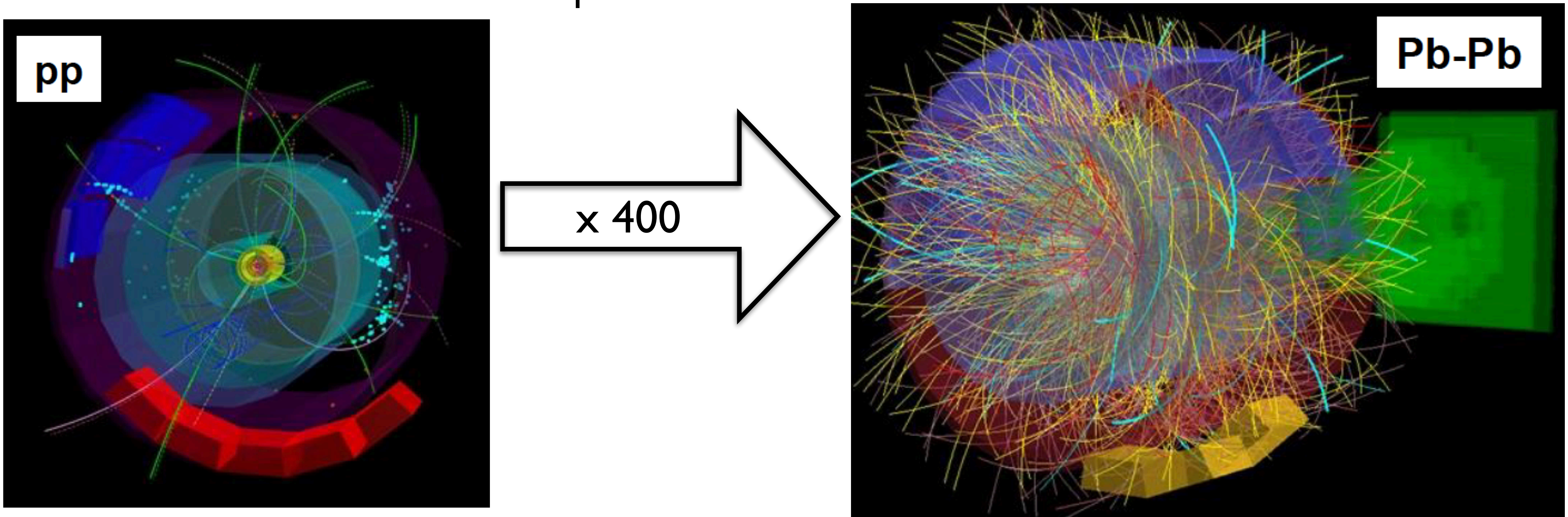
  = 400 pp MB collisions

  = 1 event with 399 pile-up events

  (ATLAS/CMS reconstruct up to 100)

- In one collision, there are in the tracker acceptances
  - 3200 tracks in ALICE | 8000 tracks in CMS/ATLAS

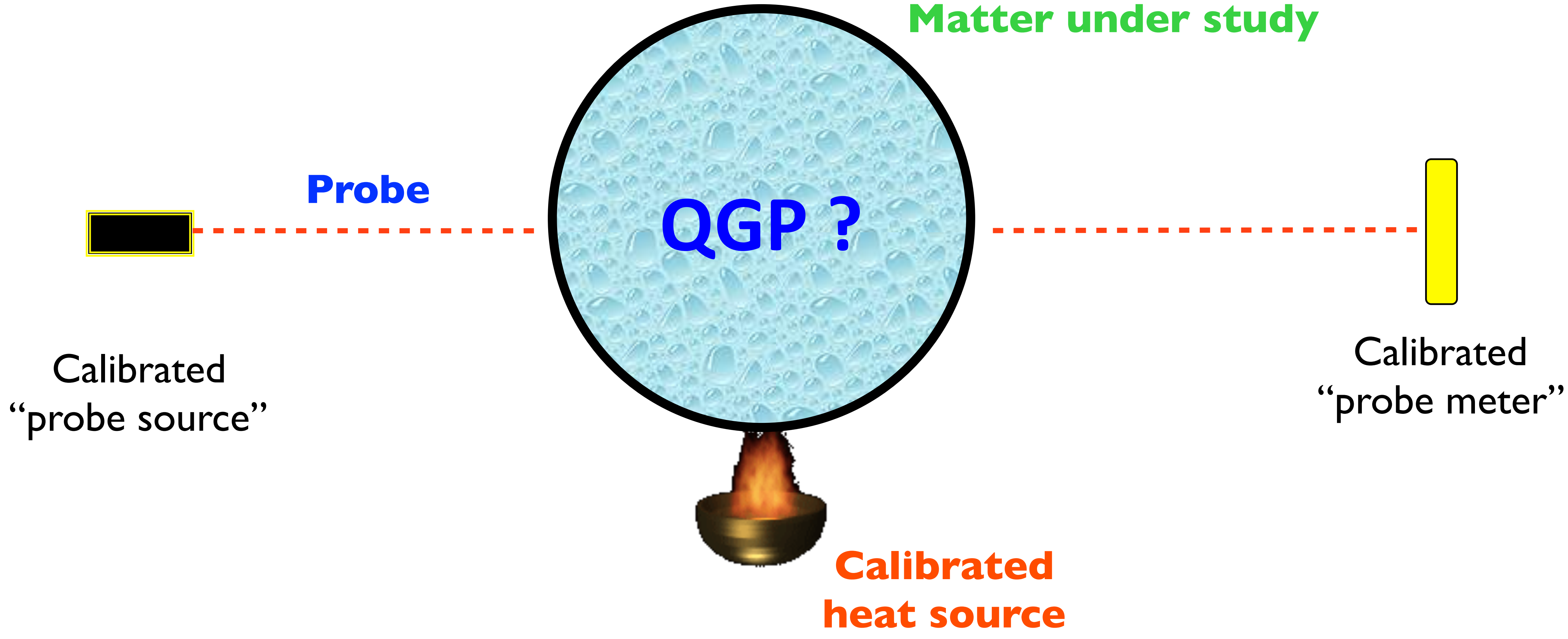
for comparison
pp: $dN_{ch}/d\eta \sim 4$



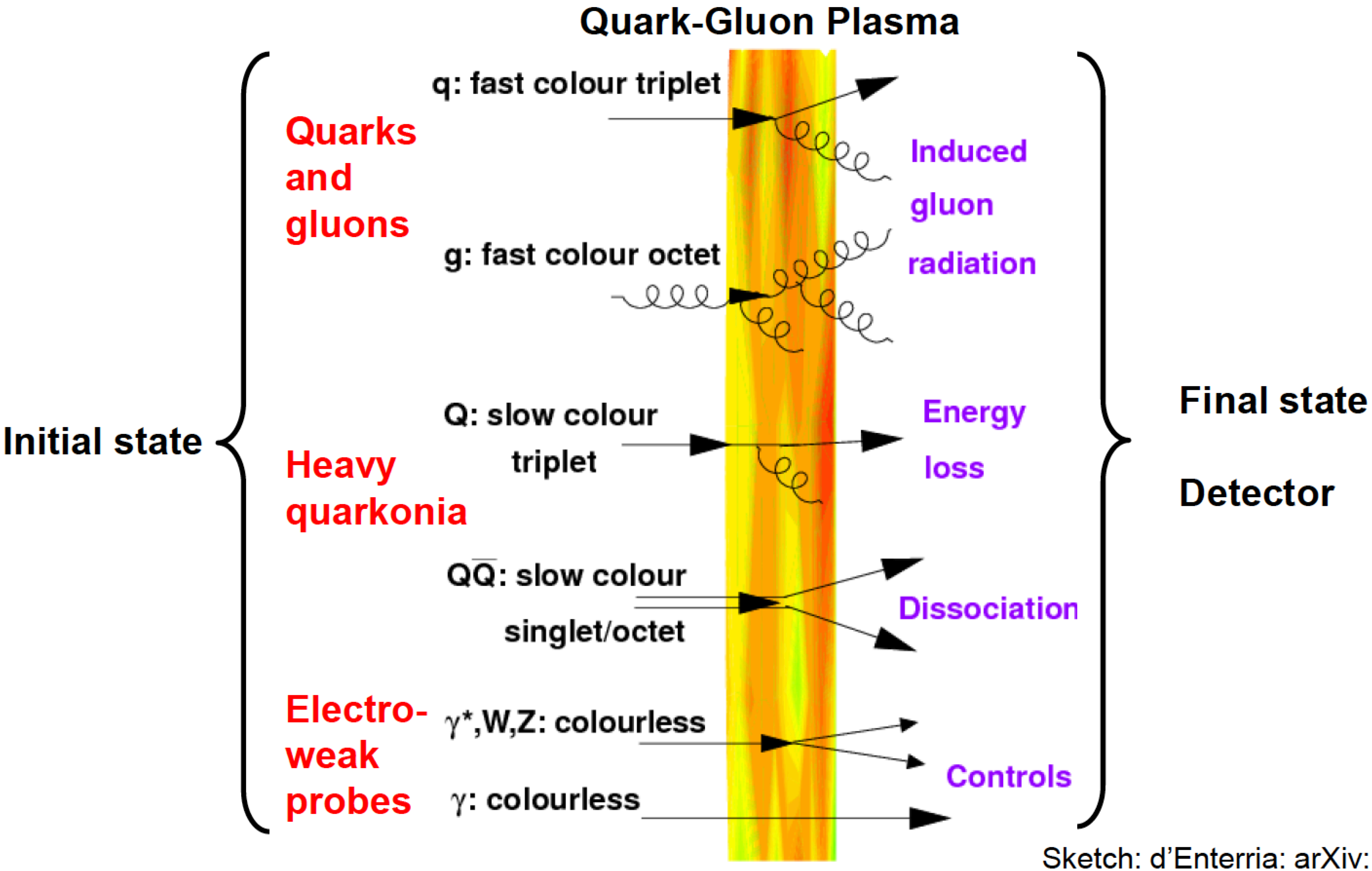
How to probe QGPs?

Probing QGP

We study the QCD matter produced in HI collisions by seeing how it affects well understood probes as a function of the temperature of the system (centrality of the collisions)



Probes traverse the QGP



Quark-Gluon Plasma

Initial state

Quarks and gluons

q: fast colour triplet

g: fast colour octet

Induced gluon radiation

Heavy quarkonia

Q: slow colour triplet

Energy loss

$Q\bar{Q}$: slow colour singlet/octet

Dissociation

Electro-weak probes

γ^*,W,Z: colourless

γ: colourless

Controls

Final state

Detector

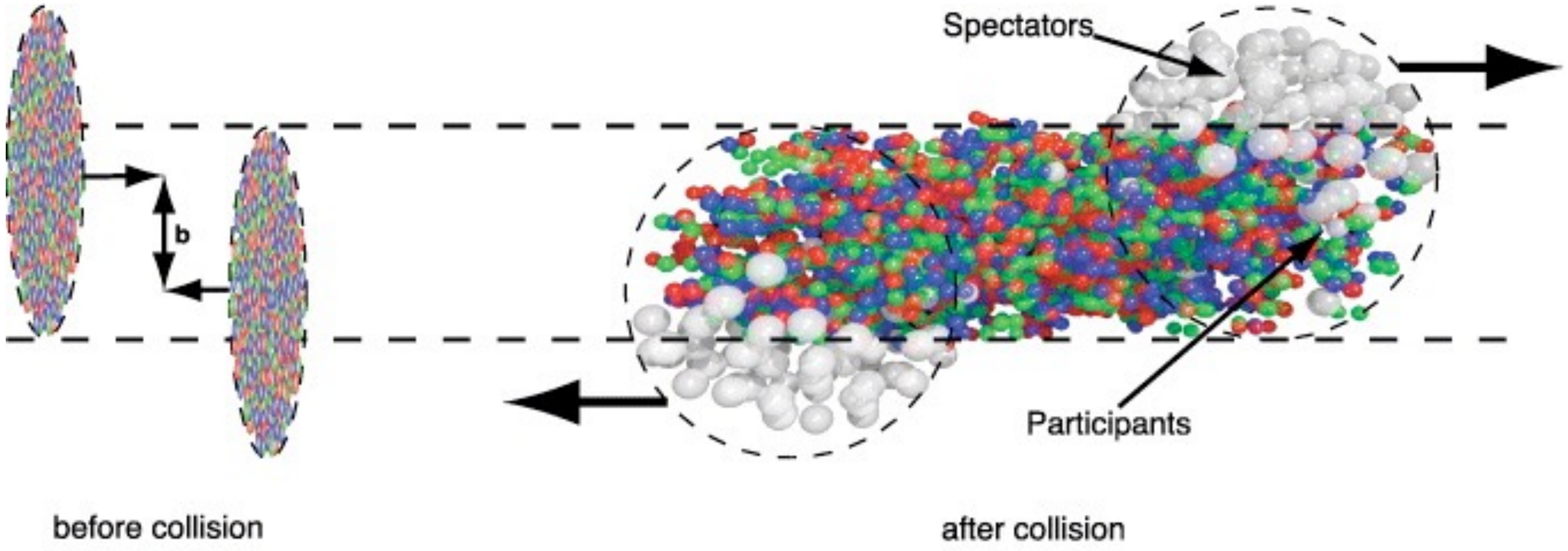
Sketch: d'Enterria: arXiv:1207.4362

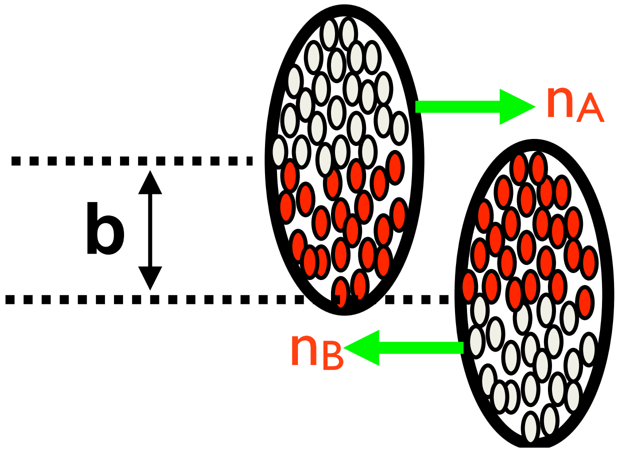
External control parameters

Collision Centrality

Controls the volume, shape and energy density of the system

➡ Multiplicity and energy of produced particles are correlated with geometry of collisions





$$N_{part} = n_A + n_B$$
$$N_{coll} = n_A \otimes n_B$$

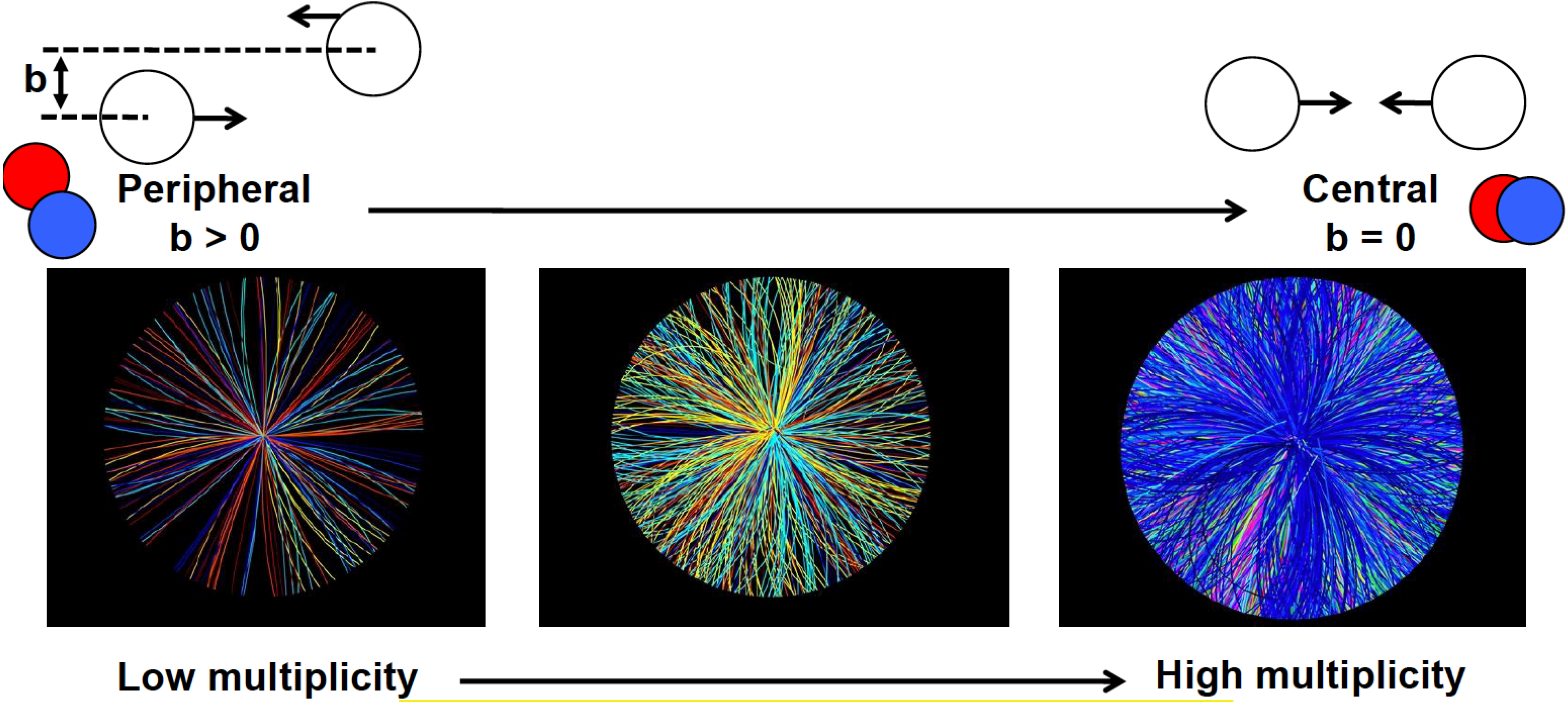
Soft processes: long timescale, large σ, $\sigma_{tot} \propto N_{part}$

Hard processes: short timescale, large σ, $\sigma_{tot} \propto N_{coll}$

How to measure the impact parameter b?

Centrality

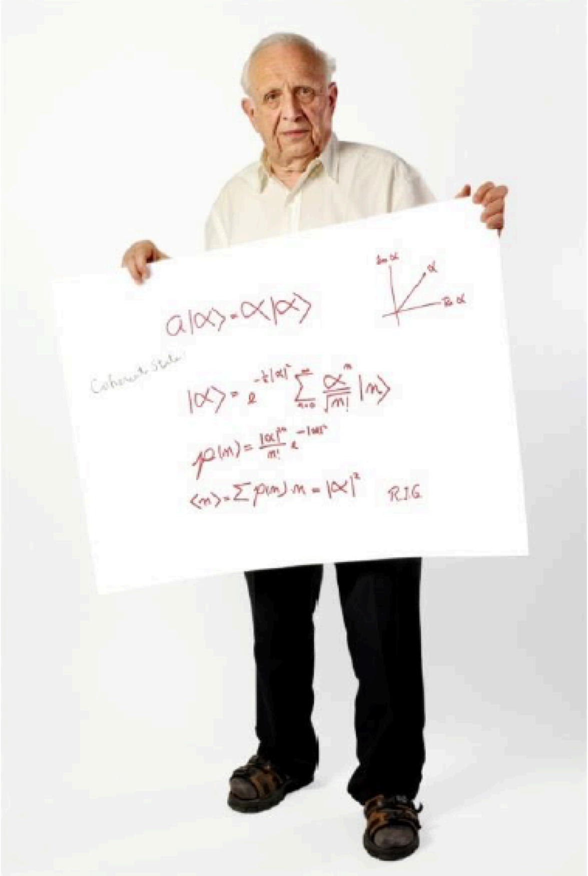
- Multiplicity anti-proportional to b
  - Glauber MC + particle production model calculates multiplicity
- Multiplicity correlated in different phase space (e.g. forward and mid-rapidity) regions in HI collisions



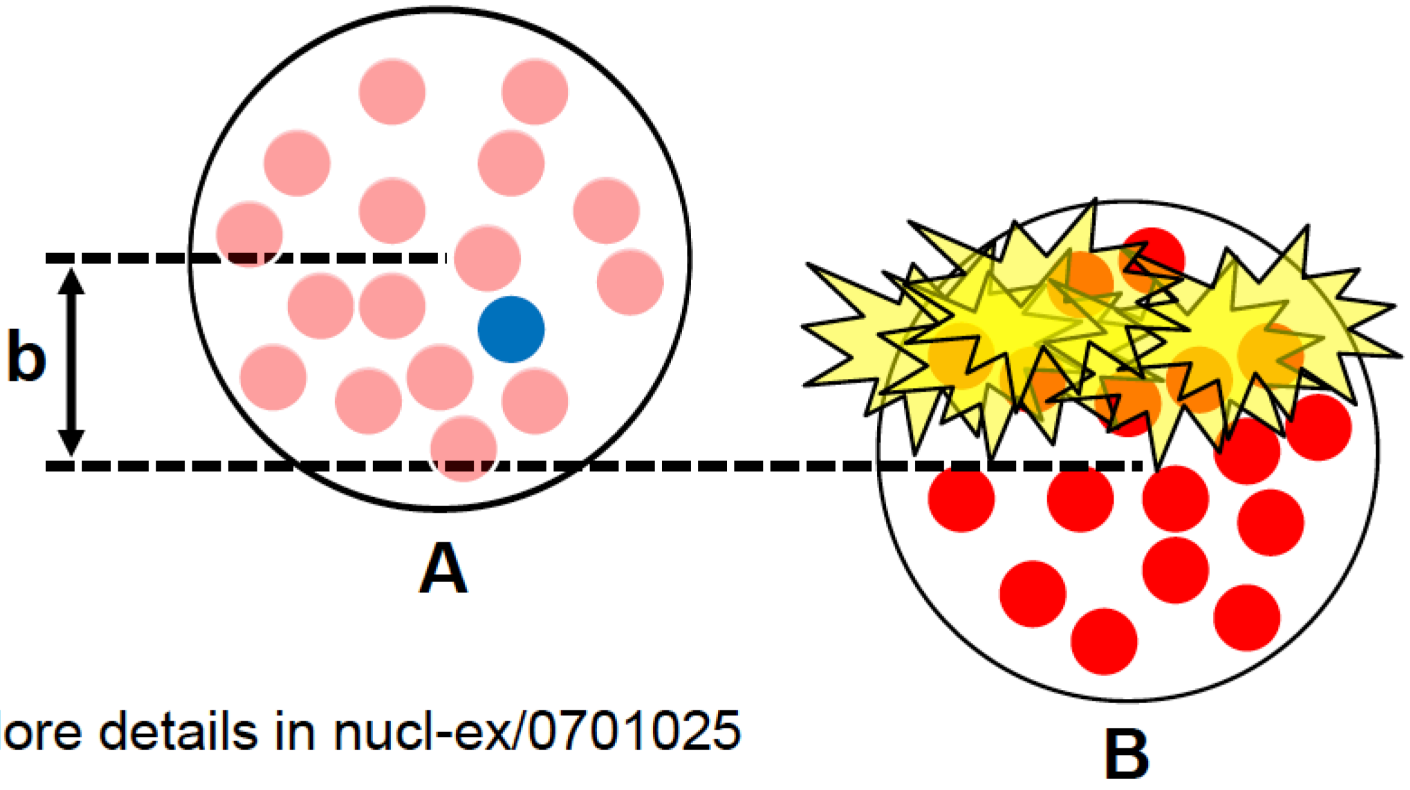
Striking relation between b and multiplicity

Glauber Monte Carlo

- Nucleons travel on straight lines
- Collisions do not alter their trajectory (energy of nucleons large enough)
- No quantum-mechanical interference
- Interaction probability for two nucleons is nucleon-nucleon cross-section



Rov Glauber



More details in nucl-ex/0701025

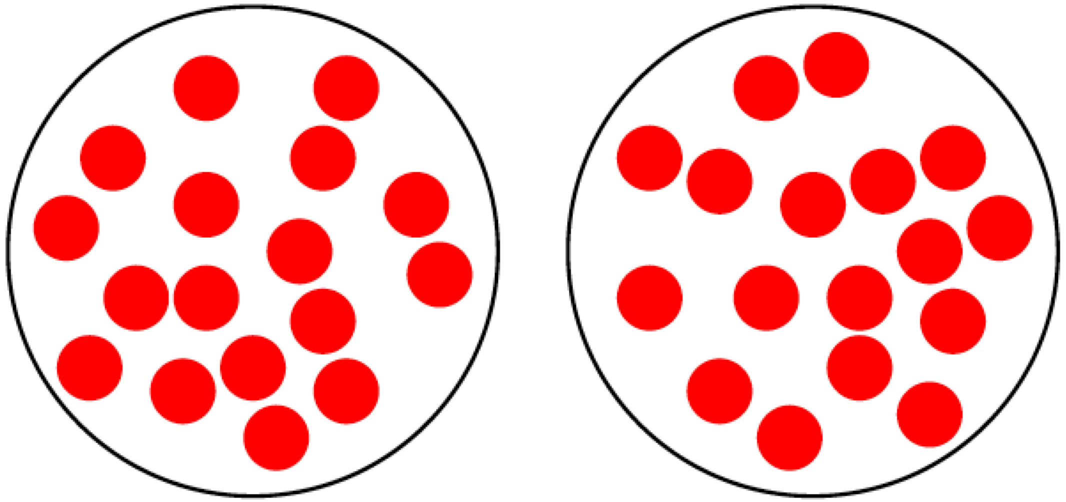
“Blue” nucleon has suffered 5 NN collisions

Need to repeat for all other nucleons in A

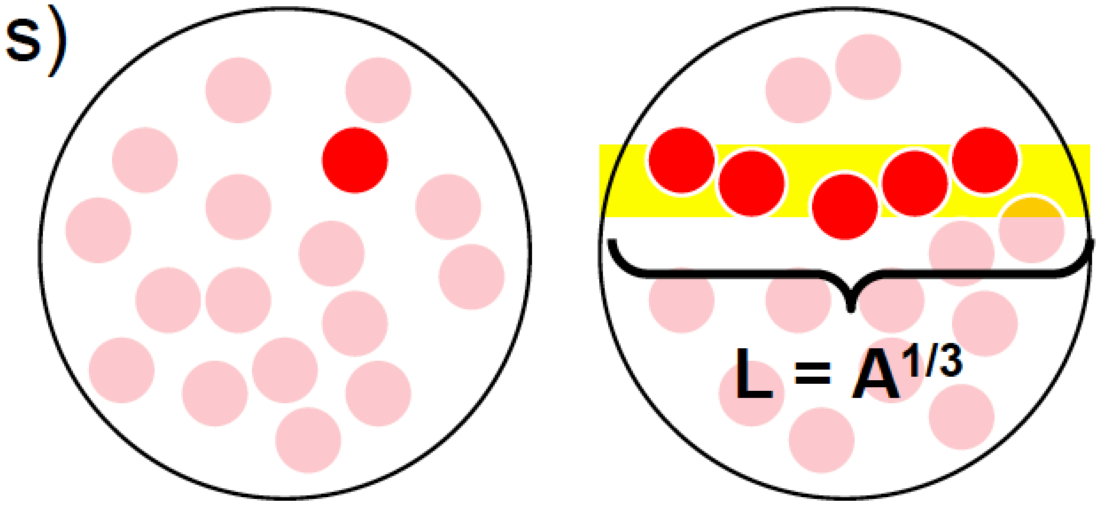
Strongly dependent on *impact parameter* b

Glauber MC Output

- Number of spectators
  - Nucleons which did not collide
- Participant/wounded nucleons
  - Collided at least once
  - Called N_{part}
  - Scale with 2A (A = number of nucleons)
- Number of binary collisions
  - Called N_{coll}
  - Scales with $A^{4/3}$
- Rule of thumb
  - Soft (low p_T) observables scale with N_{part}
  - Hard (high p_T) observables scale with N_{coll}



$N_{part} \sim A + A$

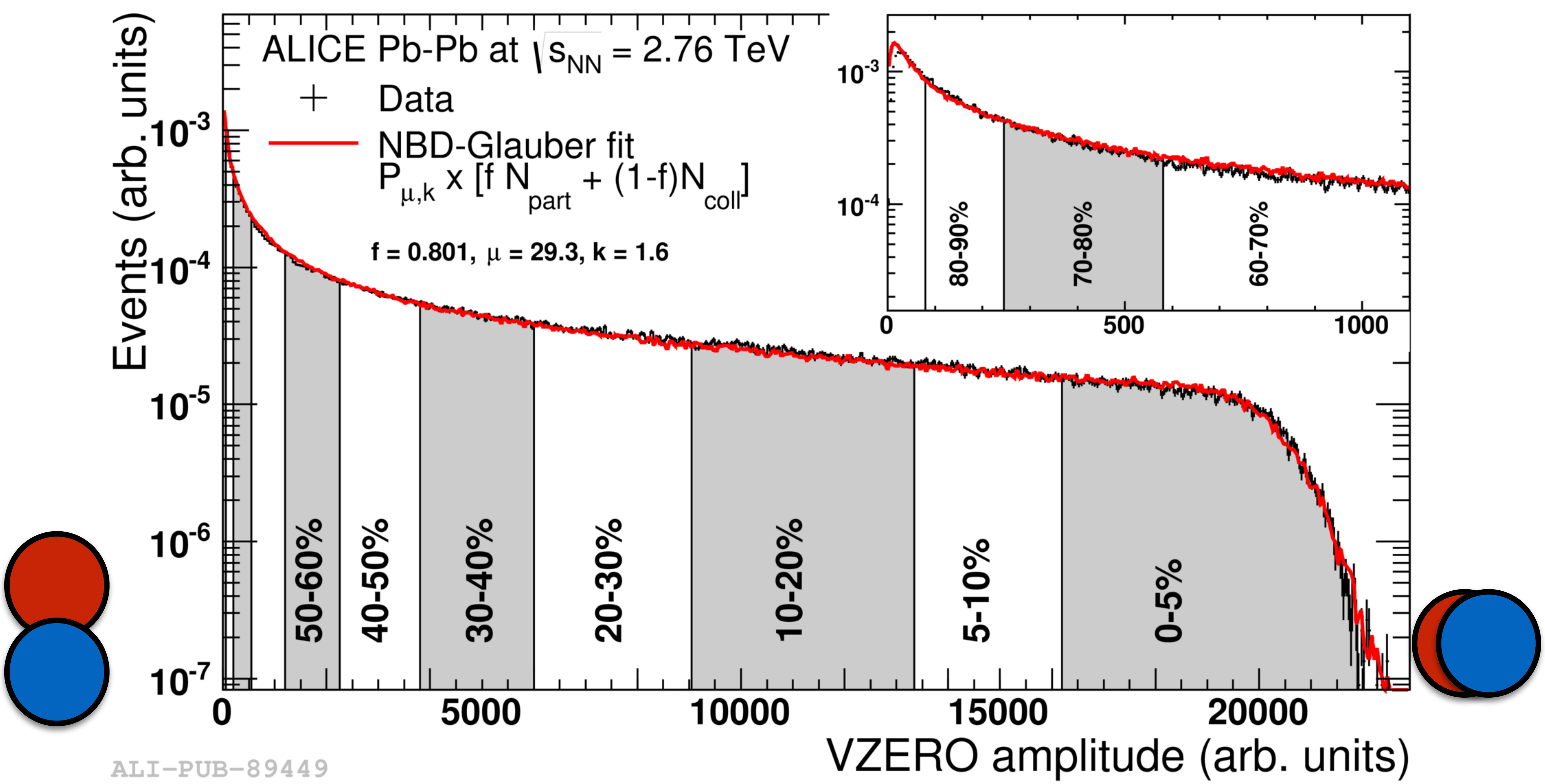


$N_{coll} \sim A \cdot L = A^{4/3}$

Centrality (3)

- Use multiplicity to split events into classes
- Calles 0-5%, 5-10%, …100% (“0%” = most central)
- Glauber MC calculates N_{part} and N_{coll} per class

Number of events vs. multiplicity

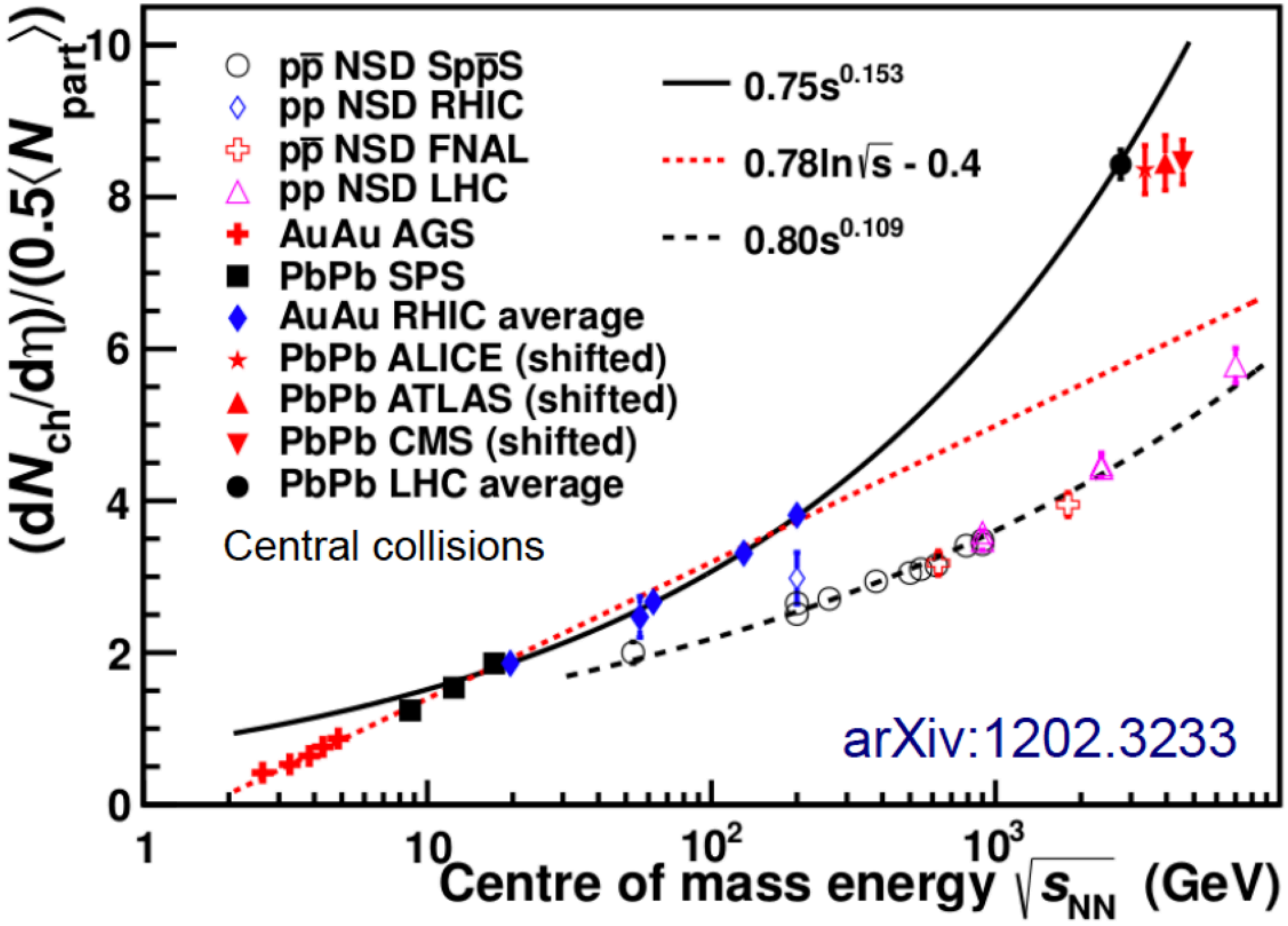


PRC88 (2013) 044909

Multiplicity and transverse energy

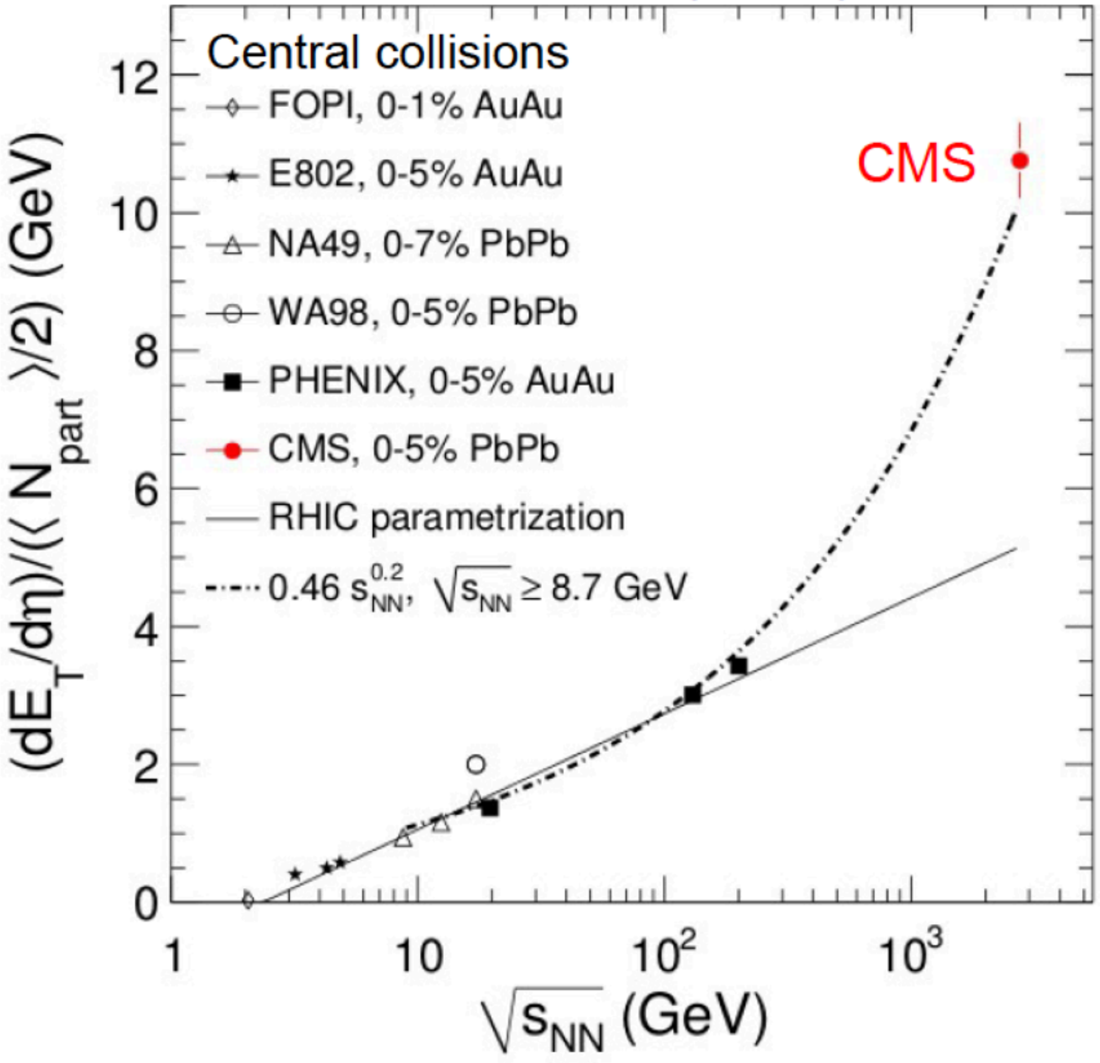
(Estimate of energy density and related to entropy)

Energy dependence of dN/dη and dE_T/dη



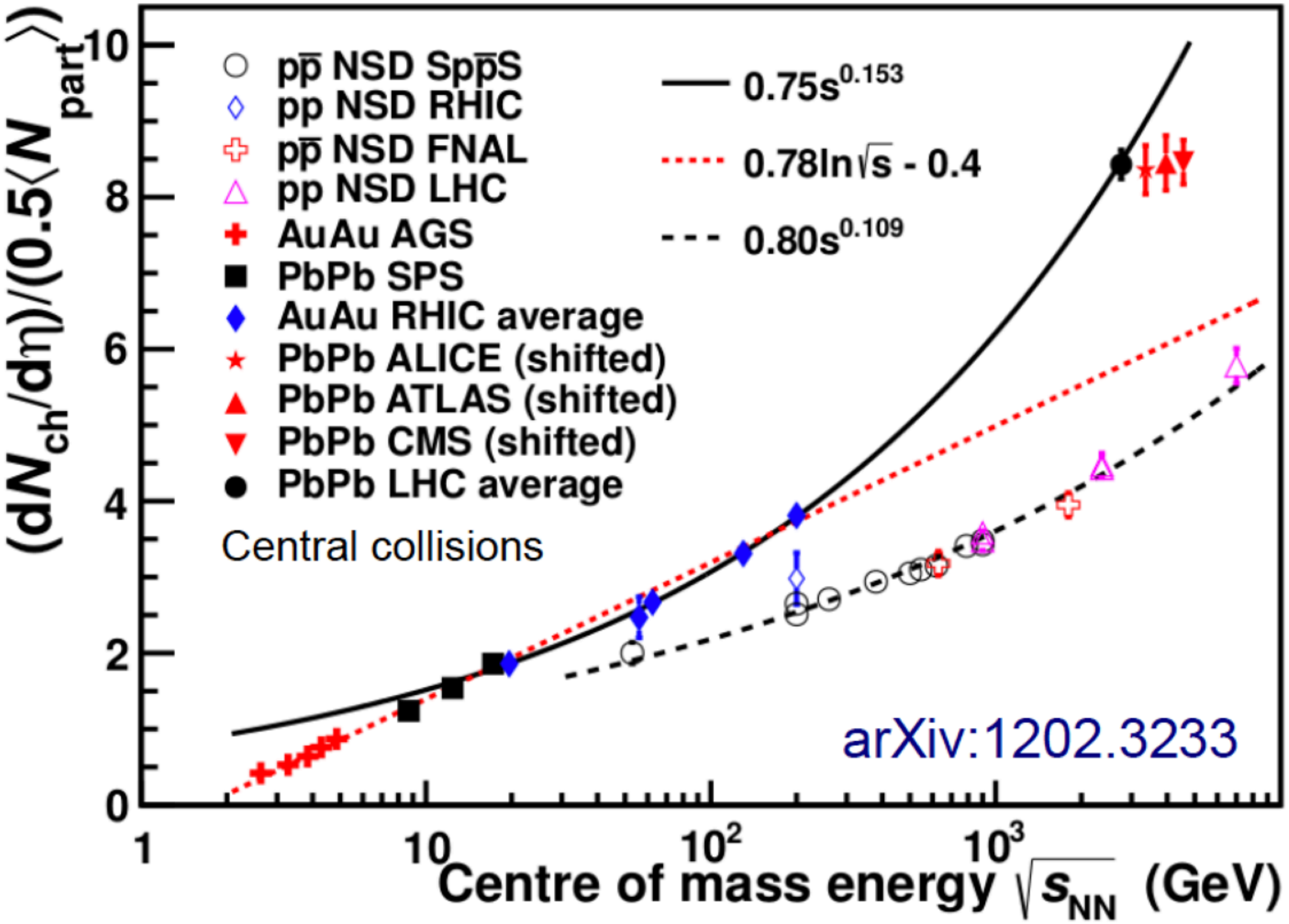
arXiv:1202.3233

PRL 109 (2012) 152303

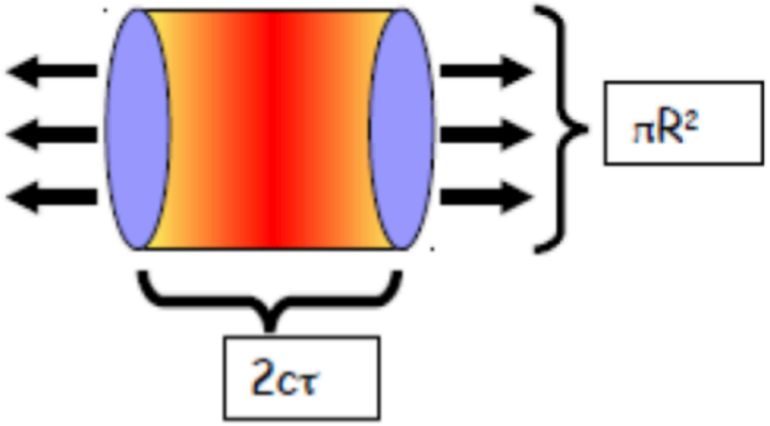


Up dN/dη ≈1600 charged particles in central PbPb at LHC

Energy dependence of dN/dη and dE_T/dη



Bjorken estimate:



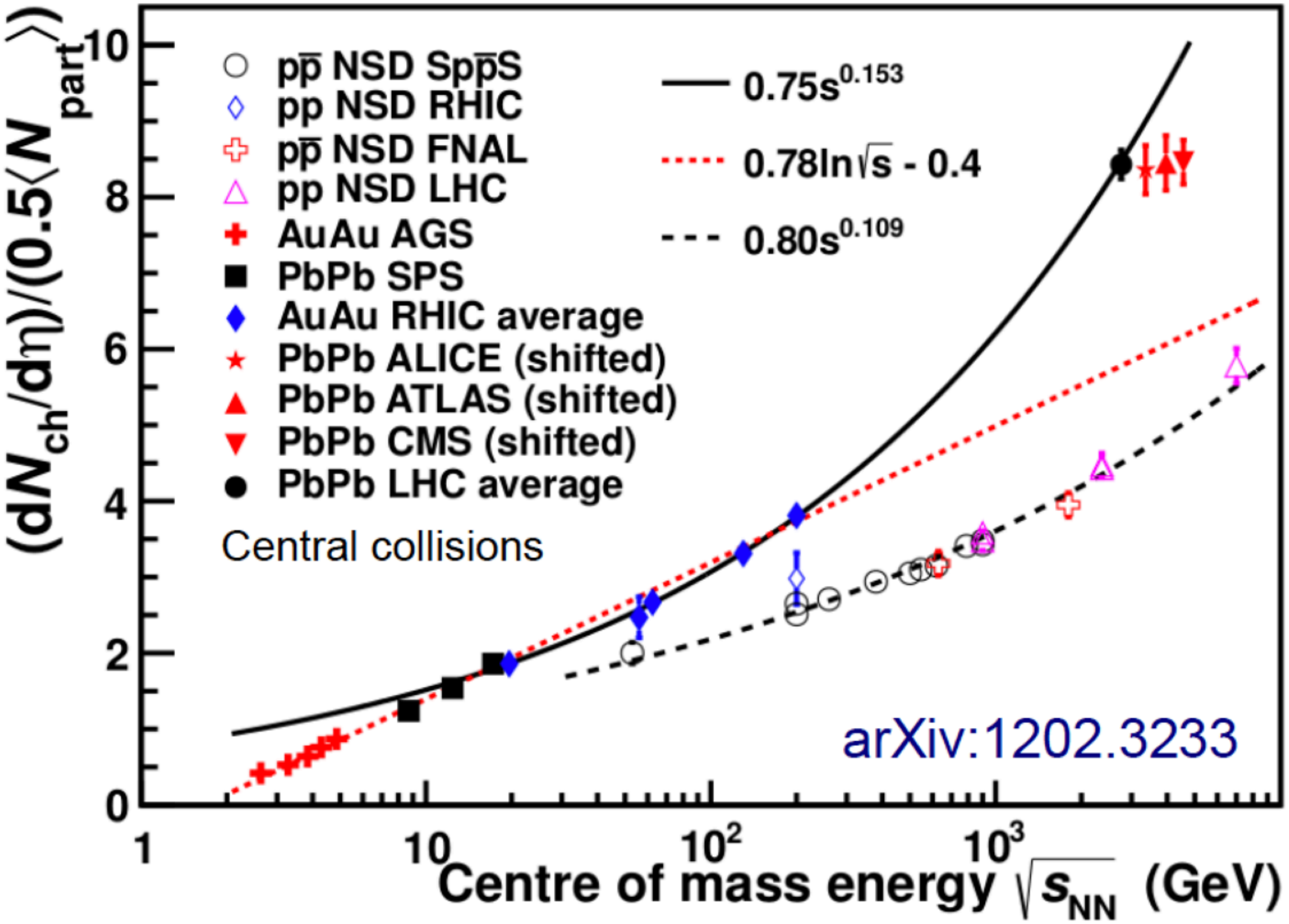
$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau\, \pi R^2} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}$$

Bjorken, PRD 27 (1983) 140

Up dN/dη ≈1600 charged particles in central PbPb at LHC

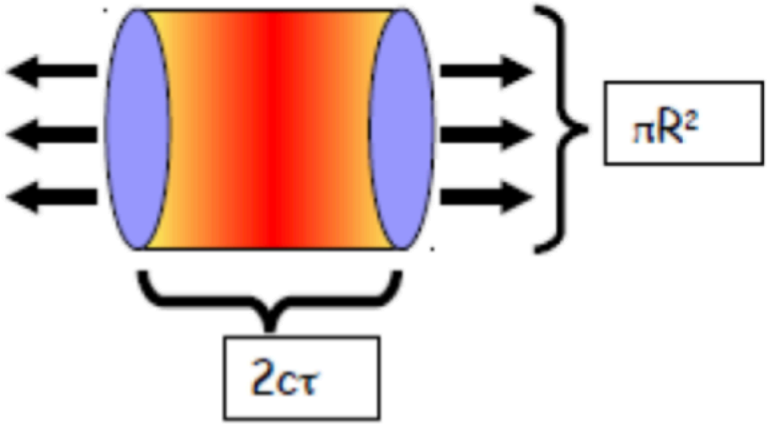
Use these measurements to get an estimate of the energy density

Estimate of energy dependence from dN/dη



arXiv:1202.3233

Bjorken estimate:



$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy}$$

Bjorken, PRD 27 (1983) 140

- System undergoes rapid evolution
    - Using 1 fm/c as an upper limit for the time needed to “thermalization”
    - Leads to densities above the transition region (also for AGS)
        - However, only necessary not sufficient condition for QPG

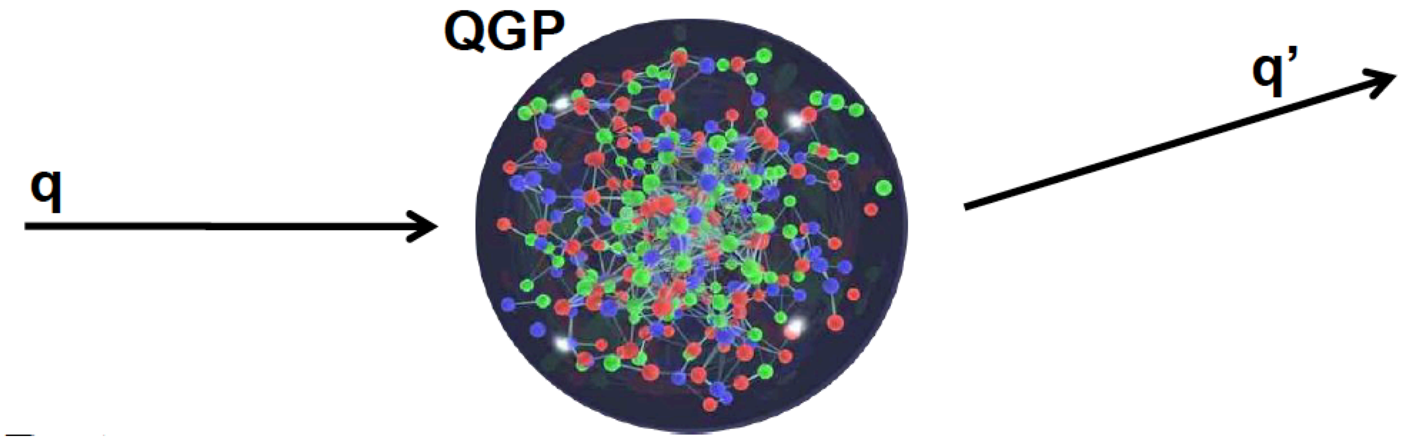
$$\varepsilon_{\mathrm{BJ}} = 1.5\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{GeV}$$
$$\varepsilon_{\mathrm{BJ}} = 2.9\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{\mathrm{NN}}} = 17\,\mathrm{GeV}$$
$$\varepsilon_{\mathrm{BJ}} = 5.4\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$$
$$\varepsilon_{\mathrm{BJ}} = 15\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$$

Jet Quenching & Energy Loss

How does a quark-gluon plasma affect particles traversing it?

Hard Probes

- Ideally: a Rutherford experiment



- But
  - QGP exists in the lab only for ~10^{-23}s
  - No free color charges as probes
- Instead
  - Use probes generated in the heavy-ion collision itself
    →"self-generated" probes

Self-Generated Probes

- Produced early, before the plasma forms
  $t \sim \hbar/Q$, $Q > 2$ GeV/c → $t < 0.1$ fm/c
- Production rate "known"
  - Ideally calculable perturbative
  - Not produced in the medium
- Interact with dense medium (QGP)
- Large cross-section

… as usual there is no such thing as a free lunch …

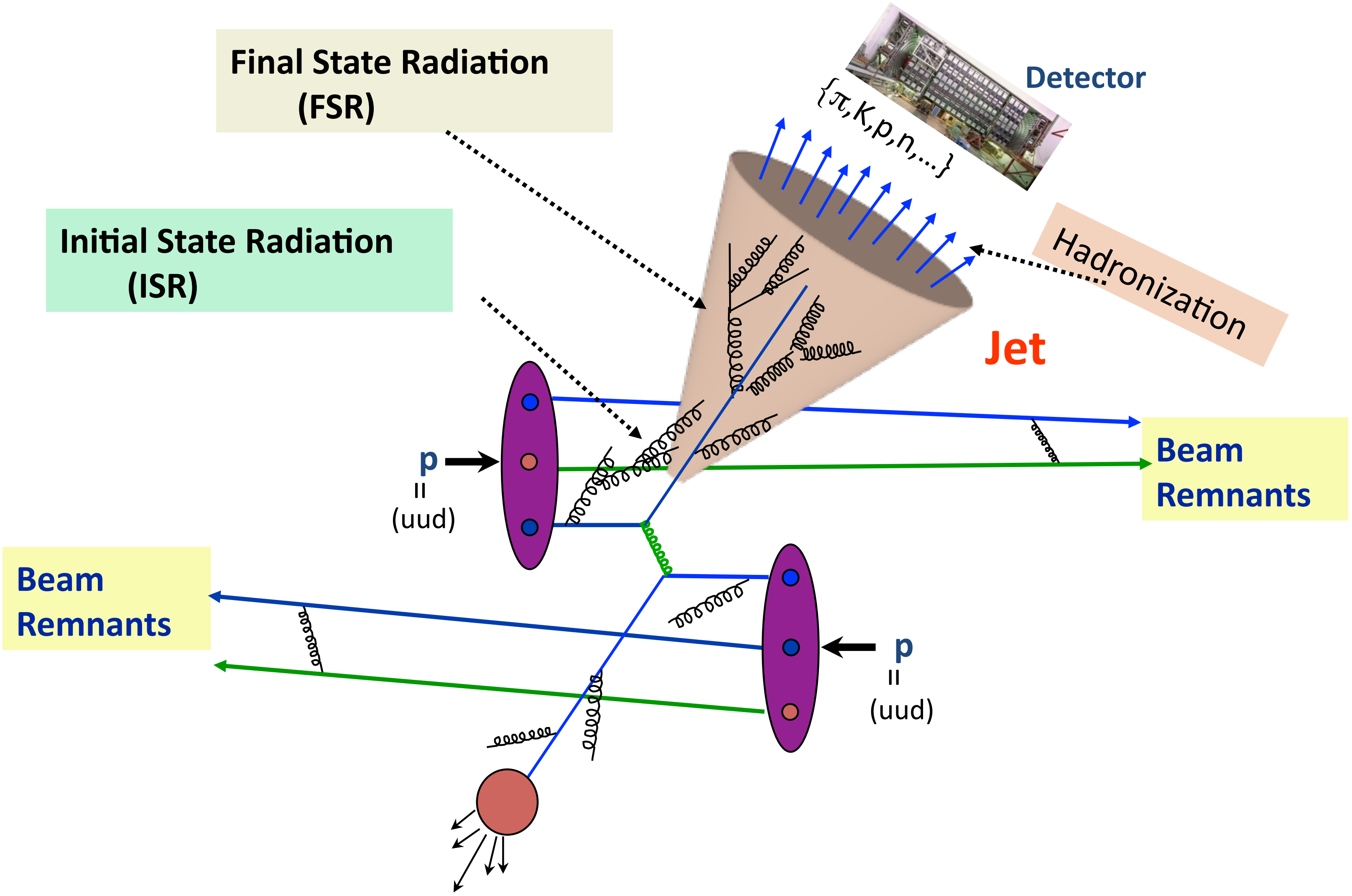
Per central LHC collision
7 D mesons (> 2 GeV/c)
0.2 B mesons (> 10 GeV/c)
10^{-3} jets above 100 GeV
10^{-6} jets above 400 GeV

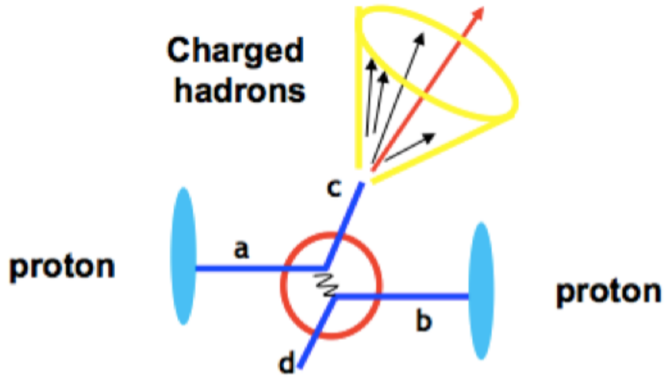
LHC Run 1 (~ 150/ub)
10^{8} D mesons (> 2 GeV/c)
10^{7} B mesons (> 10 GeV/c)
10^{5} jets above 100 GeV
120 jets above 400 GeV

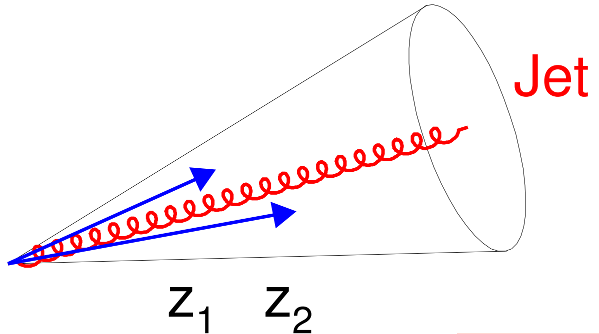
Rec. efficiency, branching ratios factors ~ 1000

Hard scattering and jet production

Study the strong force using jet production



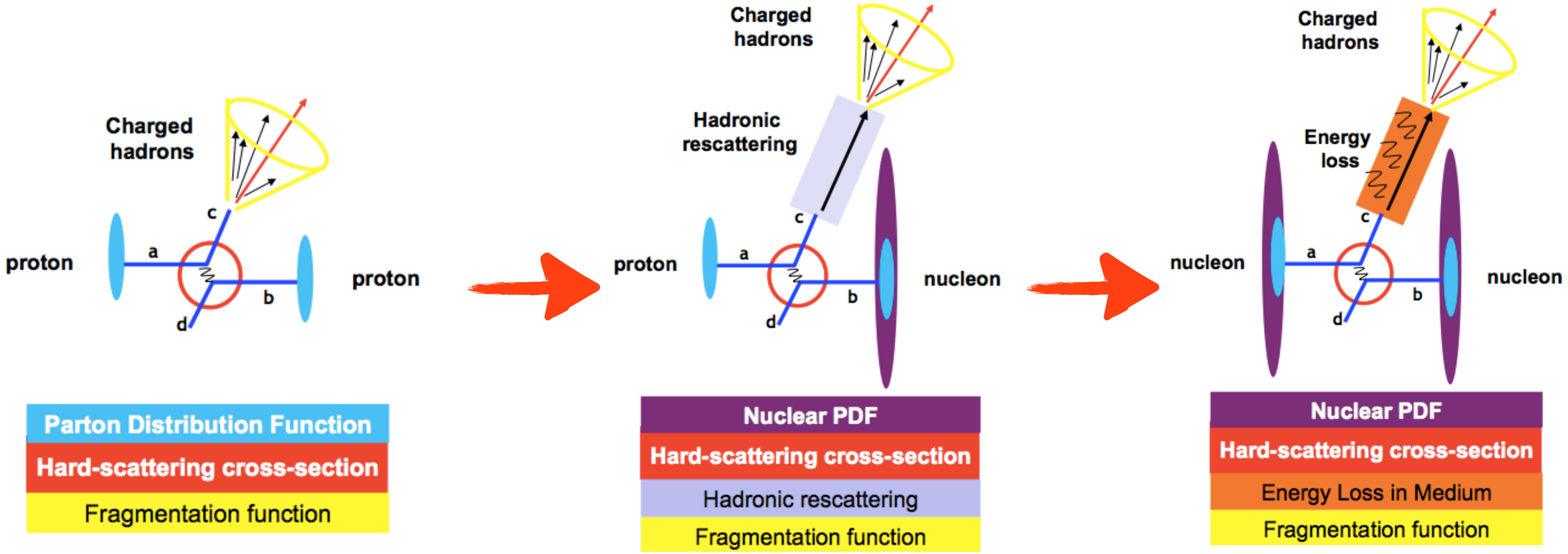




$$\boxed{z = \frac{p_{\mathrm{hadron}}}{p_{\mathrm{jet}}}}$$

- Jets of particles emerge after a high energy parton-parton scattering
- Jet fragmentation function (FF): hadron distribution as a function of z, defined as the momentum fraction taken by hadron from the jet

Nuclear effects in heavy ion collisions



Parton Distribution Function
Hard-scattering cross-section
Fragmentation function

Nuclear PDF
Hard-scattering cross-section
Hadronic rescattering
Fragmentation function

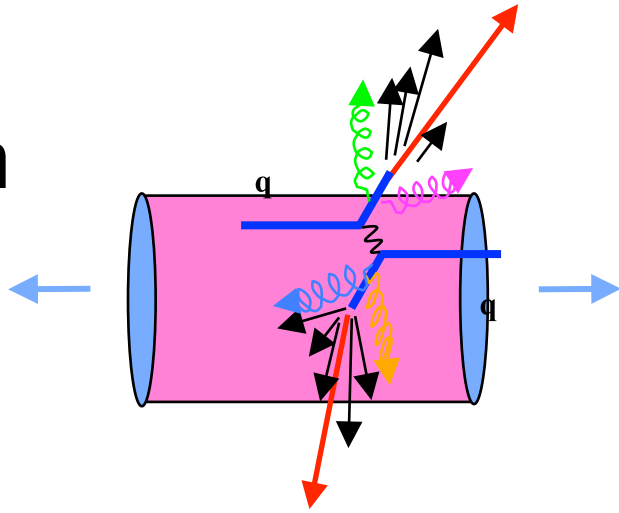
Nuclear PDF
Hard-scattering cross-section
Energy Loss in Medium
Fragmentation function

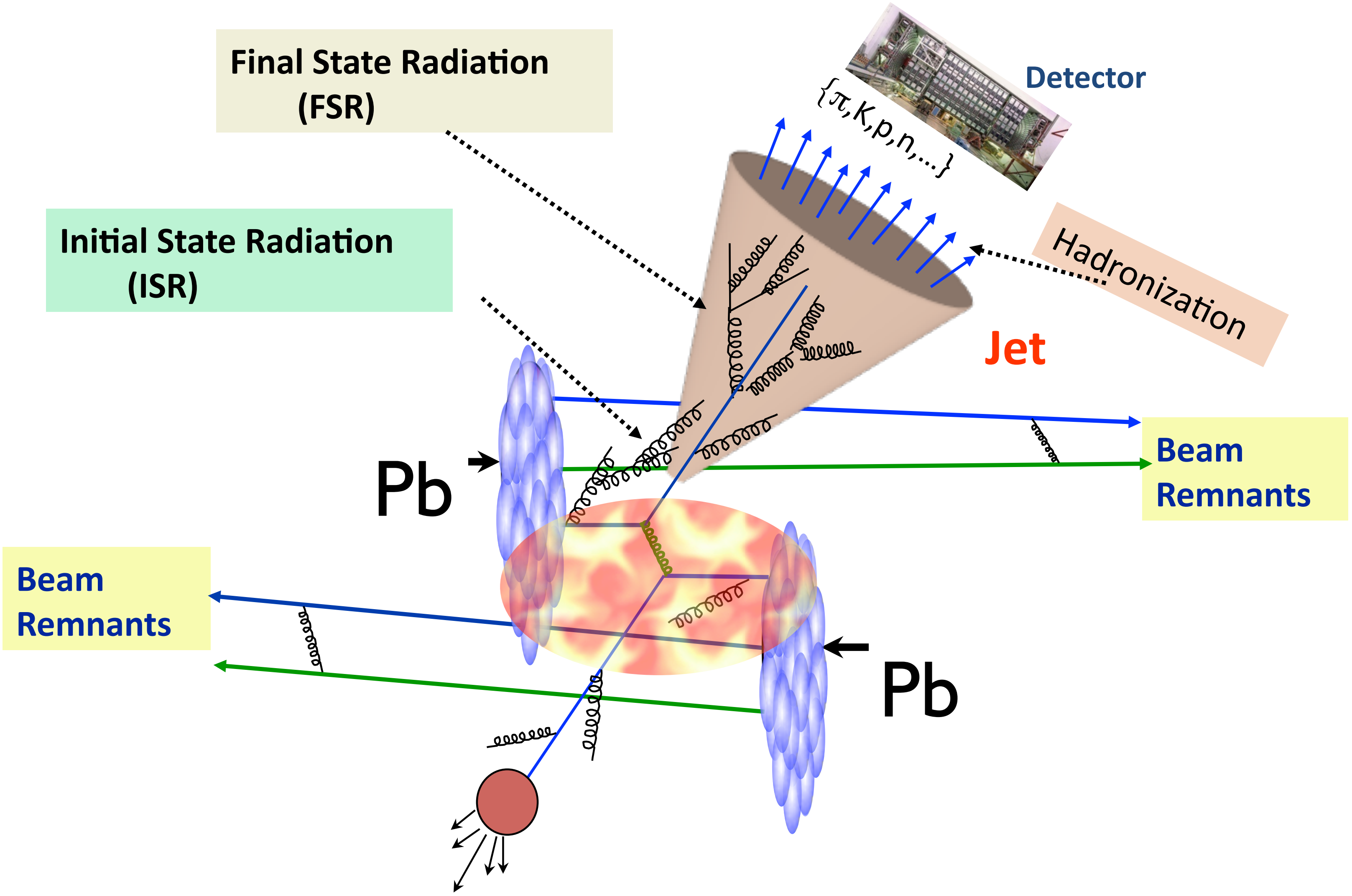
- Disentangle initial and final state effects
- Characterize nuclear PDFs

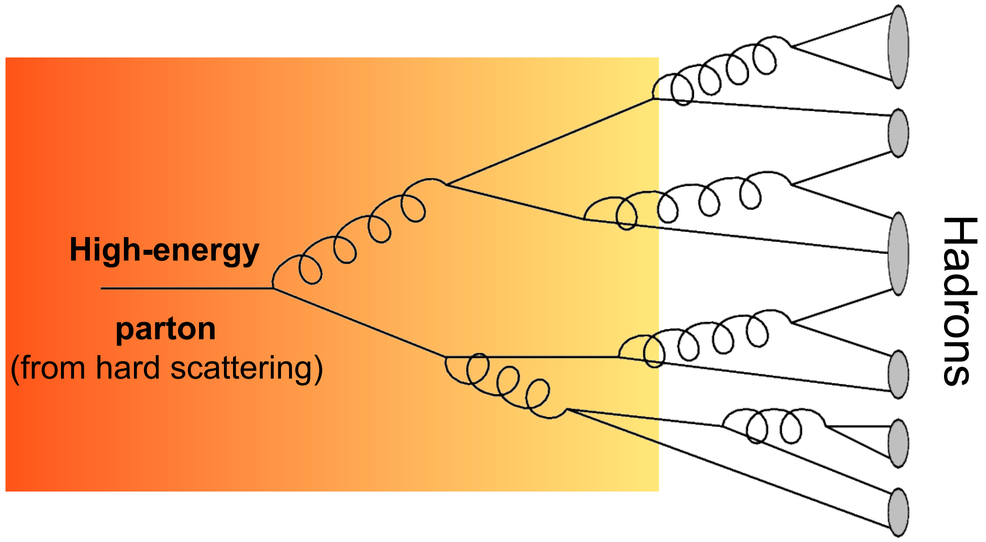
Jet-Quenching in QGP

Study the transport properties of the QGP

a color charge (g, q, Q) in a colored medium

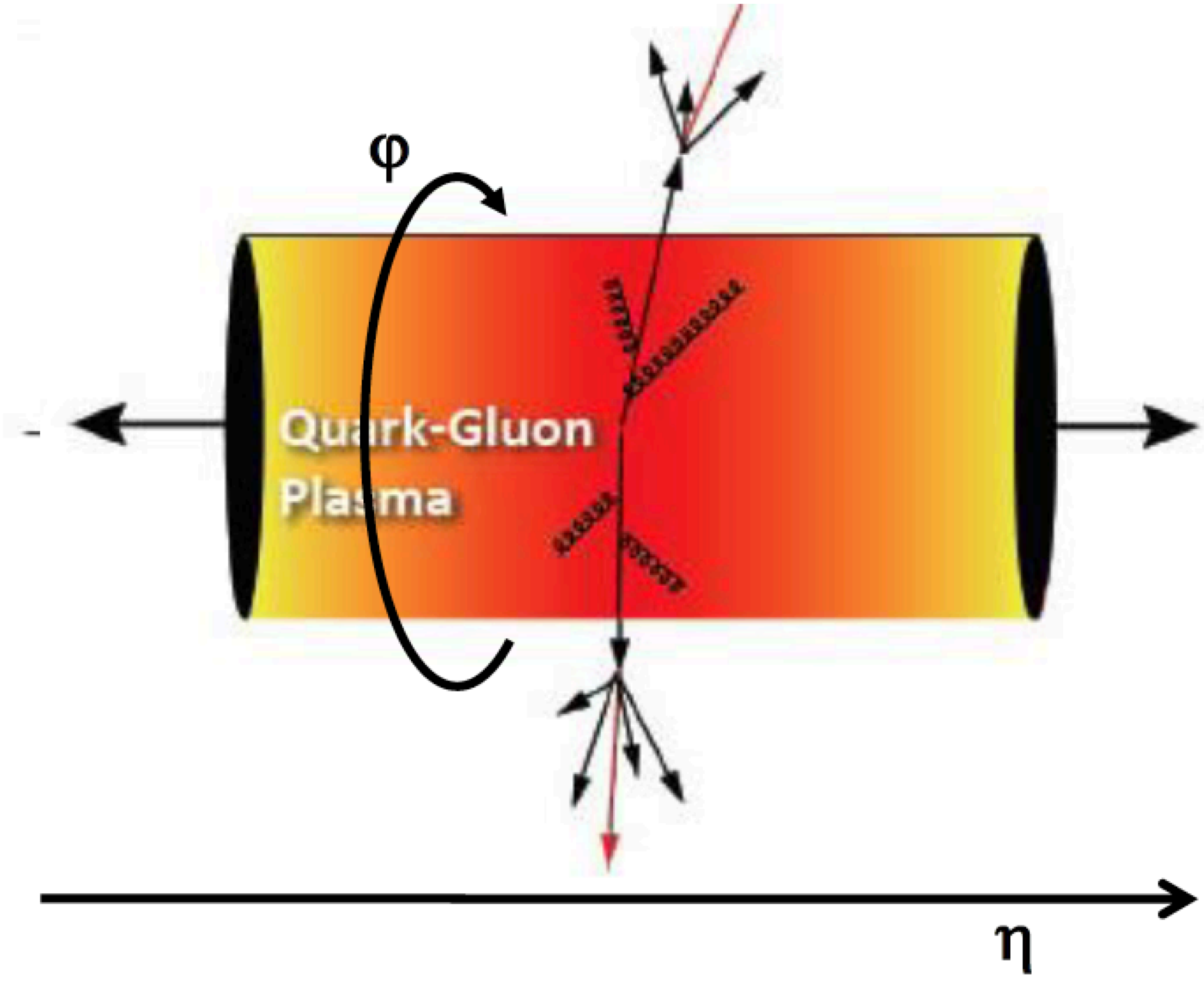


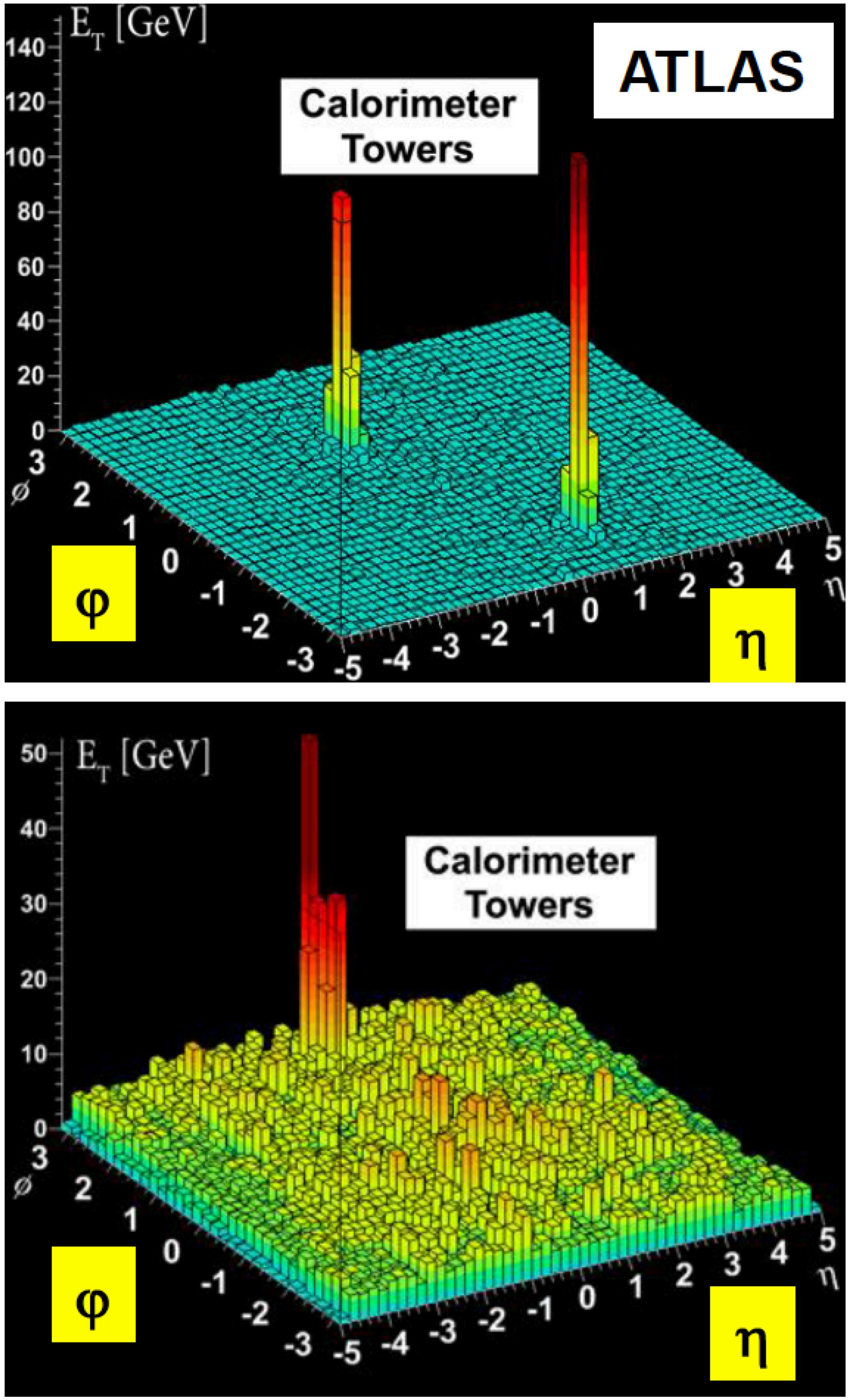




- Partons loose energy ΔE when traversing the medium (see later slides)
  - Jet(E) → Jet (E' = E-ΔE) + soft particles(ΔE)
- Jet quenching measures 'stopping power' of QGP

A Back-to-Back Jet





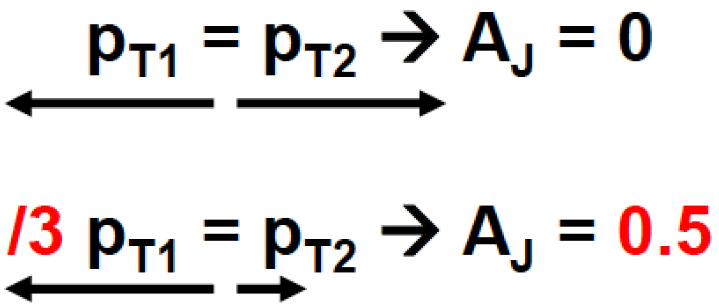
One jet disappears in the QGP
→ "Jet quenching"

ATLAS, PRL105:252303,2010
Drawing: A. Mischke

Dijet Asymmetry

- How often do jets lose lot of energy?
- Quantify by dijet asymmetry
- 2 highest energy jets with $\Delta\varphi > 2\pi/3$

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



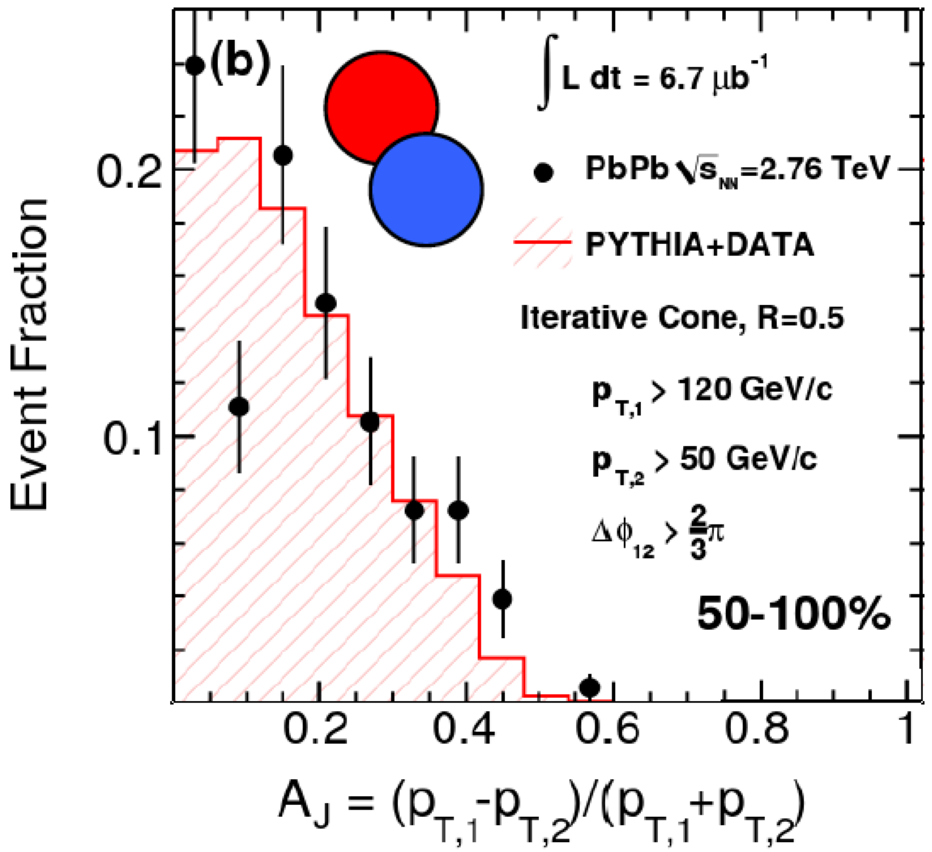
$p_{T1} = p_{T2} \rightarrow A_J = 0$

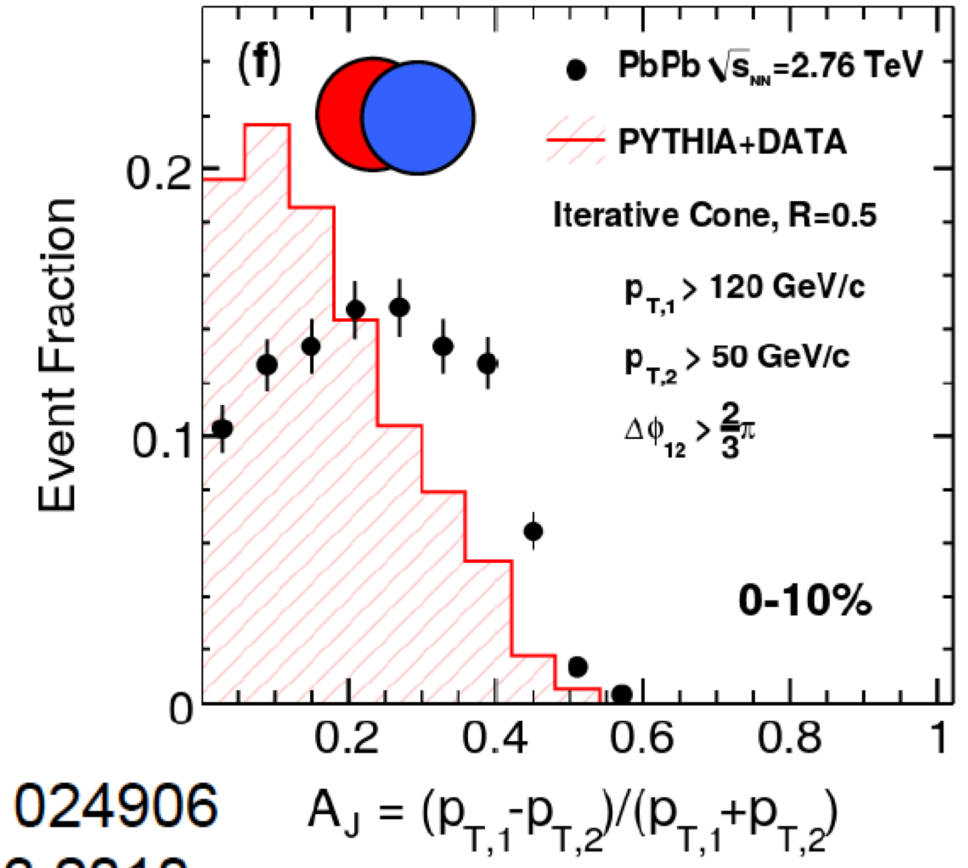
$1/3\ p_{T1} = p_{T2} \rightarrow A_J = 0.5$

- Peripheral collisions: Pb-Pb ~ Pythia
- Central collisions: Significant difference

Jets lose up to two thirds of their energy!

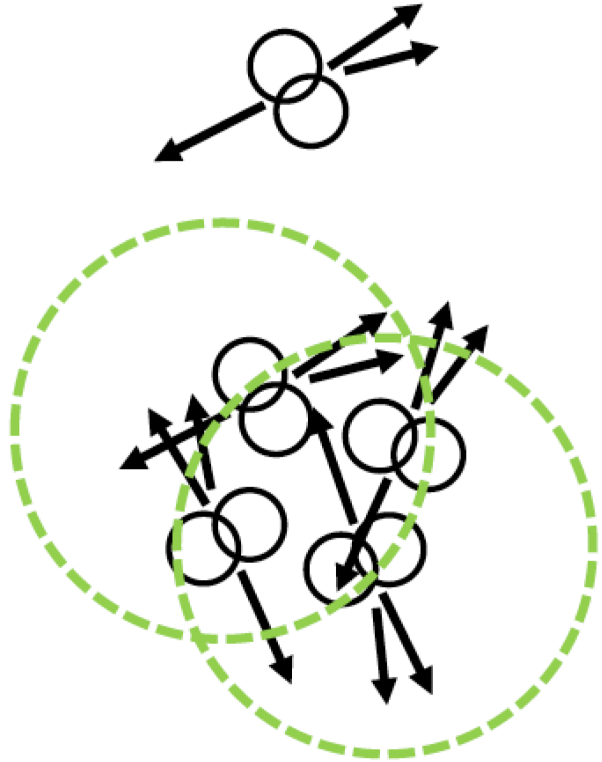
→Something significant happening in heavy-ion collisions





PRC 84 (2011) 024906
PRL105:252303,2010

Nuclear-Modification Factor



- Hard processes occur in nucleon-nucleon (NN) collisions
- Heavy-ion collision : many NN collisions
  - Hard process is independent of number of NN collisions
- Without QGP, HI collision is superposition of NN collisions with incoherent fragmentation

$$dN_{AA}/dp_T = \langle N_{coll} \rangle \boxed{dN_{pp}/dp_T} \longleftarrow$$

any object, e.g. charged particles, jets, J/ψ, D, …

- Let's turn this into an observable

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

R_{AA} = 1 → no modification

R_{AA} != 1 → medium effects

Nuclear-Modification Factor (2)

- How do we measure this quantity?

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$

For example:

p_T distributions in AA collisions

- select events
- select and count tracks
- correct for detector effects
- estimate systematic uncertainties

p_T distributions in pp collisions

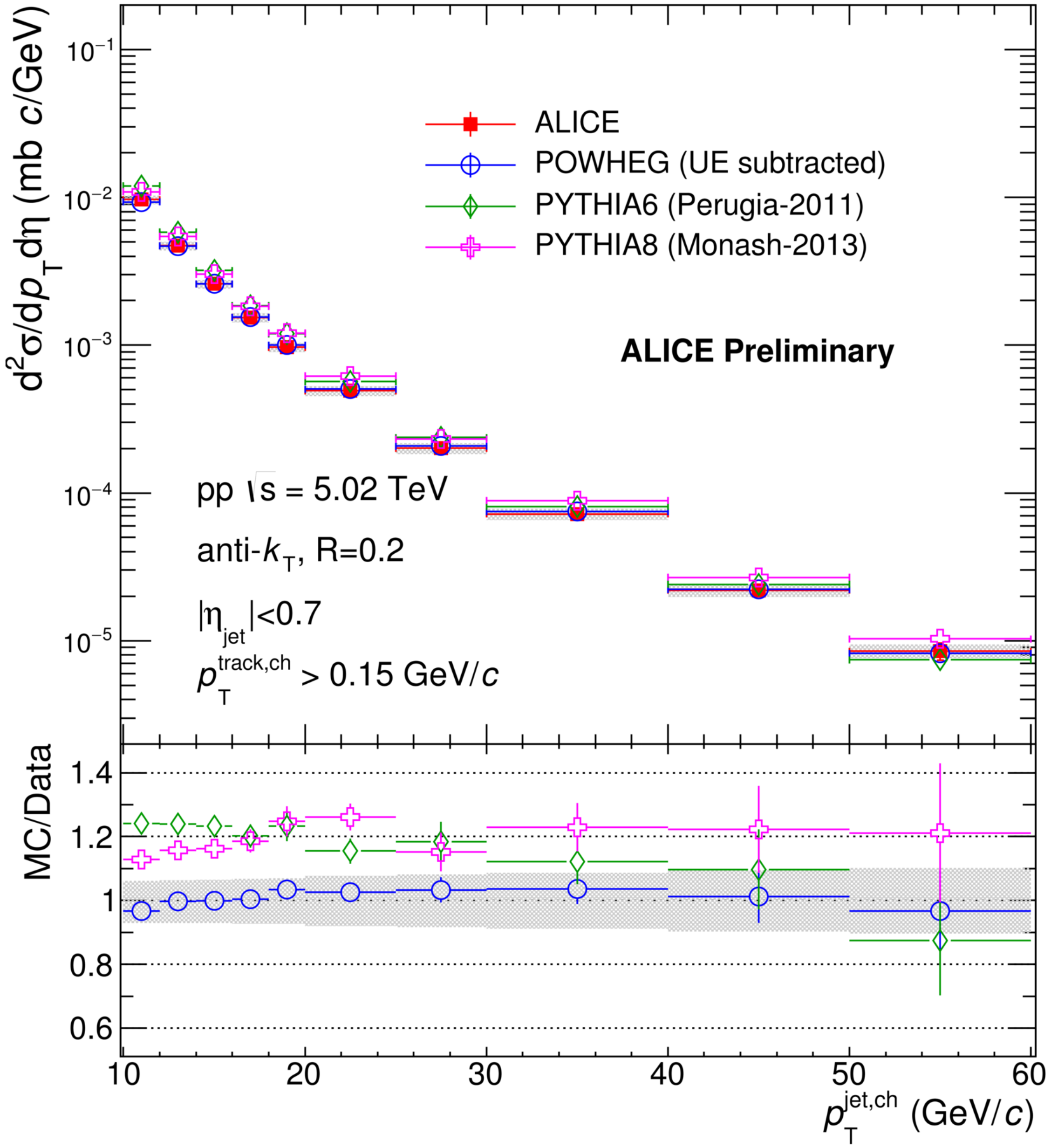
Number of binary collisions Ncoll

- Glauber modeling (<u>slide</u>)
- Centrality (<u>slide</u>)

Jet p_T distribution in pp and AA collisions

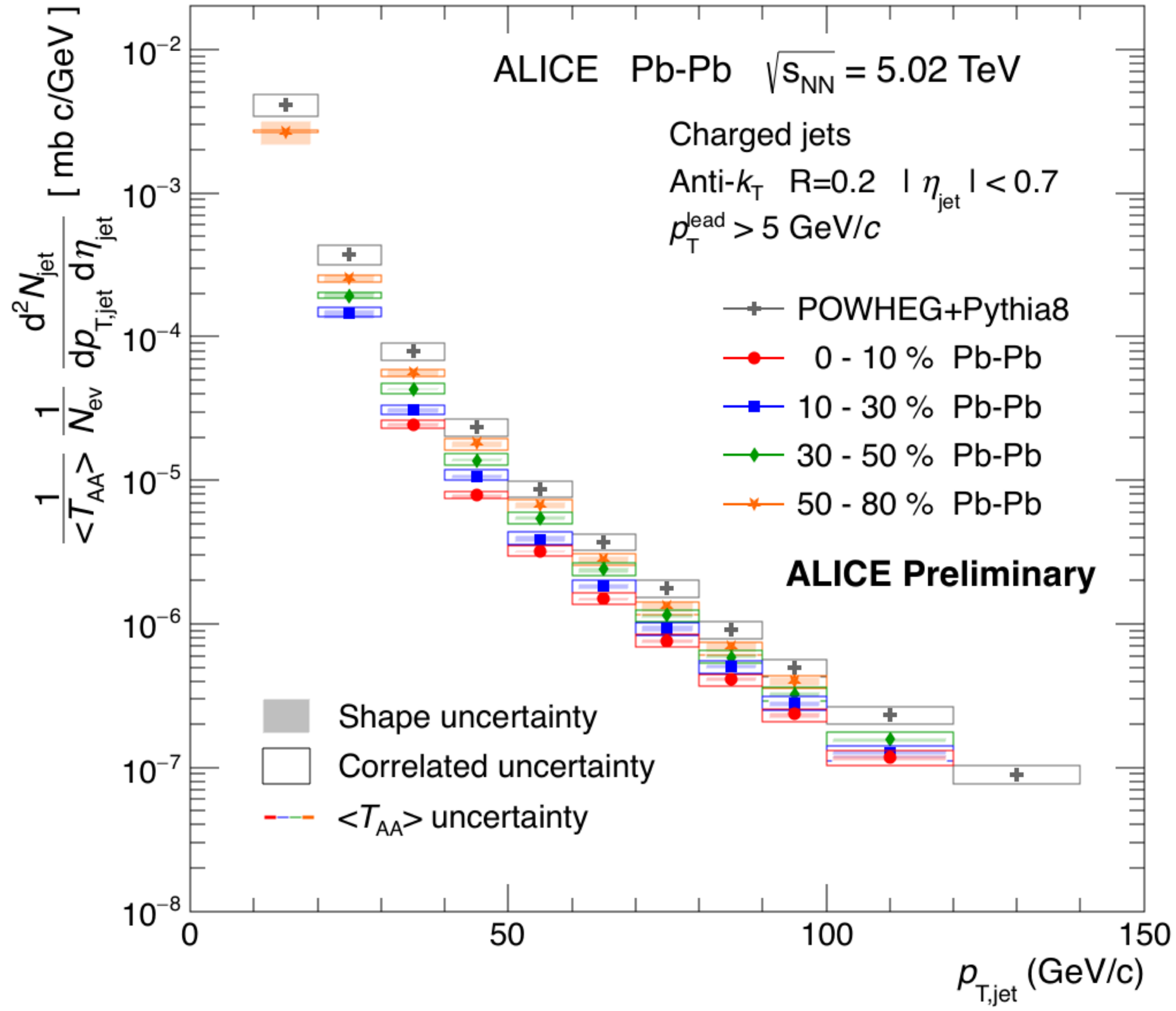
$$R_{AA} = \frac{1}{< T_{AA} >} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$

pp@5.02 TeV



ALI-PREL-113801

Pb-Pb@5.02 TeV

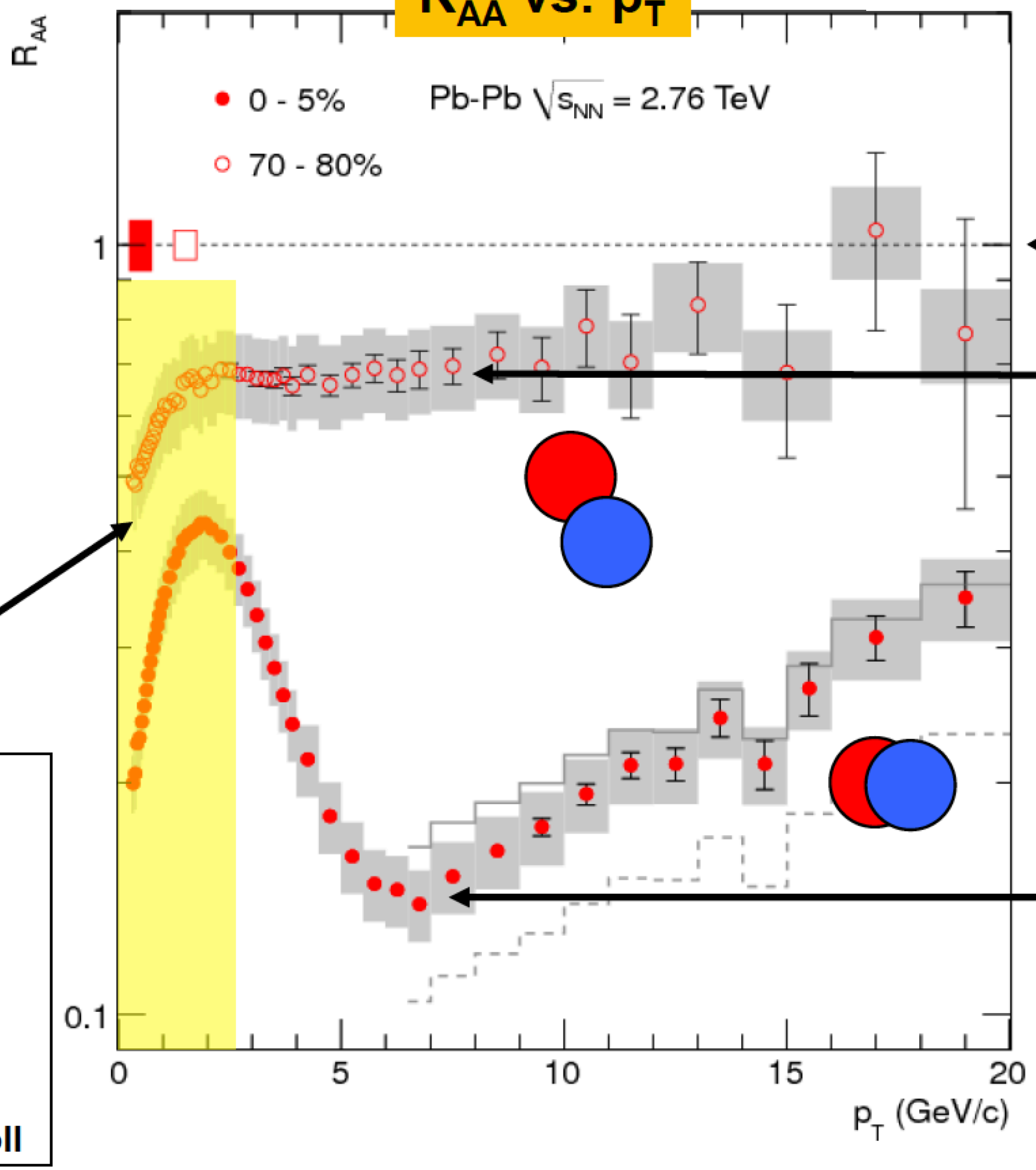


ALI-PREL-156109

R_{AA}

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$

R_{AA} vs. p_T



R_{AA} = 1
→ no modification

70-80% (peripheral)
→ R_{AA} ~ 0.7

0-5% (central)
→ R_{AA} drops to 0.14

Drop at low p_T

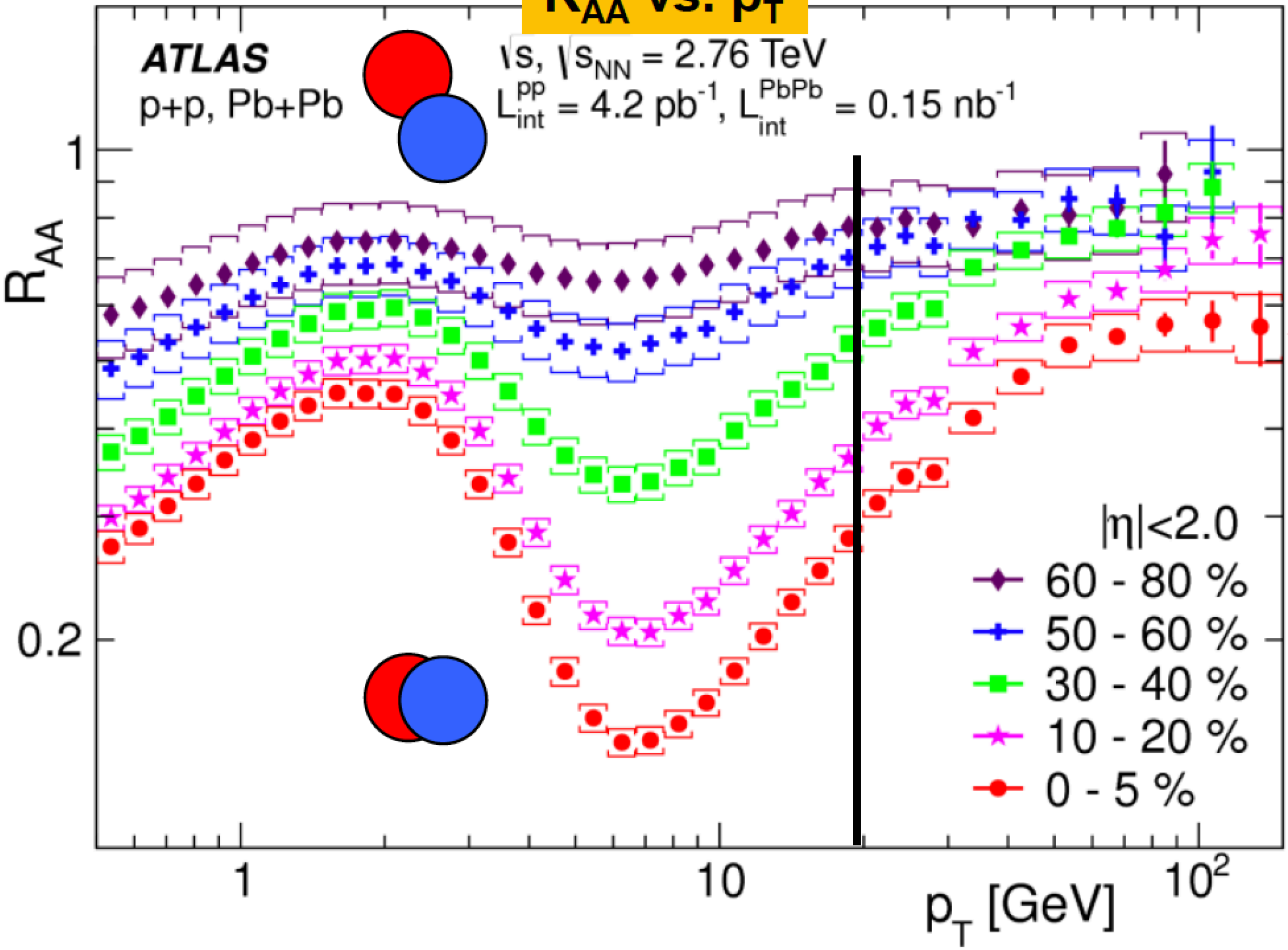
⚠

Soft particle production does not scale with N_{coll}

ALICE, PLB696 (2011) 30

R_{AA} at high p_T

R_{AA} vs. p_T



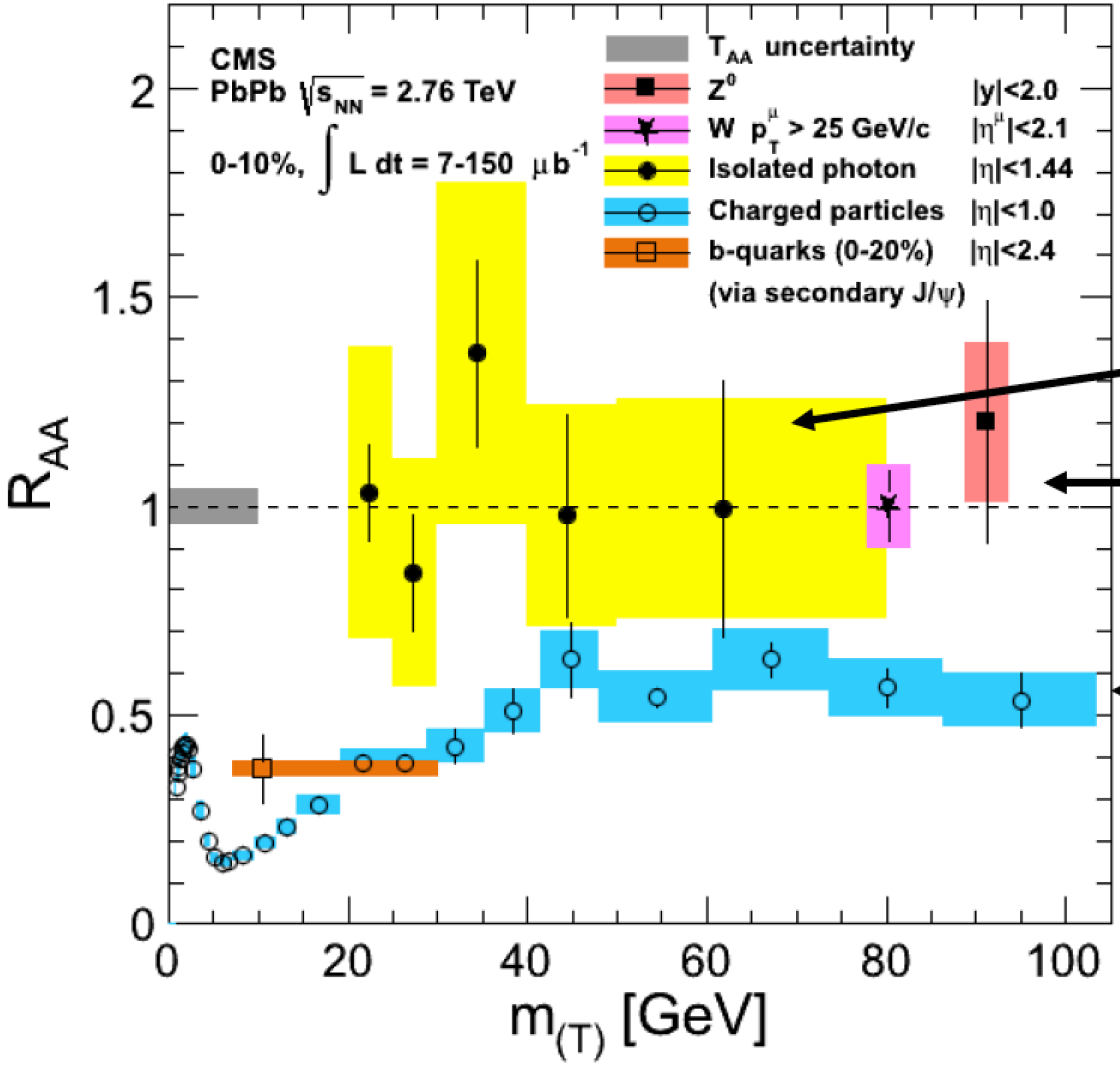
60-80% (peripheral)
→ R_{AA} increases up to 0.9

0-5% (central)
→ R_{AA} increases up to 0.6

R_{AA} reaches asymptotic value for p_T > 50 GeV/c

ATLAS, JHEP09(2015)050

R_{AA} for Color-Neutral Probes



Photons

W, Z^0

charged particles

EPJC 72 (2012) 1945

No suppression for color-neutral probes

→ No interaction with QGP

→ Experimental check on N_{coll} calculation (and nuclear PDFs)

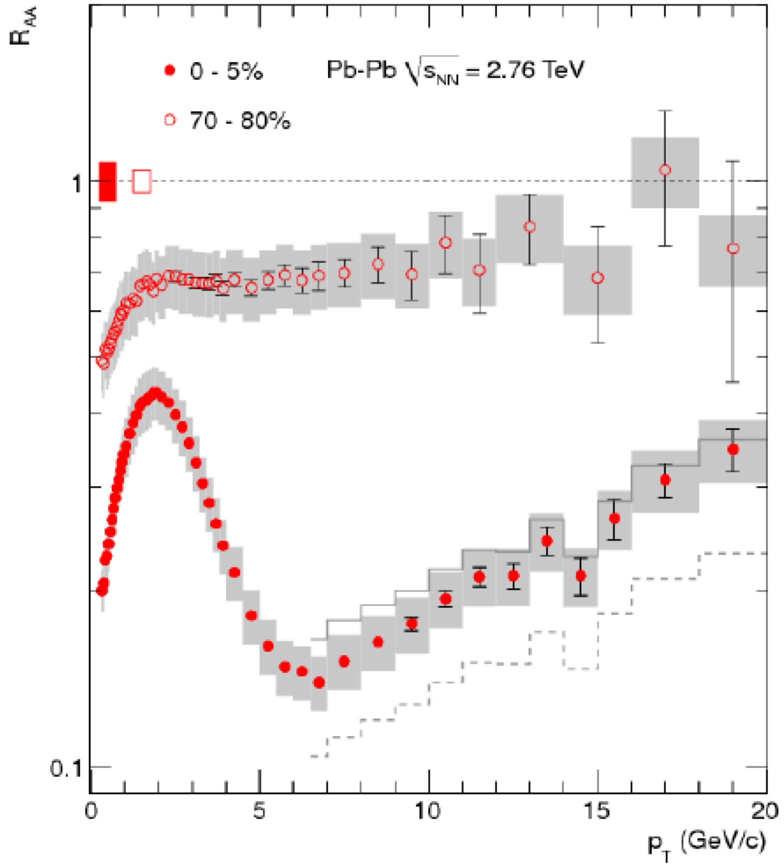
Recap

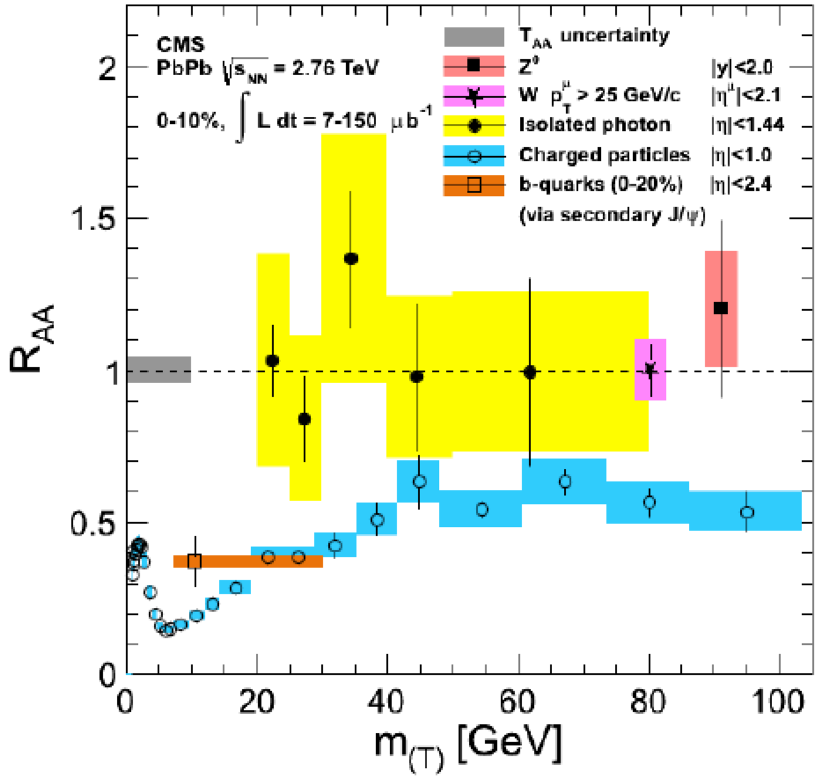
- Peripheral collisions
  - R_{AA} ~ 0.8 – 0.9 for colored probes
- Central collisions
  - R_{AA} ~ 0.14 at p_T ~ 6-7 GeV/c
  - R_{AA} ~ 0.6 at high p_T
- R_{AA} ~ 1 for color-neutral probes
- Interpretation
  - R_{AA} ~ 0.14 ~ 1/7 → naïve conclusion : only 1 out of 7 particles escape the QGP?

We are looking at a ratio and the particle spectrum is shifted by energy loss

Strong suppression for high p_T colored probes in central collisions!

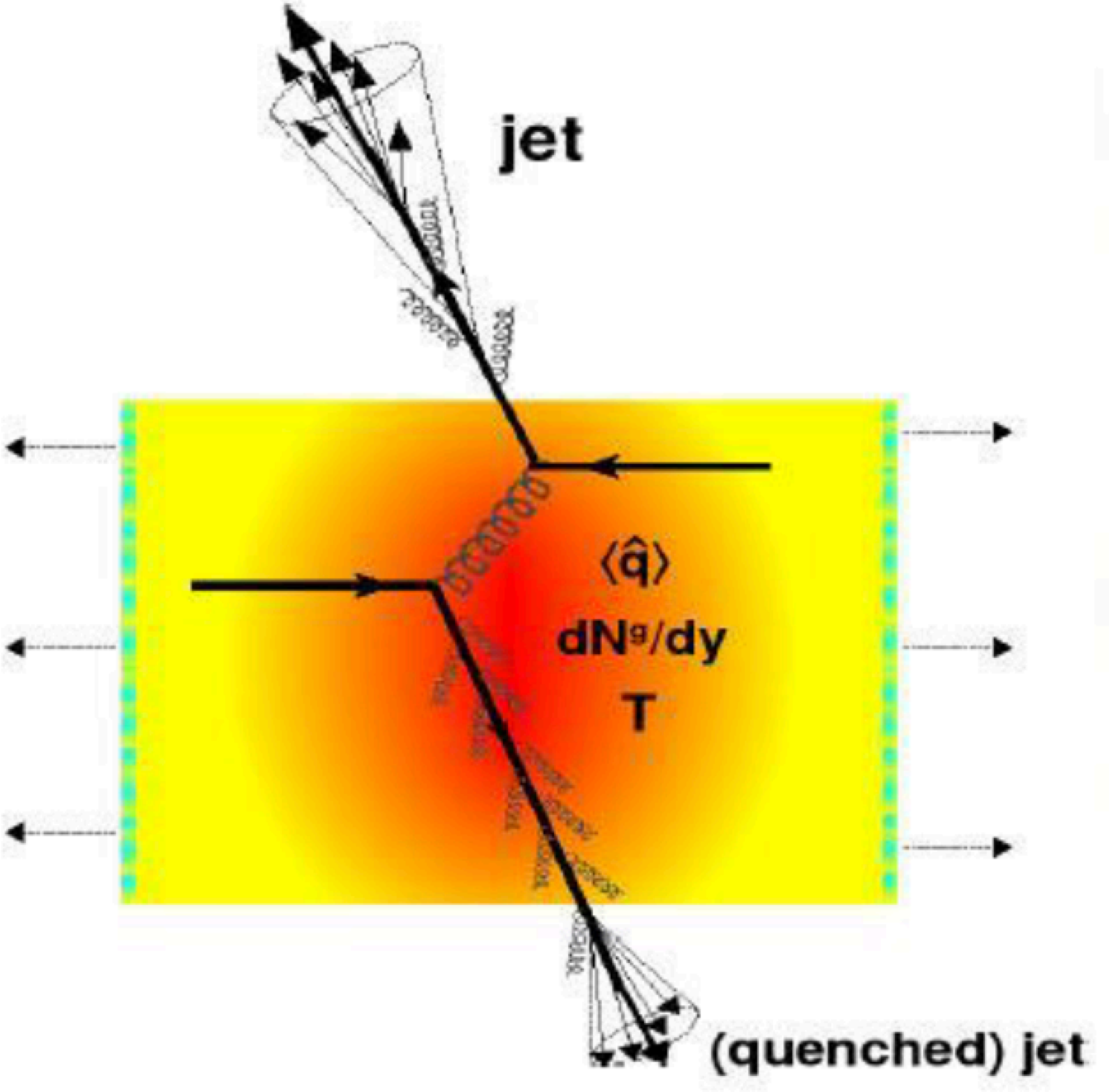
→ Jet quenching …





Energy Loss

- Particle production in central collisions is strongly suppressed

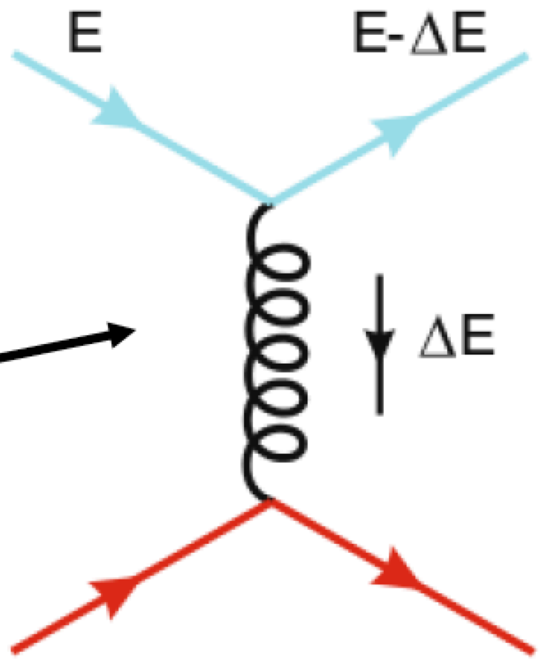


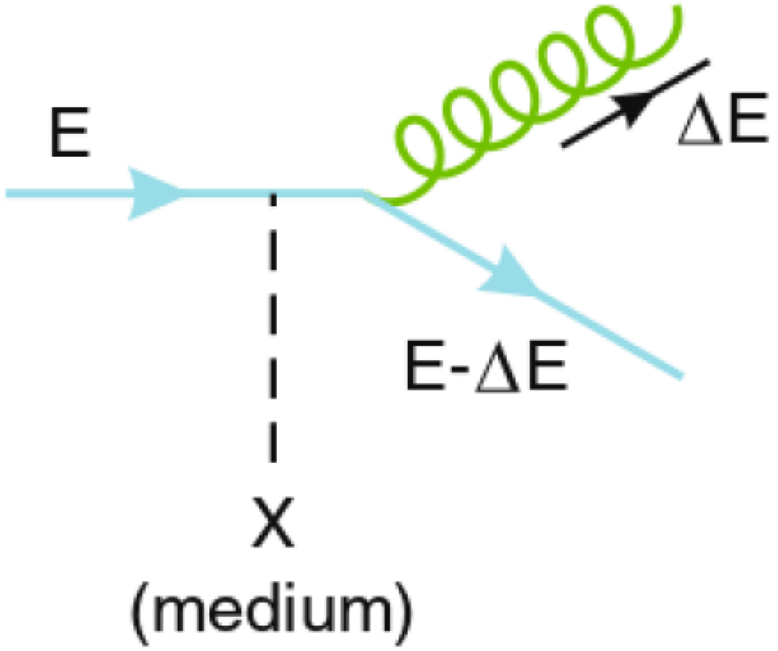
How does the medium achieve this suppression?

Energy Loss in the QGP

- QGP: high density of quarks and gluons / color sources
- Traversing quark / gluon feels color fields
- Collisional energy loss
  - Elastic scatterings
  - Dominates at low momentum
- Radiative energy loss
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung

$$\boxed{\Delta E = \Delta E_{coll} + \Delta E_{rad}}$$





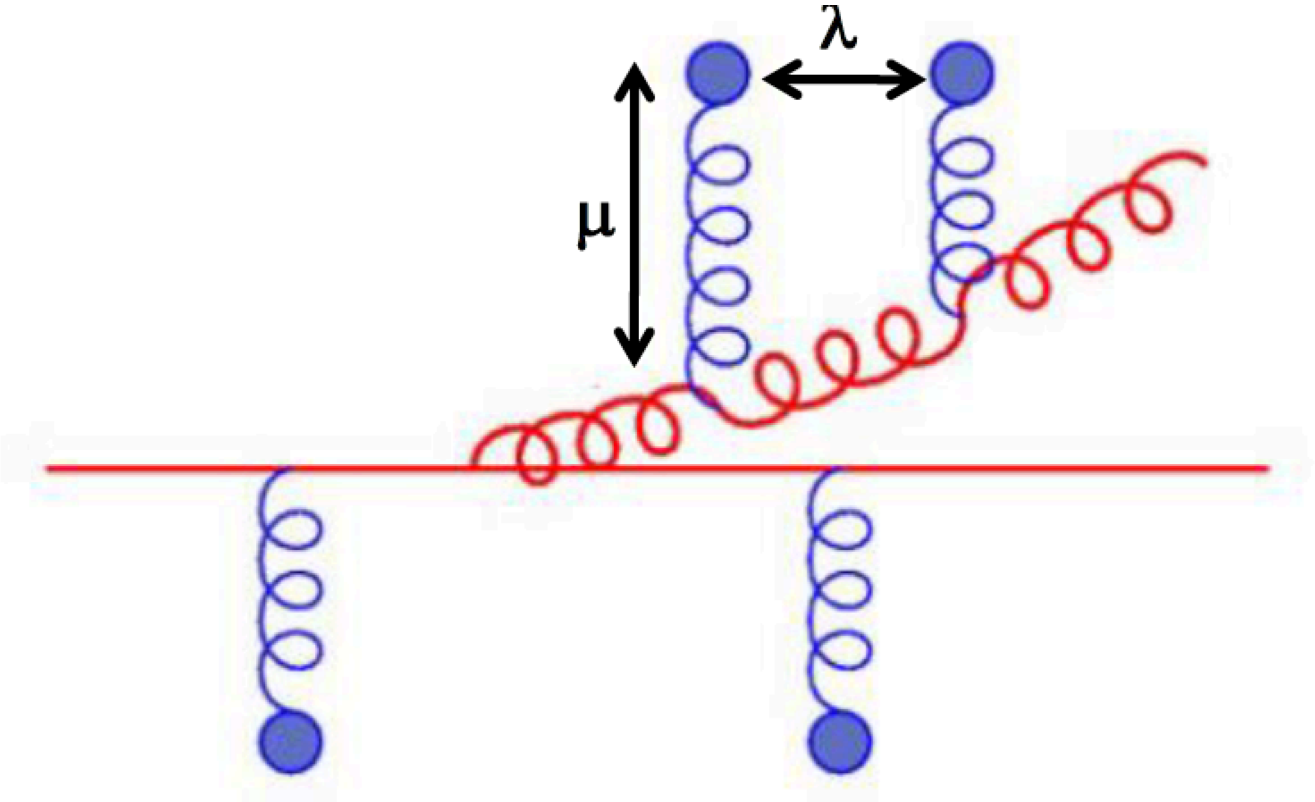
Lect. Notes Phys. 785,285 (2010)

Radiative Energy Loss

- BDPMS formalism
  - Baier, Dokshitzer, Mueller, Peigné, Schiff
  - Infinite energy limit
  - Static medium

$$\Delta E \sim \alpha_S \boxed{C_R} \hat{q} \boxed{L^2}$$

- Energy loss depends on
  - Path length through medium **squared**
  - Casimir factor
    - $C_R = 4/3$ (quarks)
    - $C_R = 3$ (gluons)
  - Medium parameter “q hat”



L path length, driven by:
- **gluon-gluon self interactions**
- **quantum interference**

$$\hat{q} = \frac{\mu^2}{\lambda}$$

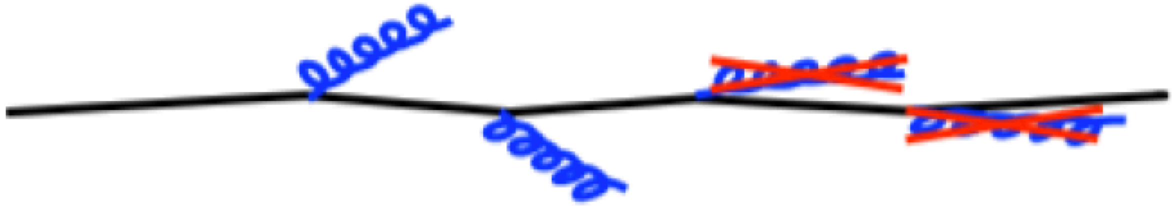
average transverse momentum transfer

mean free path

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291

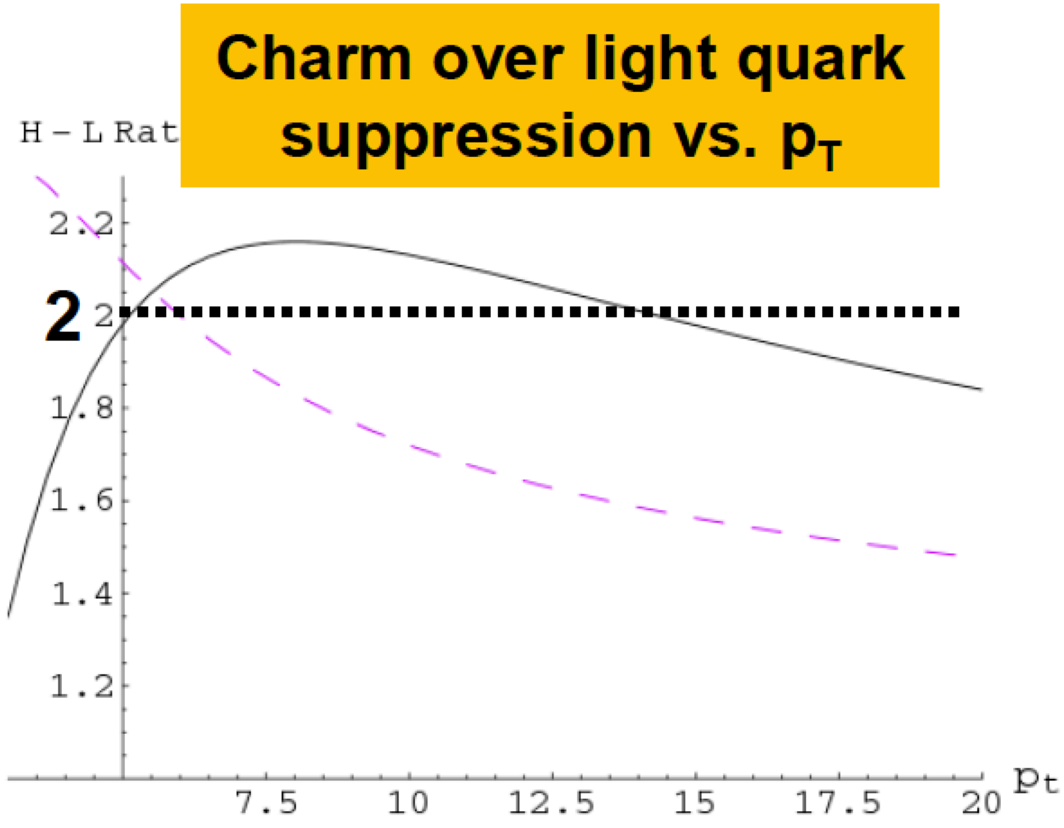
Dead Cone Effect

- Due to kinematical constraints, gluon radiation in vacuum suppressed for angles $\theta < m/E = 1/\gamma$ by $\left(1+\frac{m/E}{\theta}\right)^2$
  - Massless parton m = 0 → no suppression



- Similar effect in the medium
  - Significant for charm and beauty
  - Radiative energy loss reduced by 25% (c) and 75% (b) [μ = 1 GeV/c^2]
- Implies quark mass dependence

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$



Charm over light quark suppression vs. p_T

PLB519:199-206,2001
Lect. Notes Phys. 785,285 (2010)

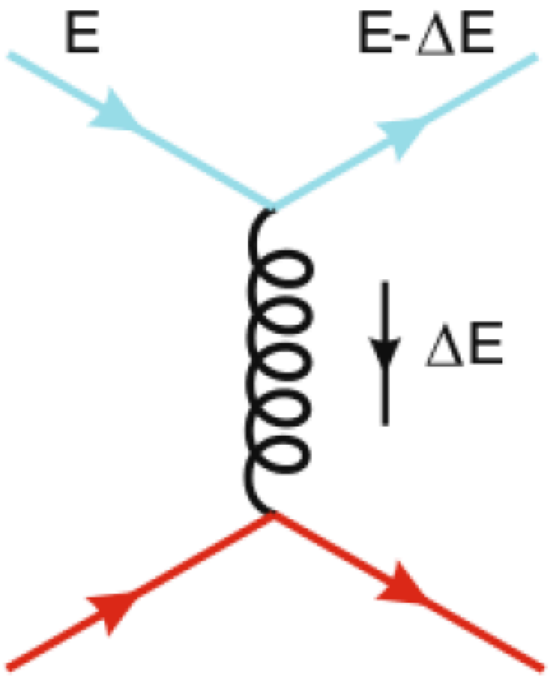
Collisional Energy Loss

- For light quarks and gluons

$$\Delta E_{q,g} \sim \alpha_S \, C_R \, \mu^2 \boxed{L} \ln \frac{ET}{\mu^2}$$

- For heavy quarks additional term

$$\alpha_s^2 T^2 \, C_R \, \mu^2 \boxed{L} \ln \frac{ET}{M^2}$$



- Energy loss depends on
  - Path length through medium **linear**
  - Parton type (light or heavy)
  - Temperature T
  - Mass of heavy quark M
  - Medium parameter μ (average transverse momentum transfer)

PRD 77, 114017 (2008) 291

Recap

- We have seen significantly suppression of charged hadron spectra
  - Dominated by light quarks / gluons…
  - … which at low p_T are also produced within the medium

- Energy loss occurs by radiative and collisional processes
- Theoretical calculations extract medium properties like density, average momentum transfer, mean free path, $\hat{q}$

- Calculations more accurate for heavy quarks
- Dependence of energy loss on quark mass expected

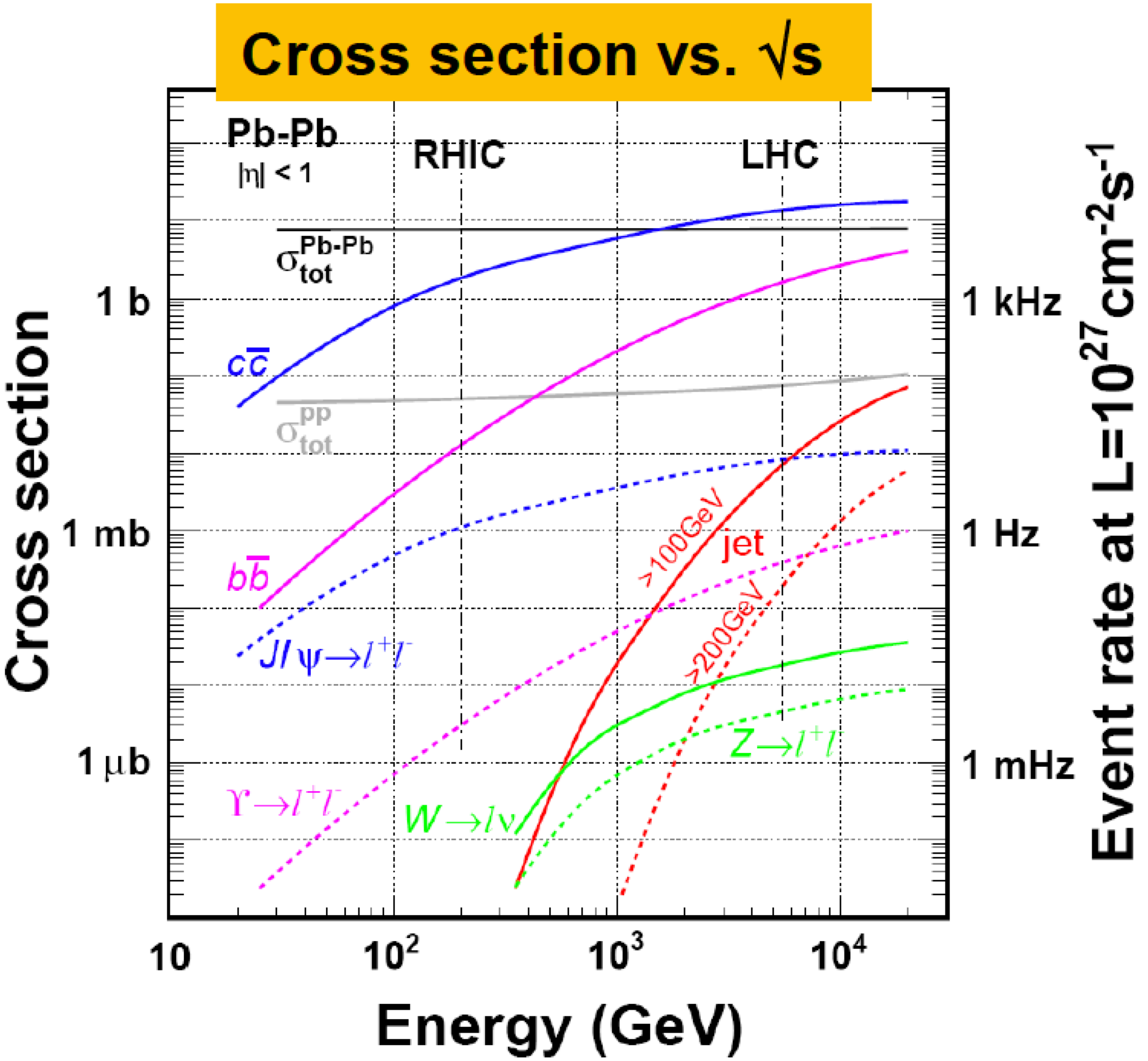
Let's measure energy loss with heavy quarks!

Heavy Quarks

- Charm (m ~ 1.3 GeV/c²)
- Beauty (m ~ 4.7 GeV/c²)
- Produced in hard scattering
- Essentially not produced in the QGP
- Expectation

$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

- LHC: ~7 D > 2 GeV/c per central event


Cross section vs. √s

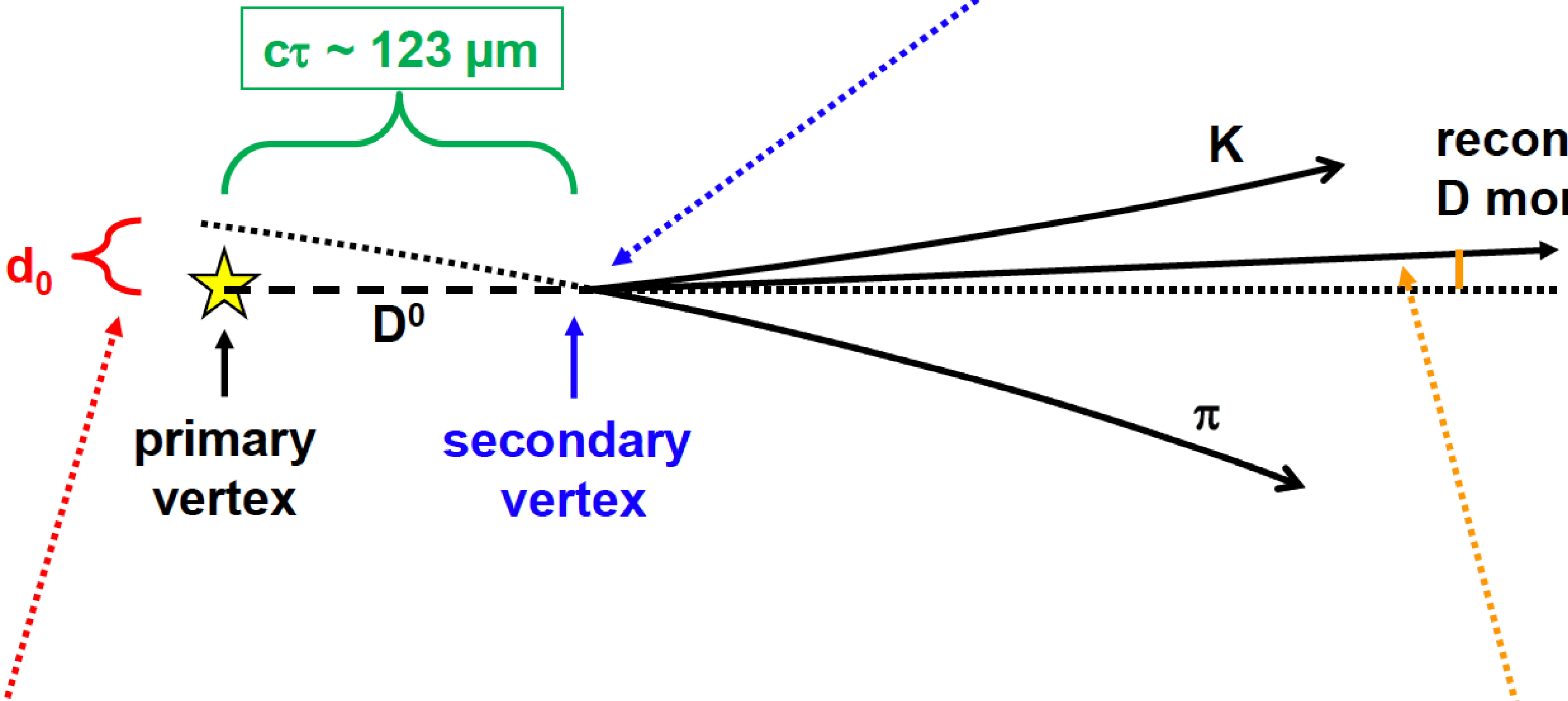
D^0 Reconstruction

- D^0 meson: $m = 1.87$ GeV/c^2 ; $c\tau = 123$ μm
  - Rather short lived
  - Many decay modes
  - $D^0 \rightarrow K\,\pi$ (branching ratio 3.9%)
- Standard method: invariant mass of opposite charge pairs
  - Per central event ($D^0 \rightarrow K\,\pi$, > 2 GeV/c, incl. efficiencies): 0.001 compared to ~700 K and up to ~2500 π
  - Signal over background far too small to extract a peak
- Reduce combinatorial background (see next slides)
  - Topological cuts
  - Particle identification (PID) of K and π

Topological Cuts

3) Require distance of primary and secondary vertex (impact parameter) [~100 μm challenging for pixel detectors!]

2) Require that K and π share a secondary vertex



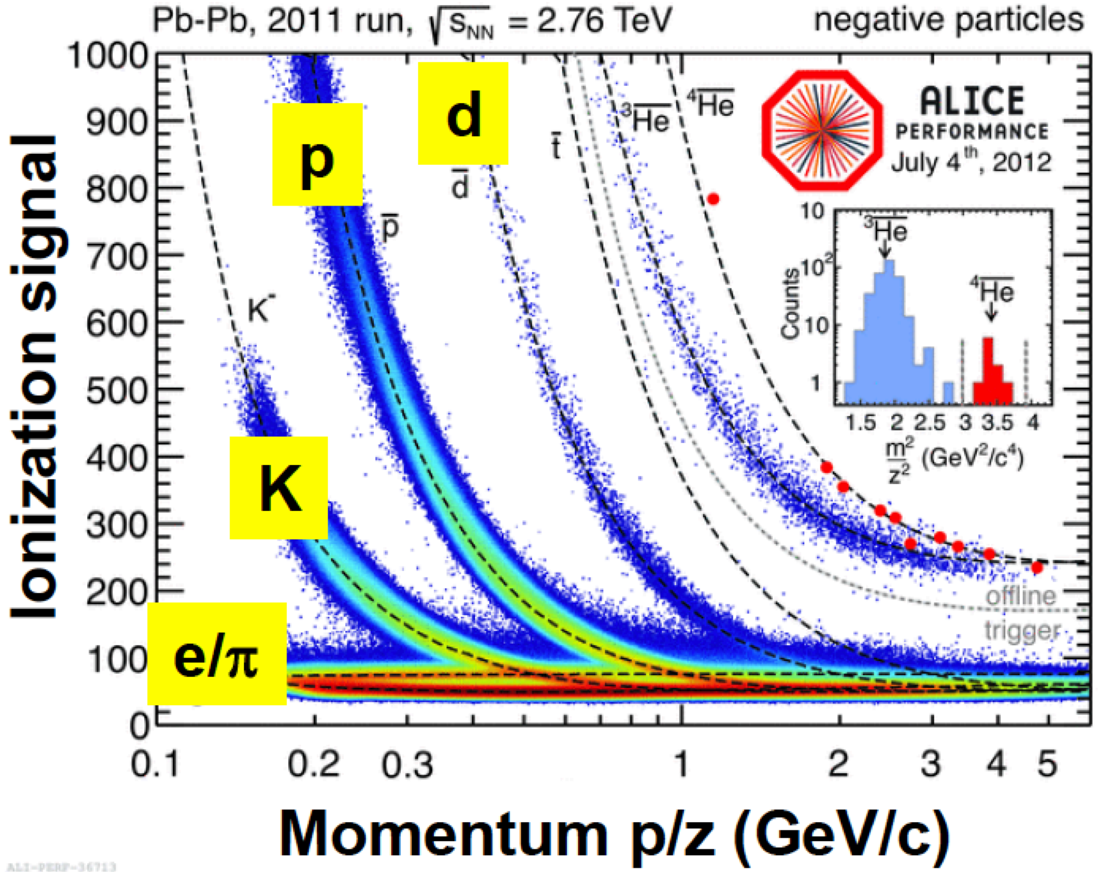
1) Require large impact parameter tracks

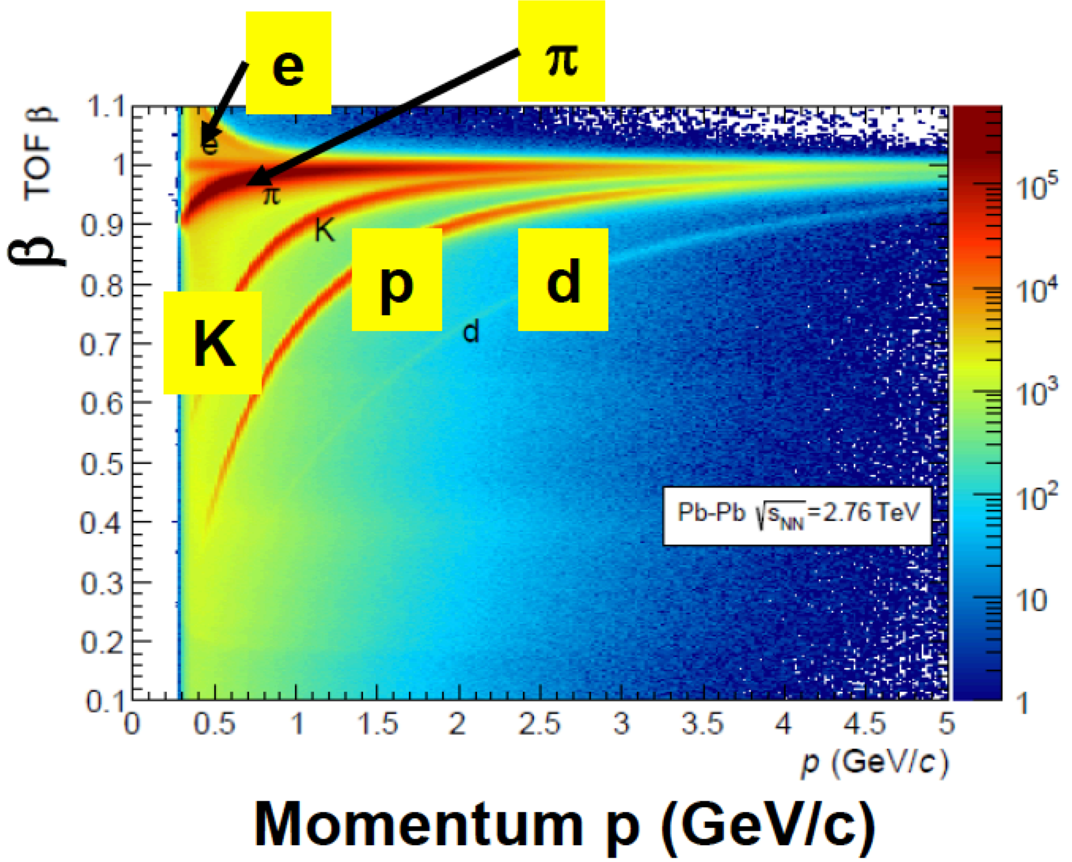
Plane transverse to beam

4) Require pointing angle θ to be small

Particle Identification (PID)

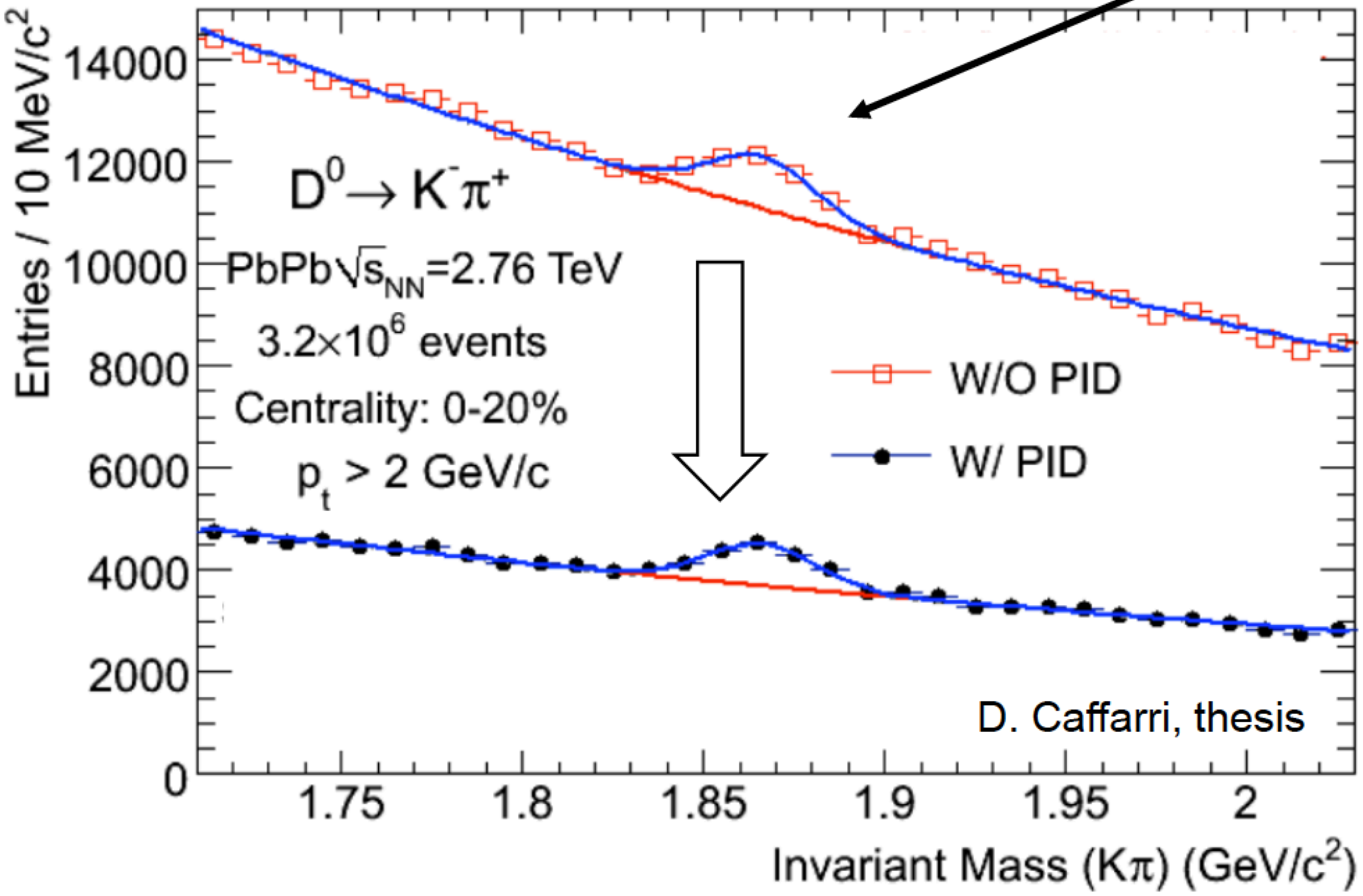
- Specific Energy Loss
  - Particles passing through matter loose energy mainly by ionization
  - Average energy loss calculated with Bethe-Bloch formula
  - Identify particle by measuring energy deposition and momentum
- Time Of Flight
  - Particles with the same momentum have slightly different speed due to their different mass
  - Needed flight time precision, e.g. for a particle with p = 3 GeV/c, flying length 3.5 m: t(π) ~ 12 ns | t(K) – t(π) ~ 140 ps
- Methods can be combined





Invariant Mass with Cuts

- $D^0 \rightarrow K\ \pi$



D^0 peak

with topological cuts

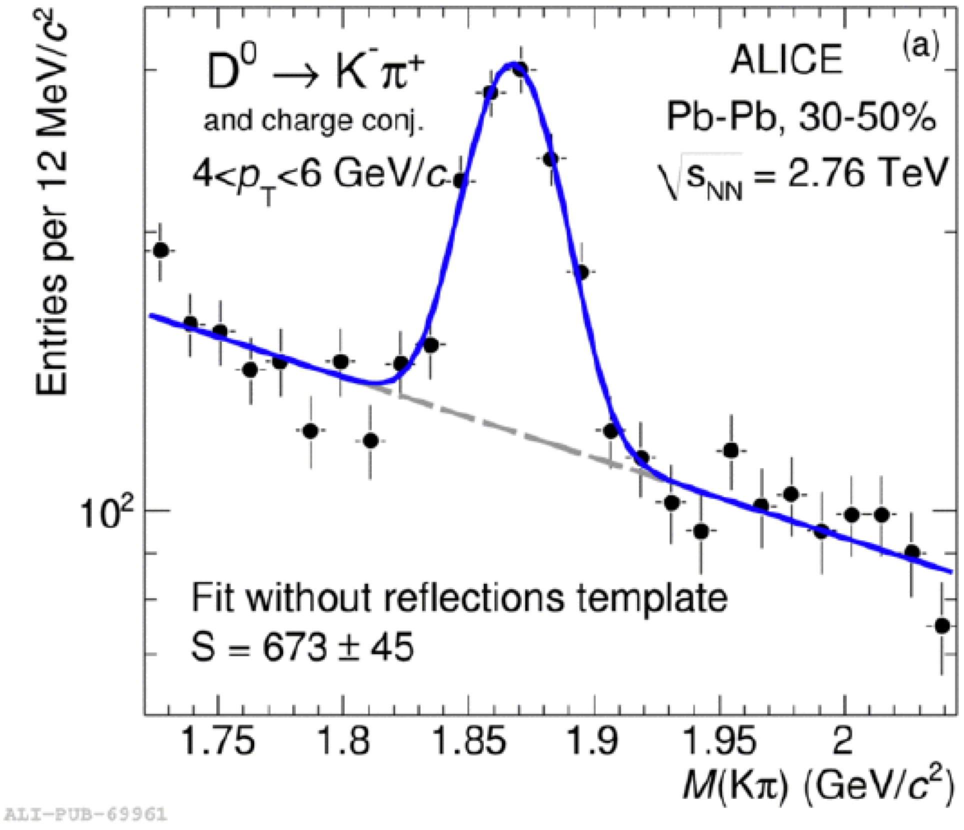
with topological cuts and PID

PID reduces background, but signal peak stays of same magnitude

Recap: D Meson Yield

- We would like to learn about the energy loss of charm

- Reconstruct D meson decay to K π
  - Rare signal
  - Combinatorial background reduced with particle identification and topological cuts
  - Invariant mass distribution
  - Background with like-sign combinations
  - Apply fit to extract yield

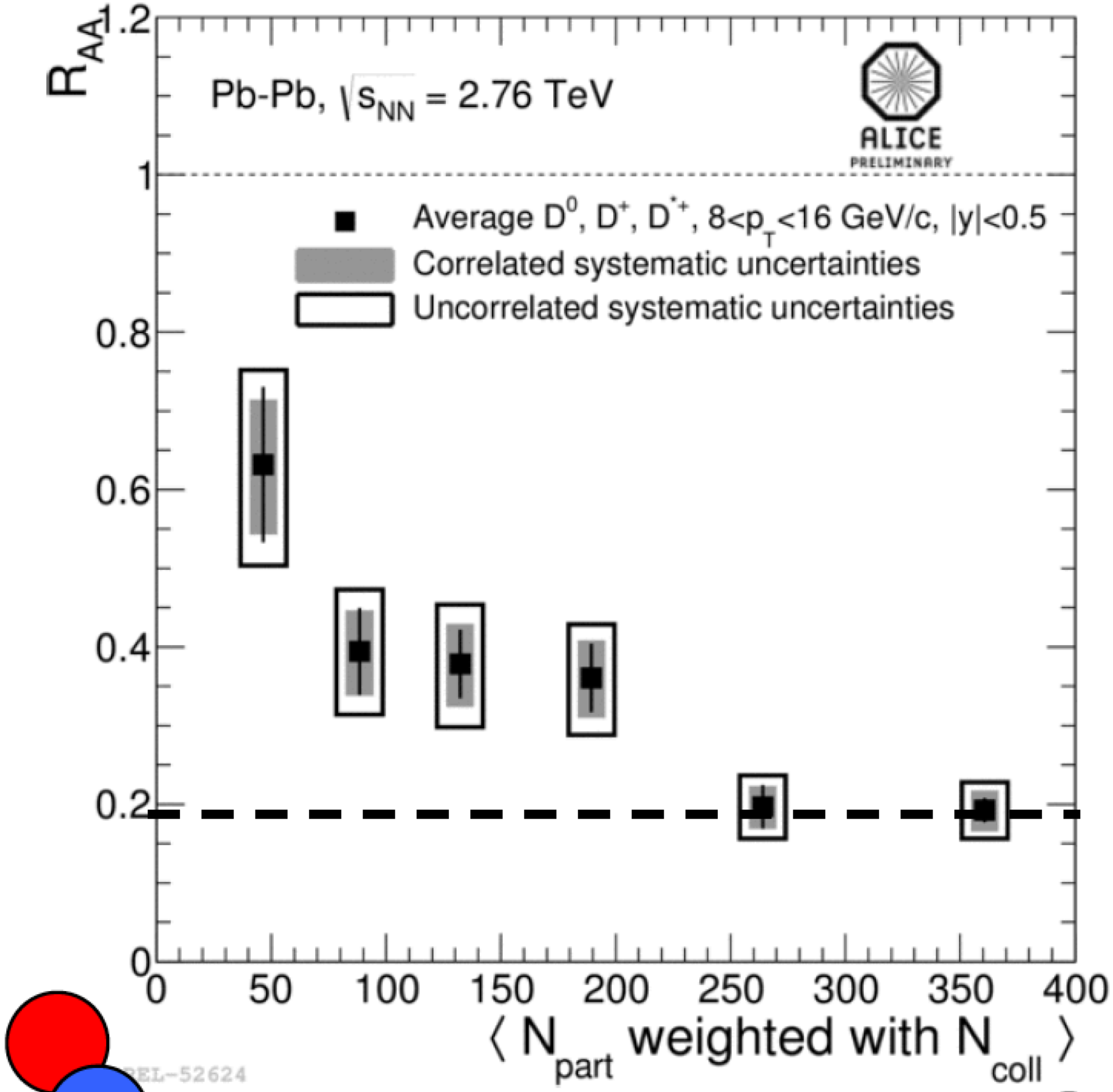


PRC 90 (2014) 034904

D R_{AA}

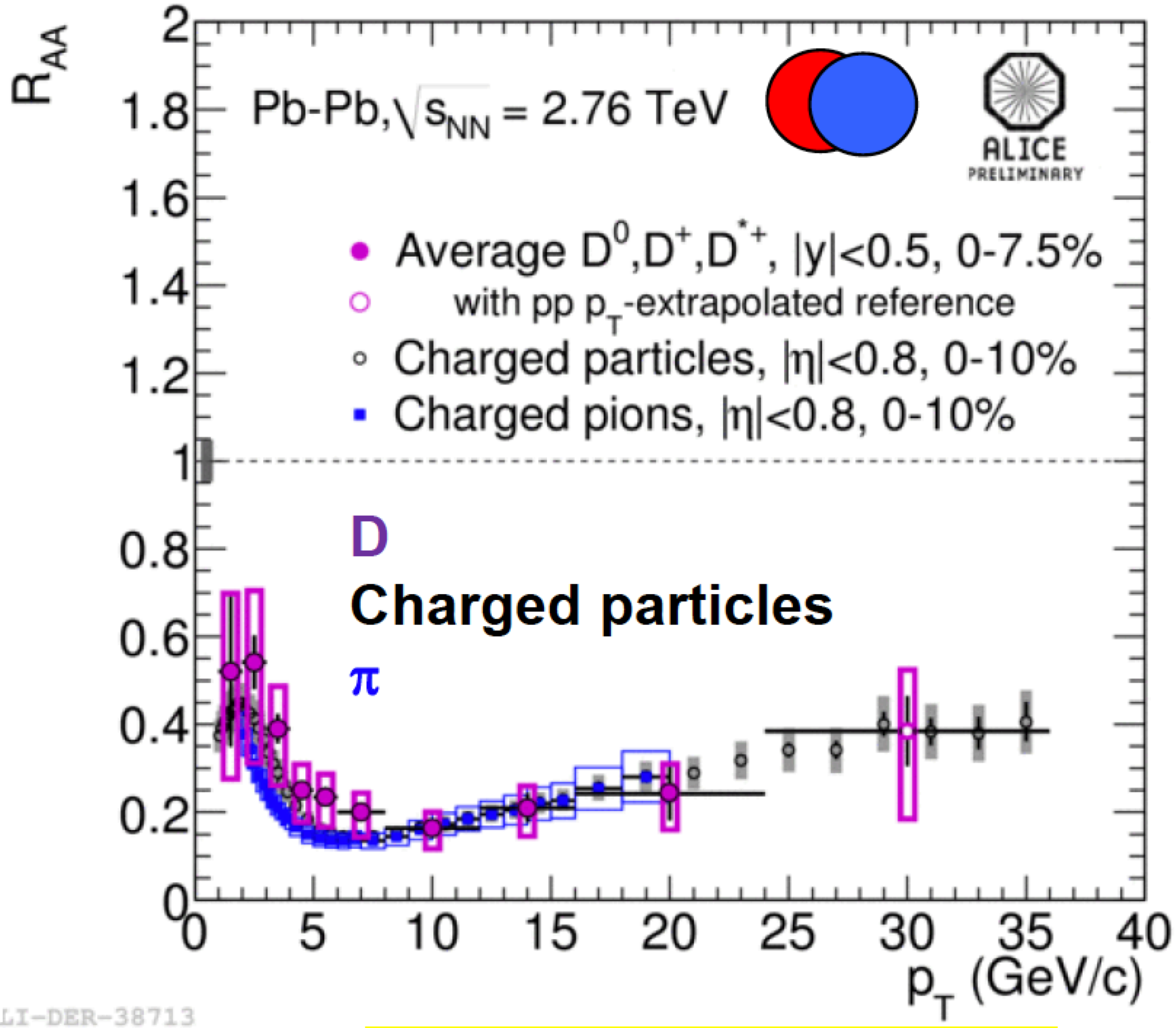
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$

R_{AA} vs. centrality



strong suppression ~ 0.2

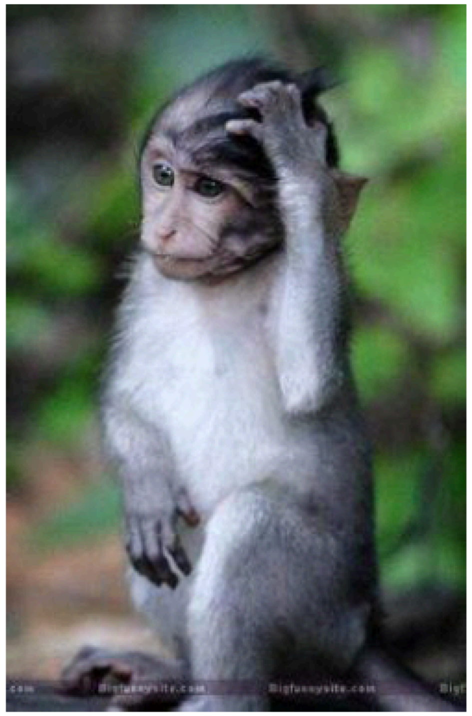
R_{AA} vs. p_T



D and π R_{AA} compatible

arXiv:1506.06604

π R_{AA} VS. D R_{AA}



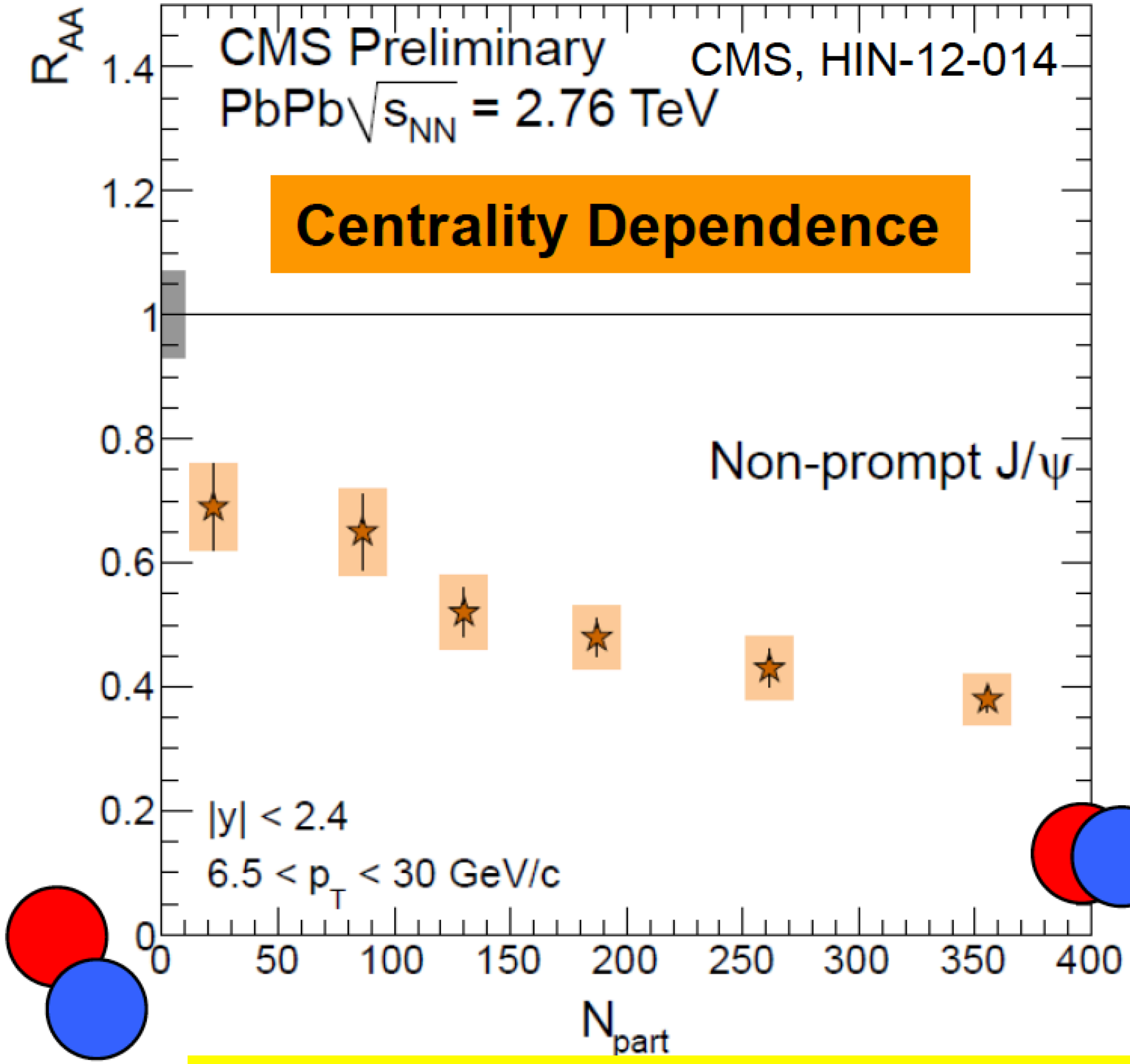
- Expectation $R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$
- However $R^{\pi}_{AA} \approx R^{D}_{AA}$
- Are the energy loss models wrong?
- Not necessarily
  - Effect expected for p_T close to charm mass (~1.3 GeV/c^2)
  - Uncertainties on D R_{AA} large for $p_T < 5$ GeV/c
  - Fragmentation (→ hadron) different for gluons and quarks

Let's have a look at particles containing a heavier b …

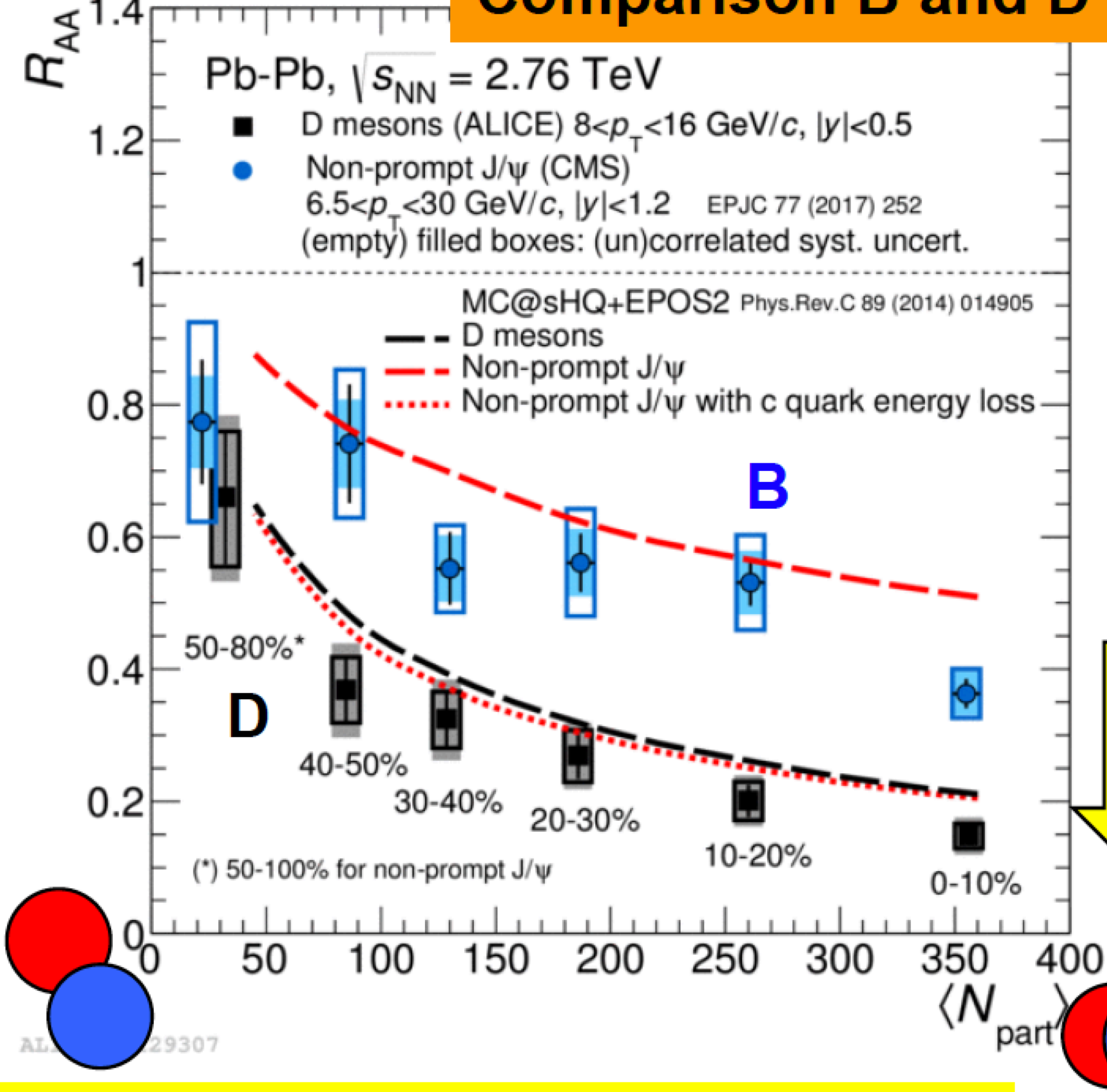
B R_{AA}

$B^{\pm} \rightarrow (J/\psi \rightarrow \mu\mu) + X$ identified by displaced secondary vertices (see backup)

Centrality Dependence



Comparison B and D



D is stronger suppressed than B ! → hint of quark mass dependence

- $R_{AA}(J/\psi \leftarrow B) > R_{AA}(D) \simeq R_{AA}(\pi)$ how to explain such mass dependence?

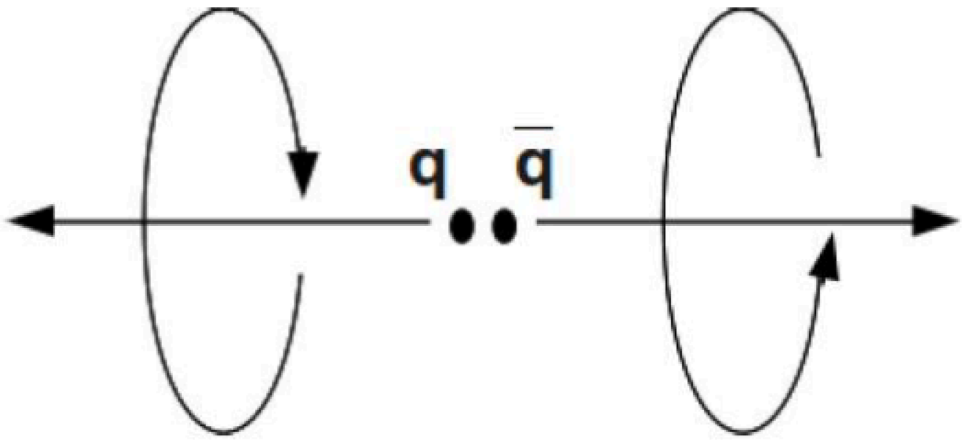
Summary

- An extremely dense and strongly coupled medium has been produced at LHC in central PbPb collisions: $T \gg T_c$
- External probes ($1/p_T$, $1/Q \gg t_0$) are used to determine the medium fundamental properties (thermodynamic properties, transport properties, degrees of freedom,...)
- The HI program has moved beyond the initial exploration phase and is now producing detailed and precise measurements
  - Need detailed and precise theoretical description of entire collision dynamics
  - Many new results and also many open questions (pA and high multiplicity pp !!)
- Improving understanding on QGP properties using newly coming data at LHC ongoing

Thank you for your attention!

Chiral Symmetry

- QCD Lagrangian symmetric under $SU(2)_L$ x $SU(2)_R$
- Light quarks have finite (small) bare masses
  - Explicit chiral symmetry breaking
- Creation of coherent q-qbar pairs in QCD vacuum (compare to cooper pairs in superconductivity)



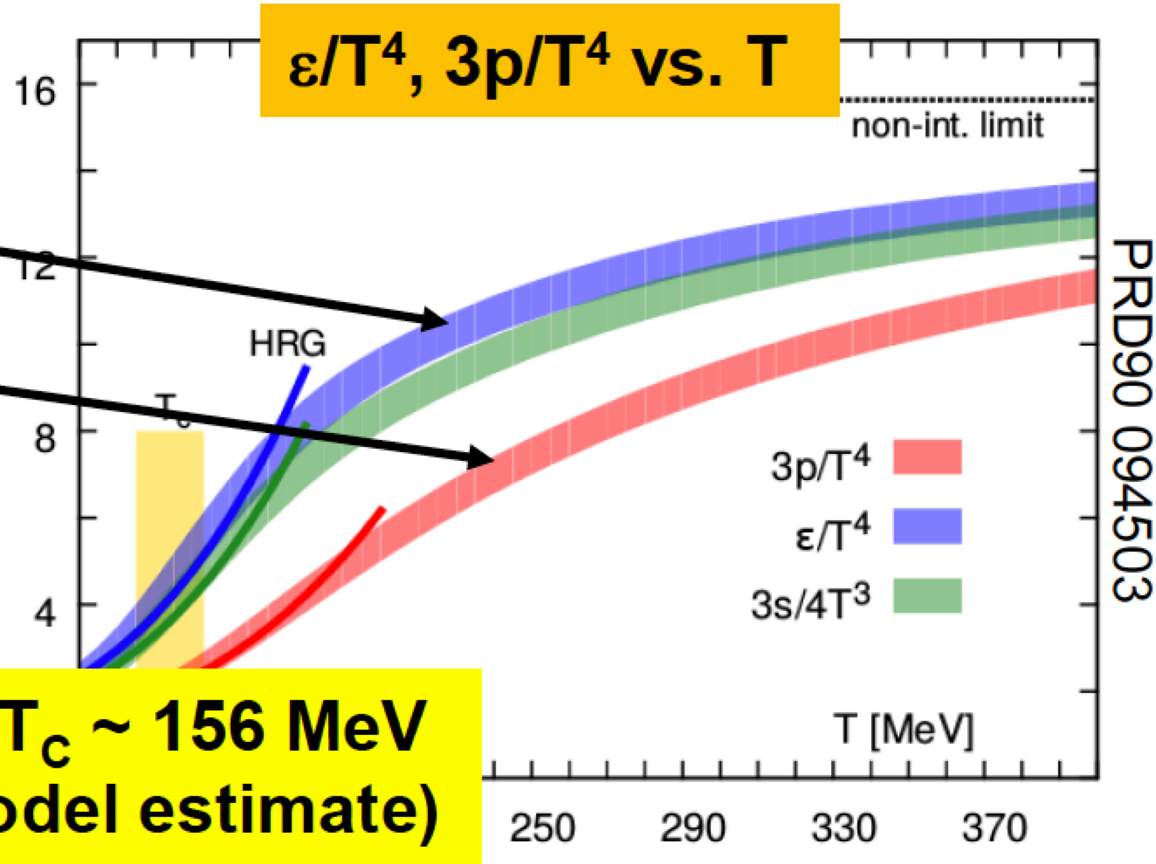
$\Sigma p = 0$ $\Sigma L = 0$
→ chirality != 0

  - Has a chiral charge
  - Not symmetric under $SU(2)_L$ x $SU(2)_R$

  → Spontaneous symmetry breaking (pseudo-goldstone bosons: pions)
- Quarks acquire ~350 MeV additional mass
  - *Constituent mass*
  - Relevant only for u, d, s

Lattice QCD

- More thorough estimate of the phase transition temperature can be done with lattice QCD
- Approach to solve non-perturbative QCD
- Discretize the QCD Lagrangian on a space-time grid
- Limited to chemical potential $\mu_B = 0$ (some workarounds exist)
- Calculate T dependence of
  - energy density
  - pressure
- Steep rise = change in number of degrees of freedom → phase transition



ε/T^4, $3p/T^4$ vs. T

156 MeV ≈ 2 10^{12} K
(Sun core: 1.5 10^7 K)

Transition temperature T_C ~ 156 MeV
(consistent with bag model estimate)