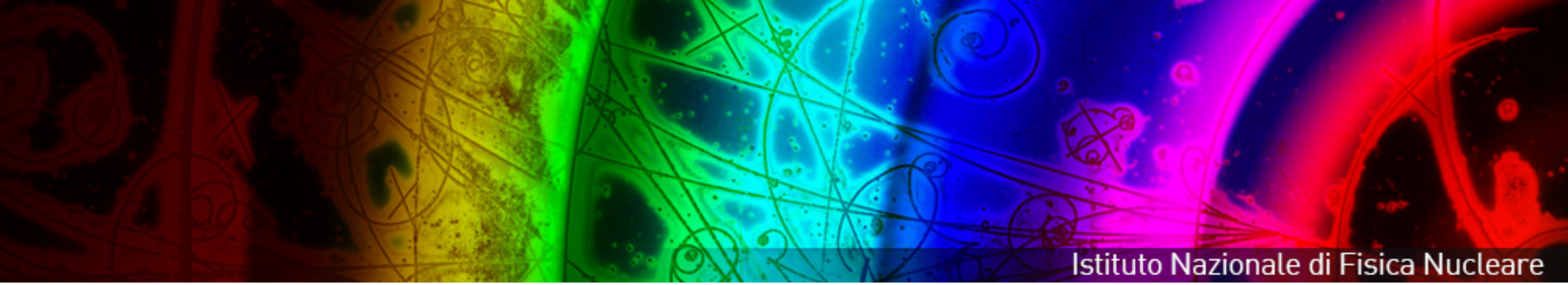


From QCD to Quark-Gluon Plasma

Pasquale Di Nezza&Simonetta Gentile

Pasquale.DiNezza@Lnf.infn.it

Università Sapienza – Nuclei e Particelle, a.a. 2018-2019

History of the Universe

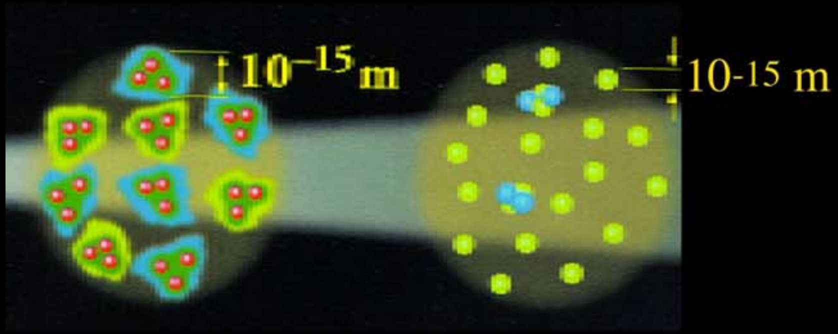
Big Bang

Today

Source: Nuclear Science
Wall Chart

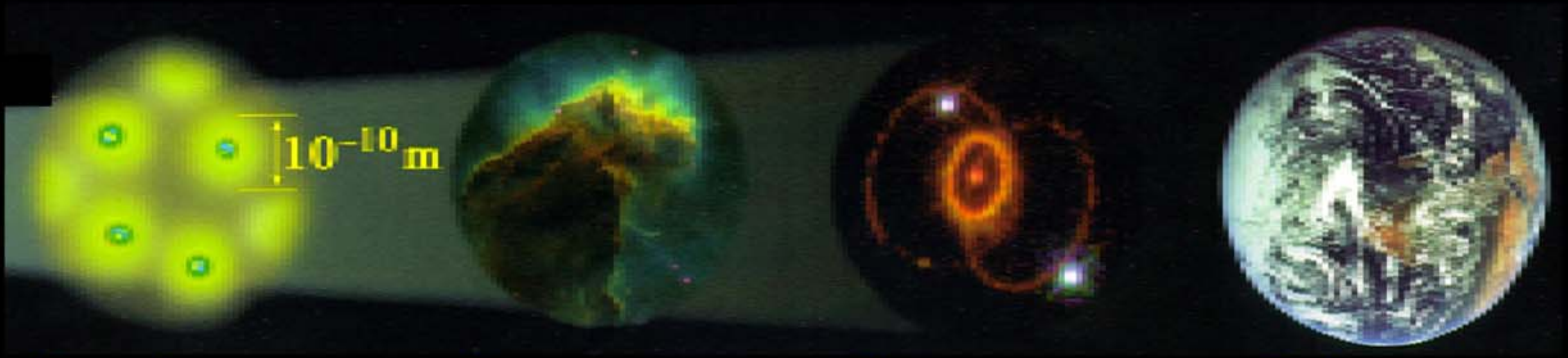
History of the Universe

Big Bang



Protons&
Neutrons
10^{12}K, 10^{-4}s

Low-mass
Nuclei
10^{9}K, 3 min



Neutral
Atoms
4000K, 10^{5}y

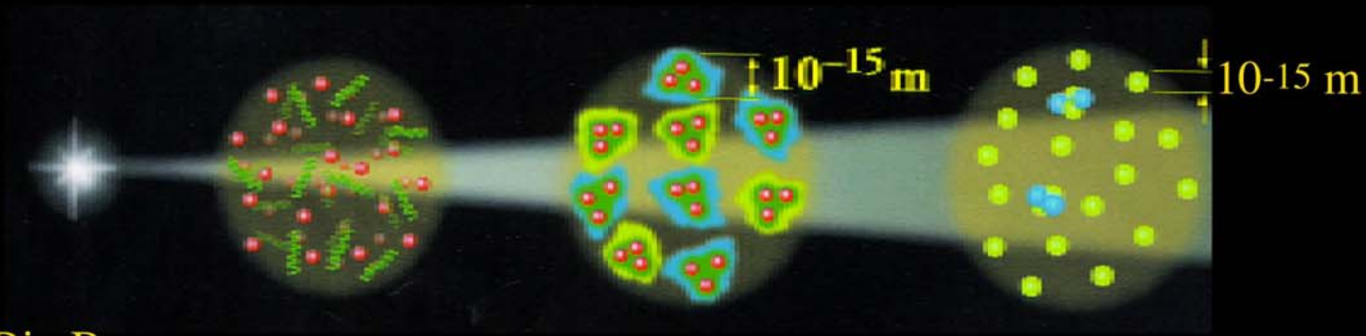
Star
Formation
10^{9}y

Heavy
Elements
$>10^{9}$y

Today

Source: Nuclear Science Wall Chart

History of the Universe

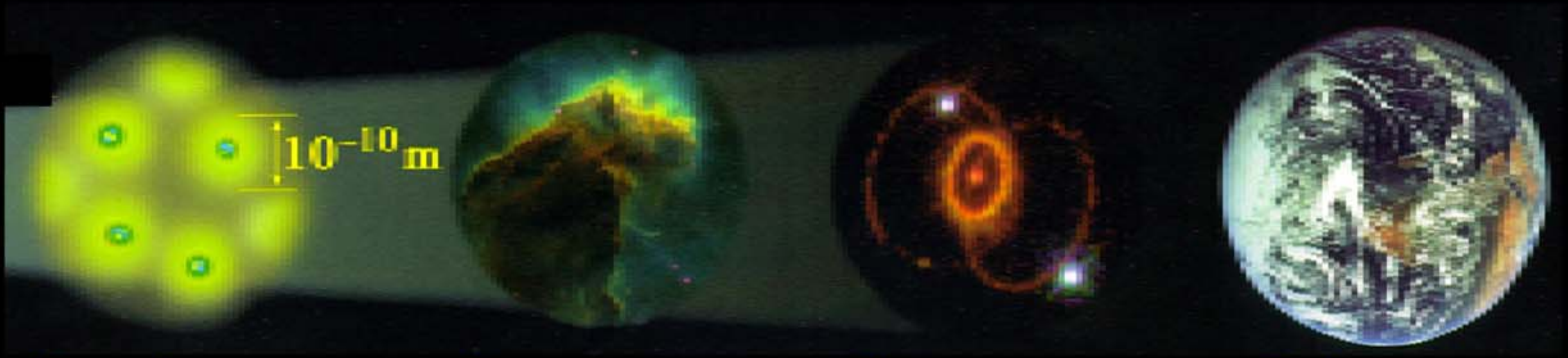


Big Bang

Quark-Gluon
Plasma
10^{13}K, 10^{-6}s

Protons&
Neutrons
10^{12}K, 10^{-4}s

Low-mass
Nuclei
10^{9}K, 3 min



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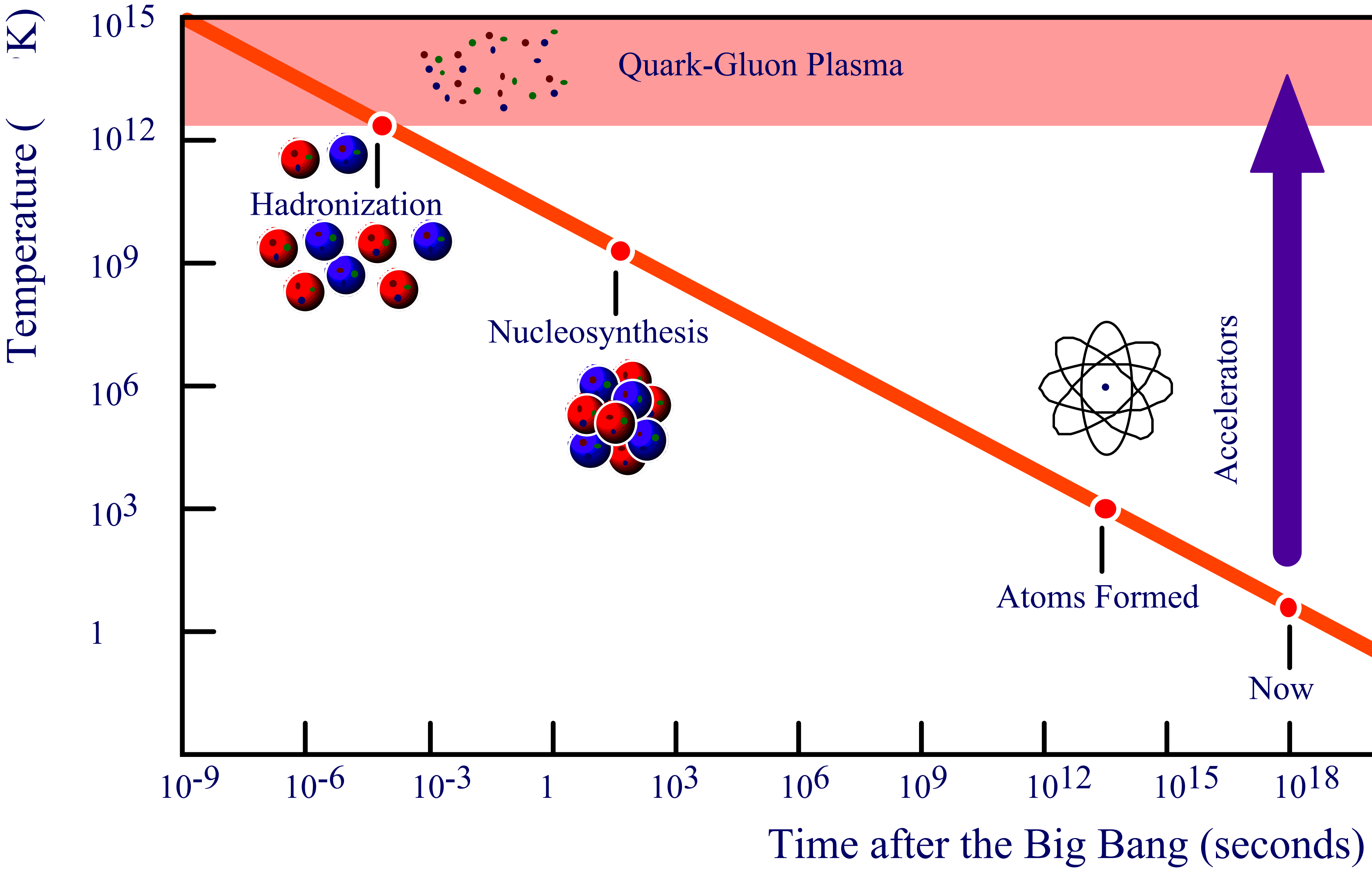
Temperature (K)
10^15
10^12
10^9
10^6
10^3
1
Quark-Gluon Plasma
Hadronization
Nucleosynthesis
Atoms Formed
Now
Accelerators
10^-9
10^-6
10^-3
1
10^3
10^6
10^9
10^12
10^15
10^18
Time after the Big Bang (seconds)

Energy Scales

- **The beginning**

The universe is a hot plasma of fundamental particles … quarks, leptons, force mediating particles (and other particles ?)

10^{-43} s	Planck scale (quantum gravity ?)	10^{19} GeV
10^{-35} s	Grand unification scale (strong+electroweak)	10^{15} GeV
	Inflationary period 10^{-35}-10^{-33} s	
10^{-11} s	Electroweak unification scale	200 GeV

- **Micro-structure**

10^{-5} s	QCD scale - protons and neutrons form	200 MeV
3 mins	Primordial nucleosynthesis	5 MeV
3×10^{5} y	Radiation and matter decouple - atoms form	1 eV

- **Large scale structure**

1 b yrs	Proto-galaxies and the first stars
3 b yrs	Quasars and galaxy spheroids
5 b yrs	Galaxy disks
Today	Life !

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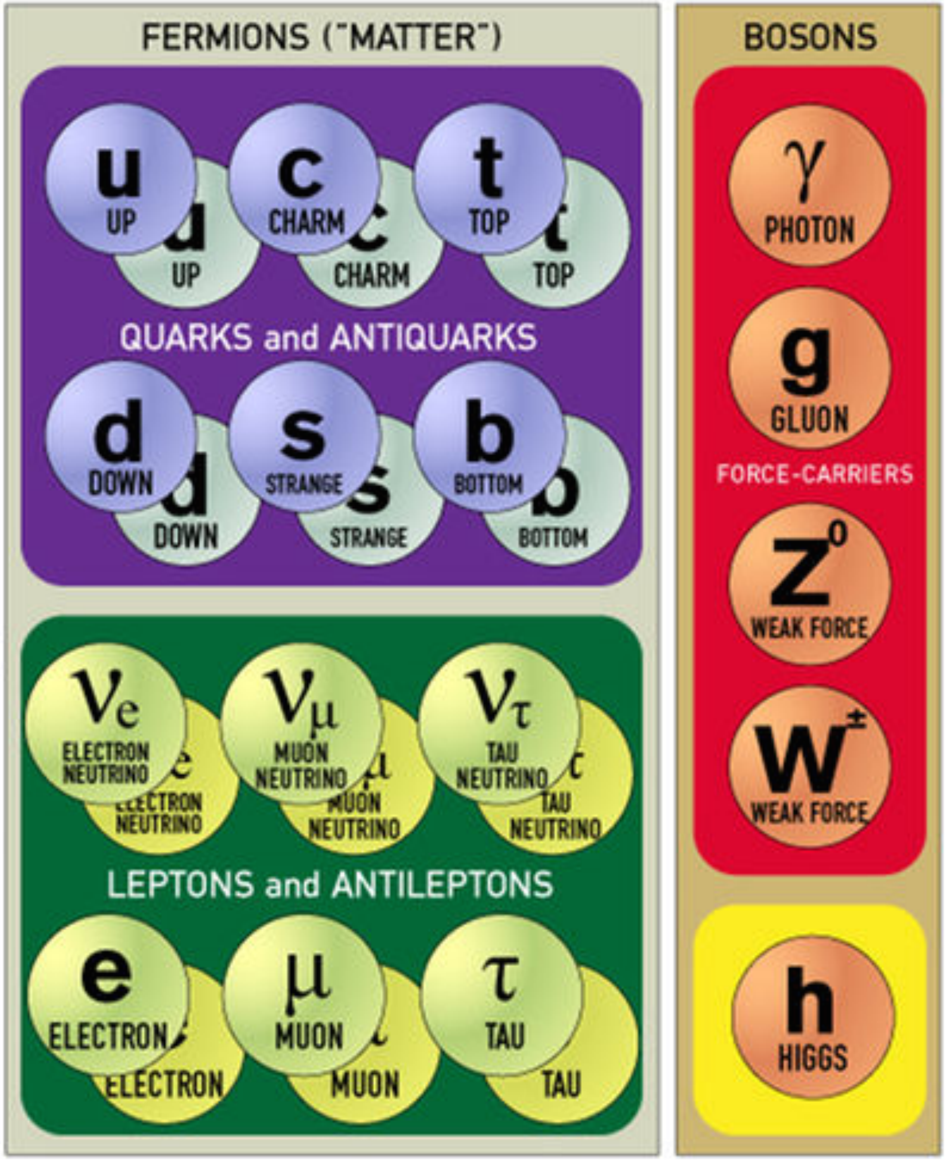
Today	Life !

Quantum Chromo Dynamics

arXiv:hep-ph/9505231

Standard Model



Quantum Chromo Dynamics

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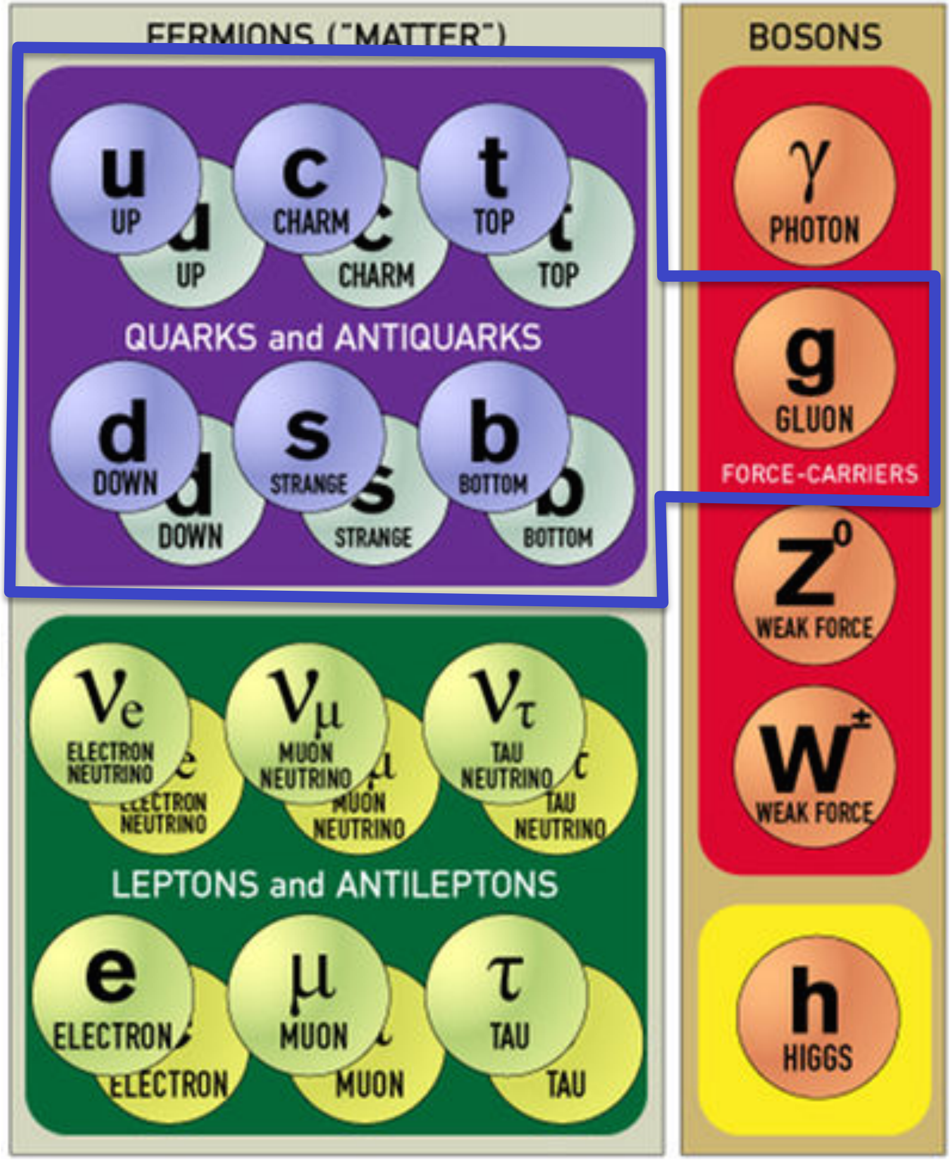


Strong Interaction:

- *binds quarks into hadrons*
- *binds hadrons into nuclei*

QCD describes:

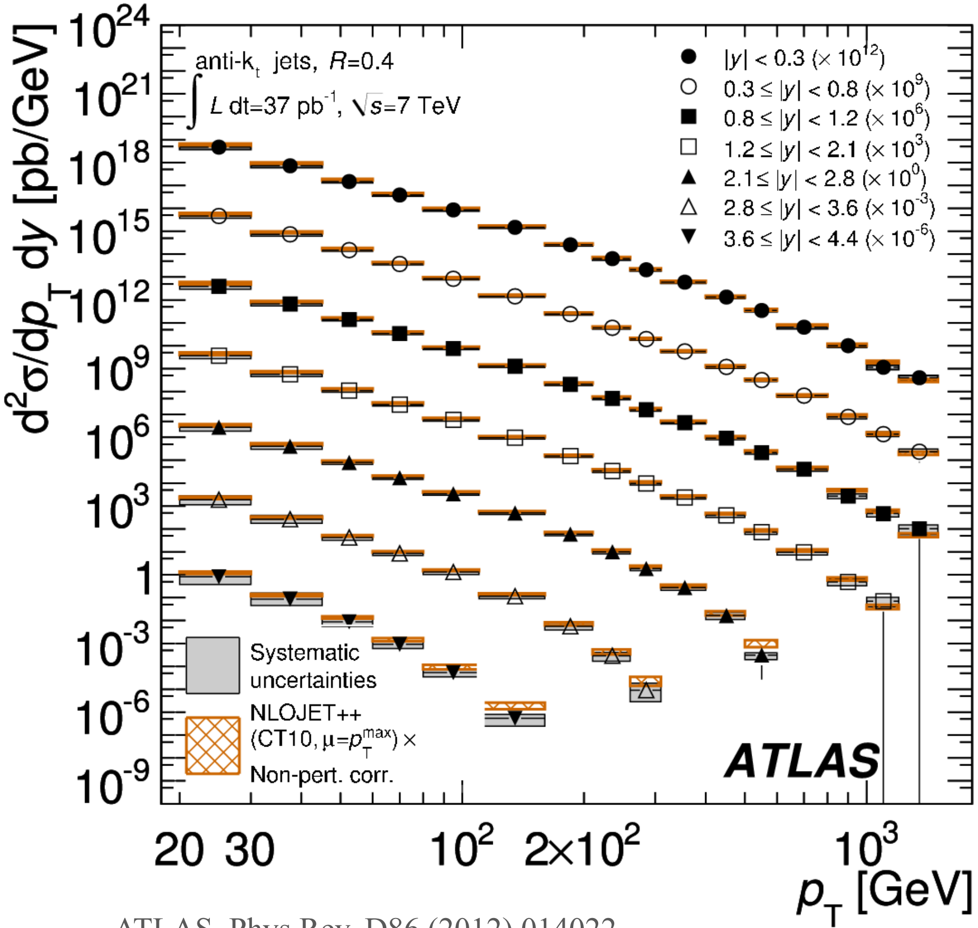
- *quark-gluon interactions*
- *gluon-gluon interactions*

Quantum Chromo Dynamics

arXiv:hep-ph/9505231

Very successful theory valid over 25 orders of magnitude and up to the TeV scale!

Comparison pQCD with hadron jet production cross section



ATLAS, Phys.Rev. D86 (2012) 014022

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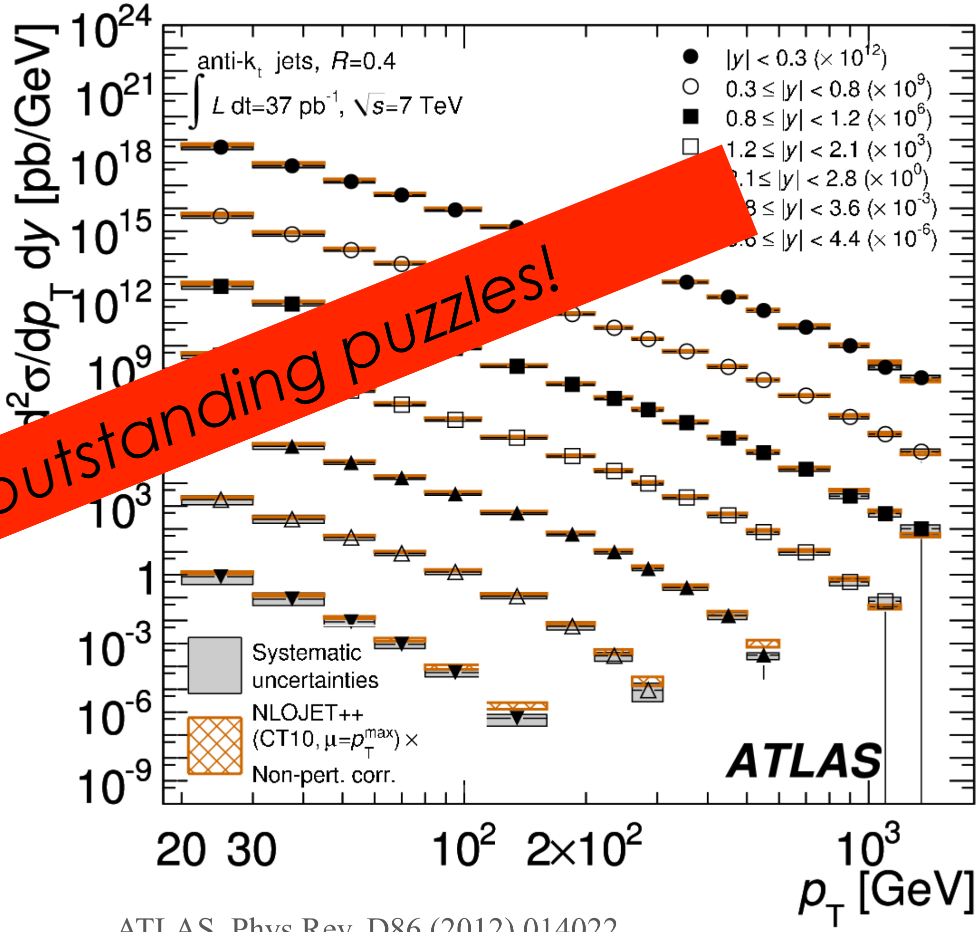


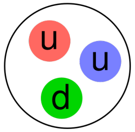
... but with outstanding puzzles!

ATLAS, Phys.Rev. D86 (2012) 014022

Quantum Chromo Dynamics

The hadron mass

- *A proton is composed out of uud quarks*



- *The proton mass is 938.3 MeV/c^2*
- *The sum of bare quark masses is only ~10 MeV/c^2*

How is the extra-mass generated?

Confinement

- *An isolated quark has never been observed*
- *The quarks seem confined within the hadrons*
- *Half of the fundamental fermions is not observable directly*

Why?

QCD Lagrangian

(SU(3)$_C$ invariant)

$$\mathcal{L}_{\mathrm{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}_f \left(i\gamma^\mu D_\mu - m_f \right) q_f$$

Structure: QED-like (generalised Maxwell (Yang-Mills) + Dirac)

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Elementary quark field

$$(q_\alpha)_f^a \begin{cases} \text{color} & a = 1, \ldots, 3 \\ \text{spin} & \alpha = 1, 2 \\ \text{flavor} & f = u, d, s, c, b, t \end{cases}$$

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Tensorial part

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} \boxed{A^b_\mu A^c_\nu}$$

$$i\not{D} q = \gamma^\mu \left(i\partial_\mu + g A^a_\mu t^a \right) q$$

Elementary gluon field

$$\boxed{A^a_\mu} \begin{cases} \text{color} & a = 1, \ldots, 8 \\ \text{spin} & \epsilon^\pm_\mu \end{cases}$$

Contrary to photons, gluons carry (color) charge and can interact among themselves creating complicated structures.

QCD Lagrangian

(SU(3)$_C$ invariant)

$$\mathcal{L}_{\mathrm{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}_f \left(i\gamma^\mu D_\mu - m_f \right) q_f$$

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Elementary gluon field

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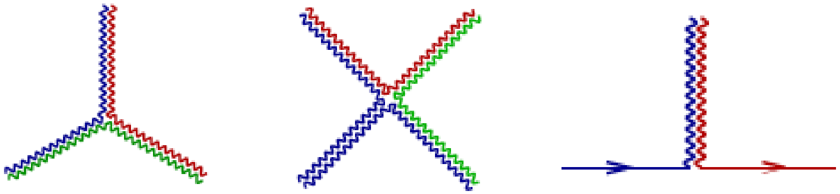
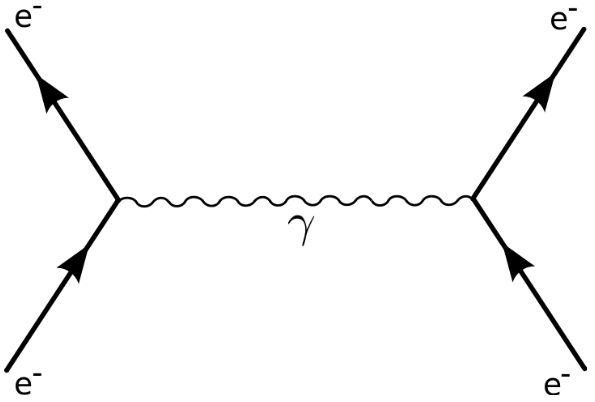
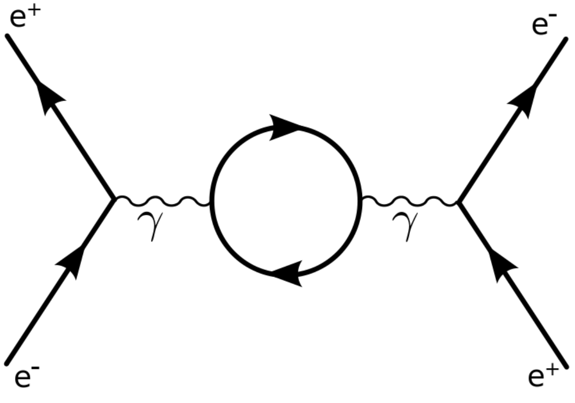
Ex. gluon-gluon interaction



Running coupling

Consider the interaction of 2 elementary particles as a function of Q^2





Because of Heisenberg U.P.:

small Q^2 → large distances
large Q^2 → small distances

Virtual pairs screen the bare interaction resulting in momentum-transfer dependent interaction strength → $\alpha(Q)$

Running coupling: α vs α_s

QED

$$\alpha(Q^2) \approx \frac{\alpha(\mu^2)}{1 - \frac{1}{3\pi}\alpha(\mu^2)\log\frac{|Q^2|}{\mu^2}}$$

Negative

Small Q^2 (large distances) → weaker α

(similar to screening of charge in dielectric materials)

Running coupling: α vs α_s

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Negative

Small Q^2 (large distances) → <u>weaker</u> α

(similar to screening of charge in dielectric materials)

QCD

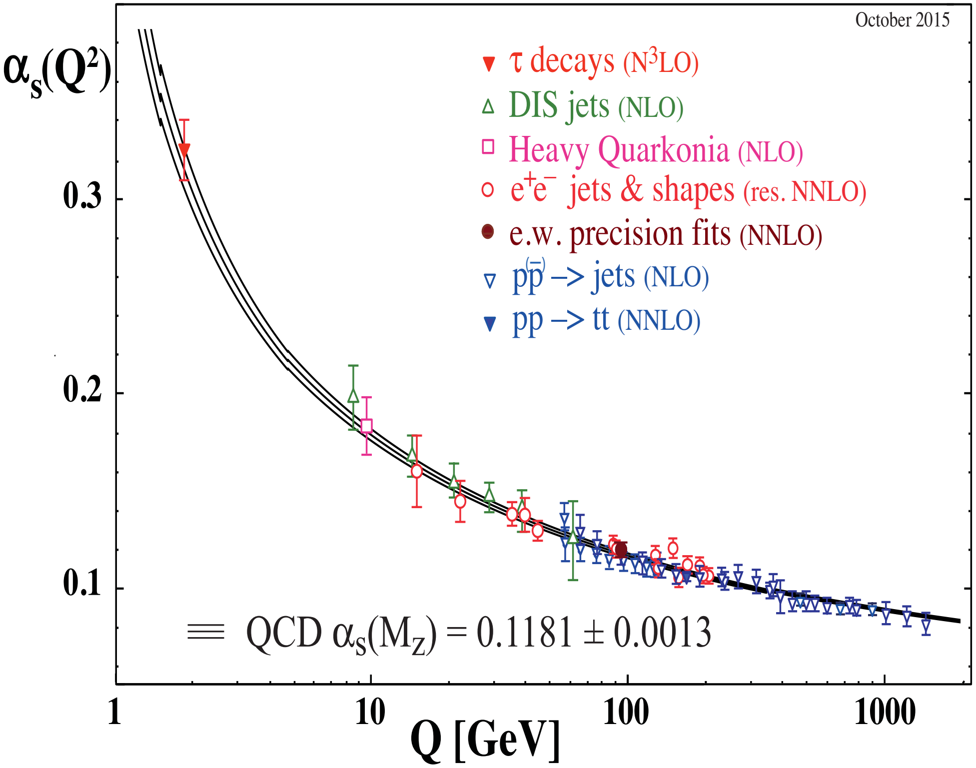
$$\alpha(Q^2) \approx \frac{\alpha(\mu^2)}{1 + \frac{11N_{color} - 2n_{flavor}}{12\pi}\alpha(\mu^2)\log\frac{|Q^2|}{\mu^2}}$$

(33-12)/12π → Positive

Small Q^2 (large distances) → <u>stronger</u> α

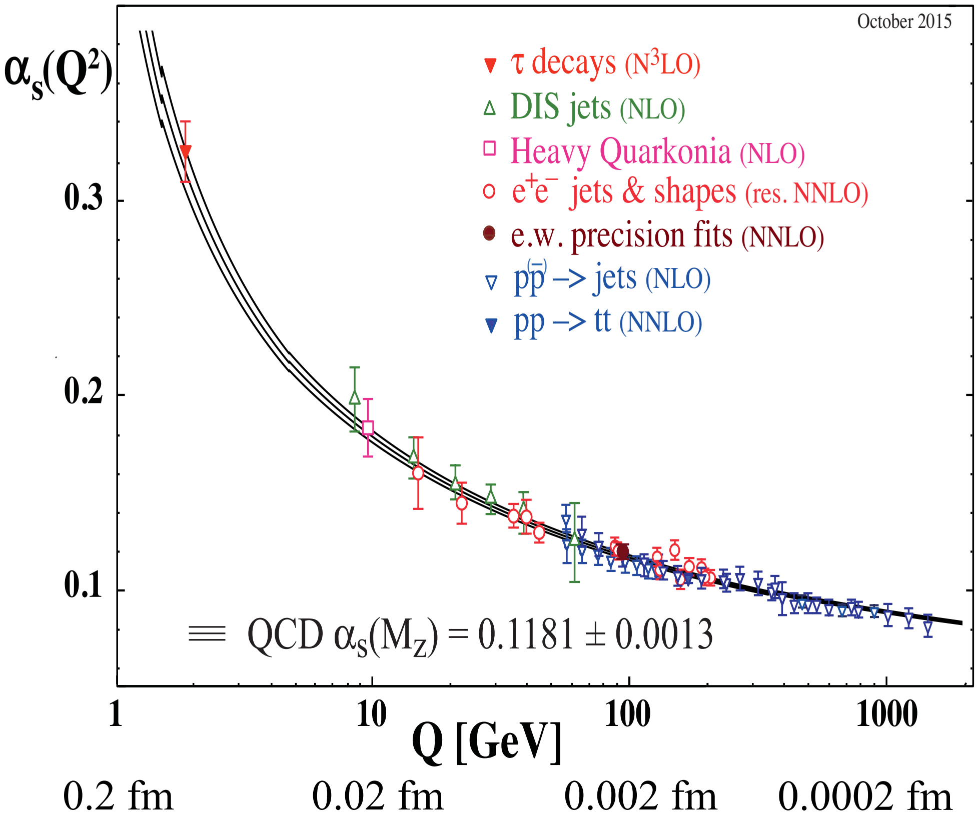
(anti-screening larger than screening)

Running coupling: $\alpha_s(Q)$

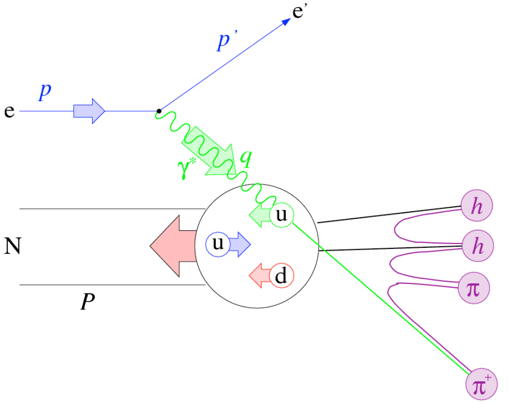


0.2 fm 0.02 fm 0.002 fm 0.0002 fm

Running coupling: $\alpha_s(Q)$

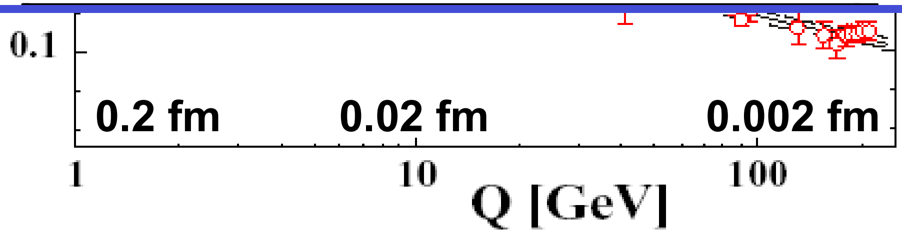


Large Q
Asymptotic Freedom



Running coupling: $\alpha_s(Q)$

2004
Nobel
Prize

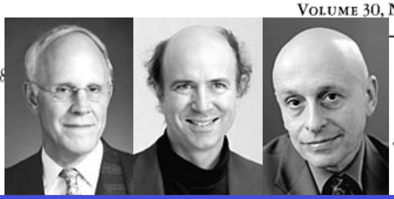


PHYSICAL REVIEW D VOLUME 8, NUMBER 10 15 NOVEMBER 1973

Asymptotically Free Gauge Theories. I*

David J. Gross[†]
National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510
and Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08

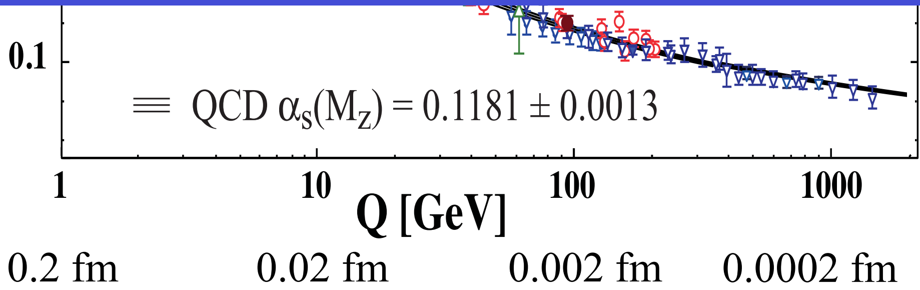
Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 23 July 1973)



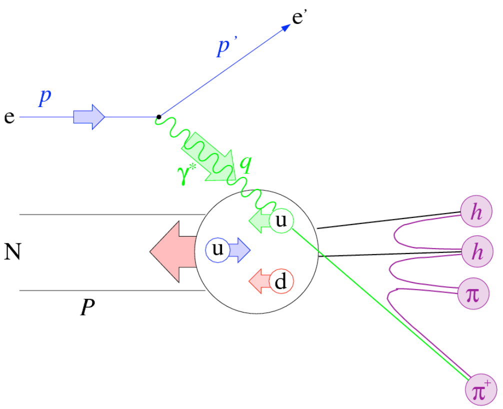
VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Reliable Perturbative Results for Strong Interactions?*

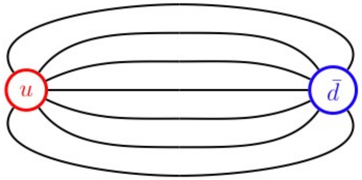
H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)



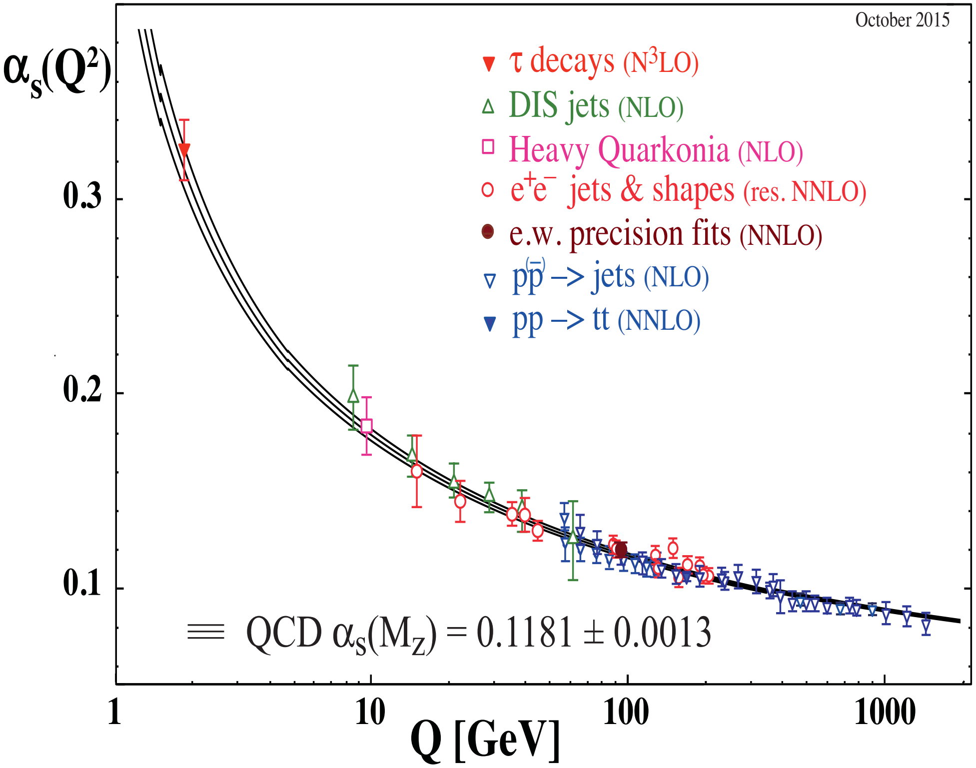
Asymptotic Freedom



Running coupling: $\alpha_s(Q)$



Low Q
Confinement



0.2 fm 0.02 fm 0.002 fm 0.0002 fm

Large Q
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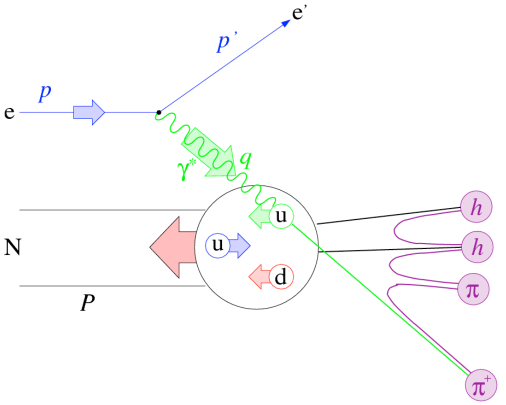


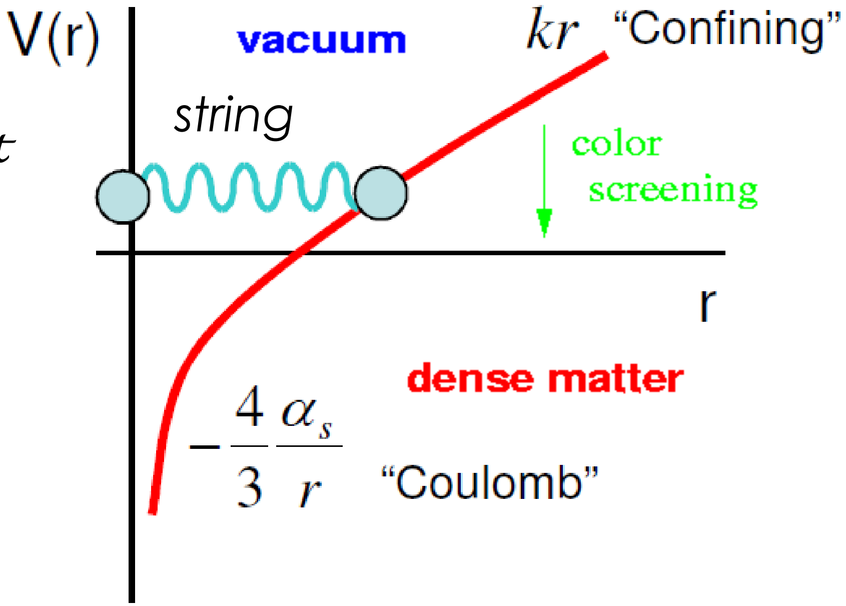
Confinement and Asymptotic freedom: a toy model

Let's parameterise the increase of the potential for a $q\bar{q}$ *pair by a potential "a la Cornell" + linear term (flux tube) which considers the confinement (semi-classic, non relativistic)*

Coulomb potential

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

Confinement



in dense and hot matter

- screening of color charges (similar to Debye screening in dense atomic matter)
- potential vanishes for large distance
- deconfinement of quarks → QGP

in vacuum:

- linear increase with distance, strong attractive force
- confinement of quarks to hadrons

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Confinement


Elongating gluon tube

Increasing "r" it become energetically favorable to convert the stored energy into a new $q\bar{q}$ pair

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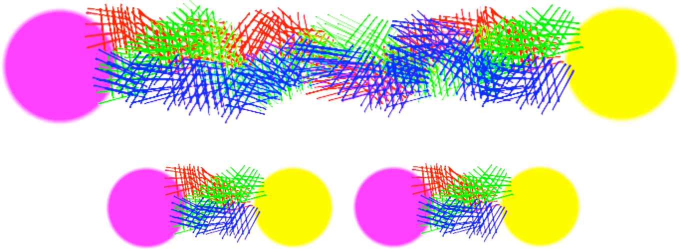
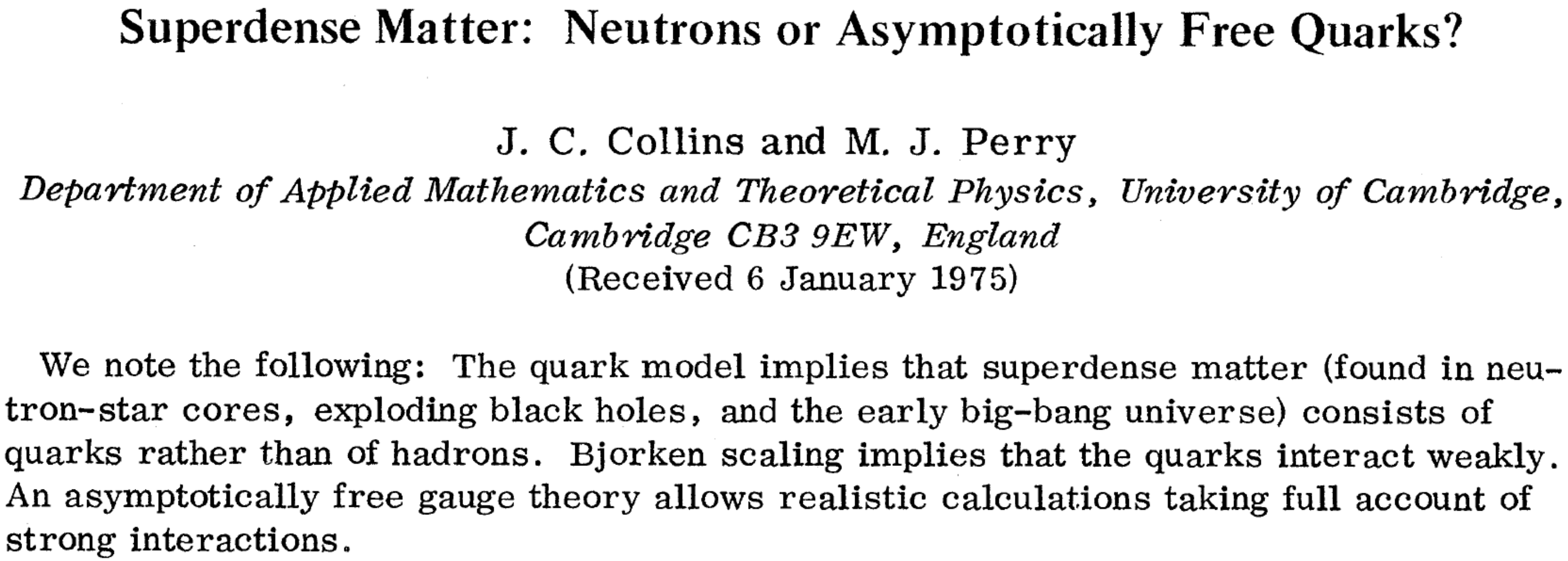


(colorless)

Increasing "r" it become energetically favorable to convert the stored energy into a new $q\bar{q}$ pair

The confinement cannot be described perturbatively.
At scales of the hadron size (~1fm) the perturbative methods lose validity. Calculations rely on approximate methods (lattice theory, effective theories). Ex: *MIT Bag Model, simple QCD inspired model*

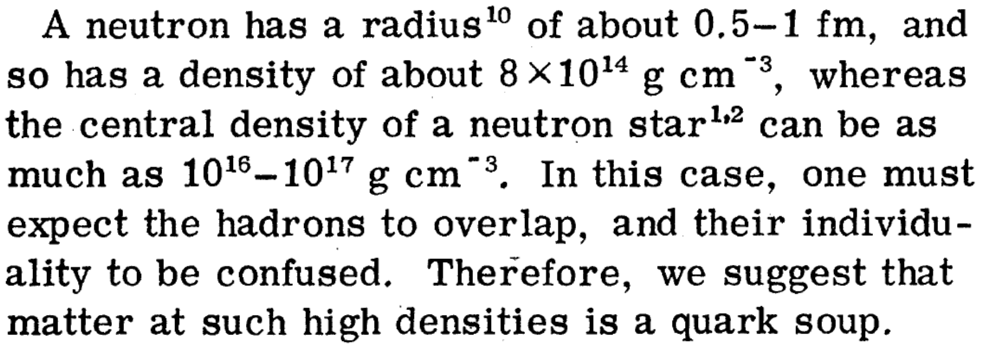


Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England

(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.



A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

How does QCD matter behave under extreme conditions of temperature and energy density?

- A question rooted in the QCD, with cosmological and astrophysical implications

Chodos et al., PRD 10 (1974) 2599

MIT Bag Model - (confinement)

The Model assumes that the quarks are confined within bags of perturbative (empty) vacuum of radius R, in which they are free to move

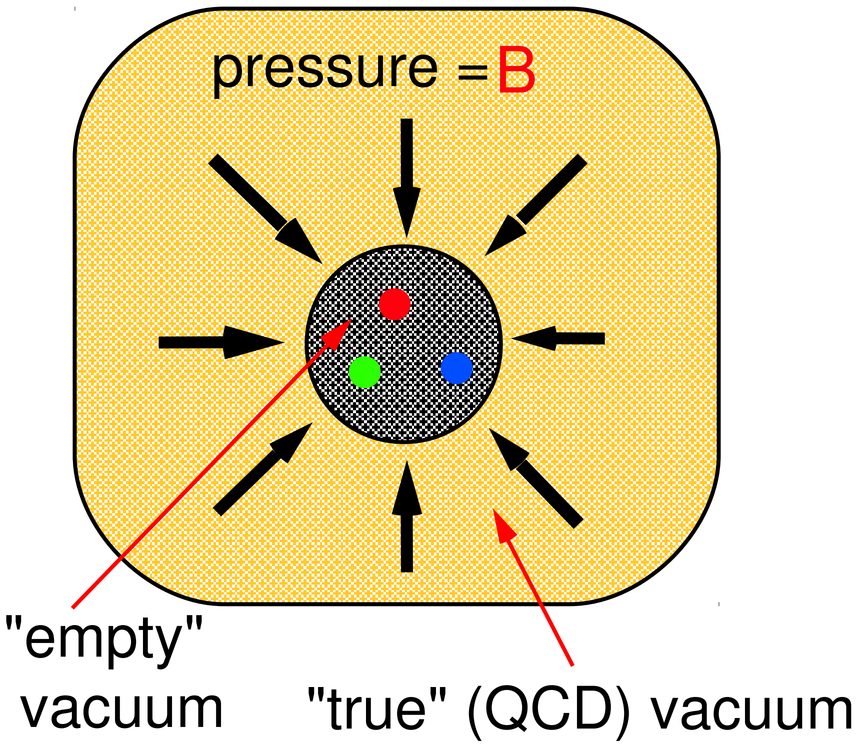
The QCD vacuum creates a confining bag with pressure B

The bag constant is obtained by balancing the vacuum with the kinetic pressure of the quarks.
By minimizing:

$$E \approx \frac{2N}{R} + \frac{4}{3}\pi R^3 B$$

With N=3 (quarks) and R=0.8 fm

$B \approx (200\ \text{MeV})^4 = 0.2\ \text{GeV/fm}^3$



At the end, 0.2 GeV/fm³ are sufficient to confine 3 quarks within the proton volume

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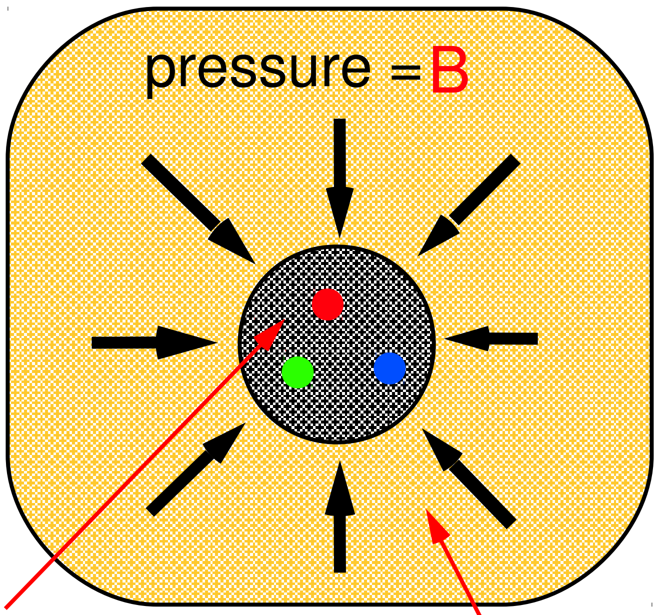
With N=3 (qua[illegible] R=0.8 fm

B ≈ (200 MeV)^4 = 0.2 GeV/fm^3

If kinetic pressure exceeds bag pressure → deconfinement



"empty" vacuum

"[illegible]e" (QCD) vacuum

At the end, 0.2 GeV/ fm^3 are sufficient to confine 3 quarks within the proton volume

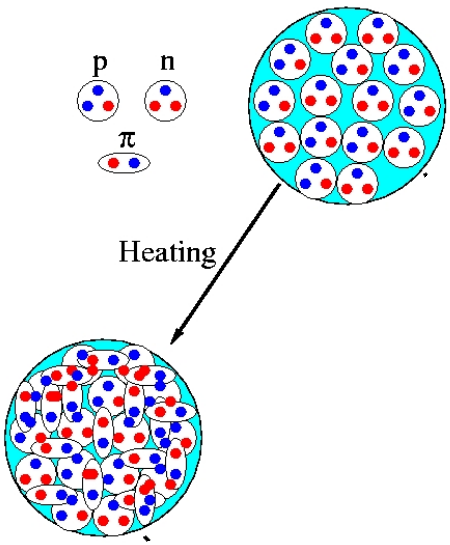
A toy model - (deconfinement)

We can heat matter so much that individual hadrons start to overlap

From statistical mechanics, for an ideal gas

$$p = \frac{\epsilon}{3} = \left(g_B + \frac{7}{8} g_F\right) \frac{\pi^2 T^4}{90}$$

$g_B=0$, $g_F=2$



A toy model - (deconfinement)

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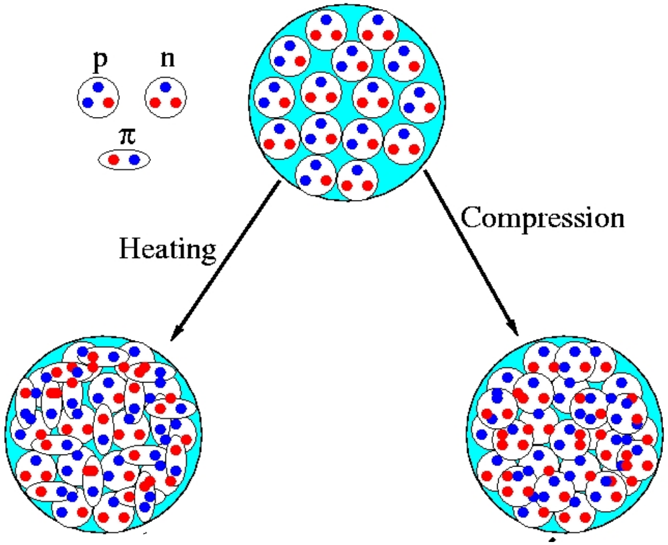
From statistical mechanics, for an ideal gas … let's add the compression too

$$p = \frac{\epsilon}{3} = \left(g_B + \frac{7}{8} g_F\right) \frac{\pi^2 T^4}{90} + g_F \left(\frac{\mu_F^2 T^2}{12} + \frac{\mu_F^4}{24\pi^2}\right)$$

g_B=0, g_F=2



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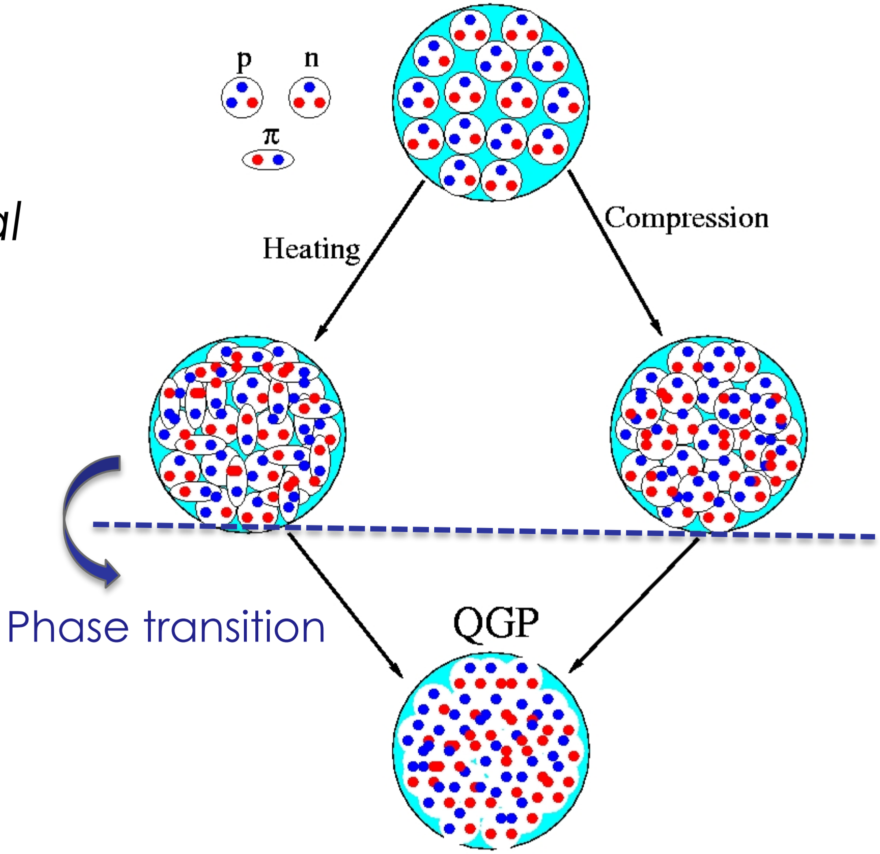
If the pression>B and/or T>T_c we have the conditions for Quark Gluon Plasma (QGP)

g_B=0, g_F=2



g_B=2x8 (spin x colors) = 16
g_F=2x2x3x3 ($q\bar{q}$ x spin x flavor x colors) = 24

A phase transition has brought the system[*] to a deconfined stage with release of degrees of freedom

---

[*] *of a non negligible dimensions*

Matter in extreme conditions

How does matter behave in such extreme conditions?

What are the properties of the Quark-Gluon Plasma and the early Universe?
Remember that even with the most powerful telescopes, we cannot go back in time to less than ~ 400,000 years after the Big Bang (except GW)

Matter in extreme conditions

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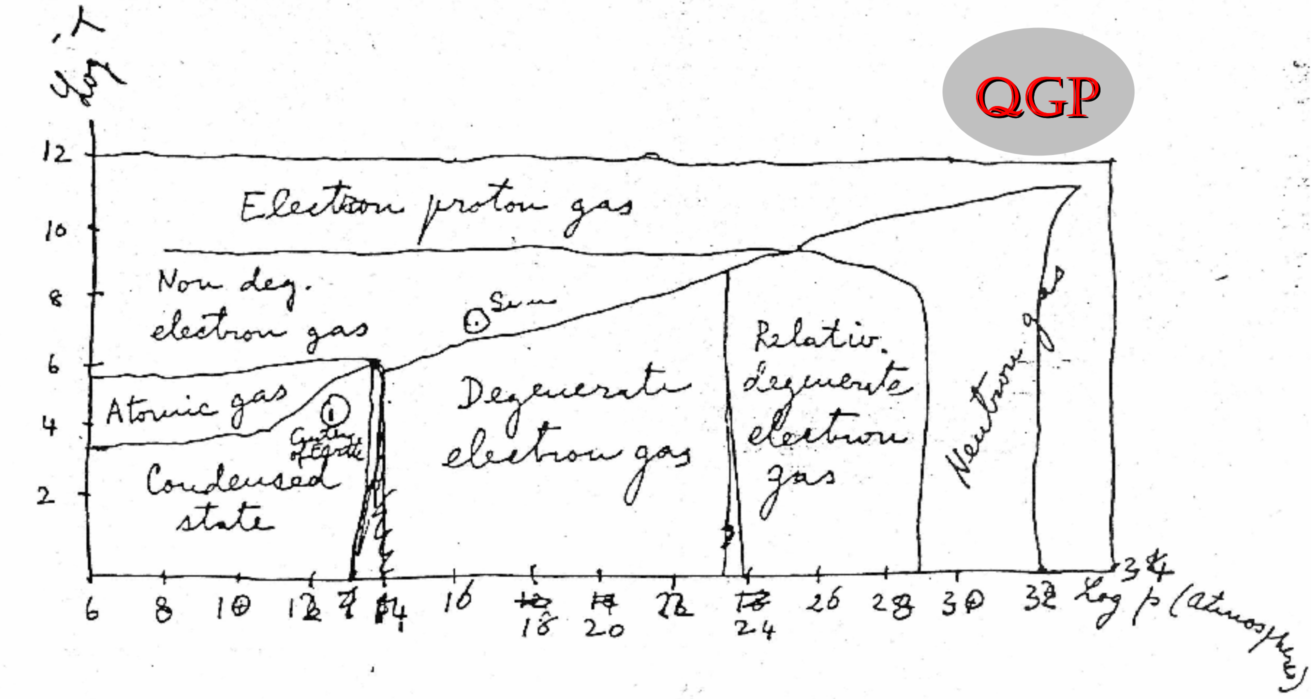
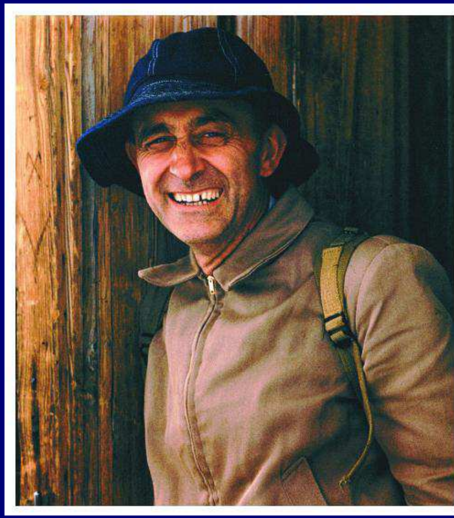
What are the properties of the Quark-Gluon Plasma and the early Universe? Remember that even with the most powerful telescopes, we cannot go back in time to less than ~ 400,000 years after the Big Bang (except GW)

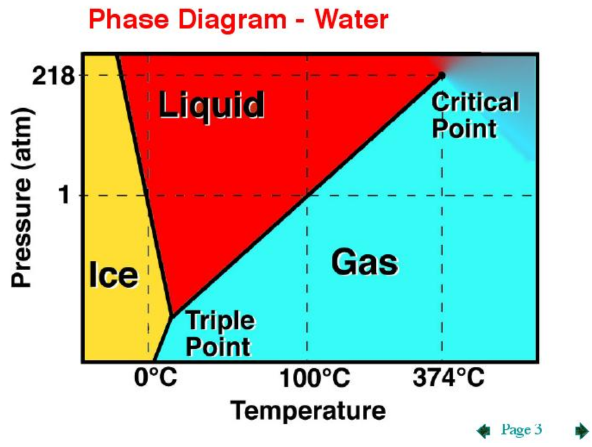
Fermi Notes on Thermodynamics

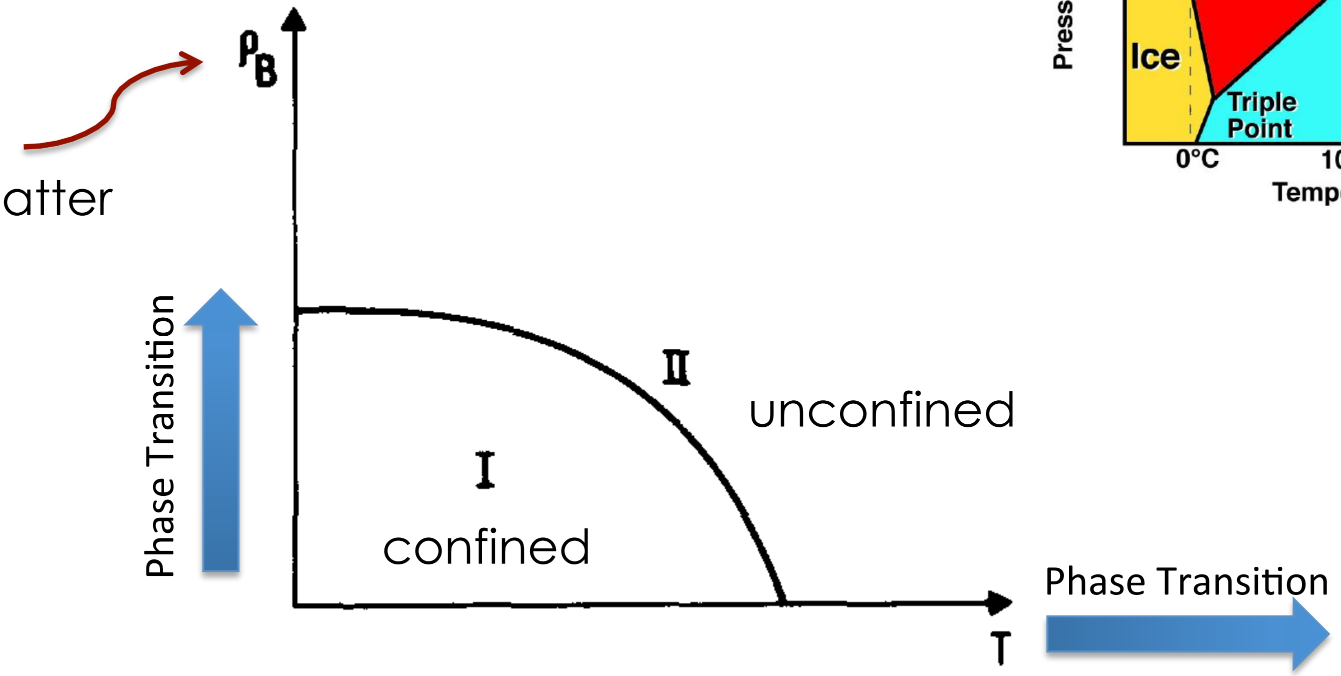


Matter in unusual conditions



QCD phase diagram





density of
baryonic matter

Phase Transition

confined

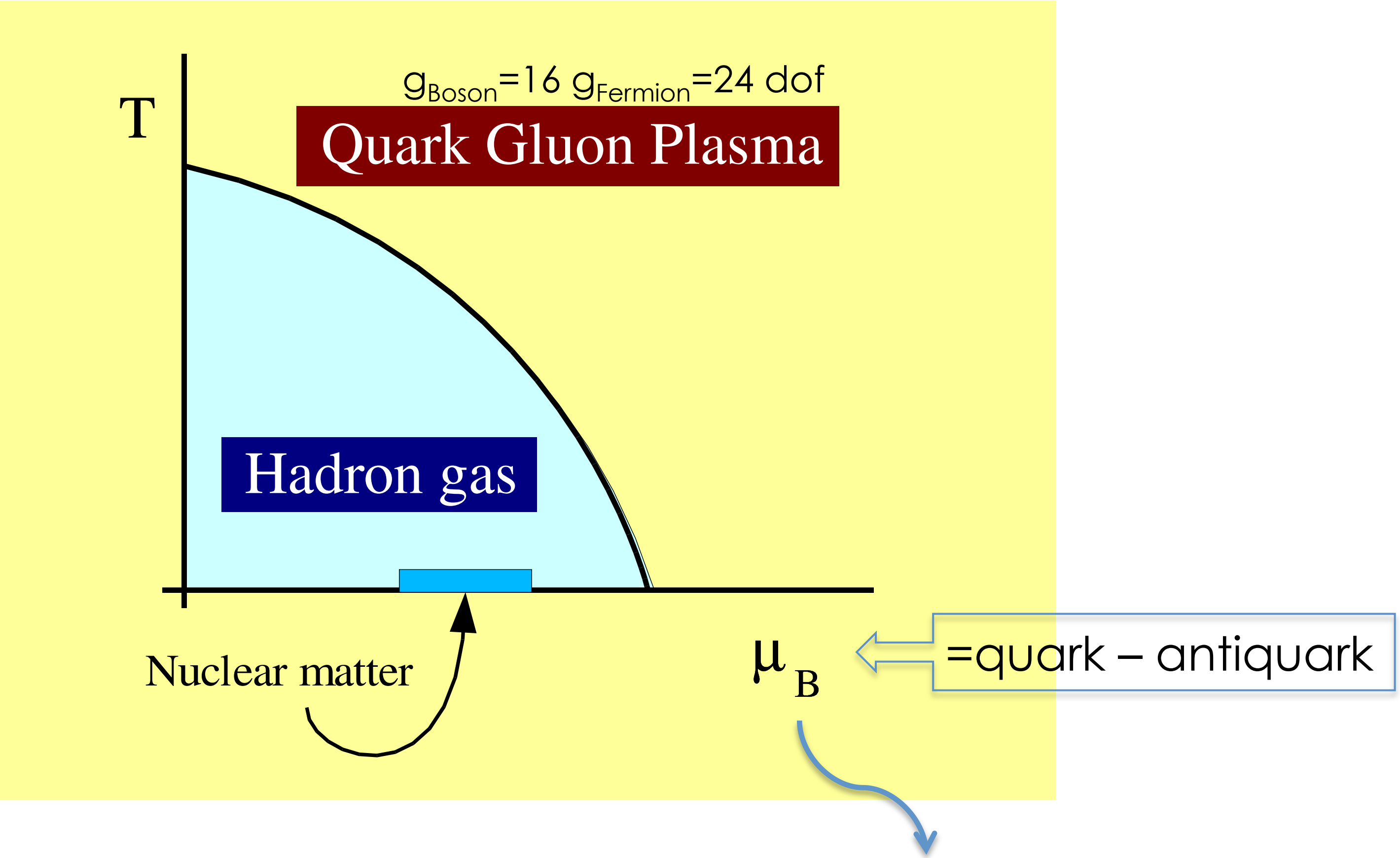
unconfined

Phase Transition

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Experimental hadronic spectrum and quark liberation
Cabibbo and Parisi, PLB59 (1975) 67

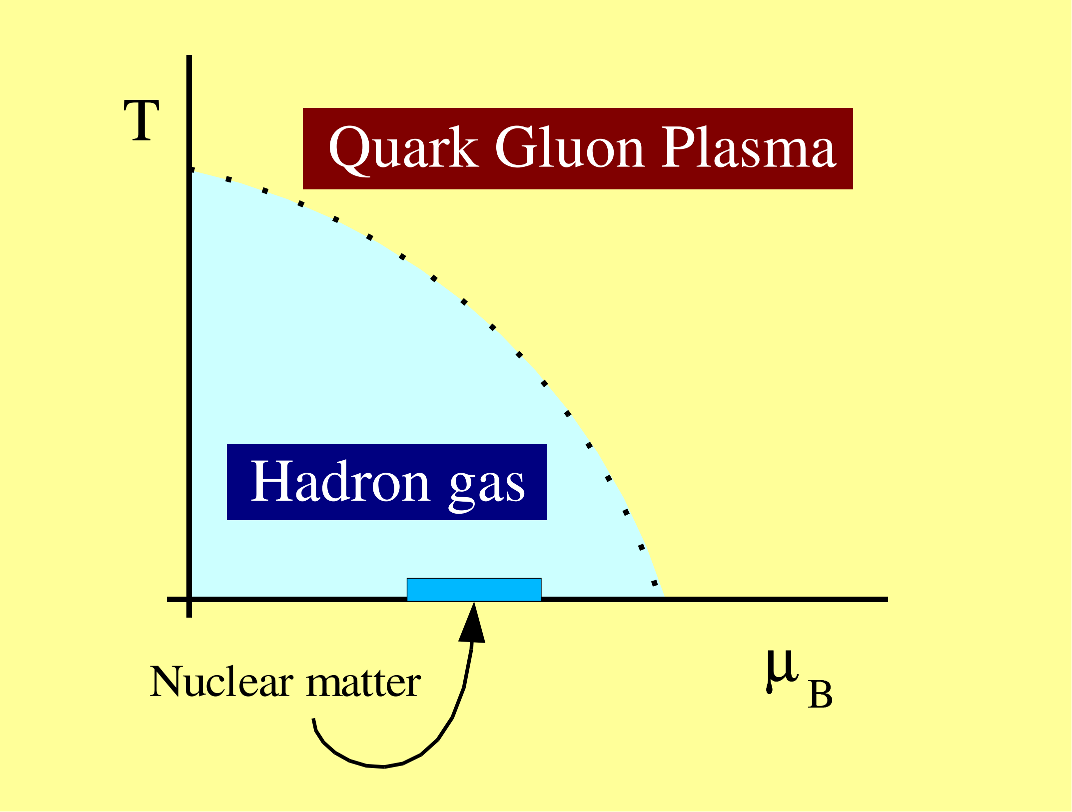
QCD phase diagram



Baryochemical potential

First order phase transition (lattice calculation)

QCD phase diagram

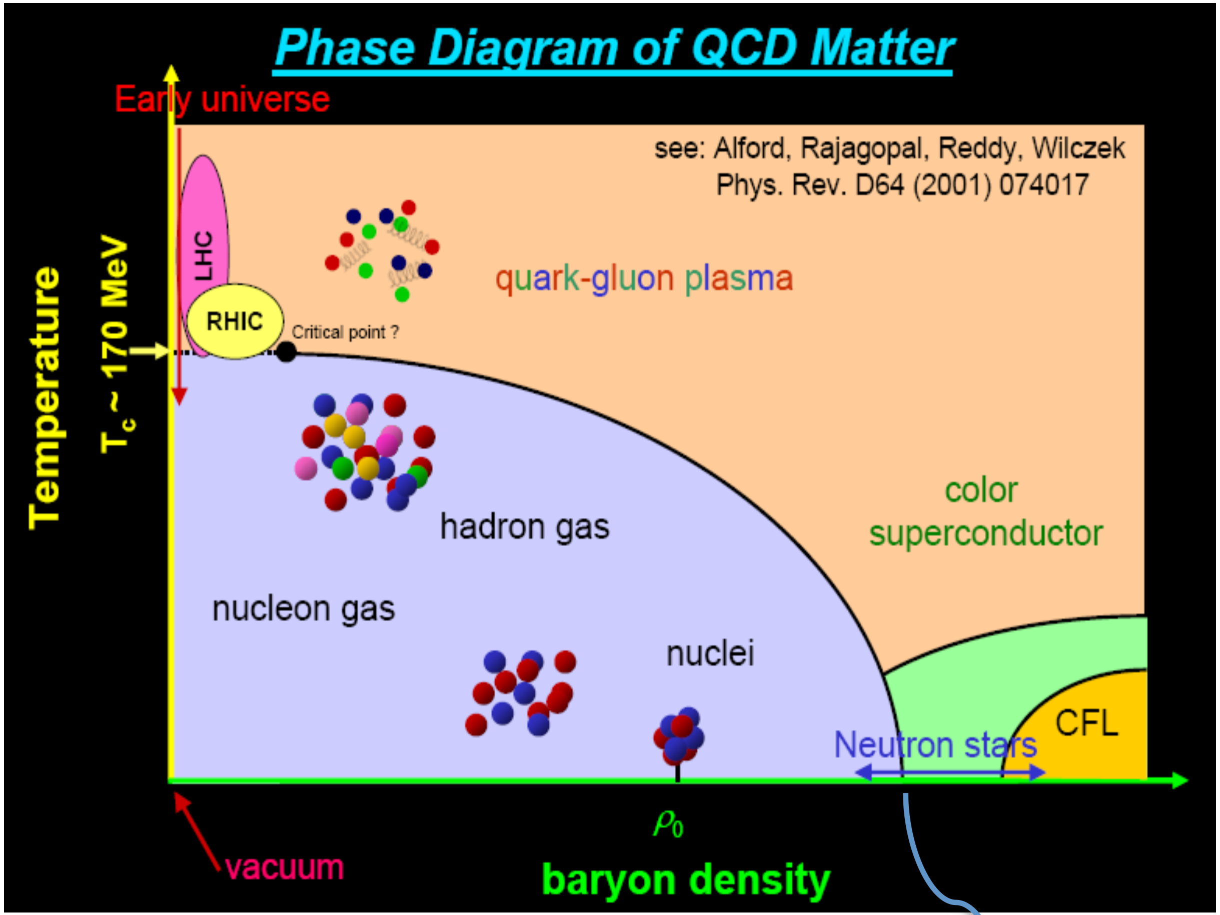


First order phase transition (lattice calculation)
Including quark masses (not at the first order)

QCD phase diagram

$T_c \approx 2 \cdot 10^{12}\mathrm{K}$

(10^5 times core of sun)



First order phase transition (lattice calculation)
Including quark masses (not at the first order)
Several different phases found (present status)

$$n_c^B \doteq 0.72\mathrm{fm}^{-3}$$

(net-baryon density of about 5 x nucleus)

T_{room}~300 K ~ 25 meV (milli-eV !)

Lattice QCD

The confinement cannot be described perturbatively.
At scales of the hadron size (~1fm) the perturbative methods lose validity.

QCD can be solved numerically by putting fields on a space-time lattice. It is a rigorous way of doing calculations in non-perturbative regime of QCD.

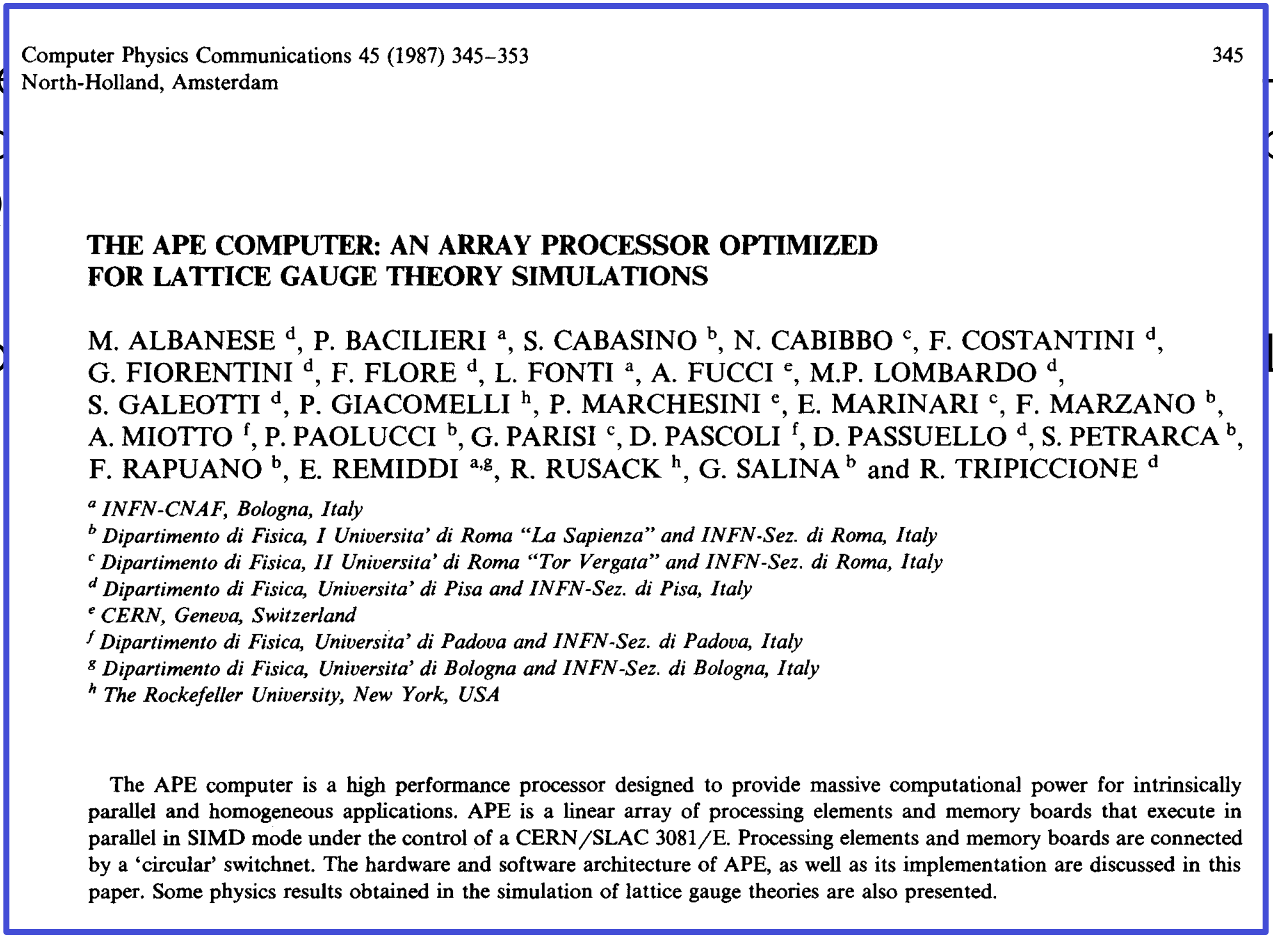
Computationally demanding: farm with 300.000 cores, petaFLOPS

Lattice QCD

The confinement cannot be described perturbatively.
At scales of the hadron size (~1fm) the perturbative methods lose validity.

QCD can b … time
lattice. It is c … bative
regime of Q

Computatio … LOPS



Computer Physics Communications 45 (1987) 345–353
North-Holland, Amsterdam

THE APE COMPUTER: AN ARRAY PROCESSOR OPTIMIZED FOR LATTICE GAUGE THEORY SIMULATIONS

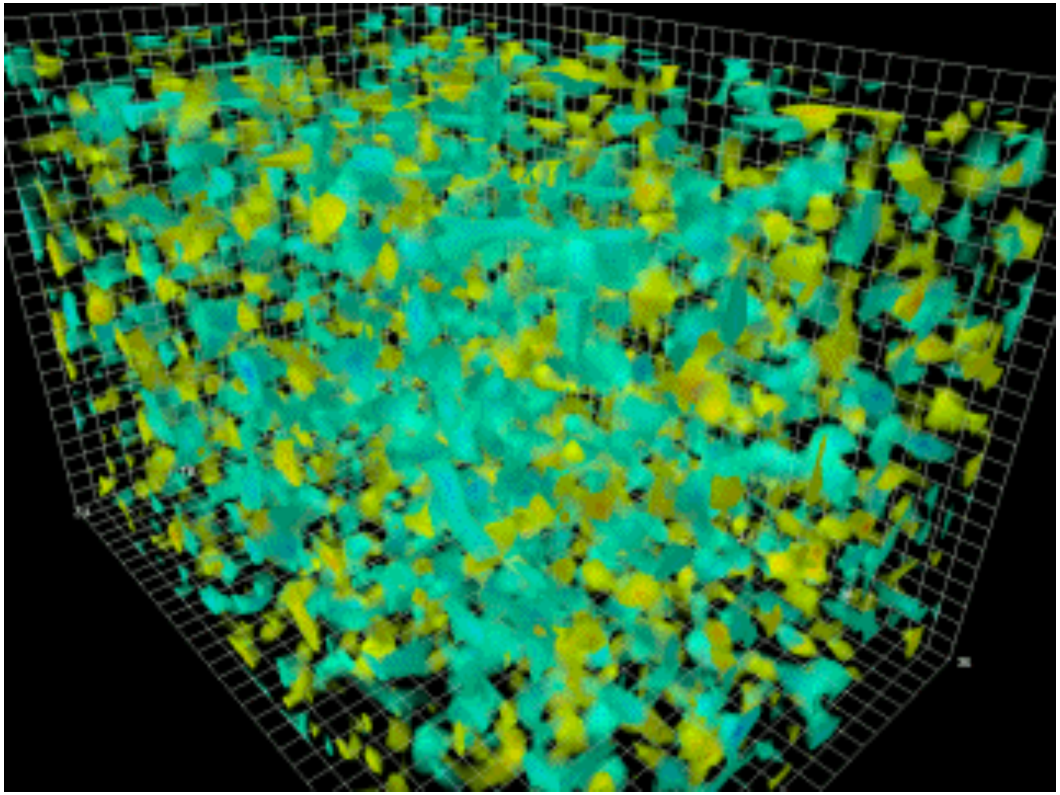
M. ALBANESE [d], P. BACILIERI [a], S. CABASINO [b], N. CABIBBO [c], F. COSTANTINI [d], G. FIORENTINI [d], F. FLORE [d], L. FONTI [a], A. FUCCI [e], M.P. LOMBARDO [d], S. GALEOTTI [d], P. GIACOMELLI [h], P. MARCHESINI [e], E. MARINARI [c], F. MARZANO [b], A. MIOTTO [f], P. PAOLUCCI [b], G. PARISI [c], D. PASCOLI [f], D. PASSUELLO [d], S. PETRARCA [b], F. RAPUANO [b], E. REMIDDI [a,g], R. RUSACK [h], G. SALINA [b] and R. TRIPICCIONE [d]

[a] *INFN-CNAF, Bologna, Italy*
[b] *Dipartimento di Fisica, I Universita' di Roma "La Sapienza" and INFN-Sez. di Roma, Italy*
[c] *Dipartimento di Fisica, II Universita' di Roma "Tor Vergata" and INFN-Sez. di Roma, Italy*
[d] *Dipartimento di Fisica, Universita' di Pisa and INFN-Sez. di Pisa, Italy*
[e] *CERN, Geneva, Switzerland*
[f] *Dipartimento di Fisica, Universita' di Padova and INFN-Sez. di Padova, Italy*
[g] *Dipartimento di Fisica, Universita' di Bologna and INFN-Sez. di Bologna, Italy*
[h] *The Rockefeller University, New York, USA*

The APE computer is a high performance processor designed to provide massive computational power for intrinsically parallel and homogeneous applications. APE is a linear array of processing elements and memory boards that execute in parallel in SIMD mode under the control of a CERN/SLAC 3081/E. Processing elements and memory boards are connected by a 'circular' switchnet. The hardware and software architecture of APE, as well as its implementation are discussed in this paper. Some physics results obtained in the simulation of lattice gauge theories are also presented.

Lattice QCD

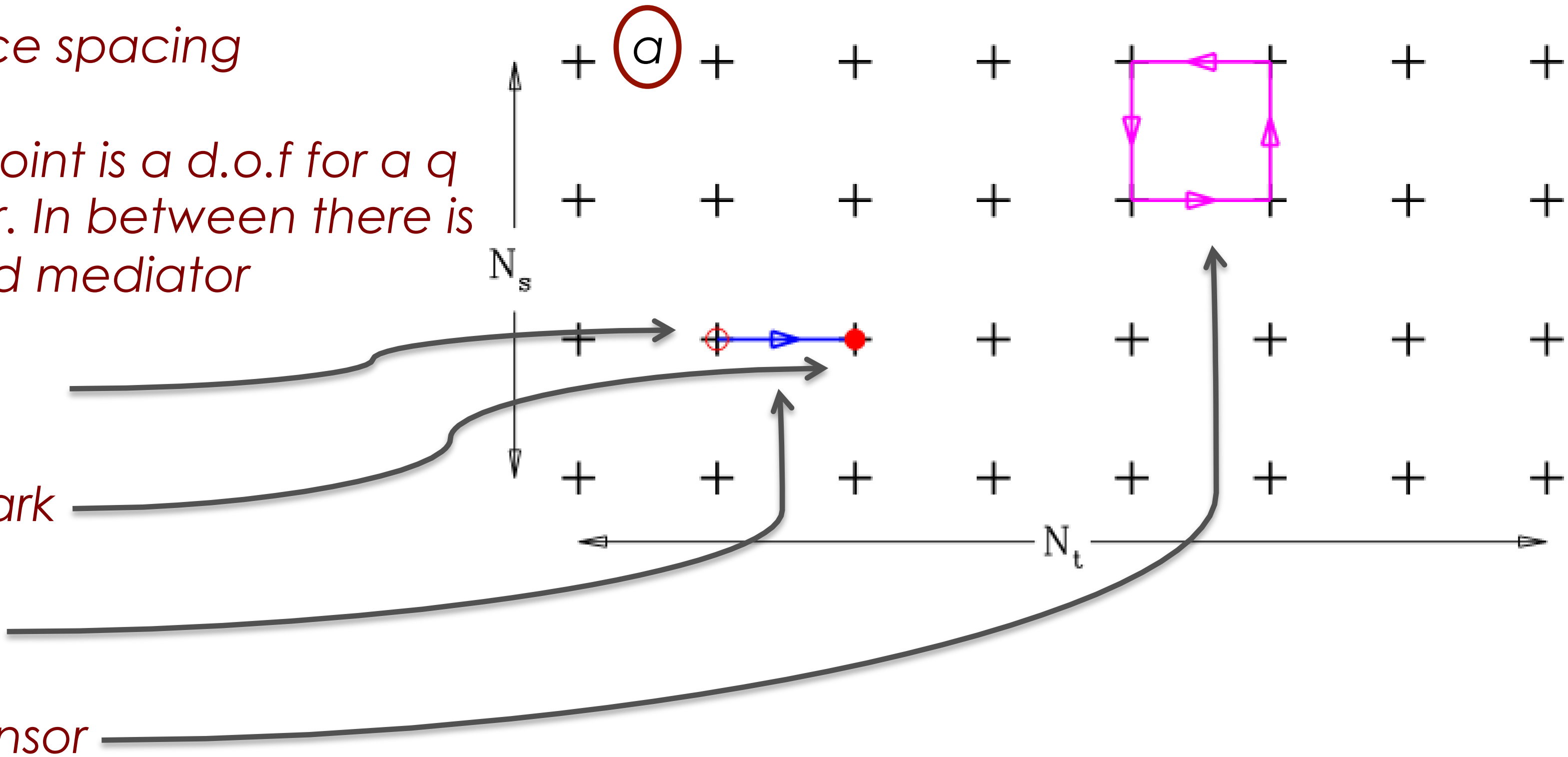
Snapshot of fluctuating quark and gluon fields on a discrete space-time lattice



Fluctuating quark and gluon fields on a discrete space-time lattice

Lattice QCD

We discretize the space-time and, on this lattice, we solve the QCD equations



a=lattice spacing

Each point is a d.o.f for a q or qbar. In between there is the field mediator

quark

antiquark

gluon

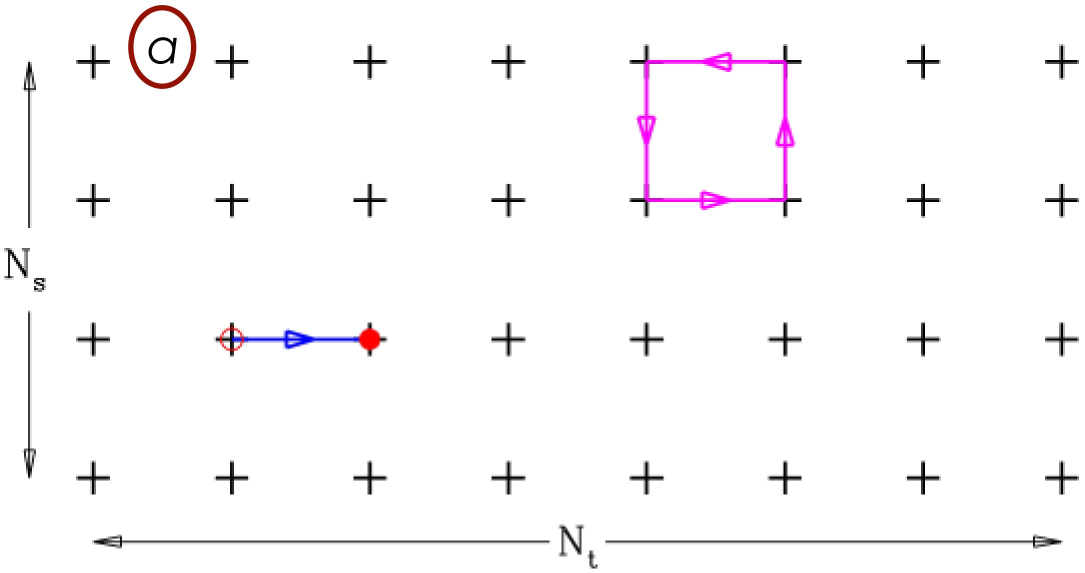
field tensor

Lattice QCD

We discretize the space-time and, on this lattice, we solve the QCD equations

a=lattice spacing

Each point is a d.o.f for a q or qbar. In between there is the field mediator.



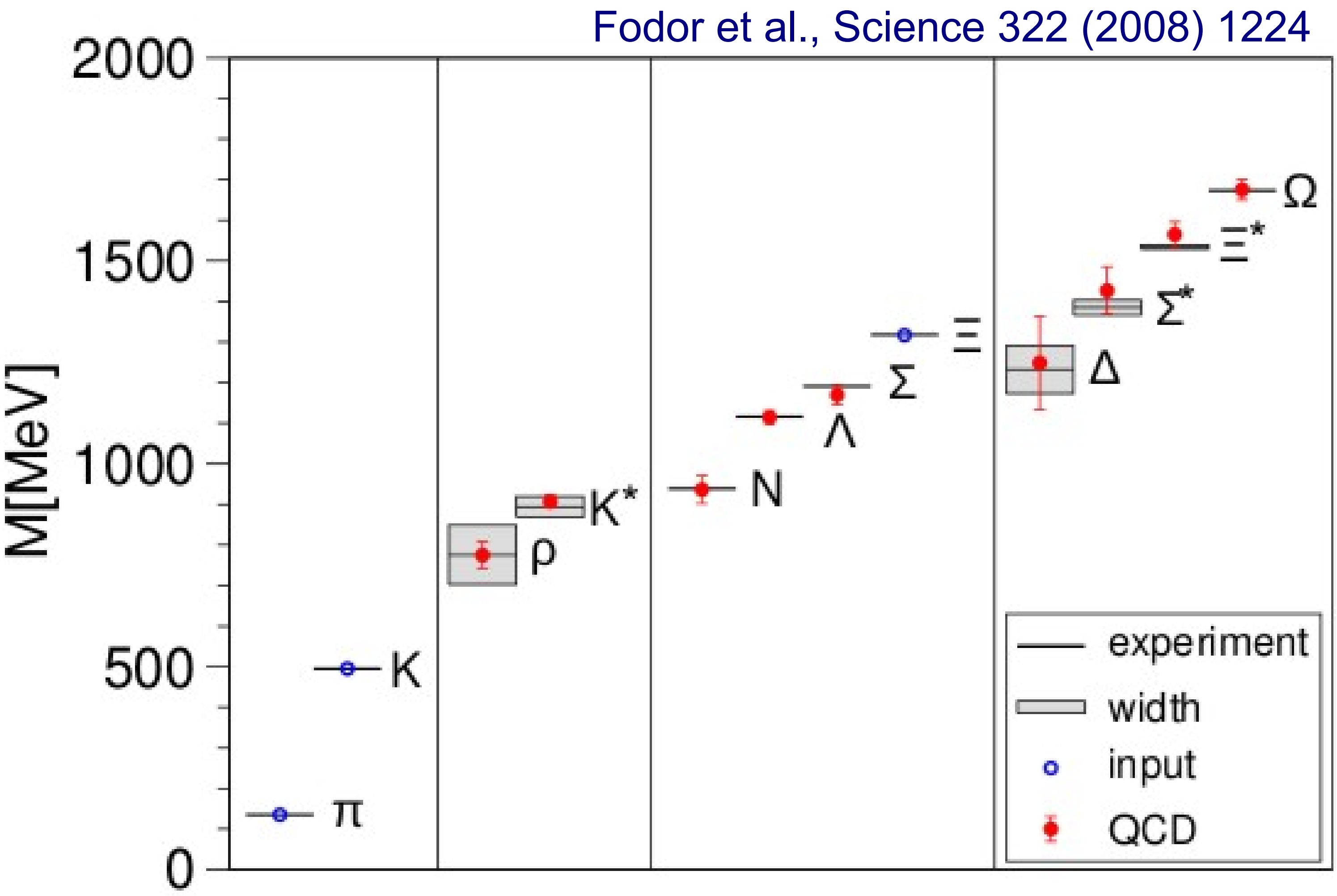
In order to go back from the lattice to the real physics we have to apply the:

- *Continuum limit $a \to 0$, infinite momenta*
- *Infinite volume limit $V \to \infty$*
- Set scales using data (e.g. hadron masses)

Problems of approach:

- 2xfermions then the real world
- Small masses ask huge CPU time, large masses are needed.
- Very difficult for finite μ

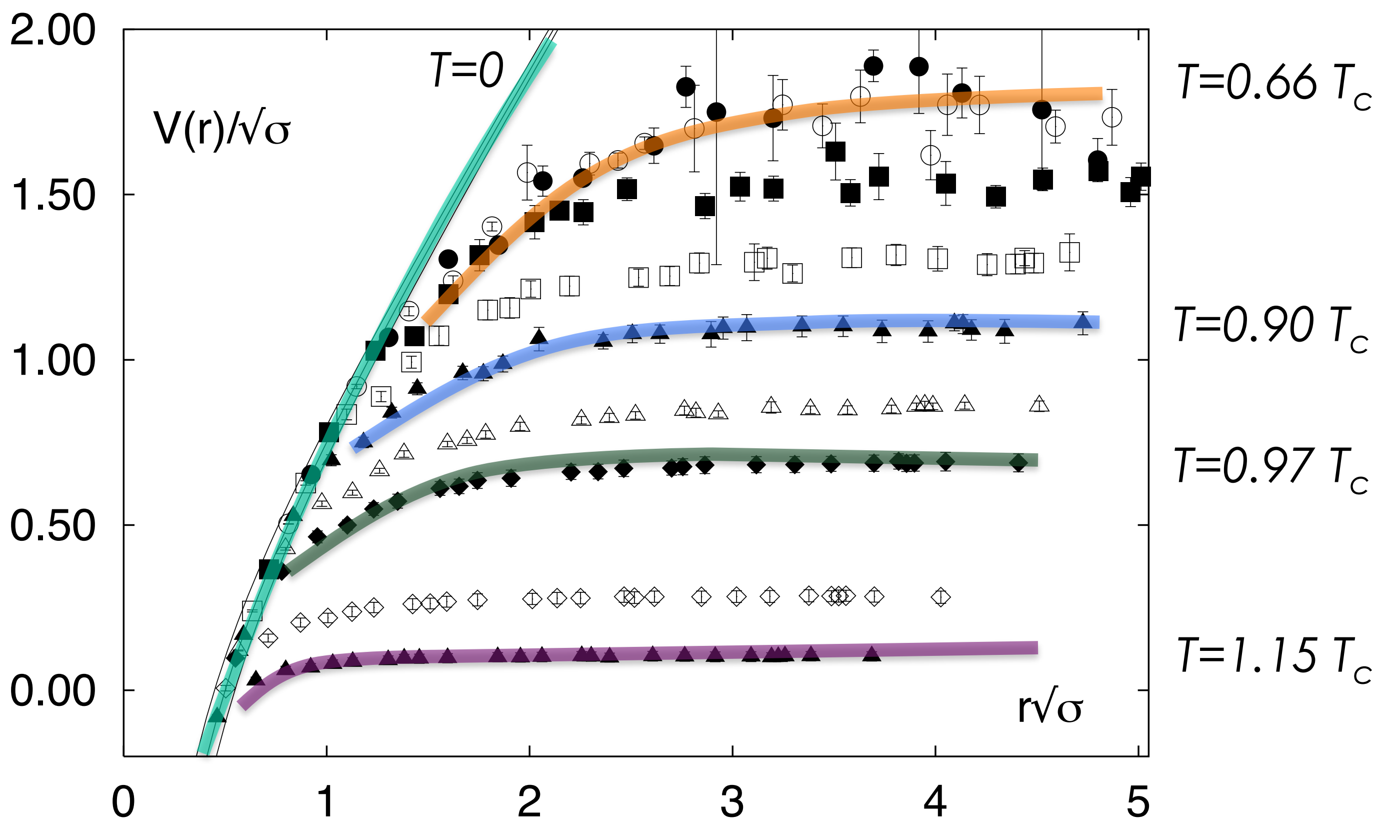
Lattice QCD

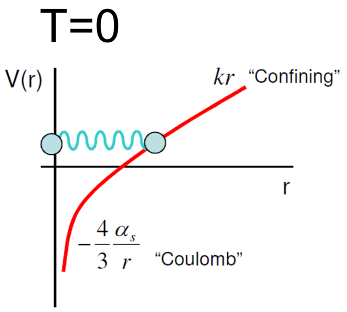


Excellent agreement between Lattice (2 flavors) and experimental data

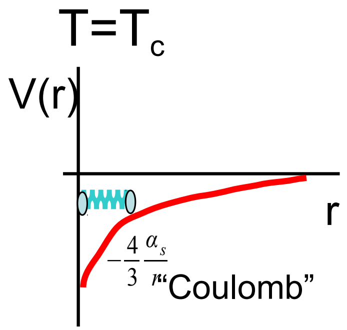
Lattice QCD

Temperature dependence of the heavy quark free energy (static potential) in 3-flavour QCD





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

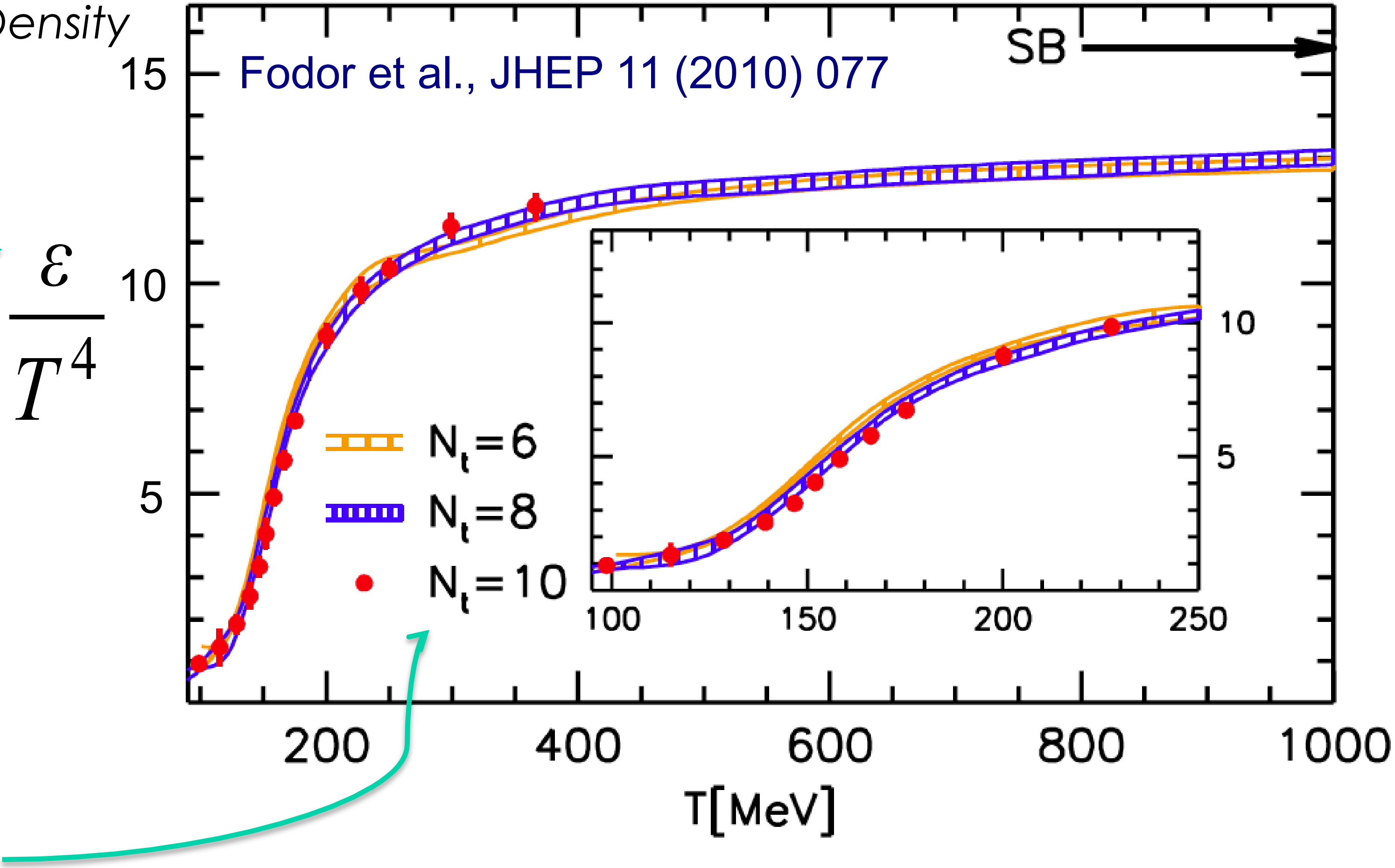


Increasing T there is the creation of spontaneous qqbar-pairs in the "heat bath"
→ exhibits screening of long range confining potential with increasing temperature

"Quasi free interaction"

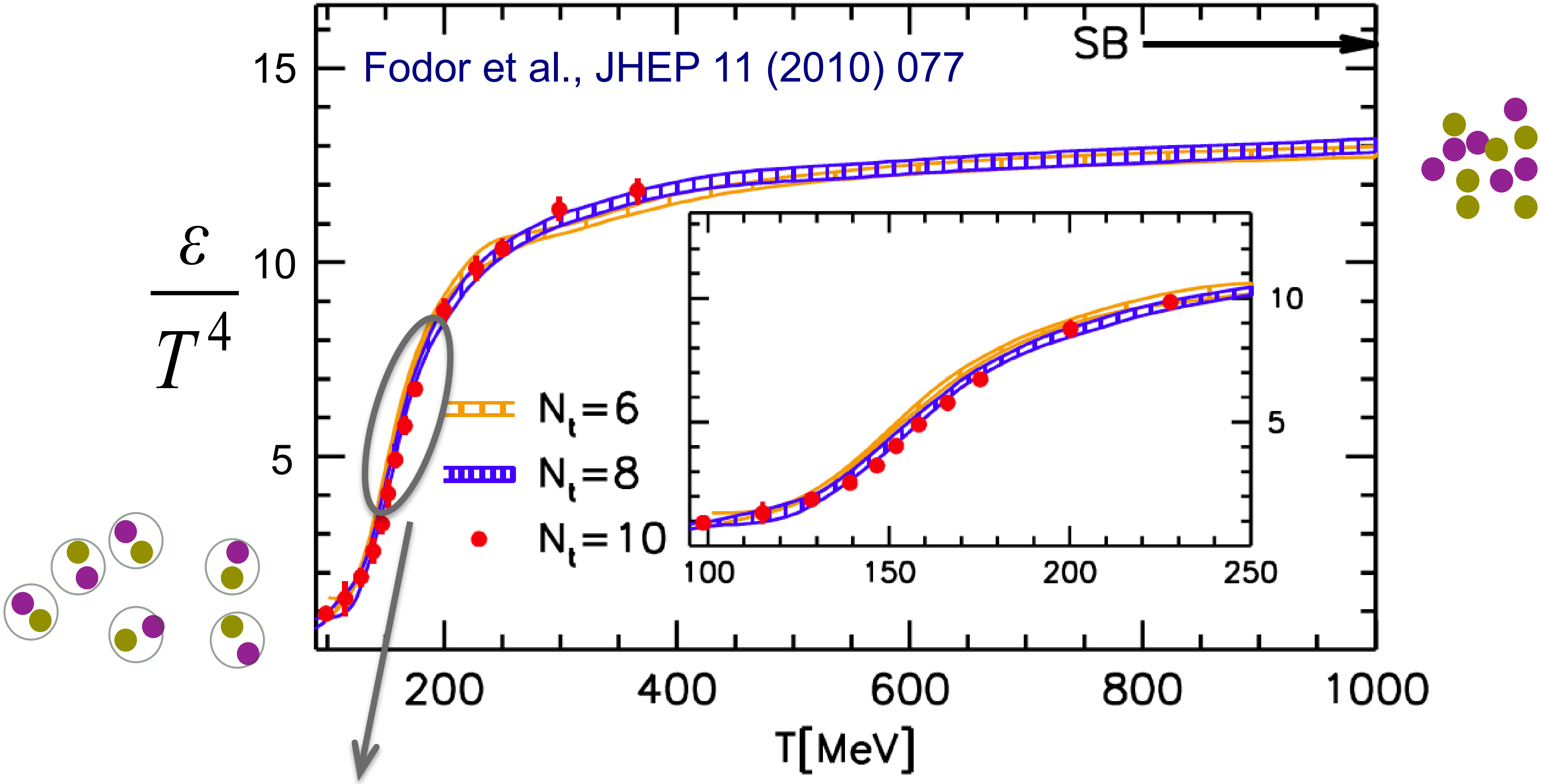
Lattice QCD

Energy Density


Fodor et al., JHEP 11 (2010) 077

Temporal extension (space-time at large volume)

Lattice QCD



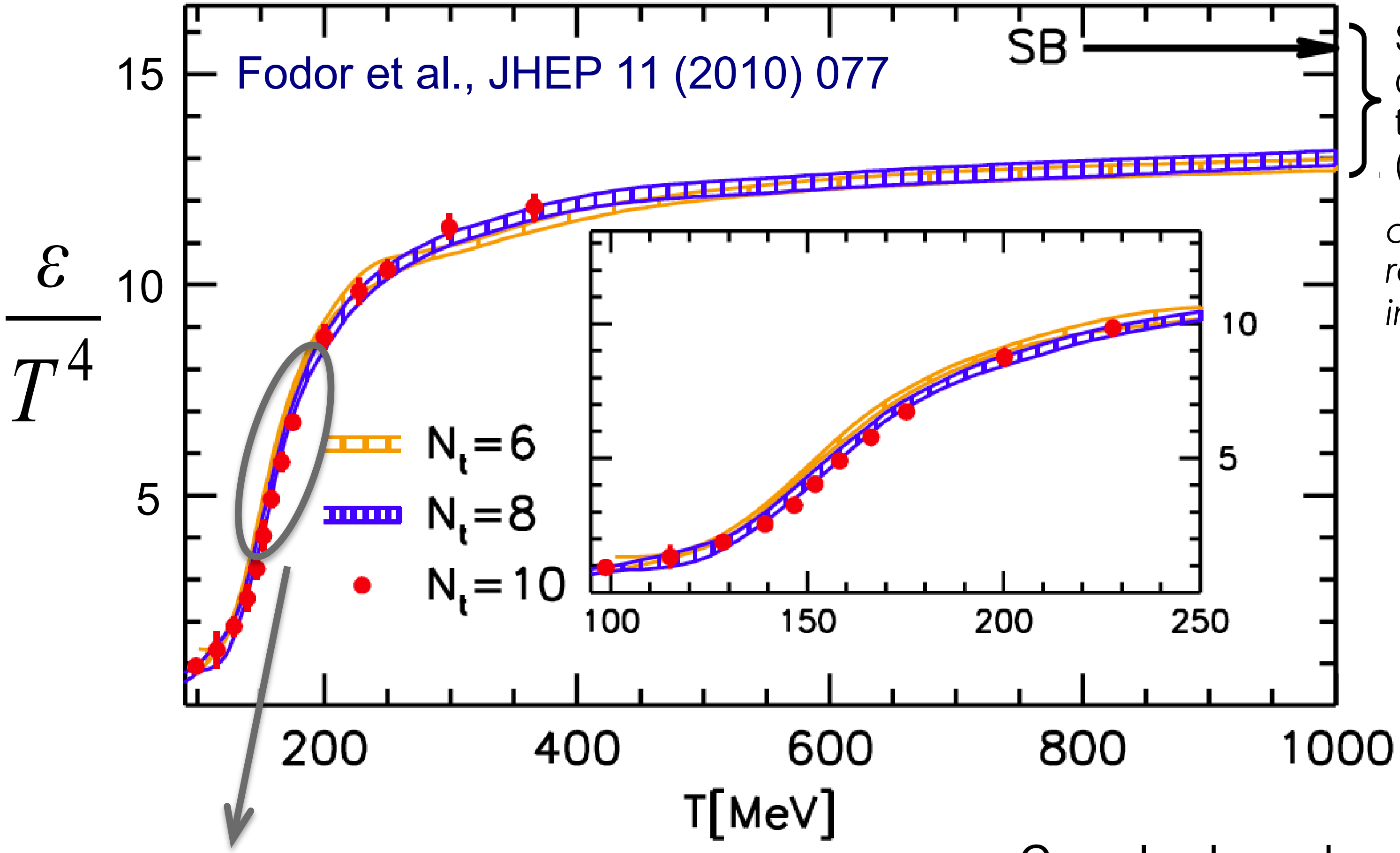
Fodor et al., JHEP 11 (2010) 077

(not sharp) Transition temperature

(T_C~170 MeV, ε_C~1 GeV/fm^3)

Lattice QCD

Stefan-Boltzman limit



Slow convergence to ideal gas (SB) limit

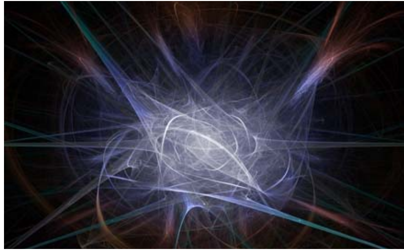
qqbar residual interaction

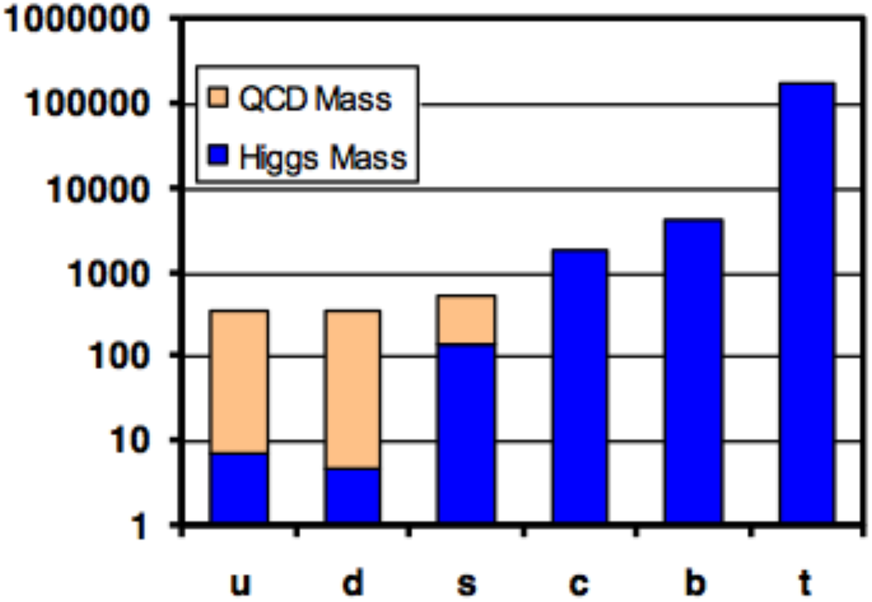
(not sharp) Transition temperature

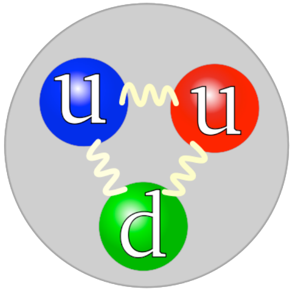
(T_C~170 MeV, ε_C~1 GeV/fm^3)

Complex bound states of q and g? Strongly coupled plasma?

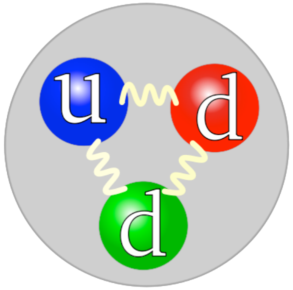
Chiral symmetry





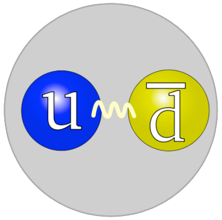


proton



neutron

source: http://de.wikipedia.org



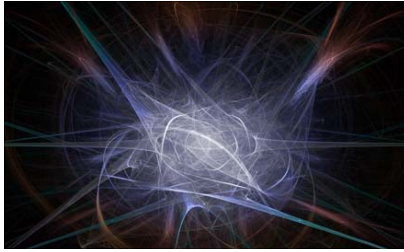
positive pion

$2\,m_u + m_d = 9.6\ \mathrm{MeV}/c^2$

$m_{\mathrm{proton}} = 938.27\ \mathrm{MeV}/c^2$!!!

- Hadron mass scale set by constituent quarks masses ($m_{u,d,\mathrm{const}} \approx 300\ \mathrm{MeV}/c^2$)
- QCD responsible for 99% of the mass of your body!
- Related to breaking of chiral symmetry

Chiral symmetry



In the absence of quark mass the QCD Lagrangian splits into two independent quark terms:

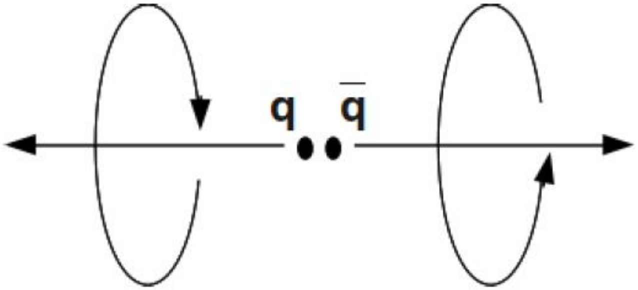
$$\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{gluons}} + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R$$

For two flavors (i=u,d) the Lagrangian is symmetric under $SU(2)_L \times SU(2)_R$

Symmetry NOT observed → solution: the vacuum is not invariant.
The "empty" vacuum is unstable. There is a state of lower energy that consists of cells, each containing a gluon pair → "Liquid" vacuum

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0$$ Chiral condensate

Chiral symmetry: Fermions and anti-fermions have opposite helicity



Σp = 0 ΣL = 0
→ chirality != 0

Spontaneous symmetry breaking
(pseudo-goldstone bosons: pions)

Restoration of bare masses

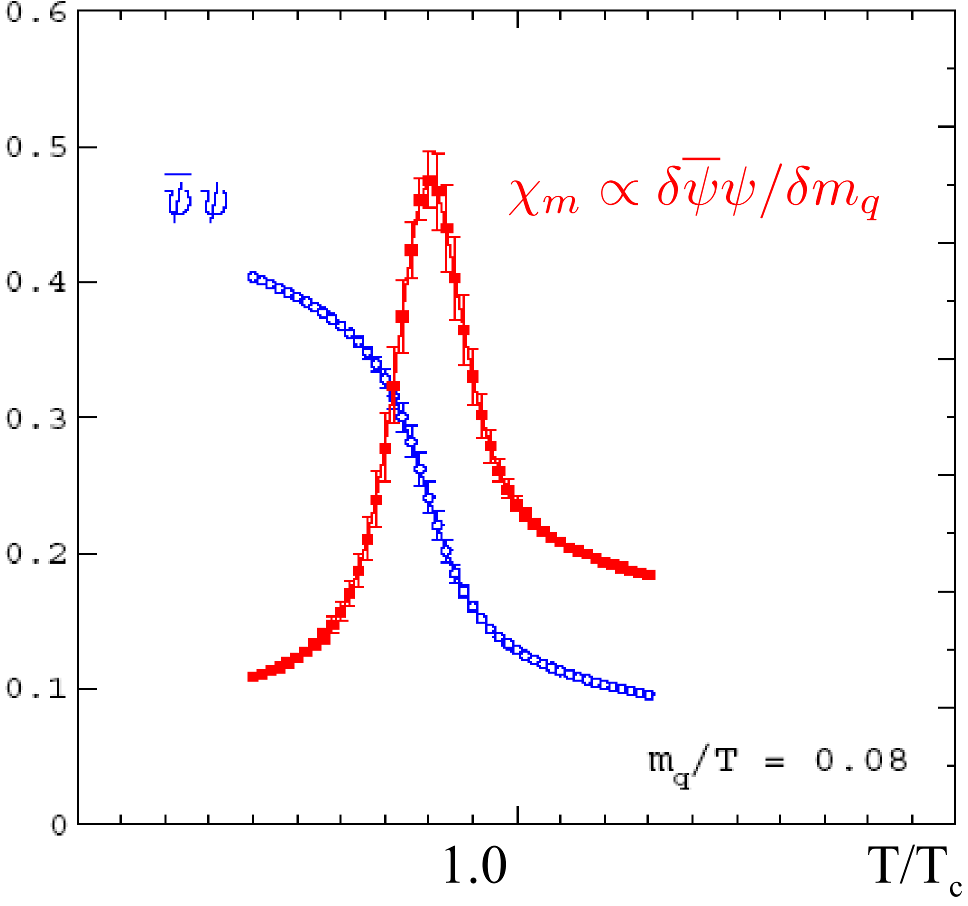
Quarks have very small masses generated by the coupling to Higgs (light q< 10 MeV)

Confined quarks (i.e. in the proton) require ~350 MeV generated dynamically through the confining effects of the strong interaction

Deconfinement must be accompanied by a restoration of the masses to the bare mass values they have in the Lagrangian:

- *m(u,d): ~350 MeV → few MeV*
- *m(s): ~500 MeV → 150 MeV*

Partial restoration of chiral symmetry computed on lattice*



**Partial because* the symmetry is exact only for massless particles, therefore its restoration here is only partial

Satz, arXiv:0803.1611

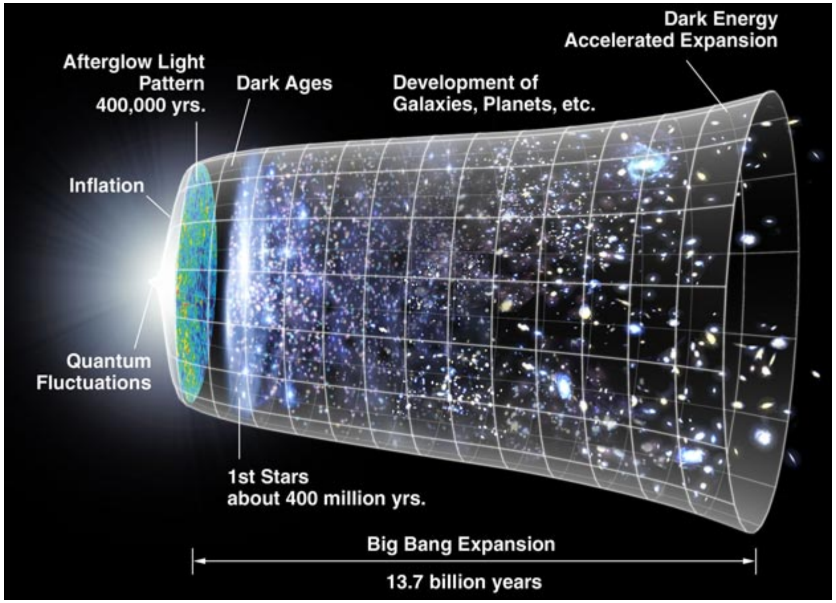
QCD , a successful theory with some fundamental problem

Is there a regime were the symmetry is restored?

QCD phase transition

Where?

At the Big Bang
we think that in the first instants of life of the Universe, quarks and gluons were not trapped inside hadrons (protons, neutrons, …) but could move freely in a "deconfined" state: the Quark-Gluon Plasma



10 μs: the birth of hadrons
after about 10 μs from the Big Bang, the Universe cooled down to less than 2 x 10^{12} degrees

at that point, the QCD phase transition took place: quarks and gluons were confined inside hadrons

the familiar particles, such as pions, kaons, protons and neutrons appeared on the stage of the Universe

… and
-in the core of the neutron stars
-in the heavy-ion collision experiments

Phase transitions of the Universe

The early Universe (Kolb, Turner)
Schwarz, astro-ph/0303574

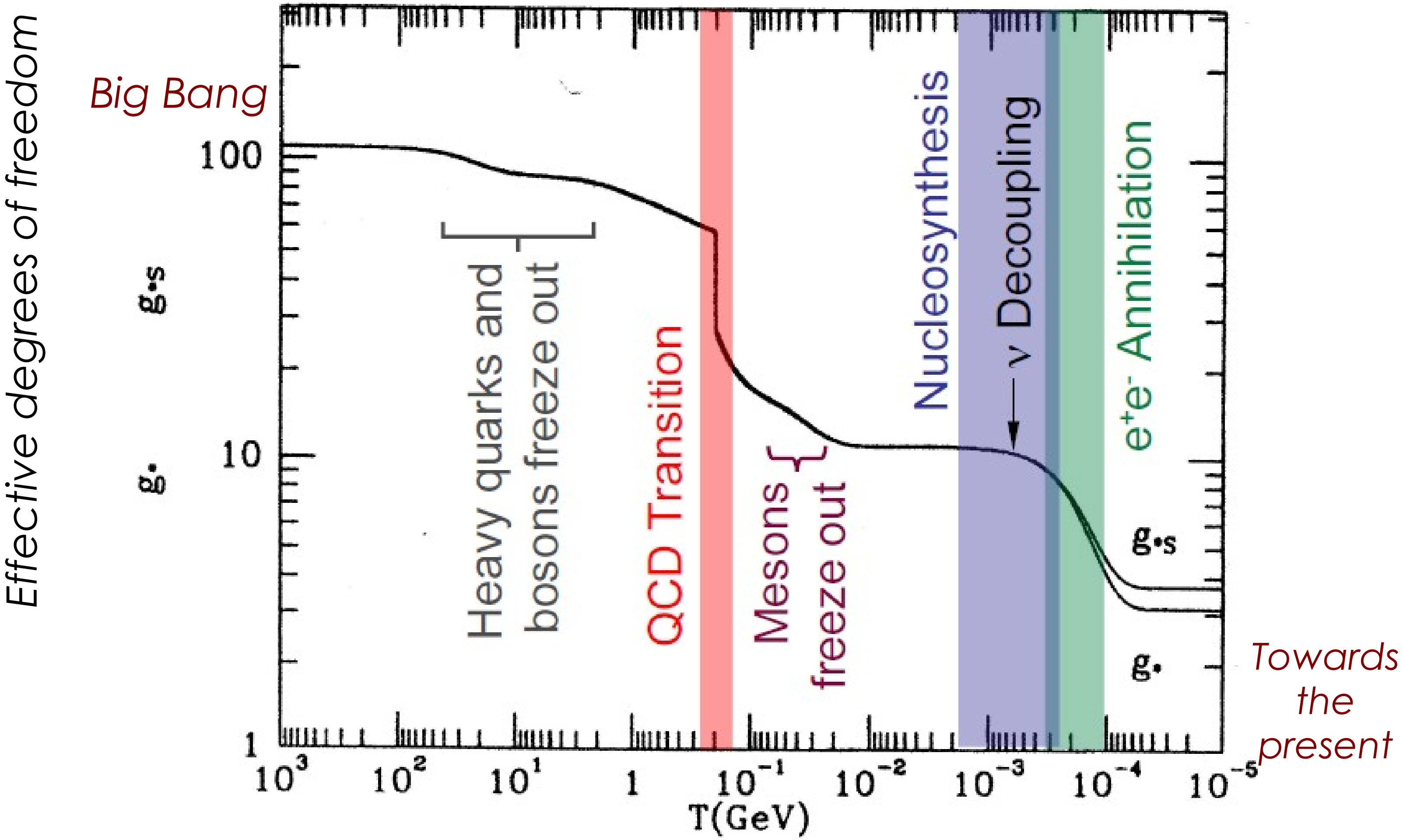


Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.

T.D.Lee,
Rev.Mod.Phys. 47 (1975) 267

In high energy physics we have concentrated on experiments, in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of “vacuum”, we must turn to a different direction; we should investigate some “bulk” phenomena by distributing high energy over a relatively large volume.

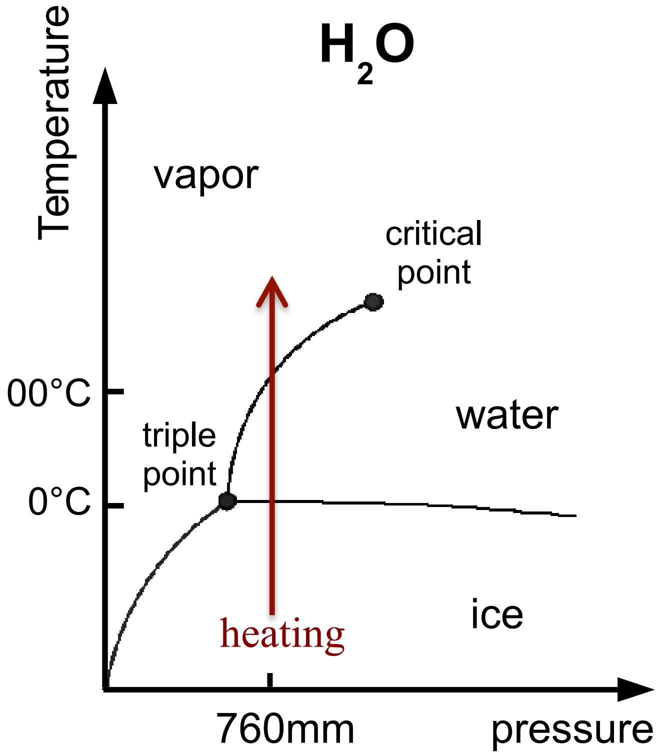
Nucleus-Nucleus Collisions

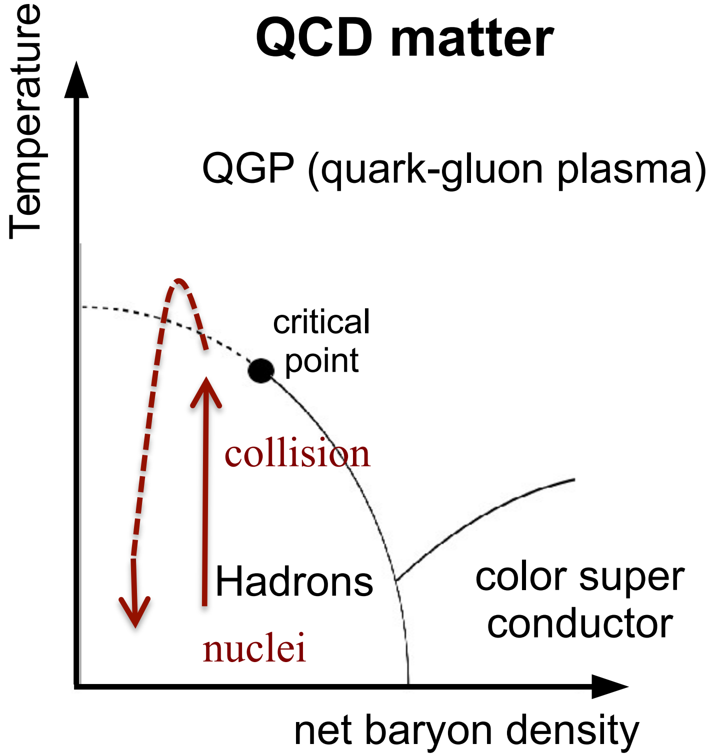
- We need a small system so that it can be accelerated to ultrarelativistic speed (99.9% c)

- That system (i.e. a chunk of matter and not just a single particle) must follow simple rules of thermodynamics and form a new state of matter in a particular phase

- We can use heavy ions (e.g. Pb). They are tiny (~10^{-14} m) and have a finite volume that can be exposed to pressure and temperature (the system is more than 1 order of magnitude larger than the pp)

Nucleus-Nucleus Collisions



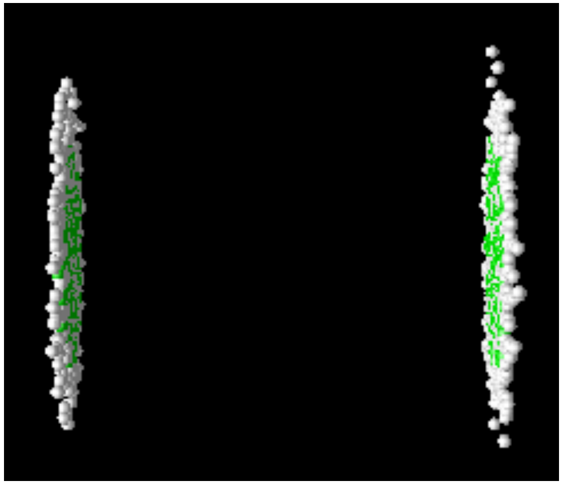


A strong and critic difference is the time scale evolution of the system

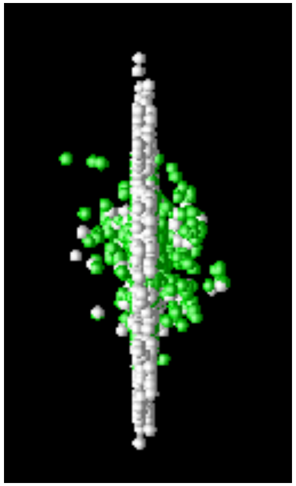
We need Heavy-Ions

2 nuclei colliding at very high energy

Colliding Heavy Ions

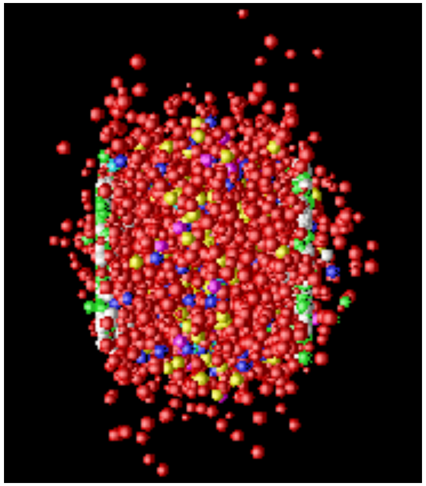


Lorentz-contracted nuclei ($\Delta z \sim R/\gamma$)



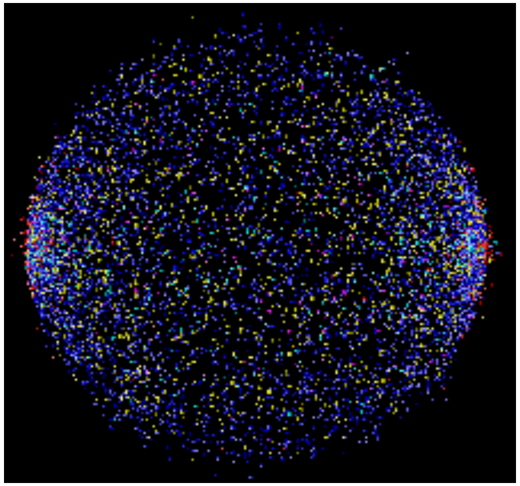
Hard Collisions

pQCD



Parton Dynamics

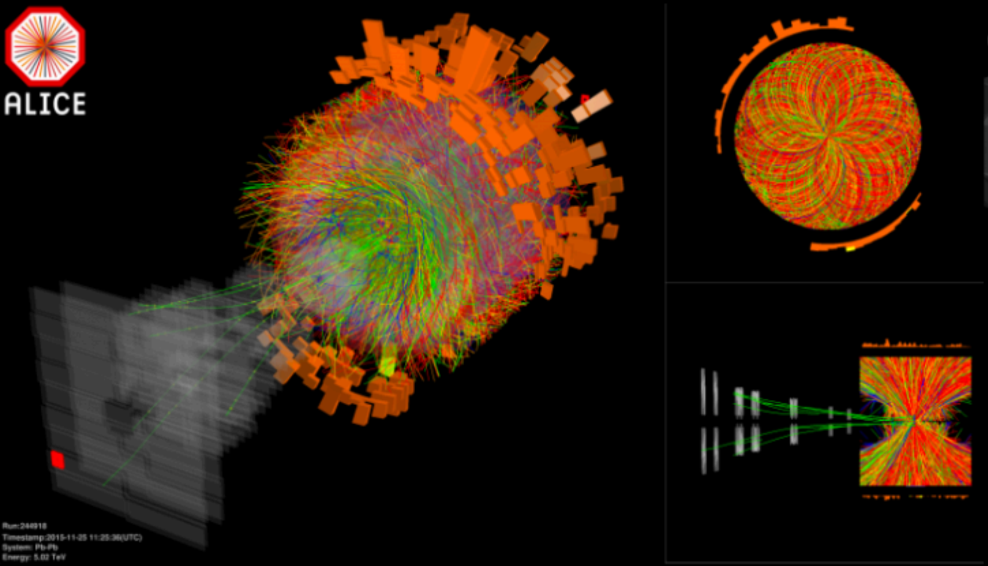
QCD Matter quarks and gluons are the relevant degrees of freedom



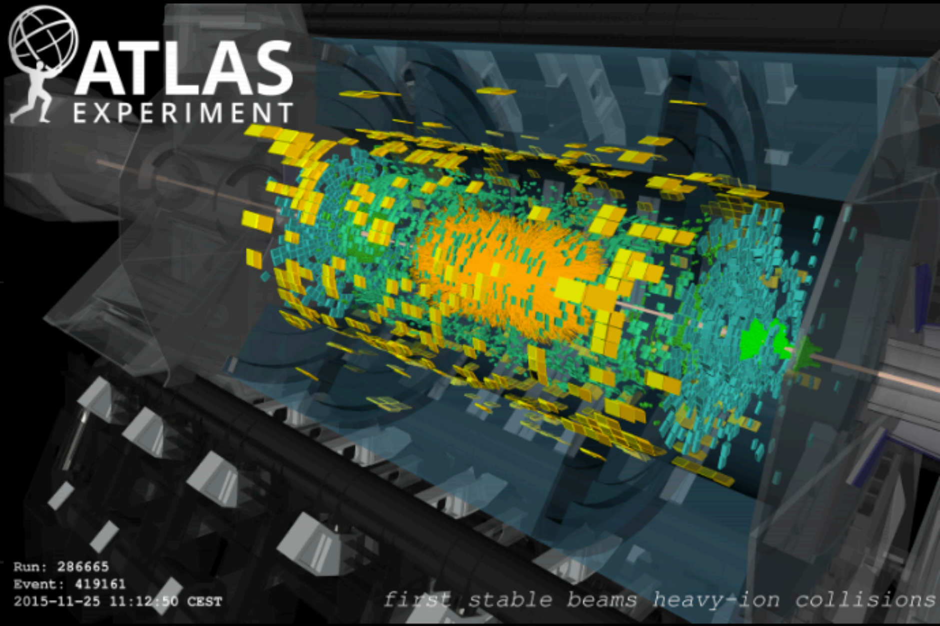
Hadron Dynamics

Mesons and Baryons are always the final degrees of freedom

Simulation “VNI” (Geiger, Longacre, Srivastava)

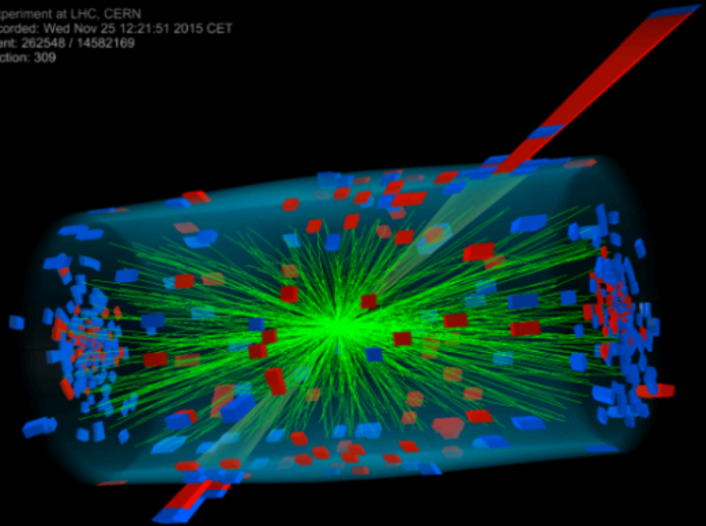


Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

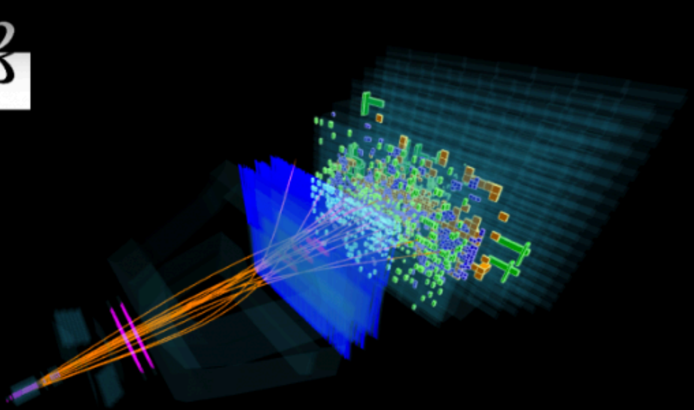


Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST

first stable beams heavy-ion collisions



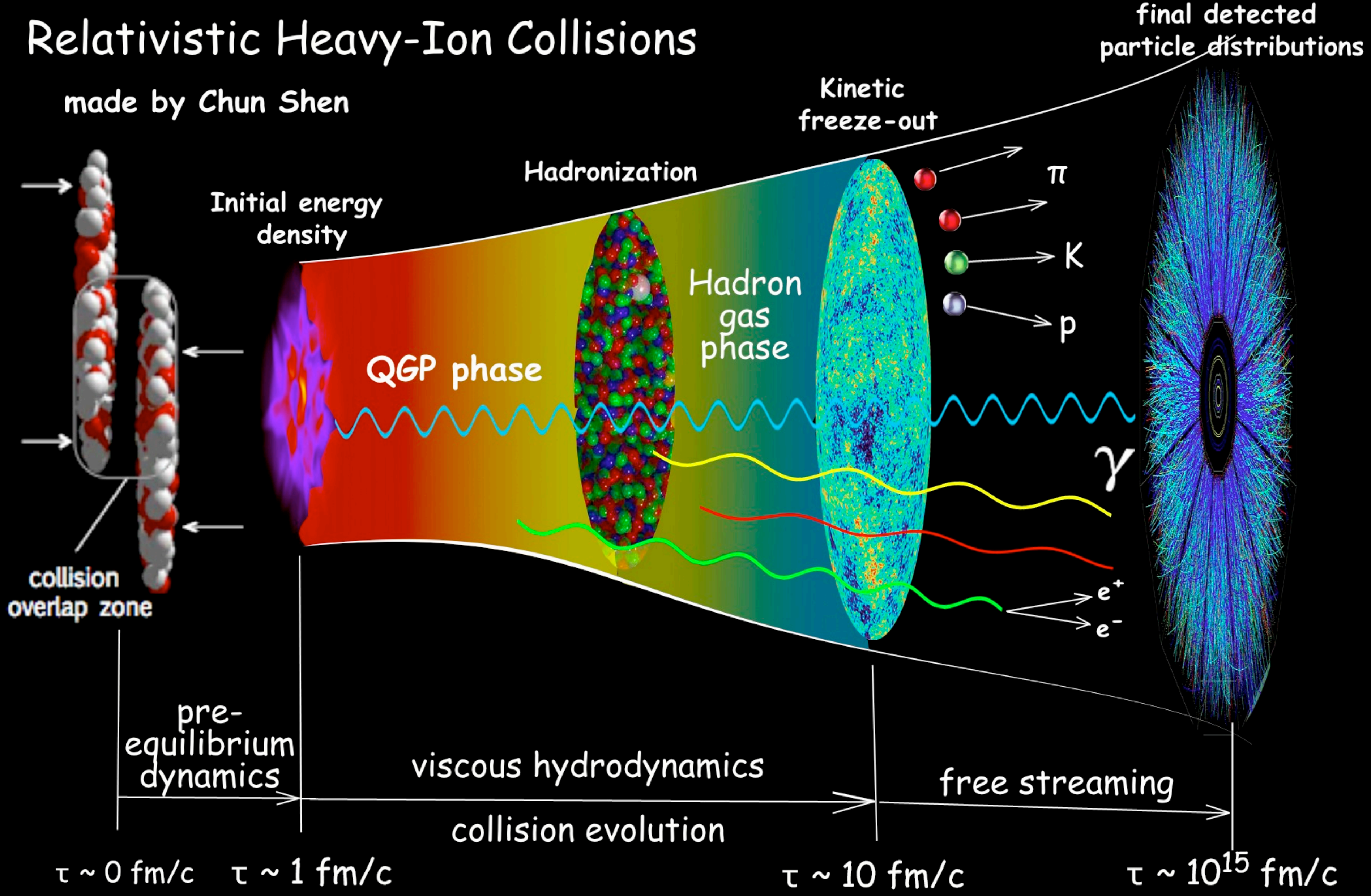
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309



Event 2598326
Run 168486
Wed, 25 Nov 2015 12:51:53

Relativistic Heavy-Ion Collisions

made by Chun Shen



final detected particle distributions

Kinetic freeze-out

Hadronization

Initial energy density

QGP phase

Hadron gas phase

π

K

p

γ

e^+

e^-

collision overlap zone

pre-equilibrium dynamics

viscous hydrodynamics

free streaming

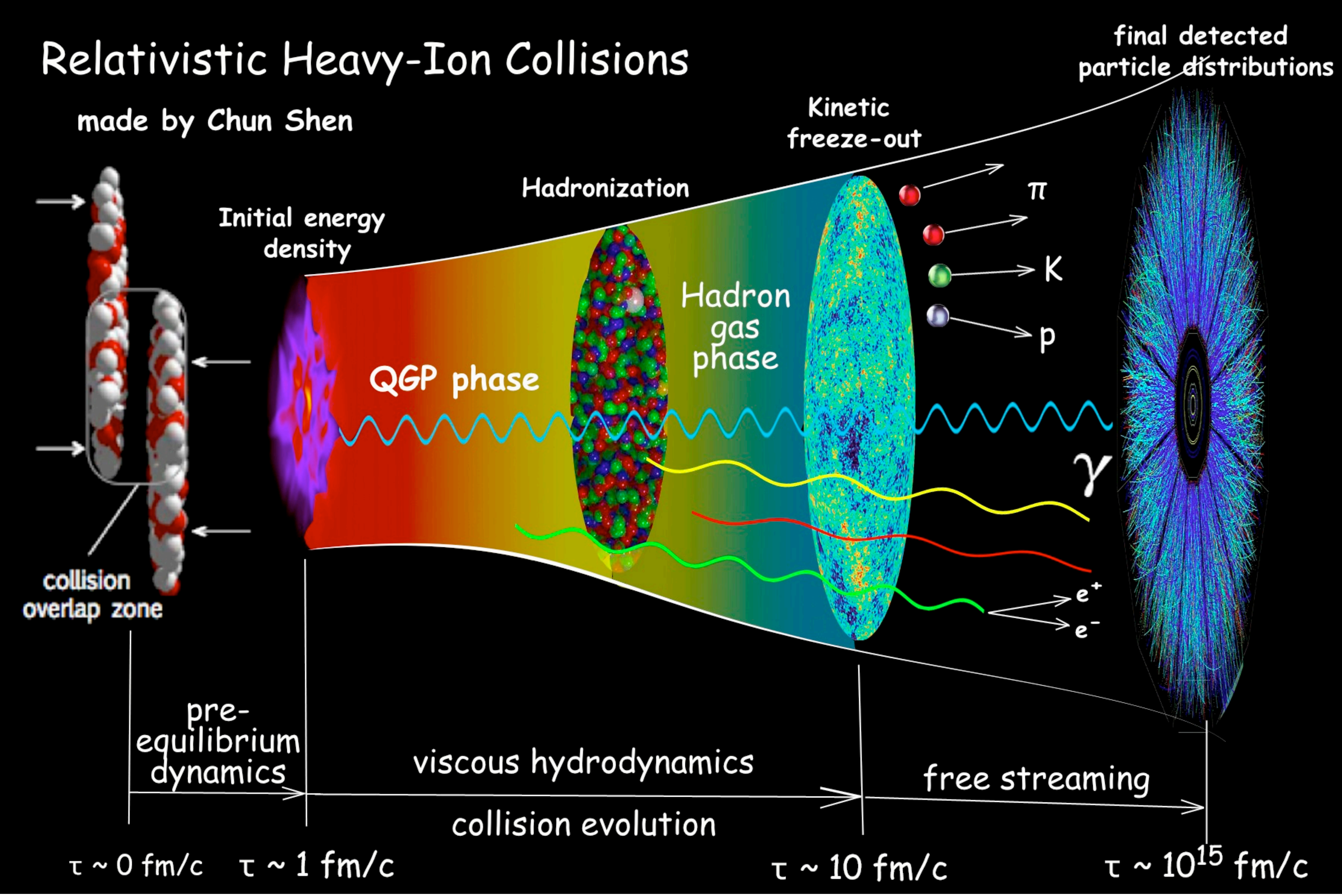
collision evolution

τ ~ 0 fm/c

τ ~ 1 fm/c

τ ~ 10 fm/c

τ ~ 10^{15} fm/c

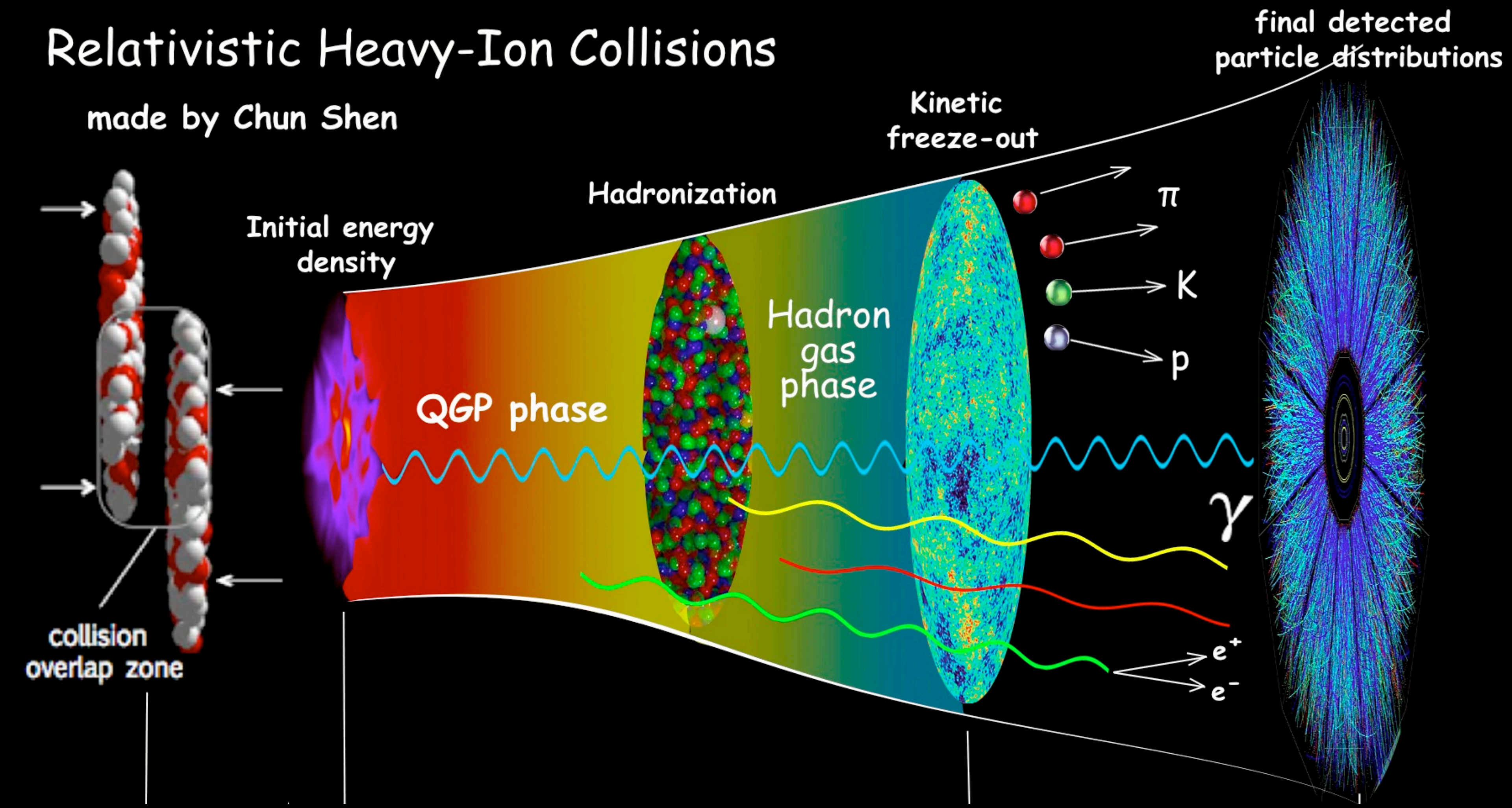


Hydrodynamic evolution (t~0.5 fm/c)

Chemical freeze-out

Kinetic freeze-out

Particle detection

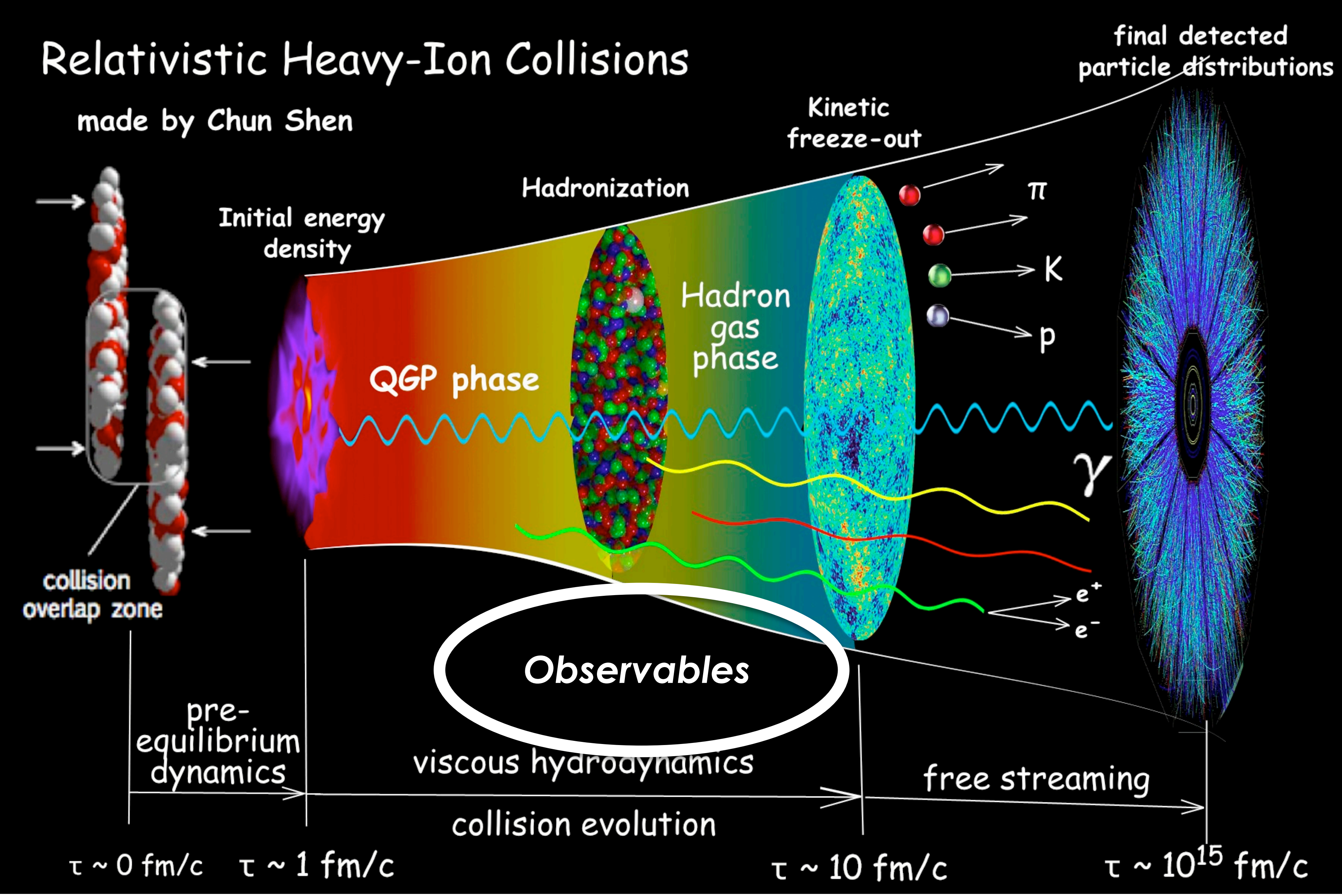


Soft processes:
- *High cross section*
- *Decouple late*

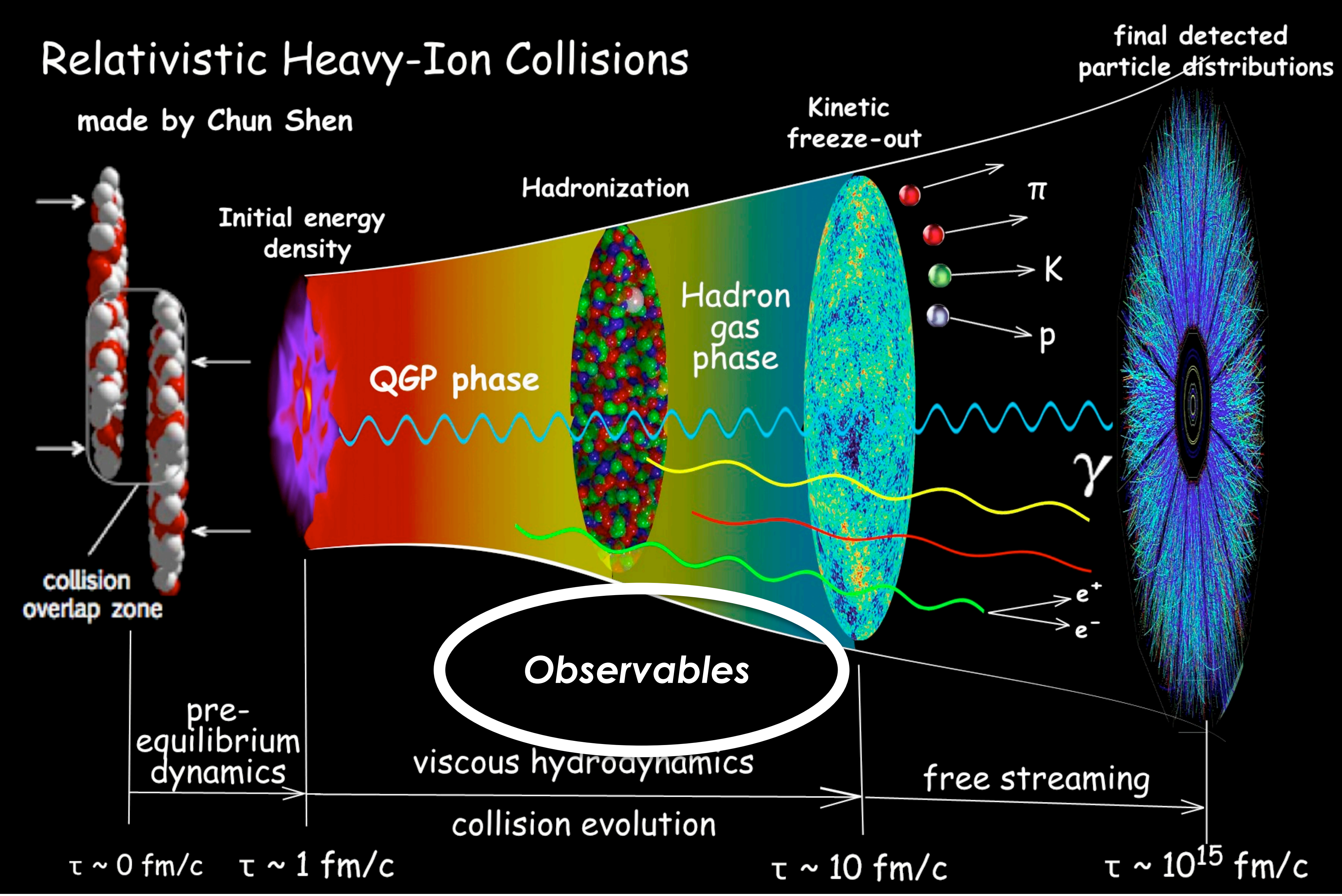
→ Indirect signals for QGP

EM probes (real and virtual photons): insensitive to the hadronization phase

Hard processes:
- *Low cross section*
- *Probe the whole evolution of the collision*



Various observables will probe different stages of the collision



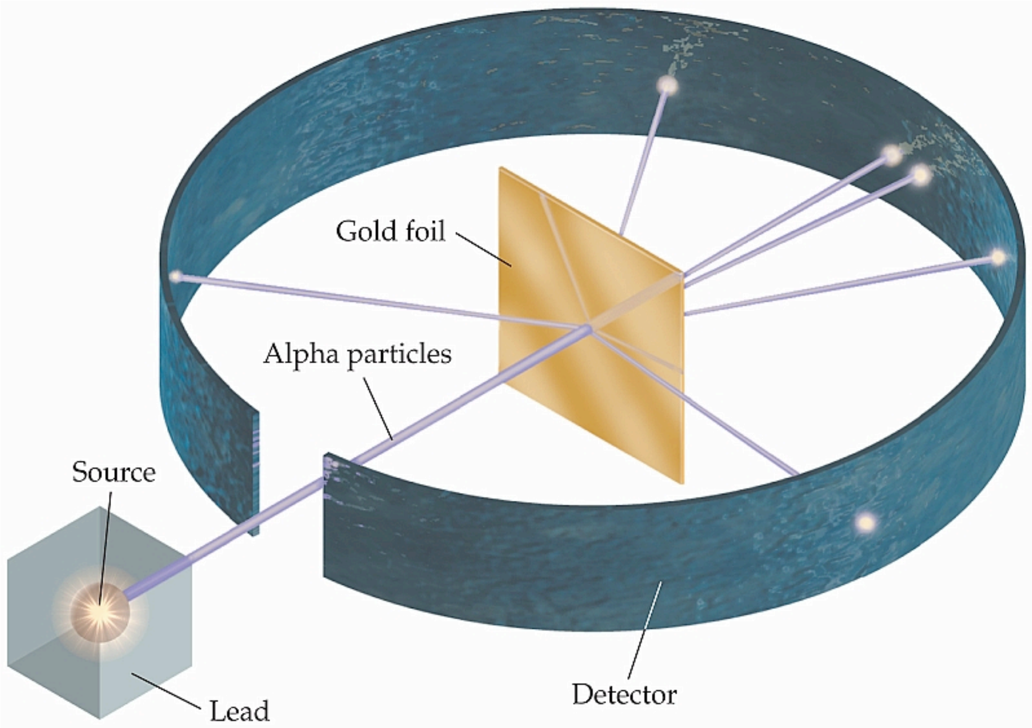
Observables

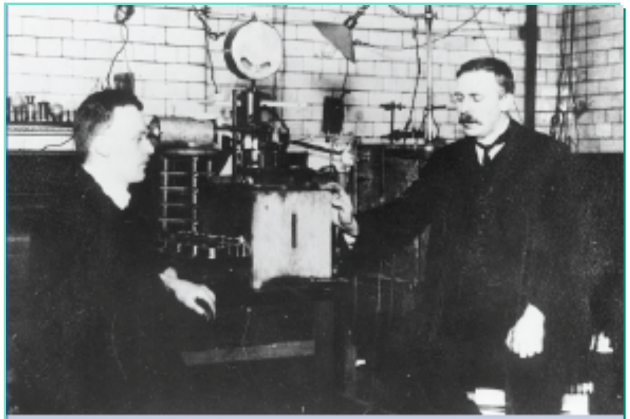
Hard probes
(jets, heavy flavor, EW bosons)

Transverse flow
Thermal photons

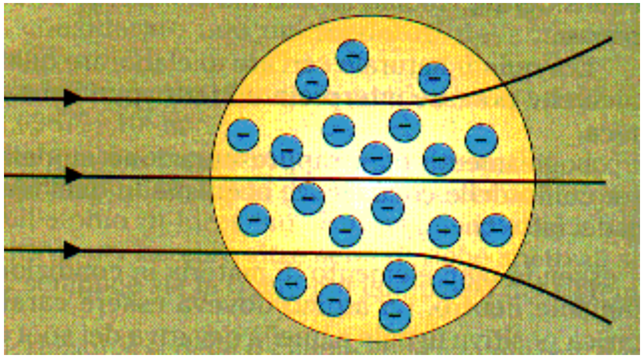
Multiplicity, HBT
Particle yields + spectra

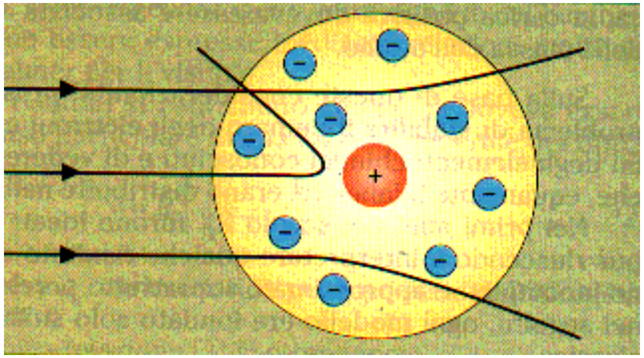
Atom not ατομοσ



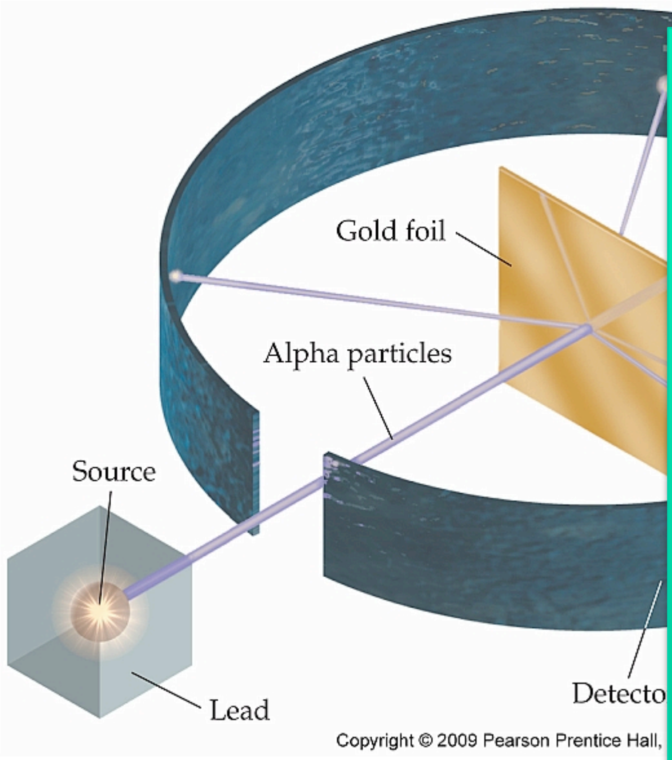


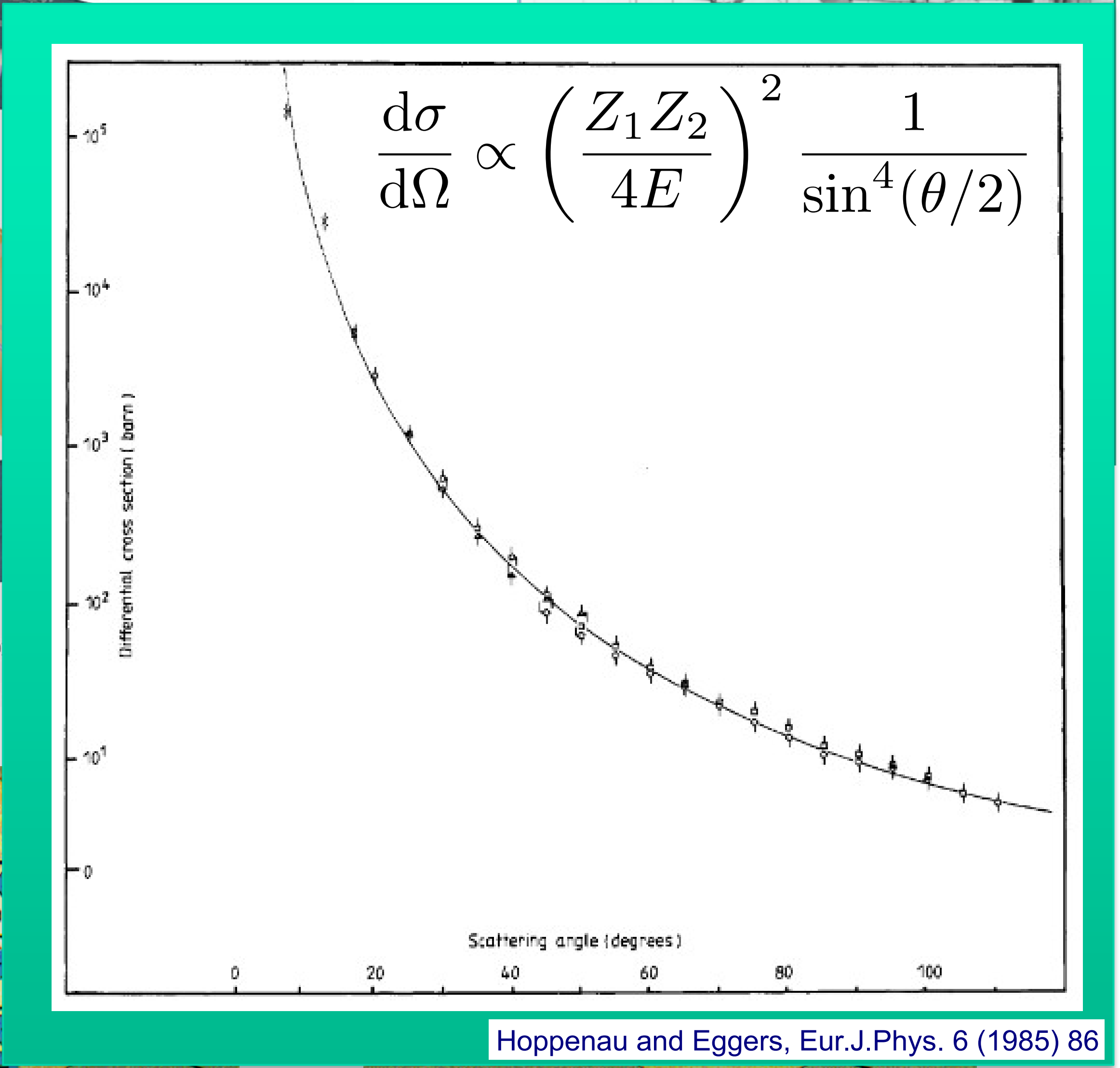
Ernest Rutherford (r) and Hans Geiger (l) in Manchester





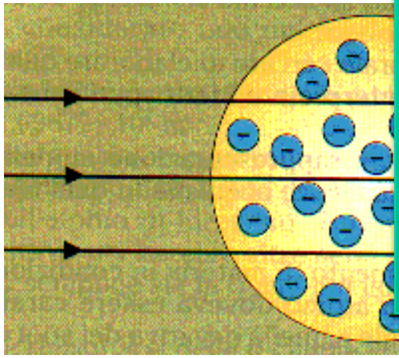
Atom not ατομοσ





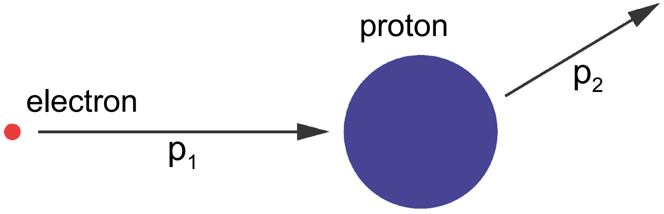
$$\frac{d\sigma}{d\Omega} \propto \left(\frac{Z_1 Z_2}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

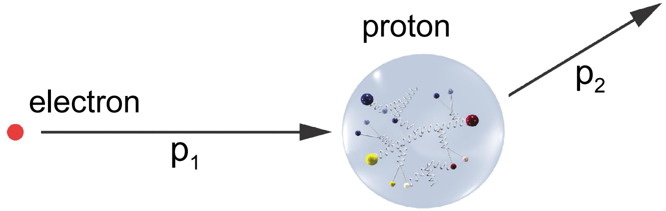
Hoppenau and Eggers, Eur.J.Phys. 6 (1985) 86

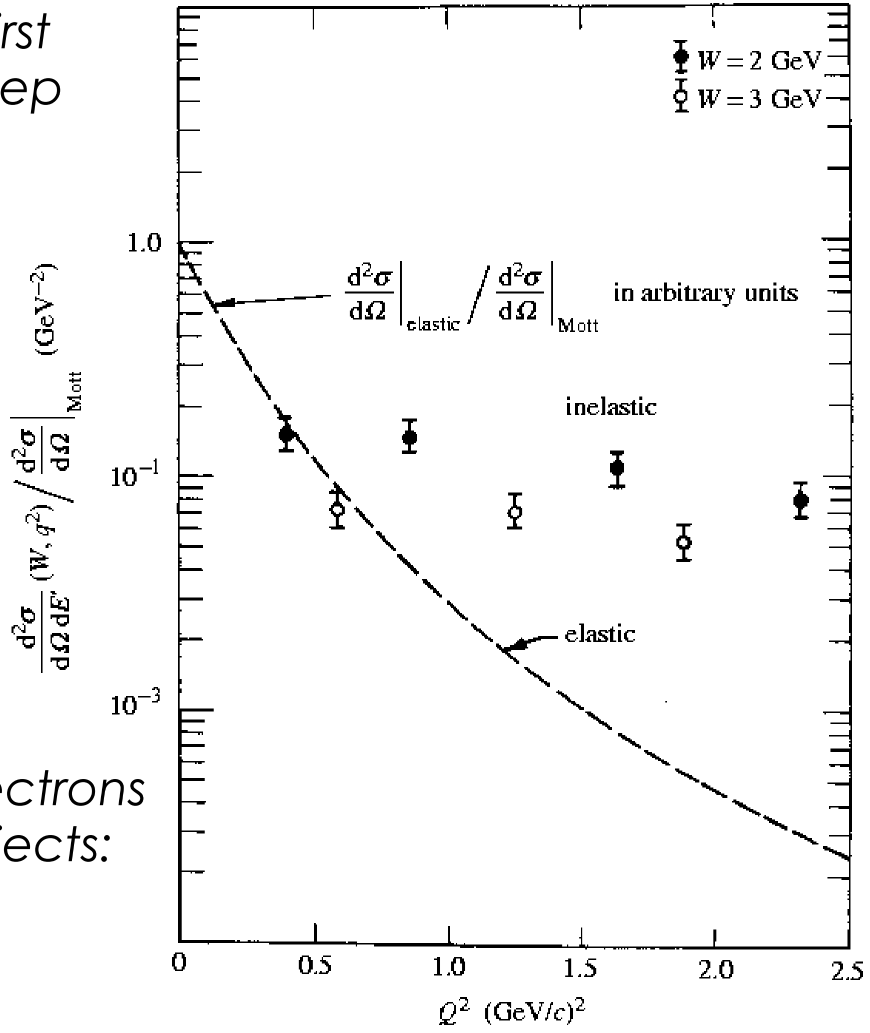


… going deeper

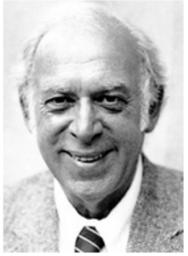
Increasing the energy, in the ‘60 at SLAC first investigation of the proton structure by Deep Inelastic Scattering



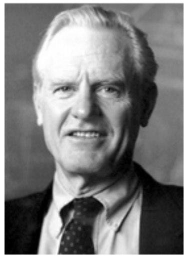




The angular distribution of the scattered electrons reflects a sub structure made of charge objects:
-scale concept, constant form factor



Jerome I. Friedman
Prize share: 1/3



Henry W. Kendall
Prize share: 1/3

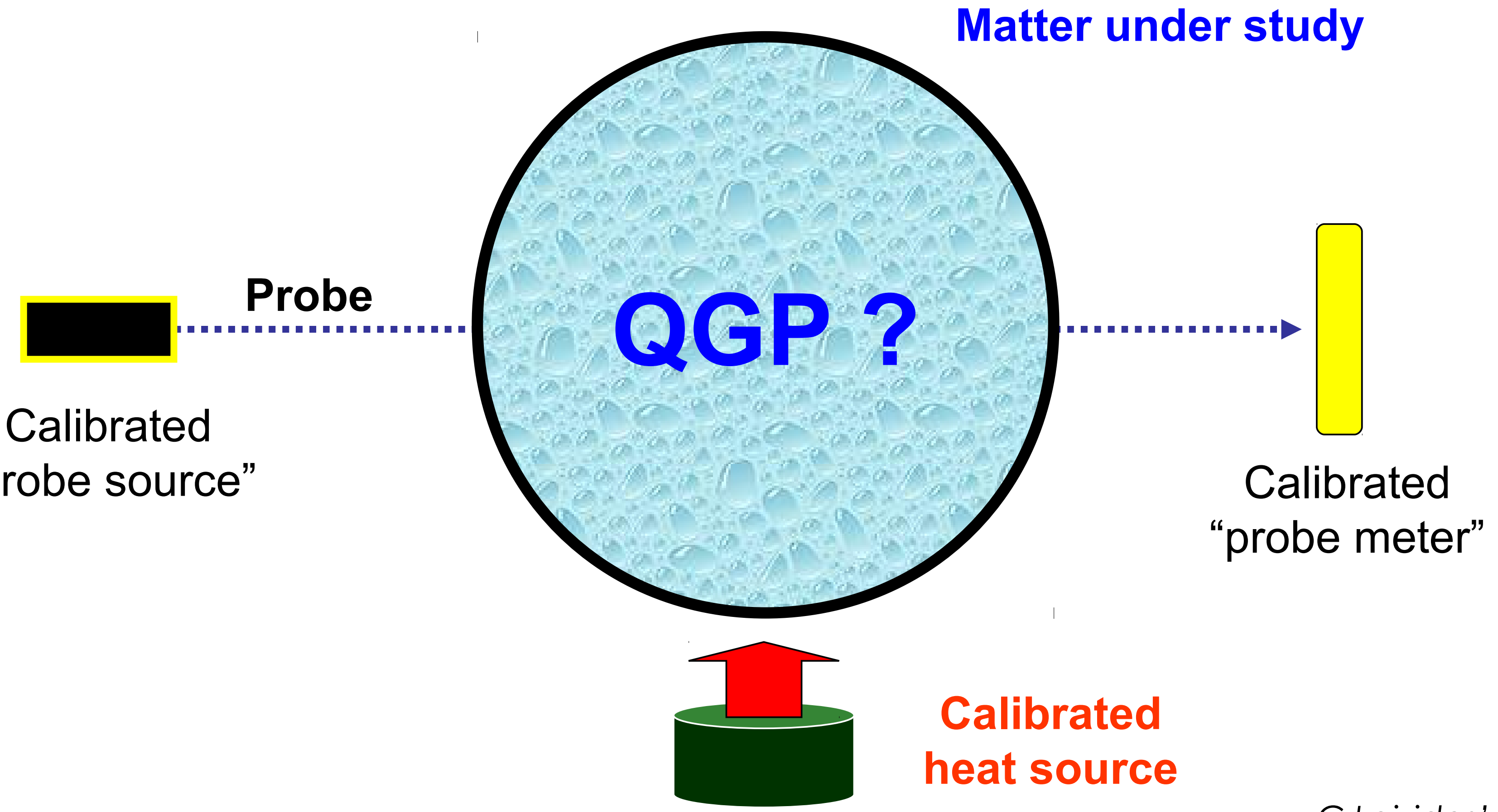
Photo: T. Nakashima
Richard E. Taylor

The discovery of quarks (still point-like objects)
1990 Nobel Prize

Same idea for exploring the QGP?

"Calibrated probes" can be used to probe the QGP

The idea is to measure how QGP can modify the probes?



C.Loizides' figure

Same idea for exploring the QGP?

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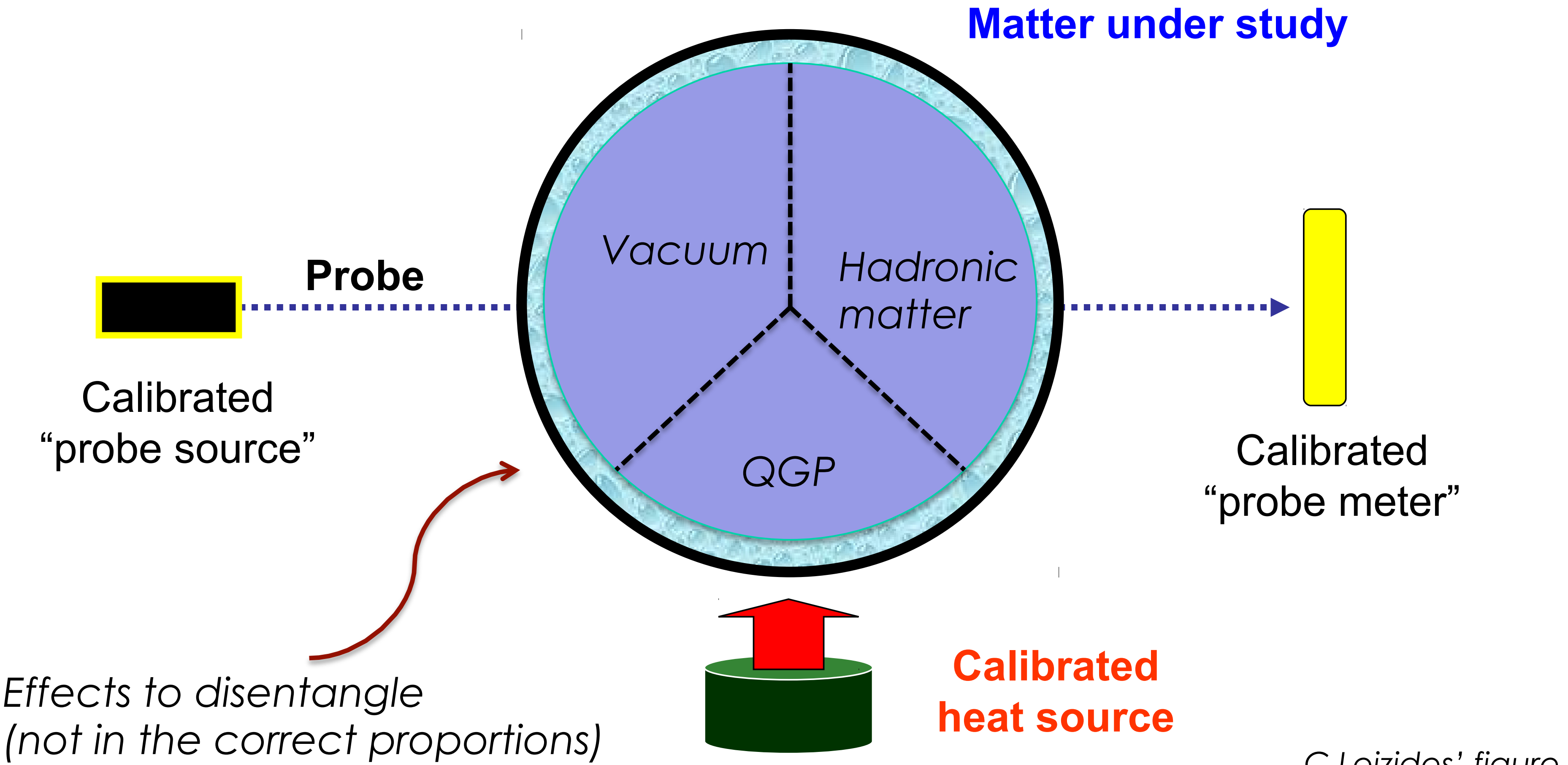
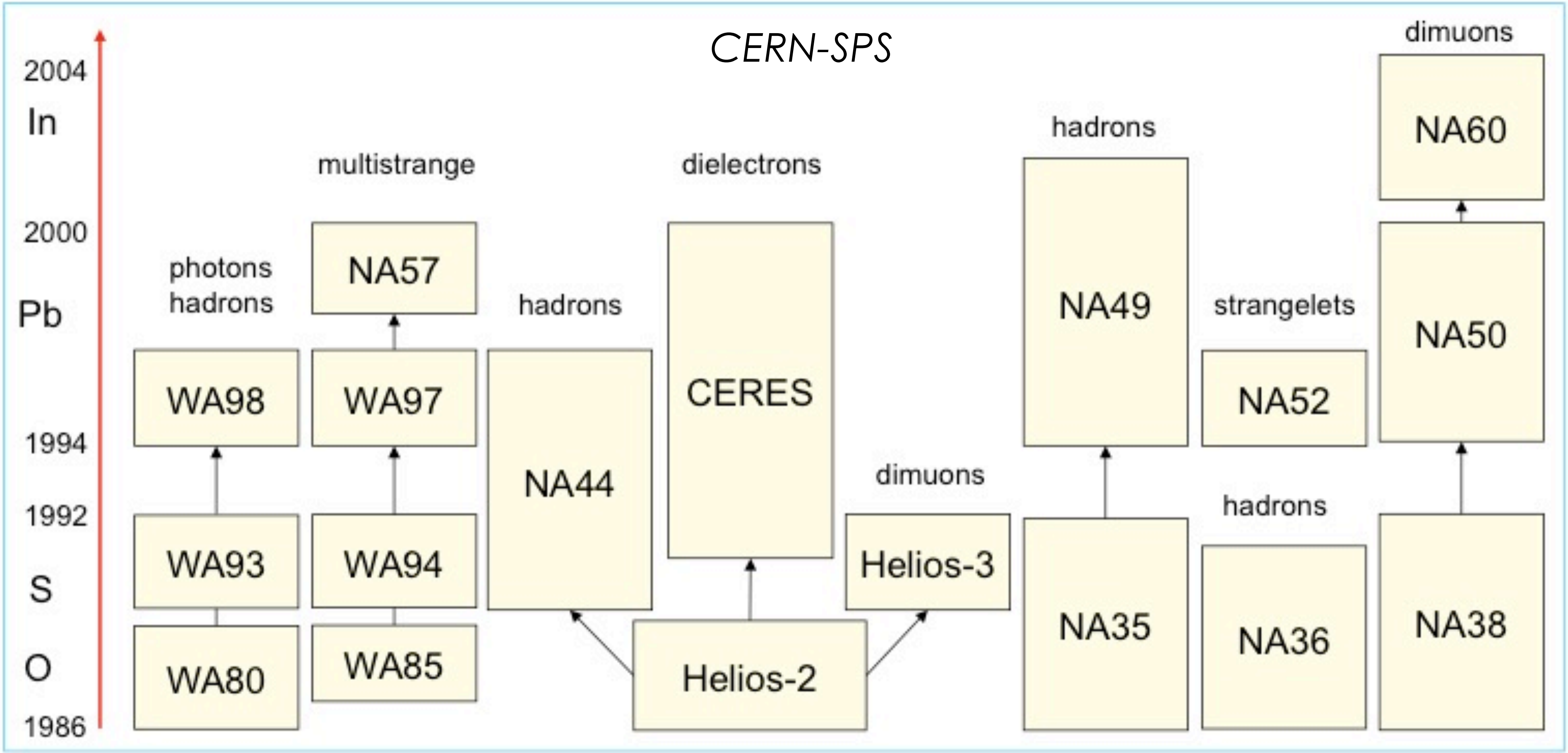


C.Loizides' figure

The path to the Heavy Ions LHC

Brookhaven National Laboratory (BNL)

- *AGS (1986-2000) Si and Au beams, √s~5 GeV (only hadronic variables)*
- *RHIC (2000-…) ^{3}He, Cu, Au beams, up to √s=200 GeV (4 experiments, 2 left)*



CERN-SPS

2004
In
2000
Pb
1994
1992
S
O
1986

photons hadrons: WA80 → WA93 → WA98

multistrange: WA85 → WA94 → WA97 → NA57

hadrons: NA44

dielectrons: CERES

dimuons: Helios-3

Helios-2 → NA44, CERES, Helios-3

hadrons: NA35 → NA49

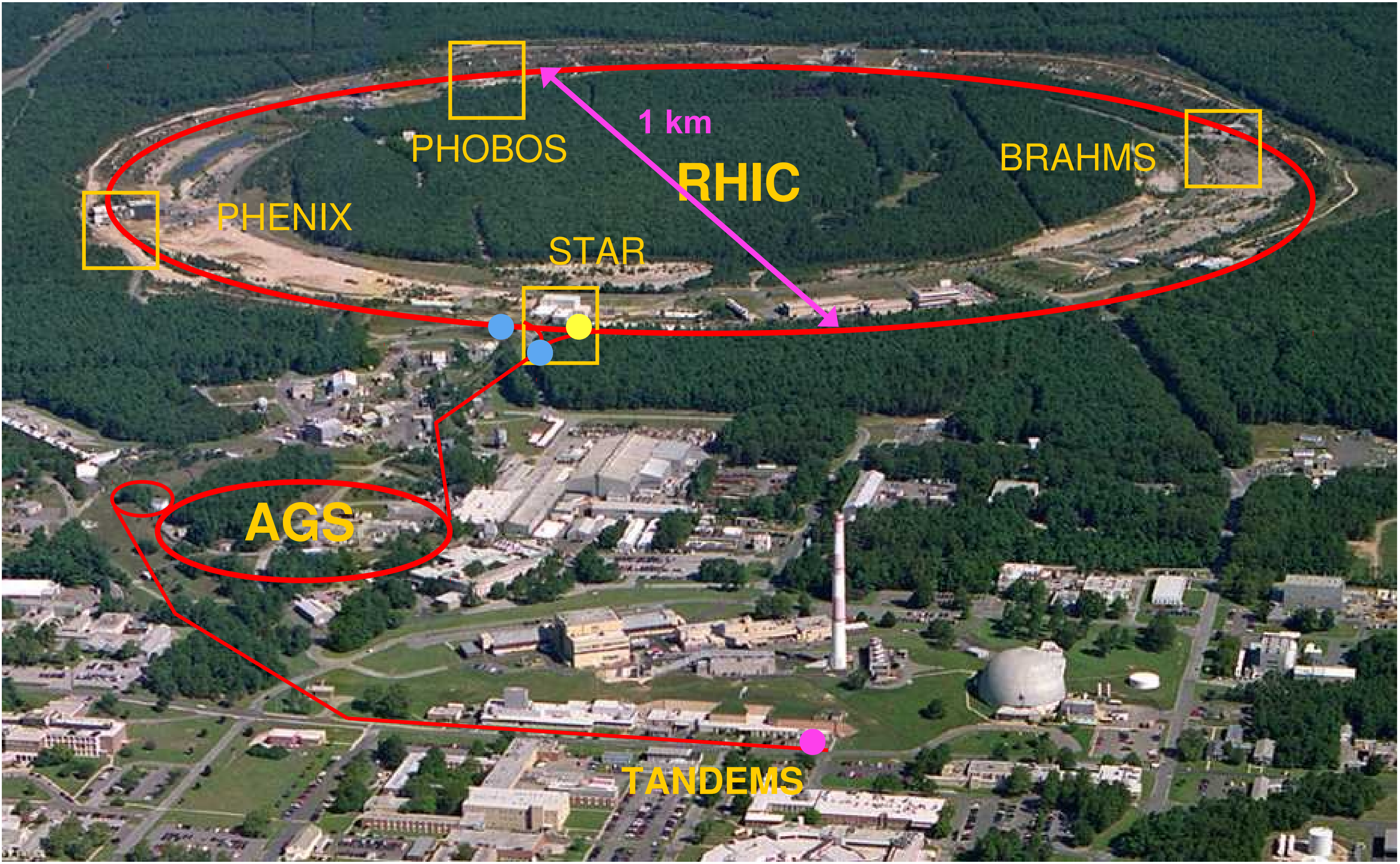
hadrons: NA36

strangelets: NA52

dimuons: NA38 → NA50 → NA60

- *CERN-LHC (2009-…) Pb beams, √s~5000 GeV (ALICE, ATLAS, CMS, LHCb)*

RHIC @ BNL



Nucleus-Nucleus Collisions at the LHC

		SPS	RHIC	LHC
$\sqrt{s_{NN}}$	[GeV]	17.3	200	5500
dN_{ch}/dy		450	800	1600
ε	[GeV/fm^3]	3	5.5	~ 10

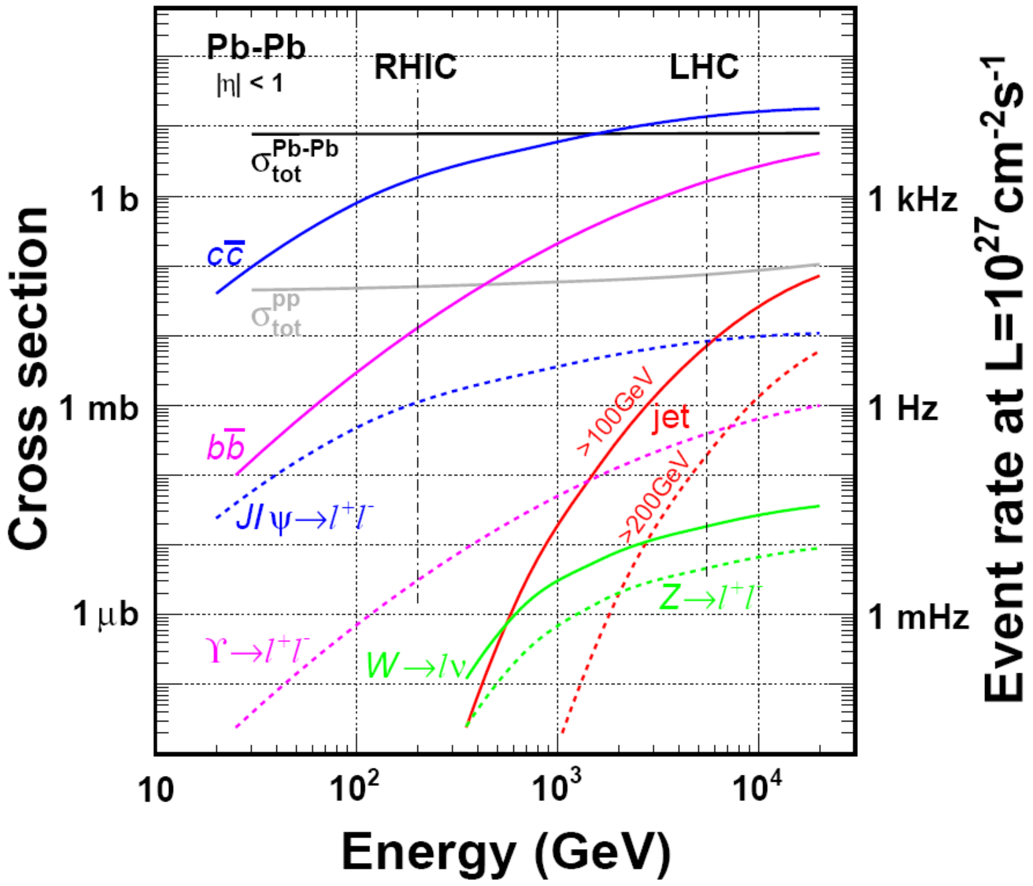
Fully ionised ^{208}Pb nucleus accelerated in the LHC (configuration magnetically identical to that for pp)

$$p_{Pb} = Zp_p = 82 \cdot 6.5 = 533 TeV$$

$$\sqrt{s_{PbPb}} = 1066 TeV$$

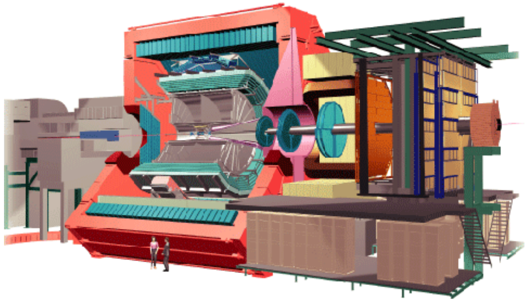
The relevant figure is √s per nucleon-nucleon collision (latest configuration):

$$\sqrt{s_{NN}} = \frac{2E_{Pb}}{A} = \frac{Z}{A}\sqrt{s_{pp}} = \frac{82}{208}\sqrt{s_{pp}} = 5.1 TeV$$

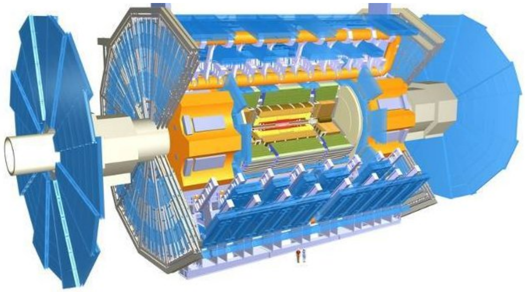


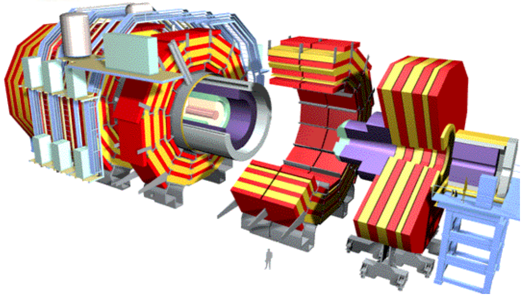
Nucleus-nucleus collisions at the LHC

Nucleus-Nucleus Collisions at the LHC

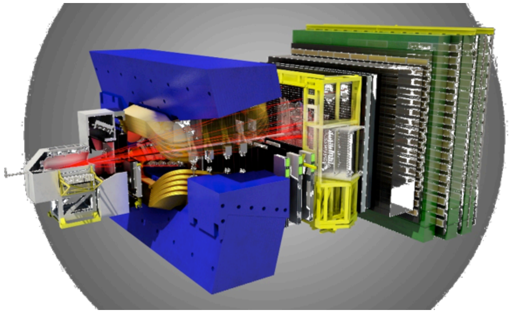


ALICE (A Large Ion Collider Experiment)
HI dedicated experiment:
-Low-p_T tracking, PID, mid-rapidity + forward muons



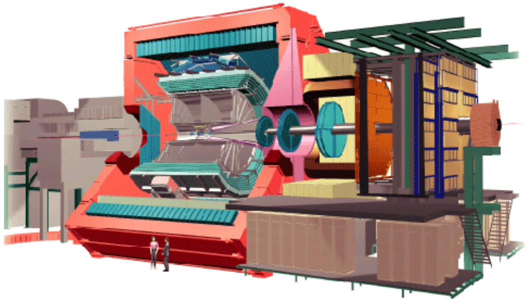


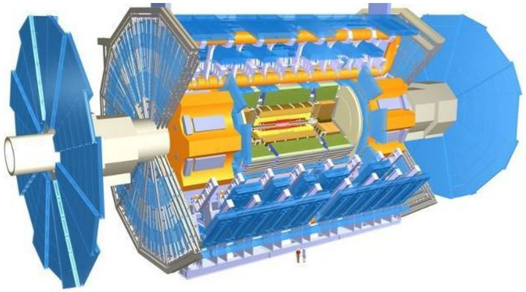
ATLAS and **CMS**, multipurpose experiments. Large capabilities for HI collisions.
Large acceptance, full calorimetry, high-p_T tracking

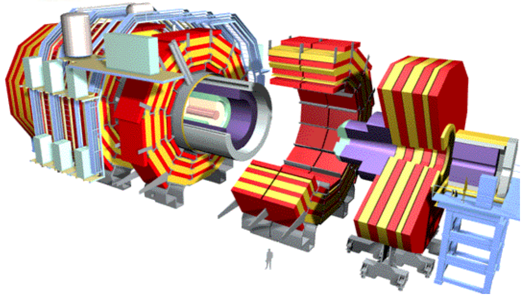


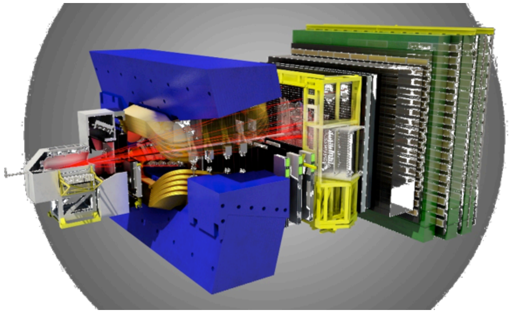
LHCb, *complementary phase space for HI collisions*
Forward tracking, PID, calorimetry
(pPb in 2013 and 2016, PbPb since 2015)

Nucleus-Nucleus Collisions at the LHC

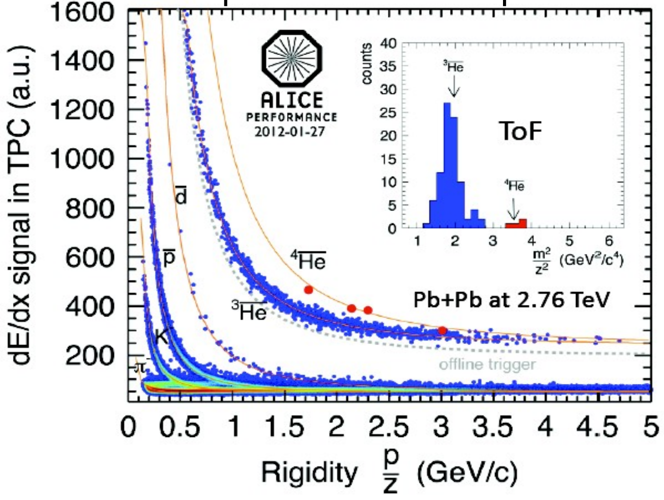


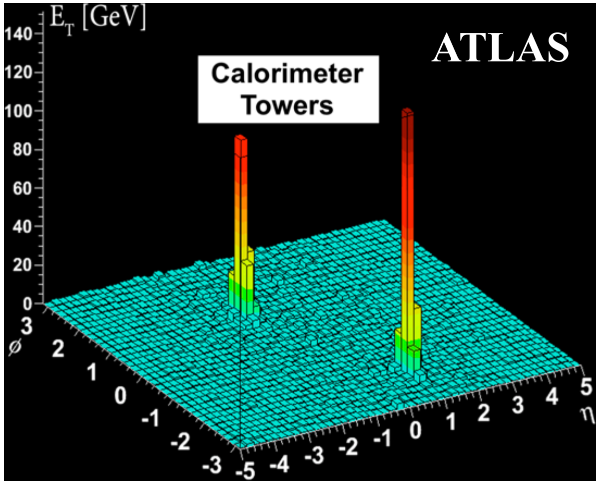


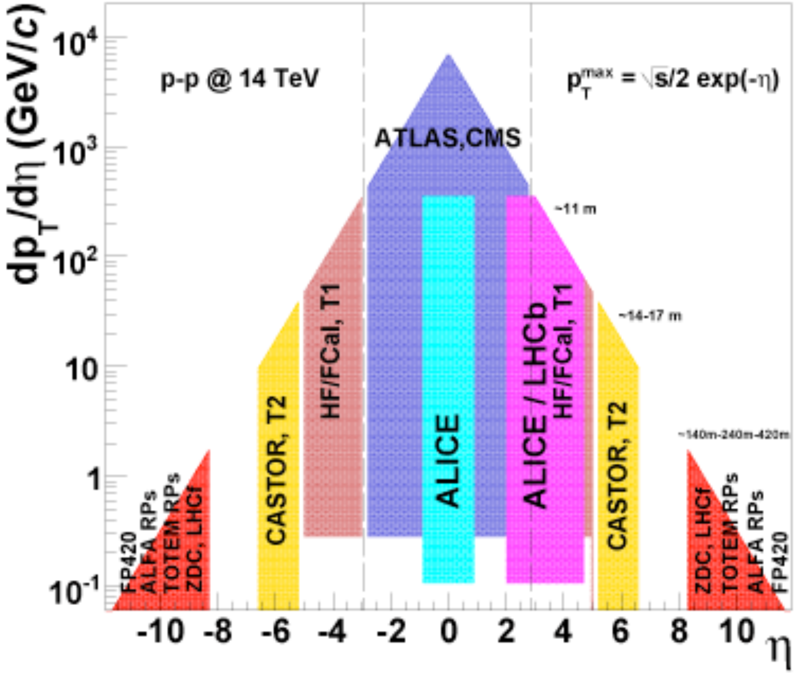




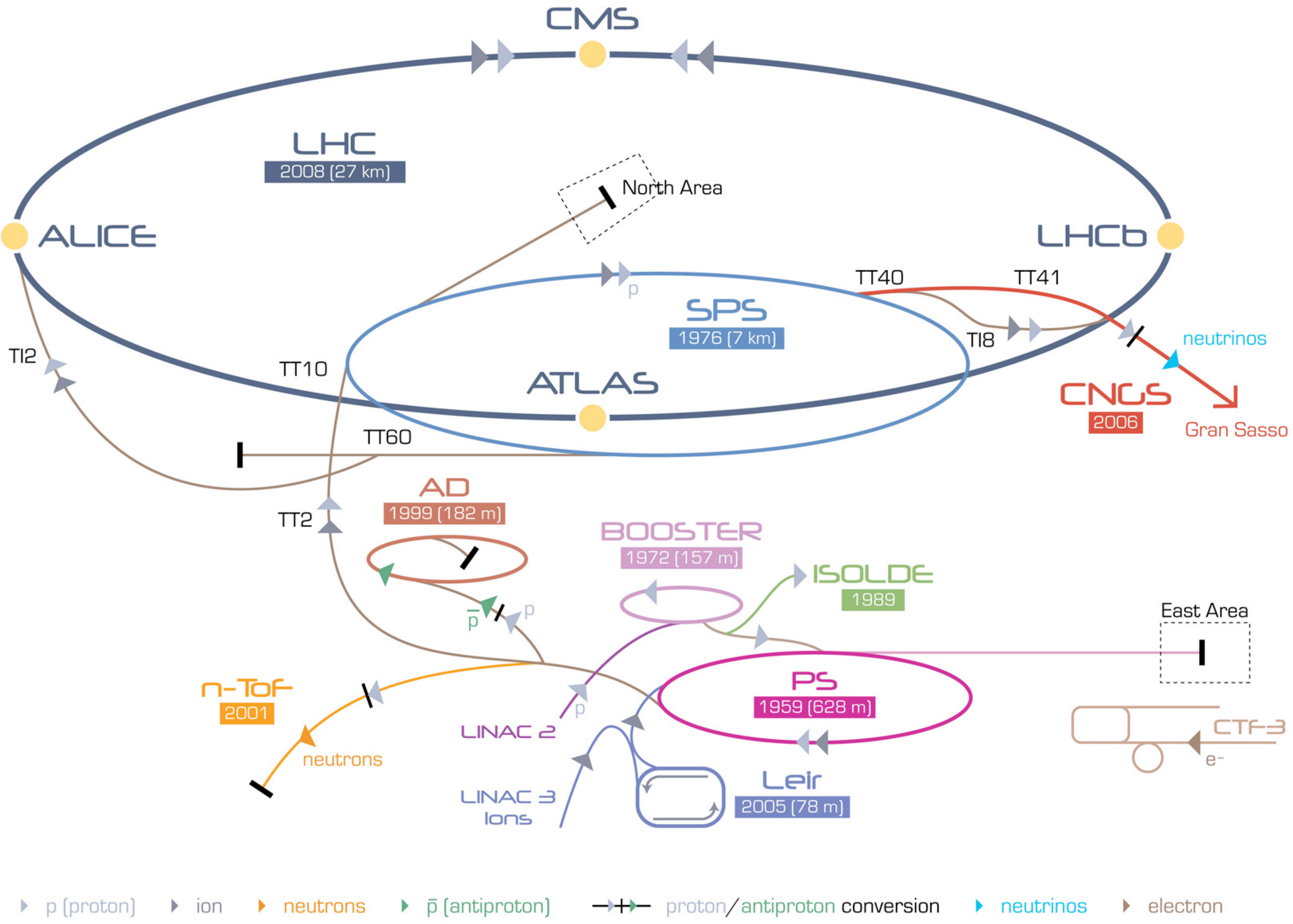
Example ALICE: PID capabilities





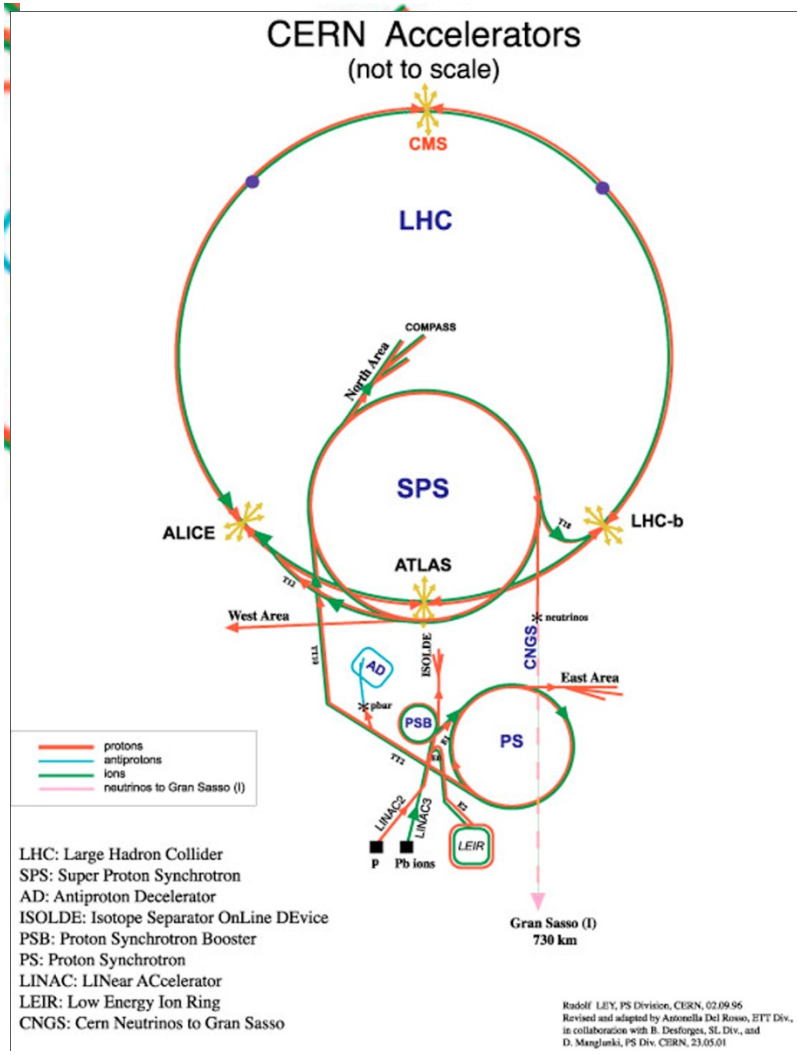


Production and acceleration of Pb ions



Production and acceleration of Pb ions

- ECR source: Pb^{27+} (80 mA)
- RFQ: Pb^{27+} to 250 A keV
- Linac3: Pb^{27+} to 4.2 A MeV
- Stripper: Pb^{53+}
- PS Booster: Pb^{53+} to 95 A MeV
- PS: Pb^{53+} to 4.25 A GeV
- Stripper: Pb^{82+} (full ionisation)
- SPS: Pb^{82+} to 158 A GeV
- LHC: Pb^{82+} to 2.76 A TeV

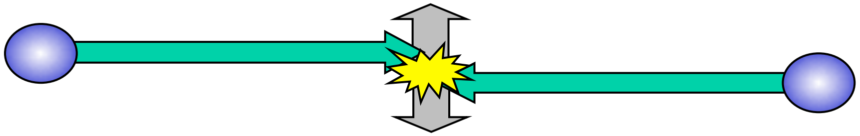


Huge differences in the delivered luminosity between PbPb (~10^{27} cm^{-2}s^{-1}) and pp (~10^{34} cm^{-2}s^{-1}) collisions

External control parameters

Kinematical variables

Hadronic collisions are characterized by limited transfer of transverse momentum



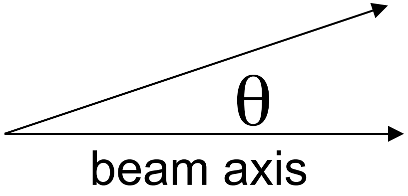
The kinematical distribution of the produced particles are usually expressed as a function of rapidity (y) and transverse momentum (p_T)

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \qquad p_T = \sqrt{p_x^2 + p_y^2}$$

p_T: Lorentz-invariant with respect to a boost in the beam direction
y: no Lorentz-invariant but additive transformation law → $y' = y - y_\beta$
(where y_β is the rapidity of the ref. system boosted by a velocity β)

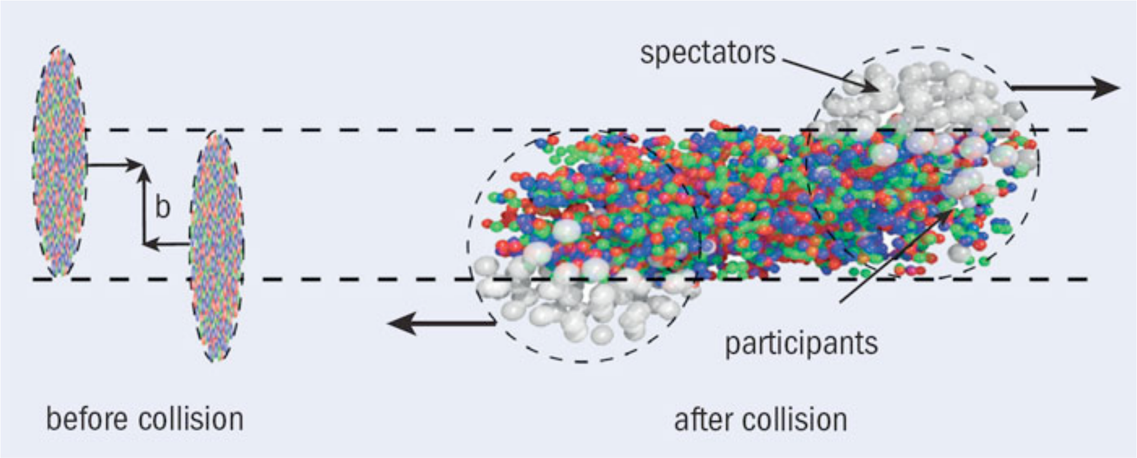
y measurement needs particle ID (measure momentum and energy)
Practical alternative: pseudorapidity (η)

$$\eta = \frac{1}{2}\log\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right) = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$



y~η for relativistic particles

Geometry of a Pb-Pb collision



- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity

➢ Many nucleons involved
➢ Many nucleon-nucleon collisions
➢ Large interaction volume
➢ Many produced particles

- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

➢ Few nucleons involved
➢ Few nucleon-nucleon collisions
➢ Small interaction volume
➢ Few produced particles

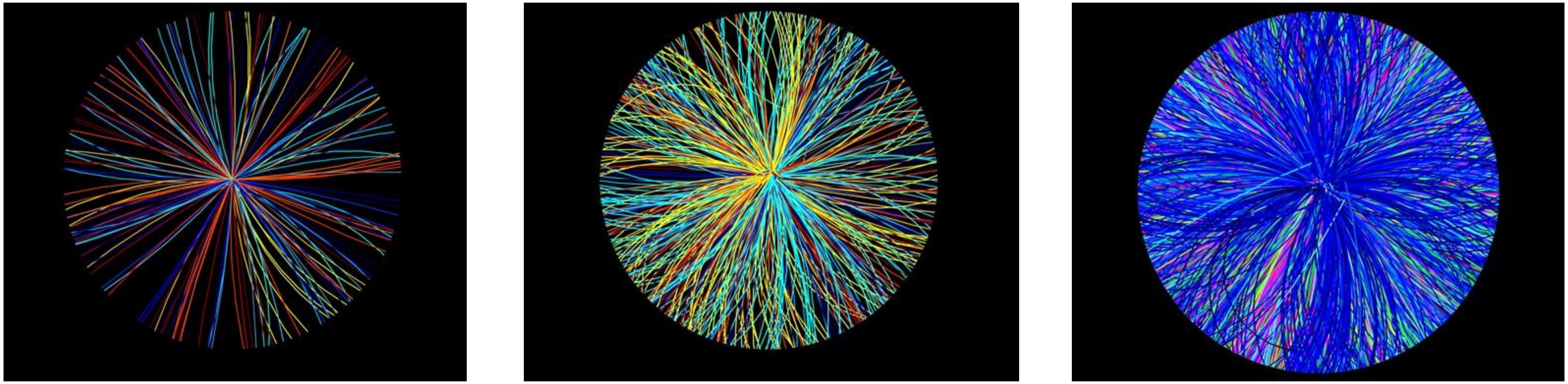
N.B. In pp there are always 2 participants

Centrality

- How do measure the impact parameter b?

Peripheral
b > 0

Central
b = 0



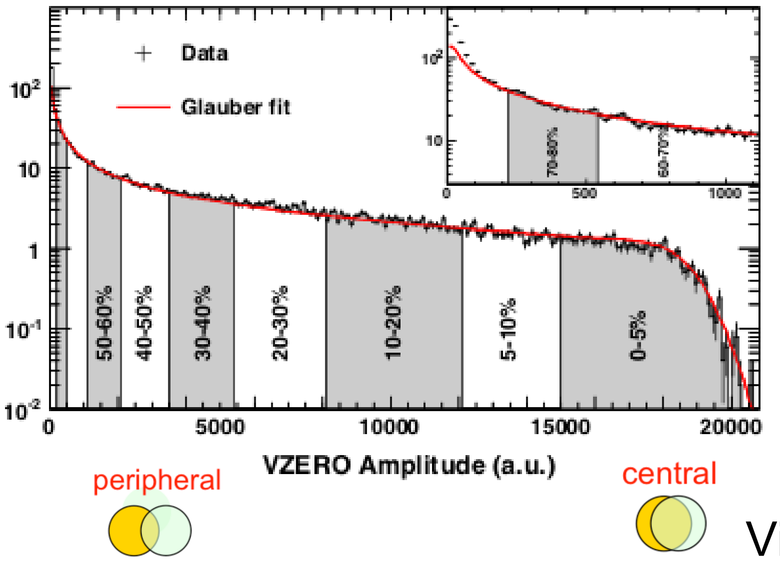
Low multiplicity → **High multiplicity**

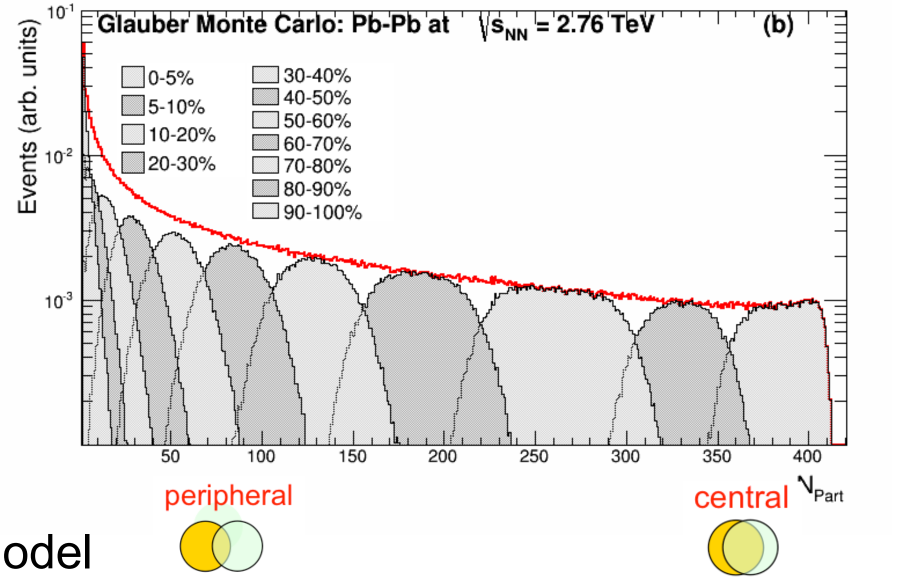
Striking relation between b and multiplicity

Glauber model

Nuclear cross-section classes (by slicing in bins of multiplicity)

Glauber model



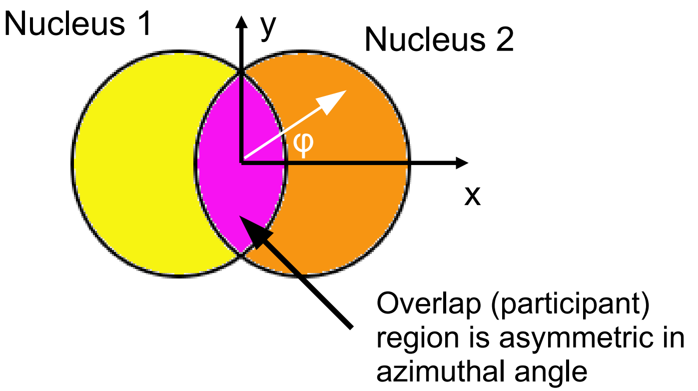


Via model

Cross-section percentile (in %) ↔ Number of participants (or collisions)

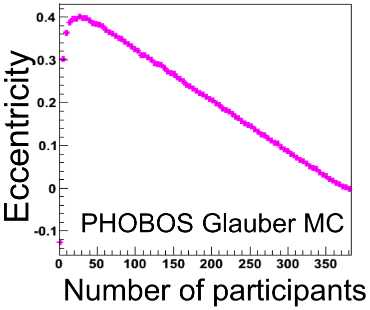
- Eccentricity

$$\epsilon_{std}=\frac{\sigma_y^2-\sigma_x^2}{\sigma_y^2+\sigma_x^2}$$



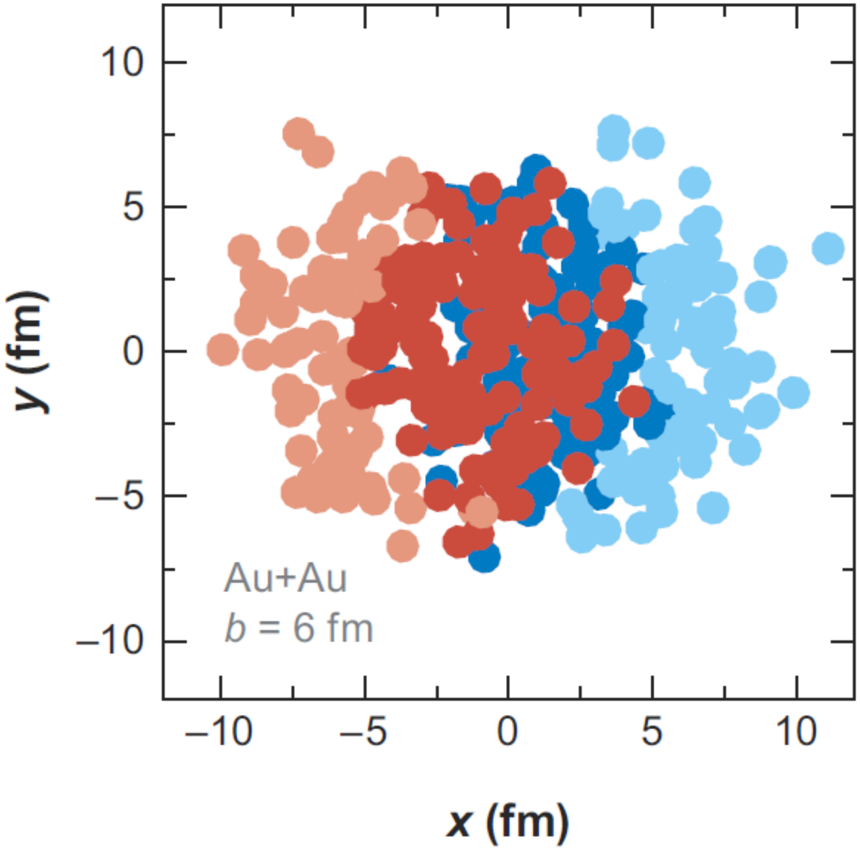
Overlap (participant) region is asymmetric in azimuthal angle

Initial state eccentricity

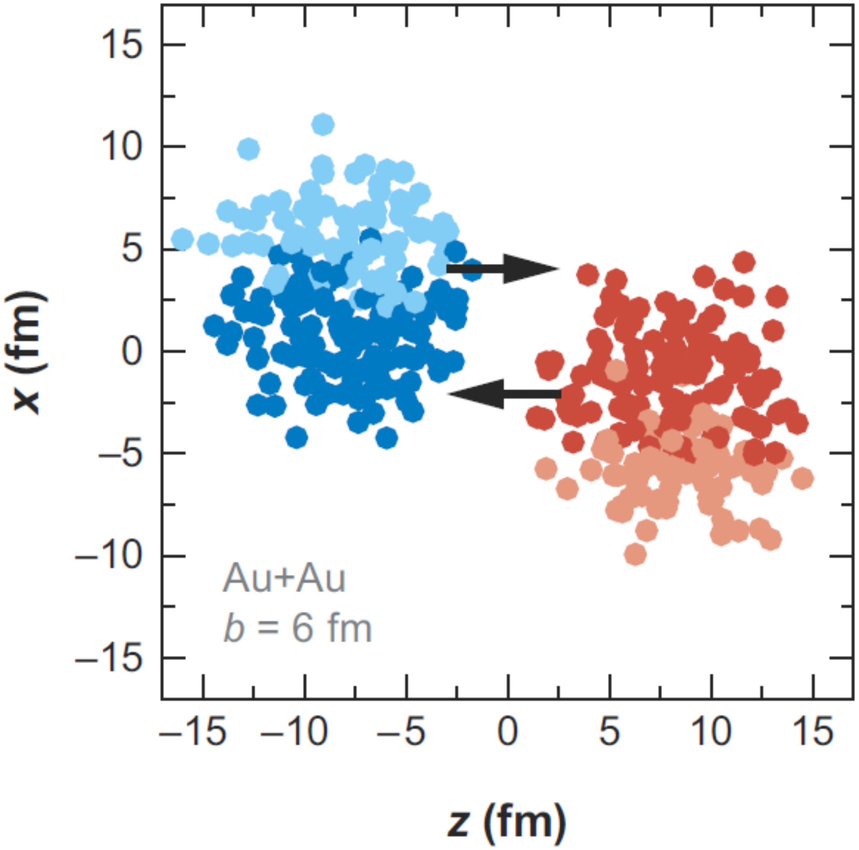


Realistic Example

Transverse view



Along the beam axis

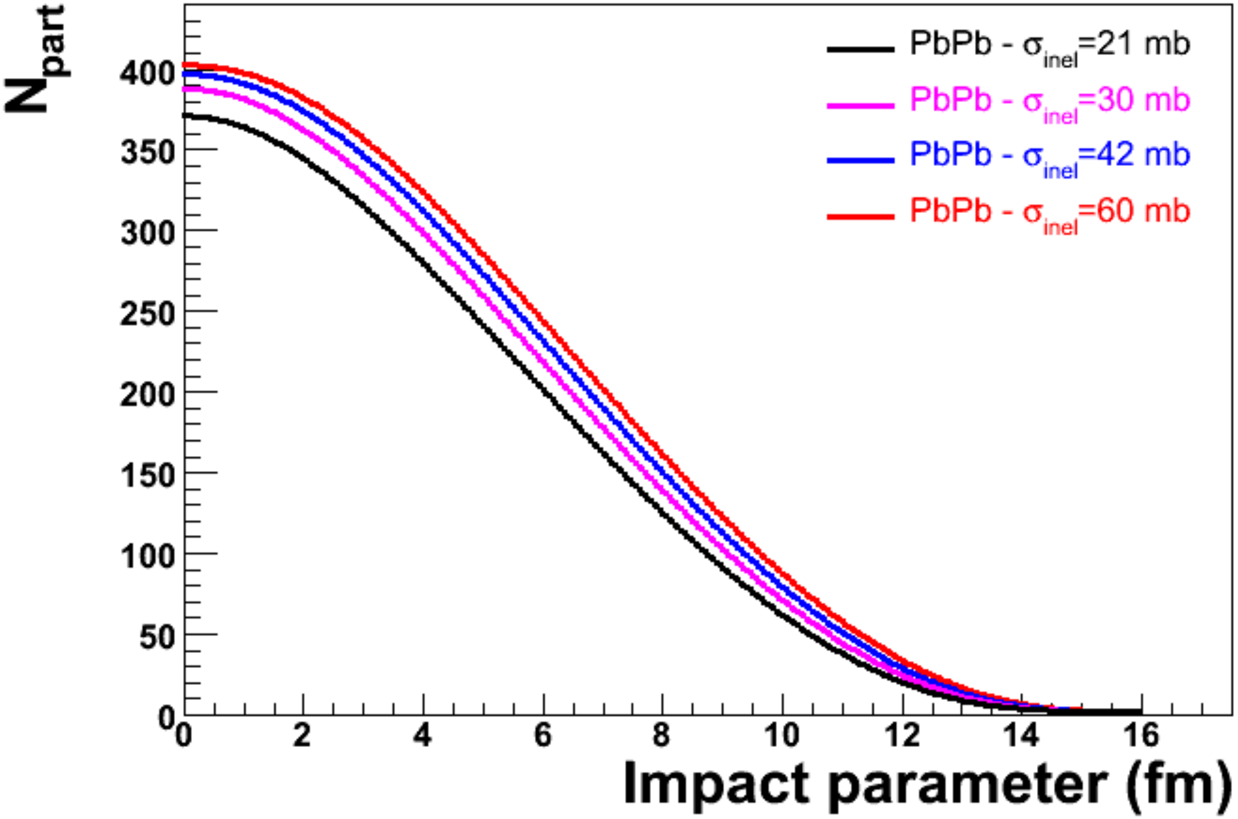


light nucleons: have not participated (spectators)
dark nucleons: have participated

Figure: nucl-ex/0701025

Number of participants vs b

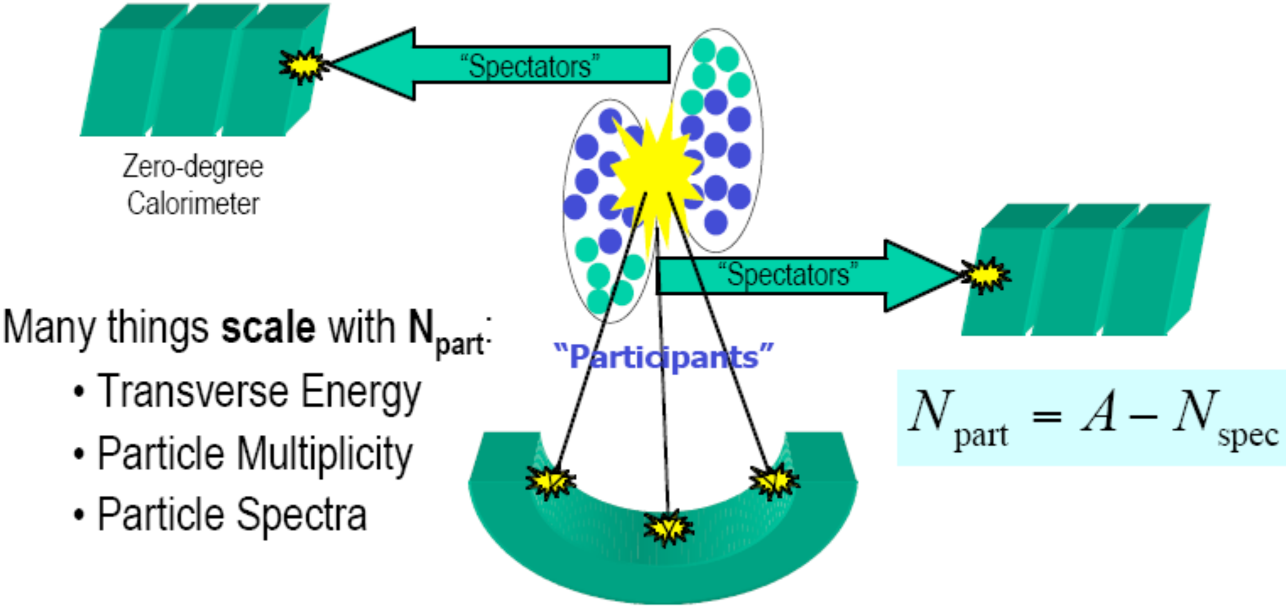
- ❑ With respect to N_{coll}, the dependence on the nucleon-nucleon cross section is much weaker
- ❑ When $\sigma_{inel} > 30$ mb, practically all the nucleons in the overlap region have at least one interaction and therefore participate in the collisions



Accel.	$\sqrt{s}$ (GeV)	σ_{total} (mb)	σ_{inel} (mb)
AGS	3-5	40	21
SPS	17	40	33
RHIC	200	50	42
LHC(Pb)	5500	90	60

Centrality: how to access experimentally

- ❑ Two main strategies to evaluate the impact parameter in heavy-ion collisions
  - ❑ Measure observables related to the energy deposited in the interaction region → charged particle multiplicity, transverse energy ($\propto N_{part}$)
  - ❑ Measure energy of hadrons emitted in the beam direction → zero degree energy ($\propto N_{spect}$)



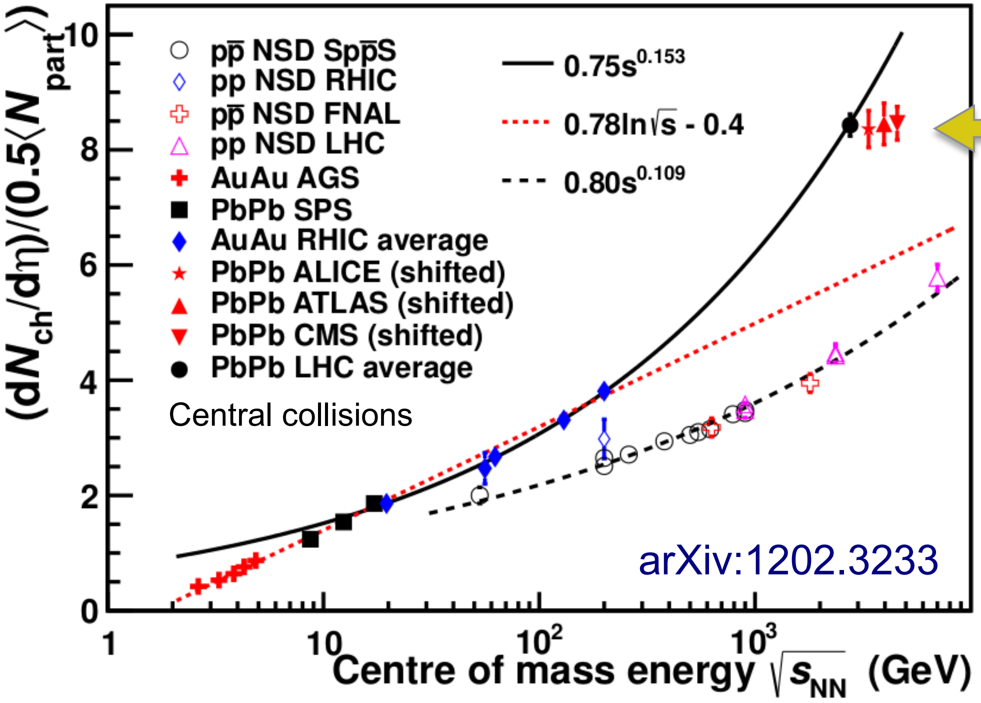

RESULTS

Multiplicity and transverse energy

(Estimate of energy density and related to entropy)

Particle multiplicity

Most central collisions at LHC: up to 1600 charged particles per unit of η



arXiv:1202.3233

The increase with beam energy
Is significantly steeper than in pp

Log extrapolation:

- OK at lower energies
- fails at the LHC

Results normalised to pp (vacuum)

- $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, $|\eta|<0.5$
- $dN_{ch}/d\eta$ / ($<N_{part}>/2$) = 8.3 ± 0.4 (sys.)

Bjorken, PRD 27 (1983) 140

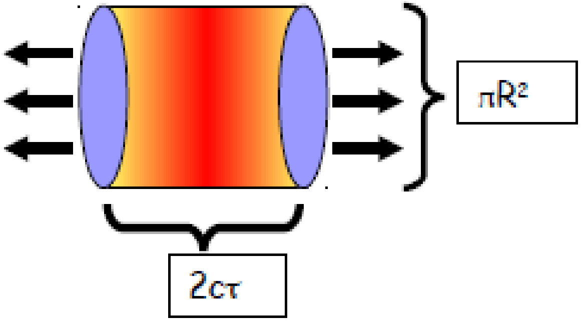
Bjorken's formula

Let's evaluate the energy density reached in the collision:

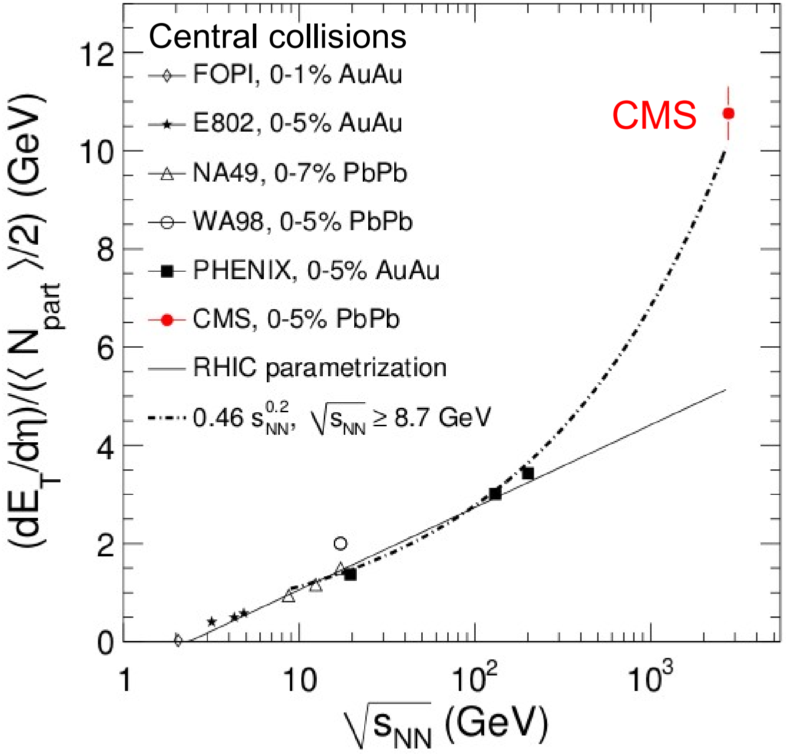
$$\boxed{\varepsilon = \frac{1}{Sc\tau_0}\left.\frac{dE_T}{dy}\right|_{y=0}}$$

S=transverse dimension of the nucleus

τ_0= formation time, from the hard scattering to a neutral color object ~1 fm/c



PRL 109 (2012) 152303



Bjorken, PRD 27 (1983) 140

Energy Density

Let's evaluate the energy density reached in the collision:

$$\boxed{\varepsilon = \frac{1}{Sc\tau_0}\left.\frac{dE_T}{dy}\right|_{y=0}}$$

S=transverse dimension of the nucleus

τ_0= formation time, from the hard scattering to a neutral color object ~1 fm/c

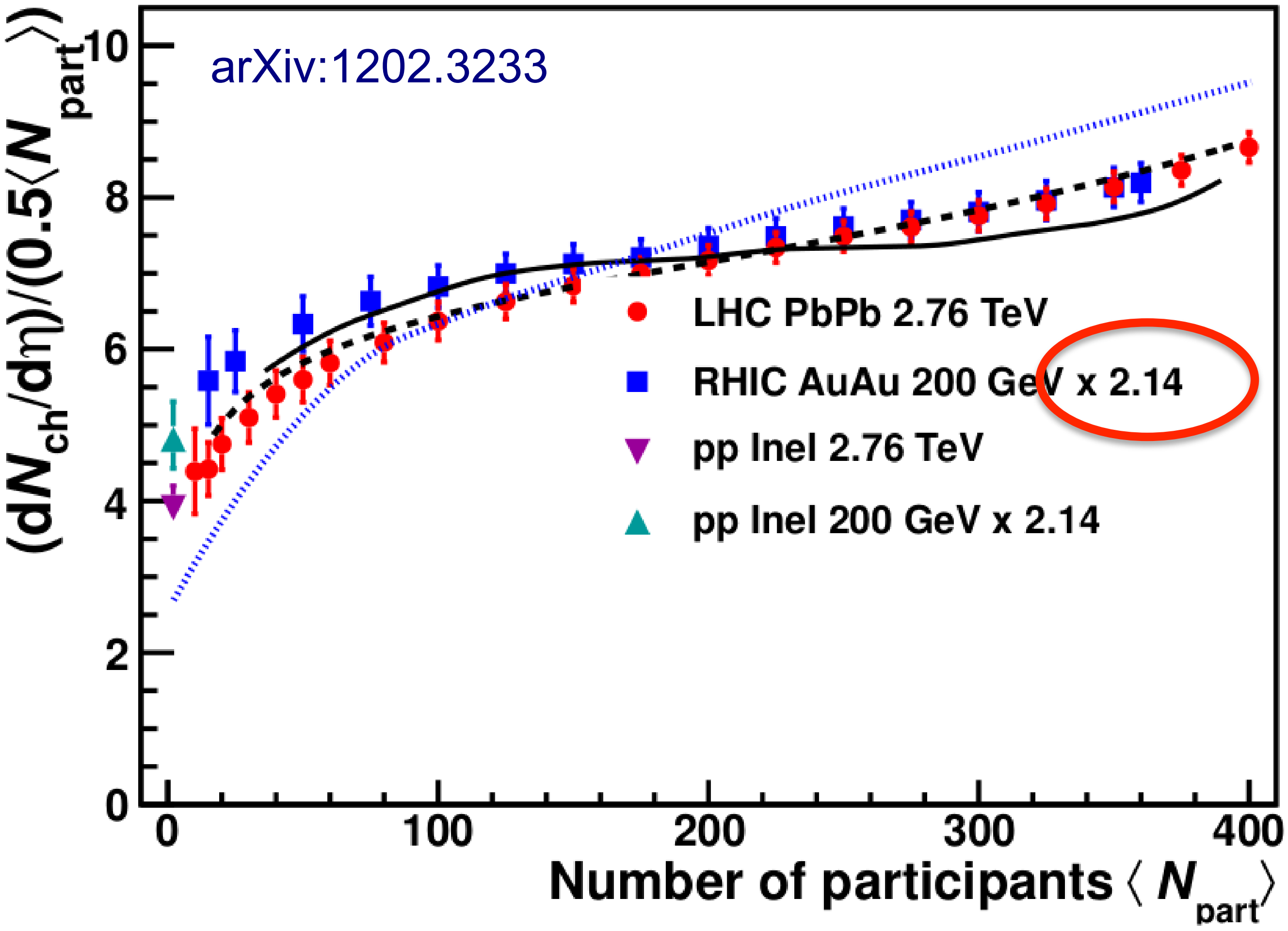
- experimentally, for central collisions at the LHC: $\left.\frac{dE_T}{dy}\right|_{y=o} \approx 1800\,\mathrm{GeV}$
- transverse dimension: $S \approx 160\,\mathrm{fm}^2 \qquad (R_A \approx 1.2A^{1/3}\,\mathrm{fm})$

$$\boxed{\varepsilon \sim (1800/160)\,\mathrm{GeV/fm}^3 \sim 10\,\mathrm{GeV/fm}^3}$$

More than enough for deconfinement!

N.B. only necessary, not sufficient condition … pp collisions

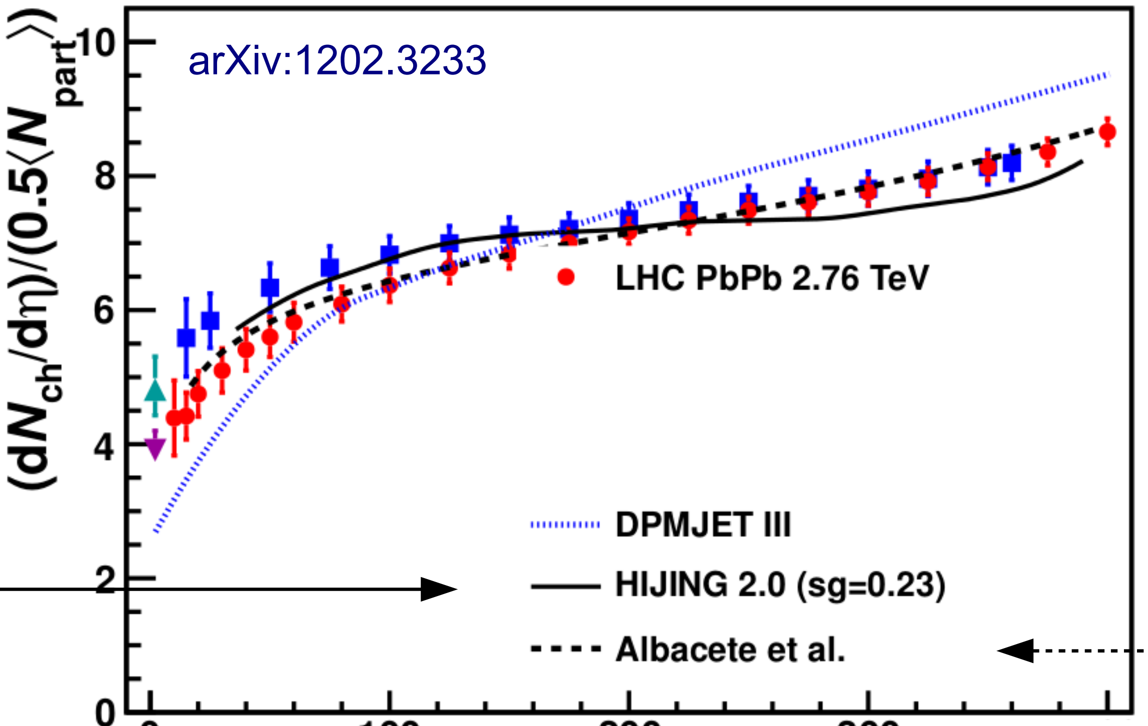
Centrality dependence of dN/dη



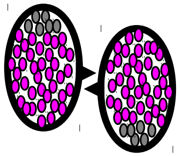
Arbitrary factor

The shapes between RHIC and LHC are very similar!
Factorization in energy and centrality

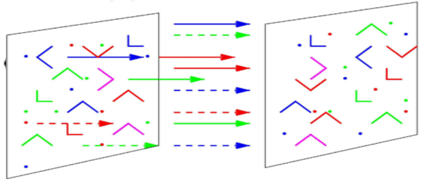
Centrality dependence of dN/dη



Glauber IC



CGC IC



Glauber IC
Two-component model

$$\frac{dN}{d\eta}=\frac{dN}{d\eta^{pp}}\left((1-x)N_{\text{coll}}+x\,N_{\text{part}}/2\right)$$

PRC 70 021902 (2004)

CGC IC
Color glass condensate

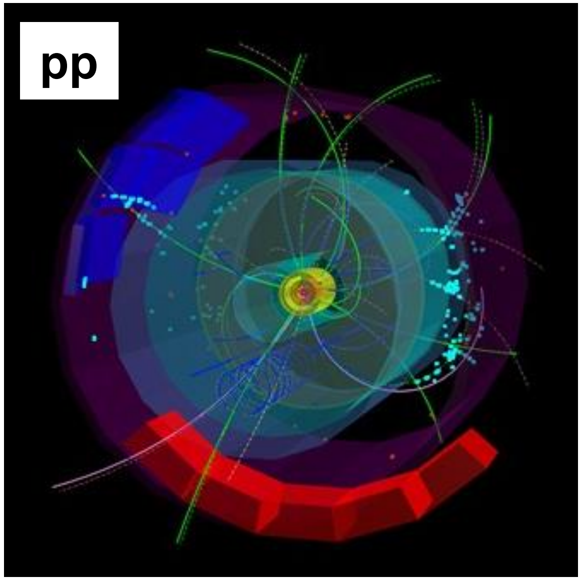
$$\frac{dN}{d\eta}\propto N_{\text{part}}^{\alpha}\sqrt{s}^{\lambda}$$

PRL 94 022002 (2005)

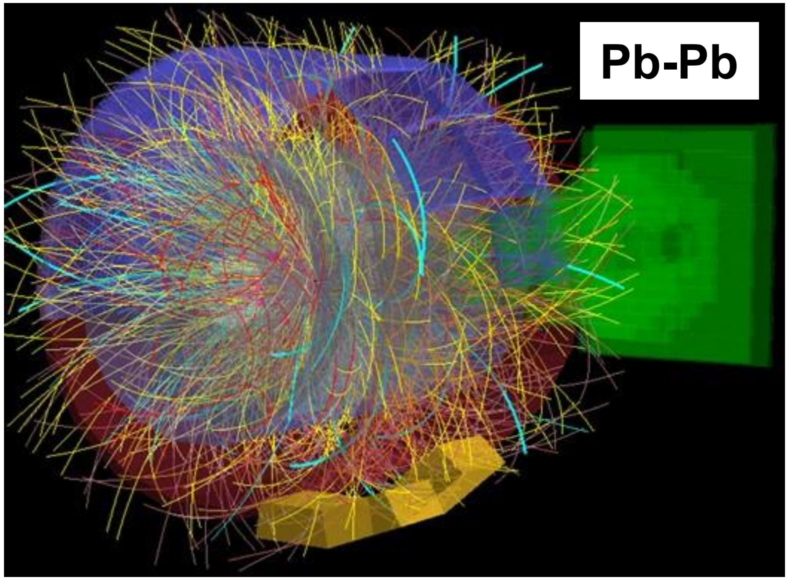
Heavy-Ion Environment

- 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

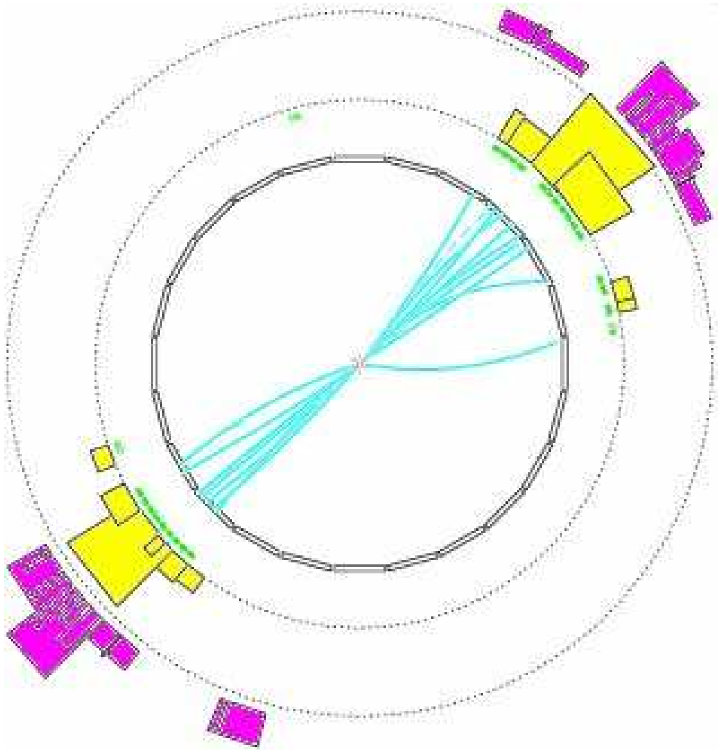
for comparison
pp : $dN_{ch}/d\eta$ ~ 4

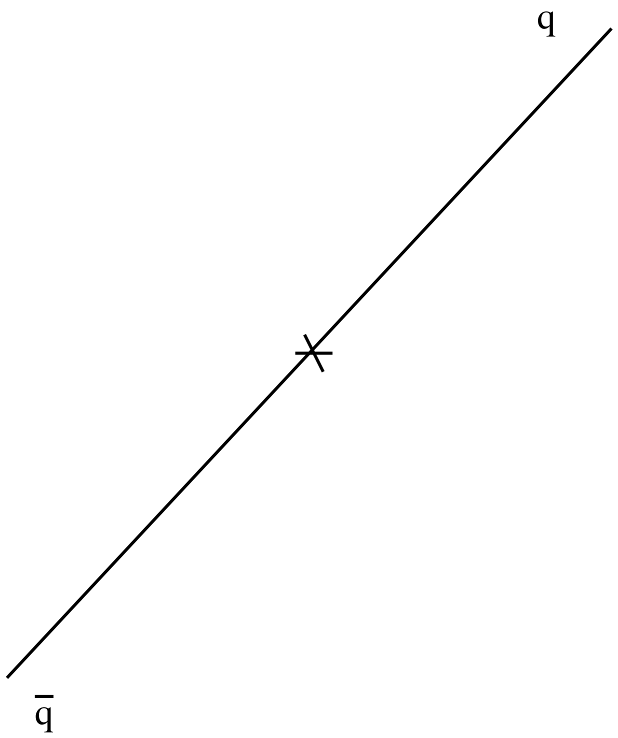


x 400



Picturing a (simple) QCD event

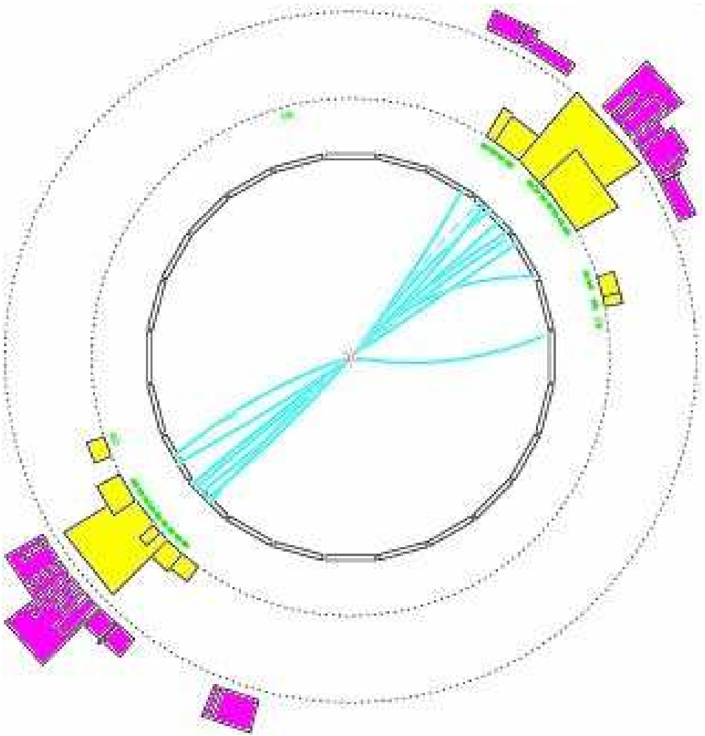


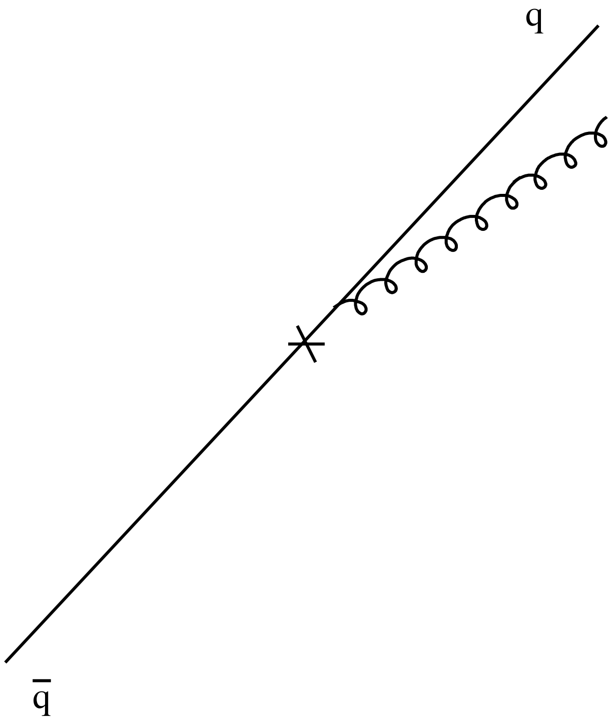


Start of with $q\bar{q}$

Image Credits: G.Salam

Picturing a (simple) QCD event

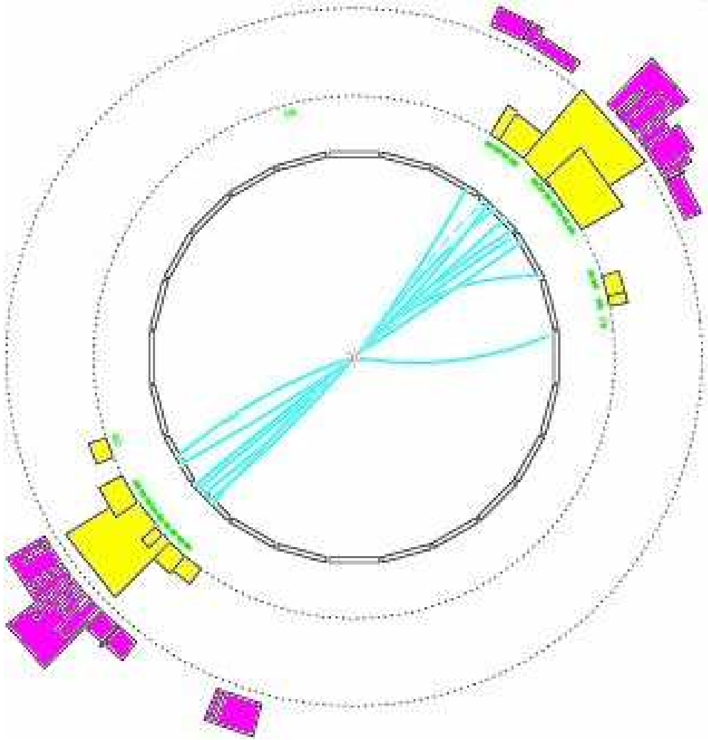


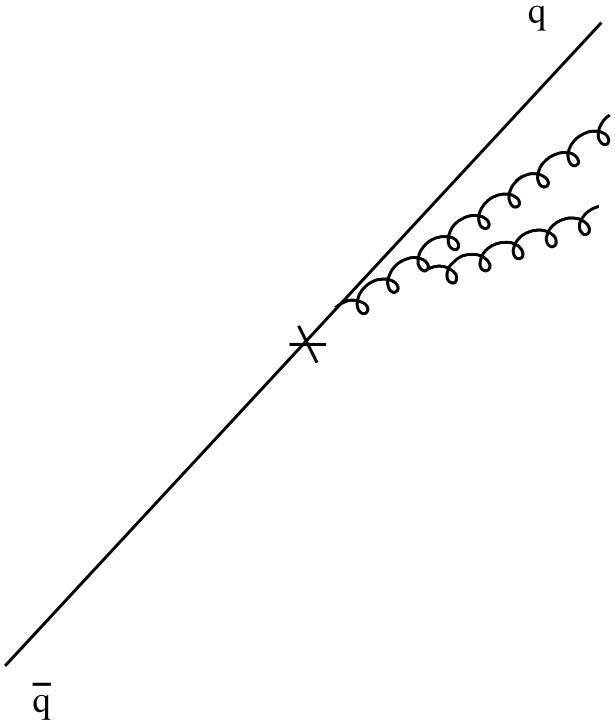


A gluon gets emitted at small angles

Image Credits: G.Salam

Picturing a (simple) QCD event

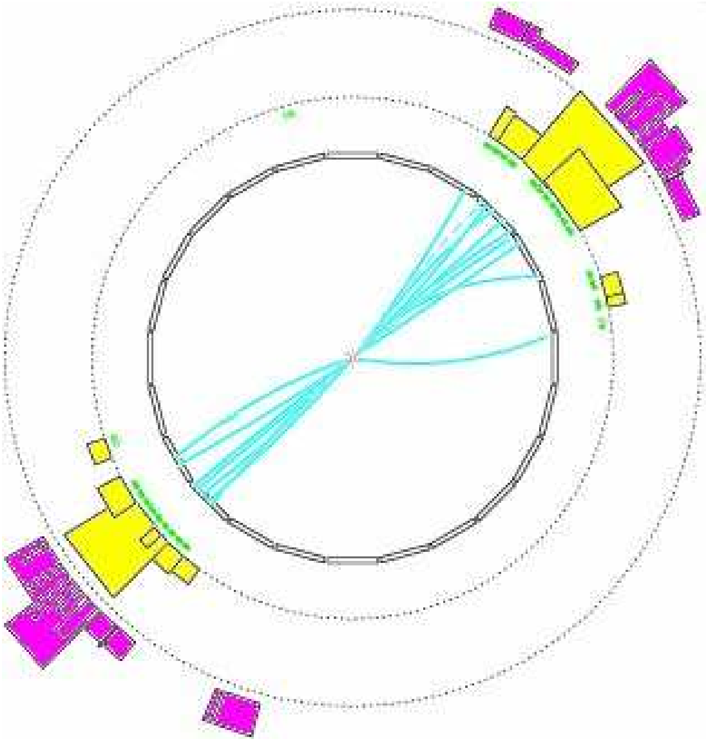


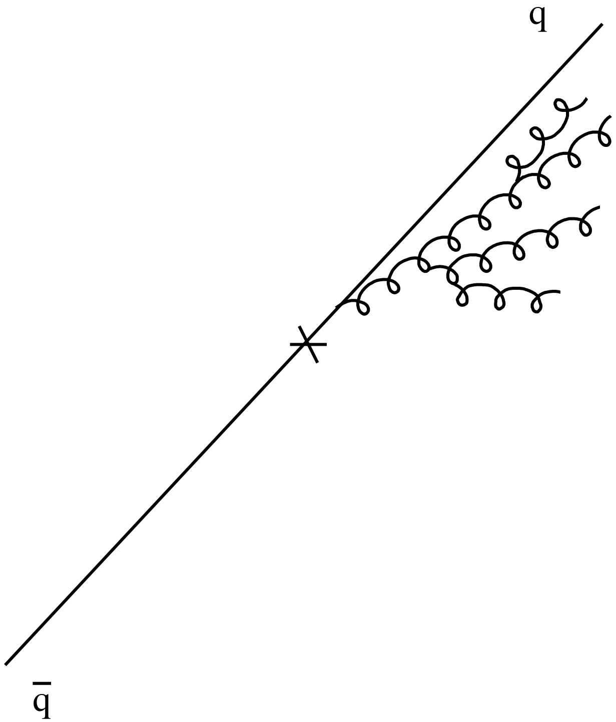


It radiates a further gluon

Image Credits: G.Salam

Picturing a (simple) QCD event

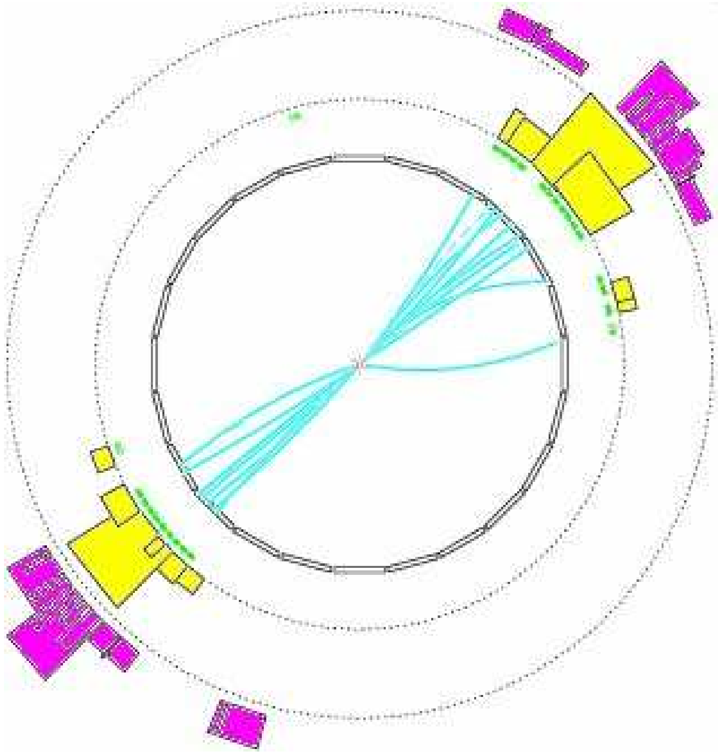


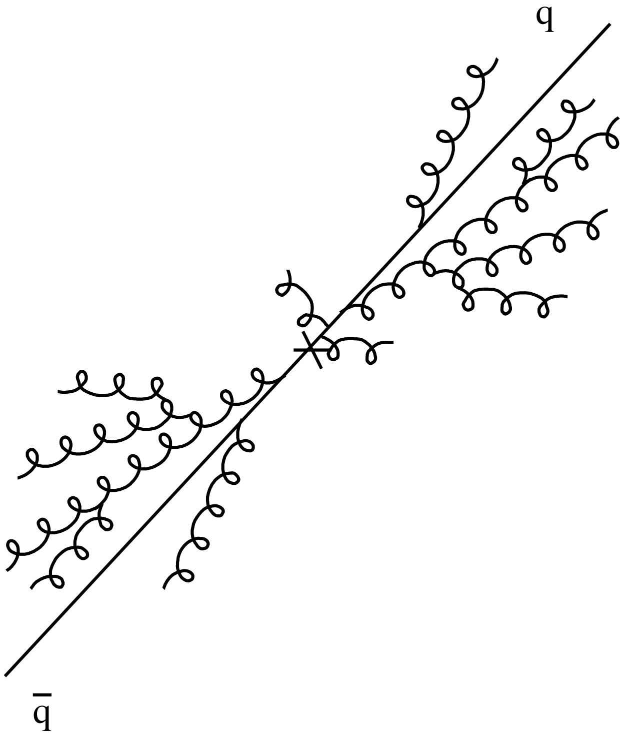


And so forth

Image Credits: G.Salam

Picturing a (simple) QCD event

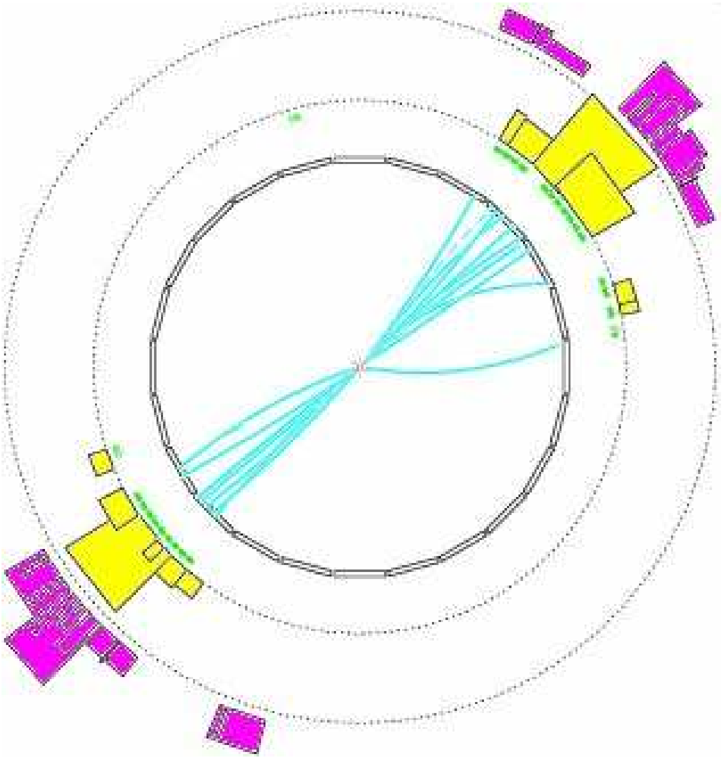


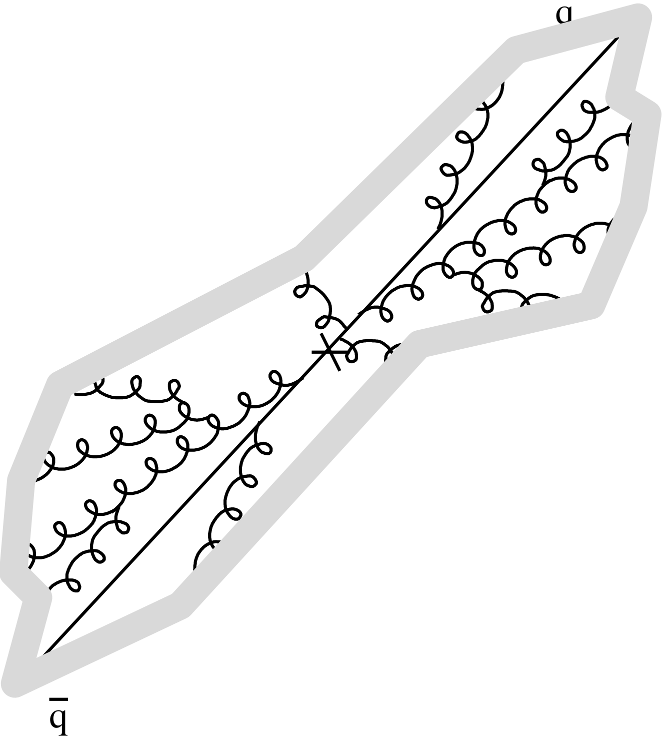


Meanwhile the same happened on other side of event

Image Credits: G.Salam

Picturing a (simple) QCD event

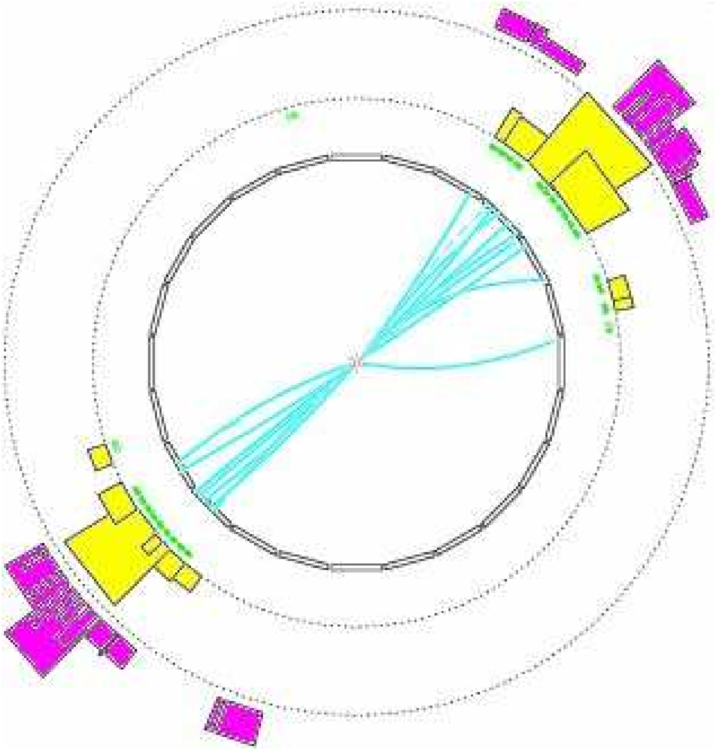


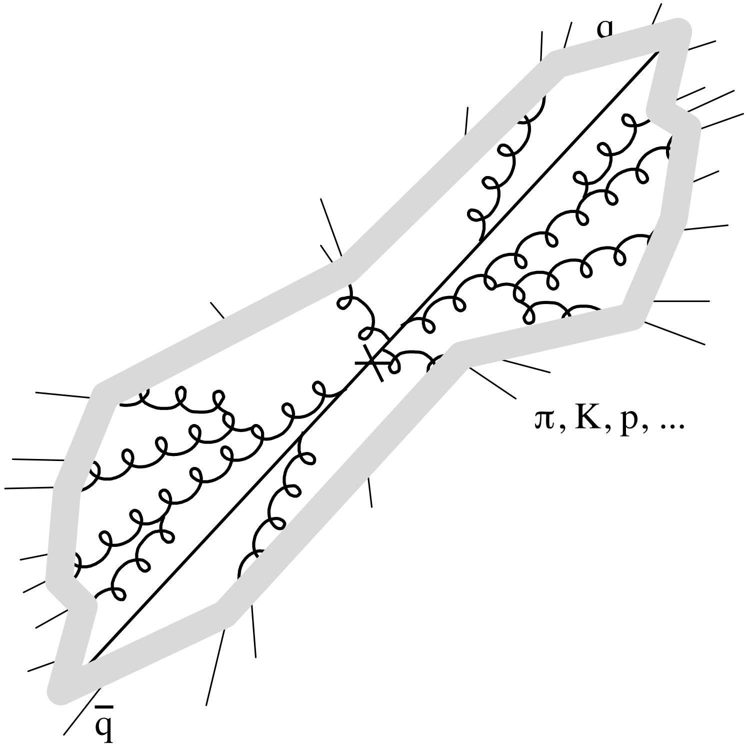


And then a non-perturbative transition occurs

Image Credits: G.Salam

Picturing a (simple) QCD event





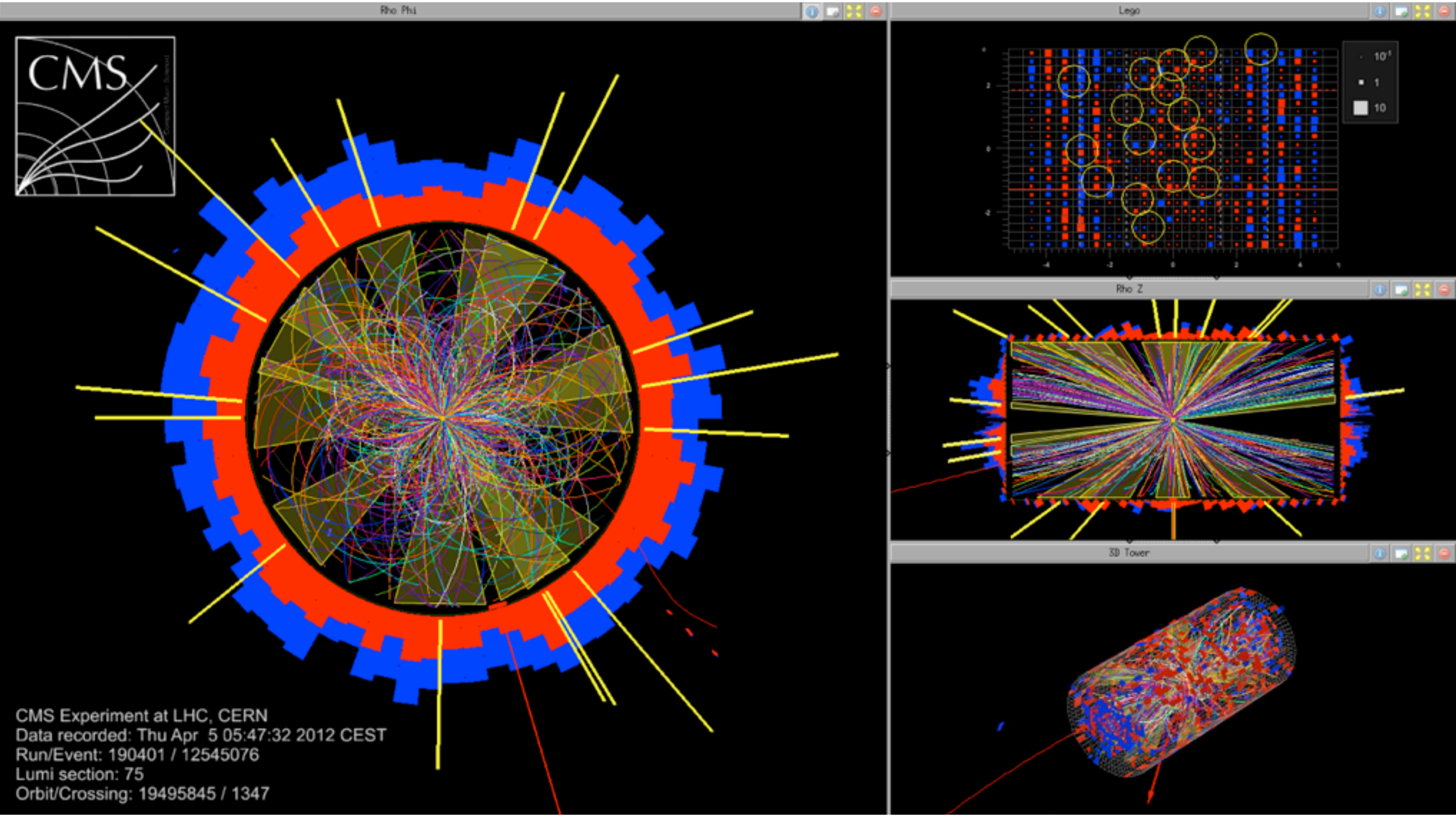
Giving a pattern of hadrons that "remembers" the gluon branching

Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy

Jets: collimated, energetic bunches of particles

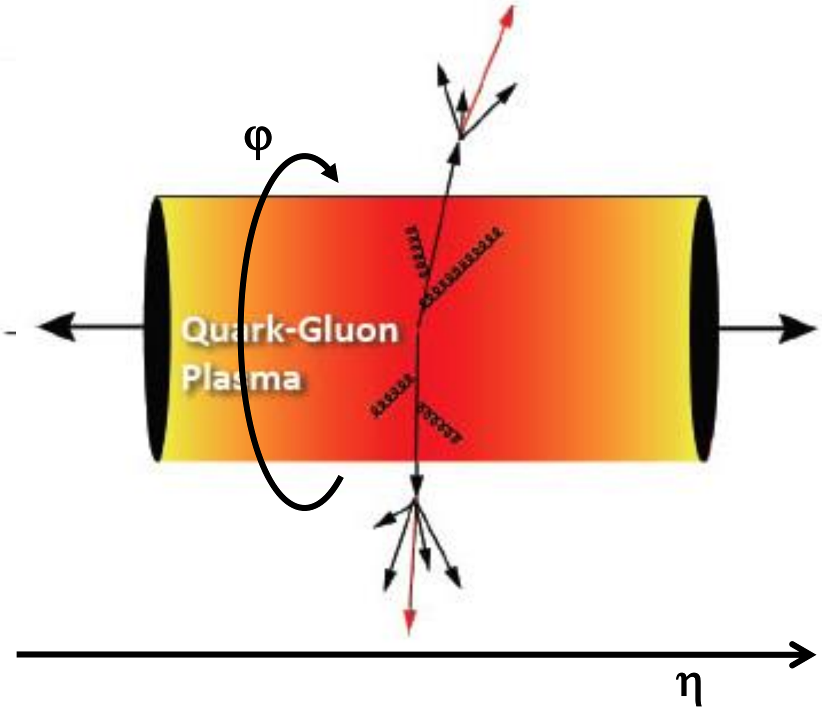
Image Credits: G.Salam

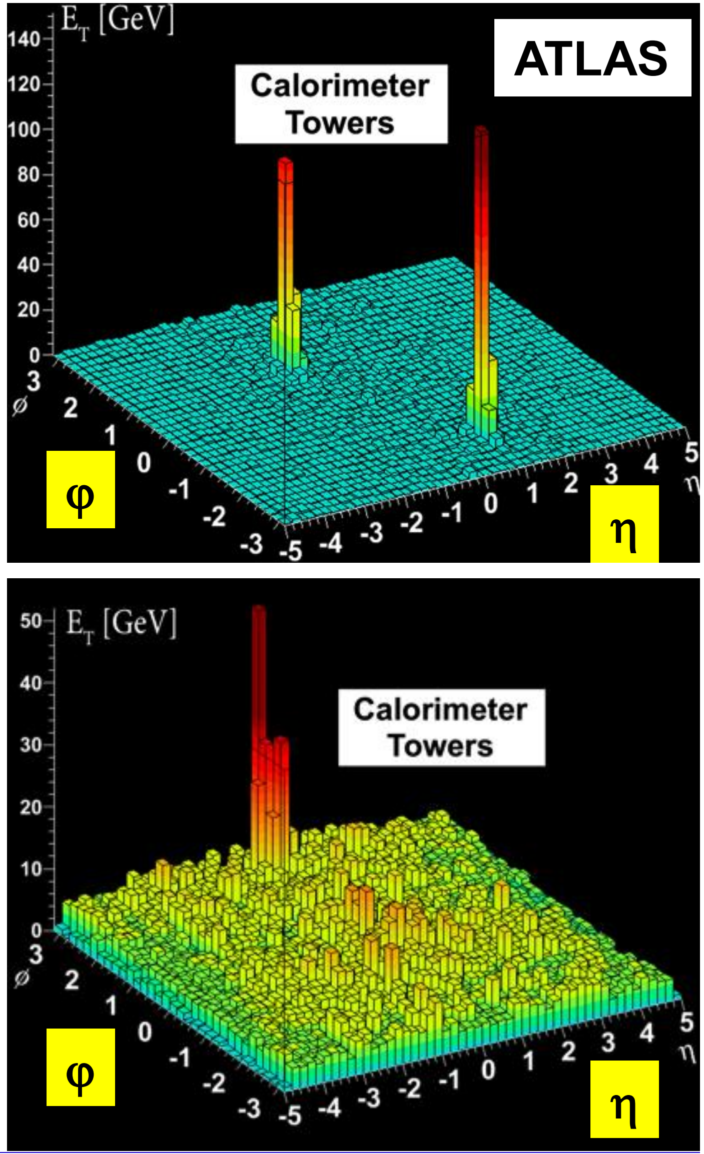
PbPb, where are the jets?



Underlying events cause locally, fluctuating, high background

A Back-to-Back Jet





One jet disappears in the QGP
→ "Jet quenching"

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

Dijet Asymmetry

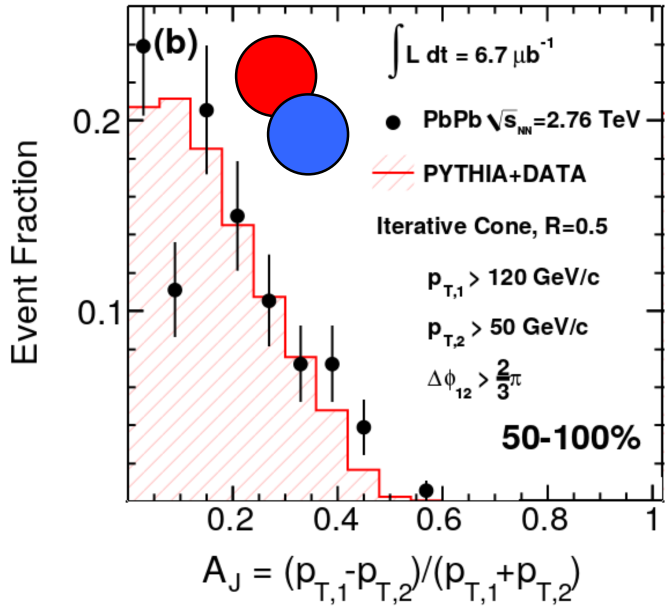
- How often do jets lose lot of energy?
- Quantify by dijet asymmetry
- 2 highest energy jets with $\Delta\varphi > 2\pi/3$

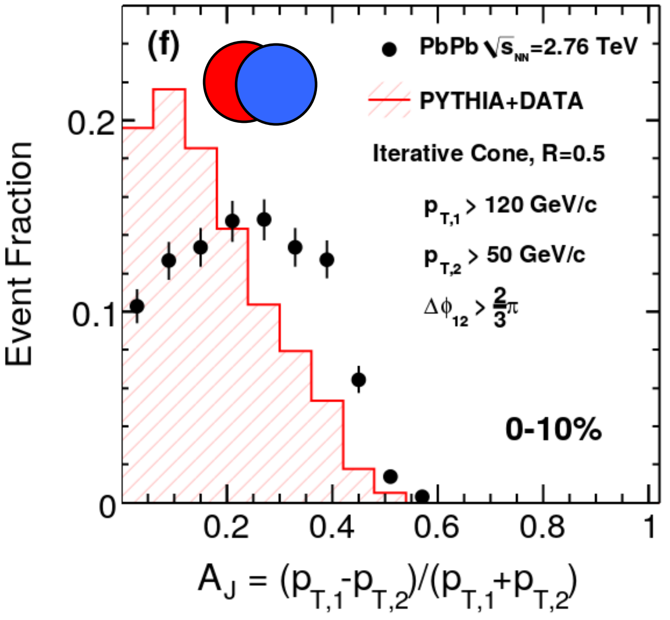
$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

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

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

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





PRC 84 (2011) 024906
PRL105:252303,2010

Dijet Asymmetry

- How often do jets lose lot of energy?
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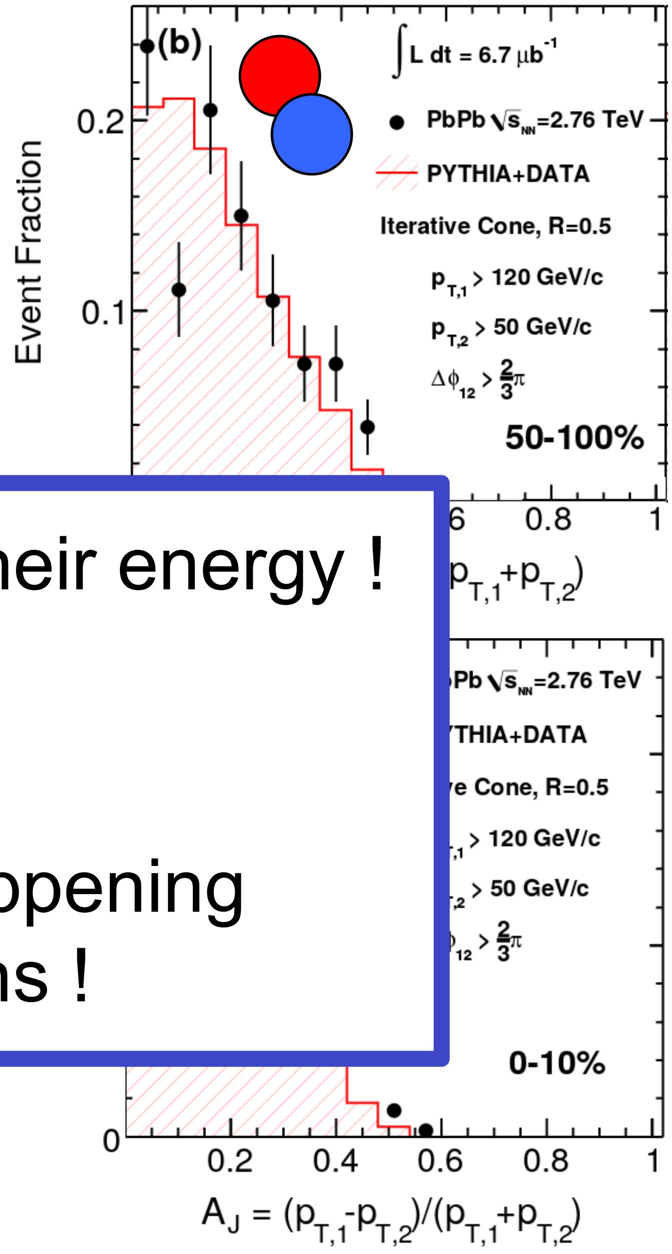


A_J

- P
- C
  d

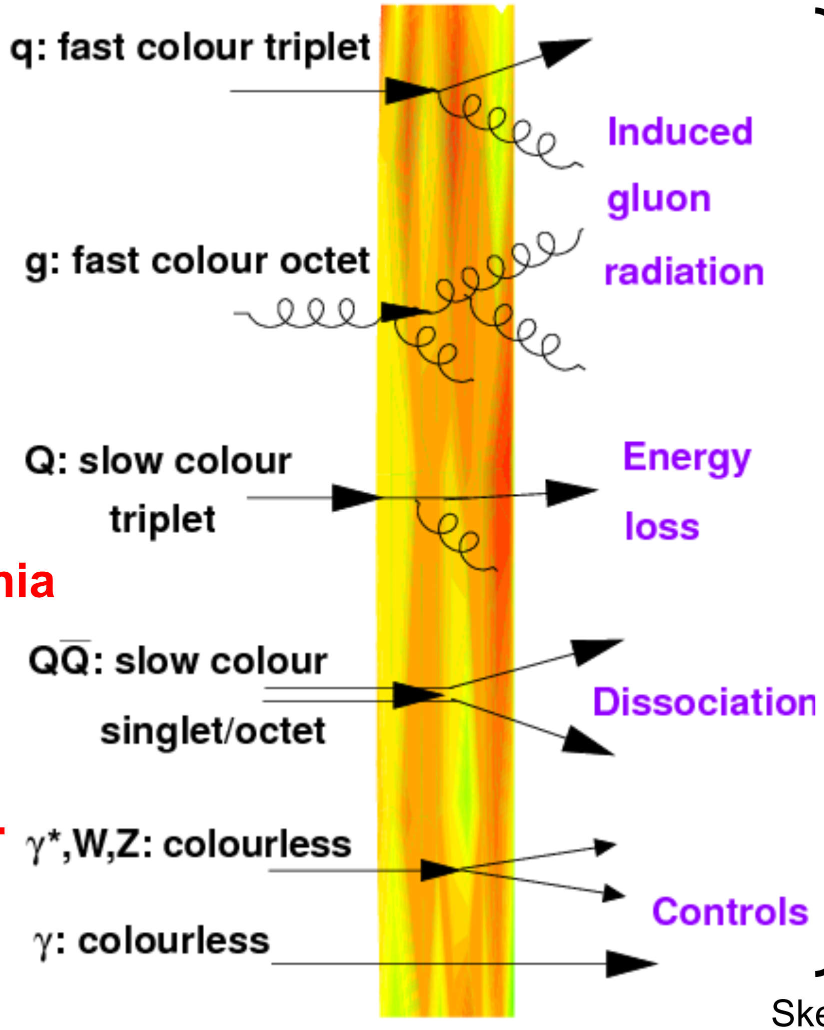
Jets lose up to two thirds of their energy !

Something significant happening
in heavy-ion collisions !

PRC 84 (2011) 024906
PRL105:252303,2010

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

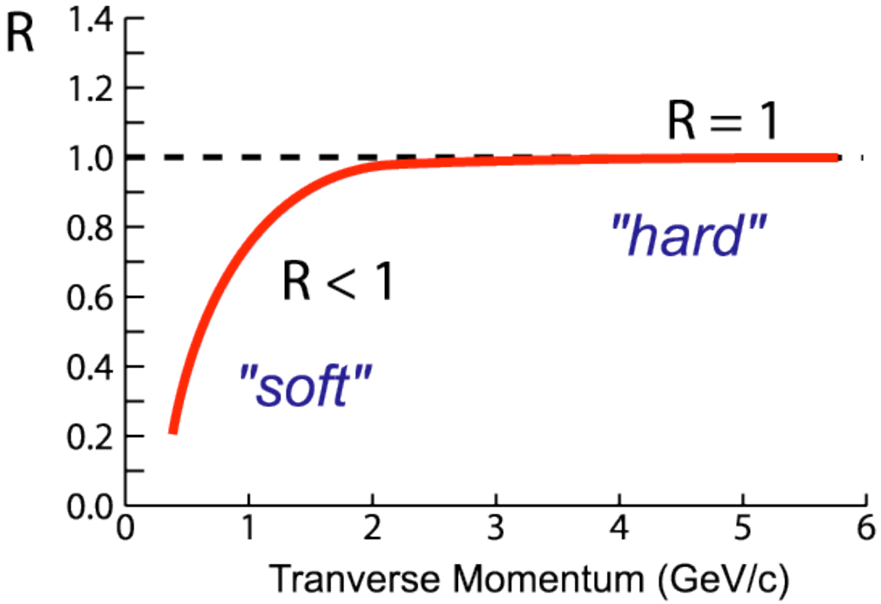
Sketch: d'Enterria: arXiv:1207.4362

The nuclear modification factor

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{Yield(Pb+Pb)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

Average number of NN collisions in PbPb



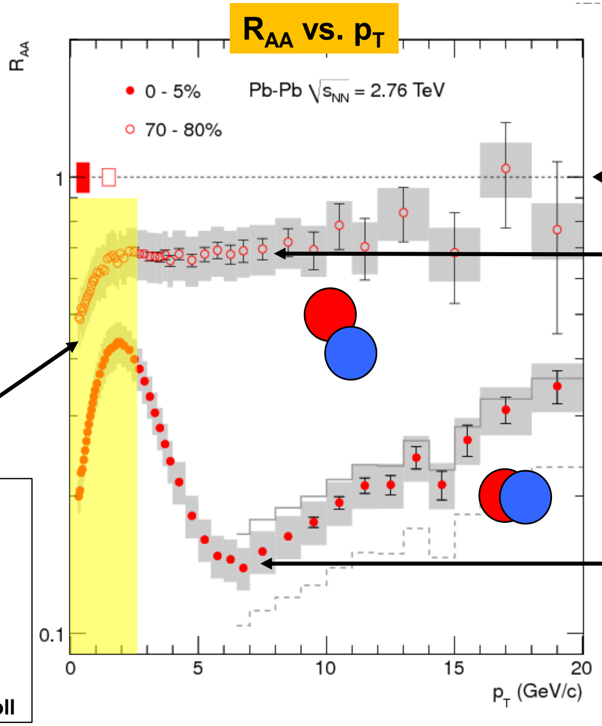
In case of “No Effect”:
-R<1 at small momenta, production from thermal bath
-R=1 at higher momenta where hard processes dominate

but if R<1 at high momenta, hot and dense medium is affecting the parton propagation

Strong suppression for hadrons

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{Yield(Pb+Pb)}{Yield(p+p) \times \langle N_{coll} \rangle}$$



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

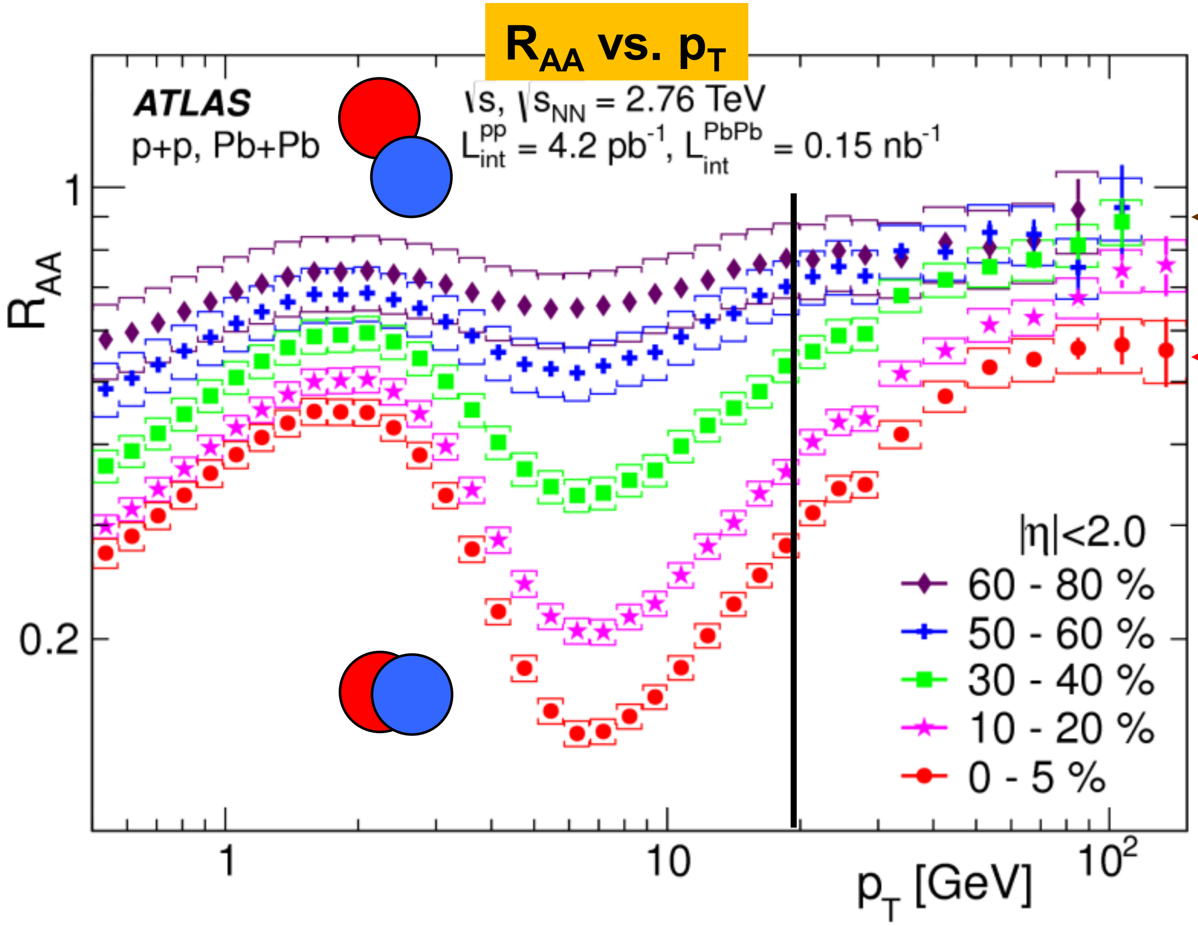
Soft particle production does not scale with N_{coll}

ALICE, PLB696 (2011) 30

- Evidence for a strong parton energy loss and a large medium density at the LHC
- Behaviour reproduced by all models/calculations. R_{AA} alone is not highly discriminating

Hadrons constrain the parton kinematics very loosely → Jets can capture the modified fragmentation process of partons: high-p_T partons interact strongly with QCD medium prior to fragmentation

R_{AA} at High p_T



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

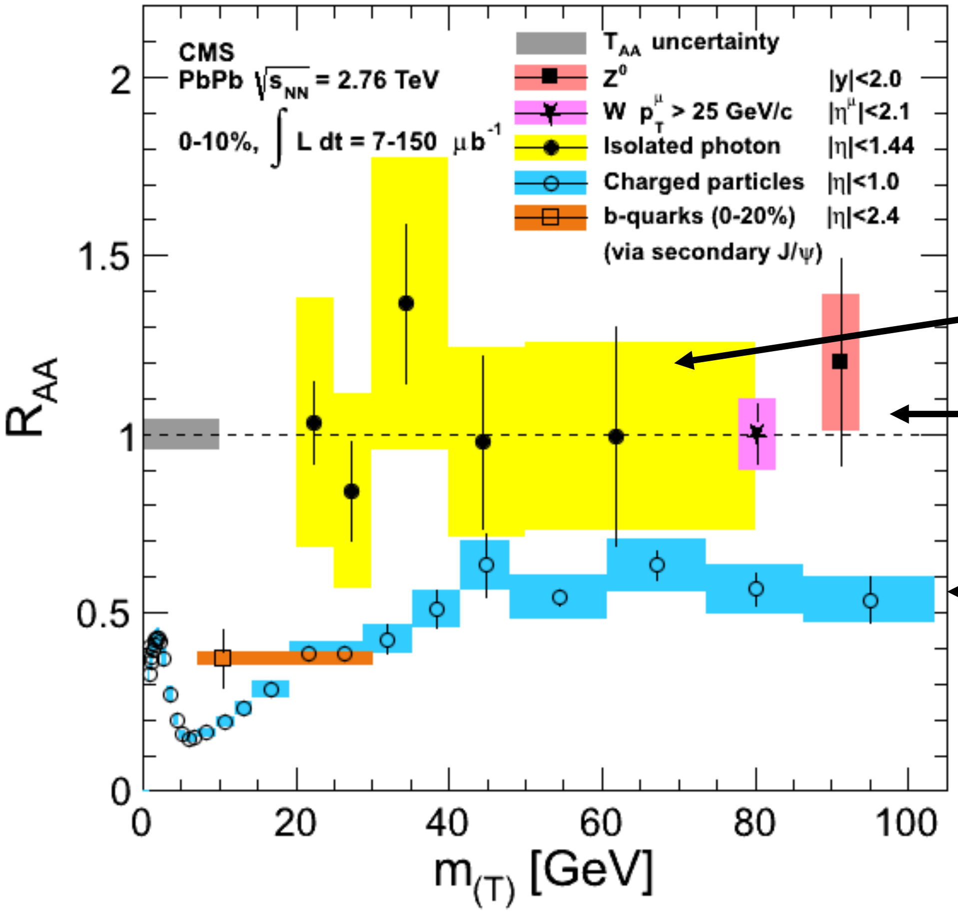
0-5% (central)
→ R_{AA} increases up to 0.6

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

R_{AA} for vector bosons

Fundamental check:

Electroweak probes are unmodified → the interacting medium is colored, interacting strongly



Photons

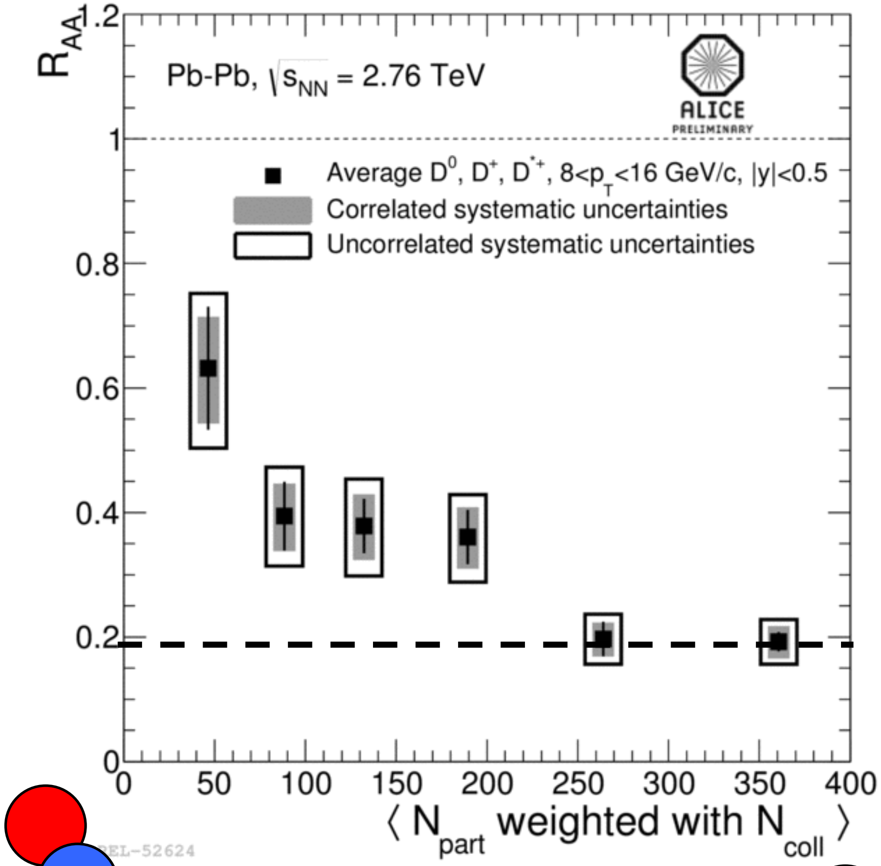
W, Z^0

charged particles

D R_{AA}

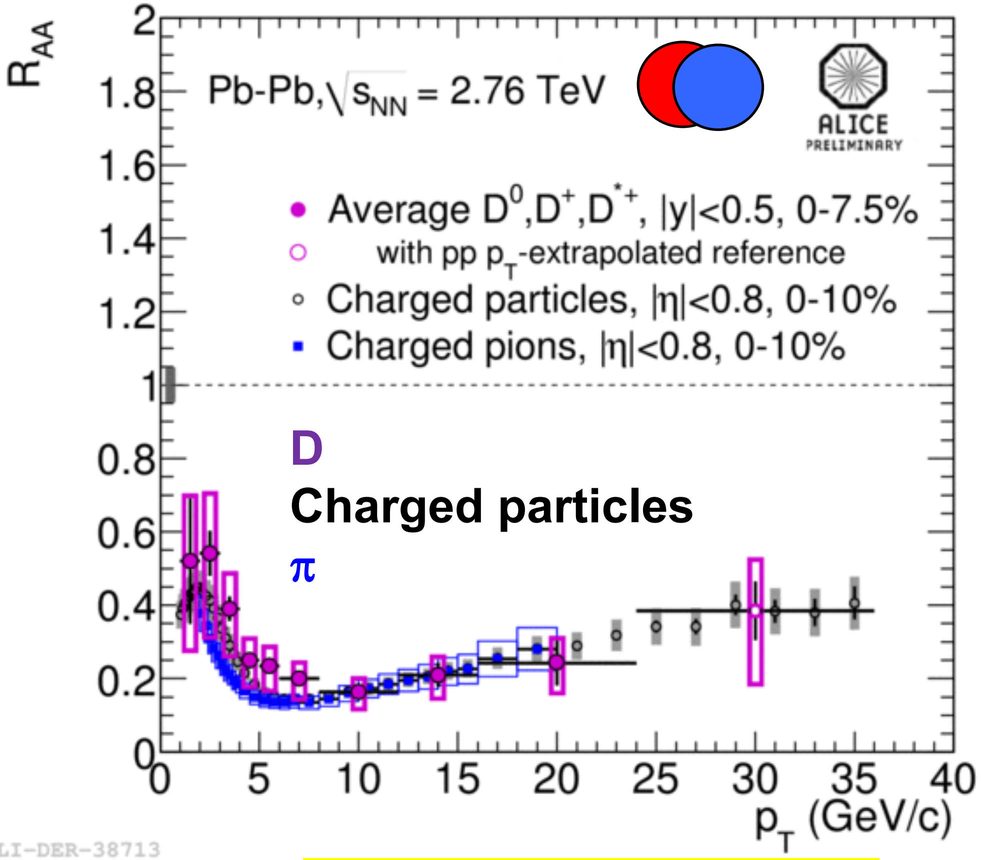
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$

R_{AA} vs. centrality



strong suppression ~ 0.2

R_{AA} vs. p_T



D and π R_{AA} compatible

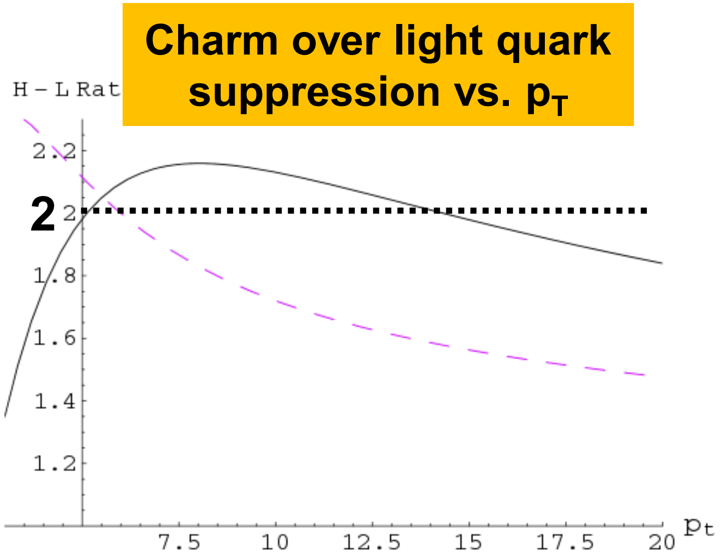
arXiv:1506.06604

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

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

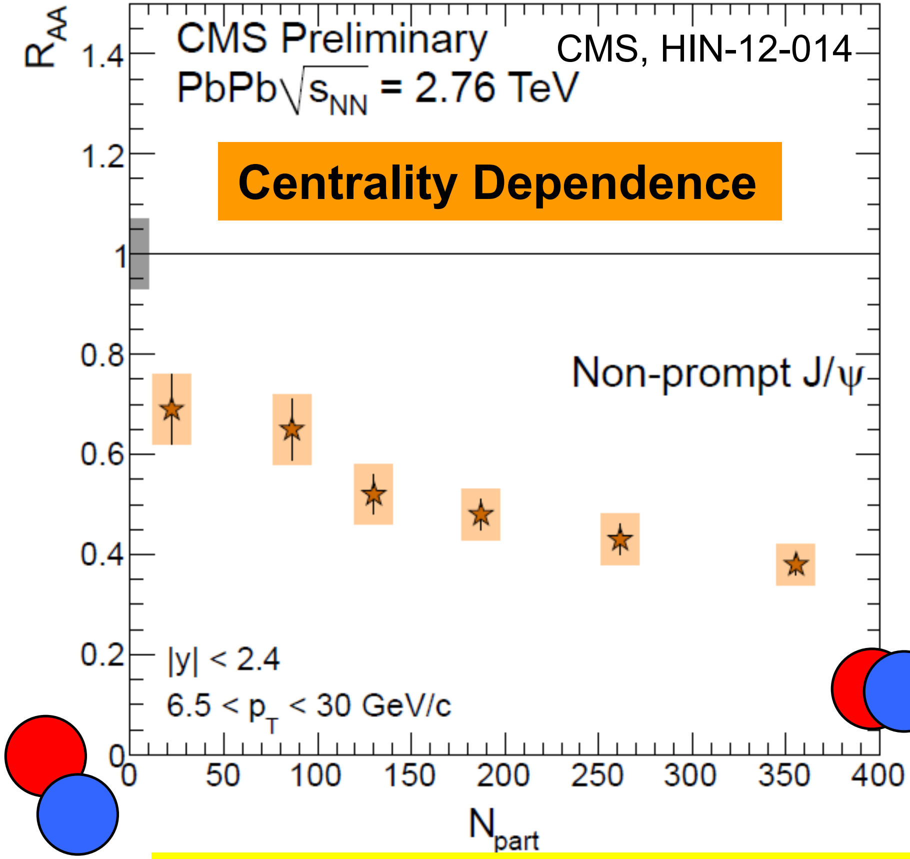


Charm over light quark suppression vs. p_T

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

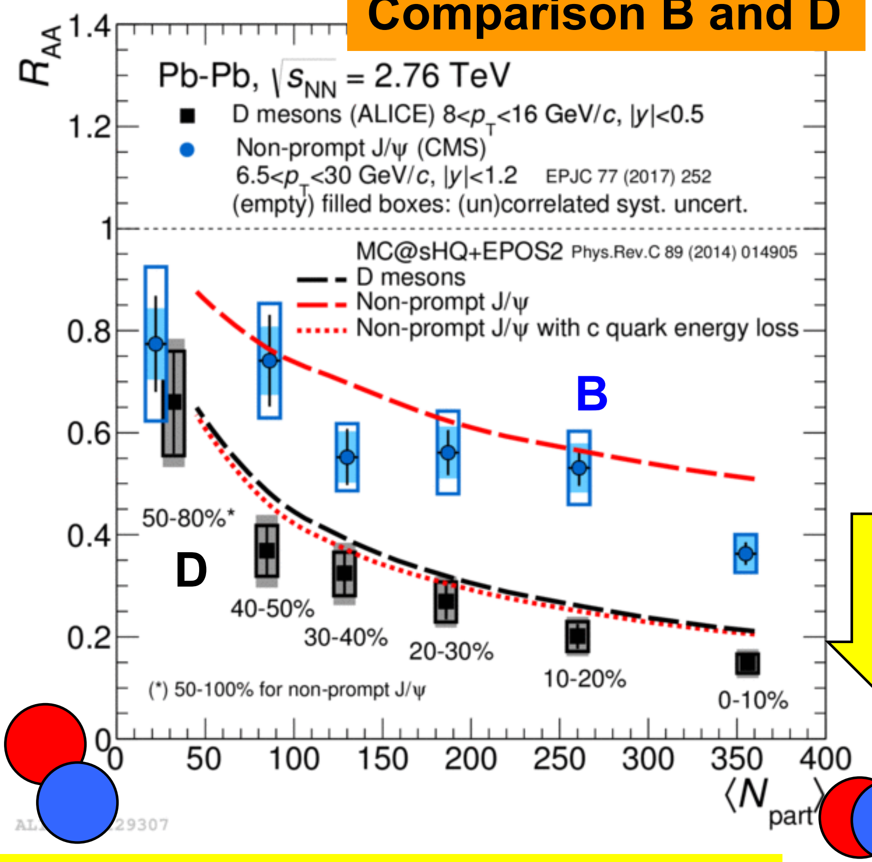
B R_{AA}

$B^{\pm}$ → (J/ψ → μμ) + X identified by displaced secondary vertices (see backup)



Centrality Dependence

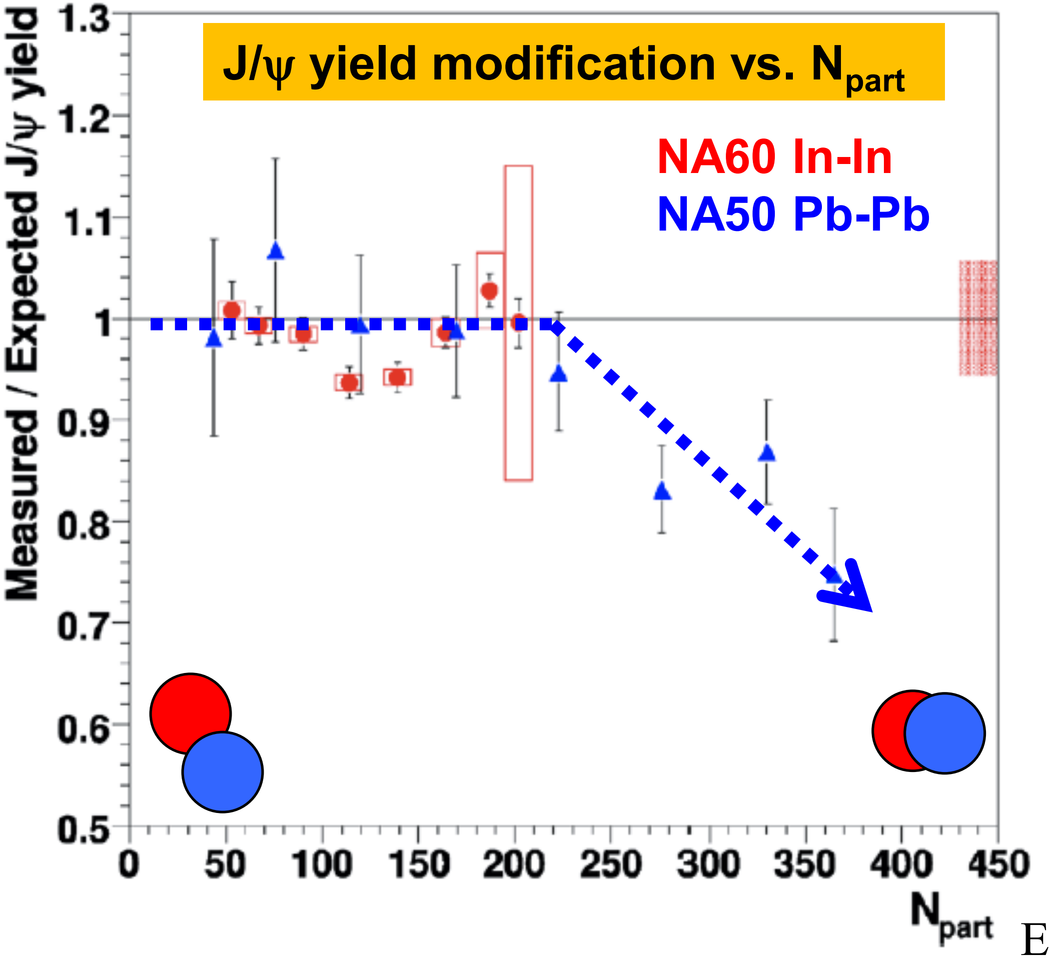
Comparison B and D



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

J/ψ Suppression

- Observed at SPS in Pb-Pb collisions ($\sqrt{s_{NN}}$ = 17 GeV)

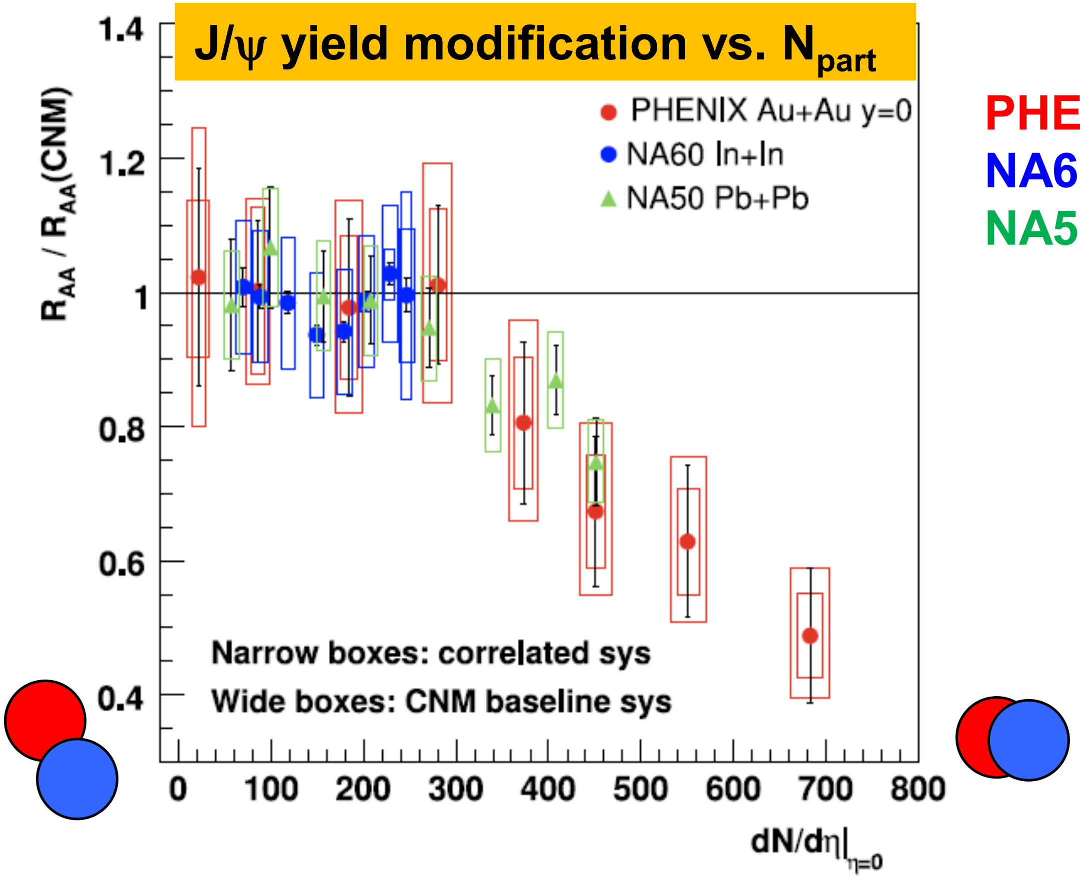


In: A = 105
Pb: A = 208

EPJC (2011) 71:1534

J/ψ Suppression (2)

- … and at RHIC ($\sqrt{s_{NN}}$ = 200 GeV)



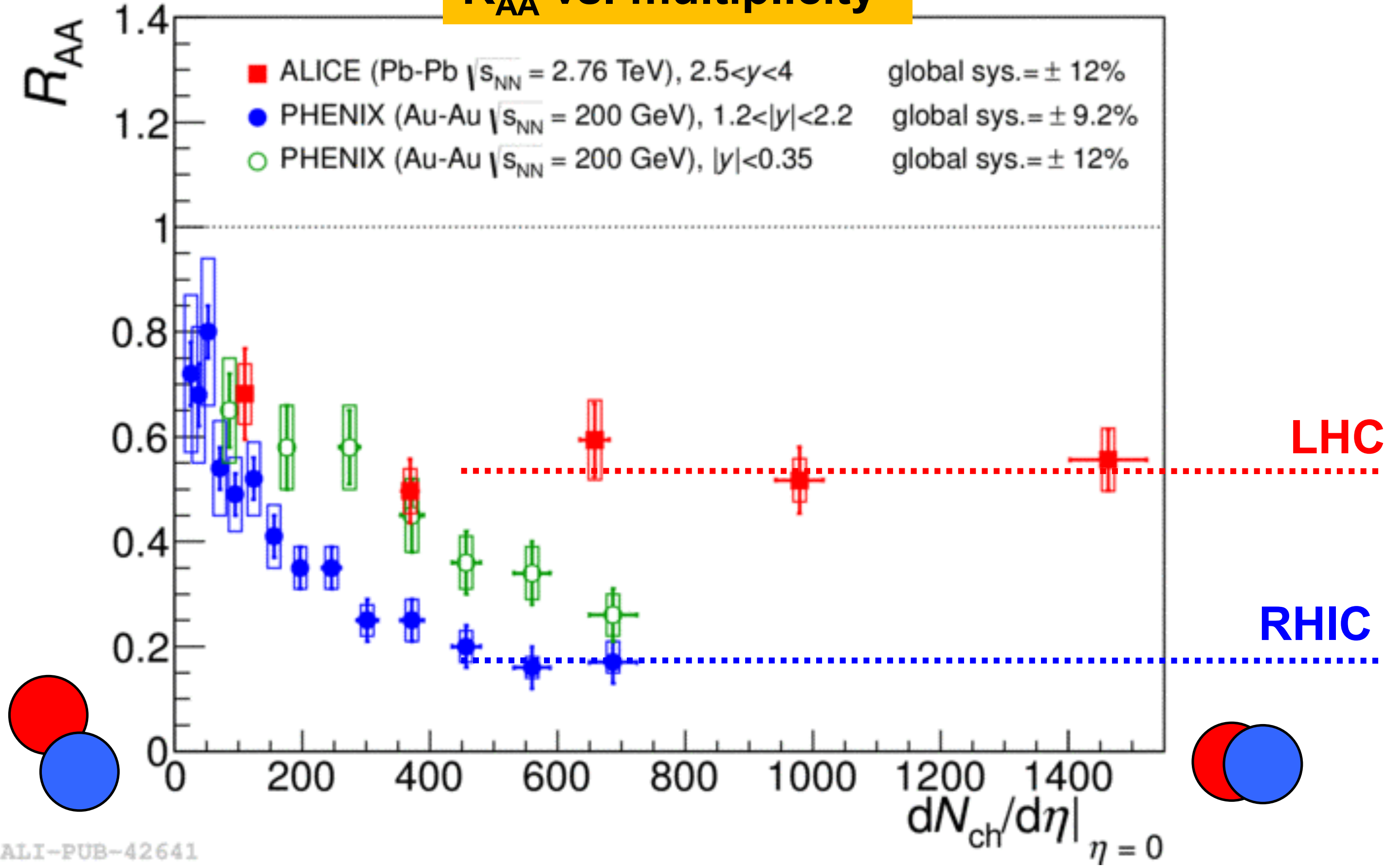
J/ψ yield modification vs. N_{part}

PHENIX Au-Au
NA60 In-In
NA50 Pb-Pb

Wouldn't we expect a stronger suppression at larger $\sqrt{s_{NN}}$?

J/ψ Suppression (3)

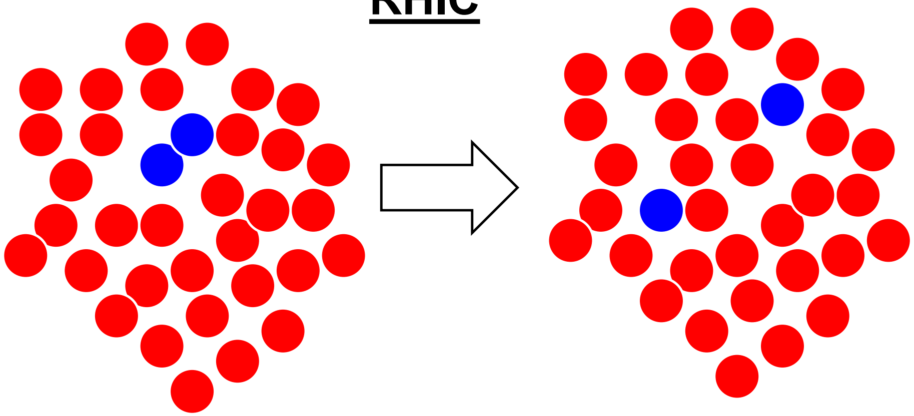
R_{AA} vs. multiplicity



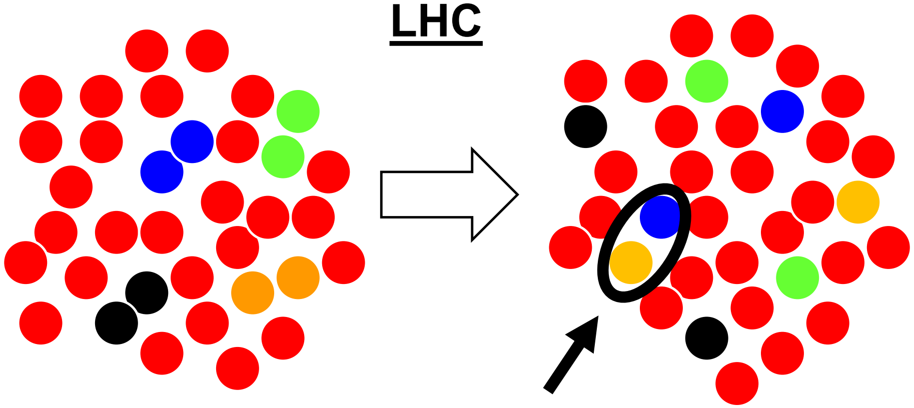
LHC → RHIC : $\sqrt{s_{NN}}$ 14 times larger … but the suppression is smaller !

J/ψ Regeneration

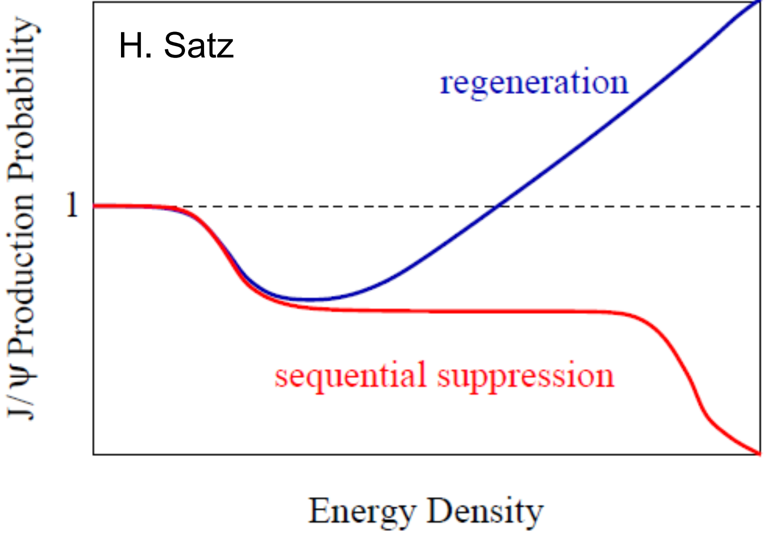
RHIC



LHC



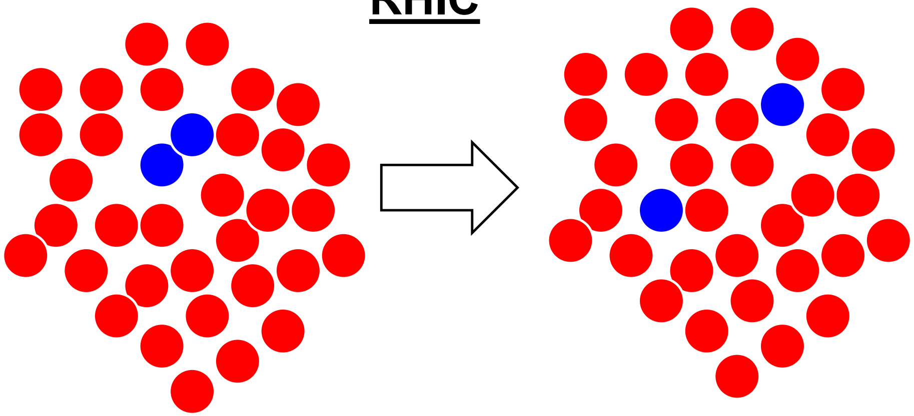
J/ψ modification vs. energy density



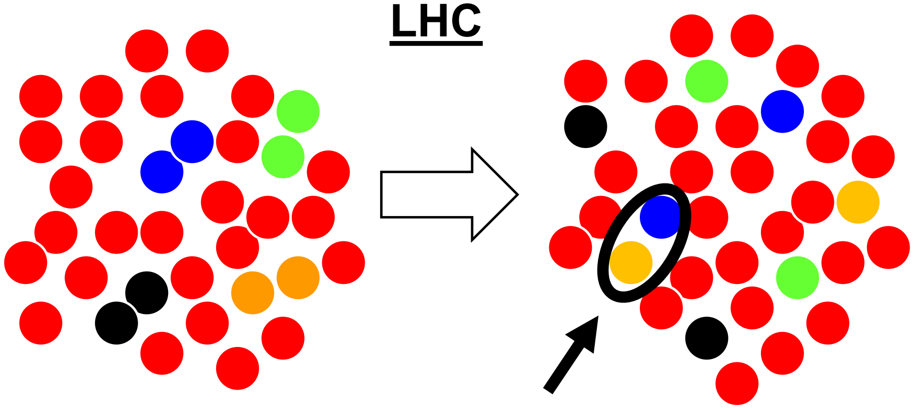
Dissociation and regeneration work in opposite directions

J/ψ Regeneration

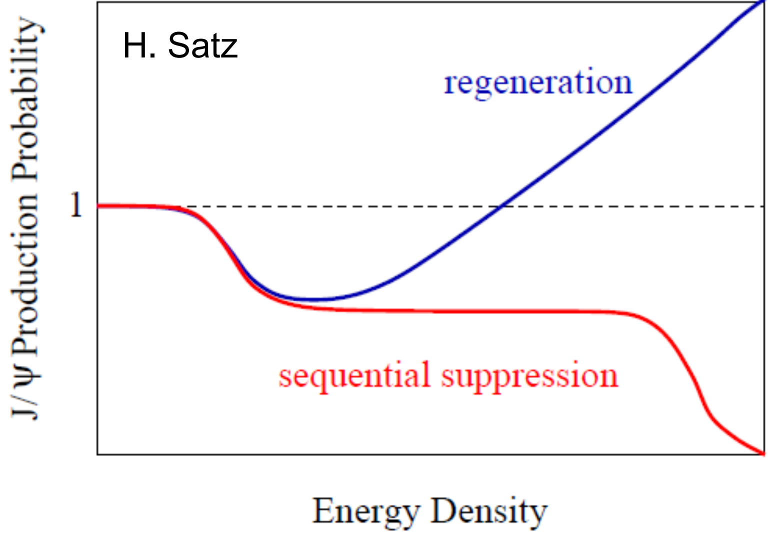
RHIC



LHC



J/ψ modification vs. energy density

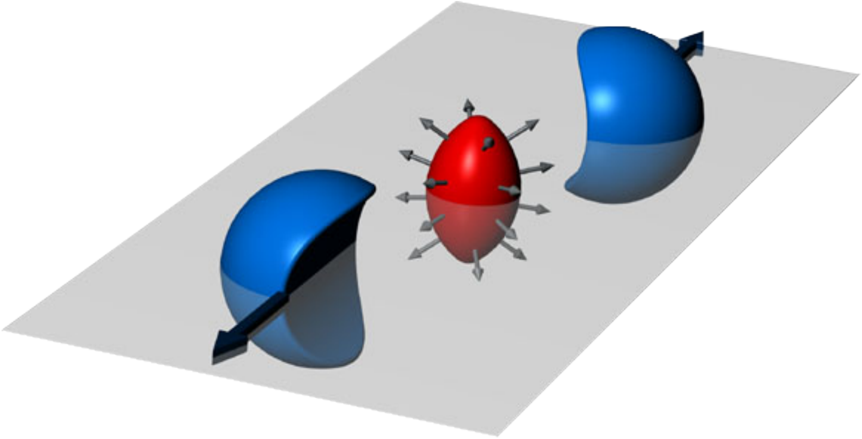


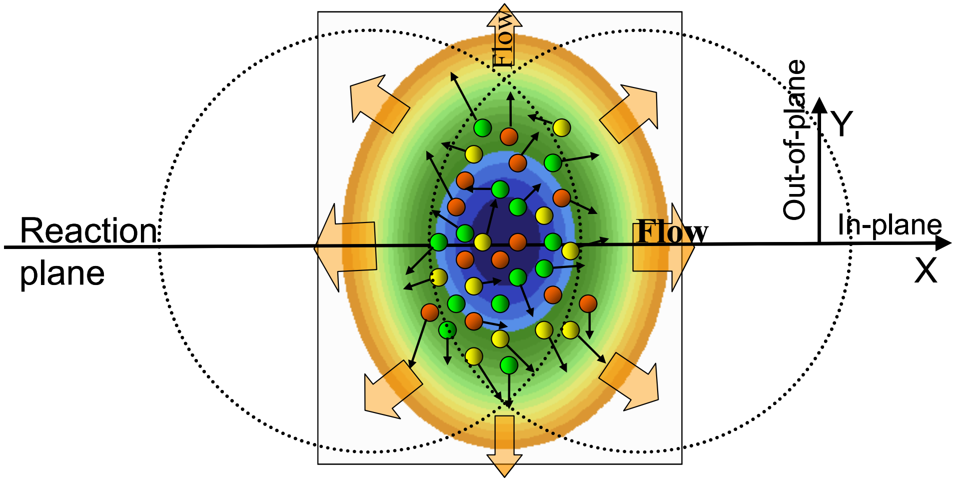
Dissociation and regeneration work in opposite directions

Other quarkonia states melt at different temperatures
→ QGP thermometer

Particle correlations: Elliptic Flow

Non-central collisions are azimuthally asymmetric



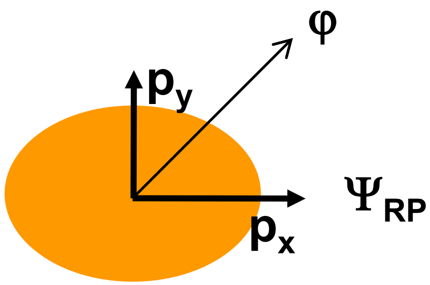


The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

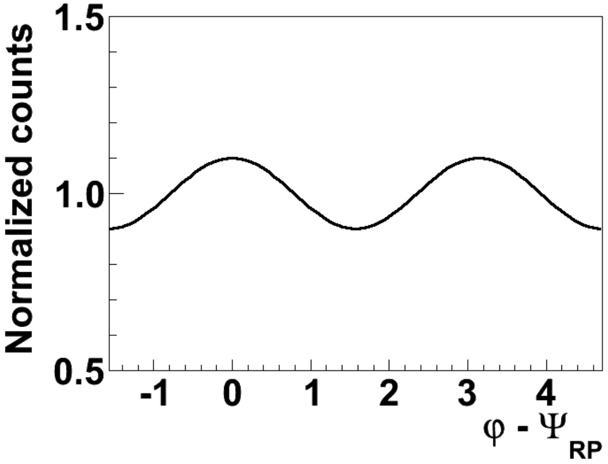
- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path
  - larger density gradient -> larger pressure gradient -> larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)

Elliptic Flow

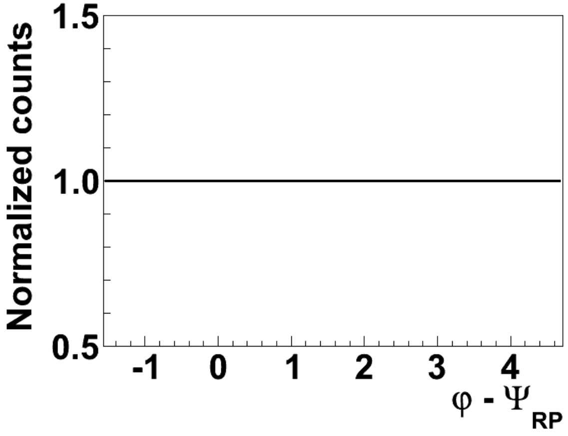
- Particles as a function of $\varphi - \Psi_{RP}$



$$\frac{dN}{d\varphi} = A\left(1 + 2v_2 \cos 2(\varphi - \Psi_{RP})\right)$$

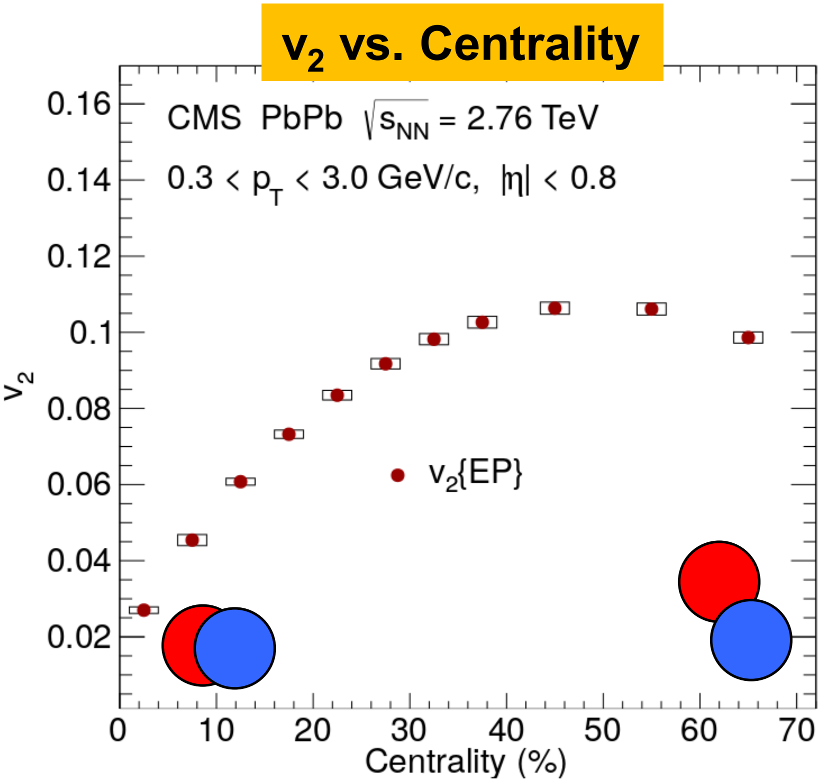


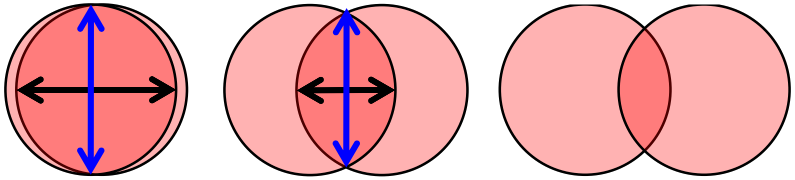
- Define $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$
  - Second coefficient of Fourier expansion
- Ψ_{RP} common *symmetry plane* (for all particles)
- What if there were no correlations with Ψ_{RP}?



Centrality Dependence

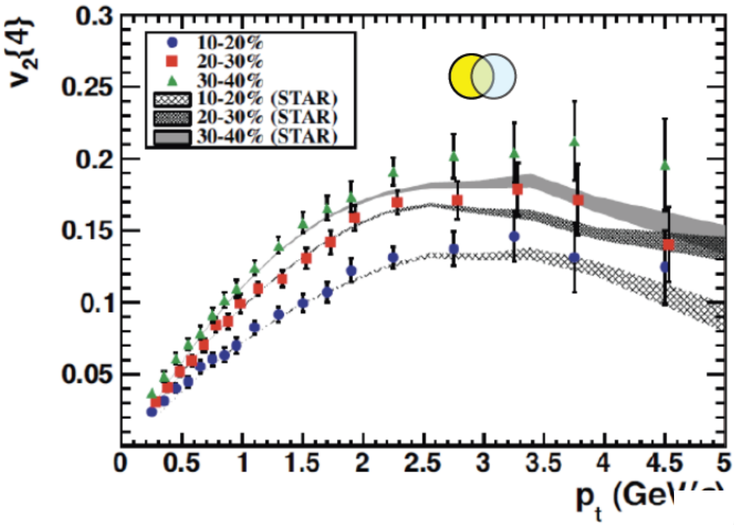
- Strong centrality dependence
- v_2 largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions





CMS, PRC 87(2013) 014902

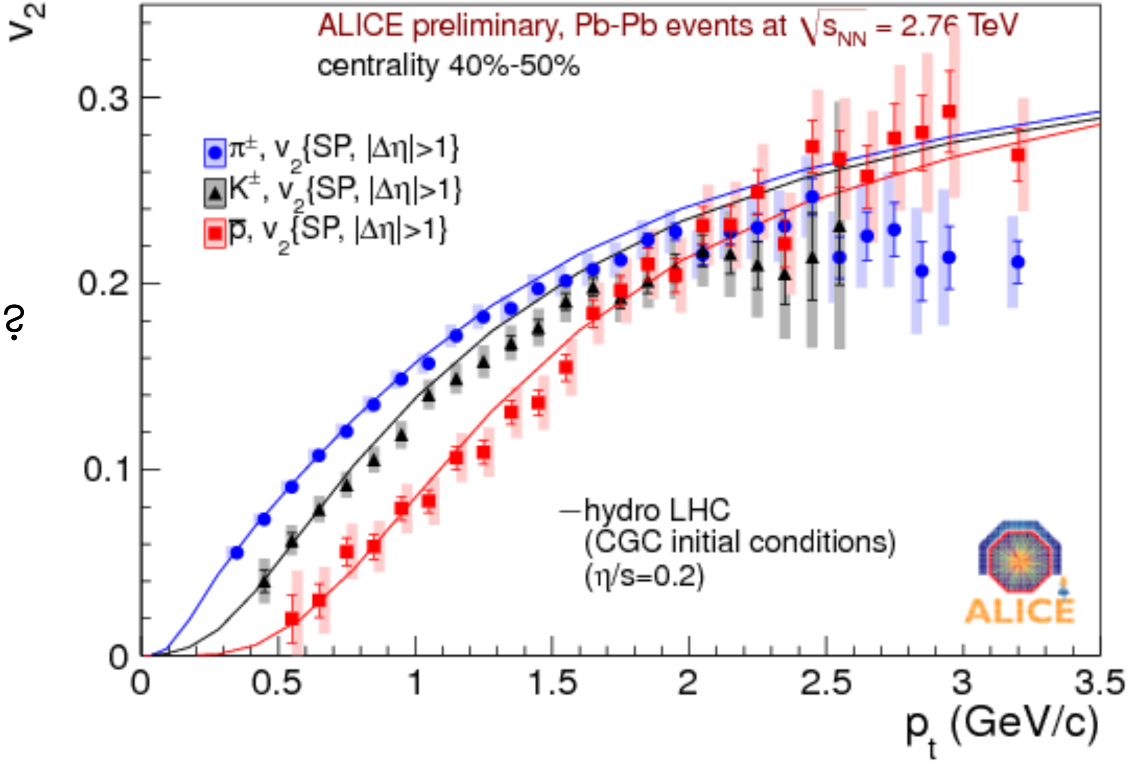
$v_2(p_T)$ very similar at LHC and RHIC



- system still have low viscosity
- similar behaviour

azimuthal asymmetry almost as large as expected at hydro limit! … "perfect liquid"?

very far from "ideal gas" picture of plasma



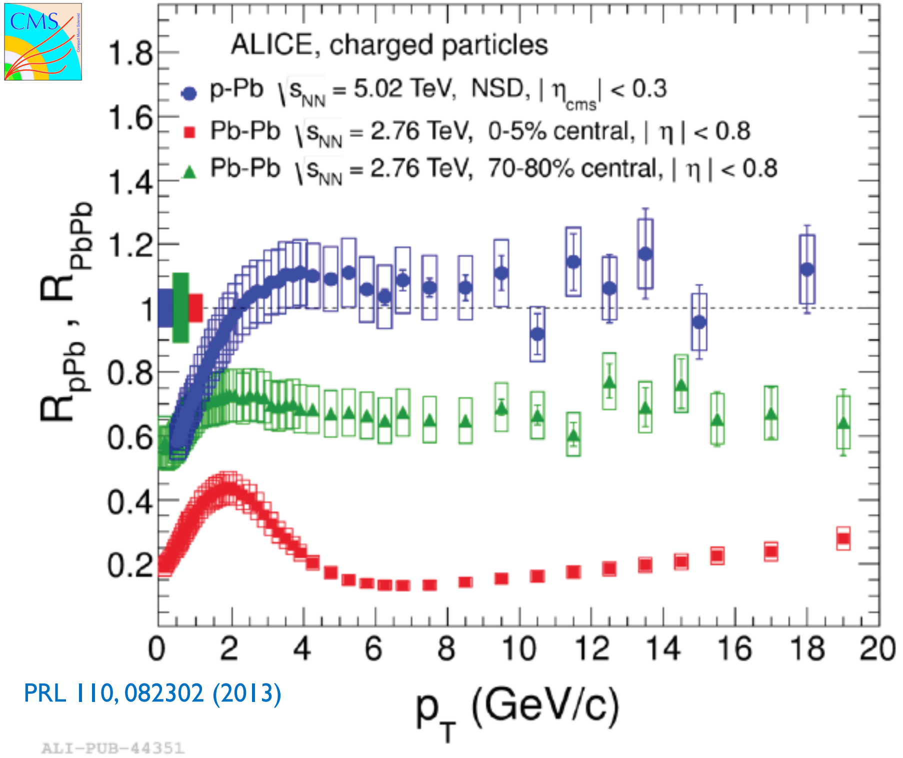
We have a liquid of quarks and gluons!

The QGP is the perfect liquid!

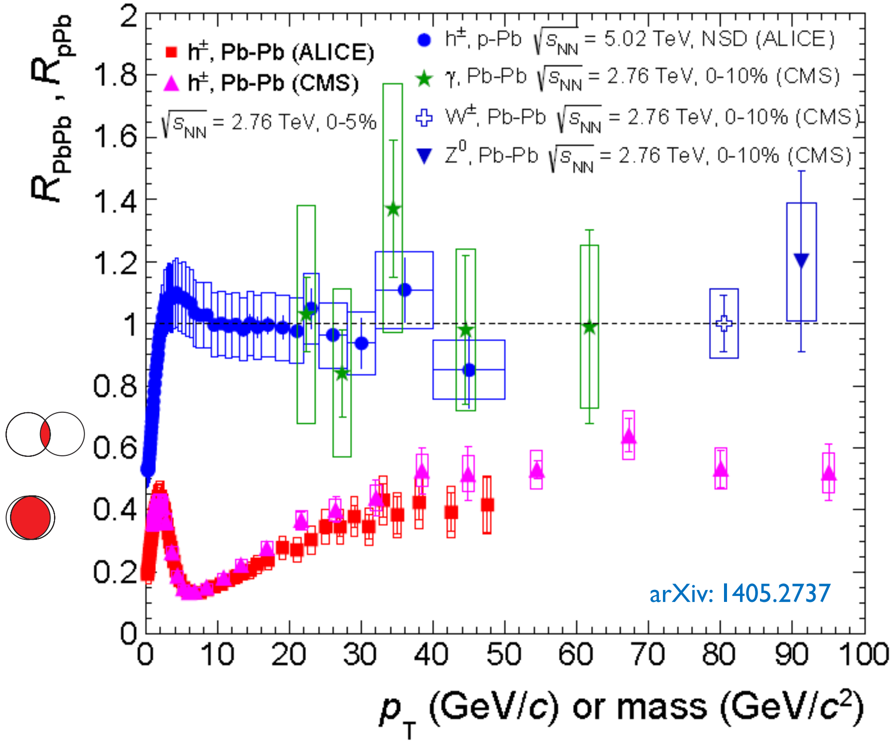
(not the gas of “free” quarks and gluons we expected)

Particles through Pb-Pb and p-Pb

Nuclear Modification Factor: $R_{AA}(p_T) = \dfrac{Yield(Pb+Pb)}{Yield(p+p)\times\langle N_{coll}\rangle}$



PRL 110, 082302 (2013)



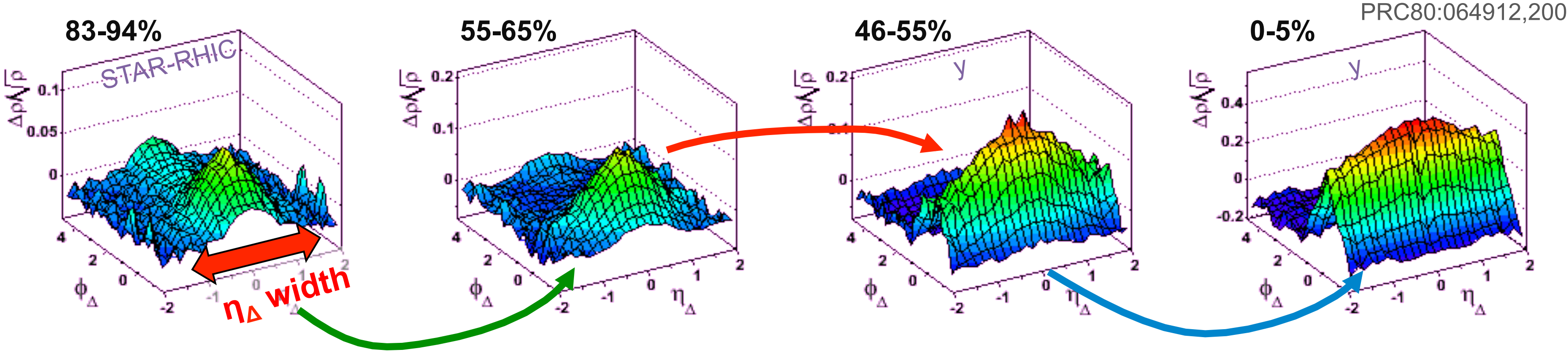
arXiv: 1405.2737

- Strong suppression of charged hadrons in Pb-Pb (wrt pp) up to very high momenta

- Direct photons, W and Z are not quenched … reference particles

- p-Pb results (consistent with unity up to 50 GeV) confirm that strong suppression in Pb-Pb is due to hot nuclear matter effects

The ridge in A+A collisions

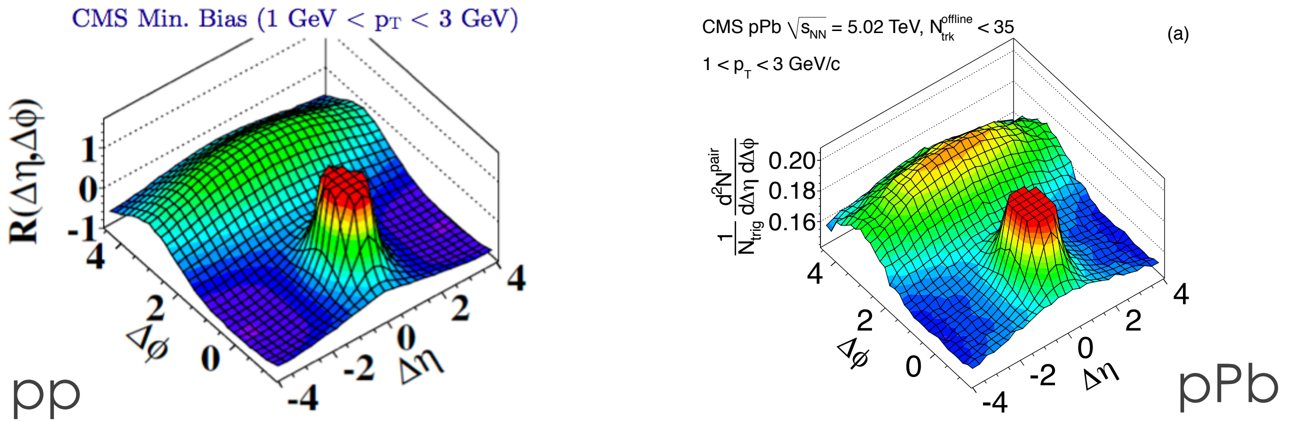


PRC80:064912,2009

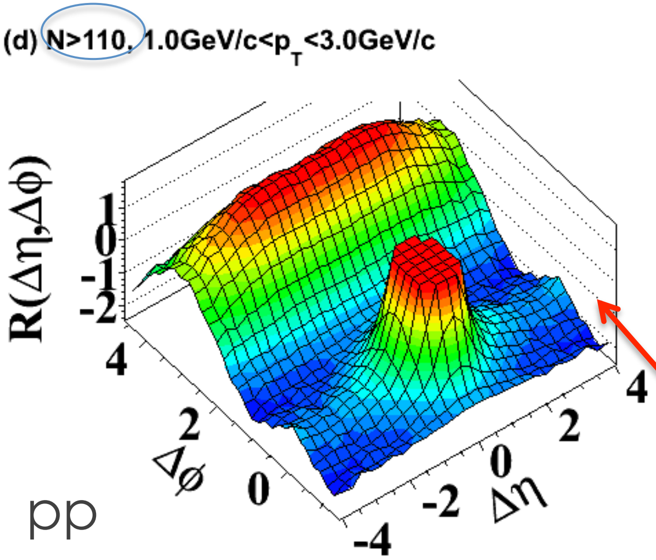
In (central) A+A, the ridge is commonly interpreted as hydrodynamic "hubble" flow of initial "stringy" structures in rapidity

The structures in the $\Delta\,\phi$ direction are decomposed and studied by the v_n Fourier "Flow moments"

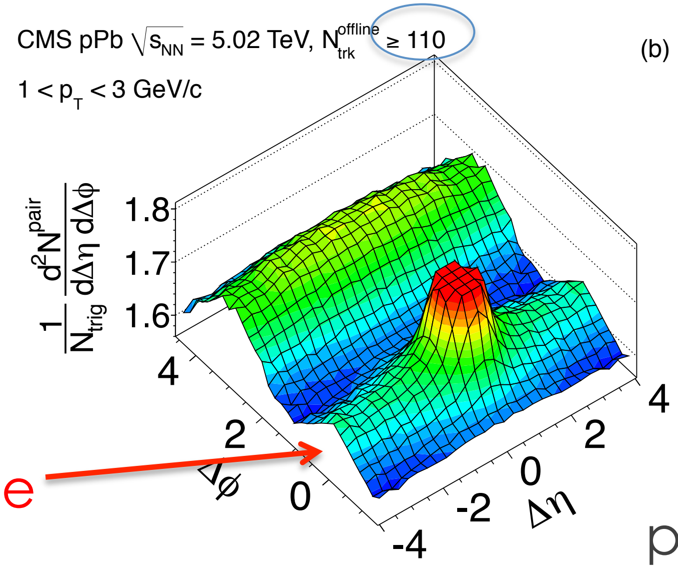
Not in pp (low multiplicity) neither in pPb (low multiplicity)



The discovery



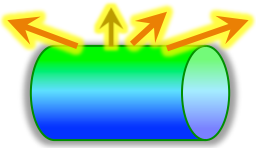
pp



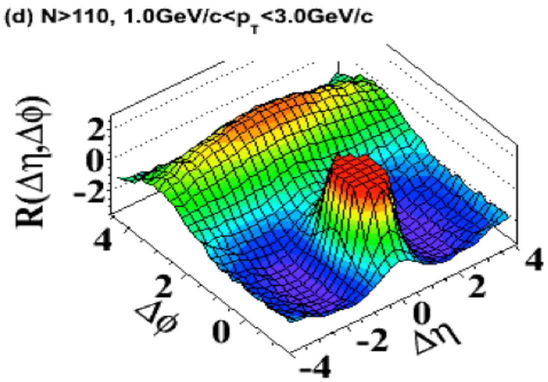
arXiv:1210.5482, PLB

pPp

Ridge



Distinct long range correlation in η collimated around $\Delta\Phi \approx 0$

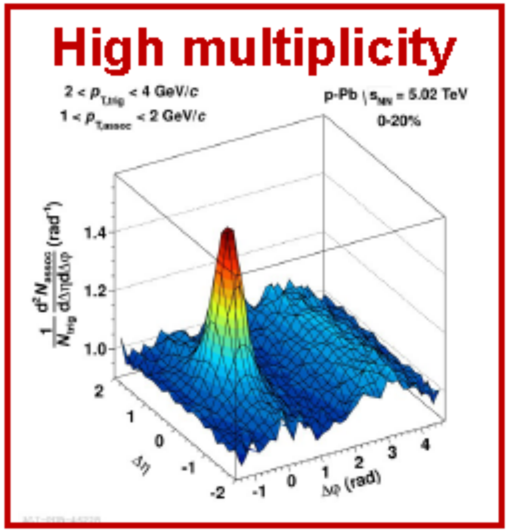


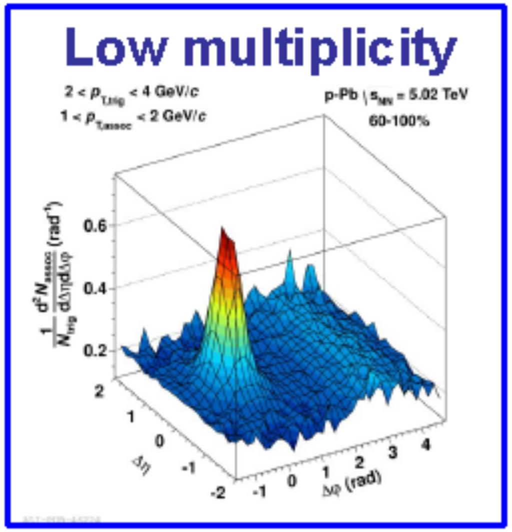
No ridge in MC

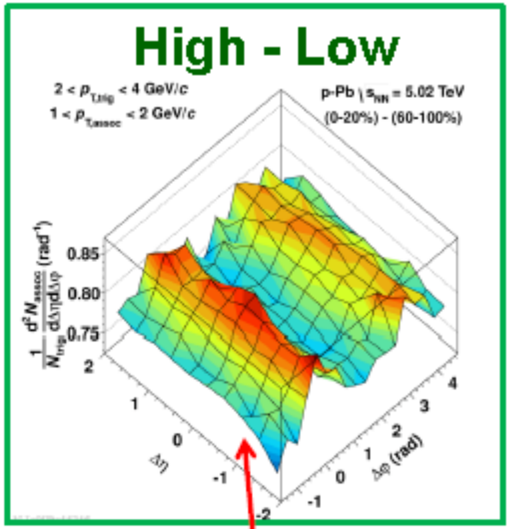
Similar for pPb (high mult), pp (high mult) and PbPb (peripheral)

Hydrodynamic flow in pp and pPb collisions?

Correlations: double ridge in p-Pb



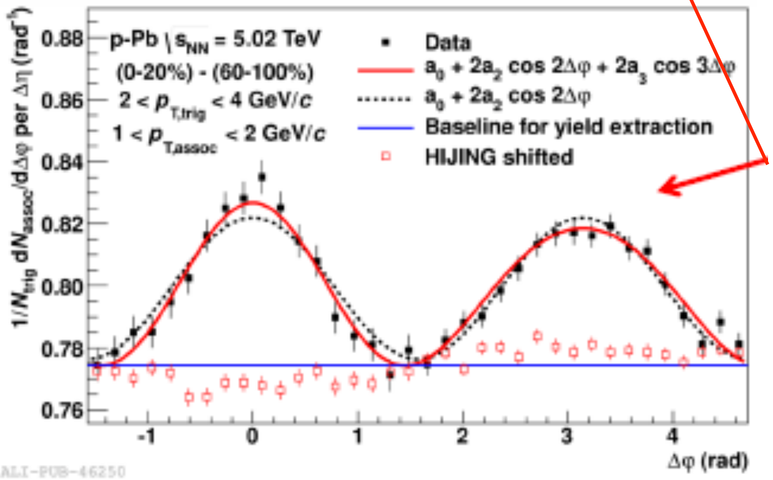




projected on Δφ

Double ridge described by both Color Glass Condensate (<u>initial state effect</u>) or hydrodynamics (<u>final state effect</u>)

PLB 719, 29 (2013)



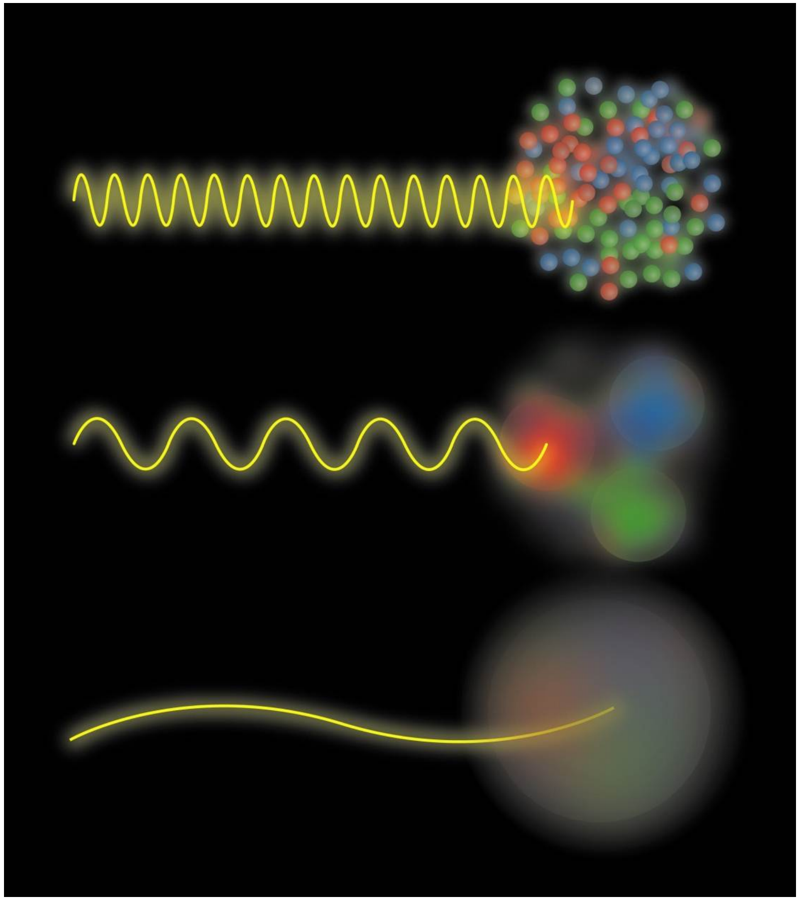
Why sometimes the particles fly in sync?

"The LHC may be uncovering a new deep internal structure of the initial protons … at these higher energies, one is taking a snapshot of the proton with higher spatial and time resolution than ever before"

Frank Wilczek

Let’s go back to “fundamentals”

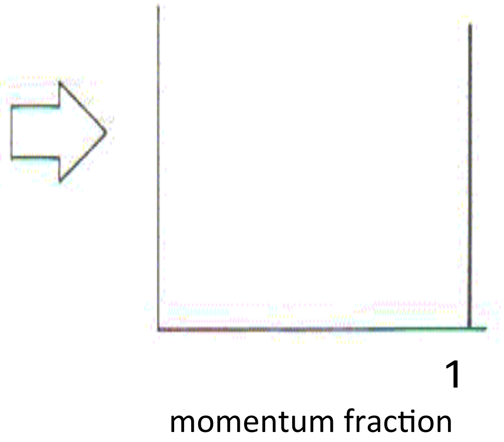
Different energy scales offer information on different aspects of proton internal structure



Unveiling the proton structure by scattering particles

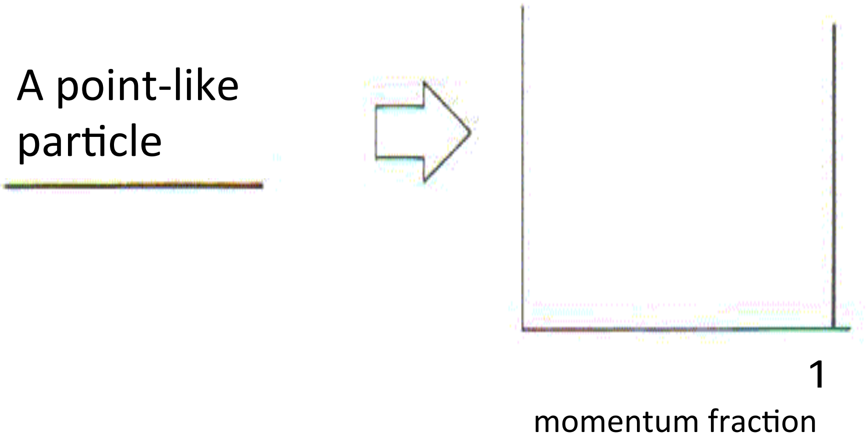
momentum fraction that the scattering particle would carry if the proton were made of …

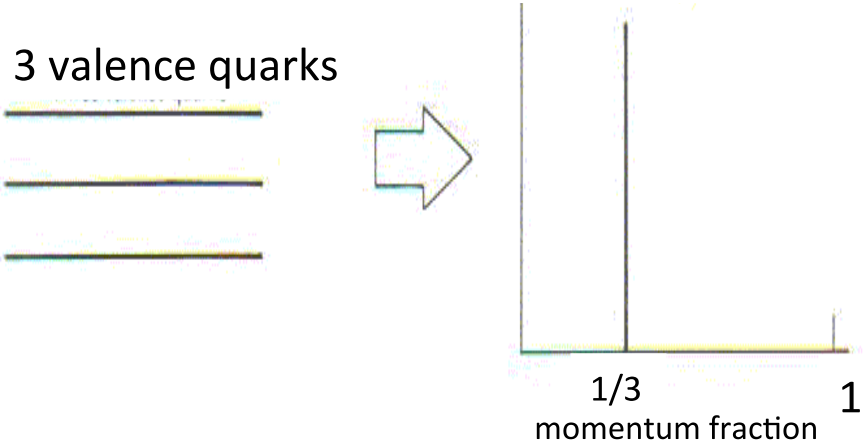
A point-like particle



Unveiling the proton structure by scattering particles

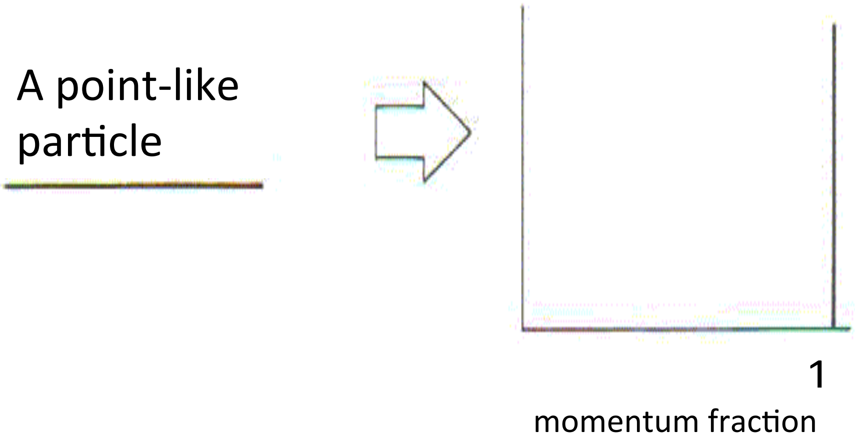
momentum fraction that the scattering particle would carry if the proton were made of …


A point-like particle

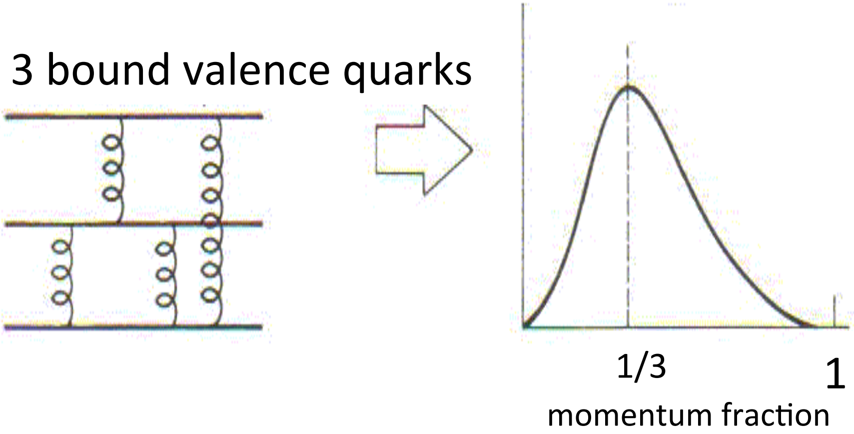

3 valence quarks

Unveiling the proton structure by scattering particles

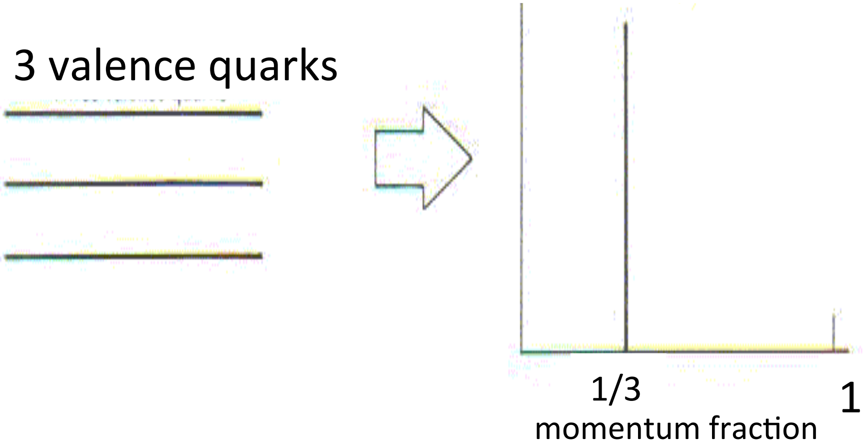
momentum fraction that the scattering particle would carry if the proton were made of …



A point-like particle



3 bound valence quarks



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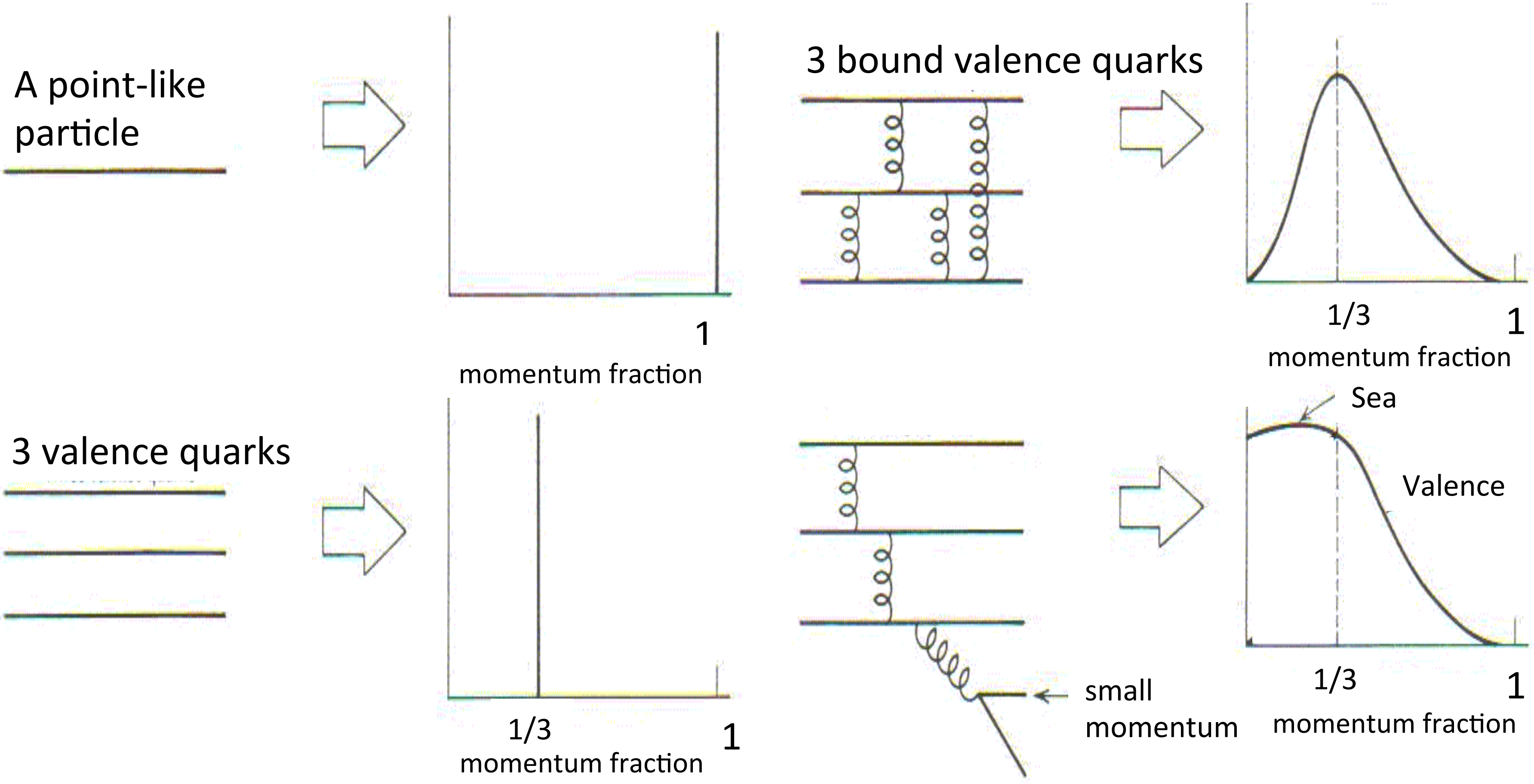


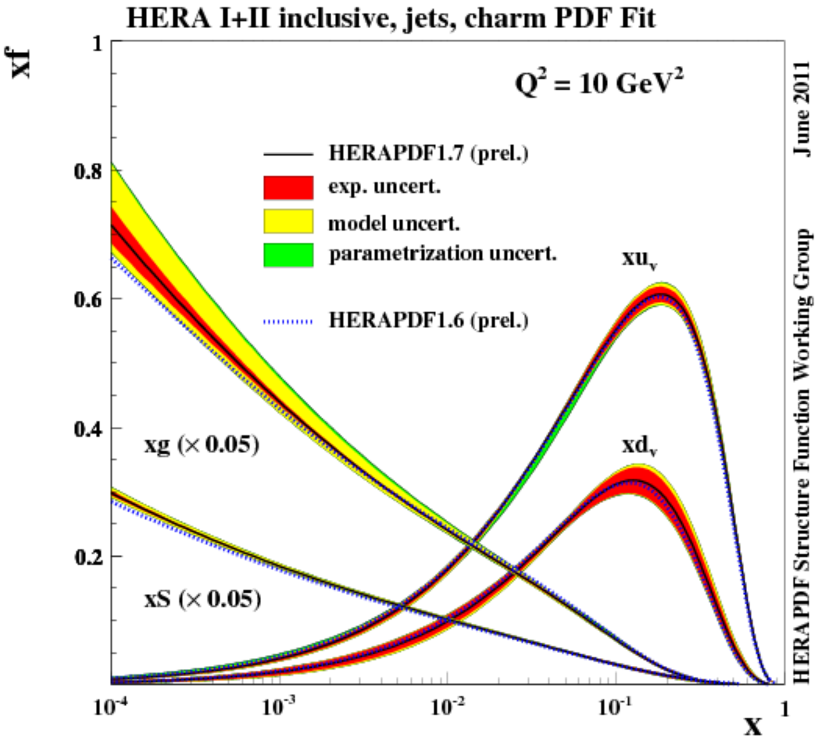
A point-like particle

3 bound valence quarks

3 valence quarks

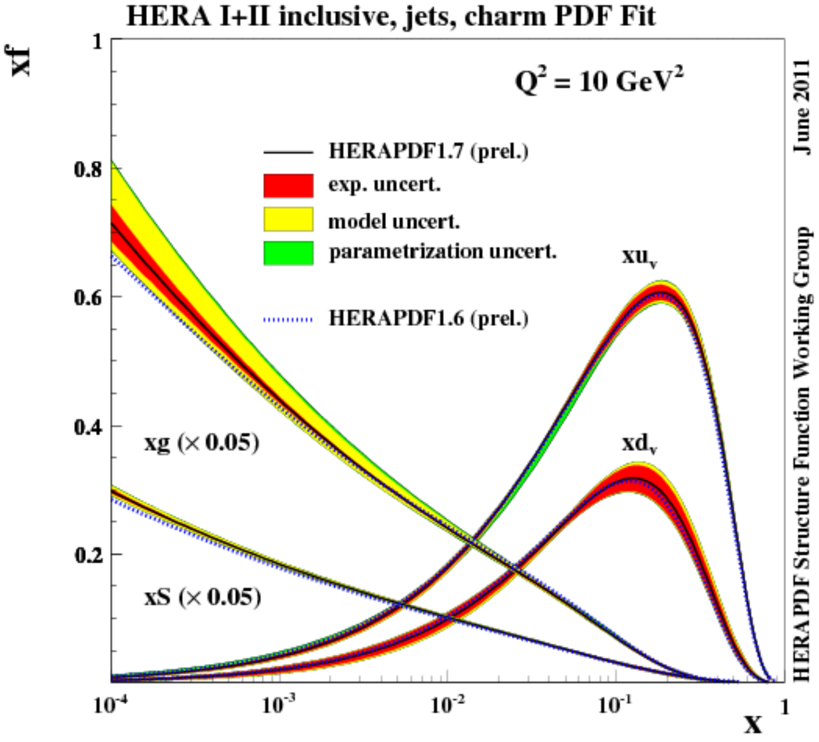
What have we learned in terms of this picture by now?

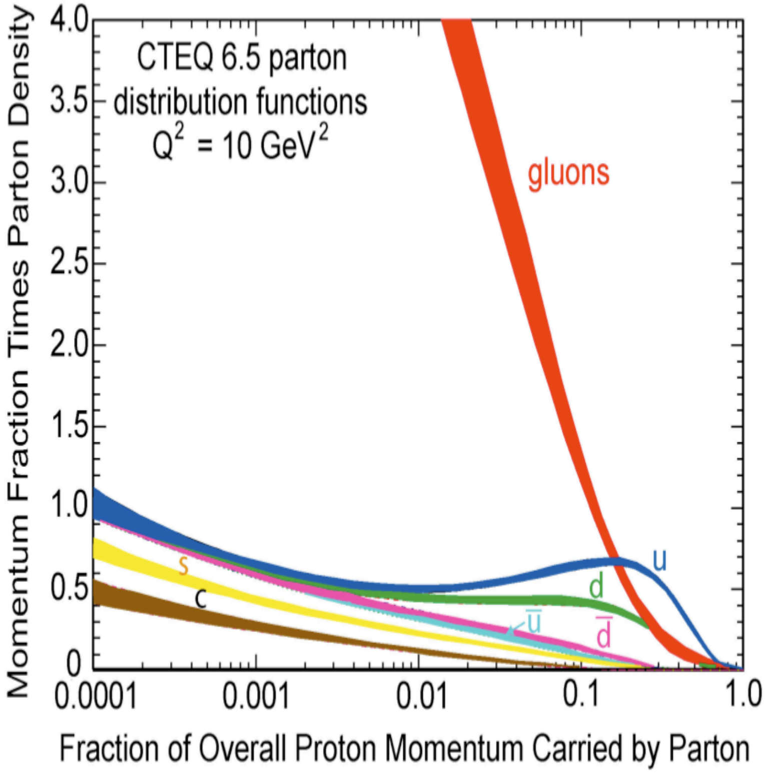
- Up and down quark "valence" distributions peaked ~1/3

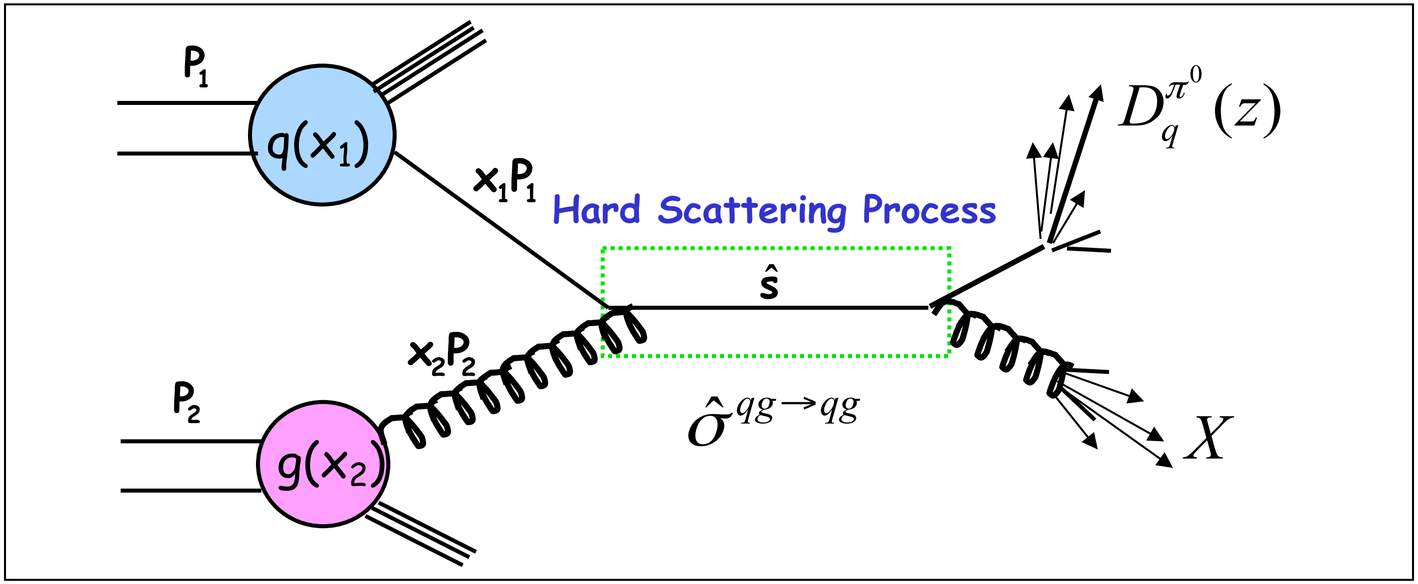


What have we learned in terms of this picture by now?

- Up and down quark "valence" distributions peaked ~1/3
- Lots of sea quark-antiquark pairs and even more gluons!







$$\sigma\left(pp\to\pi^0X\right)\propto\underbrace{q(x_1)\otimes g(x_2)}\otimes\underbrace{\hat{\sigma}^{qg\to qg}(\hat{s})}\otimes\underbrace{D_q^{\pi^0}(z)}$$

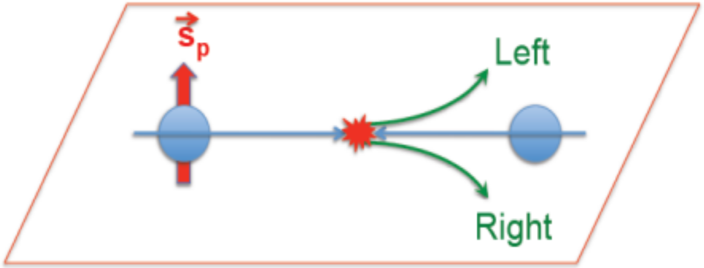
Particle production rates can be calculated using pQCD from:

- Parton distribution functions (from experiment)
- pQCD partonic scattering rates (from theory)
- "Fragmentation functions" (from experiment)

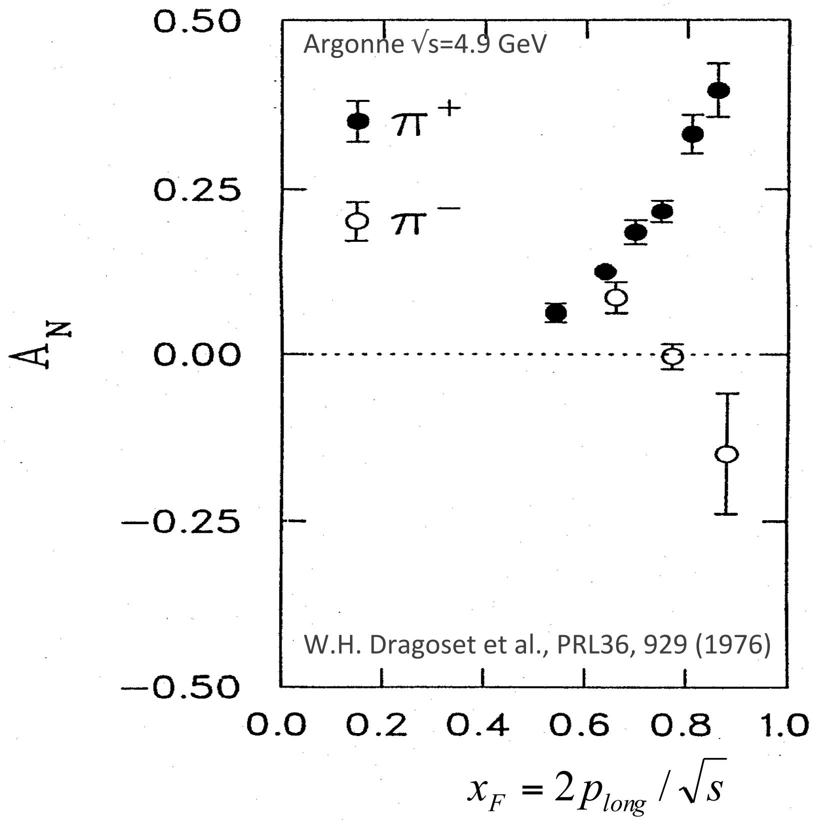
We can use *factorized* perturbative QCD (pQCD) to calculate particle production at high-energy facilities

… but then something strange happened

Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction … by up to 40%!!



Spin-momentum correlations:
1976 discovery in p+p collisions



W.H. Dragoset et al., PRL36, 929 (1976)

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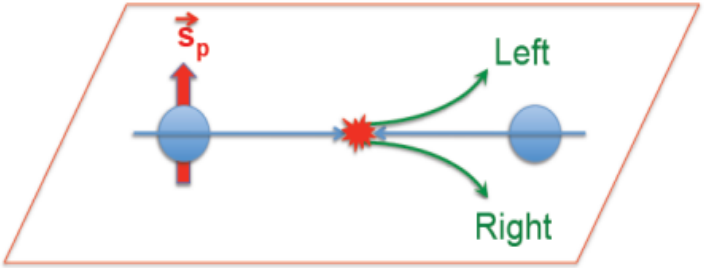

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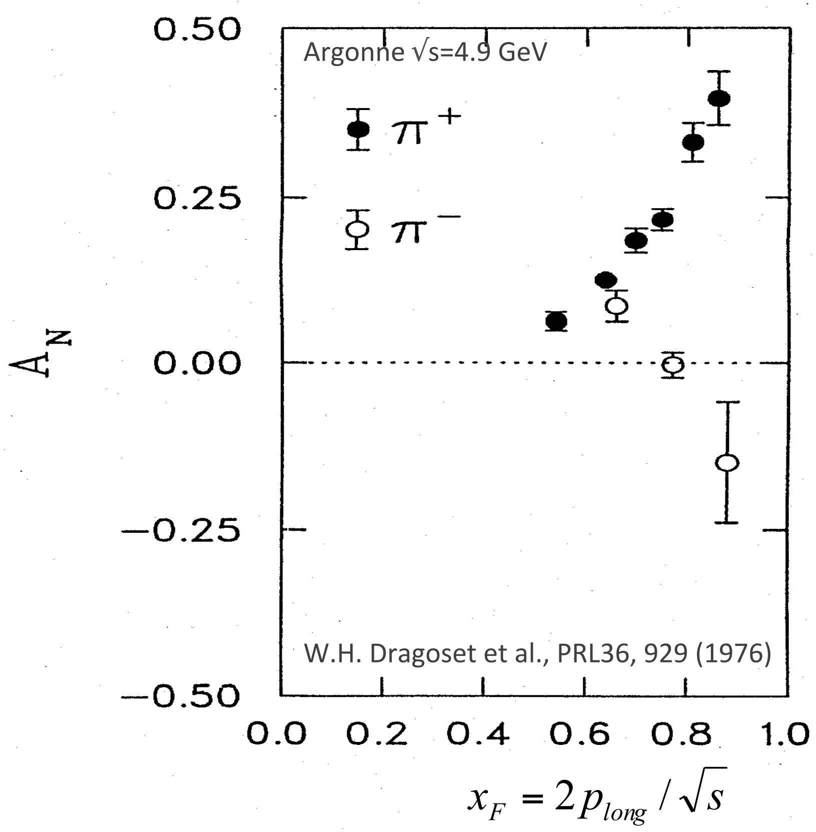


W.H. Dragoset et al., PRL36, 929 (1976)

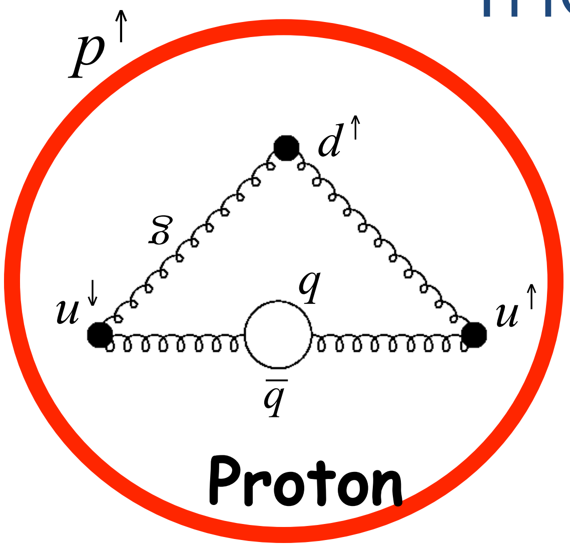
Had to wait more than a decade for the birth of a new subfield:

- In 1990 D.W. Sivers departs from traditional collinear factorization assumption in pQCD and proposes correlation between the intrinsic transverse motion of the quarks and gluons and the proton's spin

First quark distribution function describing a spin-momentum correlation in the proton

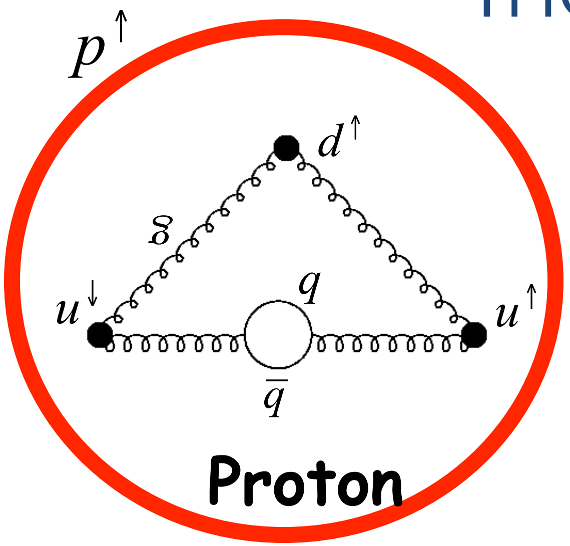
New frontier! Quark dynamics inside QCD bound states, and in their formation process

The Proton Spin Crisis



A proton has a total spin +1/2 along some axis. Most naively, you'd expect it to contain two quarks with spin +1/2 and one with spin -1/2.
1/2 + 1/2 - 1/2 = +1/2

The Proton Spin Crisis



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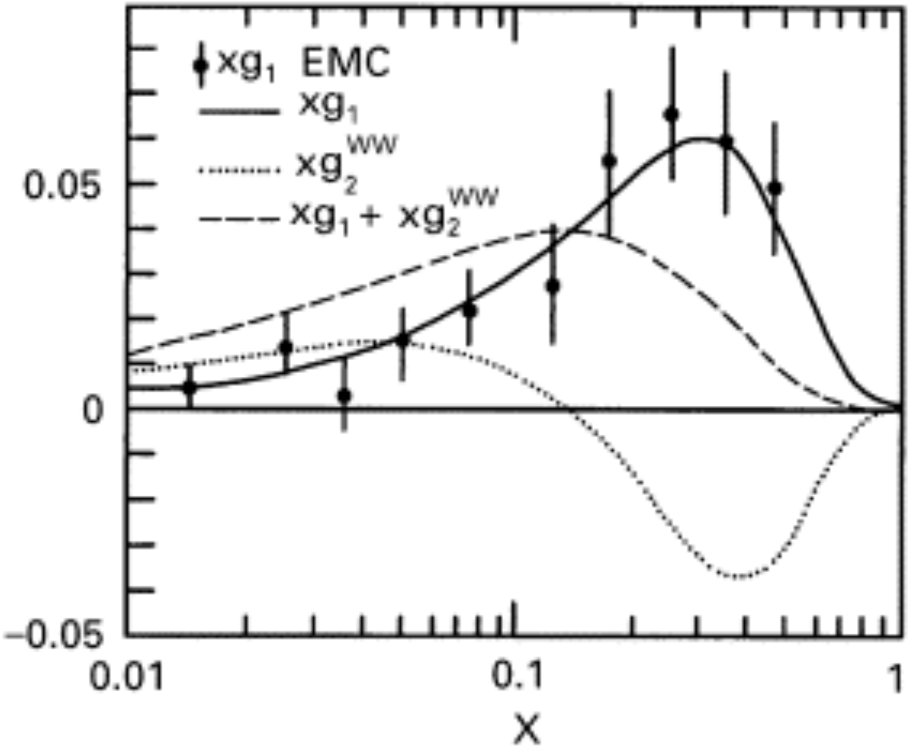
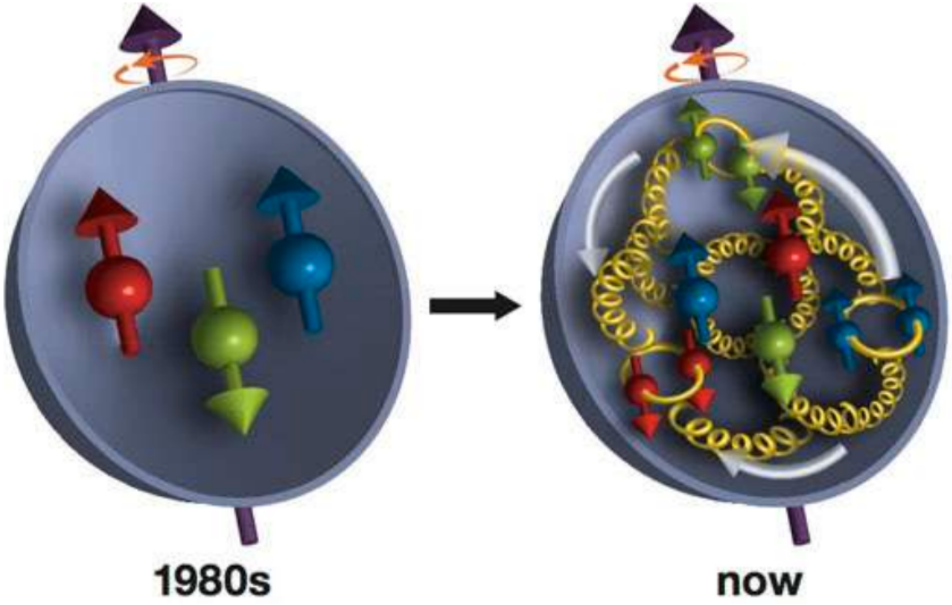


Surprising data from late 1980's!

Only ~12% of proton's spin carried by quarks' spins!

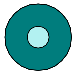
Hence ~12% of the proton spin is carried by the spin of the quarks, the remaining spin must be carried by gluons or orbital angular momentum



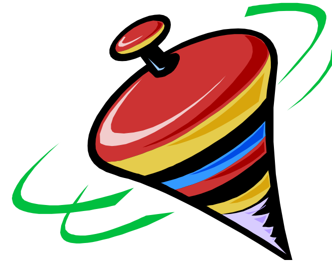
$$\frac{1}{2}\hbar = \overbrace{\sum_q \frac{1}{2} S_q^z}^{\text{Total quark spin}} + \overbrace{S_g^z}^{\text{gluon spin}} + \overbrace{\sum_q L_q^z + L_g^z}^{\text{angular momentum}}$$

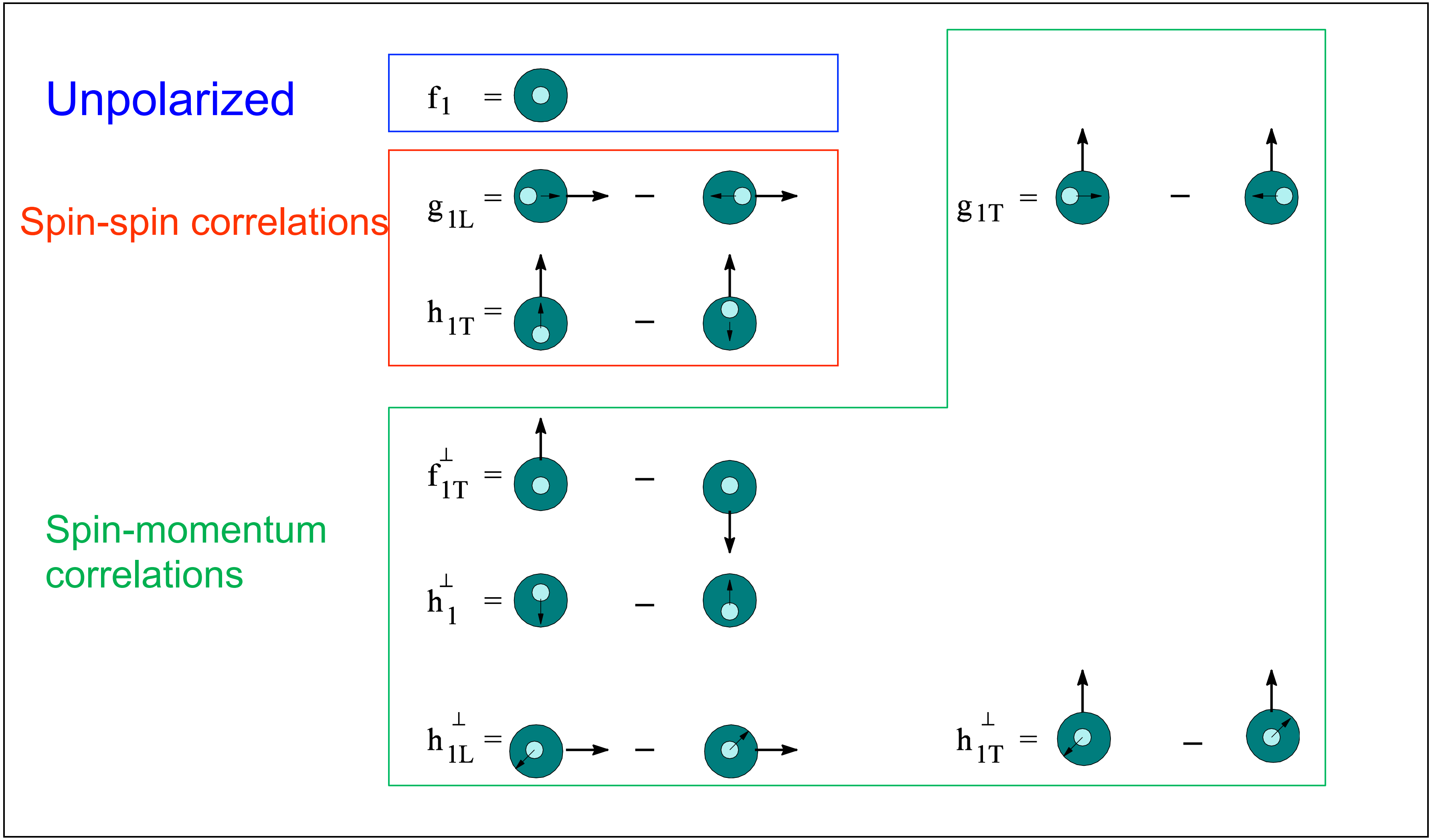
In QCD bound states we need to include Spin-spin and spin-momentum correlations

Unpolarized

f_1 = 

In QCD bound states we need to include Spin-spin and spin-momentum correlations



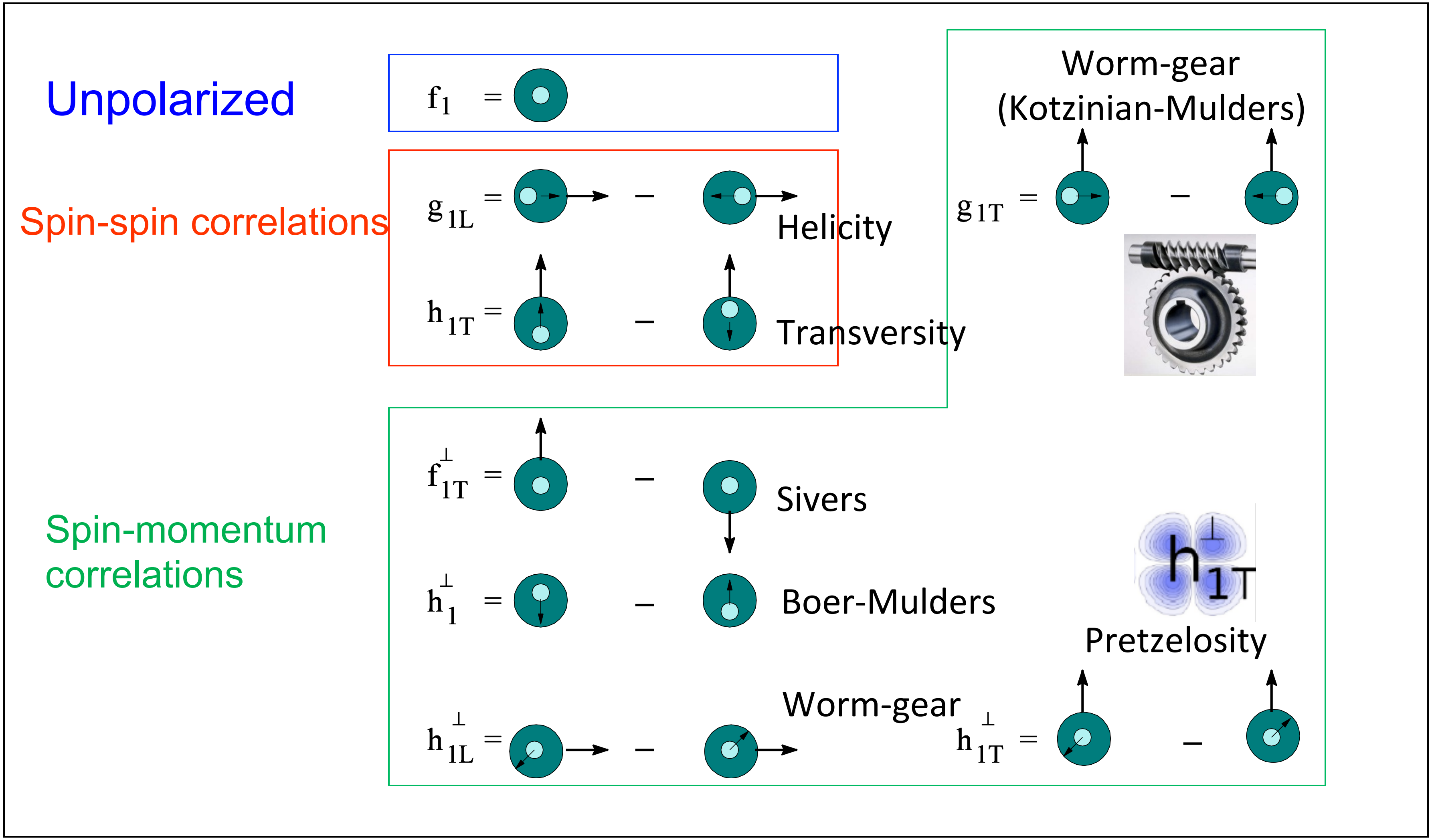


Unpolarized

Spin-spin correlations

Spin-momentum correlations

In QCD bound states we need to include Spin-spin and spin-momentum correlations



Unpolarized

$f_1 =$

Spin-spin correlations

$g_{1L} =$ − Helicity

$h_{1T} =$ − Transversity

Worm-gear (Kotzinian-Mulders)

$g_{1T} =$ −

Spin-momentum correlations

$f_{1T}^{\perp} =$ − Sivers

$h_1^{\perp} =$ − Boer-Mulders

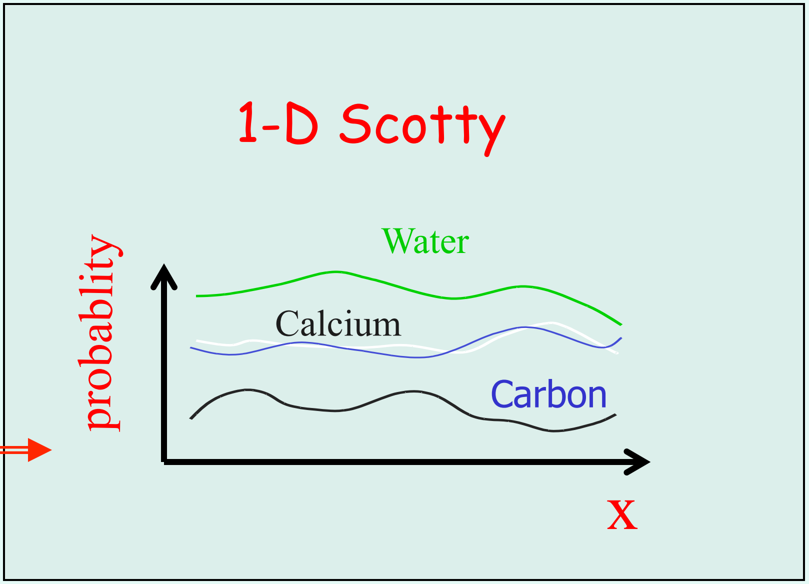
Pretzelosity

Worm-gear

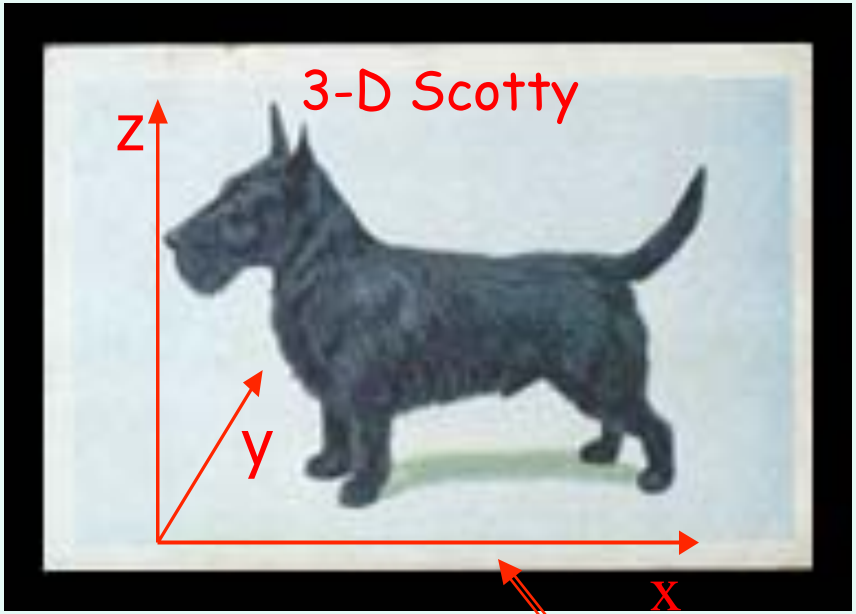
$h_{1L}^{\perp} =$ −

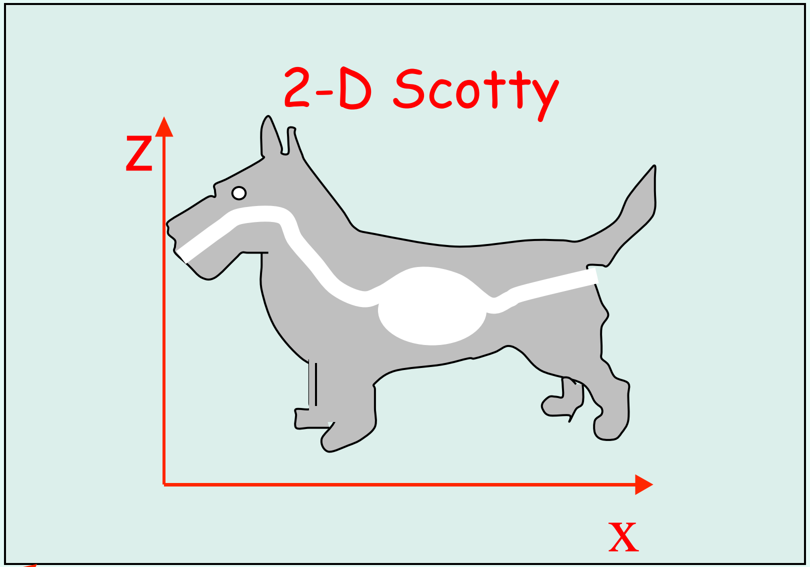
$h_{1T}^{\perp} =$ −

PDFs pre spin-spin spin-momentum correlation

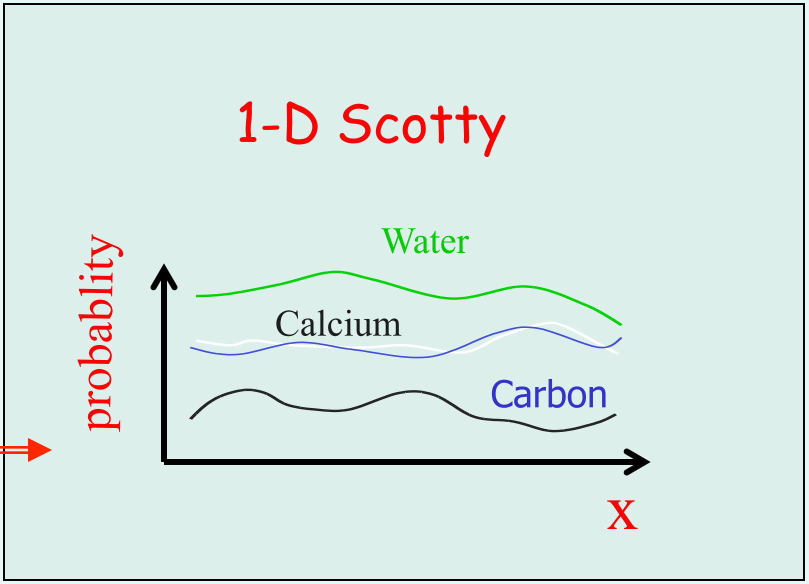


1-D Scotty



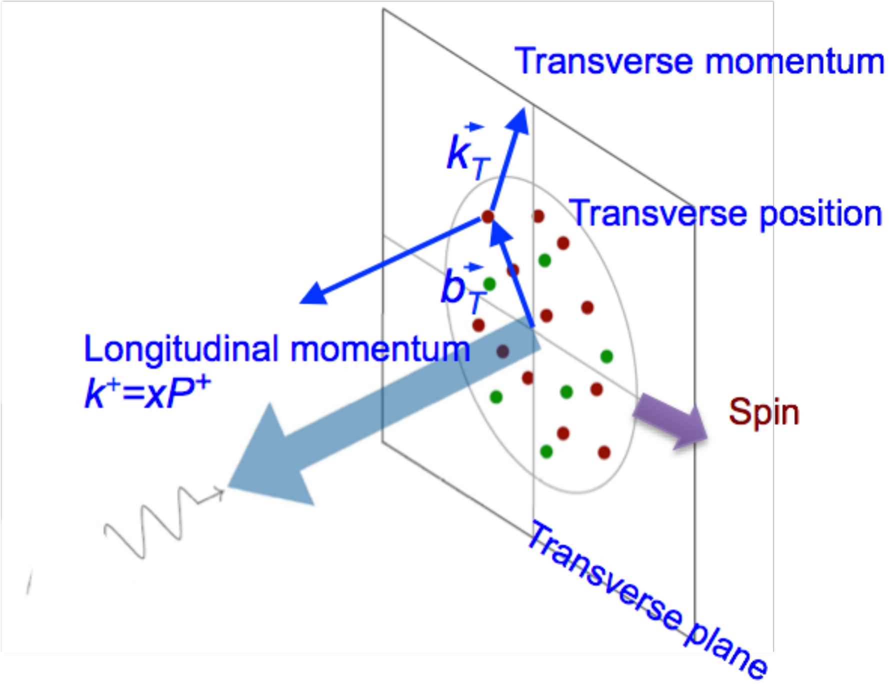


PDFs <u>post</u> spin-spin spin-momentum correlation

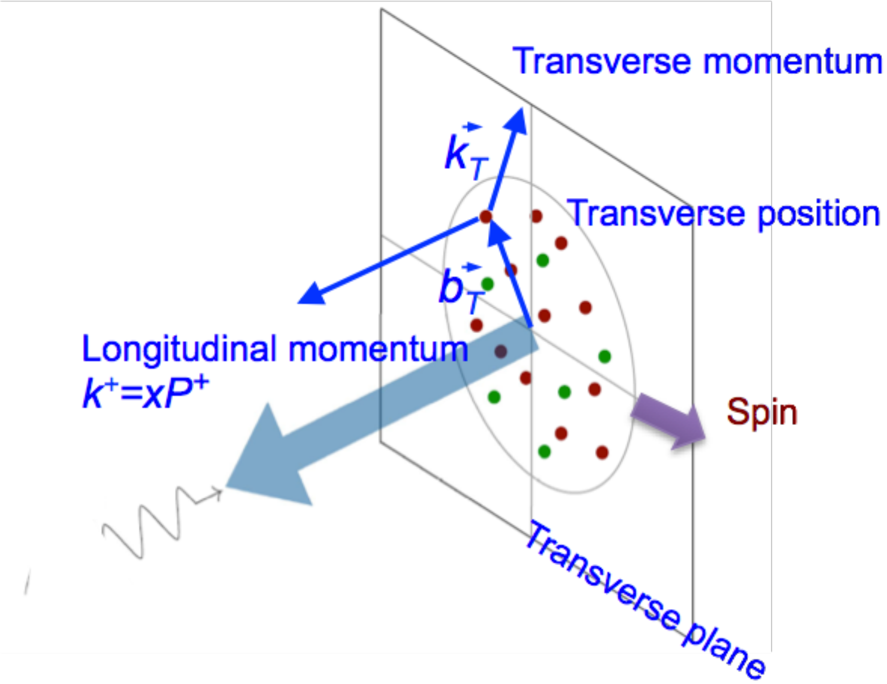


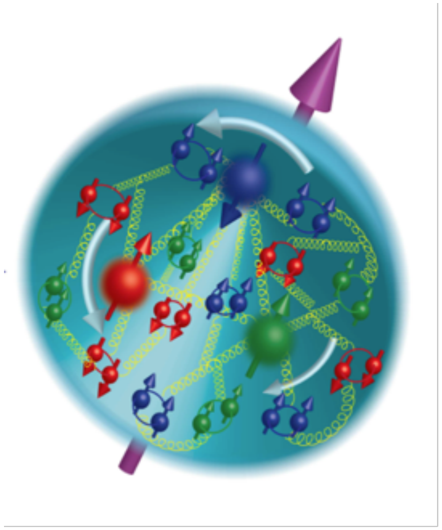
PDFs <u>pre</u> spin-spin spin-momentum correlation

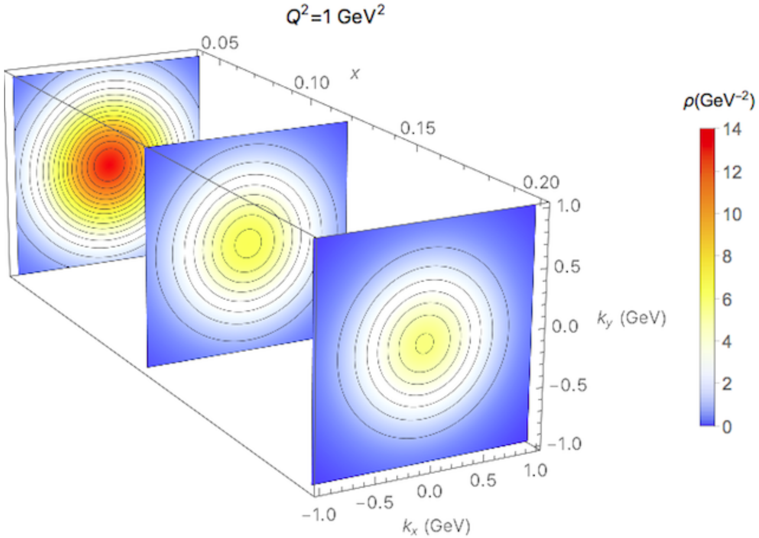
Hadron tomography



Hadron tomography





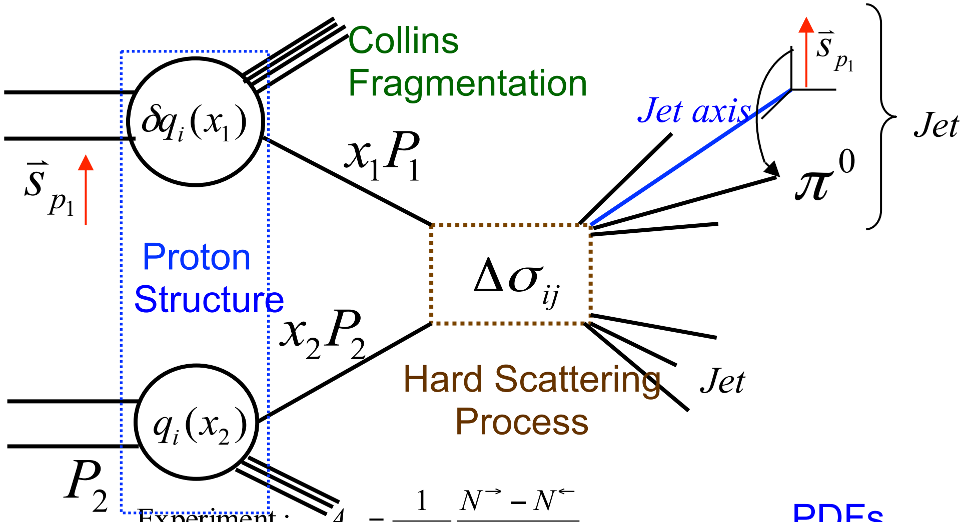


Transverse Momentum Distribution Functions (TMDs)

PDFs involving transversely polarized quarks are **chiral-odd**

-can only be observed experimentally in conjunction with a second chiral-odd function

J. Collins, Nucl.Phys. B396 (1993)161



Experiment : $A_N = \frac{1}{P_{beam}} \frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}$

PDFs

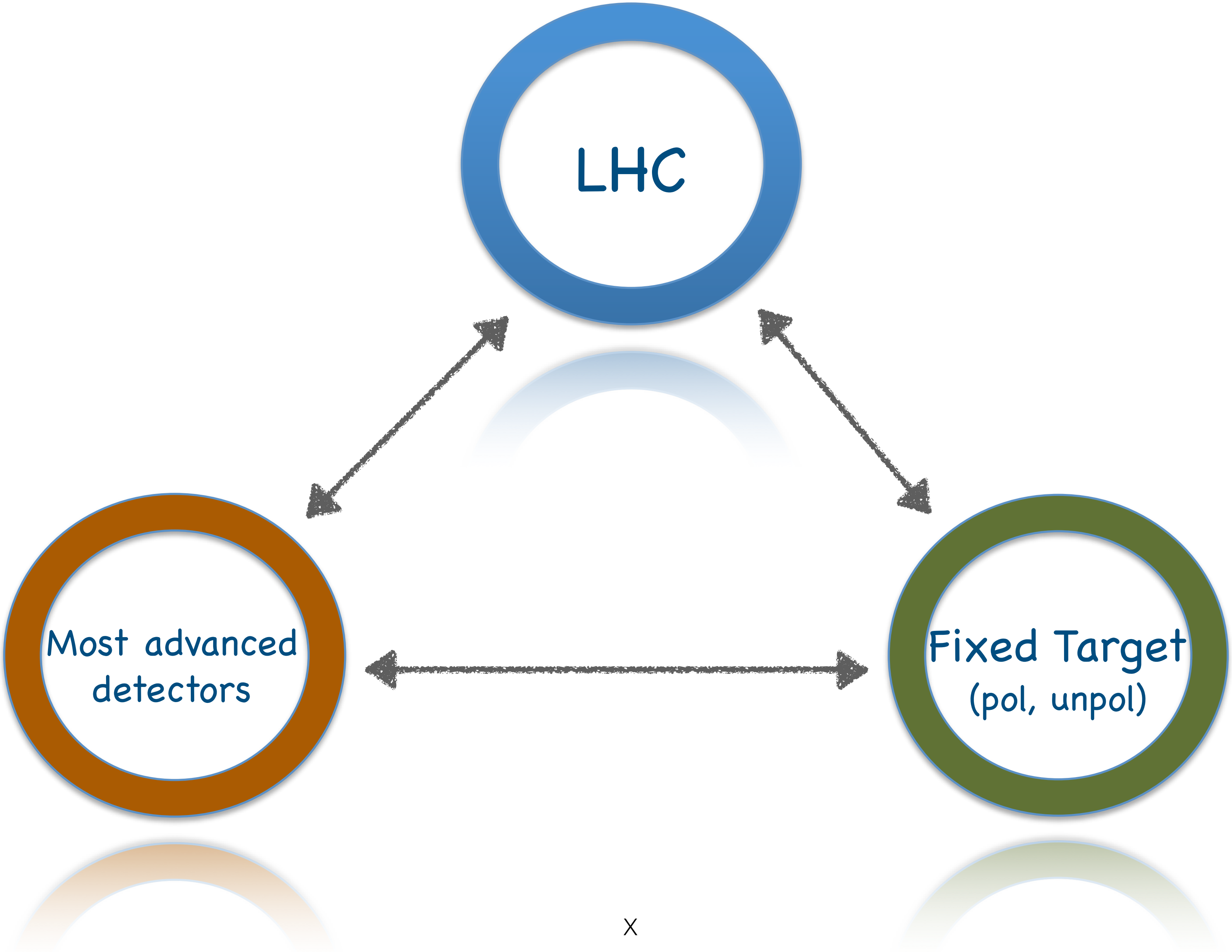
pQCD

Collins FF

$$N^{pp^{\uparrow} \to \pi^0 X}(z,\varphi) \propto h_1(x_1) \cdot f_1(x_2) \times \hat{\sigma}^{\uparrow} \times H_1^{\perp}(z)$$

transversity distributions

Merging 3 worlds



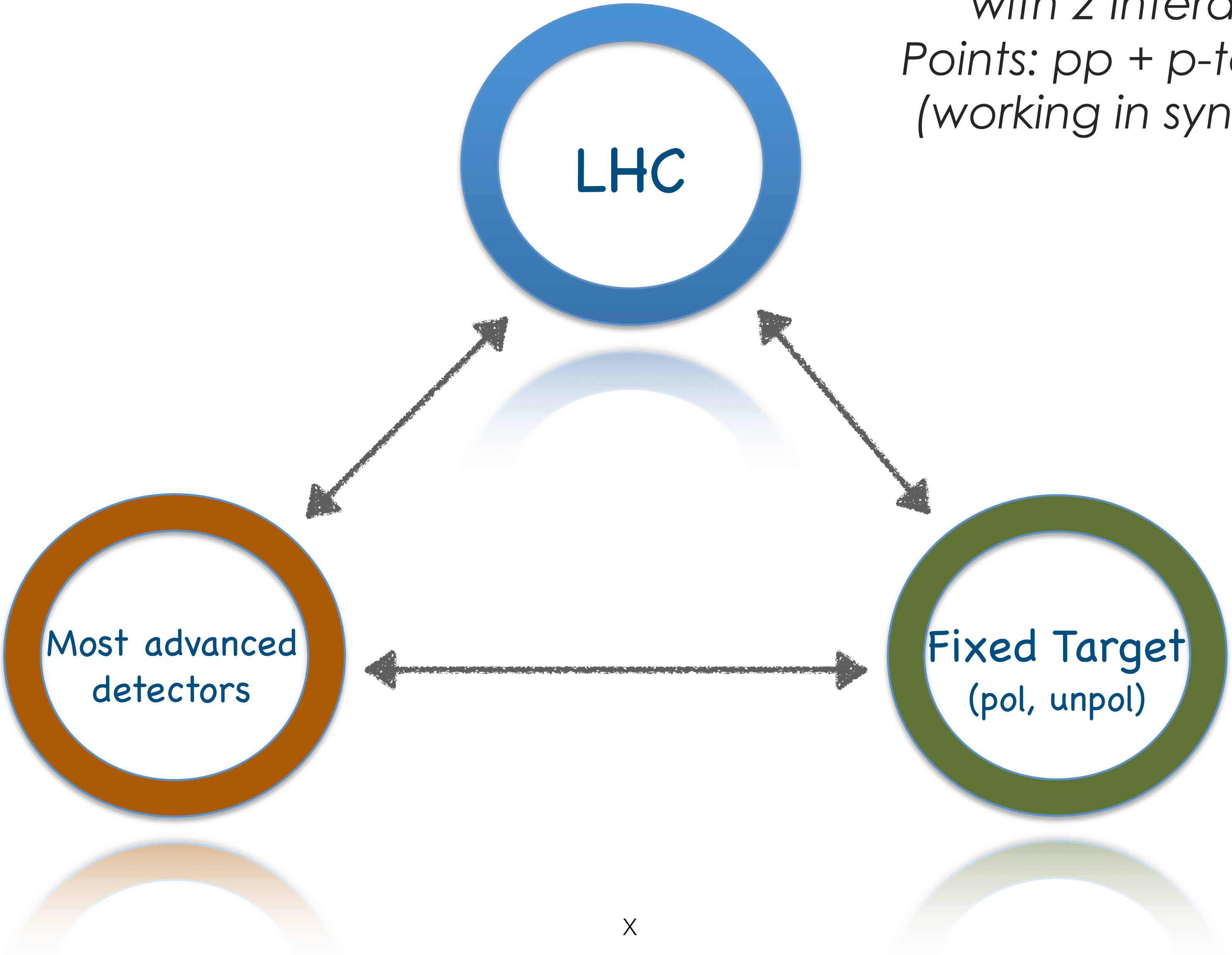
LHC

Most advanced detectors

Fixed Target (pol, unpol)

Merging 3 worlds

For the first time we will have an experiment with 2 Interaction Points: pp + p-target (working in synergy)



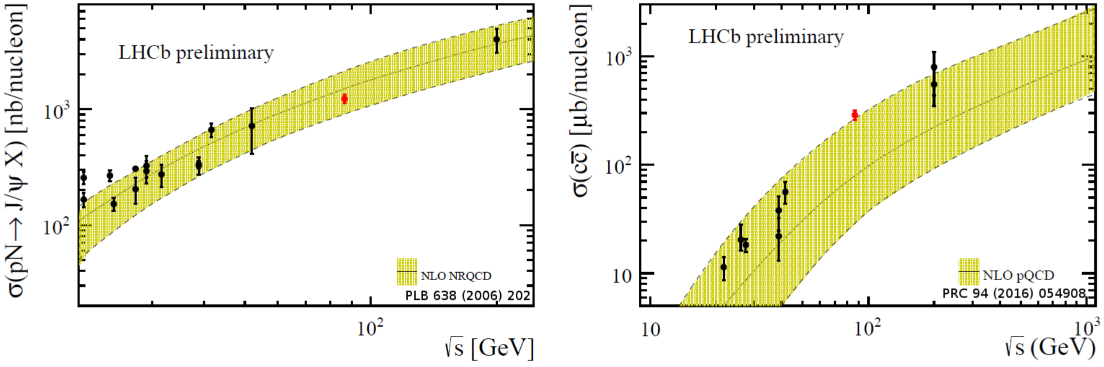
LHC

Most advanced detectors

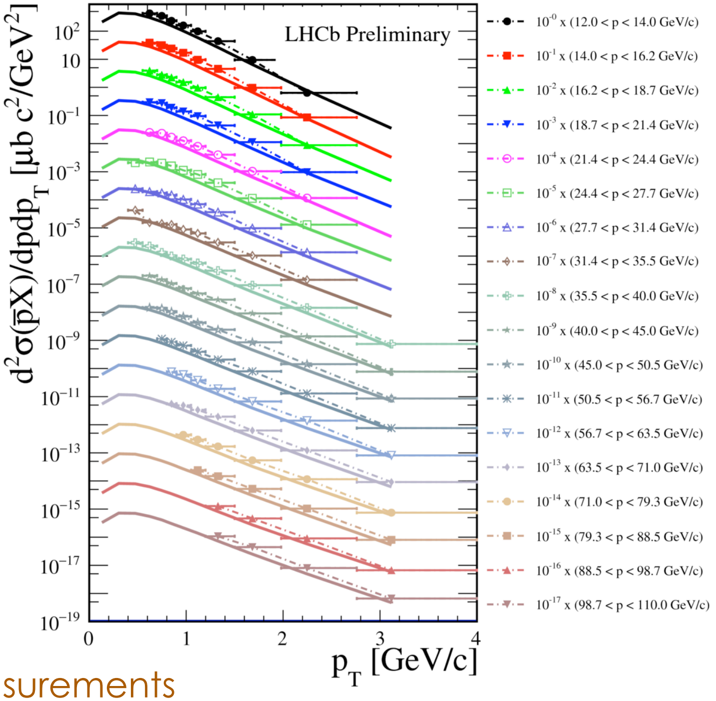
Fixed Target
(pol, unpol)

New perspectives in QCD and soft QCD for Cosmic Ray Physics

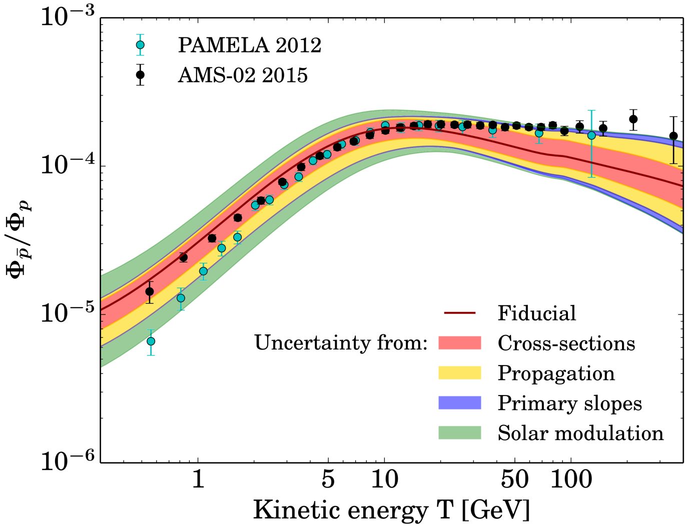
J/ψ e $c\bar{c}$ cross section as a function of the c.m. energy

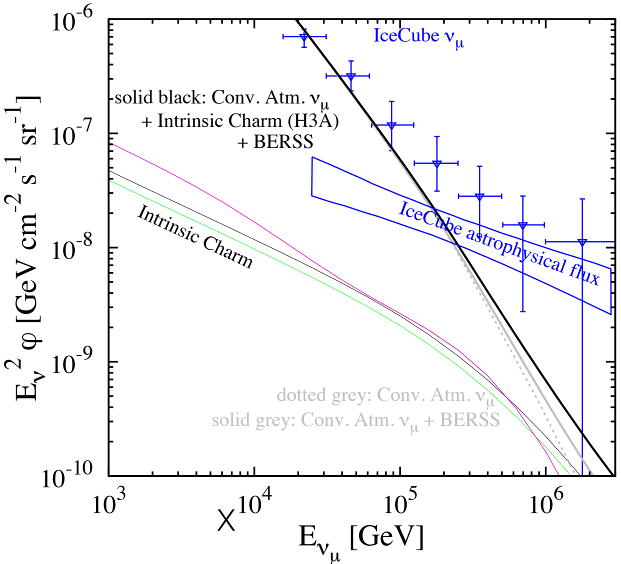


anti-p xsection

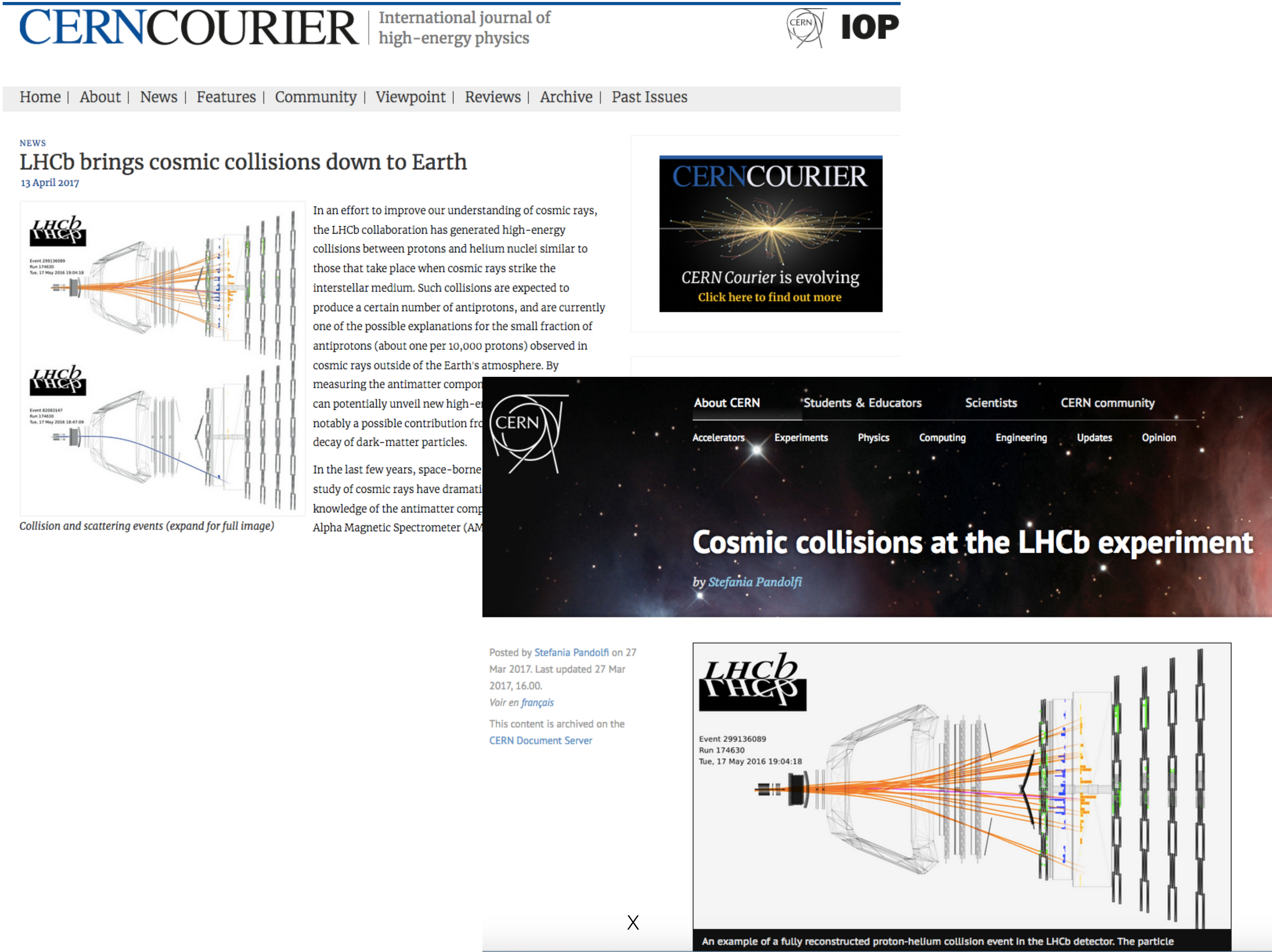


Large impact on the AMS (anti-p) and ICECUBE (open-charm) measurements





SMOG p-Neon data represent a valid model of the interaction in air. The energy corresponds to the 3rd–4th interaction for a 10^{10} GeV shower. Mid-rapidity measurements are useful for the lateral development of the showers



NEWS

LHCb brings cosmic collisions down to Earth

13 April 2017

Collision and scattering events (expand for full image)

In an effort to improve our understanding of cosmic rays, the LHCb collaboration has generated high-energy collisions between protons and helium nuclei similar to those that take place when cosmic rays strike the interstellar medium. Such collisions are expected to produce a certain number of antiprotons, and are currently one of the possible explanations for the small fraction of antiprotons (about one per 10,000 protons) observed in cosmic rays outside of the Earth's atmosphere. By measuring the antimatter compon
can potentially unveil new high-e
notably a possible contribution fro
decay of dark-matter particles.

In the last few years, space-borne
study of cosmic rays have dramati
knowledge of the antimatter comp
Alpha Magnetic Spectrometer (AM

Cosmic collisions at the LHCb experiment

by *Stefania Pandolfi*

Posted by Stefania Pandolfi on 27 Mar 2017. Last updated 27 Mar 2017, 16.00.

Voir en français

This content is archived on the CERN Document Server

An example of a fully reconstructed proton-helium collision event in the LHCb detector. The particle

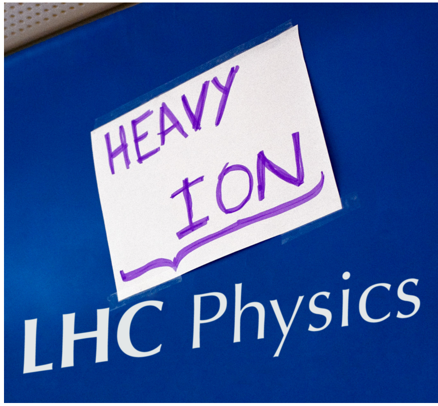
LHCspin

… where I am the responsible

I phase: 2019-2020
II phase: 2024-…

… where I am the responsible

Conclusions

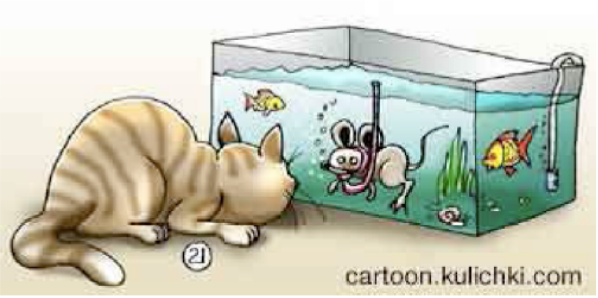


The QGP is a great tool to investigate the early Universe and to unveil the deepest "secrets" of the QCD

In November 2010, the field of ultrarelativistic nuclear collisions has entered a new era with the start of heavy-ion collisions at the LHC … an ideal place where to study the QGP

Exiting results already achieved,
the future looks bright!

Wealth of new intriguing phenomena in the medium!



Conclusions (2)

Fixed target collisions at the LHC represent a unique possibility for *a laboratory for QCD* in unexplored kinematic regions … in a realistic time schedule

The LHCspin project represents a fantastic challenge both for its physics potentialities and for the technology involved

Additional literature

- C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994
  http://books.google.de/books?id=Fnxvrdj2NOQC&printsec=frontcover
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- 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

or email to*: Pasquale.Di.Nezza@cern.ch*