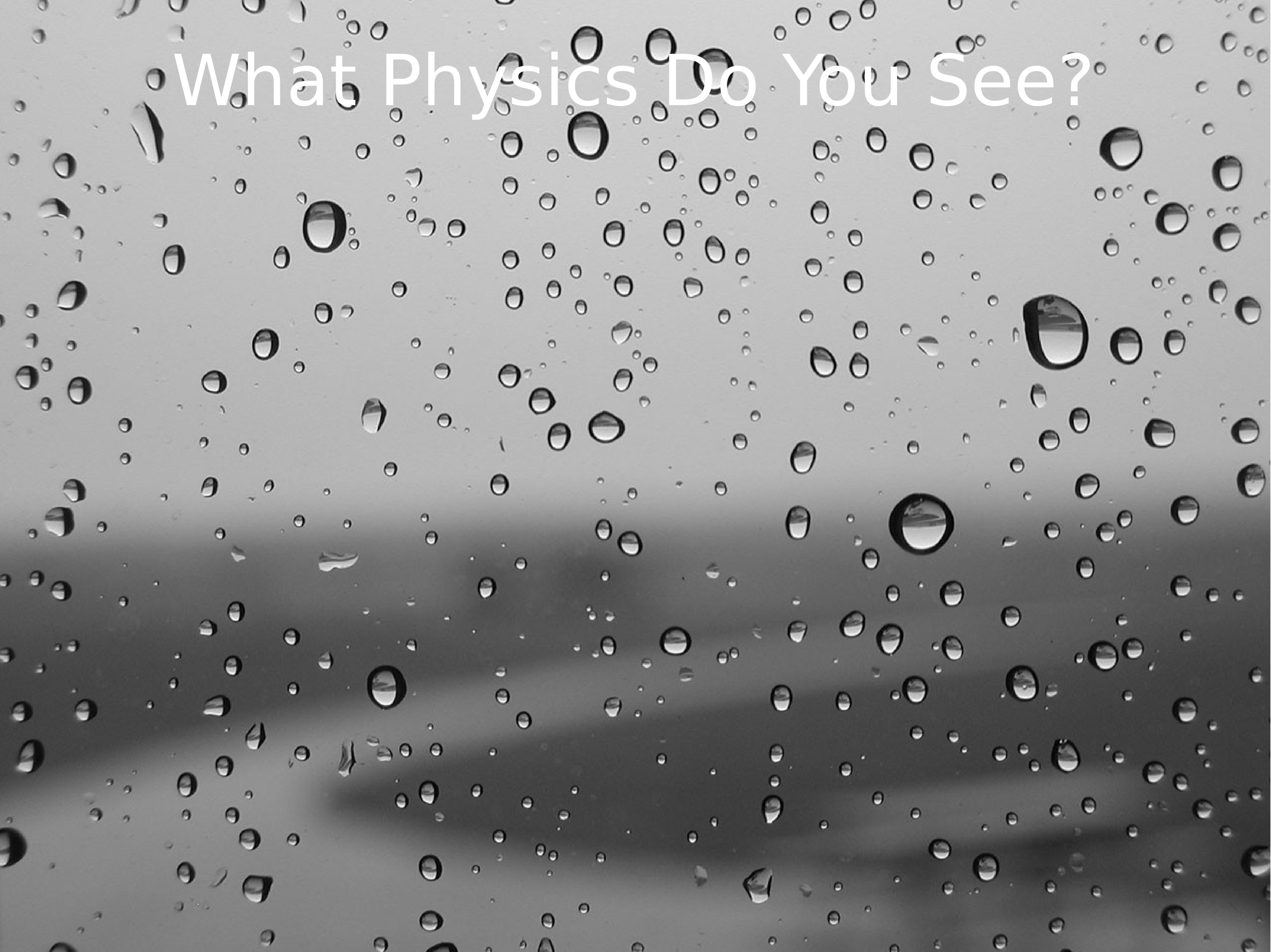
From Heavy-Ion Collisions to Quark-Gluon matter

Constantin Loizides
(LBNL)

- Part I: Introduction and background
- Part II: Results mainly related to bulk properties
- Part III: Results mainly related to hard probes

CERN summer student programme 2016

What Physics Do You See?



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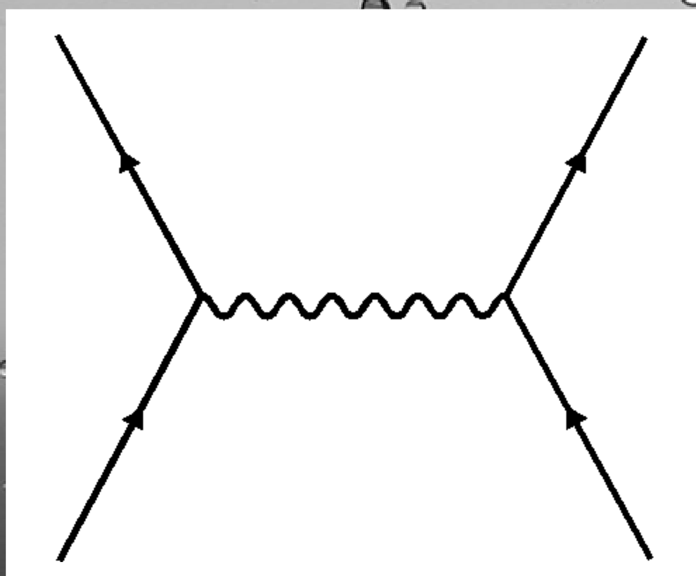
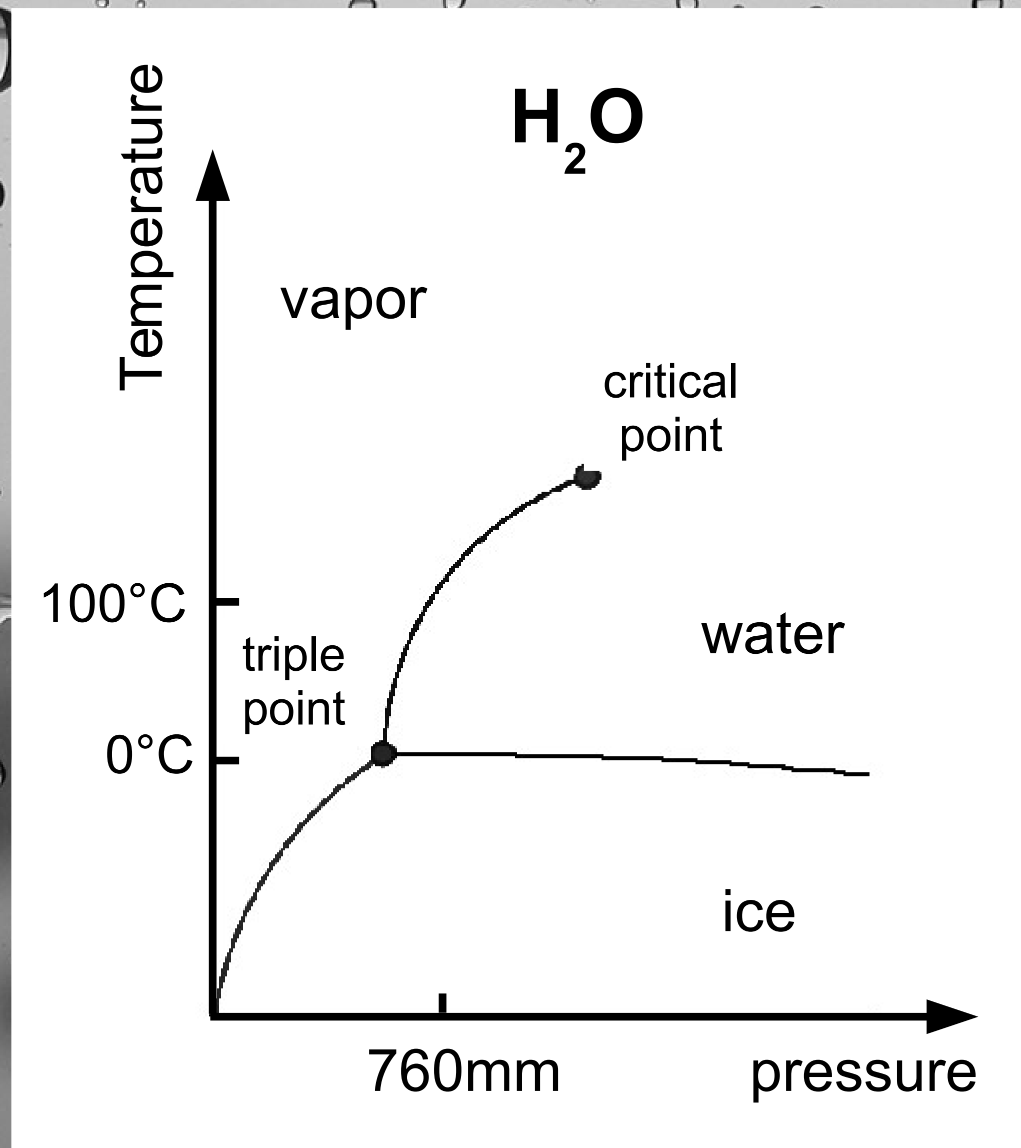
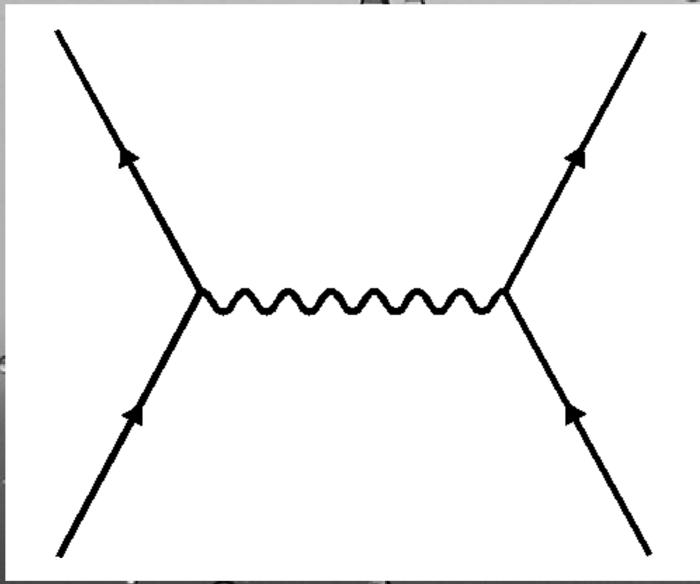


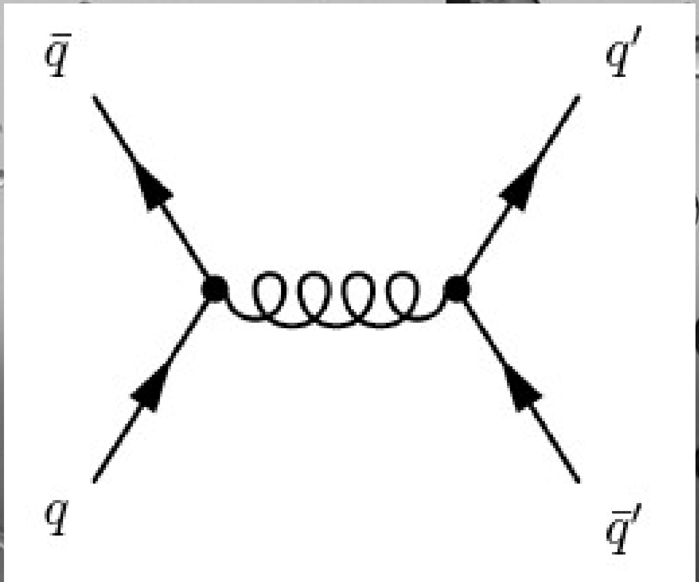
- The water droplets on the window demonstrate a principle:
  - Truely beautiful and complex physics emerges in systems whose underlying dynamics is given by QED

What Physics Do You See?



Does QCD exhibit equally beautiful properties when looked at as bulk matter?





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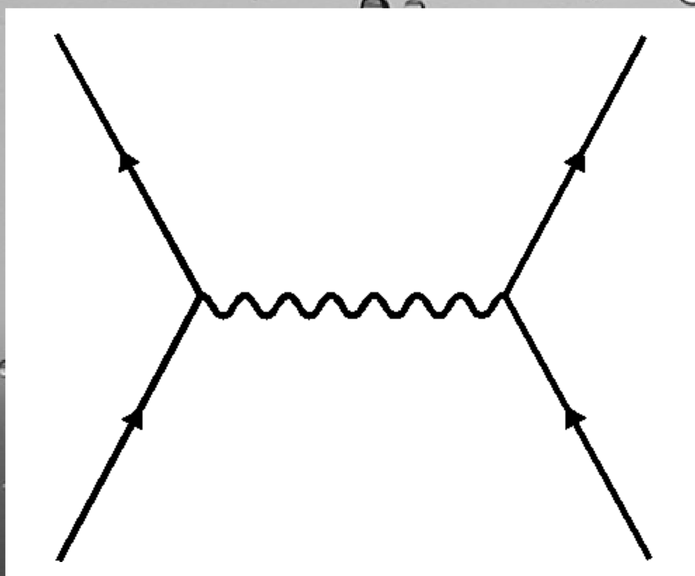

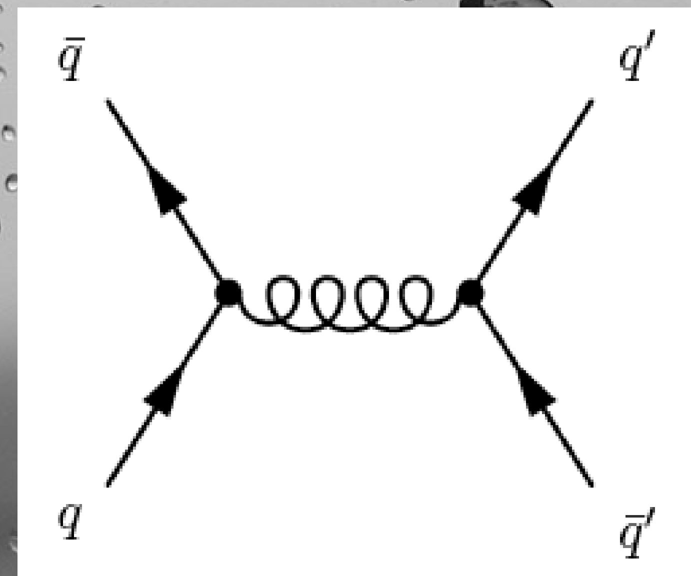

Of course, the answer is yes

as we will see …

Quantum Chromo Dynamics

(see e.g. arXiv:hep-ph/9505231)

The standard model and QCD

FERMIONS

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

Leptons spin = 1/2

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

Quarks spin = 1/2

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

BOSONS

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

Unified Electroweak spin = 1

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

Strong (color) spin = 1

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g gluon	0	0

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  - Interactions between quarks and gluons carrying color charge
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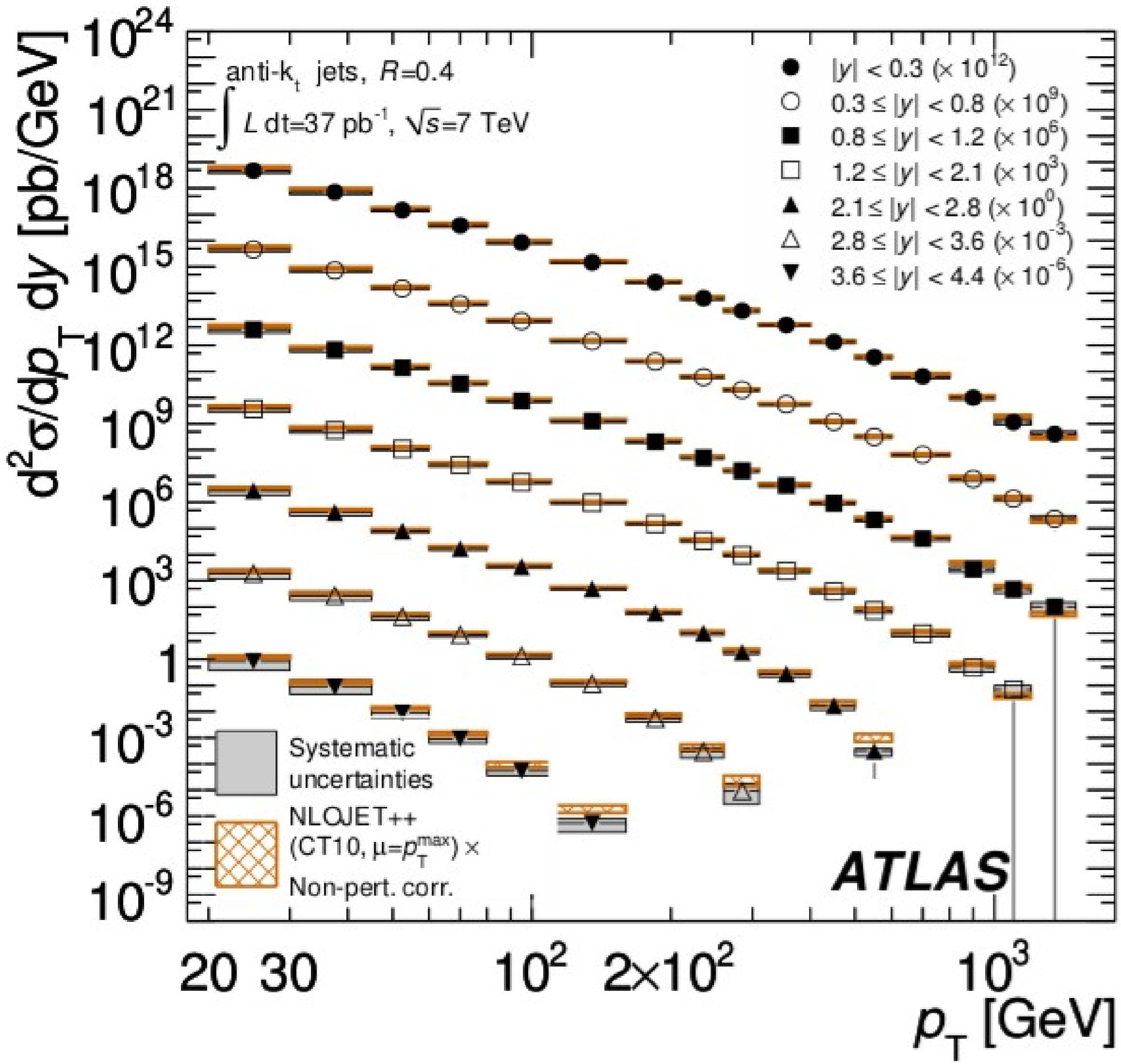

ATLAS, Phys.Rev. D86 (2012) 014022

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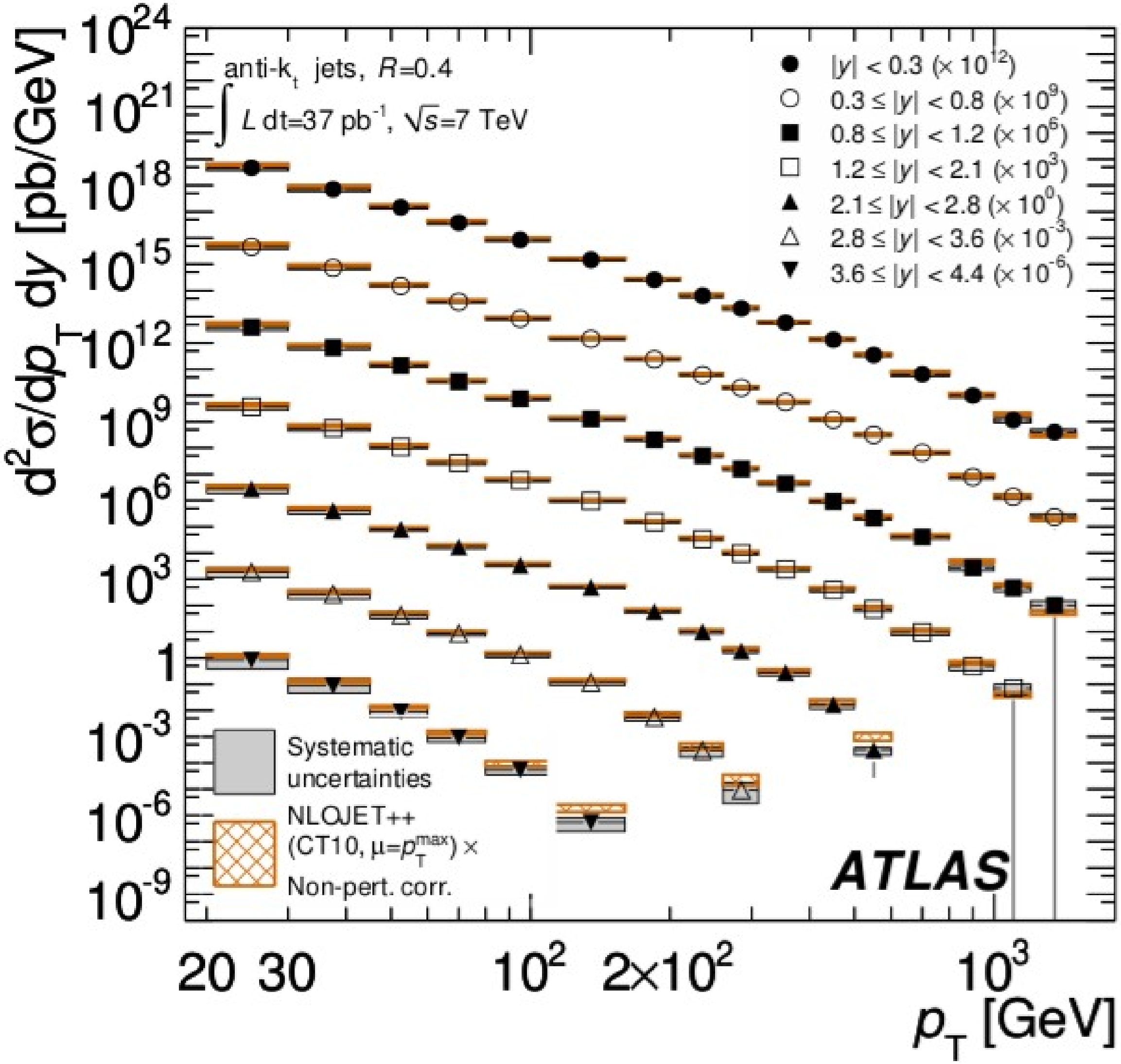

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- Very successful theory
  - e.g. pQCD vs production of high energy jets
- But with outstanding puzzles!

Two puzzles in QCD:

i) hadron masses

- A proton is thought to be composed out of uud
- The proton mass is about 938.3 MeV/c^2
- Sum of bare quark masses is only about 12 MeV/c^2
- How is the extra mass generated?

Usually among the list of top most unsolved problems in physics
(List of unsolved problems on wikipedia)

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ii) confinement

- Nobody ever succeeded in detecting an isolated quark
- Instead, quarks seem to be confined within hadrons
- It looks like one half of the fundamental fermions are not directly observable. Why?

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Quantum Chromo Dynamics (QCD)

Elementary fields: Quarks Gluons

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

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

Dynamics: Generalized Maxwell (Yang-Mills) + Dirac theory

$$\boxed{\mathcal{L} = \bar{q}_f (i \not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}}$$

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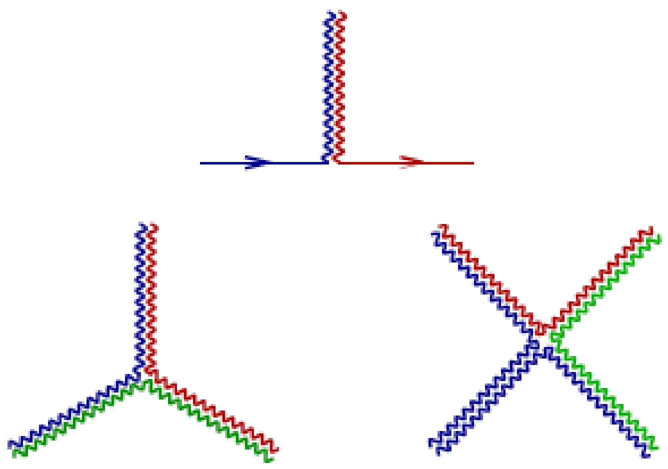

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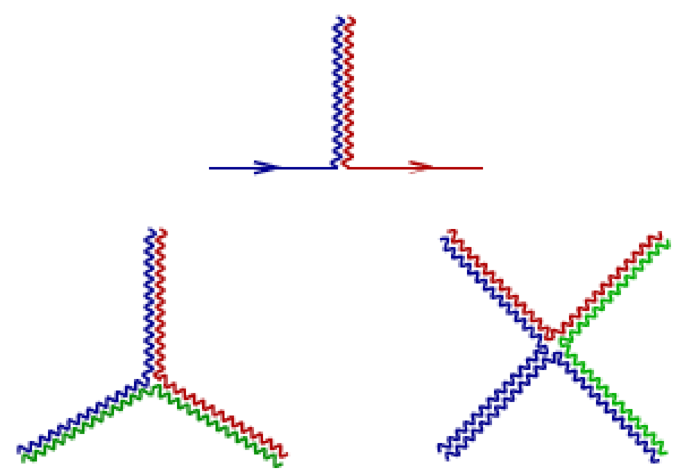

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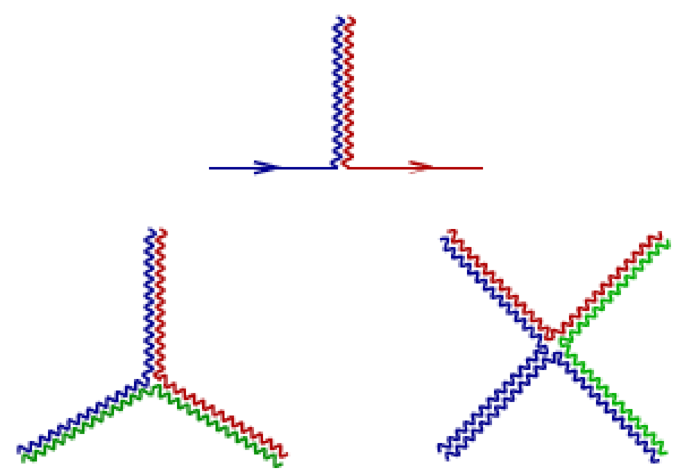

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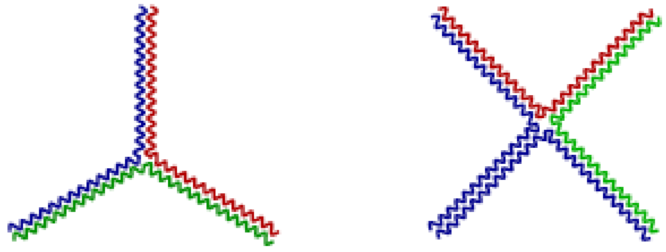
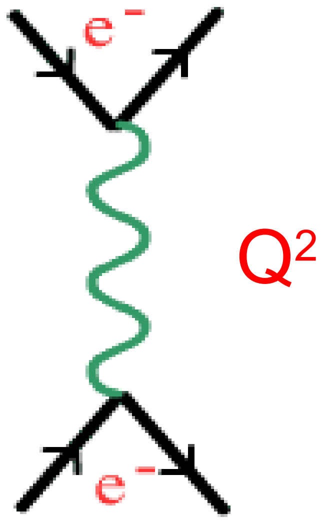
... so they interact also among themselves, generating much more complex structures



Field theory: “Running” of the coupling

Consider the interaction of two elementary particles



Momentum transfer Q^2:
Small $Q^2 \Rightarrow$ large distance scales
Large $Q^2 \Rightarrow$ small distance scales

Quantum mechanics:
Virtual pairs (loops) screen the bare interaction resulting in momentum-transfer dependent interaction strength

“Running” of the coupling: QED vs QCD

$$\alpha \equiv \frac{g^2}{4\pi}$$

negative

QED: $$\alpha\left(Q^2\right) \approx \alpha\left(\mu^2\right) / \left(1 - \frac{1}{3\pi}\alpha\left(\mu^2\right)\log\frac{|Q^2|}{\mu^2}\right)$$

Smaller $|Q^2|$ (larger distance) $\Rightarrow$ weaker coupling
(similar to screening of charge in di-electric material)

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= (33-12)/12π = positive!

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(so called anti-screening stronger than screening)

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And that makes a huge difference!

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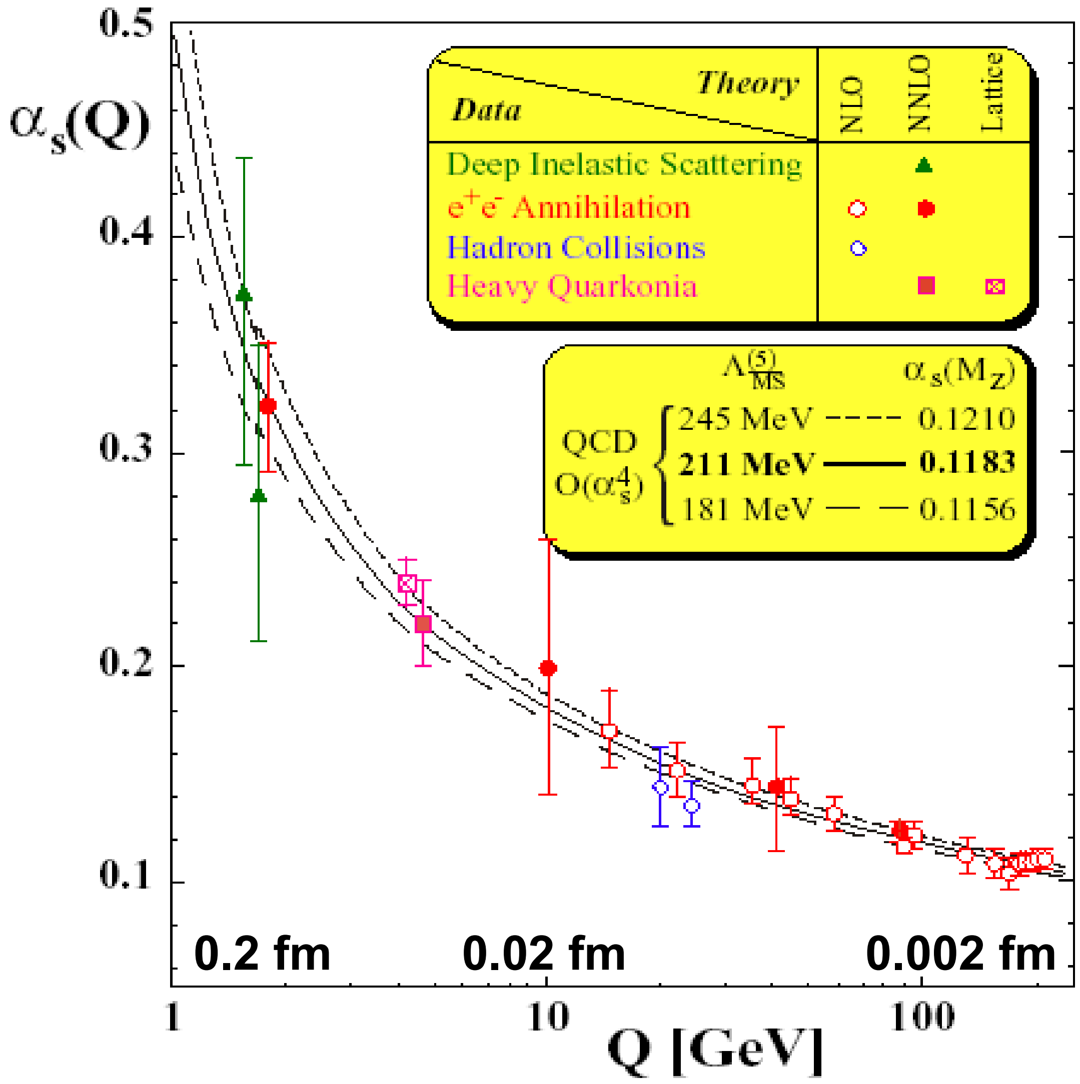

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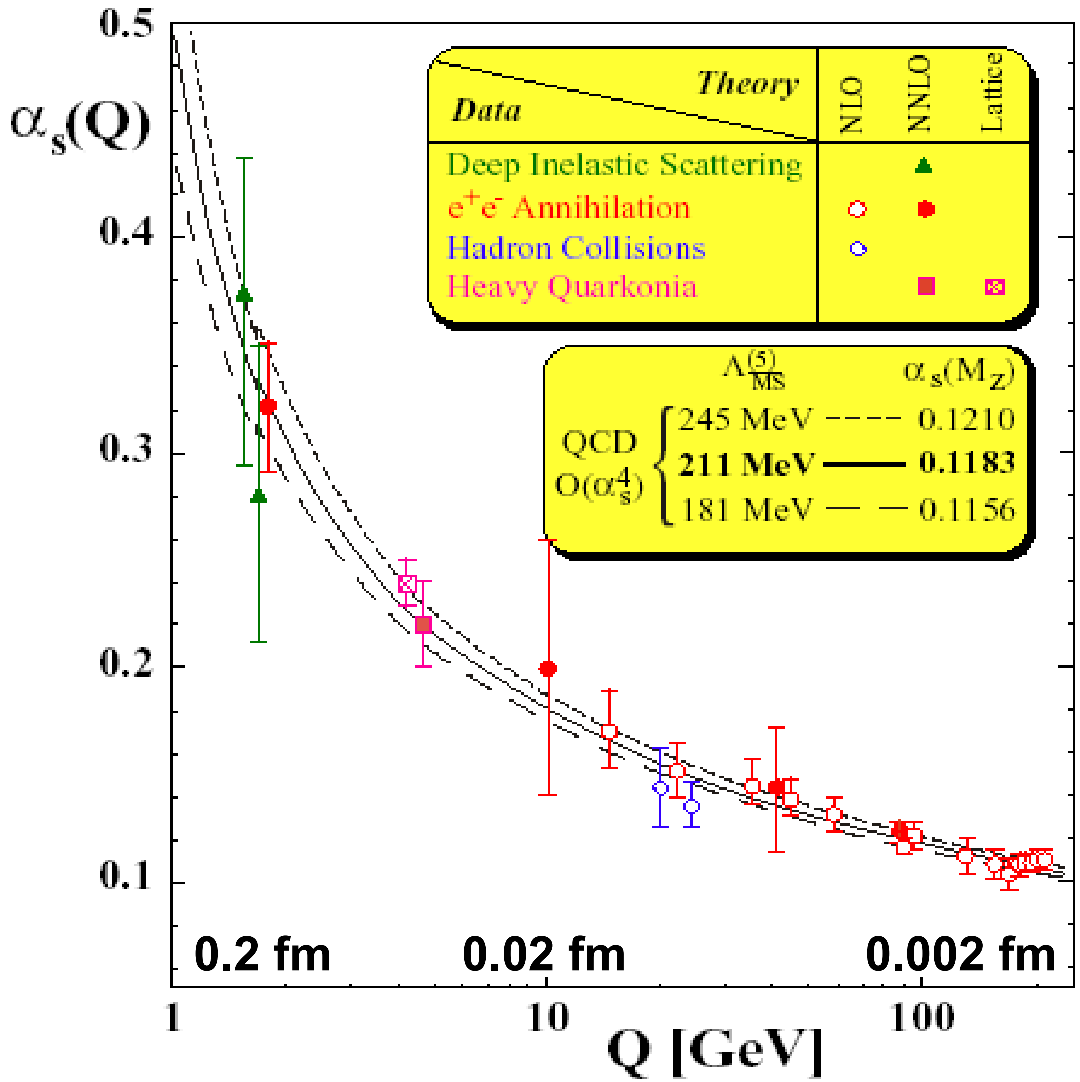
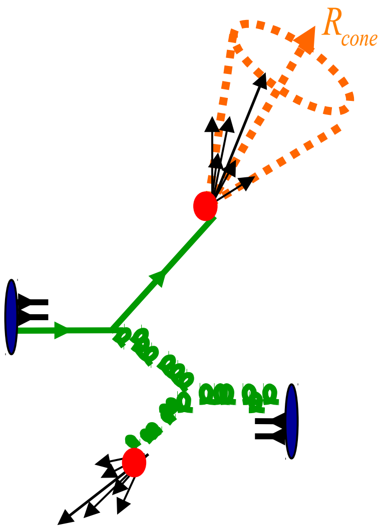


Asymptotic freedom



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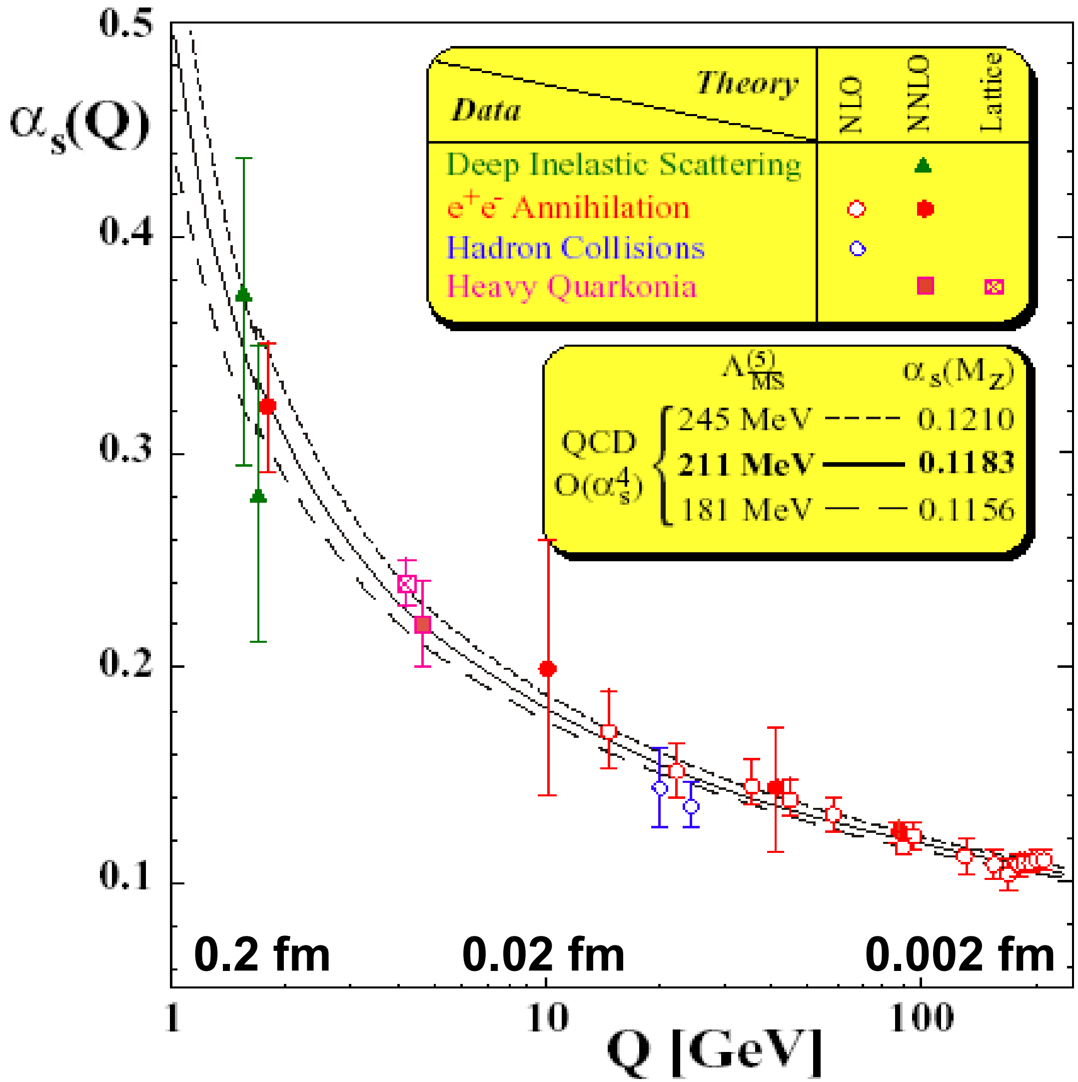

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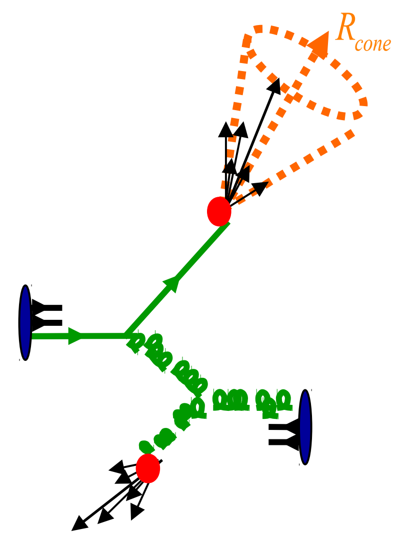

2004 Nobel Prize

PHYSICAL REVIEW D VOLUME 8, NUMBER 10 15 NOVEMBER 1973

Asymptotically Free Gauge Theories. I*

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Frank Wilczek
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(Received 23 July 1973)

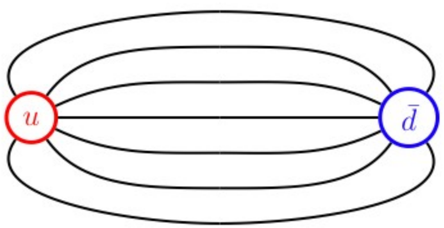
VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

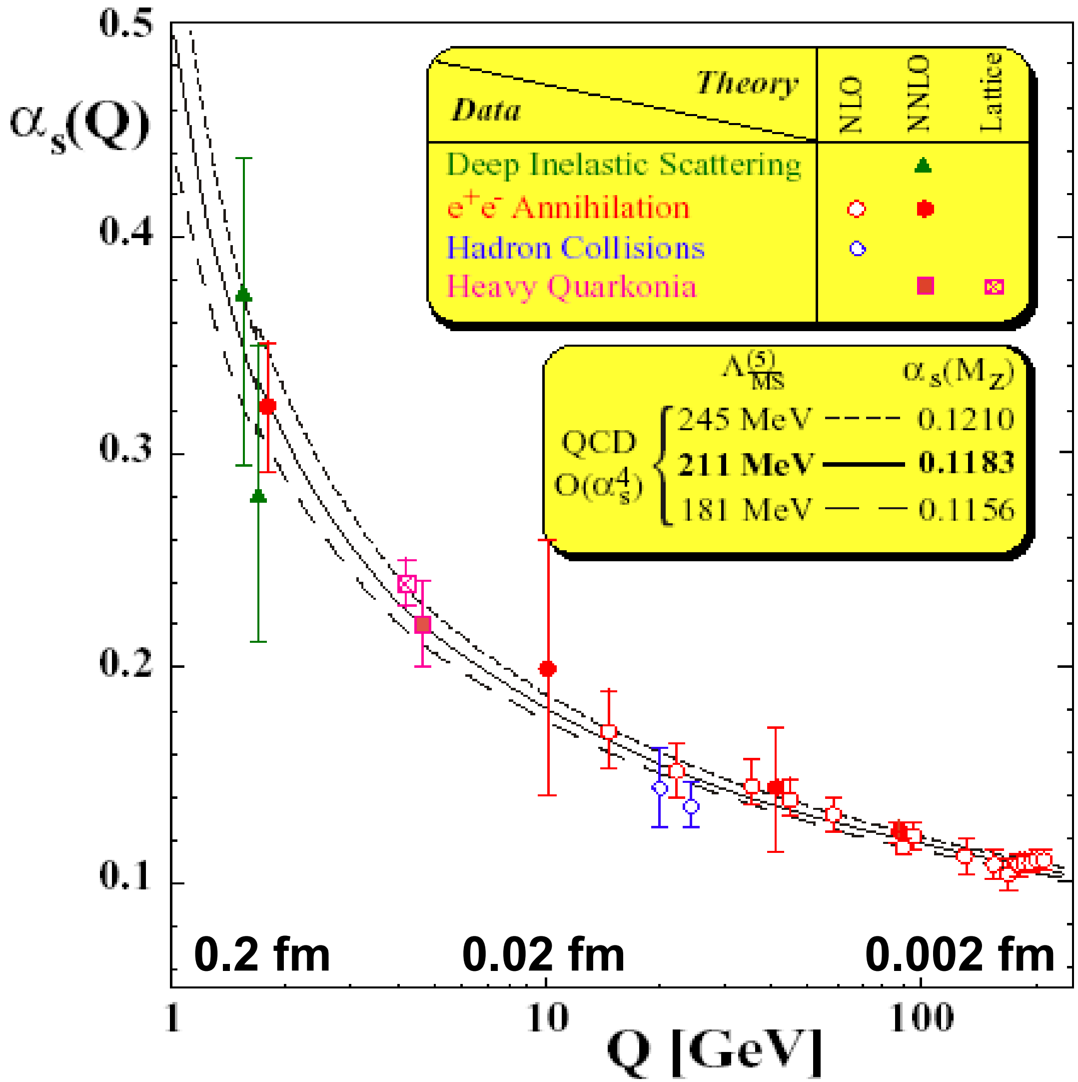
Reliable Perturbative Results for Strong Interactions?*

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

“Running” of the coupling: QCD

Confinement





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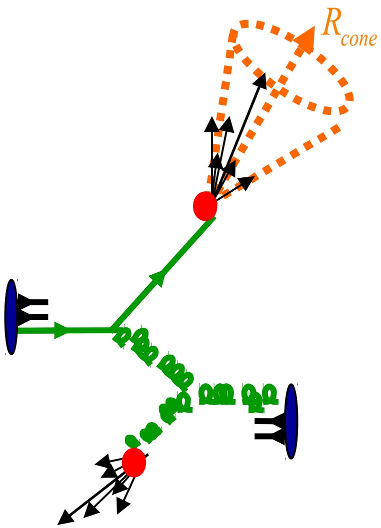

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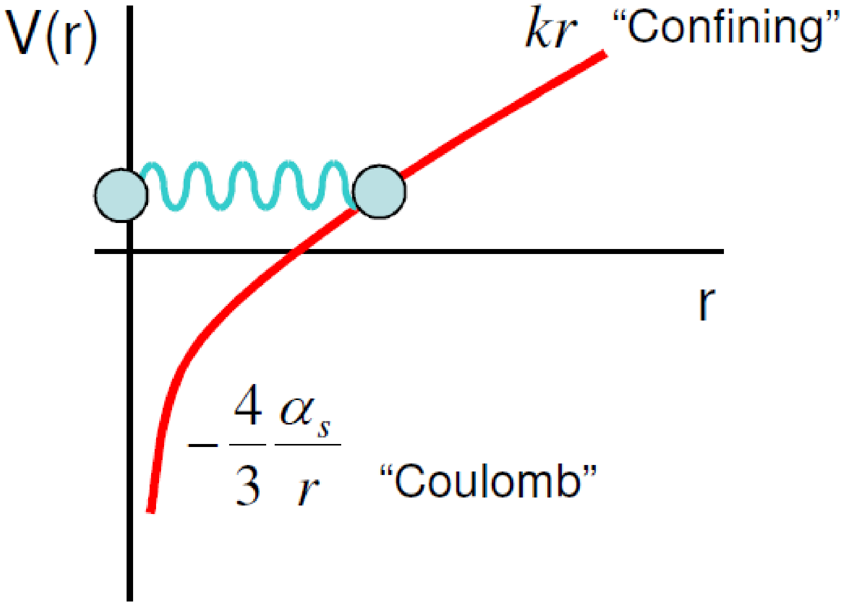
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + K\,r$$

- Kr parametrizes the effects of confinement



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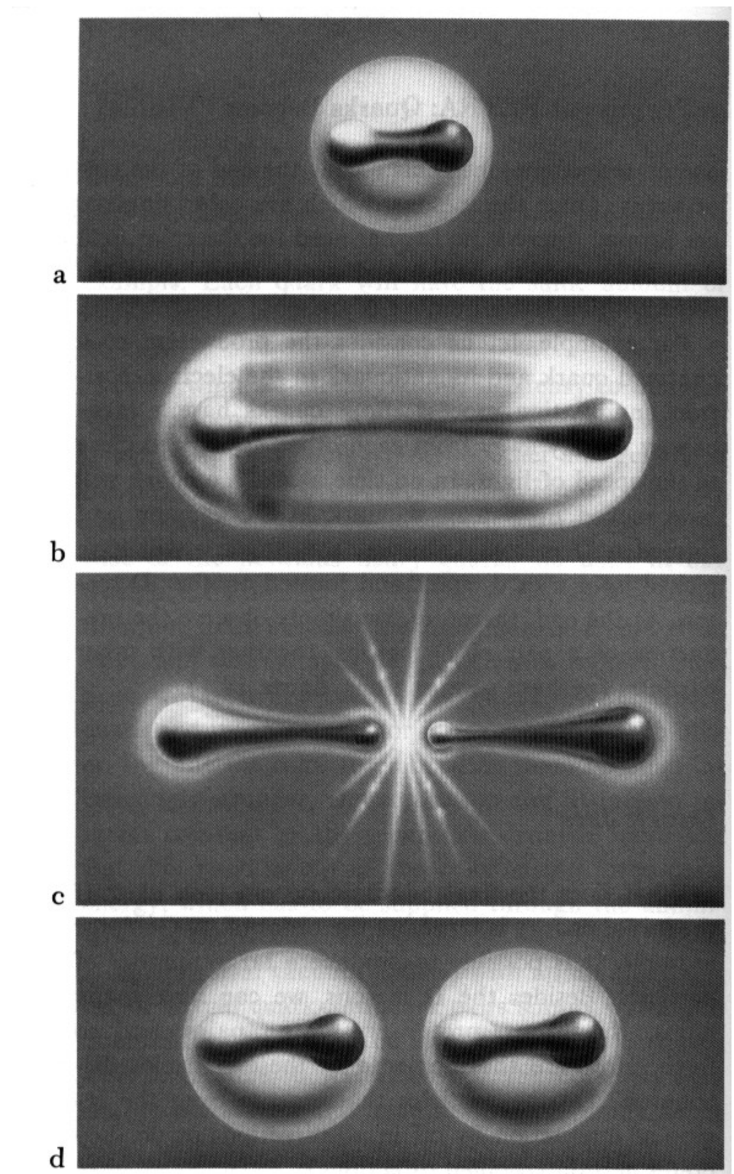
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + K\,r$$

- Kr parametrizes the effects of confinement
- When r increases, the color field can be seen as a tube
- At large r, it become energetically favorable to convert the stored energy into a new $q\bar{q}$ pair
- Confinement cannot be described perturbatively, but with lattice QCD or bag models inspired by QCD



(Illustration from Fritzsch)

QCD deconfinement phase transition

Deconfinement phase transition

- Since the interactions between quarks and gluons become weaker at small distances, it might be possible to create a deconfined phase of matter composed out of a large number of free quarks and gluons

- First ideas in the mid 1970's

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

  Superdense matter: Neutrons or asymptotically free quarks?
  Collins and Perry, PRL 34 (1975) 1353

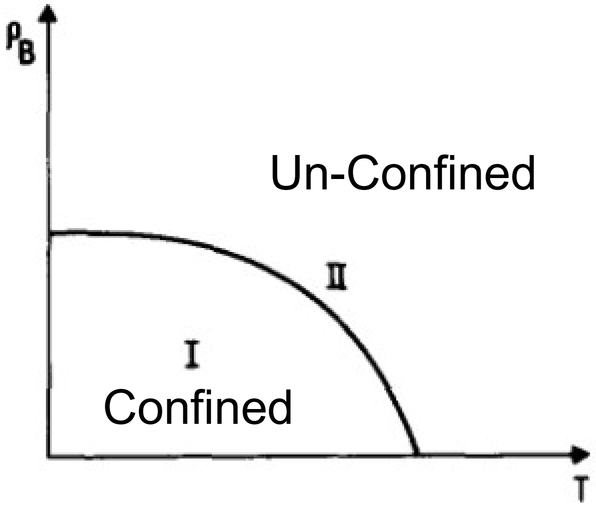


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

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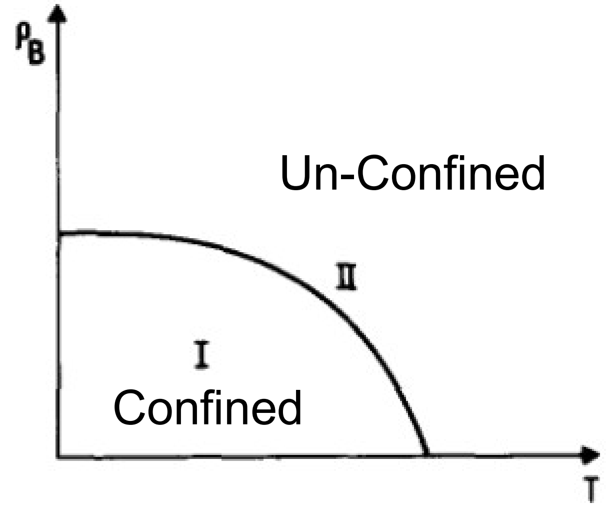

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Phase transition at large T

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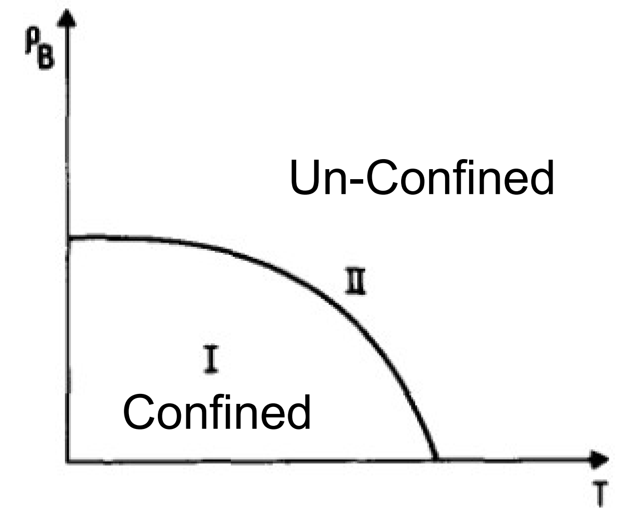


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

We expect the same transition to be also present at low temperature but high pressure, for the same reason, i.e. we expect a phase diagram of the kind indicated in fig. 1.

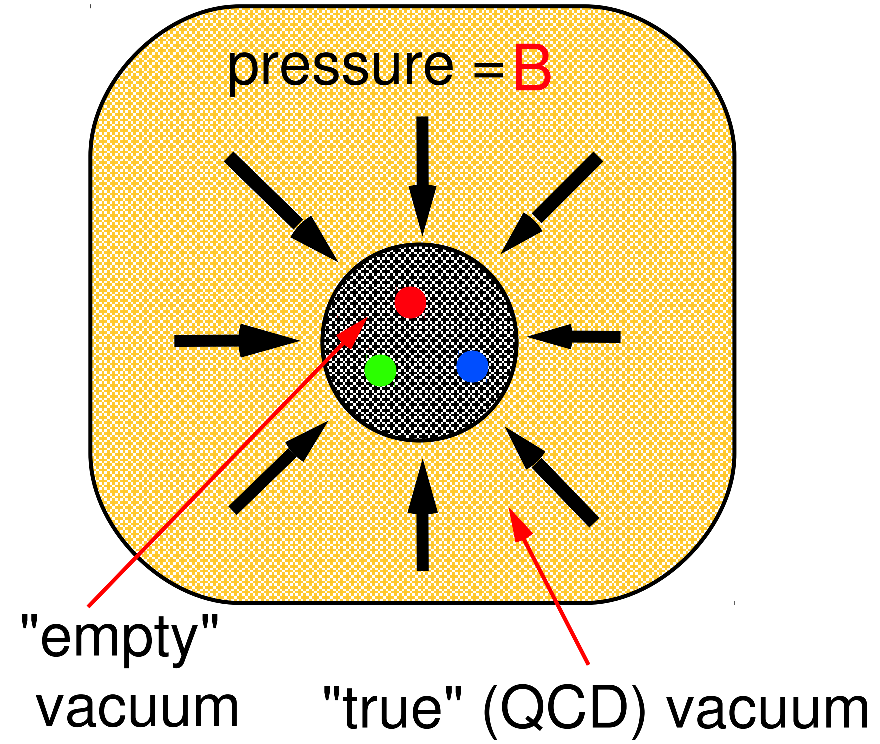
Phase transition
at large T and/or ρ_B

We expect models of this kind to give rise to a phase transition at a temperature $kT \approx m_\pi$, the high temperature phase being one where quarks can move freely in space.

The MIT Bag model

- The MIT bag model assumes that quarks are confined within bags of perturbative (empty) vacuum of radius R, in which they are free to move
- The QCD (true) vacuum creates a confining bag pressure B
- The bag constant is obtained by balancing the vacuum with the kinetic pressure of the quarks
  - By minimizing
    $$E \approx \frac{2N}{R} + \frac{4}{3}\pi R^3 B$$
  - $B \approx (200\ \text{MeV})^4 = 0.2\ \text{GeV/fm}^3$ with N=3 quarks in R=0.8fm

Bag model of a hadron:

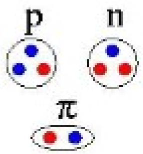


B= "bag constant" $B \approx 0.2\ \text{GeV/fm}^3$

Chodos et al., PRD 10 (1974) 2599

Deconfinement: A toy model

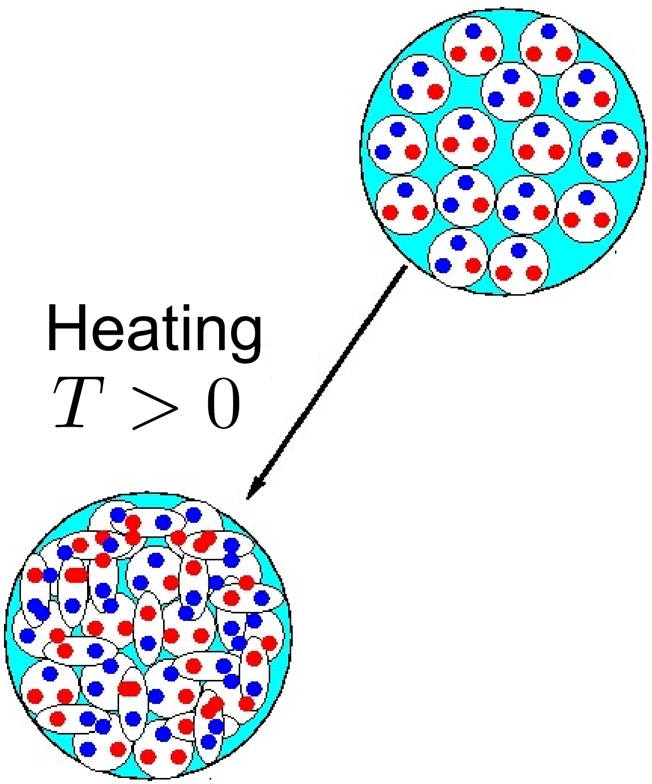
$$g_B = 0, \;\; g_F = 2$$



- Heat matter so much that individual hadrons start to overlap

- From statistical mechanics for an ideal gas

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



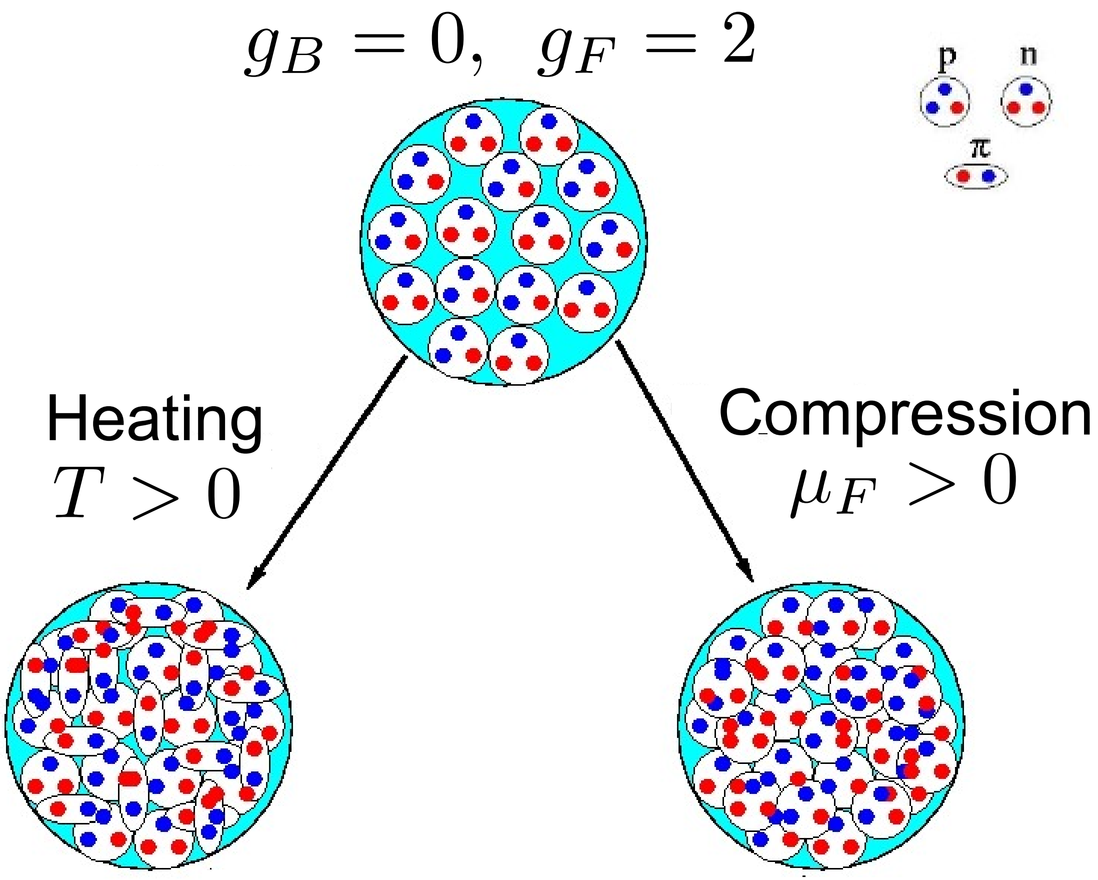
B=Boson
F=Fermion

Deconfinement: A toy model

- Heat or compress matter so much that individual hadrons start to overlap

- From statistical mechanics for an ideal gas

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



B=Boson
F=Fermion

Deconfinement: A toy model

- Heat or compress matter so much that individual hadrons start to overlap
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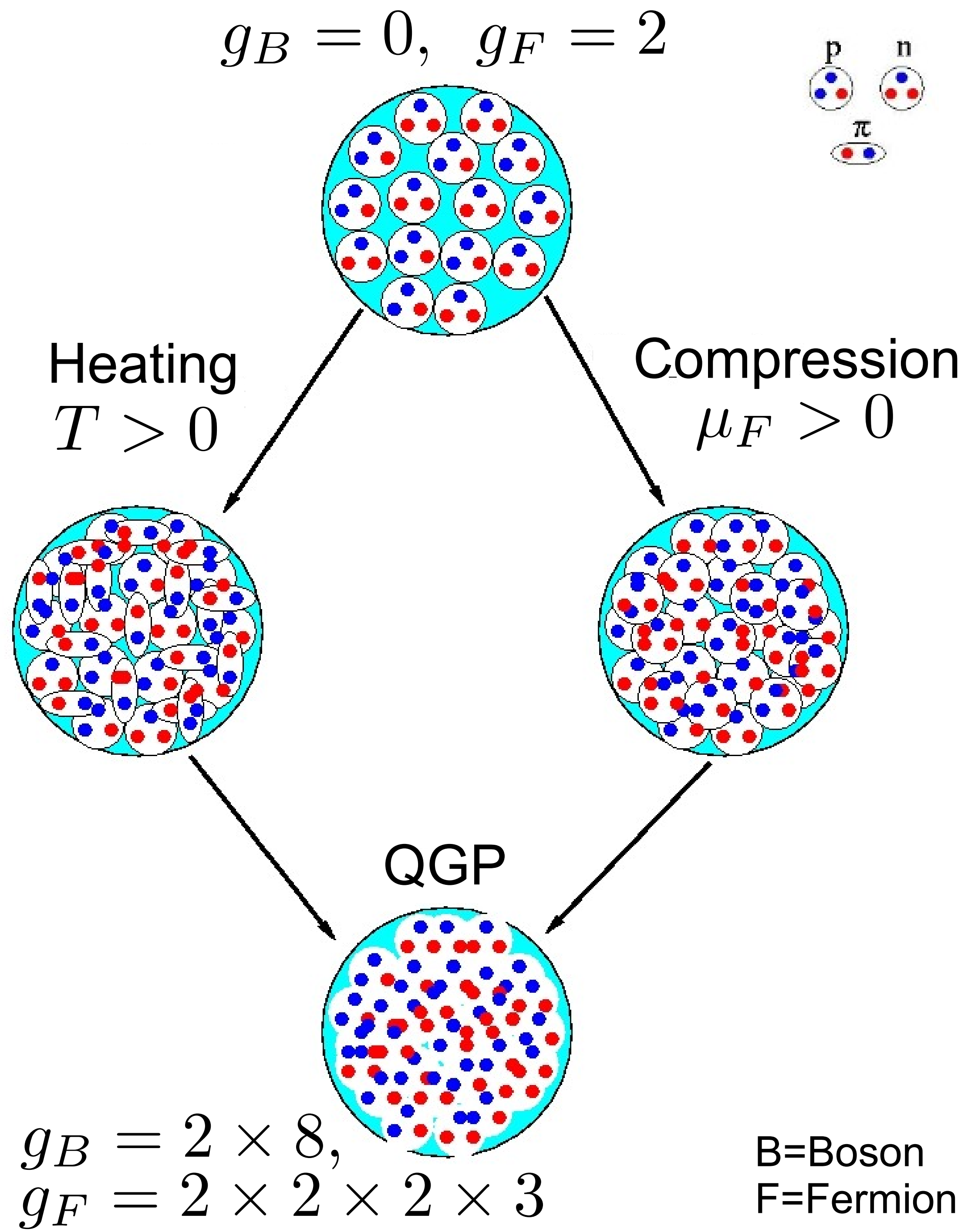

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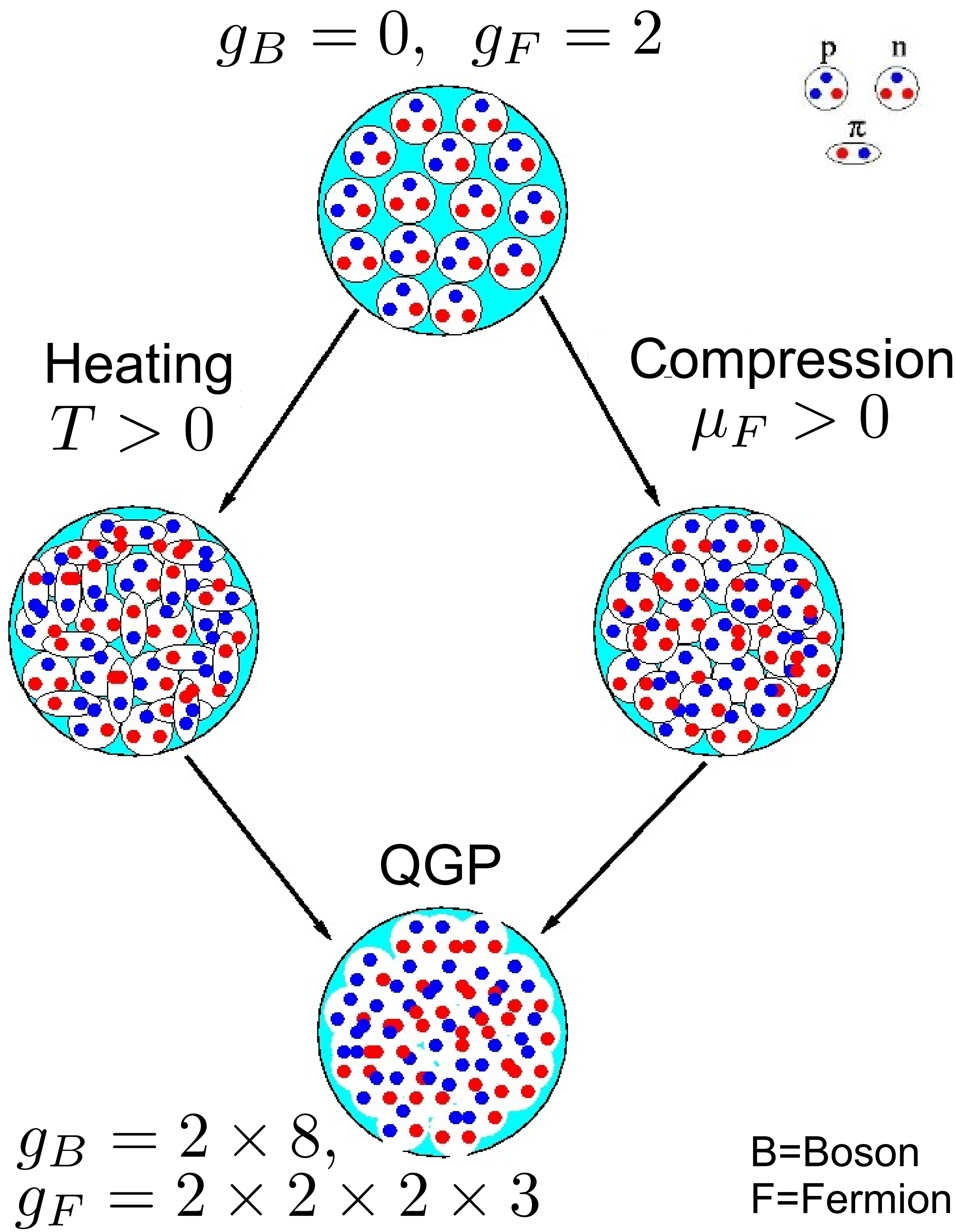
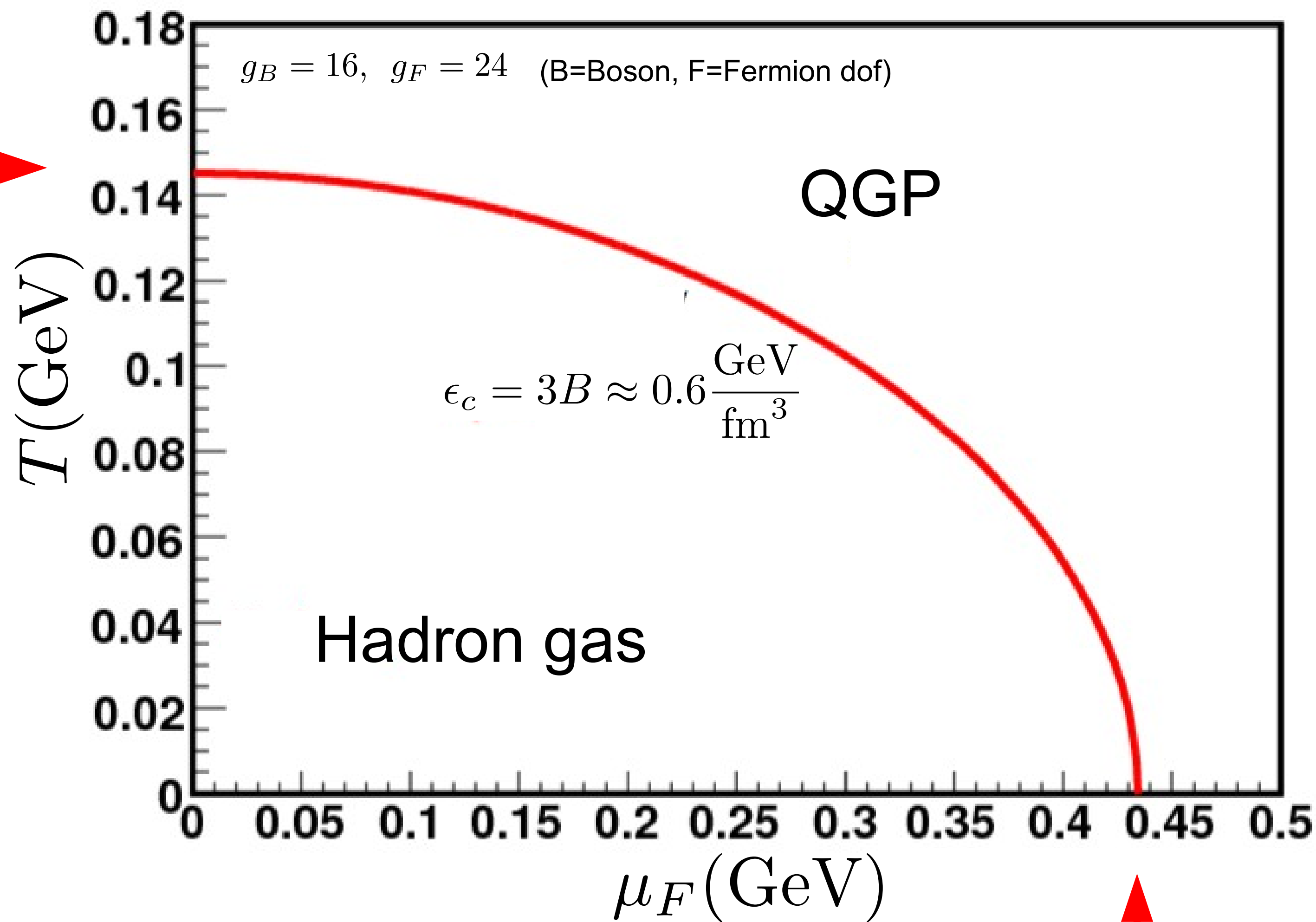


Phase diagram of non-interacting QGP

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

(10^5 times core of sun)



- Condition for QGP: Pressure ≥ B

$$p = \frac{\epsilon}{3} \stackrel{!}{=} B \Rightarrow T_c(\mu_F)$$

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

(net-baryon density of about 5 x nucleus)

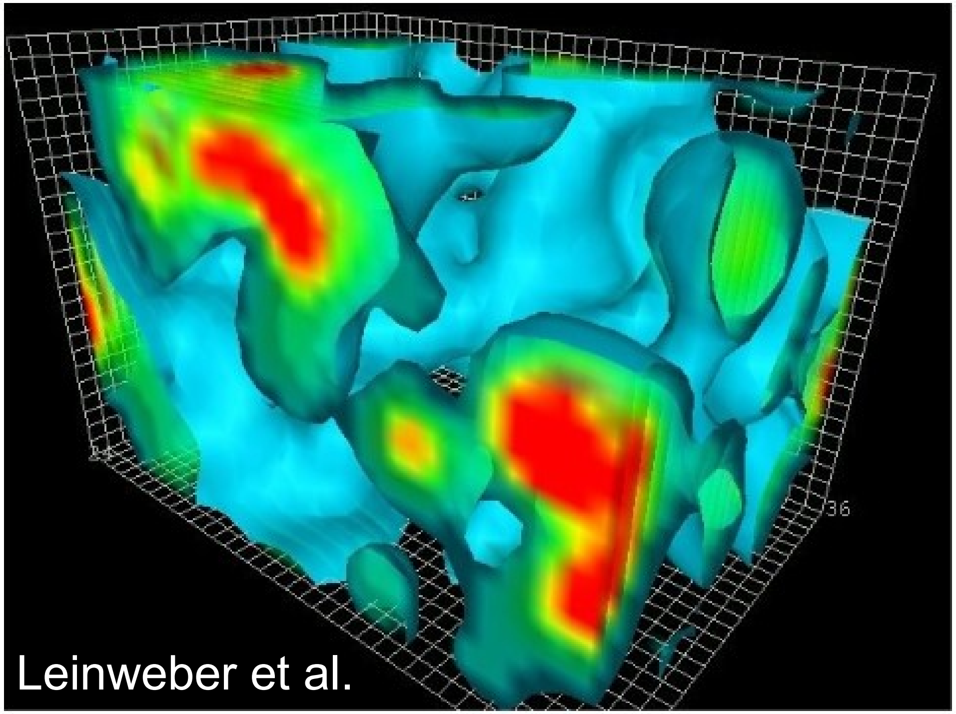
(see Reygers and Schweda)

Lattice QCD

Lattice QCD

- As QCD is asymptotically free at small distances, cannot use perturbation theory to calculate properties of e.g. hadrons
- Instead solve QCD numerically by putting fields on a space-time lattice (lattice QCD)
- First principle non-perturbative calculation
- Computationally demanding as lattice needs to be big, e.g. 16^3x32

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



JUGENE in Jülich
(294,912 cores, ~ 1 PetaFLOPSS

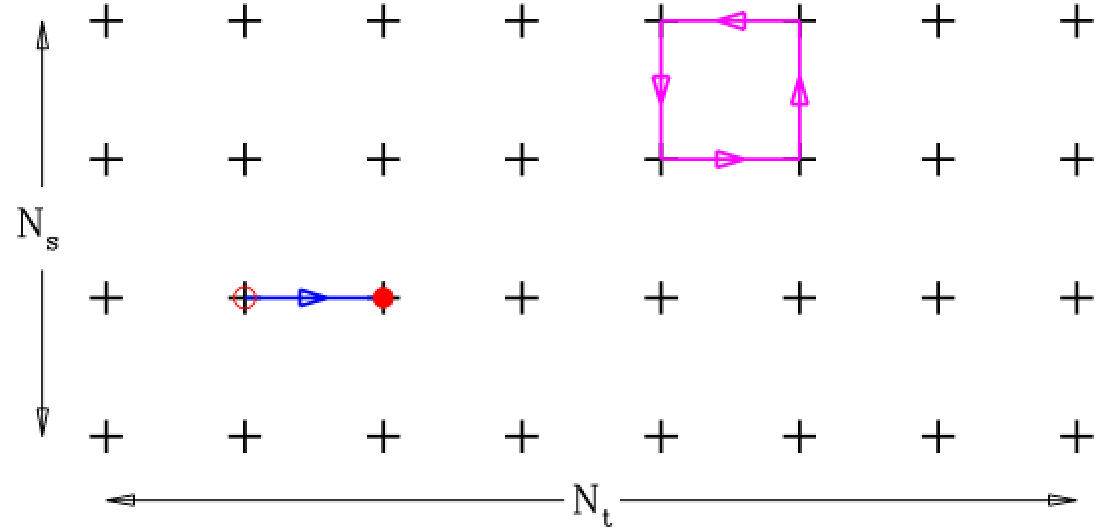
Lattice QCD: the approach

- Solve path integrals numerically in discretized Euclidean space-time

$$e^{i\,S} \to e^{-S_E}$$

Lattice spacing $a, \quad a^{-1} \sim \Lambda_{\mathrm{UV}}, \quad x_\mu = n_\mu a$

Finite volume $L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a$



(anti)quarks: $\psi(x),\ \overline{\psi}(x)$

gluons: $U_\mu(x) = \mathrm{e}^{aA_\mu(x)} \in \mathrm{SU}(3)$

field tensor: $P_{\mu\nu}(x) = U_\mu(x) U_\nu(x + a\hat{\mu}) U_\mu^\dagger(x + a\hat{\nu}) U_\nu^\dagger(x)$

$$S[U, \overline{\psi}, \psi] = S_{\mathrm{G}}[U] + S_{\mathrm{F}}[U, \overline{\psi}, \psi]$$

(see, e.g. Wittig)

Lattice QCD: the approach

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- Physical results
  - Continuum limit (a → 0)
  - Infinite volume limit (V → ∞)
  - Set scale(s) using data e.g. hadron mass(es)

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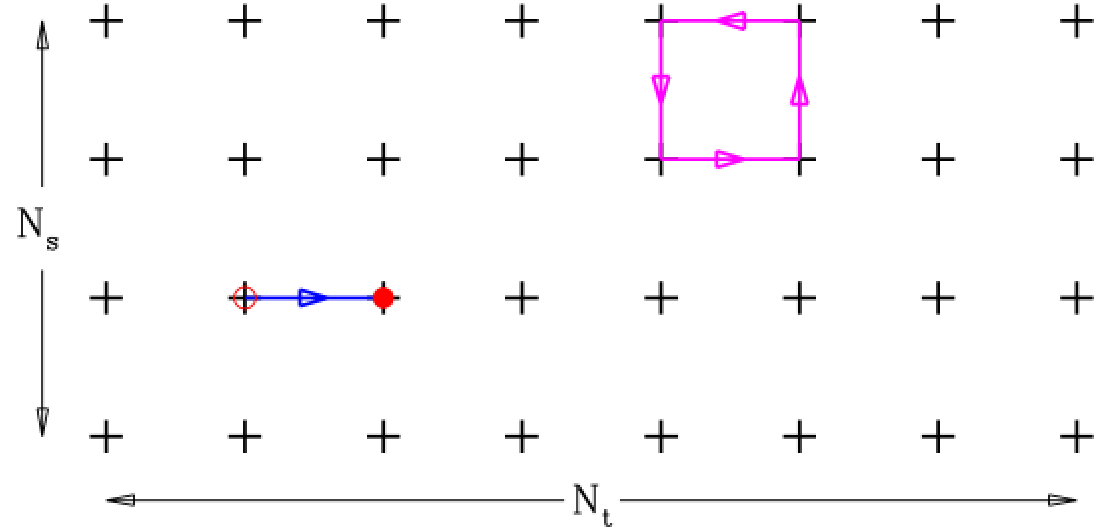

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- Problems of approach
  - Fermion doubling
  - Small physical quark masses computationally demanding
  - Sign problem for finite μ

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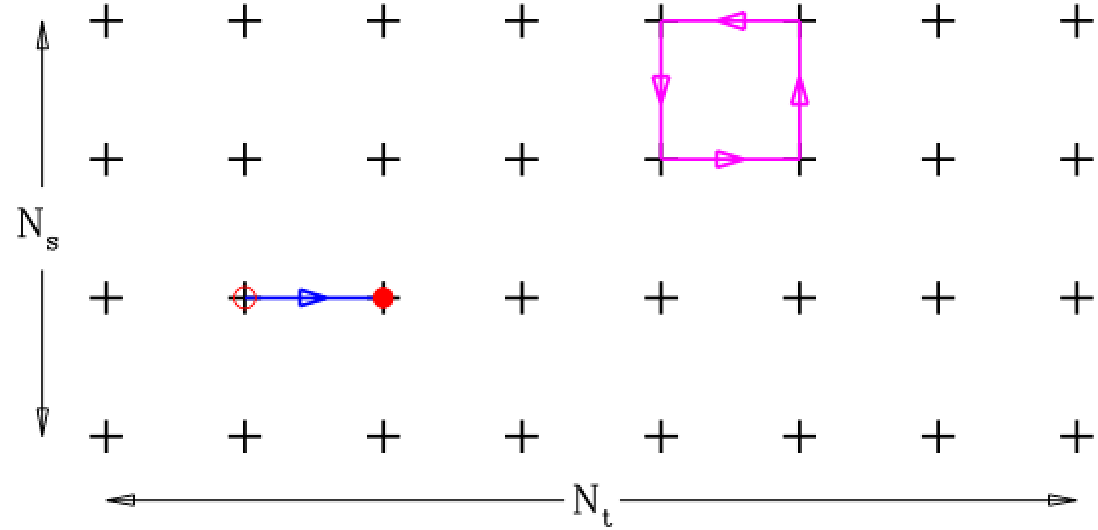
Finite volume $L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a$



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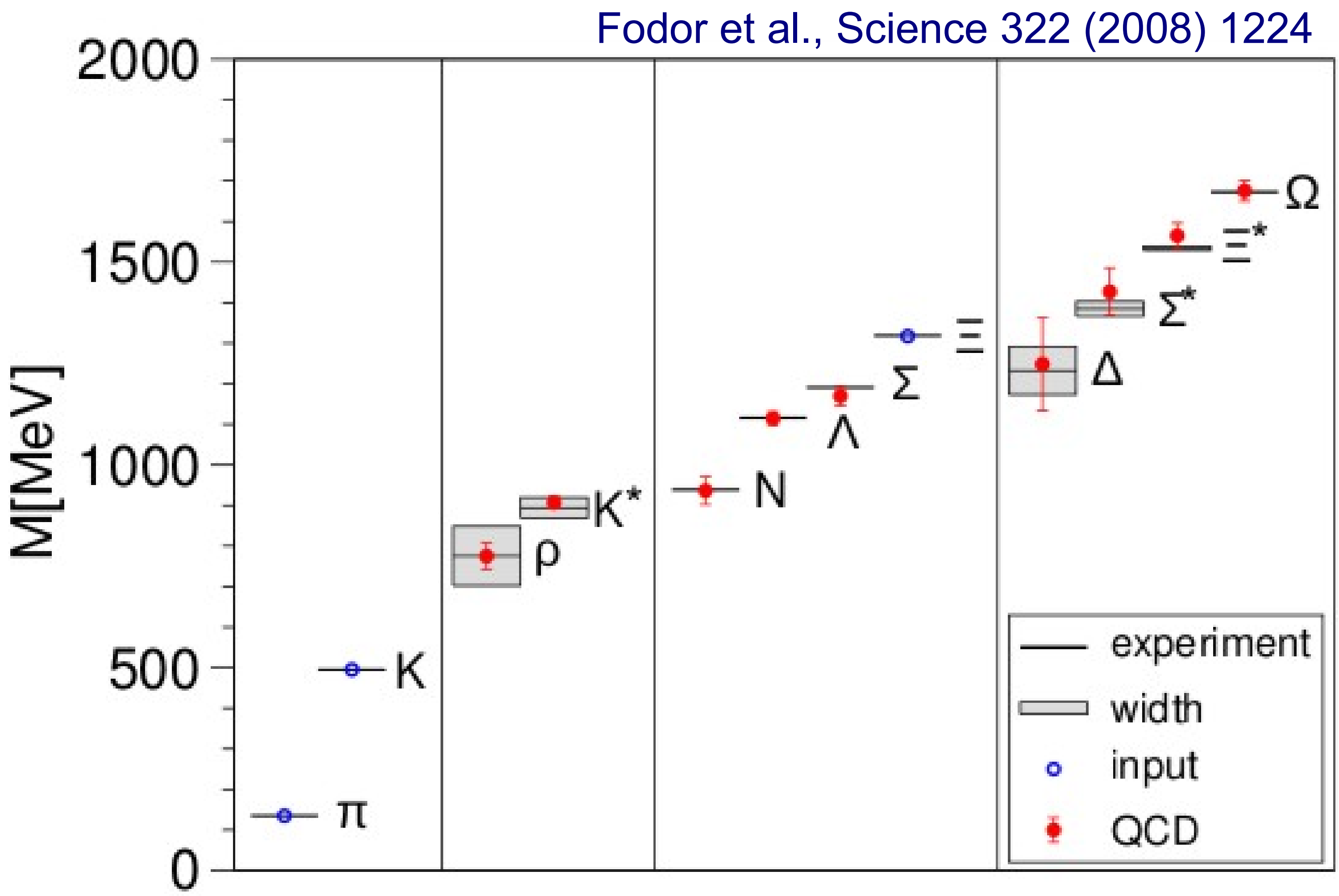
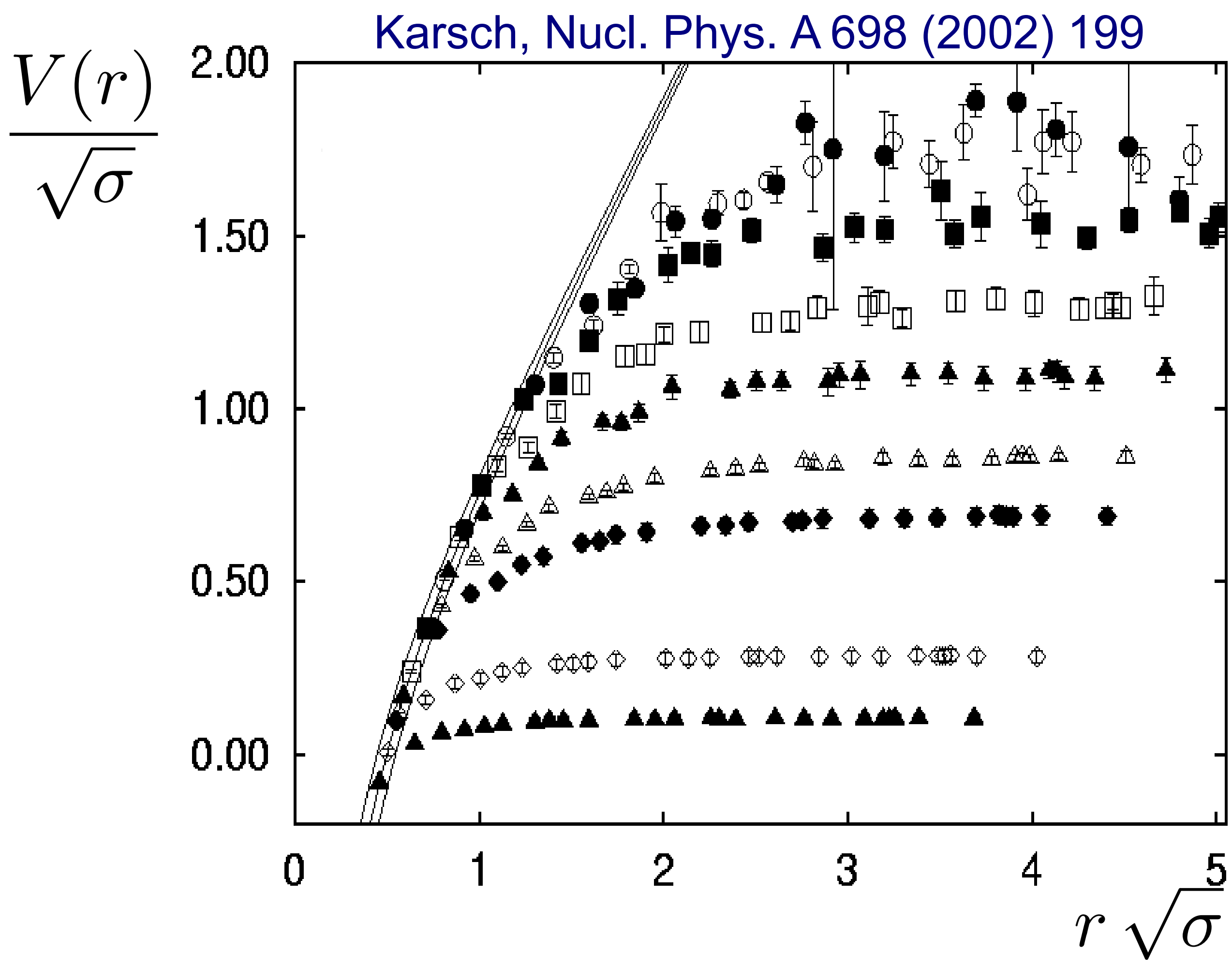
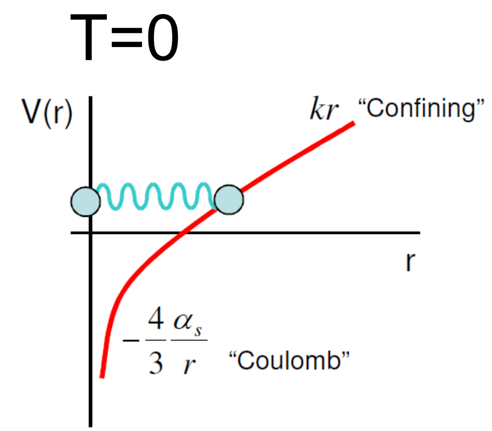
Lattice QCD: hadron spectrum



Full calculation using 2 quark flavors
in excellent agreement with experimental data

Lattice QCD: Static potential





Lattice calculation (for a heavy quark pair) exhibits screening of long range confining potential with increasing temperature

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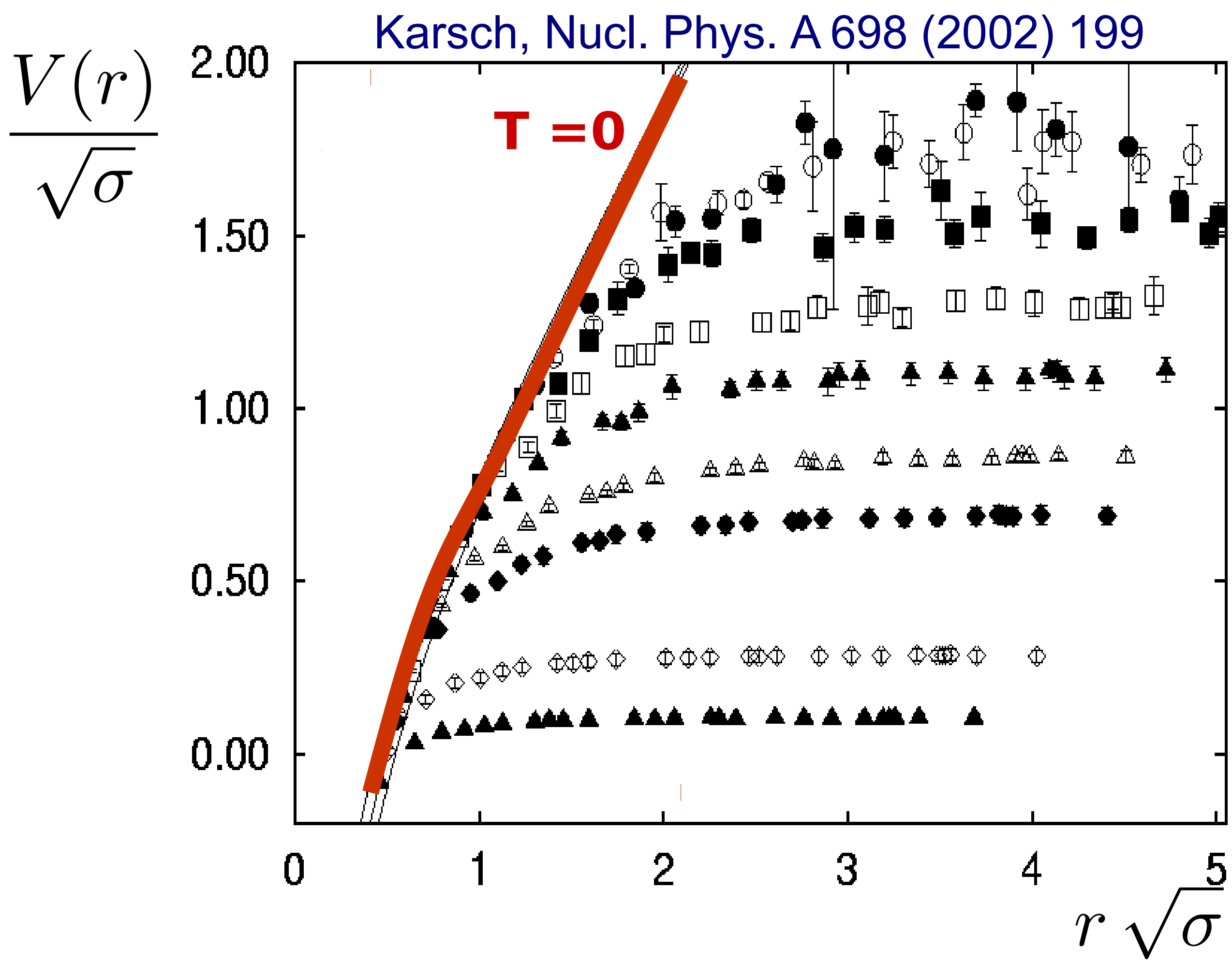

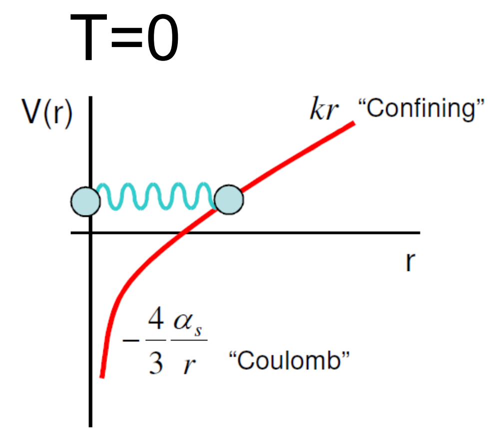

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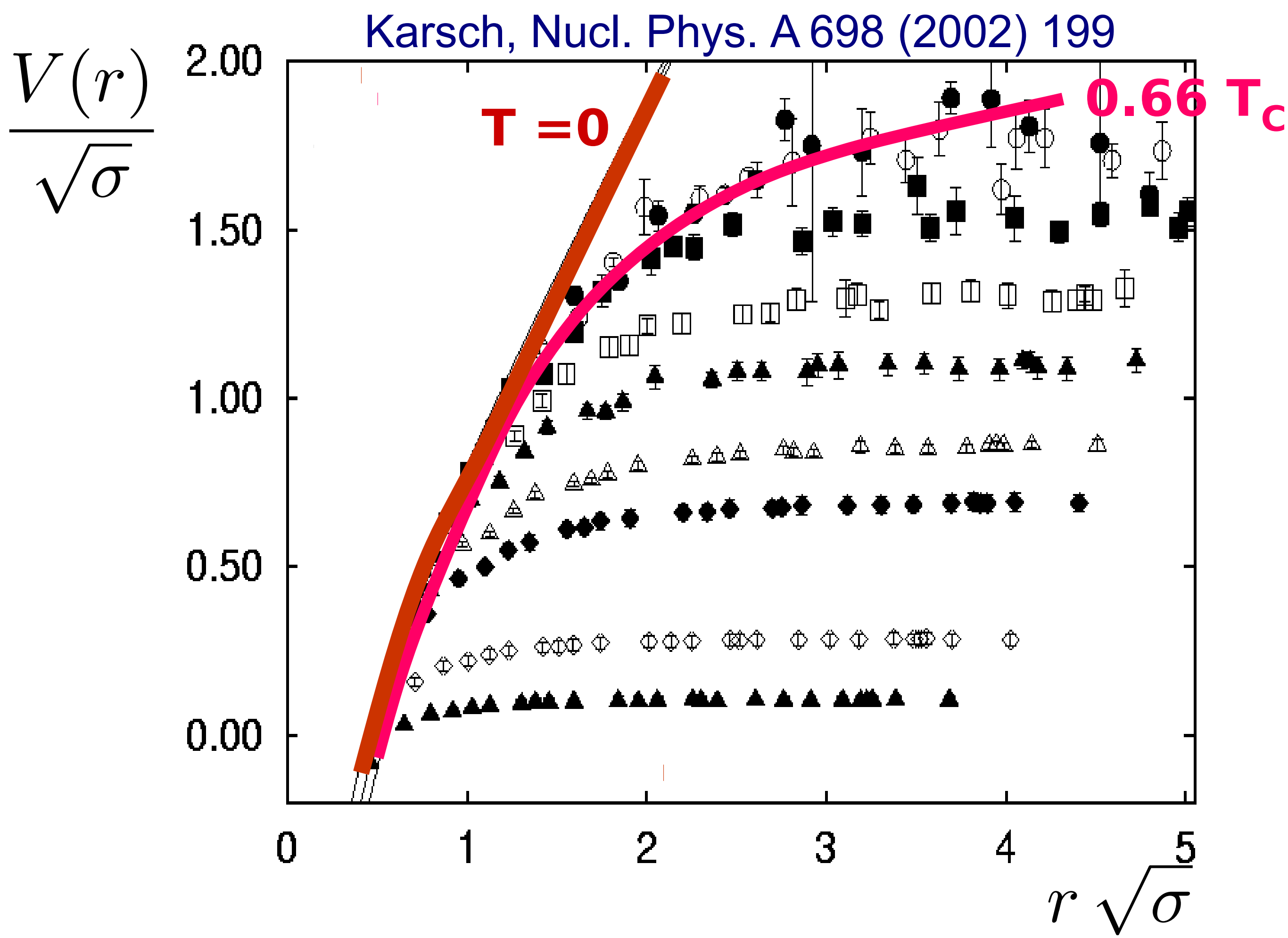

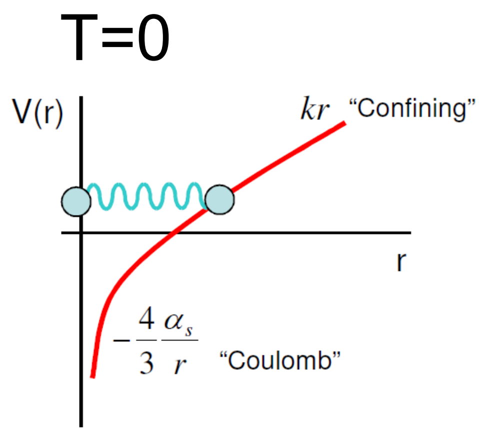

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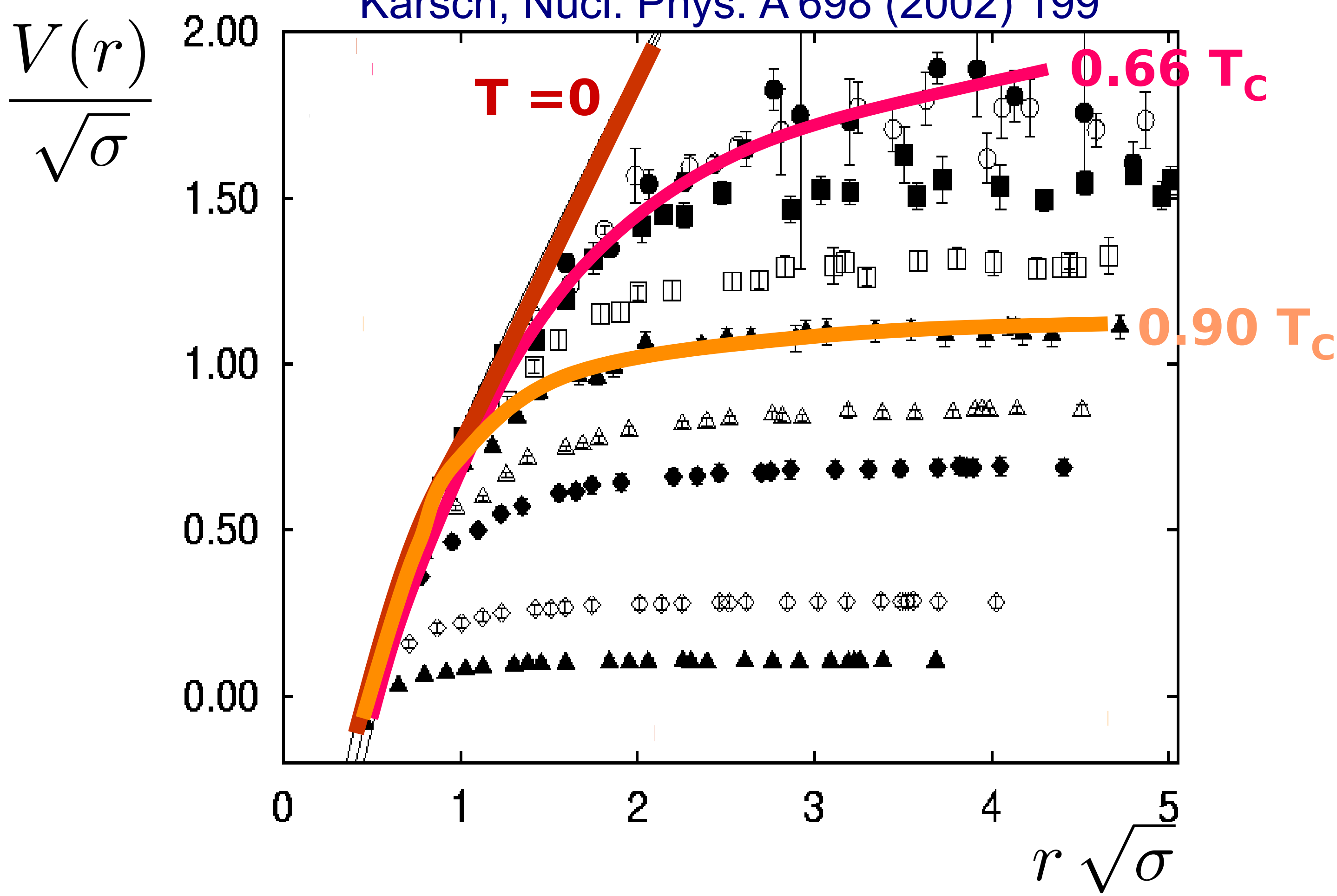
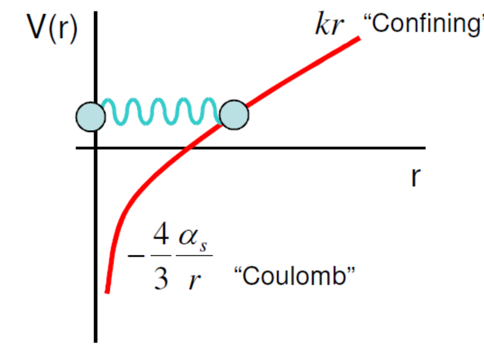
Karsch, Nucl. Phys. A 698 (2002) 199



T=0



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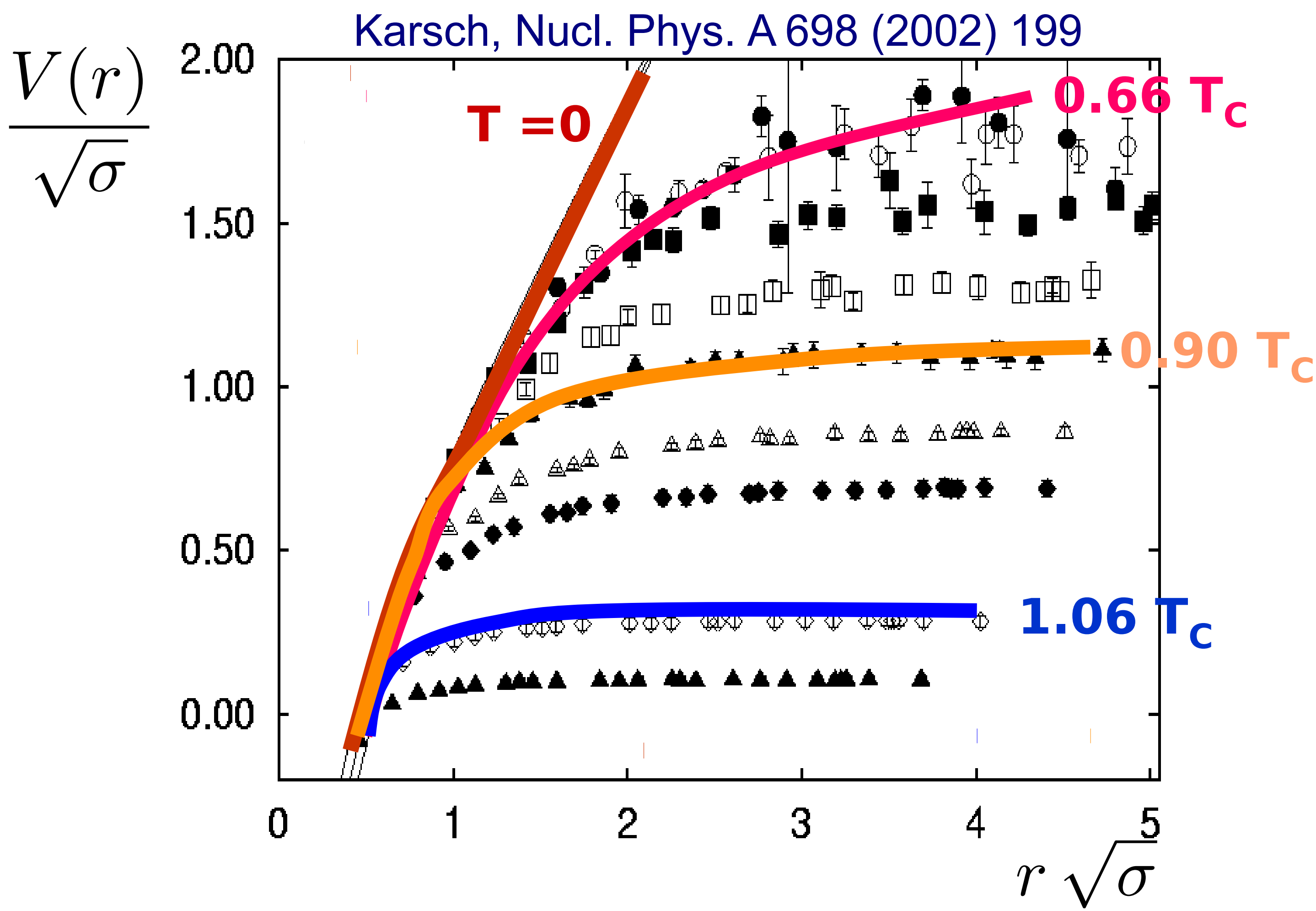

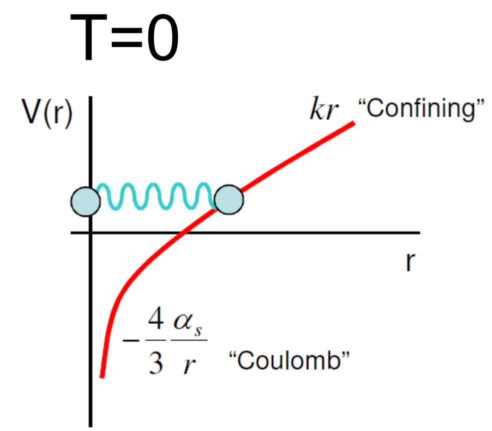

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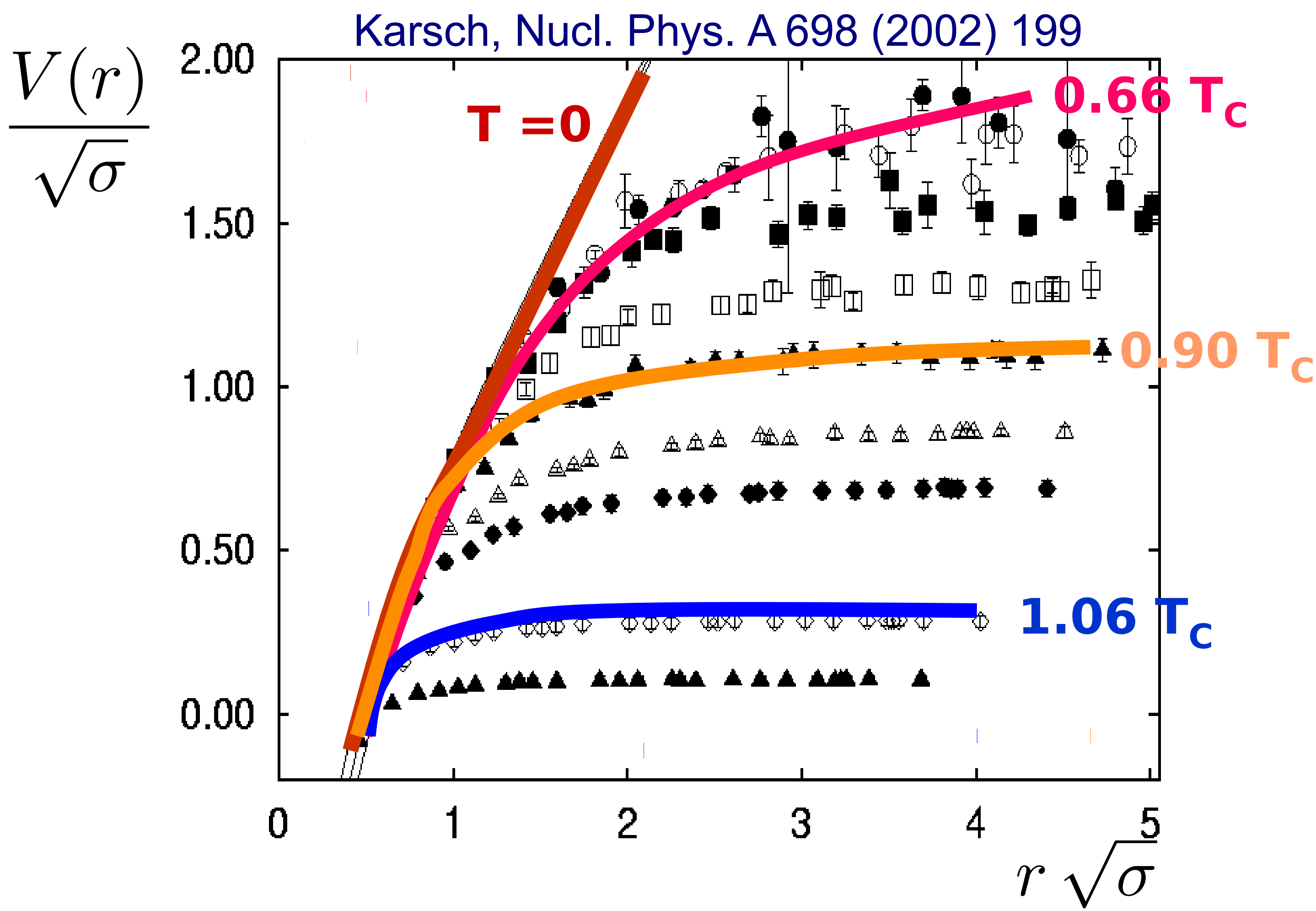

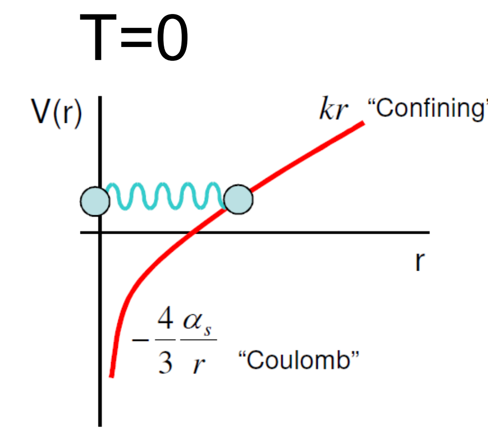

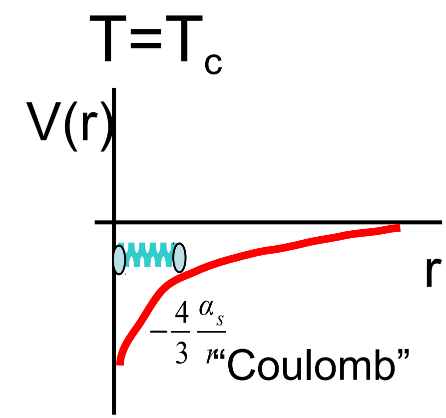

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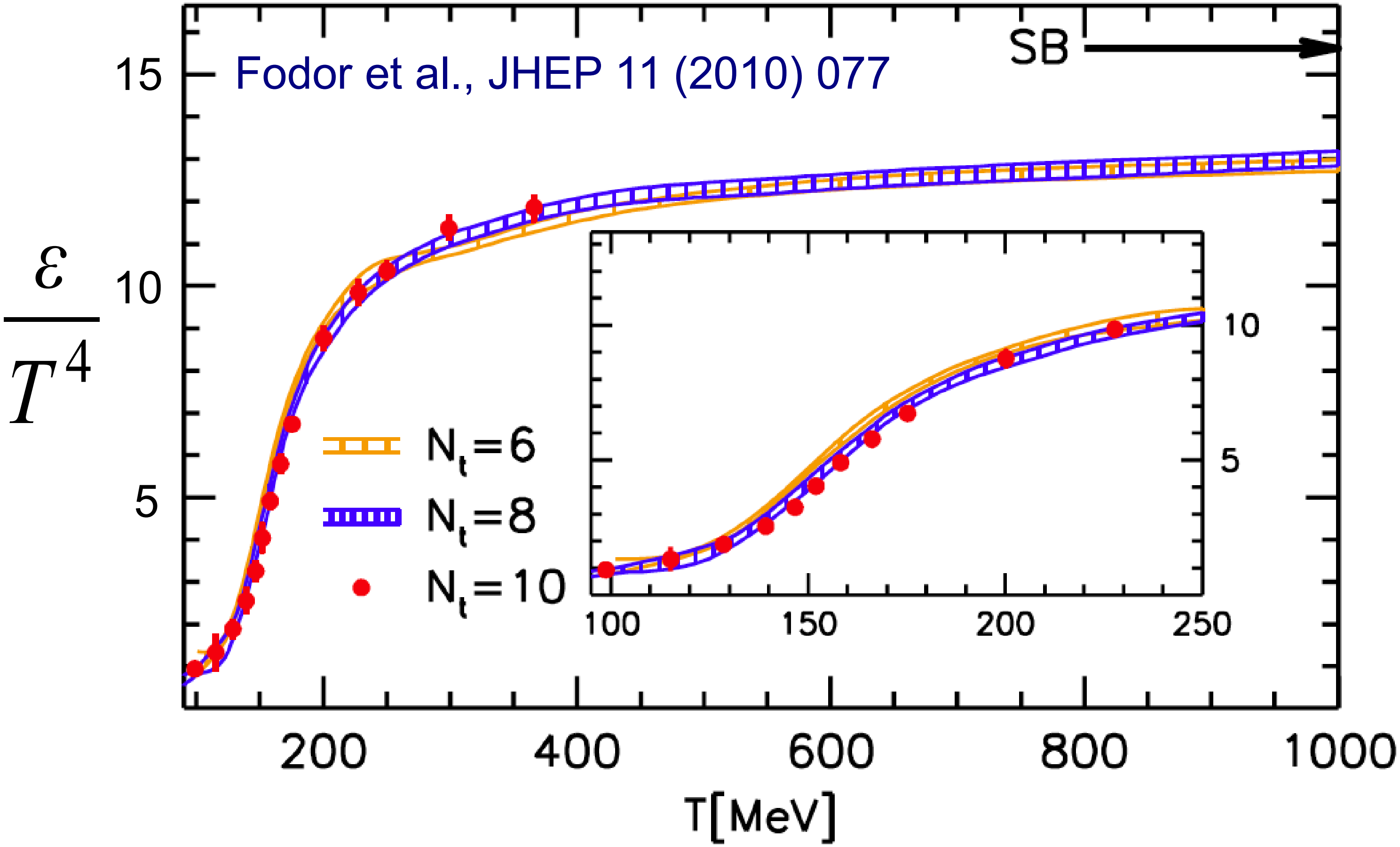
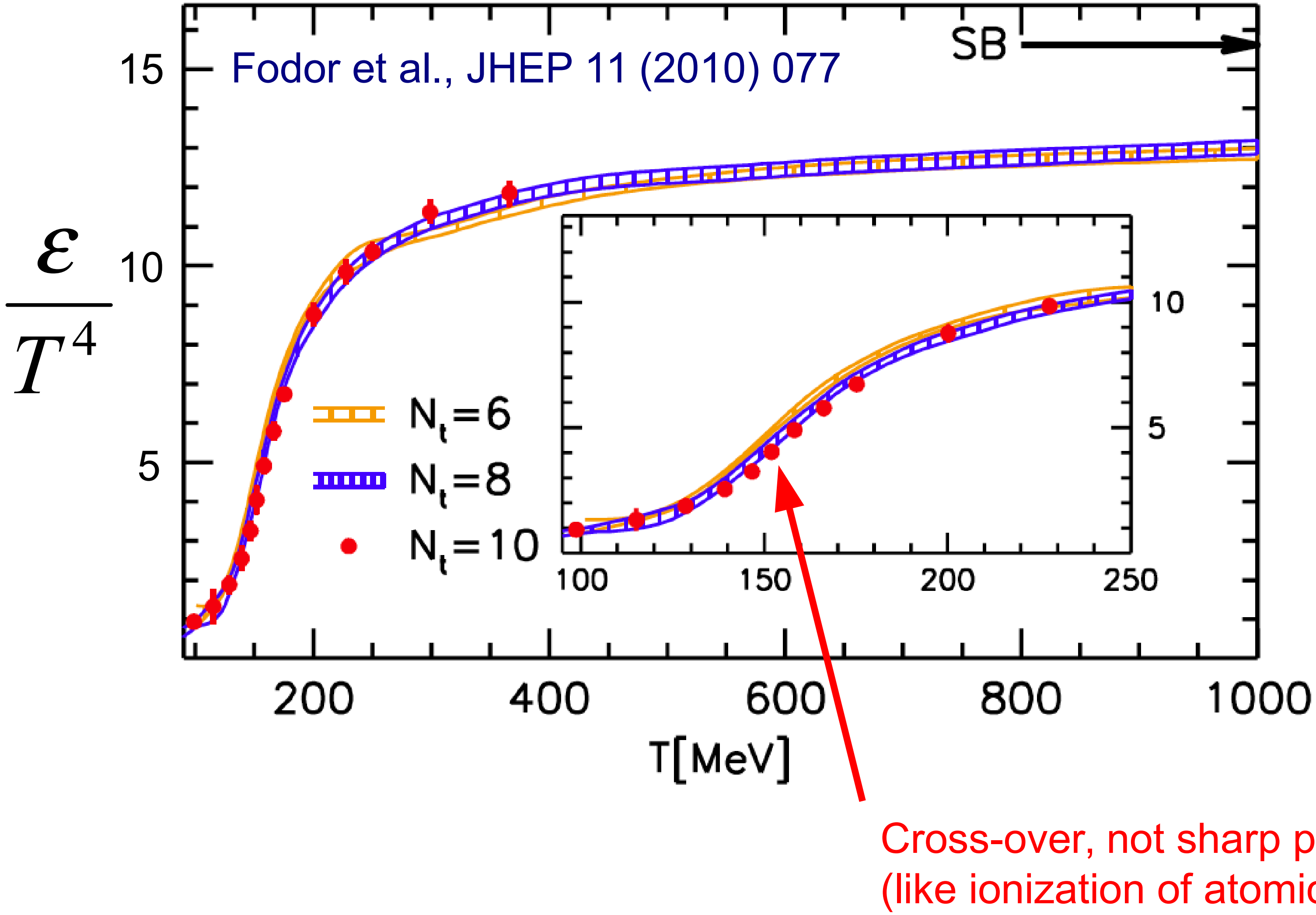
Lattice QCD: Energy density



Cross-over transition temperature region between 140 and 200 MeV with range of energy density between 0.2 and 1.8 GeV/fm^3

Remember: T_c ≈170 MeV and ε_c ≈ 1 GeV/fm^3

Lattice QCD: Energy density



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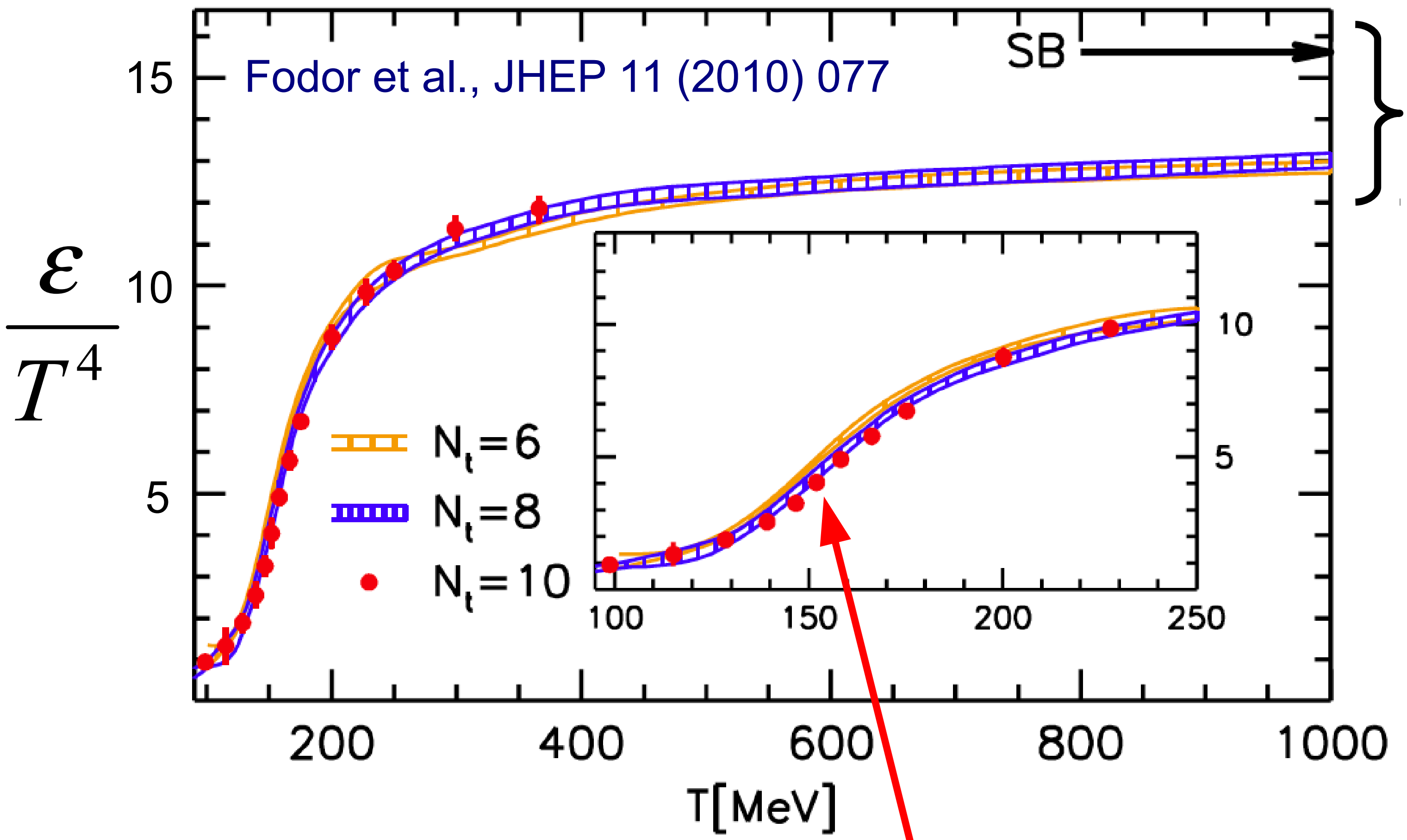


Slow convergence to ideal gas (SB) limit

What carries the energy? Complex bound states of q and g? Strongly coupled plasma?

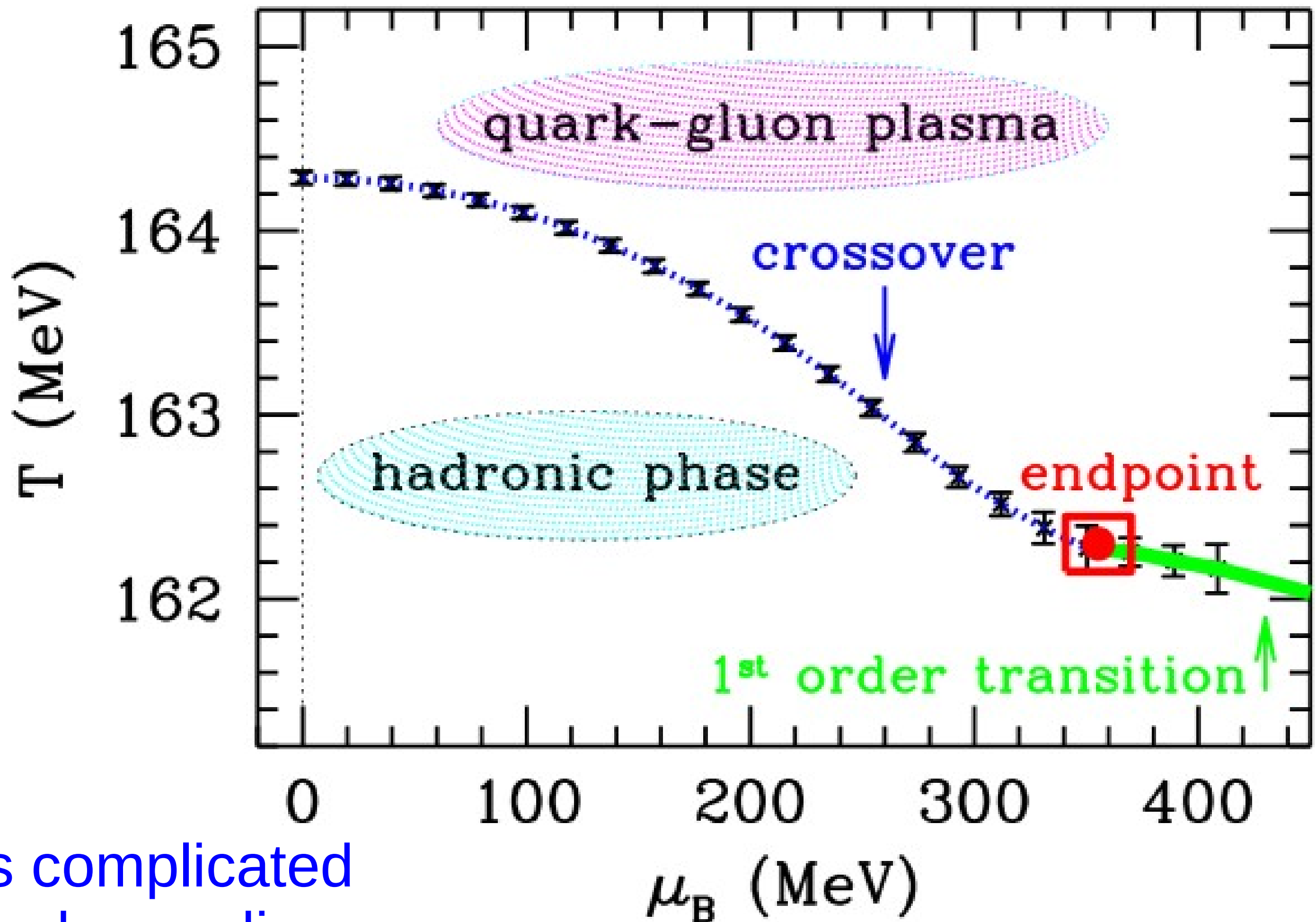
Cross-over, not sharp phase transition (like ionization of atomic plasma)

Cross-over transition temperature region between 140 and 200 MeV with range of energy density between 0.2 and 1.8 GeV/fm^3

Remember: $T_c \approx 170$ MeV and $\varepsilon_c \approx 1$ GeV/fm^3

Lattice QCD: phase diagram

Fodor and Katz,
JHEP 0404 (2004) 050

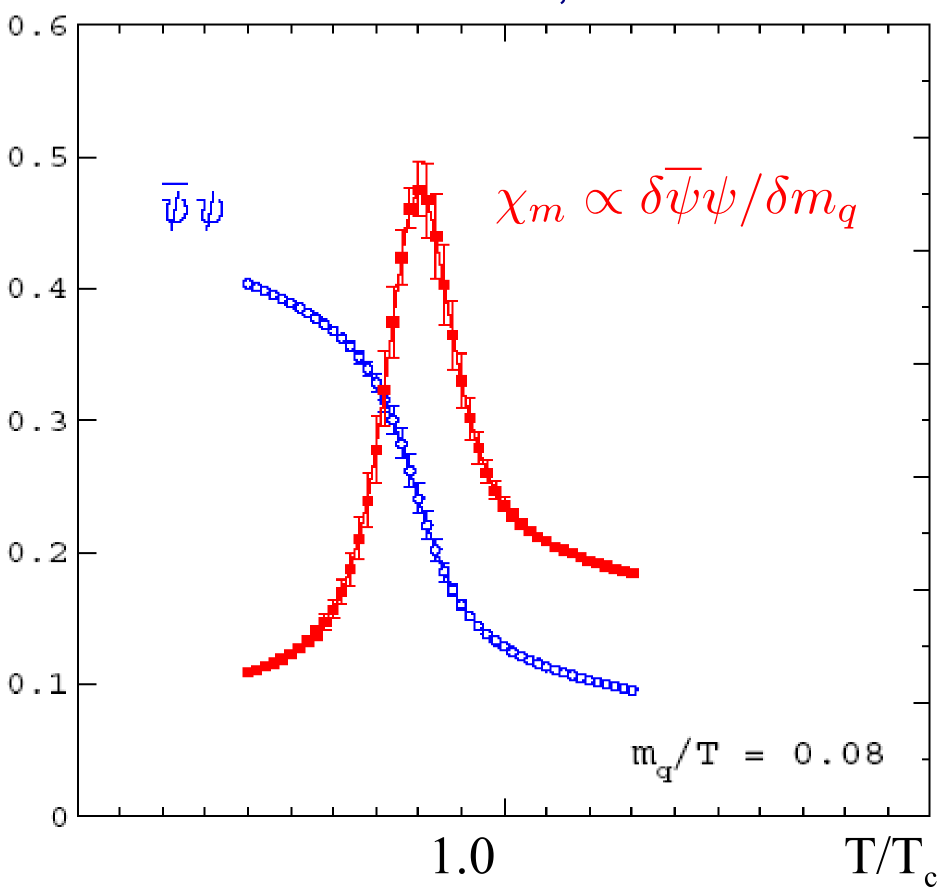


- Finite μ calculations complicated and computationally demanding
- Some calculations suggest a critical endpoint at T=162 MeV, μ_B=340 MeV with large theoretical uncertainties
- Critical endpoint existence and exact location are subject to exciting ongoing experimental and theoretical research

Restoration of bare masses

- Up and down quarks have very small (<10 MeV) bare masses (generated from the coupling to the Higgs)
- Confined quarks however require about 300 MeV dynamically through the effect of the strong interactions

Satz, arXiv:0803.1611



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  - Usually called "Partial restoration of chiral symmetry"

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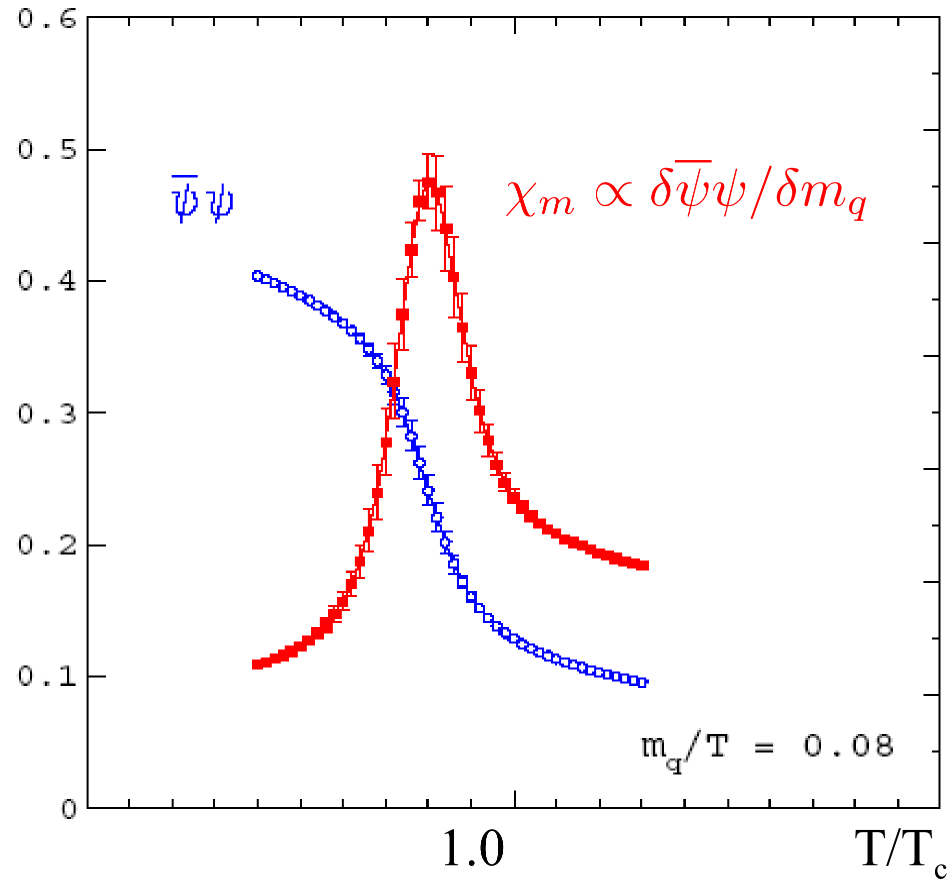

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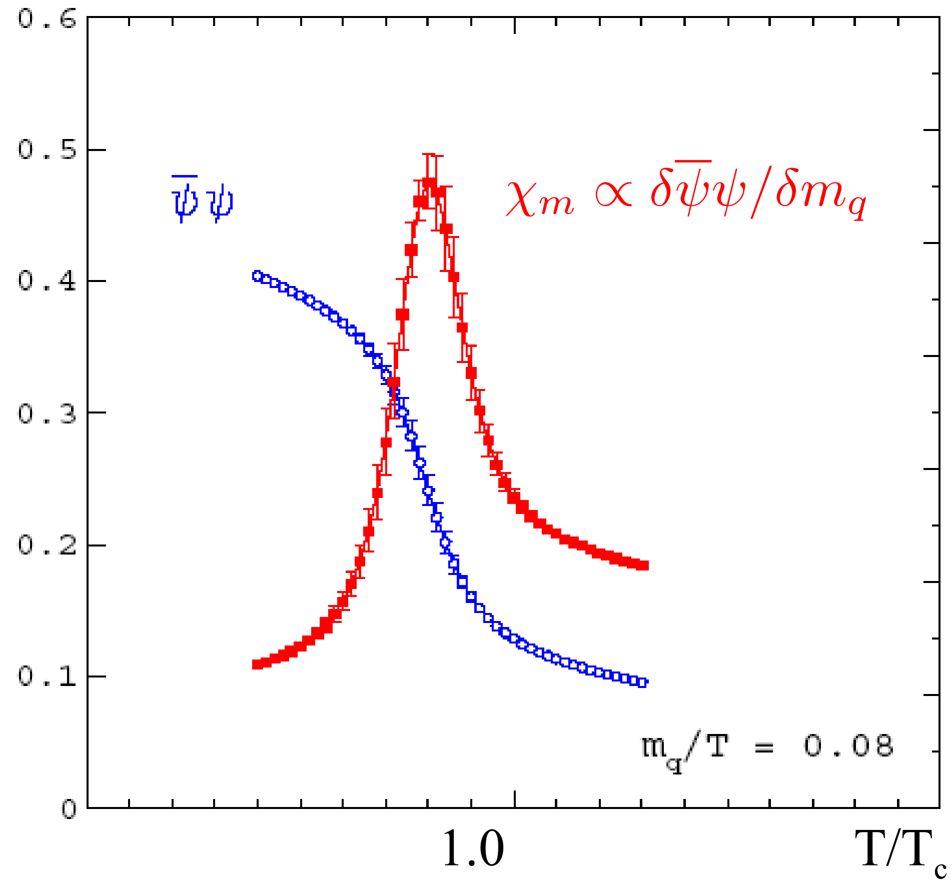
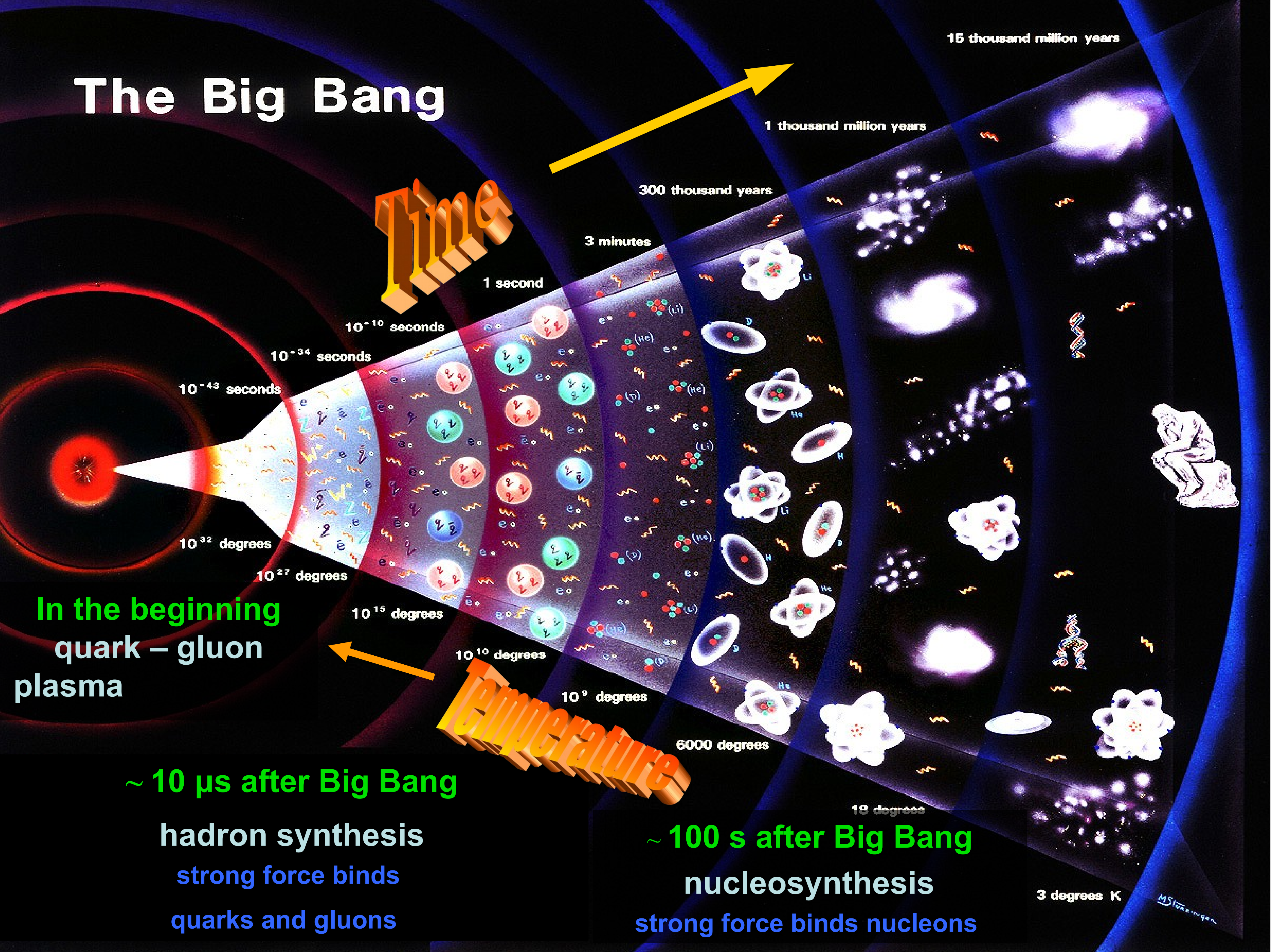
  - Usually called "Partial restoration of chiral symmetry"
- Effective quark mass from $<\bar{\psi}\psi>$ computed on lattice confirms expected behavior

Satz, arXiv:0803.1611



Natural appearance of QCD phase transition


The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
Time
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
Temperature
In the beginning
quark – gluon
plasma
~ 10 µs after Big Bang
hadron synthesis
strong force binds
quarks and gluons
~ 100 s after Big Bang
nucleosynthesis
strong force binds nucleons

QCD phase transition in the early universe

Effective degrees of freedom per relativistic particle

$$g_*(T) \equiv \frac{1}{\pi^2 T^4/30} \sum_{species} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3 p}{(2\pi)^3}$$

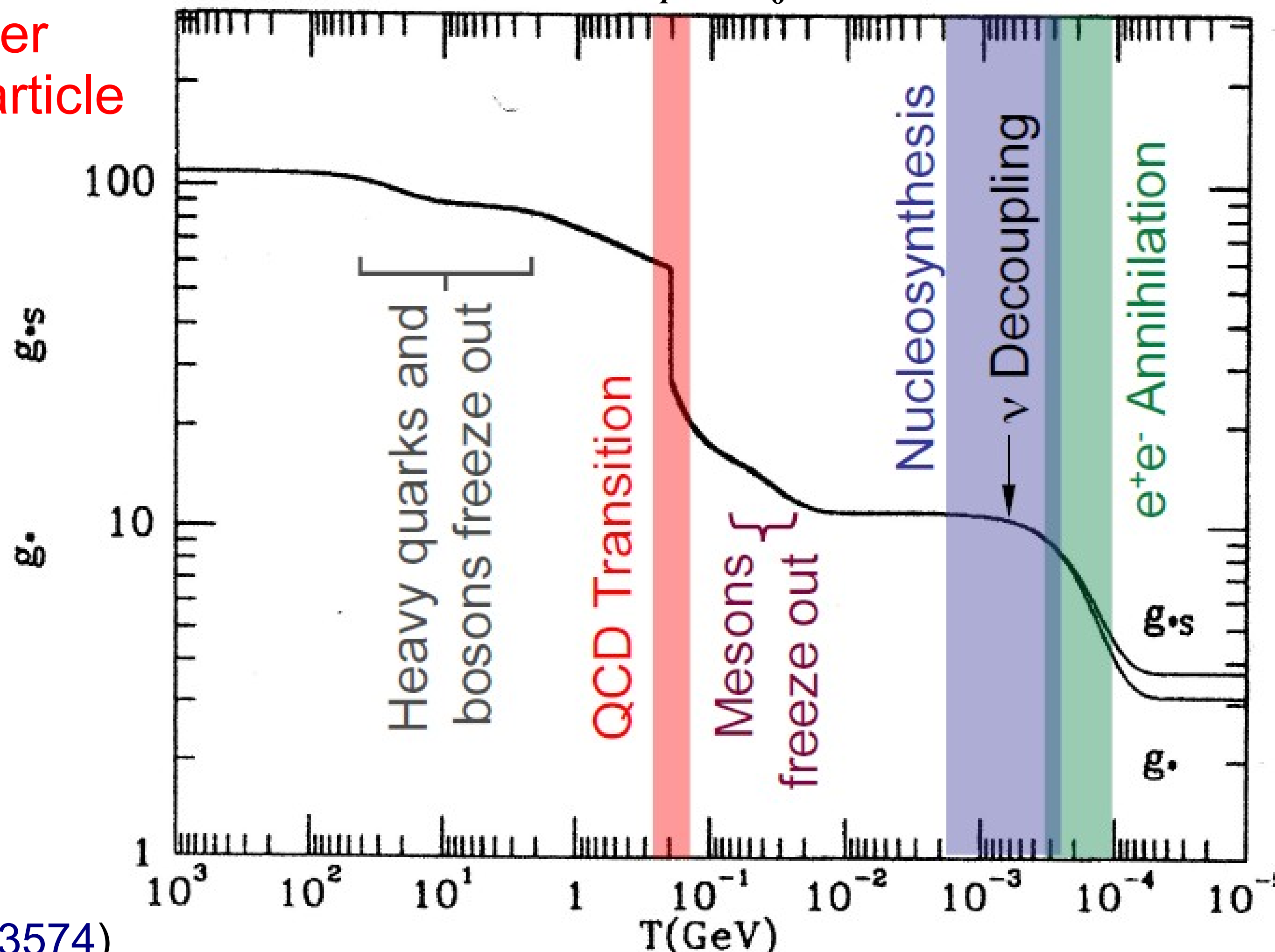


Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.

Figure from The Early Universe, Kolb and Turner (see also Schwarz, astro-ph/0303574)

QCD phase transition in the early universe

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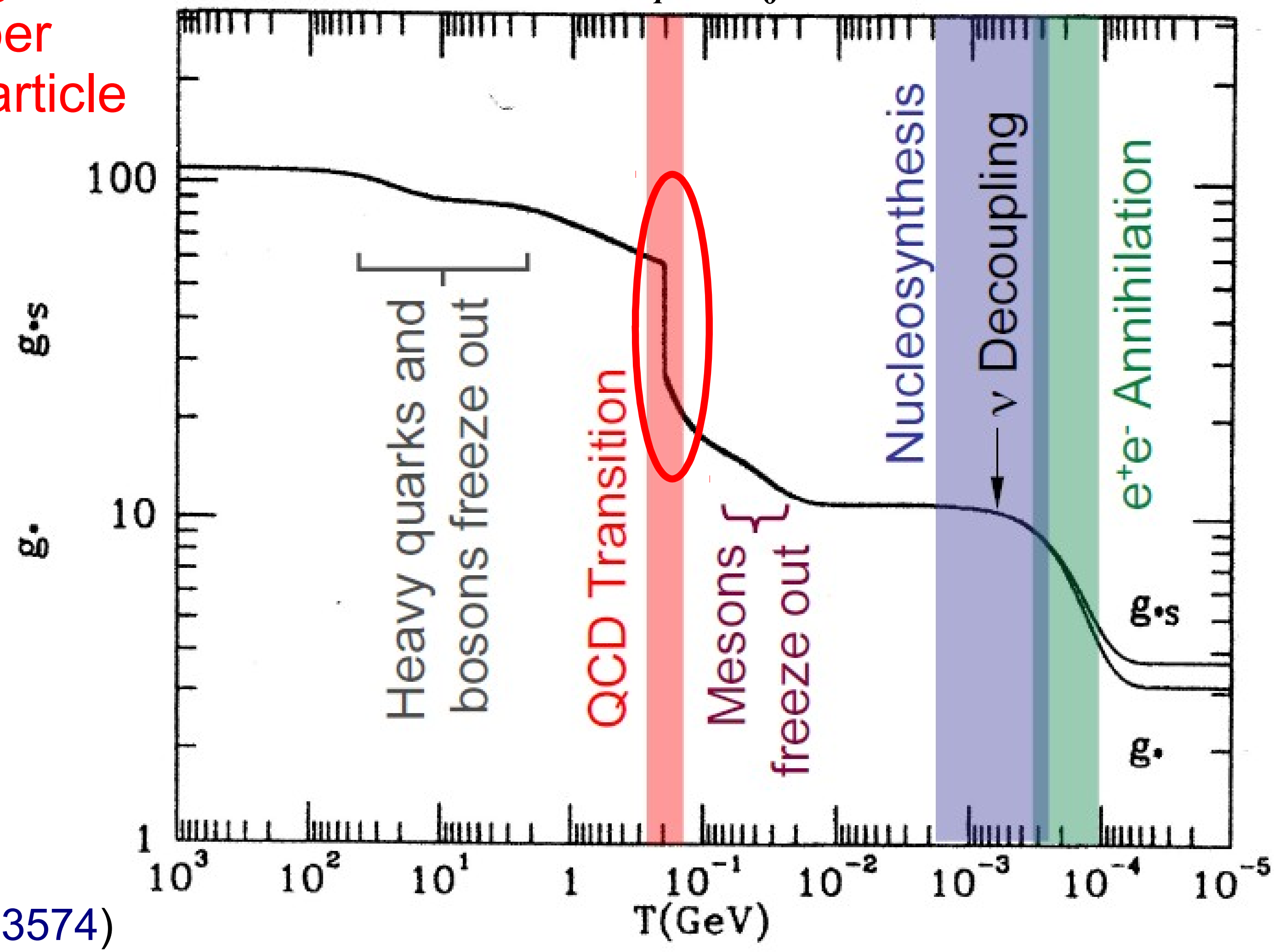

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Figure from
The Early Universe,
Kolb and Turner
(see also
Schwarz, astro-ph/0303574)

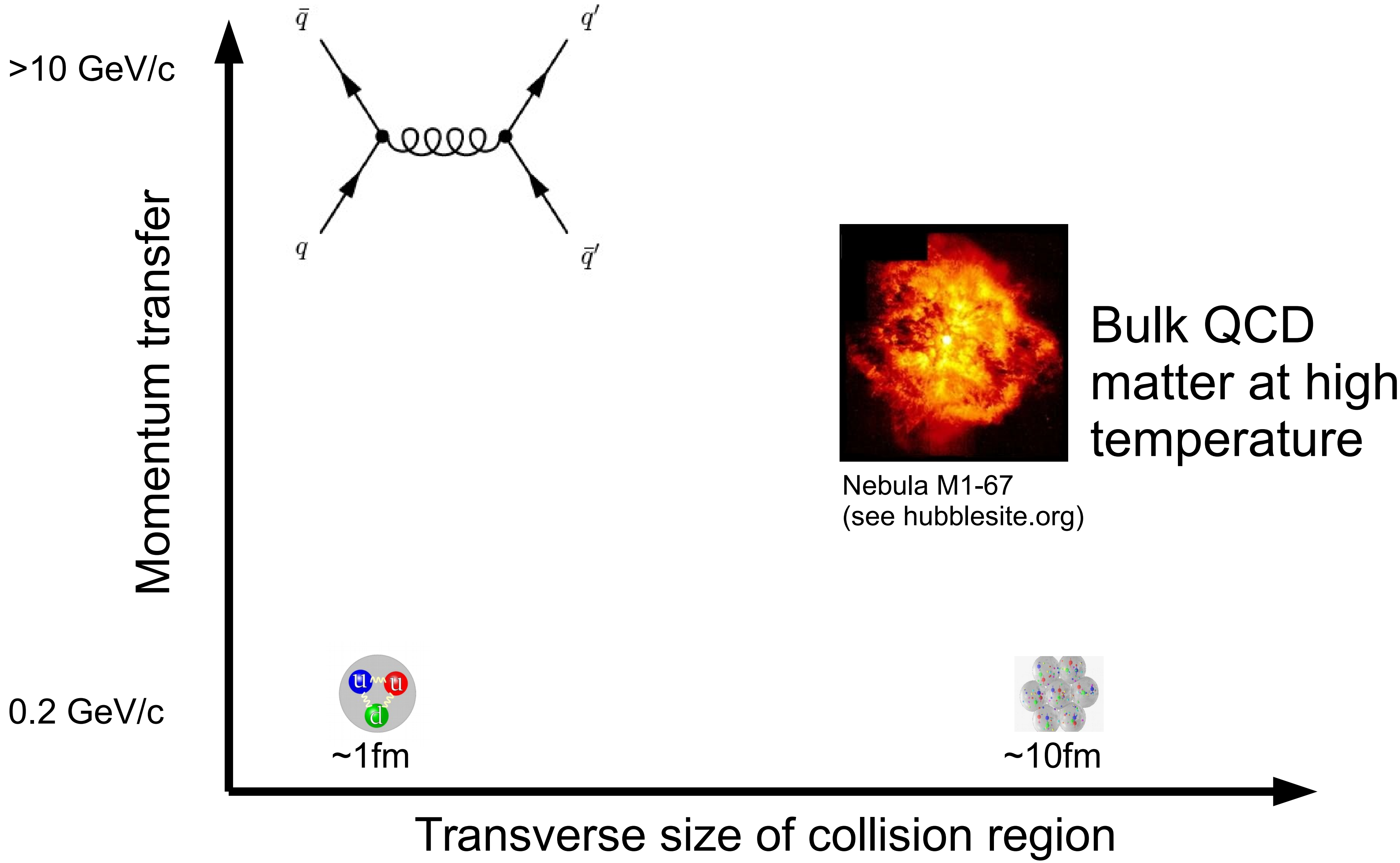
How to create the QGP in the laboratory?

Study QCD bulk matter at high temperature

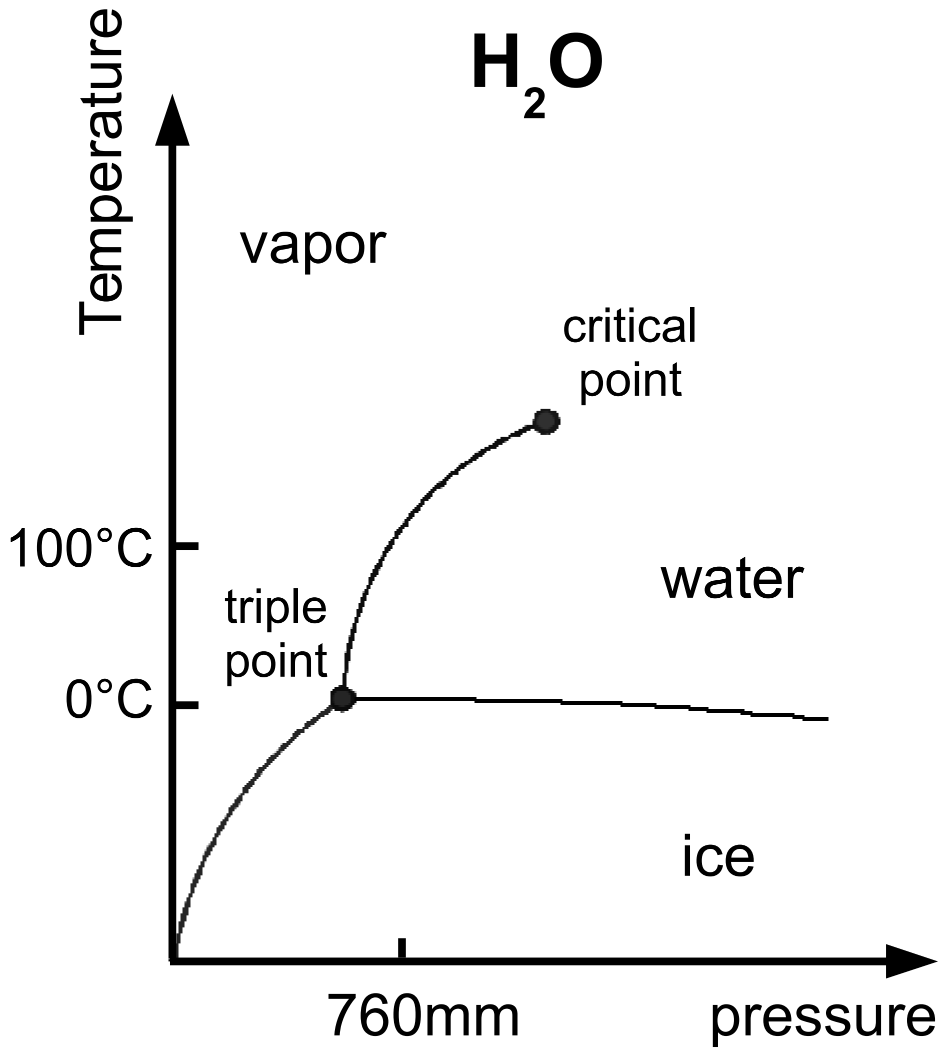
T.D.Lee,
Rev.Mod.Phys. 47 (1975) 267

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.

Study QCD bulk matter at high temperature



How can we create QCD matter?



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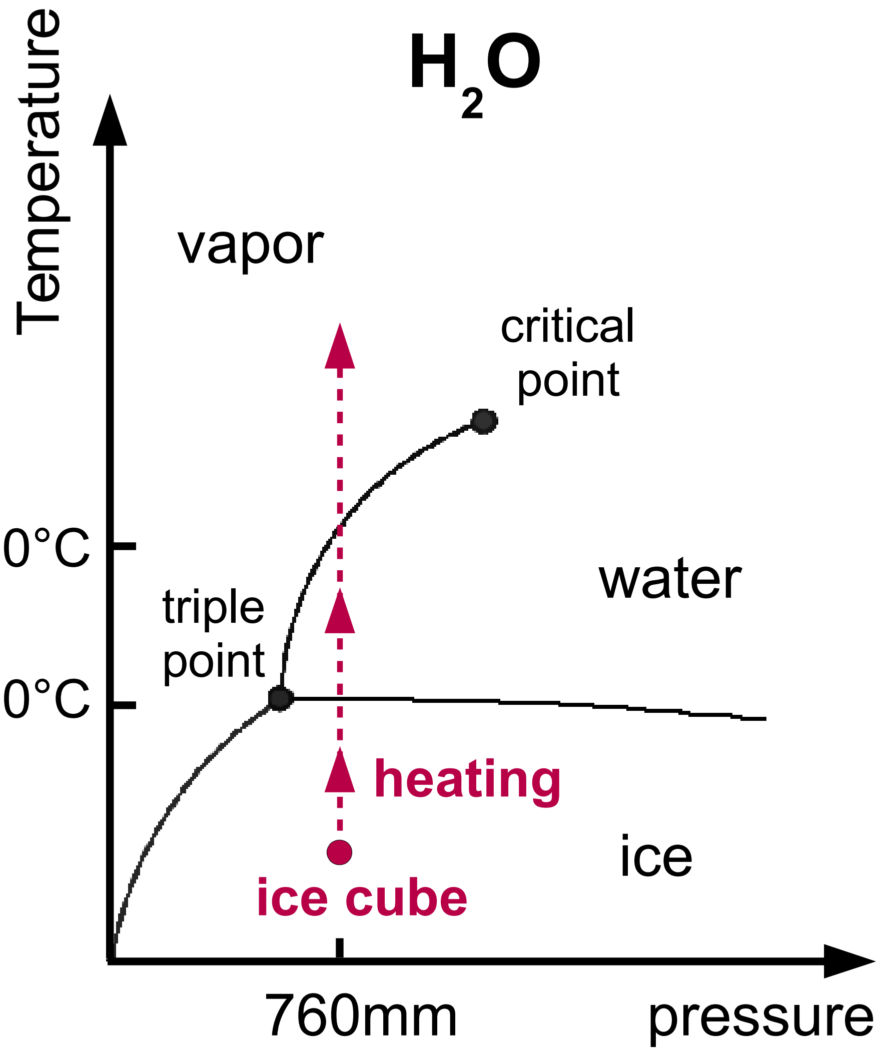

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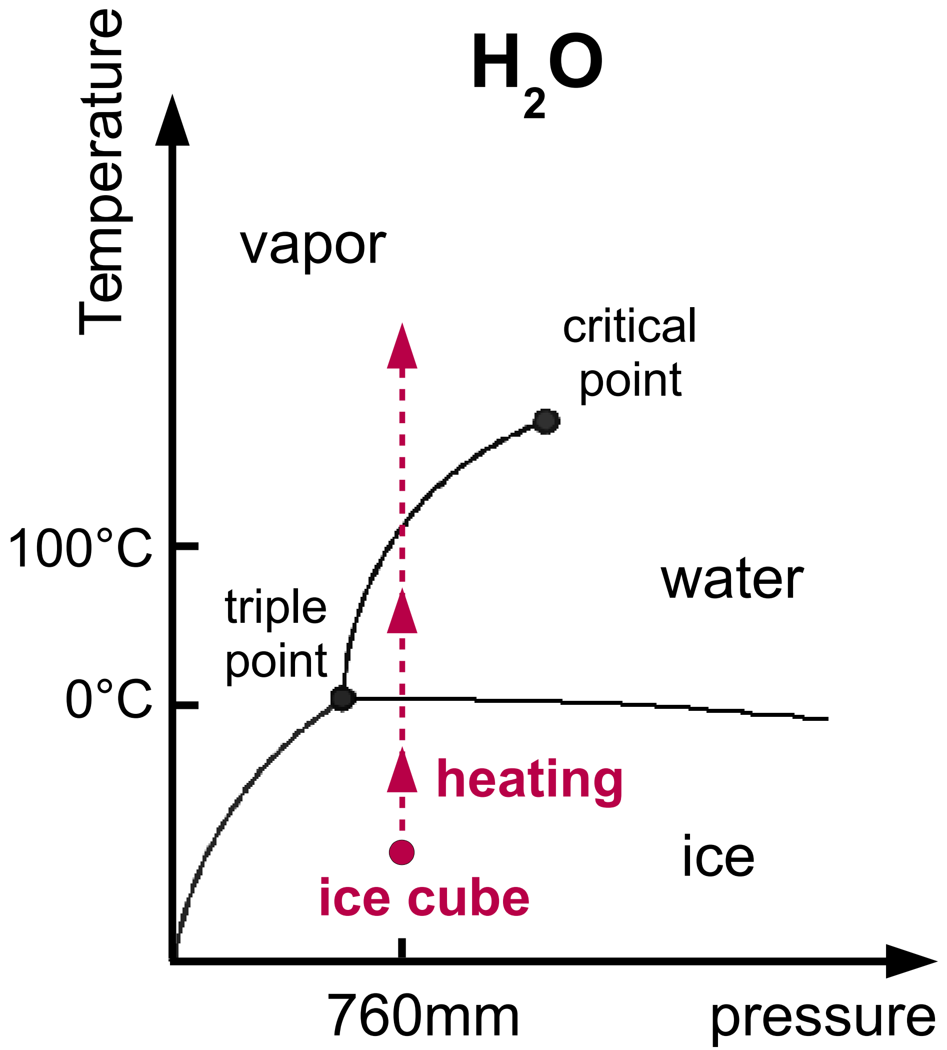

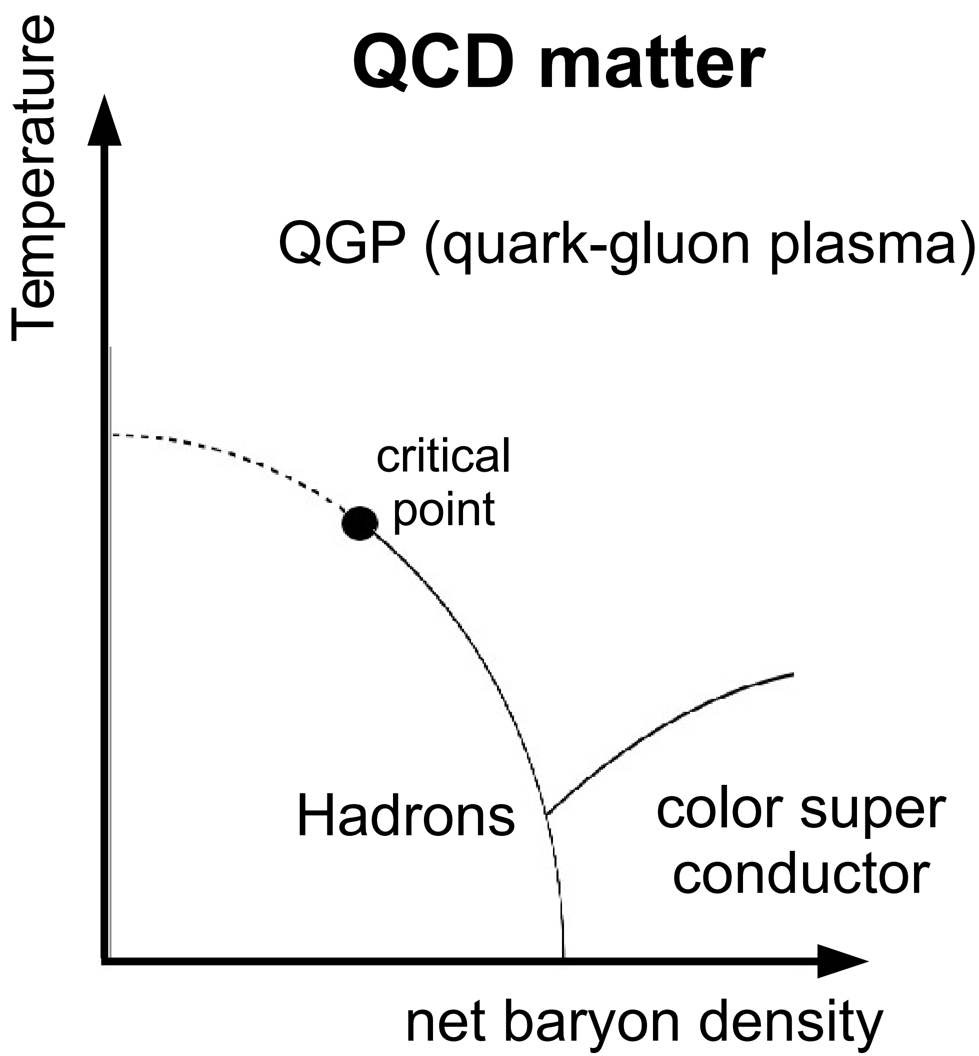

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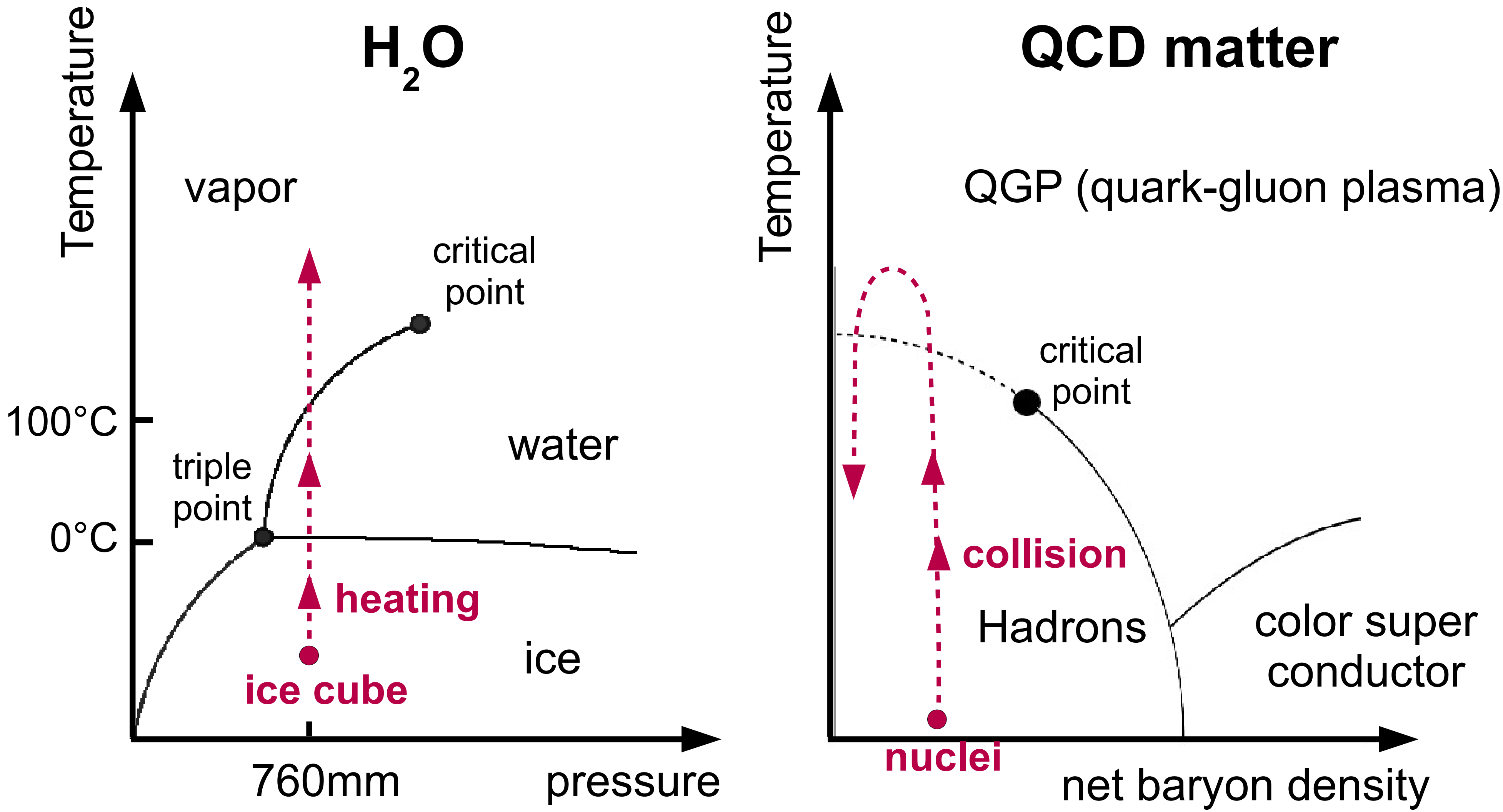

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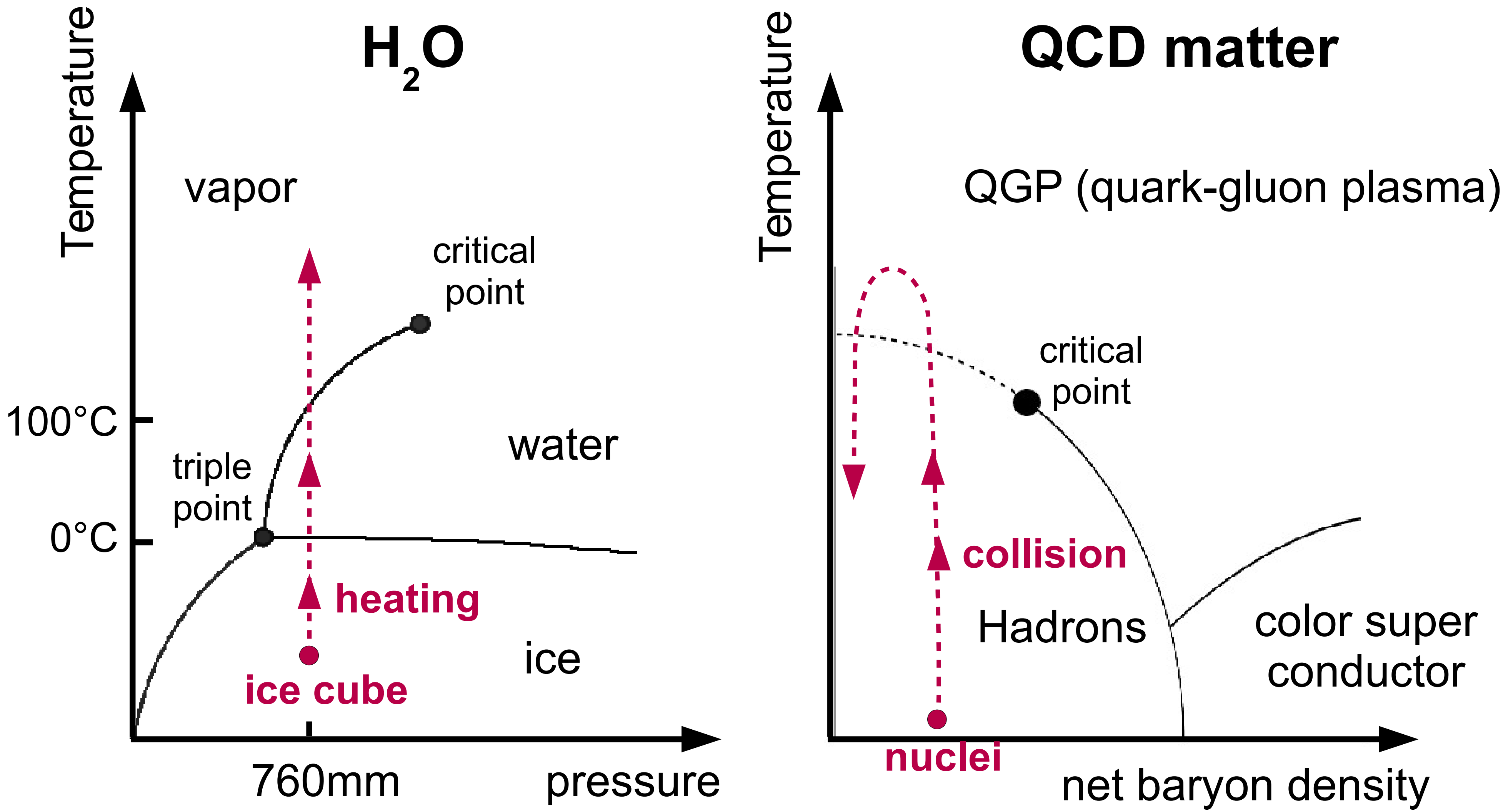
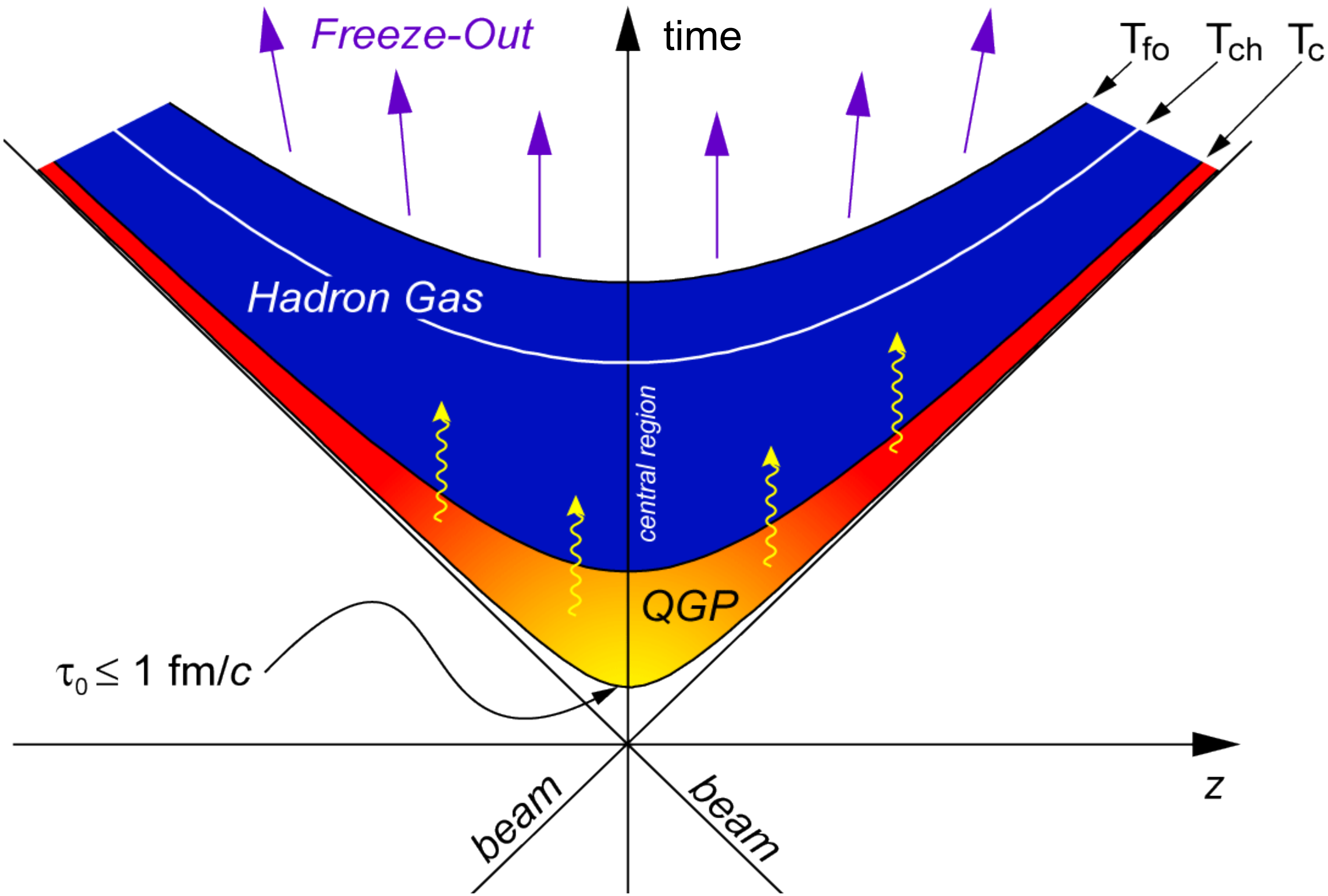


Experimental study of QCD phase diagram by colliding ultra-relativistic nuclei head-on to convert cold nuclear matter into a fireball of partons

System evolution in heavy-ion collisions



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

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

Chemical freeze-out

Hydrodynamic evolution (t~0.5fm/c)

Pre-equilibrium

Collision (t=0fm/c)

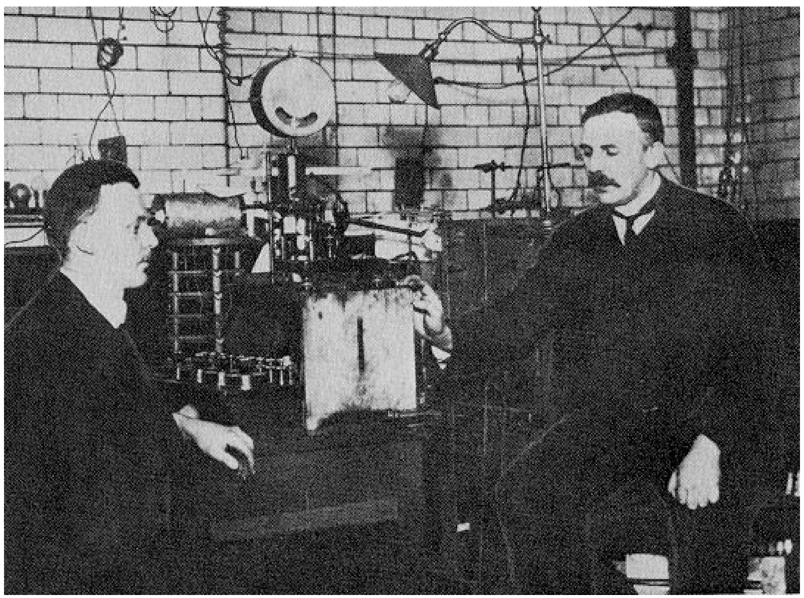
(see part II)

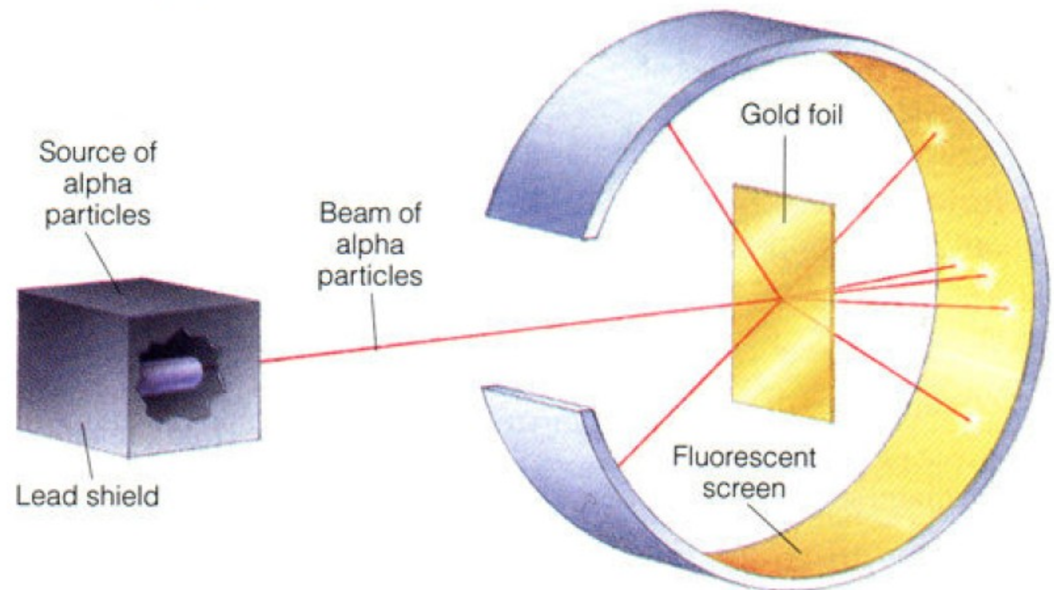
In reality, strong dynamical evolution of the system

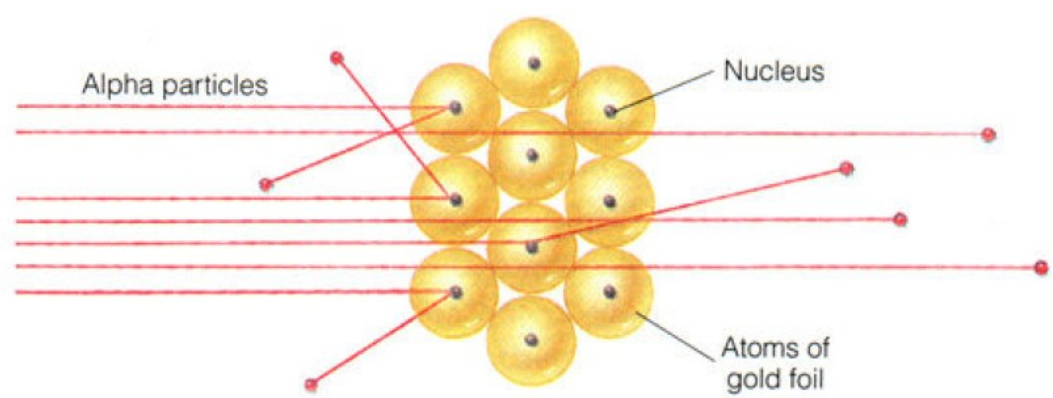
How to probe the QGP?

Exploring the structure of atoms

The first exploration of subatomic structure, by Rutherford, used Au atoms as targets and α particles as *probes*







<u>Interpretation:</u>
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions

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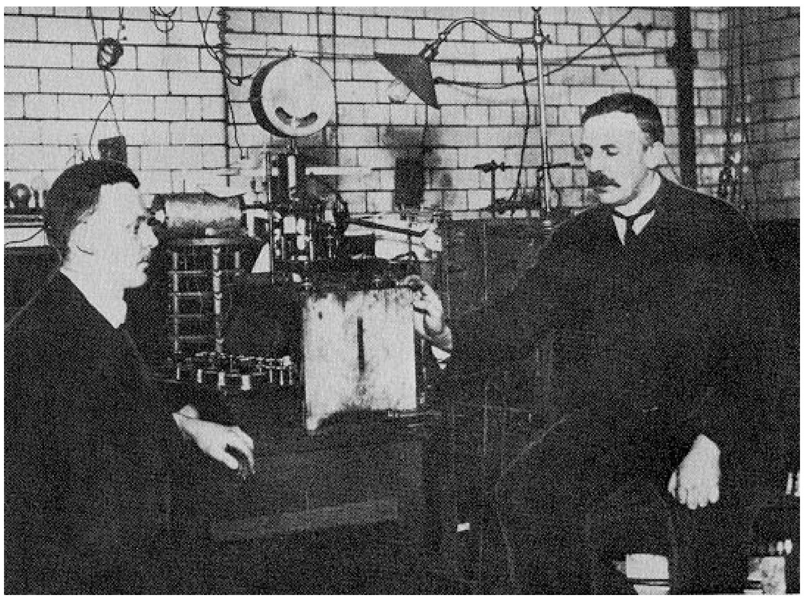
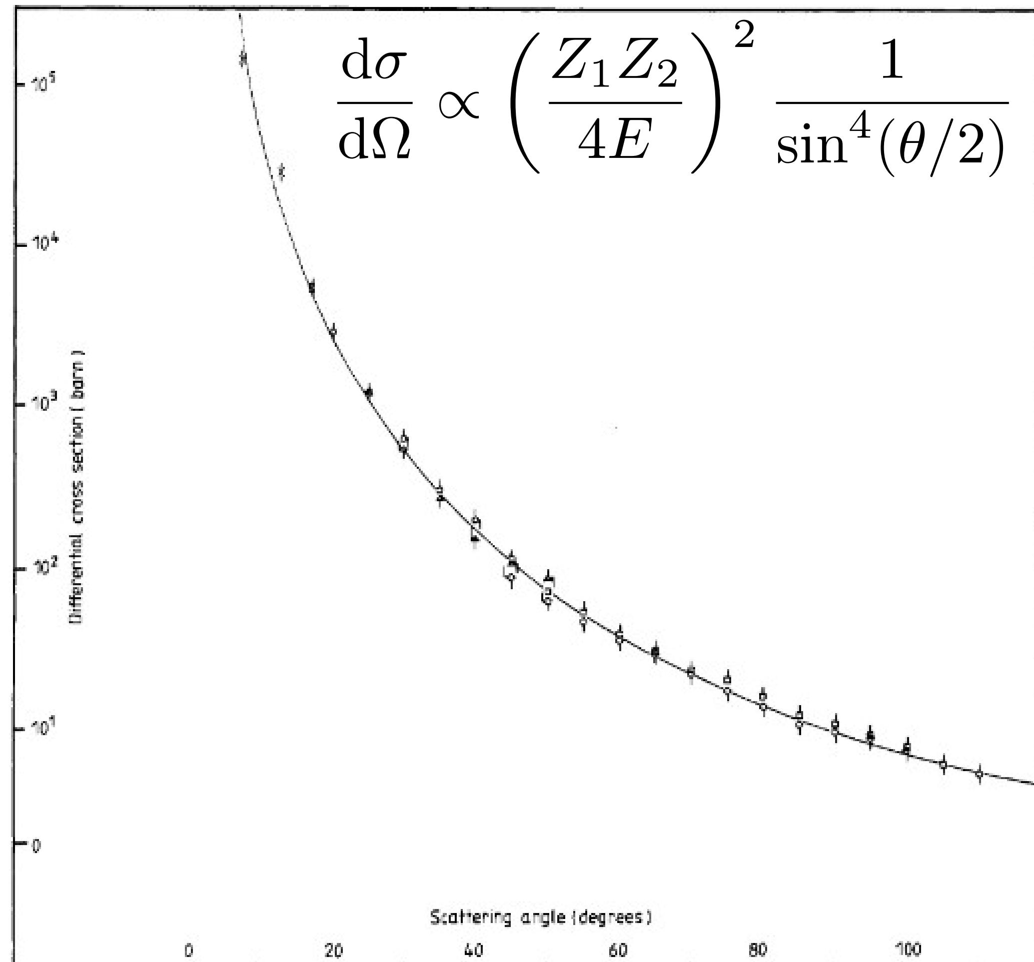




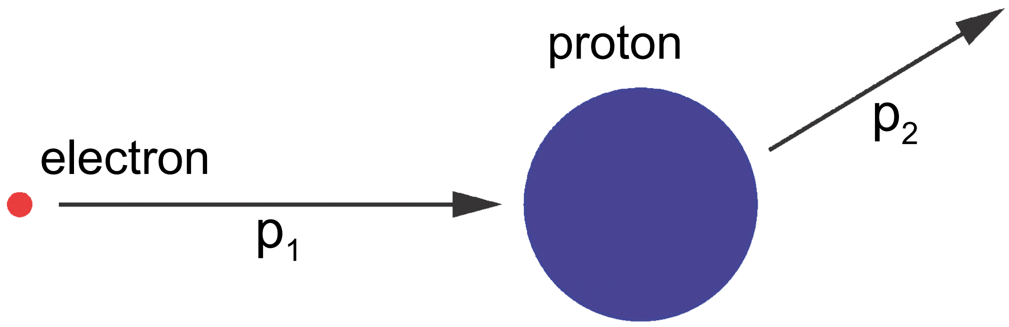
$$\frac{d\sigma}{d\Omega} \propto \left(\frac{Z_1 Z_2}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

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

<u>Interpretation:</u>
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions

Exploring the structure of protons

Deep inelastic scattering experiments at SLAC in the 1960s established the quark-parton model:



The angular distribution of the scattered electrons reflects the distribution of charge inside the proton

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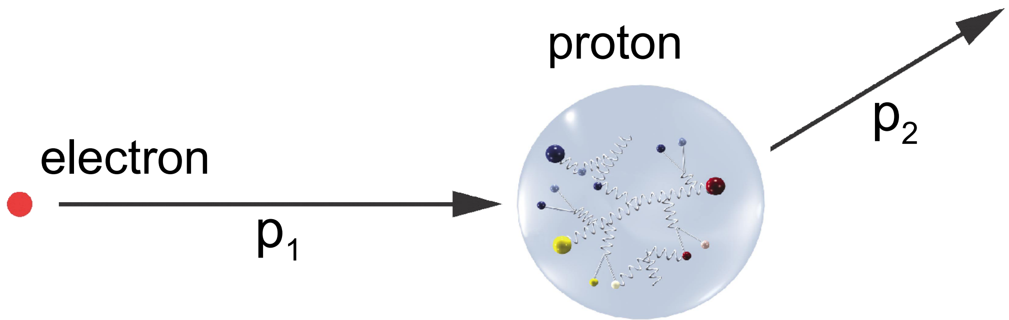

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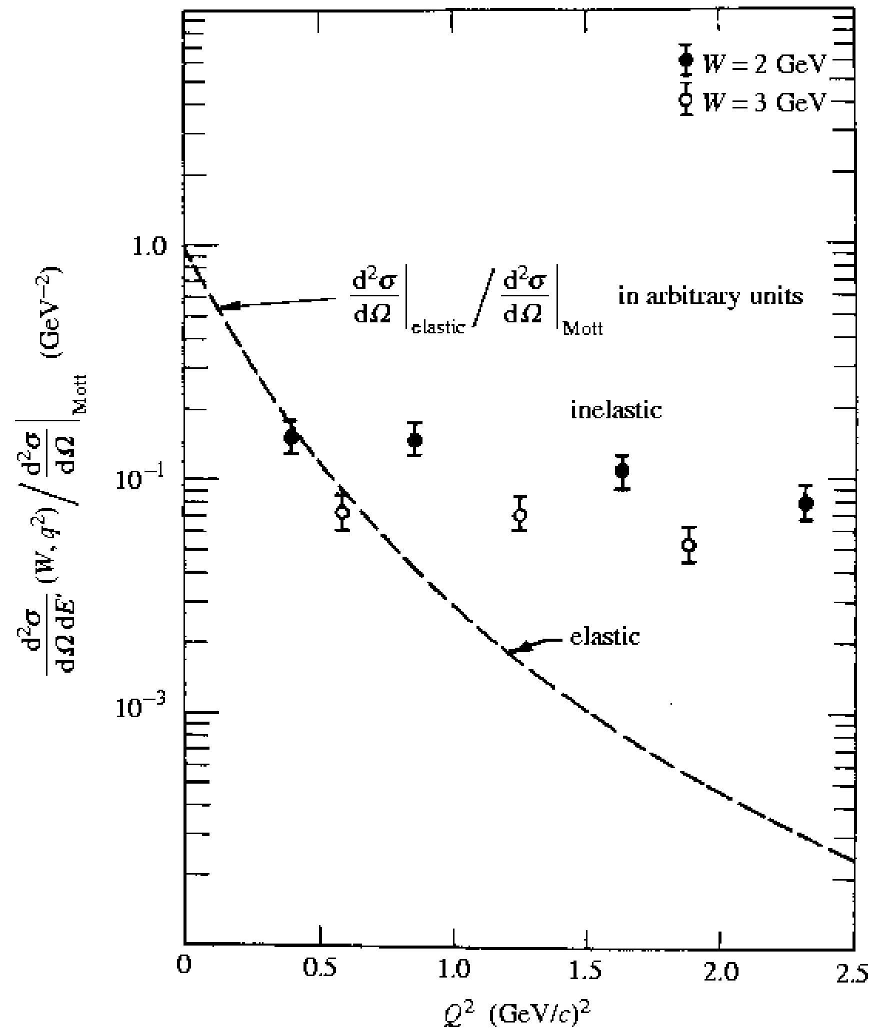

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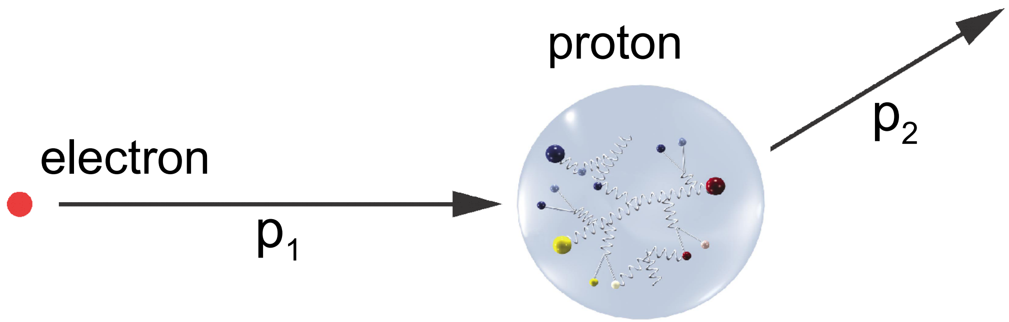

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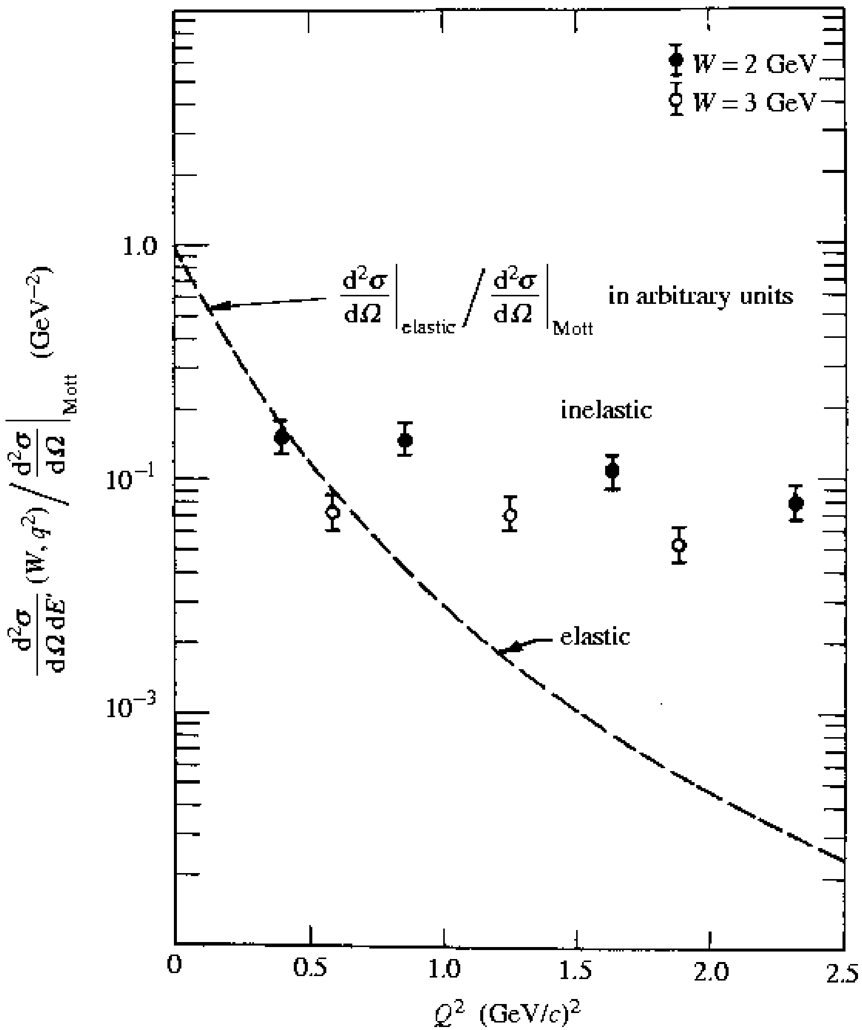

Approximately constant form factor
⇒ scattering on point-like constituents
⇒ quarks

1990 Nobel Prize in Physics

Exploring the structure of QCD matter

In analogy, we study the QCD matter produced in HI collisions by measuring how it affects well understood probes, as a function of the temperature of the system

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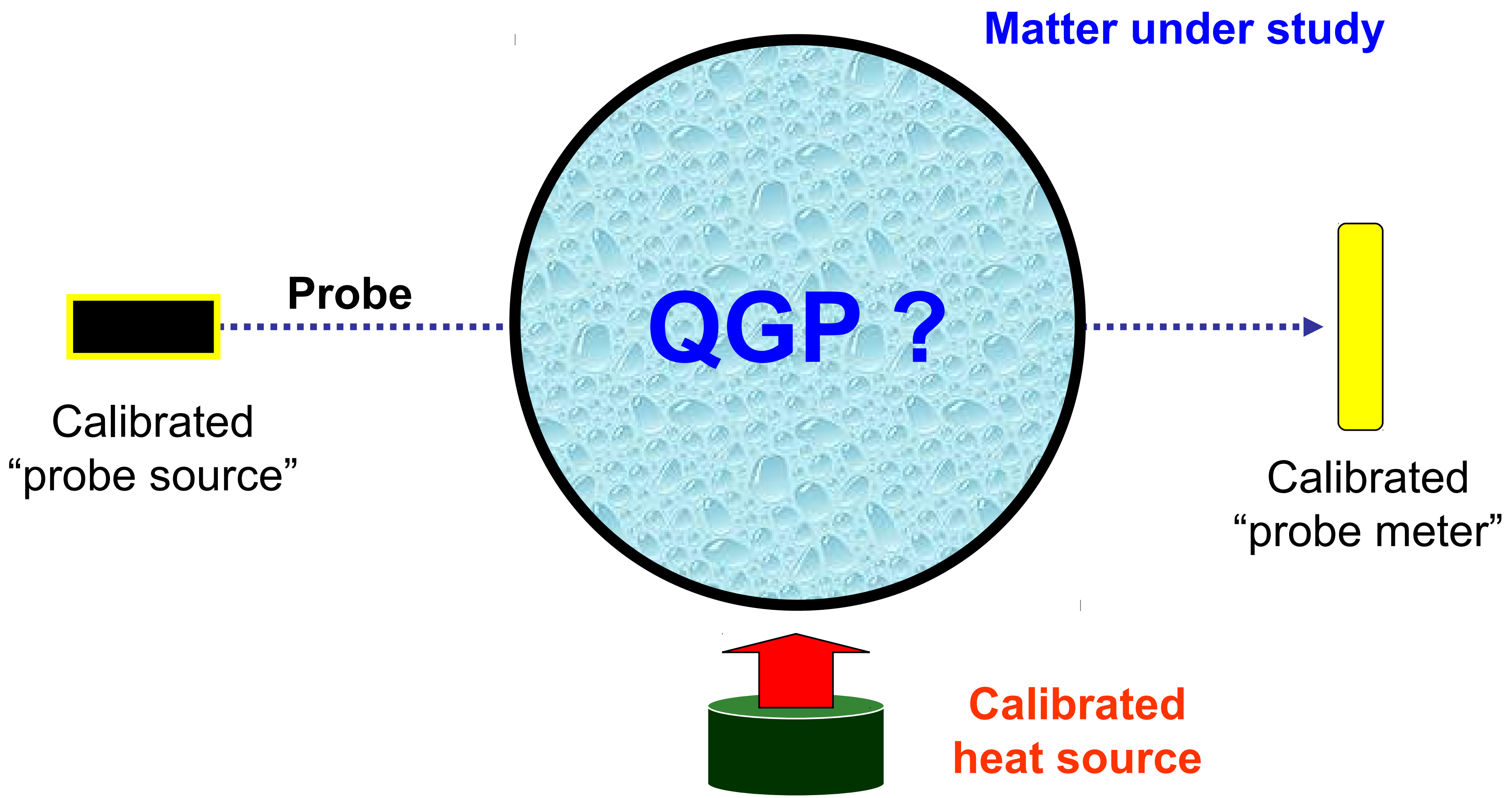
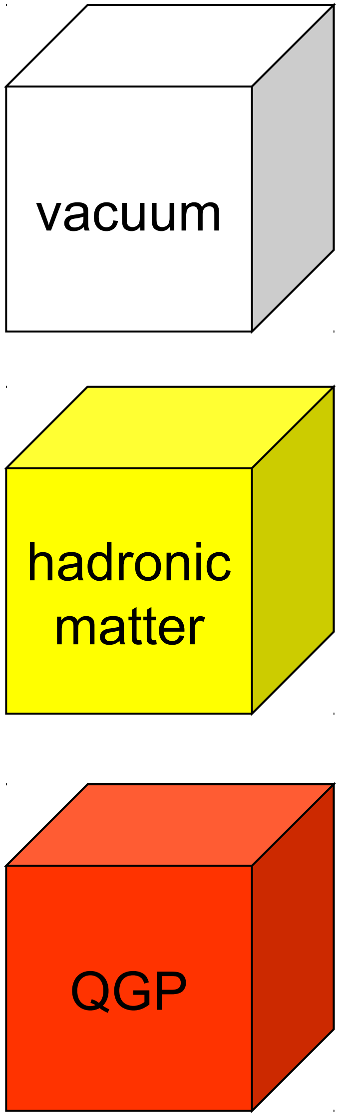


Good probes of QCD matter



(see part III)

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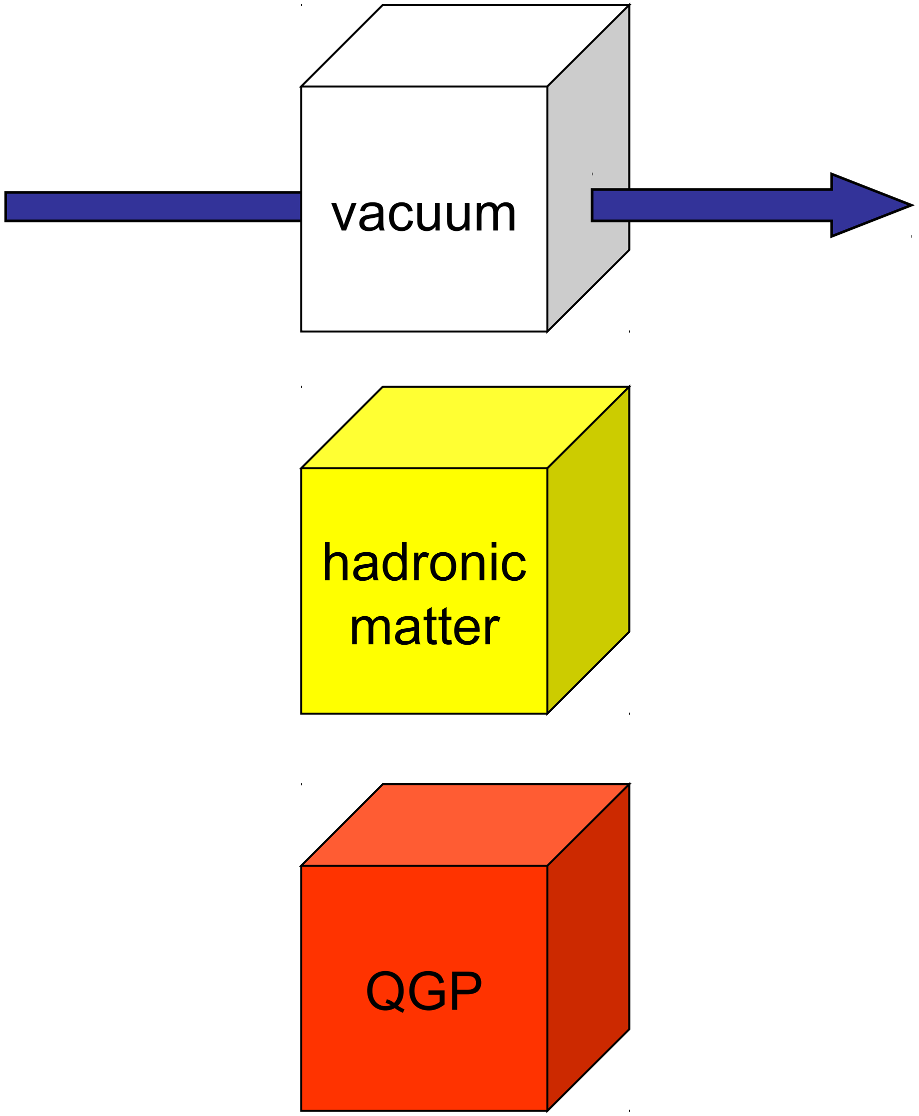
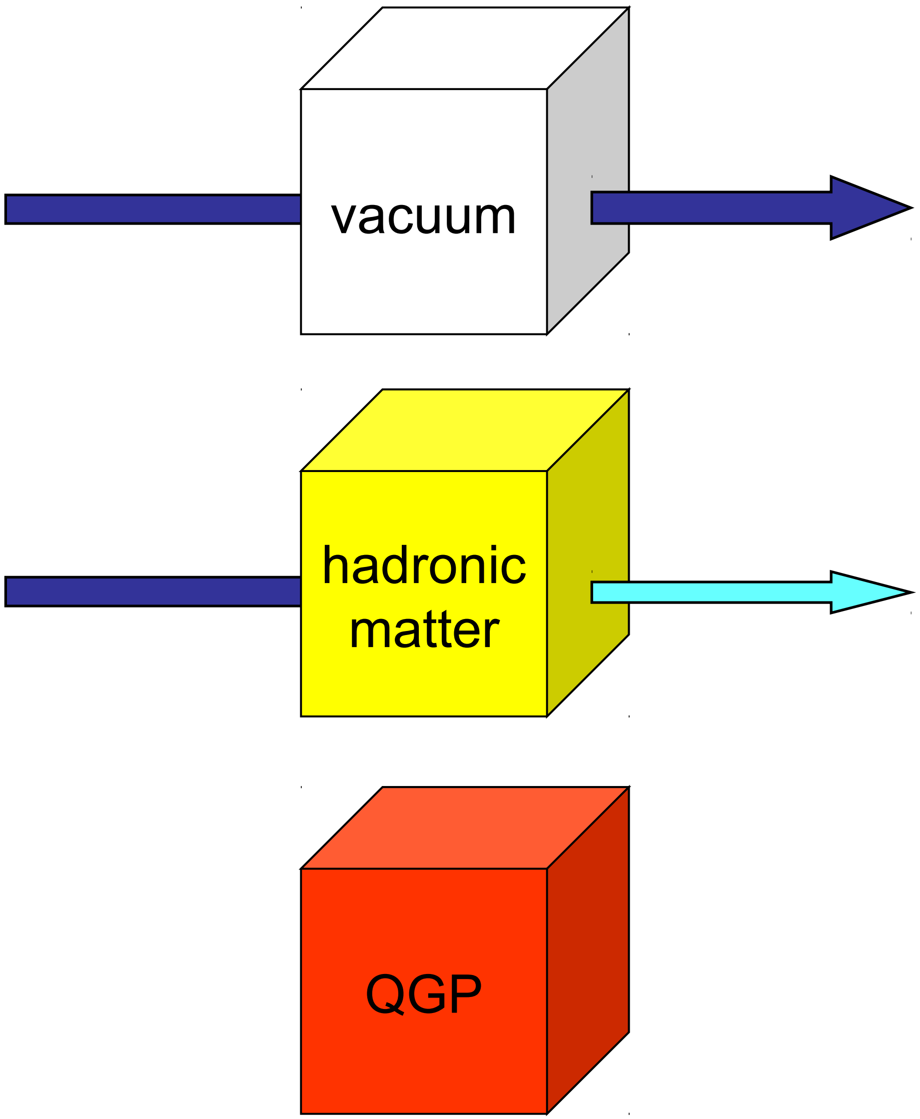


Well understood in “pp collisions”, and/or in control systems like pA

(see part III)

Good probes of QCD matter



Well understood in “pp collisions”, and/or in control systems like pA

Affected by hadronic matter, in a well understood way, which can be accounted for (or neglected)

(see part III)

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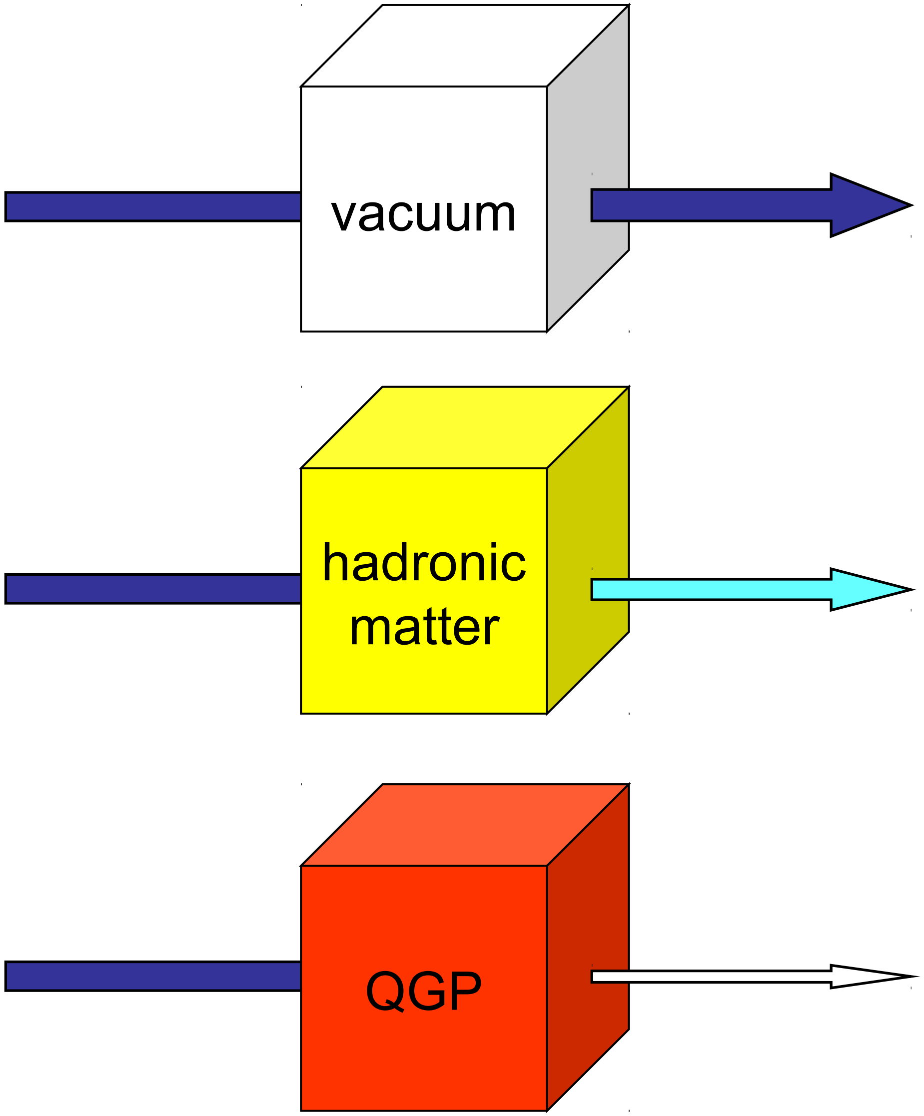


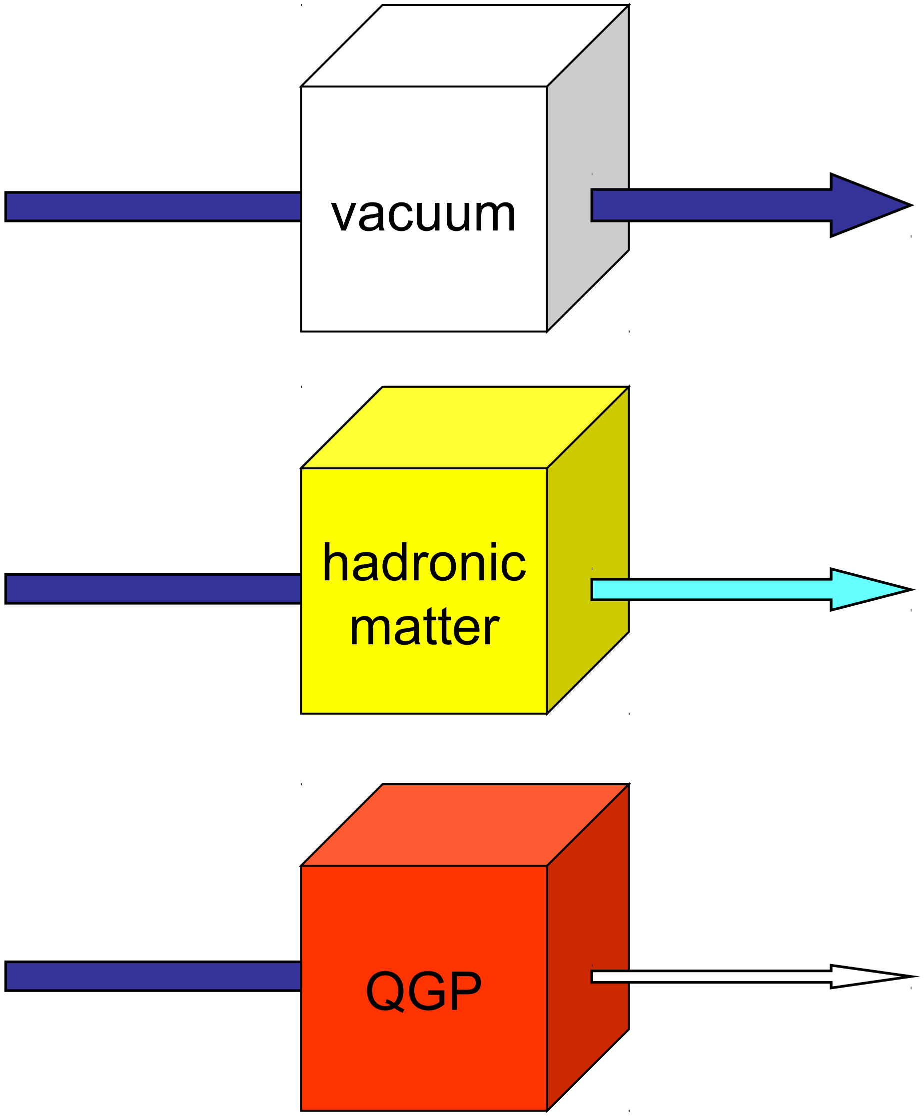
Well understood in “pp collisions”, and/or in control systems like pA

Affected by hadronic matter, in a well understood way, which can be accounted for (or neglected)

Strongly affected by the dense and deconfined QCD medium... and generated early in the collision!

(see part III)

Good probes of QCD matter



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Jets and heavy quarkonia (J/ψ, χ_c, Υ, Υ', etc) are good QCD matter probes !

(see part III)

Heavy-ion experiments

Two main laboratories for heavy-ion collisions

AGS : 1986 – 2000

- Si and Au beams ; $\sqrt{s}$ ~ 5 GeV
- only hadronic variables

RHIC : 2000 – ?

- He3, Cu, Au beams ; up to $\sqrt{s}$ = 200 GeV
- 4 experiments (only two remain)

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SPS : 1986 – 2003 + 2009 – ?

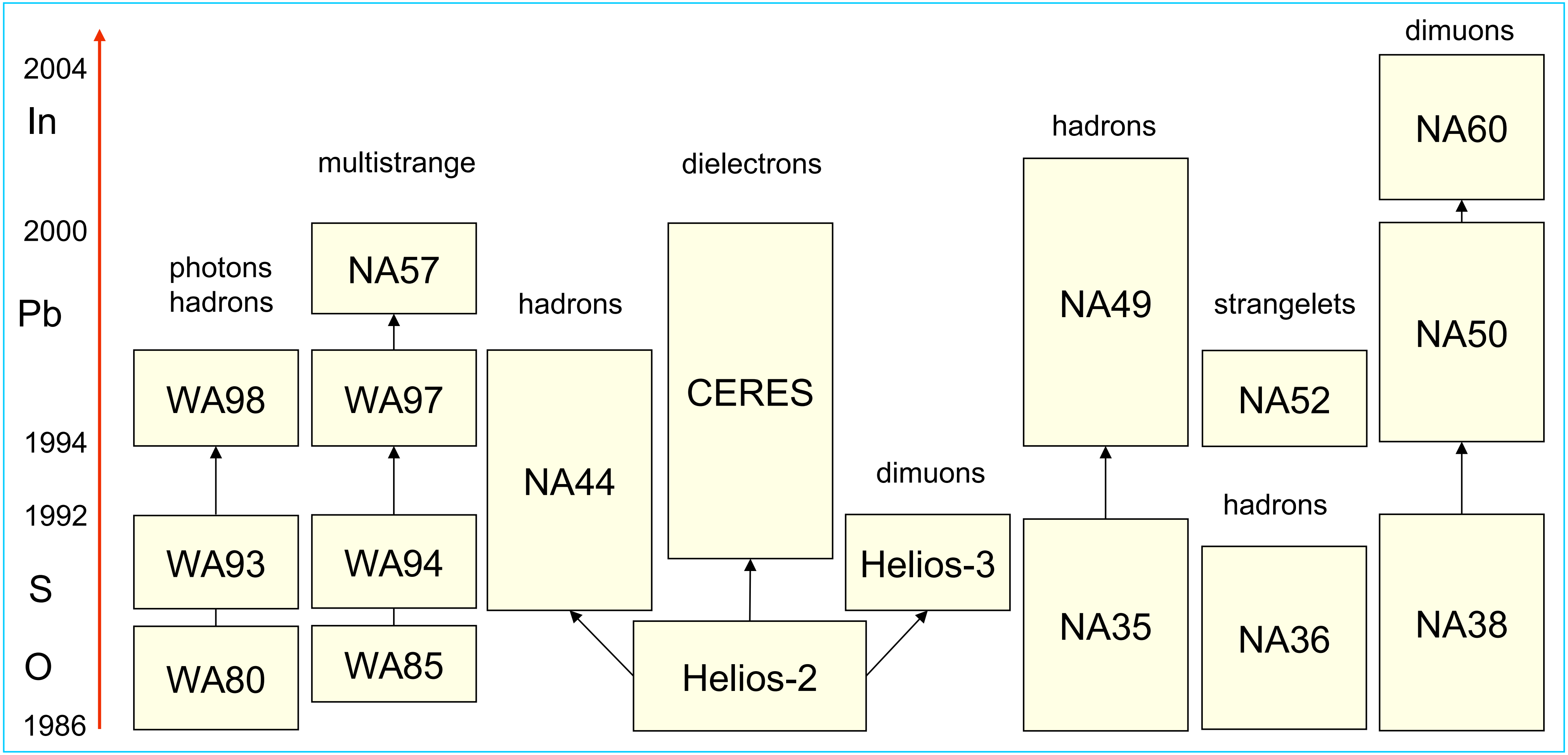
- O, S, In, Pb beams ; √s ~ 20 GeV
- Various experiments in North Area

LHC : 2009 – ?

- Pb beams ; up to √s = 5000 GeV
- ALICE, CMS, ATLAS and LHCb

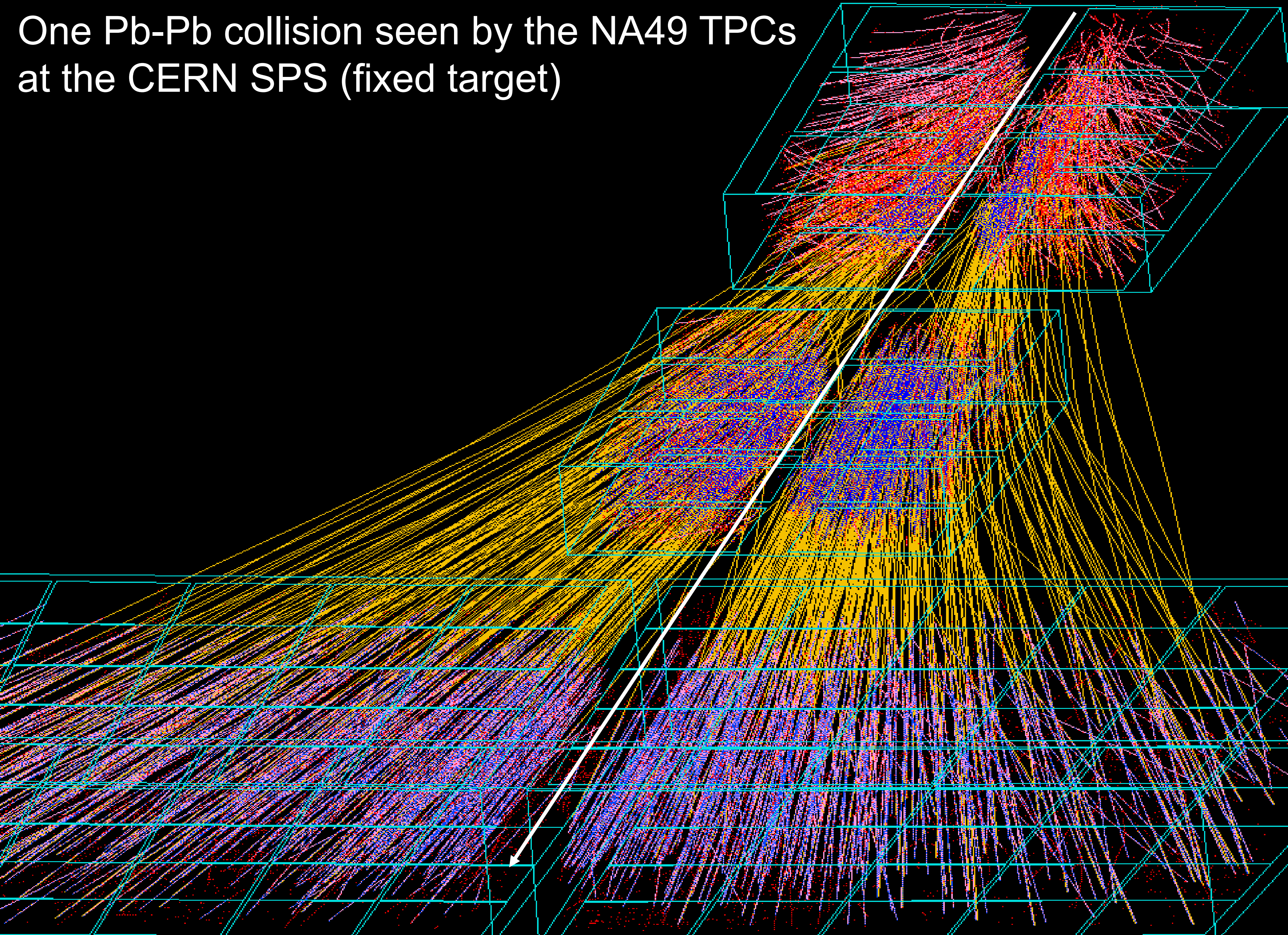
The CERN SPS physics program

Between 1986 and 2004, many experiments studied high-energy nuclear collisions at the CERN SPS, to probe hot QCD matter



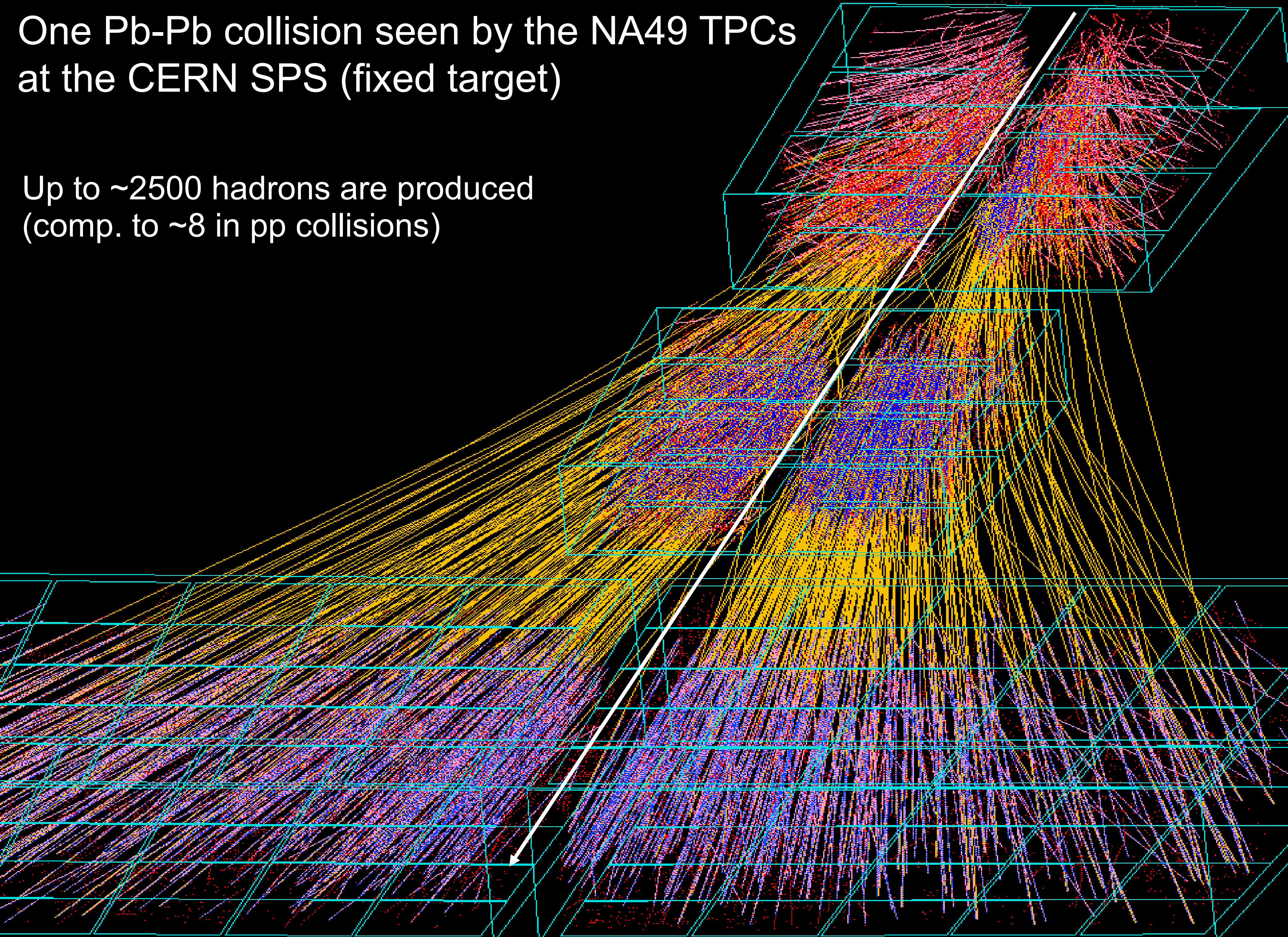
CERN scientific statement, 2000

One Pb-Pb collision seen by the NA49 TPCs at the CERN SPS (fixed target)

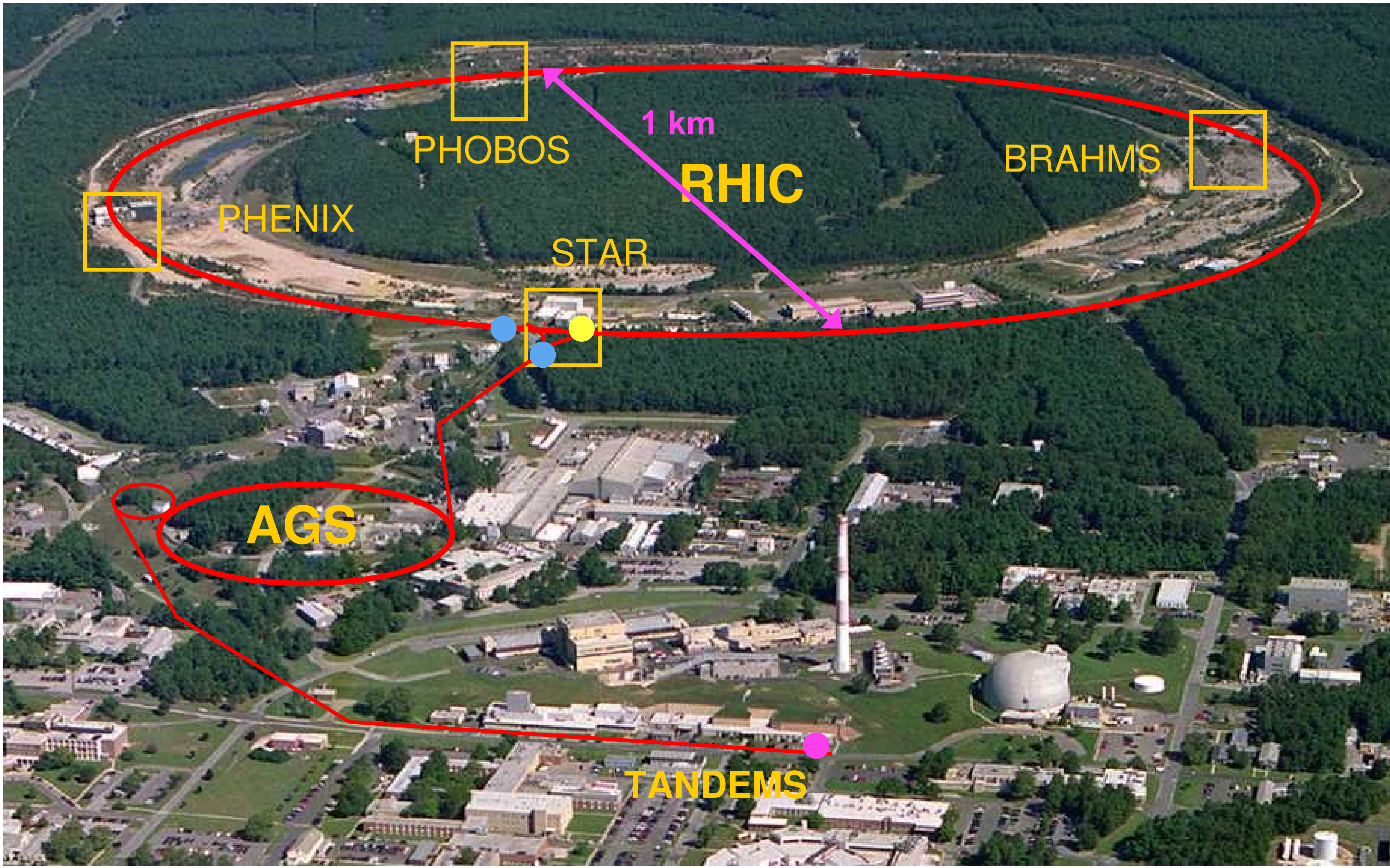


One Pb-Pb collision seen by the NA49 TPCs at the CERN SPS (fixed target)

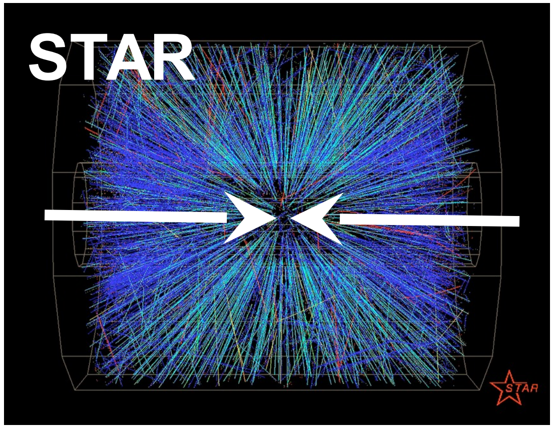
Up to ~2500 hadrons are produced (comp. to ~8 in pp collisions)



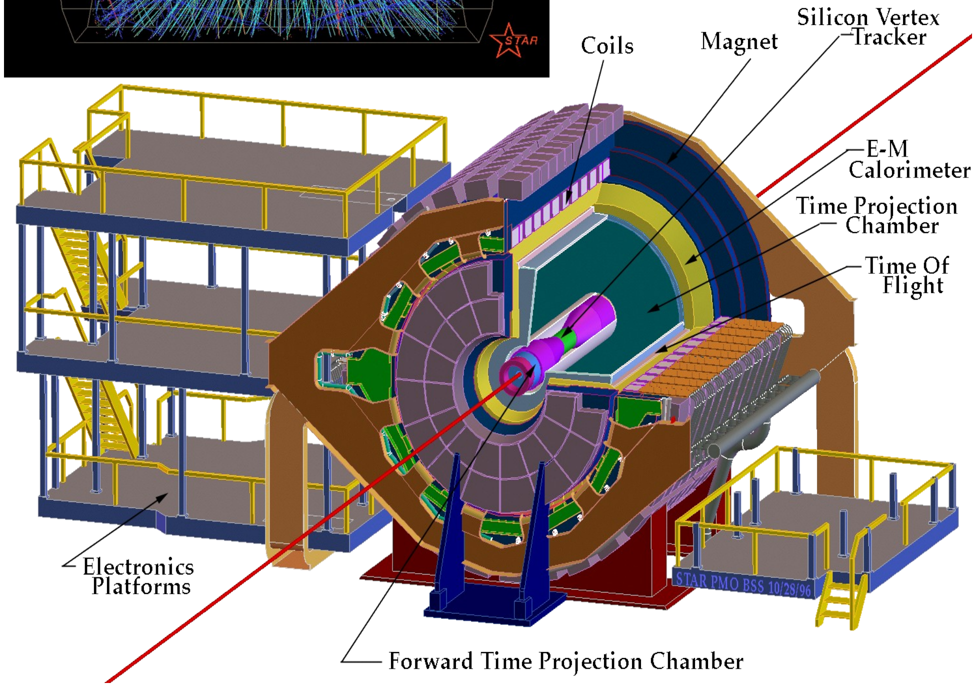
The Relativistic Heavy Ion Collider (RHIC)

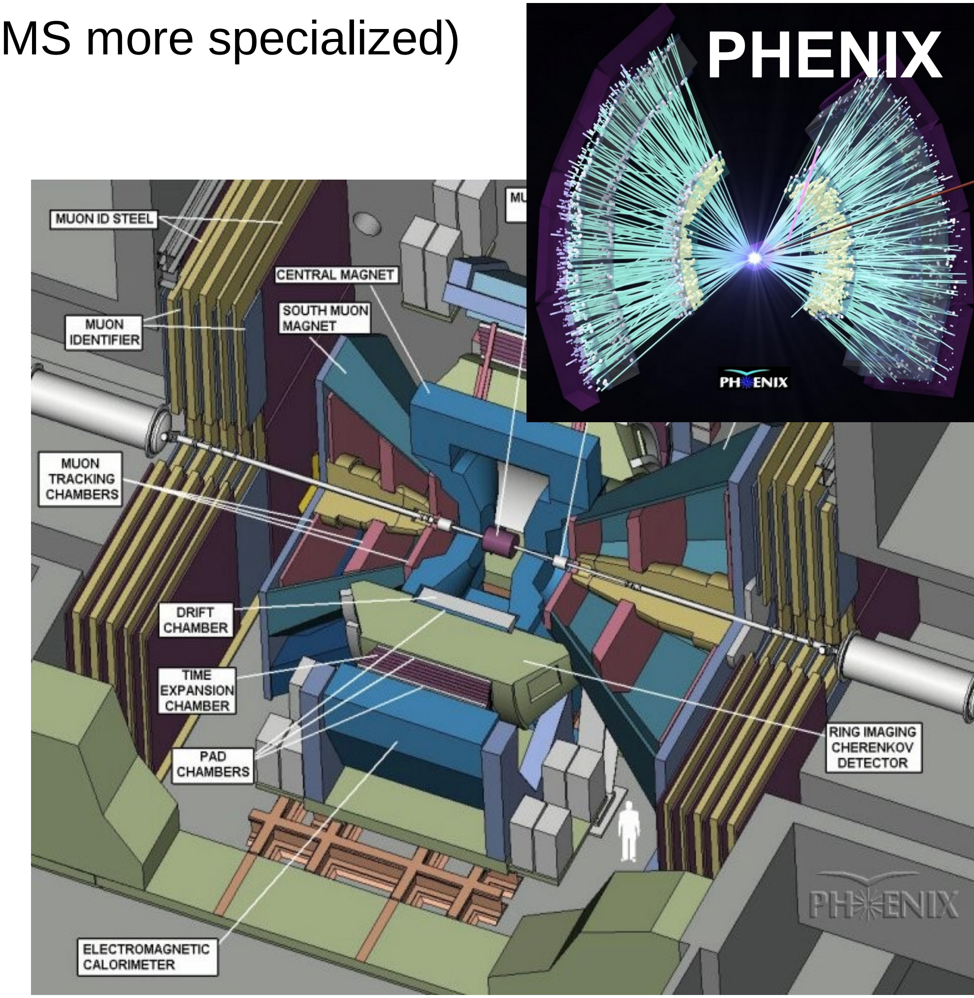


STAR and PHENIX at RHIC



(PHOBOS, BRAHMS more specialized)





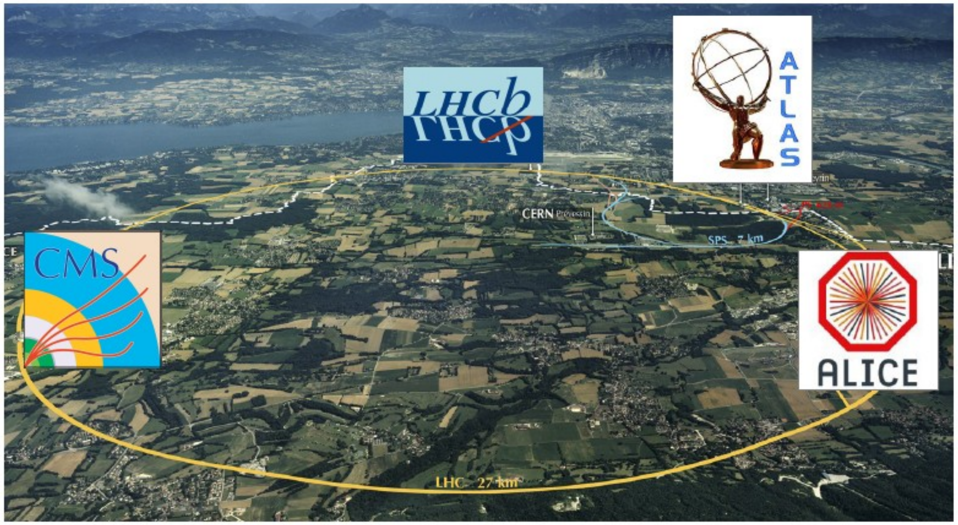
2π coverage, -1<η< 1
for tracking + (coarse) EMCal
PID by TOF, dE/dx

Optimized for acceptance
(correlations, jet-finding)

Partial cov. 2x0.5π, -0.35<η<0.35 for
tracking + (finely) segmented calorimeter
+ forward muon arm, PID by RICH

Optimized for high-pt π^0, γ, e, J/ψ
(EMCal, high trigger rates)

(Heavy-)Ion data-taking experiments at the LHC



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

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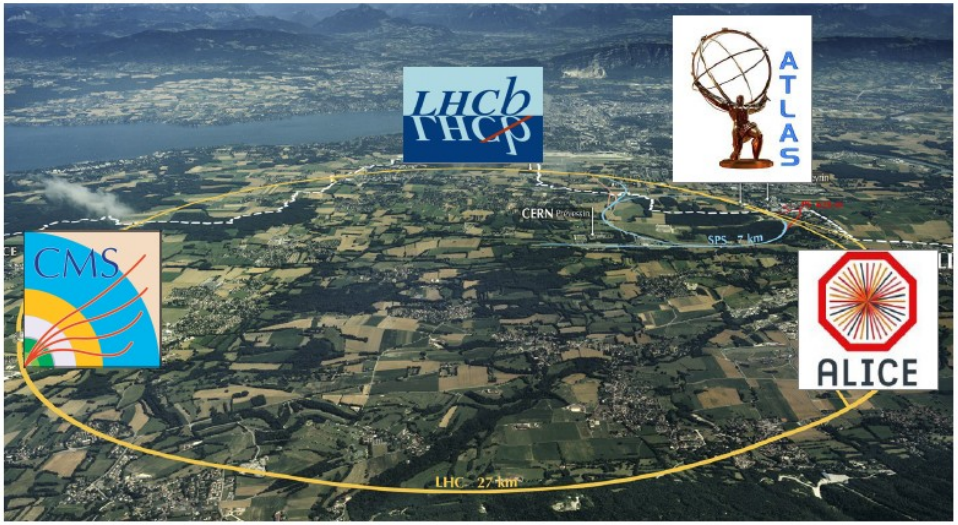
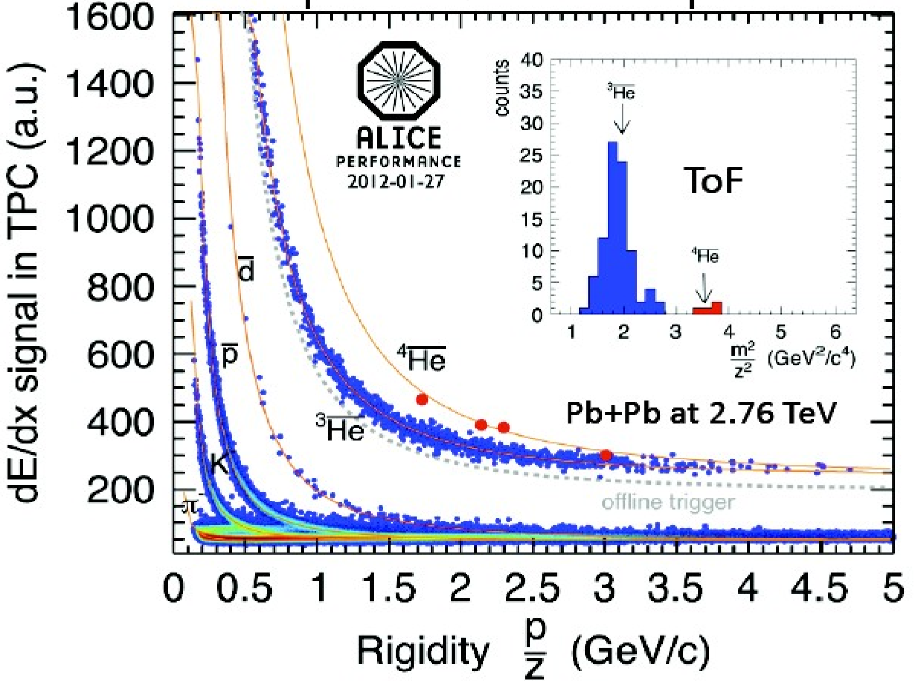


Example ALICE: PID capabilities



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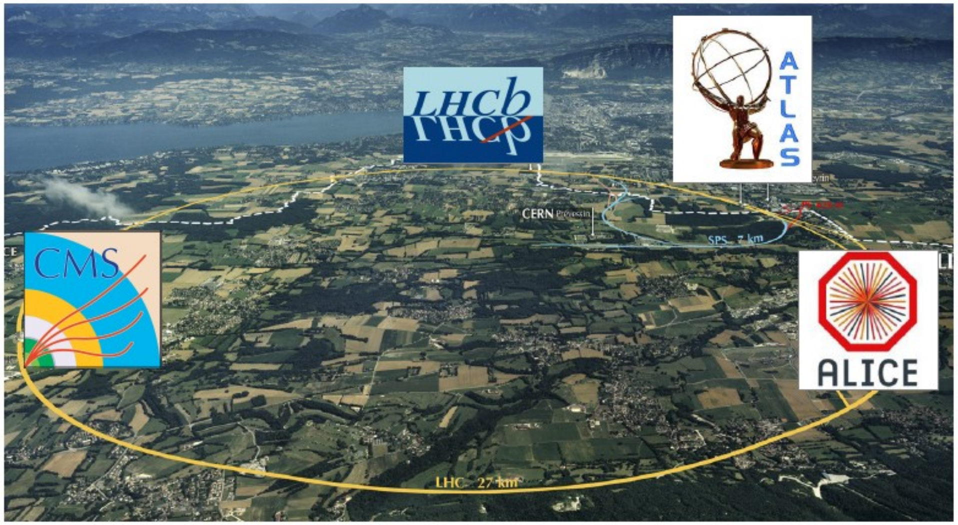

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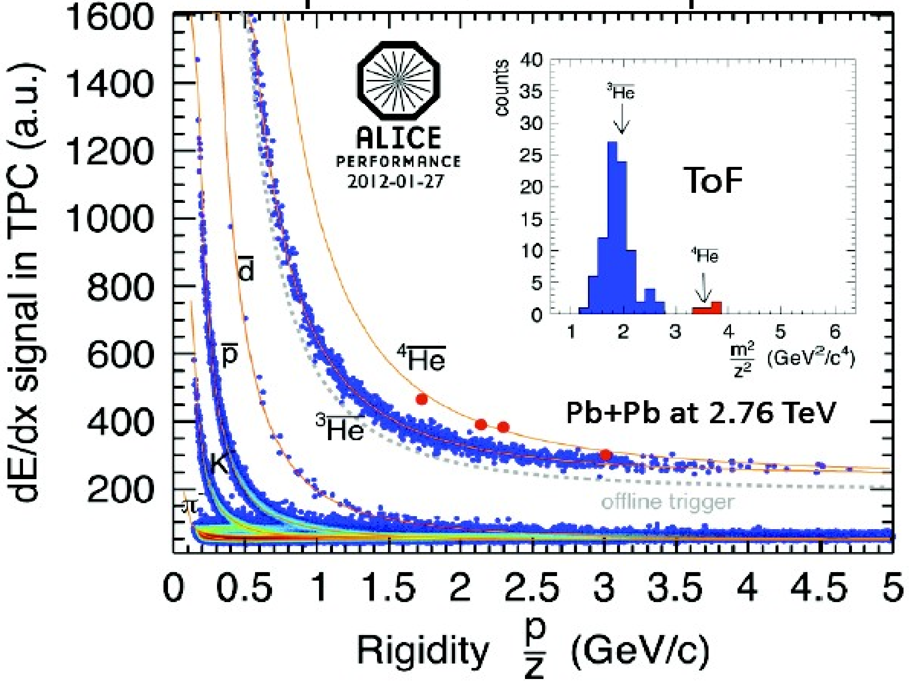

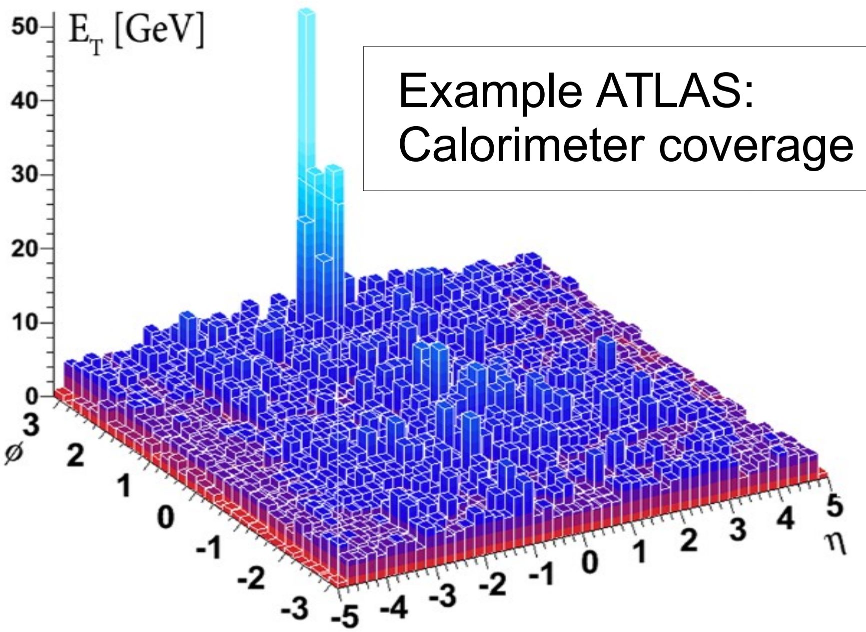

Example ATLAS: Calorimeter coverage

Summary

- QCD is a quantum field theory with rich dynamical content, complex phase structure, and important open questions
- Heavy-ion collision experiments attempt to create and probe QCD matter at high temperature and energy density
- The scientific approach is conceptually similar to conventional scattering experiments, and relies on a series of well calibrated probes and a variety of collision systems

In the next two lectures we will look at a set of important results obtained from heavy-ion collisions at RHIC and LHC

If you have questions about today's lecture please send them to “cloizides at lbl dot gov”

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