

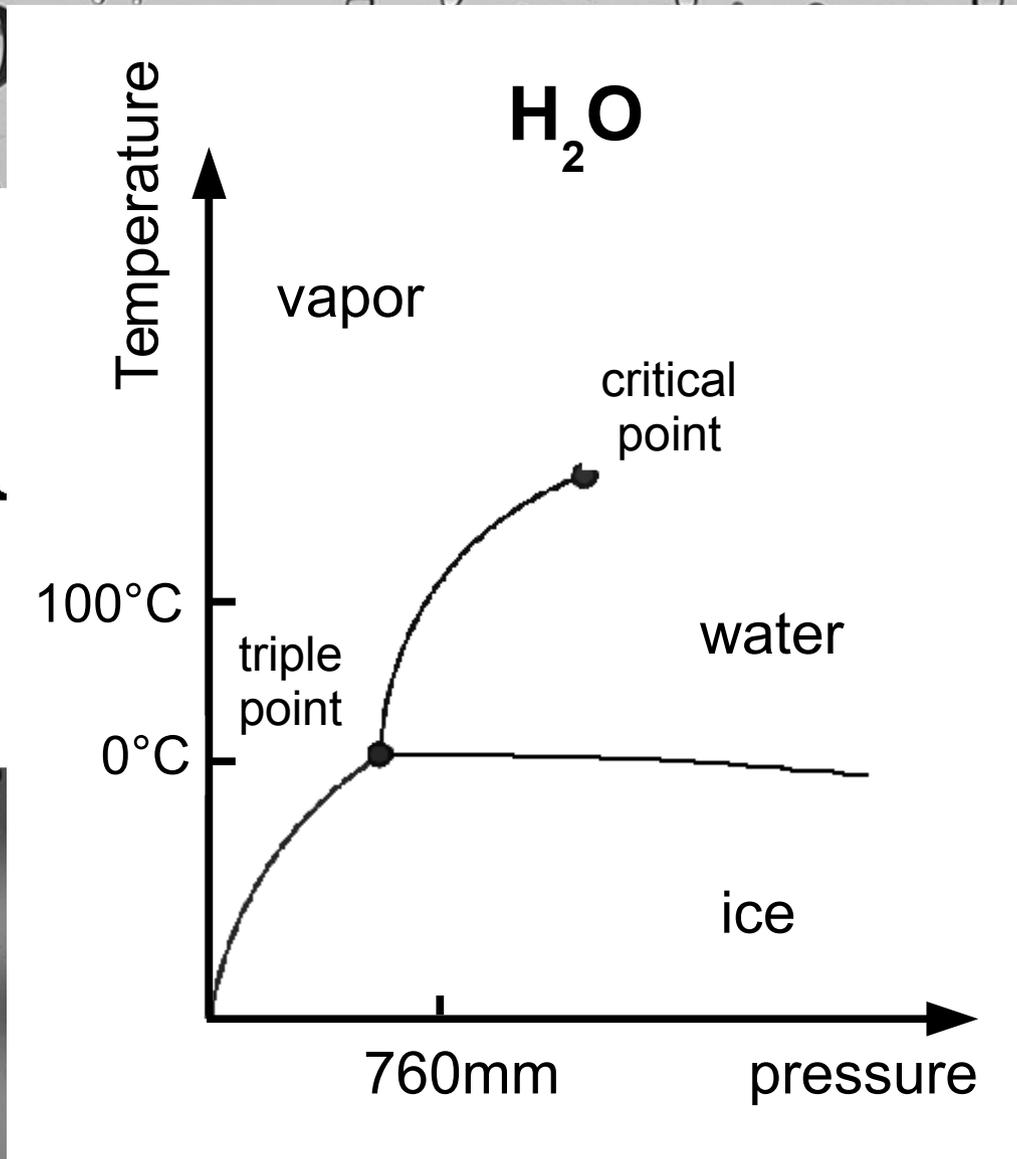
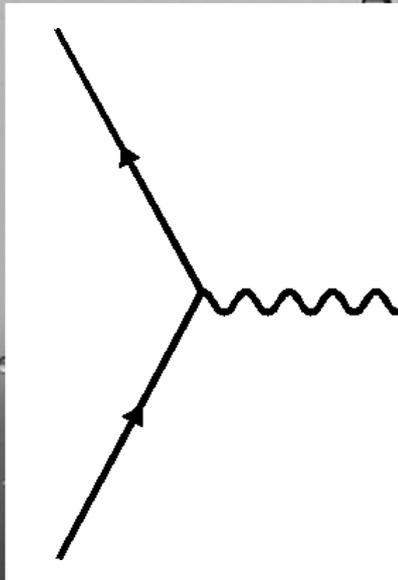


From Heavy-Ion Collisions to Quark-Gluon matter

Constantin Loizides
(LBNL)

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

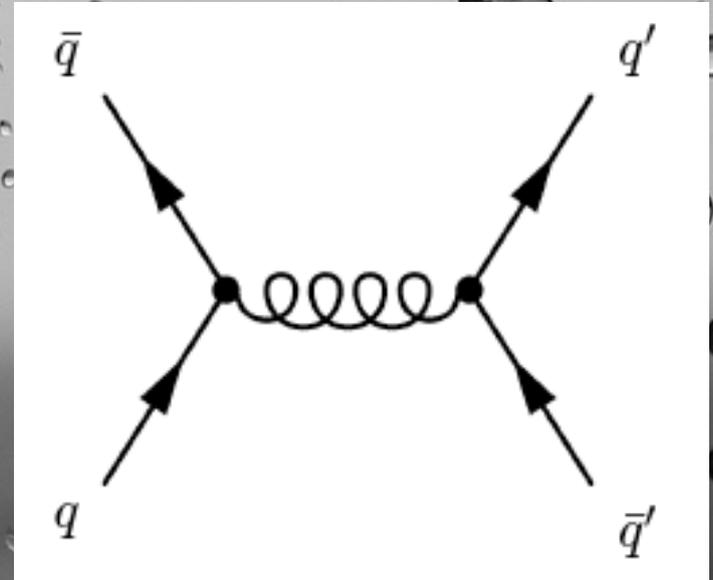
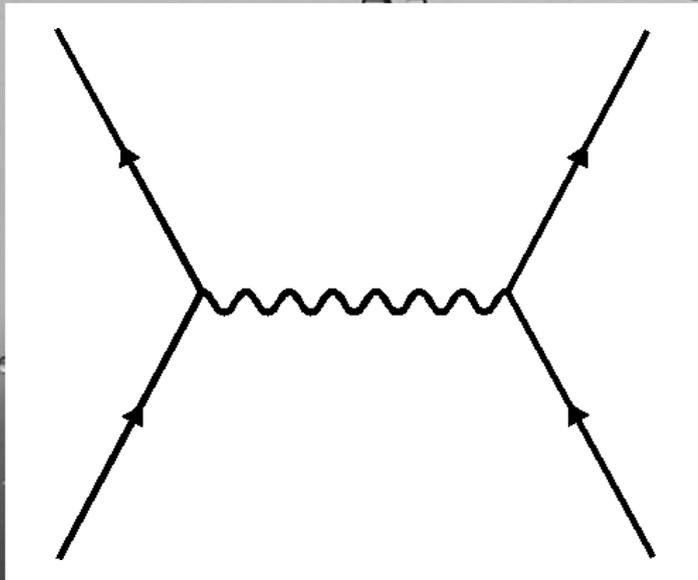
What Physics Do You See?



ts on the
rate a

and complex
es in systems
ng dynamics

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



Of course, the answer is yes
as we will see ...

Quantum Chromo Dynamics

(see e.g. [arXiv:hep-ph/9505231](https://arxiv.org/abs/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	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	-1

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

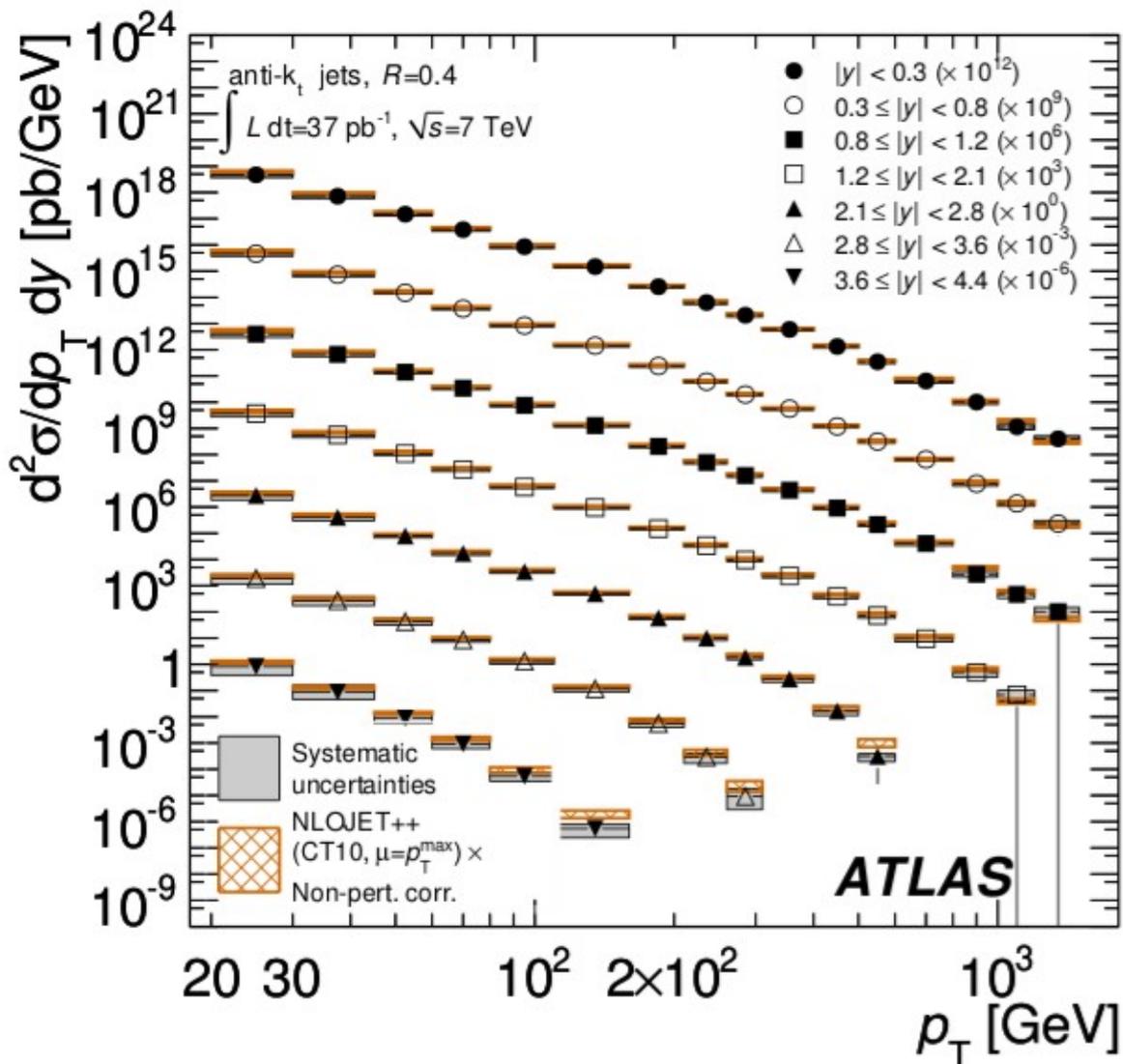
BOSONS

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

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

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

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



ATLAS, Phys.Rev. D86 (2012) 014022

- Strong interactions
 - Binds quarks into hadrons
 - Binds nucleons into nuclei
- Described by QCD
 - Interactions between quarks and gluons carrying color charge
 - Mediated by gluons, the strong force carriers
- Very successful theory
 - e.g. pQCD vs production of high energy jets
- But with outstanding puzzles!

Two puzzles in QCD:

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i) hadron masses

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

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?

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

Same basic structure as QED (electro-magnetism) ...

$$(q_\alpha)_f \left\{ \begin{array}{l} \text{color } a = 1, \dots, 3 \\ \text{spin } \alpha = 1, 2 \end{array} \right.$$

... except that gluons ("photons" of strong force) carry color charge ...

Gluons

$$A_\mu^a \left\{ \begin{array}{l} \text{color } a = 1, \dots, 8 \\ \text{spin } \epsilon_\mu^\pm \end{array} \right.$$

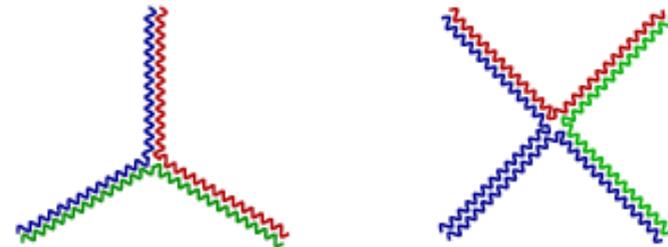
Dynamics: Generalized Maxwell (Yang-Mills)

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

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

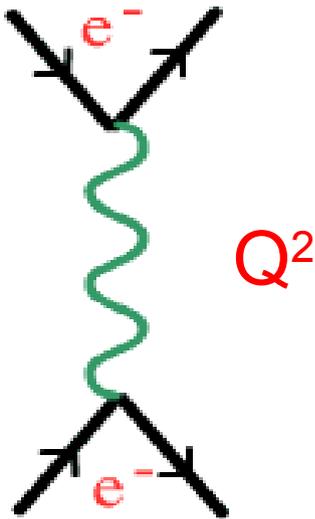
$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc} A_\mu^b A_\nu^c$$

$$i\not{D}q = \gamma^\mu (i\partial_\mu + gA_\mu^a t^a) q$$



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 dependent interaction strength

“Running” of the coupling: QED vs QCD

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

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

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

QCD:

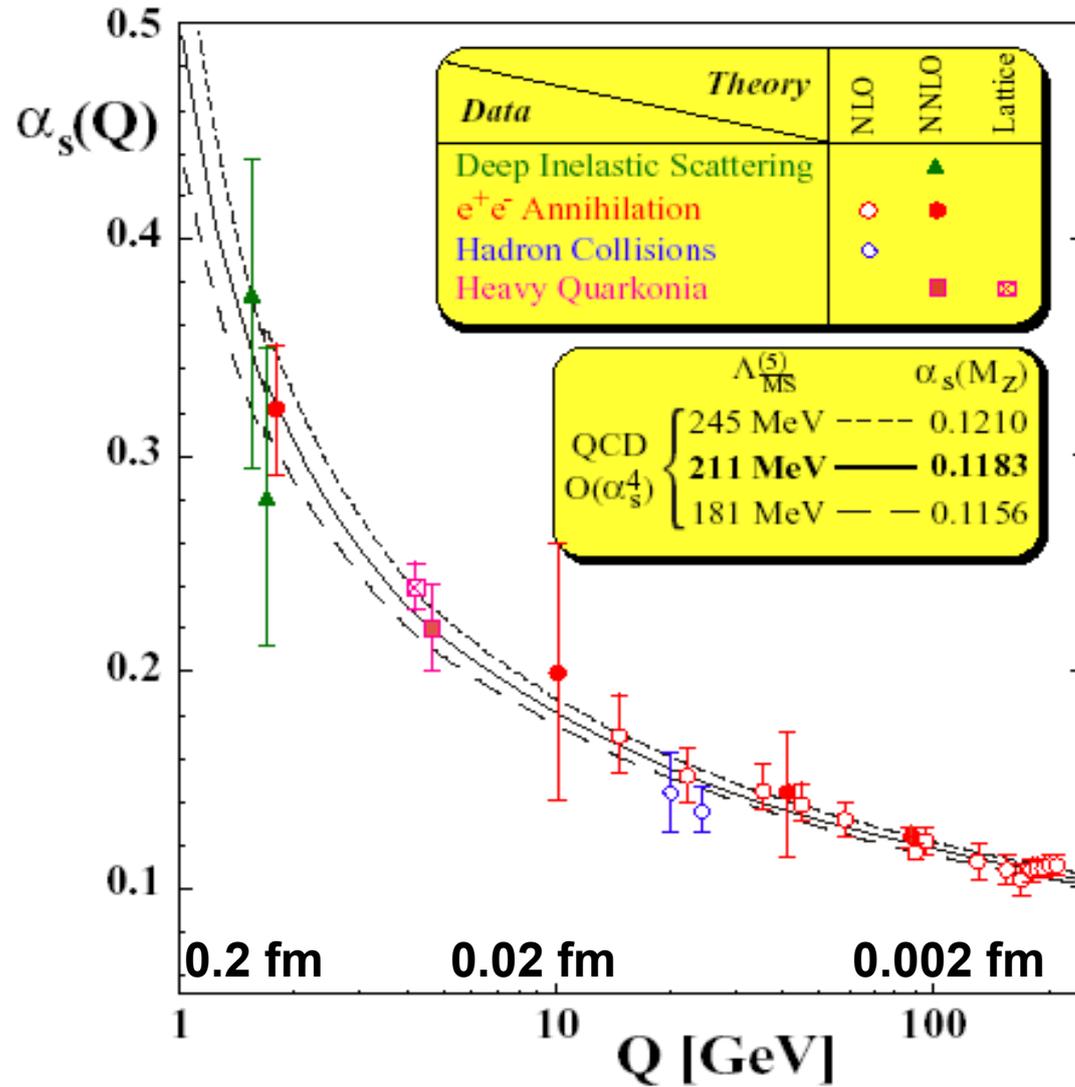
$$\alpha(Q^2) \approx \alpha(\mu^2) / \left(1 + \alpha(\mu^2) \frac{11N_{\text{color}} - 2n_{\text{flavor}}}{12\pi} \log \frac{|Q^2|}{\mu^2} \right)$$

$= (33-12)/12\pi = \text{positive!}$

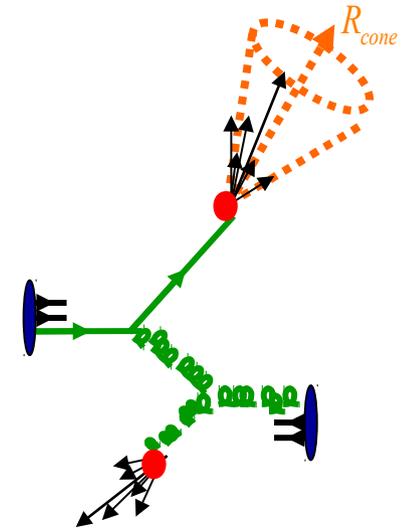
Smaller $|Q^2|$ (larger distance) \Rightarrow **stronger** coupling
(so called anti-screening stronger than screening)

And that makes a huge difference!

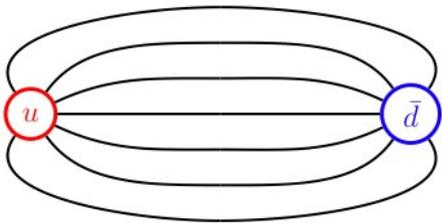
“Running” of the coupling: QCD



Asymptotic freedom



Confinement



2004
Nobel
Prize

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 08540

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

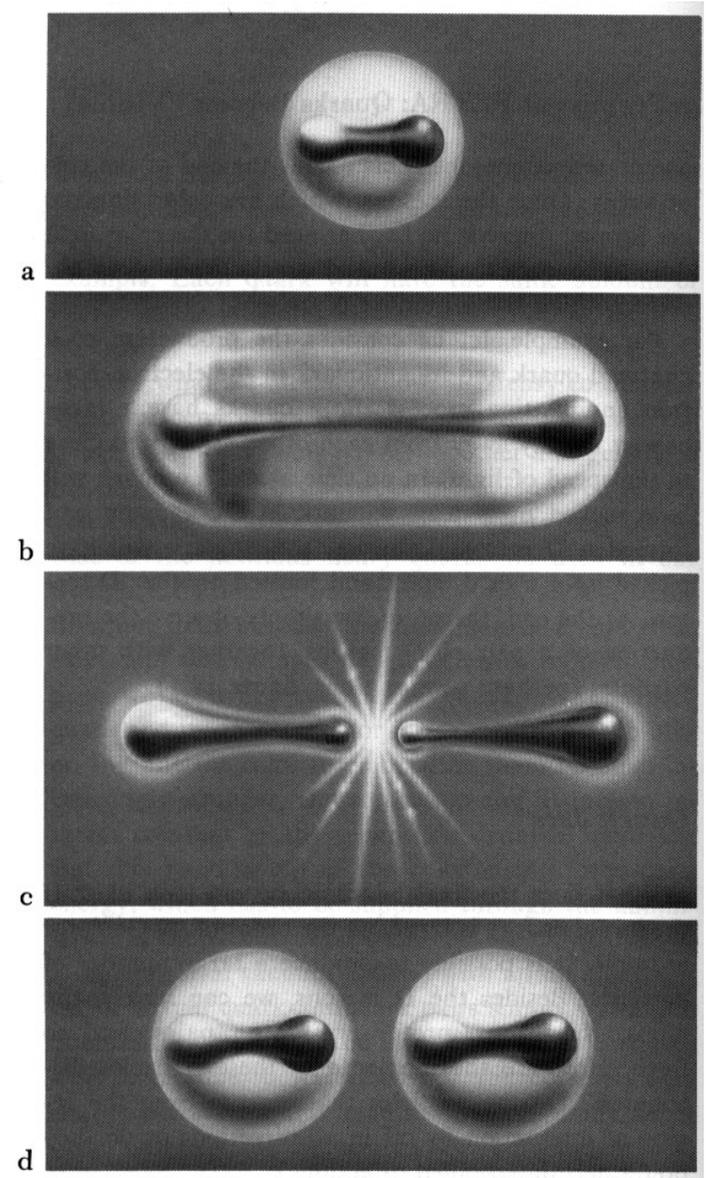
(Received 3 May 1973)

QCD deconfinement phase transition

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

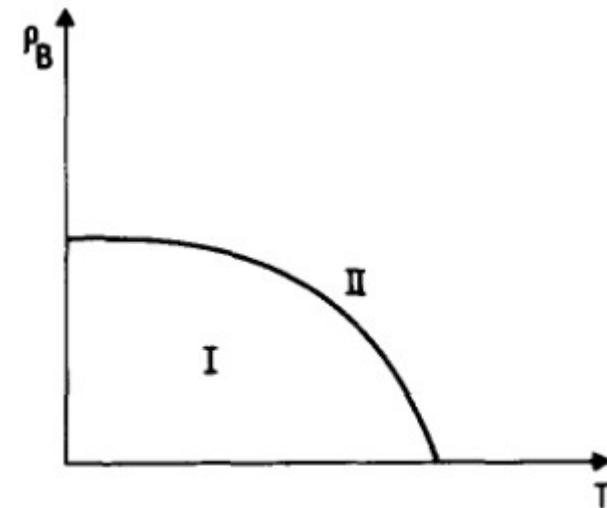
$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + Kr$$

- Kr parametrizes the effects of confinement
- When r increases, the color field can be seen as a tube
- At large r , it becomes 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 Fritzsche)

- 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



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.



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.

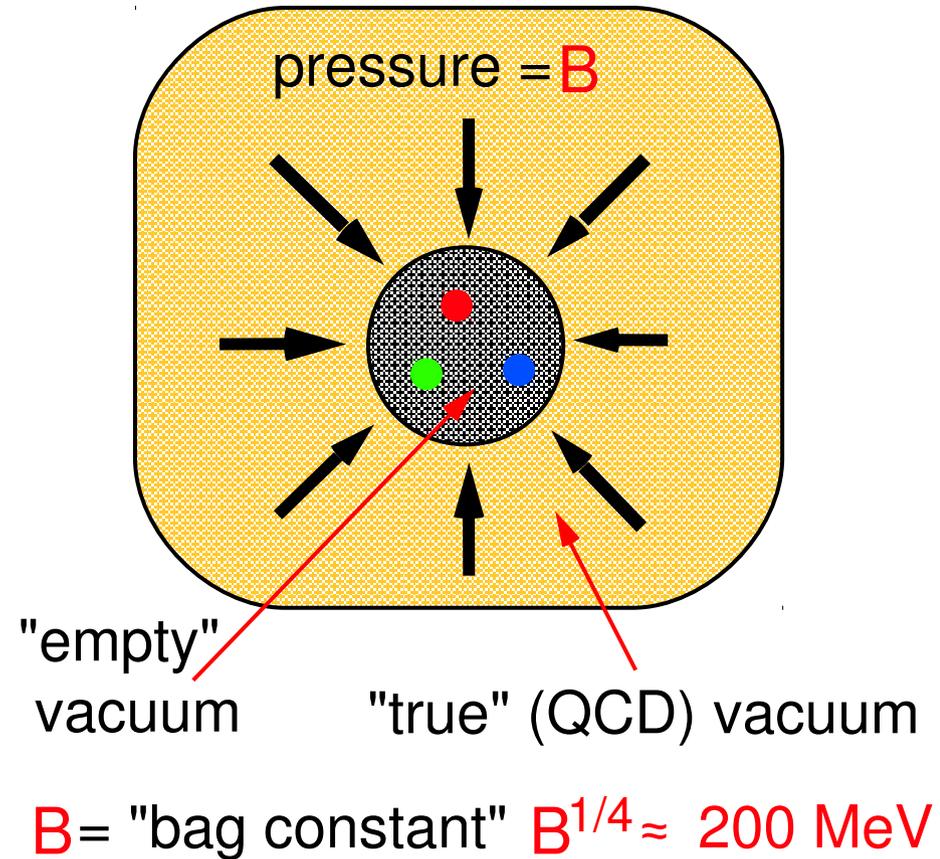
Phase transition
at large T and/or ρ_B



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 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 pressure is obtained by balancing the vacuum with the kinetic pressure of the quarks
- $B \approx (200 \text{ MeV})^4$
with $N=3$ quarks in $R=0.8\text{fm}$

Bag model of a hadron:

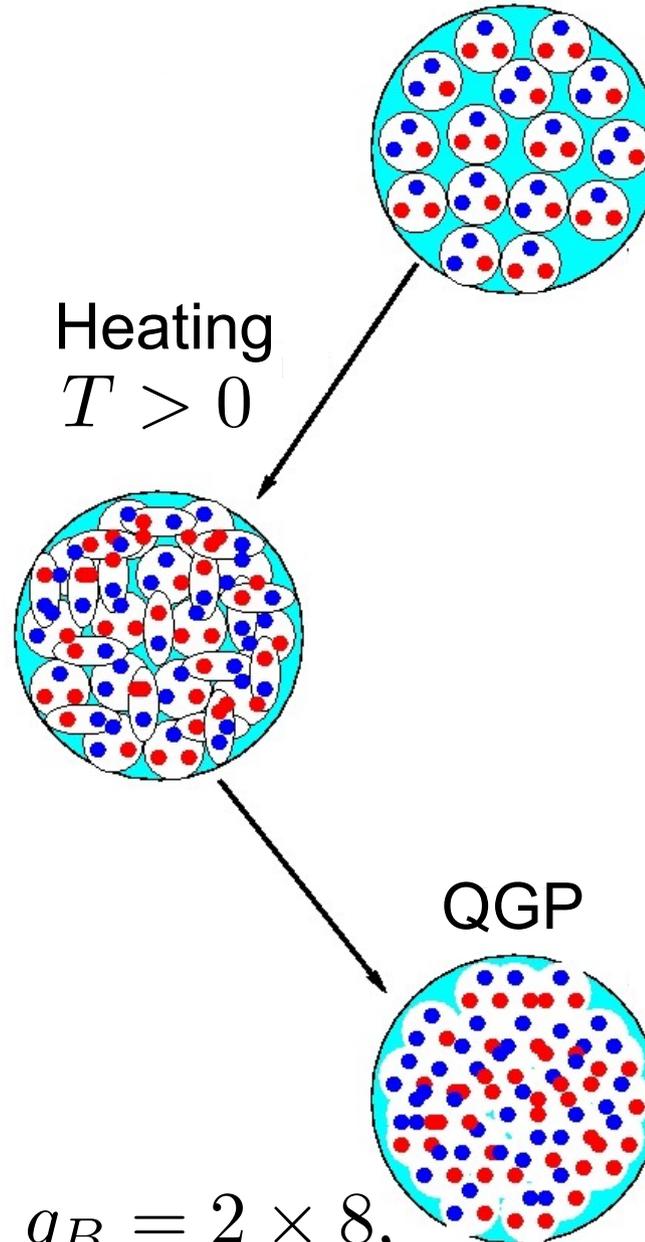


Deconfinement: A toy model

- Heat matter so much that individual hadrons start to overlap
- From statistical mechanics for an ideal gas

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

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



$$g_B = 2 \times 8,$$
$$g_F = 2 \times 2 \times 2 \times 3$$

B=Boson
F=Fermion

- Heat or compress matter so much that individual hadrons start to overlap
- From statistical mechanics for an ideal gas

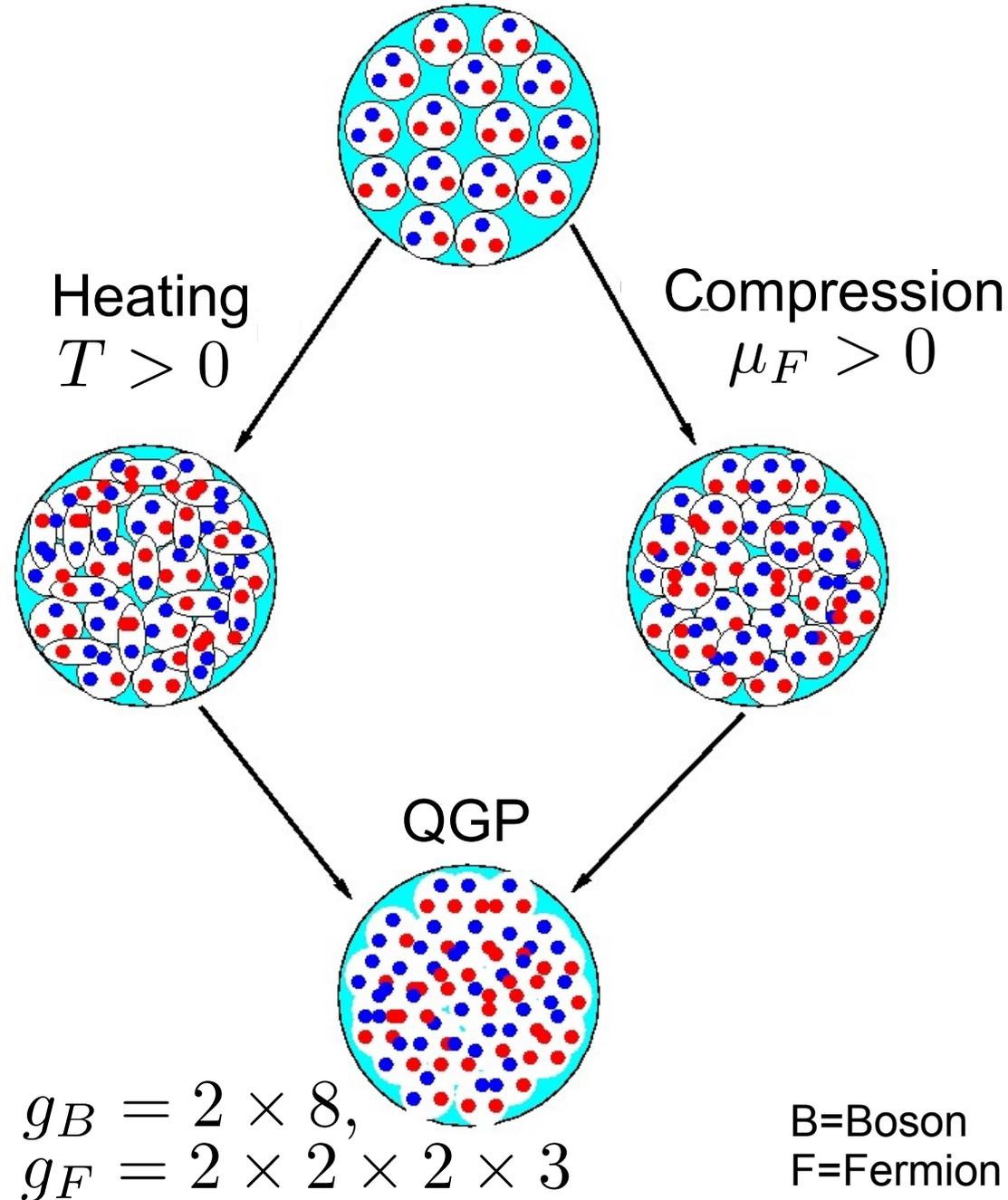
$$p = \frac{\epsilon}{3} = \left(g_B + \frac{7}{8}g_F \right) \frac{\pi^2 T^4}{90} + g_F \left(\frac{\mu_F^2 T^2}{12} + \frac{\mu_F^4}{24\pi^2} \right)$$

- Condition for QGP:
Pressure $\geq B$

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

(see [Reygers and Schweda](#))

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

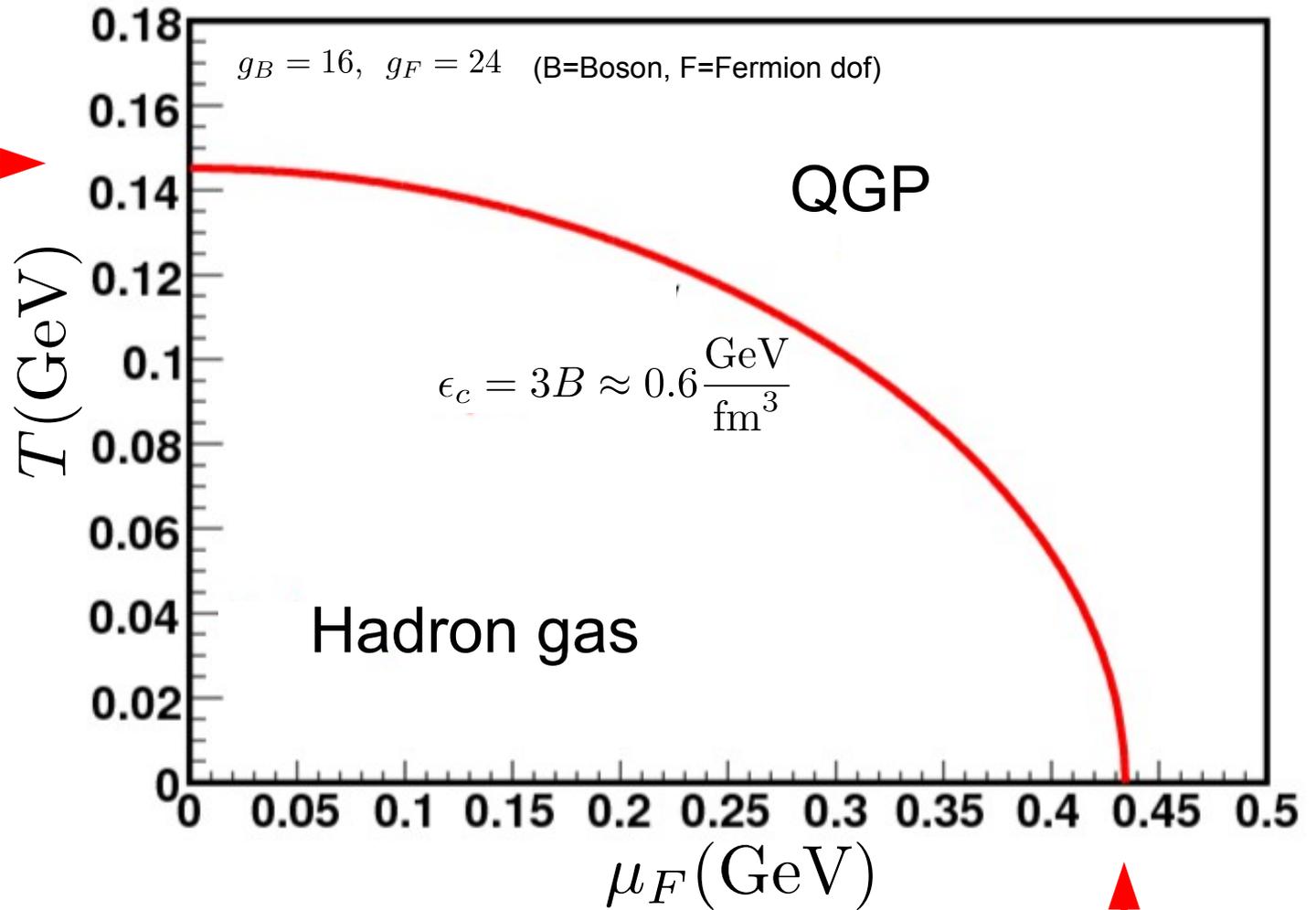


$$g_B = 2 \times 8, \\ g_F = 2 \times 2 \times 2 \times 3$$

B=Boson
F=Fermion

Phase diagram of non-interacting QGP

$T_c \approx 2 \cdot 10^{12} \text{K}$
 (10⁵ times core of sun)



- Condition for QGP:
 Pressure $\geq B$

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

$n_c^B = 0.72 \text{fm}^{-3}$
 (5 x nucleus)

(see Reygers and Schweda)

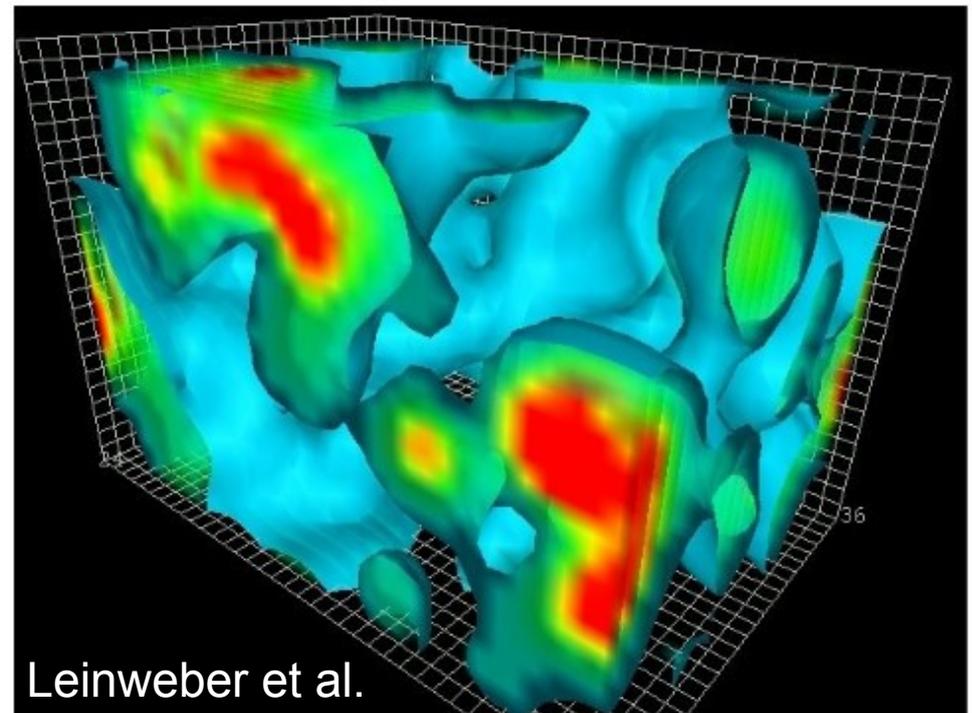
Lattice QCD

- 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. $16^3 \times 32$

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



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



Leinweber et al.

- Solve path integrals numerically in discretised Euclidean space-time

$$e^{iS} \rightarrow e^{-S_E}$$

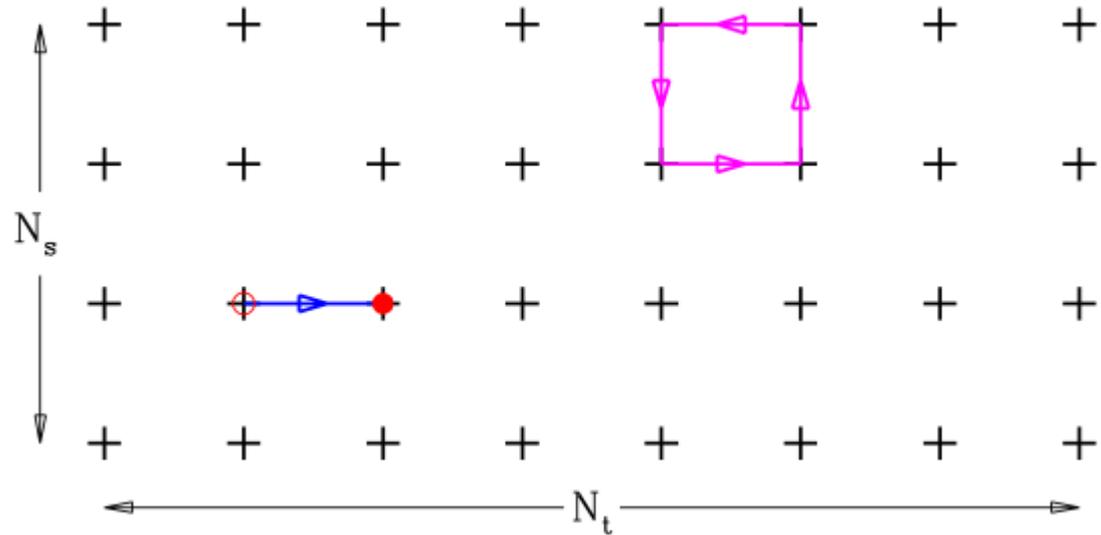
- Physical results

- Continuum limit ($a \rightarrow 0$)
- Infinite volume limit ($V \rightarrow \infty$)
- Set scale(s) using data e.g. hadron mass(es)

- Problems of approach

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

Lattice spacing $a, \quad a^{-1} \sim \Lambda_{UV}, \quad x_\mu = n_\mu a$
 Finite volume $L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a$

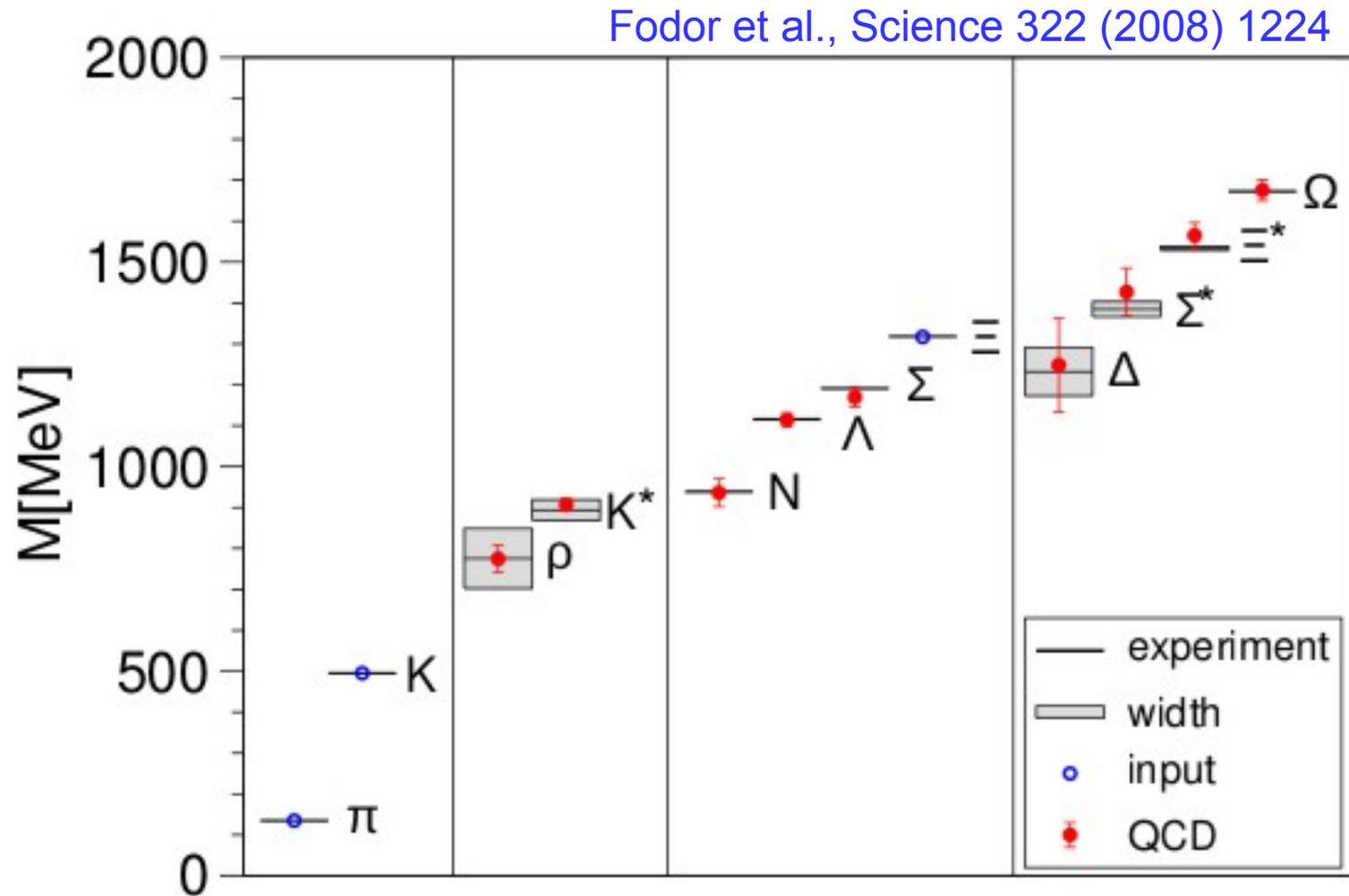


(anti)quarks: $\psi(x), \bar{\psi}(x)$

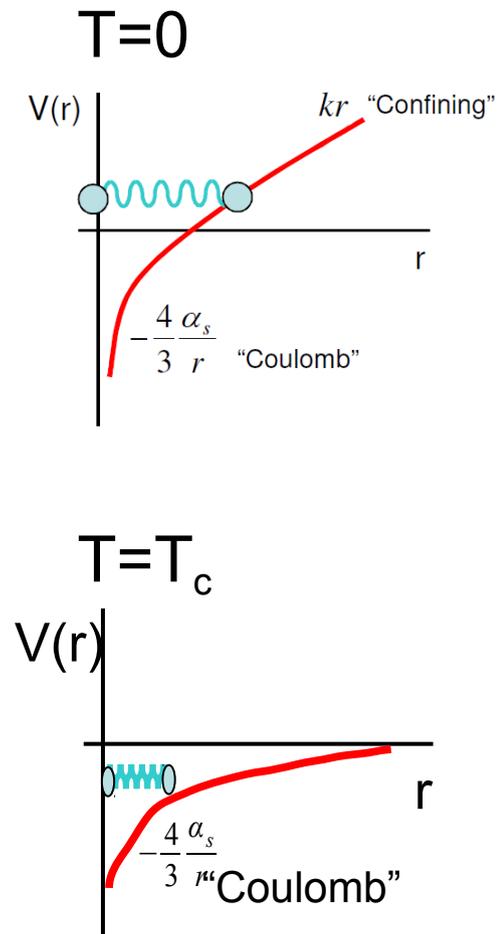
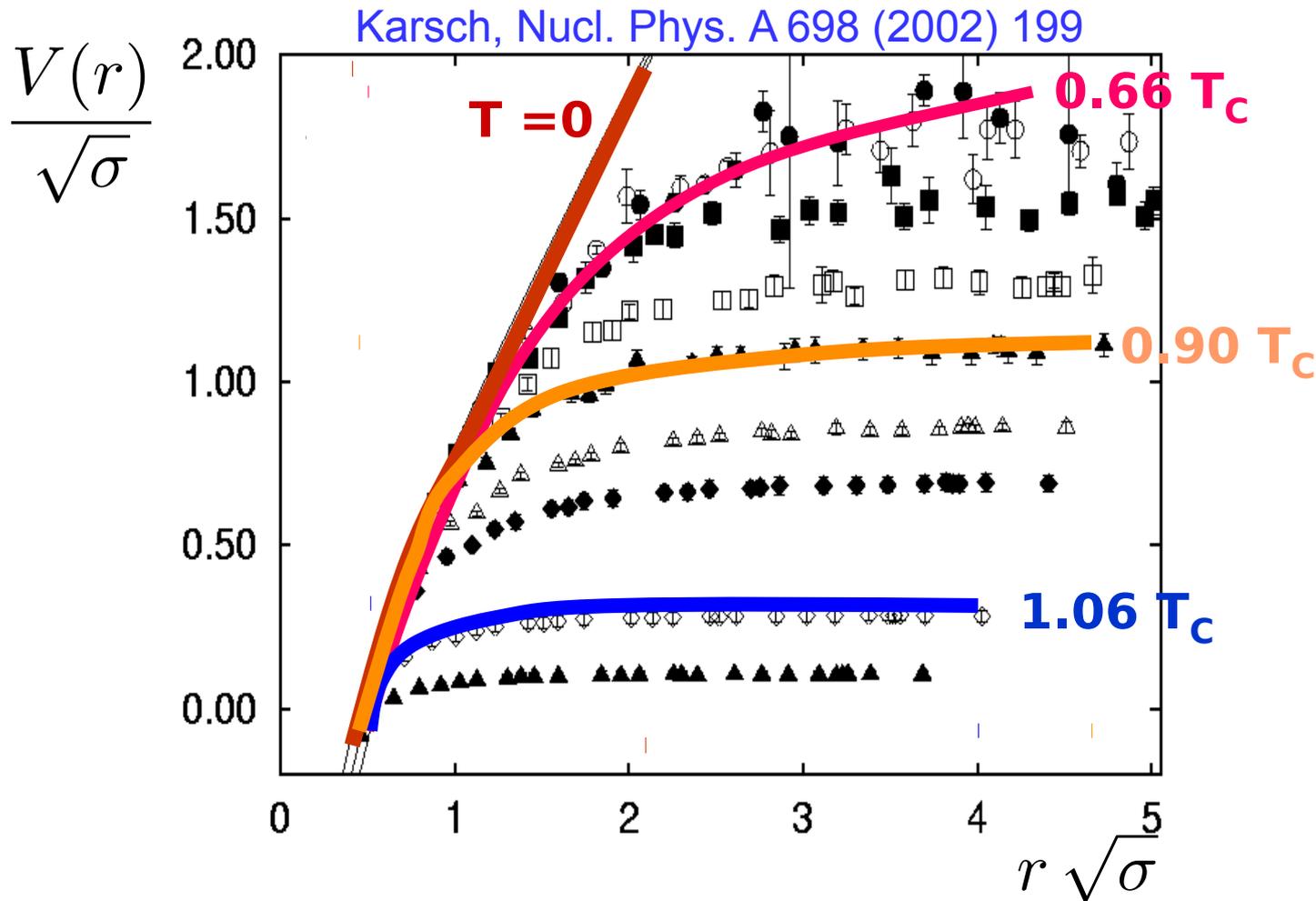
gluons: $U_\mu(x) = e^{aA_\mu(x)} \in \text{SU}(3)$

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

$$S[U, \bar{\psi}, \psi] = S_G[U] + S_F[U, \bar{\psi}, \psi]$$

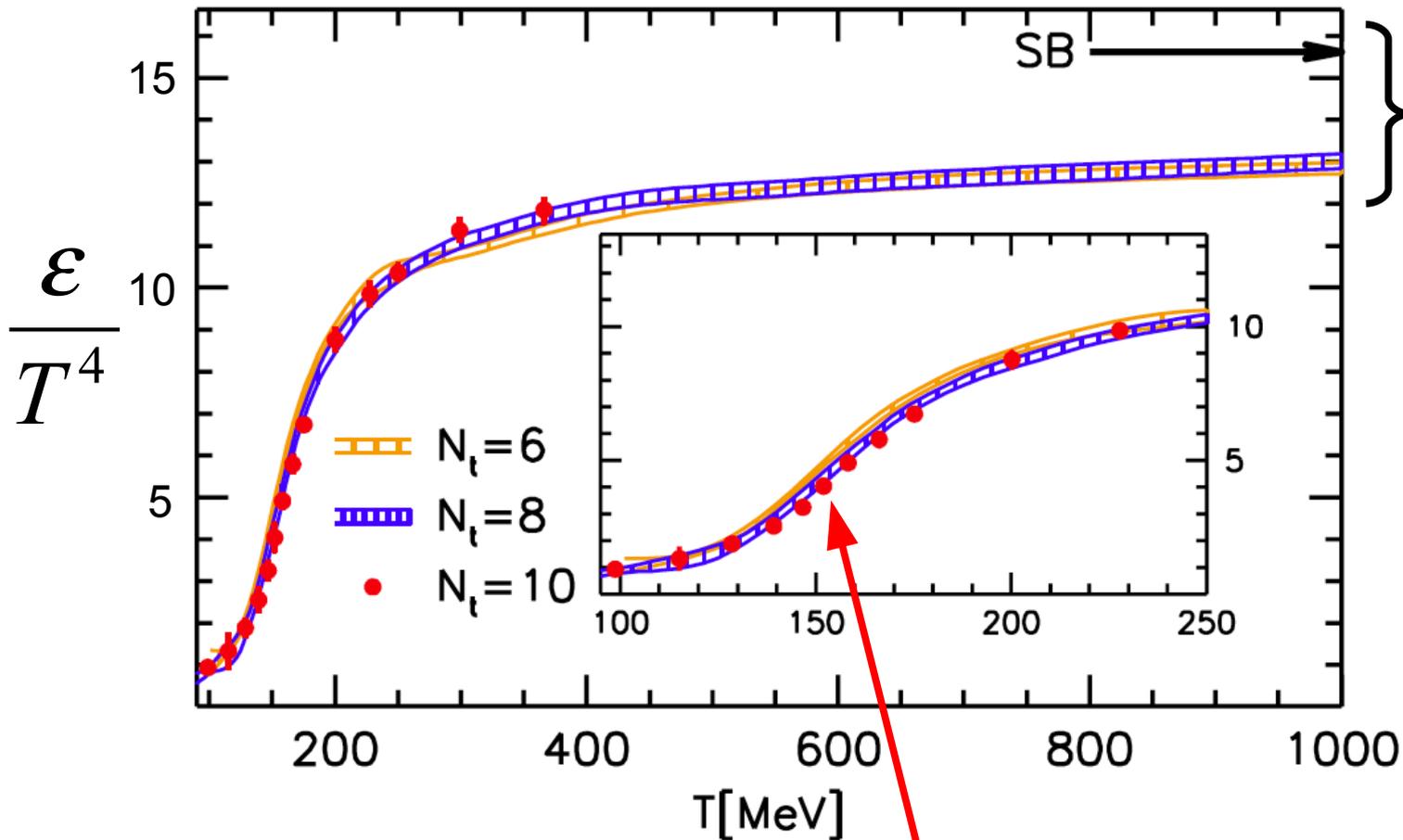


Full calculation using 2 quark flavors
in excellent agreement with experimental data



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

Fodor et al., JHEP 11 (2010) 077



Slow convergence to ideal gas (SB) limit

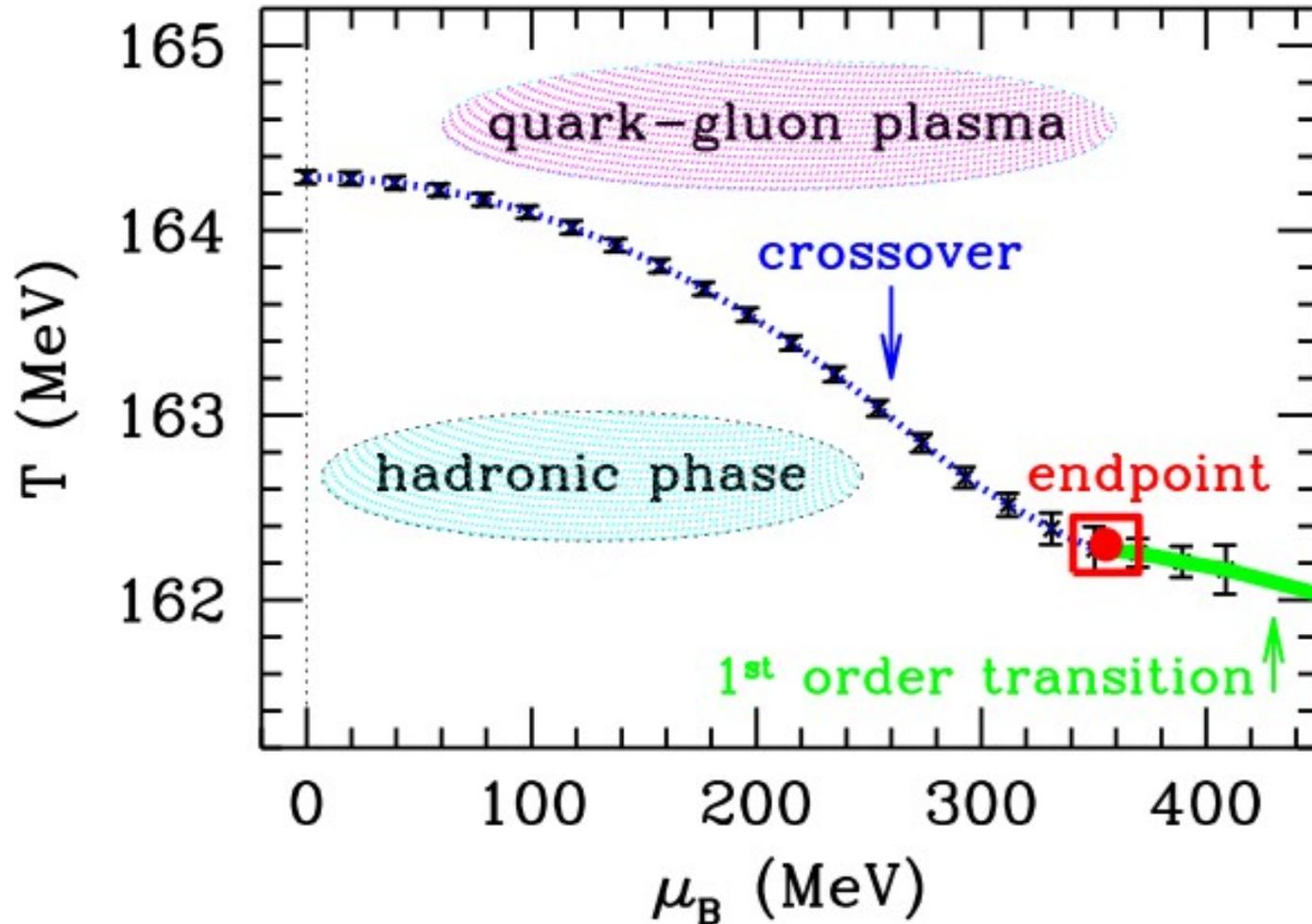
What carries the energy?
Complex bound states of q and g?
Strongly coupled plasma?

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

Transition temperature region between 140 and 200 MeV, with wide range of energy density between 0.2 and 1.8 GeV/fm³

Remember: $T_c \approx 170$ MeV and $\epsilon_c \approx 1$ GeV/fm³

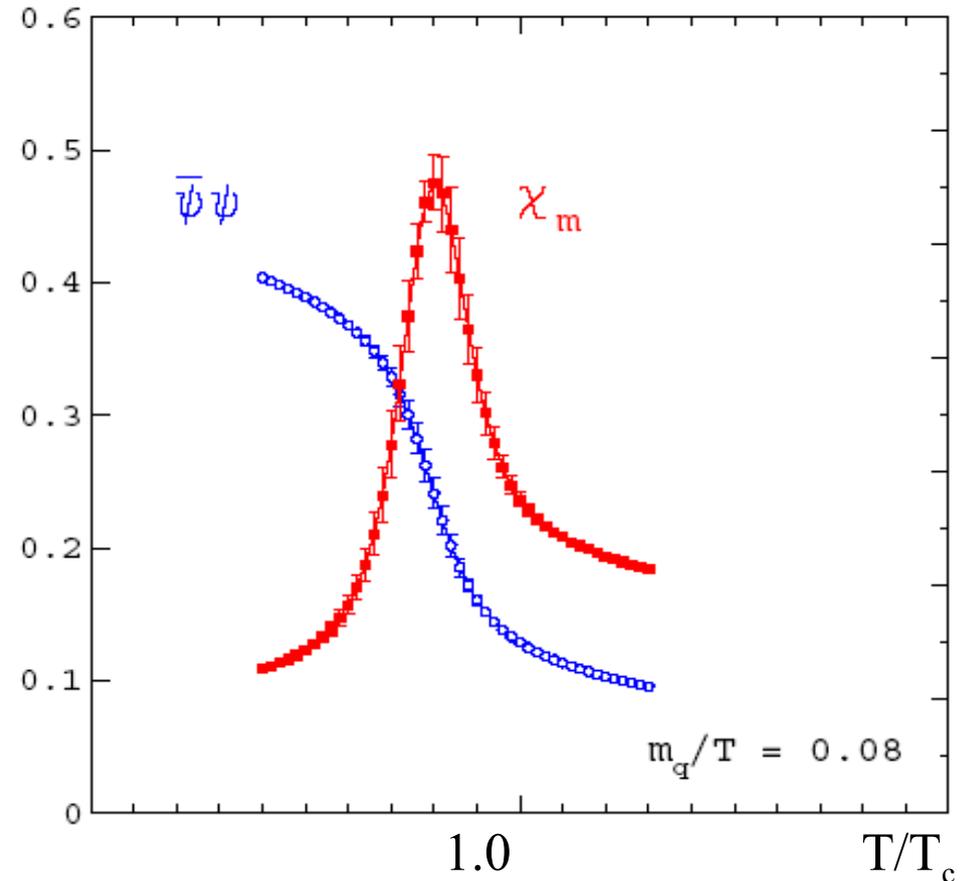
Fodor and Katz, JHEP 0404 (2004) 050



- Finite μ calculations complicated and computationally demanding
- Some calculations suggest a critical endpoint at $T=162$ MeV, $\mu_B=340$ MeV with large theoretical uncertainties
- Critical endpoint existence and exact location is an open question

- 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
- Deconfinement should be accompanied by a restoration of the masses to the bare masses of the Lagrangian
- Usually called “Partial restoration of chiral symmetry”)
- Effective quark mass from $\langle \bar{\psi}\psi \rangle$ 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

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

Time

Temperature

In the beginning
quark – gluon
plasma

~ 10 μ s after Big Bang

hadron synthesis
strong force binds
quarks and gluons

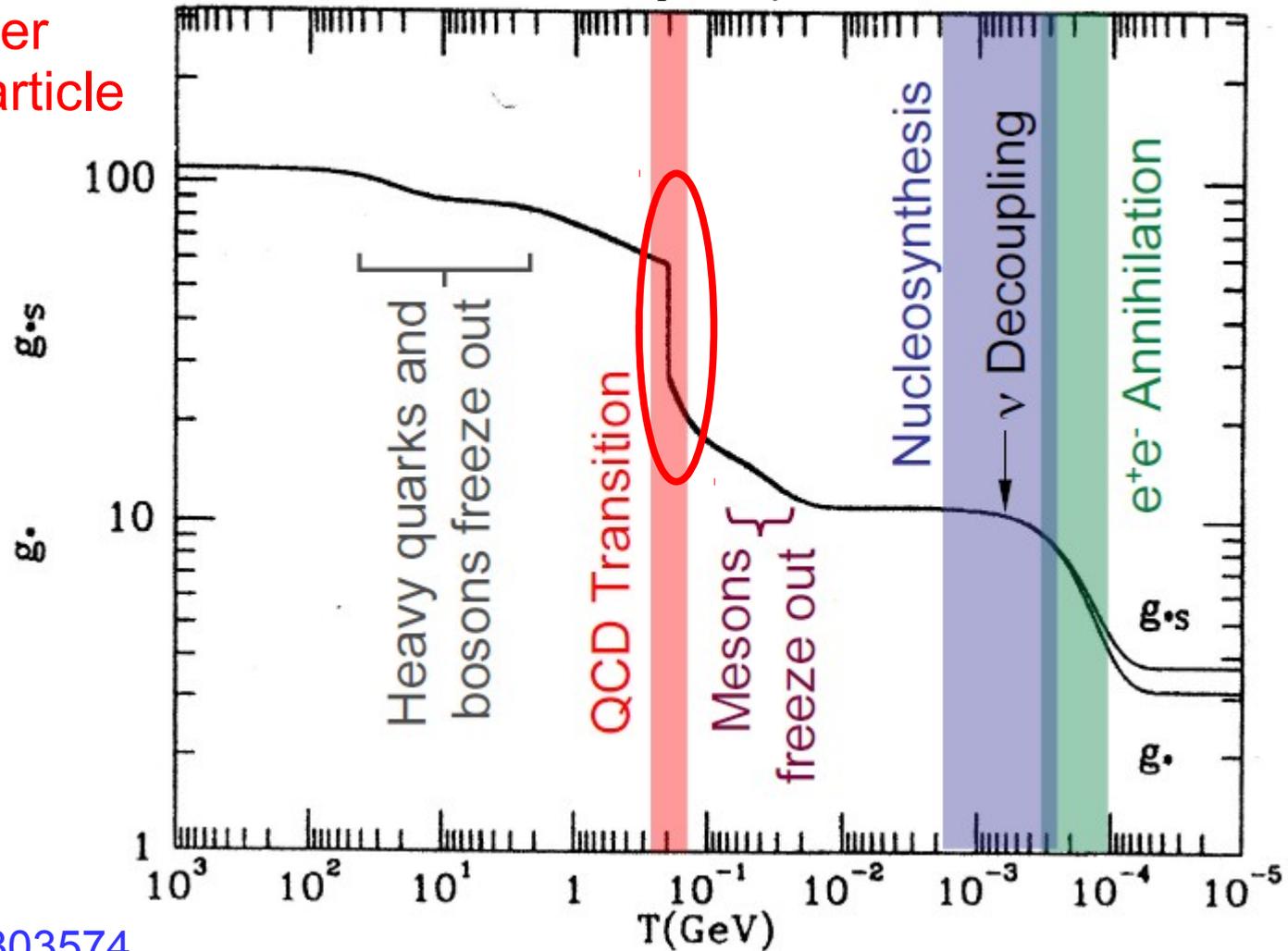
~ 100 s after Big Bang
nucleosynthesis
strong force binds nucleons



M. Storzinger

Effective degrees of freedom per relativistic particle

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



The Early Universe,
Kolb and 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.

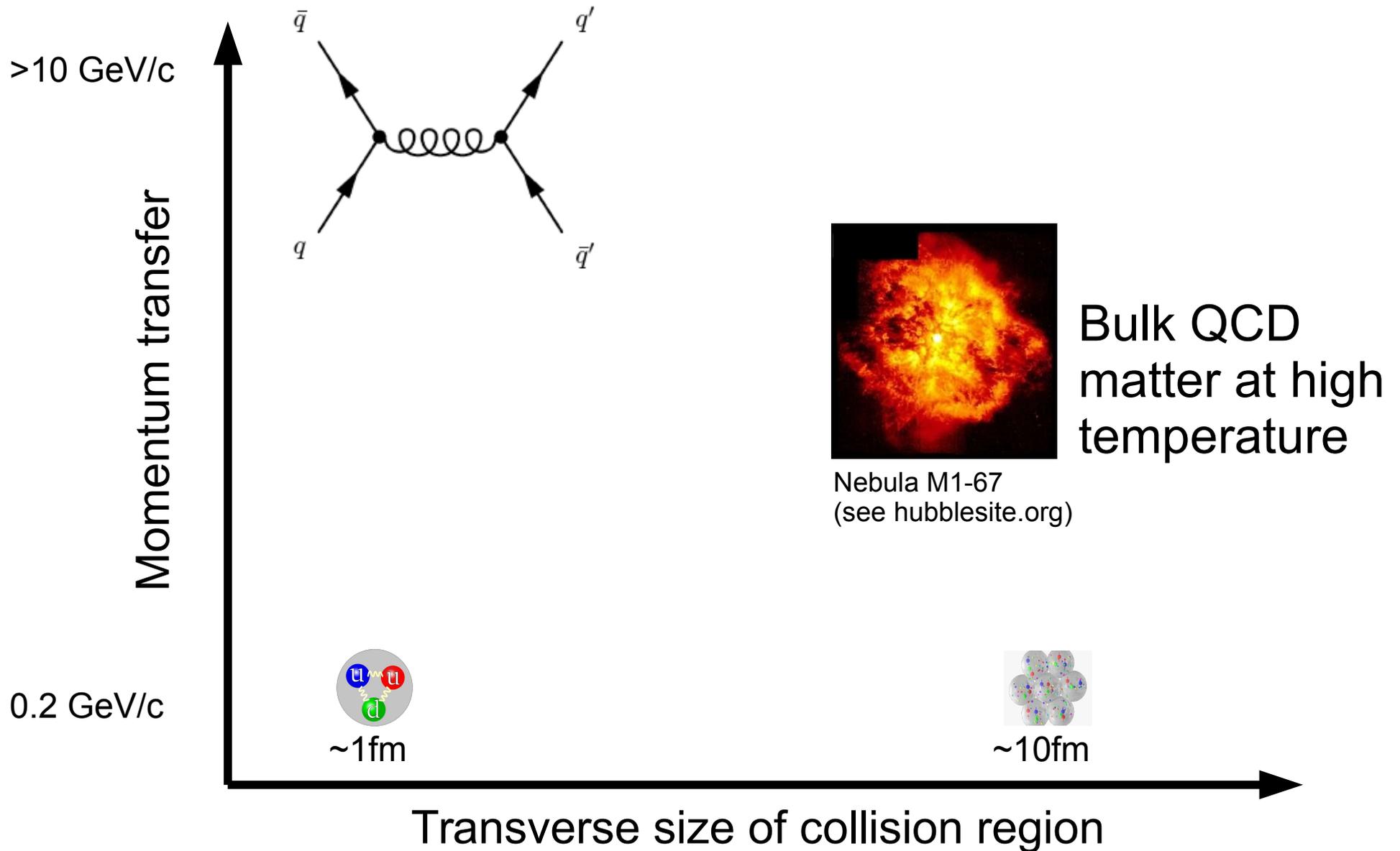
How to create the QGP?



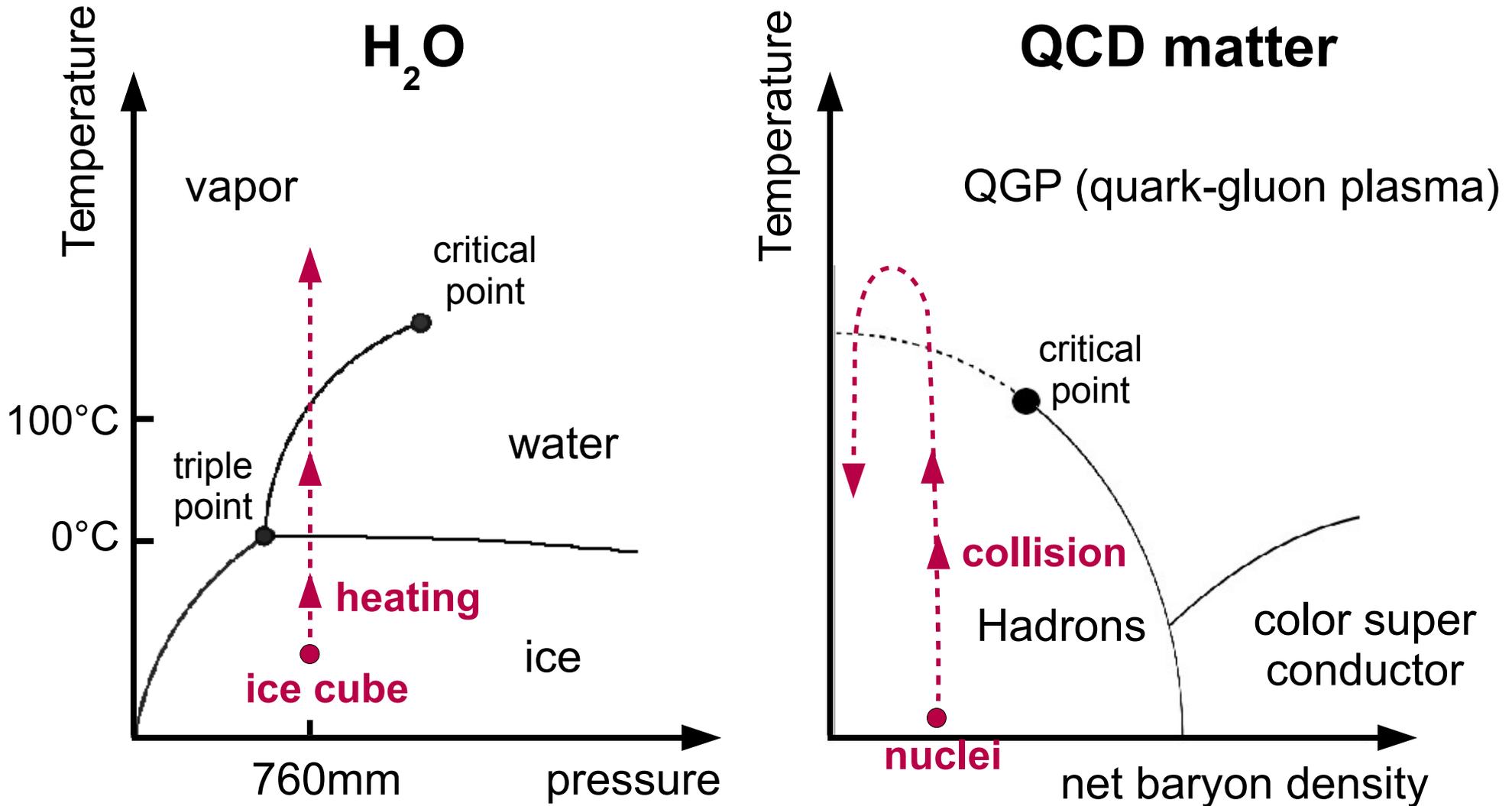
T.D.Lee,
Rev.Mod.Phys. 47 (1975) 267

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.**

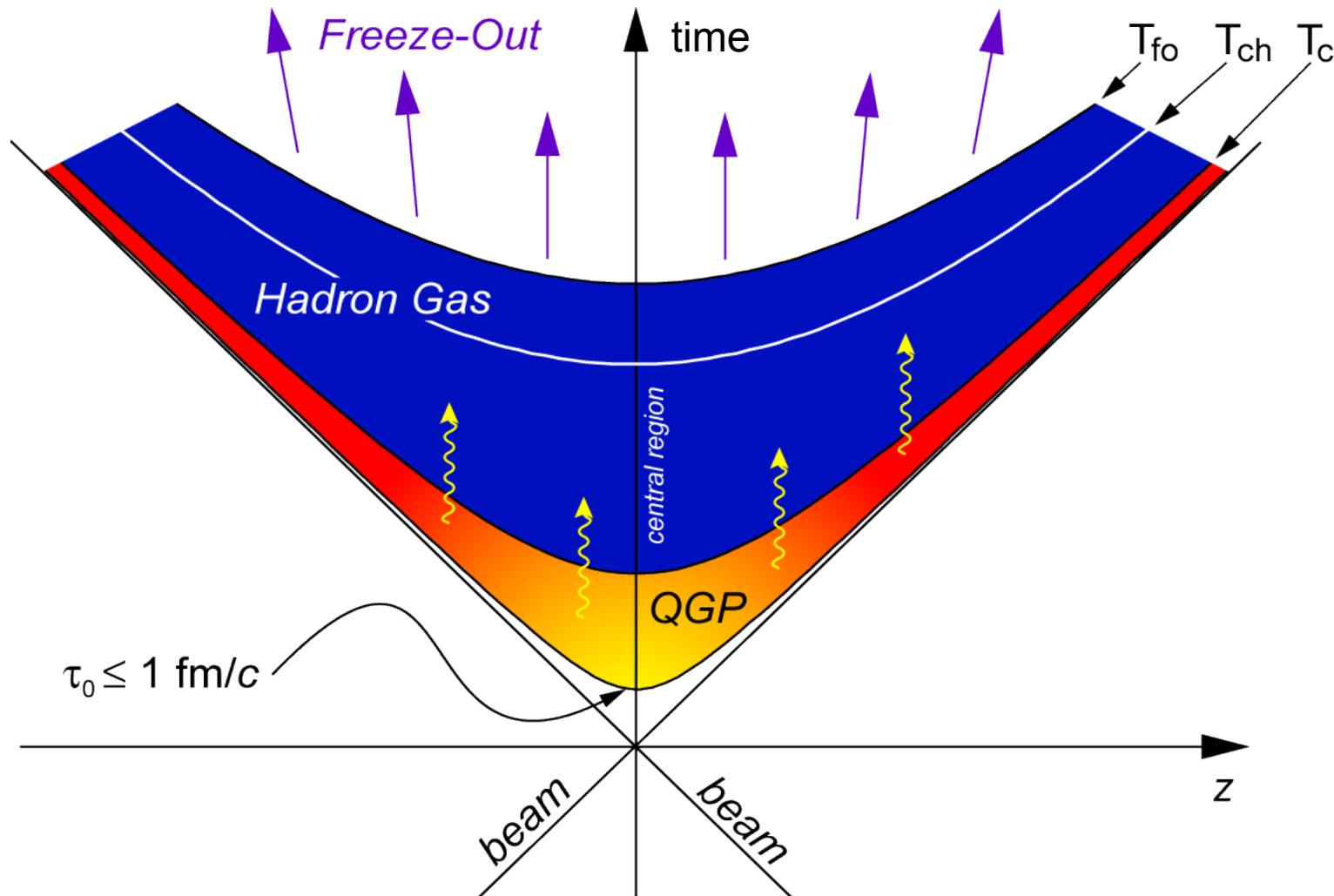
Study QCD bulk matter at high temperature



How can we create QCD matter?



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



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

Kinetic freeze-out
($t = 10 \text{ fm/c}$)

Chemical freeze-out

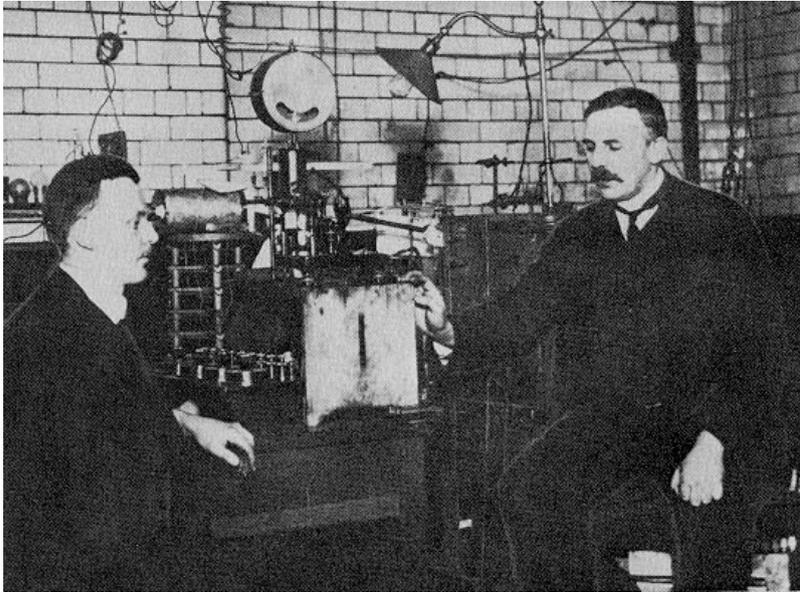
Hydrodynamic
evolution ($t \sim 0.5 \text{ fm/c}$)

Pre-equilibrium
Collision ($t = 0 \text{ fm/c}$)

In reality, strong dynamical evolution of the system

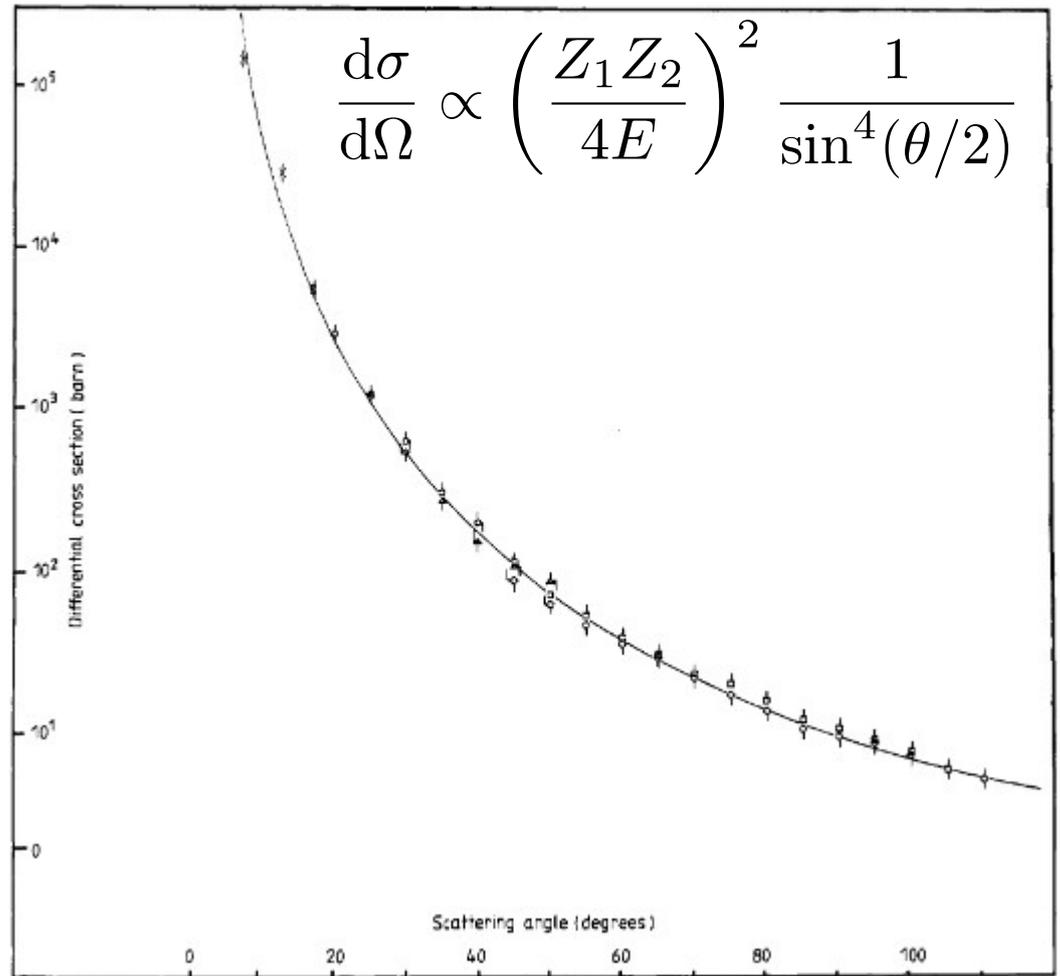
How to probe the QGP?

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



Interpretation:

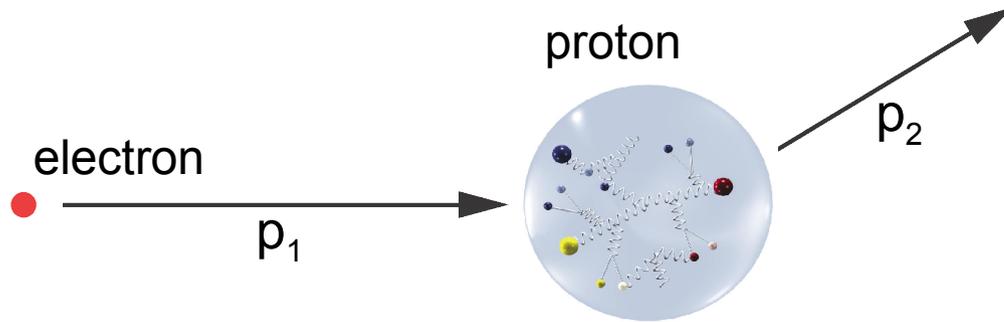
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions



Exploring the structure of protons

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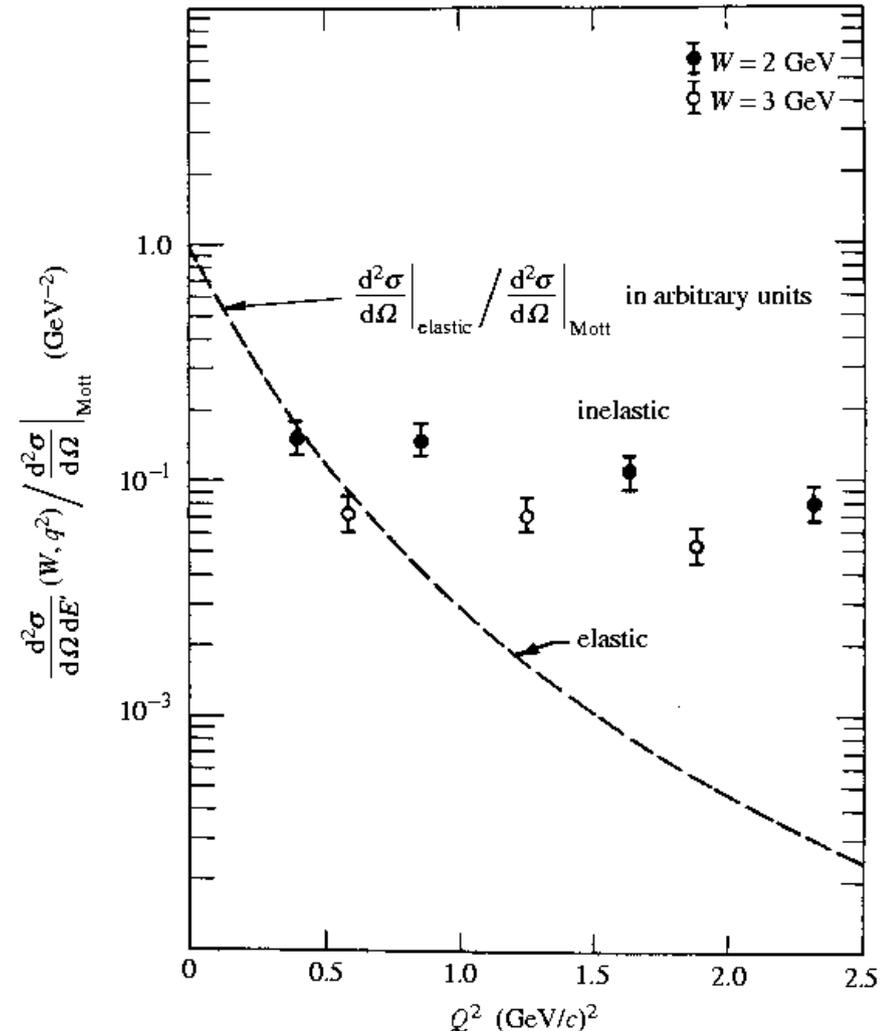
Deep inelastic scattering experiments at SLAC in the 1960s established the quark-parton model:



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

Approximately constant form factor
 \Rightarrow scattering on point-like constituents
 \Rightarrow **quarks**

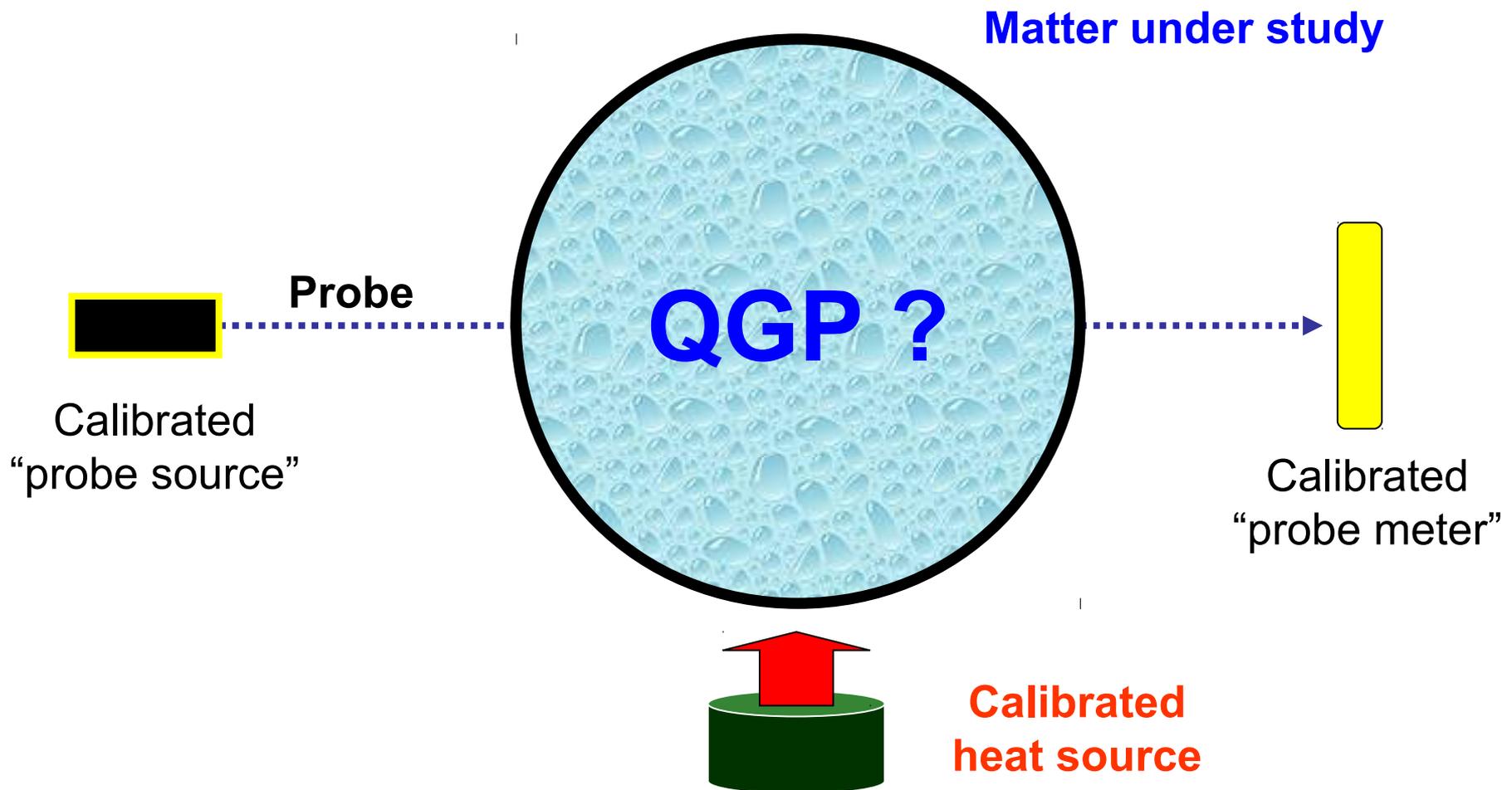
1990 Nobel Prize in Physics



Exploring the structure of QCD matter

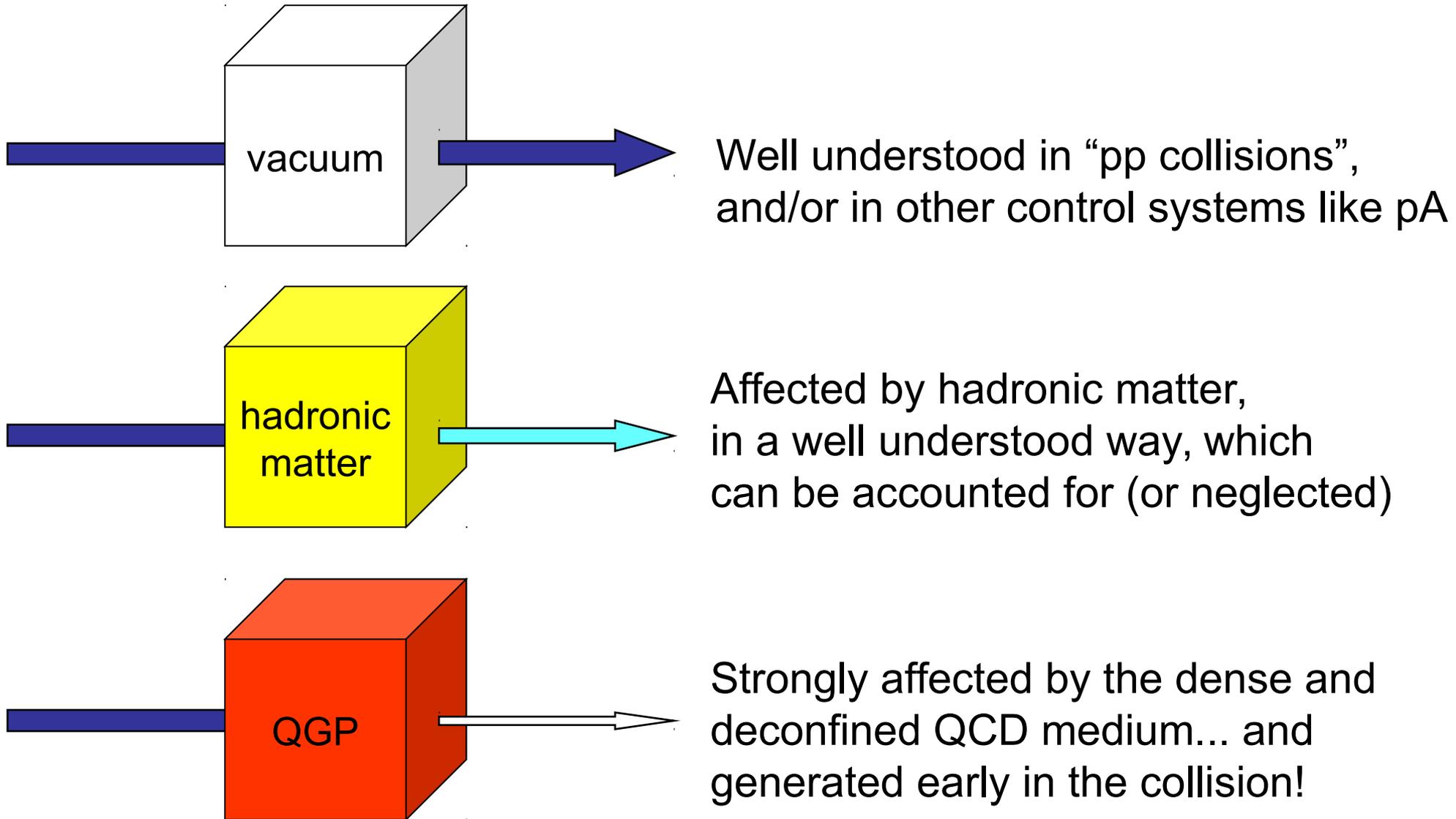
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In analogy, we study the QCD matter produced in HI collisions by measuring how it affects well understood probes, as a function of the temperature of the system



Good probes of QCD matter

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Jets and heavy quarkonia (J/ψ , χ_c , Y , Y' , etc) should be good QCD matter probes !

Heavy-ion experiments

Two main laboratories for heavy-ion collisions 41

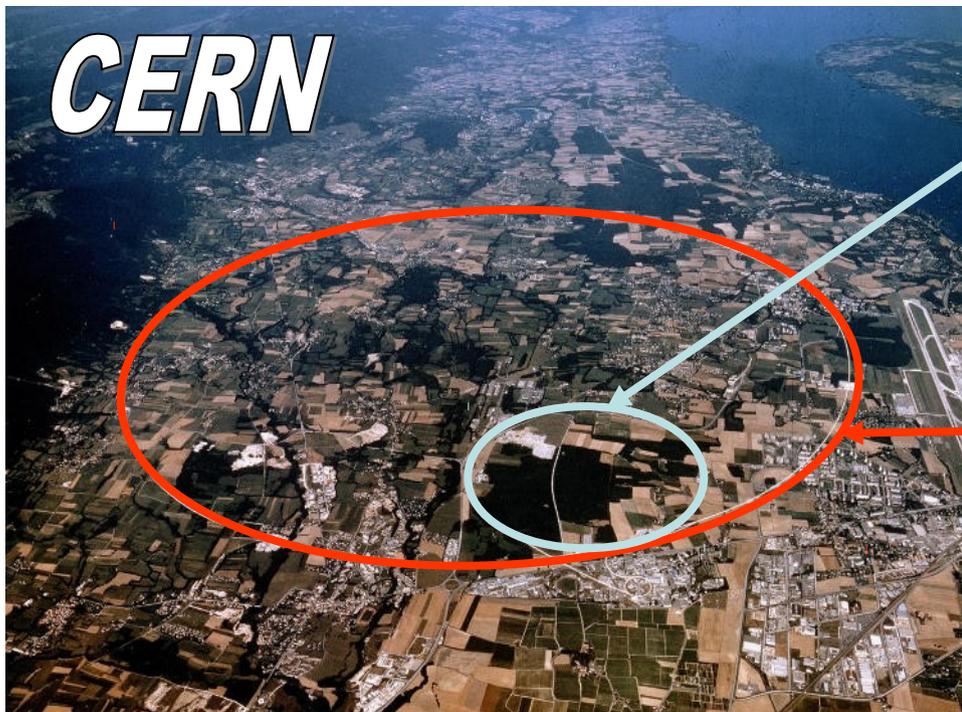


AGS : 1986 – 2000

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

RHIC : 2000 – ?

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



SPS : 1986 – 2003 + 2009 – ?

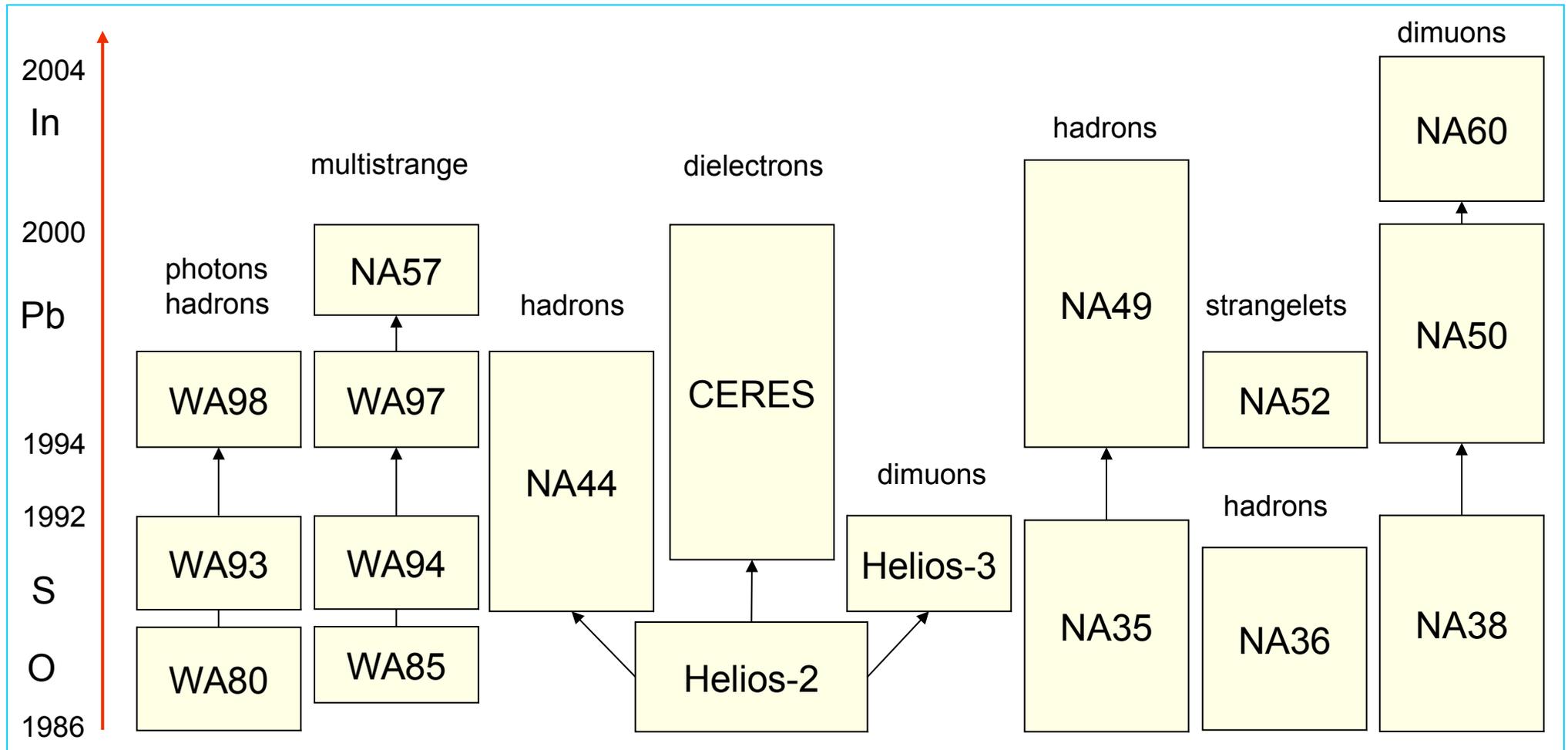
- O, S, In, Pb beams ; $\sqrt{s} \sim 20$ GeV
- Various experiments in North Area

LHC : 2009 – ?

- Pb beams ; up to $\sqrt{s} = 5500$ GeV
- ALICE, CMS and ATLAS

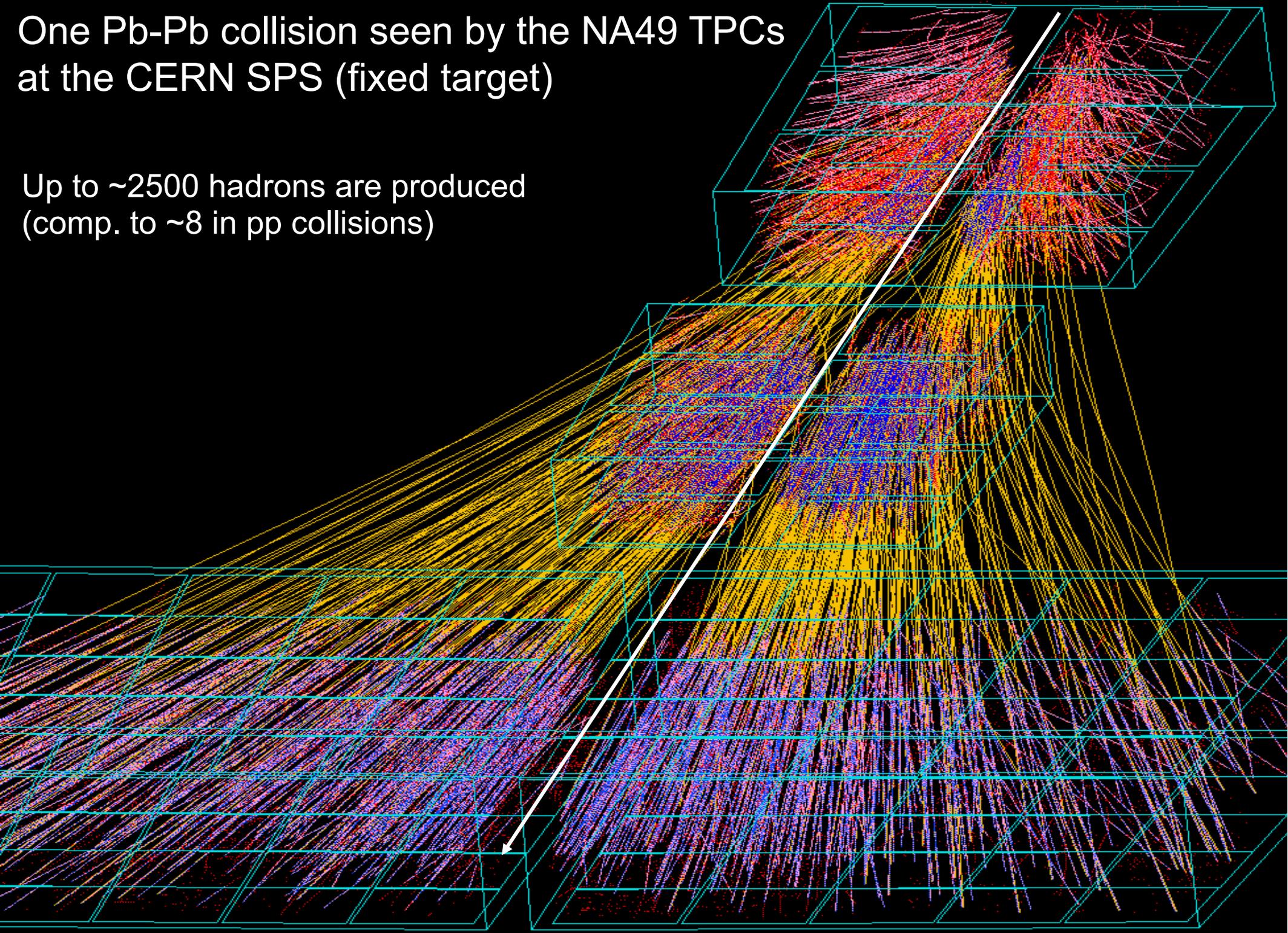
The CERN SPS physics program

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

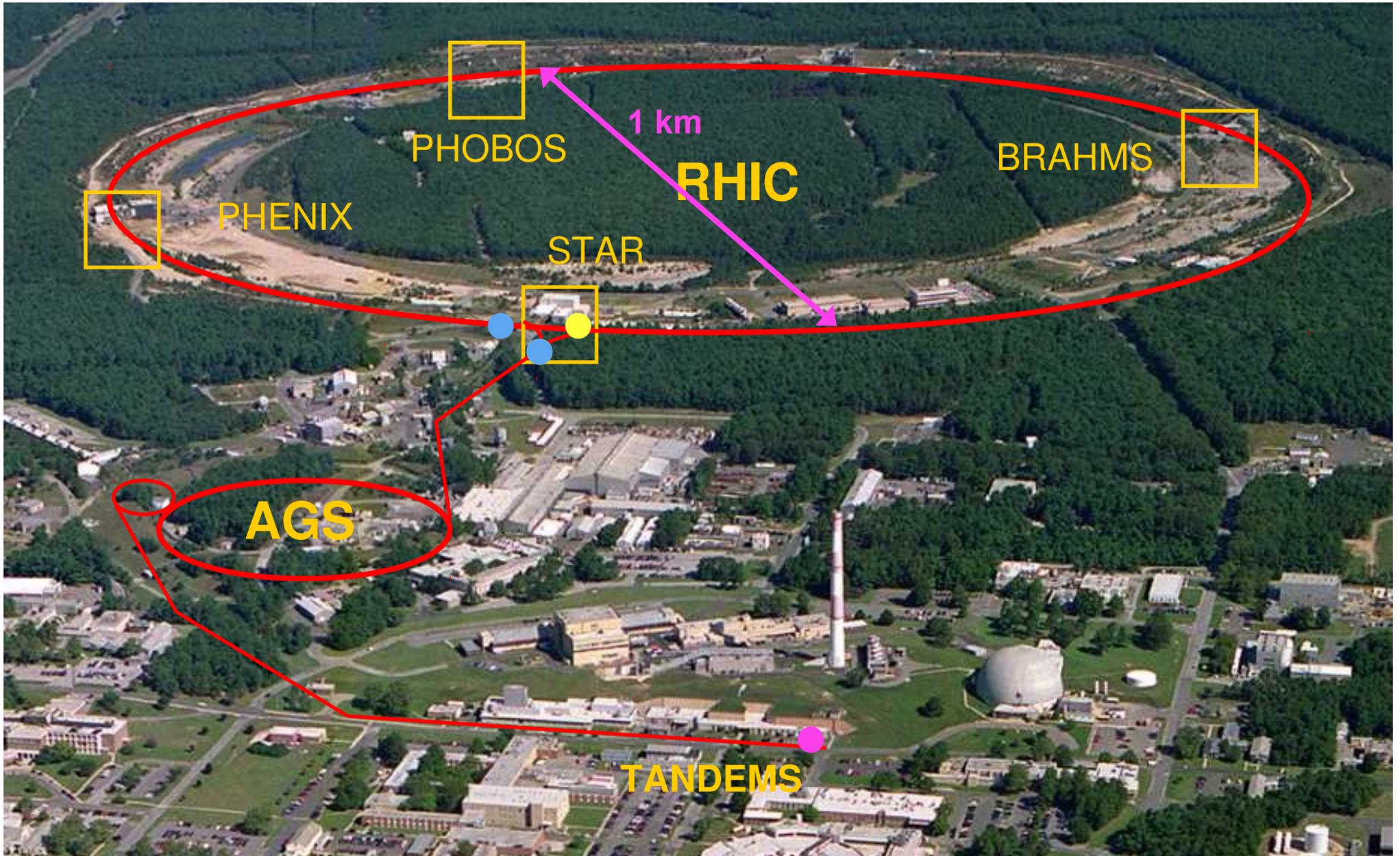


One Pb-Pb collision seen by the NA49 TPCs at the CERN SPS (fixed target)

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

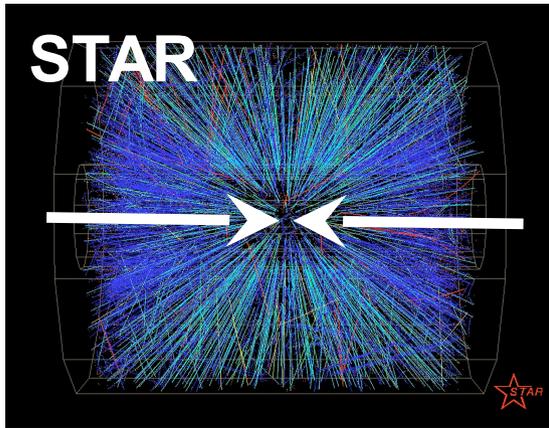


The Relativistic Heavy Ion Collider (RHIC)

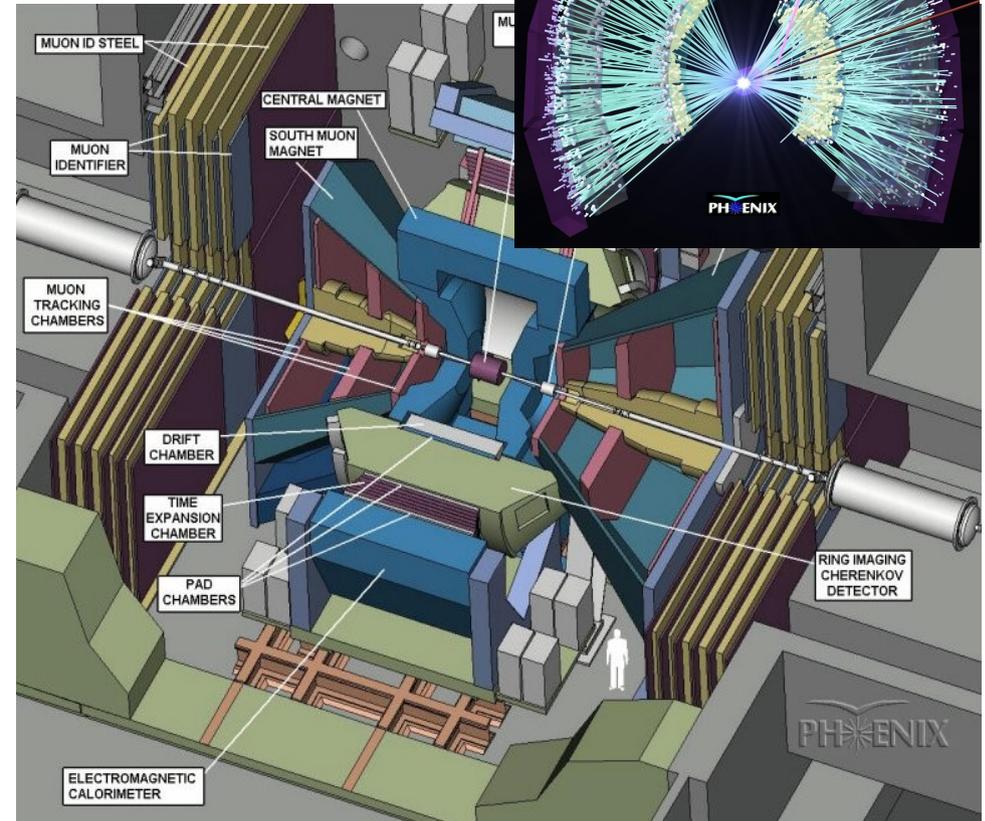
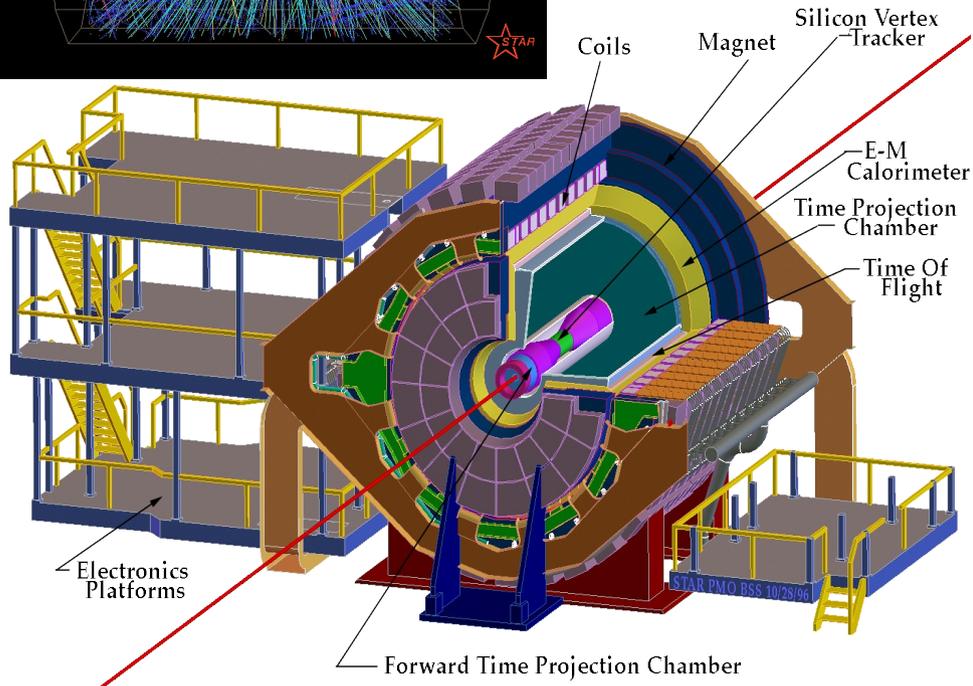


STAR and PHENIX at RHIC

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(PHOBOS, BRAHMS more specialized)



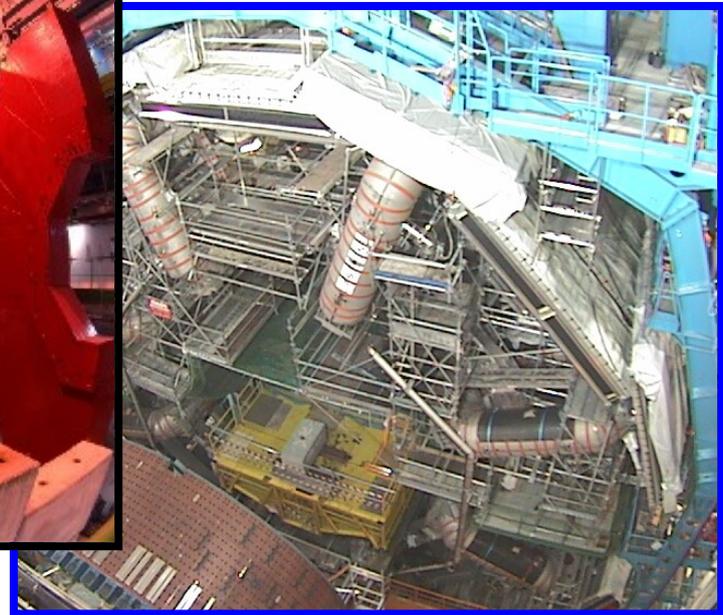
2π coverage, $-1 < \eta < 1$ TPC for tracking + (coarse) EMCal
PID by TOF, dE/dx

Optimized for acceptance (correlations, jet-finding)

Partial coverage $2 \times 0.5\pi$, $-0.35 < \eta < 0.35$
Finely segmented calorimeter + forward muon arm, PID by RICH

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

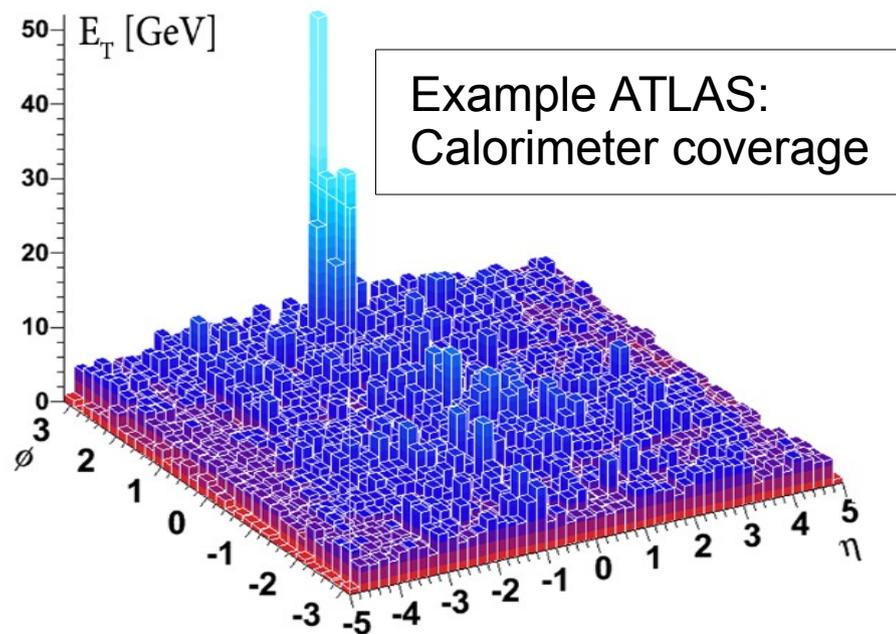
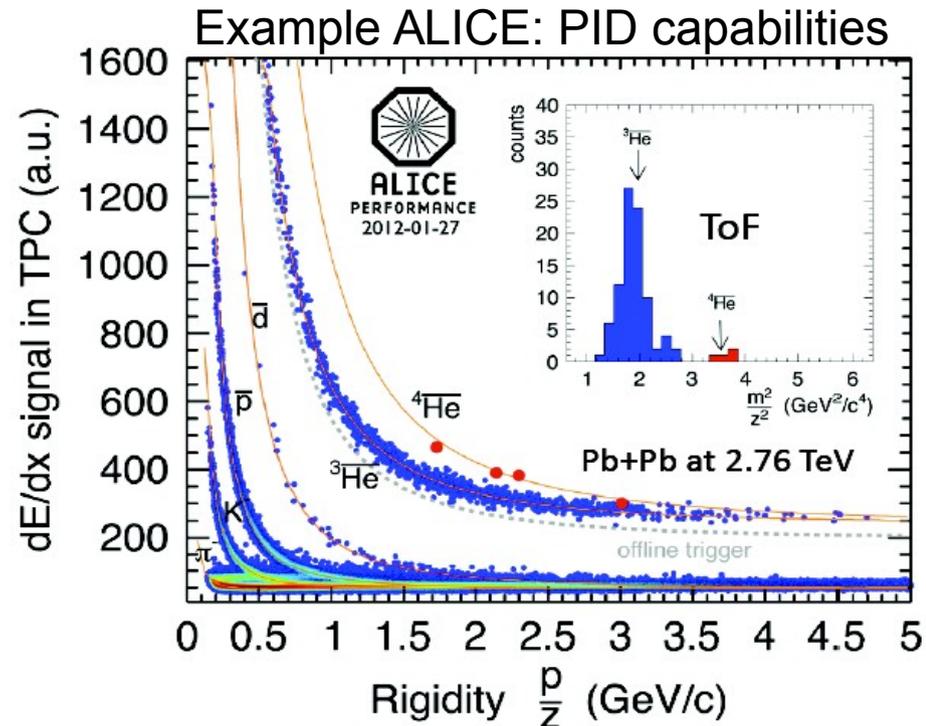
LHC: The Large ~~Hadron~~ Heavy-ion Collider



(Heavy-)Ion data-taking experiments at the LHC 47



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



- QCD is a quantum field theory with rich dynamical content, complex phase structure, and important open questions
- Heavy-ion collisions 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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- Handbook of perturbative QCD, Rev. Mod. Phys. 67 (1995) 157
- QCD and collider physics,
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Romatschke, Int. J. Mod. Phys E 19 (2010) 1
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Acknowledgments

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Lots of input (slides, graphics, discussion) from

Federico Antinori

Tom Hemmick

Peter Jacobs

Jamie Nagle

Carlos Lourenco

Klaus Reygers

Enrico Scomparin

Kai Schweda

Peter Steinberg