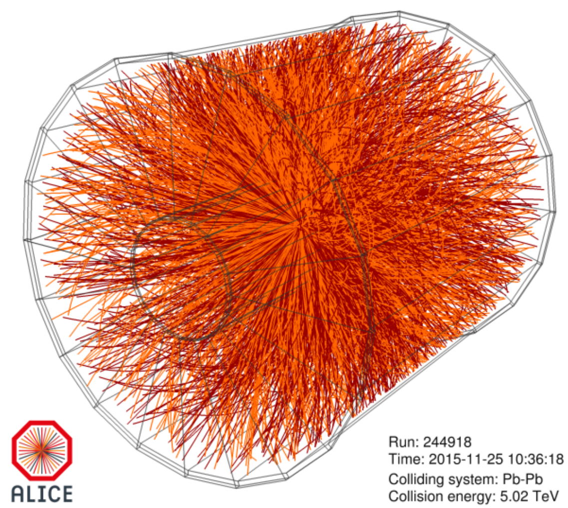
Physics at the LHC

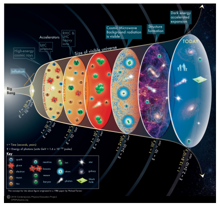
Hot QCD matter produced in ultra-relativistic heavy-ion collisions

Lecture 1
December 18, 2019

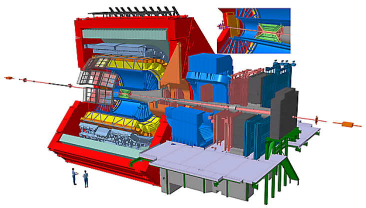


Silvia Masciocchi
GSI Darmstadt and Heidelberg University

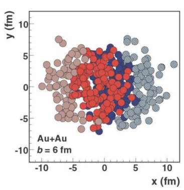
Outline



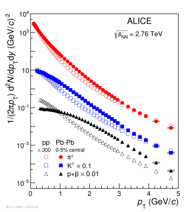
Heavy-ion collisions: Little Bangs



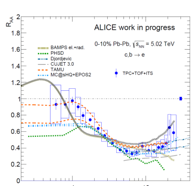
Experimental program at the LHC, ALICE



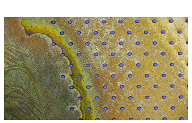
Global characteristics



Bulk particle production

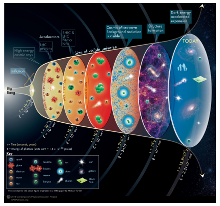


Quark-gluon plasma tomography with hard probes

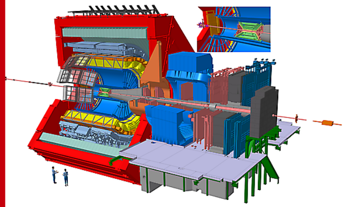


Research plans for near and further future

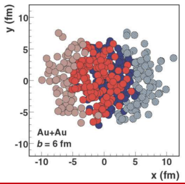
Outline



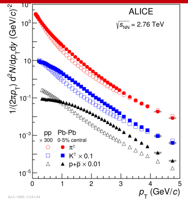
Heavy-ion collisions: Little Bangs



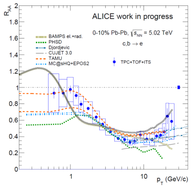
Experimental program at the LHC, ALICE



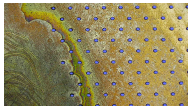
Global characteristics



Bulk particle production



Quark-gluon plasma tomography with hard probes

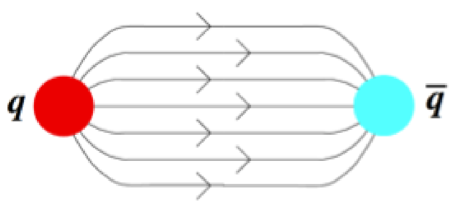


Research plans for near and further future

Quantum-chromo dynamics

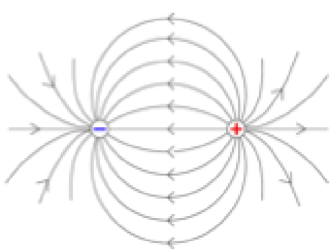
Within the Standard Model of particle physics, it is the gauge field theory that describes the strong interaction of colored quarks and gluons

QCD 1: confinement



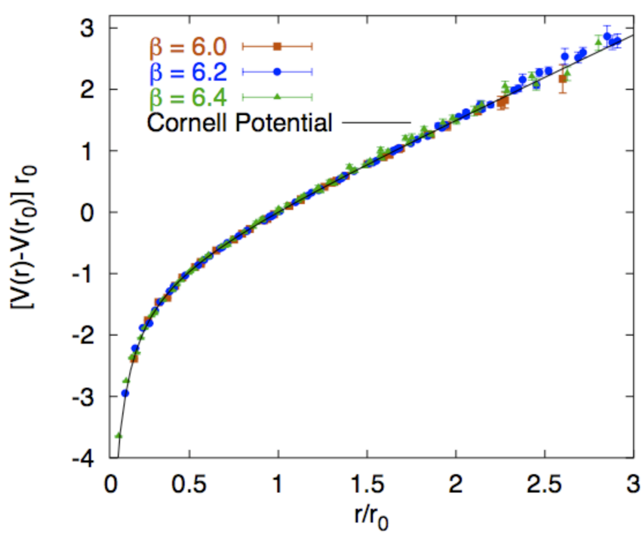
QCD vacuum: field lines are compressed in a flux tube

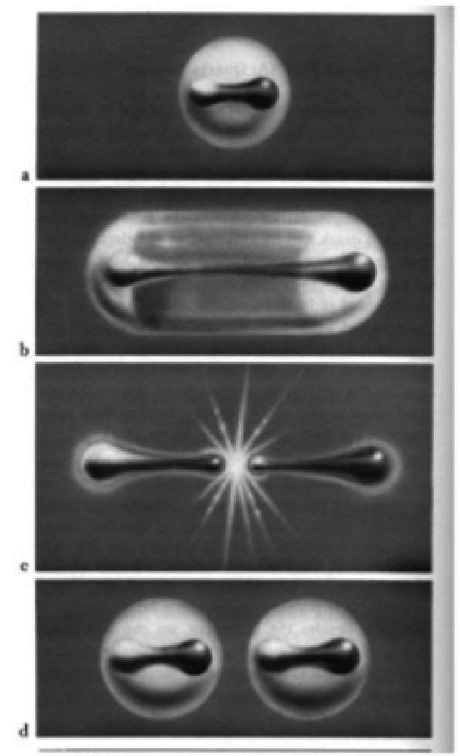
... differently from QED



Cornell potential

$$V(r) = -\frac{A(r)}{r} + K\cdot r$$





[illustration from Fritzsch]

Strongly-interacting matter

QCD 1: confinement

→ color-neutral hadrons ($q\bar{q}$, qqq)

→ no colored object

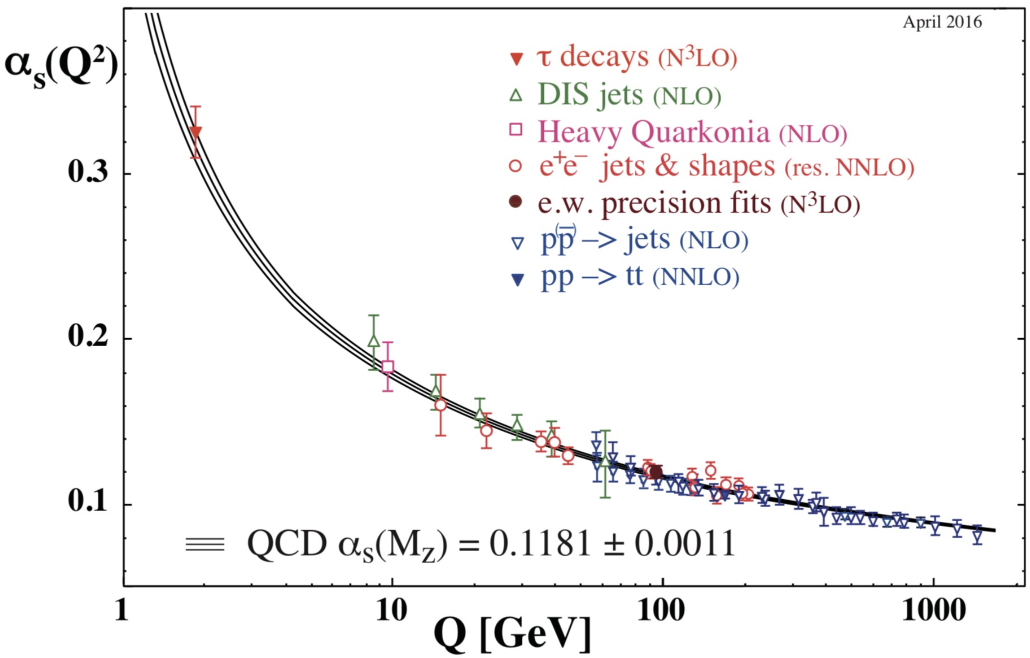
→ no fractional charge

Nobel 2004

QCD 2: asymptotic freedom

Interaction strength decreases with increasing momentum transfer:

α_S small for $Q^2 \rightarrow \infty$



pdg.lbl.gov

1975:

Cabibbo and Parisi, Collins and Perry

First formulation: at high densities or temperatures a deconfined phase of matter can be created

Quark Gluon Plasma (QGP)

Early theoretical ideas: 1975 Cabibbo and Parisi

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

PLB 59B (1975) 67

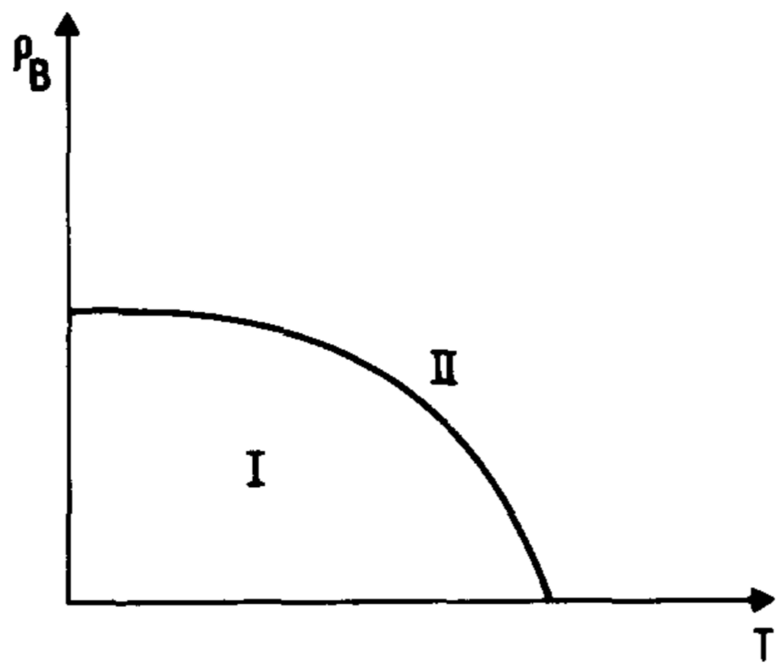


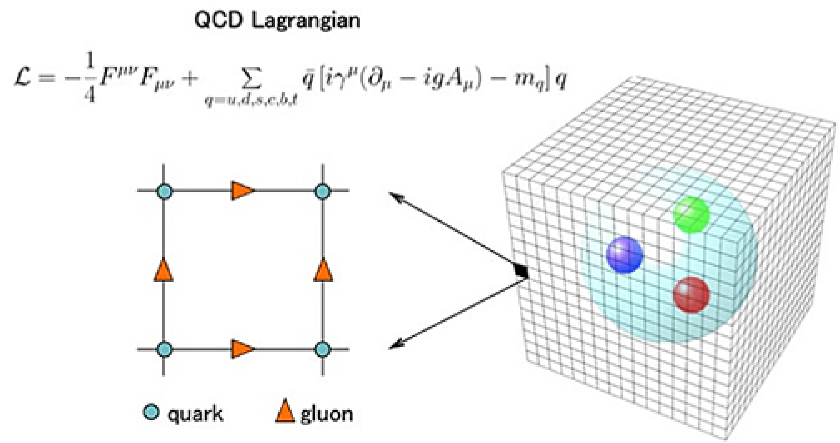
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

asymptotic freedom
→ deconfined phase of matter at high densities or temperatures

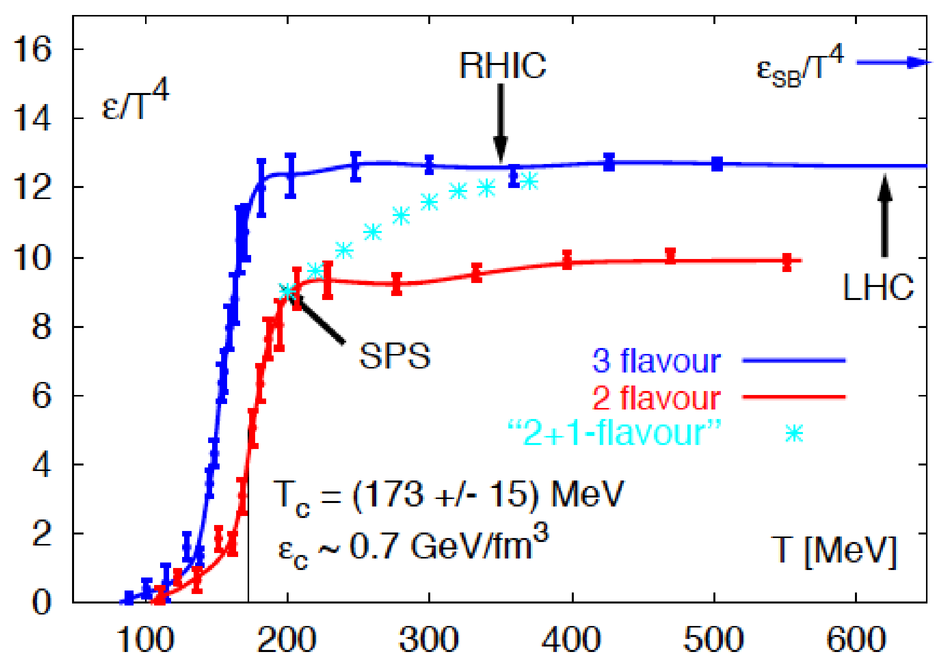
Phase transition: lattice computations

1981 on, QCD on space-time lattice: critical transition temperature from hadronic phase to the deconfined, plasma phase (partonic degrees of freedom)

J.Engels, F.Karsch, H.Satz, I.Montvay
PLB 101 (1981) 89



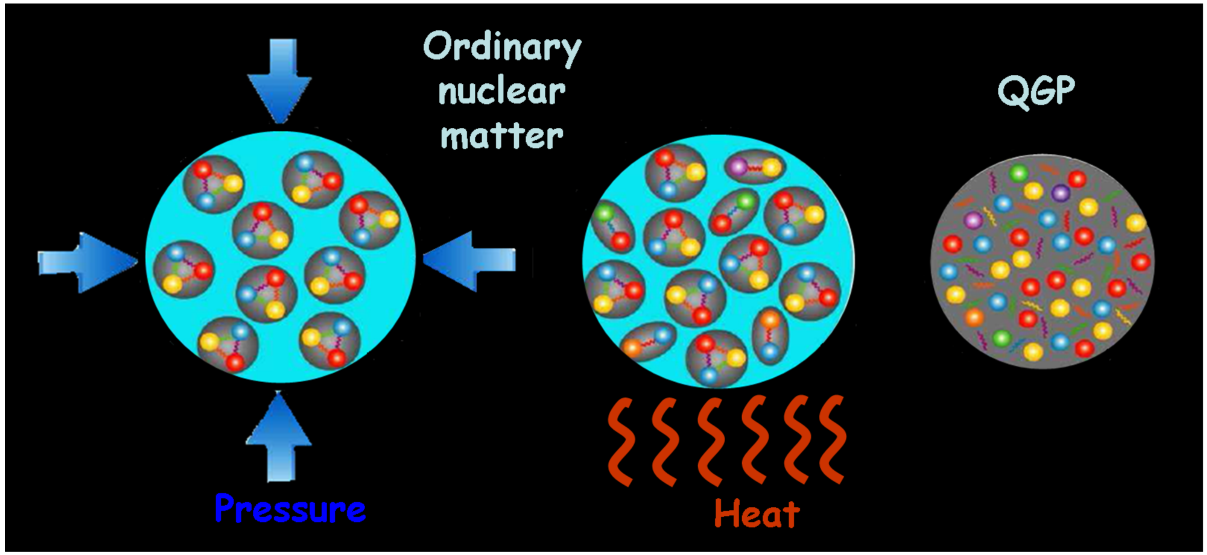
Energy density



F. Karsch, 2001
hep-lat/0106019

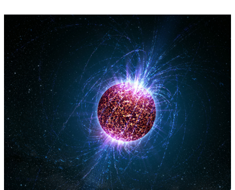
High energy density QCD

Deconfined matter at high densities and temperatures: quark-gluon plasma



Extreme conditions:

Extreme temperatures
≈ 160 MeV ≈ 2 x 10^{12} K (Sun core: 15 x 10^{6} K)



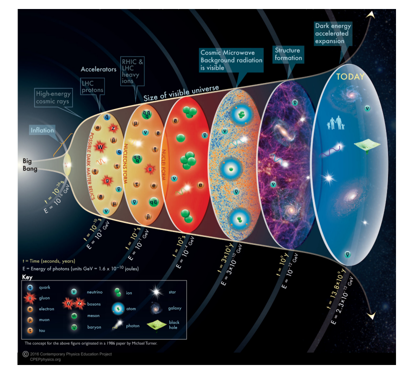
Extreme densities
≈ few GeV/fm^3 (few times ground-state nuclear matter.
$\varepsilon_{proton} \approx 0.13$ GeV/fm^3)

High energy density QCD: WHY ???

- **Fundamental QCD:**
  - **Nature of (de-)confinement**
  - **How does hadronization happens?**
  - Compressibility of nuclear matter
  - Transport coefficients

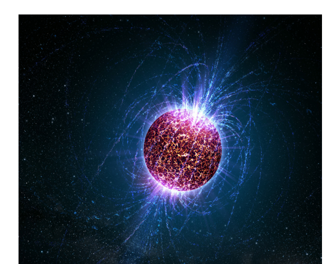
- **Hot QCD matter in nature: early universe**

  high temperature, low density QGP: state of matter a few micro-seconds after the Big Bang



- **Dense QCD matter in nature: neutron stars**

  very high density (~ GeV/fm^3) matter, dominated by baryons



Thermodynamics of strongly interacting matter and phase diagram of QCD

S. Hands, arXiv:physics/0105022

Particle production in high energy collisions

- 1950 Fermi
- 1960 Hagedorn limiting temperature

- Evidence for thermalisation comes from analysis of the distribution of transverse mass m_T, which is found to be approximately Boltzmann $\exp(-m_T/T)$ for a variety of different hadron species

- Particle yields and particle spectra recall a thermal distribution, depending on the temperature of the system and the mass of the individual state

$$\frac{1}{m_T^2}\frac{d\sigma}{dm_T} \propto \exp\left(-m_T/T\right)$$

Phase diagram

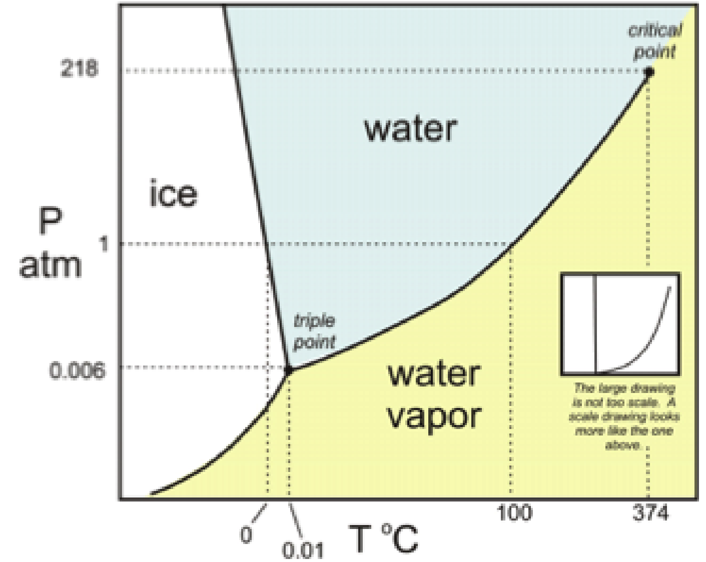
- Strongly interacting matter: rich spectrum of color-neutral hadrons, quarks, gluons (partons)
- Use thermodynamic approach to describe possible states of that matter (made of hadrons or partons, interacting among each other or not)

- Typically the states or **phases** of matter are expressed as functions of **control parameters** (e.g. temperature, density, pressure) ...
- ... and are represented in a **phase diagram**

Example:

QED: phase diagram of water

- Coexistence curves P(T): 2 phases are in equilibrium
- Phase transitions when crossing the curves
- Triple point: 3 coexisting phases
- Critical point: fluid and gas become indistinguishable critical behavior, large variations, fluctuations

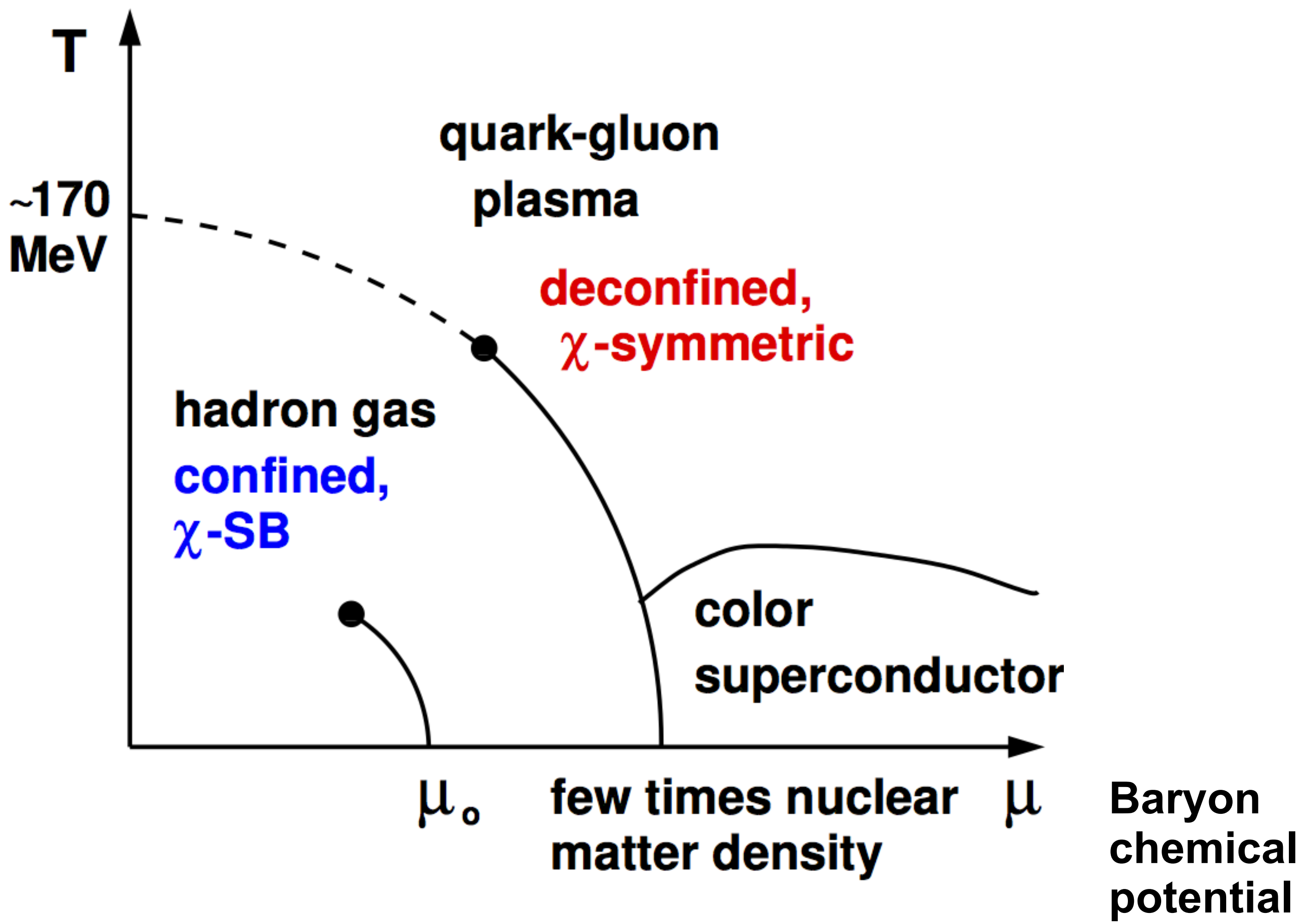


[http://serc.carleton.edu/research_education/equilibria/phaserule.html]

Phase diagram of QCD matter

Control parameters:

- Temperature T
- Baryon chemical potential μ (μ_B)

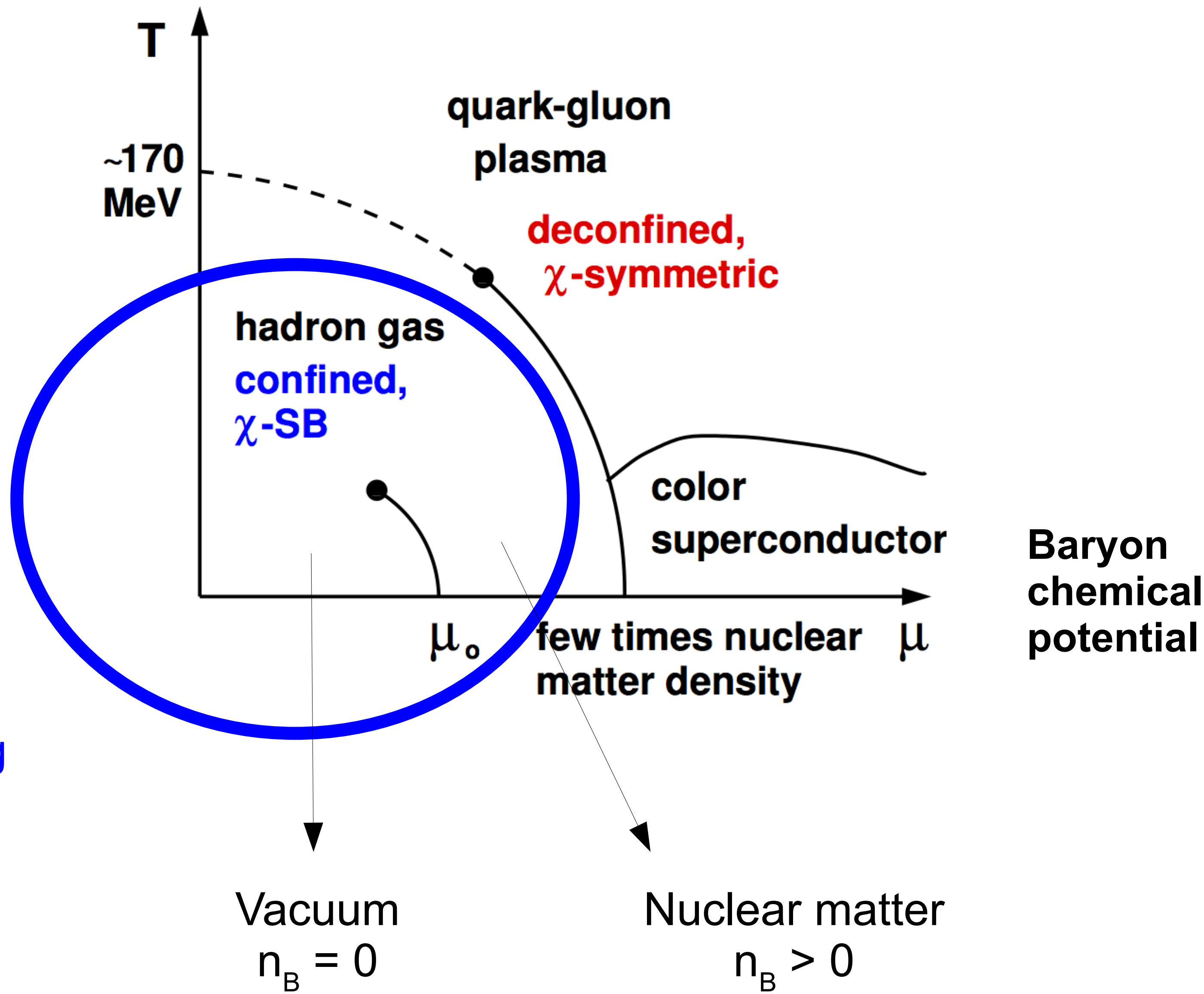


Phase diagram of QCD matter

Confined QCD matter
Color-neutral hadrons
$q_g \bar{q}_{\bar{g}}$ or $q_r q_b q_g$

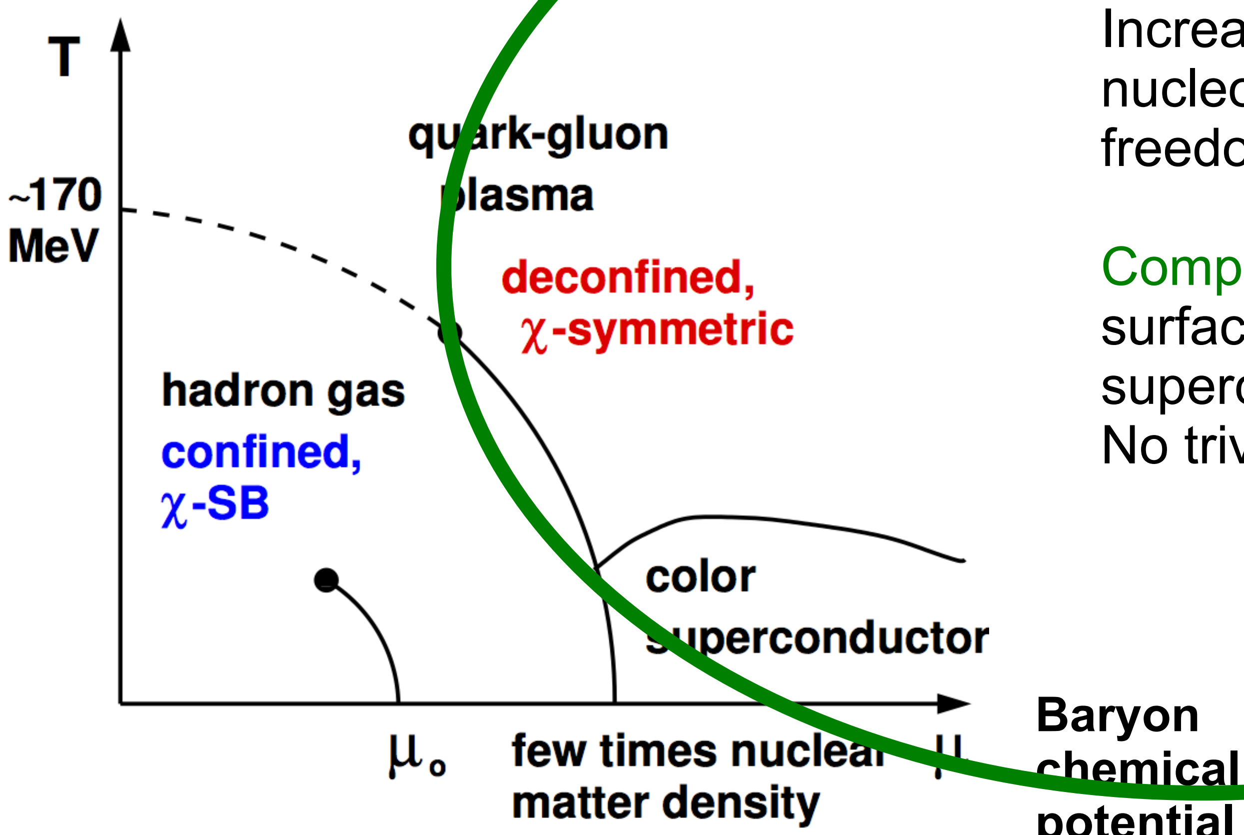
Chiral-symmetry breaking
for massive quarks:
superposition of helicity
eigenstates ($L \leftrightarrow R$)

X-SB vacuum: $\langle \bar{\psi}\psi \rangle > 0$



S. Hands, arXiv:physics/0105022

Phase diagram of QCD matter



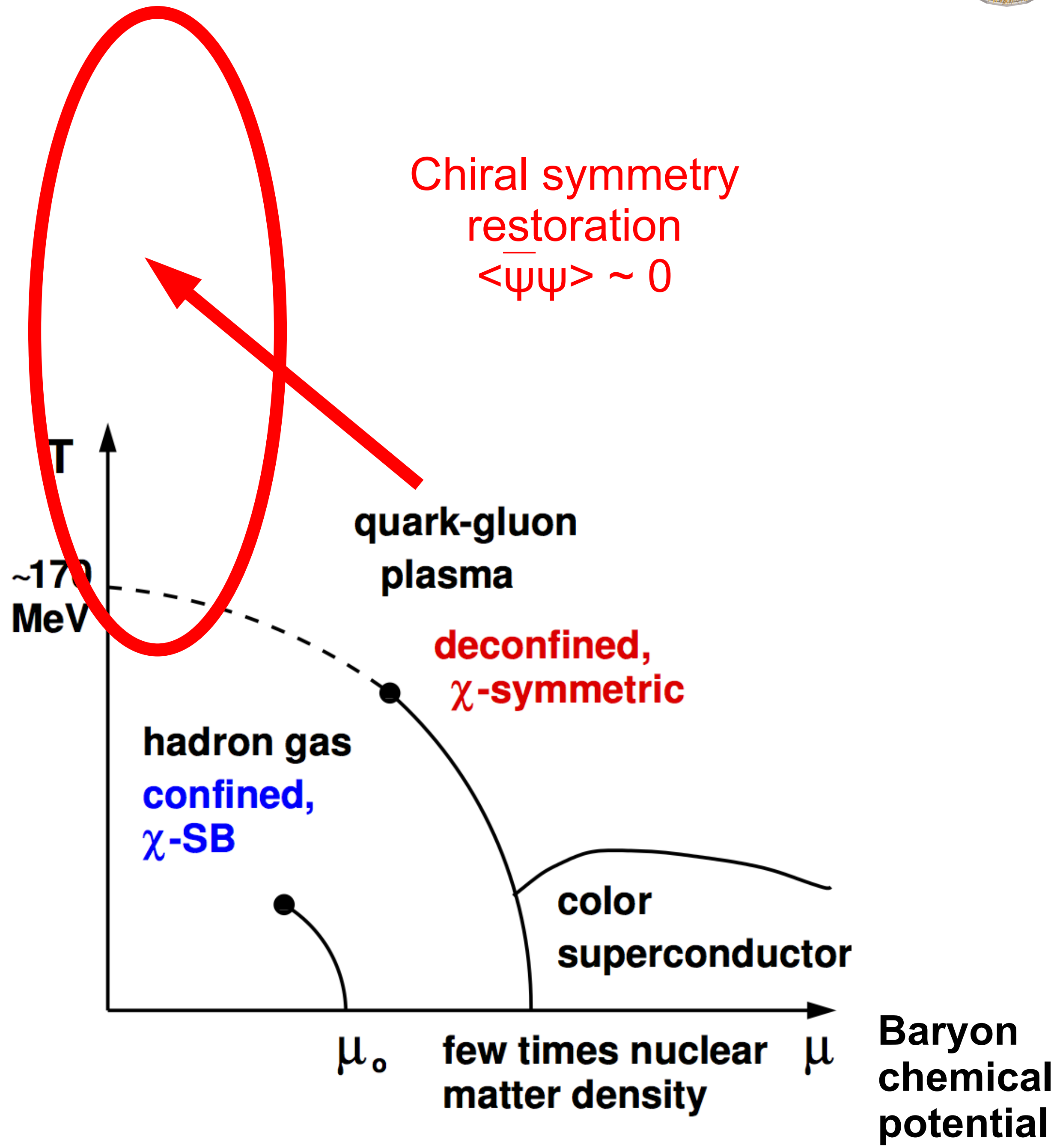
Quark matter
Increasing μ, transition from nucleons to quarks degrees of freedom

Complex structures: Fermi surface phenomena → color superconductivity? Superfluidity? No trivial features to detect

Phase diagram of QCD matter

High temperature, zero baryon chemical potential: Deconfined quark-gluon plasma

As T raises, transition to a phase where the dominant degrees of freedom are no longer hadrons but partons



Thermodynamics applied to QCD

Summary:

- Features of particle production in hadron interactions (pp on) inspire a thermodynamic treatment of QCD matter

- QCD phase diagram: μ_B and T

- With basic thermodynamic arguments, a phase transition from a hadron gas to a quark-gluon plasma is proposed

$$T_c \simeq \text{١٤٤}\,\mathrm{MeV} \qquad \epsilon_{QGP} \simeq \text{٨٥٠}\,\mathrm{MeV/fm}^{\text{٣}}$$

- Rigorous computations with Lattice QCD at $\mu_B = 0$:

$$T_C(\mu_B=\mu_Q=\mu_S=0) = (156.5 \pm 1.5)\ \mathrm{MeV}$$

$$\varepsilon_C \approx 0.42\ \mathrm{GeV/fm}^3 \qquad (\sim 2.5 \times \varepsilon_{nuclear})$$

(lattice at $\mu_B > 3T_c$ difficult. Progress in the last years!)

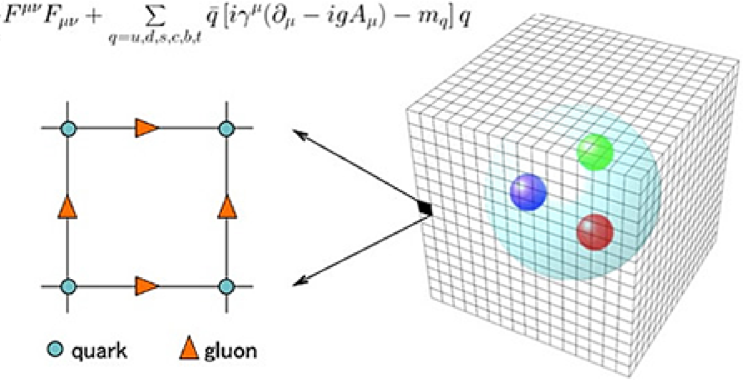
Phase transition: lattice computations

1981 on, QCD on space-time lattice: critical transition temperature from hadronic phase to the deconfined, plasma phase (partonic degrees of freedom)

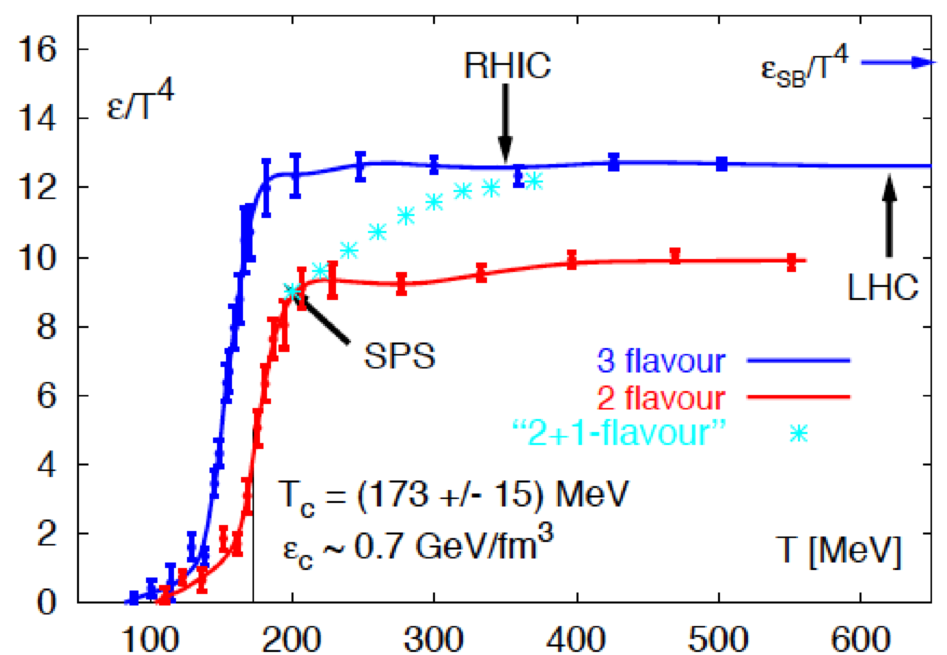
J.Engels, F.Karsch, H.Satz, I.Montvay
PLB 101 (1981) 89

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q\right]q$$



Energy density

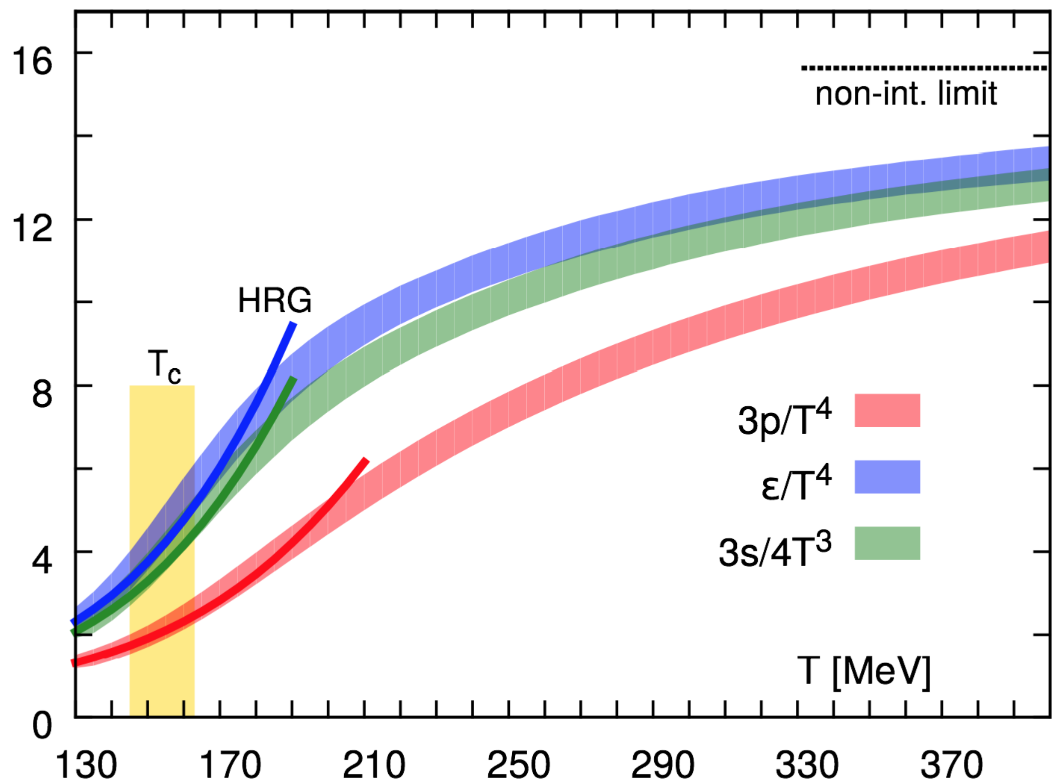


F. Karsch, 2001
hep-lat/0106019

Lattice gauge theory simulations

Energy density

A. Bazavov at al.
arXiv:1701.04325



High temperature regime: both energy density and pressure remain clearly below the non-interacting plasma limit. Strong interactions between q, $\bar{q}$ and g and gluons persist in the QGP

A. Bazavov at al.
arXiv:1812.08235

$T_C(\mu_B=\mu_Q=\mu_S=0) = (156.5 \pm 1.5)$ MeV

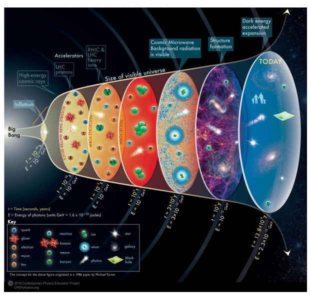
$\varepsilon_C \approx 0.42$ GeV/fm^3 $\quad$ ($\sim 2.5 \times \varepsilon_{nuclear}$)

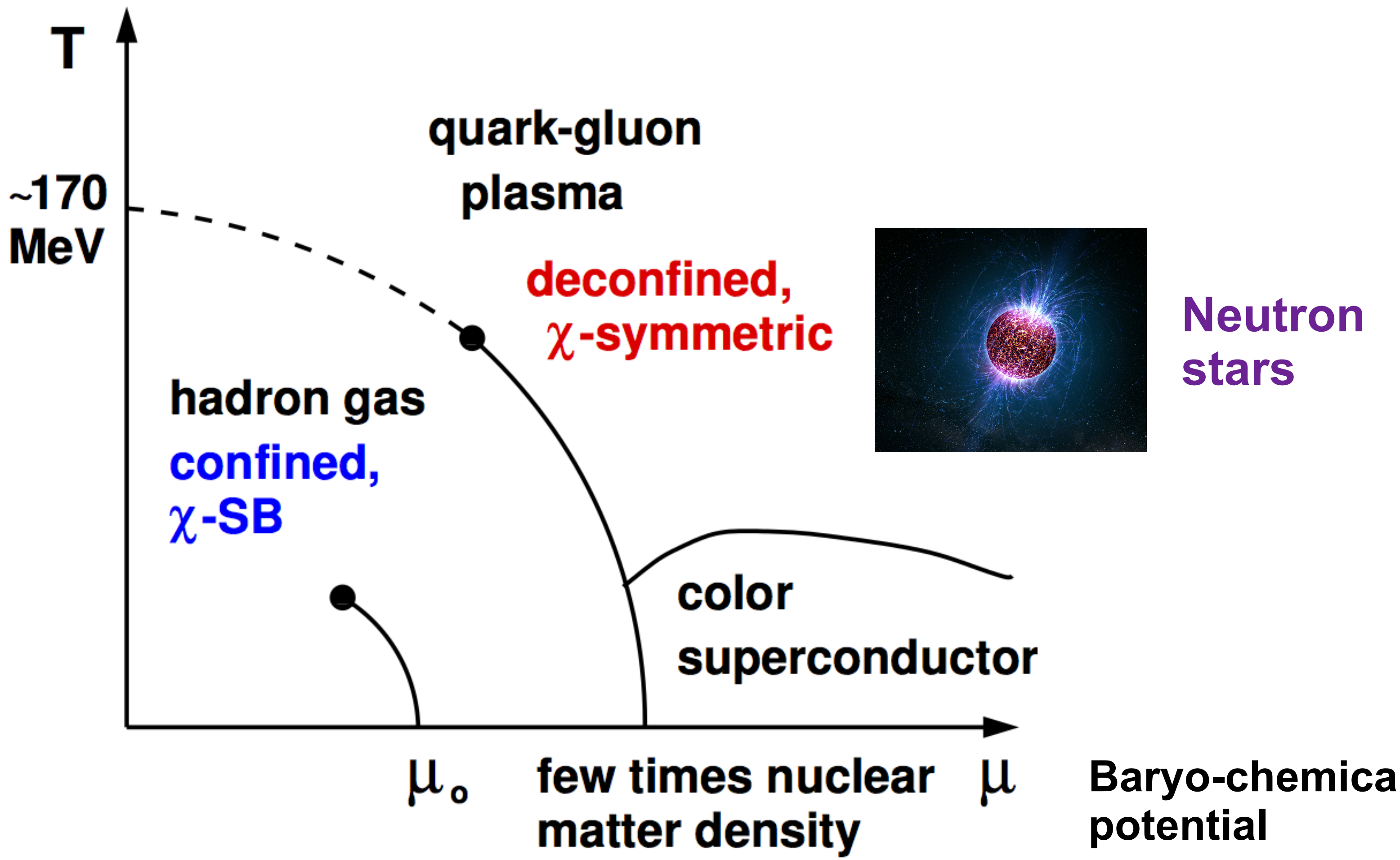
Hot and dense QCD in nature

Heavy-ion collisions in the laboratory

The QCD phase diagram

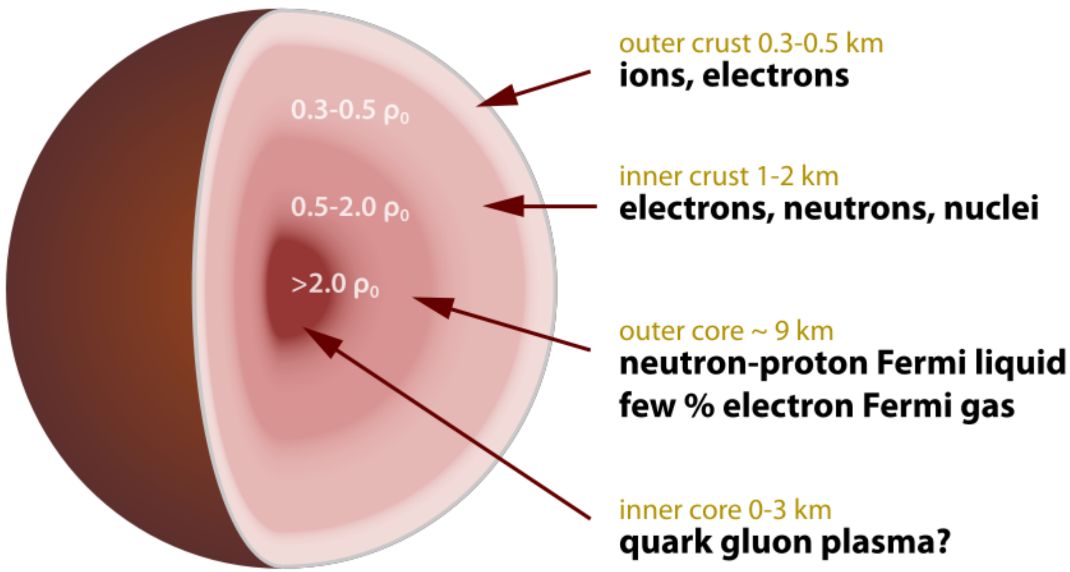
Early universe (few μs after the Big Bang)

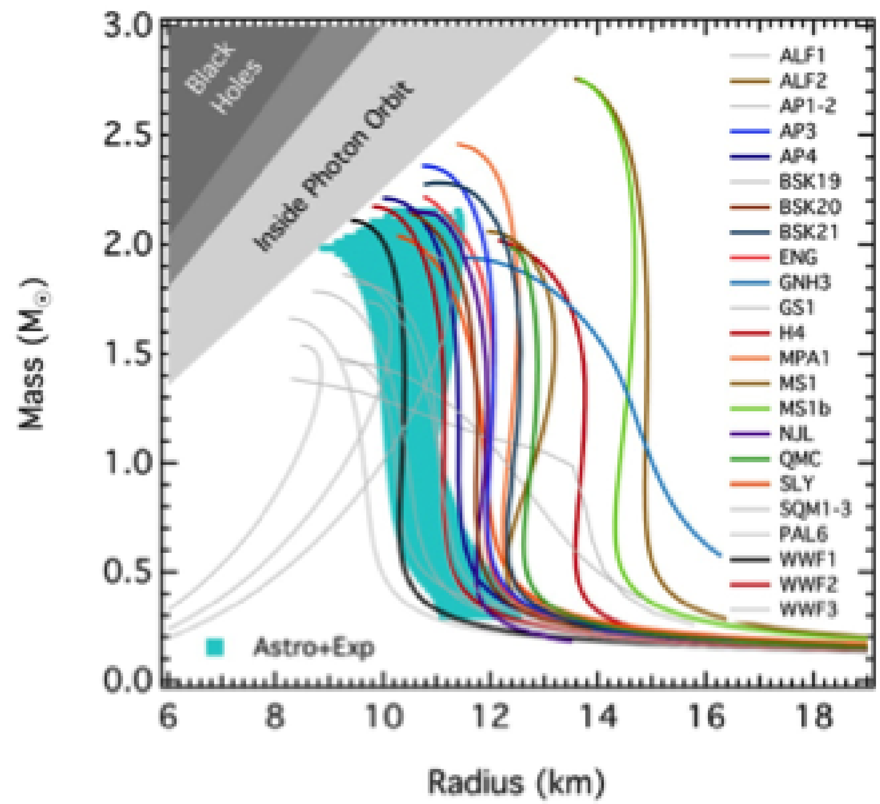




Neutron stars

Dense QCD matter in nature: neutron stars



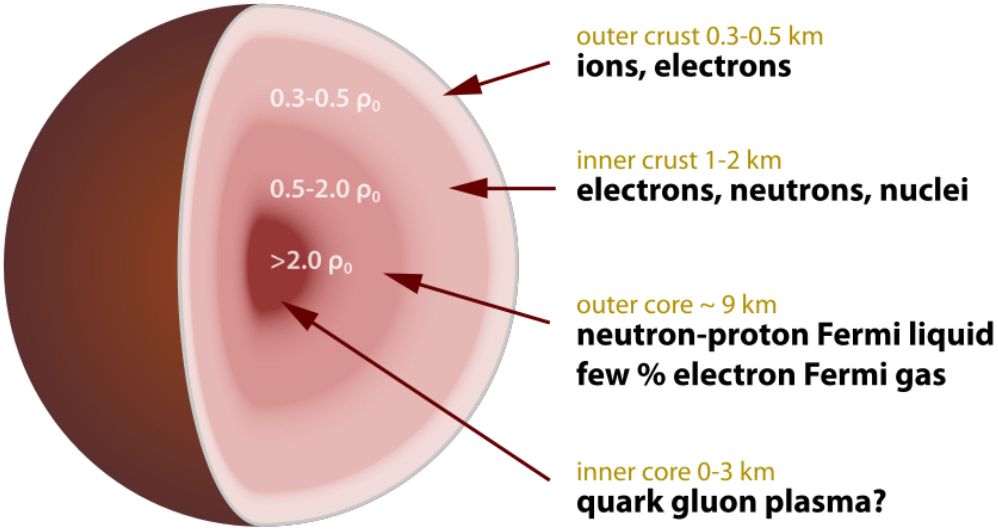


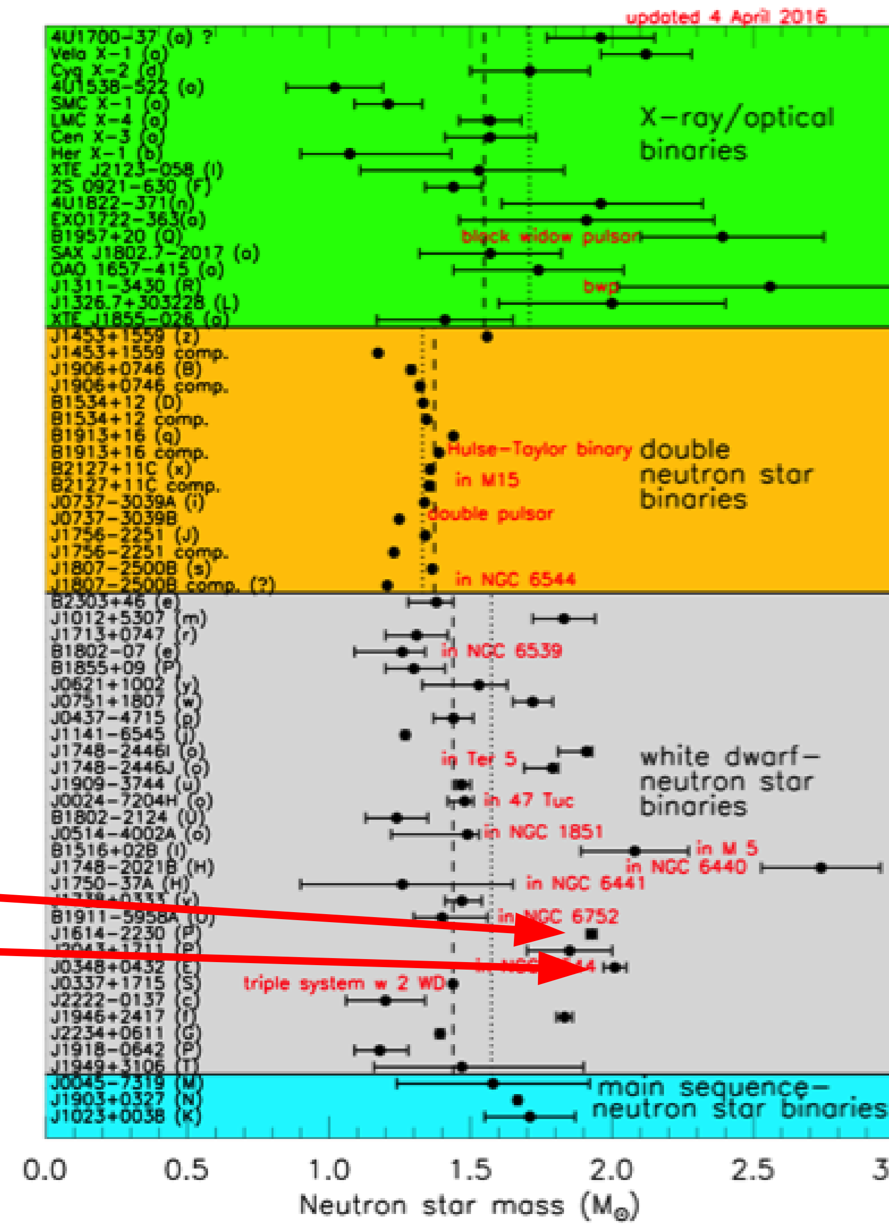
Ozel et al., ApJ 820 (2016)

Neutron star mass bound to the equation of state of nuclear matter: hydrostatic equilibrium resulting from competition between gravity and the pressure of QCD matter

Models → clustering around 1.4-1.5 M_{sun}

Dense QCD matter in nature: neutron stars





J. M. Lattimer, http://stellarcollapse.org/nsmasses

However:

Evidence for stars at 2 M_{sun}

Core composition?

EoS?

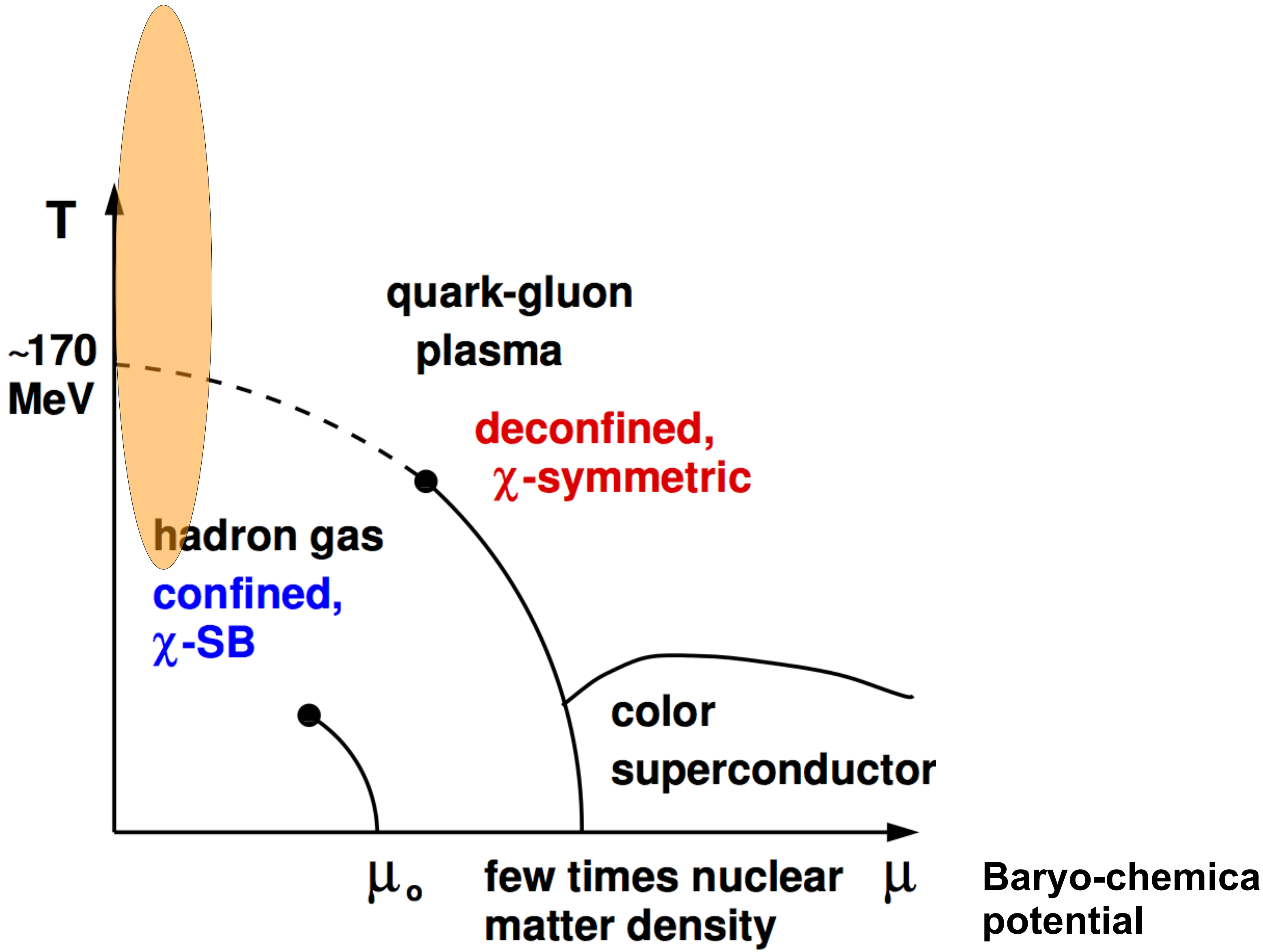
Y-N interaction? Hyperon puzzle

The QCD phase diagram

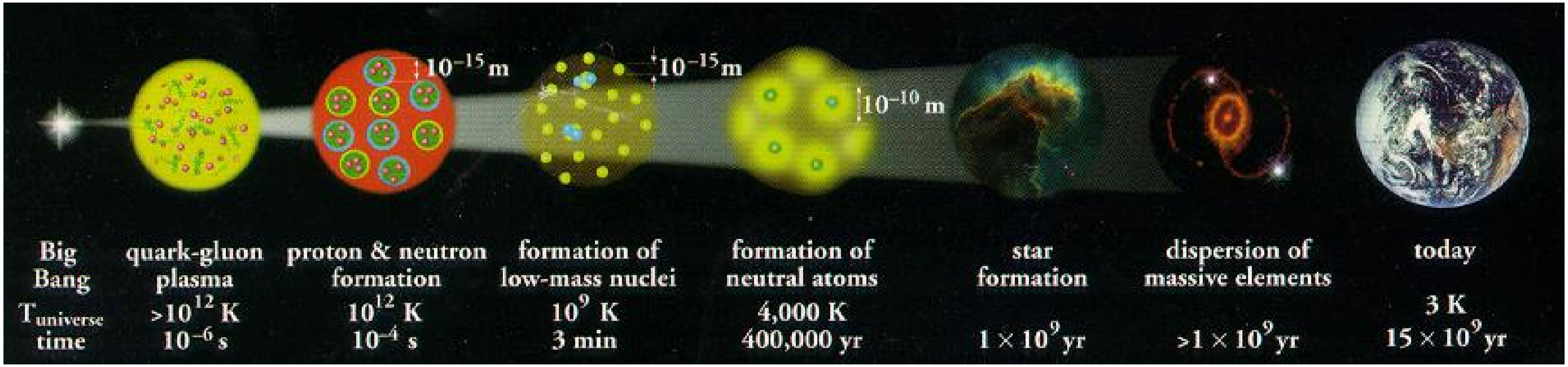
LHC

TeV energies

High temperature and low net baryon density



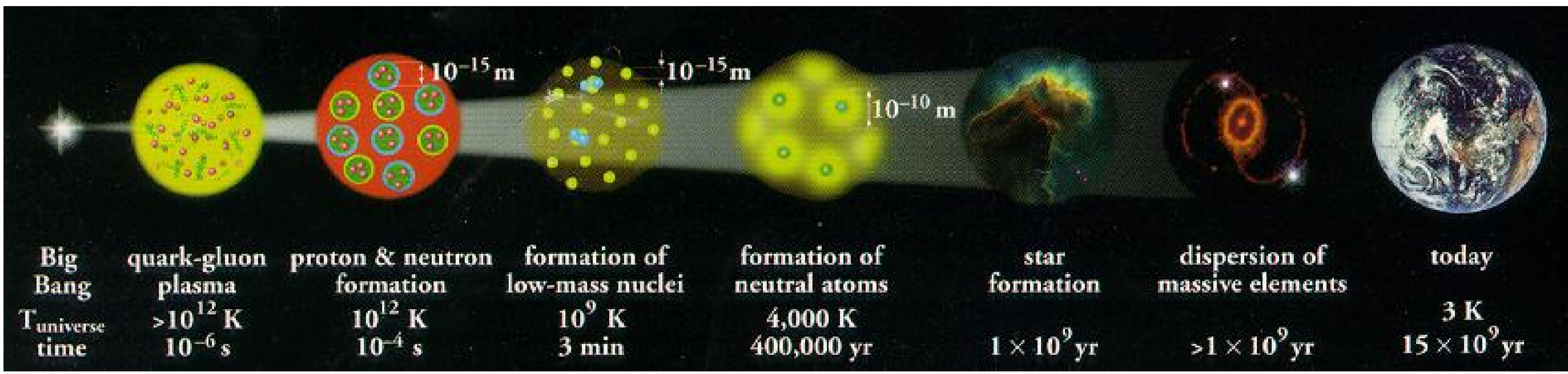
Nature



10−15 m
10−15 m
10−10 m
Big Bang
T universe
time
quark-gluon plasma
>10^12 K
10^−6 s
proton & neutron formation
10^12 K
10^−4 s
formation of low-mass nuclei
10^9 K
3 min
formation of neutral atoms
4,000 K
400,000 yr
star formation
1 × 10^9 yr
dispersion of massive elements
>1 × 10^9 yr
today
3 K
15 × 10^9 yr

History of the universe

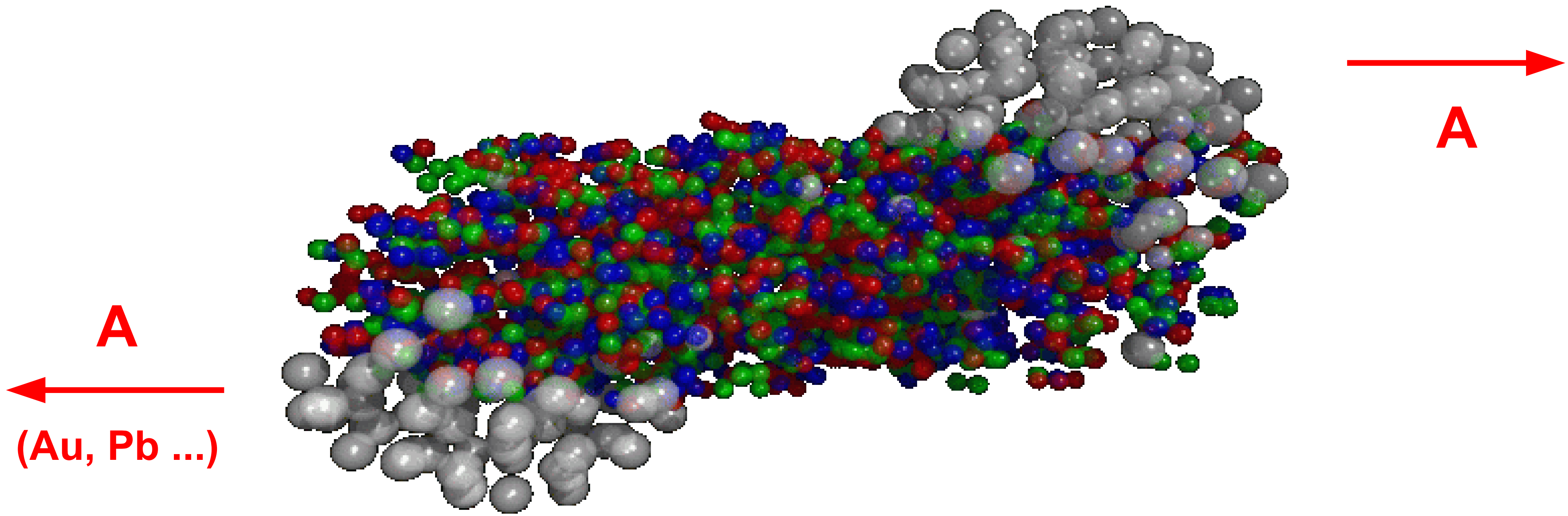
Nature



Experiment

Extreme conditions in the lab: heavy ions

Produced in the collisions of **heavy nuclei** at **high energies**



UrQMD

$\sqrt{s_{NN}}$ from few GeV at AGS, SPS, GSI
up to 200 GeV at RHIC
up to 2.76 (5.1) TeV at LHC

Heavy ions: almost 45 years

1974-1975

GSI-Marburg-Berkeley collaboration

R. Bock, R. Stock, H. Gutbrod et al.

Bevalac / Bevatron: $E_{kin}/A \sim 1$ GeV

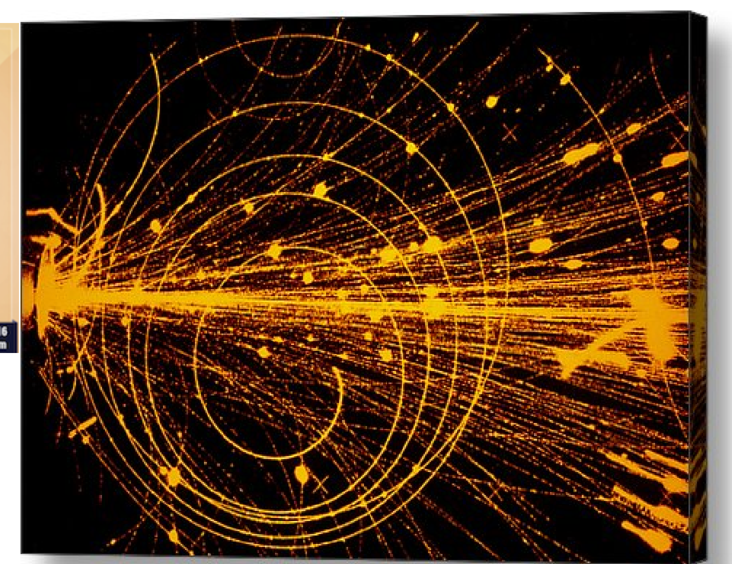
1986: AGS (BNL) and SPS (CERN)

1992: SIS (GSI)

2000: RHIC (BNL)

2010: LHC (CERN)

FUTURE: FAIR, NICA (JINR) .... FCC

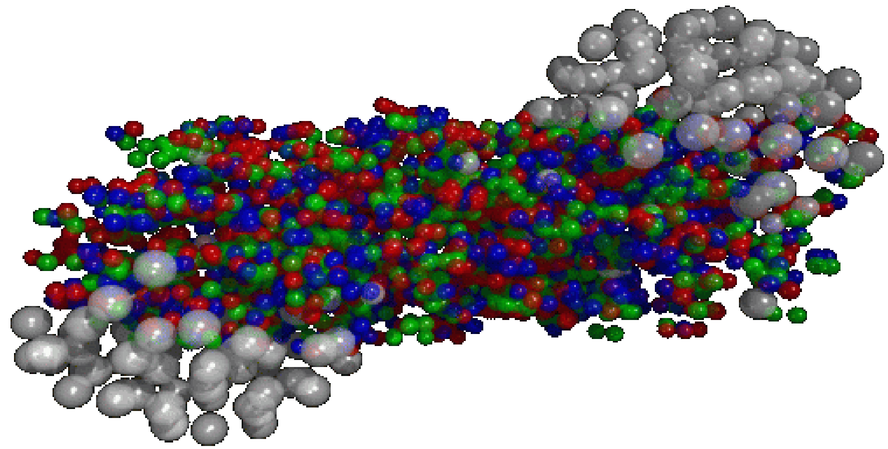


By the way .... GSI turns 50 !!!!

GSI, the former Gesellschaft für Schwerionenforschung, was founded on December 17, 1969

→ Events: www.gsi.de/50years

In the laboratory: heavy ion collisions



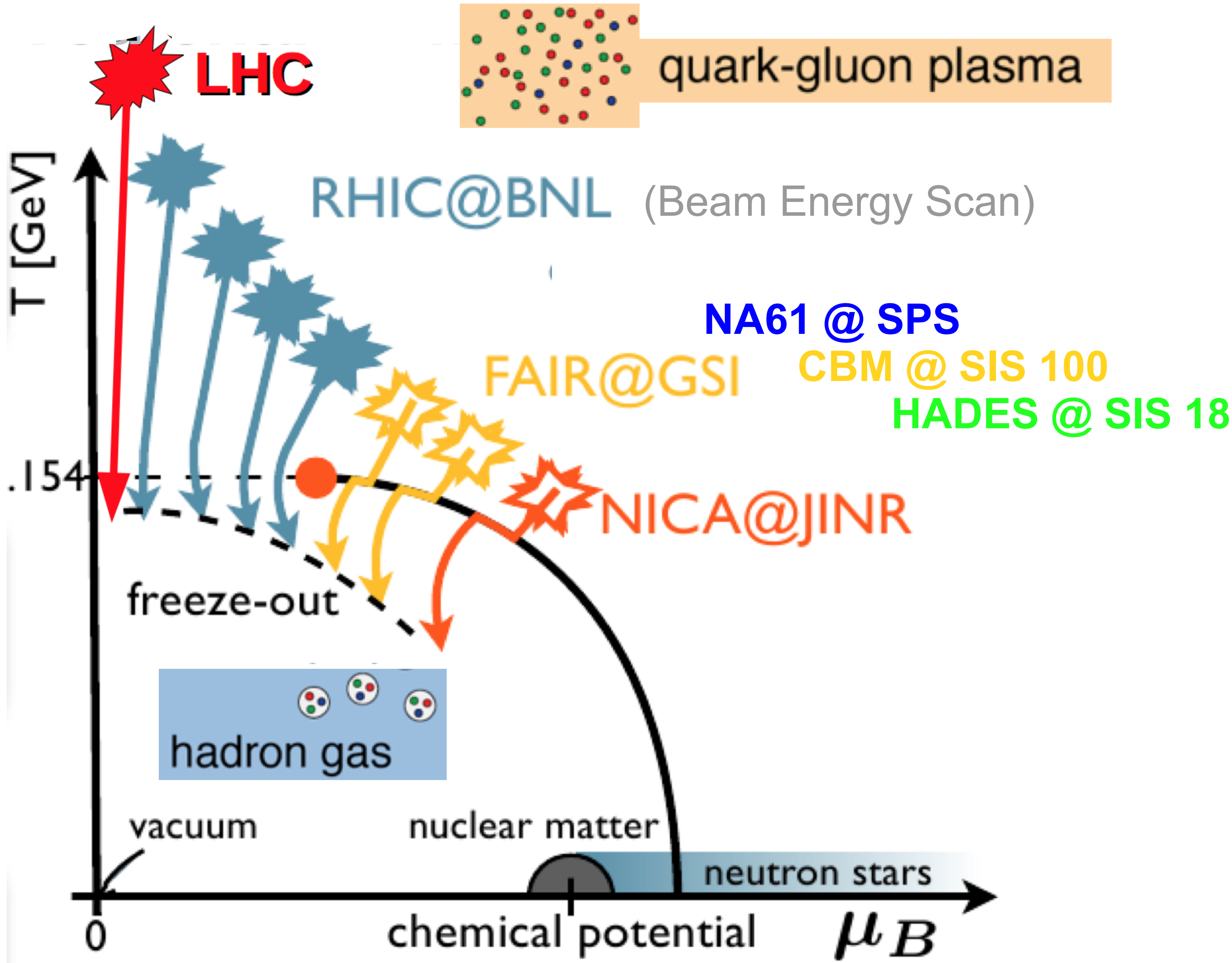
- Beam energy and experiment configuration (fixed target or collider) determine the $\sqrt{s_{NN}} \propto$ temperature

  $\sqrt{s_{NN}}$ is inverse proportional to μ_B at mid-rapidity

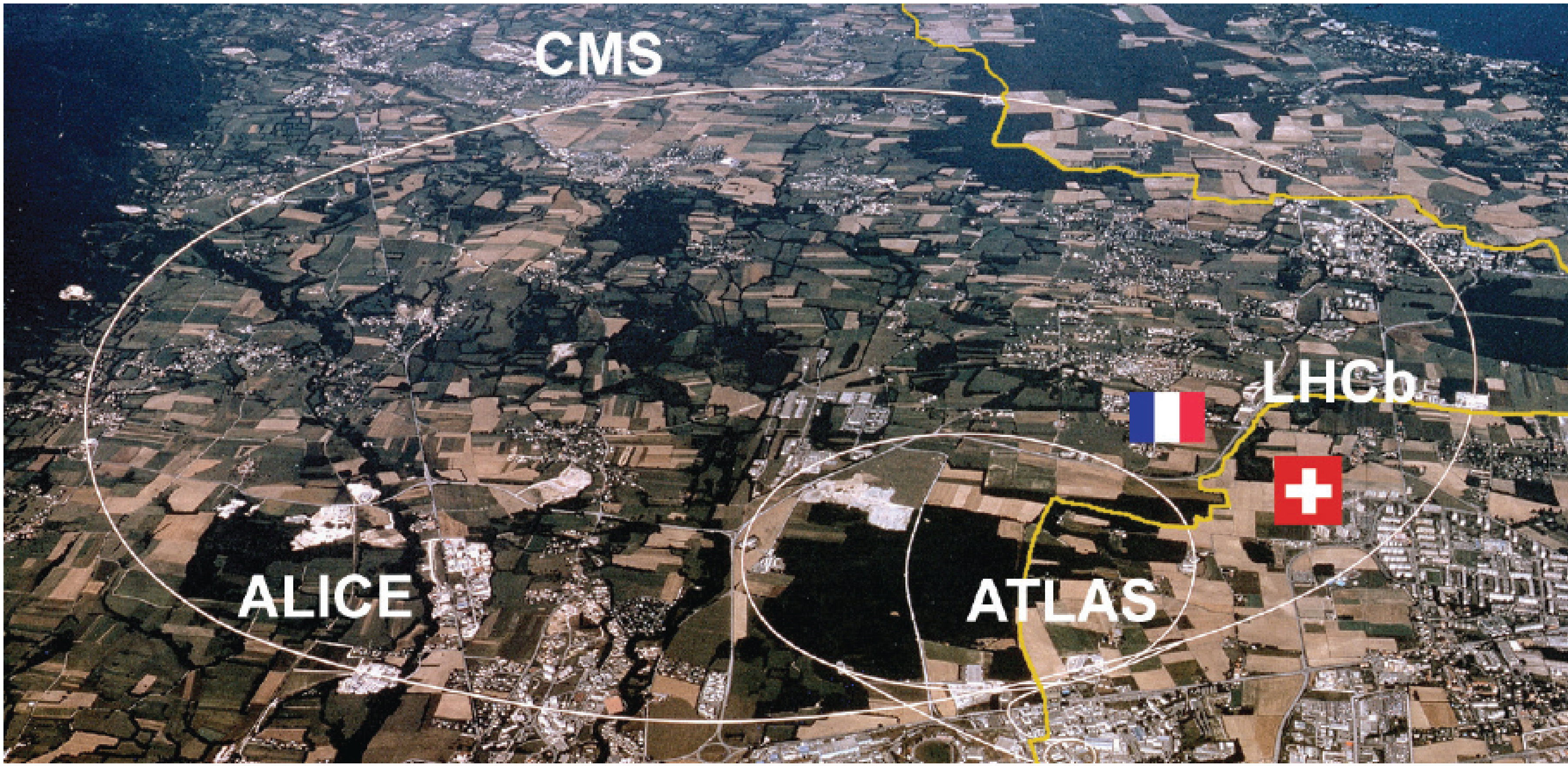
- System size:
  - Choice of ions: Au, Pb, Xe, Ru, Zr, Al, Cu, ^{3}He, d, p
  - Centrality of the collision (... in a moment)

Experimental program

ALICE
ATLAS
CMS
LHCb



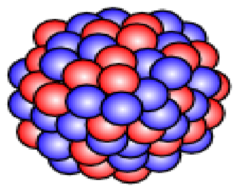
The Large Hadron Collider at CERN



Beam accelerated up to ≈ 6.5 Z TeV
Proton-proton collisions at $\sqrt{s}$ = 13 TeV

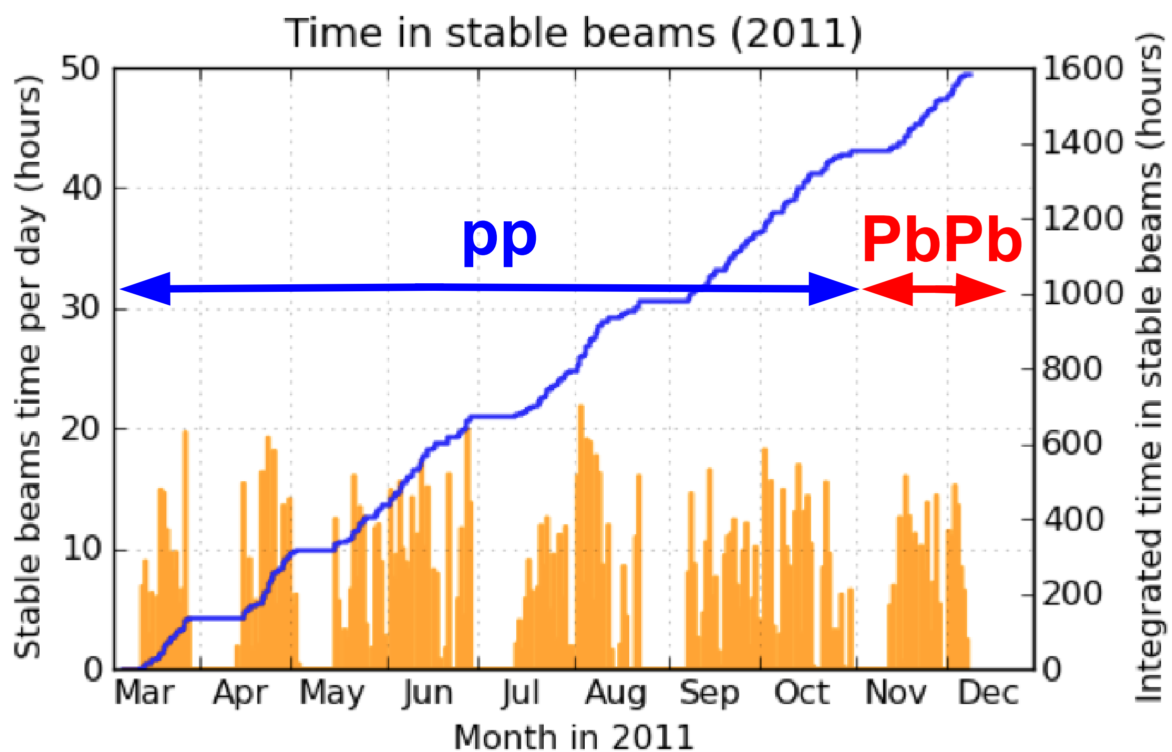
Heavy ions at the LHC

^{208}Pb



$^{208}_{82}$Pb

$^{129}_{54}$Xe



~ 4 weeks / year:

Pb-Pb (2010,2011,2015 + 2018)

p-Pb (2012,2013,2016)

pp at lower $\sqrt{s}$

(2011,2015,2017)

Heavy ions at the LHC

^{208}Pb ions

Run 2 in 2015 and 2018

E_b = 6.37 Z TeV

$\sqrt{s} = 2\ E_b > 1$ PeV

$\sqrt{s_{NN}}$ = 5.02 TeV

Design luminosity:

1 x 10^{27} cm^{-2}s^{-1}

surpassed by factor 10

LHC superb performance

Heavy ions at the LHC

^{208}Pb ions

Run 2 in 2015 and 2018

$E_b = 6.37$ Z TeV

$\sqrt{s} = 2 E_b > 1$ PeV

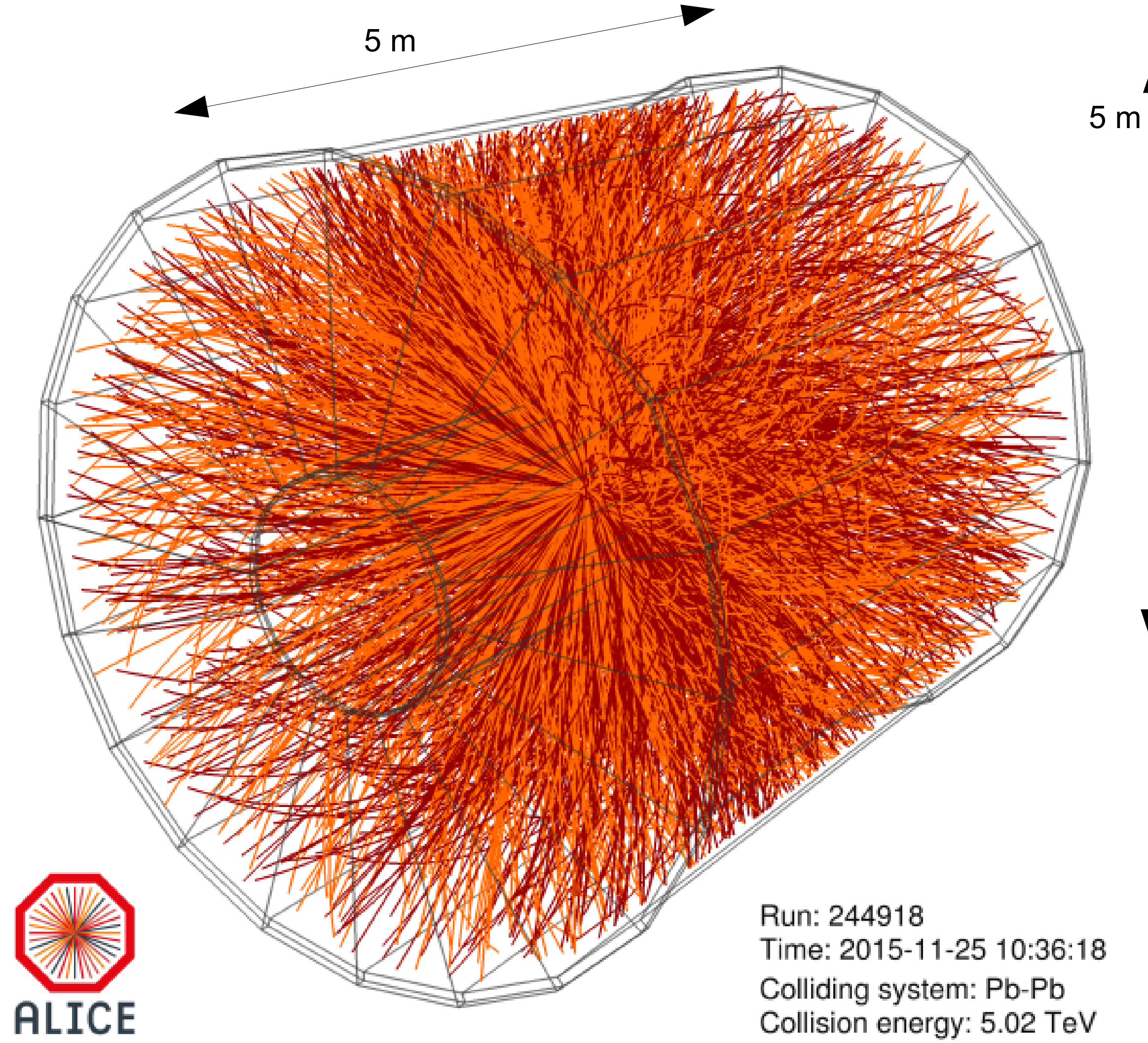
$\sqrt{s_{NN}} = 5.02$ TeV

Design luminosity:

1×10^{27} cm^{-2}s^{-1}

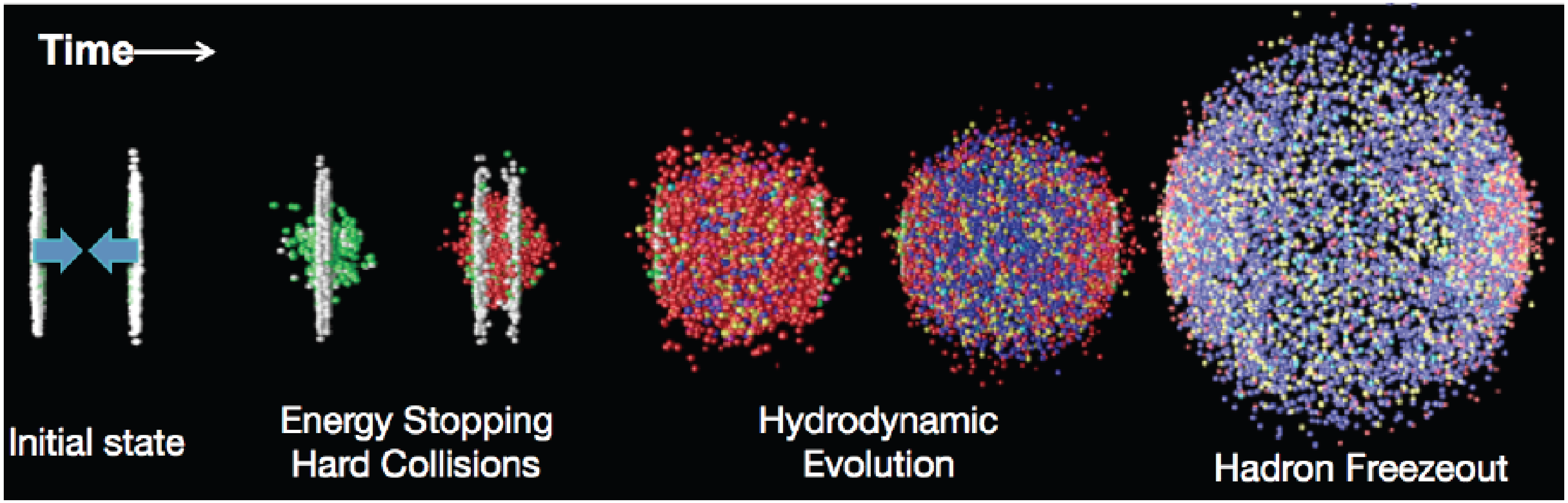
surpassed by factor 10

LHC superb performance



≈ 4000 particles in 2 units of pseudorapidity

Heavy-ion collision evolution



Non-equilibrium evolution at early times:

- Gluon dominated, plasma instabilities, thermalization via strong interactions (~1 fm/c)

Local thermal and chemical equilibrium: QGP

- Evolution of the medium described by relativistic fluid dynamics
- Expansion, dilution, cooling (10-15 fm/c)

Chemical freeze-out:

- Below a critical temperature, hadrons are formed
- Inelastic collisions cease, particles species do not change → particle yields

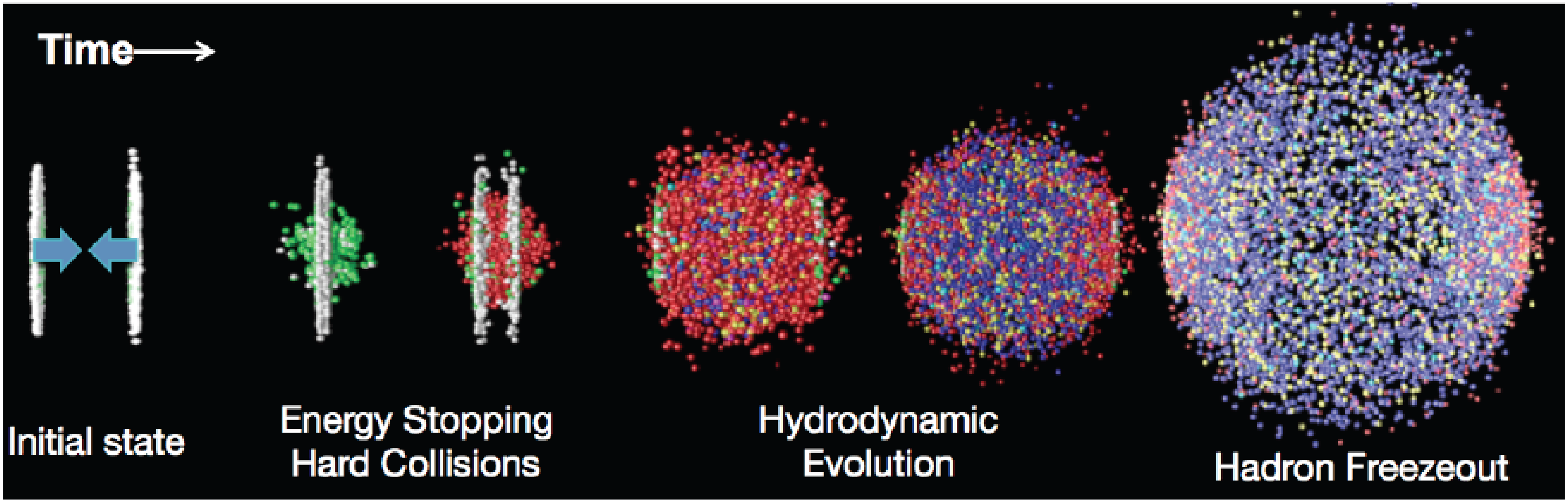
Kinetic freeze-out:

- Elastic collisions cease, particle momenta do not change → spectra

Heavy-ion collision evolution

~ 10^{-22} s

~ 5000 fm^3 < 10^{-41} m^3

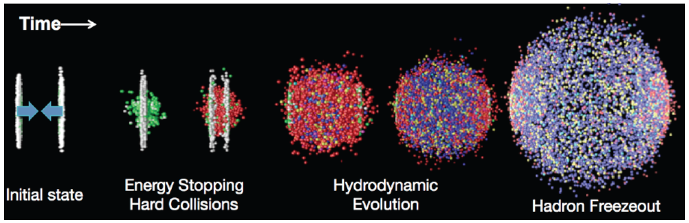


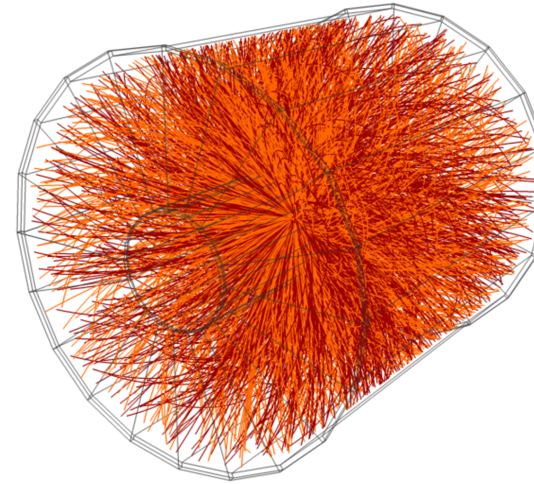
Thermalization
equilibrium is established
(t < 1 fm/*c*)

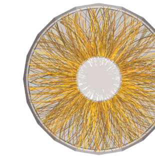
Expansion and cooling:
(t < 10-15 fm/*c*)

Chemical freeze-out
(particle yields)
Kinetic freeze-out
(particle spectra)

Our experimental work

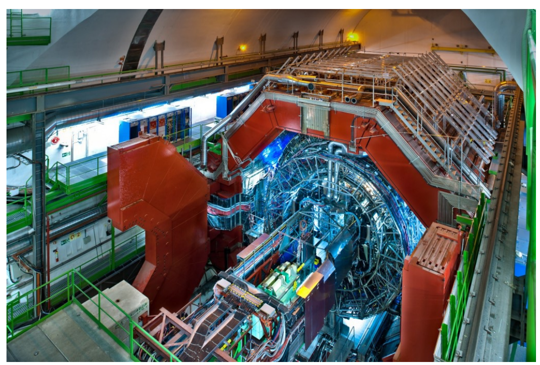


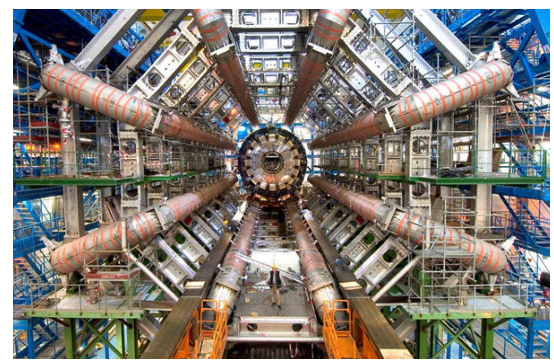




Extraordinary experiments measure the produced particles, to deduce properties of the QGP, the phase transition, etc.

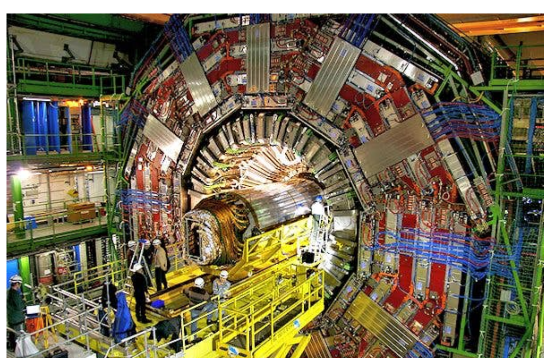
ALICE

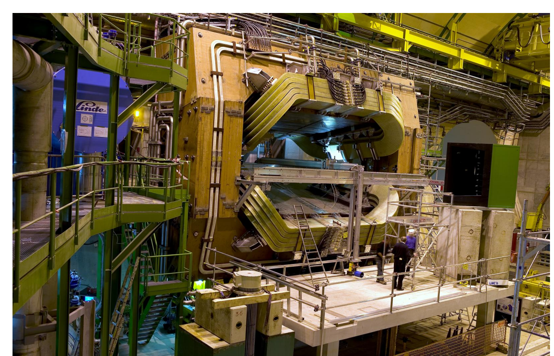




ATLAS EXPERIMENT

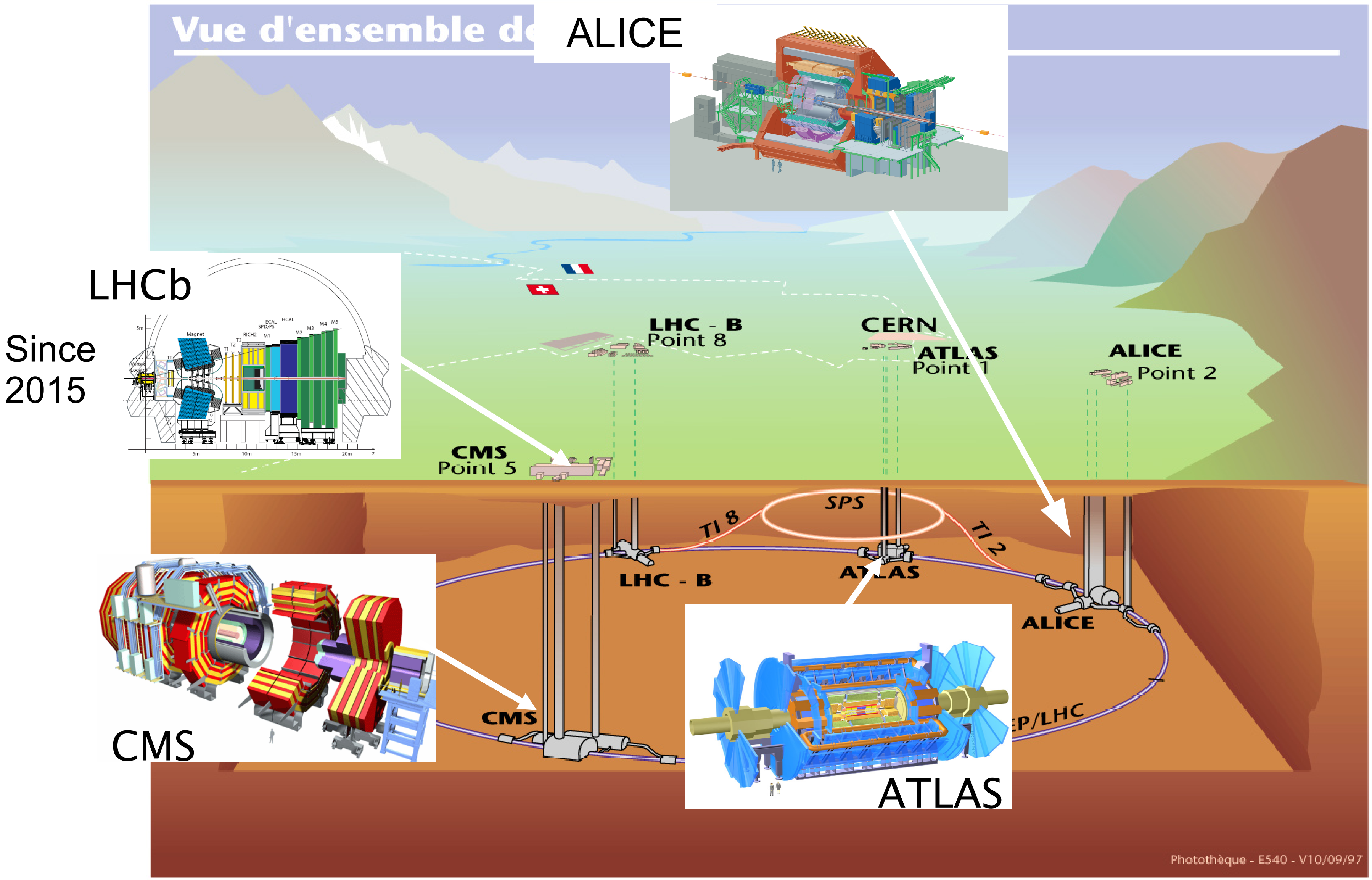
CMS



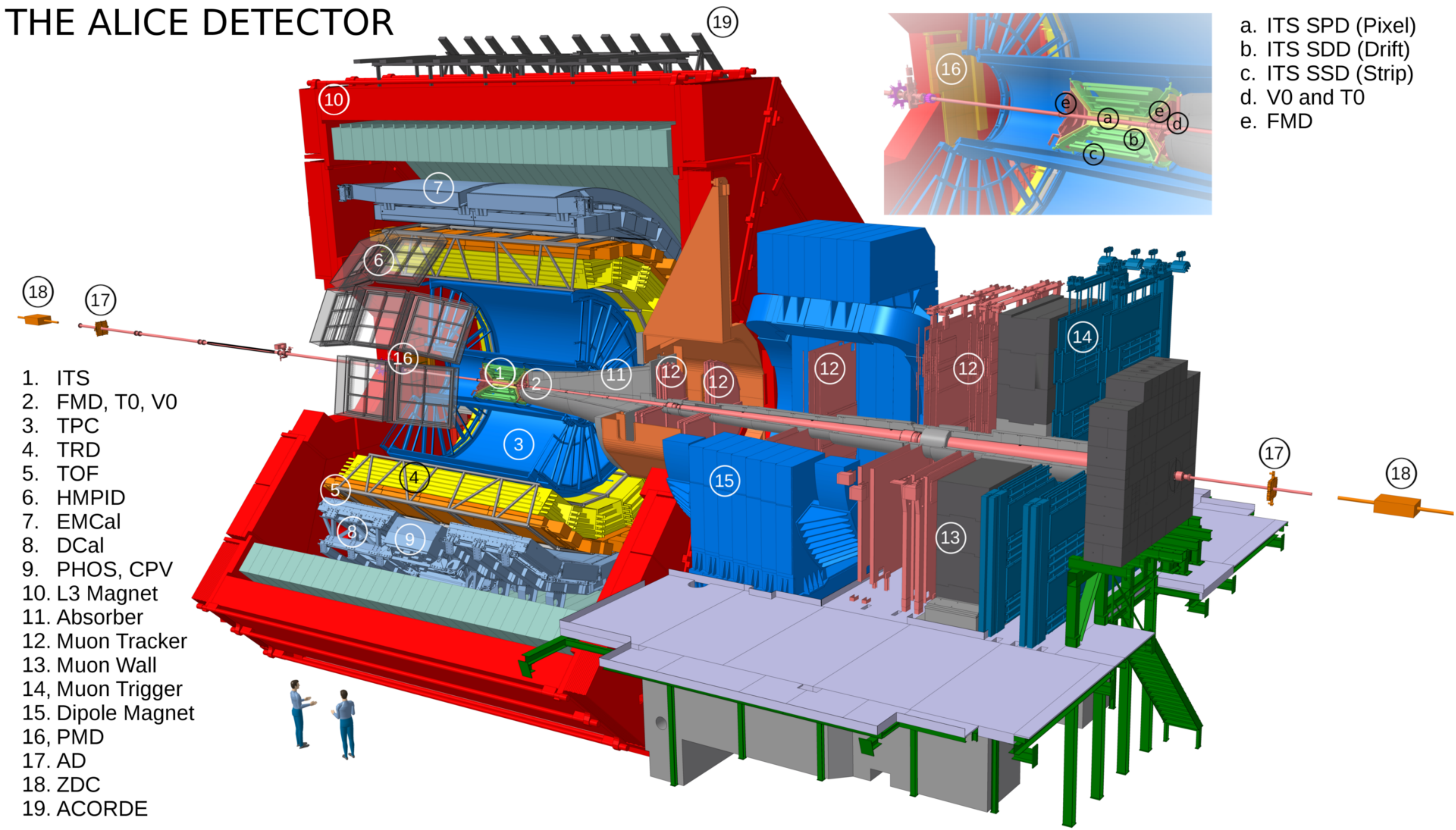


LHCb

Experimental program at the LHC



A Large Ion Collider Experiment



A Large Ion Collider Experiment

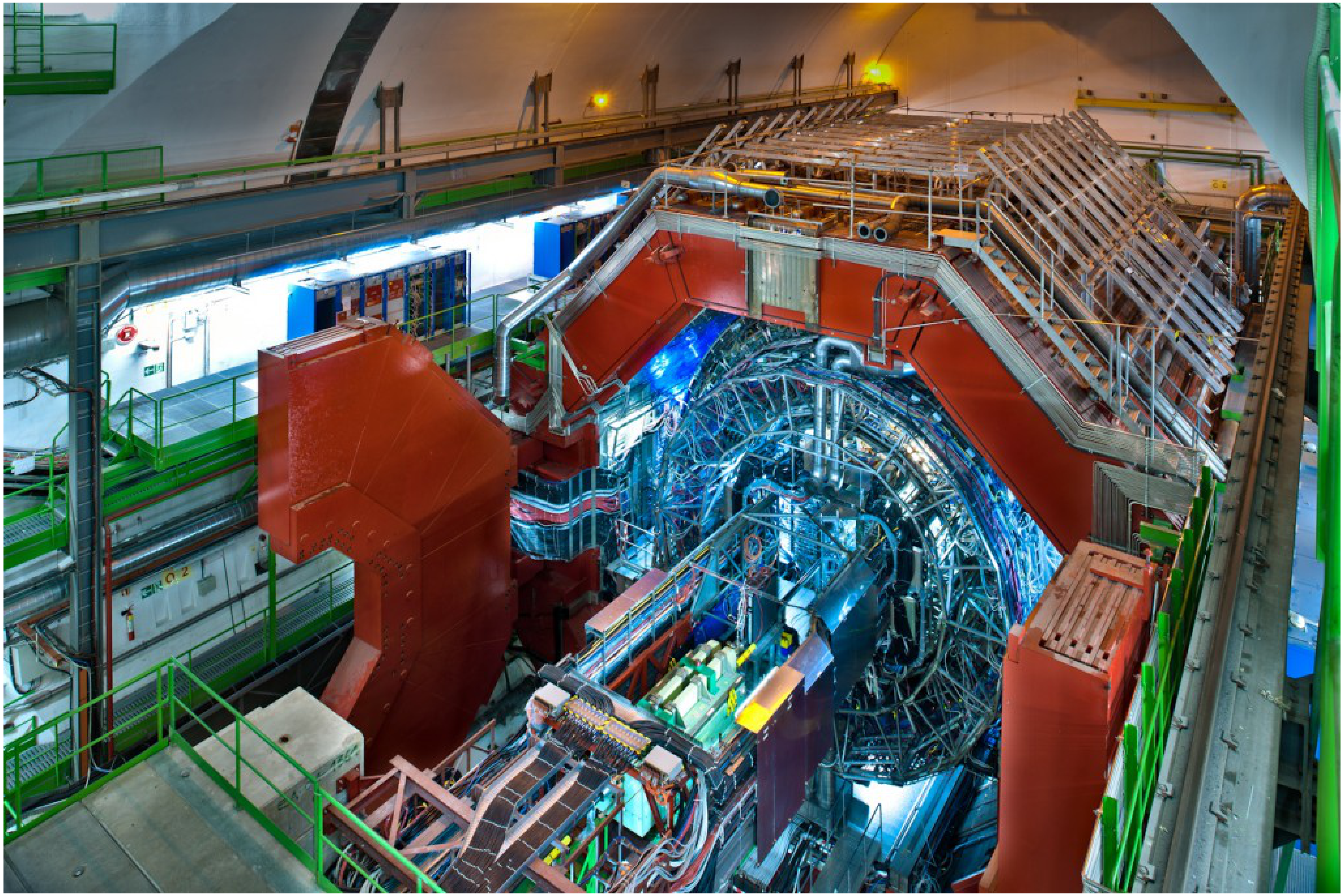
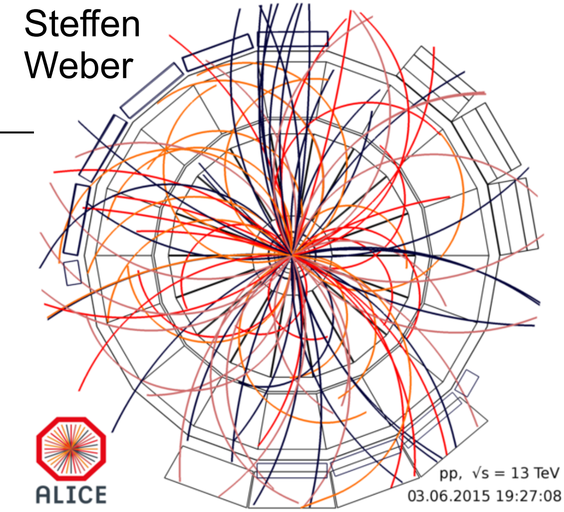
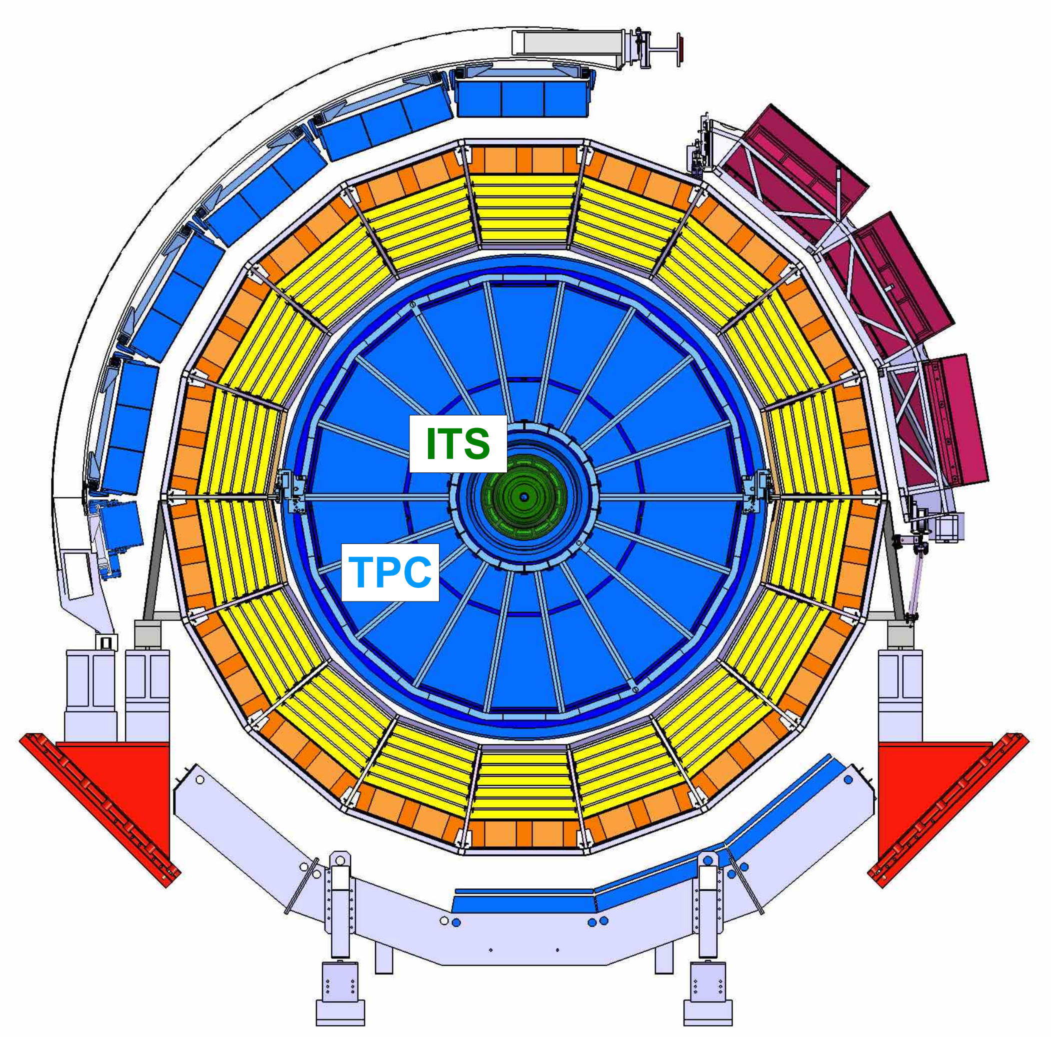


Photo:
A. Saba

Track and vertex reconstruction



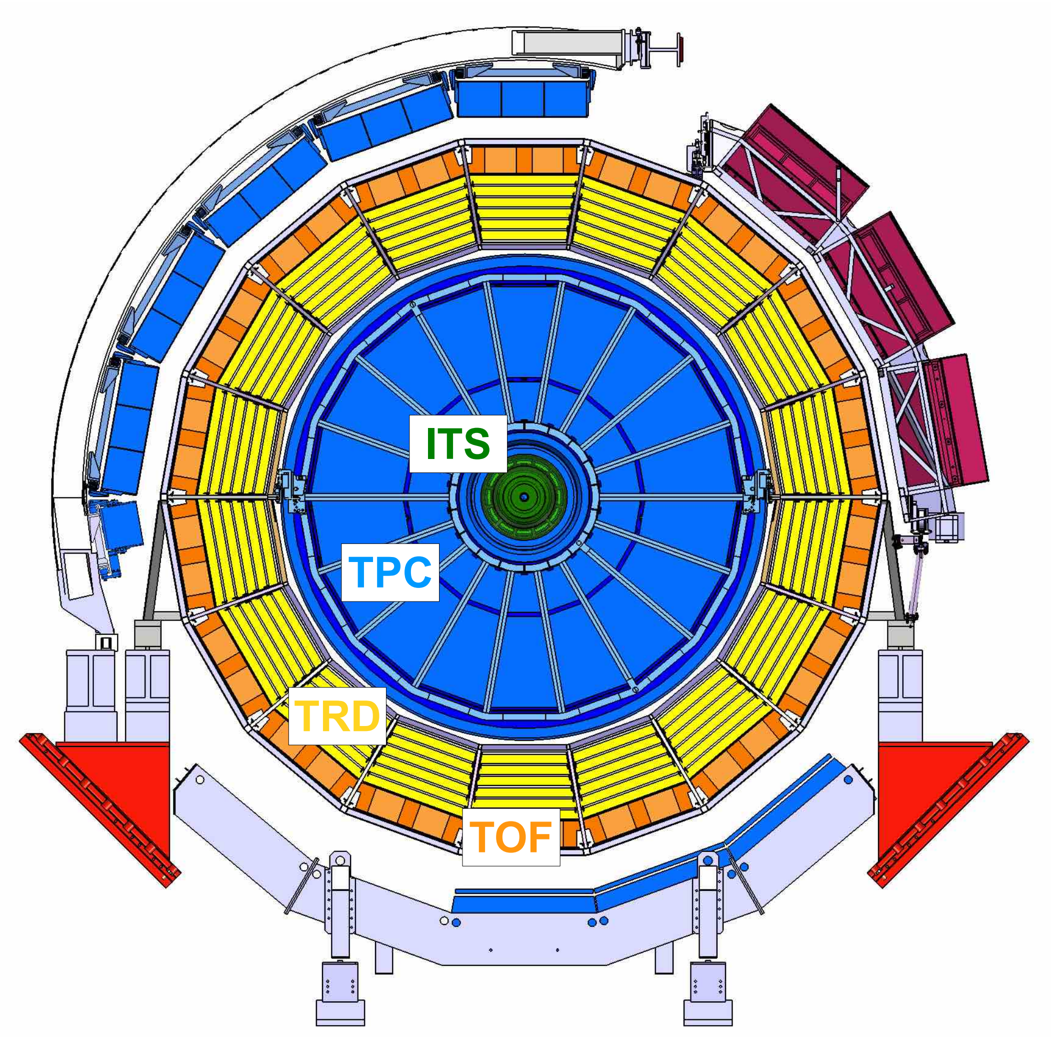


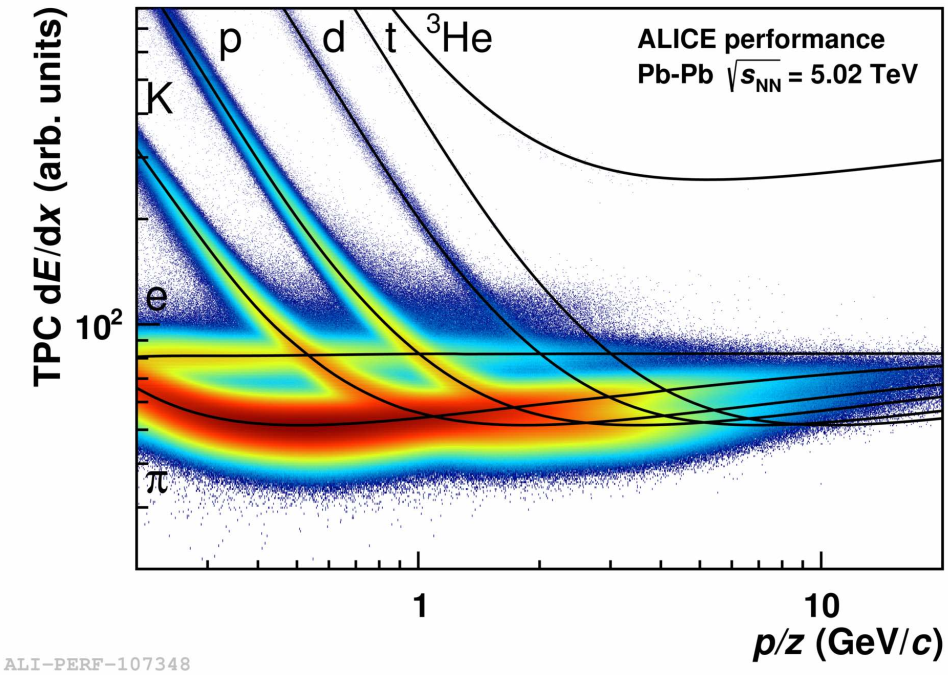
- L3 solenoid: B = 0.5 T → good acceptance for low momentum
- **Inner Tracking System ITS** in Run 1-2 with silicon pixel, drift and strip detectors
- **Time Projection Chamber TPC** 90 m^3 gas sensitive volume, in Run 1-2 now with multi-wire proportional chambers

Spatial resolution (at vertex) ≈ 10 – 20 μm

Momentum resolution (perpendicular to beam) ≈ 1 %

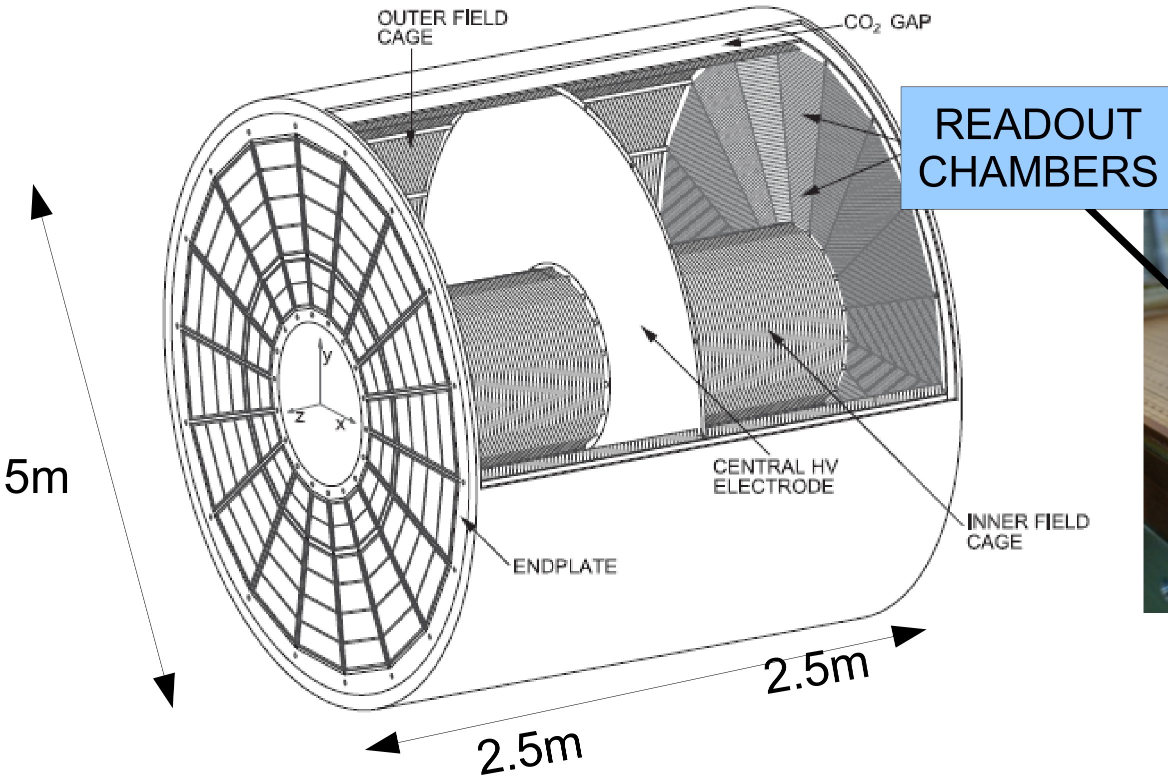
Particle identification



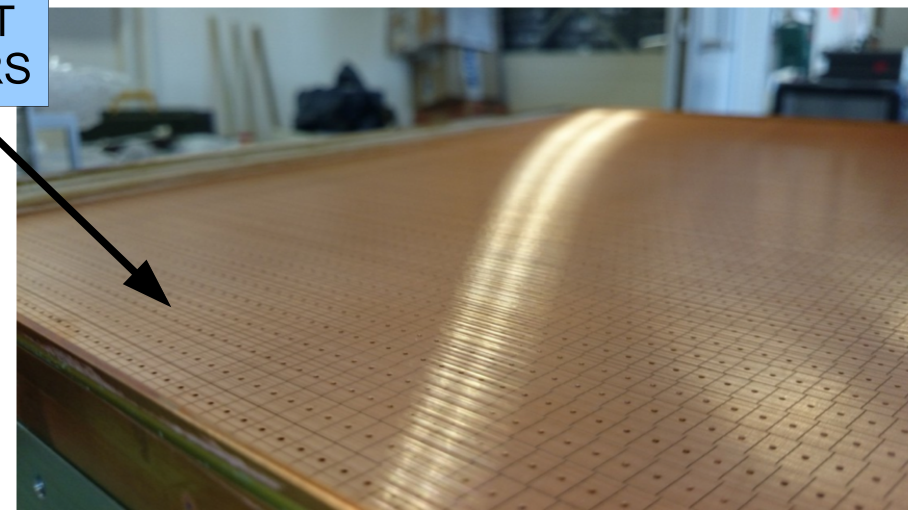


- **Time Projection Chamber TPC**
  specific energy loss dE/dx in gas
- **Inner Tracking System ITS**
  specific energy loss dE/dx in silicon
- **Transition Radiation Detector TRD**
  electron/hadron separation, trigger
- **Time-of Flight detector TOF**
  complementing the TPC at higher p
- **Calorimetry: EMCal, PHOS, DCAL**
- **Muon spectrometer**

The ALICE Time Projection Chamber

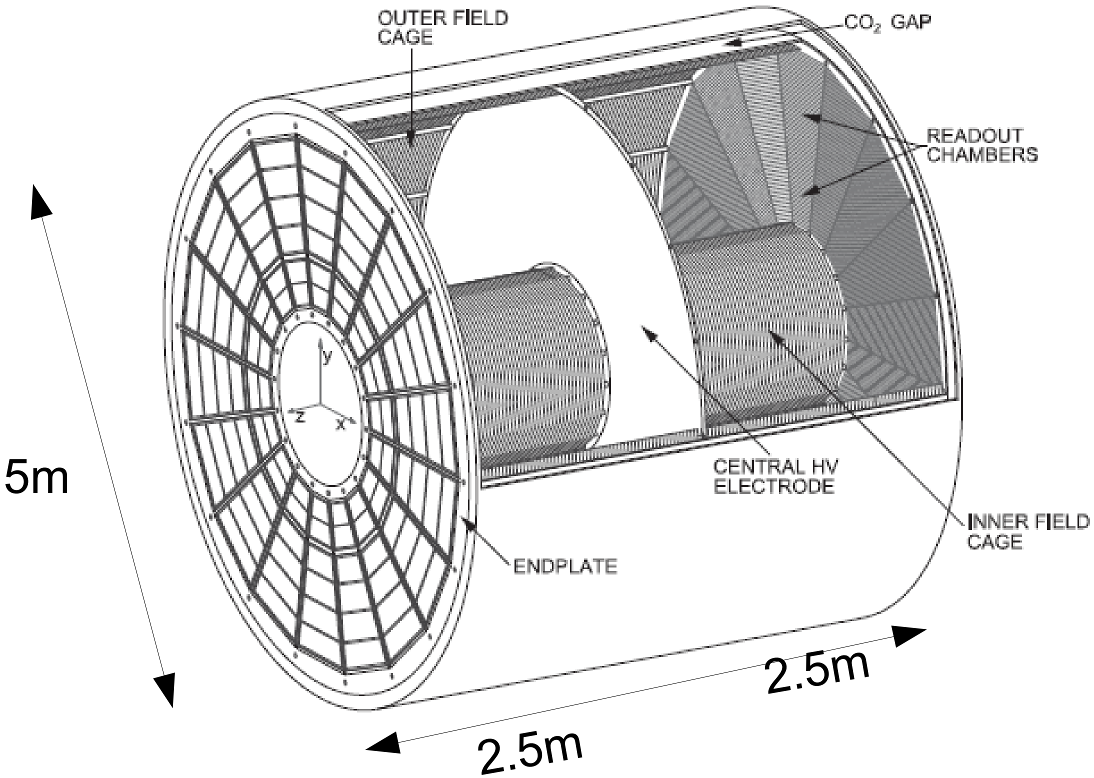


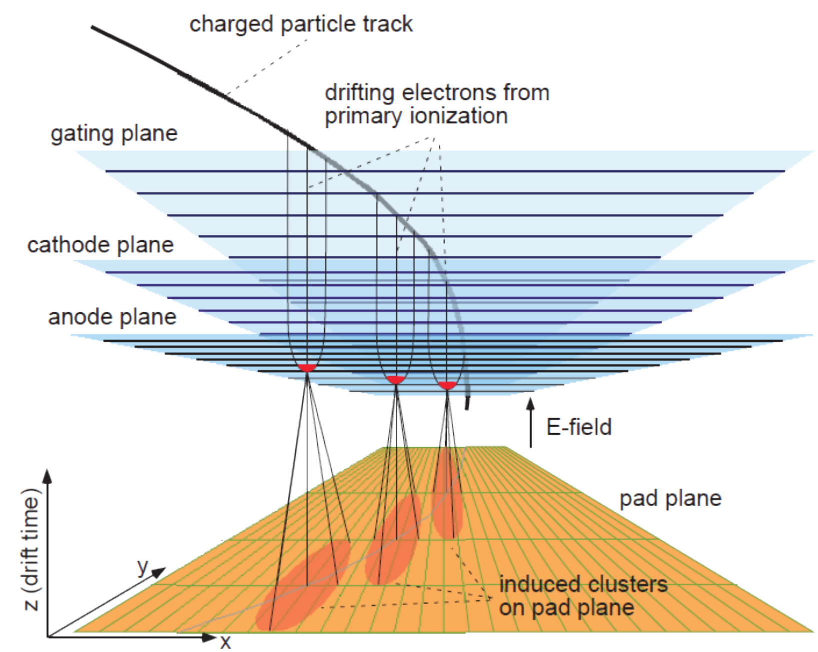
Multi-Wire Proportional Chamber



- ~ 90 m^3 gas volume ($Ne\text{-}CO_2(\text{-}N_2) \rightarrow Ar\text{-}CO_2$), equipped with **MWPC**
- Half a million readout pads
- Ions from the amplification region are prevented from reaching the drift volume by a gating grid
- Full readout time ~(100+200) μs → maximum readout rate of 3 kHz

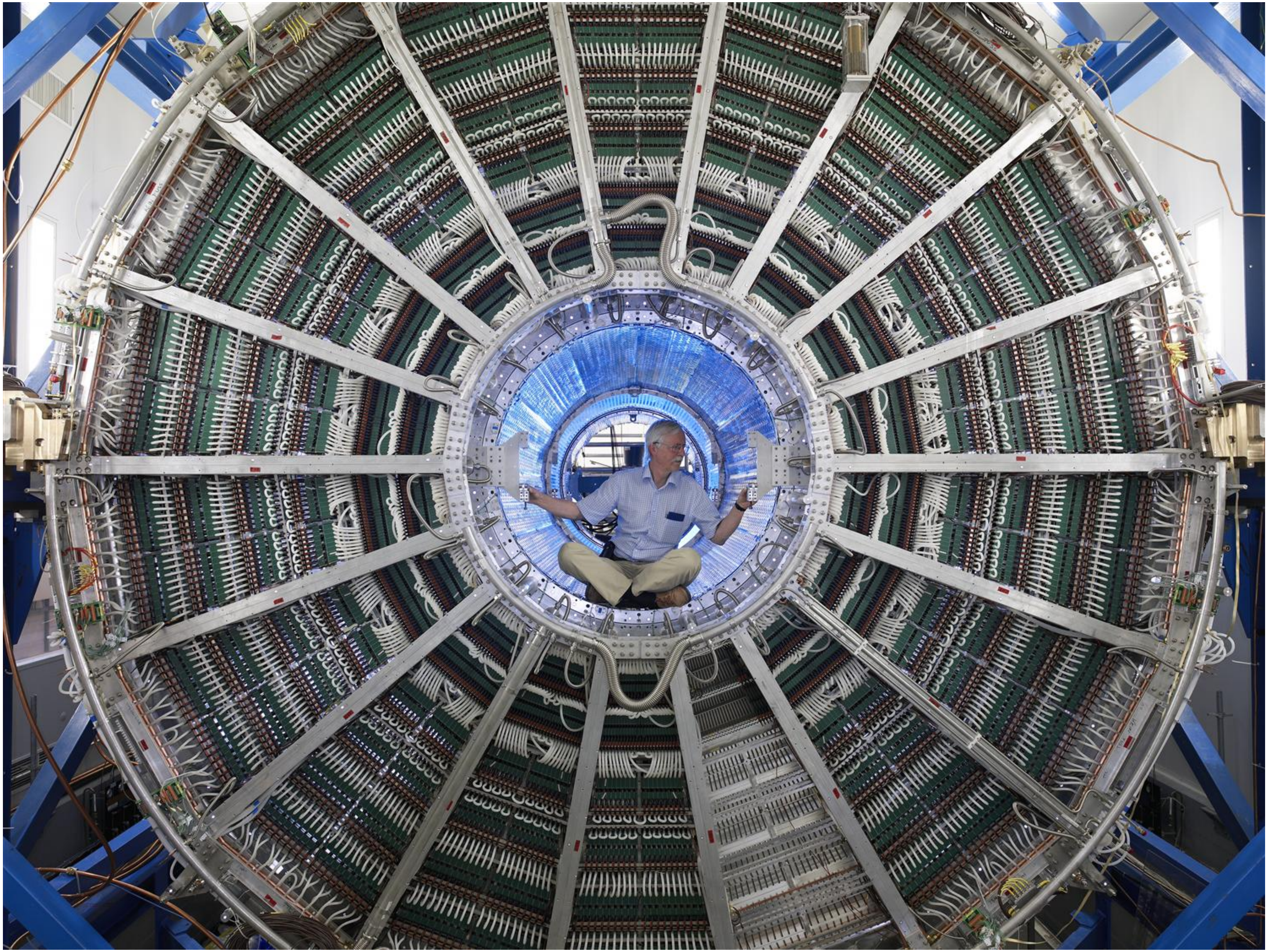
The ALICE Time Projection Chamber



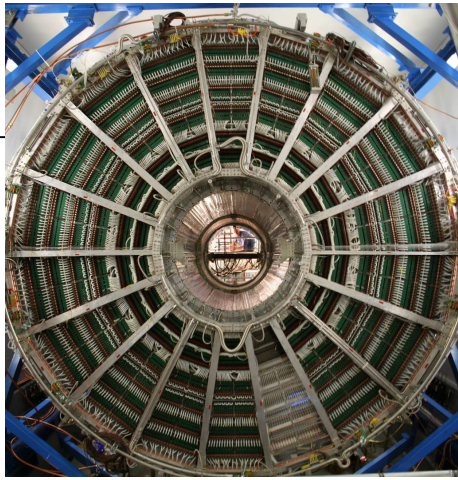


- ~ 90 m^3 gas volume ($Ne\text{-}CO_2(\text{-}N_2) \rightarrow Ar\text{-}CO_2$), equipped with **MWPC**
- Half a million readout pads
- Ions from the amplification region are prevented from reaching the drift volume by a gating grid
- Full readout time ~(100+200) μs → maximum readout rate of 3 kHz

2002-2006: TPC assembly in clean room



2007: TPC moves into ALICE



2002-2006: Assembly, MWPC and electronics installation in clean room nearby

2007: the TPC is installed in the L3 magnet

Heavy ion experiments

REALLY SPECIAL

- High granularity detectors (*) for extraordinary particle multiplicities

- The bulk particle production happens at low momenta:
  → possibly low magnetic fields
  → low material budget essential
  → minimum bias data taking (*) (vs highly selective triggers)

- Particle identification is a crucial asset

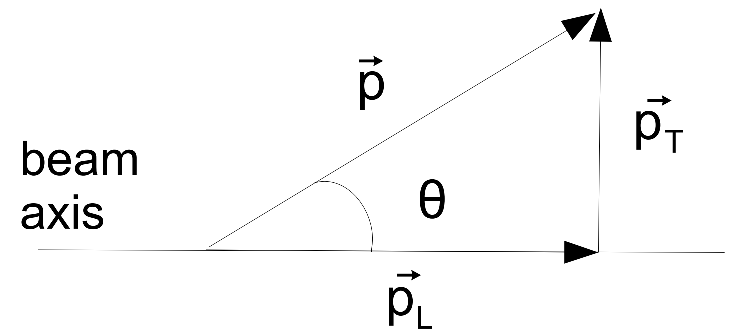
- (*) very very Big Data!
  - 1 Pb-Pb collision: 12.6 MB
  - Total disk used (ALICE): (20 [T0] + 24 [T1] + 24 [T2]) = 68 PBytes !
  - Great computing challenges!

- Transverse momentum:

$$p_T = p \cdot \sin\theta$$

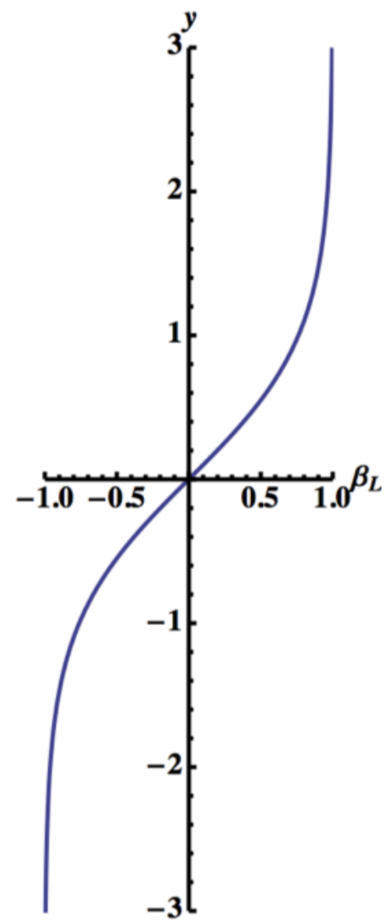
$$p = \sqrt{p_L^2 + p_T^2}$$

transverse mass: $$m_T = \sqrt{p_T^2 + m^2}$$



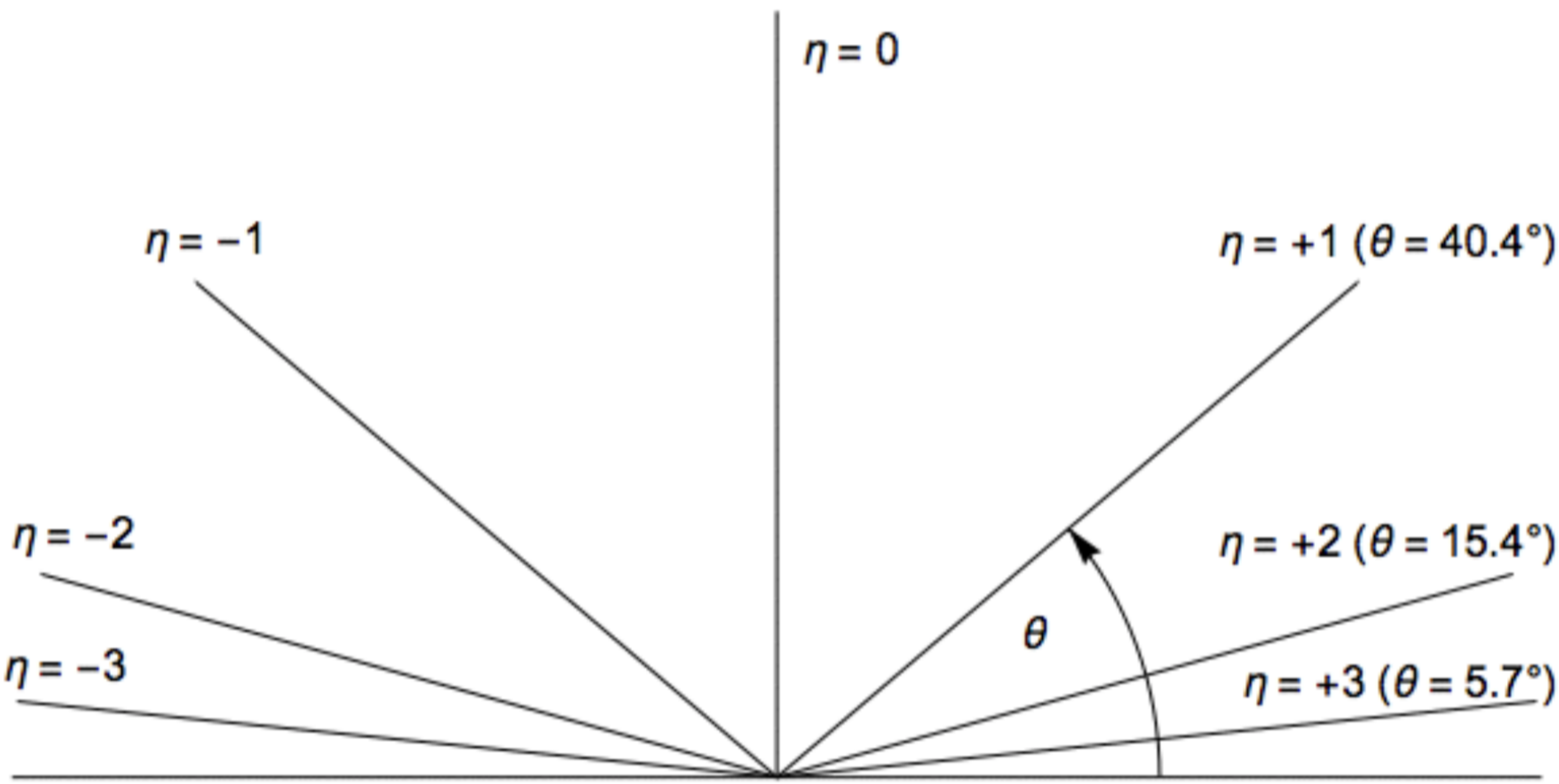
- Rapidity:
additive under Lorentz transformation

$$y = \operatorname{arctanh}\beta_L = \frac{1}{2}\frac{1+\beta_L}{1-\beta_L} = \frac{1}{2}\frac{E+p_L}{E-p_L}$$



Basic observables

- pseudorapidity $$y \approx \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\left(\tan\frac{\theta}{2}\right) = \eta$$

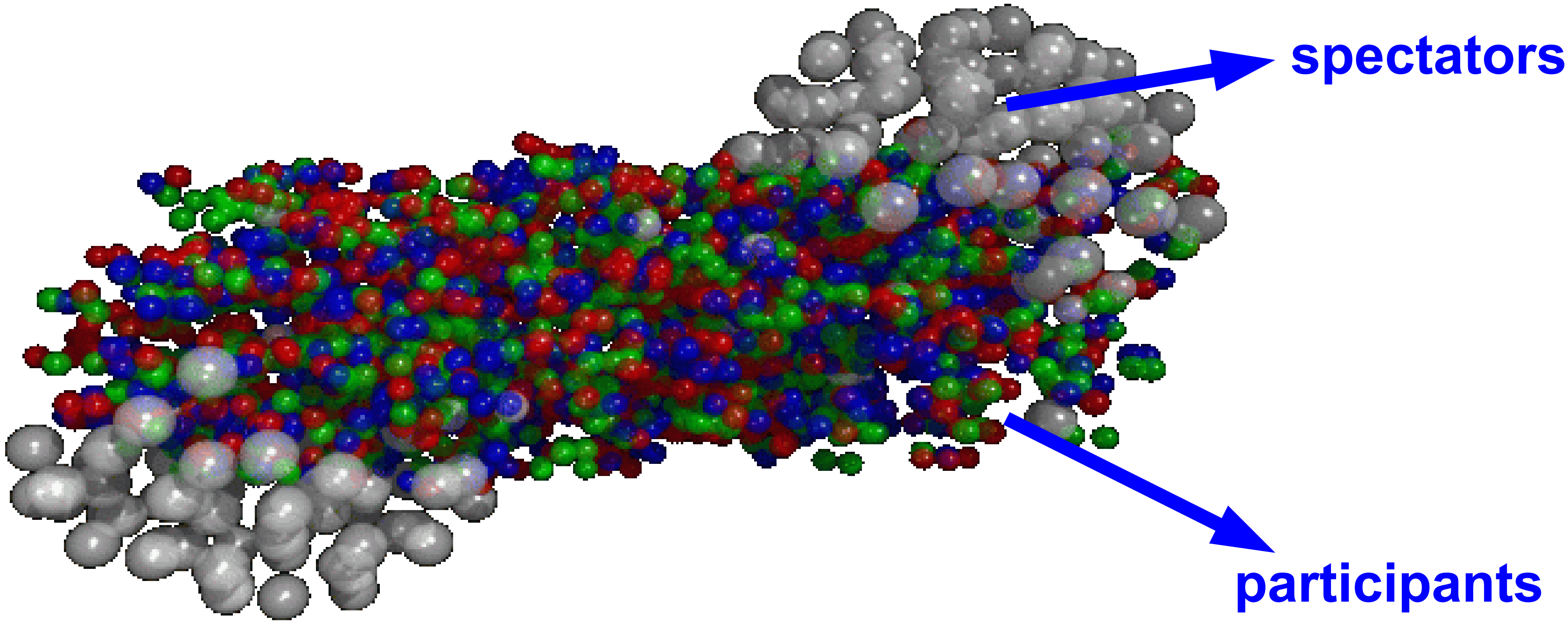


Global properties - 1

Collision geometry and event centrality

S.Masciocchi@gsi.de

Impact parameter and centrality



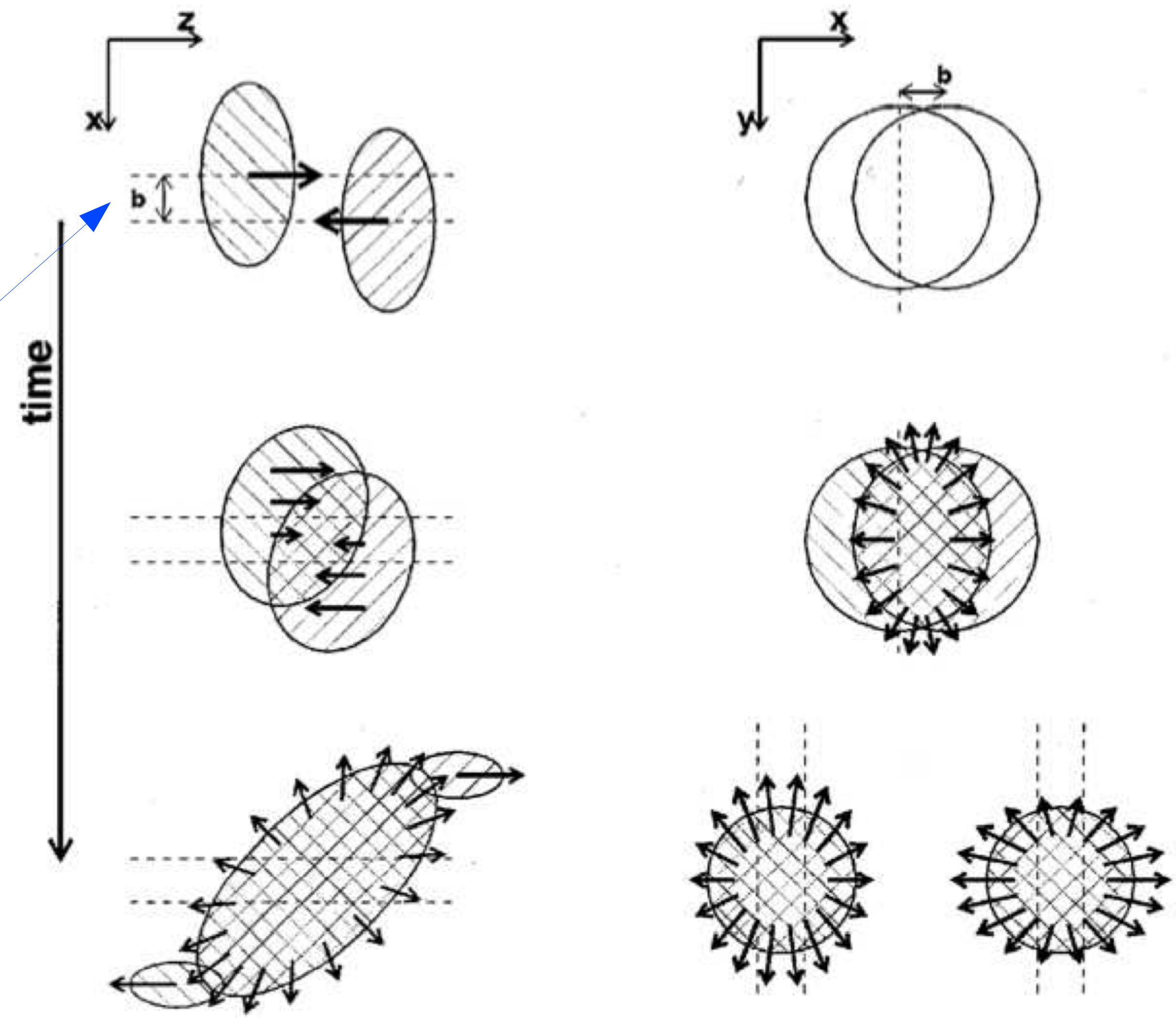
Centrality is characterized (but NOT directly measured) via:

- **b**: impact parameter
- N_{part}: number of nucleons, which took part in at least one inelastic nucleon-nucleon scattering
- N_{coll}: number of inelastic nucleon-nucleon collisions

Participants and spectators

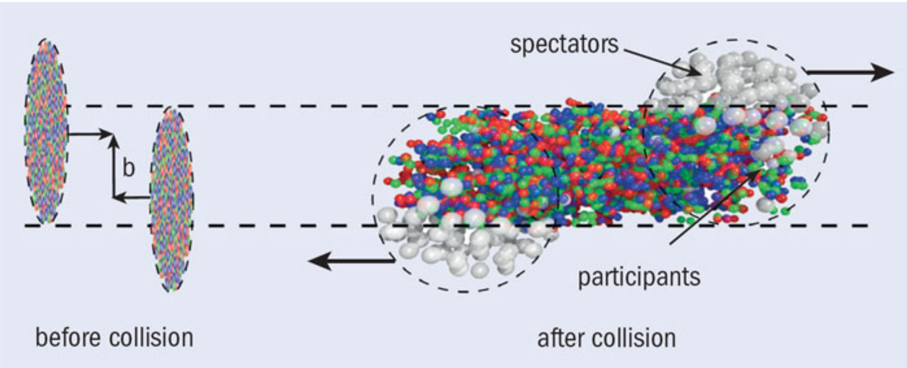
Geometric concepts
are applicable:

IMPACT PARAMETER



N.Herrmann, J.P.Wessels, T.Wienold, Ann. Rev. Nucl. Part. Sci. 49 (1999) 581

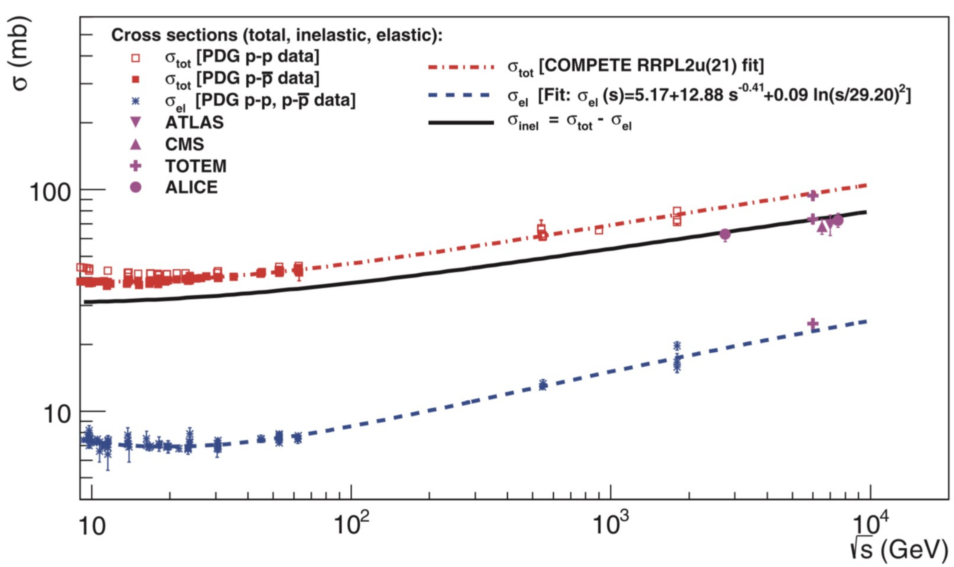
The Glauber model



- Impact parameter, number of participants/spectators and number of binary collisions are quantities which are impossible to measure directly
- Theoretical model after Roy Glauber (Nobel Prize 2005, † 26.12.2018)
- Inputs:

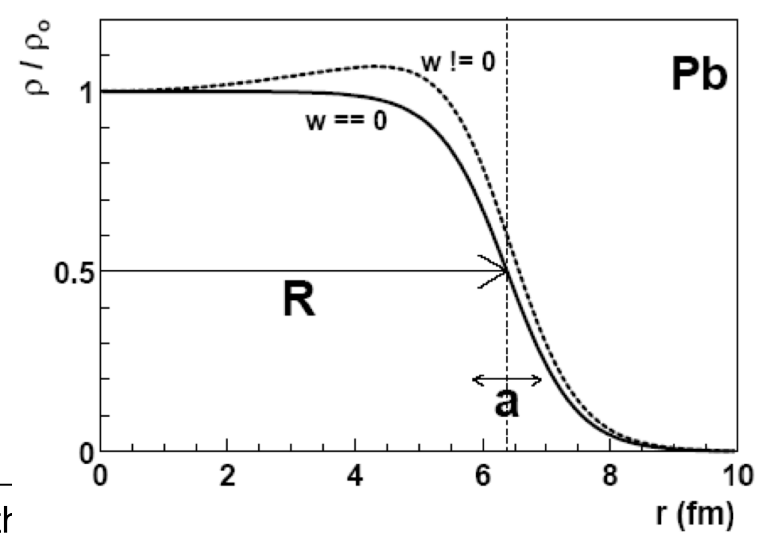
inelastic nucleon-nucleon cross section

PHYSICAL REVIEW C **88**, 044909 (2013)



density profile of nucleus

Woods-Saxon



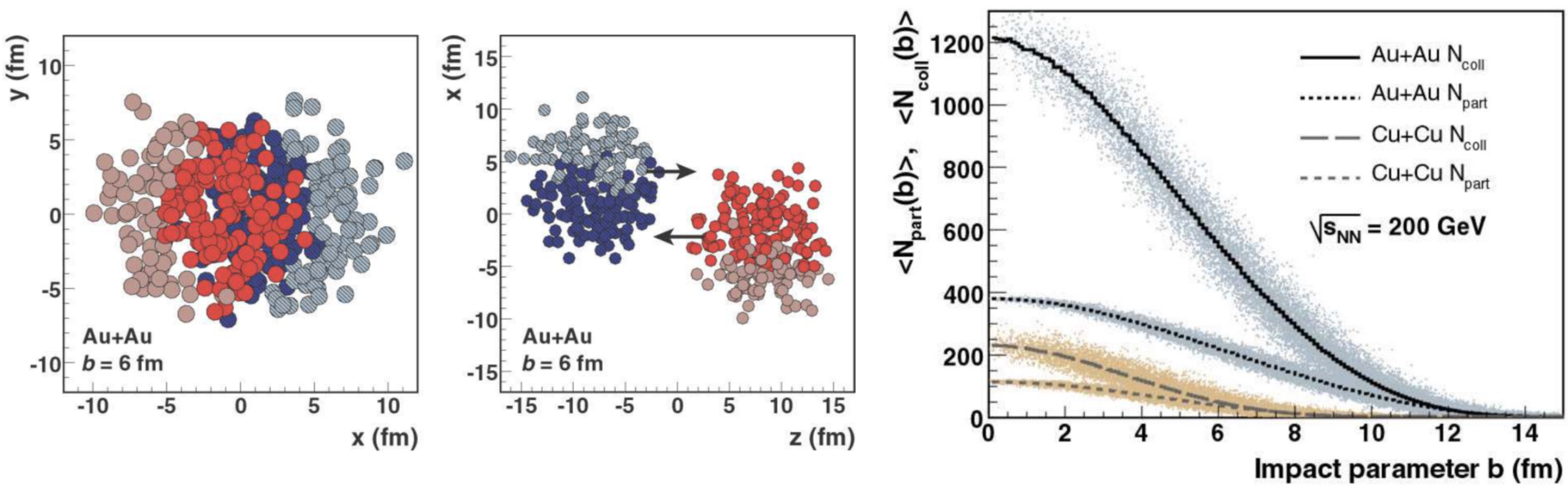
cs at th

The Glauber model

Assumptions:

- NN scattering cross section does NOT depend on the number of NN scatterings that took place before
- Nucleons travel on straight trajectories, even after NN scattering processes.

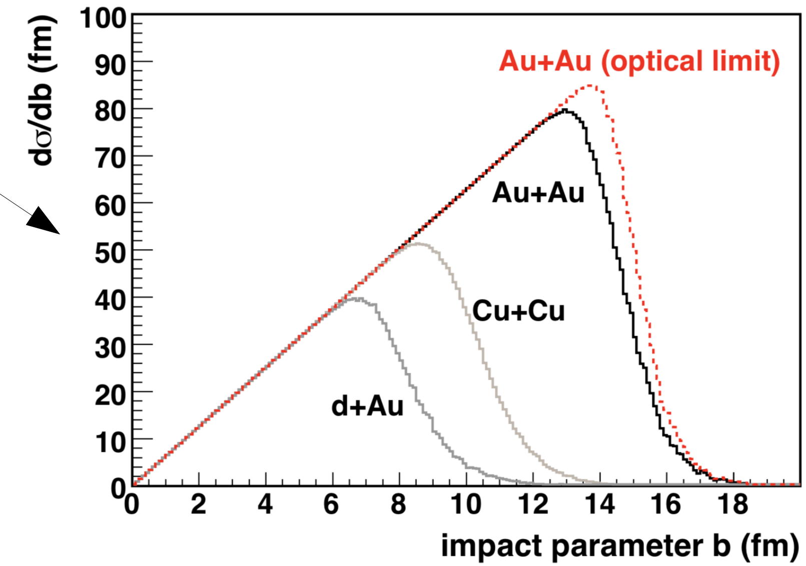
- Monte Carlo approach: initialize a nucleon distribution according to Woods-Saxon, select random b, simulate many events



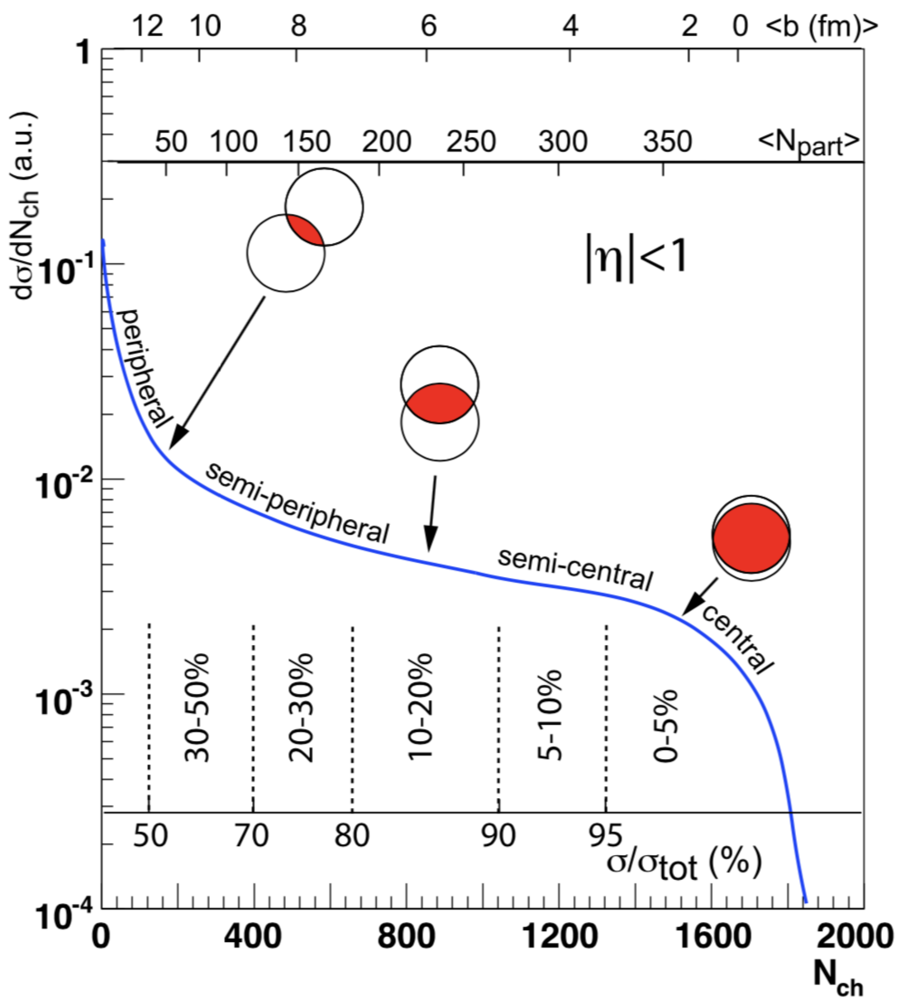
M.L.Miller et al., arXiv:nucl-ex/0701025

The Glauber model

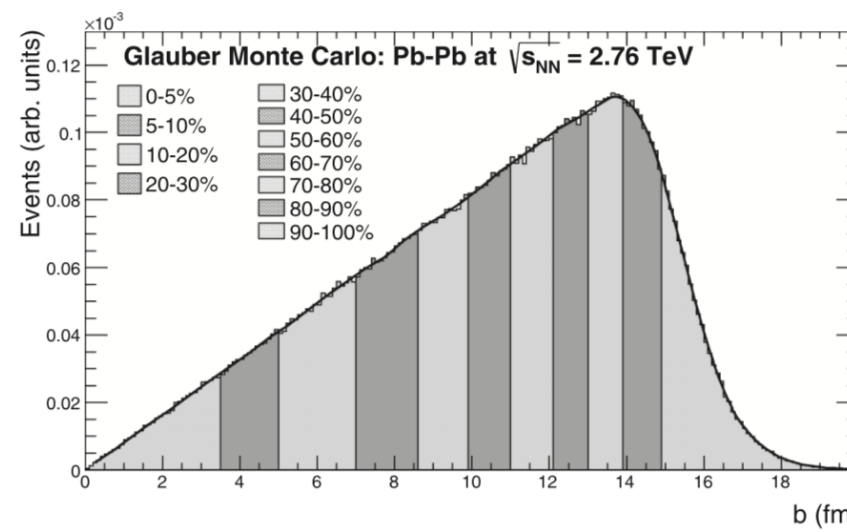
- Total geometrical cross section



- Connection to real collisions



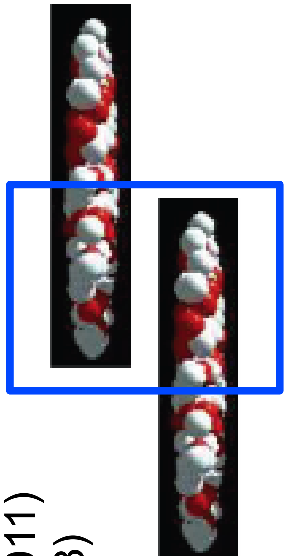
In ALICE:



Phys. Rev. C 88, 044909(2013)

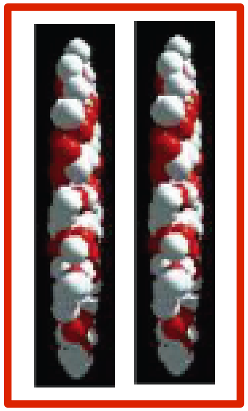
M.L.Miller et al., arXiv:nucl-ex/0701025

Centrality determination in ALICE



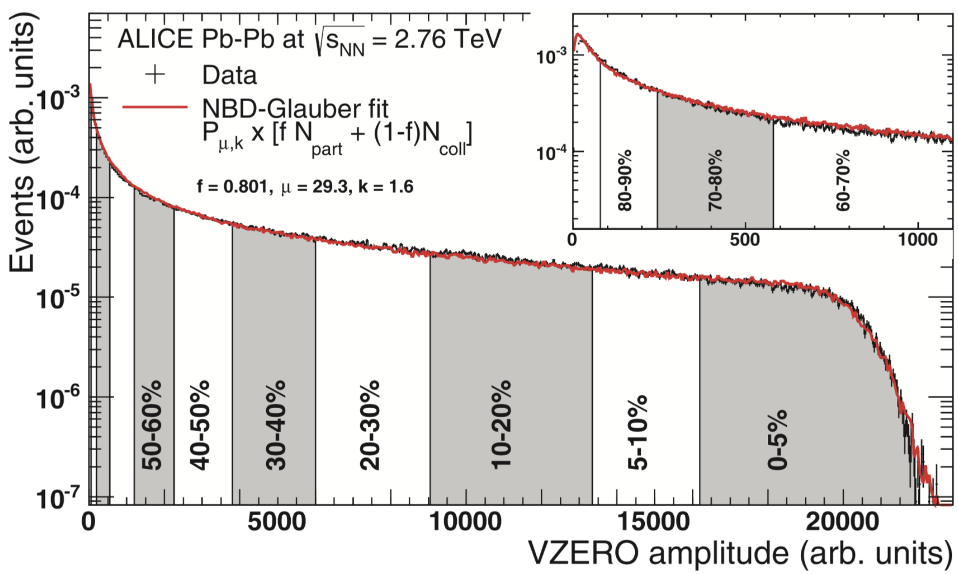
Central collisions → high number of **participants**
→ high multiplicity

Peripheral collisions → low number of **participants**
→ low multiplicity



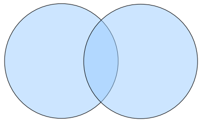
E.g. measure by VZERO scintillators +
reproduced by Glauber model fit

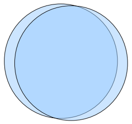
Phys. Rev. Lett. 106, 032301 (2011)
Phys. Rev. C 88, 044909(2013)



Centrality: percentile of total hadronic cross section

peripheral





central

Global properties - 2

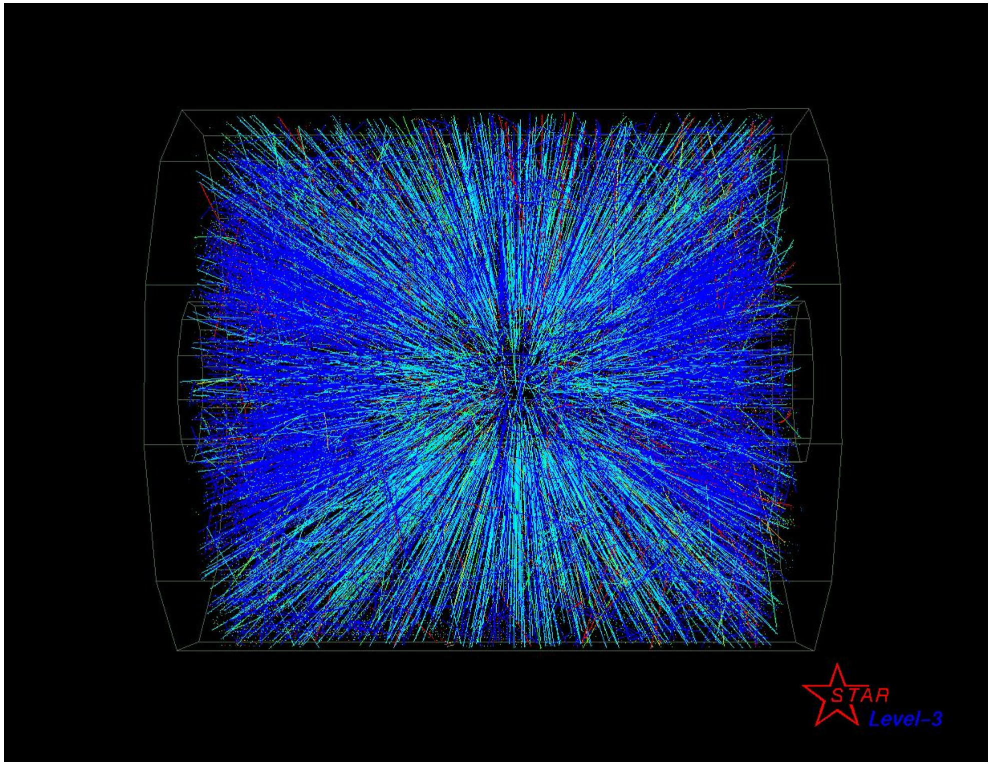
Particle multiplicities

S.Masciocchi@gsi.de

Multiplicity of particles produced

STAR at RHIC

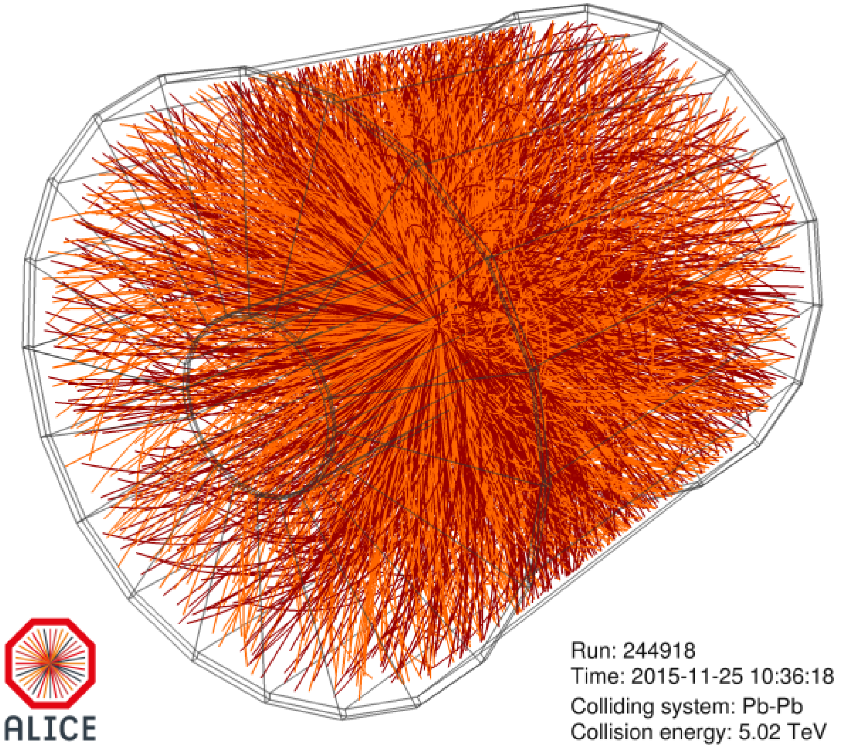
Au-Au $\sqrt{s_{NN}}$ = 200 GeV central



About 5,000 charged particles in the full rapidity range

ALICE at the LHC

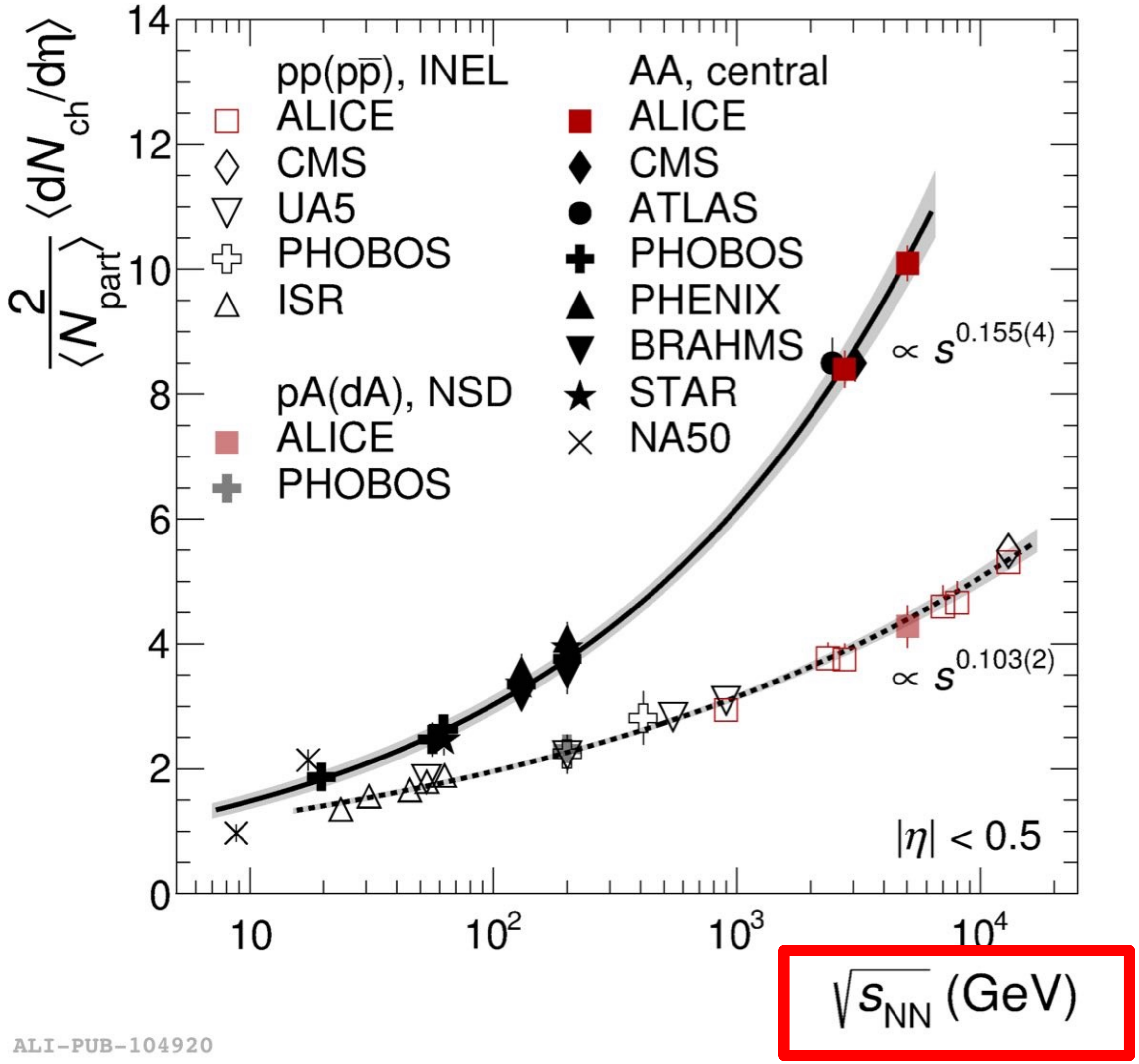
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV central



About 20,000 charged particles in the full rapidity range

Charged-particle multiplicity density at mid-rapidity

$\frac{dN_{ch}}{d\eta}$ measured at mid rapidity $|\eta| < 0.5$

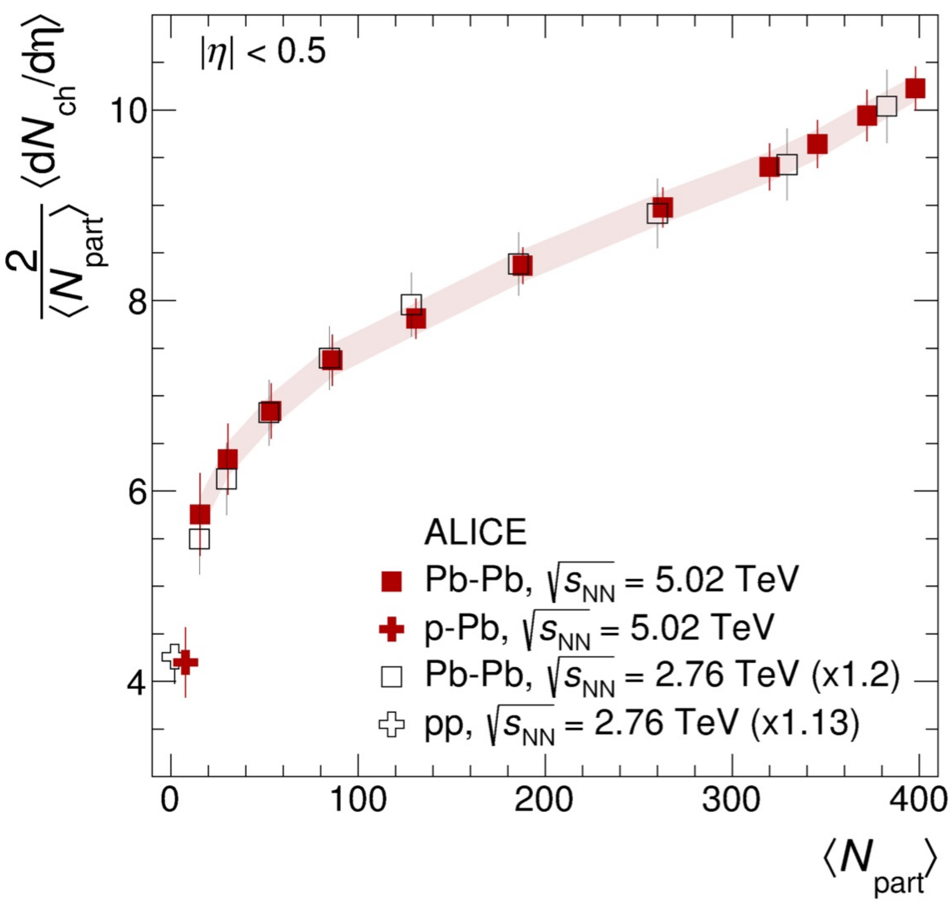


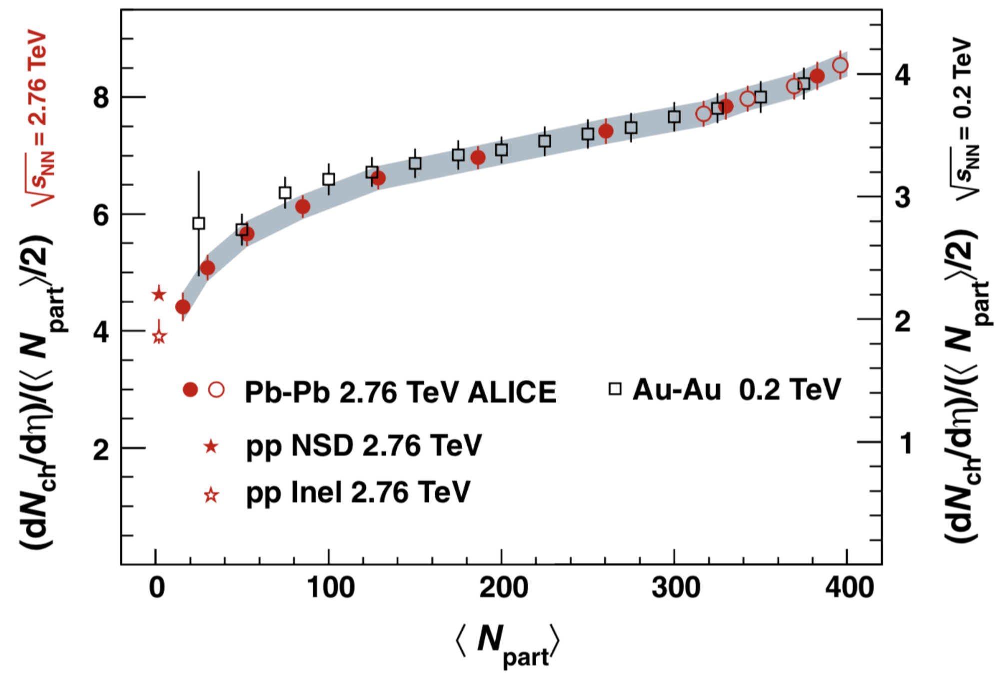
Phys. Rev. Lett. 116 (2016) 222302

- Y axis: normalization by $\langle N_{part} \rangle / 2$
- Central AA collisions: increase $\propto s^{0.155}$
- Much faster growth wrt pp collisions

$dN_{ch}/d\eta$ centrality dependence

Centrality expressed as average number of participants



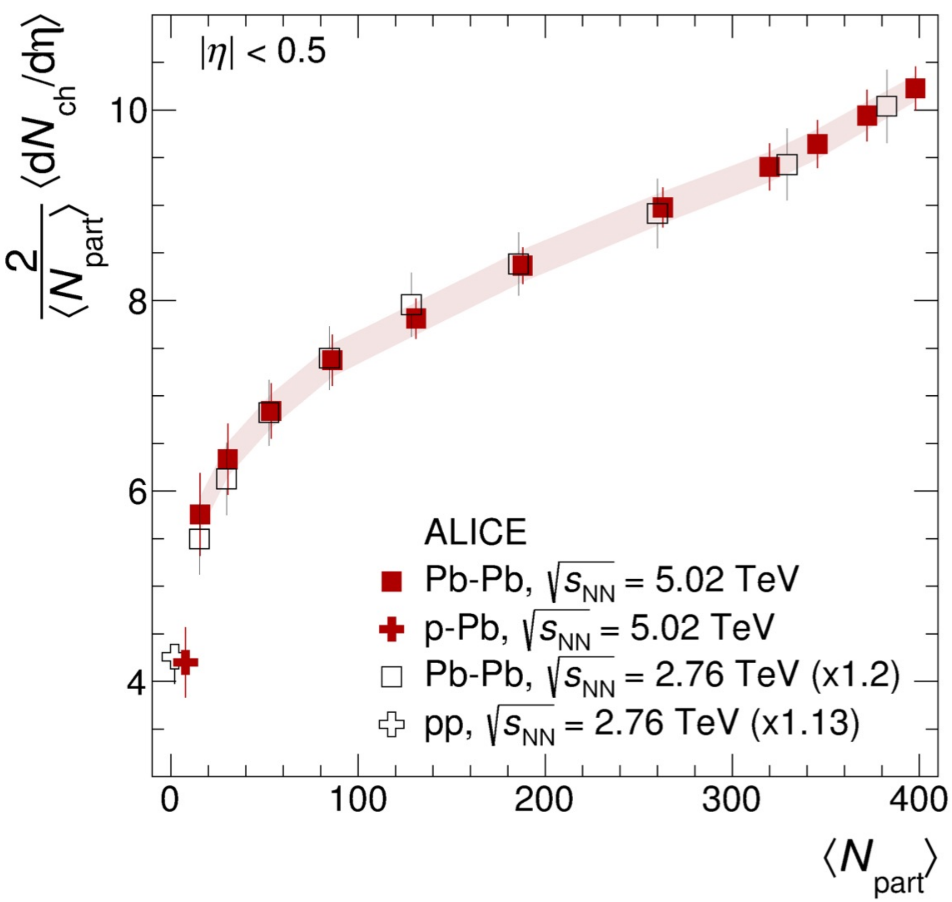


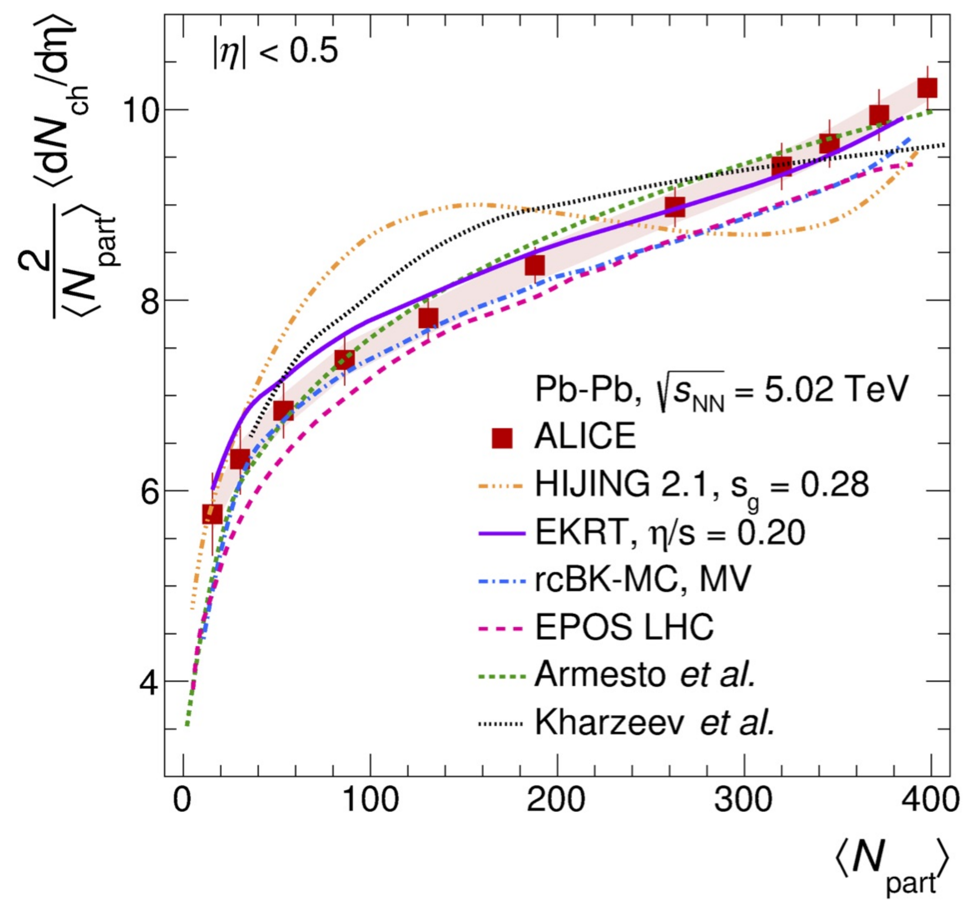
Same dependence observed in
Au-Au at 200 GeV,
Pb-Pb at 2.76 and 5.02 TeV

Phys. Rev. Lett. 116 (2016) 222302

$dN_{ch}/d\eta$ centrality dependence

Centrality expressed as average number of participants



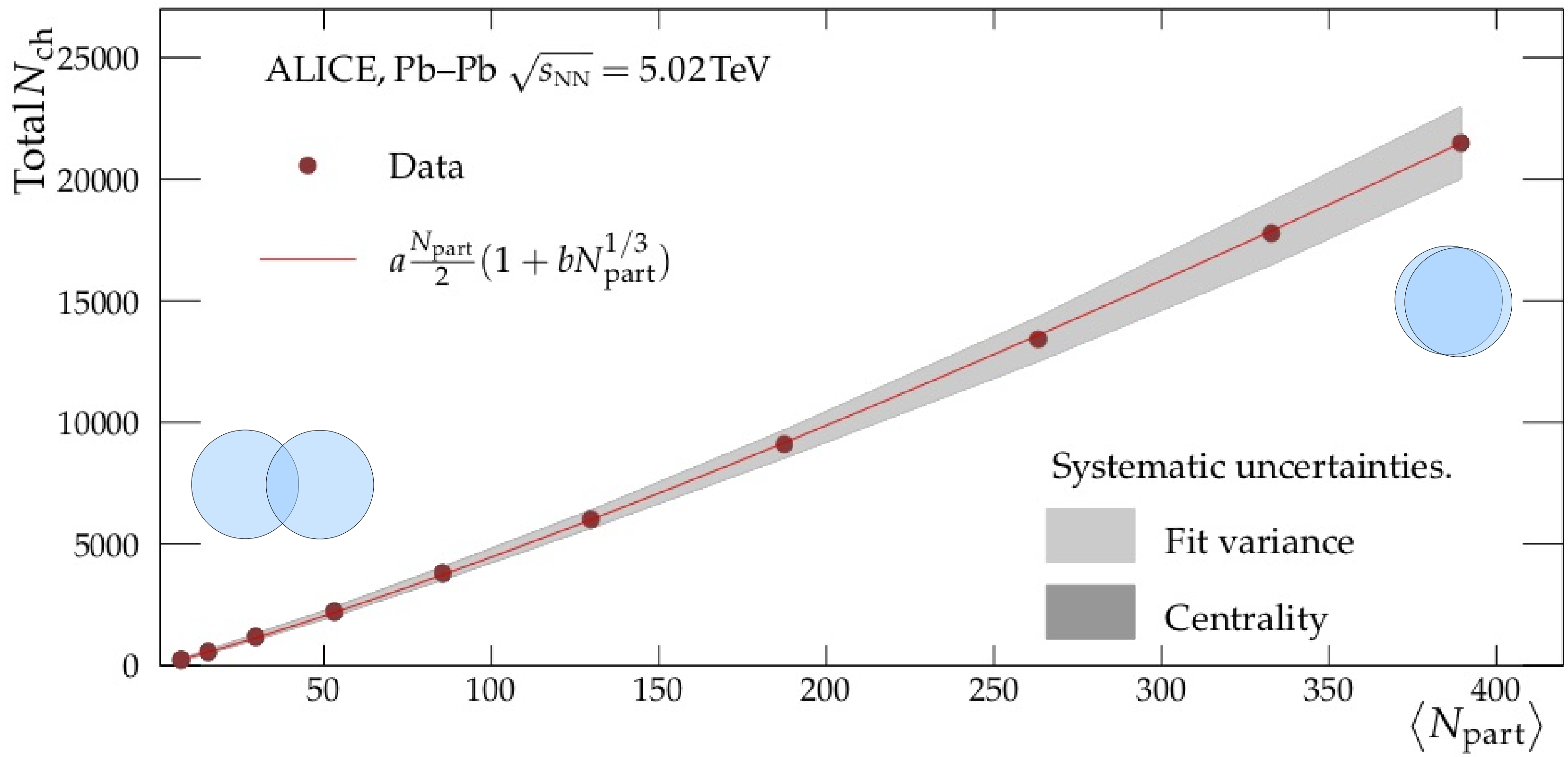


Phys. Rev. Lett. 116 (2016) 222302

Models: particle production is no trivial task!

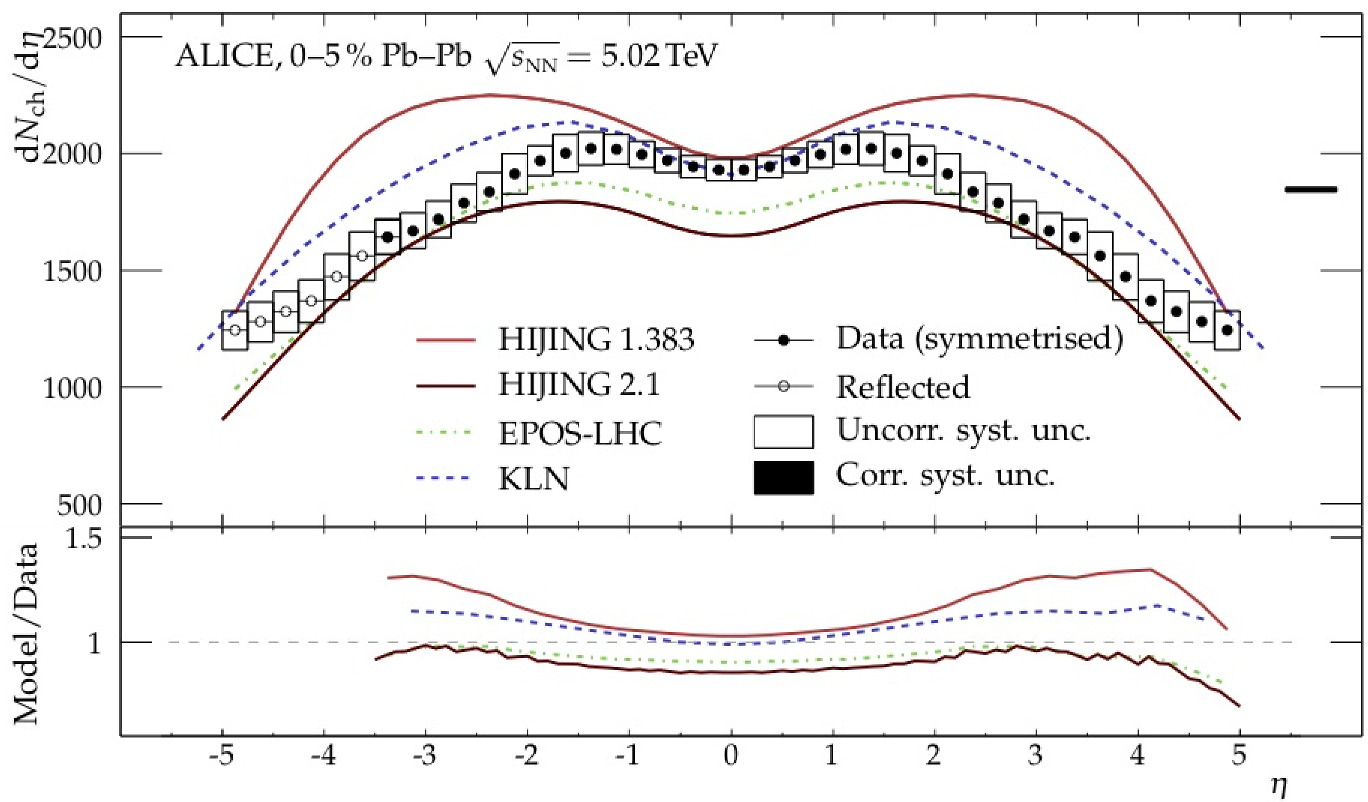
Total charged-particle yields

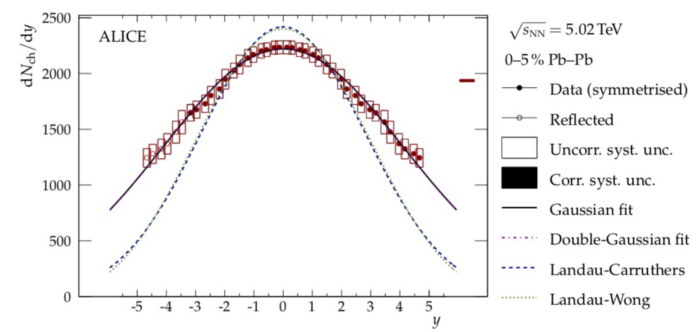
Charged-particle multiplicity extrapolated to full rapidity range

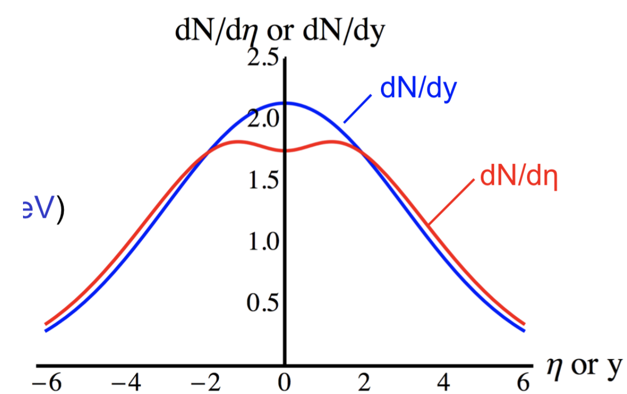


Phys.Lett. B 772 (2017) 567-577

Charged-particle pseudorapidity density







Phys.Lett. B 772 (2017) 567-577

Summary

- Up to 20,000 charged particles produced in the full rapidity range in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

- Estimates of the energy density in heavy-ion collisions at RHIC and at the LHC range between 5 and 20 GeV/fm^3

  → well above the critical energy density for the formation of the quark-gluon plasma (0.42 GeV/fm^3, lattice 2018)

- Bose-Einstein correlations of identical pions: estimate of source size and decoupling time of the fireball at freeze-out

  $\mathrm{Volume}_{LHC} \sim 2 \times \mathrm{Volume}_{RHIC}$

  $\mathrm{Time}_{LHC} \sim 1.4 \times \mathrm{Time}_{RHIC}$

Lecture 1: wrap up

- QCD matter under extreme conditions in temperature (early universe) and density (neutron stars), recreated in the laboratory with relativistic heavy-ion collisions

- Thermodynamics applied to QCD matter: phase diagram, phase transition, critical temperature and energy density

  Lattice QCD computations

- Global properties:
  - Collision geometry and centrality
  - Multiplicity of produced particles, initial energy density
  - Source size and decoupling time

- Experimental program, particle detection challenges, Big Data