High Energy Frontier – Recent Results from the LHC: Heavy Ions I

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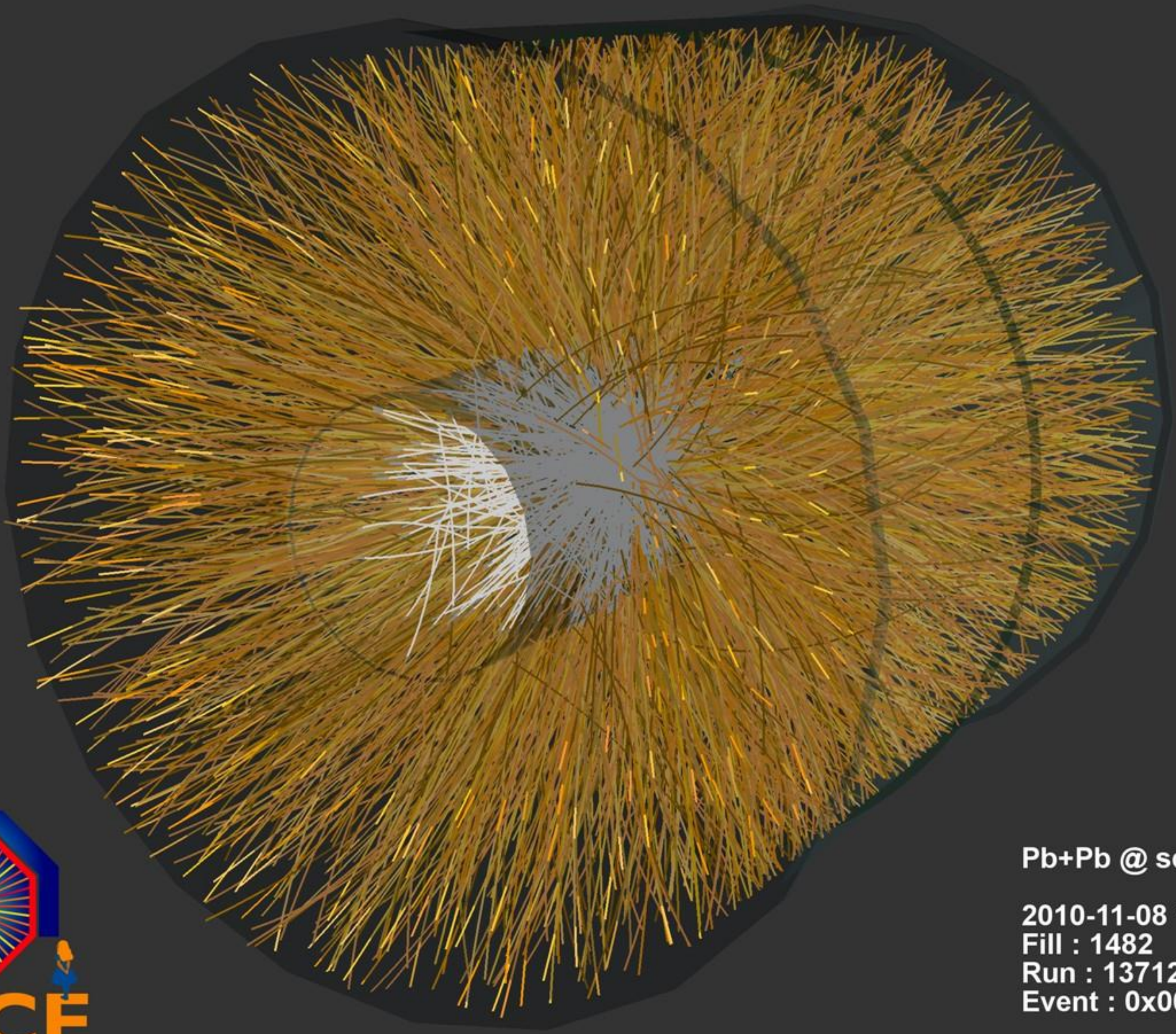
Ruprecht-Karls-University, Heidelberg



ALICE

Pb+Pb @ sqrt(s) = 2.76 ATeV

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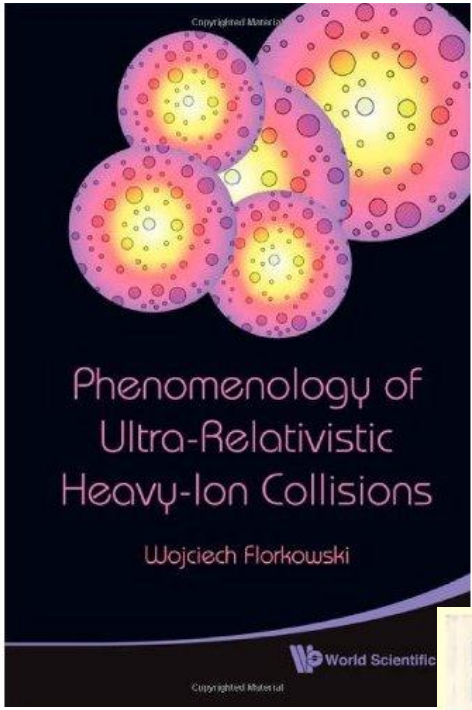
Outline

- **lecture 1 (22.11.): introduction**
  - basics of relativistic heavy-ion collisions
- **lecture 2 (29.11.): soft probes**
  - hadron yields & spectra
  - hydrodynamics & collective motion
- **lecture 3 (13.12.): hard probes**
  - jets
  - heavy-flavor hadrons
- **lecture 4 (20.12.): quarkonia & el.magn. probes**
  - quest for J/ψ suppression/enhancement
  - direct & thermal photons
  - dileptons

Some books (not needed)



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Phenomenology of Ultra-Relativistic Heavy-Ion Collisions

Wojciech Florkowski

World Scientific

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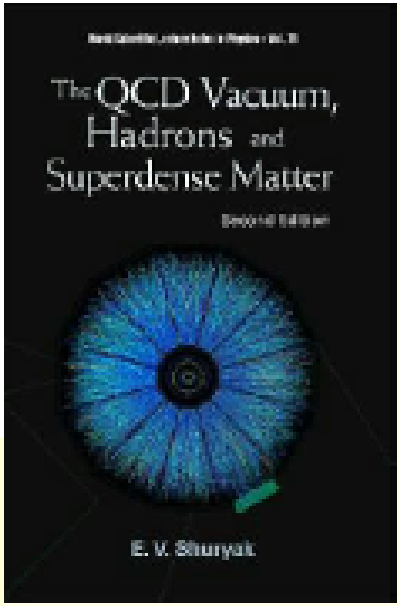
Ultrarelativistic Heavy-Ion Collisions

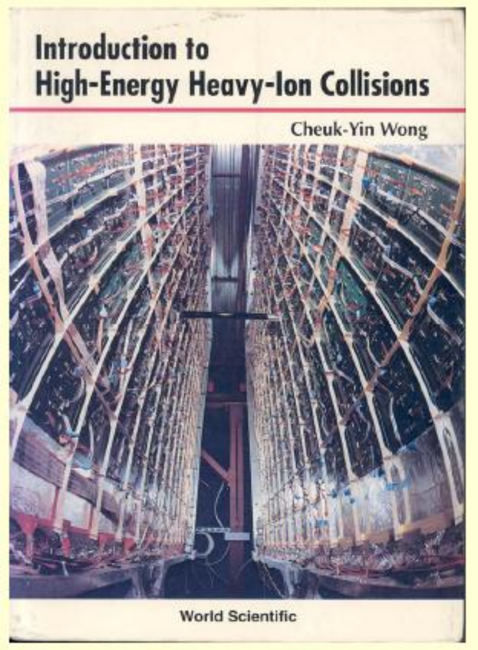
Ramona Vogt



The QCD Vacuum, Hadrons and Superdense Matter

Second Edition

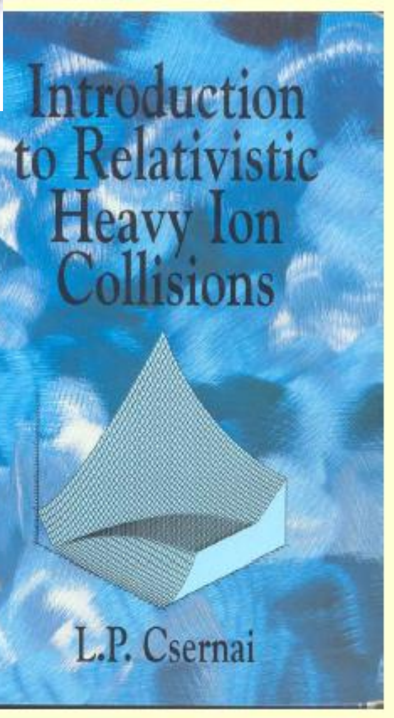
E. V. Shuryak



Introduction to High-Energy Heavy-Ion Collisions

Cheuk-Yin Wong

World Scientific

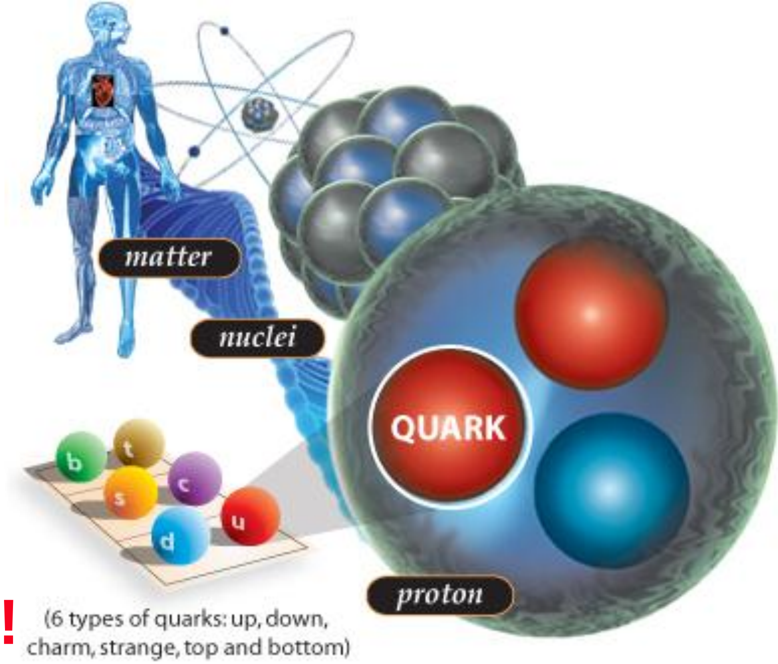


Introduction to Relativistic Heavy Ion Collisions

L.P. Csernai

QCD (Quantum Chromo Dynamics)

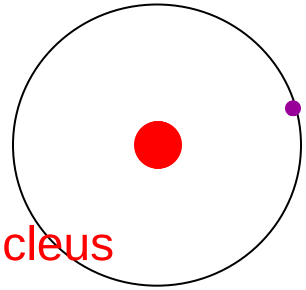
- strong interaction
  - binds quarks in hadrons
  - binds nucleons in nuclei
- described by QCD
  - interaction between particles carrying color charge
  - mediated by gluon exchange
  - gluons are colored themselves! (→ complicated vacuum)
- QCD: a very successful theory
  - jets / particle production at high pT
  - heavy-flavor production
  - ….
- with two fundamental properties/puzzles



Confinement

- **isolated quarks have never been detected**

let’s look at an atom…



electron

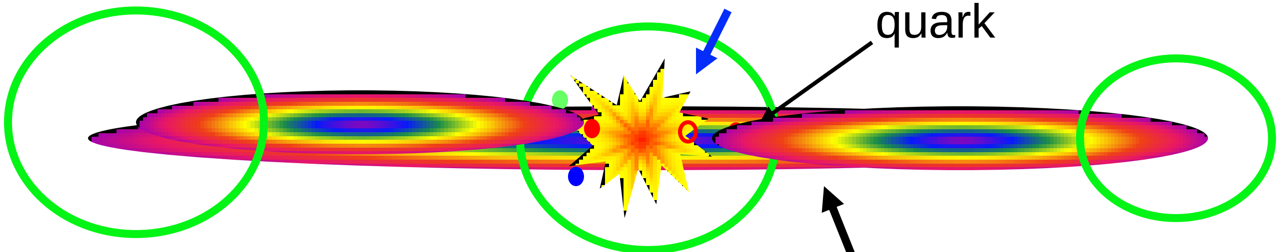
…isolating the constituents works

nucleus

neutral atom

confinement: fundamental property of QCD:
- colored objects can’t be isolated

$$V(r) \propto -\frac{\alpha_s(r)}{r} + \kappa r$$



quark-antiquark pair
from the vacuum

quark

“white” proton (baryon)
(confinement)

strong color field

“white” proton

potential energy grows with distance !!!

(confinement)

“white” π0 (meson)

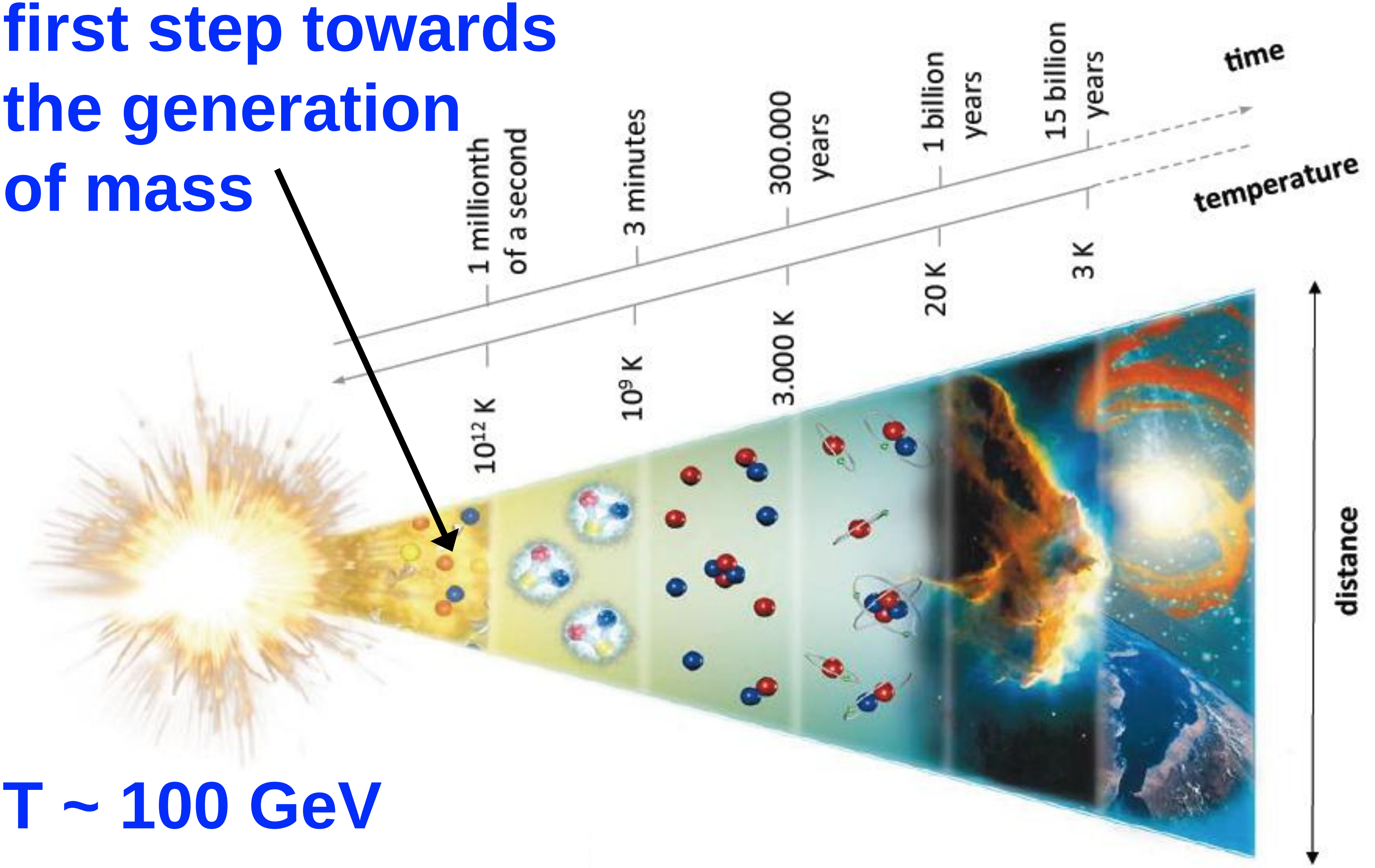
Animation: C. Markert

Hadron masses

- proton: two up quarks and a down quark
  - sum of quark masses: ~12 MeV
  - proton mass: ~938 MeV
- how does nature generate massive hadrons from (almost) massless quarks?
  - it happened a long time ago …

A short history of the universe

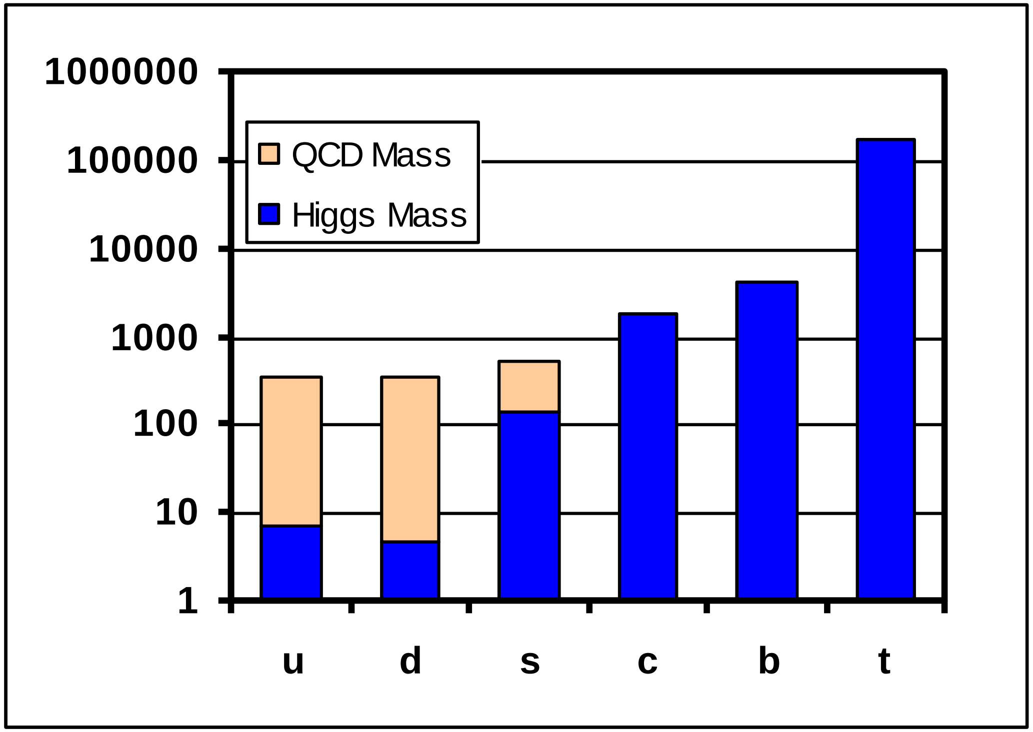
- first step towards the generation of mass



- T ~ 100 GeV
  - elementary particles get mass via Higgs mechanism

Quark masses

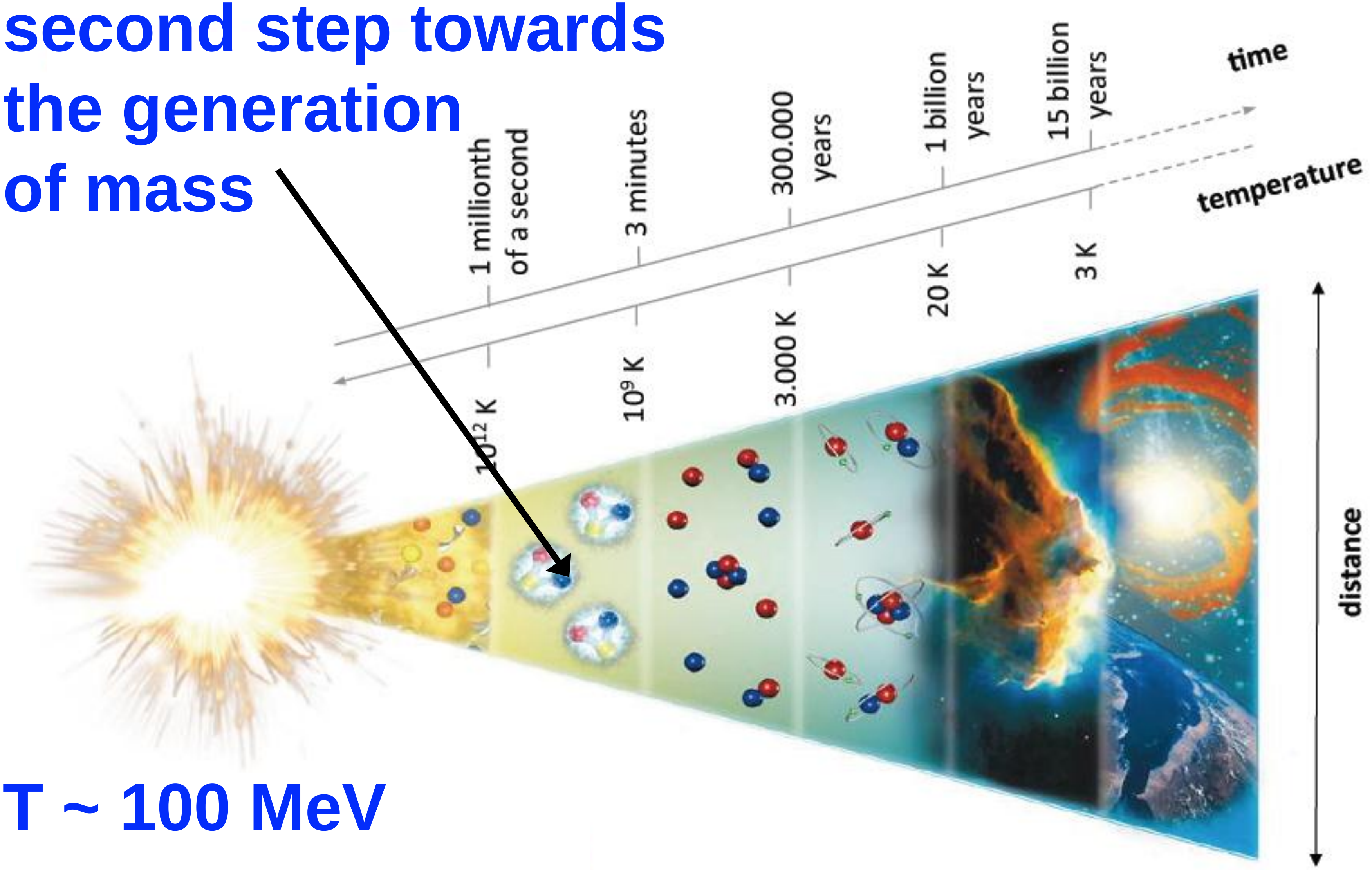
- current quark mass
  - generated by spontaneous symmetry breaking (Higgs mass)
  - contributes ~2% to the visible (our) mass



- constituent quark mass (QCD mass)
  - generated during hadronization
  - related to
    - chiral symmetry breaking
    - quark & gluon condensates

A short history of the universe

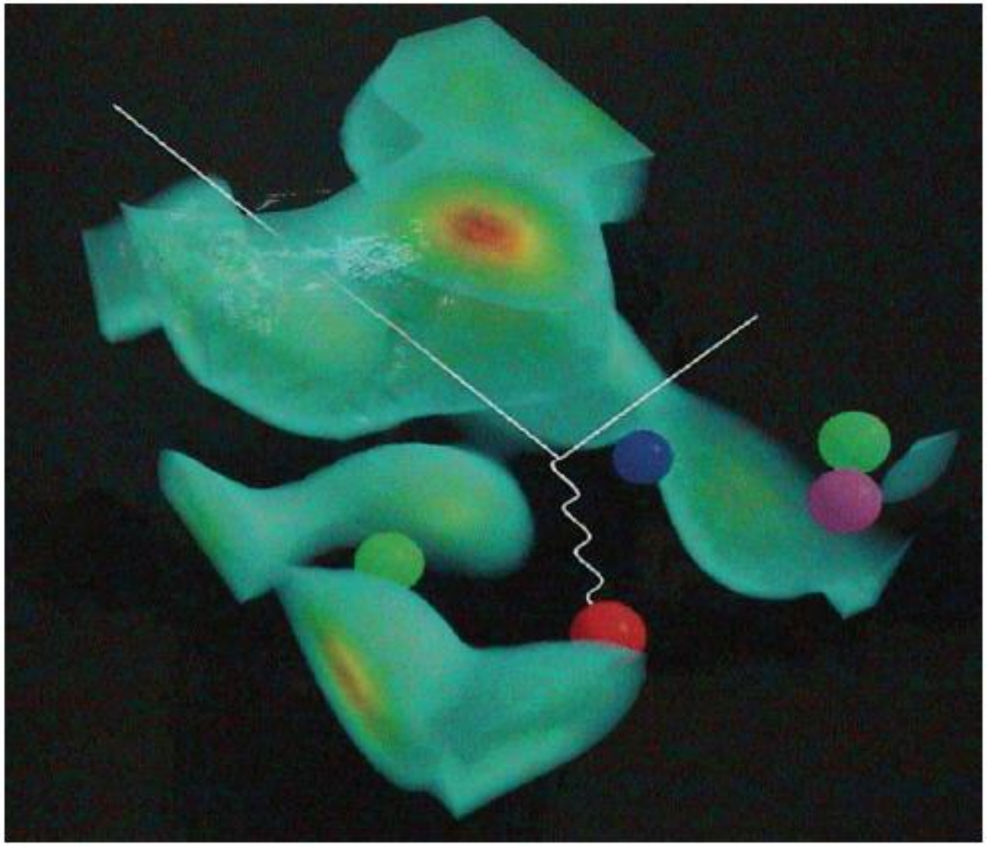
- second step towards the generation of mass



- T ~ 100 MeV
  - hadronization

Hadrons as complex objects

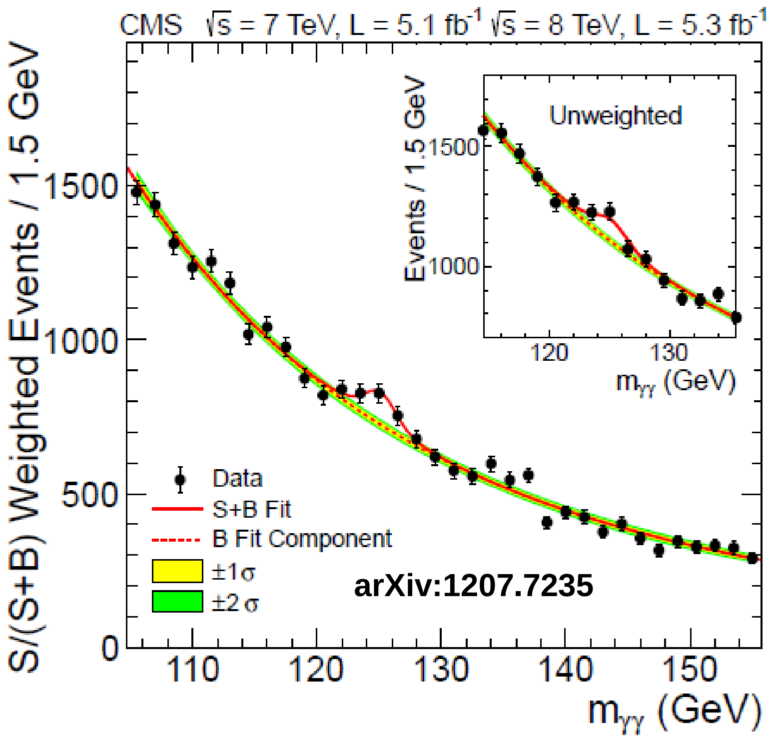
- hadron = complex excitation of valence quarks in the presence of quark and gluon condensates



- Frank Wilczek:
  - mass without mass
  - mass given by
    - energy stored in motion of quarks
    - energy in color gluon fields

Hadronization in vacuum

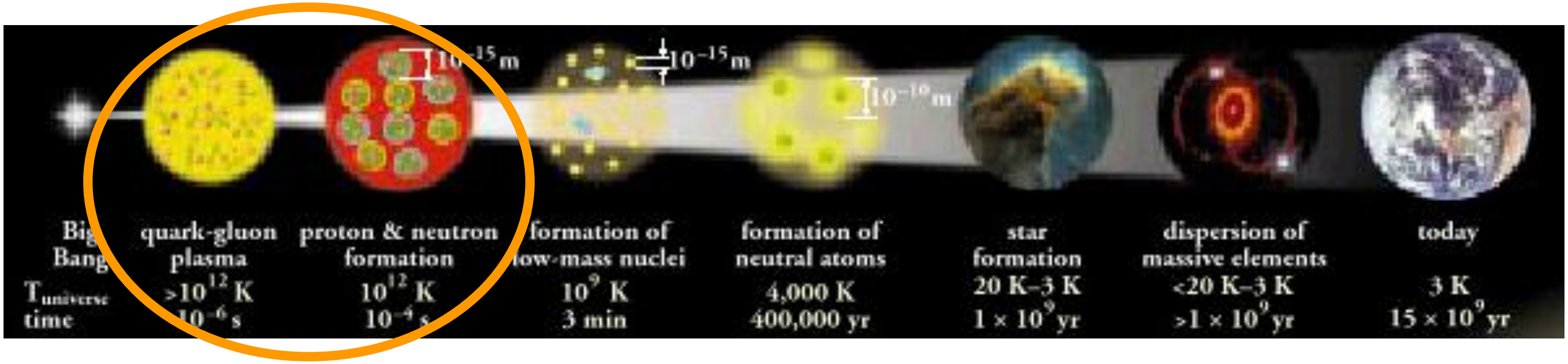
- mass of ordinary matter
  - ~2% via Higgs
  - ~98% via QCD
- can we prove this experimentally?
  - (successful?!) Higgs search at the LHC
  - QCD: study transition between quark-gluon and hadronic matter



arXiv:1207.7235

Phase transitions

- hadronization took place a few microseconds after the Big Bang



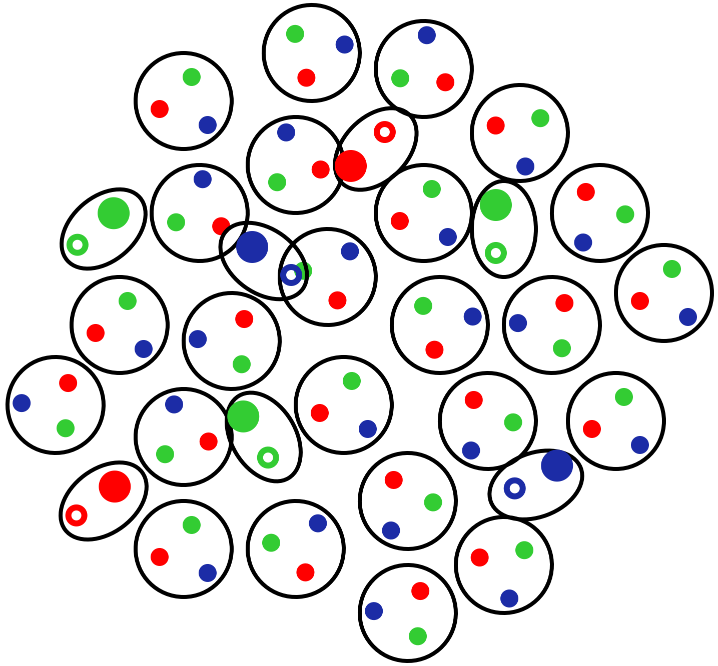
- common phenomenon: phase transition
  - examples
    - water vapor→ water → ide
      - electromagnetic interaction → QED
    - quarks/gluons → protons/neutrons → nuclei
      - strong interaction → QCD

Strongly interacting matter

- naive picture of different phases of strongly interacting matter
  - increasing temperature → thermal motion and production of mesons
  - increasing density

→ hadrons „overlap“

→ quarks and gluons become the relevant degrees of freedom

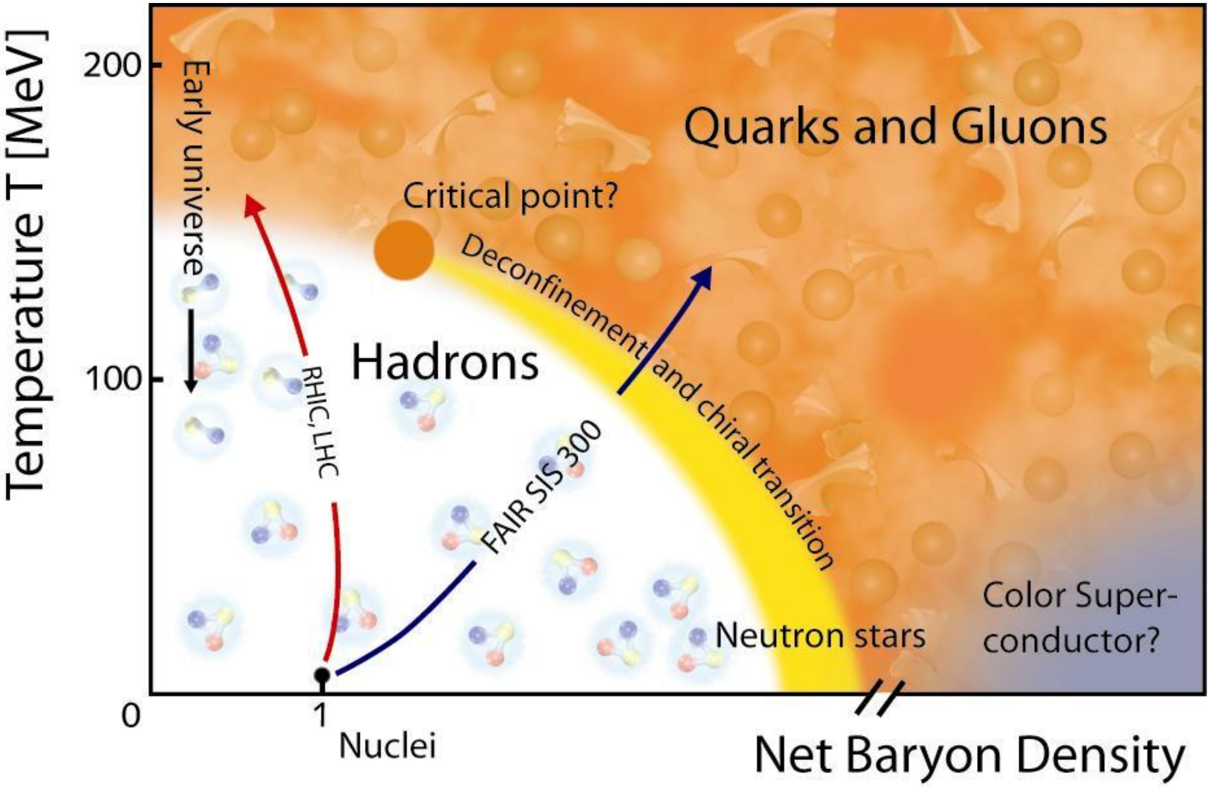


Quark-Gluon Plasma

hadronic matter

Phase diagram

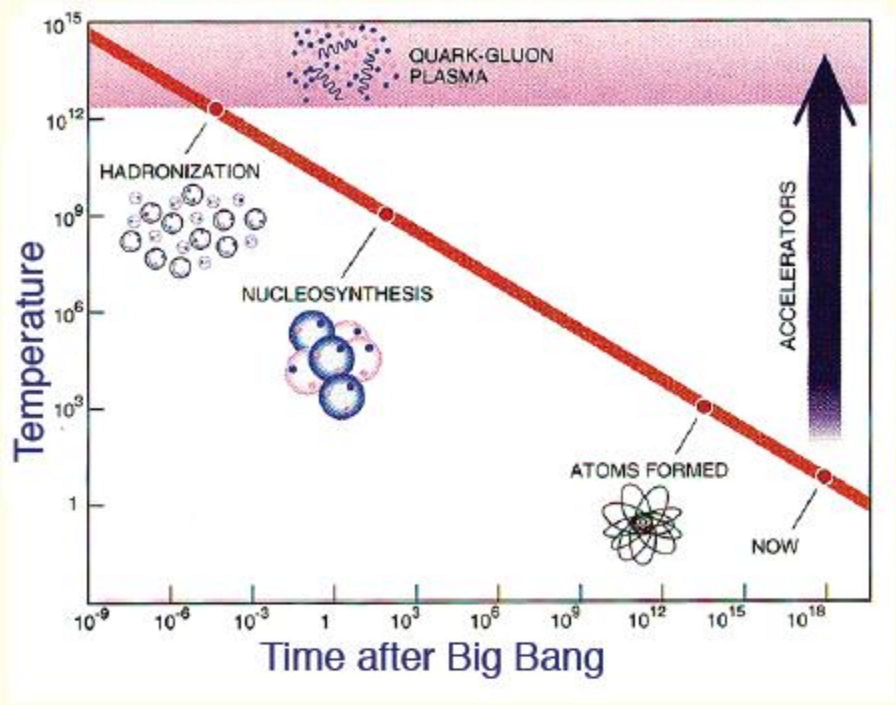
- main goal of relativistic heavy-ion physics
  - study the properties of nuclear matter, hadronic matter, and partonic matter

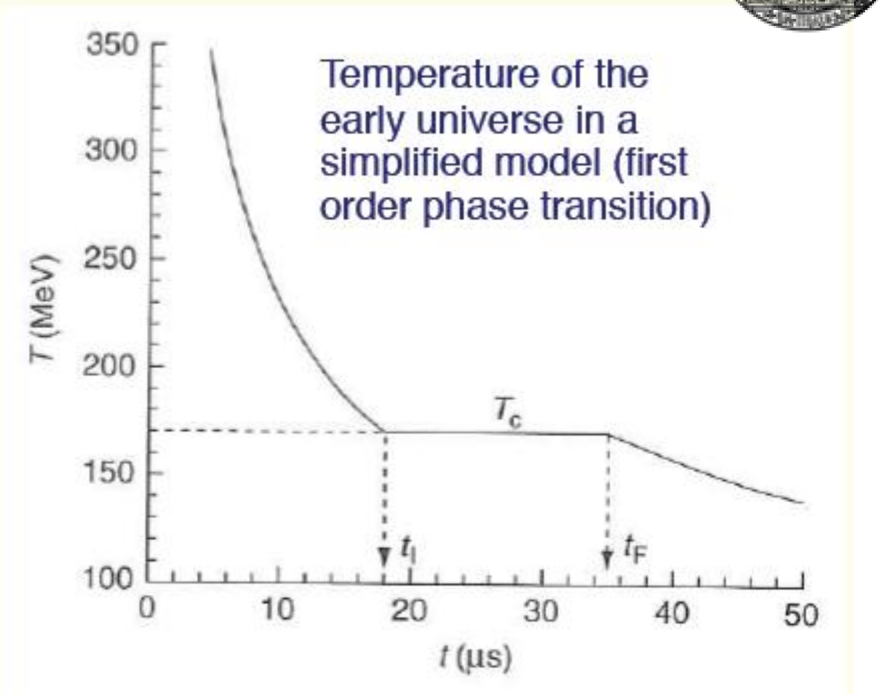


- relations to other fields
  - nuclear physics
    - collective effects
    - in-medium effects
  - astrophysics
    - neutron stars
    - Supernovae
  - cosmology
    - early universe

- only (!) experimental approach in the lab: nucleus-nucleus collisions

„Mini Bang“ in the laboratory




Temperature of the early universe in a simplified model (first order phase transition)

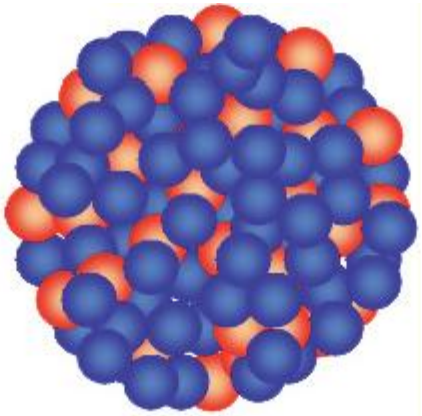
- **Quark-Gluon Plasma → hadron gas at T ~ 10^{12} K**
  - **~100000 times hotter than the core of the sun**

- **reflects the early universe at a few microseconds after the Big Bang**

Some relevant energy densities

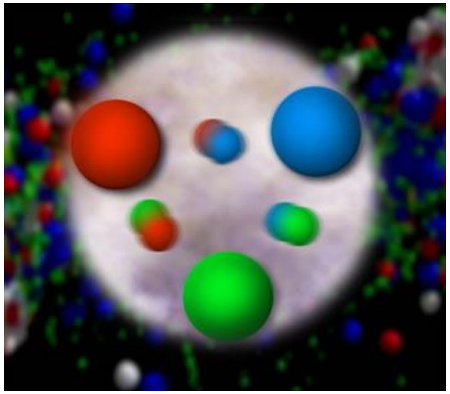
- inside an atomic nucleus
  - nucleon density: $\rho_0 = 0.16 \text{ nucleons}/fm^3$
  - nucleon mass: $M \approx 0.931\ GeV$

  → energy density:
  $\varepsilon_0 = \rho_0 M \approx 0.15\ GeV/fm^3$



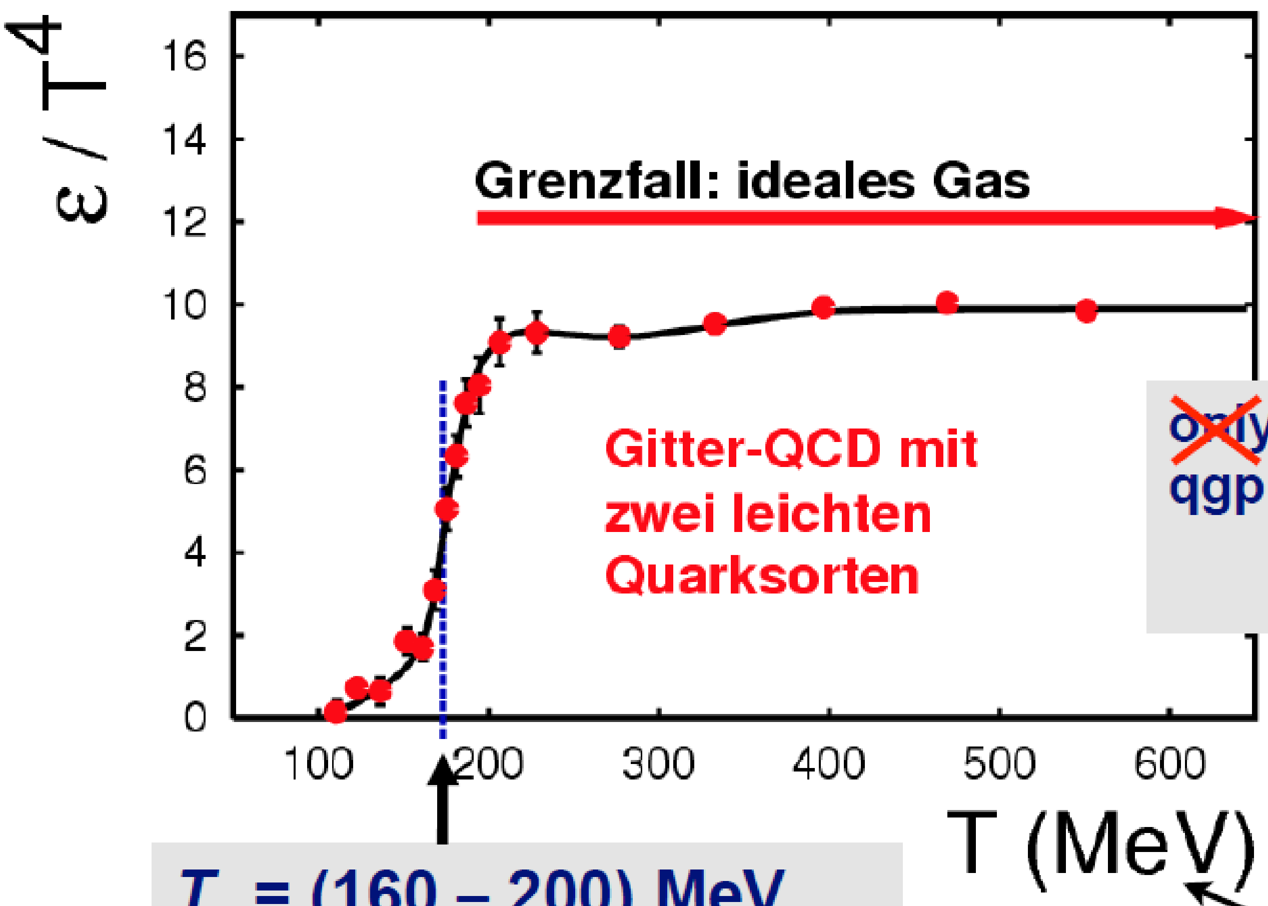
- inside a nucleon
  - radius: $r \approx 0.8\ fm$
  - mass: $M \approx 0.94\ GeV$

  → energy density:
  $\varepsilon = \frac{M}{{}^4/_3 \pi r^3} \approx 0.44\ GeV/fm^3$



Phase transition in lattice QCD

F. Karsch, E. Laermann, hep-lat/0305025



2 quark flavors:

$$\varepsilon_{SB} = g \cdot \frac{\pi^2}{30} \cdot T^4$$

with $g = 37$

~~only~~ 20% deviation:
qgp is not an ideal gas

T_c = (160 – 200) MeV

$\varepsilon_c \approx$ 0.7 – 1.0 GeV/fm³

temperatures in eV:

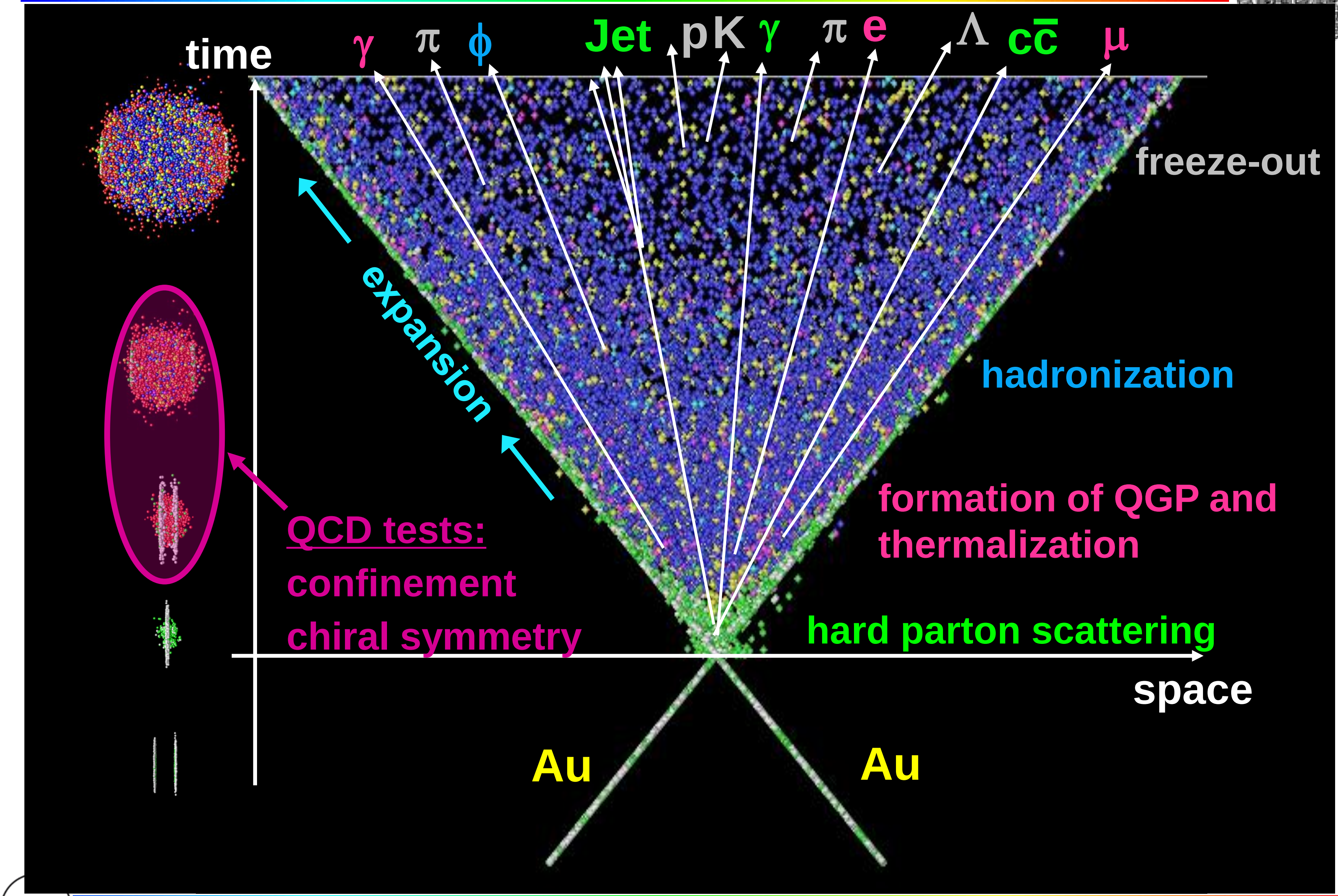
Example: room temp.

$$k \cdot T = k \cdot 300\ \mathrm{K} = 1/40\ \mathrm{eV}$$

“stolen” from K. Reygers

Pb-Pb collision in UrQMD

Schematic A-A collision



freeze-out

expansion

hadronization

formation of QGP and thermalization

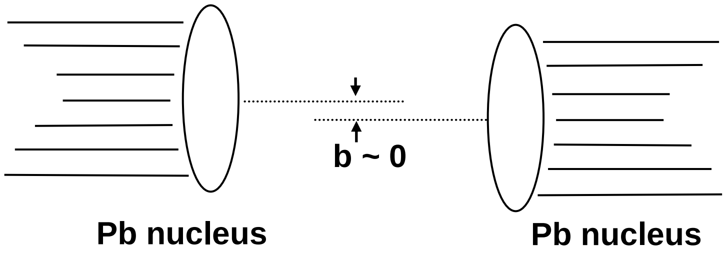
<u>QCD tests:</u>

confinement

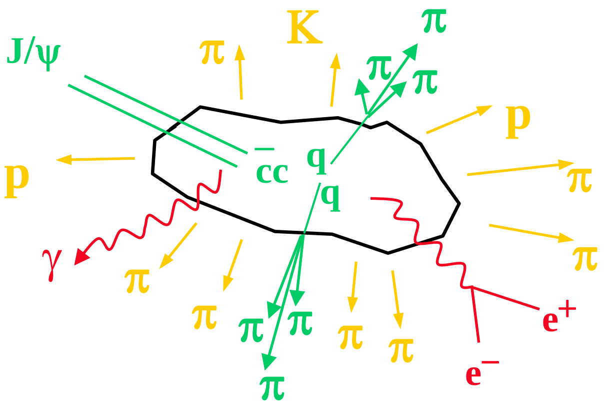
chiral symmetry

hard parton scattering

Probes for all time scales



production of ~18000 charged particles per central collision



- hard probes: jets, heavy quarks, direct γ
  - rare, produced very early (prior to QGP formation)
    - – interaction with produced hot and dense medium

- hadrons: π, K, p
  - common, produced late (at freeze out)
    - – energy density
    - – thermalization
    - – collective motion

- electromagnetic radiation: γ, e^+e^-, $\mu^+\mu^-$
  - rare, probes for all time scales, because of lack of strong final state interaction
    - – black body radiation ⇒ initial temperature
    - – in-medium properties of light vector mesons ⇒ chiral symmetry restoration

Heavy-ion physics programs

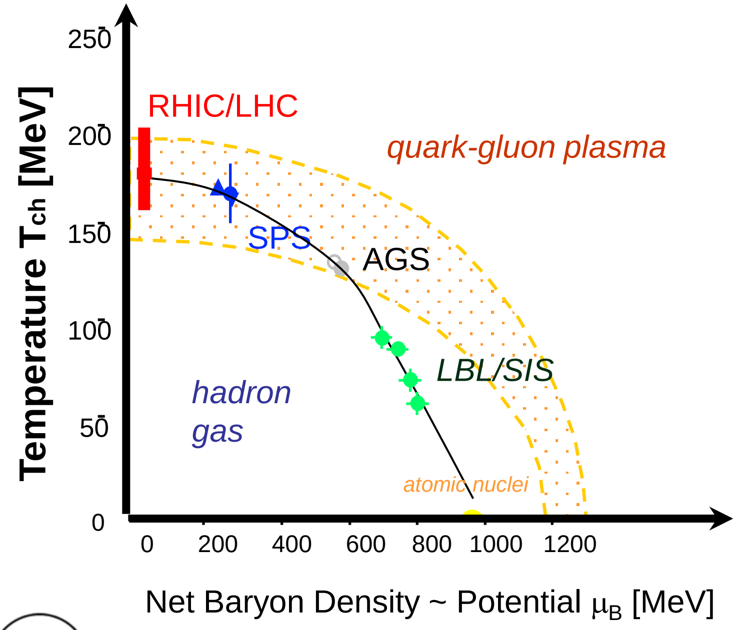
Start	Accelerator	Projectile	Max. energy per NN pair ($\sqrt{s_{NN}}$)
~1985	AGS (BNL)	Si	~5 GeV
~1985	SPS (CERN)	O, S	~20 GeV
1994	SPS (CERN)	Pb	17 GeV
2000	RHIC (BNL)	Au	200 GeV
2010 (Nov. 8)	LHC (CERN)	Pb	2760 GeV

Why high energy?

Most of the important goals have NOT changed over the last 20 years..

Properties of the produced medium depend strongly on energy.

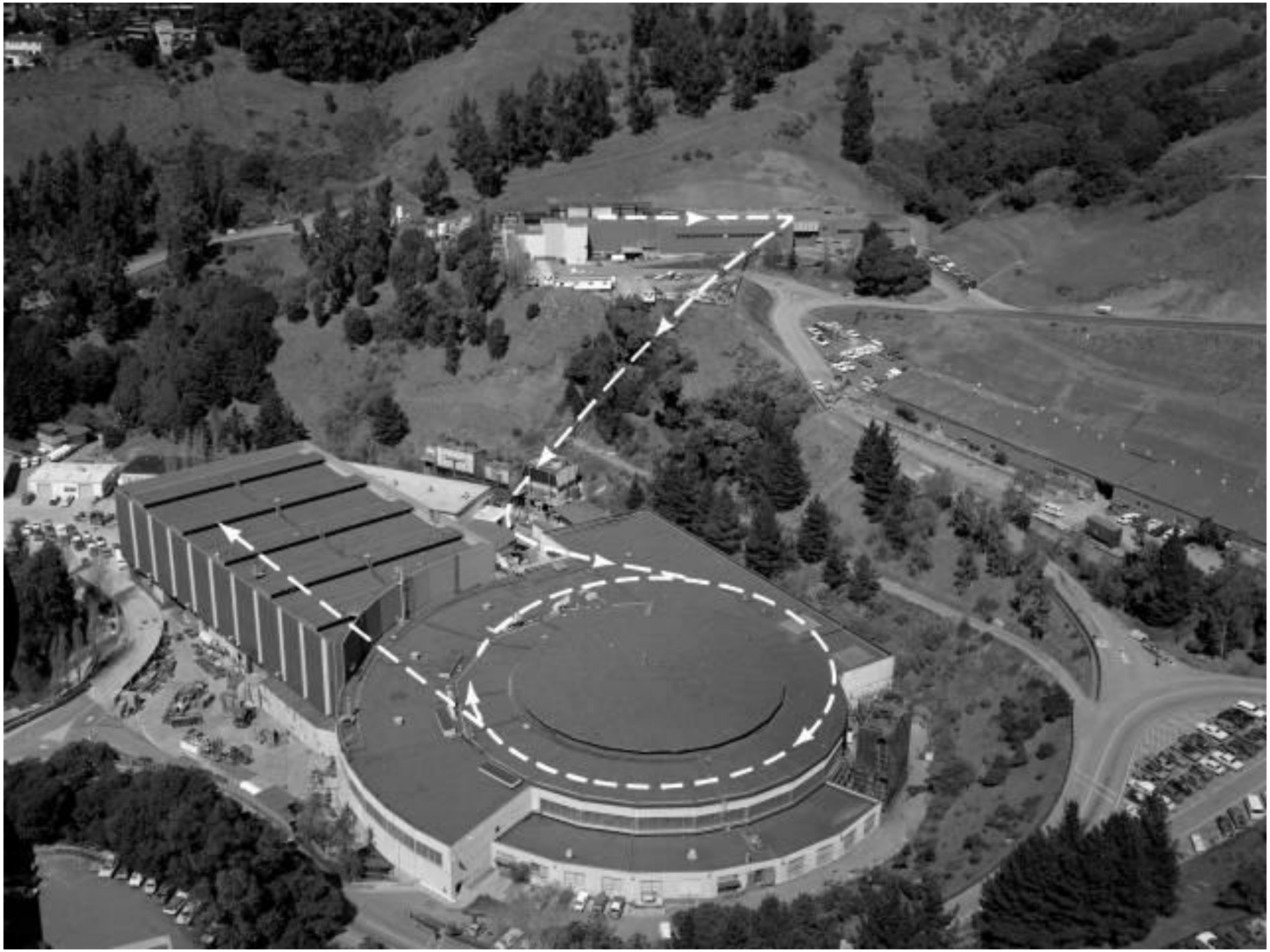
High energies give access to more experimental probes and theoretical tools.



Bevalac-LBL 2.2 GeV	nuclear fragmentation production of resonances strangeness threshold
AGS-BNL 4.8 GeV	“resonance matter” large baryon density strangeness important
SPS-CERN 17.3 GeV	charm production relevant
TEVATRON-FNAL 38.7 GeV	
RHIC-BNL 200.0 GeV	small baryon density hard parton scattering
LHC-CERN 2760.0 GeV	beauty production

BEVALAC @ Berkeley

- BEVALAC = SuperHILAC + BEVATRON



AGS @ Brookhaven

- **Alternating Gradient Synchrotron**

SPS @ CERN

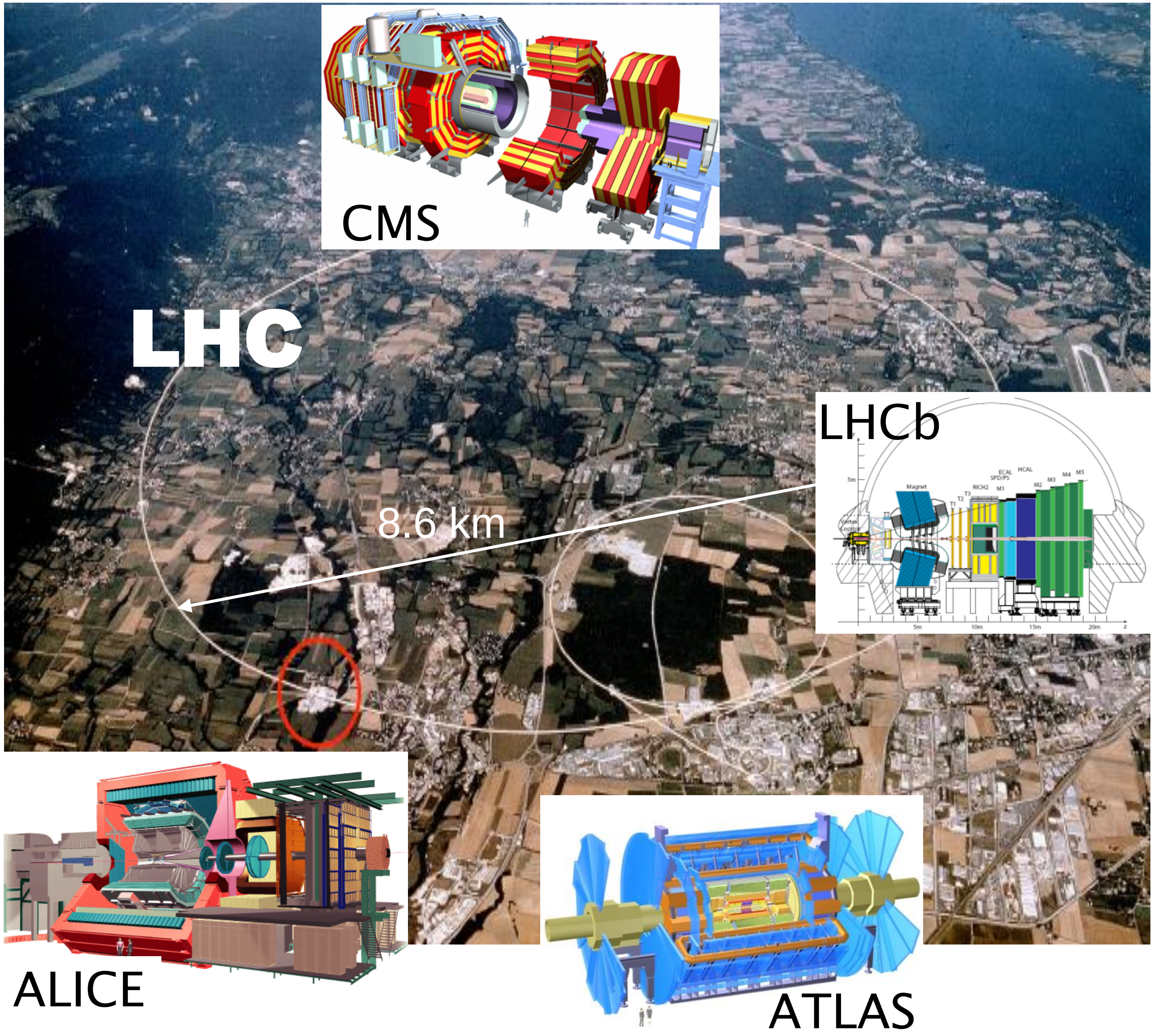
- **Super Proton Synchrotron**

RHIC @ Brookhaven

- **Relativistic Heavy-Ion Collider**
  - p+p: $\sqrt{s} \le 500$ GeV (polarized p → spin physics)
  - A+A: $\sqrt{s_{NN}} \le 200$ GeV (per nucleon-nucleon pair)

- experiments with specific focus
  - BRAHMS (- 2006)
  - PHOBOS (- 2005)
- general purpose experiments
  - PHENIX
  - STAR

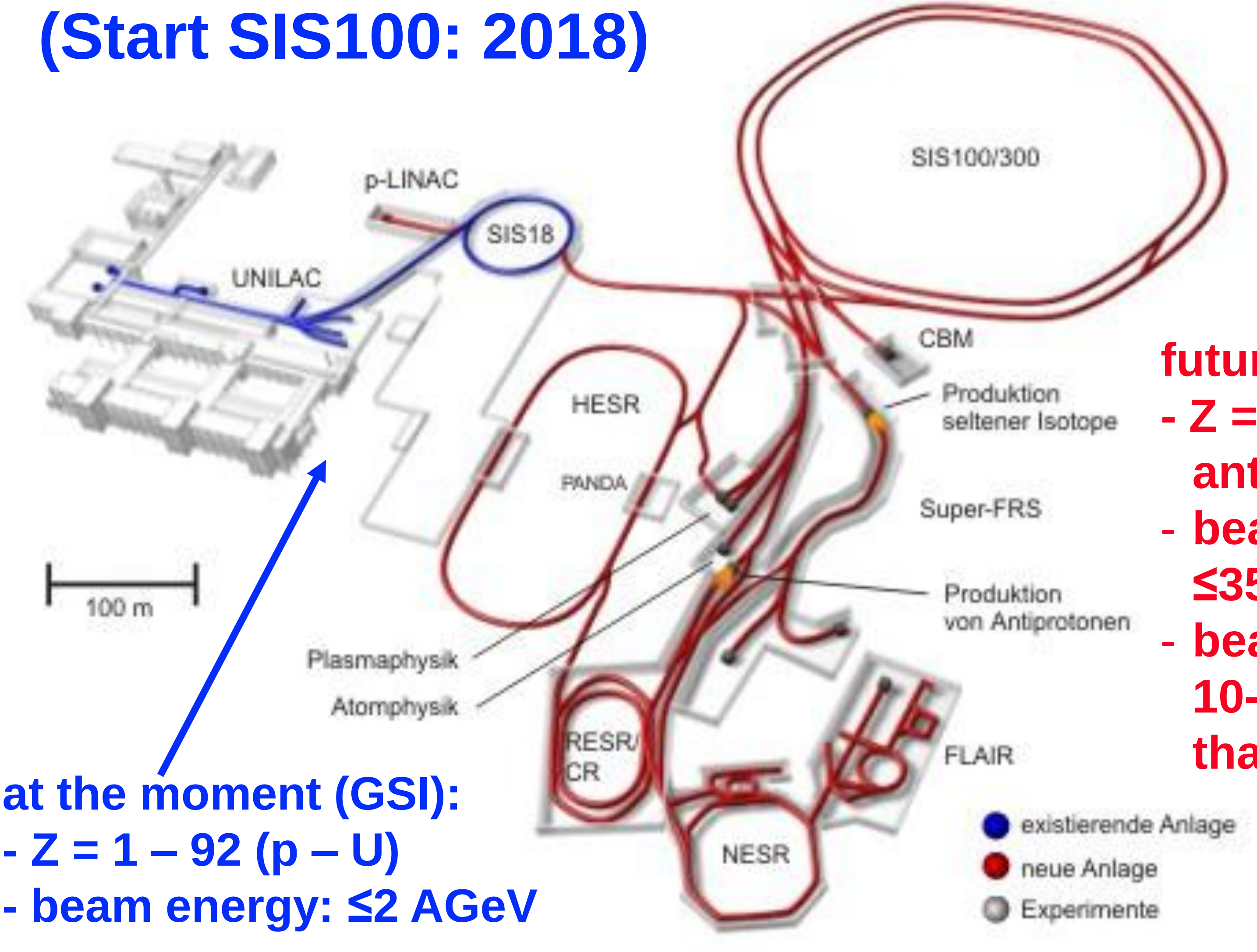
Large Hadron Collider @ CERN



- **dedicated heavy-ion experiment: ALICE**

FAIR @ GSI

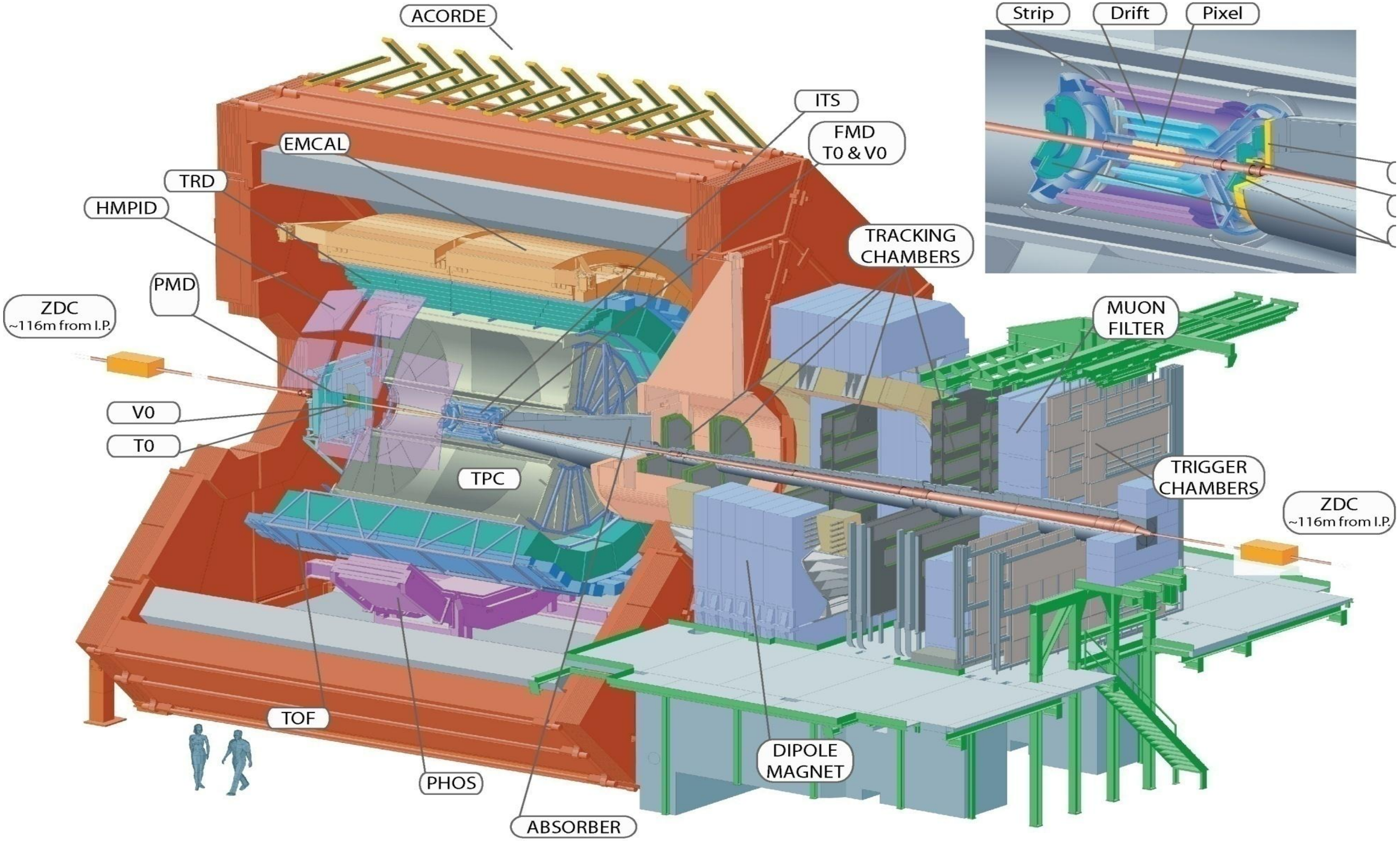
- Facility for Antiproton and Ion Research (Start SIS100: 2018)



future:
- Z = -1 – 92 (p – U, anti protons)
- beam energy: ≤35 AGeV
- beam intensities 10-1000 larger than at SIS18

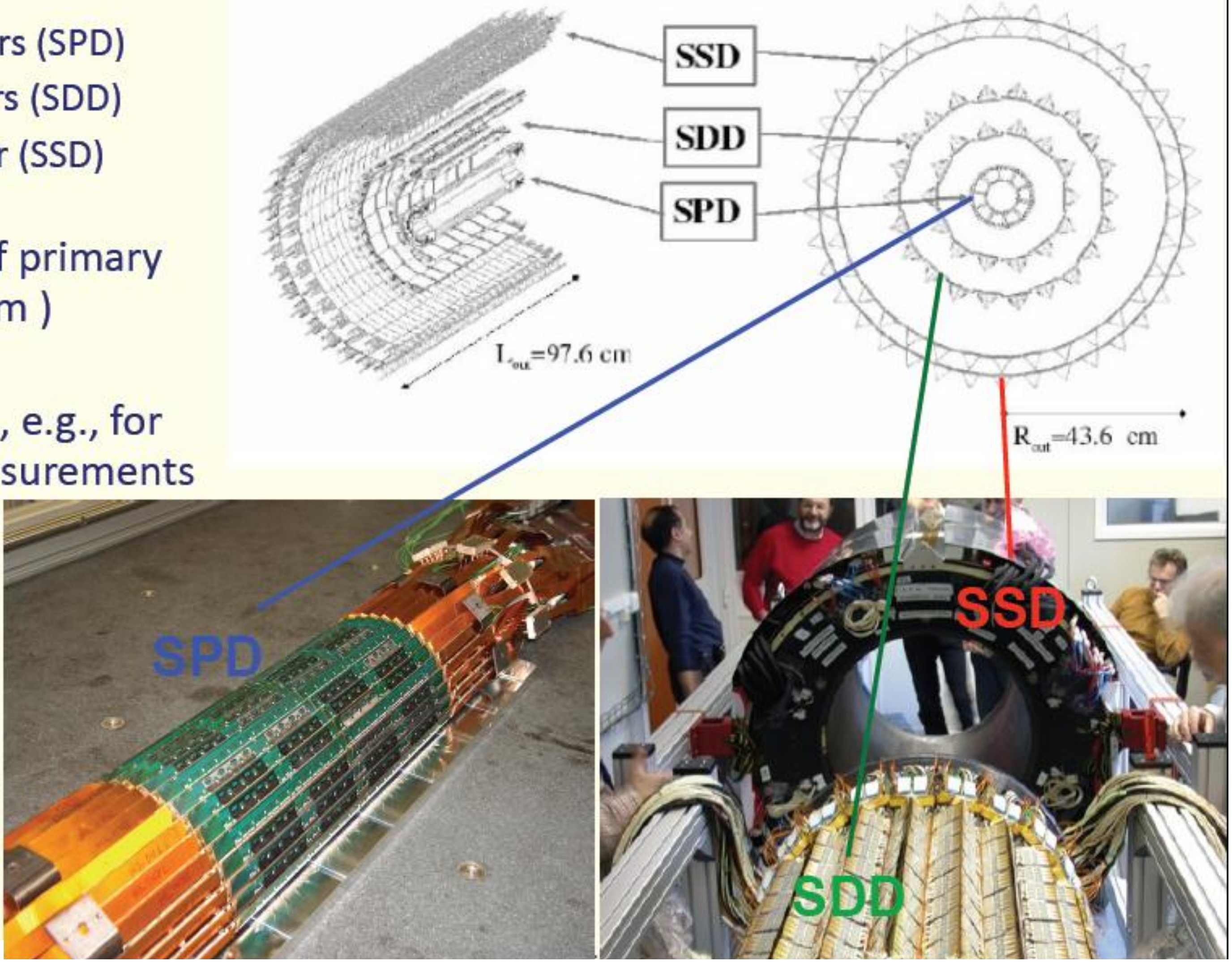
at the moment (GSI):
- Z = 1 – 92 (p – U)
- beam energy: ≤2 AGeV

ALICE at the LHC



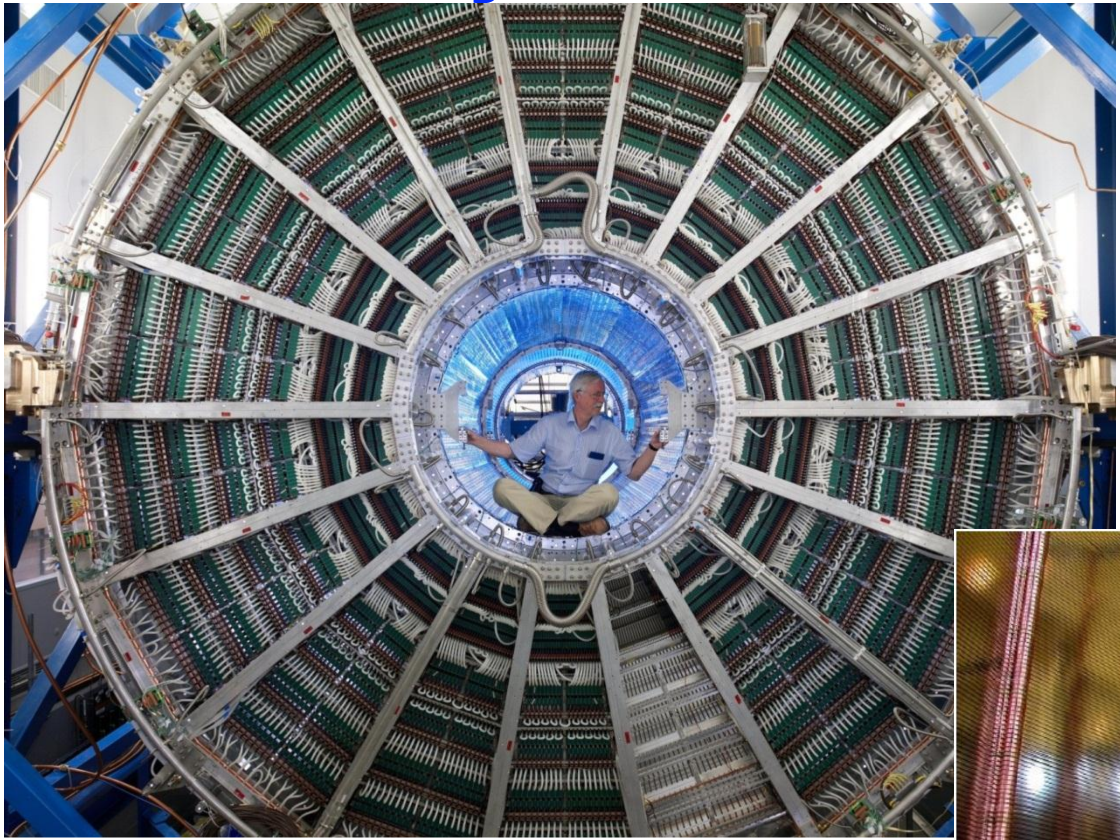
Inner Tracking System (ITS)

- 6 layers silicon
  - 2 pixel detectors (SPD)
  - 2 drift detectors (SDD)
  - 2 strip detector (SSD)
- Reconstruction of primary vertex (σ < 100 μm)
- Secondary vertex, e.g., for heavy-quark measurements (see next slide)

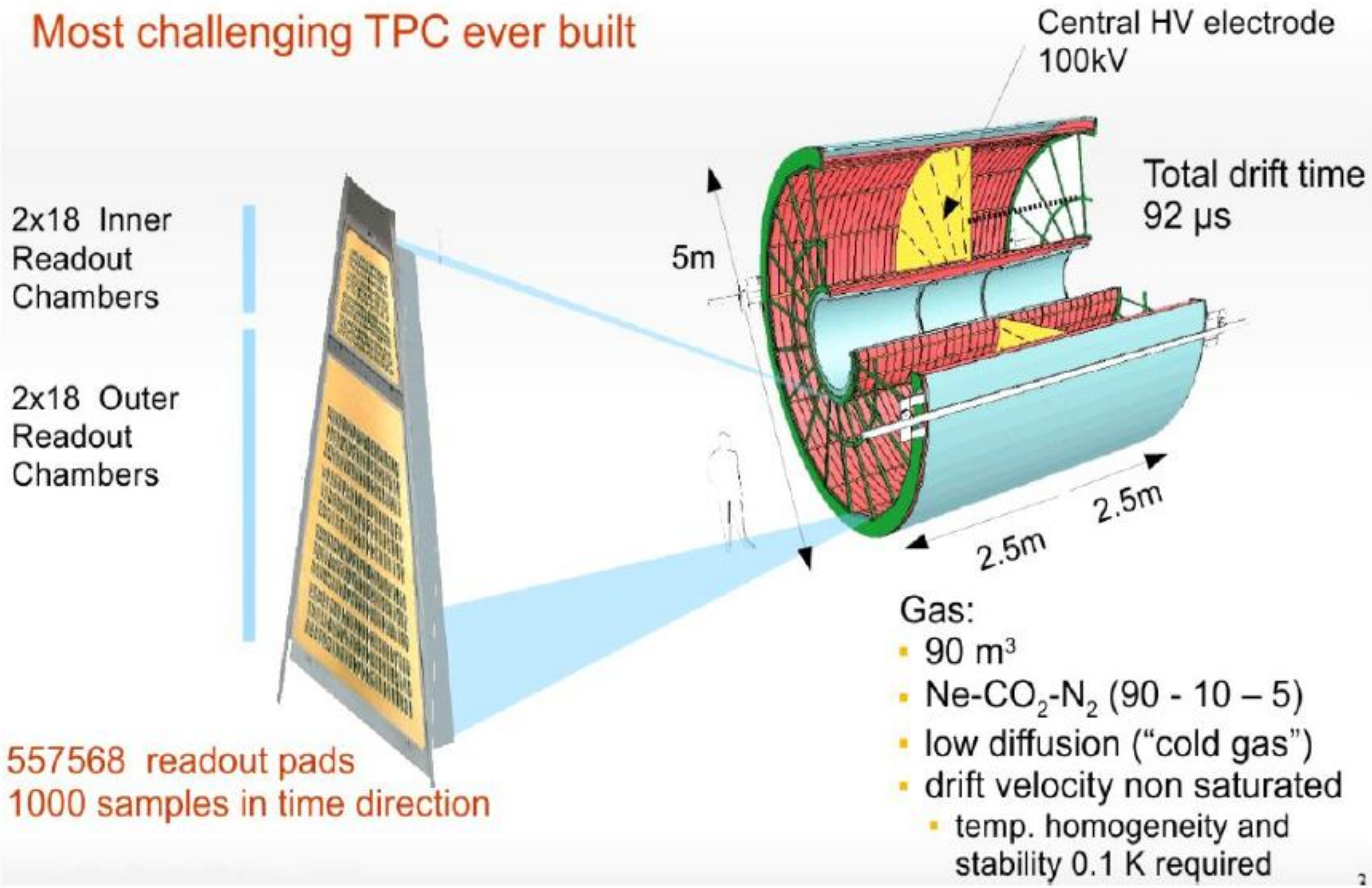


“stolen” from K. Reygers

Time Projection Chamber (TPC)



Time Projection Chamber



Most challenging TPC ever built

2x18 Inner Readout Chambers

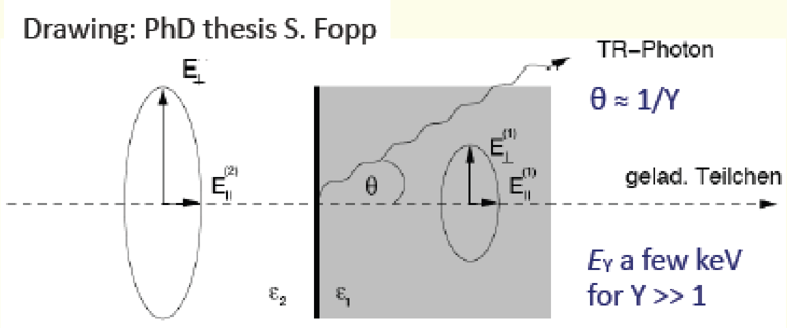
2x18 Outer Readout Chambers

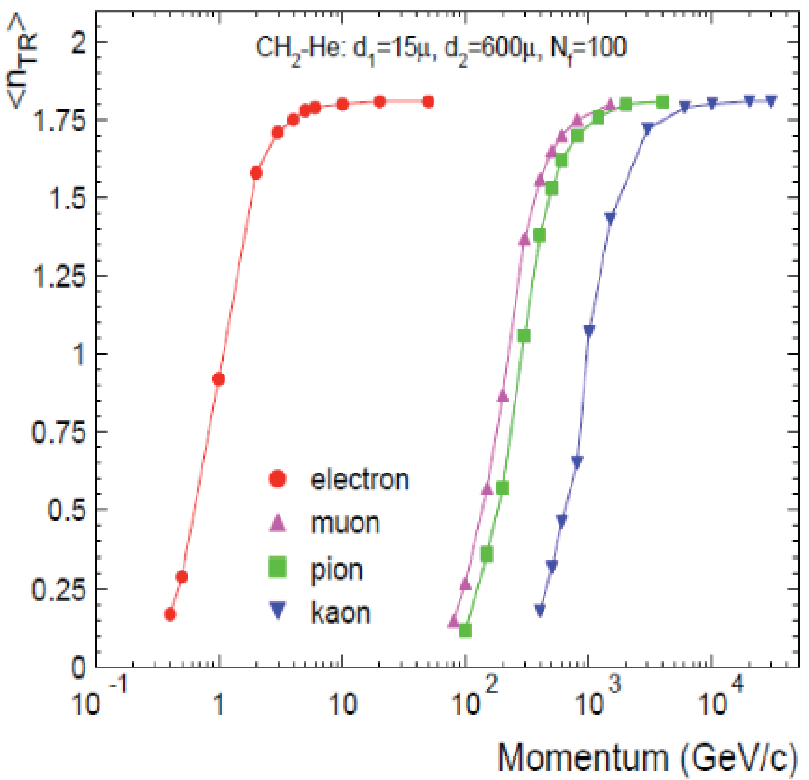
557568 readout pads
1000 samples in time direction

Gas:

- 90 m³
- Ne-CO_2-N_2 (90 - 10 – 5)
- low diffusion (“cold gas”)
- drift velocity non saturated
  - temp. homogeneity and stability 0.1 K required

Transition Radiation


Drawing: PhD thesis S. Fopp

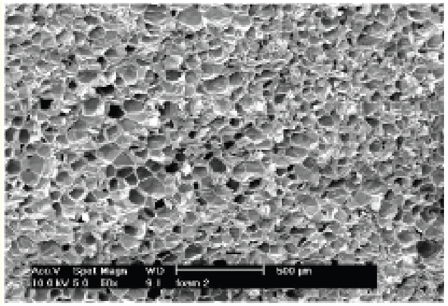


- Charged particles emit transition radiation when they cross boundaries of media with different dielectric constants ε
- Small probability for emission at single surface (~ α = 1/137) ⇒ many boundaries
- Significant TR photon production only for charged particles with Lorentz factor γ > 1000

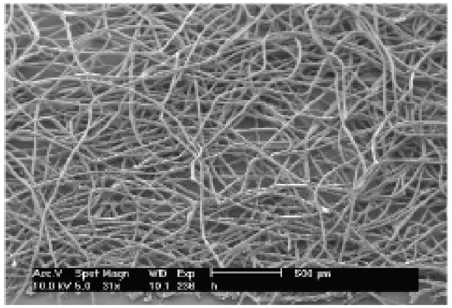
  ⇒ only electrons emit TR in the relevant momentum range 1 < p < 100 GeV/c

Typical TR radiators:

Foams



Fibers



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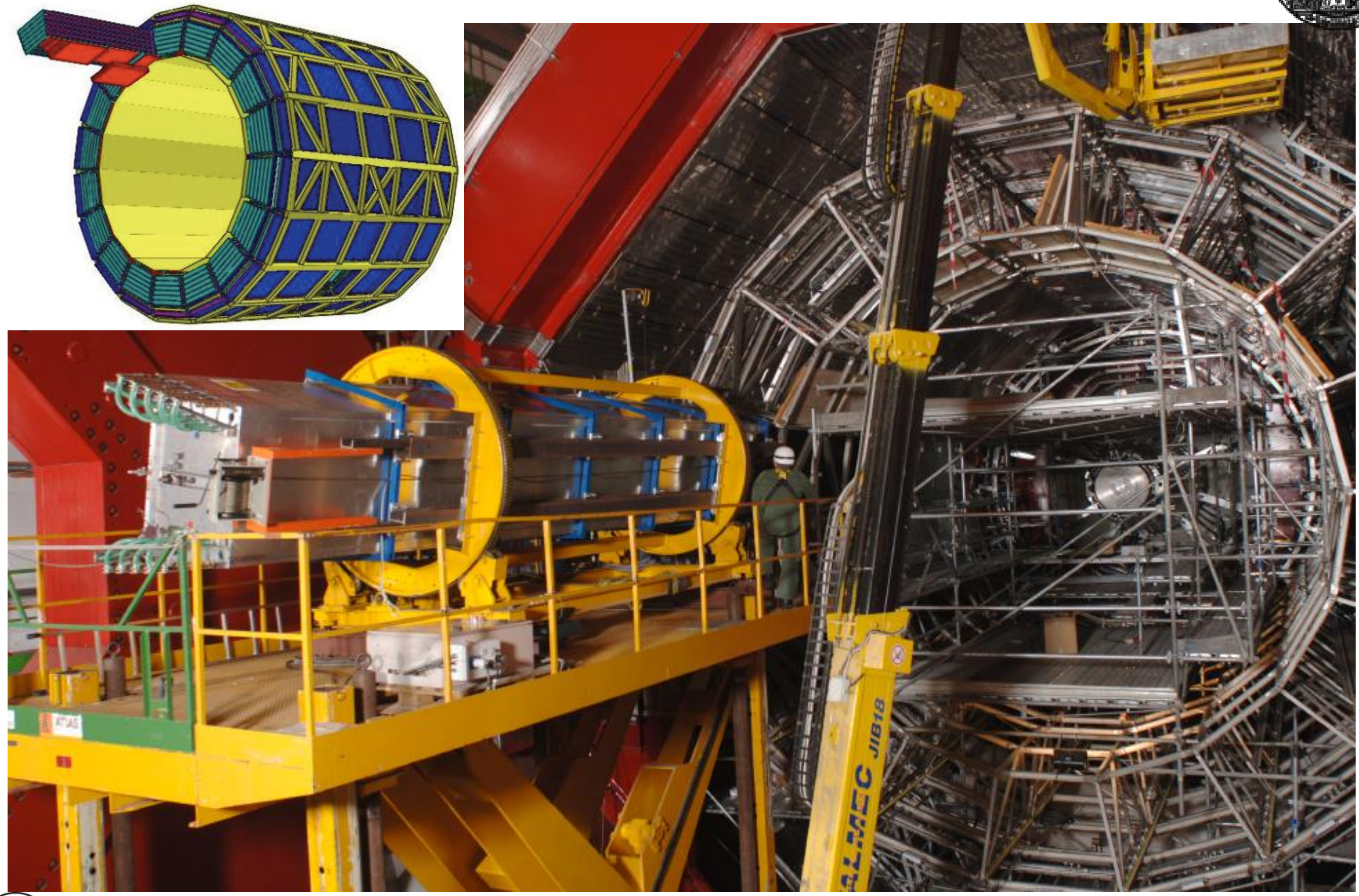
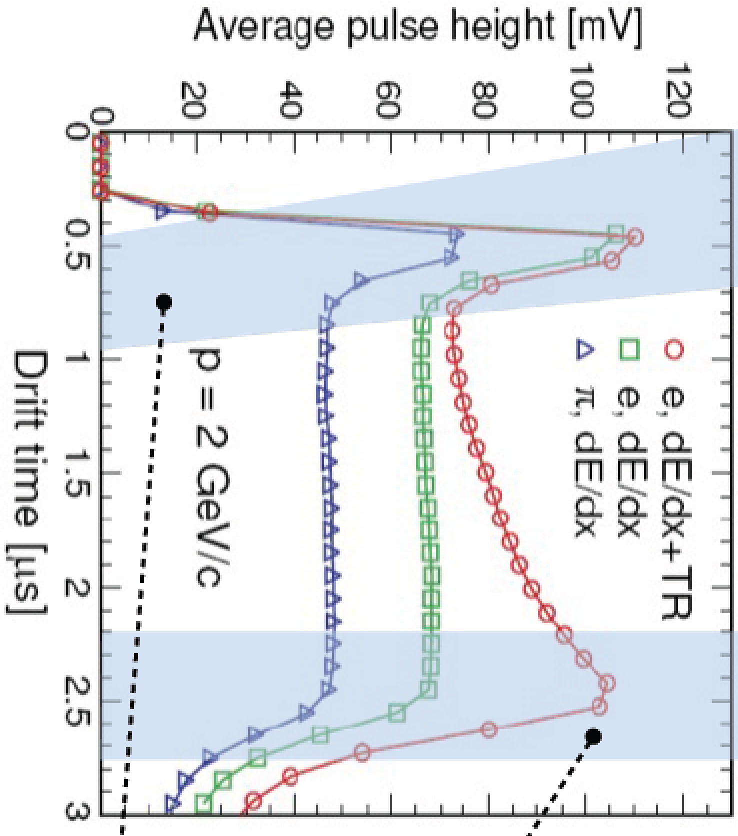
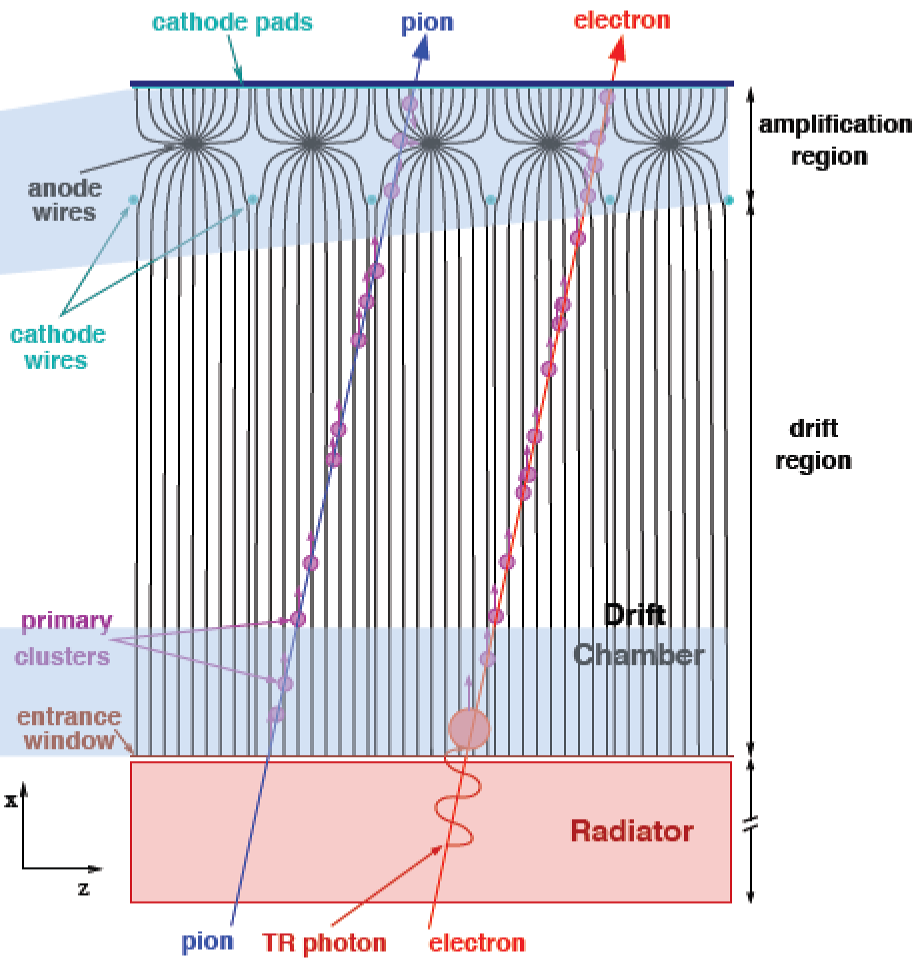
Transition Radiation Detector (TRD)



ALICE TRD





Avalanche

near anode wires
[high field]

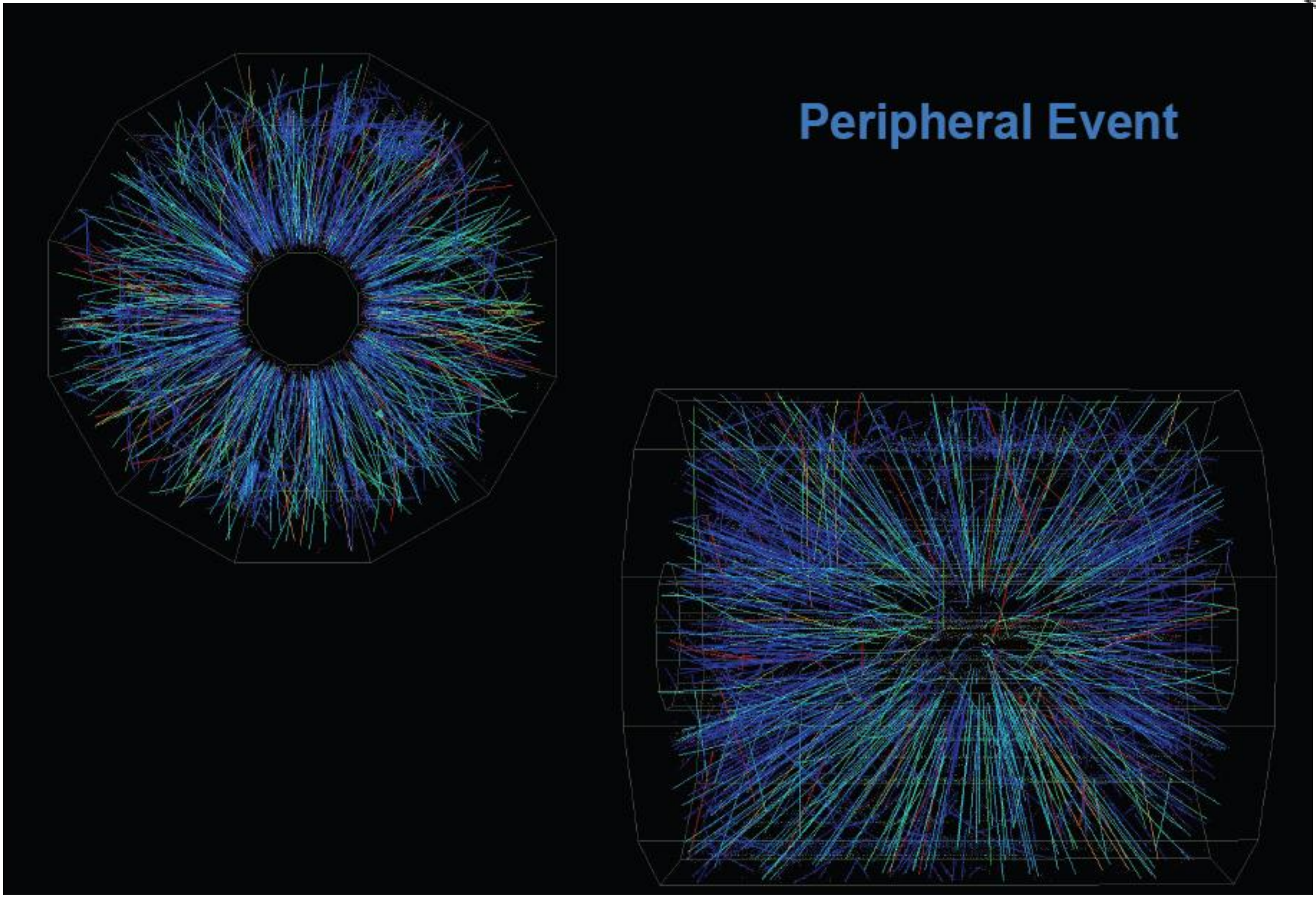
TR-Signal

Gas: Xenon
[High γ-absorption]

Transition Radiation [TR]

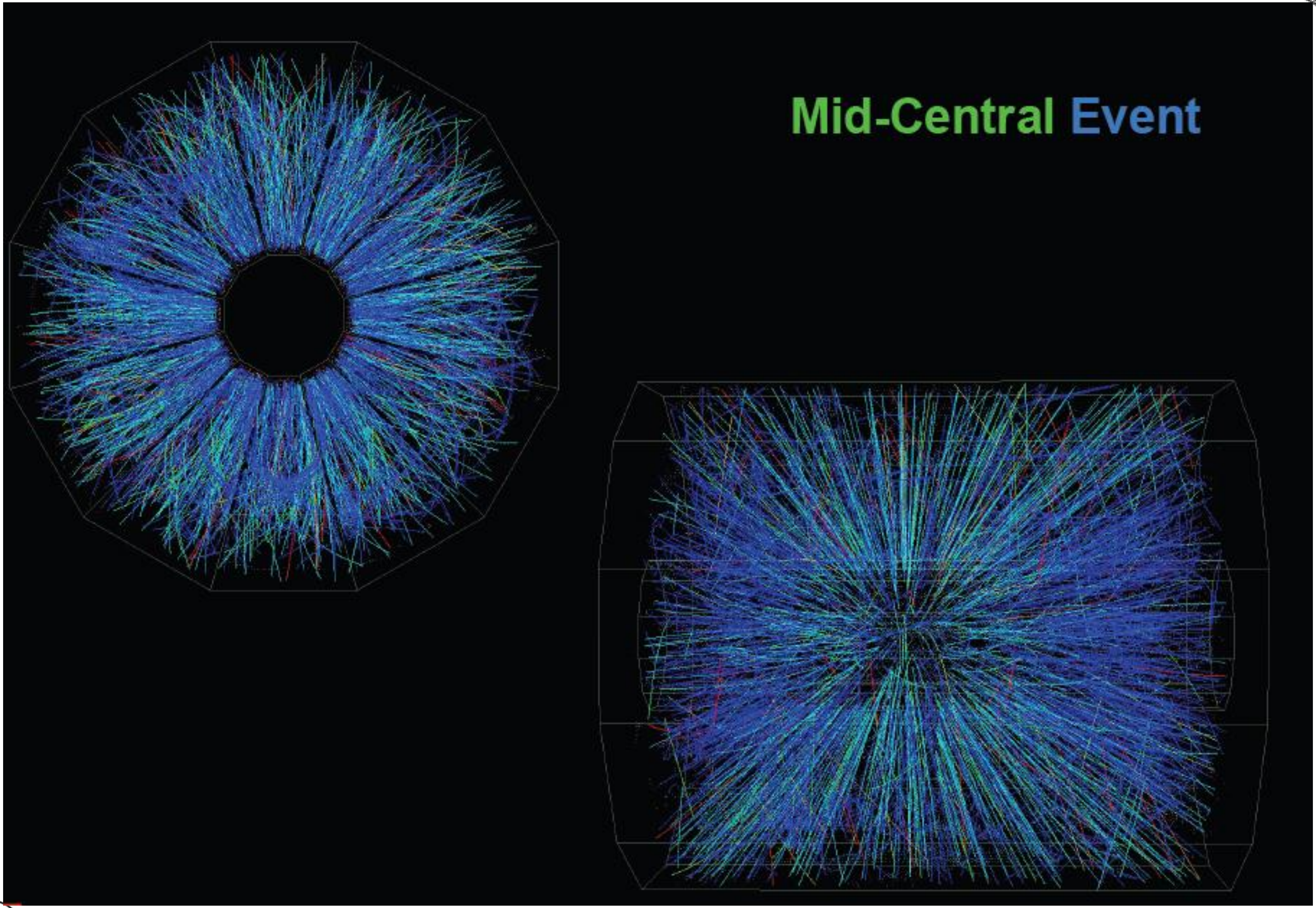
for charged Particles with γ > 1000

Collision Geometry

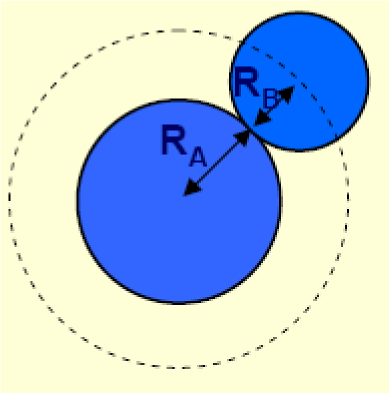


Peripheral Event

Collision Geometry

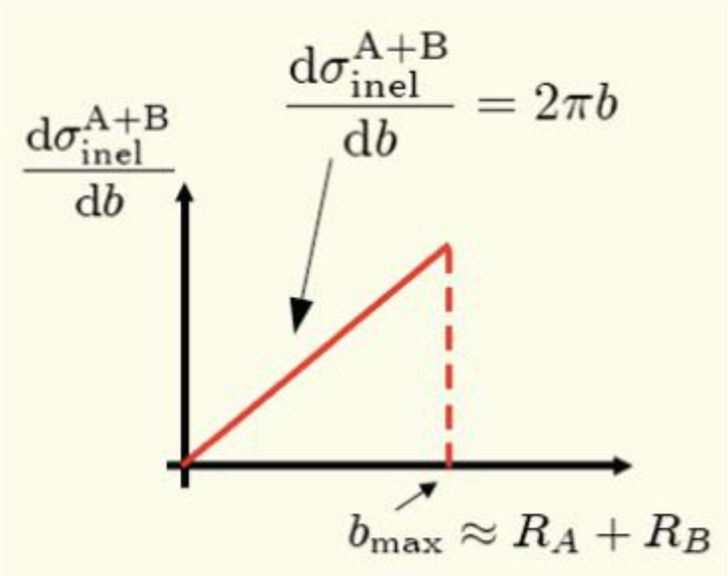


Nucleus-Nucleus Collision Geometry



- ultra relativistic energies
  - DeBroglie wave length << radius of nucleons

    → nucleon wave character can be ignored for estimate of cross section
- nucleus-nucleus collision as collision of two „black disks“

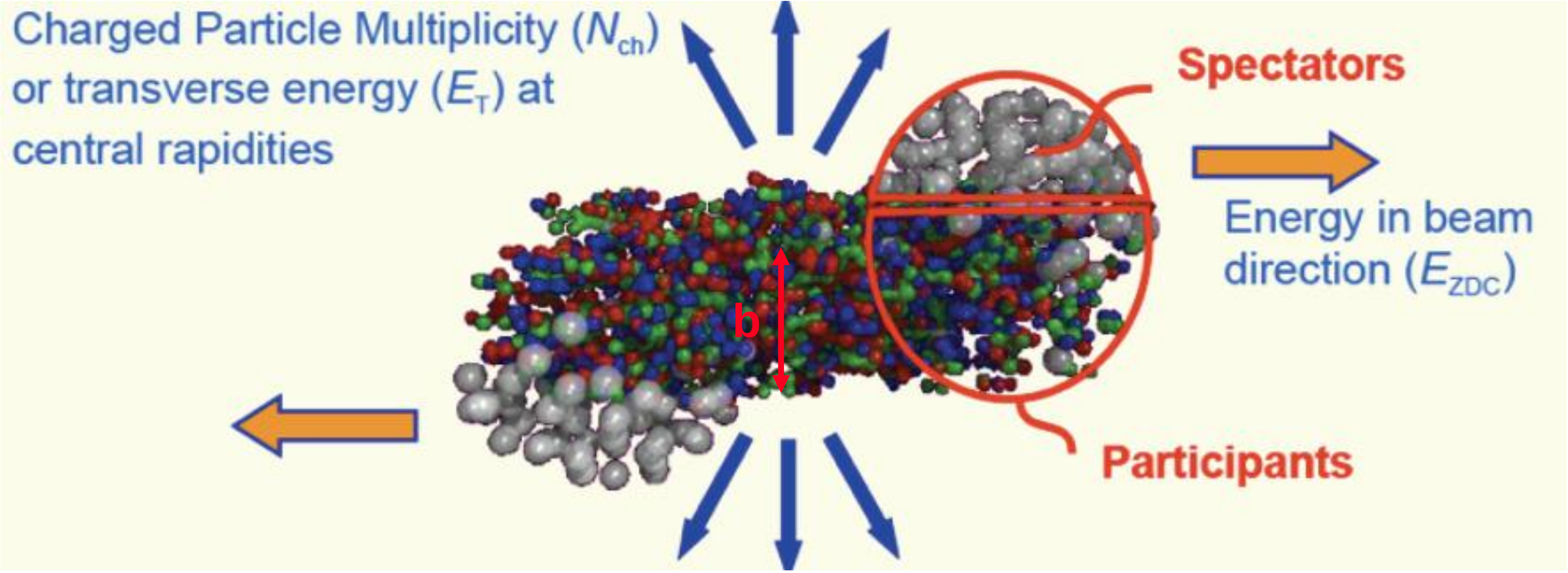


$$R_A \approx r_0 \cdot A^{1/3} \qquad \text{mit} \qquad r_0 = 1,2\ \text{fm}$$

$$\sigma_{\text{unel}}^{A+B} \approx \sigma_{geo} \approx \pi r_0^2 \left(A^{1/3} + B^{1/3}\right)^2$$

Centrality in AA Collisions

K. Reygers



- **centrality 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**

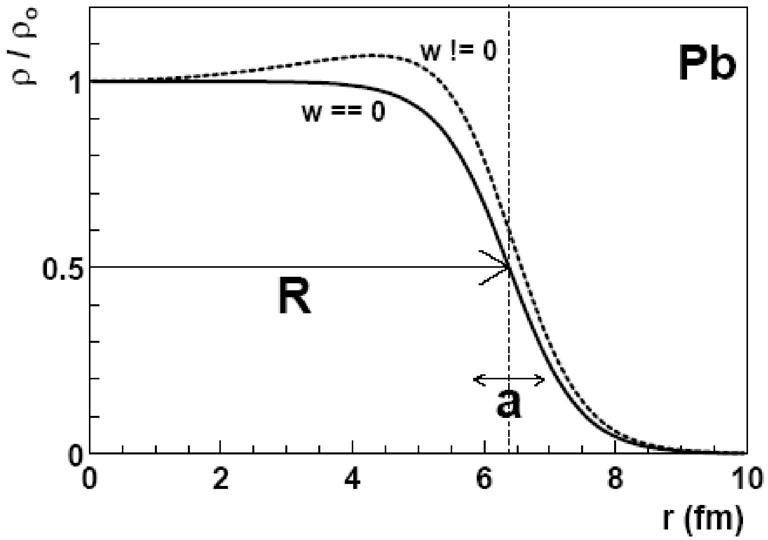
Glauber Model

- **Glauber model assumptions**
  - **nucleons travel on straight trajectories, even after (!) NN scattering processes**
  - **NN scattering cross section does NOT depend on the number of NN scatterings that took place before**

- **crucial input: nuclear geometry**
  - **Woods-Saxon parametrization**

$$\rho(r) = \frac{\rho_0\left(1 + wr^2/R^2\right)}{1 + \exp\left((r - R)/a\right)}$$

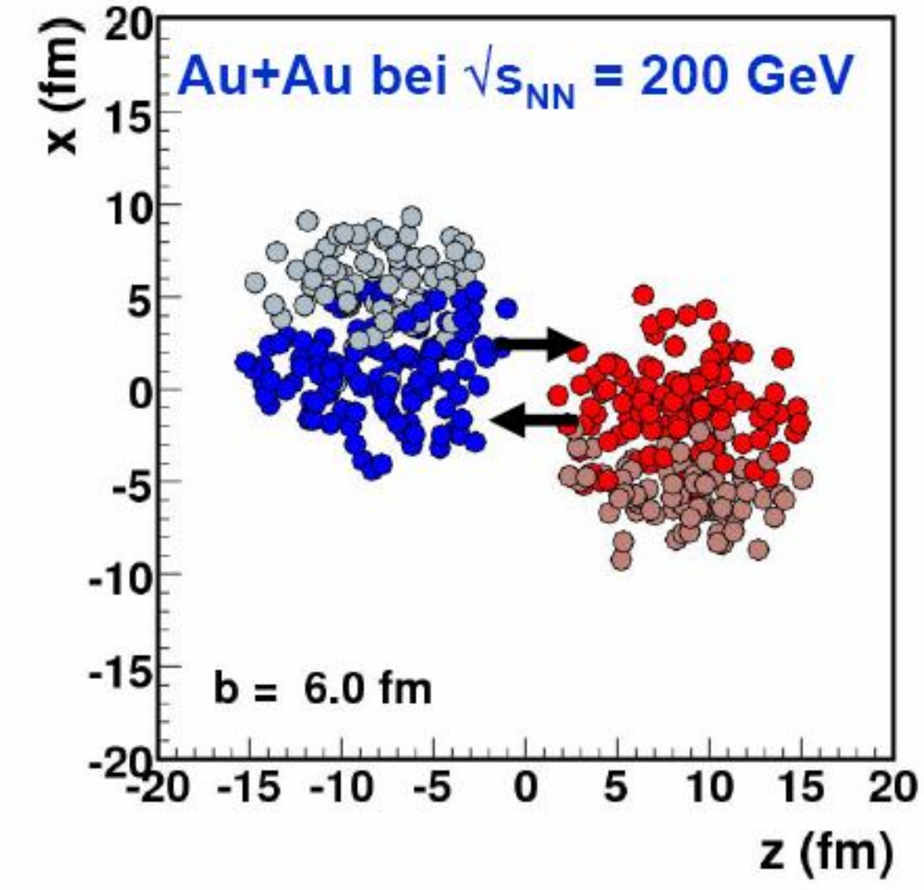
  - **parameters from e scattering**
  - **ignore possible differences between proton and neutron distributions**



MonteCarlo Approach

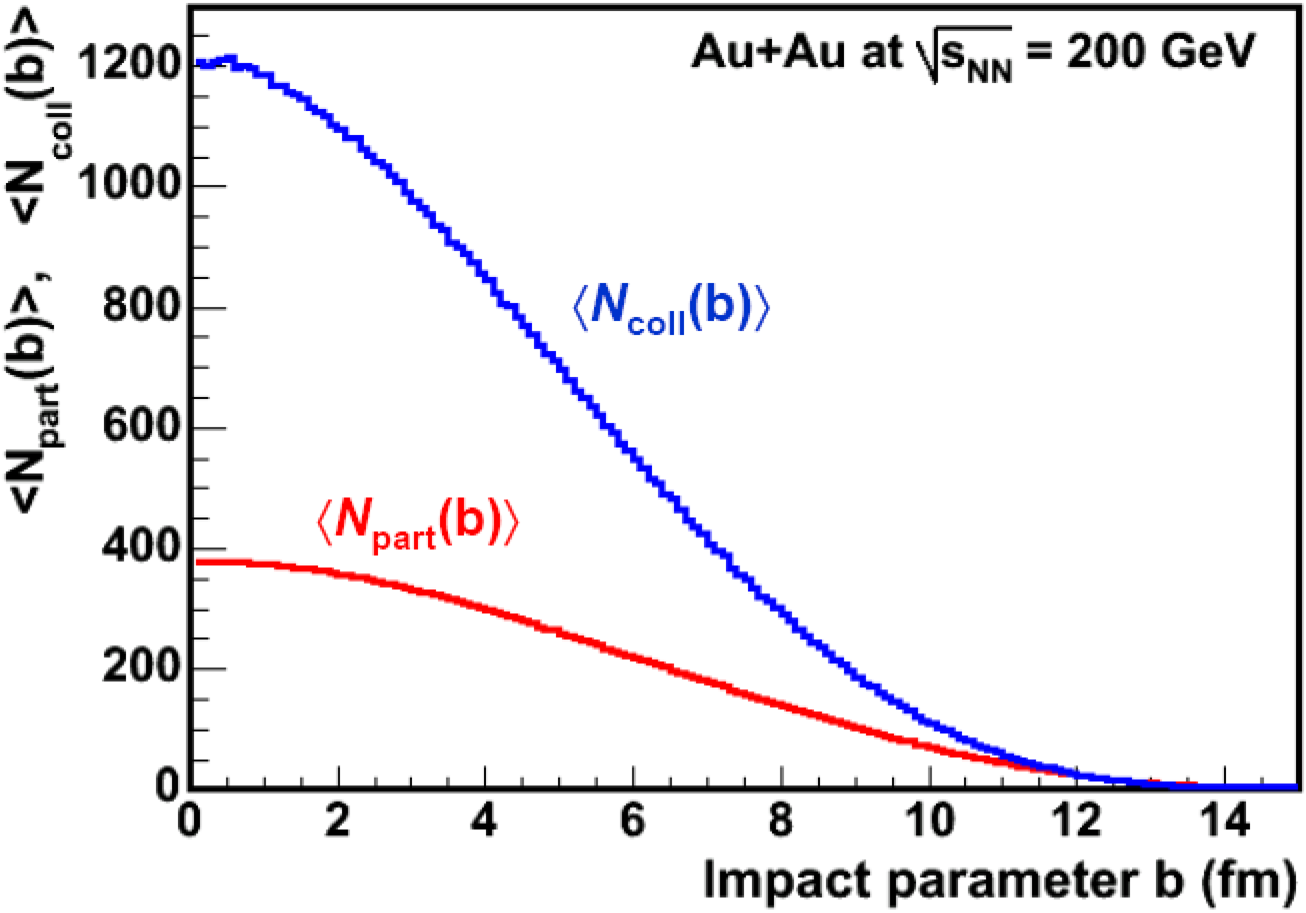
- **initialization: distribute nucleons randomly according to Woods-Saxon distribution**
- **select random impact parameter b**
- **two nucleons collide if they come close enough to each other**

$$d \le \sqrt{\sigma_{unel}^{NN} / \pi}$$



- **$\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$**
  - **from simulation of many AA collisions**

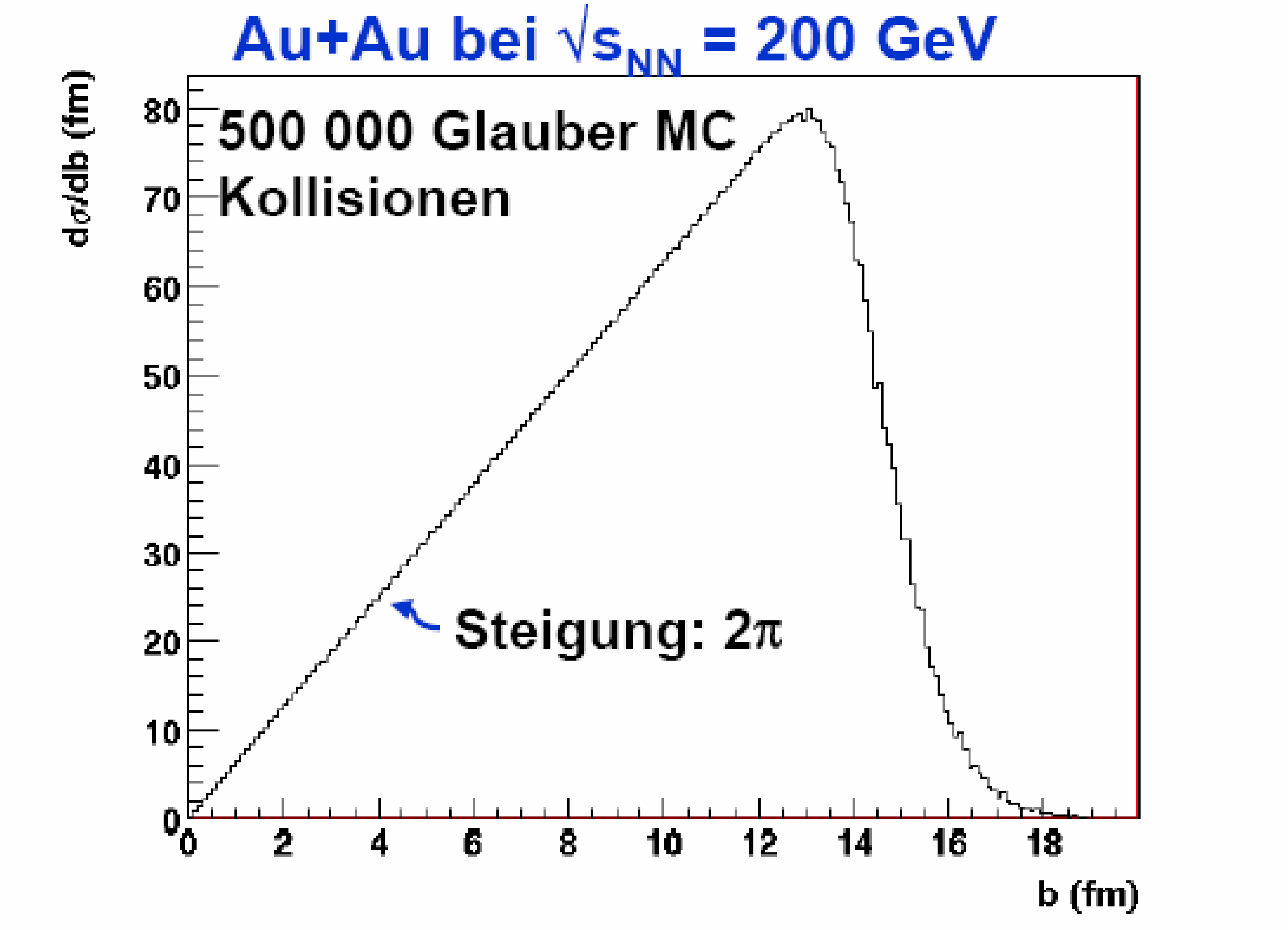
Glauber: N_{part} and N_{coll} vs. b



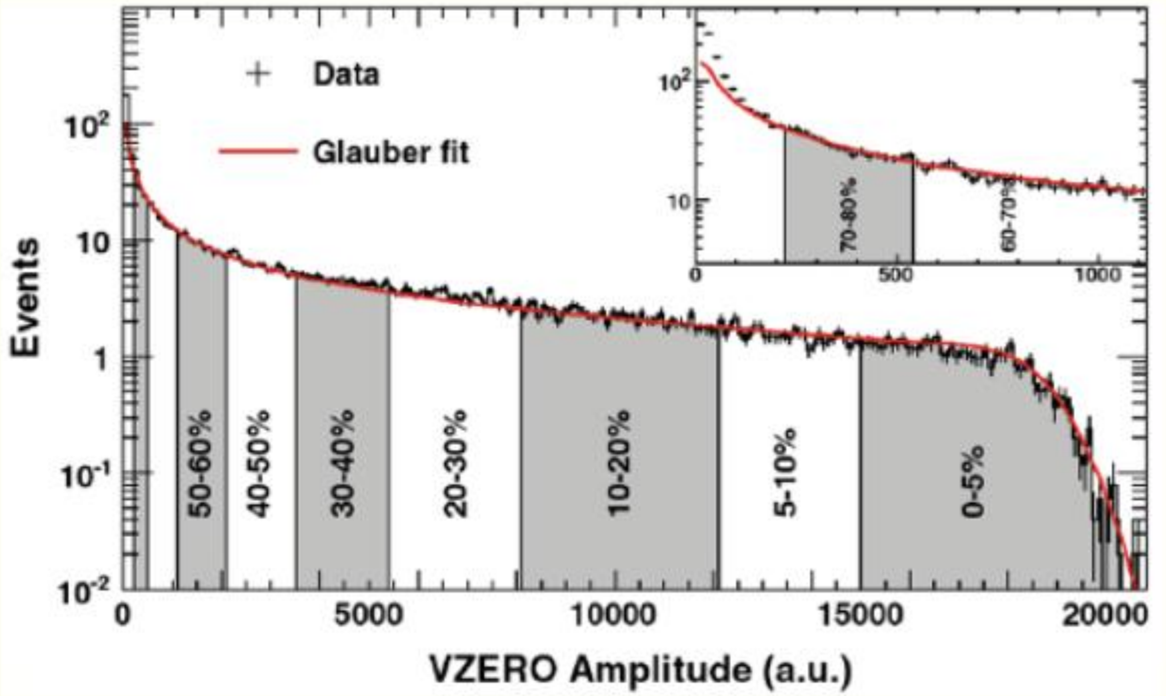
- approximately: $N_{coll} \propto N_{part}^{4/3}$

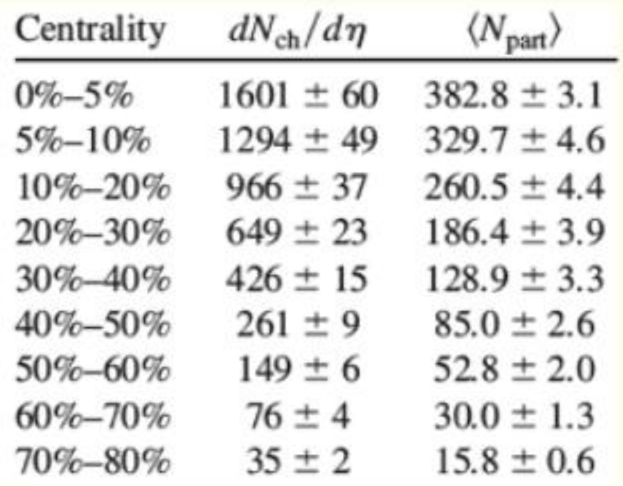
Impact parameter distribution

- **Glauber MonteCarlo:** $\sigma_{unel}^{Au+Au\ @\ 200\ GeV} \approx 6{,}9\ \mathrm{b}$



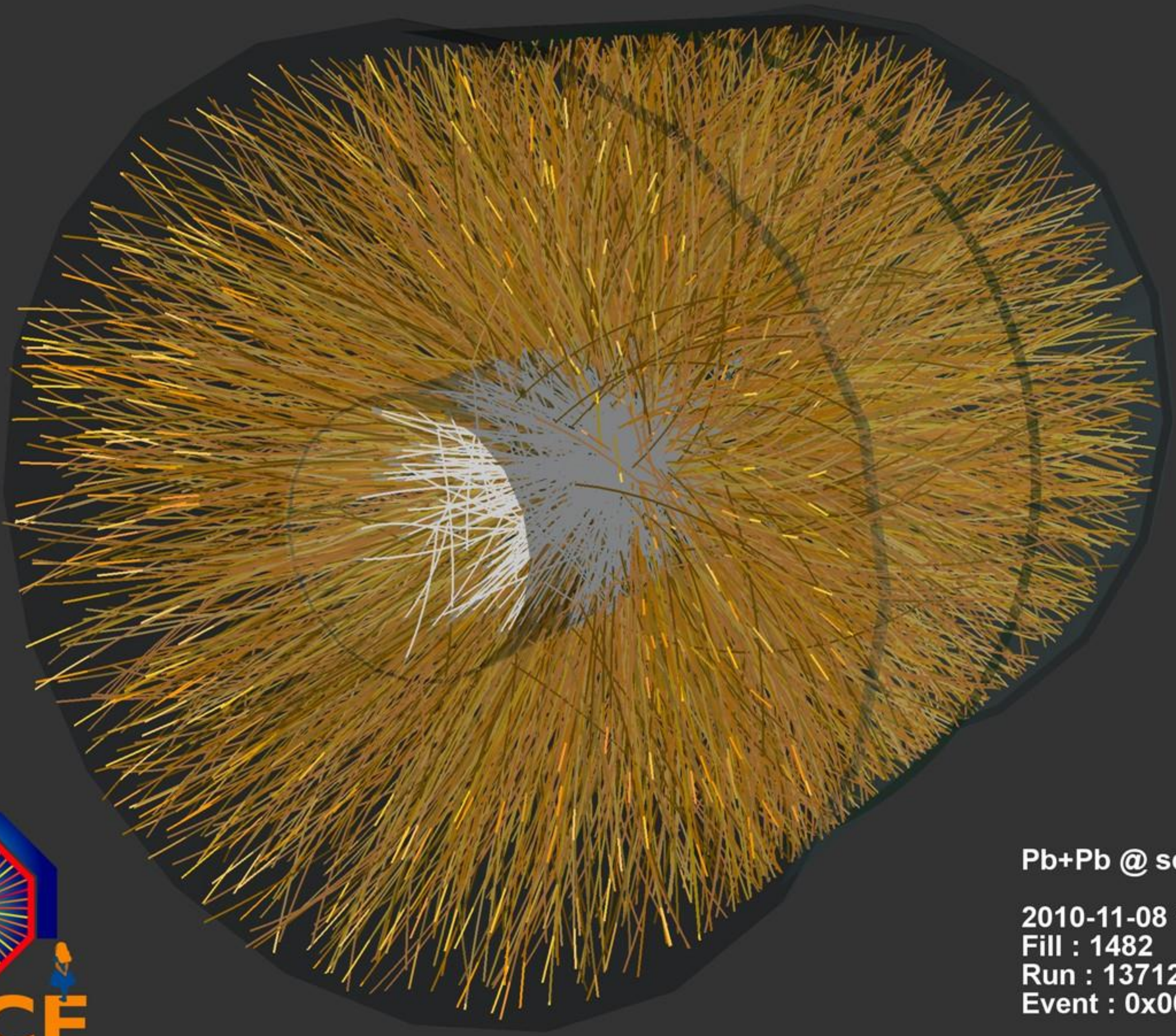
Centrality in ALICE





Centrality	$dN_{ch}/d\eta$	$\langle N_{part} \rangle$
0%–5%	1601 ± 60	382.8 ± 3.1
5%–10%	1294 ± 49	329.7 ± 4.6
10%–20%	966 ± 37	260.5 ± 4.4
20%–30%	649 ± 23	186.4 ± 3.9
30%–40%	426 ± 15	128.9 ± 3.3
40%–50%	261 ± 9	85.0 ± 2.6
50%–60%	149 ± 6	52.8 ± 2.0
60%–70%	76 ± 4	30.0 ± 1.3
70%–80%	35 ± 2	15.8 ± 0.6

- measurement ~ number of produced particles
- particle yield in Glauber MC
  - $N_{ancestor} = f \times N_{part} + (1 - f) \times N_{coll}$
  - each ancestor produces charged particles according to negative binomial distribution (NBD)
  - same centrality selection in data and MC → $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$



Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE