High-Energy Collisions with ALICE at the LHC

1. Introduction

Graduate Days

of the Graduate School of Fundamental Physics

Heidelberg, 5. - 9. October 2009

PD Dr. Klaus Reygers
Physikalisches Institut
Universität Heidelberg

Contents

Contents: The first Four Chapters

Links (Hard Scattering and Jets)

Slides will be posted at

http://www.physi.uni-heidelberg.de/~reygers/lectures/hd-graduate-days-2009/

Thomas Ulrich: Hard Probes - Jets and Photons/Leptons:

http://qm09.phys.utk.edu/indico/conferenceOtherViews.py?confId=1

Lectures on Heavy-Ion Physics (from experimentalist‘s viewpoint):

http://www.uni-muenster.de/Physik.KP/Lehre/QGP-SS06

User: qgp, password: ss06

Many useful talks/lectures on Hard Scattering and Jets:

http://cteq.org

(→ summer schools)

Books (I)

Heavy-Ions

Introduction to High-Energy Heavy-Ion Collisions
Cheuk-Yin Wong
World Scientific

K. Yagi, T. Hatsuda, and Y. Miake, Quark-Gluon Plasma
(Cambridge Monographs, ed. T. Ericson, P.V. Landshoff)
ISBN 0-521-56108-6

R. Vogt
Ultrarelativistic Heavy-Ion Collisions (Elsevier)
ISBN 978-0-444-52196-5

Quark Gluon Plasma 3
(World Scientific Publishing, ed. R.C. Hwa and X.-N. Wang)
ISBN 981-238-077-9

The Large Hadron Collider, Nature 448 (2007) 269

Books (II)

High-energy Physics

Ellis, Stirling, Webber
QCD and Collider Physics
Cambridge monographs on particle physics, nuclear physics and cosmology

Halzen, Martin
Quarks & Leptons
John Wiley & Sons

A. Bettini
Introduction to Elementary Particle Physics (Cambridge University Press)
ISBN 978-0-521-88021-3

A. Garcia and E.M. Henley,
Subatomic Physics
World Scientific Publishing, ISBN-13 978-981-270-056-8

Papers on Hard Scattering and Jets

U. Wiedemann,
Jet Quenching in Heavy-Ion Collisions
arXiv 0908.2306

M. Tannenbaum,
Review of hard scattering and jet analysis
nucl-ex/0611008

A. Accardi et al.,
Hard Probes in Heavy Ion Collisions at the LHC: Jet Physics
hep-ph/0310274

1.1 Heavy-Ion Physics and the Quark-Gluon Plasma

Strong Interaction

Nobel prize in physics (2004)

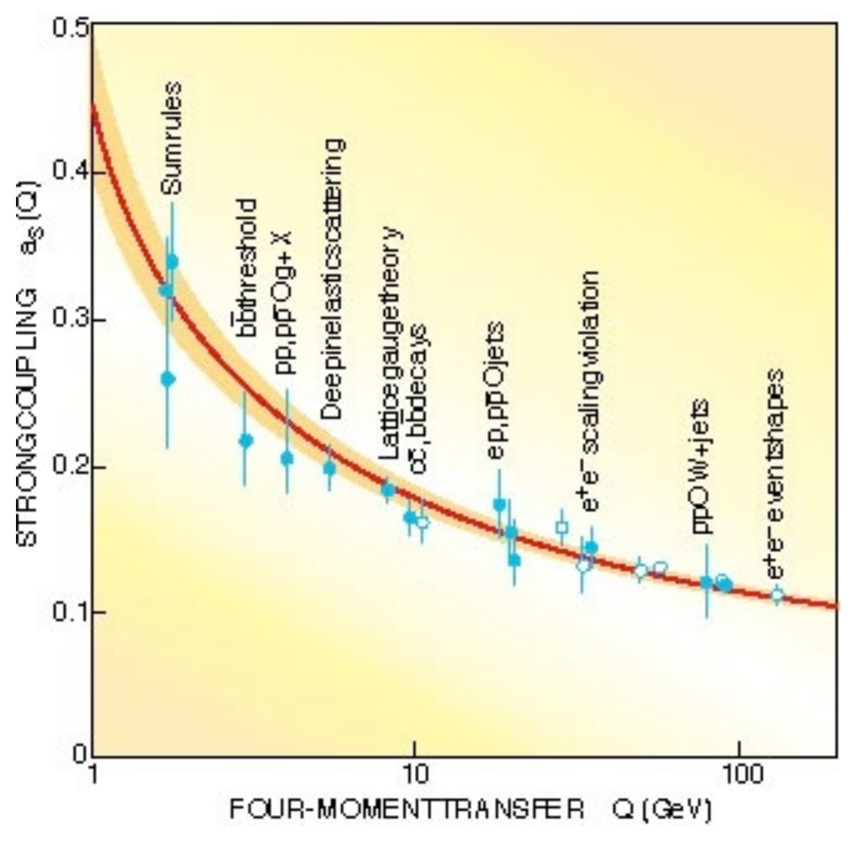
David J. Gross

H. David Politzer

Frank Wilczek

- **Confinement:**
  Isolated quarks and gluons cannot be observed, only color-neutral hadrons
- **Asymptotic freedom:**
  Coupling α_s between color charges gets weaker for high momentum transfers, i.e., for small distances (r < 1/10 fm)
- Limit of low particle densities and weak coupling experimentally well tested ($\rightarrow$ QCD perturbation theory)
- **Nucleus-Nucleus collisions: QCD at high temperatures and density („QCD thermodynamics")**

Asymptotic Freedom



QCD perturbation theory (pQCD):

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

n_f : number of quark flavors

Λ : QCD scale parameter

($\Lambda \approx 250$ MeV/c)

pQCD works for α_s << 1.

This is the case for

$Q^2 >> \Lambda^2 \approx 0{,}06\ (\mathrm{GeV}/c)^2$

Asymptotic freedom: $\alpha_s(Q^2) \to 0$ für $Q^2 \to \infty$

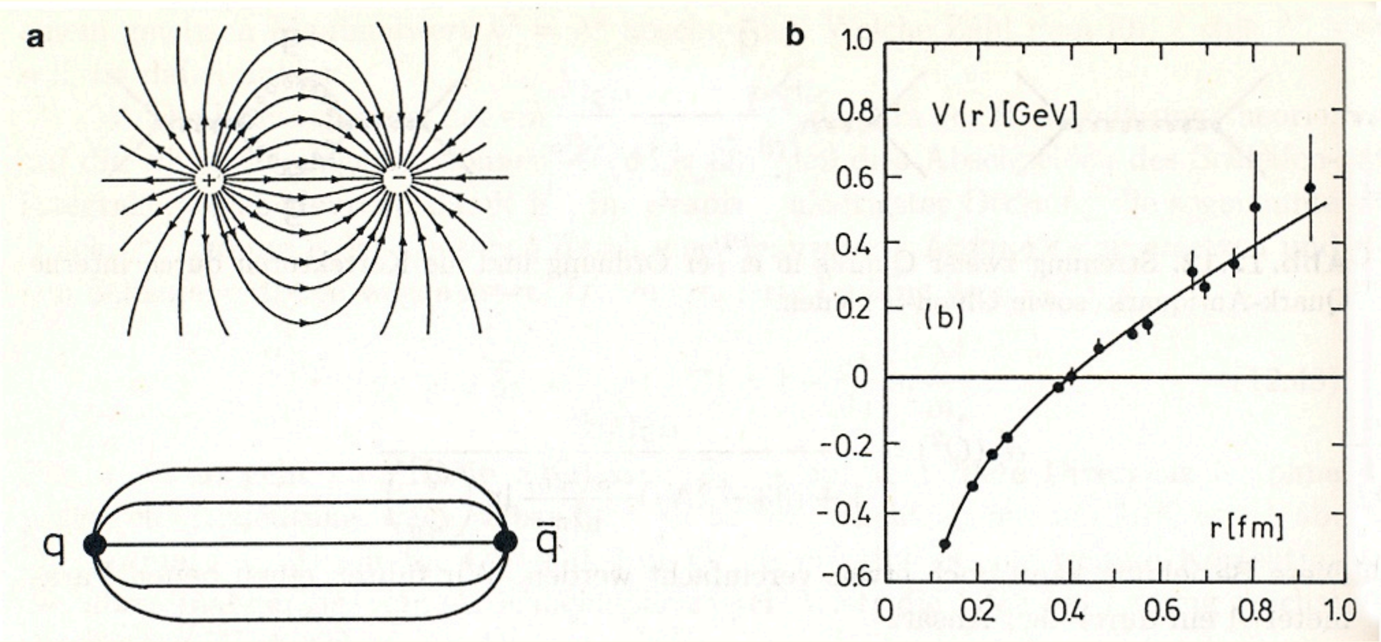
In the limit $Q^2 \to \infty$ quarks behave as free particles

Confinement

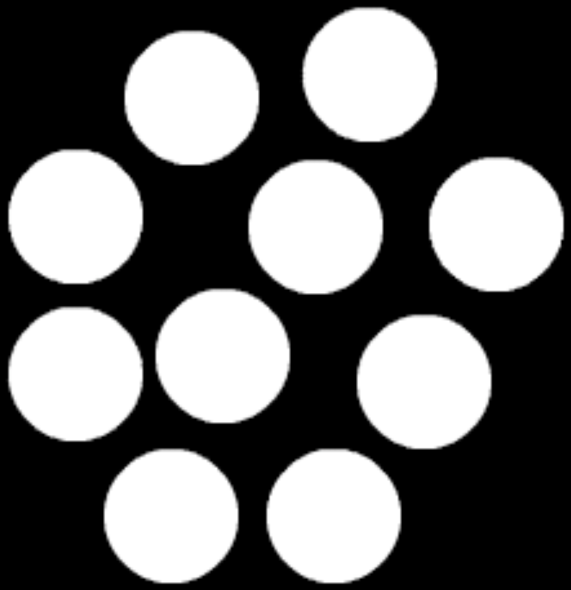
Heavy quark potential $(c\bar{c})$: $V(r) = -\frac{4}{3}\frac{\alpha_s(r)\hbar c}{r} + k \cdot r$

Dominant at small distances (1-gluon exchange)

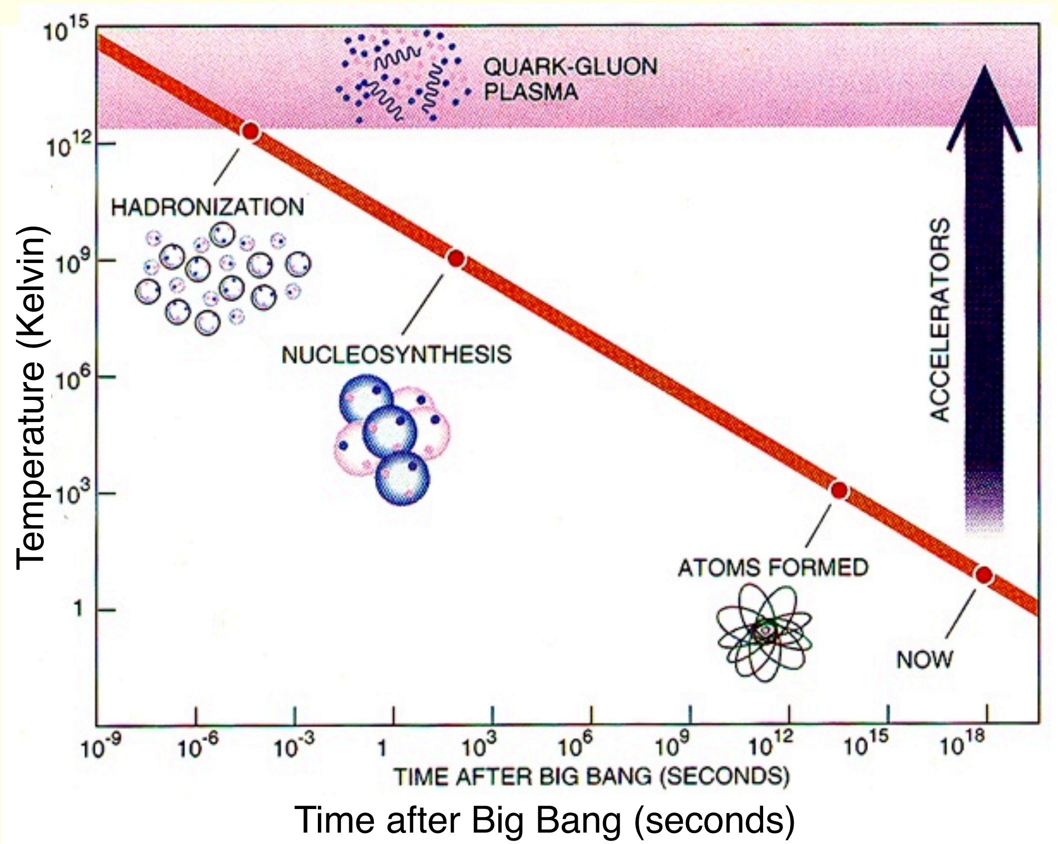
Dominant at large distances (Confinement)



Quark-Gluon-Plasma



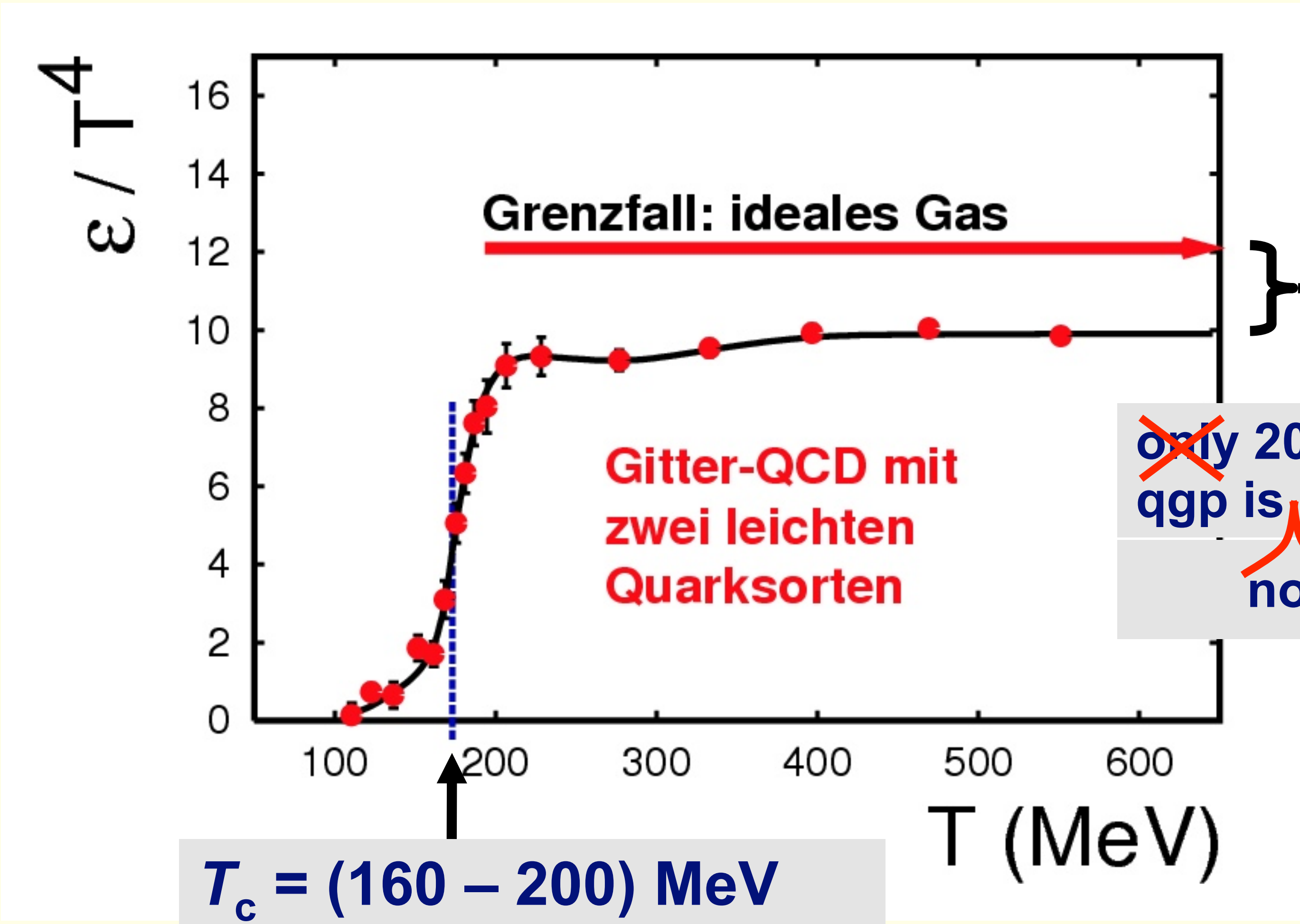
Nucleus-Nucleus Collisions: „Mini Big Bang in the Laboratory"



- **Transition from the Quark-Gluon Plasma to a gas of hadrons at ~ 10^{12} °C**
- **100 000 hotter than the core of the sun**
- **Early universe: QGP $\rightarrow$ hadron gas a few microseconds after the Big Bang**

Predictions from First principles: Lattice QCD

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



2 quark flavors:

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

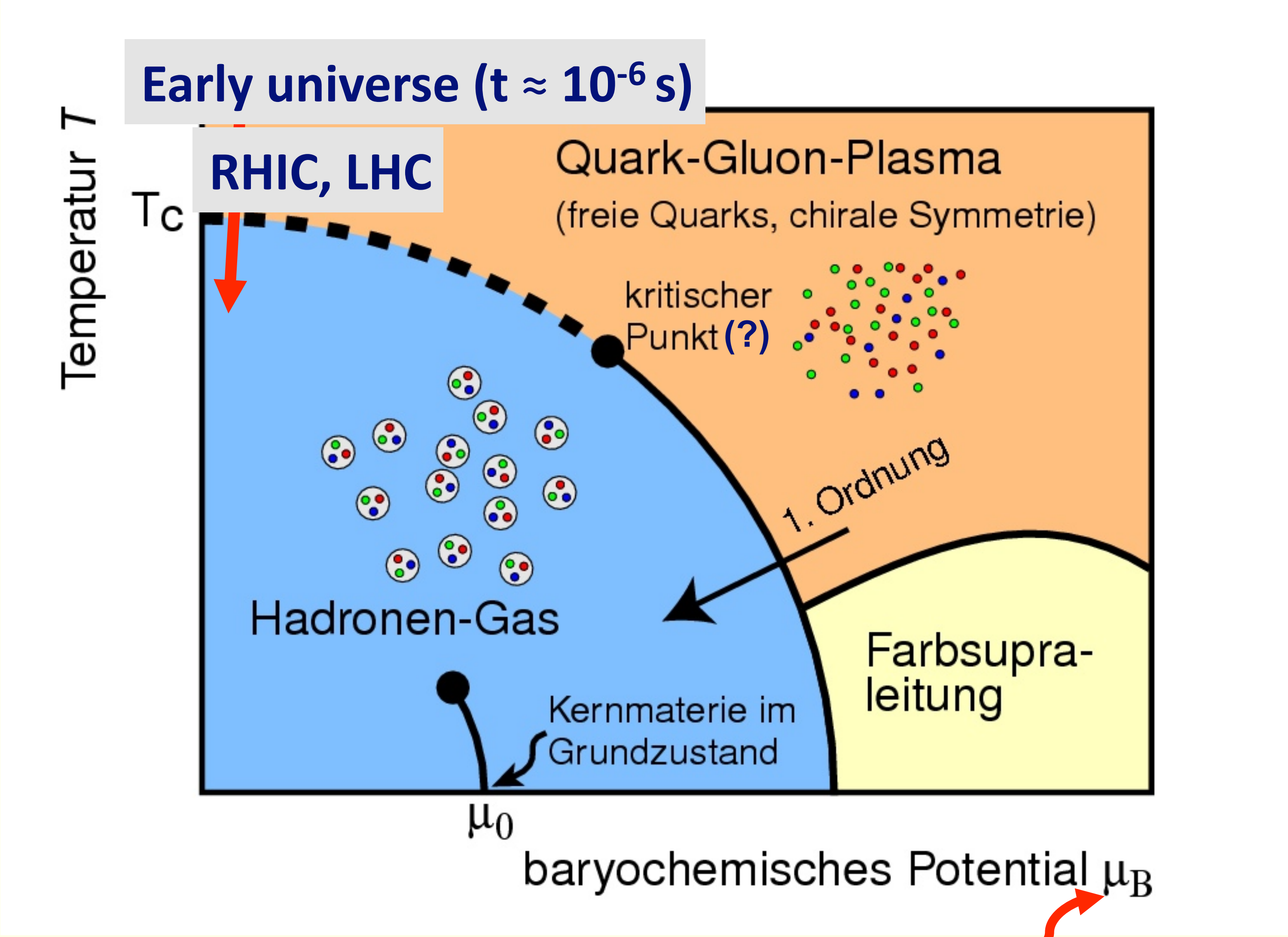
with $g = 37$

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

T_c = (160 – 200) MeV

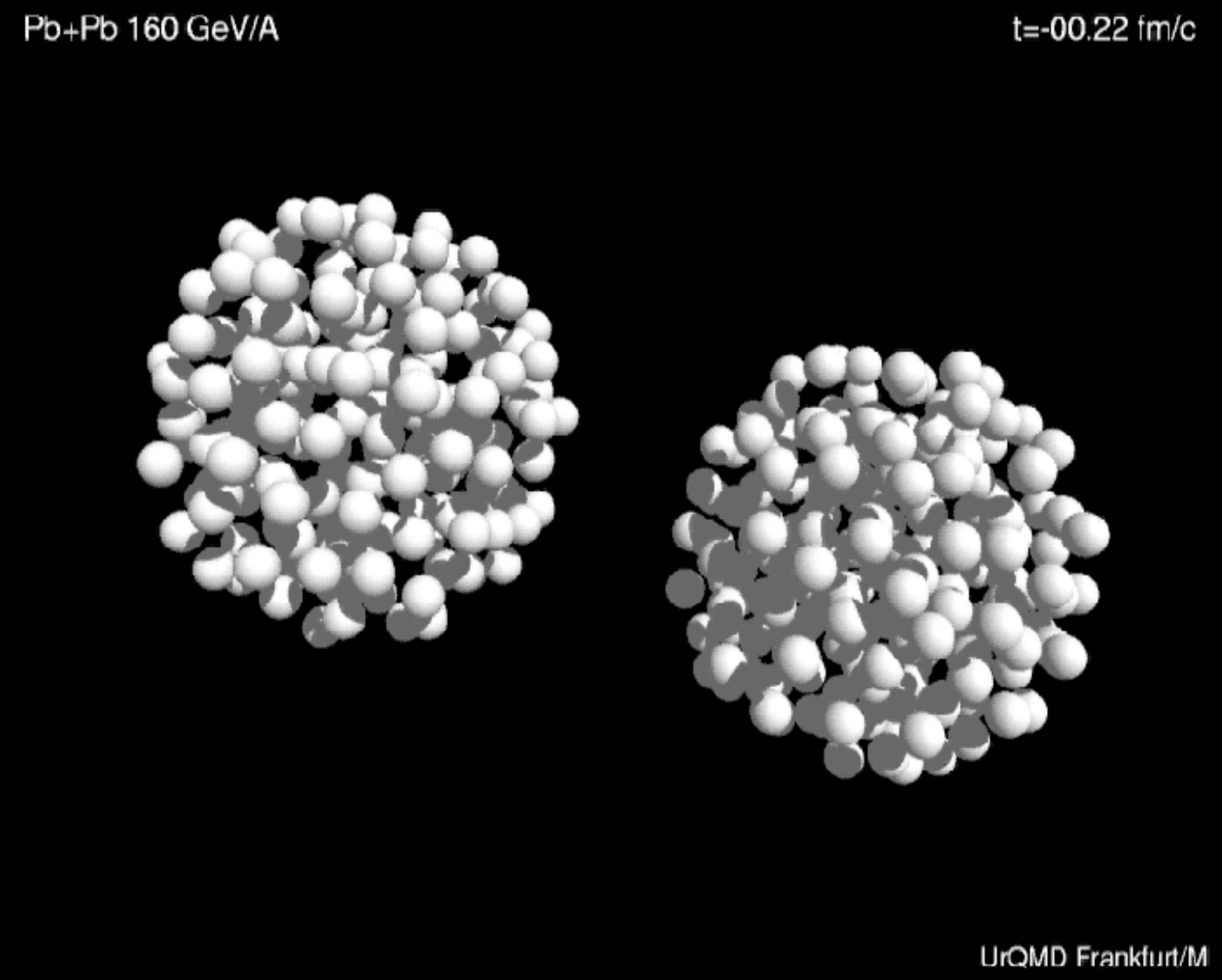
$\varepsilon_c \approx$ 0.7 – 1.0 GeV/fm^3

QCD Phase Diagram

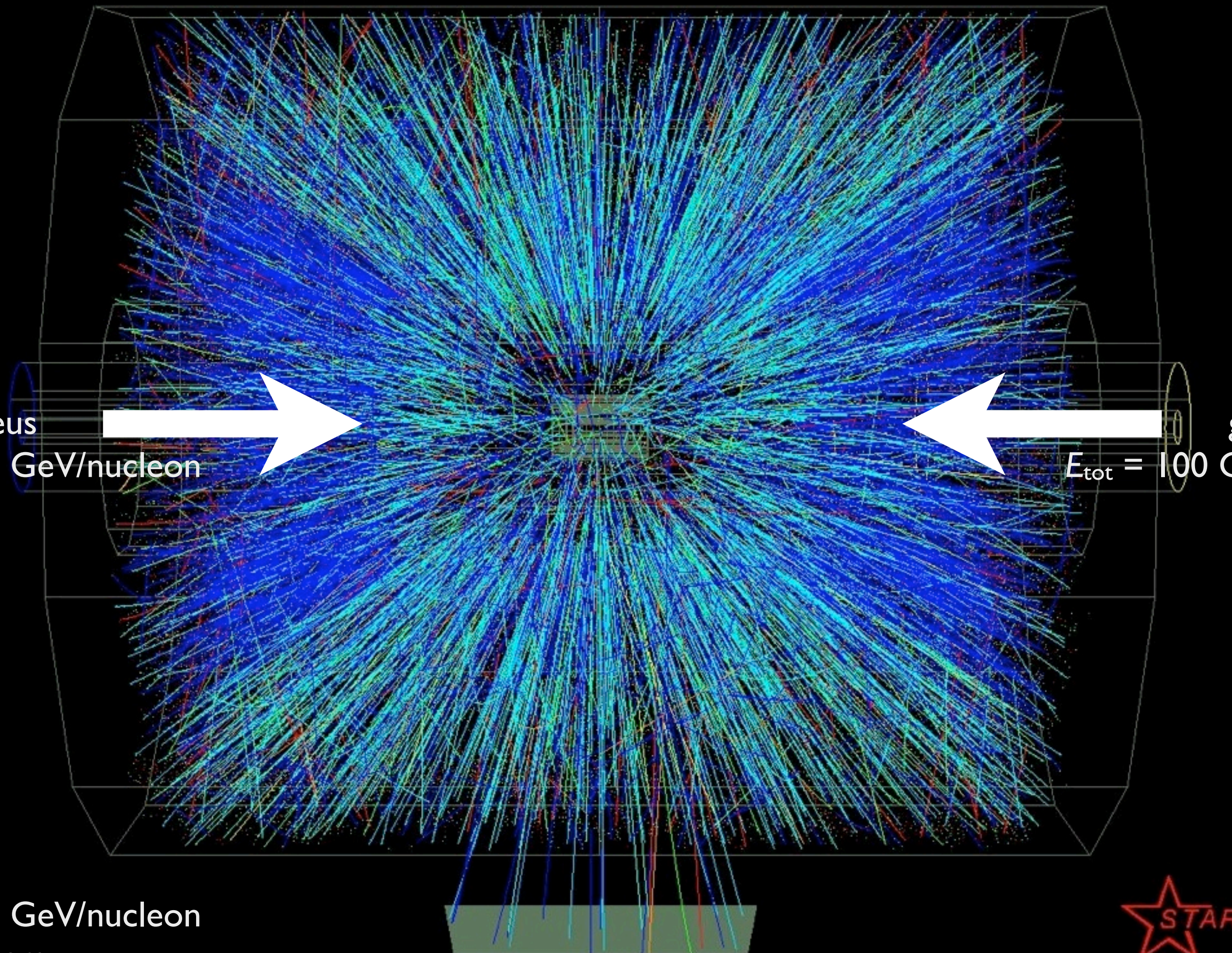


Measure of the net baryon density ρ

Ultra-Relativistische Schwerionenkollision



Au+Au Collision at the Relativistic Heavy Ion Collider (RHIC) in the USA

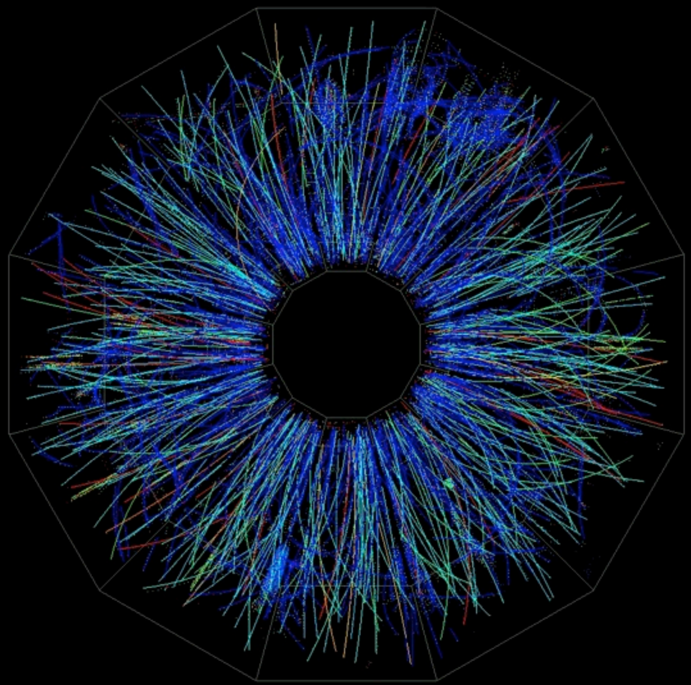


gold nucleus
E_{tot} = 100 GeV/nucleon

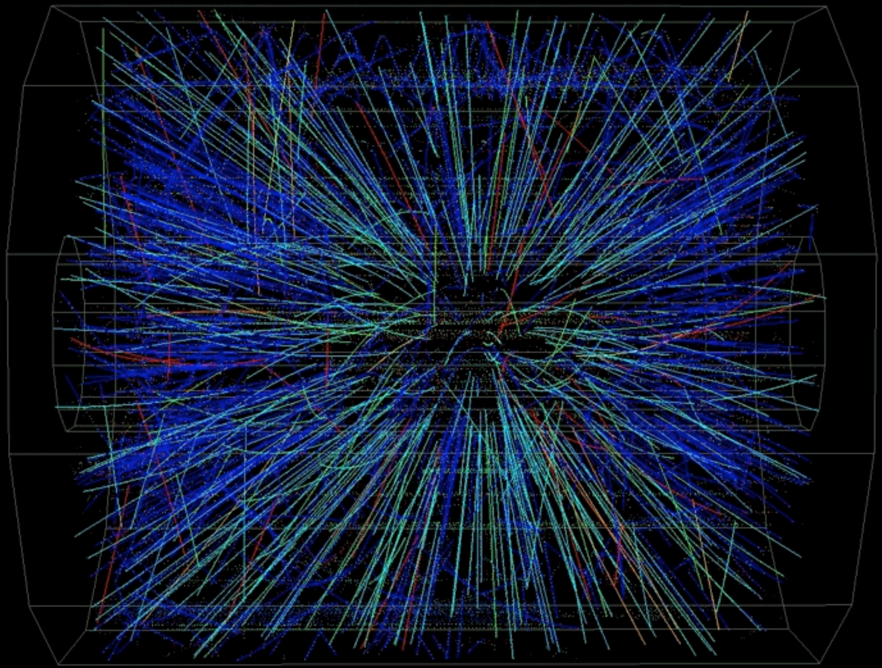
gold nucleus
E_{tot} = 100 GeV/nucleon

LHC:
E_{tot} = 2750 GeV/nucleon
for each beam

Au + Au Collisions at RHIC



Peripheral Event



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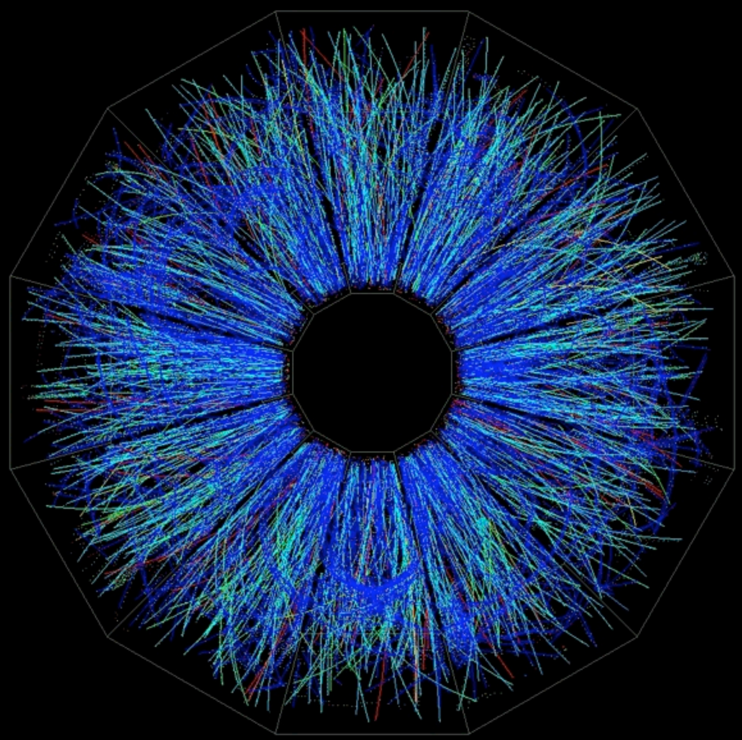
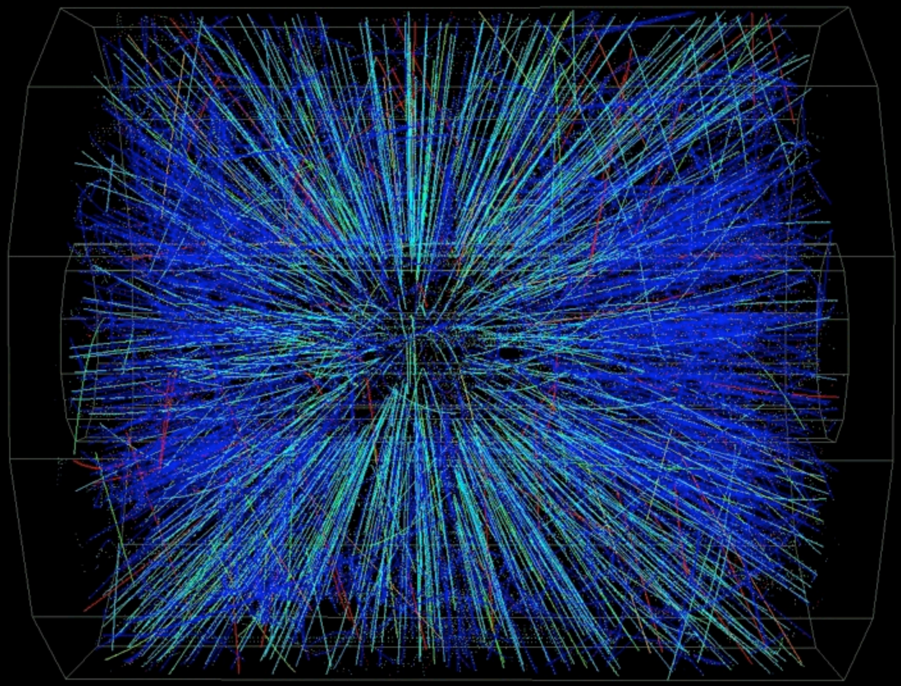
Au + Au Collisions at RHIC

Mid-Central Event





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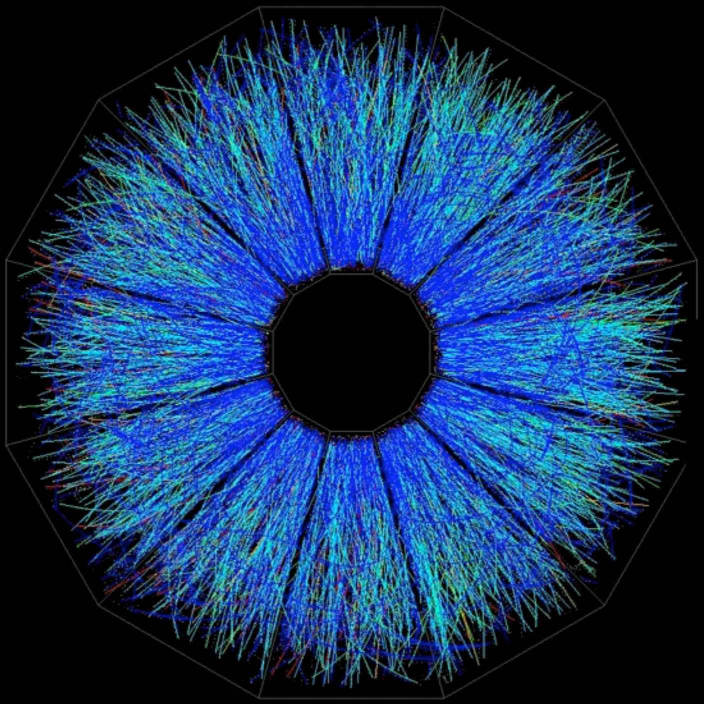
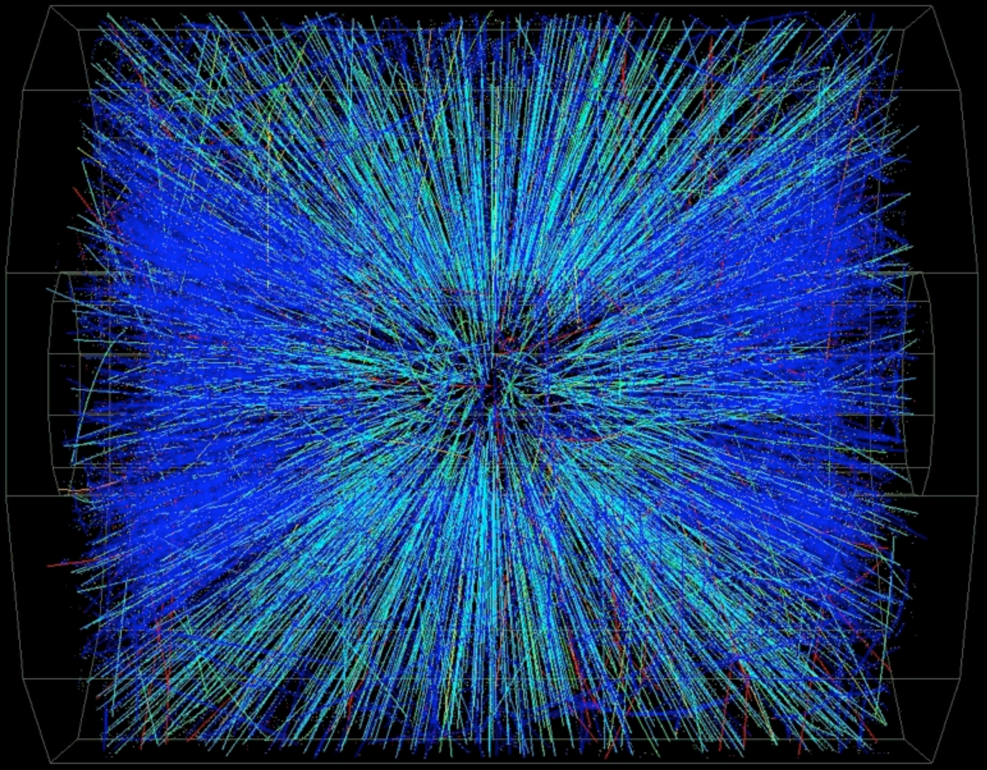
Au + Au Collisions at RHIC



Central Event



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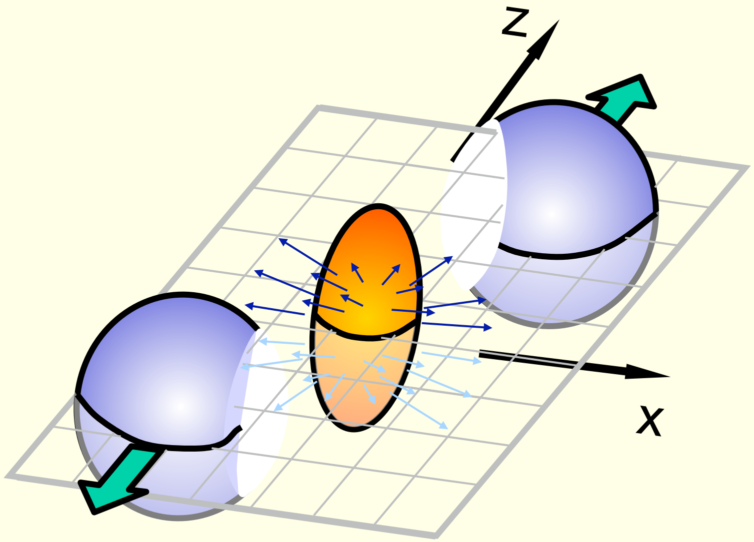
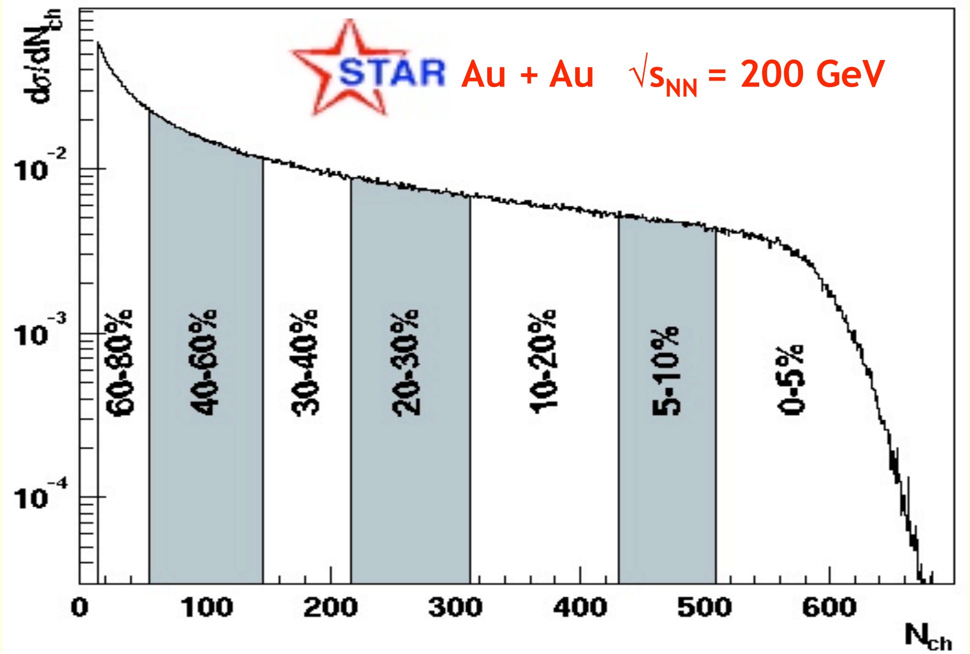
Collision Geometry



Non-central Collision



Uncorrected

Number of participants: number of nucleons in the overlap region

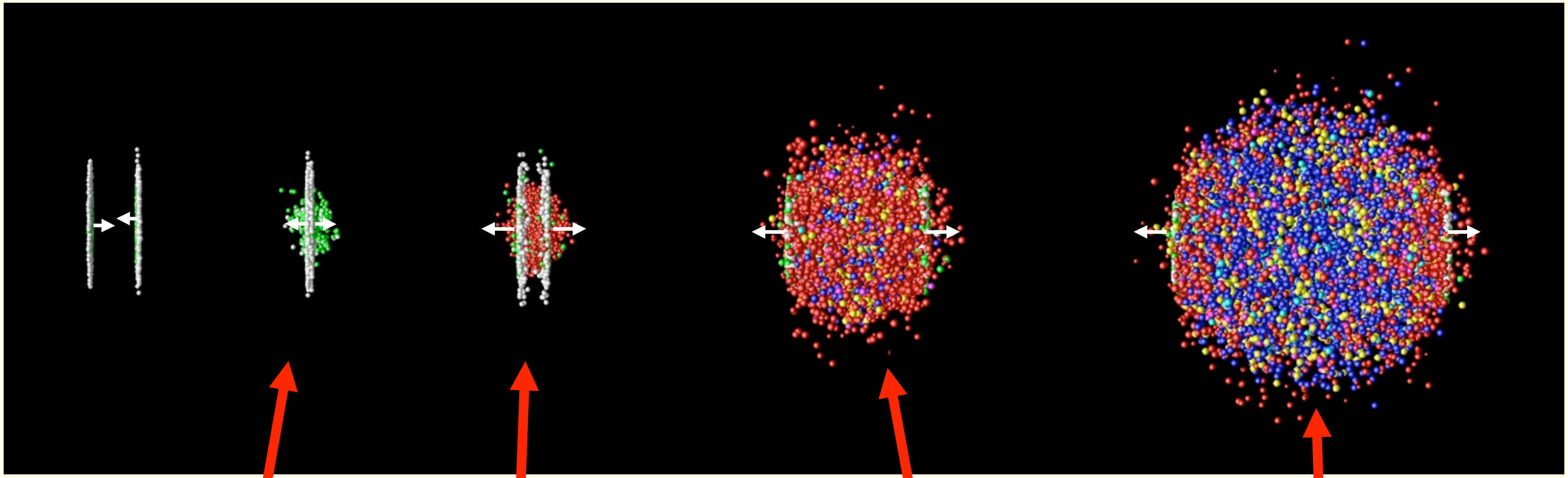
Number of binary collisions: number of inelastic nucleon-nucleon collisions

Charged particle multiplicity ⇔ collision centrality

Reaction plane: x-z plane

Ultra-Relativistic Nucleus-Nucleus Collisions

time →



Early hard parton-parton scatterings ($Q^2 >> \Lambda^2_{QCD}$)

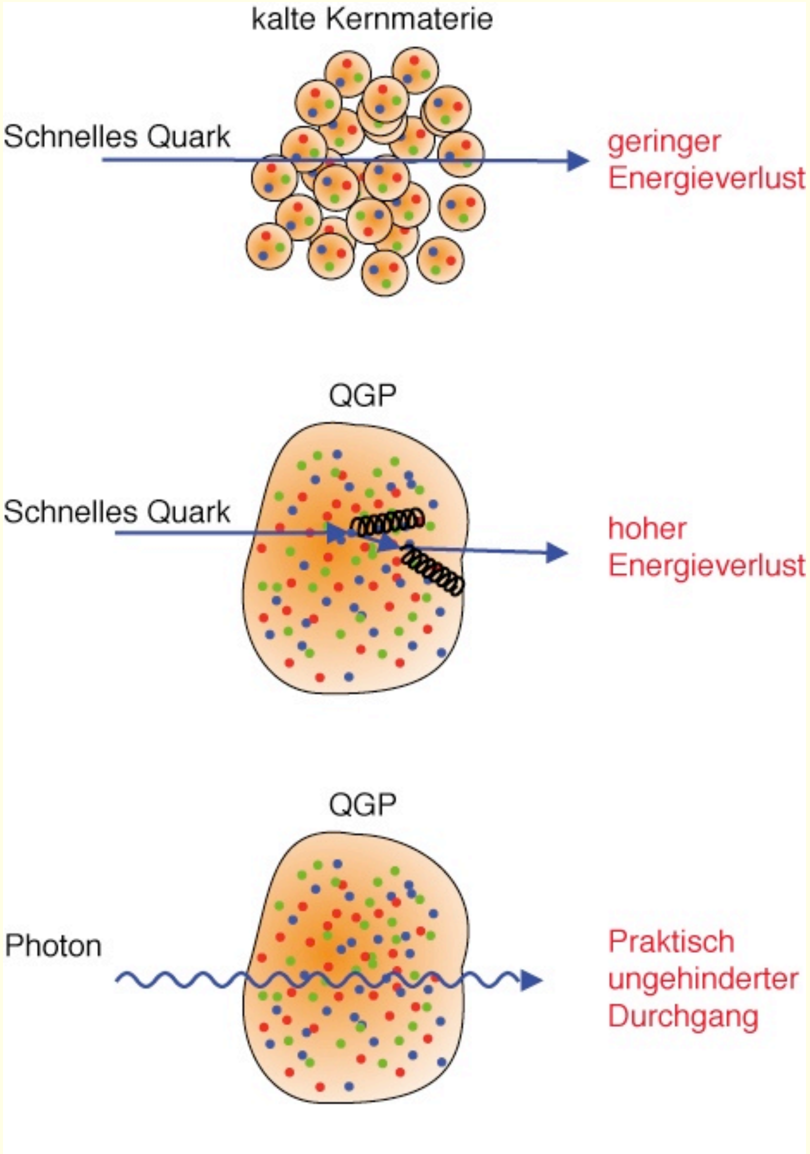
Thermalized medium (QGP!?) ($T_0 > T_c$, $T_c \approx$ 160–190 MeV)

Transition QGP → hadron gas

Freeze-out

- Time scales (RHIC, $\sqrt{s_{NN}}$ = 200 GeV):
  - Thermalization: $\tau_0 < \sim 1$ fm/c
  - QGP lifetime (center of a central Au+Au coll.): ~ 5 fm/c

Hard scatterings products as a probe for the Quark-Gluon Plasma

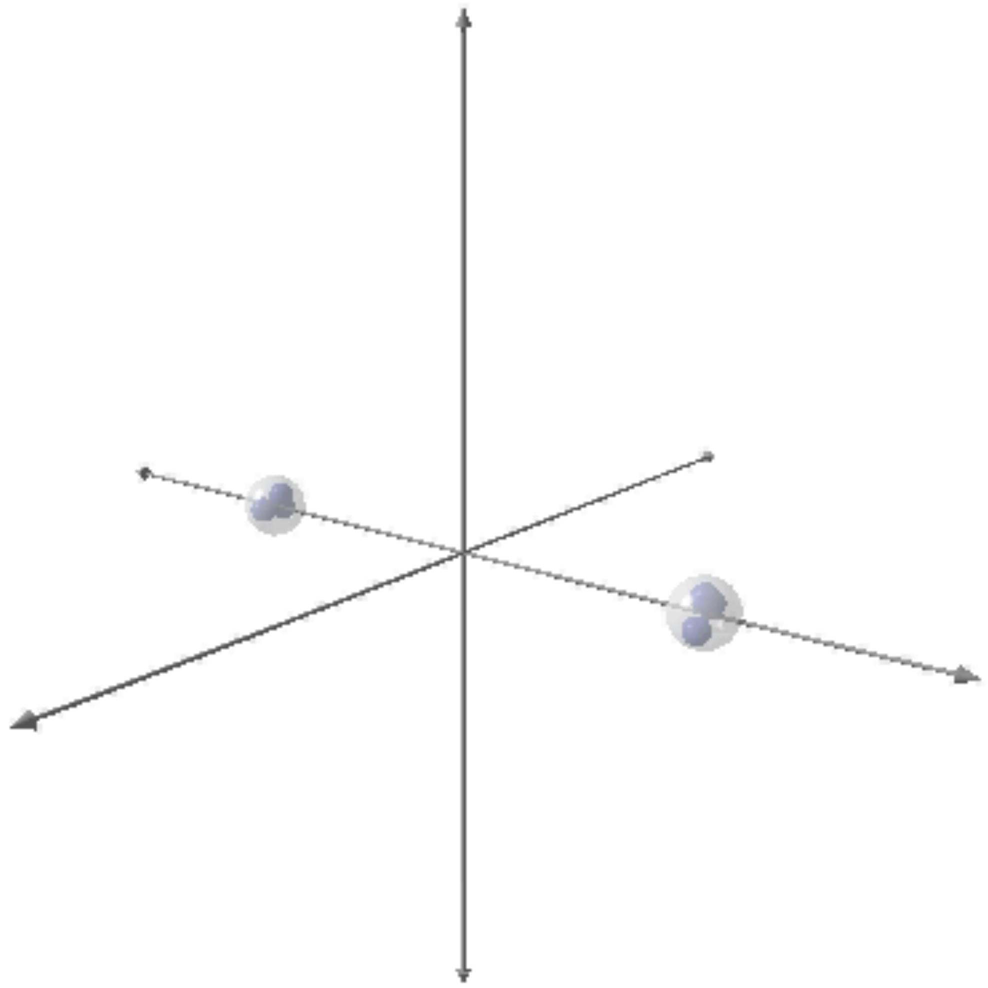


Expectation:
Simple scaling from p+p to d+Au

Expectation:
Pion suppression in A+A

Expectation:
Simple scaling from p+p to A+A for direct photons

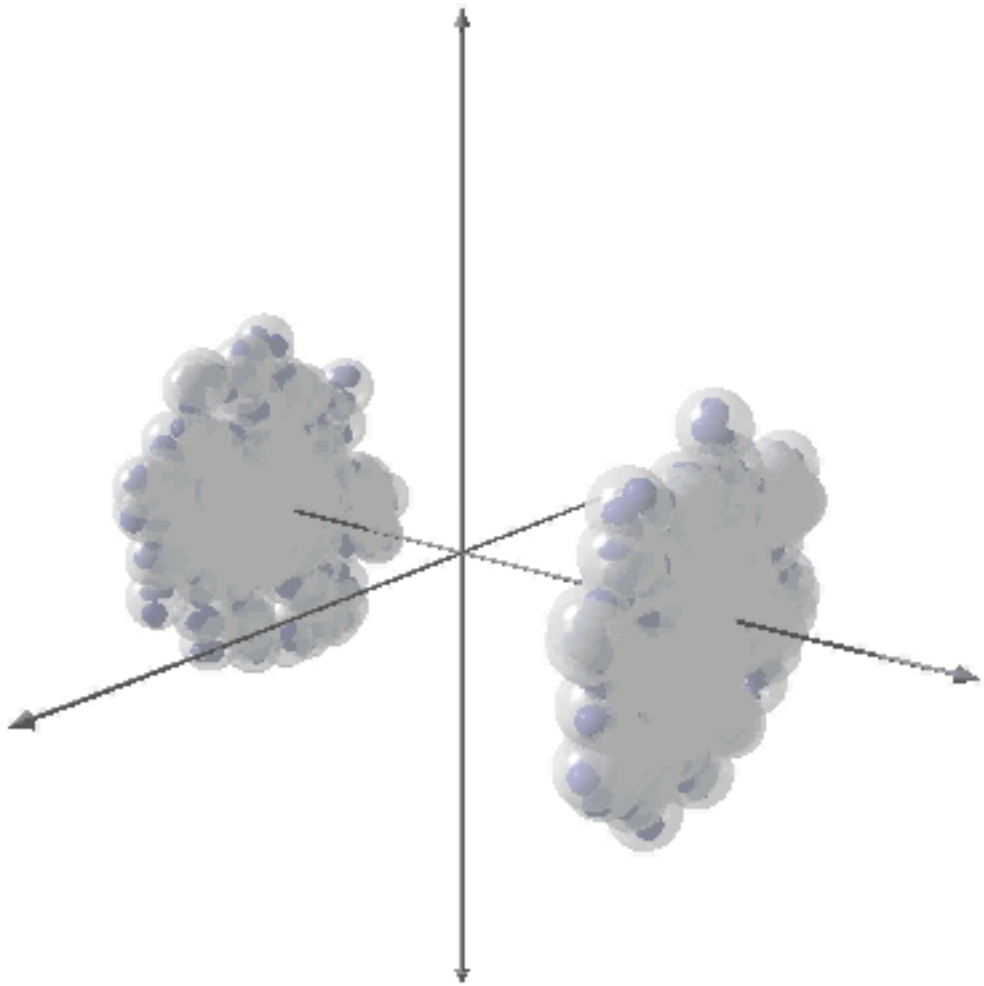
A Jet in a p+p Collision



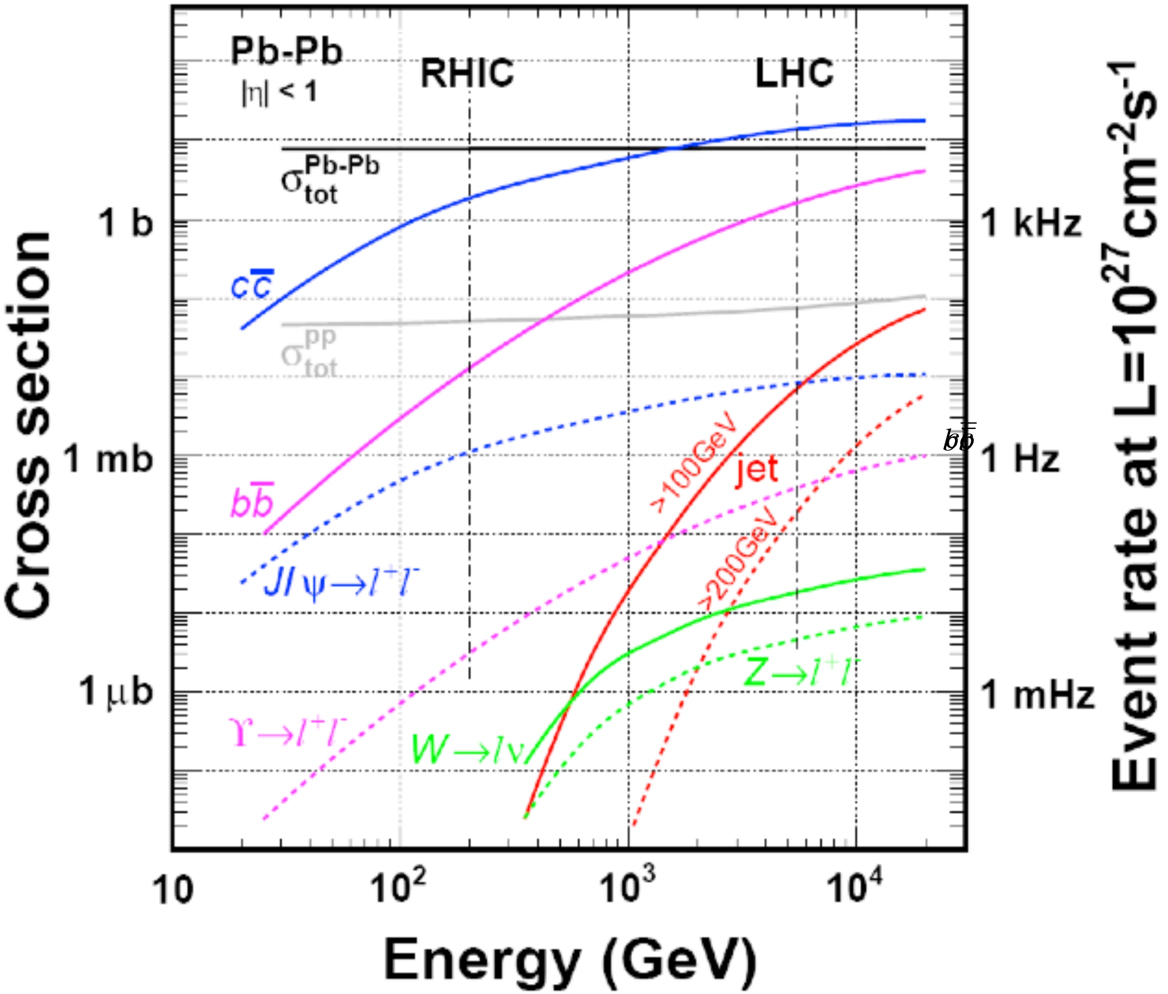
Brief History of QCD and Jets

- ← Introduction of Color and the Quark Model
- *SLAC* ← Experimental evidence of quarks in DIS scattering, Bjorken scaling
- 1970 *ISR* ← Birth of QCD: Renormalizability, Asymptotic Freedom, Confinement
- ← Discovery of the charm quark (SLAC, BNL)
- ← Observation of jets in e^+e^- as manifestation of quarks (SLAC,1975) and gluons (DESY,1979)
- *PETRA* ← Discovery of the bottom quark (FNAL)
- ← Violation of Bjorken scaling, Evolution of Parton Distribution and Fragmentation Functions
- 1980 *Sp$\bar{p}$S* ← QCD calculations start to become available for many processes
- ← Discovery of W and Z (CERN)
- *LEP*
- *HERA*
- 1990 ← Next to Leading Order predictions for jet production
- *Tevatron Run I*
- ← Discovery of the top quark (FNAL)
- 2000 ← Next to Next to Leading Order predictions for jet production
- *Tevatron Run II*

Jet-Quenching in Nucleus-Nucleus Collisions



LHC: Cross-sections and Rates



Cross-sections of interesting probes expected to increase relative to RHIC by factors

~ 10 ($c\bar{c}$) to

~ 10^2 ($b\bar{b}$) to

> 10^6 (very high p_T jets)

⇒ Hard probes become abundantly available at LHC

Questions – What Can We Hope to Learn?

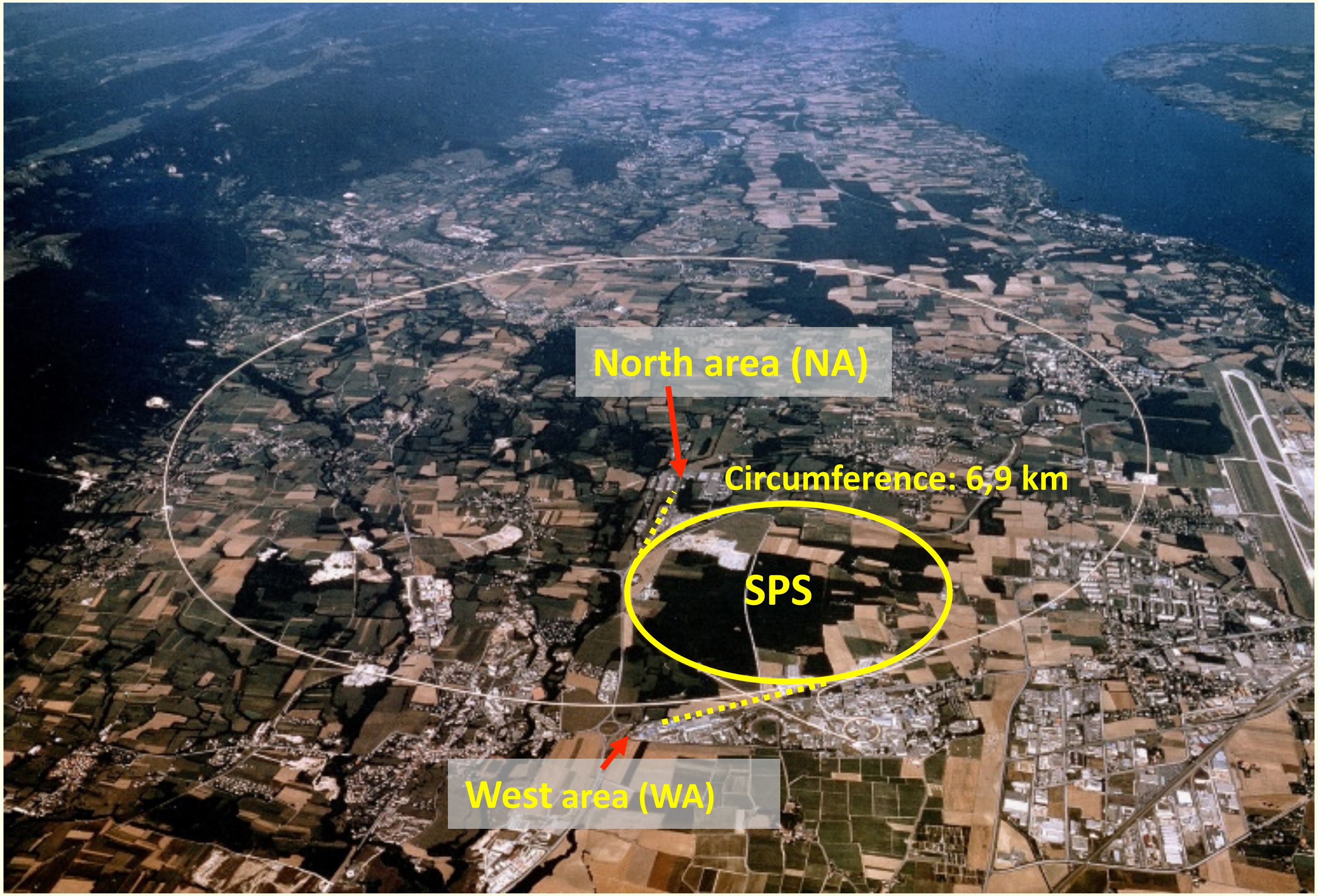
1. **QCD thermodynamics:**
   What are the properties of quark-gluon matter at high temperatures and densities?

2. **Jet-medium interaction:**
   What are the mechanisms of parton energy loss?

Brief History of Heavy Ion Physics

Start	Accelerator	Projectile	Energy ($\sqrt{s}$) per NN pair
~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
2008	LHC (CERN)	Pb	5500 GeV

CERN SPS (1985 - 2004)

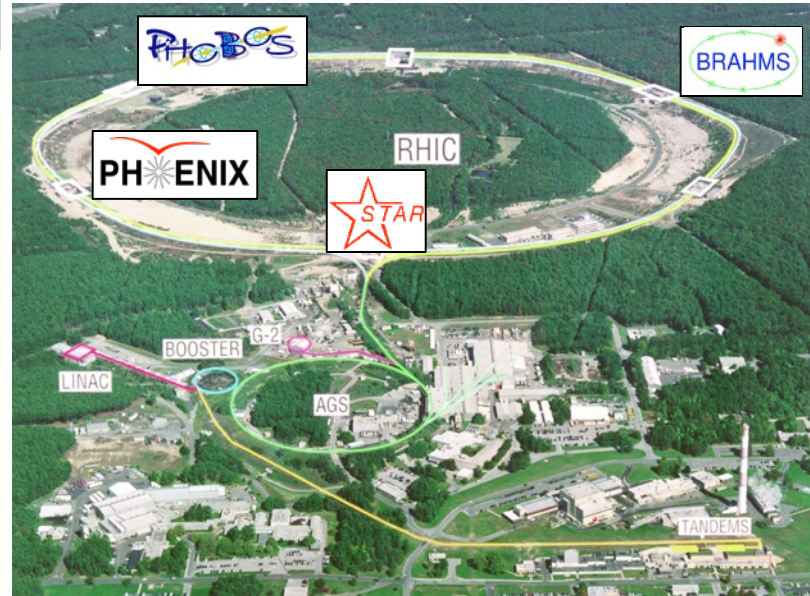


NA35/44
NA38/50/50
NA49
NA45(CERES)
NA57

WA80/98, WA97→NA57

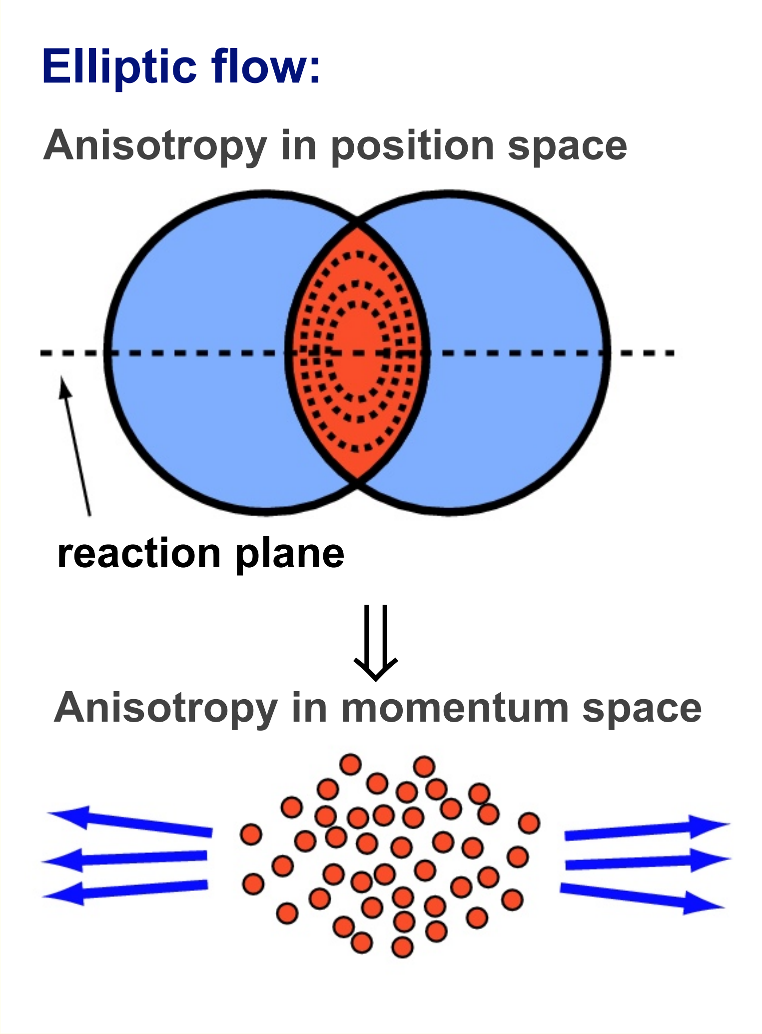
RHIC: Relativistic Heavy Ion Collider

- **Circumference 3,83 km**
- **2 independent rings**
  - **120 „bunches“**
  - **~10^9 Au-Ions per bunch**
  - **„Bunch Crossings“ every 106 ns**
- **Collisions of different particle species possible**
- **Maximum energy:**
  - **200 GeV for Au+Au:** $\sqrt{s_{NN}} \approx \frac{Z}{A}(500\,\mathrm{GeV})$
  - **500 GeV for p+p**
- **Design luminosity**
  - **Au-Au: 2 x 10^{26} cm^{-2} s^{-1}**
  - **p-p: 1,4 x 10^{31} cm^{-2} s^{-1}**
- **Studied so far**
  - **p+p, d+Au, Cu+Cu, Au+Au**

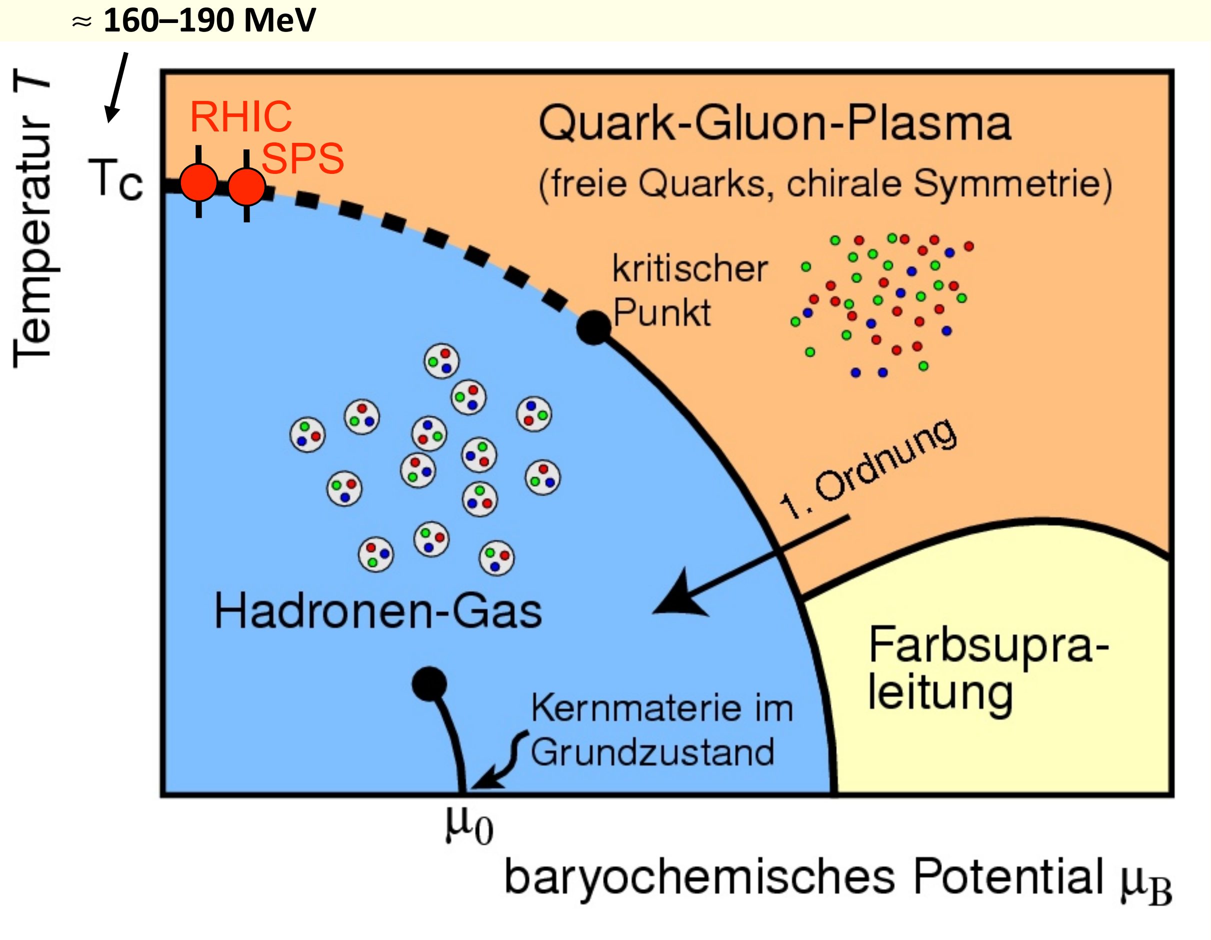


Important Results of the RHIC Heavy-Ion Program

- **Hadron suppression at high p_T**
  - **Medium is to large extent opaque for jets ("jet quenching")**
- **Elliptic Flow at low p_T**
  - **Ideal hydro close to data**
    $\Rightarrow$ Small viscosity: "perfect liquid"
  - **Evidence for early thermalization (τ <~ 1 fm/c)**
- **All hadron species in chemical equillibrium**
  ($T \approx 180$ MeV, $\mu_B \approx 30$ MeV)

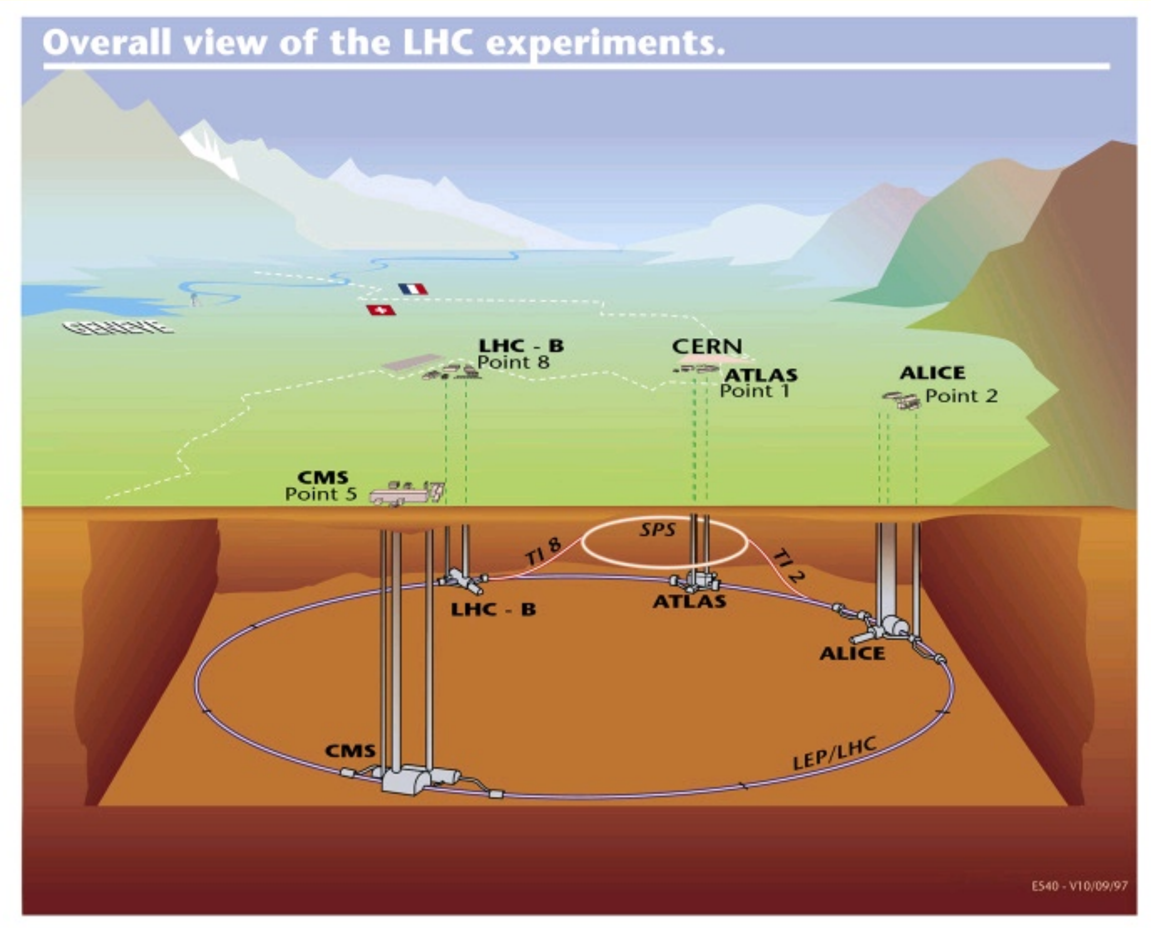


Nucleus-Nucleus Collisions: Freeze-out Parameters



Freeze-out parameters *T* and μ_B approximately at expected phase boundary

CERN: Large Hadron Collider (LHC)



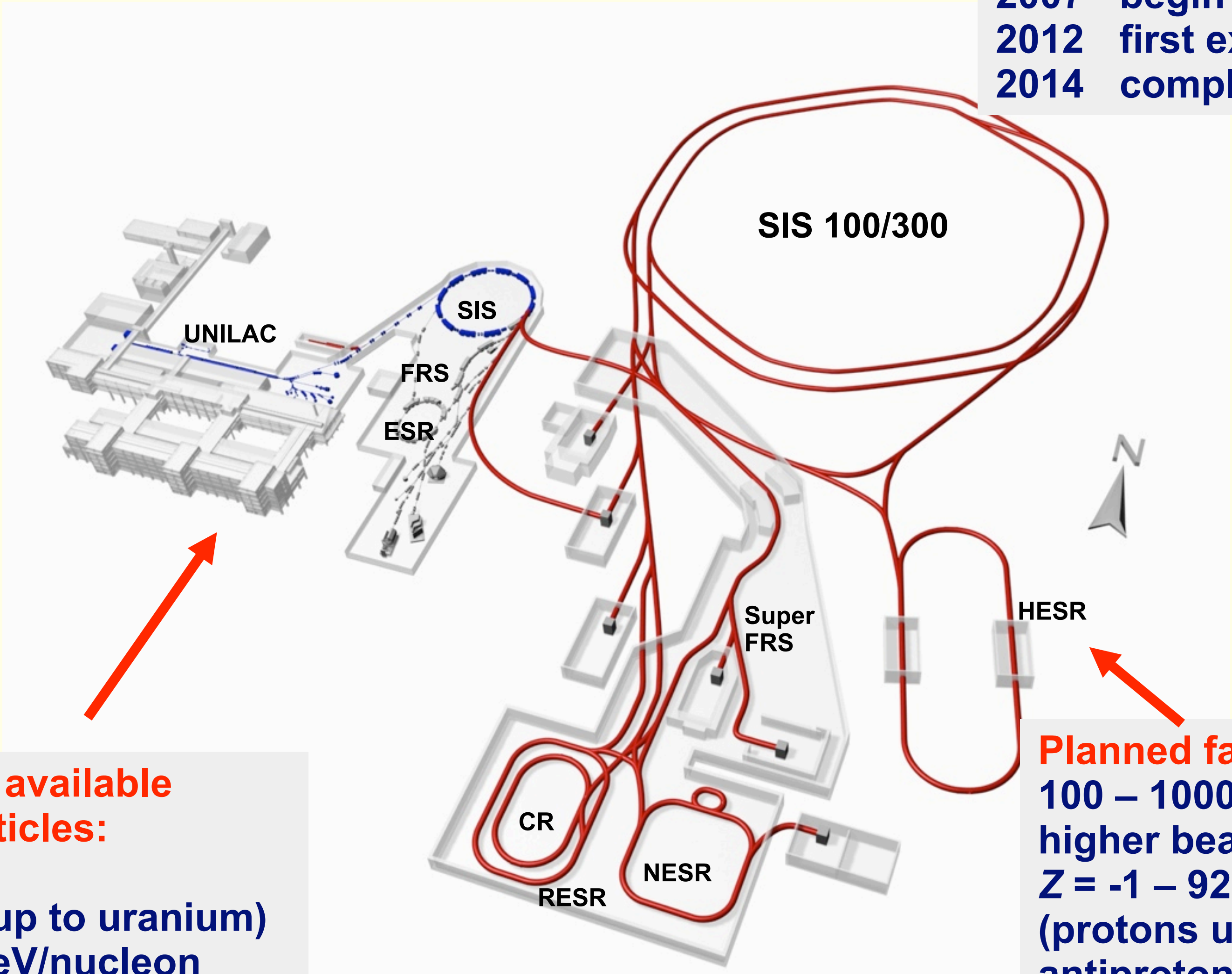
p+p collisions:
$\sqrt{s}$ = 14 TeV
collision rate: 800 MHz

Pb+Pb collisions:
$\sqrt{s}$ = 5,5 TeV
collision rate: 10 kHz

circumference: 27 km
***B*-Field: 8 T**
100 m beneath the surface
first collisions: 2008

FAIR at GSI

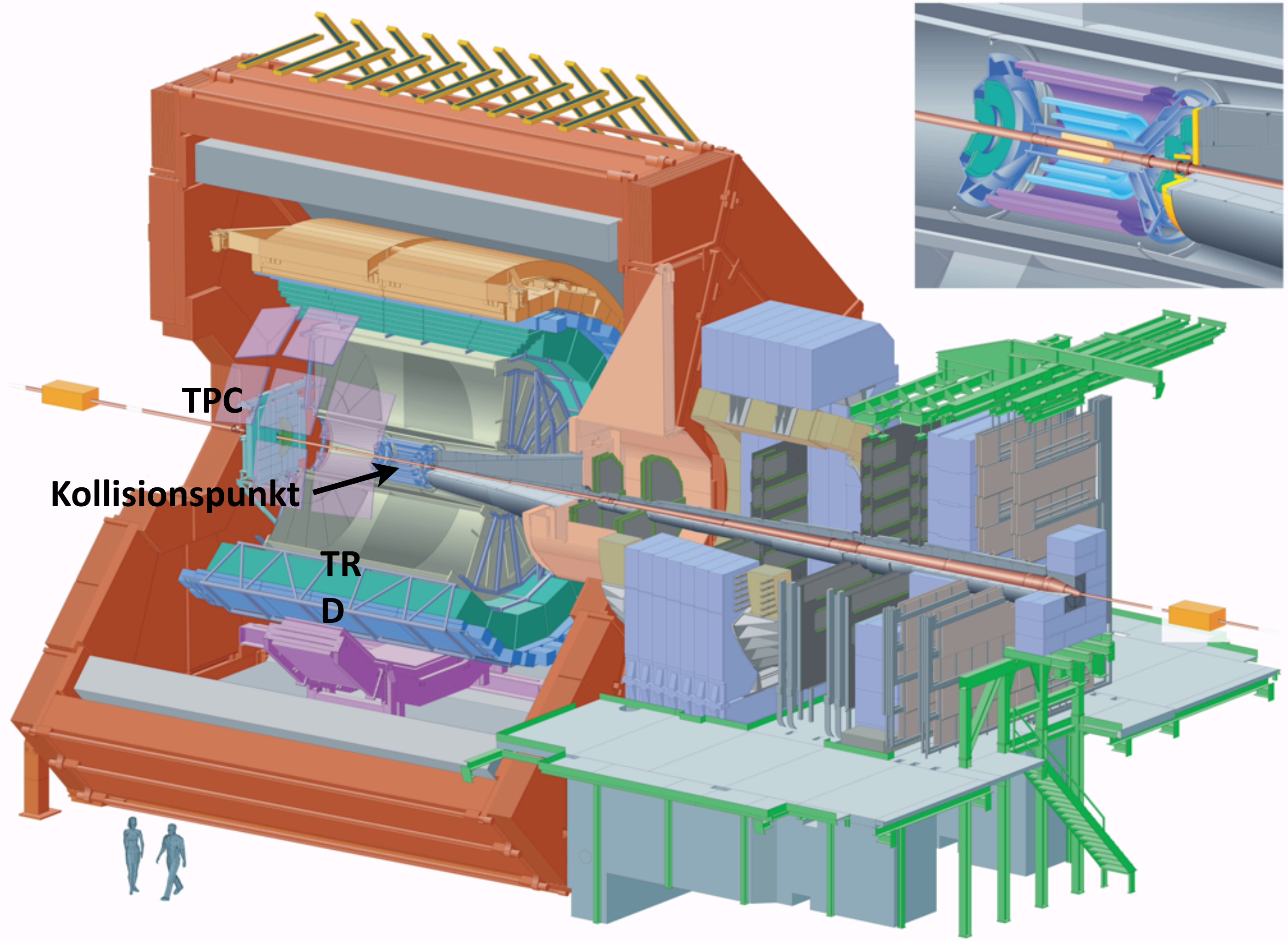
2007 begin of construction
2012 first experiments
2014 completion



Currently available beam particles:
Z = 1 – 92
(protons up to uranium)
up to 2 GeV/nucleon

Planned facility:
100 – 1000 times higher beam intensities,
Z = -1 – 92
(protons up to uranium, antiprotons),
up to 35 GeV/nucleon

Das ALICE-Experiment



- 18 detector systems
- ~ 10 000 t
- > 1000 collaborators
- p+p up to 14 000 GeV
- Pb+Pb up to 5500 GeV
- First p+p-collisions: ~ Nov. 2009

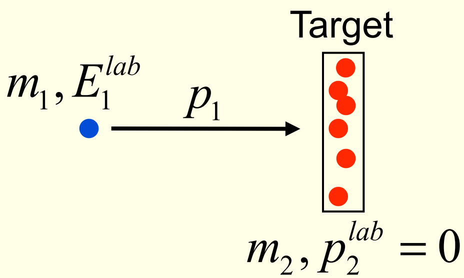
Focus of the german groups (including Heidelberg):
Time Projection Chamber (TPC) and Transition Radiation Detector (TRD)

1.2 Kinematic Variables

Center-of-mass Energy √s

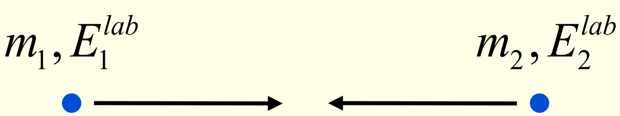
Mandelstam variable s is defined as: $$s = (P_A + P_B)^2 = (\underbrace{E_A^* + E_B^*}_{\text{Total energy in CMS}})^2$$

Fixed-Target-Experiment:



$$\sqrt{s} = \sqrt{m_1^2 + m_2^2 + 2E_1^{lab} m_2} \overset{E_1^{lab} \gg m_1, m_2}{\approx} \sqrt{2E_1^{lab} m_2}$$

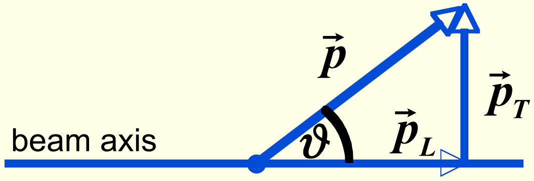
Collider:



$$\sqrt{s} = \sqrt{m_1^2 + m_2^2 + 2E_1^{lab}E_2^{lab} + 2p_1^{lab}p_2^{lab}} \overset{\vec{p}_1 = -\vec{p}_2, m_1 = m_2}{=} 2E_1^{lab}$$

The energy of heavy-ion collisions is typically given per nucleon-nucleon pair (√s_{NN})

Rapidity



$$p = \sqrt{p_L^2 + p_T^2}, \quad m_T := \sqrt{m^2 + p_T^2}$$

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

rapidity

$$y \approx \beta_L \text{ for } \beta_L \ll 1$$

$$e^y = \sqrt{\frac{E + p_L}{E - p_L}}, \quad e^{-y} = \sqrt{\frac{E - p_L}{E + p_L}}$$

$$E = m_T \cdot \cosh y, \quad p_L = m_T \cdot \sinh y$$

$$\beta_L = \frac{p_L}{E} = \tanh y$$

***y* is additive under Lorentz transformation:**

$$y = y' + y_{S'}$$

rapidity in system S

rapidity in S‘

rapidity of S‘ measured in S

Pseudorapidity η:

$$y = \frac{1}{2} \ln \frac{E + p\cos\vartheta}{E - p\cos\vartheta} \overset{p \gg m}{\approx} \frac{1}{2} \ln \frac{1 + \cos\vartheta}{1 - \cos\vartheta} = \frac{1}{2} \ln \frac{2\cos^2 \frac{\vartheta}{2}}{2\sin^2 \frac{\vartheta}{2}} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

In particular: $y = \eta$ for $m = 0$

Summary: Kinematic Variables

Transverse momentum

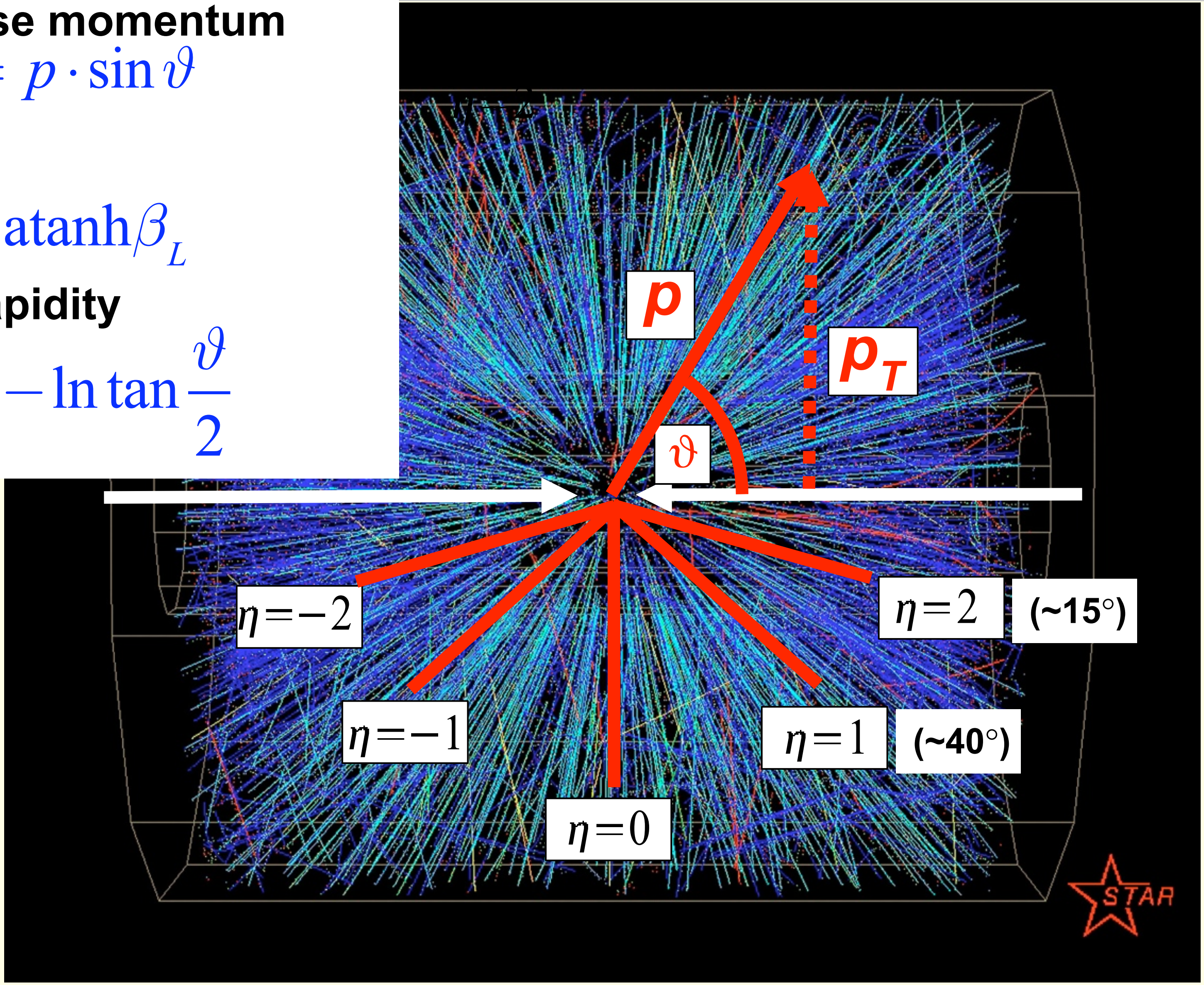
$$p_{\mathrm{T}} = p \cdot \sin\vartheta$$

Rapidity

$$y = \operatorname{atanh}\beta_L$$

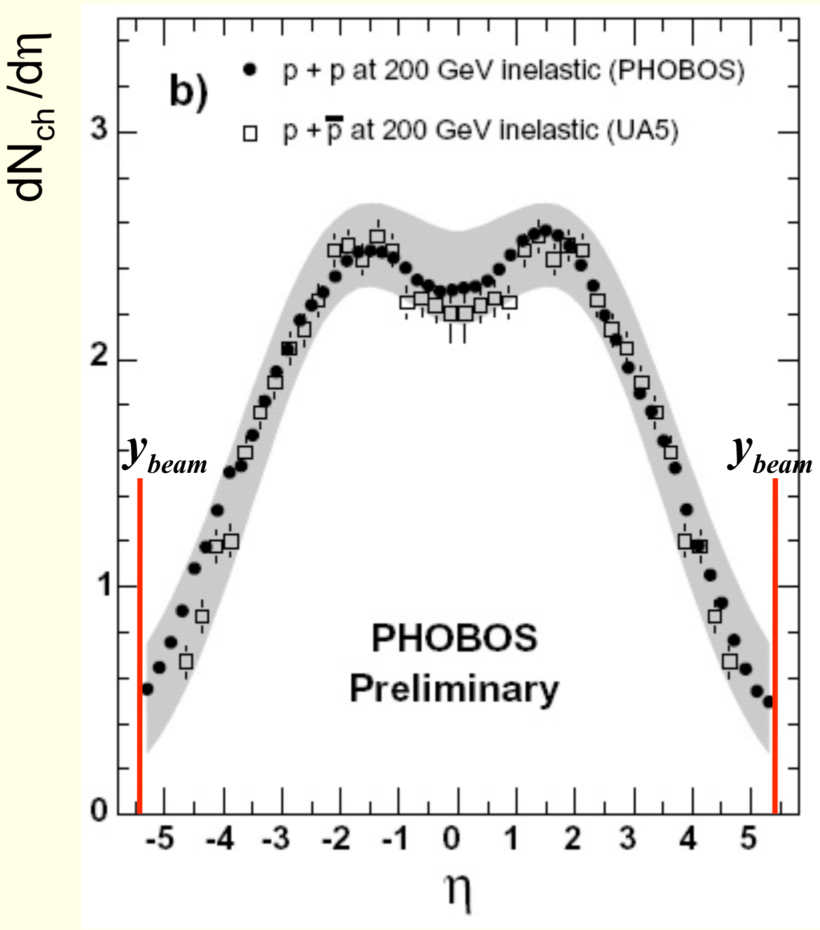
Pseudorapidity

$$\eta = -\ln\tan\frac{\vartheta}{2}$$



Example of a Pseudorapidity Distribution

p+p at $\sqrt{s} = 200$ GeV



Beam rapidity:

$$y_{\text{beam}} = \ln \frac{E+p}{m} = 5,4$$

Average number of charged particles:

$$\langle N_{ch} \rangle = \int \frac{dN_{ch}}{d\eta} d\eta \approx 20$$

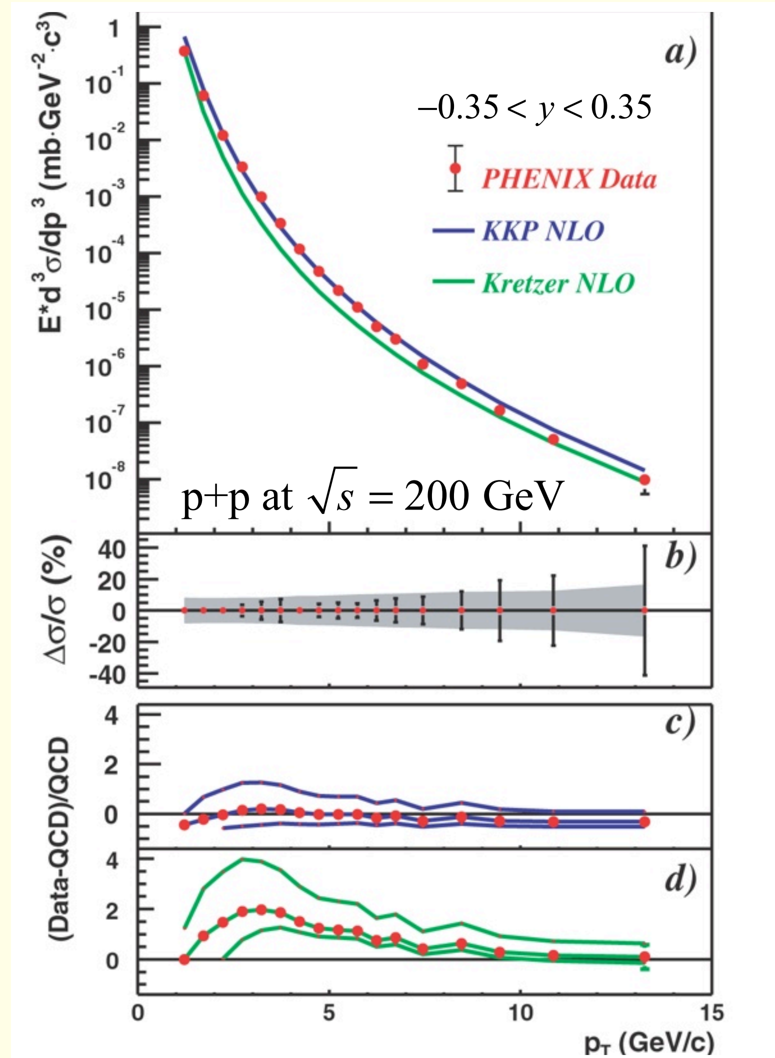
Invariant Cross Section

$$\frac{d^3\sigma}{d\vec{p}^3/E} = E\frac{d^3\sigma}{d\vec{p}^3} = E\frac{1}{p_T}\frac{d^3\sigma}{dp_T\,dp_L\,d\varphi}$$

$$\overset{\frac{dp_L}{dy}=m_T\cosh y = E}{=} \frac{1}{p_T}\frac{d^3\sigma}{dp_T\,dy\,d\varphi}$$

$$\overset{\varphi-symmetry}{=} \frac{1}{2\pi\,p_T}\frac{d^2\sigma}{dp_T\,dy}$$

Example: π^0 production



Integral of the inv. cross section:

$$\int p_T\mathrm{d}p_T\,\mathrm{d}y\,\mathrm{d}\varphi\,E\frac{d^3\sigma}{d\vec{p}^3} = \langle N\rangle\cdot\sigma_{\mathrm{inel}}$$

Average particle multiplicity per event (→ $\langle N\rangle$)

Total inel. cross section (→ σ_{inel})

Invariant Mass

Consider the decay of a particle with mass *M* into two daughter particles

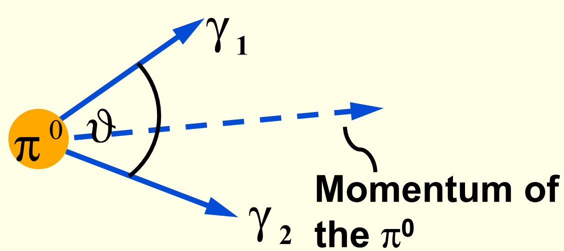
Invariant Mass:

$$M^2 = \left[\begin{pmatrix} E_1 \\ \vec{p}_1 \end{pmatrix} + \begin{pmatrix} E_2 \\ \vec{p}_2 \end{pmatrix} \right]^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

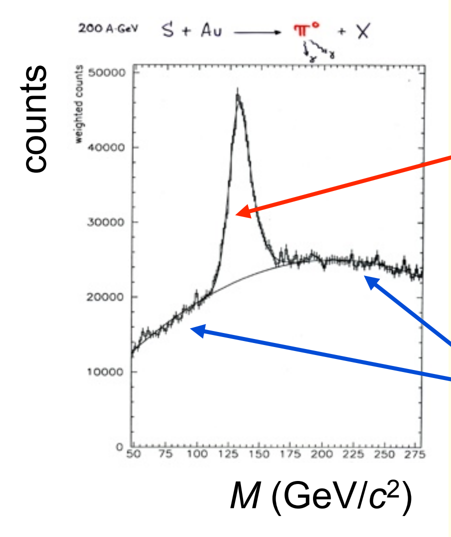
$$= m_1^2 + m_2^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2$$

$$= m_1^2 + m_2^2 + 2E_1E_2 - 2p_1p_2\cos\vartheta$$

Example: π^0 - Decay $\pi^0 \rightarrow \gamma + \gamma \text{ (BR: 98.8\%)}: m_1 = m_2 = 0,\ E_i = p_i$



$$M = \sqrt{2E_1E_2(1 - \cos\vartheta)}$$



Signal: Number of entries over combinatorial background (Peak width determined by energy resolution of the detector)

Background of γ-pairs, which don‘t originate from the same π^0 decay

Extra Slides

Lorentz Invariant Phase Space Element

Lorentz transformation of phase space element $d^3\vec{p} = dp_x \times dp_y \times dp_z$

not Lorentz Invariant!

$$p'_x = \gamma(p_x - \beta E)$$
$$E' = \gamma(E - \beta p_x)$$
$$p'_y = p_y$$
$$p'_z = p_z$$

$$\frac{\partial(p_x, p_y, p_z)}{\partial(p'_x, p'_y, p'_z)} = \begin{vmatrix} \frac{\partial p_x}{\partial p'_x} & 0 & 0 \\ 0 & \frac{\partial p_y}{\partial p'_y} & 0 \\ 0 & 0 & \frac{\partial p_z}{\partial p'_z} \end{vmatrix} = \frac{E}{E'}$$

$$dp_x dp_y dp_z = \frac{\partial(p_x, p_y, p_z)}{\partial(p'_x, p'_y, p'_z)} \times dp'_x dp'_y dp'_z$$

Invariant phase space element: $$\frac{d^3\vec{p}}{E}$$

Invariant cross section: $$\frac{d\sigma}{d^3\vec{p}/E} = E\frac{d\sigma}{d^3\vec{p}}$$