NICA Days 2023

Belgrade, Serbia
02-03
10.23

Global event characterization in heavy-ion collisions

Grigory Feofilov
(St.Petersburg State University)

02.10.2023, 14:00, 45m
Vinča Institute of Nuclear Sciences, Belgrade, SERBIA
"Belgrade Panorama" conference hall
https://indico.jinr.ru/e/nica_days2023

Literature

- C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994
- L. P. Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994 (book is freely available as pdf)
- E. Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004
- Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005
- R. Vogt, Ultrarelativistic Heavy-ion Collisions, Elsevier, 2007
- W. Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010
- S. Sarkar, H. Satz and B. Sinha, The physics of the quark-gluon plasma, Lecture notes in physics, Volume 785, 2010

Talk layout

- Introduction.
- What are we colliding.
- Multiplicity, p_T , transverse energy
  and energy density in AA collisions
- Reaction plane and Event plane
- Selection of central events
- Conclusion

✓ Introduction

” Relativistic nuclear physics” : a bit of History

A.M. Baldin

1971: the 1st relativistic nuclear beams with an energy of 4.2 AGeV at the synchrophasotron at the LHE, JINR. One of the 1st studies of nuclear effects in the high energy interactions off nuclei

A.M. Baldin et al.
Sov.J. Nucl.Phys.18,41 (1973)

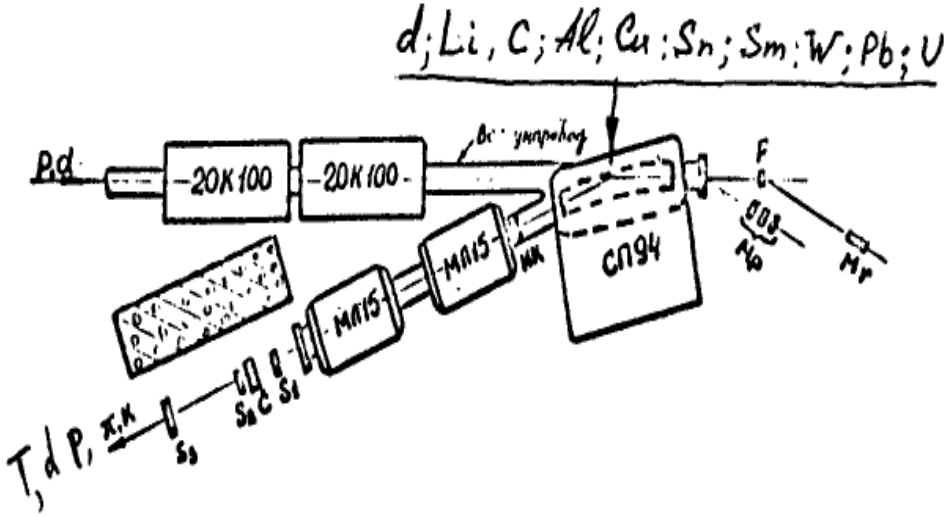


Fig. 2 Experimental layout

A.M. Baldin ,”Heavy Ion Interactions at High Energies”, report at AIP Conf. Proc. 26, 621 (1975)

BEVALAC(1972), SPS(1976), RHIC(2000), LHC(2009)

PHYSICS REPORTS (Review Section of Physics Letters) 65, No. 3 (1980) 151–229. NORTH-HOLLAND PUBLISHING COMPANY

...a bit of History...

HADRONIC INTERACTIONS OF HIGH ENERGY COSMIC-RAY OBSERVED BY EMULSION CHAMBERS

C.M.G. LATTES

Instituto de Fisica Gleb Wataghin, Universidade Estadual de Campinas, Campinas, Sao Paulo, Brasil

Y. FUJIMOTO and S. HASEGAWA

Science and Engineering Research Laboratory, Waseda University, Shinjuku, Tokyo, Japan

In 1980: "…we found that the decay temperature of a fire-ball is of the order of a pion rest-energy, $m_p c2$, much smaller than the participating energies in the collision…"

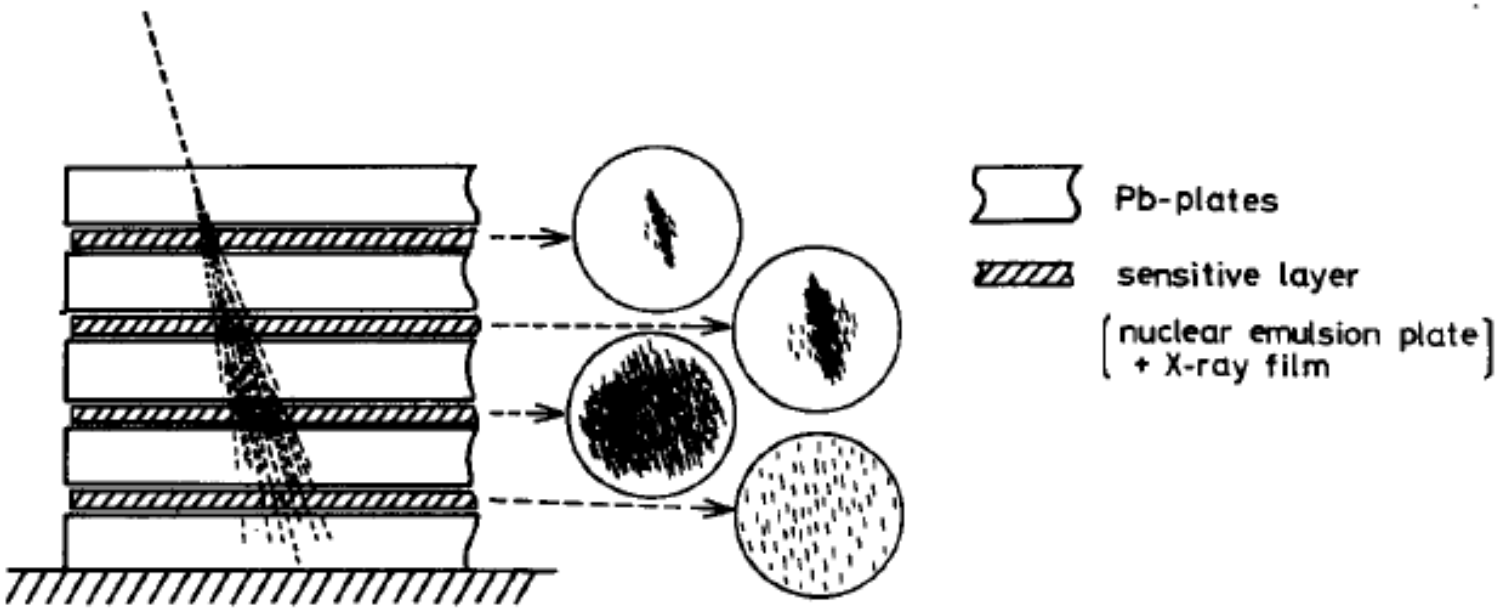


Fig. 1. Basic structure of emulsion chamber as electron shower detector.

... a bit of History: QGP

…J. C, Collins and M. J. Perry -1975, …E.Shuryak 1978…:
Шуряк Э В "Кварк-глюонная плазма" *УФН* **138** 327–328 (1982)

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

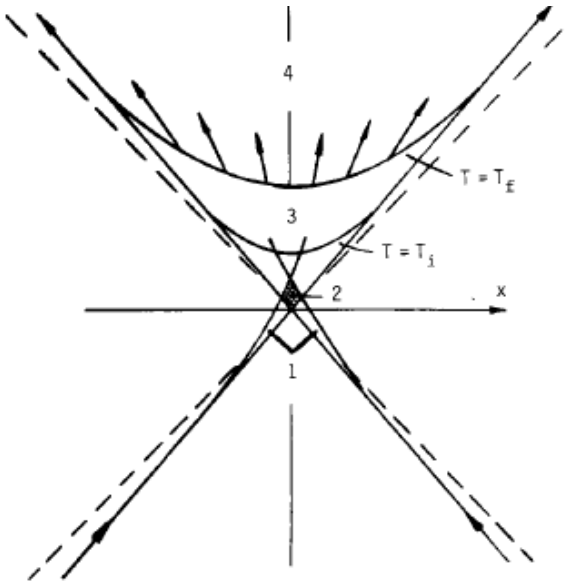


Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.

Phys. Lett. *B78 (1978) 150*

Early expectations: QGP like **an ideal gas** of quarks and gluons

At very high energy density, the coupling constant of QCD becomes weak. A gas of particles should to a good approximation become an ideal gas. Each species of particle contributes to the energy density of an ideal gas as

$$\epsilon \sim \frac{\pi^2}{30} N T^4$$

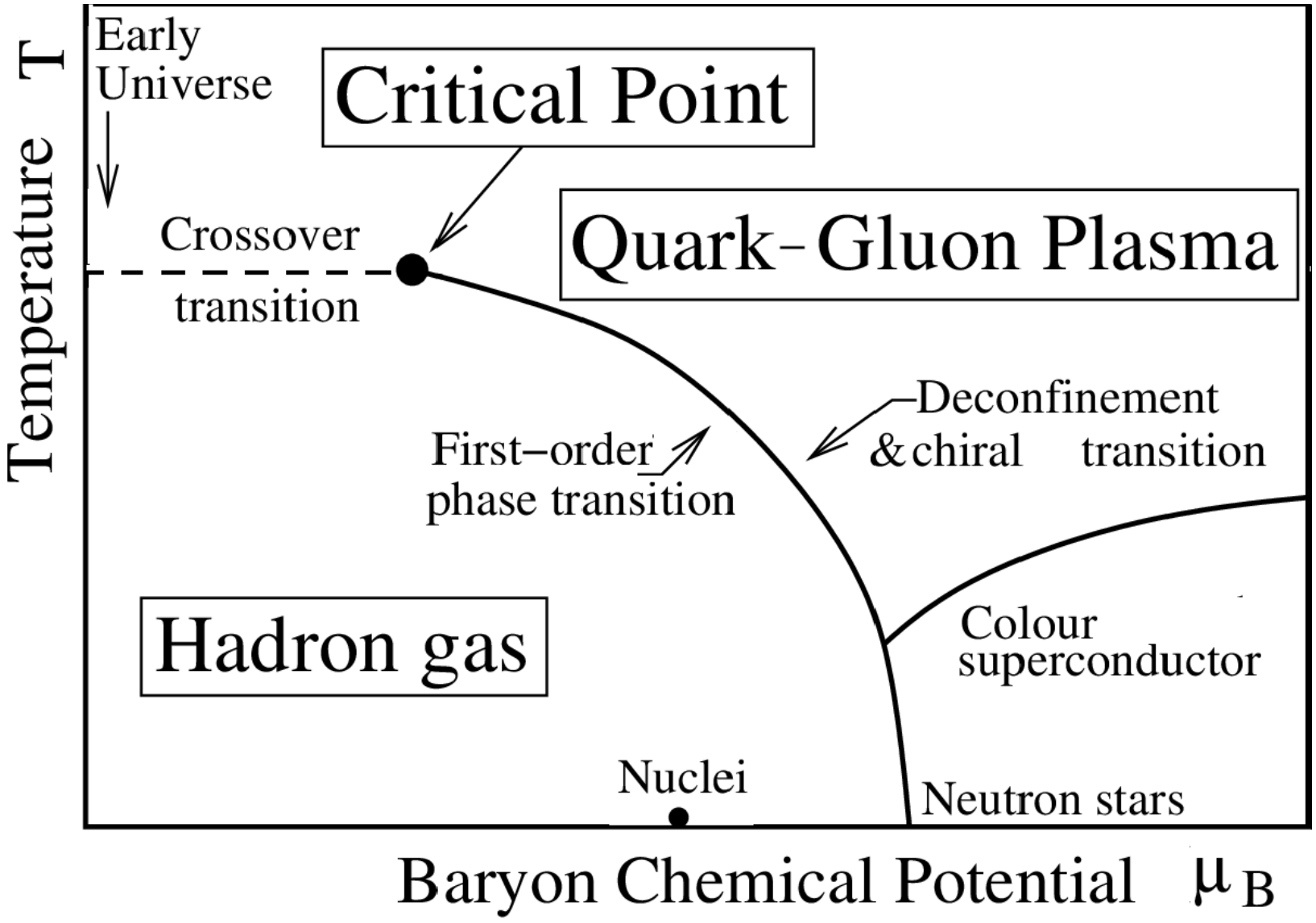
where N is the number of particle degrees of freedom. At low temperatures when masses are important, only the lowest mass, strongly interacting particle degree of freedom contributes; the pion, and the energy density approaches zero as $\epsilon \sim e^{-m_\pi/T}$. For an ideal gas of pions, the number of pion degrees of freedom is three. For a QGP there are two helicities and eight colours for each gluon, and for each quark, three colours, two spins, and a quark–antiquark pair. The number of degrees of freedom is $N \sim 2 \times 8 + 4 \times 3 \times N_F$ where N_F is the number of important quark flavours, which is about three if the temperature is below the charm quark mass so that $N \sim 50$.

Relativistic heavy-ion physics: three lectures

L. McLerran
Brookhaven National Laboratory, Upton, NY 11973, USA and RIKEN BNL Research Center,
Brookhaven National Laboratory, Upton, NY 11973, USA

➢ **QGP: lots of interesting questions to be answered !**

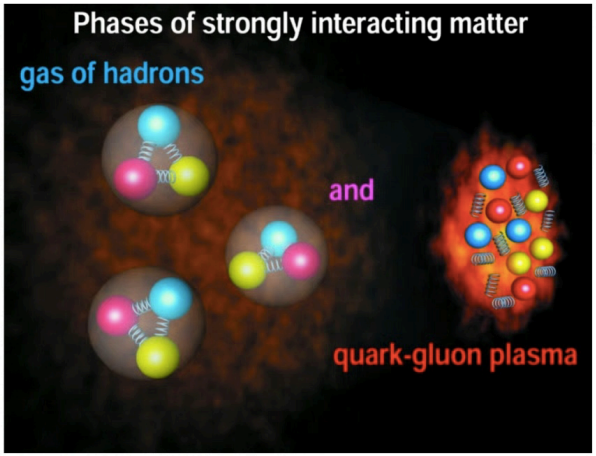
Phase diagram of strongly interacting matter

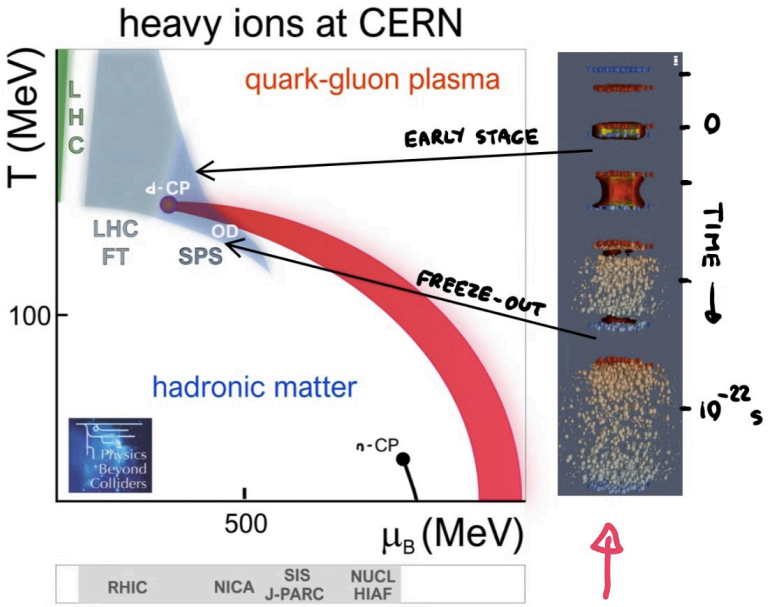


Bhalerao, Rajeev S. (2014). "Relativistic heavy-ion collisions". In Mulders, M.; Kawagoe, K. (eds.). 1st Asia-Europe-Pacific School of High-Energy Physics. CERN Yellow Reports: School Proceedings. Vol. CERN-2014-001, KEK-Proceedings-2013–8. Geneva: CERN. pp. 219–239. doi:10.5170/CERN-2014-001. ISBN 9789290833994. OCLC 801745660. S2CID 119256218.

STRONG INTERACTIONS

WHAT HAPPENS WHEN STRONGLY INTERACTING MATTER GETS HOTTER/DENSER AND ITS VOLUME CHANGES ?





NA61/SHINE: WHAT HAPPENS IN HEAVY ION COLLISIONS?

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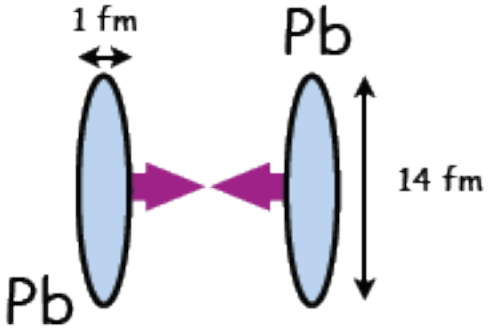
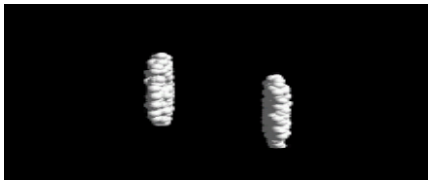
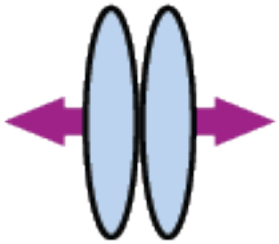
Slide by Marek Gazdzicki(**Goethe University Frankfurt**), NA61/SHINE Collaboration,
See also report by Marjan Ćirković (Faculty of Physics, University of Belgrade)**,**
"News from the NA61/SHINE" , 6 Oct,2023, 13:30 - 14:00 CET
https://indico.jinr.ru/event/3746/timetable/#20231004

Phases of nuclear collisions

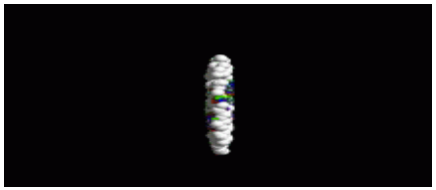


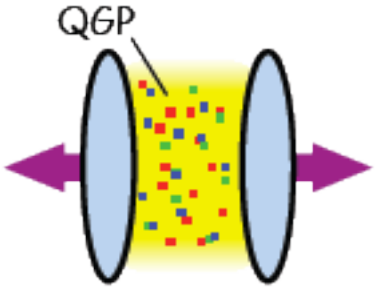
- Before collision



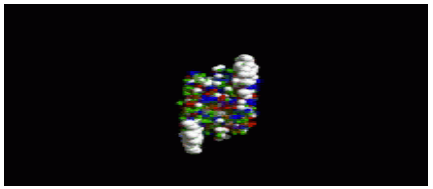


- Thermalization: (t < 1 fm/c) equilibrium is established

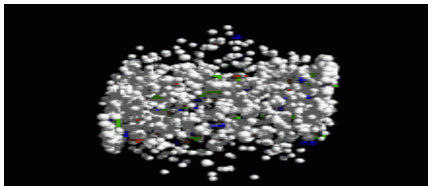


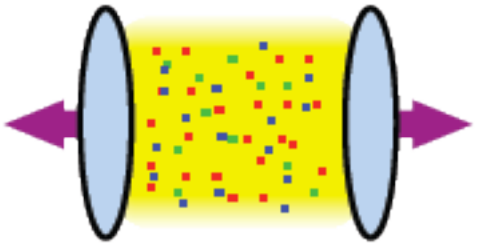


- Expansion and cooling (t < 10-15 fm/c)

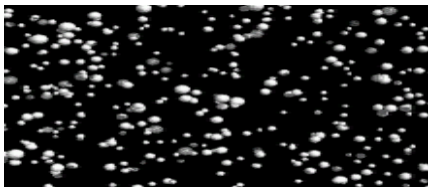


- Chemical freeze-out: inelastic collisions cease (number of particles frozen)





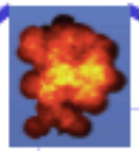
- Kinetic freeze-out: elastic collisions cease (momentum spectra frozen)



Dynamical models for HIC

Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodanamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, ...)

viscous
(Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,...)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

‚Hybrid'
QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

(‚hybrid'-UrQMD, EPOS, ...)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models
(UrQMD, IQMD, HSD, QGSM ...)

Partonic cascades
pQCD based
(Duke, BAMPS, ...)

Parton-hadron models:
- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics

(applicable for strongly interacting systems)

3

Slide by Elena Bratkovskaya, "Kruger2014: The International Workshop on Discovery Physics at the LHC", Protea Hotel Kruger Gate, South Africa, 1-5 December 2014

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Nuclear-nuclear collisions: two theoretical approaches [1]

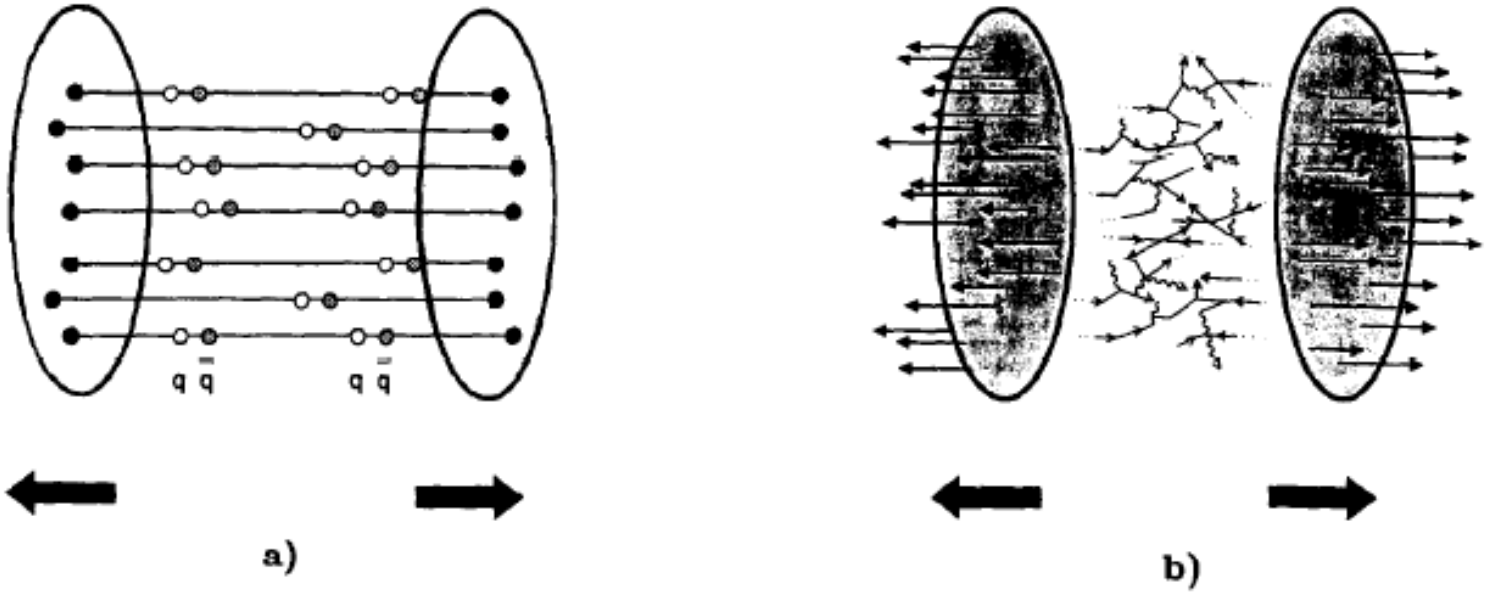


Fig. 2. (a) String picture: primary interactions lead to color flux tubes (strings) which break by qq production.
(b) Parton approach: multiple scatterings accompanied by emission and absorption of quarks and gluons are described as intermetted parton cascades.

[1] K. GEIGER, **SPACE-TIME DESCRIPTION OF ULTRA-RELATIVISTIC NUCLEAR COLLISIONS IN THE QCD PARTON PICTURE**
CERN, TH-Division, CH-121 I Geneva 23, Switzerland, ELSEVIER Physics Reports 258 (1995) 237-376

- **Experimental data can provide strong constrains on the models**

Nuclear-nuclear collisions:

what are we colliding?

K. Geiger / Physics Reports 258 (1995) 237–376

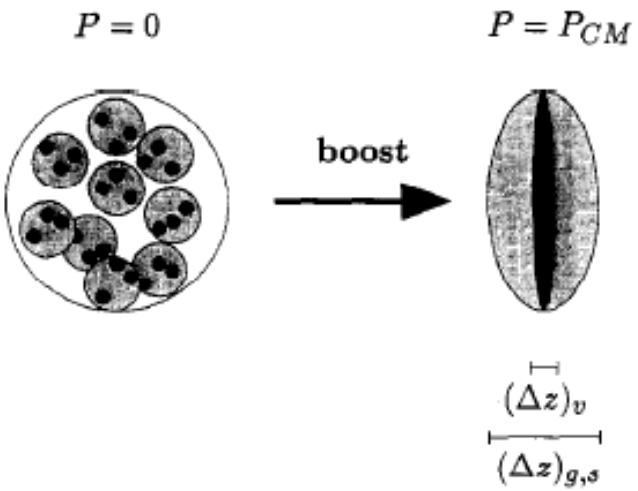
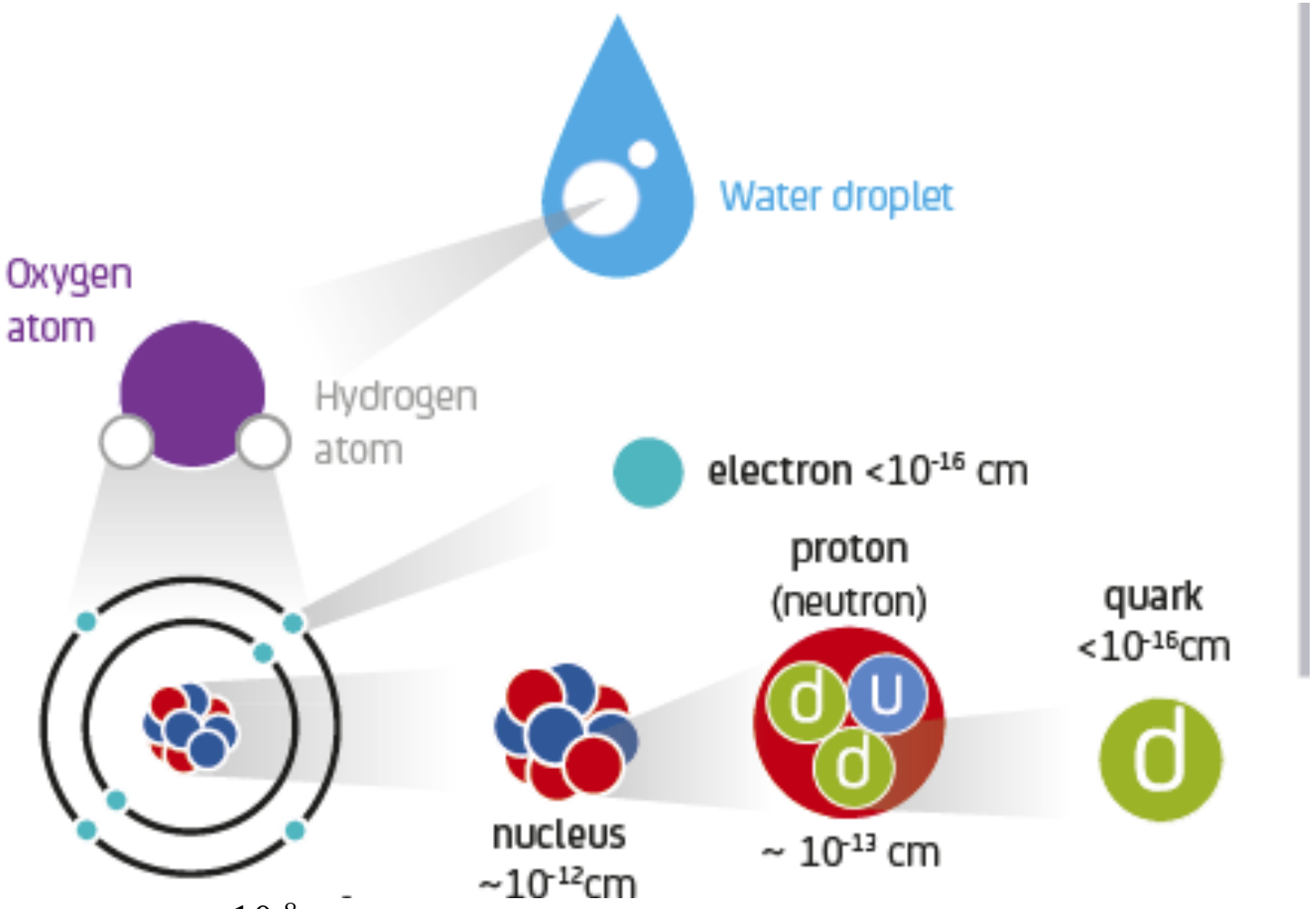


Fig. 19. Distributed Lorentz contraction: The spatial distribution of the partons in the rest frame of each nucleus becomes, after boosting to the *CM* frame, a disc of highly Lorentz contracted valence quarks of $(\Delta z)_v$, surrounded by clouds of softer gluons and sea quarks of $(\Delta z)_{g,s}$.

Микромир



Атом кислорода – 10^{-8}см

“Zoo” of particles:

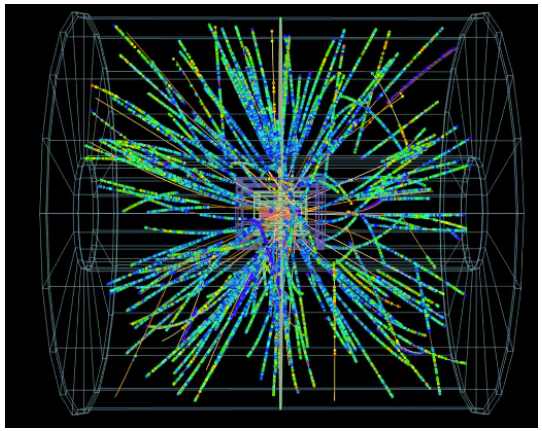
Important Notes:

1. In the detector we see only particles with a sufficiently long lifetime that allows them to be registered:

   γ, e, μ, π, K, p, n

2. To be registered, a particle must experience some interaction with the detector

   How to detect particles?



http://pdg.lbl.gov ~ 180 Selected Particles

$\gamma, W^{\pm}, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^0, \eta, f_0(600), \rho(770),$
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450),$
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680),$
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^0, K_S^0, K_L^0, K^*(892),$
$K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680),$
$K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^{\pm}, D^0, D^*(2007)^0,$
$D^*(2010)^{\pm}, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm},$
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^0, B^*, B_s^0, B_c^{\pm}, \eta_c(1S), J/\psi(1S),$
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440),$
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
$\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-,$
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-,$
$\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c'^+, \Xi_c'^0, \Xi(2645)$
$\Xi_c(2790), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

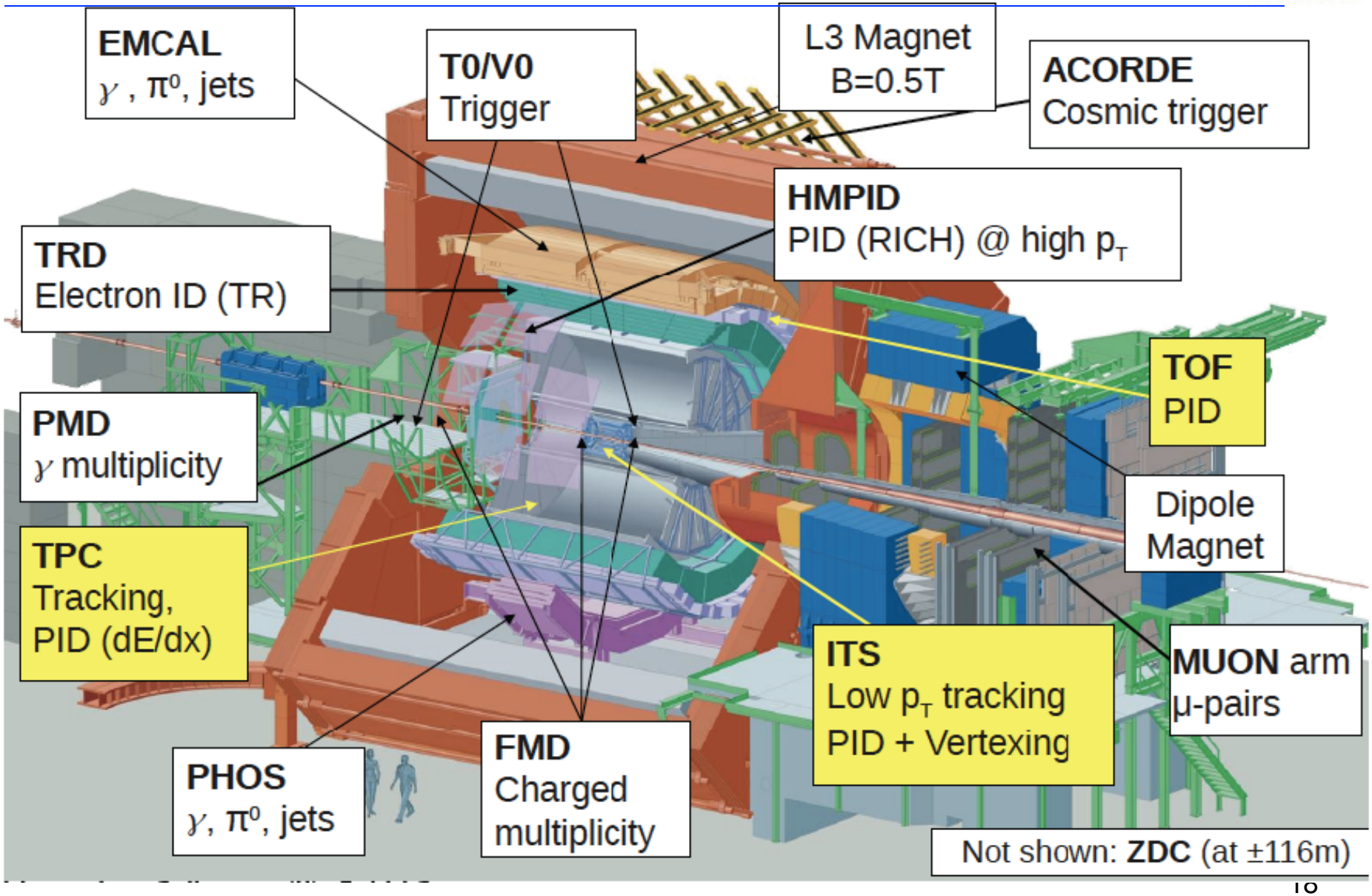
There are Many more

Footprints in the snow

Footprints in the snow

- And what are the footprints of different particles?

A Large Ion Collider Experiment

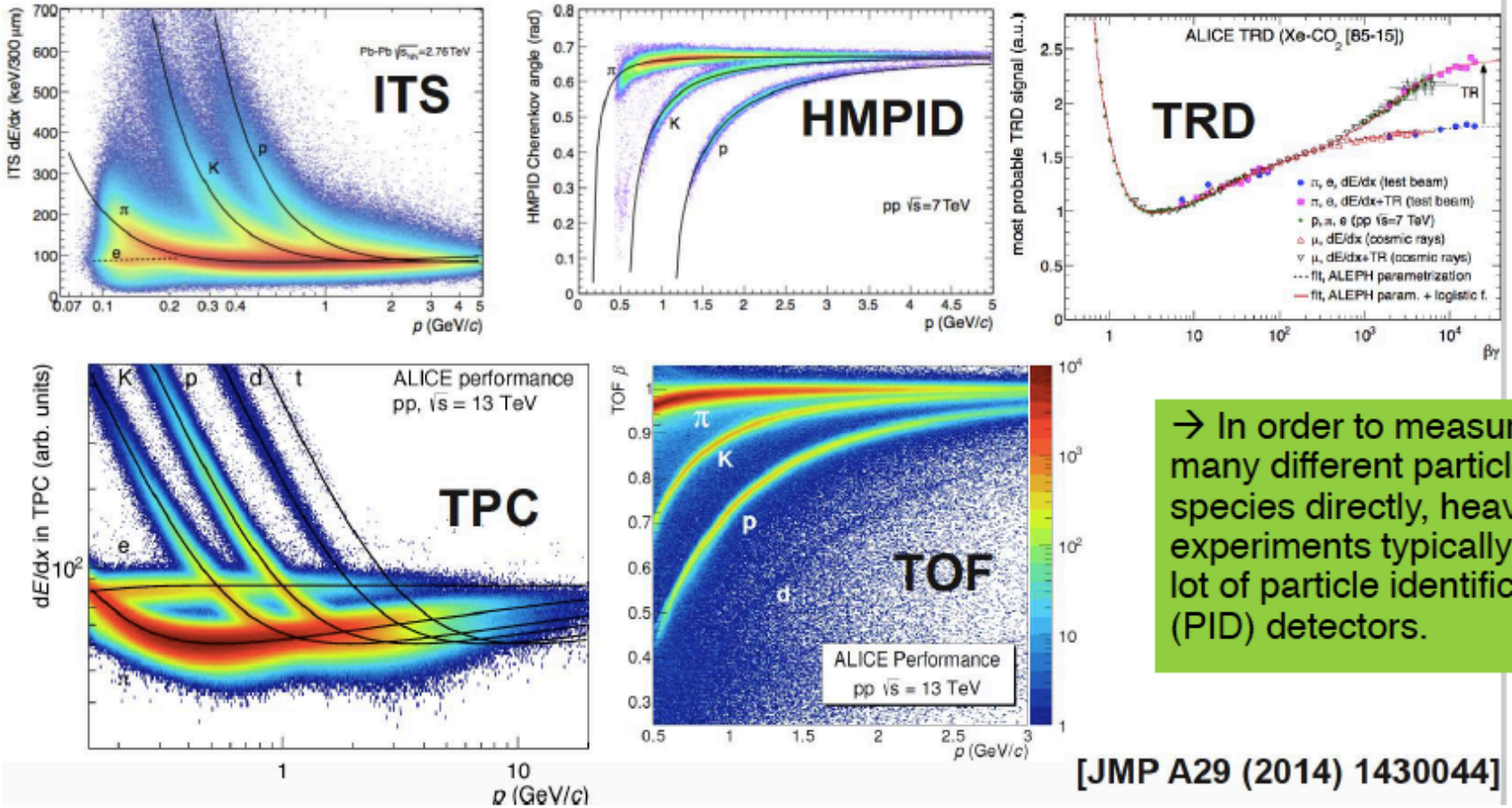


K. Aamodt et al. (ALICE), JINST, 3 , S08002 (2008)

Nuclear-nuclear collisions:
What do we usually measure?

Particles tracking and identification

Instrumentation for heavy-ion experiments: PID



→ In order to measure as many different particle species directly, heavy-ion experiments typically have a lot of particle identification (PID) detectors.

[JMP A29 (2014) 1430044]

Observables

(measured event by event)

- Number of particle tracks, primary and secondary vertices
- Total event charge particle multiplicity (N_{ch})
- Rapidity distribution of charged particles
- Event plane
- Azimuthal flows
- Types of particles and particle ratios (Particle Identification – PID)
- Total event transverse energy(E_T)

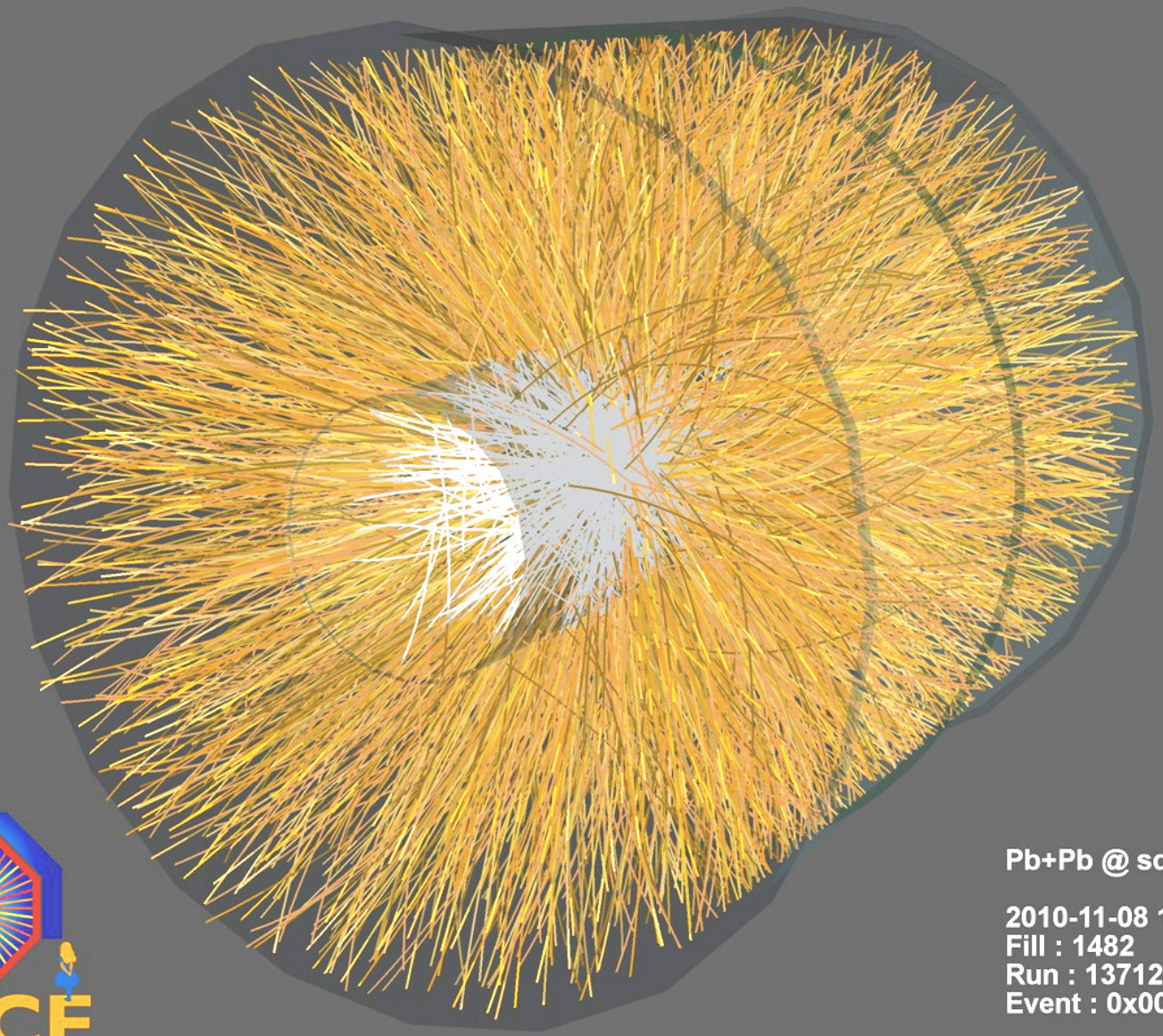
It is important to select the classes of events with similar properties related to the initial conditions

→ Centrality determination and different estimators

— multiplicity classes

— spectator nucleons (**N_{spect}**) and number of nucleon-participants (**N_{part}**)

- ✓ Multiplicity of charged particles in hadronic collisions



ALICE

Pb+Pb @ sqrt(s) = 2.76 ATeV

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

Nucleus-collisions: what are we observing?

For each particle, you can introduce a rapidity variable:

One can also define a rapidity variable:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z c}{E - p_z c} \right) .$$

Distribution of particles by rapidity:

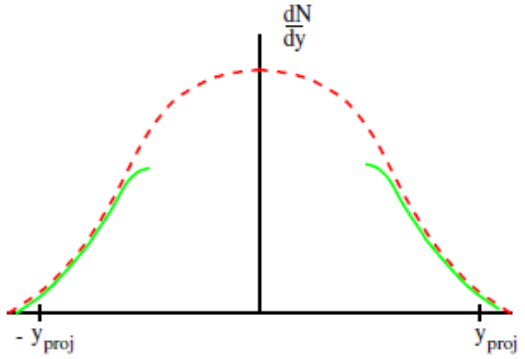
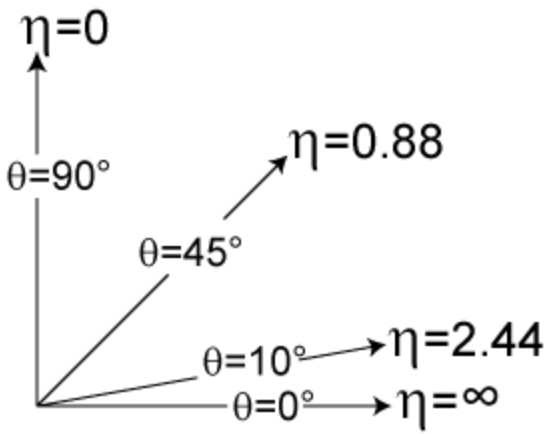


Fig. 18: The rapidity distributions of particles at two different energies

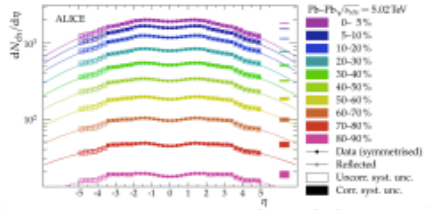
Pseudo-rapidity:

$$\eta = -\ln \left[\mathrm{tg} \left(\frac{\theta}{2} \right) \right] ,$$

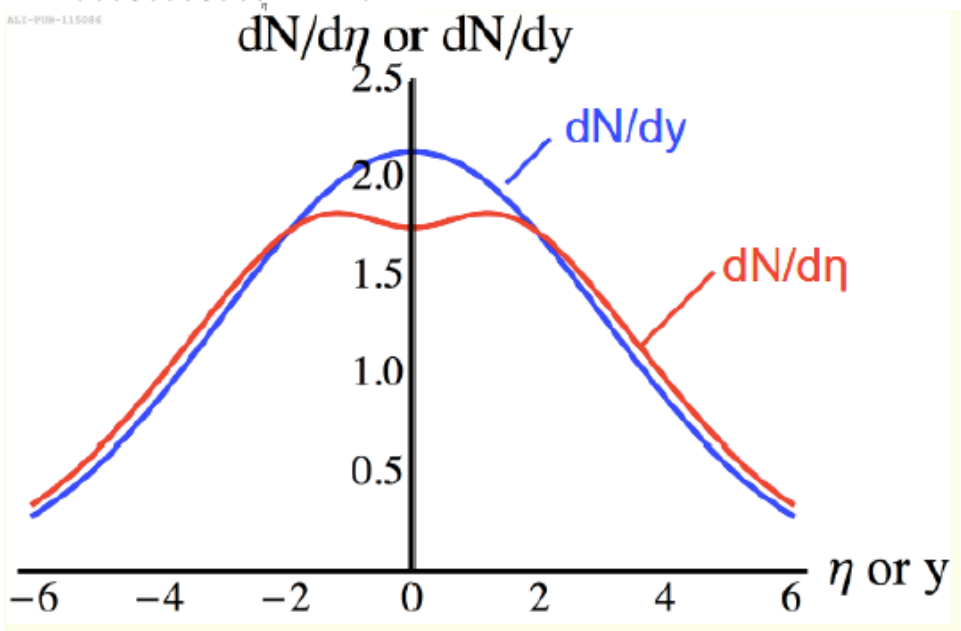


RAPIDITY AND PSEUDORAPIDITY

Short reminder: (Pseudo-)rapidity

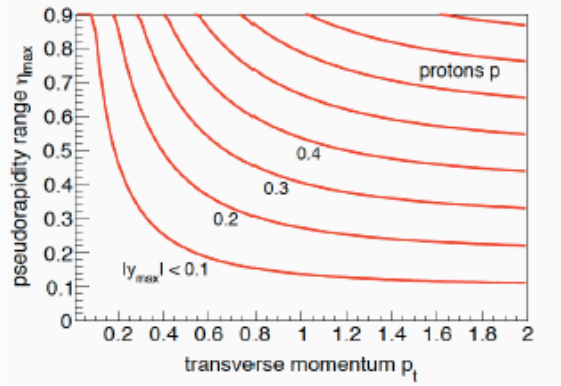


$$\frac{dN}{d\eta} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}}\,\frac{dN}{dy}$$



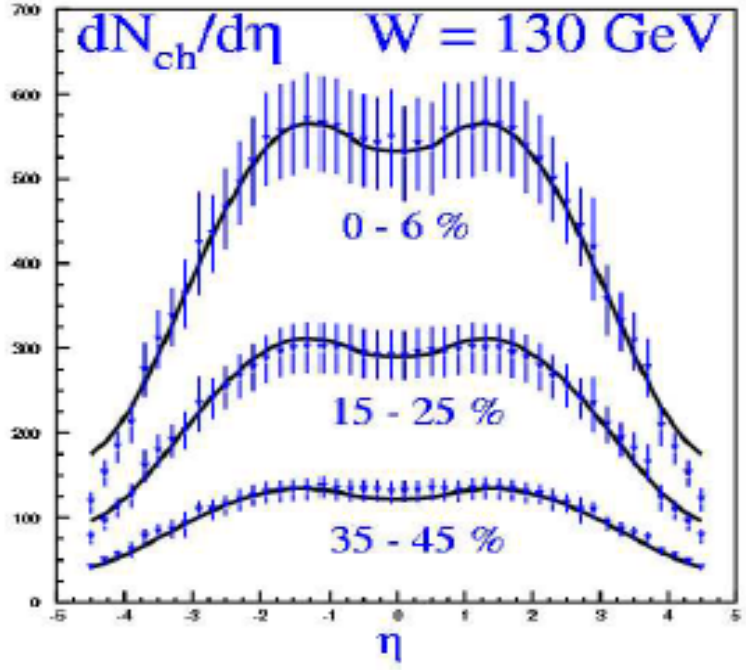
From: K. Reygers

→ Always keep in mind: Rapidity and pseudo-rapidity are not the same, especially at low transverse momenta!



Nucleus-nucleus collisions: what are we observing?

Pseudorapidity distribution of particle yields in experiments at RHIC:



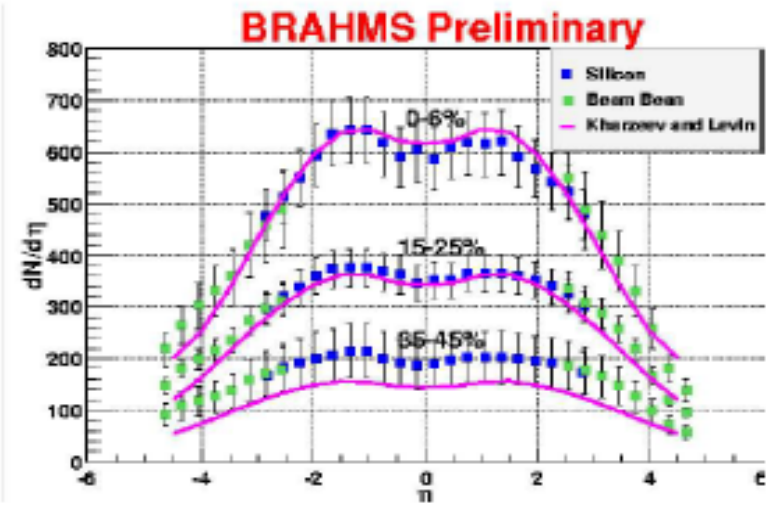


Fig. 28: Colour glass condensate fits to the rapidity density measured in the PHOBOS and BRAHMS experiments

Relativistic heavy-ion physics: three lectures

L. McLerran
Brookhaven National Laboratory, Upton, NY 11973, USA and RIKEN BNL Research Center,
Brookhaven National Laboratory, Upton, NY 11973, USA

Multiplicity distributions in pp collisions

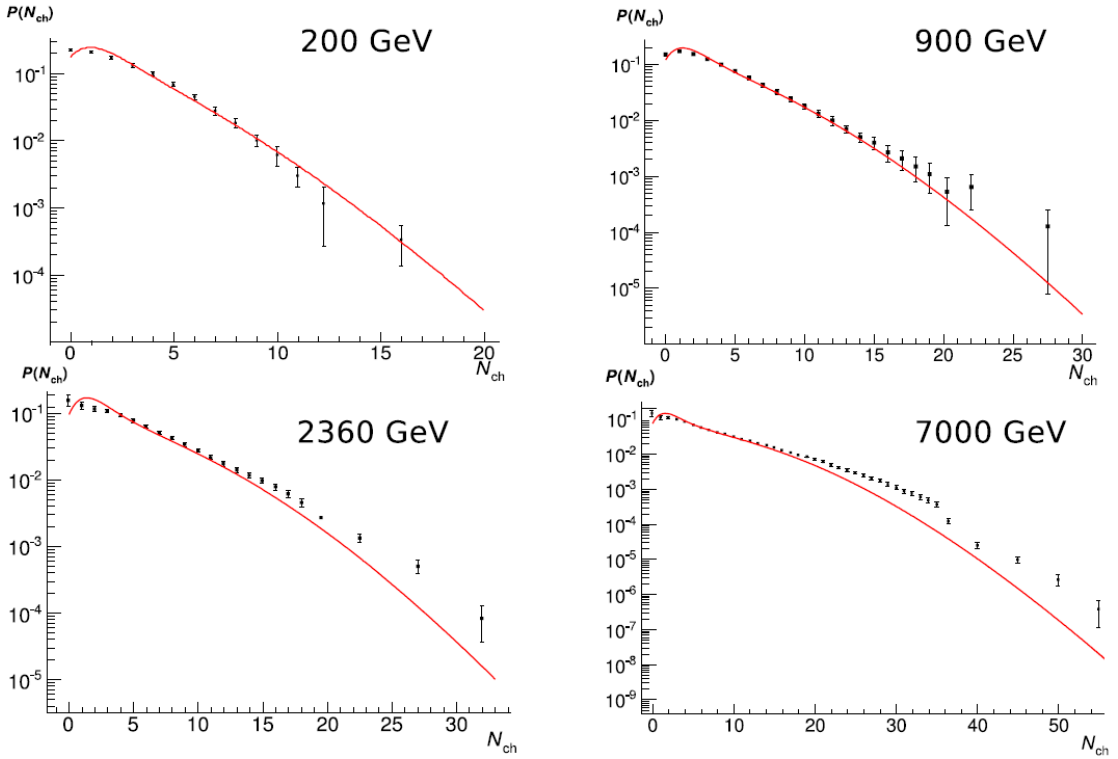


FIGURE 8. Charged particles multiplicity distributions in $p\bar{p}$ collisions at various energies $\sqrt{s}$ (200 GeV, 900 GeV) [25] and in pp collisions (2360 GeV, 7 TeV) [26] in pseudorapidity interval $|\eta| < 0.5$ (dots). The results of the modified multi-pomeron exchange model (lines) are calculated with the model parameters β and t as defined in Fig. 1, 6.

25. V. Khachatryan, et al. (CMS Collaboration), JHEP **1101**, 079 (2011).

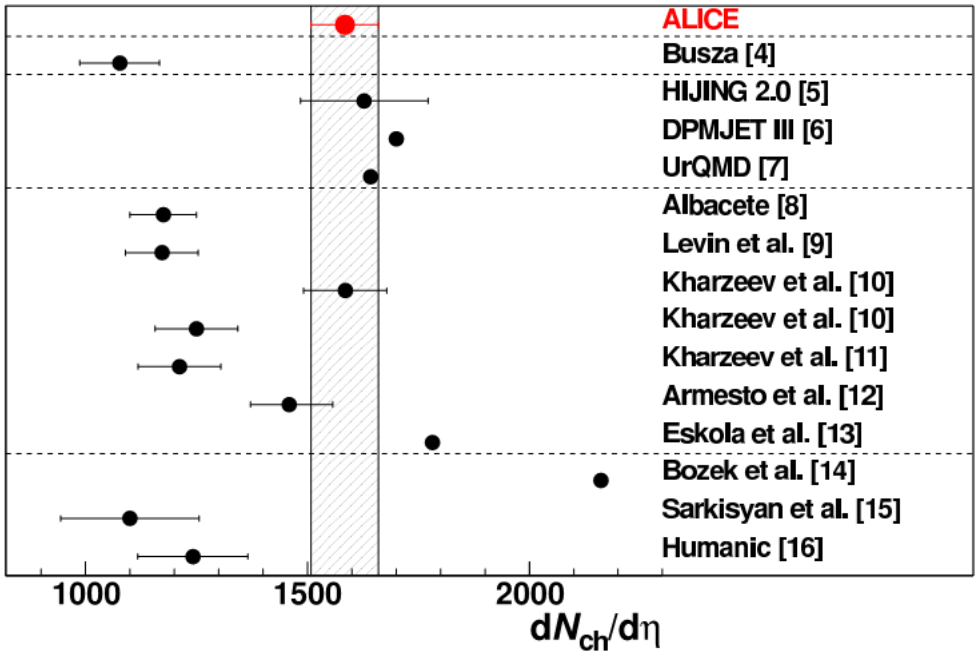
Model: see E.O.Bodnya*, V.N.Kovalenko†, A.M.Puchkov† and G.A.Feofilov†, "Correlation between mean transverse momentum and multiplicity of charged particles in pp and pp collisions: from ISR to LHC", PoS, 2013

Charged-particle multiplicity density at mid-rapidity in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV: :

Multiplicity:

- is essential to estimate **the initial energy density** and it is the 1st important constraint for the models!

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$



Comparison of ALICE measurement with model predictions.

- **Bjorken energy density: 2.8 x RHIC for 5% of most central collisions**

arXiv:1011.3916 [nucl-ex]. *Phys. Rev. Lett.* 105 (2010) 252301

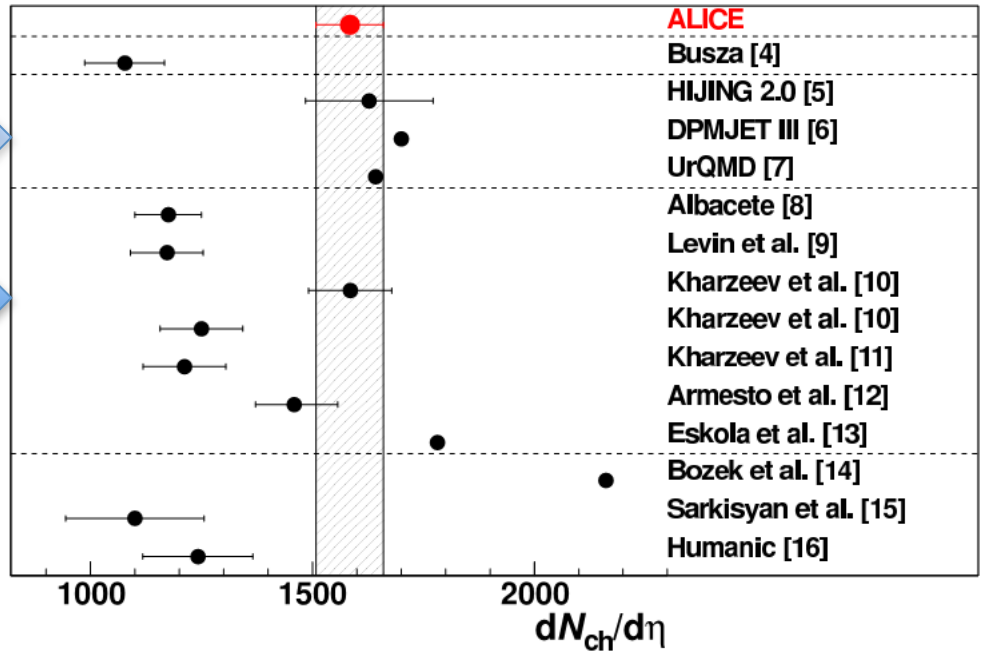
Charged-particle multiplicity density at mid-rapidity in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV: :

Empirical extrapolation

pQCD-inspired MC

Initial-state gluon density saturation models

Some other approaches



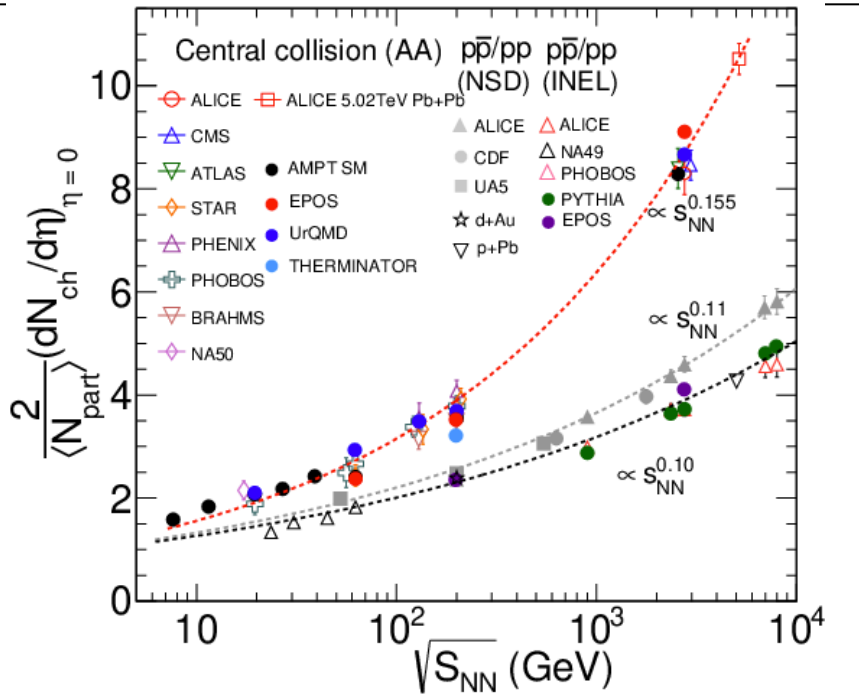
]

ALICE measurement and model predictions

arXiv:1011.3916 [nucl-ex]. *Phys. Rev. Lett.* 105 (2010) 252301

Charged particle pseudo-rapidity density per participant pair for central nucleus-nucleus and non-single diffractive pp (pp) collisions , as a function of $\sqrt{s_{NN}}$

- an increase of about a factor ~1.9 relative to pp collisions at similar collision energies,
- an increase of about a factor ~ 2.2 to central Au-Au collisions at $\sqrt{s_{NN}}$ = 0. 2 TeV !



Basu, Sumit et al - arXiv:2008.07802

- Faster growth with $\sqrt{s_{NN}}$ in AA than in pp!
- Logarythmic extrapolation is rulled out
- Important constraint for the models!

arXiv:1011.3916 [nucl-ex]. *Phys. Rev. Lett.* 105 (2010) 252301

- ✓ Measurement of p_T of charged particle

Particles tracking and identification

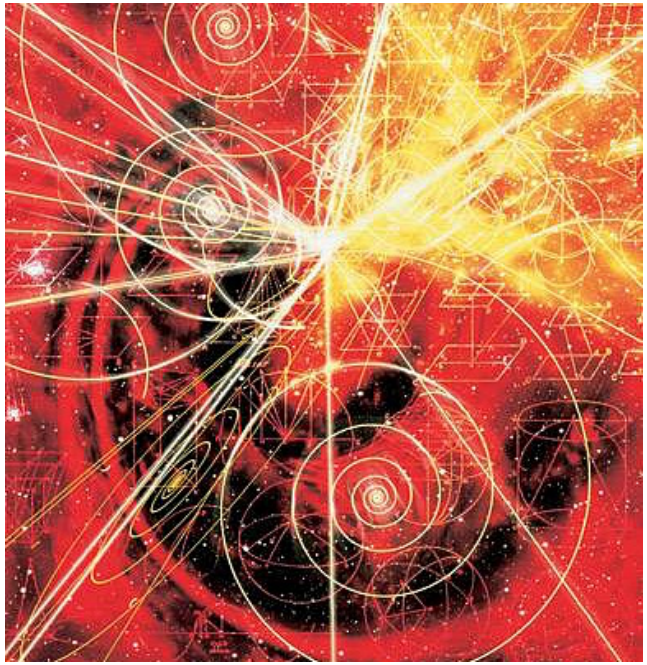
For a particle with charge q,
moving with speed V in a magnetic field
with intensity B, the Lorentz force acts:

$$F_л = qVB.$$

$$qVB = \frac{mV^2}{R}$$

m- particle mass
R – radius of the circle

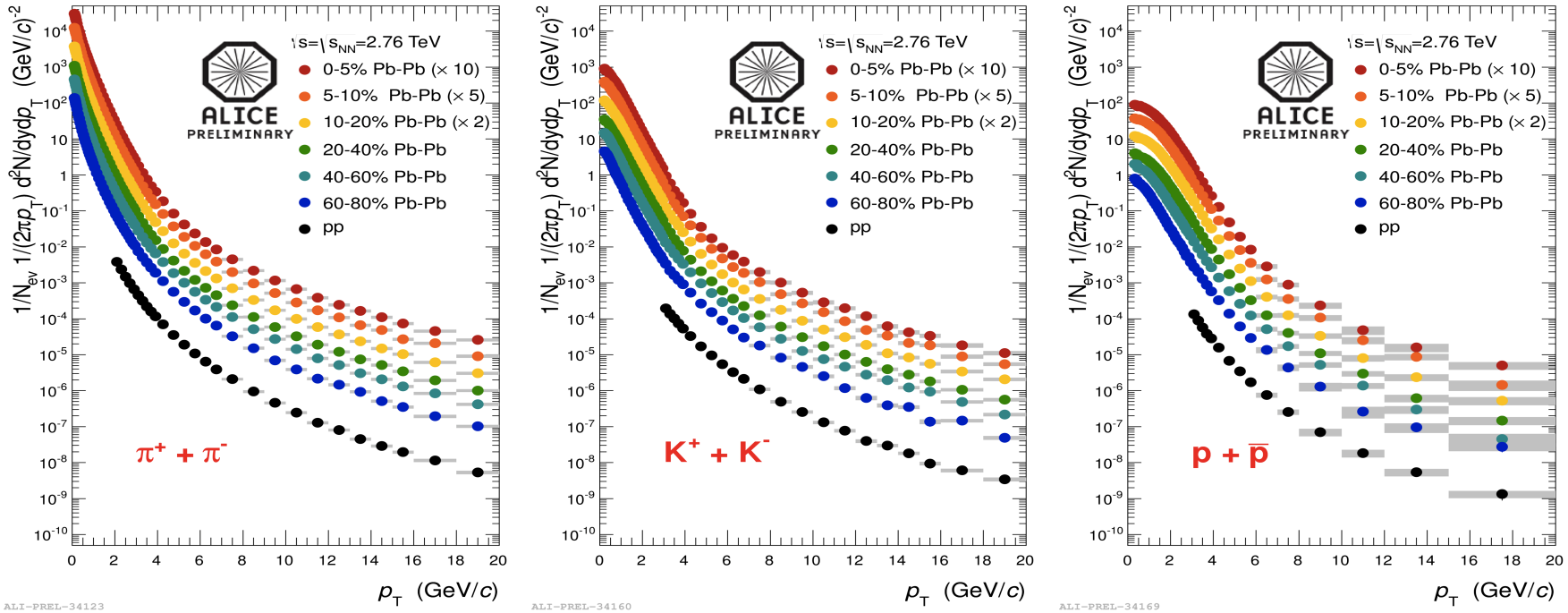
Having measured R, we will find the transverse momentum p_T=mV



http://www.popmech.ru/science/8036-fotografiya-na-pamyat-puzyrkovaya-kamera/

Nucleus-nucleus collisions: what are we observing? Particle distribution by transverse momentum:

Identified-particle p_T spectra up to 20 GeV/*c*



95 % of all particles below 1.5 GeV/*c* : particle production non-perturbative process

- **Low-p_T < 2 GeV/*c* :** dynamics of bulk matter described by **R**elativistic **H**ydrodynamic **M**odels **(RHD)**
- **High-p_T > 8 GeV/*c* :** spectra reflect interaction of partons from hard scatterings with the medium
- **Intermediate p_T 2 < p_T < 8 GeV/*c* :** interplay of soft and hard processes

33

- ✓Transverse energy in the event

Transverse energy of charged particles and Bjorken energy density

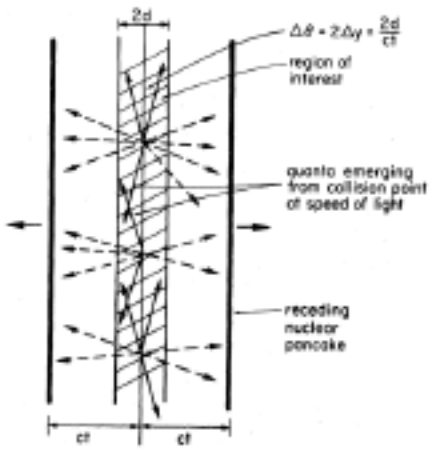
S⊥ – is the transverse overlap area of the colliding nuclei

$$\langle m_\perp \rangle = \sqrt{\langle p_\perp \rangle^2 + m^2}$$

$$\varepsilon \cdot \tau = \frac{dE_\perp}{dy}\frac{1}{S_\perp}$$

$$\varepsilon = \frac{dE_\perp}{dy}\frac{1}{S_\perp \cdot \tau}$$

[1]



E⊥ – is the total transverse energy

τ - is the formation time

$\tau \sim 1\ fm/c$

[2]

$$\frac{d\langle E_\perp \rangle}{dy} \approx \frac{3}{2}\left(\langle m_\perp \rangle \frac{dN}{dy}\right)_{\pi^\pm} + 2\left(\langle m_\perp \rangle \frac{dN}{dy}\right)_{K^\pm, p, \bar{p}}$$

The factors 3/2 and 2 compensate for the neutral particles.

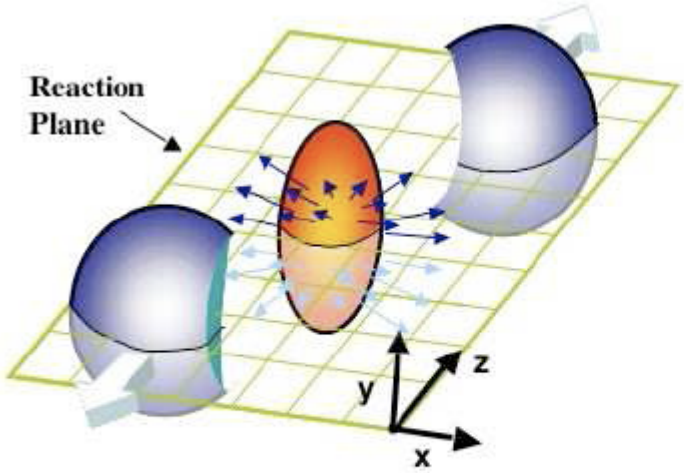
$\varepsilon \approx 1$ GeV/fm^3 is critical energy density

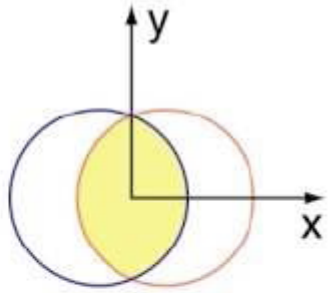
[1] J. D. Bjorken, Phys. Rev. D 27, 140 (1983)

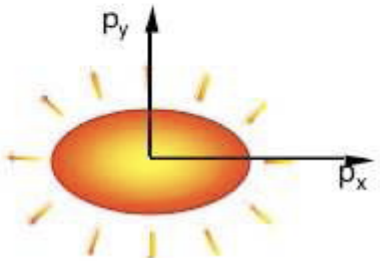
[2] B. I. Abelev, M. M. Aggarwal et al.

✓ Reaction and Event planes in AA collisions

Эллиптический поток в Pb-Pb столкновениях при энергии $\sqrt{s_{NN}}$ =2.76 TeV:







Tannebaum' 06

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[n(\phi-\Psi_R)]\right)$$

$$v_2 = \langle \cos 2(\phi - \Psi_R)\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

Excintricity: $\epsilon_x = \dfrac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}$

2- and 4-particle cumulant methods: $v_2\{2\}$ and $v_2\{4\}$

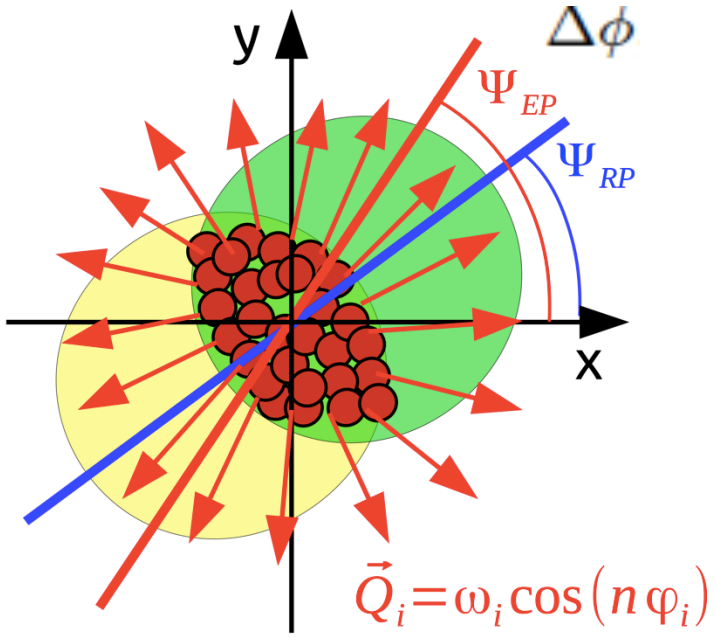
arXiv:1011.3914v1 [nucl-ex] 17 Nov 2010; *Phys. Rev. Lett.* 105 (2010) 252302

Reaction Plane (RP) and Event plane (EP) [1]

- **Reaction plane** (RP) –the plane formed by the impact parameter *b* and the beam line

RP cannot be measured in the experiment since we cannot measure *b*

- **Event plane** (EP) is the observable estimation of the reaction plane

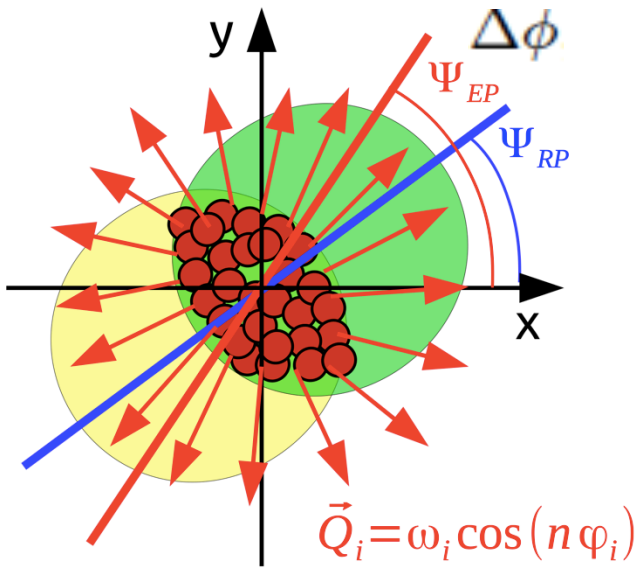


[1] Jean-Yves Ollitrault, Reconstructing azimuthal distributions in nucleus–nucleus collisions, arXiv:nucl-ex/9711003v2

Reaction Plane (RP) and Event plane (EP) [1]

The following relation between measured and true Fourier coefficients[1]:

$$\langle \cos n\psi \rangle = \langle \cos n\phi \rangle \langle \cos n\Delta\phi \rangle .$$



, the vector obtained by summing all the transverse momenta of the particles produced in the projectile (target) rapidity region is parallel (antiparallel) to the impact parameter. One constructs a vector **Q**:

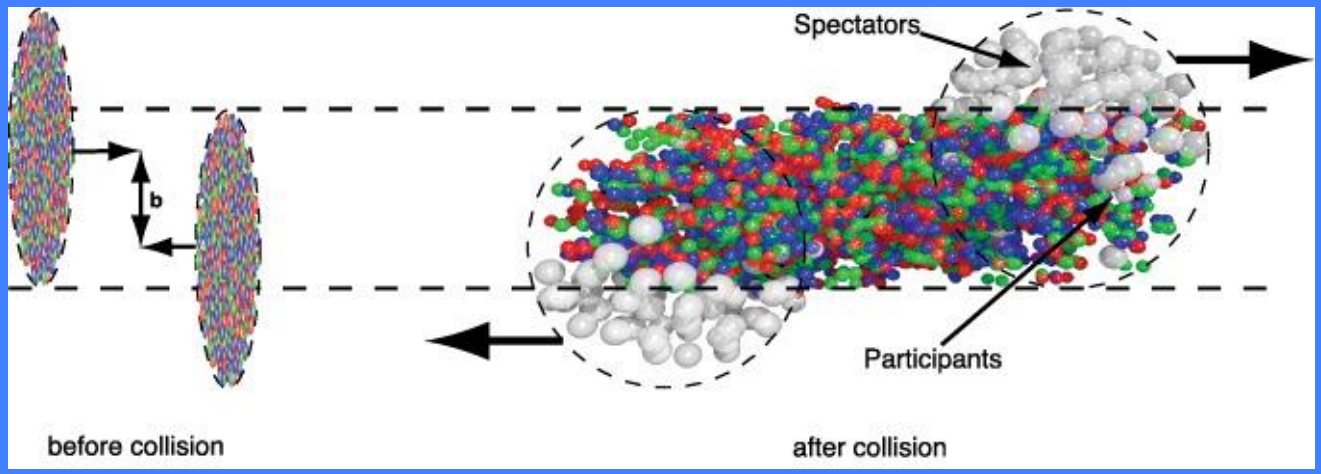
$$\mathbf{Q} = \sum_{k=1}^{N} w_k \, \mathbf{u}_k$$

where the sum runs over all the detector particles in the event, ω_k – weght, u_k – is a unit vecror parallel to transverse momentum of the particle

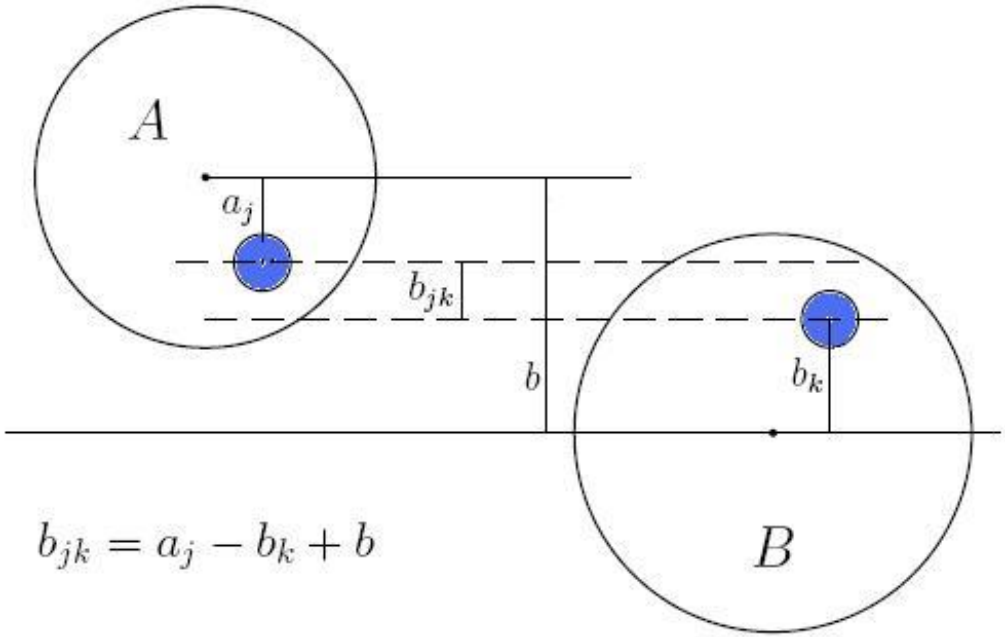
Q- lies in the true reaction plane and azimutal distributions can be measured from **Q**

[1] Jean-Yves Ollitrault, Reconstructing azimuthal distributions in nucleus–nucleus collisions, arXiv:nucl-ex/9711003v2

✓Selection of central events in AA collisions



Centrality of collisions



Nucleons

participants and spectators

$N_{spec} = 2A - N_{part}$,

Binary collisions – N coll

$$\rho(r) = \rho_0 \left\{1 + \exp\left(\frac{r - R_A}{a}\right)\right\}^{-1} \quad \text{or} \quad \rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}$$

$R_A = R_0 \cdot A^{1/3}$

R_0 = 1.07 fm,

a = 0.545 fm

$$\int \rho(r) d^3r = A$$

The parameters are based on data from low-energy electron-nucleus scattering experiments [22].

[22] H. De Vries, C. W. De Jager, and C. De Vries, At. Data Nucl. Data Tables **36**, 495 (1987).

We require a hard-sphere exclusion distance of d_{min} = 0.4 fm between the centers of the nucleons, i.e., no pair of nucleons inside the nucleus has a distance less than d_{min}.

The centrality percentile *c* of A-A collision with an impact parameter b

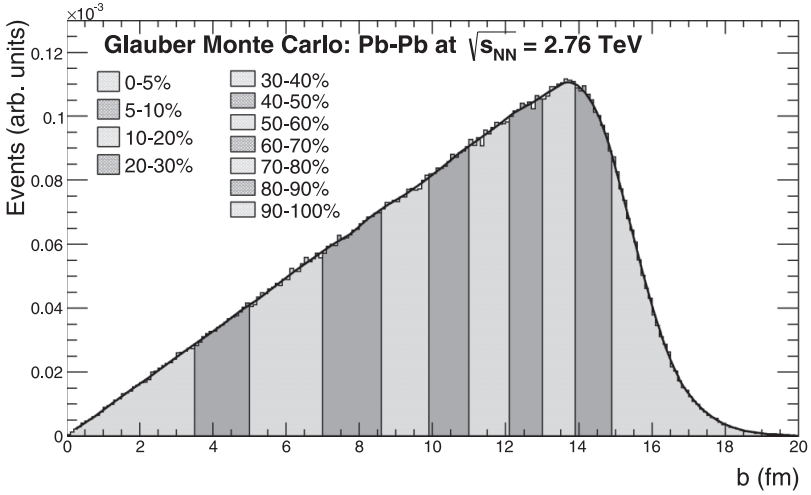
$$c = \frac{\int_0^b d\sigma/db'\,db'}{\int_0^\infty d\sigma/db'\,db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'}\,db'. \qquad (1)$$

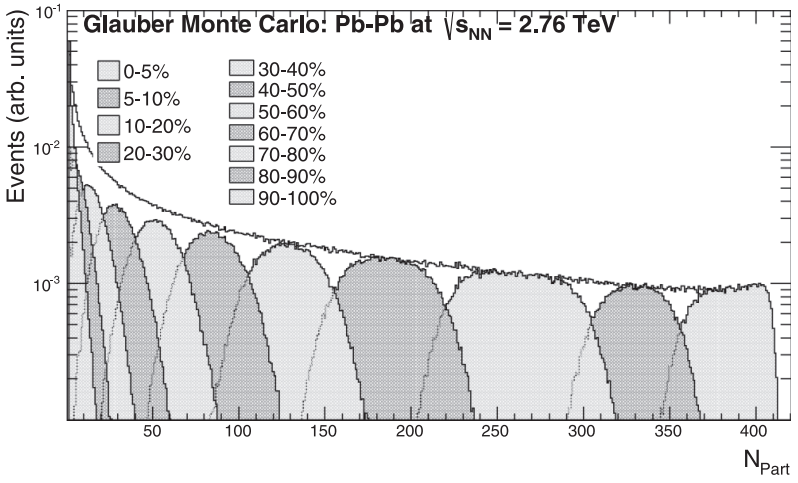
$$c \approx \frac{1}{\sigma_{AA}} \int_{N_{\mathrm{ch}}^{\mathrm{THR}}}^{\infty} \frac{d\sigma}{dN'_{\mathrm{ch}}}\,dN'_{\mathrm{ch}} \approx \frac{1}{\sigma_{AA}} \int_0^{E_{\mathrm{ZDC}}^{\mathrm{THR}}} \frac{d\sigma}{dE'_{\mathrm{ZDC}}}\,dE'_{\mathrm{ZDC}}. \qquad (2)$$

db

Centrality of relativistic heavy ion collisions In various experiments: ALICE as an example

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





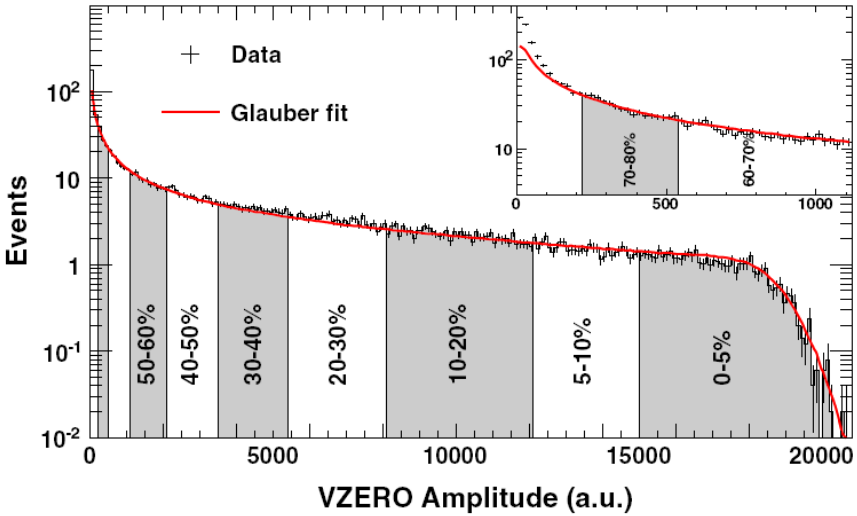
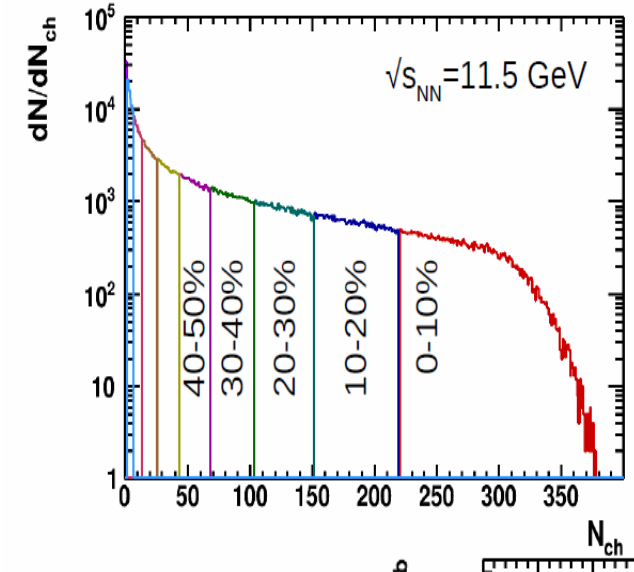
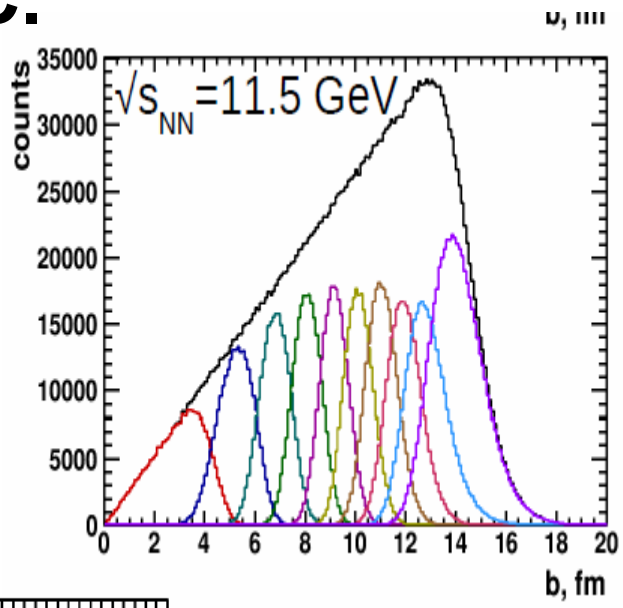
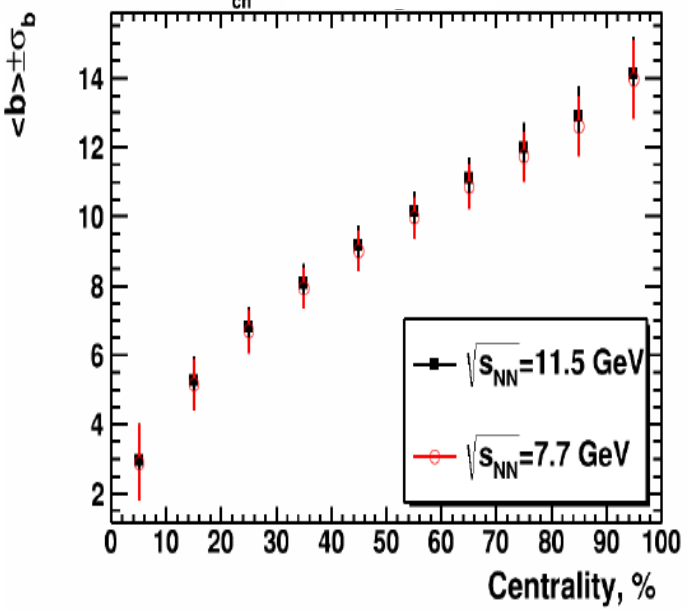


FIG. 10. (Color online) Distribution of the sum of amplitudes in the VZERO scintillators. The distribution is fitted with the NBD-Glauber fit (explained in the text), shown as a line. The centrality classes used in the analysis are indicated in the figure. The inset shows a zoom of the most peripheral region.

Example: Centrality determination with multicity in TPC.







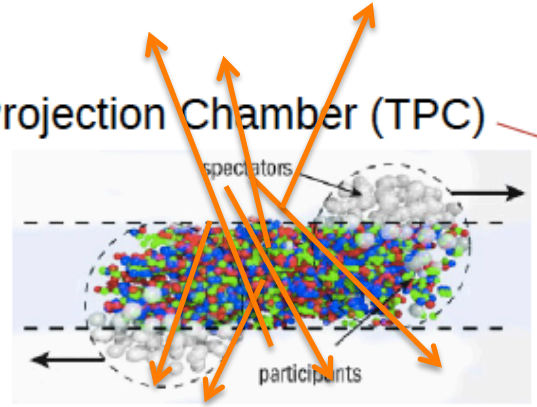
Report by Alexander Ivashkin, Petr Parfenov, Classes of centrality for the 1st MPD data analysisdata, PWG1 meeting, 16.01.2020

Two main approaches to centrality classes selection at MPD:

1) Charged particle Multiplicity classes by the TPC (or…)
and

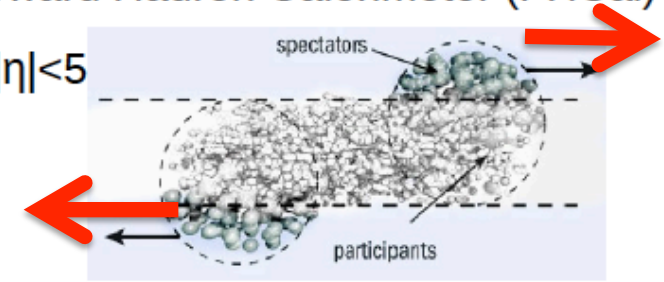
- Time Projection Chamber (TPC)

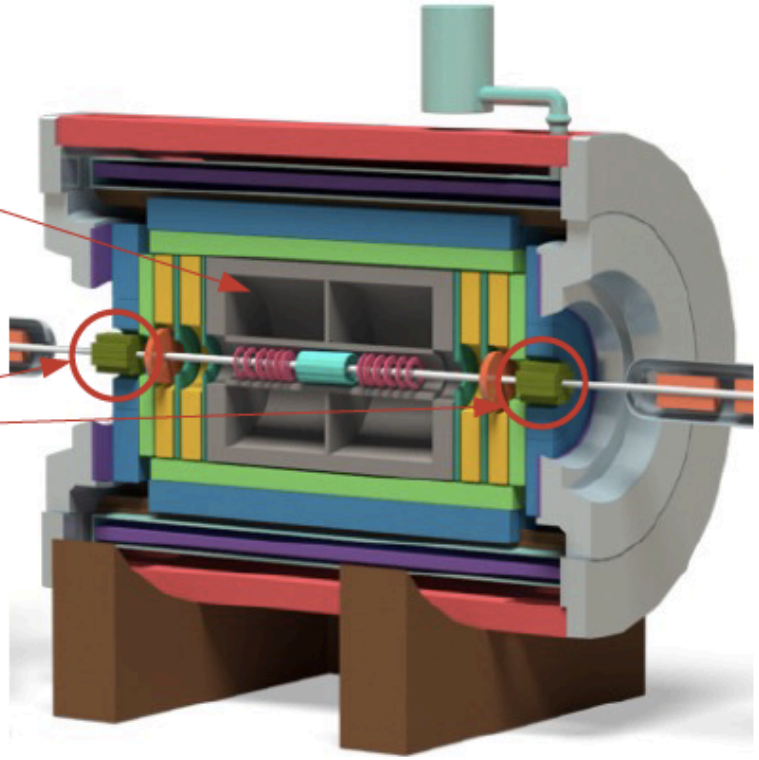
|η|<1.5



- Forward Hadron Calorimeter (FHCal)

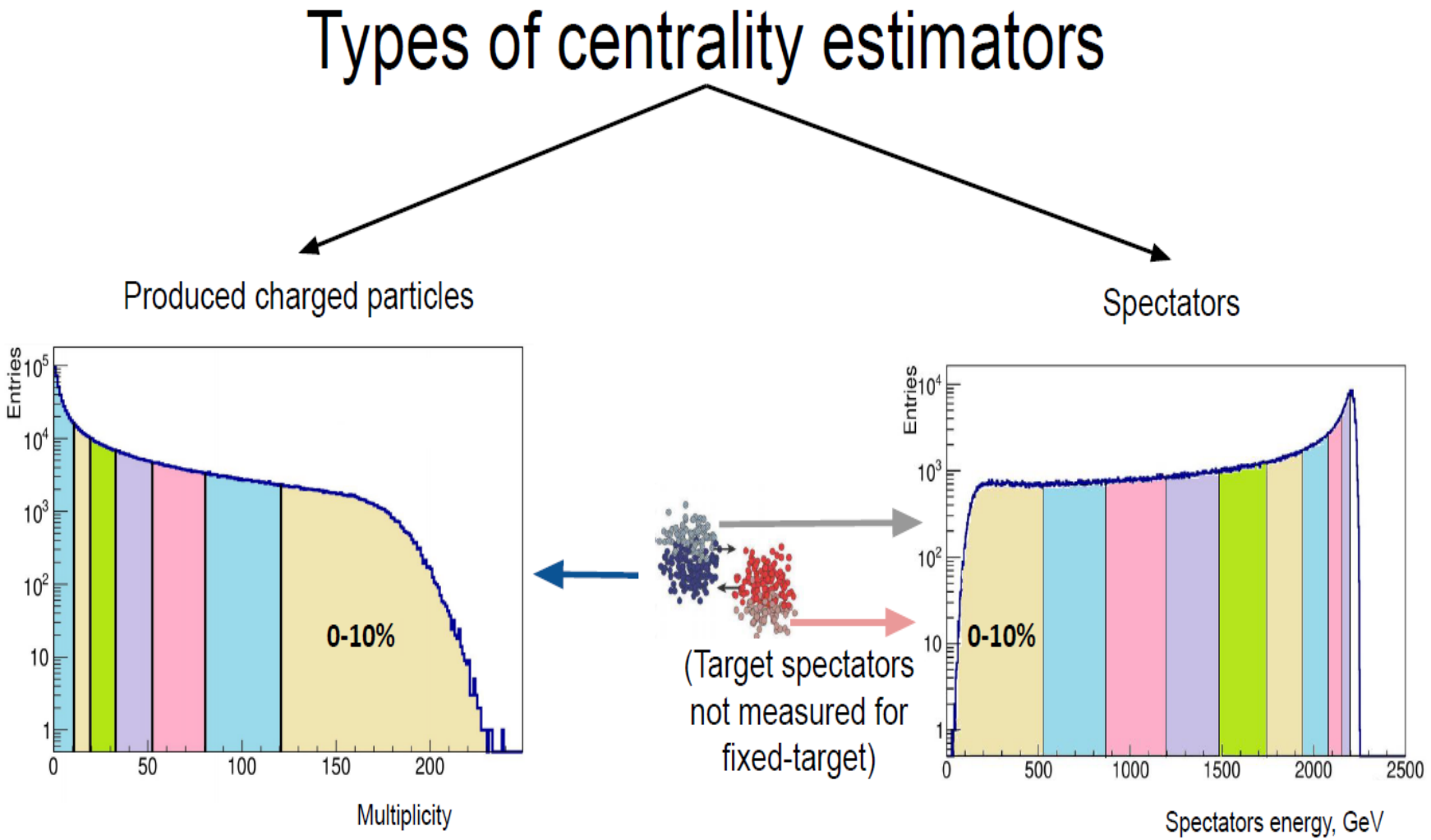
2<|η|<5





2) Spectator energy classes by FHCal

Centrality estimations



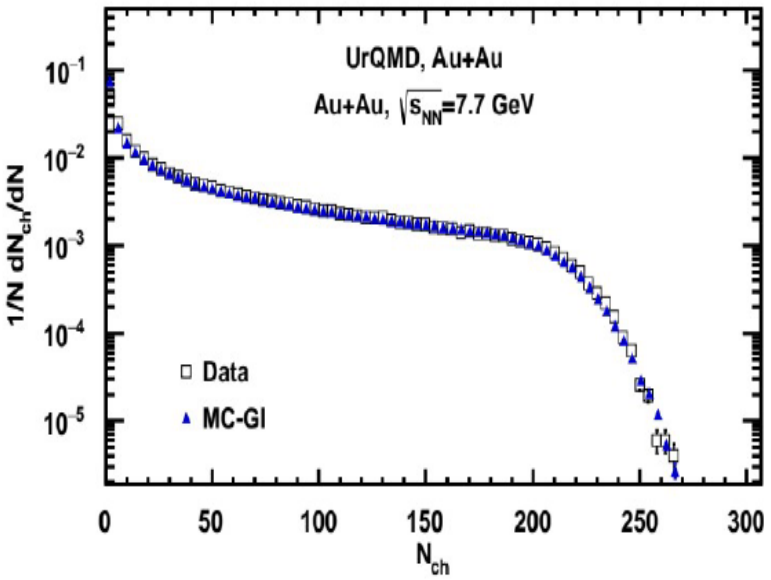
Centrality from TPC multiplicity: usual procedure

MC Glauber data → Evaluate N_a: $N_a = fN_{part} + (1-f)N_{coll}$ → Call NBD(μ,k) x N_a → Evaluate χ^2

Call NBD(μ,k) x N_a → Build multiplicity fitting function

Input multiplicity distribution → Evaluate χ^2

Evaluate χ^2 → Minimize χ^2 to find f, μ, k



NBD – negative binomial distribution

Parameters of the fit:

- **f** – fraction of the production from the soft component
- **μ** – mean multiplicity value
- **k** – width of the multiplicity distribution, can be connected to the fluctuations

Glauber model assumptions:

MC Glauber model provides a description of the initial state of a heavy-ion collision

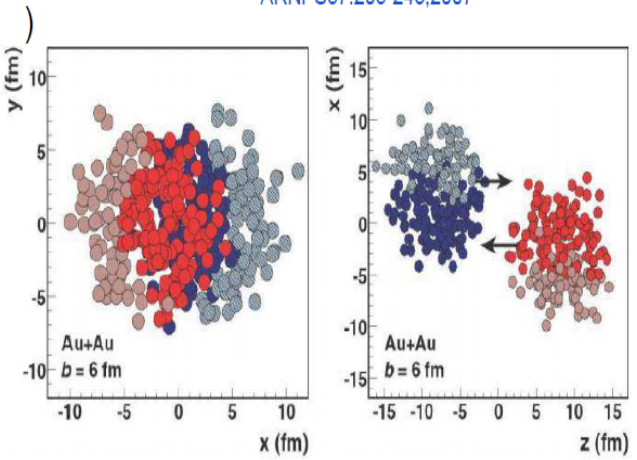
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

Main model parameters

- Colliding nuclei
- Inelastic nucleon-nucleon cross section (σ^{NN}_{inel}) (depends on collision energy)
- Nuclear charge densities (Wood-Saxon distribution)

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

Glauber Modeling in High Energy Nuclear Collisions:
ARNPS57:205-243,2007



Geometry parameters

b – impact parameter

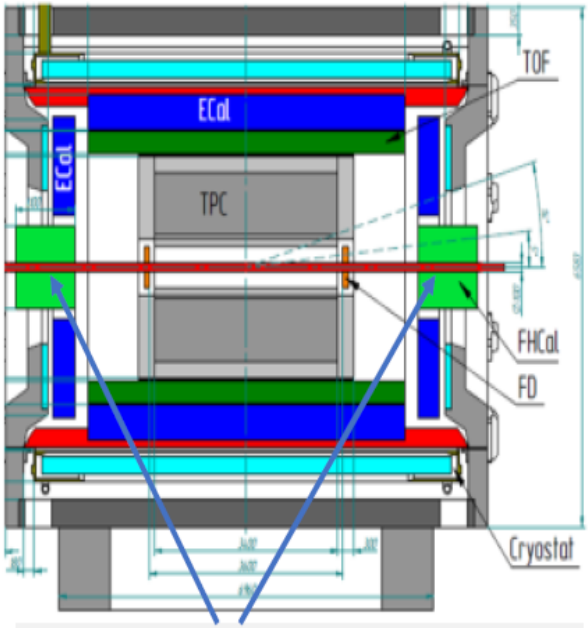
N_{part} – number of nucleons participating in the collision

N_{spec} – number of spectator nucleons in the collision

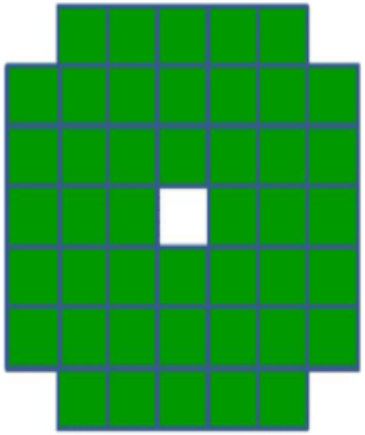
N_{coll} – number of binary NN collisions

➢ **NB! These assumptions can produce a noticable bias in N_{coll} and in R_{AA} (!)**
see [1] G.Feofilov et al, PEPAN, 52, № 4 ,2021, 584-590,
https://link.springer.com/article/10.1134/S1063779621040043

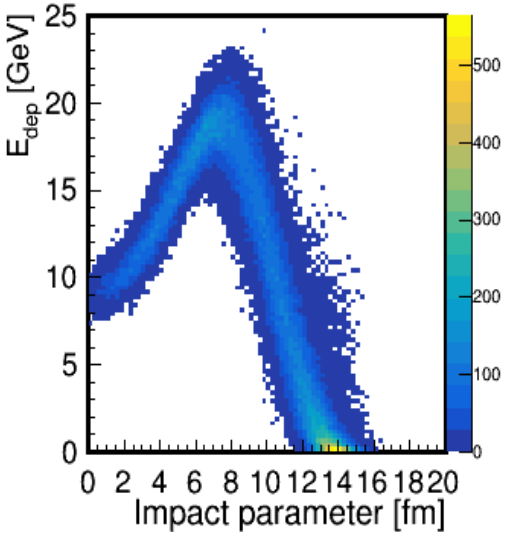
FHCal for centrality



Two upstream/downstream parts

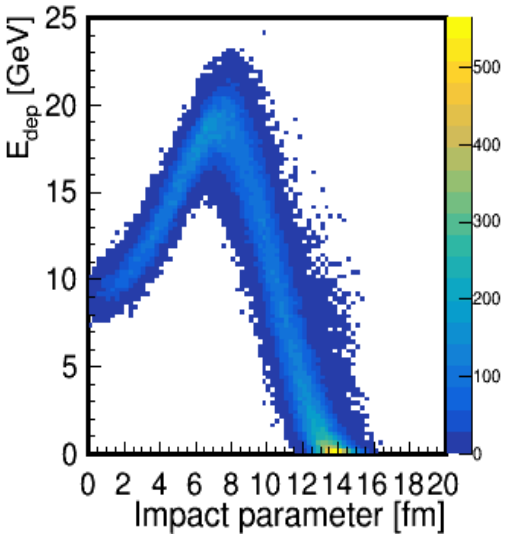


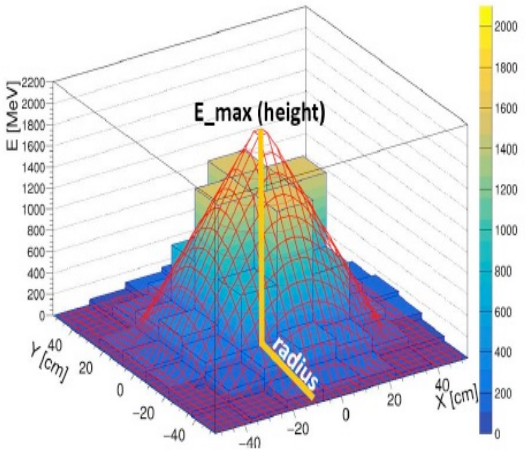
FHCal modules

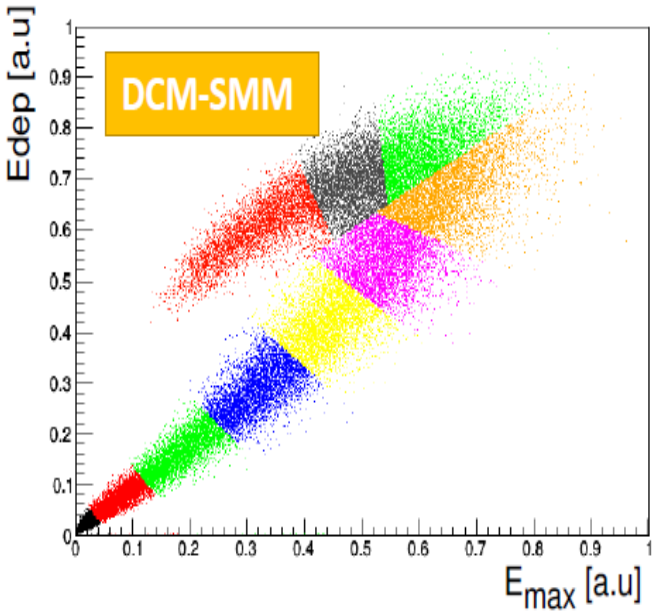


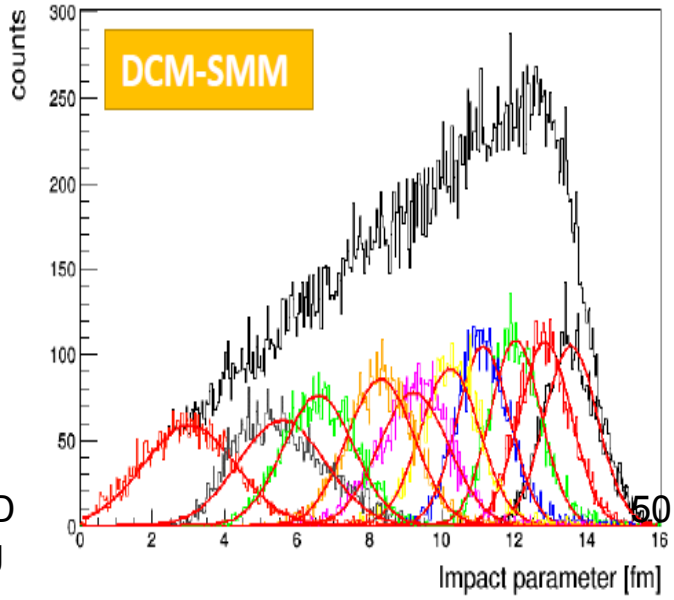
Due to the central hole in FHCal for the beam pipe some spectators can escape detection which will lead to the horn shape in the total deposited energy distribution

FHCal for centrality









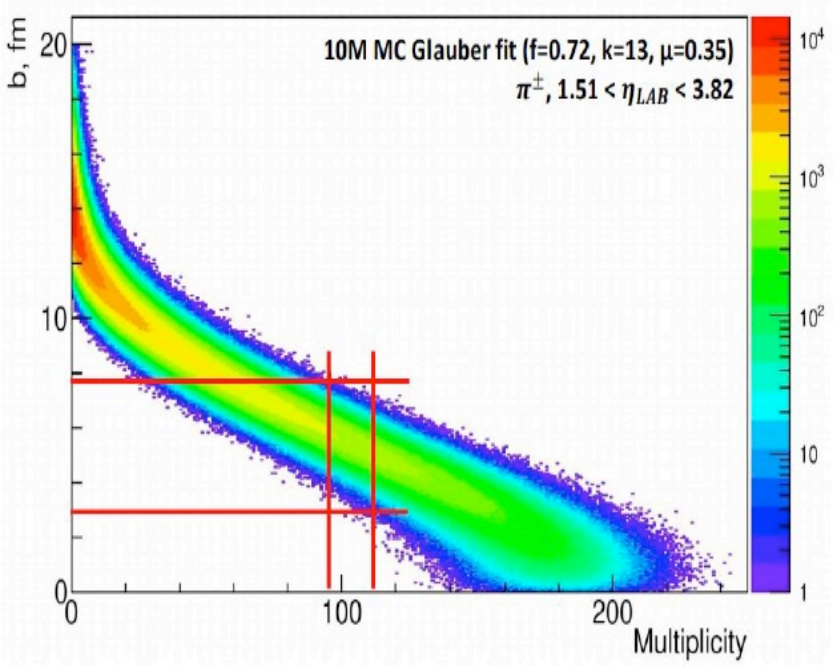
The main smearing factor in the spectator energy deposit estimator for the centrality would be the spectators which escaped detection.

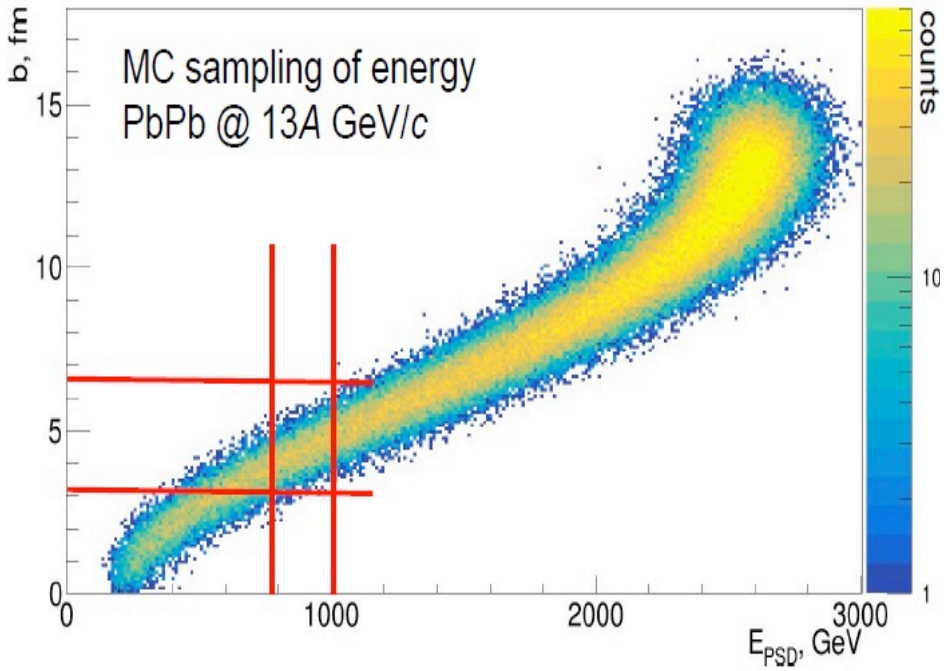
This leads to the possibility of mismatching centrality classes from very central with very peripheral events

Centrality estimations vs. impact parameter

Centrality estimators based on charged track multiplicity in TPC and spectator energy deposit in FHCal both give only a rather wide estimation of actual impact parameter of the collision

It can be worth it to have a method of combined estimation of the centrality to reduce these fluctuations of the centrality vs. impact parameter





Problems:
Centrality and widths of centrality class in relativistic heavy ion collisions

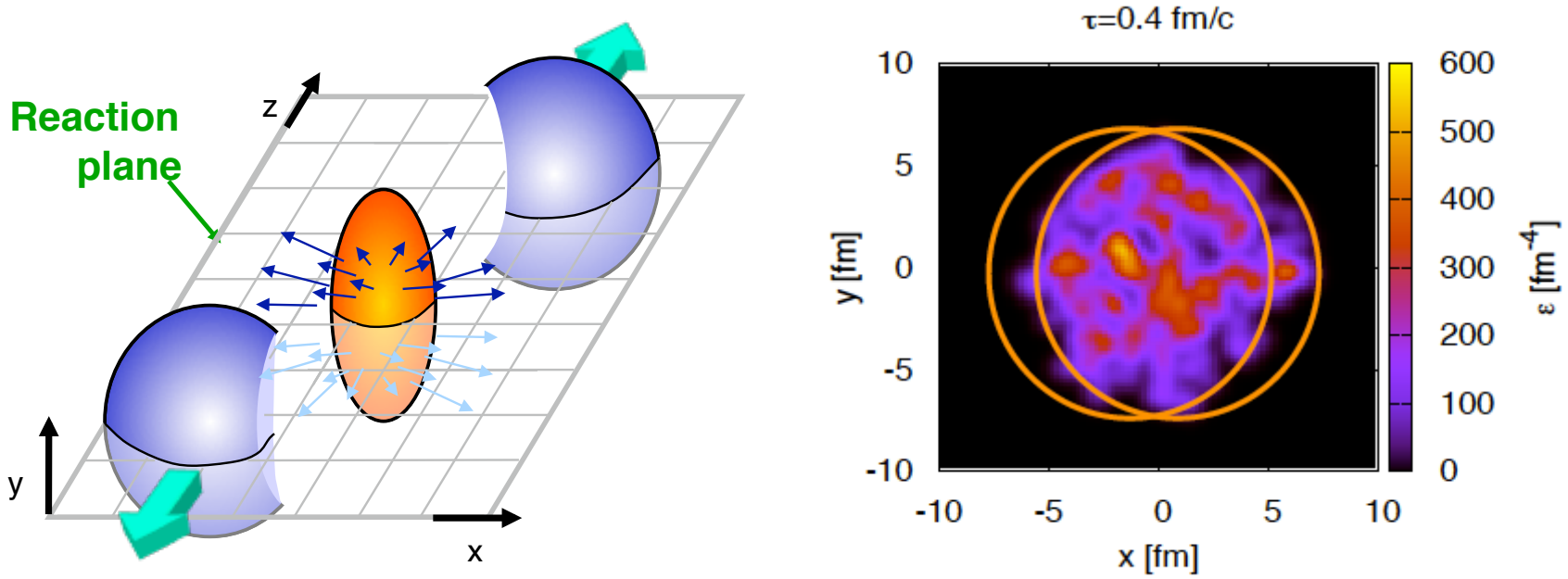
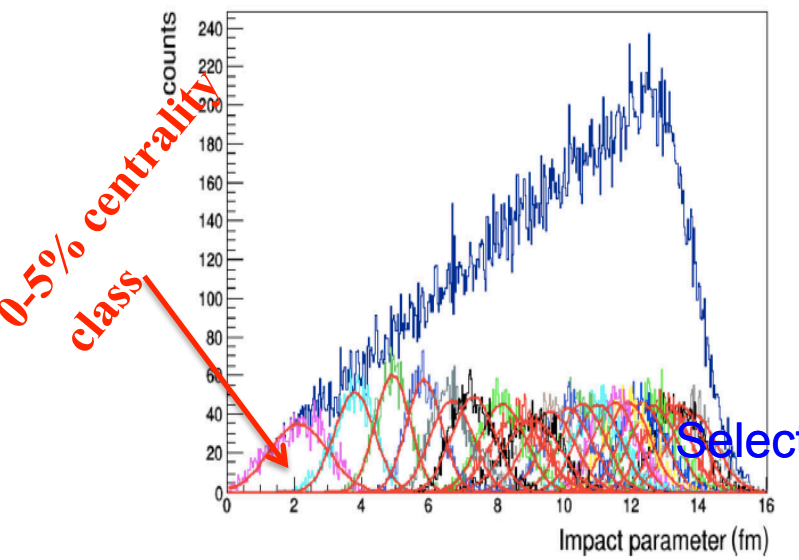


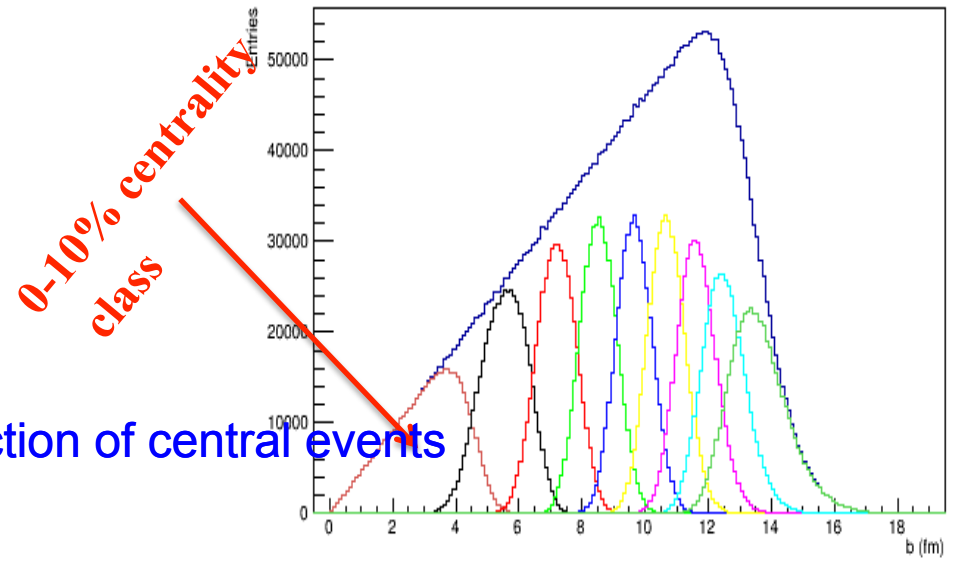
Figure 3. Geometry of a non-central heavy ion collision (left panel). Density fluctuations in the transverse plane in a sample collision event (right panel).

Berndt Mu¨ller, Arxiv 1309.7612v2 12 Oct2013

- Density fluctuations in any single event and trivial volume fluctuations could be mixed in case of the wide width of centrality class

Centrality class width





Selection of central events

Fig. 44 Top: correlation of the energy deposition in the FHCal and the height of the cone, obtained from the linear fit of the two two-dimensional energy distributions in the FHCal modules. The different colors indicate groups of events within 5% centrality ranges. Bottom: distributions of the MC-generated impact parameters for each 5% group of events fitted to a Gaussian

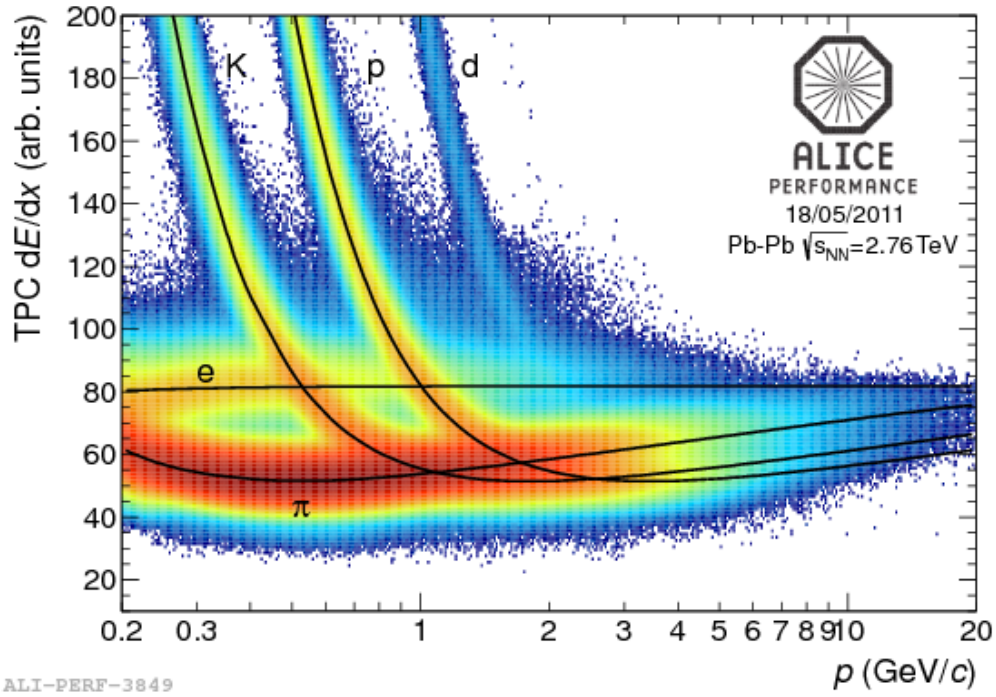
- we need more precise selection of centrality classes
- we need events with well defined initial conditions and optimized class width
- we need combination of several observables – proxies of centrality, capable to minimize trivial volume fluctuations

- ✓ **A short addition: one important application in medicine**

In addition: ionization losses and applications in hadron therapy of oncololgy desease

Bethe-Bloch formula:
Energy loss *dE* for ionization of atoms after passing through a layer of thickness *dx* by the particle with charge Z_{eff} flying with speed β in a medium with electron density n_e and average ionization energy *I*.

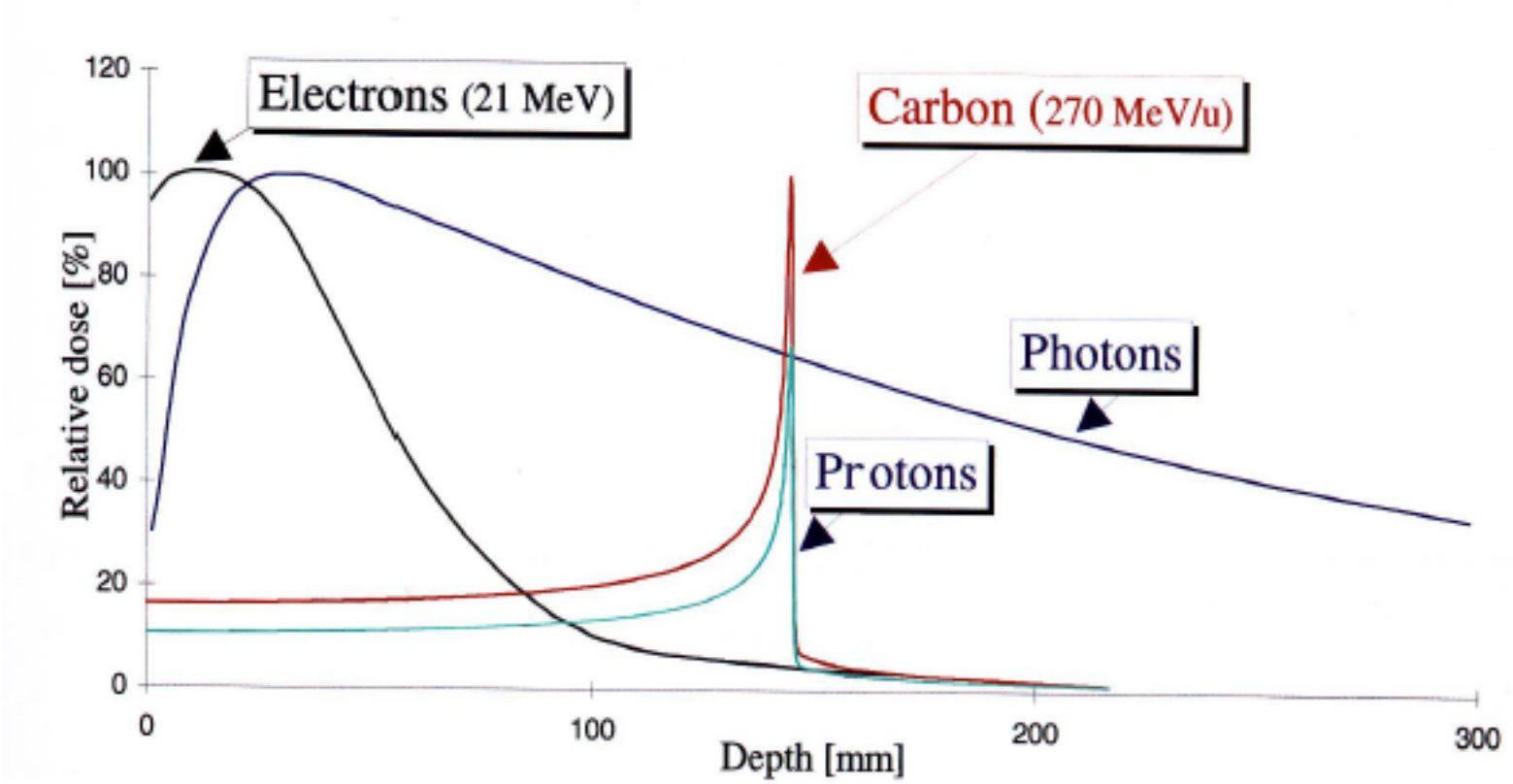
$$\frac{dE}{dx} = Kn_e \frac{Z_{eff}^2}{\beta^2}\left\{\ln\left[\frac{2m_e c^2\beta^2}{(1-\beta^2)I}\right]-\beta^2\right\}.$$



https://upload.wikimedia.org/wikipedia/commons/thumb/2/25/ALICE_TPC_1.jpg/800px-ALICE_TPC_1.jpg

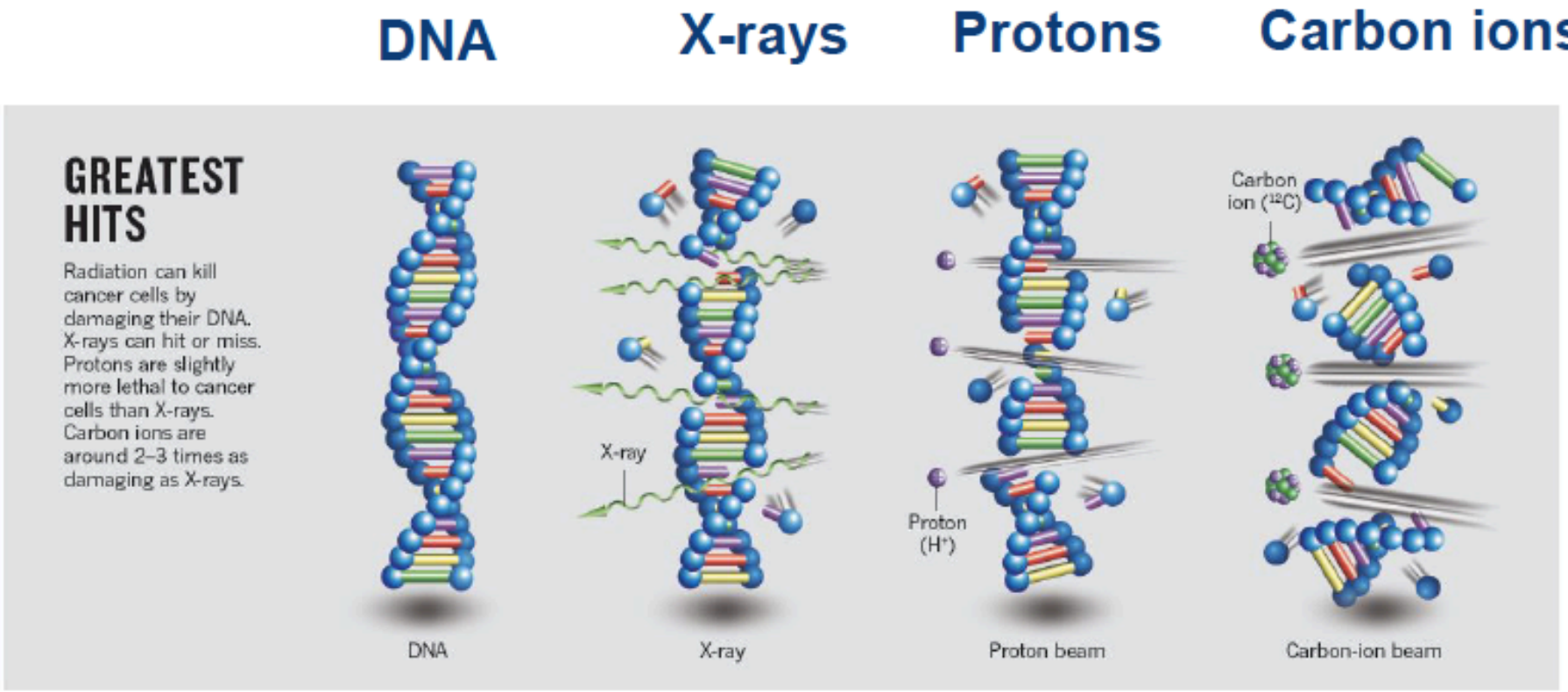
➢ How does the $1/\beta^2$ factor for charged particles work in this formula?

"Bragg Peak": Irradiate only the tumor!



Manjit Dosanjh, CERN, "Hadron Therapy and European funded projects"
"LHC and beyond" Workshop, St Petersburg, 11 June 2010
http://indico.cern.ch/conferenceDisplay.py?confId=89411

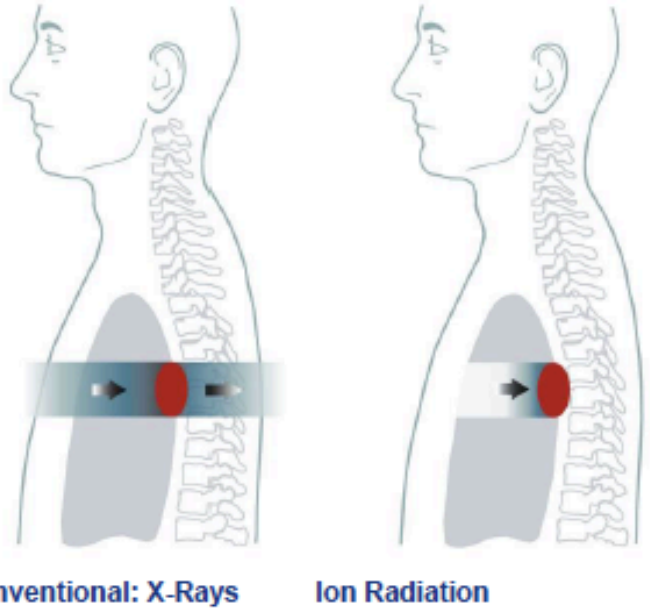
Comparison of DNA damage for gamma rays and charged particles with Bragg peak

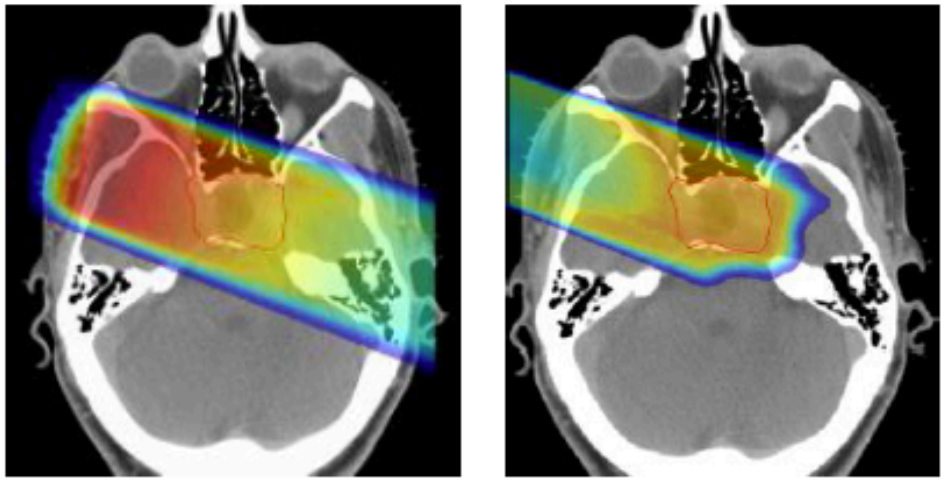


Marx, Nature, 2014

Why is hadron therapy needed?

Image courtesy MedAustron





- During hadron therapy, healthy tissue is practically not irradiated!
- Critical organ could be sparred
- See ENLIGHT, https://enlight.web.cern.ch

✓ Conclusions

Conclusions

- Clobal observables in high energy nuclear collisions are defining the base-line platform for interesting physics of HI collisions (including the search for the critical phenomena and study of the nature of quark confinement)

- Instrumentation in fundamental academic studies is bringing always the various spin-offs of very high importance for human society !
(See also the report on Tuesday at 16:00
by Oleg Belov “Applied research with heavy-ion beams”)

Thank you for your attention!