Centrality & Glauber at low/high energies

Grigory Feofilov (St.Petersburg State University,RF),

The International Workshop

https://indico.jinr.ru/event/4973/

25 - 27 November ,11:15—12:00 2024 (**Moscow time**).

ZOOM connection

https://us06web.zoom.us/j/82553592212?pwd=HTaX6PPzNr0yp1aF8KdMDsyU0xGNhj.1

The author acknowledges Saint-Petersburg State University for a research project 95413904

Layout

- Introduction.
- Initial state & Centrality of collision
- Centrality estimators
- Widths of centrality classes in A+A collisions
- Modified Glauber Model
- Classes of centrality in AA and pA
- Conclusion

”Relyativistic 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)

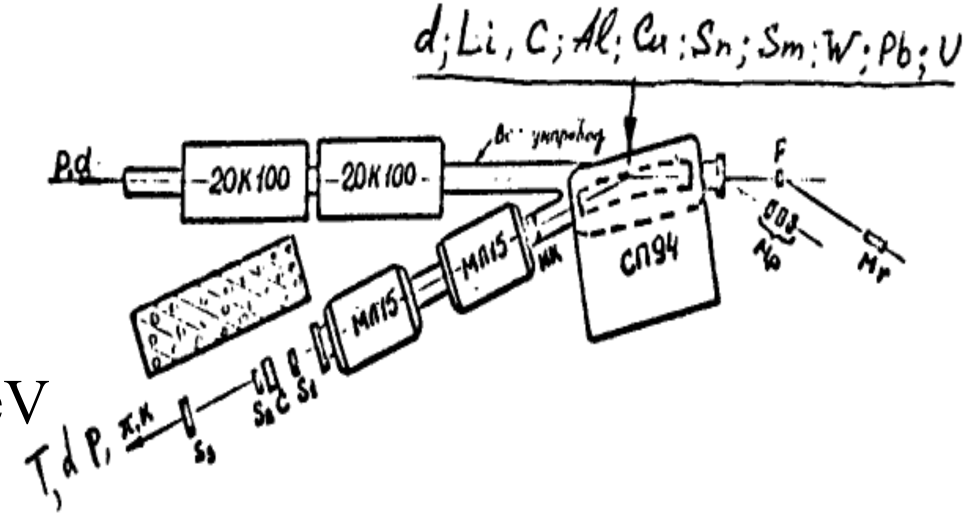


Fig. 2 Experimental layout

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

From JINR (1971) to:

→ **BEVALAC(1974), SPS(1976), RHIC(2000), → LHC(2009)**

Today: quark-gluon plasma produced in nuclear collisions at LHC and RHIC

"a new form of matter with unique properties" [1]

• It is relativistic, yet strongly coupled;
• it is a liquid that cools into a gas;
• it is a nearly "perfect" liquid near the quantum limit of shear viscosity;
• it thermalizes as fast as causality permits;
• it creates its own new vacuum state to exist…

➢ **New studies of properties of this strongly interacting medium formed in A+A collisions including:**

1) Studies of phase diagram and search for QCD Critical Point CP)
2) EOS of baryonic dense nuclear matter

[1] B. V. Jacak and B. Mu¨ller, Science 337, 310 (2012). Berndt Muller arxiv:1309.7612v2 12 Oct2013
[2] A.Sorensen et al.,, Dense nuclear matter equation of state from heavy-ion collisions, Progress in Particle and Nuclear Physics, V.134, January 2024, 104080

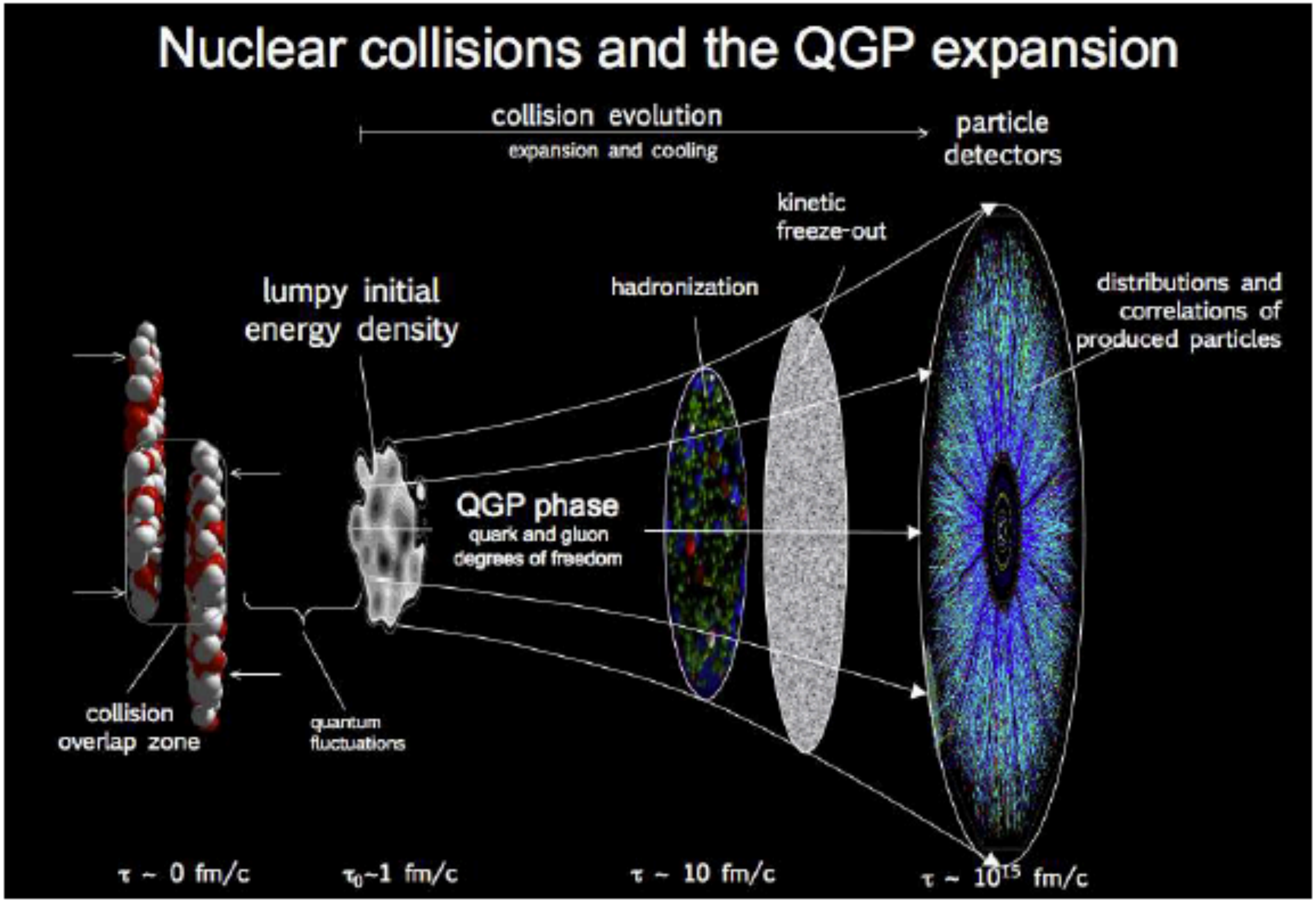
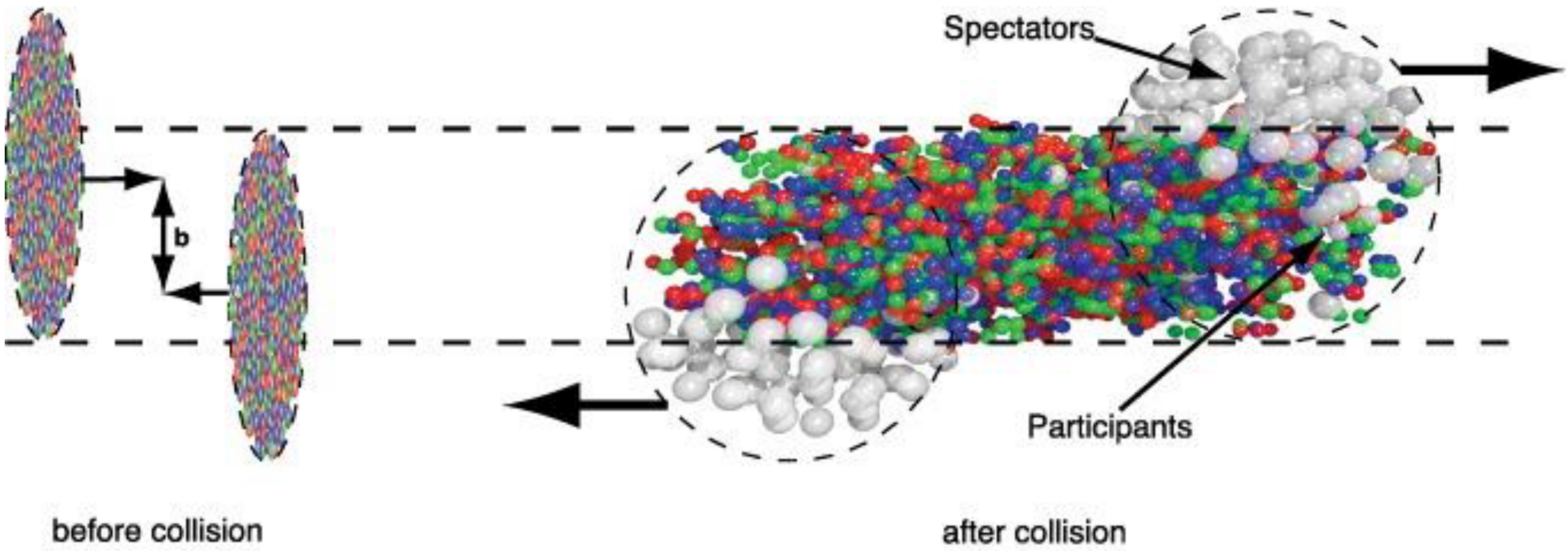


Fig. 1. A schematic diagram of the expansion after an ultra-relativistic heavy-ion collision.

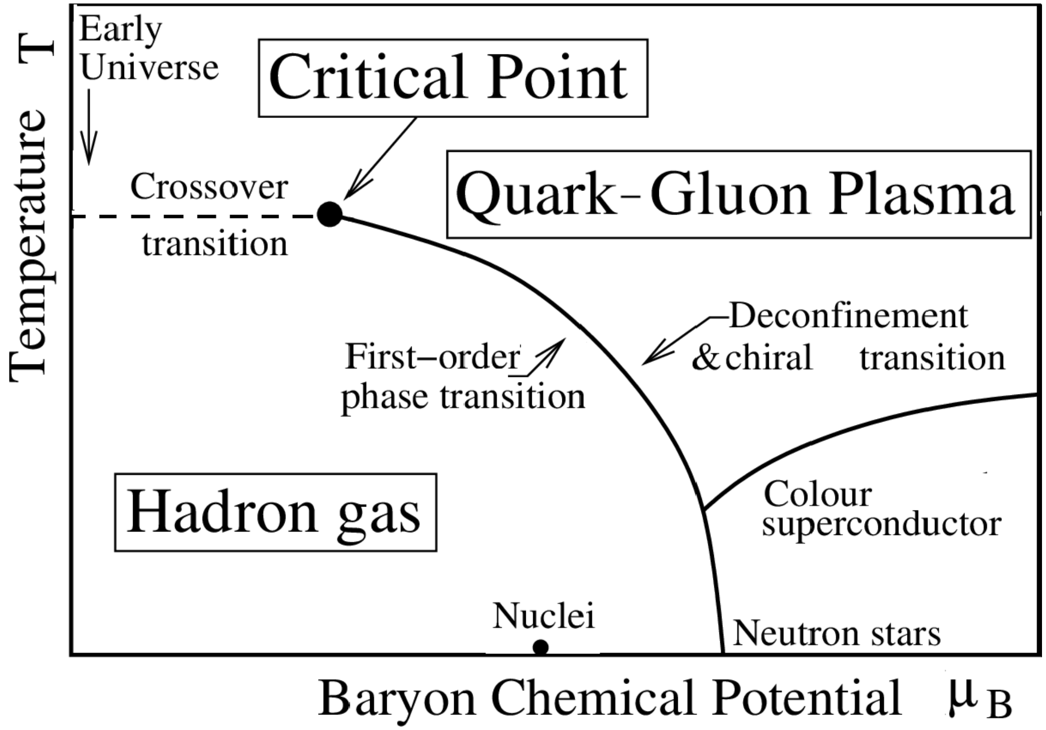
P.Sorensen, Elliptic Flow: A Study Of Space-momentum Correlations In Relativistic Nuclear Collisions, arXiv:0905.017

Some terminology and definitions



- Impact parameter – b
- Nucleon-participants ($Npart$) – nucleons collided at least once
- Nucleon-spectators ($Nspec = 2A - Npart$) nucleons which didn't interact
- Number of nucleon-nucleon collisions ($Ncoll$)
- Multiplicity of charged particles (Nch)
- Centrality class of events (C)

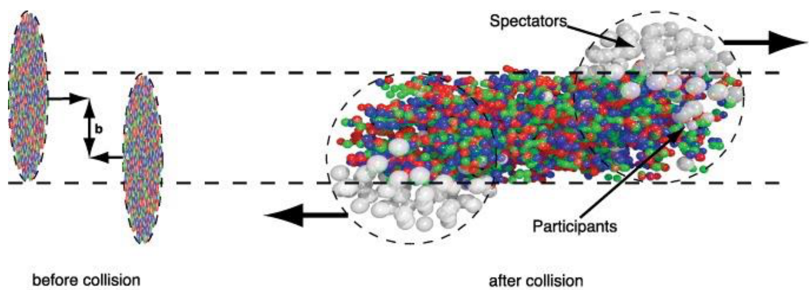
Phase diagram of strongly interacting matter



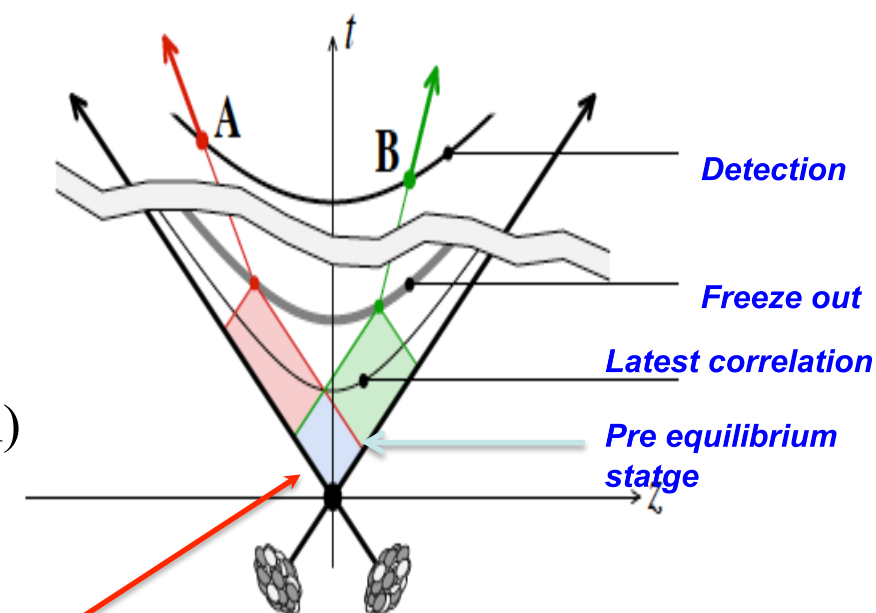
- At μ_B ~0 -- smooth cross-over transition
- The 1st order phase transition is expected at some large μ_B (the QCD critical point)
- What is the role of the initial state of collision of heavy nuclei?
- Evolution from this pre equilibrium stage?

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.

Some terminology and definitions



Stages of AA collision



A.Dumitru et al., arXiv: 0804.3858

Centrality of collision

➢ Proxies for the impact parameter *b:*

- Multiplicity of charged particles(Nch)
- Nucleon-participants ($Npart$)
- Transverse energy (E_T)
- …other?

The initial state of collision is defined by the collision centrality and dynamics

➢ *Fluctuations and Long-range correlations*

Assumptions of Standard Glauber Model

- The nucleus-nucleus interaction in terms of elementary nucleon-nucleon interaction.
- Model inputs:

  1) the nuclear charge densities measured in low-energy electron scattering experiments

  2) the inelastic nucleon-nucleon cross section σ_{inel} that is fixed in all NN collisions for the relevant initial $\sqrt{s_{NN}}$
- Independent linear trajectories of nucleons
- No energy (or momentum) losses in NN collisions

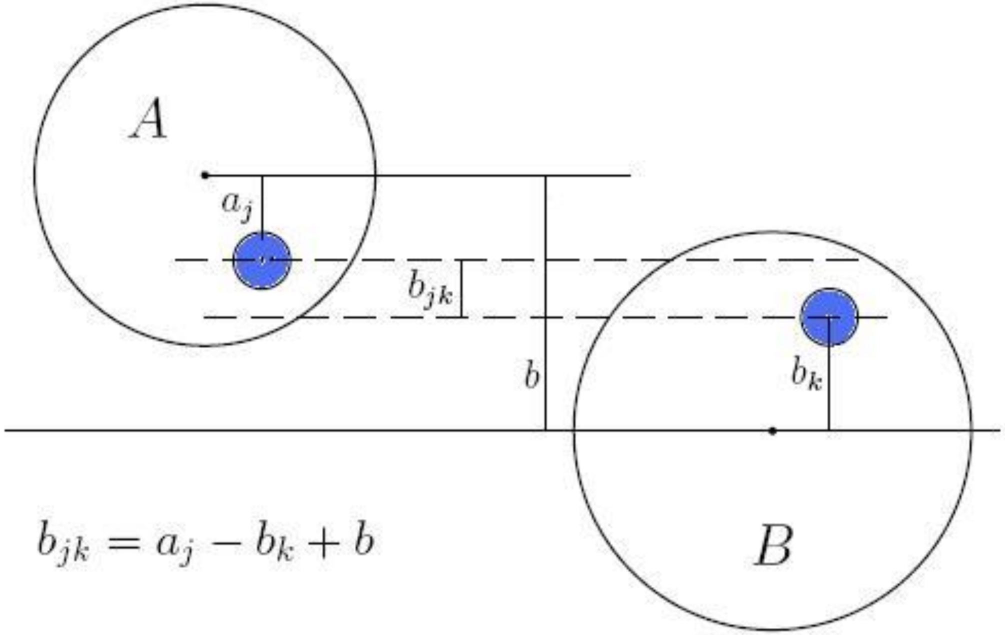
Initial state & Centrality of collision

Nucleons –

participants and spectators

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

Binary collisions – N coll



$$\rho(r) = \rho_0 \left\{1 + \exp\left(\frac{r - R_A}{a}\right)\right\}^{-1}$$

or

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

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

$R_0 = 1.07$ fm,

a = 0.545 fm

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

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}.

Centrality percentile *c* of A-A collisions with an impact parameter *b*

In theory:

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

In experiment:

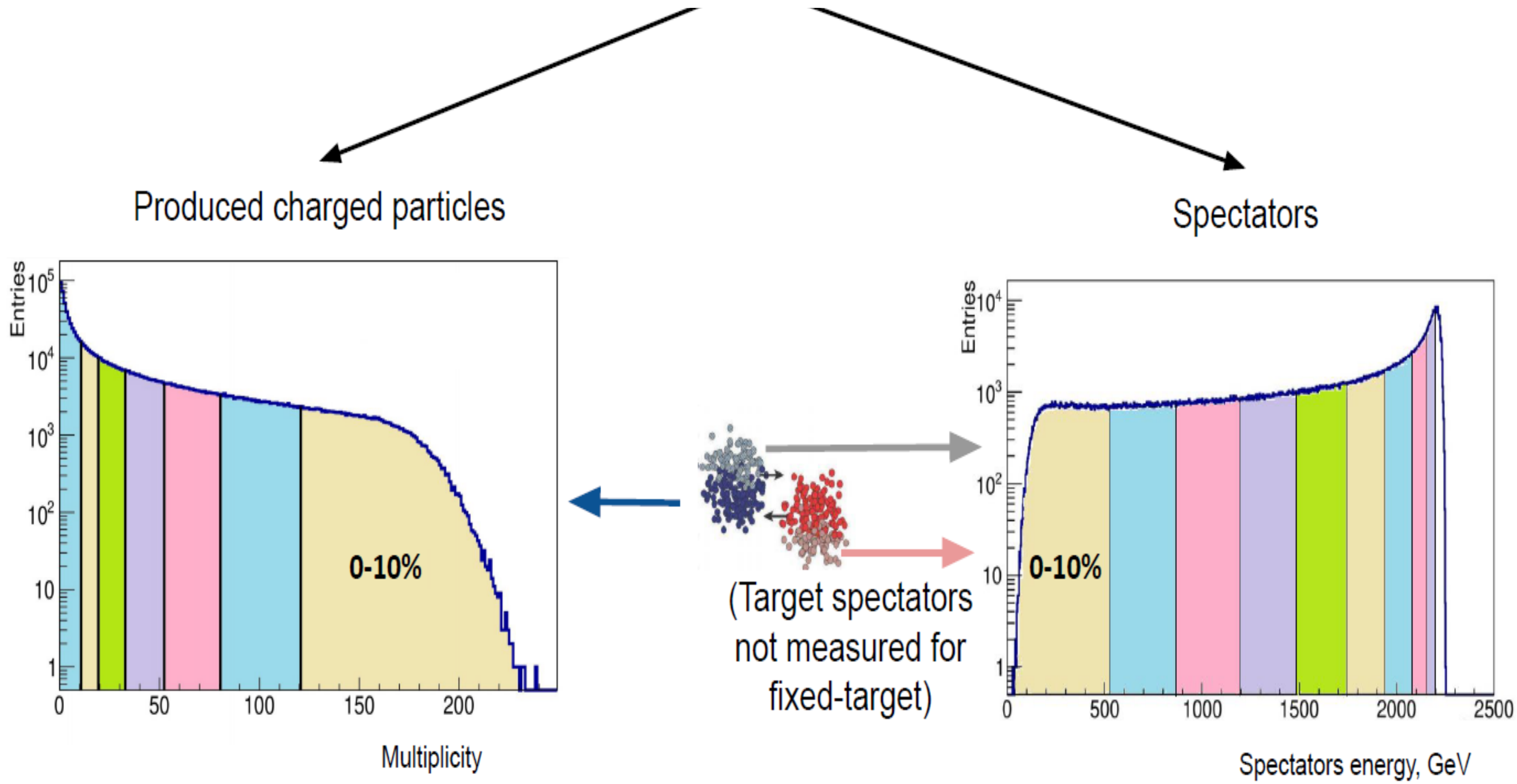
$$c \approx \frac{1}{\sigma_{AA}} \int_{N_{\rm ch}^{\rm THR}}^{\infty} \frac{d\sigma}{dN'_{\rm ch}}\,dN'_{\rm ch} \approx \frac{1}{\sigma_{AA}} \int_0^{E_{\rm ZDC}^{\rm THR}} \frac{d\sigma}{dE'_{\rm ZDC}}\,dE'_{\rm ZDC}.$$

db

$$(2)$$

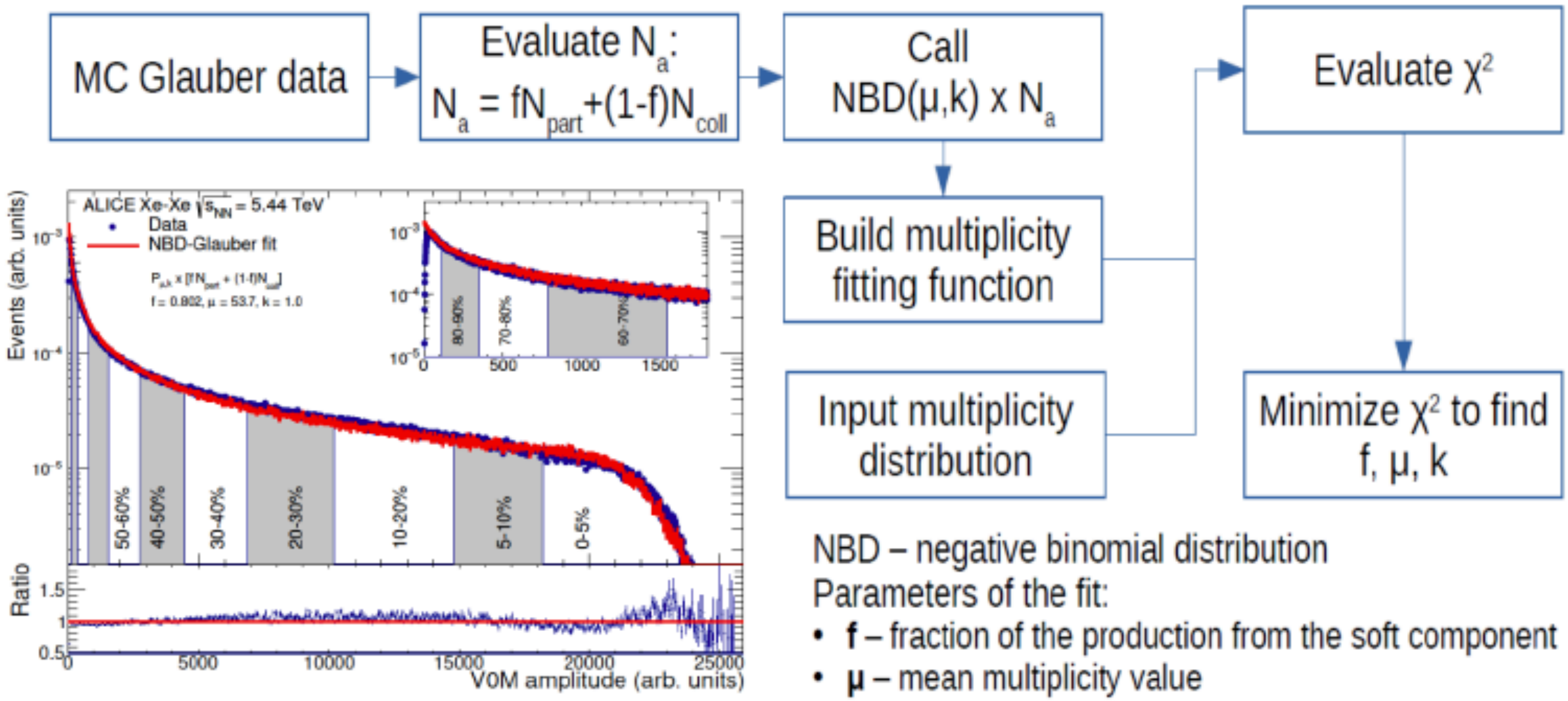
Global observables: selection of collision centrality classes

Two major type of centrality estimators



Proxies for the impact parameter *b*: Multiplicity of charged particles(Nch)

MULTIPLICITY AS A PROXY FOR CENTRALITY CLASS: USUAL PROCEDURE



NBD – negative binomial distribution

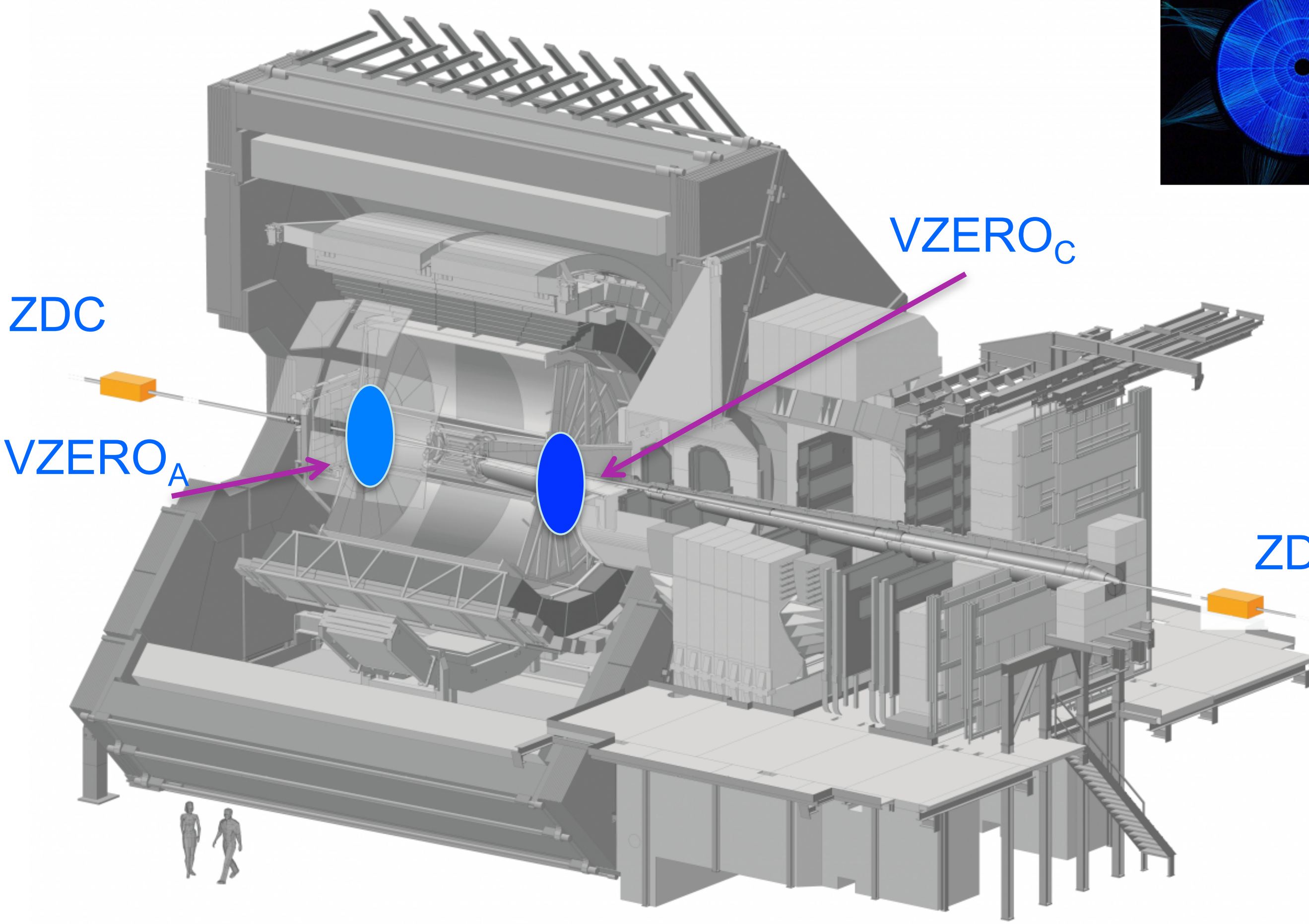
Parameters of the fit:

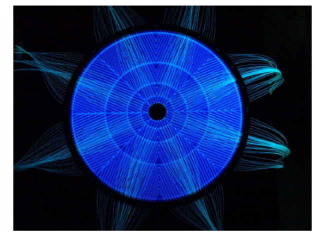
- **f** – fraction of the production from the soft component
- **μ** – mean multiplicity value
- **k** – width of the multiplicity distribution, can be connected to the fluctuations

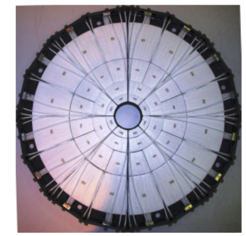
ALICE-PUBLIC-2018-003 Title Centrality determination using the Glauber model in Xe-Xe collisions at √sNN=5.44 TeV https://cds.cern.ch/record/2315401?ln=ru

➢ **That is how the values of $Npart$ and $Ncoll$ are usually obtained!**

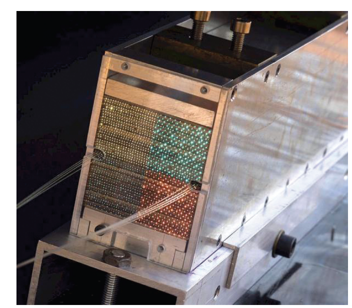
Centrality in ALICE: Zero Degree Calorimeters and VZERO multiplicty detectors





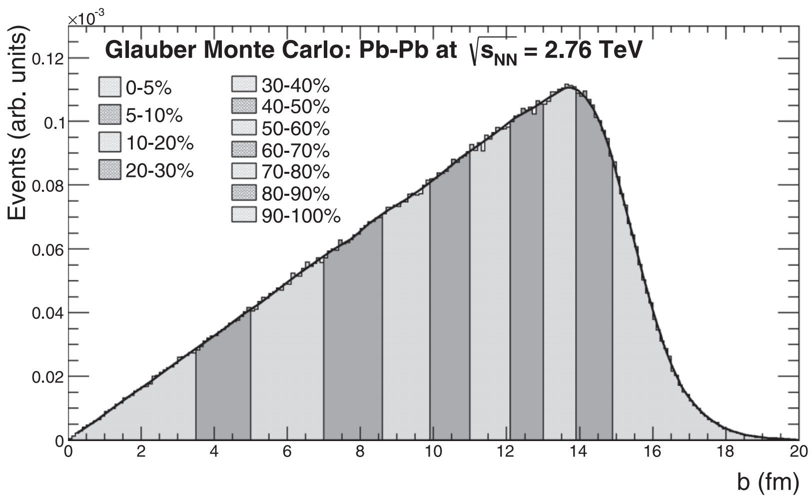


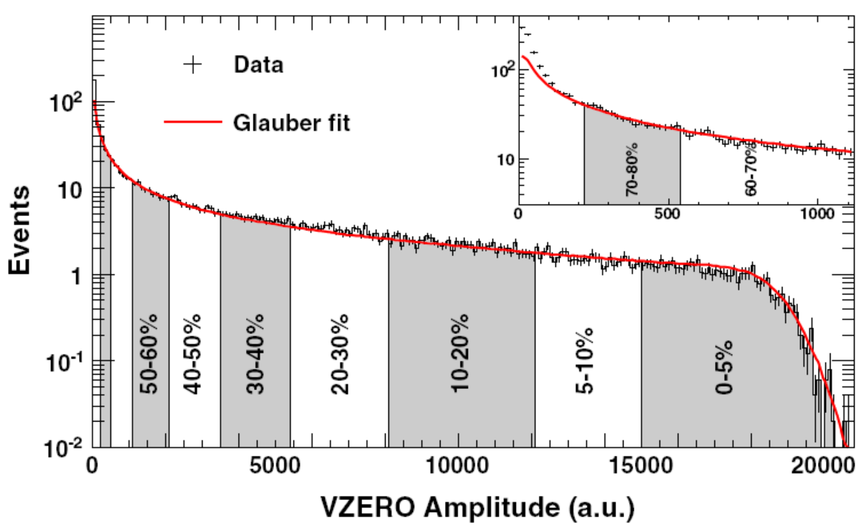
Hodoscopes
of scintillator cells



quartz-fiber
spaghetti calorimeters

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





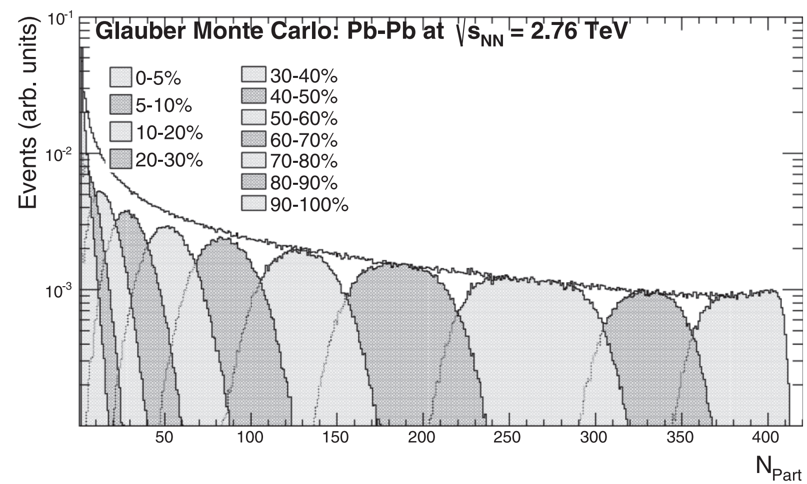
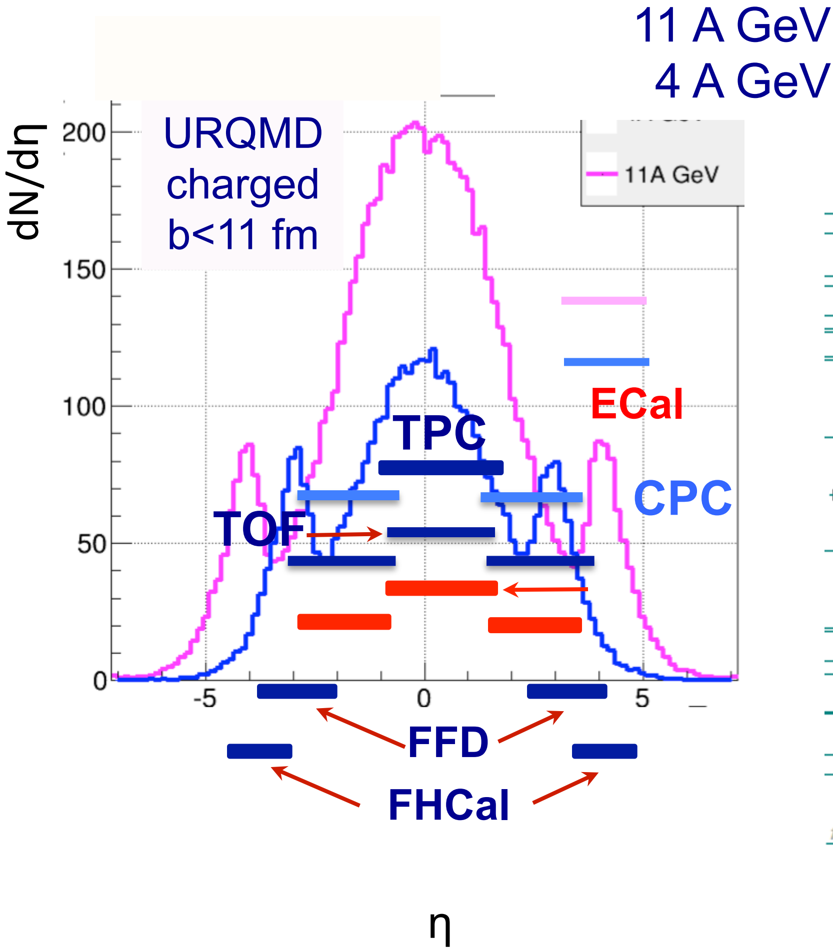
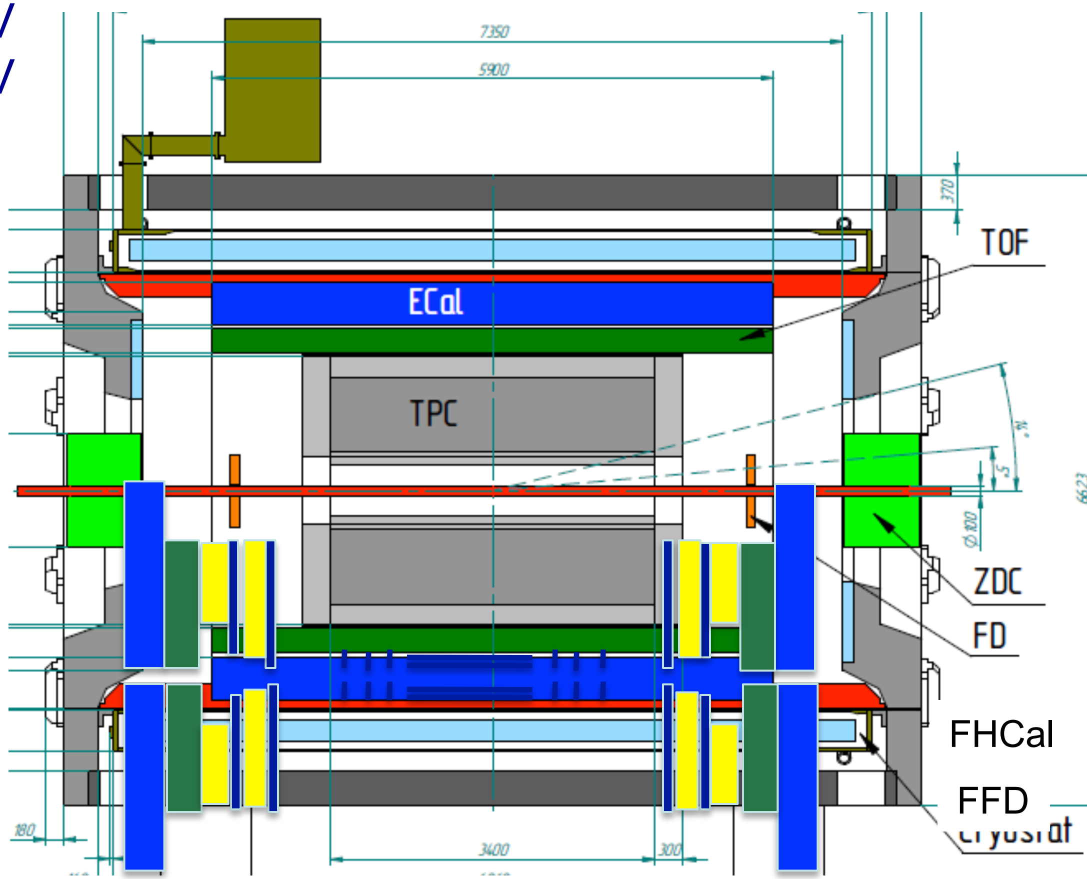


FIG. 10. (Color online) Distribution of the sum of amplitudes in the VZERO scintillators. The distribution is fitted with the NBD-Glauber fit (explained in the text), shown as a line. The centrality classes used in the analysis are indicated in the figure. The inset shows a zoom of the most peripheral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

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

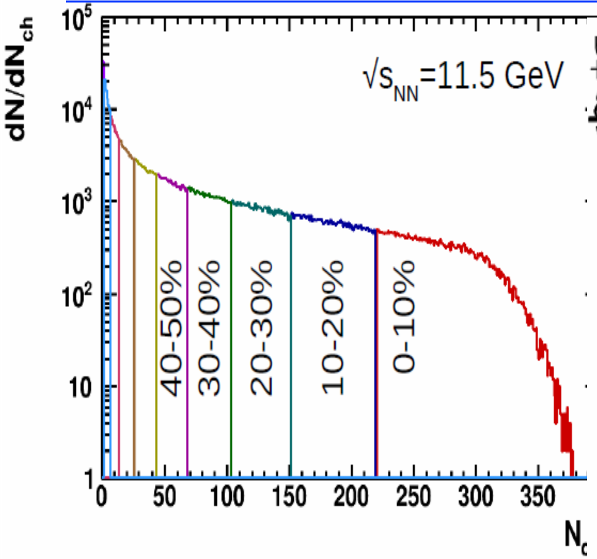
Multi-Purpose Detector (MPD)

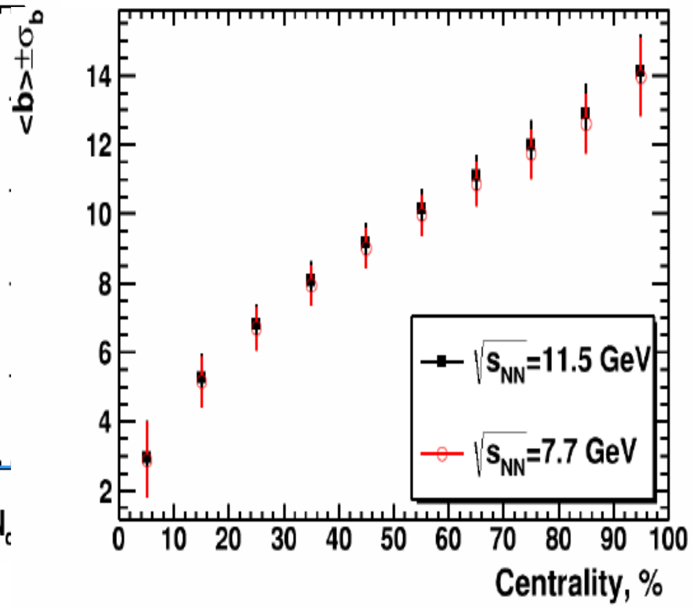


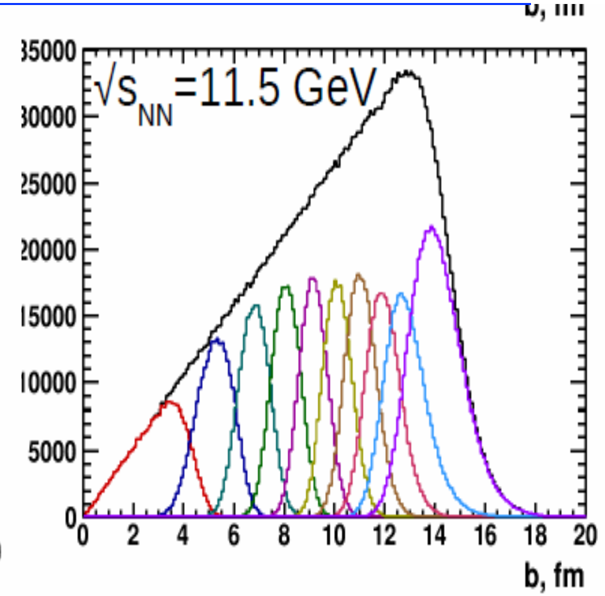


Selection of classes of events: FFD, FHCal, Ecal… +Beam-Beam collisions counters

Example: Centrality determination with multicity in TPC at MPD/NICA.







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

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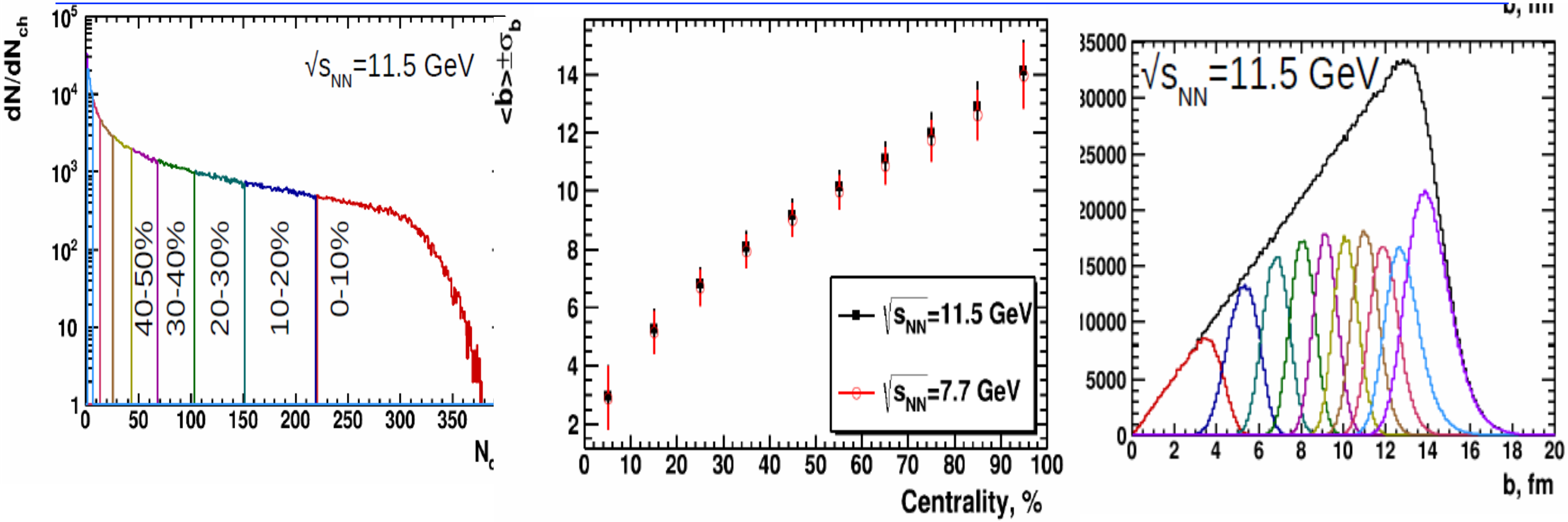


Report by Alexander Ivashkin, Petr Parfenov, Classes of centrality for the 1st MPD data analysis, PWG1 meeting, 16.01.2020

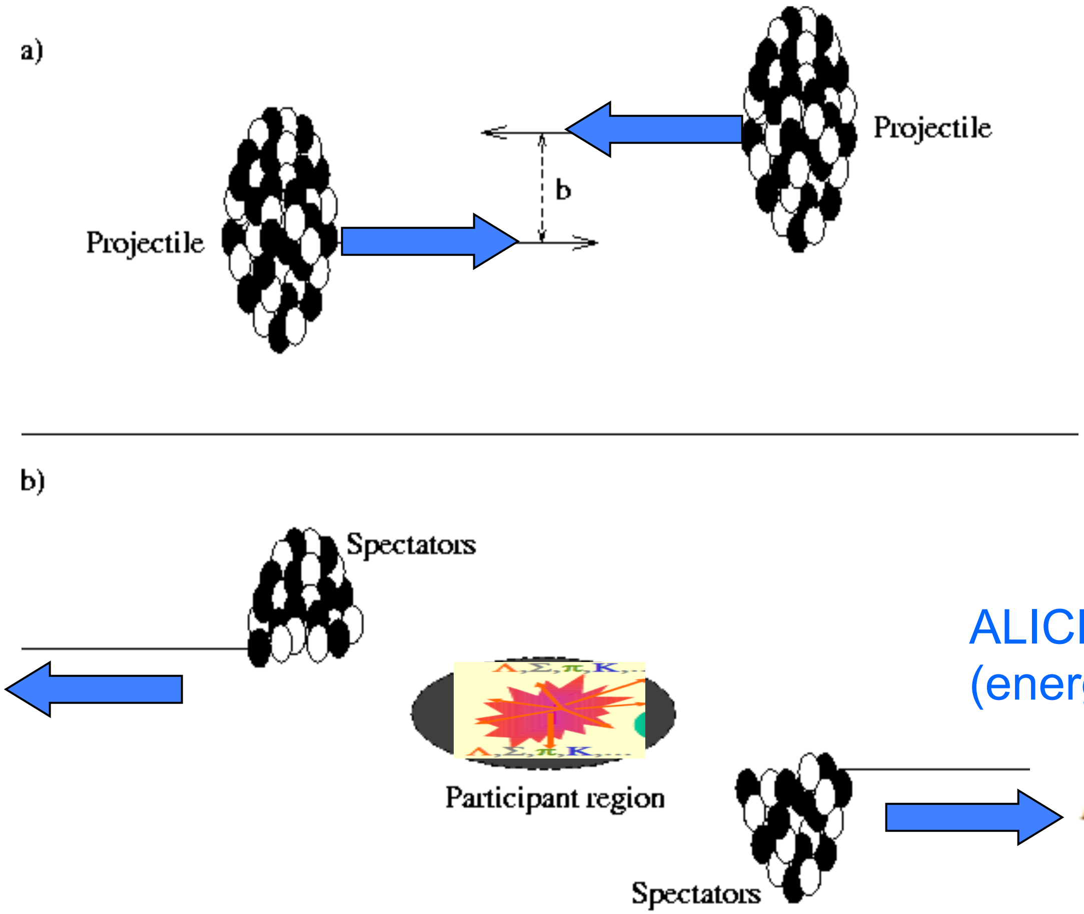
➢ However, the applicability of Standard Glauber model at NICA energies in the region of $\sqrt{s_{NN}}$ = 2,5-11 GeV is under the question due to:

--low multiplicity

--possible autocorrelations

\- --stopping of nucleons (see further below)

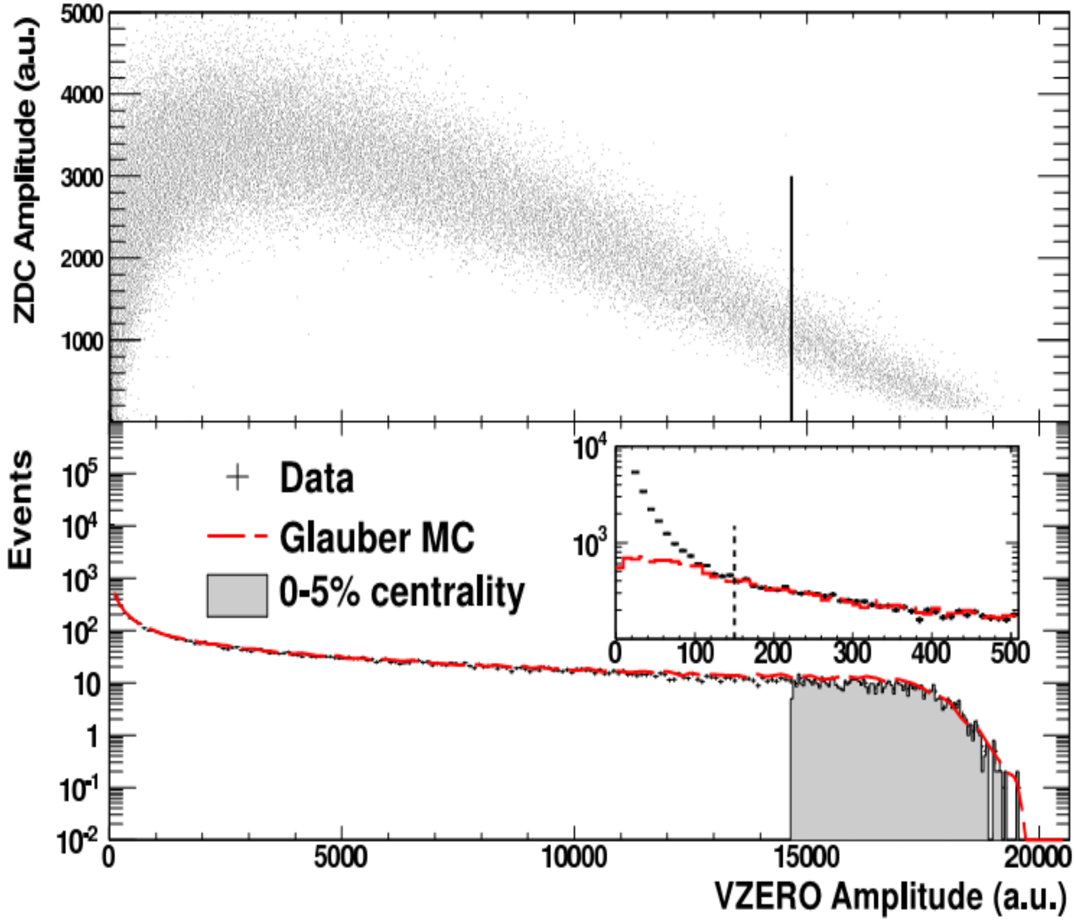
Centrality estimators: N_{part}



ALICE
(energy of spectators in the ZDC):

$$E_{ZDC}(\text{TeV}) = 2.76 \times N_{\text{spectators}}$$
$$N_{\text{participants}} = A - N_{\text{spectators}}$$

Centrality estimators in ALICE: ZDC and multiplicity signal - (anti)correlation plot



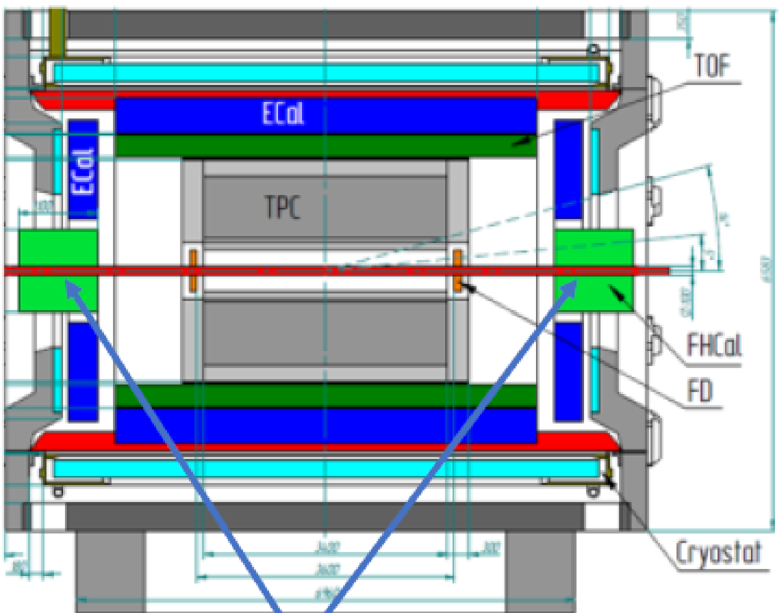
ZDC

VZERO

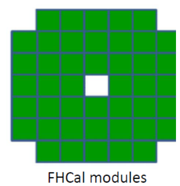
arXiv:1011.3916 [nucl-ex]. *Phys. Rev. Lett.* 105 (2010) 252301

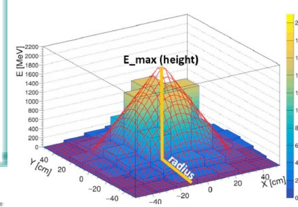
K. Aamodt et al. (ALICE), JINST, 3 , S08002 (2008)

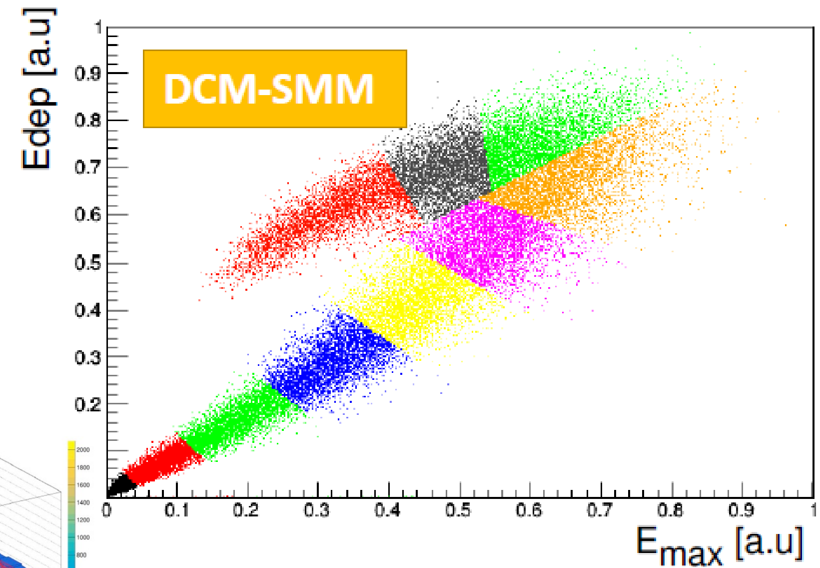
Global observables:
Spectators in FHCal for centrality class selection

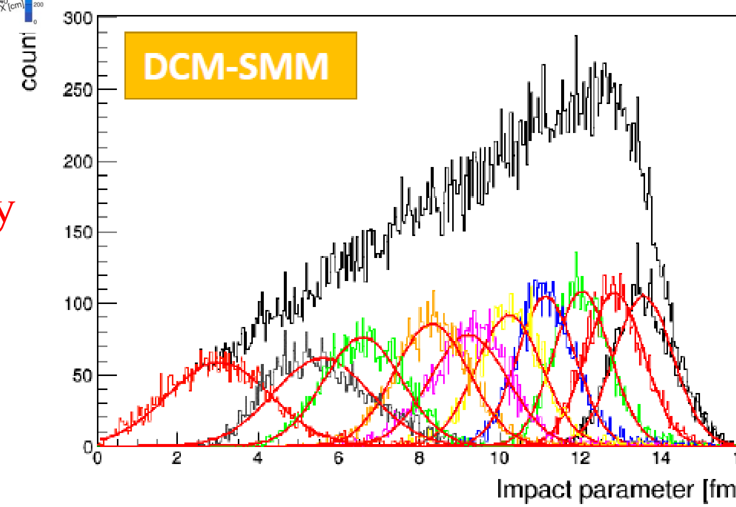


Two upstream/downstream parts









- Possibility to mismatch centrality classes from very central with very peripheral events
- Broad distribution in any impact parameter class selected via FHCal energy
- **Combination of several observables/proxies of centrality – work is in progress by the MPD**

Proxies for the impact parameter *b* using the Hadron Calorimeter

[1] Idrisov, D., Segal, I., Golosov, O. *et al.* Centrality Determination Method in Nuclear Collisions by Using Hadron Calorimeter. *Phys. Part. Nuclei Lett.* **21**, 627–630 (2024). https://doi.org/10.1134/S1547477124700845

[2] Ilya Segal Centrality Determination in Heavy-Ion Collisions Based on Monte-Carlo Sampling of Spectator Fragments
Particles **2023**, *6*(2), 568-579;**https://doi.org/10.3390/particles6020032**

New approach…Using Hadron Calorimeter to measure the energy of spectator fragments [1]

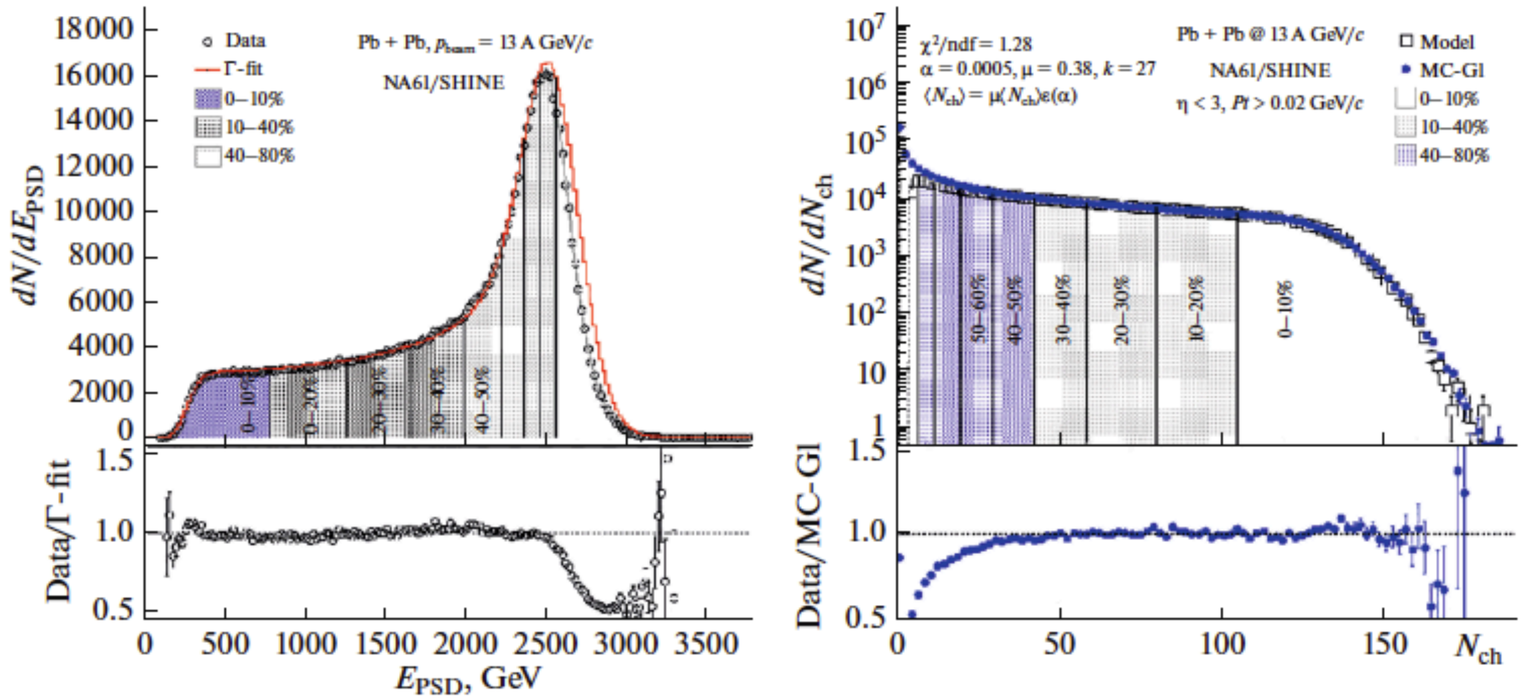


Fig. 2. Results of the Γ-fit of the distribution of the total energy E_{PSD} of spectators measured in the PSD calorimeter (left) and MC-Glauber fit of the the multiplicity N_{ch} of produced charged particles (right).

[1] Idrisov, D., Segal, I., Golosov, O. *et al.* Centrality Determination Method in Nuclear Collisions by Using Hadron Calorimeter. *Phys. Part. Nuclei Lett.* **21**, 627–630 (2024). https://doi.org/10.1134/S1547477124700845

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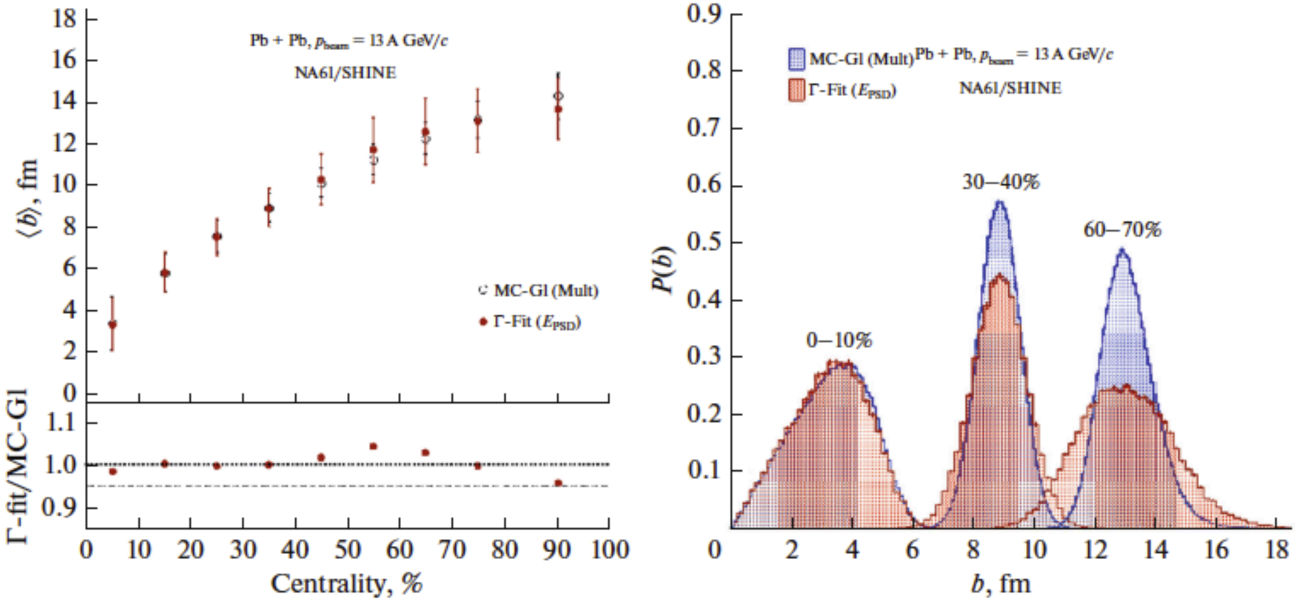


Fig. 3. (left) Dependence of the average value of the impact parameter ⟨b⟩ on centrality. (right) Distributions of the impact parameter for different centrality classes obtained from two methods, see text for the details.

[1] Idrisov, D., Segal, I., Golosov, O. *et al.* Centrality Determination Method in Nuclear Collisions by Using Hadron Calorimeter. *Phys. Part. Nuclei Lett.* **21**, 627–630 (2024). https://doi.org/10.1134/S1547477124700845

Impact parameter (b) and centrality of collision

- Why the geometrical term “centrality” is so important?

--- We need the accurate knowledge of the energy density in the interaction region in the events selected in a given class of centrality of A+A collisions

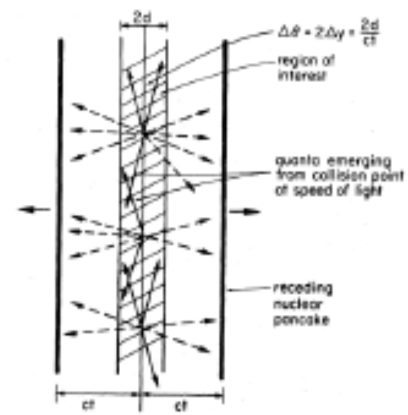
Transverse energy of charged particles and Bjorken energy density

$S_\perp$ – 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]



$E_\perp$ – 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

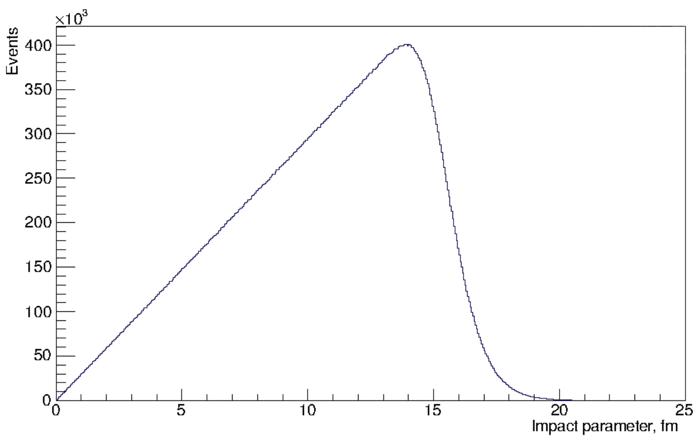
[1] J. D. Bjorken, Phys. Rev. D 27, 140 (1983)
[2]B. I. Abelev, M. M. Aggarwal et al.

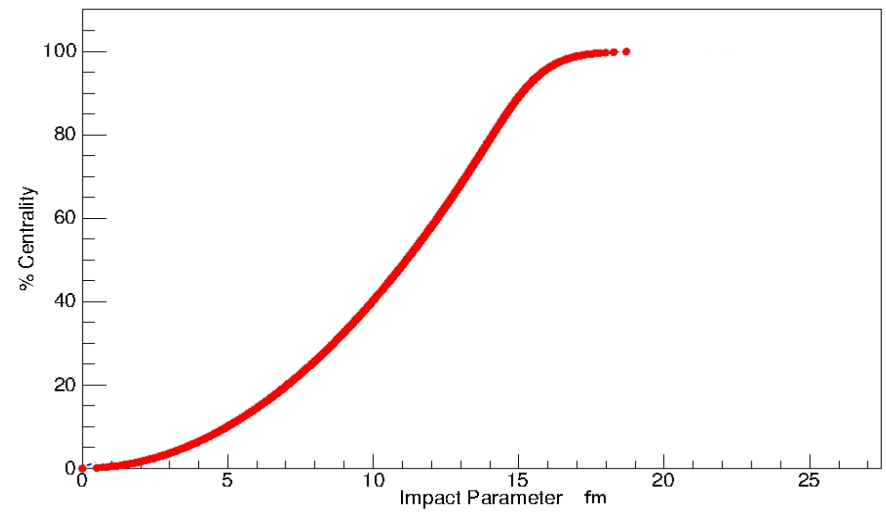
- Transverse overlap area S_T of the colliding nuclei requires an accurate estimate of *b*

Centrality and widths of centrality classes in relativistic heavy ion collisions

Impact parameter b and N_{part} in MC Glauber model

MC Glauber, PbPb 2.76TeV

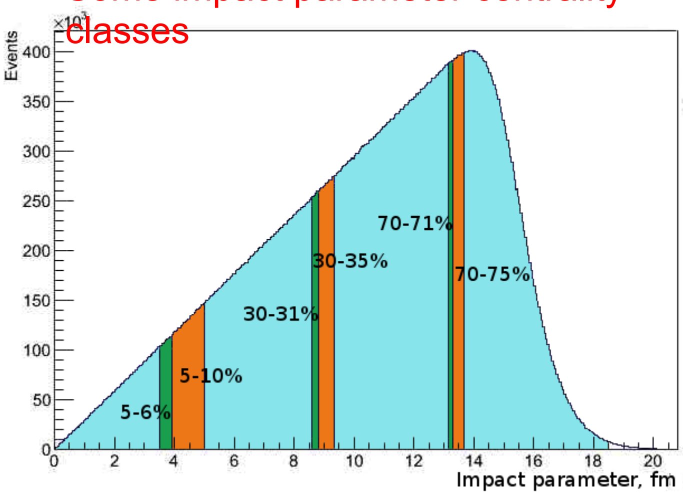


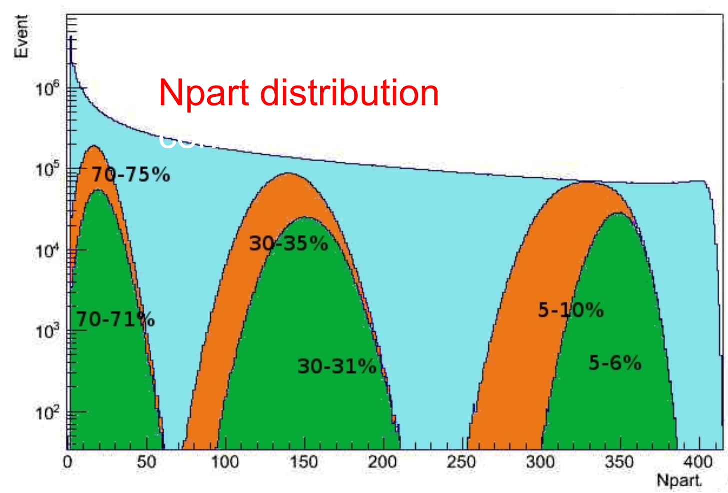


b

b

Some impact parameter centrality classes



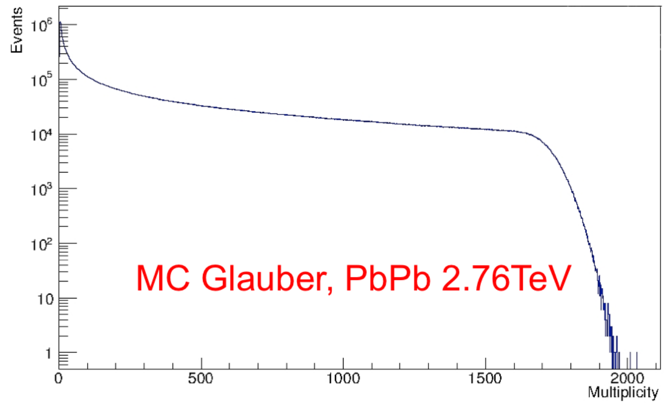


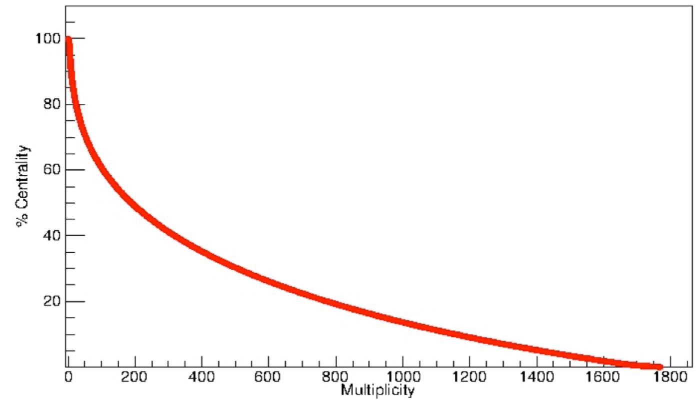
T. A. Drozhzhova,V. N. Kovalenko,A. Yu. Seryakov,G. A. Feofilov, Physics of Atomic Nuclei, September 2016, Volume 79, Issue 5, pp 737–748

b

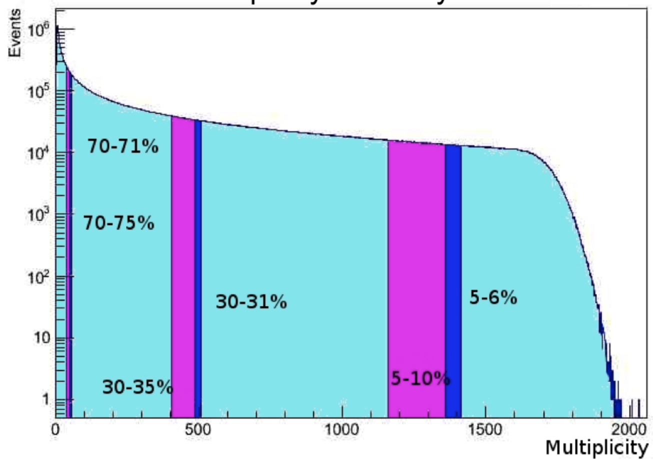
N_{part}

Multiplicity and N_{part} in MC Glauber model

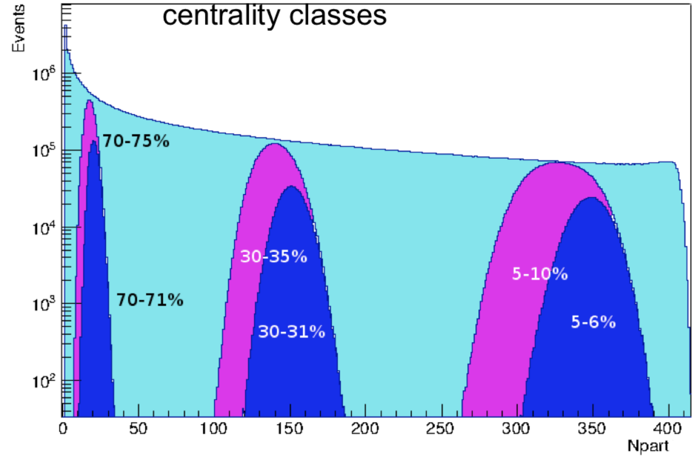




Some multiplicity centrality classes

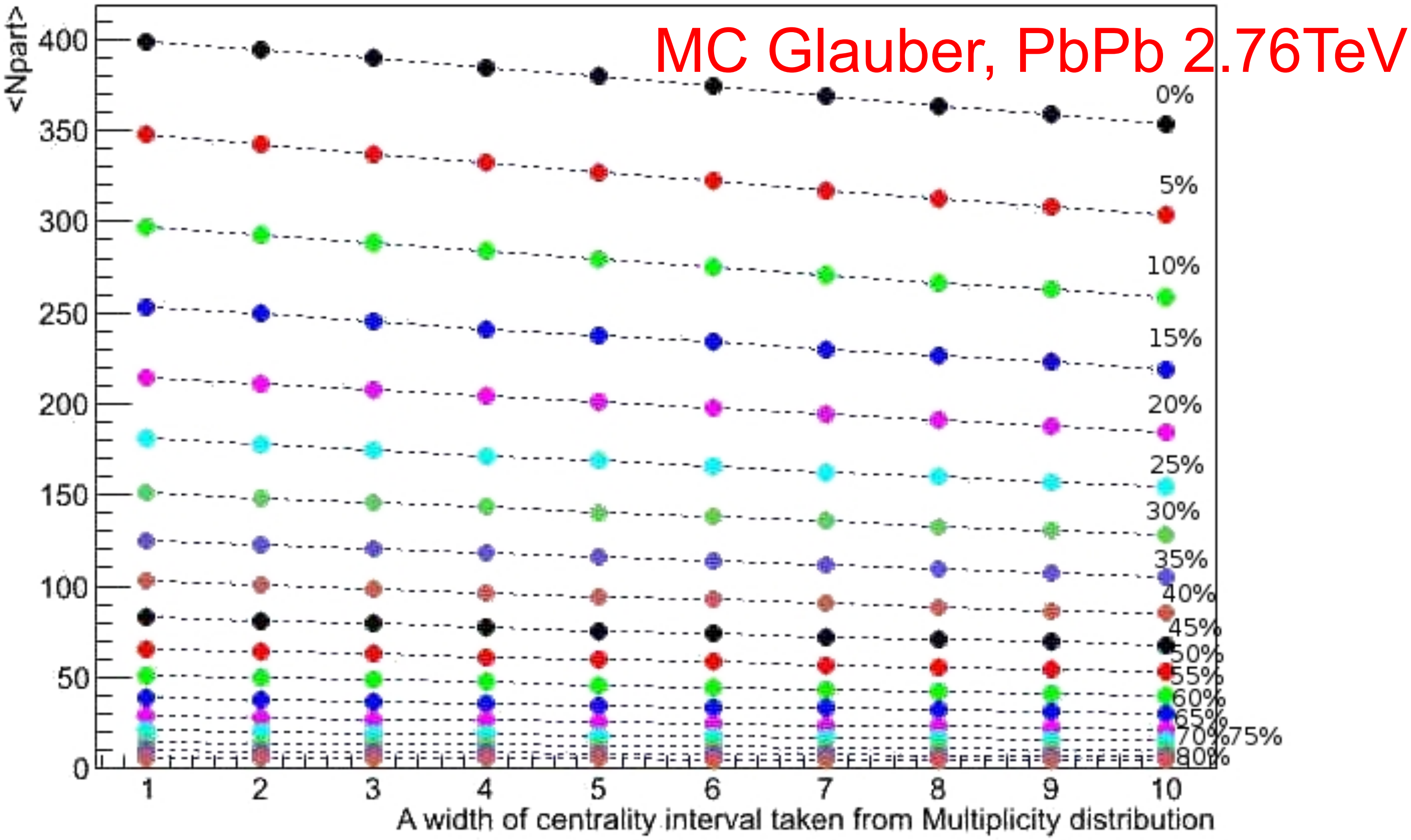


Npart distribution in the different centrality classes



T. A. Drozhzhova,V. N. Kovalenko,A. Yu. Seryakov,G. A. Feofilov, Physics of Atomic Nuclei, September 2016, Volume 79, Issue 5, pp 737–748

Width of multiplicity classes of centrality and <Npart>



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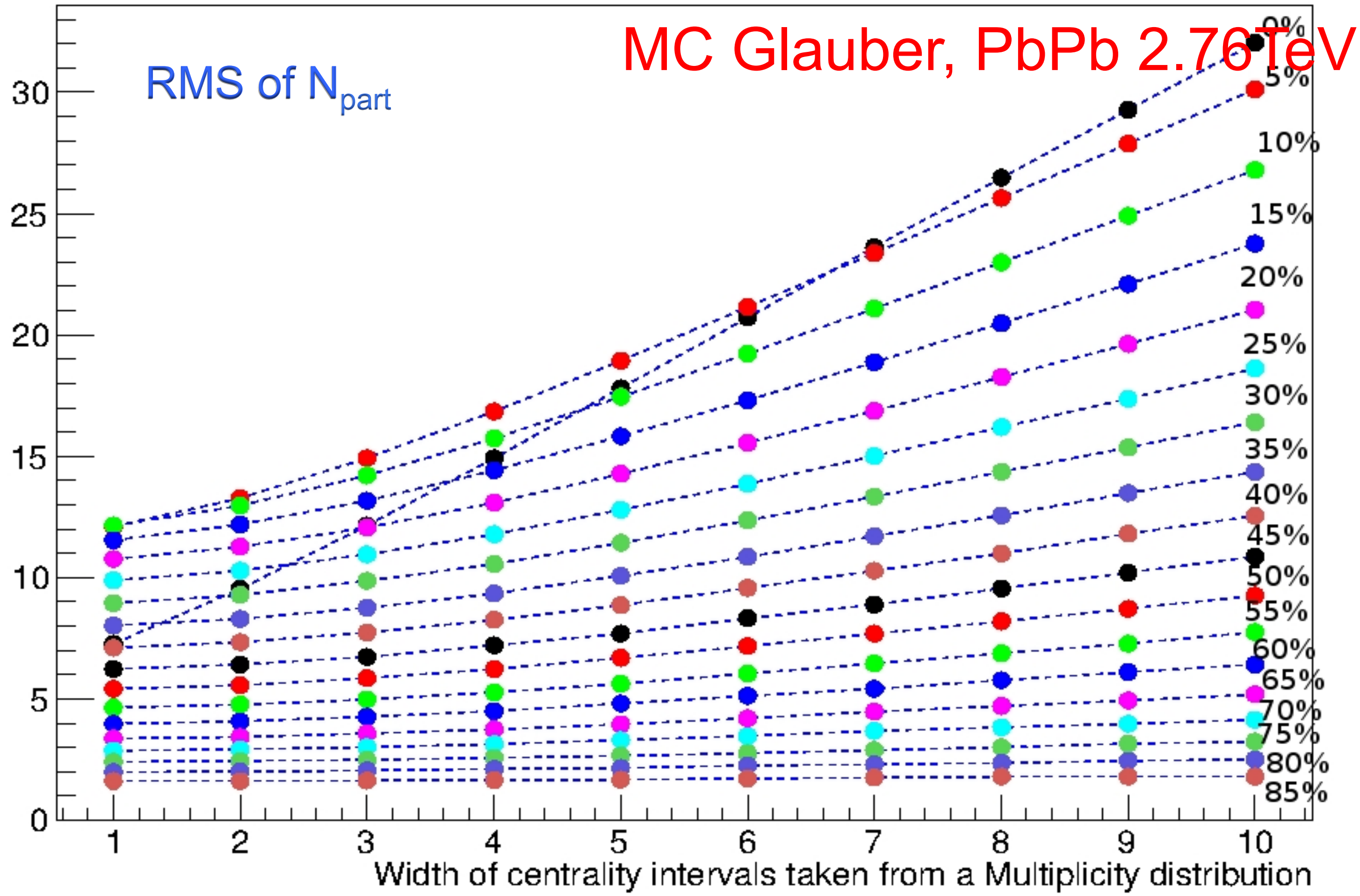
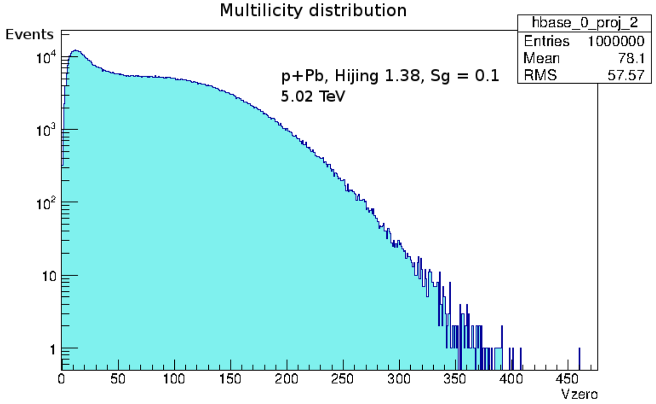
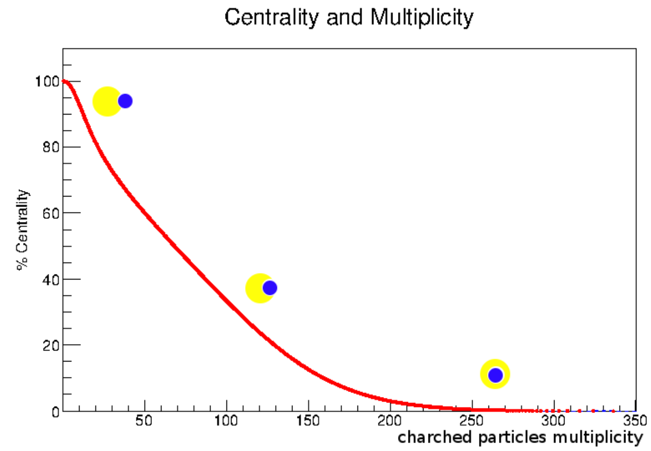
RMS of N_{part} in the different centrality classes from Multiplicity centrality selection

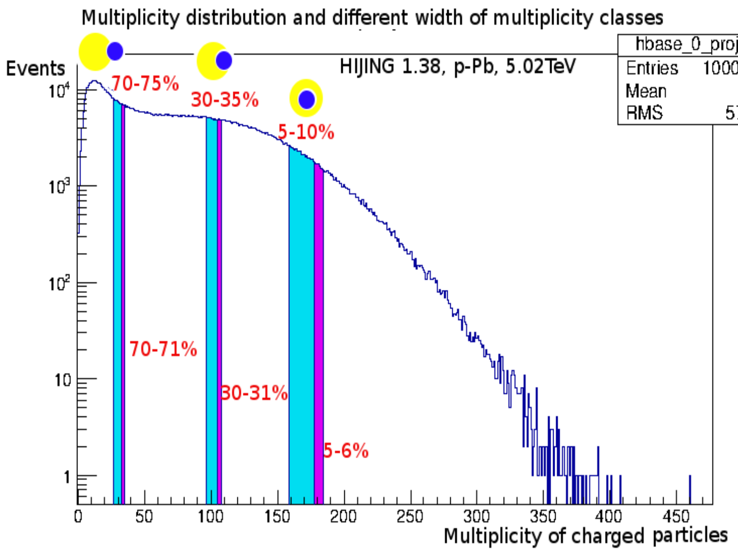


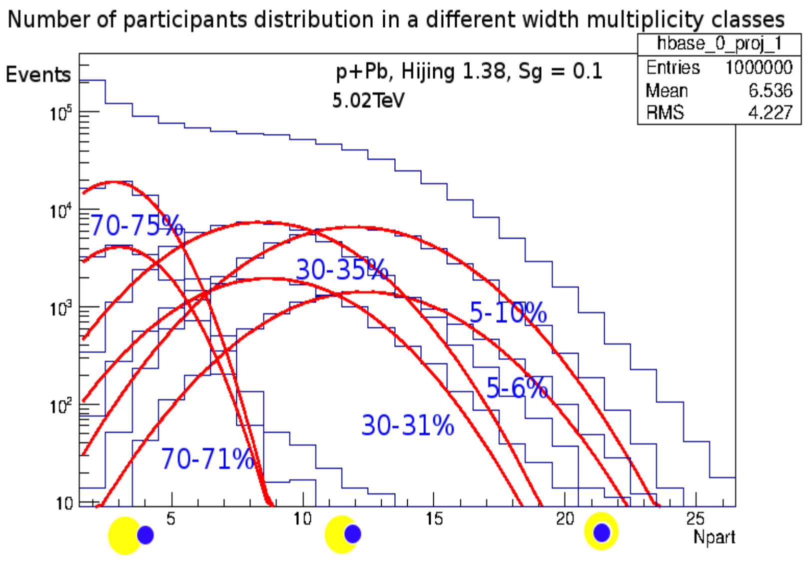
T. A. Drozhzhova,V. N. Kovalenko,A. Yu. Seryakov,G. A. Feofilov, Physics of Atomic Nuclei, September 2016, Volume 79, Issue 5, pp 737–748

N_{part} for p-Pb collisions centrality classes from Multiplicity selection





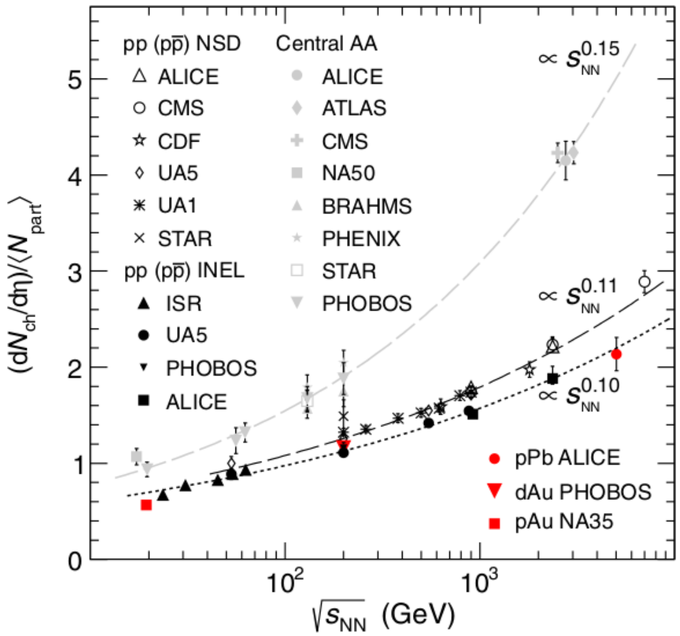




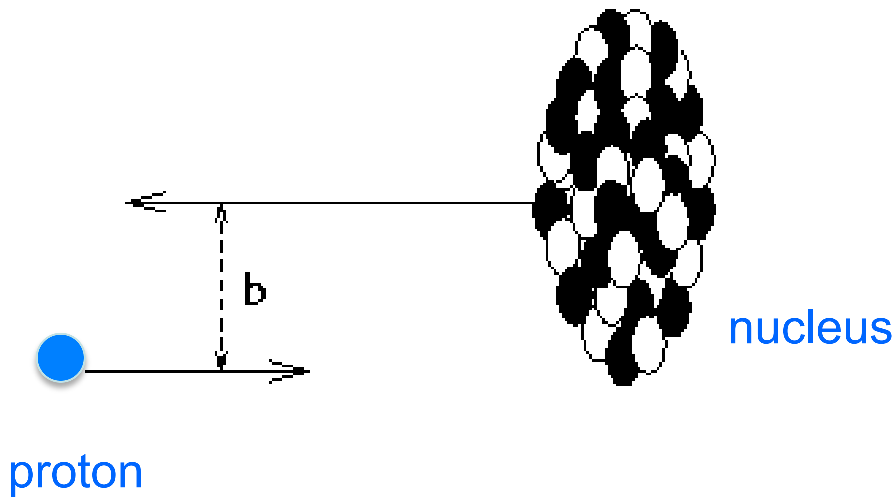
Conclusions from MC Glauber calculations:

- Results indicate that selection of a narrow centrality class in multiplicity does not assume real selection of very central events in terms of the impact parameter
- At the same time RMS of distributions in N_{part} could be very large unless the narrow centrality class in multiplicity is selected - this is important for any study of fluctuations
- In case of p-Pb collisions centrality classes from Multiplicity selection should not be used - the results could be ambiguous

Centrality classes in p-A collisions?

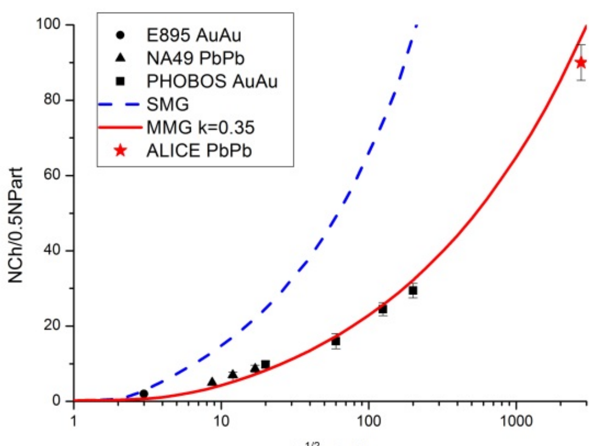


PRL 110,032301



Modified Glauber Model[1]

- Each nucleon in collisions loses in the inelastic collision
the fixed portion (1-k) of momentum in the center of mass system [1].
- The next inelastic collision will occur at lower collision energy and with different value of σ_{inel}
- This loss of momentum(energy) goes to the production of charged and neutral particles
- One can define parameter k by fitting the available experimental data on charged-particle multiplicity yields in AA collisions



$\sqrt{s_{NN}}$

[1] G.Feofilov, A.Seryakov, A new look on signals of collective effects in AA and pA at LHC based on Modified Glauber Model, AIP, 2015.
[2] PHOBOS Collaboration, arXiv:nucl-ex/0301017.
[3] ALICE Collaboration, Centrality dependence of the pseudorapidity density distribution for charged particles in Pb–Pb collisions at √S = 2.76 TeV, arXiv:1304.0347v2 [nucl-ex] , 2013.

Momenta of nucleons in MGM

COLLISIONS CALCULATION MGM

Before collision: $P_1 = -P_2 = \sqrt{(\frac{\sqrt{S}}{2})^2 - m^2}$

After collision: $P_1' = k \cdot P_1, P_2' = k \cdot P_2$

COLLISIONS CALCULATION MGM

In next collisions:

Nucleon energies: $E_1 = \sqrt{(P_1')^2 + m^2}$, $E_2 = \sqrt{(P_2')^2 + m^2}$

Energy per nucleon pair in the center-of-mass system: $\sqrt{S} = \sqrt{(E_1 + E_2)^2 - (P_1' + P_2')^2}$

Energy and momentum of the nucleon in the center-of-mass system: $E_{CM} = \frac{\sqrt{S}}{2}$, $P_{CM} = \sqrt{E_{CM}^2 - m^2}$

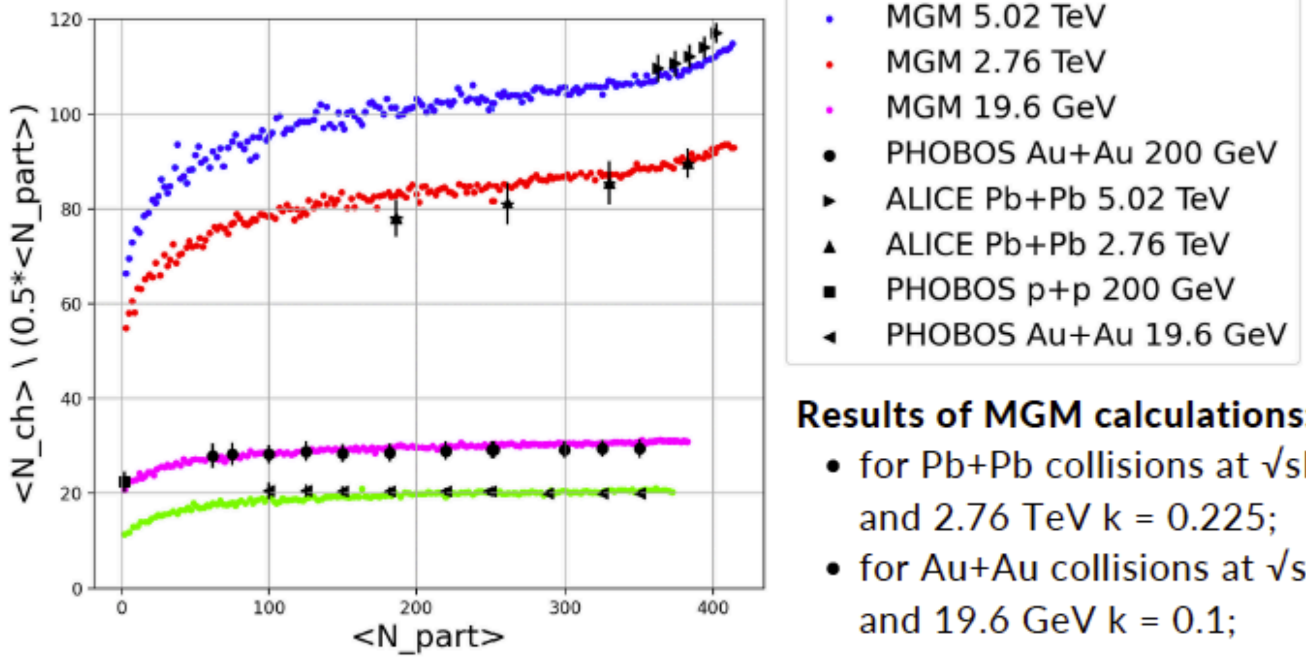
Lorenz boost: $\beta = \frac{P_{CM} \cdot E_1 - E_{CM} \cdot P_1}{P_{CM} \cdot P_1 - E_{CM} \cdot E_1}$

Momentum and energy after collision: $P_{CM}^{new} = k \cdot P_{CM}, E_{CM}^{new} = \sqrt{(P_{CM}^{new})^2 + m^2}$

Reverse Lorenz boost: $P_1^{new} = \frac{P_{CM}^{new} + \beta \cdot E_{CM}^{new}}{\sqrt{1-\beta^2}}, P_2^{new} = \frac{-1 \cdot P_{CM}^{new} + \beta \cdot E_{CM}^{new}}{\sqrt{1-\beta^2}}$

MGM

RESULTS

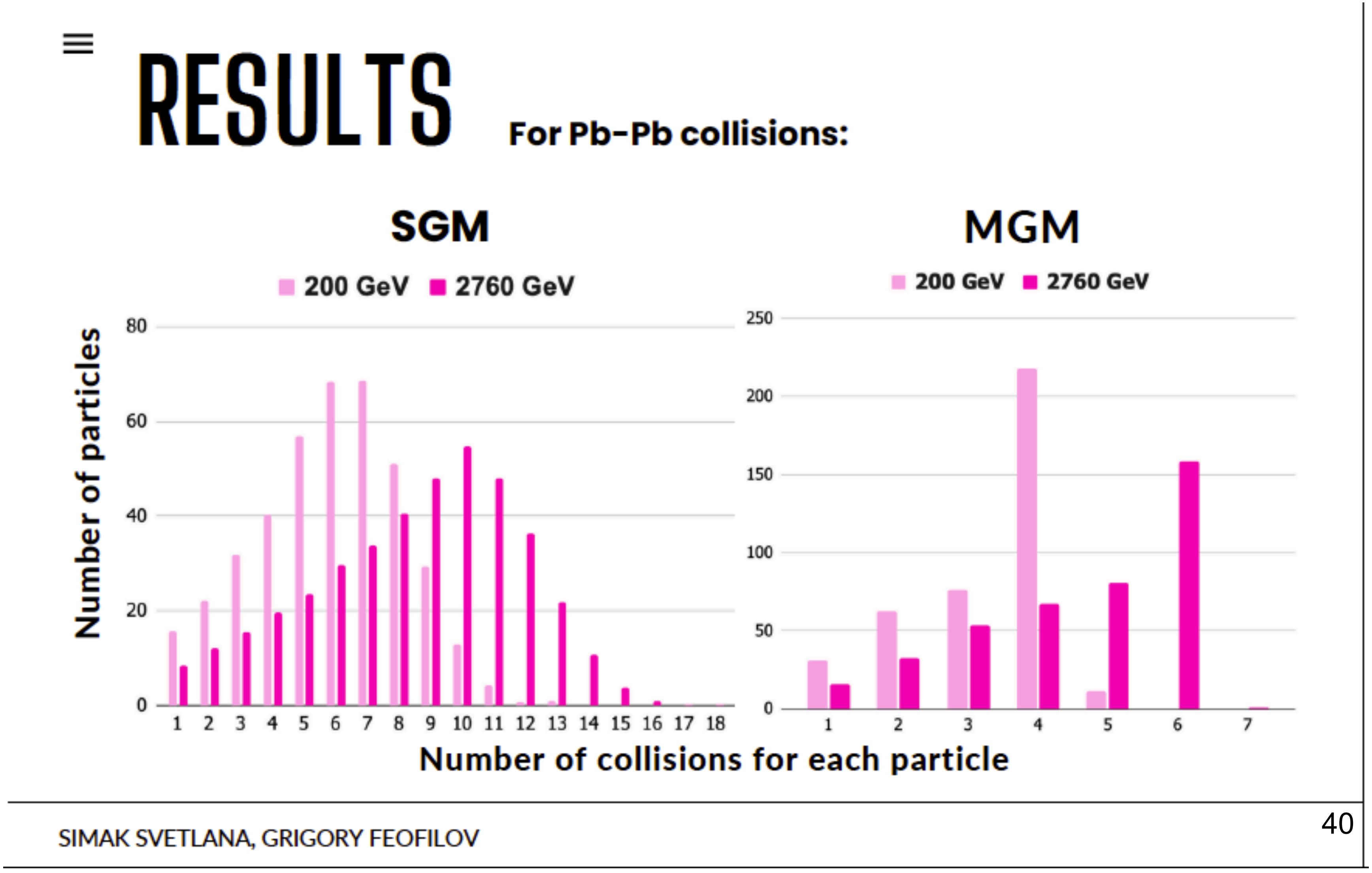


Results of MGM calculations:

- for Pb+Pb collisions at √sNN = 5.02 TeV and 2.76 TeV k = 0.225;
- for Au+Au collisions at √sNN = 200 GeV and 19.6 GeV k = 0.1;

Experimental data: Back B.B., et al, PHOBOS Collaboration // arXiv.nucl-ex/0301017.2003.5 p.,
Acharya, S. et al., (ALICE Collaboration)// Phys.Lett.B. 790 .2019. P. 35-48,
ALICE Collaboration // Phys. Lett. B. 726. 2013. P. 610-622

MGM

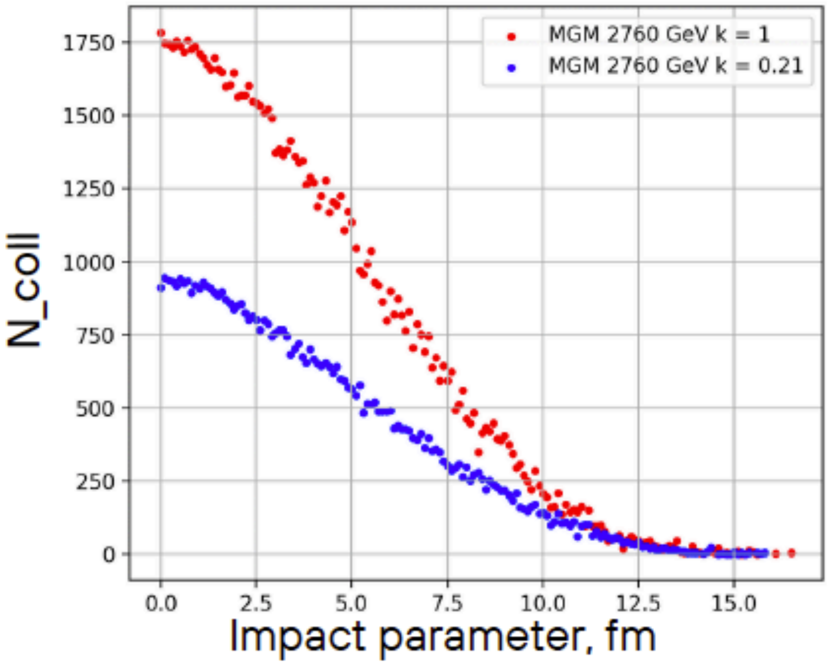


RESULTS
For Pb-Pb collisions:
SGM
200 GeV
2760 GeV
Number of particles
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
MGM
200 GeV
2760 GeV
250
200
150
100
50
0
1 2 3 4 5 6 7
Number of collisions for each particle
SIMAK SVETLANA, GRIGORY FEOFILOV

Number of <N_{coll}> in SGM and MGM

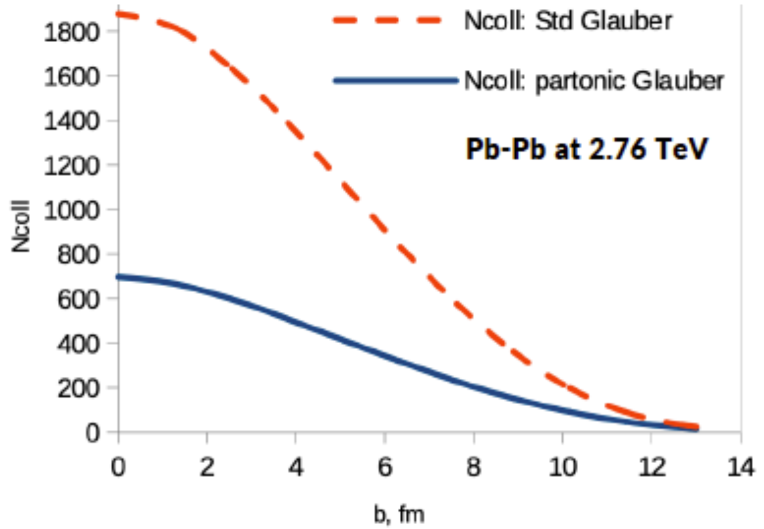
RESULTS

For Pb-Pb collisions:



A **large difference** is observed between the values obtained by MGM and SGM, which is **extremely important** in the processing of experimental data.

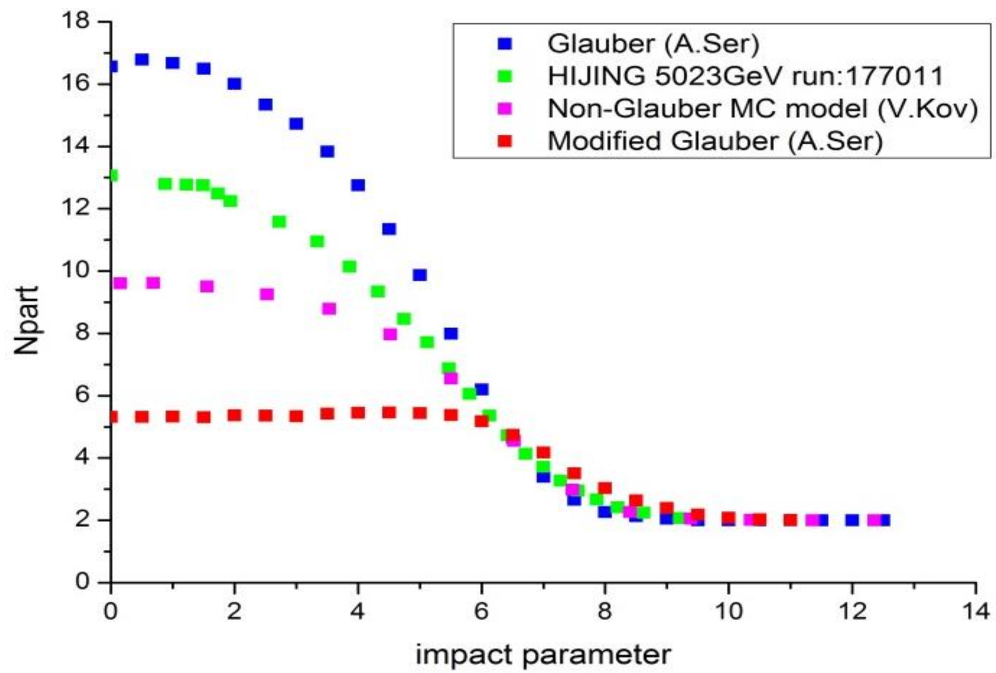
Number of <N_{coll}> in SGM and partonic Glauber



Vladimir Kovalenko, Glauber modeling hadron-nucleus collisions at the parton level, Scientific session of the nuclear physics section of the Division of Physical Sciences of the Russian Academy of Sciences, JINR, 2024

Stopping of nucleons in AA and pA interactions at the LHC energies

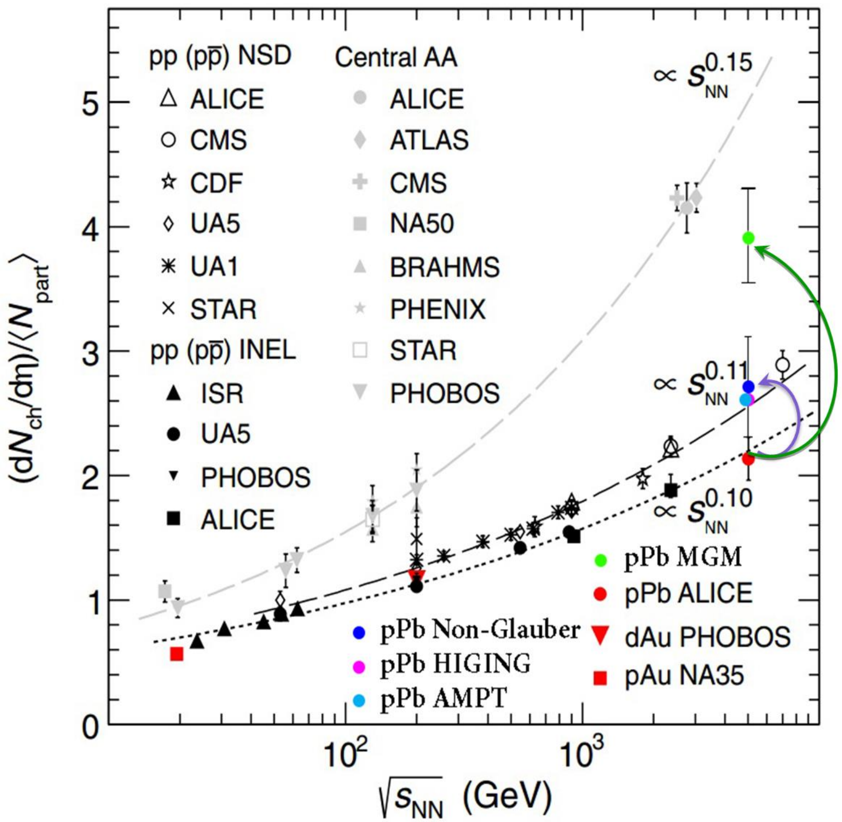
MinBias	*<Npart> at 5.02 TeV* *ALICE p-Pb*
Glauber	7.87 (A.Ser) 7.9±0.6 (ALICE)
MGM	4.3±0.3
Non-Glauber	6.2±0.6
HIJING	6.5



MGM, non-Glauber, HIJING **and AMPT (???)** – all these models gives smaller values of $\langle N_{part} \rangle$ compared to Glauber

Results for p-Pb

Charged-particle pseudorapidity density at midrapidity normalized to Npart



MinBias	*<Npart> at 5.02 TeV* *ALICE p-Pb*
Glauber	7.87 (A.Ser) 7.9±0.6 (ALICE)
MGM	4.3±0.3
Non-Glauber	6.2±0.6
HIJING	6.5

Data from: PRL 110,032301

T. Drozhzhova, G. Feofilov, V. Kovalenko, A. Seryakov, Geometric properties and charged particles yields behind Glauber model in high energy pA and AA collisions. Proceedings of the "The XXI International Workshop High Energy Physics and Quantum Field Theory" in St.Petesburg Area, in June 23–30 2013.

Summary and outlook

- The initial conditions of nucleus-nucleus and proton-nucleus collisions at high energies are important for any analysis and haracterization of the expected quark-gluon plasma formation

- The impact parameter *b,* and its relevant values N_{part} and so-called binary collisions N_{coll}, are widely used to normalize the measured fractional cross sections both of soft and hard processes of particle production in collisions of heavy ions

- We compare methods of centrallity determination based on the Glauber model and multiplicity estimators to the modified Glauber, HIJING MC event generators to non-Glauber approach calculations. We show that the correct inclusion of energy-momentum consevation in multiprticle production process decreases considerably values of N_{coll}, the result is especially striking for **p-Pb collisions**

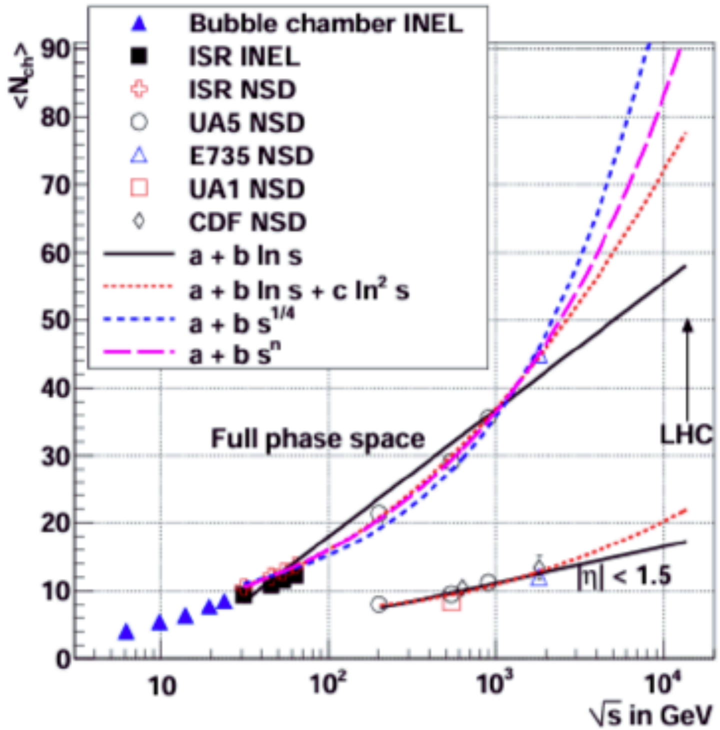
- Binary collisions N_{coll} should be treated differently for soft and hard processes in order to exclude in the analysis any possible biases to initial conditions

BACK-UP SLIDES

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

COLLISIONS CALCULATION MGM



Jan Fiete Grosse-Oetringhaus, Klaus Reygers, arXiv:0912.0023

In each binary collision number of produced charged particles (N_ch) is calculated for √S(NN) for this collision;

$$N_{ch}^{pp} = a + b \cdot ln(S) + c \cdot ln^2(S)$$

a = 16.65, b = -3.147, c = 0.334

Compare to the dimension of Pb nucleus filled with nucleons

The diameter of a proton is around **1.7fm**

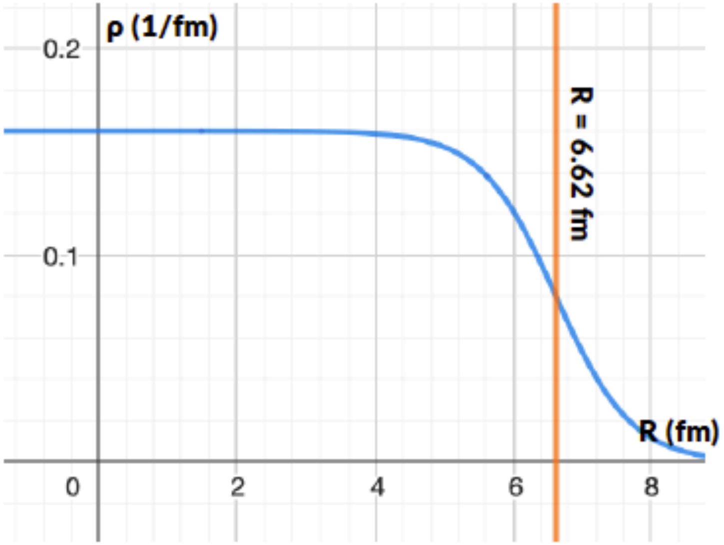
NUCLEUS GENERATION

Two-parameter Fermi model for nucleon density distribution:

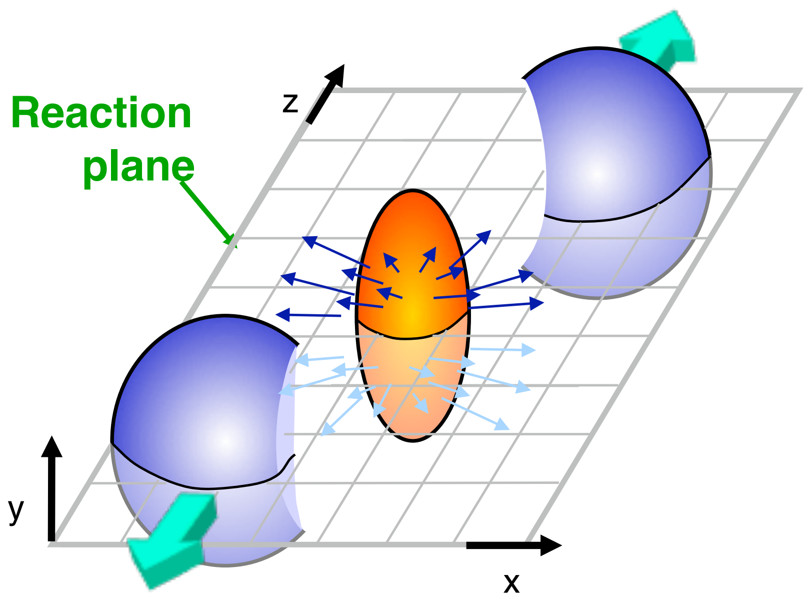
	Pb-208	Au-197	Bi-209
a (fm)	0.546	0.535	0.468
R (fm)	6.62	6.38	6.75

H. DE VRIES, C. W. DE JAGER, and C. DE VRIES, ATOMIC DATA AND NUCLEAR DATA TABLES 36,495536 (1987)

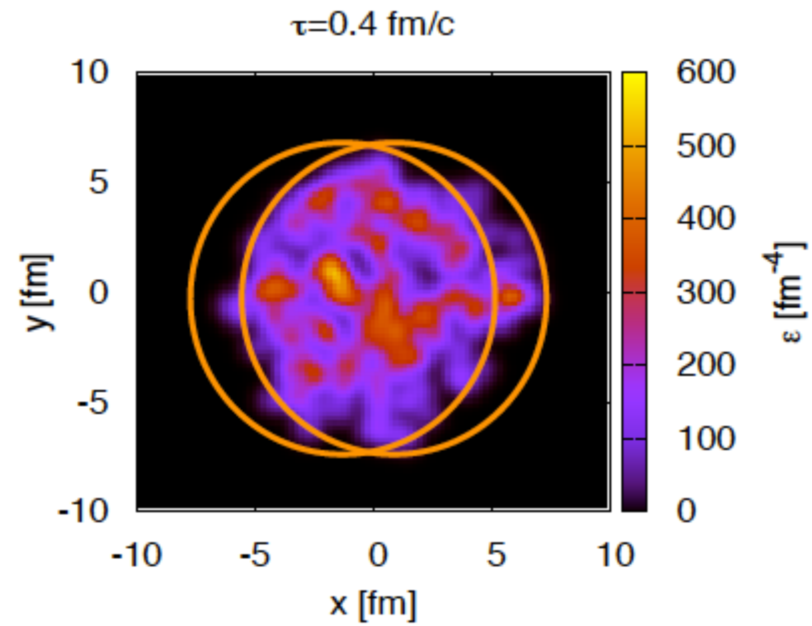
$$\rho(r) = \rho_0 \frac{1}{1 + exp(\frac{r-R}{a})}$$



Centrality and widths of centrality class in relativistic heavy ion collisions

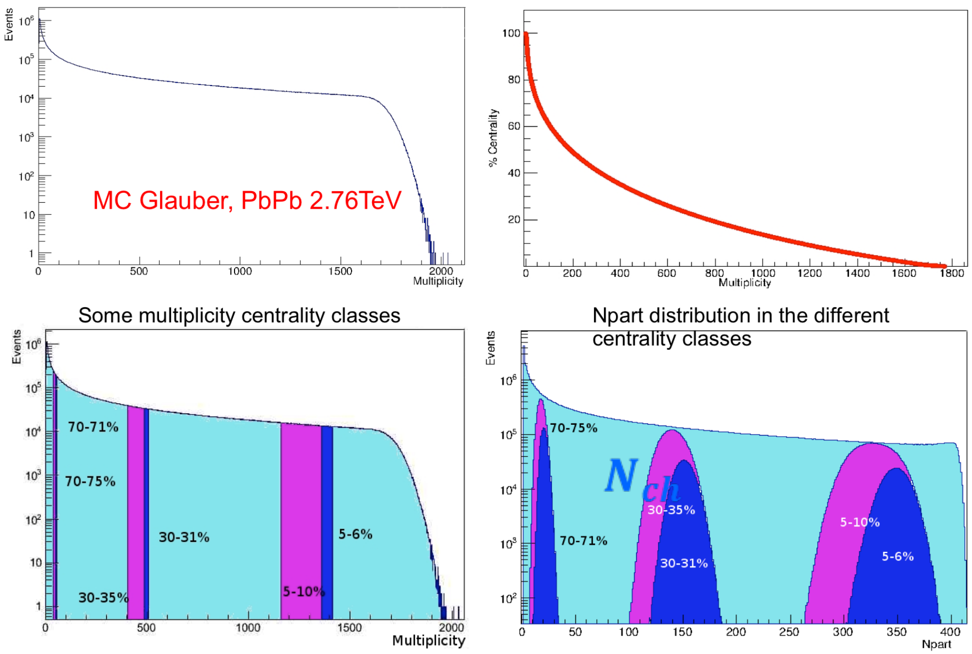


Tannebaum, 2006



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

Multiplicity and N_{part} in MC Glauber model

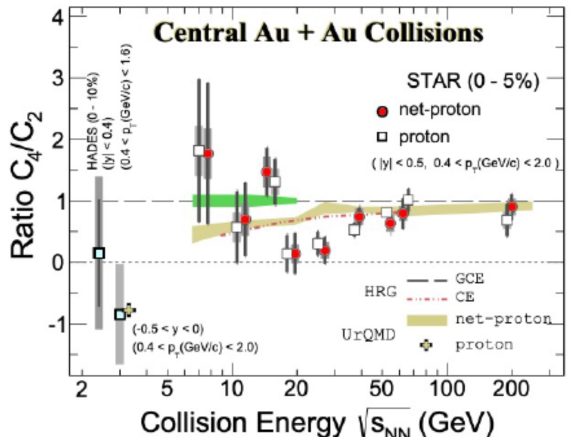


- Narrow distribution in N_{ch} DOES NOT mean narrow distribution in N_{part}!

- So, **in case of any fluctuation studies,** centrality determination and selection of wide classes should be taken with definite concern!

T. A. Drozhzhova,V. N. Kovalenko,A. Yu. Seryakov,G. A. Feofilov, Physics of Atomic Nuclei, September 2016, Volume 79, Issue 5, pp 737–748

Global observables
in high-sensitivity studies with MPD at high μ_B



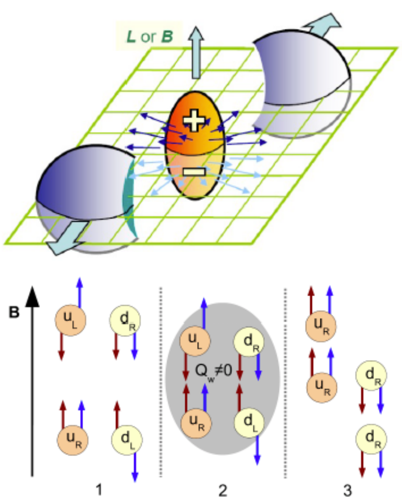
PRL)2021) 092301; PRL 128 (2022)202303

- **Strong competition with RHIC and SPS experiments!**
- **A couple of hot topics :**

--- Search for QCD critical point and non-monotonic energy dependence of net-proton $k\sigma^2 = C_4/C_2$ for 5% most central events recently observed by STAR;

--- Chiral magnetic effect search in isobar collisions: charge separation due to anomaly induced chiral imbalance and large (10^{15} T) magnetic field. The Chiral Magnetic Effect can only operate in the deconfined, chirally symmetric phase. See search for CME in arxi

$$\frac{dN_\alpha}{d\phi^*} \approx \frac{N_\alpha}{2\pi}\left[1 + 2v_{1,\alpha}\cos(\phi^*) + 2a_{1,\alpha}\sin(\phi^*) + 2v_{2,\alpha}\cos(2\phi^*) + \cdots\right],$$



$\Phi^* = \Phi - \Psi_{RP}$, with Φ and Φ_{RP} being the azimuthal angle of a particle and of the Reaction Plane (RP).

The "γ correlator: $\gamma_{\alpha\beta} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$. Here φ_α and φ_β are the azimuthal angles of particles of interest (POIs).

D.Kharzeev, arXiv:1312.3348

- **Both items require precise event centrality and reaction plane (RP) definition**

Non-Glauber MC model (V. Kovalenko)

V. Kovalenko, Phys. Atom Nucl 76 (accepted), arXiv:1211.6209 [hep-ph];
V. Kovalenko, V. Vechernin. PoS (Baldin ISHEPP XXI) 077, 2012, arXiv:1212.2590 [nucl-th]

- Partonic picture of nucleons interaction.
- Every parton can interact with other one only once

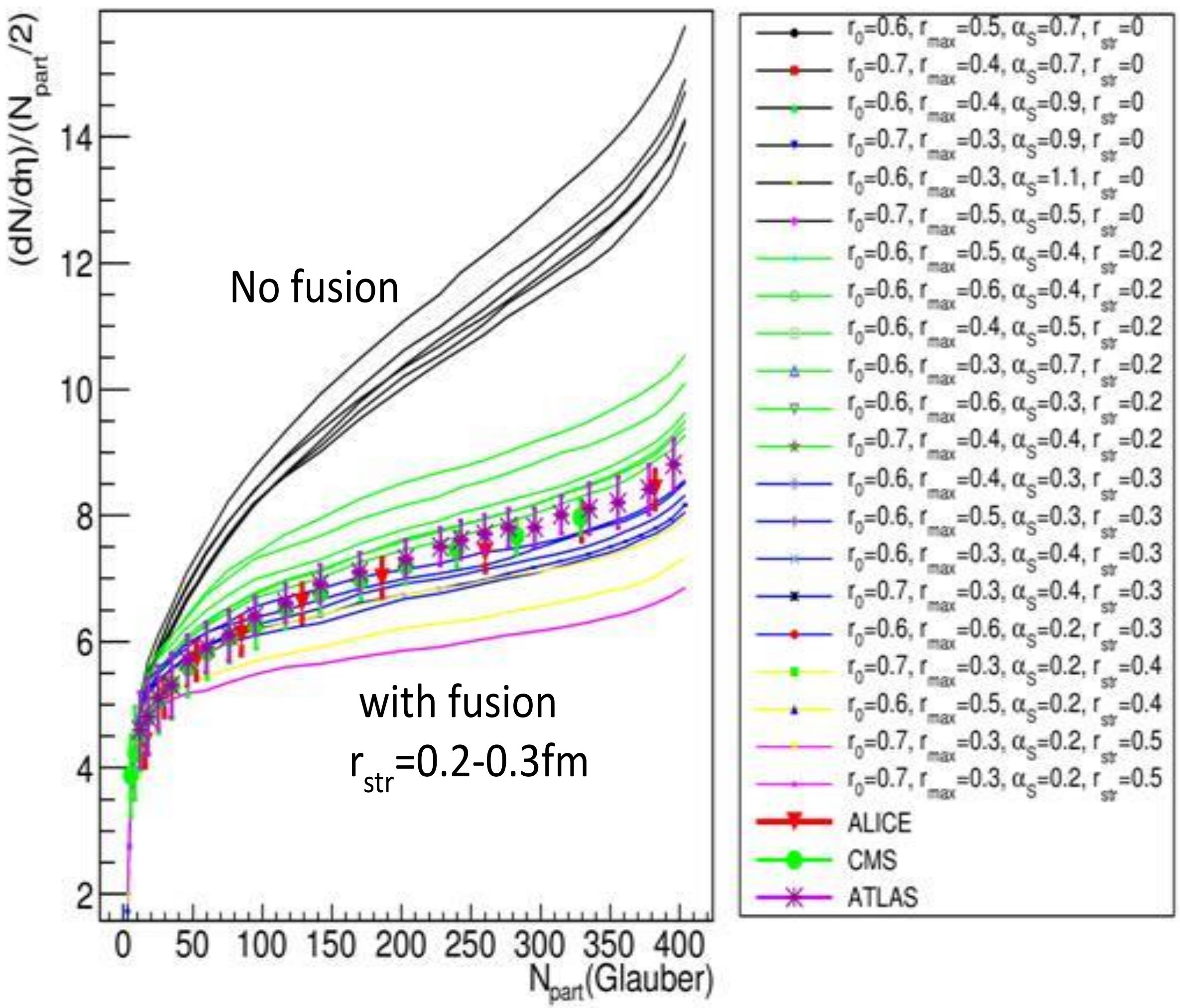
(contrary to Glauber supposition of constant nucleon cross section)

- Nucleon is participating in the collision if at least one of it's partons collides with parton from another nucleus.
- Parameters of the model are constrained from the p-p

data on total inelastic cross section and multiplicity

- Additional requirement is consistent description of the multiplicity in min. bias p-Pb collisions

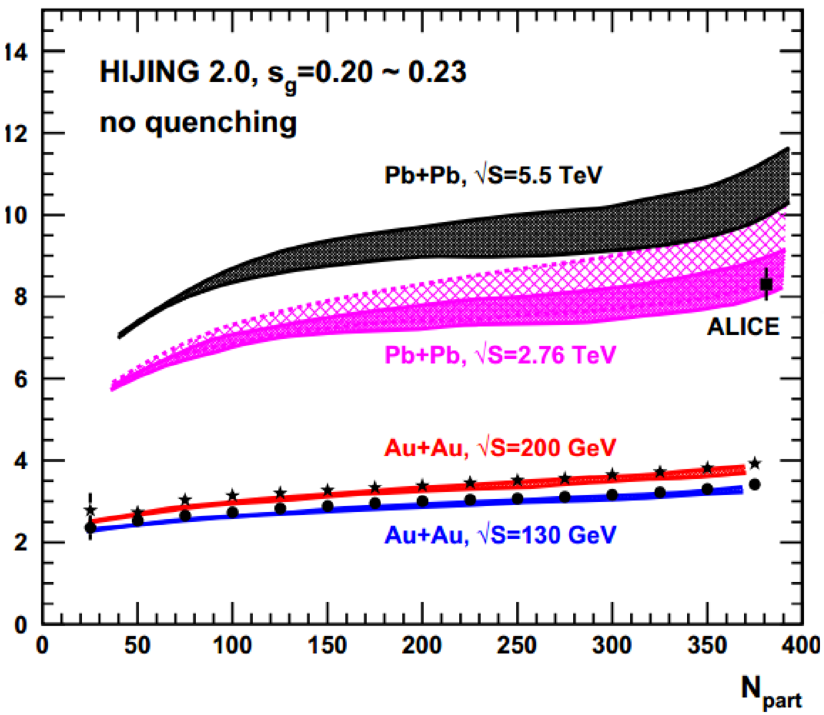
Non-Glauber MC model (V. Kovalenko)

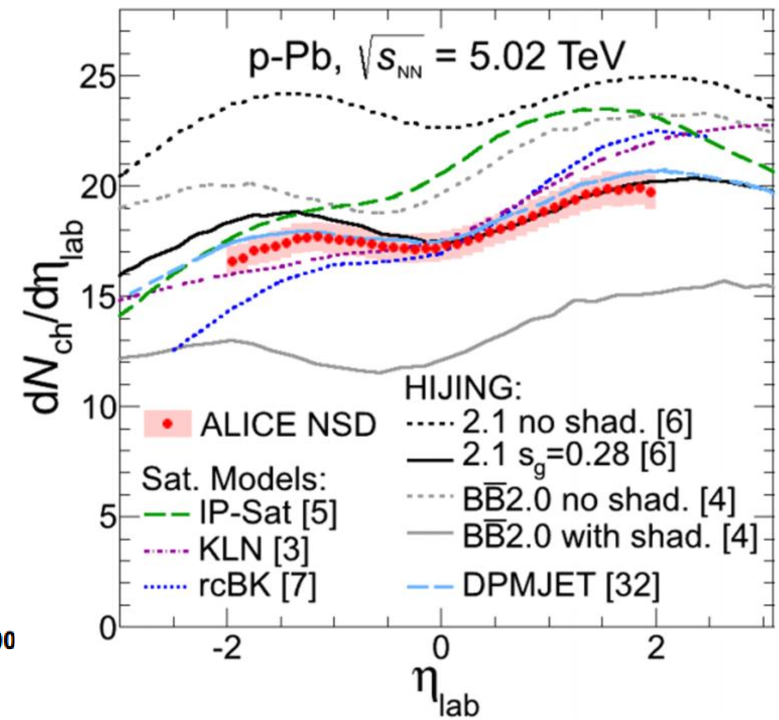


V. Kovalenko, Phys. Atom. Nucl. 76, 1189–1195 (2013).

HIJING

• HIJING is the MC event generator for hadron production in high energy pp, pA, AA collisions.
• Gives reasonable description of multiplicity yields.





ǐ, R. Xu, W.-T. Deng, and X.-N. Wang, arXiv:1204.1998