Rudimentary introduction to ultrarelativistic heavy-ion collisions

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NCBJ

06-12-2021

Online seminar : Selected topics in heavy-ion collisions

Indico page: https://indico.cern.ch/event/1103564/

Goal

Familiarise basic terminologies, ideas and concepts in the field of heavy-ion collisions

Outline

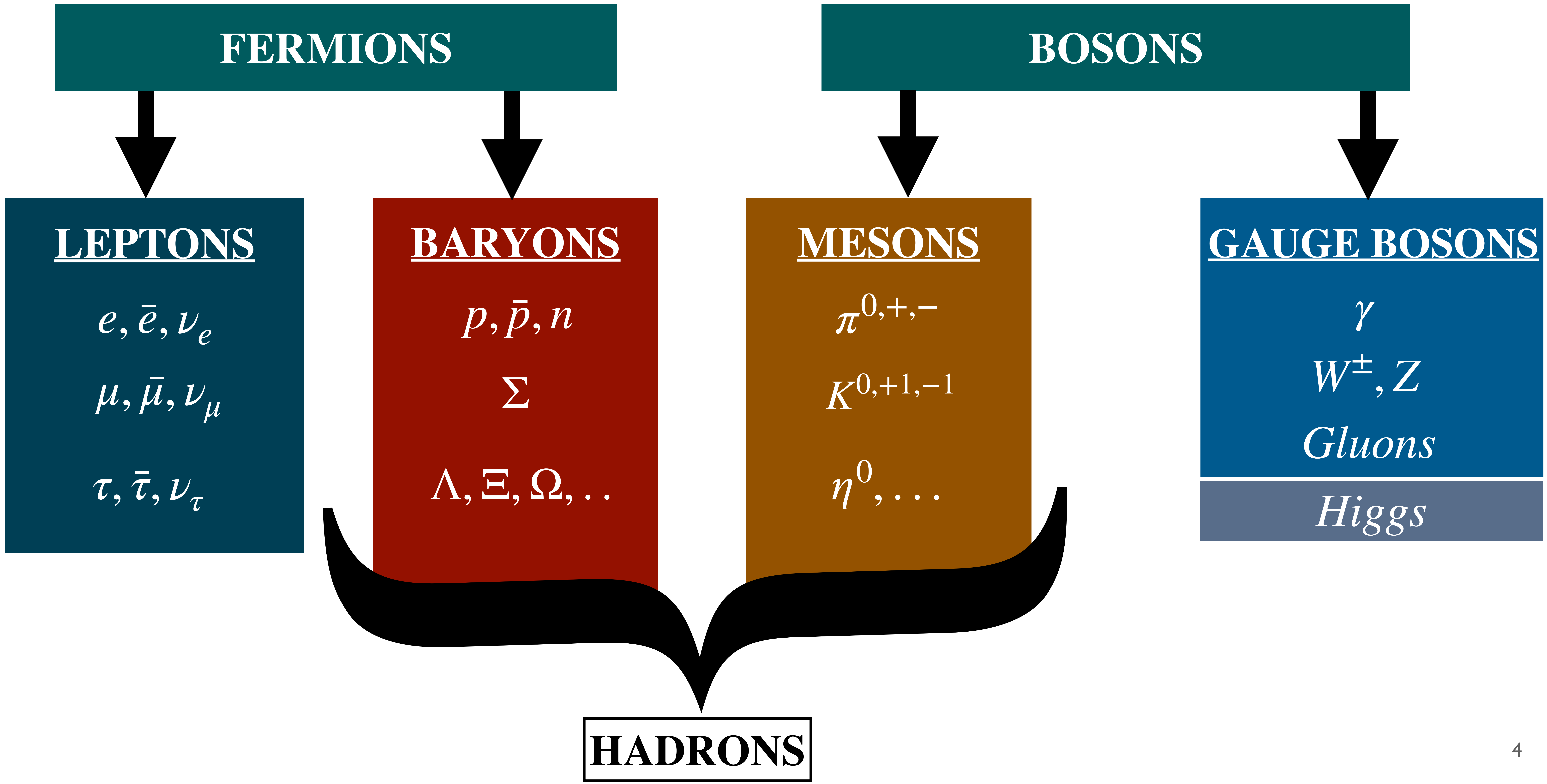
- Why we study heavy-ion collisions
- Geometry and kinematics of high energy collisions
- Impact parameter, centrality and Glauber model
- Uncertainties and normalisation
- Bjorken scenario of heavy ion collisions

1. Basics

- The Alternating Gradient Synchrotron at BNL (AGS)
- The Super Proton Synchrotron at CERN (SPS)
- The Relativistic Heavy Ion Collider at BNL (RHIC)
- The Large Hadron Collider at CERN (LHC)

2. Experiments

Classification of standard model particles



Basic Terminology

$An\ event$: A collision

$Multiplicity$: Number of particles (usually in an event)

$\sqrt{s}$: Available centre of mass energy ($s \equiv Mandelstam\ variable$)

$\sqrt{s_{NN}}$: Available centre of mass energy per nucleon pair

$e^+e^-\ collisions$: Electron - Positron Collisions → Elementary collision

$pp\ collisions$: Proton-Proton

$p\bar{p}\ collisions$: Proton- Antiproton

$hh\ collisions$: Hadron- Hadron ($h \equiv p, \pi, K\ etc$)

$pA\ collisions$: Proton-Nucleus Collisions

(pp, $p\bar{p}$, hh, pA collisions) } Small systems

$AA\ collisions$: Nucleus -Nucleus Collisions ($A \equiv Au, Pb, Xe, O, Mg\ etc$)

$< N >$: Average over an event

$<< N >>$: Average over all the events

$E.O.S$: Equation of state

η/s : Shear viscosity to entropy ratio

MPI : Multi Particle Interaction

Particlisation & Hadronisation

Why do we study heavy-ion collisions

- When the universe was only a few microseconds old it is believed to be filled with deconfined state of quarks and gluons.

- Heavy-ion collisions are believed to recreate in the labs, such droplets of matter that filled the universe $\sim 1\ \mu s$ after the big bang.

Rep. Prog. Phys. 42: 389 (**1979**); Phys. Rev. Lett. 34: 1353 (**1975**)

- We cannot use cosmological observations to see the primordial hot QCD matter that filled the early Universe (Why ?: At small μ_B, QCD phase transition is a crossover).

- With heavy-ion collisions we can learn about its material properties (Not possible with telescopes or satellites) and explore QCD phase diagram.

Nucl. Phys. A 698: 199 (**2002**); Nature 443: 675 (**2006**)

Why do we study heavy-ion collisions

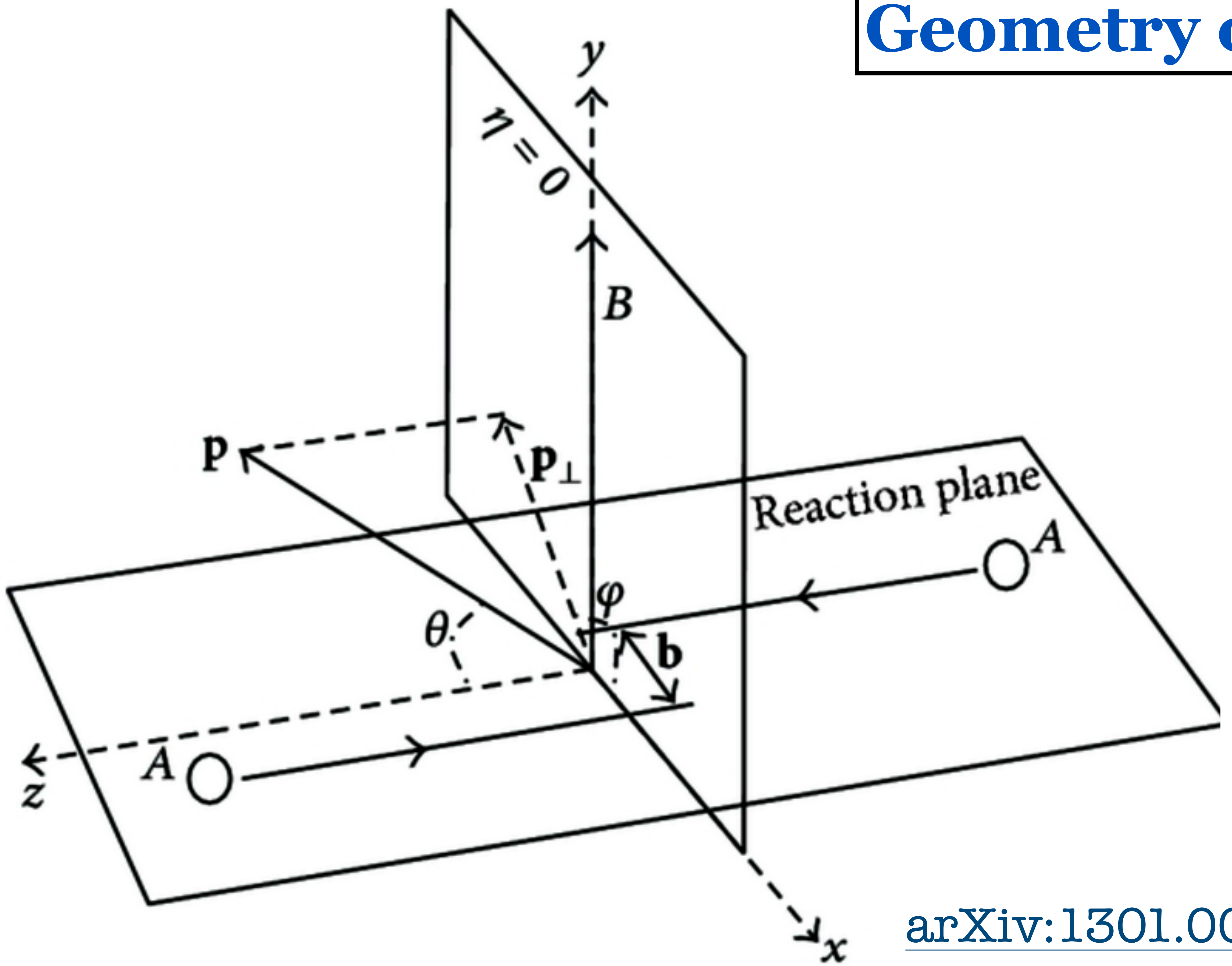
- Learn the phase diagram of hot QCD matter, in thermal equilibrium, as a function of T and baryon doping.
- A study of the debris produced at very high rapidity in the highest-energy heavy ion collisions might be a way to study QGP doped with a significant excess of quarks over antiquarks
- **Critical Point?:** Know whether the continuous crossover between liquid QGP and hadronic matter turns into a first-order phase transition above some nonzero μB

Phys. Rev. Lett. 102: 032301 (**2009**); Phys. Rev. D 82: 074008 (**2010**); Proc. Sci. CPOD2014: 019 (**2015**)

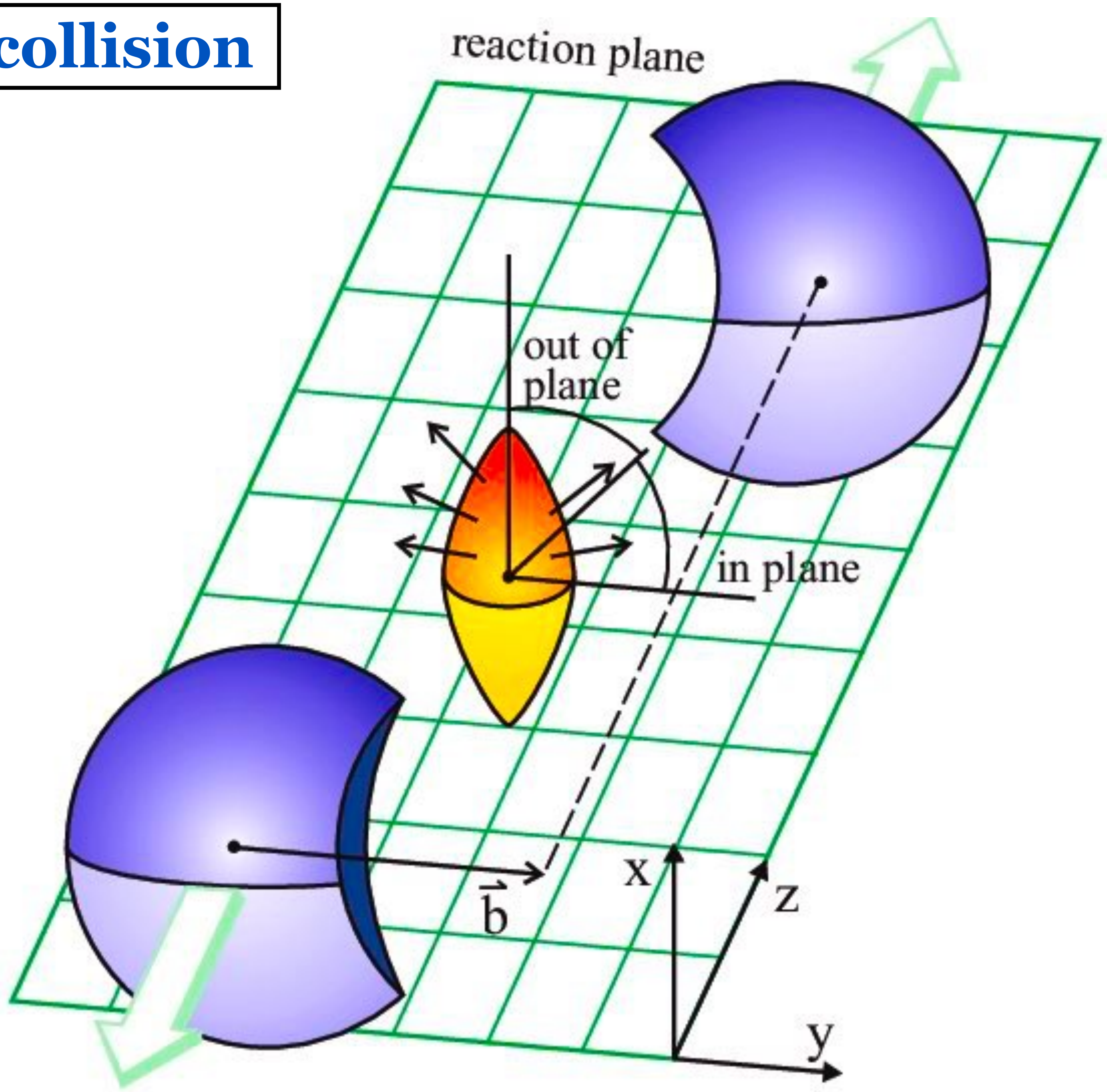
- **Questions derived from observations**
  - Hydrodynamical behaviour of the matter and related problems
  - Jets and their propagation in a strongly coupled QGP medium
  - And lot more…..

Annu. Rev. Nucl. Part. Sci. 63: 123 (**2013**); Prog. Theor. Phys. 5:570 (**1950);** Izv.Akad. Nauk. Ser. Fiz. 17:51 (**1953**);

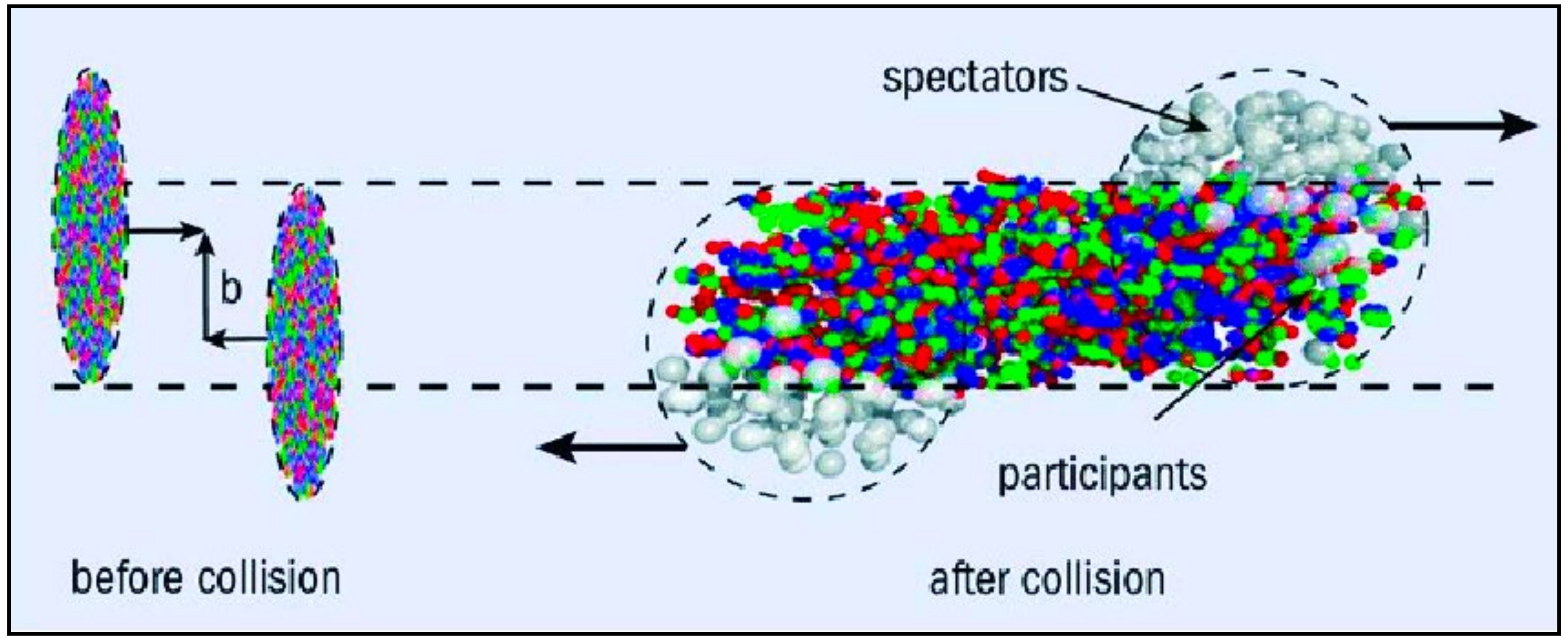
Geometry of a collision



arXiv:1301.0099



arXiv:0910.4114



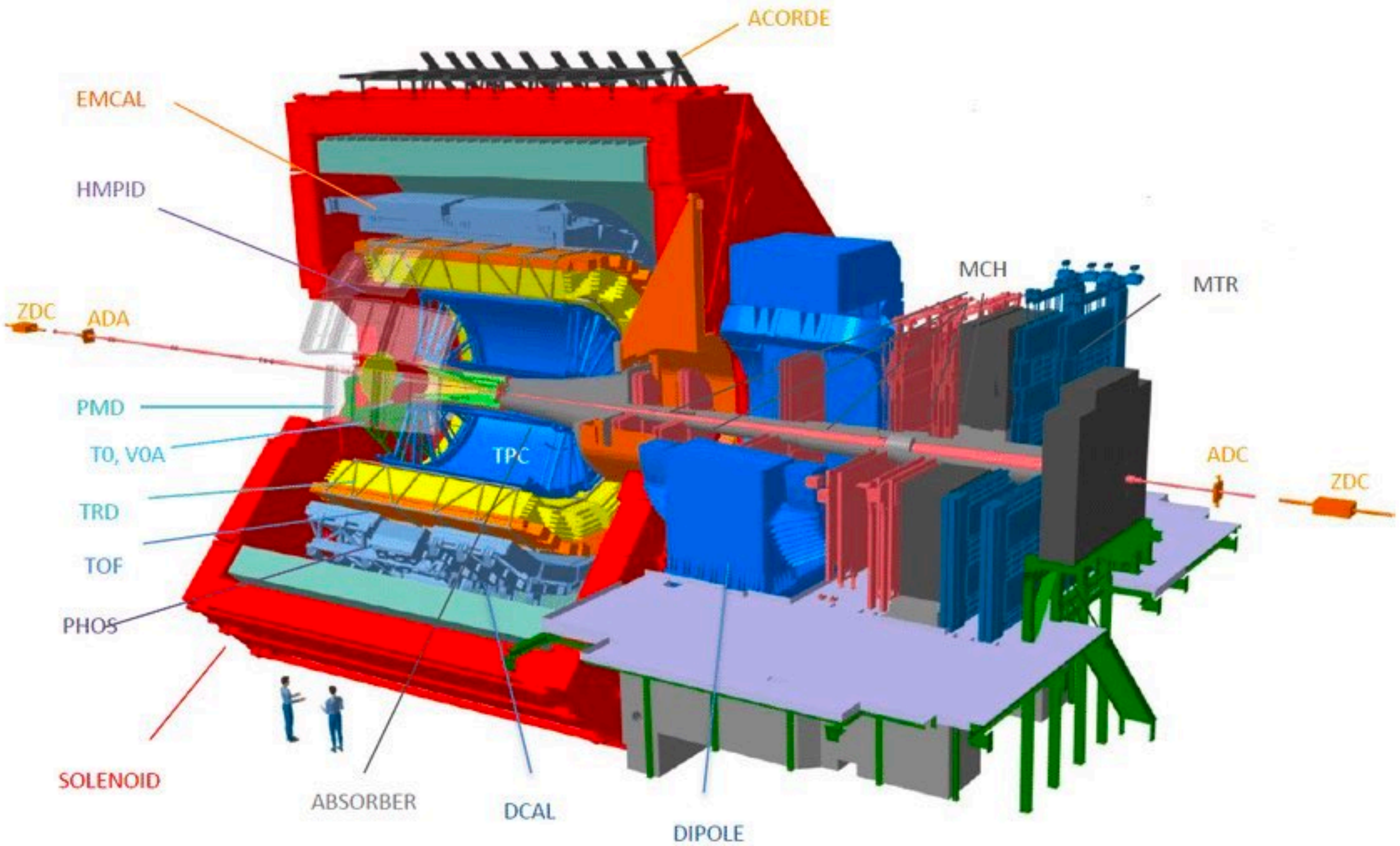
CERN Courier, 26 April 2013

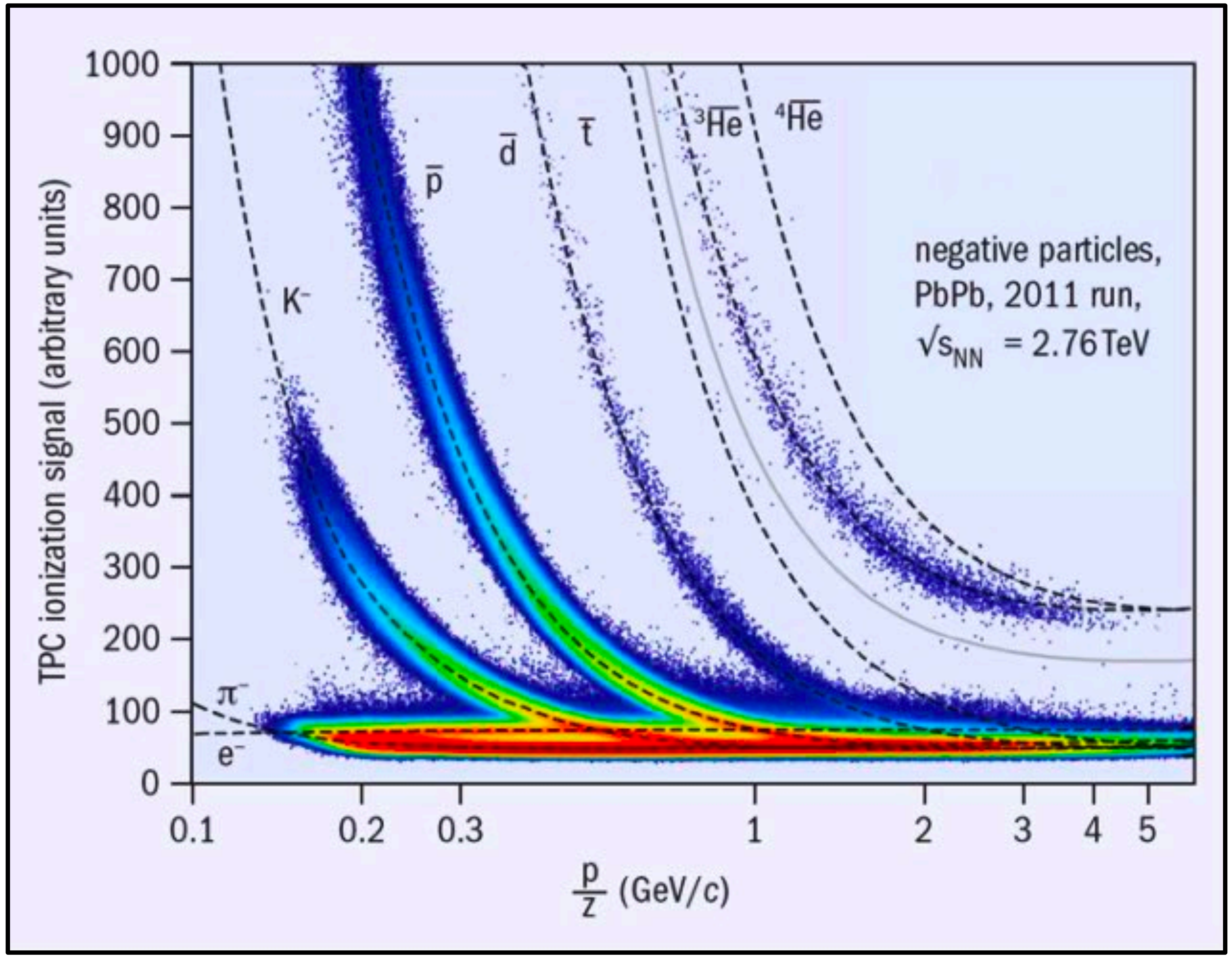
Impact parameter, centrality and Glauber model

- **Impact parameter (b):** The distance between the centres of two colliding nuclei projected to the transverse plane defines the impact parameter of the collision.
- **Reaction plane:** The reaction plane in a heavy-ion collision is the plane defined by the impact parameter and the beam axis, along which the nuclei comes to collide.
- **Centrality is a measure of impact parameter:** A central collision is the one with a small impact parameter in which the two nuclei collide almost head-on. Peripheral collision is the one with large impact parameter . In the ultraperipheral collision, two nuclei interact only through the photons created by the large electromagnetic field of the ions of measurement with multiplicity.
- **Glauber Monte Carlo model:** The set of techniques used to estimate the number of participating nucleons, number of binary collisions etc from experimental data (named after Roy Glauber). The steps usually involves preparing a model of the two nuclei by defining stochastically the position of the nucleons in each nucleus & simulating a collision. To reproduce the experimental multiplicity distribution, the Glauber Monte Carlo is coupled to a model for particle production, based on a negative binomial distribution (NBD)

ALICE Experiment and Particle Identification

Charged hadrons are unambiguously identified if their mass and charge are determined



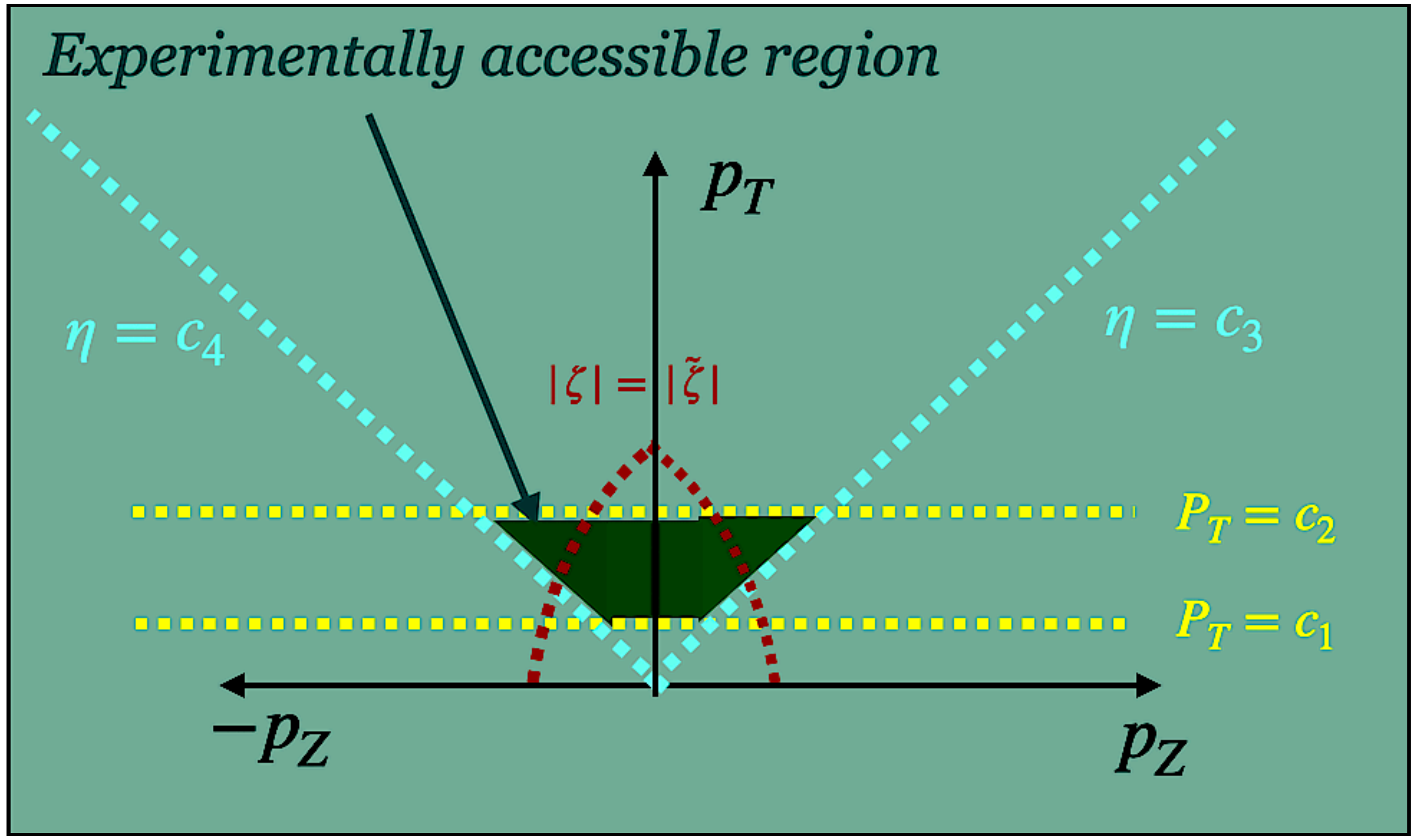


Particle Identification: The characteristics of the ionisation process caused by fast charged particles passing through a medium can be used for PID.

Bethe-Bloch formula: Describes the average energy loss of charged particles through inelastic Coulomb collisions with the atomic electrons of the medium (velocity dependence of the ionisation strength)

Picture Courtesy: ALICE Collaboration, CERN Courier

Some basic variables of particles produced in high energy collisions



y : Rapidity

η : Pseudorapidity

P_T : Transverse Momentum

ζ : Light front variable

ϕ : Azimuthal angle

θ : Polar angle

Analytic expressions

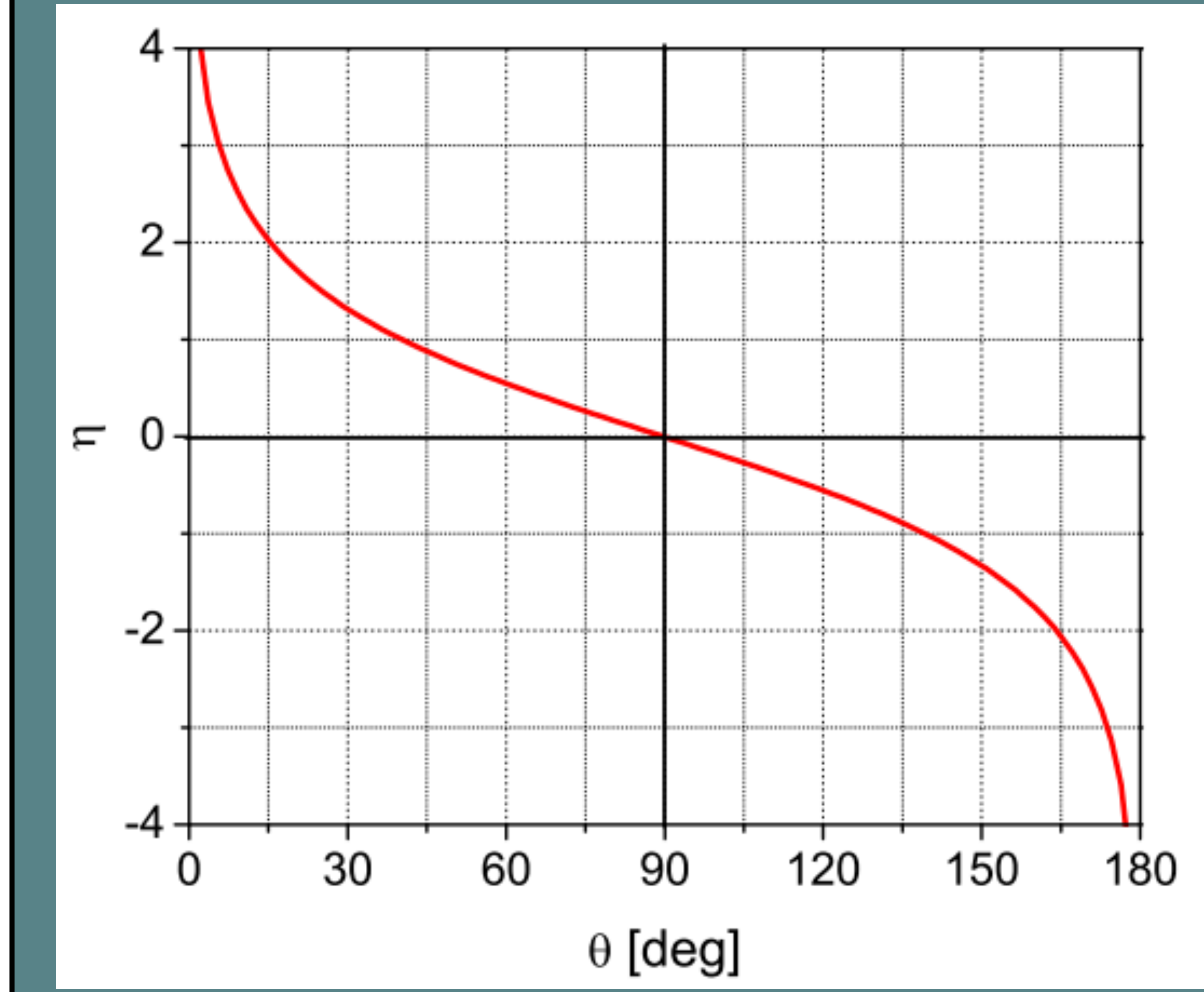
1. $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$

2. $\eta = -\ln \left[tan \left(\frac{\theta}{2} \right) \right]$

3. $\xi^{\pm} = \pm \frac{E + |p_Z|}{\sqrt{s}}$

4. $\zeta^{\pm} = \mp ln(\xi^{\pm})$

$P \equiv (\eta, p_T, \phi)$



η vs θ

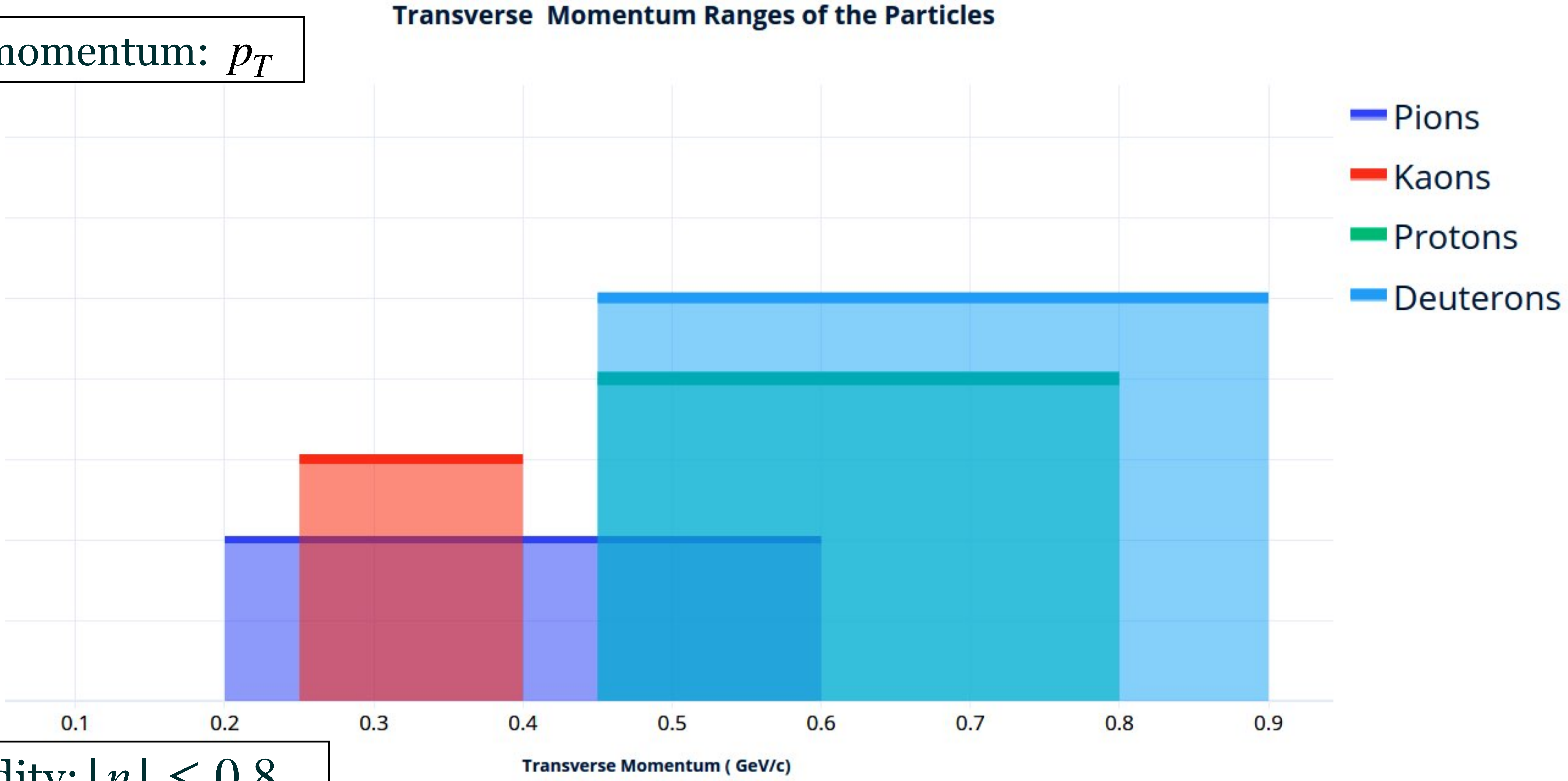
Kinematic and acceptance restrictions of a detector

$c_4 \leq \eta \leq c_3$ & $c_1 \leq p_T \leq c_2$

The cut values varies for various species and detectors

Kinematic & acceptance restrictions

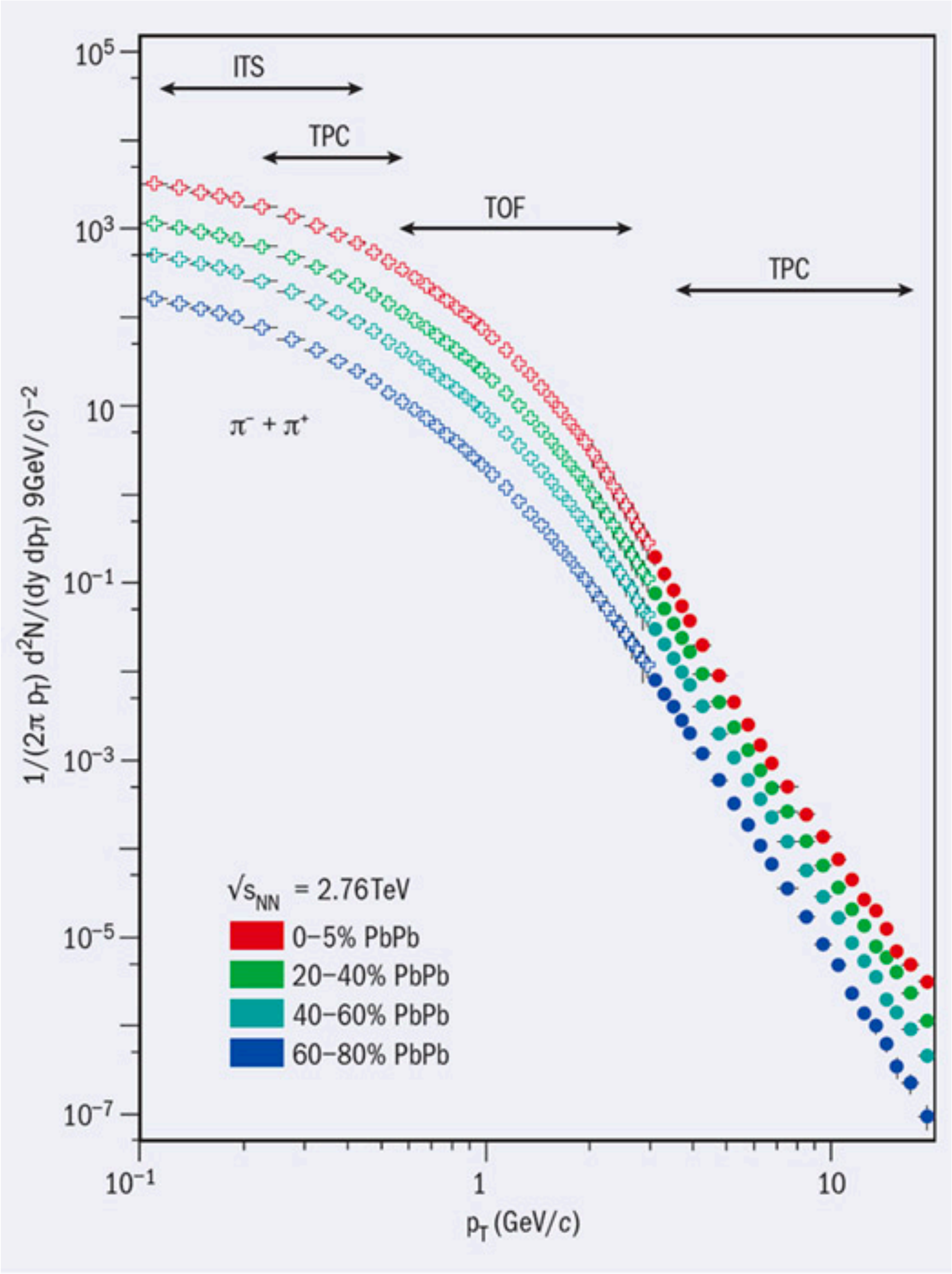
1. Transverse momentum: p_T



2. Pseudorapidity: $|\eta| \leq 0.8$

- The cut on pseudo rapidity and the transverse momentum will constrain the experimentally accessible region in the phase space.

ALICE Detectors used for identification of charged particles in various ranges of transverse momentum



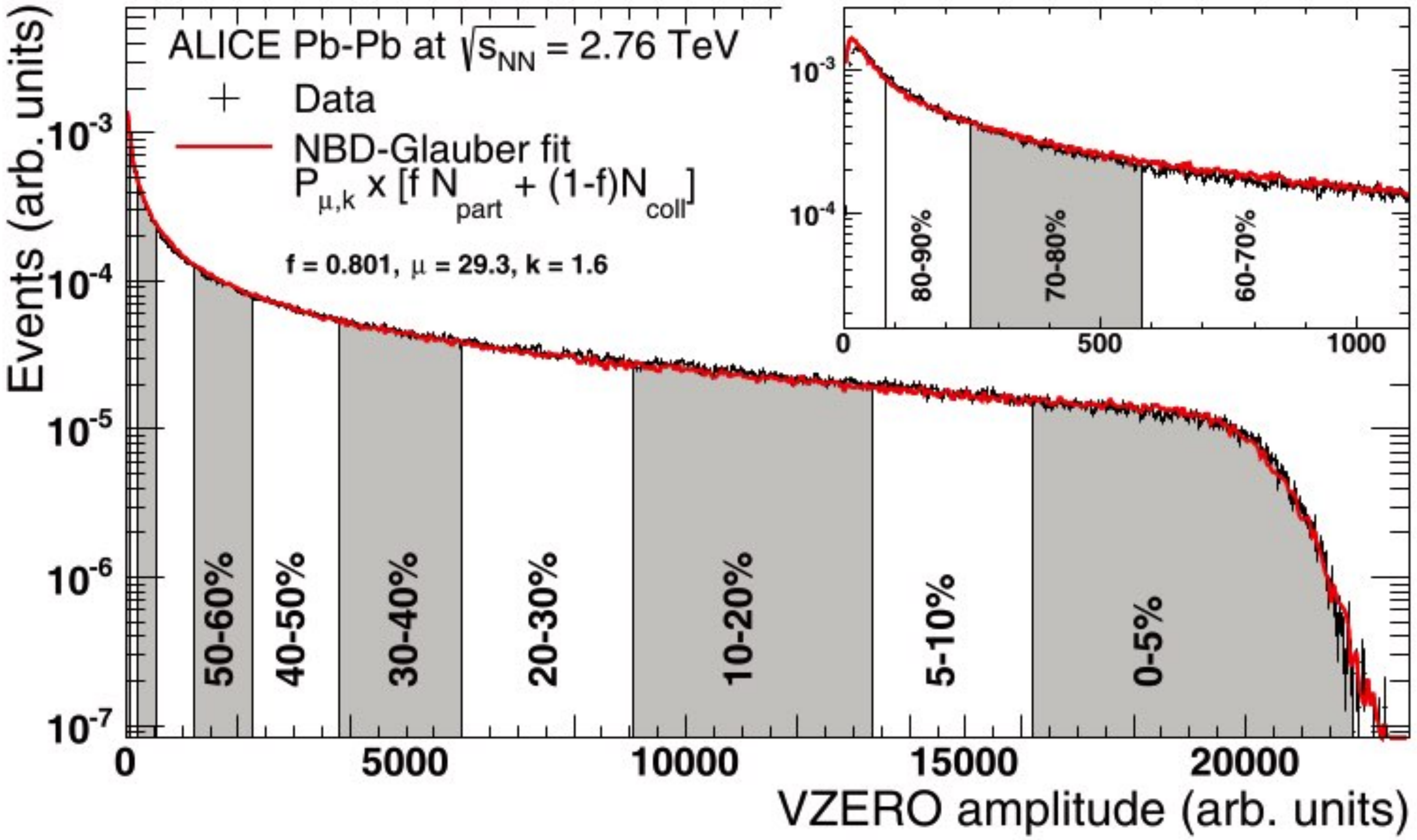
Picture Courtesy: ALICE Collaboration, CERN Courier

Estimation of centrality using the information about multiplicity

- We use "centrality percentile" to quantify the geometry of the collisions.
- The Glauber Monte Carlo defines, for an event with a given impact parameter b, the corresponding N_{part} and N_{coll}

  N_{part} = Number of participating nucleons
  N_{coll} = Number of binary nucleon collisions

- The particle multiplicity per nucleon-nucleon collision is parametrised by a Negative Binomial Distribution(NBD).
- The centrality classes are defined by sharp cuts in the impact parameter b calculated with the Glauber model
- The VZERO detector consists of scintillator arrays. The amplitude measured by V0 is monotonic with the multiplicity of the particles hitting the detector.
- Fitting the V0 amplitude with G-NBD will tell us the centrality region the collision belongs to.



The distribution of V0 amplitudes for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with a vertex within 10 cm, fitted by a G-NBD. The centrality is defined as the percentile of the hadronic cross section corresponding to a particle multiplicity, or an energy deposited, measured in ALICE, above a given threshold.

Negative Binomial Distribution (NBD)

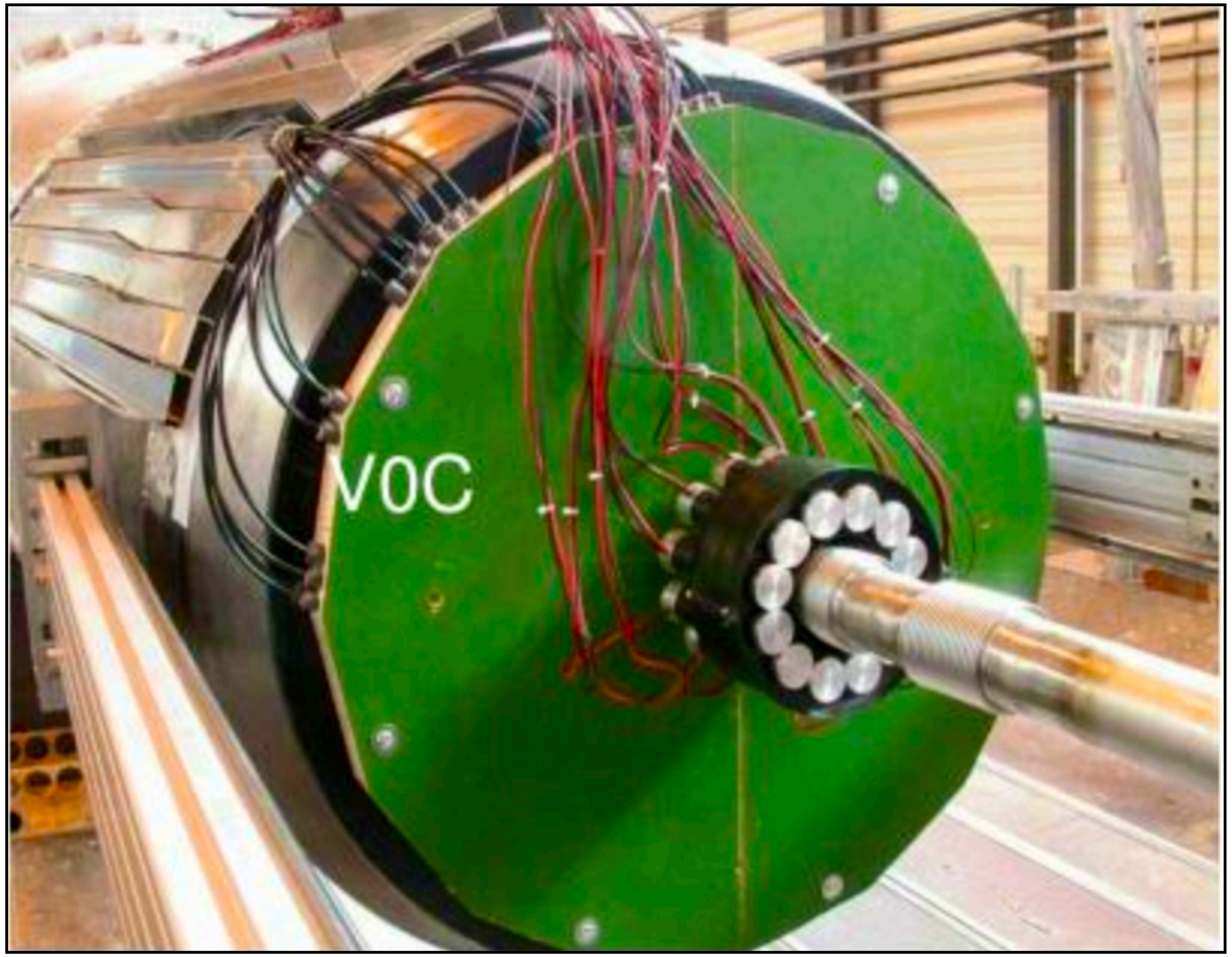
$$p_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \cdot \frac{(\mu/k)^n}{(\mu/k+1)^{n+k}}$$

Phys. Rev. C **88**, 044909 (2013); Eur. Phys. J. C 68 (2010) 89–108.
https://cds.cern.ch/record/2636623/files/centrality%20determination%20note.pdf

Centrality classes versus geometrical properties estimated in ALICE

Table 1: Geometric properties (N_{part}, N_{coll}, T_{AA}) of Pb–Pb collisions for centrality classes defined by sharp cuts in the impact parameter b (in fm). The mean values, the RMS, and the systematic uncertainties are obtained with a Glauber Monte Carlo calculation.

Centrality	b_{min} (fm)	b_{max} (fm)	$\langle N_{part} \rangle$	RMS	(*sys.*)	$\langle N_{coll} \rangle$	RMS	(*sys.*)	$\langle T_{AA} \rangle$ 1/mbarn	RMS 1/mbarn	(*sys.*) 1/mbarn
0–1%	0.00	1.57	403.8	4.9	1.8	1861	82	210	29.08	1.3	0.95
1–2%	1.57	2.22	393.6	6.5	2.6	1766	79	200	27.6	1.2	0.87
2–3%	2.22	2.71	382.9	7.7	3.0	1678	75	190	26.22	1.2	0.83
3–4%	2.71	3.13	372.0	8.6	3.5	1597	72	180	24.95	1.1	0.81
4–5%	3.13	3.50	361.1	9.3	3.8	1520	70	170	23.75	1.1	0.81
5–10%	3.50	4.94	329.4	18	4.3	1316	110	140	20.56	1.7	0.67
10–15%	4.94	6.05	281.2	17	4.1	1032	91	110	16.13	1.4	0.52
15–20%	6.05	6.98	239.0	16	3.5	809.8	79	82	12.65	1.2	0.39
20–25%	6.98	7.81	202.1	16	3.3	629.6	69	62	9.837	1.1	0.30
25–30%	7.81	8.55	169.5	15	3.3	483.7	61	47	7.558	0.96	0.25
30–35%	8.55	9.23	141.0	14	3.1	366.7	54	35	5.73	0.85	0.20
35–40%	9.23	9.88	116.0	14	2.8	273.4	48	26	4.272	0.74	0.17
40–45%	9.88	10.47	94.11	13	2.6	199.4	41	19	3.115	0.64	0.14
45–50%	10.47	11.04	75.3	13	2.3	143.1	34	13	2.235	0.54	0.11
50–55%	11.04	11.58	59.24	12	1.8	100.1	28	8.6	1.564	0.45	0.082
55–60%	11.58	12.09	45.58	11	1.4	68.46	23	5.3	1.07	0.36	0.060
60–65%	12.09	12.58	34.33	10	1.1	45.79	18	3.5	0.7154	0.28	0.042
65–70%	12.58	13.05	25.21	9.0	0.87	29.92	14	2.2	0.4674	0.22	0.031
70–75%	13.05	13.52	17.96	7.8	0.66	19.08	11	1.3	0.2981	0.17	0.020
75–80%	13.52	13.97	12.58	6.5	0.45	12.07	7.8	0.77	0.1885	0.12	0.013
80–85%	13.97	14.43	8.812	5.2	0.26	7.682	5.7	0.41	0.12	0.089	0.0088
85–90%	14.43	14.96	6.158	3.9	0.19	4.904	4.0	0.24	0.07662	0.062	0.0064
90–95%	14.96	15.67	4.376	2.8	0.10	3.181	2.7	0.13	0.0497	0.042	0.0042
95–100%	15.67	20.00	3.064	1.8	0.059	1.994	1.7	0.065	0.03115	0.026	0.0027
0–5%	0.00	3.50	382.7	17	3.0	1685	140	190	26.32	2.2	0.85
5–10%	3.50	4.94	329.4	18	4.3	1316	110	140	20.56	1.7	0.67
10–20%	4.94	6.98	260.1	27	3.8	921.2	140	96	14.39	2.2	0.45
20–40%	6.98	9.88	157.2	35	3.1	438.4	150	42	6.850	2.3	0.23
40–60%	9.88	12.09	68.56	22	2.0	127.7	59	11	1.996	0.92	0.097
60–80%	12.09	13.97	22.52	12	0.77	26.71	18	2.0	0.4174	0.29	0.026
80–100%	13.97	20.00	5.604	4.2	0.14	4.441	4.4	0.21	0.06939	0.068	0.0055



V0 detector used for the centrality estimation
Picture courtesy : Tapan Nayak, NISER.

Phys. Rev. C **88**, 044909 (2013)

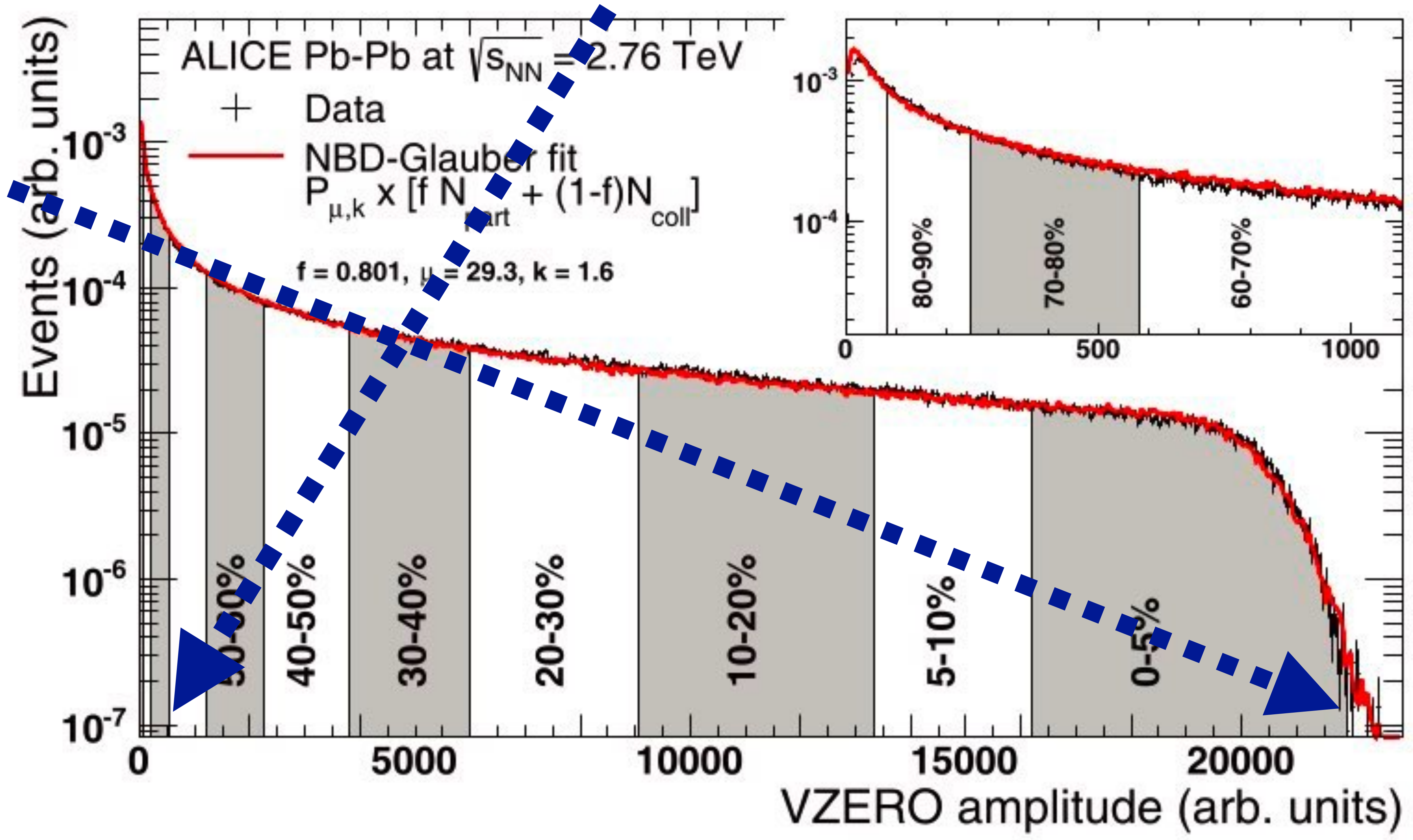
For a conceptual understanding

Centrality of the collision: A quantitative picture for Pb-Pb Collisions at $\sqrt{s}$ = 2.76 TeV

Centrality	b_{min} (fm)	b_{max} (fm)
0–5%	0.00	3.50
5–10%	3.50	4.94
10–20%	4.94	6.98
20–40%	6.98	9.88
40–60%	9.88	12.09
60–80%	12.09	13.97
80–100%	13.97	20.00

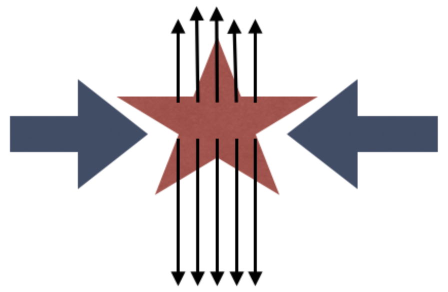
Phys. Rev. C **88**, 044909 (2013)

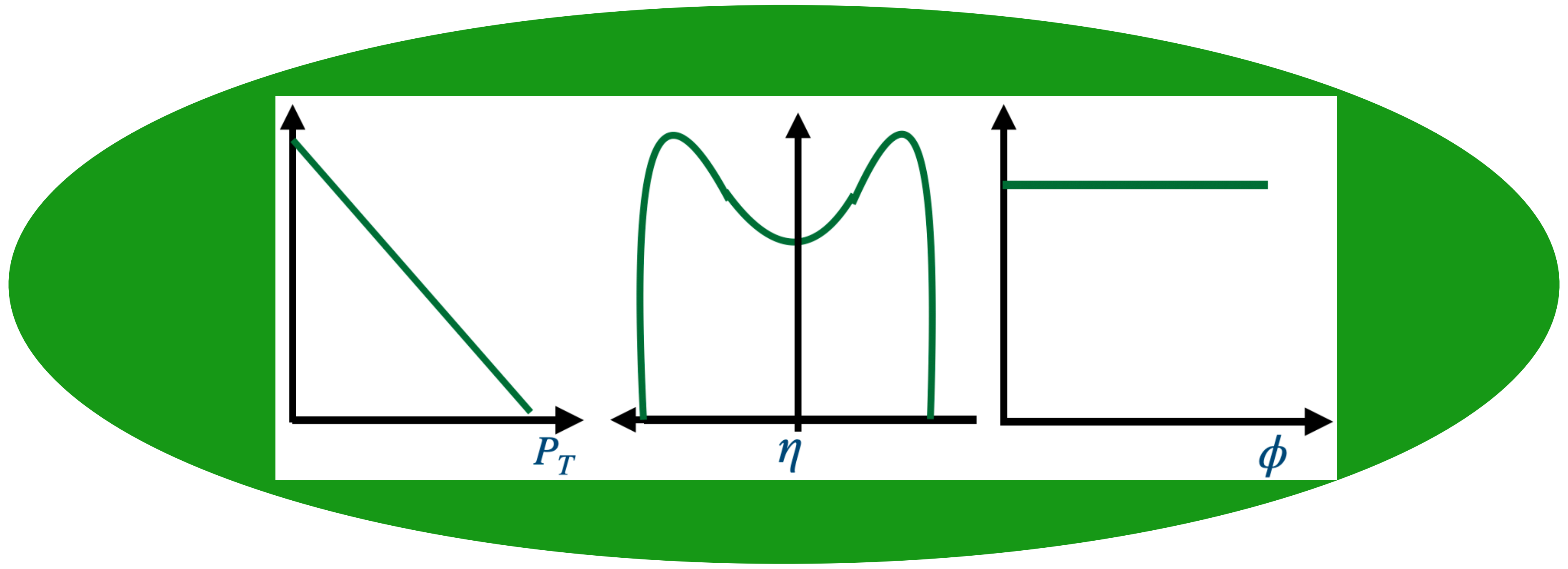
Glauber MC Calculations



A naive picture of experimental corrections

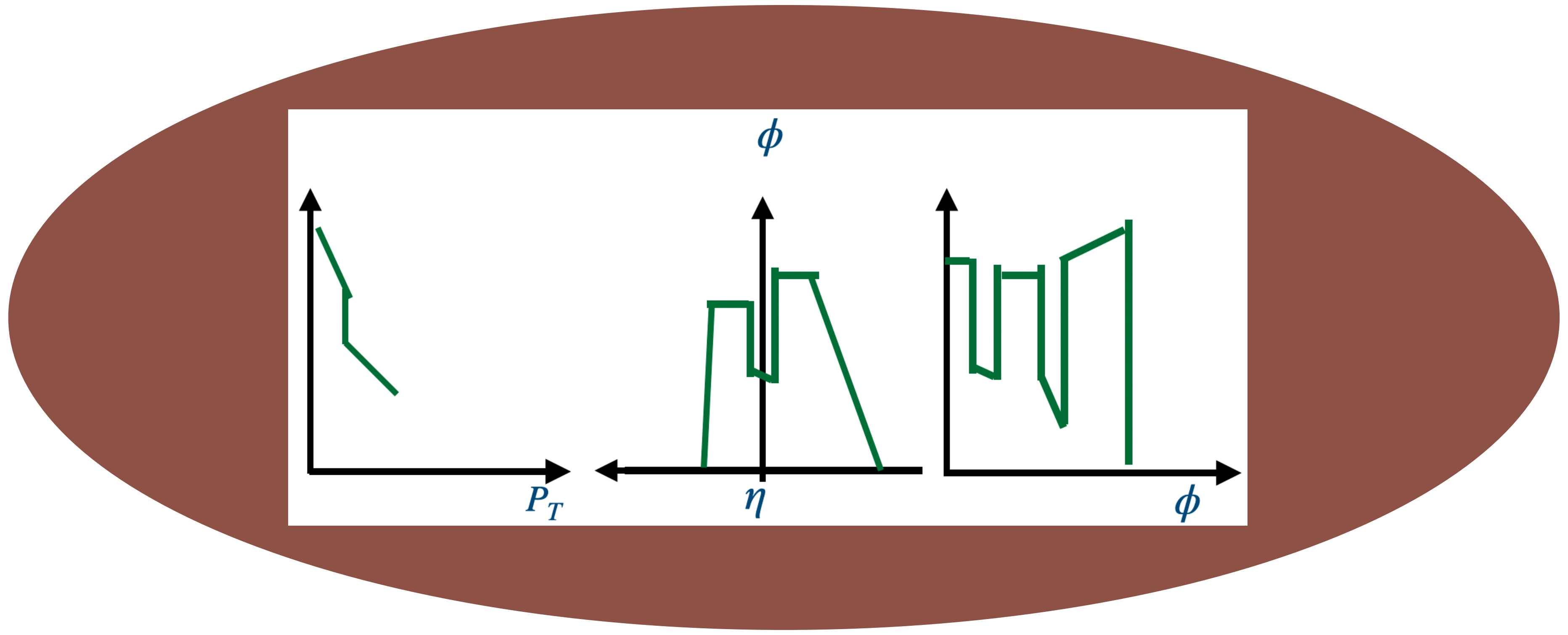
Collision





Actual

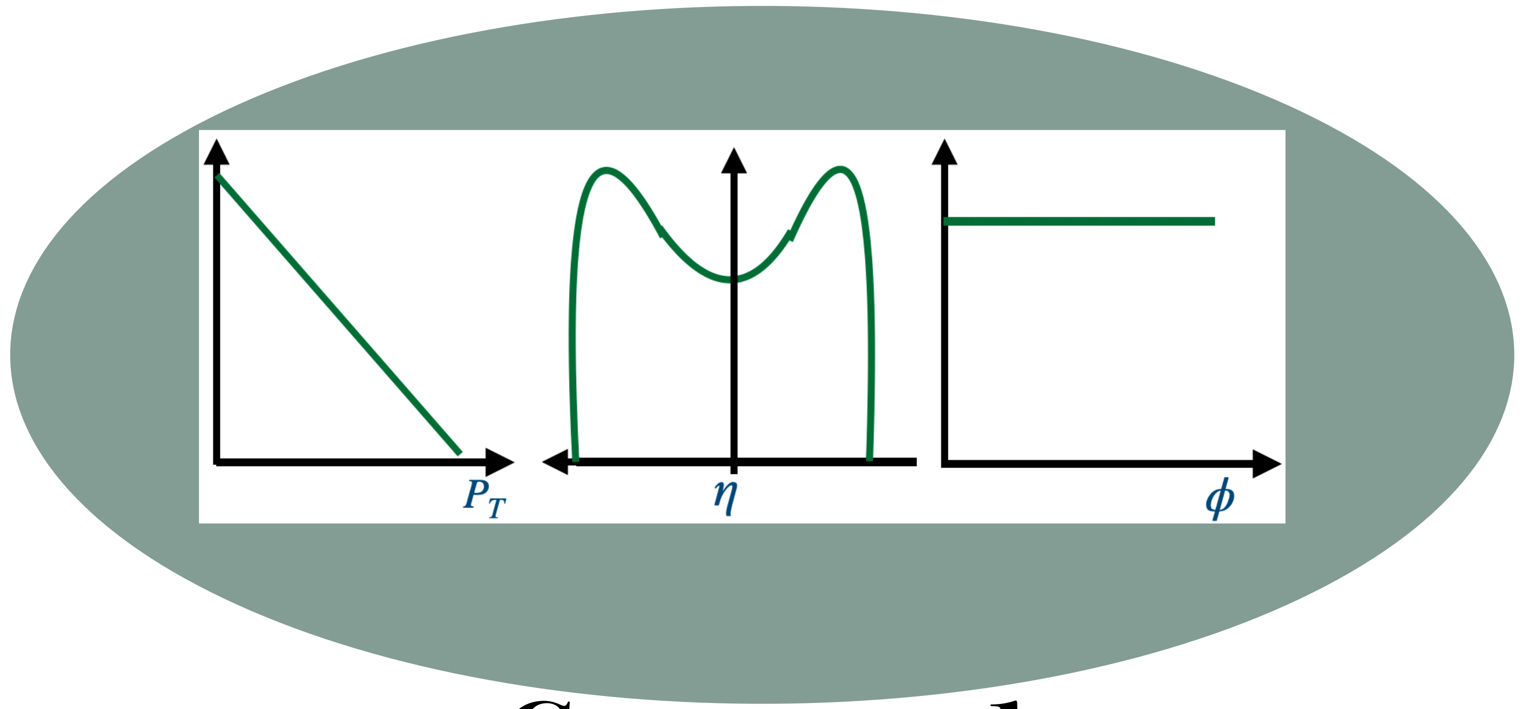
Detector



Raw measure

Monte Carlo collision Simulator

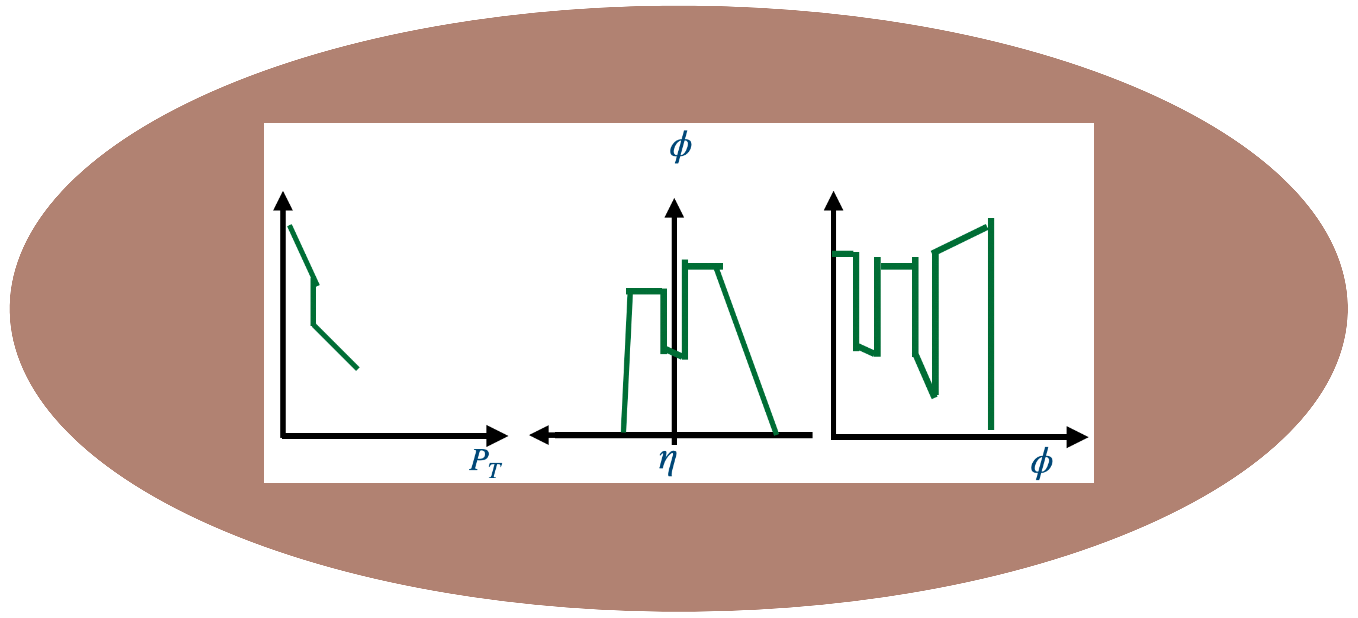
PYTHIA, HIJING



Generated

Detector Simulation

GEANT



Reconstructed

$$Efficiency = \frac{Reconstructed}{Generated}$$

$$Final = \frac{Raw}{Efficiency} \approx Actual\ (within\ acceptance)$$

Error Estimation

Uncertainty in measurements

Statistical errors

1. Arise from stochastic fluctuations
2. Uncorrelated with previous measurements
3. Follow well-developed theory
4. Can be reliably estimated by repeating measurements
5. They follow a known distribution (empirically found from the distribution of a sufficiently large unbiased sample).

   Eg: Radioactive decays (Poisson distribution)

   Eg: Efficiency of a detector (Binomial distribution)
6. Relative uncertainty reduces as $\frac{1}{\sqrt{N}}$
7. A statistical error is usually given by the standard deviation

   $\sigma = \sqrt{variance}; variance = < (x-\mu)^2 >$

$$V[x] = \int_{-\infty}^{+\infty} (x-\mu)^2 f(x)dx = \sigma^2$$

Uncertainty in measurements

Systematic errors

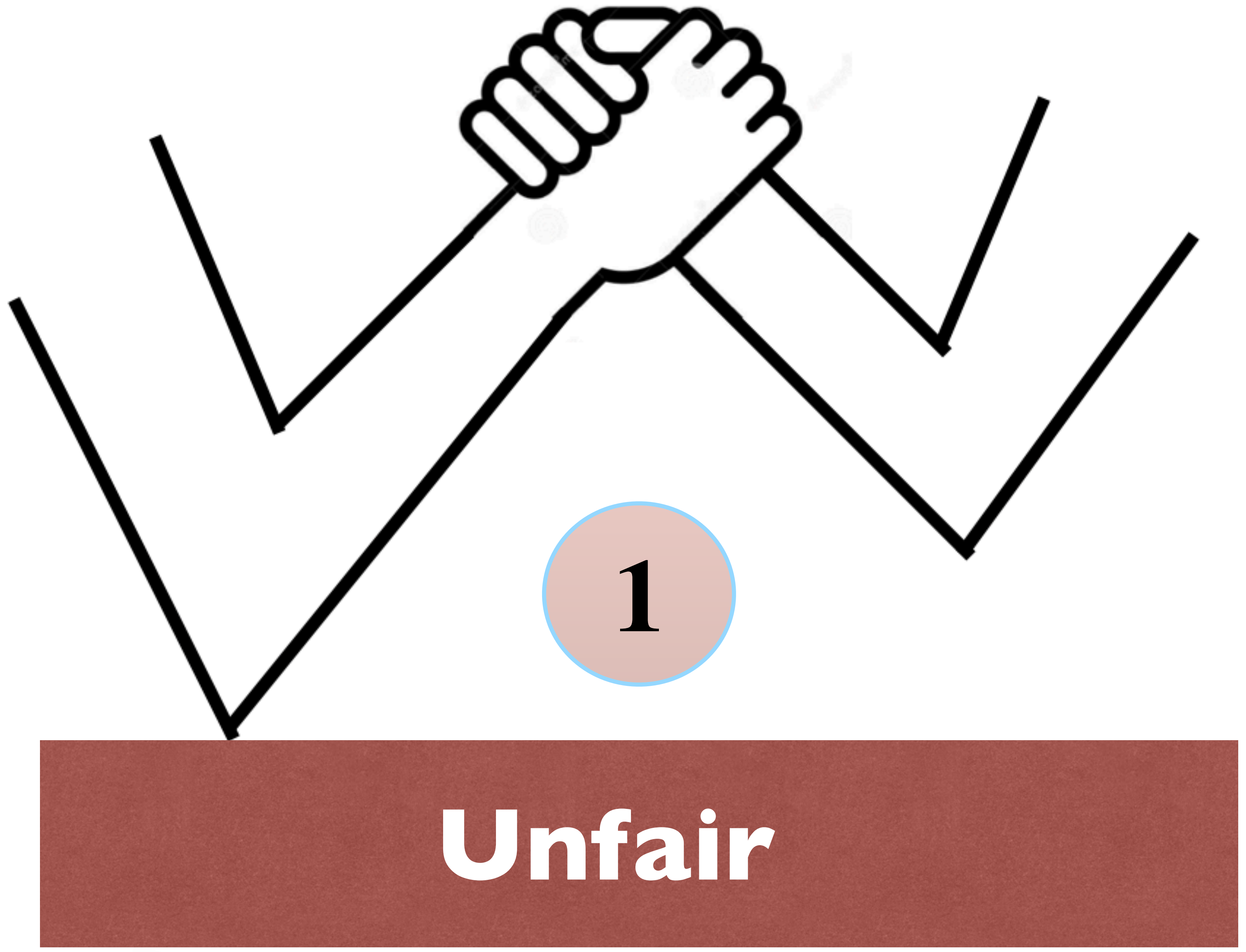
1. Experimental biases, acceptance and kinematical restrictions imposed on the analysis (and even unknown biases) etc can affect the final result.
2. Systematic errors reflects the quantity of uncertainty coming from such sources.
3. Cannot be calculated solely from sampling fluctuations
4. In most cases don't reduce as $\frac{1}{\sqrt{N}}$

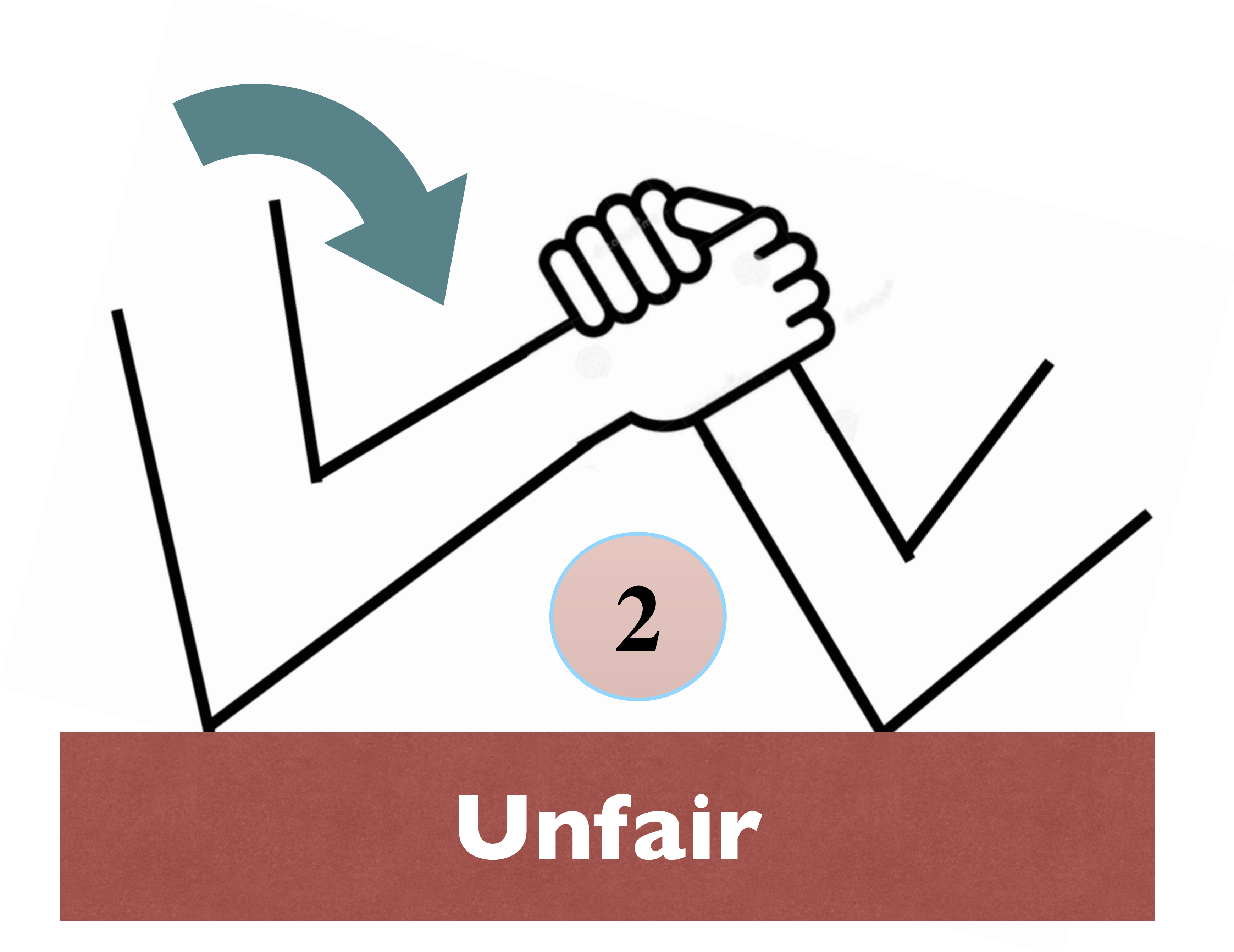
<u>**Estimation**</u>

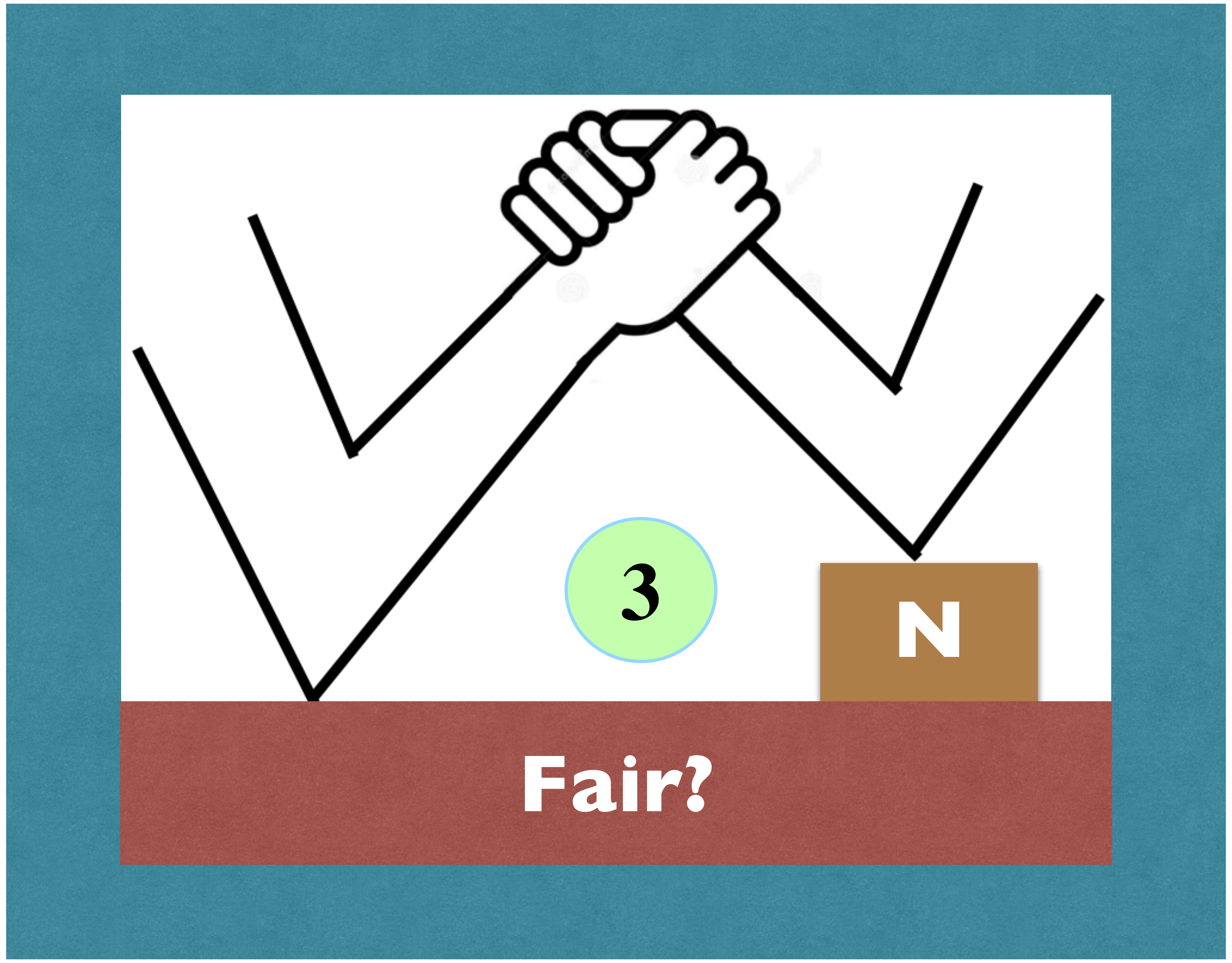
1. **Top-Down approach :** Think about all possible sources of potential systematics : **Game of an expert**
2. Bottom-Up Approach: Normally people do this.

Systematics estimation - A bottom-Up method

A conceptual picture







$$W(N) = (h_1 - h_2)$$?

$$W(N) = \left(\frac{h_1}{L_1} - \frac{h_2}{L_2}\right) L_1$$

$$W(N) = \left(\frac{h_1}{L_1} - \frac{h_2}{L_2}\right) L_2$$

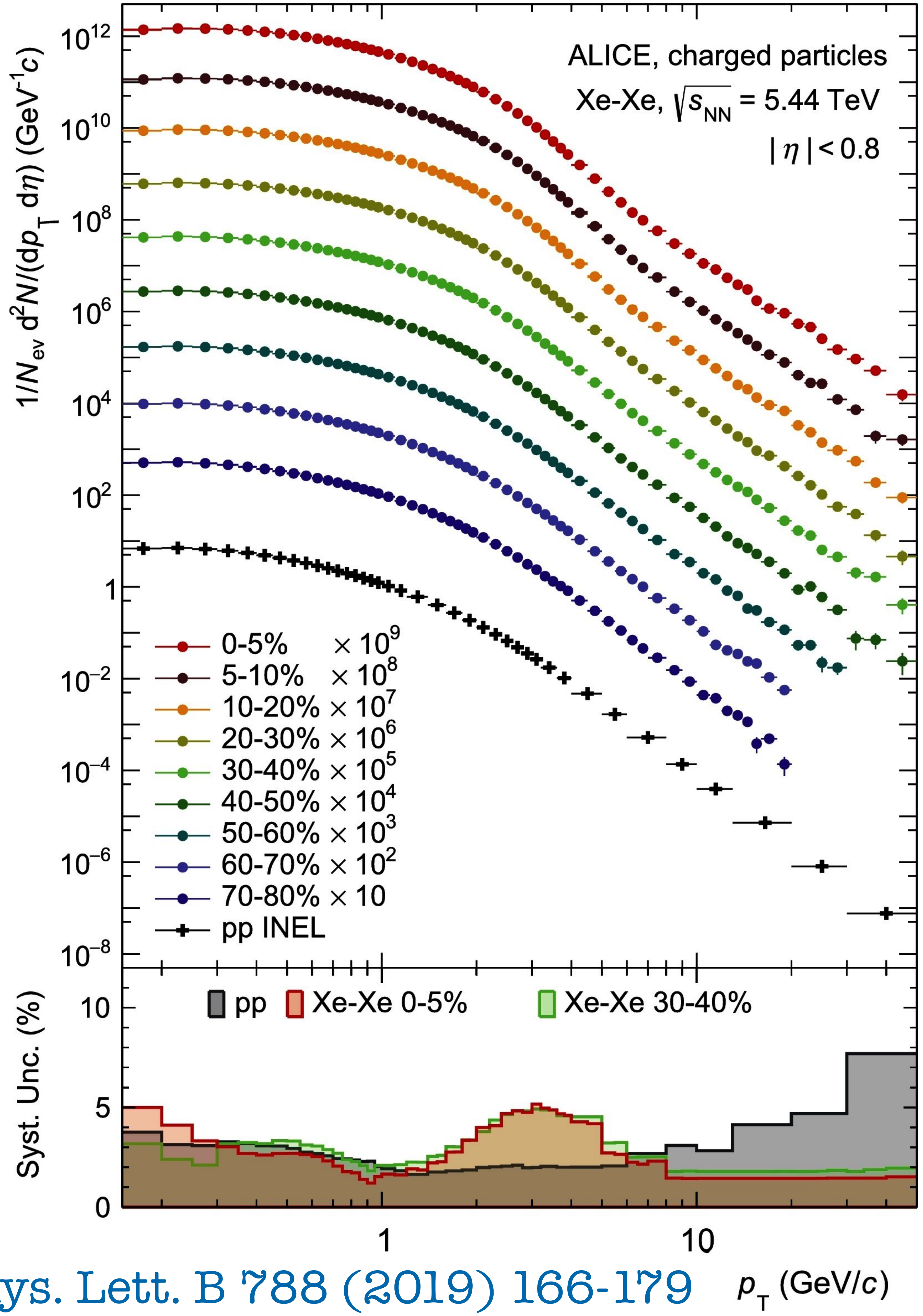
$$W(N) = \frac{(h_1 - h_2)}{\left(\frac{h_1}{L_1} - \frac{h_2}{L_2}\right)}$$

$$W(N) = \left(\frac{h_1}{L_1} - \frac{h_2}{L_2}\right)(h_1 - h_2)$$

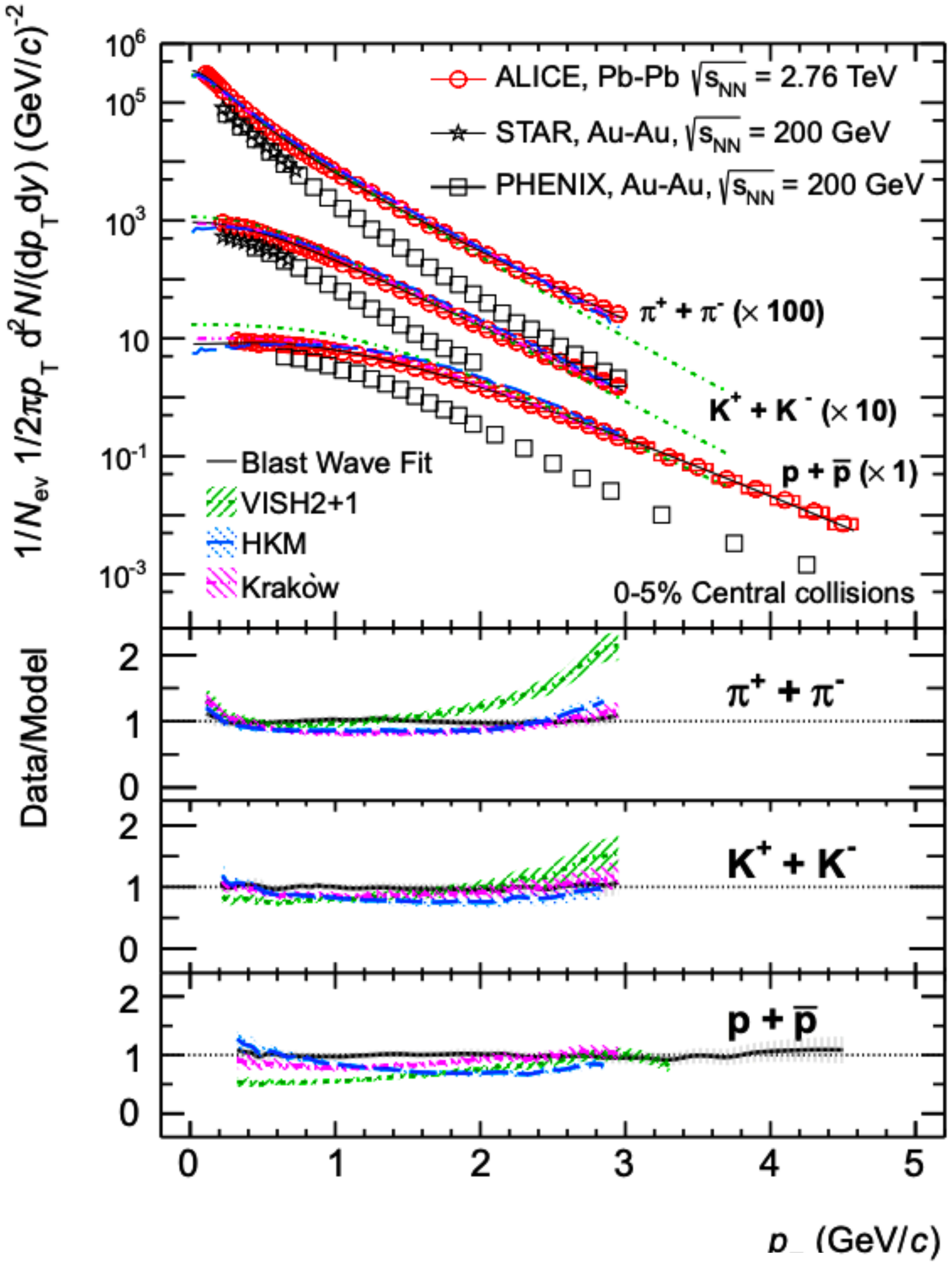
Normalisation is a contextually determined sensible function of the characteristic properties of the parties involved in a process.


A typical physics analysis
Collision
Detector
PID ; Momentum
Raw observable distribution
Monte Carlo &
Detector simulation
Efficiecy etc
Correction &
Error analysis
Detector
Centrality
Theoretical Hypothesis
Parameter estimation
Physics insights
Fitting

A typical physics analysis



Phys. Lett. B 788 (2019) 166-179



Phys. Rev. Lett. **109**, 252301

Formation criterion for QGP in a laboratory

- In order to create a drop of QGP in the laboratory energy density of about 1.0 GeV/fm^3 has to be reached.

- **<u>A bad but useful hypothesis:</u>** All the available energy in the centre- of-mass is dissipated, during the collision, into the internal degrees of freedom of the nucleus- nucleus system.

- The energy density of the drop will approximately be given by $\epsilon \approx \sqrt{2E_b \times m} \times A/V$

- Assume $V \approx 4/3\pi \times (1.124)^3 \times A\ fm^3$: For E_b below $\sim 20\ GeV/nucleon$ (It corresponds to $\sqrt{s_{NN}} = 6\ GeV$), the available energy in CMS frame is insufficient to heat a nucleus to energy densities above 1 GeV/fm. Hence there is a less chance of a QGP production.

Formation criterion for QGP in a laboratory

- If we take into account a possible dilution of the hypothesis in a real world scenario, E_b noticeably larger than 20 GeV per nucleon would be needed to reach the critical density of the QGP phase transition.
- American physicist J.D Bjorken imagined a scenario where the QGP would be efficiently formed. He described what would be the initial energy density and it's evolution with time.
- The QGP would be formed at baryonic potentials close to zero under this scenario

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

At ultra-relativistic energies, nuclei are seen as pancakes in the C.M.S due to the Lorentz contraction

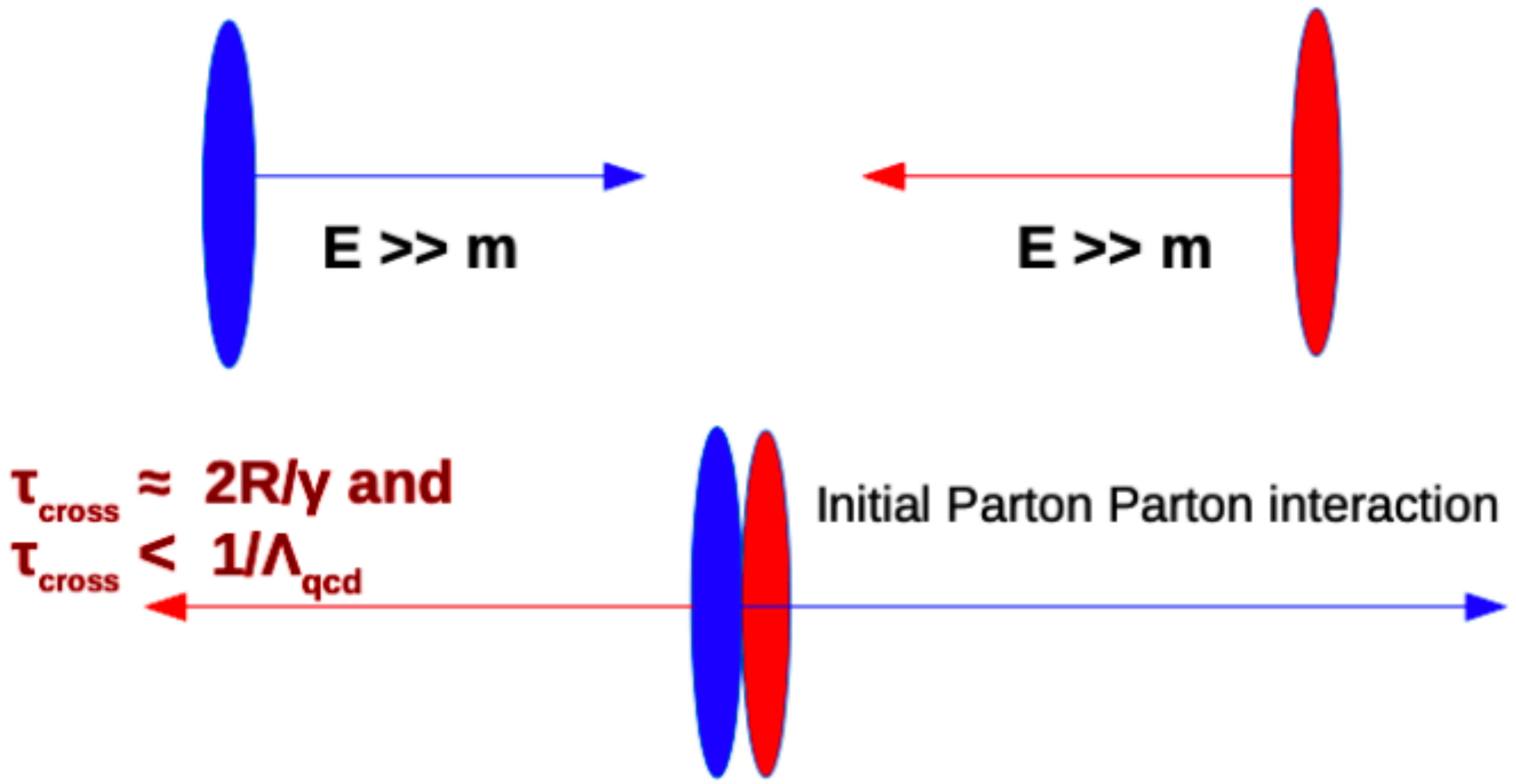
The nucleus crossing time: $\tau_{cross} = \frac{2R}{\gamma}$, **where R = Radius of the nuclei and γ = Lorentz factor.**

G.Martinez, Advances in Quark Gluon Plasma, Proceedings of the 2011 Joliot Curie School: arXiv:1304.1452

Bjorken scenario for the formation of hot QCD matter

Assumptions by Bjorken & it's implications

1. **The crossing time τ_{cross} is smaller than the time scale of the strong interaction τ_{strong}.**
   - The particles generated by the strong interaction are created once the nuclei have already crossed each other. This is possible for AA collisions only if $\gamma < 12$ which means $\sqrt{s_{NN}} > 25$ GeV.
2. **The distribution of the particle multiplicity as a function of the rapidity is assumed to be uniform.**
   - It causes to create a uniform energy density in different rapidity slices simplifying the description of the hydrodynamical evolution of the system. It ensures the rapidity symmetry of the system.



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

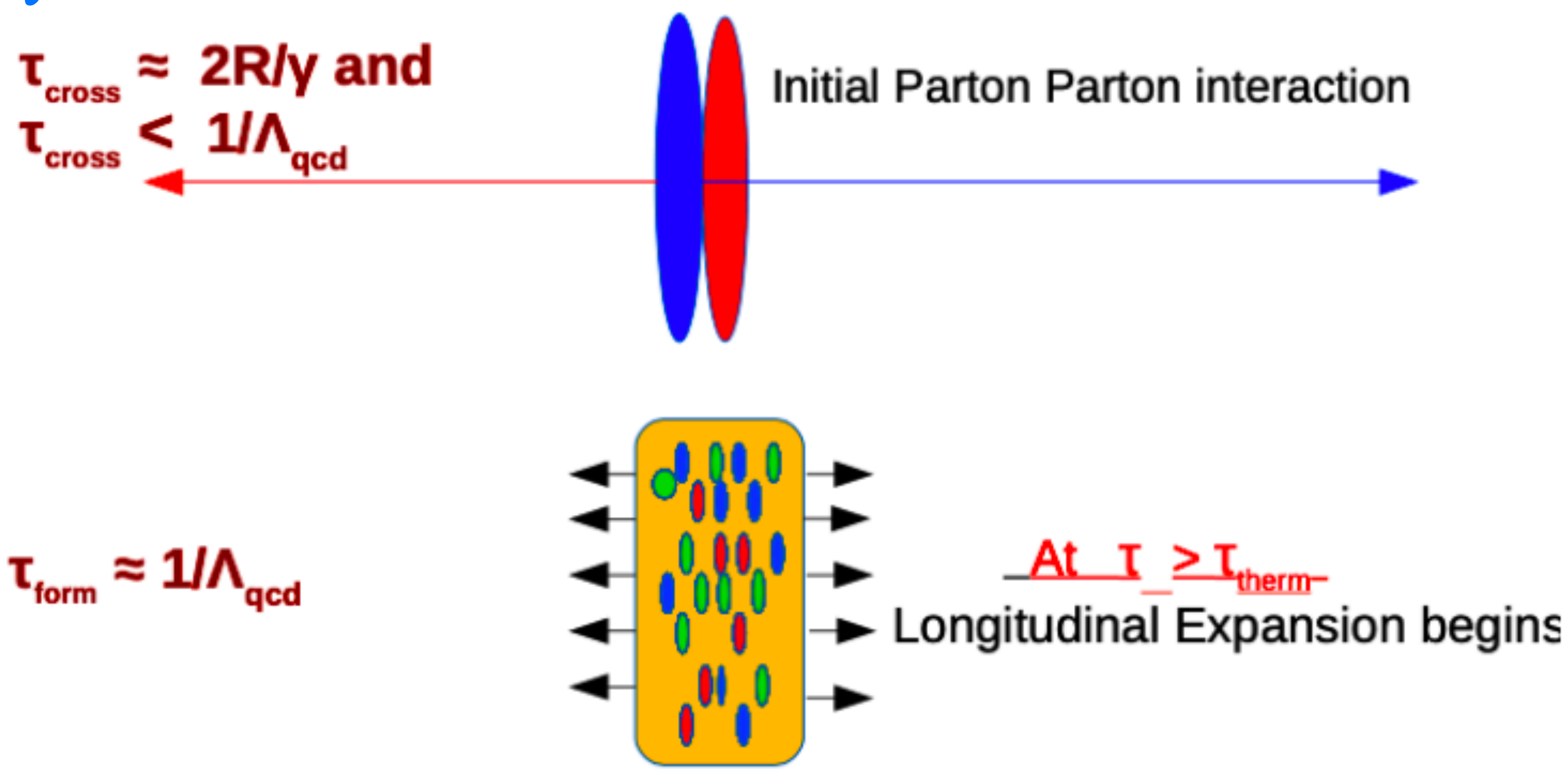
Bjorken scenario for the formation of hot QCD matter

Consider the volume centred in the nucleus crossing plane at a time τ after the nucleus crossing.

- It has a cylindrical shape with a thickness $2\Delta d$ along the beam axis direction and a radius $R \sim 1.124A^{1/3}$ in the transverse plane. It contains all the particles produced with a speed along the beam axis below $\beta_z \leq \Delta d/\tau$ spread around a rapidity range of $\Delta y = \dfrac{2\Delta d}{\tau}$ Assuming $y \to 0 : \beta_z \sim y$

- The total energy in the volume will be : $E = \left|\dfrac{dE}{dy}\right|_{y=0} \times \dfrac{2\Delta d}{\tau}$ with an energy density of

$$\epsilon(y) = \left|\frac{dE_T}{dy}\right| \times \frac{1}{\pi R^2 \tau}$$



- **Bjorken's estimation** of initial energy density at $\sqrt{s} \sim 500$ GeV per nucleon: ~ 2-20 $\frac{GeV}{fm^3}$
- **At Tevatron energies** $\sqrt{s} \sim 1.28$ **TeV:** Initial energy density would be 4-30 $\frac{GeV}{fm^3}$

Thermalisation

- The particles produced inside the volume considered will interact.
- Assuming a mean energy $\langle E \rangle = 500$ MeV, $\epsilon / \langle E \rangle \sim$ 8 - 60 $\frac{particles}{fm^3}$ will be reached.
- **With an estimated average path length** $\lambda \sim 0.02 - 0.12$ **fm and an interaction cross-section of 10 mb:** One hopes that the system will thermalise at a time $\tau = \tau_{ther}$
- Experimental results seem to agree with the assumption of **a fast thermalisation** of the system.

Mechanism responsible for this fast thermalisation is not conclusively understood

Longitudinal expansion

- At stages $\tau \geq \tau_{ther}$ the system evolve following the laws of the relativistic hydrodynamics.

- First a longitudinal expansion will take place since the pressure gradient in the beam direction will be larger than that in the transverse plane.

- Energy density is expected to evolve as $\epsilon \sim 1/\tau^n$ with $1 \leq n \leq 4/3$, which is obtained from the hydrodynamic law

$$\frac{d\epsilon}{d\tau} = -\frac{\epsilon + p}{\tau}$$

For an ideal ultra-relativistic gas: $\epsilon = 3p$ and thus $n = 4/3$.

- The longitudinal expansion stays as a good approximation for stages $\tau \leq \tau_{long} \sim R$.

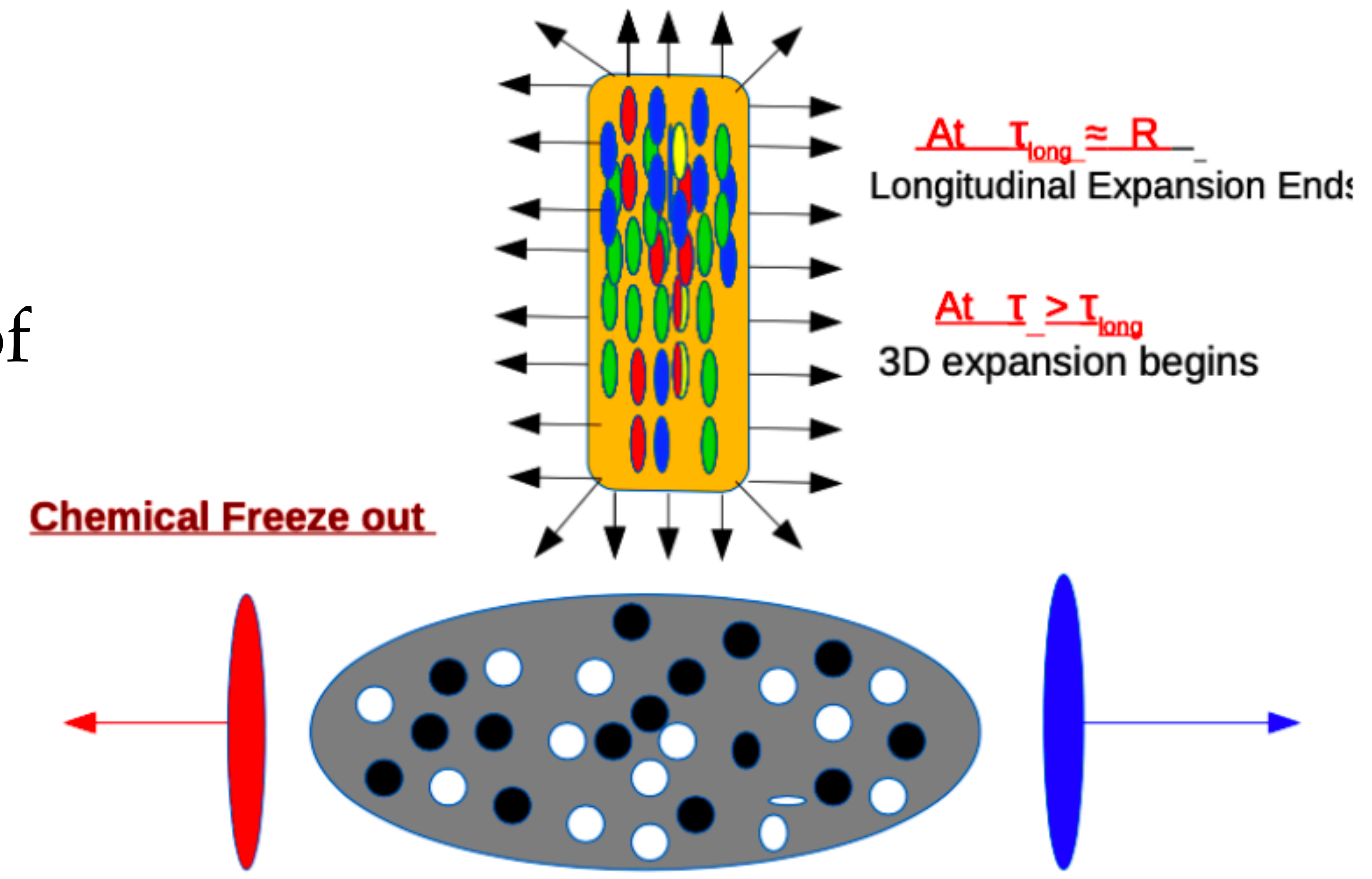
Three dimensional expansion and freeze out

- **For $\tau \geq \tau_{long}$** : The system will evolve via a 3 dimensional expansion until the freeze-out stage is reached.

- **At freeze-out:** Particle density is low enough to assume that particles do not interact. They travel in the vacuum, decay and finally reach the detector.

- The freeze-out will take place when the average path length of particles is similar to the size of the system $\lambda \sim R$.

- **For a cross-section of 10 mb: Freezeout @** $0.15\ particles/fm^3$ with $\epsilon_f \sim 0.15\ \text{fm}^{-3} \times 0.5\ \text{GeV} \sim 0.075\ \text{GeV/fm}^3$. Freeze-out is expected to takes place as a hadron gas phase.



- For a freeze-out temperature of $T_f = 150$ MeV, one gets $\epsilon/T^4 \sim 1.2$ which goes well with the prediction of lattice QCD calculations

F. Karsch. Lecture Notes of Physics, vol. 583, 2002.

Formation to detection within the Bjorken picture

After a formation time τ_{form} a volume with a high energy density is created.

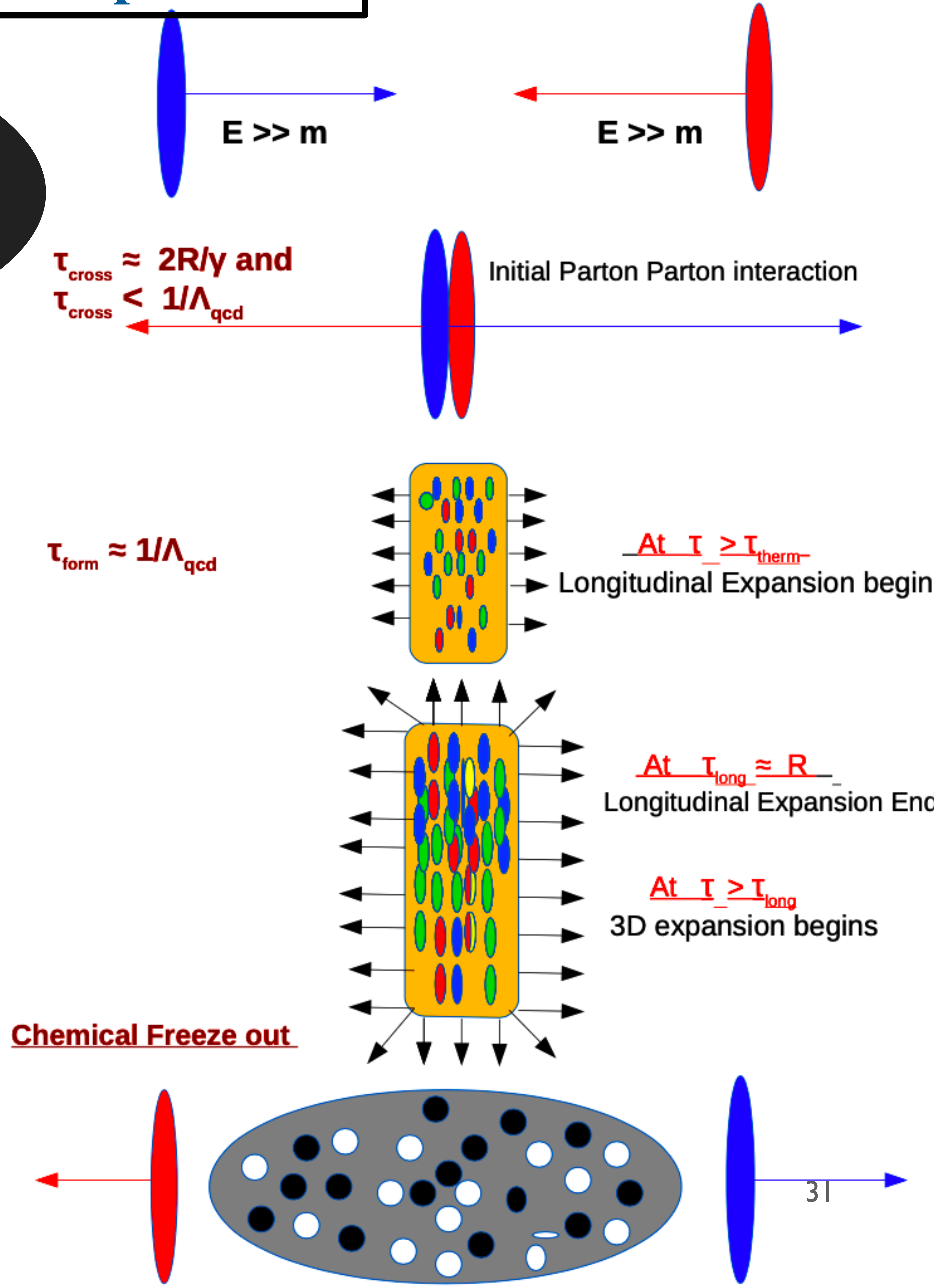
After equilibration at τ_{therm} the evolution of the hot QCD matter follows the laws of the relativistic hydrodynamics.

First, there is a longitudinal expansion until the system reaches a longitudinal size close to its transverse size

3D expansion : Until the density is so low that no more inelastic (elastic) collision takes place called chemical freeze-out phase.

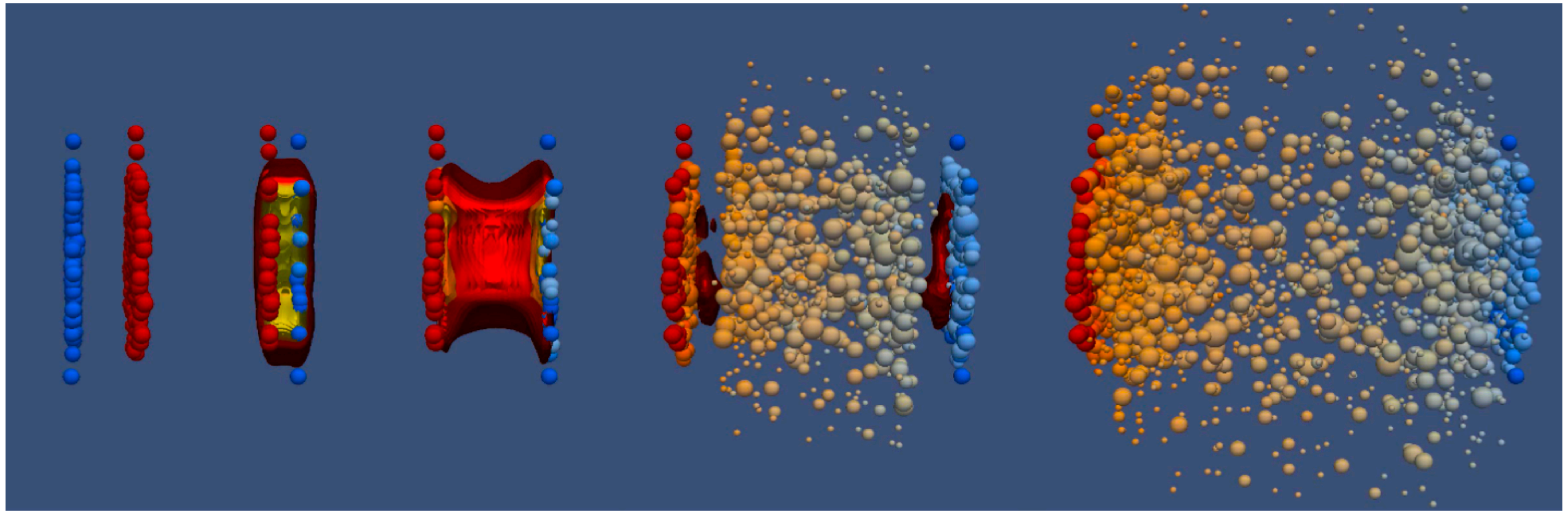
All the particles will fly decaying to their daughter particles or reaching the detector.

Please make sure that you will read this paper if you haven't already:
J. D. Bjorken, Phys. Rev. D 27, 140 (1983)



Picture From: R. Nair, PhD Thesis (NCBJ)

Stages of a heavy-ion collision



Initial stages

Gluon-dominated
Color Glass Condensate?
Isotropisation/
hydrodynamisation

QGP fluid expansion

Equation of State
Shear, bulk viscosity: η, ζ
Heavy quark transport
⇒ approach to thermalisation
Parton energy loss
Melting of quarkonia

Hadronisation

Chiral symmetry breaking
Statistical hadronisation
Quark (re-)combination

Final state scattering

Resonance decays
Laboratory for hadron physics

Electromagnetic radiation ($\propto T^2$)

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances 'hadrochemistry'

Picture courtesy : Marco Van Leeuwen, Nikhef.

The Alternating Gradient Synchrotron (AGS) at BNL

- The AGS synchrotron was built in 1957.
- It initially allowed the acceleration of high intensity proton beams at 33 GeV.
- **Important discoveries**
  - Observation of the CP violation of the weak interaction in 1963.
  - The discovery of the muon neutrino (1962).
  - J/ψ discovery in 1974.
- **Since 1986:** Used to accelerate Si ions at energies of 14 GeV per nucleon using Tandem Van de Graaf built in 1970.
- **AGS booster constructed in 1991:** AGS beam intensity was increased and could accelerate heavier ions (Au) up to 11 GeV per nucleon.
- **Main experiments**
  - **Several fixed target heavy-ion experiments took place for 14 years:** E866, E877, E891, E895, E896, E910, 15 E917 to study the hadronic matter at high temperature

The Super Proton Synchrotron (SPS) at CERN

- The SPS was built in 1976 allowing for proton acceleration up to 500 GeV
- **Operation:** Protons are accelerated by LINAC2 and then injected into the booster of the PS (Proton Synchrotron) and finally they are injected into the SPS.
- **Stochastic-cooling technique in the SPS ring:** SPS became a proton-antiproton collider
- **Electron-Cyclotron Resonance (ECR) ion source:** Allowed the injection of multi charged heavy ions in the CERN accelerator system from 1986
- **Nuclei:** Initially O and S were accelerated at energies about 60 and 200 GeV per nucleon, and In ions were used later for the NA60 experiment.
- **Experiments:** WA80, WA93, WA98, WA85, WA94, WA97, NA57, Helios-2, NA44, CERES, Helios-3, NA35, NA49, NA36, NA52, NA38, NA50 et NA60. **(Currently it is the LHC injector)**
- <u>**Important Discoveries**</u>
  - **In 1983 :** The electroweak bosons were discovered by the UA1 and UA2 experiments.
  - Stochastic cooling (Nobel prize in 1984)

The Relativistic Heavy Ion Collider (RHIC) at BNL

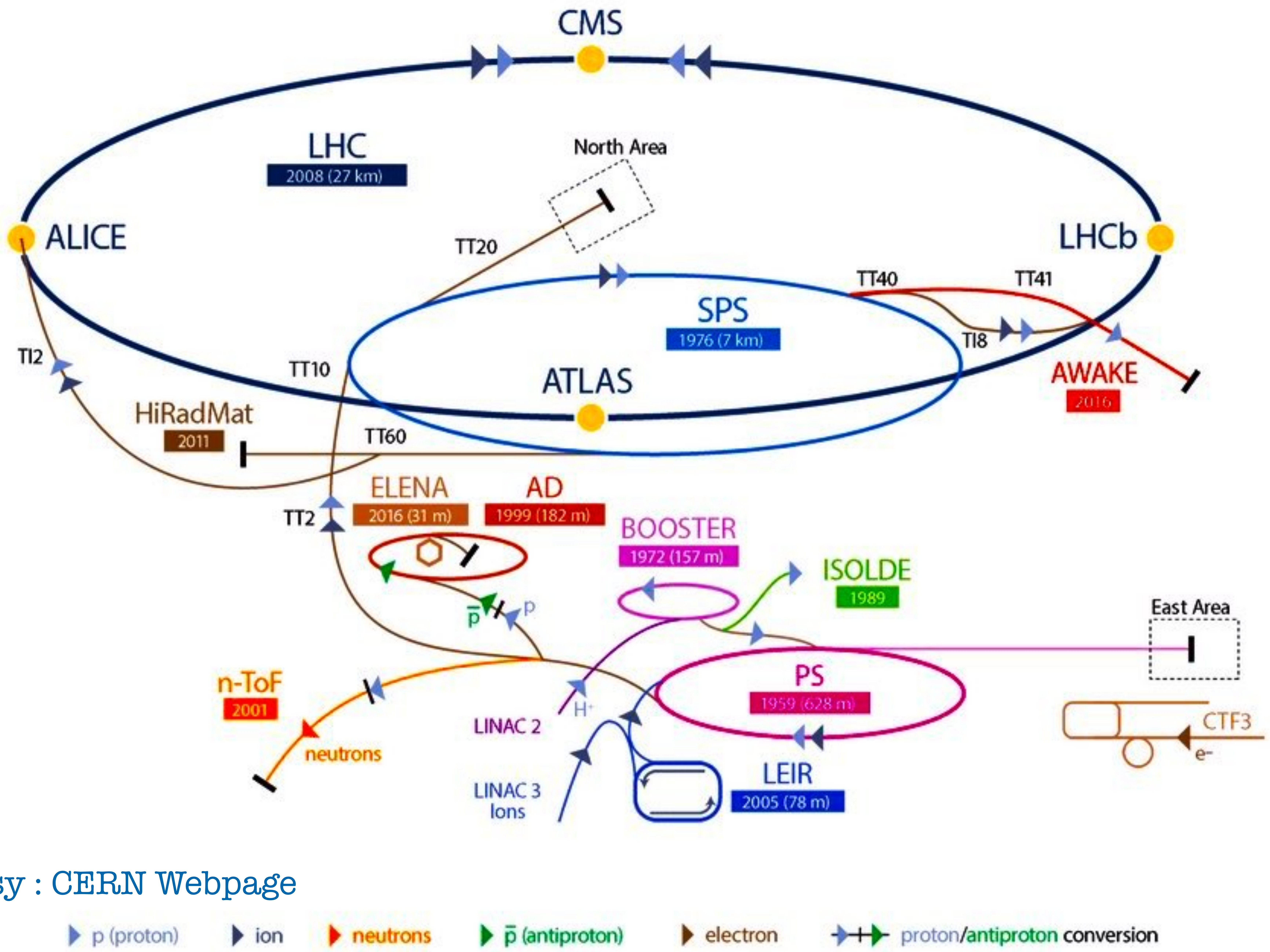
- The first Au-Au collisions at 130 GeV per nucleon pair took place in June 2000 in RHIC at BNL
- It was the first collider ever built for heavy ions with AGS as it's injector.
- **Major experiments:** STAR, PHENIX, PHOBOS and BRAHMS
- **Important contributions:** Arguably the ever first laboratory creation of quark gluon plasma

Large Hadron Collider (LHC) at CERN

- The LHC at CERN uses SPS as injector.
- SPS was upgraded to generate a Pb ions beam at 177 GeV per nucleon, that are accelerated to a beam energy of 1.38 TeV.
- First Pb-Pb collisions at 2.76 TeV in November 2010.
- **Main experiments with heavy-ion programs:** ALICE, ATLAS and CMS

We will see some of the main results from these experiments in the coming sessions

Collider Schematics



Picture Courtesy : CERN Webpage

What Next?

- We have seen some basic terminologies and elementary ideas to read a heavy-ion collision paper.
- In the next talk we will see some of the observables that are used for studying these collisions
- In the third talk we will see some of the recent results obtained from such studies.

Observables


ALICE
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

Thank You!

Bethe-Bloch equation

Considering quantum mechanical effects:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] [\cdot \rho]$$

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle

M : Mass of incident particle

Z : Charge number of medium

A : Atomic mass of medium

I : Mean excitation energy of medium

δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$

[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm

[Classical electron radius]

$m_e = 511$ keV

[Electron mass]

$\beta = v/c$

[Velocity]

$\gamma = (1-\beta^2)^{-2}$

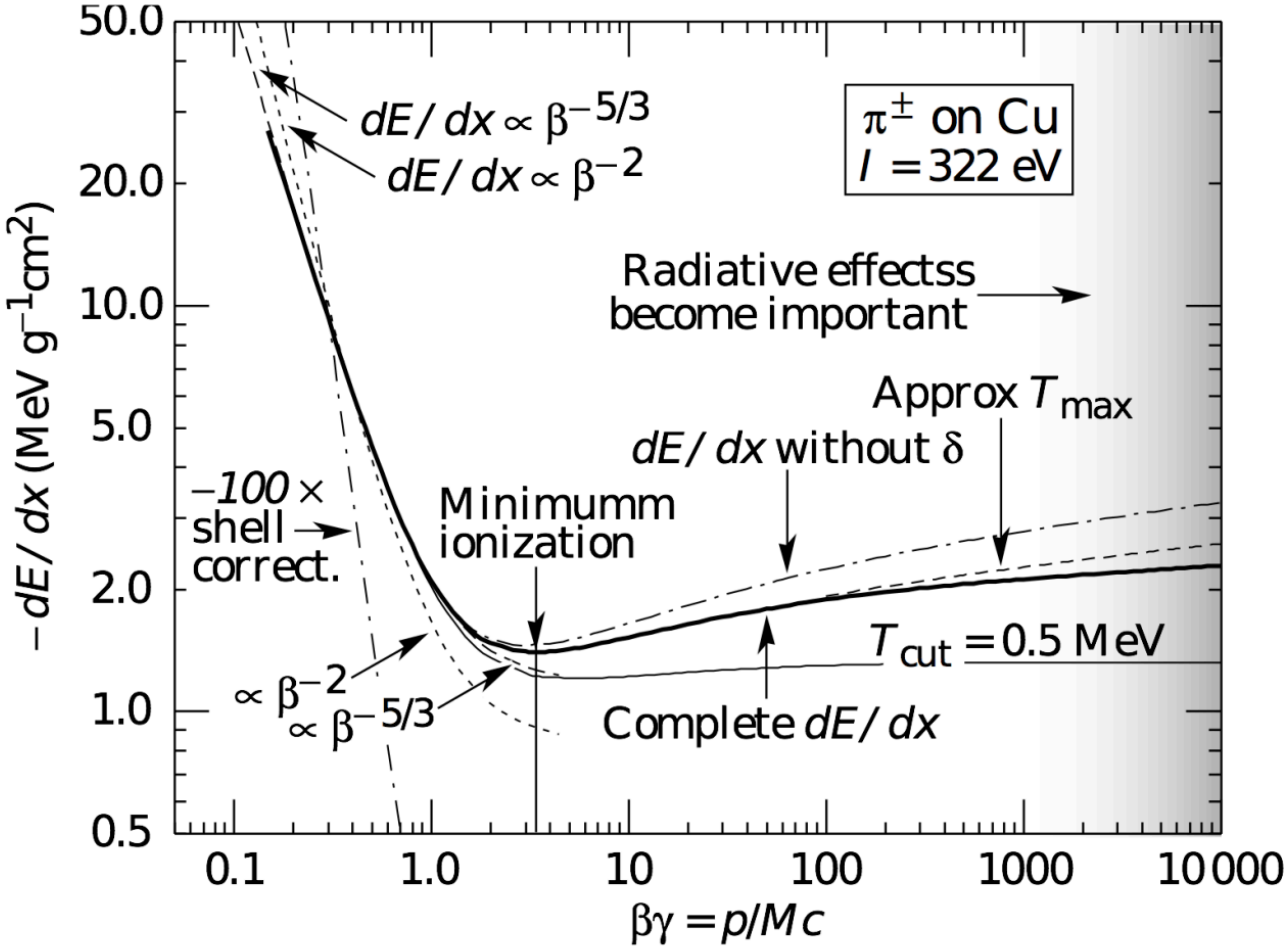
[Lorentz factor]

Validity:

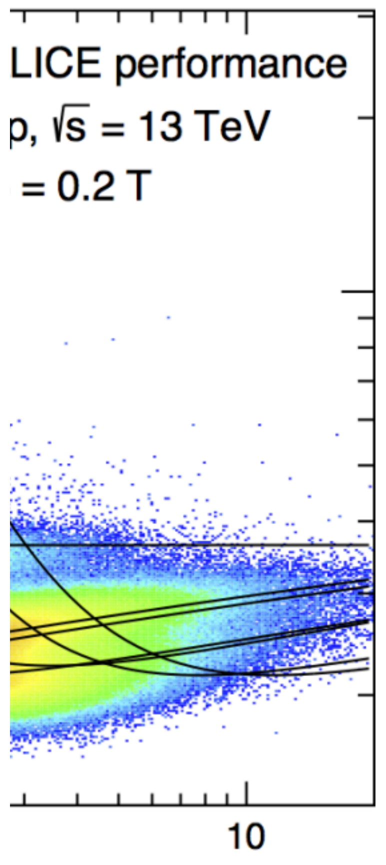
$.05 < \beta\gamma < 500$

$M > m_\mu$

dE/dx of pions in copper



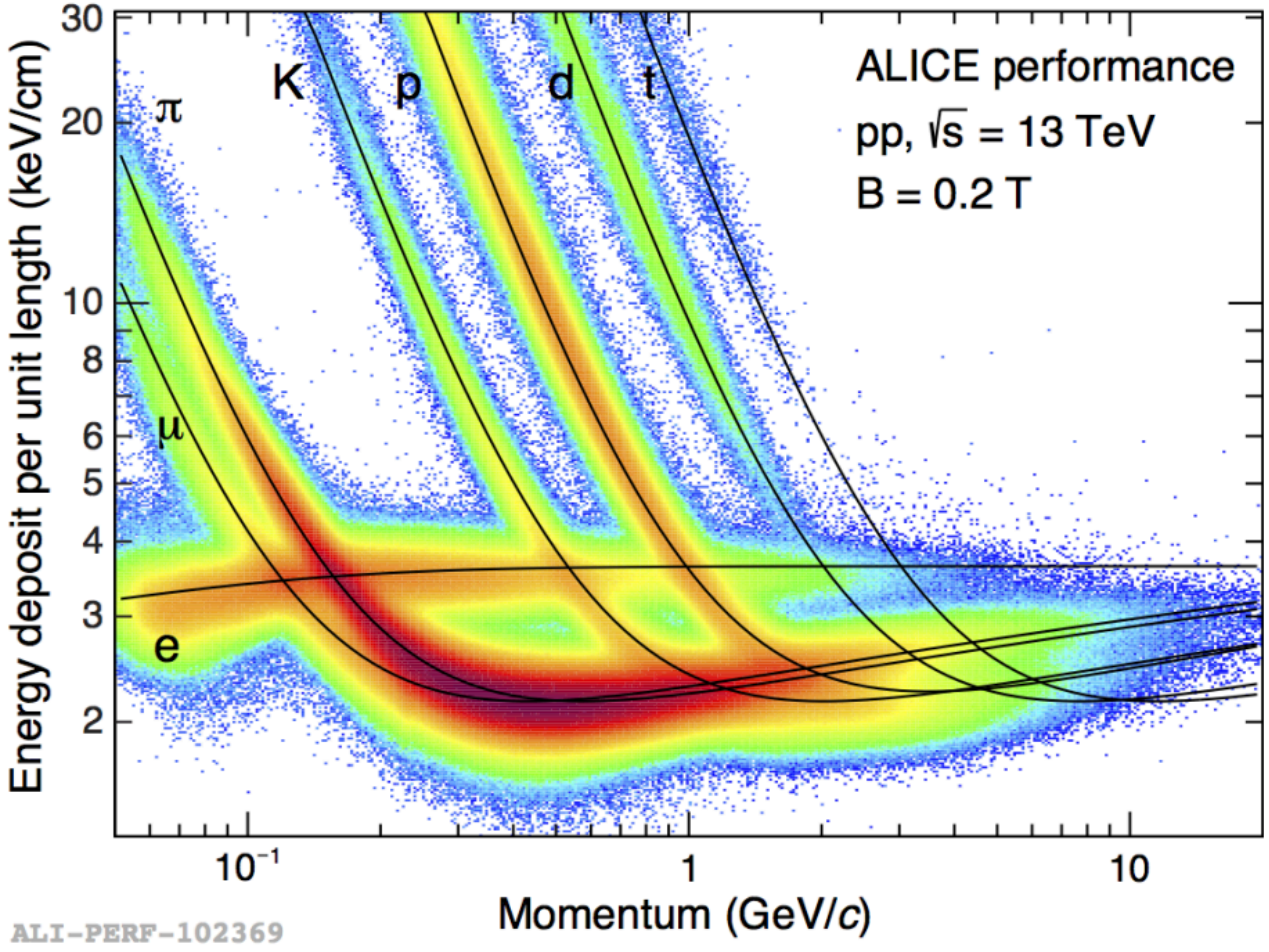
ıamber



dE/dx used in practice

the ALICE Time Projection Chamber

Ri**gidity** is the effect of particular magnetic fields on the motion of the charged particles. It is a measure of the momentum of the particle, and it refers to the fact that a higher momentum particle will have a higher resistance to deflection by a magnetic field. It is defined as $R = B\rho = p/q$, where B is the magnetic field, ρ is the gyroradius of the particle due to this field, p is the particle momentum, and q is its charge. It is frequently referred to as simply "$B\rho$"



Lee, S.Y. (2004). *Accelerator Physics, Second Edition*. World Scientific. p. 576.

where **b** is the collision impact parameter and **s** denotes a position in the transverse plane. The interaction probability $\sigma(\mathbf{s})$ is normalized to give the nucleon–nucleon inelastic cross section $\sigma_{NN} = \int d^2s\, \sigma(\mathbf{s})$. The *nuclear thickness function* $T_A(\mathbf{b}) = \int dz\, \rho_A(\mathbf{b}, z)$ describes the transverse nucleon density by integrating the nuclear density ρ along the longitudinal direction (z).

2

In the so-called *optical* limit of the Glauber model derived in [9], local density fluctuations and correlations are ignored so that each nucleon in the projectile interacts with the incoming target as a flux tube described with a smooth density. The total cross section then reduces to

$$\sigma_{AB} = \int d^2b \left\{1 - [1 - \sigma_{NN} T_{AB}(\mathbf{b})]^{AB}\right\} , \tag{2}$$

where

$$T_{AB}(\mathbf{b}) = \int d^2s\, T_A(\mathbf{s})\, T_B(\mathbf{s} - \mathbf{b}) \tag{3}$$

is known as the *nuclear overlap* function, normalized as $\int d^2b\, T_{AB}(b) = A\,B$ by integrating over all impact parameters. Expressions (1) and (2) give identical results for large enough nuclei and/or for sufficiently small values of σ_{NN}.