Status of physics studies by MEPhI group

E.Soldatov

National Research Nuclear University "MEPhI"

on behalf of the group

Introduction

Together with our contribution to BBC detector R@D, we are starting to work on the physics tasks:

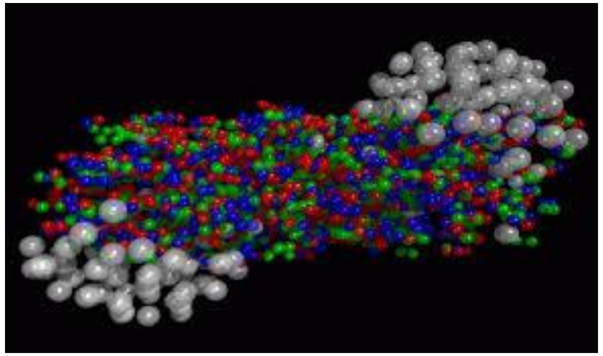
- Inclusion of UrQMD MC generator in the SPDRoot simulation chain

- Study of the particle reconstruction by the BBC detector in SPDRoot

- Ion program: study of π/K/p spectra in ion collisions to obtain kinetic freeze-out temperature using fit with Blast-wave model

- $J/\psi \rightarrow ll$ angular coefficients study

UrQMD: motivation



The Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model is a transport model for simulating heavy ion collisions in the energy range from SIS to RHIC. UrQMD is designed as multipurpose tool for studying a wide variety of heavy ion related effects ranging from multifragmentation and collective flow to particle production and correlations.

UrQMD provides a reasonable description of many observables (particle spectra and yields, flow, etc.) for hadron–hadron, hadron–nucleus and nucleus–nucleus reactions across a large range of beam energies.

The used UrQMD setup considers only elastic and inelastic scatterings and may reproduce particle multiplicities and collective motion measured by experiments.

UrQMD is planned to be used by us in ion physics studies and also to test occupancy constraints of planned SPD detectors for different ions.

UrQMD: status

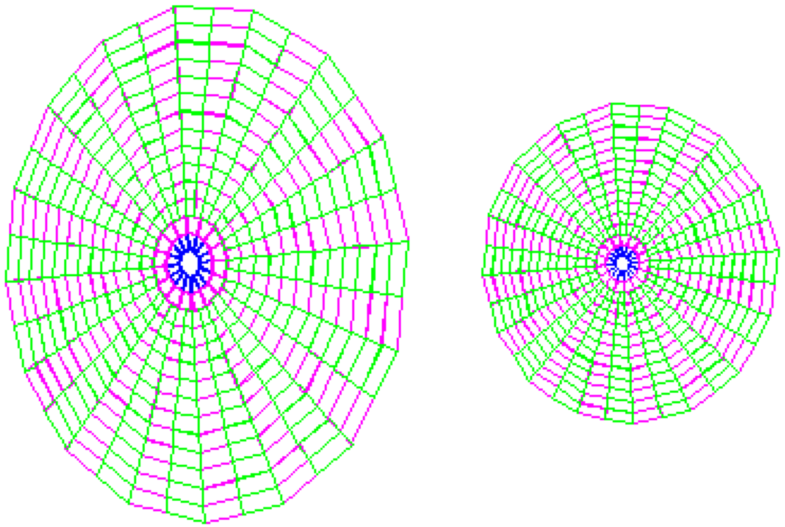
- UrQMD can be installed in the same docker container alongside SPDROOT for easy distribution.
- Current version of SPDROOT includes possibility to read .f14 event output format of UrQMD. It has been modified to read also .f13 output format, which is used by MEPhI group. (Comparison of the formats see in the back-up)
- It was checked that further simulation of events from URQMD in Géant4 is possible in SPDROOT

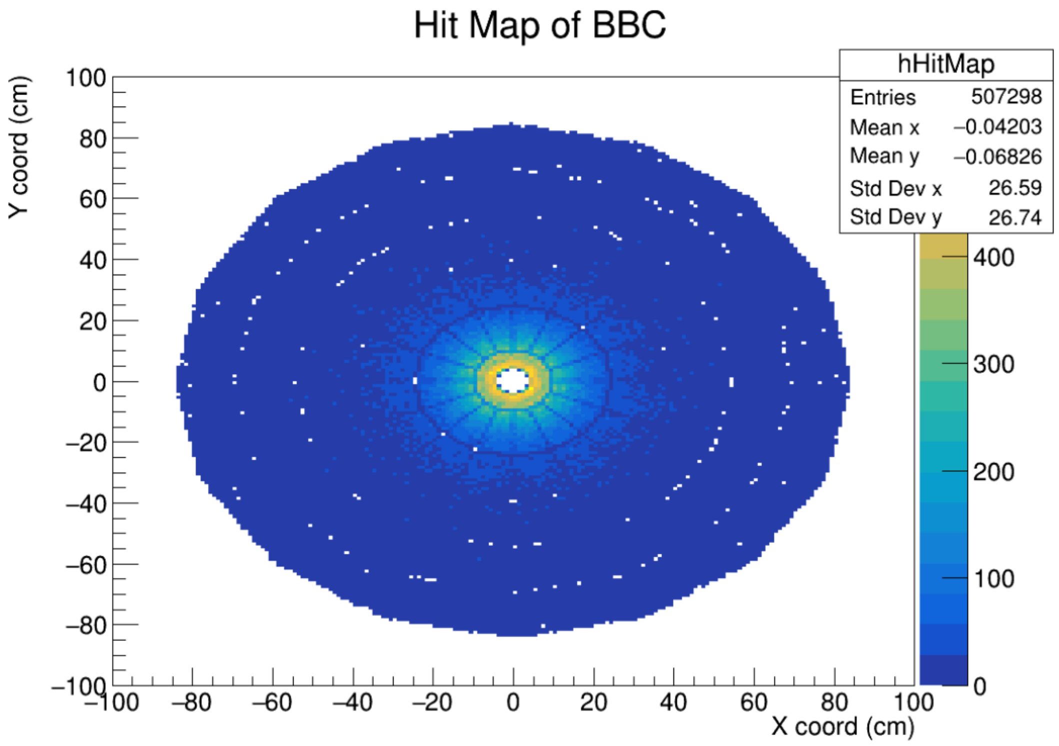
Further steps:

- Include information about vertex and time for simulation (currently default values 0,0,0,0 are used)
- Include McDst converter to SPDROOT (allows to convert output from many MC generators to uniform .root format)
- Include possibility to events from .root files in McDst format

BBC geometry

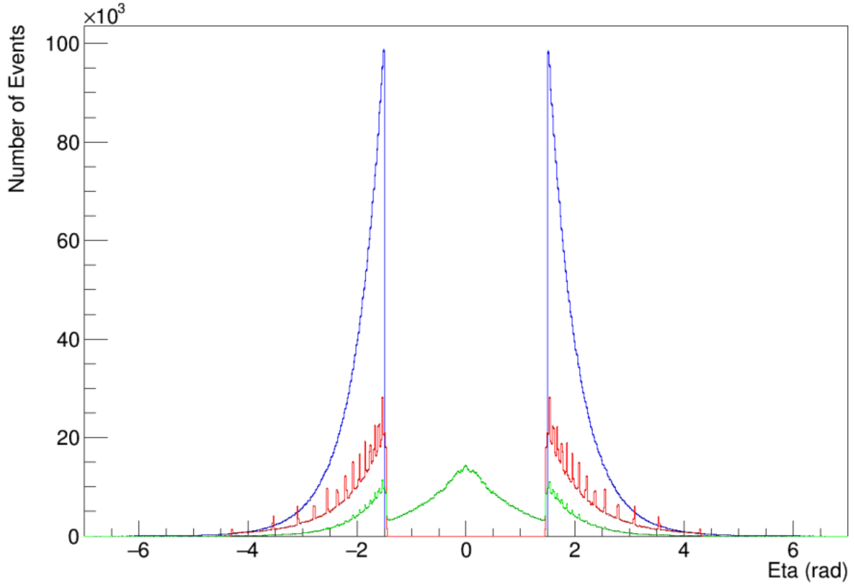
The updated BBC geometry was used in all simulations (left figure); an example of simulations in which the load of the detector BBC can be seen (right figure).

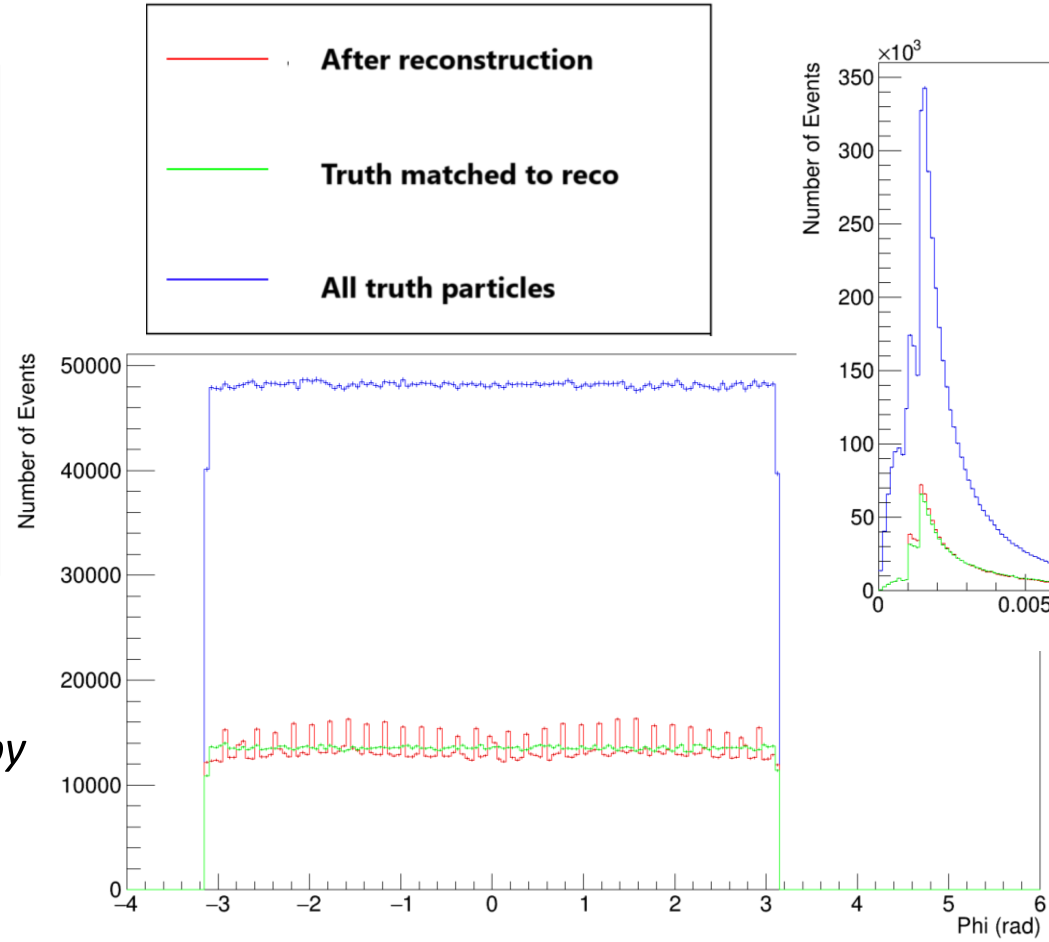


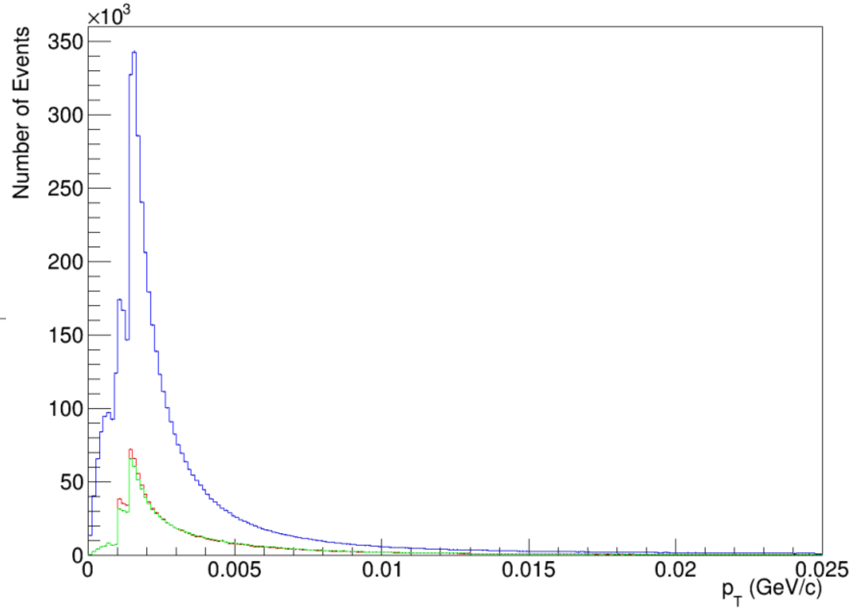


Testing BBC geometry with different physics processes

Current work is to test geometry model of BBC. Some bugs were found and fixed. Still ongoing.
Figures below are for e, μ and γ from J/ψ production. Some additional plots are in back-up.







Only BBC is enabled.
All truth particles are constrained by BBC acceptance cuts.

Next: to check the BBC occupancies with p/d and different ions.

Ion physics at SPD

Study the quark-gluon matter properties in small systems (p+p, d+d, O+O, Ar+Ar, ...)
- Influence of the initial state.
- Dynamics and final state effects, transport coefficients.

Vortical structure
- Access via various particle decays (hyperons, meson resonance and J/psi) in a broad acceptance.
- Energy dependence of vortical structure.

Charm production
- Dissociation and recombination, partonic energy loss.
- Access to J/psi and charmonium via dimuon channel.

Need of pA collisions to study nuclear parton distribution functions and gluon saturation effects.

Ion physics: What we want to estimate?

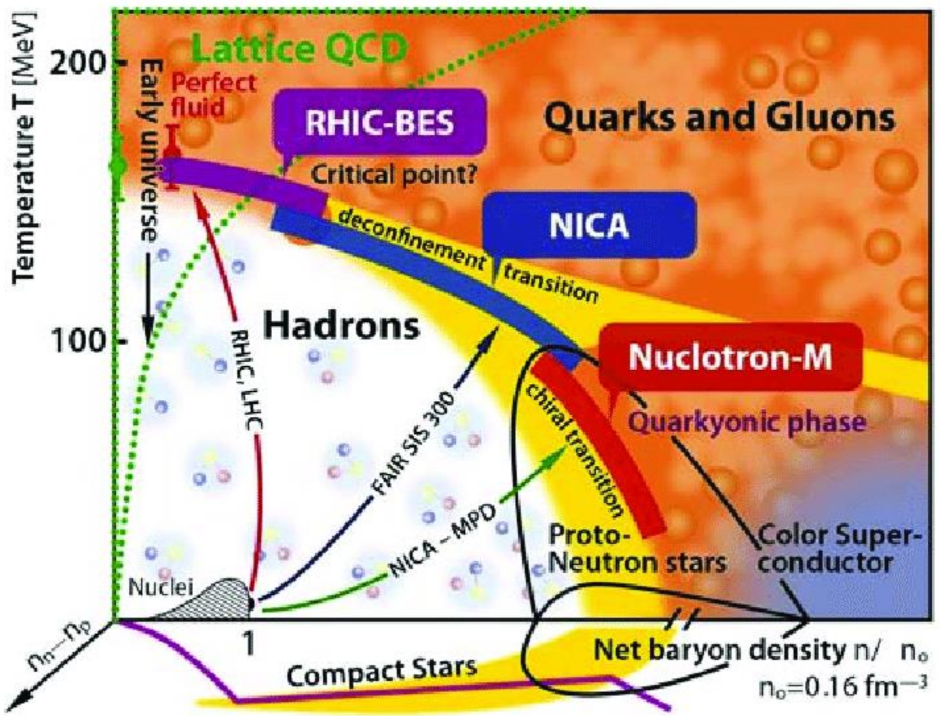
- Searching for the critical point and phase boundary in the QCD phase diagram is currently a focus of experimental and theoretical nuclear physics research.

- However, before looking for signatures, it is important to know the (T, μB) region of the phase diagram we can access. The spectra of produced particles allow us to infer the T and μB values at freeze-out.

- The systematic study of these bulk properties may reveal the evolution and change in behavior of the system formed in ion collisions as a function of collision energy.

- Why SPD?

- High trigger rates and spatial resolution.
- Large pseudorapidity acceptance.



Ion physics: Blast Wave fit of spectra

- The kinetic freeze-out parameters are obtained by fitting the spectra with a **Blast-Wave model**.
- The model assumes that the particles are locally thermalized at a kinetic freeze-out temperature (**T_{kin}**) and are moving with a common transverse collective flow velocity.
- Assuming a radially boosted thermal source, with **T_{kin}** and a transverse radial flow velocity **β**, the **p_T** distribution of the particles is given by equation:

$$\frac{dN}{p_T\,dp_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{\rm kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{\rm kin}}\right),$$

m_T - transverse mass, **ρ (r)** = $\tanh^{-1}(\beta)$
I_0, K_1 - Bessel functions, **β** = $2 * \beta_S / (2+n)$
β_S - surface velocity, **n** - exponent of flow velocity profile
Fit parameters: T_{kin}, β

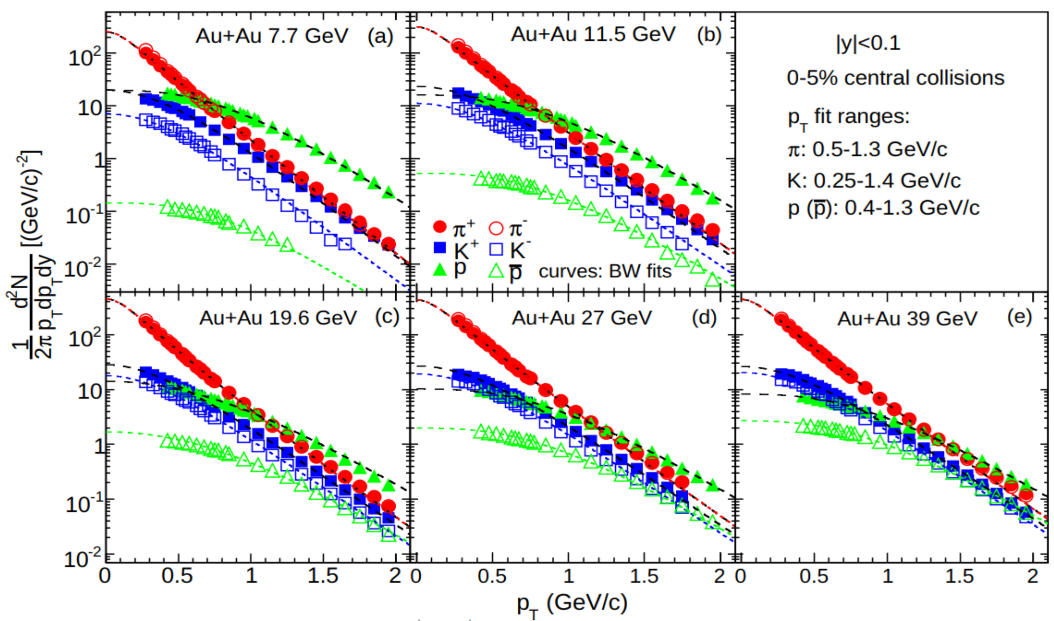


FIG. 36: (Color online) Blast wave model fits of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ p_T spectra in 0–5% central Au+Au collisions at $\sqrt{s_{NN}}$ = (a) 7.7 GeV, (b) 11.5 GeV, (c) 19.6 GeV, (d) 27 GeV, and (e) 39 GeV. Uncertainties on experimental data represent statistical and systematic uncertainties added in quadrature. Here, the uncertainties are smaller than the symbol size.

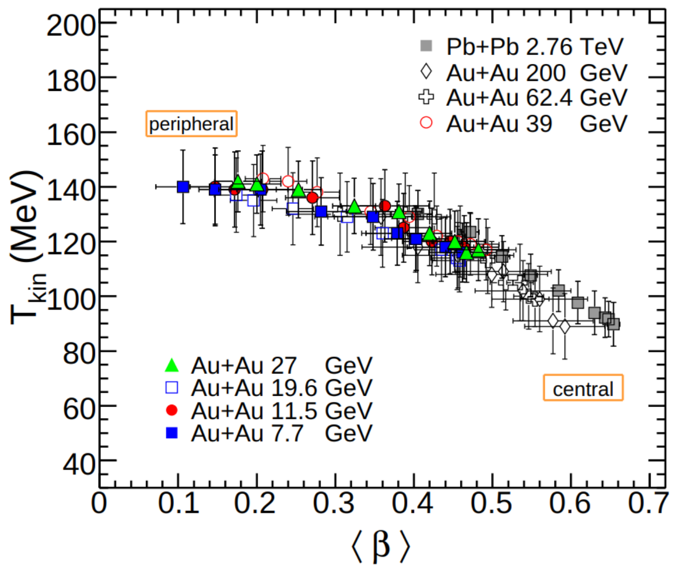


FIG. 37: (Color online) Variation of $T_{\rm kin}$ with $\langle\beta\rangle$ for different energies and centralities. The centrality increases from left to right for a given energy. The data points other than BES energies are taken from Refs. [43, 66]. Uncertainties represent systematic uncertainties.

Experimental results from STAR: Phys. Rev. C 96, 044904 (2017)

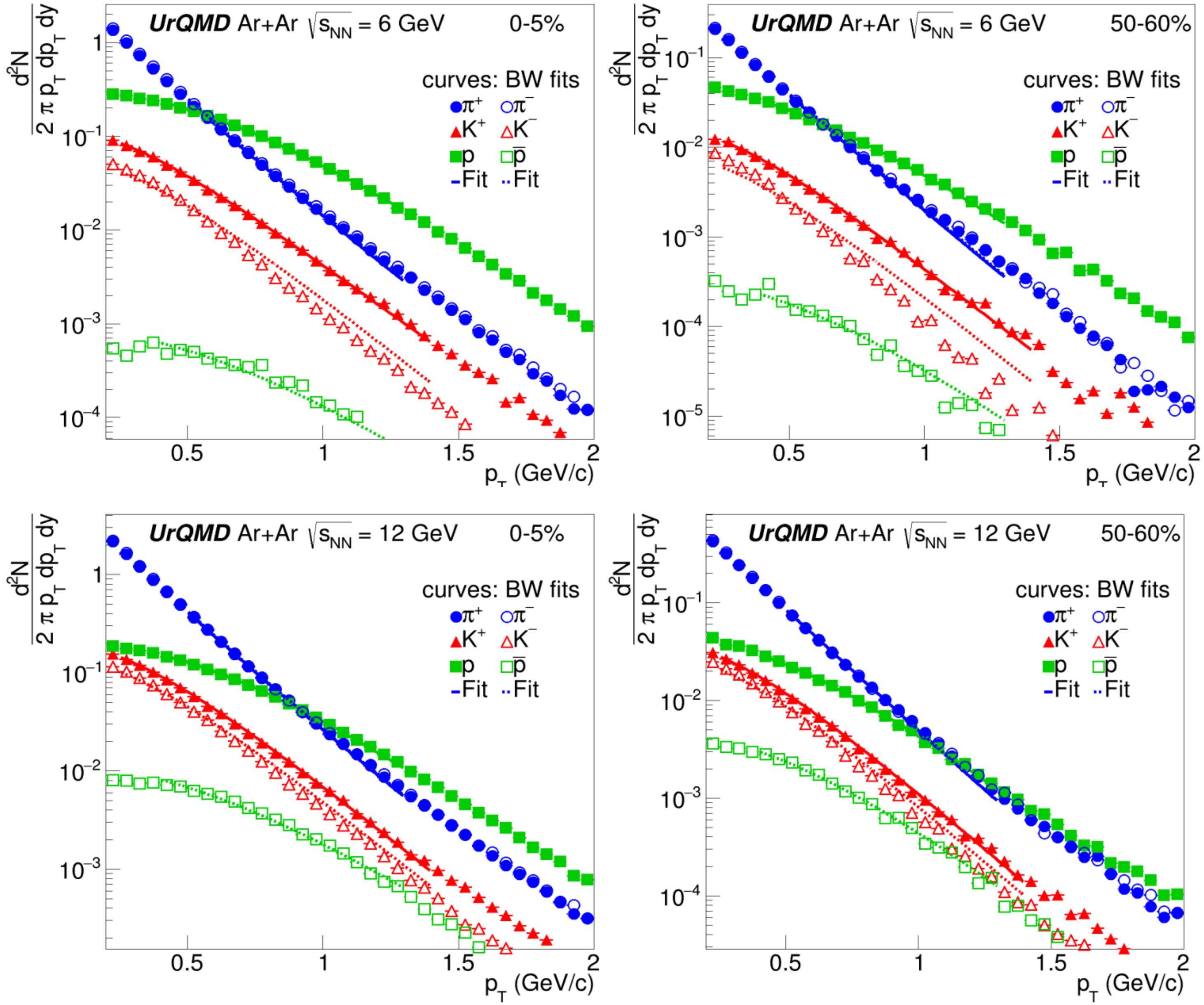
Ion physics: Blast Wave fits of pT spectra for Ar+Ar

Blast-Wave fits of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ p_T spectra in 0-5% and 50-60% centrality regions Ar+Ar collision at $\sqrt{s_{NN}}$ = 6 and 12 GeV.

T_{kin} =

- 113 MeV at 0-5% at $\sqrt{s_{NN}}$ = 6 GeV
- 127 MeV at 50-60% at $\sqrt{s_{NN}}$ = 6 GeV

- 116 MeV at 0-5% at $\sqrt{s_{NN}}$ = 12 GeV
- 136 MeV at 50-60% at $\sqrt{s_{NN}}$ = 12 GeV



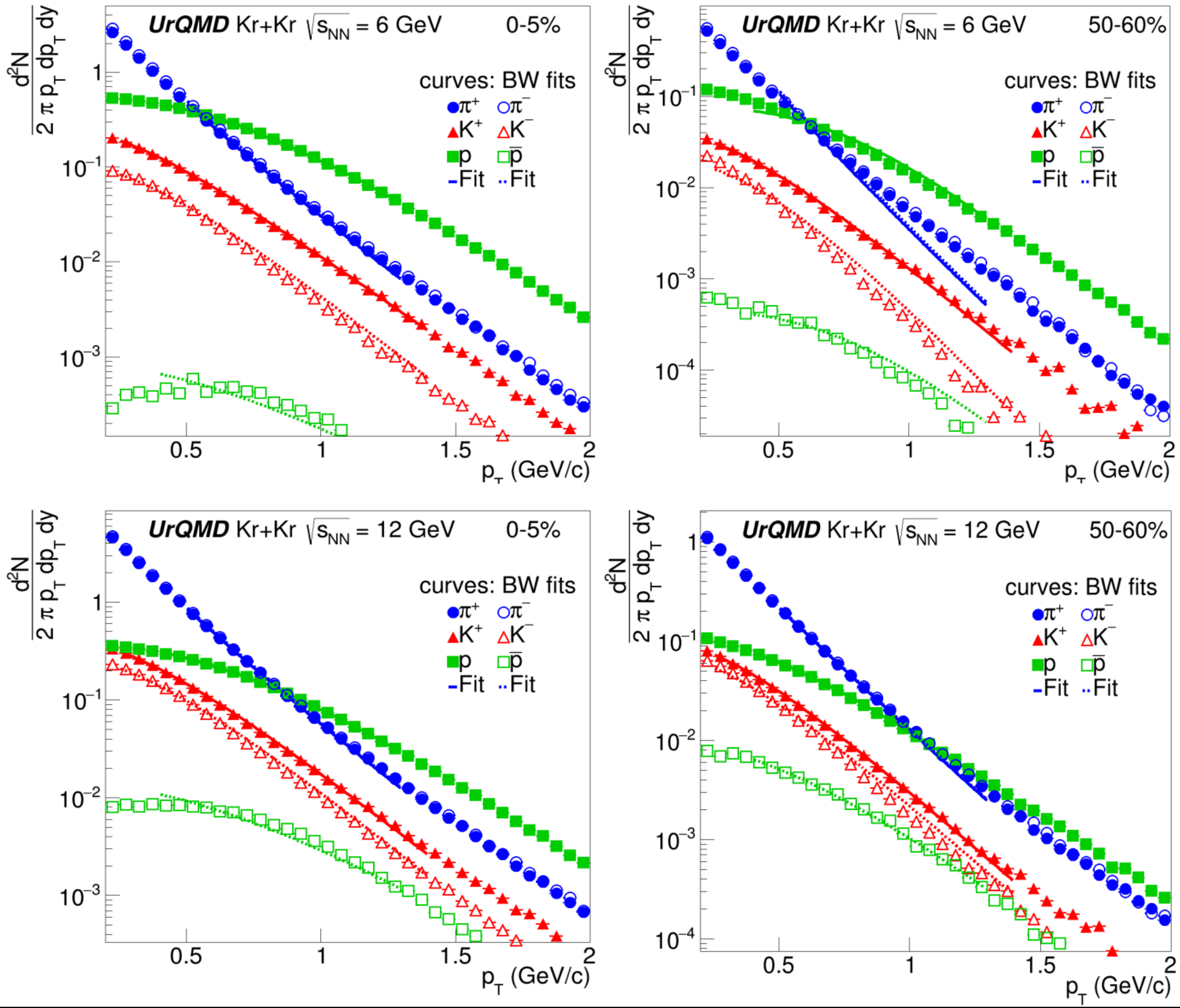
Ion physics: Blast Wave fits of pT spectra for Kr+Kr

Blast-Wave fits of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ p_T spectra in 0-5% and 50-60% centrality regions Ar+Ar collision at $\sqrt{s_{NN}}$ = 6 and 12 GeV.

T_{kin} =

- 106 MeV at 0-5% at $\sqrt{s_{NN}}$ = 6 GeV
- 72 MeV at 50-60% at $\sqrt{s_{NN}}$ = 6 GeV

- 106 MeV at 0-5% at $\sqrt{s_{NN}}$ = 12 GeV
- 134 MeV at 50-60% at $\sqrt{s_{NN}}$ = 12 GeV



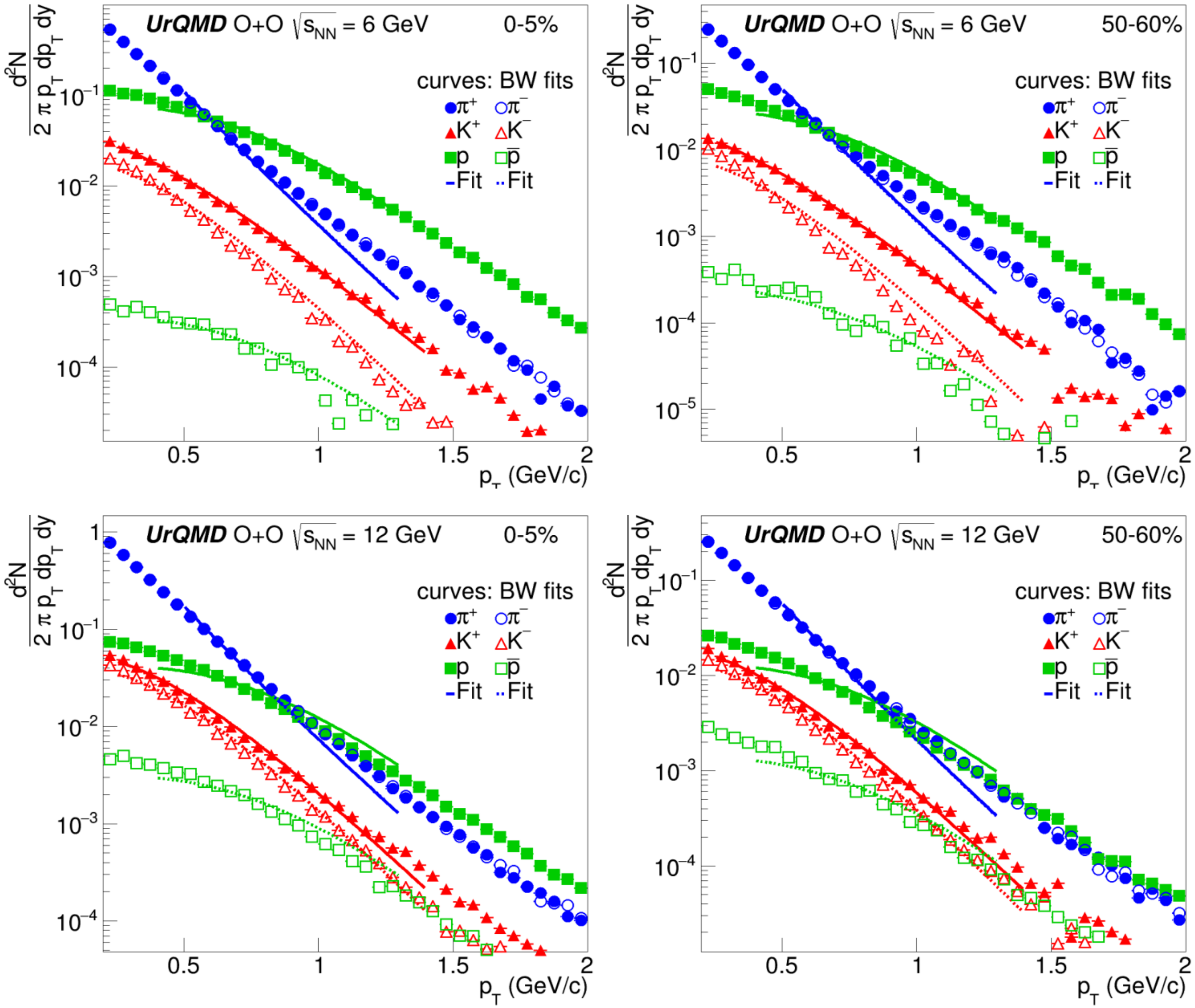
Ion physics: Blast Wave fits of pT spectra for O+O

Blast-Wave fits of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ p_T spectra in 0-5% and 50-60% centrality regions Ar+Ar collision at $\sqrt{s_{NN}}$ = 6 and 12 GeV.

T_{kin} =

- 72 MeV at 0-5% at $\sqrt{s_{NN}}$ = 6 GeV
- 72 MeV at 50-60% at $\sqrt{s_{NN}}$ = 6 GeV

- 72 MeV at 0-5% at $\sqrt{s_{NN}}$ = 12 GeV
- 72 MeV at 50-60% at $\sqrt{s_{NN}}$ = 12 GeV



J/ψ angular coefficients

It is planned to measure the decay lepton distribution of the J/ψ as a detailed test of the production mechanism of the $c\bar{c}$ bound state.

For J/ψ's produced with transverse momentum pT balanced by the additional photon one can define an event plane spanned by the beam and the J/ψ momentum direction which provides a reference plane for a detailed study of angular correlations. The decay lepton distribution in J/ψ → $l^- l^+$ in the J/ψ rest frame is determined by the polarization of the J/ψ.

Therefore, the study of the **angular distribution** can be used as an analyzer of the J/ψ-polarization. It is thus possible to test the underlying J/ψ-production dynamics in much more detail than is possible by rate measurements alone. [more details]

$$\frac{d\sigma}{dp_T^2\, dy\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^2\, dy}\left[(1+\cos^2\theta) + \frac{1}{2}A_0\ (1-3\cos^2\theta) + A_1\ \sin 2\theta\cos\phi\ + \frac{1}{2}A_2\ \sin^2\theta\cos 2\phi\right]$$

$$A_0 = \frac{2\, d\sigma^L}{d\sigma^{U+L}}\,, \qquad A_1 = \frac{2\sqrt{2}\, d\sigma^I}{d\sigma^{U+L}}\,, \qquad A_2 = \frac{4\, d\sigma^T}{d\sigma^{U+L}}$$

σ^L, σ^T, σ^I - the longitudinal, the transverse and the longitudinal-transverse interference cross sections

σ^{U+L} - the unpolarized production cross section

J/ψ angular coefficients

The dependence on the J/ψ p_T and y is entirely contained in the Ai coefficients and σ^{U+L}. Therefore, all hadronic dynamics from the production mechanism are described implicitly within the structure of the Ai.

When acceptance cuts are imposed on the leptons, the angular distributions are dominated by kinematical effects rather than polarization effects. It may be possible to retain J/ψ polarization effects by "dividing out" the kinematic effects, i.e., if the histogrammed data are divided by the theoretical result for isotropic J/ψ decay.

Current status - study of existing algorithms for muon track reconstruction for further signal modeling under SPD experiment conditions.

Conclusions

MEPhI group started to contribute for SPD physics.

- The first way how to use the most detailed output of UrQMD with SPDRoot is developed. Now working on more convenient way.

- BBC reconstruction was checked. Bug in BBC geometry was found. Still have some unclear moment with reconstruction. Investigating. Plan: to start looking in occupancies.

- Spectra for the $\pi^{\pm}$, $K^{\pm}$, p and pBar were constructed for Ar+Ar, Kr+Kr, O+O at SPD energies using UrQMD.
  - The spectra were fitted using the BlastWave (BW) model.
  - Extracted fit parameters T_{kin} and $\langle\beta\rangle$.

- Other plans such as measurement of J/ψ angular coefficients were presented.

Back-up

UrQMD: status

- Scientific groups use .f13 output, which contains more information such as freeze-out time and coordinates (see table with comparison of UrQMD output files on the right).
- Corresponding method SpdUrqmdGenerator::ReadEvent(FairPrimaryGenerator* primGen) in SPDROOT can be easily updated to read multiple types of UrQMD output files.
- FairRoot also uses .f14 output as input.
- TTree output is not yet checked to be correct.

f13	f14	f15	f16	contents
		1		ind: index of particle (see `CTOption(56)`)
1	1	2	1	t: time of particle
2	2	3	2	r_x: x coordinate
3	3	4	3	r_y: y coordinate
4	4	5	4	r_z: z coordinate
5	5	6	5	E: energy of particle
6	6	7	6	p_x: x momentum component
7	7	8	7	p_y: y momentum component
8	8	9	8	p_z: z momentum component
9	9	10	9	m: mass of particle
10	10	11	10	ityp: particle-ID
11	11	12	11	iso3: $2 \cdot I_3$ (see Section 1.2)
12	12	13	12	ch : charge of particle
13	13	14	13	parent collision number (see Table 10)
14	14	15	14	N_{coll} number of collisions
		16		S : strangeness
15	15		15	parent process type (see Table 11)
		17		history information (debugging only)
16				t^{fr} : freeze-out time of particle
17				r_x^{fr} : freeze-out x coordinate
18				r_y^{fr} : freeze-out y coordinate
19				r_z^{fr} : freeze-out z coordinate
20				E^{fr} : freeze-out energy of particle
21				p_x^{fr} : freeze-out momentum x component
22				p_y^{fr} : freeze-out momentum y component
23				p_z^{fr} : freeze-out momentum z component
	16*			τ_{dec} decay time of particle
	17*			τ_{form} formation time of particle
	18*			R_σ cross section reduction factor
	19*			unique particle number (not ID!)
			16*	ityp_1^{old} : particle-ID of parent particle # 1
			17*	ityp_2^{old} : particle-ID of parent particle # 2

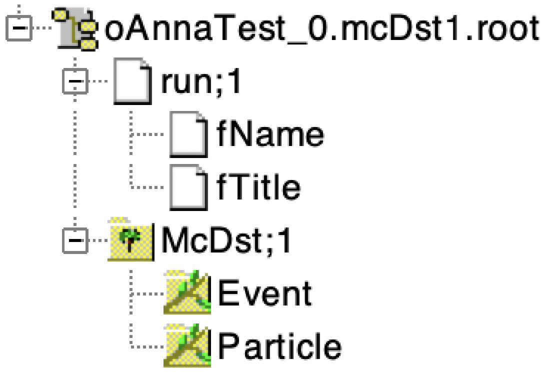
UrQMD: McDst converter

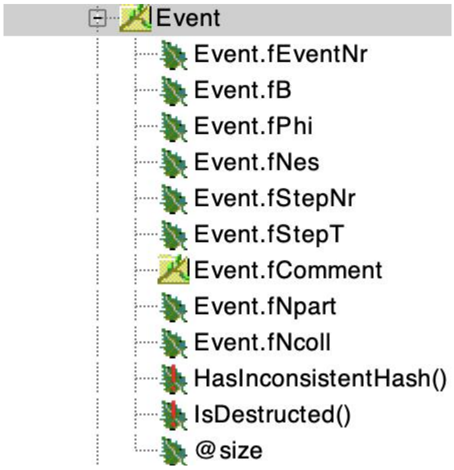
Another way to convert .f13 format to TTree .root is using McDst converter made by Grigori Nigmatkulov

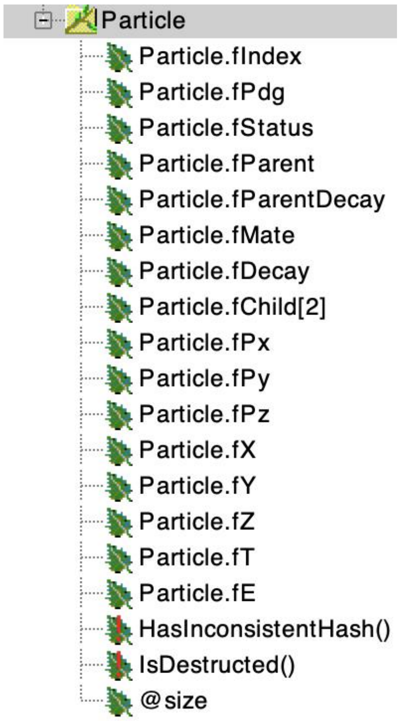
Advantages:

- Has possibility to filter events with elastic collisions and filter spectator particles
- Has information both about event and particles
- Already successfully tested
- Already implemented in MPDroot: can use their experience
- Can convert output from other generators

File structure







Reconstruction in BBC: settings

All simulations are done in an updated docker image with SPDRoot.

All simulations are performed using the Pythia8 generator.

At the current moment, the simulation parameters are as follows:
$\sqrt{s}=10 GeV$

In all simulations, only the bbc detector was used, the other detectors were disabled.

Simulations were produces using J/Psi and SoftQCD processes.

To produce all histograms, cuts by particle types were used (muons + electrons + photons - for the J/Psi process and protons - for the Soft QCD process), as well as cuts by theta θ for the initial MC particles in the bbc detector region

Reconstruction in BBC: J/ψ

Current work is to simulate the processes in the SPD experiment regarding the use of the bbc detector. The figures show examples of work-in-process histograms, which are currently being analyzed and adjusted for future simulations updates

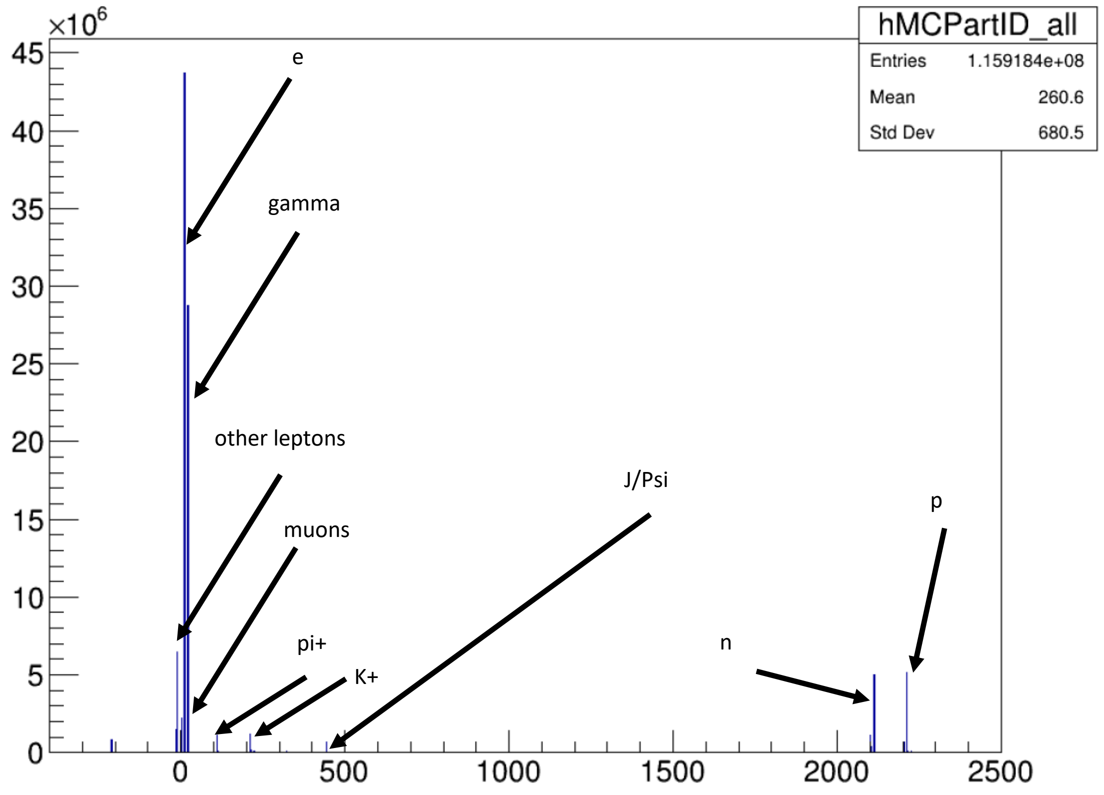


Fig. 7 - All particles produced by Pythia8

Muons, electrons, photons
in the bbc region
for the J/Psi process

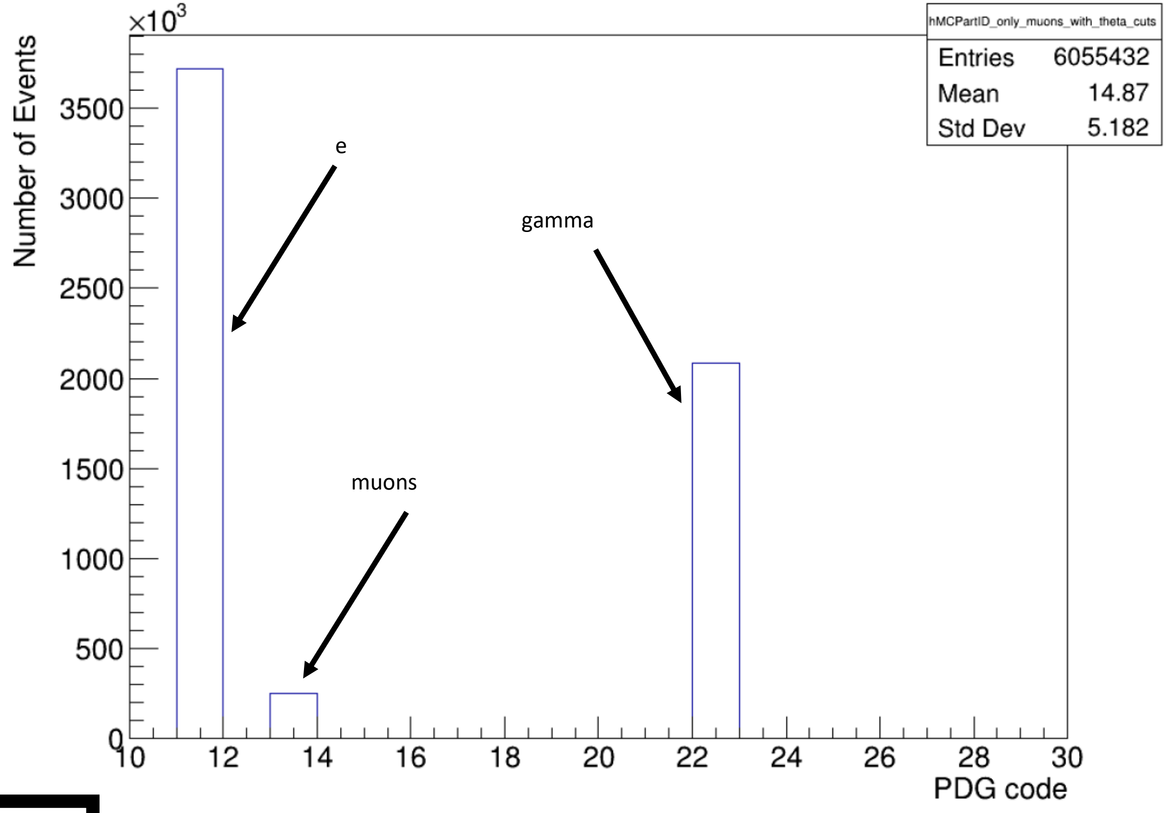
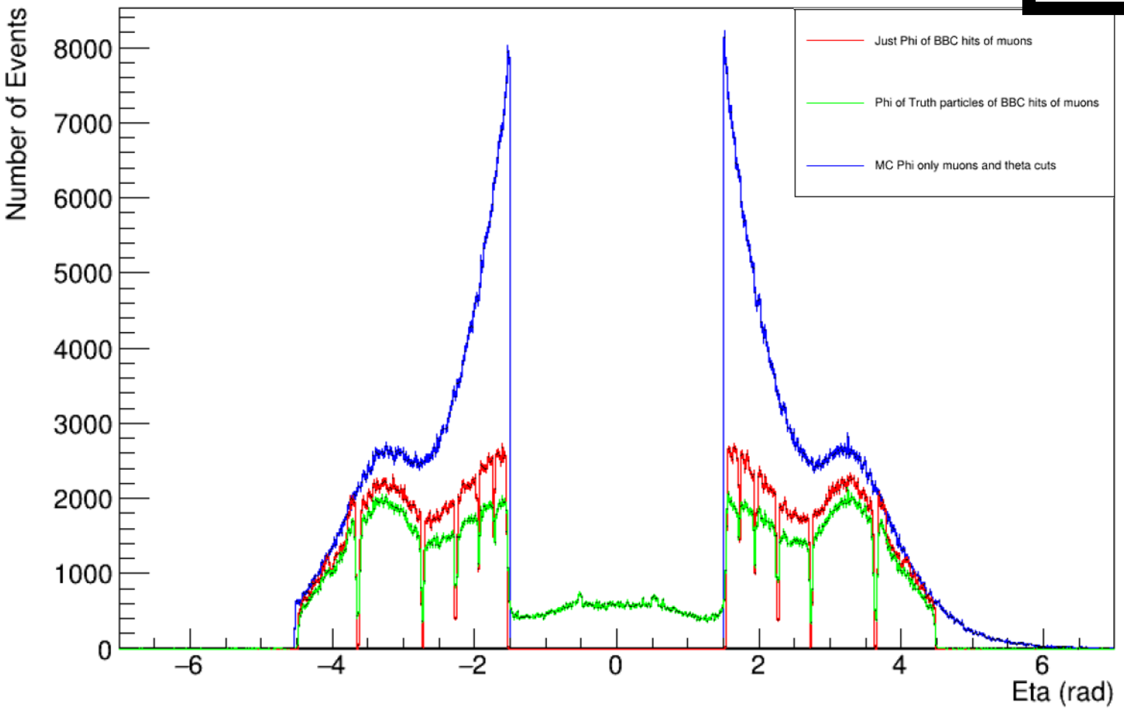


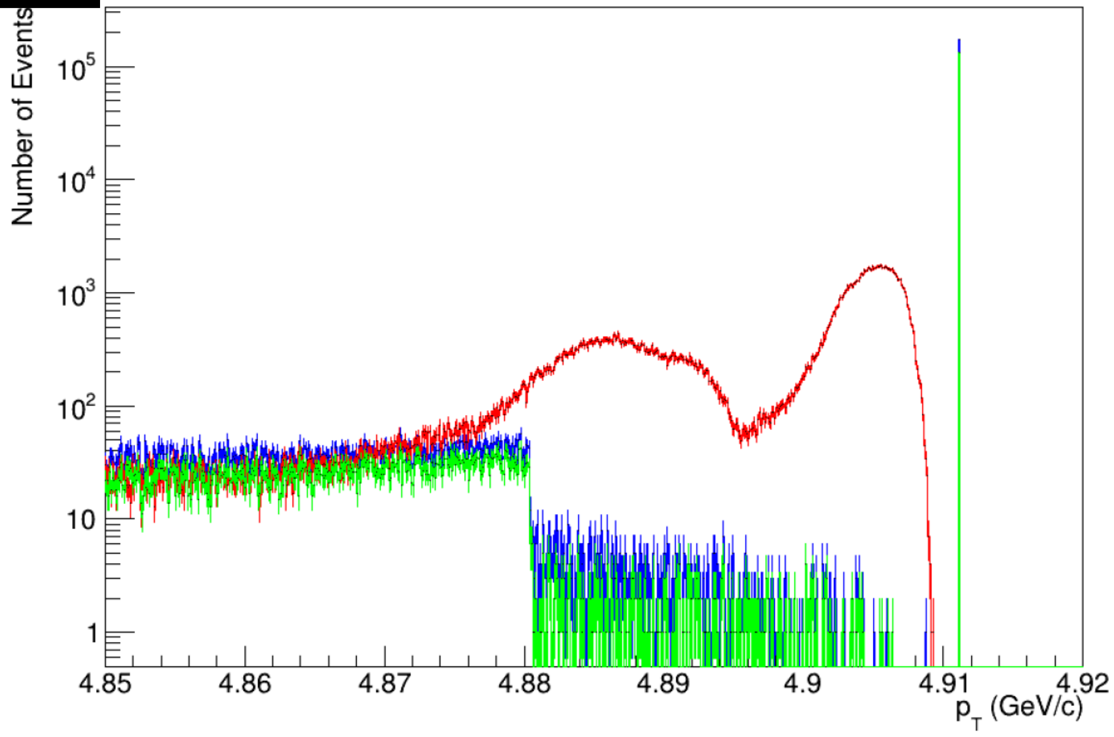
Fig. 8 - All muons μ , electrons e and photons γ reached bbc region

Reconstruction in BBC: soft QCD

Current work is to simulate the processes in the SPD experiment regarding the use of the bbc detector. The figures show examples of work-in-process histograms, which are currently being analyzed and adjusted for future simulations updates



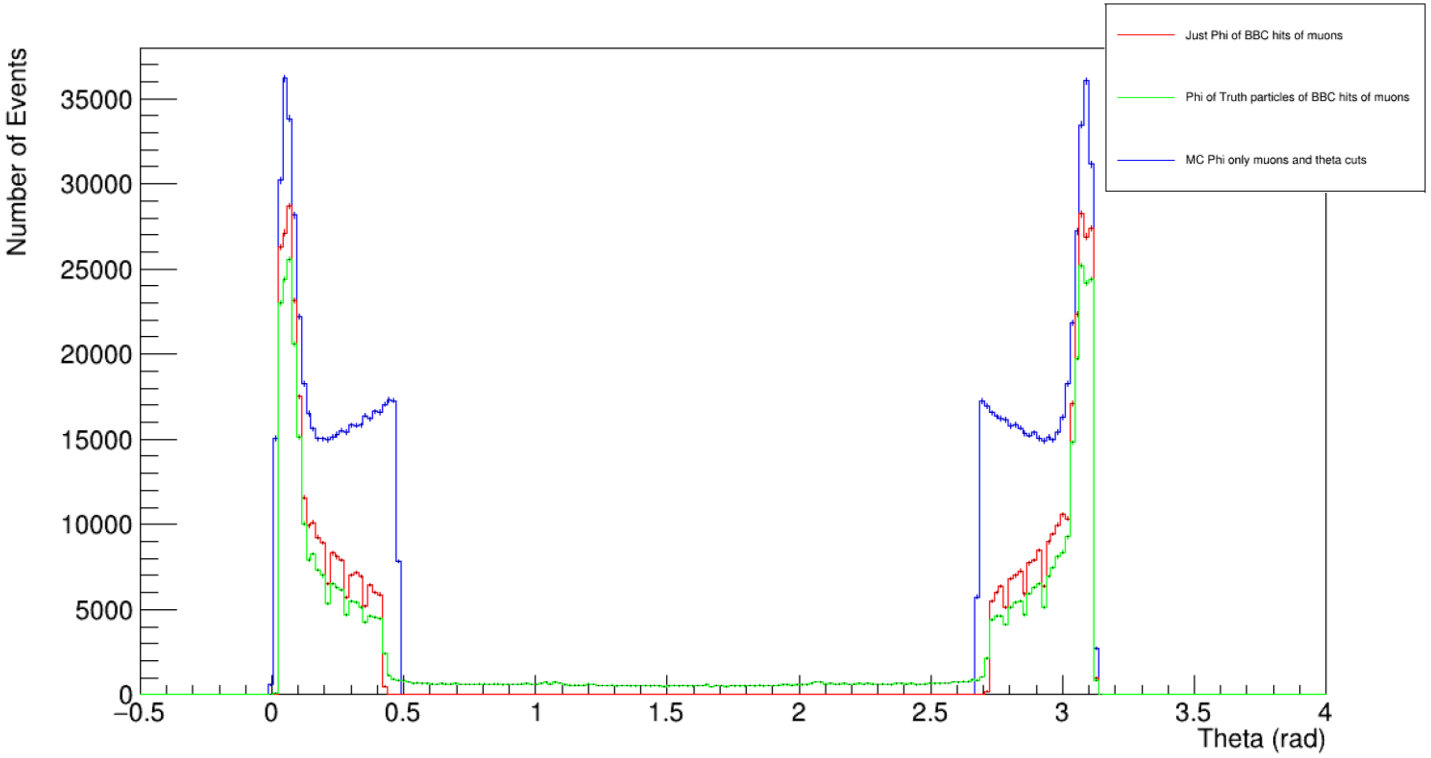
Protons
in the bbc region
for the SoftQCD process

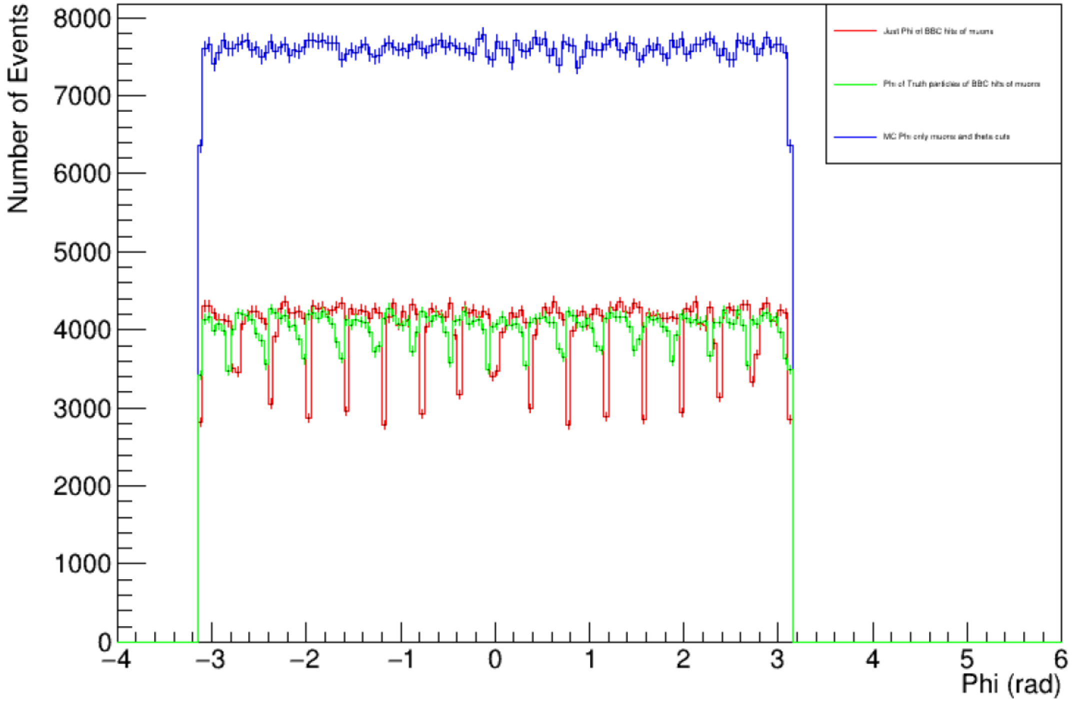


Reconstruction in BBC: soft QCD

Current work is to simulate the processes in the SPD experiment regarding the use of the bbc detector. The figures show examples of work-in-process histograms, which are currently being analyzed and adjusted for future simulations updates

Protons
in the bbc region
for the SoftQCD process





Reconstruction in BBC: soft QCD

Current work is to simulate the processes in the SPD experiment regarding the use of the bbc detector. The figures show examples of work-in-process histograms, which are currently being analyzed and adjusted for future simulations updates

Protons
in the bbc region
for the SoftQCD process

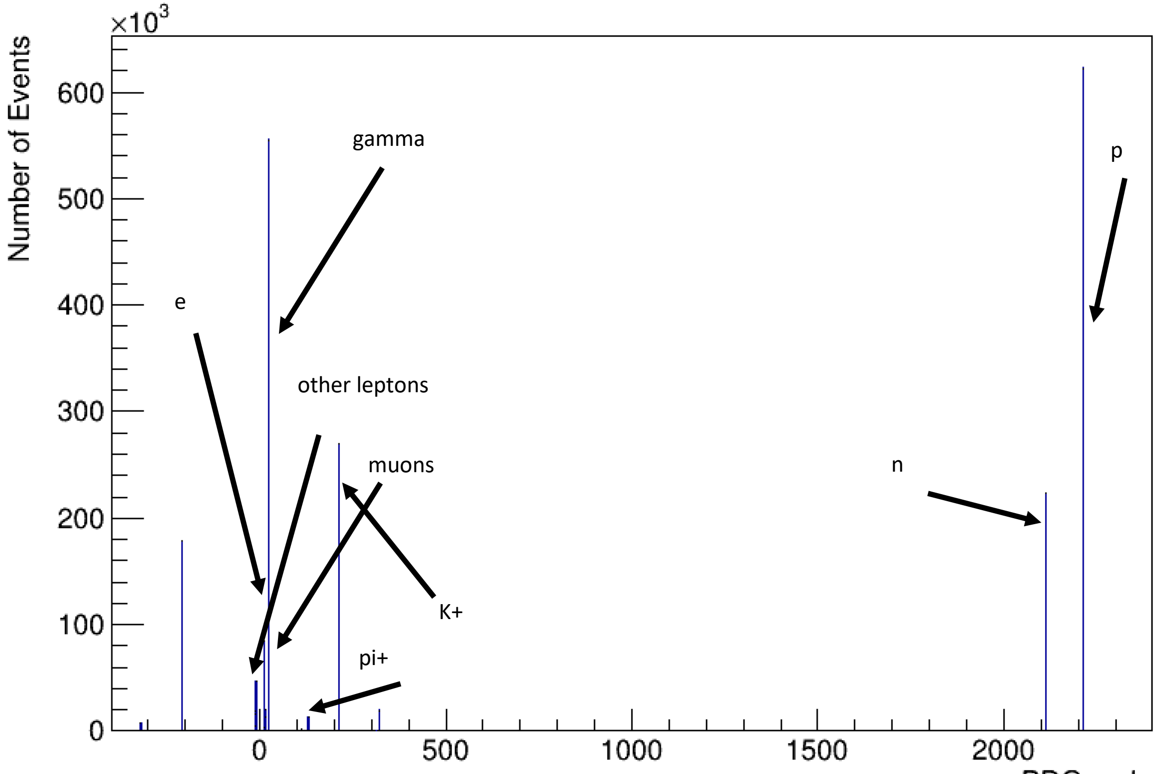


Fig. 13 - All particles produced by Pythia8

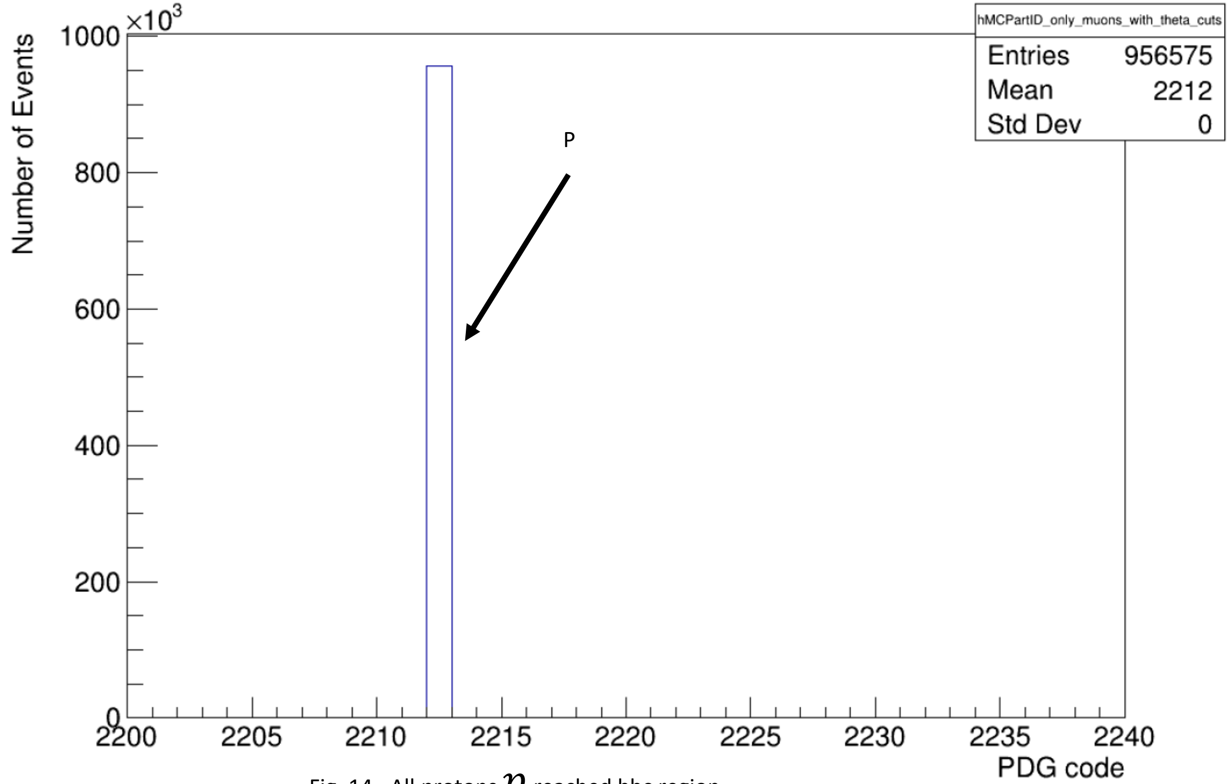
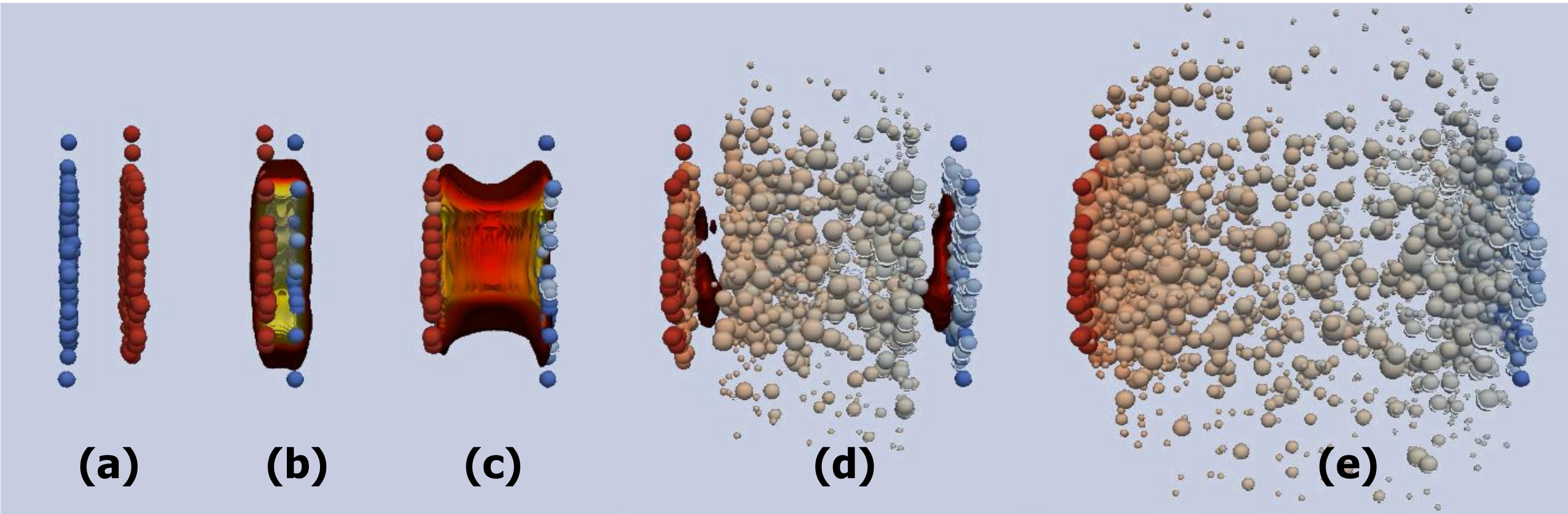


Fig. 14 - All protons p reached bbc region

Ion physics: collisions of heavy ions in experiment

1. The colliding nuclei fly towards each other **(a)**,
2. pass through each other, forming excited matter **(b)**.
3. The hot region expands and cools **(c)**,
4. a gas of interacting hadrons is formed **(d)**,
5. which expands, cools and disintegrates into final hadrons **(e)**

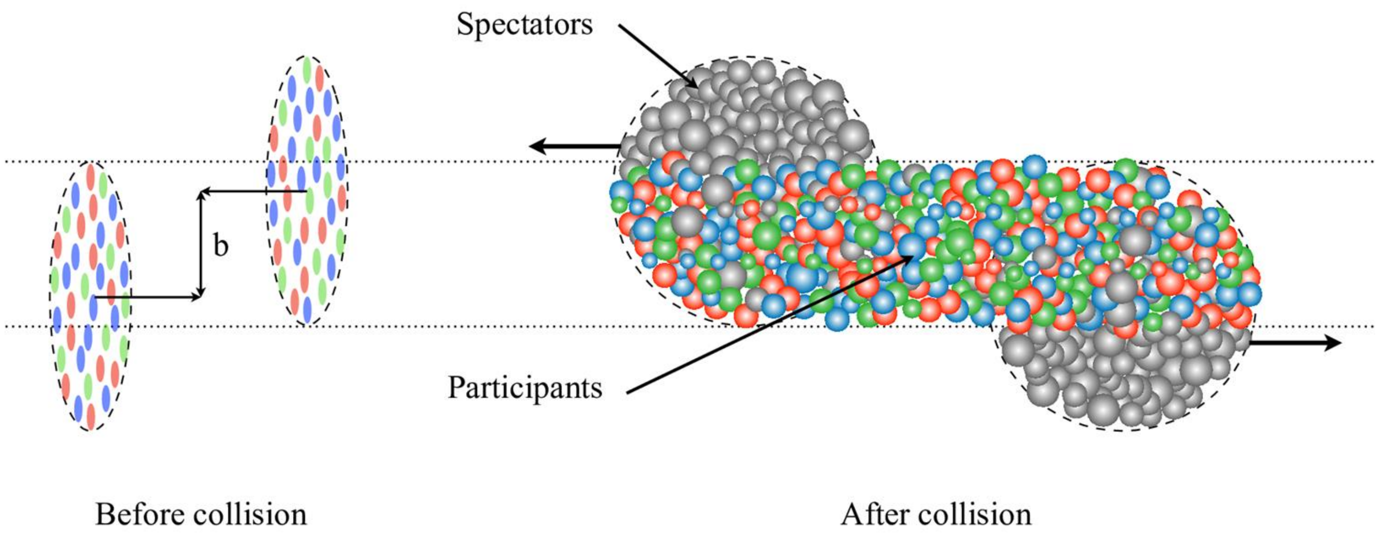


Schematic representation of a heavy ion collision.

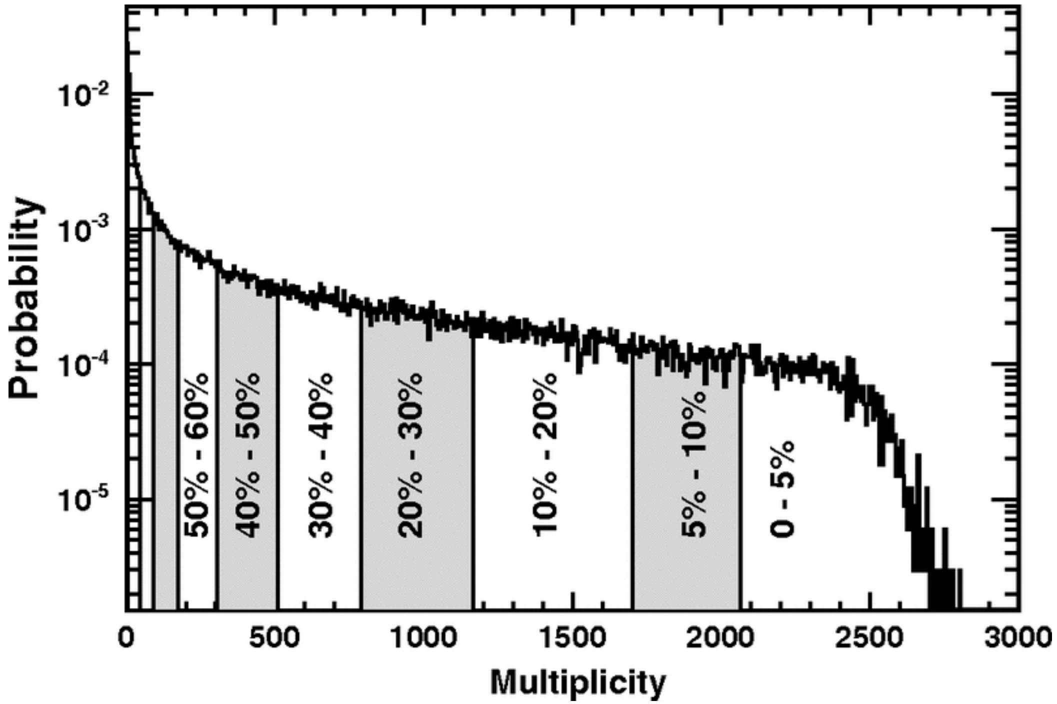
- **Chemical freeze-out** occurs at a temperature (**T_{ch}**) when inelastic processes that convert one kind of hadronic species into a different one cease and the hadronic abundances stop changing.
- **Kinetic freeze-out** occurs at a temperature (**T_{kin}**) when the momenta of the particles stop changing, i.e., elastic and inelastic scatterings cease

Ion physics: Collision centrality

- **Impact parameter b** represents a vector connecting the ion centers.
- Collision **centrality** was selected according to the fraction of integral of the impact parameter distribution.
- Central collisions correspond to the small length of b, while peripheral to the large length of impact parameter.



A schematic view of a heavy-ion collision.



Example of multiplicity distribution of charged particles