π^- production in central Pb+Pb collision at 30*A* GeV/*c* from NA61/SHINE

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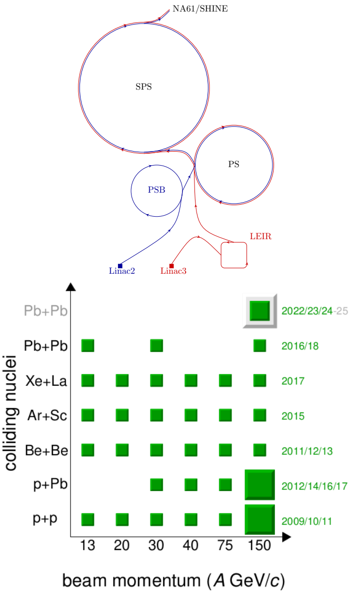
Outline

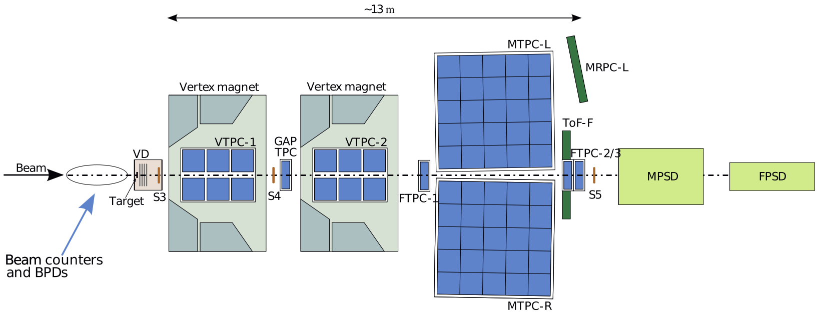
- Experiment and theoretical background:
  - NA61/SHINE experiment and detector system
  - Signatures of onset of deconfinement predicted by Statistical Model of the Early Stage (SMES)
- Analysis and results:
  - h^- particle identification method
  - Spectra of π^-
  - π^- yields in Pb+Pb collision at 30A GeV/c and comparison with NA49 results

NA61/SHINE Experiment



- Particle physics experiment at SPS at CERN.
- Fixed target.
- The main physics goals:
  - Study the properties of the onset of deconfinement and search of the critical point of strongly interaction matter.
  - Reference measurements for neutrino and cosmic ray physics (Hadron+Nucleus collisions).
- 2D scan in collision energy and mass of colliding nuclei
- *p*+*p* and Nucleus+Nucleus collisions.

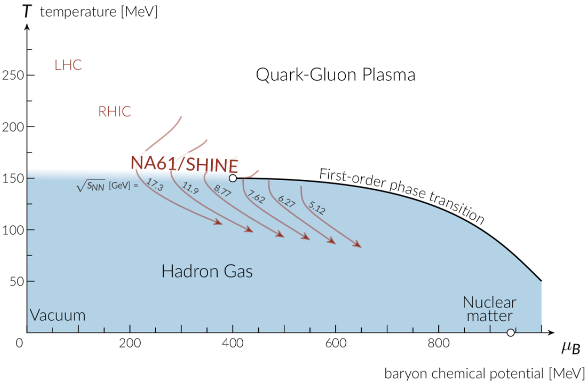
NA61/SHINE detector



- Beam counters and Beam Position Detectors (BPDs)
- Time Projection Chambers (TPCs): for particle identification
- Time-of-Flight detectors (ToF)
- Projectile Spectator Detectors (PSDs): for centrality determination
- Ion beams (Be, Ar, Xe, Pb) at 13*A*-150*A* GeV/*c*
- Coverage of the full forward hemisphere, down to transverse momentum $p_T = 0$

N. Abgrall et al., "NA61/SHINE facility at the CERN SPS: beams and detector system," JINST, vol. 9, p. P06005, 2014

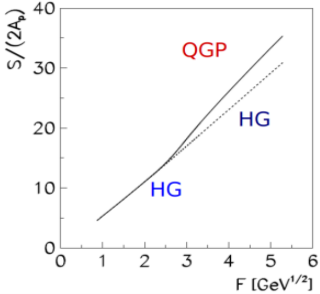
Phase diagram of strongly interacting matter



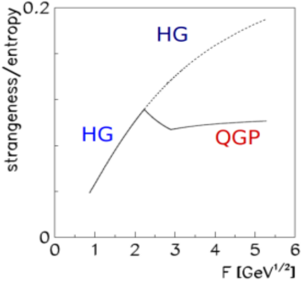
- For low μ_{B} and $T \approx 155$ MeV a crossover between hadron gas and QGP occurs.
- For higher values of μ_{B} (sufficiently high density), confined hadronic matter undergoes a phase transition to a deconfined state of QGP.
- SMES proposes a number of signals of the onset of deconfinement that can be tested experimentally.

Signature of onset of deconfinement by SMES

KINK



HORN

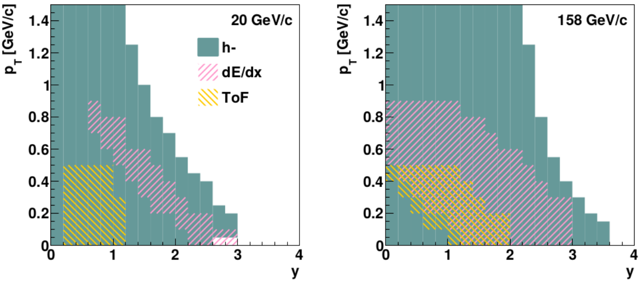


KINK: Collision energy vs entropy normalized to number of wounded nucleons.
HORN: Collision energy vs strangeness to entropy ratio.

- $F \approx (s_{NN})^{1/4}$ is fermi energy variable, $(s_{NN})^{1/2}$ is collision energy per nucleon pair in the center of mass
- π yield related to entropy production
- K yield related to strangeness production
- HORN plot: Strangeness to entropy ratio is measured as K^+/π^+
- Increase of $\langle \pi \rangle / \langle W \rangle$ can be related to activation of additional quark-gluon degrees of freedom
- KINK plot: $W \rightarrow MC$, $\langle \pi \rangle \rightarrow experiment$

As predicted in: Gazdzicki, Gorenstein; Acta Phys.Polon.B 30 (1999) 2705

Motivation and the analysis methods



- h^-: Estimates multiplicities of π^- using the fact that about (90%) of all negatively charged hadrons are π^-, very large phase space coverage.
- dE/dx: Estimates multiplicities of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ using energy loss measurements in TPCs.
- *tof*-dE/dx: Estimates multiplicities of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ using energy loss and particle time of flight measurements in ToFs.
- Main motivation:

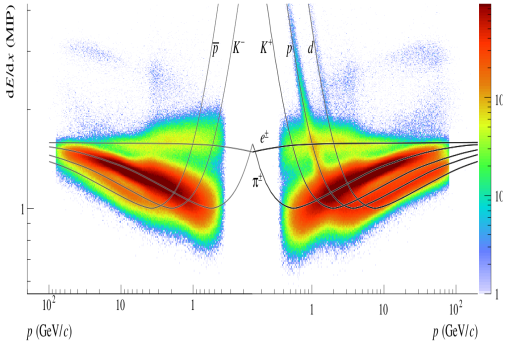
  tof-dE/dx+ dE/dx + h^- analysis method $\longrightarrow$ HORN

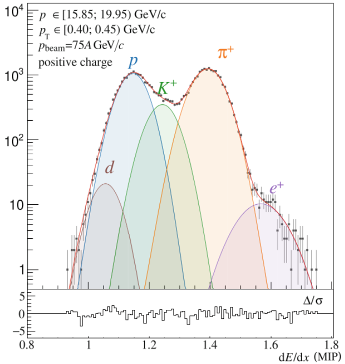
  h^- analysis method $\longrightarrow$ KINK

h^- analysis method

- The experimental data undergoes a series of quality cuts.
- Event centrality classes are chosen based on the projectile spectator energy (E_{F}) measured by the Projectile Spectator Detector (PSD).
- A spectra of negatively charged particles are determined using the selected events and tracks.
- The spectra are corrected for acceptance, reconstruction efficiency and contamination of particles (like K^-, $\bar{p}$,...) other than primary π^- by Monte Carlo EPOS model.
- Mean multiplicity $\langle\pi\rangle$ in 4π is estimated by summing up the measured spectra and correcting it for missing acceptance by extrapolation.

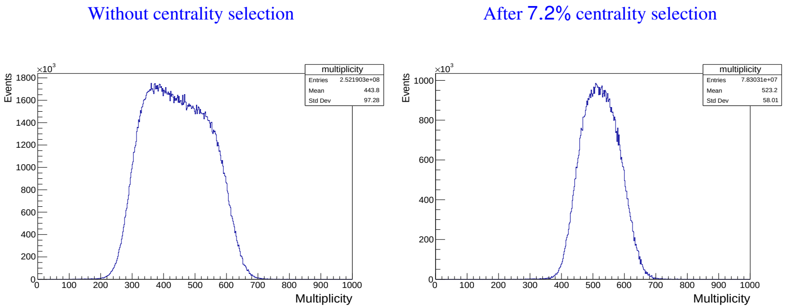
Identification of charged particles (dE/dx method)





dE/dx method uses energy loss information of charged particles in TPCs for identification. The curves calculated using the Bethe-Bloch function show the expected dependence of the mean dE/dx on momentum for various particles.

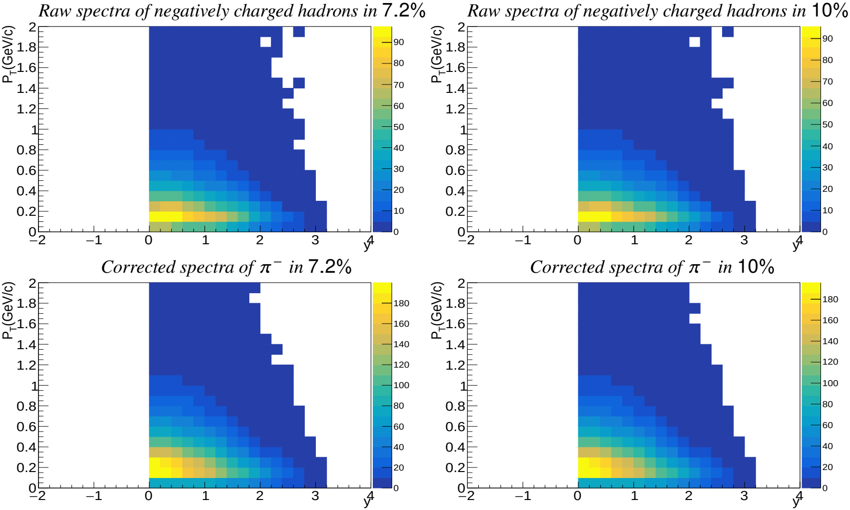
Multiplicity distributions



Multiplicity distribution of Vertex Tracks per Events in Pb+Pb collision at 30*A* GeV/*c*

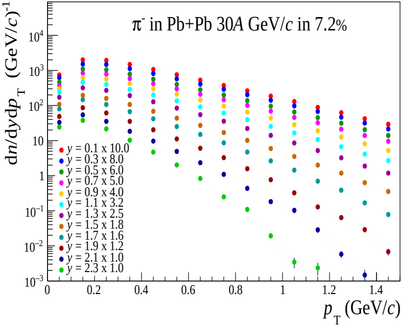
- Online event selection by the hardware trigger (T2) used sum of electronic signals from the 16 central modules of the PSD set to accept≈30%.
- The energy deposited in the PSD is proportional to the number of projectile spectators and therefore can be a measure of event centrality.
- Centrality was measured from forward energy using PSD acceptance map.
- Results on central collisions allow a precise comparison with predictions of models.

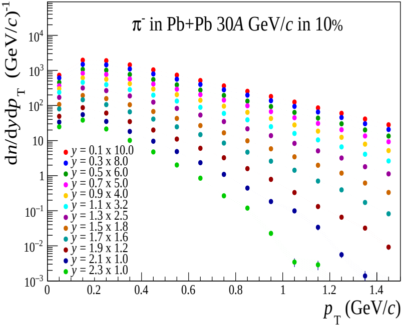
$d^2n/dy\,dp_T$ spectra and MC corrections



- Rapidity (y) is calculated in the nucleon-nucleon collision center of mass system
- Double-differential spectra are normalized using number of data and MC events
- To compute y in full phase-space and mean multiplicity $\langle \pi^- \rangle$, measured data are extrapolated to unmeasured regions

p_T spectra of π^-





- The p_T distributions in each rapidity bin were extrapolated using :

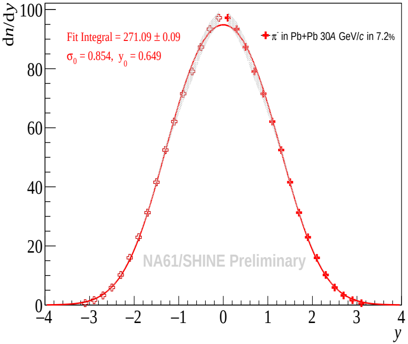
$$\frac{d^2n}{dy\,dp_T} = C\,p_T\ exp\left[\frac{-(m_T - m_{\pi^-})}{T}\right] \qquad (1)$$

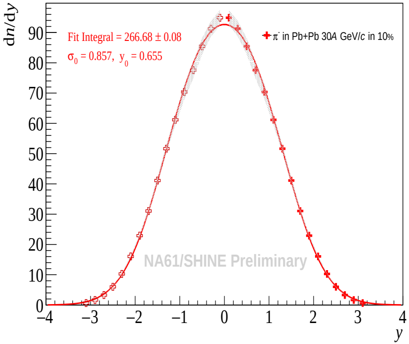
m_{π^-}, m_T: mass and transverse mass of pion

- $d^2n/dy\,dp_T$ is integrated up to p_T 1.5 GeV/c. To obtain rapidity spectra dn/dy, the measured p_T data bins are summed and the integral of the extrapolated curve is added:

$$\frac{dn}{dy} = \sum_{0}^{p_T^{max}} dp_T \left(\frac{d^2n}{dy\,dp_T}\right)_{measured} + \int_{p_T^{max}}^{100} f(p_T)\,dp_T \qquad (2)$$

Rapidity spectra of π^-



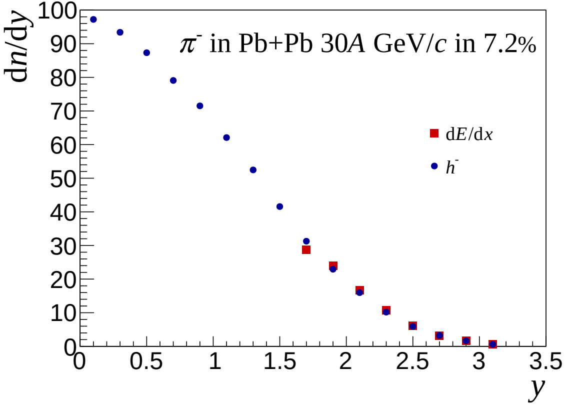


- To extrapolate rapidity spectra to the missing rapidity acceptance a sum of two symmetrically Gaussian functions is used:

$$P(y) = \frac{A}{\sigma_0\sqrt{2\pi}}\left[exp\left(\frac{-(y-y_0)^2}{2\sigma_0{}^2}\right) + exp\left(\frac{-(y+y_0)^2}{2\sigma_0{}^2}\right)\right] \quad (3)$$

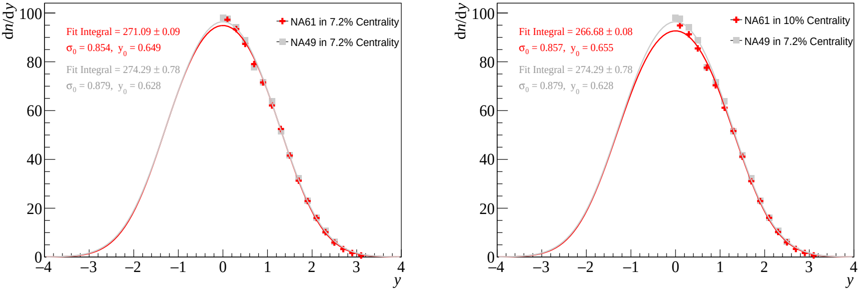
- Mean pion multiplicity is calculated as fit integral..
- For all spectra open points are reflected measured data points.

Rapidity spectra - comparison of methods



- Due to overlapping of all particles in d*E*/d*x* method, it used for $p_{tot} > 5$ GeV/*c*
- h^- provides the largest phase space coverage
- Good agreement of both results within uncertainties

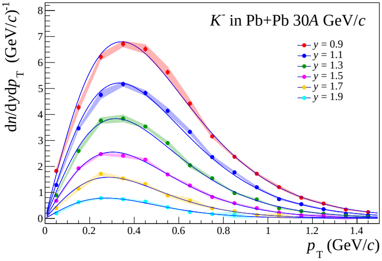
Comparison with NA49 results

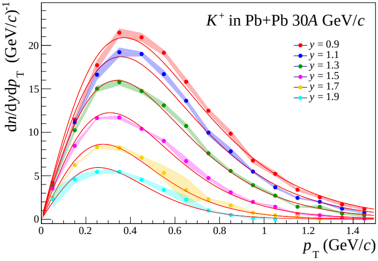


	$\langle \pi^- \rangle$	$(\frac{dn}{dy})_{y \approx 0.1}$
NA49 in 7.2%	274 ± 1 ± 14	96.5 ± 0.5 ± 4.8
NA61 in 7.2%	271.09 ± 0.09 ± 14.69	97.23 ± 0.09 ± 2.38
NA61 in 10.0%	266.68 ± 0.08 ± 15.06	94.88 ± 0.07 ± 2.53

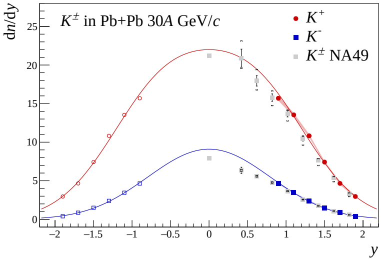
"Pion and kaon production in central Pb+Pb collisions at 20A and 30A GeV: Evidence for the onset of deconfinement,"PHYSICAL REVIEW C 77, 024903 (2008)

Spectra of K^+ and K^-



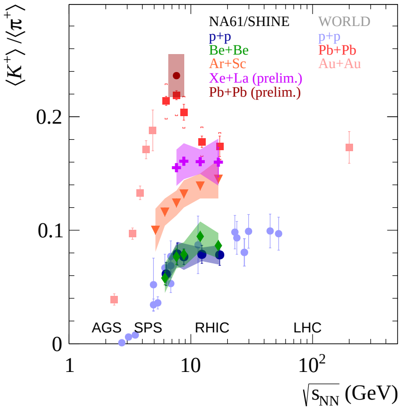


- K^+ and K^- are measured by dE/dx method.
- p_T spectra is fitted by equation (1).
- $d^2n/dydp_T$ is integrated up to p_T 1.5 GeV/c and added with the integral of extrapolation of fit function in selected rapidity intervals to get the dn/dy.
- Rapidity is fitted by equation (3).
- The fit parameters are taken from NA49 at Pb+Pb 30A GeV/c and mean kaons multiplicities are measured by extrapolation of the fit.



Horn plot

- NA61/SHINE $\langle \pi^- \rangle$ was obtained by h^- method while $\langle \pi^+ \rangle$ was calculated from $\langle \pi^+ \rangle / \langle \pi^- \rangle$ NA49 results.
- NA61/SHINE $\langle K^+ \rangle$ was obtained by dE/dx method.
- The $\langle K^+ \rangle / \langle \pi^+ \rangle$ in central Pb+Pb 30A GeV/c measured by NA61/SHINE is in agreement with NA49 data and *horn* plot.
- In previous results: Horn is observed in Pb+Pb, Au+Au data but not in p+p, Ar+Sc and Xe+La.



Summary

- Double-differential spectra of π^- in central Pb+Pb collisions at 30A GeV/c were calculated.
- dn/dy spectra and mean multiplicity of π^- in central Pb+Pb collision at 30A GeV/c were obtained.
- Mean multiplicity of K^+ in central Pb+Pb collision at 30A GeV/c were measured by dE/dx method.
- The $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio in central Pb+Pb 30A GeV/c measured by NA61/SHINE (shown in *horn* plot) is in agreement with NA49 and STAR data.

Thank you very much for your attention!

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Backup slides

Simplified analytical prediction of KINK

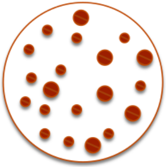
$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln\left[1 \pm e^{-\frac{E_i - \mu_i}{T}}\right]$$

$$m = 0,\ \mu = 0$$

$$\varepsilon = \frac{E}{V} = \frac{\pi^2}{30} g T^4 \qquad S = \frac{2\pi^2}{45} g V T^3$$

Hadron Gas

QGP



$$S \propto V \varepsilon^{3/4} g^{1/4}$$

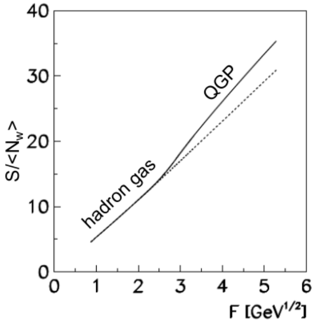
$$S_{ES} \propto \langle N_w \rangle \frac{1}{\sqrt{s_{NN}}} \left[\left(\sqrt{s_{NN}} - 2m_N\right)\sqrt{s_{NN}}\right]^{3/4} g^{1/4}$$

$$\frac{S_{ES}}{\langle N_w \rangle} \propto g^{1/4} F$$

$$\langle \pi \rangle \propto S_{FO} = S_{ES}$$

$$\frac{\langle \pi \rangle}{\langle N_w \rangle} \propto g^{1/4} F$$

$$g_{QGP} > g_{HG}$$



Simplified analytical prediction of HORN

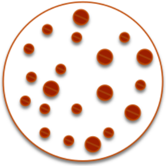
$$\langle N_i \rangle = -T \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i V}{2\pi^2} \int_0^\infty p^2 dp e^{-\frac{\sqrt{p^2+m^2}}{T}}$$ Boltzmann limit

hadron gas

$$m/T \to \infty, \quad \sqrt{p^2+m^2} \equiv \frac{p^2}{2m} + m, \quad \langle N \rangle \propto T^{3/2} e^{-m/T}$$

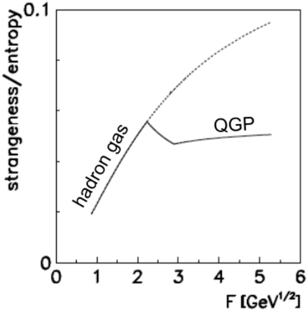
$$\frac{\text{strangeness}}{\text{entropy}} \propto T^{-3/2} e^{-m/T}$$

QGP



$$m/T \to 0, \quad \langle N_i \rangle \propto T^3$$

$$\frac{\text{strangeness}}{\text{entropy}} = \text{const}$$



Systematic uncertainty calculations for rapidity spectra

- 1) Reconstruction quality: It is all mostly affect by detector properties that we try to regulate with certain cuts:

- WFA S11: $\pm 20\mu s$
- Vertex z-axis($\pm 5cm$): position $-597.9cm < z < -585.9cm$
- Vertex z-axis($\pm 2cm$): position $-594.9cm < z < -588.9cm$
- VTPC > 10
- VTPC > 20
- Impact parameter: $|b_x| < 5cm$ and $|b_y| < 3cm$
- Impact parameter: $|b_x| < 3cm$ and $|b_y| < 1cm$

The total systematic uncertainties are:

$$\sigma_{sys} = \sqrt{\sum_i \sigma_i^2}$$

where σ_i represents uncertainty due to each parameter.

- 1) Uncertainties due to reconstruction quality:
  - The contribution to the systematic uncertainty of mean multiplicity in 7.2% and 10% centrality is on the level of: ± 7.21 and ± 7.67
- 2) Uncertainty of extrapolation in p_T is taken 25% of the fit integral:
  - The contribution to the systematic uncertainty of mean multiplicity in 7.2% and 10% centrality is on the level of: ± 0.22 and ± 0.25
- 3) Uncertainty of extrapolation in y is taken 5% of the fit integral:
  - The contribution to the systematic uncertainty of mean multiplicity in 7.2% and 10% centrality is on the level of: ± 7.26 and ± 7.14

Multiplicative and additive correction models

Multiplicative and additive corrections are respectively:

$$n_i^{corrected} = n_i^{raw\,(all\ particles)} \times \frac{n_i^{MCsim\,(only\ pions)}}{n_i^{MCrec\,(all\ particles)}}$$

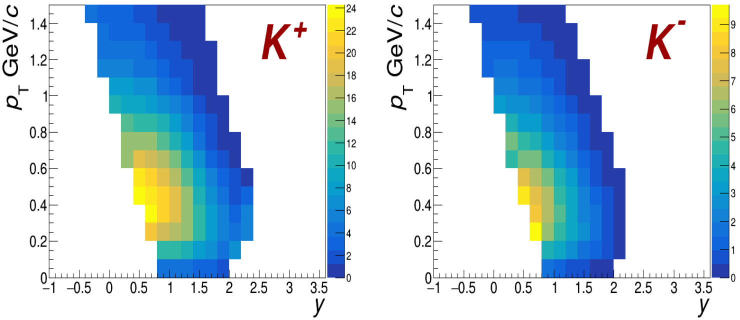
$$n_i^{corrected} = [n_i^{raw\,(all\ particles)} - C_r] \times \frac{n_i^{MCsim\,(only\ pions)}}{C_p}$$

$$C_r = n^{rec}_{decay\ of\ K^-, \bar{p}\ and\ others}$$

$$C_p = n^{rec}_{primary+\ secondary\ not\ from\ decay}$$

The global tuning factor is obtained by comparing published data with MC-generated multiplicities.

2D spectra of identified charged kaons (dE/dx)



The y vs p_T spectra of identified $K^{\pm}$ in Pb+Pb 30*A* GeV/*c* are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions using EPOS.