

# Investigation of the onset of deconfinement with the NA61/SHINE experiment

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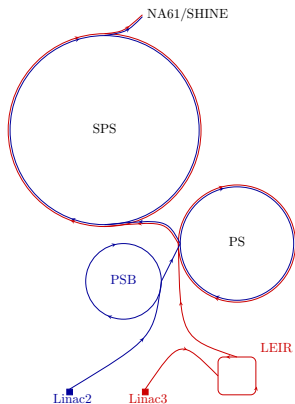
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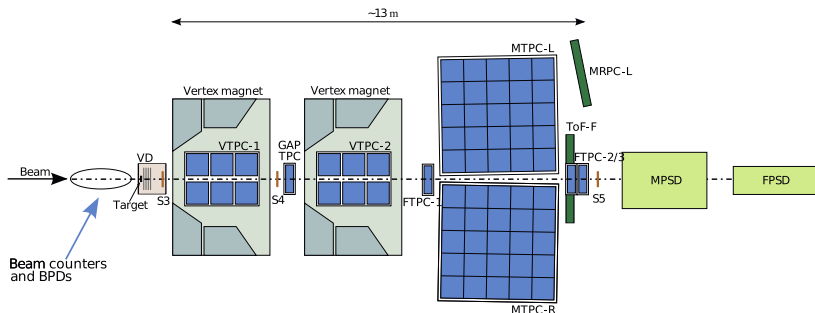
- NA61/SHINE experiment
- Phase diagram and the onset of deconfinement
- Particle identification methods
- Results for Pb+Pb collisions at 30A GeV/c
- Horn and Kink plots
- Summary

# NA61/SHINE experiment



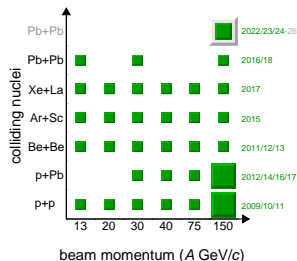
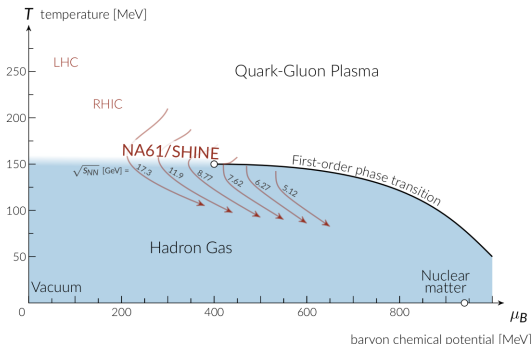
- Fixed target experiment at CERN SPS.
- The main physics goals:
  - Study the properties of the onset of deconfinement and search for the critical point of strongly interacting matter
  - Reference measurements for neutrino and cosmic-ray physics

# NA61/SHINE detector



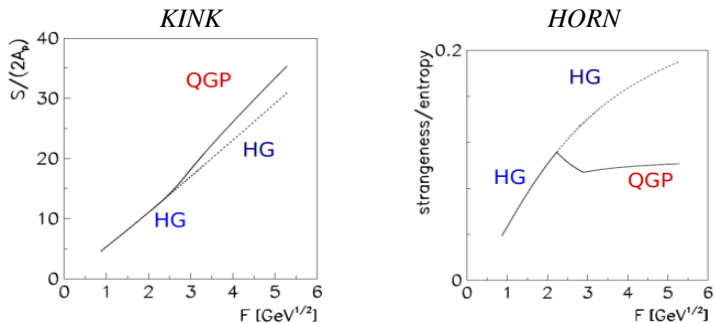
- Beam counters and Beam Position Detectors (BPDs)
- Time Projection Chambers (TPCs): for particle identification
- Time-of-Flight detectors (ToF): for particle identification
- Projectile Spectator Detectors (PSDs): for centrality determination
- Coverage of the full forward hemisphere
- High momentum resolution, down to  $p_T = 0$

# Phase diagram of strongly interacting matter



- Crossover at low  $\mu_B$  and  $T \approx 157$  MeV  
*PLB795(2019)15 and PRL125(2020)5,052001*
- First-order phase transition at higher  $\mu_B$
- 2D scan in beam momentum and mass of colliding nuclei including  $p+p$ ,  $p+p_b$  and  $A+A$  collisions
- Statistical Model of Early Stage (SMES) model proposes signals of the onset of deconfinement that can be tested experimentally  
*Statistical Model of Early Stage (SMES): APP B30 (1999) 2705*

# Signature of onset of deconfinement by SMES



KINK: Entropy normalized to the number of wounded nucleons vs Fermi energy

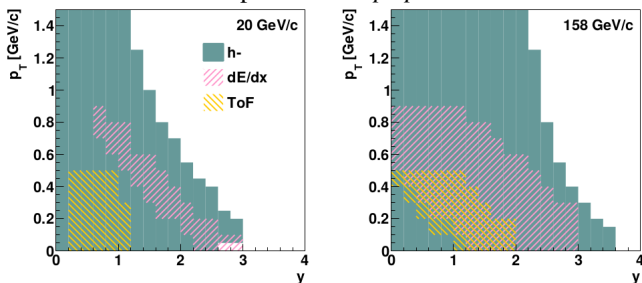
HORN: Strangeness to entropy ratio vs Fermi energy

$F \approx (s_{NN})^{1/4}$ : fermi energy variable,  $(s_{NN})^{1/2}$ : collision energy per nucleon pair in the center of mass

- $\pi$  yield related to entropy production
- $K$  yield related to strangeness production
- HORN plot:  $K^+/\pi^+$  is approximately proportional to strangeness to entropy ratio
- KINK plot: The larger number of effective degrees of freedom in QGP

*As predicted in: APP B30 (1999) 2705*

## Acceptance from $p+p$ collisions

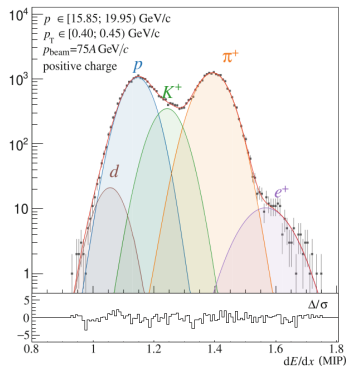
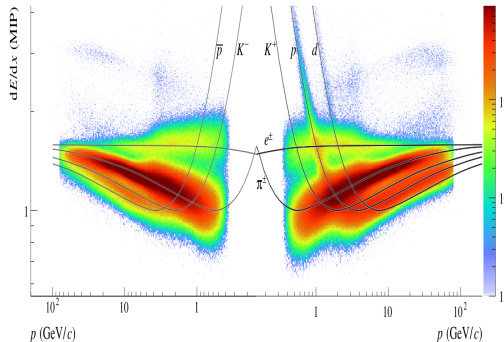


- $h^-$ : Based on the fact that  $\approx 90\%$  of negatively charged particles are  $\pi^-$ .  
The contribution of other particles subtracted using EPOS MC
- $dE/dx$ : Based on energy loss measurements in TPCs
- $tof-dE/dx$ : Based on energy loss measurements in TPCs and time of flight from ToFs
- **Main motivation:**

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

$h^-$  analysis method  $\rightarrow$  KINK

# $dE/dx$ method



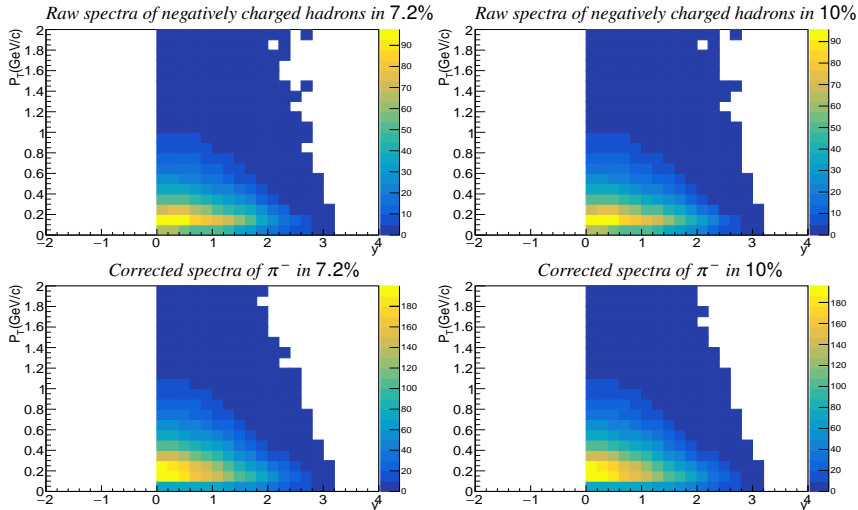
$dE/dx$  method uses energy loss measurements of charged particles in TPCs for identification. The curves calculated using the Bethe-Bloch function show the expected dependence of the mean  $dE/dx$  on momentum for various particles

# Analysis steps

- The experimental data undergoes a series of quality cuts
- Event centrality classes are chosen based on the projectile spectator energy measured by the Projectile Spectator Detector (PSD)
- The 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  $\pi^-$  by Monte Carlo EPOS model (for  $h^-$  method)
- Mean multiplicity  $\langle \pi^- \rangle$  in  $4\pi$  is estimated by summing up the measured spectra and correcting them for missing acceptance by extrapolation (for  $h^-$  method)

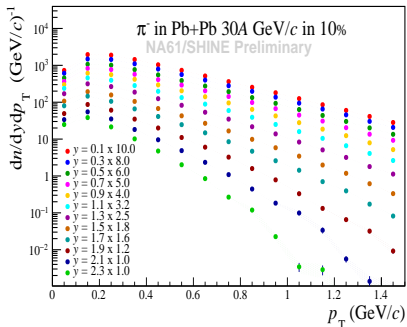
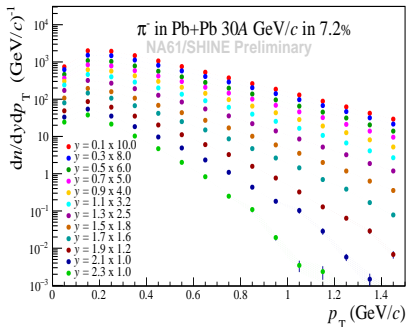
# Results for Pb+Pb at 30A GeV/c

# $d^2n/dydp_T$ and MC corrections of Pb+Pb at 30A GeV/c



- 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

# $p_T$ spectra of $\pi^-$



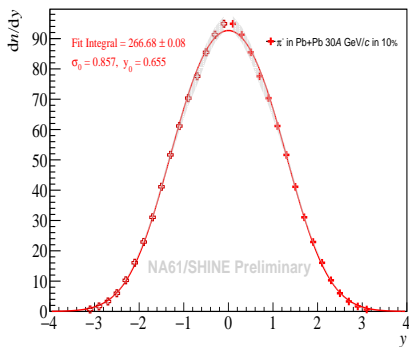
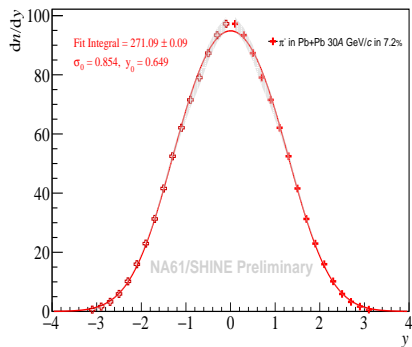
- The  $p_T$  distributions in each rapidity bin were extrapolated using :

$$\frac{d^2n}{dydp_T} = C_{p_T} \exp\left[\frac{-(m_T - m_{\pi^-})}{T}\right] \quad m_{\pi^-}, m_T: \text{mass and transverse mass of pion} \quad (1)$$

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

$$\frac{dn}{dy} = \sum_0^{p_T^{\max}} dp_T \left( \frac{d^2n}{dydp_T} \right)_{\text{measured}} + \int_{p_T^{\max}}^{\infty} f(p_T) dp_T \quad (2)$$

# Rapidity spectra of $\pi^-$

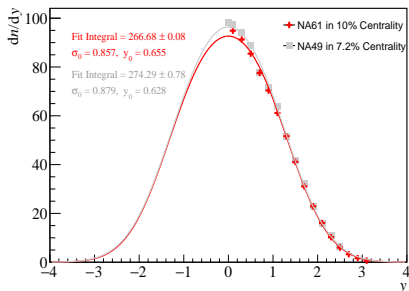
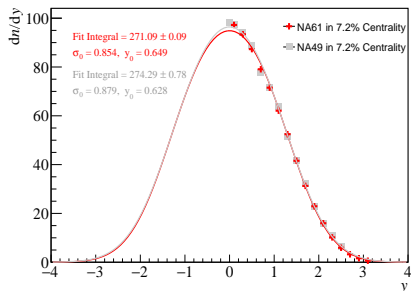


- To extrapolate rapidity spectra to the missing rapidity acceptance a sum of two symmetrically Gaussian functions is used:

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

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

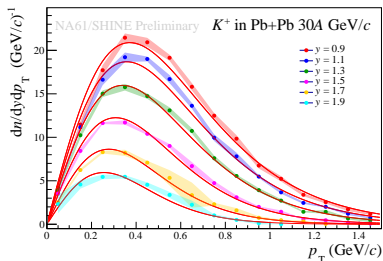
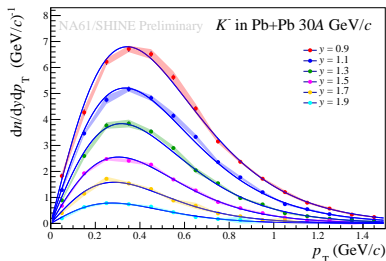
# Comparison with NA49 results



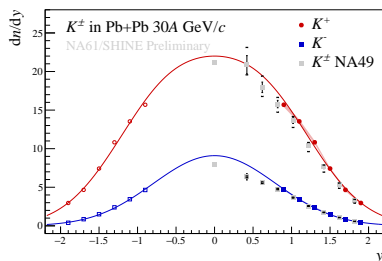
	$\langle \pi^- \rangle$	$(\frac{dn}{dy})_{y=0.0-0.2}$
NA49 in 7.2%	$274 \pm 1 \pm 14$	$97.6 \pm 0.8 \pm 4.9$
NA61 preliminary in 7.2%	$271.09 \pm 0.09 \pm 15$	$97.23 \pm 0.09 \pm 2.4$
NA61 preliminary in 10%	$266.68 \pm 0.08 \pm 15$	$94.88 \pm 0.07 \pm 2.5$

NA49: PRC 77 (2008) 024903

# Spectra of $K^+$ and $K^-$ in 7.2% centrality

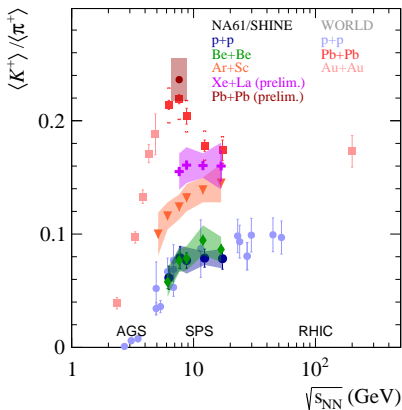


- $K^+$  and  $K^-$  are measured by  $dE/dx$  method
- $p_T$  spectra is fitted by function (1)
- $d^2n/dydp_T$  is summed up to  $p_T=1.5$  GeV/c and added with the integral of extrapolation of fit function in selected rapidity intervals to get the  $dn/dy$ .
- Rapidity is fitted by function (3)
-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



# Horn plot

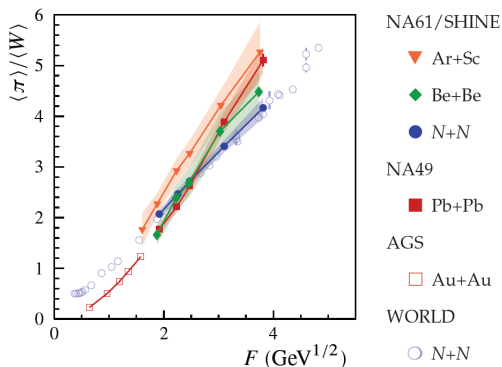
- NA61/SHINE  $\langle\pi^+\rangle$  in Pb+Pb at 30A GeV/c was obtained by scaling  $\langle\pi^-\rangle$  with ratio  $\langle\pi^+\rangle/\langle\pi^-\rangle$  calculated by NA49
- NA61/SHINE  $\langle K^+\rangle$  in Pb+Pb at 30A GeV/c was obtained by  $dE/dx$  method
- The  $\langle K^+\rangle/\langle\pi^+\rangle$  in central Pb+Pb at 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  $p+p$ , Be+Be, Ar+Sc and Xe+La



World data:EPJC 84(2024) 4,416

# Kink plot

- Results for inelastic nucleon-nucleon reactions and central nucleus-nucleus collisions are compared
- The steepening of the slope of the  $\langle \pi \rangle / \langle W \rangle$  is observed in central Pb+Pb collisions but it not visible in central Ar+Sc collisions
- The suppression of the  $\langle \pi \rangle / \langle W \rangle$  in central Pb+Pb collisions compared to N+N reactions is observed only at low energies



*EPJC* 81 (2021) 5, 397.

- Pb+Pb collisions at 30A GeV/c were analyzed to study the properties of the onset of deconfinement in the NA61/SHINE experiment
- Double-differential spectra of  $\pi^-$  in central Pb+Pb collisions were calculated
- $dn/dy$  spectra and mean multiplicities of  $\pi^-$  in central Pb+Pb collision were obtained
- Mean multiplicities of  $K^+$  and  $K^-$  in central Pb+Pb collision were measured by  $dE/dx$  method
- The  $\langle K^+ \rangle / \langle \pi^+ \rangle$  ratio in central Pb+Pb collisions at 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!

# Backup slides

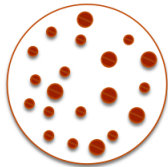
# Simplified analytical prediction of KINK

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

Hadron Gas



QGP



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

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

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

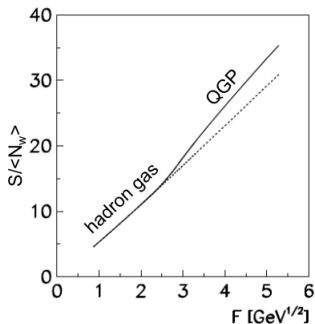
$$S_{ES} \propto \langle N_w \rangle \frac{1}{\sqrt{s_{NN}}} \left[ (\sqrt{s_{NN}} - 2m_N) \sqrt{s_{NN}} \right]^{3/4} g^{1/4}$$

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

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

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

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



# Simplified analytical prediction of HORN

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

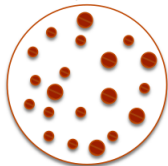
hadron gas



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

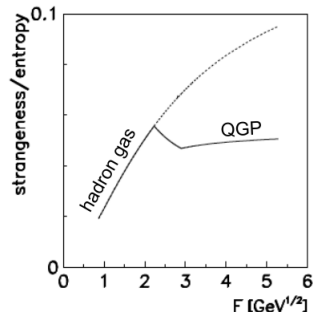
$$\frac{\text{strangeness}}{\text{entropy}} \propto T^{-3/2} e^{-m/T}$$

QGP



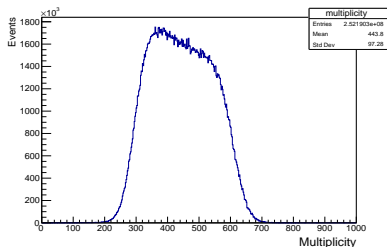
$$m/T \rightarrow 0, \quad \langle N_i \rangle \propto T^3$$

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

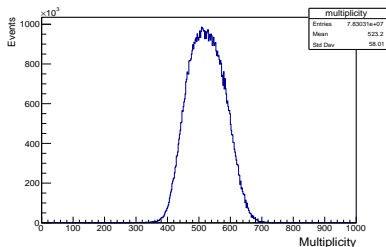


# Multiplicity distributions

Without centrality selection



After 7.2% centrality selection



Multiplicity distribution of Vertex Tracks per Events in Pb+Pb collision at 30A 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  $\approx 30\%$  of the most central interactions
- 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

# Multiplicative and additive correction models

Multiplicative and additive corrections are respectively:

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

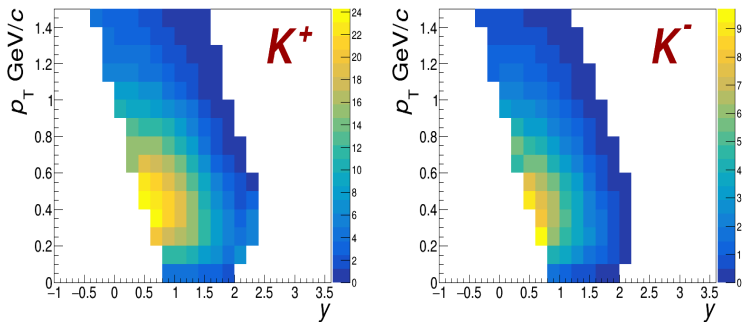
$$n_i^{\text{corrected}} = [n_i^{\text{raw (all particles)}} - C_r] \times \frac{n_i^{\text{MCsim (only pions)}}}{C_p}$$

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

$$C_p = n_{\text{primary+ secondary not from decay}}^{\text{rec}}$$

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

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



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