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Collision energy dependence of identified hadron spectra in p+p interactions and beyond

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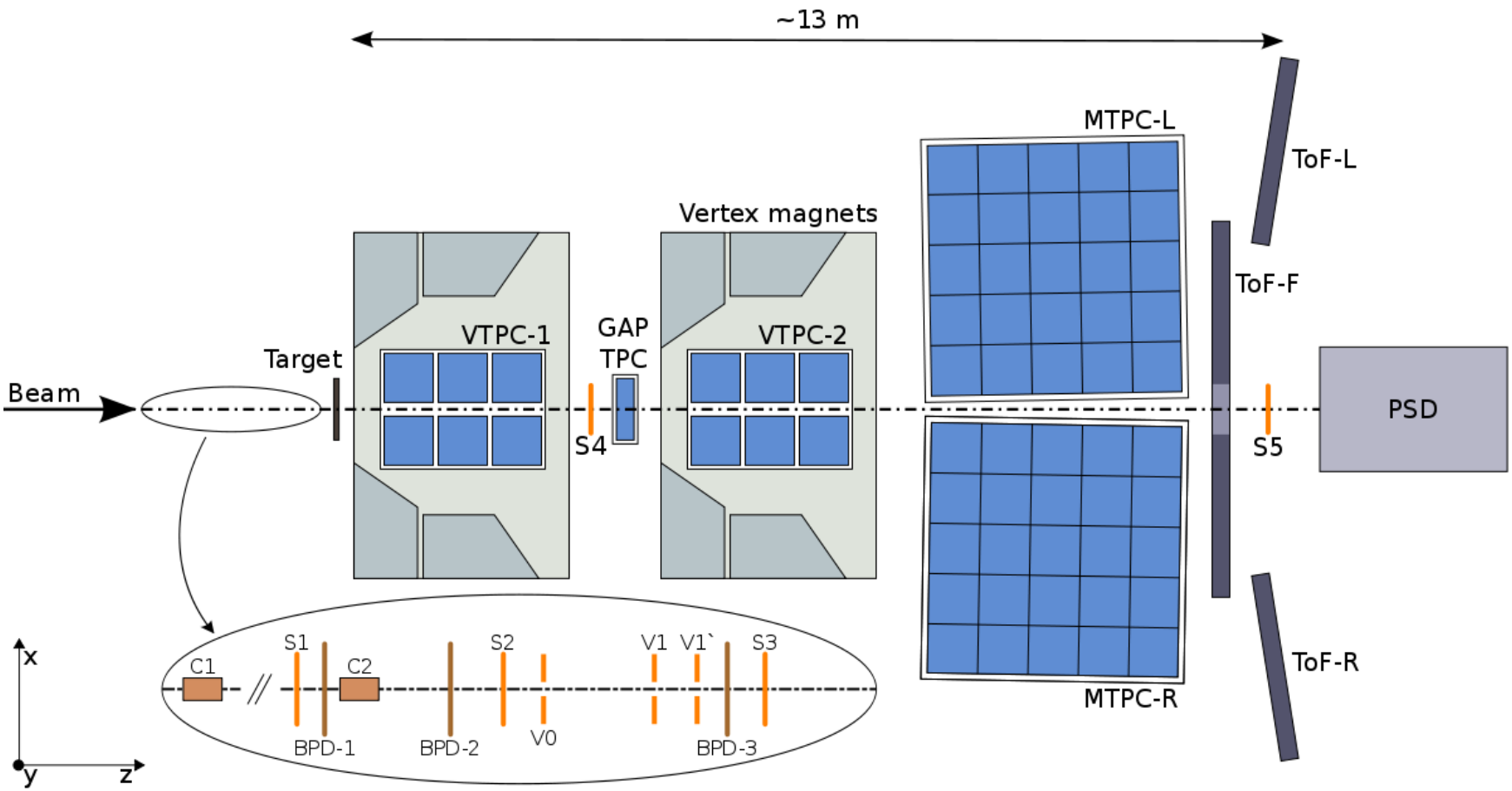
Outline

- NA61 experiment
- Preliminary results
  - Identification method
  - Spectra transverse momentum vs rapidity
  - Comparison with NA49 results
  - Comparison with model
  - Transverse mass spectra
  - Study of the onset of deconfinement
    - Comparison with Pb+Pb data from NA49
- Summary

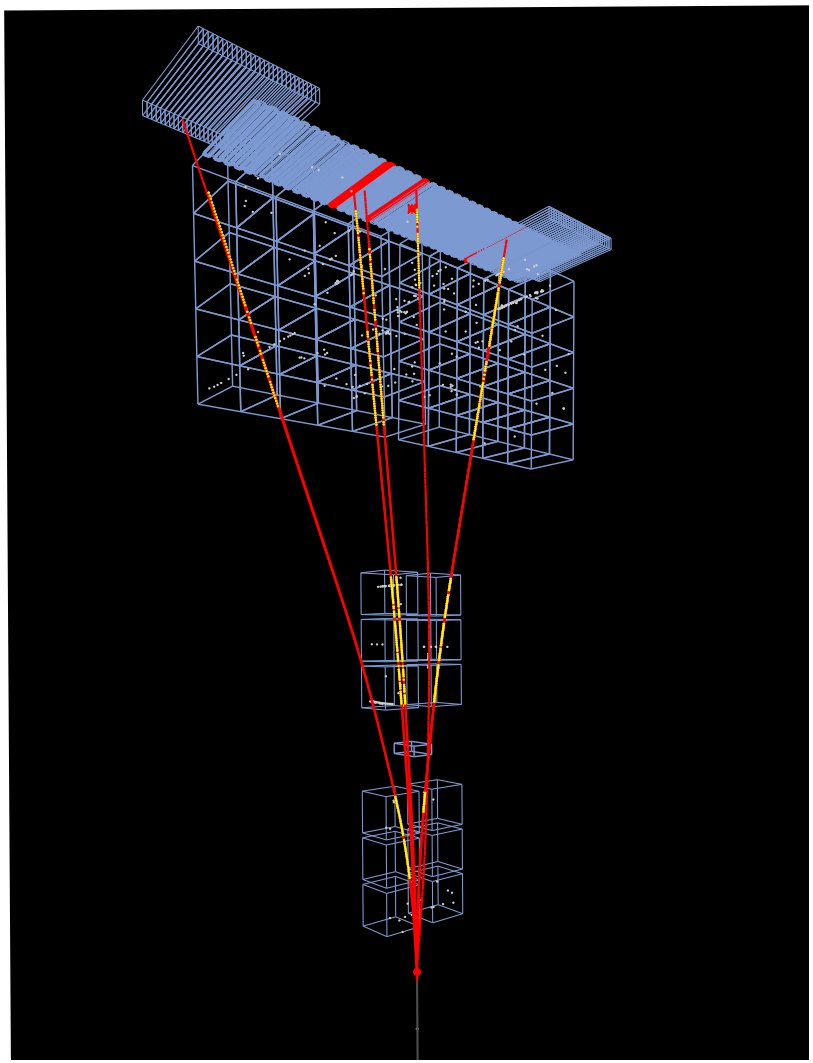
NA61/SHINE - few facts

- Fixed target experiment on primary (ions) and secondary (ions, hadrons) beams (updated NA49 detector system)
- Located at the CERN SPS (North Area, H2 beam line)
- Proposal November 2006, pilot run 2007, first physics run 2009
- NA61 is the second largest non-LHC experiment at CERN
  - TPC read-out channels (181k) = 40% of ALICE TPC
- 140 physicists from 26 institutes and 15 countries

NA61/SHINE detector system

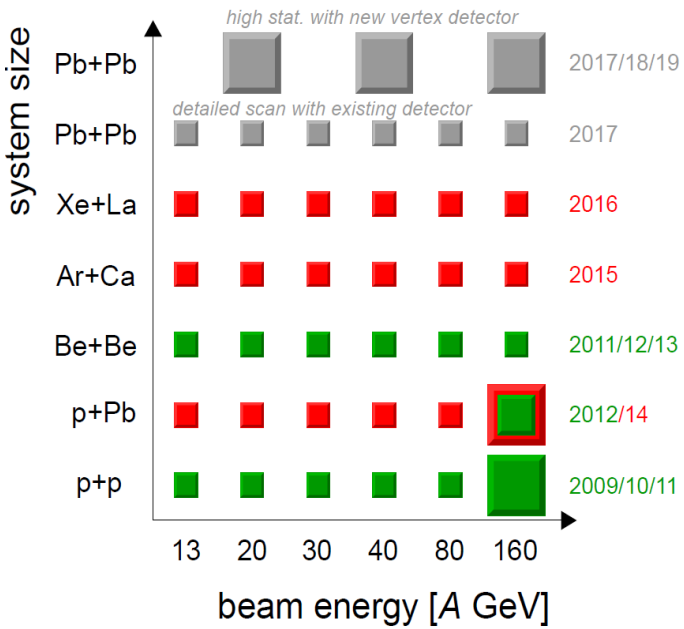


NA61/SHINE detector system

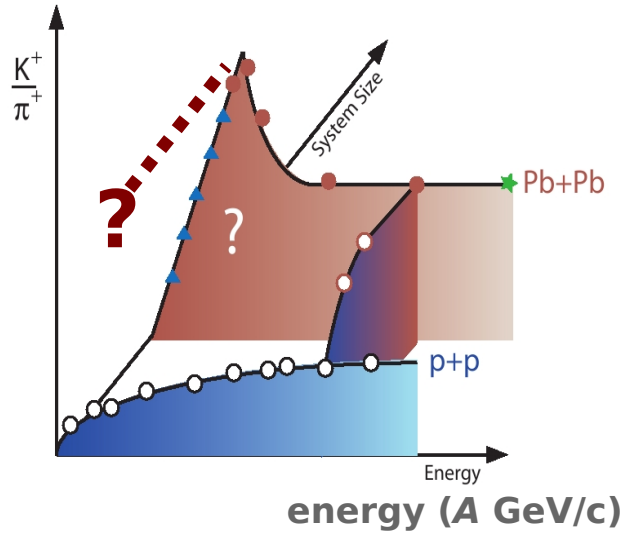


- Large acceptance:$\approx$ 50%
- High momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}\ (GeV/c)^{-1}$ (at full B=9 T m)
- ToF walls resolution: ToF-L/R: $\sigma(t) \approx 60ps$; $ToF-F : \sigma(t) \approx 120ps$
- Good particle identification: $\sigma(dE/dx)/ < dE/dx > \approx 0.04$; $\sigma(m_{inv}) \approx 5MeV$
- High detector efficiency: 95%
- Event rate: 70 events/sec

NA61/SHINE 2D scan goals



Precision measurements
Study of the onset of deconfinement



Discovery potential
Search for the critical point

Be+Be

Preliminary results on p+p interactions

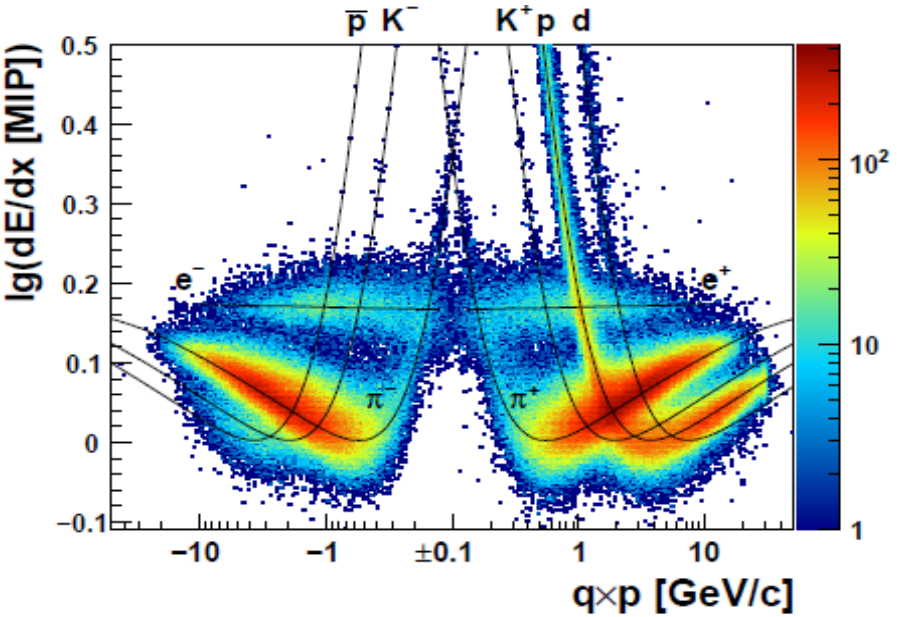
- Data analyzed:

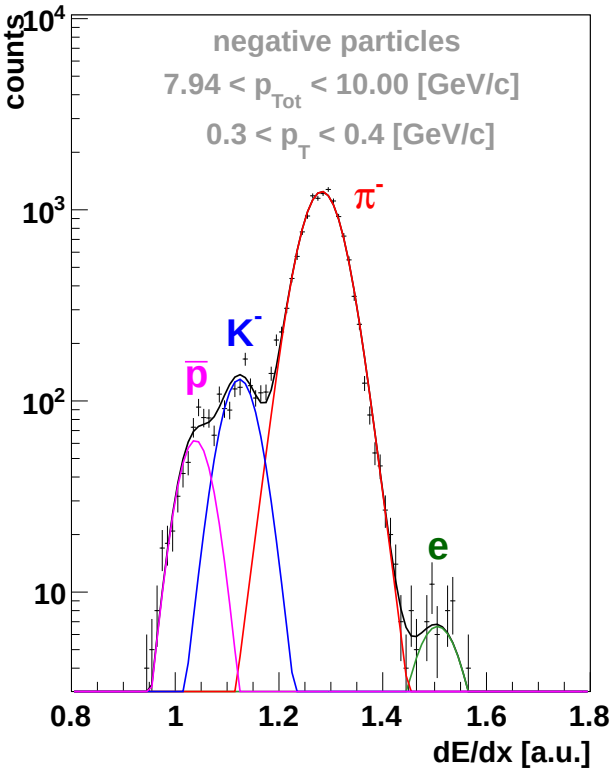
Reaction	Momentum	$\sqrt{s}$	Number of events
p+p	20 GeV/c	6.2 GeV	$1.3 \cdot 10^6$
p+p	31 GeV/c	7.7 GeV	$3.1 \cdot 10^6$
p+p	40 GeV/c	8.8 GeV	$5.2 \cdot 10^6$
p+p	80 GeV/c	12.3 GeV	$4.3 \cdot 10^6$
p+p	158 GeV/c	17.3 GeV	$3.5 \cdot 10^6$

- Analysis of hadrons produced in inelastic p+p collisions.
- Particle spectra:
  - h^- analysis* based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of the other particles is subtracted using VENUS and EPOS Monte-Carlo
  - dE/dx analysis uses TPC energy loss information to identify particles
  - The results are corrected for particles from weak decays (feed-down) and detector effects using Monte-Carlo models
  - Out of target interactions are subtracted using events recorded with empty liquid hydrogen target

*A. Aduszkiewicz EuNPC 2012

dE/dx identification method



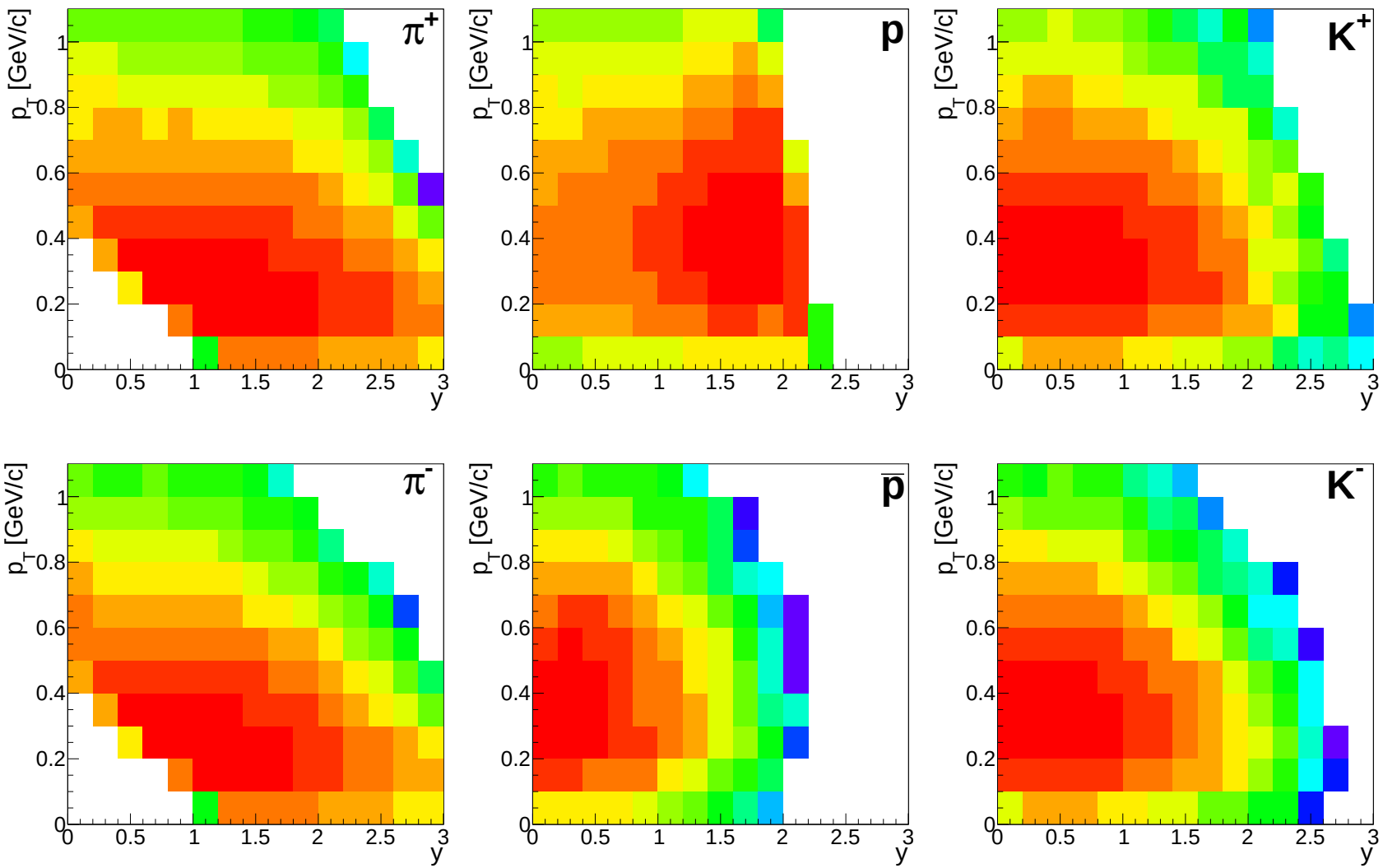


In each bin in p, p_T and q sum of Gauss functions G are fitted to the dE/dx spectrum. For each track its Likelihood values for being a given hadron is calculated based on the fitted dE/dx distribution:

$$L_{\pi,K,p,e}(p_{tot}, p_T, dEdx) = \frac{G_{\pi,K,p,e}(p_{tot},p_T,dEdx)}{\sum_{i=\pi,K,p,e} G_i(p_{tot},p_T,dEdx)}$$

Sum of Likelihoods gives the mean multiplicity of the identified hadrons.

Sum of Likelihoods - Raw data p+p at 158 GeV/c



Rapidity y is in center of mass system

Multiplicative correction

The h^- inverse multiplicative correction is defined as:

$$E_{h^-} = \left(\frac{n_{h^-}}{N}\right)^{MC}_{acc} / \left(\frac{n_{\pi^-}}{N}\right)^{MC}_{gen}$$

This formula corrects both for the detector effect and for the non-π^- contribution.

For the identified spectra the formula is very similar:

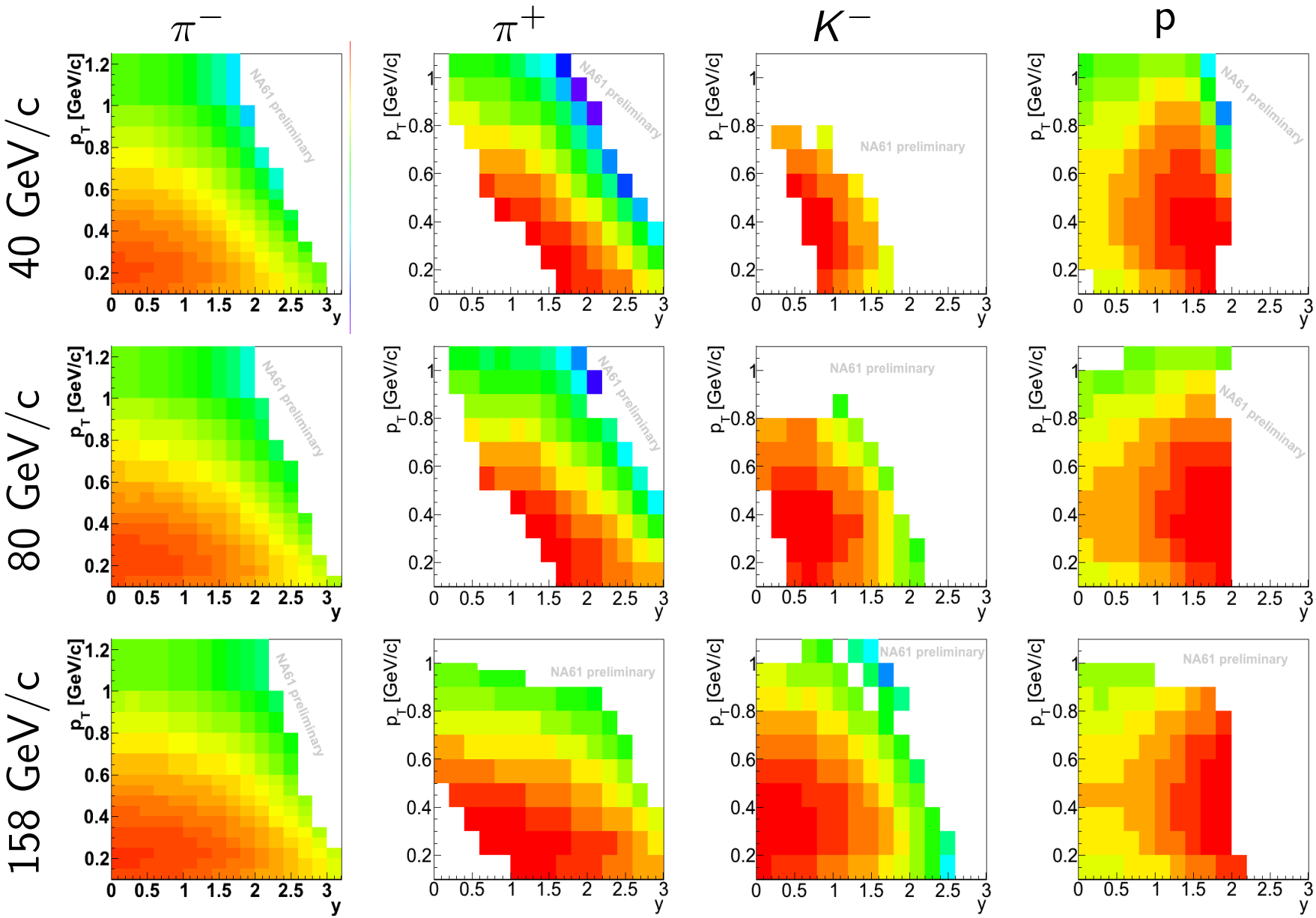
$$E_x = \left(\frac{n_x}{N}\right)^{MC}_{acc} / \left(\frac{n_x}{N}\right)^{MC}_{gen}$$

where x is the identified particle type (like π, K^+ etc). Identified accepted particles are selected using matching.

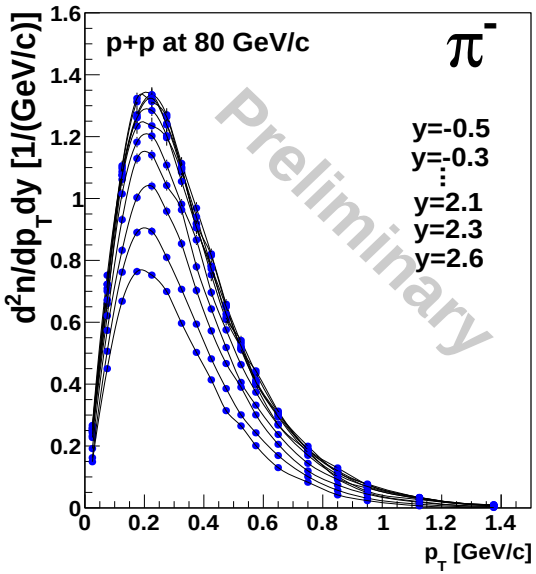
Application of the inverse multiplicative correction is quite obvious:

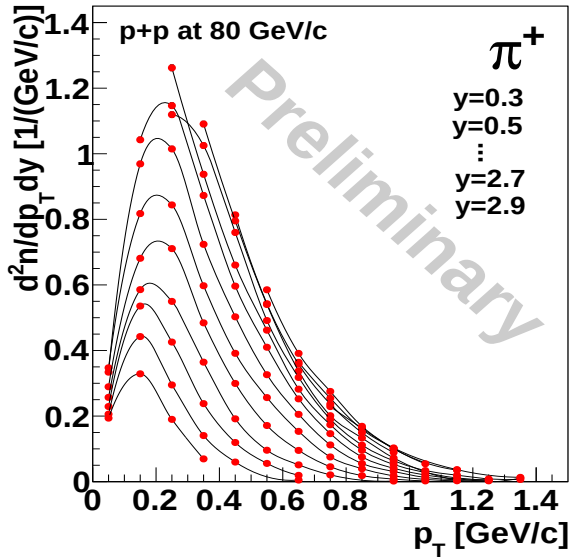
$$\frac{n}{N} = \frac{1}{E}\left(\frac{n_{h^-}}{N}\right)^{data}_{acc}$$

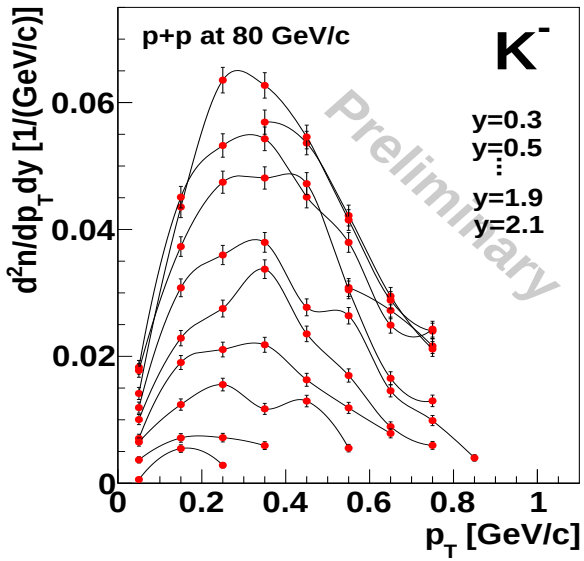
Examples of 2D spectra: transverse momentum p_T vs rapidity y

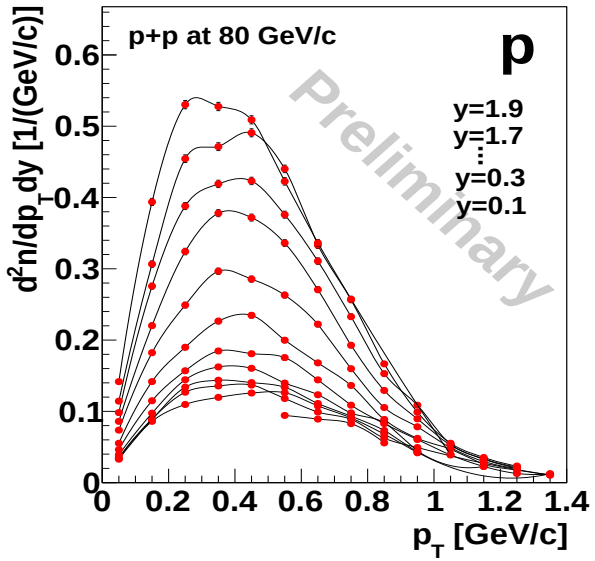


Examples of transverse momentum spectra

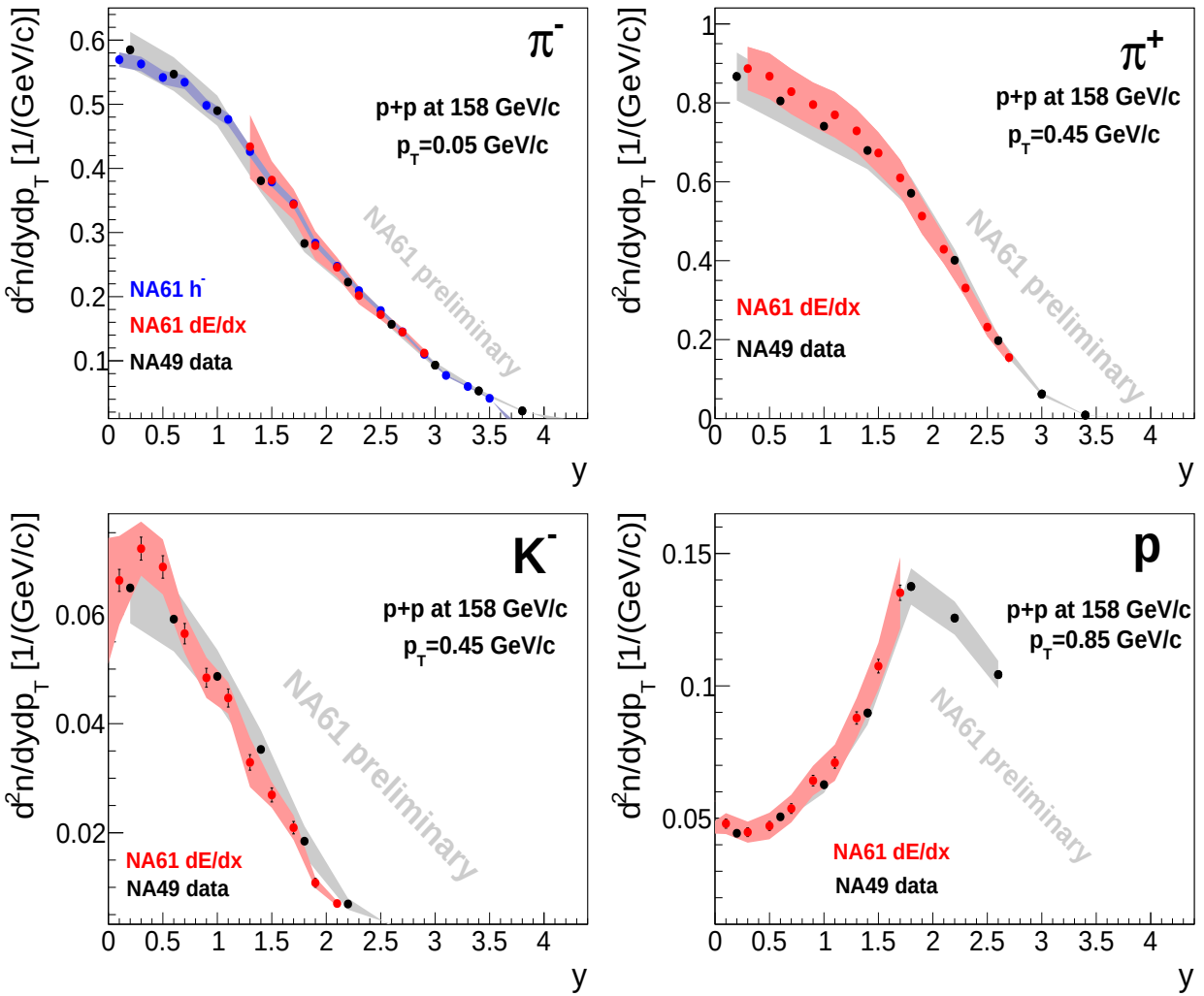








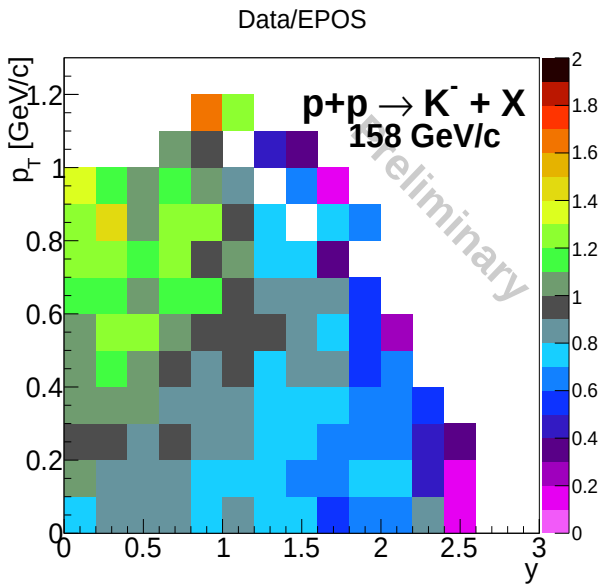
Rapidity spectra - comparison of NA61 and NA49 results

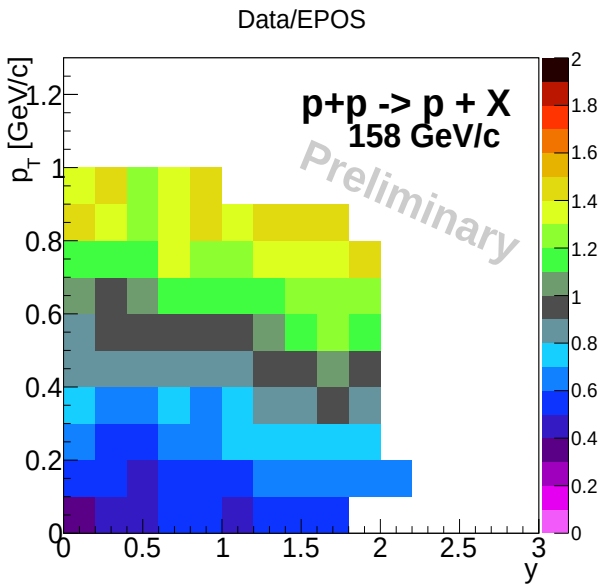


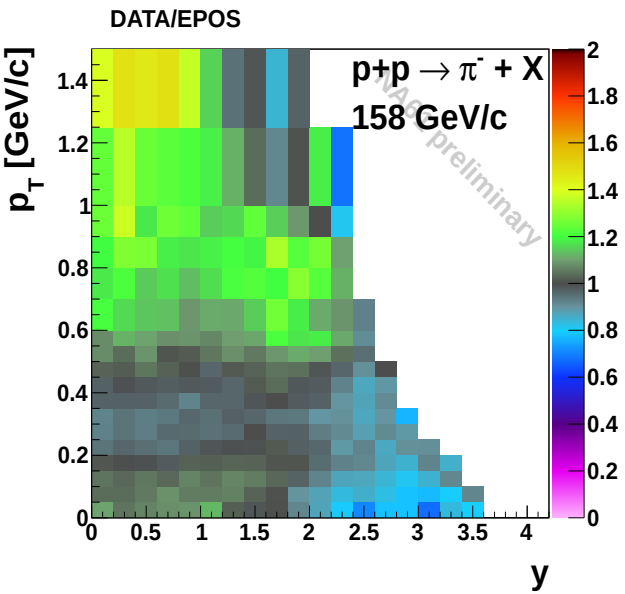
Results from different methods (dE/dx and h^-) and from NA49 agree.

NA49 pp data: Eur. Phys. J., C45 343, 2006., Eur. Phys. J., C65 9, 2010., Eur. Phys. J., C68 1, 2010.

Comparison with EPOS (Data/Model)



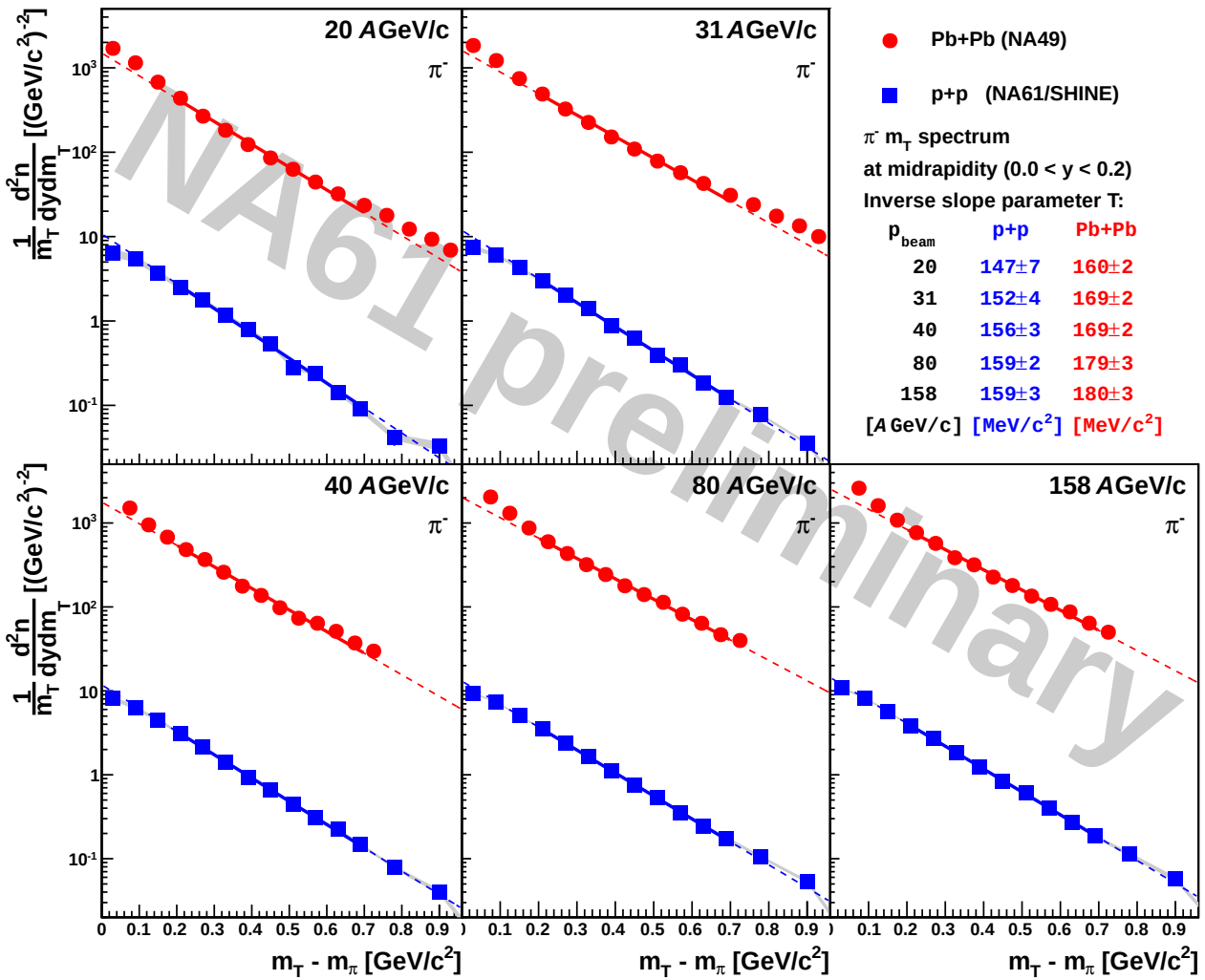




Large differences between data and EPOS (1.99).

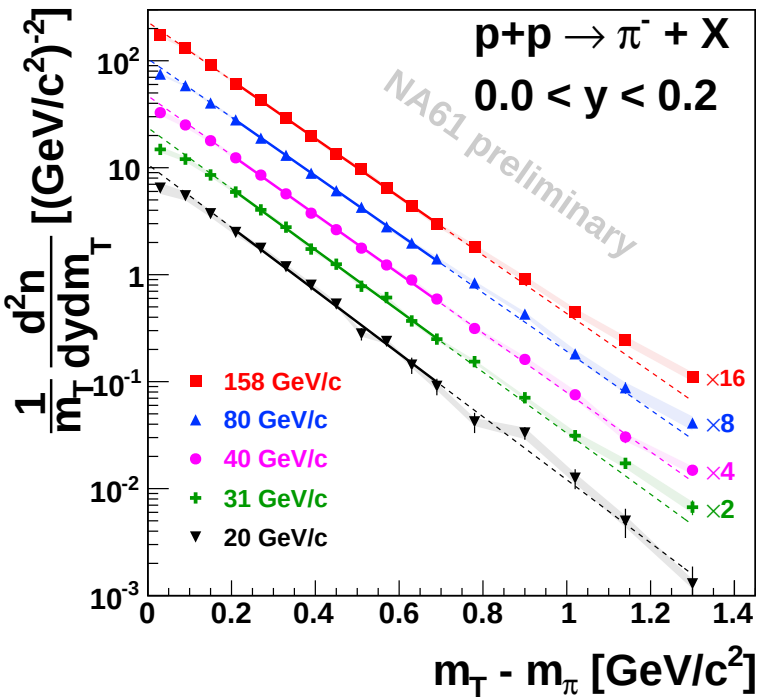
*Nucl. Phys. B (Proc. Suppl.) 175–176 (2008) 81–87

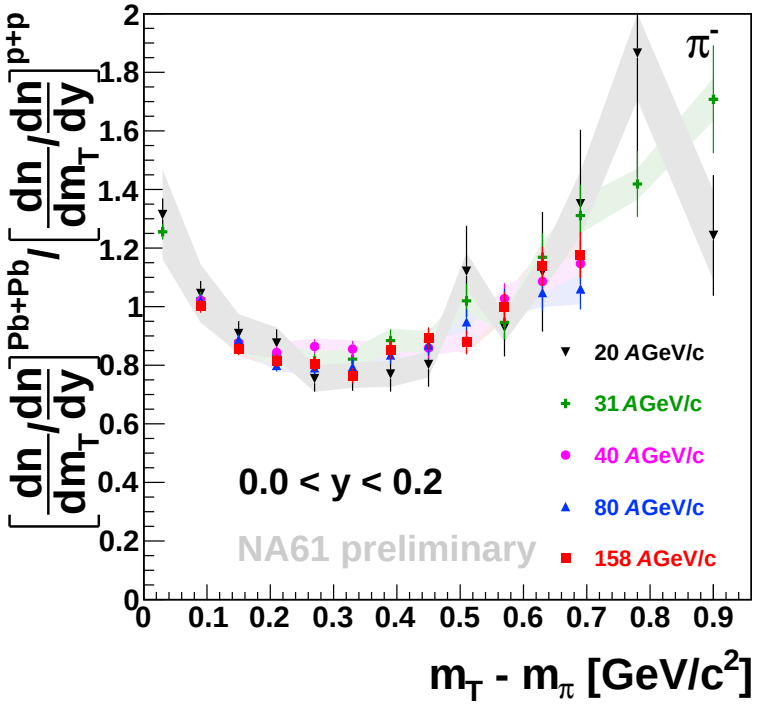
π^- m_T spectra



π yield scaled with number of wounded nucleons

π^- m_T spectra

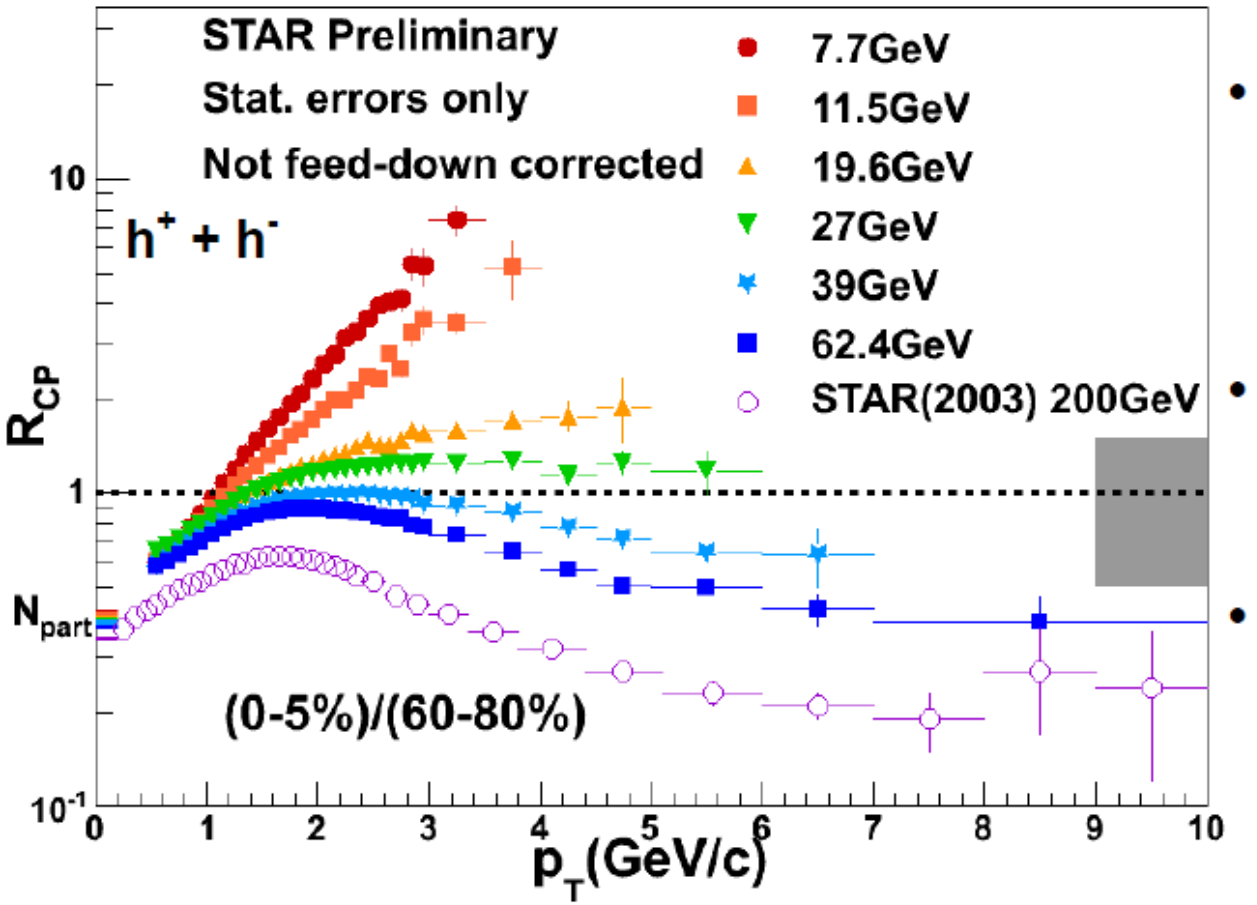




Shape differs significantly between p+p and central (7%) Pb+Pb due to transverse collective flow in Pb+Pb. Difference does not change with the incident energy (consistent with STAR R_{CP} results).

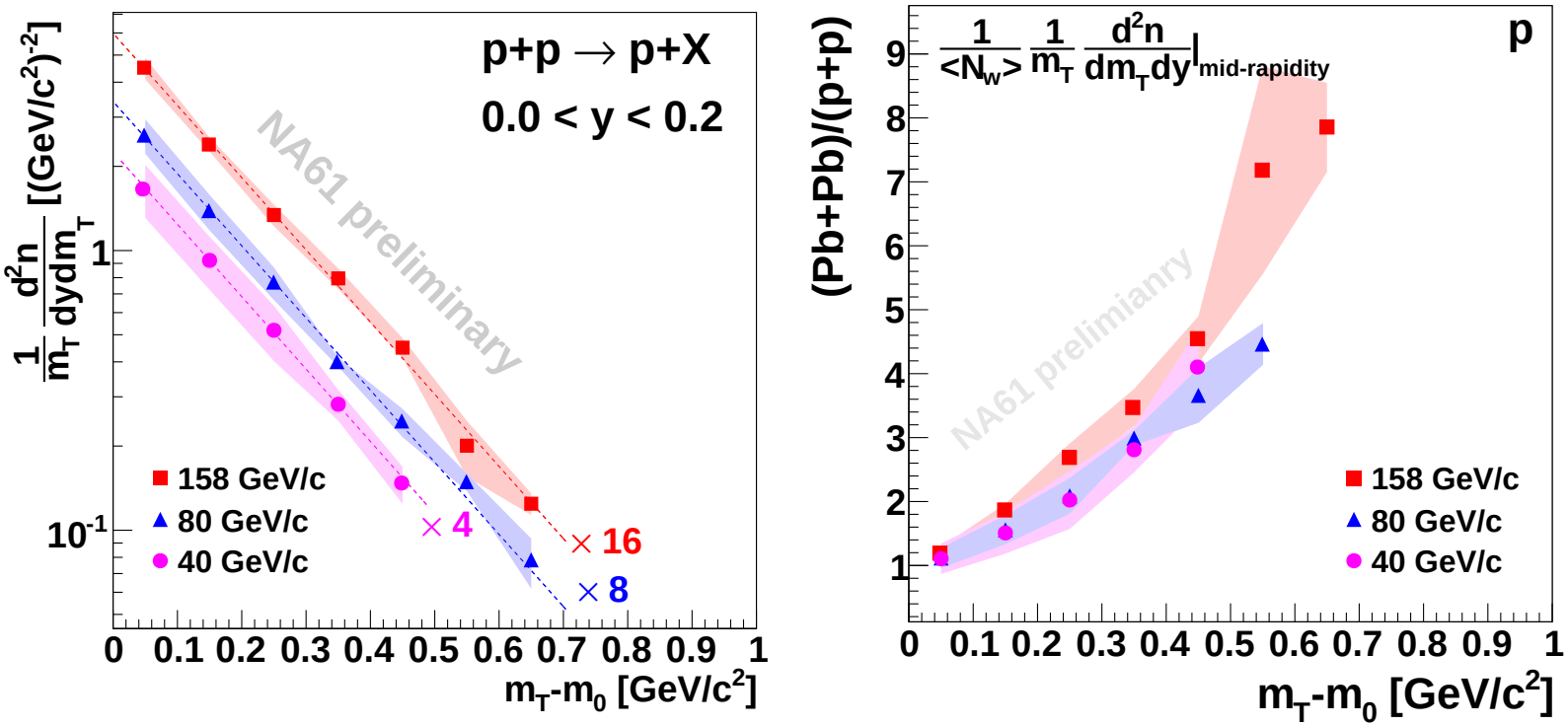
Pb+Pb results on central (7%, 5%) collisions measured by NA49
Phys. Rev. C 66, 054902 (2002), Phys. Rev. C 77, 024903 (2008)

STAR R_{CP}



STAR measures R_{CP} from $p_T > 0.5 GeV/c$ and in the region $0.5 - 1 GeV/c$ finds it increasing and approximately energy independent like as NA61.

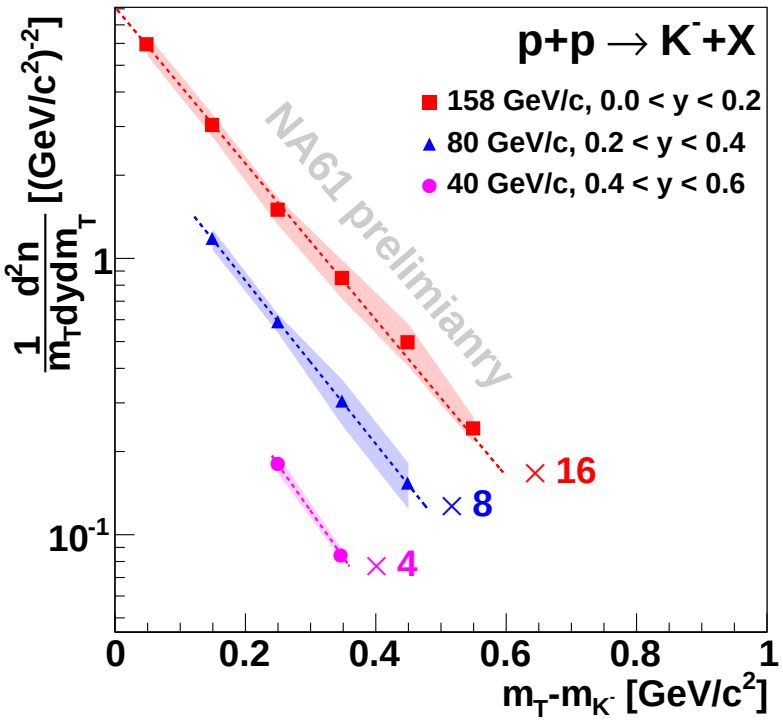
proton m_T spectra

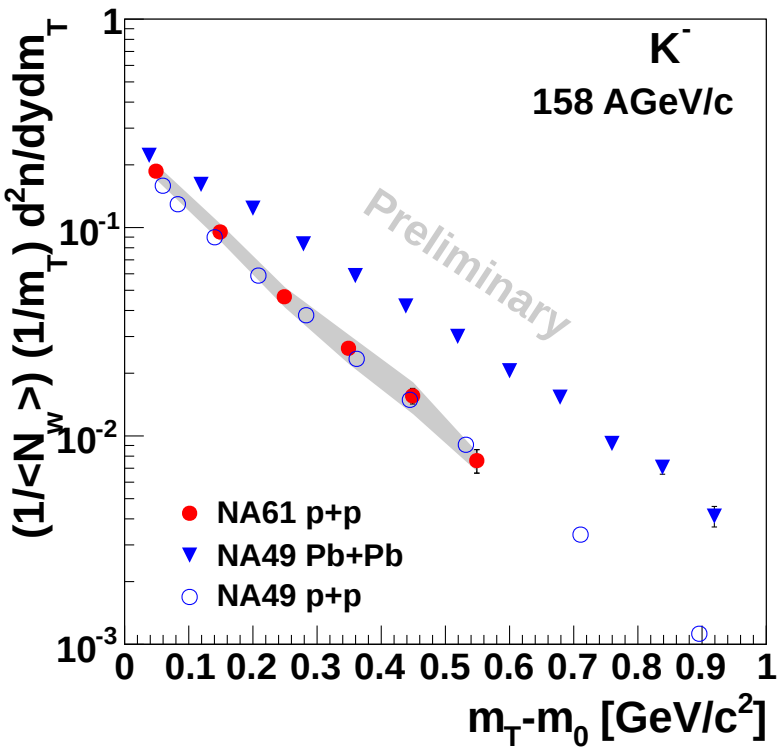


Shape differs significantly between p+p and central (7%) Pb+Pb due to transverse collective flow in Pb+Pb. Differences are weakly, if at all, dependent on collisions energy.

Pb+Pb results on central (7%, 5%) collisions measured by NA49 Phys. Rev. C 73,044910 (2006)
(y intervals: -0.32 $< y <$ 0.80 for 40 AGeV/c -0.37 $< y <$ 0.30 for 80 AGeV/c, -0.50 $< y <$ -0.1 for 158 GeV/c)

K^- m_T spectra



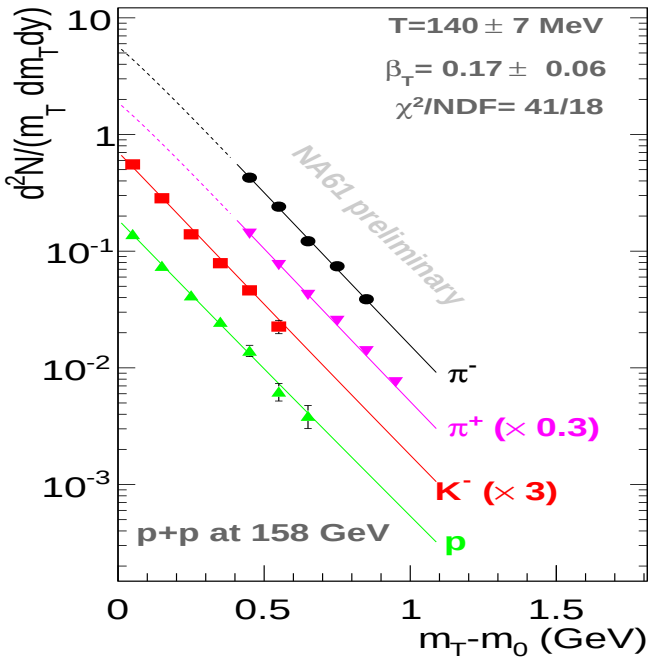


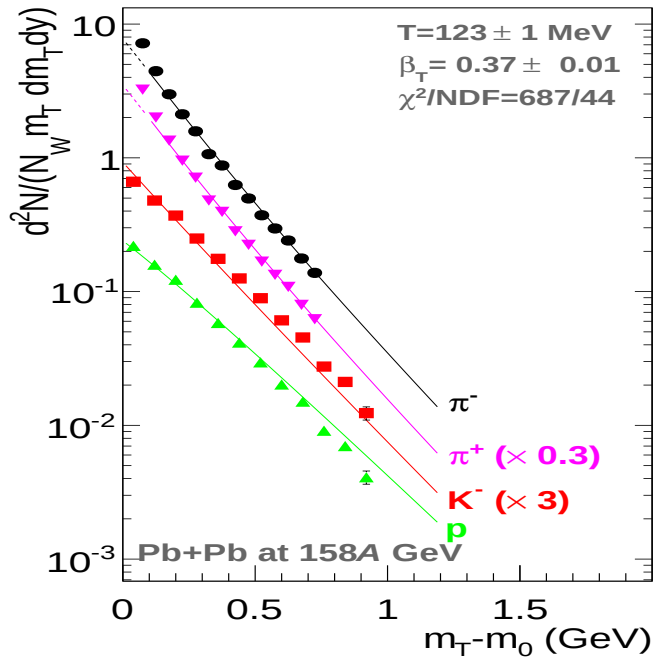
The inverse slope parameter is significantly larger in central Pb+Pb than in p+p interactions. Since dE/dx is not enough to identify kaons near mid-rapidity at low energies, TOF analysis is necessary and in progress.

Pb+Pb results on central (7%, 5%) collisions measured by NA49
Phys. Rev. C 66, 054902 (2002), Phys. Rev. C 77, 024903 (2008)

Transverse mass spectra at mid-rapidity

fitted by Blast Wave Model: comparison p+p and central Pb+Pb





Transverse mass spectra are approximately exponential in p+p interactions. In central Pb+Pb collisions the exponential dependence is modified by the transverse flow.

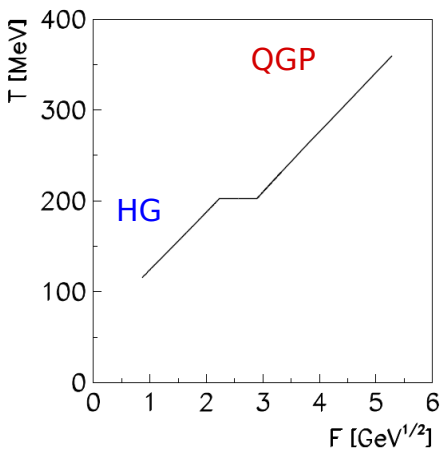
fitted function: $\frac{dN_i}{m_T\, dm_T\, dy} = A_i m_T K_1(\frac{m_T \cosh\rho}{T}) I_0(\frac{p_T \sinh\rho}{T})$ from Schnedermann, Sollfrank, Heinz, PRC 48, 2462 (1993)

$\rho = a\tanh\beta_T$

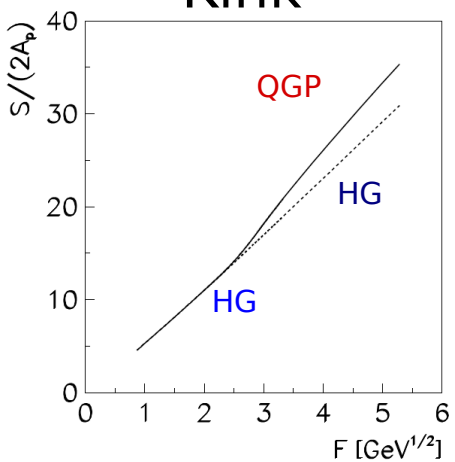
Study of the onset of deconfinement

- Statistical Model of the Early Stage (SMES)
  - 1st order phase transition to QGP between top AGS and top SPS energies
  - Constant temperature and pressure in mixed phase
  - Number of internal degrees of freedom increases HG $->$ QGP
  - Total entropy and total strangeness are the same before and after hadronization (cannot decrease QGP $->$ HG)
  - Mass of strangeness carriers decreases HG $->$ QGP ($m_{\Lambda,K,...} > m_s$)

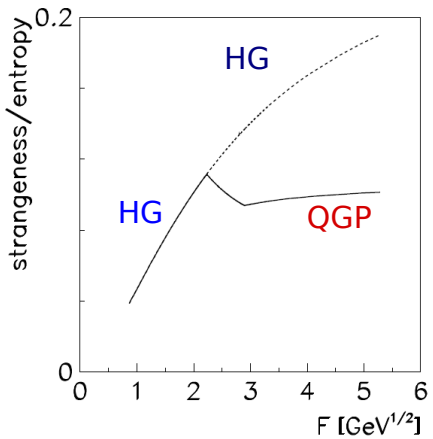
"Step"



"Kink"



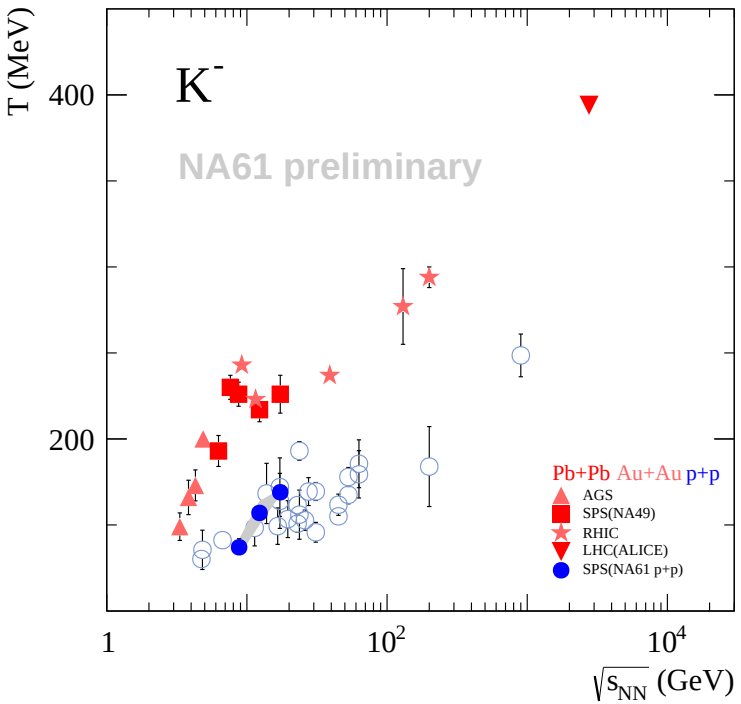
"Horn"



$$F \approx \sqrt[4]{s_{NN}}$$

Gaździcki, Gorenstein, Acta Phys. Polon. B30, 2705 (1999)

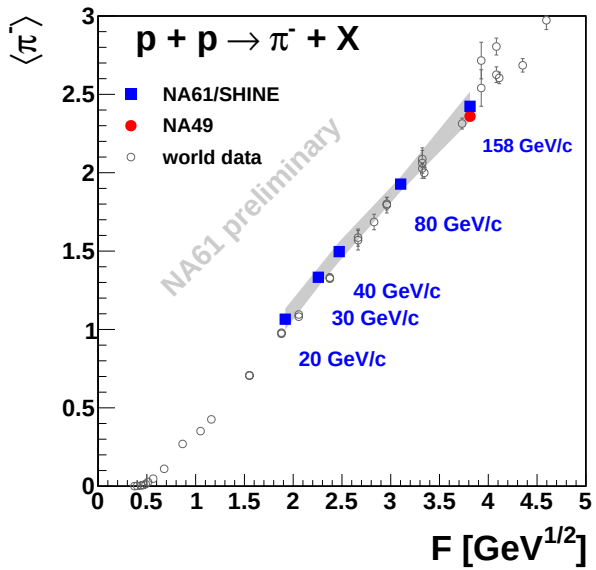
Study of the onset of deconfinement - Step

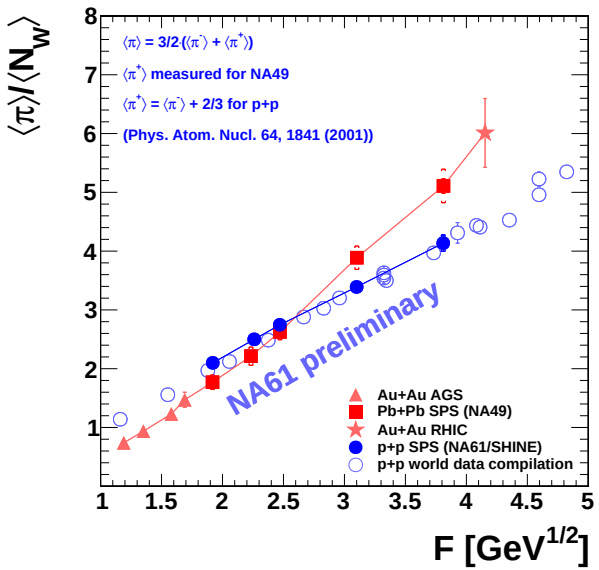


$$\frac{d^2n}{m_T dm_T dy} = Cexp(\frac{-m_T}{T})$$

- NA61 results on p+p agree with the previous measurements
- Inverse slope parameter T at the SPS energies shows different behavior in central Pb+Pb ("Step") than in p+p (smooth increase)
- NA61 precision sufficient to study properties of the onset of deconfinement: here system size dependence of energy dependence of T

Study of the onset of deconfinement - Kink

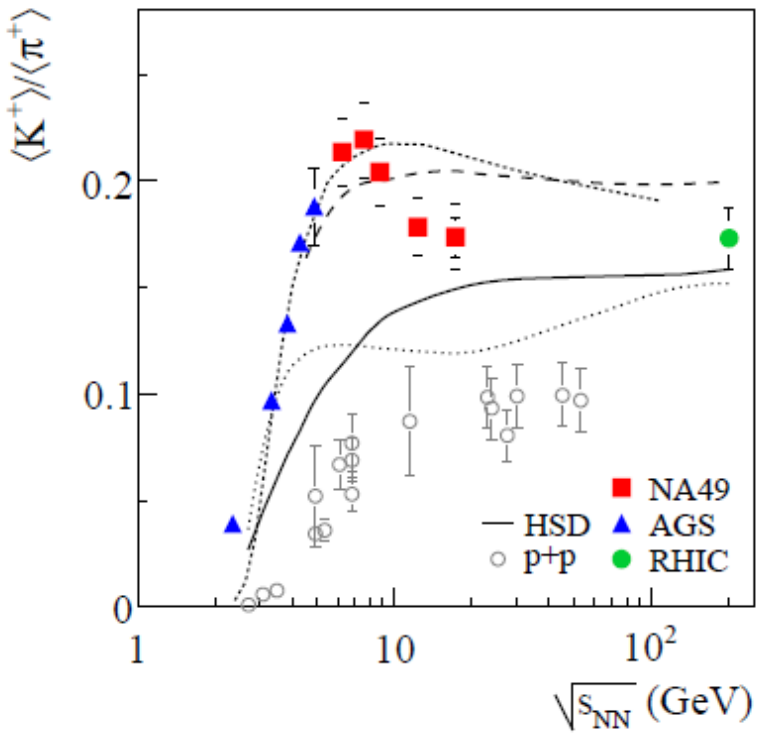


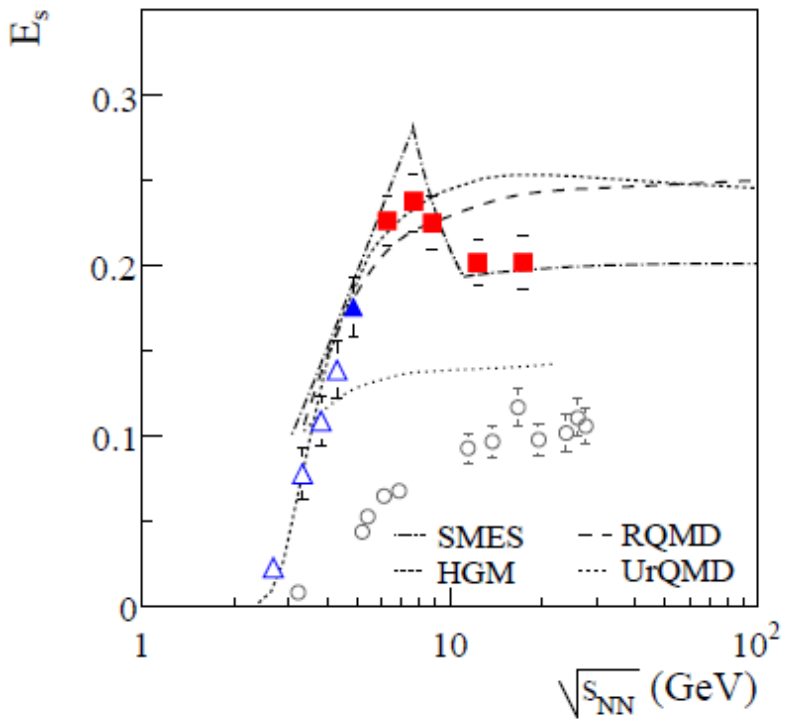


$$F \approx \sqrt[4]{s_{NN}}$$

- NA61 results agree with the previous measurements
- π multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p ("kink")
- The two dependencies cross at about 40A GeV/c
- NA61 precision sufficient to study properties of the onset of deconfinement: here system size dependence of energy dependence of mean pion multiplicity

Study of the onset of deconfinement - Horn

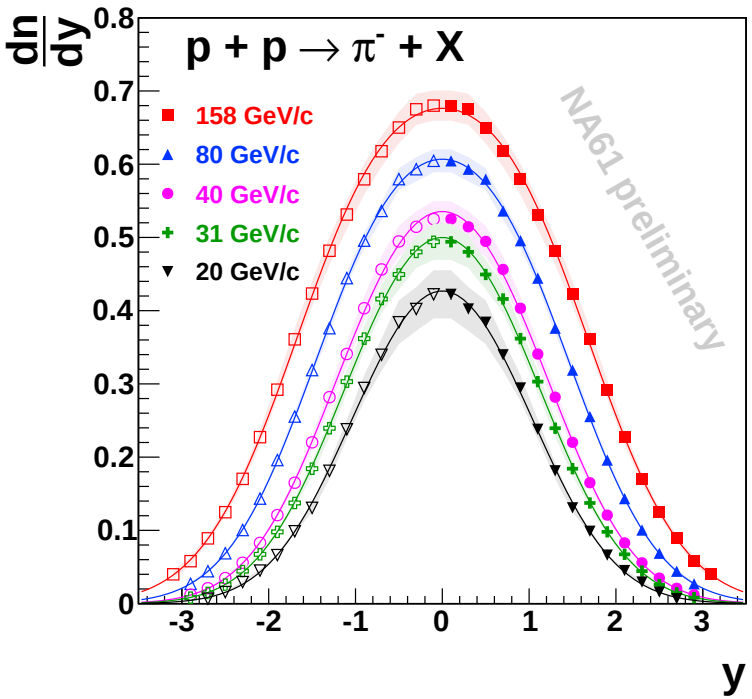


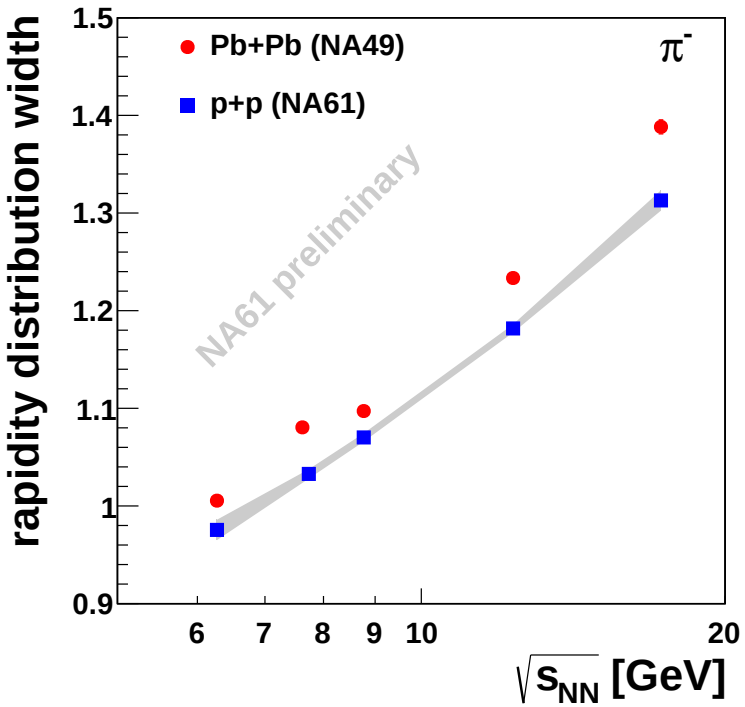


$$E_S = (< \Lambda > + < K + \bar{K} >)/ < \pi >$$

C. Alt et al (NA49 Collaboration) (2008). "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

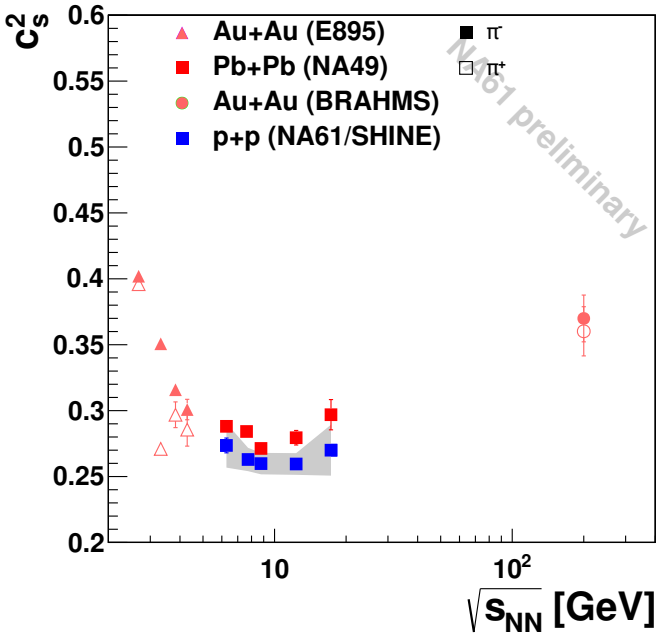
π^- rapidity distribution

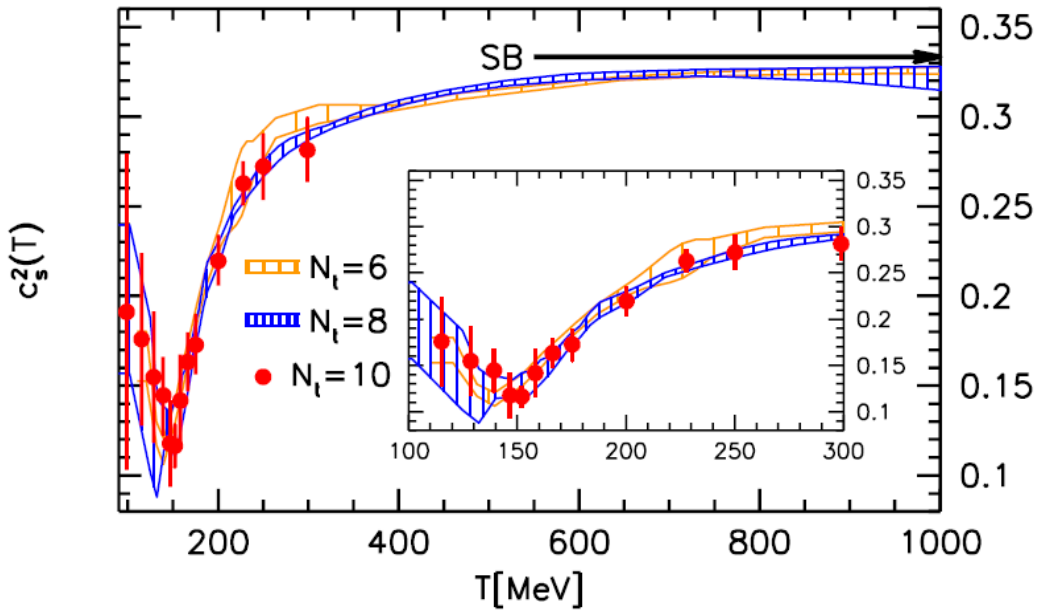




- full symbols are measured, open symbols are reflected at mid-rapidity
- dn/dy distribution is approximately Gaussian, best fit by sum of two Gauss distributions
- In the first approximation the width of the rapidity distribution scales with y_{BEAM}

Dale plot





$$c_S^2 = -\frac{4}{3}\frac{ln(\sqrt{s}_{NN}/2m_p)}{\sigma_y^2} + \sqrt{[\frac{4}{3}\frac{ln(\sqrt{s}_{NN}/2m_N)}{\sigma_y^2}]^2 + 1}$$

c_s^2 energy dependence is similar in p+p and central Pb+Pb.

Pb+Pb: Phys. Rev. C 66, 054902 (2002), Phys. Rev. C 77, 024903 (2008)

c_S^2: Edward V. Shuryak Yad. Fiz. 16 (1972) 395-405

M. Bleicher et al. Phys. Rev. C 60, 024904

S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, HEP 1011 (2010) 077

Summary

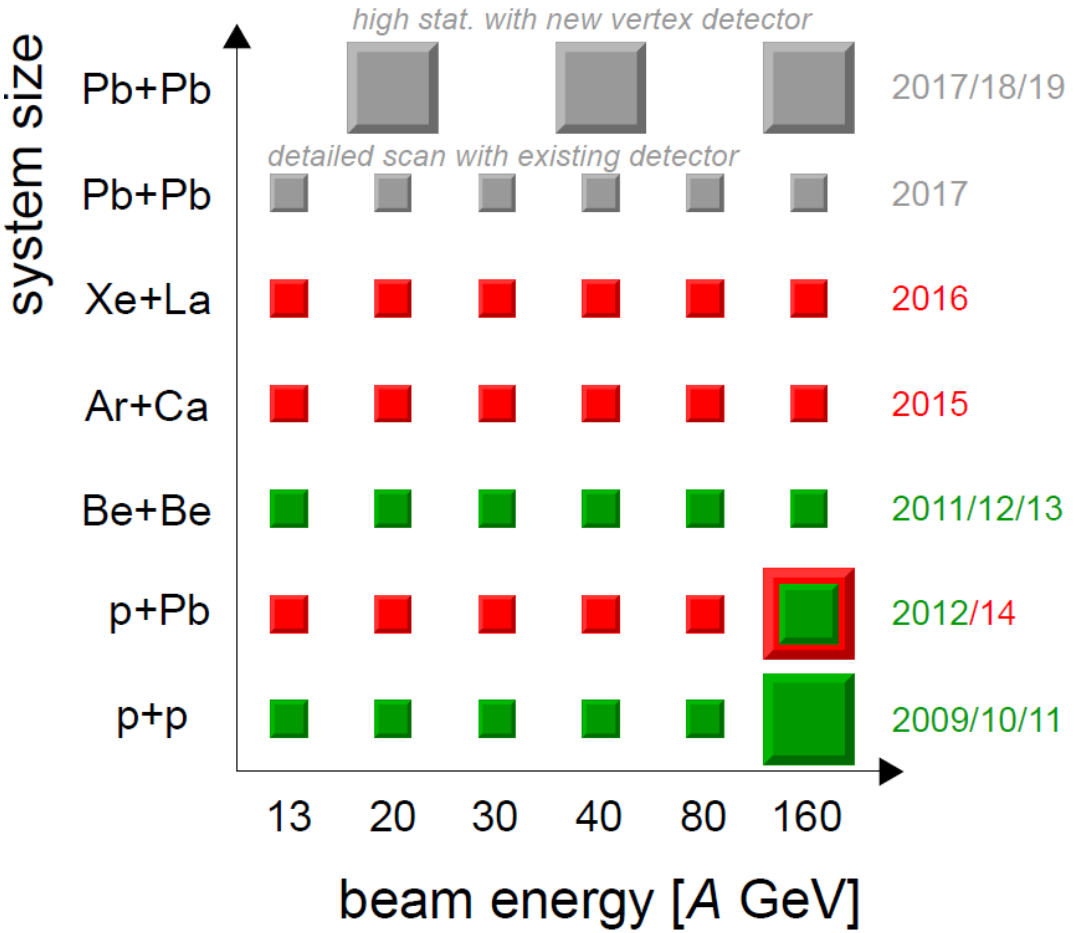
- NA61/SHINE 2D energy-system size scan is advancing: data for p+p and Be+Be collisions were already recorded
- they are needed as reference for the study of the onset of deconfinement and search for the critical point
- preliminary NA61/SHINE results on p+p interactions and their comparison to central Pb+Pb collisions were presented

Summary II

- transverse momentum spectra are significantly steeper in p+p than central Pb+Pb collisions. The difference is likely due to transverse collective flow in central Pb+Pb and is found to be collision energy independent
- rapidity spectra: The dale may be also present in p+p interactions.
- $< \pi > / < N_W >$ increases with energy more slowly in p+p than in central Pb+Pb. The two dependencies cross at about $40A$ GeV/c
- EPOS does not reproduce well $y - p_T$ spectra of identified hadrons in p+p interactions

Backup slides

Available data



Proof of methode

1. Let us first consider the simplest case of N uncorrelated particles and assume that for all of them the probability to be a pion is the same and equal p.
Then we repeat the experiment (drawing a new set of N particles) and count the pion number, N_π. By construction N_π is distributed according to the binomial distributions:

$$B(N_\pi; N, p) = \frac{N}{N_{pi}} p^{N_\pi} (1-p)^{N-N_\pi}$$

with the mean value $< N_\pi >= Np$

Proof of methode

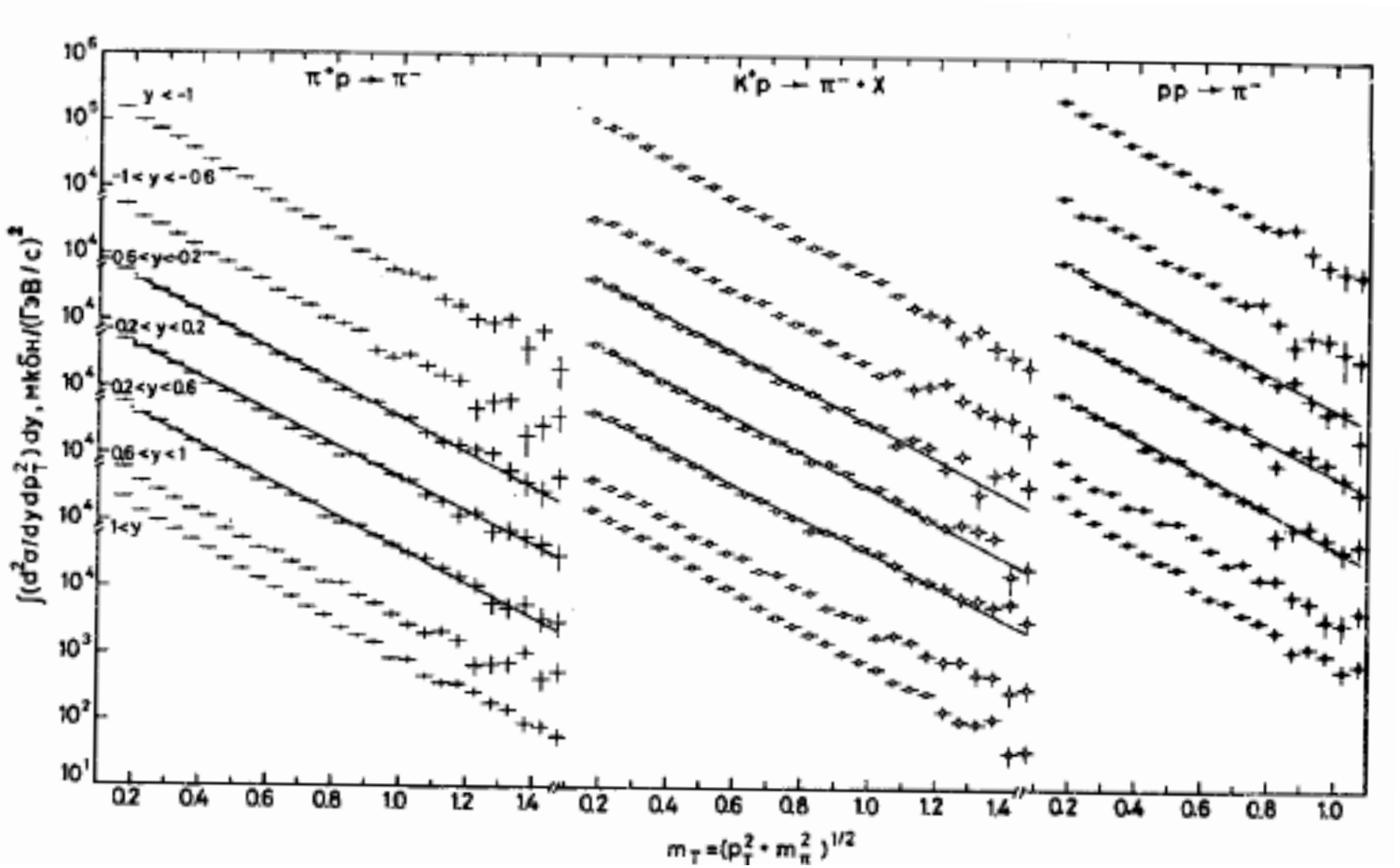
2. In case of spectra p vary from particle to particle and for a particle i we denote it by p_i For this single particle the pion number distribution (following 1. with N =1, $p = p_i$ and $N_\pi = N_{pi_i}$) is given by:

$$B(N_{\pi_i}, 1, p_i) \text{ with the mean value } < N_{\pi_i} >= 1 p_i = p_i$$

The mean is additive and thus the mean pion number for all particles give us:

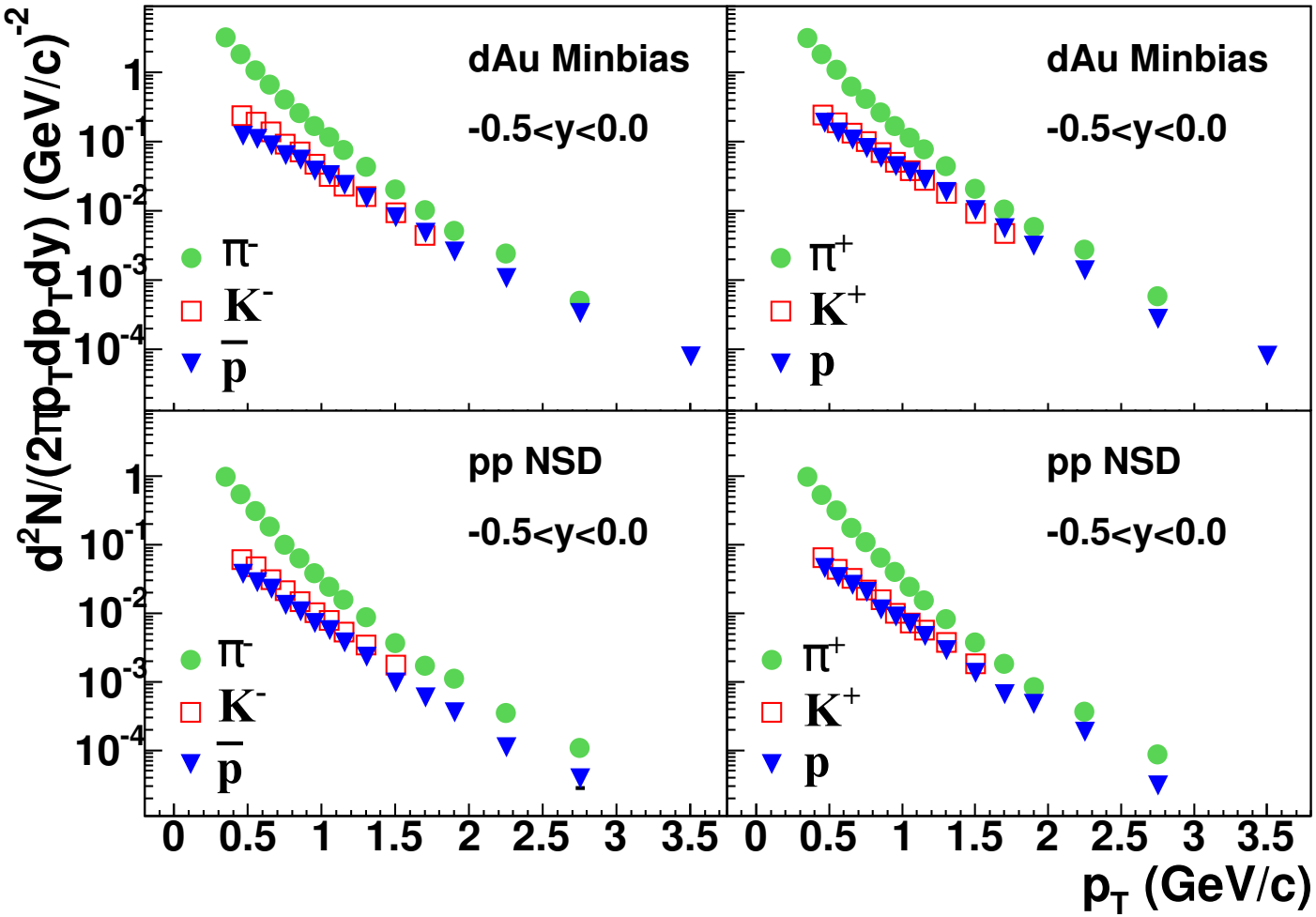
$$< N_\pi >= \sum_{i=1}^{N} p_i$$

NA22 π^- spectra - $p+p$, π^-+p and K^-+p at 250A GeV



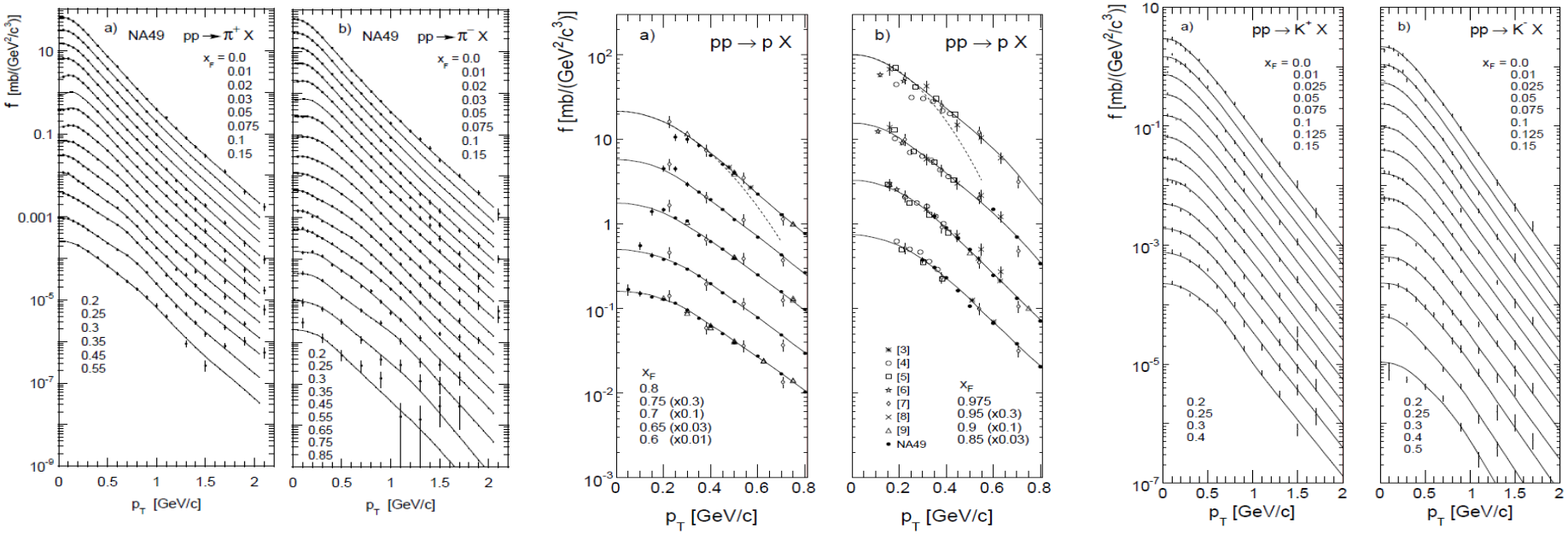
M. Adamus et al. (the NA22 Collaboration), Z.Phys. C39, 1988

STAR hadron spectra - $p + p$ at $\sqrt{s_{NN}} = 200A$ GeV



J. Adams, et al (the Star Collaboration), Phys. Lett. B, 616, 2005

NA49 hadron spectra - $p + p$ at 158A GeV/c



C. Alt, et al (the NA49 Collaboration), Eur. Phys. J., C45 343, 2006.
T.Anticic, et al (the NA49 Collaboration), Eur. Phys. J., C65 9, 2010.
T.Anticic, et al (the NA49 Collaboration), Eur. Phys. J., C681, 2010.