International school of nuclear physics
Erice, 16–24 September 2012

Strange things happened in cold nuclear matter

Kirill Lapidus for the HADES collaboration
Excellence Cluster 'Universe'
TU Munich

Erice, 18.09.12

Kaon in-medium properties

Low-density theorem

$$\Pi_K = -4\pi t_{\mathrm{KN}} \cdot \rho$$

Self energy

$$\Pi_K = 2EU_{opt}$$

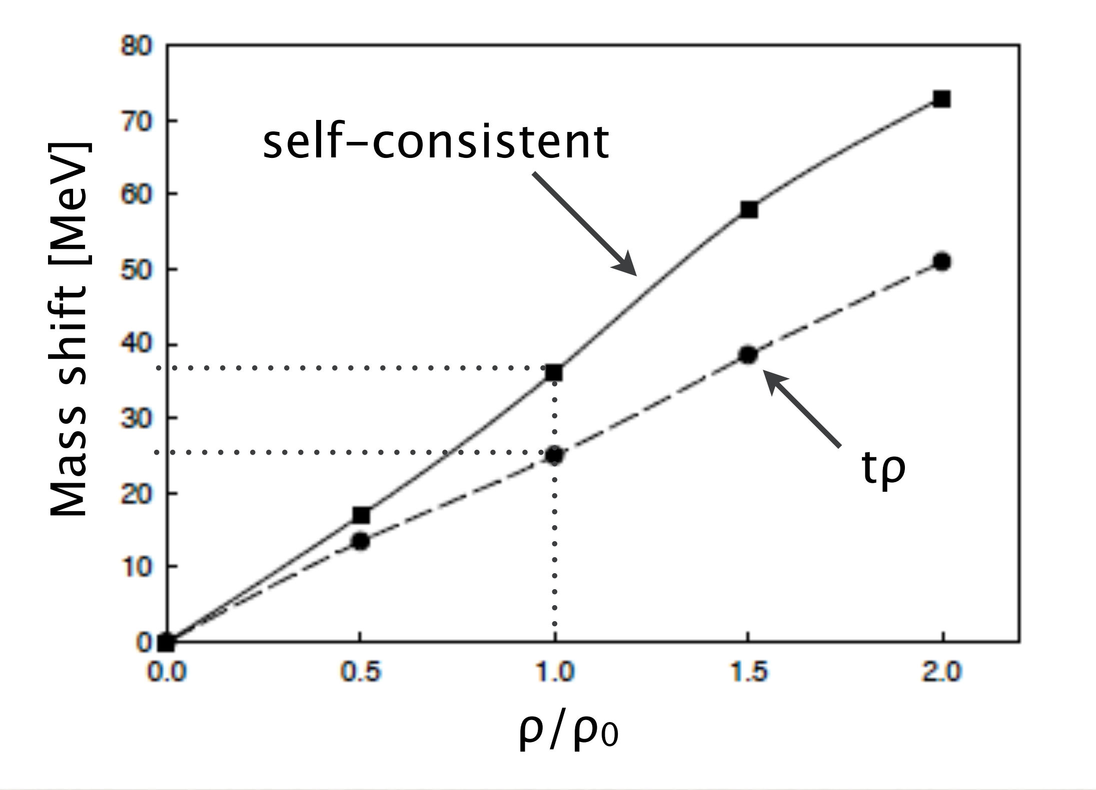
For K^+/K^0:
a repulsive optical potential
of $U_{opt} \sim +30$ MeV at $q = 0$, $\rho = \rho_0$

$m^* = E^*(q=0) = m_{vac} + 30 \text{ MeV} \cdot \rho/\rho_0$

Linked to antikaon production in HI collisions:

$N + N \rightarrow N + K + Y$
$\pi + Y \Leftrightarrow \bar{K} + N$

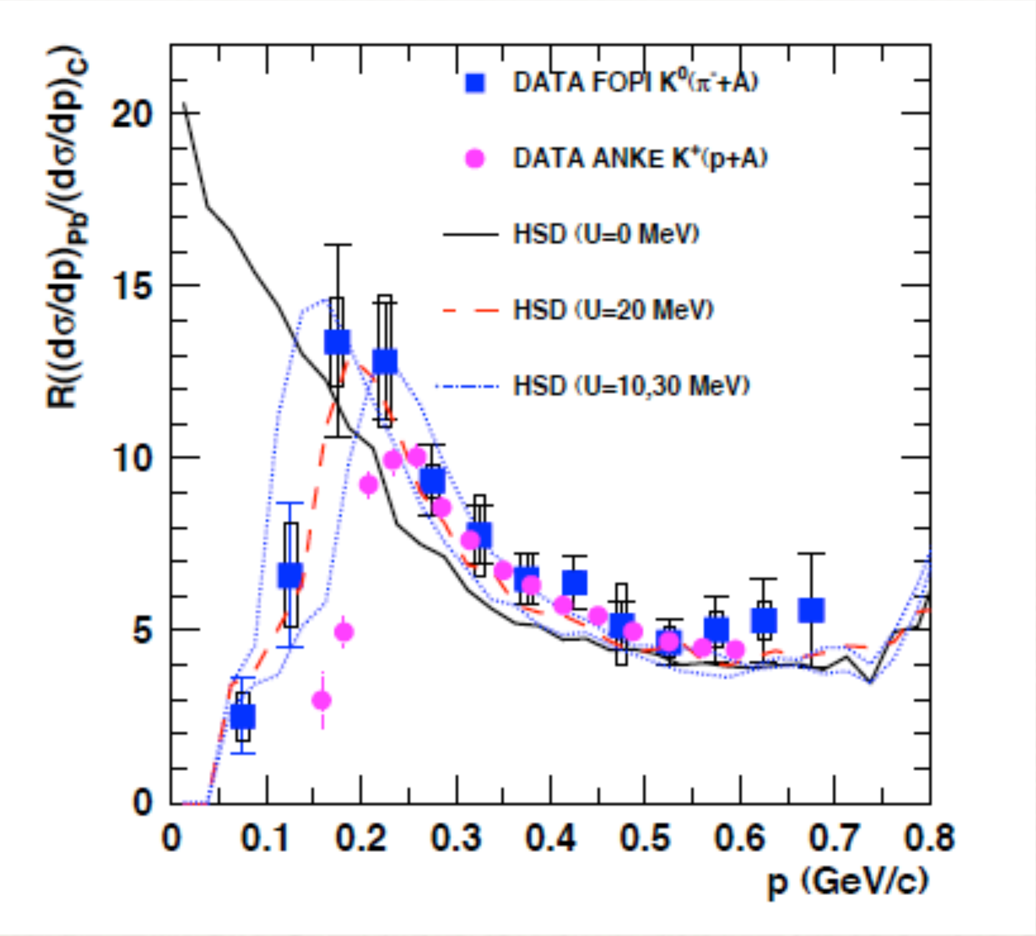
K^+ mass shift vs. density



C.L. Korpa, M.F.M. Lutz
Acta Phys. Hung. A22 2005 21.

Kaon in-medium potential

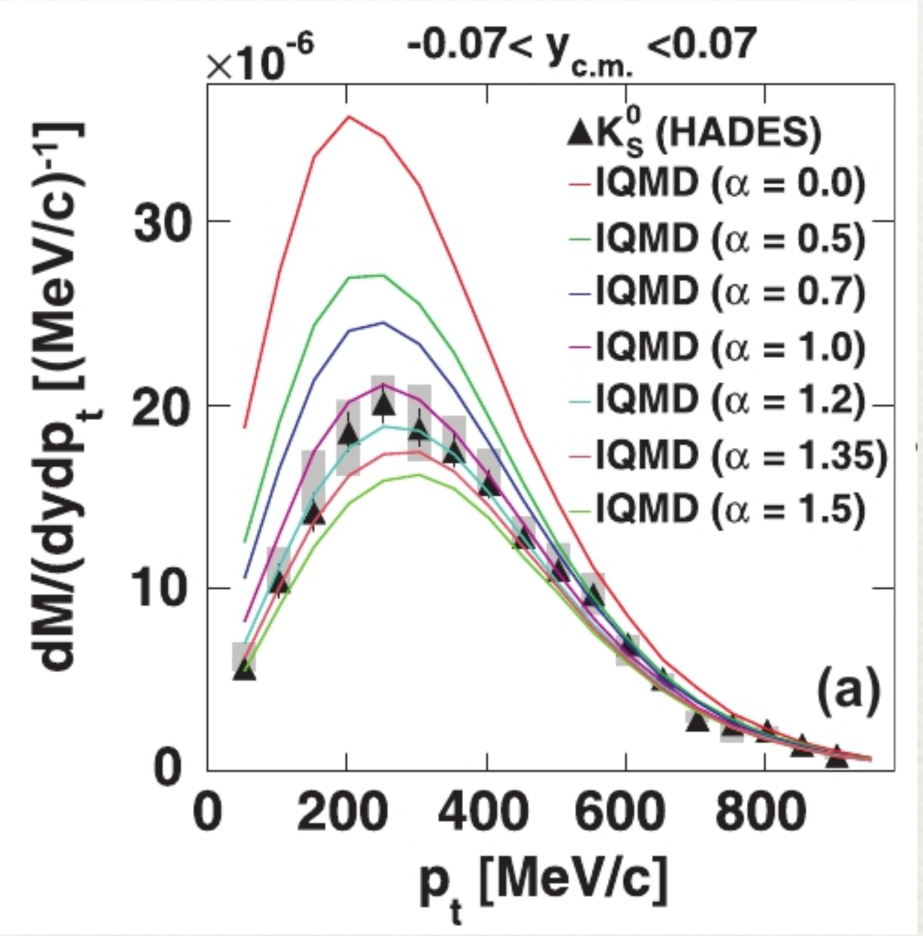
FOPI π+A, ANKE p+A



M. Benabderrahmane et al.,
Phys. Rev. Lett. 102 (2009) 182501.

U_{opt} = +20±5 MeV extracted
from comparison with transport (HSD)

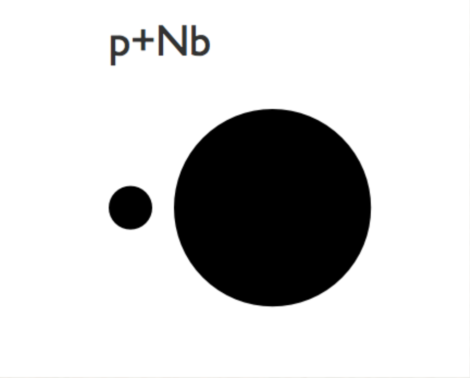
HADES Ar+KCl $K^0_S \rightarrow \pi^+\pi^-$



G. Agakishiev et al.,
Phys. Rev. C 82 (2010) 044907.

Transport simulations (IQMD) with
U_{opt} = +39 MeV fit the data best

HADES measurement: K^0 in $p+^{93}Nb$



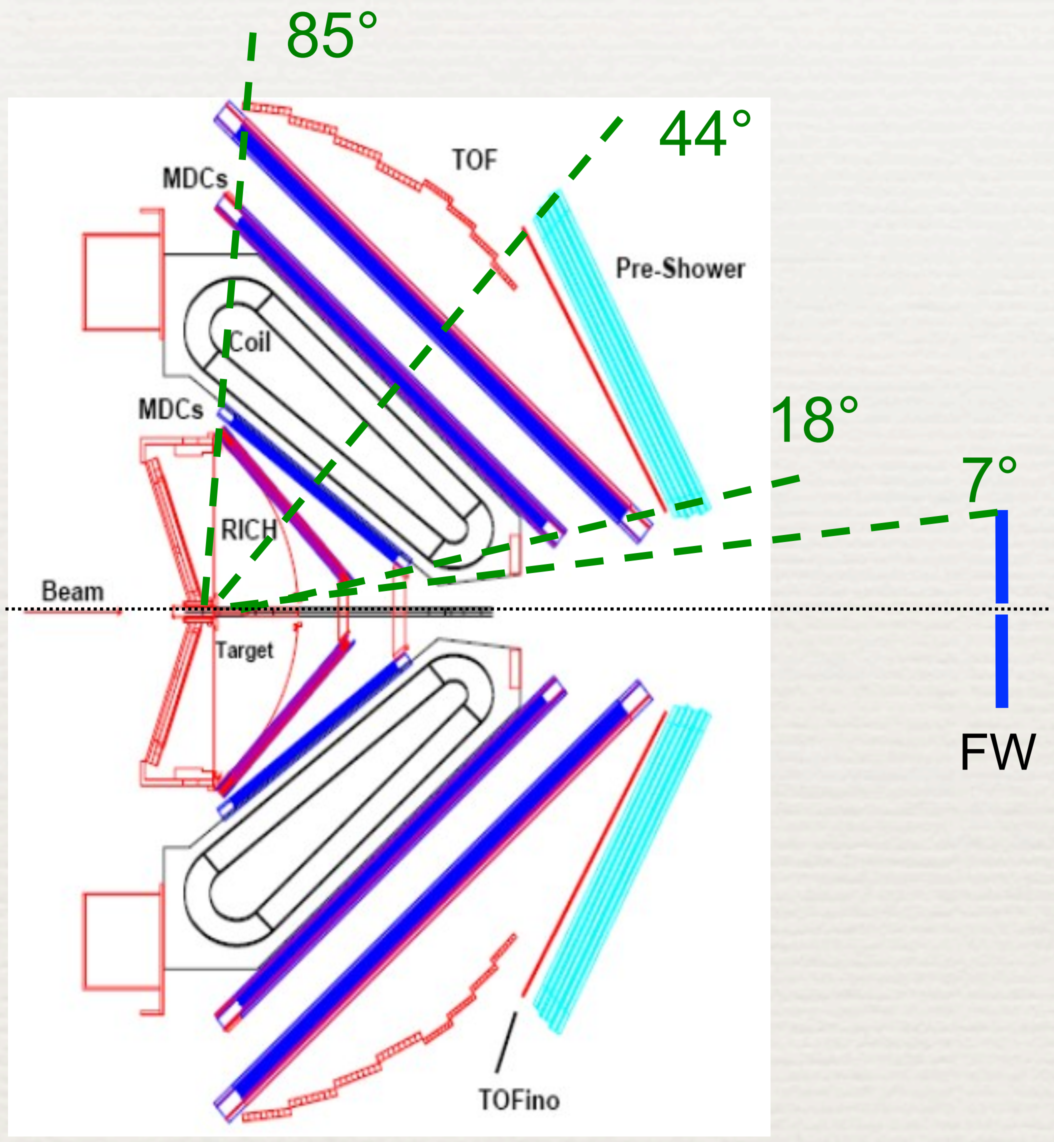
HADES data sample:
$p+^{93}Nb$ at 3.5 GeV, ~4 billion events.

Objectives:
1. Reconstruct K^0 kinematical distributions.
2. Compare with transport models: KN potential on/off, validate KN scattering.
4. Compare with the reference measurement: p+p at 3.5 GeV.

Features:
1. High acceptance and statistics.
2. No Coulomb interaction.

Limitations:
1. Rather high kinetic energy.
2. No light nuclear target as a reference.

The HADES experiment



High Acceptance Di-Electron Spectrometer

Location: GSI, Darmstadt

Fixed-target experiment,

SIS18, beam E_{kin} = 1—3 GeV/nucl.

Full azimuthal coverage, 18°-85° in polar angle

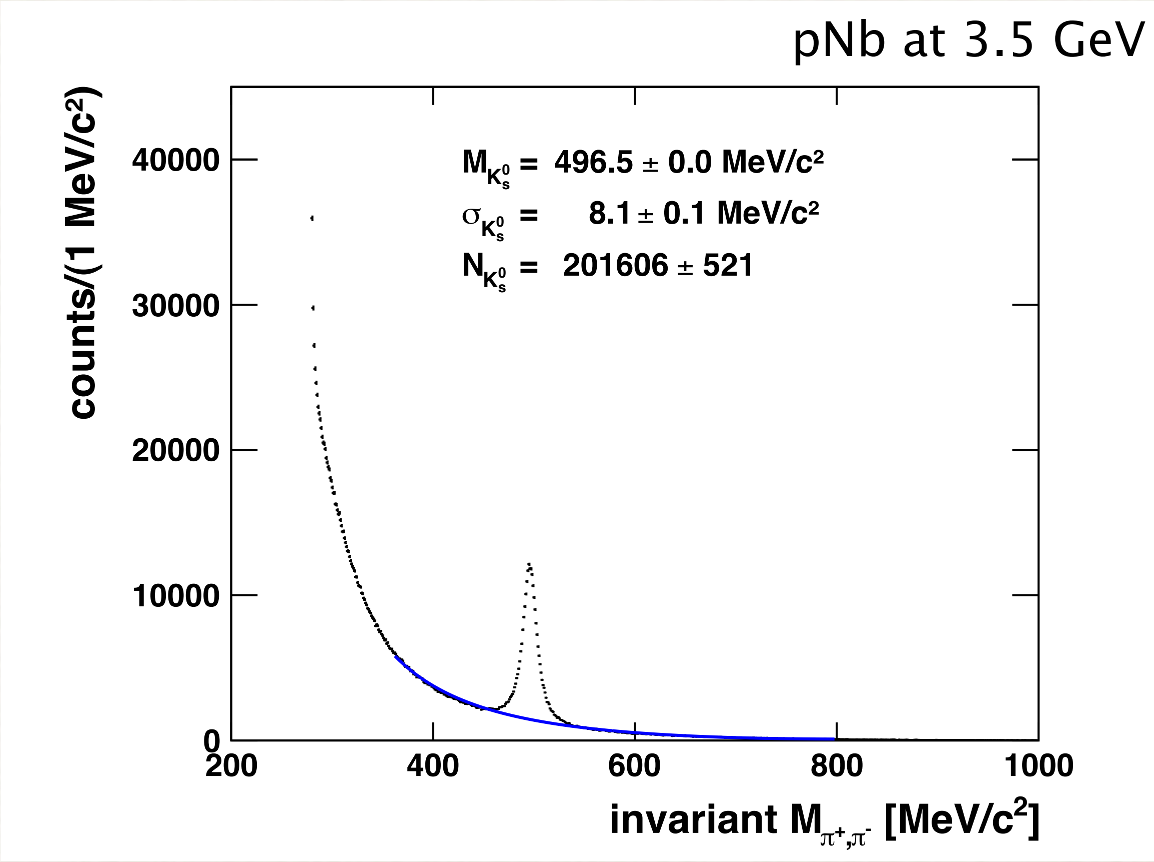
Sub-detectors:

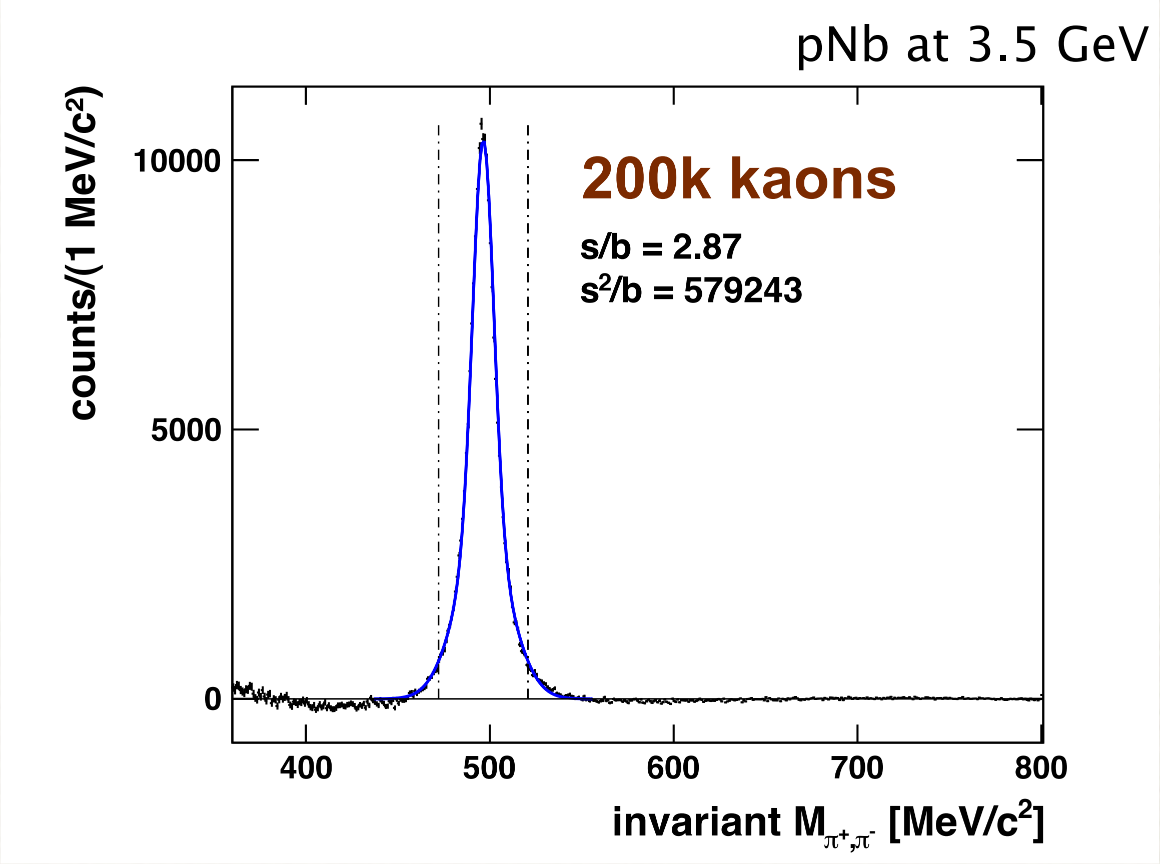
- MDCs
- RICH, Time-of-flight (TOF and RPCs)
- Pre-Shower detector
- Forward Wall detector at small angles

Analysis procedure

$K^0_S \rightarrow \pi^+\pi^-$

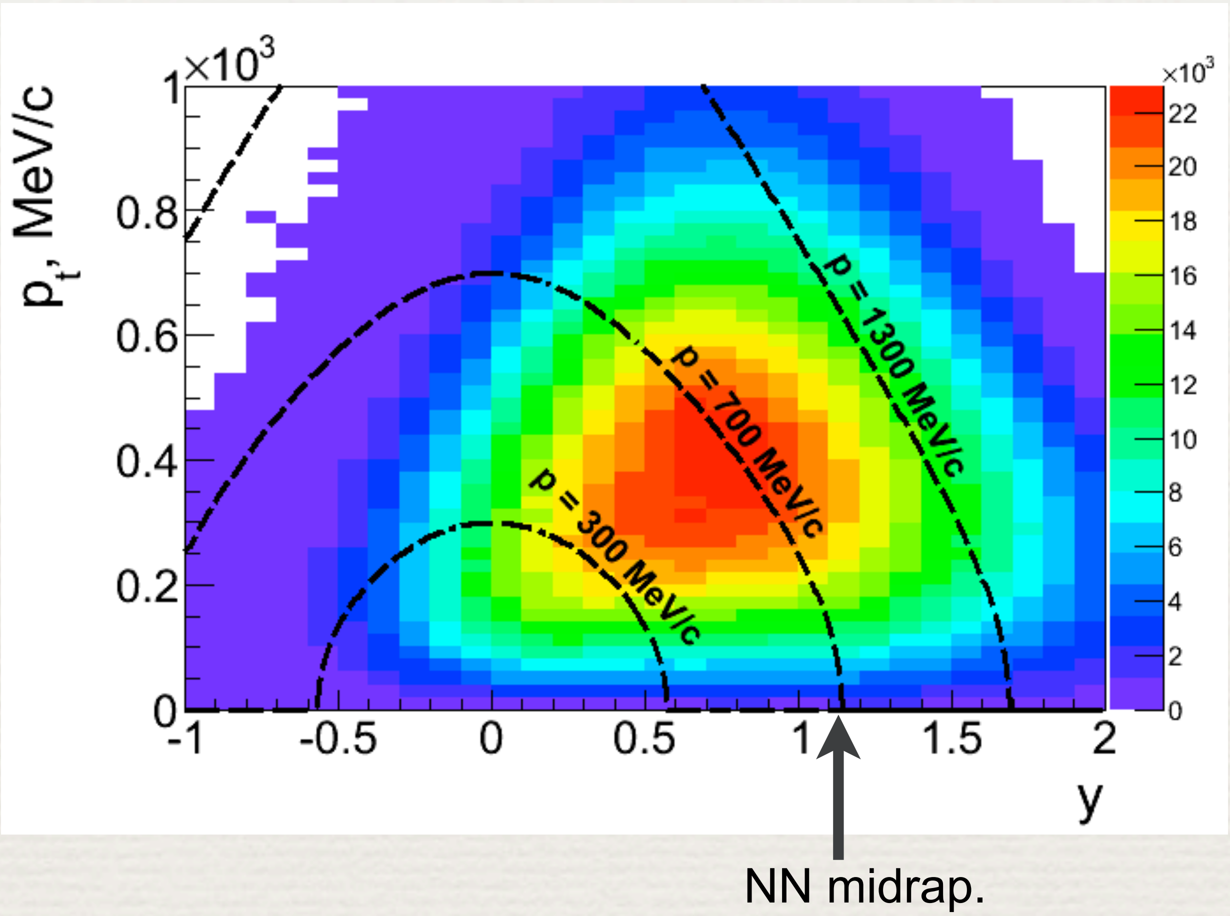
1. Identify charged pions (via MDC dE/dx).
2. Construct pairs.
3. Apply primary and secondary vertex cuts.
4. Plot invariant mass spectra.
5. Extract (differentially) K^0 yields: (p_t, y), (p, θ), ...
6. Correct for the efficiency and acceptance with help of simulations.



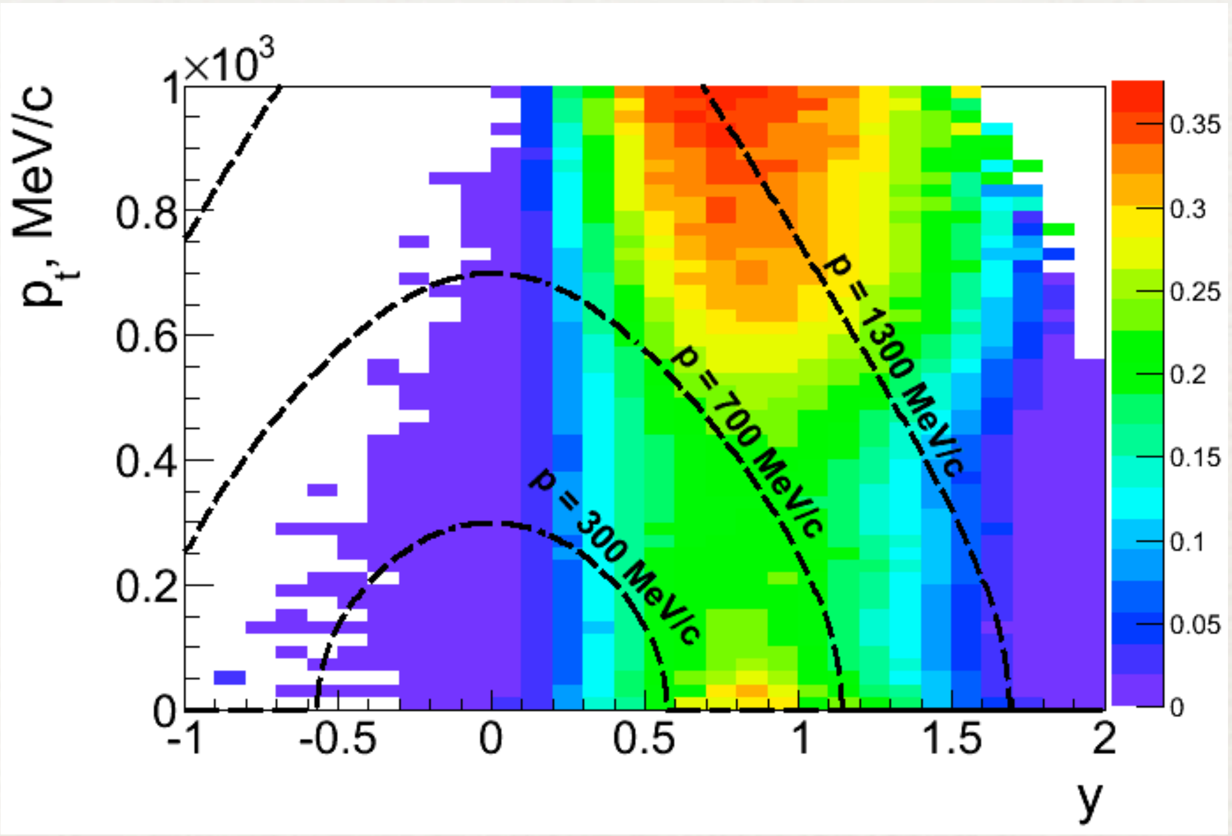


Phase space coverage

K^0 phase space (UrQMD sim.)



HADES acceptance



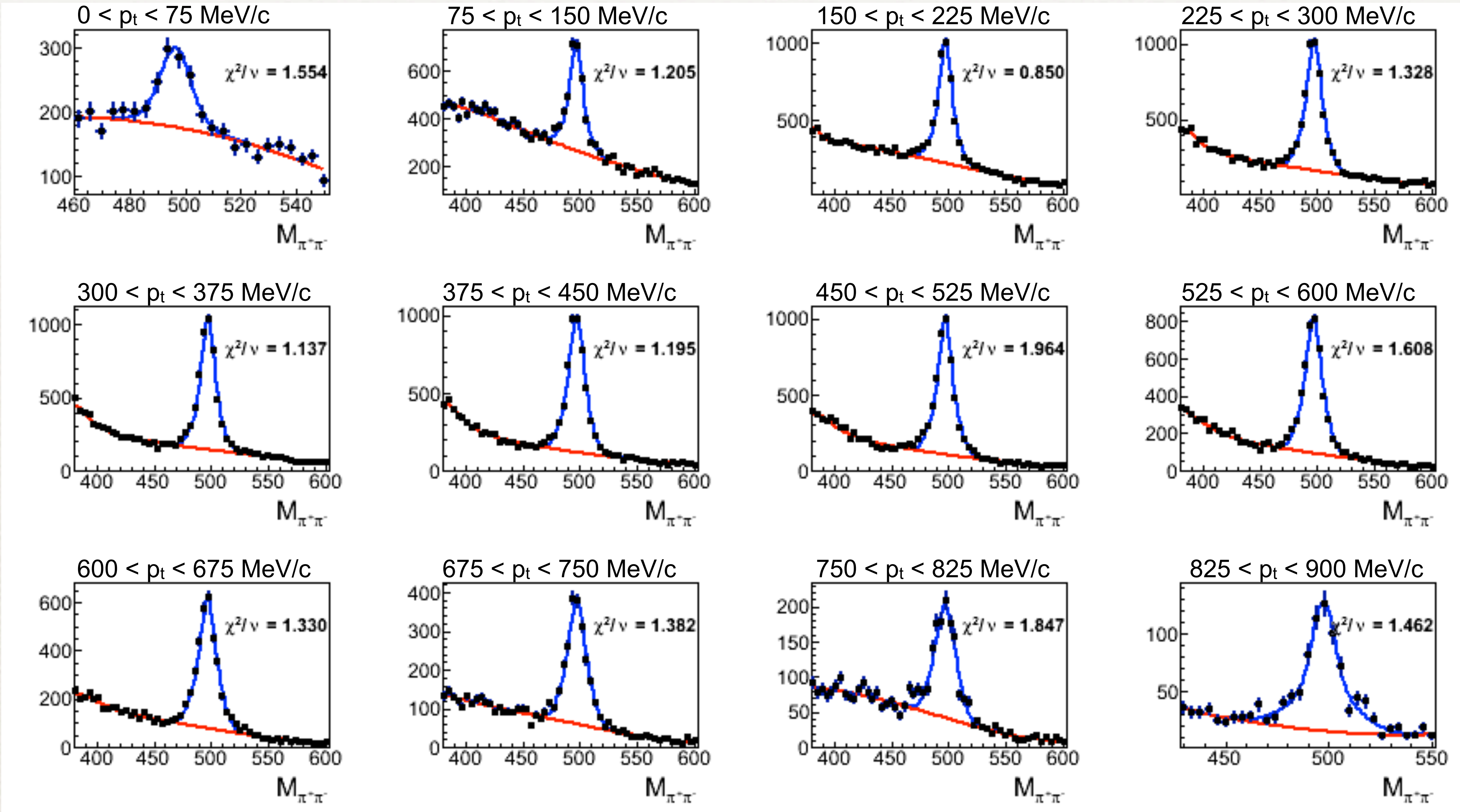
We reconstruct K^0_S — what about $\overline{K}^0$ contribution? HSD gives $\mathbf{\overline{K}^0/K^0 < 4\%}$.

KaoS: p+Au 3.5 GeV $\mathbf{K^-/K^+ = 2.3\%}$

W. Scheinast et al.
Phys.Rev.Lett. 96 (2006) 072301

Differential signal extraction: an example

0.67 < y < 0.77

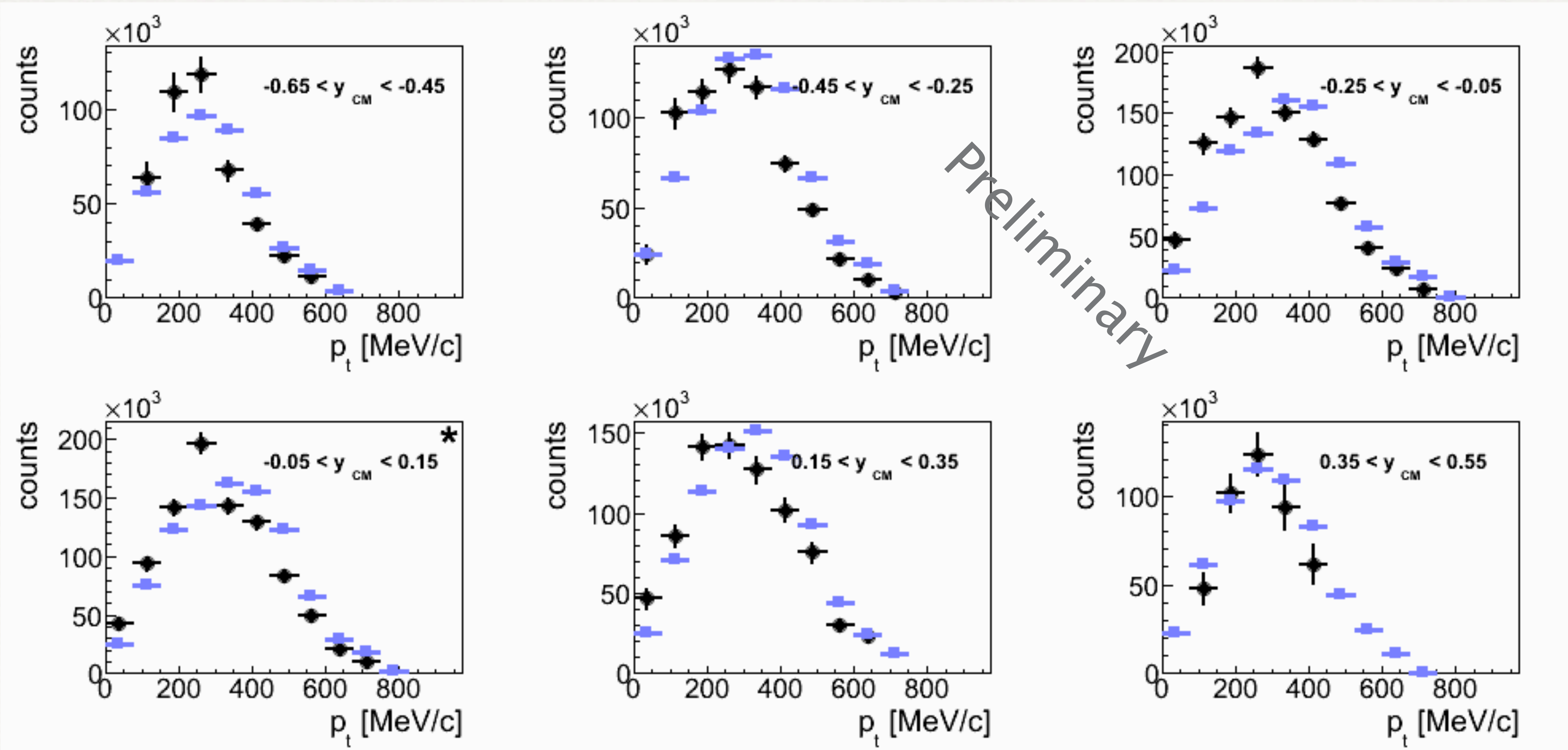


Fit function: Landau + polynomial (background) and double gaussian (signal)

p+p

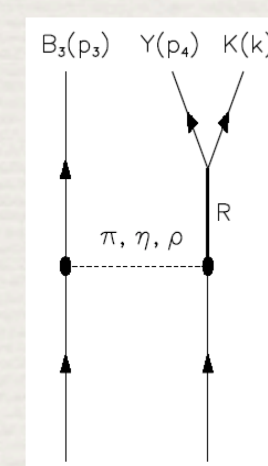
K^0 phase space in pp collisions

• EXP
• GiBUU



GiBUU:
O. Buss et al. Phys.Rept. 512 (2012) 1-124

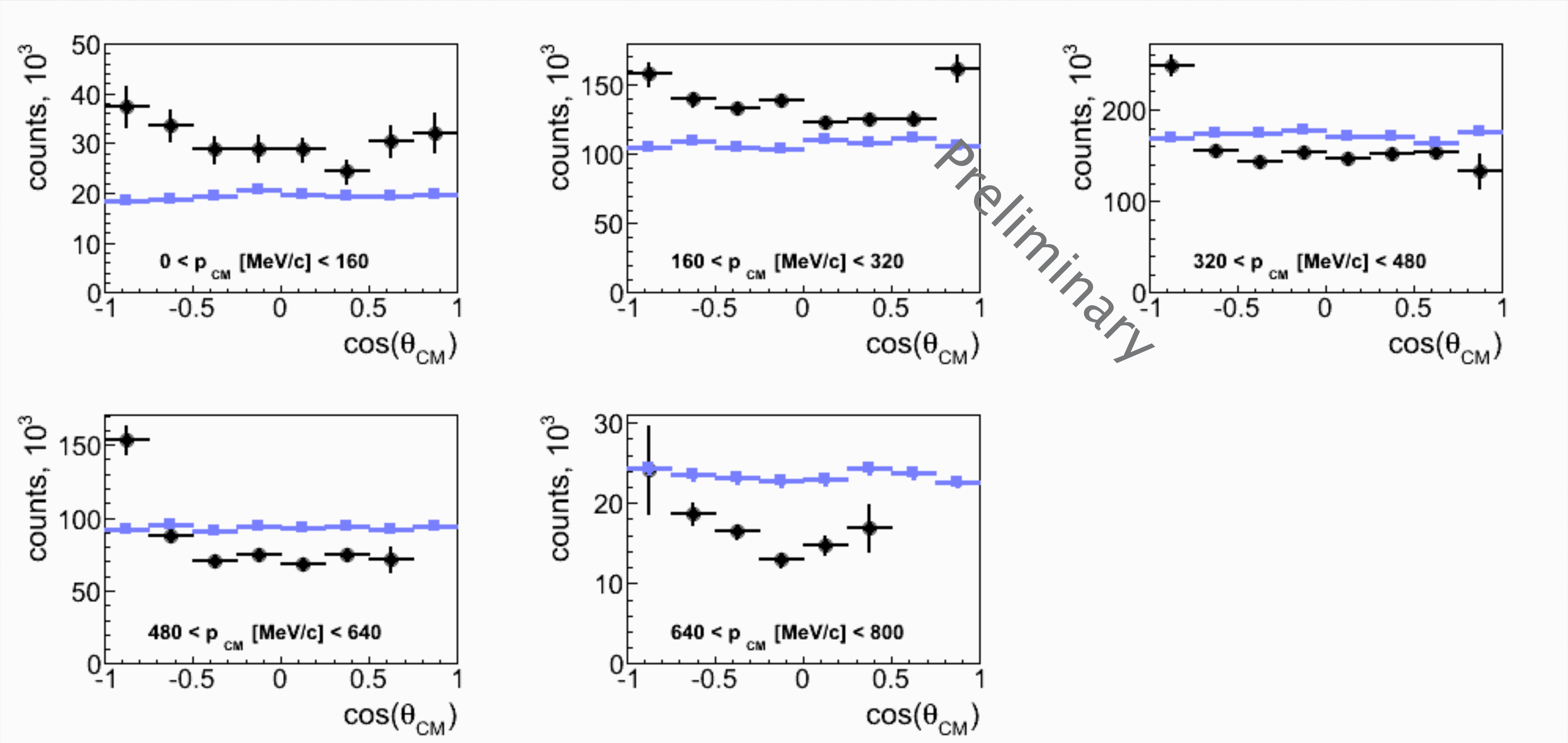
- GiBUU: kaon production via **resonance model**.
- Normalized to the mid-rapidity bin (one global scaling factor).
- Description is bad.



p+p

K^0 phase space in pp collisions

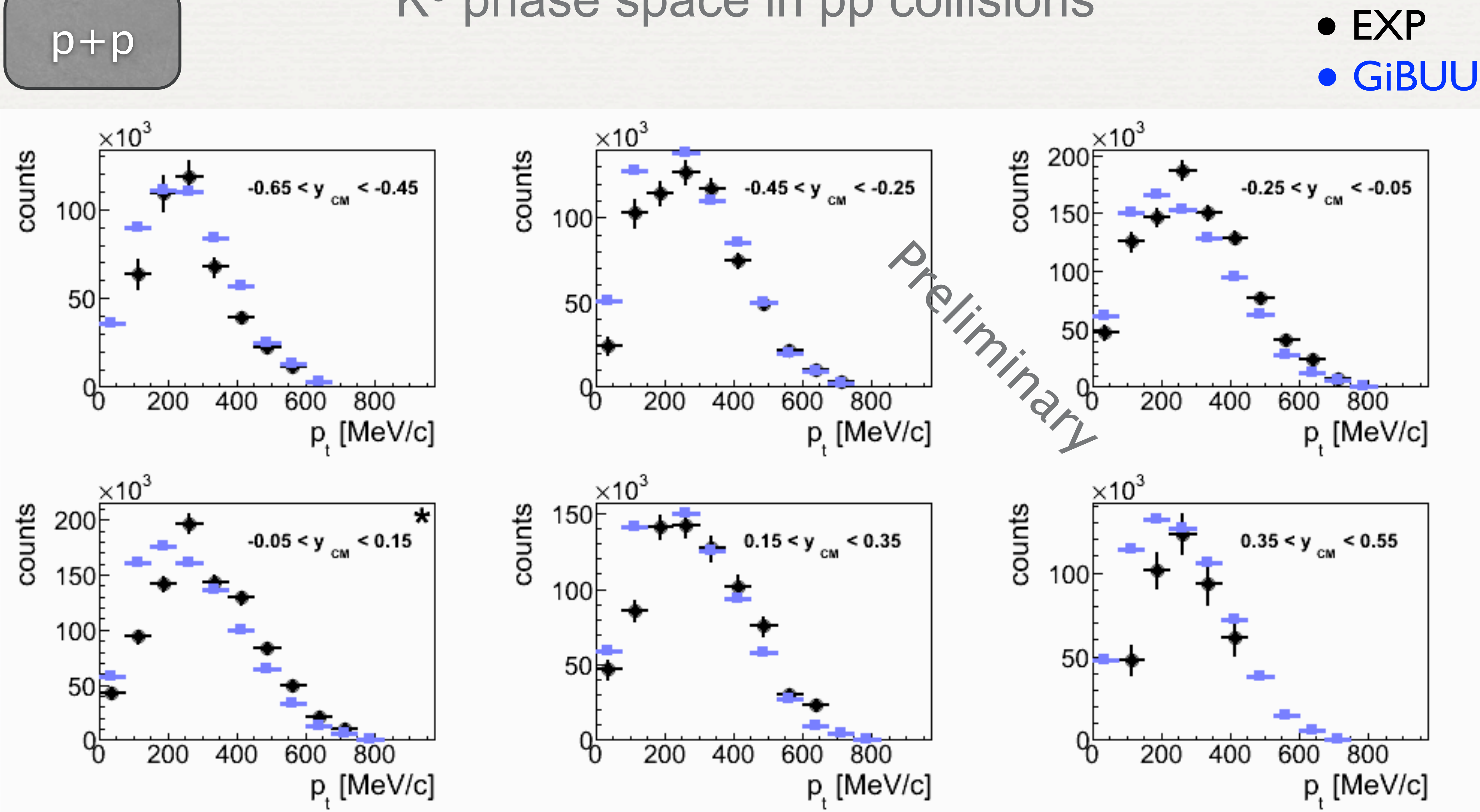
- EXP
- GiBUU



- Angular anisotropy of kaon production.
- GiBUU: kaon production via **resonance model**.
- Normalization from (p_t,y) analysis.

p+p

K^0 phase space in pp collisions

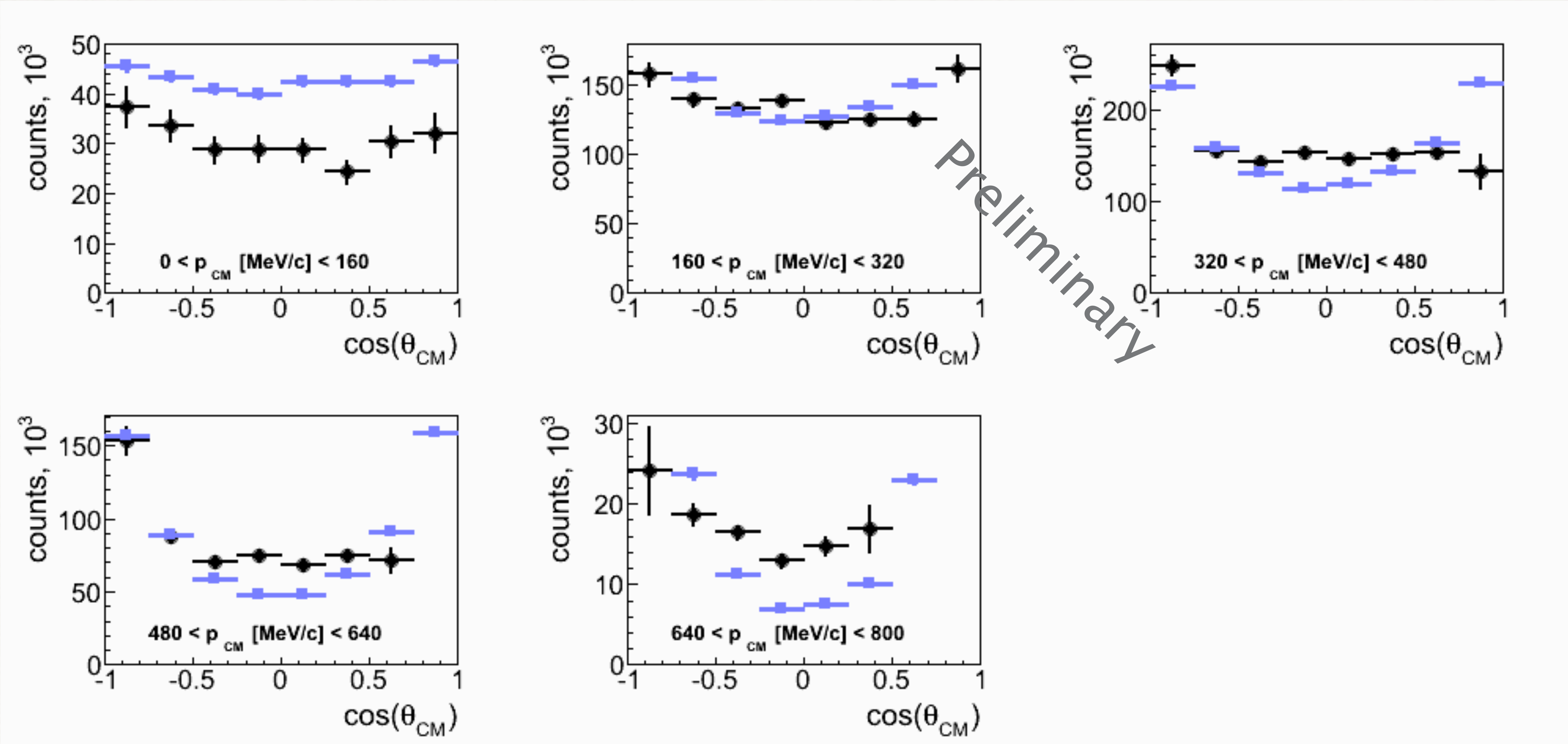


- GiBUU: kaon production via **PYTHIA**.
- Normalized to the mid-rapidity bin (one global scaling factor).
- Description is bad.

p+p

K^0 phase space in pp collisions

- EXP
- GiBUU

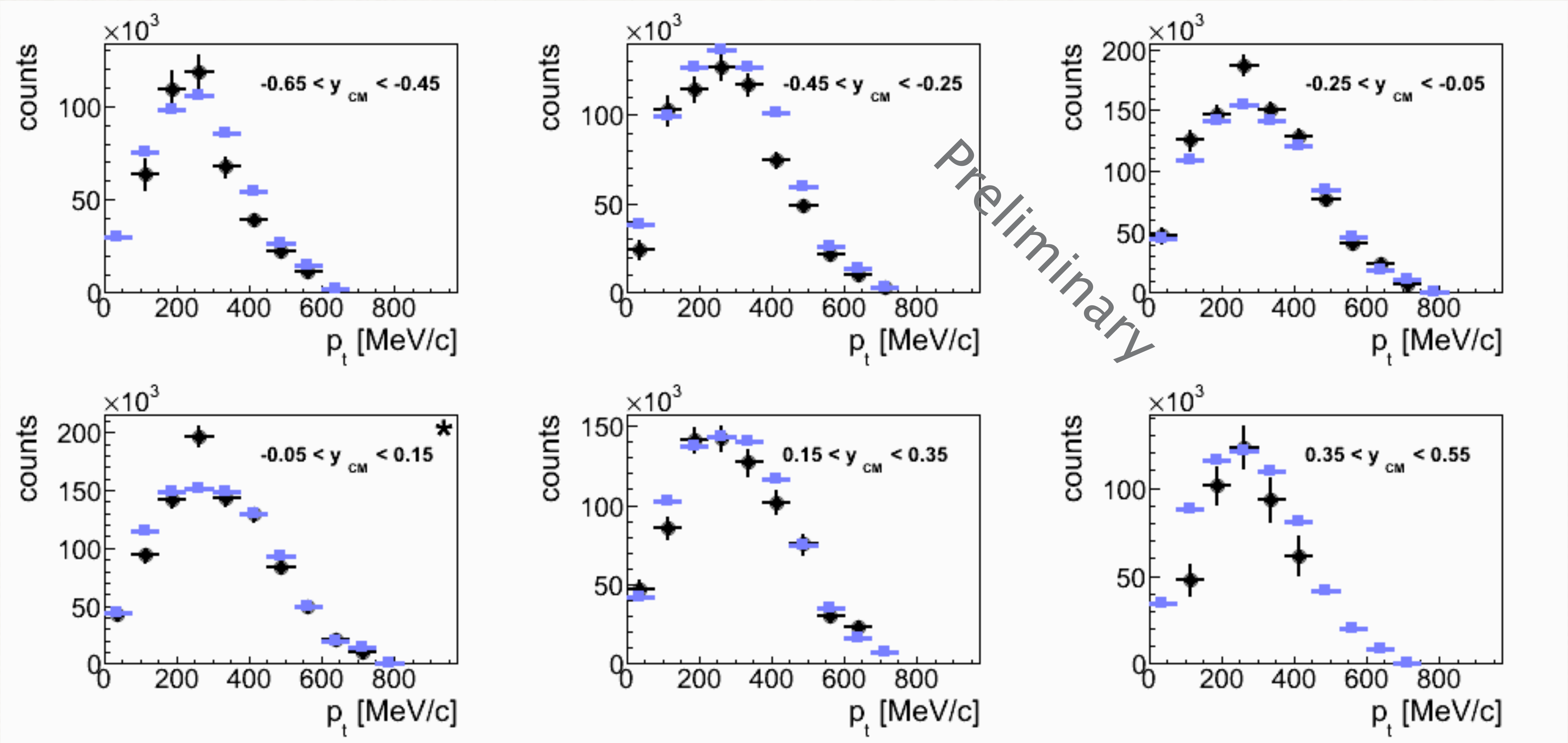


- GiBUU: kaon production via **PYTHIA.**

p+p

K^0 phase space in pp collisions

- EXP
- GiBUU

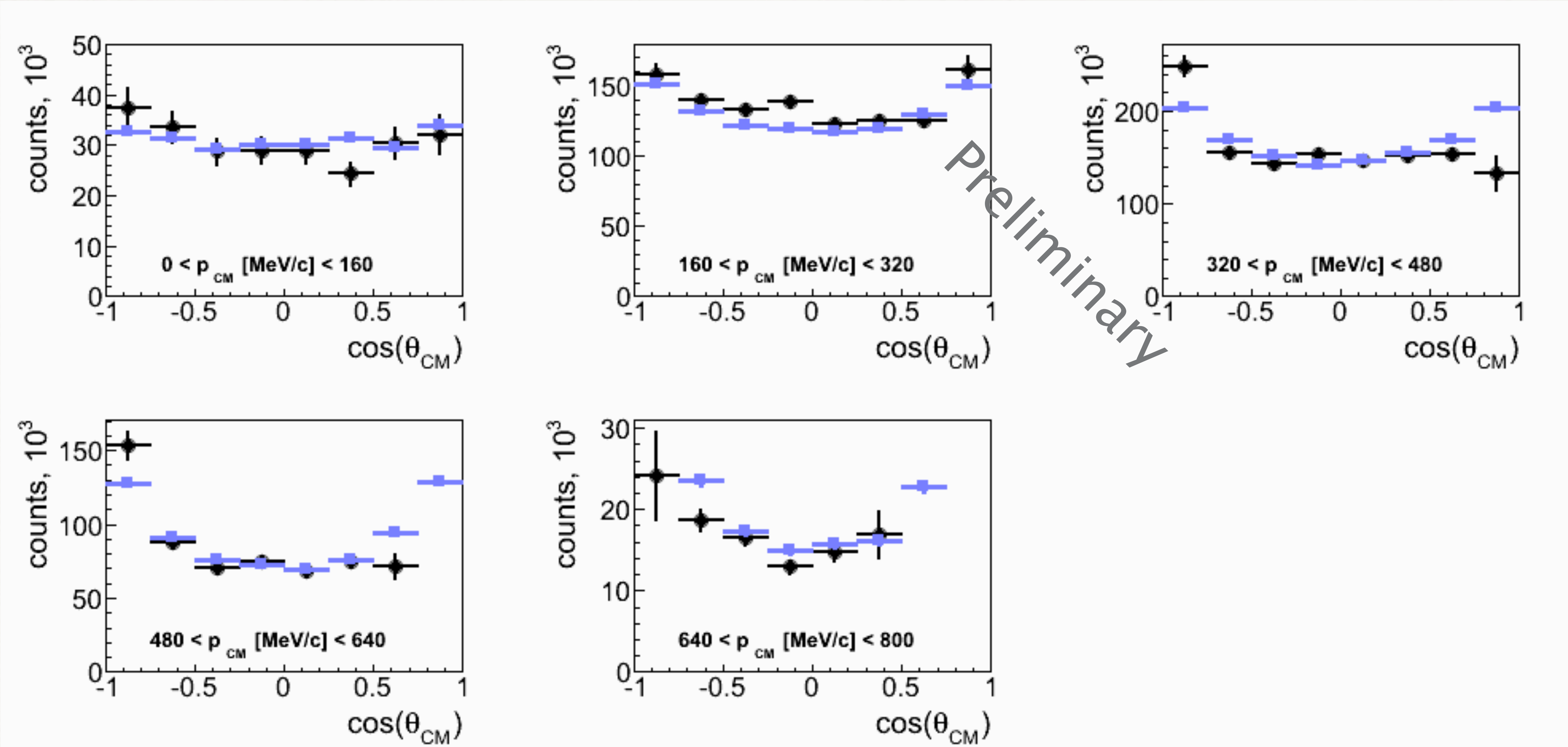


- GiBUU: kaon production via mixed approach **resonance model** + **PYTHIA.**
- Good description of the data.

p+p

K^0 phase space in pp collisions

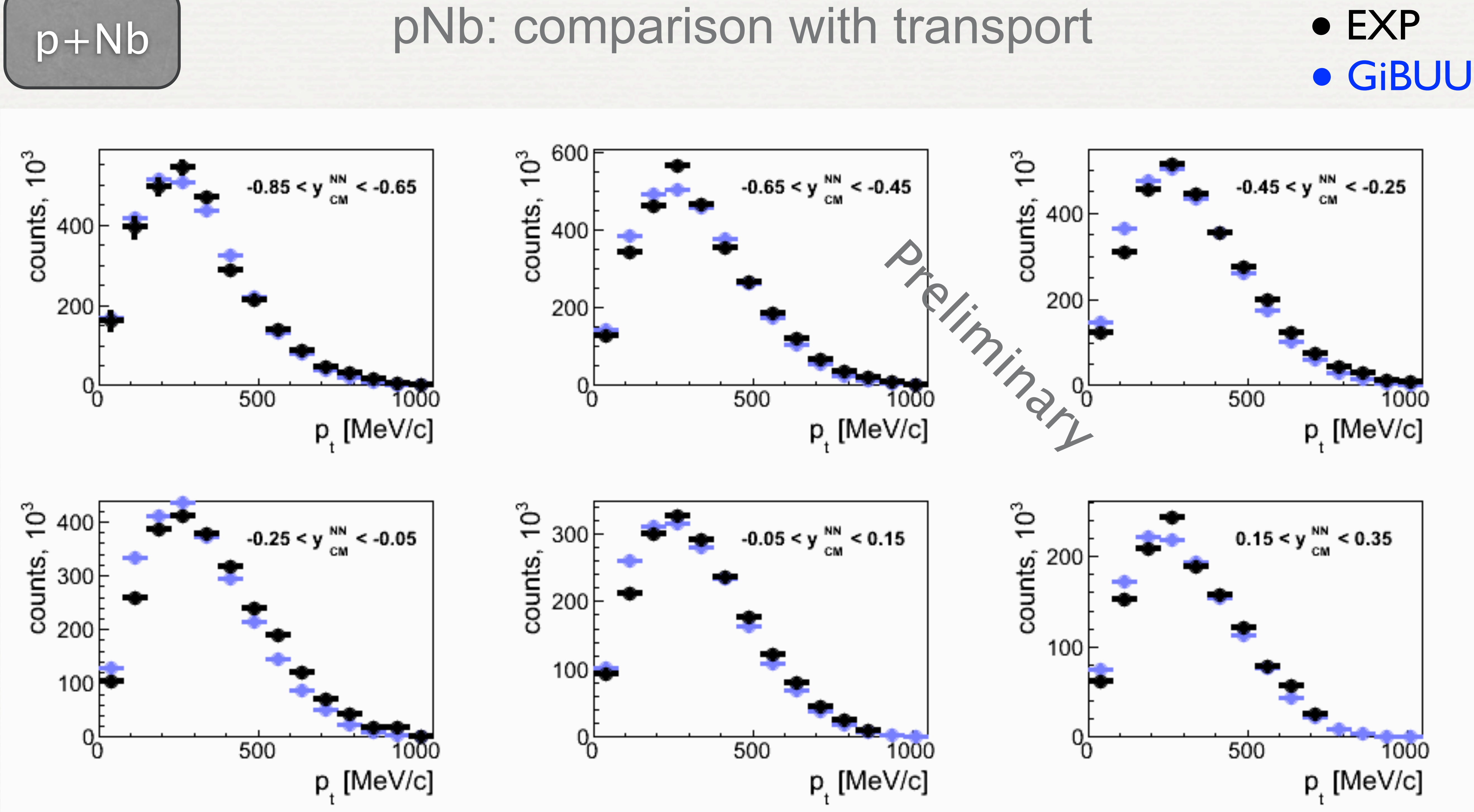
- EXP
- GiBUU



- GiBUU: kaon production via mixed approach **resonance model** + **PYTHIA**.
- Good description of the data.
- Kaon production is fixed in simulations.

p+Nb

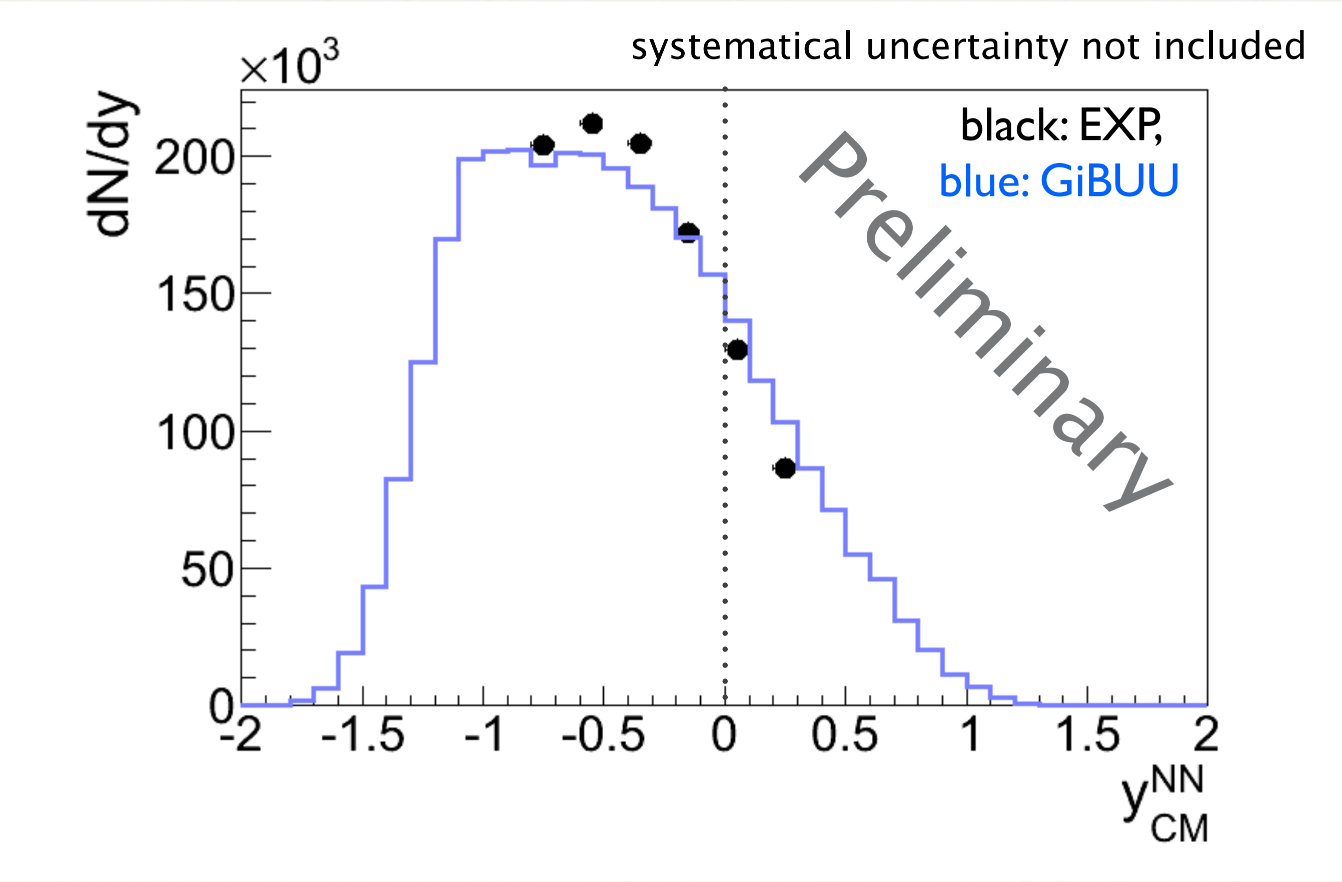
pNb: comparison with transport

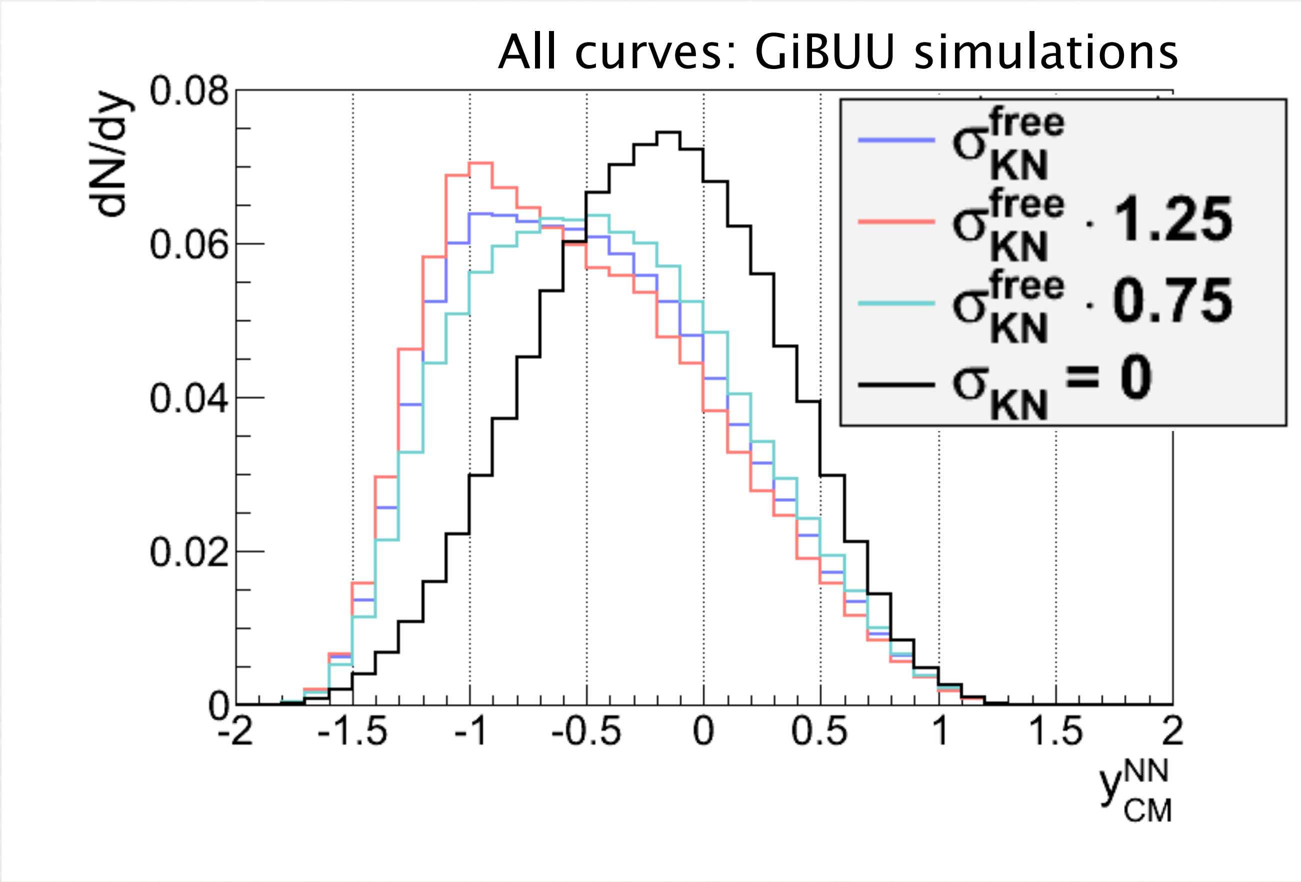


- Each rapidity bin normalized individually to the area.
- Good description of the shape, but systematic overshoot at low p_t → tentative effect of repulsive potential.
- No KN potential available in simulations.

p+Nb

Rapidity distribution



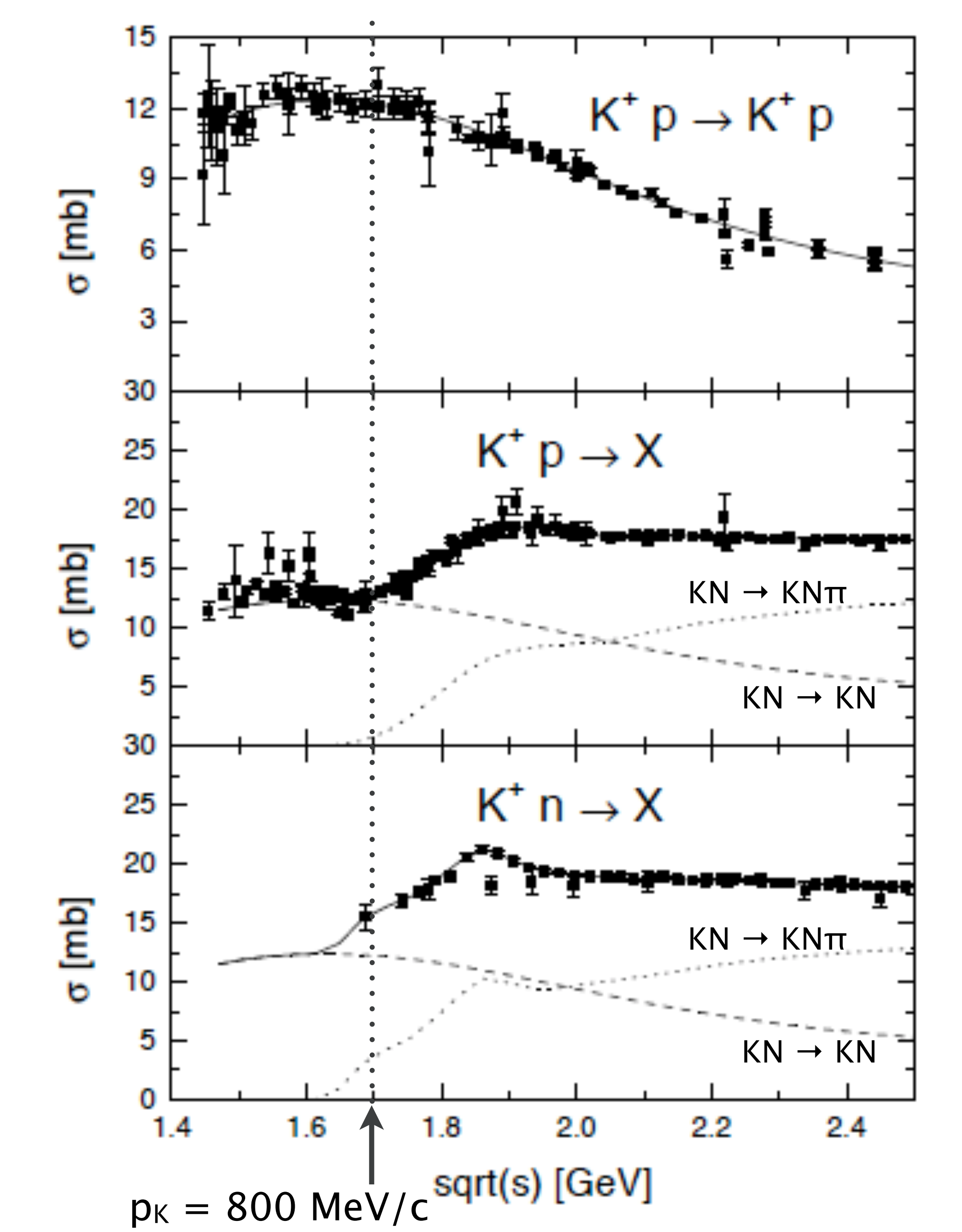


- Strong shift to the target rapidity, qualitatively reproduced by the GiBUU transport model.
- Sensitivity to the potential?

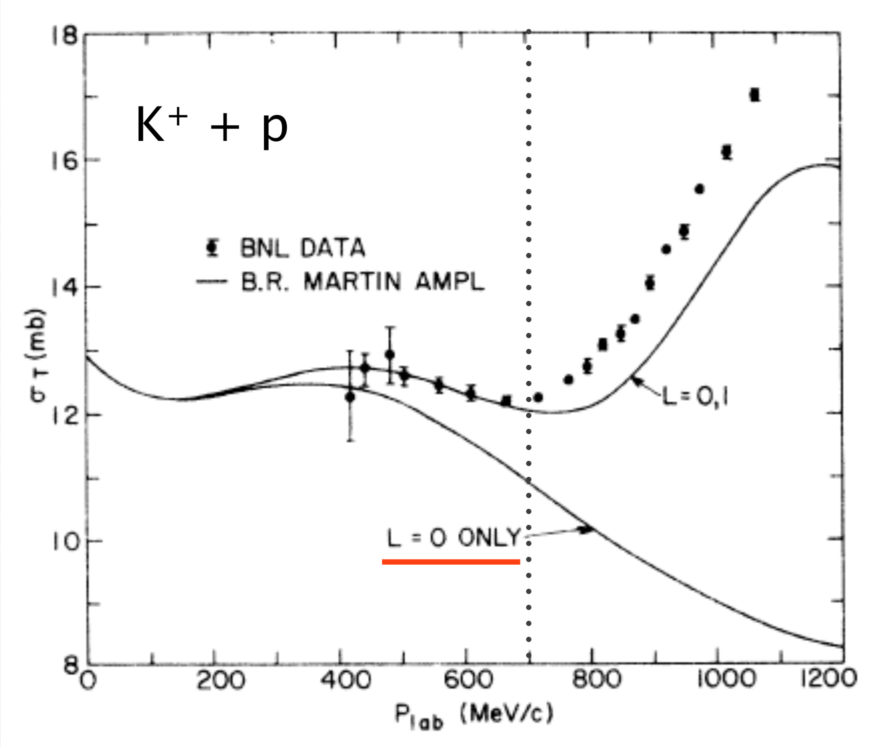
- KN scattering has a strong effect on the rapidity distribution.
- Almost symmetrical shape for $\sigma_{KN} = 0$.

Free KN scattering

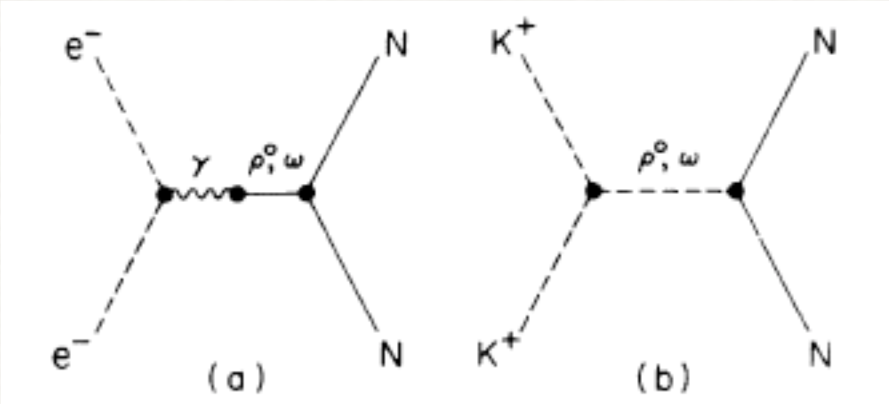
is known rather well:



Picture: M. Effenberger, PhD. Giessen, 1999.



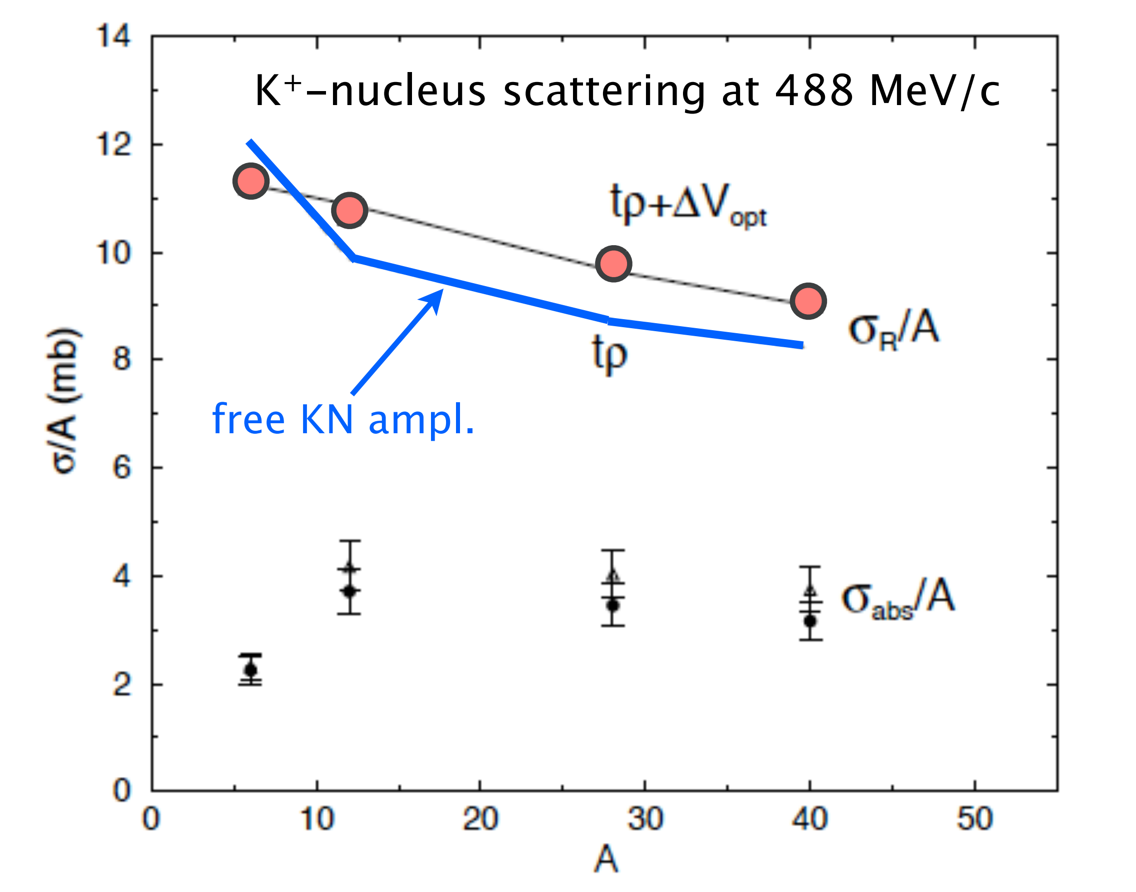
For L = 0 VM exchange:



C. Dover and P. Moffa, Phys. Rev. C 16 1977

In-medium KN scattering

Free KN amplitudes underestimate the K^+-nucleus reaction c.s. by ~15%



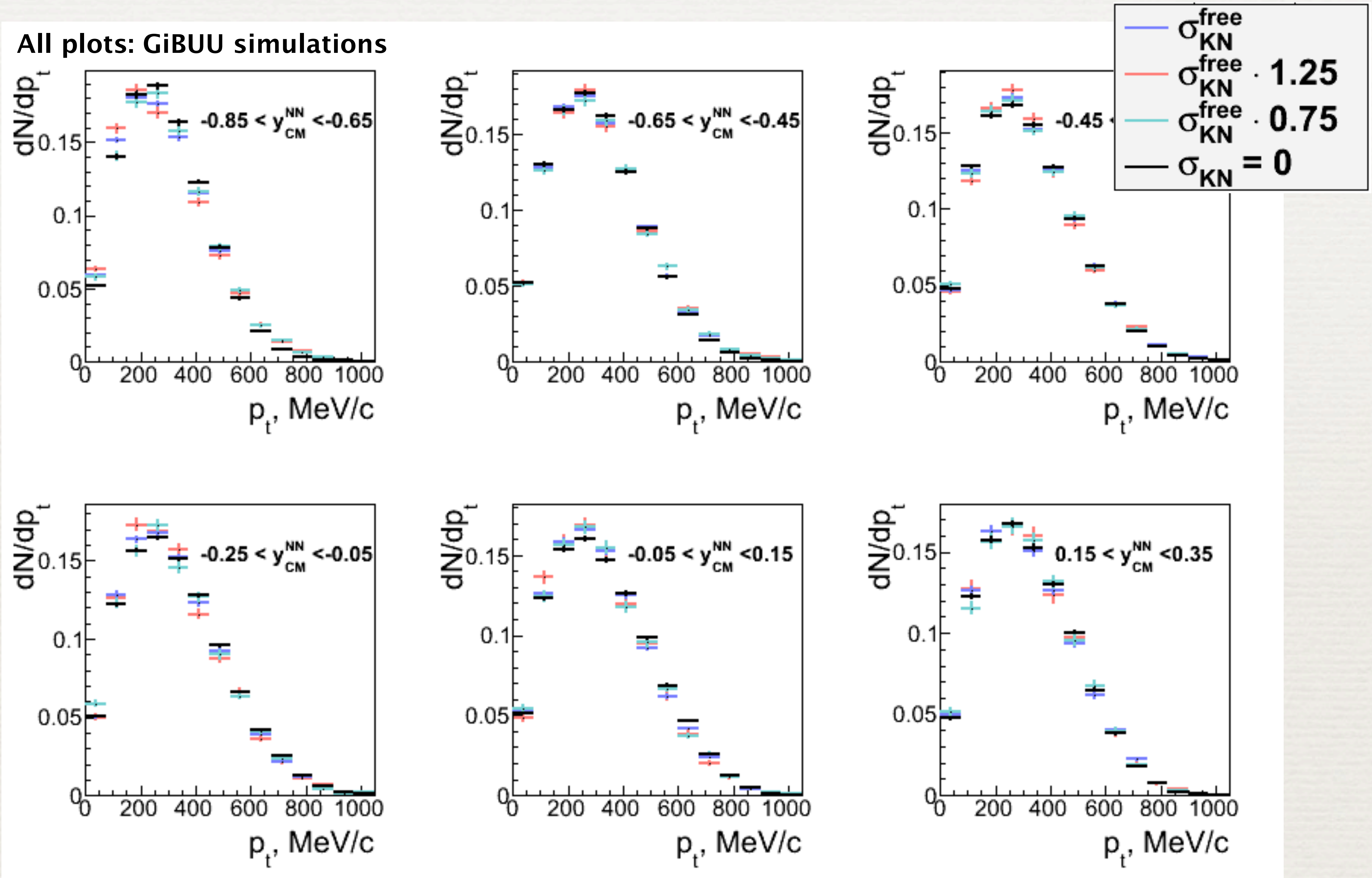
E. Friedman, A. Gal. Phys. Rept. 452 (2007) 89.

Number of mechanisms proposed to explain the difference:

- Swelling of nucleons in nuclear matter.
  P.B. Siegel et al. Phys. Rev. C 31 (1985) 2184.
- Modification of exchanged vector mesons.
  G.E. Brown et al. Phys. Rev. Lett. 60 (1988) 2723.
- Meson exchange-current contribution.
  M.F. Jiang et al. Phys. Rev. C. 46 (1992) 6.
- In-medium formation of the Θ^+ pentaquark: $KNN \to \Theta^+ N$.
  A. Gal, E. Friedman. Phys. Rev. Lett. 94 (2005) 072301.
  L. Tolos et al. Phys. Lett. B 632 (2006) 219.

Is there a way to disentangle between possible modification of the KN scattering and potential effects?

KN scattering: effect on p_t distributions in pNb



- Spectra in each rapidity bin are normalized to the same area.
- **Shape** of p_t-spectra is **not sensitive** to the KN scattering.

Comparison with KaoS results

Experiment	Colliding system	Number of participants (minimum bias)	Total cross section at 3.5 GeV, mb
KaoS (K^+)	p + ^{197}Au	3.1	1616
	p + ^{12}C	2.1	243.4
HADES (K^0)	p + ^{93}Nb	2.4	848
	p + p	2	43.3

Number of participants estimated with a nuclear overlap model http://www-linux.gsi.de/~misko/overlap/interface.html

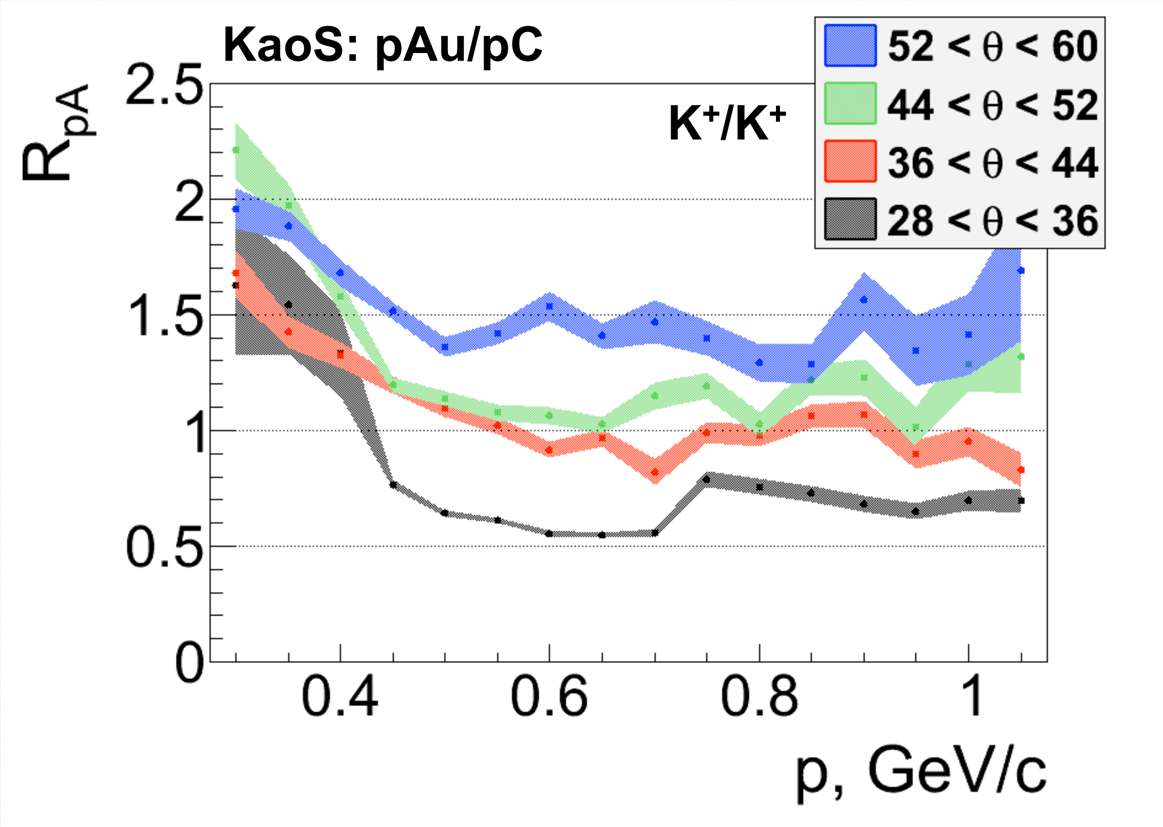
Total cross sections for pAu and pC from R.K. Tripathi et al. NIM B 117 (1996) 347.

KaoS data provided by W. Scheinast Phys.Rev.Lett. 96 (2006) 072301.

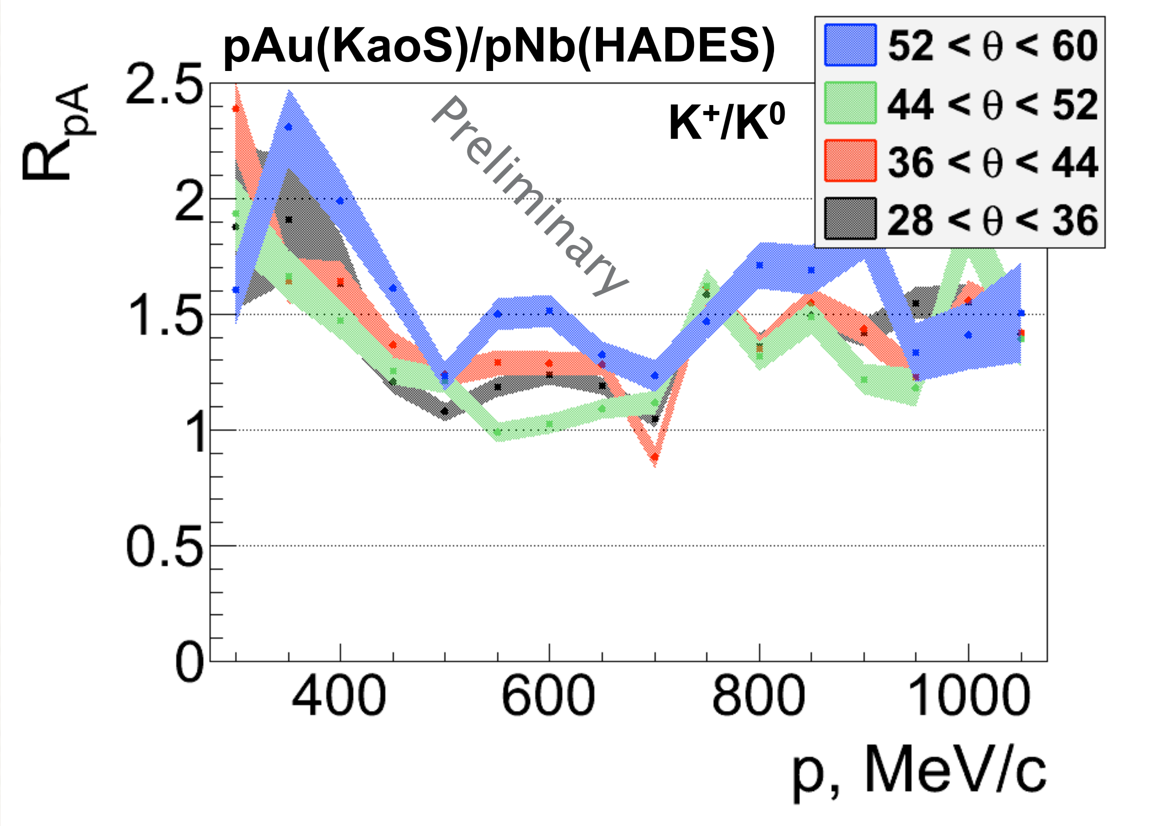
$$R_{pA}(p) = \frac{d\sigma_{pA}/dp}{d\sigma_{pp}/dp} \cdot \frac{N_{part}^{pp}}{N_{part}^{pA}} \cdot \frac{\sigma_{tot}^{pp}}{\sigma_{tot}^{pA}}$$

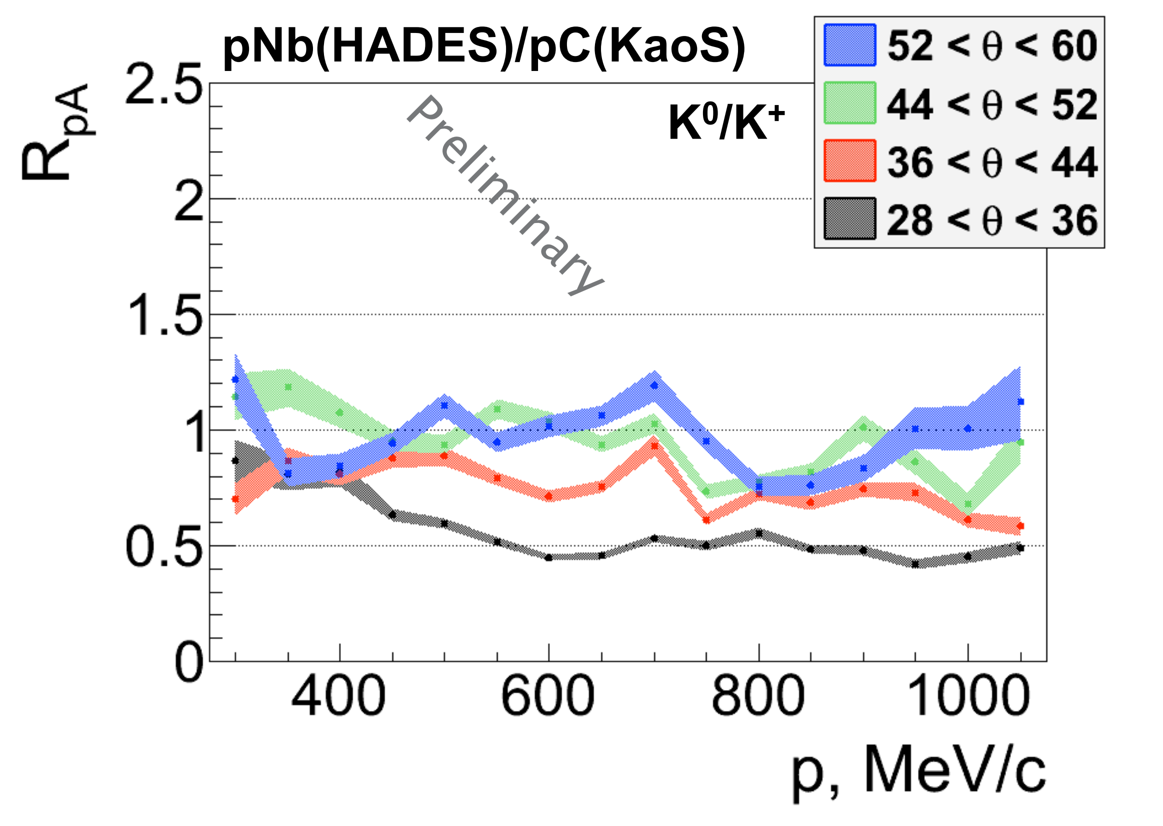
analogous scaling used for comparison between two nuclear targets, e.g. pAu/pC

R_{pA}: HADES vs KaoS (K^0 vs K^+) at 3.5 GeV

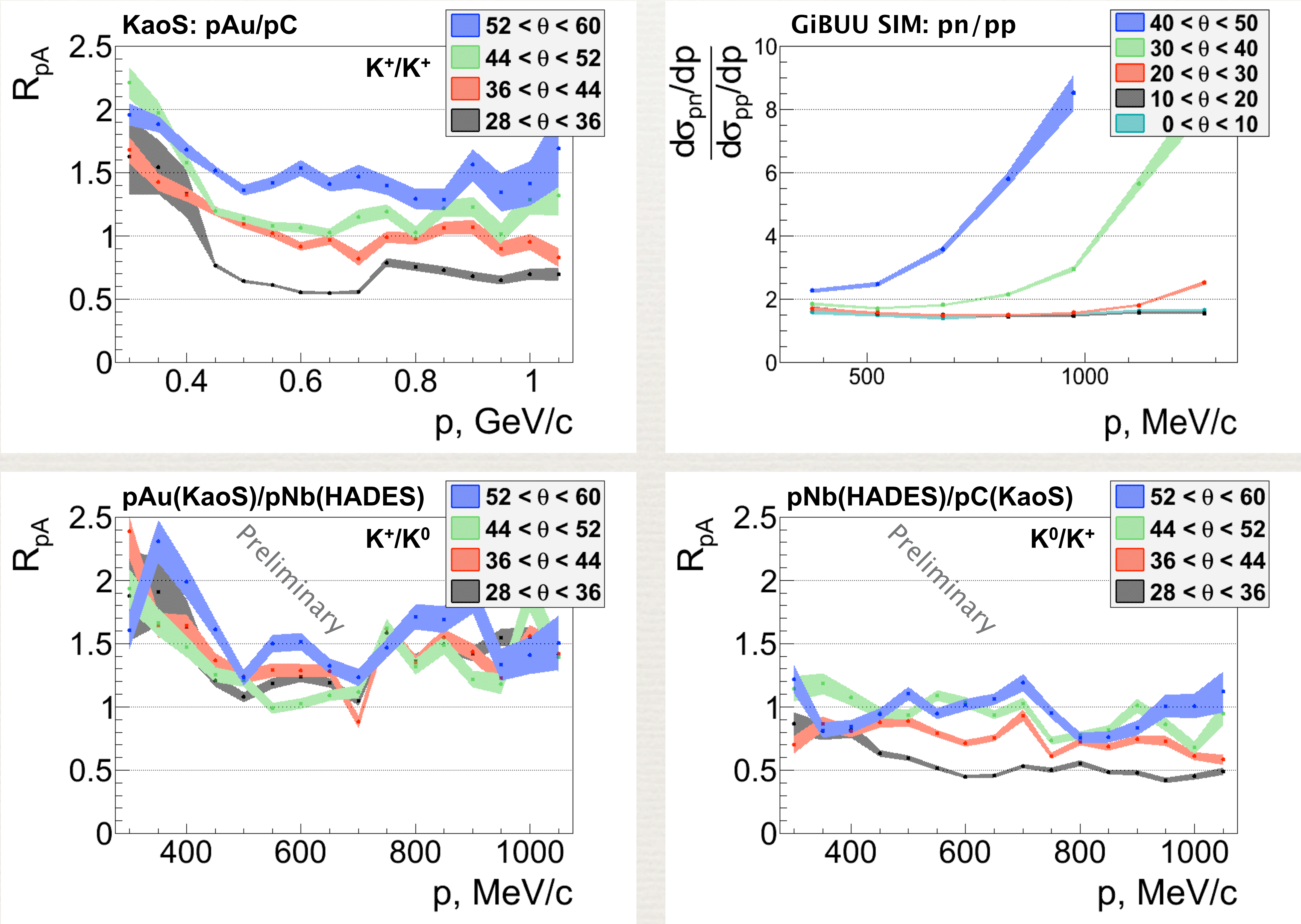


- Single scaling factor $K^+/K^0 \approx 1.1$ (from GiBUU).
- Ratios ~1, cross-check of the data.
- "Line splitting" due to KN scattering and isospin effects.



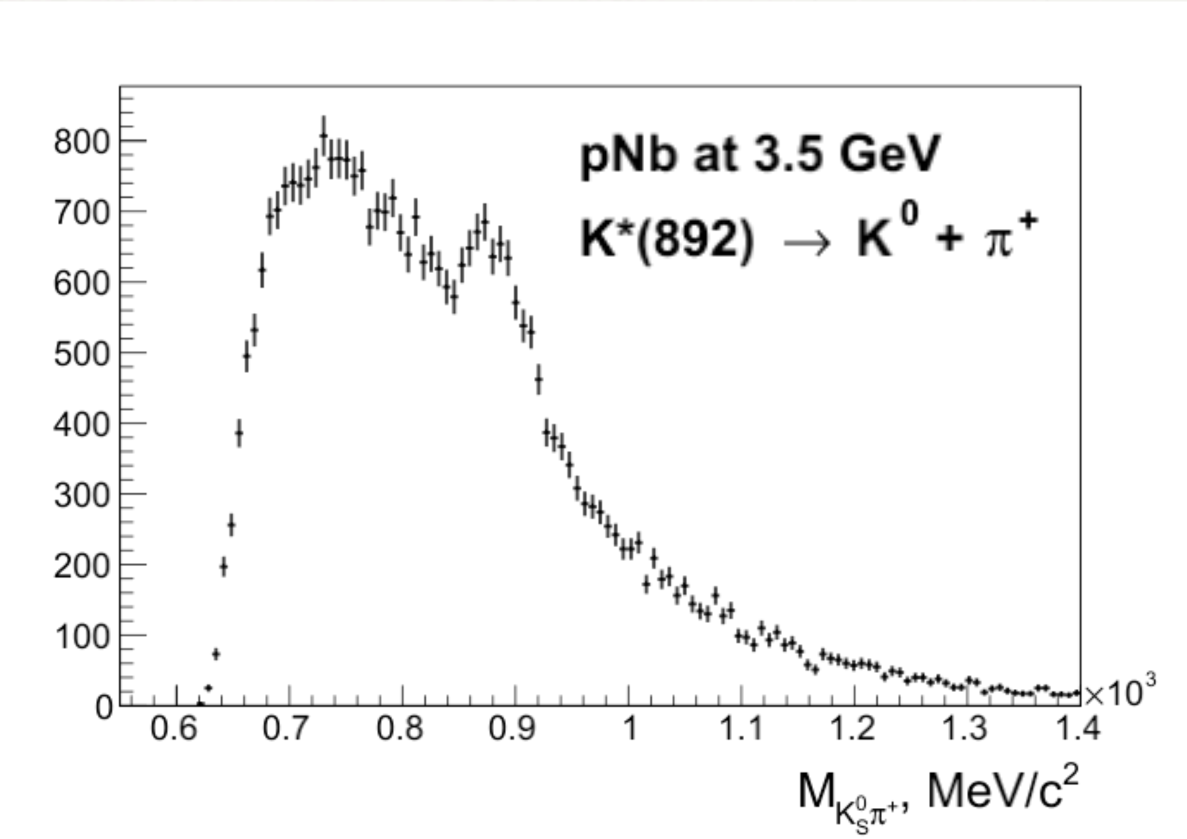


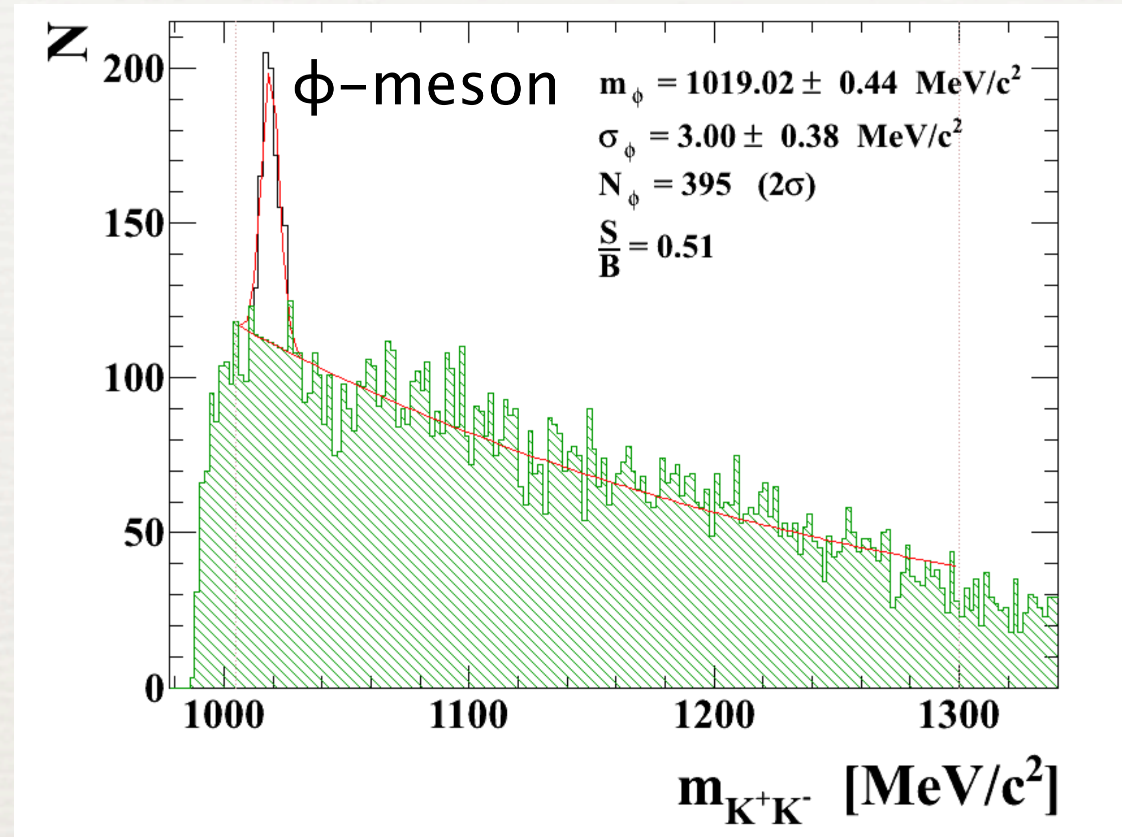
R_{pA}: HADES vs KaoS (K^0 vs K^+) at 3.5 GeV

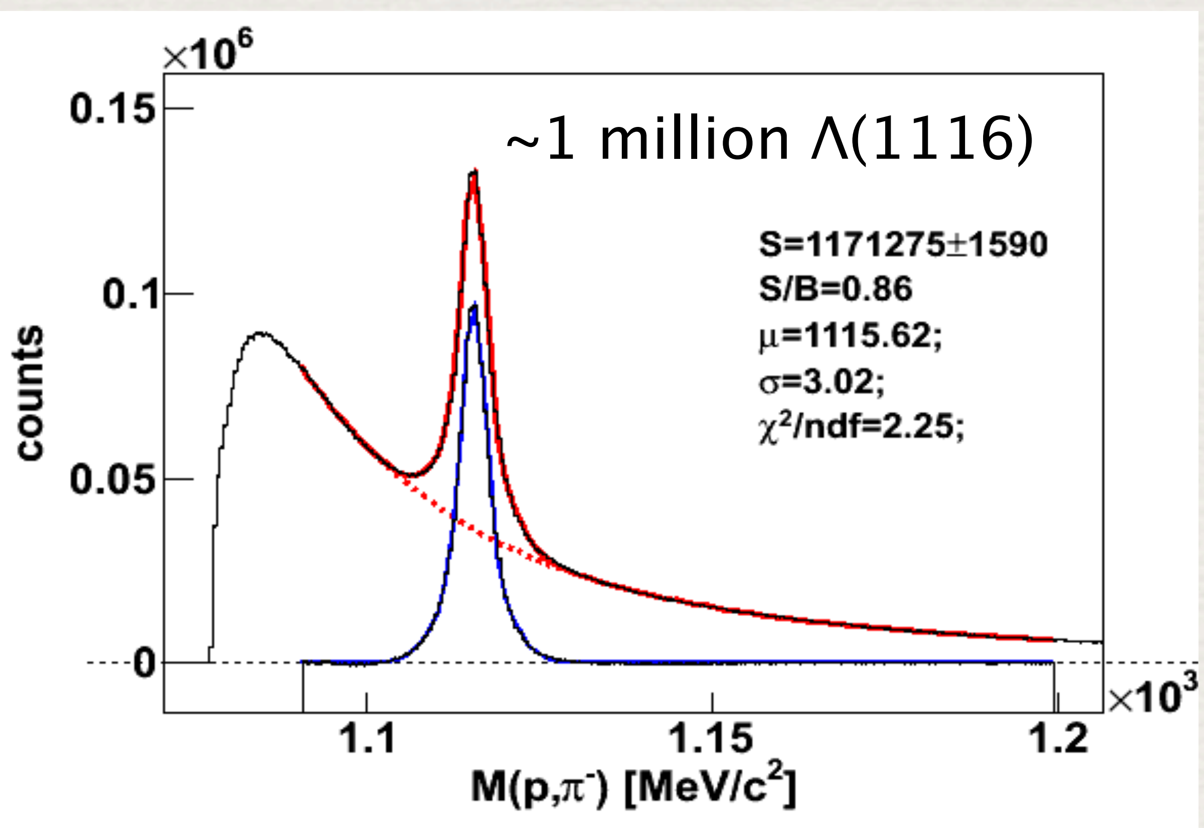


More strange things going on in pNb

raw signals





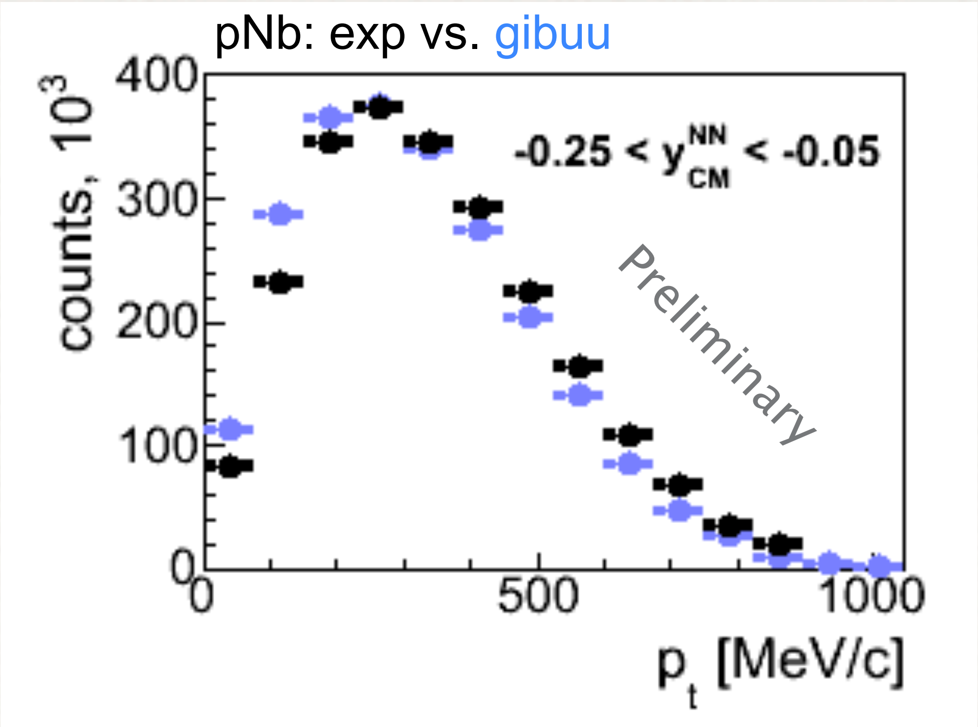


- Production and propagation of $S=\pm1$ and hidden strangeness in cold nuclear matter.

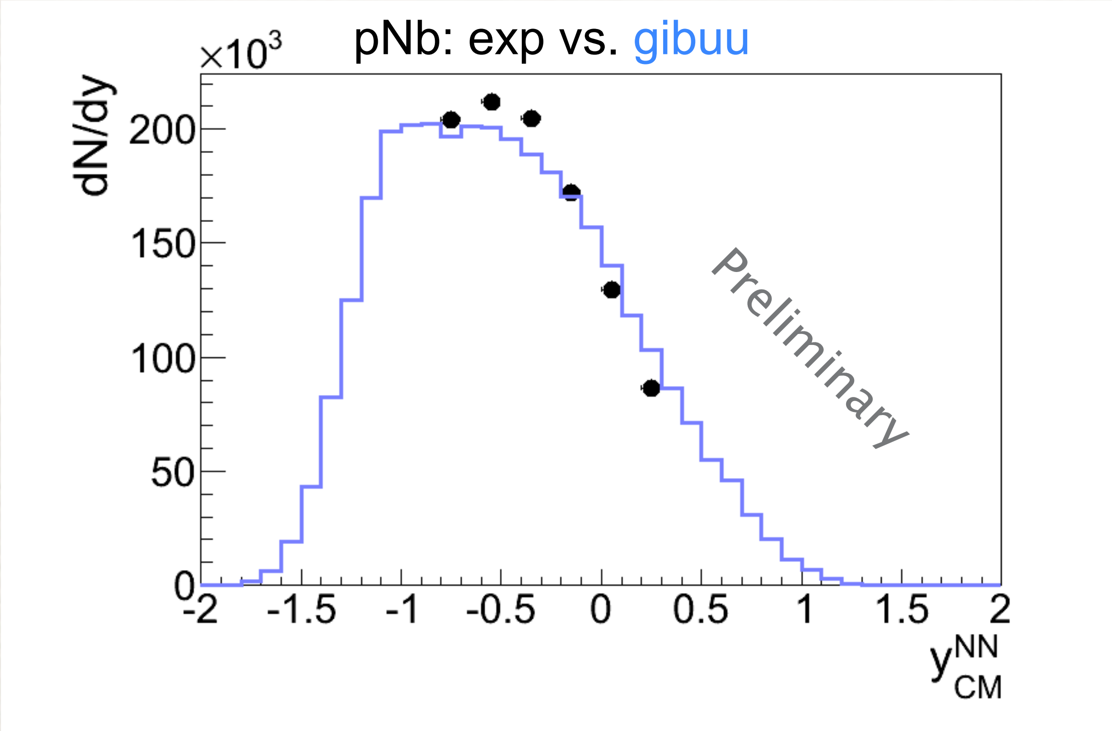
Summary

1. Analysis of K^0 emission pattern in p+p and p+^{93}Nb reactions at 3.5 GeV.
2. Comparison with the GiBUU transport model.
3. Comparison with the KaoS data (p+Au, p+C) in terms of R_{pA}.

Low p_t — K-nucleus potential.



dN/dy — KN scattering.



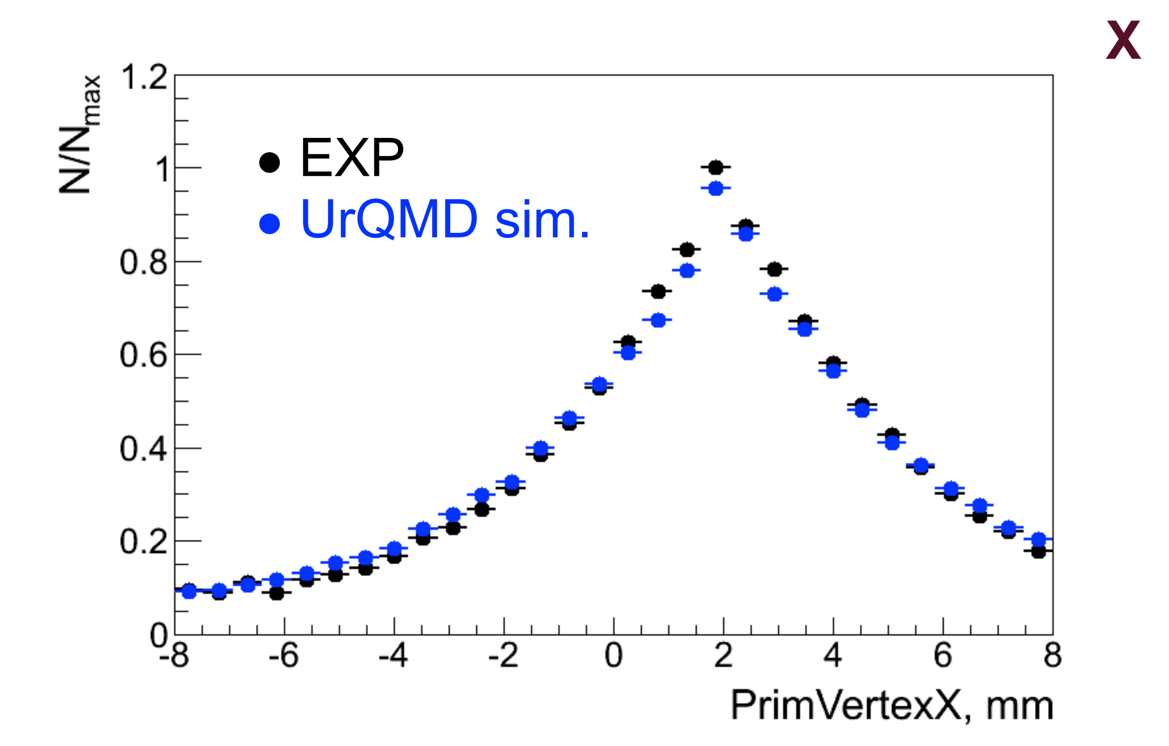
Outlook:
extract **quantitative** information on the potential and in-medium KN scattering with help of transport models
⇒ input for the heavy-ion data interpretation

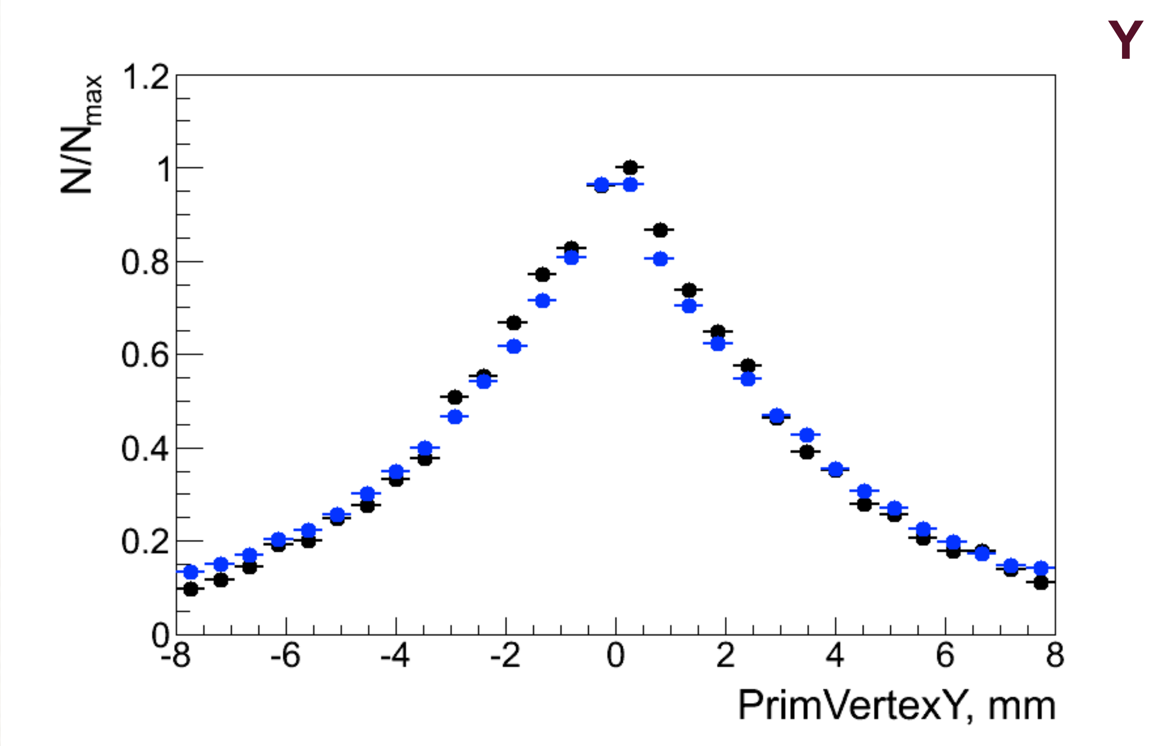
HADES Collaboration

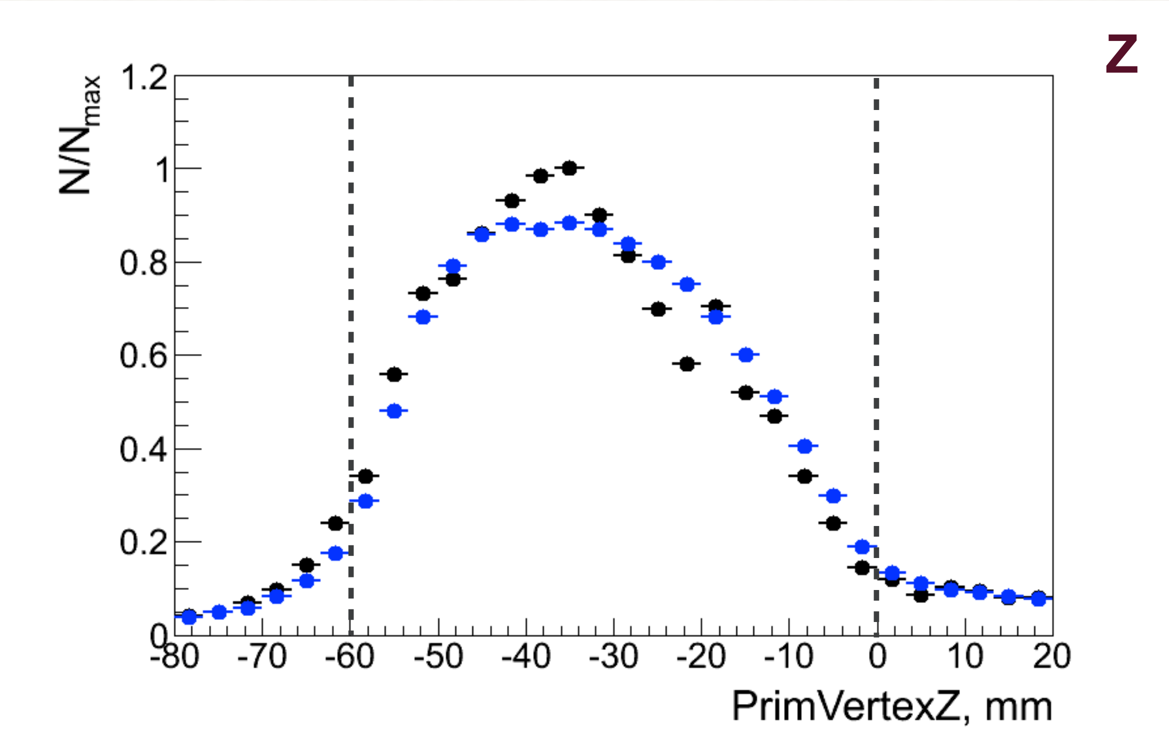
Jörn Adamczewski-Musch, Geydar Agakishiev, Claudia Behnke, Alexander Belyaev, Jia-Chii Berger-Chen, Alberto Blanco, Christoph Blume, Michael Böhmer, Pablo Cabanelas, Nuno Carolino, Sergey Chernenko, Jose Díaz, Adrian Dybczak, Eliane Epple, Laura Fabbietti, Oleg Fateev, Paulo Fonte, Jürgen Friese, Ingo Fröhlich, Tetyana Galatyuk, Juan A. Garzón, Roman Gernhäuser, Alejandro Gil, Marina Golubeva, Fedor Guber, Malgorzata Gumberidze, Szymon Harabasz, Klaus Heidel, Thorsten Heinz, Thierry Hennino, Romain Holzmann, Jochen Hutsch, Claudia Höhne, Alexander Ierusalimov, Alexander Ivashkin, Burkhard Kämpfer, Marcin Kajetanowicz, Tatiana Karavicheva, Vladimir Khomyakov, Ilse Koenig, Wolfgang Koenig, Burkhard W. Kolb, Vladimir Kolganov, Grzegorz Korcyl, Georgy Kornakov, Roland Kotte, Erik Krebs, Hubert Kuc, Wolfgang Kühn, Andrej Kugler, Alexei Kurepin, Alexei Kurilkin, Pavel Kurilkin, Vladimir Ladygin, Rafal Lalik, Kirill Lapidus, Alexander Lebedev, Ming Liu, Luís Lopes, Manuel Lorenz, Gennady Lykasov, Ludwig Maier, Alexander Malakhov, Alessio Mangiarotti, Jochen Markert, Volker Metag, Jan Michel, Christian Müntz, Rober Münzer, Lothar Naumann, Marek Palka, Vladimir Pechenov, Olga Pechenova, Americo Pereira, Jerzy Pietraszko, Witold Przygoda, Nicolay Rabin, Béatrice Ramstein, Andrei Reshetin, Laura Rehnisch, Philippe Rosier, Anar Rustamov, Alexander Sadovsky, Piotr Salabura, Timo Scheib, Alexander Schmah, Heidi Schuldes, Erwin Schwab, Johannes Siebenson, Vladimir Smolyankin, Manfred Sobiella, Yuri Sobolev, Stefano Spataro, Herbert Ströbele, Joachim Stroth, Christian Sturm, Khaled Teilab, Vladimir Tiflov, Pavel Tlusty, Michael Traxler, Alexander Troyan, Haralabos Tsertos, Evgeny Usenko, Taras Vasiliev, Vladimir Wagner, Christian Wendisch, Jörn Wüstenfeld, Yuri Zanevsky

Backup

Primary vertex cuts







Vertex reconstruction:

N_tracks > 1: mean of all tracks intersections

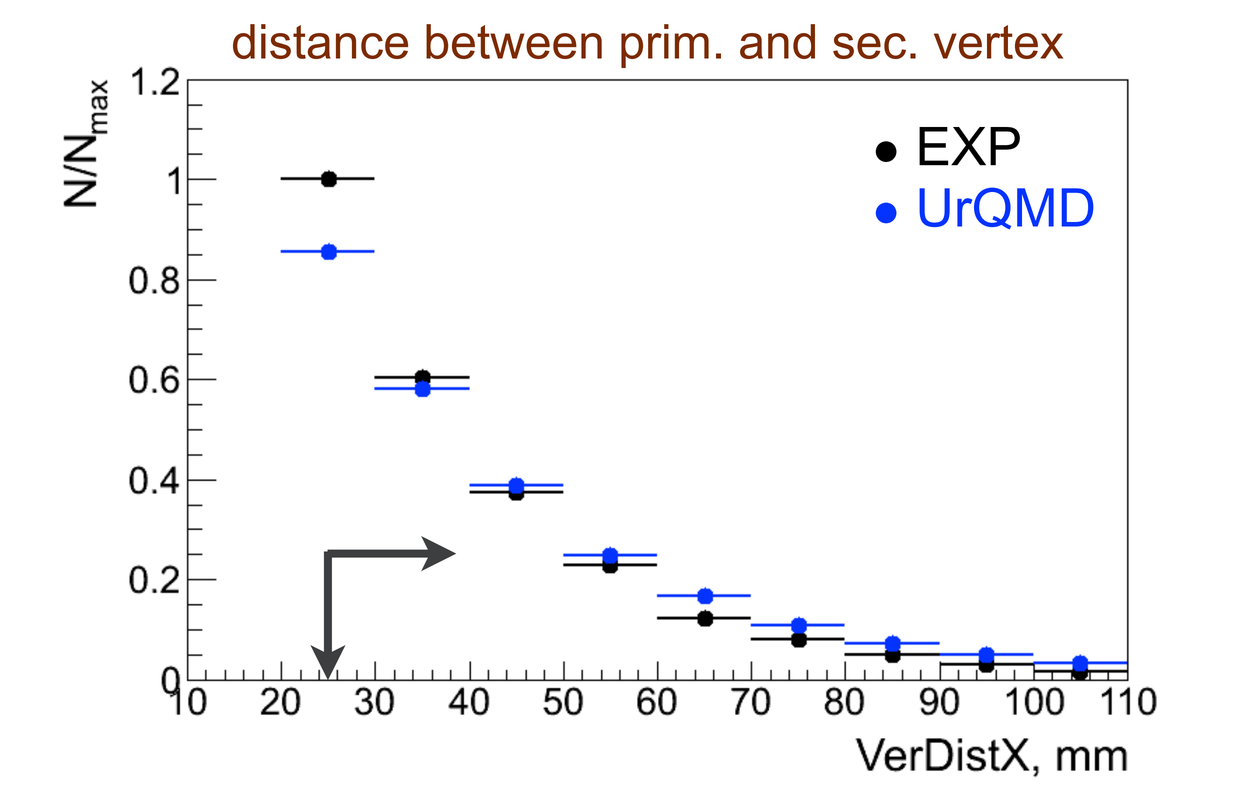
N_tracks = 1: track - beam axis intersection

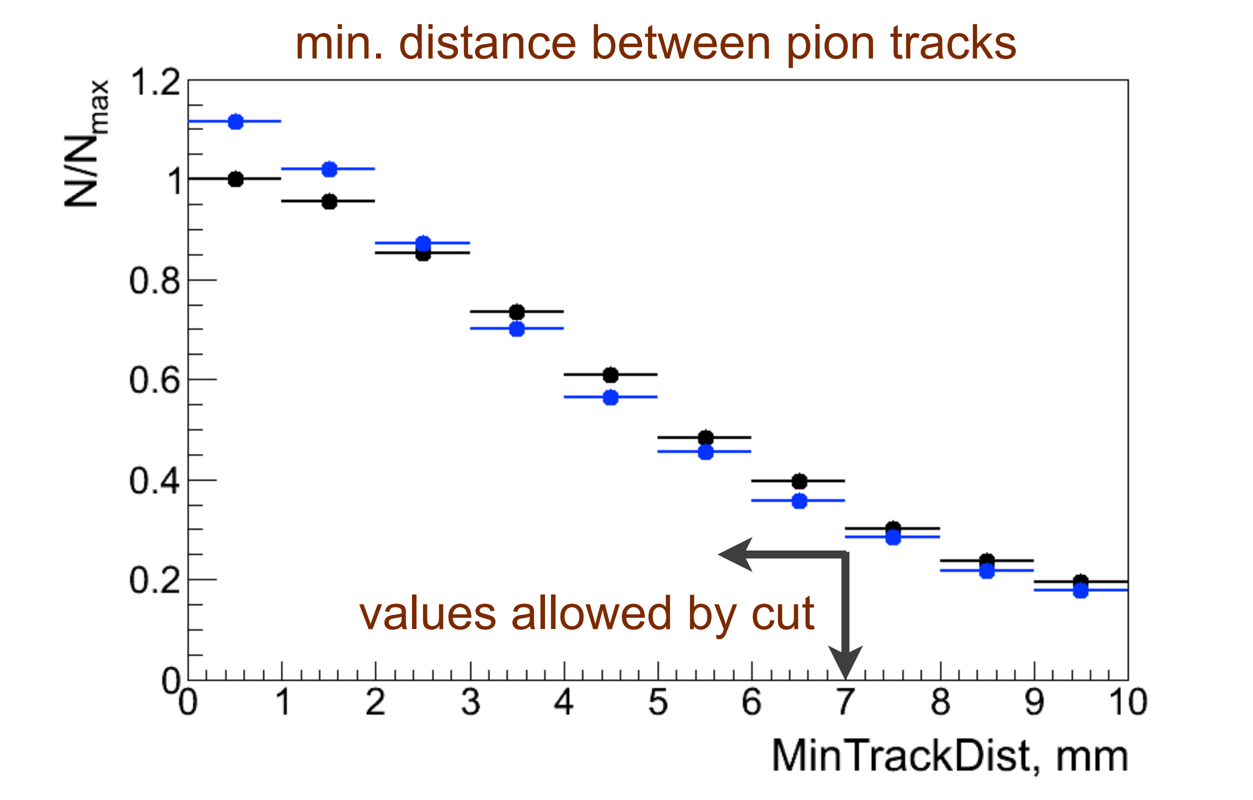
Primary vertex cuts:

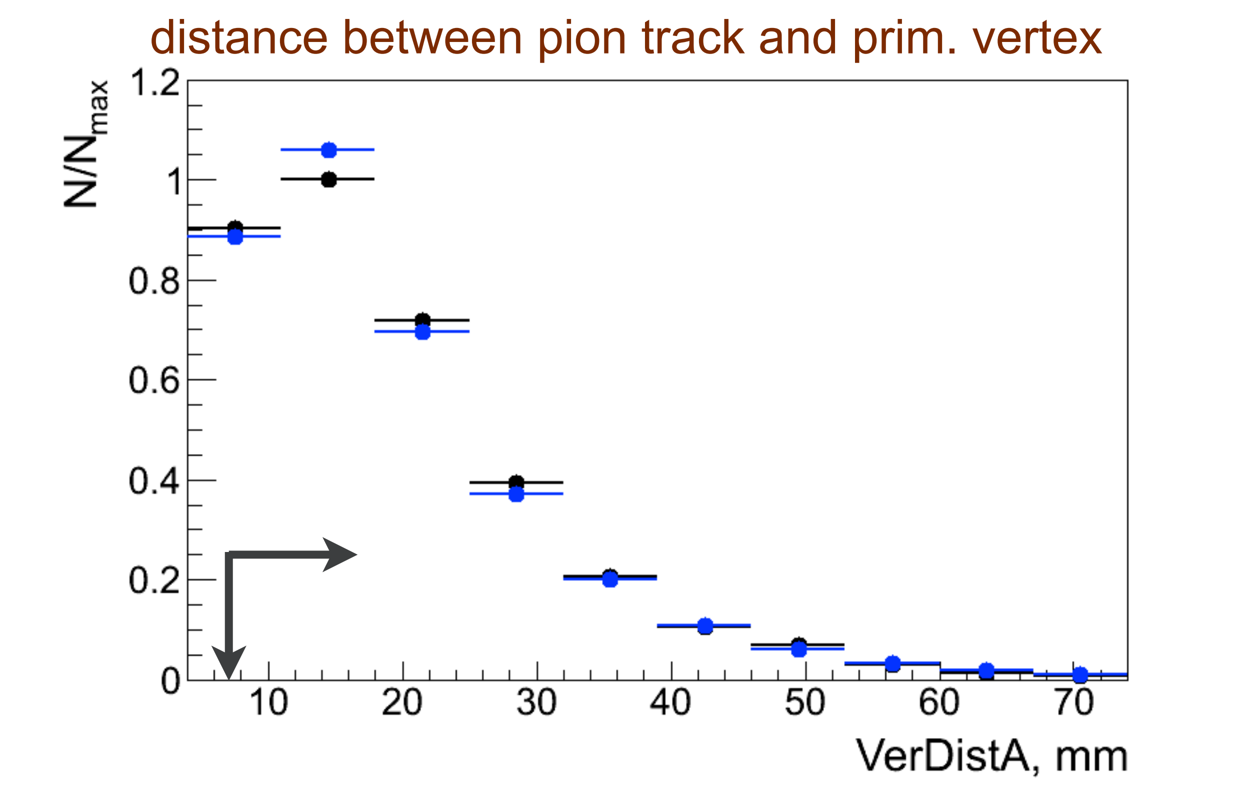
-60 mm $< z < 0$ mm

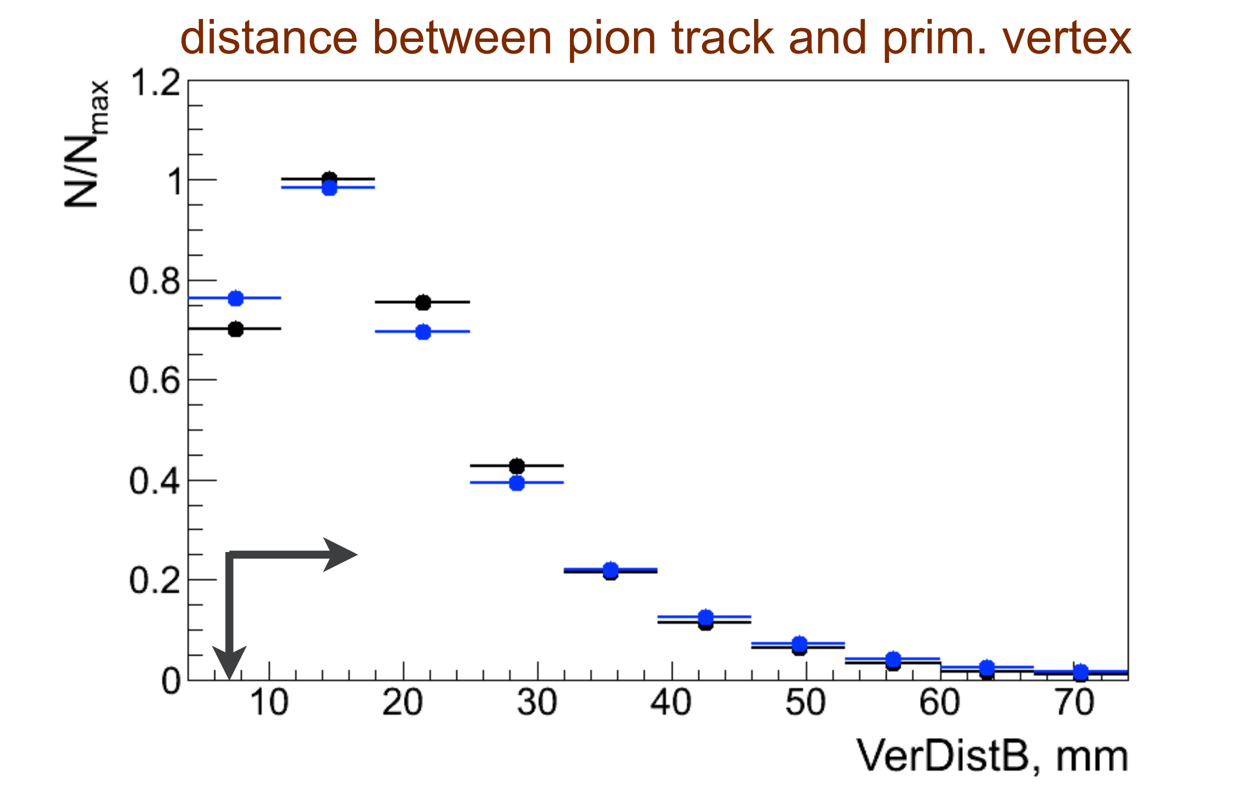
$(x-2)^2 + y^2 < 25\,\mathrm{mm}^2$

Topological observables



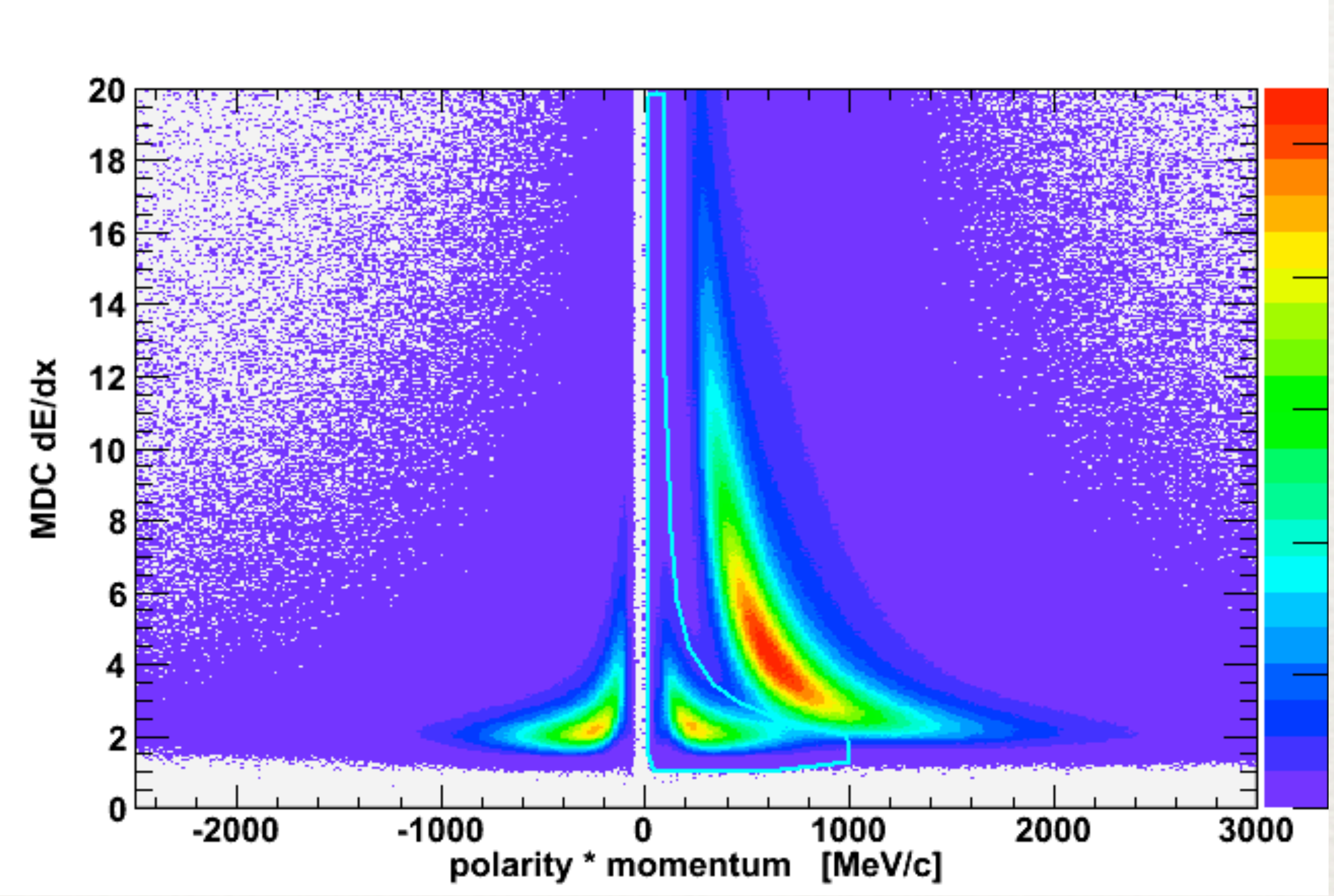




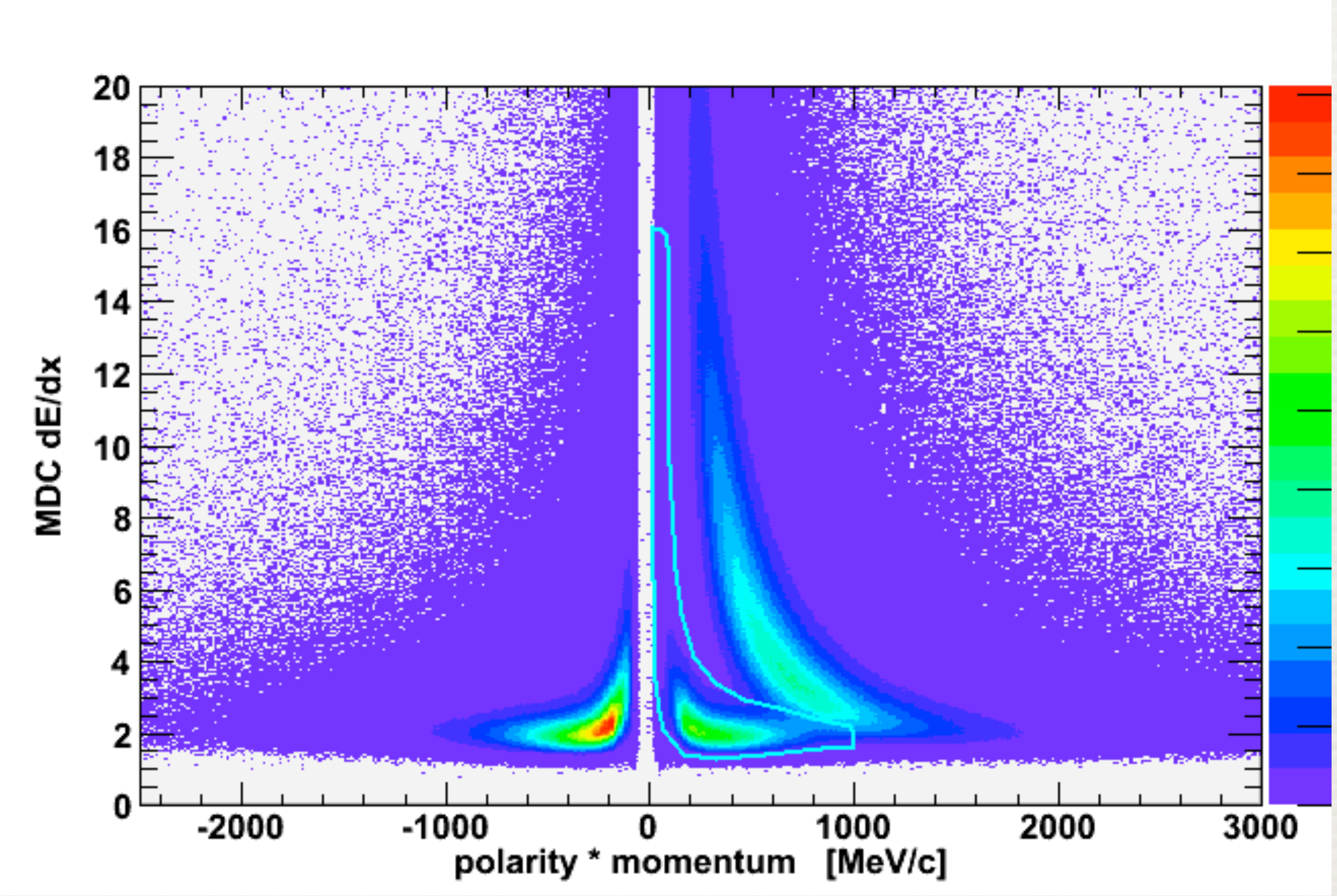


Pion selection with MDC dE/dx cuts

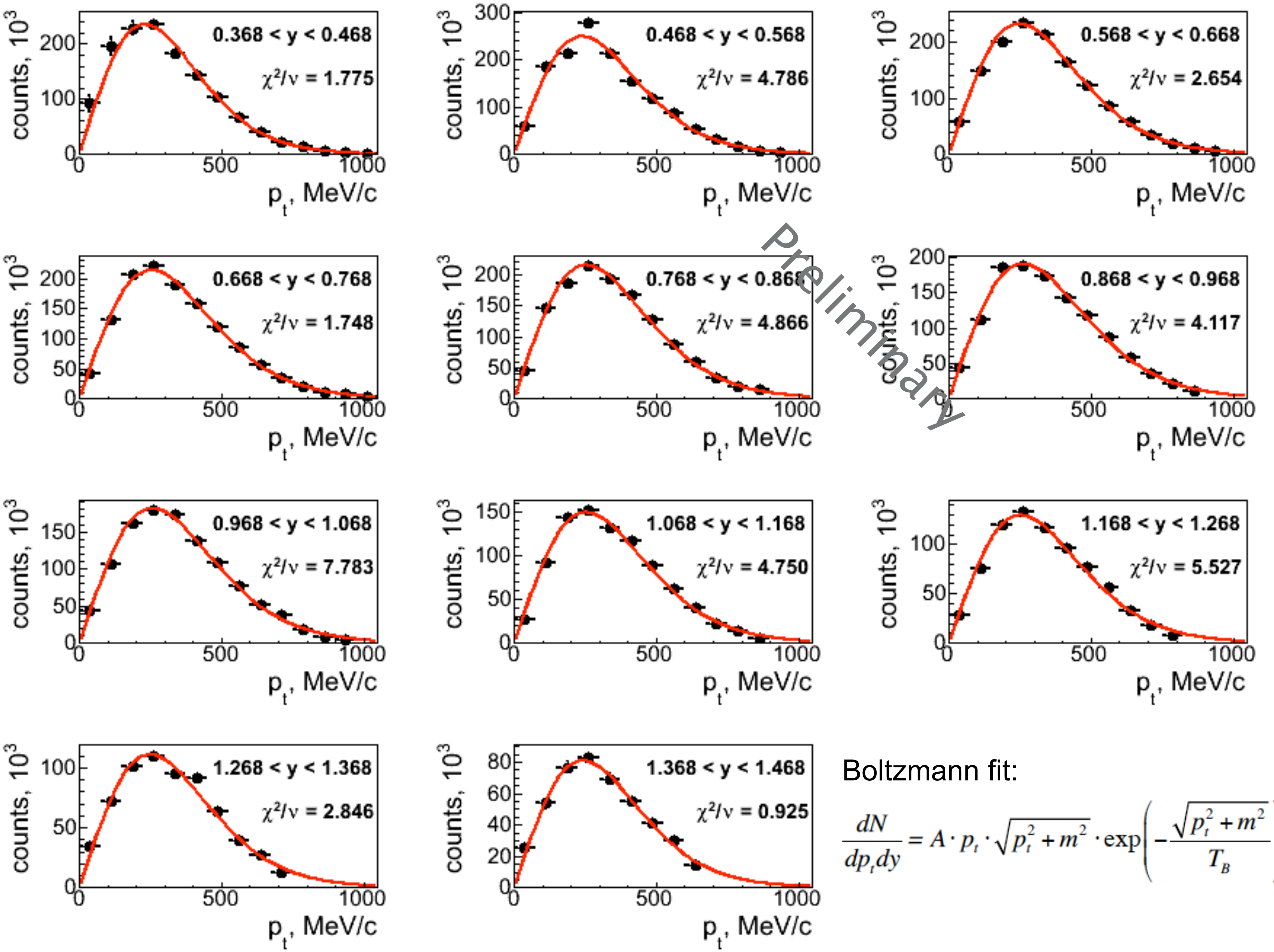
Exp.



Simulation (UrQMD)



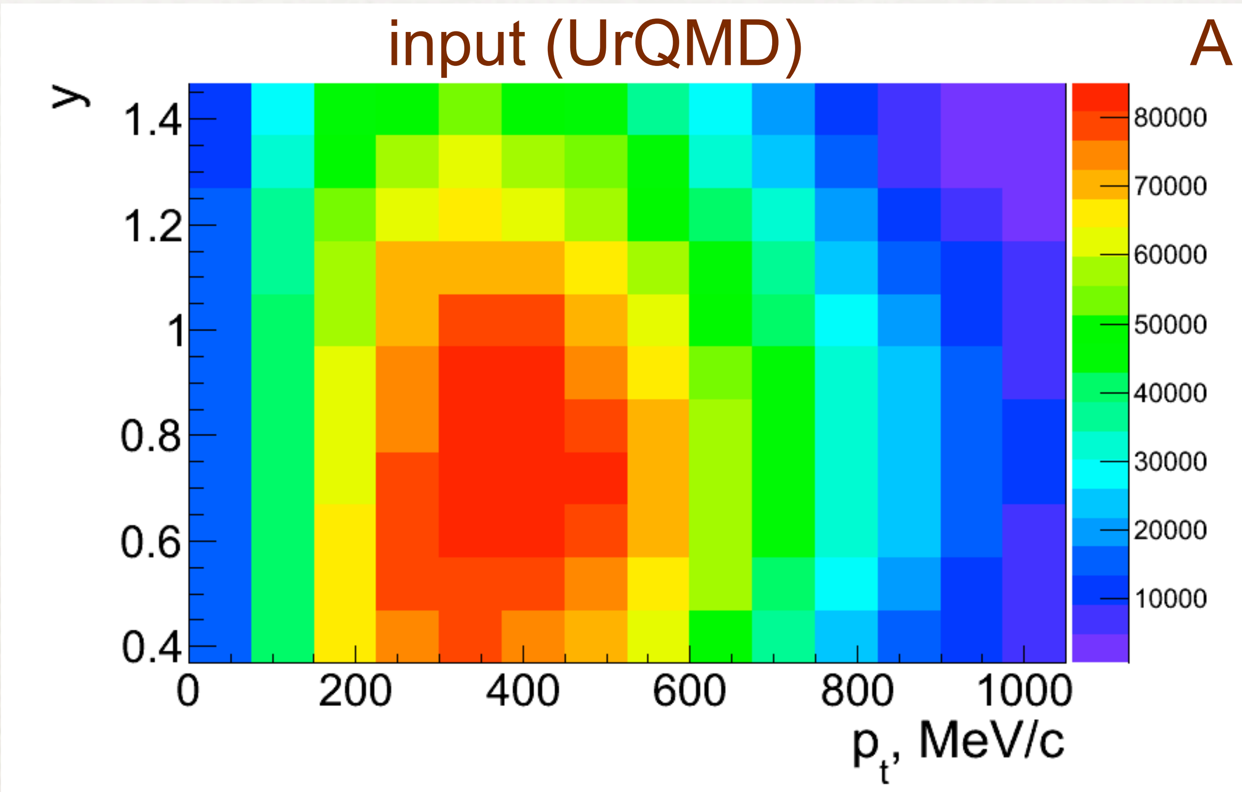
Corrected p_t spectra: Boltzmann fits

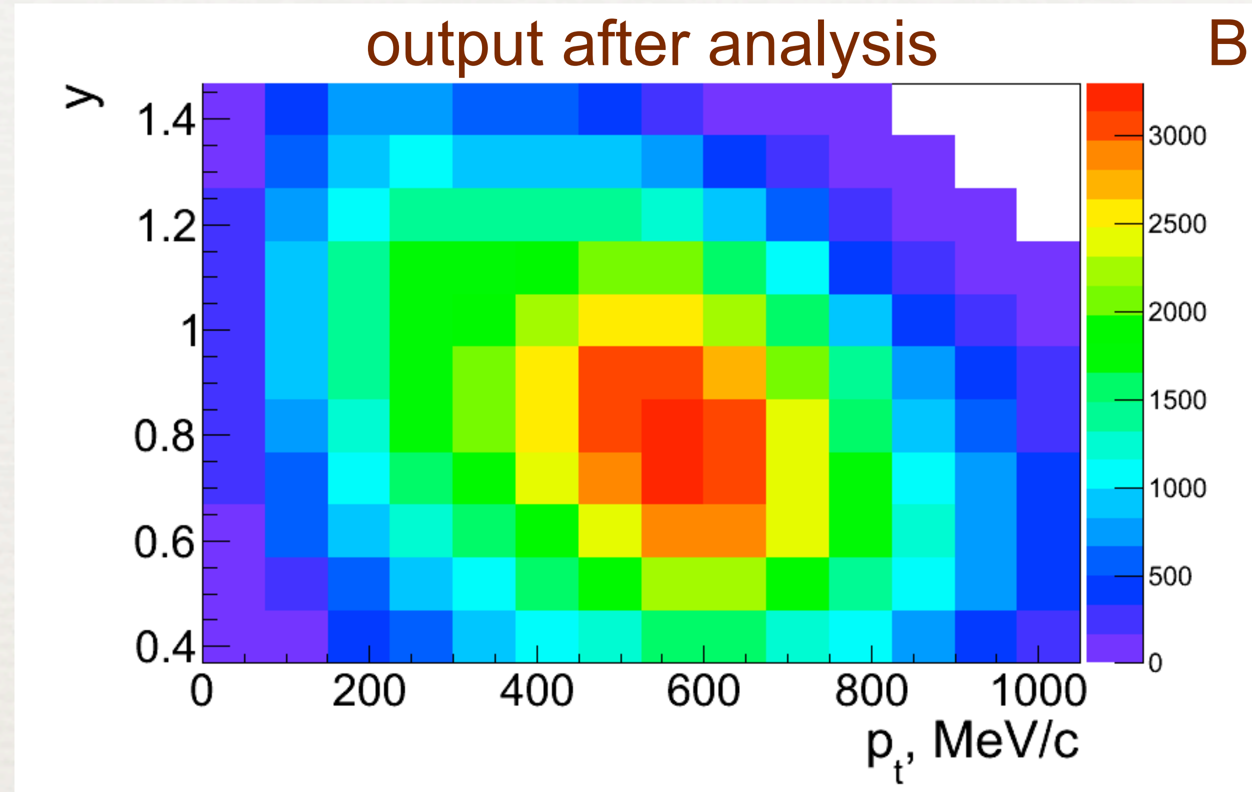


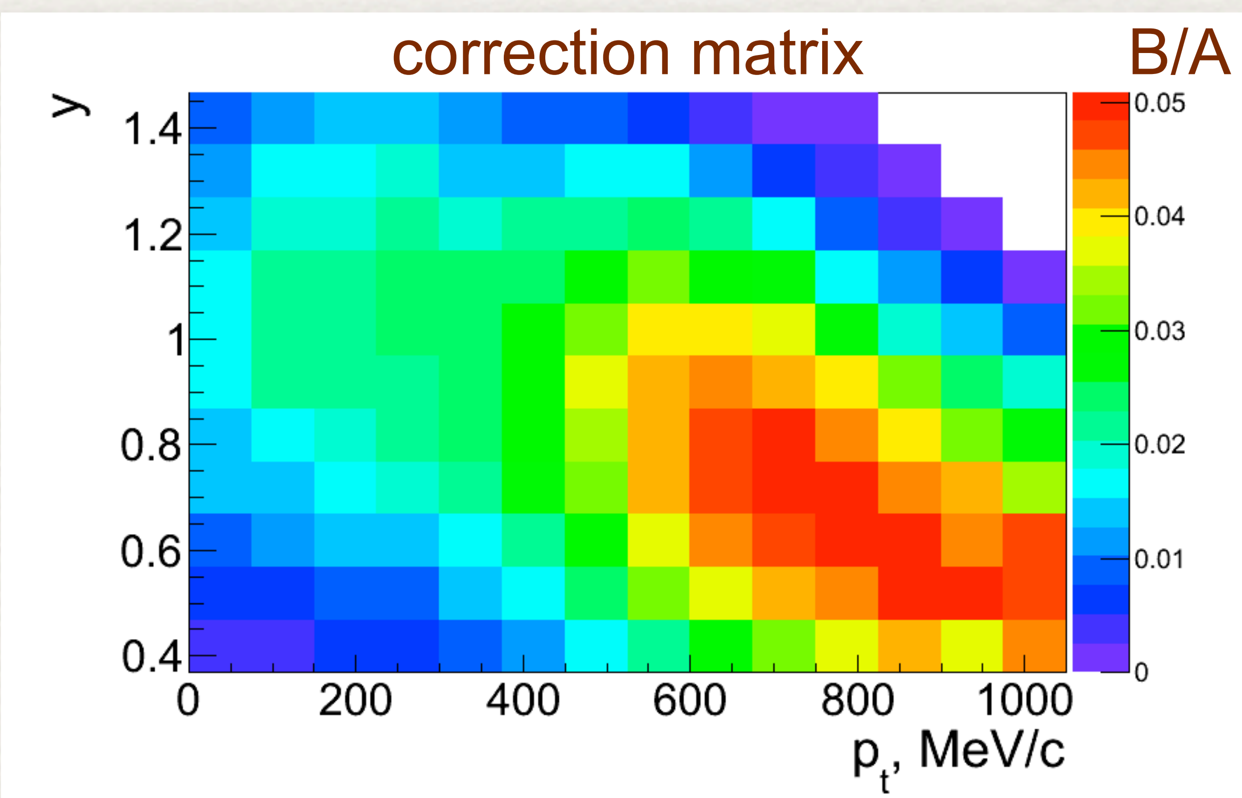
Boltzmann fit:

$$\frac{dN}{dp_t dy} = A \cdot p_t \cdot \sqrt{p_t^2 + m^2} \cdot \exp\left(-\frac{\sqrt{p_t^2 + m^2}}{T_B} \right)$$

Acceptance and efficiency correction





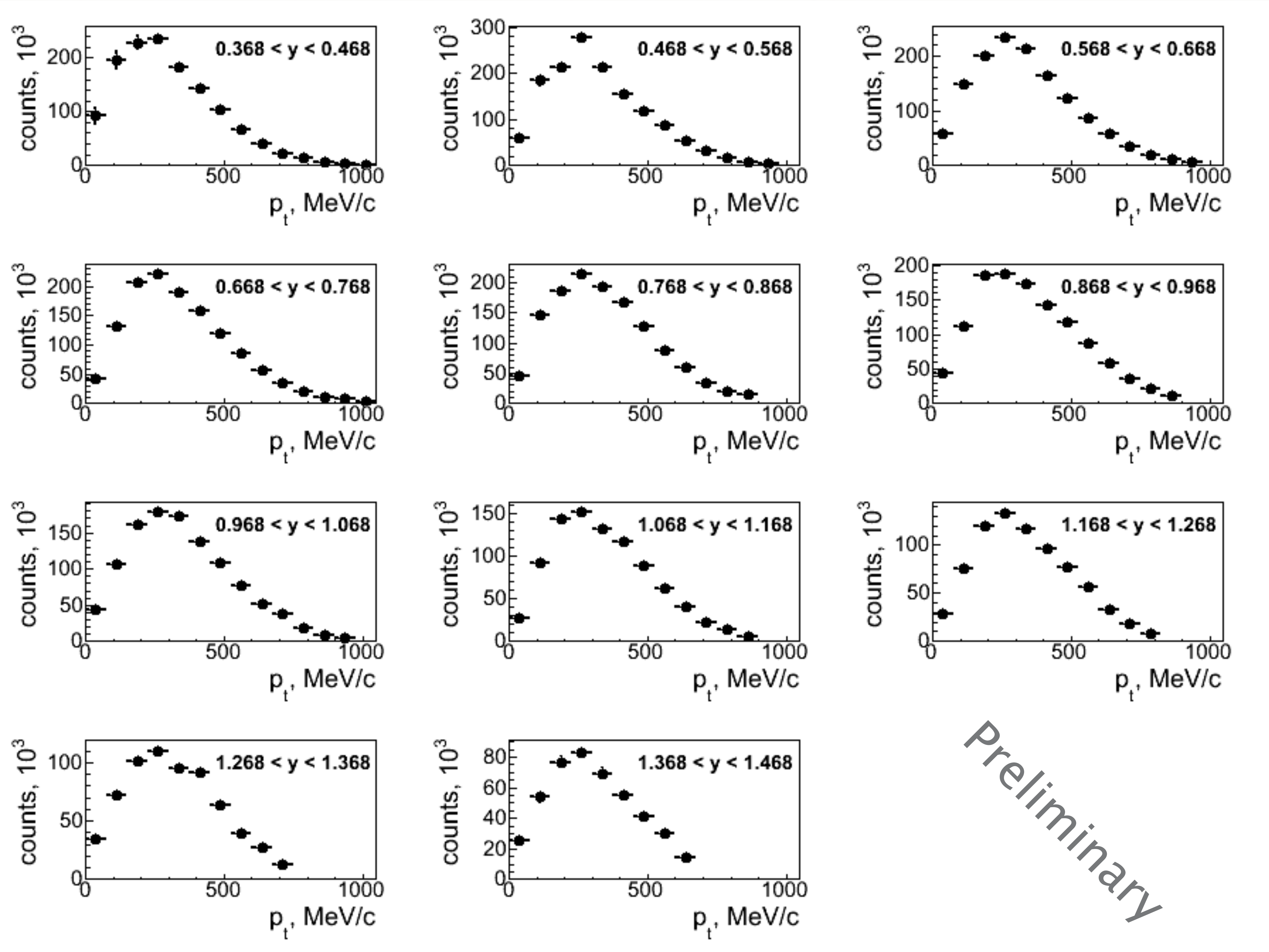


Note:

$d(p_t)^2dy$ ~ invariant phase space volume.

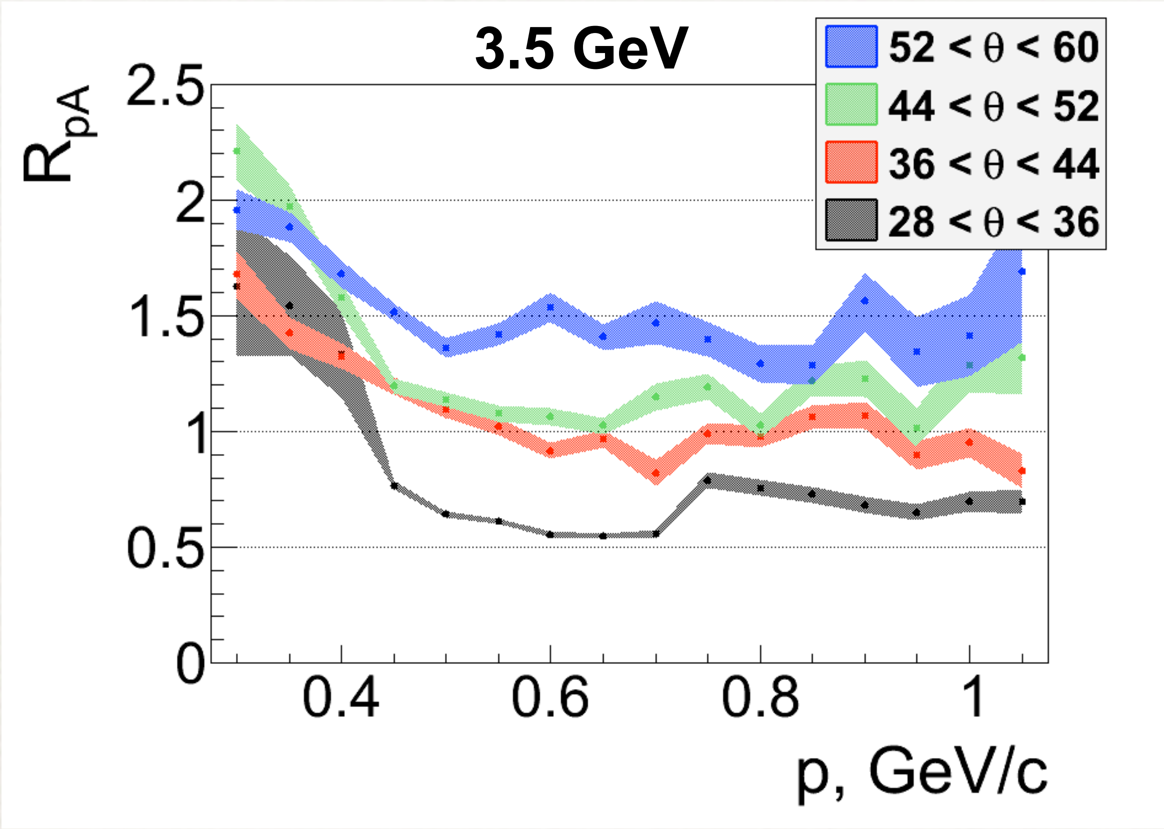
Correction only in the region of non-zero acceptance.

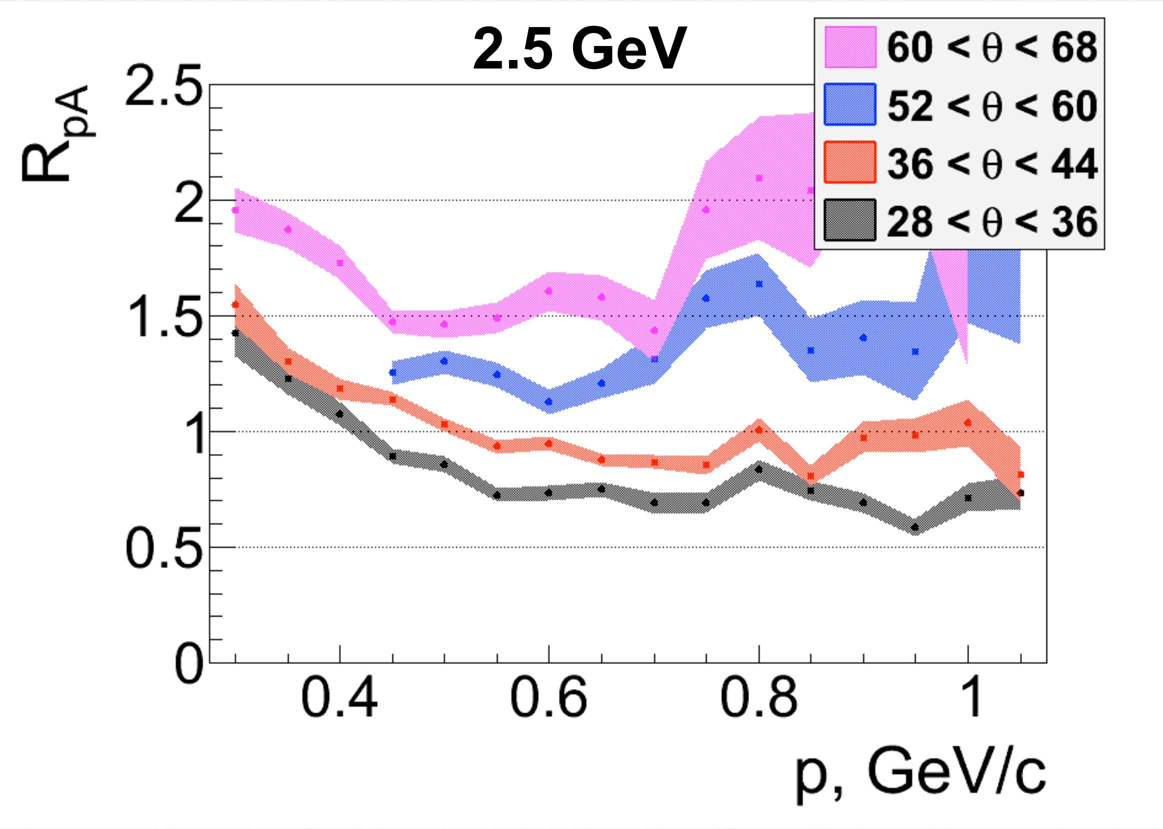
Eff. and acc. corrected p_t spectra

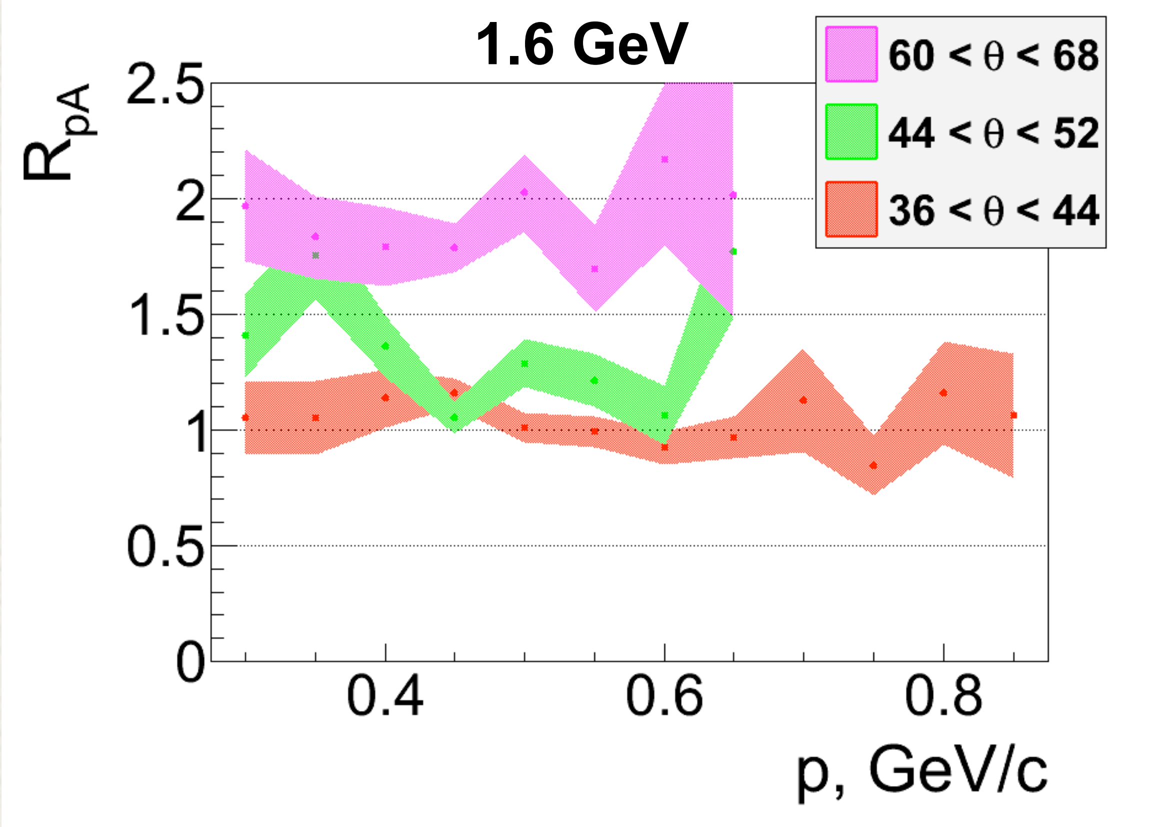


KaoS R_{pA}

All plots on this slide: KaoS K^+ data, pAu/pC. θ is the lab. polar angle.







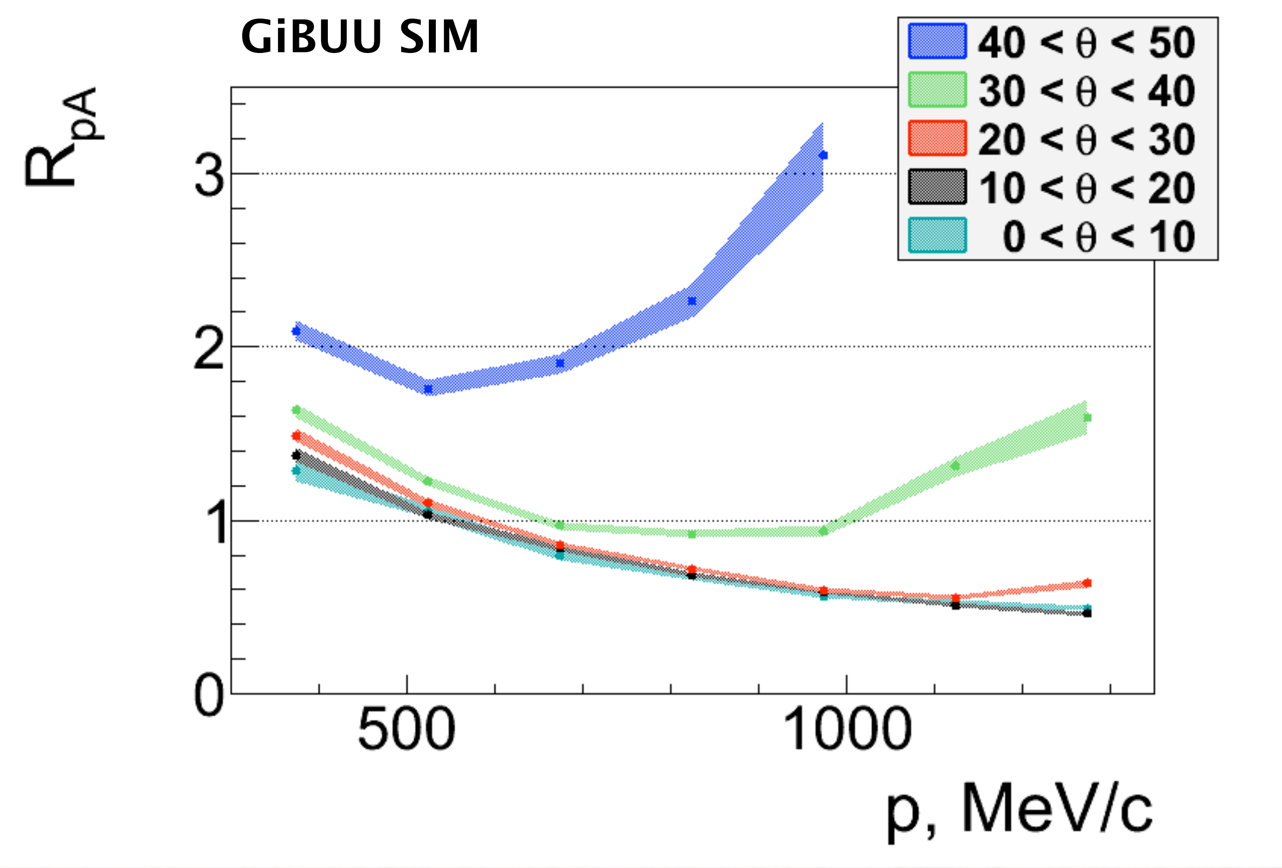
Bands show stat. uncertainties only.

At all energies **the very same pattern**:
$R_{pA} < 1$ for small angles
$R_{pA} > 1$ for higher angles

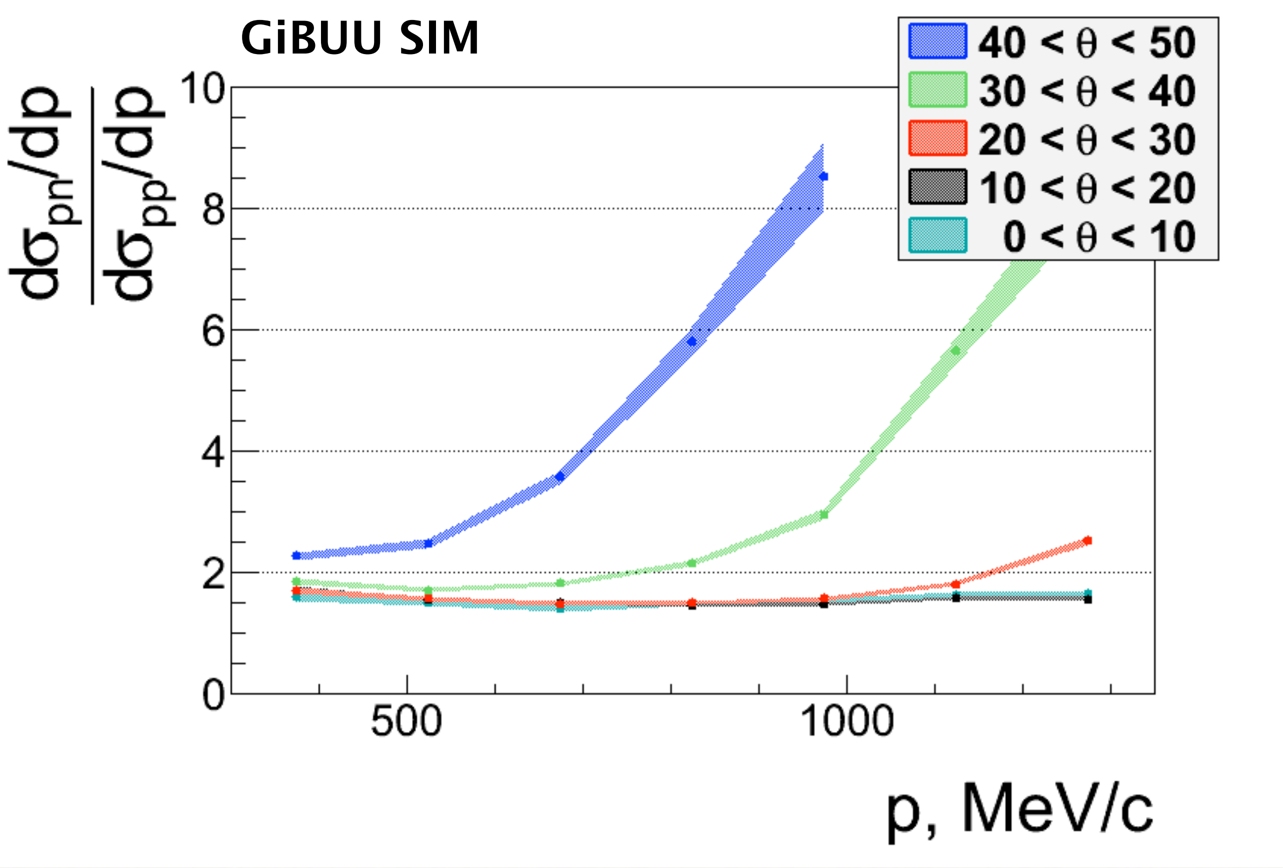
Interpretation:
rescattering of forward kaons
(both K^+ and K^0 via charge exchange)
to larger polar angles
slightly amplifying with the momentum

K^0 production in pn/pp (GiBUU simulations)

pNb/pp



pn/pp



- R_{pA}(pNb/pp) roughly follows np/pp ratio.
- Influence of the KN scattering.

Kaon production within the resonance model

K. Tsushima et al., PRC59 (1999) 369

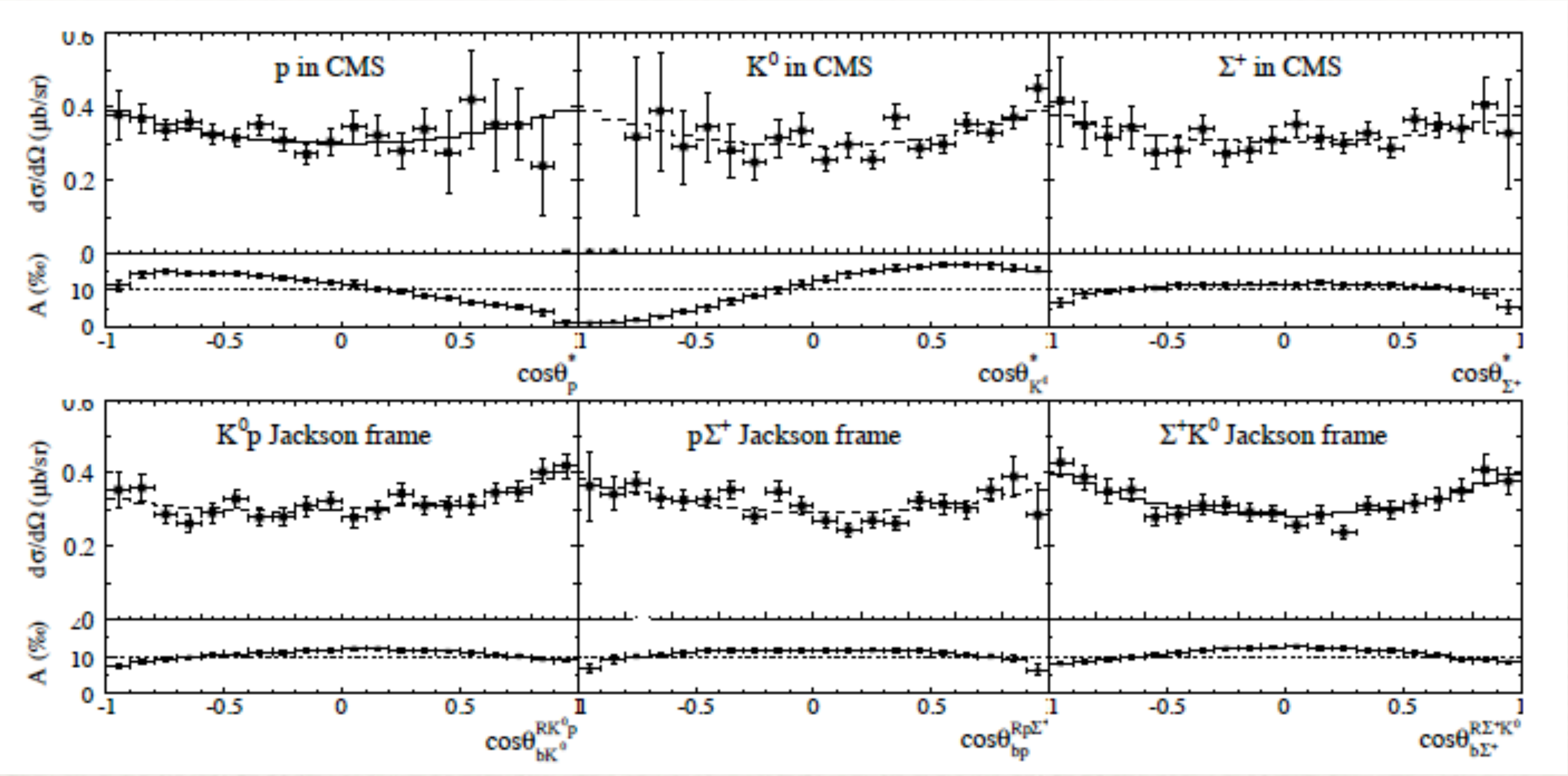
Resonance (J^P)	Width (MeV)	Decay channel	Branching ratio	Adopted value
N(1650) ($\frac{1}{2}^-$)	150	$N\pi$	0.60 – 0.80	0.700
		$N\eta$	0.03 – 0.10	0.065
		$\Delta\pi$	0.03 – 0.07	0.050
		ΛK	0.03 – 0.11	0.070
N(1710) ($\frac{1}{2}^+$)	100	$N\pi$	0.10 – 0.20	0.150
		$N\eta$	0.20 – 0.40	0.300
		$N\rho$	0.05 – 0.25	0.150
		$\Delta\pi$	0.10 – 0.25	0.175
		ΛK	0.05 – 0.25	0.150
		ΣK	0.02 – 0.10	0.060
N(1720) ($\frac{3}{2}^+$)	150	$N\pi$	0.10 – 0.20	0.150
		$N\eta$	0.02 – 0.06	0.040
		$N\rho$	0.70 – 0.85	0.775
		$\Delta\pi$	0.05 – 0.15	0.100
		ΛK	0.03 – 0.10	0.065
		ΣK	0.02 – 0.05	0.035
Δ(1920) ($\frac{3}{2}^+$)	200	$N\pi$	0.05 – 0.20	0.125
		ΣK	0.01 – 0.03	0.020

$$\sigma(B_1B_2 \to B_3YK) = a\left(\frac{s}{s_0}-1\right)^b\left(\frac{s_0}{s}\right)^c,$$

No.	Reaction
1	$pp \to p\Lambda K^+$
2	$pn \to n\Lambda K^+$
3	$pp \to p\Sigma^0 K^+$
4	$nn \to n\Sigma^- K^+$
5	$pn \to n\Sigma^0 K^+$
6	$np \to p\Sigma^- K^+$
7	$pp \to n\Sigma^+ K^+$
8	$nn \to \Delta^-\Lambda K^+$
9	$pp \to \Delta^{++}\Sigma^- K^+$
10	$\Delta^{++}n \to p\Lambda K^+$
11	$\Delta^- p \to n\Sigma^- K^+$
12	$\Delta^{++}p \to \Delta^{++}\Lambda K^+$
13	$\Delta^+ n \to \Delta^0\Lambda K^+$
14	$\Delta^+ p \to \Delta^+\Lambda K^+$
15	$\Delta^{++}n \to \Delta^{++}\Sigma^- K^+$
16	$\Delta^0 p \to \Delta^+\Sigma^- K^+$
17	$\Delta^+ n \to \Delta^+\Sigma^- K^+$
18	$\Delta^{++}p \to \Delta^{++}\Sigma^0 K^+$
19	$\Delta^+ n \to \Delta^0\Sigma^0 K^+$
20	$\Delta^+ p \to \Delta^+\Sigma^0 K^+$
21	$\Delta^+ p \to \Delta^0\Sigma^+ K^+$
22	$\Delta^+\Delta^{++} \to \Delta^{++}\Lambda K^+$
23	$\Delta^0\Delta^{++} \to \Delta^+\Lambda K^+$
24	$\Delta^0\Delta^+ \to \Delta^0\Lambda K^+$
25	$\Delta^{++}\Delta^0 \to \Delta^{++}\Sigma^- K^+$
26	$\Delta^-\Delta^0 \to \Delta^-\Sigma^- K^+$
27	$\Delta^0\Delta^{++} \to \Delta^+\Sigma^0 K^+$
28	$\Delta^-\Delta^+ \to \Delta^0\Sigma^- K^+$

Kaon production anisotropy

$pp \to pK^0\Sigma^+$



M. Abdel-Bary et al.
Eur.Phys.J. A48 (2012) 37.

Kaon angular distributions in pNb