FAIRNESS
16-21 September 2013
Berlin

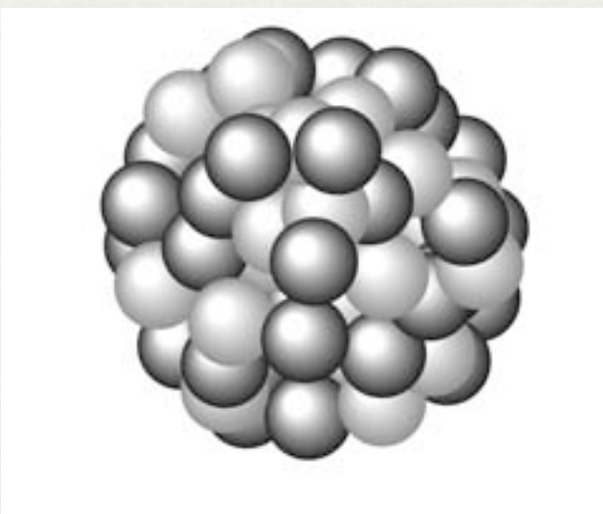
Recent results on dilepton and strangeness production with HADES and perspectives at FAIR

Kirill Lapidus (HADES Collaboration)
Excellence Cluster ‘Universe’
TU Munich

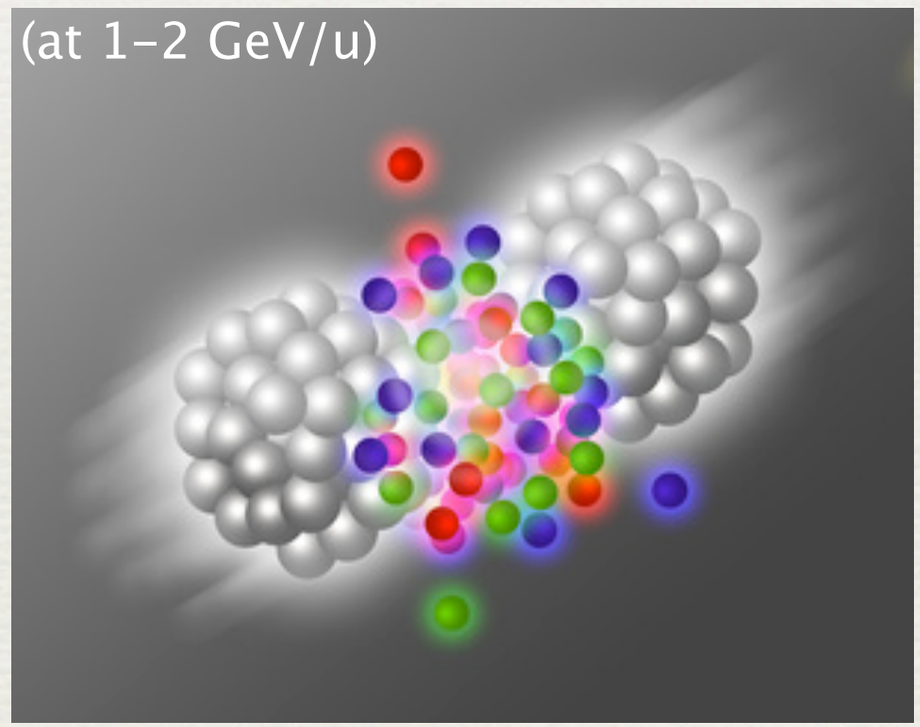
Motivation

Fundamental problem: how a hadron change its properties
when implanted in a strongly-interacting many body system?

Nucleus $\rho_B \leq \rho_0$

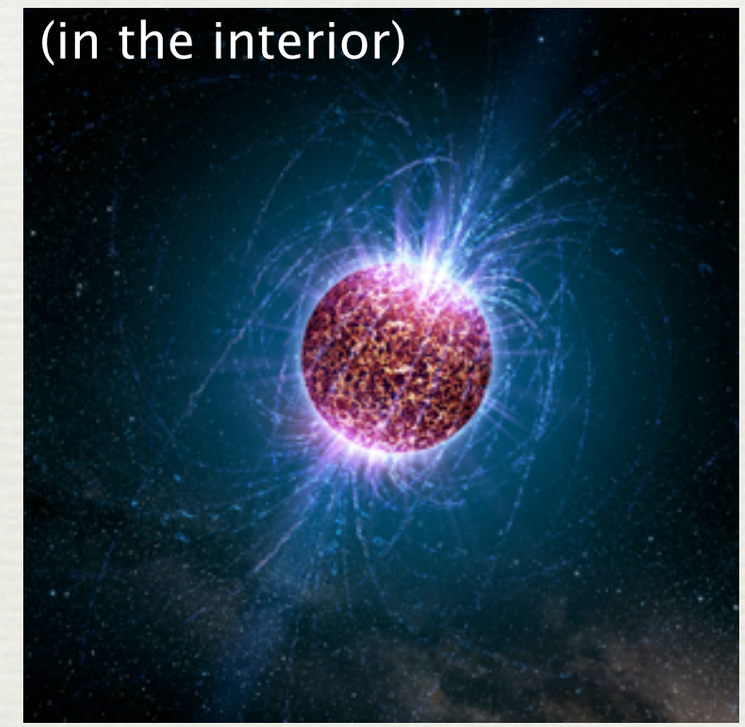


Heavy-ion collisions $\rho_B \leq 2\text{-}3\rho_0$



Vienna University of Technology

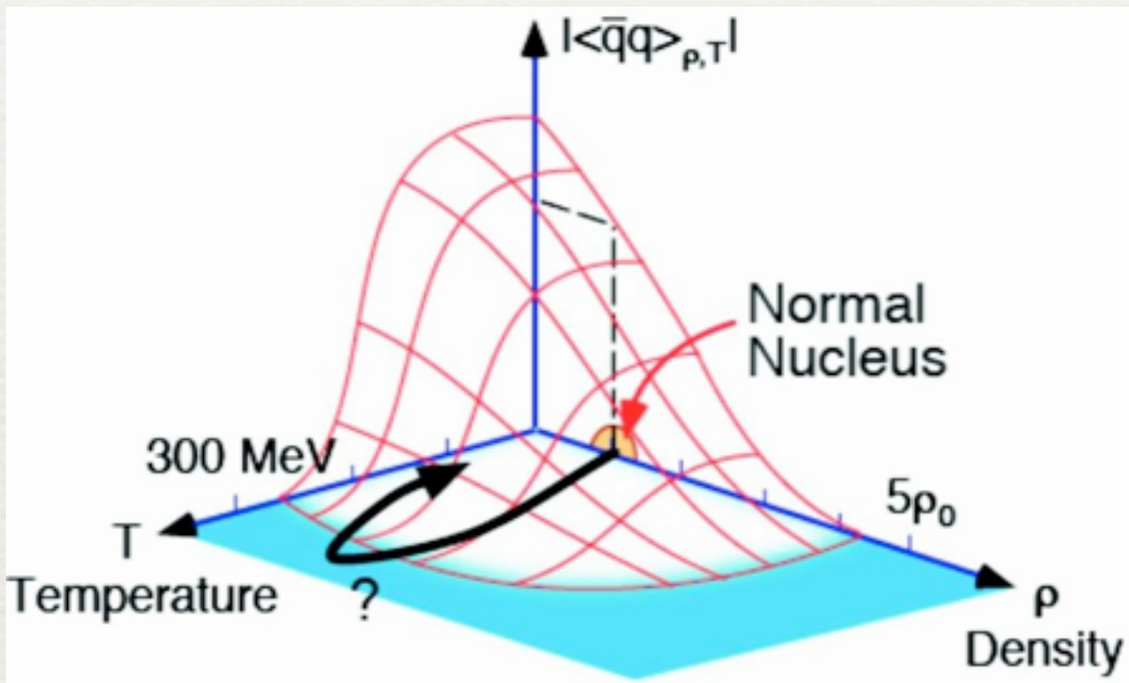
Neutron star $\rho_B \leq 3\text{-}8\ \rho_0$



Casey Reed, courtesy of Penn State

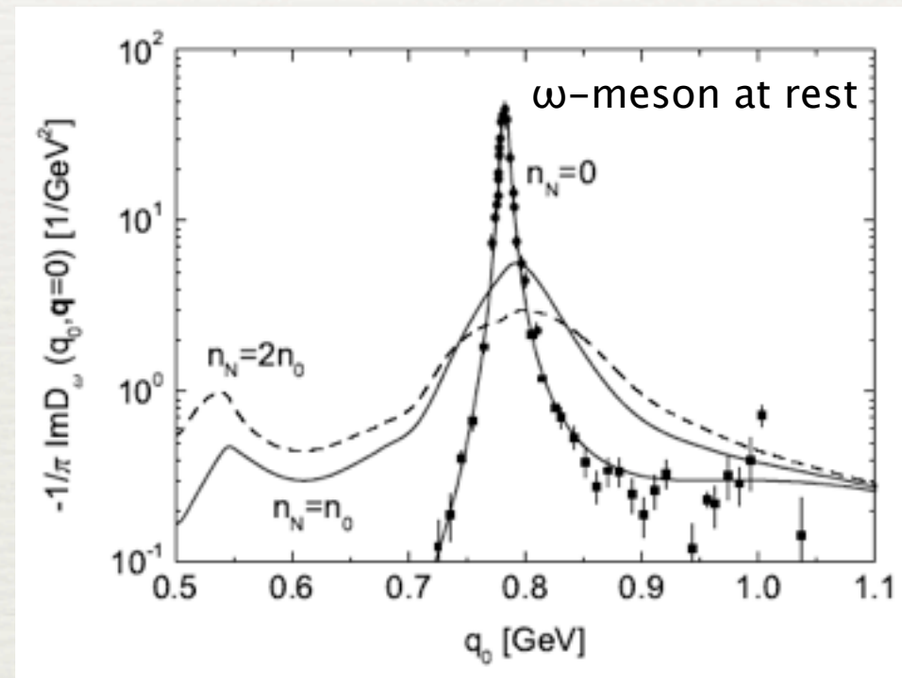
Motivation

Restoration of the SB chiral symmetry



- Drop of the order parameter – chiral condensate – by ~30% already at normal nuclear density

Light vector mesons ρ, ω, ϕ



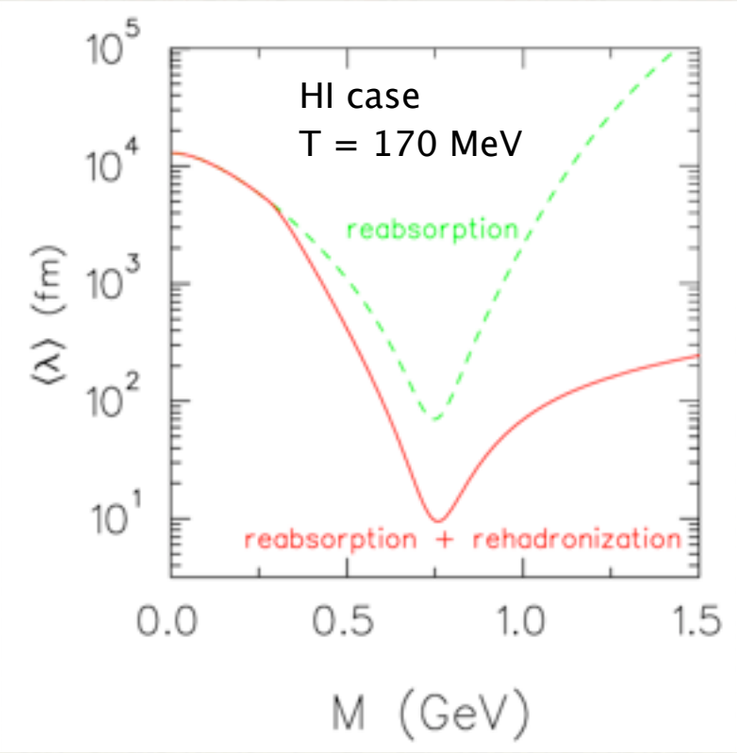
P. Muehlich et al. Nucl.Phys.A780:187–205,2006

- Early expectations: $m_V \sim \langle q\bar{q}\rangle$
- Most of modern predictions: significant broadening, no substantial mass shift

Penetrating probes

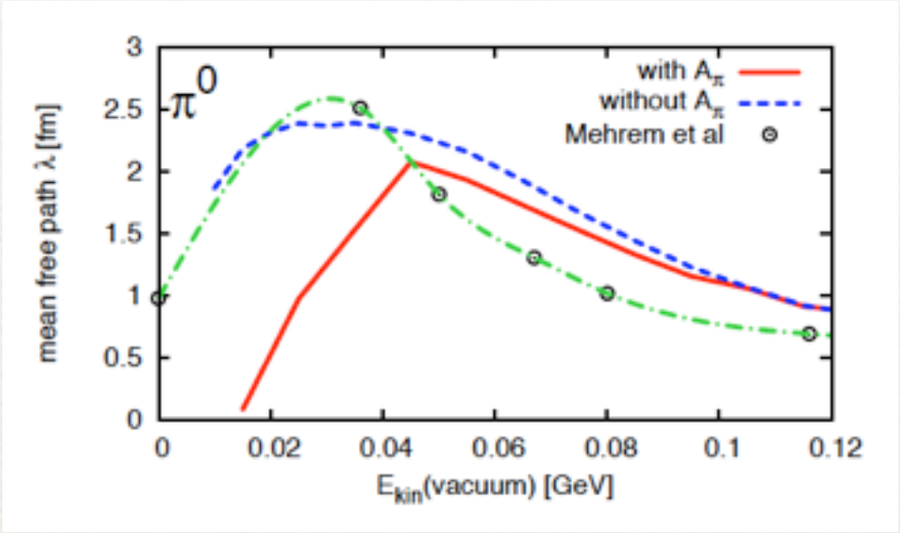
- Vector mesons $J^P = 1^-$, $V \rightarrow e^+e^-$
- Minimal final state interaction
- Small branchings ~ 10^{-5}
- Instrumental challenge: e/h separation

- Virtual photon in a hot fireball



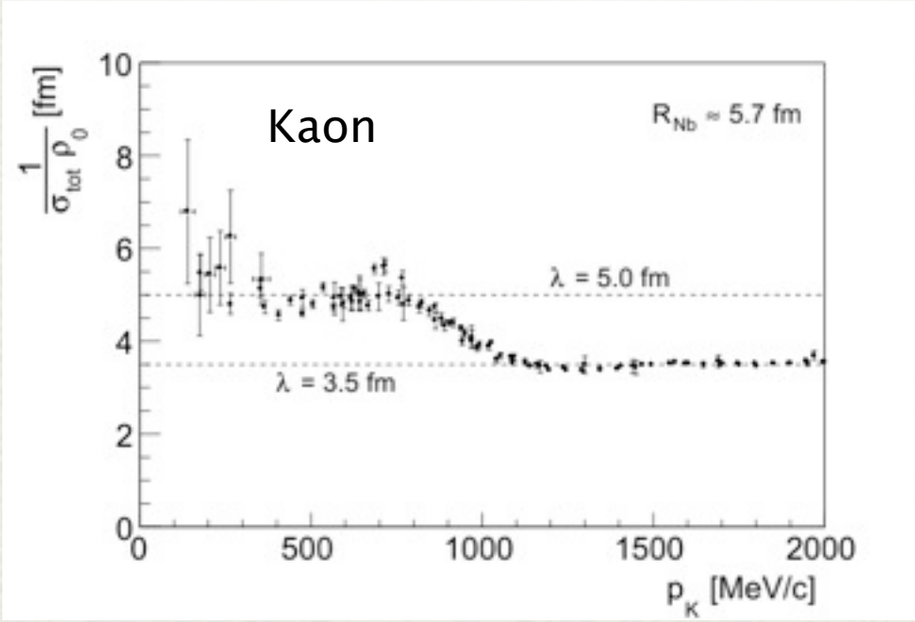
K. Haglin et al. arXiv:0205050 [nucl-th]

- Hadrons interact strongly → rescattering



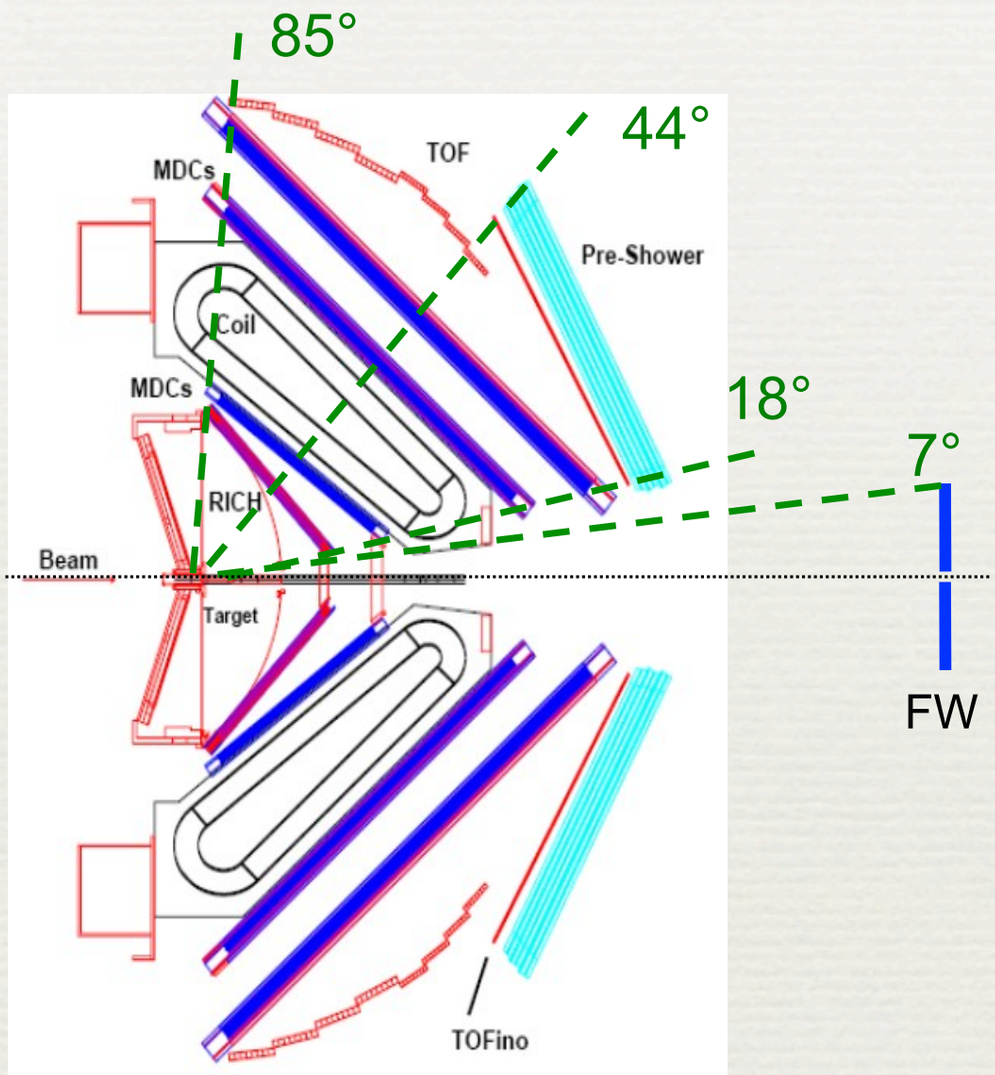
O. Buß, PhD Thesis, Justus-Liebig Universität Gießen, 2008

- Particular case of the kaon (S=+1)



Note: from K^+p total cross section

The HADES experiment



High Acceptance Di-Electron Spectrometer

Location: GSI, Darmstadt

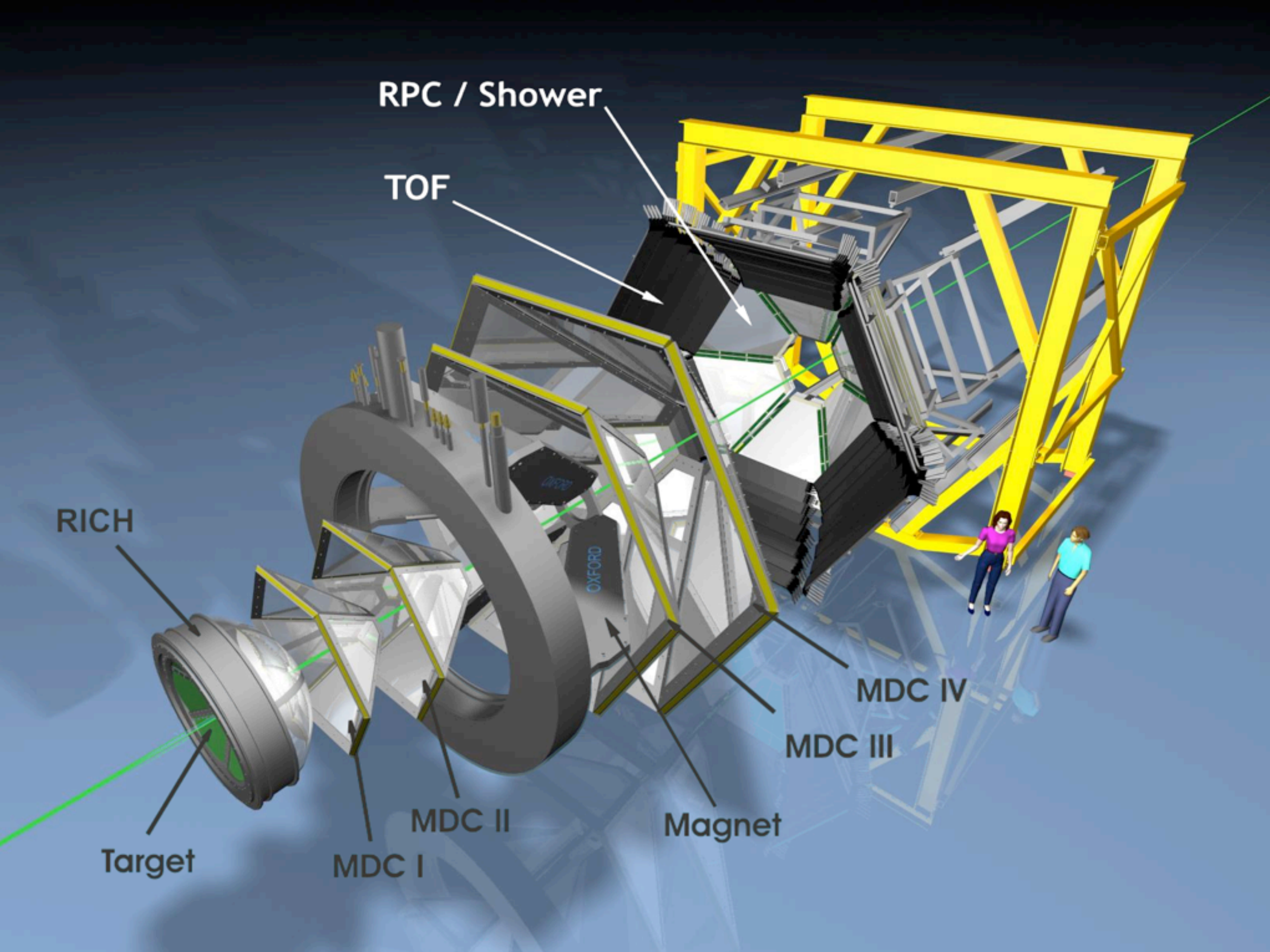
Fixed-target experiment,

SIS18, beam E_{kin} = 1—3 GeV/nucl.

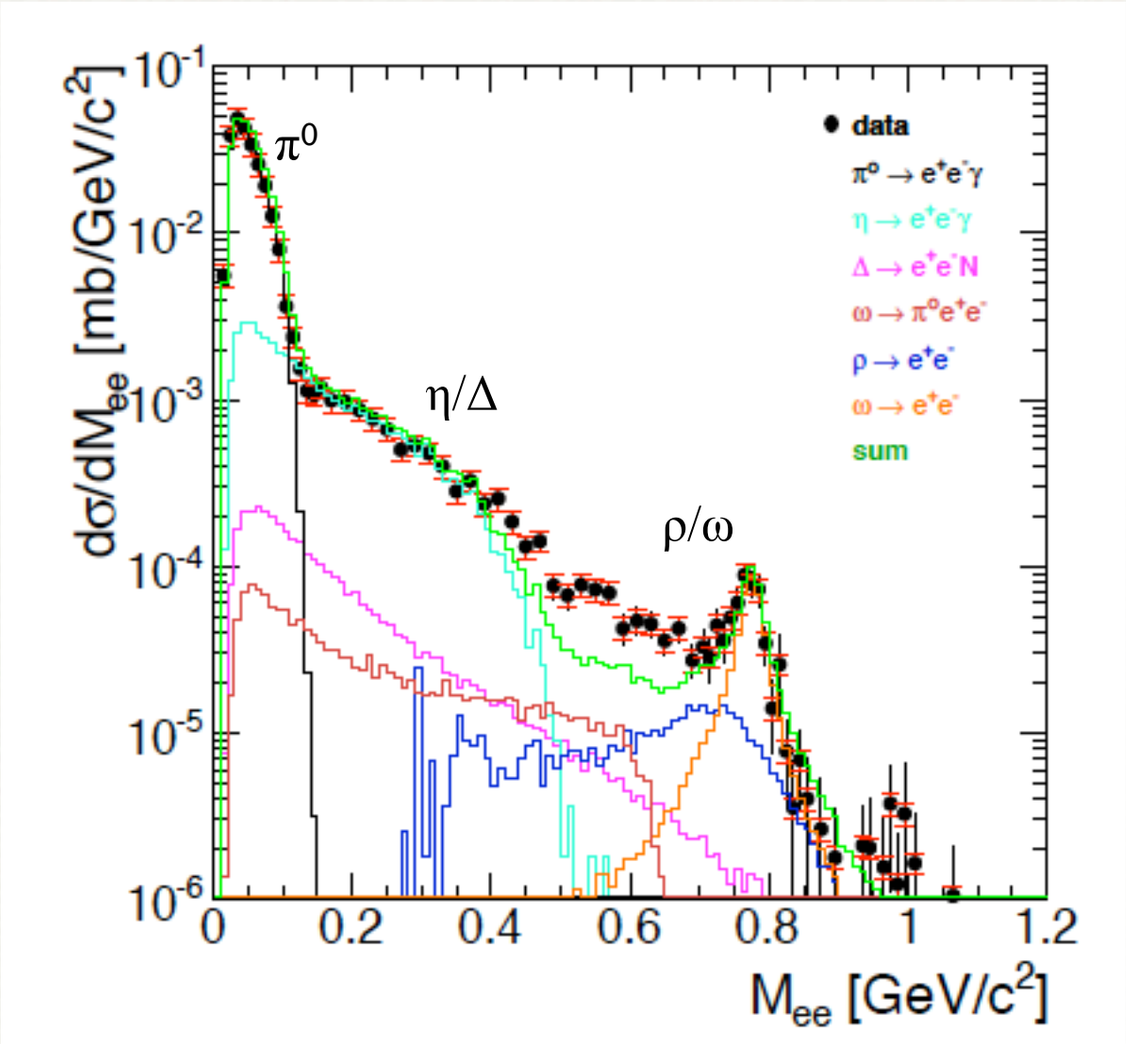
Full azimuthal coverage, 18°-85° in polar angle

Sub-detectors:

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

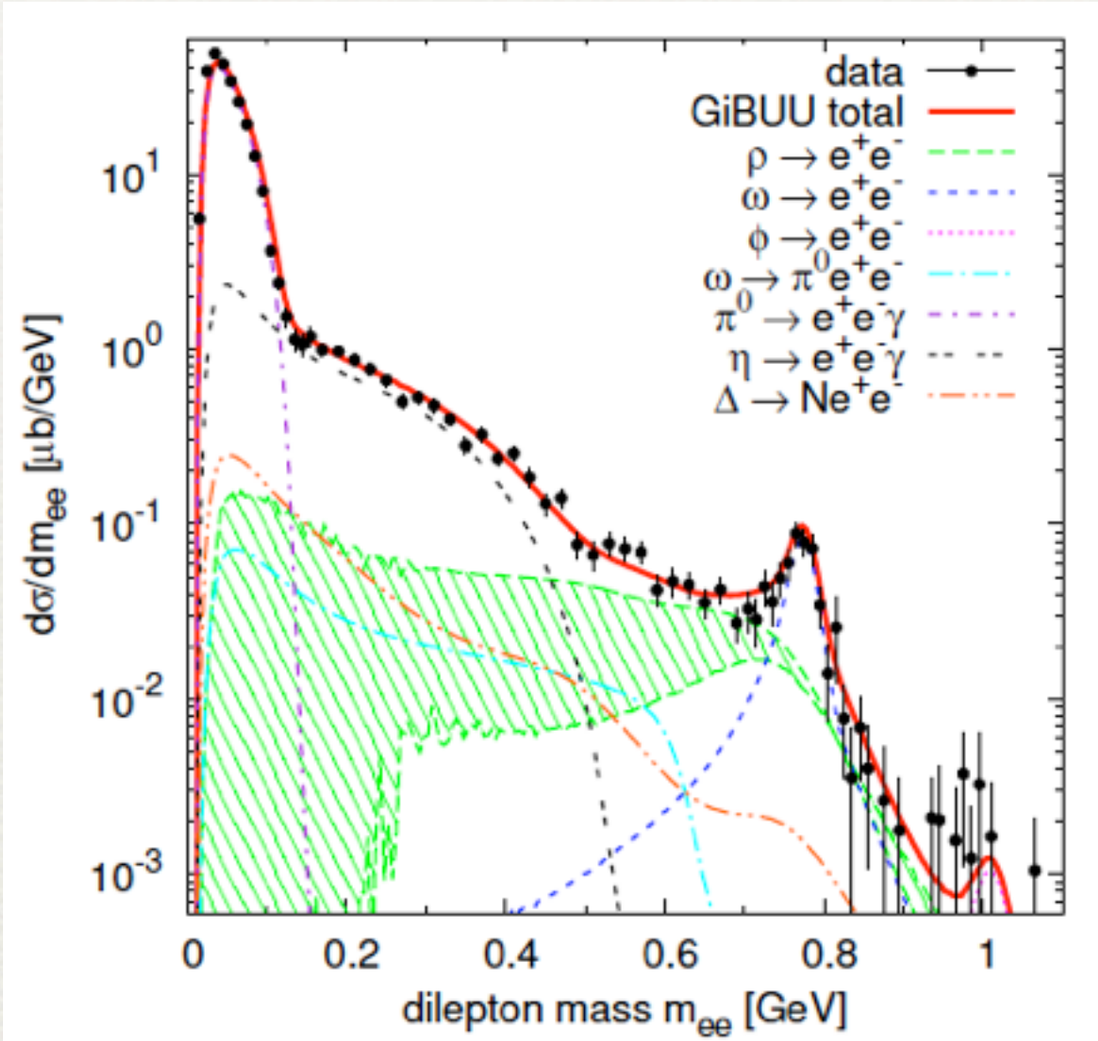

RPC / Shower
TOF
RICH
Target
MDC I
MDC II
Magnet
MDC III
MDC IV
OXFORD

p+p at 3.5 GeV: reference measurement



G. Agakishiev et al. [HADES]
Eur. Phys. J. A 48 (2012) 64.

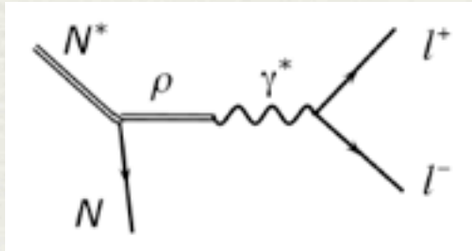
Interpretation with a transport model



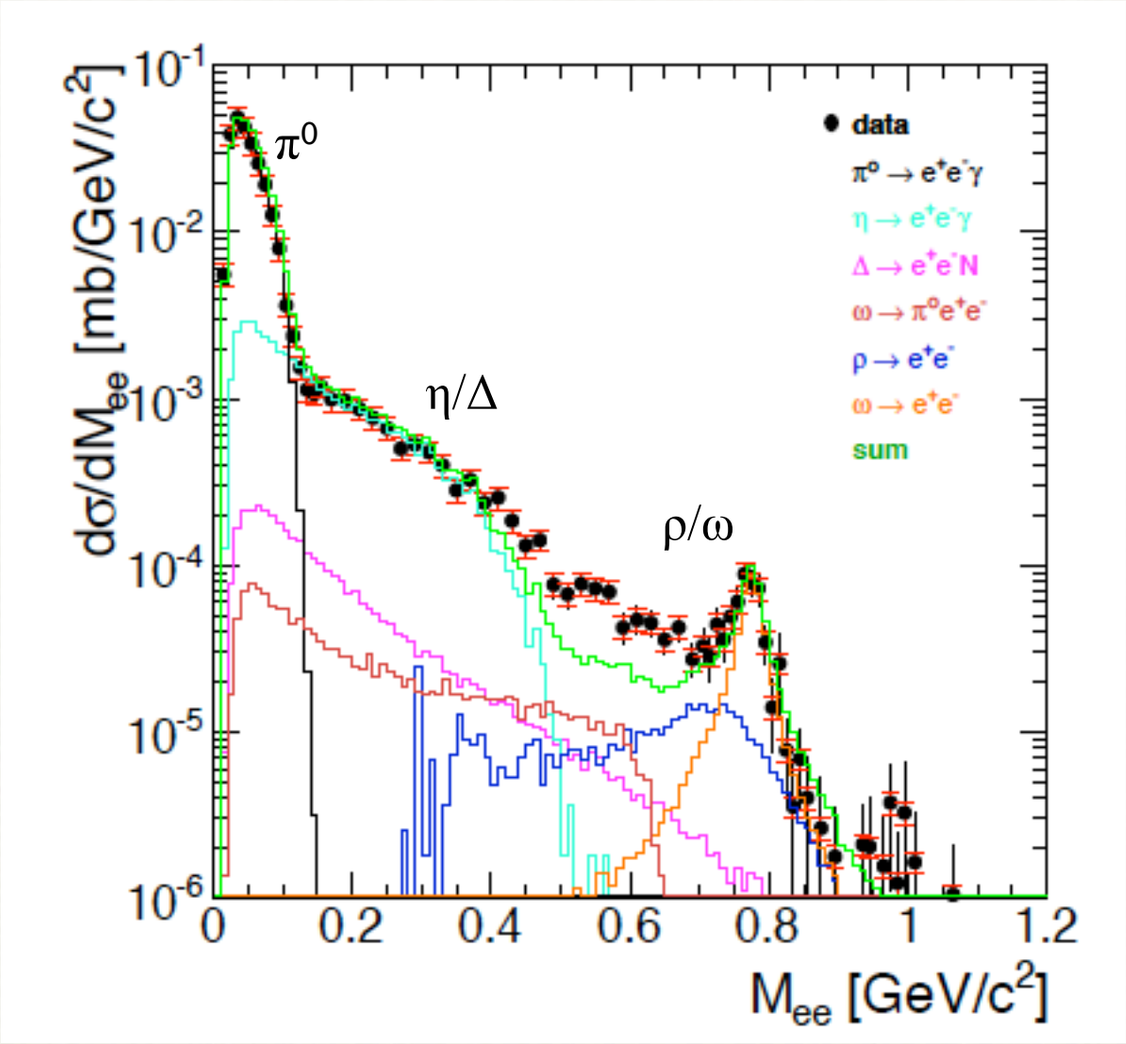
GiBUU model, J. Weil, ECT* Workshop 2013

- Gap below the omega pole

- ρ-meson contribution ~ contribution of resonances
  R → ρ + N → e⁺e⁻ + N

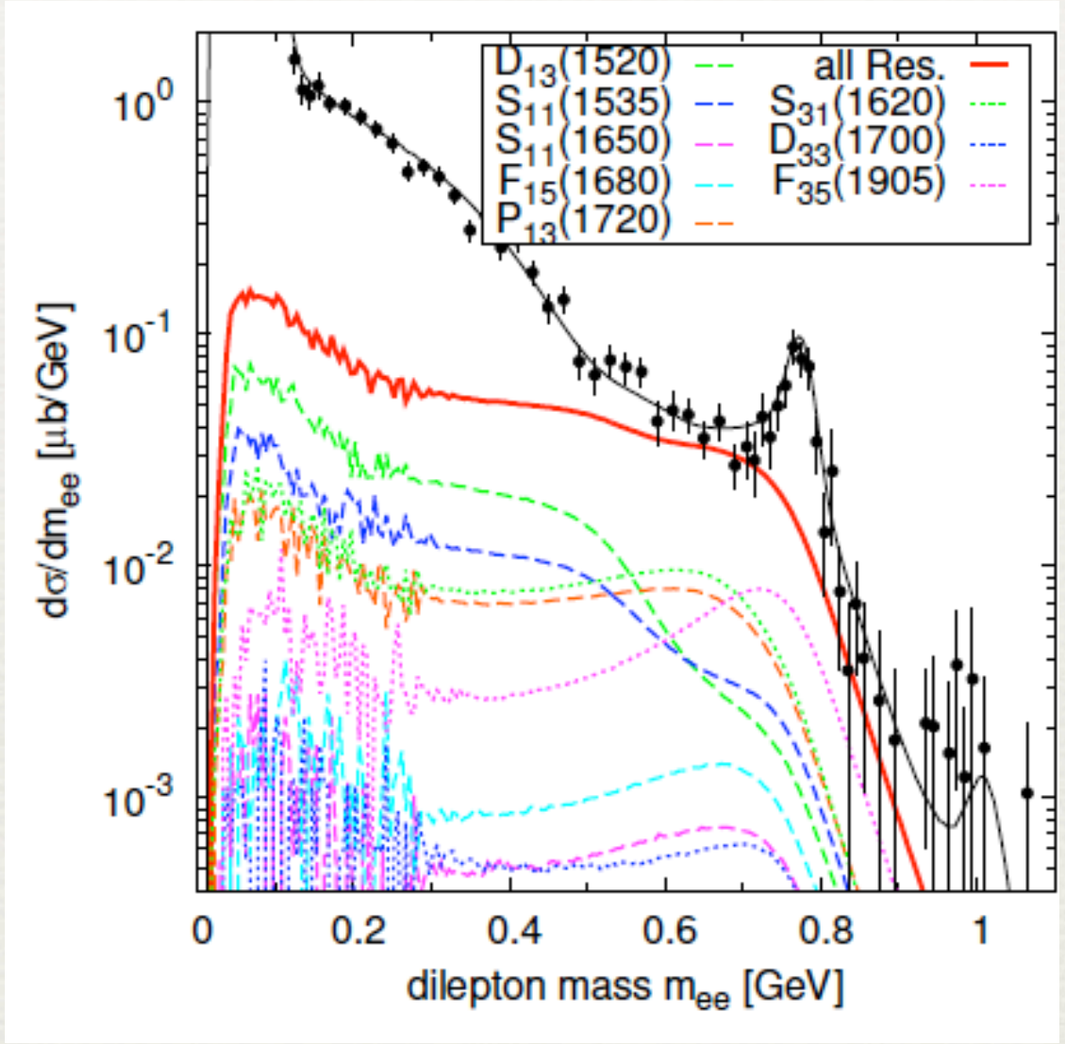


p+p at 3.5 GeV: reference measurement



G. Agakishiev et al. [HADES]
Eur. Phys. J. A 48 (2012) 64.

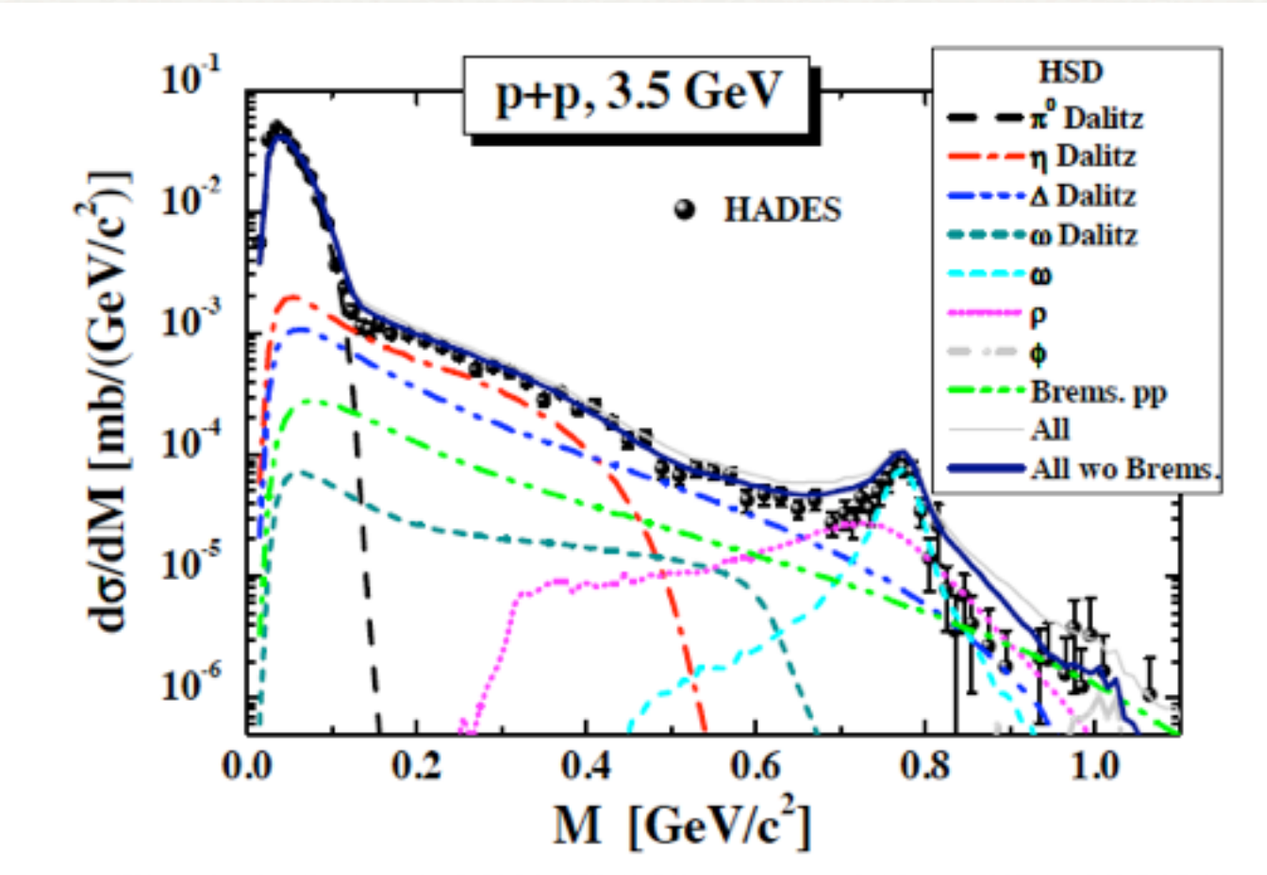
Interpretation with a transport model



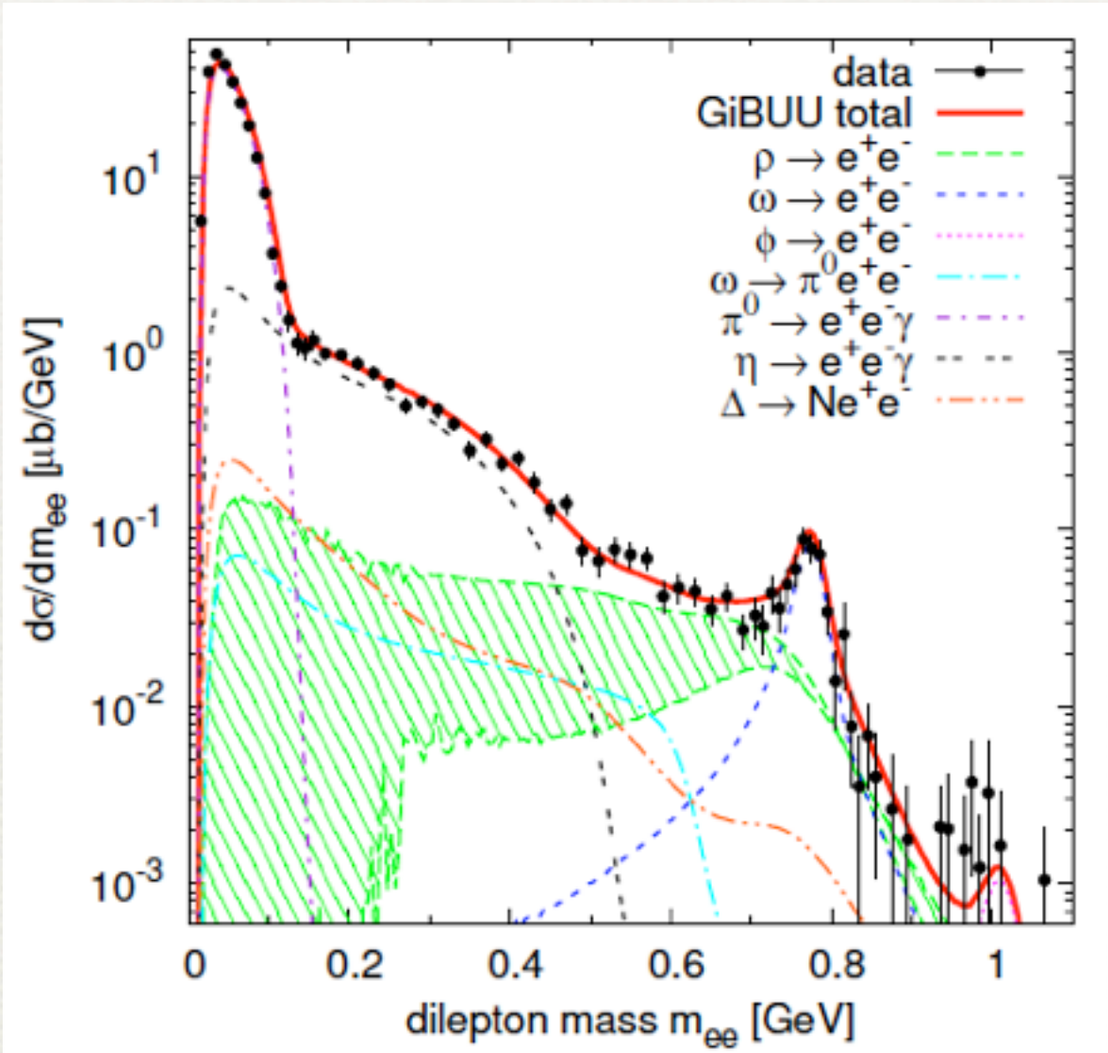
GiBUU model, J. Weil, ECT* Workshop 2013

- Gap below the omega pole
- "Modification" of the the ρ-meson in vacuum

p+p at 3.5 GeV: different models



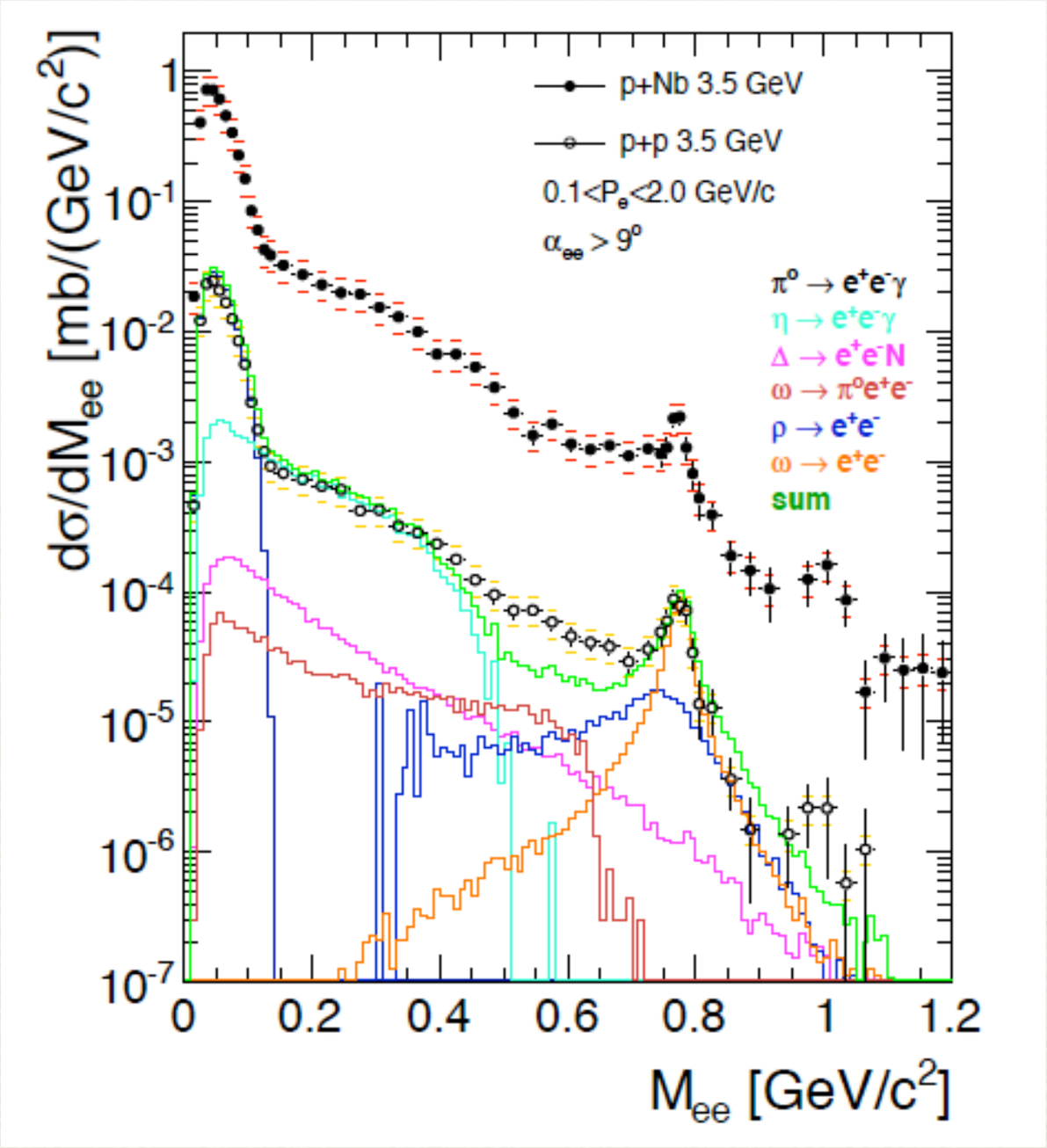
HSD model
E. Bratkovskaya et al.,
Phys. Rev. C 87, 064907 (2013)



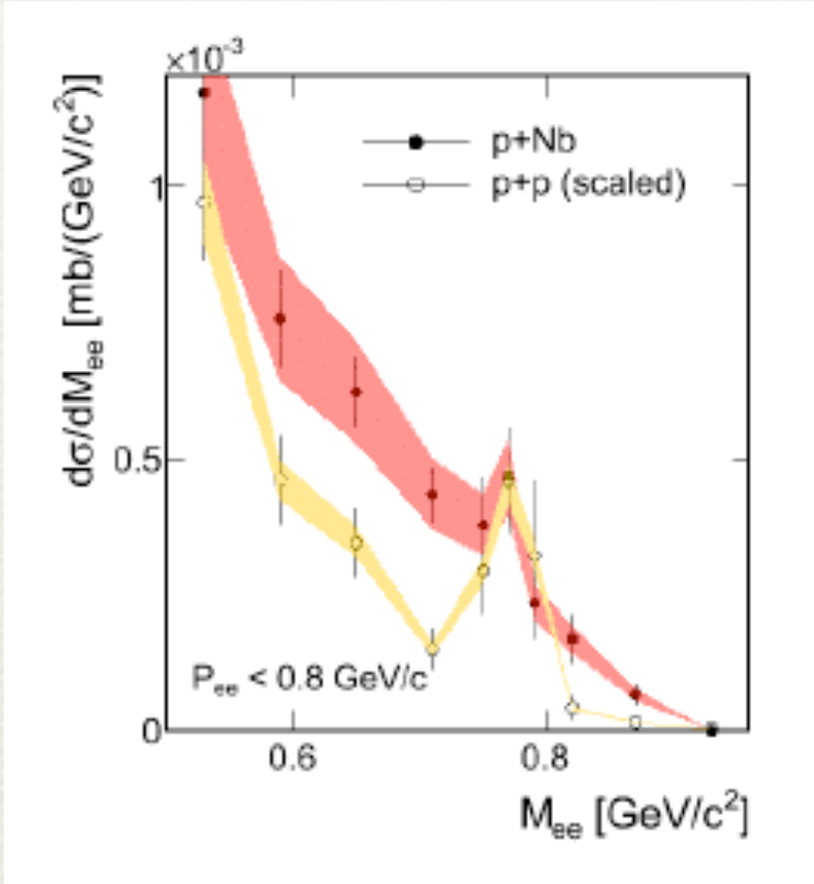
GiBUU model, J. Weil, ECT* Workshop 2013

- Very different treatment of the Δ and bremsstrahlung contributions

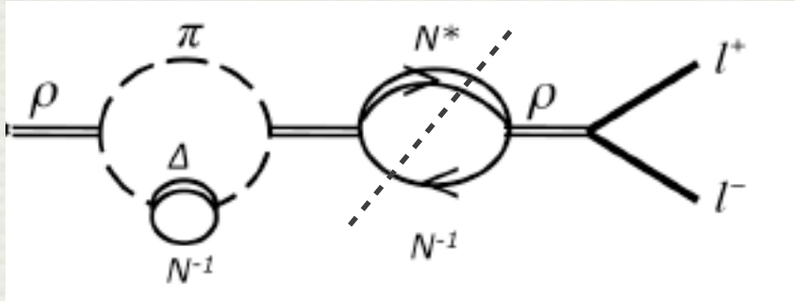
Cold nuclear environment: p+Nb at 3.5 GeV



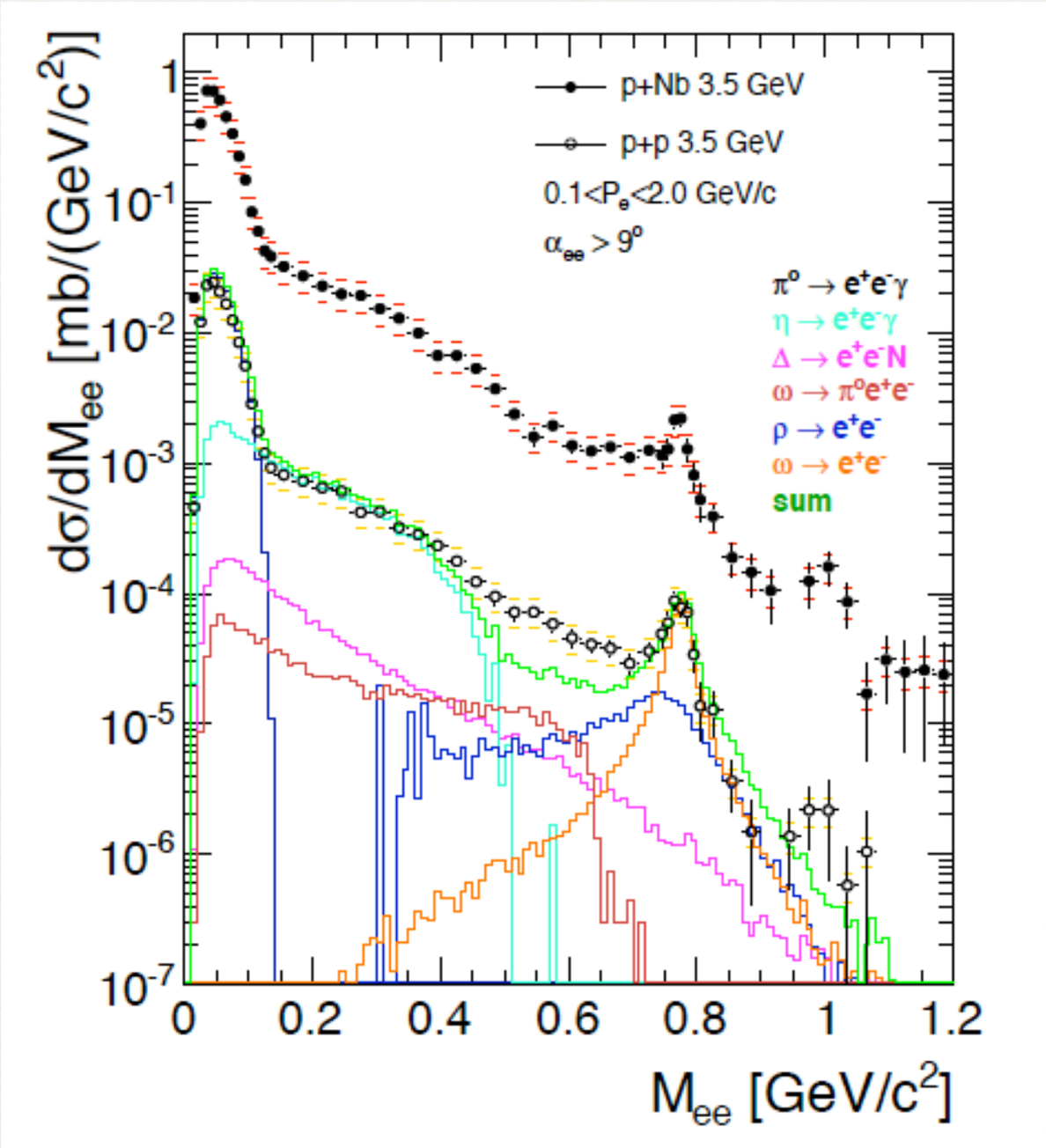
G. Agakishiev et al. [HADES]
Phys. Lett. B 715 (2012) 304.



- Excess on the left shoulder of the omega-peak, rho-like contribution, observed for slow pairs



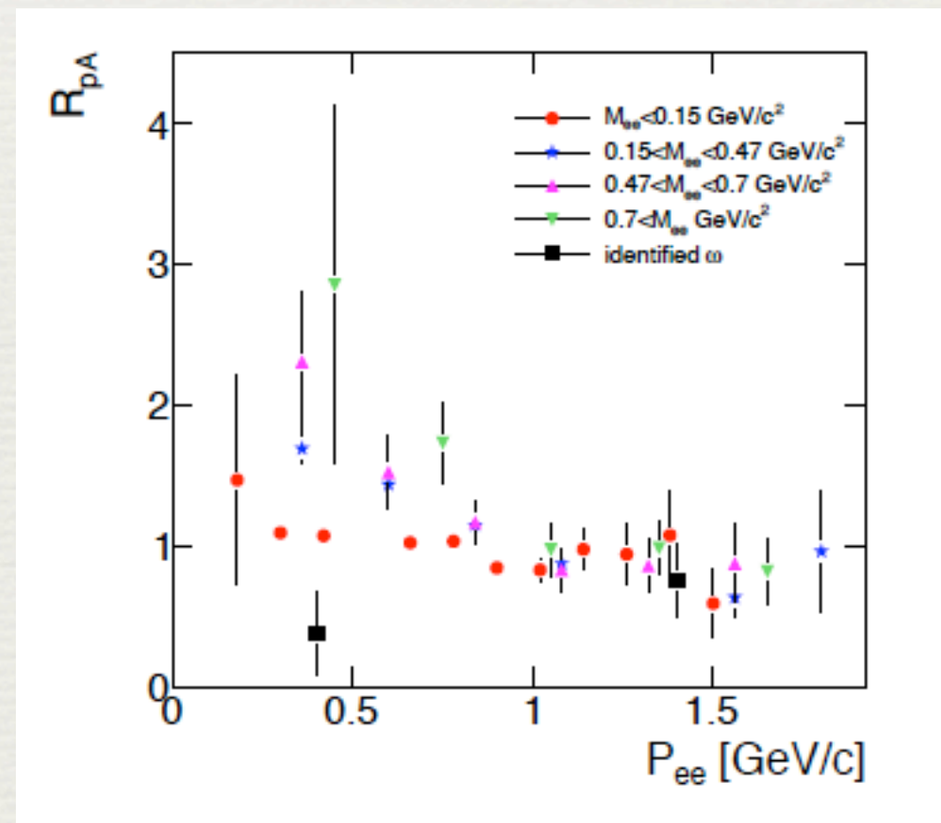
Vector mesons in cold nuclear matter



G. Agakishiev et al. [HADES]
Phys. Lett. B 715 (2012) 304.

- Nuclear modification factor

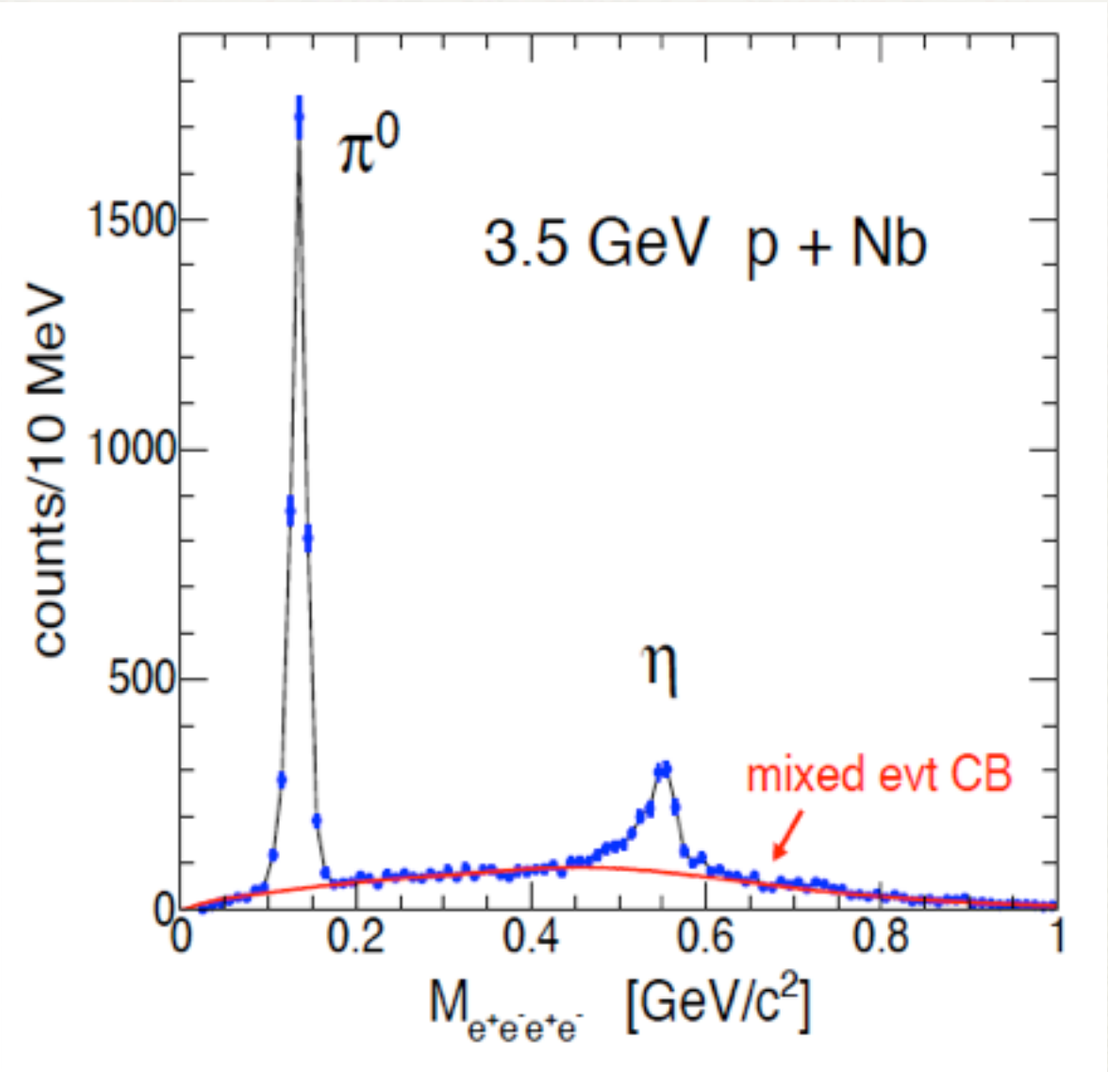
$$R_{pA} = \frac{d\sigma^{pNb}/dp}{d\sigma^{pp}/dp} \times \frac{\langle A^{pp}_{part}\rangle}{\langle A^{pNb}_{part}\rangle} \times \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}.$$



- Indication for slow omega's absorption
- Related to the in-medium width

Measuring the cocktail components

G. Agakishiev et al. [HADES]
Phys. Rev. C 88 (2013) 024904.

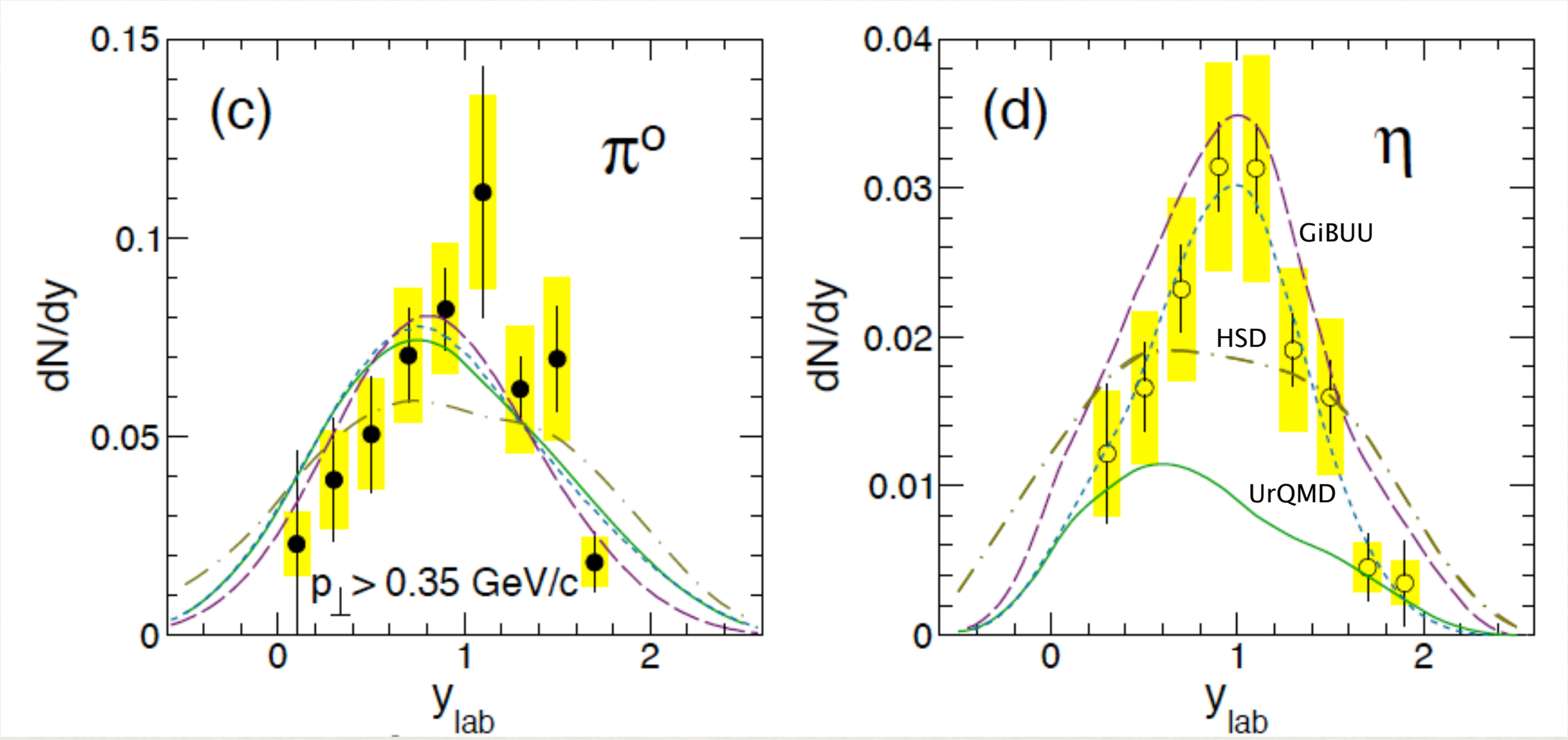


identified meson	π^0	η
signal [counts]	3800 ± 63	1240 ± 49
signal/CB	18.1	1.1
position [MeV]	134 ± 1	547 ± 2
width [MeV]	8.0 ± 0.6	19 ± 2

- Exploit main decay branch $P \rightarrow \gamma\gamma$ and photon conversion

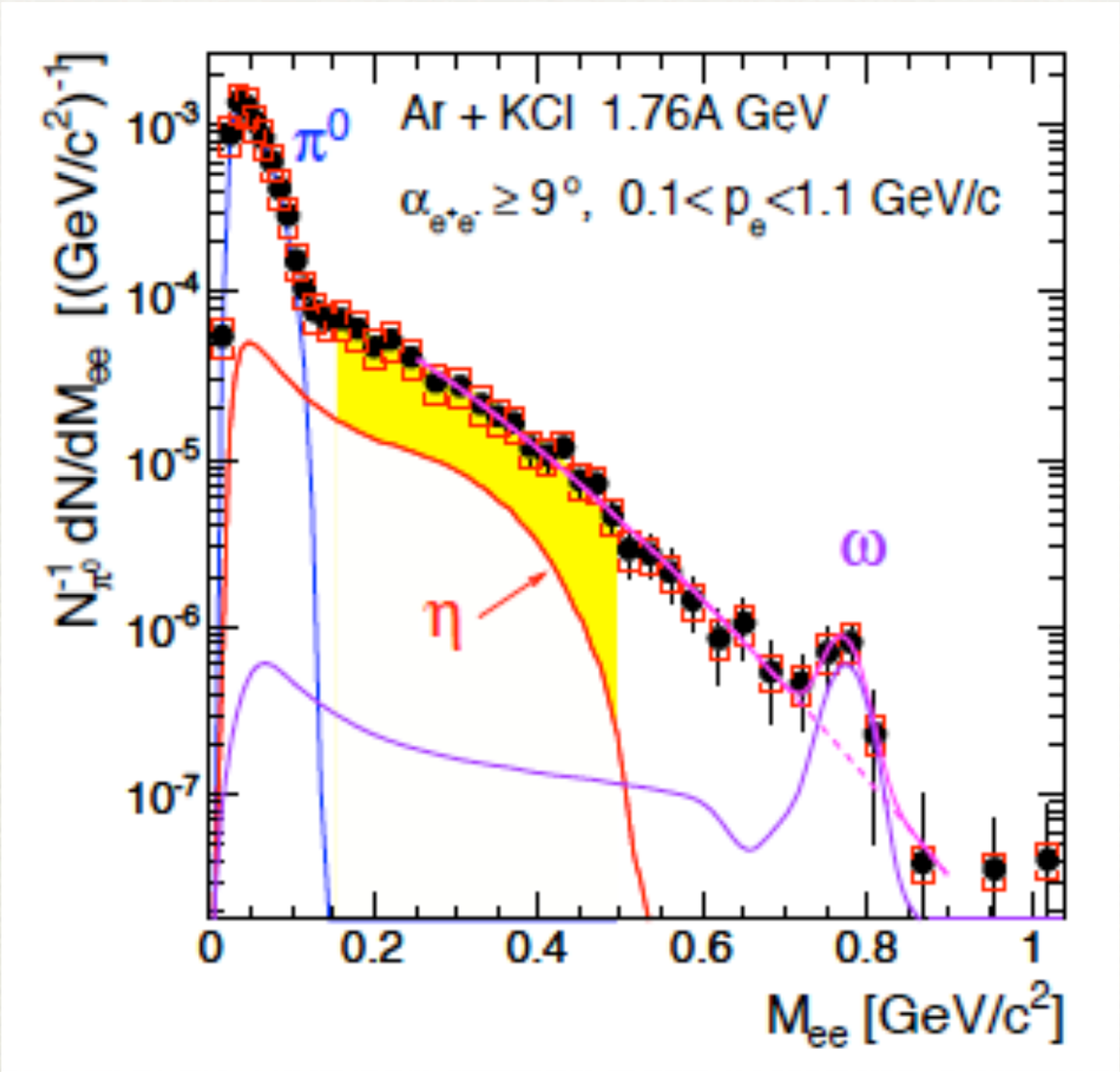
Phase space of neutral mesons in pNb

G. Agakishiev et al. [HADES]
Phys. Rev. C 88 (2013) 024904.



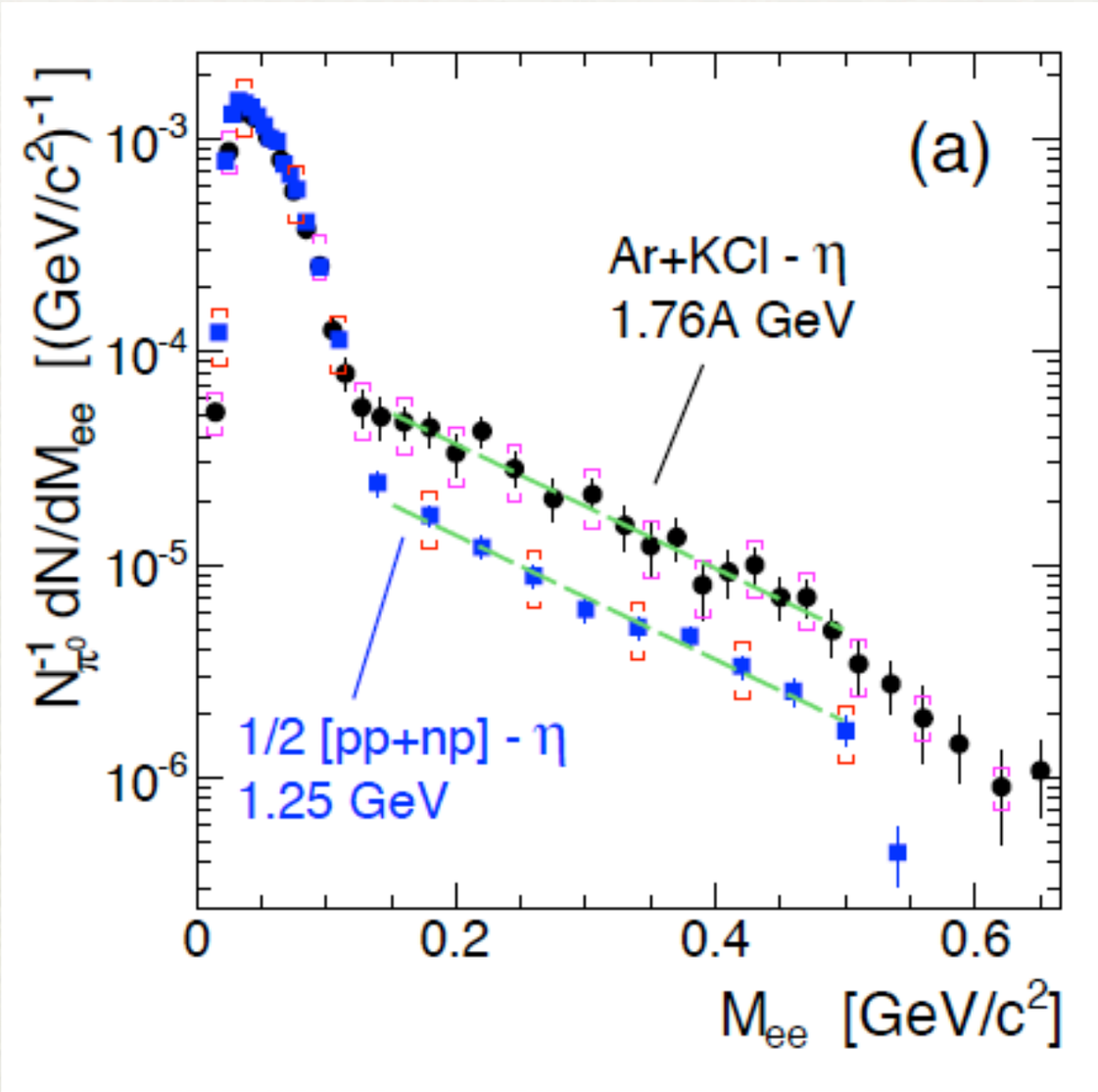
- Test/input for models that interpret e^+e^- data
- Au+Au data → talk by C. Behnke

Heavy ions: Ar + KCl at 1.76 GeV



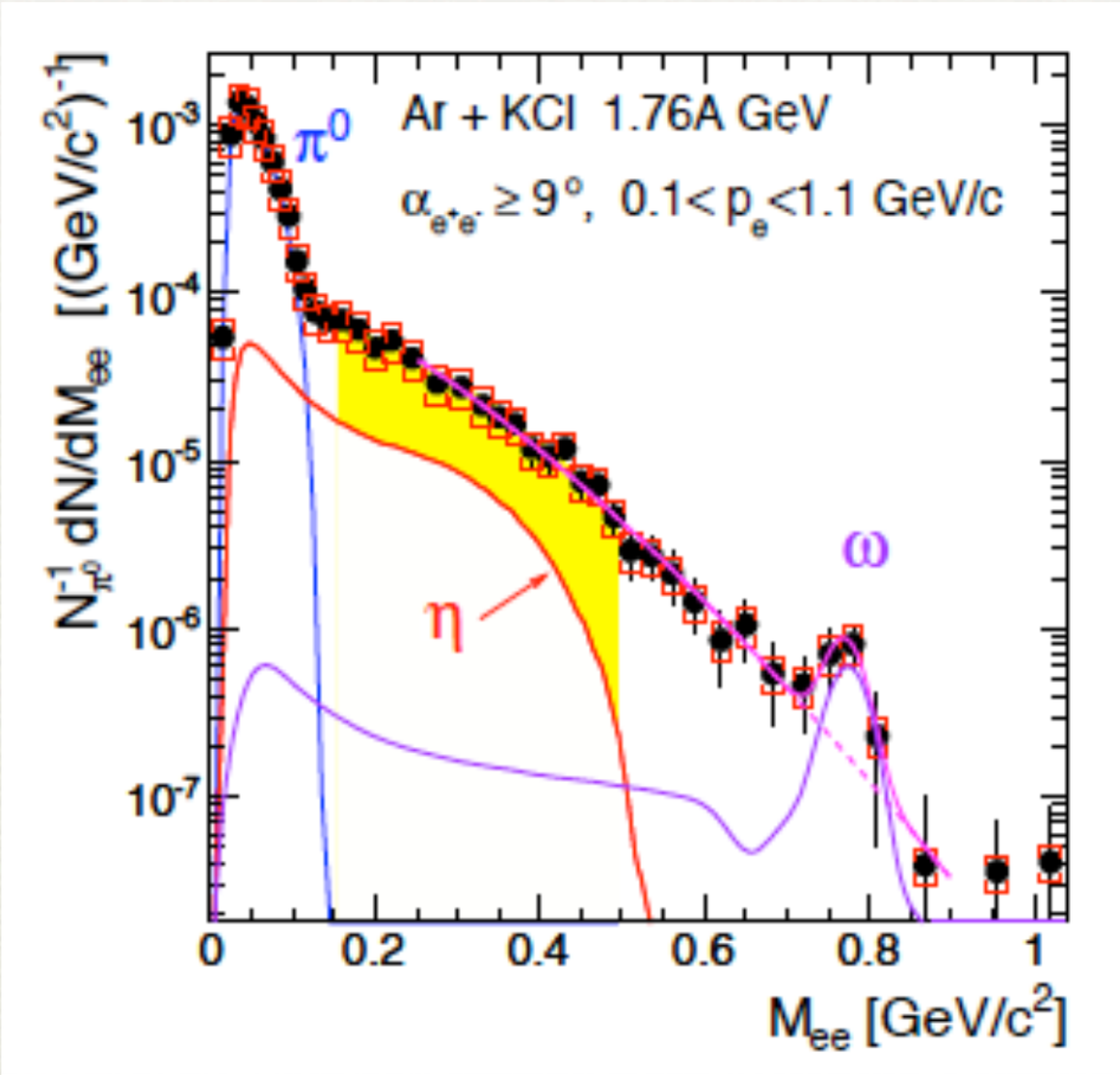
G. Agakishiev et al. [HADES]
Phys. Rev. C 84 (2011) 014902.

- First measurement of the omega-meson sub-threshold

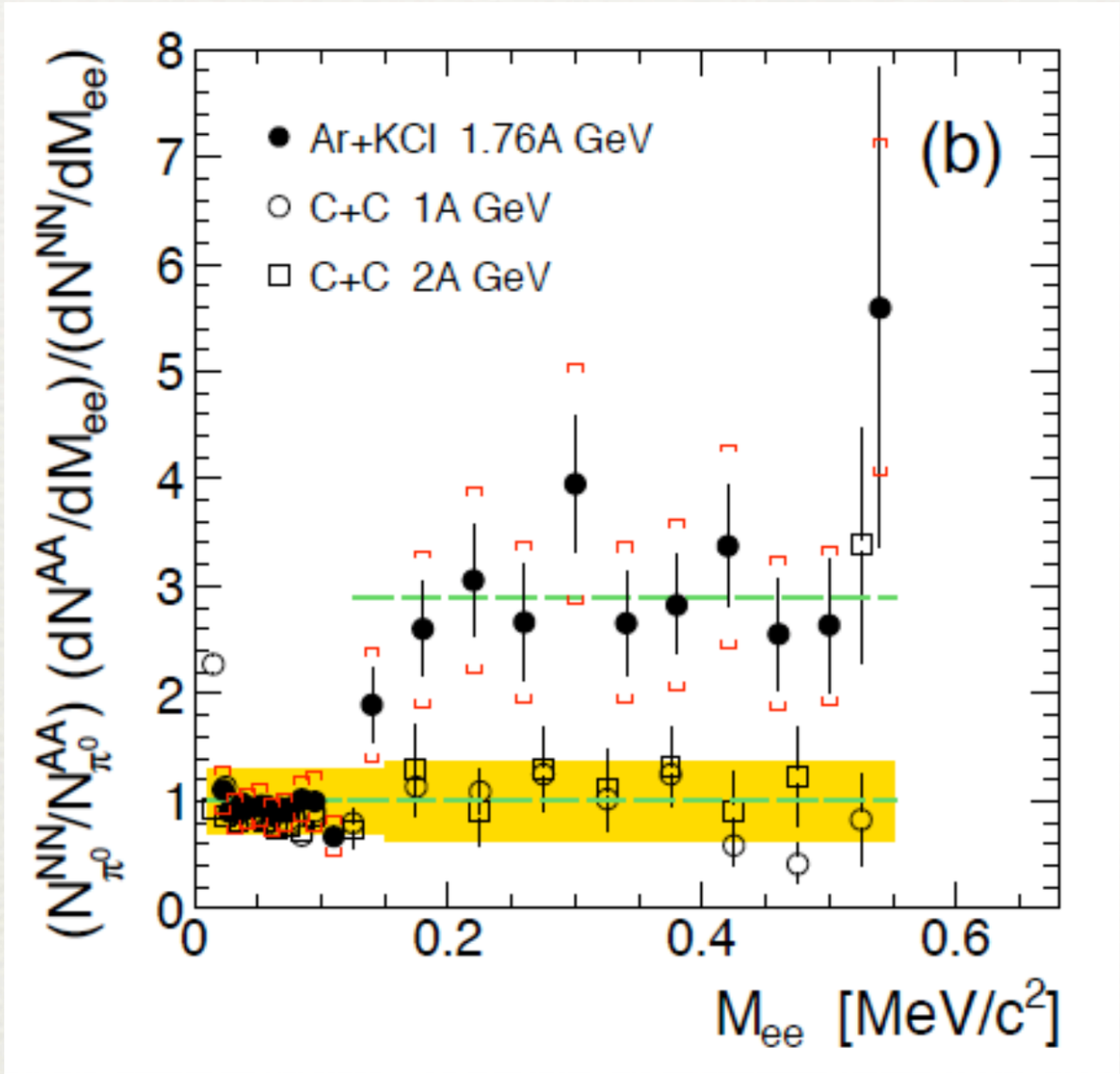


- Excess over the reference spectrum
- Dilepton emission beyond binary NN collisions

Excess yield in Ar + KCl



G. Agakishiev et al. [HADES]
Phys. Rev. C 84 (2011) 014902.

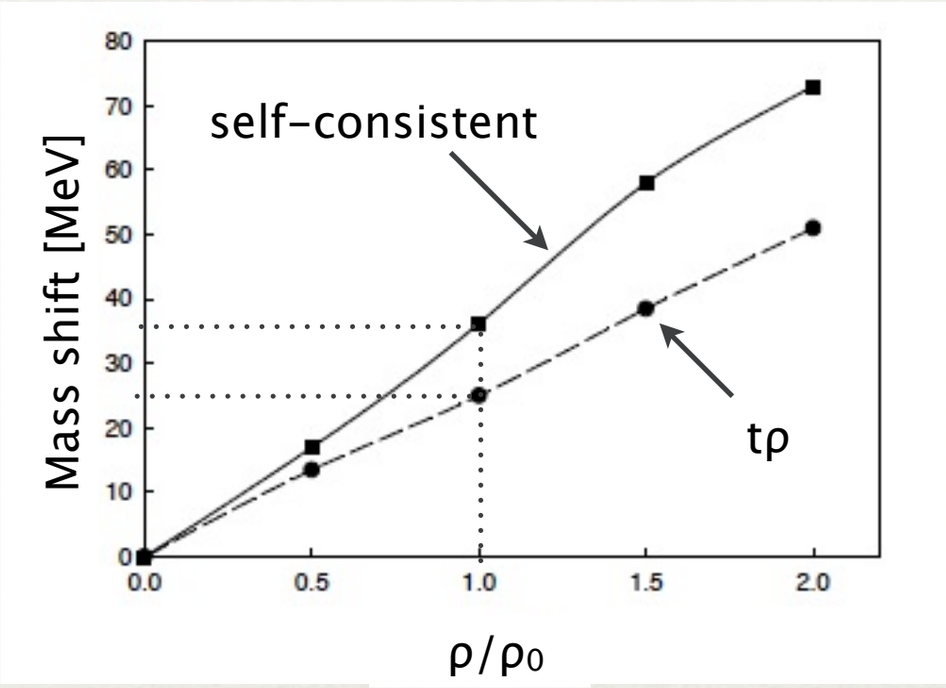


- First measurement of the omega-meson sub-threshold

- Excess over the reference spectrum
- To be continued with Au+Au data (May 2012), talk by S. Harabasz

Strangeness in medium: mesons

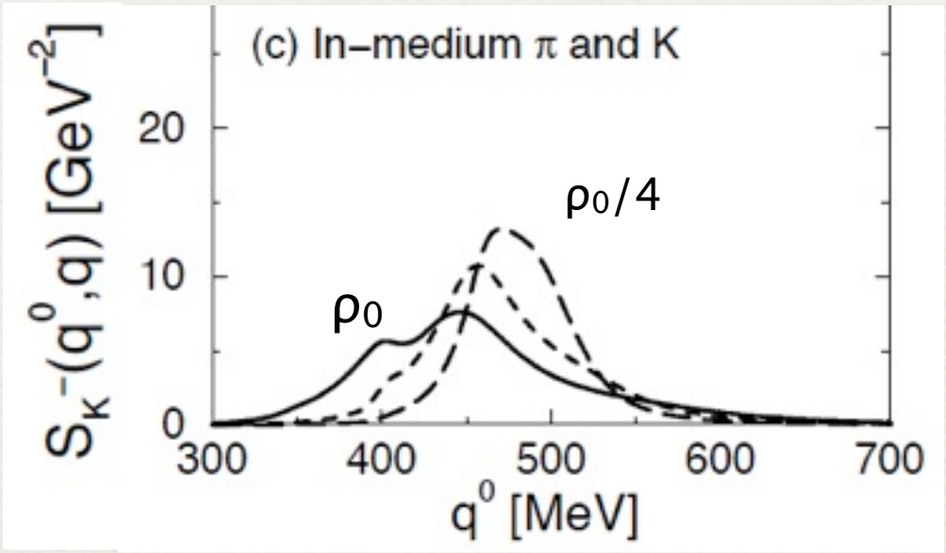
Kaon



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

- Repulsive in-medium potential, moderate increase of the effective mass

Antikaon

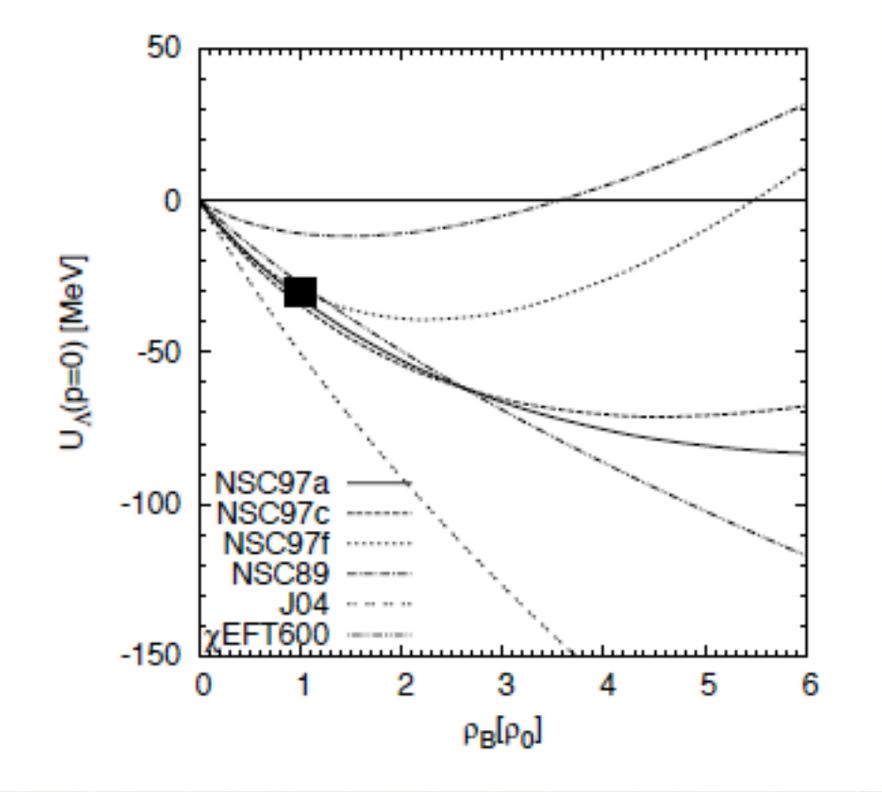


A. Ramos, E. Oset
Nucl. Phys. A 671 (2000), 481.

- Attractive in-medium potential, strong decrease of the effective mass, major broadening

Strangeness in medium: baryons

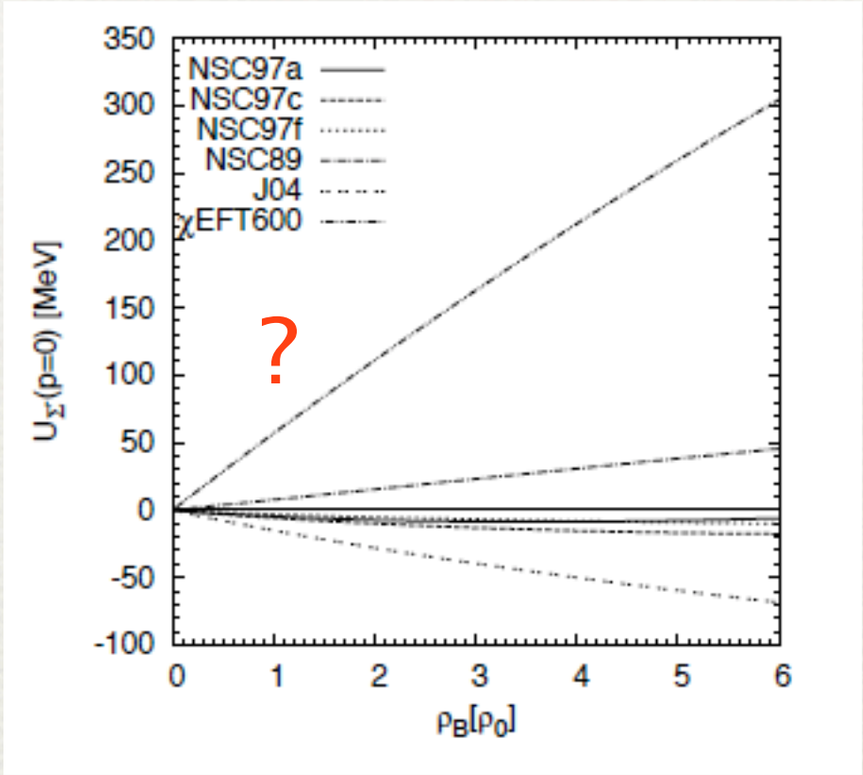
Λ(1116)



H.Dapo et al. EPJ A **36**, 101 (2008)

- U ~ −30 MeV (attractive) at saturation density
- Density/momentum dependence?

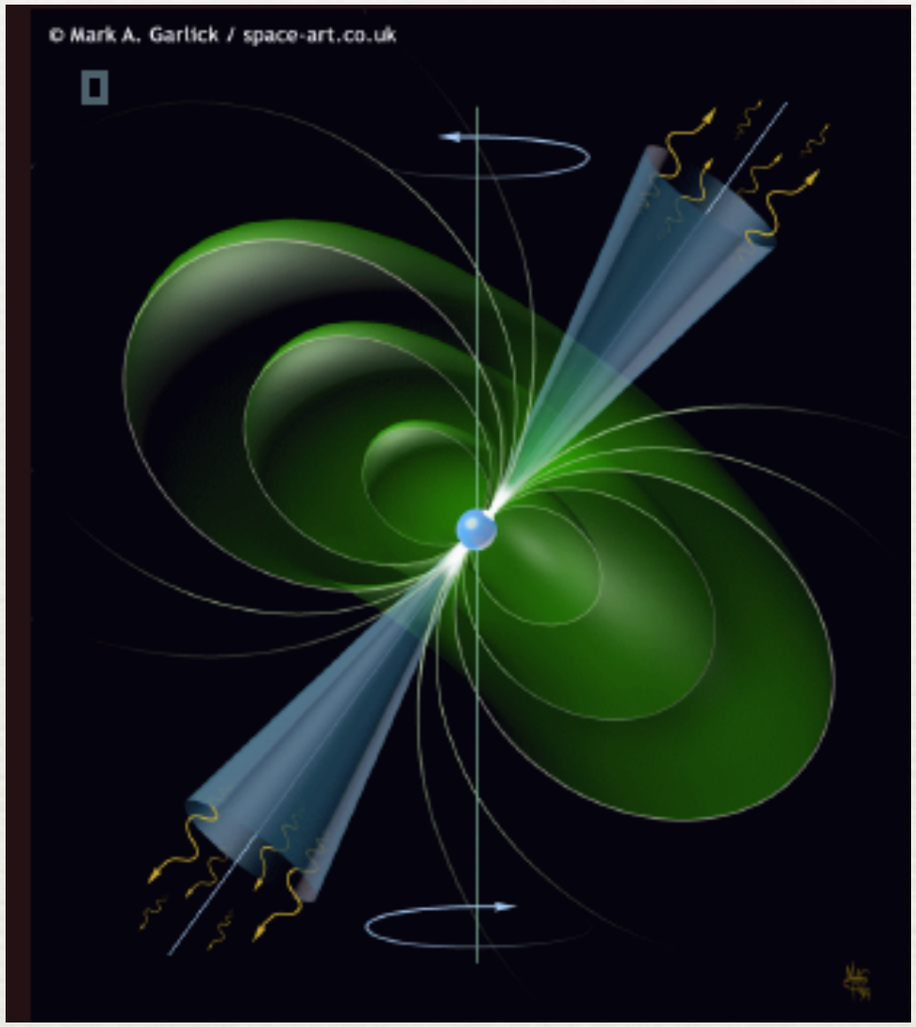
Σ^-(1197)



H.Dapo et al. EPJ A **36**, 101 (2008)

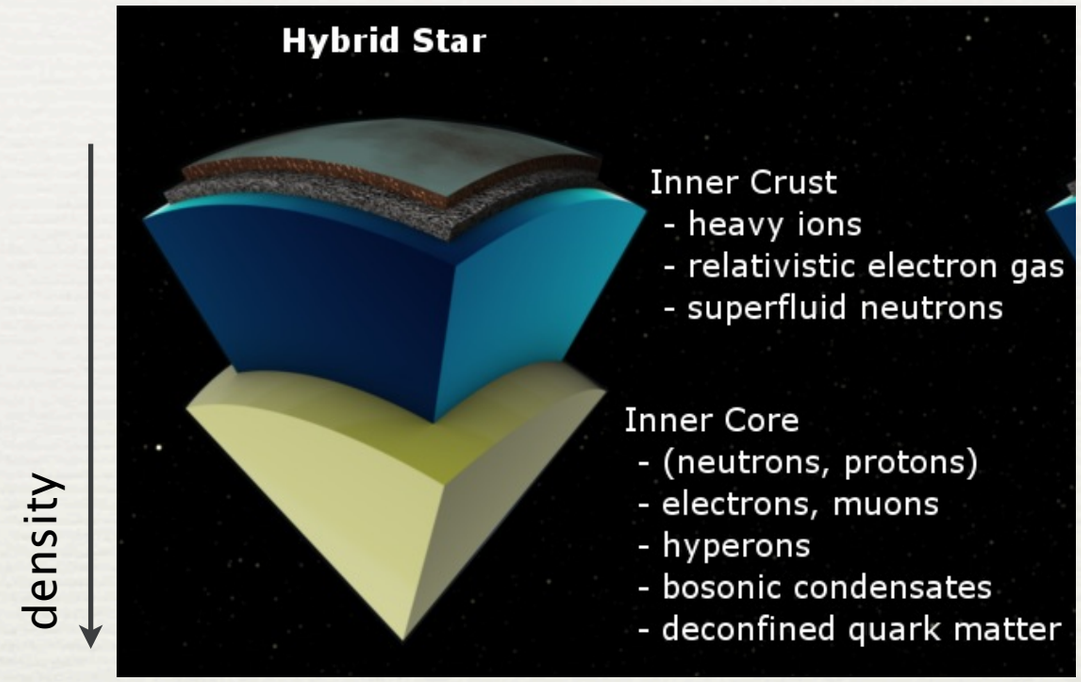
- Ambiguity in the potential value
- Hard to measure experimentally: $\Sigma^- \rightarrow n\,\pi^-$
- Calorimetry give a chance (neutron detection)

Appearance of strangeness in a neutron star



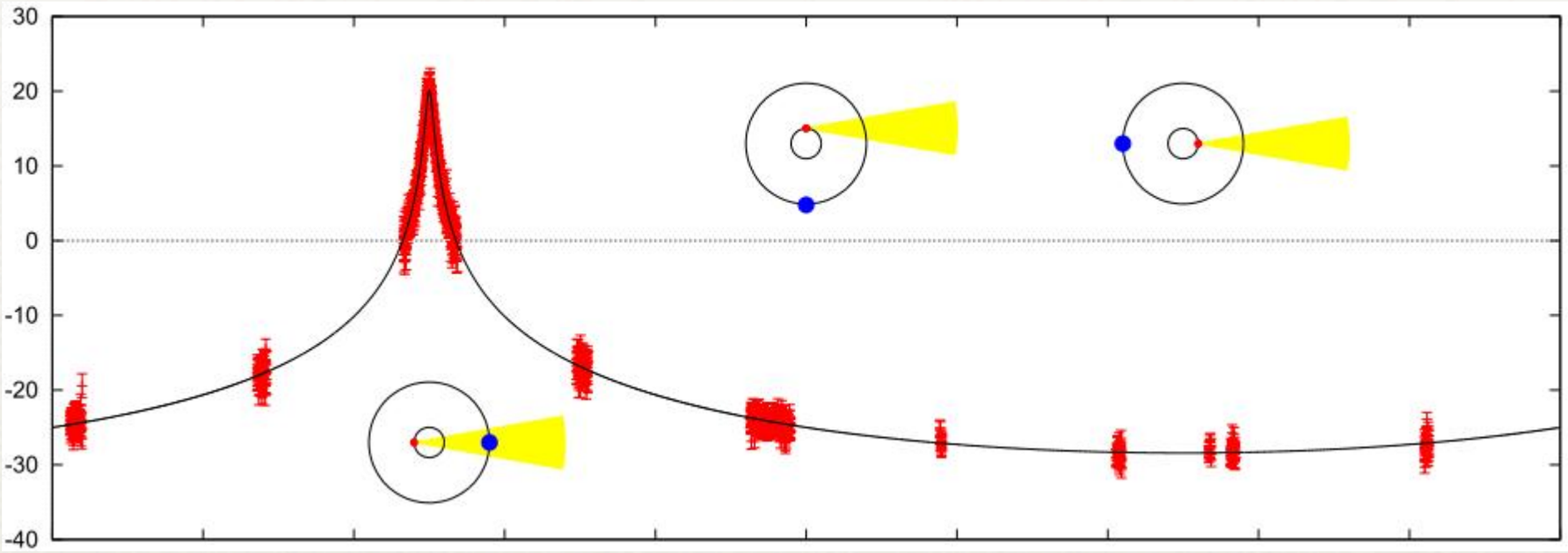
R ~ 10–15 km

M ~ 1.5 M⊙



- Very high density in the interior
- Production of strangeness is energetically favorable (relieve Fermi pressure of neutrons and electrons)
- Decrease of the pressure softens the matter (→ soft EoS)
- Decrease of the maximum mass of the star

Heavy pulsar J1614-2230



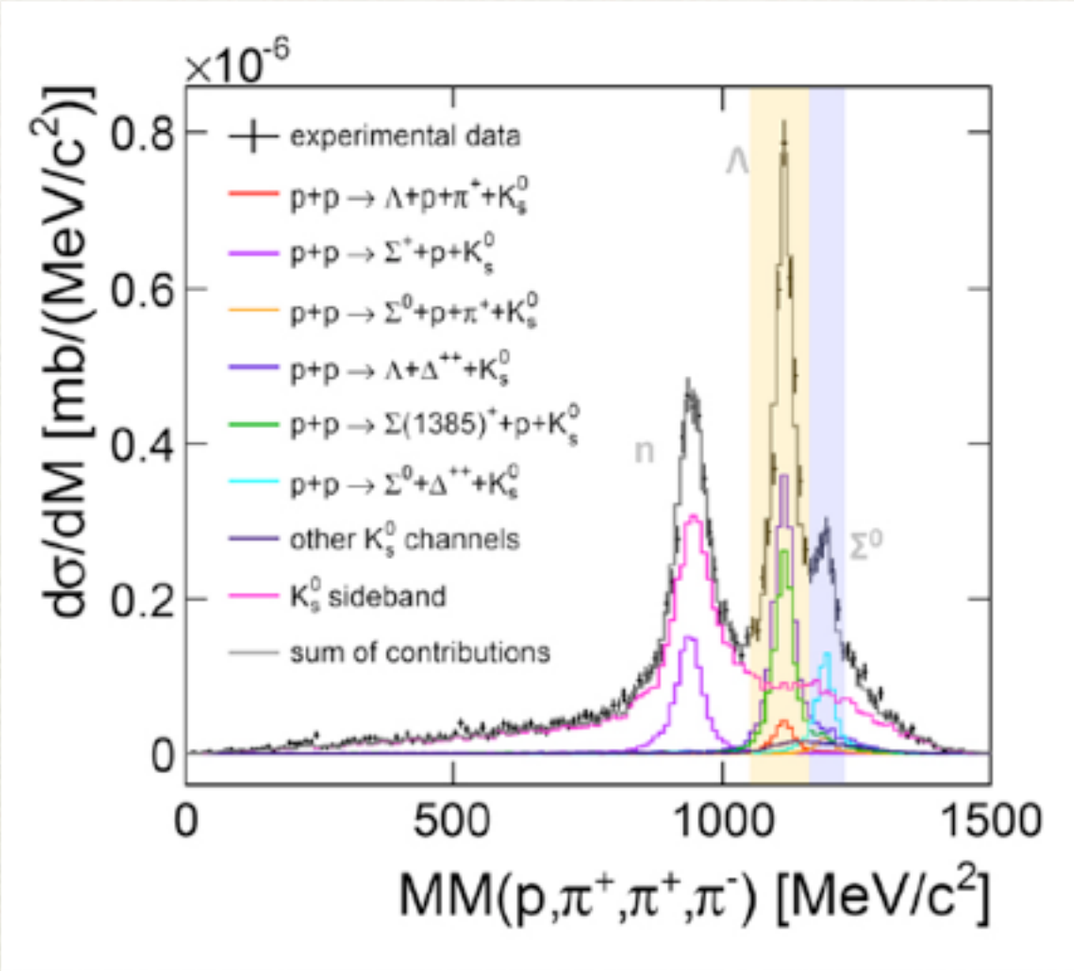
P. Demorest et al. Nature (467) (2010) 1081

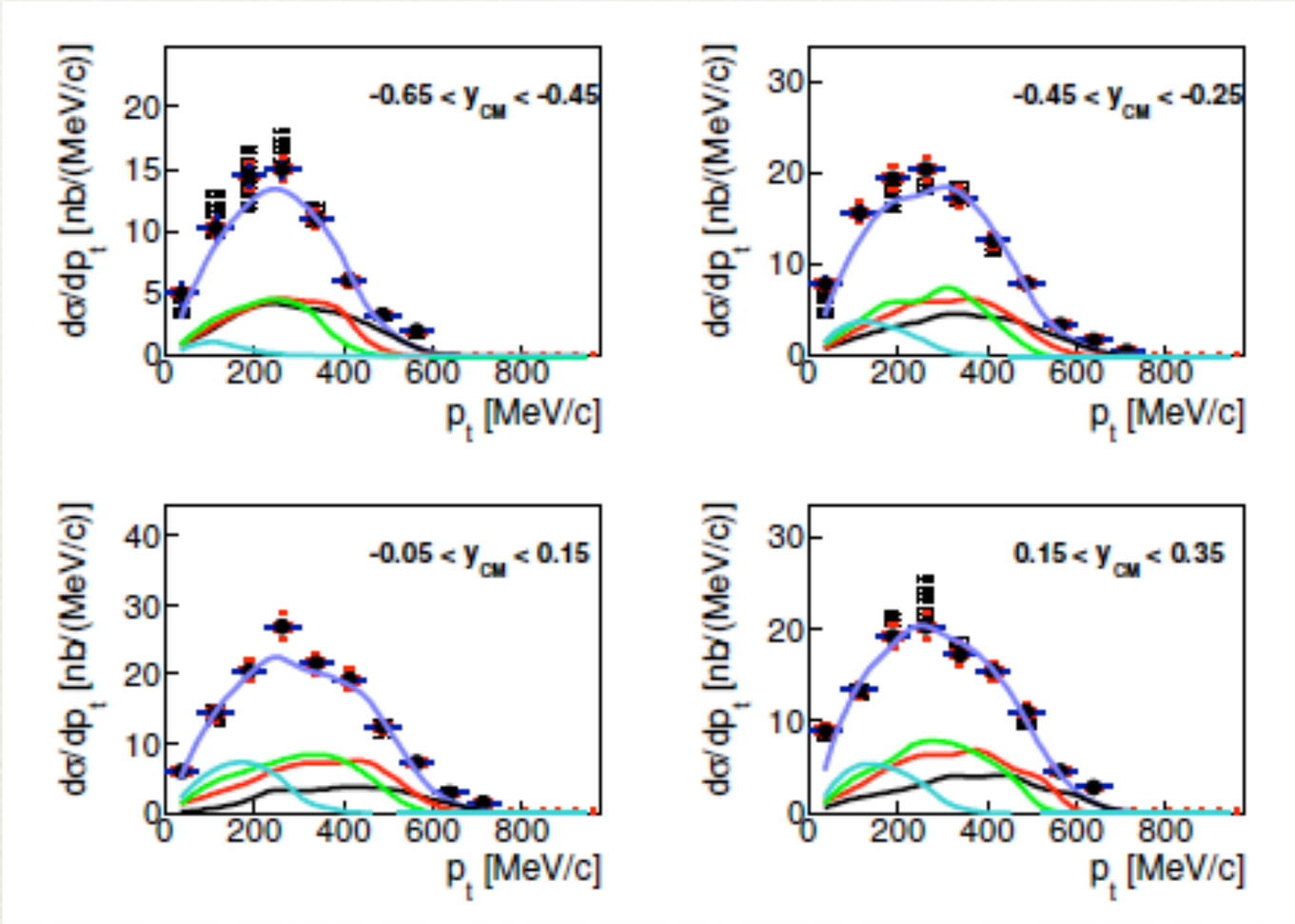
- Precise measurement of a pulsar mass via Shapiro delay
- $M = 1.97 \pm 0.04\ M_\odot$
- Excludes soft EoS and thus strangeness content

"There is still lack of information about the nucleonic EOS at suprasaturation densities as well as on the **hyperon interactions in nuclear matter** that may allow for an unambiguous answer to whether the mass of the pulsars J1614-2230 or J0348+0432 could rule out exotic degrees of freedom from the interior of compact stars."

C. Providência et al. arXiv:1307.1436 [nucl-th]

Neutral kaon production in pp reactions at 3.5 GeV



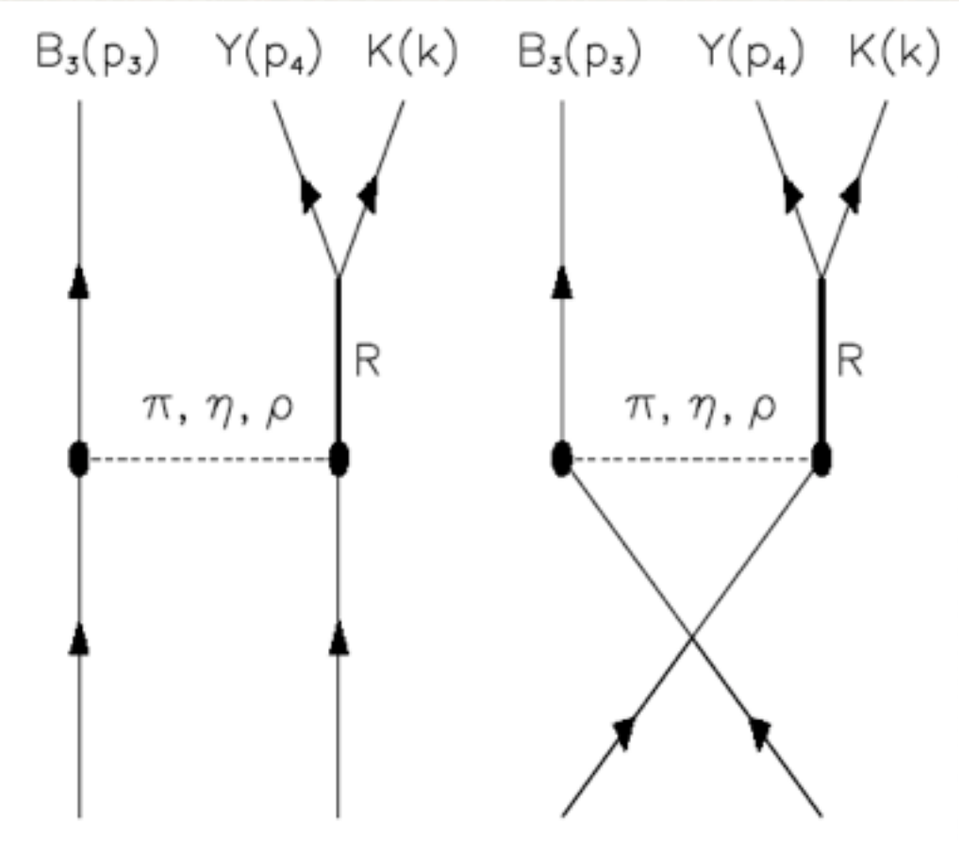


- Exclusive measurement, extraction of production cross sections

- Tune of the resonance model (GiBUU) to exclusive and inclusive data
- Use the tuned model to interpret the pNb data

Kaon production in NN collisions: role of baryonic resonances

K. Tsushima, A. Sibirtsev, A.W. Thomas, G.Q. Li, PRC59 (1999) 369
"Resonance model study of kaon production in baryon baryon reactions for heavy ion collisions"



B = N or Δ

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

Note:
these heavy resonances are not produced in the GiBUU code, only cross sections parameterizations are used.

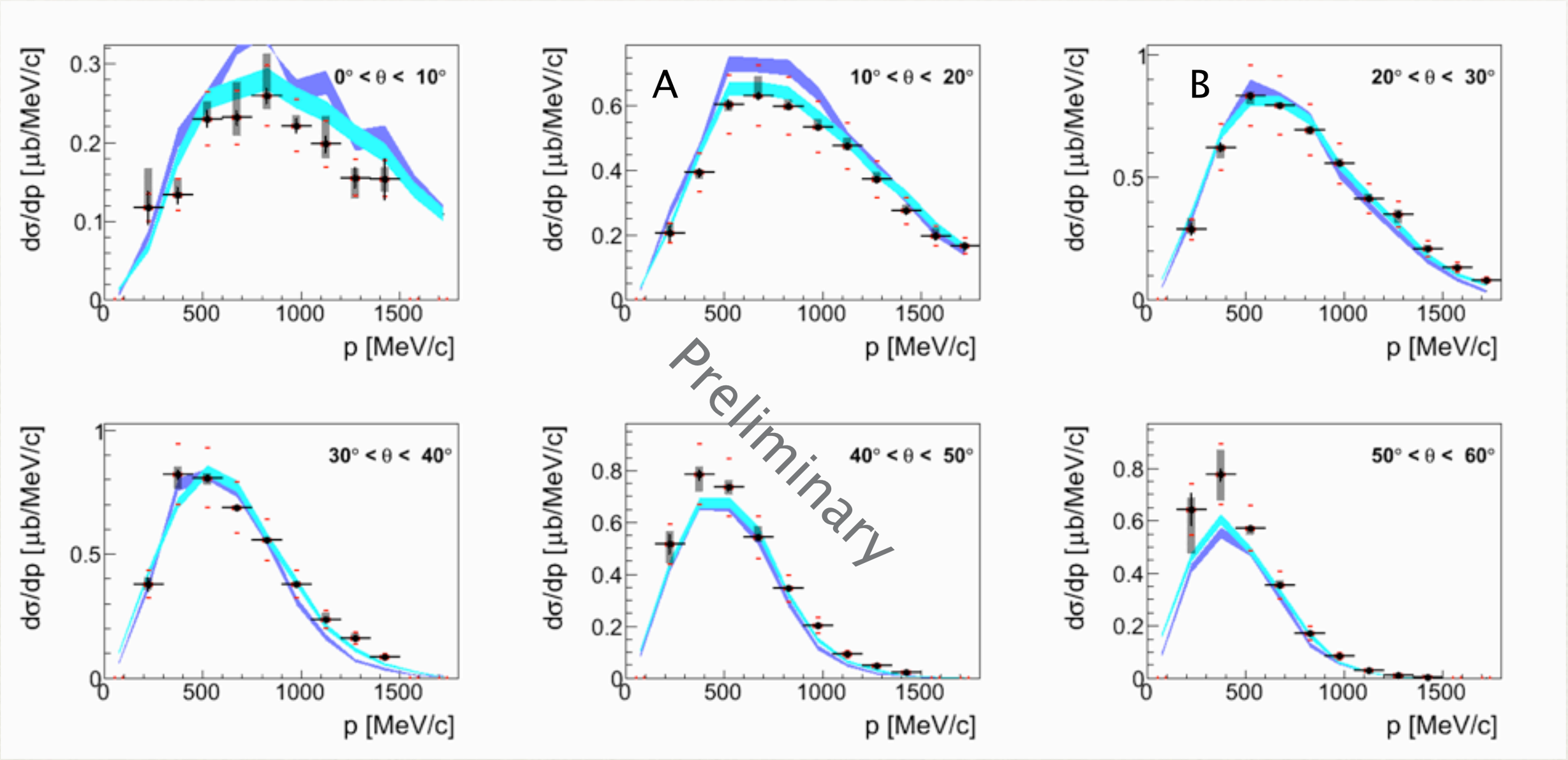
- Completely detached from the resonance model(s) used for dilepton data interpretation

Neutral kaons: effect of the potential in pNb at 3.5 GeV

GiBUU w/o pot.
GiBUU w. pot.

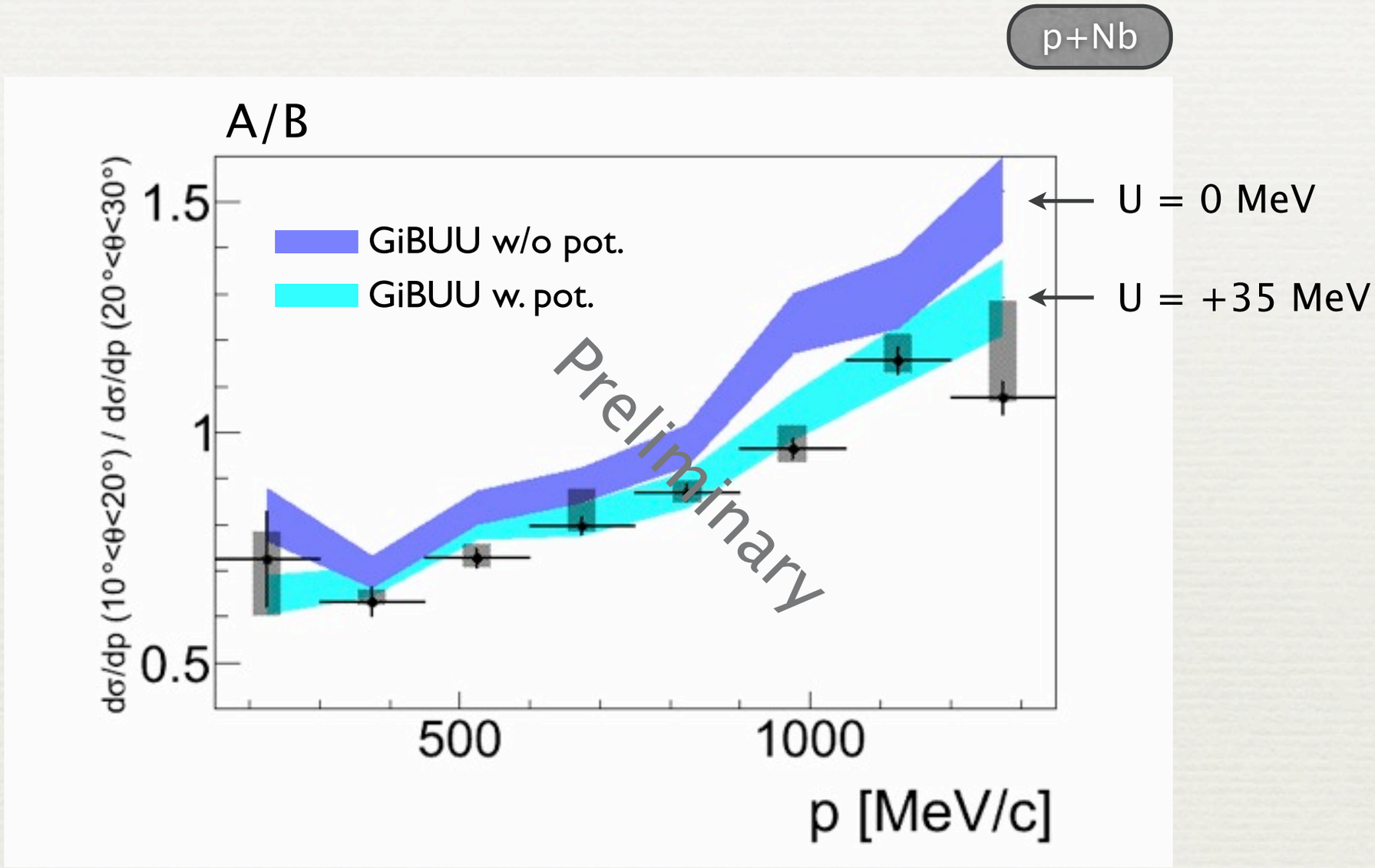
- $F = -\nabla U \Rightarrow$ kinematics of particles.

p+Nb



- Maximal effect of the potential at $10° < \theta_{LAB} < 20°$
- Build the ratio of two spectra (A/B)

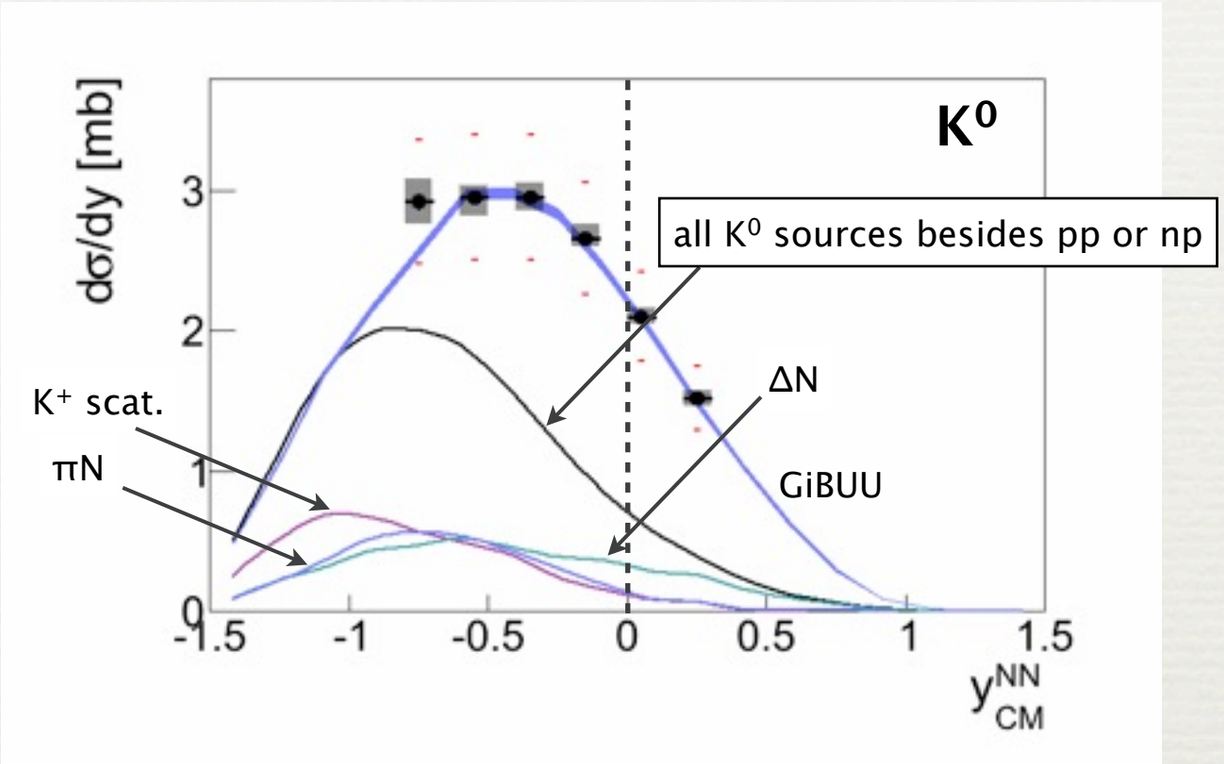
Neutral kaons: effect of the potential in pNb at 3.5 GeV



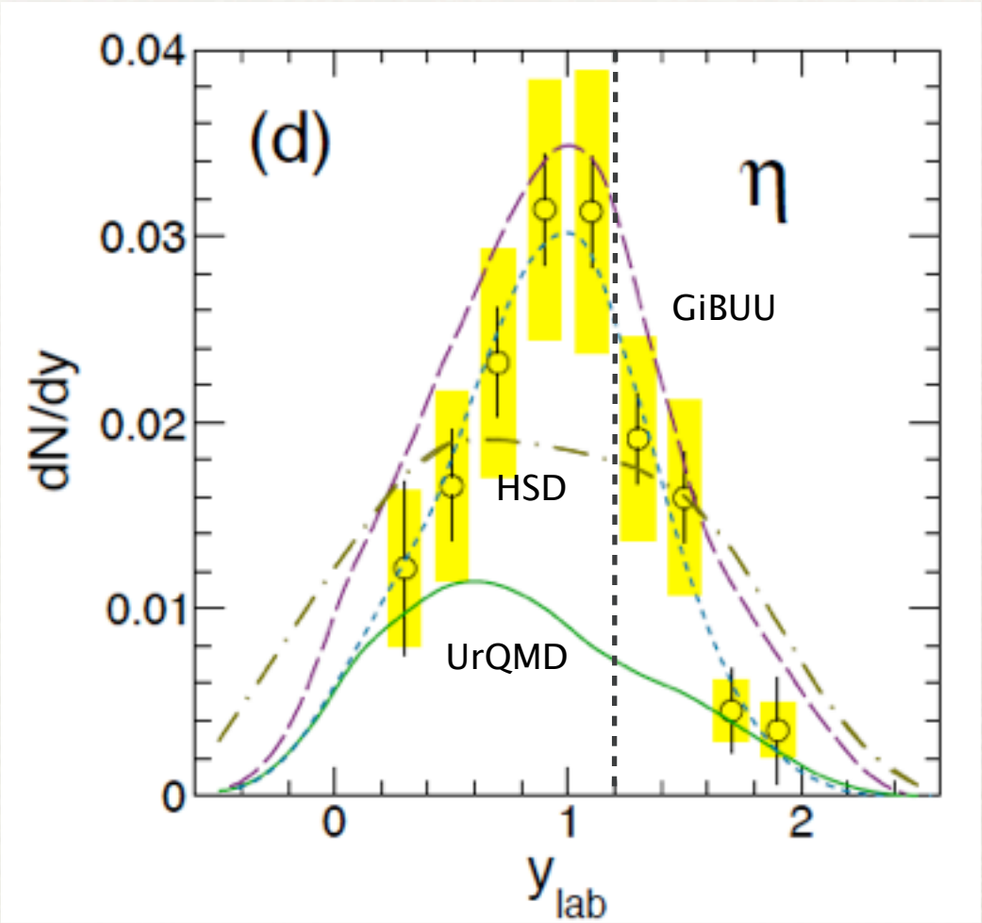
- Ongoing analyses: measure particles that might be relevant for neutron stars (hyperons)

Rapidity distribution in pNb: scattering and secondary processes

p+Nb

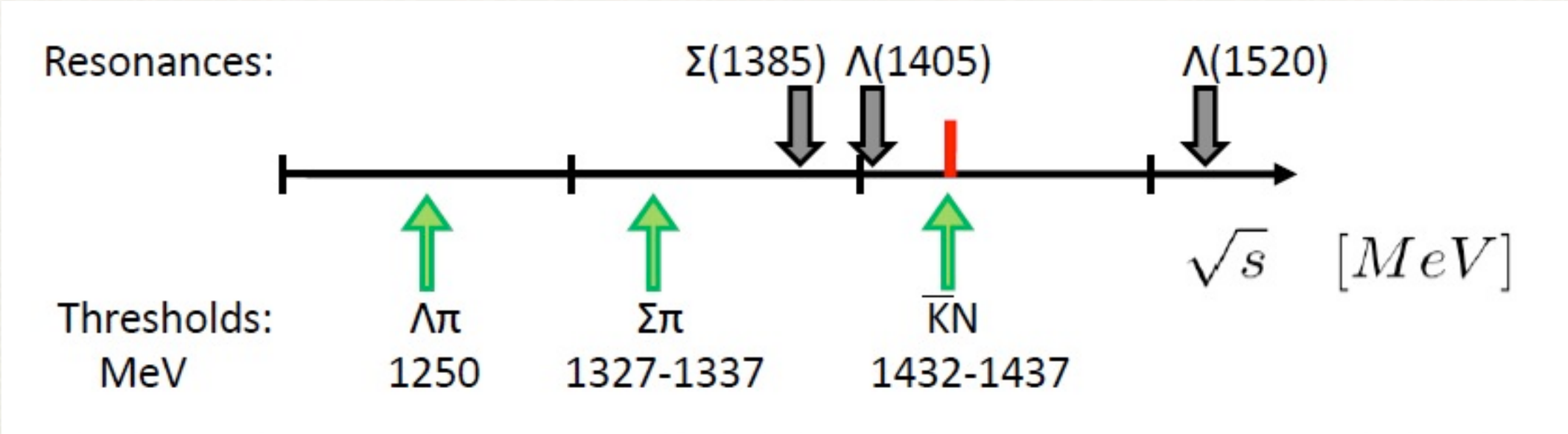


p+Nb



- Very different behaviour of two species, reflecting different interaction with nucleonic environment
- Important constraints/input for transport

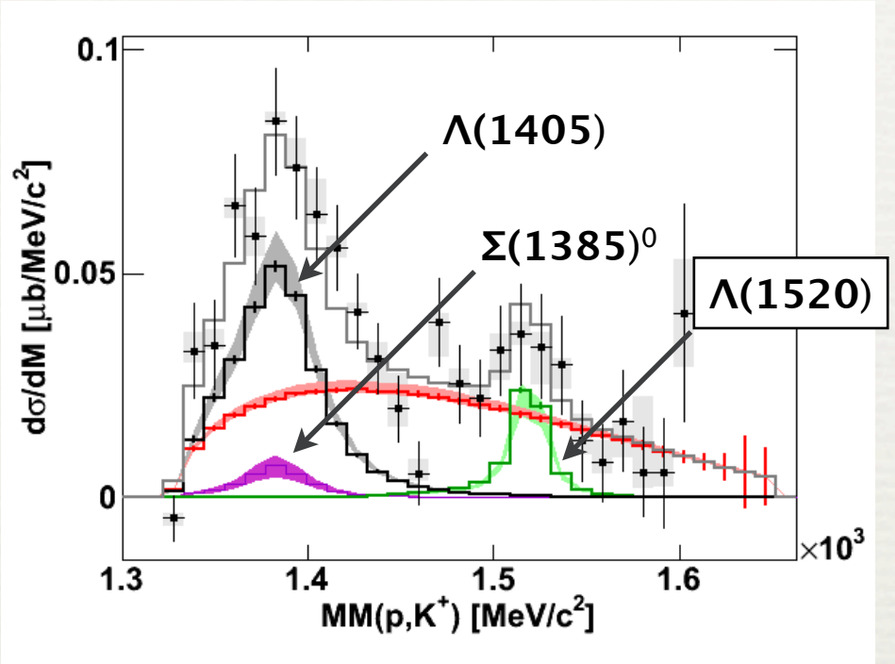
Antikaon–nucleon interaction



- Λ(1405) is crucial for understanding of the **free and in-medium** $\bar{K}N$ interaction.
- Predicted as a $\bar{K}N$ bound state.
- Within coupled channel approach generated as a $\bar{K}N$ bound state and a Σπ resonance.

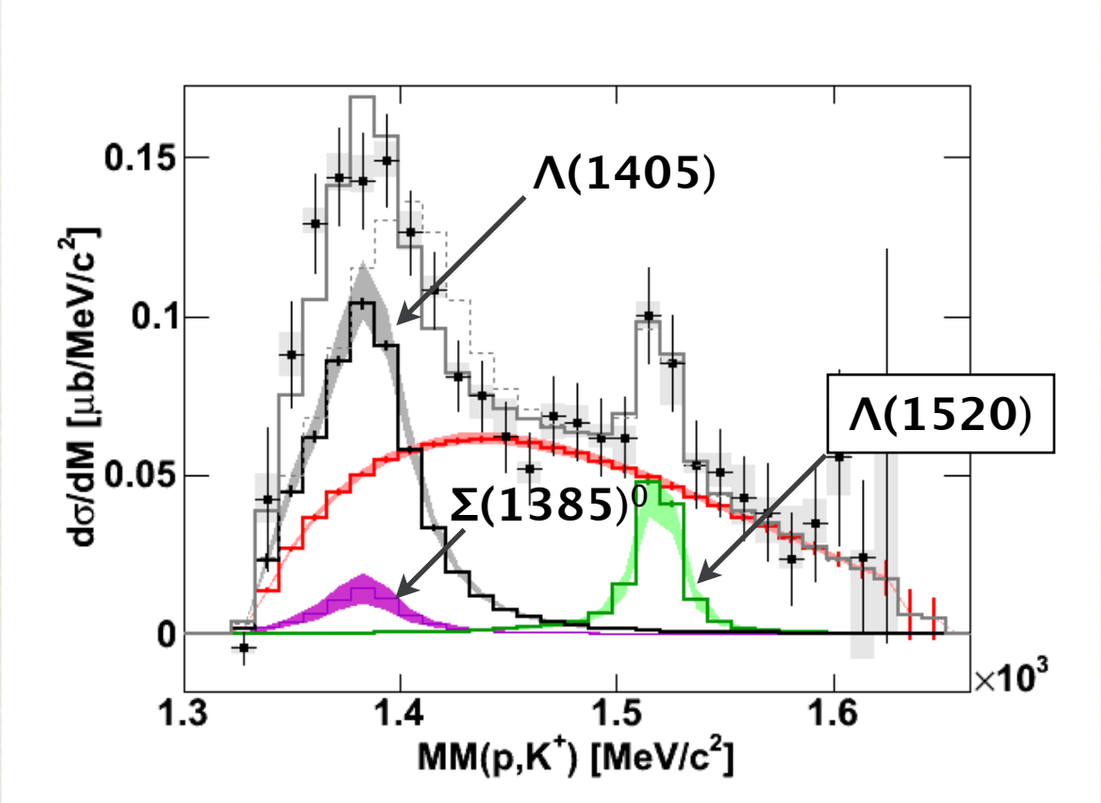
Λ(1405) line shape

$\Sigma^+\pi^-$ channel

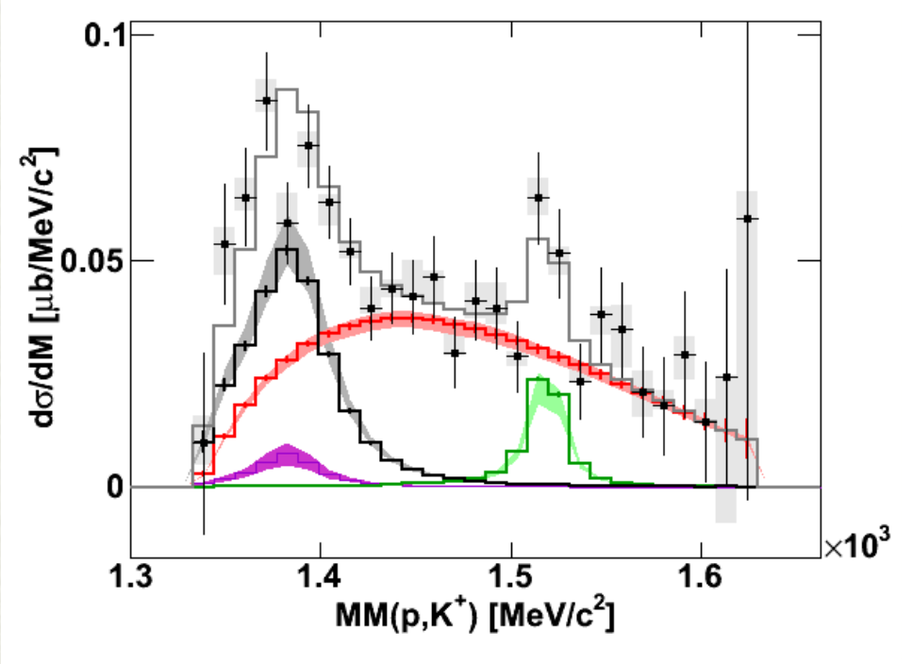


$$p + p \xrightarrow{3.5GeV} \Lambda(1405) + \boxed{K^+ + p}$$
$$\hookrightarrow \Sigma^\pm + \pi^\mp$$
$$\hookrightarrow \pi^\pm + n$$

Sum of both charged decay channels



$\Sigma^-\pi^+$ channel

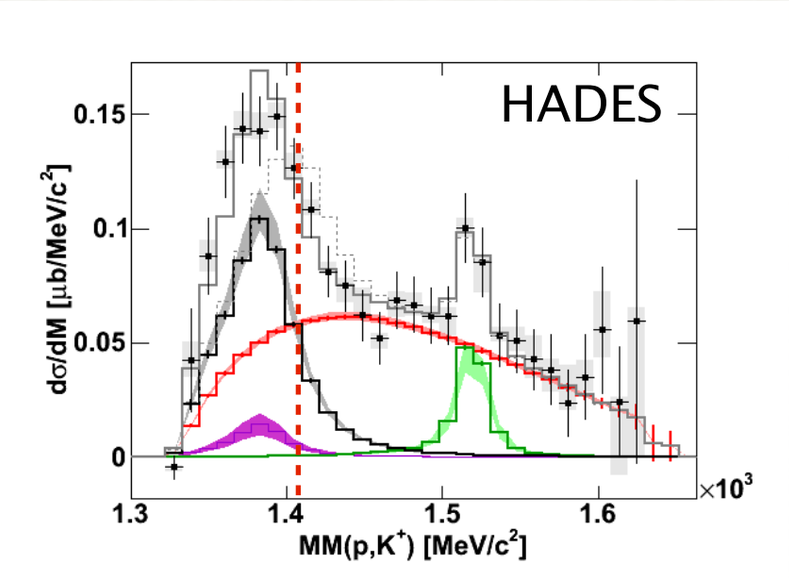


- First measurement of Λ(1405) in p+p reactions in charged decay mode.
- Mass distribution peaked below 1405 MeV/c^2.

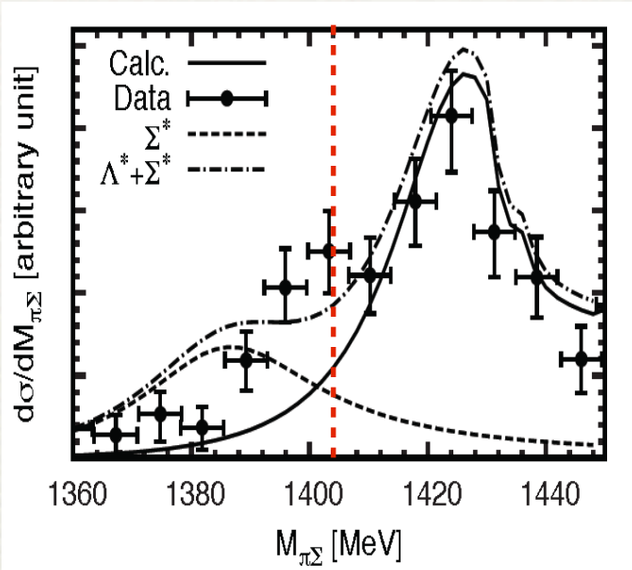
G. Agakishiev et al. [HADES]
Phys. Rev. C 87 (2013) 025201

Different reactions → different lineshapes

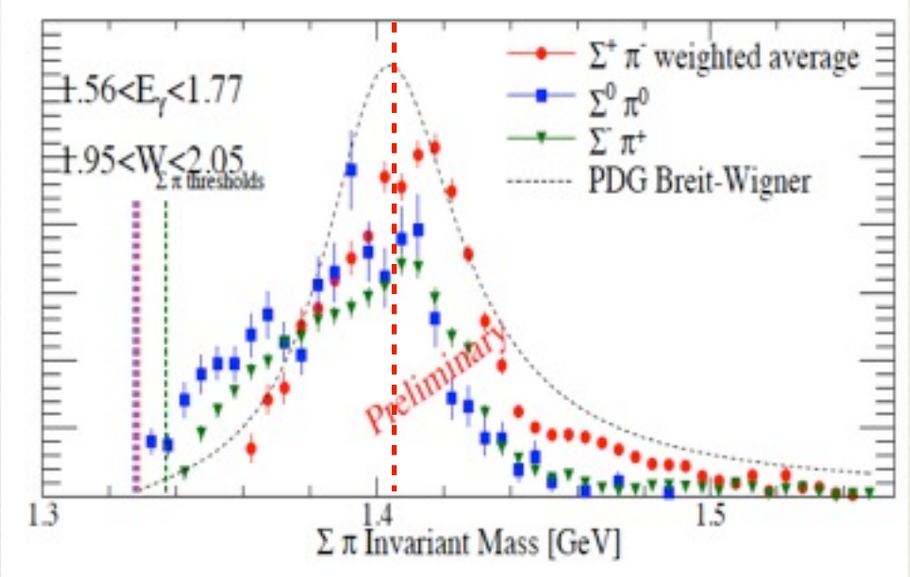
p+p at 4.3 GeV/c



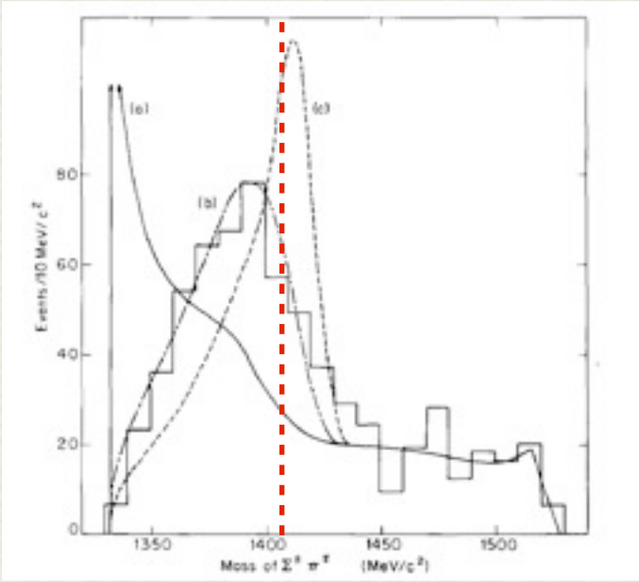
K⁻+d at 0.7–0.85 GeV/c



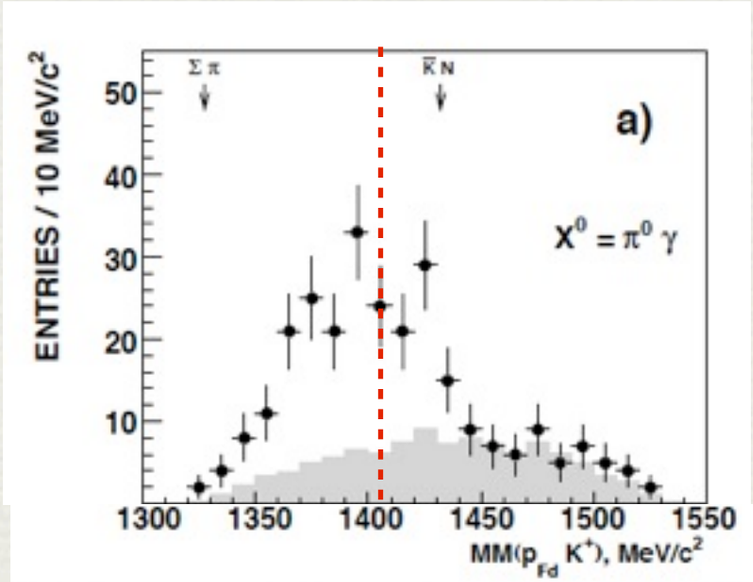
γ+p at 1.6–1.8 GeV/c



π⁻+p at 1.69 GeV/c



p+p at 3.65 GeV/c

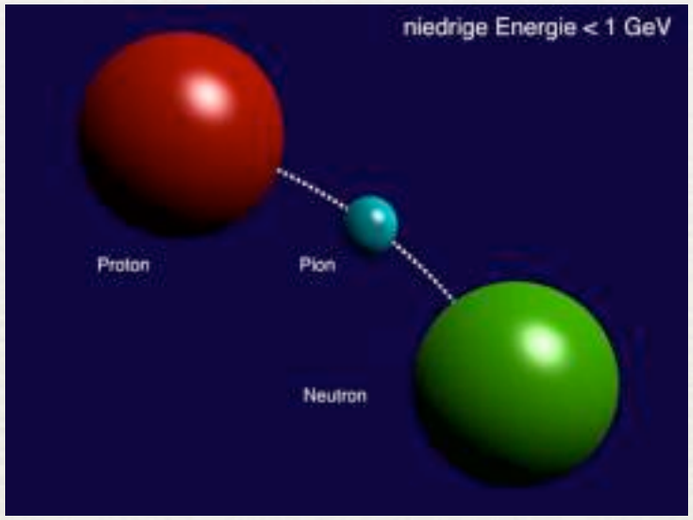


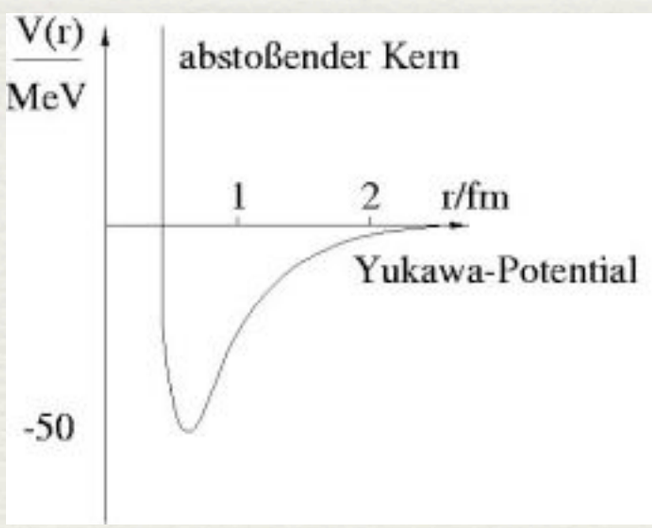
O. Braun et al. Nucl. Phys. B129 (1977) 1.
K. Moriya et al. arXiv:1110.0469 [nucl-ex].
D.W. Thomas et al. Nucl. Phys. B56 (1973) 15.
I. Zychor et al. Phys. Lett. B660 (2008) 167–171.

Pion beam program:
HADES has a unique opportunity to measure Λ(1405) in two different reactions

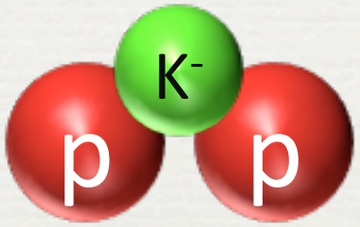
Hypothesis of a Kaonic Cluster

strong force
mediated by **virtual** pion

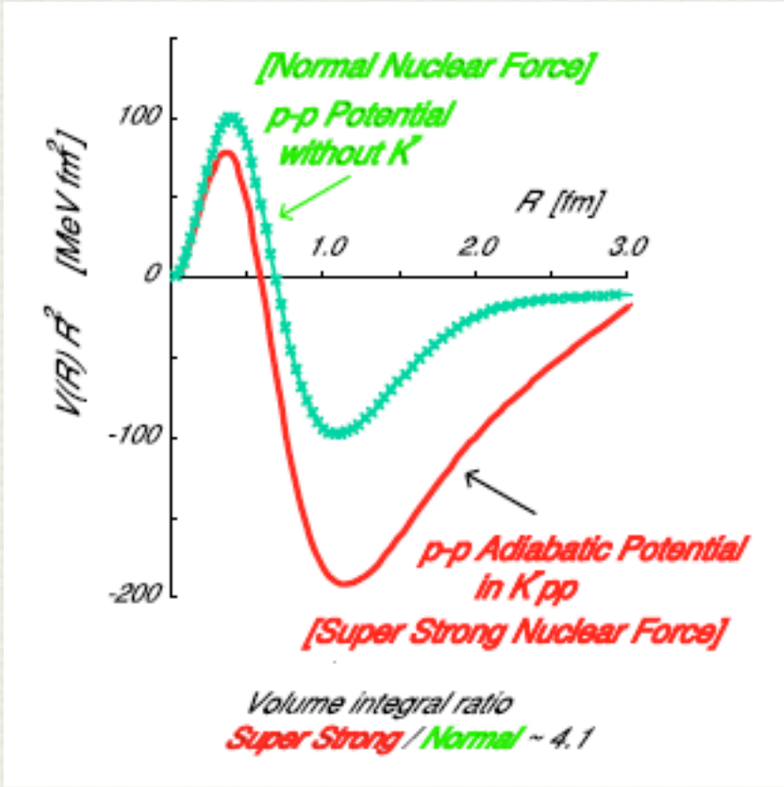




"super-strong nuclear force"
mediated by **real** antikaon



S. Wycech, Nucl.Phys. A450 399 (1986)
T. Yamazaki and Y. Akaishi, Phys Lett. B 535 (2002)
T. Yamazaki and Y. Akaishi, Phys Rev. C 65 (2002)



T. Yamazaki and Y. Akaishi, Proc.JapanAcad.B83:144 (2007)

HADES search for a simplest strange cluster in pp reactions

Most theoretical works predict existence of the bound state.

$B(ppK^-) \approx 14\text{-}80$ MeV
$\Gamma(ppK^-) \approx 40\text{-}110$ MeV/c^2

T. Yamazaki, Y. Akaishi Phys. Rev. C76 (2007)
A. Doté, T. Hyodo, W. Weise Nucl. Phys. A804 (2008)
A. Doté, T. Hyodo, W. Weise Phys. Rev. C79 (2009)
S. Wycech, A. M. Green, Phys. Rev. C79 (2009)
N. Barnea, A. Gal, E. Z. Liverts, Phys. Lett. B712 (2012)
N.V. Shevchenko, A. Gal, J. Mares, Phys. Rev. Lett. 98 (2007)
N.V. Shevchenko, A. Gal, J. Mares, J. Révay, Phys. Rev. C76 (2007)
Y. Ikeda, T. Sato, Phys. Rev. C76 (2007)
Y. Ikeda, T. Sato, Phys. Rev. C79 (2009)
Y. Ikeda, H. Kamano T. Sato, Prog. Theor. Phys. 124 (2010)
E. Oset et al. Nucl. Phys. A881 (2012)

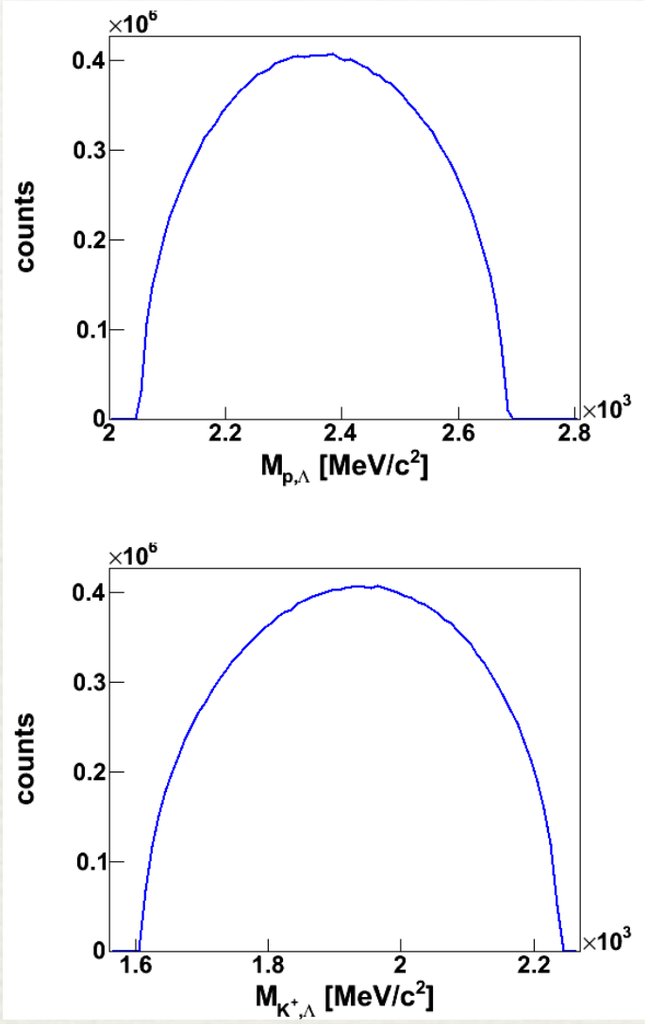
main decay channel “ppK^-” → $p\Lambda$ ⇒ search in pp → $p\Lambda K^+$ at 3.5 GeV

pΛK⁺ analysis with HADES

$$p + p \xrightarrow{3.5GeV} p + K^+ + \Lambda$$

$$p + p \xrightarrow{3.5GeV} N^{*+} + p$$
$$\hookrightarrow \Lambda + K^+$$
$$\hookrightarrow \Sigma^0 + K^+$$

$$p + p \xrightarrow{3.5GeV} \text{"}ppK^-\text{"} + K^+$$
$$\hookrightarrow \Lambda + p$$
$$\hookrightarrow \Sigma^0 + p$$

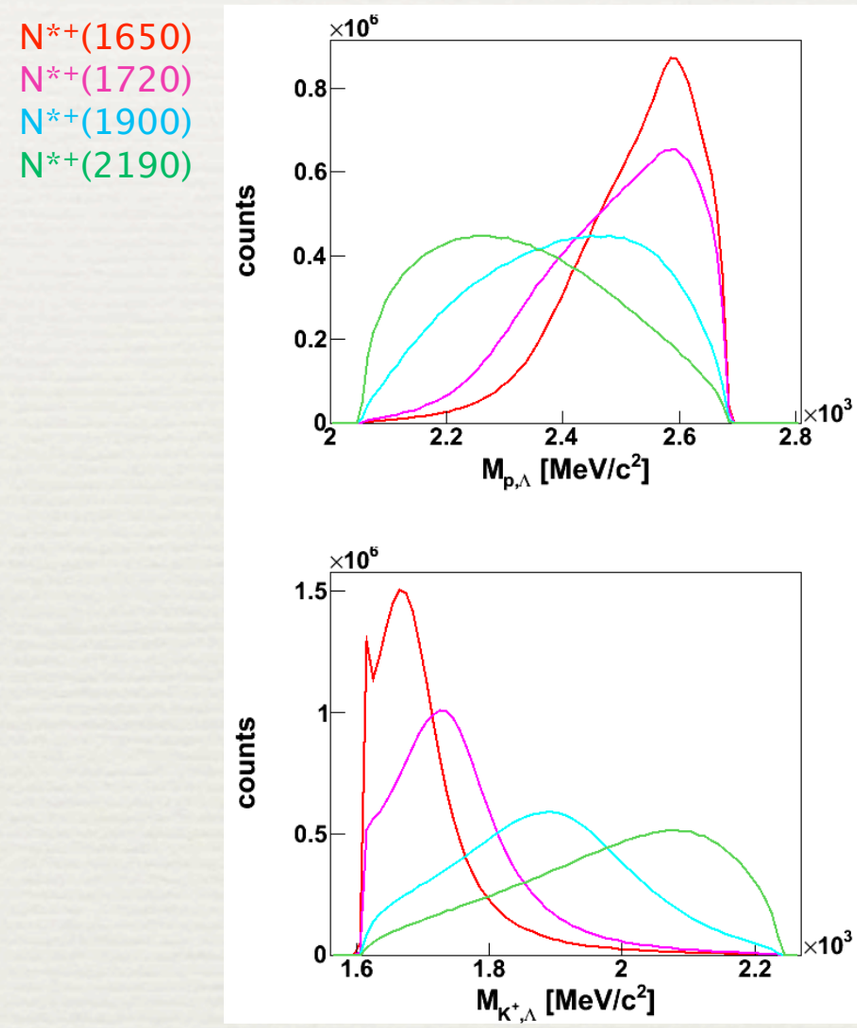


pΛK⁺ analysis with HADES

$$p + p \xrightarrow{3.5GeV} p + K^+ + \Lambda$$

$$p + p \xrightarrow{3.5GeV} N^{*+} + p$$
$$\hookrightarrow \Lambda + K^+$$
$$\hookrightarrow \Sigma^0 + K^+$$

$$p + p \xrightarrow{3.5GeV} \text{"}ppK^-\text{"} + K^+$$
$$\hookrightarrow \Lambda + p$$
$$\hookrightarrow \Sigma^0 + p$$

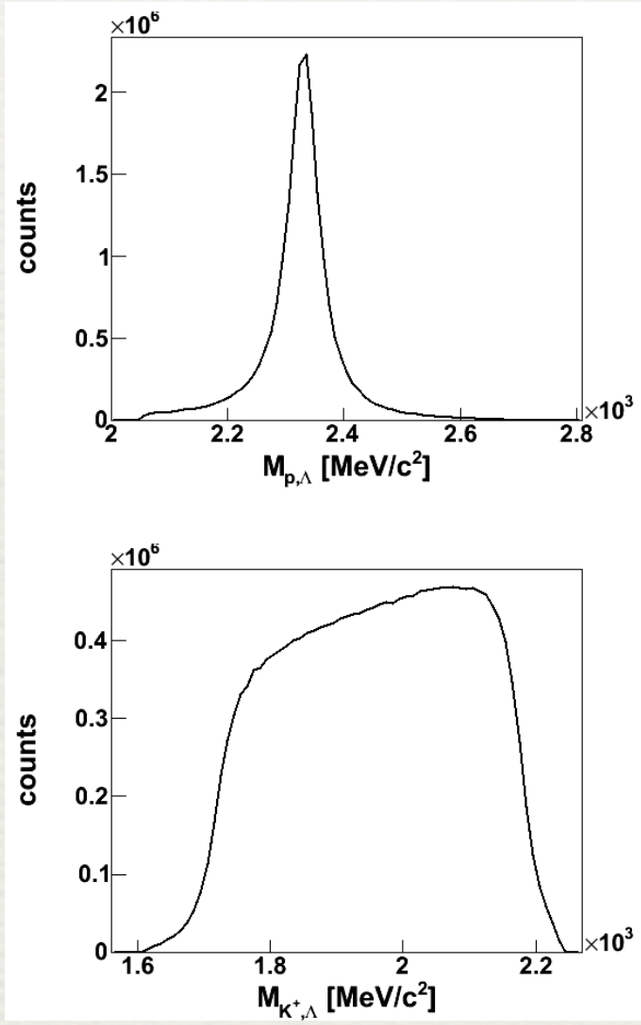


pΛK⁺ analysis with HADES

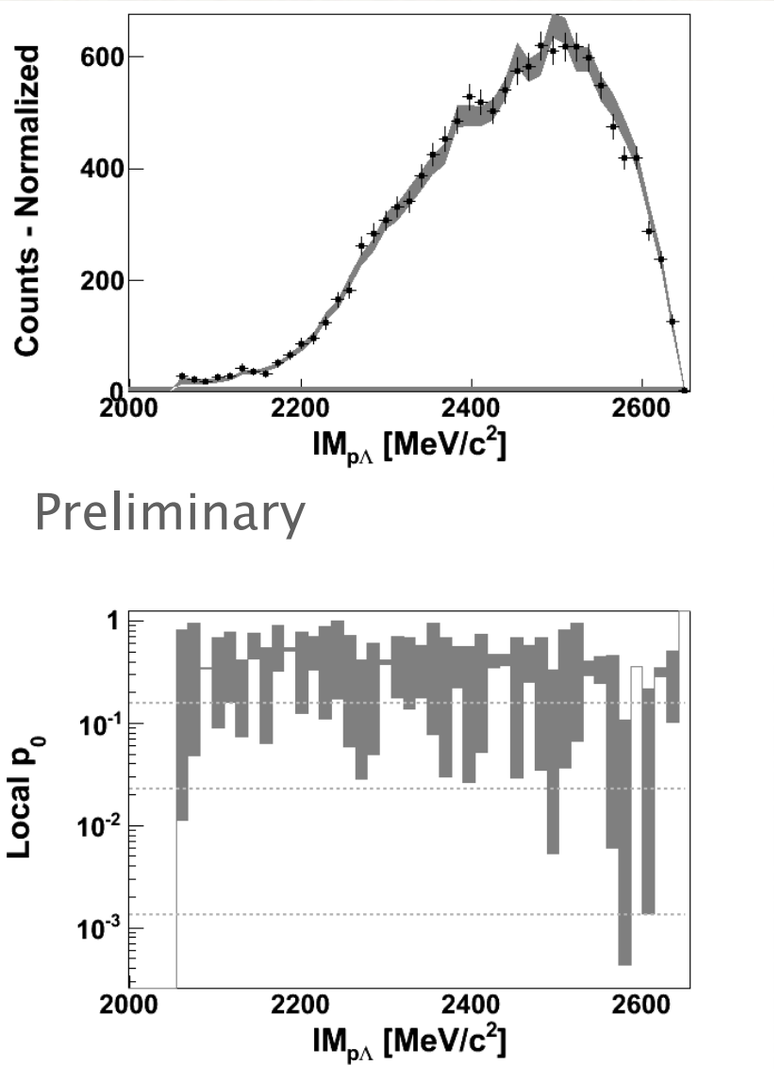
$$p + p \xrightarrow{3.5GeV} p + K^+ + \Lambda$$

$$p + p \xrightarrow{3.5GeV} N^{*+} + p$$
$$\hookrightarrow \Lambda + K^+$$
$$\hookrightarrow \Sigma^0 + K^+$$

$$p + p \xrightarrow{3.5GeV} \text{"}ppK^-\text{"} + K^+$$
$$\hookrightarrow \Lambda + p$$
$$\hookrightarrow \Sigma^0 + p$$



Search for kaonic cluster signal



Partial wave analysis
with the Bonn-Gatchina framework

http://pwa.hiskp.uni-bonn.de/

A.V. Anisovich, V.V. Anisovich, E. Klempt, V.A. Nikonov and A.V. Sarantsev
Eur. Phys. J. A 34, 129152 (2007)

Coherent sum of baryonic resonances
reproduces the spectrum well.

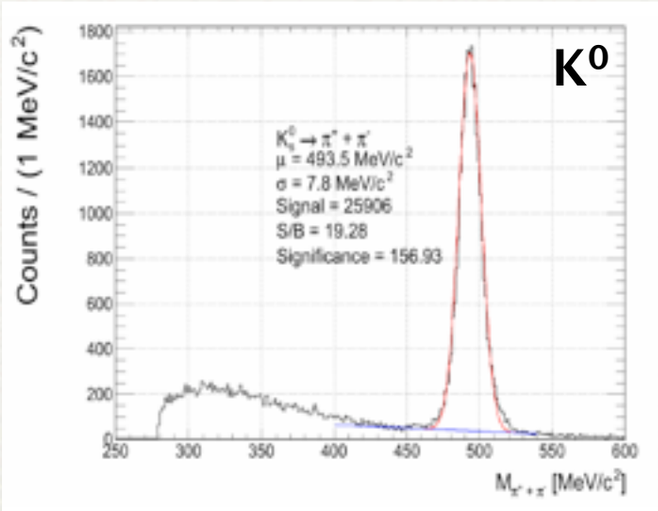
Not much room for the kaonic cluster in
pp at 3.5 GeV.

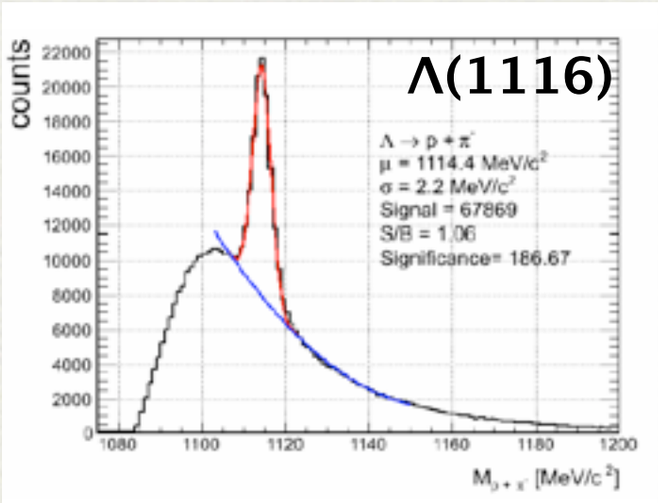
Resonances considered in the solution

Notation in PDG	old	Mass GeV/c^2	Width GeV/c^2	$\Gamma_{\Lambda K}/\Gamma_{All}$
N(1650) $\frac{1}{2}^-$	N(1650)S_{11}	1.655	0.150	3-11%
N(1710) $\frac{1}{2}^+$	N(1710)P_{11}	1.710	0.200	5-25%
N(1720) $\frac{3}{2}^+$	N(1720)D_{13}	1.720	0.250	1-15%
N(1875) $\frac{3}{2}^-$	N(1875)D_{13}	1.875	0.220	?
N(1880) $\frac{1}{2}^+$	N(1880)P_{11}	1.870	0.235	?
N(1895) $\frac{1}{2}^-$	N(1895)S_{11}	1.895	0.090	?
N(1900) $\frac{3}{2}^+$	N(1900)P_{13}	1.900	0.250	0-10%

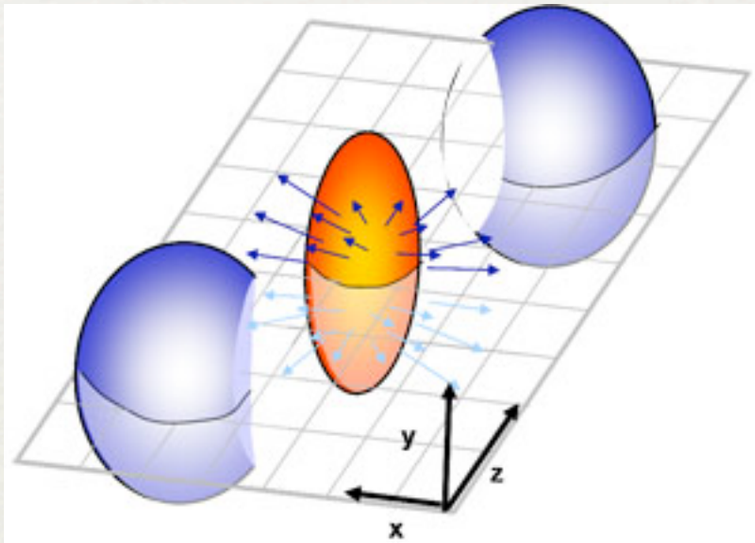
Heavy ion collisions at HADES

May 2012: Au+Au at 1.23 GeV/u





Flow of strangeness w.r.t. reaction plane



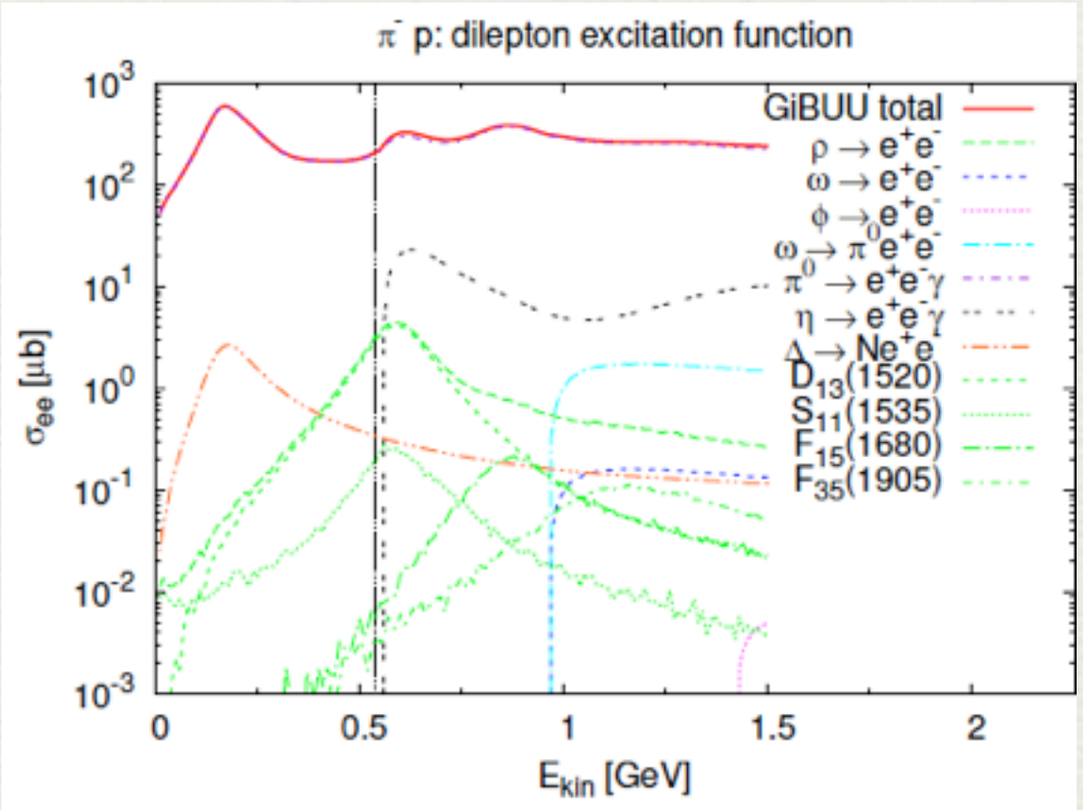
- Reconstruct event-by-event reaction geometry.
- Look at the preferred direction of strangeness emission.
- Infer potentials from the comparison with models.

Experiments with pion beams (2014)

Why pion beam?

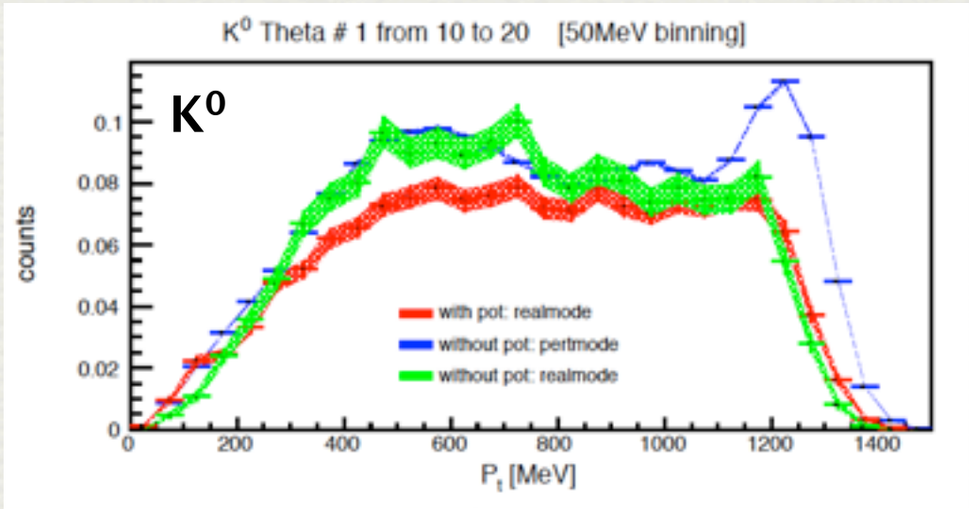
- Continue studies started in pp/pA.
- Light projectile — favorable kinematics for in-medium effects.
- Simpler production mechanisms ($\pi N \to N^* \to e^+e^- + N$; $\pi N \to N^* \to YK$).
- Light and heavy targets (C, Cu, W).

GiBUU simulations

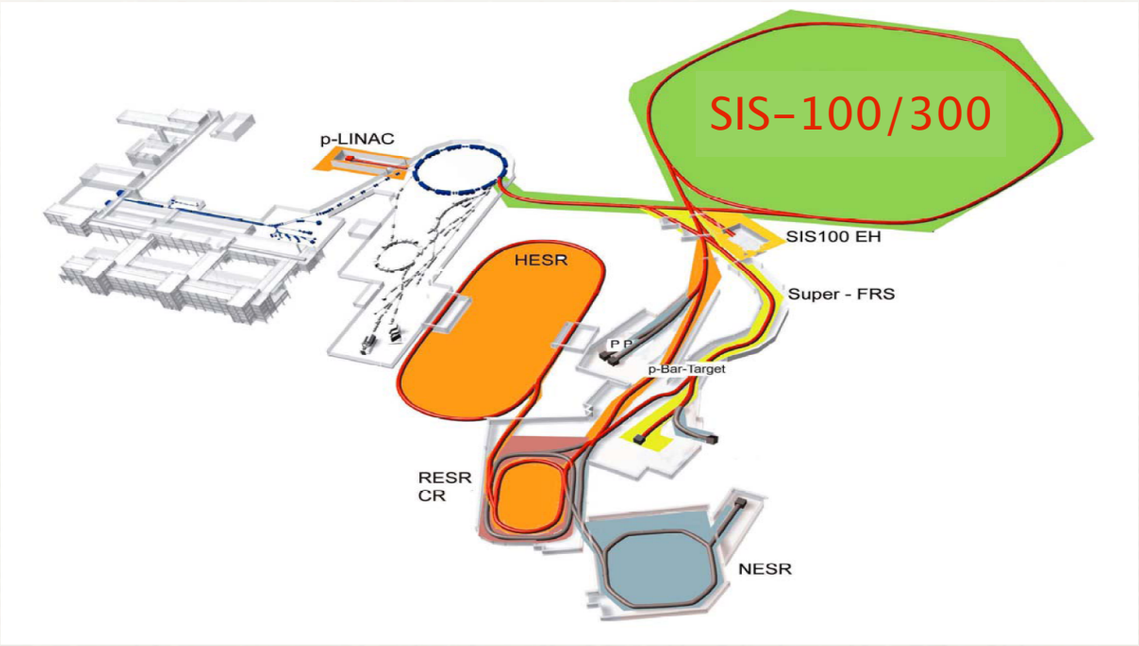


J. Weil, ECT* Workshop 2013

GiBUU simulation πCu at 1.61 GeV

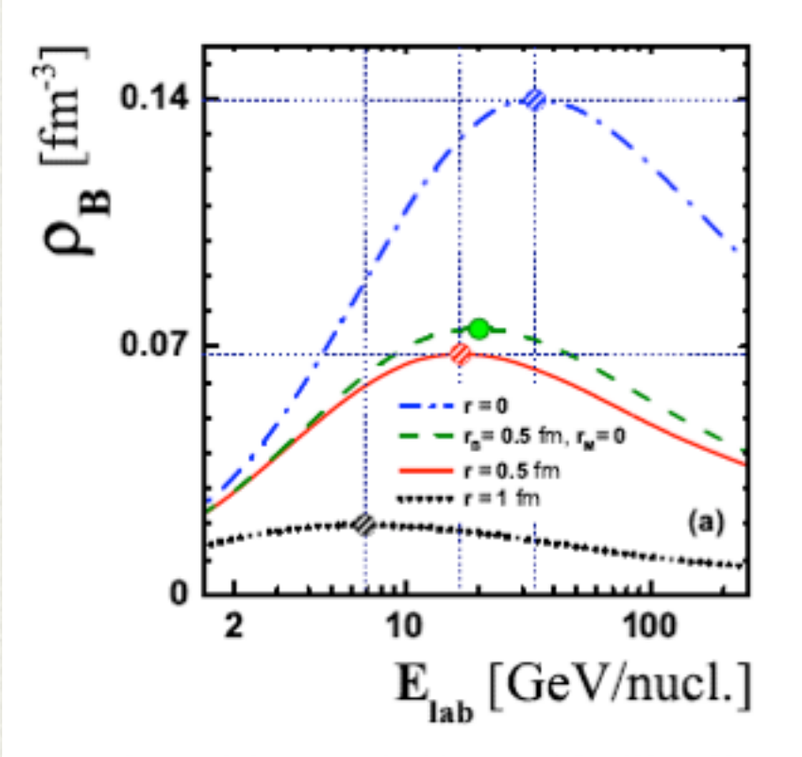


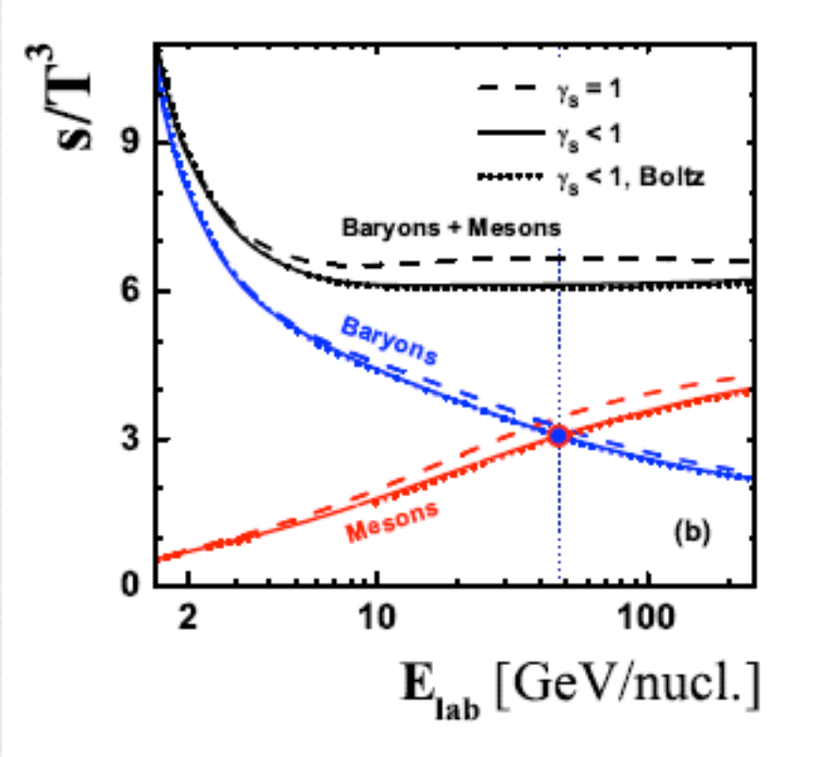
HADES at SIS-100



Hadron properties in dense matter at 2-8 GeV/nucl.
EoS at high baryonic densities

- Vector mesons: production above the threshold
- No dilepton measurements in this energy range
- Multistrange baryons (Ξ, Ω)
- Bridge to CBM, NA61

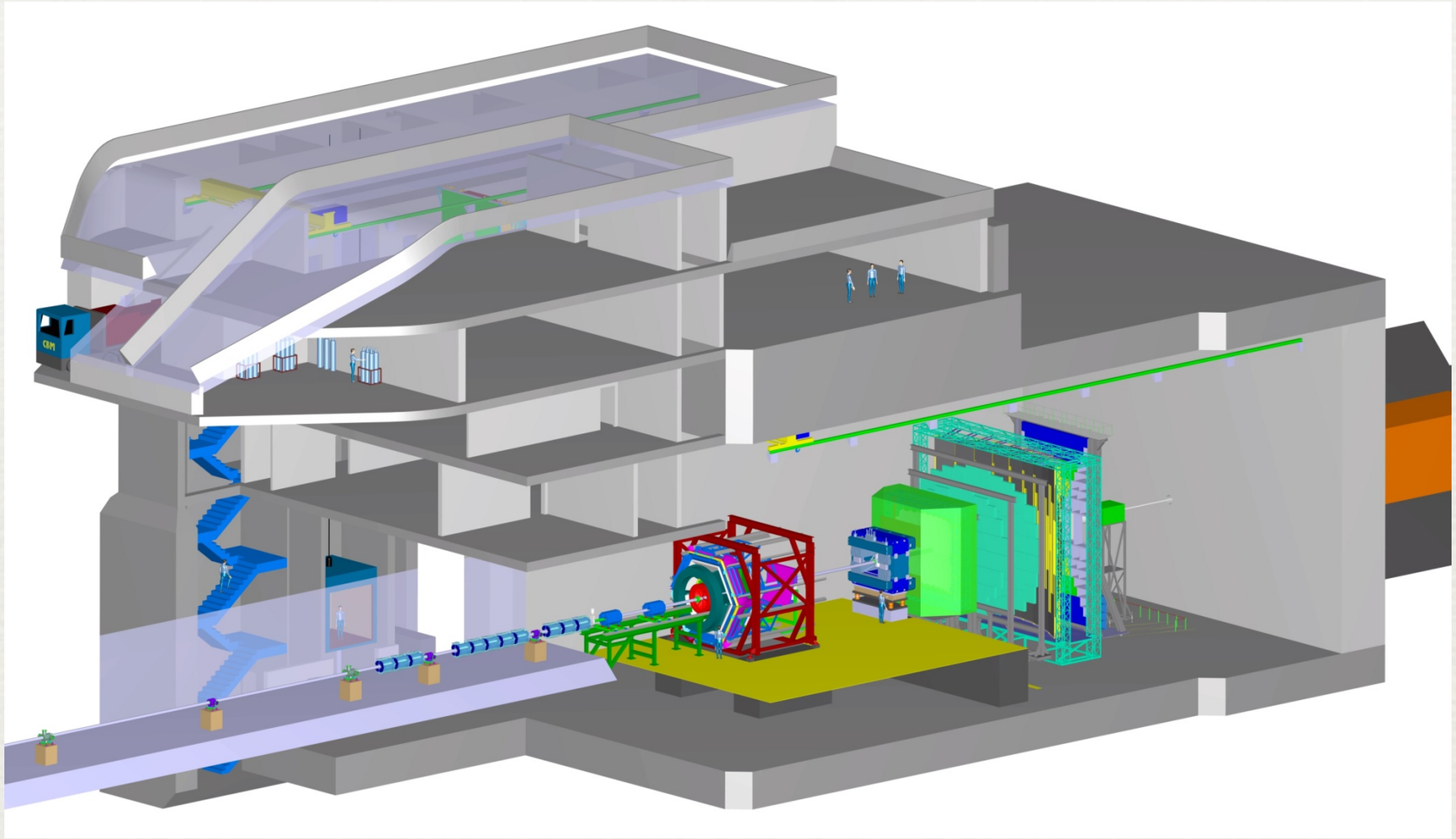




V. V. Begun et al.
Phys. Rev. C 88 (2013) 024902.

HADES at SIS-100

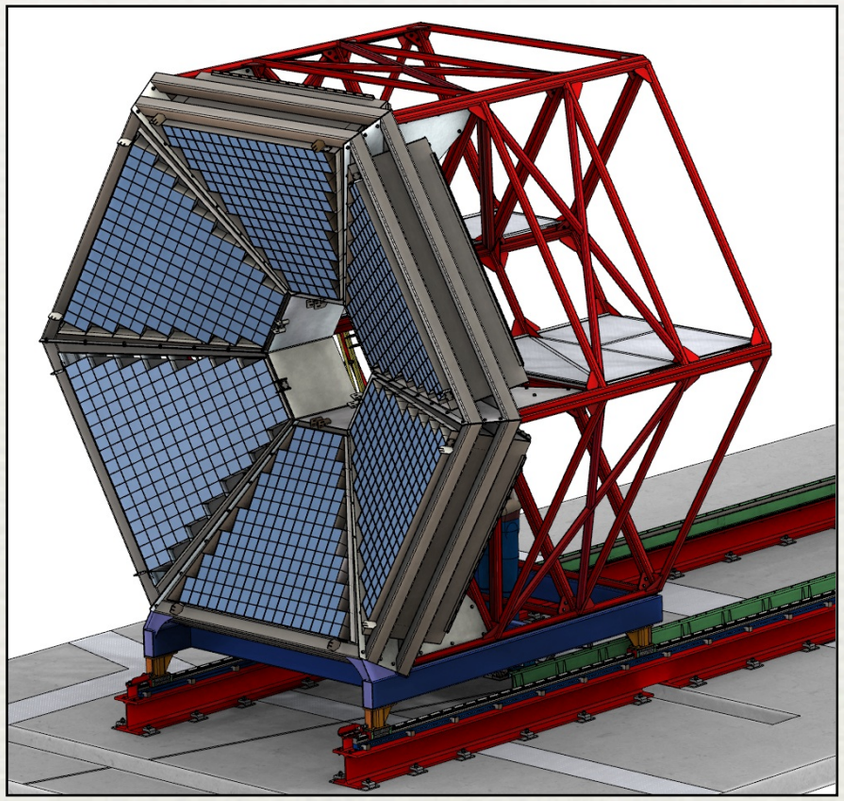
- Detector performance tested with Au+Au at 1.23 GeV

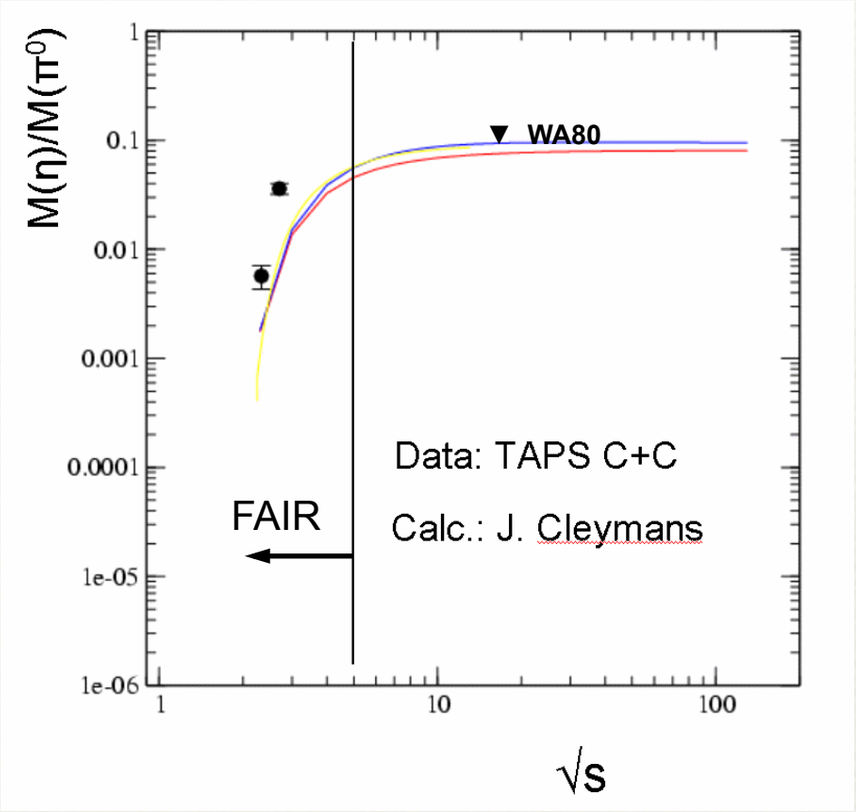


W. Niebur

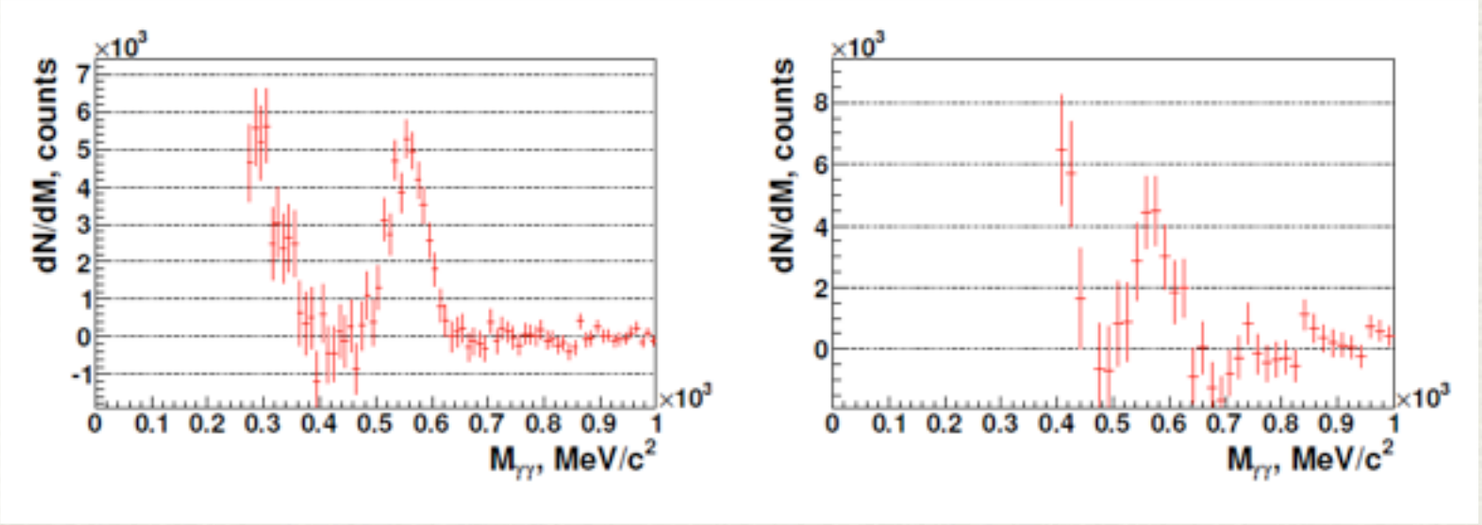
Detector upgrade: lead-glass calorimeter

Motivation
1. Pseudoscalar meson reconstruction.
2. Better e/π-separation at high momenta.





Feasibility study: η-meson in CC and NiNi at 8 GeV/nucl.



(Instead of) Summary

- Measurements of elementary collisions are a vital reference for pA and AA. Rich physics case by itself.

- Resonances are ubiquitous. Does it change at SIS-100 energies? How to model the particle production in the transition region?

- Dileptons&strangeness: same transport frameworks but different underlying models. Unified description?

- Pion beam program: elementary channels and in-medium effects.

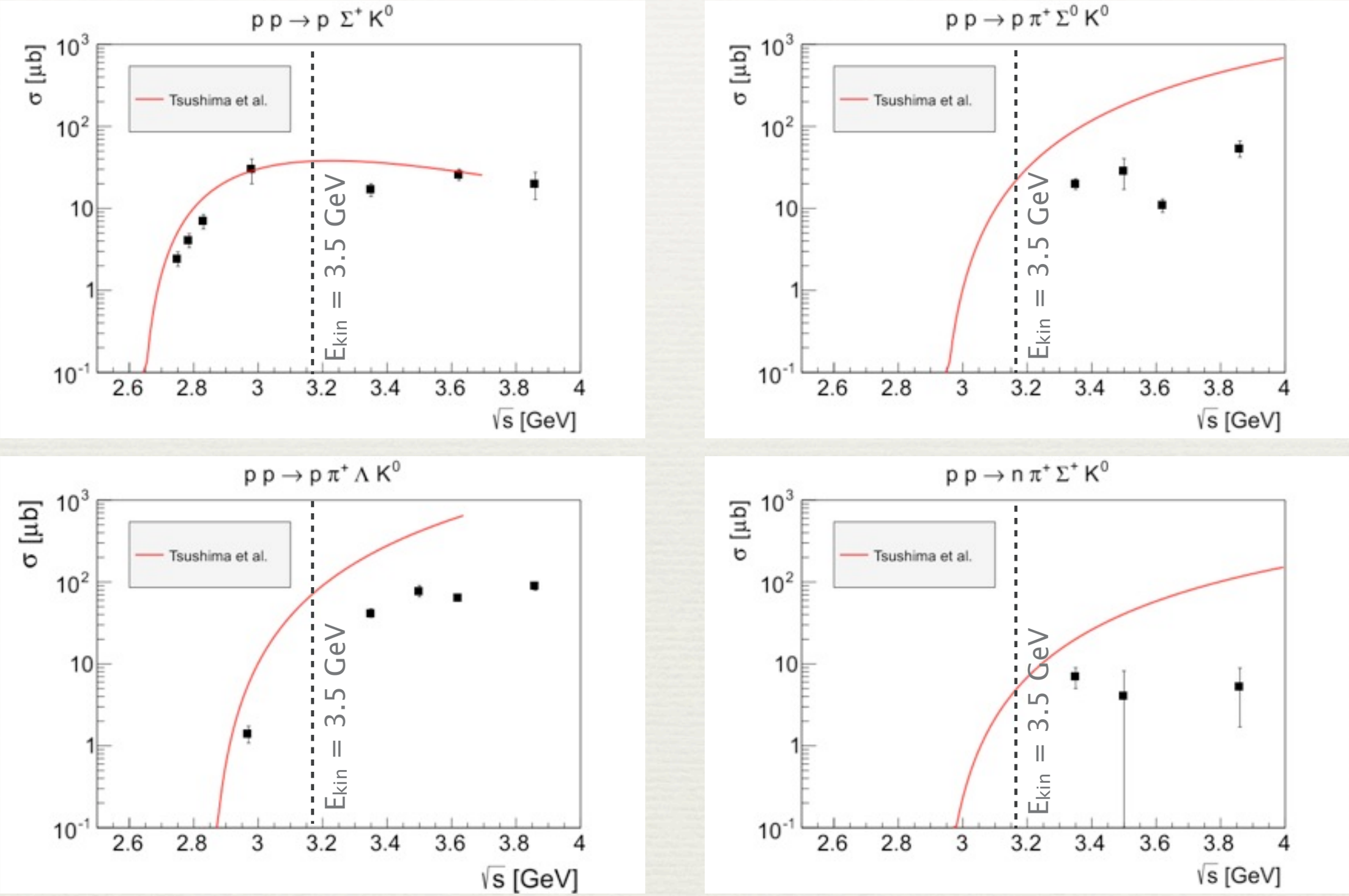
- SIS-100: measurements at densities relevant for neutron stars.

The 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

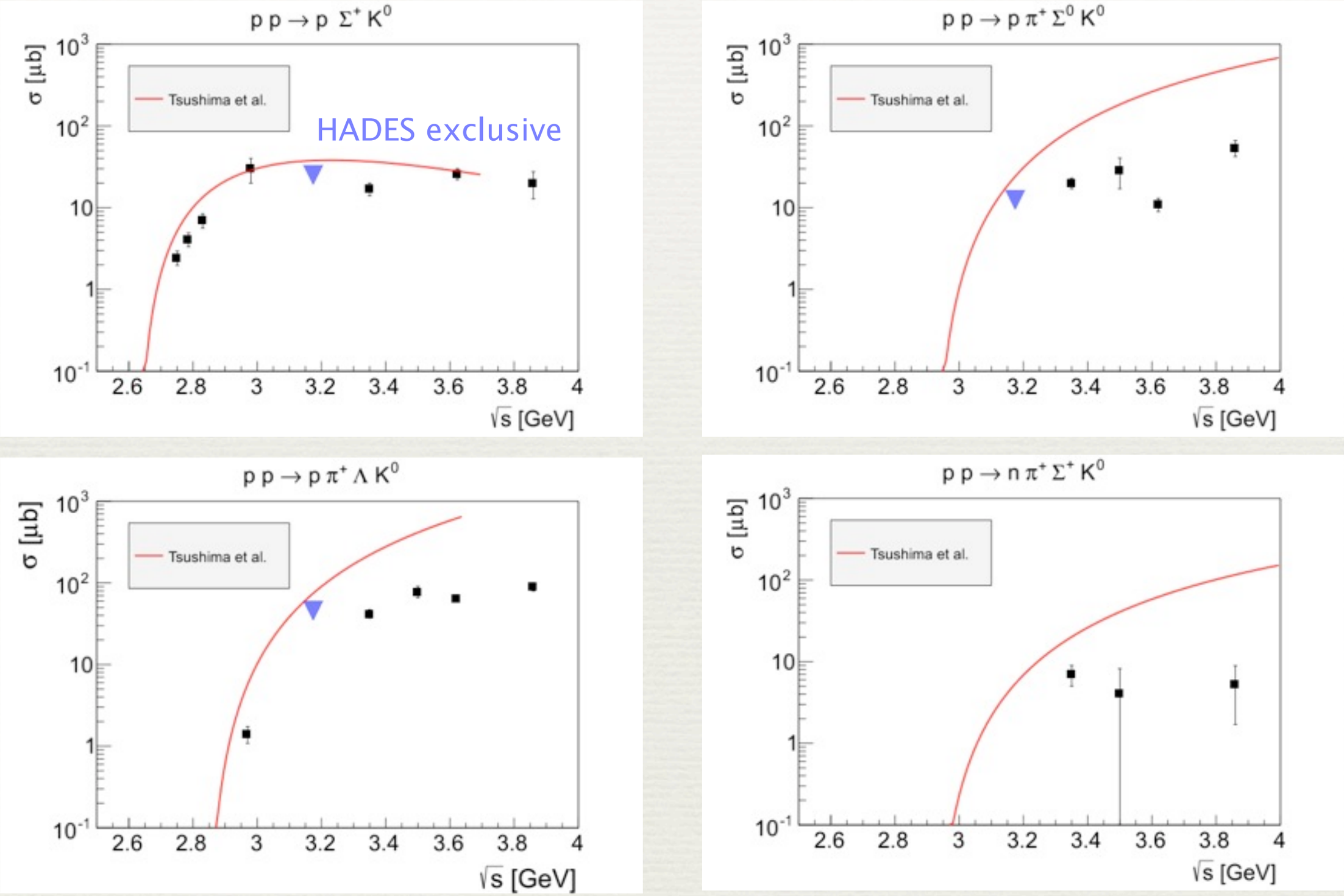
Extra slides

How well the resonance model works for K^0 in pp?



- All exclusive channels are overestimated by the model

Exclusive measurements by HADES

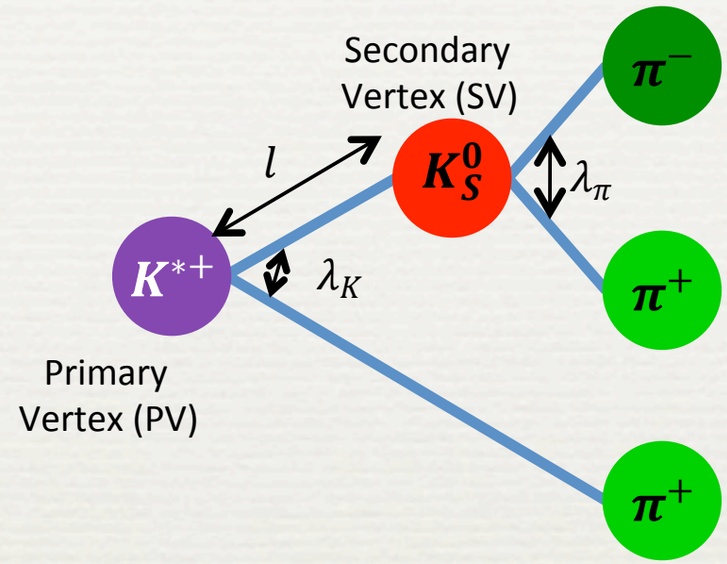


- Exclusive analyses (done by J.-C. Berger-Chen) set further constraints, sensitive to the contribution of resonances Δ(1232), Σ(1385) in final states

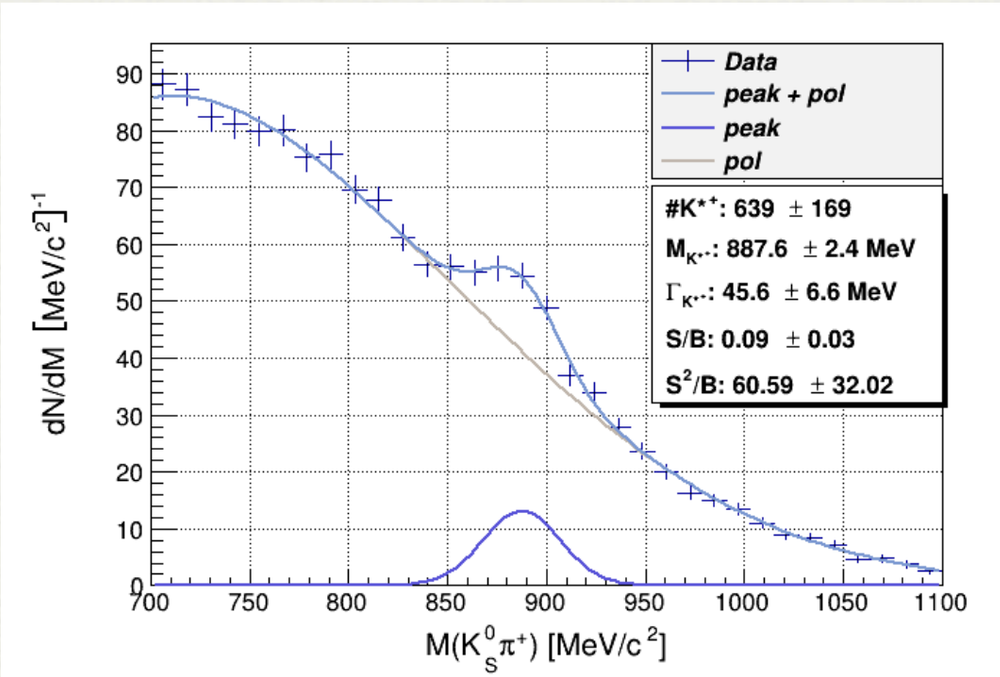
Outlook: K*(892)

Analysis by Dimitar Mihaylov

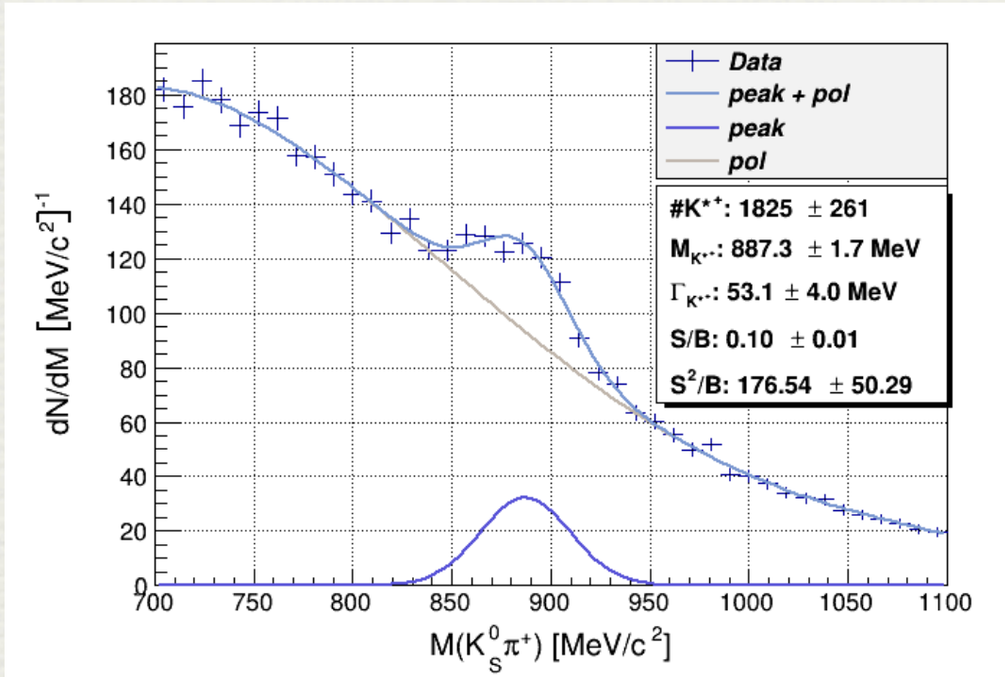
- Short-lived kaon-pion resonance
- In-nucleus decay possible



p+p



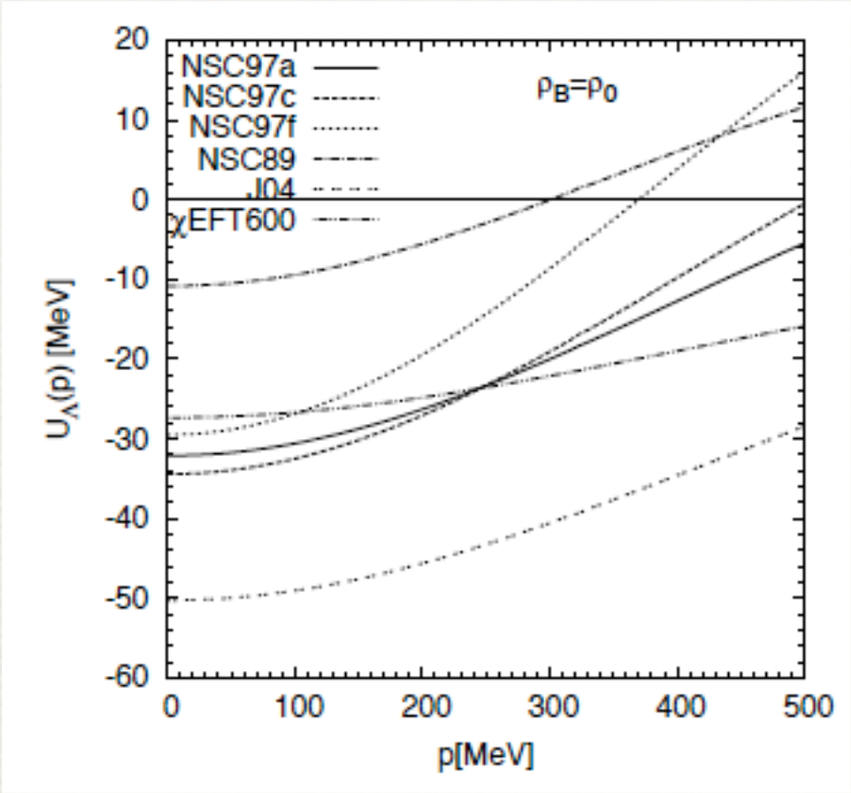
p+Nb



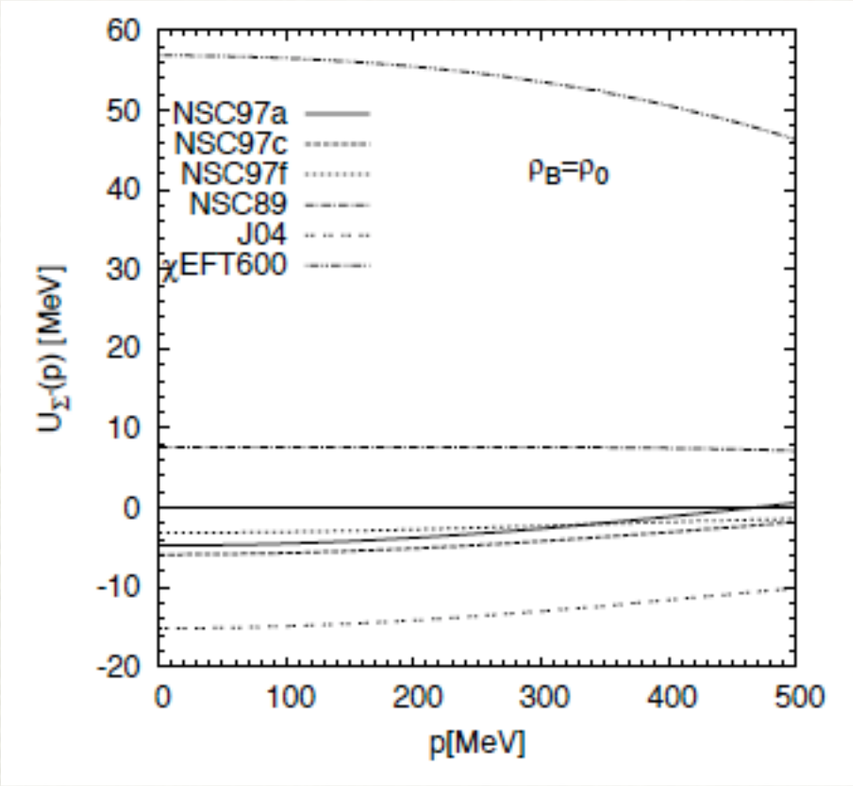
Strange baryons in medium

Momentum dependency of the in-medium energy

Λ(1116)



Σ⁻(1197)



Resonance model: channel decomposition

Original resonance model

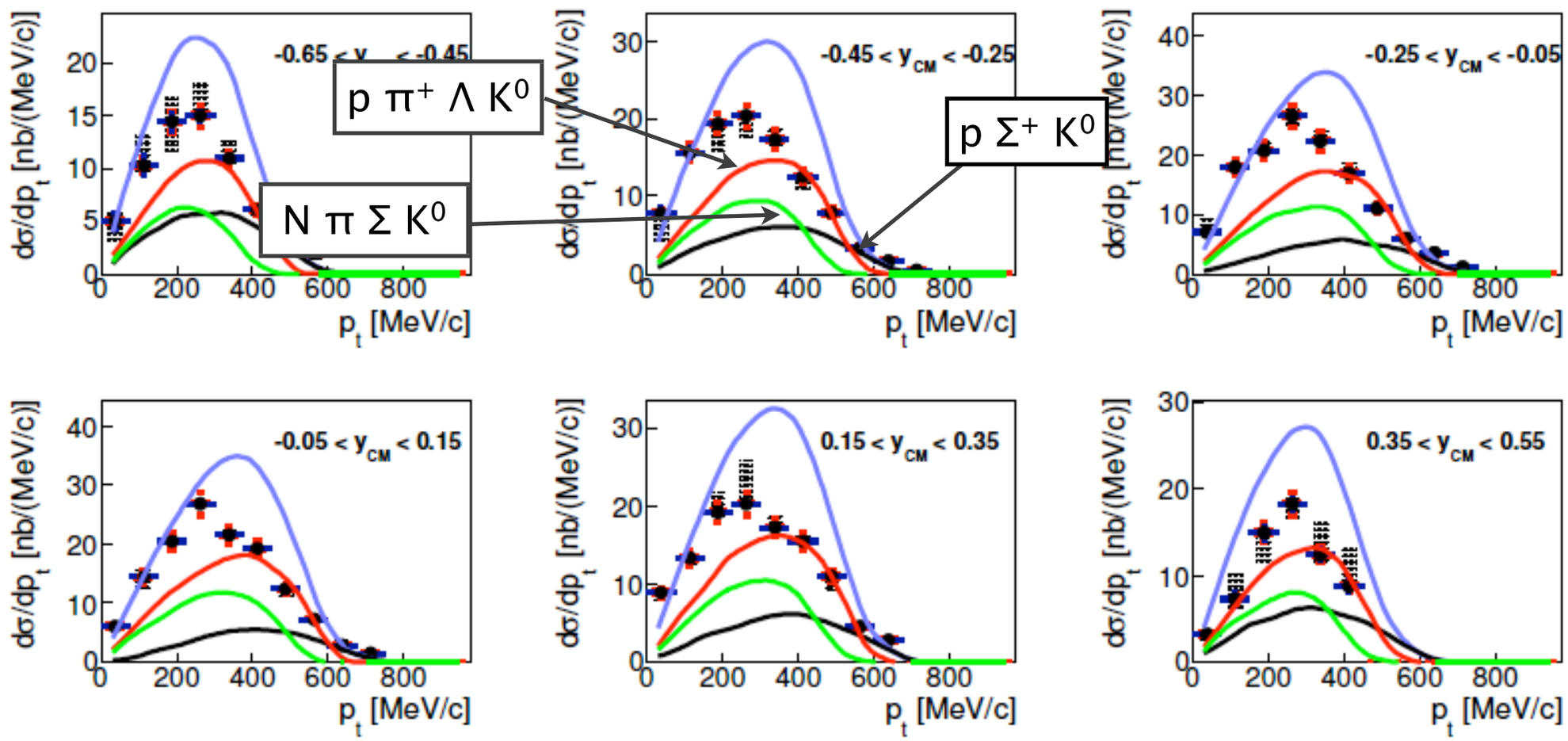
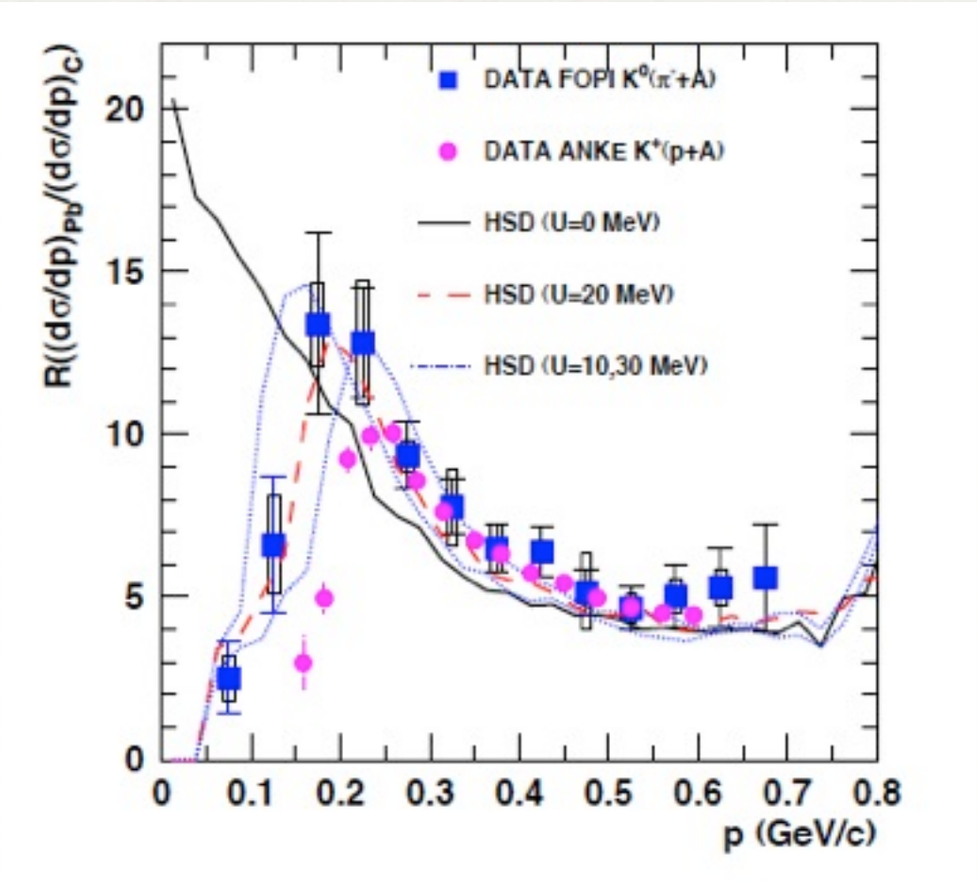


FIG. 36. K^0_S transverse momentum spectra in $p+p$ collisions (black circles) and GiBUU transport model simulations within the **original** resonance model by Tsushima *et al.* [3]. Blue line shows the total contribution of all K^0 production channels included in the model. Individual contributions are: $pp \to p\Sigma^+K^0$ (black), $pp \to p\pi^+\Lambda K^0$ (red), $pp \to p\pi\Sigma K^0$ (green).

How to observe the kaon in-medium potential

General idea: look at the kinematics of escaped kaons

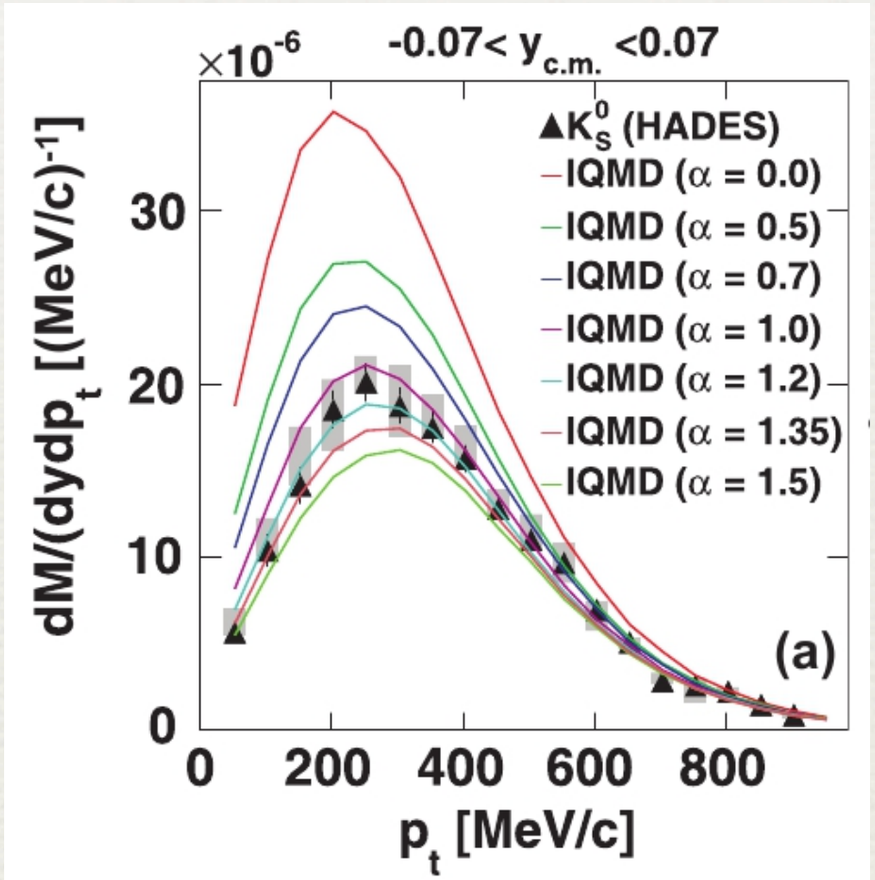
FOPI π+A, ANKE p+A



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

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

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



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

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

Resonance model: channel decomposition

Original resonance model

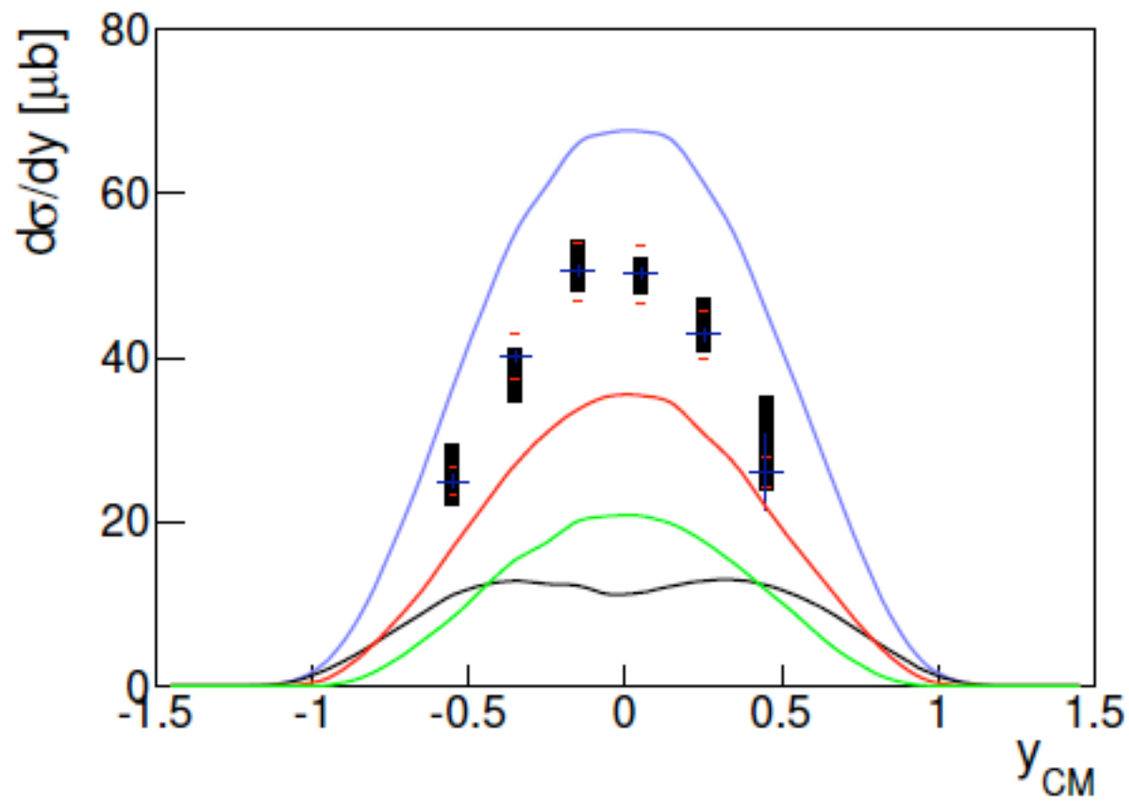


FIG. 37. K^0_S rapidity distribution in $p+p$ collisions (black circles) and GiBUU transport model simulations within the **original** resonance model by Tsushima *et al.* [3]. Blue line shows the total contribution of all K^0 production channels included in the model. Individual contributions are: $pp \to p\Sigma^+K^0$ (black), $pp \to p\pi^+\Lambda K^0$ (red), $pp \to p\pi\Sigma K^0$ (green).

Resonance model: channel decomposition

Modified resonance model

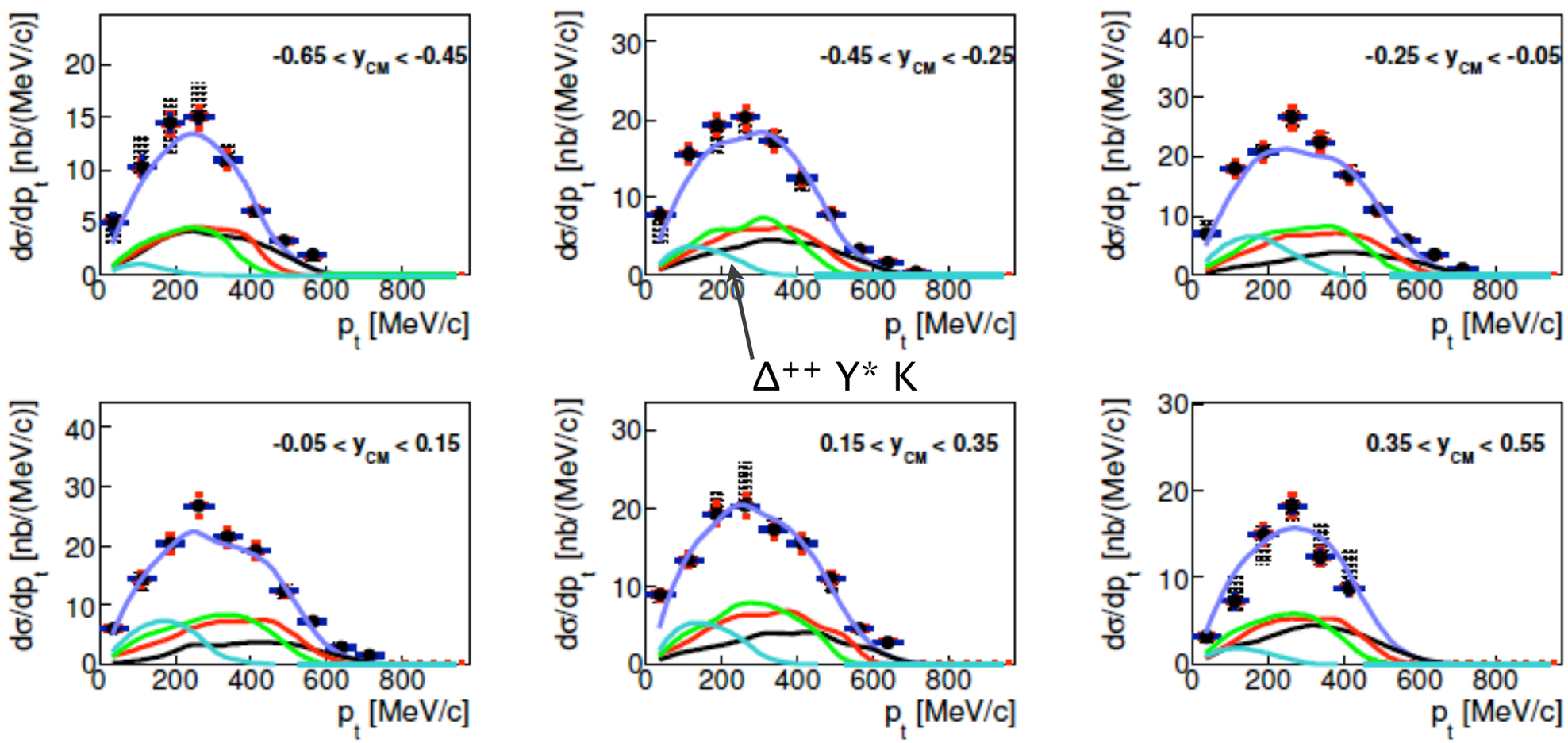


FIG. 38. K^0_S transverse momentum spectra in $p+p$ collisions (black circles) and GiBUU transport model simulations within the **tuned and modified** resonance model. Blue line shows the total contribution of all K^0 production channels included in the model. Individual contributions are: $pp \to p\Sigma^+K^0$ (black), $pp \to p\pi^+\Lambda K^0$ (red), $pp \to p\pi\Sigma K^0$ (green), $pp \to N\pi\pi Y K^0$ (cyan). In the last reaction N denotes proton or neutron and Y denotes Λ or Σ.

Resonance model: channel decomposition

Modified resonance model

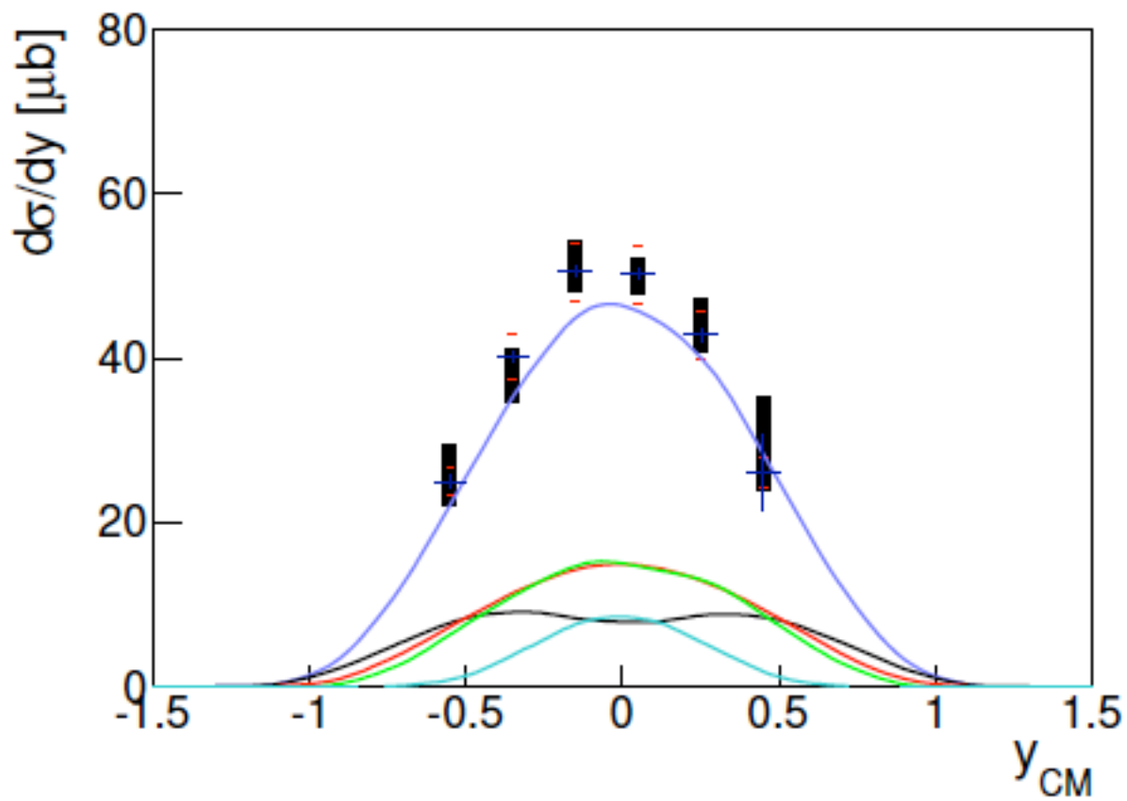


FIG. 39. K^0_S rapidity distribution in $p+p$ collisions (black circles) and GiBUU transport model simulations within the **tuned and modified** resonance model. Blue line shows the total contribution of all K^0 production channels included in the model. Individual contributions are: $pp \to p\Sigma^+K^0$ (black), $pp \to p\pi^+\Lambda K^0$ (red), $pp \to p\pi\Sigma K^0$ (green), $pp \to N\pi\pi Y K^0$ (cyan). In the last reaction N denotes proton or neutron and Y denotes Λ or Σ.

Table with cross sections

TABLE V. Cross sections for K^0 production channels in p+p collisions at $E_{beam}^{kin.} = 3.5$ GeV. All values are in μb. The numbers in brackets are scaling factors that should be applied to the values given by the resonance model (Tsushima *et al.*).

Reaction, $p + p \rightarrow$	Tsushima resonance model	Exclusive measurement	Inclusive measurement
$p + \Sigma^+ + K^0$	37.8	26.2 (0.69)	26.5 (0.70)
$p + \pi^+ + \Lambda + K^0$	75.9	44.5 (0.59)	31.9 (0.42)
$p + \pi^+ + \Sigma^0 + K^0$	24.6	11.5 (0.47)	17.7 (0.72)
$p + \pi^0 + \Sigma^+ + K^0$	10.9	n/a	7.8 (0.72)
$n + \pi^+ + \Sigma^+ + K^0$	5.5	n/a	3.9 (0.72)
$\Delta^{++} + \Lambda(1405) + K^0$	n/a	n/a	5.3
$\Delta^{++} + \Sigma(1385)^0 + K^0$	n/a	n/a	3.5
$\Delta^+ + \Sigma(1385)^+ + K^0$	n/a	n/a	2.3

p-θ spectra: secondary processes

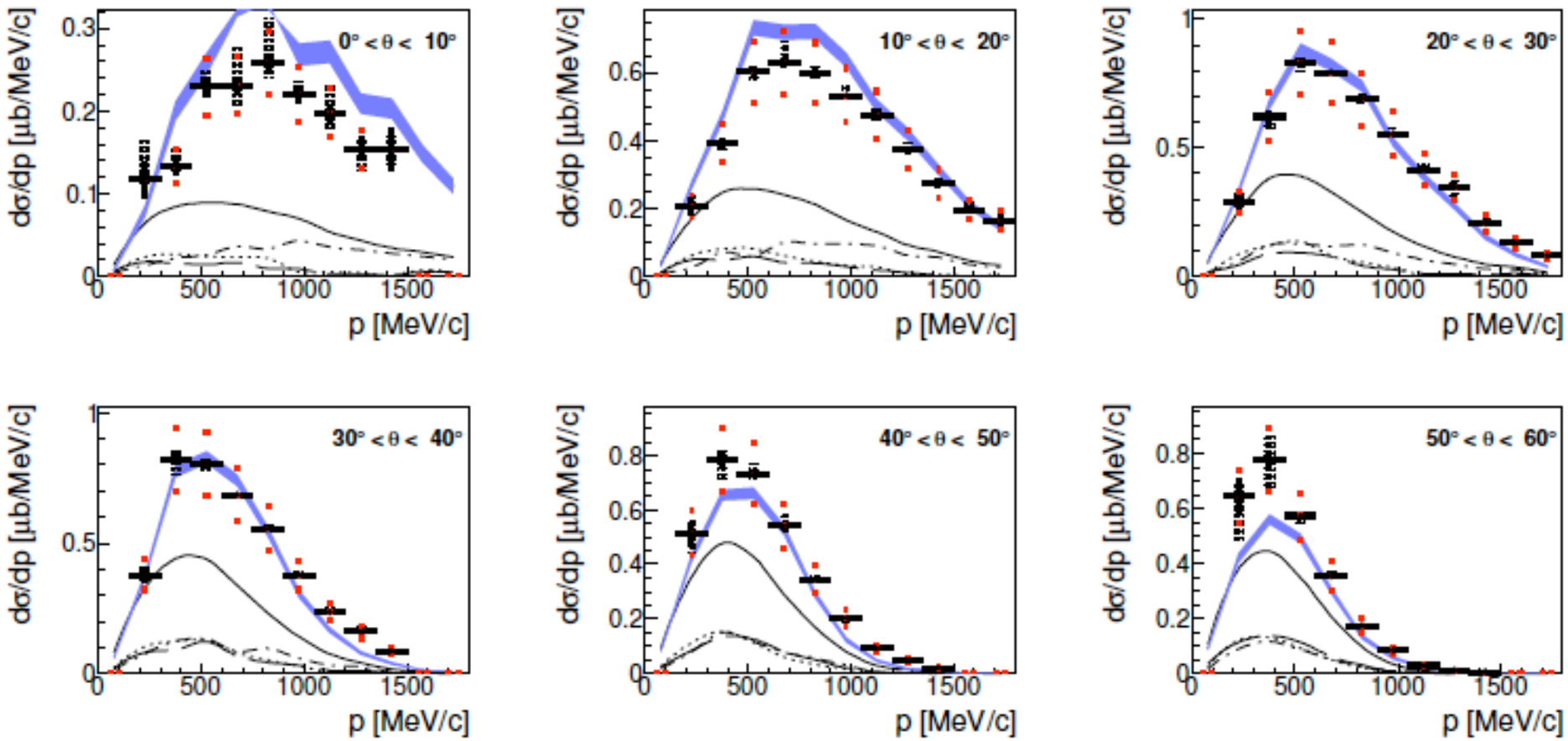


FIG. 43. K^0_S momentum spectra in p+Nb collisions (black circles) and GiBUU transport model simulations. Black solid line shows the total contribution of all K^0 sources *besides pp* and *np* collisions: ΔN- (dash-dotted line), πN-reactions (dotted line) and a contribution from K^+N-scattering accompanied with a charge exchange (dashed line).

R_{pA}: experiment vs. GiBUU

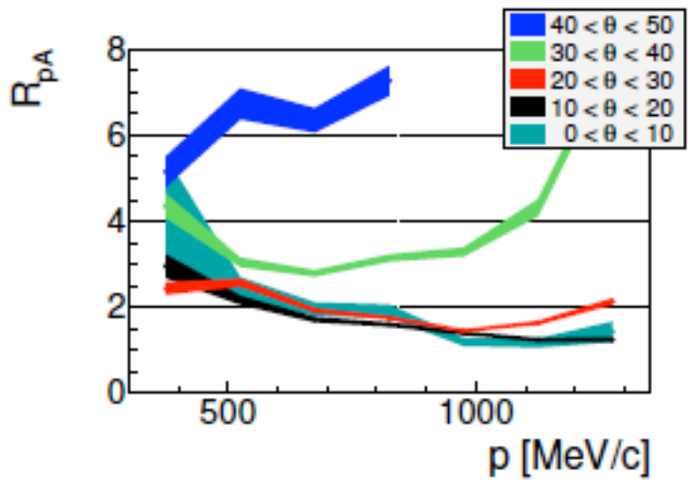


FIG. 54. Nuclear modification factor $R_{pA}(p) \propto \sigma^{K^0}_{pNb}/\sigma^{K^0}_{pp}$ **(experimental data)**

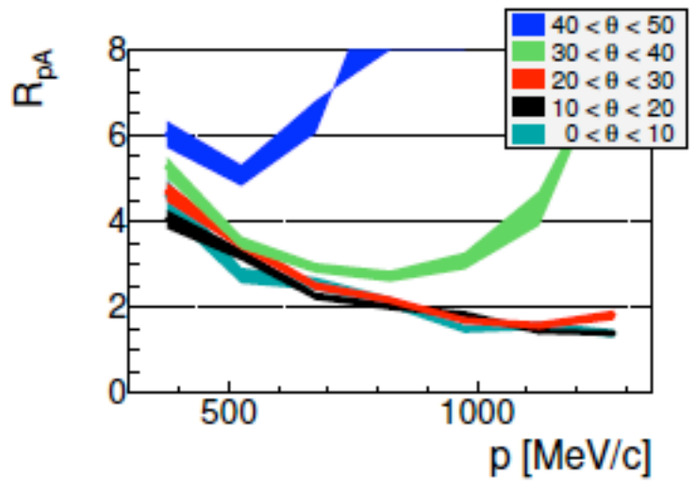


FIG. 55. Nuclear modification factor $R_{pA}(p) \propto \sigma^{K^0}_{pNb}/\sigma^{K^0}_{pp}$ as simulated with the GiBUU transport model. **The in-medium ChPT KN potential is OFF.** Only statistical uncertainties are shown

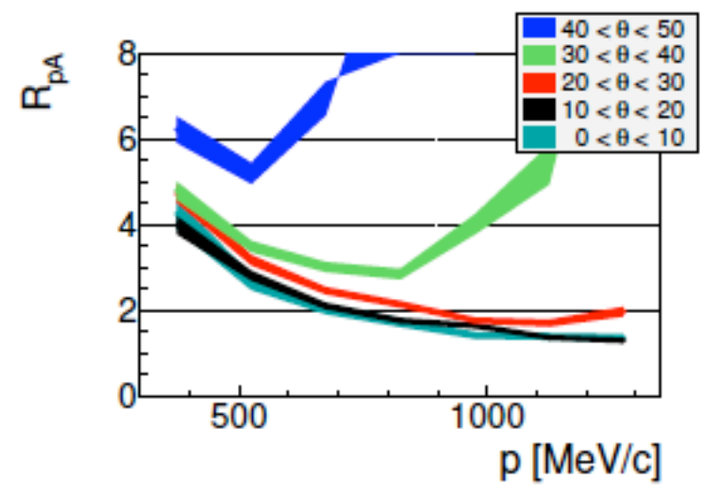
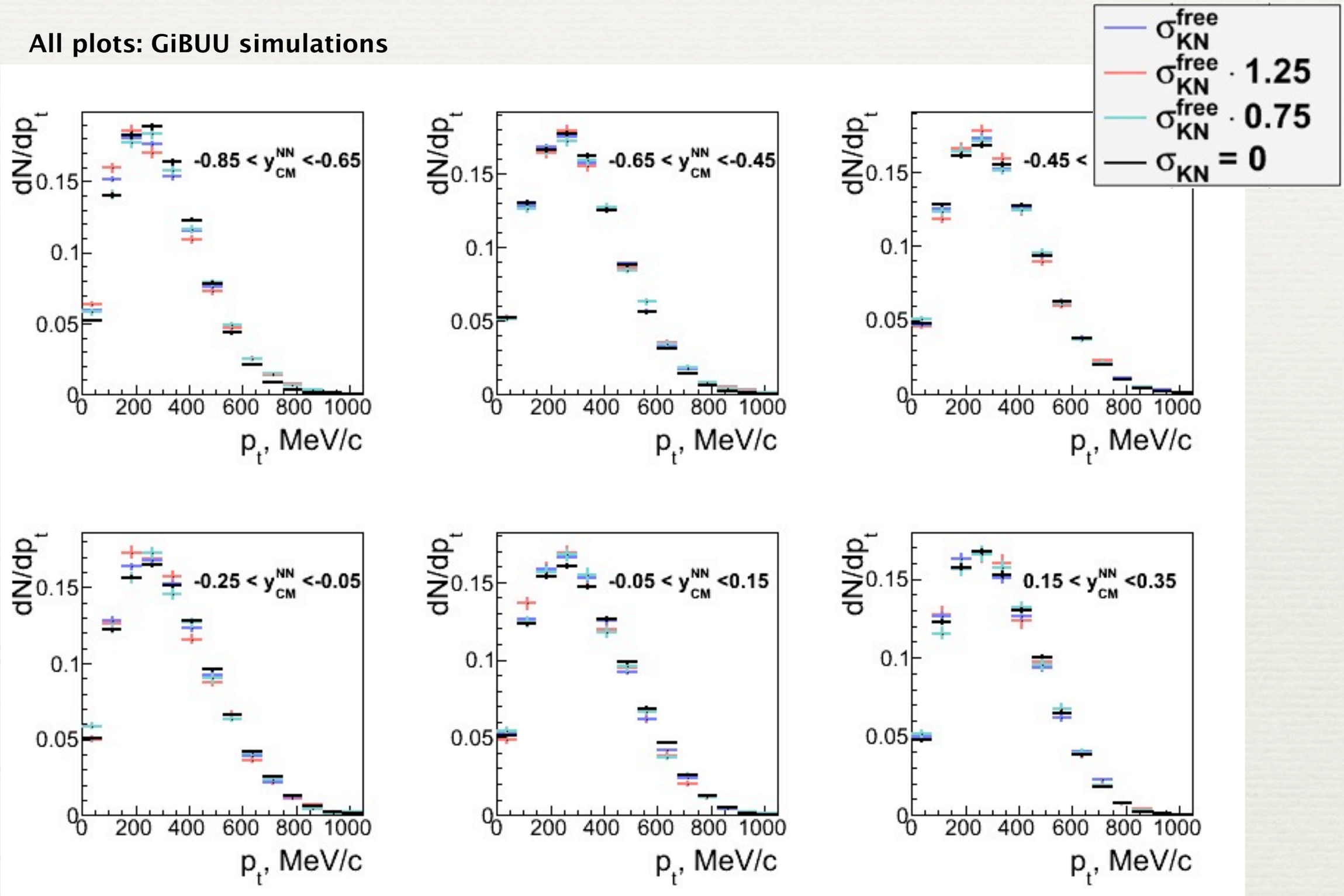


FIG. 56. Nuclear modification factor $R_{pA}(p) \propto \sigma^{K^0}_{pNb}/\sigma^{K^0}_{pp}$ as simulated with the GiBUU transport model. **The in-medium ChPT KN potential is ON.** Only statistical uncertainties are shown

KN scattering: effect on p_t distributions in pNb

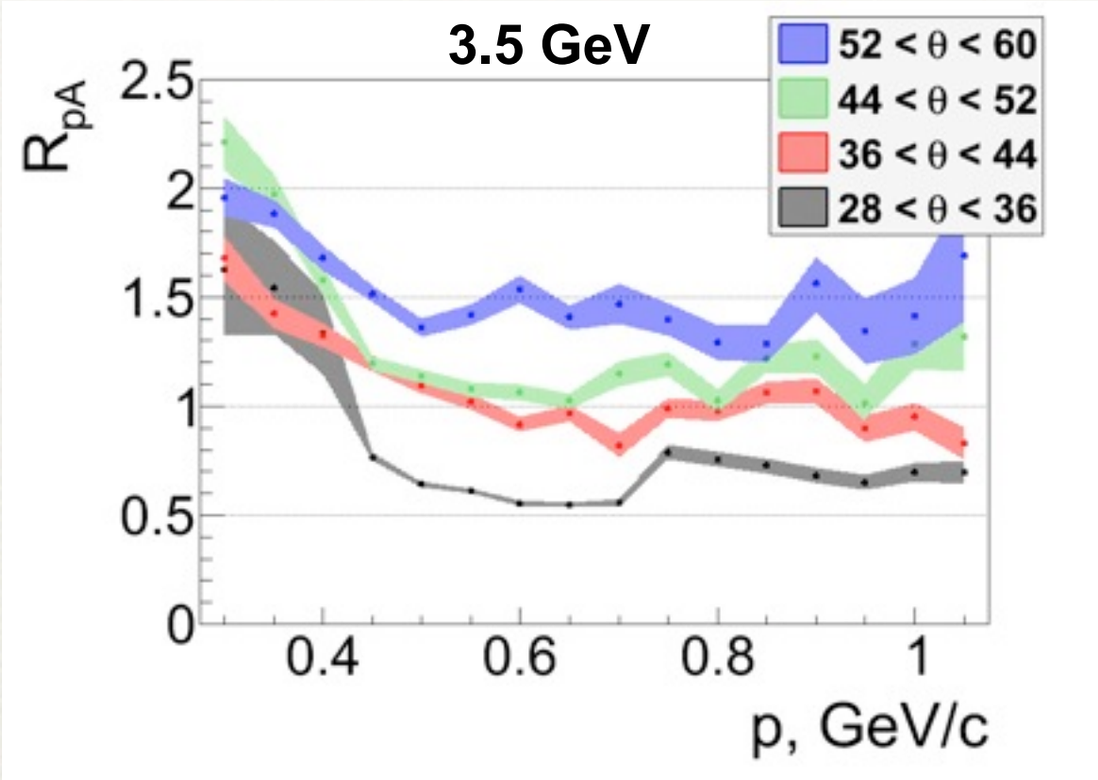
All plots: GiBUU simulations

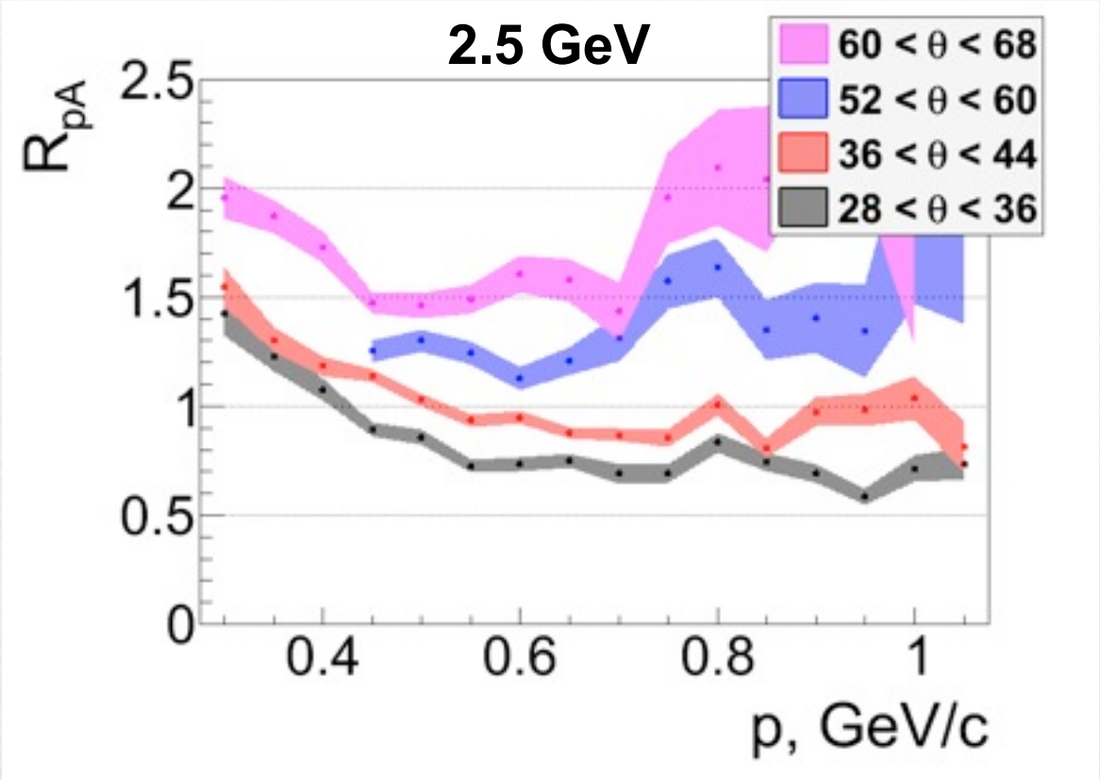


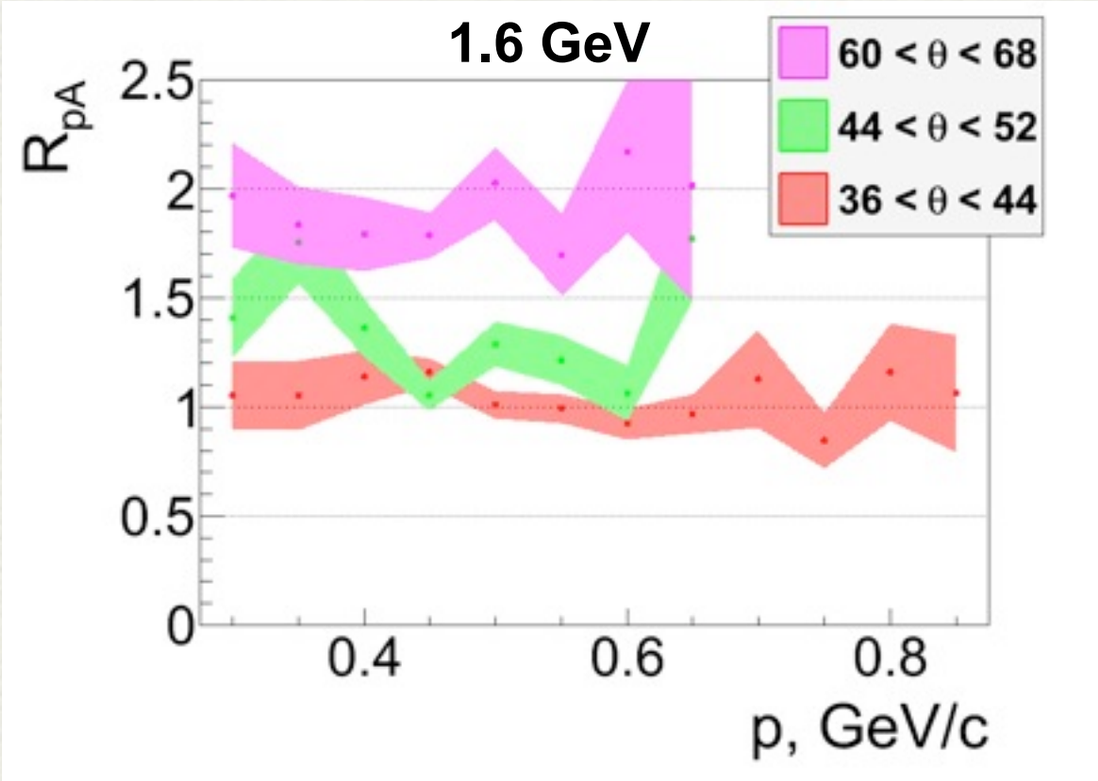
- Spectra in each rapidity bin are normalized to the same area.
- **Shape** of p_t-spectra is **not sensitive** to the KN scattering.

KaoS R_{pA}

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







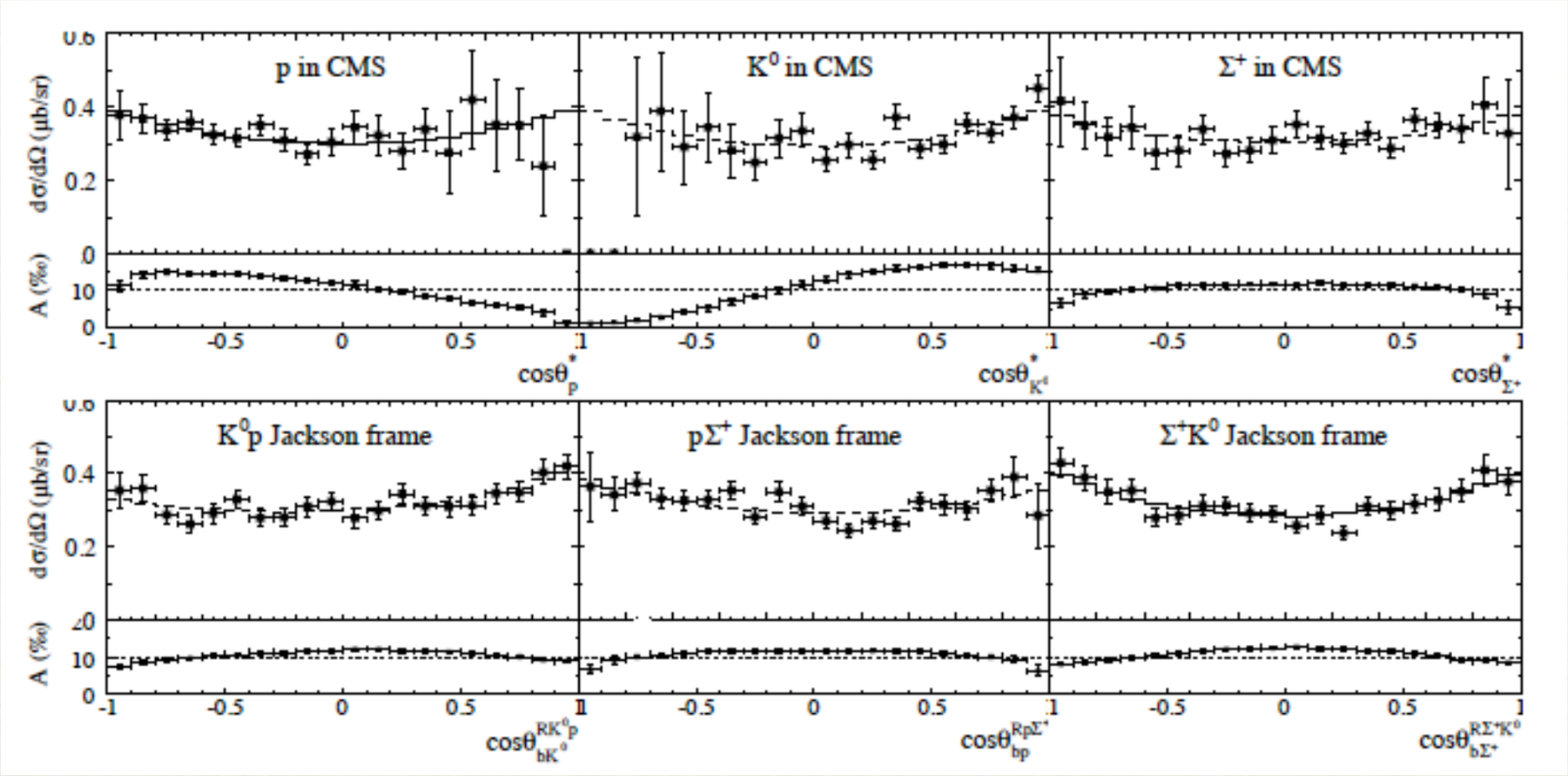
Bands show stat. uncertainties only.

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

Kaon production anisotropy

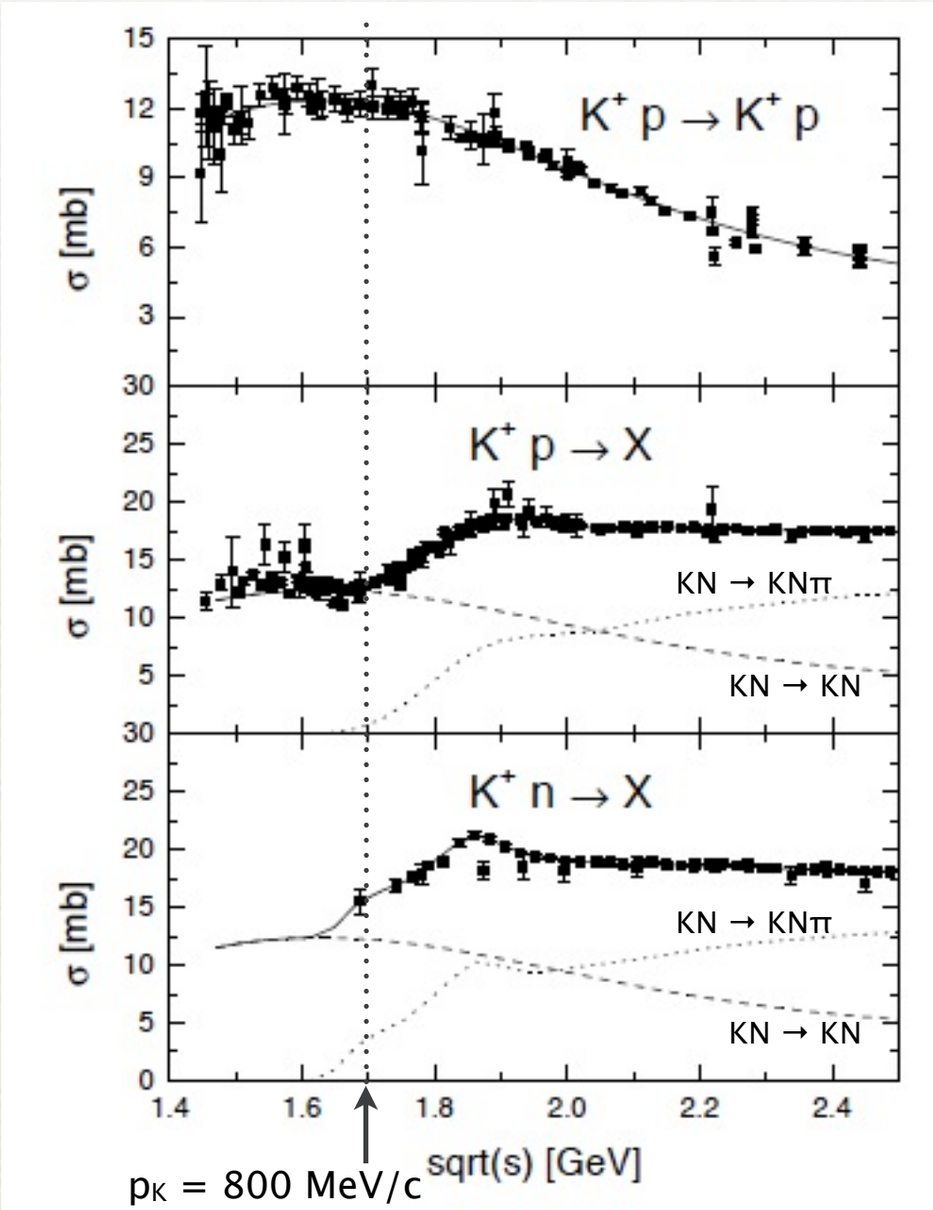
$pp \to pK^0\Sigma^+$



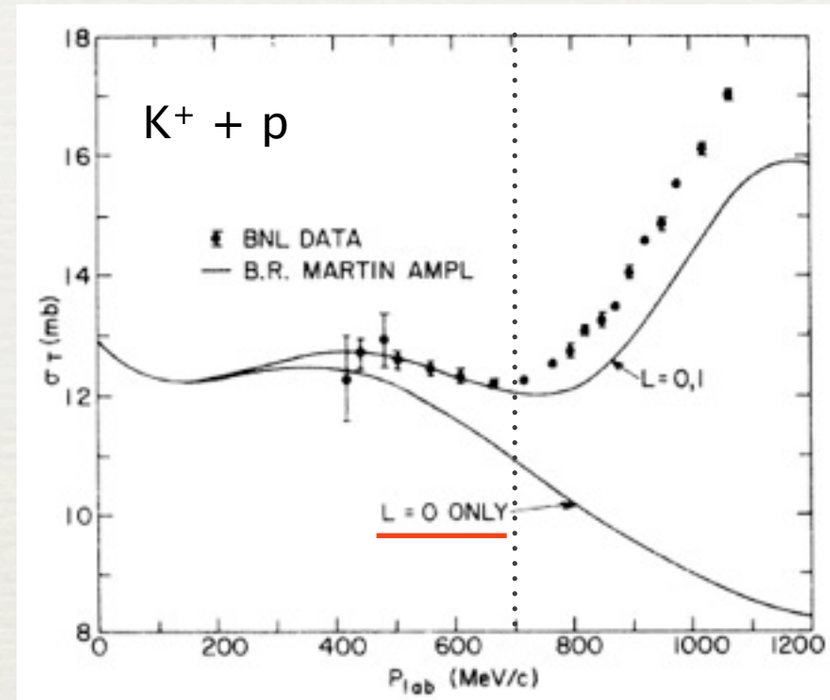
M. Abdel-Bary et al.
Eur.Phys.J. A48 (2012) 37.

Free KN scattering

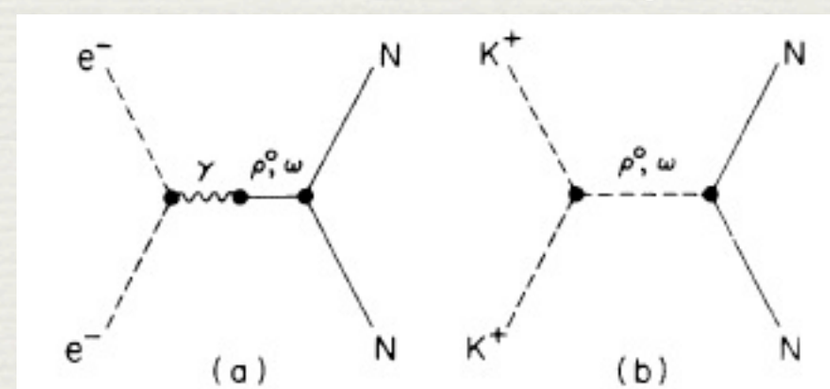
is known rather well:



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



For L = 0 VM exchange:



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

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

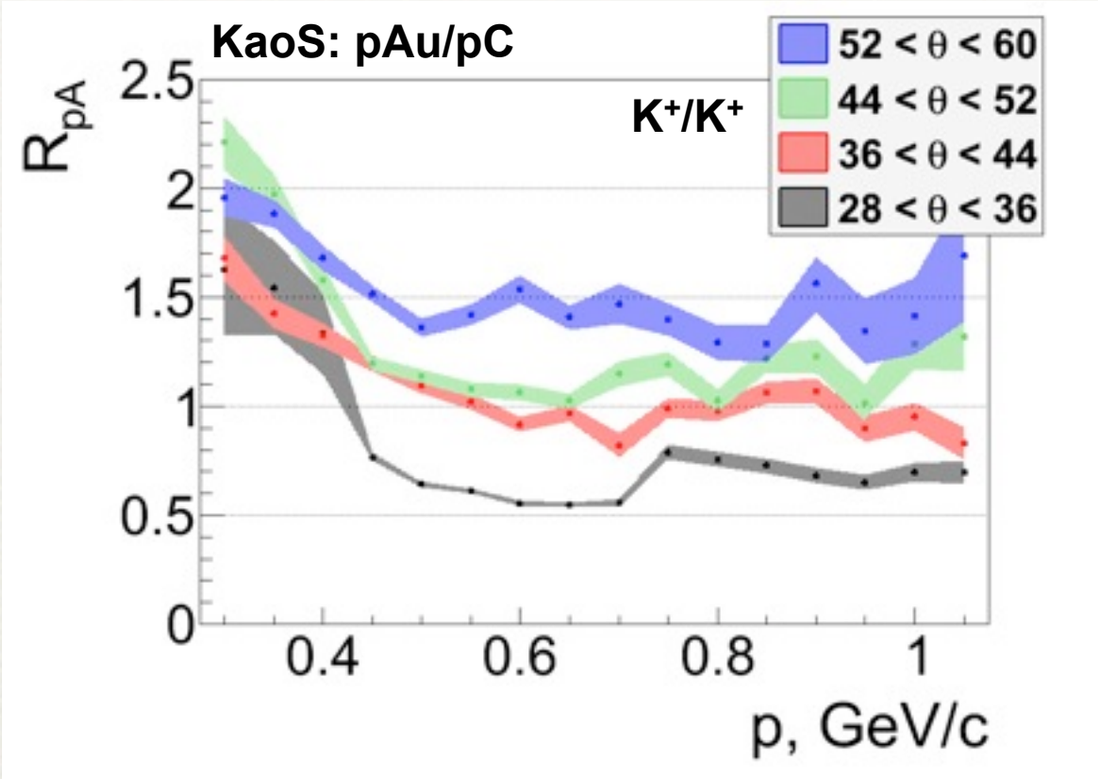
KaoS data provided by W. Scheinast Phys.Rev.Lett. 96 (2006) 072301.

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

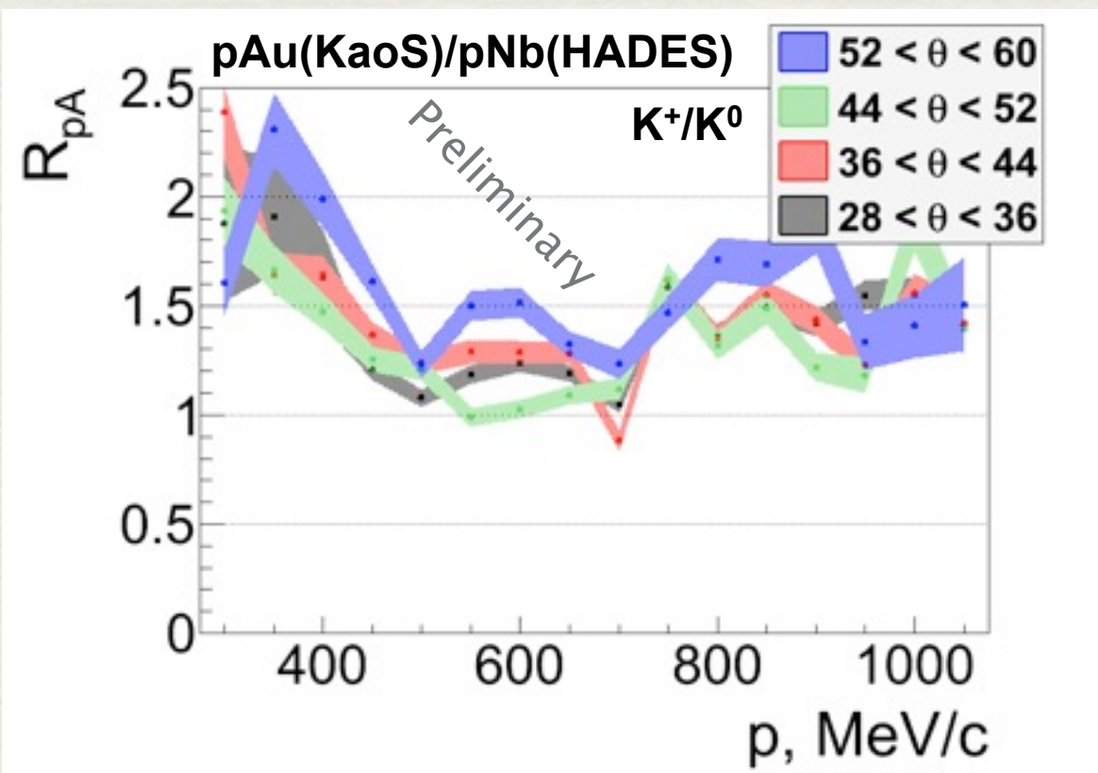
$$R_{pA}(p) = \frac{d\sigma_{pA}/dp}{d\sigma_{pp}/dp} \cdot \frac{N_{part}^{pp}}{N_{part}^{pA}} \cdot \frac{\sigma_{tot}^{pp}}{\sigma_{tot}^{pA}}$$

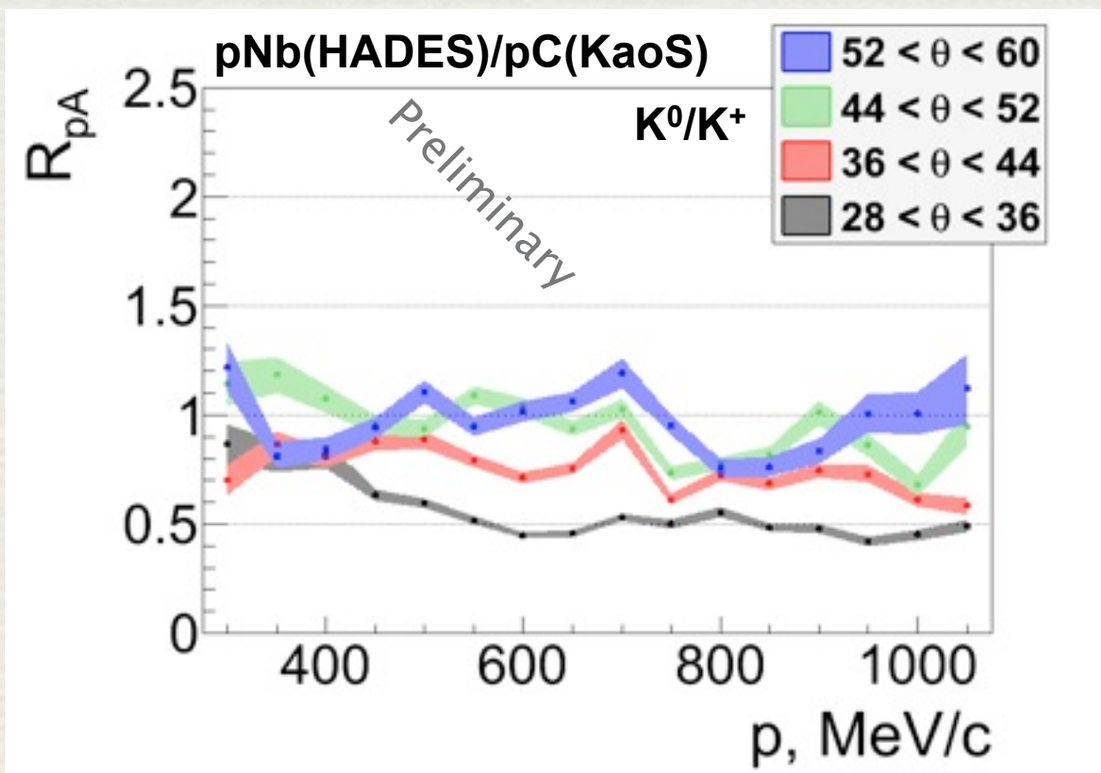
analogous scaling used for comparison between two nuclear targets, e.g. pAu/pC

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

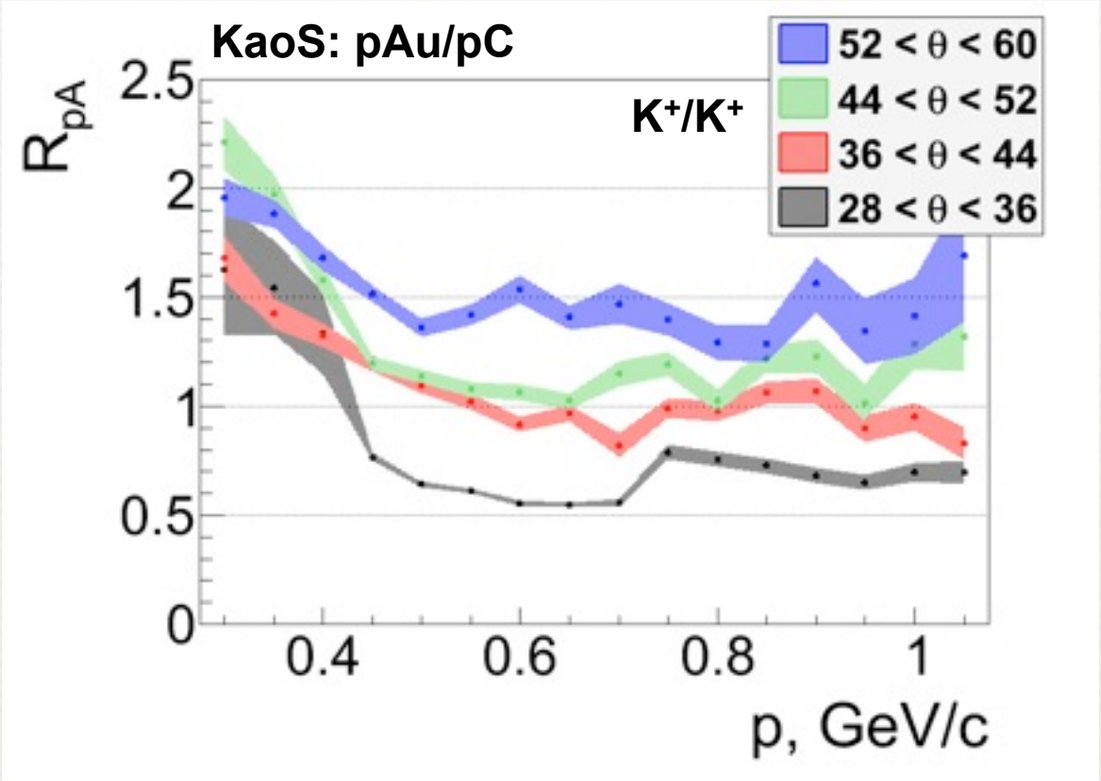


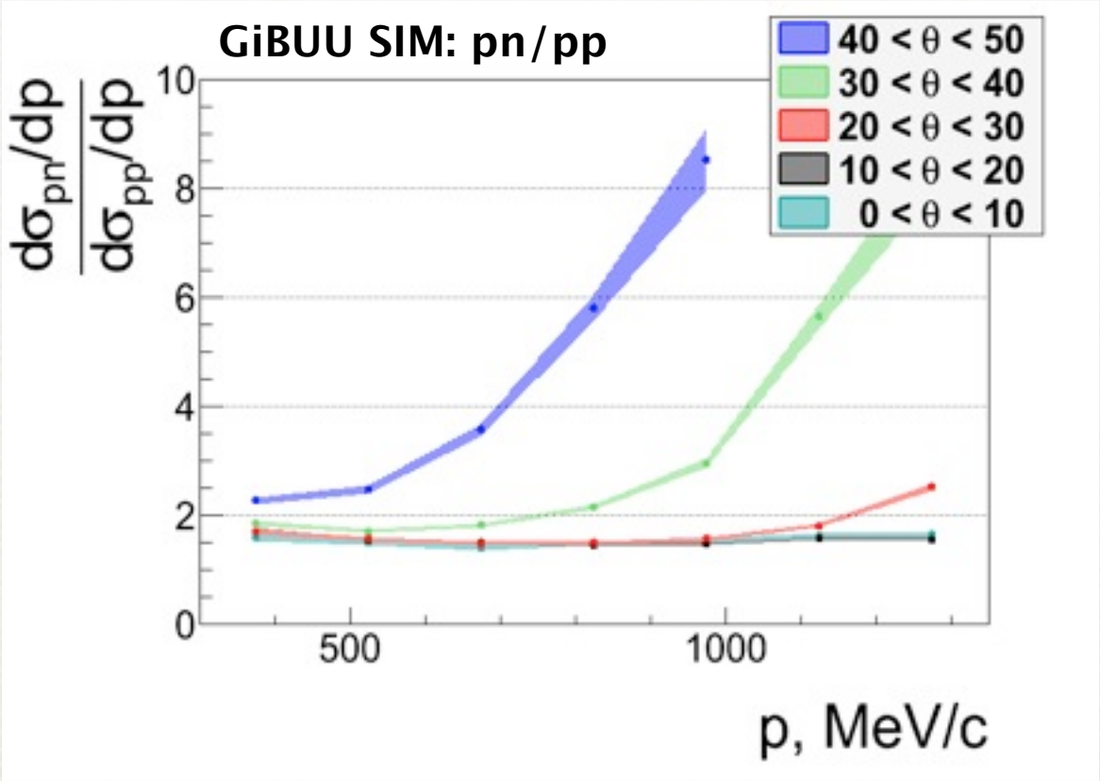
- Single scaling factor $K^+/K^0 \approx 1.1$ (from GiBUU).
- Ratios ~1, cross-check of the data.
- "Line splitting" due to KN scattering and isospin effects.

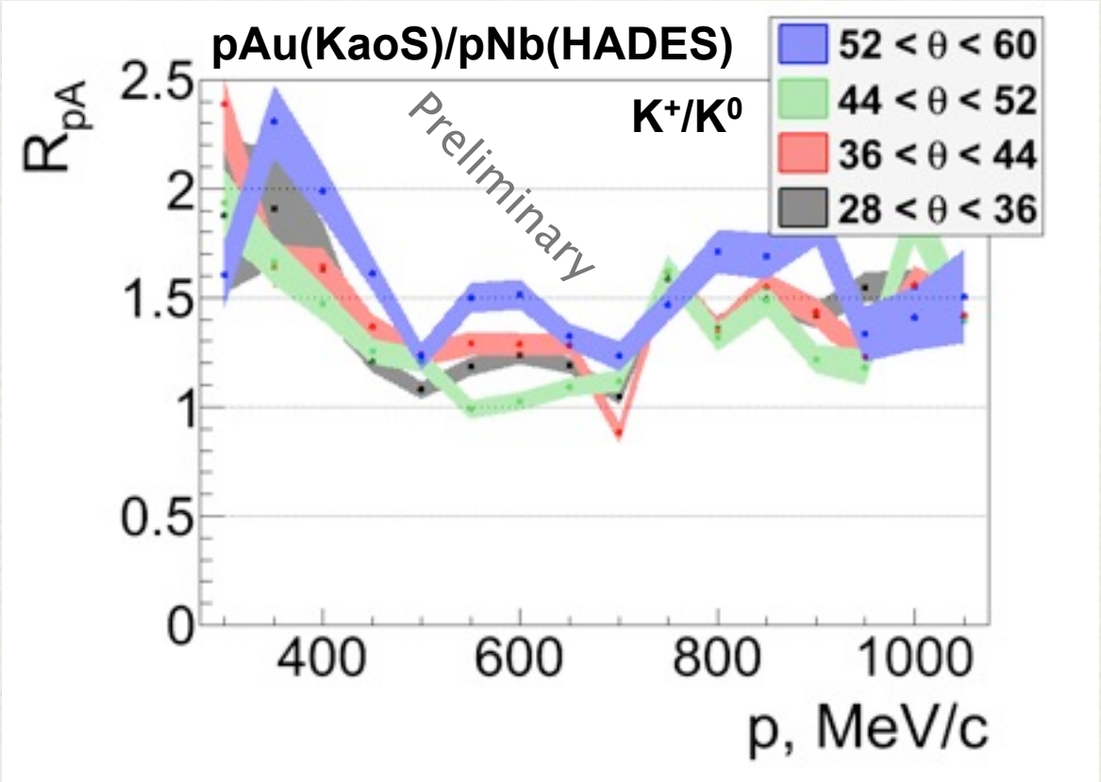


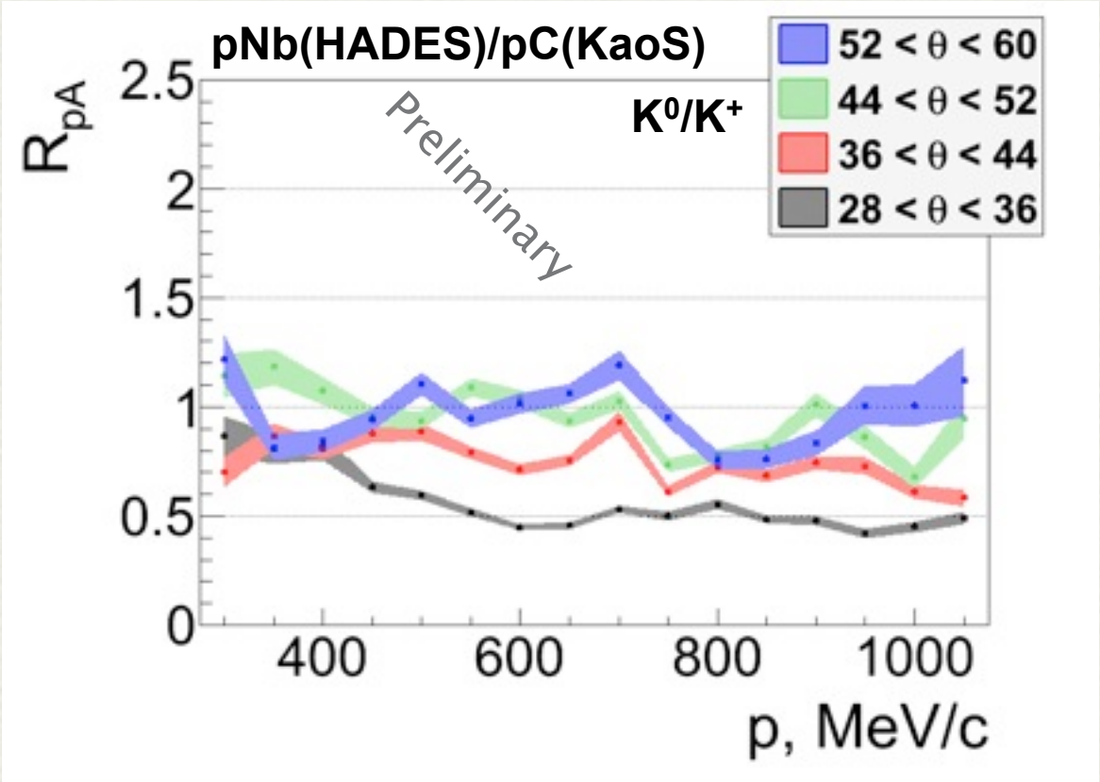


R_{pA}: HADES vs KaoS (K^0 vs K^+) at 3.5 GeV









Extending the model with 5-body final states

$$p + p \rightarrow p + \pi^+ + \Sigma^+ + \pi^- + K^0$$

$$\sqrt{s} \approx 2.90 \text{ GeV}$$

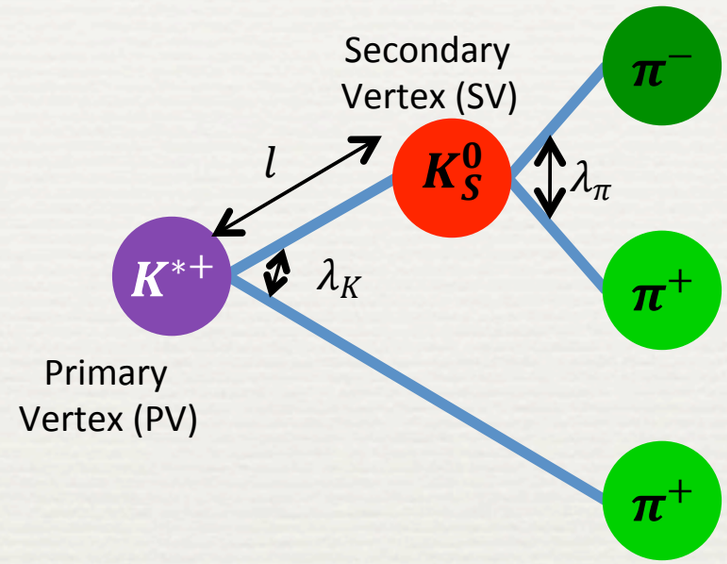
p+p at 3.5 GeV $\sqrt{s} \approx 3.18 \text{ GeV}$

- Well enough energy to produce 5-body final states.

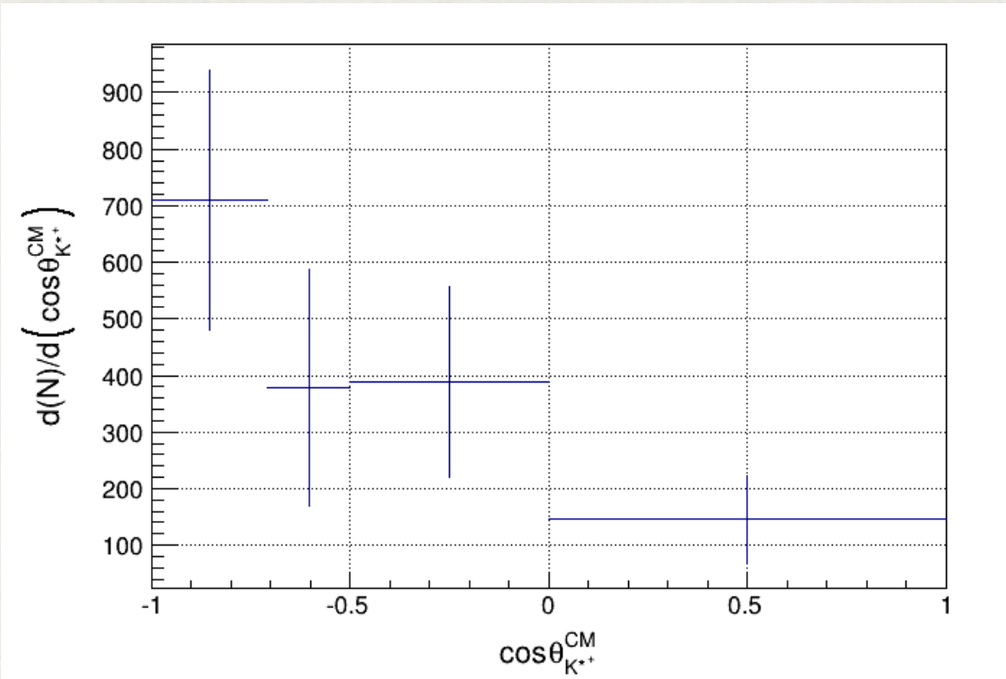
number of particles in fin. state	final state	what is added to the model
5-body	$p\ \pi^+\ \Lambda\ \pi^0\ K^0$	$\Delta^{++}\ \Sigma(1385)\ K^0$
	$p\ \pi^+\ \Sigma^+\ \pi^-\ K^0$	$\Delta^{++}\ \Lambda(1405)\ K^0$
	$p\ \pi^+\ \Sigma^0\ \pi^0\ K^0$	
	$p\ \pi^+\ \Sigma^-\ \pi^+\ K^0$	

K*(892) angular distributions

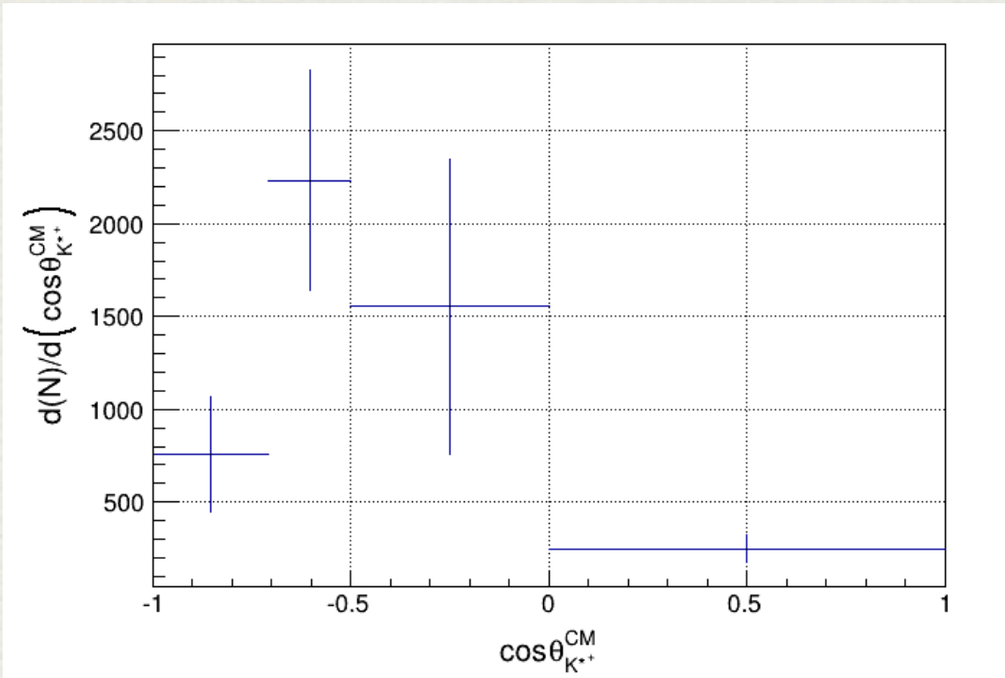
Analysis by Dimitar Mihaylov



p+p

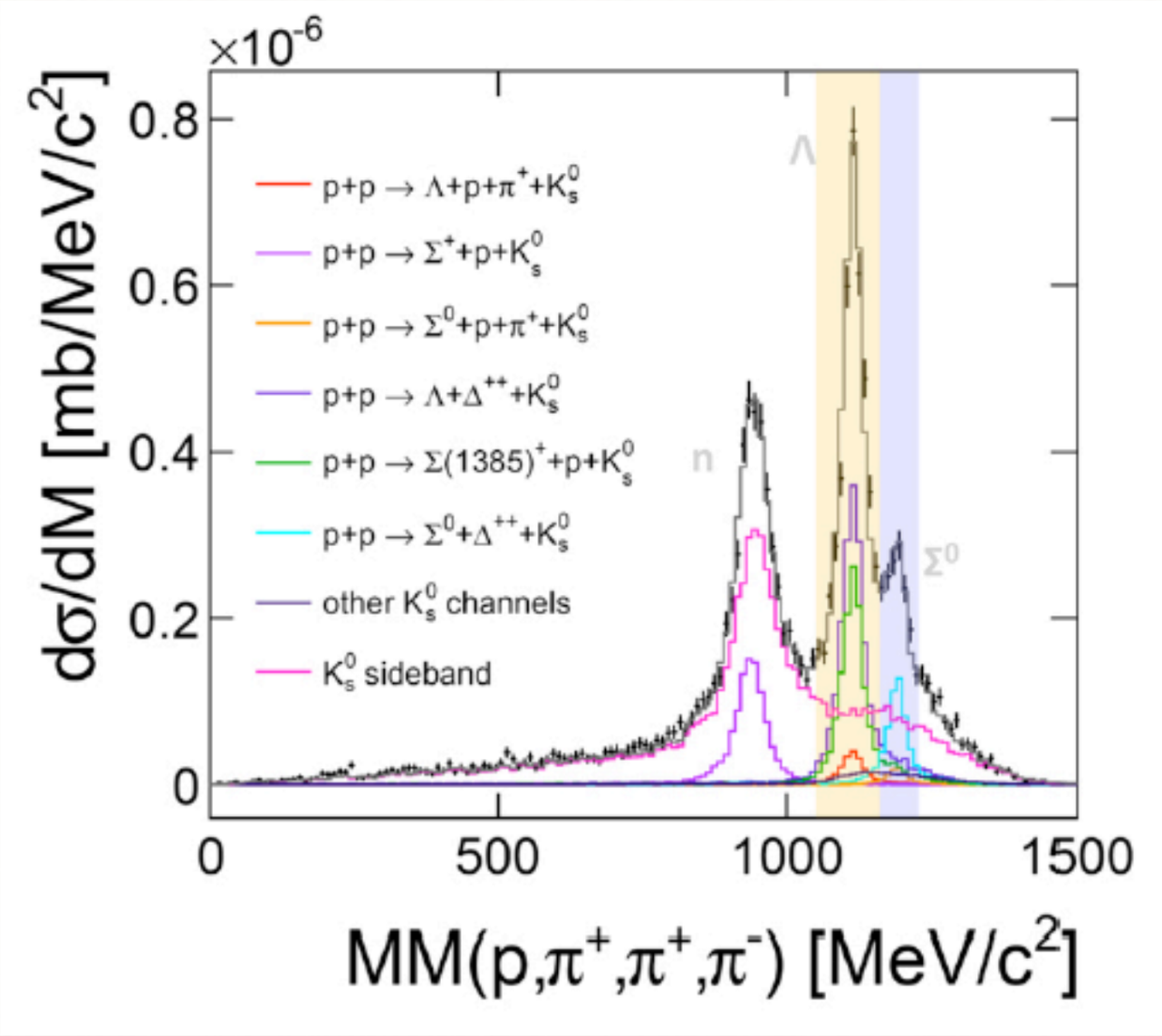


p+Nb



Exclusive analysis

Analysis by Jia-Chii Berger-Chen



Exclusive analysis

Analysis by Jia-Chii Berger-Chen

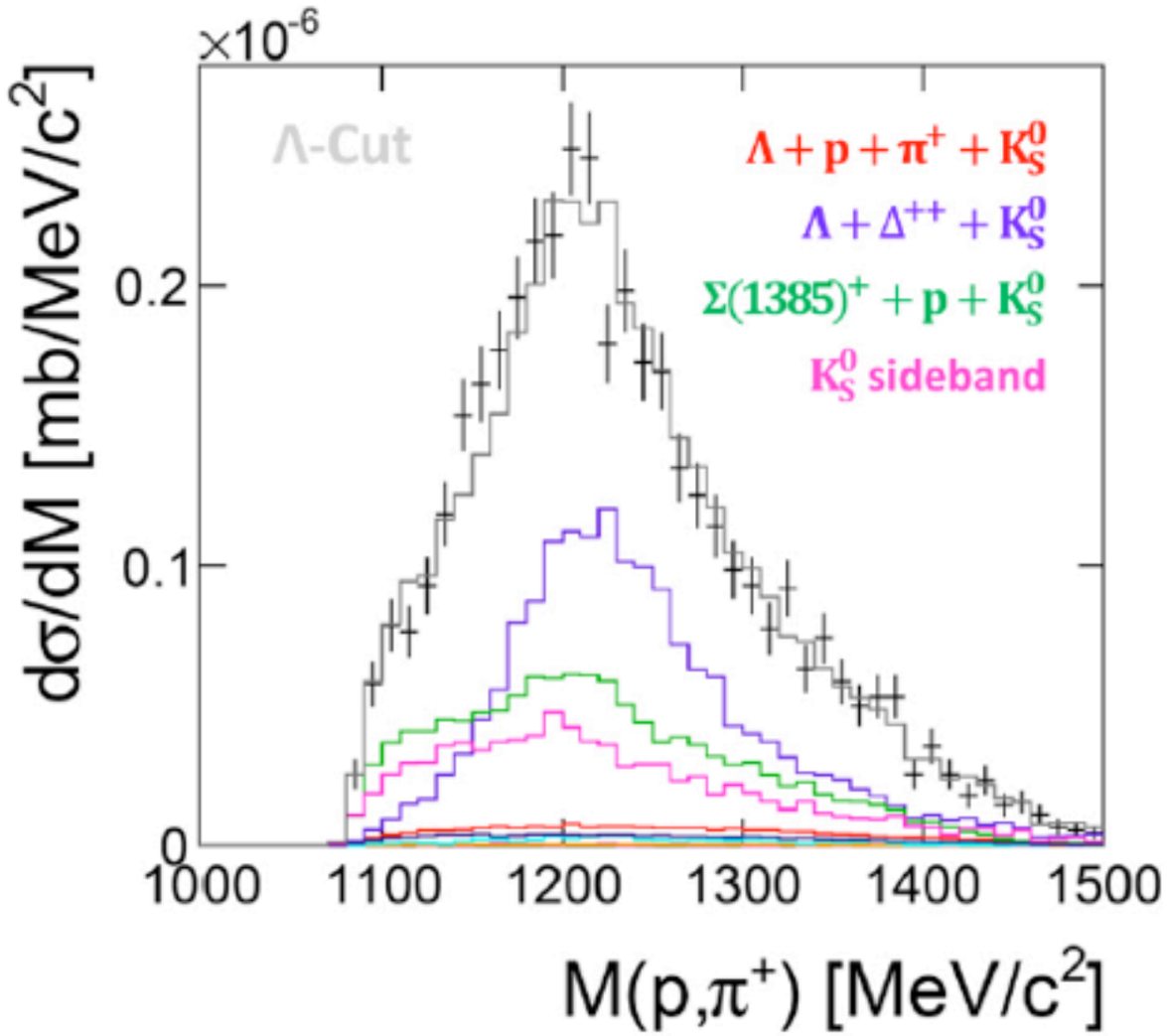


FIG. 28. Invariant mass p, π^+ with the Λ-cut in MM(p, π^+, π^+, π^-).

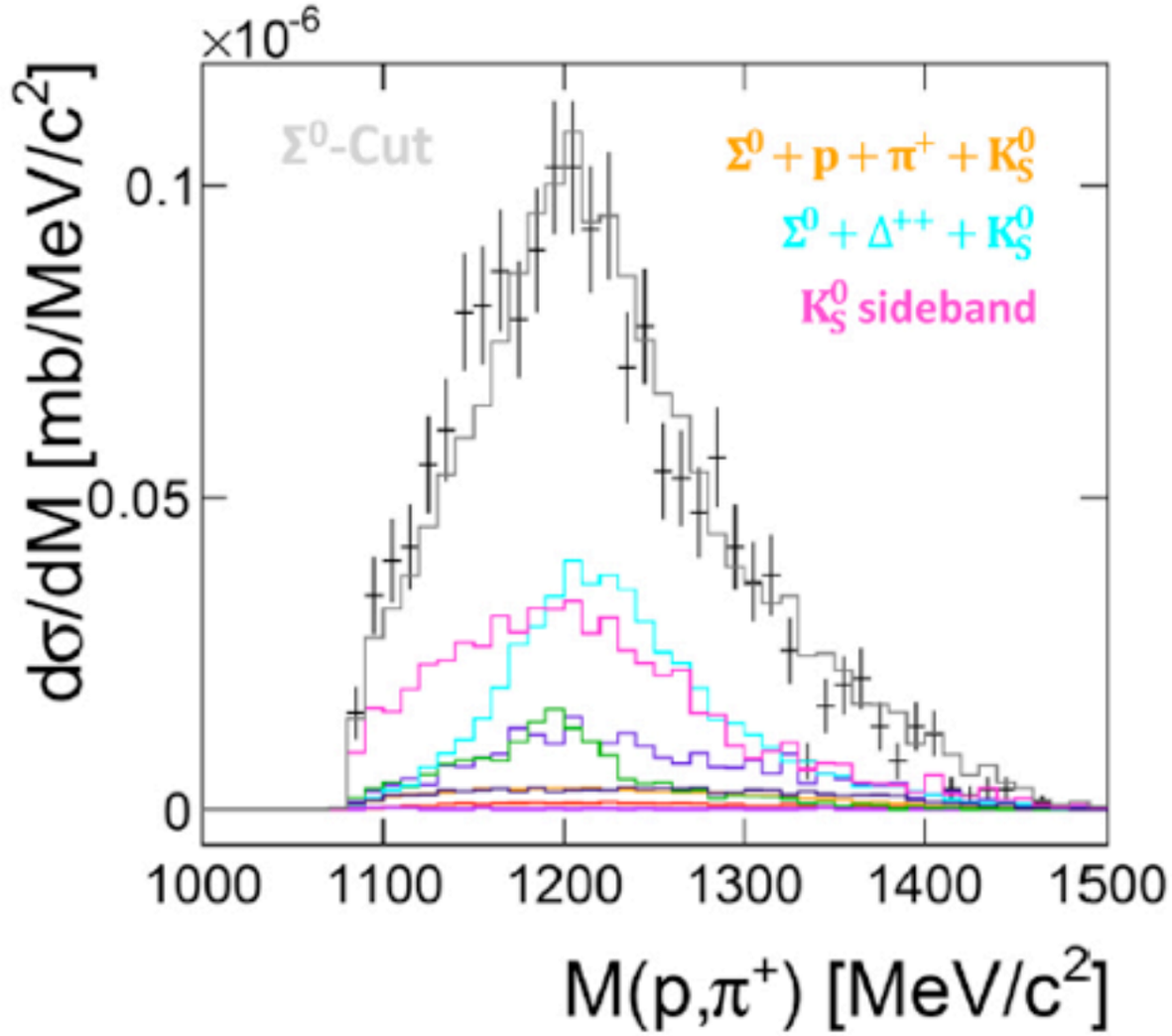


FIG. 29. Invariant mass p, π^+ with the Σ^0-cut in MM(p, π^+, π^+, π^-).

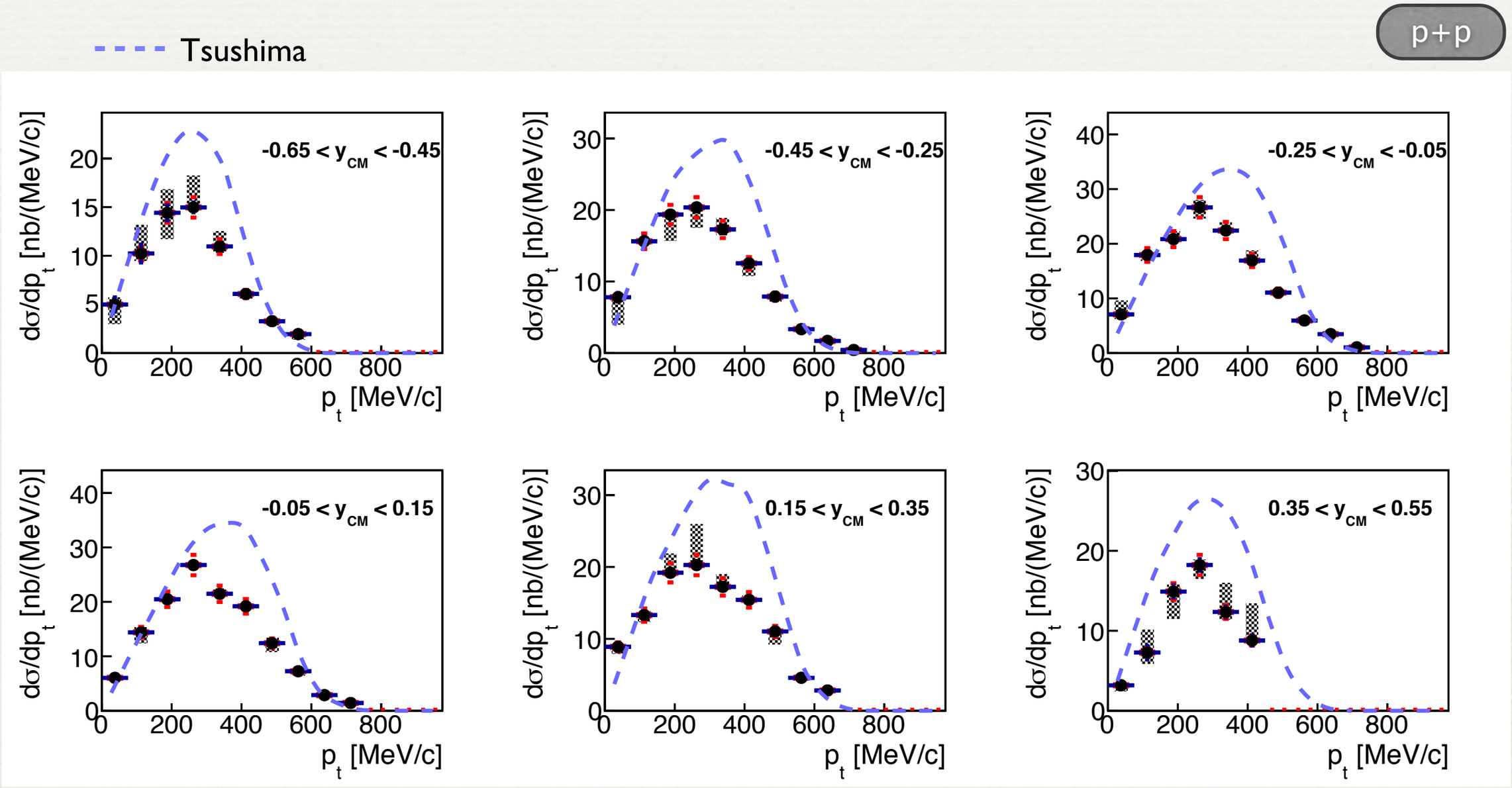
Variables used

1. Transverse (to the beam direction) momentum p_t
   - Lorentz invariant under a boost along the beam axis.

2. Rapidity $$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$
   - Easily transformed under such a boost: $y' \to y + c$

- Transverse momentum and rapidity fix the kinematics of a particle (up to azimuthal angle).
- Invariant phase space element $\sim dp_t^2 dy$

K^0 in pp: experimental data versus resonance model by Tsushima et al.*



- Absolute normalization (all plots in this talk).
- Resonance model overestimates the inclusive yield.

* K. Tsushima, A. Sibirtsev, A.W. Thomas, G.Q. Li, PRC59 (1999) 369

Resonance model of kaon production

All production channels:

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	$\Delta^- \Delta^+ \to \Delta^0 \Sigma^- K^+$

Cross section parameterization:

$$\sigma(B_1 B_2 \to B_3 Y K) = a \left(\frac{s}{s_0} - 1\right)^b \left(\frac{s_0}{s}\right)^c,$$

Note: this is what's inside transport code

np-reactions isospin interrelations (one example):

$$\begin{aligned} \sigma(nn \to \Delta^- \Lambda K^+) &= \sigma(pp \to \Delta^{++}\Lambda K^0) \\ = 3\sigma(pn \to \Delta^0 \Lambda K^+) &= 3\sigma(np \to \Delta^+ \Lambda K^0) \\ = 3\sigma(pp \to \Delta^+ \Lambda K^+) &= 3\sigma(nn \to \Delta^0 \Lambda K^0), \end{aligned}$$

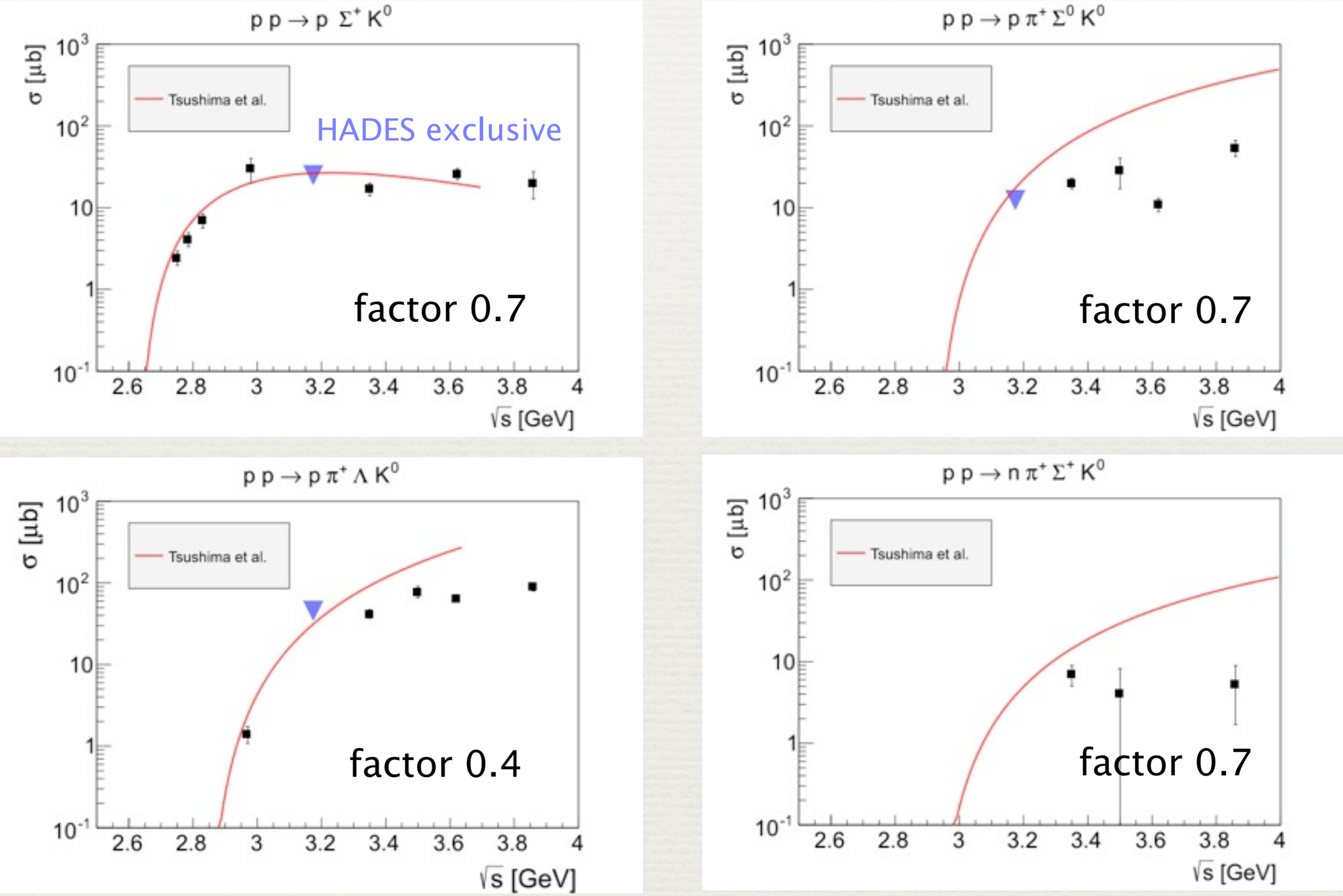
almost no experimental data for np!

K^0 production channels:

Number of particles	Final state	What is in the model
3-body	$p\ \Sigma^+\ K^0$	$p\ \Sigma^+\ K^0$
4-body	$p\ \pi^+\ \Lambda\ K^0$	$\Delta^{++}\ \Lambda\ K^0$
	$p\ \pi^+\ \Sigma^0\ K^0$	$\Delta^{++}\ \Sigma^0\ K^0$
	$n\ \pi^+\ \Sigma^+\ K^0$	$\Delta^+\ \Sigma^+\ K^0$
	$p\ \pi^0\ \Sigma^+\ K^0$	

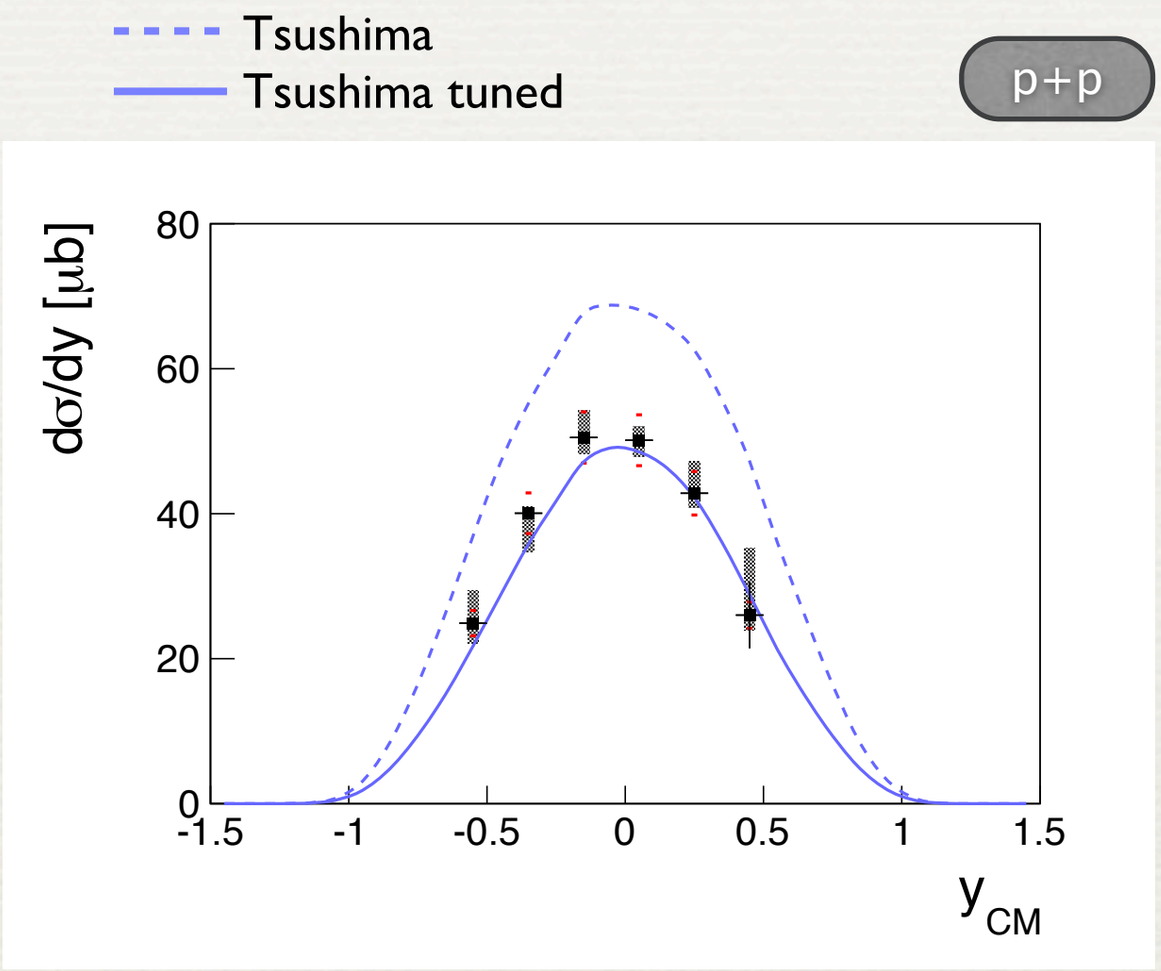
Note:
1. Pion production goes exclusively through Δ.
2. No angular anisotropies in production.

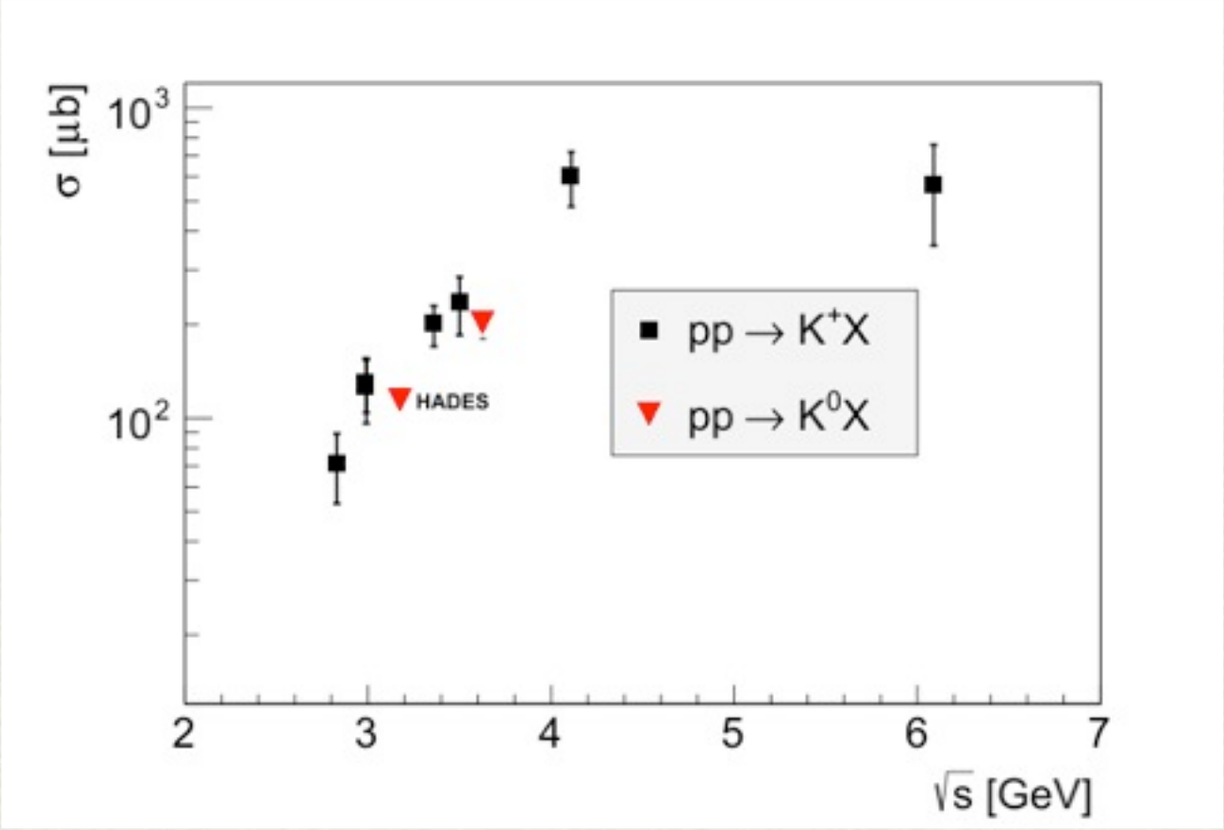
Tuning the resonance model



- Downscaling of exclusive channels in the model

K^0 in pp vs. tuned resonance model



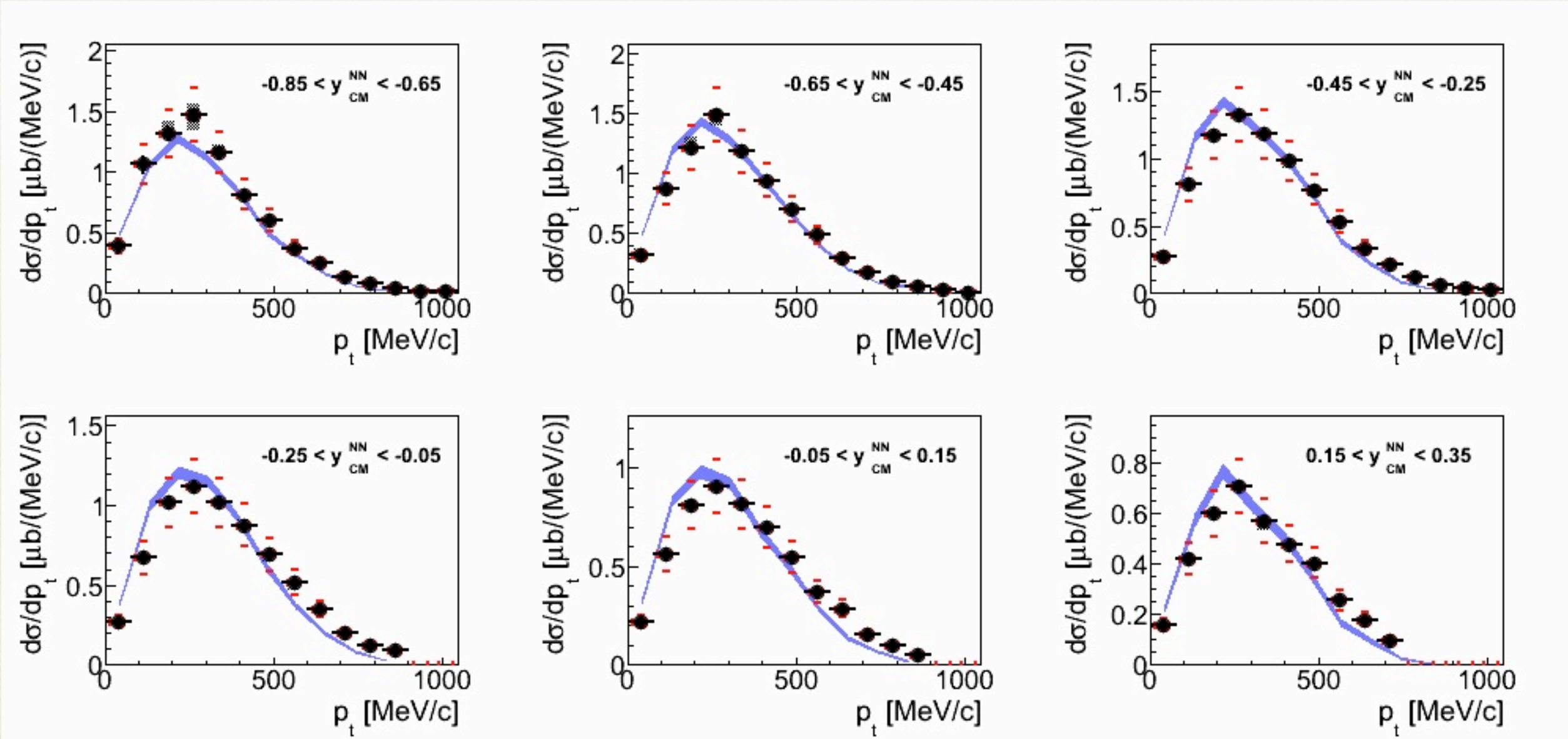


- Analysis procedure benchmarks:
  - Symmetric rapidity distribution.
  - Systematics of the total cross section.

pNb data vs. tuned resonance model

GiBUU w/o pot.

p+Nb



- KN potential is OFF.
- 3-body reactions in np (np → NYK) poorly constrained, scale factor 0.5 is applied to the Tsushima parameterizations.
- GiBUU simulations based on tuned resonance model describe data.

Kaon potential

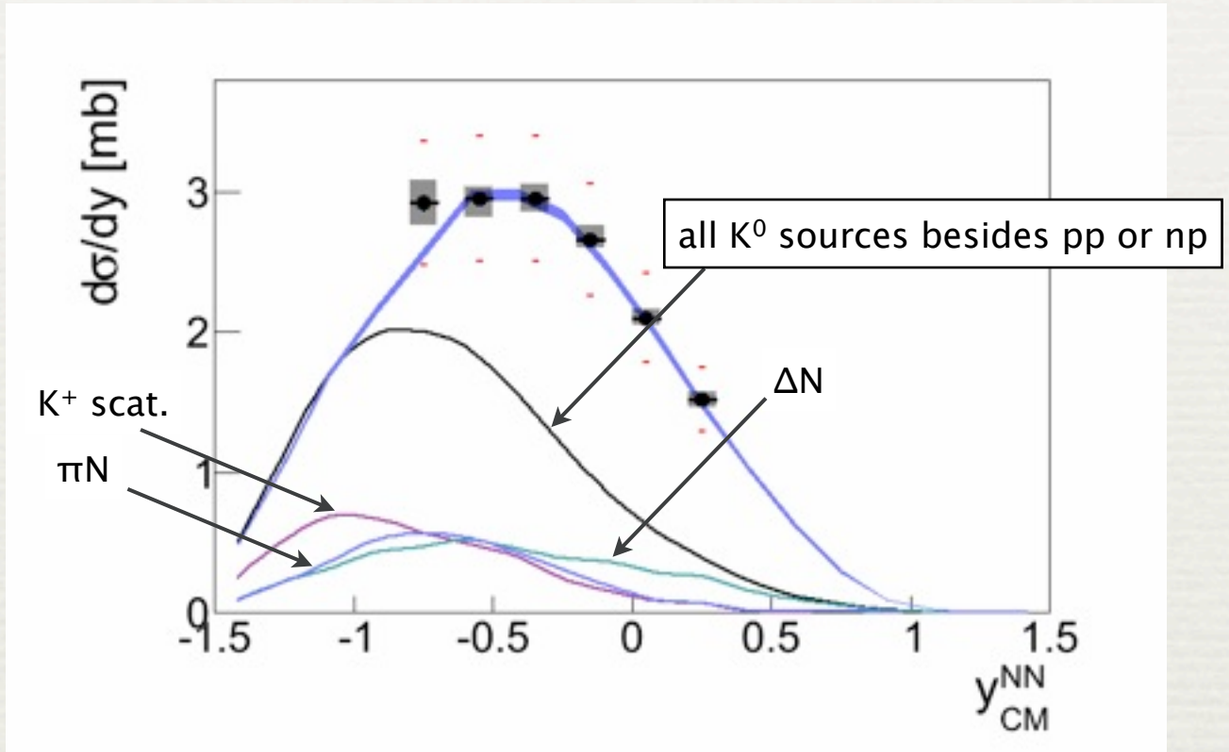
Kaon-nucleon scattering

K^0 production in secondary processes

K^0 production in nucleon-nucleon reactions

Rapidity distribution and role of secondary reactions

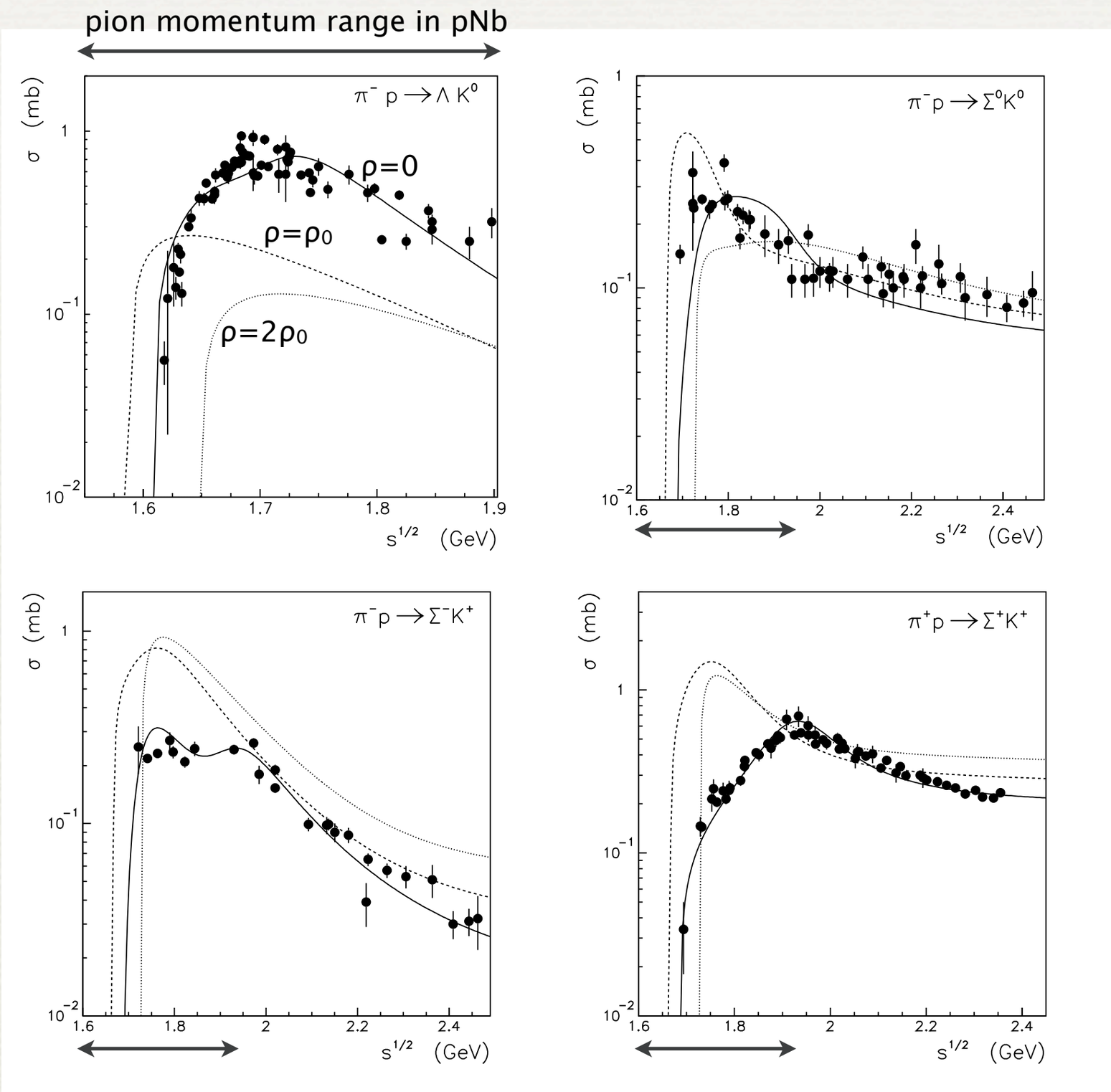
p+Nb



- Significant contribution of secondary reactions at backward rapidities (~70%).
- Three main sources:
  - ΔN-reactions. Rely on the resonance model (Tsushima et al.).
  - πN-reactions.
  - KN scattering.

How well the two last processes are known?

Secondary processes: pion-nucleon reactions



- Elementary cross sections are known well and parametrized in the model.
- No angular distributions implemented in the model.

Pictures from K. Tsushima, A. Sibirtsev, A.W. Thomas, PRC62 (2000) 064904

Kaon potential

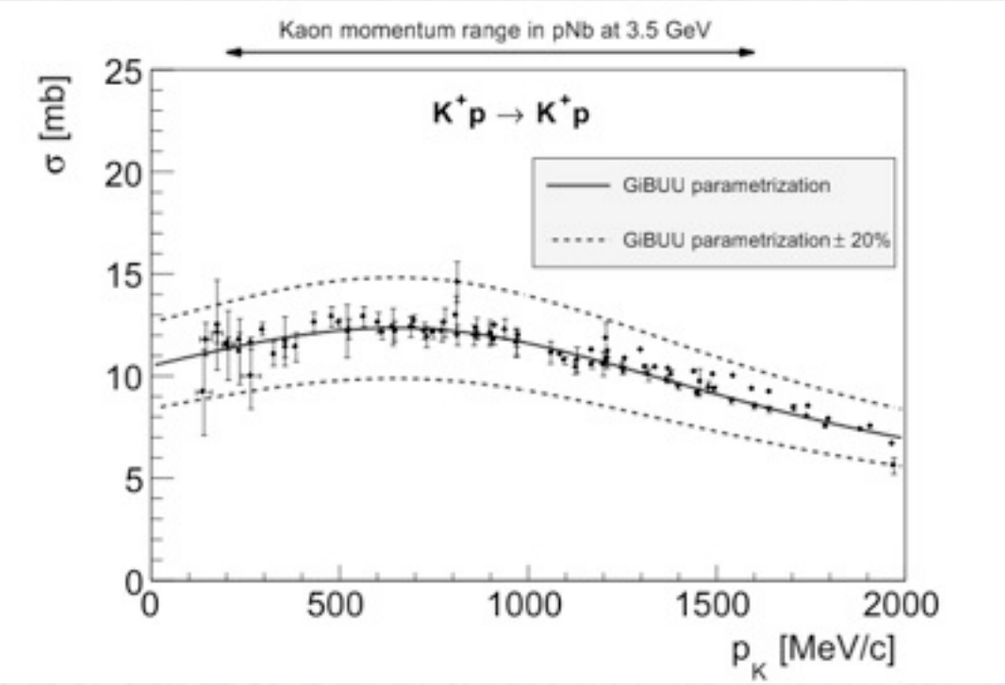
Kaon-nucleon scattering

K^0 production in secondary processes

K^0 production in nucleon-nucleon reactions

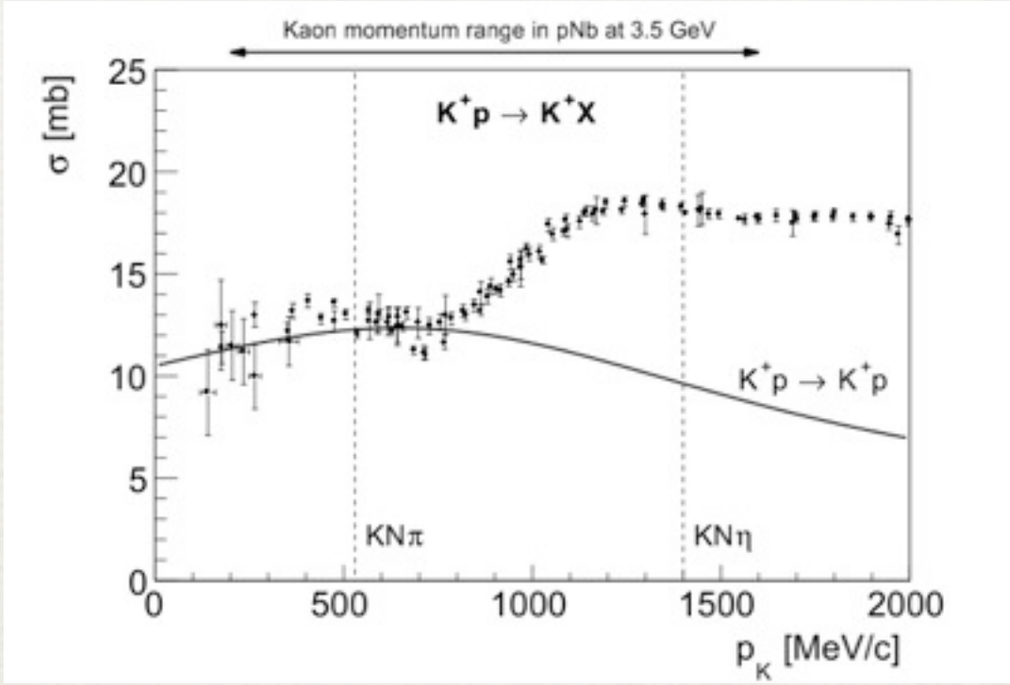
Kaon-nucleon scattering

Elastic cross section



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

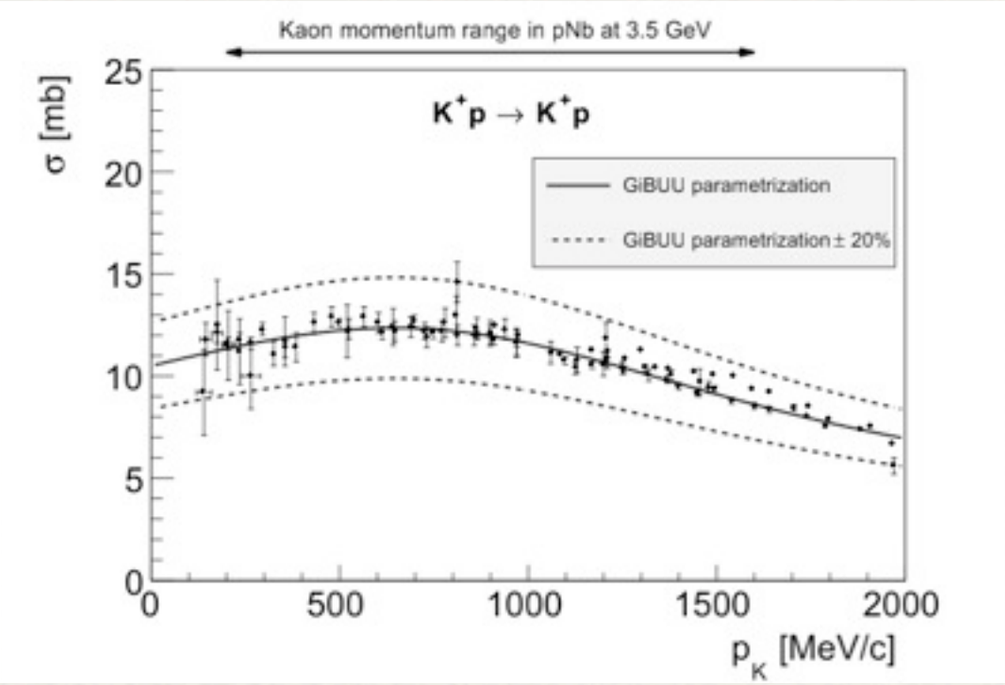
Total cross section



- Vacuum cross sections are well known.
- K^0N scattering from isospin considerations.
- No angular distributions implemented in the model (some data are available).

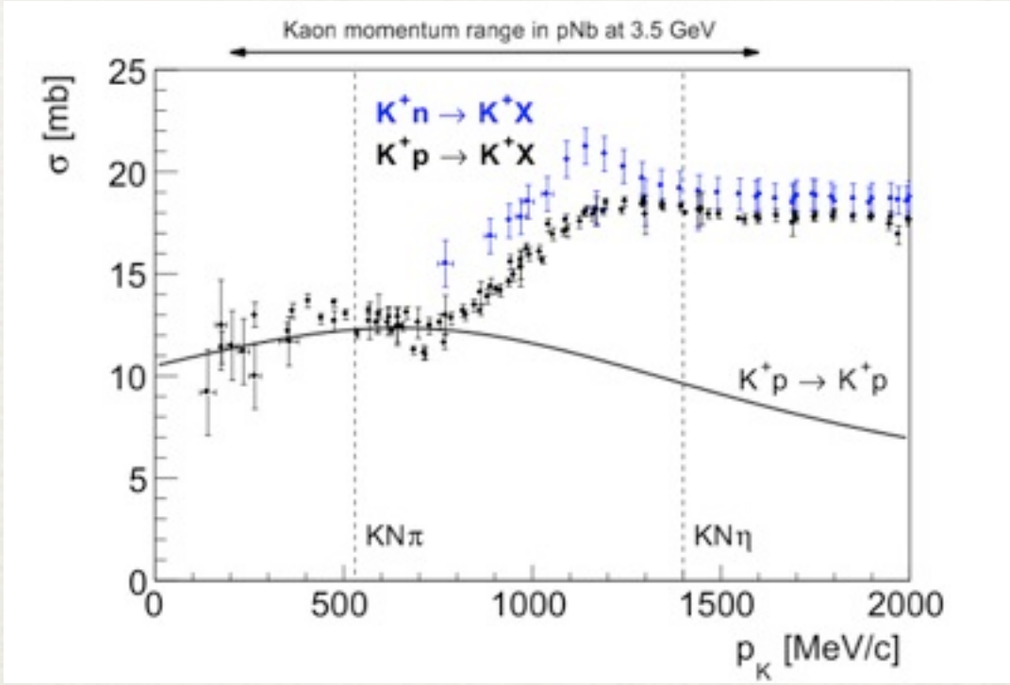
Kaon-nucleon scattering

Elastic cross section



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

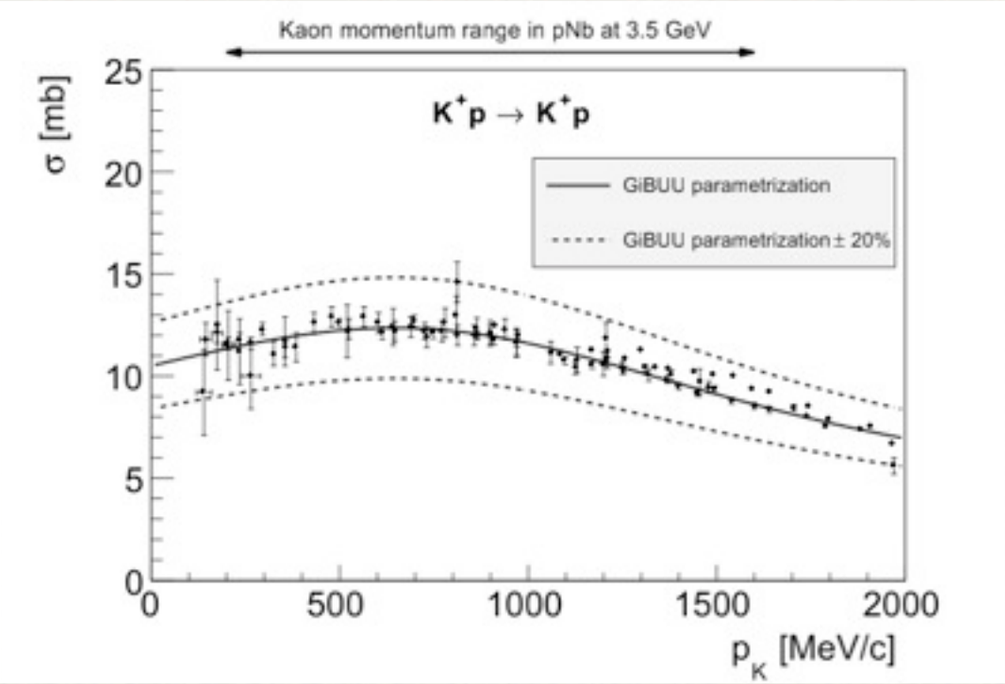
Total cross section



- Vacuum cross sections are well known.
- K^0N scattering from isospin considerations.
- No angular distributions implemented in the model (some data are available).

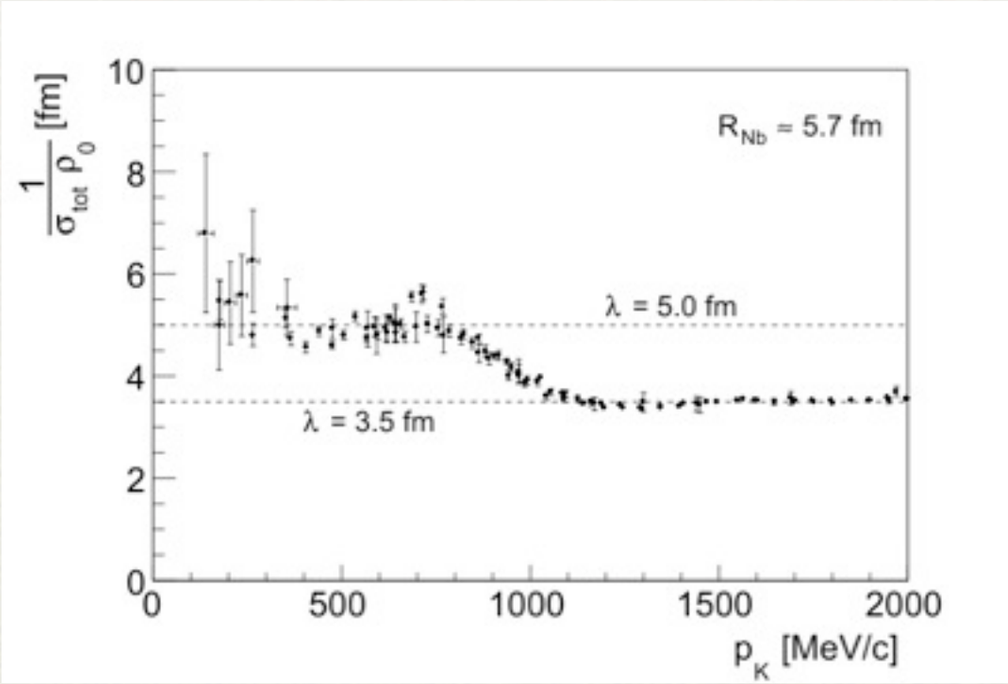
Kaon-nucleon scattering

Elastic cross section



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

Mean free path at normal nuclear density

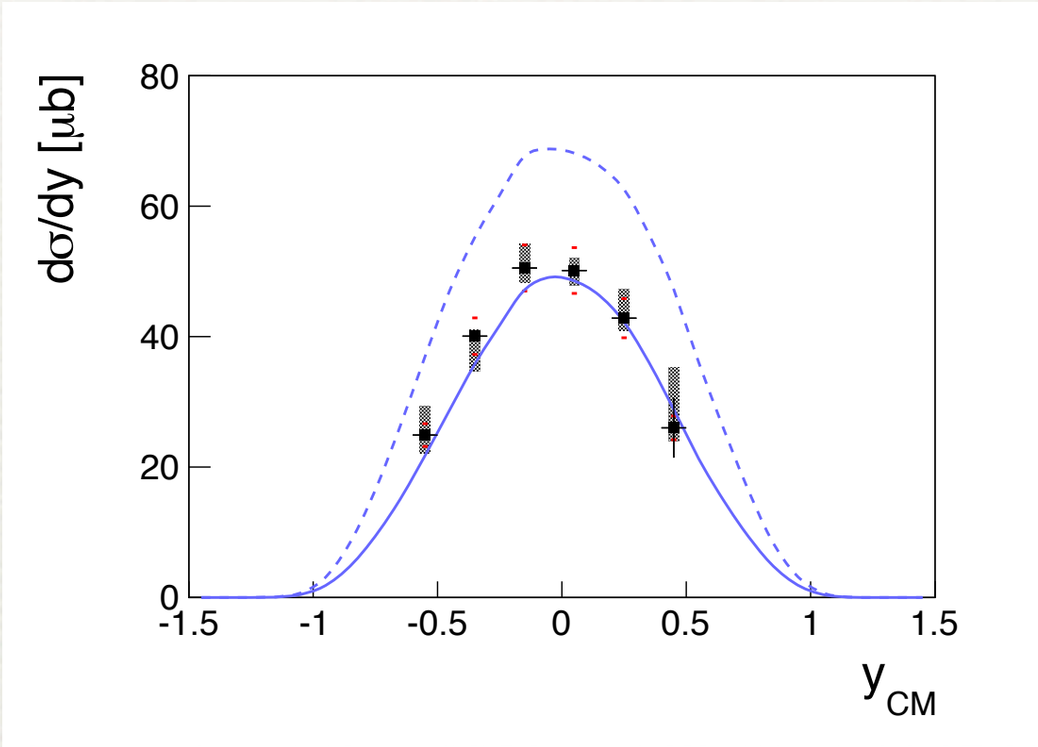


Note: from K^+p total cross section

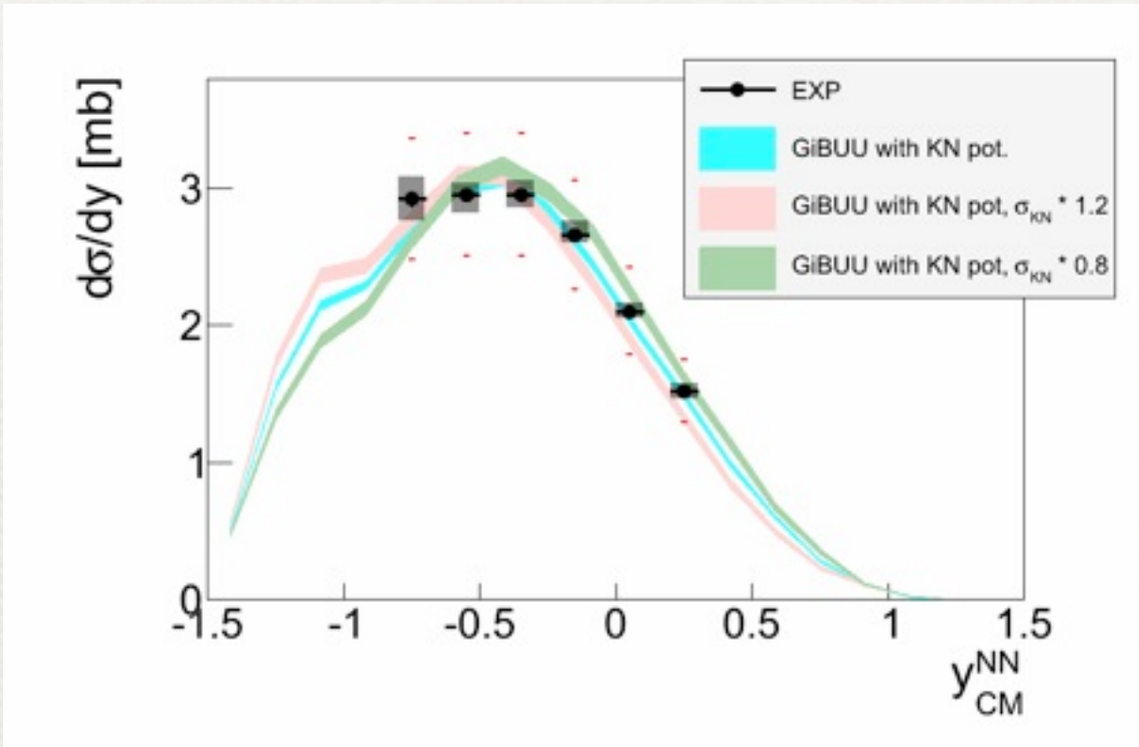
- Vacuum cross sections are well known.
- K^0N scattering from isospin considerations.
- No angular distributions implemented in the model (some data are available).

Rapidity distribution in pNb: sensitivity to the KN scattering

p+p



p+Nb



- Rapidity distribution is sensitive to the KN scattering.
- Data consistent with the vacuum KN cross sections.

Kaon potential

Kaon-nucleon scattering

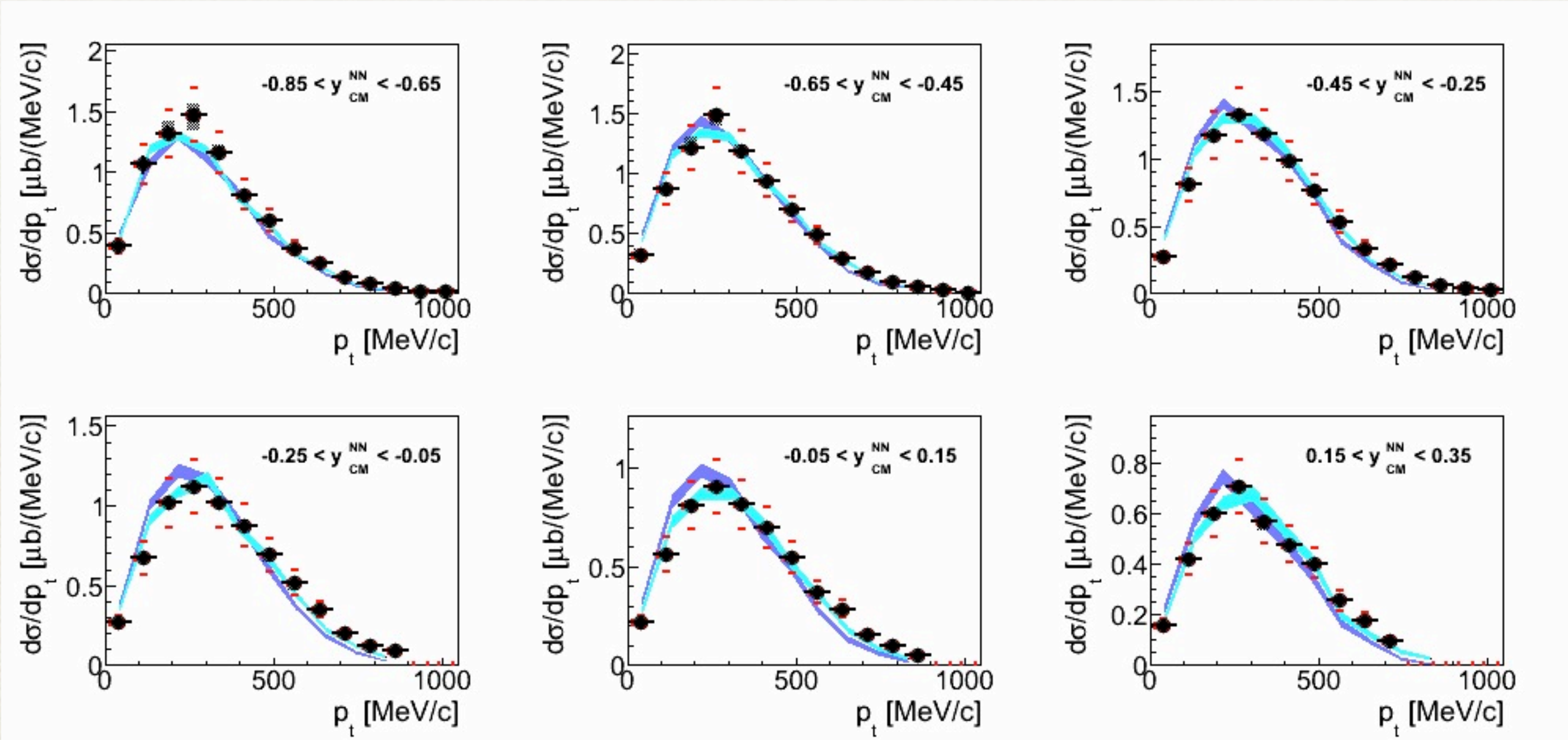
K^0 production in secondary processes

K^0 production in nucleon-nucleon reactions

Effect of the potential in pNb: p_t–y spectra

GiBUU w/o pot.
GiBUU w. pot.

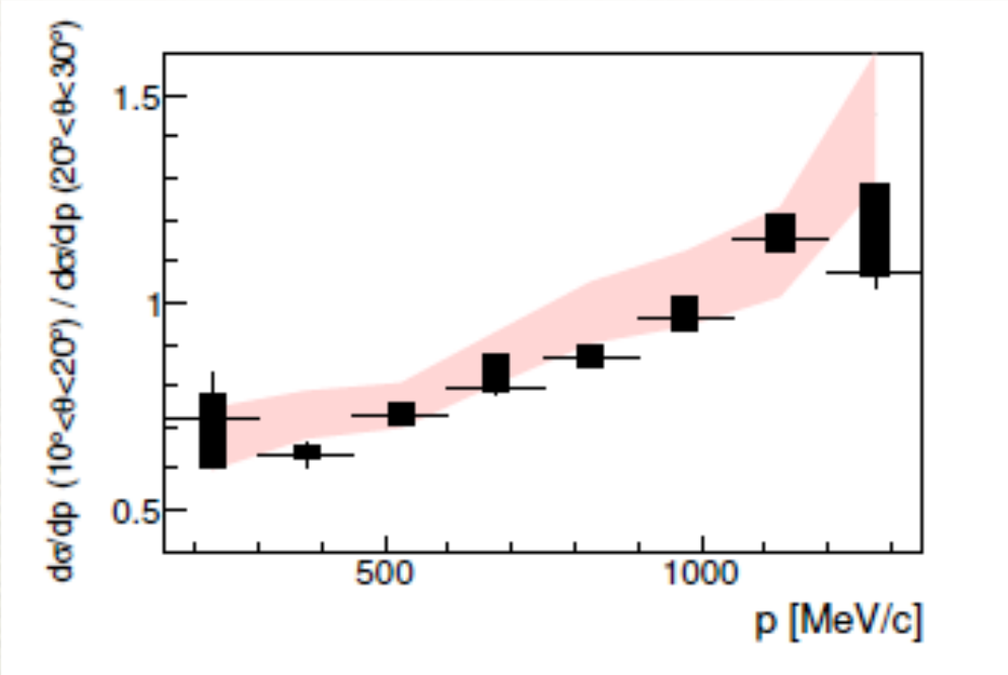
p+Nb



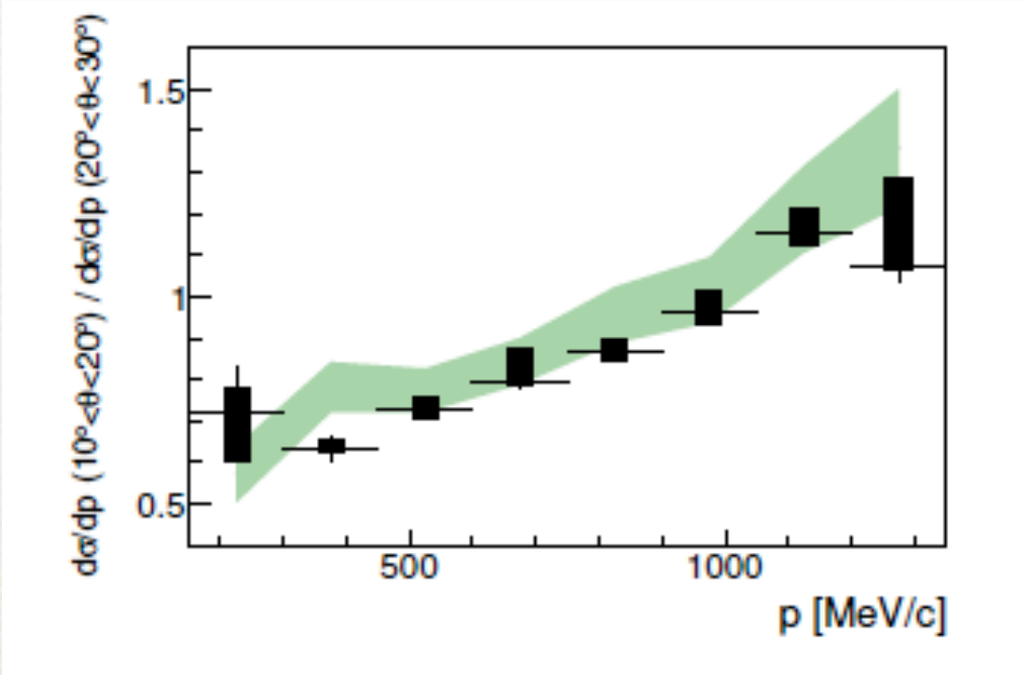
- Small systematical shift of p_t–spectra owe to the repulsive potential, favored by data.
- Uncertainties in the model parameters (np cross sections, ...).
- A better observable is needed to judge on the potential strength.

Ratio plots, variation of the model parameters

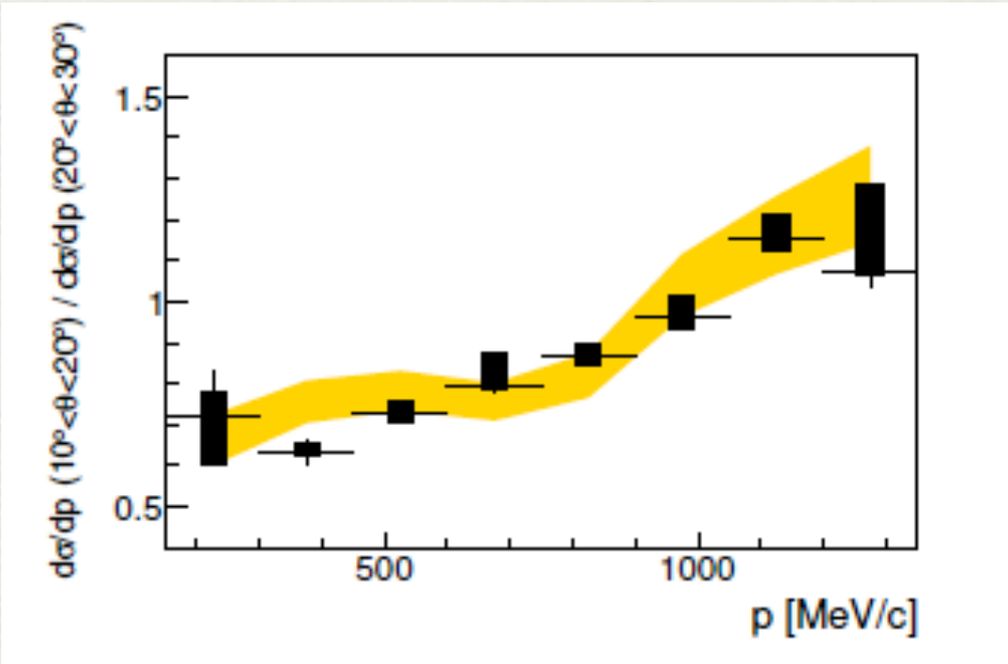
GiBUU **w. pot. KN scattering +20%**



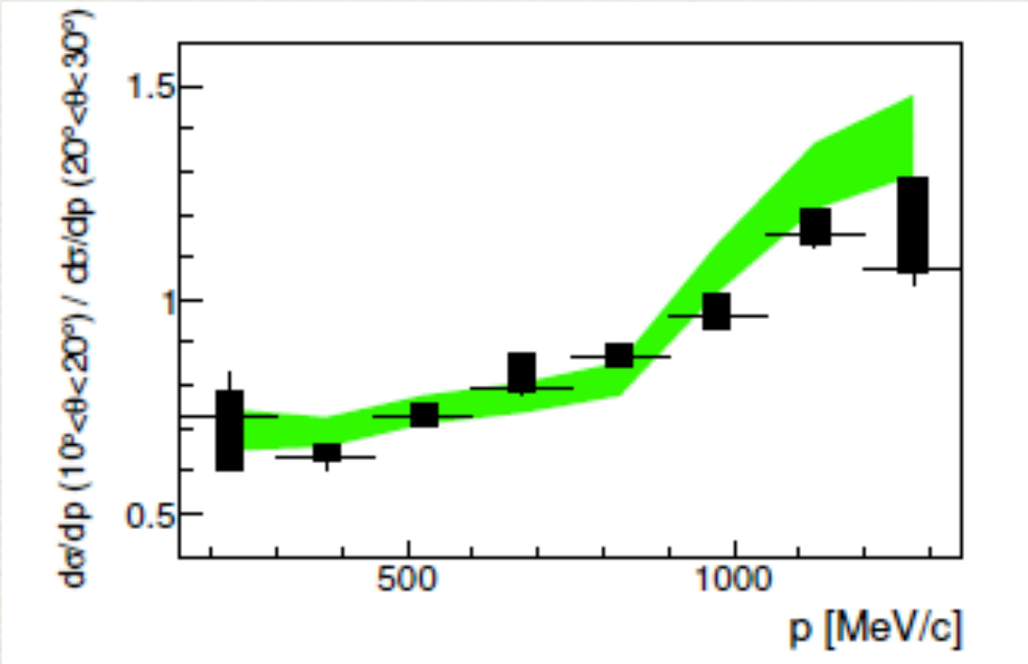
GiBUU **w. pot. KN scattering −20%**



GiBUU **w. pot. np 3body −20%**

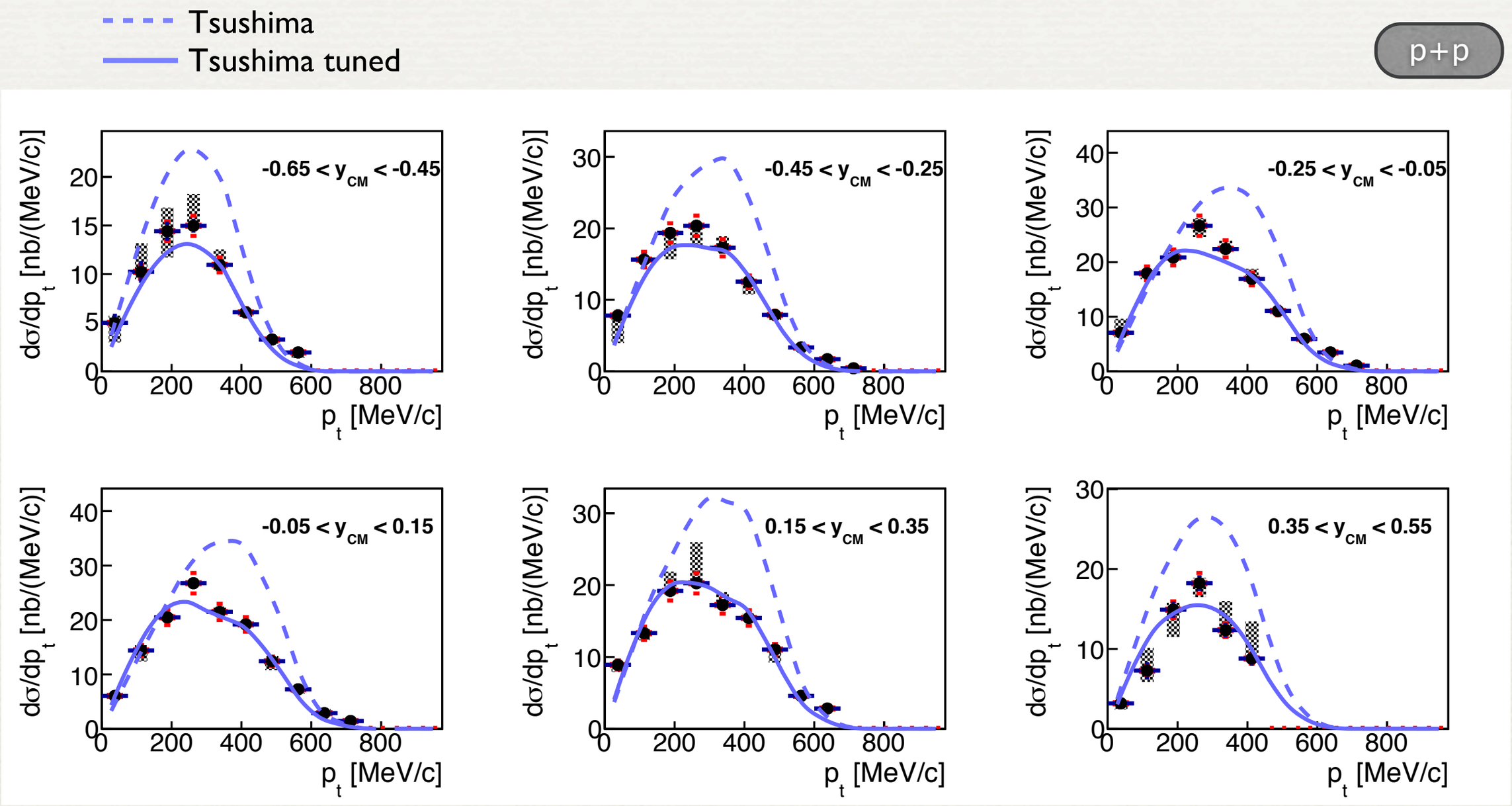


GiBUU **w. pot. np 3body +25%**



- Check if the ratio is stable against variation of the poorly known parameters.
- Further systematical checks are running (ΔN, ...)

K^0 in pp vs. tuned resonance model

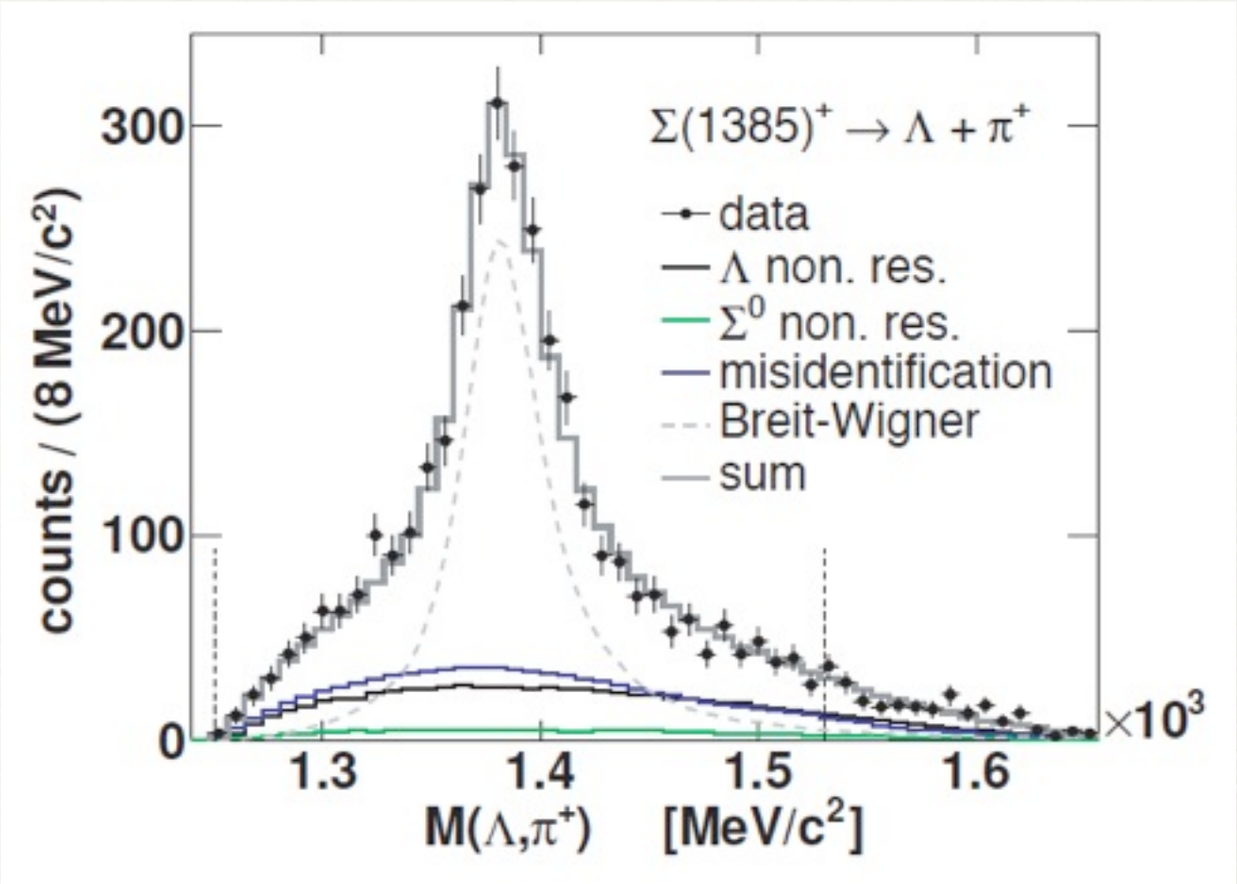


- Final states with two pions (5-body) added to the model via NN → Δ^{++} Y* K, Y* is Σ(1385) or Λ(1405).
- Good description of the data.

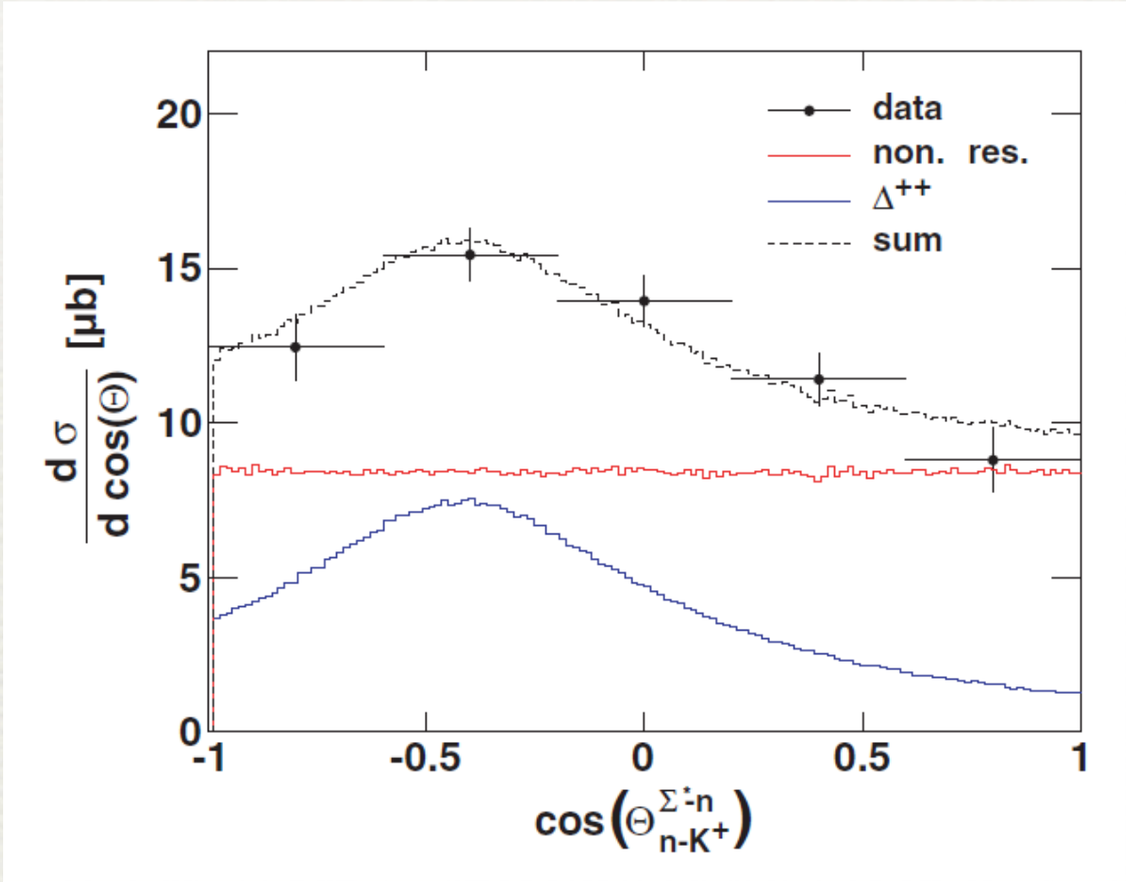
$\Sigma^+(1385)$

$$p(3.5GeV) + p \rightarrow \Sigma(1385)^+ + K^+ + n$$
$$\hookrightarrow \Lambda + \pi^+$$
$$\hookrightarrow p + \pi^-.$$

$$p(3.5GeV) + p \rightarrow \boxed{\Sigma(1385)^+ + K^+ + n}$$
$$p(3.5GeV) + p \rightarrow \Delta^{++} + n$$
$$\hookrightarrow \Sigma(1385)^+ + K^+$$

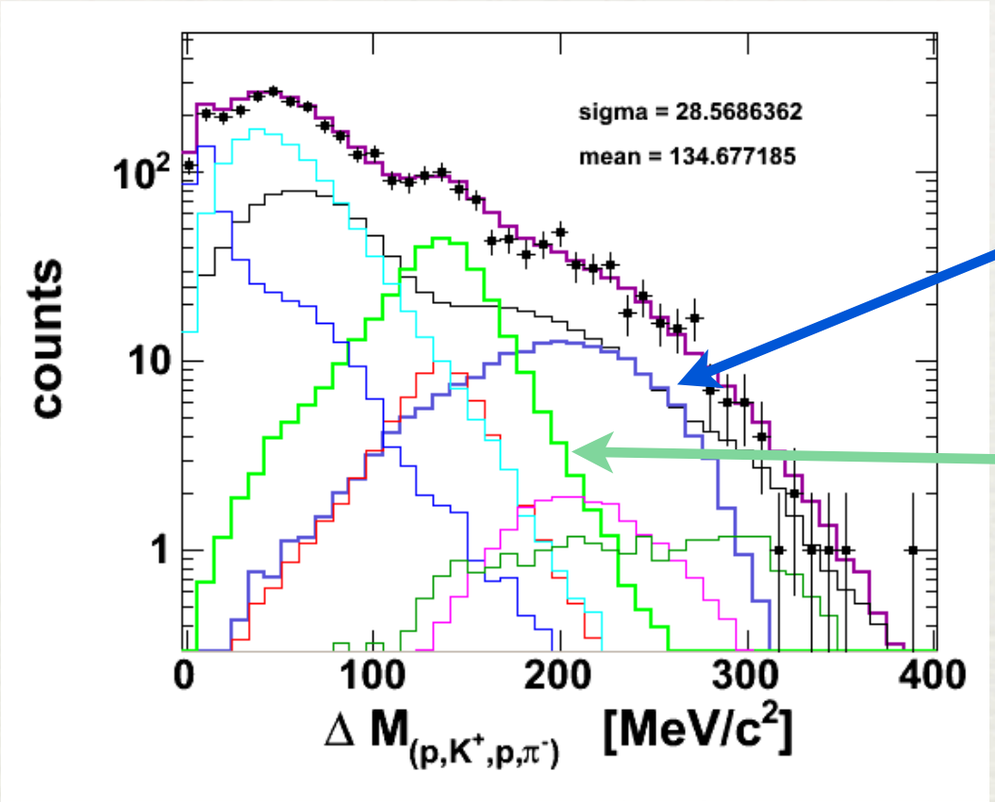


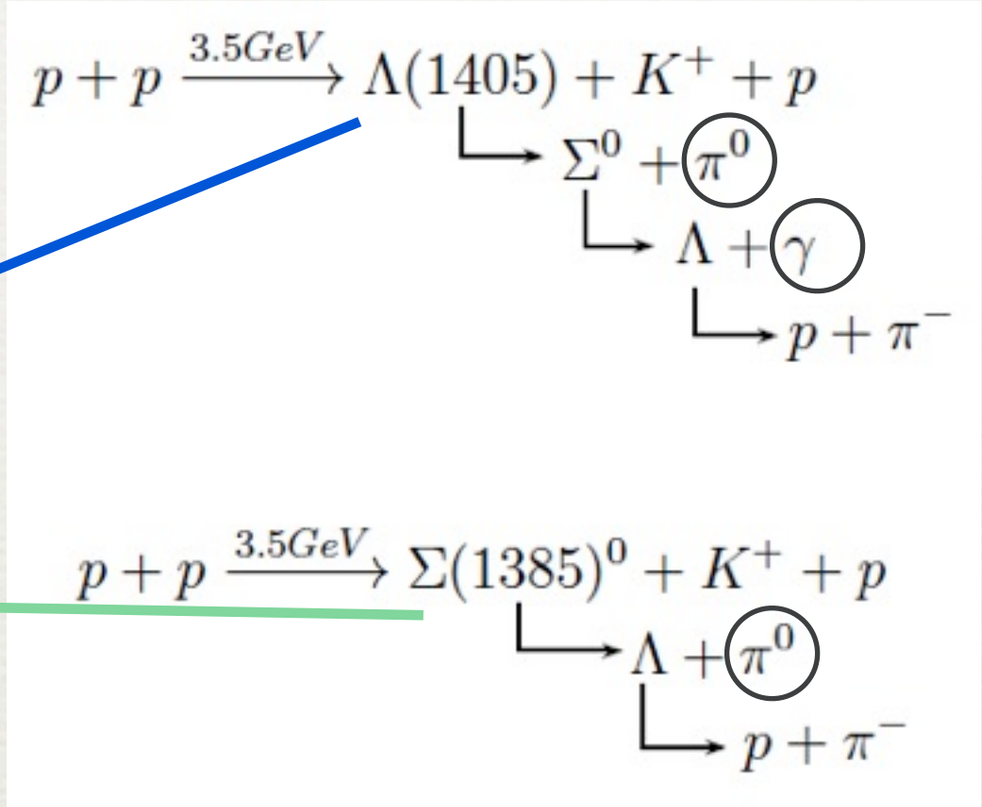
G. Agakishiev et al. [HADES] Phys. Rev. C 85 (2012) 035203.



- Important benchmark measurement.
- Information about production mechanism.

$\Sigma^0(1385)$ contribution





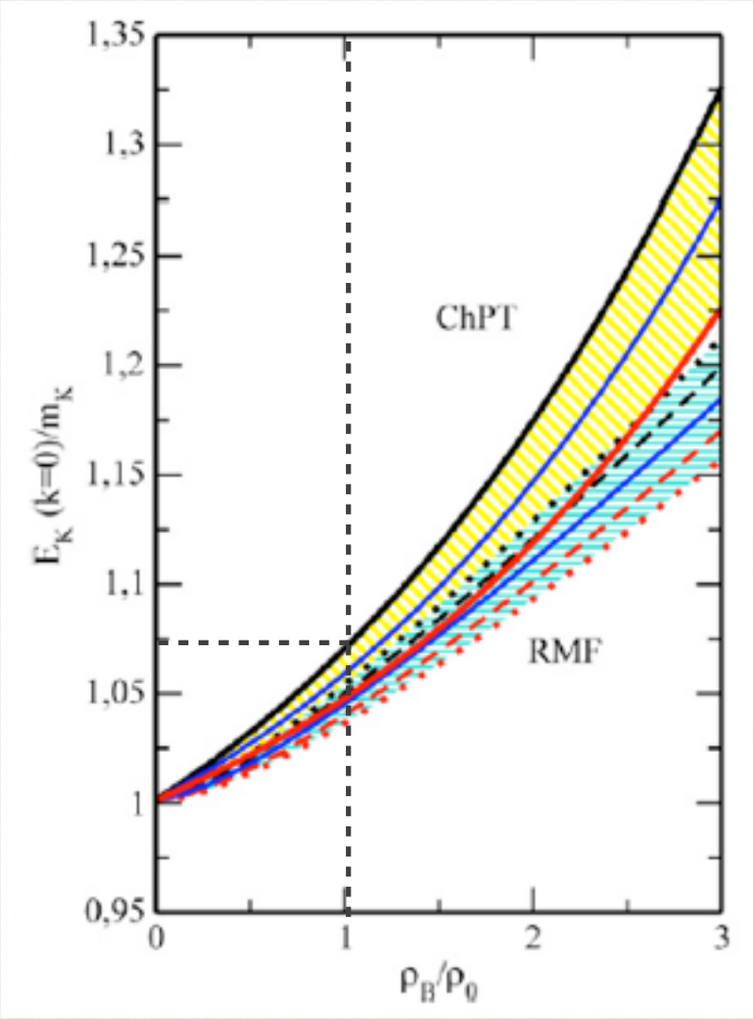
G. Agakishiev et al. [HADES]
Hyperfine interactions 210 (2012), 45.

- Separation of $\Sigma^0(1385)$ and $\Lambda(1405)$ possible.
- $\Sigma^0(1385)$ cross section is found to be 6±2 μb.

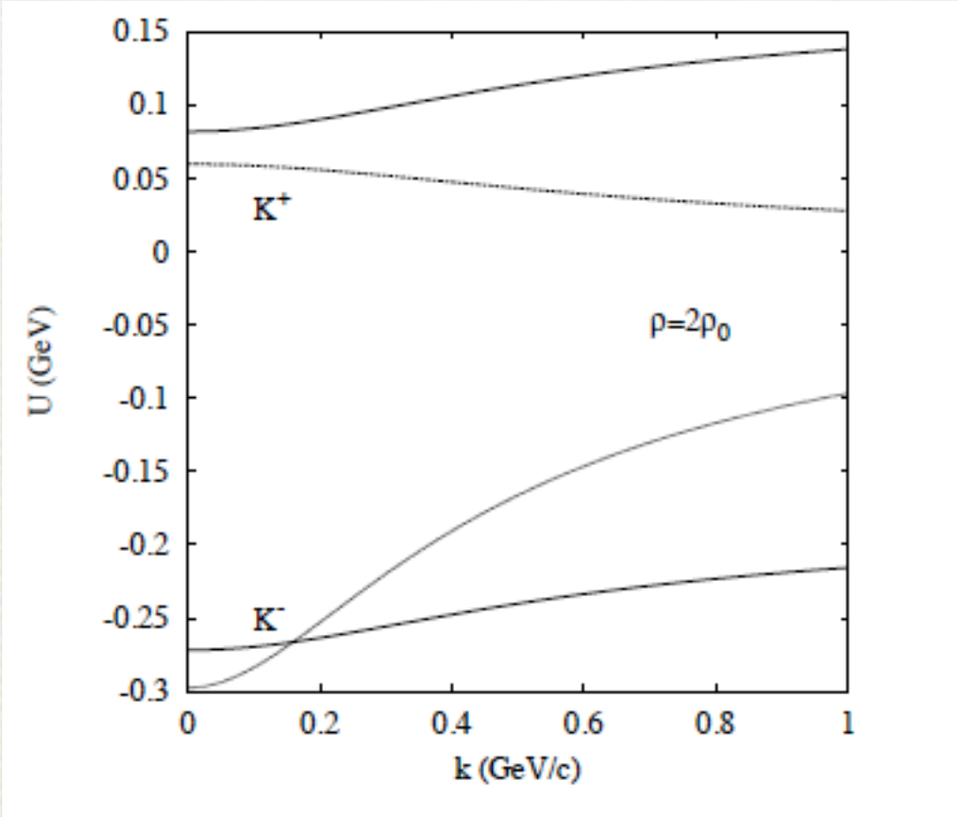
In-medium K^0 potential

In-medium ChPT repulsive potential, ~35 MeV ($\rho=\rho_0$, k=0)

$$m_K^\star = \sqrt{m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho_s \mp \frac{C}{f_\pi^2}\rho_{s3} + V_\mu V^\mu}$$

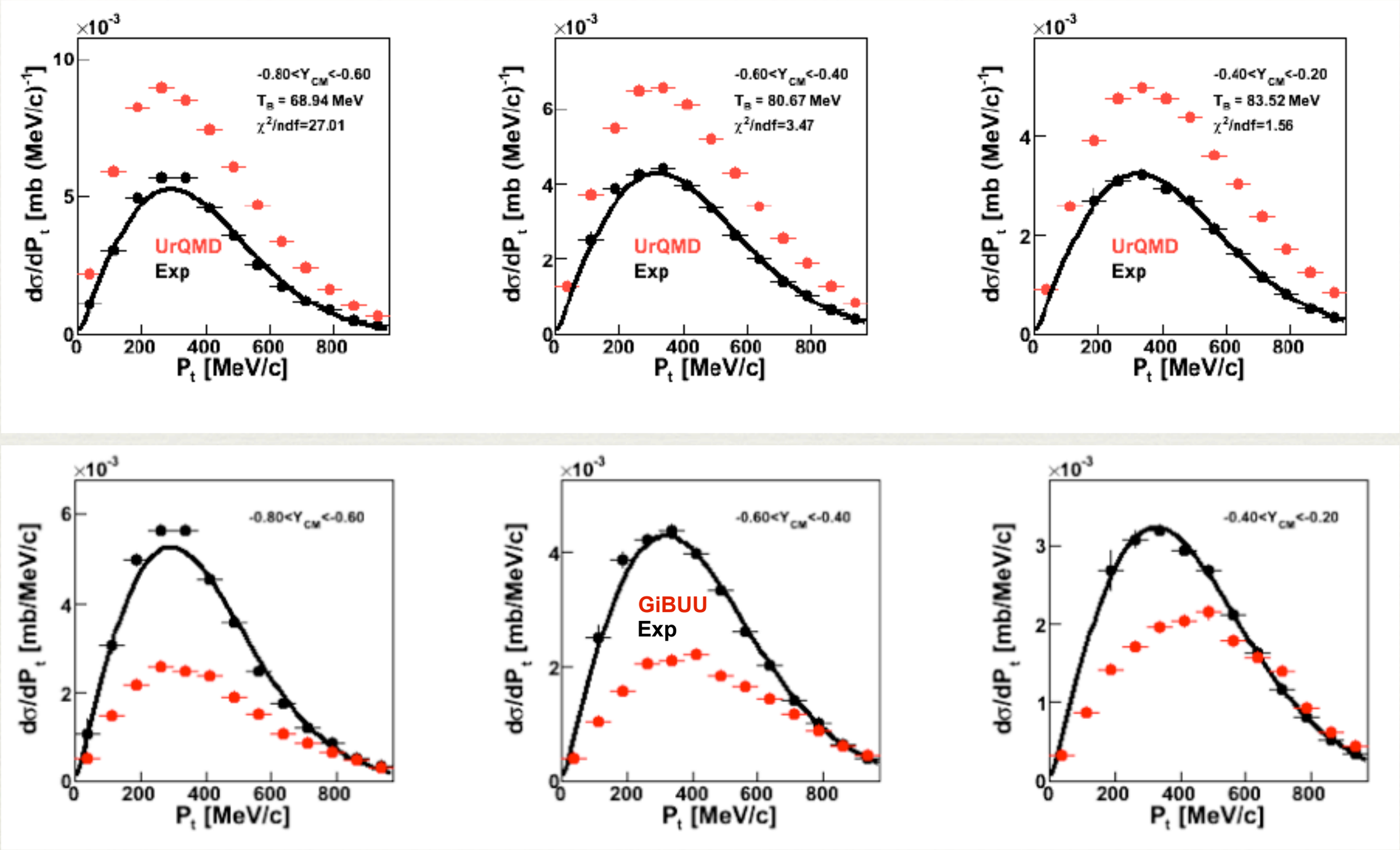


V. Prassa et al. Nucl.Phys. A789 (2007) 311



A. Larionov, private communication

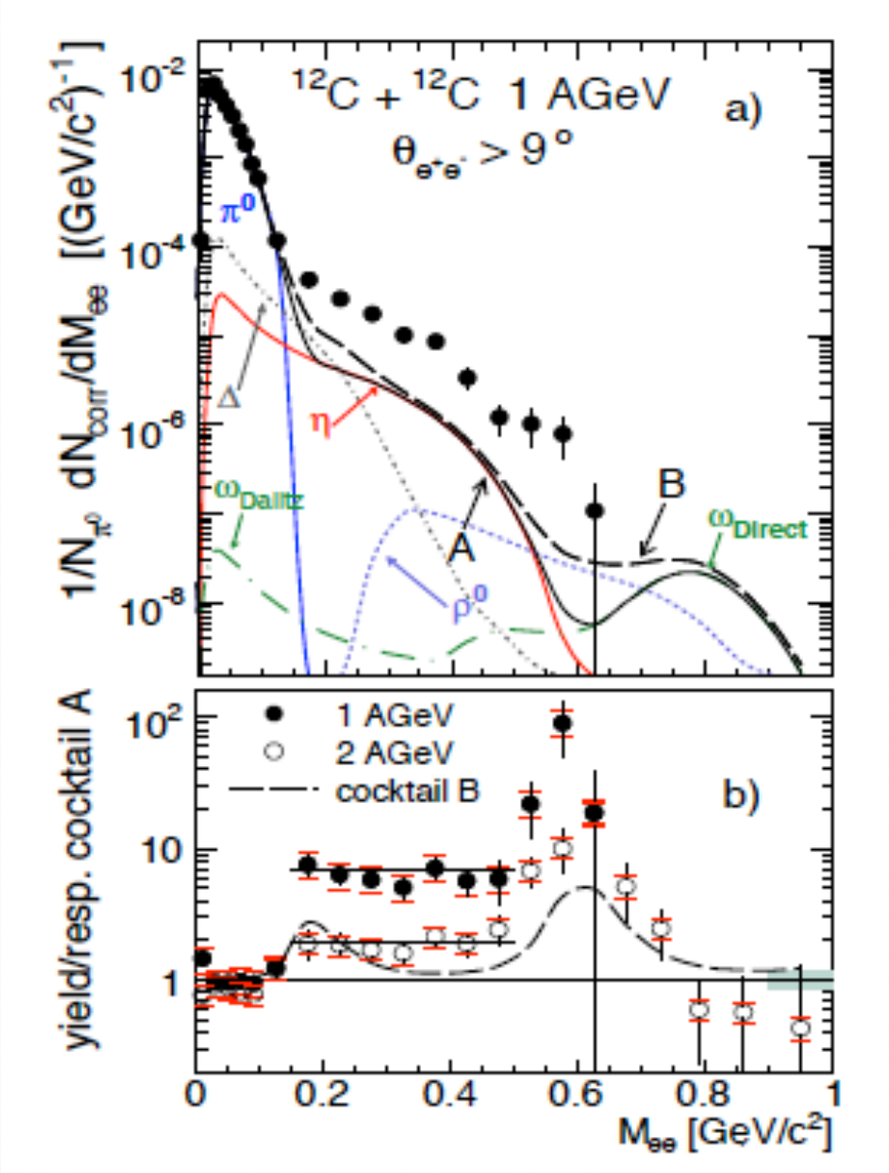
Λ(1116) in pNb at 3.5 GeV



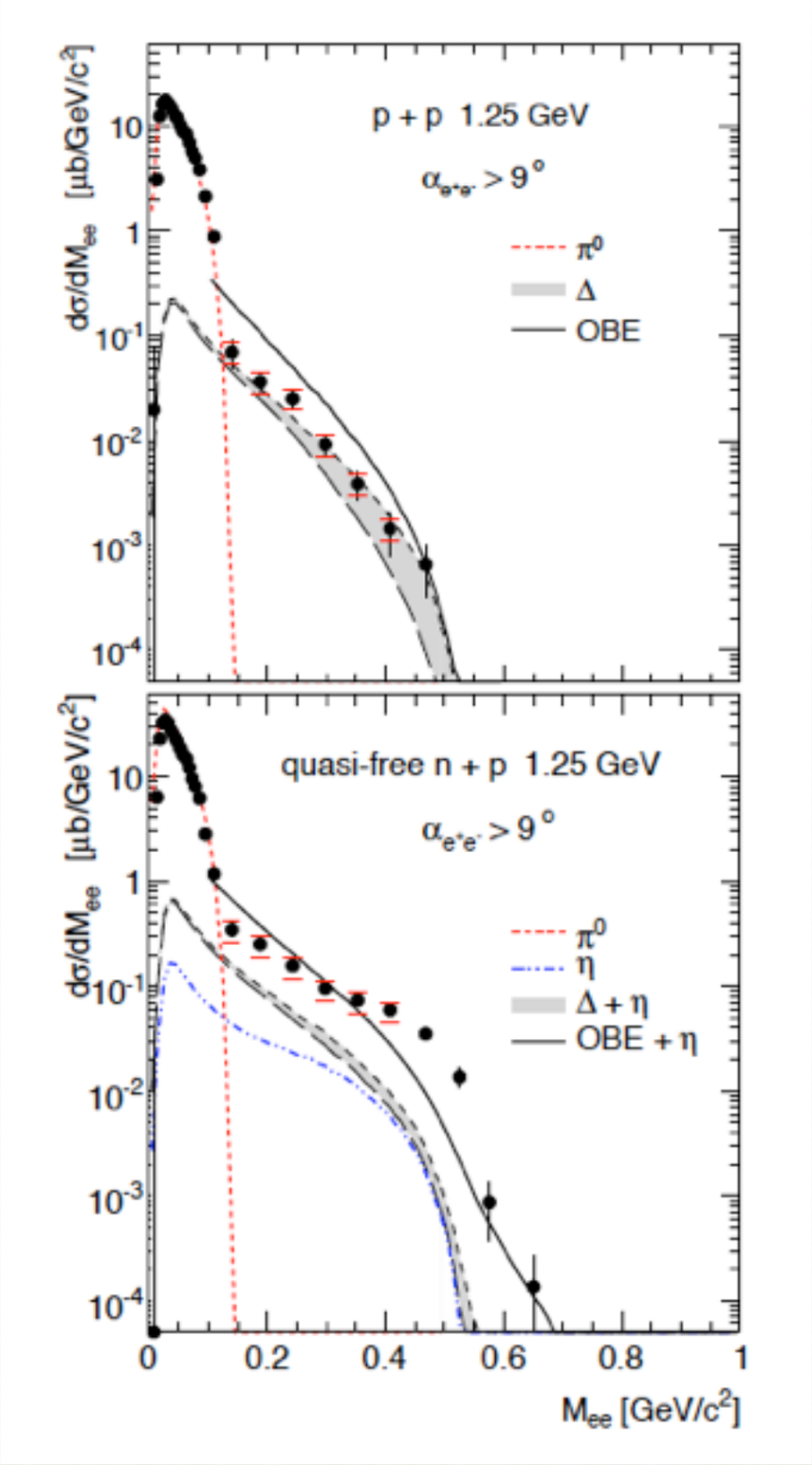
Courtesy O. Arnold

- High precision measurement done (1M Lambdas).
- Models don't describe data well (yet).
- Role of baryonic resonances? N* → K Λ.

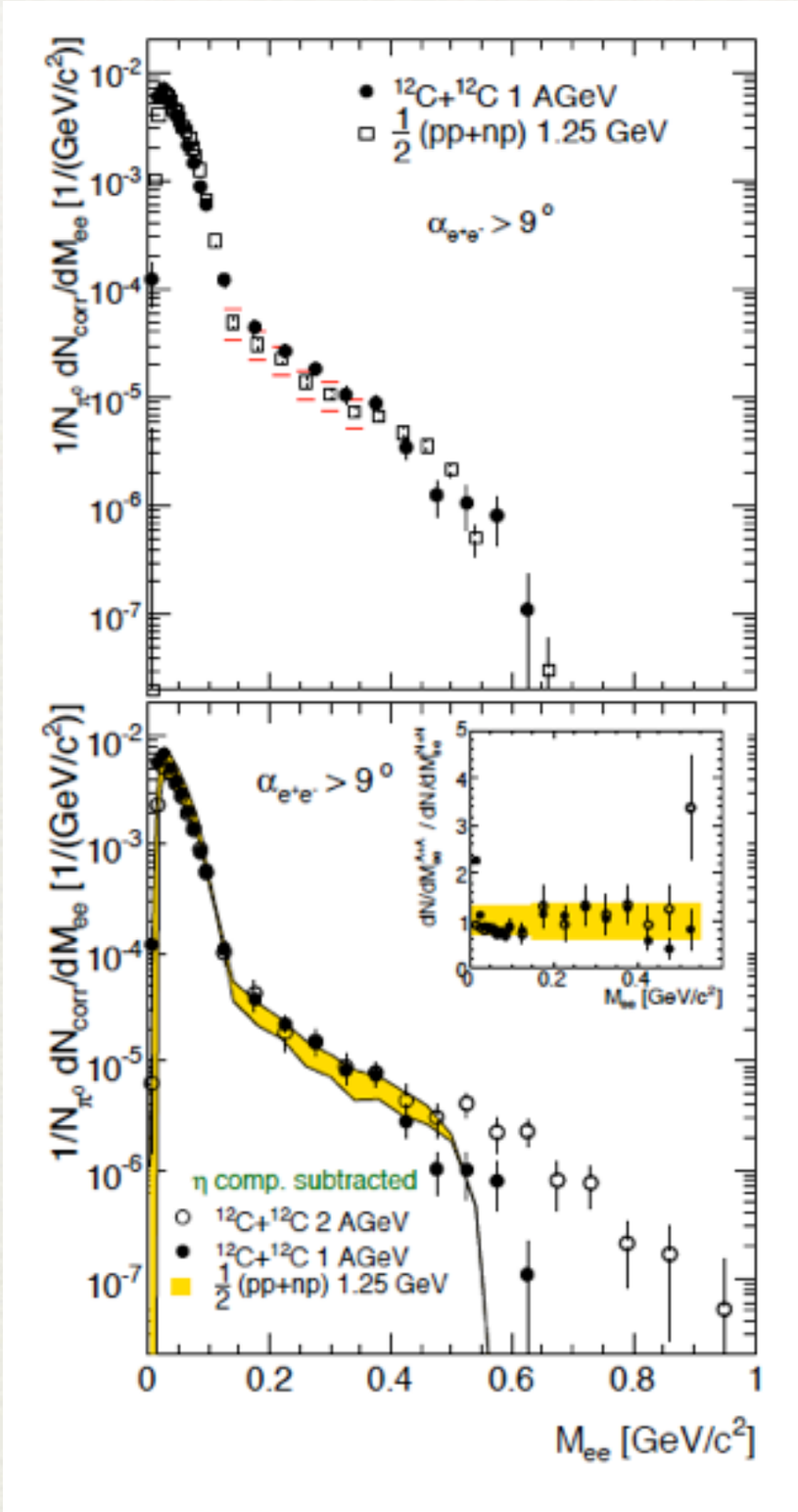
Dileptons: excess in light nuclear systems



Dileptons in nucleon-nucleon collisions



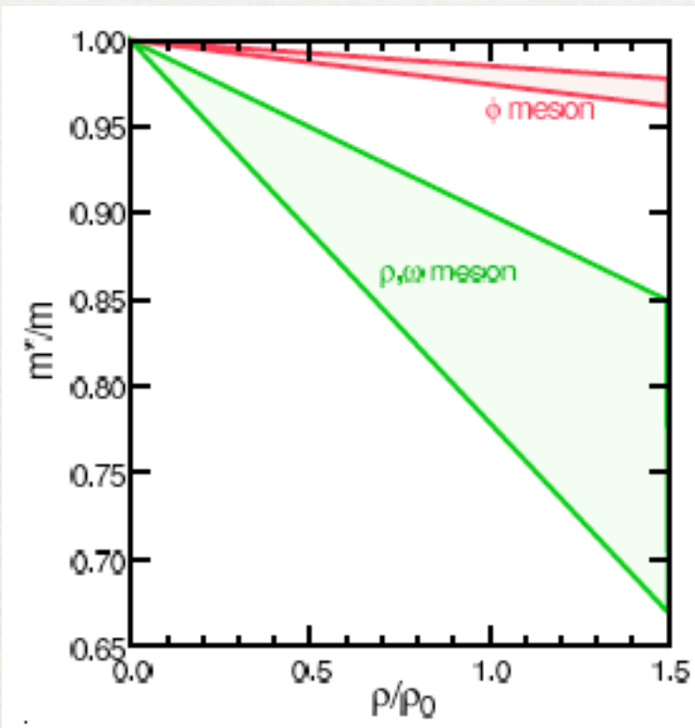
Dileptons: reference spectrum

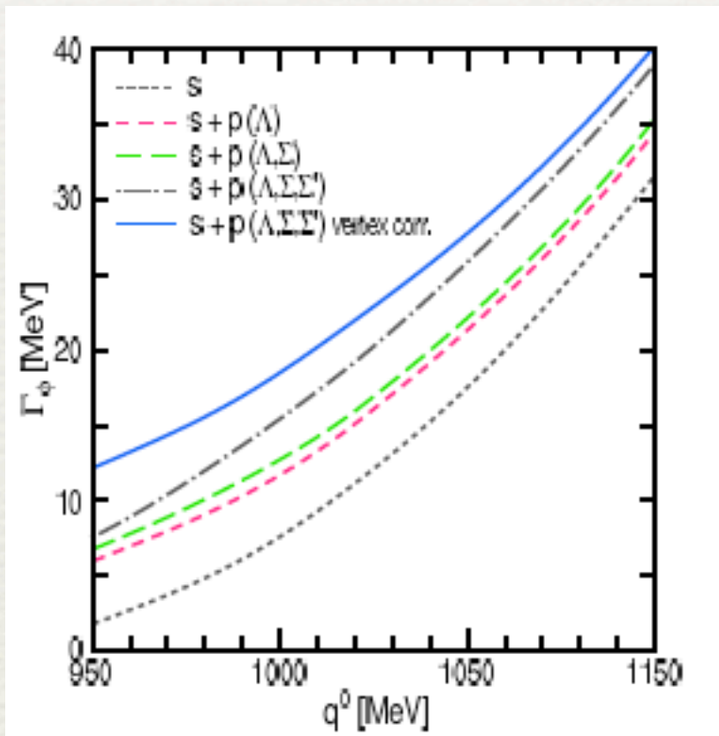


Physics case: ϕ-meson in matter

Strangeonium $|\phi\rangle = |s\bar{s}\rangle$
$M = 1020\ \mathrm{MeV}/c^2$
$\Gamma = 4\ \mathrm{MeV}/c^2$

Theoretical predictions

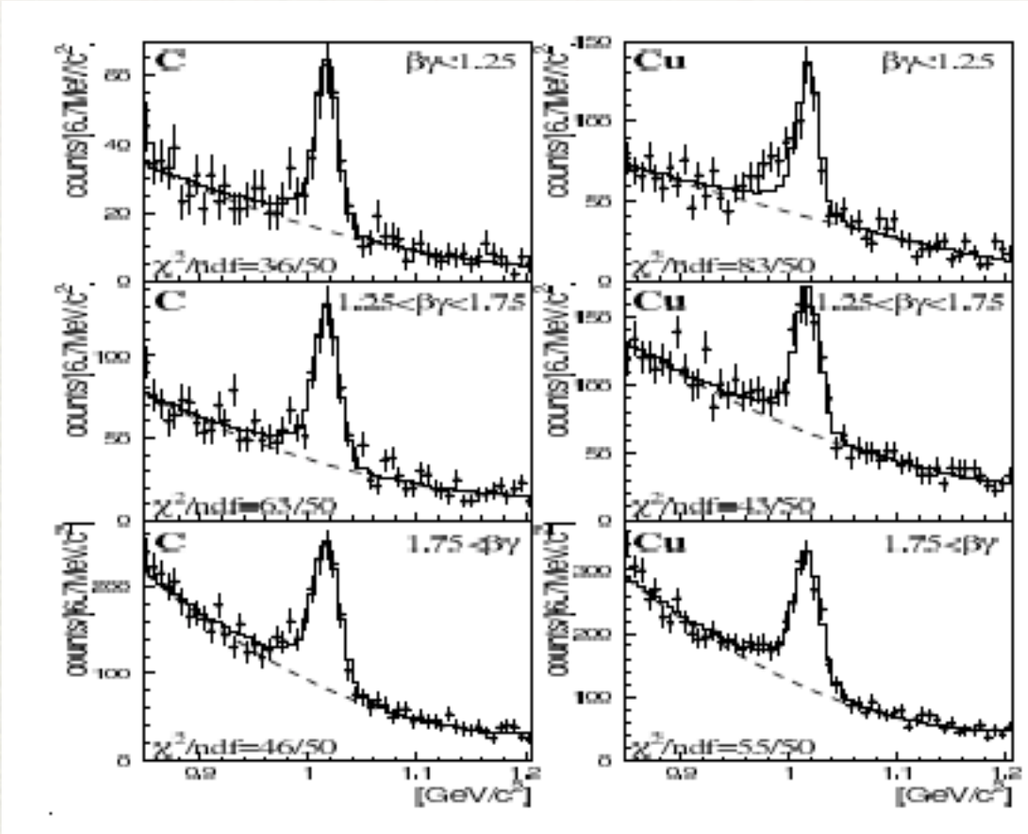




Most approaches (QCD sum rules, coupled channel calculations) predict a substantial broadening (factor 5 to 10) and a small mass shift (2-3%) of the ϕ-meson at normal nuclear density.

T. Hatsuda et al. Prog.Theor.Phys. 95 (1996) 1009-1028.
E. Oset et al. Acta Phys. Hung. A 27 (2006) 115.

Experimental information



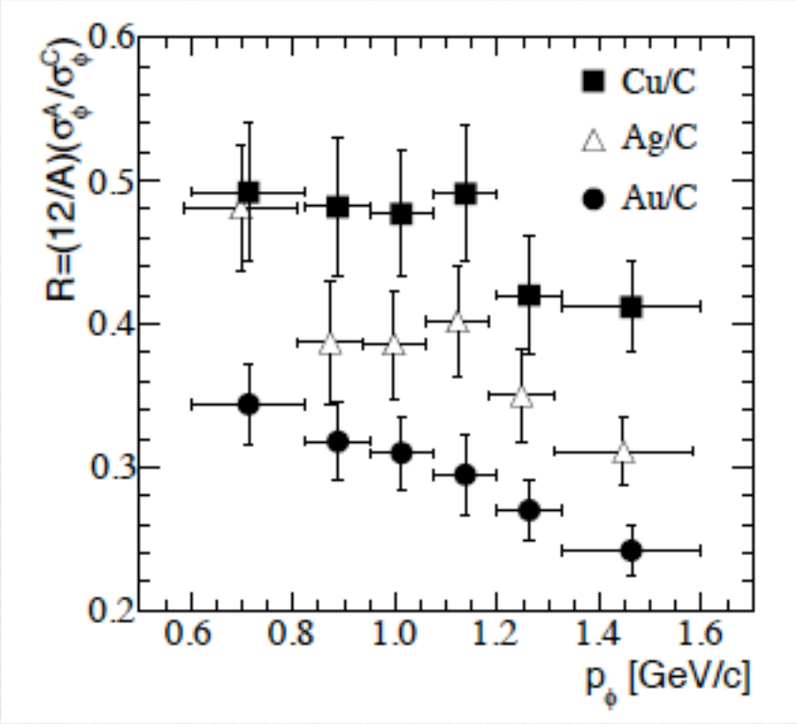
KEK-PS E325 Collaboration reported a mass shift of the ϕ-meson of 3.4%, the only observation of the ϕ mass modification.

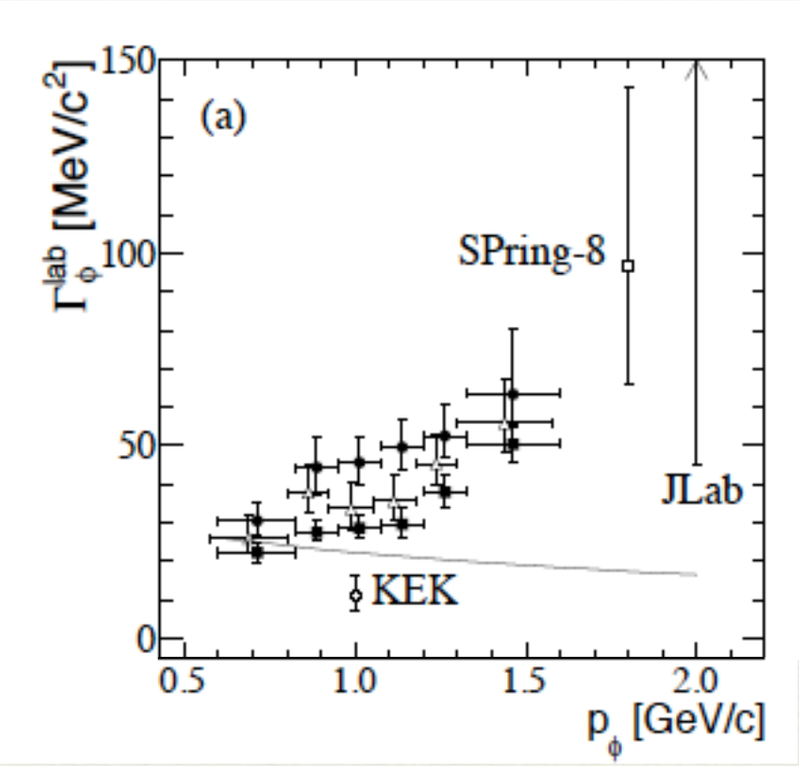
R. Muto et al. Phys. Rev. Lett. 98 (2007) 042501.

Physics case: ϕ-meson in matter

ANKE results pA at 2.83 GeV

M. Hartmann et al.
Phys.Rev. C85 (2012) 035206





- Only very forward mesons were measured: accessible $\theta_\phi < 8°$.
- Experience with kaons shows importance of a broad phase space coverage.
- HADES can do better here.

Partial Wave decomposition

$$A = \sum A^{\alpha}_{tr}(s) Q^{in}_{\mu_1 \ldots \mu_J}(SLJ) A_{2b}(i, S_2 L_2 J_2)(s_i) \times \; Q^{fin}_{\mu_1 \ldots \mu_J}(i, S_2 L_2 J_2 S' L' J) \; . \quad (2)$$

$$A^{\alpha}_{tr}(s) = \left(a^{\alpha}_1 + a^{\alpha}_3 \sqrt{s}\right) e^{i a^{\alpha}_2}$$

S,L,J – spin, orbital mom. and total angular momentum of the pp system
S_2, L_2, J_2 – spin, orbital mom. and total angular momentum of the two particle system in fin. state
S',L' – spin, orbital mom. between the two particle system and the third particle with four mom. q_i
multiindex α – possible combinations of the S, L,J, S_2, L_2, J_2, S', L' and i
A_{tr}^{α} (s) - transition Amplitude
A_{2b}^{α} (i,S_2,L_2,J_2) – rescattering process in he final two-particle channel (e.g. production of Δ)

http://pwa.hiskp.uni-bonn.de/

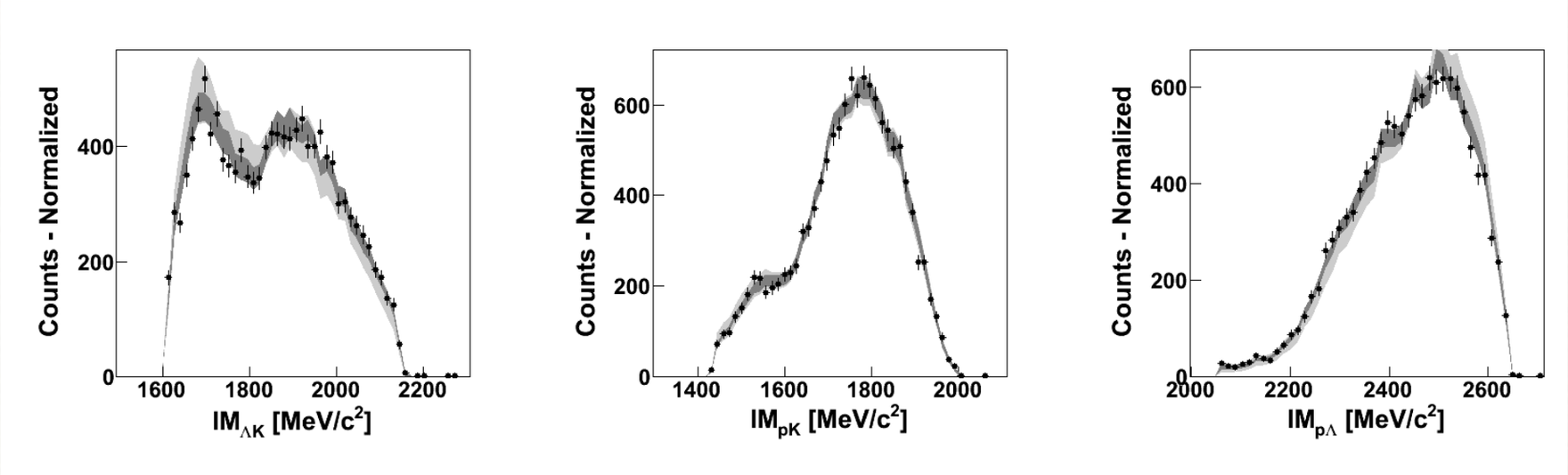
A.V. Anisovich, V.V. Anisovich, E. Klempt, V.A. Nikonov and A.V. Sarantsev
Eur. Phys. J. A 34, 129152 (2007)

Resonances included in the solution

Notation in PDG	old	Mass GeV/c^2	Width GeV/c^2	$\Gamma_{\Lambda K}/\Gamma_{All}$
N(1650) $\frac{1}{2}^-$	N(1650)S_{11}	1.655	0.150	3-11%
N(1710) $\frac{1}{2}^+$	N(1710)P_{11}	1.710	0.200	5-25%
N(1720) $\frac{3}{2}^+$	N(1720)D_{13}	1.720	0.250	1-15%
N(1875) $\frac{3}{2}^-$	N(1875)D_{13}	1.875	0.220	?
N(1880) $\frac{1}{2}^+$	N(1880)P_{11}	1.870	0.235	?
N(1895) $\frac{1}{2}^-$	N(1895)S_{11}	1.895	0.090	?
N(1900) $\frac{3}{2}^+$	N(1900)P_{13}	1.900	0.250	0-10%

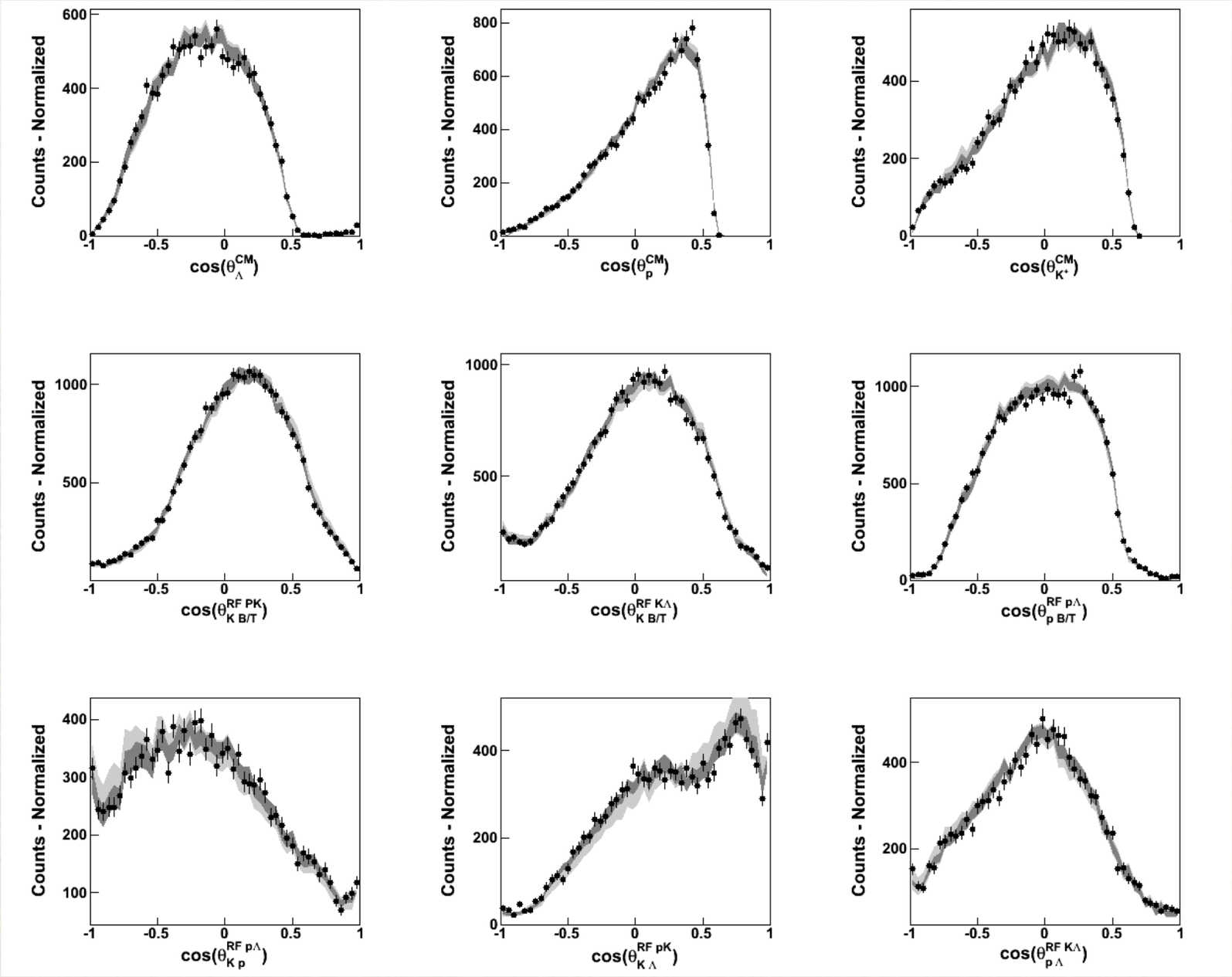
Solution for pp → pΛK⁺: mass spectra

Data
10 solutions
4 best solutions

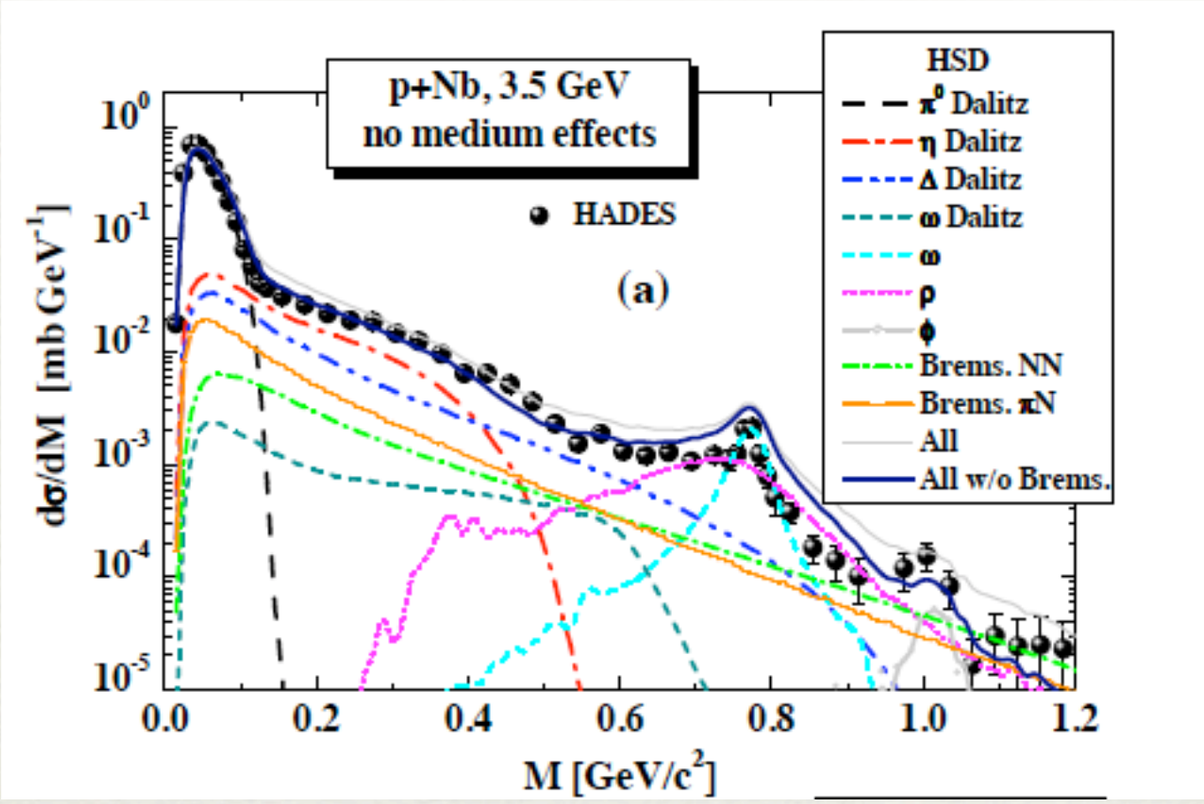


Solution for pp → pΛK⁺: angular distributions

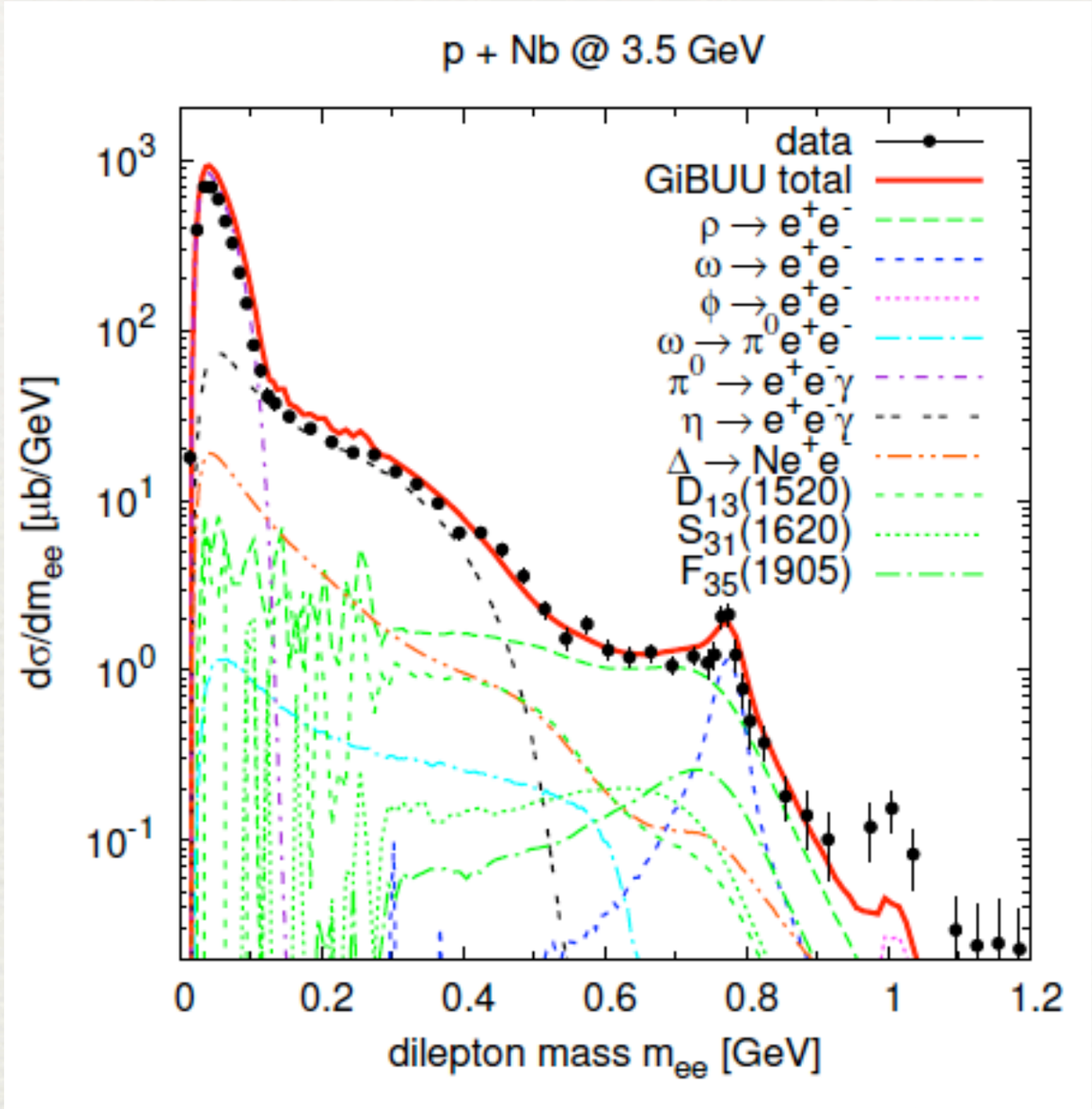
Data
10 solutions
4 best solutions



Vector mesons in cold nuclear matter: models



E. Bratkovskaya et al.,
Phys. Rev. C 87, 064907 (2013)



GiBUU model, J. Weil, ECT* Workshop 2013