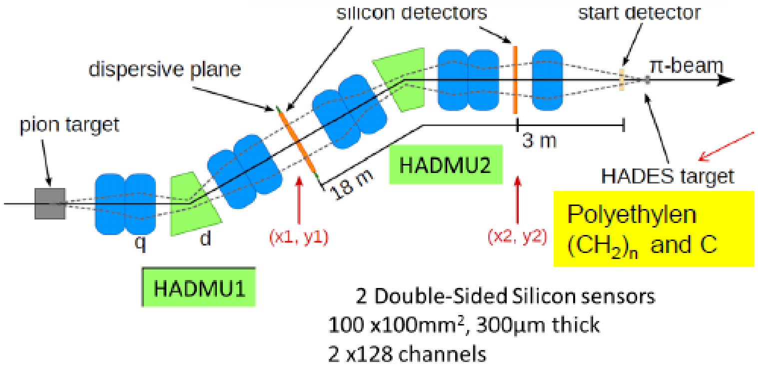
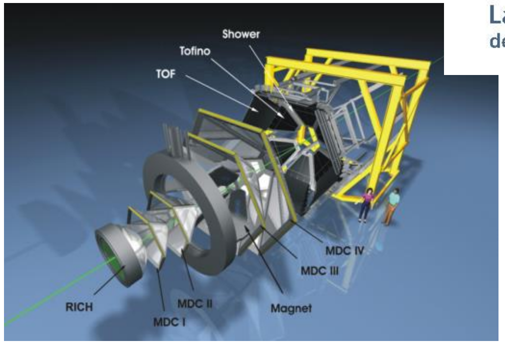


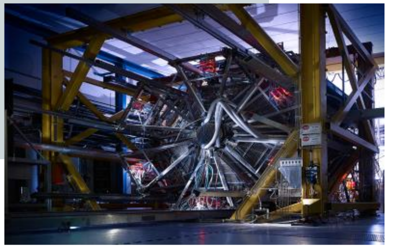


Results from pion beam experiments with HADES

Béatrice Ramstein, IJCLab, Orsay, France

EMMI Workshop
Probing dense baryonic matter with hadrons II: FAIR Phase-0
GSI, February 19-21 , 2024

Outline



❑ Motivations:

- hadronic physics studies (π^- + p)
- Cold matter studies (π^- + A)

Ahmed Foda's talk

→ *Validation of hadronic models*

❑ HADES data vs transport models :

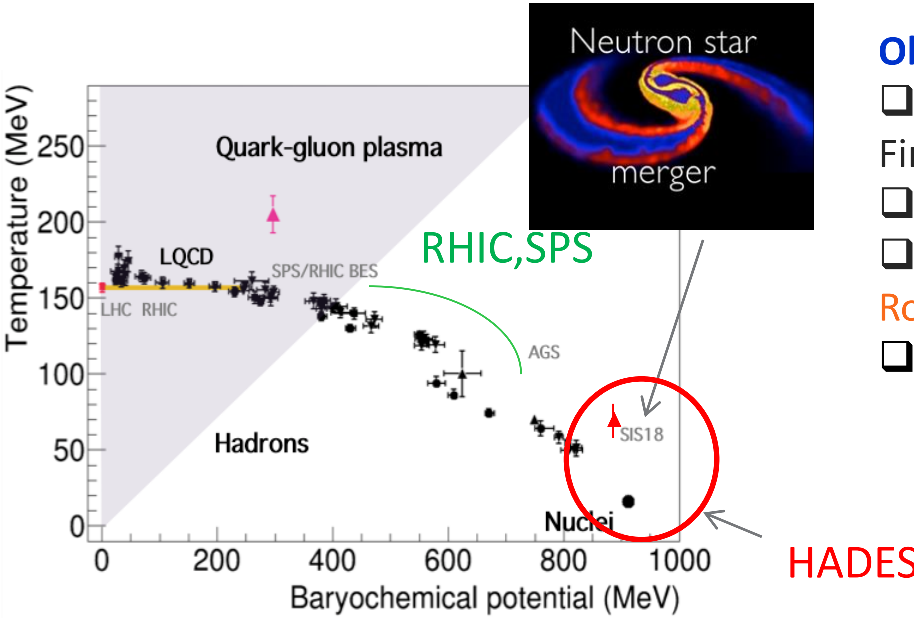
Examples from Heavy-ion and proton induced reactions (focus on hadron production)

❑ Results of HADES pion beam experiment

- π^- + C 0.69 GeV/c
- π^- + W/C 1.7 GeV/c

❑ Conclusion-outlook

HADES: exploring dense QCD matter



T. Galatyuk, NPA-D-18-00411 (2018) QM18

Objectives

- ❑ Equation-of-State:

First order transition ? Search for a critical point

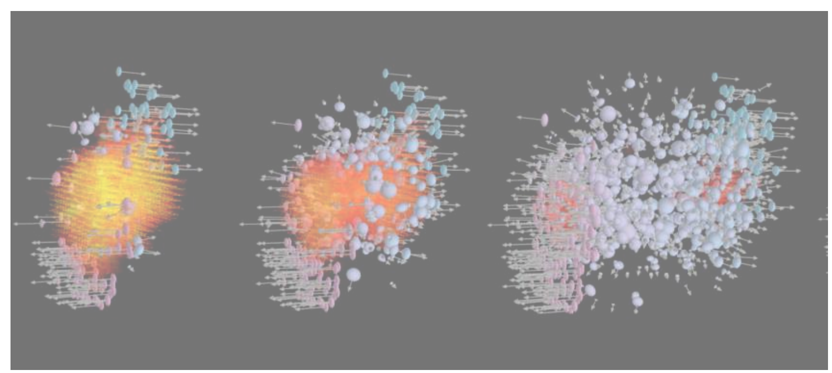
- ❑ Chiral symmetry restoration
- ❑ Microscopic structure of baryon dominated matter

Role of baryonic resonances, hyperons

- ❑ Complementary to SPS,RHIC,..

A+A: 1-3A GeV

√s=2-2.4 GeV



Observables:

- ✓ Correlations and fluctuations

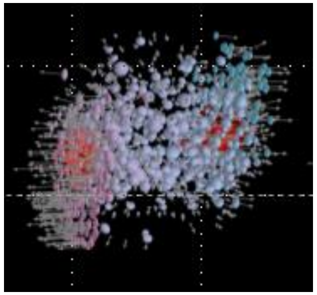
(Romain Holzmann's talk)

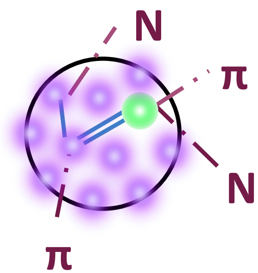
- ✓ Collective effects

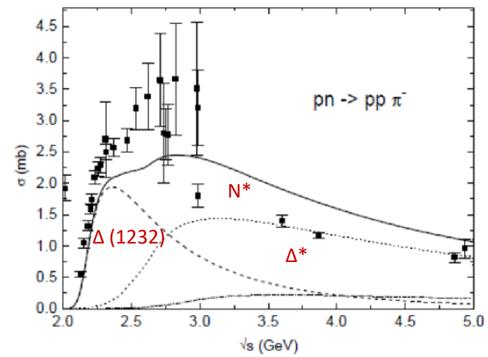
(Behruz Kardan's talk)

- ✓ Strangeness
- ✓ Dileptons
- ✓ Hadron yields

Pion dynamics for heavy ion collisions at a few AGeV







Pion production dominates the inelastic NN cross section

→ Pion-nucleus dynamics crucial to describe the evolution of HI collisions

→ thermalization processes of nuclear medium

→ particle yields

- $\sqrt{s_{NN}}$ < 2.6 GeV (A+A SIS18@GSI)

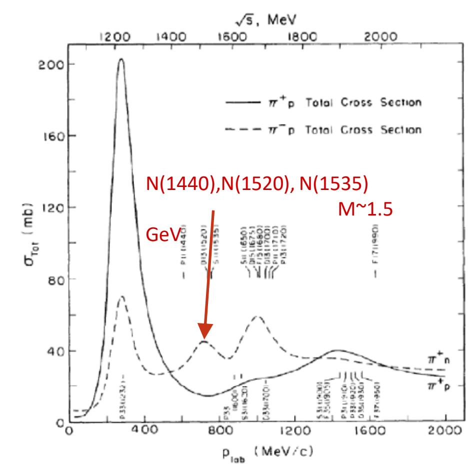
  most pions in the Δ(1232) region

  well studied experimentally → Δ-hole model

- $\sqrt{s_{NN}}$ > 2.6 GeV basically not investigated

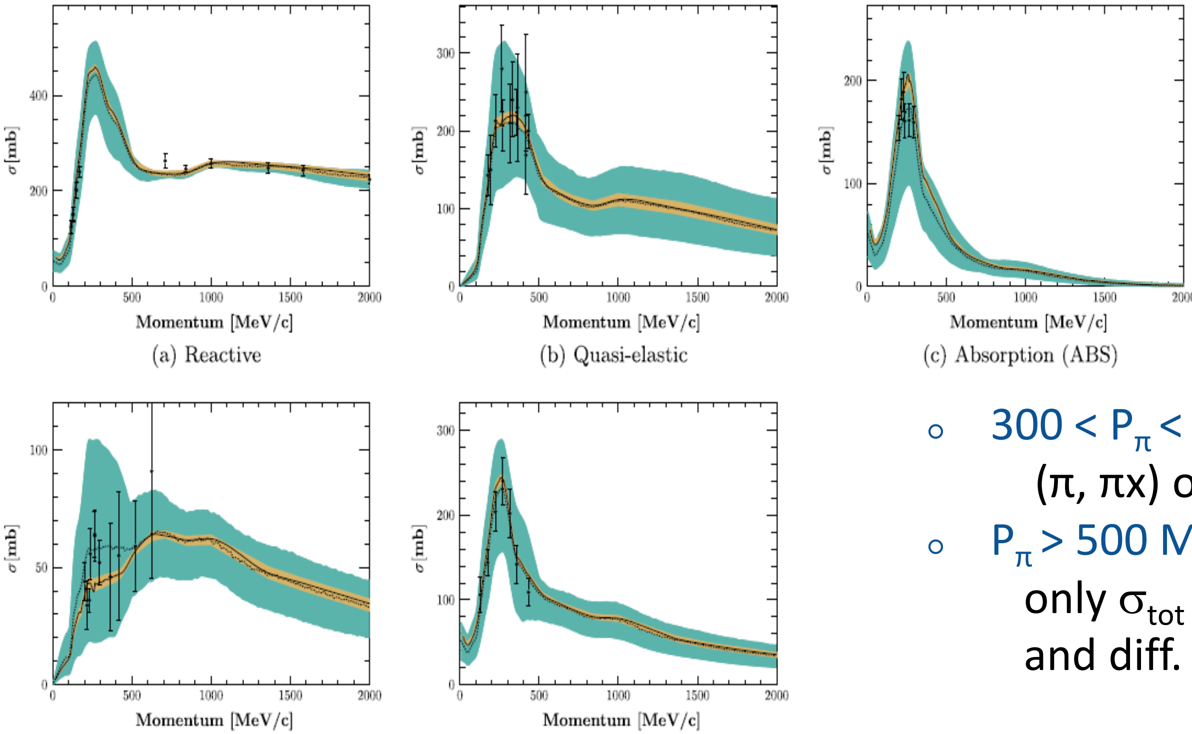
Future experiments: p+A (SIS18@GSI & SIS100@FAIR) or A+A (SIS100)

Higher lying resonances contribute.



Data base for pion-nucleus reactions

$\pi^+ + {}^{12}C$



(a) Reactive (b) Quasi-elastic (c) Absorption (ABS) (d) Charge exchange (CX) (e) ABS+CX

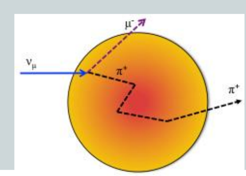
E.S. Pinzon Guerra et al.,
Phys. Rev. D 99, 052007 (2019)

($\pi^- + {}^{12}C$ data even more scarce !)

- $300 < P_\pi < 500$ MeV/c : few measurements (π, πx) or (π, $\pi\pi$x) (LAMPF, TRIUMF, KEK).
- $P_\pi > 500$ MeV/c : only σ_{tot} (Saturne-1, NIMROD, BNL) and diff. elast. cross sections (KEK).

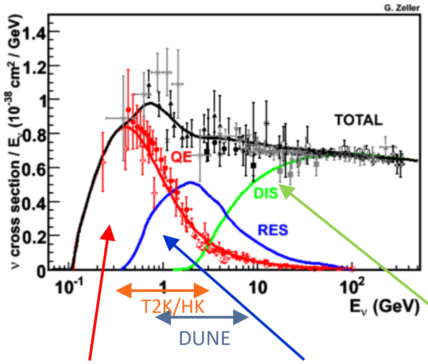
Missing measurements for $p_\pi > 500$ MeV to validate hadronic/cascade models

- for hadronic matter studies at $\sqrt{s_{NN}} > 2.6$ GeV
- for detector studies (e.g. e/π discrimination in calorimeters)
- for neutrino physics (ν flux and ν detection)



ν/π−nucleus interactions

ν cross sections

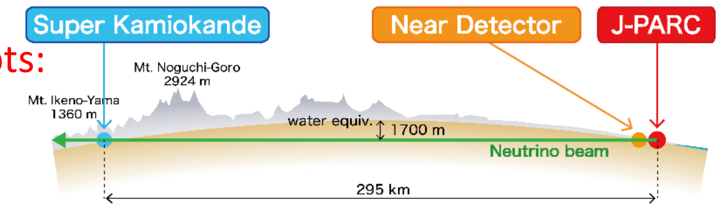


Long Based Line (LBL) ν oscillation expts:

ν/ $\bar{\nu}$ yields measured as a function of energy in Near and Far detectors

Detector material:

T2K/HK : $H_2 0$ and CH ; DUNE: Ar

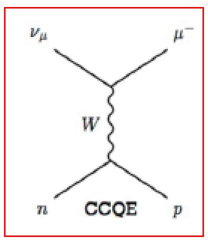


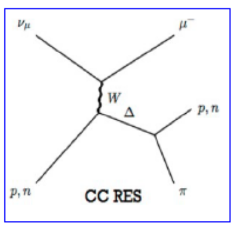
a large fraction (~50%) of the uncertainties on ν oscillation parameters is due to hadronic models (INCL++, GIBUU,…needed to reconstruct ν energy) !

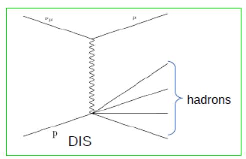
Quasi-elastic

Resonance excitation (1 pion emission)

Deep Inelastic (multi-particle emission)

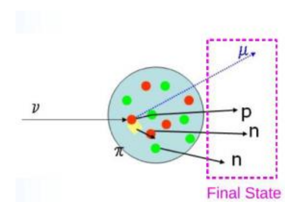






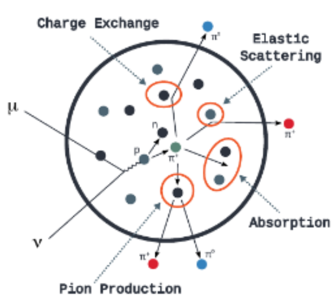
Evolution of LBL experiments :

→ detect as many reaction products as possible (p, π, n,…)



well constrained

large uncertainties



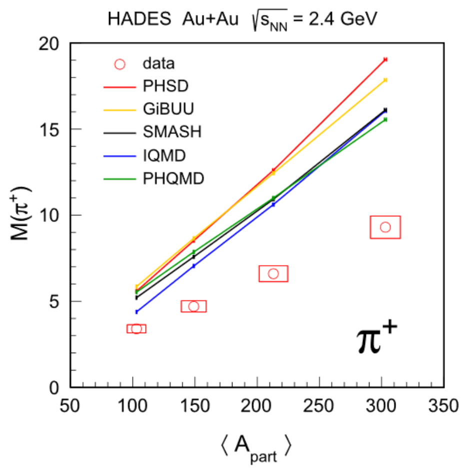
Hadronic channels in pion beam (HADES) data can help !

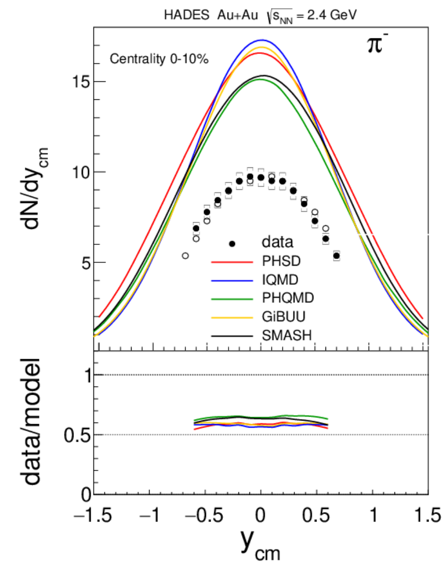
- different primary interaction w.r.t. neutrino-nucleus interaction, but similar energy dissipation processes (elastic/inelastic reactions, baryon resonance propagation, pion regeneration)
- can validate models in well constrained conditions (known energy transfer)

HADES data vs transport models (I)

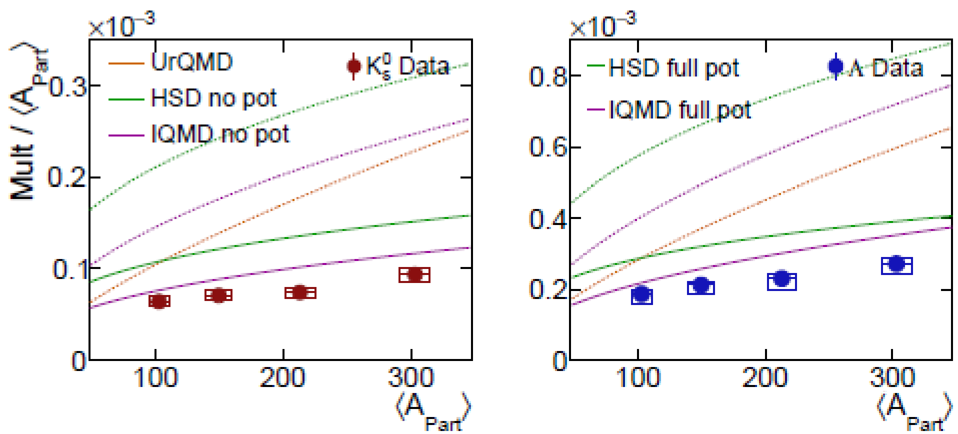
Au+Au @ 1.25A GeV

HADES: Eur.Phys.J.A 56 (2020) 259





Overestimation of pion yields
(about x 2)



HADES: Phys.Lett.B 793 (2019) 457-463

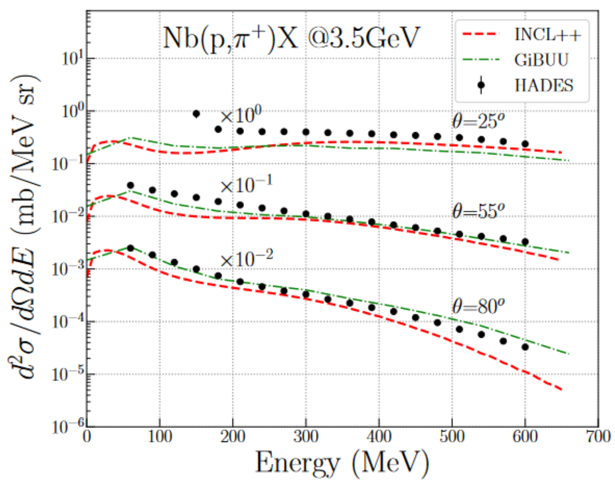
No fully consistent picture:
No clear conclusion
about K-N potentials
can be drawn

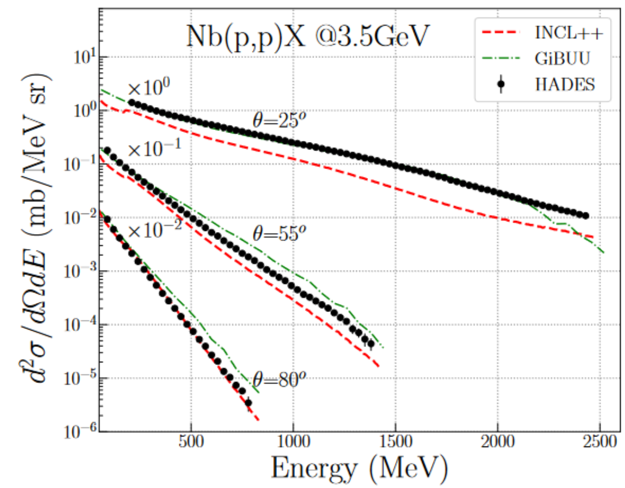
HADES data vs transport models (II)

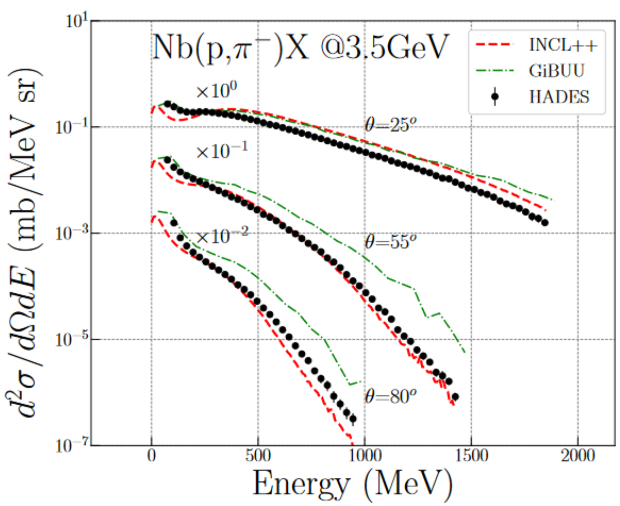
p+Nb @ 3.5 A GeV

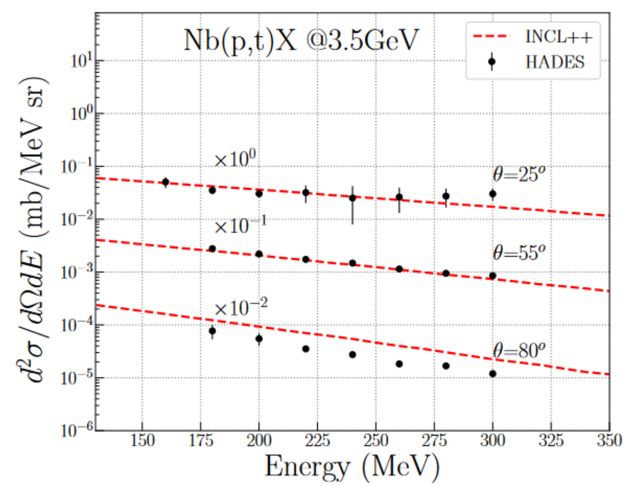
HADES Phys. Rev. C 108, 064902

Deviations of hadron yields w.r.t GIBUU by up to a factor 2

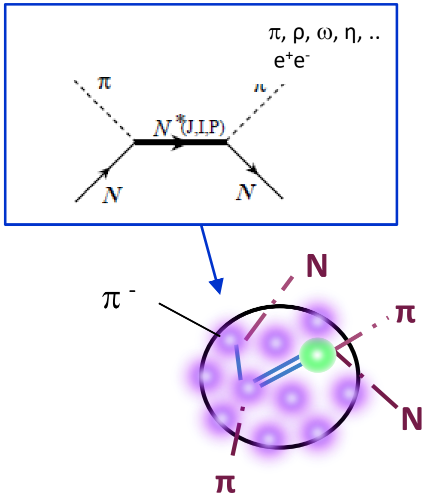




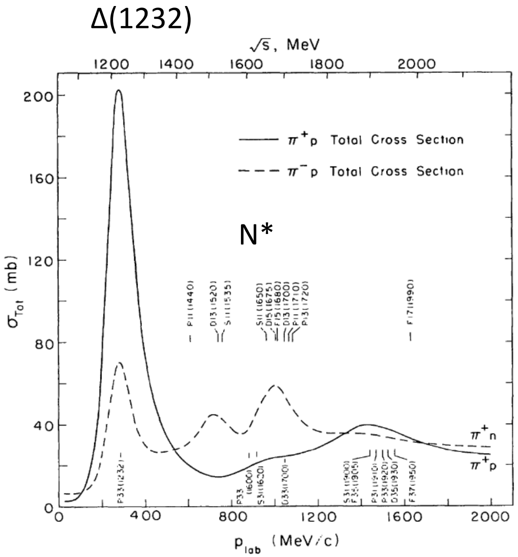




Interest of π induced reactions for hadronic matter studies



1. π^{-} + A: direct test of pion dynamics in nucleus
   different mechanisms: elastic/inelastic channels, pion absorption



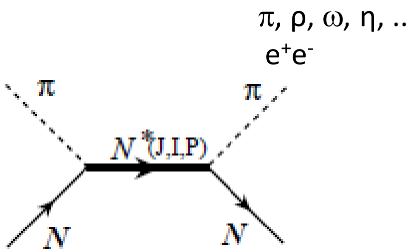
2. Well defined energy deposit in the nucleus
   production of baryon resonances
   with given mass in s-channel

$$M_R \sim \sqrt{s_{\pi p}}$$

→ Test models in « simpler » conditions

3. Medium effects : « recoilless » production of particles,
→ higher sensitivity to medium effects than p+A collisions

Interest of π induced reactions for baryon structure studies



Production of baryon resonance with given mass in s-channel

$M_R=\sqrt{s_{\pi p}}$

- Very precise data base for γ induced reactions (polarization)
- π+N data are very scarce and date back to the 80's in many channels (few differential cross sections,…)
- Baryon structure knowledge relies on Partial Wave Analysis or coupled channel analysis which need both types of information !

This knowledge is also needed for hadronic matter studies !

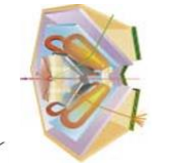
See Foda 's talk

	All	πN	γN	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\sigma$
$N(1440)\frac{1}{2}^+$	****	****	****	(*)			***	***
$N(1710)\frac{1}{2}^+$	***	***	***	***	***	**	*(*)	
$N(1880)\frac{1}{2}^+$	**	*	*		**	*		
$N(1535)\frac{1}{2}^-$	****	****	****	****			*	
$N(1650)\frac{1}{2}^-$	****	****	***	***	***	**	**(*)	
$N(1895)\frac{1}{2}^-$	**	*	**	**	**	*		
$N(1720)\frac{3}{2}^+$	****	****	****	****	**	**	***	
$N(1900)\frac{3}{2}^+$	***	**	***	**	***	**	**	
$N(1520)\frac{3}{2}^-$	****	****	****	***			****	
$N(1700)\frac{3}{2}^-$	***	**	**	*	*(*)	*	***	
$N(1875)\frac{3}{2}^-$	***	*	***		***	**		***
$N(2150)\frac{3}{2}^-$	**	**	**		**		**	
$N(1680)\frac{5}{2}^+$	****	****	****	*			**(*)	**
$N(1860)\frac{5}{2}^+$	*	*	*					
$N(2000)\frac{5}{2}^+$	***	*(*)	**	**	**	*		
$N(1675)\frac{5}{2}^-$	****	****	***(*)	*	*		***(*)	*
$N(2060)\frac{5}{2}^-$	***	**	***	*		**		
$N(1990)\frac{7}{2}^+$	**	*(*)	**					
$N(2190)\frac{7}{2}^-$	****	****	***		**			
$N(2220)\frac{9}{2}^+$	****	****						
$N(2250)\frac{9}{2}^-$	****	****						
$\Delta(1910)\frac{1}{2}^+$	****	****	**			**	**	
$\Delta(1620)\frac{1}{2}^-$	****	****	***				****	
$\Delta(1900)\frac{1}{2}^-$	**	**	**			**	**	
$\Delta(1232)\frac{3}{2}^+$	****	****	****					
$\Delta(1600)\frac{3}{2}^+$	***	***	***				***	
$\Delta(1920)\frac{3}{2}^+$	***	***	**			***	**	
$\Delta(1700)\frac{3}{2}^-$	***	***	***				**	
$\Delta(1940)\frac{3}{2}^-$	*	*	**				|* from $\Delta\eta$|	
$\Delta(1905)\frac{5}{2}^+$	****	****	****			***	**(**)	
$\Delta(1950)\frac{7}{2}^+$	****	****	***			***	***	

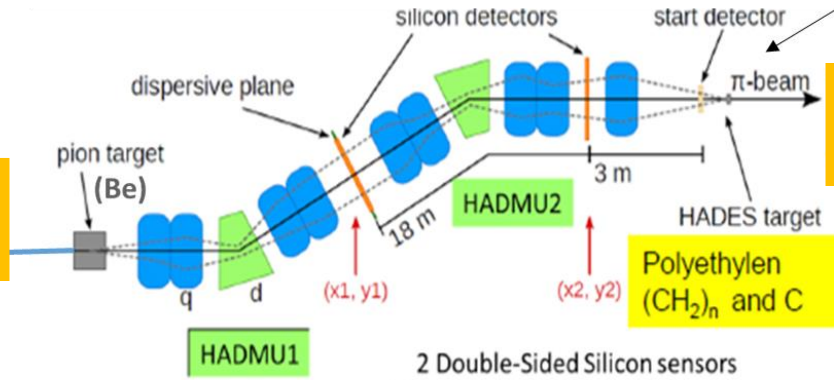
(Eur. Phys. J. A 48, 15 (2012)

HADES pion beam line at GSI

HADES coll. Eur. Phys. J. A (2017) 53: 18

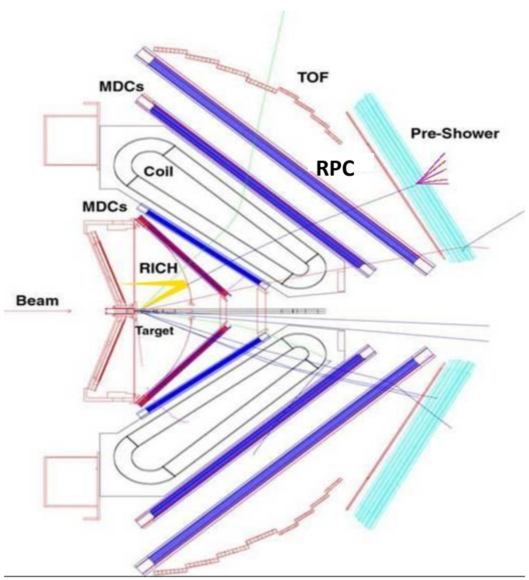


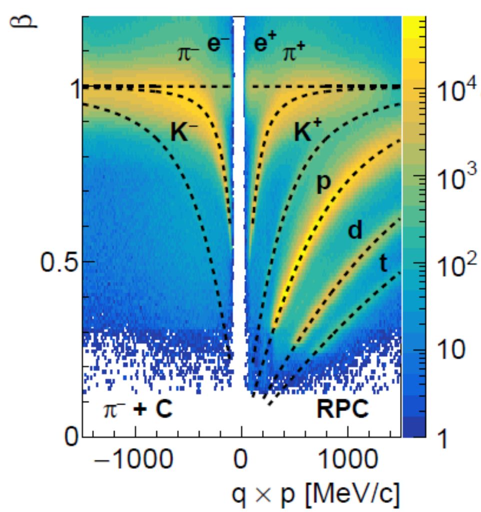
^{14}N 2 AGeV
4 x10^{10} ions/s



2 x10^5 π^-/s
Δp=1.7 % (rms)

2 Double-Sided Silicon sensors
100 x100mm^2, 300μm thick
2 x128 channels





- Acceptance: θ: 18° - 85°
  ϕ : 85% (6 sectors)
- Magnet (toroïdal field)
- Tracking: drift chambers
- RICH: e+/e-
- Time of flight : RPC (θ < 45°)
  and scintillators (θ > 45°)
- Trigger : 2 charged particles

HADES pion beam experiments

August 2014 : **N(1520) region** (12 days)
C and CH_2 targets

Main interest: baryon studies in π^-+p reaction

- $\pi\pi$ channels: (4 measurements $\sqrt{s}$ =1.46-1.55 GeV)

hadronic couplings to $\Delta\pi$, ρN and σN channels

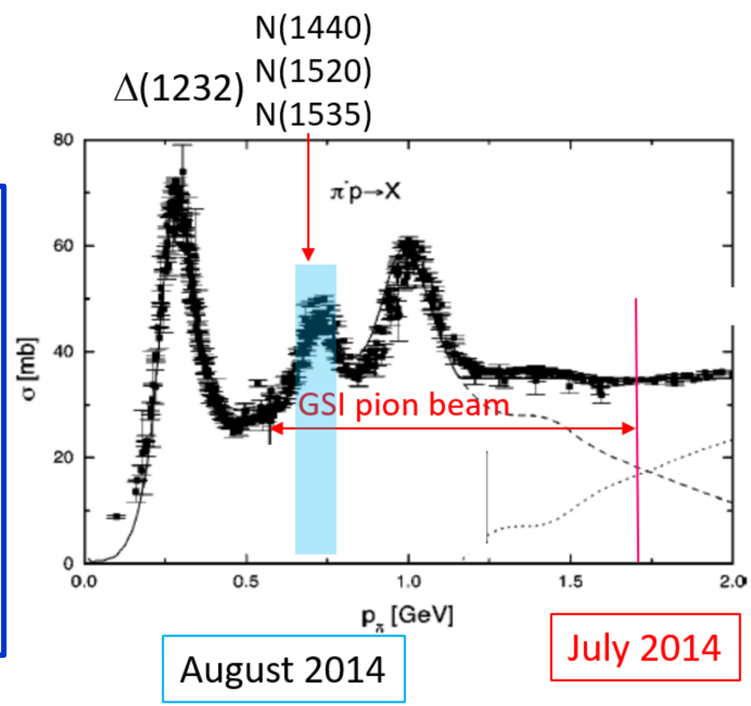
HADES Phys.Rev. C102 (2020) 024001.

- e^+e^- channels : $\sqrt{s}$ =1.49 GeV/c^2 (p=0.685 GeV/c)

time-like electromagnetic baryon transitions.

HADES arXiv: 2205.15914 [nucl-ex]

HADES arXiv: 2309.13357 [nucl-ex]



⋆ Data on carbon mainly used for subtraction of π^-+C interactions in CH_2 target to access the π^-+p reaction

⋆ Large statistics for hadronic channels (π^+, π^- ,p, d, t) on C target can be exploited !

Fatima Hojeij's PhD, Paris-Saclay, Nov. 2023

Spectra obtained for different exit channels compared to predictions of SMASH, GIBUU, RQMD.RMF and INCL++ (full GEANT simulations)

Main reaction channels in $\pi^-+^{12}C$ at 0.69 GeV/c

- π^-+N initial collision:

Quasi-elastic and charge exchange:

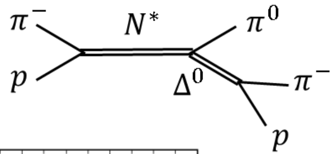
- $\pi^- + p \rightarrow \pi^- + p$ 17.8 mb quasi-elastic scattering
- $\pi^- + n \rightarrow \pi^- + n$ 12 mb quasi-elastic scattering
- $\pi^- + p \rightarrow \pi^0 + n$ 10 mb charge exchange

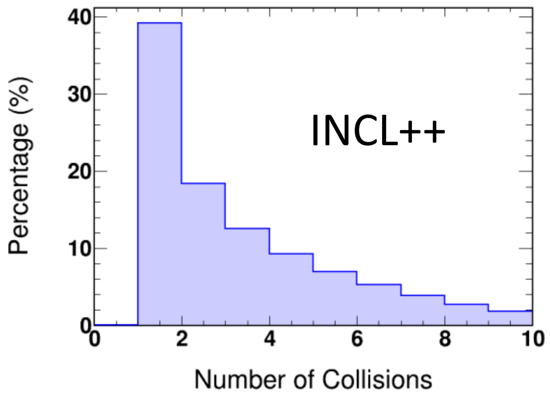
Modifications of kinematics expected for π^-+C :
- Potential
- Fermi motion

Inelastic (pion production)

- $\pi^- + p \rightarrow n + \pi^- + \pi^+$ 5.9 mb
- $\pi^- + p \rightarrow p + \pi^- + \pi^0$ 3.77 mb
- $\pi^- + p \rightarrow n + \pi^0 + \pi^0$ 2.2 mb
- $\pi^- + n \rightarrow p + \pi^- + \pi^-$ 2.1 mb
- $\pi^- + n \rightarrow n + \pi^- + \pi^0$ 0.39 mb

Main contribution from s-channel N* excitations,
N*→πΔ, σN, ρN





- Multi step (rescattering)

πN→πN, πN→ππN, NN→NN

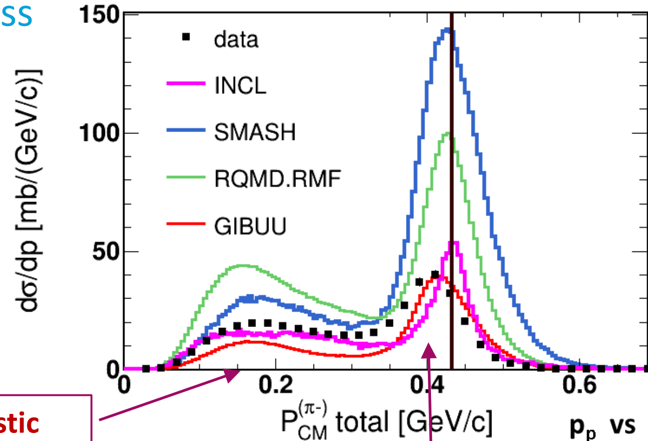
πN→πN followed by NN→NNπ kinematically suppressed :
Two-pion production occurs mainly in the same step, via πN→ππN.

Collision number not so large.
Try to identify specific reaction chains ?

First look at $p\pi^-$ events : quasi-elastic/inelastic

$\pi^- + {}^{12}C$ at 0.69 GeV/c

Center-of-mass



Large differences between model predictions for both quasi-elastic and inelastic

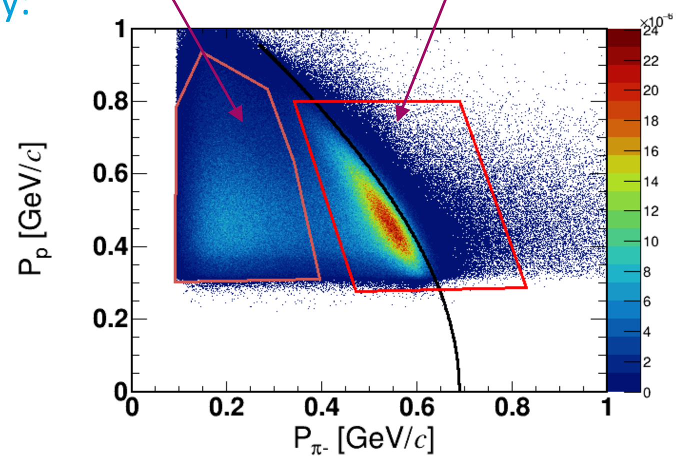
Cross sections ?
Nucleon momentum distribution ?
Density ?
Potentials ?

Inelastic $p\pi\pi$

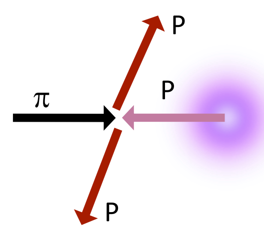
p_p vs p_π typical of binary reaction $\pi^- + p \rightarrow \pi^- + p$

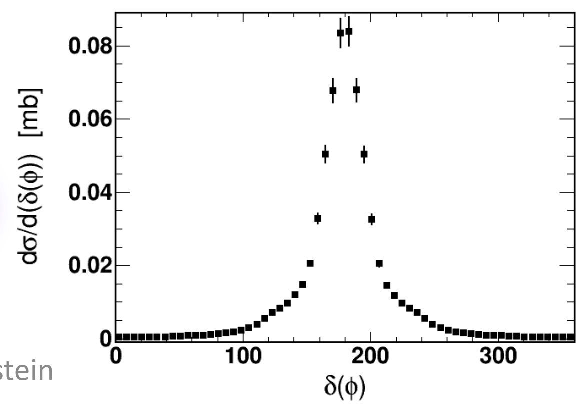
Quasi-Elastic

Laboratory:



« Quasi-Elastic (QE) selection » :
Momentum correlation + coplanarity condition

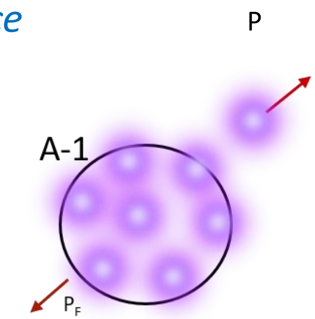




(p,π^-) quasi-elastic (QE) channel

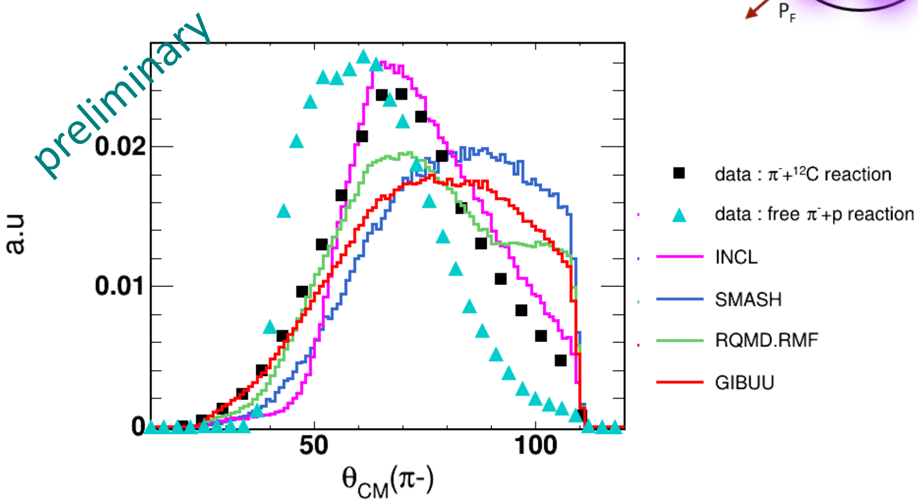
π^-+^{12}C at 0.69 GeV/c

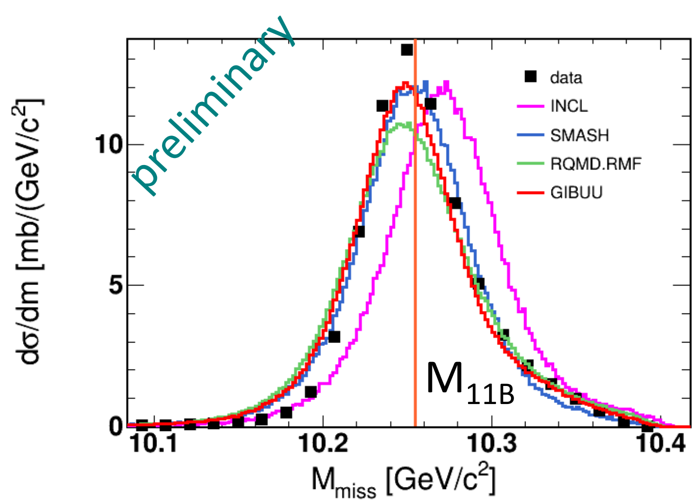
Distributions are normalized to the surface in order to compare shapes



$$M_{miss} = M_{(\pi^- + ^{12}C \to \pi^- + p + X)}$$

π^- angular distributions
for π^- **+^{12}C** compared to π^- +p





Broadening of angular distribution
w.r.t. π^- + p too large, except in INCL++
Effect of nucleon momentum distribution, pion rescattering,…

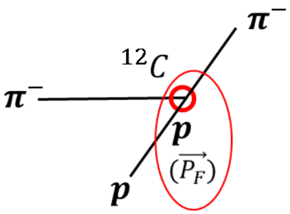
Residual ^{11}B is not much excited
INCL++ has too large excitation energies by ~ 20 MeV
(too large nucleon potential ?)

Short Range correlations in carbon nucleus

$\pi^- + {}^{12}C$ at 0.69 GeV/c

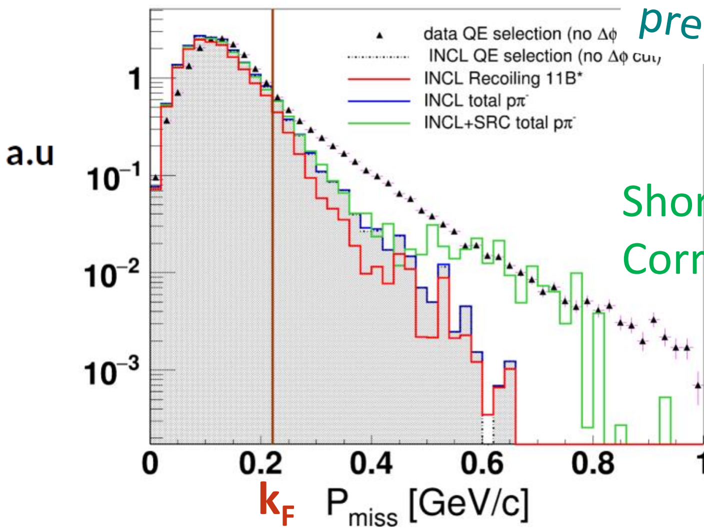
Pure quasi-elastic: access to proton momentum in ^{12}C

$$\vec{p}_{miss} = \vec{p}_{\pi}^{\,i} - \vec{p}_{\pi}^{\,f} - \vec{p}_{p}^{\,f} = -\vec{p}_{p}^{\,i}$$



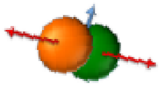
Cut applied to suppress rescatterings

π^- p events with p_π>600 MeV/c compared to INCL++ w/wo SRC



preliminary

Short Range Correlations ?



SRC: Nucleon pairs (mostly pn) with high relative momentum and small pair momentum

A. Schmidt et al., Nature 578, 540 (2020)
M. Patsyuk et al., Nat. Phys. 17, 693 (2021).

- ✓ Excess yield at large p_{miss} (>500 MeV/c) consistent with Short Range Correlations implemented in INCL++ (parametrization based on existing data)
- ✓ Further SRC Search for pp SRC pairs in $pp\pi^-$ events: not conclusive, kinematics can not disentangle SRC and sequential emission
- ✓ Dedicated experiment foreseen with HADES : p+Ag 4.5 GeV (pp and pn SRC pairs will be investigated

J. Ritman's talk

$\pi^- + {}^{12}C \rightarrow p + \pi^- + \pi^- + X$

$\pi^- + {}^{12}C$ at 0.69 GeV/c

a) Single step production:

$\pi^- + n \rightarrow \pi^- + \pi^- + p$, ($\sigma$=2.1 mb) recoiling ${}^{11}C$

Minimum missing mass

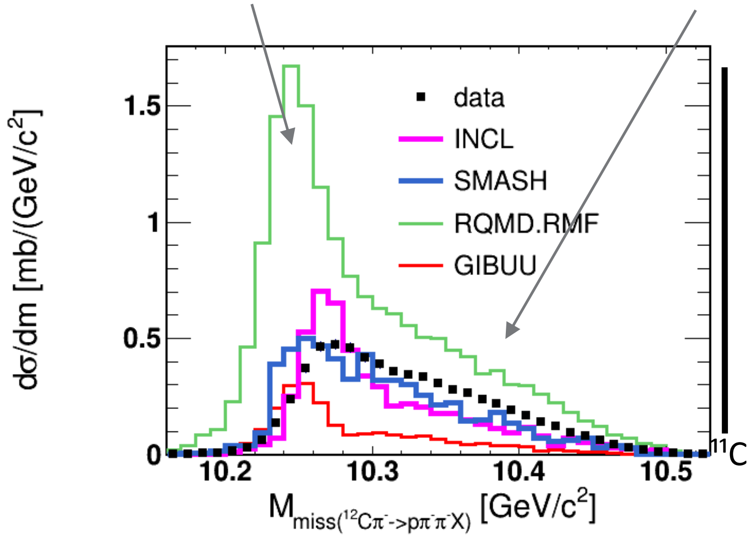
b) Two step production:

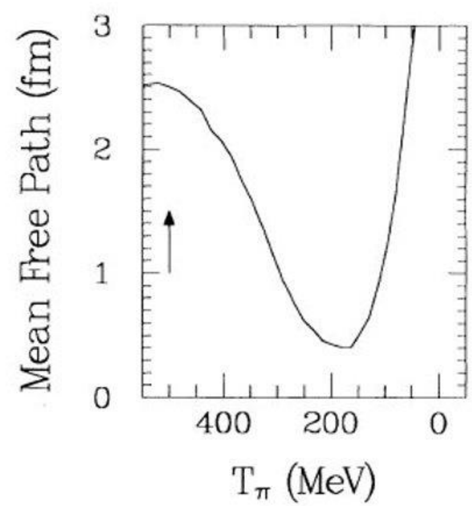
$\pi^- + p \rightarrow \pi^- + p$ (17.8 mb); $\pi^- + n \rightarrow p + \pi^- + \pi^-$

$\pi^- + p \rightarrow \pi^- + \pi^0 + p$ (3.3 mb); $\pi^0 + n \rightarrow \pi^- + p$

$\pi^- + n \rightarrow \pi^- + \pi^0 + n$ (0.4 mb); $\pi^0 + n \rightarrow \pi^- + p$

Larger missing mass, lower inv. Mass





- Disentangle single and multi step processes
- In overall too strong proportion of single step processes in models w.r.t. data

$\pi^- + {}^{12}C \rightarrow p + p + \pi^- + X$

$\pi^- + {}^{12}C$ at 0.69 GeV/c

Two-step processes with 2π production (inelastic): e.g.

(a) $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ (3.8 mb); $p + p \rightarrow p + p$ (p rescatt)
(b) $\pi^- + p \rightarrow \pi^- + p$ (17.8 mb); $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ (π rescatt.)
(c) $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ (3.8 mb); $\pi^- + p \rightarrow \pi^- + p$ (π rescatt)
(d) $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ (3.8 mb); $\pi^0 + p \rightarrow \pi^0 + p$ (π rescatt)
(e) $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ (3.8 mb); $\pi^0 + n \rightarrow \pi^- + p$ (π rescatt)

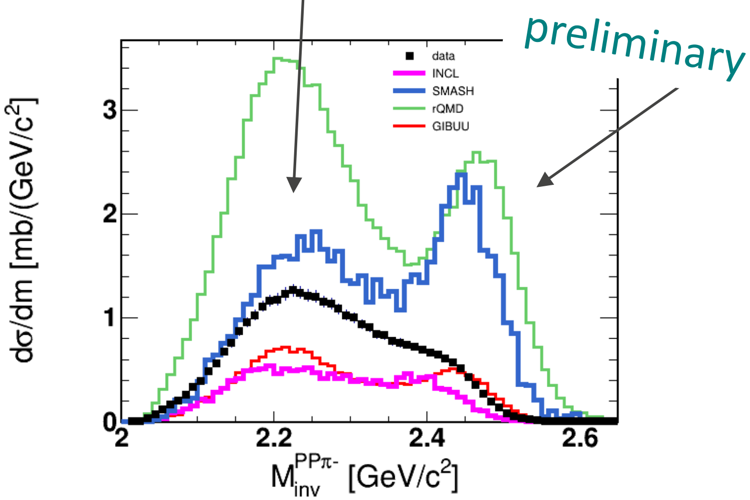
Two-step processes with 1π production (elastic): e.g.

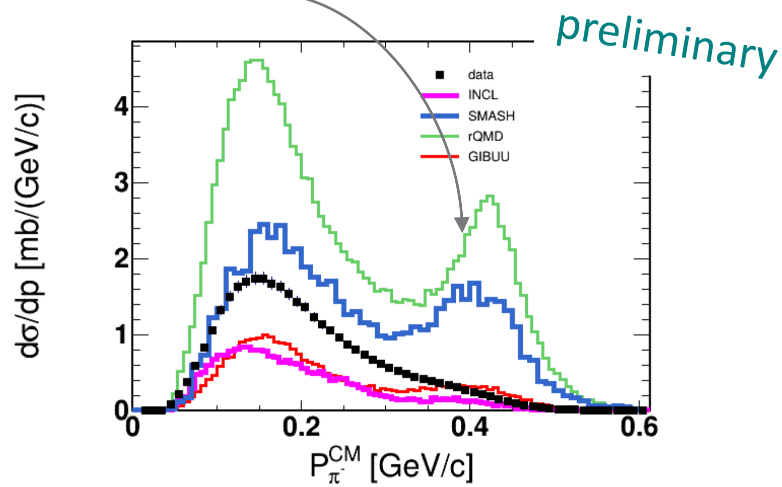
(a) $\pi^- + p \rightarrow \pi^- + p$ (17.8 mb) ; $p + p \rightarrow p + p$ (p rescatt)
(b) $\pi^- + p \rightarrow \pi^- + p$ (17.8 mb) ; $\pi^- + p \rightarrow \pi^- + p$ (π rescatt)

smaller Minv

max Minv

Quasi-elastic kinematics





Allows to distinguish sequences of inelastic from elastic processes.

Cross section summary table

$\pi^- + {}^{12}C$ at 0.69 GeV/c

Integrated cross sections in HADES acceptance

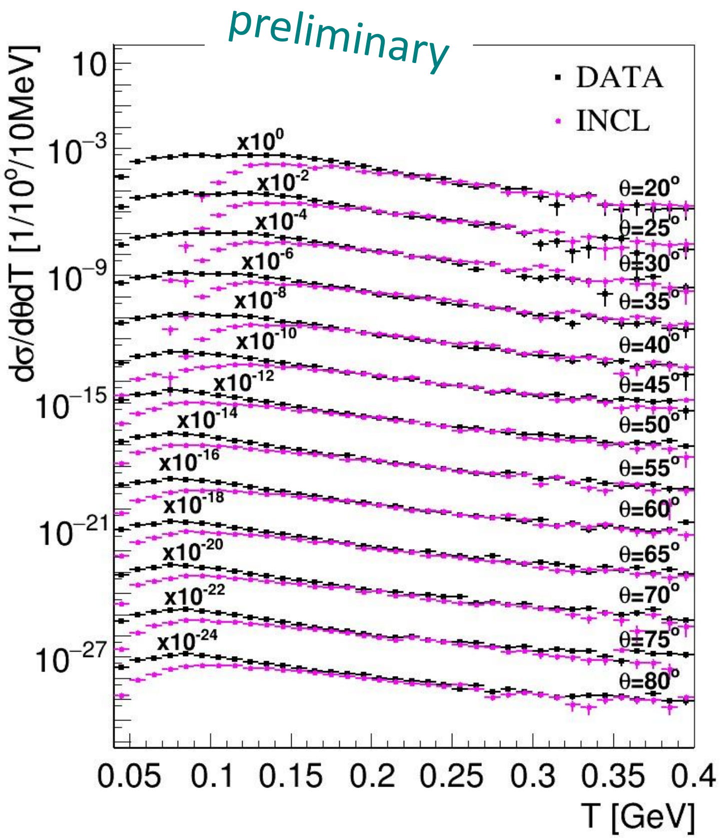
$\pi^- + {}^{12}C \rightarrow$ reaction 2-3 charged particles channels	σ^{acc}_{data} [mb]	σ^{acc}_{SMASH} [mb]	σ^{acc}_{rQMD} [mb]	σ^{acc}_{GIBUU} [mb]	σ^{acc}_{INCL} [mb]
$p\pi^-$ quasi-elastic	3.05749	12.6985	6.96586	3.44757	2.61393
$p\pi^-$ inelastic	3.35684	4.83481	7.45256	1.76097	2.15597
$\pi^-\pi^-$	0.229554	0.187058	0.438986	0.0529949	0.324116
$\pi^-\pi^+$	1.06115	2.17662	2.39893	0.459961	1.46397
$\pi^+\pi^+$	0.00207372	0.00755551	0.00636384	0.000245144	0.00305625
$p\pi^+$	0.320214	0.774002	1.12059	0.140976	0.300638
pp	1.8327	3.30951	6.35023	1.19376	1.06719
$p\pi^-\pi^+$	0.0463039	0.134989	0.202082	0.021943	0.0525704
$p\pi^-\pi^-$	0.0646787	0.0596407	0.16292	0.0228274	0.0536891
$pp\pi^-$	0.337741	0.617297	1.07159	0.192891	0.153924
ppp	0.047972	0.082285	0.300865	0.039017	0.0238212

Preliminary conclusion:

- rQMD.RMF and SMASH strongly overestimate particle yields
- INCL and GIBUU give the best overall description

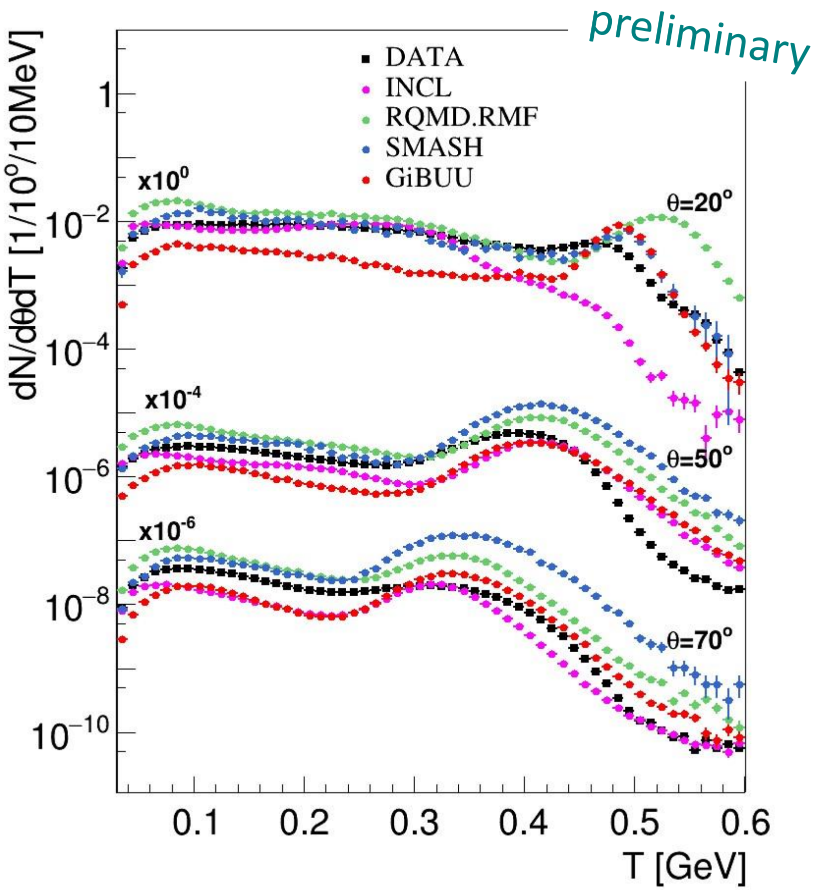
Inclusive hadronic channels in π^-+C at 0.69 GeV/c

tritons



+ inclusive π^+ , p and deuterons,

π^-



HADES pion beam experiments

$\pi^- + {}^{12}C/W$ at 1.7 GeV/c

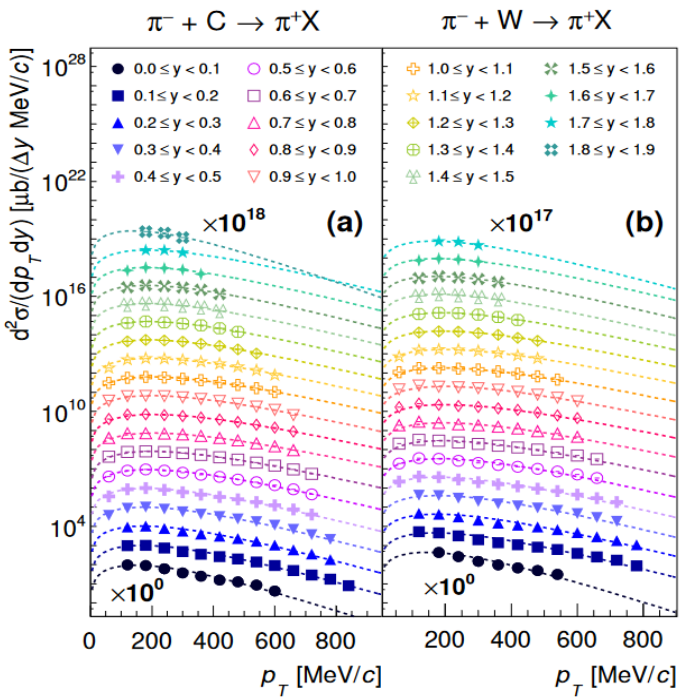
July 2014 :

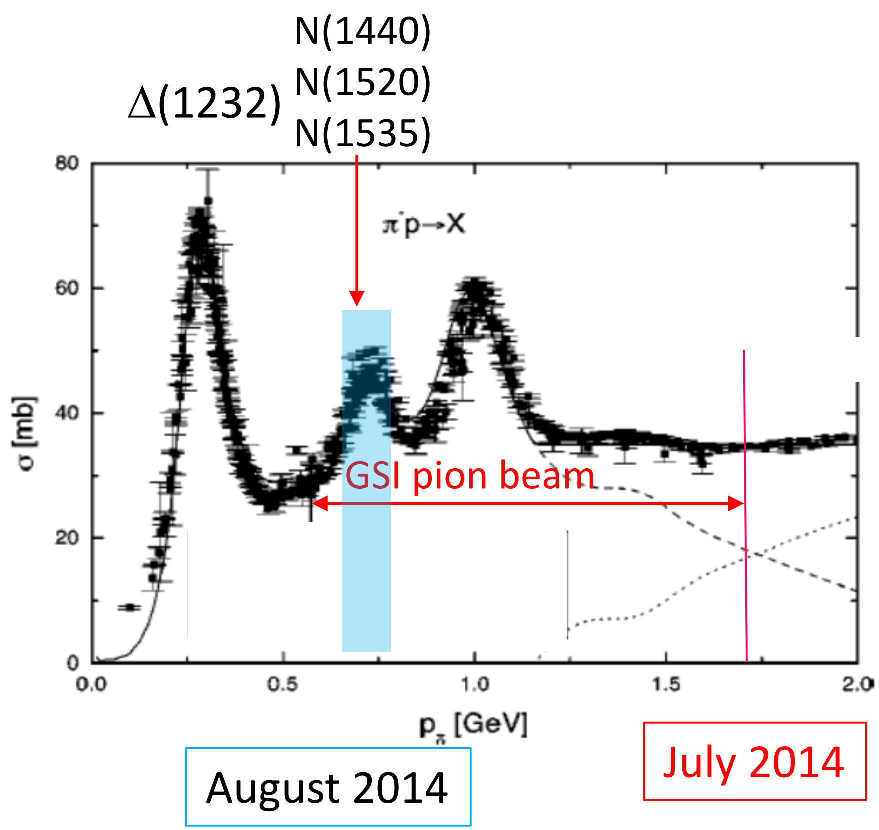
3 10^5 K^+ and 6.5 10^3 K^- in π^- + W

2.5 10^5 K^+ and 1 10^4 K^- in π^- + C

hadronic ϕ, Λ, K^0_S, $K^\pm$, $\pi^\pm$, p channels

p =1.7 GeV/c $\sqrt{s}$ =2 GeV/c^2



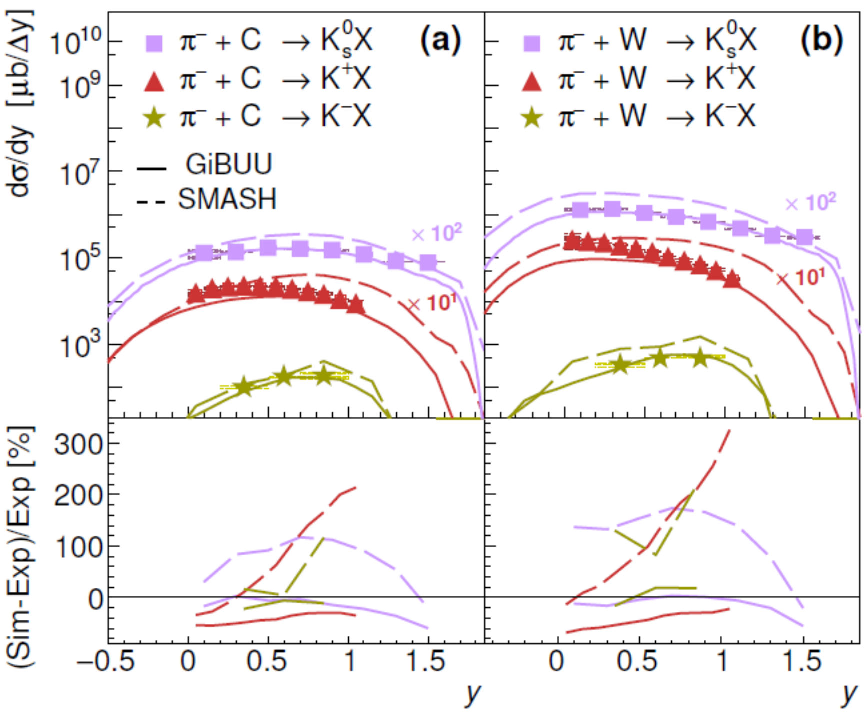


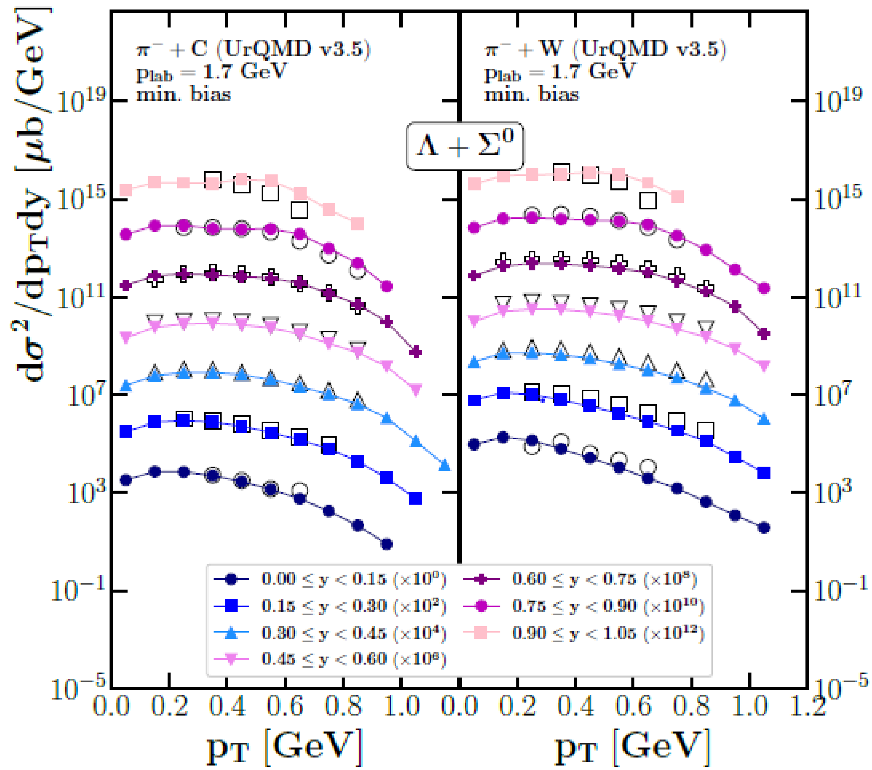
Strangeness production

$\pi^{-}+{}^{12}C/W$ at 1.7 GeV/c

UrQMD:Kittiratpattana et al., 2305.09208 [nucl-th]

Hades data: arXiv:2301.03940 [nucl-ex]





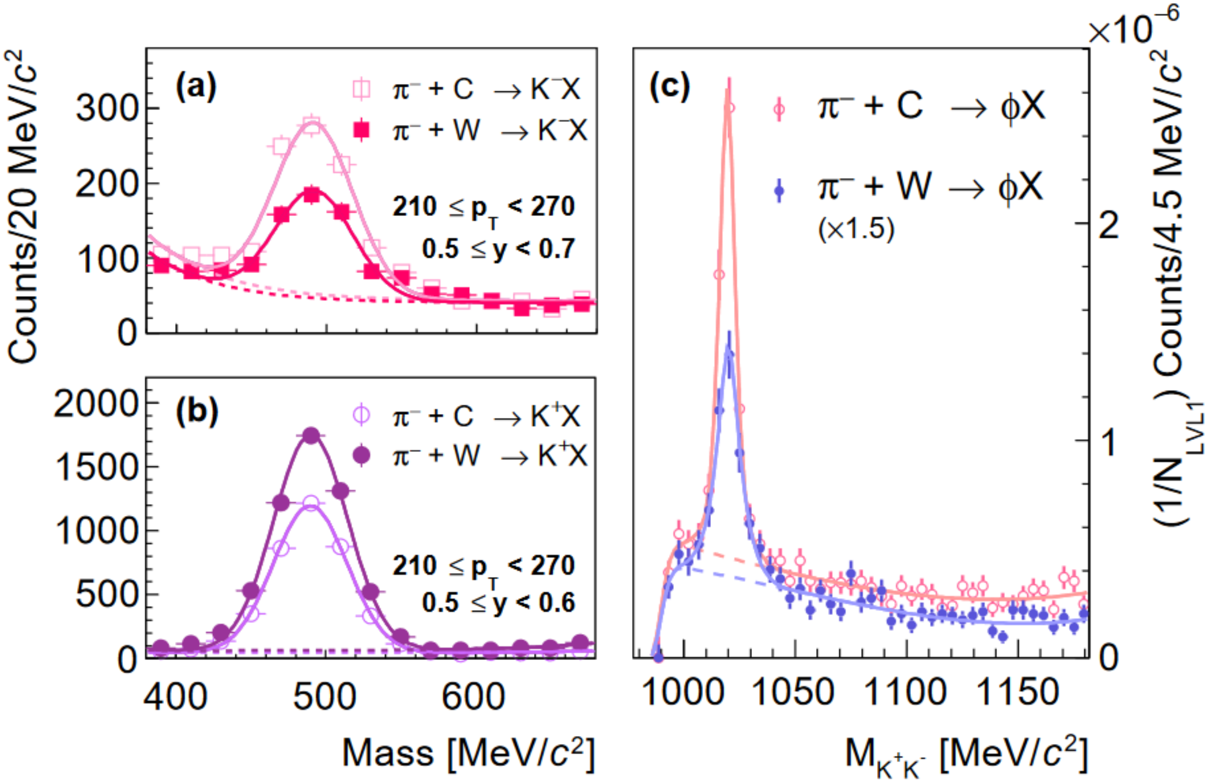
Important data base for interpretation of strangeness channels in heavy-ion reactions (KN potential,..)

Kaon and ϕ absorption

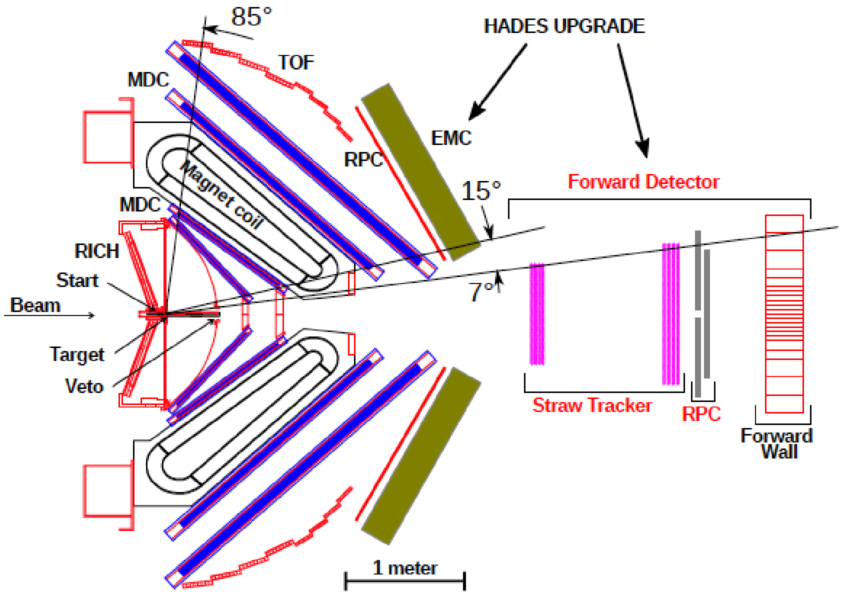
$\pi^- + {}^{12}C/W$ at 1.7 GeV/c

HADES Phys.Rev.Lett. 123 (2019) 2, 022002

- *Strong coupling between K^- and ϕ*
- *Evidence for substantial K^- and ϕ* absorption



Improvements since 2014 experiment



detectors:
RICH x3 efficiency for e+e- pair reconstruction
+ optimized conversion rejection (reduction of CB)

ECAL :possibility to detect neutral mesons

pion beam:
Better extraction → Higher primary beam intensity (x2)
was confirmed November-December 2023

HADES+ GSI pion beam : unique set-up in world
Needs to be further exploited !!

HADES pion beam experiments: future plans

GPAC 2022: π^- + CH_2 and C p_π =1.1 GeV/c
5 energy points in the region $\sqrt{s}$ = 1.76 GeV (One extended measurement for e^+e^- channels)
95 A^- shifts could now be scheduled (2025 ?)

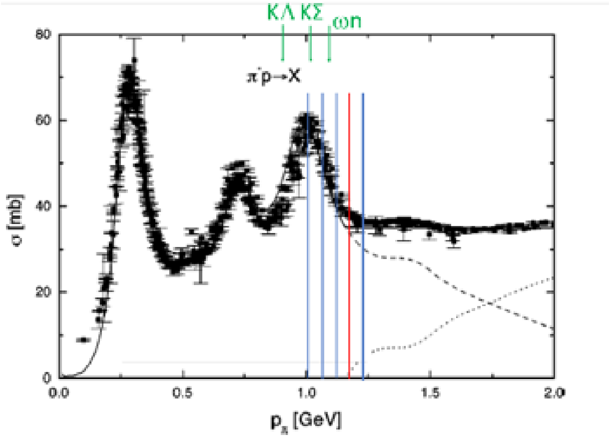
✓ π^- + p : **hadronic couplings (PWA) + time-like electromagnetic structure of baryons (Foda's talk)**

Expected statistics for π^- + p (one energy point = 1.2 shift)

$\pi^+\pi^- n$	$\pi^0\pi^- p$	$\pi^0\pi^0$ n	$K^0\Lambda$	$\Sigma^0 K^0$	$\Sigma^+ K^-$	ηn	ω n
$4.1\ 10^6$	$1.7\ 10^6$	$5.8\ 10^4$	$2.3\ 10^4$	$9.8\ 10^3$	$8.7\ 10^4$	$1.4\ 10^4$	$5.8\ 10^4$

✓ π^- + C : **cold matter studies.**

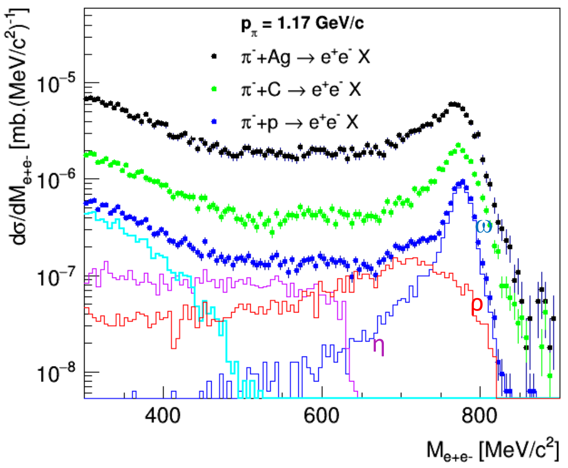
- Channels : π, K, η, ρ, ω, Λ, subthreshold ϕ.
- Multi-differential cross-sections + correlations in various exit channels
- Validation of hadronic models at higher energies
- Data base for general purpose (neutrino physics ,…)



Further cold matter studies

After 2025 $\pi^- + Ag$ p_π =1.1 GeV/c

Full GEANT simulations with realistic stat. fluctuations (Ag : 43 shifts)



Pion induced reactions
→ small momentum of reaction products
(detection by HADES down to 200 MeV/c)
→ higher sensitivity to medium effects than p+A

Cold matter studies:

- Dilepton channels : π^-+Ag :

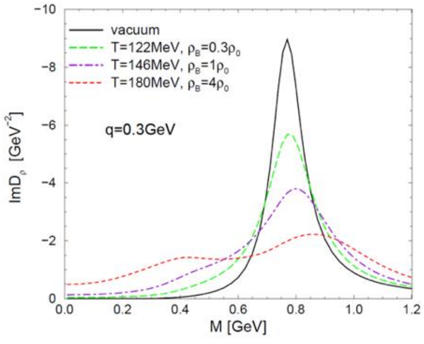
→ ρ : test predictions of ρ meson broadening

use updated baryon-meson couplings from π^-+p

→ ω : quantify absorption

In-medium ρ meson broadening

R. Rapp and J. Wambach EPJA 6 (1999) 415



- Hadronic channels (including strangeness) copiously produced:

  Medium effects on meson production, potentials,...

Conclusion

- The 2014 experiment has demonstrated the high potential of pion induced reactions for cold matter studies studied with HADES at GSI
  - ✓ p=0.69 GeV/c N(1520) region: pion dynamics
  - ✓ p=1.7 GeV/c strangeness channels
  - → New data base available for model validation
  - → Interest for hadronic matter and neutrino oscillation studies

- Will be further extended
  - ✓ next experiment π^-+p /^{12}C p=1.1 GeV/c
  - ✓ to be complemented in near future by π^-+Ag

Longer term program ? Systematic studies of π^-+A in complement to π^-+p hadronic couplings of N*/Δ, electromagnetic baryon transitions

Unique opportunity at SIS18 that should not be missed !

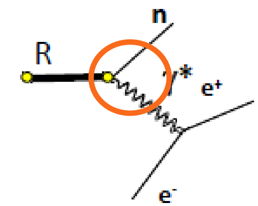
HADES Collaboration, Feb 22nd 20018

Thank you

BACK-UP SLIDES

Models for $\pi^- p \rightarrow n e^+ e^-$

$R_{QED} = (d\sigma/dM) / (d\sigma/dM)_{QED}$



- **Covariant form factor model**

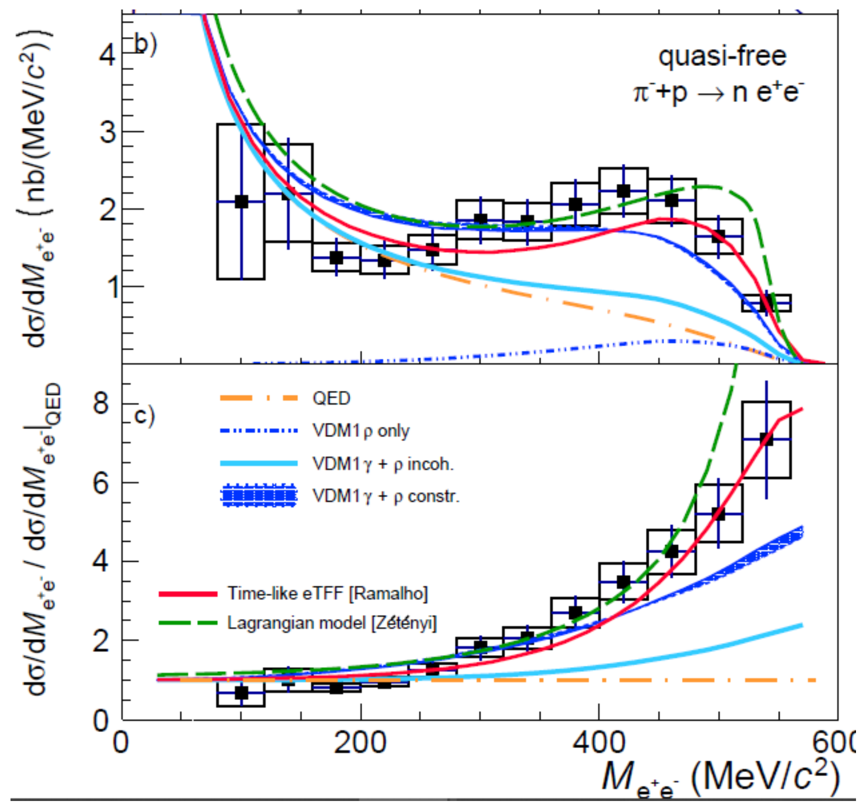
(quark core+ meson cloud)

G. Ramalho and M. T. Pena, Phys. Rev. D95, 014003 (2017)

Phys. Rev. D101, 114008 (2020)

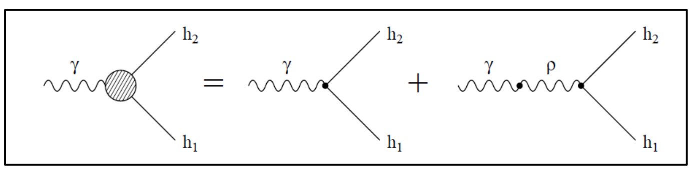
n-N1520 and n-N1535 transitions

HADES coll. arXiv:2205.15914 [nucl-ex]



- 2 component VDM model with constructive

γ-ρ interference (with inputs from $\pi^- p \leftrightarrow n\gamma$ and $\pi^- p \rightarrow \rho n$)

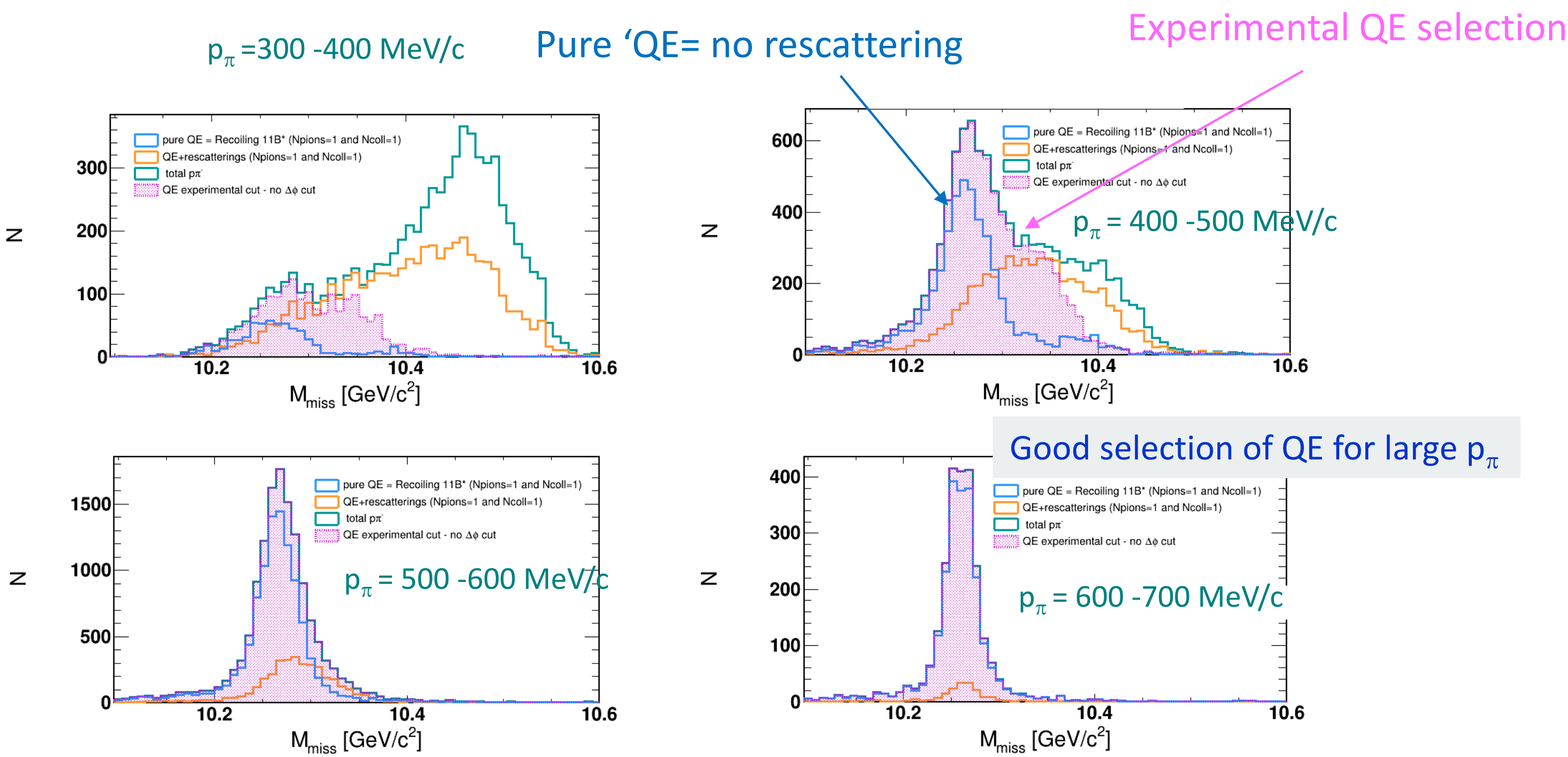


- Lagrangian model: resonant+non-resonant transitions with VDM form factors

M. Zetenyi et al. Phys.Rev. C 104, 015201 (2021)

More in An Di 's talk !

Rescattering effects studied with INCL++



INCL++ predictions : quality of our quasi-elastic selection

- Strong effect of rescatterings at small pion momentum.
- "pure" quasi-elastic processes for p_π > 600 MeV/c.

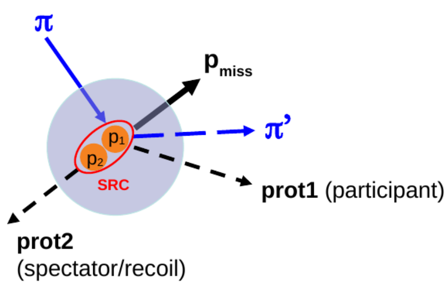
Investigation of $pp\pi^-$ for SRCs

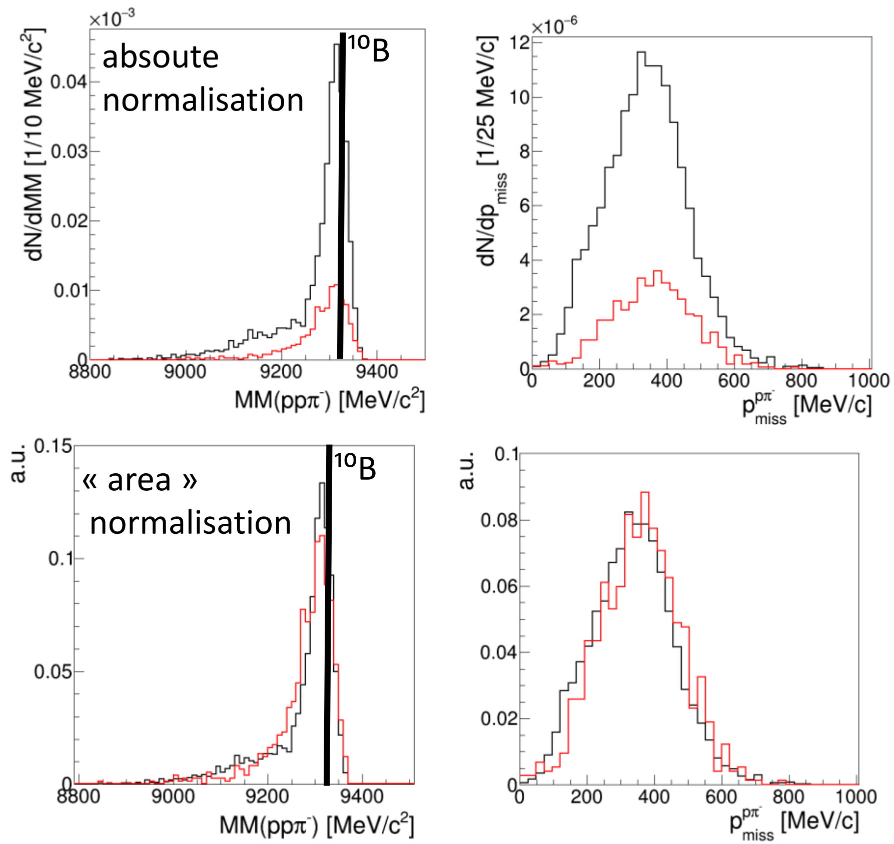
1) Select $p\pi^-$ pairs from quasi-elastic process :

Graphical cut on P_p^{CM} vs $P_{\pi^-}^{CM}$

2) Suppress rescatterings :

$P_{\pi^-} > 500$ MeV/c.





In INCL++, the two protons are emitted sequentially.Yield smaller than in the data, but distributions look similar. → no signals of SRCs

Angular distribution as a signal for SRC ?

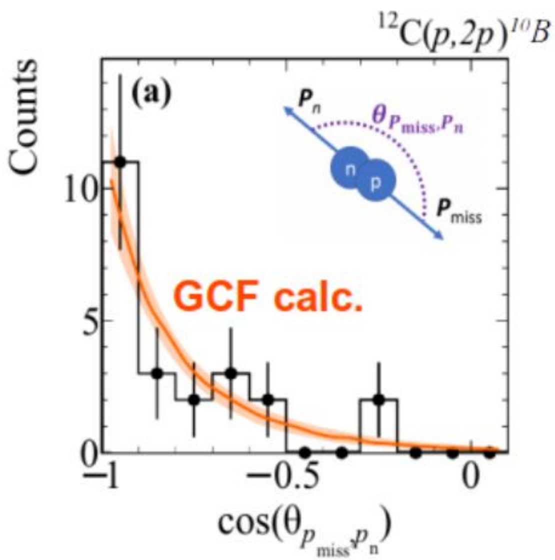
In the case of SRC:
the two nucleons move almost back-to-back in the 12C nucleus

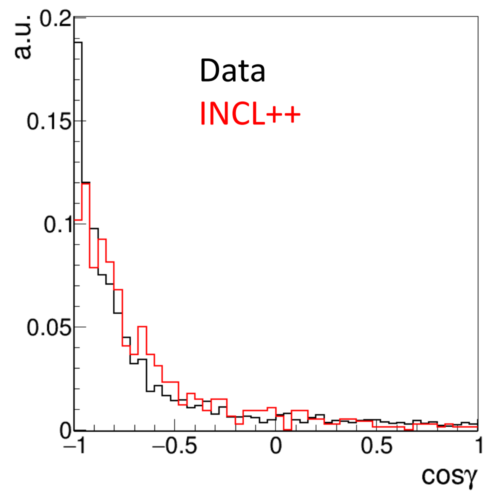
Dubna experiment ^{12}C + p @ 48 GeV/c

M. Patsyuk et al. , Nat. Phys. 17, 693 (2021

Reconstruction of the angle between participant and recoiling nucleons

→ peaking at 180° taken as a confirmation of SRC origin





In the π⁻ + 12C reaction@0.685 GeV/c , peaking observed in data, but also in INCL++ model without SRC.