Pion & proton emission channels in π^-+C reaction at 0.7 GeV/c with HADES

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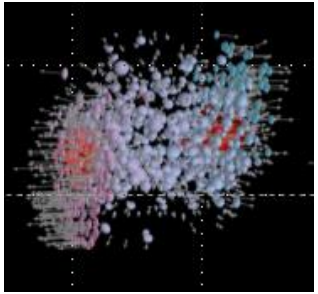
for the HADES collaboration

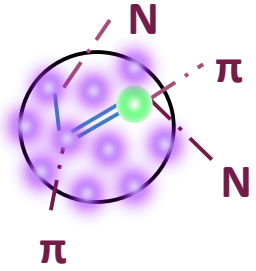
Based on Fatima Hojeij's PhD (IJCLab)

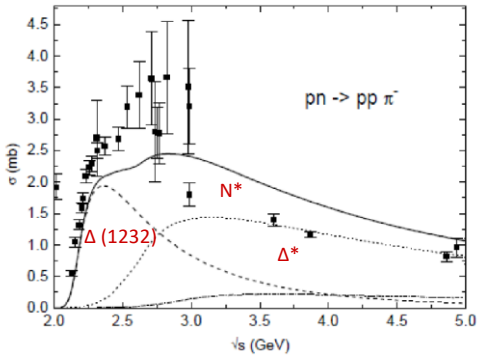
Co-supervision: Izabela Ciepal (IFJ PAN)

June 26, 2023

Pion dynamics for heavy ion collisions at a few AGeV





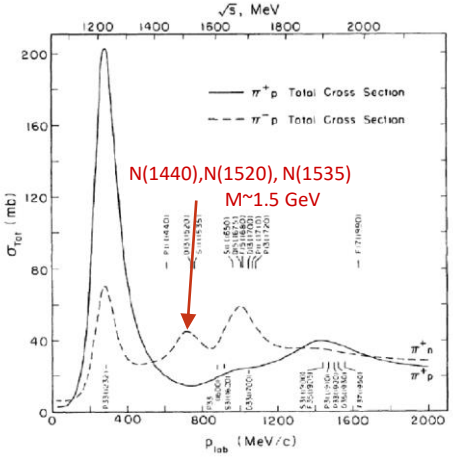


Pion production dominates the inelastic NN cross section

→ pion dynamics crucial to describe the evolution of HI collisions and drives the thermal properties of nuclear medium

- $\sqrt{s_{NN}} < 2.6$ GeV (A+A SIS18@GSI)
  most pions in the Δ(1232) region
- $\sqrt{s_{NN}} > 2.6$ GeV

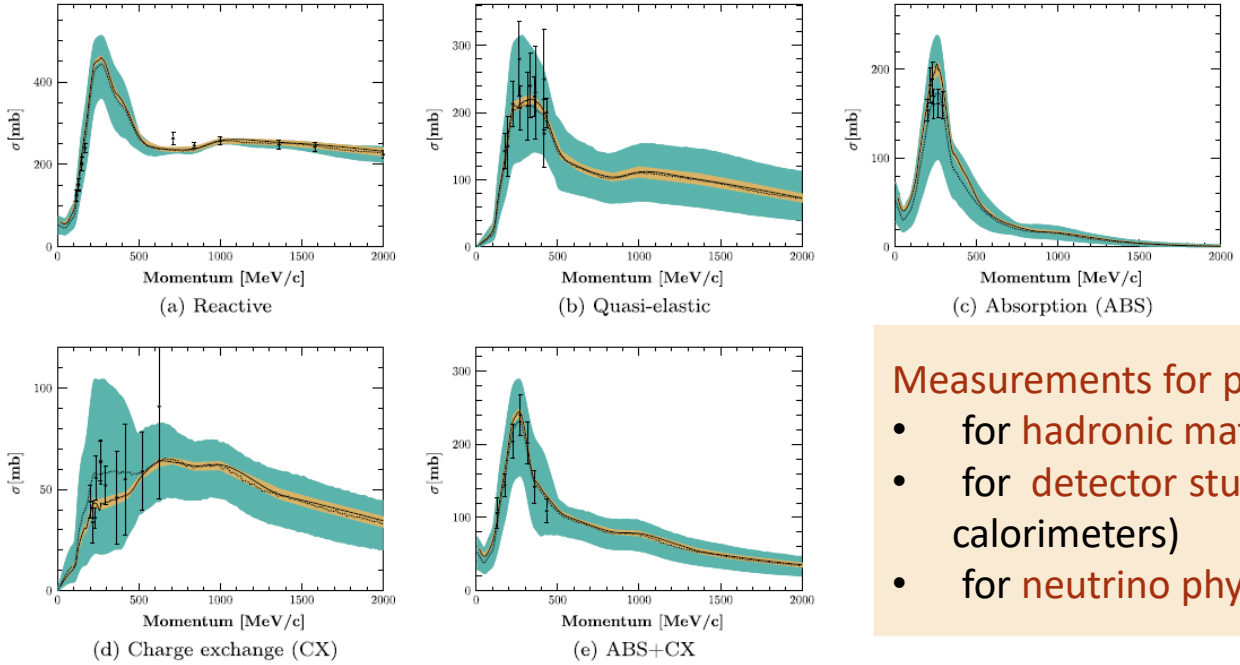
Future experiments: p+A (SIS18@GSI & SIS100@FAIR) or A+A (SIS100)) :
Higher lying resonances contribute.



Data base for pion-nucleus reactions

- $P_\pi < 250$ MeV/c : Δ(1232) resonance region rather well-known.
- $300 < P_\pi < 500$ MeV/c : few measurements (π, πx) or (π, ππx) (LAMPF, TRIUMF, KEK).
- $P_\pi > 500$ MeV/c : only σ_{tot} (Saturne-1, NIMROD, BNL) and differential elastic cross sections (KEK).

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



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

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

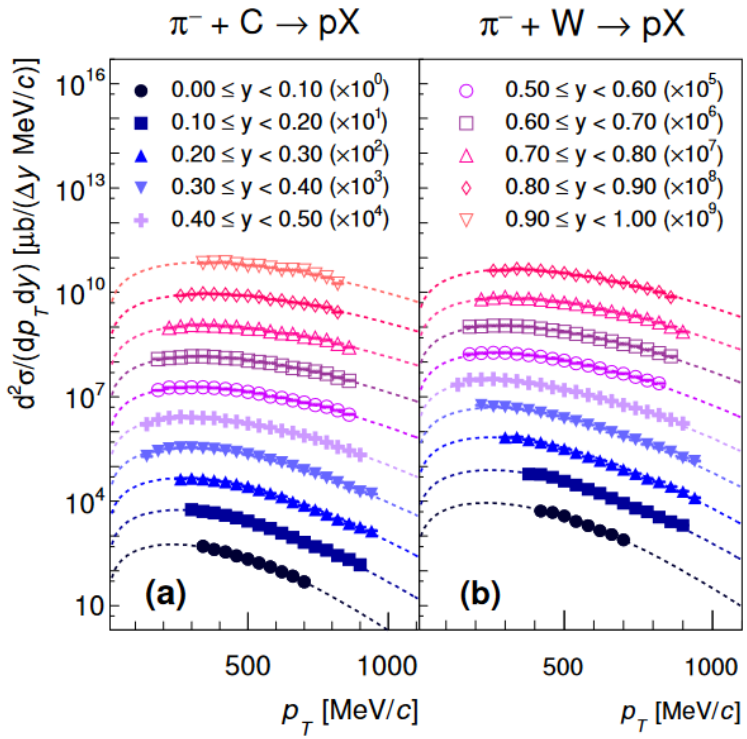
Measurements for $p_\pi > 500$ MeV/c are highly needed

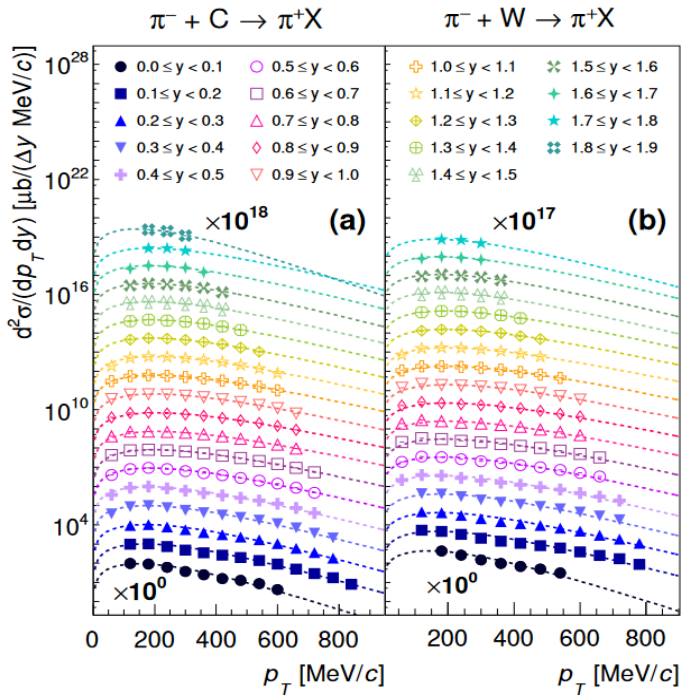
- for hadronic matter studies at $\sqrt{s_{NN}} > 2.6$ GeV
- for detector studies (e.g. e/π discrimination in calorimeters)
- for neutrino physics (ν flux and ν detection)

HADES results at p_π = 1.7 GeV/c

π^- + W/C : ϕ and kaon absorption *Phys. Rev. Lett.* 123 (2019), 022002

Λ + K^0_S+X and inclusive Λ, K^0_S, $K^\pm$, $\pi^\pm$, p spectra arXiv:2301.03940 [nucl-ex]

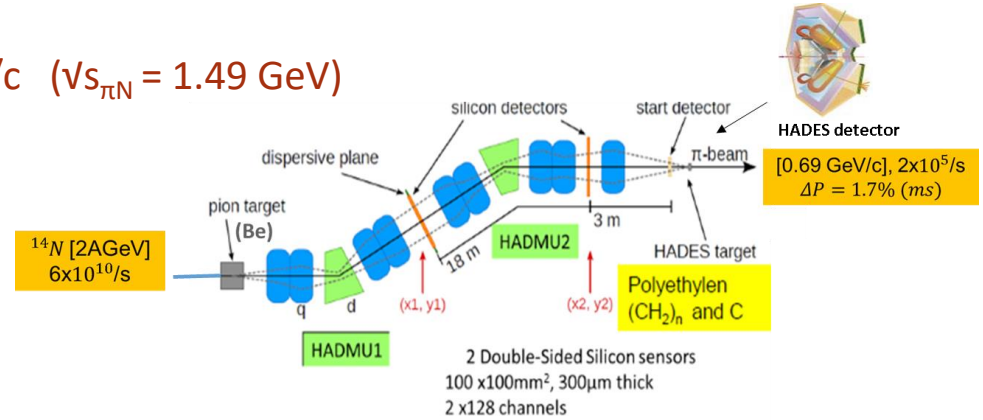


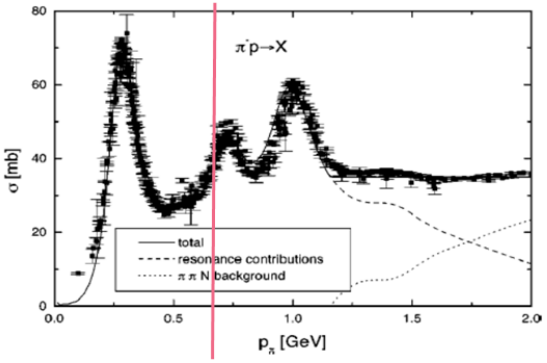


Pion beam experiment @ GSI

August 2014 commissioning experiment

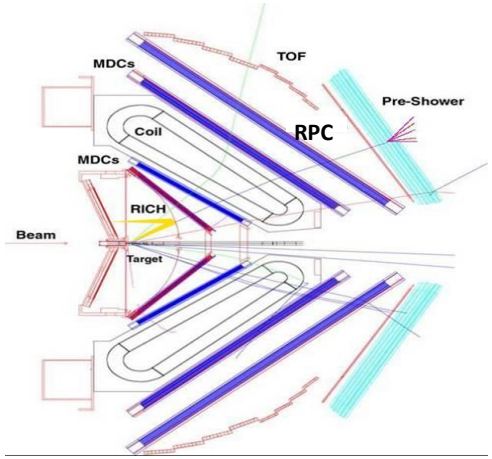
- Total ~15 days of measurements
- Main run: momentum P_{π^-} = 0.690 GeV/c ($\sqrt{s_{\pi N}}$ = 1.49 GeV)
- Polyethylene (CH2) and carbon targets





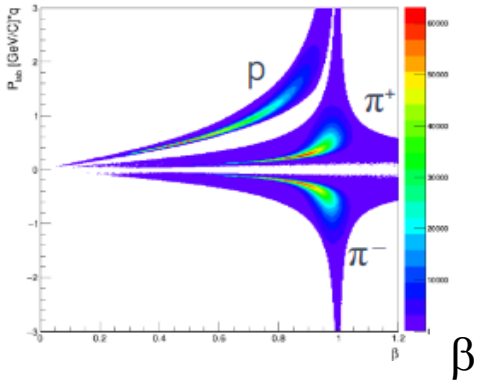
- ★ Data on carbon mainly used for subtraction of π^-+C interactions in CH_2 target $\rightarrow \pi^-$+p reaction (e^+e^- production)
  [HADES collab.], Phys.Rev. C102 (2020) 024001.
  [HADES collab.], 2205.15914 [nucl-ex] **Izabela Ciepal talk, Saturday June 24**
- ★ Large statistics for hadronic channels (π^+, π^- ,p) on C target to be used for dedicated analysis.

Data analysis (π^+,π^-,p) with HADES



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

❖ Particle identification



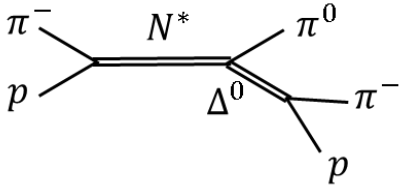
❖ Uncertainties:

- ➢ Normalisation ±4%
- ➢ Point to point systematic errors 5%, (mainly due to rec. efficiency)

Main channels in $\pi^- + {}^{12}C$

- Quasi-elastic and charge exchange:
  - $\pi^- + p \rightarrow \pi^- + p$ 17.8 mb (SAID)
  - $\pi^- + n \rightarrow \pi^- + n$ 12 mb (SAID)
  - $\pi^- + p \rightarrow \pi^0 + n$ 10 mb (SAID)
- Inelastic (pion production)
  - $\pi^- + p \rightarrow n + \pi^- + \pi^+$ 6.1 mb
  - $\pi^- + p \rightarrow p + \pi^- + \pi^0$ 3.3 mb
  - $\pi^- + n \rightarrow p + \pi^- + \pi^-$ 0.4 mb

Main contribution from s-channel N* excitations



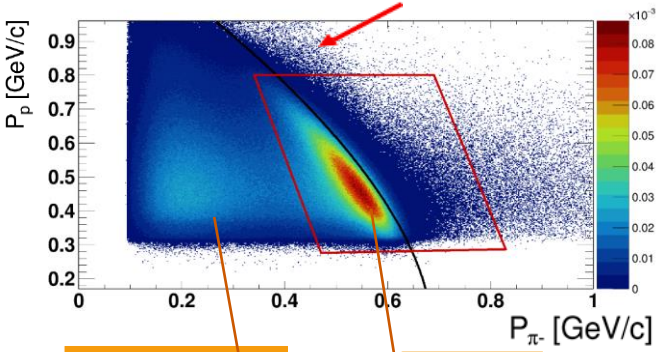
+ rescatterings (multi step) $\pi N \rightarrow \pi N$, $\pi N \rightarrow \pi\pi N$, $NN \rightarrow NN$,
but $NN \rightarrow NN\pi$ kinematically suppressed

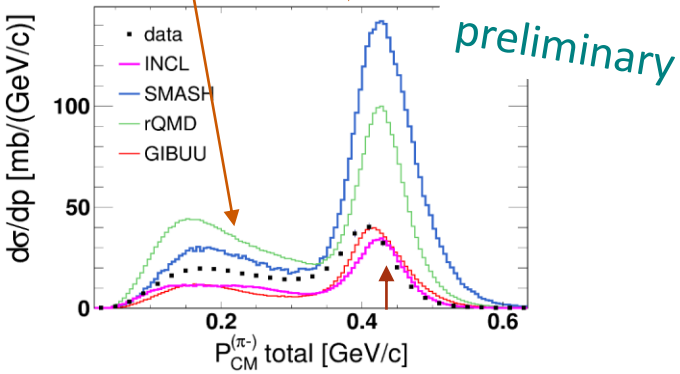
+ absorption $\pi NN \rightarrow NN$

- Analysis of many exit channels : $\pi^- p$, $\pi^+ p$, pp, $\pi^- pp$, $\pi^+\pi^- p$, ...
- Comparison between reconstructed events (in HADES acceptance) from measurements and from Geant simulations
  - RQMD.RMF, GiBUU, SMASH (transport models)
  - INCL++ cascade model (GEANT4 hadronic model)

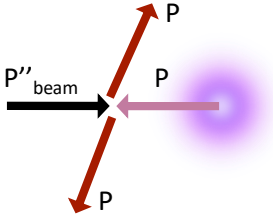
Selection of quasi-elastic (π^-p) channel

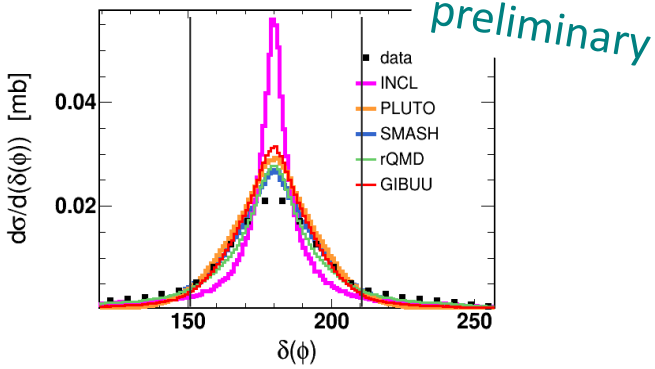
p_p vs p_π typical of binary reaction $\pi^- + p \rightarrow \pi^- + p$





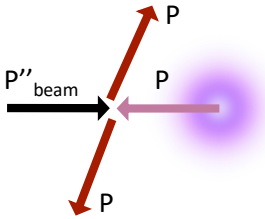
« Quasi-Elastic (QE) selection » :
Momentum correlation + coplanarity condition





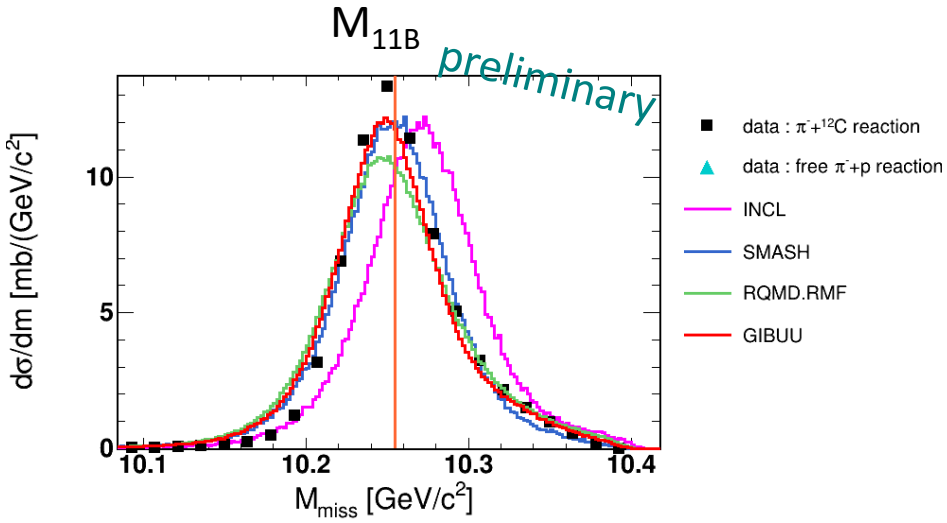
Large differences between model predictions for both quasi-elastic and inelastic

(p,π⁻) quasi-elastic (QE) channel

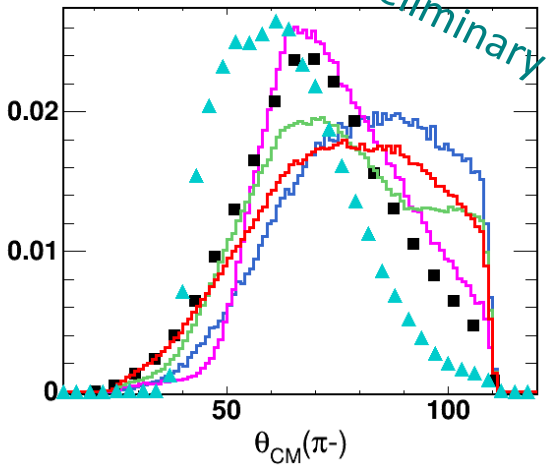


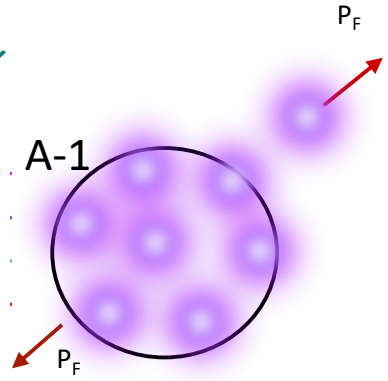
Distributions are normalized to the surface in order to compare shapes

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



π⁻ angular distributions for π⁻ +¹²C compared to π⁻ +p



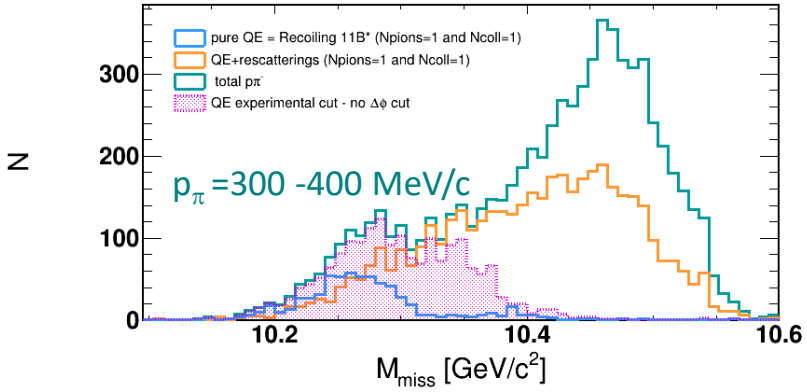


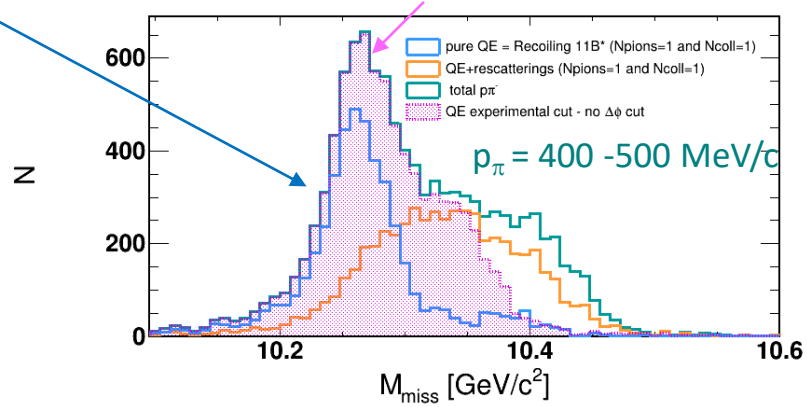
INCL++ provides the best description of angular distributions, but too large excitation energies by ~ 20 MeV

Rescattering effects for QE channel in INCL ++

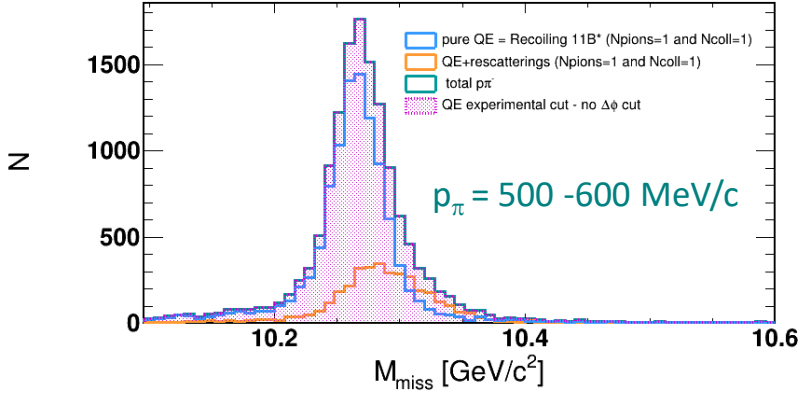
Pure 'QE= no rescattering

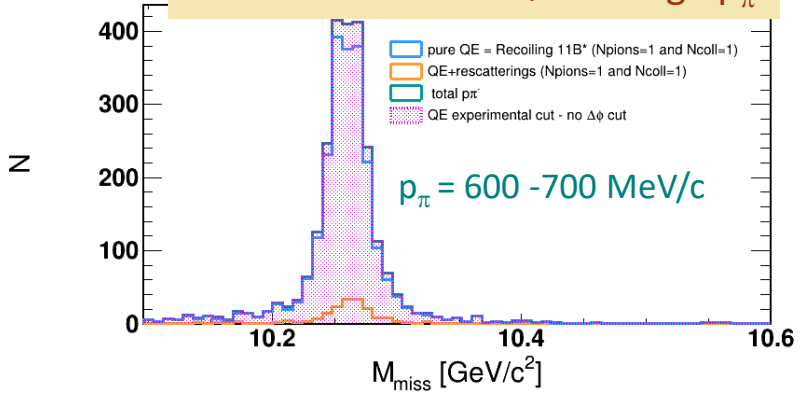
Experimental QE selection





Good selection of QE for large p_π



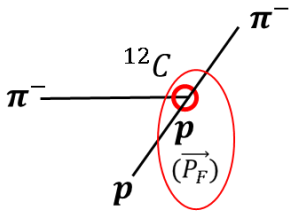


Proton momentum in carbon nucleus

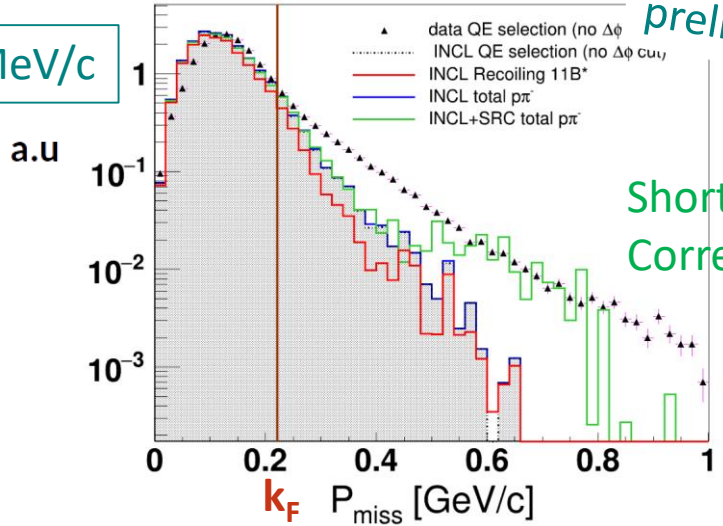
Pure quasi-elastic: access to proton momentum in ^{12}C

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

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

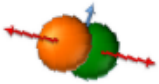


P_{π}>600 MeV/c



preliminary

Short Range Correlations ?



Nucleon pairs 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).

Tail at large p_{miss} (>500 MeV/c) consistent with Short Range Correlations implemented in INCL++ (parametrization based on existing data)

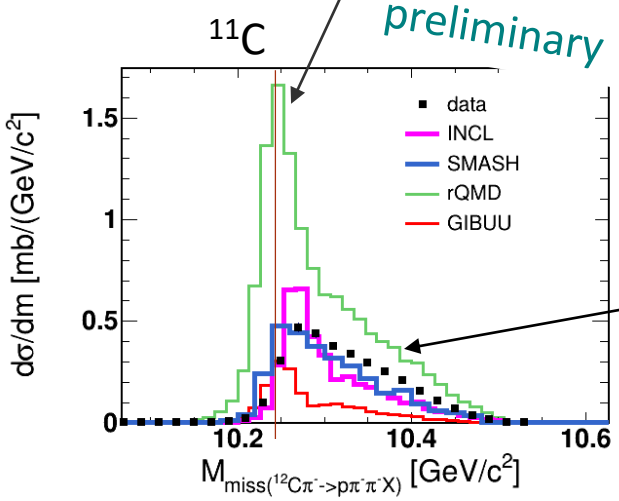
$\pi^- + {}^{12}C \rightarrow p + \pi^- + \pi^- + X$

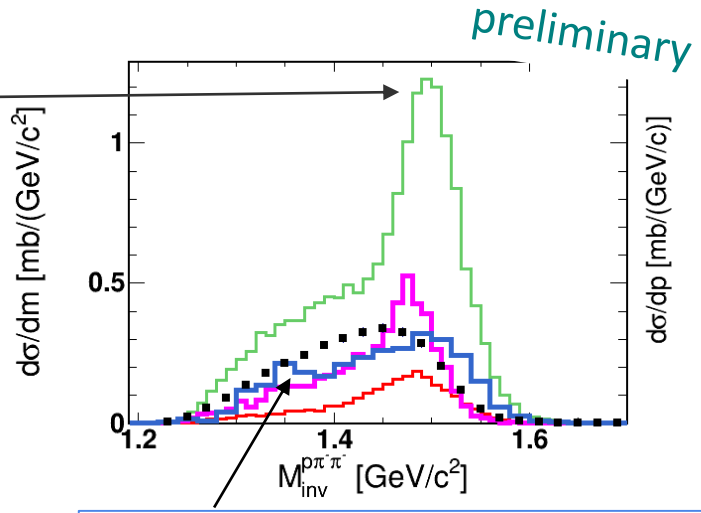
a) pure quasi-free:

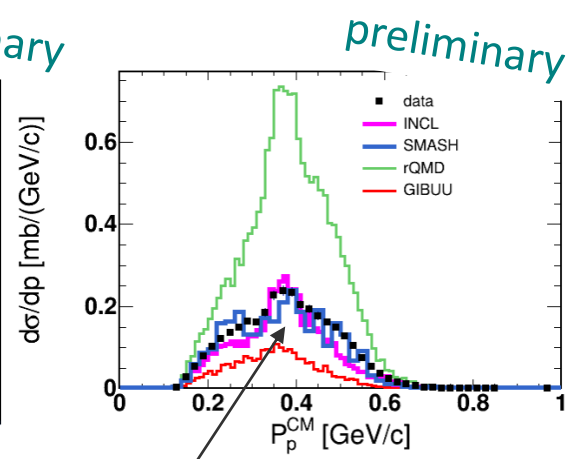
$\pi^- + n \rightarrow p + \pi^- + \pi^-$; recoiling ^{11}C 0.4 mb

Minimum missing mass, max inv. Mass

Rescatterings underestimated ?







b) Two step production:

$\pi^- + p \rightarrow \pi^- + p$ Elastic kinematics $p_{CM} \sim 0.4$ GeV/c

$\pi^- + n \rightarrow p + \pi^- + \pi^-$

Larger missing mass, lower inv. Mass

Not seen in GiBUU, present in data, overestimated by rQMD.rMF

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

2-step inelastic processes :

$\pi^- + p \rightarrow \pi^- + p$

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

$\pi^- + n \rightarrow p + \pi^- + \pi^-$

$\pi^- + n \rightarrow \pi^0 + p$

$\pi^0 + n \rightarrow p + \pi^- + \pi^0$

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

favored by data

2-step elastic processes

a) $\pi^- + p \rightarrow \pi^- + p$ 17.8 mb

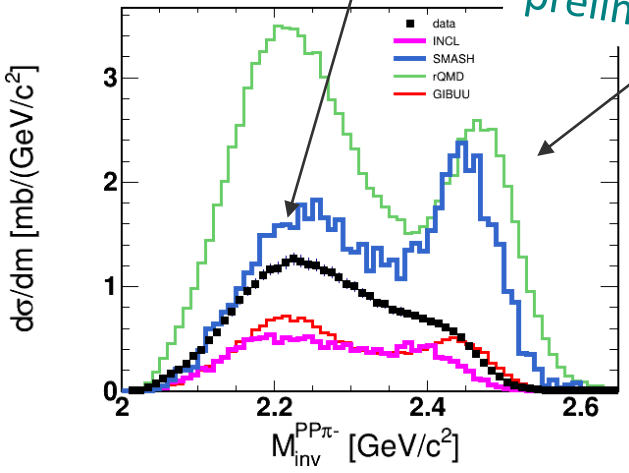
$p + p \rightarrow p + p$

a) $\pi^- + p \rightarrow \pi^- + p$ 17.8 mb

$\pi^- + p \rightarrow \pi^- + p$

Overestimated by rQMD and SMASH
impact for hadronic matter studies ?

preliminary



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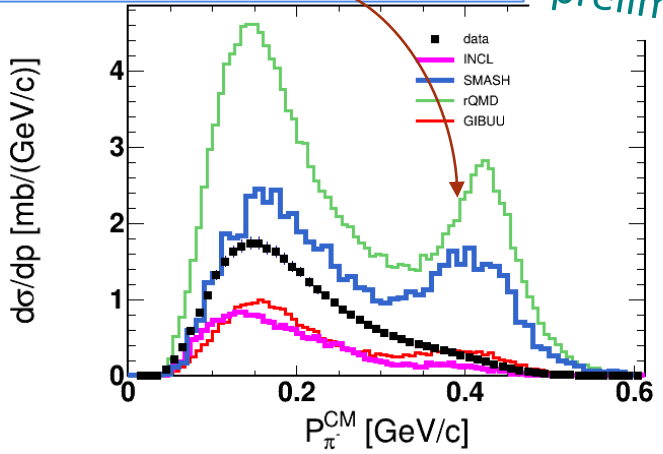


Cross section summary table

Integrated cross sections in HADES acceptance

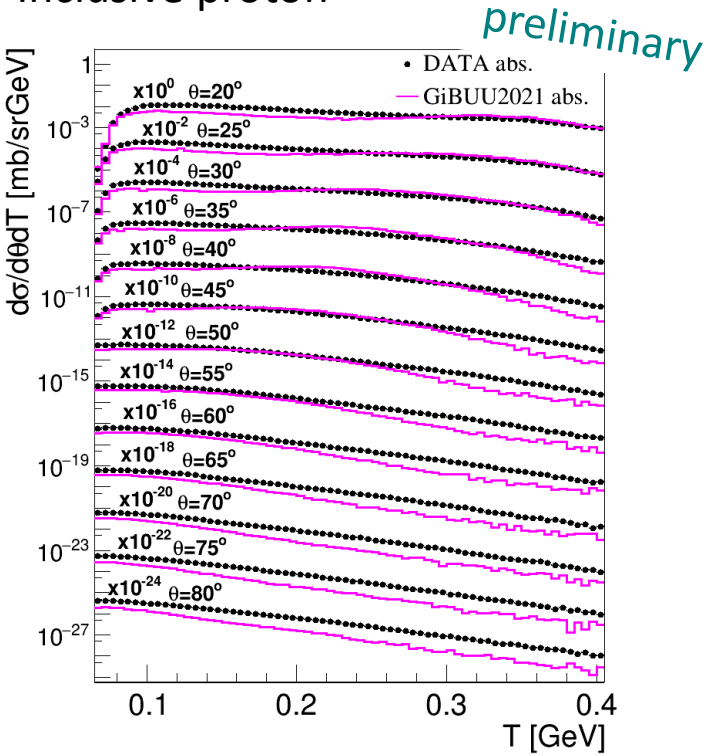
$\pi^- + {}^{12}C \rightarrow$ reaction 2-3 charged particles channels	σ^{acc}_{data} [mb]	σ^{acc}_{SMASH} [mb]	σ^{acc}_{rQMD} [mb]	σ^{acc}_{GIBUU} [mb]	σ^{acc}_{INCL} [mb]
$p\pi^-$ quasi-elastic	3.05749	12.6985	6.96586	3.44757	2.61393
$p\pi^-$ inelastic	3.35684	4.83481	7.45256	1.76097	2.15597
$\pi^-\pi^-$	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
p p π^-	0.337741	0.617297	1.07159	0.192891	0.153924
ppp	0.047972	0.082285	0.300865	0.039017	0.0238212

Preliminary conclusion:

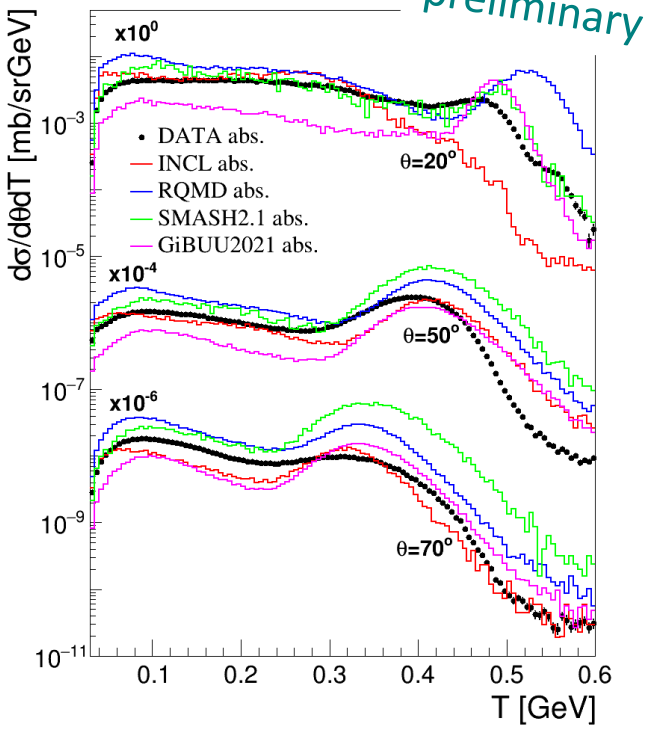
- rQMD.RMF and SMASH strongly overestimate particle yields
- INCL and GIBUU give the best overall description

Inclusive channel analysis: work in progress

Inclusive proton



Inclusive π^-



+ inclusive π^+ and deuterons,

Conclusion

Pion and proton spectra measured with HADES in different exit channels in the $\pi^- + {}^{12}C$ reaction @0.69 GeV/c

→ detailed comparison with model predictions

- ✓ transport models used for hadronic matter studies
- ✓ INCL++ (GEANT4 hadronic model)

can be used to improve implementation of various processes (quasi-elastic, pion production, absorption, …)

→ crucial benchmark for a realistic treatment of energy dissipation in Heavy-Ion collisions

→ information about pion-nucleus dynamics in the second resonance region

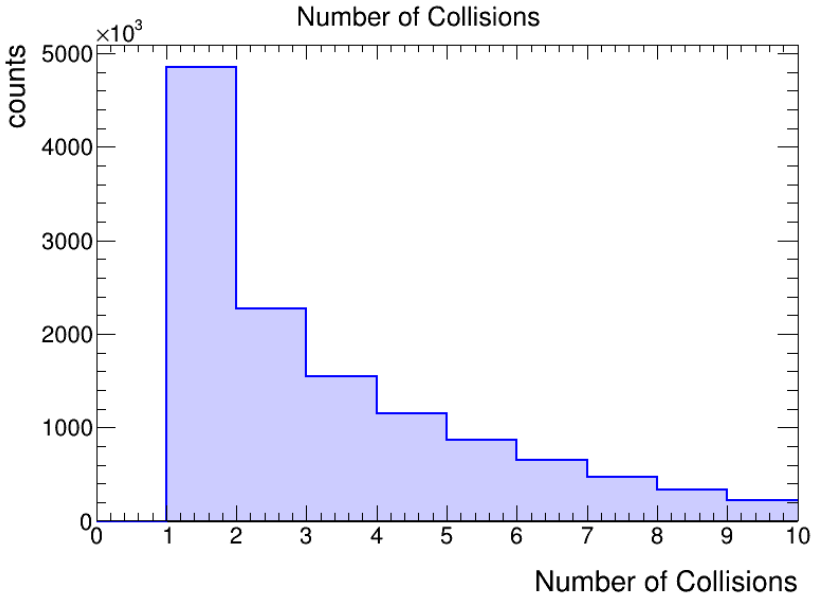
→ New data base of general interest

→ possibility to explore Short Range Correlations in the π^-+C reaction at 1.7 GeV/c

Thank you for your attention !

Number of collisons in $\pi^- + {}^{12}C$ $p_\pi = 0.69$ GeV/c

INCL++ prediction in 4π



Main properties

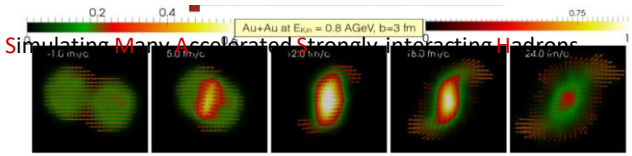
- Nucleon Fermi Gas.
- Binary interactions: Inelastic collisions through resonance/string excitation and decay
- All baryonic resonances included (Δ(1232), N(1440), N(1520), ... up to M=2 GeV/c²)
- Elementary cross-sections adjusted to data (c.f. slide 6).

SMASH

1. Potential Mean field

$$f(\boldsymbol{r},\boldsymbol{p},t) = \sum_{i=1}^{A_{beam}+A_{target}} \delta(\boldsymbol{r}-\boldsymbol{r}_i)\ \delta(\boldsymbol{p}-\boldsymbol{p}_i)$$

Distribution of nucleons



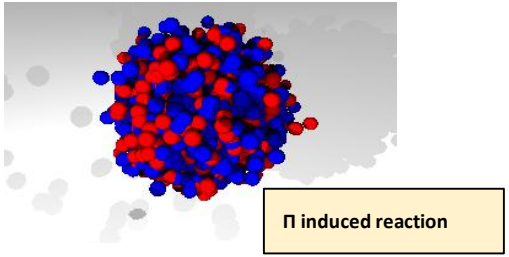
Simulating Many Accelerated Strongly Interacting Hadrons

https://smash-transport.github.io/

GIBUU :

1. Potential mean field
2. Momentum-dependent potential

Giessen Boltzmann-Uehling-Uhlenbeck



https://gibuu.hepforge.org/trac/wiki/movies

RQMD :

1. Sum of nucleons potentials; the mean field propagation is the same for nucleons and baryonic resonance.
2. Momentum-dependent potential

$$\Psi = \prod_i \psi_i \sim \prod_i \exp\left[-\frac{(\boldsymbol{x}_i-\boldsymbol{r}_i(t))^2}{L}\right] \cdot \exp\left[i\,\boldsymbol{x}_i\,\boldsymbol{p}_i(t)\right]$$

gaussian wave packets

Relativistic Quantum Molecular Dynamics

http://web.archive.org/web/20130219223256/https://quark.phy.bnl.gov/~ynara/jam/

Pion absorption investigation with INCL

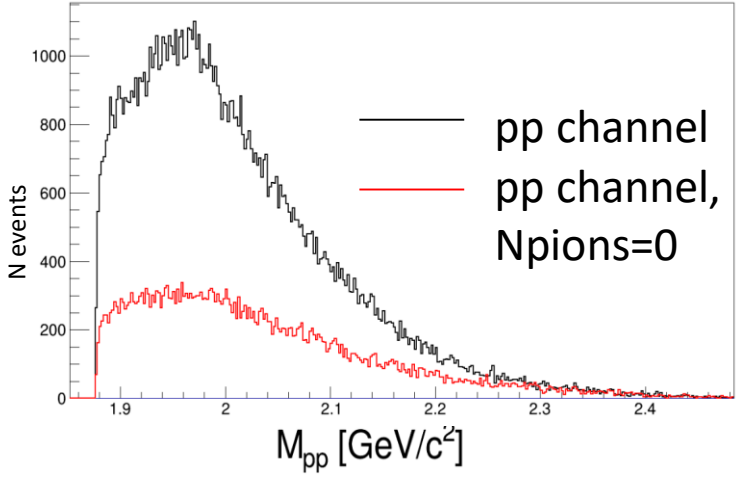
➢ $\pi^- + p \rightarrow \pi^- + p$

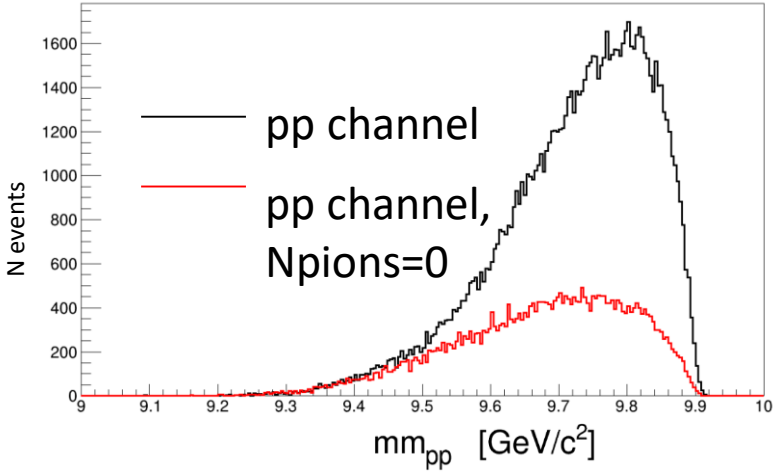
followed by (a) $\pi^- + p + p \rightarrow n + p$; $n + p \rightarrow n + p$

or (b) $\pi^- + p \rightarrow \pi^0 + n$; $\pi^0 + p + p \rightarrow p + p$

★ INCL predicts >20% of absorption in channels with 2 protons but kinematics are not very different.

★ Better investigation of pion absorption would need neutron reconstruction.





Intranuclear cascade model INCL

Implementation of short range correlations

Constraints for the “extra” momentum generated by the SRCs