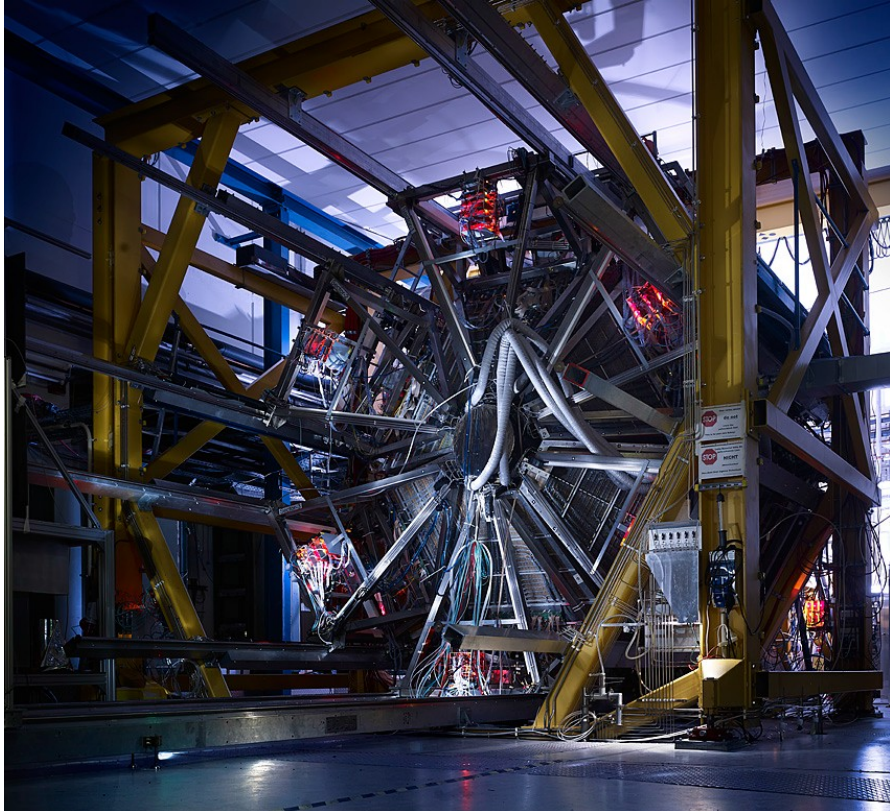
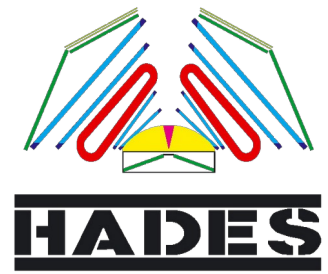


Studies of inclusive production of protons and charged pions and semi-exclusive channels in π^-+C collisions at 0.7 GeV/c with HADES



Outline:

- 1) Motivations for studies of $\pi+A$ reactions,
- 2) HADES detector and pion beam @ GSI,
- 3) Results for inclusive π , π^+ and p emission,
- 4) Results for semi-exclusive channels,
- 5) Summary and outlook.

**Izabela Ciepał, IFJ PAN Kraków
for the HADES Collaboration**



Motivations for studies of π^+A reactions

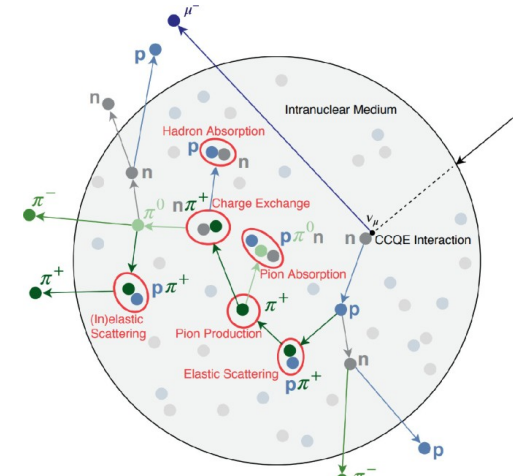
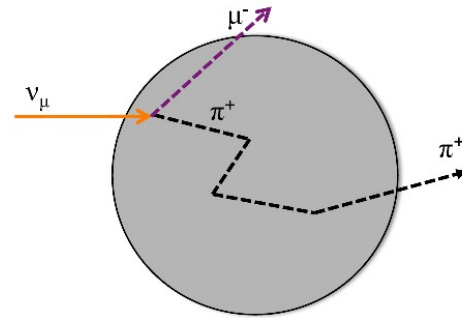
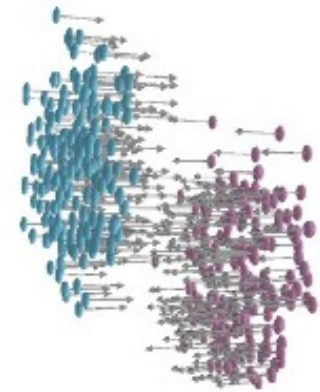
Ultimate goal: studies of microscopic structure of baryon dominated matter and role of baryonic resonances.

- **test of transport models:** a tool to identify medium effects in heavy-ion collisions at a few AGeV,
- **pion-nucleus dynamics:** crucial to describe the evolution of the A+A, p/π +A collisions:
 - thermalization processes of nuclear medium
 - particle yields

real pions are copiously produced

- **Geant4 physics models**
- **input for neutrino-nucleus reaction modelling**

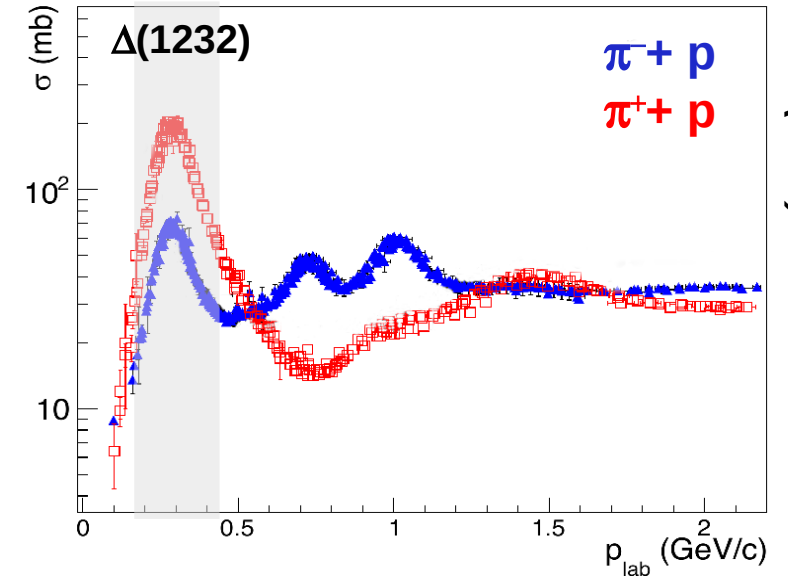
- The precision era of ν oscillations => precise models for ν energy reconstruction needed
- FSI models are tuned to external π/p +A data



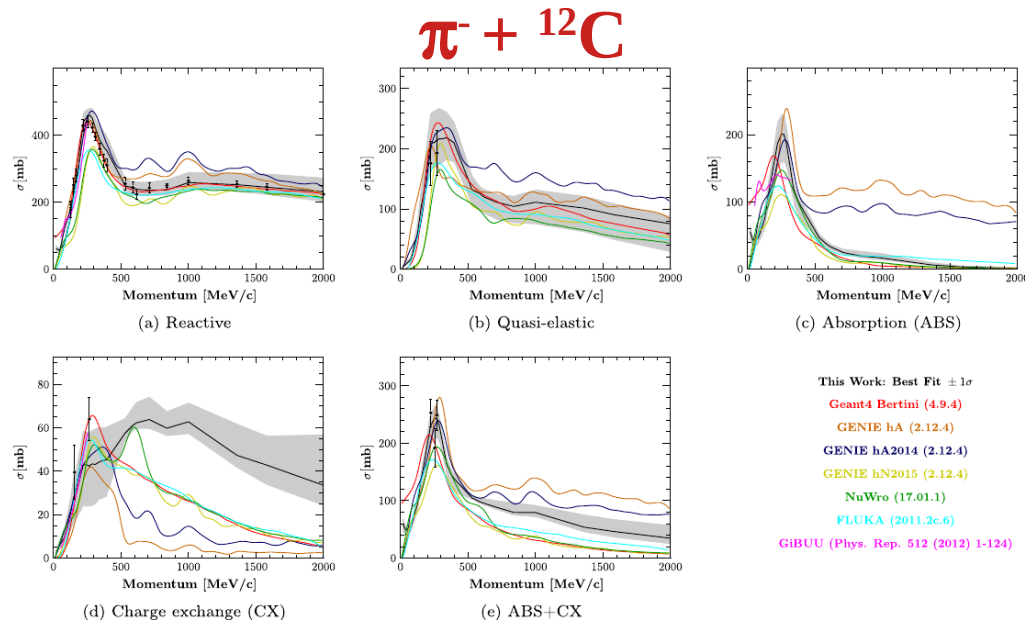
Database for π^+A reactions

Previous investigations with pion beam:

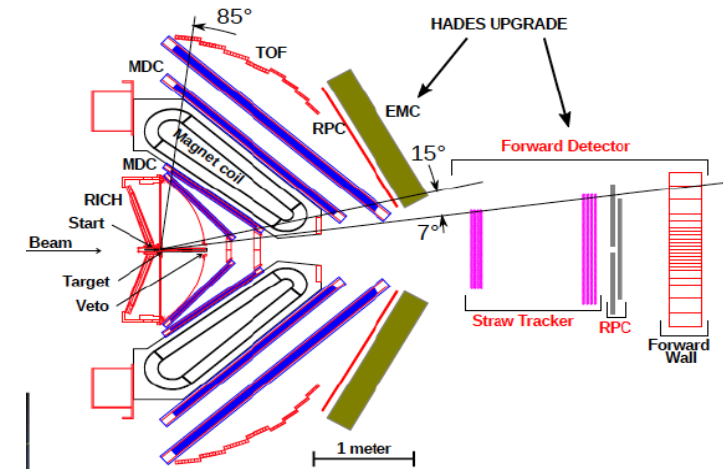
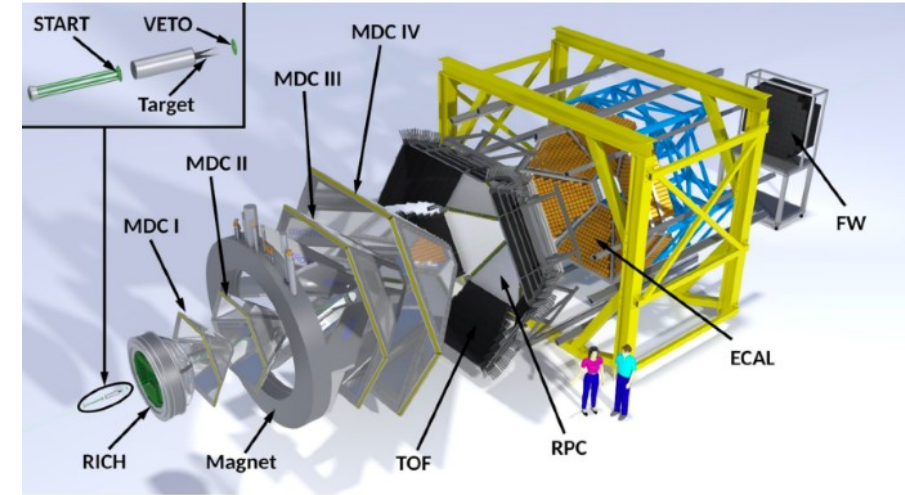
- $P_\pi < 250$ MeV/c: $\Delta(1232)$ resonance region well-known.
- $300 < P_\pi < 500$ MeV/c: few measurements (π , πX) or (π , $\pi\pi X$) (LAMPF, TRIUMF, KEK).
- $P_\pi > 500$ MeV/c: total cross sections (Saturne-1, NIMROD, BNL) and differential elastic cross sections (KEK).
- **Recent data from:**
 - DUET@ TRIUMF: $\pi^+ + C$ @ 200-300 MeV
 - HADES $\pi^- + C/W$ @ $p_\pi = 0.6-0.8, 1.7$ GeV/c



**Very scarce data base
 $\pi + C/Fe/Pb$
especially for QE,
absorption,
charge exchange !**

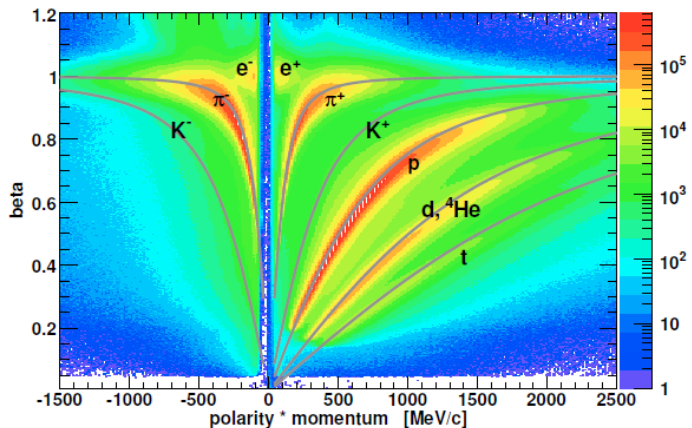


- ✓ SIS18 beams: protons (1-4.5 GeV), nuclei (1-2 A GeV), pions (0.4-2 GeV) secondary beam
- ✓ Spectrometer with $\Delta M/M \sim 2\%$ at ρ/ω
- ✓ PID ($\pi/p/K$): ToF (TOF/RPC, T0 detector), tracking (dE/dx)
- ✓ momenta, angles: MDC+ magnetic field
- ✓ e^+, e^- : RICH
- ✓ neutral particles: ECAL
- ✓ full azimuthal, polar angles $18^\circ - 85^\circ$
- ✓ e^+e^- pair acceptance ~ 0.35



FAIR - Phase0 upgrade:

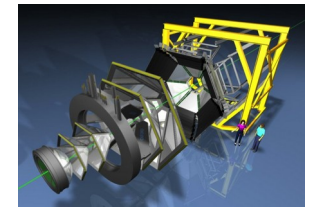
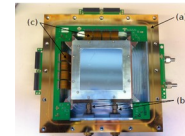
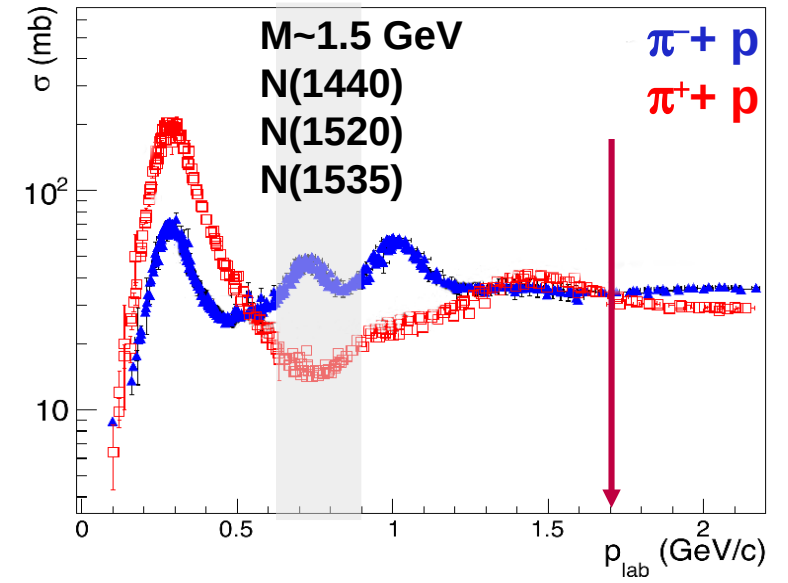
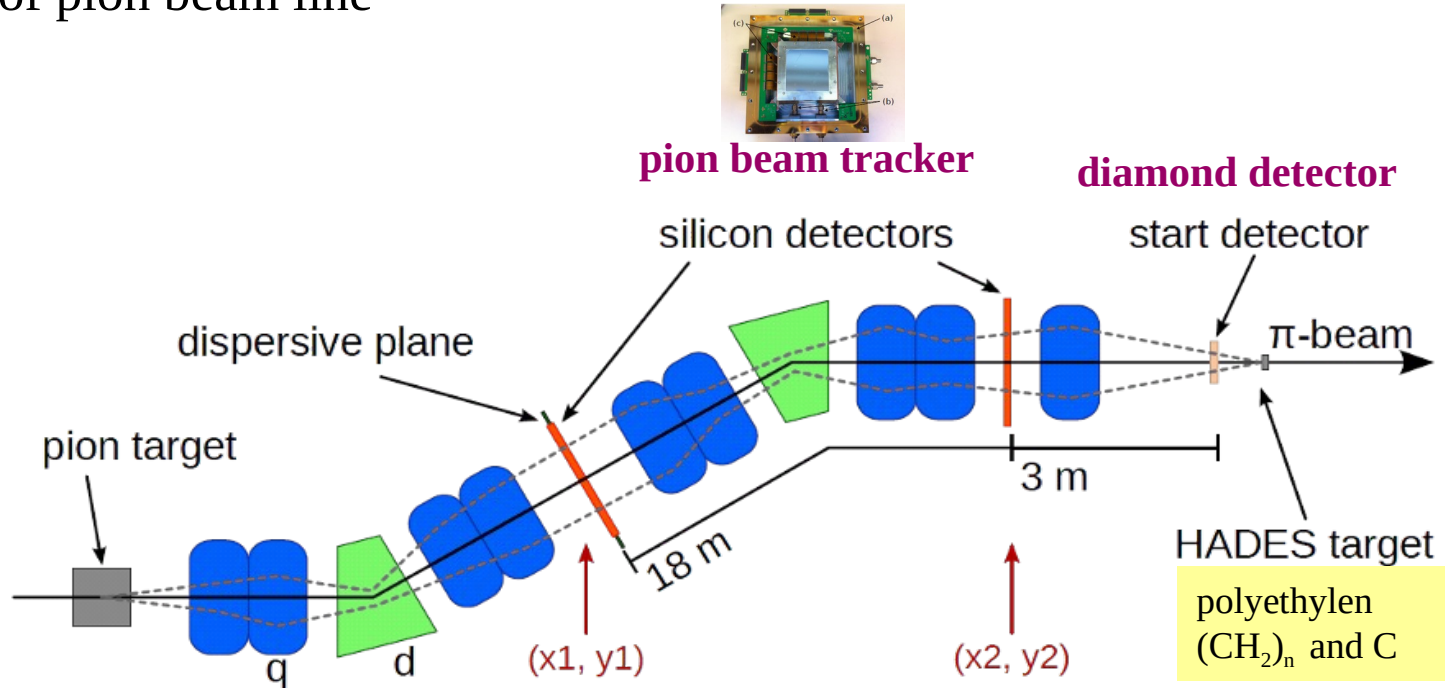
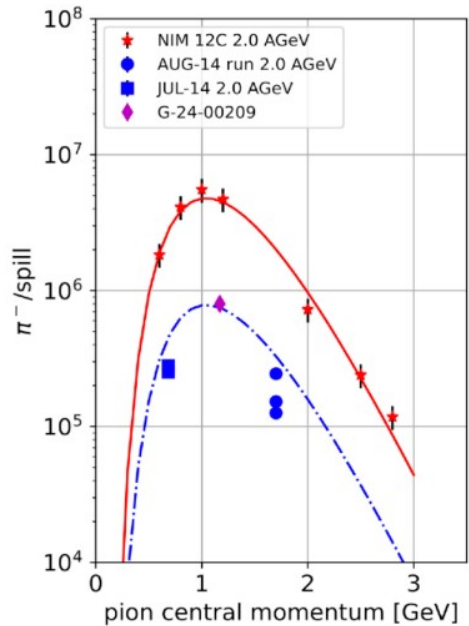
- **ECAL** (2017-2021)
- RICH (2018)
- **Forward Detector** (2021)
- **iTOF** (2021)
- **START - LGAD**



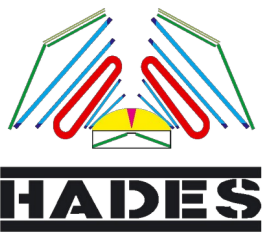
Pion Beam @ GSI

- reaction **N+Be**, $8-10 \cdot 10^{10}$ N_2 ions/spill (4s)
- secondary π^- with $I \sim 2-3 \cdot 10^5/s$
- **PE (CH₂)_n, C targets: $p = 654, 686, 748, 787$ MeV/c**
(2nd resonance region)
- **C/W targets: 1700 MeV/c**

- pion momentum $\Delta p/p = 2.2\%$ (σ)
- $\sim 50\%$ acceptance of pion beam line

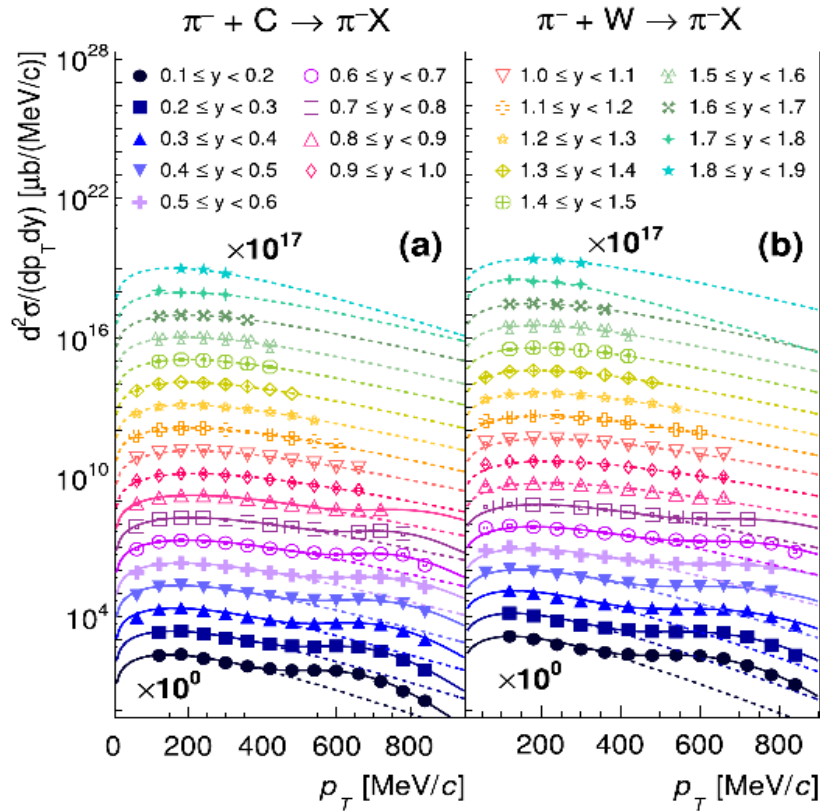


π^+C/W @ $p=1.7$ GeV/c

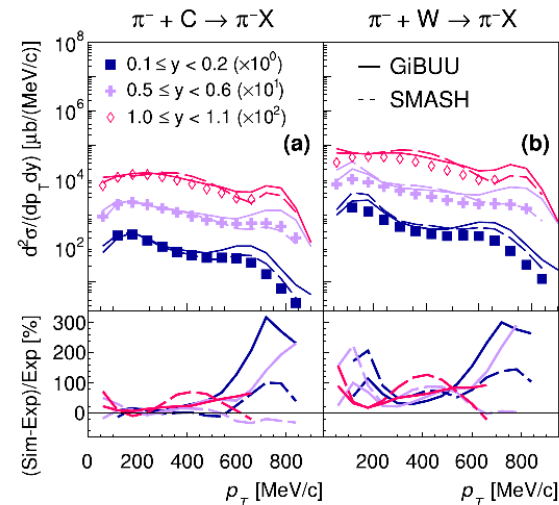


Kaon and ϕ absorption *Phys. Rev. Lett.* **123** (2019), 022002

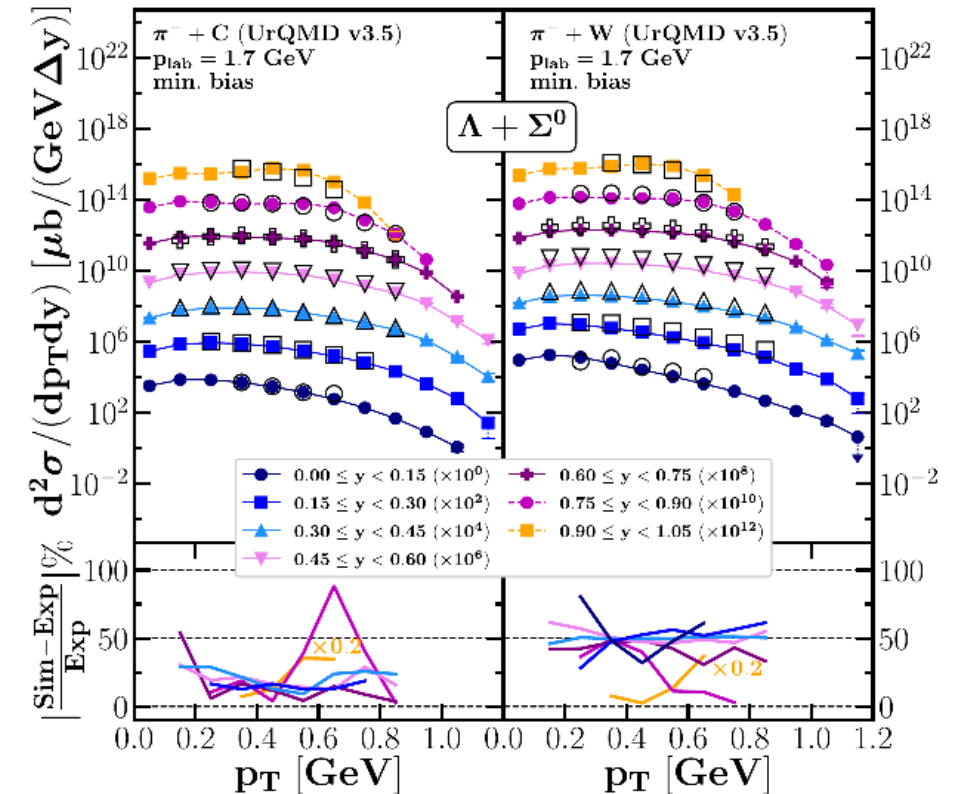
Inclusive production: $\pi^{+/-}$, ρ , $\Lambda+\Sigma^0$, K^0 , $K^{+/-}$ *Eur.Phys. J. A60*, 7, 156 (2024)



- SMASH
- GiBUU
- UrQMD



UrQMD: Phys.Rev.C 109, 044913 (2024)



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

→ Baryon resonance properties in the 2nd resonance region:

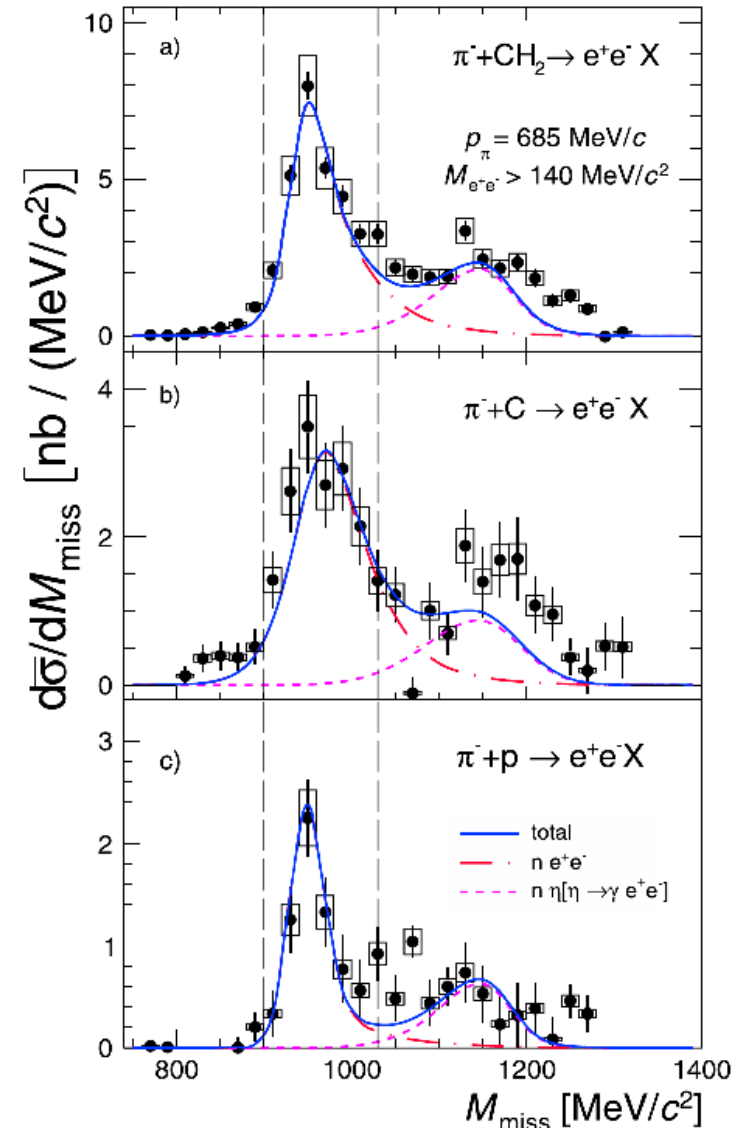
$\pi^+\text{C}$: reference measurement to the study of $\pi^+\text{p}$

- $\pi^+\text{p} \rightarrow \text{N}\pi\pi$: C data used for $\text{CH}_2\text{-C}$ subtraction:
Phys. Rev. C 102, 024001 (2020)
- $\pi^+\text{CH}_2/\text{C}/\text{p} \rightarrow \text{e}^+\text{e}^-\text{X}$: *Phys. Rev. C* 111, 024908 (2025)
- quasi-free $\pi^+\text{p} \rightarrow \text{e}^+\text{e}^-\text{n}$ ($\pi^+\text{C}/\text{CH}_2$ data):
Phys. Lett. B 875, 140338 (2026)

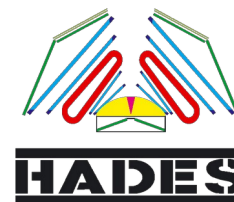
→ Cold matter studies:

$\pi^+\text{C}$ reaction @ $p_\pi=0.7 \text{ GeV}/c$

- pion dynamics in the 2nd resonance region
Fatima Hojeij : PHD University Paris-Saclay, 2023
EPJ Web Conf. 291, 04004 (2024)



$\pi^+\text{CH}_2/\text{C}$ @ $p=0.61, 0.66, 0.7, 0.8$ GeV/c



→ Baryon resonance properties in the 2nd resonance region:

$\pi^+\text{C}$: reference measurement to the study of $\pi^+\text{p}$

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→ Cold matter studies:

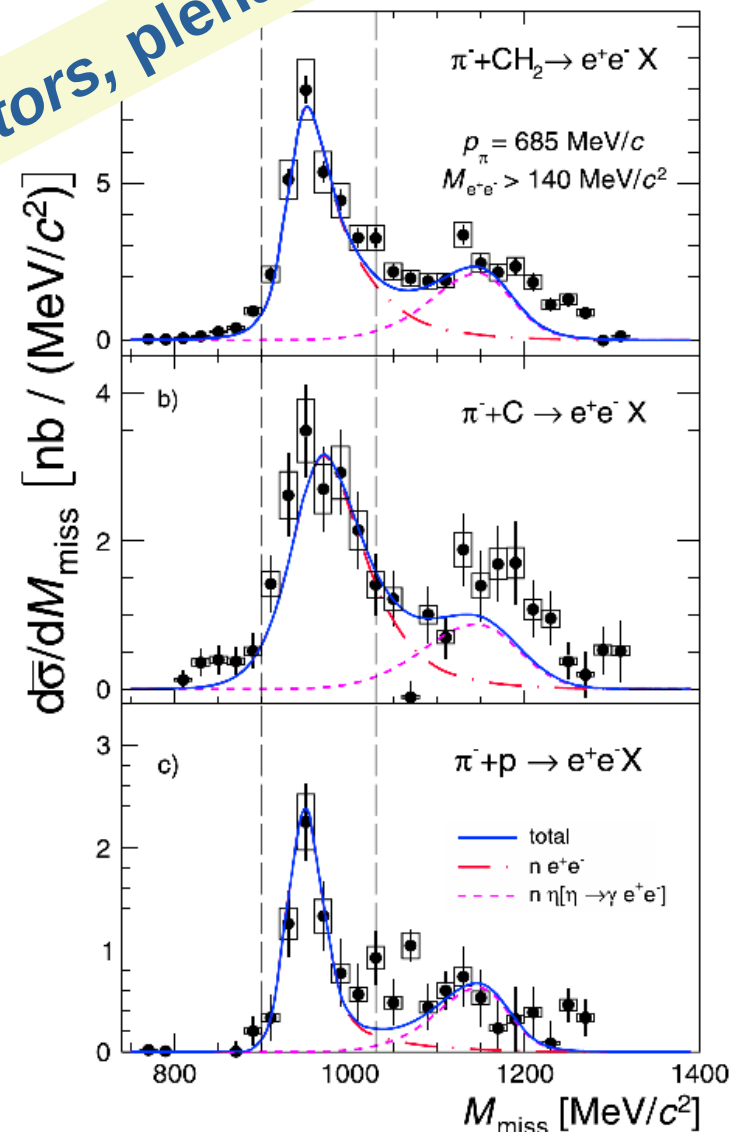
$\pi^+\text{C}$ reaction @ $p=0.61, 0.66, 0.7, 0.8$ GeV/c

- pion dynamics in the 2nd resonance region

Fatima, PHD University Paris-Saclay, 2023

Conf. 291, 04004 (2024)

B. Ramstein, HADES results on baryon transition form factors, plenary



Main channels in $\pi+C @ 0.7 \text{ GeV}/c$

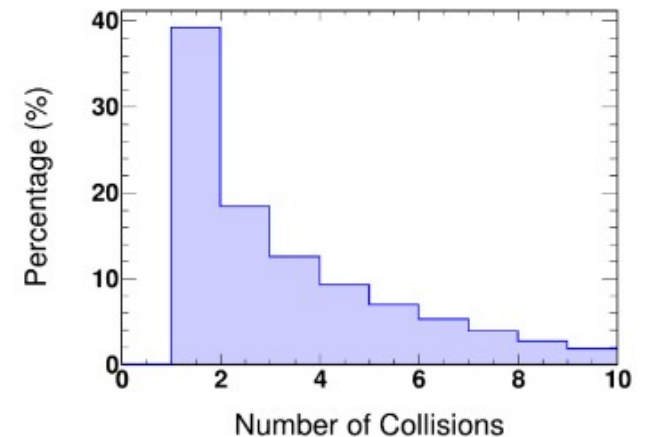
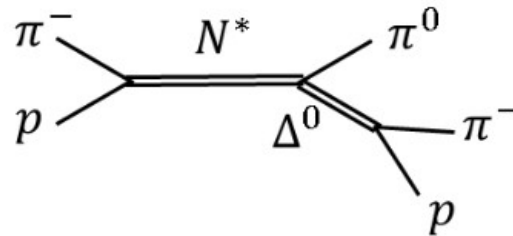
Quasi-elastic and charge exchange (SAID):

- $\pi^- + p \rightarrow \pi^- + p$ 17.8 mb
- $\pi^- + n \rightarrow \pi^- + n$ 12 mb
- $\pi^- + p \rightarrow \pi^0 + n$ 10 mb

+ **rescattering** (multi step) $\pi N \rightarrow \pi N$, $\pi N \rightarrow \pi\pi N$, $NN \rightarrow NN$
+ **absorption** $\pi NN \rightarrow NN$

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



Analysis of various exit channels: inclusive (π^- , π^+ , p), semi-exclusive (πp , $\pi^+ p$, $\pi^- p p$, $\pi \pi^+ p$, $\pi \pi^- p$...)

- the data are compared to: transport SMASH, GiBUU, JAM2/RQMD.rmf, and to the INCL++ cascade models
- the semi-exclusive data are compared to models inside HADES acceptance (Geant simulations+reconstruction)

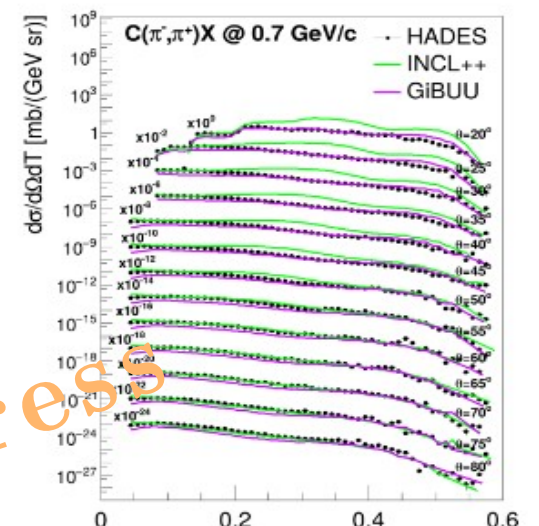
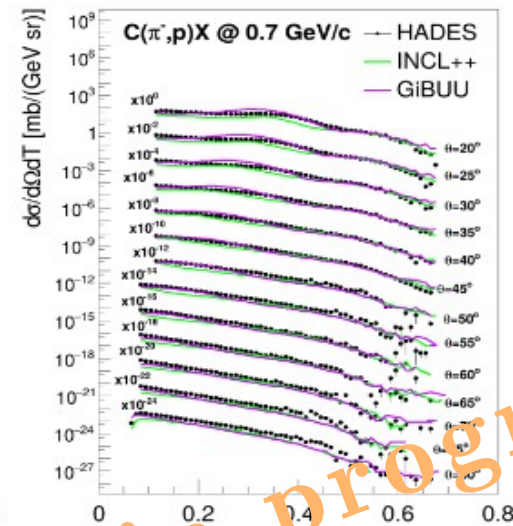
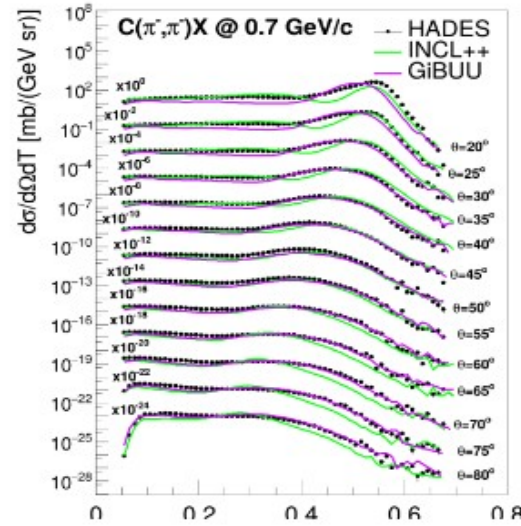


π^+C @ $p=0.7$ GeV/c – inclusive analysis

π^-

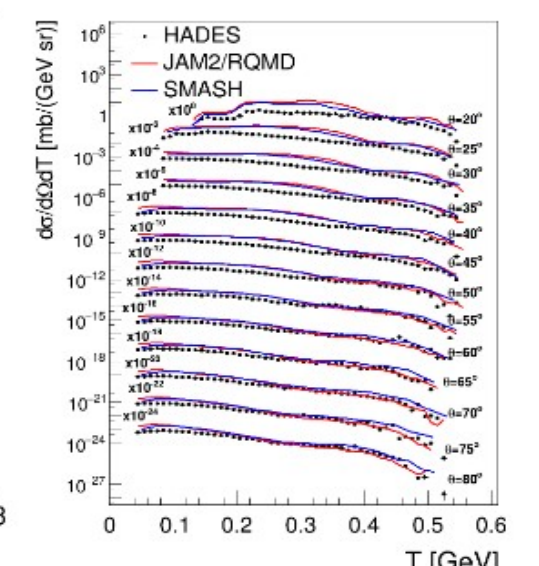
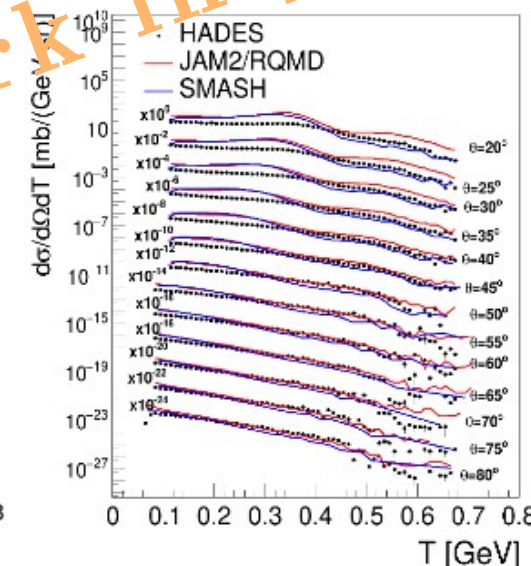
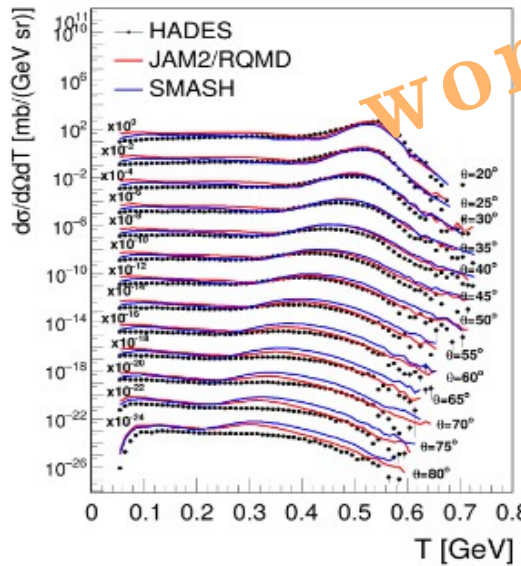
p

π^+



INCL and GiBUU:

SMASH and JAM2



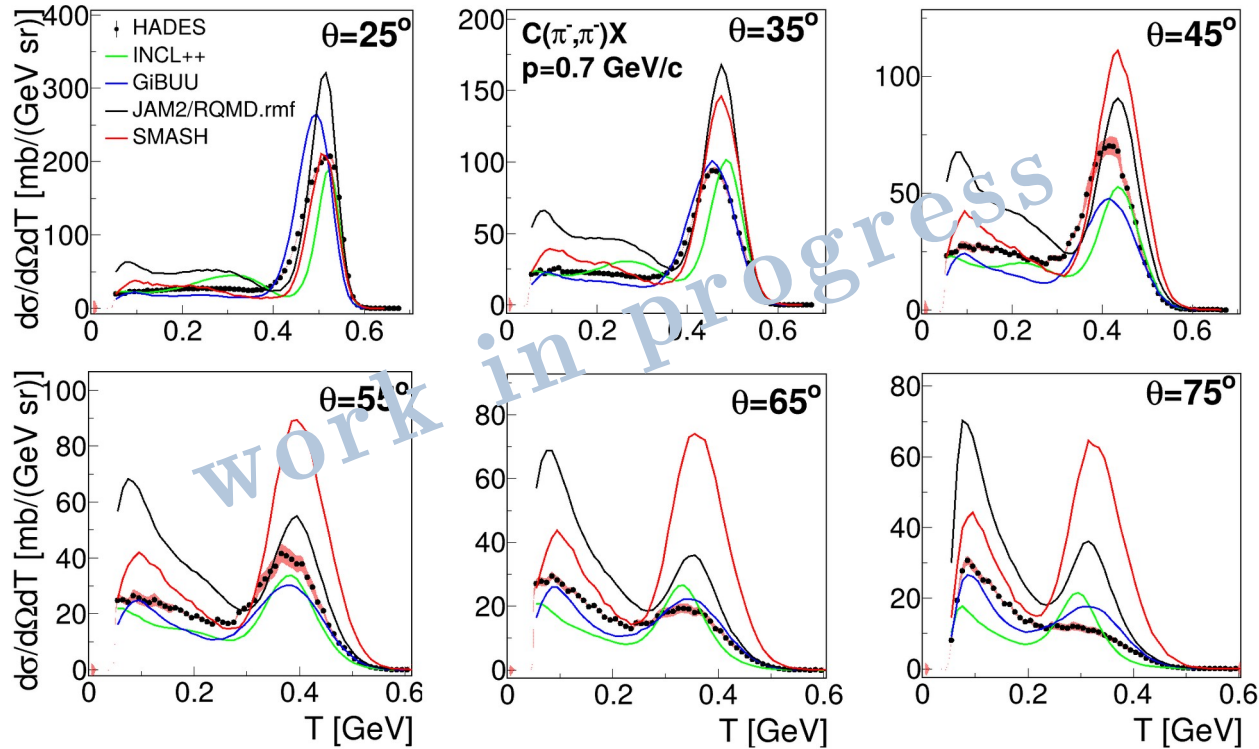
Inclusive double differential cross sections of π^- , π^+ and p

High statistics data ideal base for model benchmarking

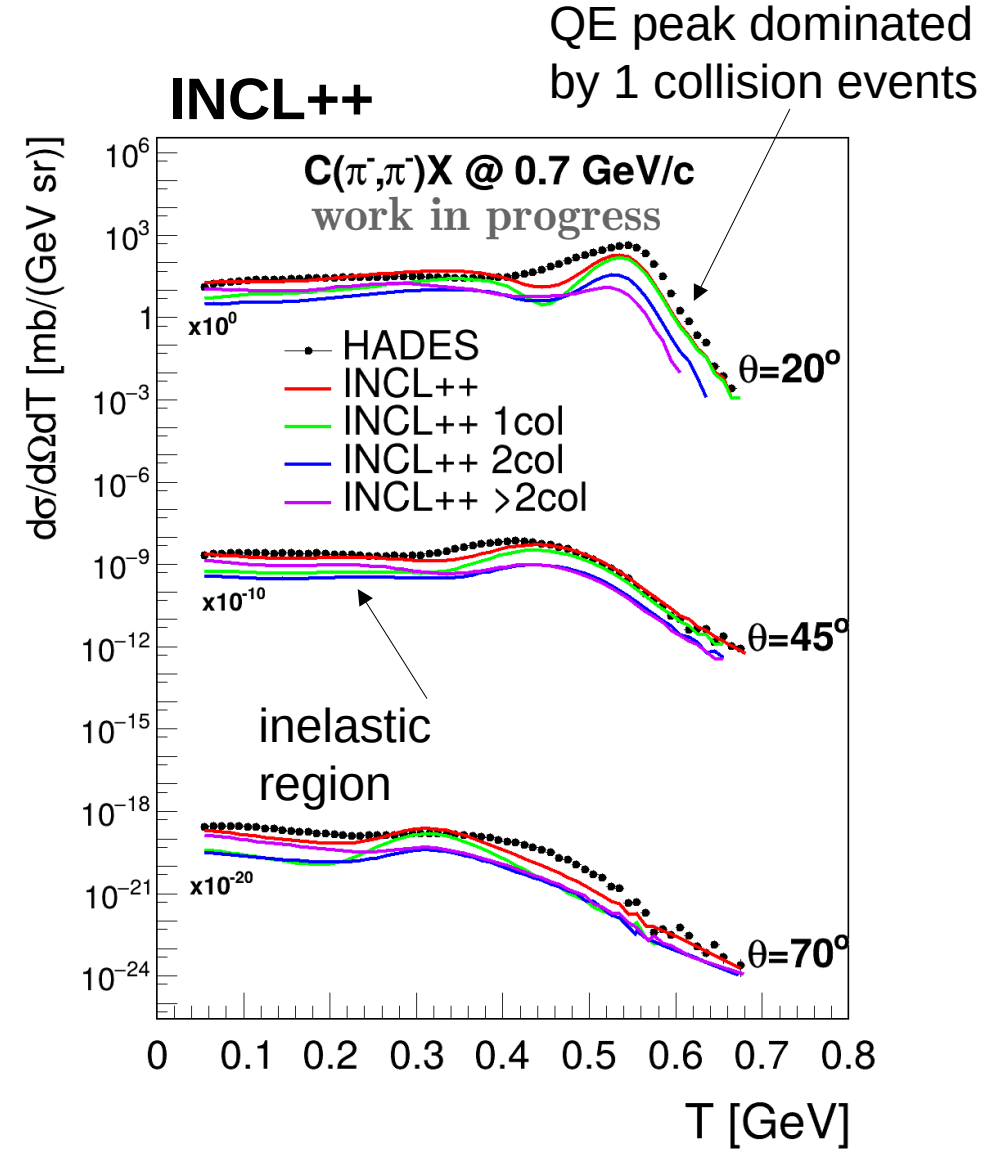
work in progress

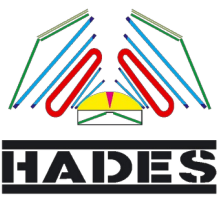
$\pi^- + C \rightarrow \pi^- + X @ p = 0.7 \text{ GeV/c}$

➤ dominated by quasi-elastic process

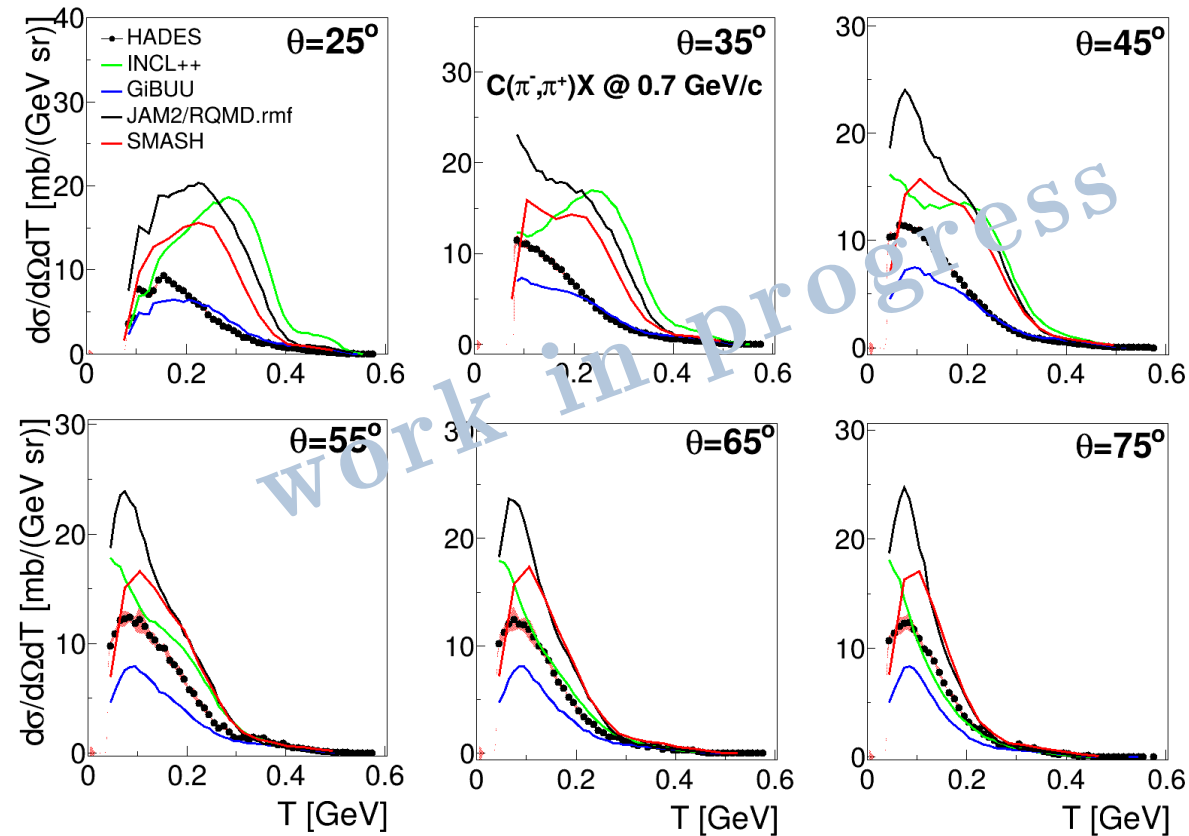


- INCL and GiBUU: rather good description of the data
- SMASH and JAM2: strongly overestimate the yields

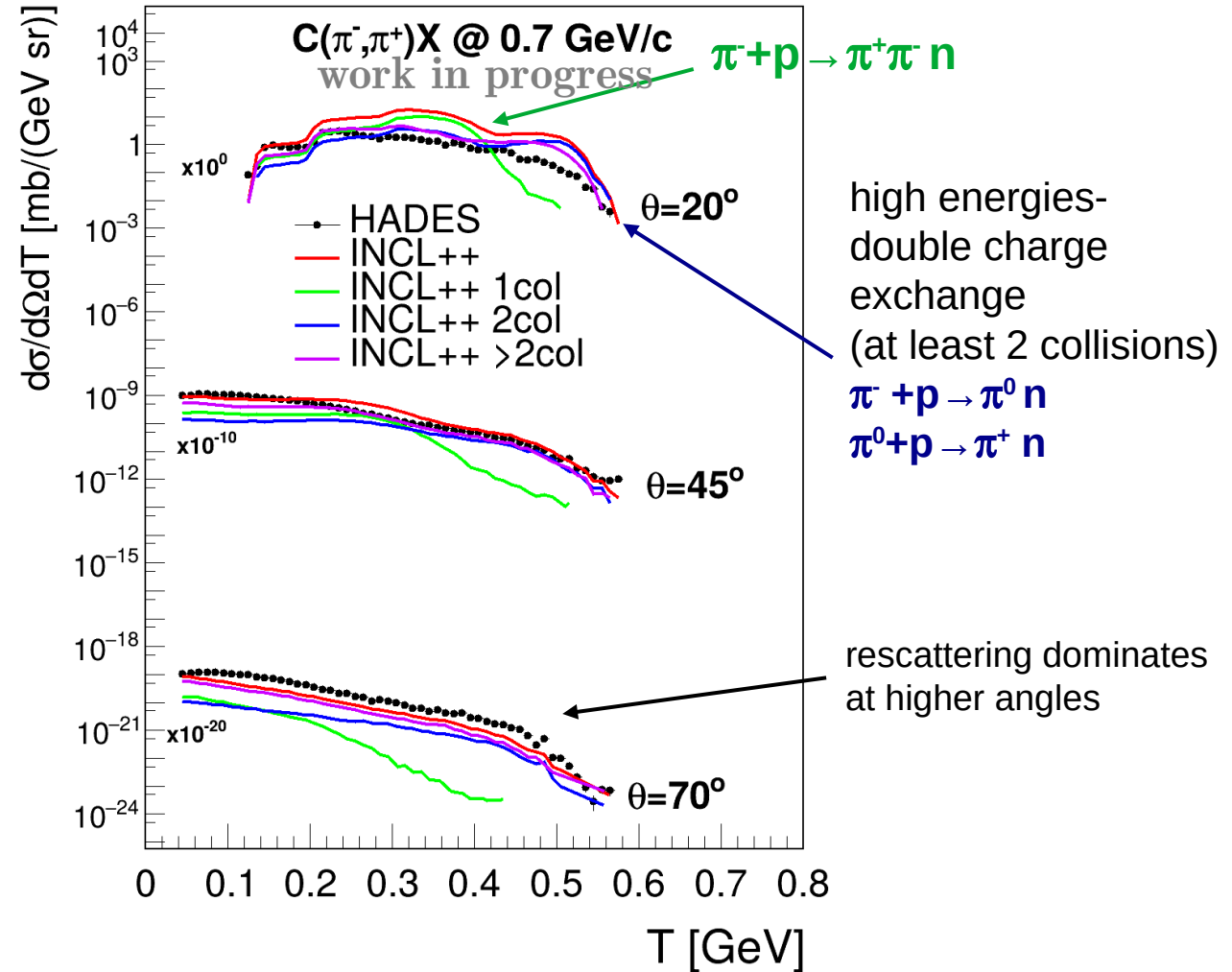




$\pi^- + C \rightarrow \pi^+ + X$ @ $p = 0.7$ GeV/c



INCL++



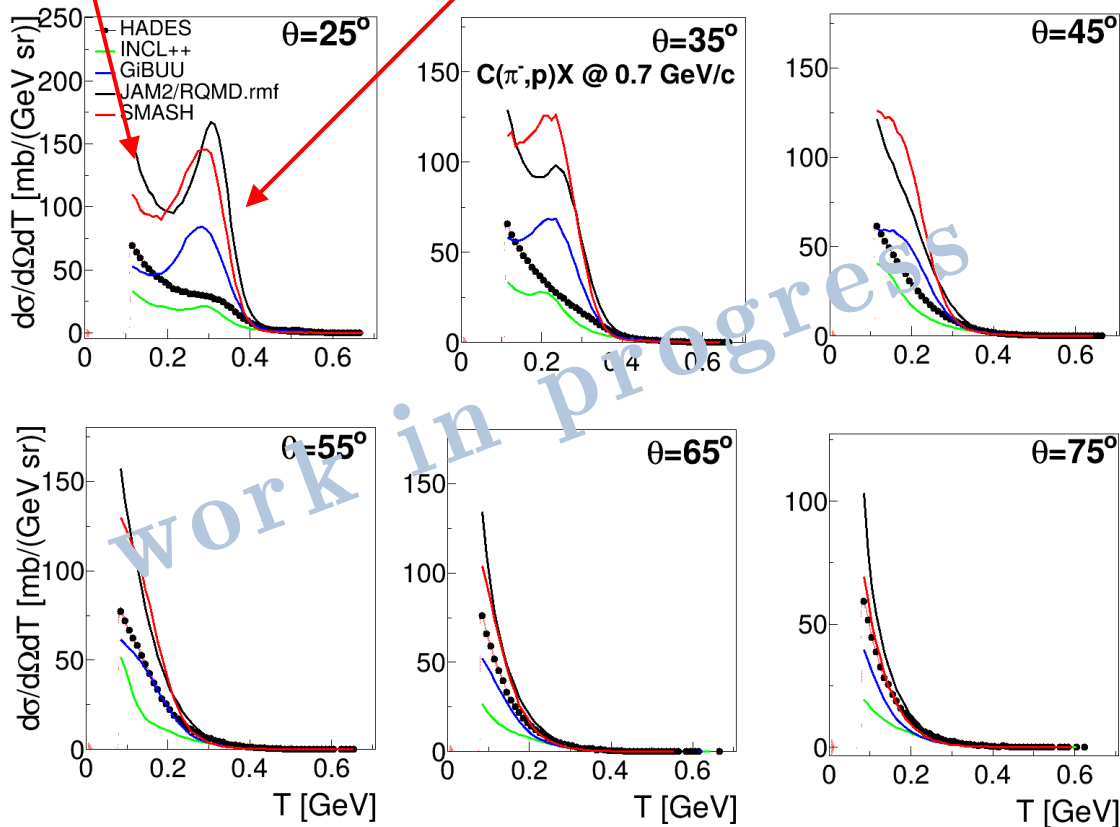
- π^+ produced in inelastic processes ($\pi^- + p \rightarrow \pi^+ \pi^- n$ or multistep)
- large differences between the models, with additional structures



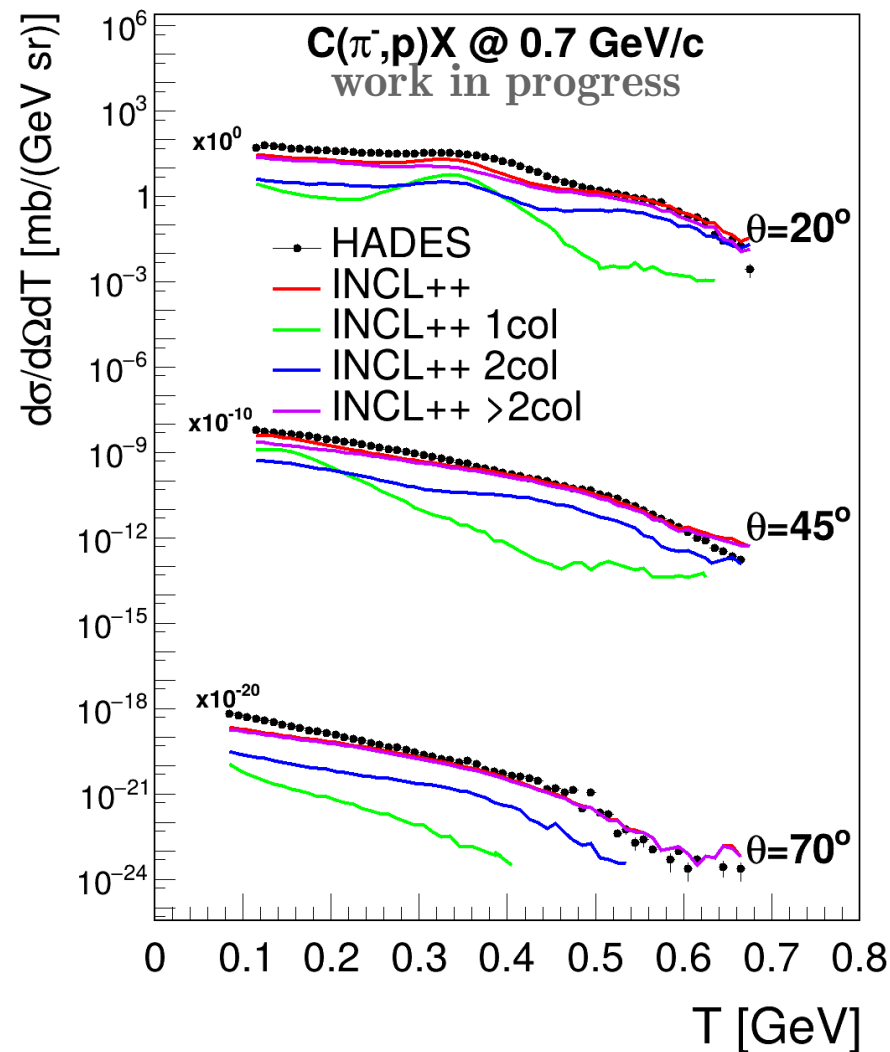
$\pi+C \rightarrow p+X$ @ $p=0.7$ GeV/c

Inelastic $\pi N \rightarrow \pi\pi N$

$\pi N \rightarrow \pi N$ (backward π scatt.)



INCL++

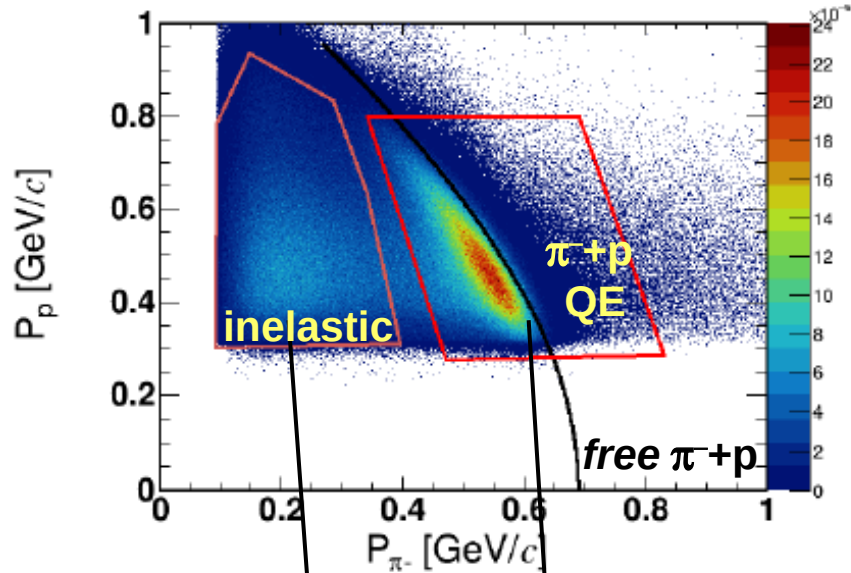
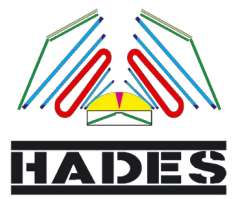


protons are mostly detected after rescatterings

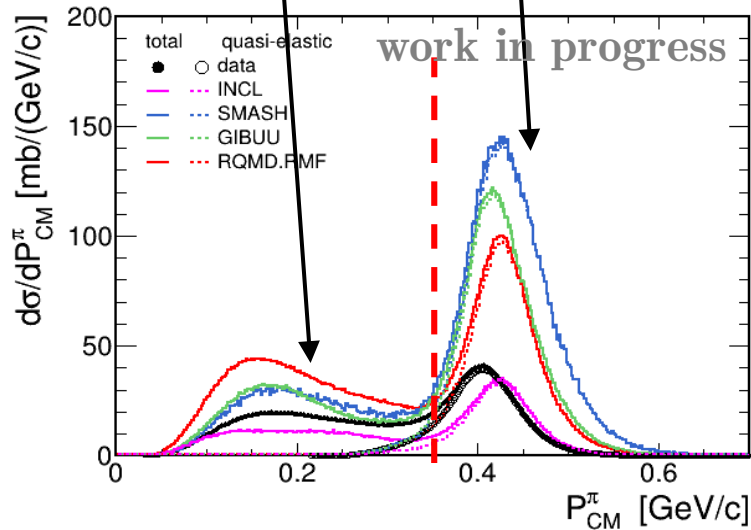
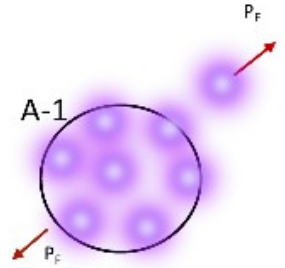
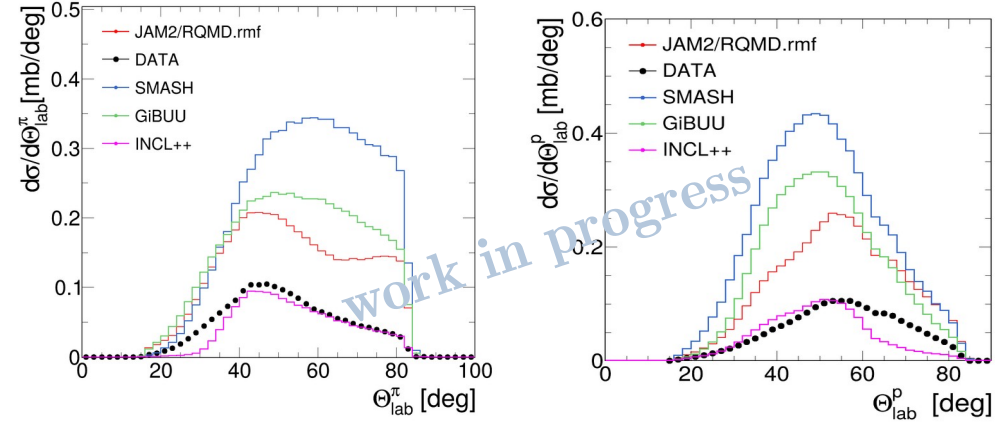
high energy tails- only rescatterings

- backward elastic π^- scattering overestimated in all transport models: no visible peak in data
- INCL performs better

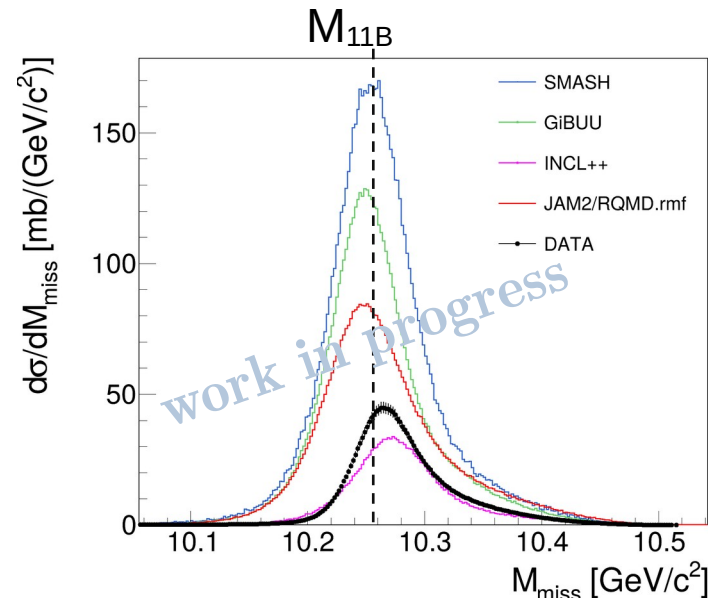
Semi-exclusive: quasi-elastic π^-+p channel



Angular distributions:



$$M_{\text{miss}} = M(\pi + C \rightarrow \pi + p + X)$$



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

F. Hojeij PhD, IJCLab 2023

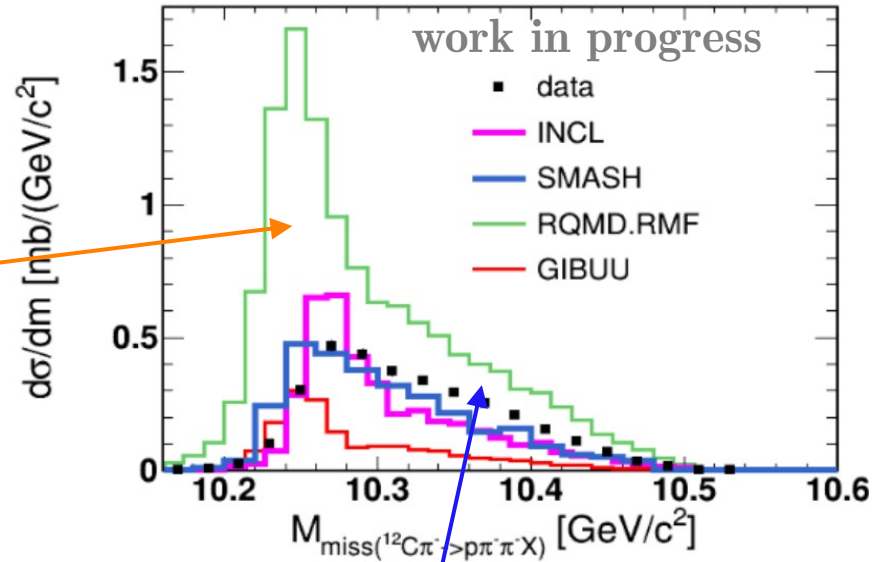
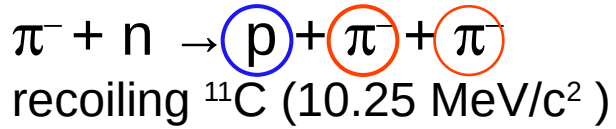
EPJ Web Conf. 291, 04004 (2024)

QE selction: $p_{\text{CM}}^{\pi} > 0.35$ GeV/c

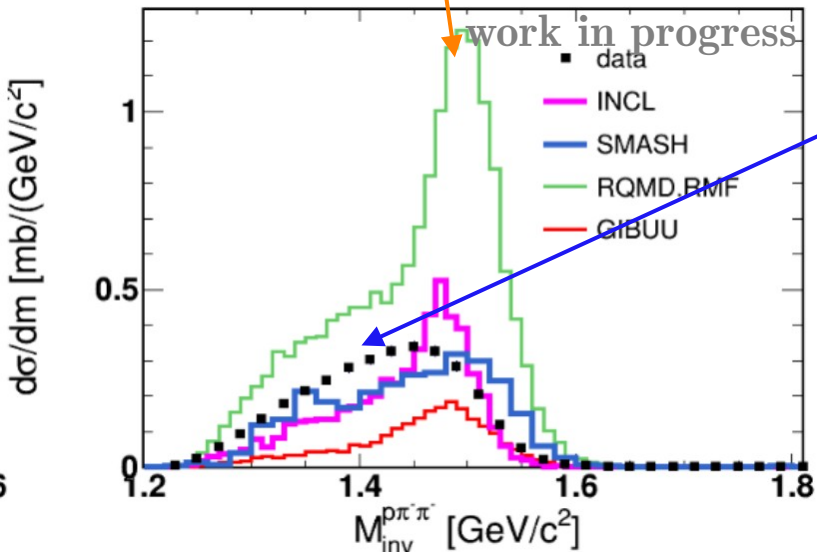
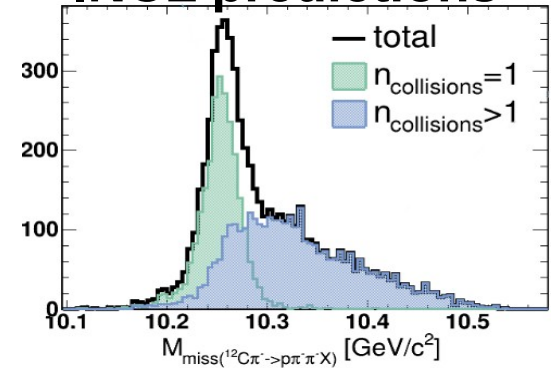


Semi-exclusive: $\pi + C \rightarrow p + \pi + \pi + X$

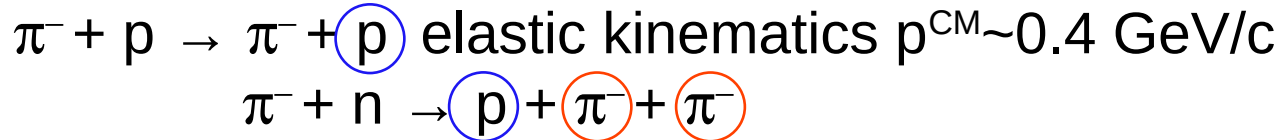
$n_{\text{collisions}} = 1$:



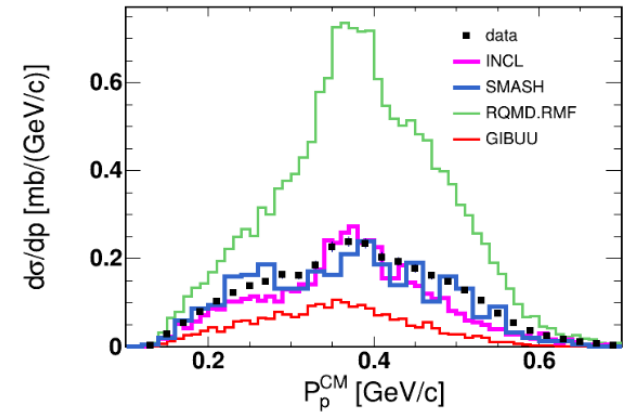
INCL predictions



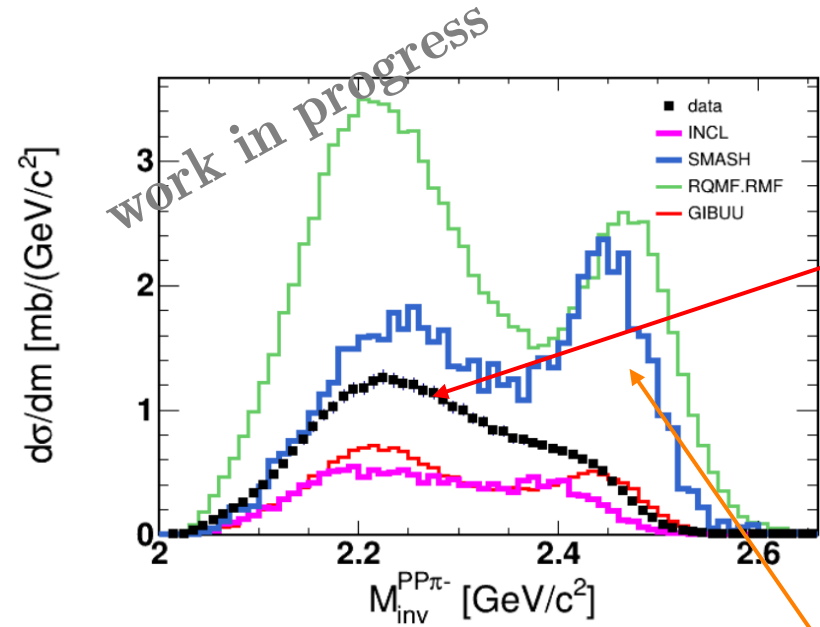
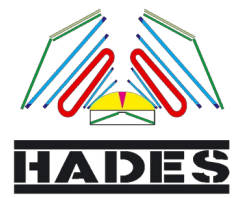
$n_{\text{collisions}} > 1$:



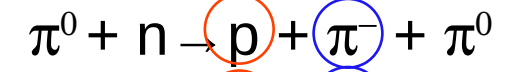
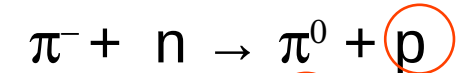
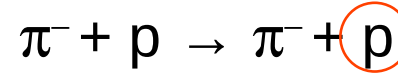
➤ suppressed in GiBUU, but present in data, overestimated by JAM2



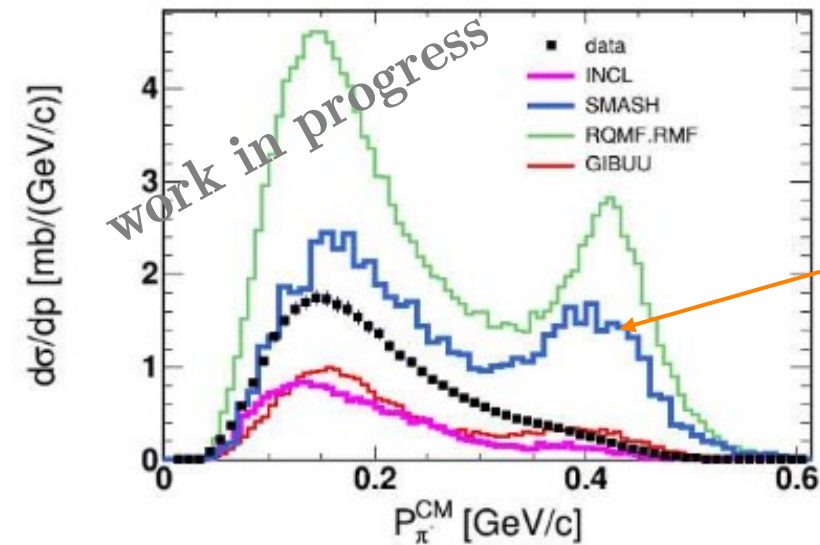
Semi-exclusive: $\pi^- + C \rightarrow p + p + \pi^- + X$



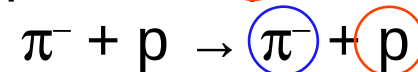
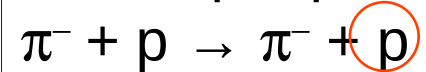
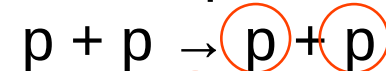
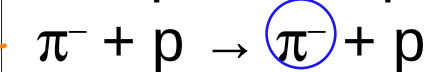
2-step inelastic processes:



➤ data favor the inelastic processes



2-step elastic processes:



➤ totally overestimated by JAM2 and SMASH

Summary & Outlook

- Precise pion and proton emission spectra have been measured with HADES in different exit channels in the $\pi^{-}+^{12}\text{C}/\text{W}$ systems @0.7 and 1.7 GeV/c.
- **Very first investigation of particle emission in $\pi+A$ reactions above the $\Delta(1232)$ resonance !**
- **Data provide extremely stringent test of models** used for the comparison:
 - transport models (GiBUU, SMASH, JAM2) used for hadronic matter studies,
 - cascade model INCL++ (GEANT4 hadronic model),revealing that the models need improvement
- New data base is important to tune the FSI models for the neutrino physics.
- **Future measurements with pion beams** in energy range 0.5-3 GeV/c and various nuclear targets CH_2 , C, SiO_2 , KCl, Fe.



GSI pion beam: Marvin Kohls (C3 26.06 15:00)

THANK U FOR YOUR ATTENTION !



EMMI Workshop (7-11 December 2026)
GSI Helmholtzzentrum für Schwerionenforschung GmbH
***Long-Baseline Neutrino Reference Measurements
with Hadron Beams at GSI/FAIR***
<https://indico.gsi.de/event/25390/>

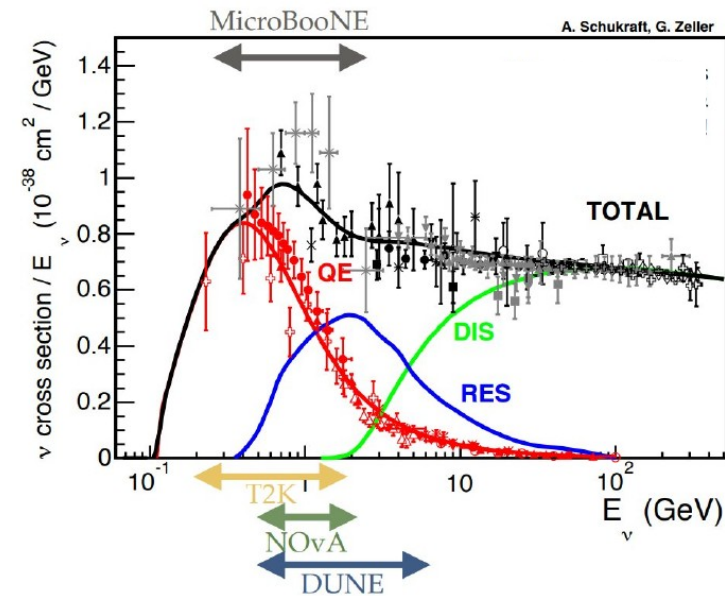
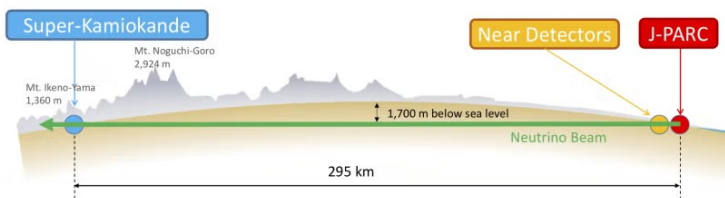
BACKUP

π^+A for neutrino physics

- Neutrino oscillations – 2015 Nobel Prize in Physics - neutrinos have a mass, in disagreement with SM
- Neutrino mass hierarchy ?
- Indication of **CP violation** ! currently largely limited by statistics ...

The precision era of ν oscillations

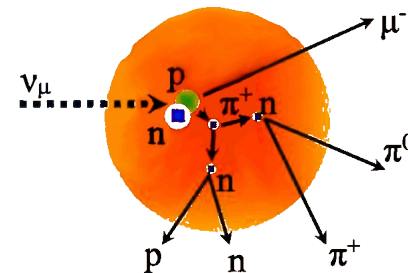
Long Baseline experiments:
T2K/DUNE/Hyper-Kamiokande/...



Neutrino energy is not known and is reconstructed from the interaction products measured in the detector:

- knocked-out nucleons,
- leptons, mesons, gammas,
- nuclear breakup

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E_\nu}$$



➤ FSI models are tuned to external $\pi/p+A$ data

Neutrinos vs. pions:

- different primary interactions
- similar energy dissipation processes (elastic/inelastic reactions, baryon resonance propagation, pion regeneration, rescattering)



Ratios = Model/Data - 1

Red contour: 90% of max. exp. yield
Blue contour: 10% of max. exp. yield

