Investigation of hadronic exit channels of the π^-+C reaction at an incident momentum of 0.7 GeV/c

QNP 2022, 8th September

Fatima Hojeij
IJCLab
HADES Collaboration

QCD phase diagram studies

HADES objectives :

- Study hadronic matter at moderate temperature and high baryonic density.

A+A: 1-3A GeV

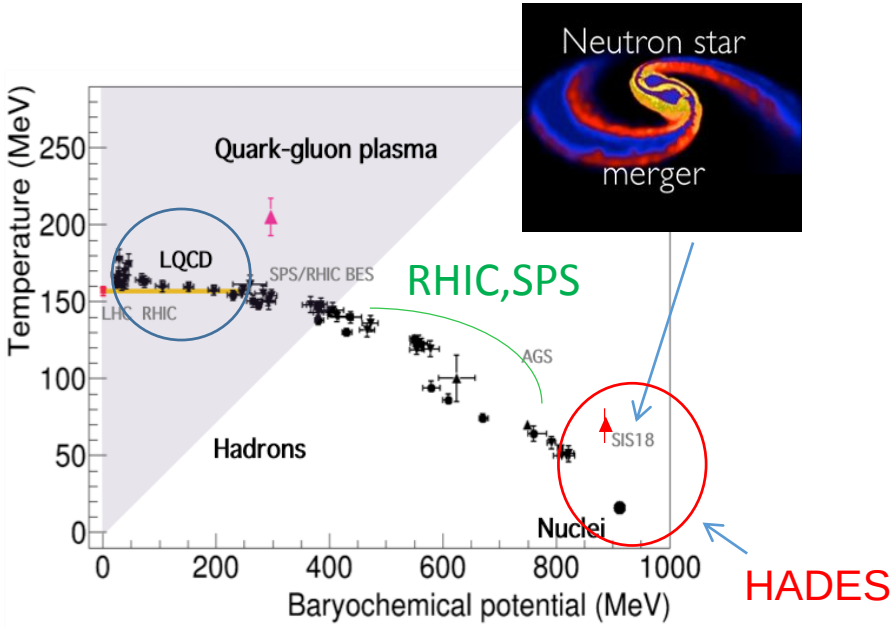
$\sqrt{s_{NN}}$=2-2.4 GeV

(compl. to LHC, SPS, RHIC,...)

- Microscopic structure of baryon dominated matter

Role of baryonic resonances (excited states of nucleons), hyperons

$\boldsymbol{\Delta(1232)}$
$\boldsymbol{N^*(1440)}$
$\boldsymbol{N^*(1520)}$
$\boldsymbol{N^*(1535)}$
Etc ...

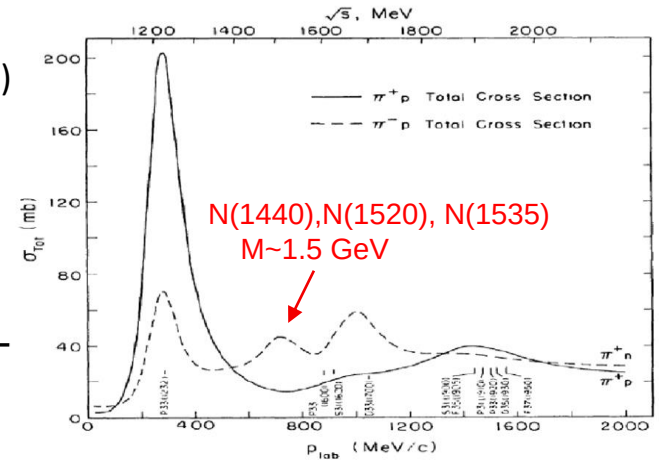


[T. Galatyuk, NPA-D-18-00411 (2018) QM18]

The heavy ion context

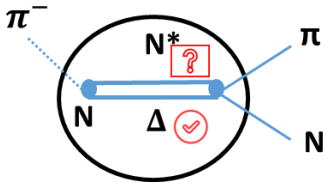
In heavy-ion collisions at a few AGeV, pion dynamics crucial to describe the evolution of the collision :

- ✓ real pions copiously produced $(NN \rightarrow NN\pi, \pi + N \rightarrow N^*/\Delta)$
- ✓ NN interaction driven by pion exchange

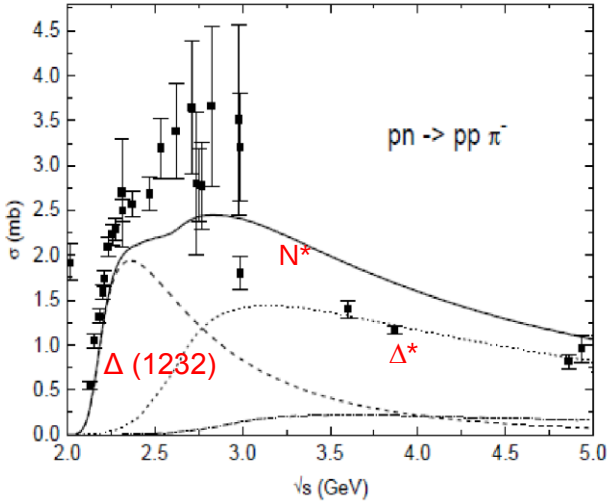


[D. R. Marlow et al., Phys. Rev. C30, 1662 (1984), Pion cattering From C and Ca at 800-MeV/c.]

- ✓ p+A or A+A at $\sqrt{s_{NN}}$ < 2.6 GeV Δ(1232) region (p_π =250 MeV/c) well-known
- ➢ p+A or A+A at $\sqrt{s_{NN}}$ > 2.6 GeV, information on higher lying resonances needed : N(1520) region p_π ~ 700 MeV/c has not been explored.



- 300<p<500 MeV/c : few measurements (π, πx) or (π, π πx) (LAMPF, TRIUMF, KEK)
- p>500 MeV/c : only total cross sections (Saturne-1, NIMROD, BNL) and differential elastic cross sections (KEK).



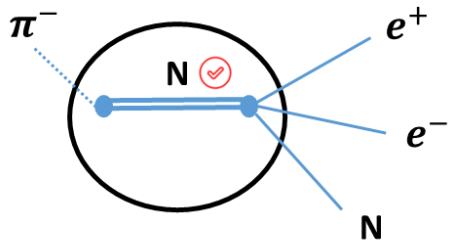
[S. Teis et al. Pion production in heavy ion collisions at sis energies. Z. Phys.,A356 :421, 1997.]

❖ p+A (SIS18 & SIS100) or A+A (SIS100)

π^-+C in the 2nd resonance region

1st investigation of the 2nd resonance region with HADES :

- π^-+ C → $e^+ e^-$ + X @ 0.685 GeV/c consistent with quasi-free process : π^-+ p → $e^+ e^-$ + n.



e+/e-: no rescattering
very different for hadronic channels

[HADES collab., to be submitted]

Our aim :

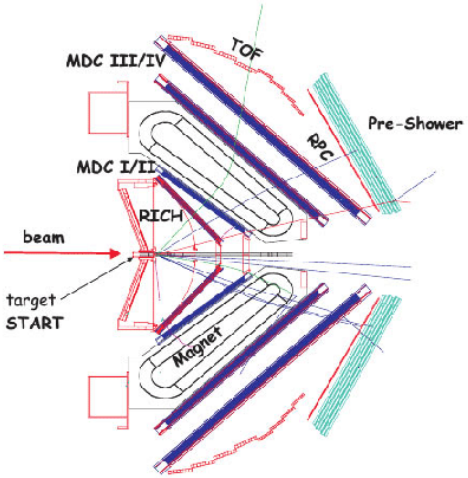
Investigate different hadronic exit channels in π^- + ^{12}C reaction for 2nd resonance region :

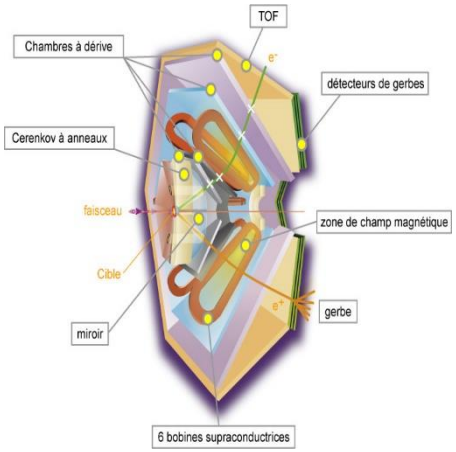
- Information on pion-nucleus dynamics in the second resonance region (N1520).
  - study reaction mechanisms: quasi-elastic, rescattering, pion absorption,...
  - Sensitive test INCL cascade and transport models (Smash, RQMD, GIBUU…).

- INCL is used in toolkits for the simulation of the passage of particles through matter (Geant).
- SMASH, rQMD & GIBUU are used for the description of heavy ion collisions.
- PLUTO event generator is also used for quasi-free simulations.

HADES

High Acceptance DiElectron Spectrometer (GSI, Darmstadt)





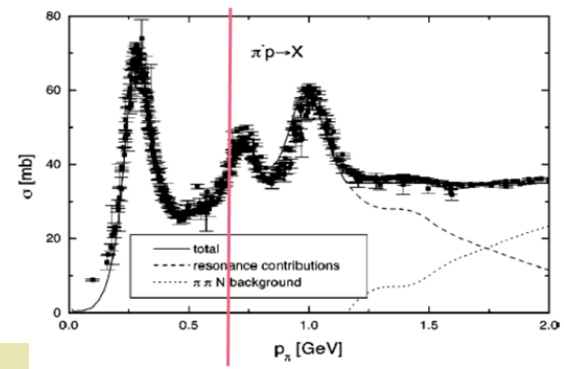
Experiments (2004-2014)

- Hadronic matter studies :
  - C+C 1 & 2 AGeV,
  - Ar+KCl 1.75 AGeV
  - Au+Au 1.25 AGeV
  - Ag+Ag 1.65 AGeV
- Elementary reactions :
  - p+ p 1.25, 2.2 , 3.5 GeV,
  - d+p 1.25 GeV/nucléon
  - π^-+CH_2/C 0.7 GeV/c
- Cold matter :
  - p+Nb 3.5 GeV,
  - π^-+C/W 1.7 GeV/c

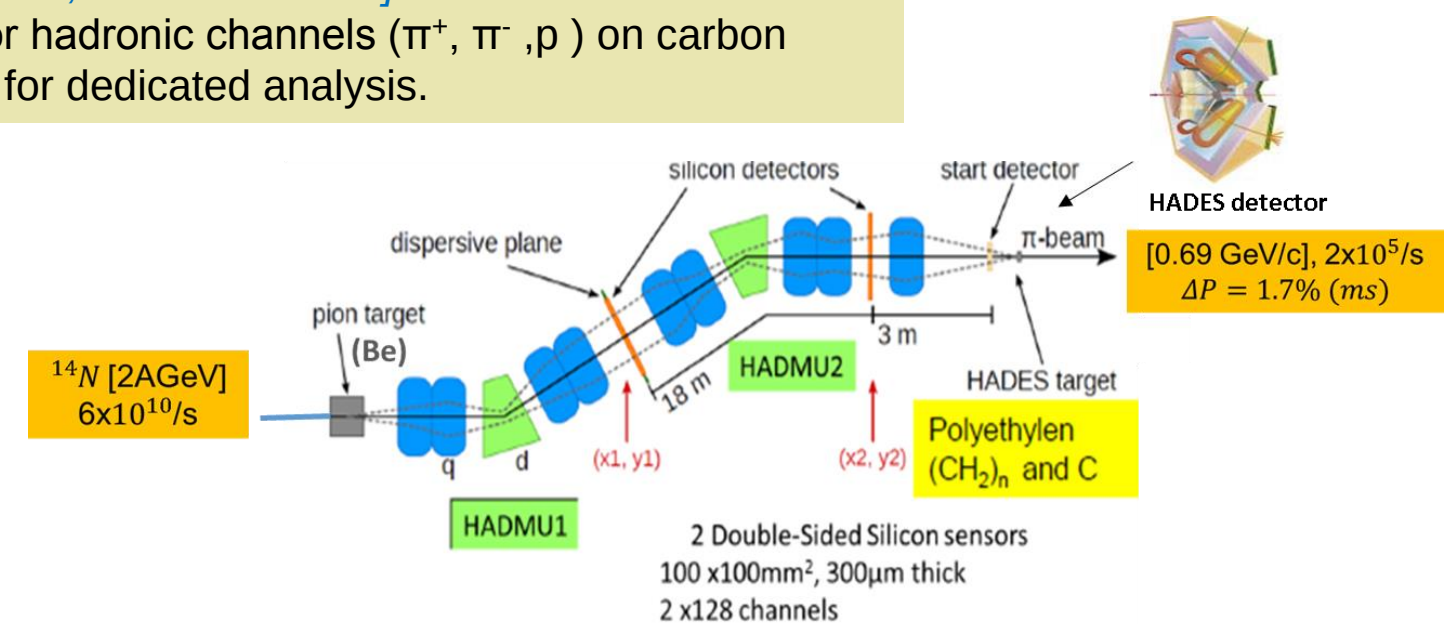
- Acceptance: Azimuthal angles 85% (6 sectors)
  polar angles: 18° - 85°
- Detected particles: $e^{\pm}$, p, $\pi^{\pm}$, $K^{\pm}$
- Tracking: MDC
- $e^{\pm}$ identification with RICH, TOF/PreShower
- p, $\pi^{\pm}$, $K^{\pm}$ identification TOF-Tracking

Pion beam experiment @ GSI

- August 2014 commissioning experiment
- Total ~15 days of measurements
- Main run: momentum p_π = 0.690 GeV/c (√s=1.49 GeV)
- Polyethylene (CH_2) and carbon targets
- Secondary pion beam
- Trigger on at least 2 charged particles.



- Data on carbon mainly used for subtraction of π^-+C interactions in CH2 target to study π^-+p reaction.
  [HADES collab., Phys.Rev. C102 (2020) no.2, 024001]
  [HADES collab., to be submitted]
- Large statistics for hadronic channels (π^+, π^- ,p) on carbon target to be used for dedicated analysis.



Benchmark of models

Participant-spectator model : PLUTO

- ^{12}C = participant off-shell proton + spectator on-shell 11B
- π- interact with an off-shell proton moving with momentum distribution in agreement with $(e, e'p)$ (1)
- Further interaction of particles not taken into account
- Only elastic channels included (by choice).

IntraNuclear Cascade model : INCL

- ^{12}C= (on-shell nucleons) nucleon Fermi gas
- π- + p (moving and on-shell) → π- + p + X
- Further interaction of particles taken into account, depending on cross section
  Nuclear mean field is acting on products.
- inelastic channels are also included
  Only $\Delta(1232)$ resonance is included

SMASH & rQMD & GIBUU

- ^{12}C =(on-shell nucleons) nucleon Fermi gas ?
- $\pi^- + p$ moving and on-shell → π^-+p+X
- Further interactions are taken into account
- inelastic channels are included
- All baryonic resonances included

- ❑ Pluto is a Monte Carlo simulation framework developed by the HADES collaboration for heavy ion and hadronic-physics reactions.
- ❑ Simulations processed in GEANT; comparison data with simulations in acceptance.

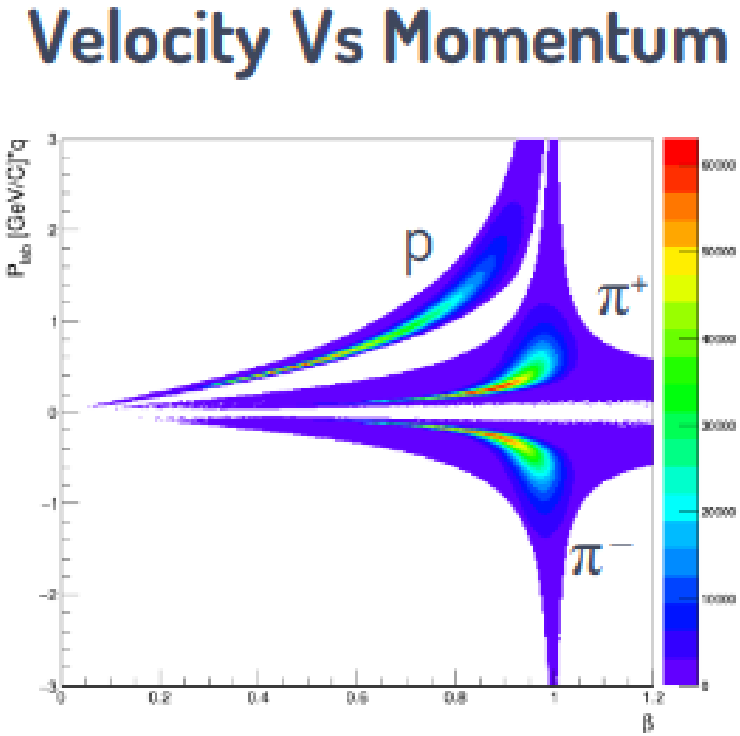
(1) [K. Nakamura et al.,Nuclear Physics A, Volume 268, Issue 3, 21 September 1976, Pages 381-407]

PID & Normalization

Particle identification is done using

on momentum-velocity correlation

$$p = \beta \times m/\sqrt{(1 - \beta^2)}$$

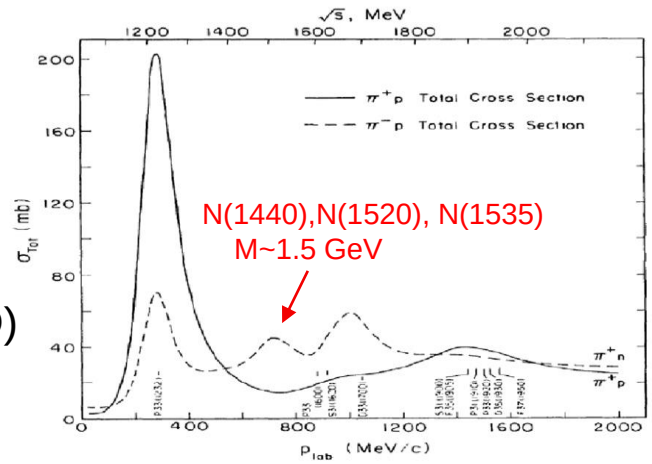


Data normalisation (counts -> mb/unit) :

Using measurements on C and CH2 targets and known π^-+ p elastic scattering cross-section, global systematic error = 4%.

statistical errors are negligible, point to point systematic errors (diff dist) : 5%

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



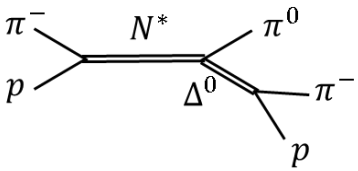
- Quasi-elastic and charge exchange:
- $\pi^- + p \rightarrow \pi^- + \mathrm{p}$ quasi-elastic scattering σ= 17.8 mb (SAID)
- $\pi^- + p \rightarrow \pi^0 + \mathrm{n}$ charge exchange σ = 10 mb (SAID)

- Inelastic (pion production)
- $\pi^- + \mathrm{p} \rightarrow \mathrm{n} + \pi^- + \pi^+$ σ= 6.1 mb

[HADES collab., Phys.Rev. C102 (2020) no.2, 024001]

- $\pi^- + \mathrm{p}$ □ $\mathrm{p} + \pi^- + \pi^0$ σ= 3.3 mb *(idem)*
- $\pi^- + n \rightarrow \mathrm{p} + \pi^- + \pi^-$ σ= 0.4 mb

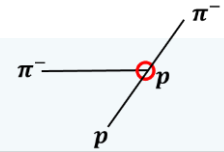
Main contribution from s-channel N* excitations, N* → π Δ, σN, ρN



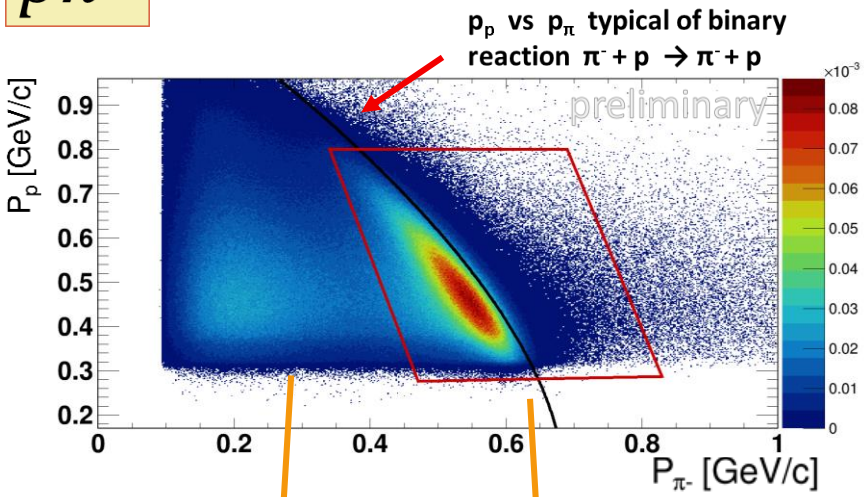
- Multi-step: rescattering πN→ πN, NN → NN
- π^-N→ πN followed by NN → NNπ kinematically suppressed

→ two-pion production occurs mainly in the same step, via πN→ π π N

Selection of quasi-elastic channel



$p\pi^-$



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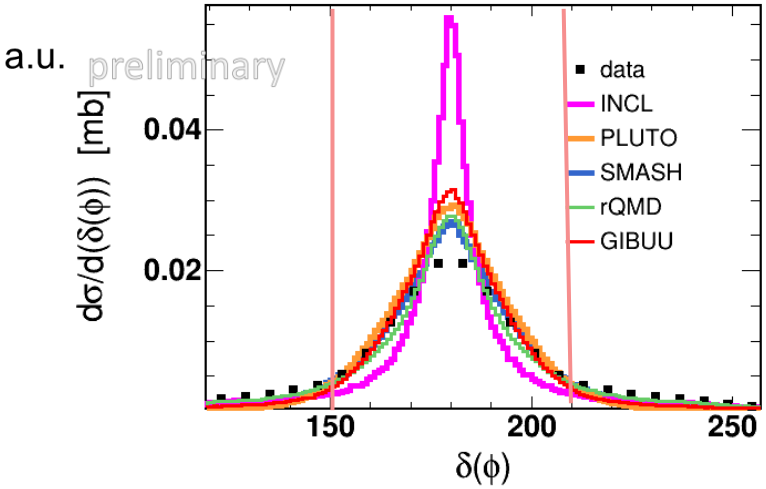
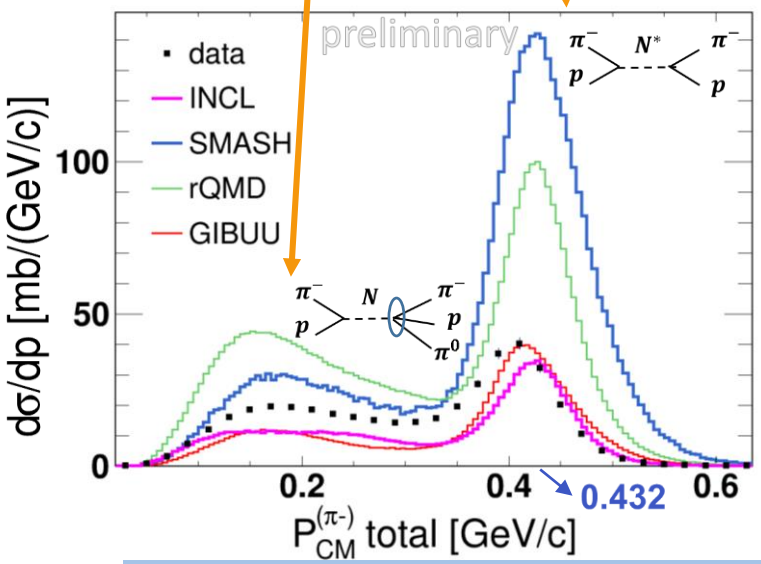


Inelastic ($p\pi\pi$)

« QE » $p\pi^-$



$p\pi^-$ « QE selection » :

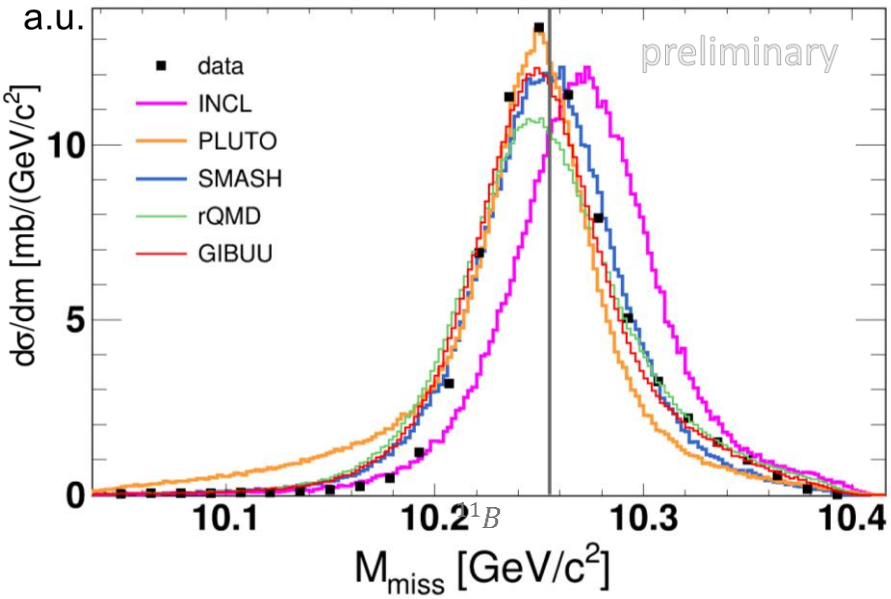
Momentum correlation + coplanarity condition :

$150° < \Delta\varphi < 210°$

- SMASH & rQMD overestimate $p\pi^-$ channel.
- INCL : underestimates $p\pi^-$ channel espacially inelastic channel.
- GIBUU reproduces quite well $p\pi^-$ total cross section with difference in yields (« QE » and inelastic).

$p\pi^-$: "quasi − elastic"

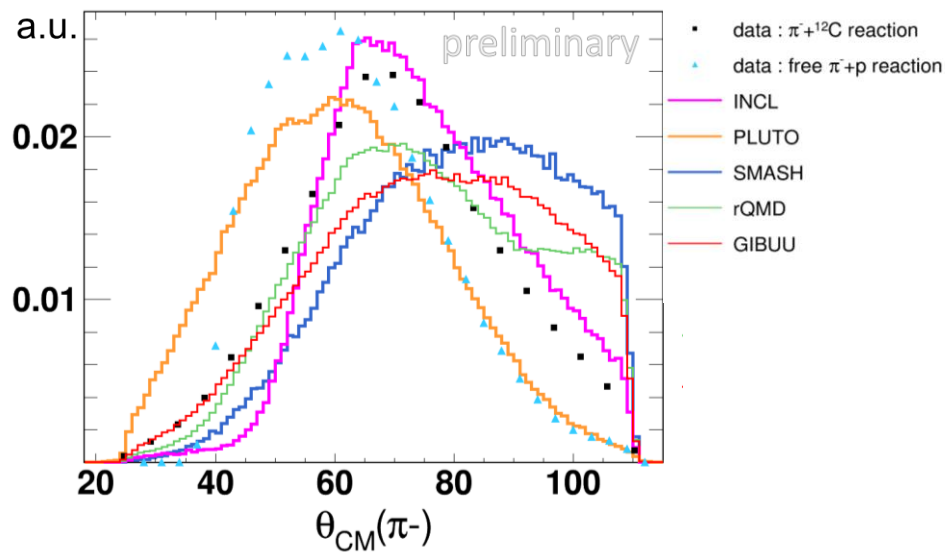
$$M_{miss} = M_{(\pi^- + {}^{12}C \to \pi^- + p + X)}$$



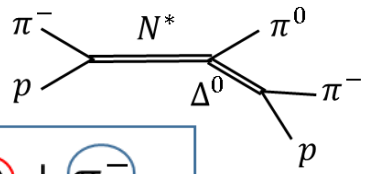
- Data and transport models: missing mass close to ^{11}B mass.
- Missing mass shifted in INCL.

Distributions are normalized to the surface in order to compare shapes.

- Ang. distrib. different from free π^-+p elastic scattering.
- INCL reproduces well pion angular distribution.
- PLUTO closer to free π^-+p data especially for high angles.
- Transport models have a too broad angular distribution.



$p\pi^-$: Inelastic



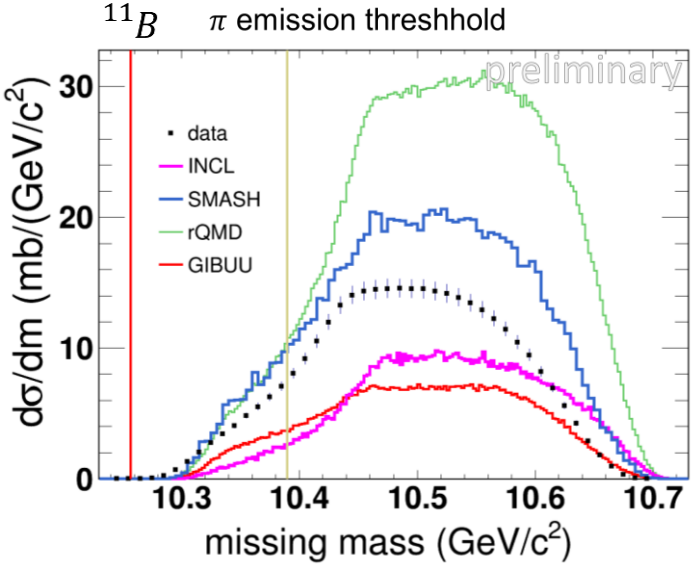
Single step

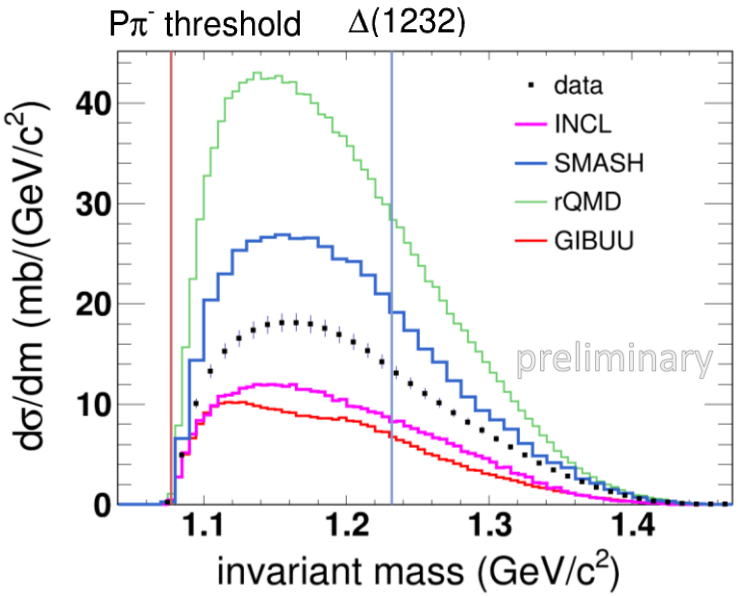
$$\pi^- + p \rightarrow \pi^0 + p + \pi^-$$

Multi step

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

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





- No clear presence of Δ^0 in data, some structure seen in GIBUU.
- GIBUU underestimates the yields.
- rQMD & SMASH in agreement with data, but overestimate yields.
- INCL & GIBUU underestimate yields. They favor multi step processes

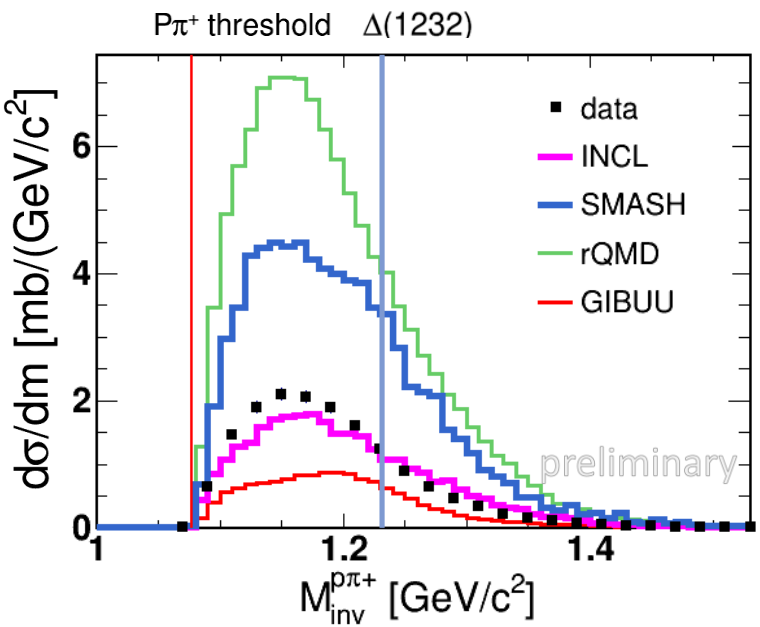
$p\pi^+$

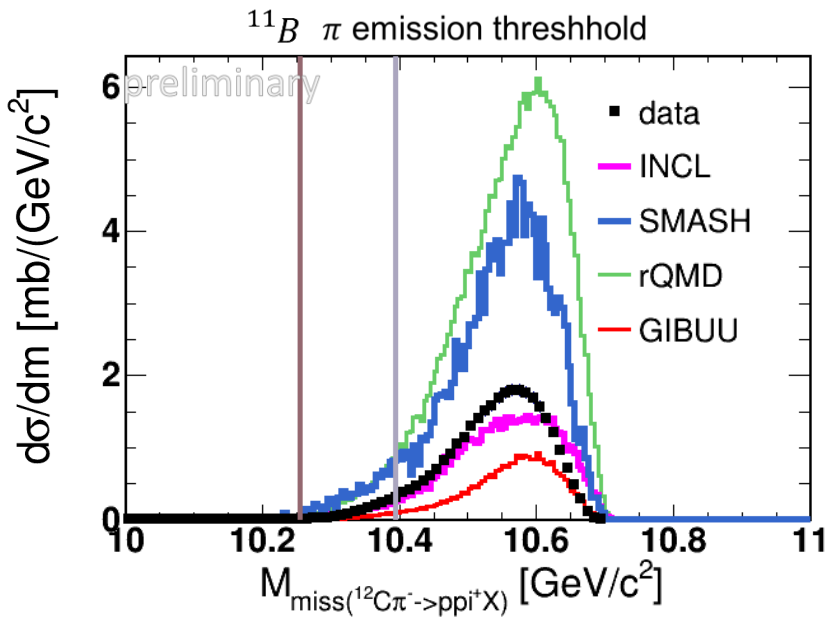
- $p\pi^+$ is necessarily an inelastic channel with two steps.
- Yields much lower than for $p\pi^-$ inelatic.
- Shifted missing mass w.r.t $p\pi^-$ inelastic .
- No clear sign of Δ++ in data.

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

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

(c) $\pi^- + p \rightarrow \pi^0 + p + \pi^-$
$\pi^0 + p \rightarrow n + \pi^+$





Two pion production (1)

$p\pi^-\pi^+$

(a) $\pi^- + p \rightarrow \pi^- + p$

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

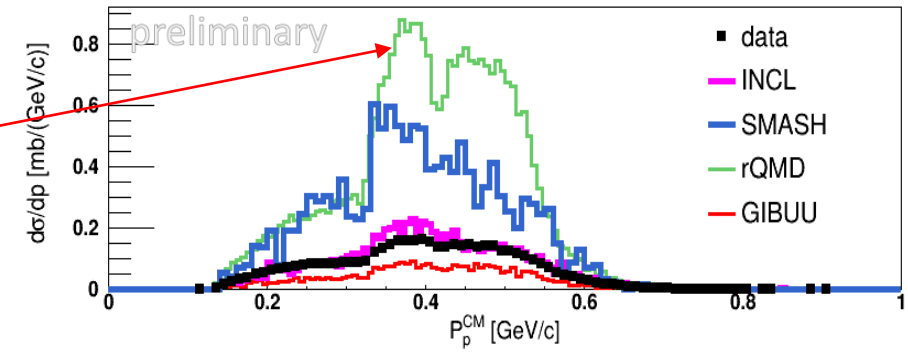
Elastic $p\pi^-$ kinematics $P_{cm} \sim 0.4$ GeV/c

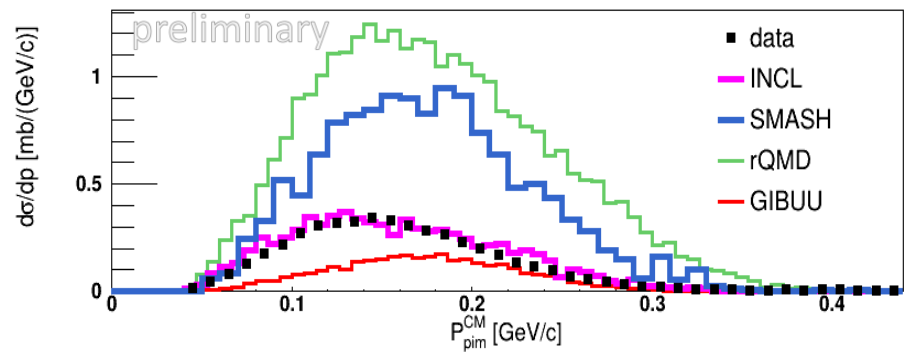
(b) $\pi^- + p \rightarrow \pi^0 + n$

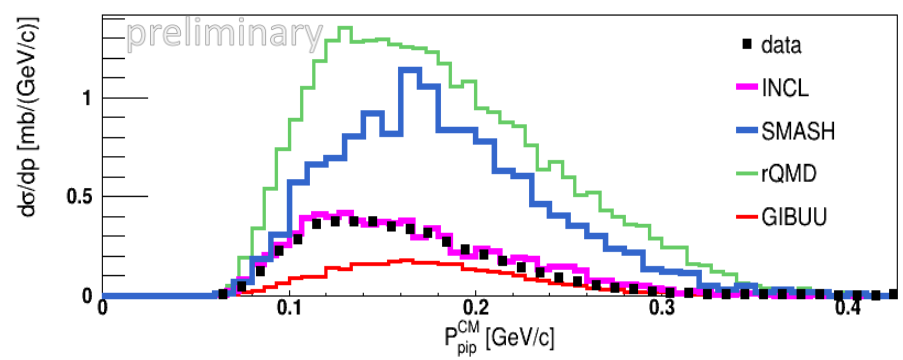
$\pi^0 + p \rightarrow p + \pi^- + \pi^+$

(c) $\pi^- + p \rightarrow \pi^0 + p + \pi^-$

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







- SMASH and rQMD way too large yield, GIBUU small yield, very good decsription by INCL.
- In particular, too large contribution in rQMD of quasi elastic $p\pi^-$ scattering in first step (a).
- $\pi^- and\ \pi^+$ play a symmetrical role. Dominance of (a) and (b).
- INCL++ does a good job

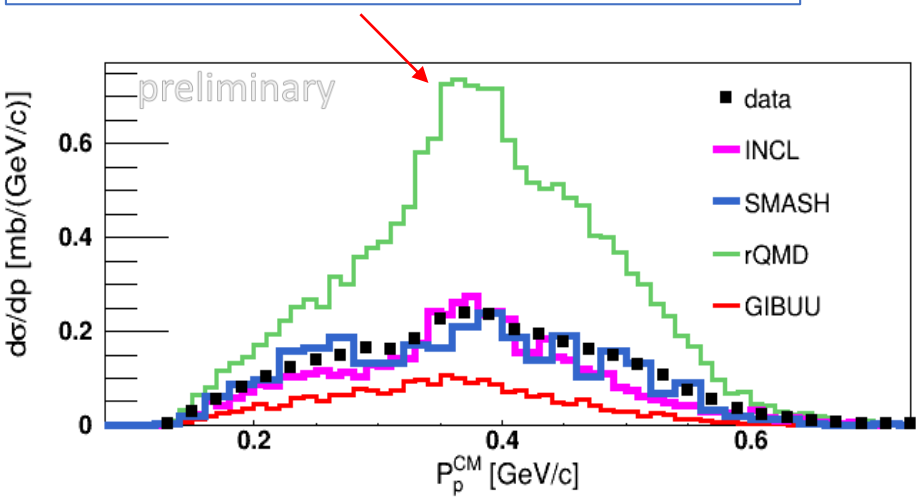
Two pion production (2)

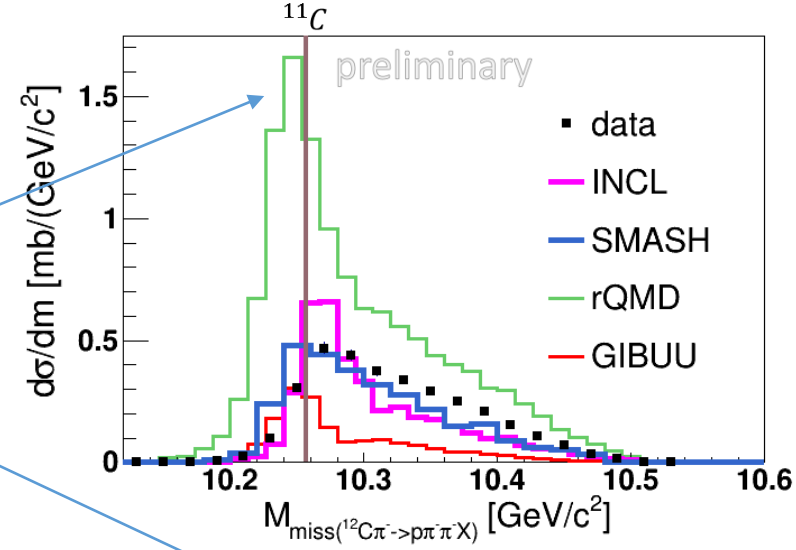
$p\pi^-\pi^-$

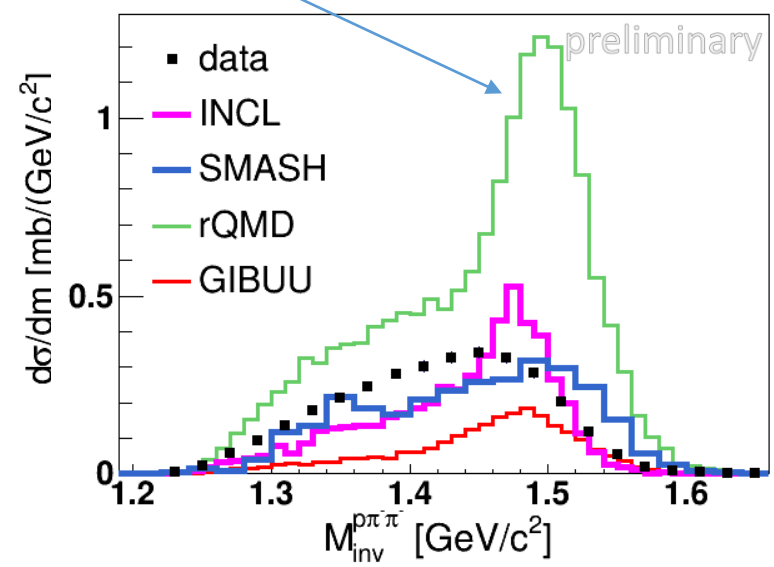
Single step production:
$\pi^- + n \rightarrow p + \pi^- + \pi^-$; **recoiling 11C**
→ Minimum missing mass, max inv. mass

Two step production:
$\pi^- + p \rightarrow \pi^- + p$
$\pi^- + n \rightarrow p + \pi^- + \pi^-$
→ larger missing mass, lower inv. mass

Elastic $p\pi^-$ kinematics P_{cm} ~ 0.4 GeV/c







$pp\pi^-$

2-step processes with 2 π production

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

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

Overestimated by rQMD

2-step processes with 1 pion production -> max inv. mass

$(a)\ \pi^- + p \rightarrow p + \pi^-$

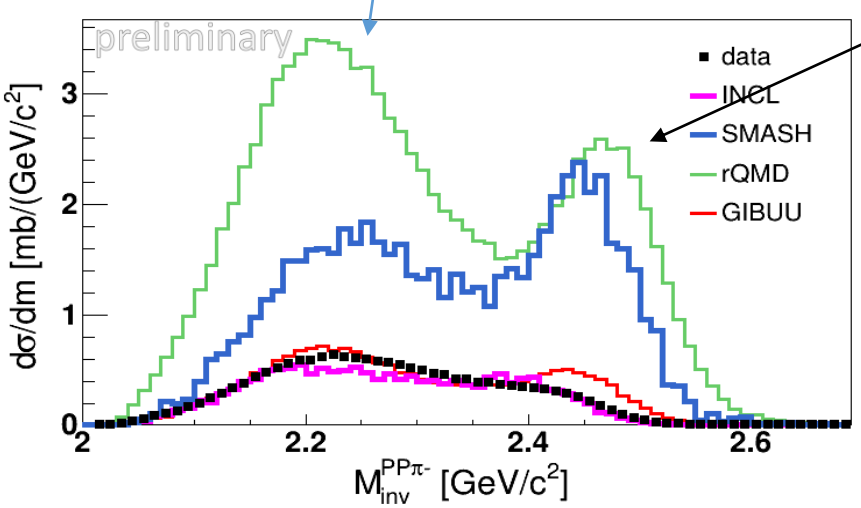
$p + p \rightarrow p + p$

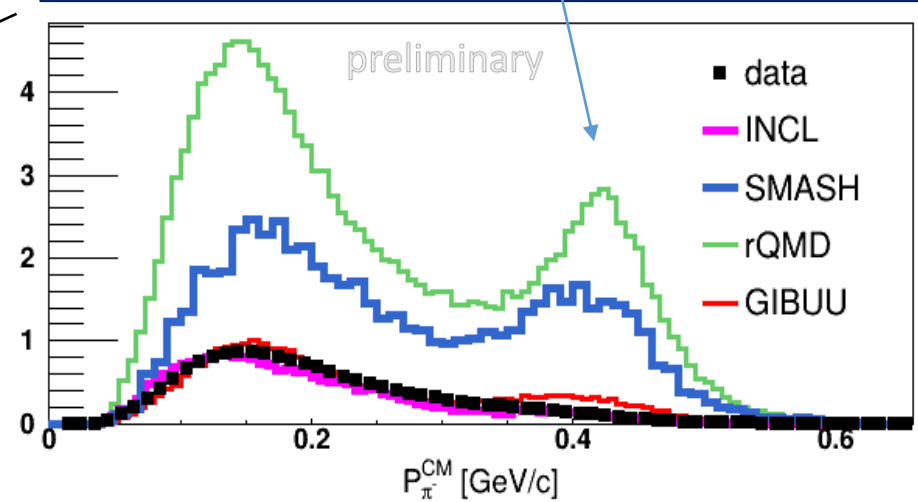
(b) $\pi^- + p \rightarrow \pi^- + p$

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

not favored by data nor GIBUU nor INCL

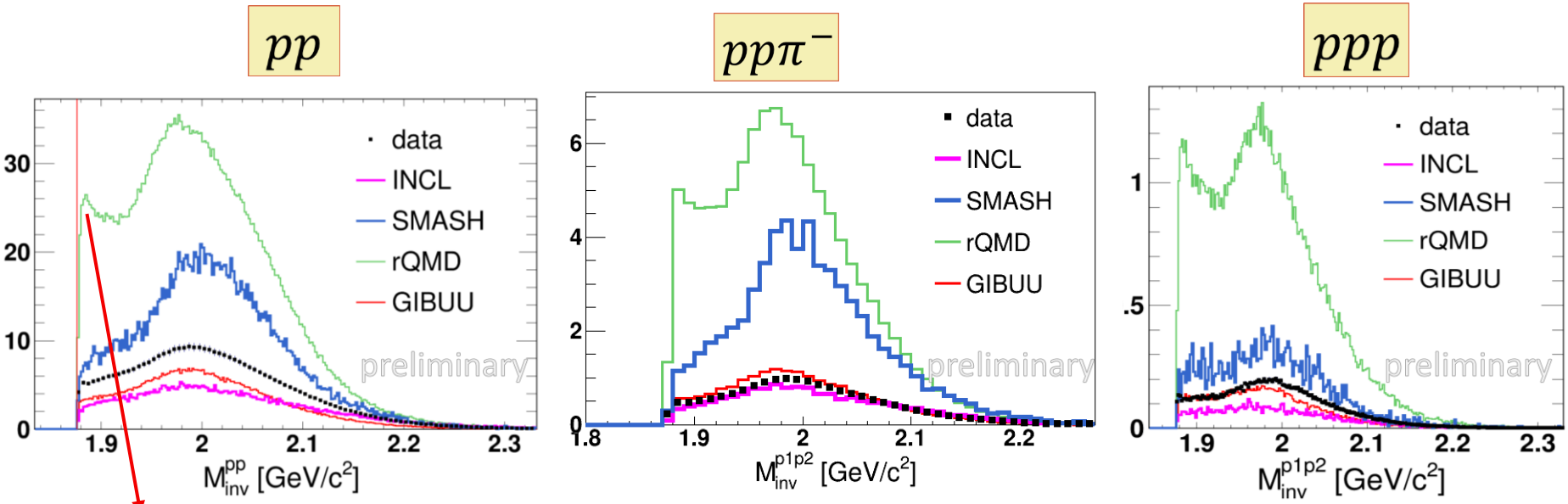
Overestimated by rQMD and SMASH





Pion absorption investigation

- 3p channel needs 3 steps (π^-N or π N rescattering step)
  Possibility of pion absorption ? $\pi^- + p \rightarrow \pi^- + p$
  followed by (a) $\pi^- + p + p \rightarrow n + p$; $n + p \rightarrow n + p$
  or (b) $\pi^- + p \rightarrow \pi^0 + n$; $\pi^0 + p + p \rightarrow p + p$



Small M_{inv}^{pp} due to proton rescattering
$\pi^- + p \rightarrow p + \pi^-$
$p + p \rightarrow p + p$ overestimated by rQMD

Inv. mass very similar in the 3 channels, no sign of π absorption ?
Better investigation of pion absorption would need neutron reconstruction

Cross sections

$\pi^- + {}^{12}C \rightarrow$ 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^-	0.16887	0.617297	1.07159	0.192891	0.153924
ppp	0.047972	0.082285	0.300865	0.039017	0.0238212

Conclusion

- Study of different hadronic channels of $\pi^-+{}^{12}C$ reaction @0.69 GeV/c measured with HADES

- Sensitive test of implementation of different processes: quasi-elastic, pion production, absorption in INCL++ and transport models (RQMD,SMASH, GIBUU)

  - Large dispersion of model predictions:
    1. INCL++ does a rather good job for channels with a detected pion in contrast to transport models.
    2. Improvements needed for transport models.

- Outlook:

  Access to Short Range Correlation Effects in Quasi-elastic process ?
  Estimate total cross sections.
  Neutron reconstruction to test pion absorption.

Backup

Cross sections

$\sigma_{p+\pi^- \to p\pi^-} = 17.8$ mb

$\sigma_{p+\pi^- \to n\pi^0} = 10$ mb

$\sigma_{p+\pi^- \to n\pi^-\pi^+} = 6.21$ mb

$\sigma_{n+\pi^- \to n\pi^-} = 12.4$ mb

$\sigma_{n+\pi^- \to p\pi^-\pi^-} = 0.37$ mb