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

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HADES Collaboration

QCD phase diagram studies

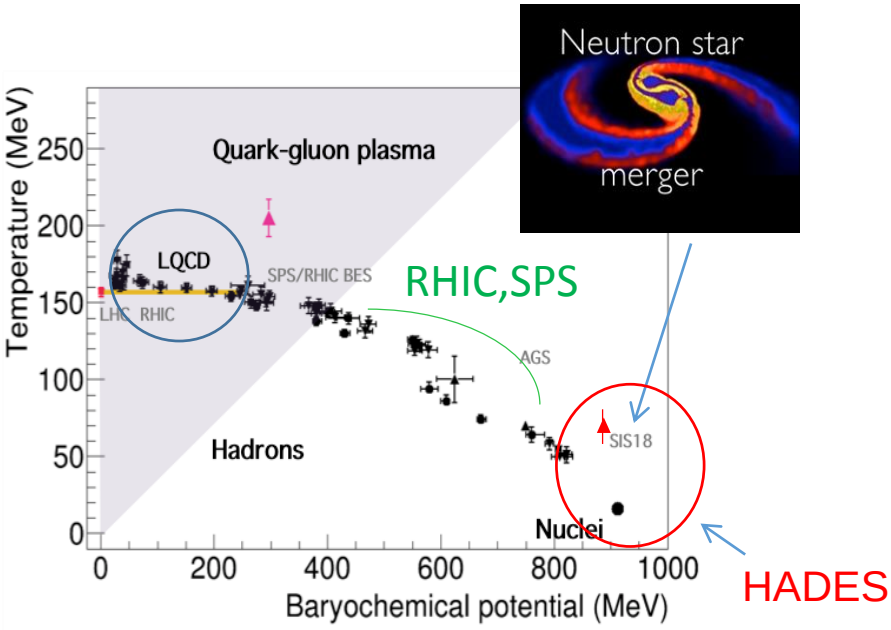
HADES objectives :

- 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,...)



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

- Microscopic structure of baryon dominated matter

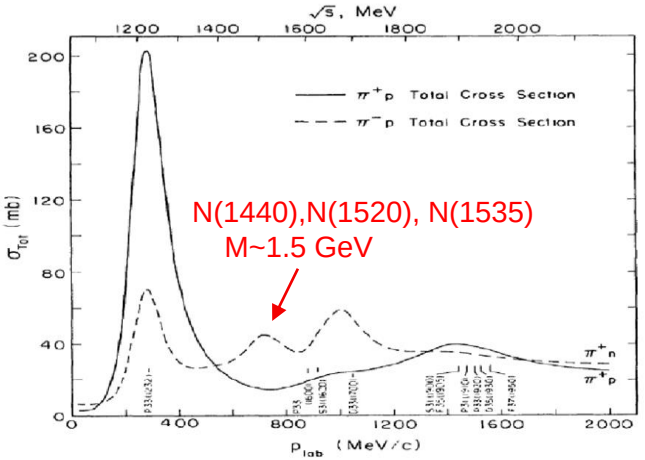
Role of baryonic resonances (excited states of nucleons), hyperons

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

The heavy ion context

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

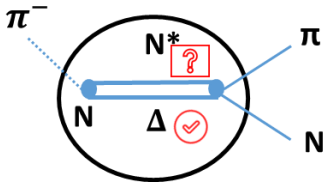
- ✓ real pions copiously produced $(NN \rightarrow NN\pi, \pi + N \rightarrow N^*/\Delta)$
- ✓ NN interaction driven by pion exchange



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

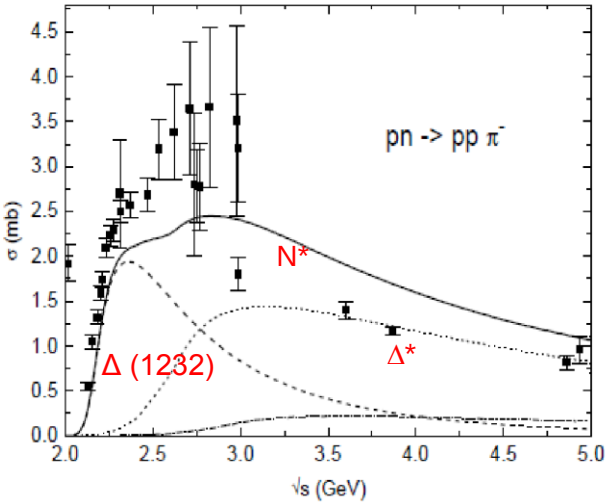
✓ p+A or A+A at $\sqrt{s_{NN}}$ < 2.6 GeV Δ(1232) region (p_π =250 MeV/c) well-known

➢ 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).

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

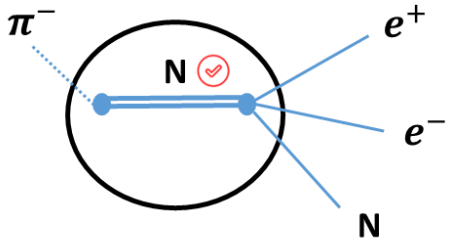


[S. Teis et al. Pion production in heavy ion collisions at sis energies. Z. Phys.,A356 :421, 1997.]

π^-+C in the 2^{nd} 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 :

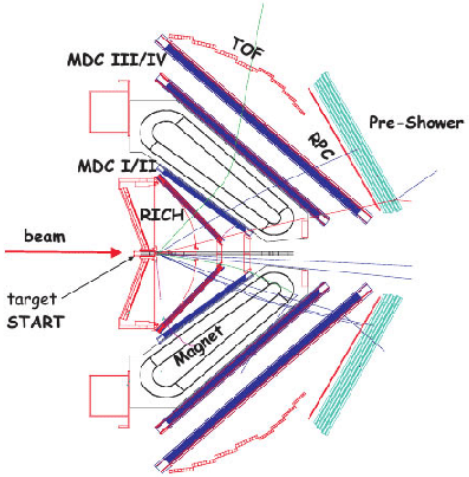
Investigate different hadronic exit channels in π^- + ^{12}C reaction for 2nd resonance region :

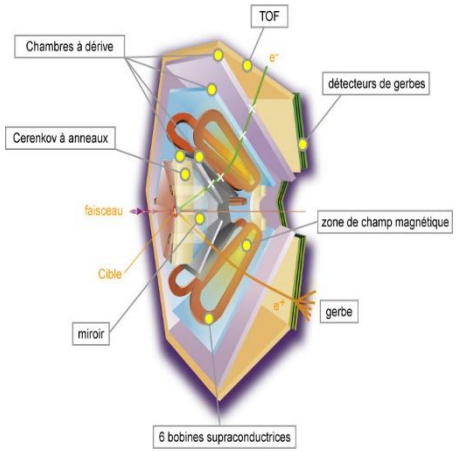
- Information on pion-nucleus dynamics in the second resonance region (N1520).
  - study reaction mechanisms: quasi-elastic, rescattering, pion absorption,...
  - Sensitive test INCL cascade and transport models (Smash, RQMD…).

- INCL is used in toolkits for the simulation of the passage of particles through matter (Geant).
- SMASH & rQMD 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)





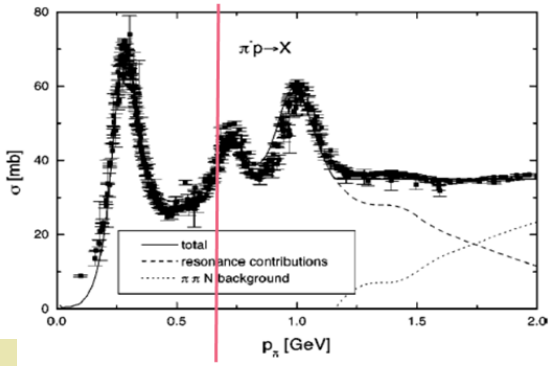
Experiments (2004-2014)

- 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

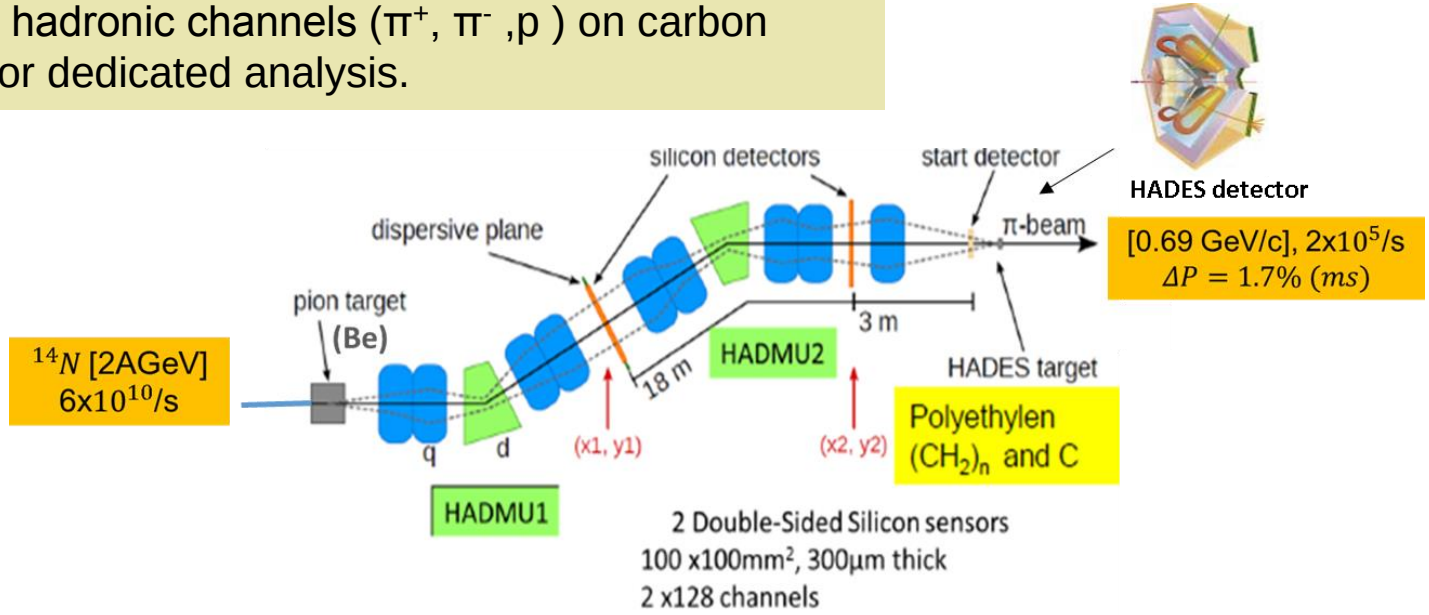
- Acceptance: Azimuthal angles 85% (6 sectors)
  polar angles: 18° - 85°
- Detected particles: $e^{\pm}$, p, $\pi^{\pm}$, $K^{\pm}$
- Tracking: MDC
- $e^{\pm}$ identification with RICH, TOF/PreShower
- p, $\pi^{\pm}$, $K^{\pm}$ identification TOF-Tracking

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.

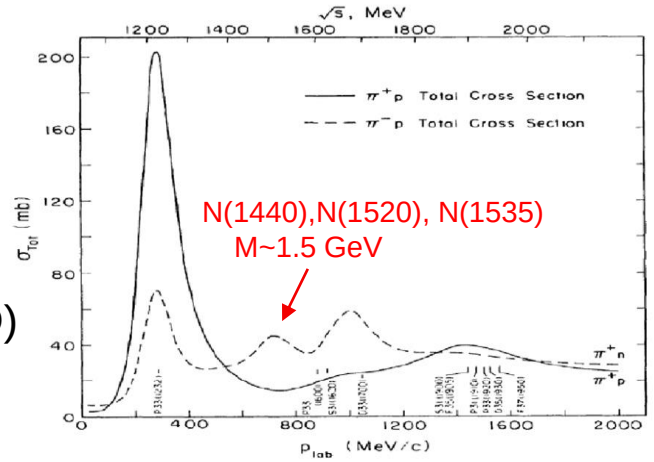


- Data on carbon mainly used for subtraction of π⁻+C interactions in CH2 target to study π⁻+p reaction.
  [HADES collab., Phys.Rev. C102 (2020) no.2, 024001]
  [HADES collab., to be submitted]
- Large statistics for hadronic channels (π^+, π^- ,p) on carbon target to be used for dedicated analysis.



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

Channels with 2 charged particles



❑ Quasi-elastic and charge exchange:

- $\pi^- + p \rightarrow \pi^- + p$ quasi-elastic scattering σ= 17.8 mb (SAID)
- $\pi^- + n \rightarrow \pi^0 + p$ charge exchange σ = 10 mb (SAID)

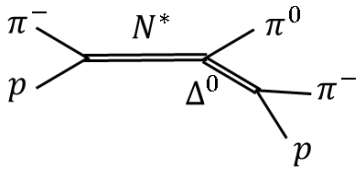
❑ Inelastic (pion production)

- $\pi^- + p \rightarrow n + \pi^- + \pi^+$ σ= 6.1 mb

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

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

Main contribution from s-channel N* excitations,
$N^* \rightarrow \pi\,\Delta$, σN, ρN



❑ Multi-step: rescattering $\pi N \rightarrow \pi N$, $NN \rightarrow NN$

❑ $\pi N \rightarrow \pi N$ followed by $NN \rightarrow NN\pi$ kinematically suppressed

$\rightarrow$ two-pion production occurs mainly in the same step, via $\pi N \rightarrow \pi\,\pi\,N$

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

SMASH & rQMD

- ^{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.

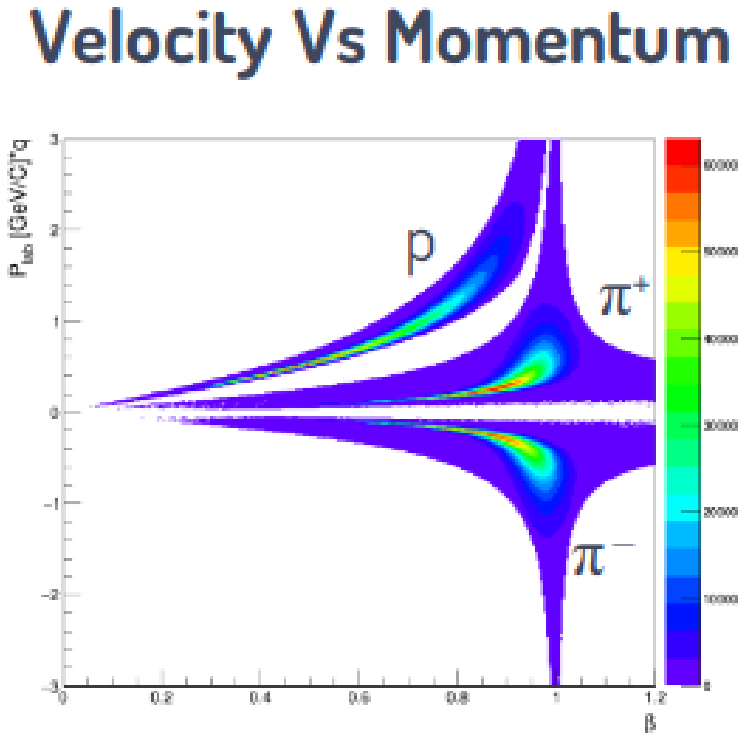
(1) [K. Nakamura et al.,Nuclear Physics A, Volume 268, Issue 3, 21 September 1976, Pages 381-407]

PID & Normalization

Particle identification is done using

Cuts

on momentum-velocity correlation

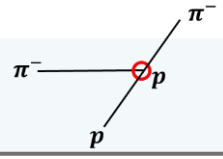


Data normalisation (counts -> mb/unit) :

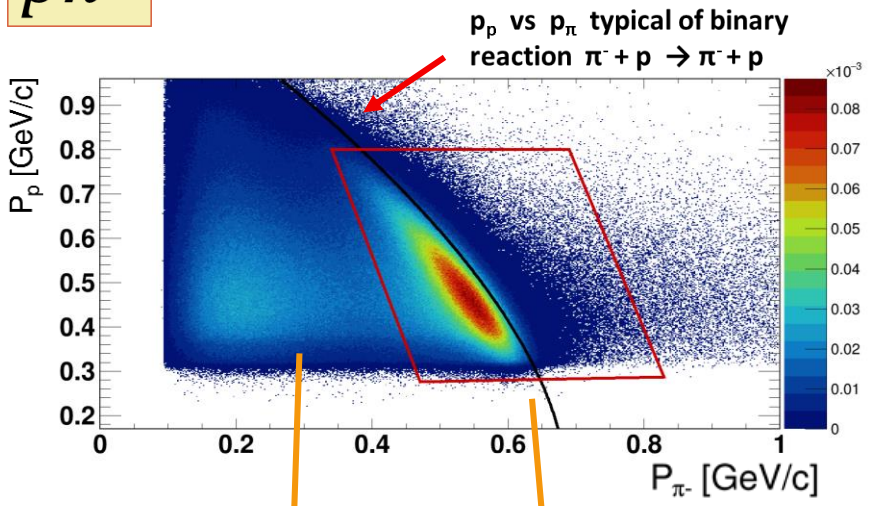
Using measurements on C and CH2 targets and known π^-+ p elastic scattering cross-section, global systematic error = 4%.

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

Selection of quasi-elastic channel



$p\pi^-$



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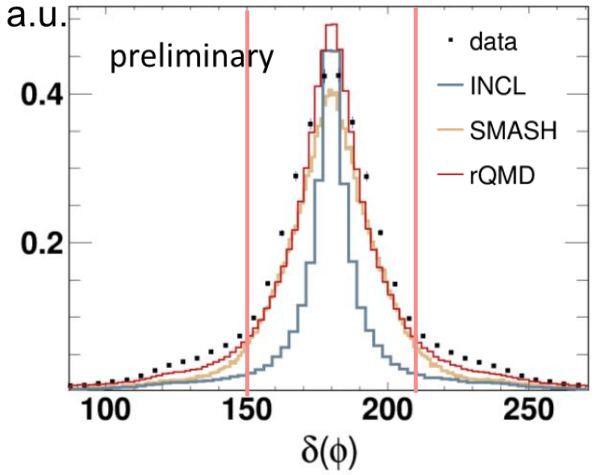
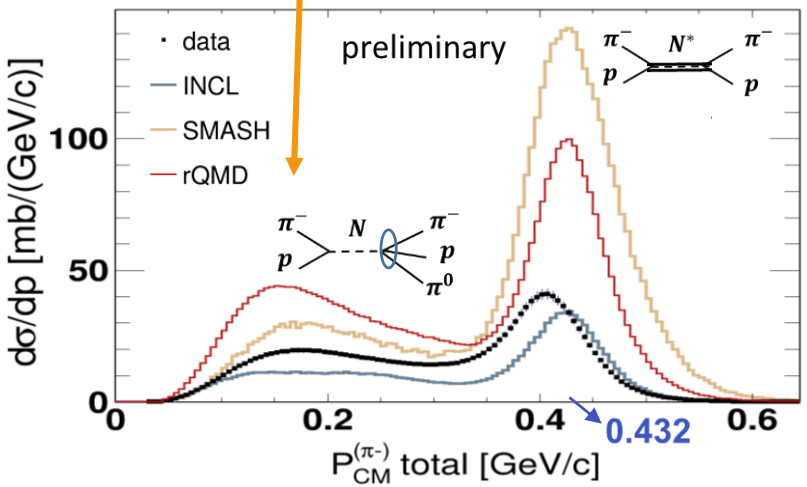


Inelastic ($p\pi\pi$)

« QE » $p\pi^-$



$p\pi^-$ « QE selection » :

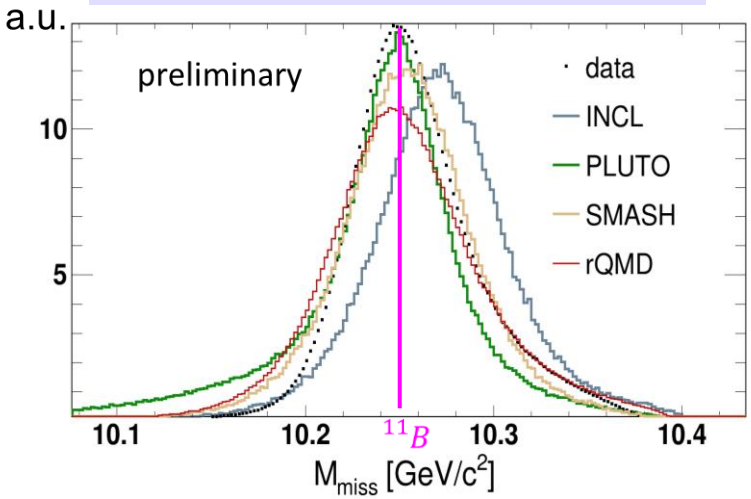
Momentum correlation + coplanarity condition :

$150° < \Delta\varphi < 210°$

- SMASH & rQMD overestimate $p\pi^-$ channel.
- INCL : best description of yields

$p\pi^-$:"quasi − elastic"

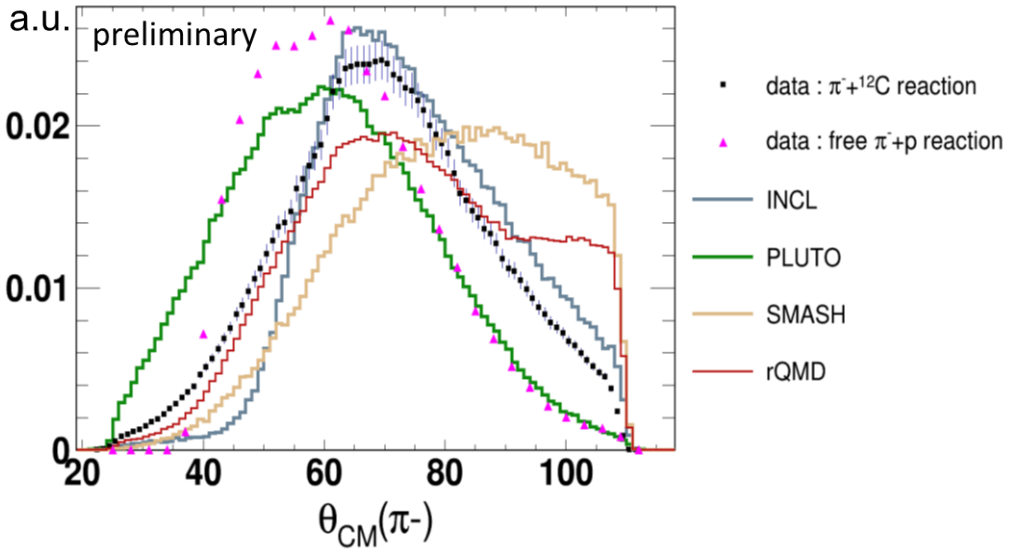
$M_{miss} = M_{(\pi^- + {}^{12}C \to \pi^- + p + X)}$



- 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.

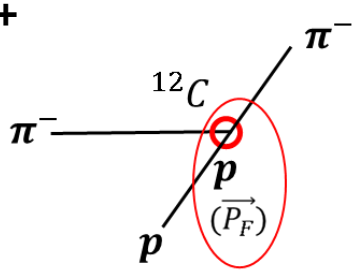
- Ang. distrib. different from free π^-+p elastic scattering.
- INCL reproduces well pion angular distribution.
- PLUTO closer to free π^-+p data especially for high angles.
- rQMD reproduces well small angles but overestimates very high angles.
- SMASH does not reproduce well angular distribution.



Search for Short Range Correlations

$p\pi^-$: "QE"

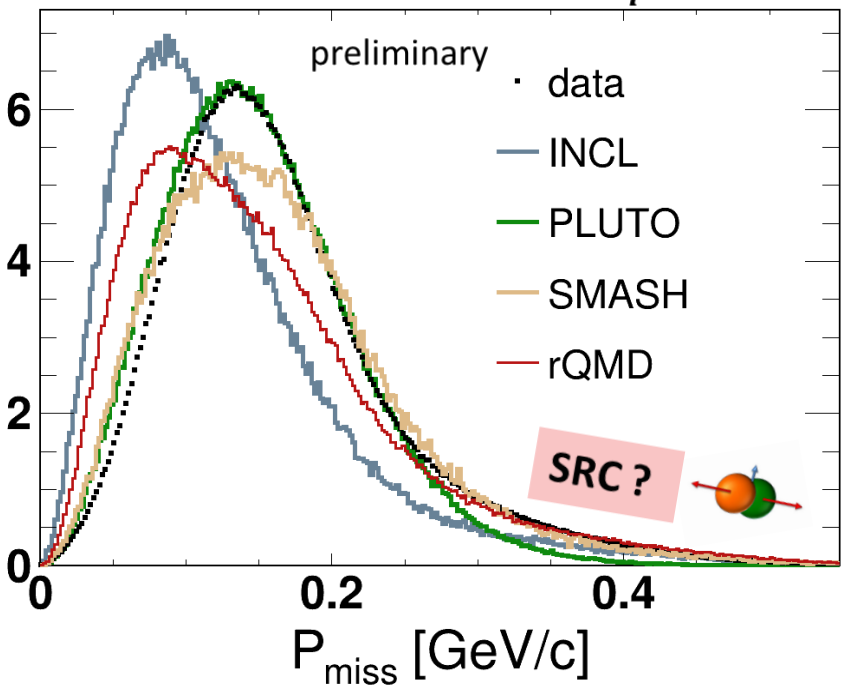
« pure quasi-elastic » :
off-shell participant (p) +
on-shell spectator (^{11}B)



$$\vec{P}_\pi^i + \vec{P}_p^i = \vec{P}_p^f + \vec{P}_\pi^i$$
$$\vec{P}_{miss} = \Delta\vec{P} = -\vec{P}_p^i$$

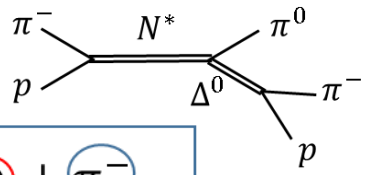
SRC :
Nucleon pairs that are close together in the nucleus high relative and low c.m. momentum, compared to the Fermi momentum (kF)

$$\vec{P}_{miss} = \vec{P}_\pi^i - \vec{P}_\pi^f - \vec{P}_p^f$$



- Pluto : describes the missing momentum very well.
- INCL : proton momentum underestimated by Fermi gas distribution + rescattering.
- Data : Large tail for high proton momentum in Carbon. SRC or rescattering effects?

$p\pi^-$: Inelastic



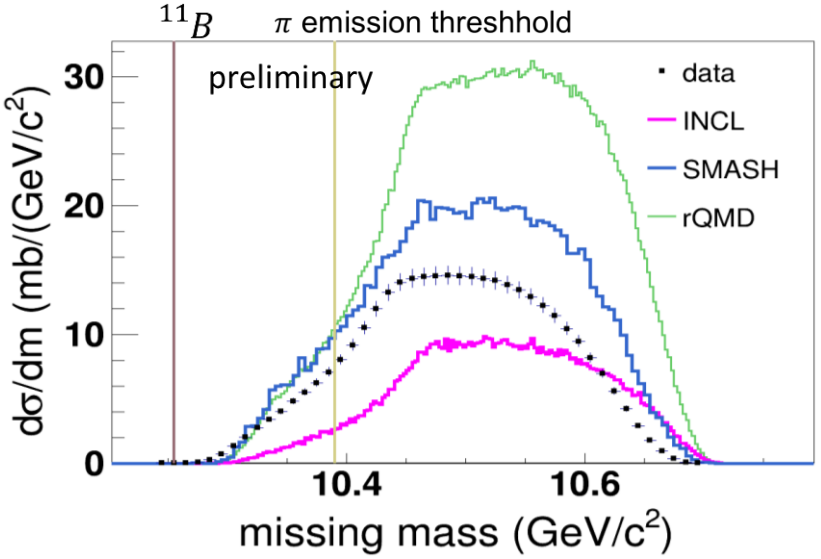
Single step

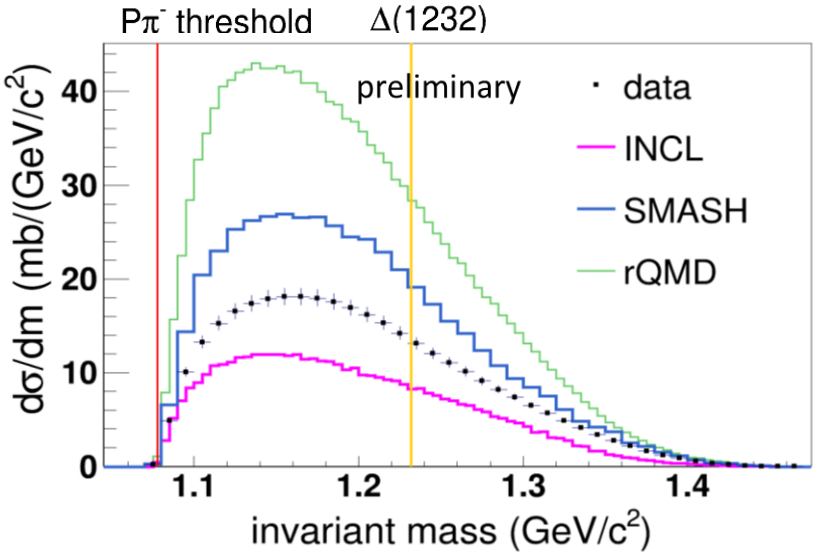
$$\pi^- + p \rightarrow \pi^0 + p + \pi^-$$

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 .
- rQMD in agreement with data, but overestimates yields.

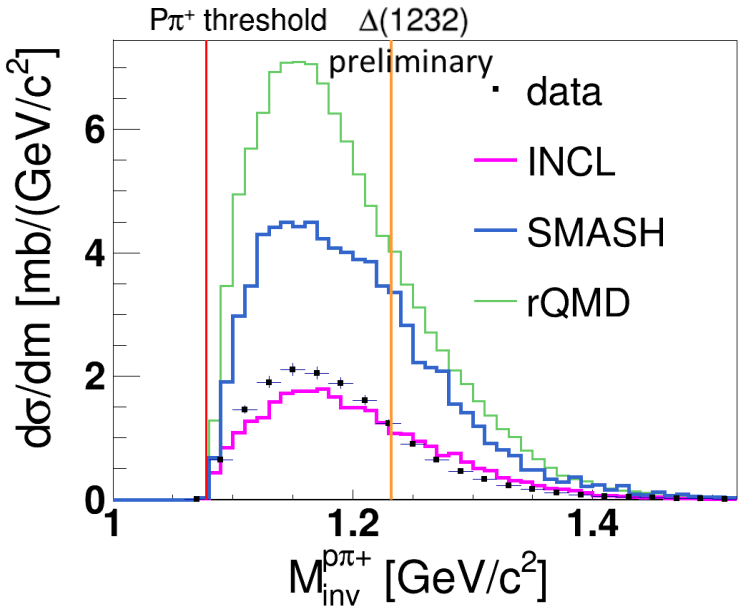
$p\pi^+$

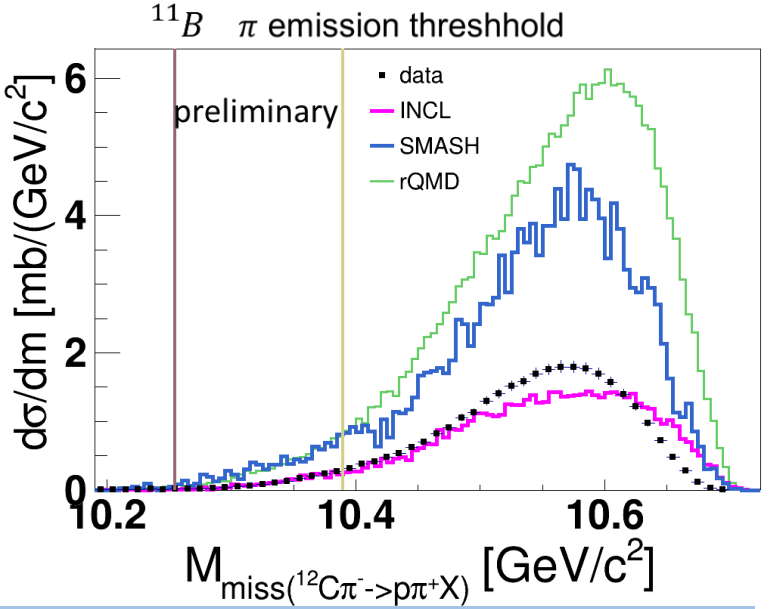
- $p\pi^+$ is necessarily an inelastic channel with two steps.
- Yields much lower than for $p\pi^-$ inelatic.
- Shifted missing mass w.r.t $p\pi^-$ inelastic .
- No clear sign of Δ++ in data.

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

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

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





Two pion production (1)

$p\pi^-\pi^+$

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

$\pi^- + p \rightarrow$ n + π^- + π^+

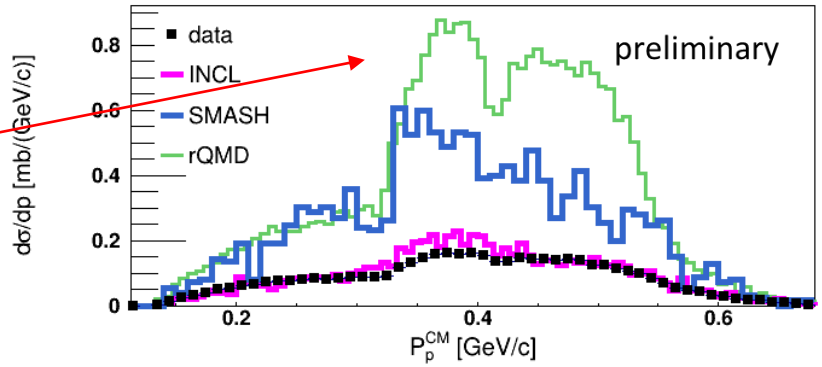
Elastic pπ^- kinematics P_{cm} ~ 0.4 GeV/c

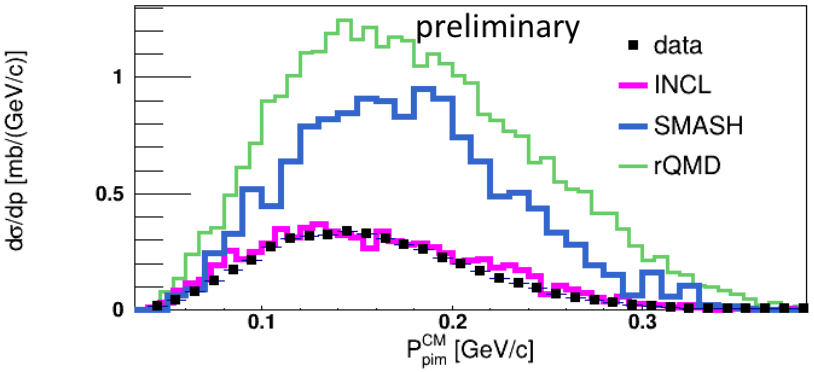
(b) $\pi^- + p \rightarrow \pi^0 +$ n

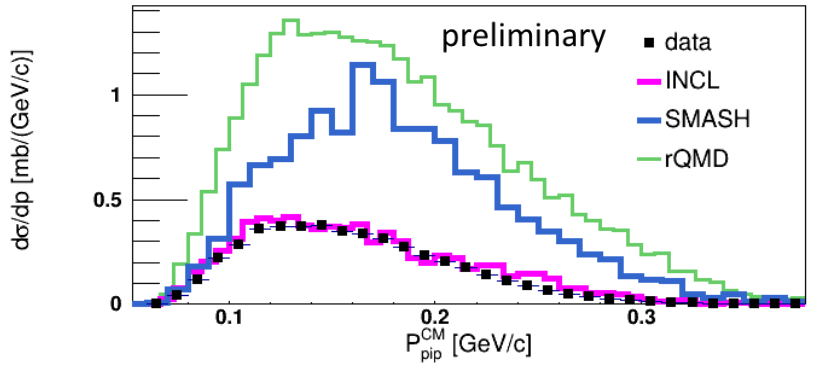
$\pi^0 + p \rightarrow$ p + π^- + π^+

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

$\pi^0 + p \rightarrow$ n + π^+







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

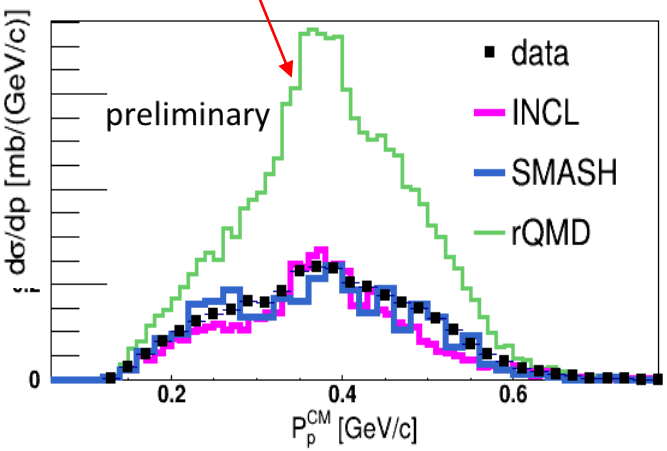
Two pion production (2)

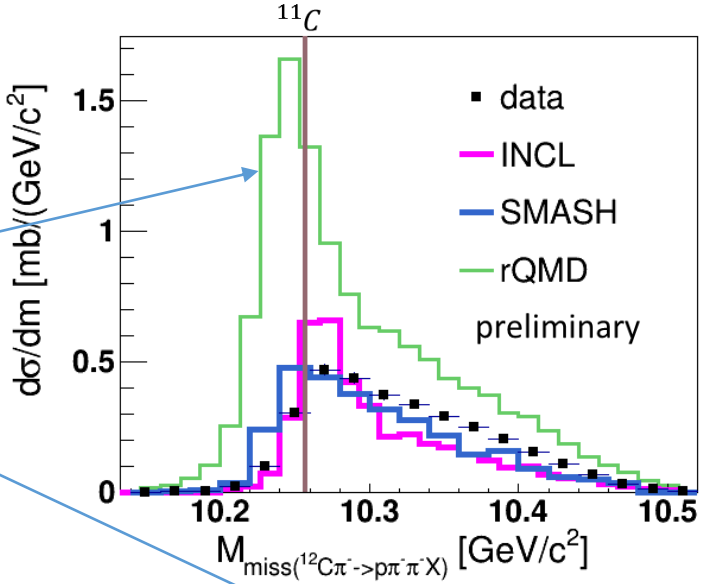
$p\pi^-\pi^-$

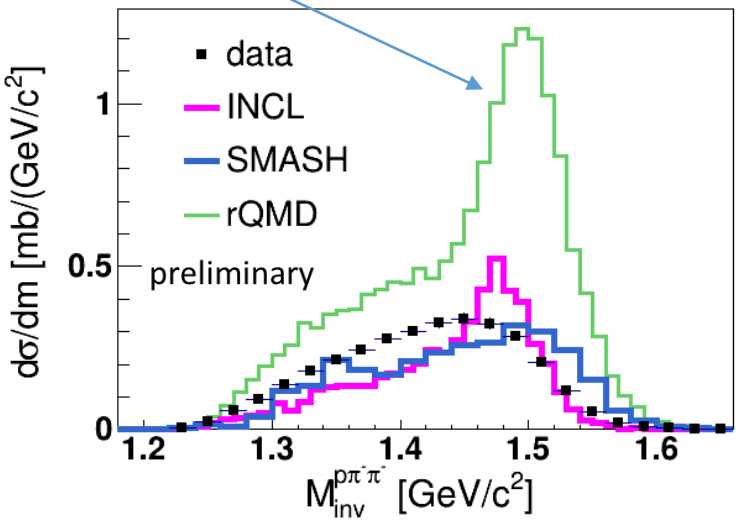
Single step production:
$\pi^- + n \rightarrow p + \pi^- + \pi^-$; **recoiling 11C**
$\rightarrow$ Minimum missing mass, max inv. mass

Two step production:
$\pi^- + p \rightarrow \pi^- + p$
$\pi^- + n \rightarrow p + \pi^- + \pi^-$
$\rightarrow$ 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

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

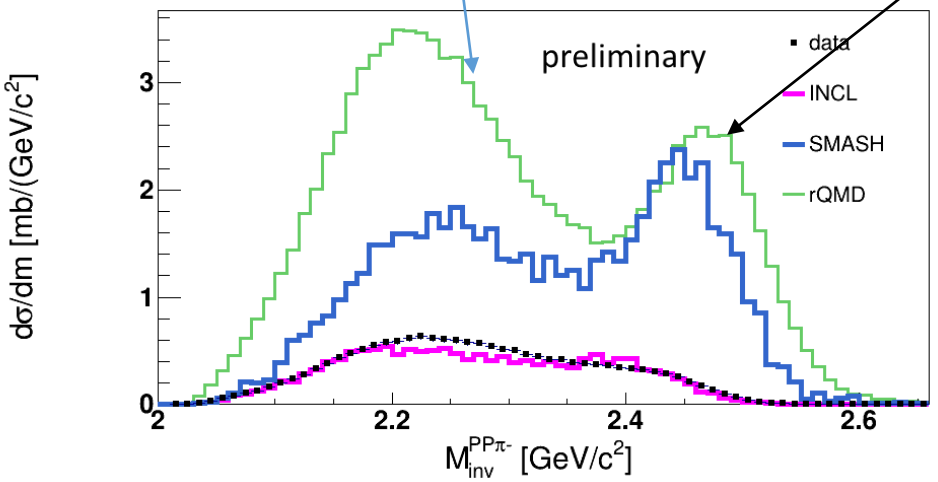
Overestimated by rQMD
Ok in SMASH

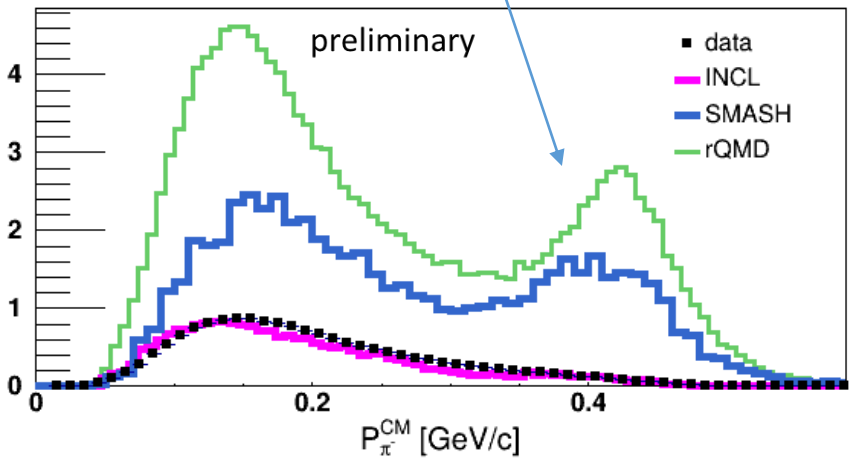
2-step processes with 1 pion production -> max inv. mass

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

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

not favored by data
Overestimated by rQMD and SMASH
Underestimated by INCL++

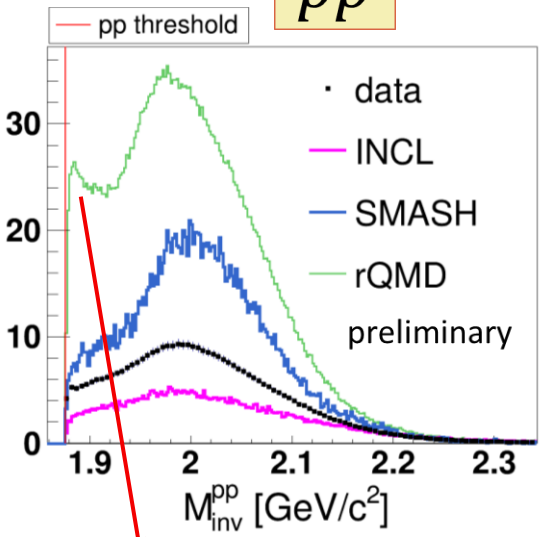




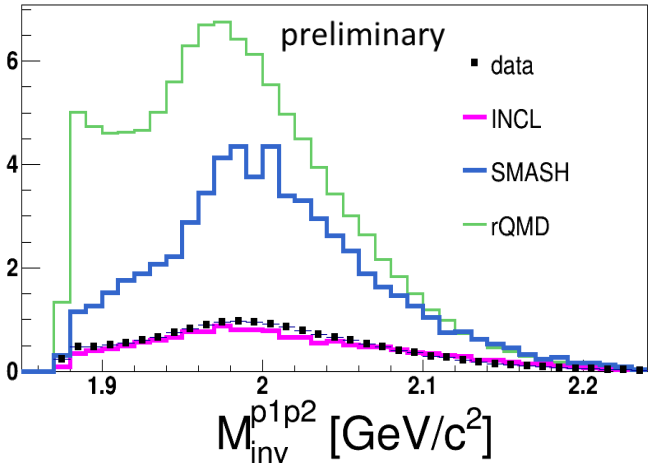
Pion absorption investigation

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

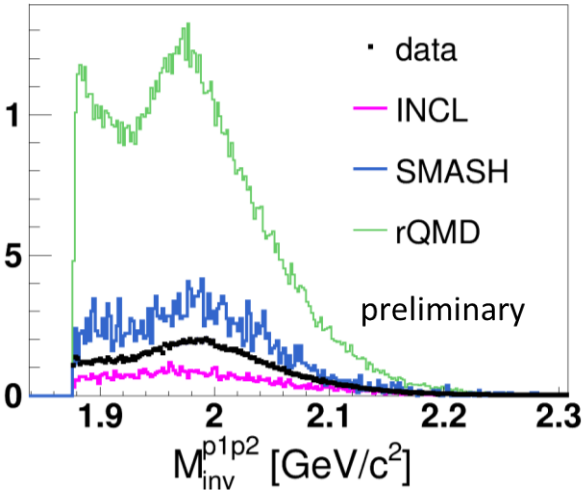
pp



$pp\pi^-$



ppp



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

Conclusion

- Study of different hadronic channels of π^-+^{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)

  - Large dispersion of model predictions:
    INCL++ does a rather good job for channels with a detected pion.
    Overestimation of experimental yields by rQMD and SMASH, except $p\pi^-\pi^-$ and $\pi^-\pi^-$ in SMASH, to be discussed with experts

- Comparison with GiBUU on-going

❖ Outlook:

Access to Short Range Correlation Effects in Quasi-elastic process ?

Correct diff. distr. to 4pi -> estimate total cross sections.

Backup

Normalization

Data : $F_{Norm} = 2 \times \frac{\sigma_{el}}{N_{el}} \times F_{C/CH2}$.

- **Normalisation for pi-+p cross section CH2 target (all statistics):** $\frac{\sigma_{el}}{N_{el}} = 1.107 \times 10^{-7}$
  - σ_{el} - known cross-section of elastic scattering in full solid angle.
  - N_{el} - number of elastic scattering events in full solid angle
- **relative normalisation C (all stat.)/CH2 (all stat.) =** $F_{C/CH2} = 1./0.2178$.

SMASH & rQMD : $F_{Norm} = \frac{\pi^* b^2}{\text{Number of shots}}$

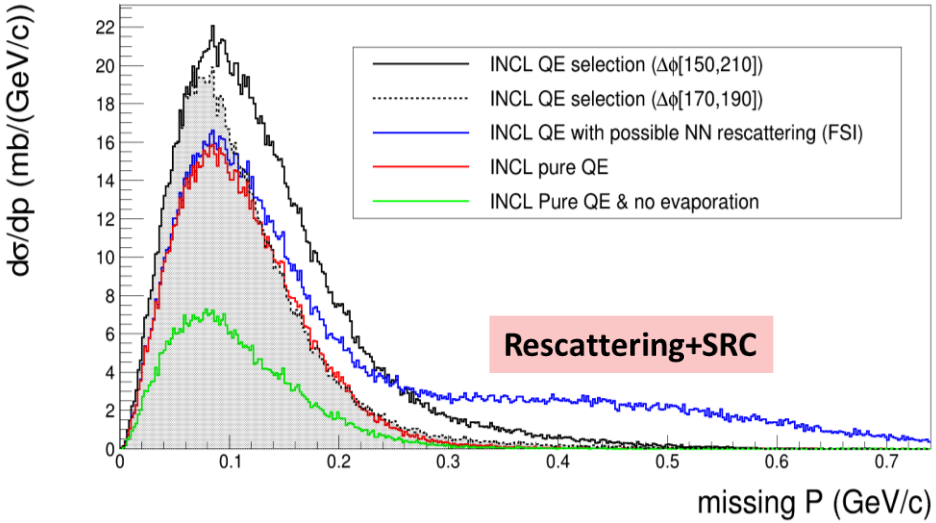
- **b= 5 fm.**
- **Number of shots =** $9.9*10^7$ (rQMD) & $9.9*10^6$ (SMASH)

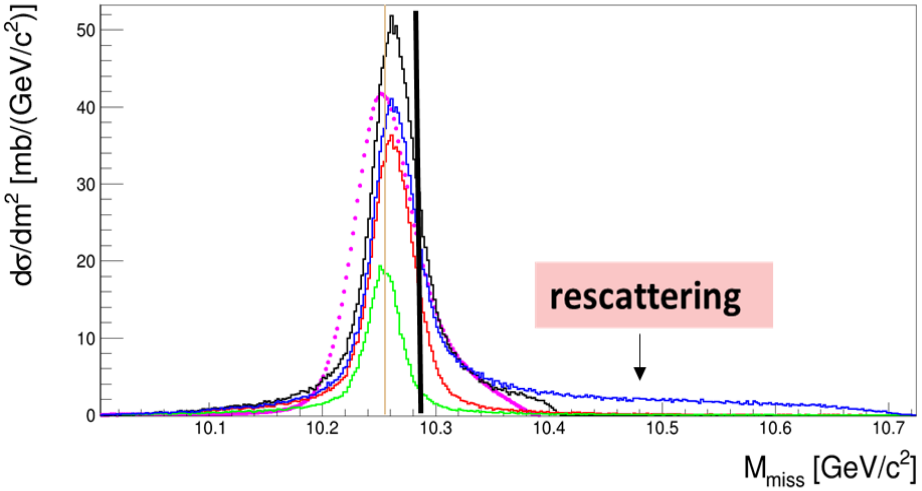
INCL : $F_{Norm} = \frac{\sigma_{reaction}}{\text{Number of shots}}$ ($9.9*10^7$)

- $\sigma_{reaction} = 1462.32$ mb.
- **Number of shots = 100 000 000.**

SRC preliminary study

$p\pi^-$:"QE"

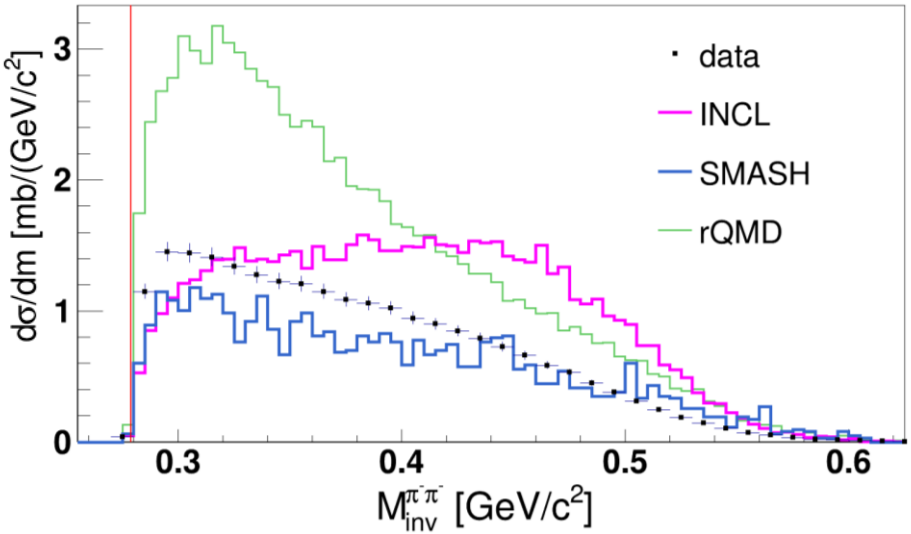


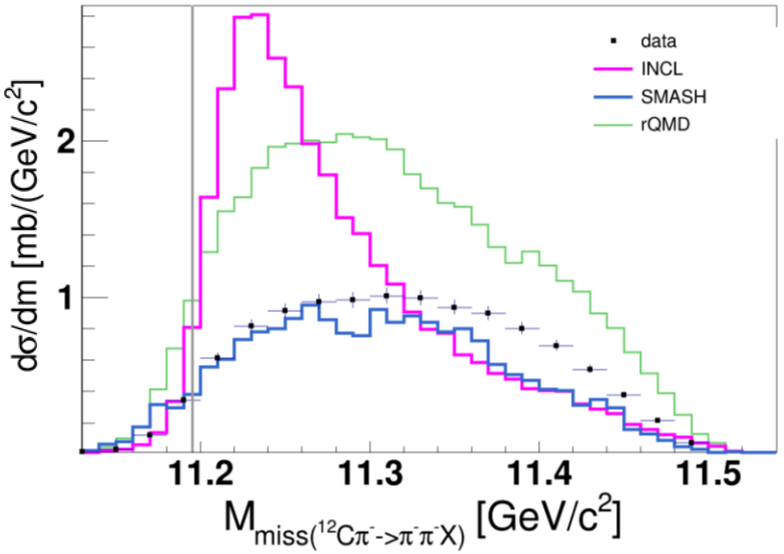


Adjusting cuts to reduce rescattering effects :

- Restrict $\Delta\varphi$ (coplanarity condition of p and π^-)
- Cut high excitation missing mass values

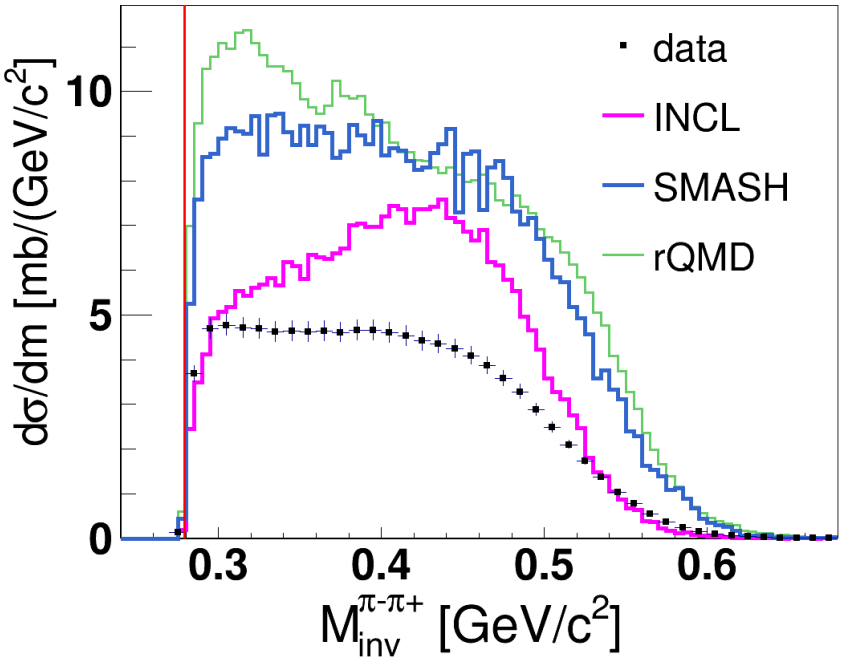
$\pi^-\pi^-$

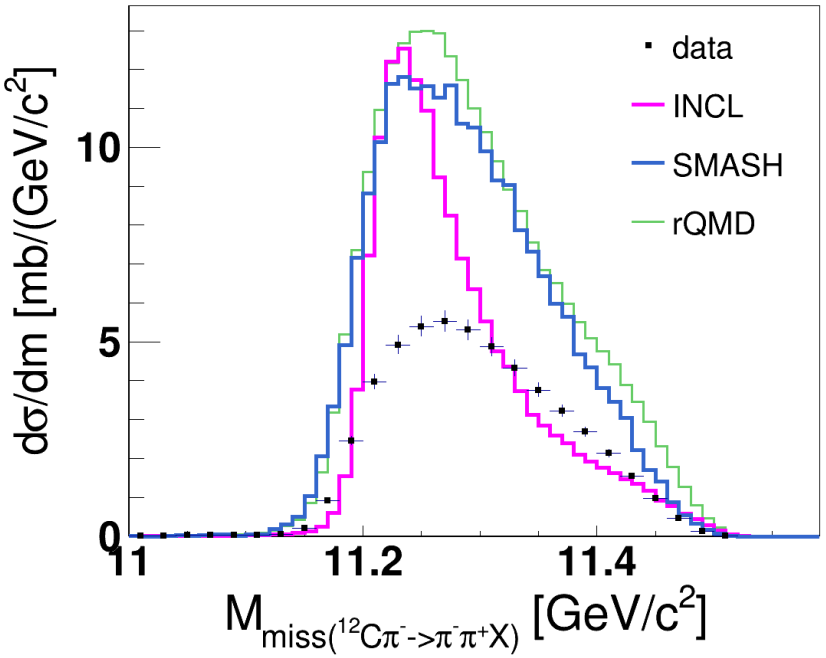




- **INCL : Mmiss low and Minv high**
- **RQMD : Minv more peaked at low values**

$\pi^-\pi^+$

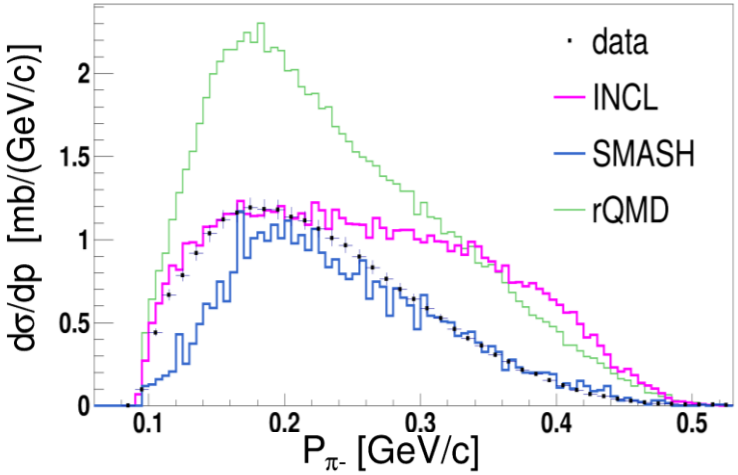




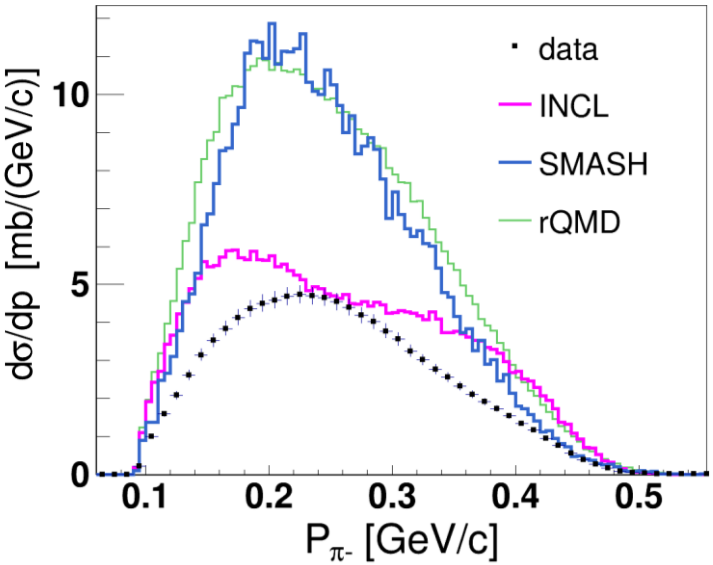
- **INCL : Mmiss low and Minv high**
- **RQMD : Minv more peaked at low values**

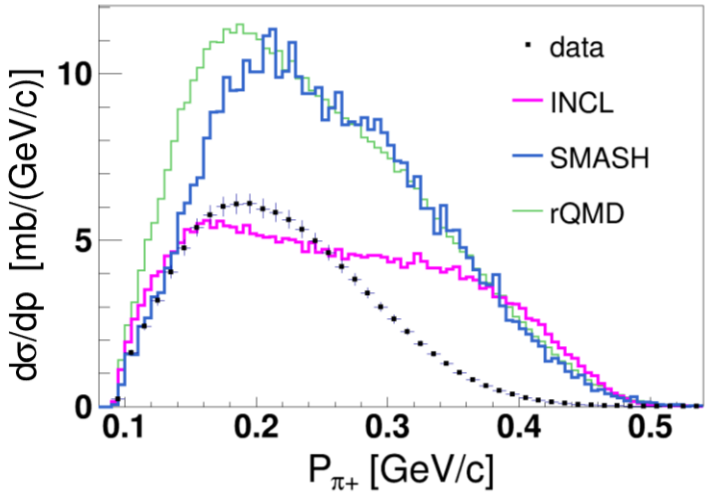
Two pion production (3)

$\pi^-\pi^-$



$\pi^-\pi^+$

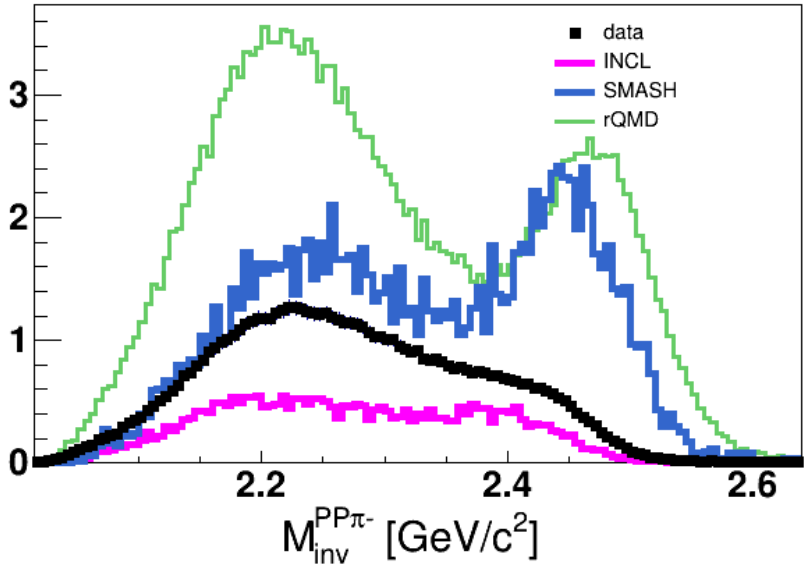


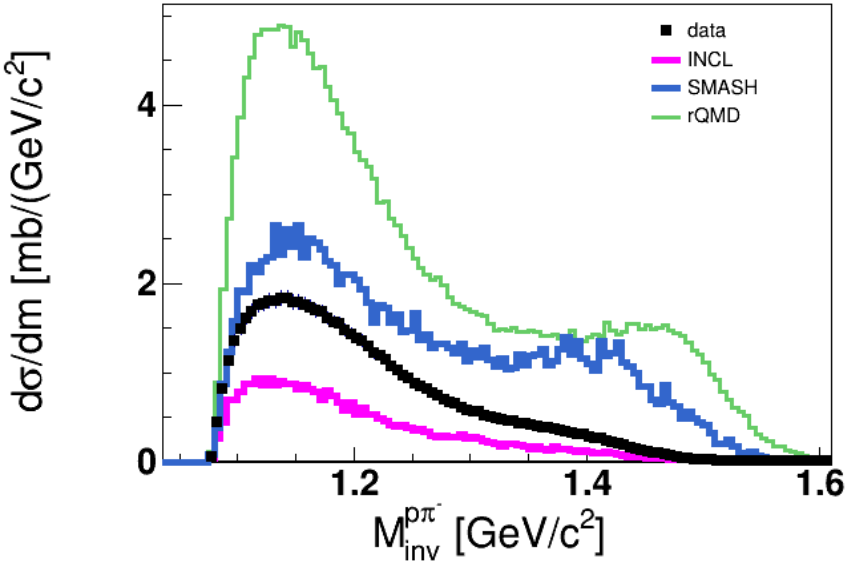


- $\pi^-\pi^-$ **same 2-step processes as** p $\pi^-\pi^-$
- $\pi^-\pi^+$ **can be produced in** π^- + p $\rightarrow$ n + π^- + π^+
  σ = 6.2 mb $\rightarrow$ higher yields

- Data : same distribution for π^- and π^+ momenta in $\pi^-\pi^+$. For $\pi^-\pi^-$, π^- momenta shifted to lower values. Consistent with $p\pi^-\pi^-$.
- INCL : two broad pion momentum distributions
- SMASH: overestimates $\pi^-\pi^+$ yields, but $\pi^-\pi^-$ are fine (consistent with p $\pi^-\pi$)

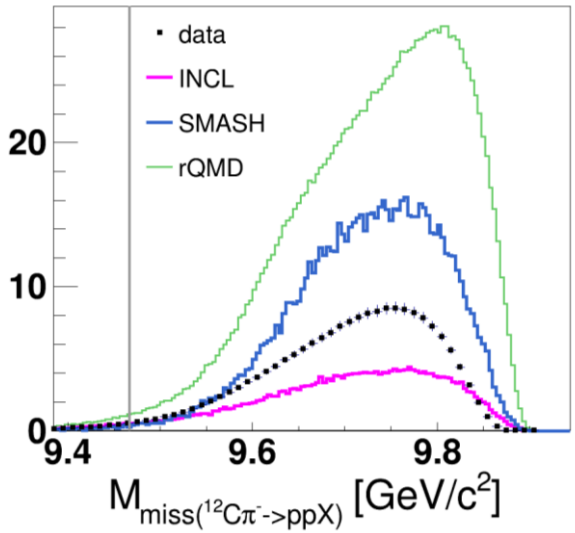
$pp\pi^-$

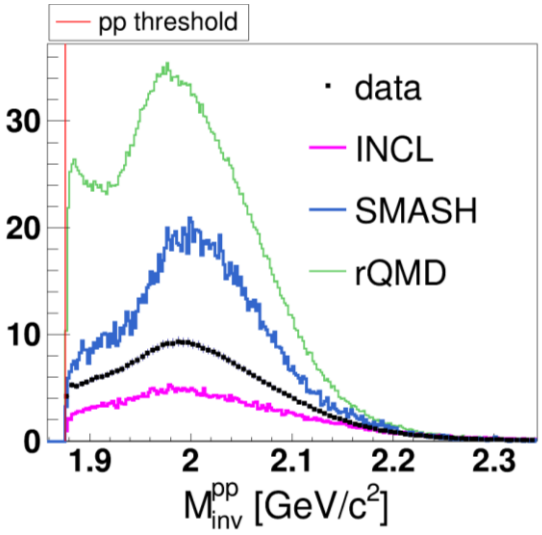

data
INCL
SMASH
rQMD
3
2
1
0
2.2
2.4
2.6
$M_{inv}^{PP\pi^-}$ [GeV/c^2]

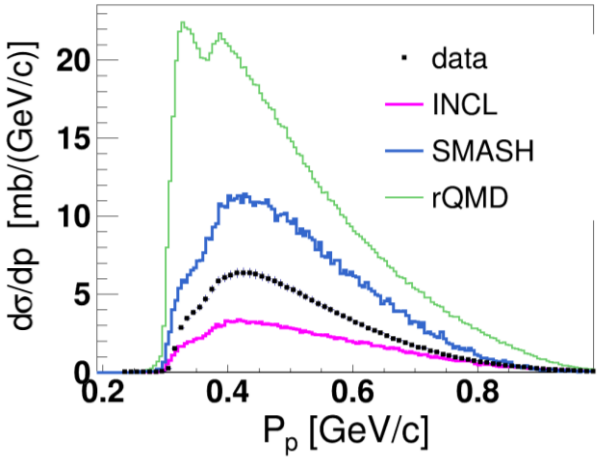

dσ/dm [mb/(GeV/c^2)]
data
INCL
SMASH
rQMD
4
2
0
1.2
1.4
1.6
$M_{inv}^{p\pi^-}$ [GeV/c^2]

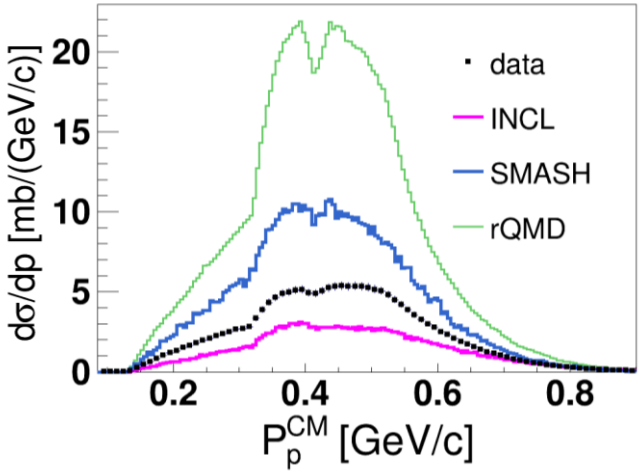
pp

π emission threshhold



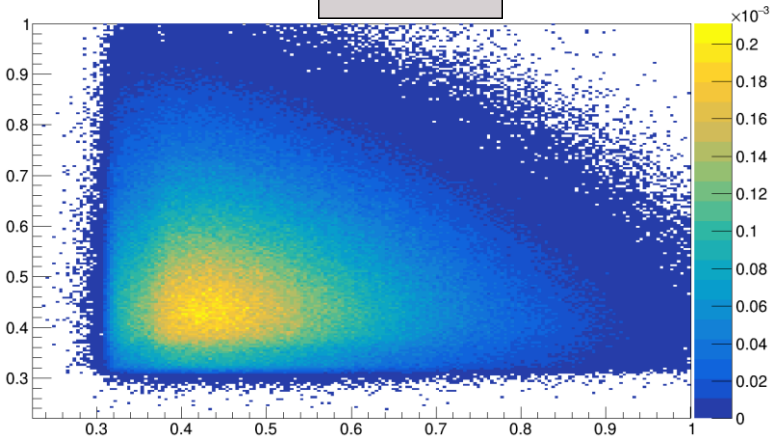




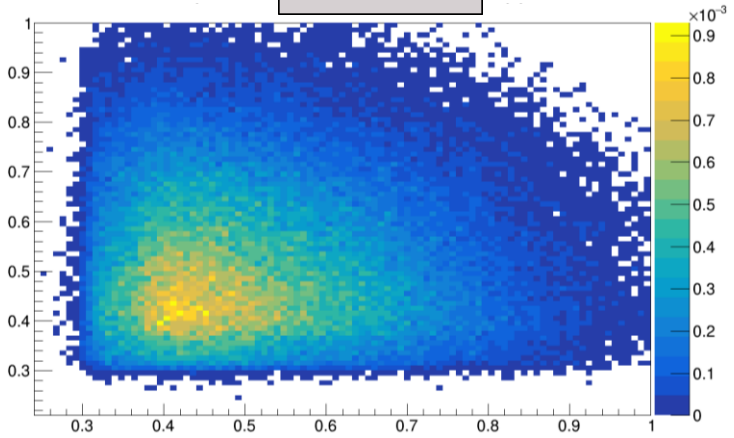


pp

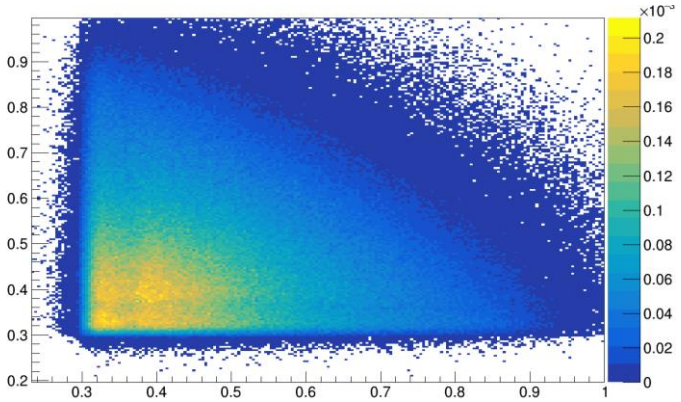
$Data$



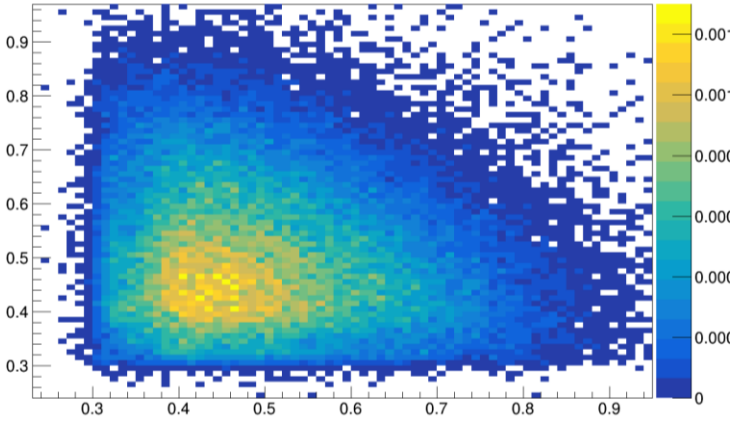
$INCL$



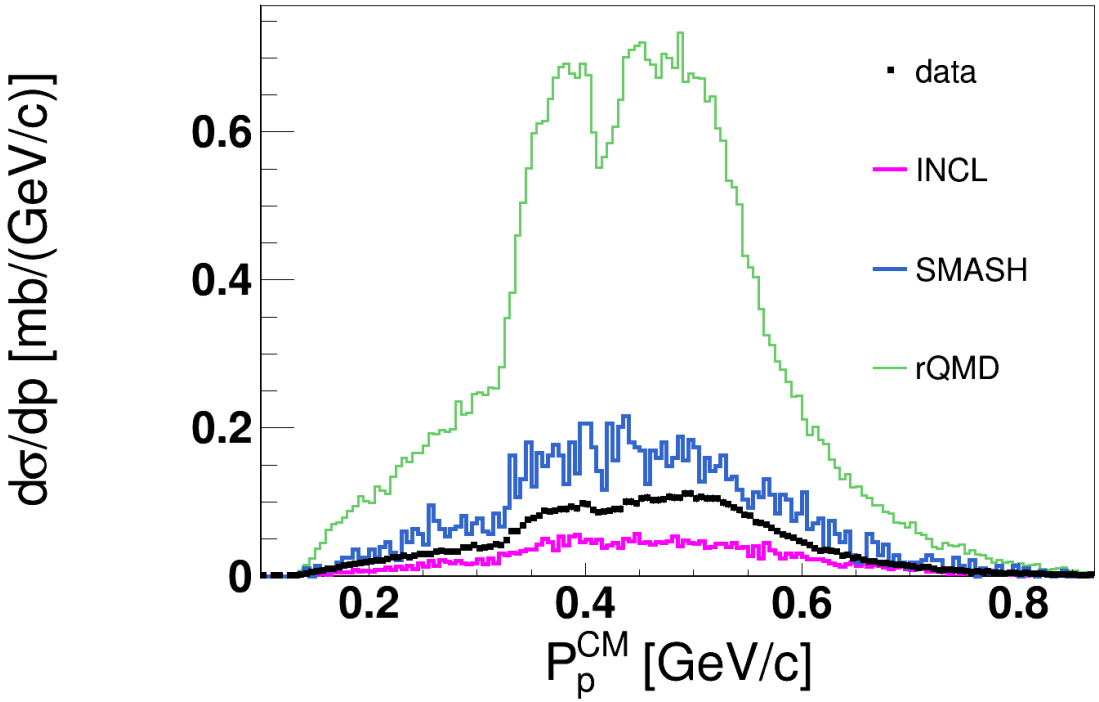
$rQMD$



$SMASH$



ppp


dσ/dp [mb/(GeV/c)]
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
P_p^{CM} [GeV/c]
data
INCL
SMASH
rQMD