Measurement of Cosmic-Ray Fragmentation Cross Sections with NA61/SHINE

Michael Unger (KIT) for the NA61/SHINE Collaboration

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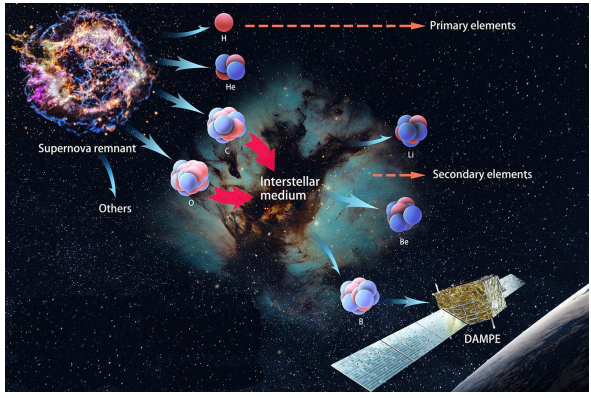
Primary and Secondary Cosmic-Ray Nuclei



Sci.Bull. 67 (2022) 2162

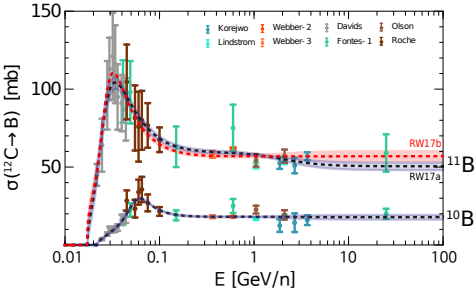
- CR-grammage X (**"target thickness"**) from secondary nuclei, e.g. B/C flux ratio
- halo size (**"target length"**) from unstable secondaries, e.g. $^{10}\mathrm{Be}/\,^{9}\mathrm{Be}$

$\rightarrow$ need to know production cross sections of nuclear fragments

Uncertainties of Fragmentation Cross Sections

example: ^{12}C+p→B (including ^{11}C)

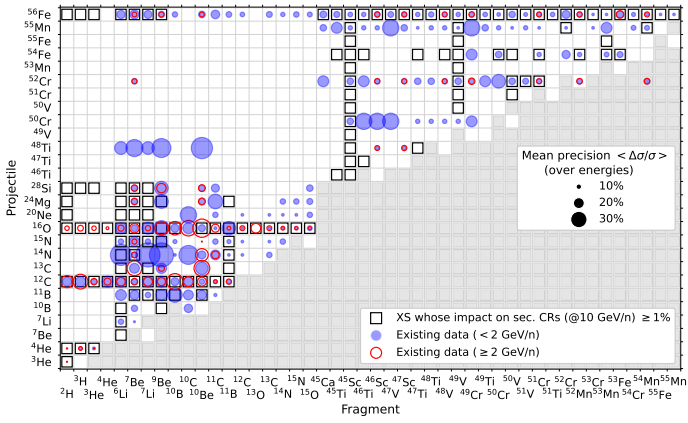
adapted from Reinert&Winkler, arXiv:1712.00002



asymptotic ^{12}C→B cross section:

- 61.0 mb (WSKR03)
- (68.6±2.6) mb (RW17a)
- (75.8± 4.2) mb (RW17b)

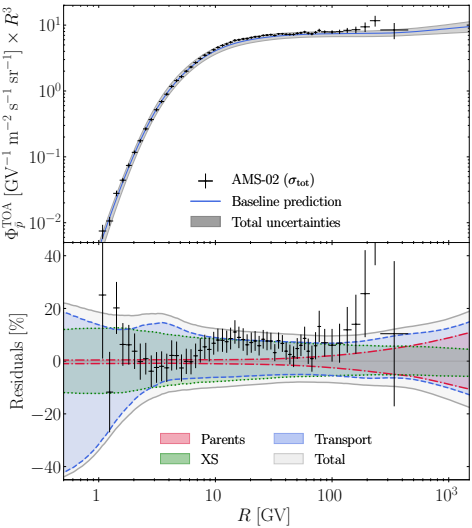
all relevant cross sections:



XSCR24 summary, Maurin et al, arXiv:2503.16173

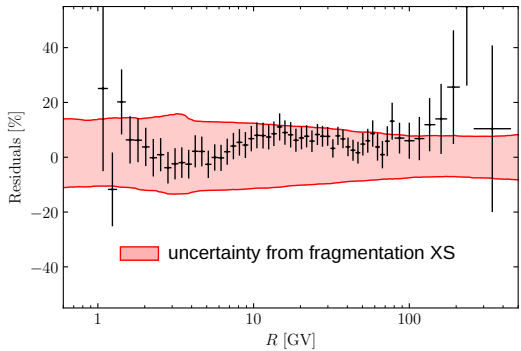
Example: Uncertainty of Anti-Proton Flux Predictions

AMS data, model, residuals:



M. Boudaud et al PRR **2** (2020) 023022

contribution from nuclear fragmentation cross sections:



Genolini et al Phys.Rev.C 109 (2024) 6, 064914

Impact of New Fragmentation Data

measure all reactions relevant for the production of light secondary CR nuclei

reaction	N_{int}	reaction	N_{int}
$^{16}\text{O}+p$	60k	$^{28}\text{Si}+p$	50k
$^{12}\text{C}+p$	50k	$^{24}\text{Mg}+p$	50k
$^{11}\text{B}+p$	10k	$^{20}\text{Ne}+p$	50k
$^{15}\text{N}+p$	10k	$^{22}\text{Ne}+p$	20k
$^{14}\text{N}+p$	10k	$^{27}\text{Al}+p$	10k
$^{10}\text{B}+p$	5k	$^{26}\text{Mg}+p$	10k
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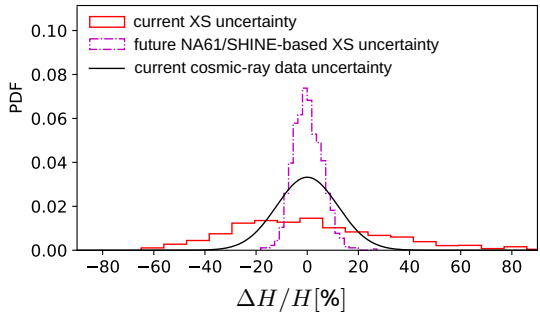
$^{7}\text{Li}+p$	5k	$^{25}\text{Mg}+p$	10k
		$^{21}\text{Ne}+p$	10k
		$^{32}\text{S}+p$	5k
		$^{29}\text{Si}+p$	5k

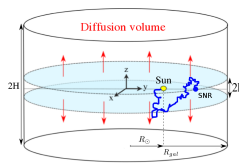
$\Sigma N_{\text{int}} = 3.8 \times 10^5$

number of desired interactions from Genolini et al Phys.Rev.C 109 (2024) 6, 064914

→ expected improvement of CR prop. parameters

a) height of MW diffusion halo





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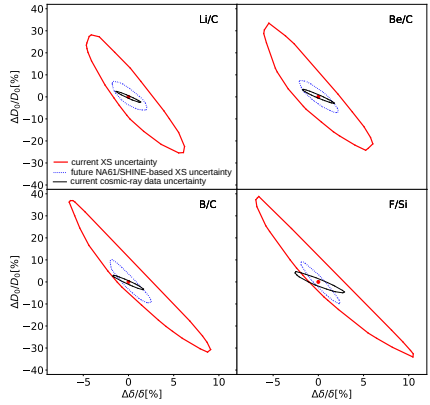
$\rightarrow$ expected improvement of CR prop. parameters

b) diffusion coefficient



$D(E/Z) = D_0\,(E/Z)^{\delta}$

number of desired interactions from Genolini et al Phys.Rev.C 109 (2024) 6, 064914

Impact of New Fragmentation Data

measure all reactions relevant for the production of light secondary CR nuclei

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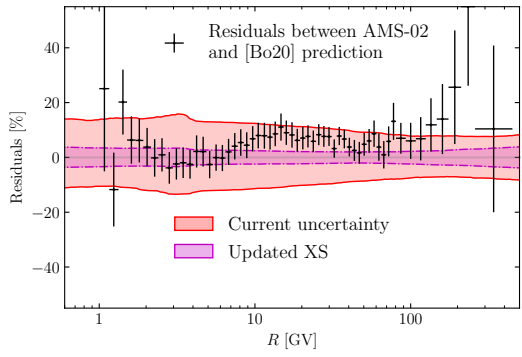
		^{32}S+p	5k
		^{29}Si+p	5k

$\Sigma N_{\text{int}} = 3.8 \times 10^5$

c) $\bar{p}$ flux

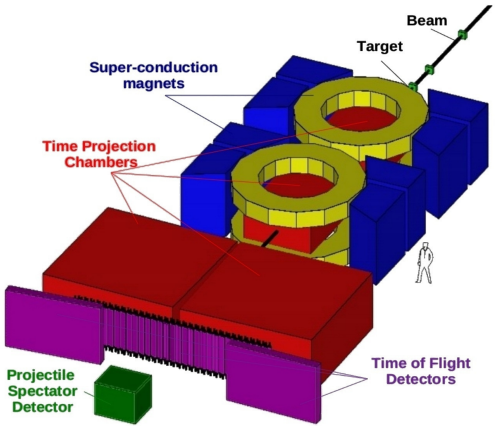


$D(E/Z) = D_0 \, (E/Z)^{\delta}$

number of desired interactions from Genolini et al Phys.Rev.C 109 (2024) 6, 064914

Measurement of Nuclear Fragmentation with NA61/SHINE

"SPS Heavy Ion and Neutrino Experiment"



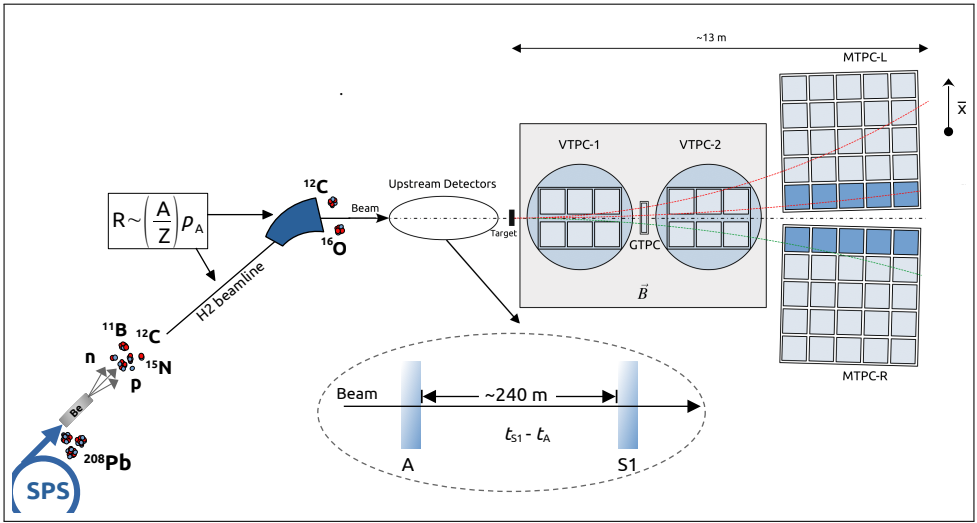
cosmic-ray program:

- particle production in air showers
- cosmic-ray anti-matter
- cosmic-ray propagation

- large acceptance $\approx 50\%$ at $p_T \leq 2.5$ GeV/c
- momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\text{GeV/c})^{-1}$
- tracking efficiency: $> 95\%$, pid with dE/dx and ToF

Measurement of Nuclear Fragmentation with NA61/SHINE

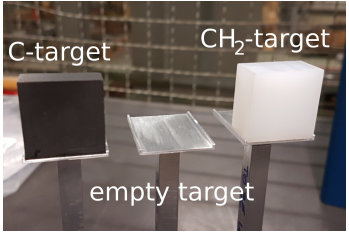
- fragmented Pb beam or primary O beam from SPS
- isotope id with NA61/SHINE: dE/dx in TPCs $\propto Z^2$, deflection Δx in mag. field $\propto A/Z$



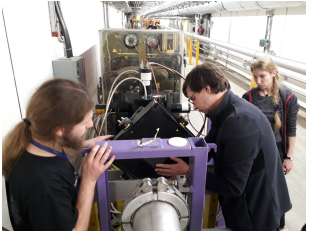
Nuclear Fragmentation with NA61/SHINE

- 2018: pilot run, C projectiles at 13 GeV/c (0.3M ^{12}C beam triggers)
- 2024: physics run, Li to Si projectiles at 12.5 GeV/c (46M beam triggers)
- 2025: physics run, ^{16}O projectiles at 150 GeV/c (5M interaction triggers)

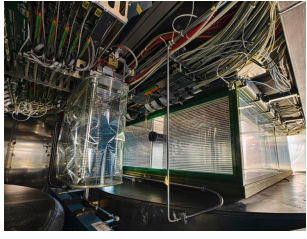
H2 beam line



targets



time-of-flight detector



time projection chamber

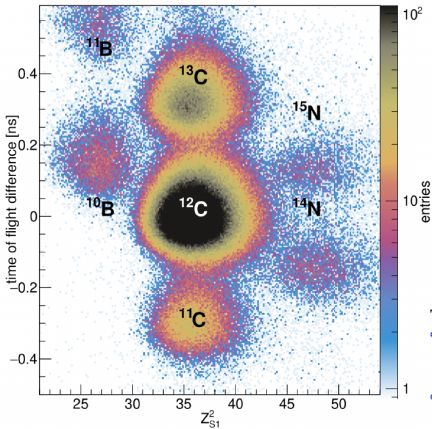
2018 Pilot Data: Particle Identification

projectiles upstream of target

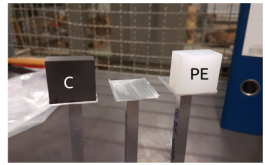
- 240 m time-of-flight → A/Z
- dE/dx in beam scintillator → Z^2

fragments downstream of target

- deflection Δx in magnetic field → A/Z
- dE/dx in TPC → Z^2

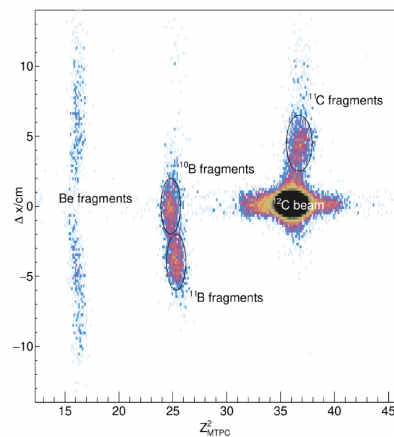


^{12}C+p at 13.5A GeV/c

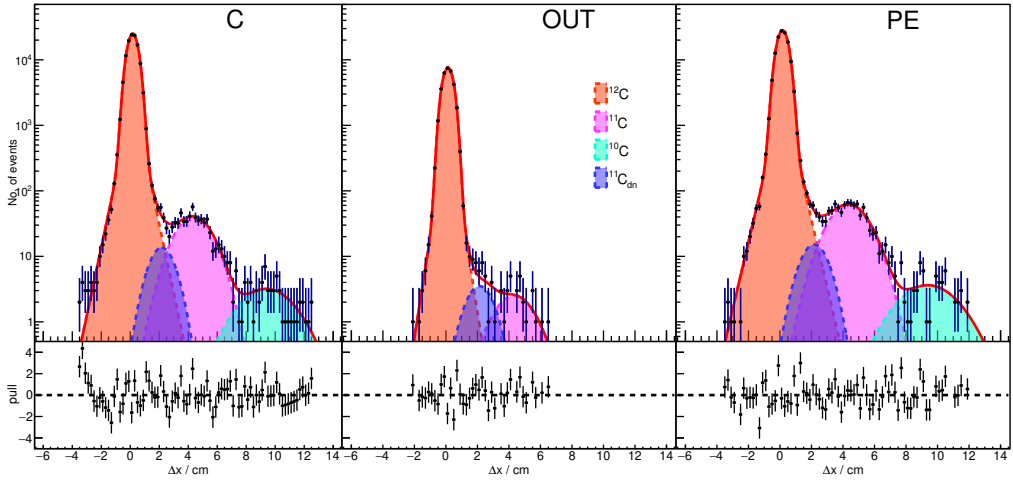


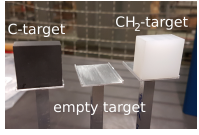
Targets used:

- Polyethylene (PE)
- Graphite (C)



2018 Pilot Data: Carbon Isotopes in TPC





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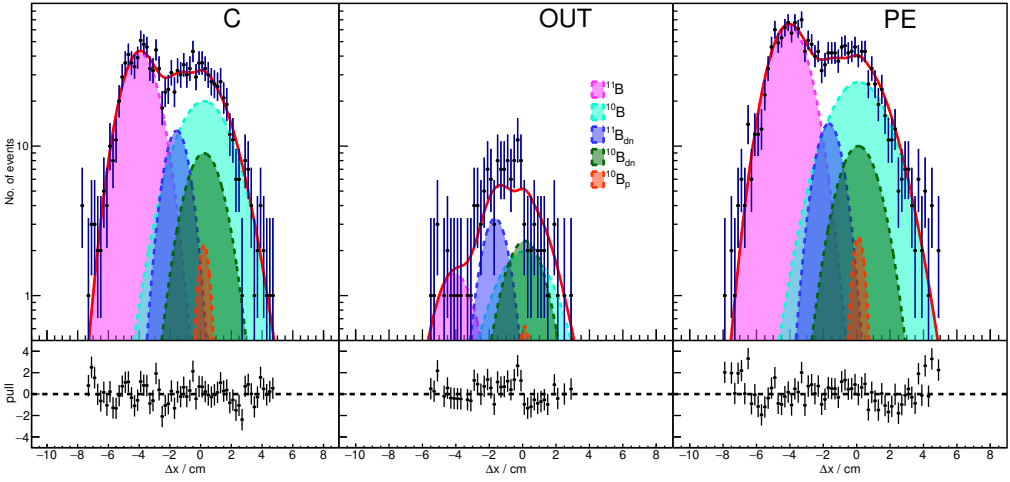
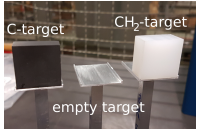
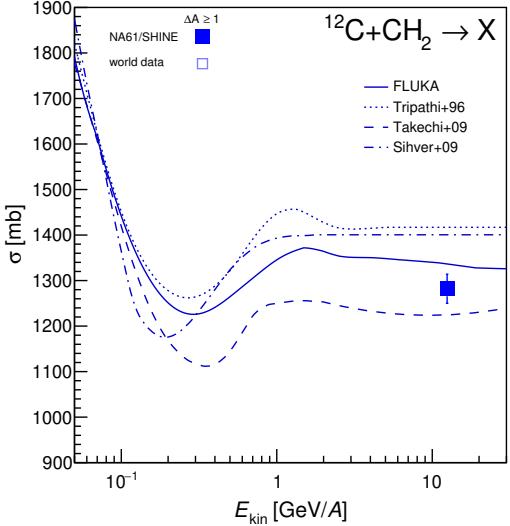
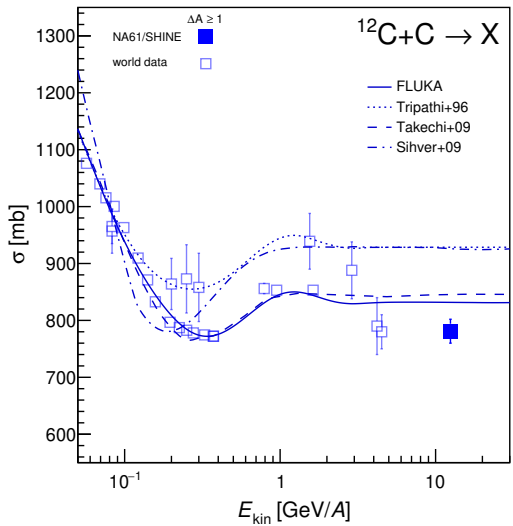




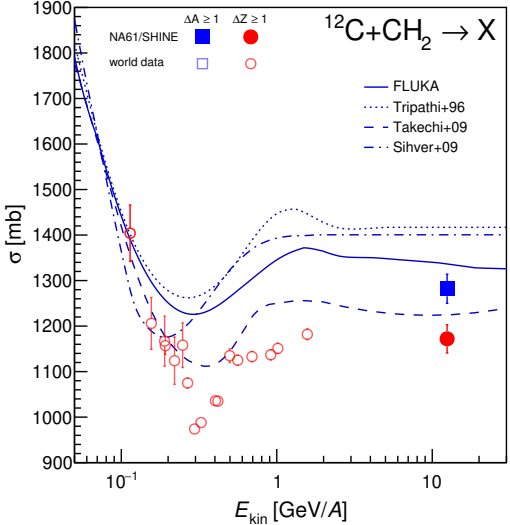
Pilot Data Results: Mass-Changing Cross Section

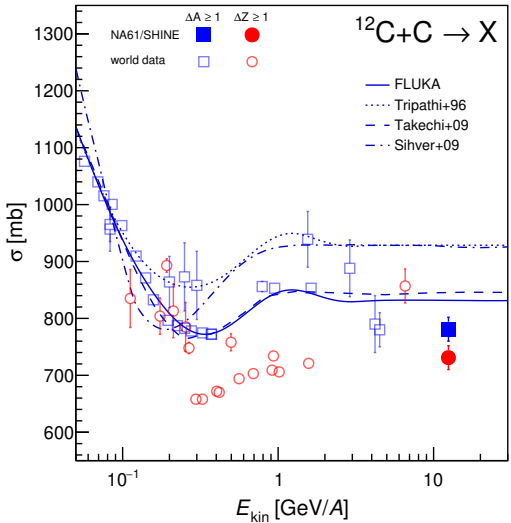




Marta Urbaniak PhD Thesis, University of Silesia, 2025
Poster #714, PO-1 session
Phys.Rev.C 111 (2025) 5, 054606

Pilot Data Results: Charge-Changing Cross Section





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Phys.Rev.C 111 (2025) 5, 054606

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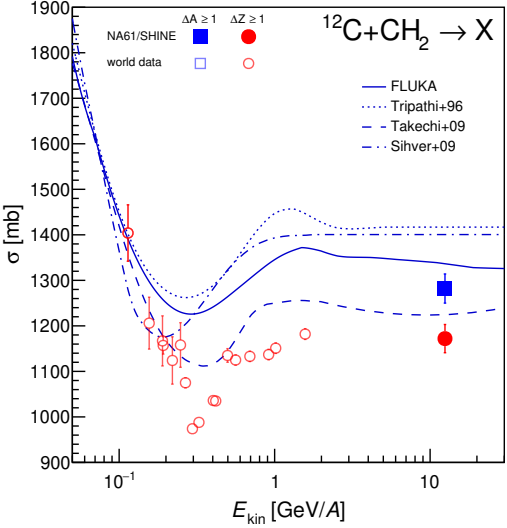

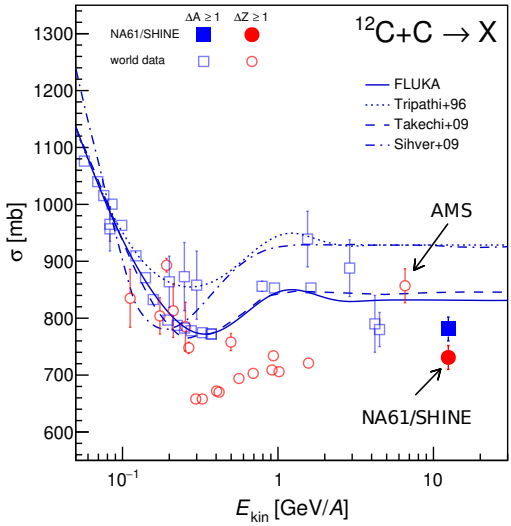

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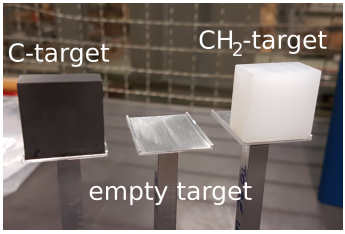
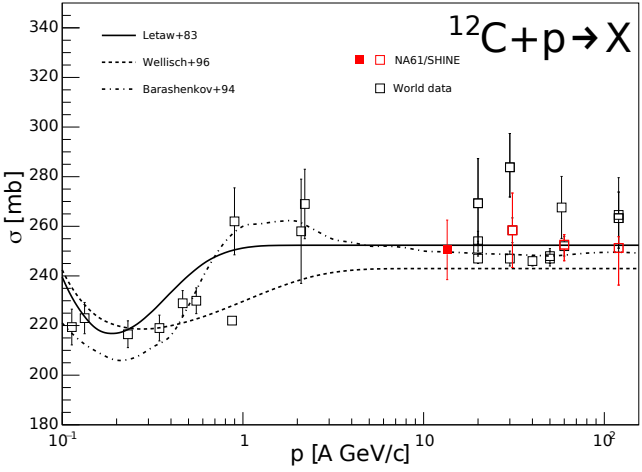
Pilot Data Results: C+p Mass-Changing Cross Section

C+p from C+C and C+PE

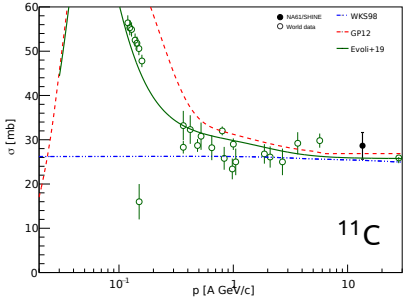
$$\sigma(C+p) = \frac{\sigma(C+CH_2) - \sigma(C+C)}{2}$$

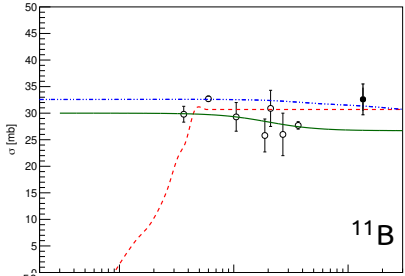


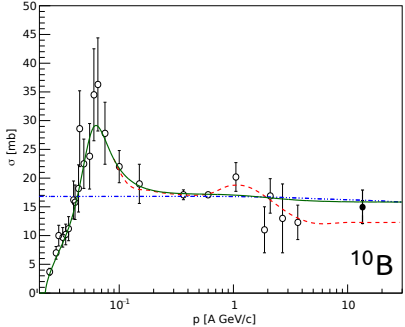
inferred cross section compared to previous measurements



Pilot Data Results: Boron Production in C+p







- pilot run succesful
- precision of pilot result limited by statistical uncertainty

$$\sigma_{C+p \rightarrow B} = 77 \pm 5 \text{ mb}$$

- high-statistics physics run in 2024!

Neeraj Amin, PhD Thesis, KIT, 2024
Phys.Rev.C 111 (2025) 5, 054606

Fragmentation Run December 2024 – Projectiles

- 46M beam triggers, 12.5 GeV/n, targets (10%λ_C): PE,C,OUT
- upstream isotopes (uncalibrated, few % of full data set):

required interactions

reaction	N_{int}	reaction	N_{int}
^{16}O+p	60k	^{28}Si+p	50k
^{12}C+p	50k	^{24}Mg+p	50k
^{11}B+p	10k	^{20}Ne+p	50k
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$\Sigma N_{\text{int}} = 3.8 \times 10^5$

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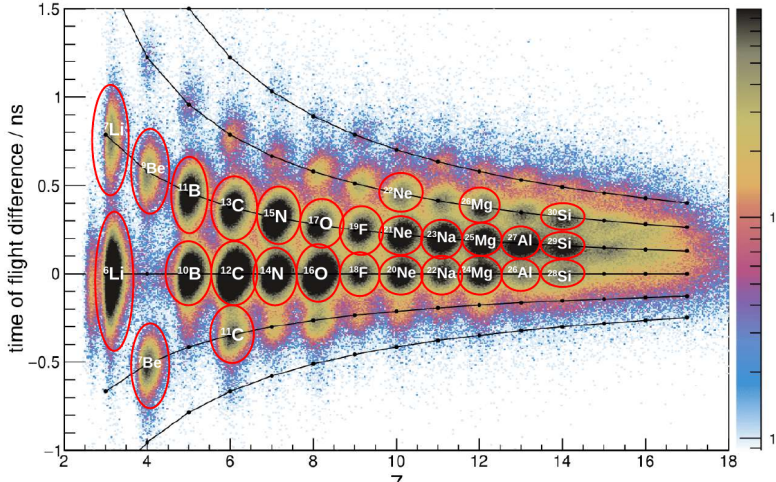
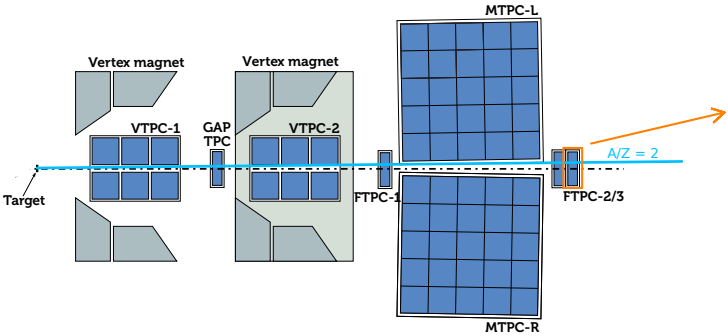
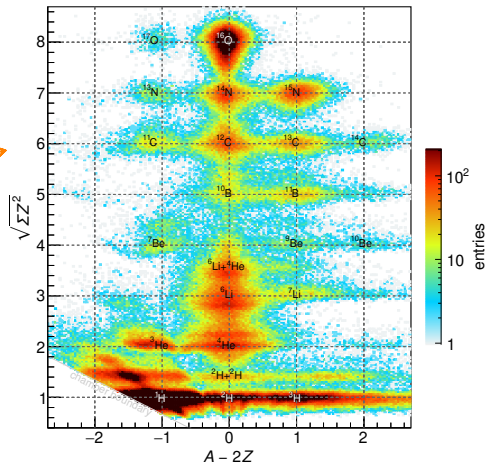


→ e.g. $N_{\text{int}}(^{12}\text{C} + \text{p}) \approx 80$ k

Fragmentation Run July 2025 – Isotopes in Beam TPCs

- 5M interaction triggers, 150 GeV/n ^{16}O beam, targets (10%λ_C): PE,C,OUT
- downstream isotopes (uncalibrated):





Summary

CR studies at SPS with NA61/SHINE:

- $\pi^{\pm}$+C & p+C interactions

→ particle production in air showers

- p+p interactions

→ nucleon coalescence

→ $\bar{p}$ production

- nuclear fragmentation

→ particle production in Galaxy

→ pilot run in 2018 PRC **111** (2025) 054606

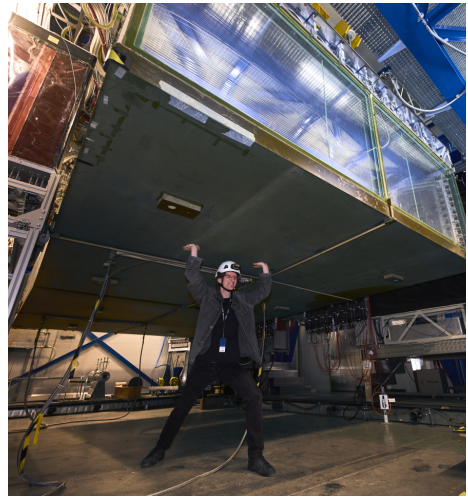
→ 12.5 GeV/n Li-Si in 2024

→ 150 GeV/n ^{16}O in 2025

Outlook

Upcoming CR-related measurements:

- **2025** high statistics p+p 600M
  nucleon coalescence, anti-deuterons
- **20XX** fragmentation of heavy nuclei?



inside NA61 Julien Ordan/CERN)

see also:

→ Anirvan Shukla *Deuteron Production*
Monday 21st CRI 15:20

→ Marta Urbaniak ^{12}*C Cross Sections*
Thursday 17th PO-01 17:00