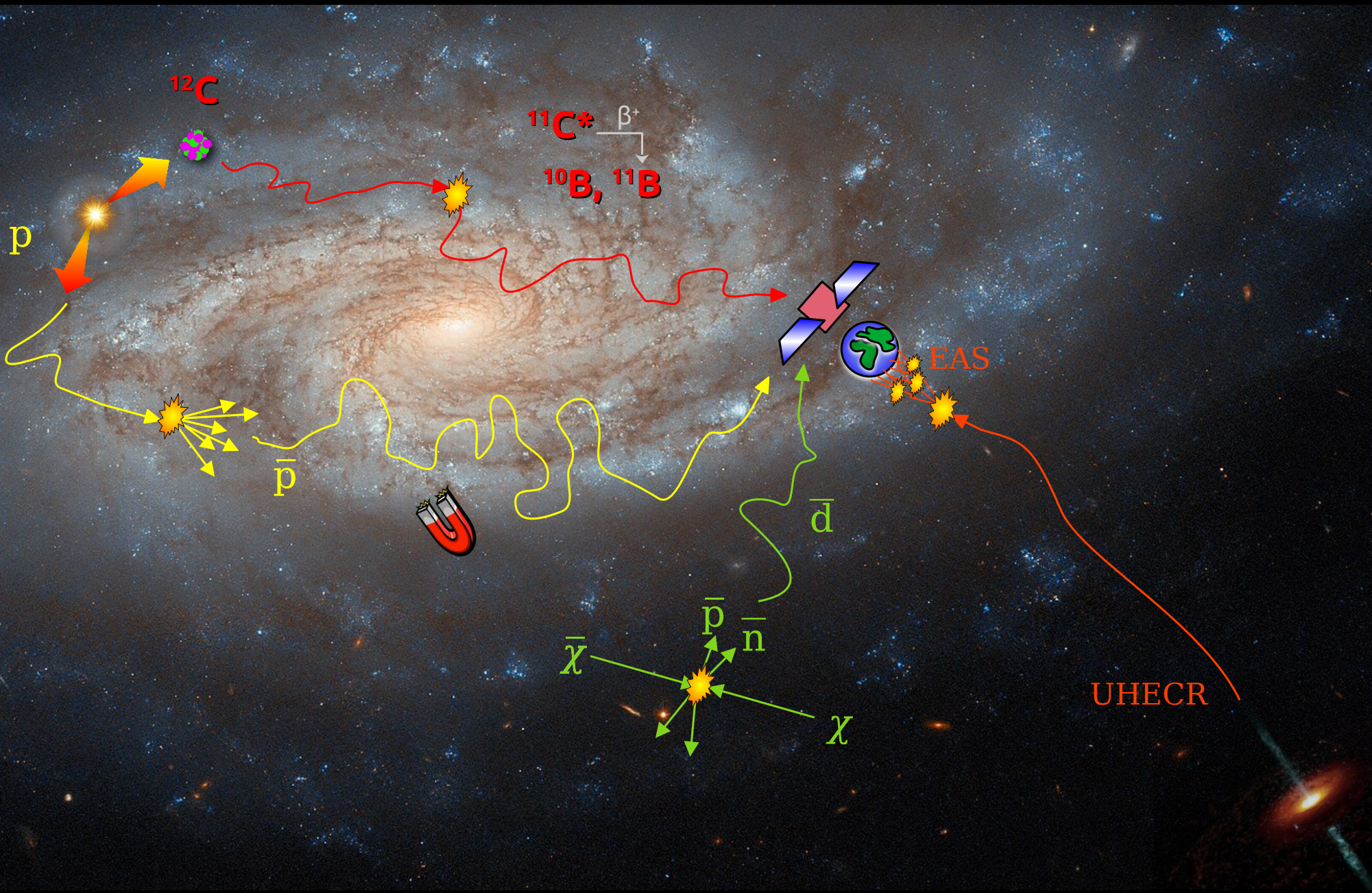
Measurements of Cosmic-Ray Cross Sections with NA61/SHINE

Michael Unger (KIT) for the NA61/SHINE Collaboration

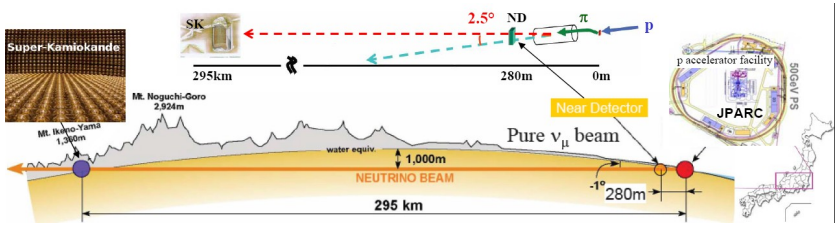


NA61/SHINE

≈ 140 physicists from 14 countries and 28 institutions

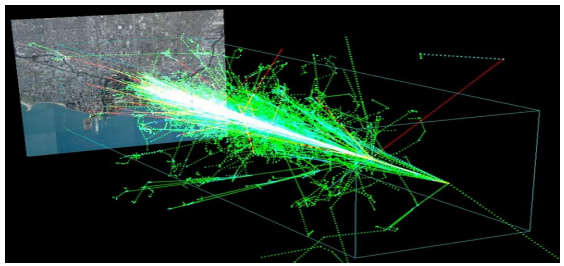
Strong interactions physics

- search for the critical point of strongly interacting matter
- study of the properties of the onset of deconfinement
- heavy quarks: direct measurement of open charm at SPS energies



Neutrino and cosmic ray physics

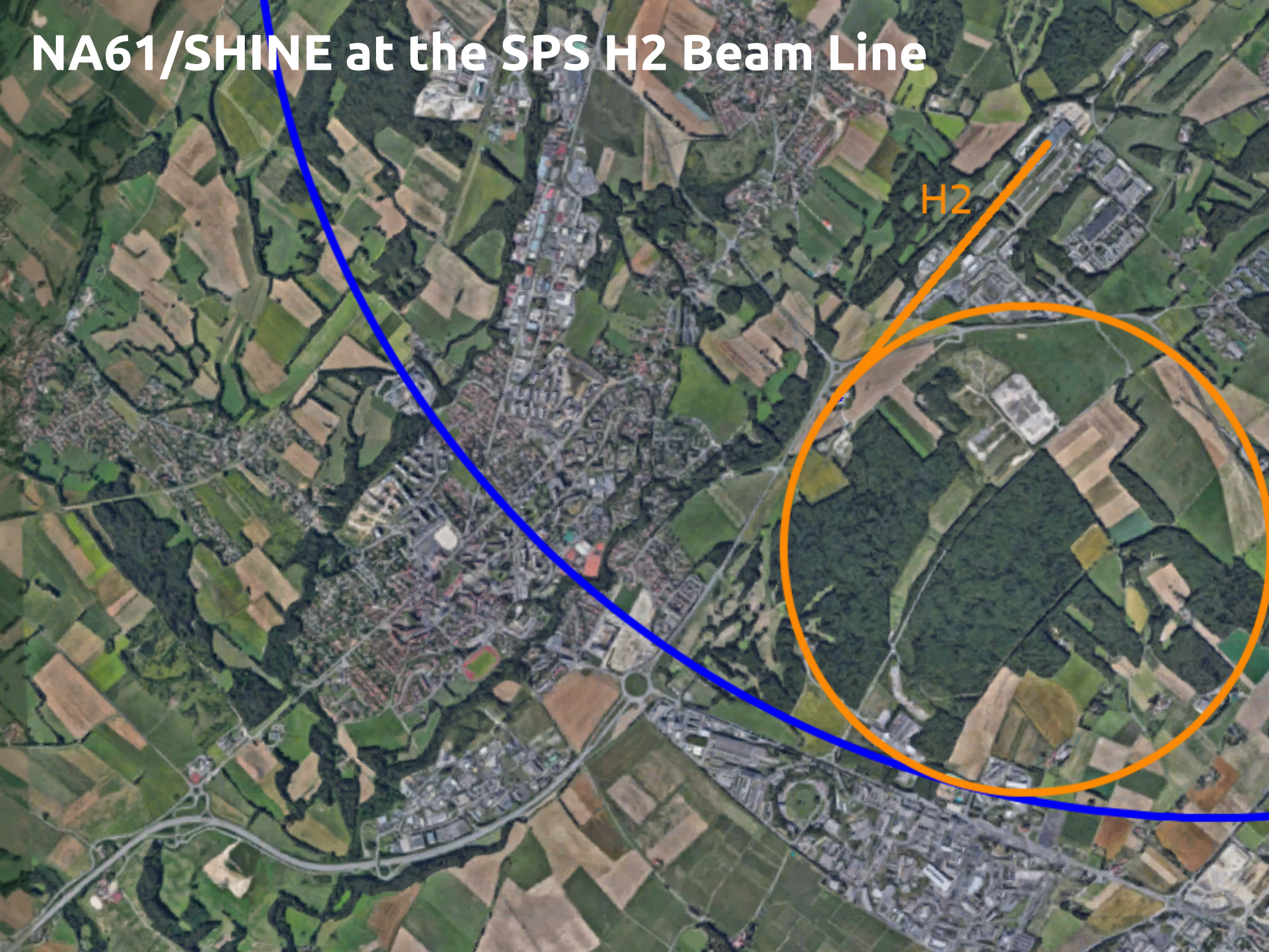
- hadron measurements for the J-PARC neutrino program
- hadron measurements for the Fermilab neutrino program
- measurements for cosmic ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
- measurements of nuclear fragmentation cross sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy



cosmic ray groups: KIT (Germany), Uni. Hawaii (USA), Uni. Silesia (Poland)

associate member: Goddard Space Flight Center (USA)

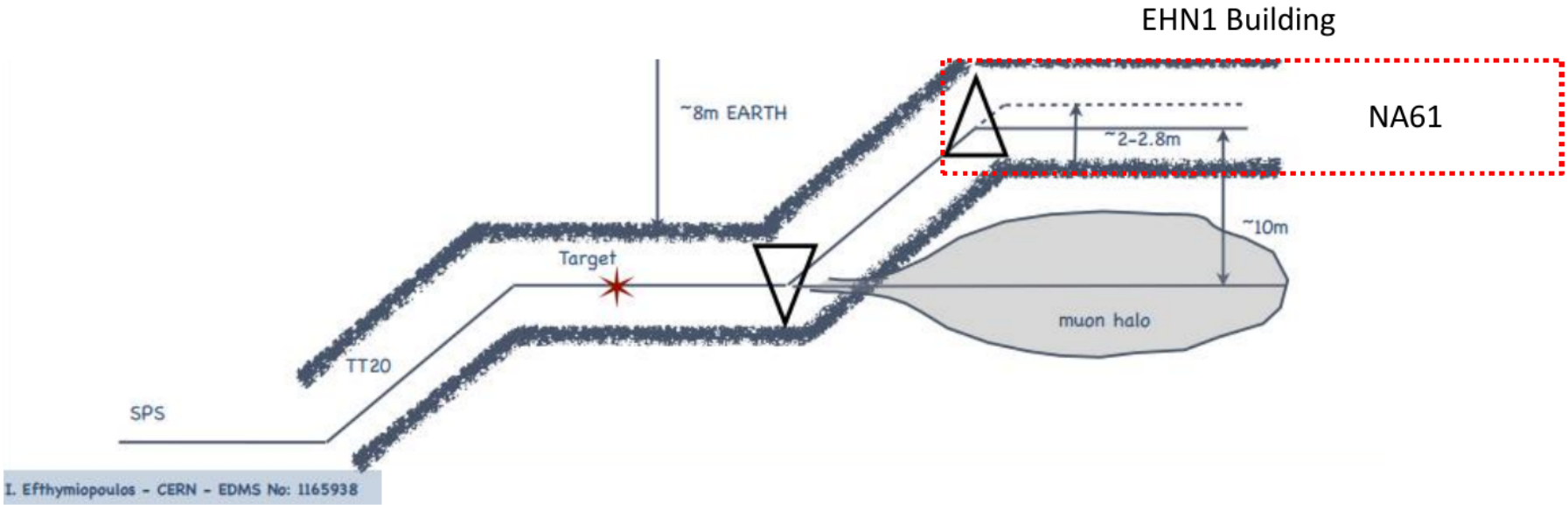
NA61/SHINE at the SPS H2 Beam Line



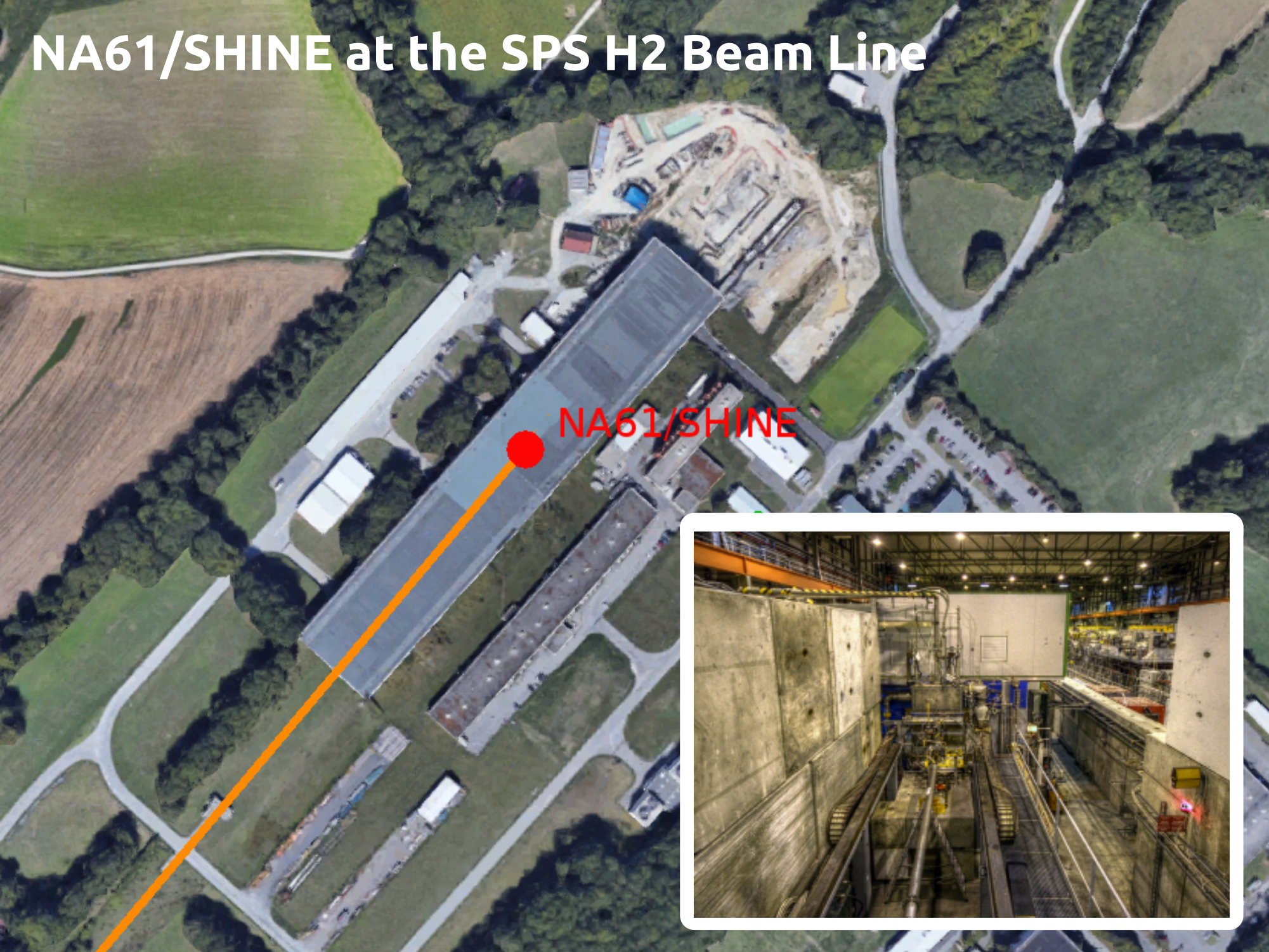
NA61/SHINE at the SPS H2 Beam Line

H2

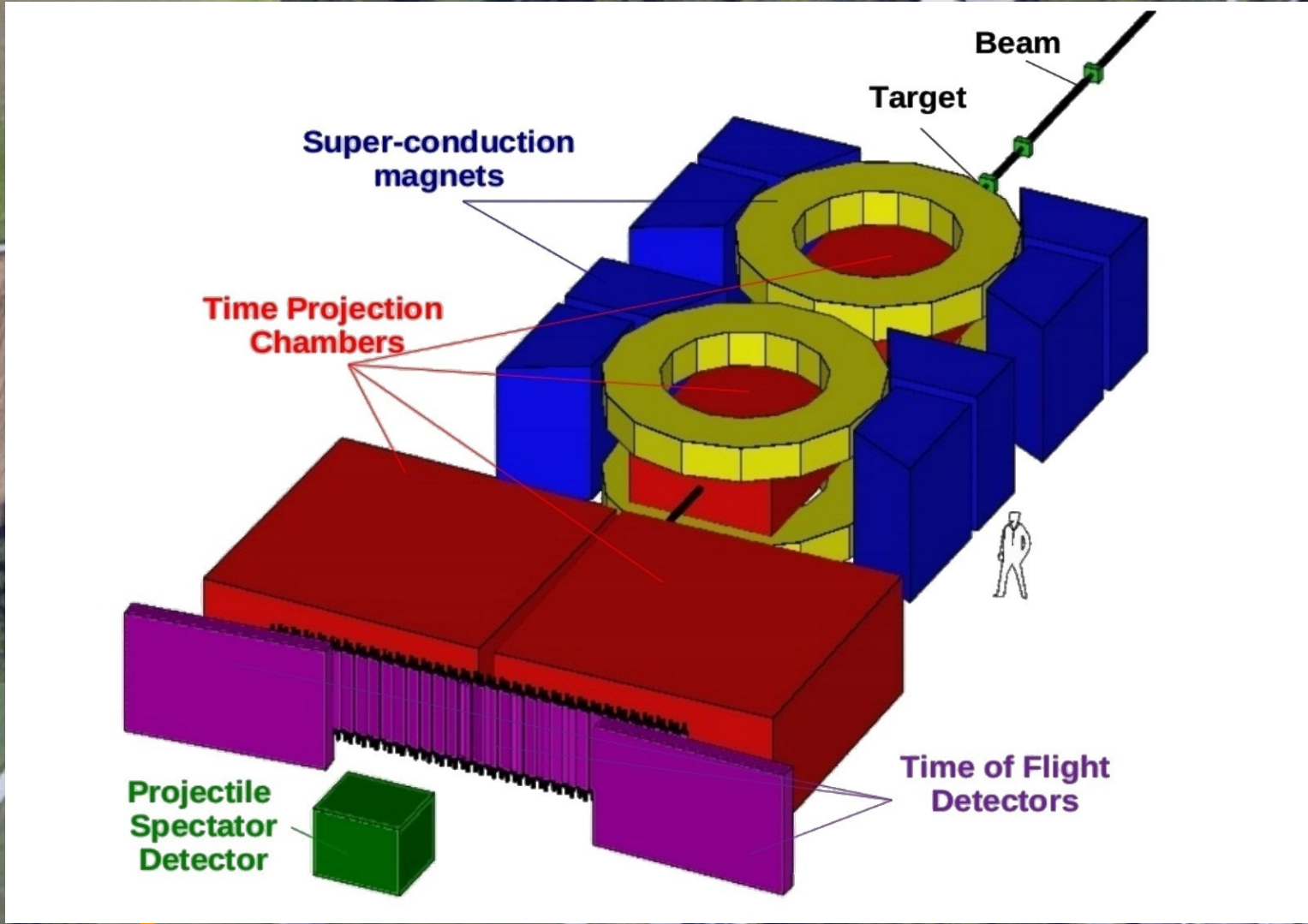
A **precise** (2% dp/p acceptance), robust, flexible magnetic spectrometer



NA61/SHINE at the SPS H2 Beam Line

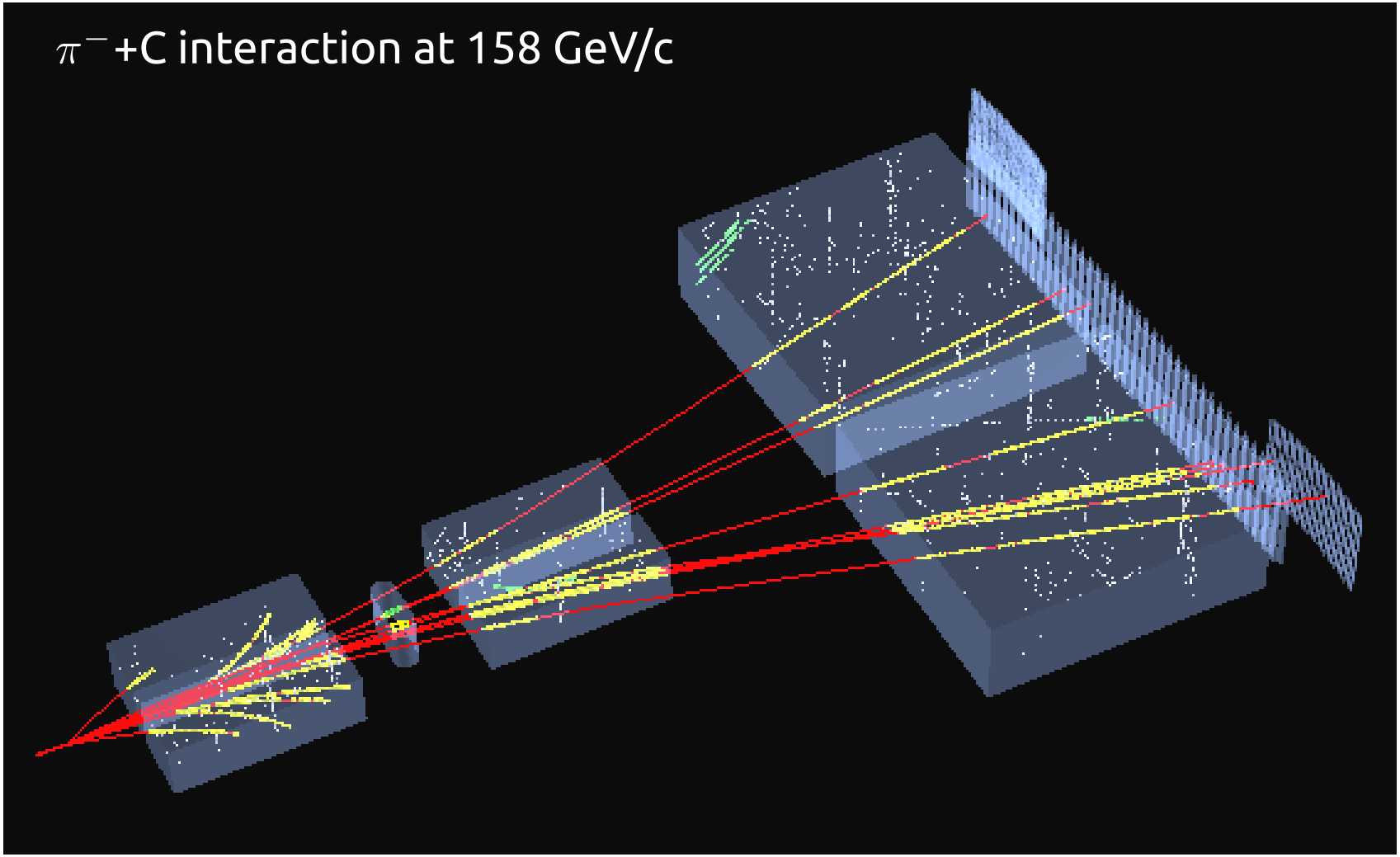


NA61/SHINE Detector



- 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

Particle Production Measurement with NA61/SHINE



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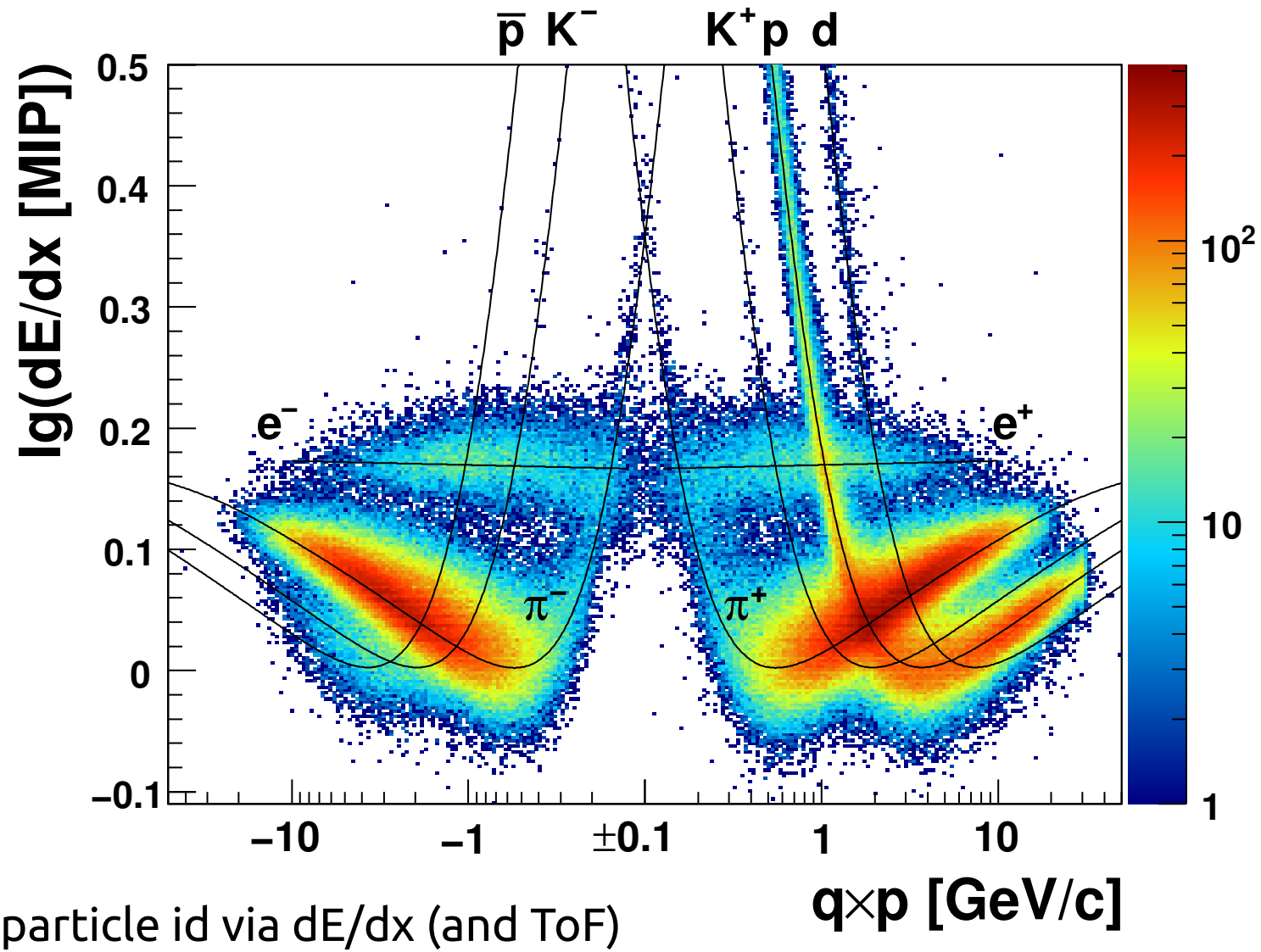
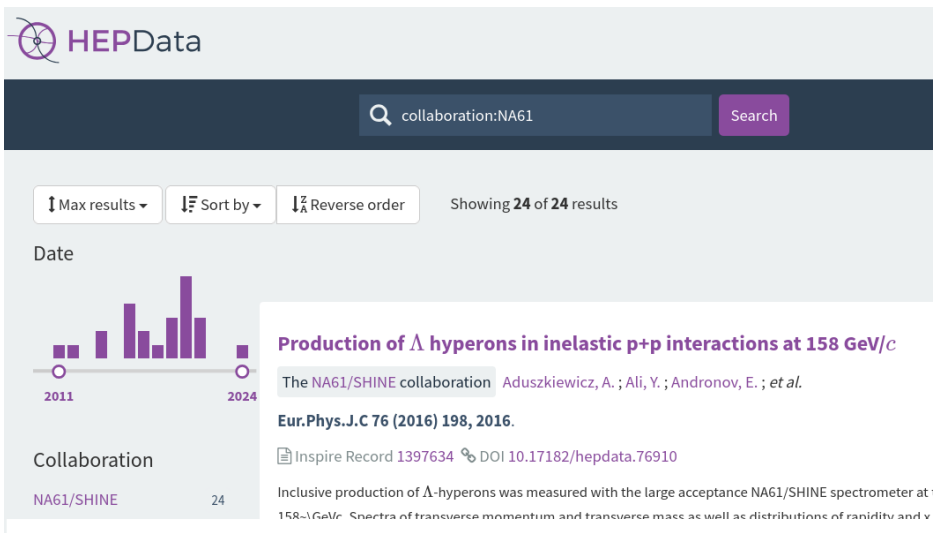


particle id via dE/dx (and ToF)

Particle Production Measurements of Relevance for Cosmic-Ray Physics from NA61/SHINE (published)

reaction	energy	π^+	π^-	K^+	K^-	p	$\bar{p}$	Λ	$\bar{\Lambda}$	K^0_S	ρ^0	ω	K^{*0}	Ξ^0	$\bar{\Xi}^0$	Ξ^+	Ξ^-	ϕ
p+C	31	✓	✓	✓	✓	✓		✓		✓								
p+C	120	✓	✓	✓	✓	✓	✓	✓	✓	✓								
π^++C	60	✓	✓	✓	✓	✓		✓	✓	✓								
π^-+C	158	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
π^-+C	350	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
p+p	20	✓	✓	✓	✓	✓	✓											
p+p	31	✓	✓	✓	✓	✓	✓			✓								
p+p	40	✓	✓	✓	✓	✓	✓			✓			✓					✓
p+p	80	✓	✓	✓	✓	✓	✓			✓			✓					✓
p+p	158	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓



The Cosmic-Ray Program of the NA61/SHINE Facility

- Particle Production in Air Showers
  - p+C Interactions
    (31, 60, 90, 120 GeV/c)
  - π+C Interactions
    (30, 60, 158, 350 GeV/c)
- Galactic Cosmic Rays
  - d, $\bar{d}$, $\bar{p}$ Production
    (p+p at 20, 31, 40, 80, 158, 400 GeV/c)
  - $e^{\pm}$ and ν from pion and kaon decays
    (p+p at 20, 31, 40, 80, 158, 400 GeV/c)
  - Nuclear Fragmentation
    (C+C, C+CH_2 at 13.5 AGeV/c)

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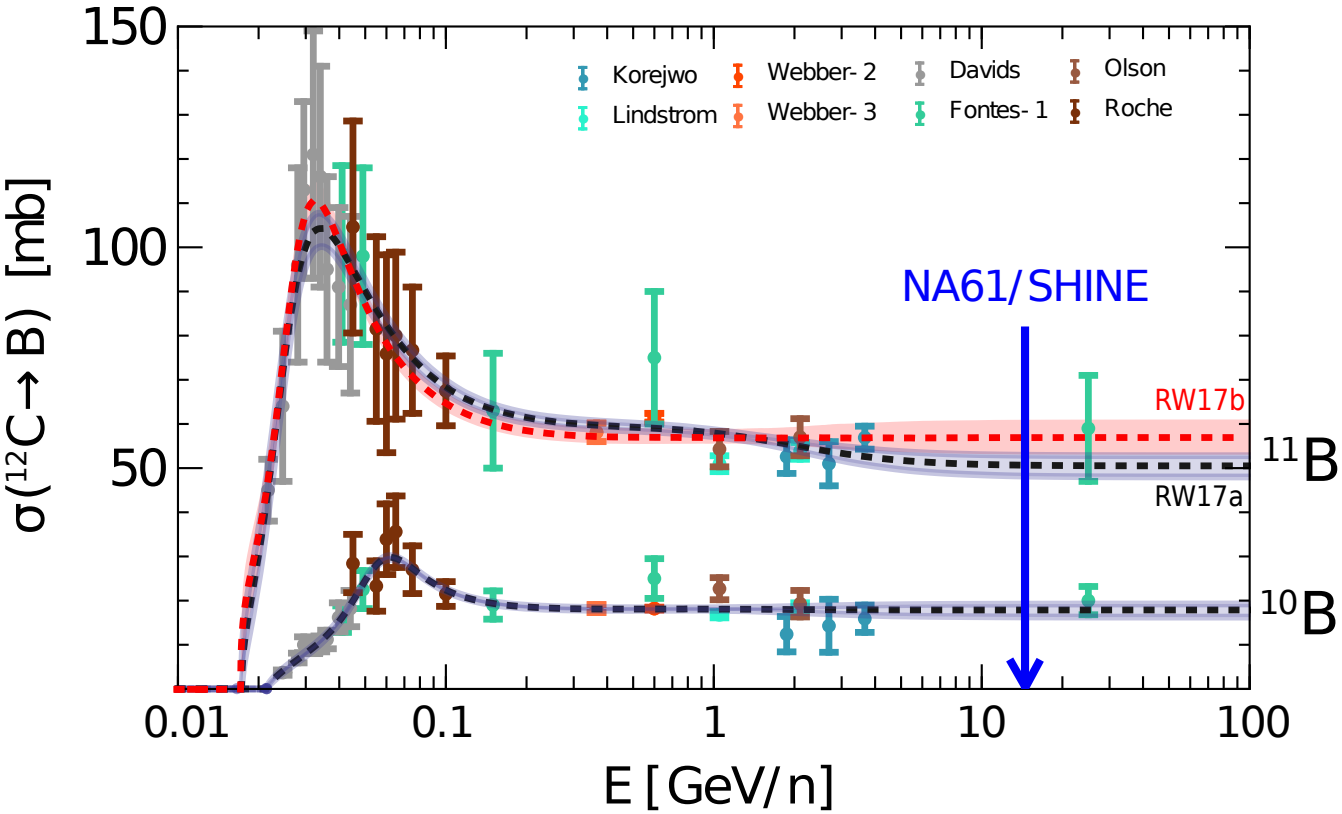
  - Nuclear Fragmentation ← this talk
    (C+C, C+CH_2 at 13.5 AGeV/c)

Nuclear Fragmentation at SPS energies

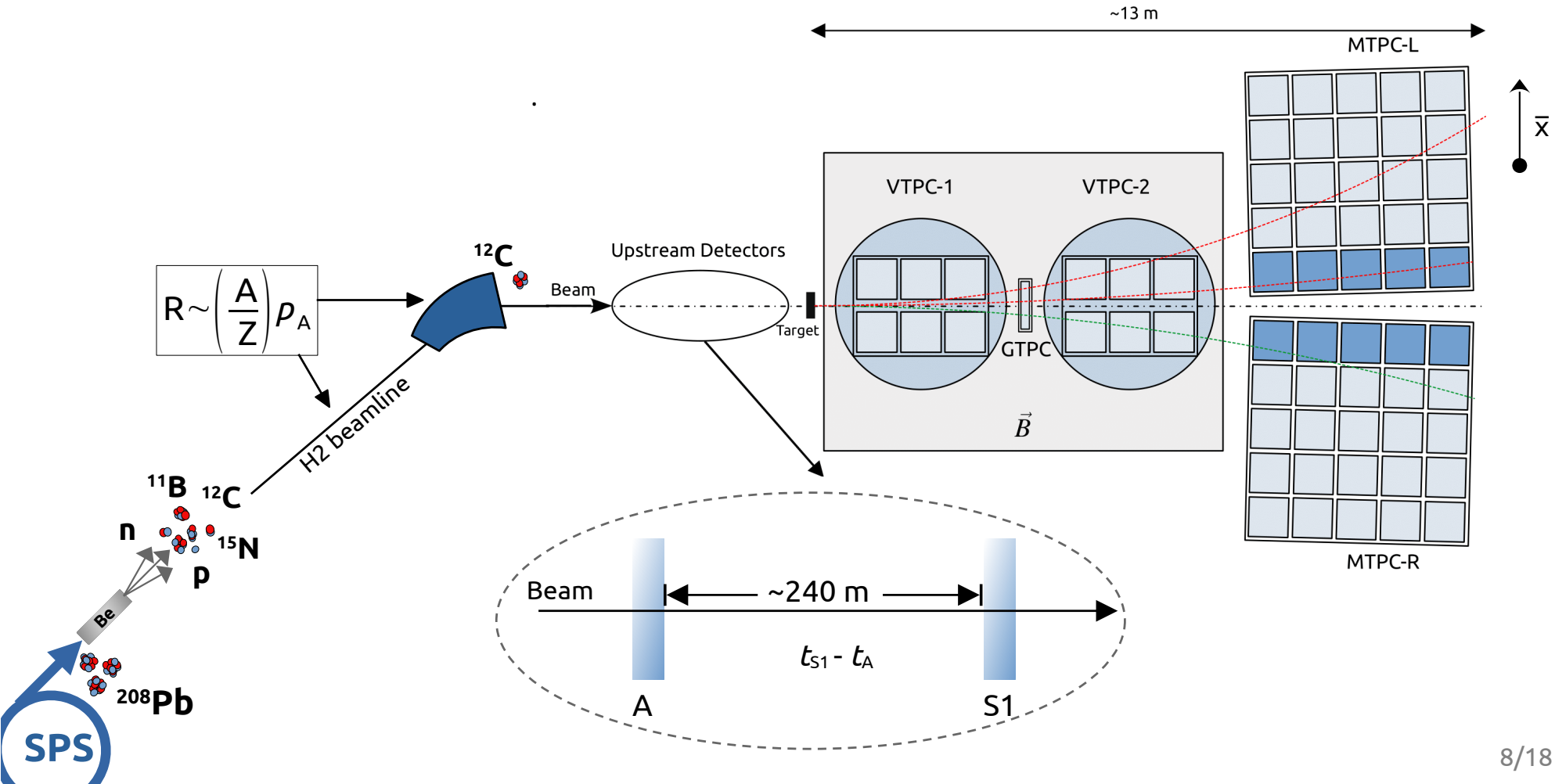
- $E/n \gtrsim 10$ GeV $\rightarrow$ "asymptotic" XS-values for AMS/DAMPE/CALET energies
- scan of projectiles: Li...Si (XS ranking from Genolini+2023)



$\rightarrow$ see talks by Carmelo and David!

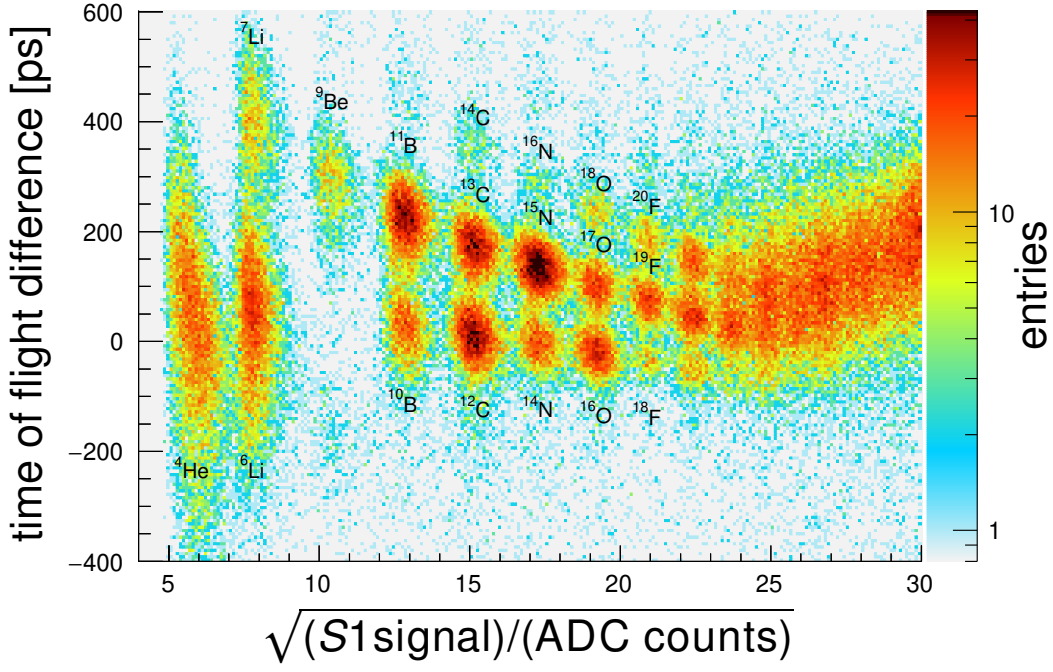
NA61/SHINE Pilot Run on Fragmentation in 2018

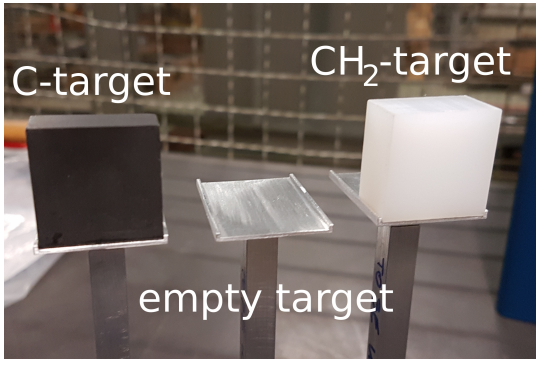
- fragmented Pb beam from SPS, $p = 13.5\,A\text{GeV}/c$
- isotope identification with NA61/SHINE

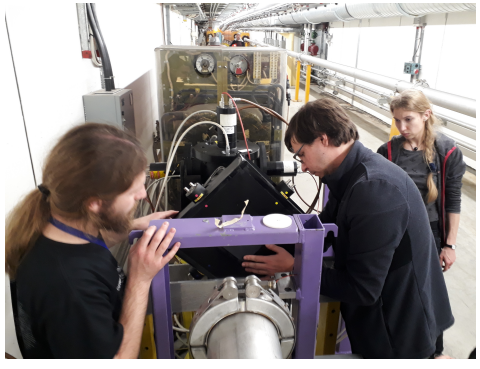


NA61/SHINE Pilot Run on Fragmentation in 2018

raw composition of projectiles from SPS during setup:





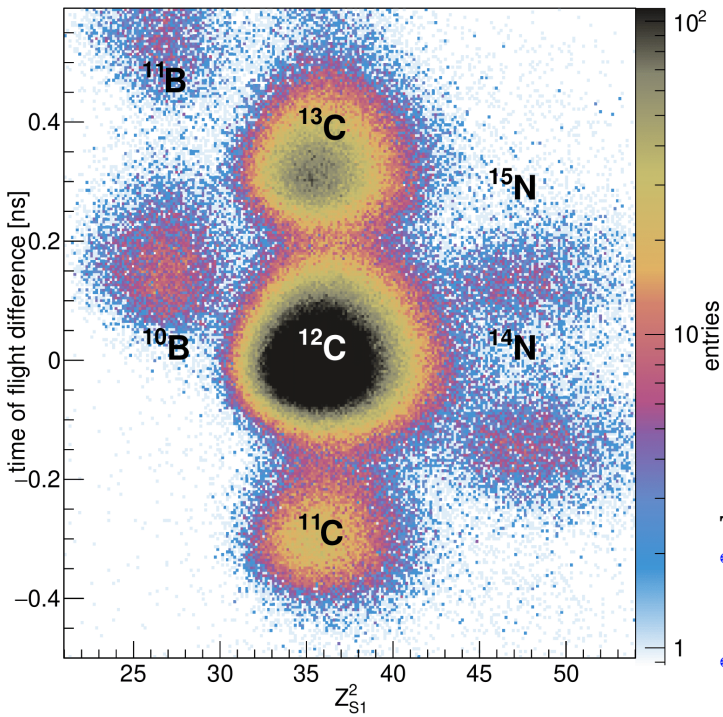


- 2.5 days data taking at 13.5 AGeV/c
- events after upstream ^{12}C selection:
  - 1.7×10^5 CH_2-target
  - 1.5×10^5 C-target
  - 0.4×10^5 empty-target

Particle Identification

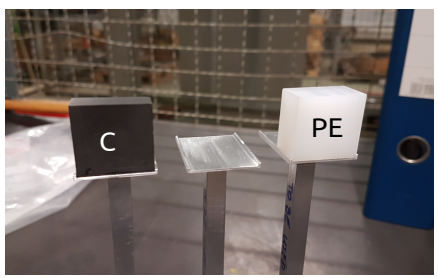
projectiles upstream of target

- (A/Z) from *t.o.f.* difference = t_{S1} - t_A



Triggered beam particles.

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



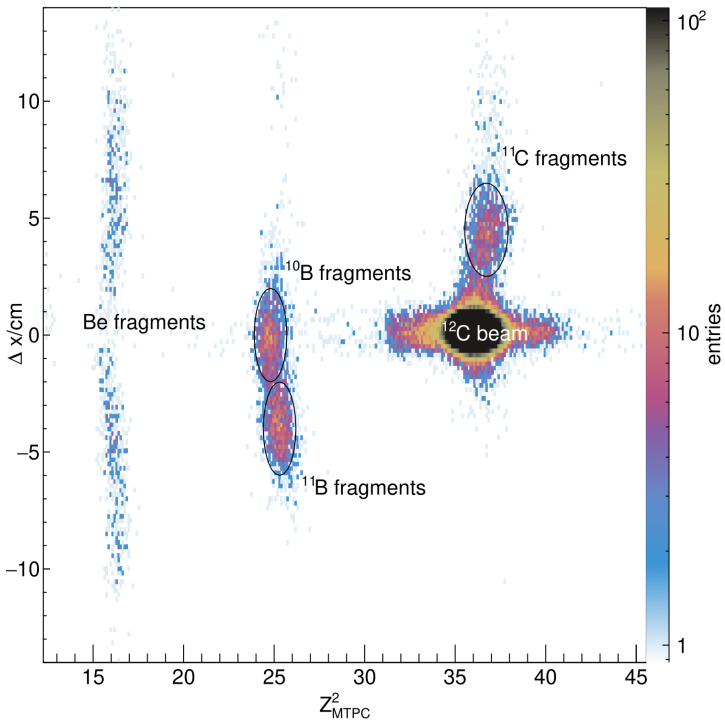
Targets used:

- Polyethylene (PE)

- Graphite (C)

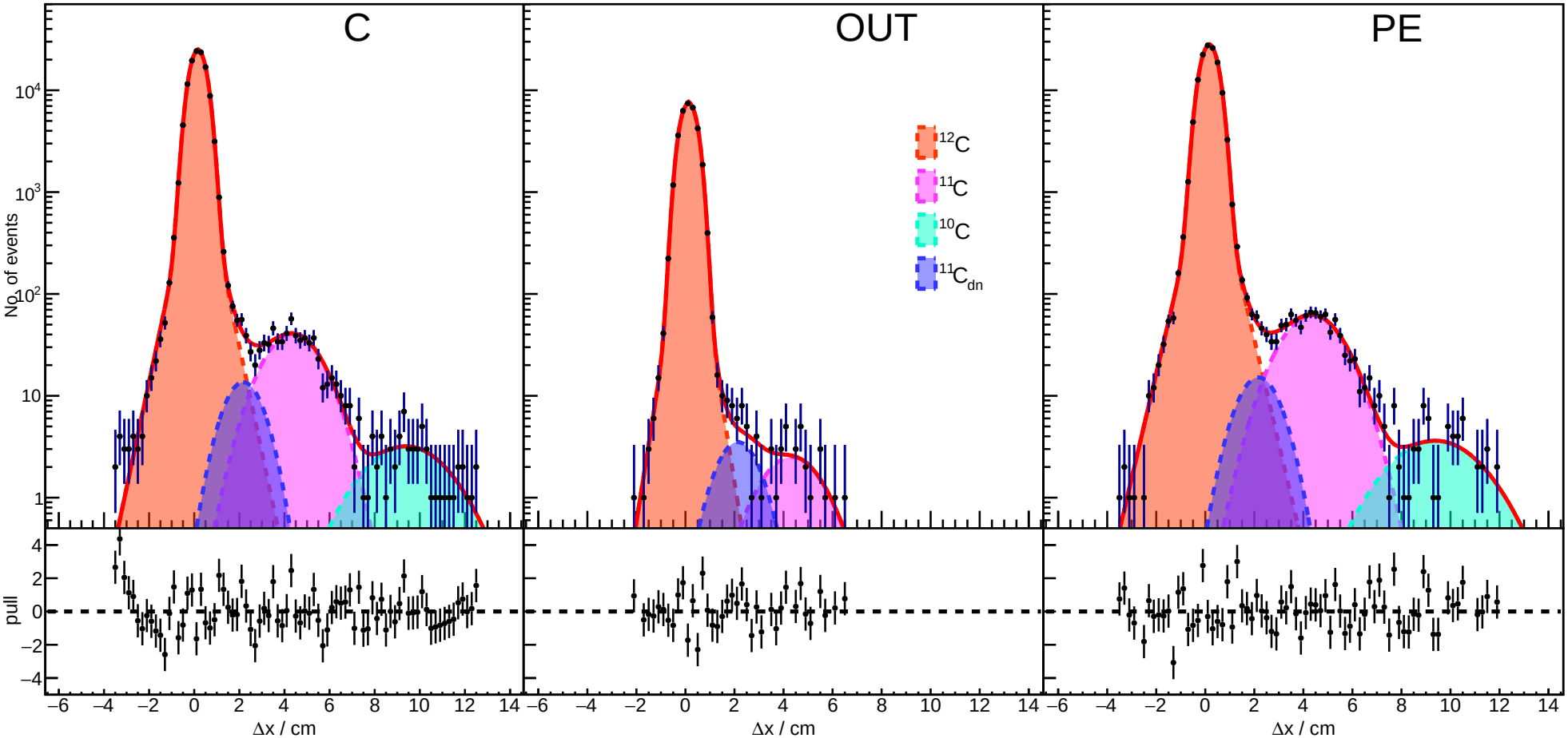
fragments downstream of target

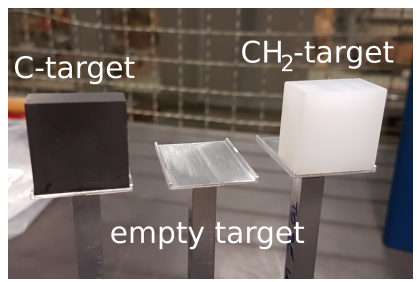
- (A/Z) from $\Delta x \propto R(A,Z)$



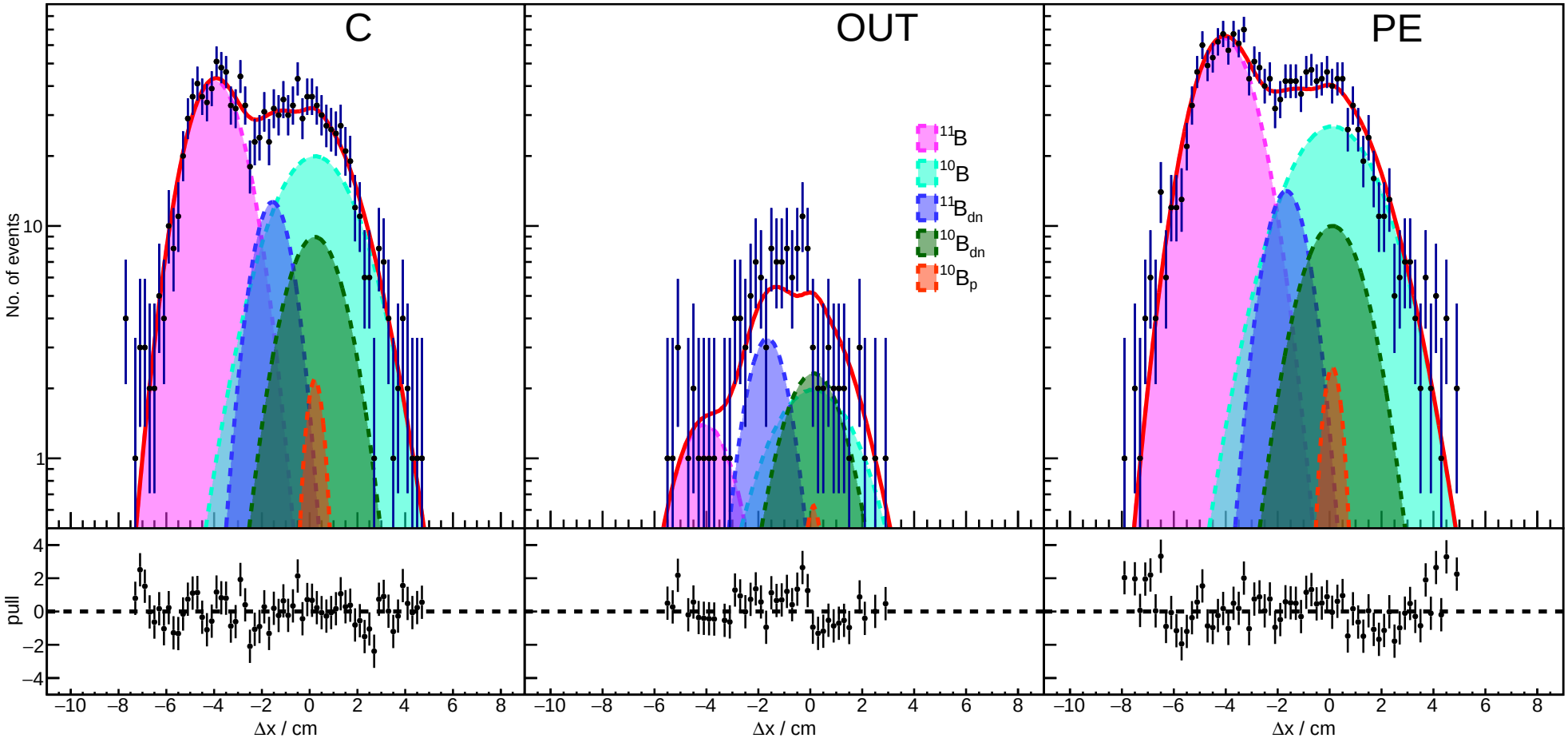
Fragments as measured in the MTPC.

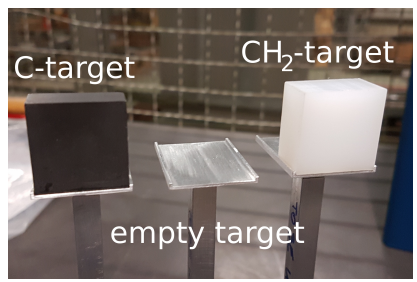
Carbon Isotopes in TPC



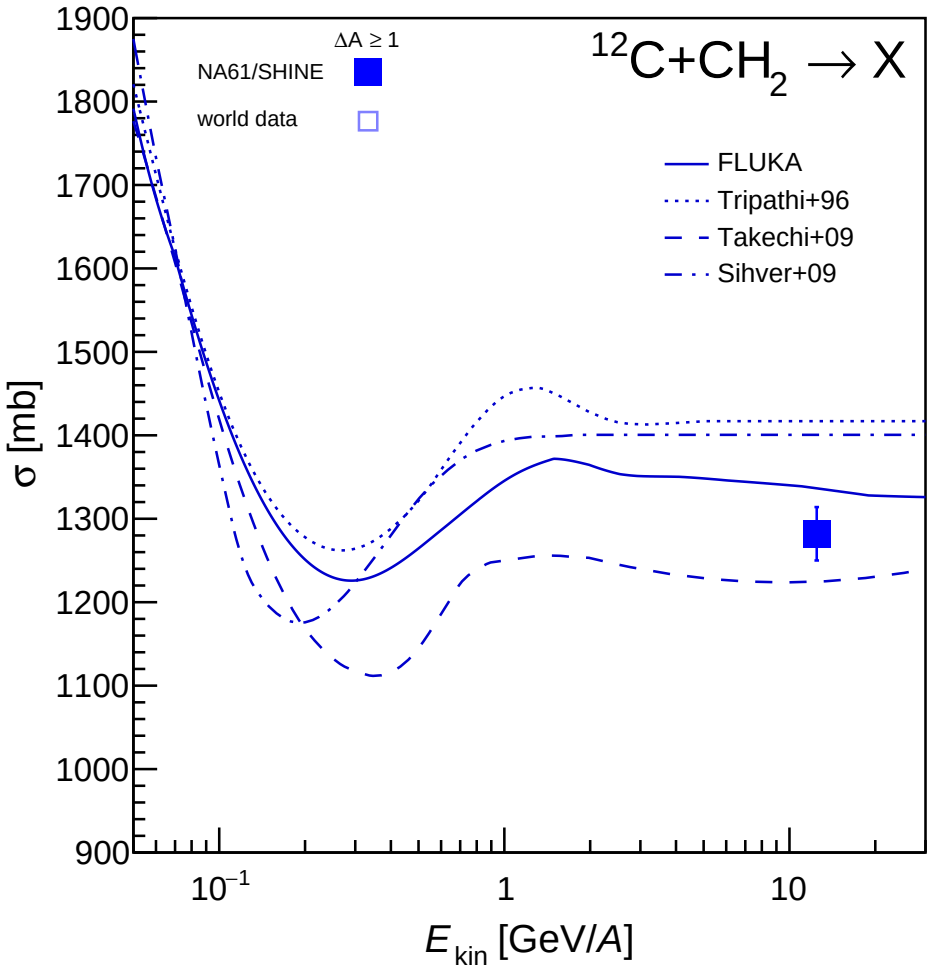


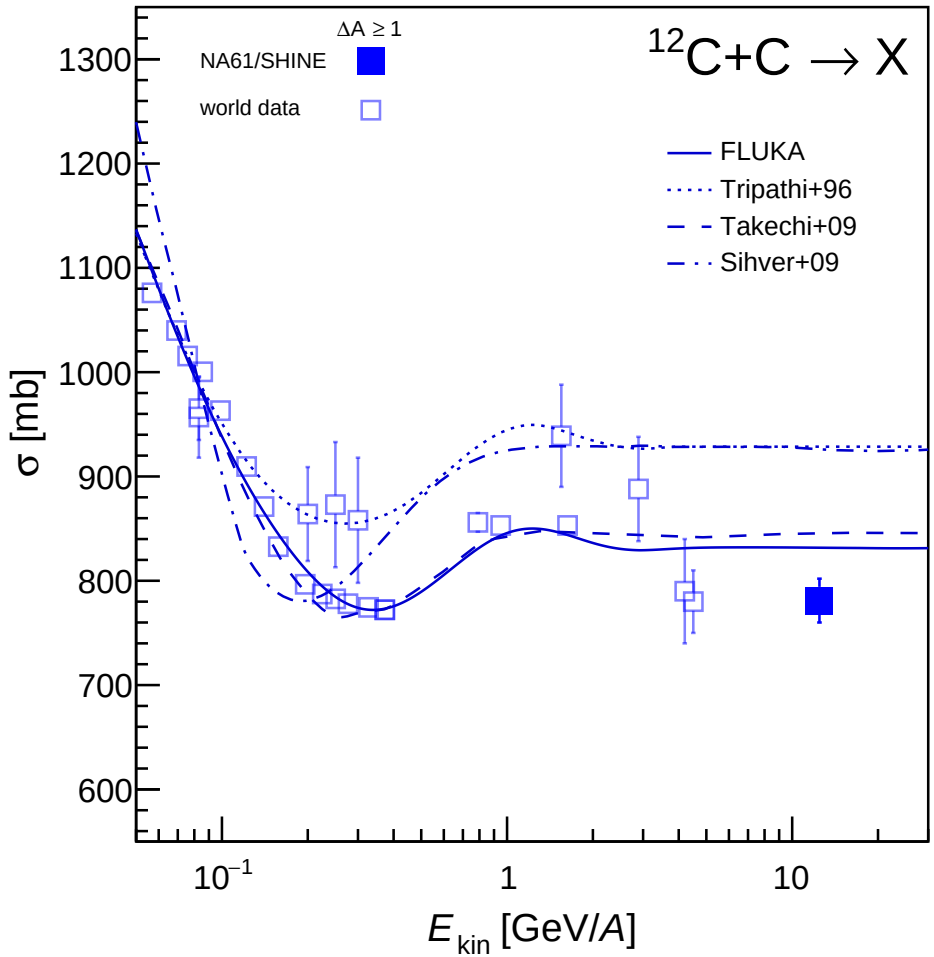
Boron Isotopes in TPC



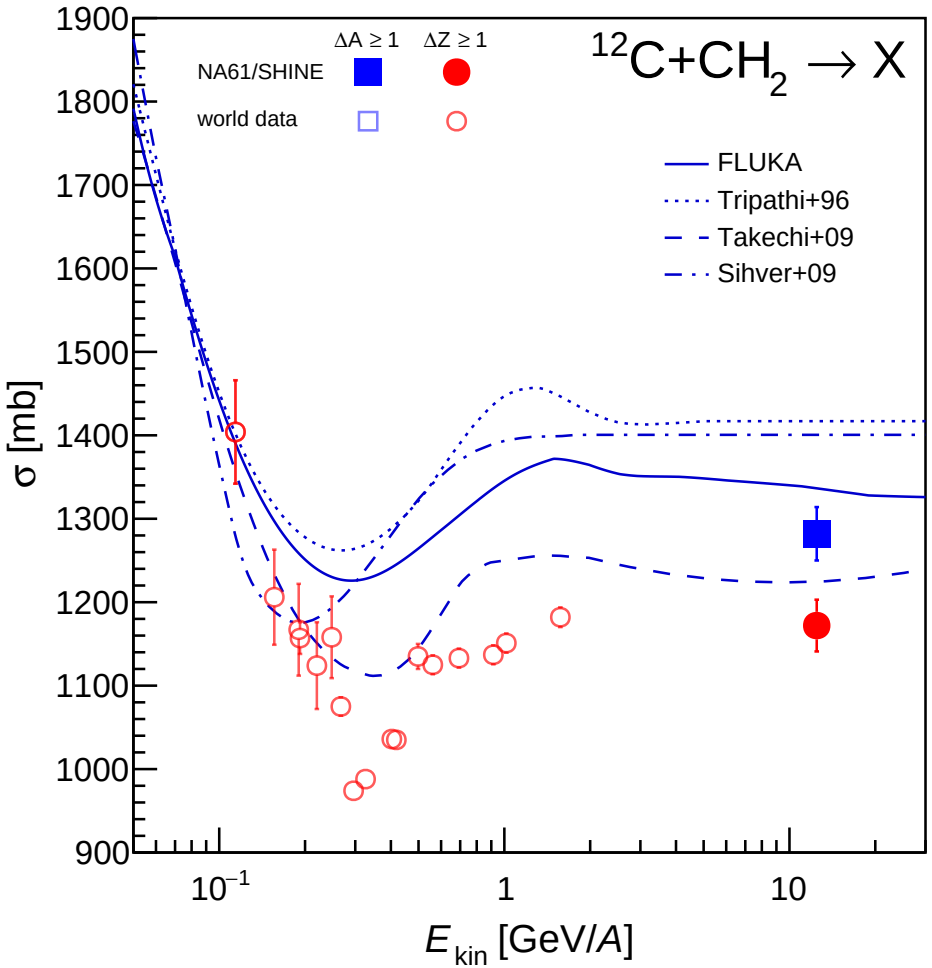


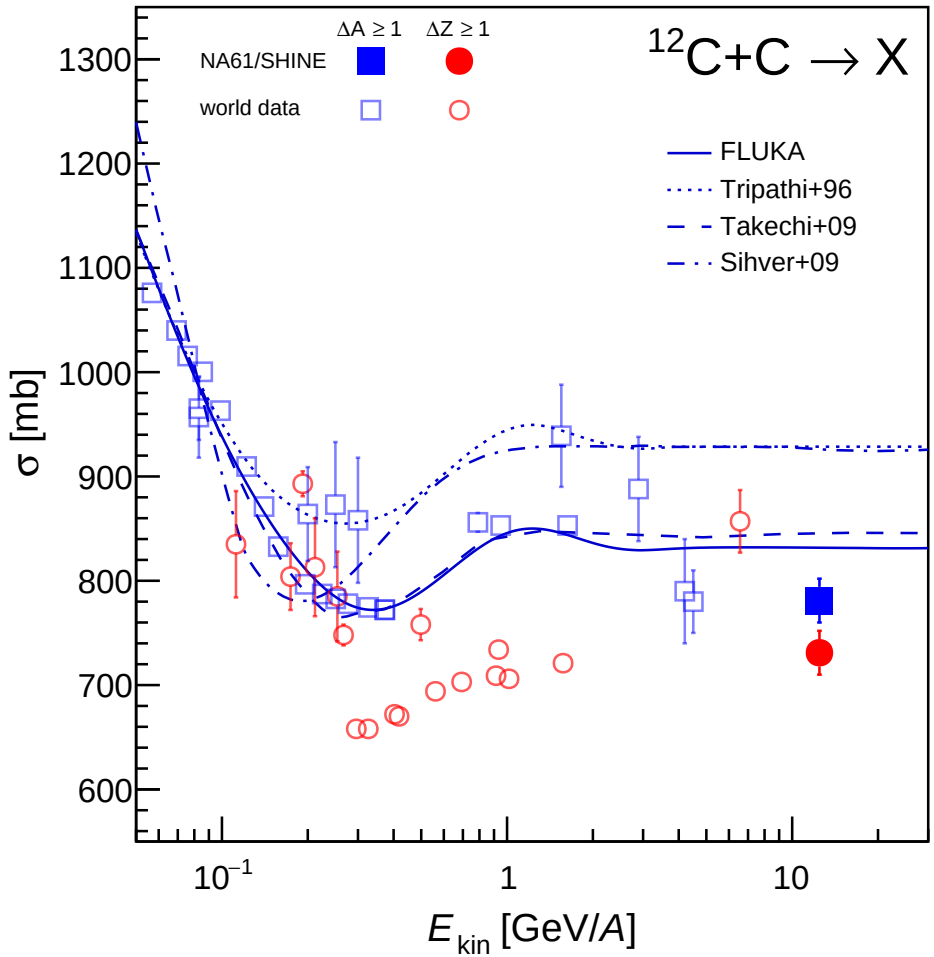
Results: Mass-Changing Cross Section



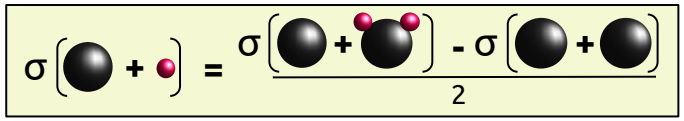


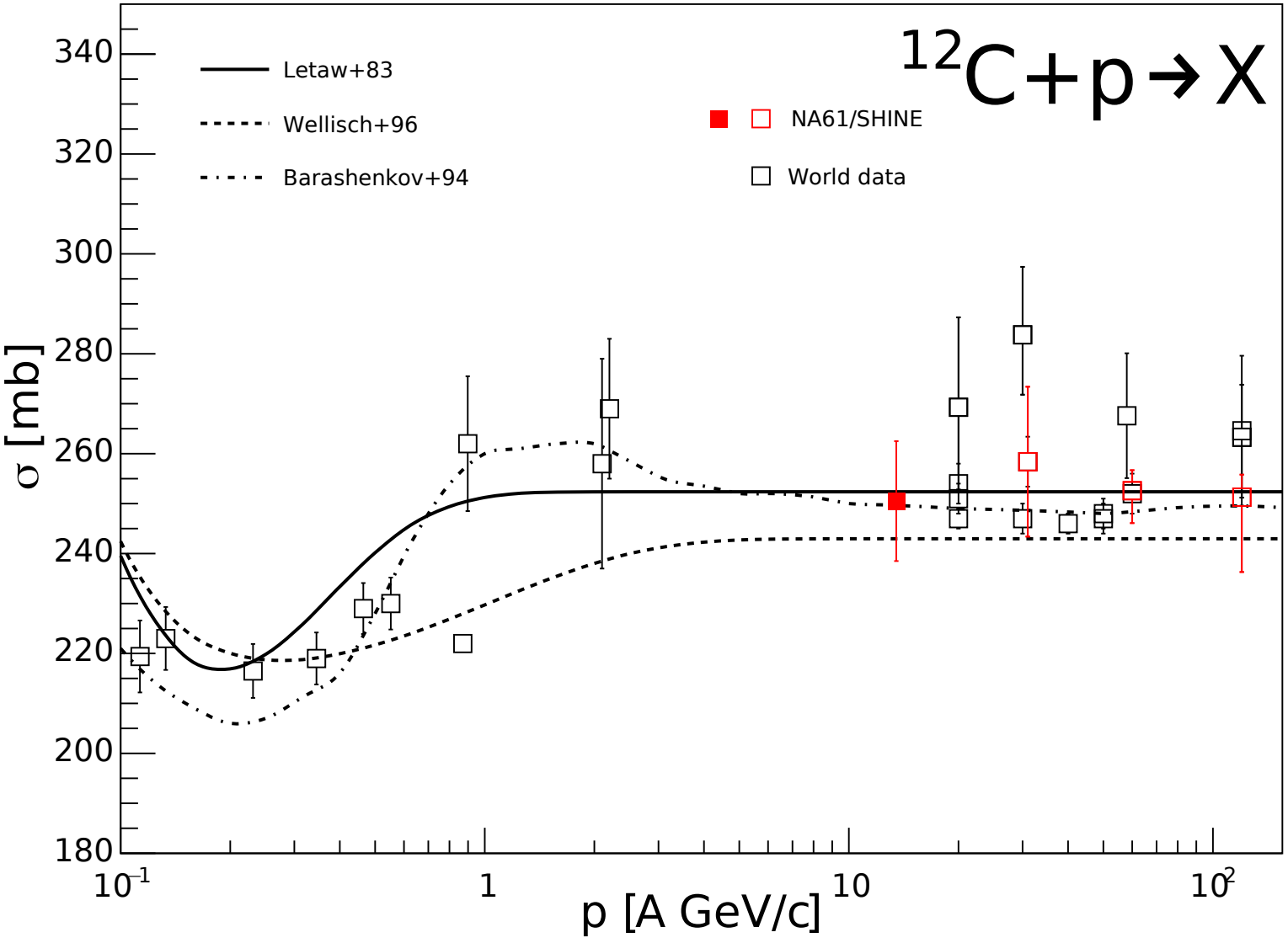
Results: Mass- and Charge-Changing Cross Section



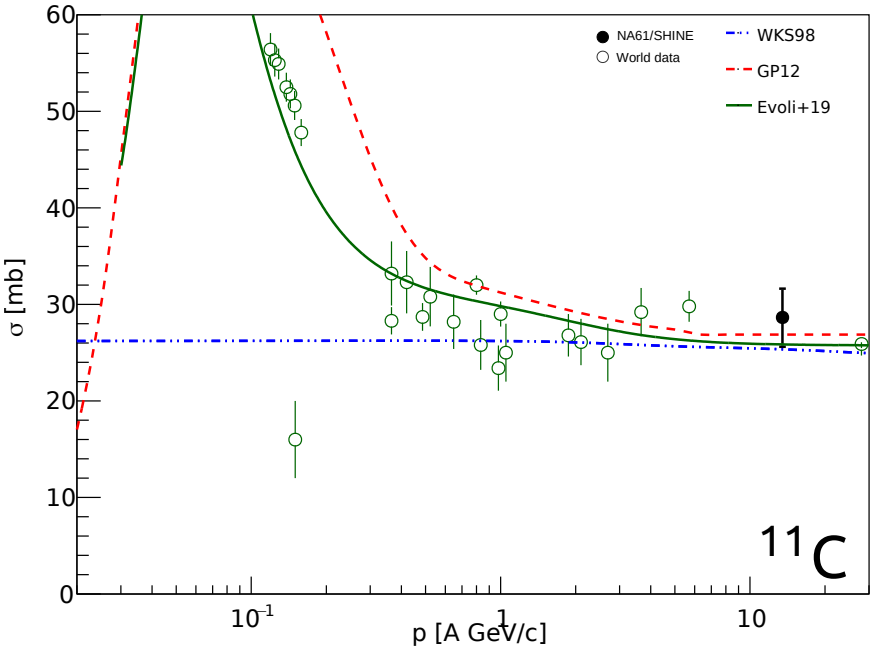


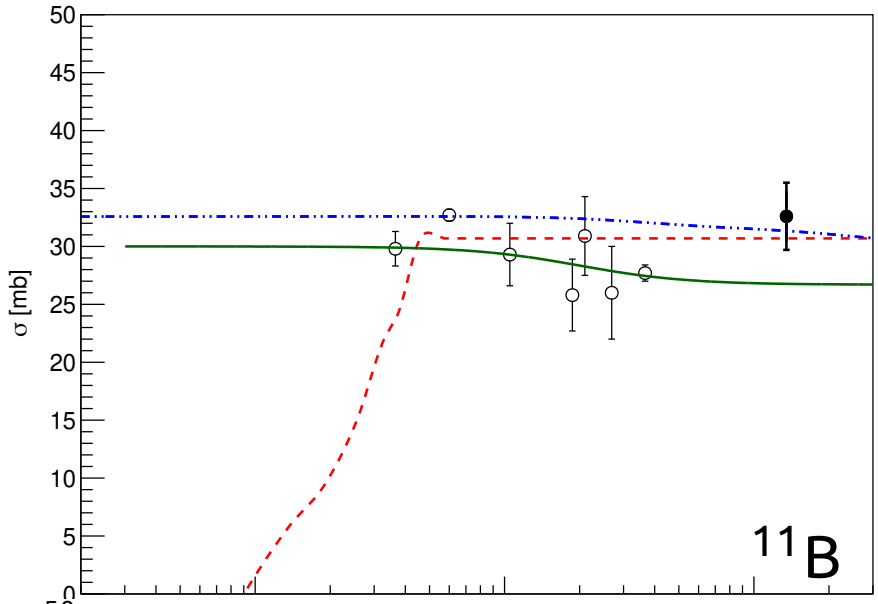
Results: Derived C+p Mass-Changing Cross Section

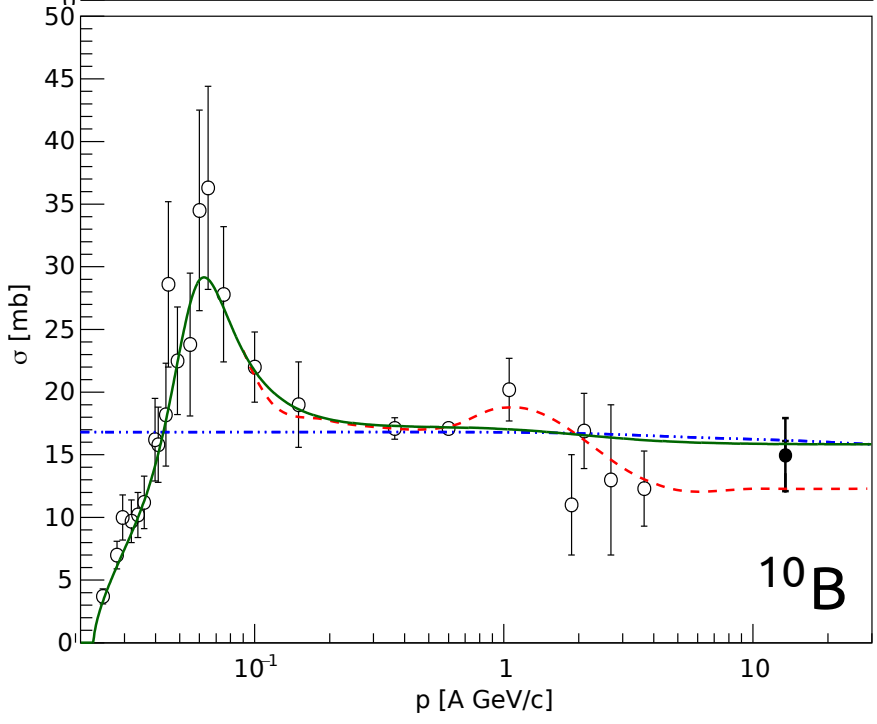




Results: Boron Production in C+p







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

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

- need high-statistics physics run!

Neeraj Amin *Measurement of the Production of Boron from the Fragmentation of Cosmic Ray Carbon with NA61/SHINE* PhD Thesis, KIT, 2024

Planned Fragmentation Measurements in 2024

- one week fragmented Pb beam scheduled end November
- NA61 upgrade: 10-fold increase of readout-rate wrt. pilot run

reactions to be measured:

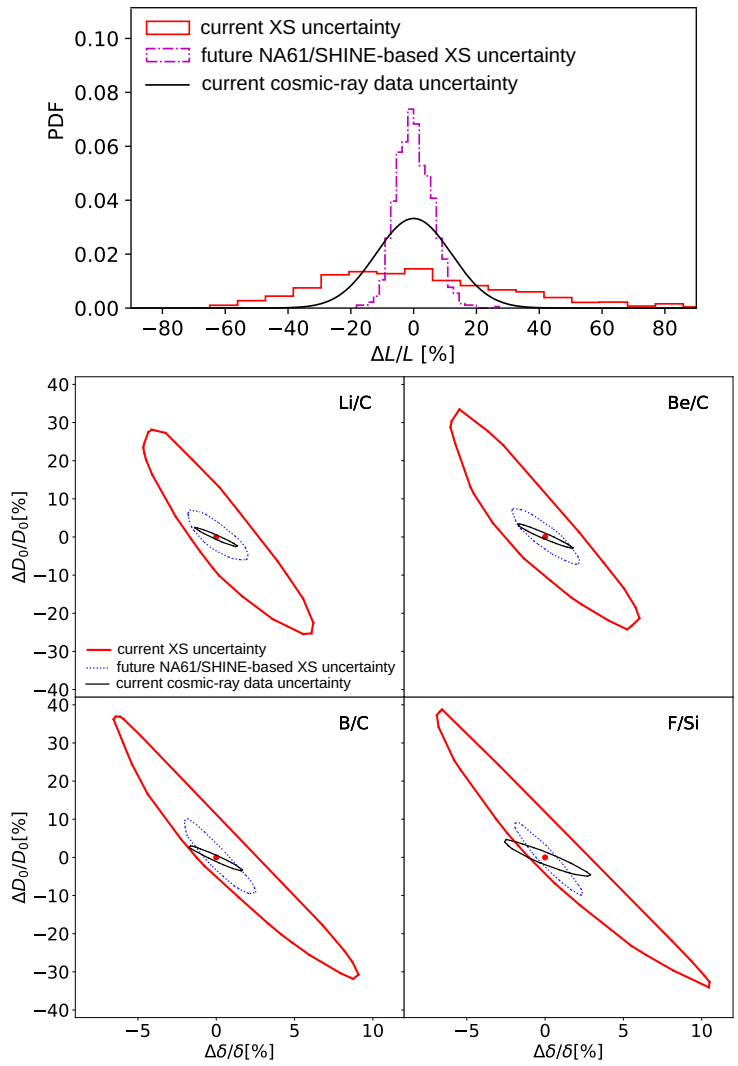
Run A: Li-F Run B: F-Si

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
^{15}N+p	10k	^{22}Ne+p	20k
^{14}N+p	10k	^{27}Al+p	10k
^{10}B+p	5k	^{26}Mg+p	10k
^{13}C+p	5k	^{23}Na+p	10k
^{7}Li+p	5k	^{25}Mg+p	10k
		^{21}Ne+p	10k
		^{32}S+p	5k
		^{29}Si+p	5k

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

based on Genolini+23

expected improvement of CR prop params.:



Summary

CR studies at SPS with NA61/SHINE:

- π^-+C & p+C interactions

  $\rightarrow$ particle production in air showers
- p+p interactions

  $\rightarrow$ nucleon coalescence

  $\rightarrow$ tuning of air shower models
- nuclear fragmentation

  $\rightarrow$ particle production in Galaxy

  $\rightarrow$ air shower fluctuations

Outlook

Upcoming Cosmic-Ray Measurements:

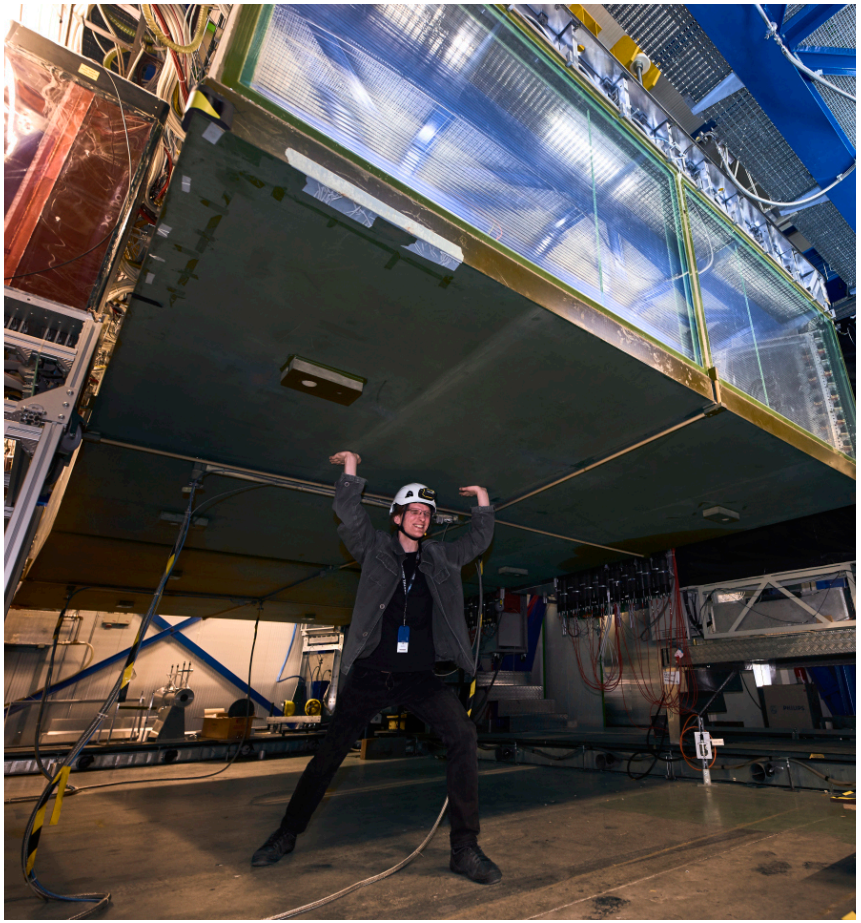
- **2024** fragmented Pb beam

  production of GCR secondaries Li, Be, B
- **2024** $\pi^{\pm}$+C at 158 GeV/c

  π^0 and η production in EAS
- **2025** primary oxygen?

  O+O interactions, CR fragmentation
- **2025** high statistics p+p

  nucleon coalescence, anti-deuterons



inside NA61 (Julien Ordan/CERN)