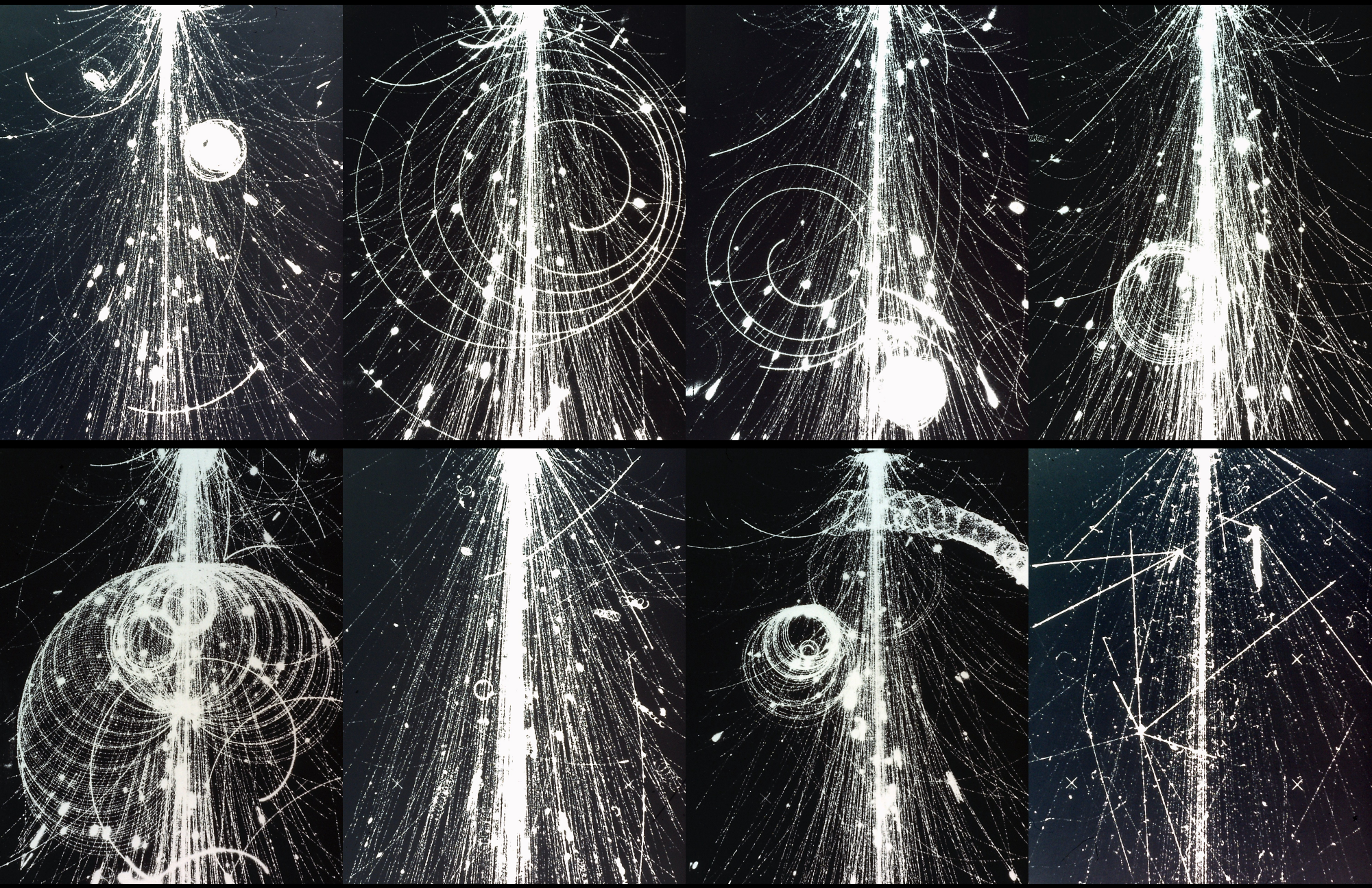
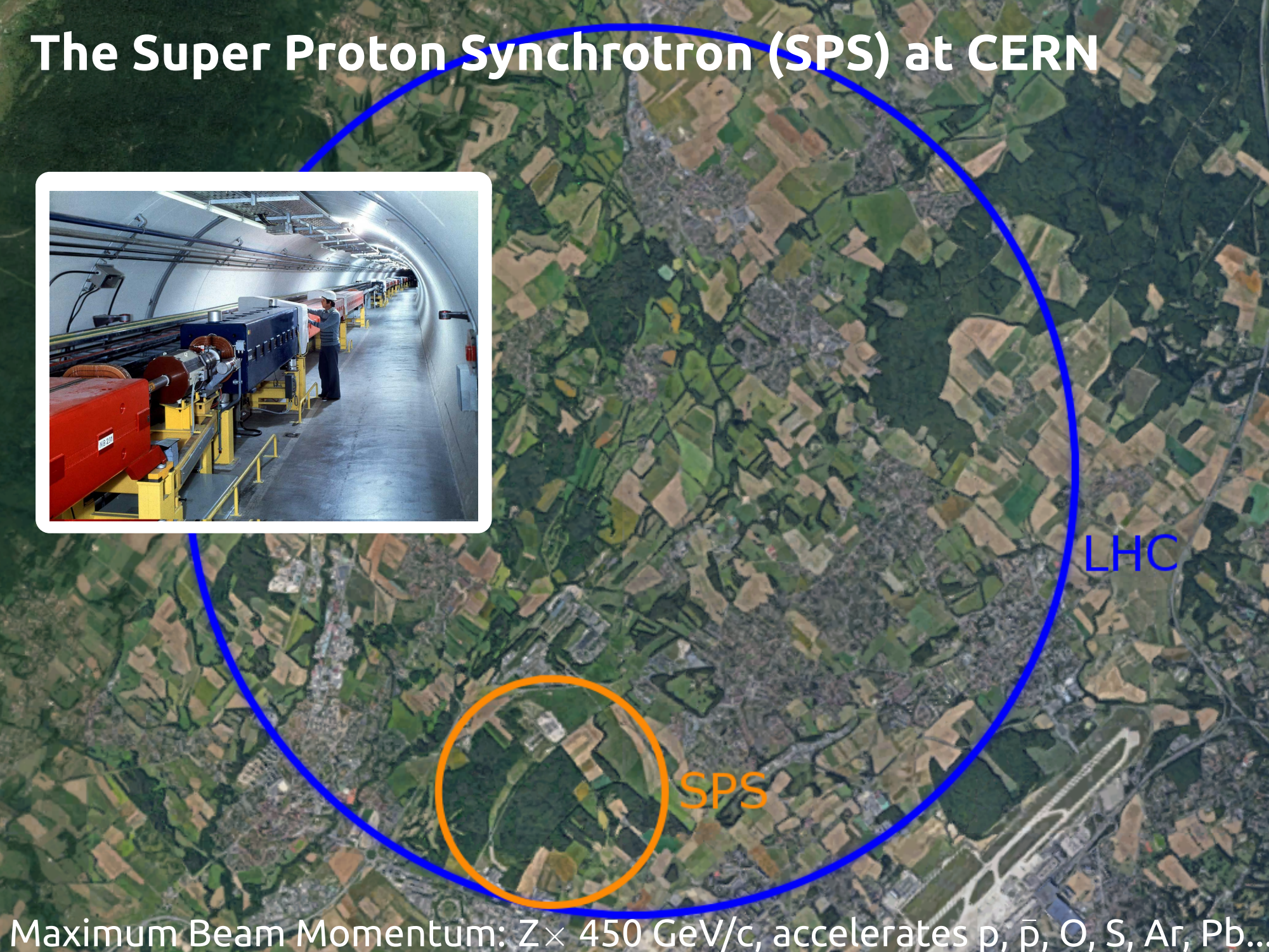
The Cosmic-Ray Program of the NA61/SHINE Facility

M. Unger (KIT) for the NA61/SHINE Collaboration



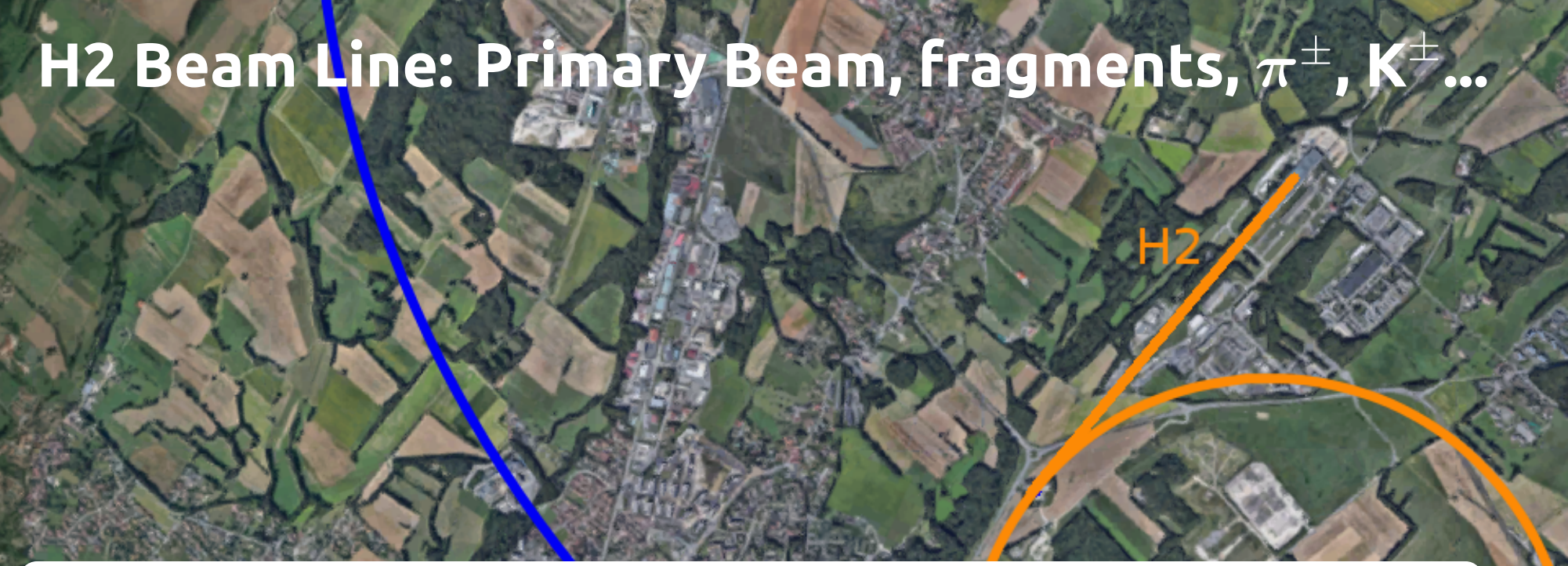
NA35 3.2 TeV O+Pb interactions

The Super Proton Synchrotron (SPS) at CERN

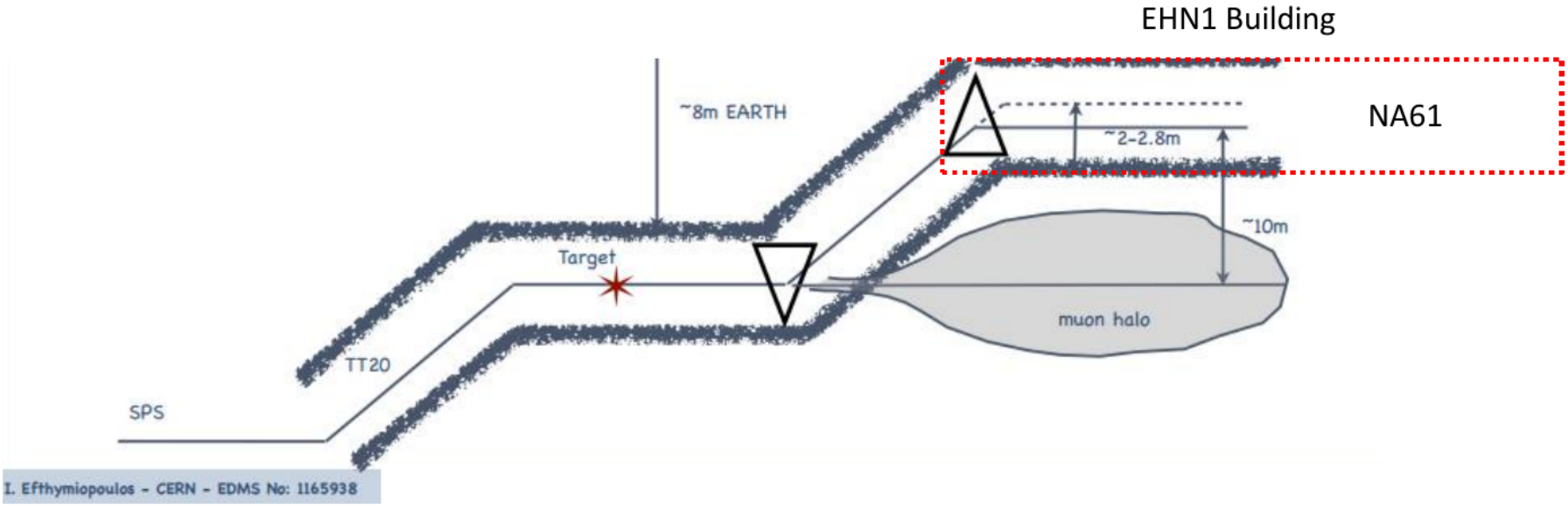


Maximum Beam Momentum: Z$\times$ 450 GeV/c, accelerates p, $\bar{p}$, O, S, Ar, Pb...

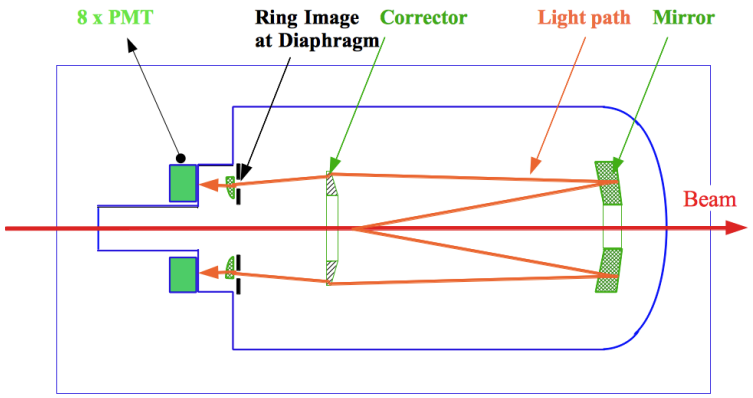
H2 Beam Line: Primary Beam, fragments, $\pi^{\pm}$, $K^{\pm}$...



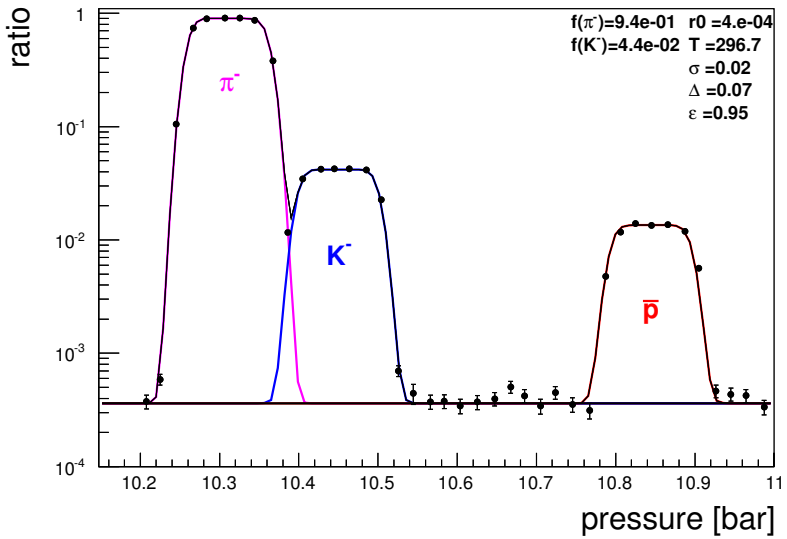
A **precise** (2% dp/p acceptance), robust, flexible magnetic spectrometer



Beam Particle Id (Mass via Cherenkov Angle)



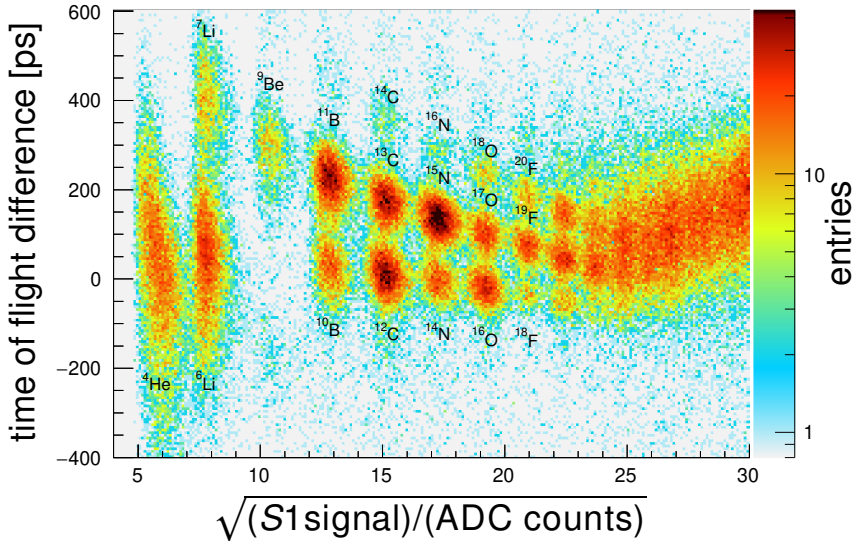
CEDAR (CErenkov Differential counters with Achromatic Ring focus)



pressure scan

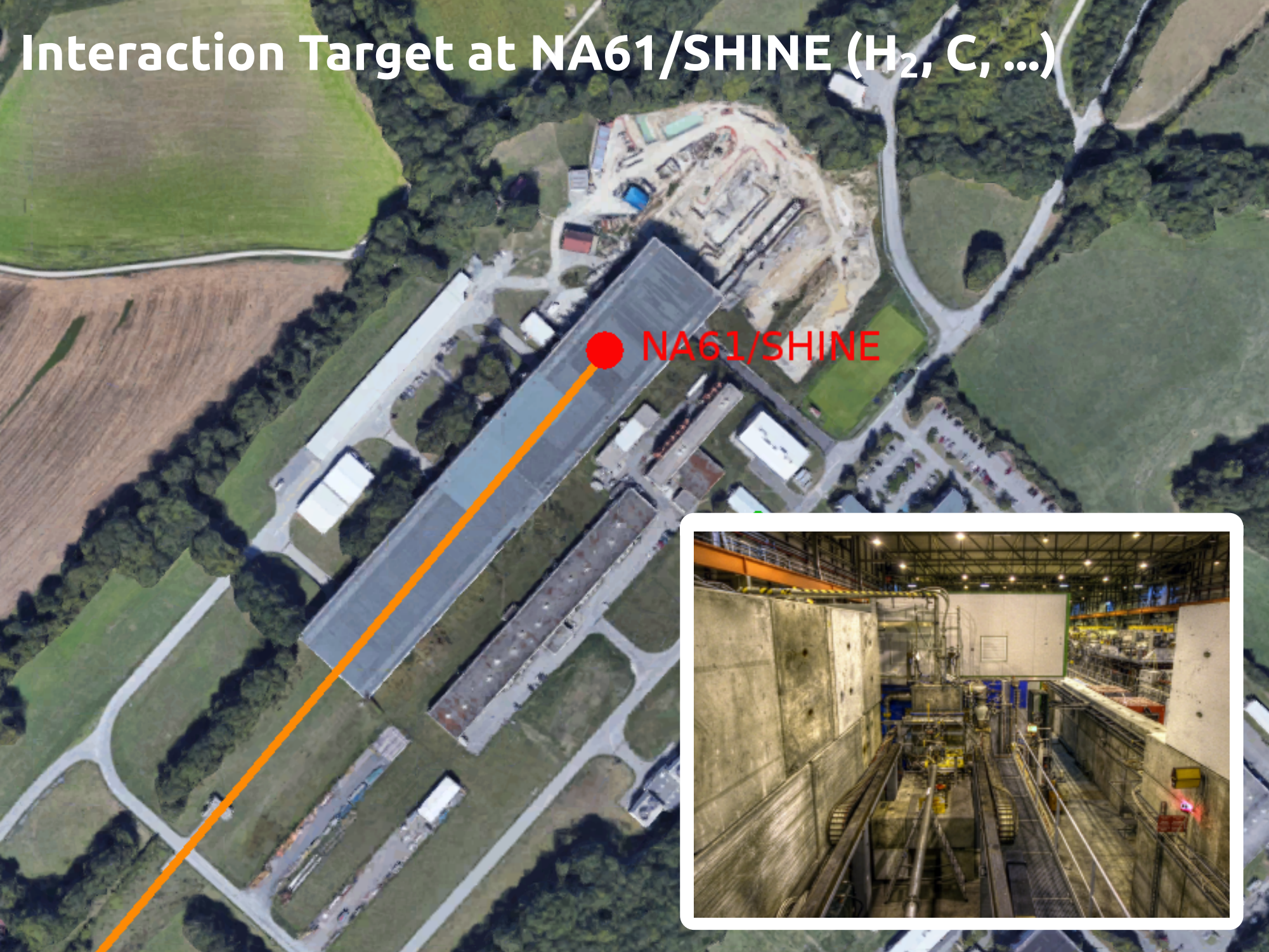
Beam Particle Id (A and Z with ToF, dE/dX, Č)

installation of ToF cable along H2 beam line, Feb 2018

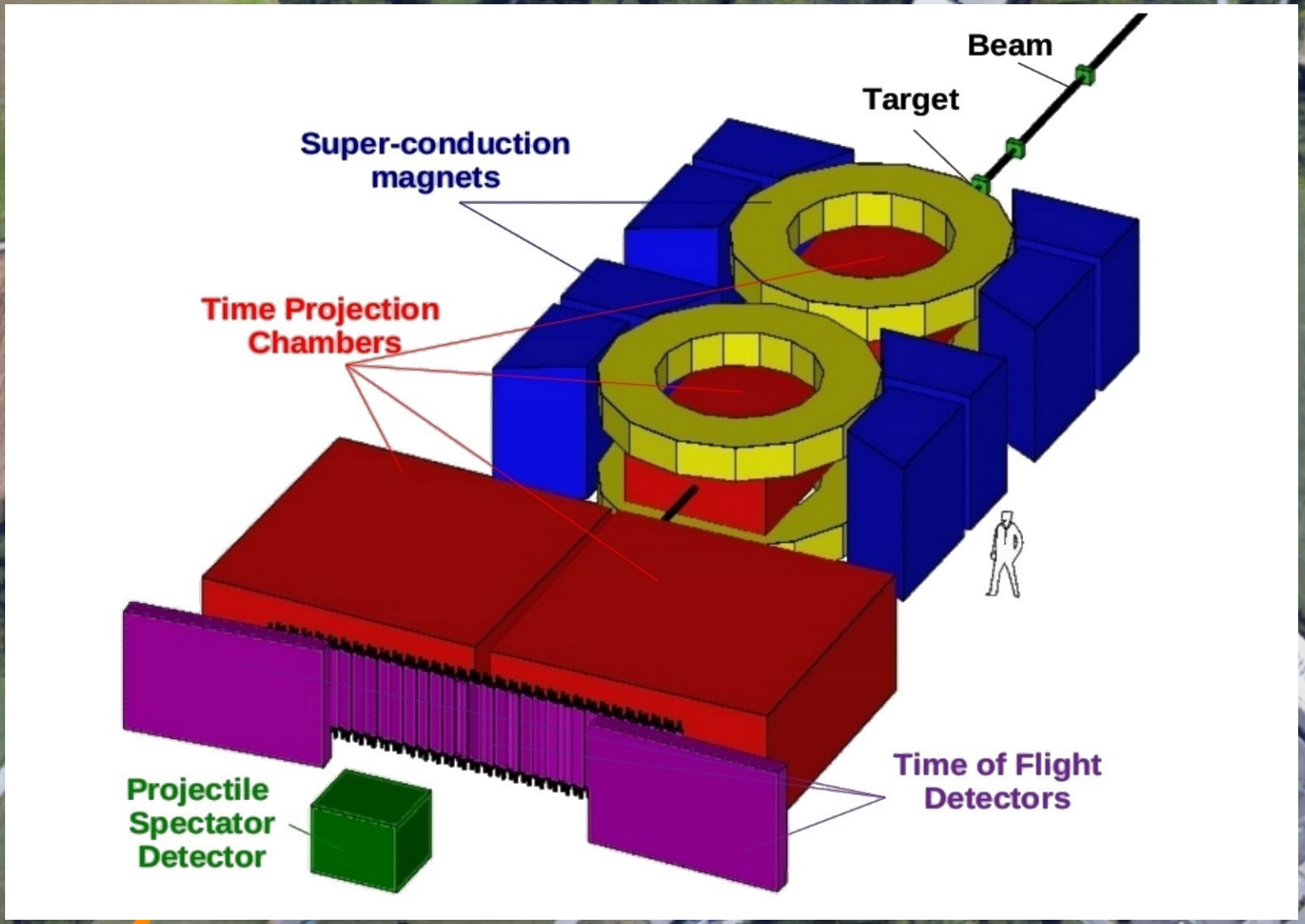


ToF and dE/dx, Fragmentation run Dec 2018

Interaction Target at NA61/SHINE (H_2, C, ...)



Particle Production Measurement at NA61/SHINE



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

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, $\bar{d}$ and $\bar{p}$ Production
    (p+p at 20, 31, 40, 80, 158, 400 GeV/c)
  - Nuclear Fragmentation
    (C+C, C+CH_2 at 13.5 AGeV/c)

PRC **84** (2011) 034604, PRC **85** (2012) 035210, PRC **89** (2014) 025205, EPJ **C74** (2014) 2794, EPJ **C76** (2016) 84, EPJ **C76** (2016) 198, EPJ **C77** (2017) 671
EPJ **C77** (2017) 626, PRD **98** (2018) 052001

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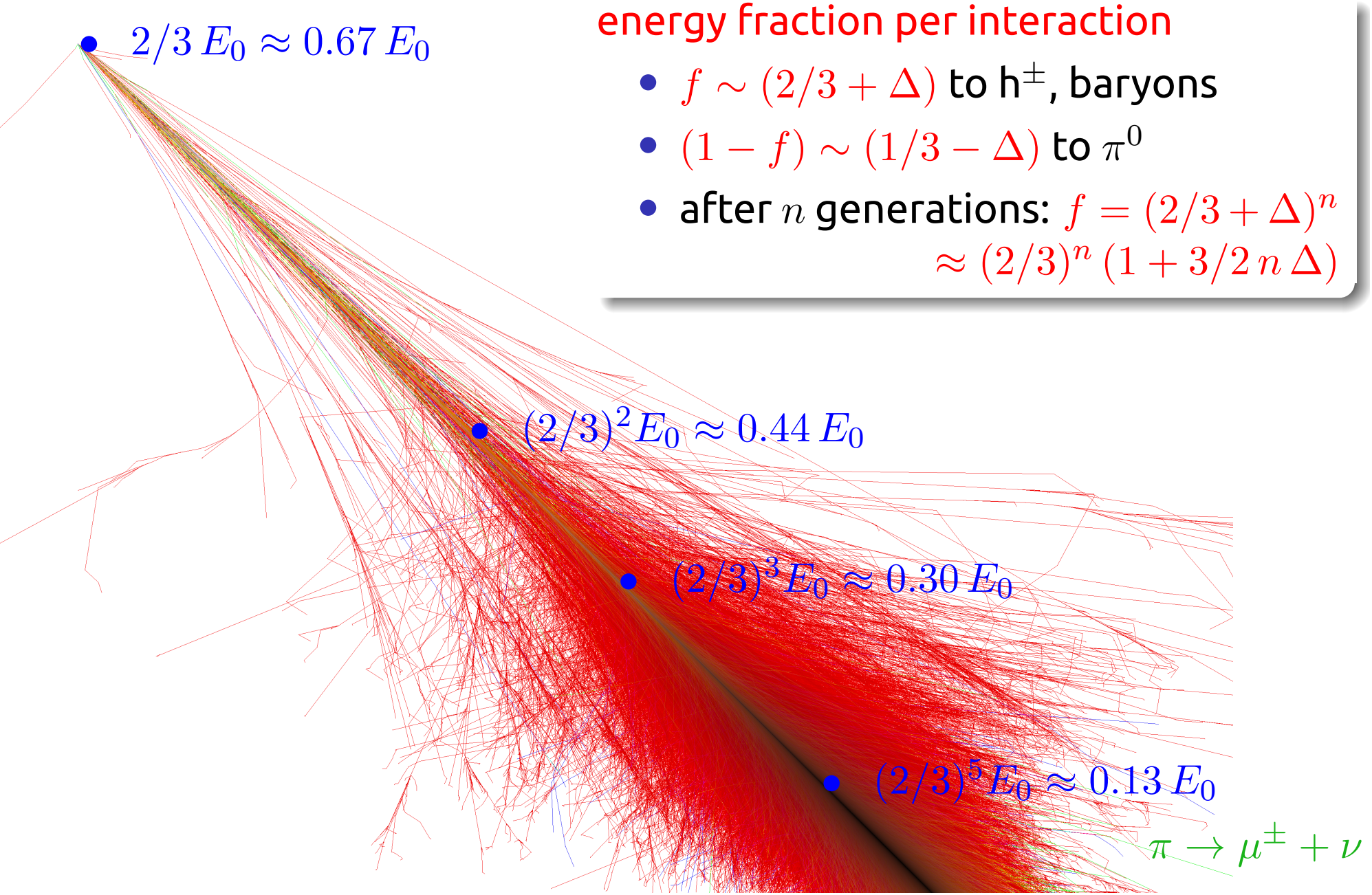
EPJ **C77** (2017) 626, PRD **98** (2018) 052001

Muons in UHE Air Showers

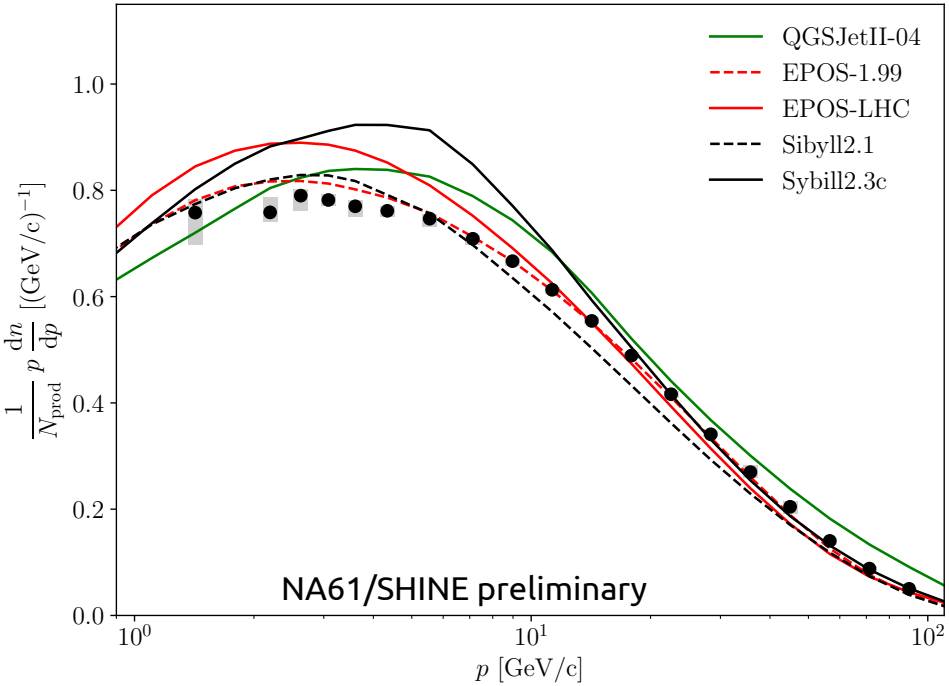


energy fraction per interaction

- $f \sim (2/3 + \Delta)$ to $h^\pm$, baryons
- $(1 - f) \sim (1/3 - \Delta)$ to π^0
- after n generations: $f = (2/3 + \Delta)^n$
  $\approx (2/3)^n\,(1 + 3/2\,n\,\Delta)$

Pion Production in π^--C at 158 GeV/c ("the 2/3")

$$\pi^- + C \to \pi^+ + X$$



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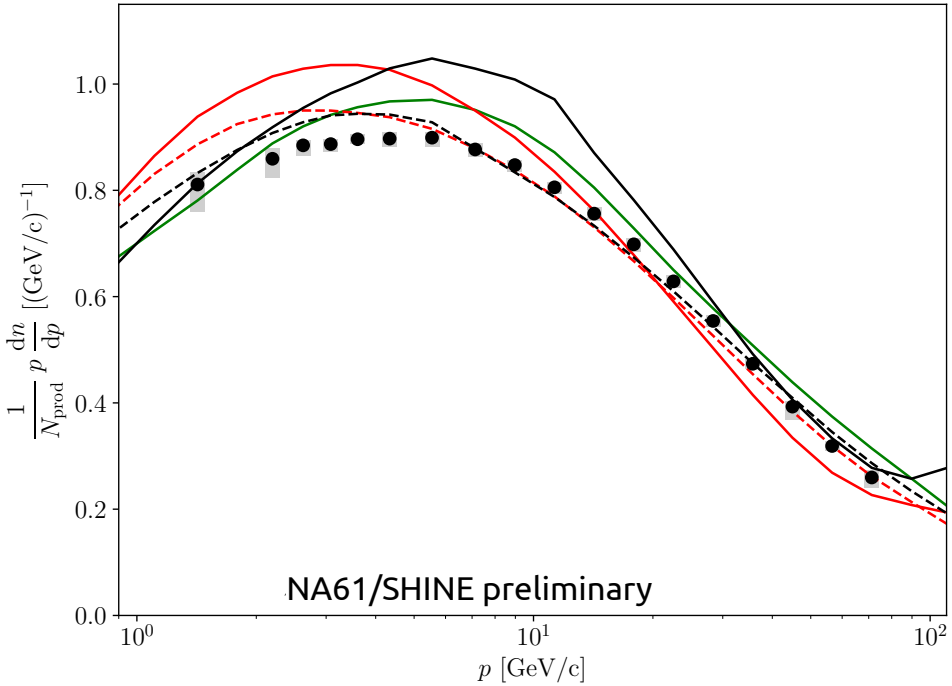
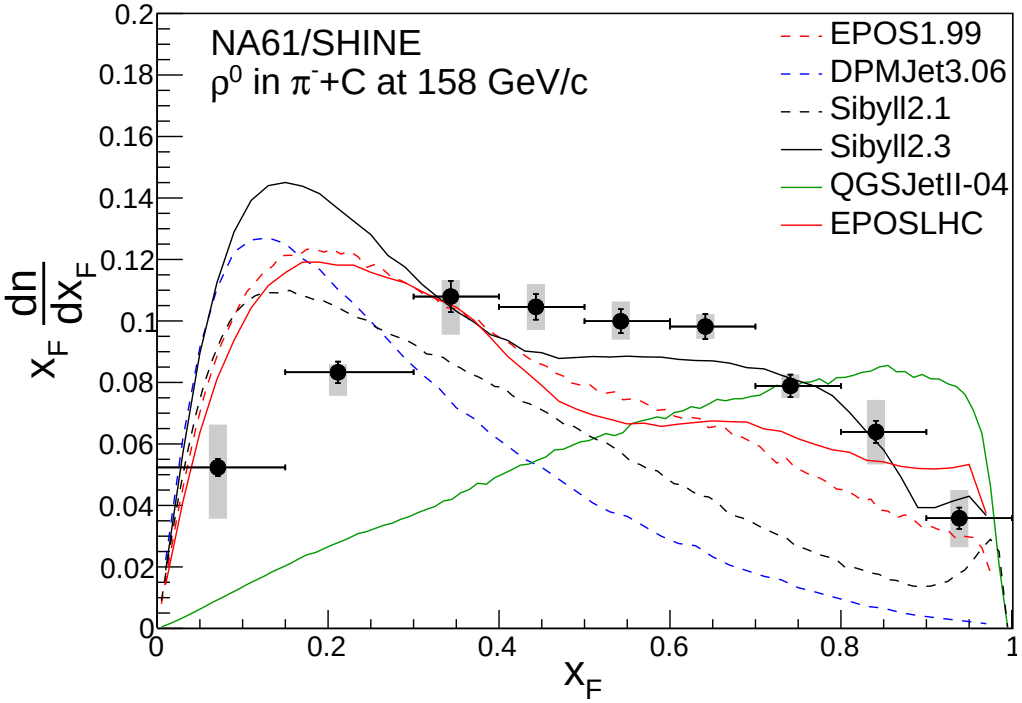


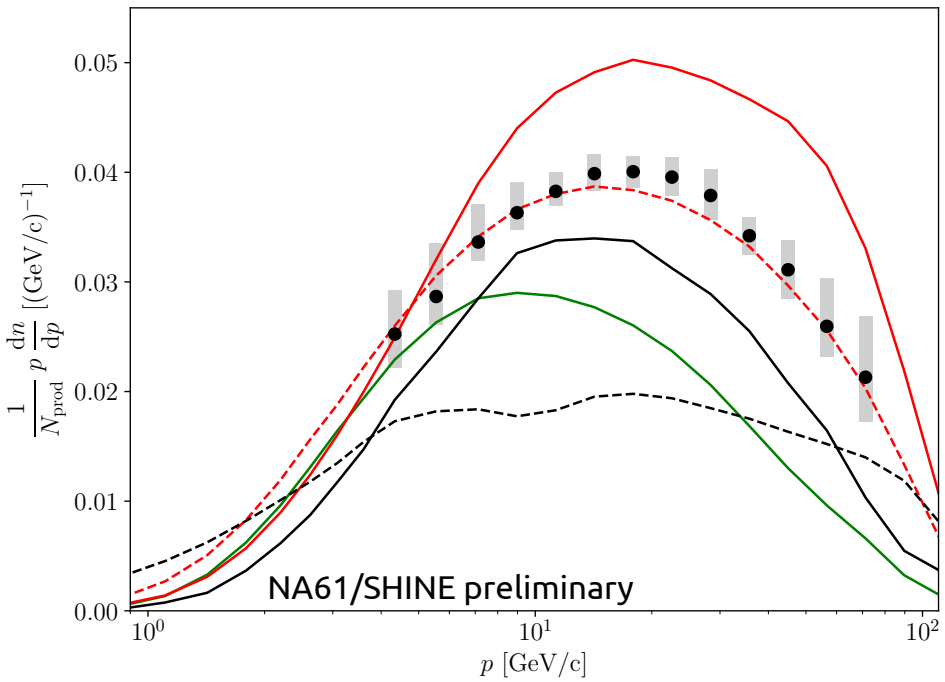
R. Prado for the NA61/SHINE Collaboration, ISVHECRI 2018, arXiv:1810.00642

- $p_{\rm T}$-integrated spectra
- area under curves: $\frac{1}{N_{\rm prod}} \int p \frac{dn}{dp} dp = f_\pi \cdot p_{\rm beam}$

ρ^0 and p̄ Production in π^--C at 158 GeV/c ("the Δ"*)



NA61/SHINE EPJ **C77** (2017) 626



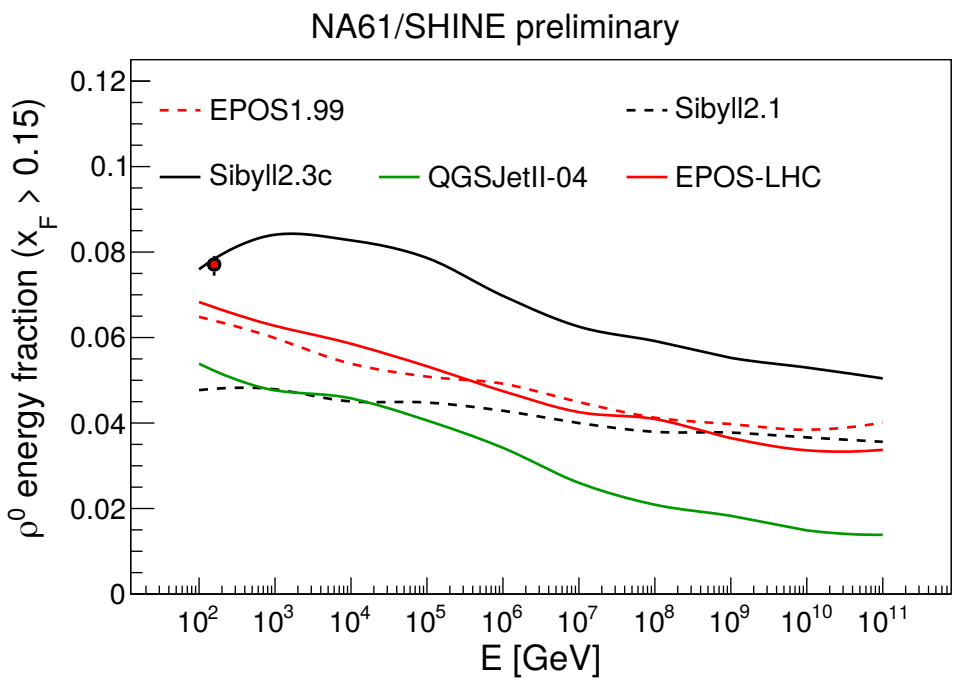
NEW! feeddown-corrected using data

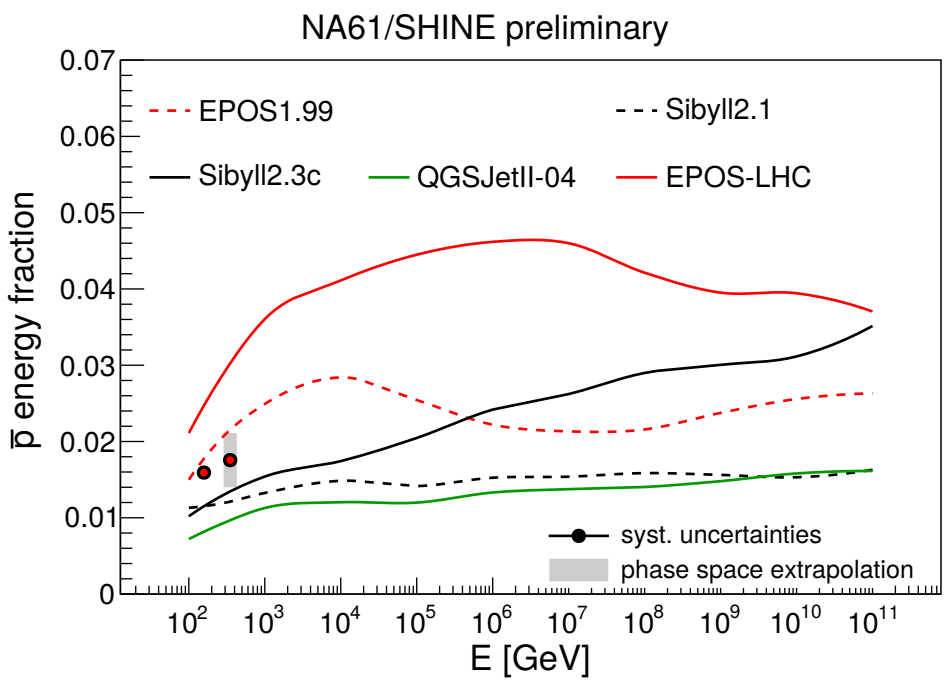
- forward ρ^0 can replace $\pi^0 \to \gamma\gamma$
- p̄ is proxy for baryon production (p, p̄, n, n̄)

* and Λ, $\bar{\Lambda}$, $K^{\pm}$, K^0_S...

ρ^0 and $\bar{p}$ Production in π^--C at 158 GeV/c ("the Δ"*)

energy fraction of ρ^0 and $\bar{p}$:





* and Λ, $\bar{\Lambda}$, $K^{\pm}$, K^0_S...

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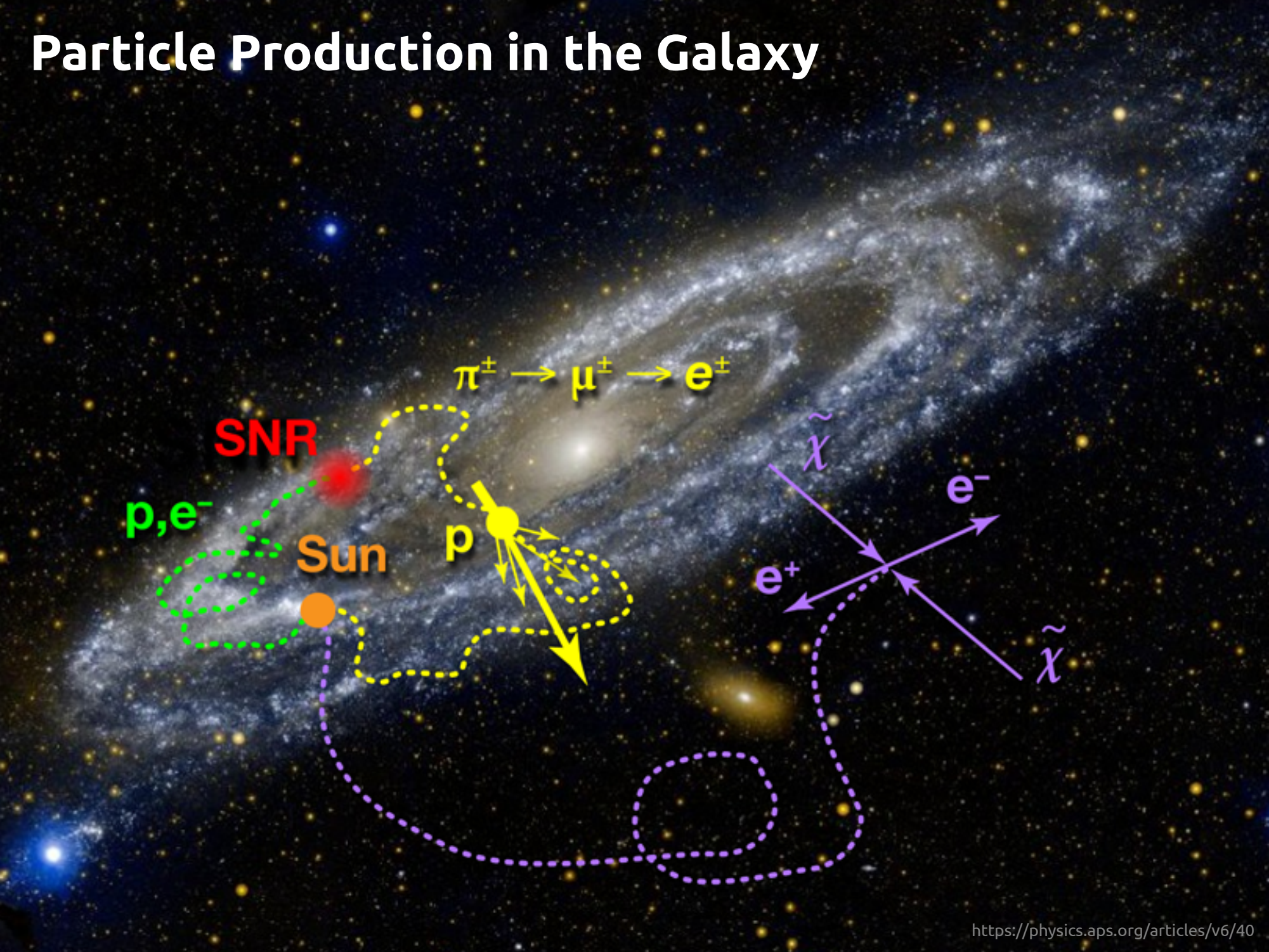
PRC **84** (2011) 034604, PRC **85** (2012) 035210, PRC **89** (2014) 025205, EPJ **C74** (2014) 2794, EPJ **C76** (2016) 84, EPJ **C76** (2016) 198, EPJ **C77** (2017) 671
EPJ **C77** (2017) 626, PRD **98** (2018) 052001

Particle Production in the Galaxy



https://physics.aps.org/articles/v6/40

Particle Production in the Galaxy

- CR-grammage X ("target thickness") from secondary nuclei, e.g.

$$(\mathrm{B/C}) \sim \frac{(1 - e^{-X/\lambda_{\mathrm{prod}}})\, e^{-X/\lambda_B}}{e^{-X/\lambda_{\mathrm{prod}}}}.$$

$$\lambda_{\mathrm{prod}} = \frac{m_p}{\sigma_{\mathrm{prod}}} = m_p \left(\frac{\sum \Psi_i \times \sigma(i + p \to B)}{\sum \Psi_i} \right)^{-1}, \qquad i = \mathrm{C, N, O, \ldots}$$

- $X \ll \lambda_{XB}$ and $X \ll \lambda_B$

$$X \sim (\mathrm{B/C})\, \frac{m_p}{\sigma_{\mathrm{prod}}}$$

- prediction for e.g. anti-protons ($X \ll \lambda_{p\bar{p}}$):

$$(\bar{p}/p) \sim X/\lambda_{p\bar{p}} = (\mathrm{B/C})\, \frac{\sigma_{p\bar{p}}}{\sigma_{\mathrm{prod}}}$$

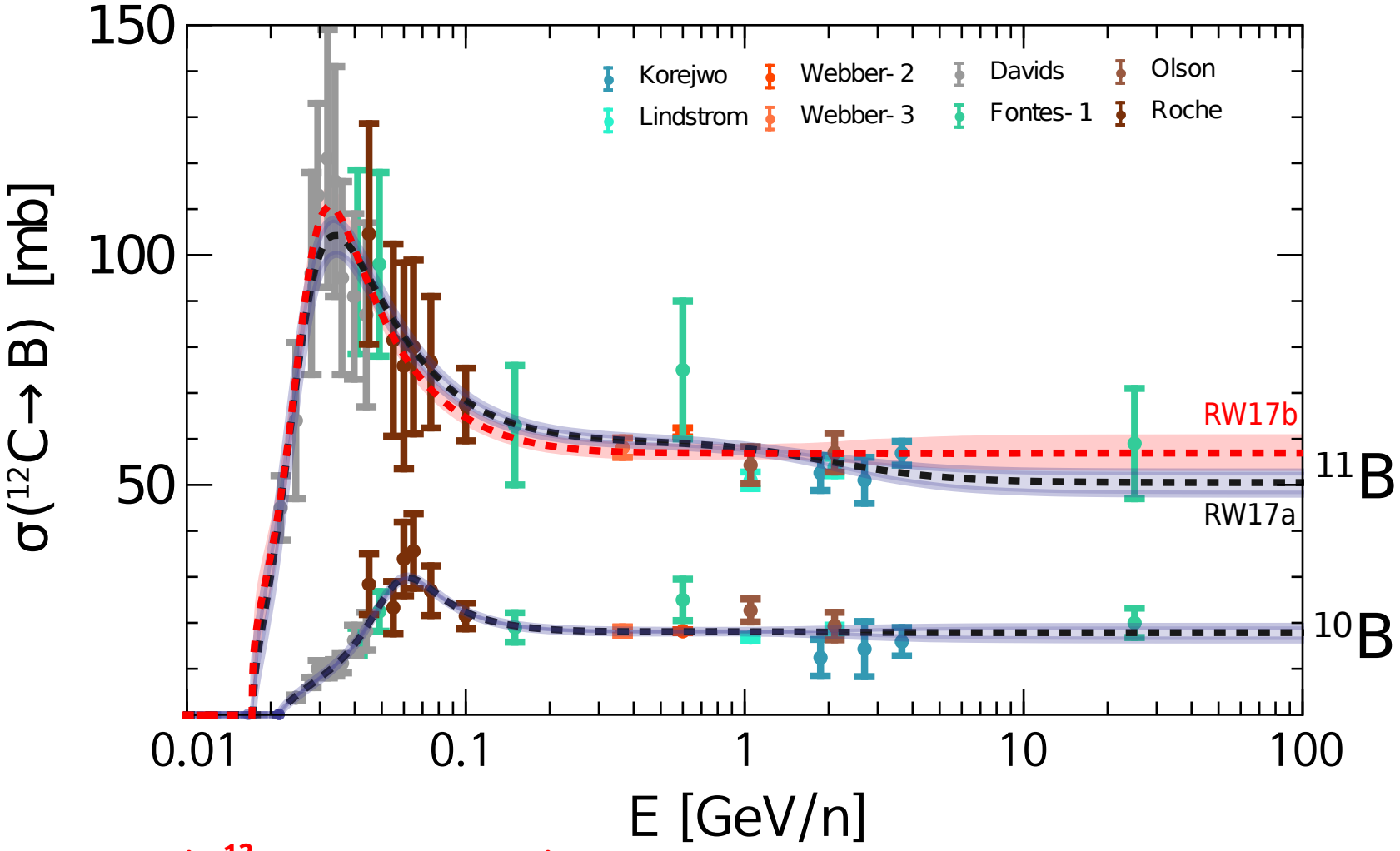
- relative uncertainty $\delta_X = \delta(X)/X$

$$\delta^2_{\bar{p}/p} \sim \delta^2_{(\mathrm{B/C})} + \delta^2_{\sigma_{p\bar{p}}} + \delta^2_{\sigma_{prod}} \sim \underline{0.03^2 + 0.2^2 + 0.2^2}$$

Uncertainties of Fragmentation Cross Sections

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

adapted from Reinert&Winkler, arXiv:1712.00002

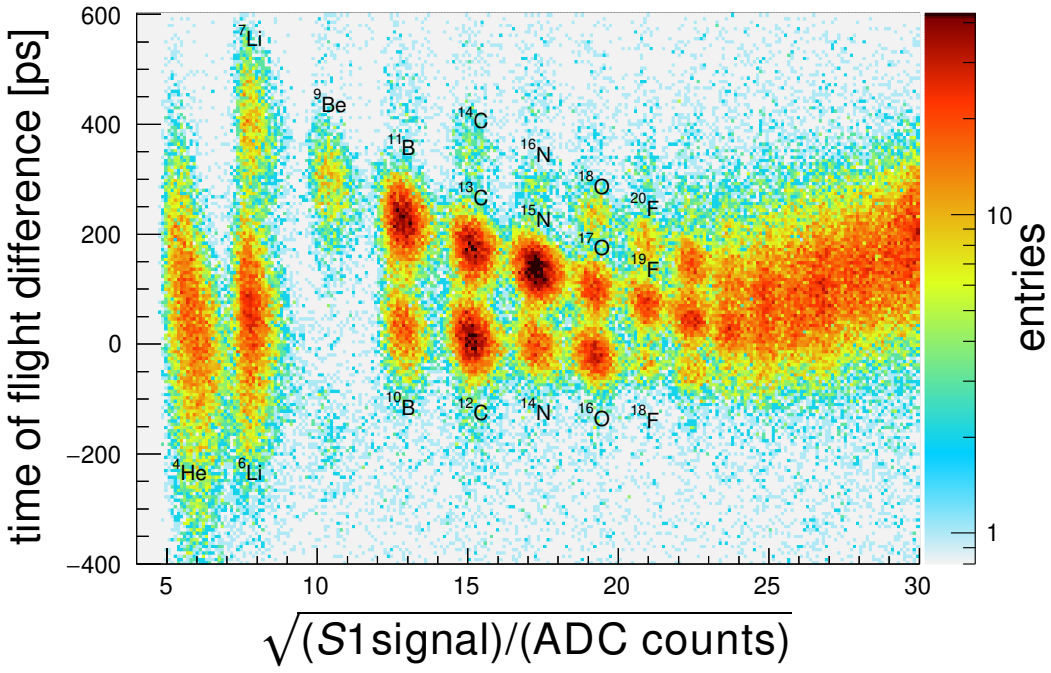


asymptotic ^{12}C→B cross section:

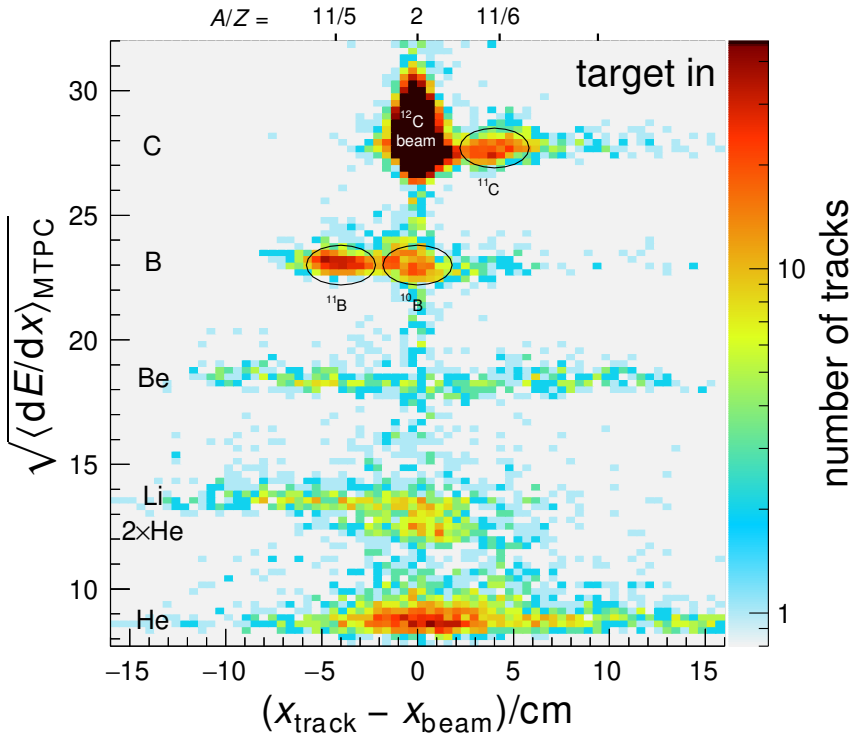
61.0 mb (WSKR03) (68.6±2.6) mb (RW17a), (75.8± 4.2) mb (RW17b)

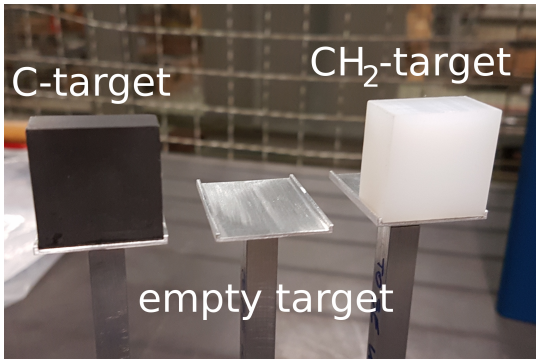
NA61/SHINE Pilot Run on Fragmentation, Dec 2018

SPS beam-fragment identification



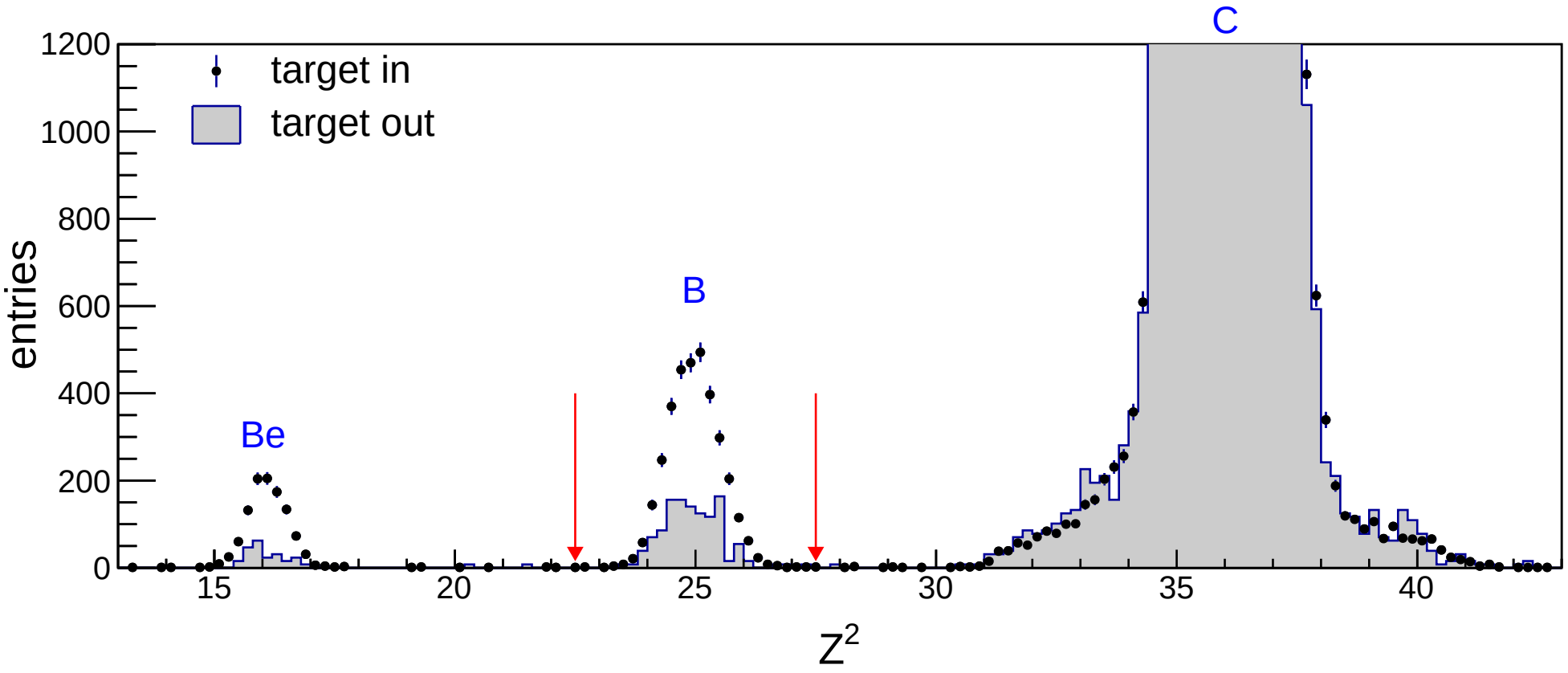
reaction-fragment identification





- 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

Preliminary Result on Direct* ^{10}B + ^{11}B Production

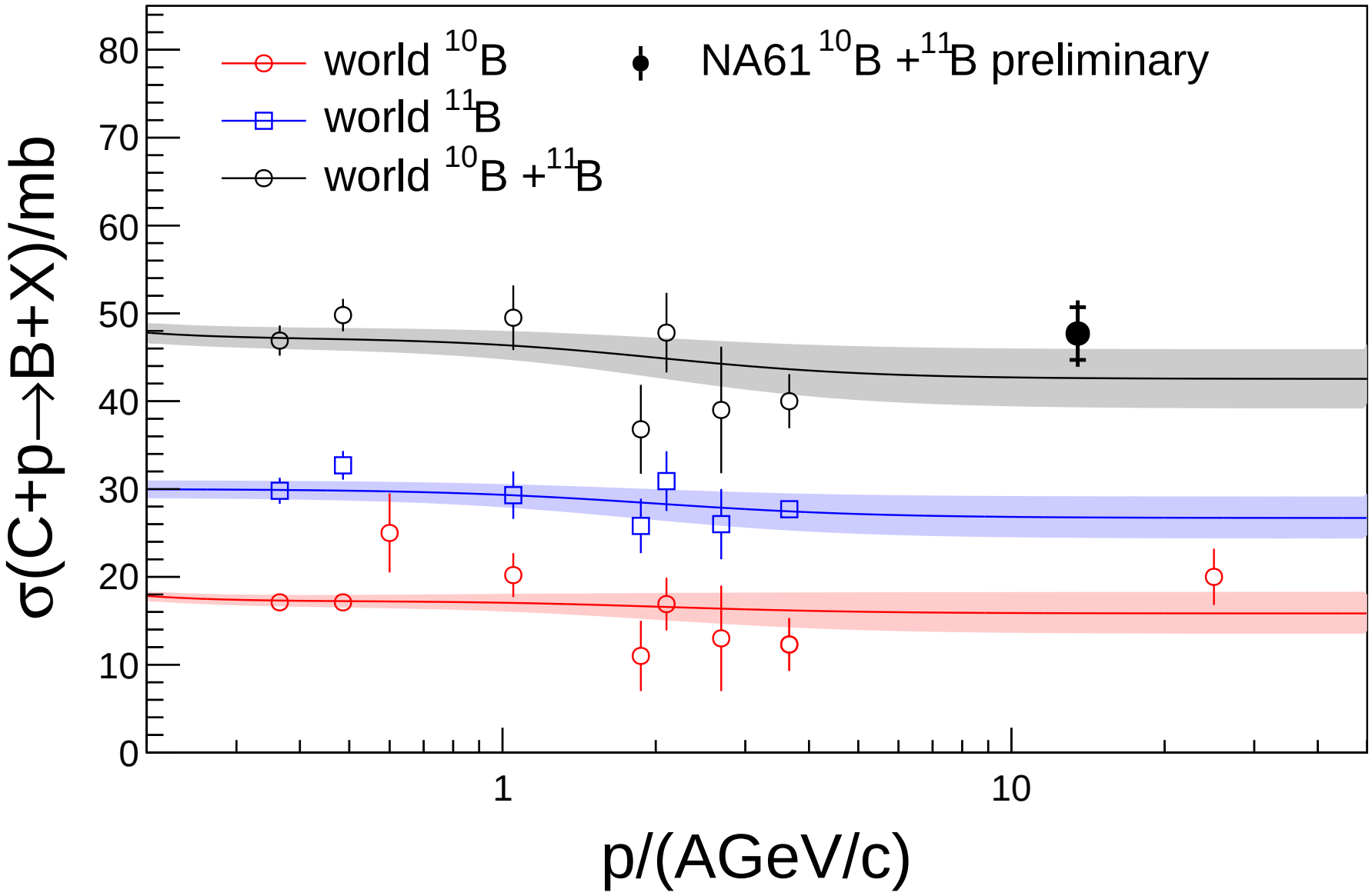


$\sigma(\mathrm{C} + \mathrm{p} \rightarrow \mathrm{B})$ = 47.7 $\pm$ 3.0 (stat.) $\pm$ 2.3 (syst.) mb

* without "ghost nucleus" ^{11}C

F. Sutter, Master Thesis KIT, Sept. 2019

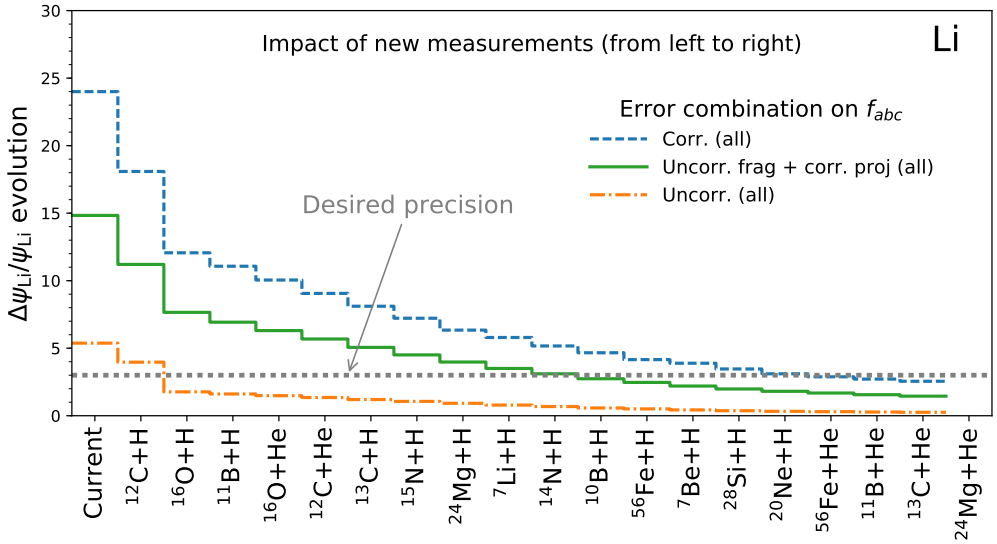
Preliminary Result on Direct $^{10}B + ^{11}B$ Production

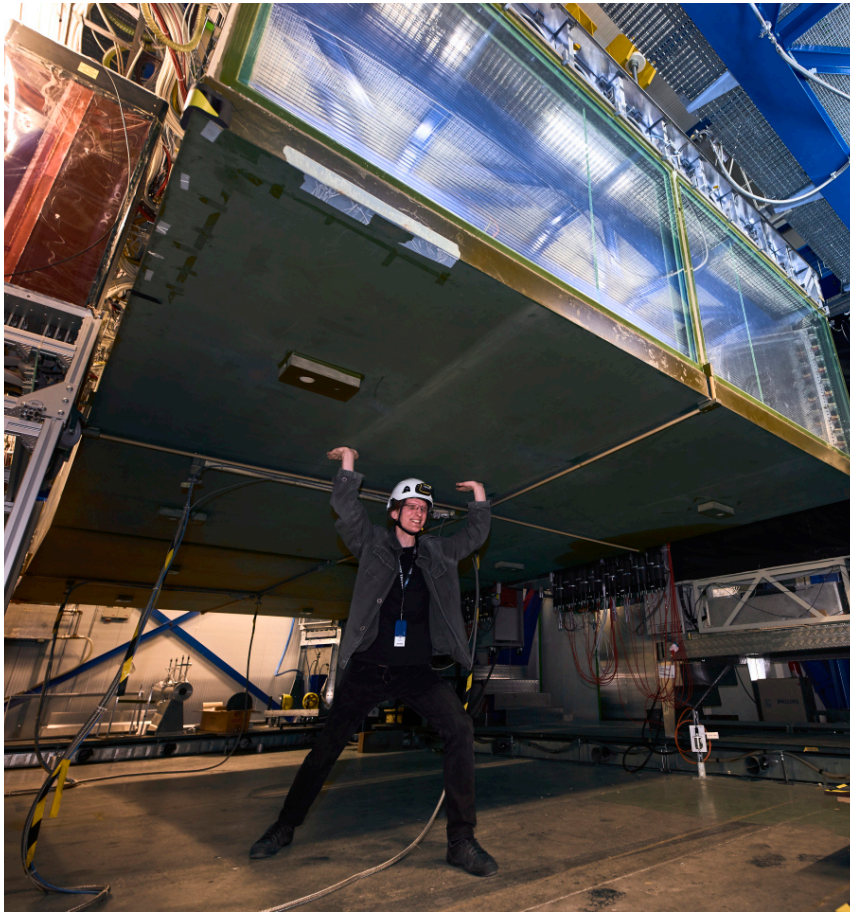


Fit: Evoli+19, Data: Korejwo+02, Korejwo+99, Webber+98, Webber90, Olson+83, Fontes+77

Summary and Outlook

- precise spectra of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, ρ^0, ω, K^{*0}, K^0_S, Λ, $\bar{\Lambda}$ in π^-+C interactions at 158 and 350 GeV/c for UHECR EAS
- first result from pilot run on nuclear fragmentation for GCR
- NA61/SHINE plans for $\geq$ 2021:
  - TPC upgrade: increase readout rate from 80 Hz to 1000 Hz
  - high-statistics fragmentation data, all channels relevant for Li, Be, B, C, N GCRs





inside NA61 (Julien Ordan/CERN)

Genolini et al, PRC **98** (2018) 034611