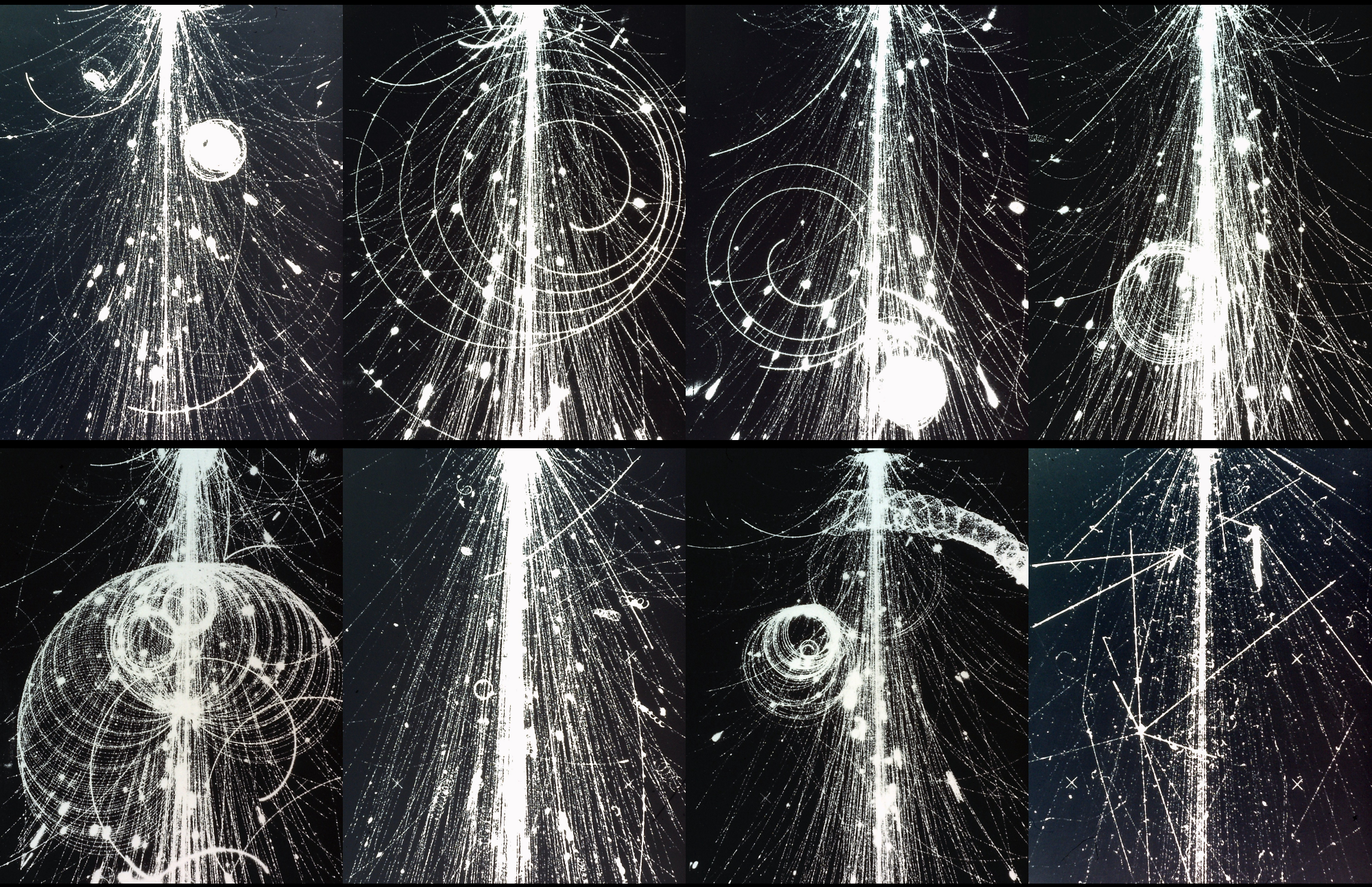
Measurements of Relevance for Cosmic-Ray Physics from NA61/SHINE

Michael Unger (KIT) for the NA61/SHINE Collaboration



NA35 3.2 TeV O+Pb interactions

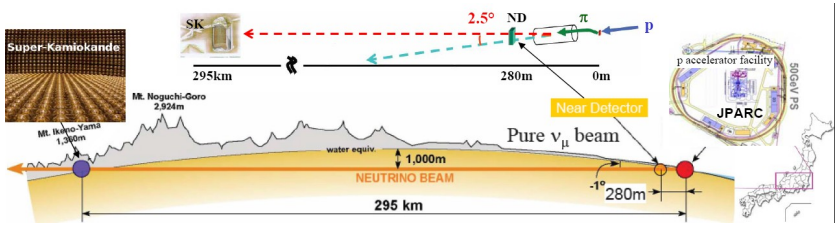
Workshop on the tuning of hadronic interaction models, Wuppertal, January 2024

NA61/SHINE

≈ 140 physicists from 14 countries and 28 institutions

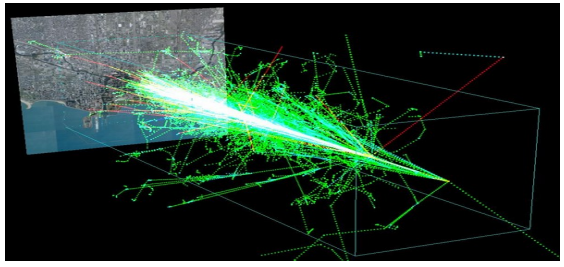
Strong interactions physics

- 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



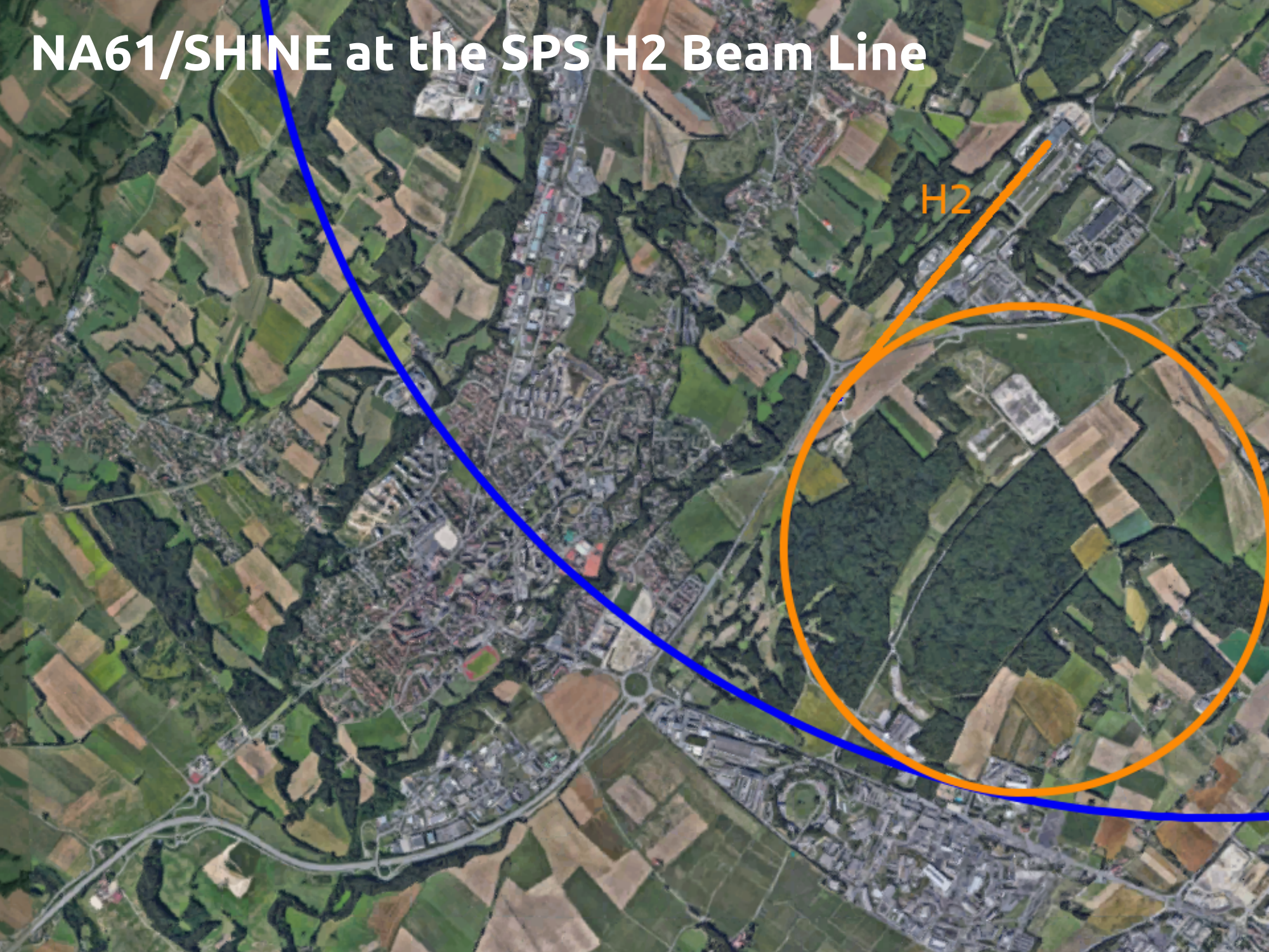
Neutrino and cosmic ray physics

- 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)

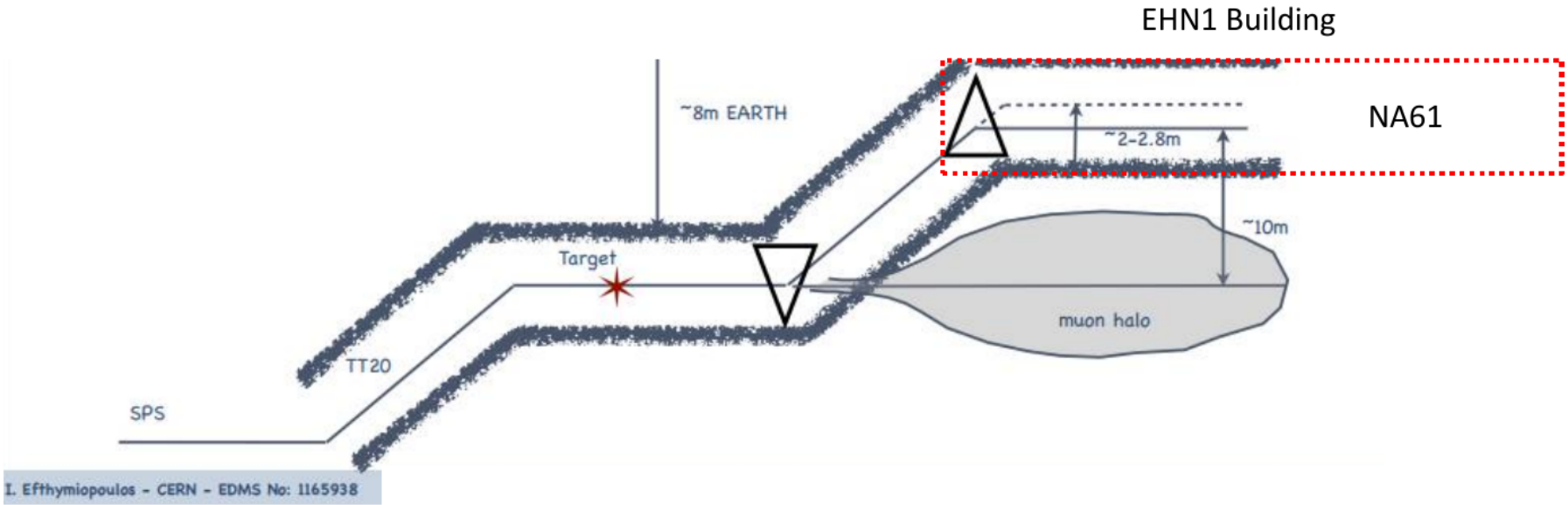
NA61/SHINE at the SPS H2 Beam Line



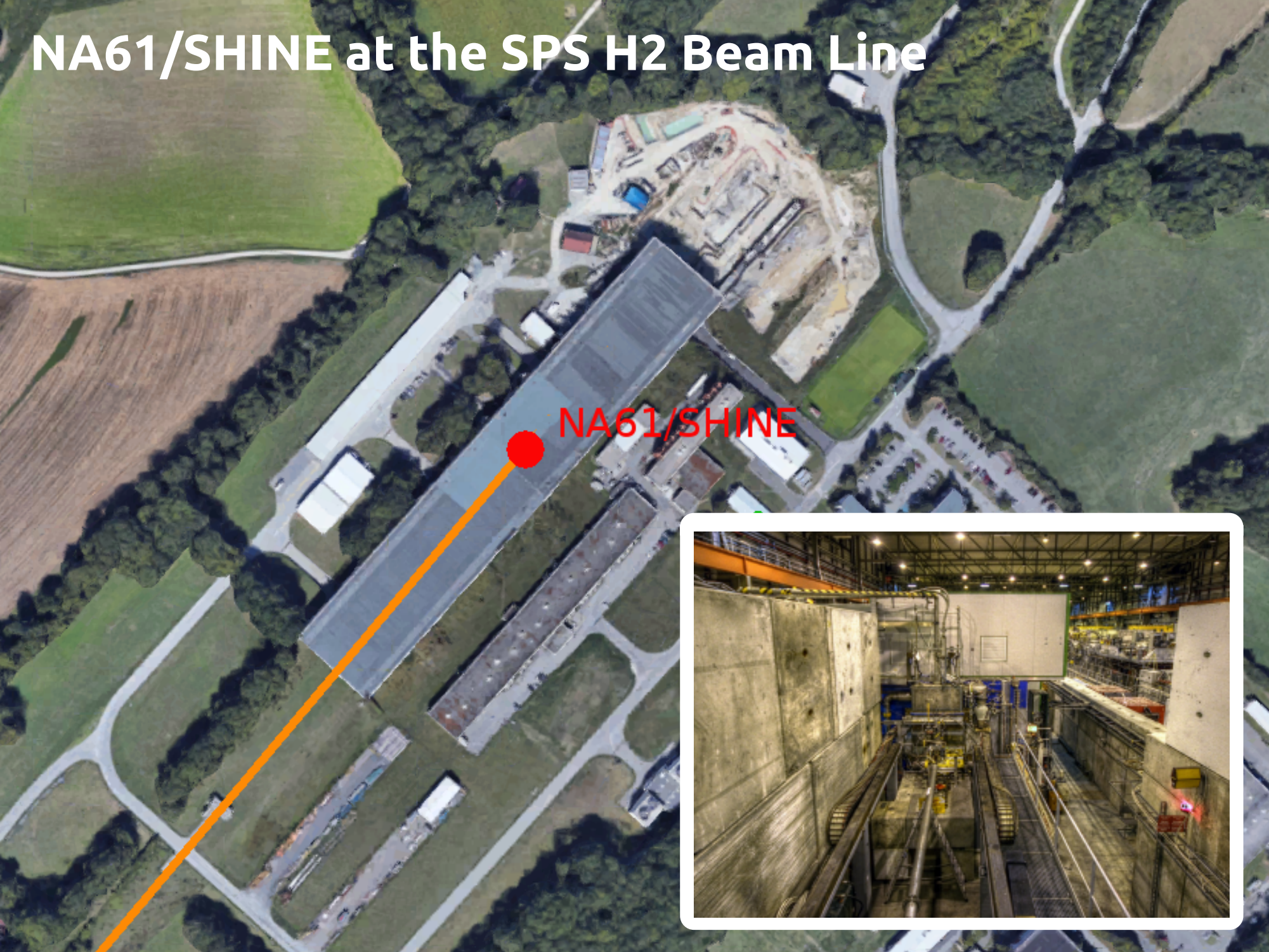
NA61/SHINE at the SPS H2 Beam Line

H2

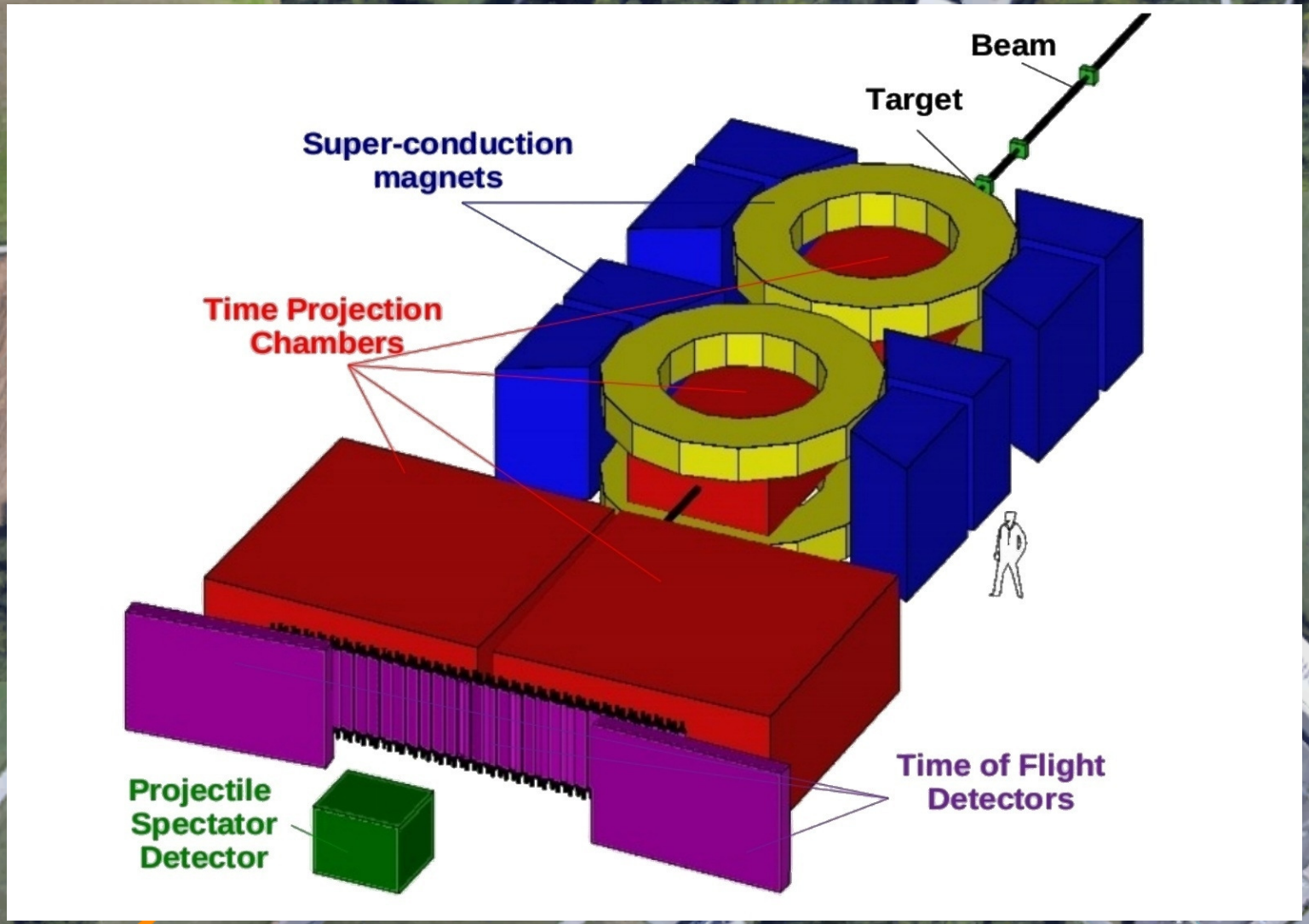
A **precise** (2% dp/p acceptance), robust, flexible **magnetic spectrometer**



NA61/SHINE at the SPS H2 Beam Line

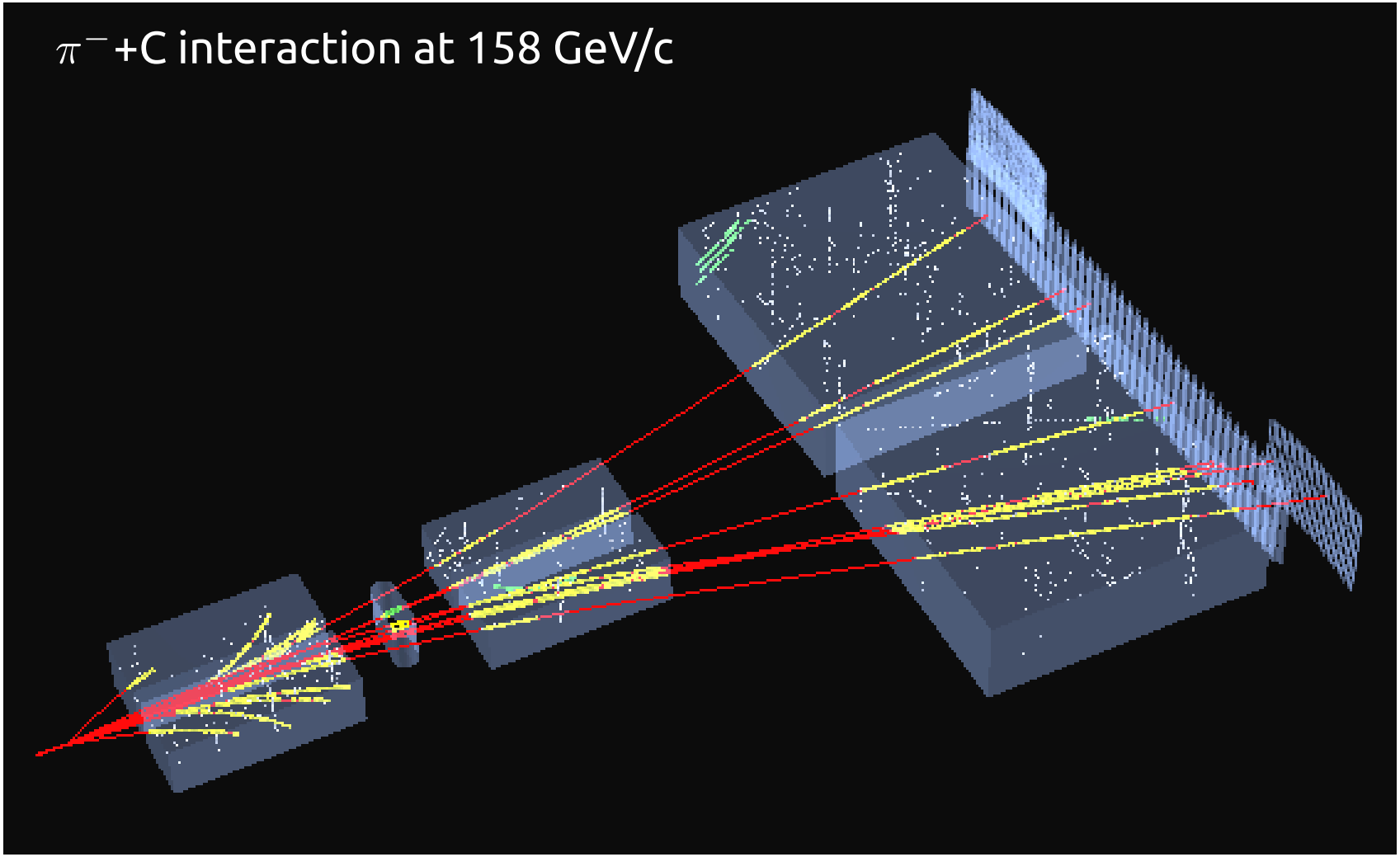


NA61/SHINE Detector



- 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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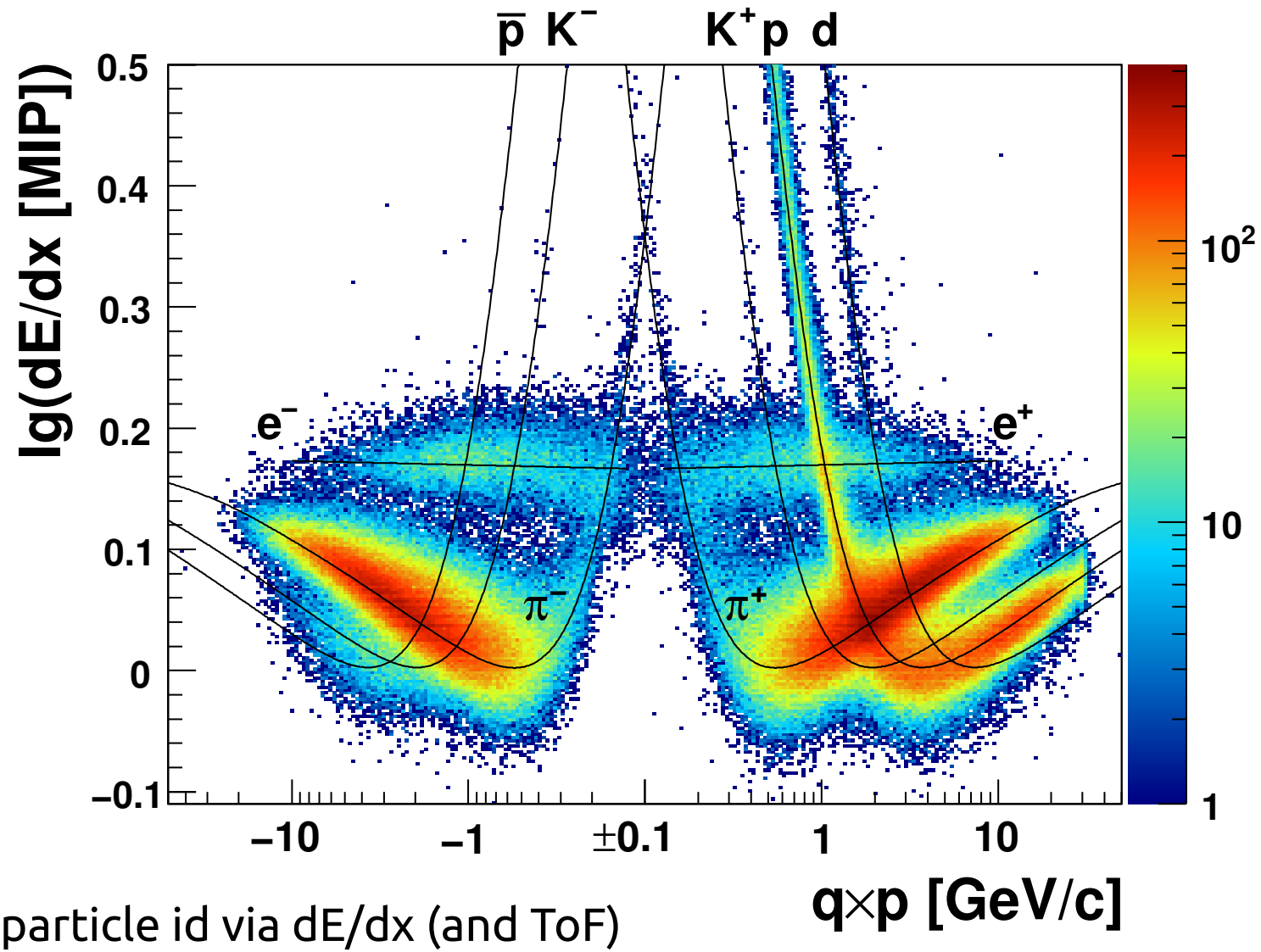

particle id via dE/dx (and ToF)

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, arXiv:2107.12275 (ICRC21), PRD **107** (2023) 062004, PRD **107** (2023) 072004, PRD **108** (2023) 072013.

The Cosmic-Ray Program of the NA61/SHINE Facility

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Muons in UHE Air Showers

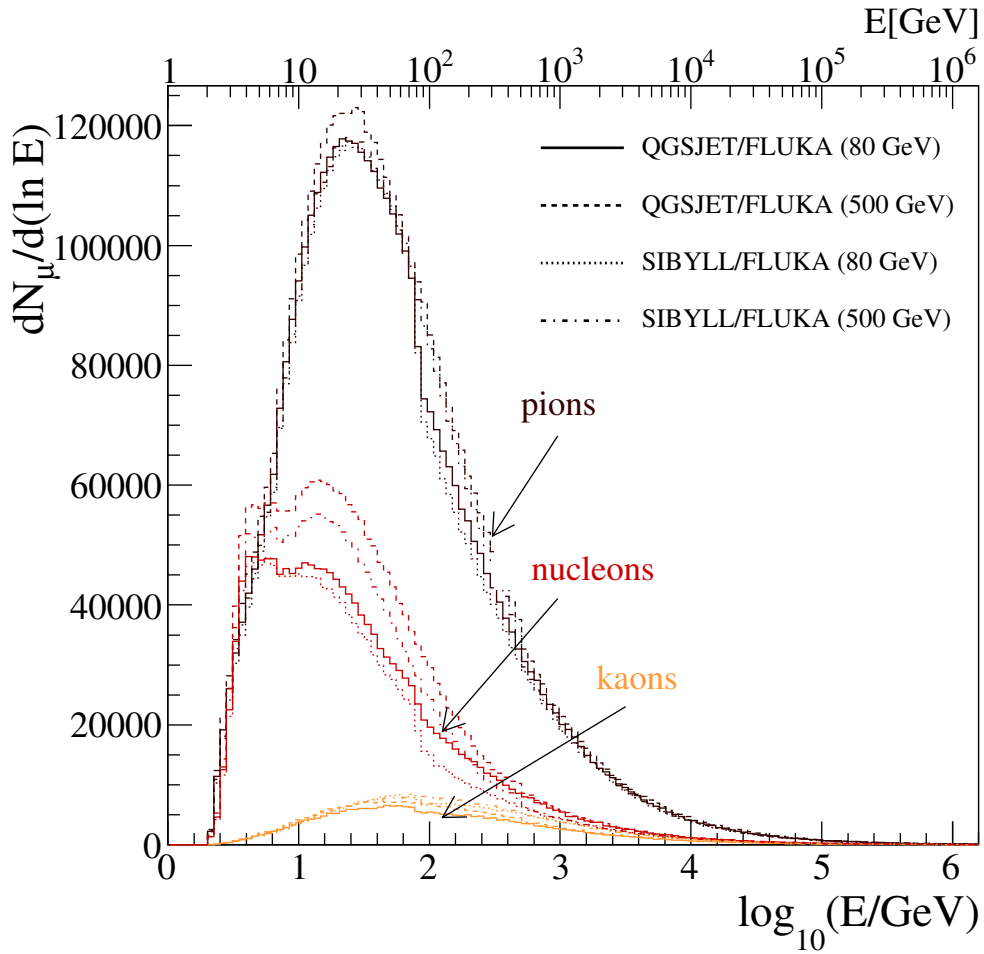
energy of last interaction before decay to μ

$$\text{air shower} \rightarrow \text{hadron} + \text{air} \rightarrow \pi/K + X \searrow \mu + \nu_\mu$$

ultrahigh-energy air shower

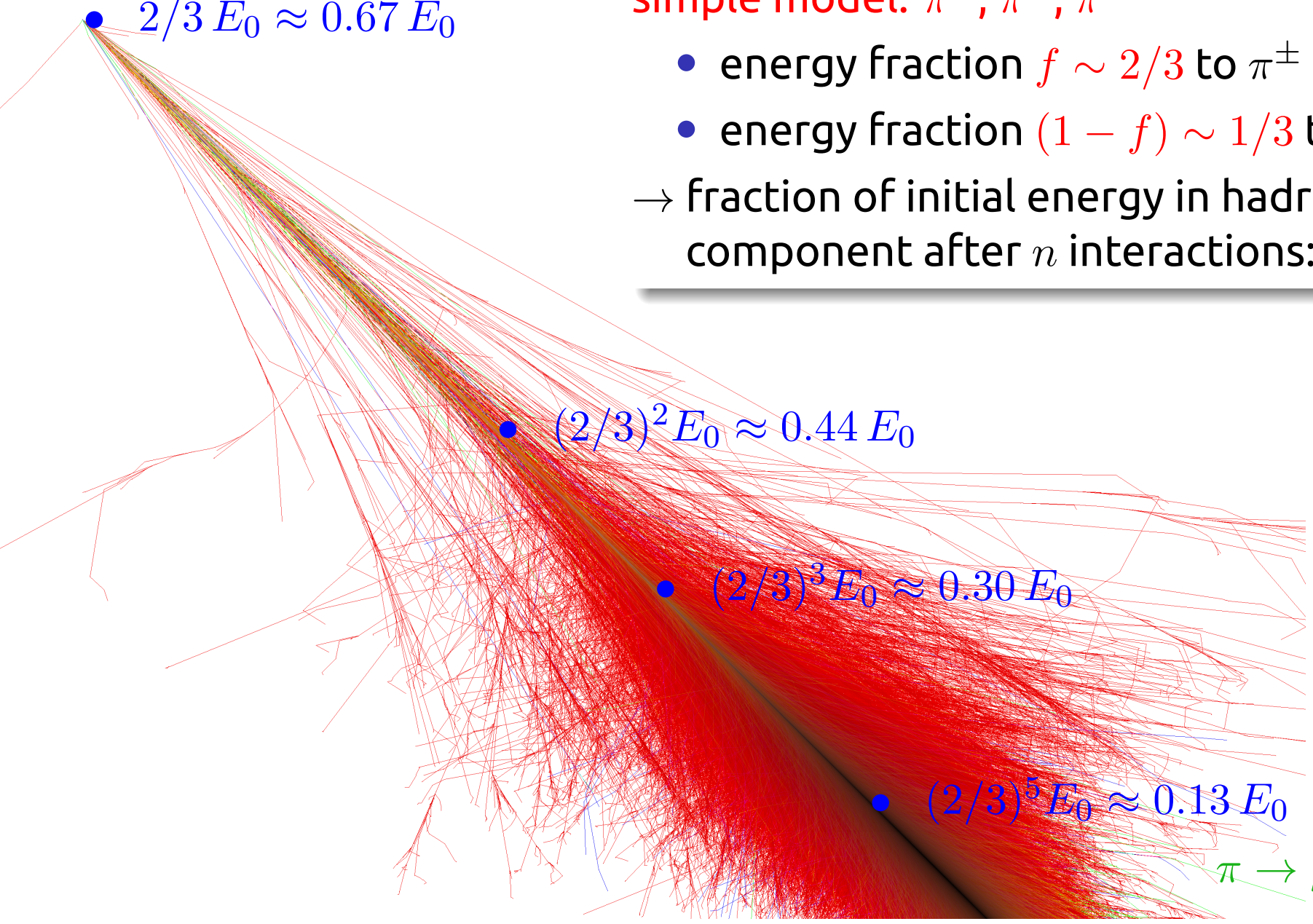
e.g. Auger:

- $E_0 = 10^{19}$ eV
- $r = 1000$ m
- $E_\mu \geq 150$ MeV



I.C. Mariş for NA61/SHINE, Proc. 31st ICRC, (2009)

Muons in UHE Air Showers

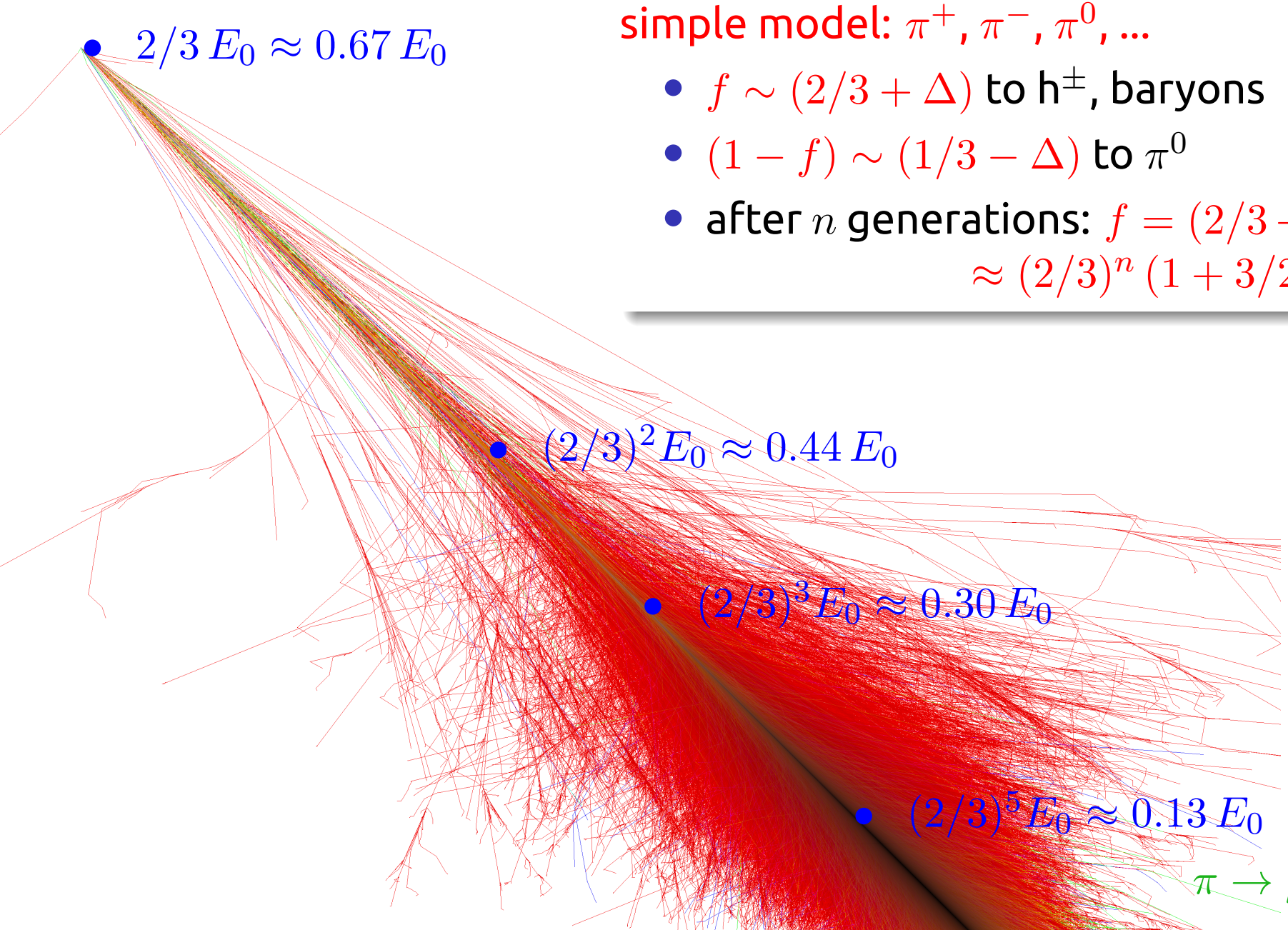


simple model: π^+, π^-, π^0

- energy fraction $f \sim 2/3$ to $\pi^{\pm}$
- energy fraction $(1 - f) \sim 1/3$ to π^0

$\to$ fraction of initial energy in hadronic component after n interactions: f^n

Muons in UHE Air Showers



simple model: π^+, π^-, π^0, ...

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

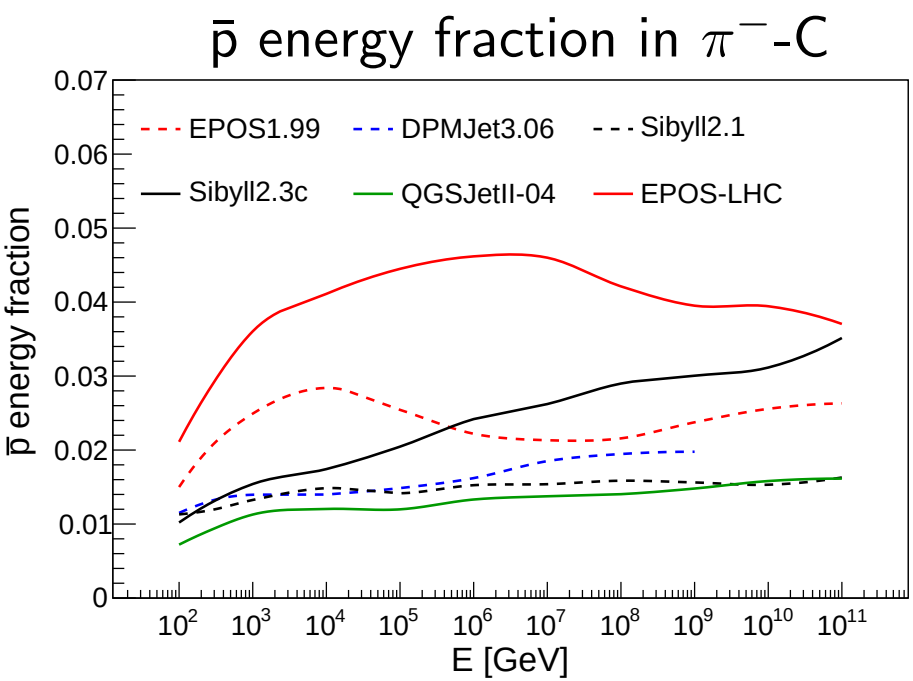
Muons in UHE Air Showers

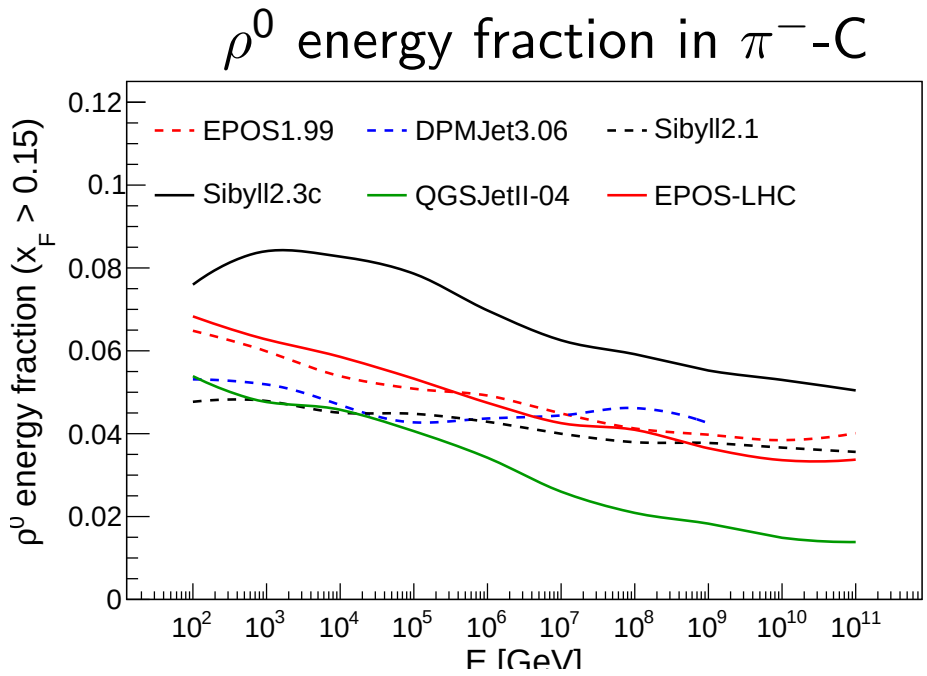
number of muons depends on energy fraction f of produced hadrons

- $\pi^0 \rightarrow$ electromagnetic shower
- $\pi^{\pm}$
- $\rho^0 \rightarrow \pi^+\pi^-$
- (anti-) baryons

$\rightarrow$ hadronic shower

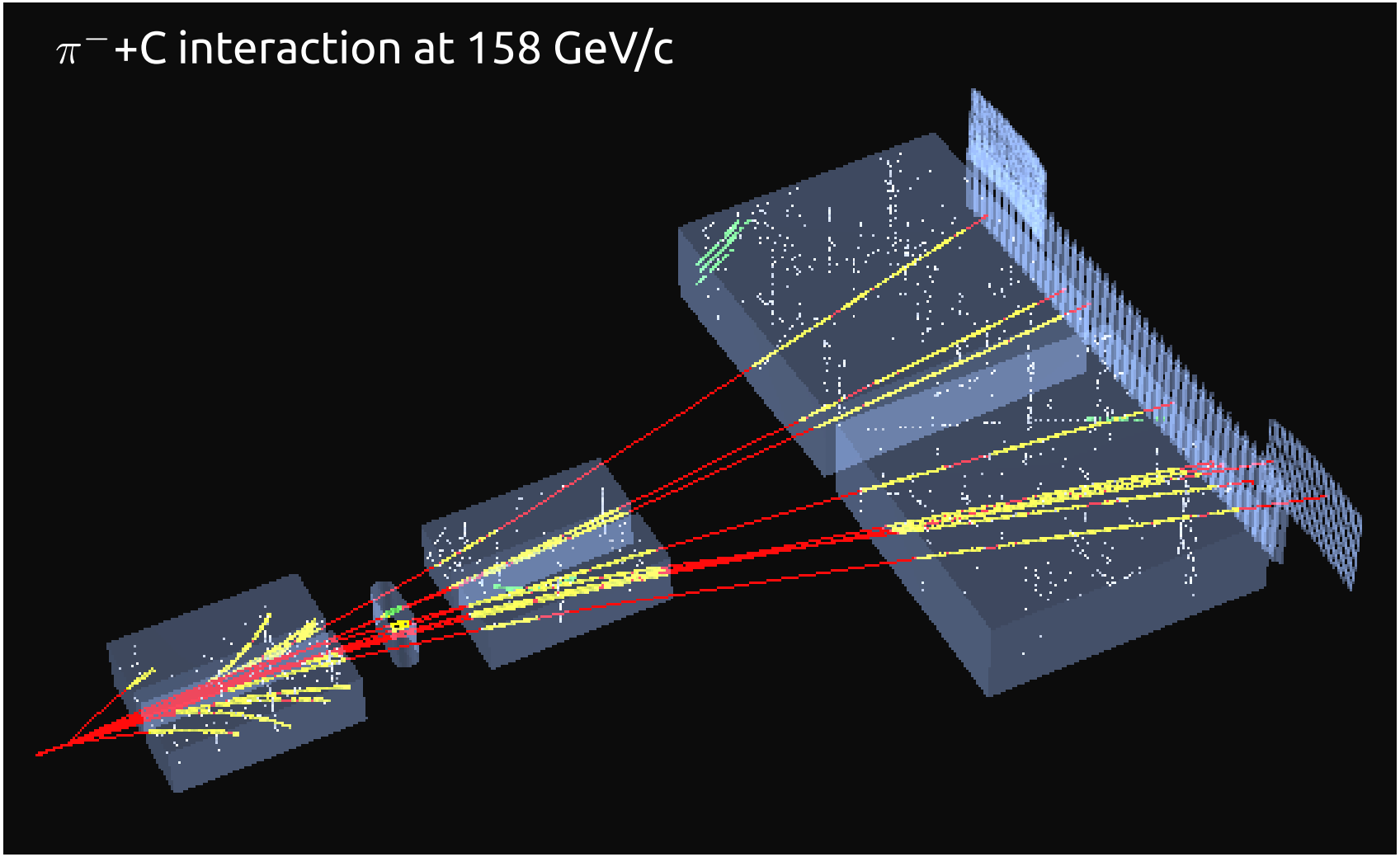
$$N_\mu \propto \Pi_{i=1}^{n_{\text{int}}} f_i$$





R.Prado ISVHECRI18, Pierog&Werner PRL17, Drescher PRD08

Particle Production Measurement with NA61/SHINE



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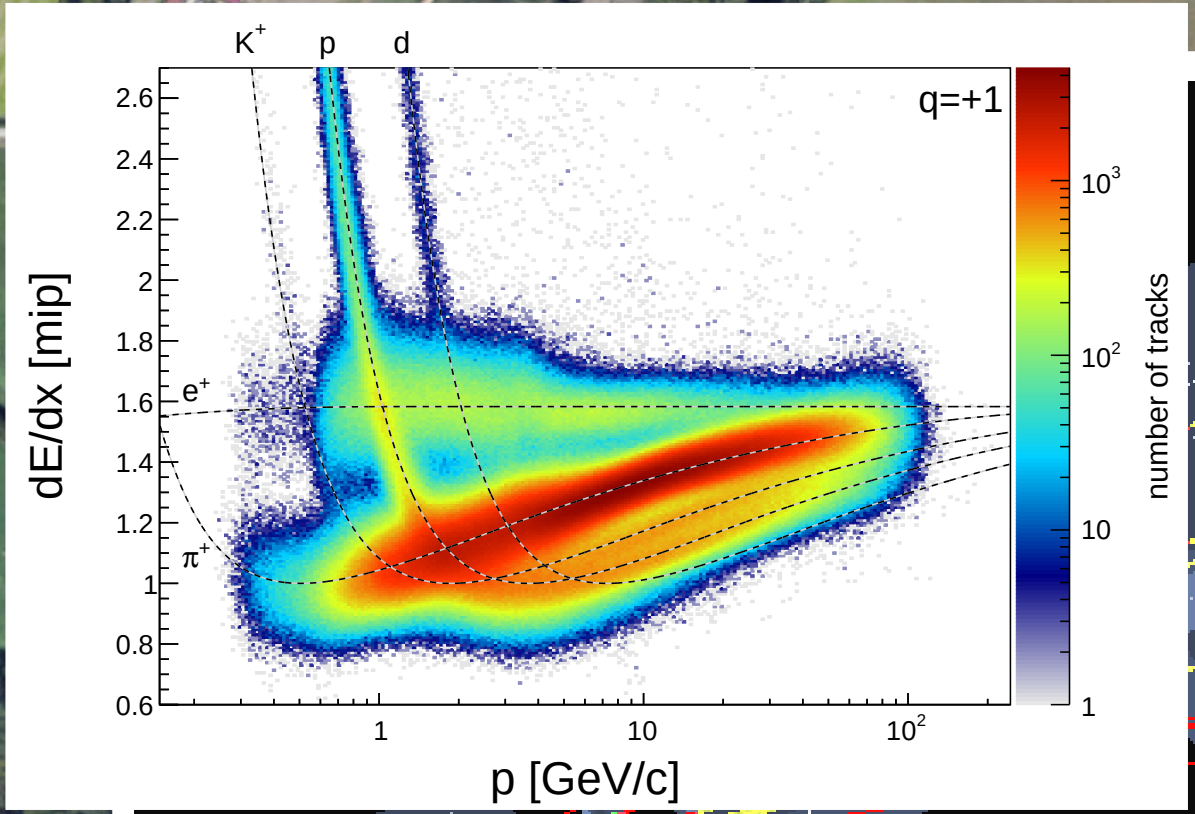

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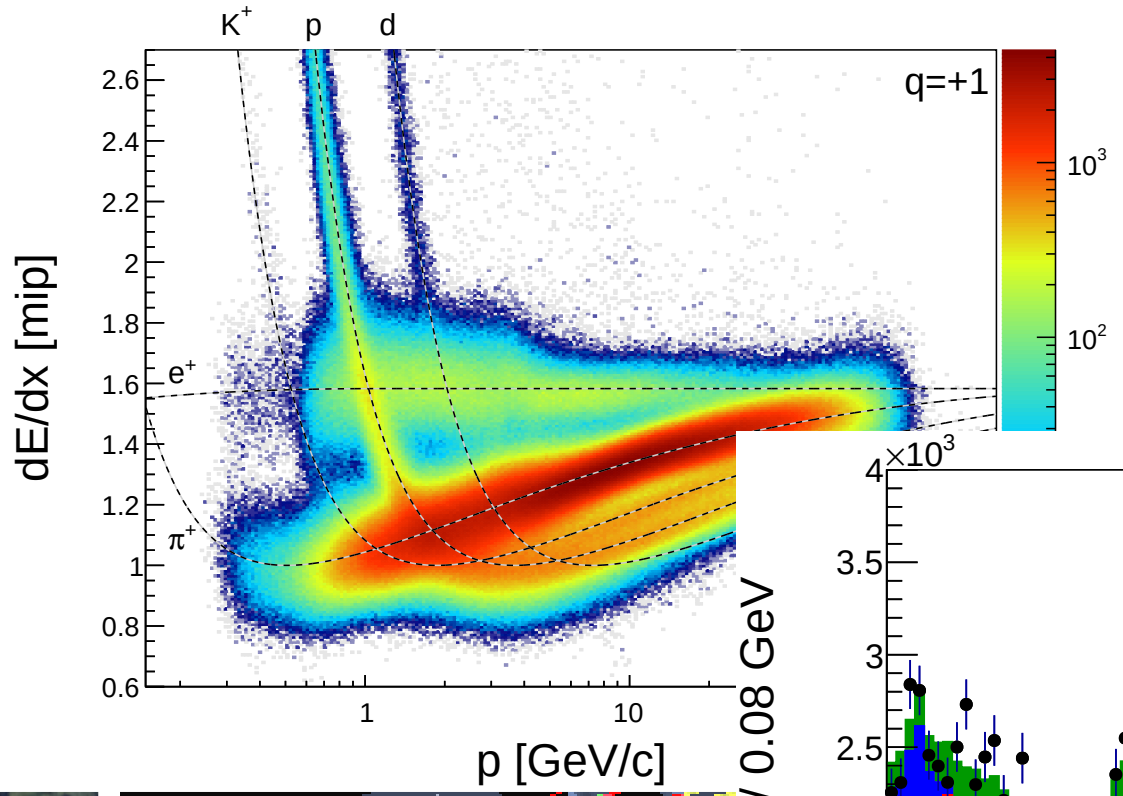
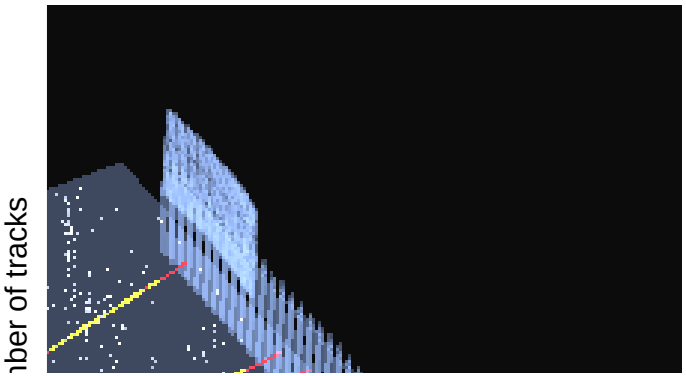
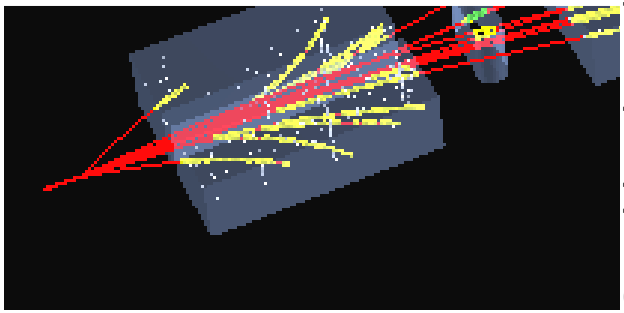
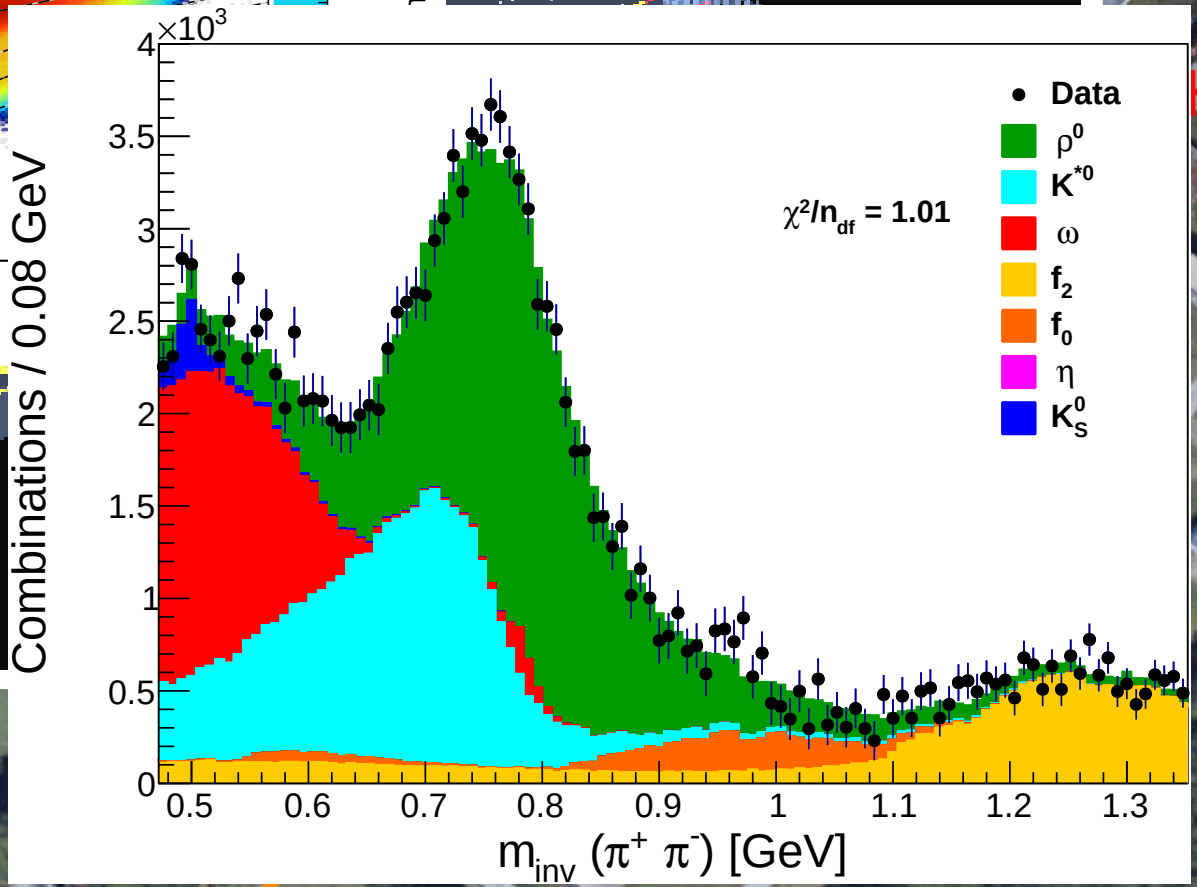








PHYSICAL REVIEW D **107,** 062004 (2023)

Measurement of hadron production in π^--C interactions at 158 and 350 GeV/c with NA61/SHINE at the CERN SPS

Eur. Phys. J. C (2017) 77:626
DOI 10.1140/epjc/s10052-017-5184-z

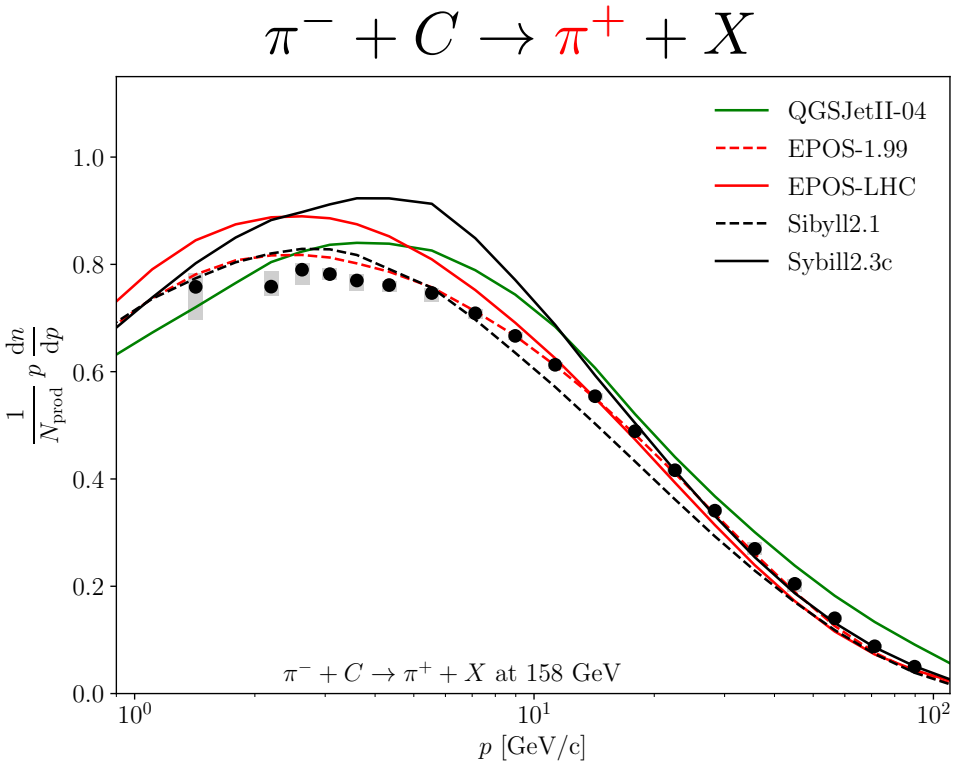
THE EUROPEAN PHYSICAL JOURNAL C

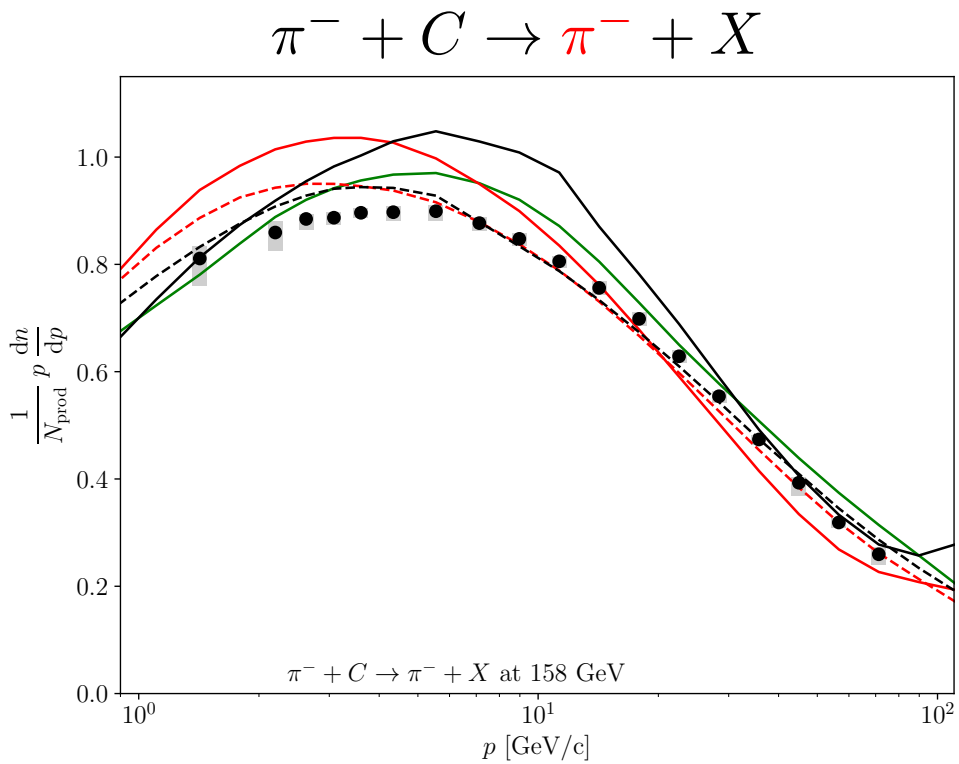
Measurement of meson resonance production in π^-+ C interactions at SPS energies

- projectile: π^- (charged pions are most numerous air-shower particles)
- target: C (very close to to air)
- beam momenta: 158 and 350 GeV/c
- 5×10^6 minimum bias interactions at each energy
- p-p_T spectra of π^+, π^-, K^+, K^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, K^0_S
- x_F spectra of ρ^0, ω and K^{*0}

$\rightarrow$ precision data for the tuning of air shower simulations

Pion Production in π^--C at 158 GeV/c

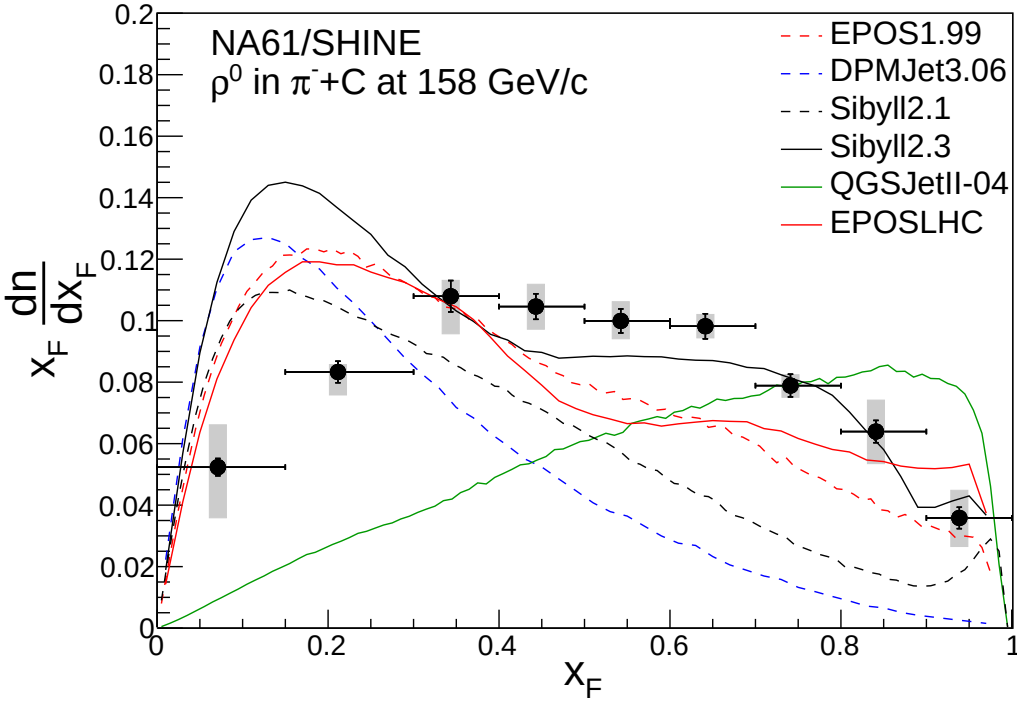




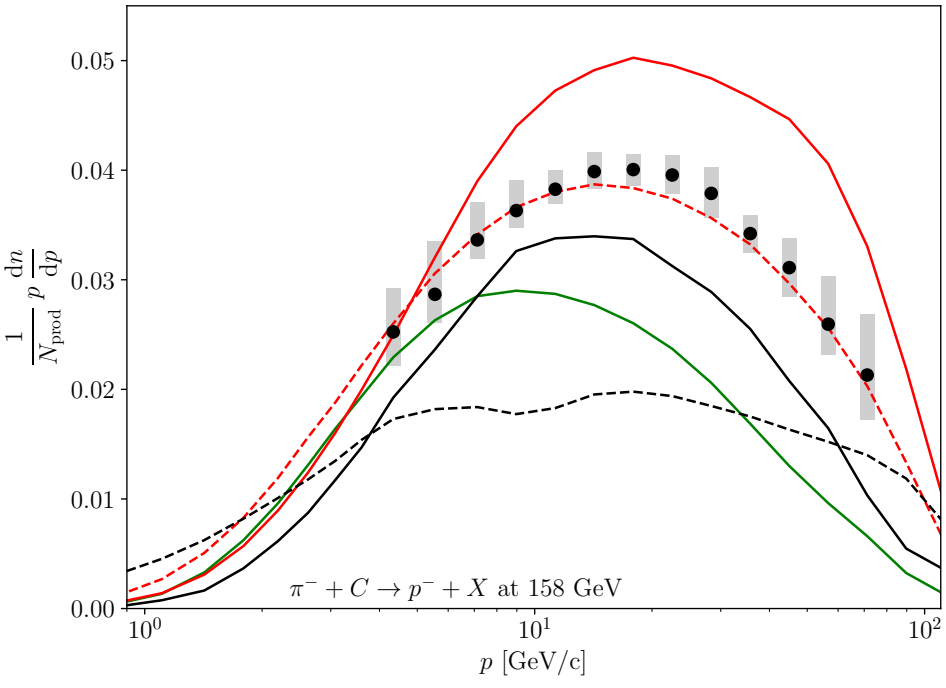
NA61/SHINE Collaboration PRD **107** (2023) 062004

- p_T-integrated spectra
- $\frac{1}{N_{\text{prod}}} \int p \frac{dn}{dp} dp = \langle f_\pi \rangle \cdot p_{\text{beam}}$

ρ^0 and $\bar{p}$ Production in π^--C at 158 GeV/c



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



NA61/SHINE PRD **107** (2023) 062004

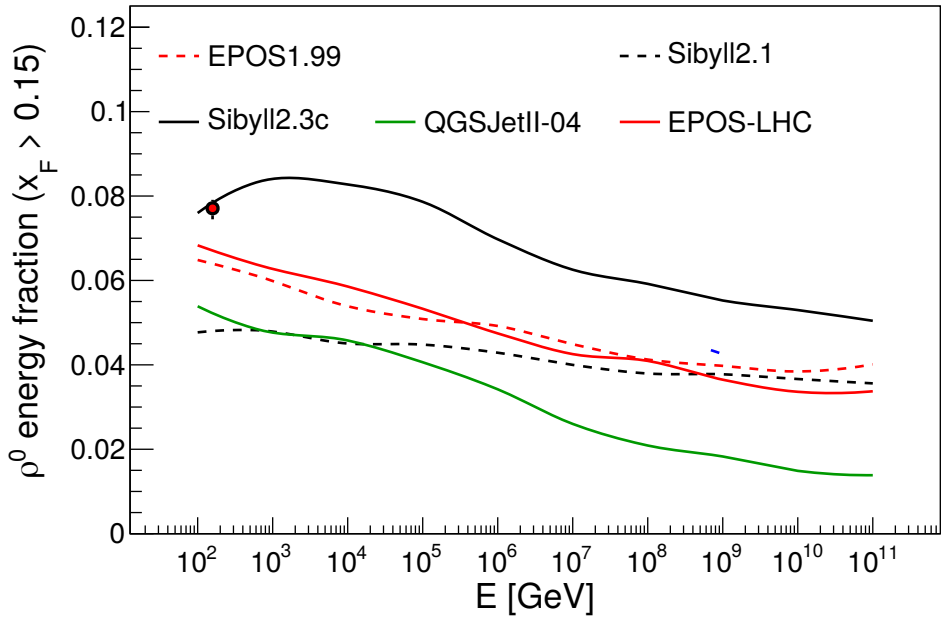
- forward ρ^0 can replace $\pi^0 \to \gamma\gamma$
- $\bar{p}$ is proxy for baryon production (p, $\bar{p}$, n, $\bar{n}$)

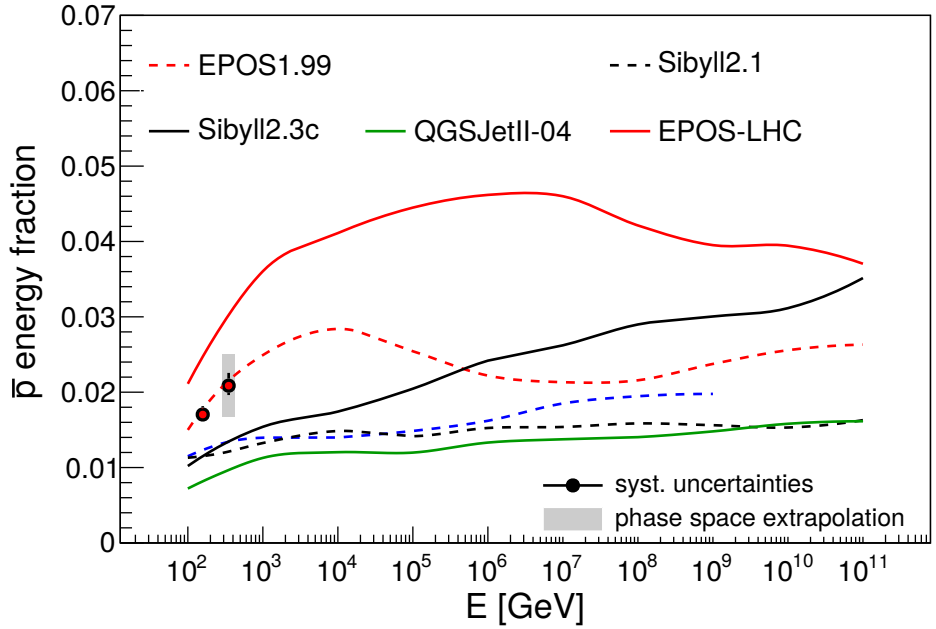
ρ^0 and $\bar{p}$ Production in π^--C at 158 GeV/c

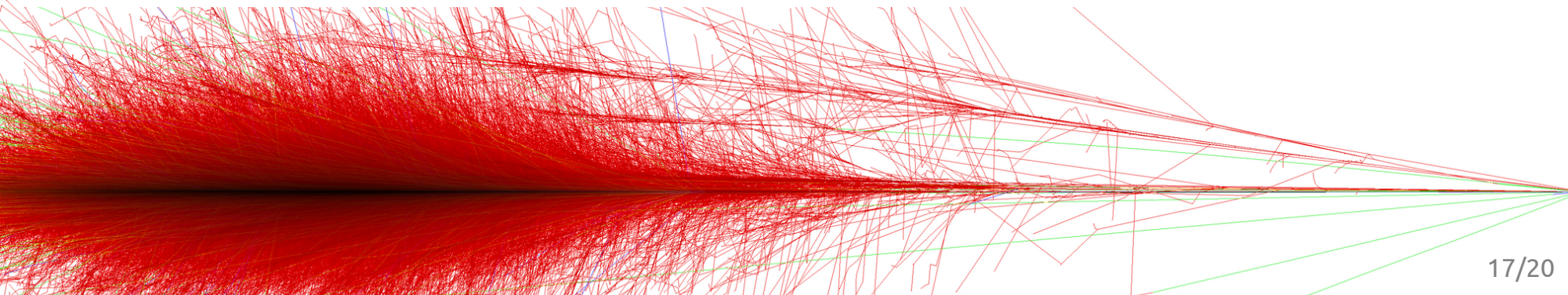
energy fraction in air shower development:

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

energy fraction of ρ^0 and $\bar{p}$:



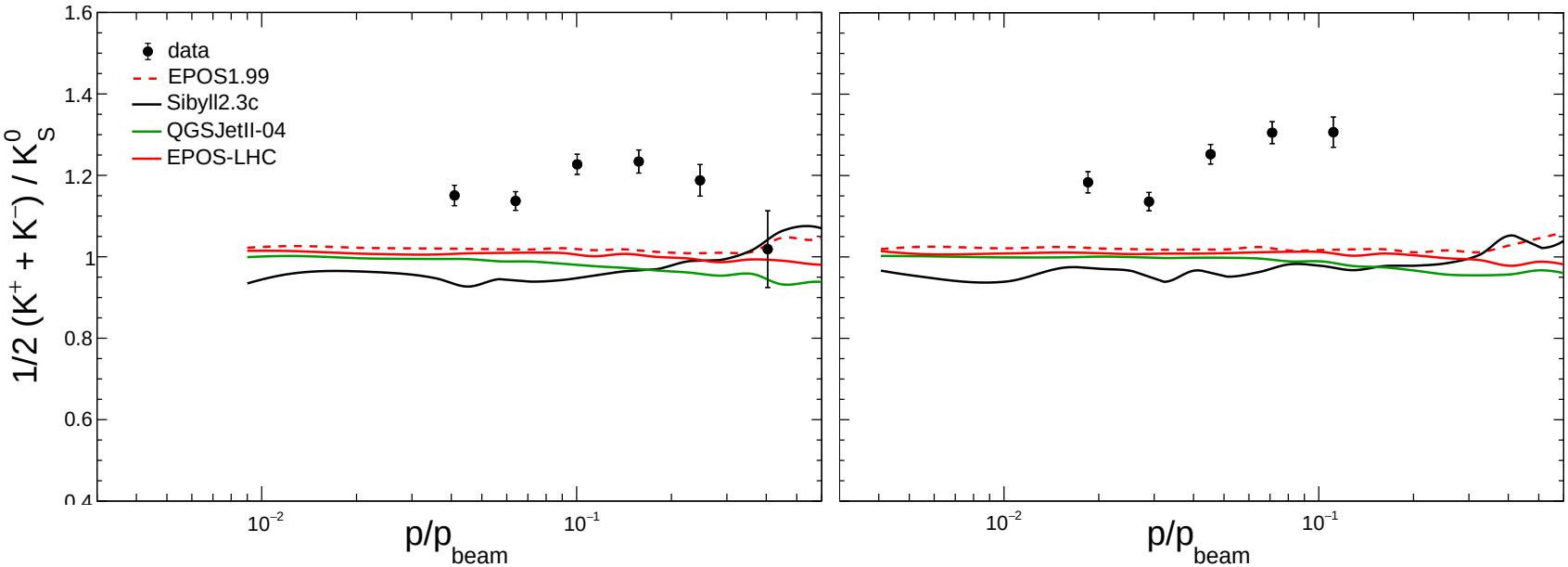




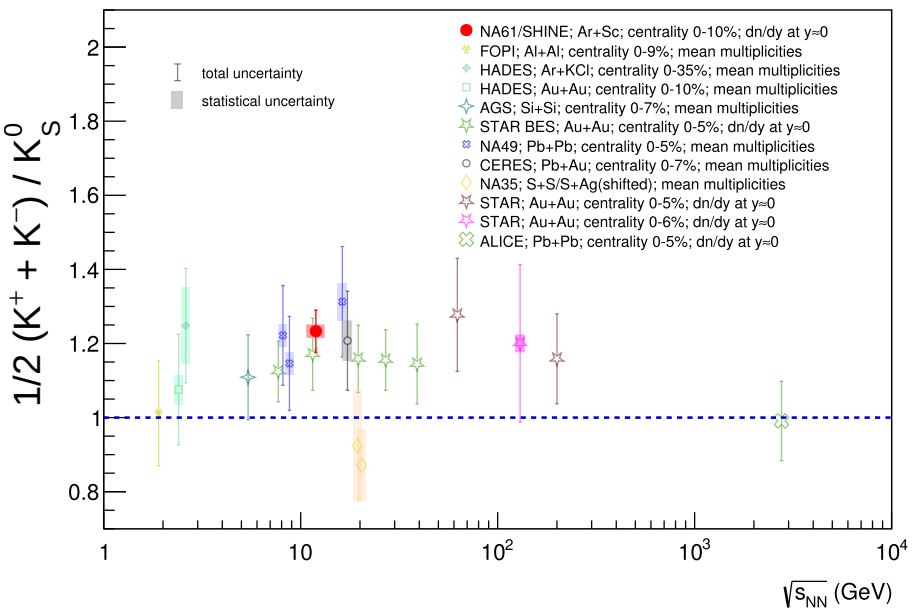
“Kaon Puzzle”

PRD **107** (2003) 062004 and arXiv:2312.06572

π^-+C at 158 and 350 GeV/c:

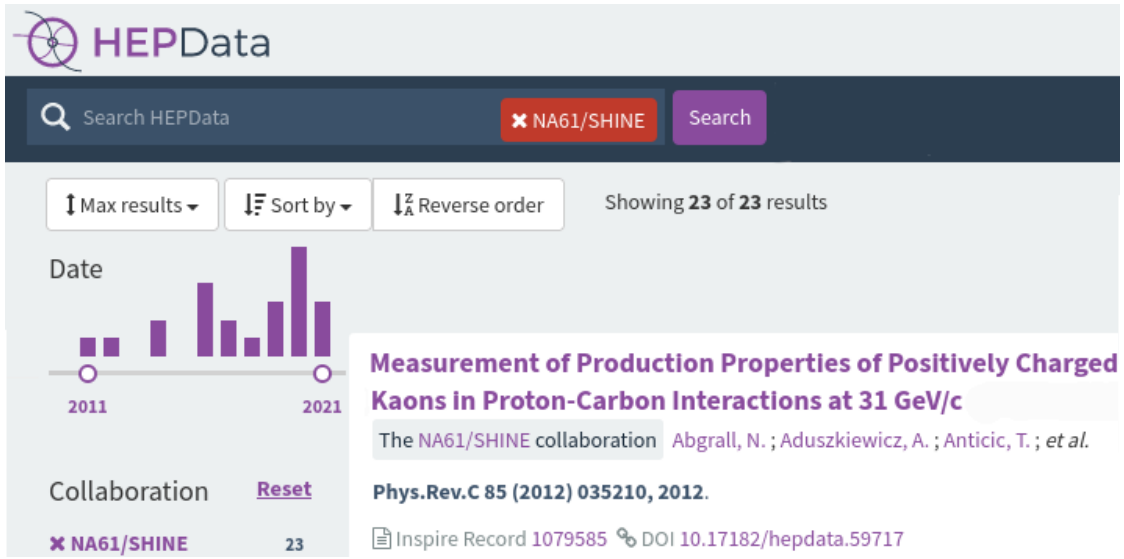


Ar+Sc at 75 A GeV/c:



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	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓



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

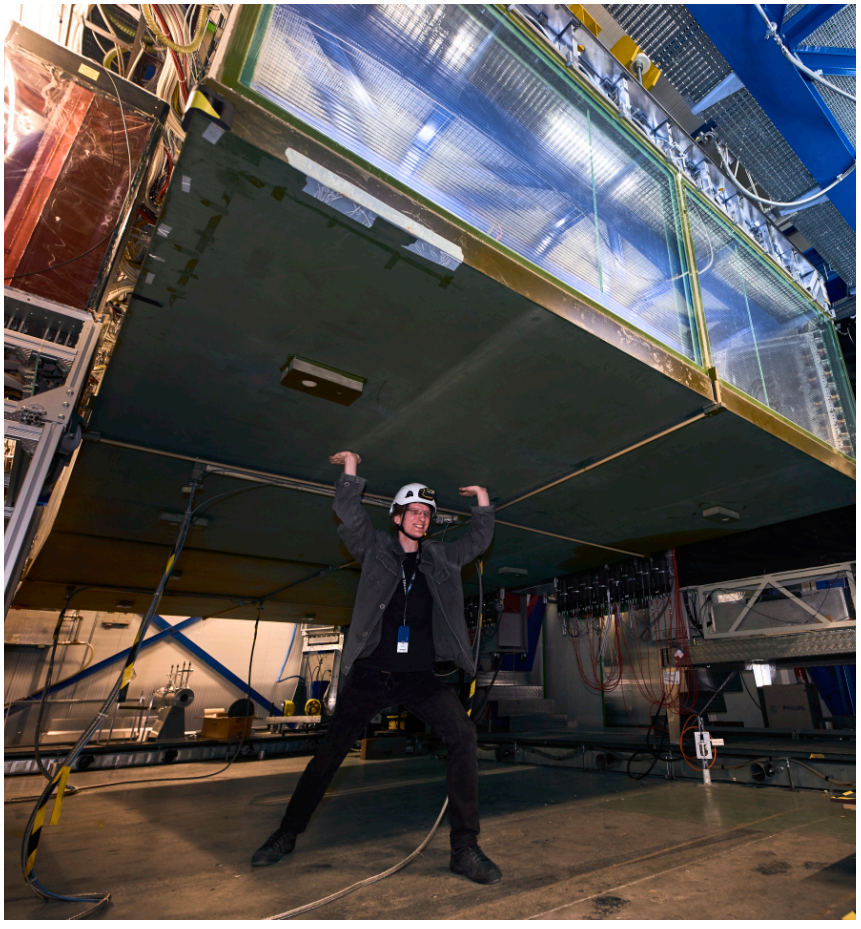
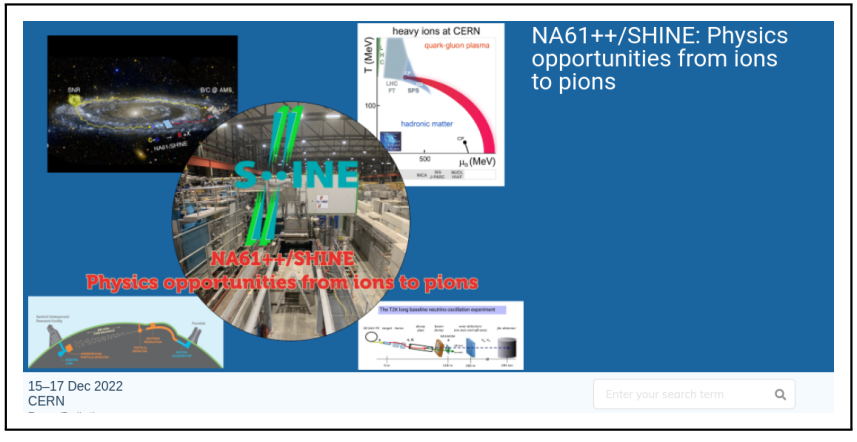
Upcoming Cosmic-Ray Measurements:

- **2024** fragmented Pb beam

  production of GCR secondaries Li, Be, B
- **2025** primary/fragmented oxygen?

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

  nucleon coalescence, anti-deuterons
- physics program after LS3 ($>$ 2028)?



inside NA61 (Julien Ordan/CERN)