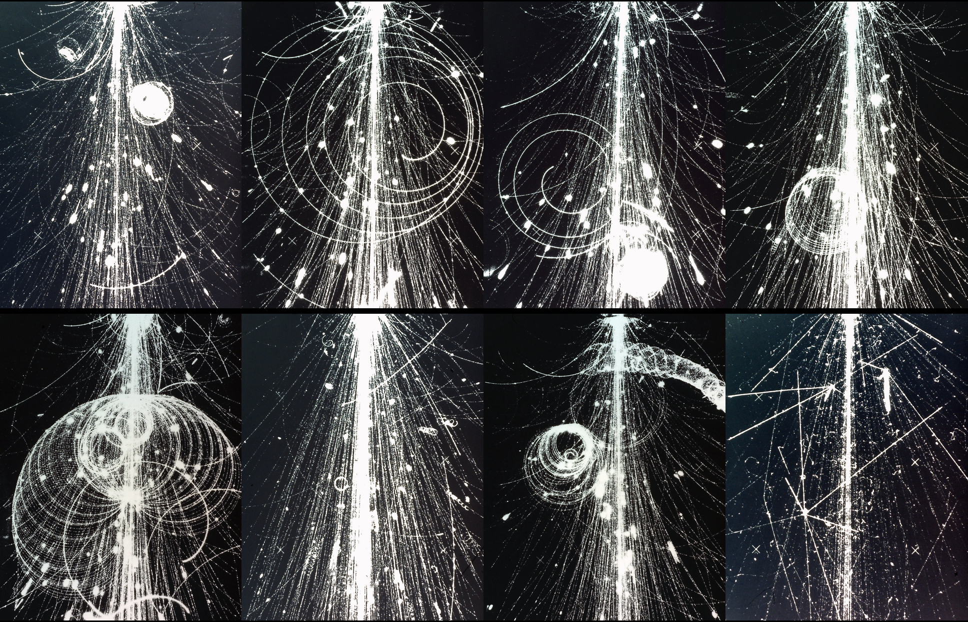
Cosmic-Ray Insights from NA61/SHINE at the CERN SPS

Michael Unger (KIT)



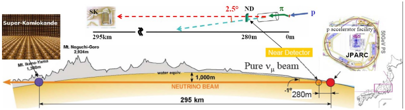
NA35 3.2 TeV O+Pb interactions

NA61/SHINE

≈ 140 physicists from 14 countries and 28 institutions

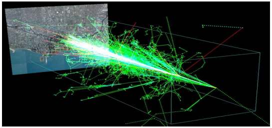
Strong interactions physics

- 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

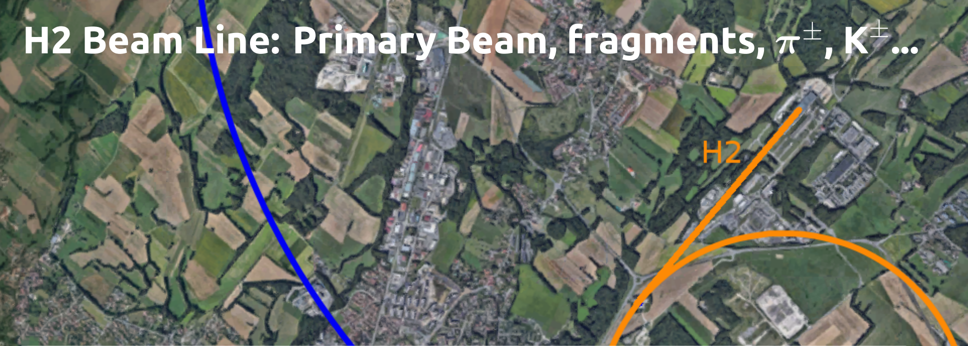


cosmic ray groups: KIT (Germany), Uni. Hawaii (USA), Uni. Silesia (Poland)

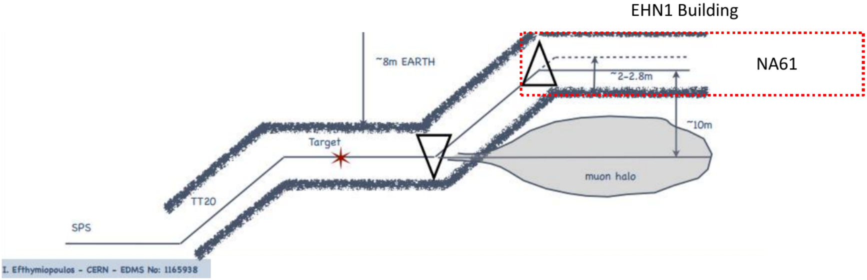
The Super Proton Synchrotron (SPS) at CERN

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

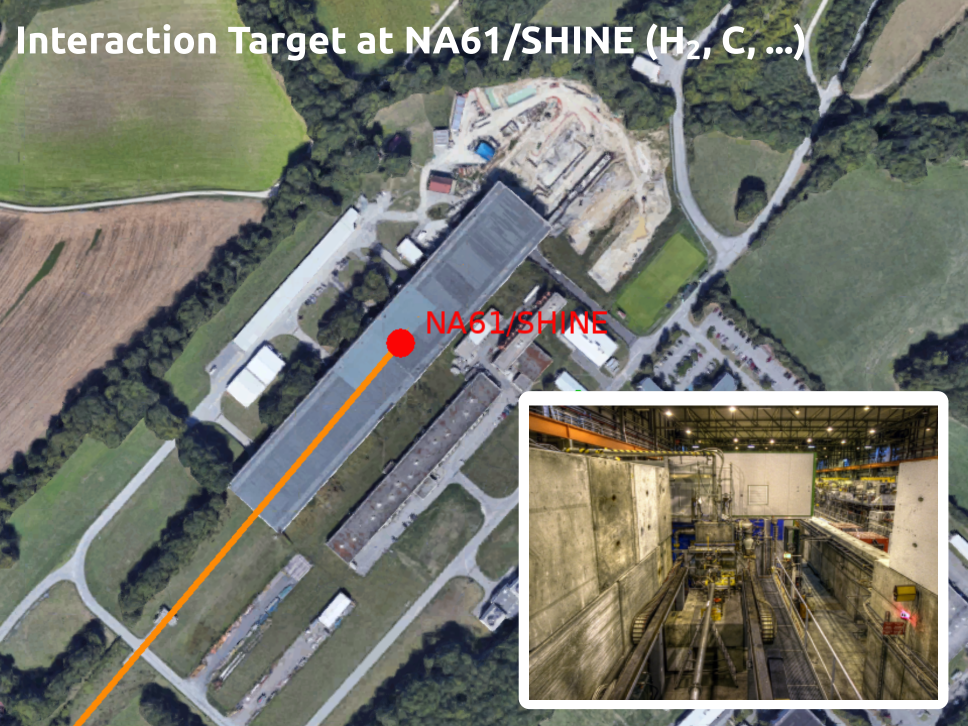
H2 Beam Line: Primary Beam, fragments, $\pi^{\pm}$, $K^{\pm}$...



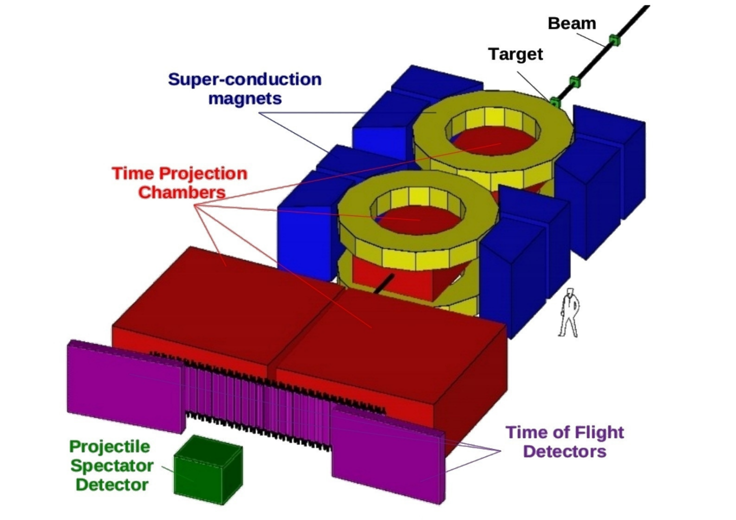
A **precise** (2% dp/p acceptance), robust, flexible **magnetic spectrometer**



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

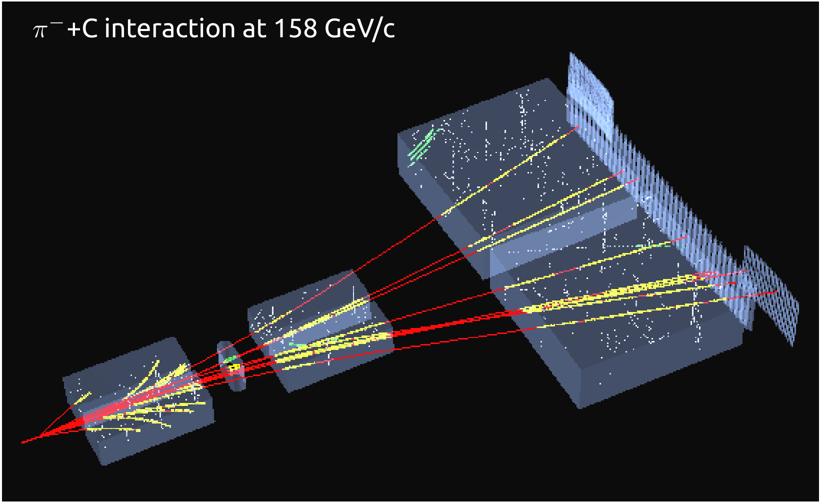


Particle Production Measurement at NA61/SHINE

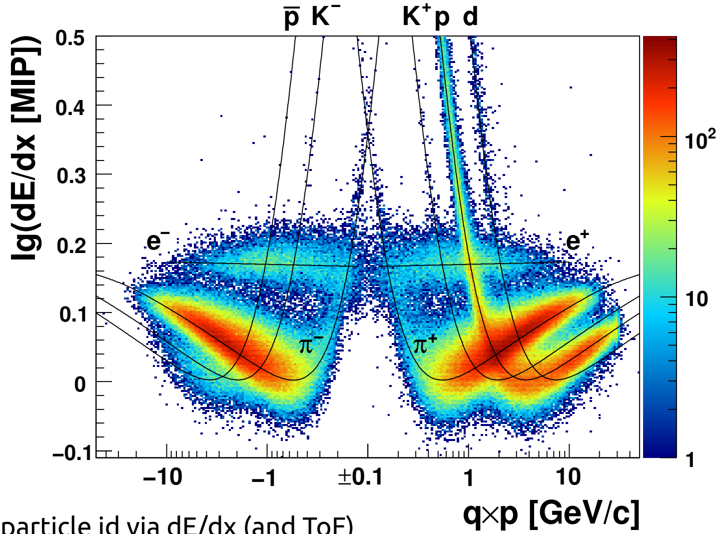


- large acceptance $\approx 50\%$ at $p_T \leq 2.5$ GeV/c
- momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\text{GeV/c})^{-1}$
- tracking efficiency: $> 95\%$, pid with dE/dx and ToF

Particle Production Measurement at NA61/SHINE



Particle Production Measurement at NA61/SHINE



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), arXiv:2209.10561 (submitted to PRD).

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

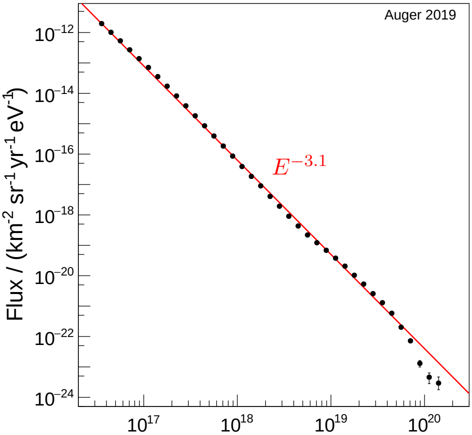
PRC **84** (2011) 034604, PRC **85** (2012) 035210, PRC **89** (2014) 025205, EPJ **C74** (2014) 2794, EPJ **C76** (2016) 84, EPJ **C76** (2016) 198, EPJ **C77** (2017) 671 EPJ **C77** (2017) 626, PRD **98** (2018) 052001, arXiv:2107.12275 (ICRC21), arXiv:2209.10561 (submitted to PRD).

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 $\leftarrow$ this talk
    (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 $\leftarrow$ this talk
    (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), arXiv:2209.10561 (submitted to PRD).

Energy Spectrum of Ultrahigh-Energy Cosmic Rays

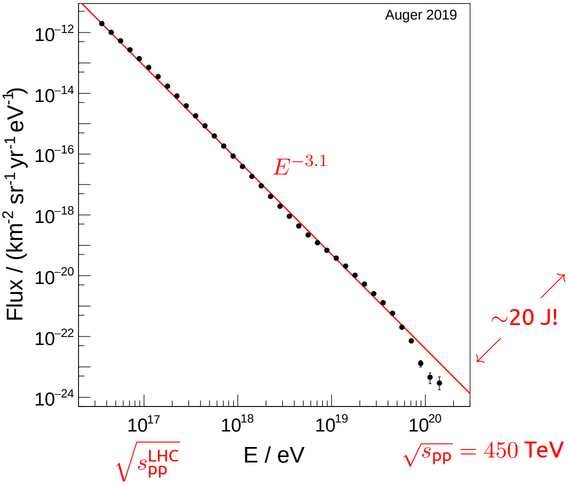


$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

$\sqrt{s_{\text{pp}}} = 450$ TeV

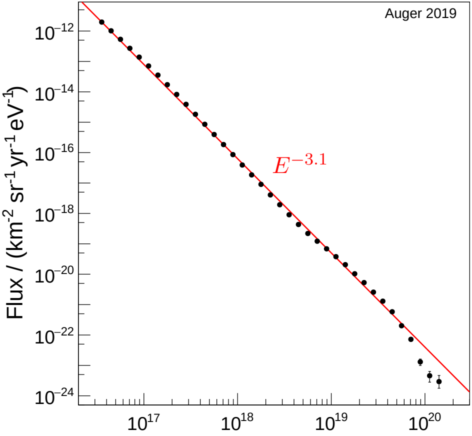
Energy Spectrum of Ultrahigh-Energy Cosmic Rays



Serena Williams' 2nd serve

$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

Energy Spectrum of Ultrahigh-Energy Cosmic Rays

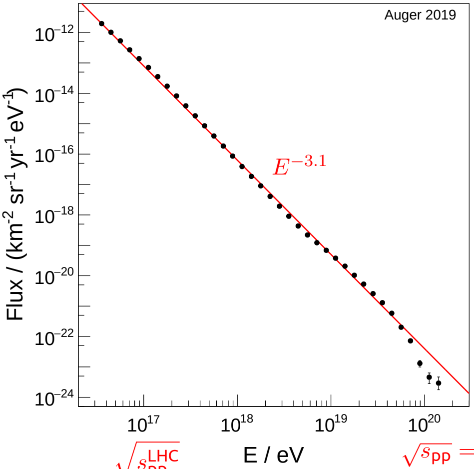


$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

$\sqrt{s_{\text{pp}}} = 450$ TeV

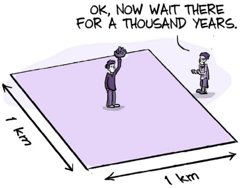
Energy Spectrum of Ultrahigh-Energy Cosmic Rays



$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

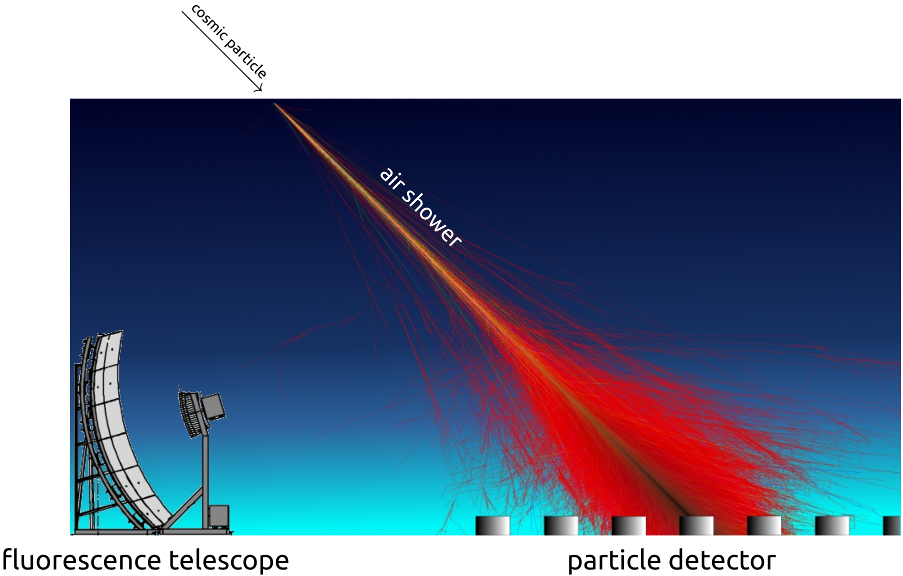
$\sqrt{s_{\text{pp}}} = 450$ TeV

$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV



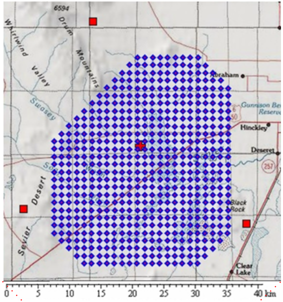
J. Cham&D. Whiteson "We have no idea", Penguin, 2018

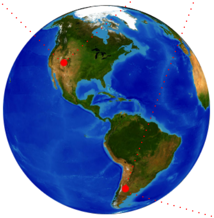
Detection of Ultrahigh-Energy Cosmic Rays



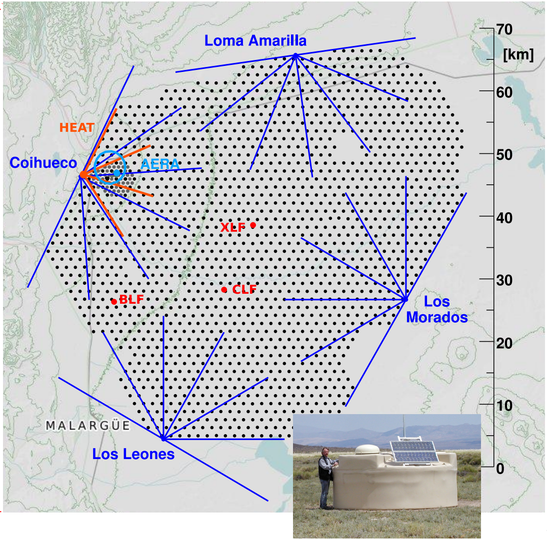
Detection of Ultrahigh-Energy Cosmic Rays

Telescope Array



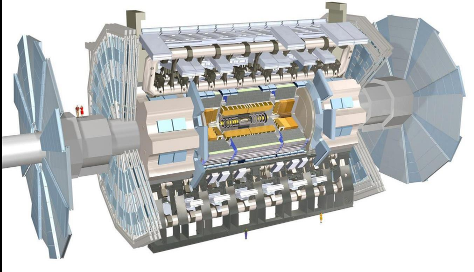


Pierre Auger Observatory



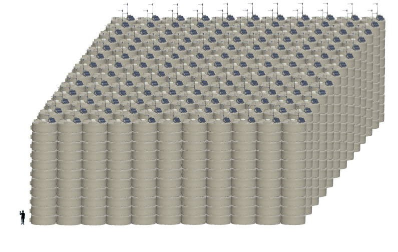
Particle Physics at UHE

ATLAS@LHC



- $E_{\text{beam}} = 6.5$ TeV
- $\sqrt{s} = 13$ TeV
- 7 kt detector

Pierre Auger Observatory*

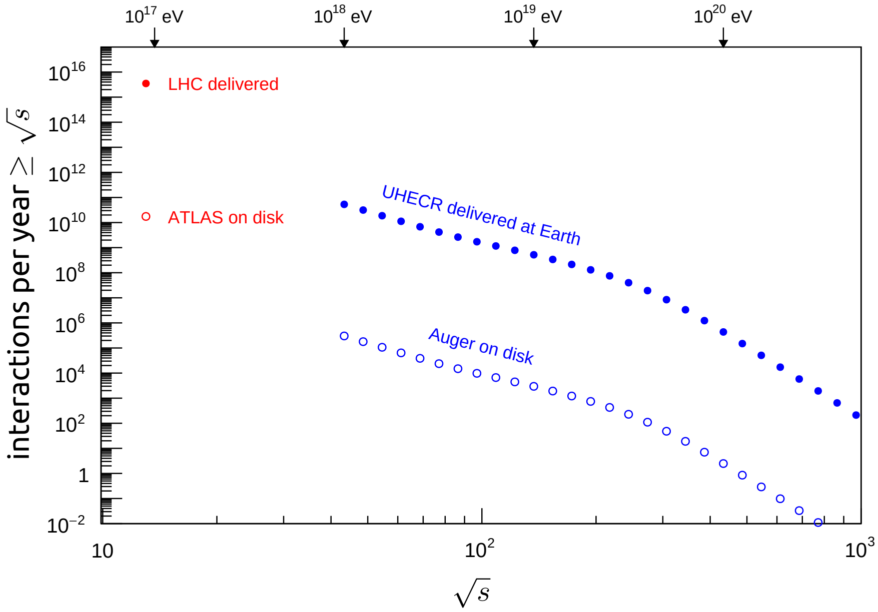


- $E_{\text{beam}} > 1 \times 10^8$ TeV
- $\sqrt{s} > 400$ TeV**
- 20 kt water-Cherenkov
- 25 Gt air calorimeter

* to scale but stacked, actual area: 3000 km^2

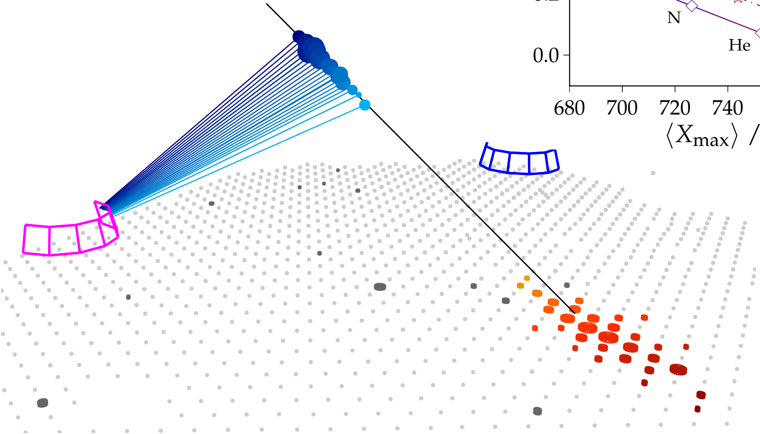
** for p+air ($>$ 60 TeV for Fe+air)

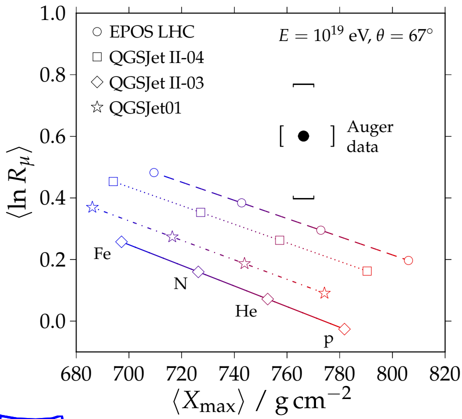
LHC and UHECR Luminosity



Muon Production in Air Showers

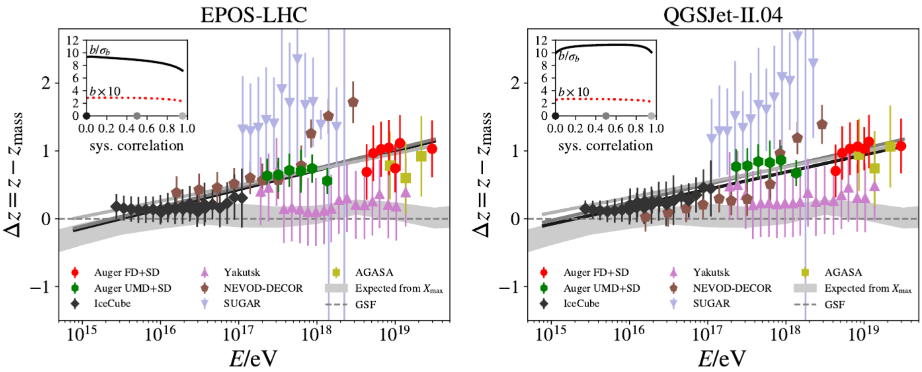
$$R_\mu \sim N_\mu/(1.5 \times 10^7)$$





Pierre Auger Coll., PRD **D91** (2015) 3, 032003

The UHE “Muon Puzzle”



Working Group on Hadronic Interactions and Shower Physics (D.Soldin et al) PoS ICRC2021 349, arXiv:2108.08341

Muons in UHE Air Showers

energy of last interaction before decay to μ

air shower $\rightarrow$ hadron $+$ air $\rightarrow \pi/K + X$

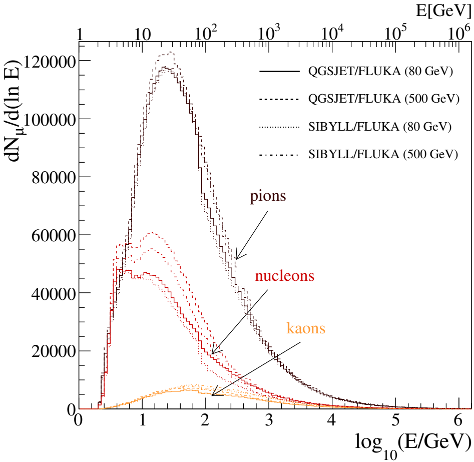
$\searrow$

$\mu + \nu_\mu$

ultrahigh-energy air shower

e.g. Auger:

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



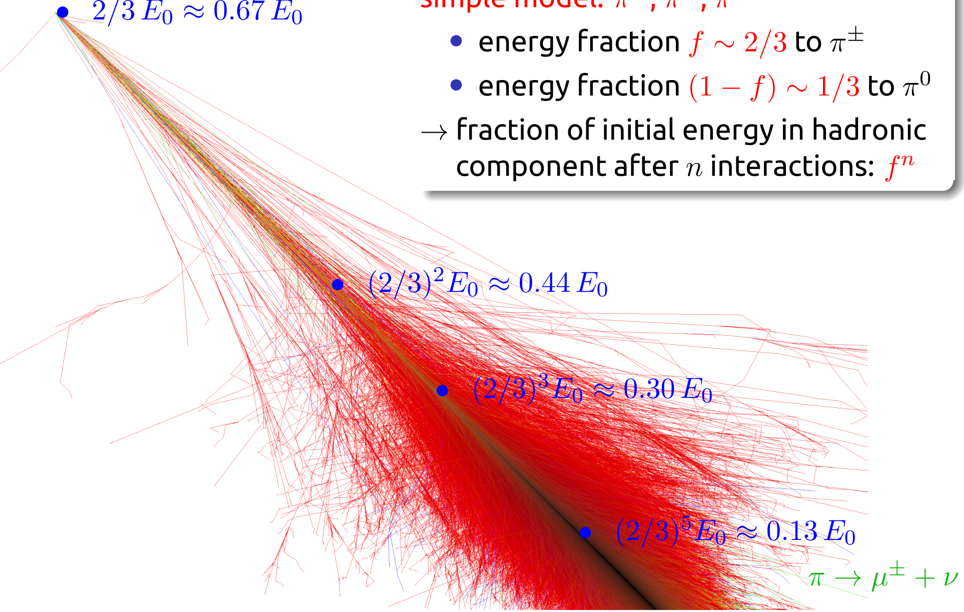
I.C. Mariş for NA61/SHINE, Proc. 31st ICRC, (2009)

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

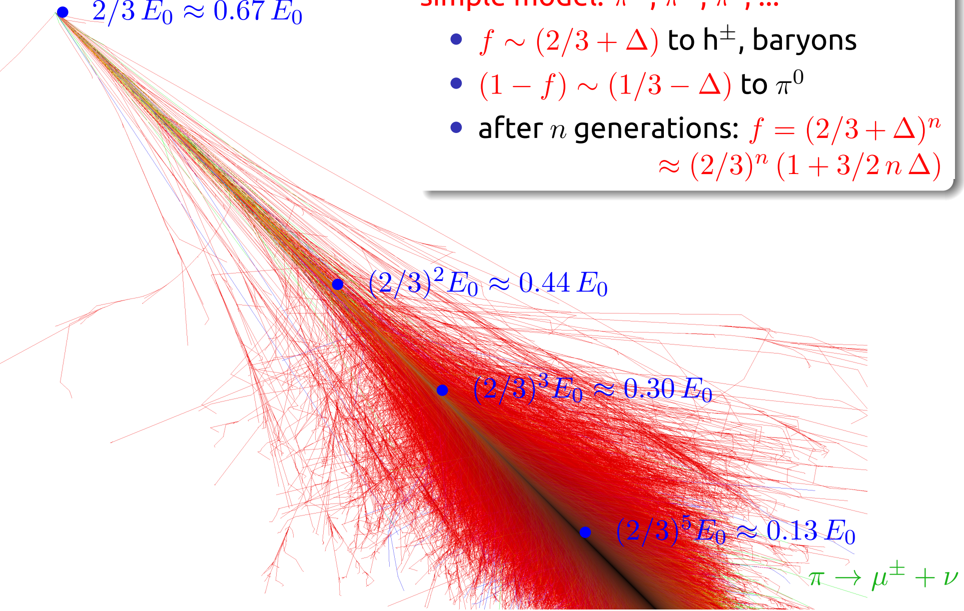
$\rightarrow$ fraction of initial energy in hadronic component after n interactions: f^n



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

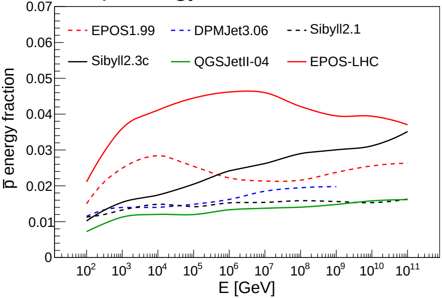
number of muons depends on energy fraction f of produced hadrons

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

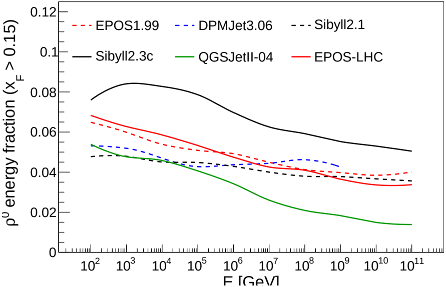
$\} \rightarrow$ hadronic shower

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

$\bar{p}$ energy fraction in π^--C

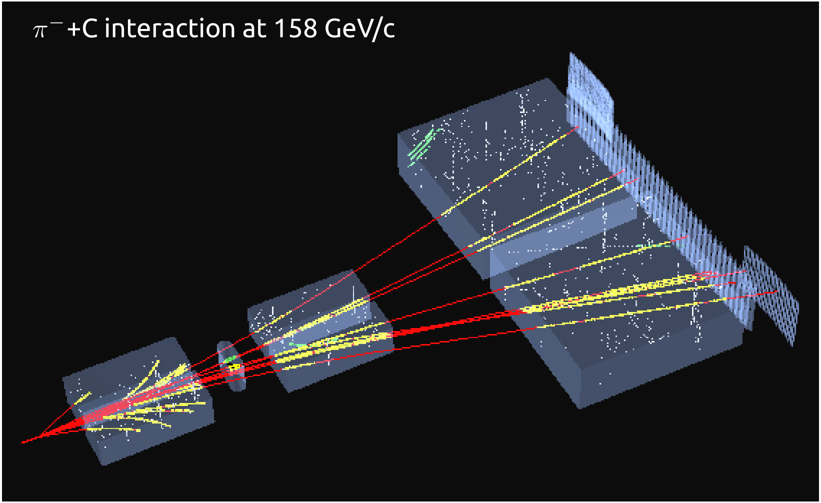


ρ^0 energy fraction in π^--C

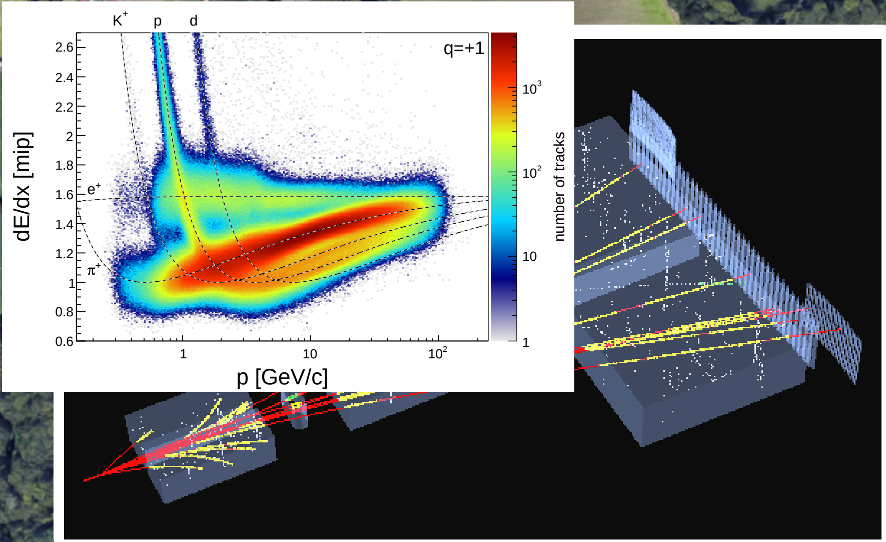


R.Prado ISVHECRI18, Pierog&Werner PRL17, Drescher PRD08

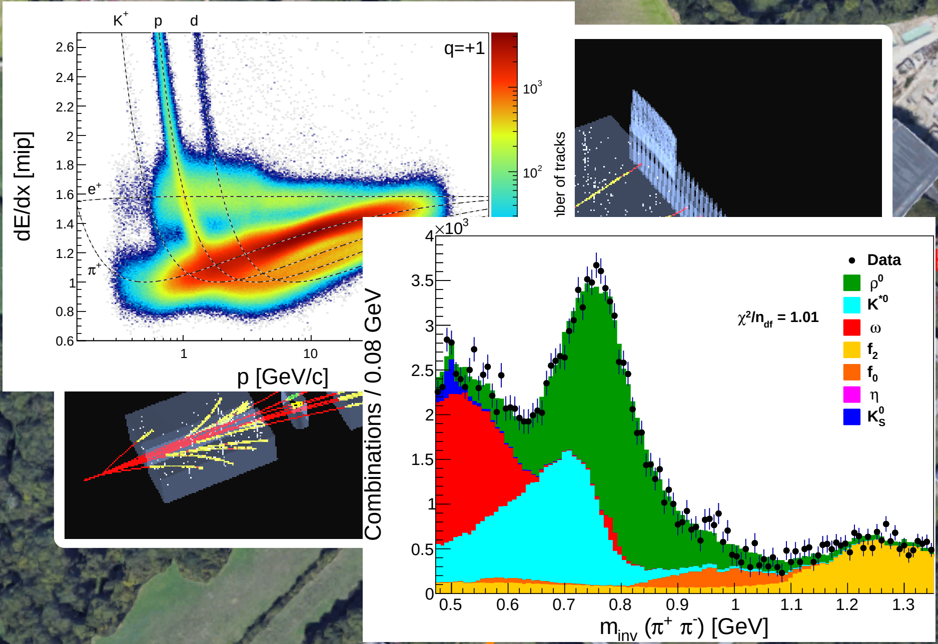
Particle Production Measurement with NA61/SHINE



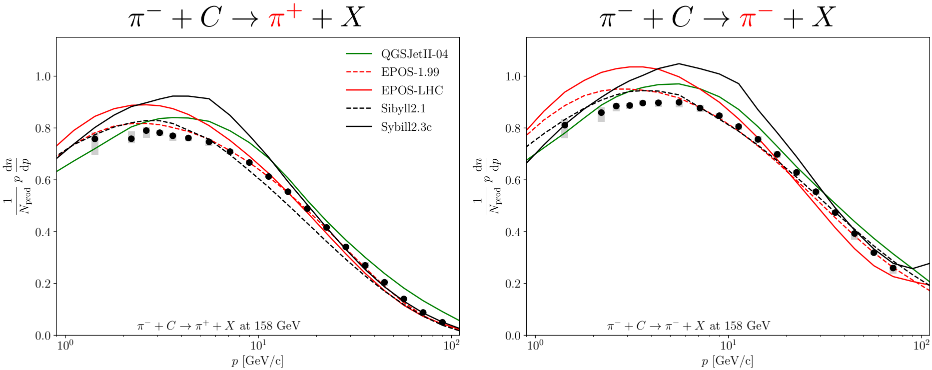
Particle Production Measurement with NA61/SHINE



Particle Production Measurement with NA61/SHINE



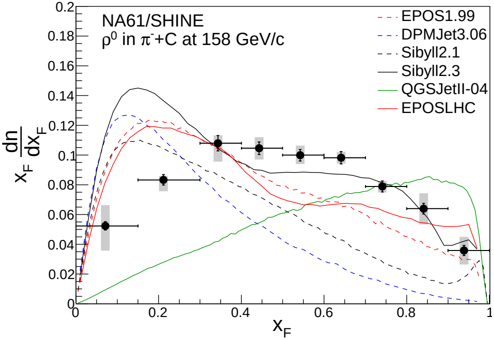
Pion Production in π^--C at 158 GeV/c (“the 2/3”)



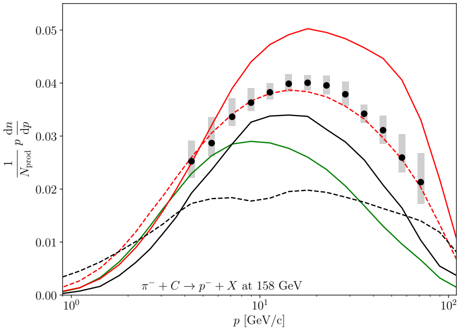
NA61/SHINE Collaboration, arXiv:2209.10561

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

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



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



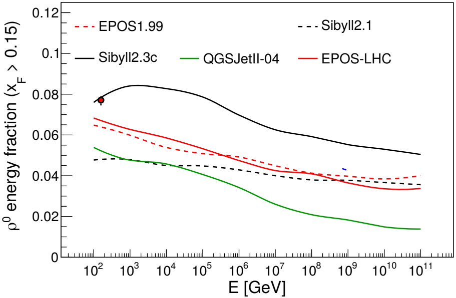
NA61/SHINE Collaboration, arXiv:2209.10561

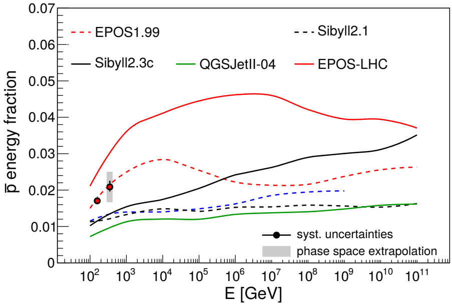
- forward ρ^0 can replace $\pi^0 \to \gamma\gamma$
- $\bar{p}$ is proxy for baryon production (p, $\bar{p}$, n, $\bar{n}$)

* 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 $\bar{p}$:

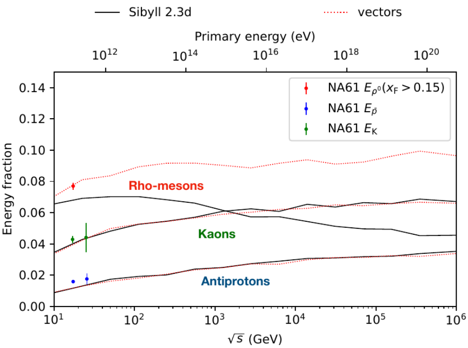




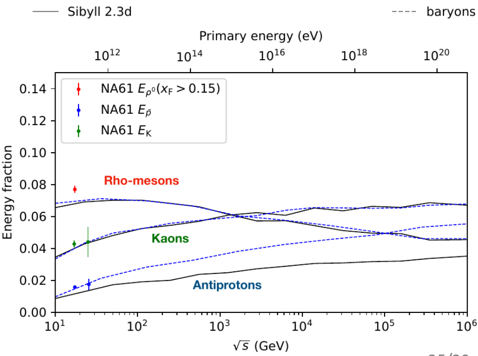
* and Λ, $\bar{\Lambda}$, $K^{\pm}$, K^0_S...

Solution to the “Muon Puzzle”?

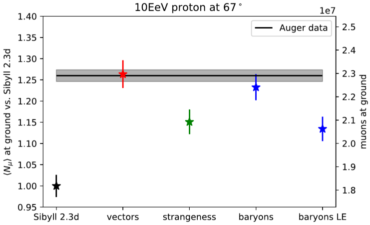
$$P_{\pi^0 \to \rho^0} = 0.6 \times (x_\mathrm{F})^{0.4}$$



$$P_{\pi\pi \to p\bar{p}} = 0.5 \times (x_\mathrm{F})^{0.7}$$

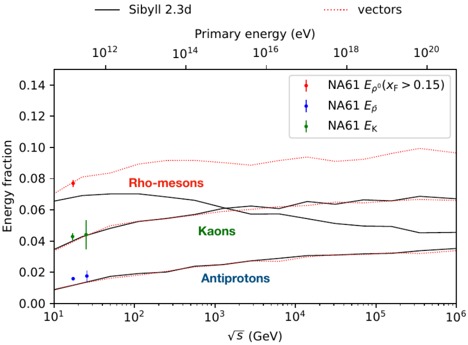


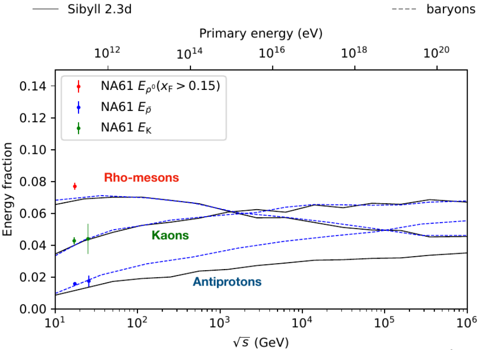
Riehn, Fedynitch, Engel UHECR22



$$P_{\pi^0 \to \rho^0} = 0.6 \times (x_F)^{0.4}$$

$$P_{\pi\pi \to p\bar{p}} = 0.5 \times (x_F)^{0.7}$$





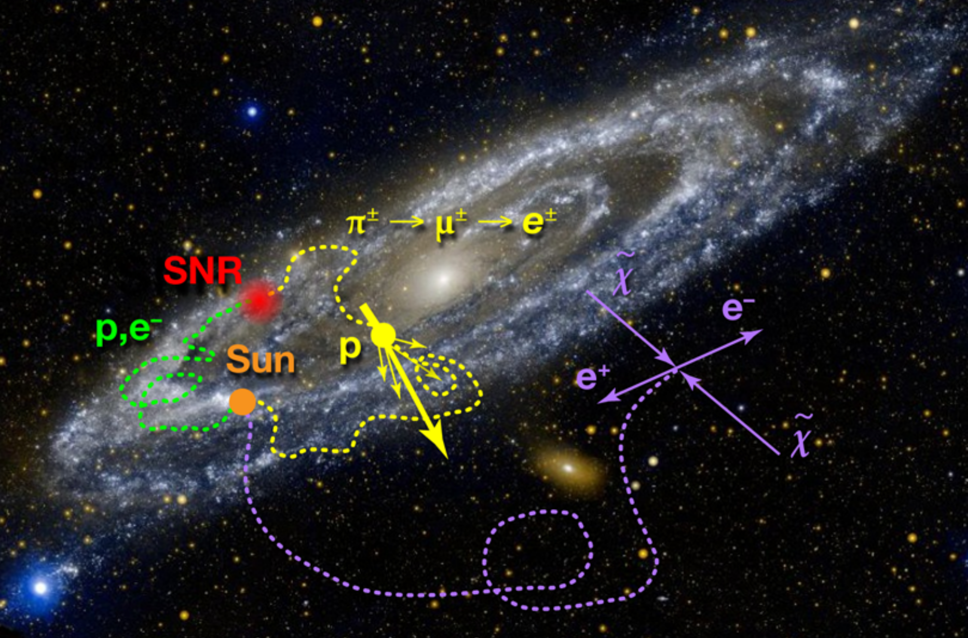
The Cosmic-Ray Program of the NA61/SHINE Facility

- Particle Production in Air Showers
  - p+C Interactions
    (31, 60, 90 120 GeV/c)
  - π+C Interactions ← this talk
    (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 ← this talk
    (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), arXiv:2209.10561 (submitted to PRD).

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. boron/carbon flux ratio (B/C)
- halo size ("target length") from unstable secondaries e.g. ^{10}Be/^{9}Be
- thin target approximation $\rightarrow$ $X \sim (\mathrm{B/C}) \, \frac{m_p}{\sigma_{\mathrm{prod}}}$

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

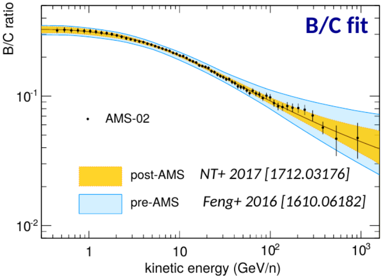
- prediction for e.g. anti-protons ($X \ll \lambda_{p\bar{p}}$):

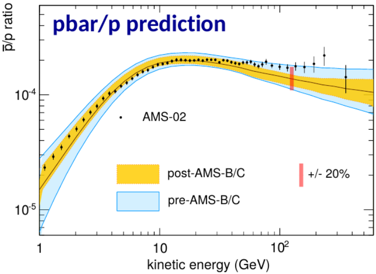
$$(\bar{p}/p) \sim X/\lambda_{p\bar{p}} = (\mathrm{B/C}) \, \frac{\sigma_{p\bar{p}}}{\sigma_{\mathrm{prod}}}$$

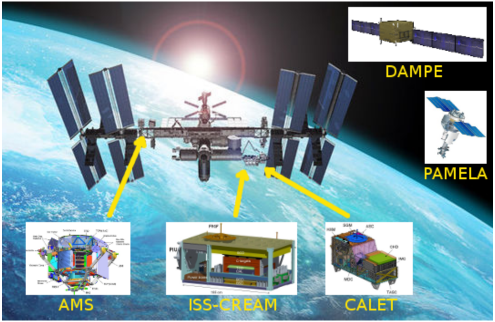
- relative uncertainty $\delta_X = \delta(X)/X$

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

Uncertainties of Cosmic-Ray Fluxes



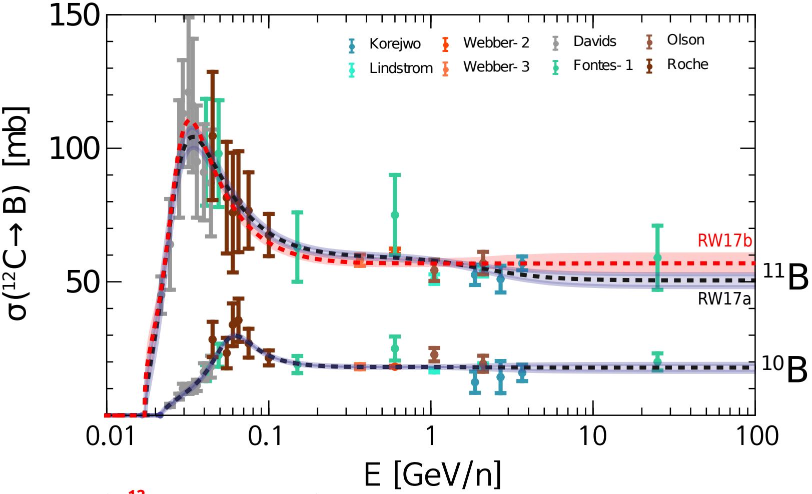




Uncertainties of Fragmentation Cross Sections

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

adapted from Reinert&Winkler, arXiv:1712.00002

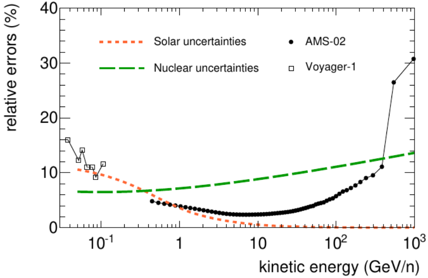


asymptotic ^{12}C→B cross section:

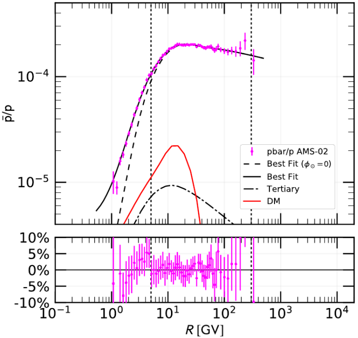
61.0 mb (WSKR03) (68.6±2.6) mb (RW17a), (75.8± 4.2) mb (RW17b)

Uncertainty of CR grammage ("target thickness")

N. Tomassetti, PRD 2017

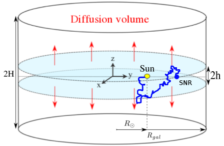


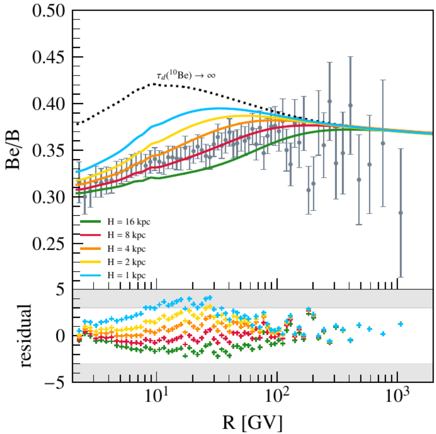
Heisig+2021

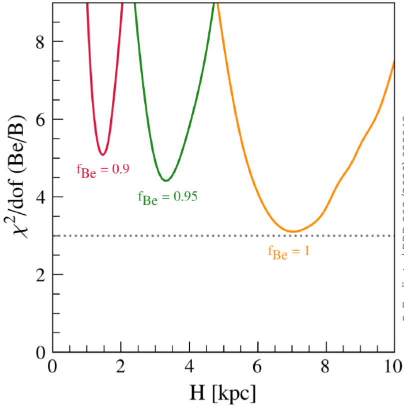


→ dominated by cross-section uncertainties!

Size of the Galactic Halo (“target length”)





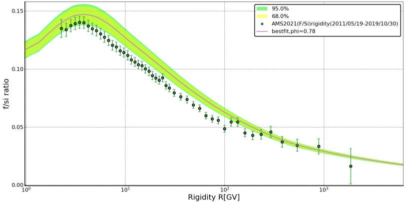


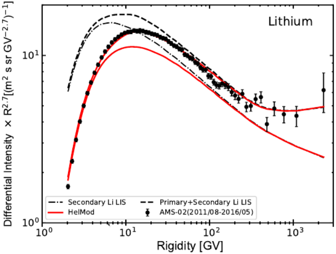
C. Evoli et al PRD 202 (2020) 023013

→ large uncertainties due to cross-section uncertainties!

Weinrich+20, Evoli+20, Luque+21, Maurin+22

New Cosmic-Ray Surprises: F Anomaly and Li Excess



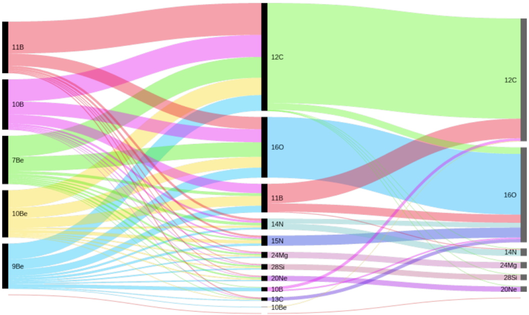


primary source of Li? spatial dependent diffusion? fragmentation cross sections?

2209.03799,2208.01337,2006.01337,2203.00522,2102.13238,2002.11406,2006.01337

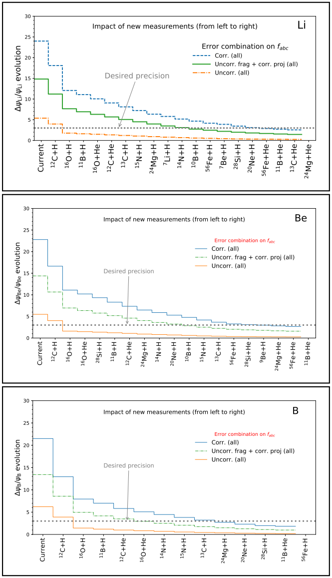
New Measurements of Nuclear Fragmentation Needed!

relevant reaction channels for Li, Be, B:



Tomassetti 2018

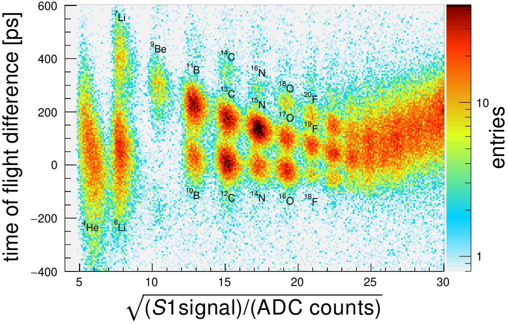
→ study production of light nuclei at SPS!



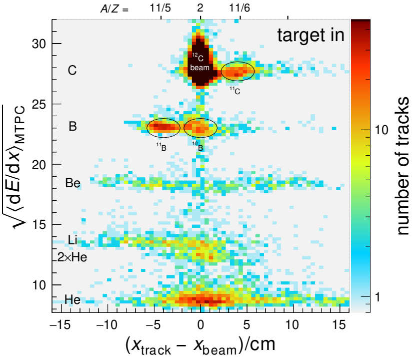
Genolini+18

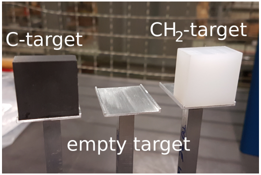
NA61/SHINE Pilot Run on Fragmentation, Dec 2018

SPS beam-fragment identification



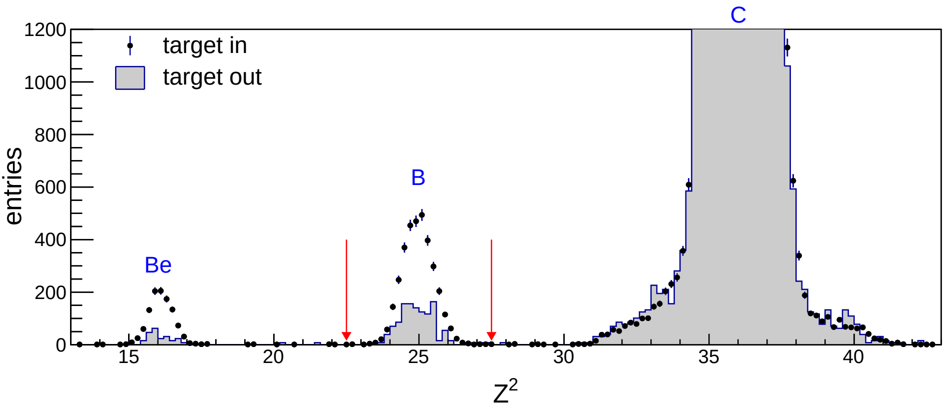
reaction-fragment identification





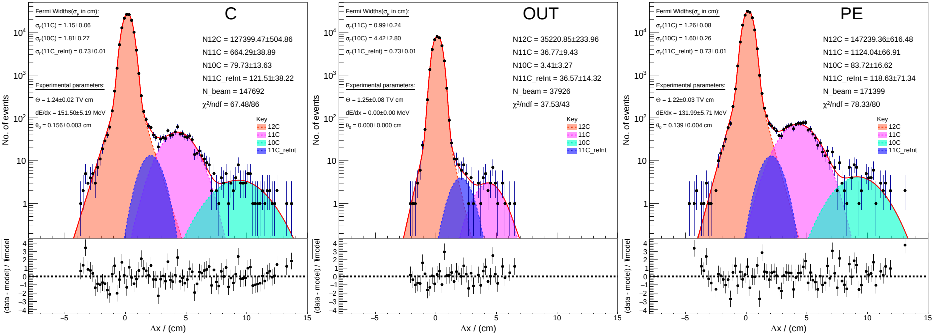
- 2.5 days data taking at 13.5 AGeV/c
- events after upstream ^{12}C selection:
  - 1.7×10^5 CH_2-target
  - 1.5×10^5 C-target
  - 0.4×10^5 empty-target

Particle Id in TPC: a) Z^2 via dE/dx



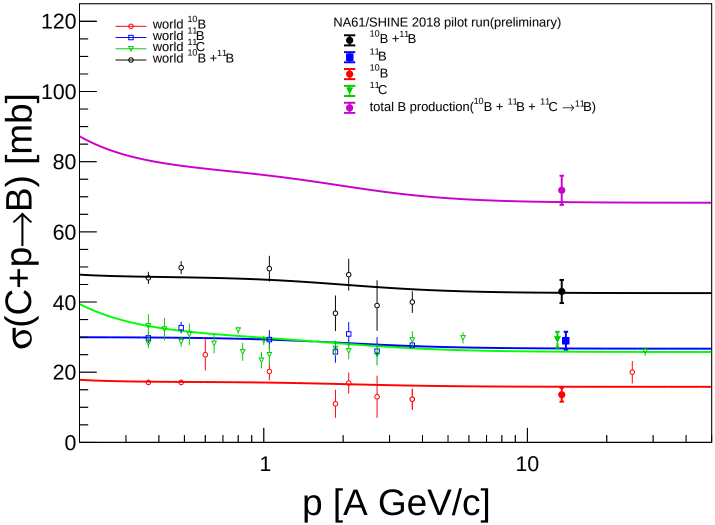
NA61/SHINE@ICRC19, arXiv:1909.07136

Particle Id in TPC: b) A/Z via in deflection in B-field



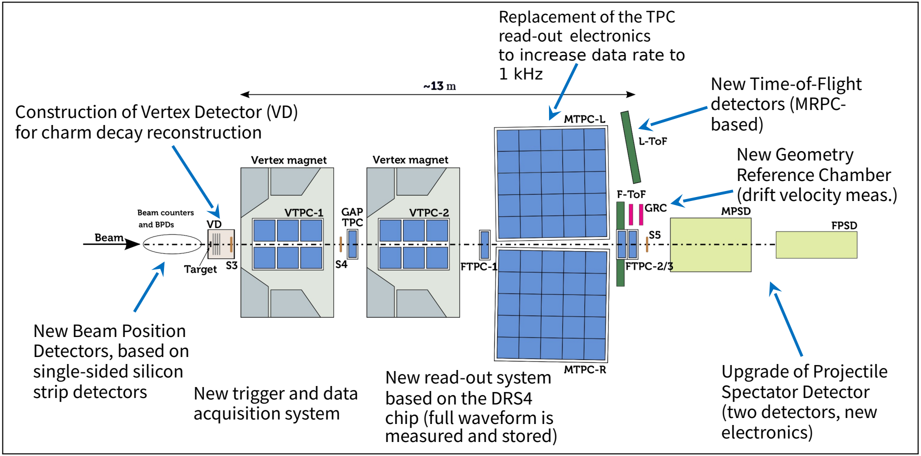
NA61/SHINE@ICRC21, arXiv:2107.12275

Results from Pilot Run on Boron Production (preliminary)



NA61/SHINE Status Report 2022, lines from C.Evoli, R.Aloisio, P.Blasi PRD 2019

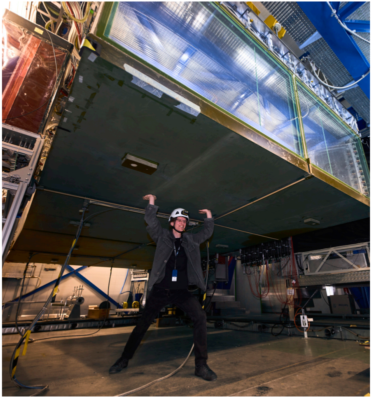
Recent Detector LS2 Upgrades



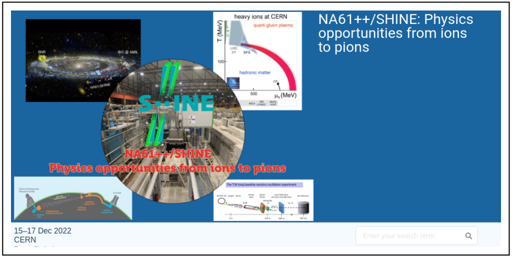
Outlook

Upcoming Cosmic-Ray Possibilities

- **2023** fragmented Pb beam?
  production of GCR secondaries Li, Be, B
- **2024** primary/fragmented oxygen?
  energy dependence, low-mass CR fragmentation
- **2025** hight statistics p-p?
  nucleon coalescence, anti-deuterons
- physics program after LS3 (> 2028)?

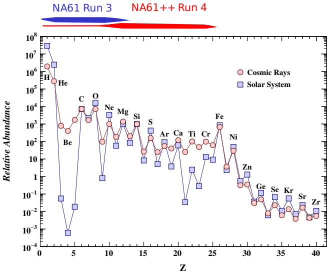


inside NA61 (Julien Ordan/CERN)

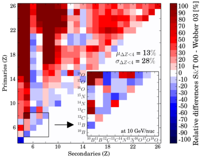


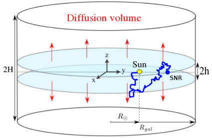
backup slides

Propagation of GCRs: High-Mass Nuclei



Particle Data Group 2022

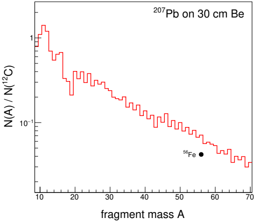




Y. Genolini et al. A&A **580** (2015) A9 and TAUP 2015

High-Mass Nuclei: Experimental Challenges

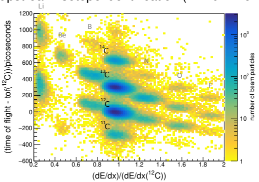
fragmented Pb beam



FLUKA simulation (N. Charitonidis)

→ high-mass group can saturate DAQ

upstream isotope identification (∼240 m ToF)



- pilot run at 14 AGeV/c: $\sigma(\mathrm{ToF}) \sim 30$ ps
- $\Delta t(^{12}\mathrm{C} - ^{13}\mathrm{C}) = 300$ ps
- $\Delta t(^{56}\mathrm{Fe} - ^{57}\mathrm{Fe}) = 75$ ps

→ difficult, but feasable

Nuclear Fragmentation in Air Showers

Model Predictions: Heavy Nuclei

Naive superposition:

mean: $\mu_X(A, E) = \mu_X(p, E/A)$

fluctuations: $\sigma_X(A) = \frac{1}{\sqrt{A}}\sigma_X(p)$

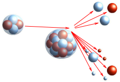
Nuclear cross sections and fragmentation:

mean: $\mu_X(A, E) \approx \mu_X(p, E/A)$ (!)

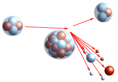
fluctuations: $\sigma_X(A) \ll \frac{1}{\sqrt{A}}\sigma_X(p)$

extreme cases:

spectator nucleons

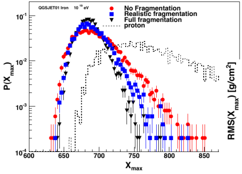


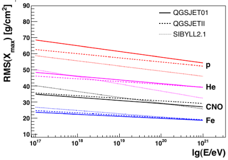
single spectator nucleus



$s_X(A) \quad < \sigma_X(A) < \quad S_X(A)$

Importance of nuclear fragmentation for fluctuations





RMS(Xmax) = 29 g/cm²
21 g/cm²
16 g/cm²

Nuclear fragmentation is important for quantitative predictions

Engel&Pierog ISVHECRI 2010