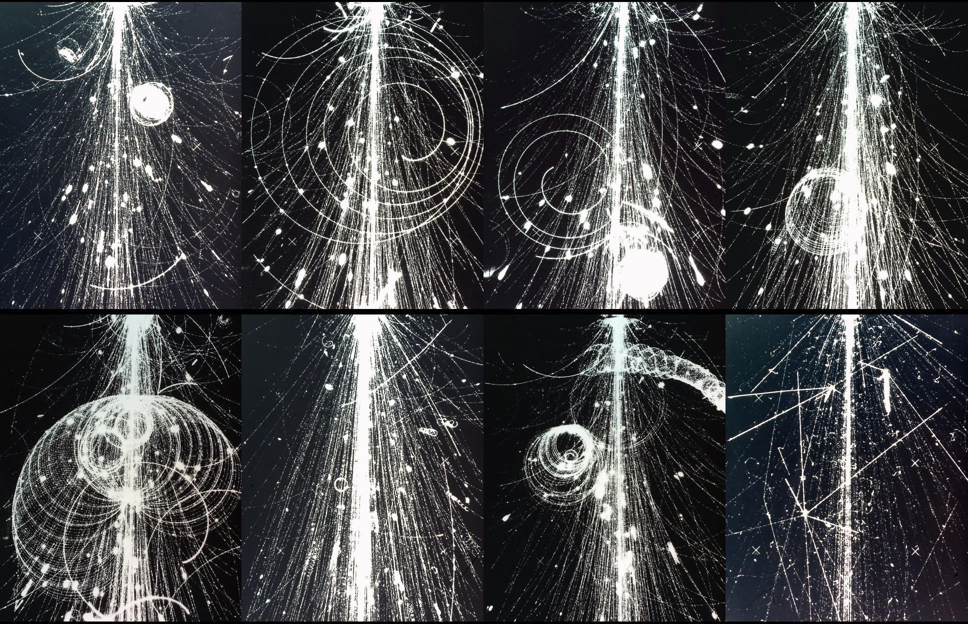
Cosmic-Ray Insights from NA61/SHINE at the CERN SPS

Michael Unger (KIT) for the NA61/SHINE Collaboration



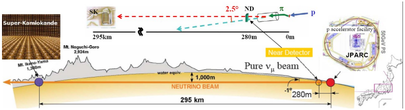
NA35 3.2 TeV O+Pb interactions

NA61/SHINE

≈ 140 physicists from 14 countries and 28 institutions

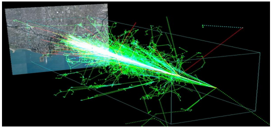
Strong interactions physics

- 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



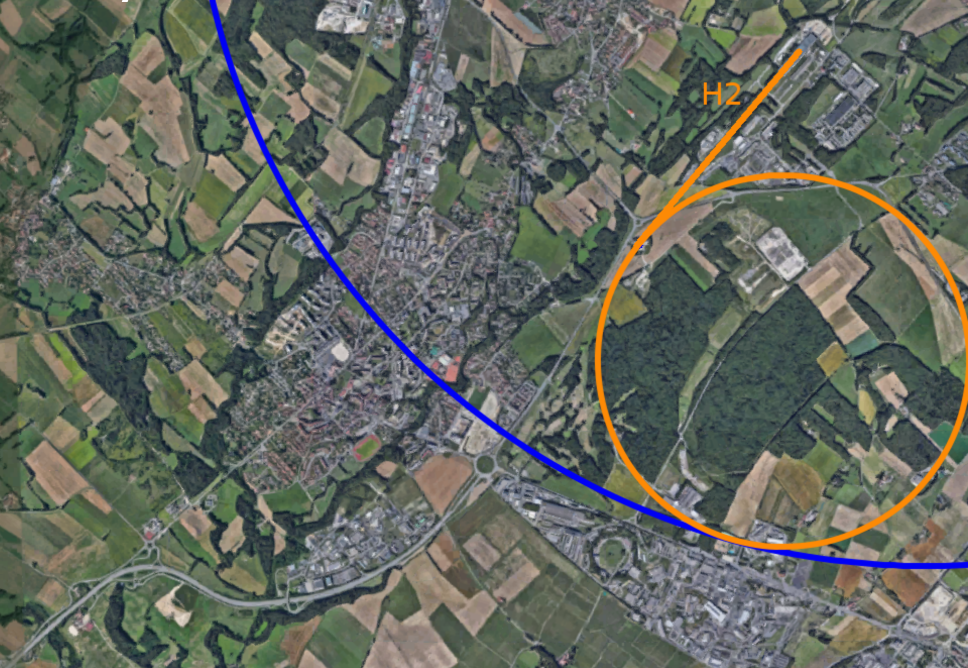
Neutrino and cosmic ray physics

- 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



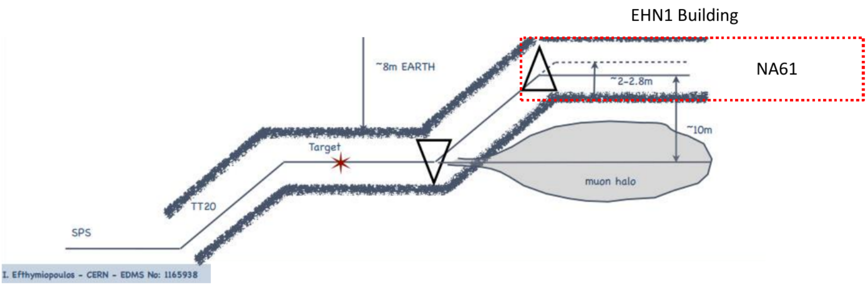
cosmic ray groups: KIT (Germany), Uni. Hawaii (USA), Uni. Silesia (Poland)

NA61/SHINE at the SPS H2 Beam Line



NA61/SHINE at the SPS H2 Beam Line

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



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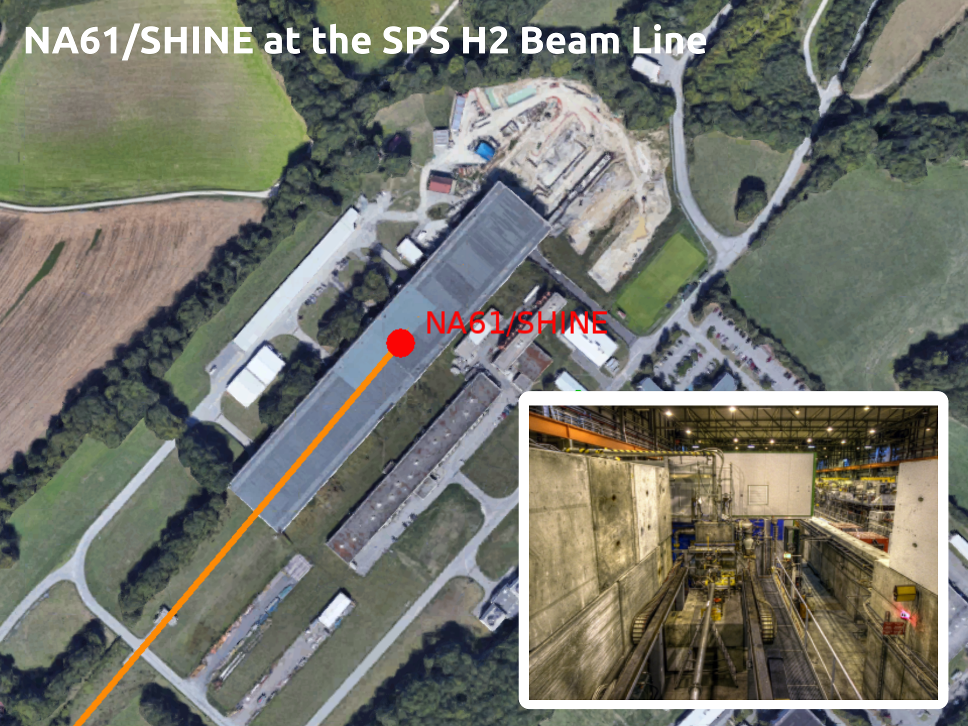
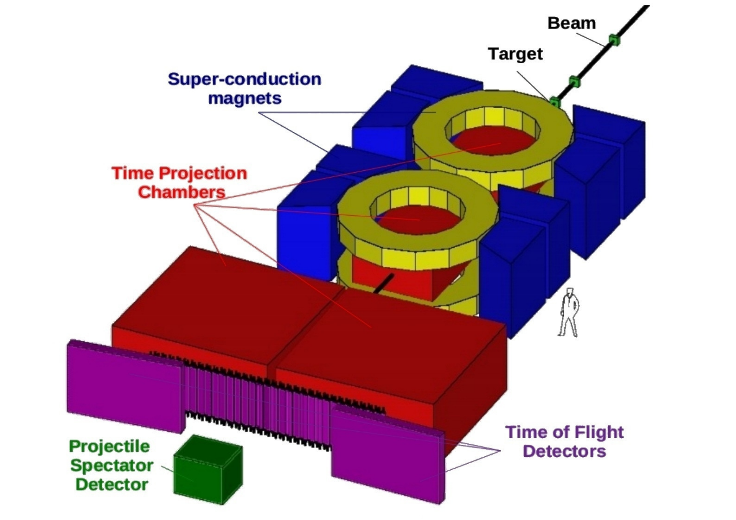
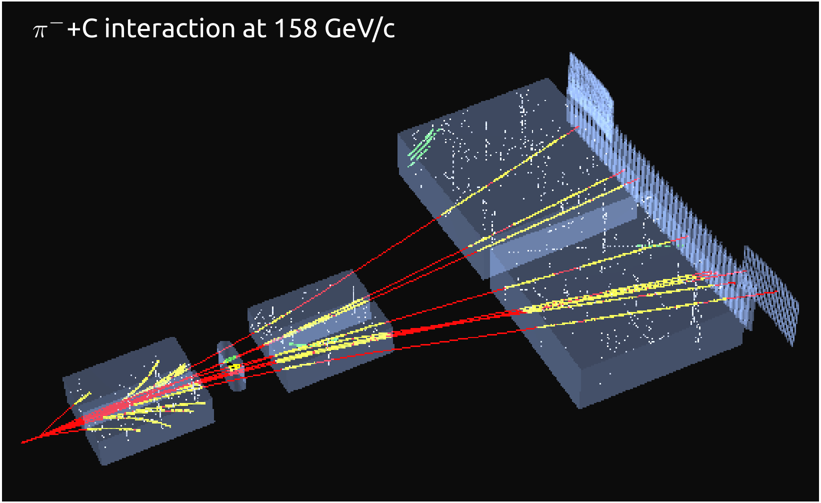


NA61/SHINE Detector



- 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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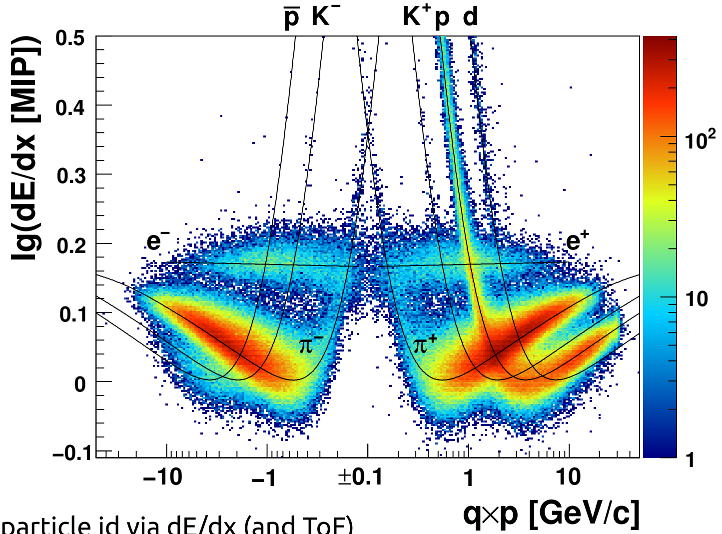

particle id via dE/dx (and ToF)

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.

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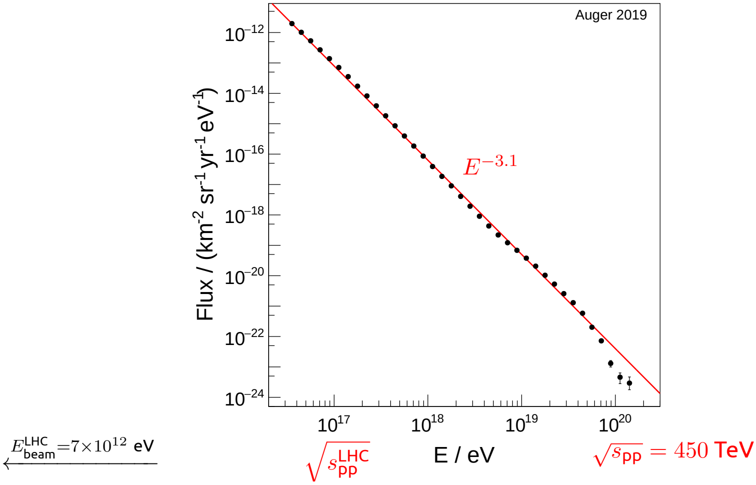
Energy Spectrum of Ultrahigh-Energy Cosmic Rays



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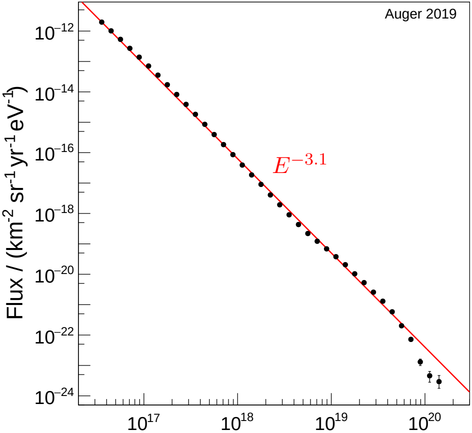


$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

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

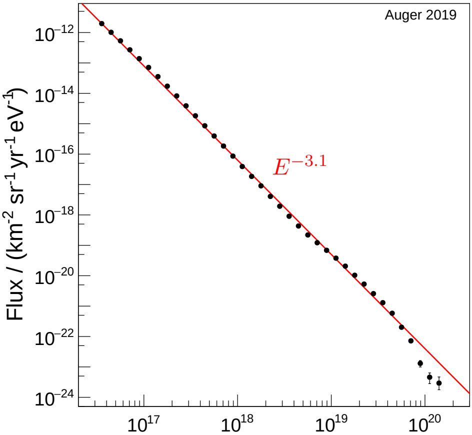
$\sim$20 J!

Serena Williams' 2nd serve

$E_{\text{beam}}^{\text{LHC}} = 7\times10^{12}$ eV

$E_{\text{kin}} \sim 4$ TeV

Energy Spectrum of Ultrahigh-Energy Cosmic Rays

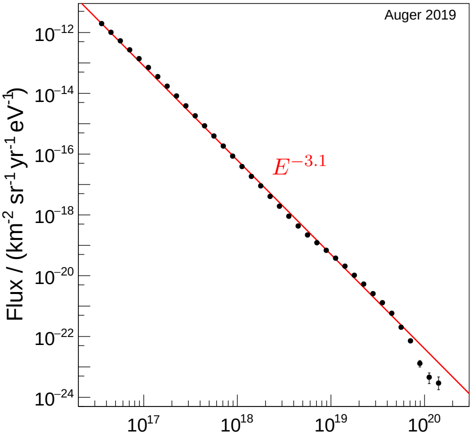


$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

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

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

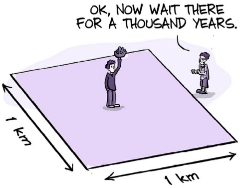
Energy Spectrum of Ultrahigh-Energy Cosmic Rays



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

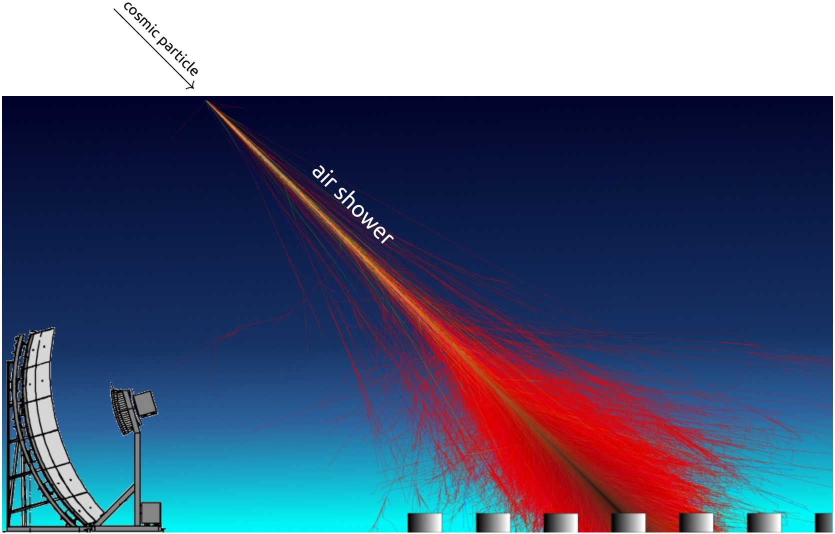
$E_{beam}^{LHC} = 7 \times 10^{12}$ eV

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



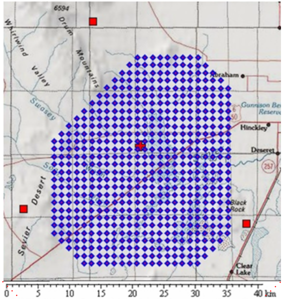
J. Cham&D. Whiteson "We have no idea", Penguin, 2018

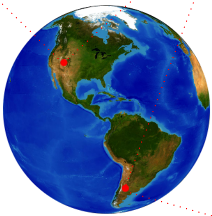
Detection of Ultrahigh-Energy Cosmic Rays



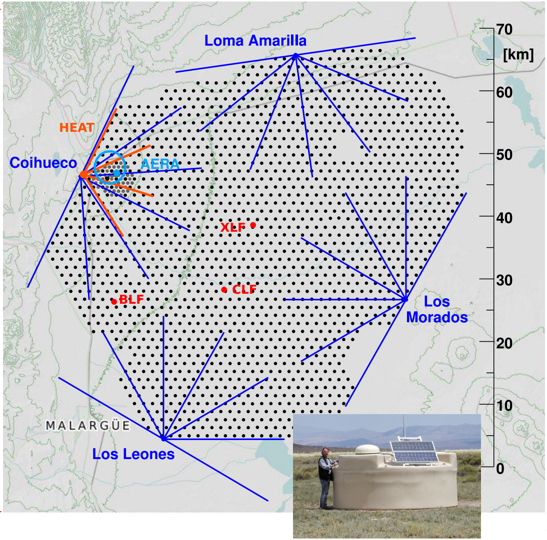
Detection of Ultrahigh-Energy Cosmic Rays

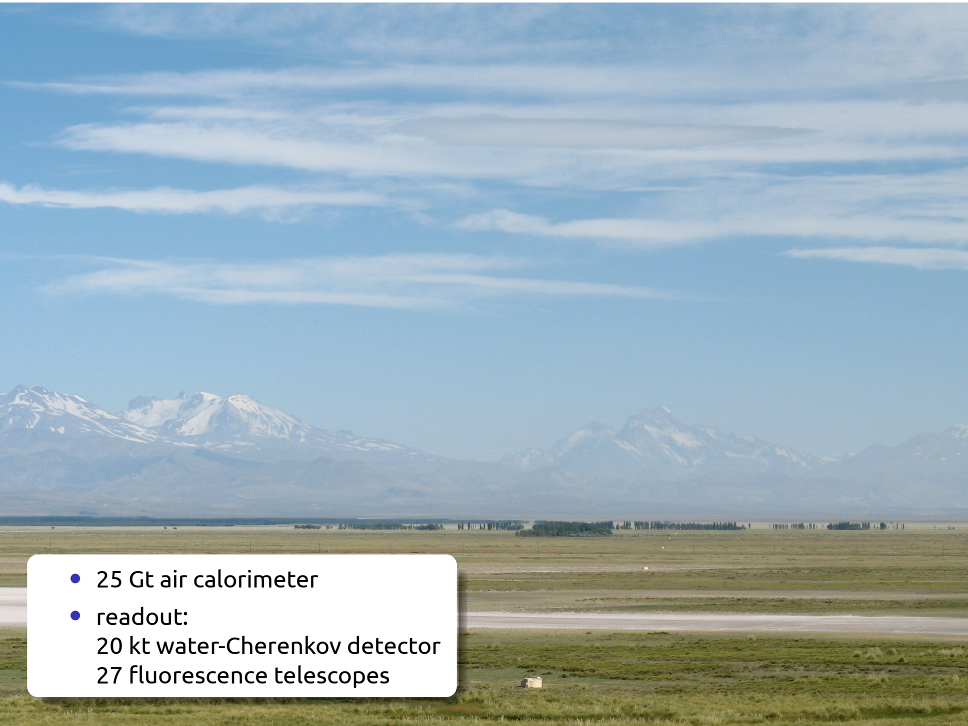
Telescope Array





Pierre Auger Observatory

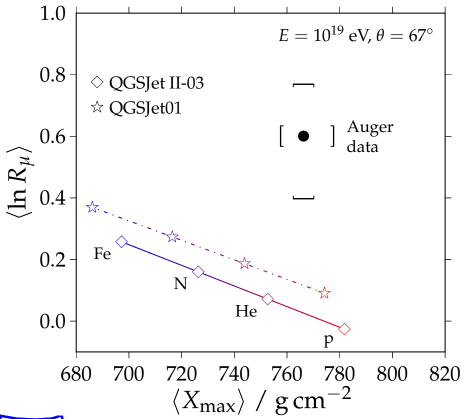


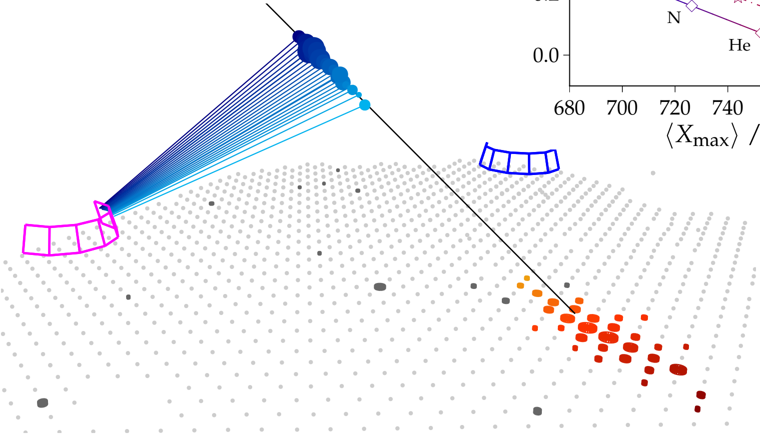


- 25 Gt air calorimeter
- readout:
  20 kt water-Cherenkov detector
  27 fluorescence telescopes

Muon Production in Air Showers

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





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

Muon Production in Air Showers

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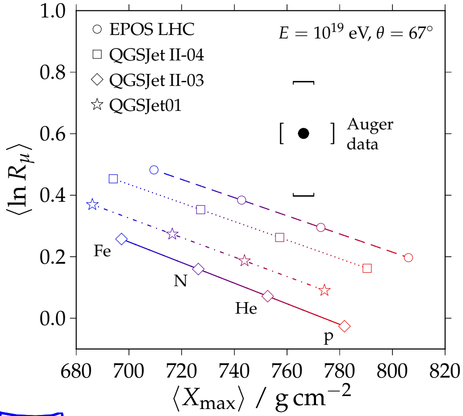
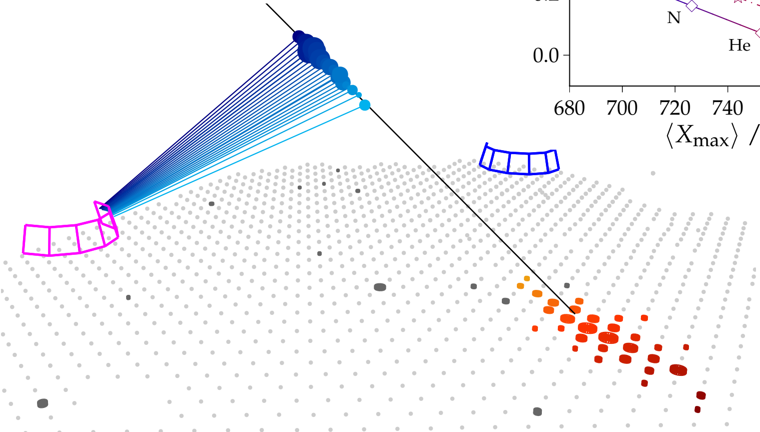
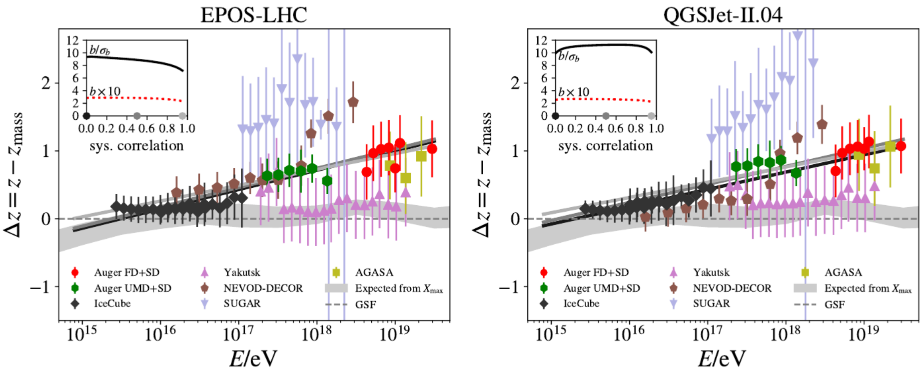




Pierre Auger Coll., PRD **D91** (2015) 3, 032003

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 $\rightarrow \pi/K + X$

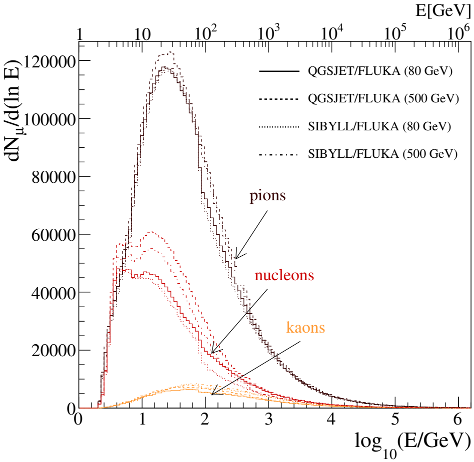
$\searrow$

$\mu + \nu_\mu$

ultrahigh-energy air shower

e.g. Auger:

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



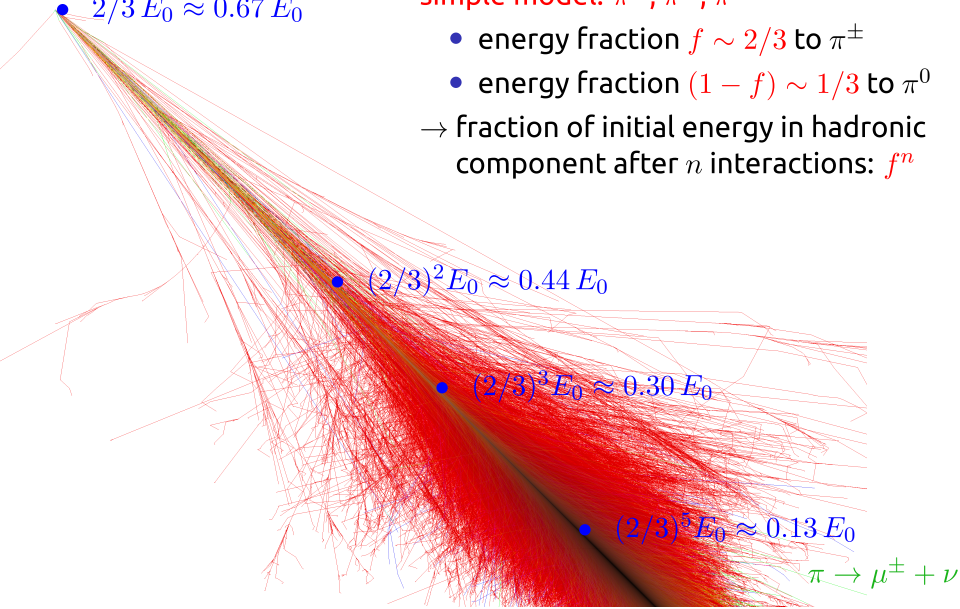
I.C. Mariş for NA61/SHINE, Proc. 31st ICRC, (2009)

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

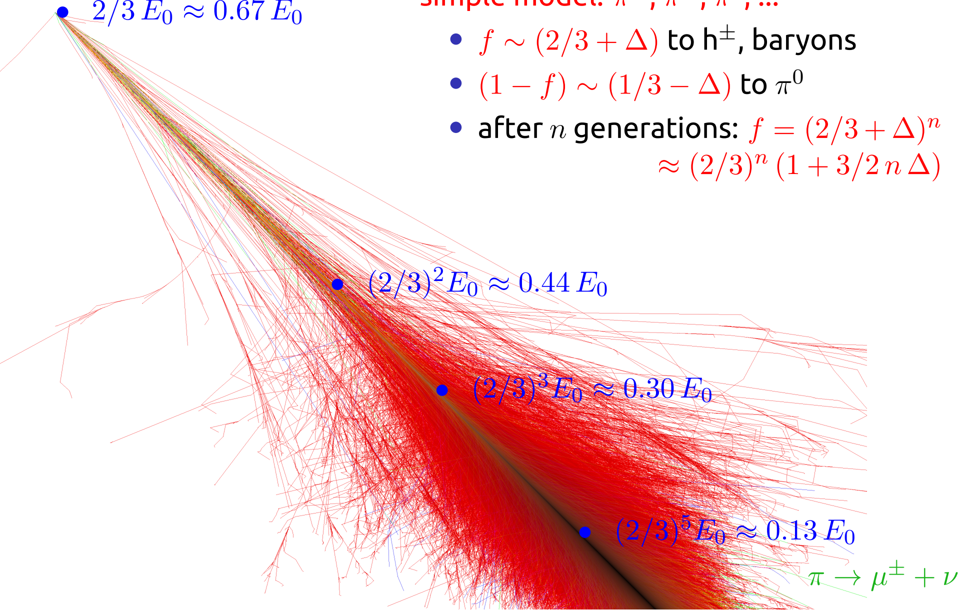
$\rightarrow$ fraction of initial energy in hadronic component after n interactions: f^n



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: $f = (2/3 + \Delta)^n$
  $\approx (2/3)^n \, (1 + 3/2 \, n \, \Delta)$



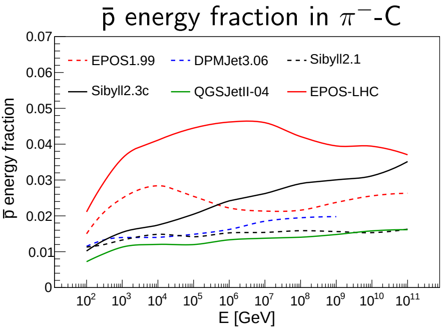
Muons in UHE Air Showers

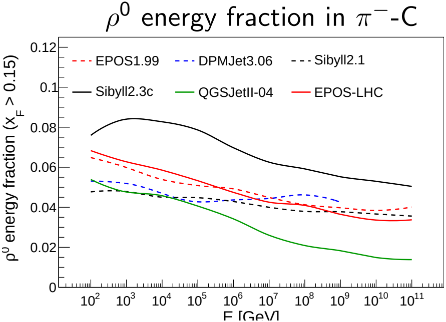
number of muons depends on energy fraction f of produced hadrons

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

} $\rightarrow$ hadronic shower

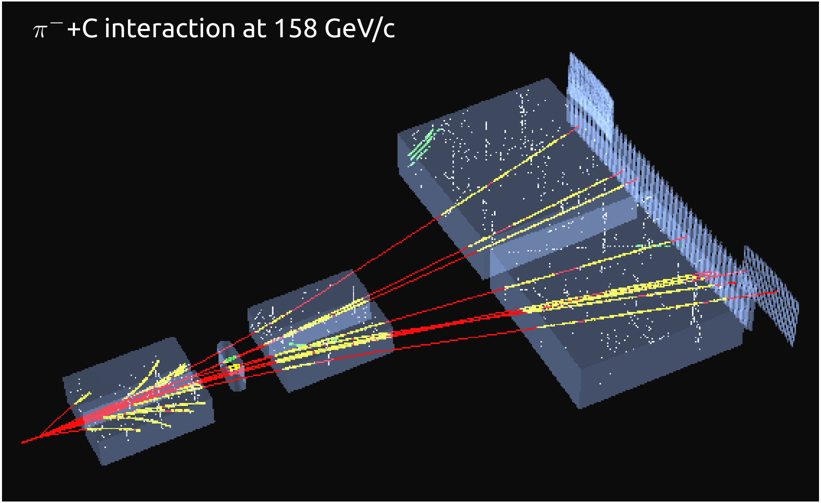
$$N_\mu \propto \Pi_{i=1}^{n_{\text{int}}} f_i$$





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

Particle Production Measurement with NA61/SHINE



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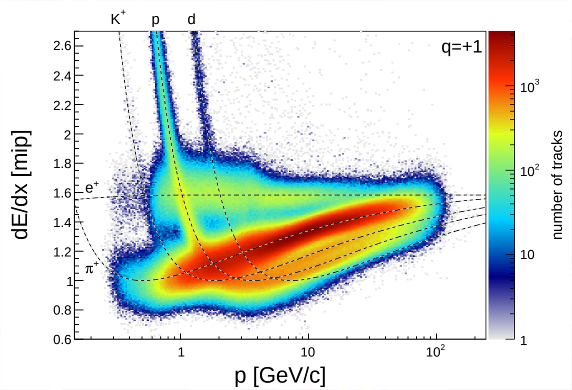

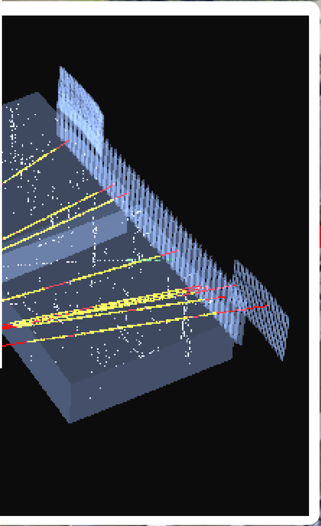

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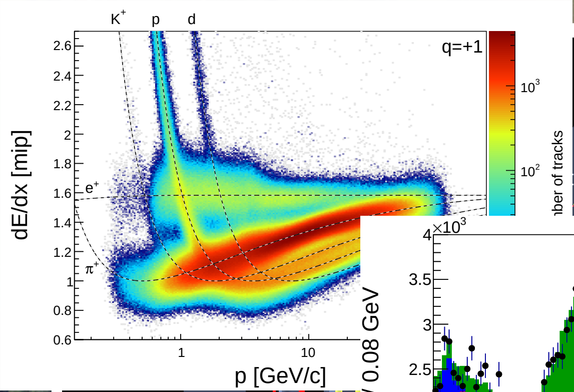
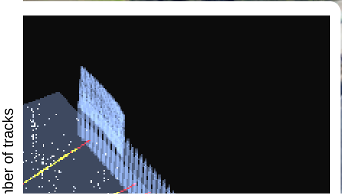
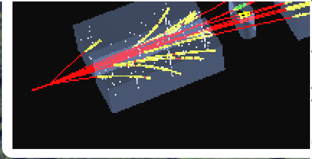
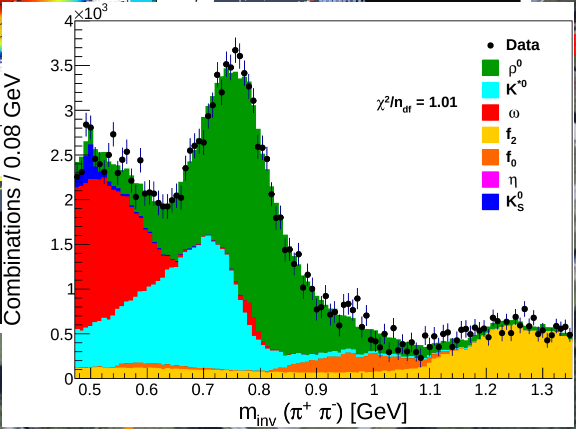








PHYSICAL REVIEW D **107**, 062004 (2023)

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

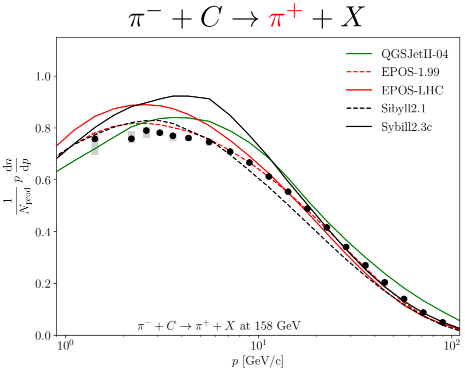
THE EUROPEAN PHYSICAL JOURNAL C

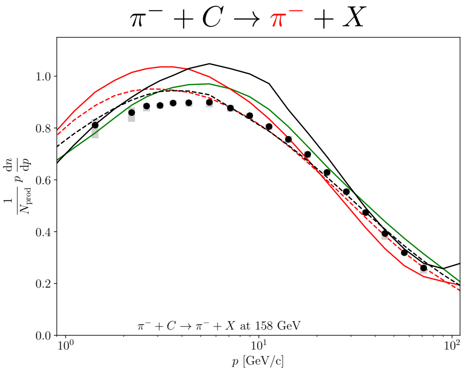
Measurement of meson resonance production in π^-+ C interactions at SPS energies

- 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 ("the 2/3")

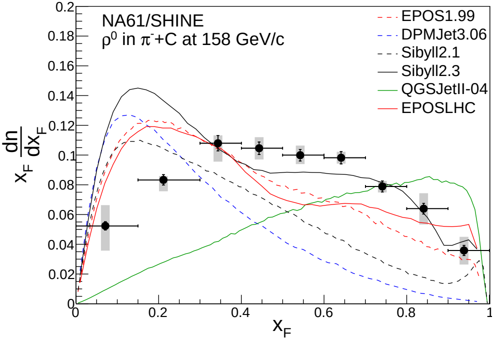




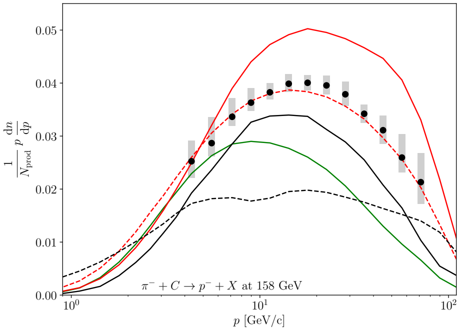
NA61/SHINE Collaboration PRD **107** (2023) 062004

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



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



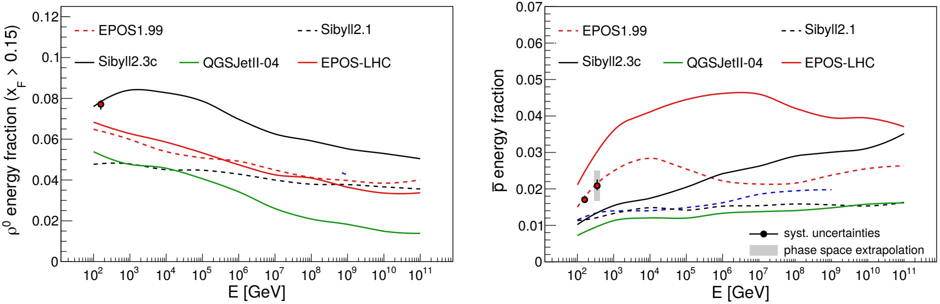
NA61/SHINE PRD **107** (2023) 062004

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

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

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

energy fraction of ρ^0 and $\bar{p}$:

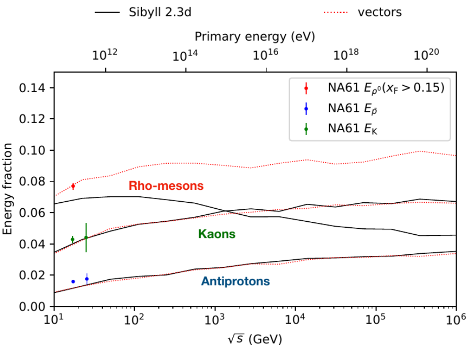


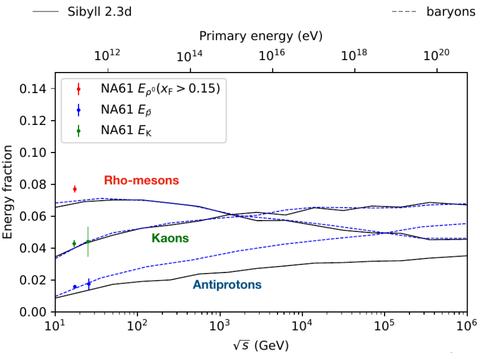
* and Λ, $\bar{\Lambda}$, K$^{\pm}$, K^0_S...

Solution to the "Muon Puzzle"?

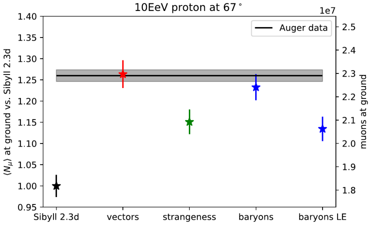
$$P_{\pi^0\to\rho^0} = 0.6 \times (x_F)^{0.4}$$

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





Riehn, Fedynitch, Engel UHECR22



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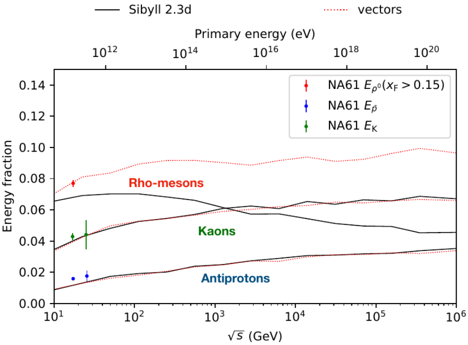

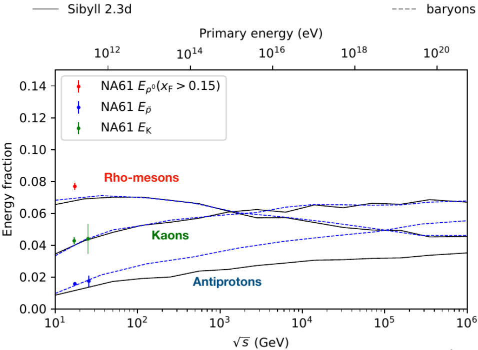

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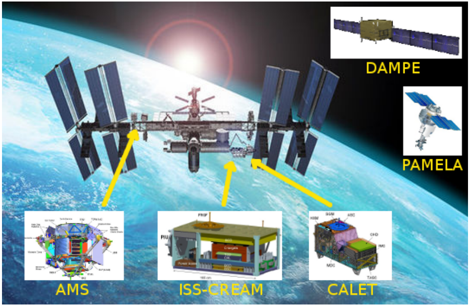
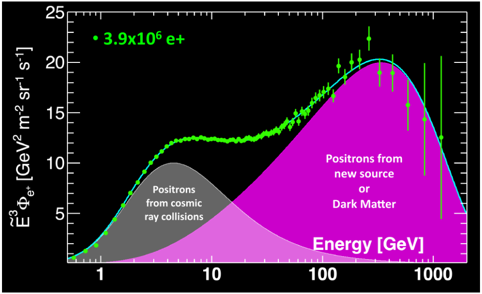
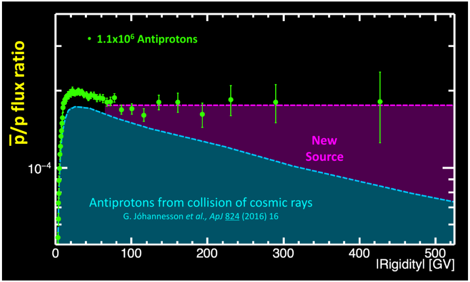
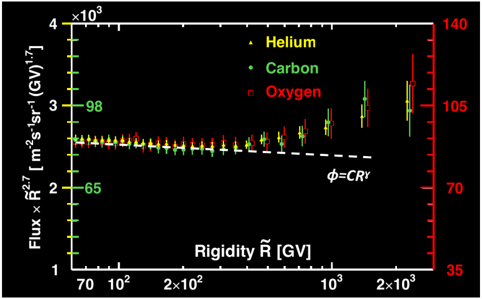
“A Cosmic Ray Renaissance” P. Blasi, EuCAPT 2021



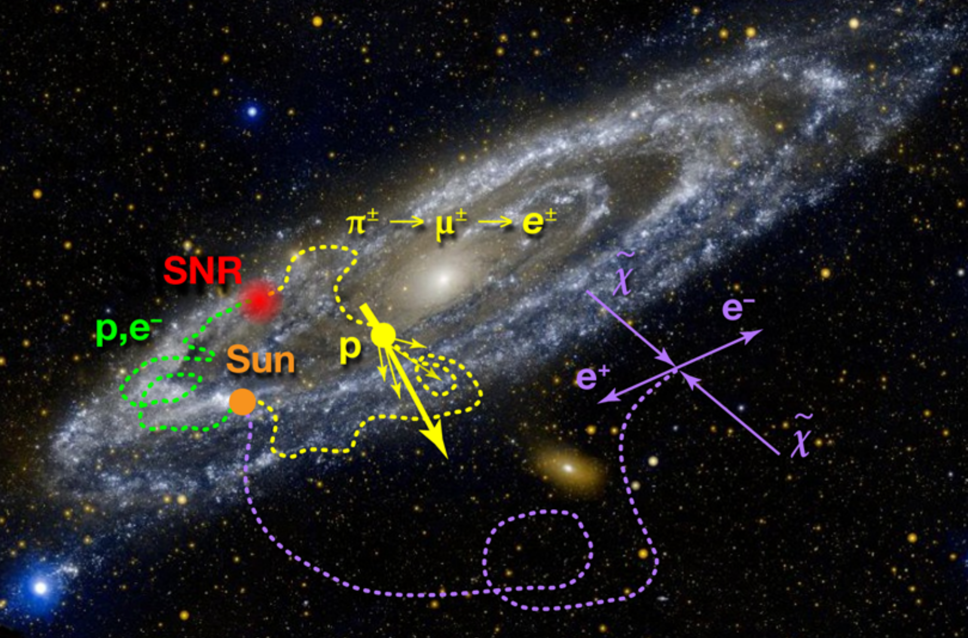






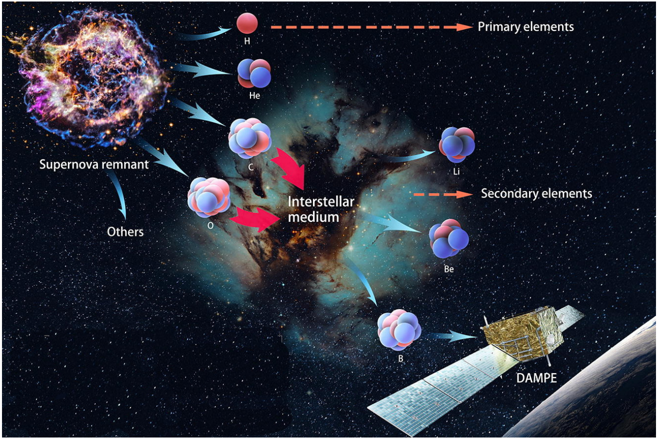
slides from S. Ting / AMS Collaboration, CERN Colloqium June 8 2023

Particle Production in the Galaxy



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

Calibration: Primary and Secondary Cosmic-Ray Nuclei



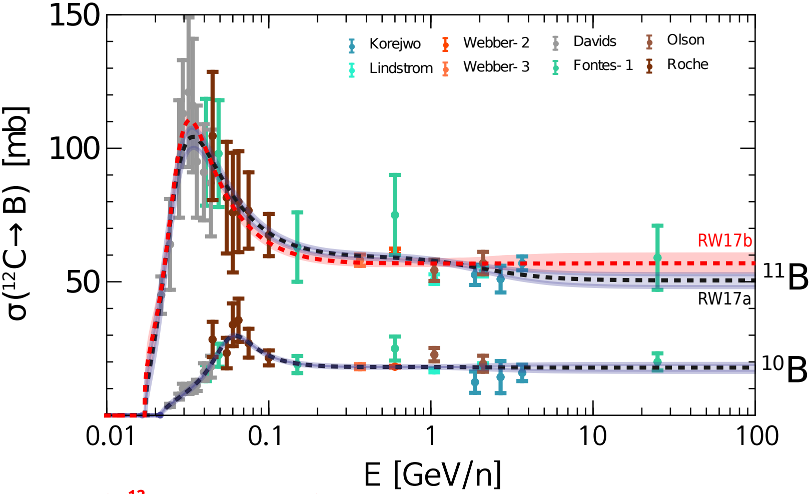
Sci.Bull. 67 (2022) 2162

- 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 $\rightarrow$ need to know fragmentation cross sections!

Uncertainties of Fragmentation Cross Sections

Example: $^{12}C+p \to B$ (including ^{11}C)

adapted from Reinert&Winkler, arXiv:1712.00002

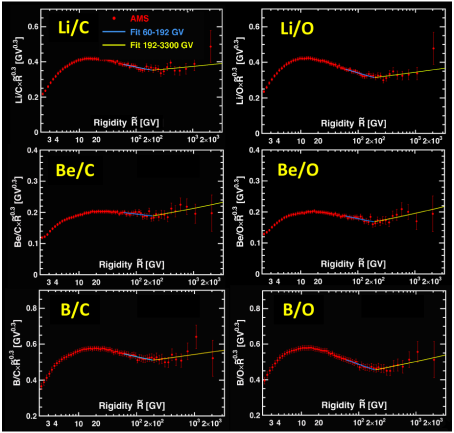


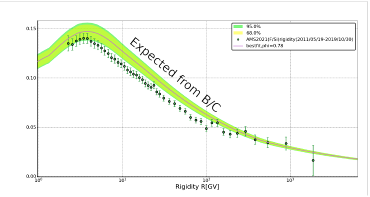
asymptotic $^{12}C \to B$ cross section:

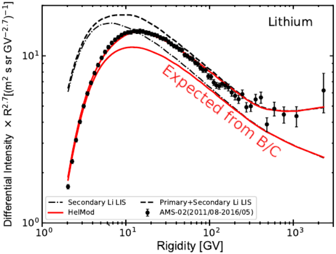
61.0 mb (WSKR03) (68.6±2.6) mb (RW17a), (75.8± 4.2) mb (RW17b)

Secondary/Primary CRs: F Anomaly and Li Excess

S. Ting / AMS Collaboration, CERN Colloqium June 8 2023



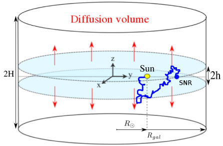


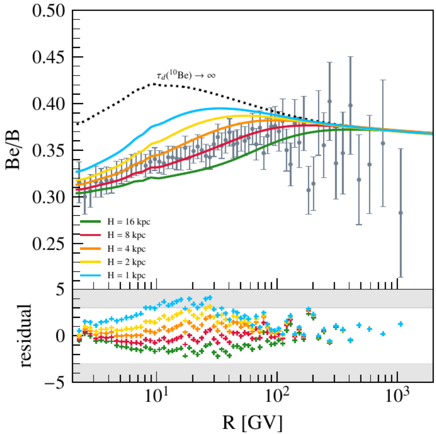


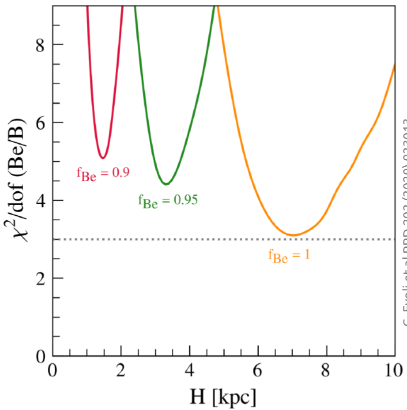
primary source of Li? spatial dependent diffusion? fragmentation cross sections?

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

Size of the Galactic Halo ("target length")







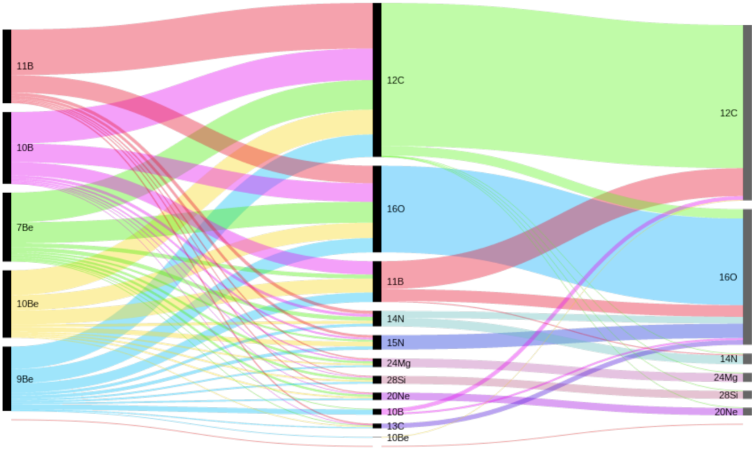
C. Evoli et al PRD 202 (2020) 023013

→ large uncertainties due to cross-section uncertainties!

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

New Measurements of Nuclear Fragmentation Needed!

relevant reaction channels for Li, Be, B:



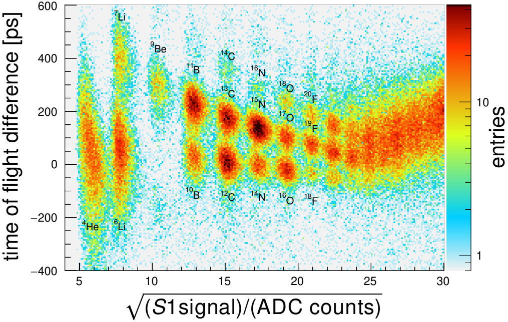
Tomassetti 2018

→ study production of light nuclei at SPS!

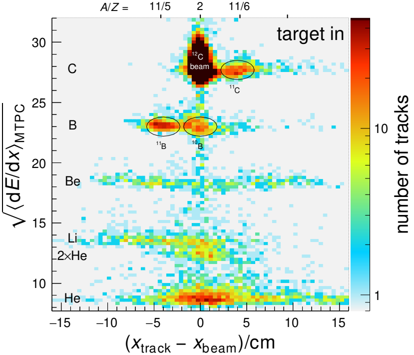
NA61/SHINE Pilot Run on Fragmentation, Dec 2018

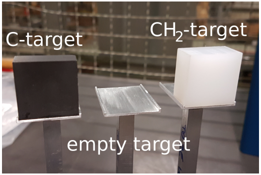
13.5 A GeV/c fragmented Pb beam

SPS beam-fragment identification



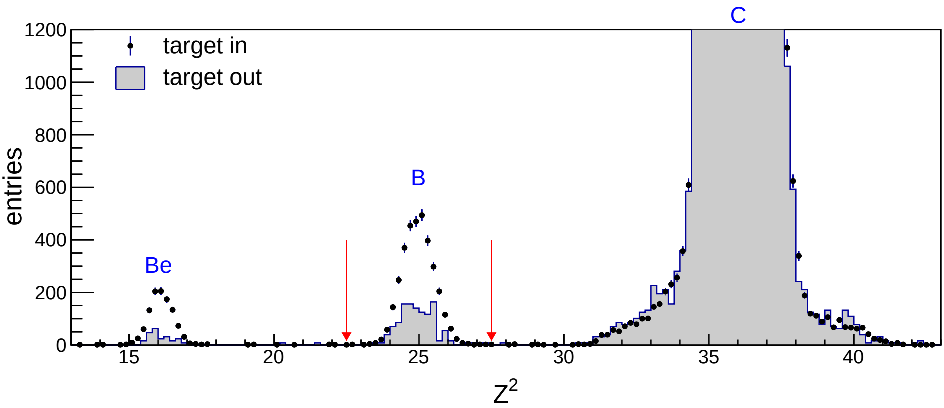
reaction-fragment identification





- 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

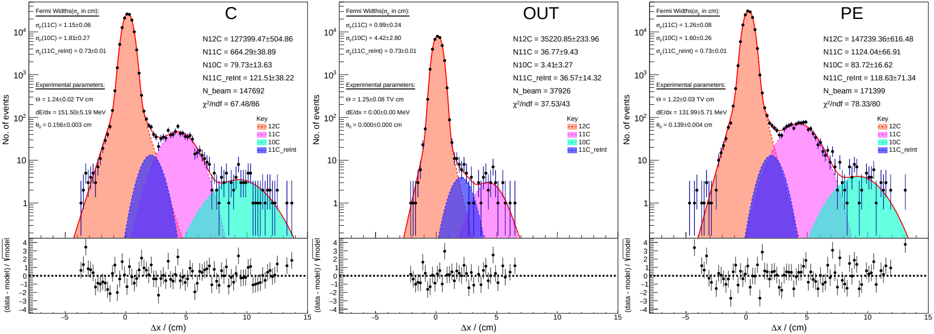
Particle Id in TPC: a) Z^2 via dE/dx



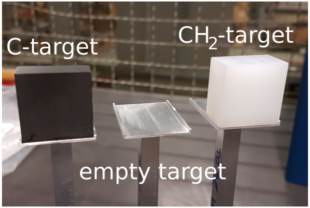
NA61/SHINE@ICRC19, arXiv:1909.07136

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

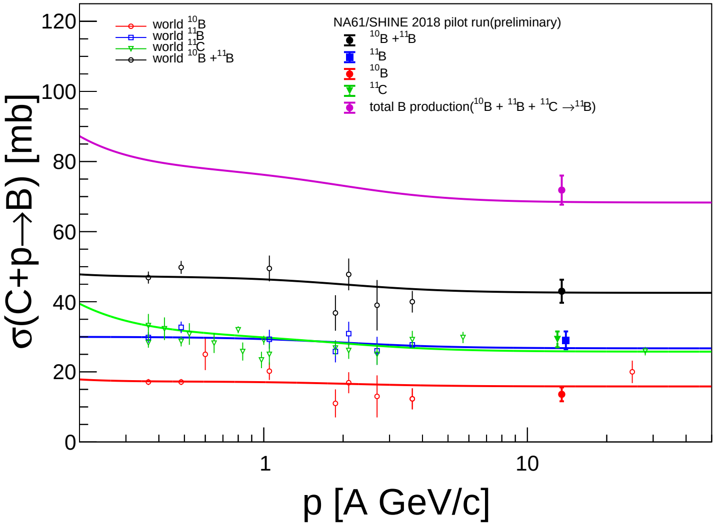
carbon fragments:



NA61/SHINE@ICRC21, arXiv:2107.12275



Results from Pilot Run on Boron Production (preliminary)



NA61/SHINE Status Report 2022, PoS ICRC2019 446, PoS ICRC2021 102, lines from C.Evoli, R.Aloisio, P.Blasi PRD 2019

Timeline towards a Physics Run

2017
- first ideas at XSCRC at CERN
- Proposal of Test Run CERN-SPSC-2017-035

2018
- quantification of needed data Phys. Rev. C 98, 034611 (Editors' Suggestion)
- Proposal of early post-LS2 Measurements CERN-SPSC-2018-008
- three days of pilot data taking in December 2018

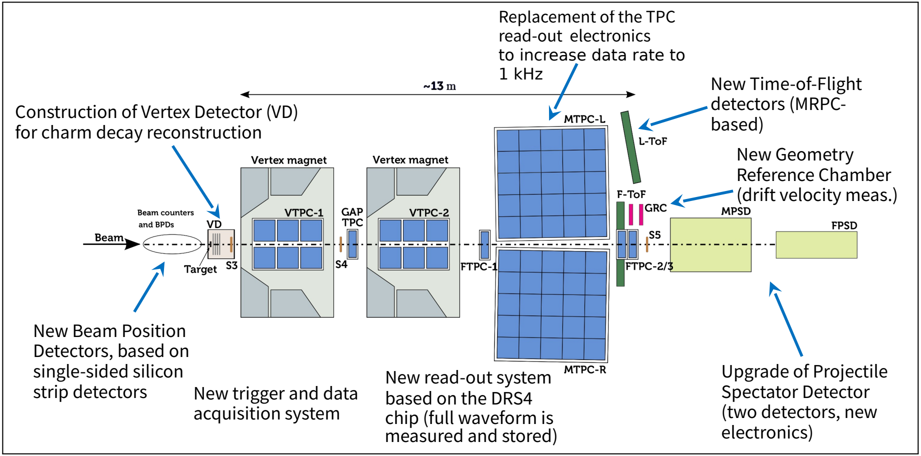
2019
- preliminary release of $\sigma(^{12}\mathrm{C} + \mathrm{p} \to \mathrm{B} + \mathrm{X})$ at ICRC and at XSCRC at CERN
- NCN/DFG Beethoven grant for NA61 upgrade (cosmic rays)
- SPSC recommendation
  "The SPSC notes with satisfaction the promising results the pilot run with the fragmented ion setup to understand cosmic radiation, and is looking forward to further measurements and results with the setup."

2021
- preliminary release of $\sigma(^{12}\mathrm{C}+\mathrm{p} \to {}^{11}\mathrm{C}+\mathrm{X})$ at ICRC

2022
- fragmented lead beam canceled due to early YETS

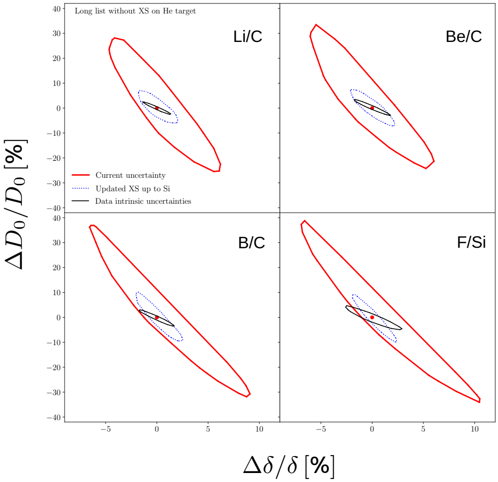
2023
- 1 week fragmented lead? (CERN-SPSC-2022-034)

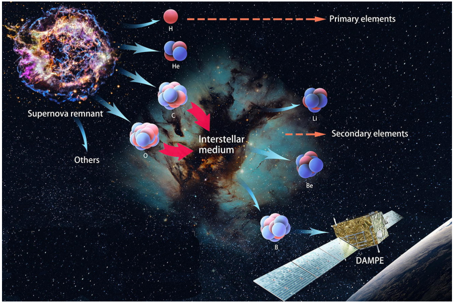
Detector Upgrades for Run 3



Impact of One Week of Fragmented Pb at NA61/SHINE

Diffusion coefficient from CR secondaries, **"Galactic target thickness"**





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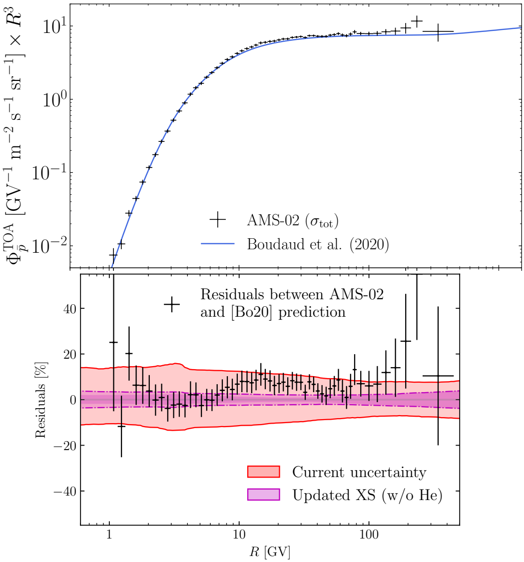
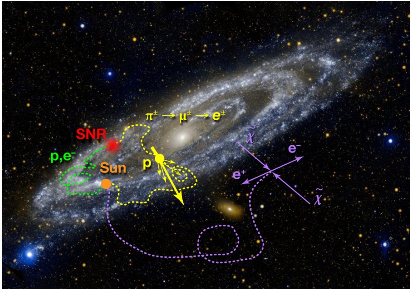
diffusion coefficient $D \propto D_0\,(E/Z)^{\delta}$

Genolini, Maurin, Moskalenko, MU in preparation

Impact of One Week of Fragmented Pb at NA61/SHINE

anti-protons at Earth



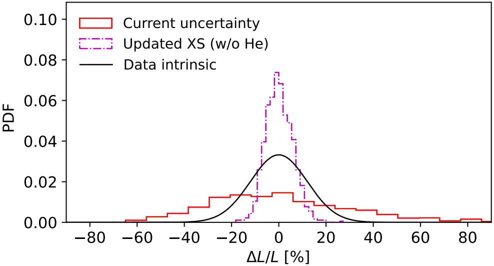


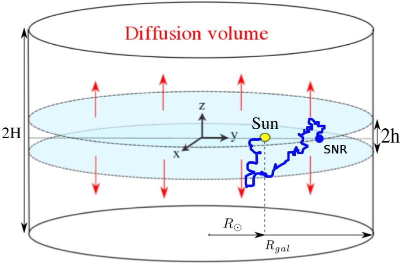
Genolini, Maurin, Moskalenko, MU in preparation

Impact of One Week of Fragmented Pb at NA61/SHINE

size of Galactic halo

from "cosmic clock" ^{10}Be





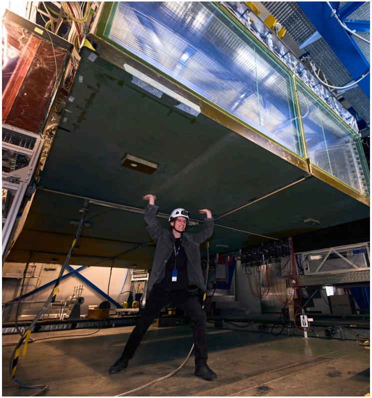
- AMS best fit 2023:
  $L = 3.6^{+0.5}_{-0.4}$ (stat.) kpc
  soon to improve further (HELIX)
- but: current cross section uncertainty on derived $L \sim 30\%$

Genolini, Maurin, Moskalenko, MU in preparation

Summary

CR studies at SPS with NA61/SHINE:

- precise measurement of π+C
  $\rightarrow$ particle production in air showers
- nuclear fragmentation
  $\rightarrow$ particle production in Galaxy

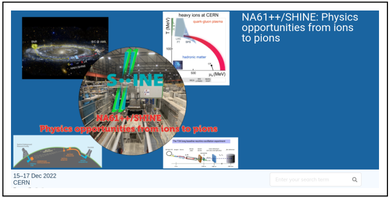


inside NA61 (Julien Ordan/CERN)

Outlook

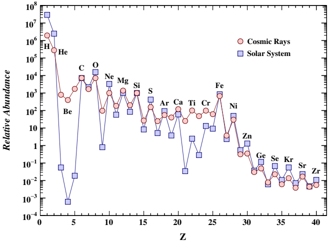
Upcoming Cosmic-Ray Possibilities:

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

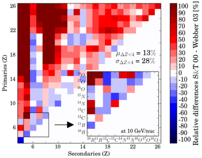


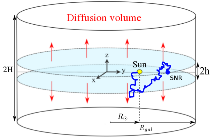
backup slides

Propagation of GCRs: High-Mass Nuclei



Particle Data Group 2022

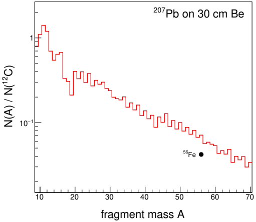




Y. Genolini et al. A&A. **580** (2015) A9 and TAUP 2015

High-Mass Nuclei: Experimental Challenges

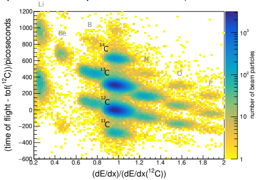
fragmented Pb beam



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:

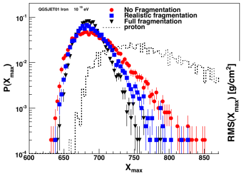
mean: $\mu_X(A, E) \approx \mu_X(p, E/A)$ (!)

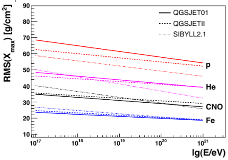
fluctuations: $\sigma_X(A) \ll \frac{1}{\sqrt{A}}\sigma_X(p)$

extreme cases:

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

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