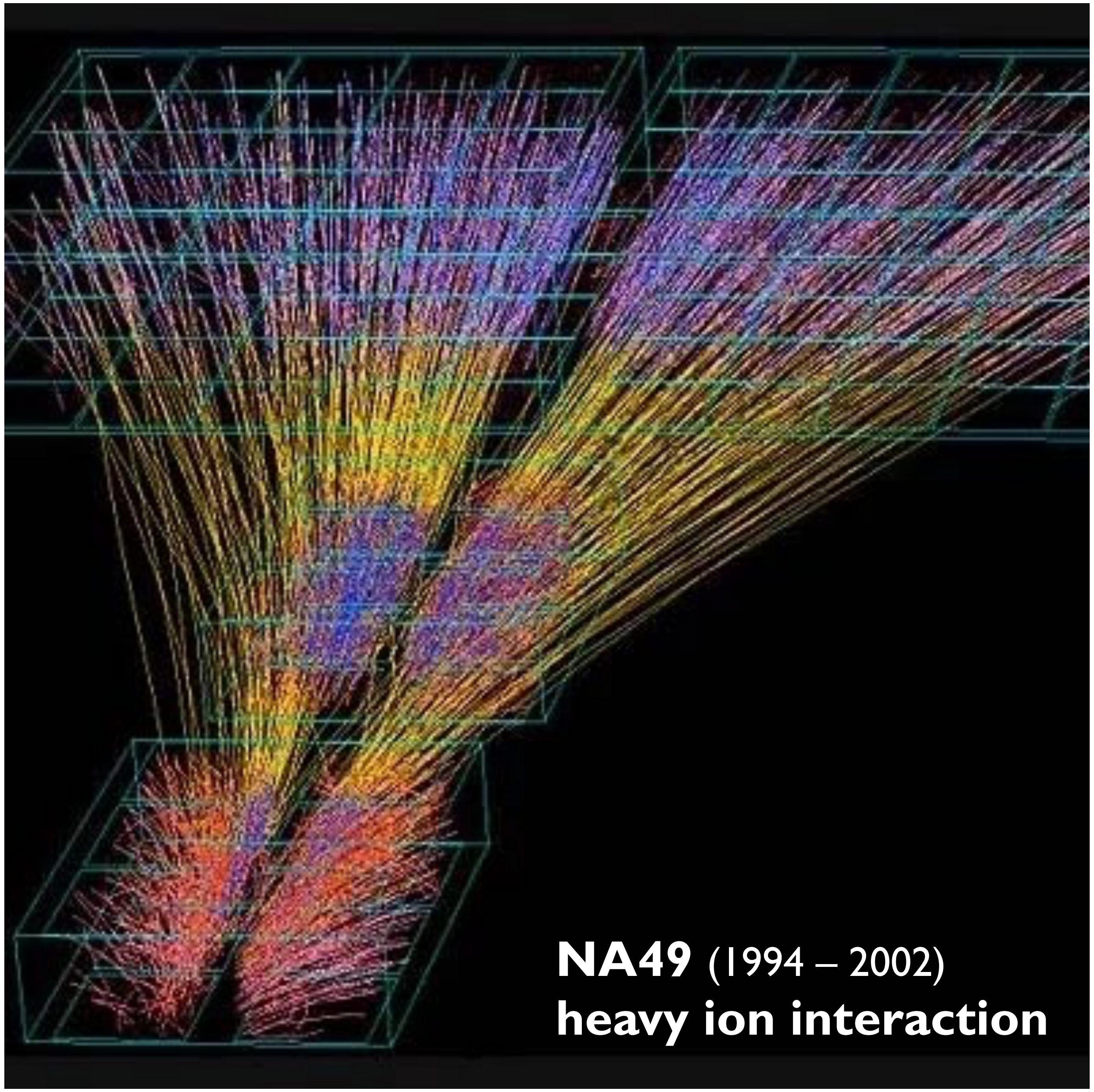
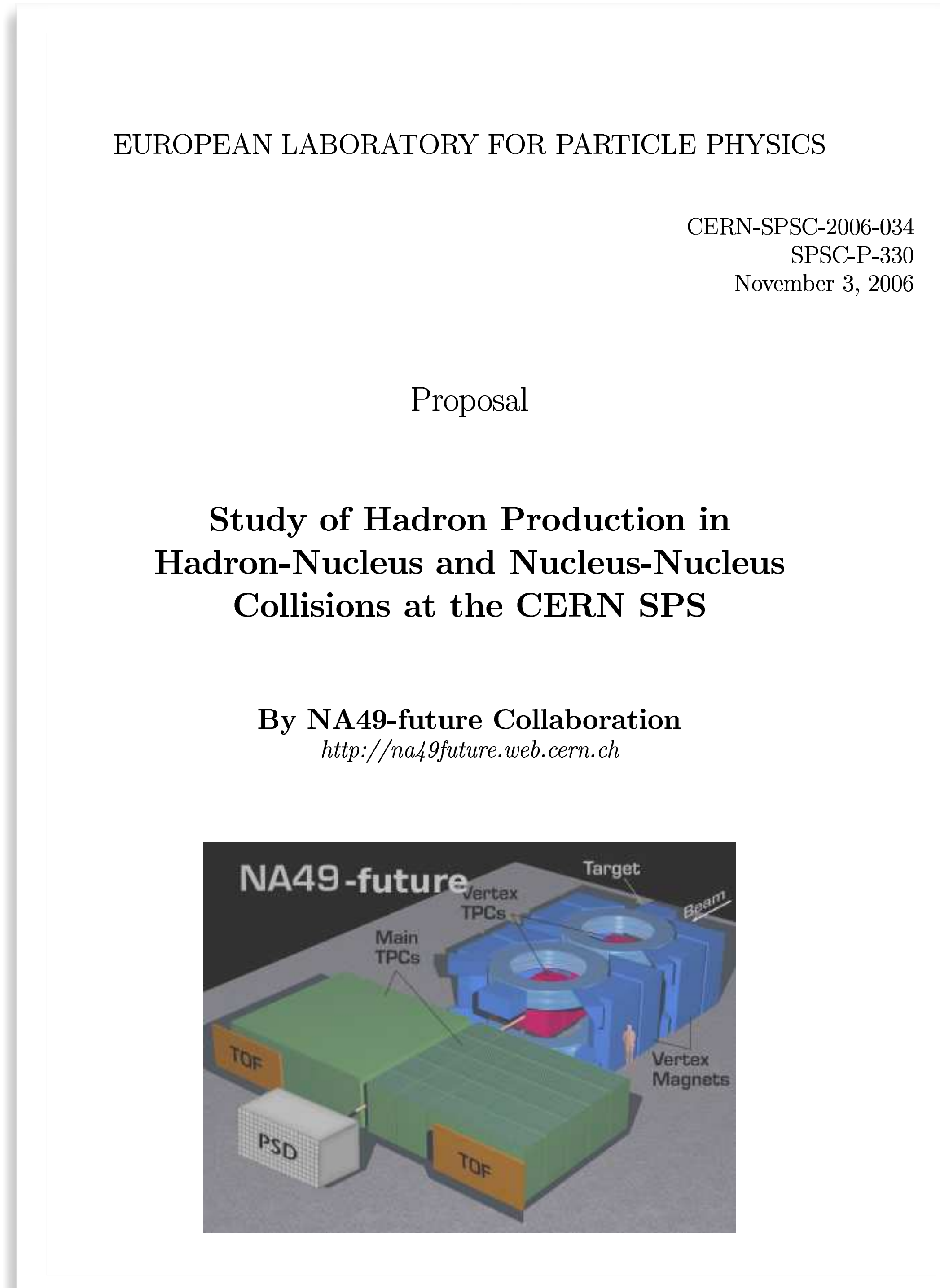
Measurements of Hadronic Particle Production with NA61/SHINE

Ralph Engel & Michael Unger, for the NA61/SHINE Collaboration

Karlsruhe Institute of Technology (KIT)

NA61/SHINE, the successor to NA49





EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-SPSC-2006-034
SPSC-P-330
November 3, 2006

Proposal

Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS

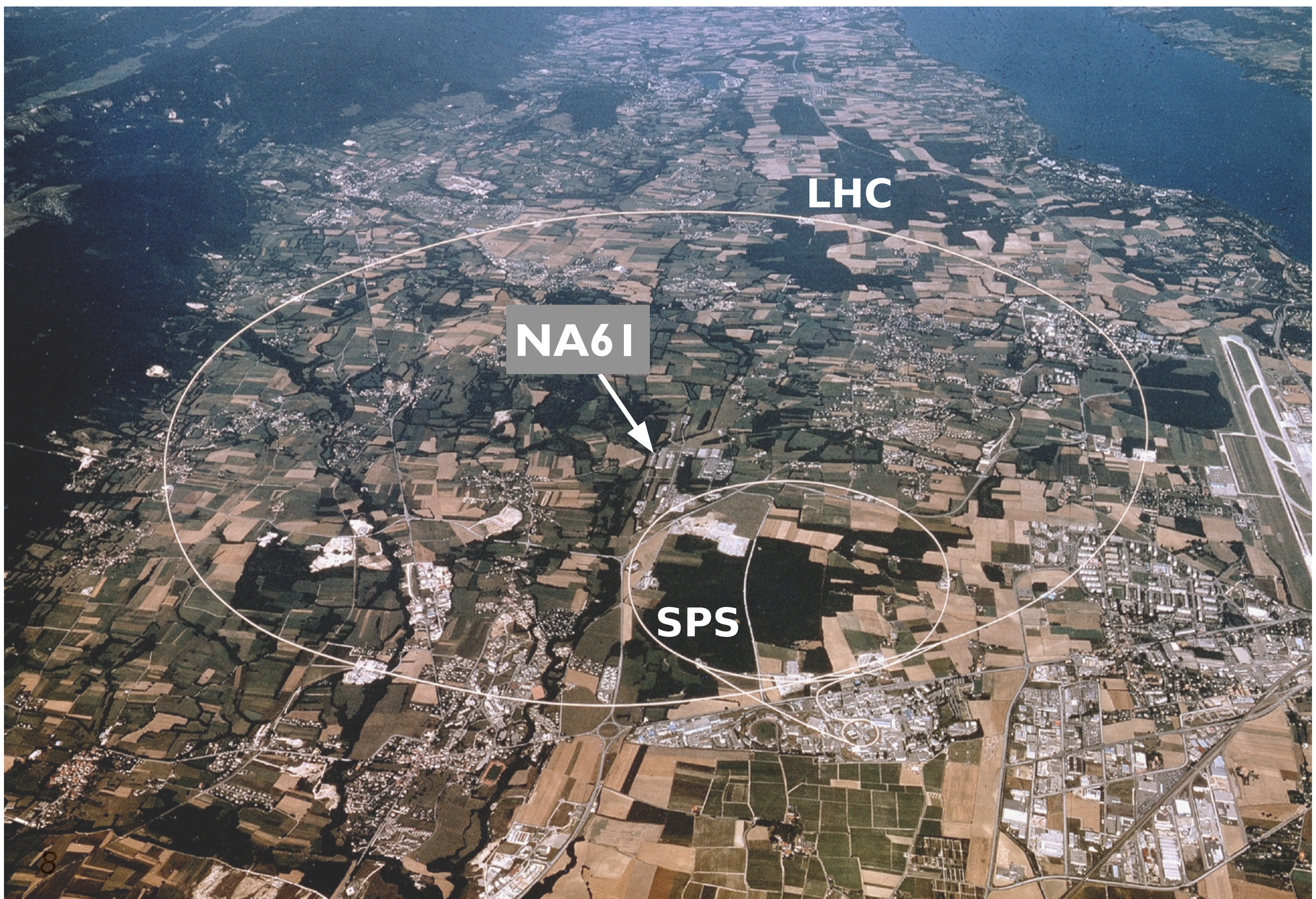
By NA49-future Collaboration
http://na49future.web.cern.ch

Proposal:	*CERN-SPSC-2006-034, SPSC-P-330 (November 3, 2006)*
Addendum:	*CERN-SPSC-2007-004, SPSC-P-330 (January 25, 2007)*
Status Report:	*CERN-SPSC-2006-023, SPSC-SR-010 (September 5, 2006)*
LoI:	*CERN-SPSC-2006-001, SPSC-I-235 (January 6, 2006)*
EoI:	*CERN-SPSC-2003-031, SPSC-EOI-001 (November 21, 2003)*

NA61/SHINE, the successor to NA49

Aims:

- Search for QCD critical point at SPS energies
- Reference measurements for neutrino beams
- Reference measurements for cosmic ray physics
- Study of particle production at high pt



SPS **H**eavy **I**on and
Neutrino **E**xperiment

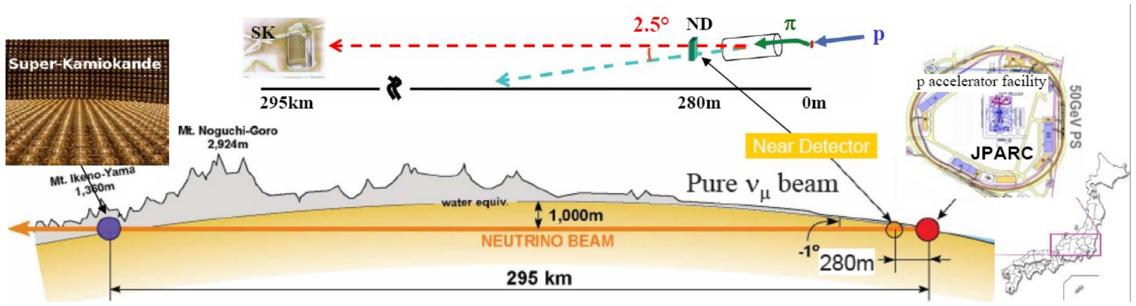
*Collaboration of
~140 physicists from
28 institutes and 14 countries*

Physics program of NA61/SHINE

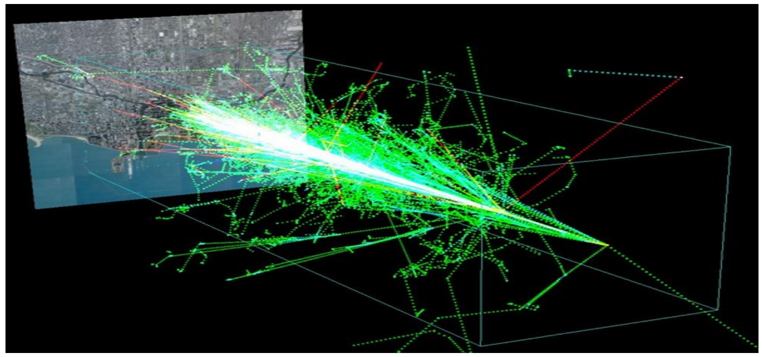
Strong interactions physics

- 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



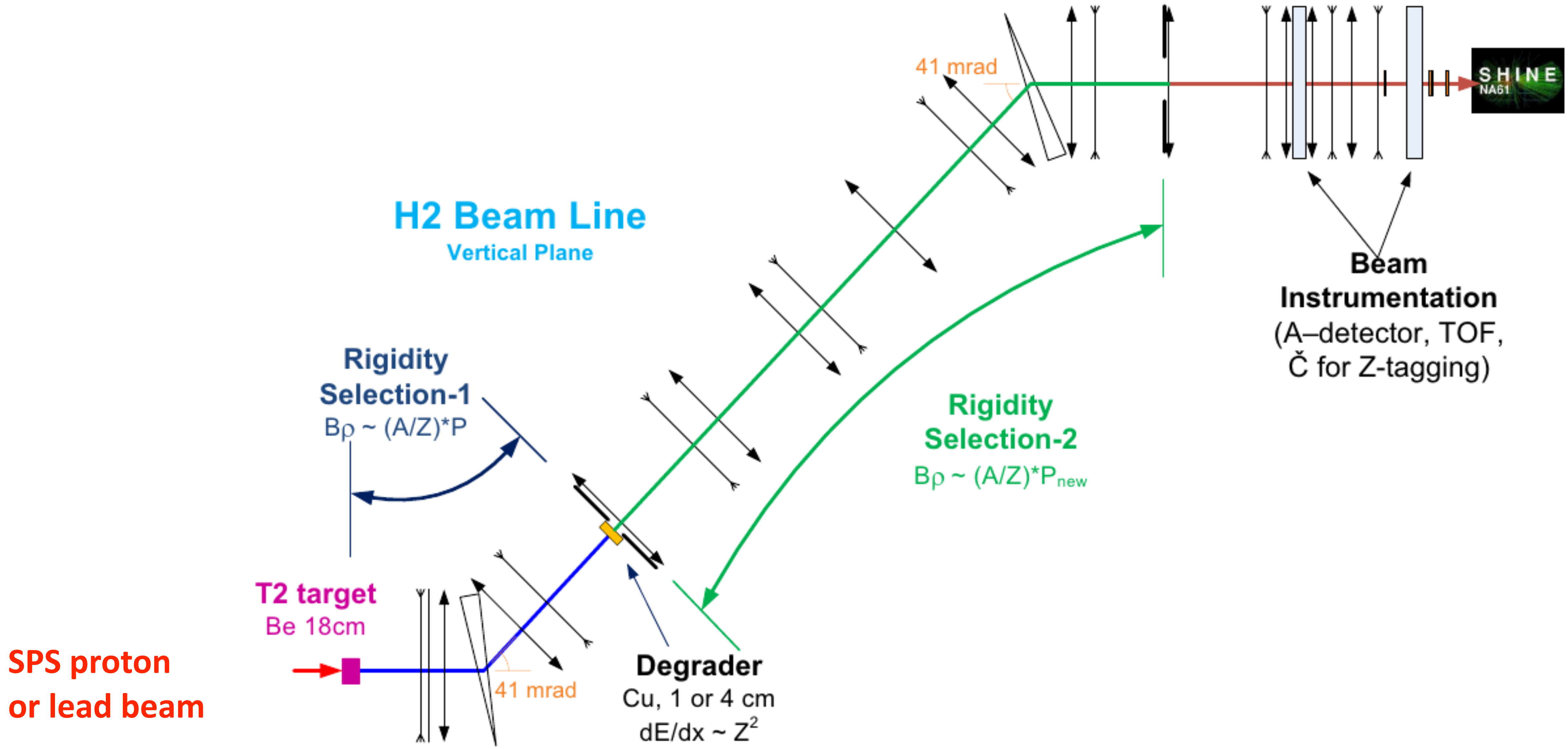
- hadron measurements for the J-PARC neutrino program
- hadron measurements for the Fermilab neutrino program
- measurements for cosmic ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
- measurements of nuclear fragmentation cross sections of intermediate mass nuclei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



Groups mainly interested in cosmic-ray physics:

KIT (Germany), Uni. Hawaii (USA), Uni. Silesia (Poland)

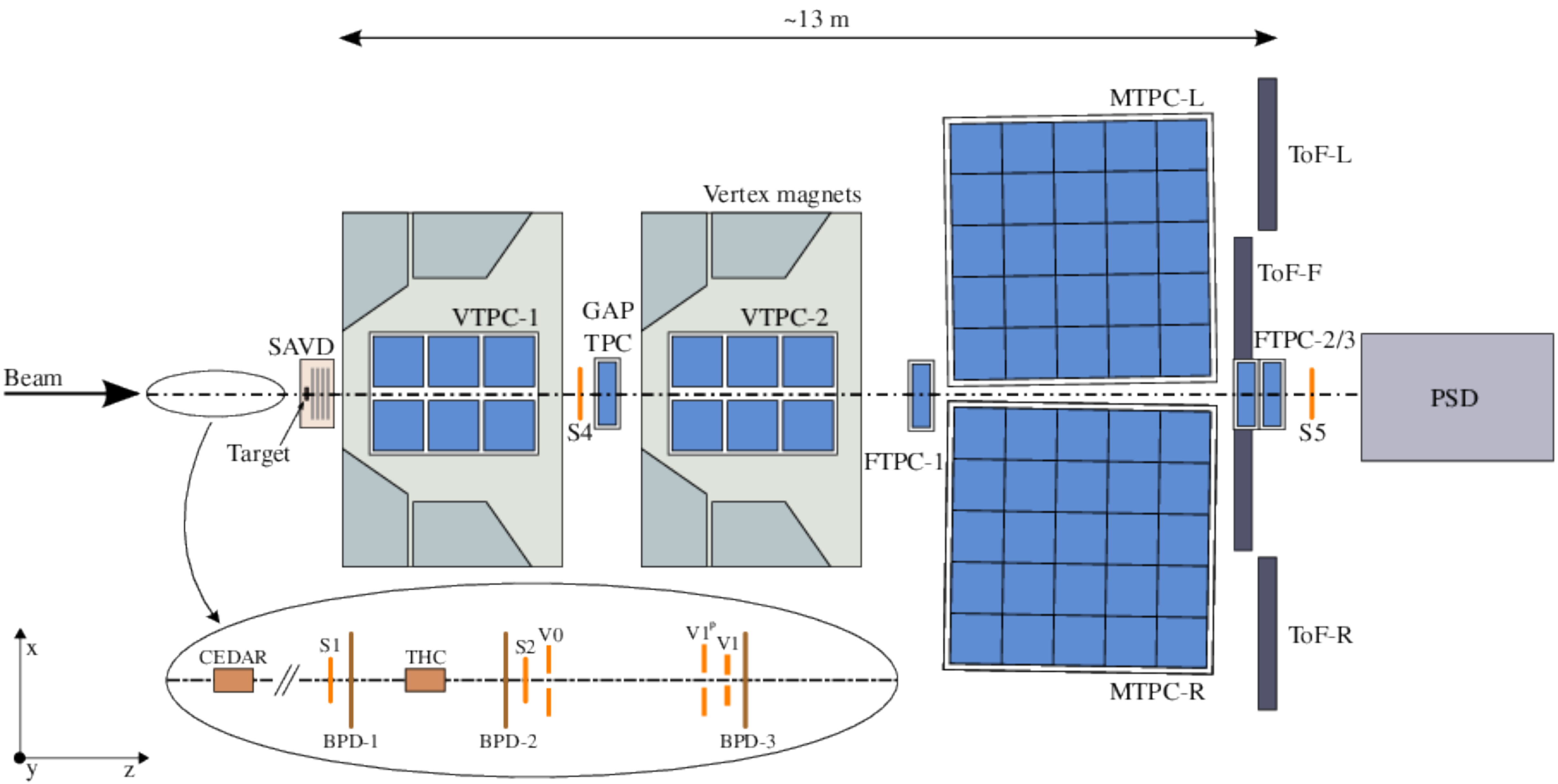
SPS secondary particle beam



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

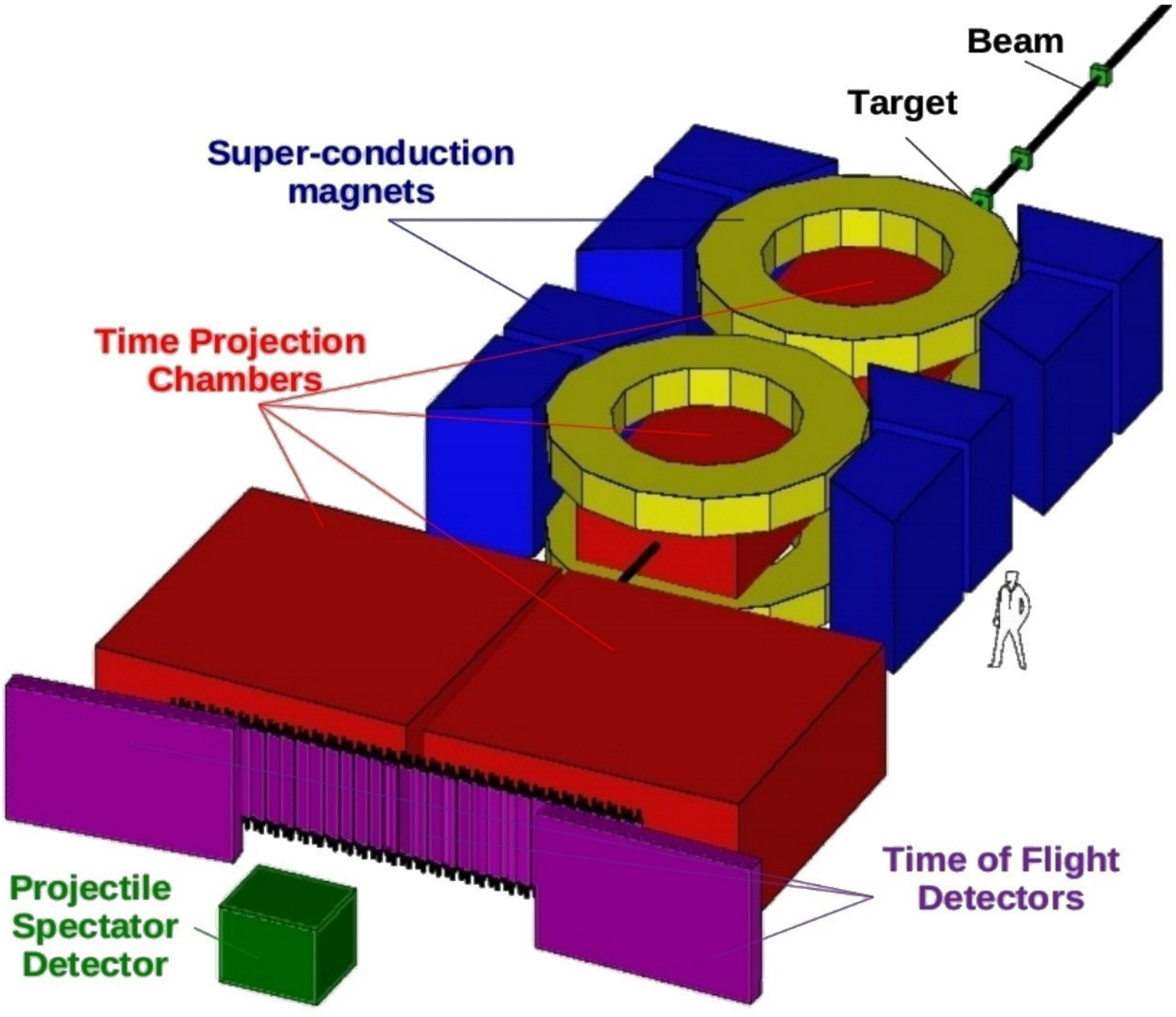
Different energies and secondary particles or spallation products from ion beams possible

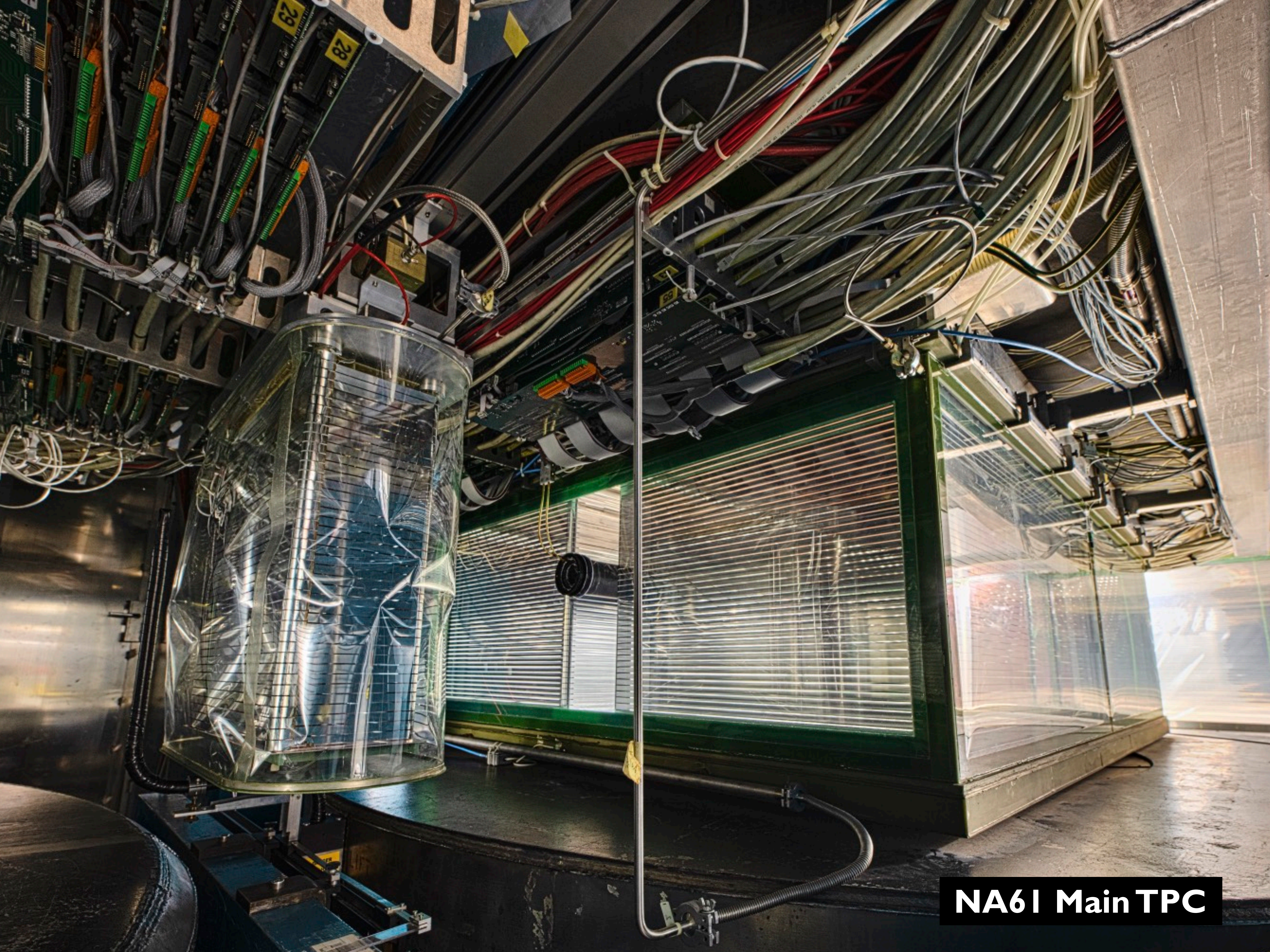
Detector components and layout (i)



- 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

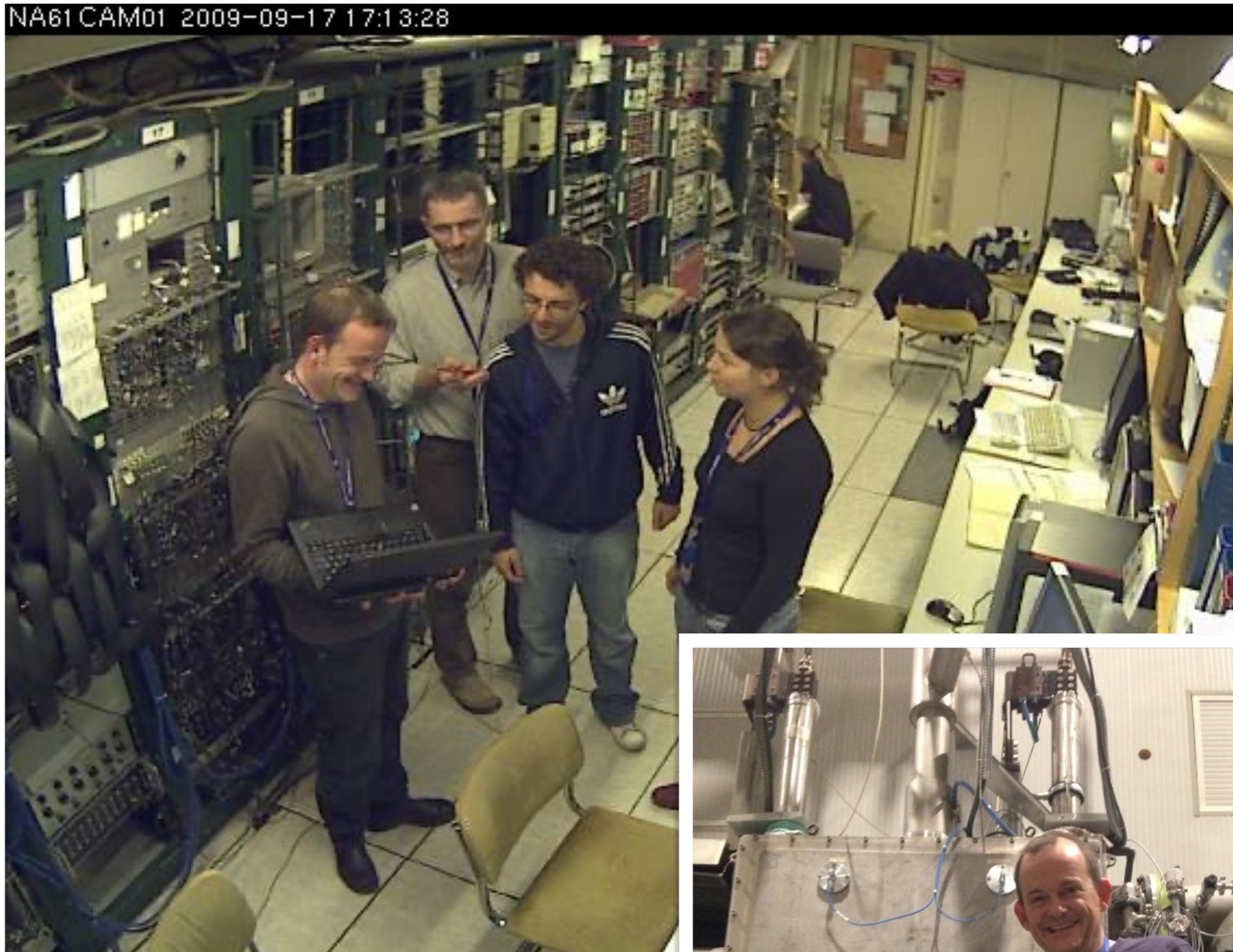
Detector components and layout (ii)

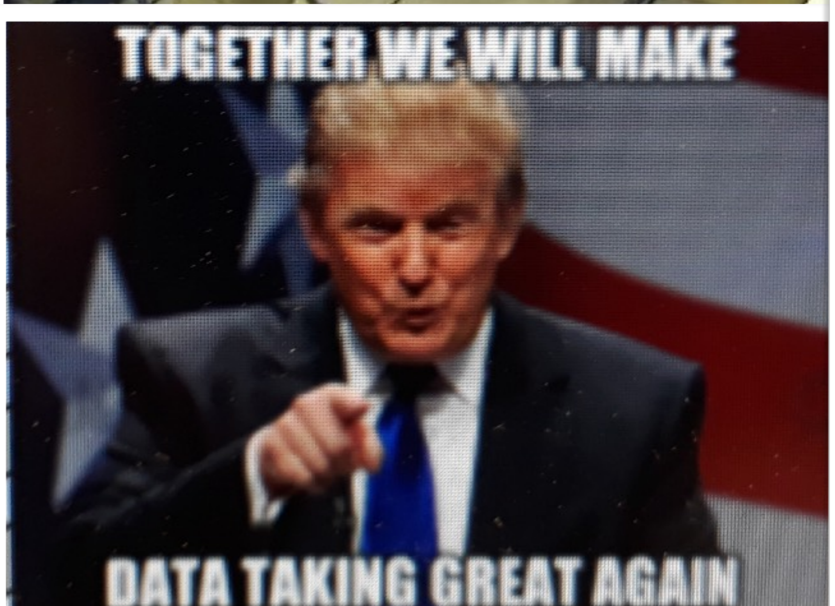


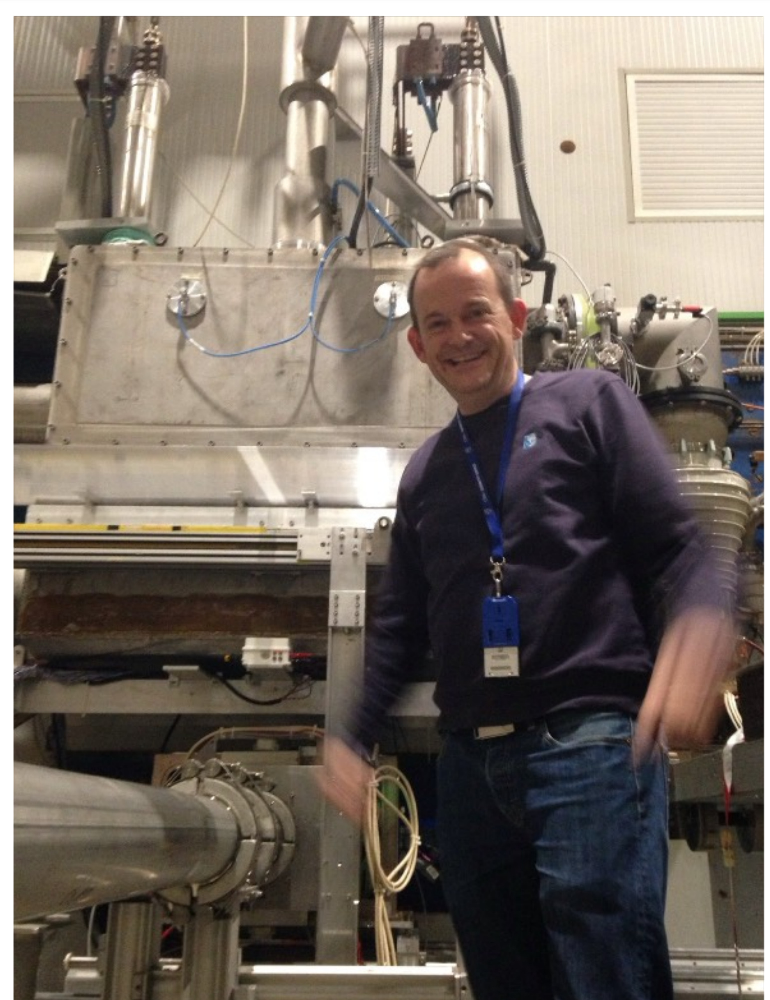


NA61 Main TPC

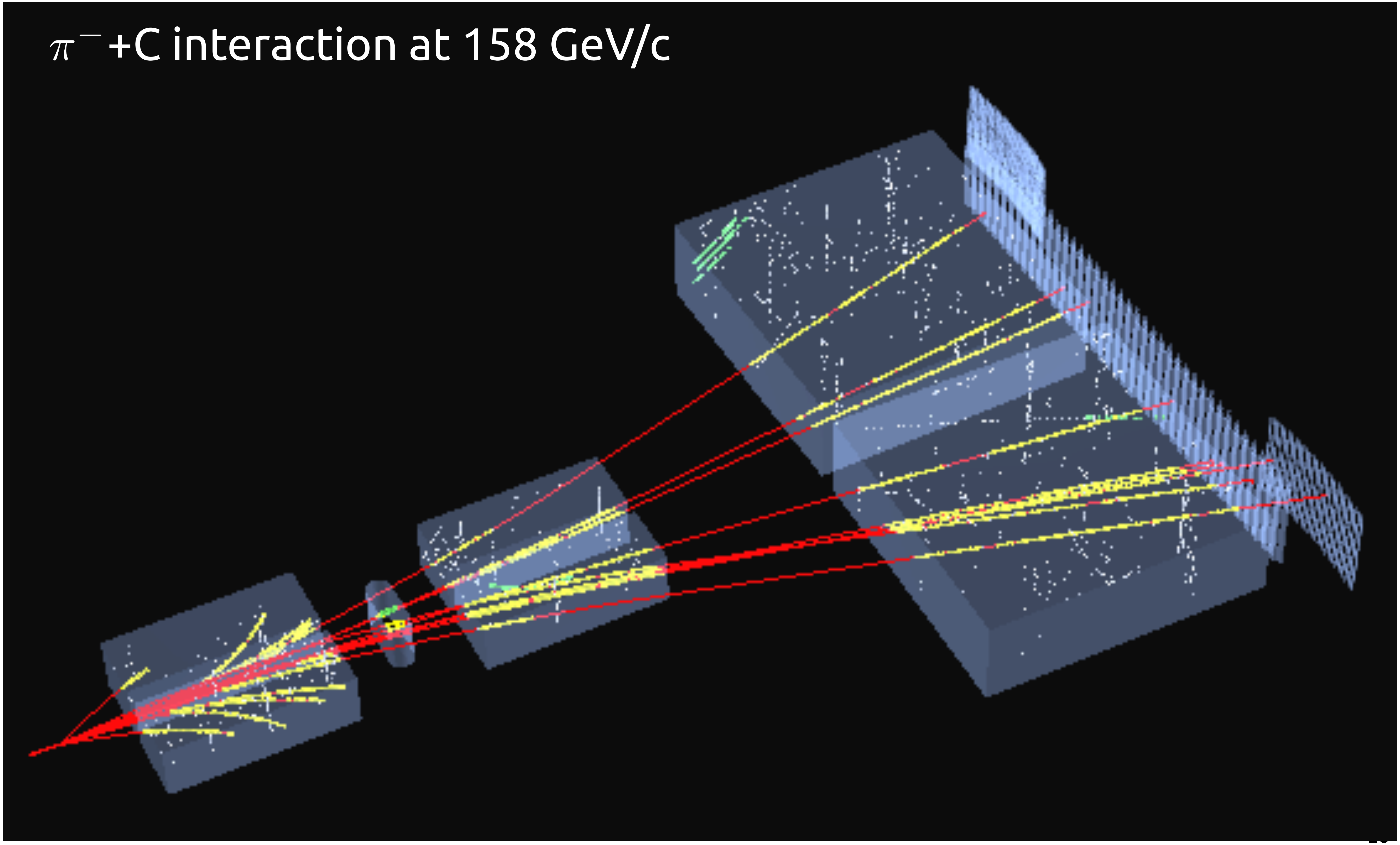
Cosmic-ray physics with NA61 (2009, 2018)



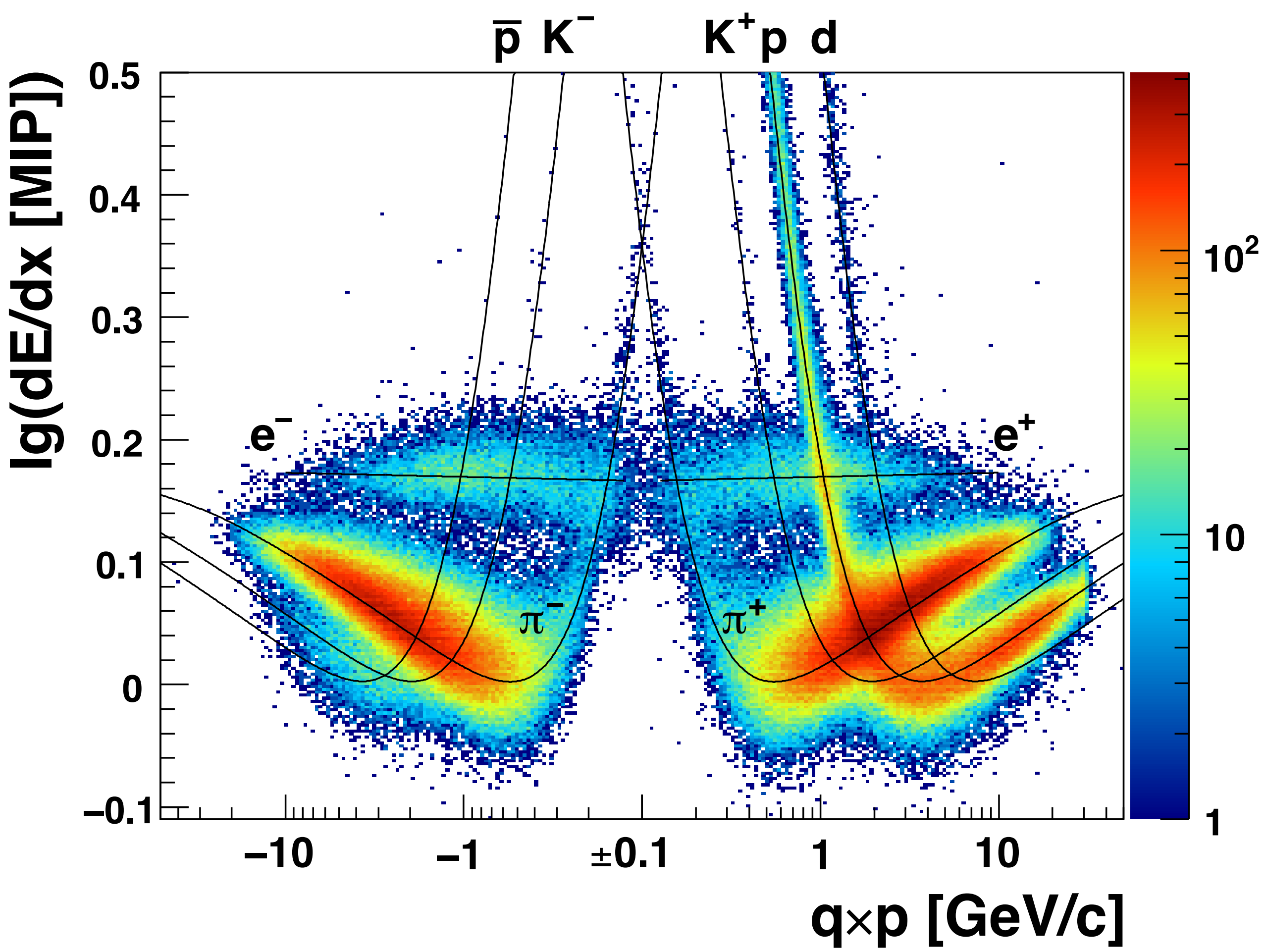


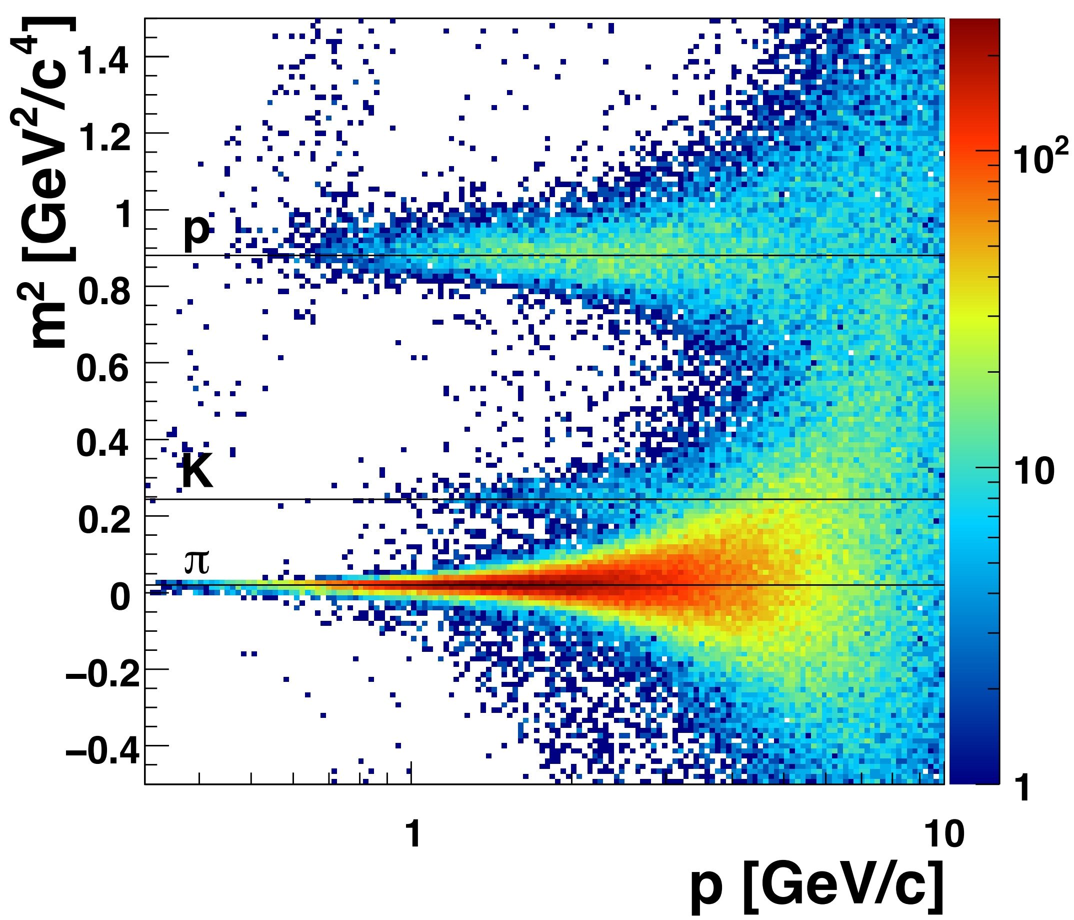


Example: display of typical NA61 event



Particle identification (i)





Energy deposit from TPCs

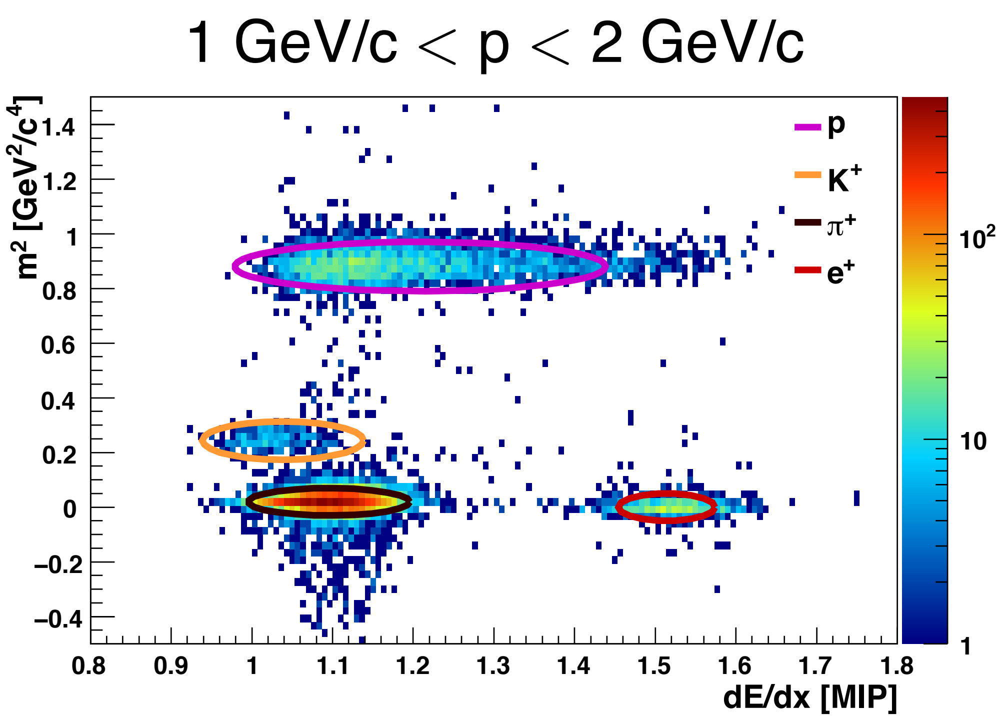
$$\sigma(\mathrm{d}E/\mathrm{d}x)/ < \mathrm{d}E/\mathrm{d}x > \approx 0.04$$

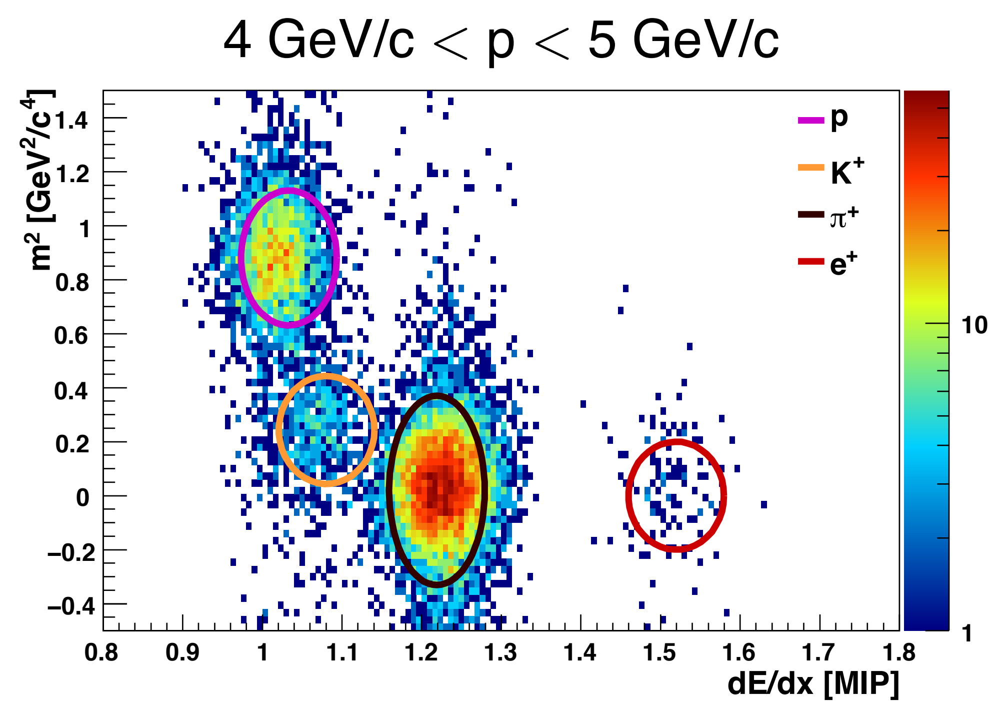
Mass estimate from time of flight

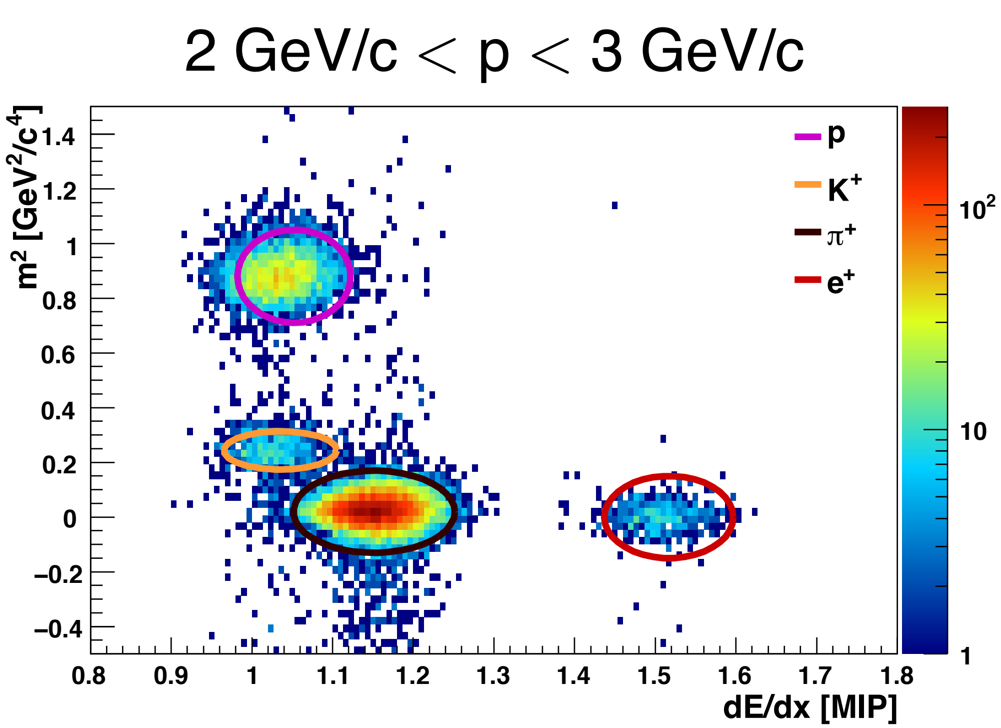
$$\sigma(t_{flight}^{ToF-L/R}) \approx 60\ ps$$

$$\sigma(t_{flight}^{ToF-F}) \approx 120\ ps$$

Particle identification (ii)







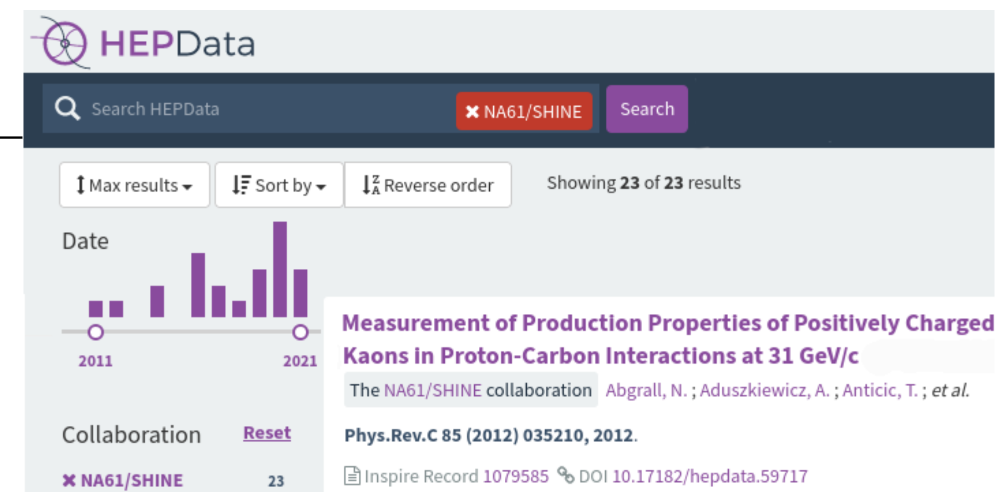
- Momentum and charge sign from deflection
  $\sigma(p)/p^2 \approx 10^{-4}\ (GeV/c)^{-1}$
- Combining dE/dx and TOF improves particle identification at high energy
- dE/dx needed for electron subtraction

Cosmic-ray program of NA61/SHINE

- Particle Production in Air Showers
  - p+C Interactions
    (31, 60, 90, 120 GeV/c)
  - π+C Interactions
    (30, 60, 158, 350 GeV/c)

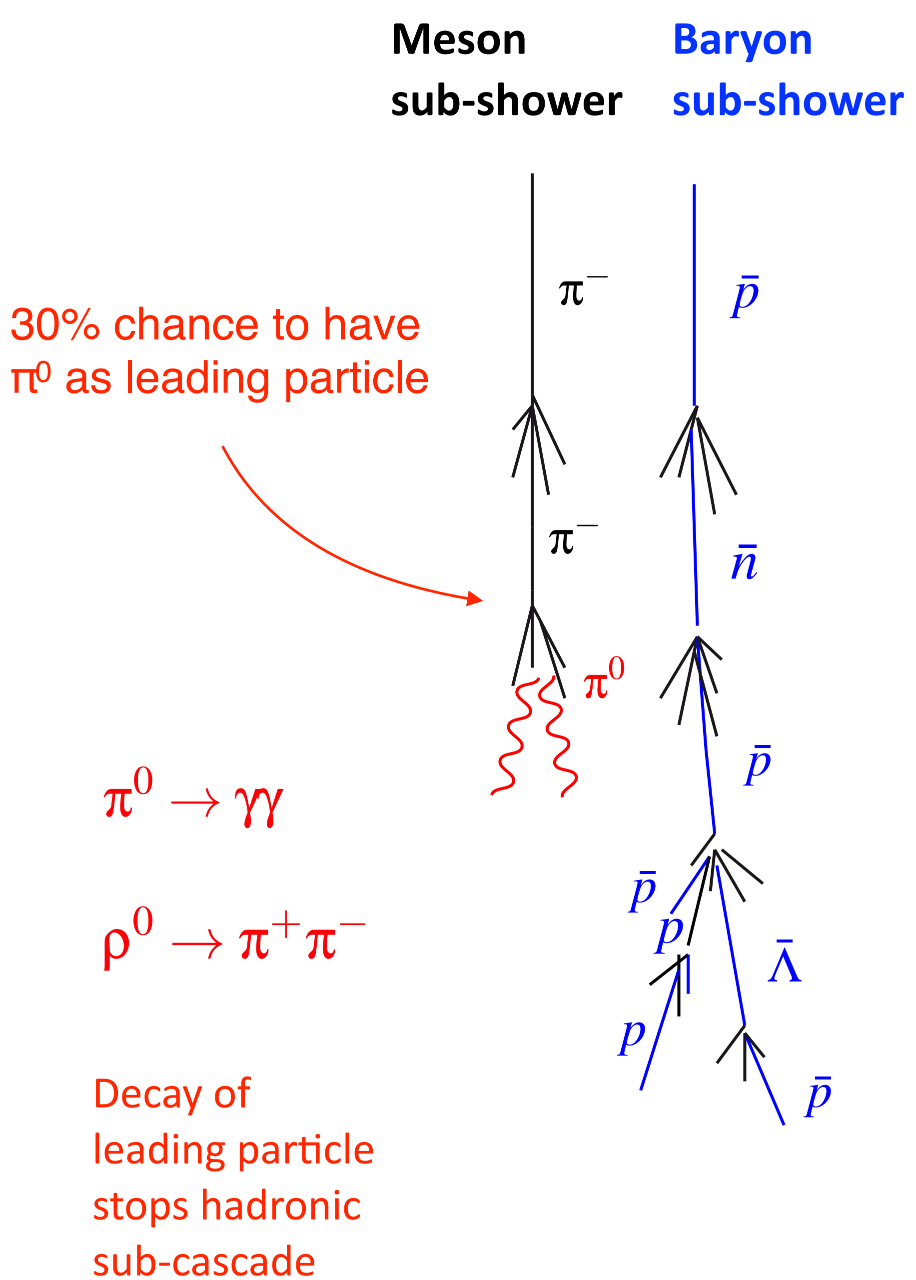
- Galactic Cosmic Rays
  - d, $\bar{d}$ and $\bar{p}$ Production
    (p+p at 20, 31, 40, 80, 158, 400 GeV/c)
  - Nuclear Fragmentation
    (C+C, C+CH_2 at 13.5 AGeV/c)

reaction	energy	π^+	π^-	K^+	K^-	p	$\bar{p}$	Λ	$\bar{\Lambda}$	K^0_S	ρ^0	ω	K^{*0}					
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	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓



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.

Muon production depends on hadronic energy



1 Baryon-Antibaryon pair production *(Pierog, Werner 2008)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly **low-energy** muons

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

2 Enhanced kaon/strangeness production *(Anchordoqui et al. JHEAp 2022)*

- Similar effects as baryon pairs
- Decay at higher energy than pions (~600 GeV)

3 Leading particle effect for pions *(Drescher 2007, Ostapchenko 2016)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 to 100% into two charged pions

4 New hadronic physics at high energy *(Farrar, Allen 2012, Salamida 2009)*

- Inhibition of π^0 decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

Several of these effects: Core-Corona model (Pierog et al.)

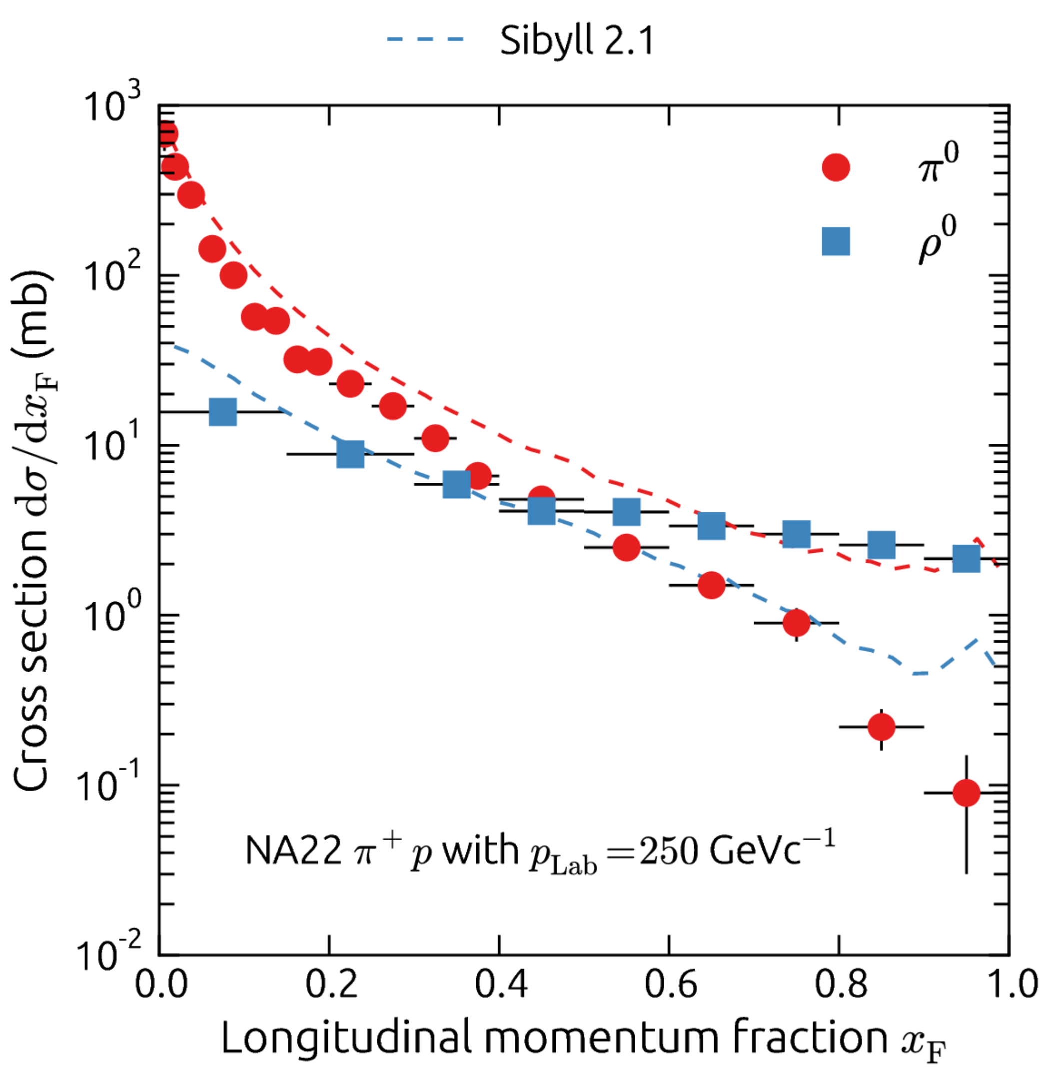
Rho production in π-p interactions (Sibyll 2.1 → Sibyll 2.3)

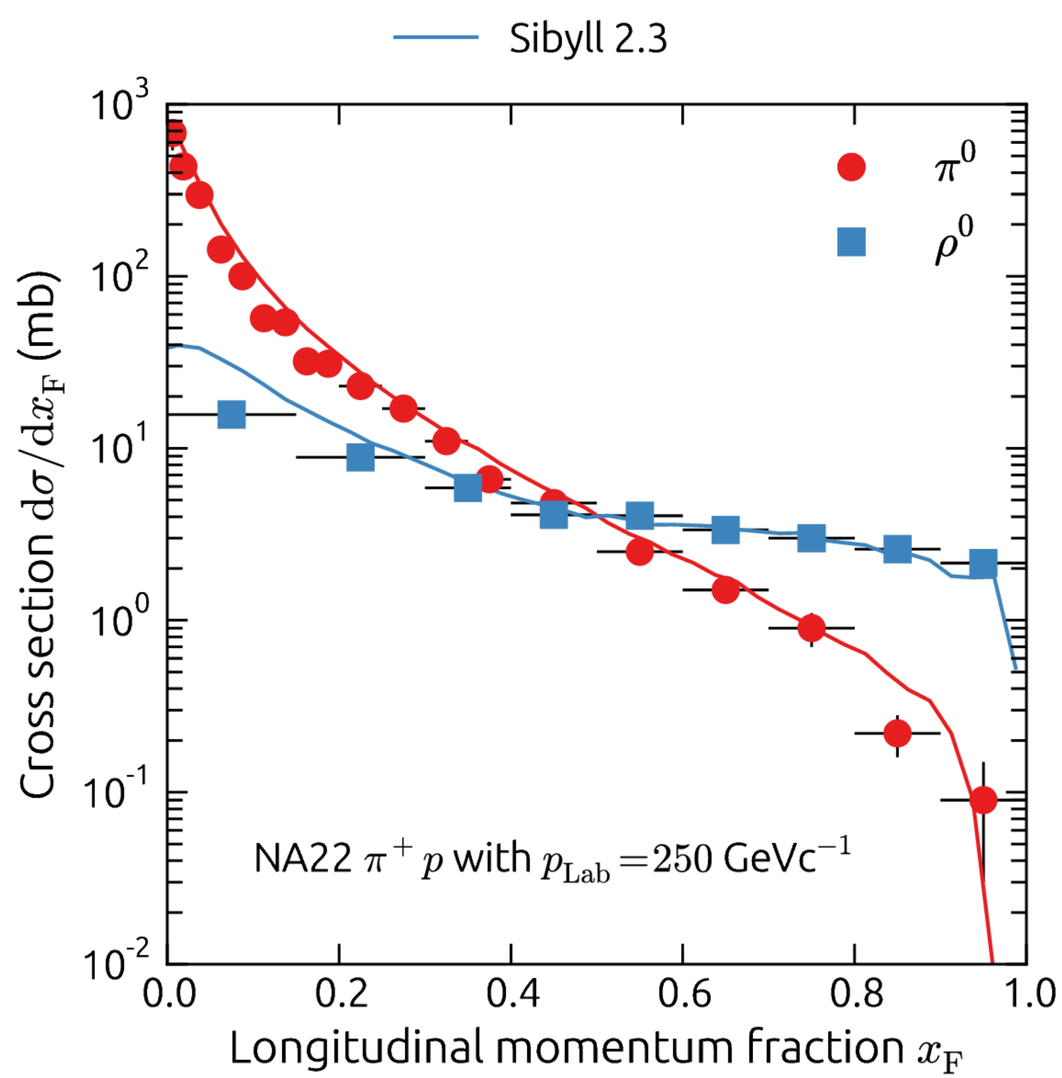
Leading particle production

$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$

$\pi^+ p \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

$E_{\text{lab}} = 250\,\text{GeV}$

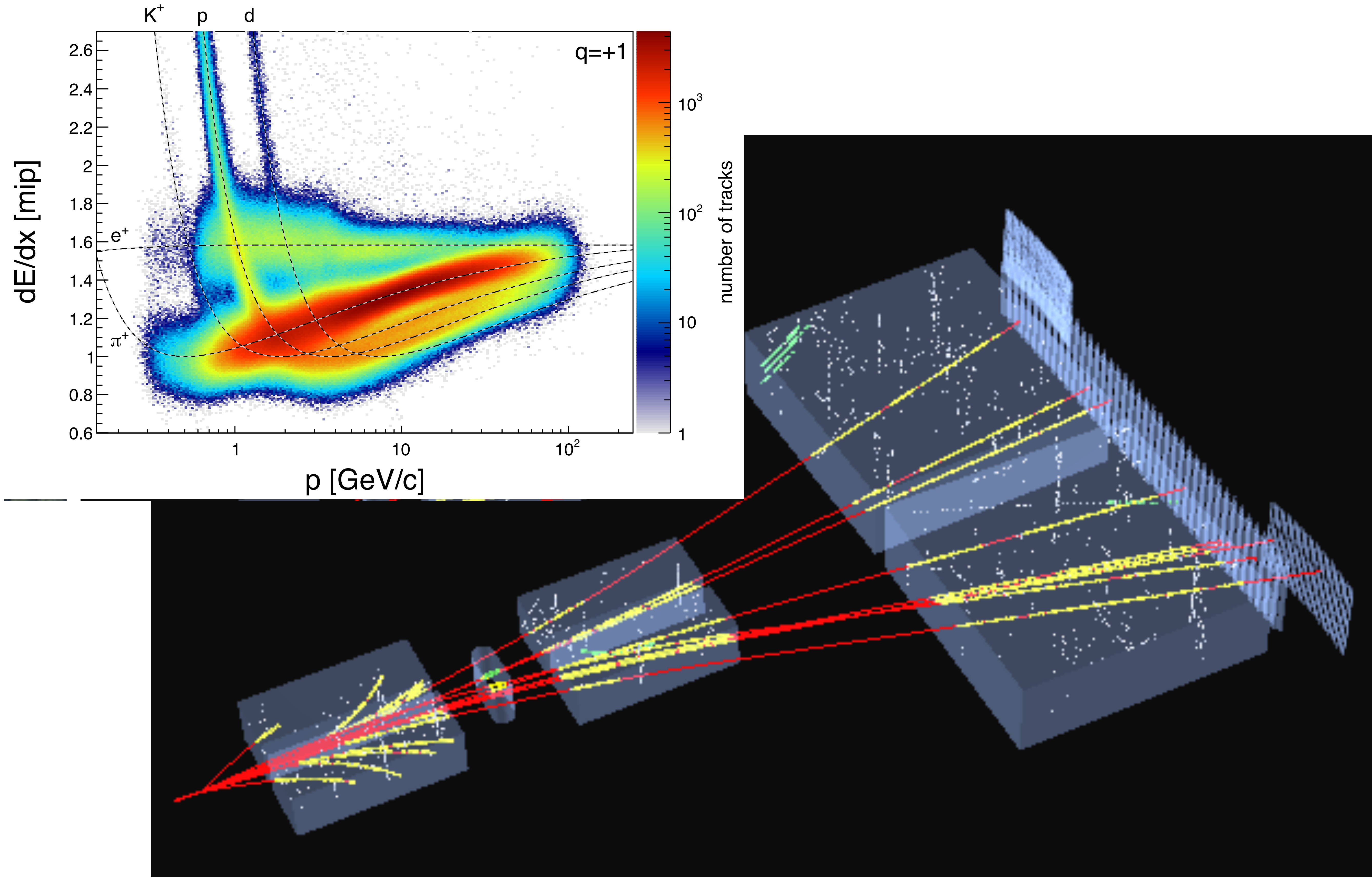




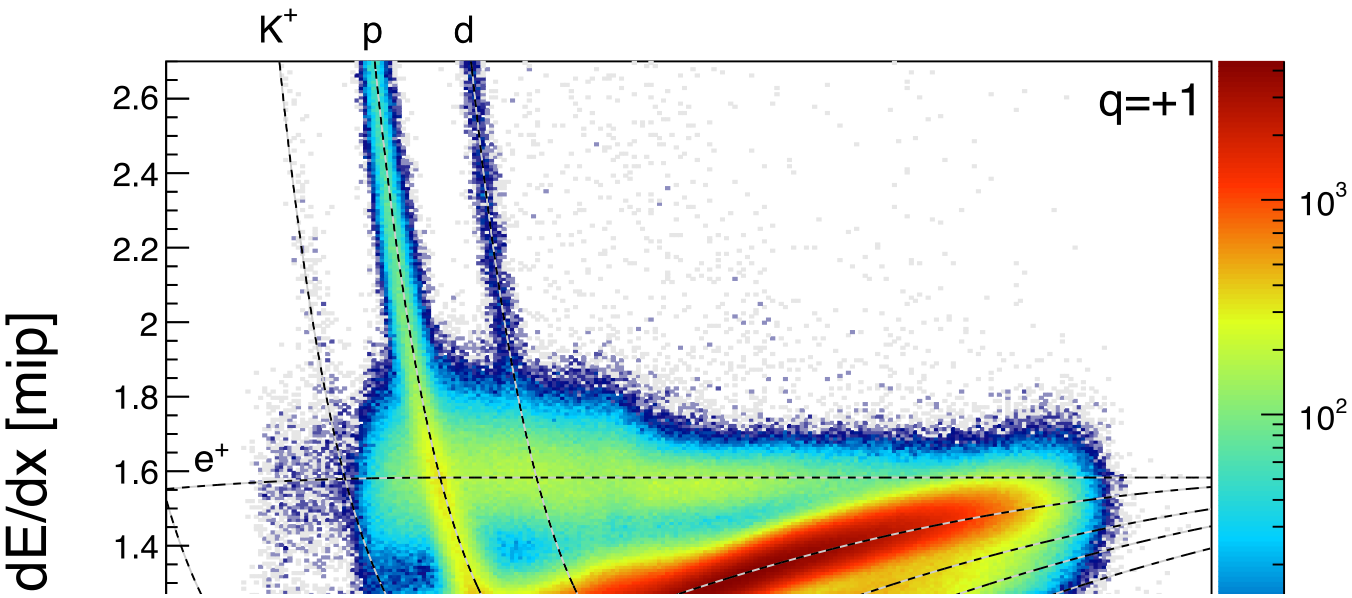
$$x_F = p_{\parallel}/p_{\max}$$

(Riehn et al., ICRC 2015)

Data taking for resonance measurement (158, 350 GeV)

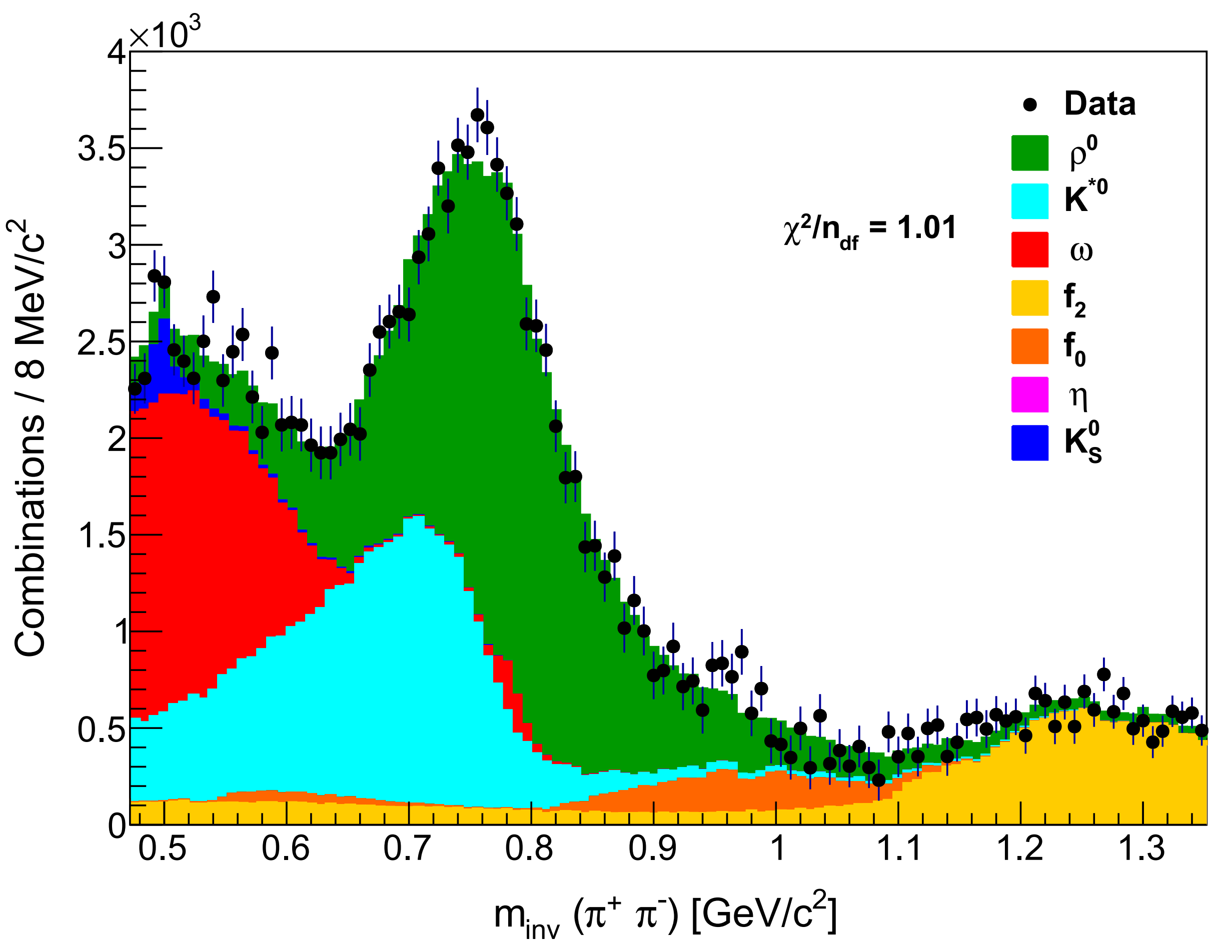


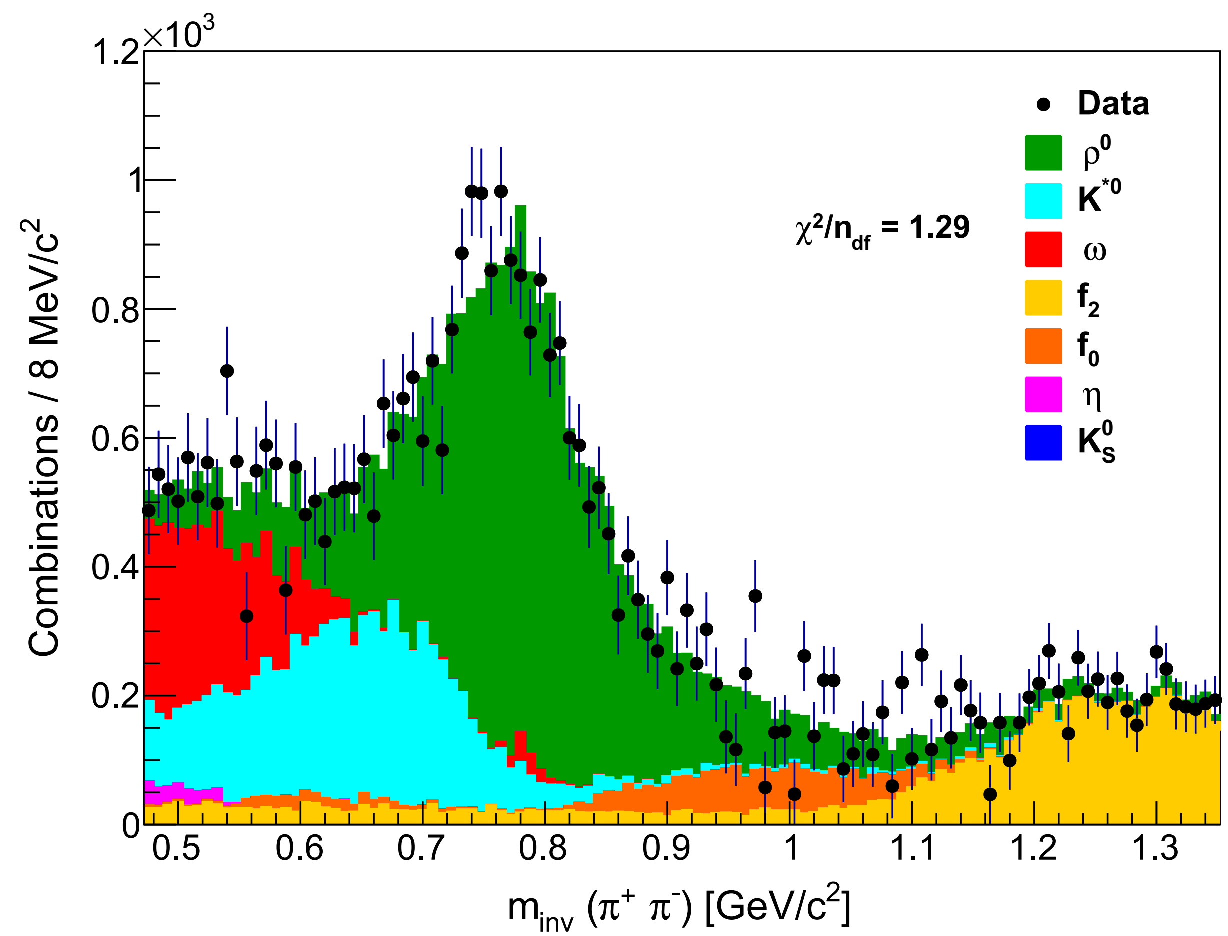
Data taking for resonance measurement (158, 350 GeV)



158 GeV

350 GeV





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

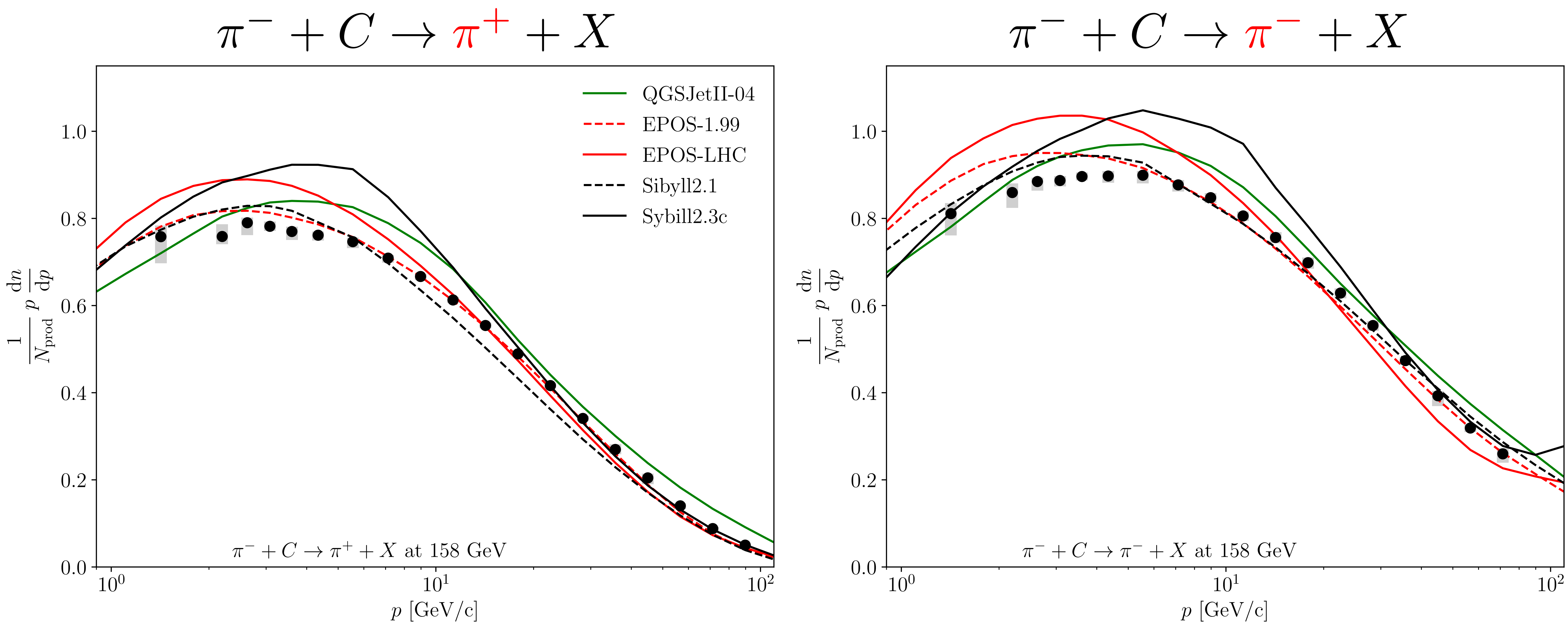
Eur. Phys. J. C (2017) 77:626
DOI 10.1140/epjc/s10052-017-5184-z

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}

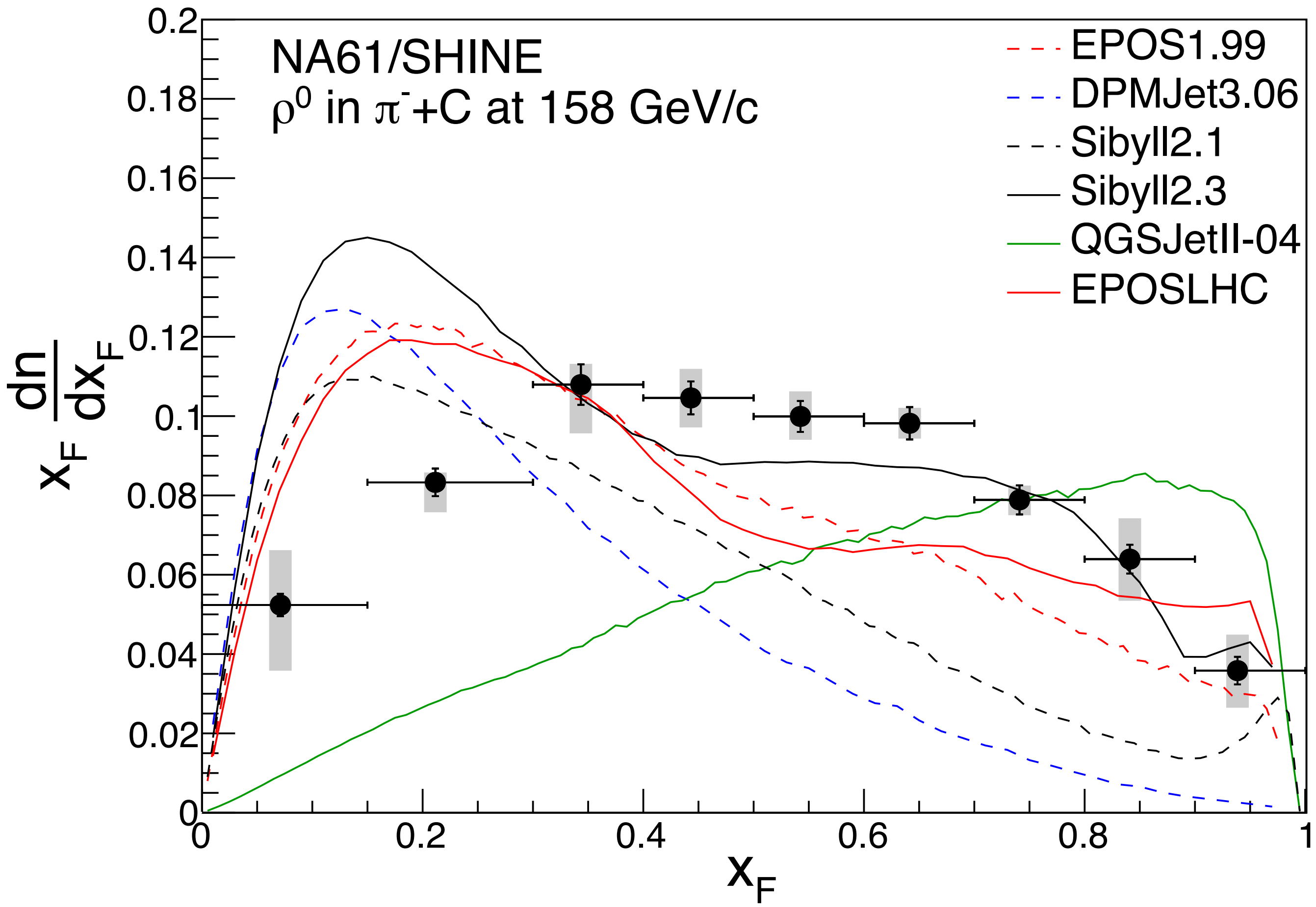
Pion Production in π^--C at 158 GeV/c



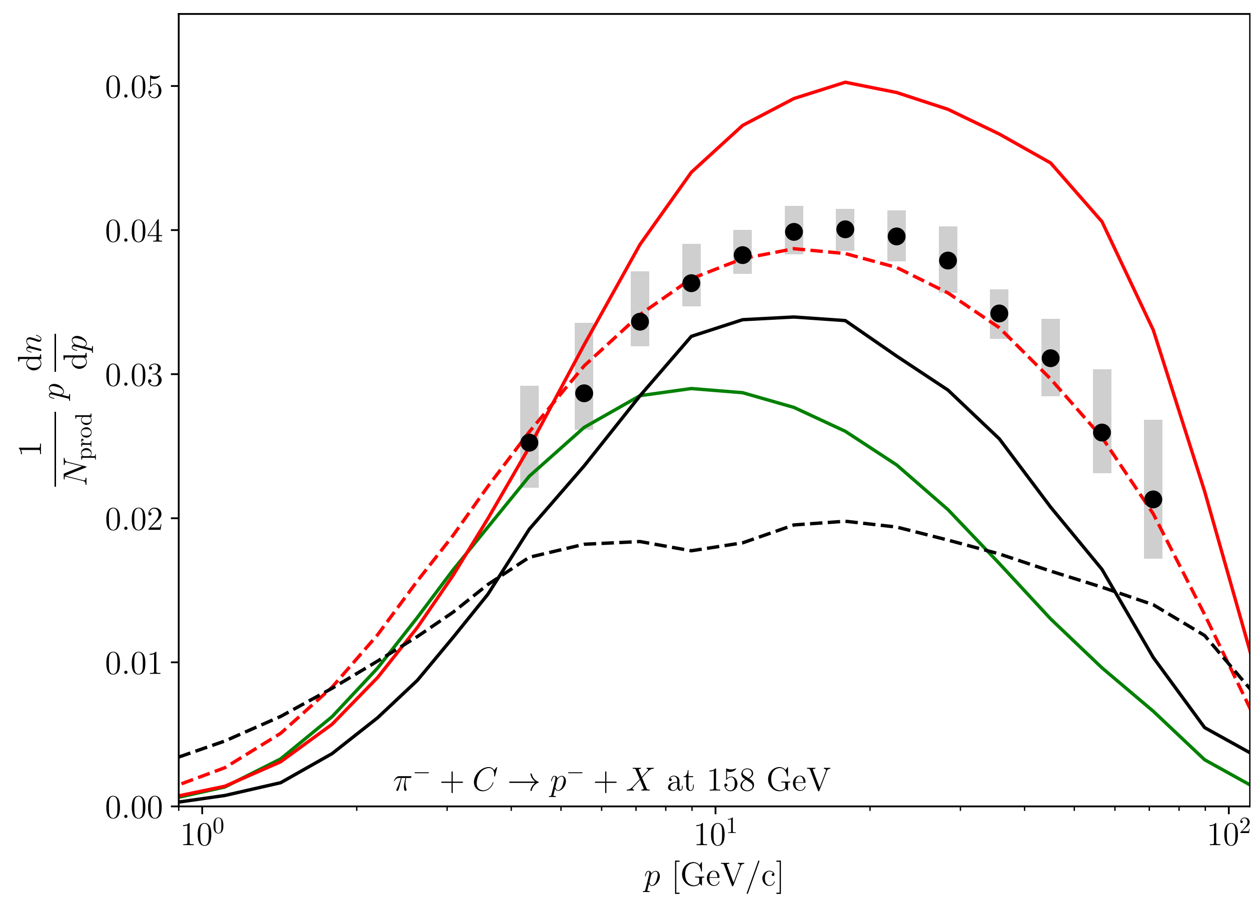
NA61/SHINE Collaboration PRD **107** (2023) 062004

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

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

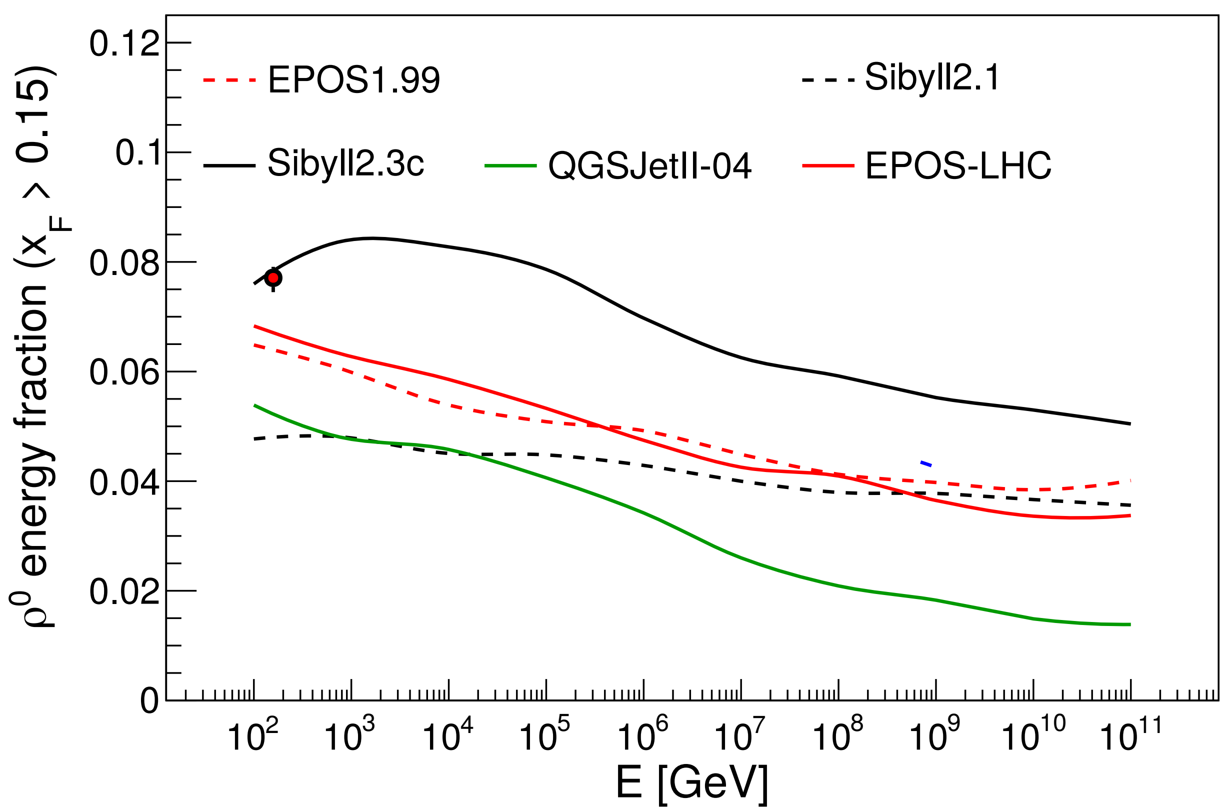
- forward ρ^0 can replace $\pi^0 \to \gamma\gamma$
- $\bar{p}$ is proxy for baryon production (p, $\bar{p}$, n, $\bar{n}$)

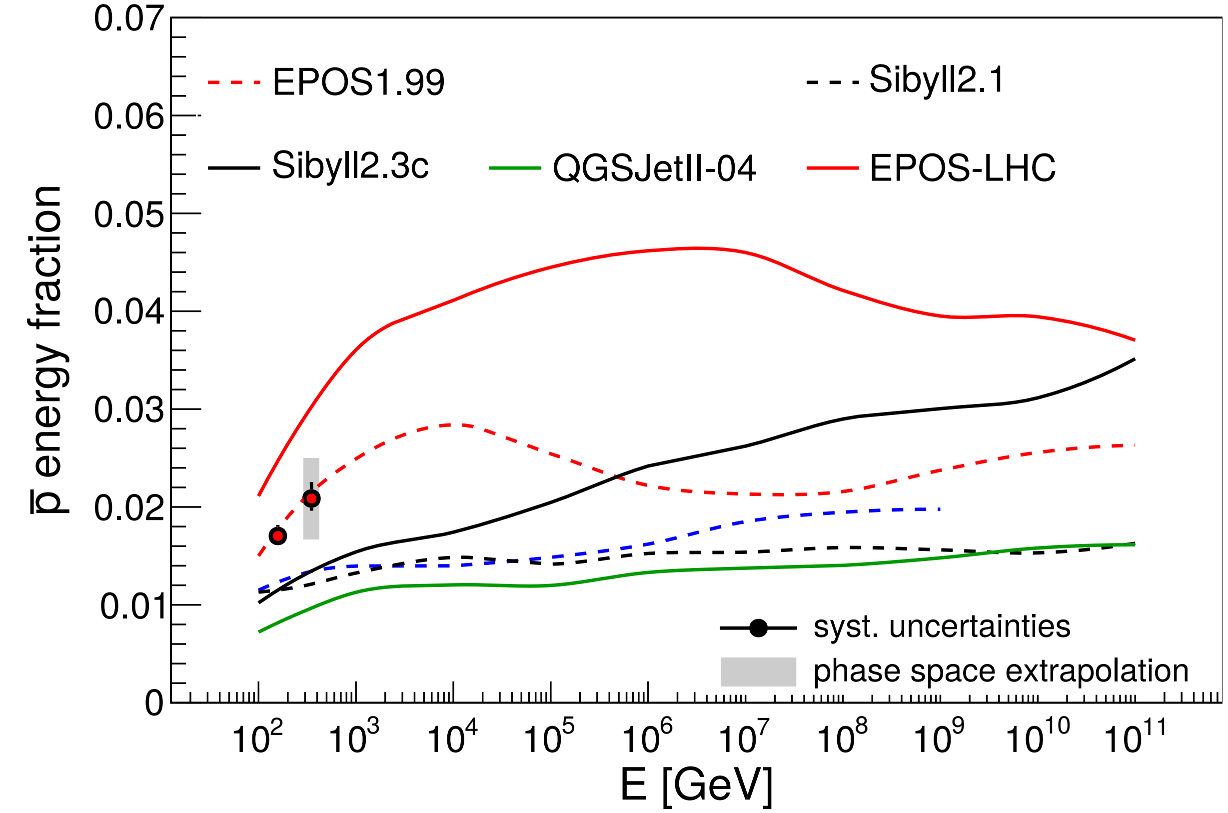
ρ^0 and p̄ Production in π^--C at 158 GeV/c

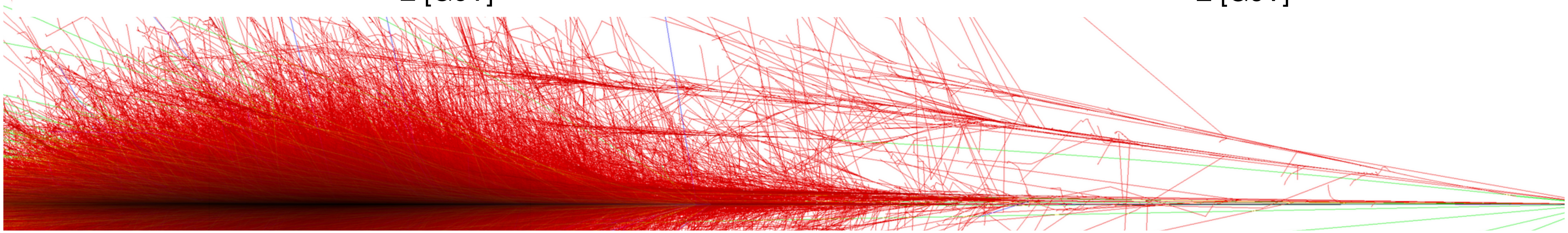
energy fraction in air shower development:

- $f \sim (2/3 + \Delta)$ 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 $\bar{p}$:





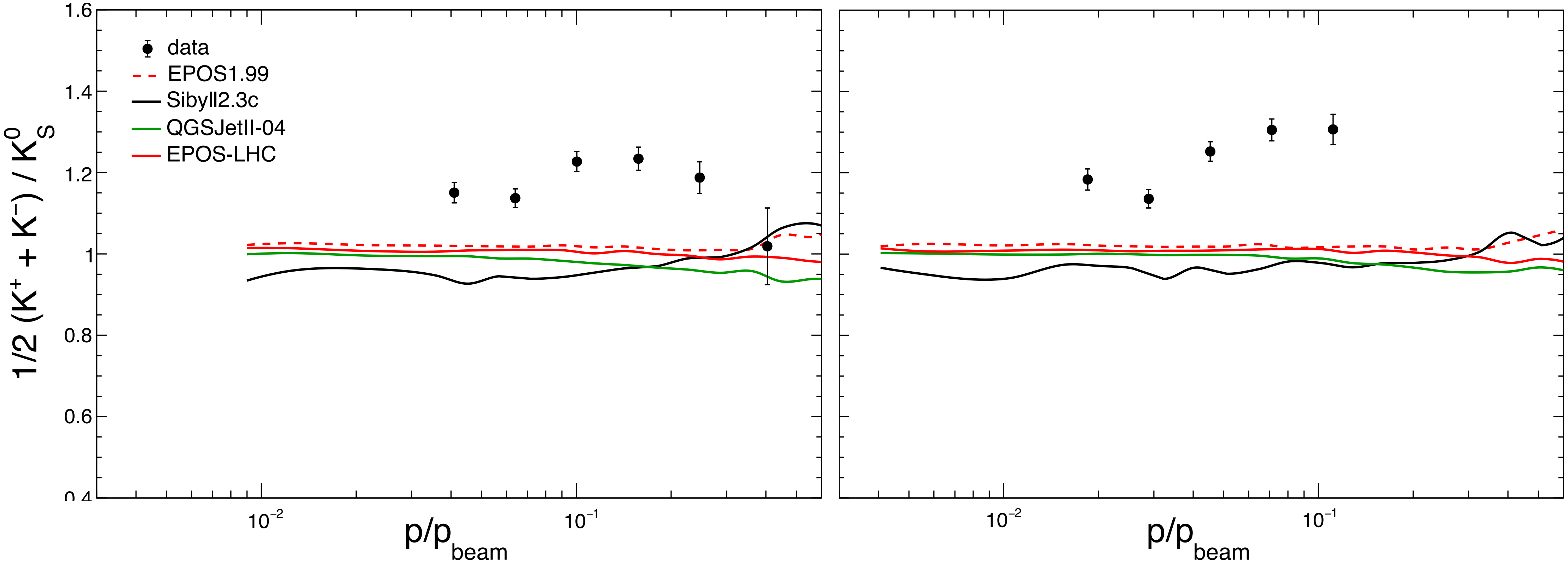


(NA61, Unger, Herve, Prado, et al. EPJ 77, 2017 & PRD 107, 2023)

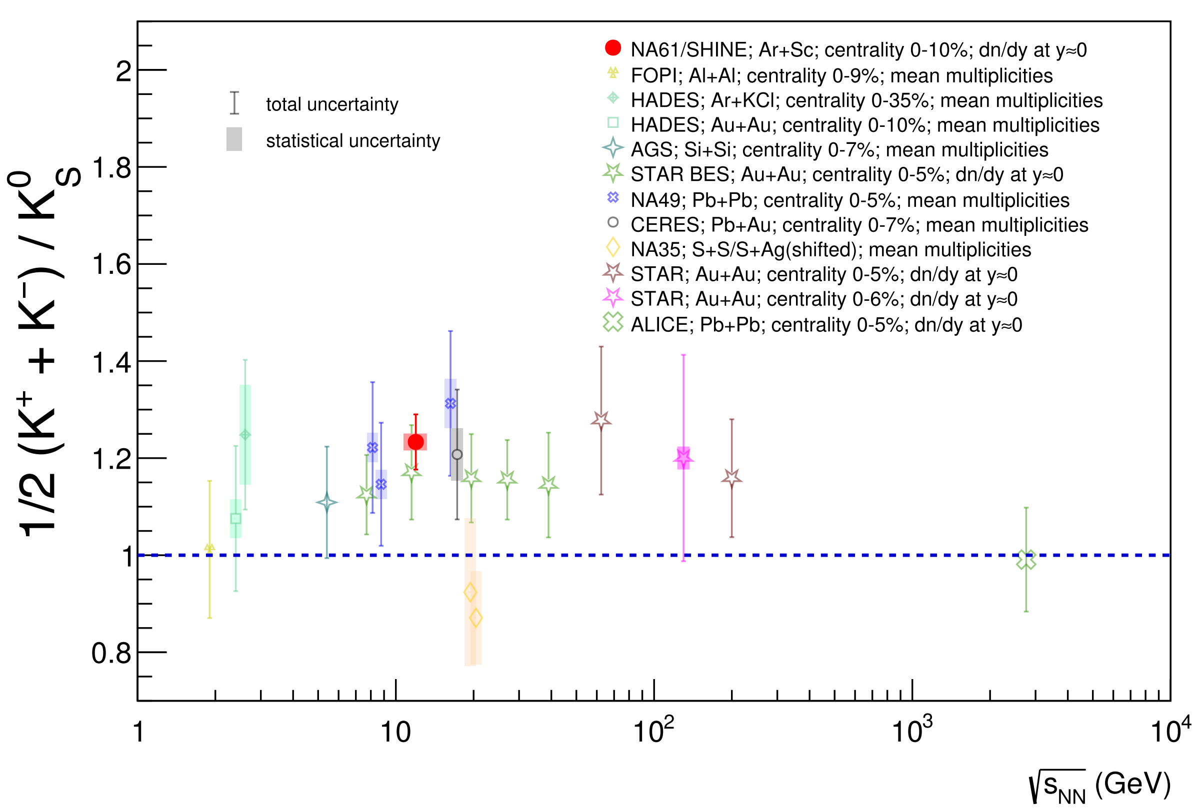
"Kaon Puzzle"

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

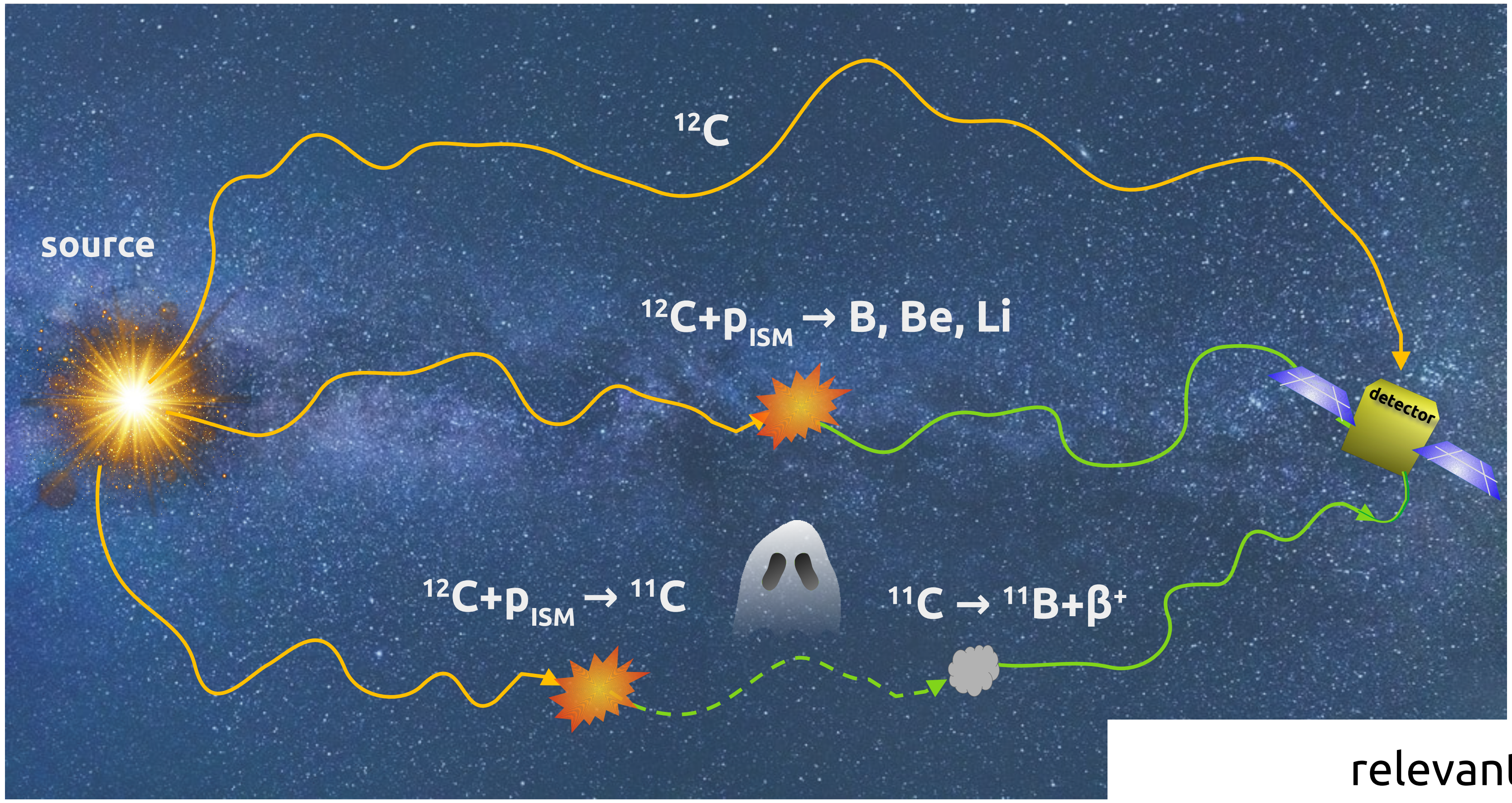
π^-+C at 158 and 350 GeV/c:

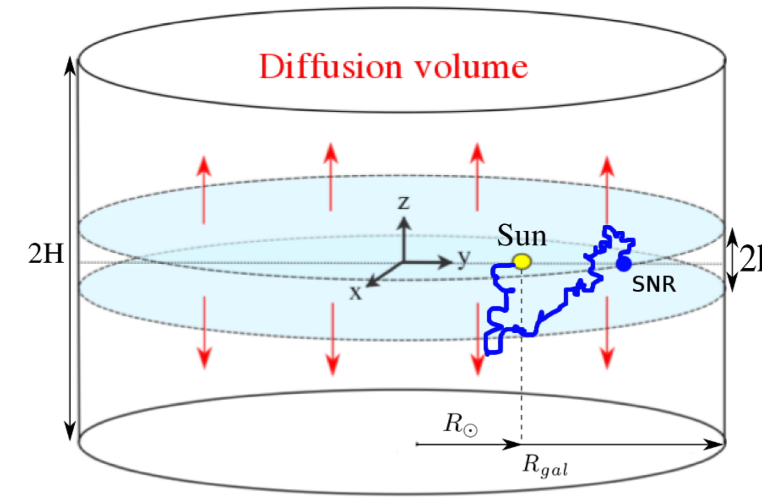


Ar+Sc at 75 A GeV/c:

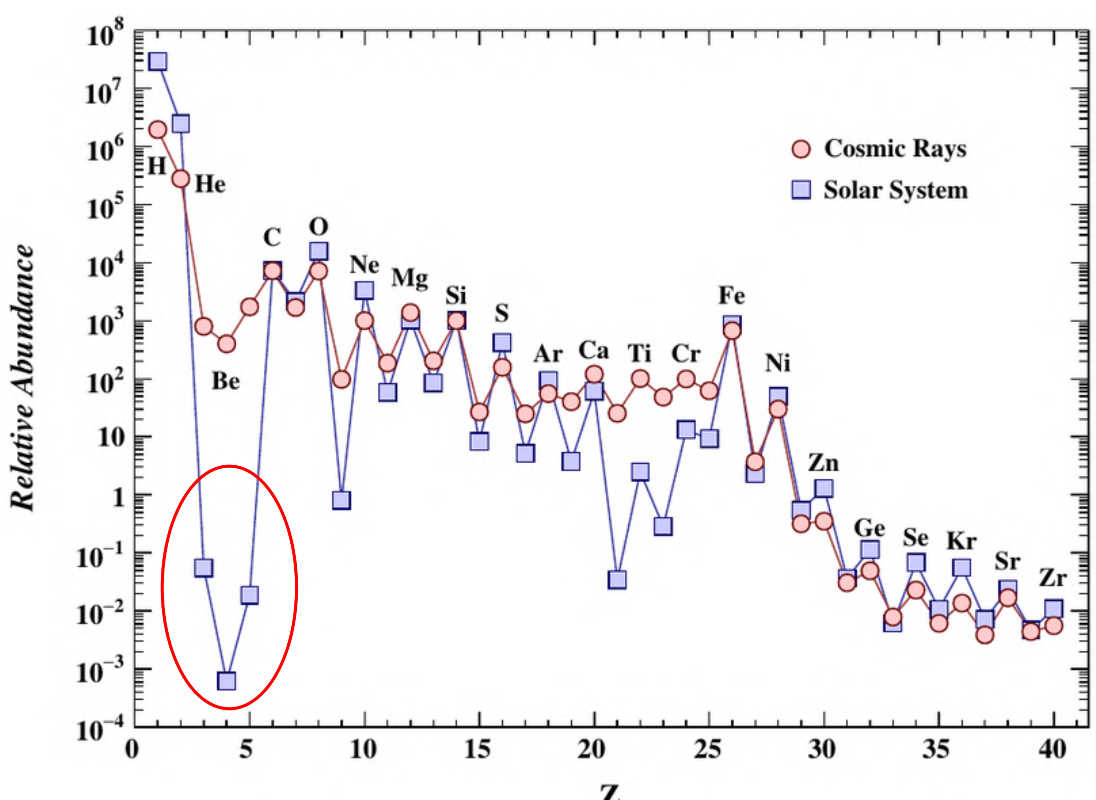


NA61 data for cosmic ray propagation

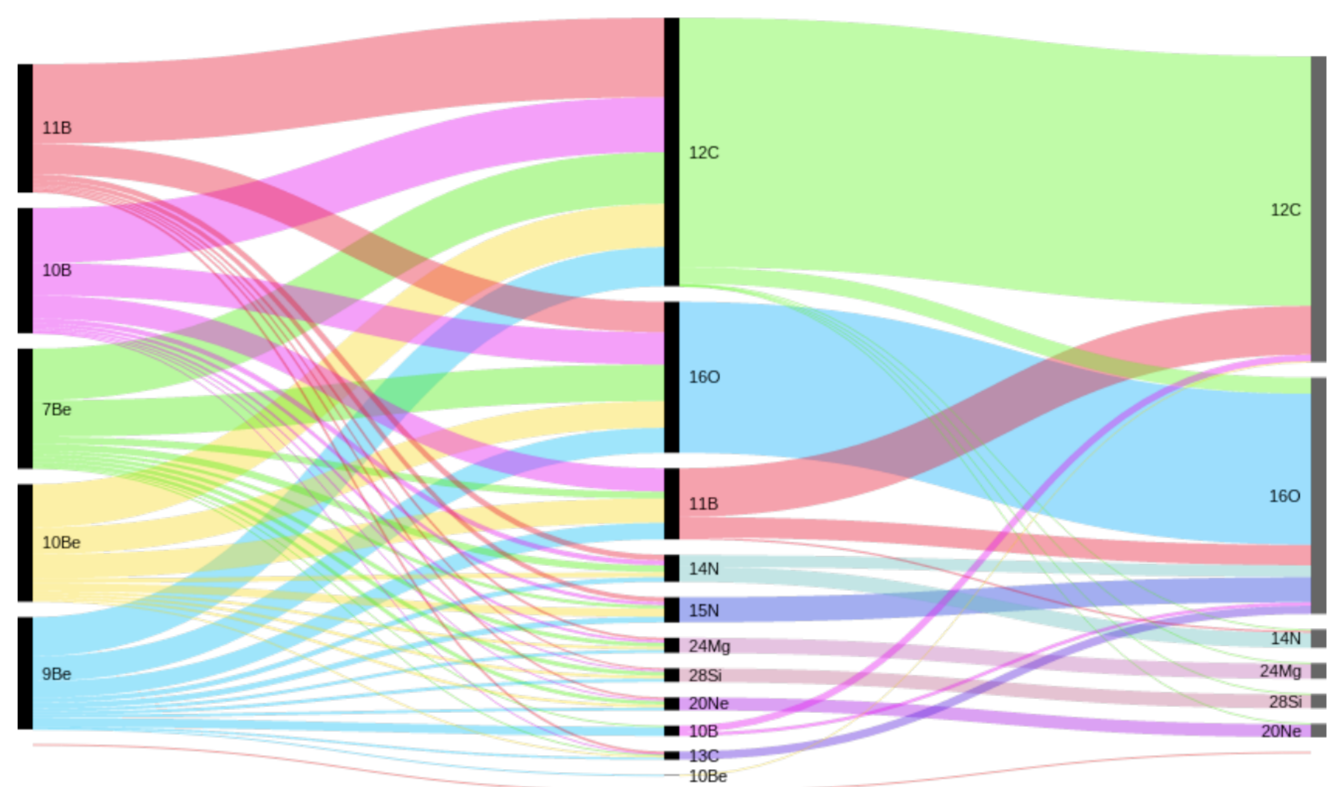




relevant reaction channels for Li, Be, B:



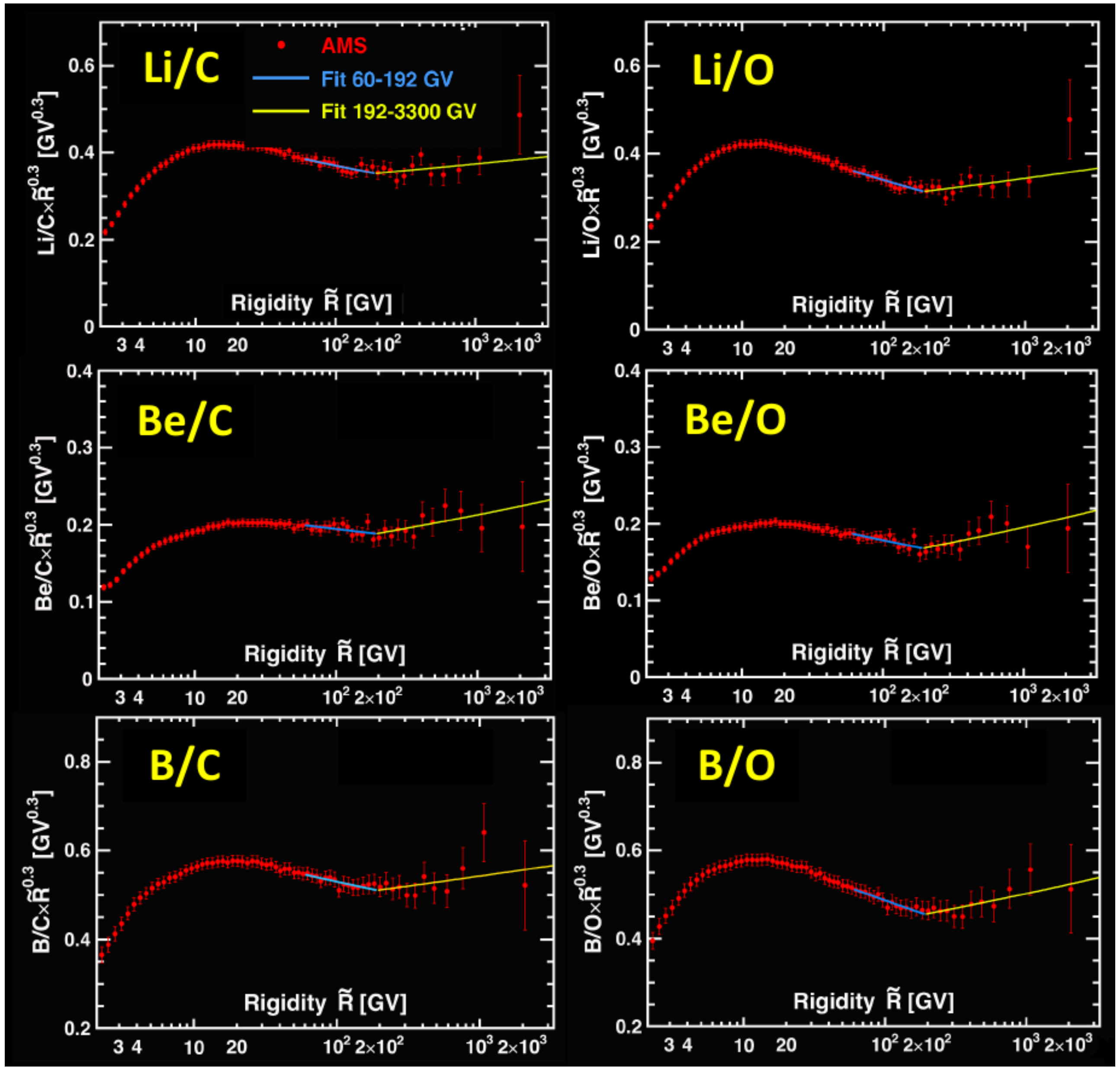
(PDG 2024)

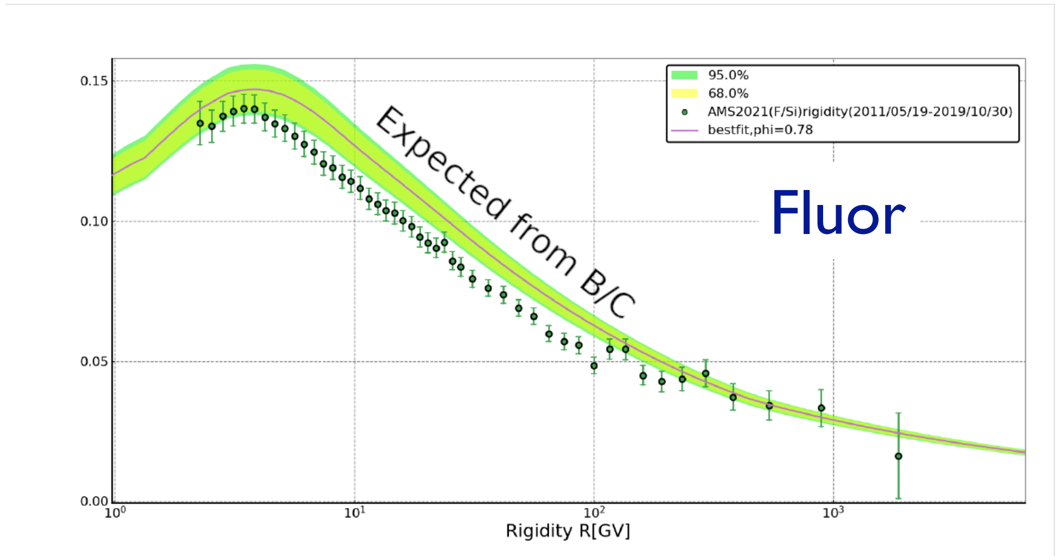


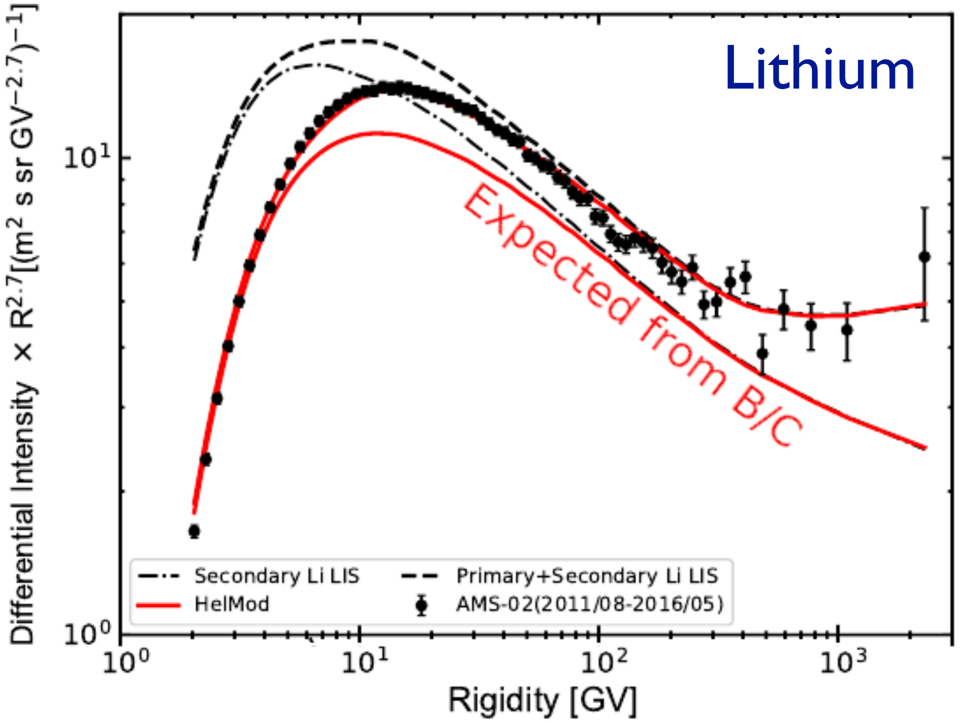
(Tomassetti 2018)

Secondary/Primary CRs: F Anomaly and Li Excess

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



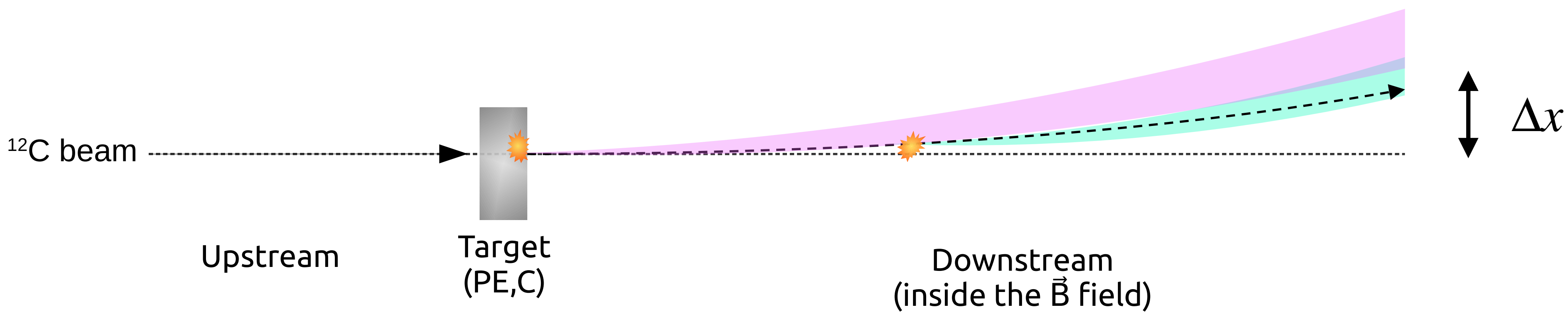




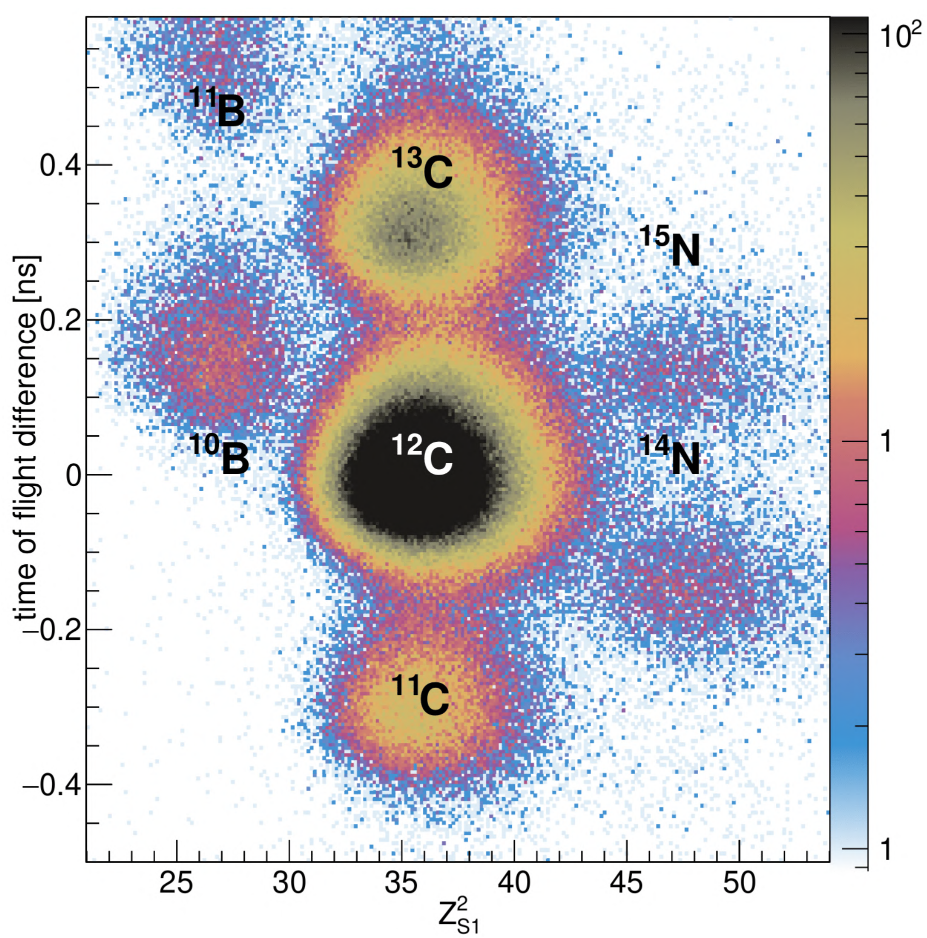
primary source of Li? spatial dependent diffusion? fragmentation cross sections?

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

Pilot run for fragmentation measurement (2018)

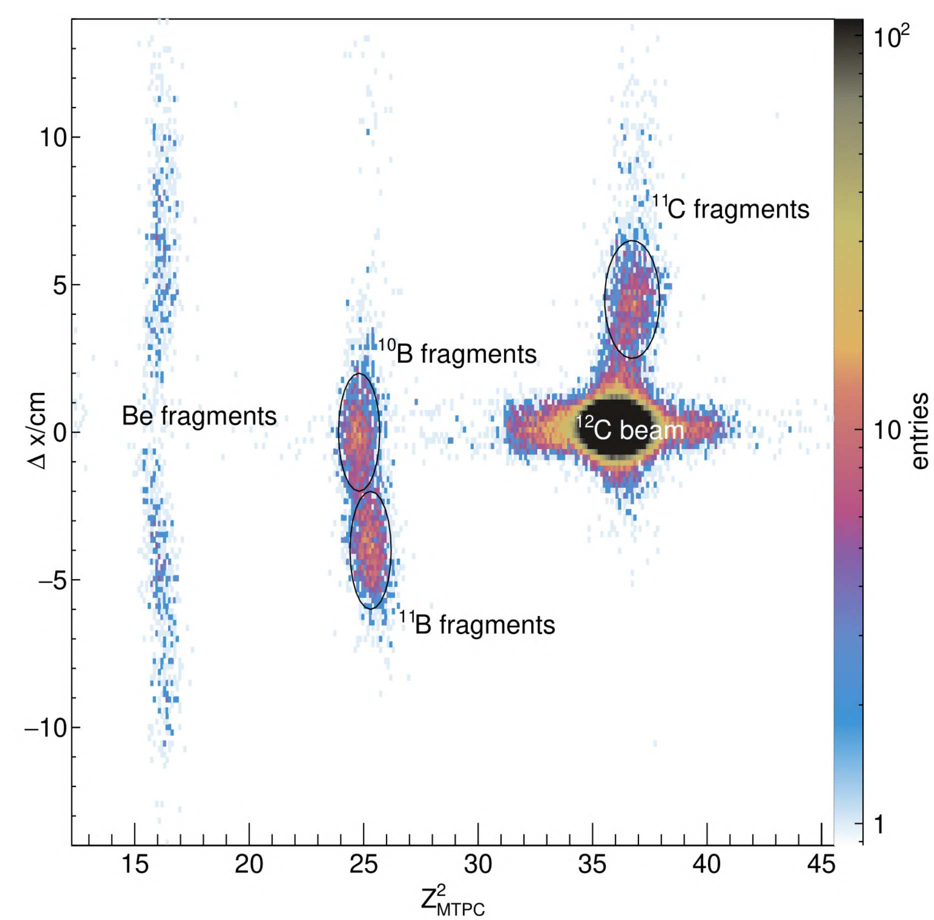


- Z^2 from $(dE/dx)_{S1}$
- (A/Z) from *t.o.f.* difference = $t_{S1} - t_A$



Triggered beam particles.

- Z^2 from $(dE/dx)_{MTPC}$
- (A/Z) from Δx ∝ R(A,Z)

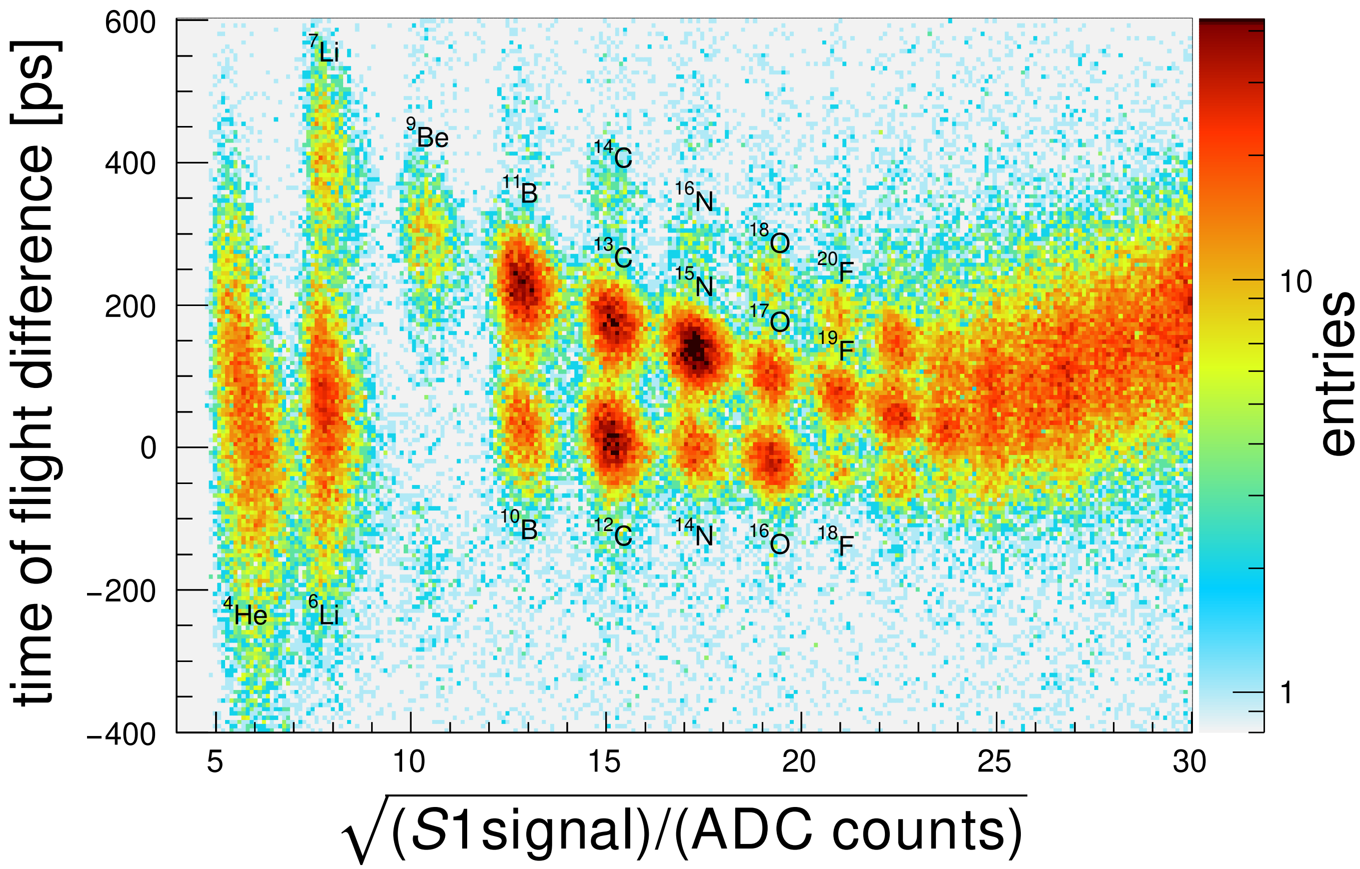


Fragments as measured in the MTPC.

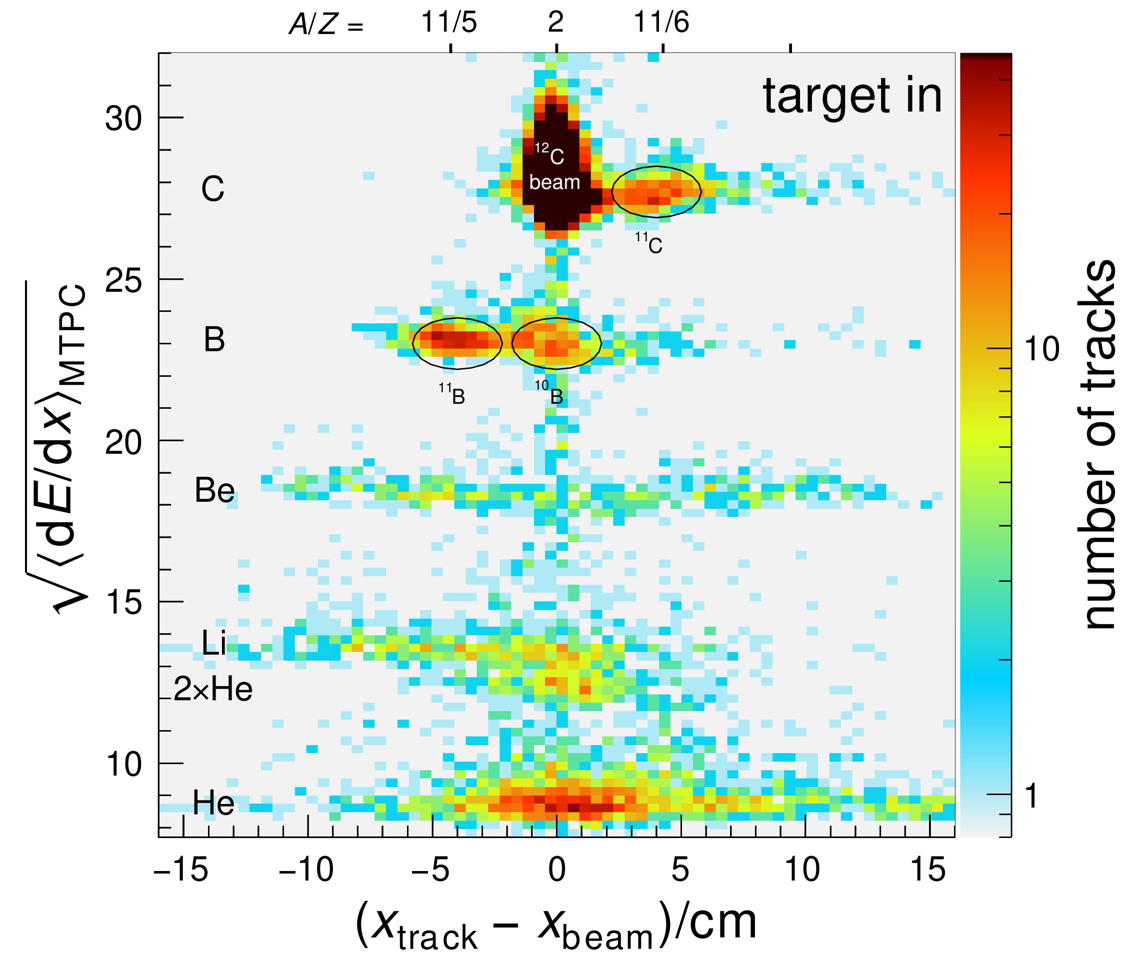
NA61/SHINE Pilot Run on Fragmentation, Dec 2018

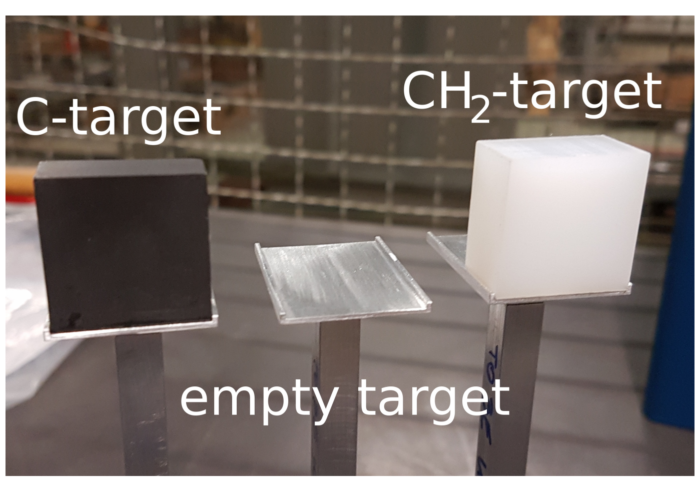
13.5 A GeV/c fragmented Pb beam

SPS beam-fragment identification



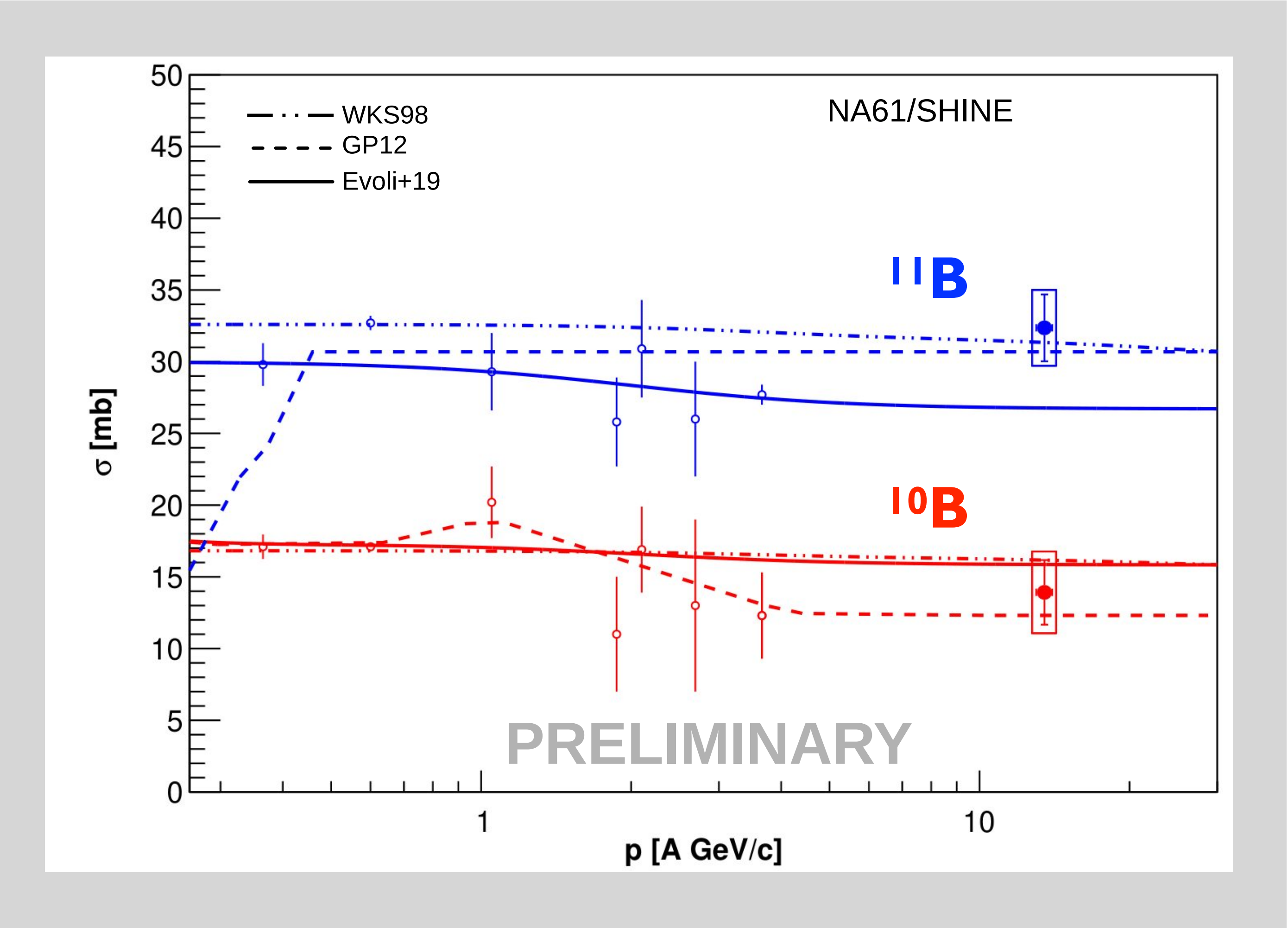
reaction-fragment identification





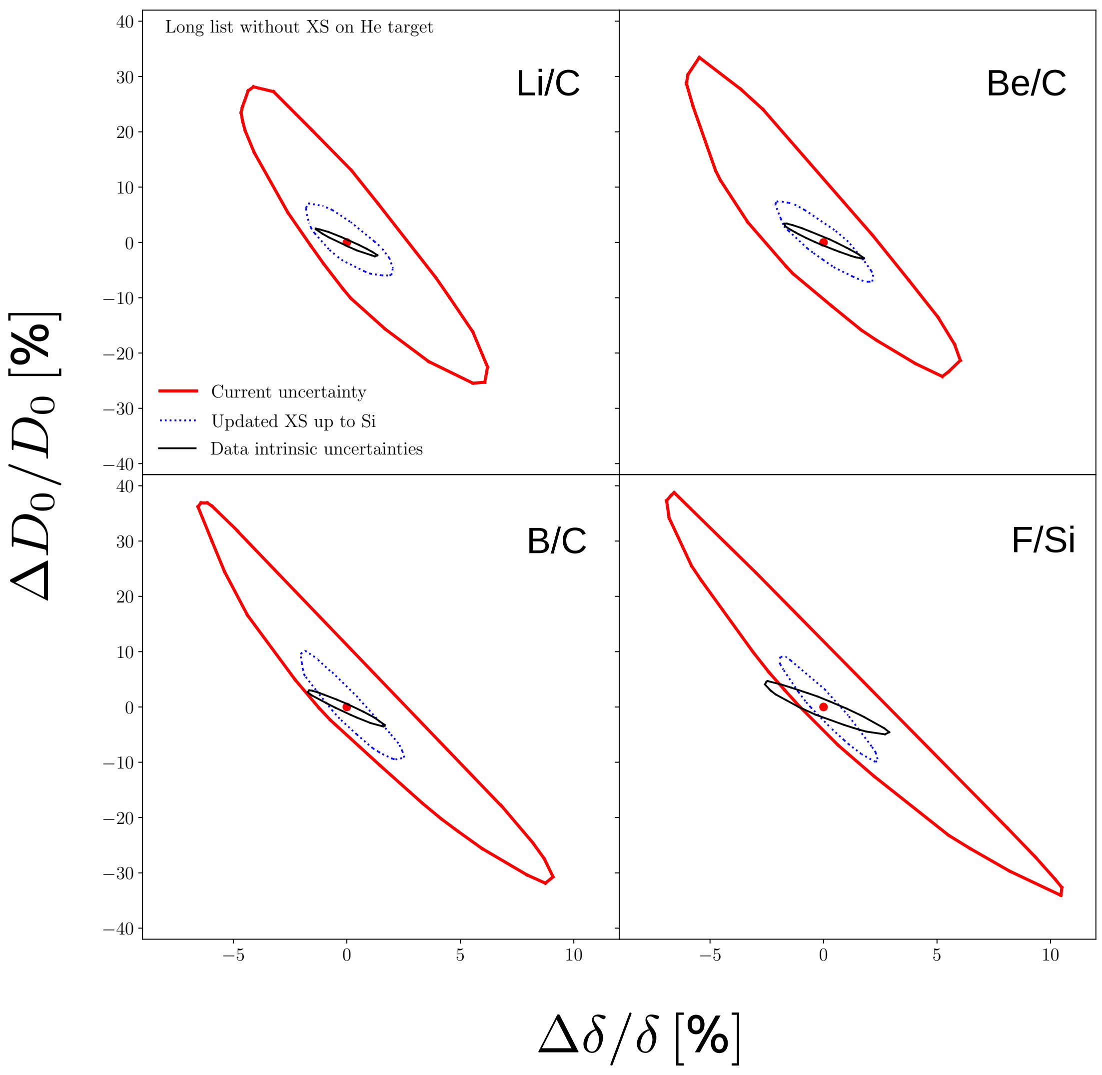
- 2.5 days data taking at 13.5 AGeV/c
- events after upstream ^{12}C selection:
  - 1.7×10^5 CH_2-target
  - 1.5×10^5 C-target
  - 0.4×10^5 empty-target

First fragmentation results and outlook

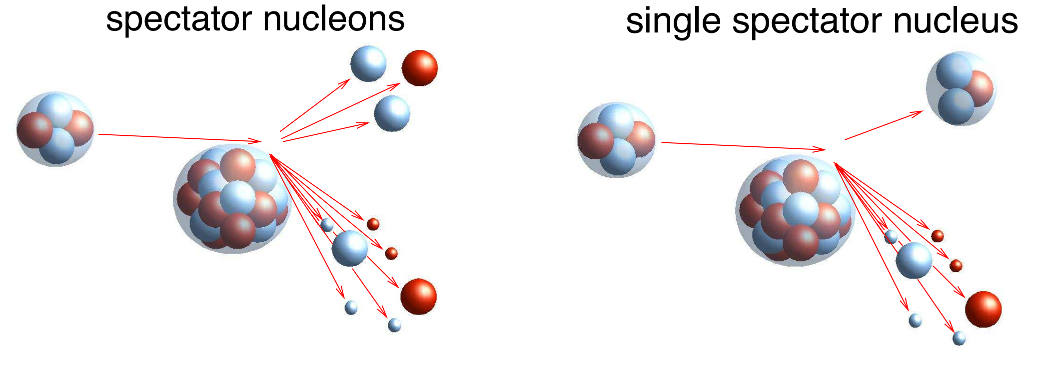


Expected impact of one week of NA61 fragmentation run

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



Possible relevance for air shower physics



Timeline towards a full NA61 fragmentation 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 $\sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow \mathrm{B} + \mathrm{X})$ 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 $\sigma(^{12}\mathrm{C{+}p} \rightarrow {}^{11}\mathrm{C{+}X})$ at ICRC

2022
- fragmented lead beam canceled due to early YETS

~~2023~~ **2024**
- 1 week fragmented lead? (CERN-SPSC-2022-034)

N. Amin (KIT) 2022

Detector Upgrades for Run 3