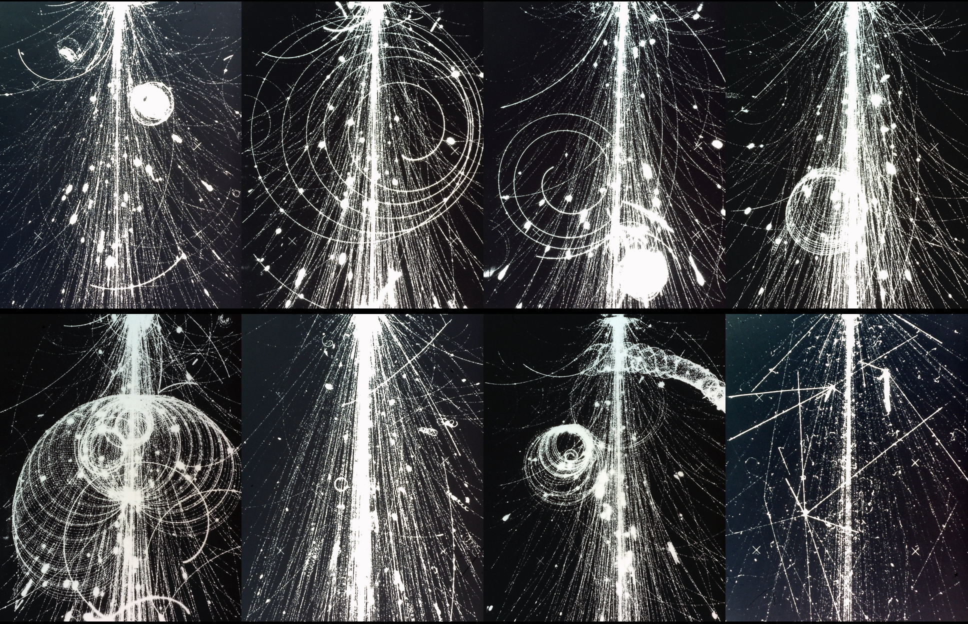
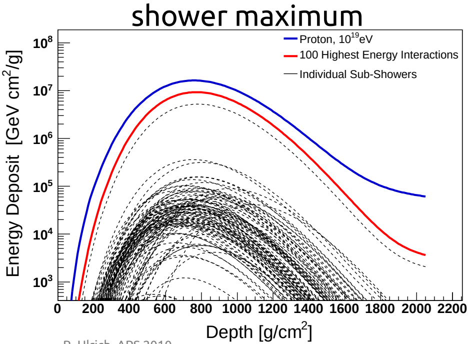
Results from NA61/SHINE on Hadronic Interactions in Cosmic-Ray Air Showers

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

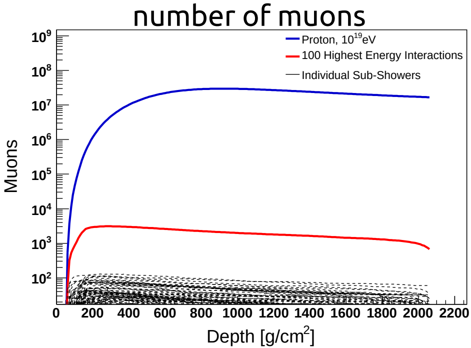


NA35 3.2 TeV O+Pb interactions

Air Shower Observables and Hadronic Interactions



R. Ulrich, APS 2010



- X_{max} is dominated by first interaction
  $\rightarrow$most relevant data from LHC
- muons from $\pi^{\pm}$ decay at late stage of cascade ($\lambda_{\mathrm{dec}} \sim \lambda_{\mathrm{int}}$)
  $\rightarrow$all interaction energies relevant!

Muons in UHE Air Showers

energy of last interaction before decay to μ

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

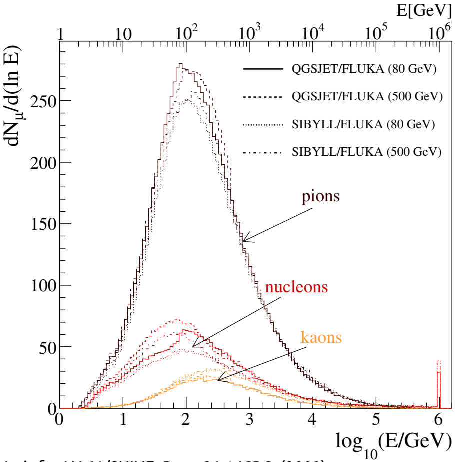
$\searrow$

$\mu + \nu_\mu$

high-energy air shower

e.g. KASCADE:

- $E_0 = 10^{15}$ eV
- $r =$ 40-200 m
- $E_\mu \geq$ 250 MeV



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

Muons in UHE Air Showers

energy of last interaction before decay to μ

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

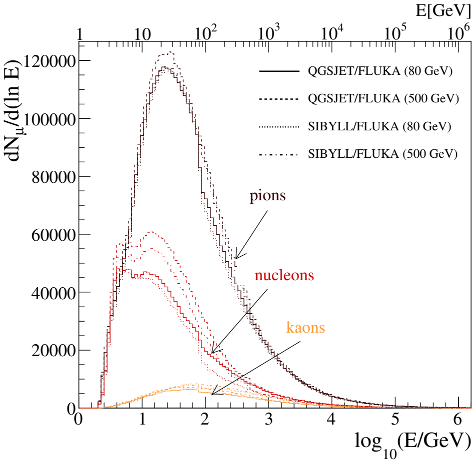
$\searrow$

$\mu + \nu_\mu$

ultrahigh-energy air shower

e.g. Auger:

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



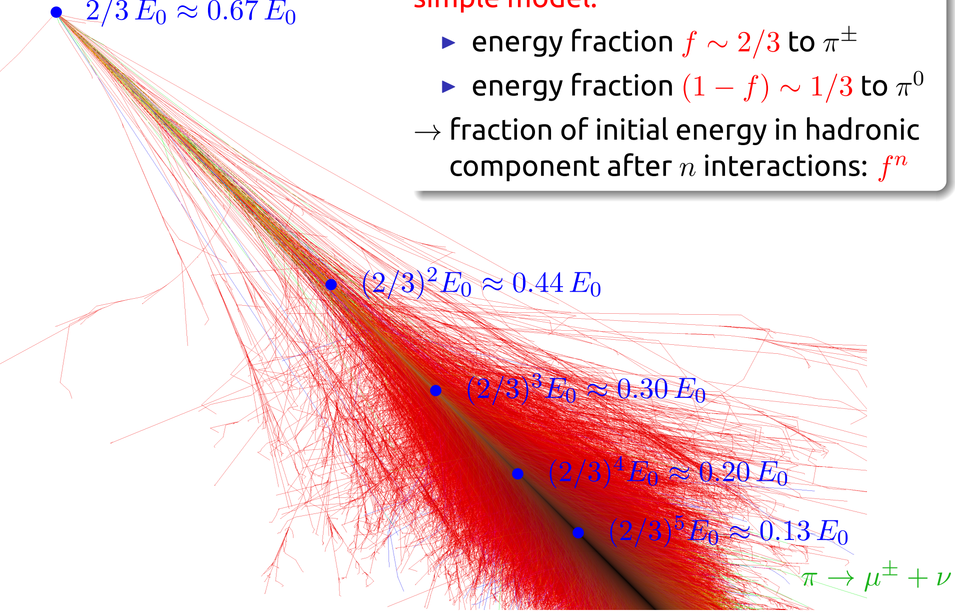
I.C. Mariş for NA61/SHINE, Proc. 31st ICRC, (2009)

Muons in UHE Air Showers

simple model:

- 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

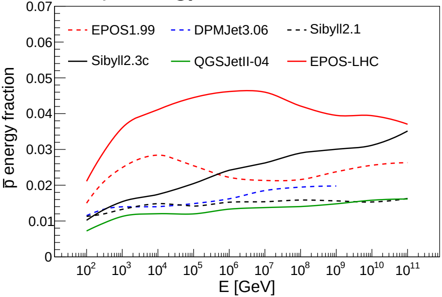
number of muons depends on energy fraction f of produced hadrons

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

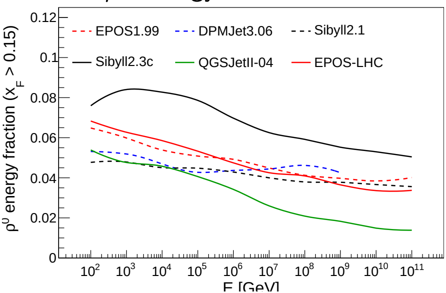
} $\rightarrow$ hadronic shower

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

$\bar{p}$ energy fraction in π^--C

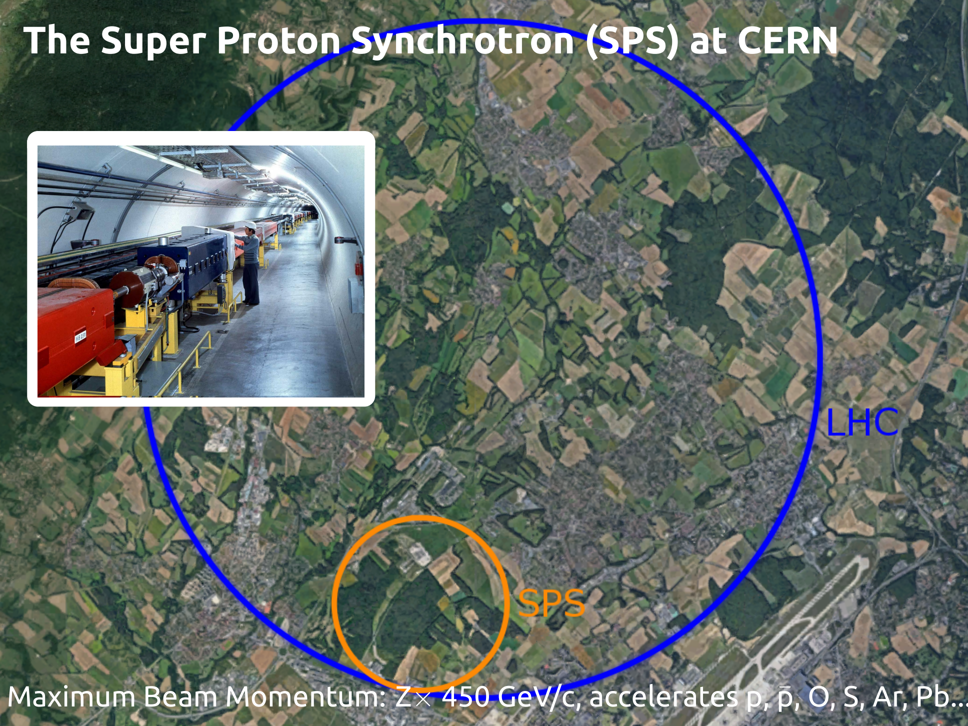


ρ^0 energy fraction in π^--C



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

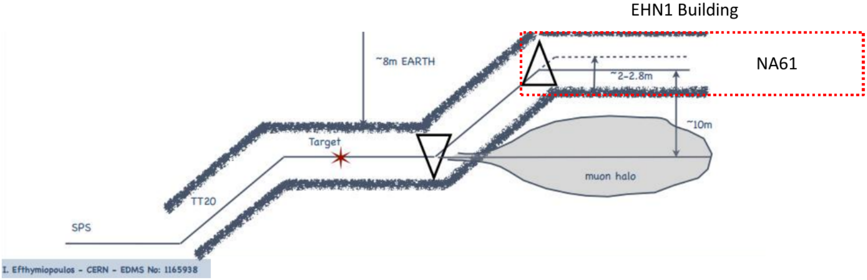
The Super Proton Synchrotron (SPS) at CERN



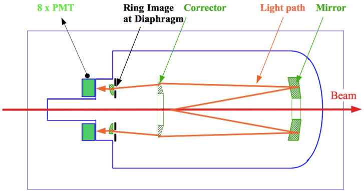
Maximum Beam Momentum: Z× 450 GeV/c, accelerates p, p̄, O, S, Ar, Pb...

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

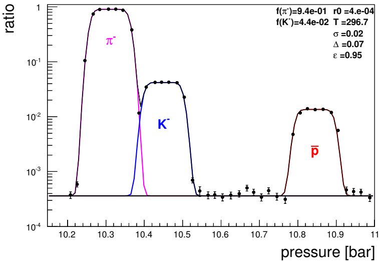
A **precise** (2% dp/p acceptance), robust, flexible **magnetic spectrometer**



Beam Particle Id (Mass via Cherenkov Angle)



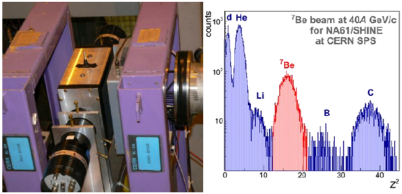
CEDAR (CErenkov Differential counters with Achromatic Ring focus)



pressure scan

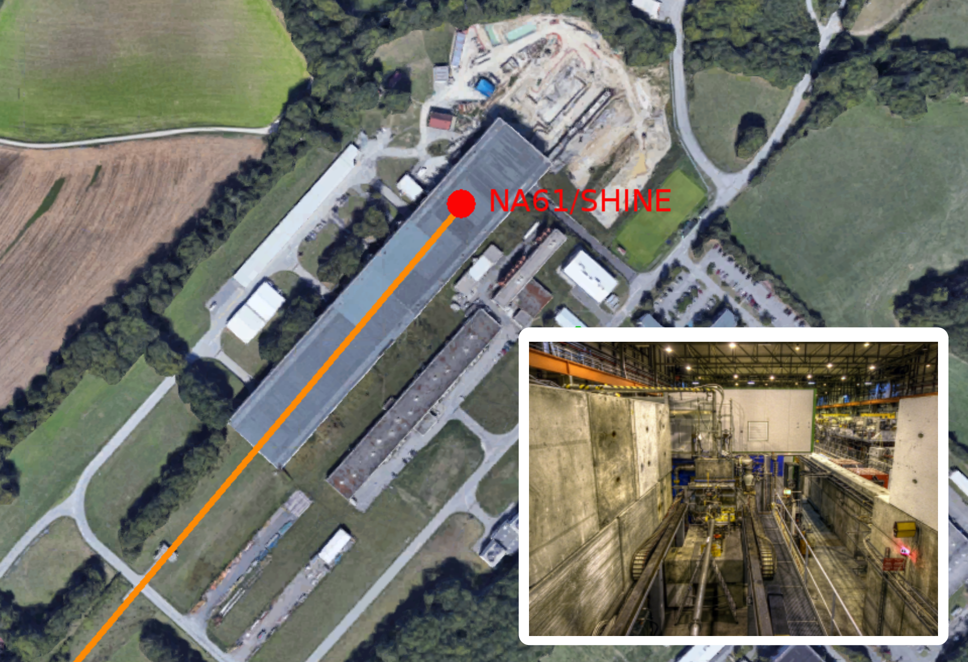
Beam Particle Id (A and Z with ToF, dE/dX, Č)

installation of ToF cable along H2 beam line, Feb 2018

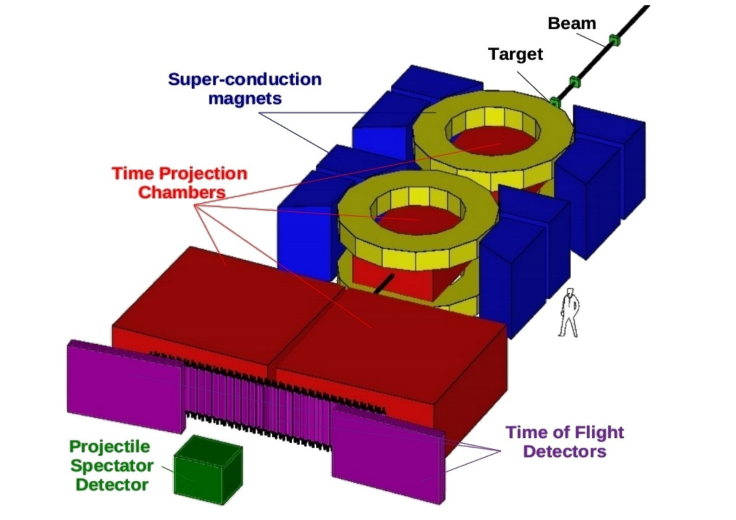


Z^2 detector, Be run (Cherenkov in Quartz)

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

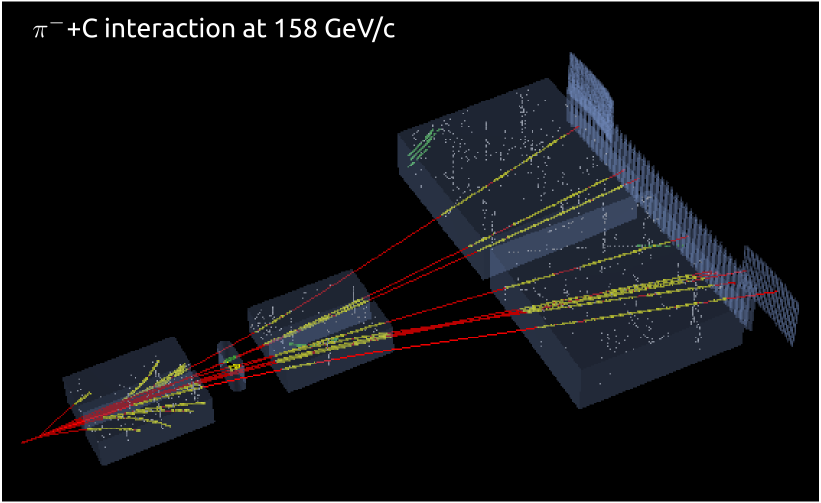


Particle Production Measurement at NA61/SHINE

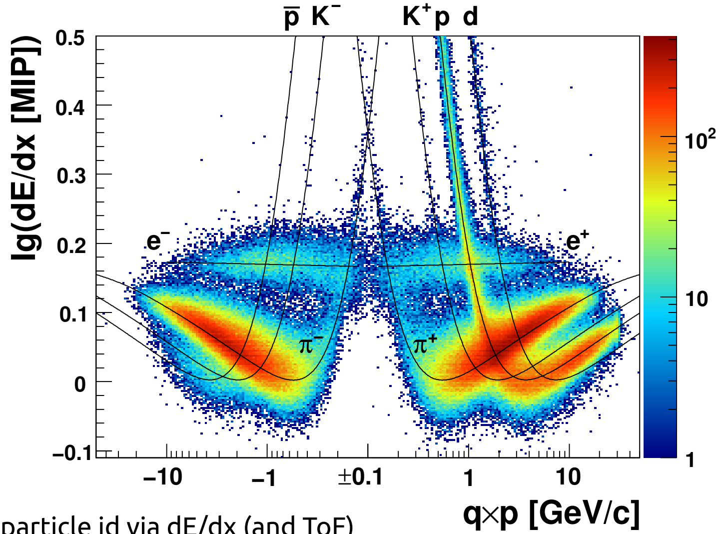


- large acceptance $\approx 50\%$ at $p_T \leq 2.5$ GeV/c
- momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\text{GeV/c})^{-1}$
- tracking efficiency: $> 95\%$

Particle Production Measurement at NA61/SHINE

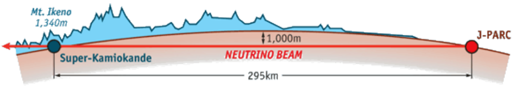


Particle Production Measurement at NA61/SHINE

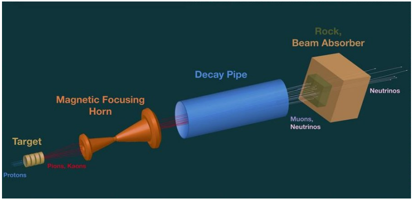


particle id via dE/dx (and ToF)

NA61 Data on Hadron+Carbon Interactions



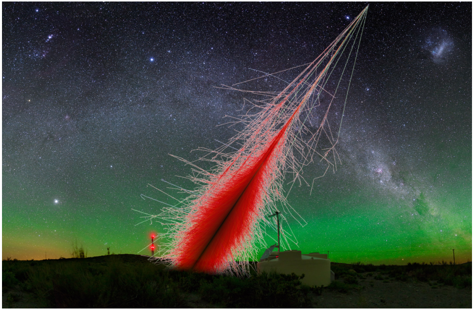
T2K, MINERνA, MINOS, NOνA, DUνE



	p	year	$N_{\text{trig}}/10^6$
p+C	31	2007/09	6.1
p+C	60	2016	3.1
p+C	90	2017	2.4
p+C	120	2012	1.1*
p+C	120	2017	2.6
π^++C	30	2017	2.2
π^-+C	60	2017	2.6
π^-+C	158	2009	5.5
π^-+C	350	2009	4.6
K^++C	60	2015	0.7*

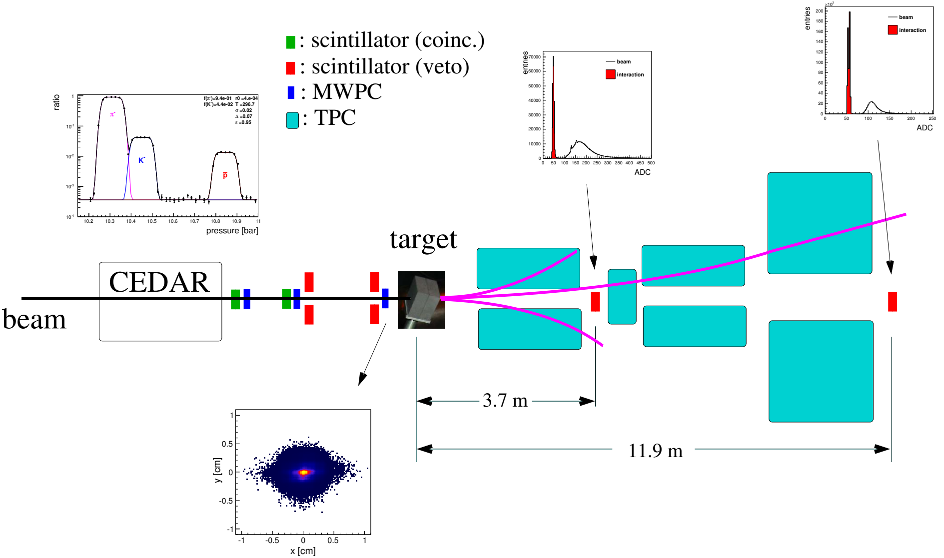
*without magnetic field, ** $\sim 15 \times 10^6$ events in total

Pierre Auger Observatory, Telescope Array, IceTop



Cross Section Measurements with NA61

Schematic of Beam Line:



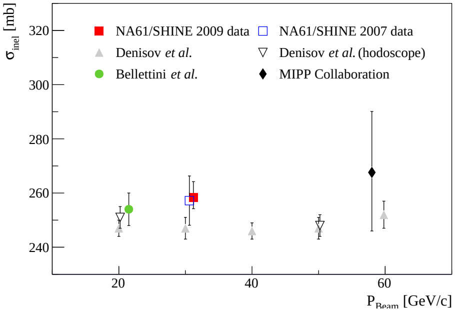
Cross Section Measurements with NA61

inelastic and production cross sections:

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{ela}}$$

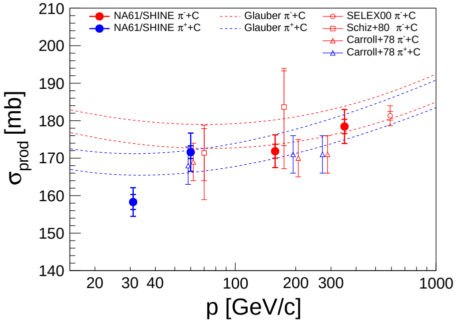
$$\sigma_{\mathrm{prod}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{qela}} - \sigma_{\mathrm{ela}}$$

p+C at 31 GeV/c



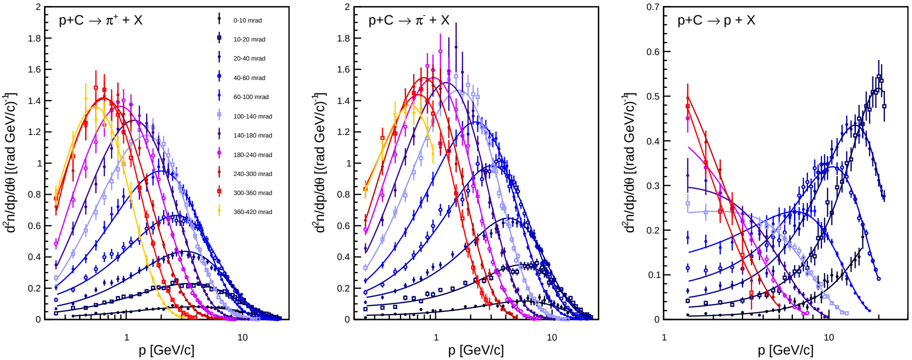
NA61/SHINE, Eur.Phys.J. **C76** (2016) 84

π^-+C at 158 and 350 GeV/c



NA61/SHINE, ISVHECRI 2012 and PRD98 (2018)

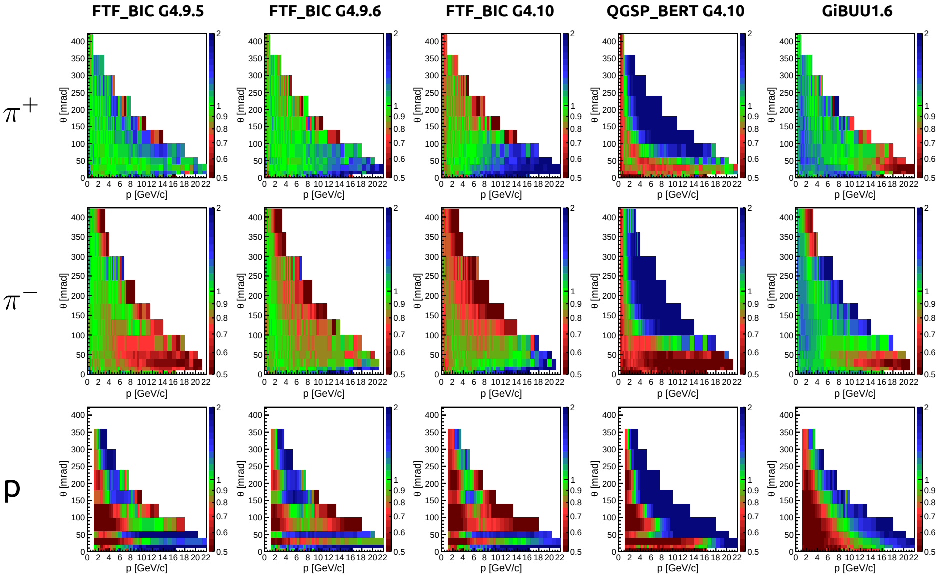
$\pi^{\pm}$ and p multiplicities in p+C at 31 GeV/c



(lines to guide the eye)

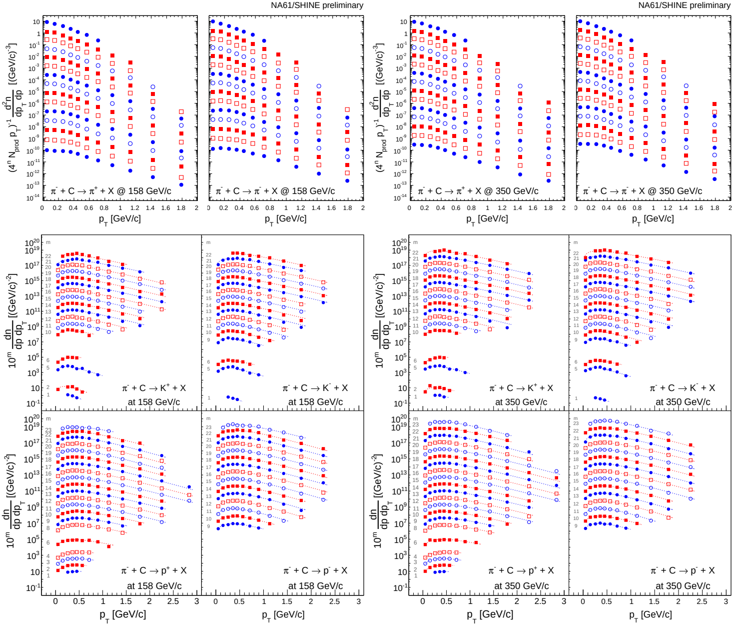
- NA61/SHINE, Eur.Phys.J. C76 (2016) 84
- also: $K^{\pm}$, K^0_S, Λ

Inclusive $\pi^{\pm}$ and p spectra in p+C at 31 GeV/c

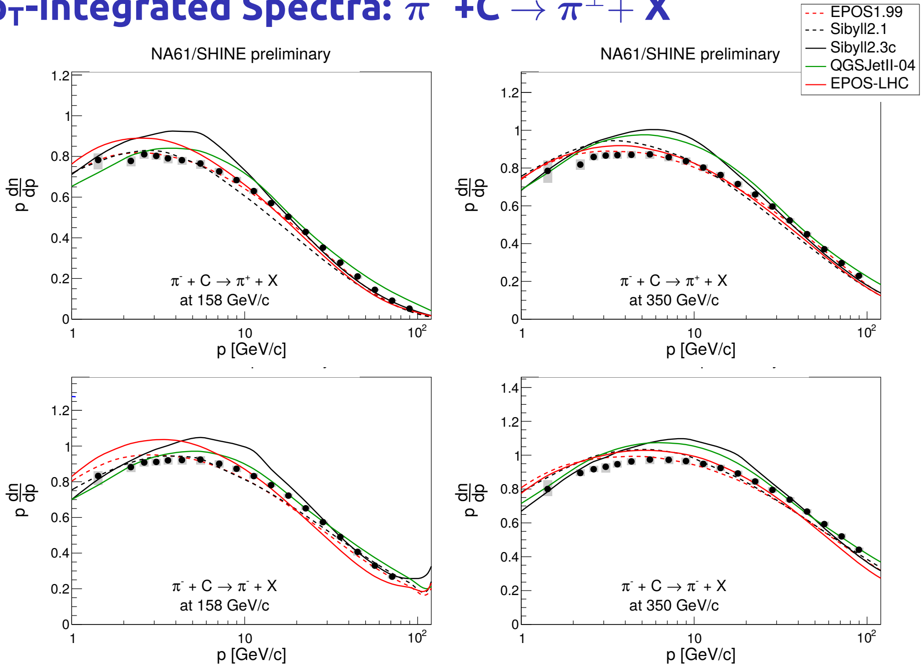


colors: data/MC, dark-red = 0.5, green = 1, dark-blue = 2

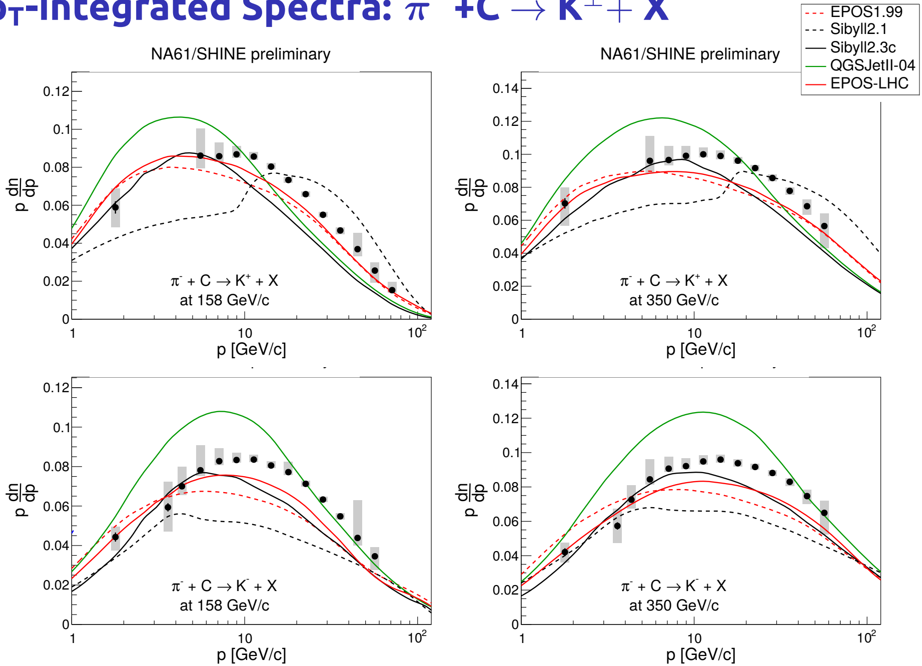
$\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra in π^{-}+C at 158 and 350 GeV/c



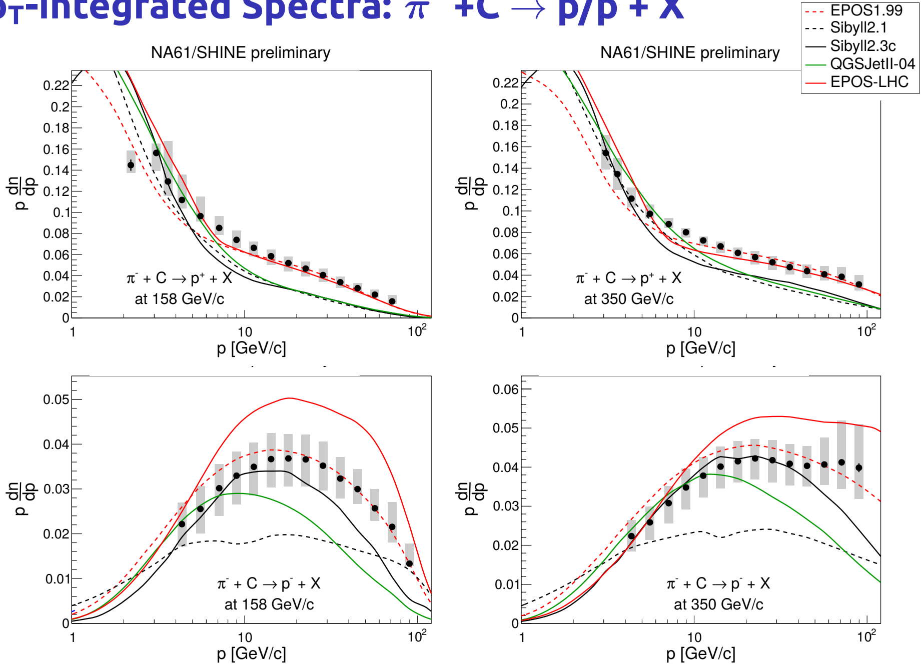
p_T-integrated Spectra: $\pi^- + C \to \pi^\pm + X$



p_T-integrated Spectra: $\pi^- + C \rightarrow K^\pm + X$

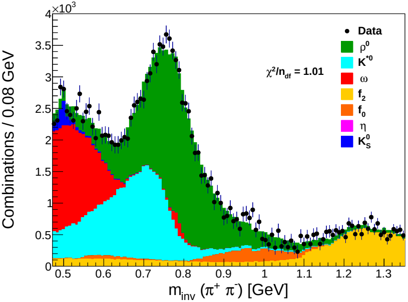


p_T-integrated Spectra: $\pi^- + C \rightarrow p/\bar{p} + X$

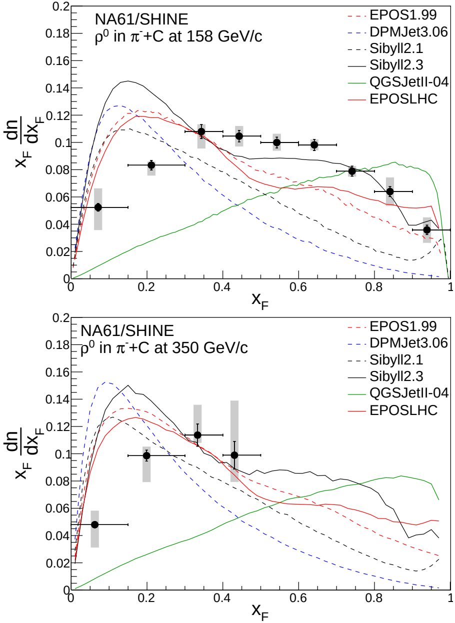


ρ^0 Production in π^-+C at 158 and 350 GeV/c

two-track invariant mass fit:



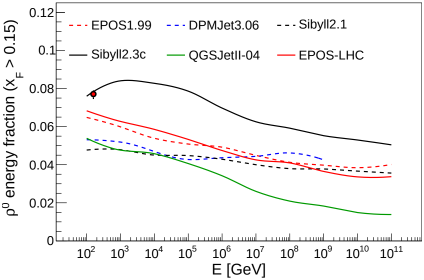
$(0.3 < x_F < 0.4)$ of the 158 GeV/c



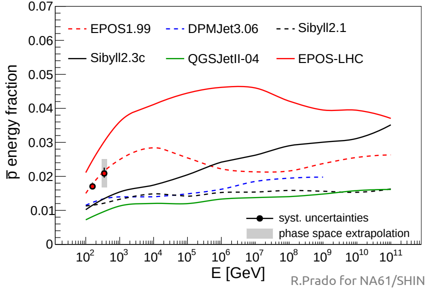
NA61/SHINE Collaboration, EPJ **C77** 626 (2017)

Measured Energy Fractions

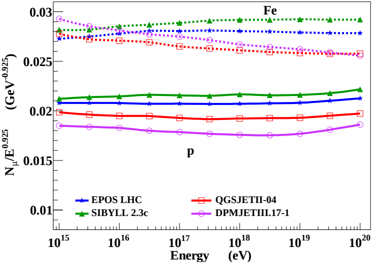
ρ^0 energy fraction in π^--C



$\bar{p}$ energy fraction in π^--C



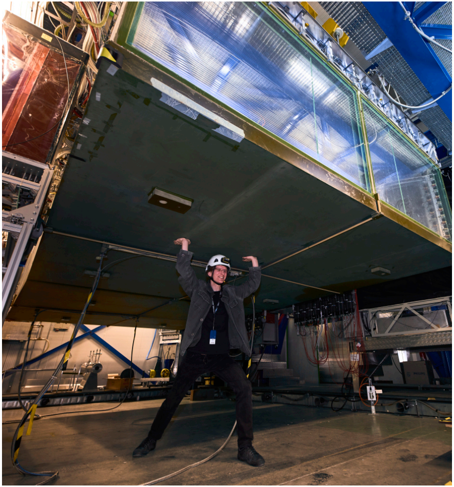
muon production in air showers:



T.Pierog, ICRC2017

Summary and Outlook

- precise lab measurements of last stages of UHECR air shower development with NA61/SHINE
- 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
- energy fractions of (anti-)baryon and ρ^0 production relate directly to muon production in air showers
- next up in CR-related program: measurement of nuclear fragmentation*



inside NA61 (Julien Ordan/CERN)

* mainly C+p for Galactic CRs, but C+C-fragmentation at $E = 180$ GeV could also be interesting for air shower fluctuations (see CERN-SPSC-2017-035)