

Results from NA61 relevant for CR physics

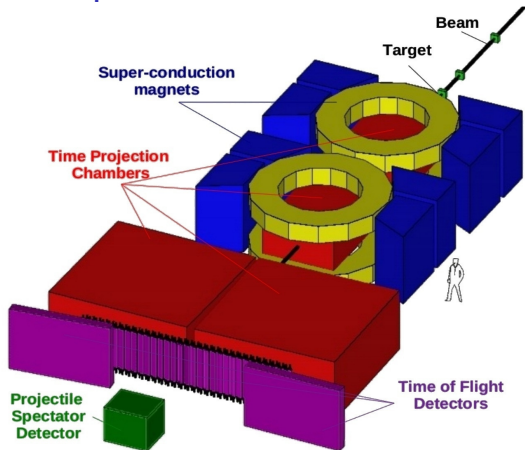
M. Unger* for the NA61/SHINE[†] Collaboration

*Karlsruher Institut für Technologie

[†] SHINE = SPS heavy ion and neutrino experiment

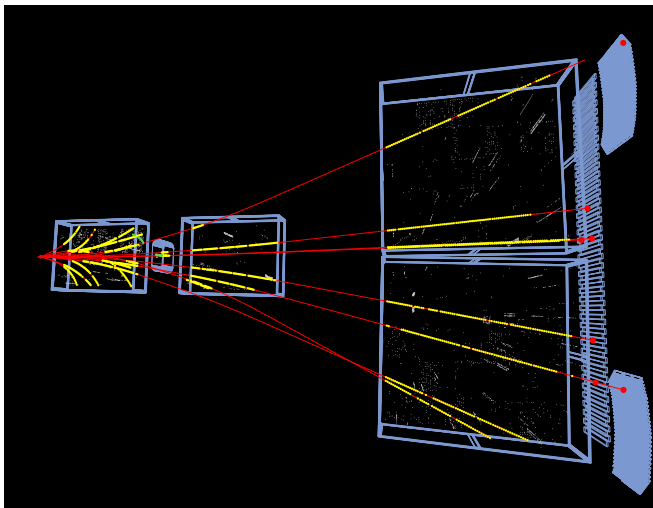


NA61/SHINE Experiment at the SPS



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

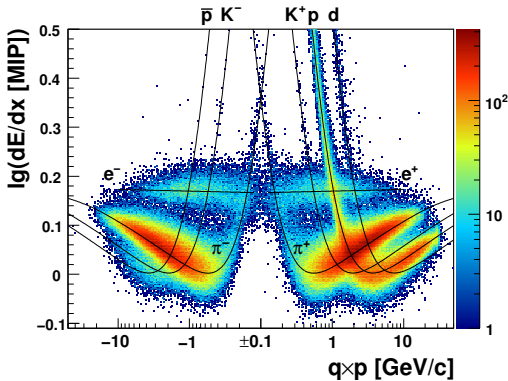
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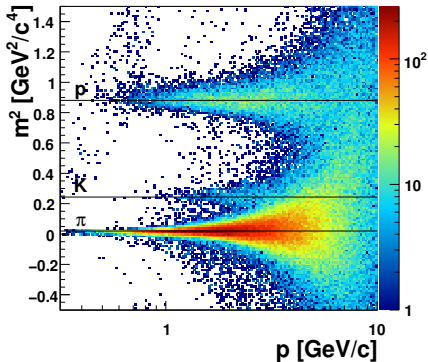
Particle Identification

energy deposit in TPC:



$$\sigma \left(\frac{dE}{dx} \right) / \frac{dE}{dx} \approx 4\%$$

time of flight:

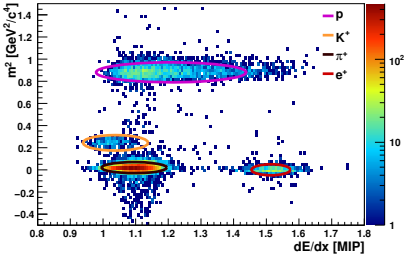


$$\sigma(t) \approx 100 \text{ ps}$$

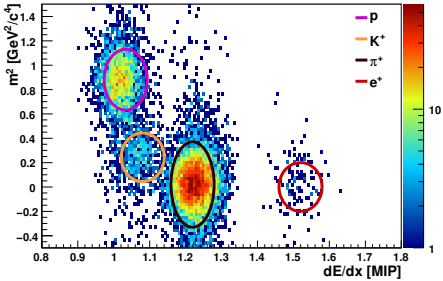
(p+C at 31 GeV/c)

Particle Identification

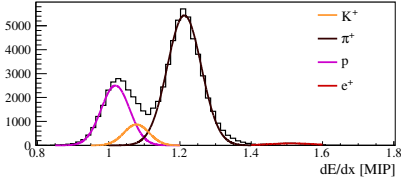
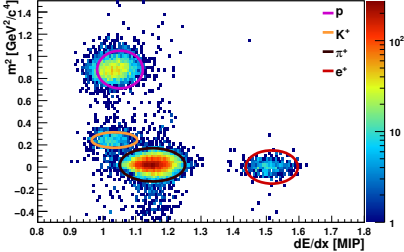
1 GeV/c < p < 2 GeV/c



4 GeV/c < p < 5 GeV/c



2 GeV/c < p < 3 GeV/c



The NA61/SHINE Collaboration

N. Abgrall, A. Aduszkiewicz, [T. Anticic](#), N. Antoniou, J. Argyriades, B. Baatar, A. Blondel, [J. Blümer](#), M. Bogomilov, A. Bravar, W. Brooks, J. Brzychczyk, A. Bubak S. A. Bunyatov, O. Busygina, P. Christakoglou, C. Pistillo, T. Czopowicz, N. Davis, S. Debieux, [H. Dembinski](#), F. Diakonou, S. Di Luise, W. Dominik, T. Drozhzhova, J. Dumarchez, K. Dynowski, [R. Engel](#), A. Ereditato, L. Esposito, G. A. Feofilov, Z. Fodor, A. Ferrero, A. Fulop, M. Gaździcki, M. Golubeva, B. Grabez, K. Grebieszko, A. Grzeszczuk, F. Guber, H. Hakobyan, T. Hasegawa, M. Hierholzer, R. Idczak, S. Igolkin, Y. Ivanov, A. Ivashkin, [K. Kadija](#), A. Kapoyannis, N. Katrynska, D. Kielczewska, D. Kikola, M. Kirejczyk, J. Kisiel, T. Kiss, S. Kleinfelder, T. Kobayashi, V. I. Kolesnikov, D. Kolev, V. P. Kondratiev, A. Korzenev, S. Kowalski, A. Krasnoperov, S. Kuleshov, A. Kurepin, D. Larsen, A. Laszlo, V. V. Lyubushkin, M. Mackowiak-Pawlowska, Z. Majka, B. Maksiak, A. I. Malakhov, D. Maletic, A. Marchionni, A. Marcinek, V. Marin, [I. Mariş](#), K. Marton, [H.J. Mathes](#), T. Matulewicz, V. Matveev, G. L. Melcumov, St. Mrówczyński, S. Murphy, T. Nakadaira, M. Nirkko, K. Nishikawa, T. Palczewski, G. Palla, A. D. Panagiotou, [T. Paul](#), A. Redij, W. Peryt, O. Petukhov R. Planeta, J. Pluta, B. A. Popov, M. Posiadala, S. Puławski, J. Puzovic, W. Rauch, M. Ravonel, R. Renfordt, A. Robert, D. Röhrich, E. Rondio, [M. Roth](#), A. Rubbia, A. Rustamov, M. Rybczynski, A. Sadovsky, K. Sakashita, M. Savic, T. Sekiguchi, P. Seyboth, M. Shibata, R. Sipos, E. Skrzypczak, M. Słodkowski, P. Staszal, G. Stefanek, J. Stepaniak, H. Stroebele, [T. Šuša](#), [M. Szuba](#), M. Tada, V. Tereshchenko, T. Tolyhi, R. Tsenov, L. Turko, [R. Ulrich](#), [M. Unger](#), M. Vassiliou, [D. Veberič](#), V. V. Vechernin, G. Vesztergombi, L. Vinogradov, A. Wilczek, Z. Włodarczyk, A. Wojtaszek, O. Wysztyński, L. Zambelli W. Zipper

142 scientists, 27 institutions, [14 Auger members](#)

Muons in UHE Air Showers

energy of last interaction before decay to μ

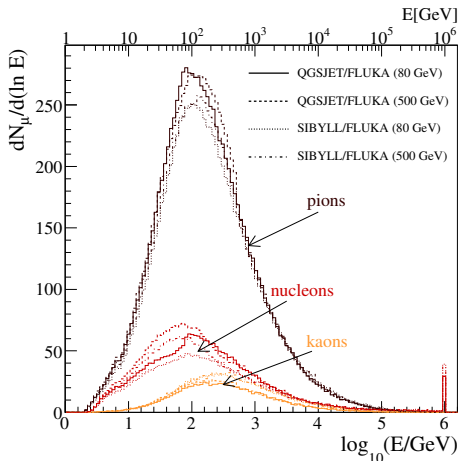
air shower \rightarrow hadron + air $\rightarrow \pi/K + X$

$\mu + \nu_\mu$

Low energy air shower:

e.g. KASCADE:

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



Muons in UHE Air Showers

energy of last interaction before decay to μ

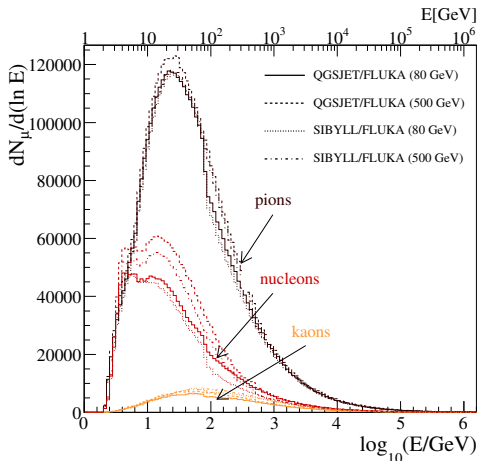
air shower \rightarrow hadron + air $\rightarrow \pi/K + X$

$\mu + \nu_\mu$

High energy air shower:

e.g. P. Auger Observatory:

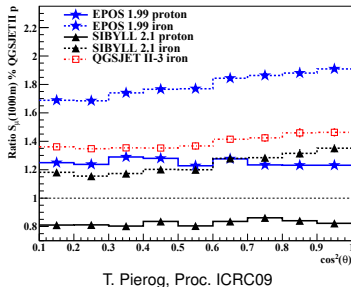
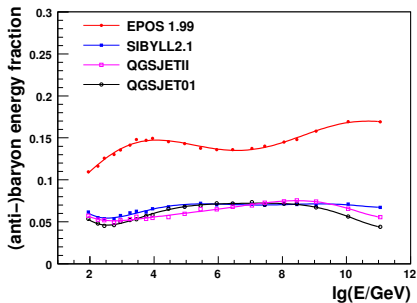
- ▶ $E_0 = 10^{19}$ eV
- ▶ $r = 1000$ m
- ▶ $E_\mu \geq 150$ MeV



Muons in UHE Air Showers

Number of muons depends on energy fraction of produced hadrons

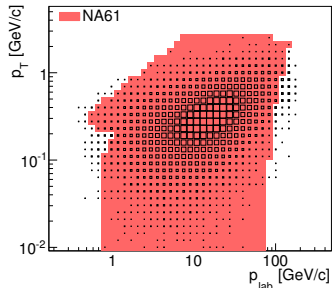
- ▶ $\pi^0 \rightarrow$ electromagnetic shower
 - ▶ π^\pm
 - ▶ $\rho^0 \rightarrow \pi^+\pi^-$
 - ▶ (anti-) baryons
- } \rightarrow hadronic shower



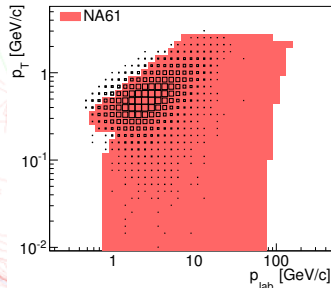
Muons in UHE Air Showers

Muon production at fixed energy of grand-mother particle

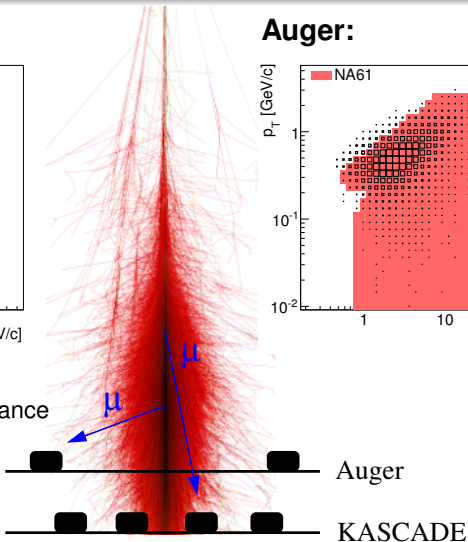
KASCADE:



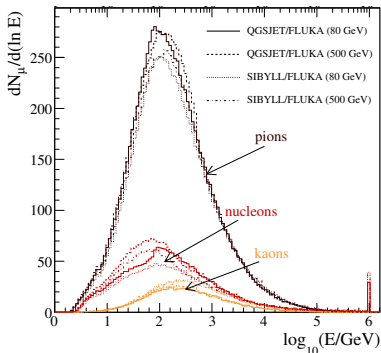
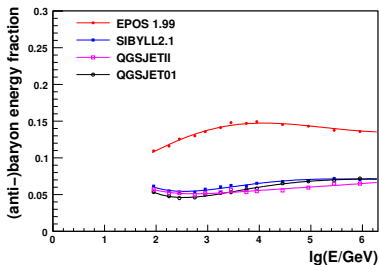
Auger:



- ▶ boxes: air shower
- ▶ red area: NA61 acceptance
- ▶ $E_{grand} = 158$ GeV



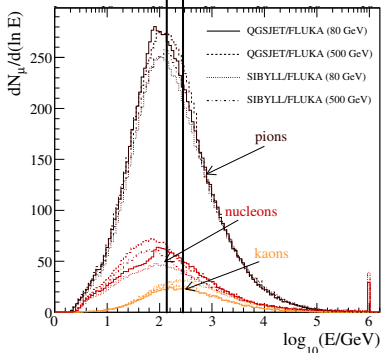
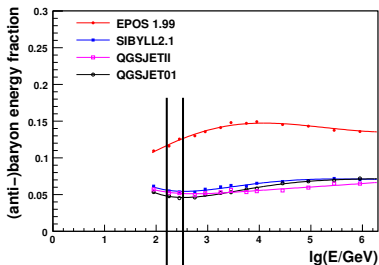
NA61 hadron production data (hadron-nucleus)



	p	yr	N_{trig}
$\pi^- + \text{C}$	158	2009	5.5
$\pi^- + \text{C}$	350	2009	4.6
$p + \text{C}$	31	2007	0.7
$p + \text{C}$	31	2009	5.4
$p + p$	13	2010	0.7
$p + p$	13	2011	1.4
$p + p$	20	2009	2.2
$p + p$	31	2009	3.1
$p + p$	40	2009	5.2
$p + p$	80	2009	4.5
$p + p$	158	2009	3.5
$p + p$	158	2010	44
$p + p$	158	2011	15
$p + \text{Pb}$	158	2012	4.5

- beam momentum p in [GeV/c],
- number of triggers N_{trig} in [10^6] ($\sim 85\%$ interaction triggers and $\sim 15\%$ beam triggers)

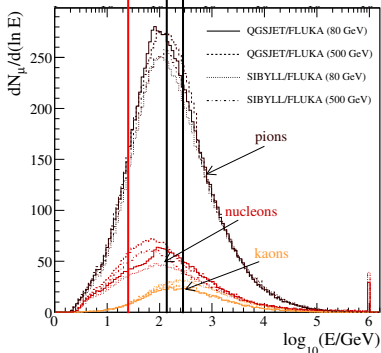
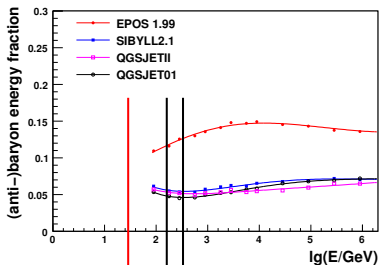
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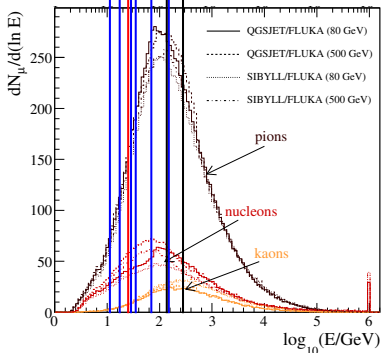
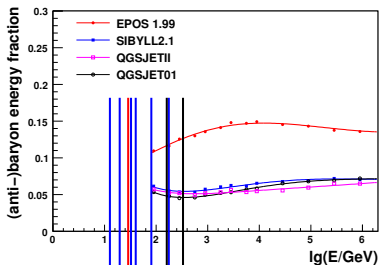
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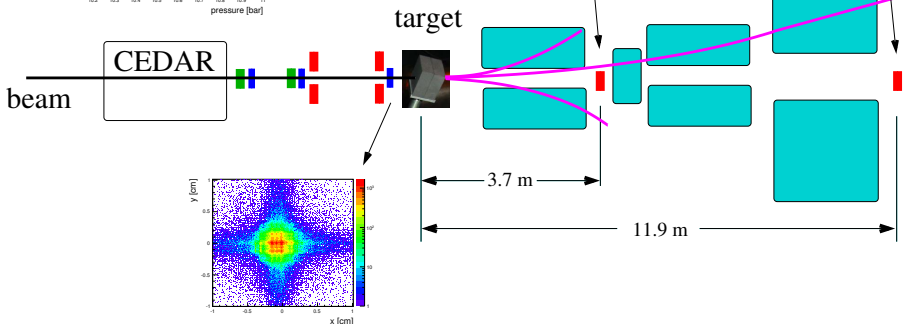
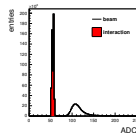
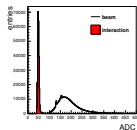
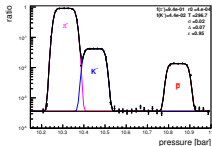
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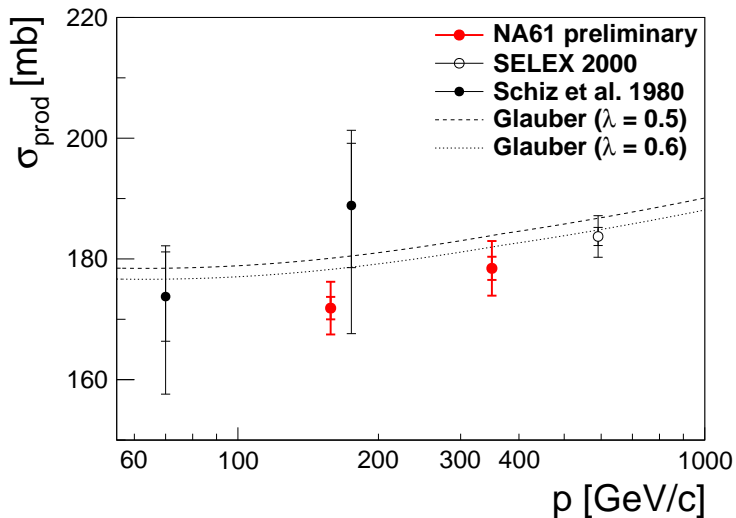
Production Cross Section in $\pi^- + C$ Interactions

Schematic of Beam Line:

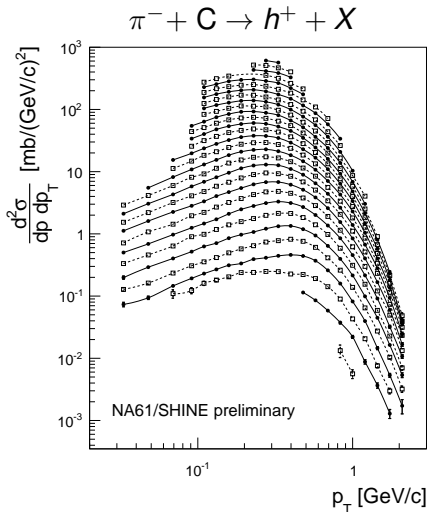
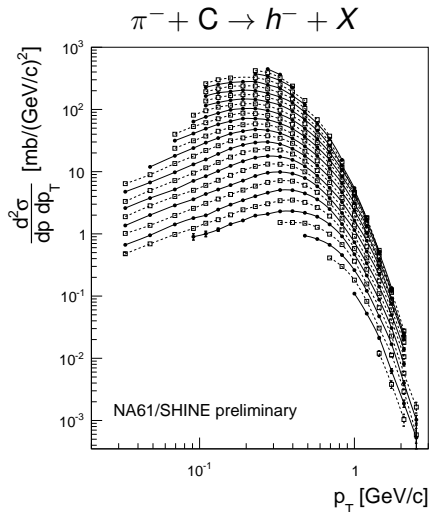
- : scintillator (coinc.)
- : scintillator (veto)
- : MWPC
- : TPC



Production Cross Section in π^-+C Interactions

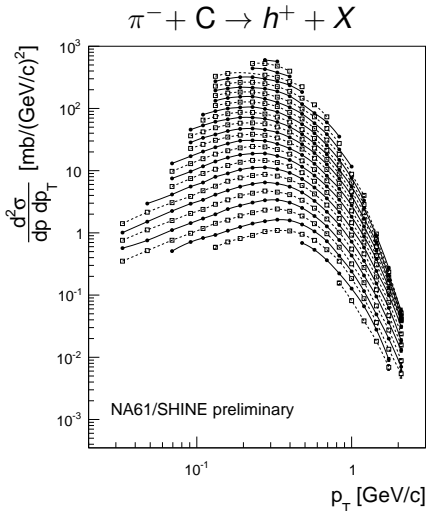
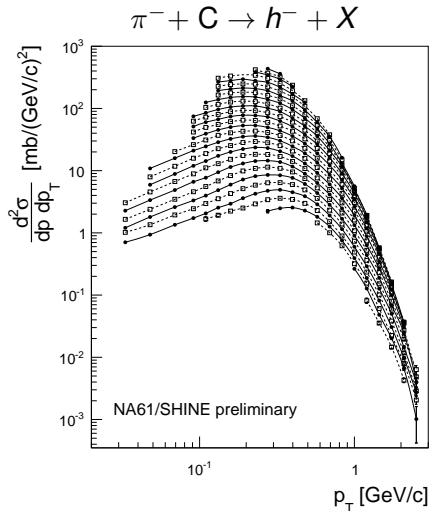


Charged Hadron Production in $\pi^- + \text{C}$ at 158 GeV/c



$p = 0.6 \dots 121 \text{ GeV}/c$ in steps of $\lg p/(\text{GeV}/c) = 0.08$

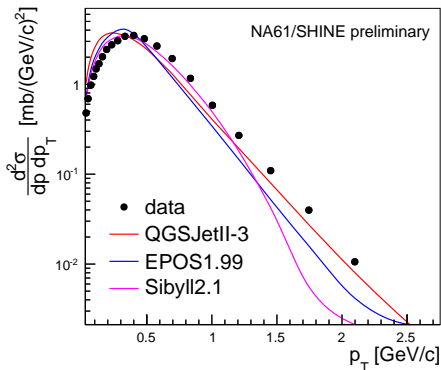
Charged Hadron Production in $\pi^- + C$ at 350 GeV/c



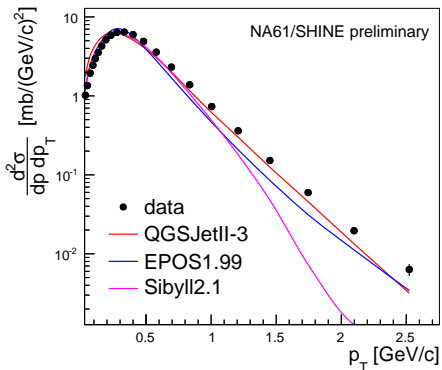
$p = 0.6 \dots 121 \text{ GeV/c}$ in steps of $\lg p / (\text{GeV/c}) = 0.08$

Comparison to Interaction Models (examples)

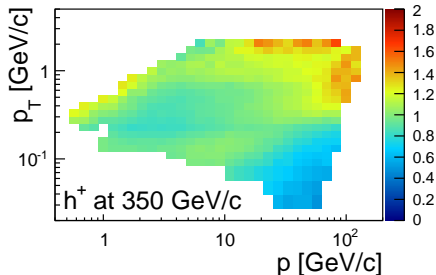
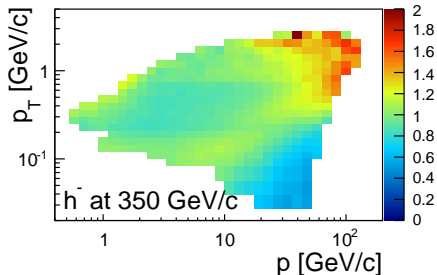
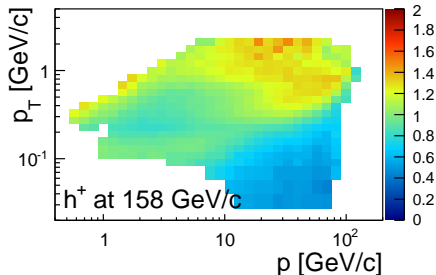
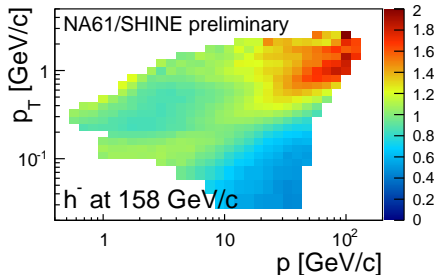
h^- at $p_{\text{beam}} = 158 \text{ GeV}/c$, $p = 10.8 \text{ GeV}/c$



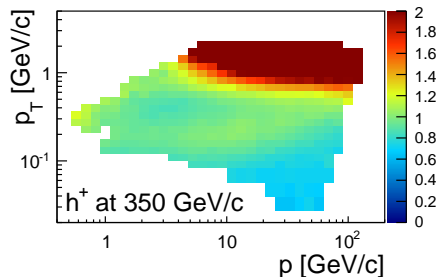
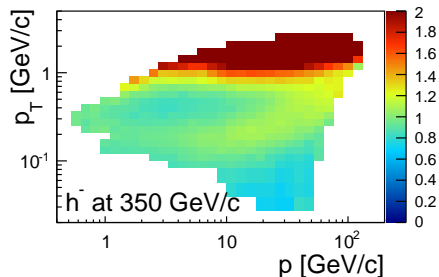
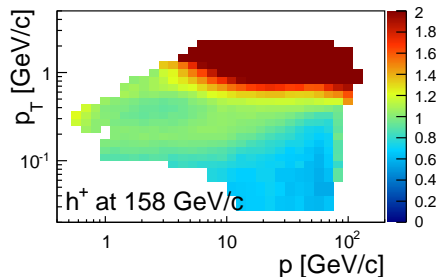
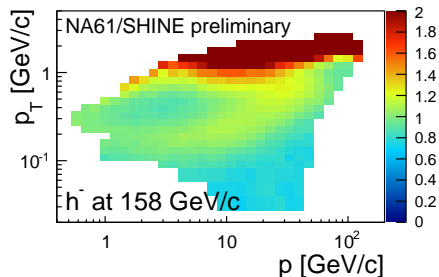
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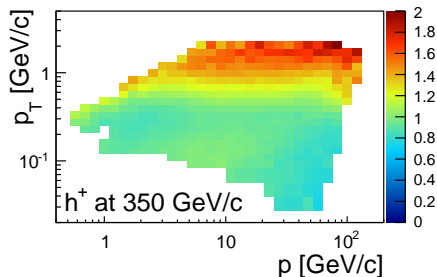
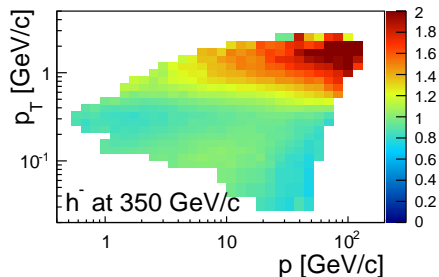
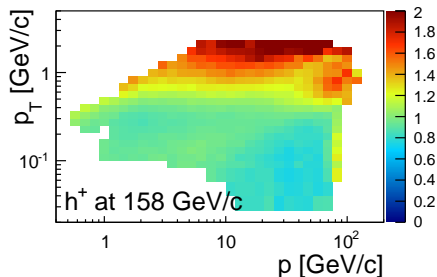
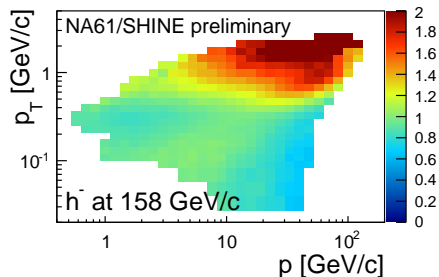
Comparison to QGSJetII-03 (data/MC)



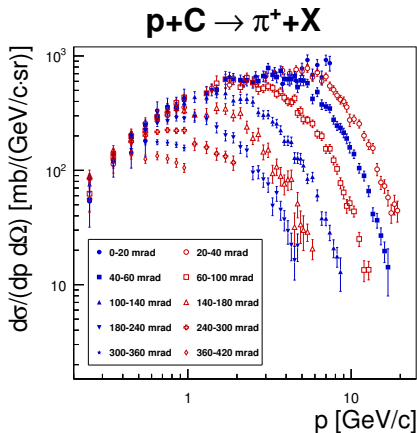
Comparison to Sibyll2.1 (data/MC)



Comparison to EPOS1.99 (data/MC)



Pion&Kaon Production in p+C at 31 GeV/c

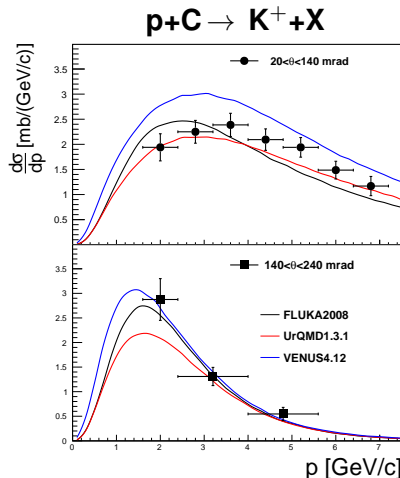


NA61/SHINE, Phys. Rev. C84 (2011) 034604

NA61/SHINE, Nucl. Instrum. Meth. A701 (2013) 99

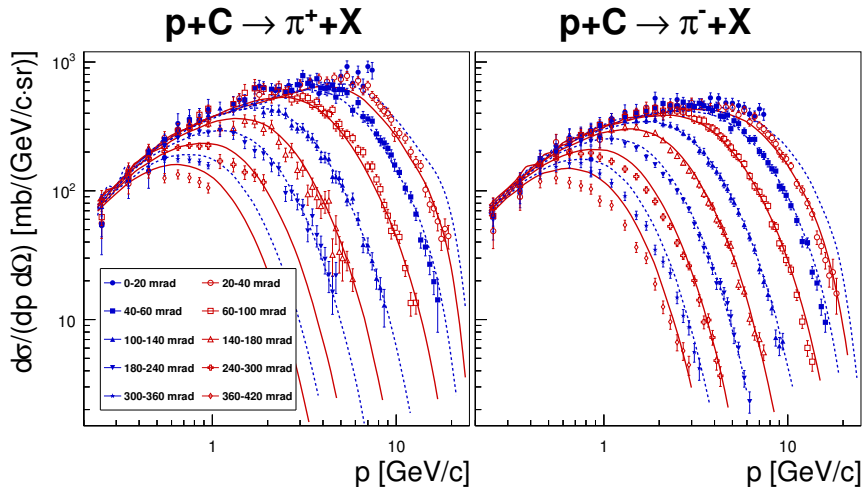
already used by T2K Collab., Phys.Rev.Lett. 107 (2011) 041801

Phys. Rev. D85 (2012) 031103 and Phys. Rev. D87 (2013) 012001.



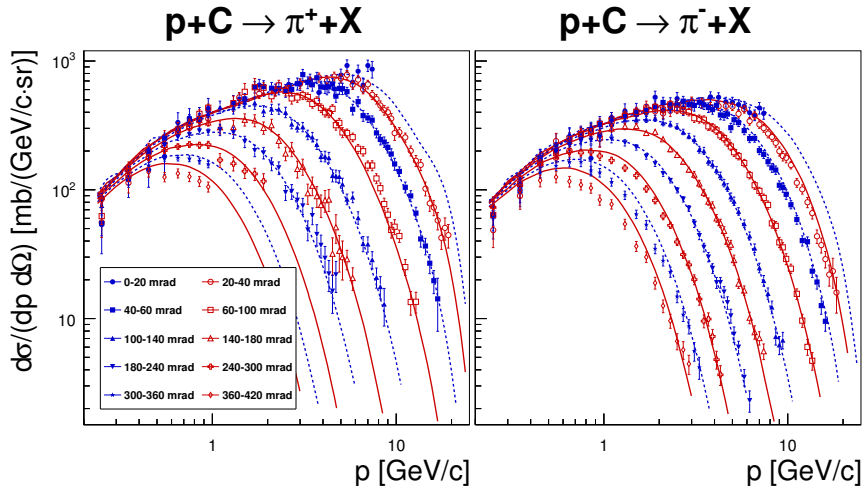
NA61/SHINE, Phys. Rev. C85 (2012) 035210

Inclusive π^\pm spectra in p+C at 31 GeV/c



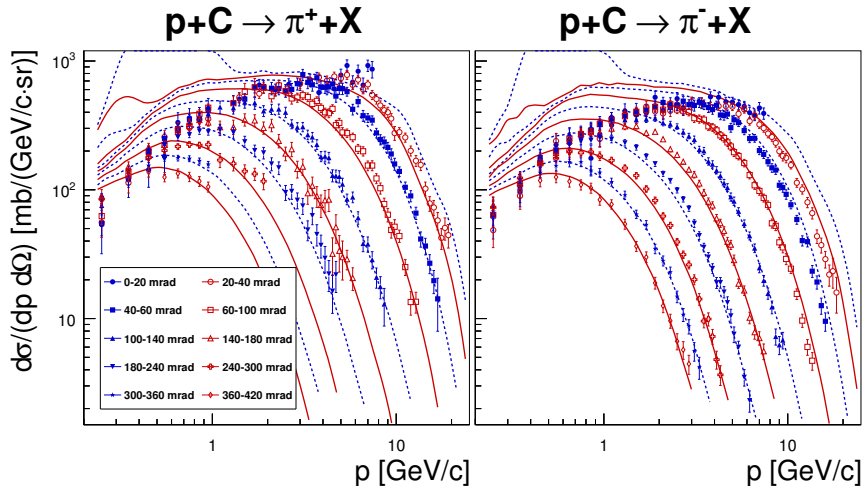
comparison to FLUKA2008.3b

Inclusive π^\pm spectra in p+C at 31 GeV/c



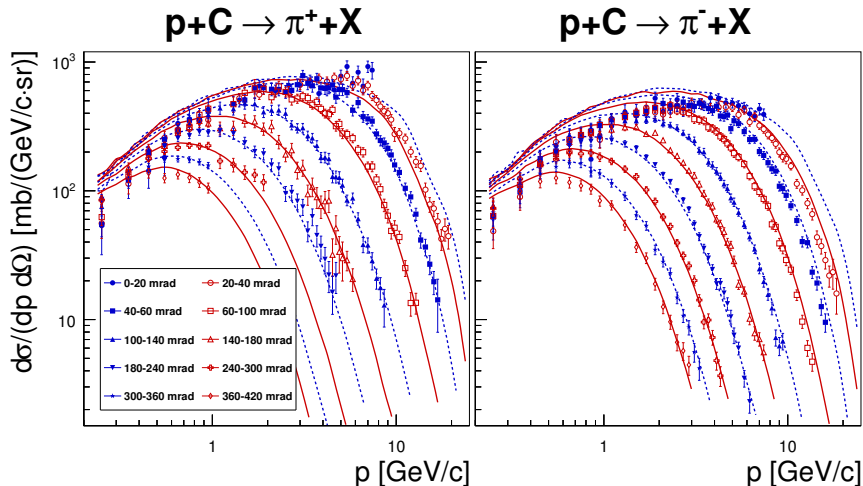
comparison to FLUKA2011.2.8

Inclusive π^\pm spectra in p+C at 31 GeV/c



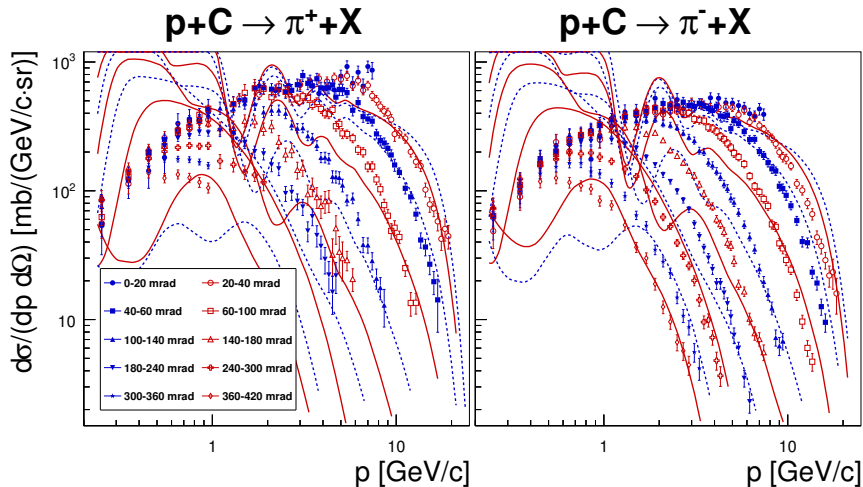
comparison to UrQMD1.3.1

Inclusive π^\pm spectra in p+C at 31 GeV/c



comparison to patched UrQMD1.3.1
(V. Uzhinsky, arXiv:1107.0374v1 [hep-ph])

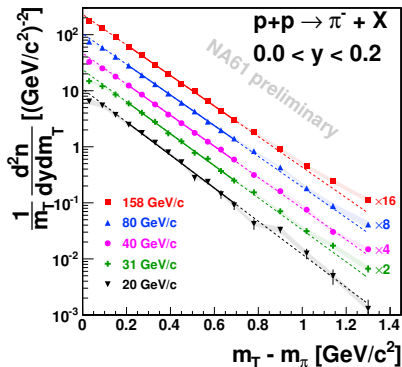
Inclusive π^\pm spectra in p+C at 31 GeV/c



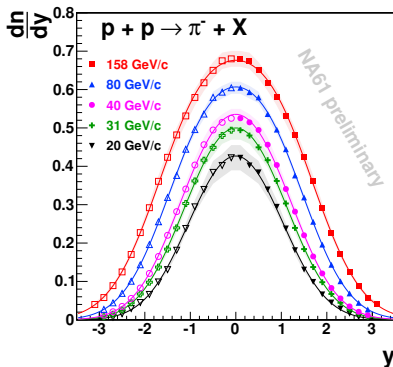
comparison to Gheisha2002

Measurements of $p+p$

m_T spectra at mid-rapidity

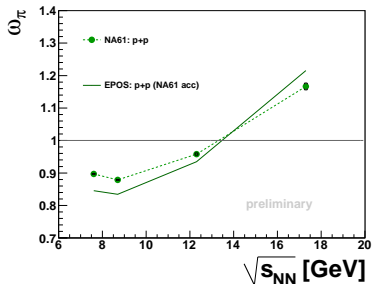


m_T -integrated π^- -spectra



p+p energy scan for heavy ion physics

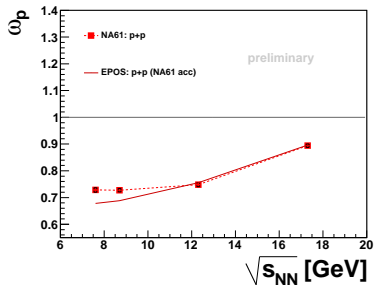
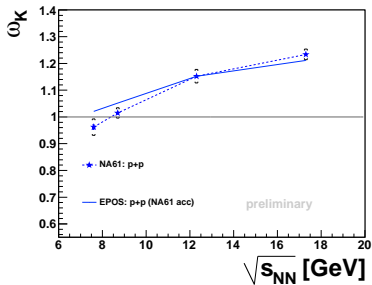
Multiplicity fluctuations in $p + p$ interactions (prel.)



- ▶ scaled variance:

$$\omega_i = \frac{\langle N_i^2 \rangle - \langle N_i \rangle^2}{\langle N_i \rangle}$$

- ▶ for Poisson: $\omega_i = 1$



Summary & Outlook

preliminary NA61 results on low energy interactions in air showers ($\pi+C$):

- ▶ too few charged secondaries at large p_T in models
- ▶ reasonable agreement of Glauber with measured $\sigma_{\text{prod}}^{\pi+C}$

Stay tuned:

further refinements of $\pi+C$ analysis:

- ▶ fully identified spectra of π^\pm , K^\pm , ρ , $\bar{\rho}$
- ▶ ρ^0 mesons
- ▶ strange baryons

other NA61 data sets of interest for CR physics:

- ▶ $p+p$ at 13, 20, 31, 40, 80 and 158 GeV
- ▶ $p+C$ at 31 and 120 GeV
- ▶ K^-+C at 158 GeV/c (test run)

Summary & Outlook

scan of energy and system size:

