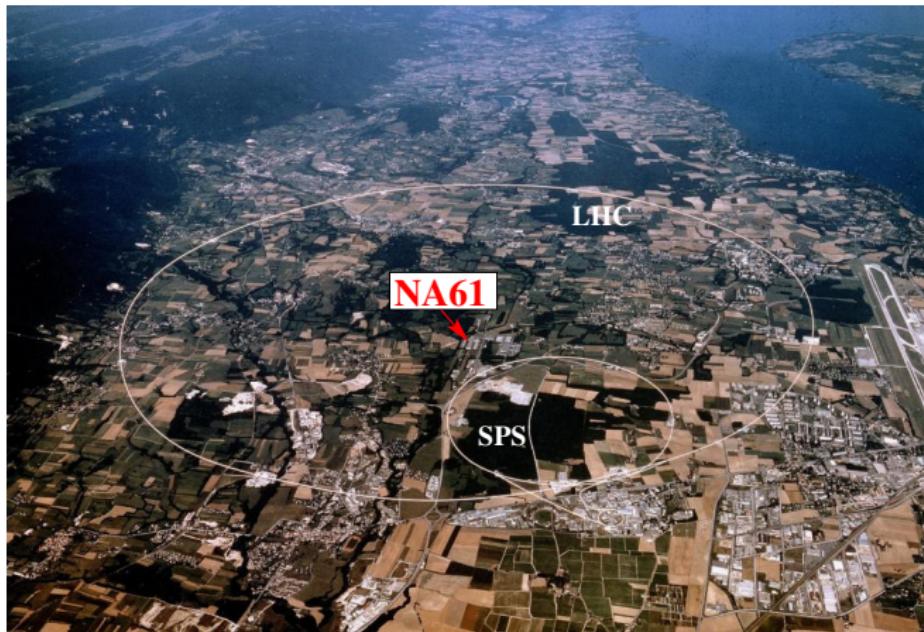


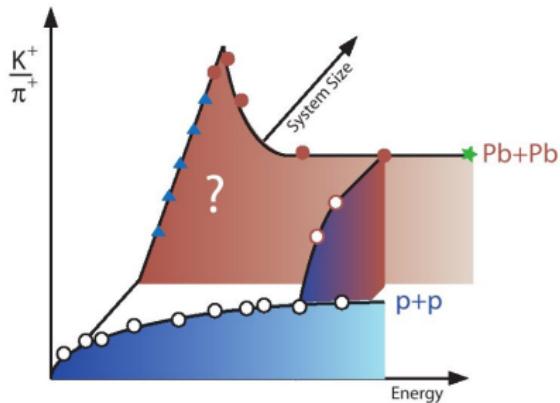
Results from NA61/SHINE

M. Unger* for the NA61 Collaboration

* Karlsruher Institut für Technologie, New York University

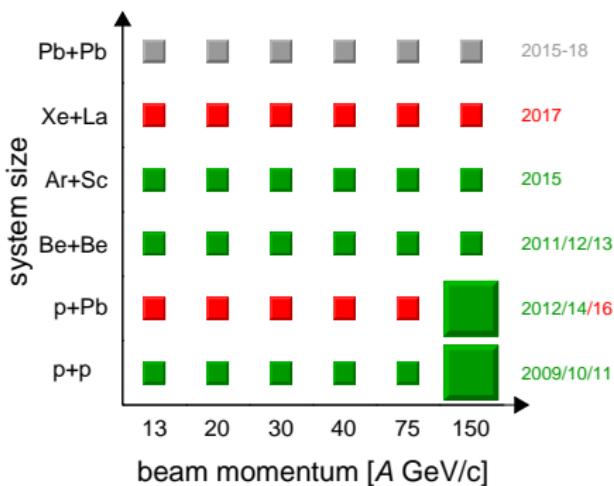
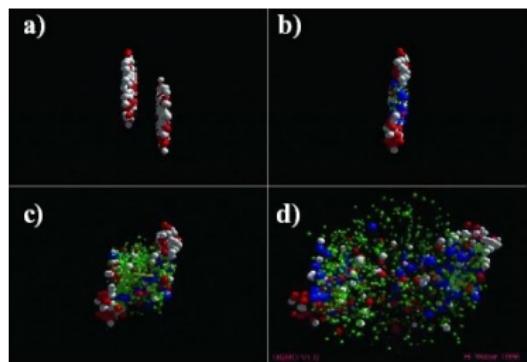


NA61 Physics Program - a) Heavy Ions



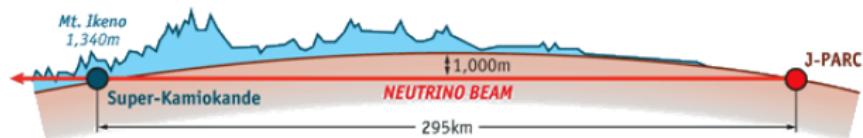
Onset of deconfinement and search for the critical point of strongly interacting matter

scan of system size and energy:



NA61 Physics Program - b) Hadro-Production Measurements for Neutrino Experiments

ν -beams for long-baseline neutrino oscillation experiments

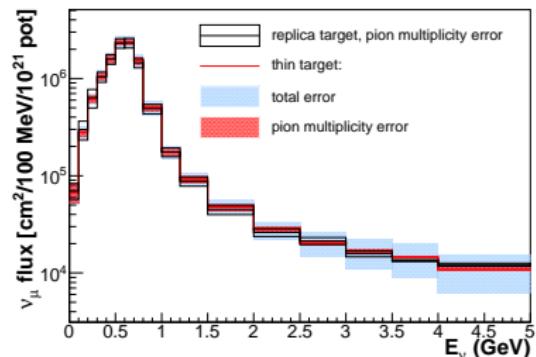


T2K replica target at NA61
 $l=90\text{ cm}$, $d=2.6\text{ cm}$, $\lambda_{\text{int}} = 1.9$



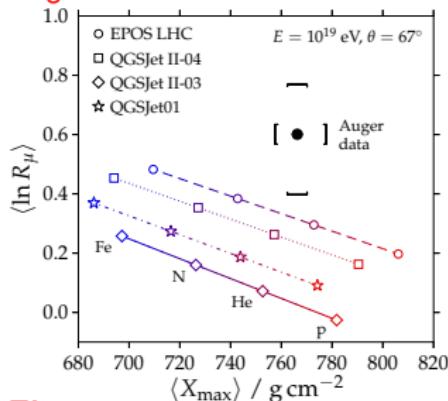
ν -program extended for MINER ν A, MINOS,
NO ν A, DU ν E at LBNF

reweighting of T2K beam-MC to match NA61 measurements:

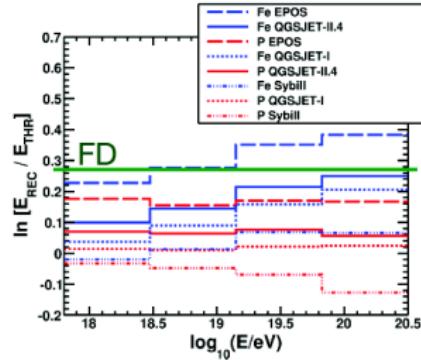


NA61 Physics Program - c) Hadro-Production Measurements for Air Shower Experiments

Auger:



TA:



(incomplete) list of air shower puzzles:

- muon number (HiRes/MIA)
- muon number (Auger)
- energy scale (Auger, TA)
- muon production height (Auger)
- rise-time asymmetry (Auger)
- muon attenuation (KASCADE-Grande)

Muons in UHE Air Showers

energy of last interaction before decay to μ

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

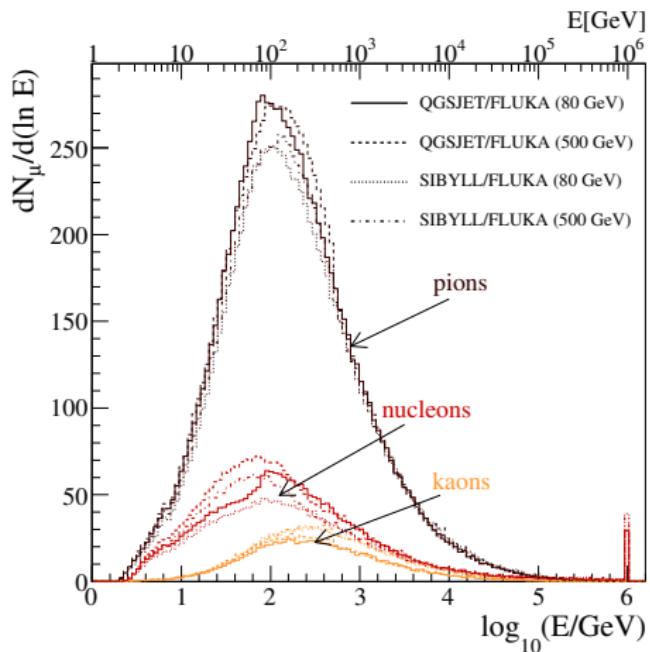


$\mu + \nu_\mu$

low energy air shower

e.g. KASCADE:

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



Muons in UHE Air Showers

energy of last interaction before decay to μ

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

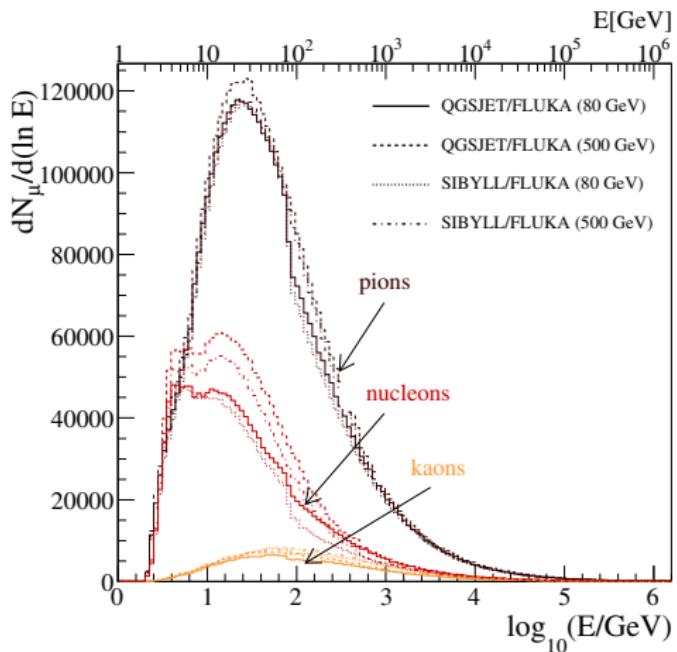


$\mu + \nu_\mu$

low energy air shower

e.g. Auger:

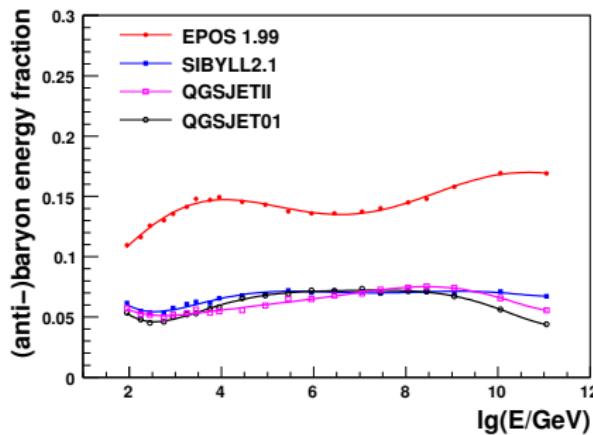
- $E_0 = 10^{19}$ eV
- $r = 1000$ m
- $E_\mu \geq 150$ MeV



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
- }
- hadronic shower

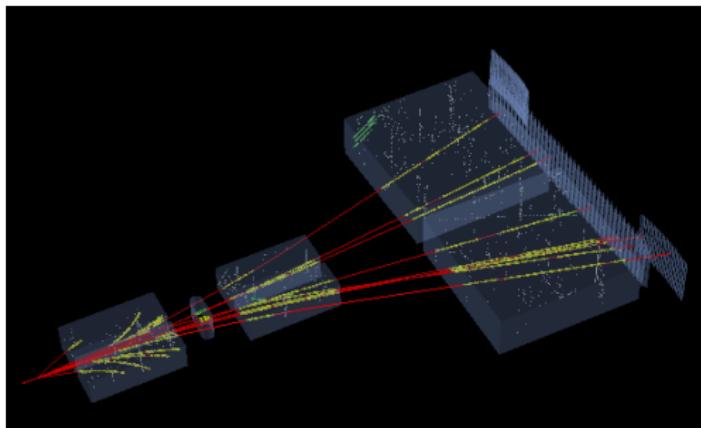
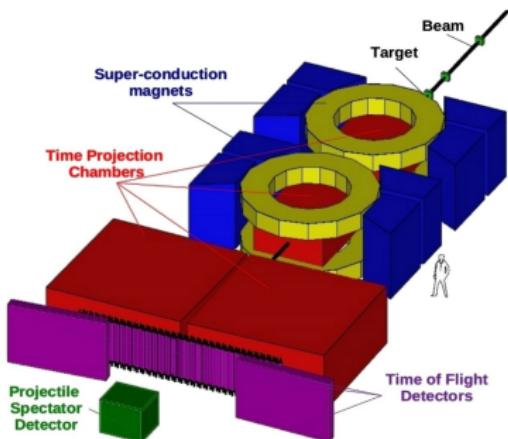


and:

- multiplicity
- $p_T \leftrightarrow \rho_\mu(R)$
- ...

NA61/SHINE Experiment at SPS

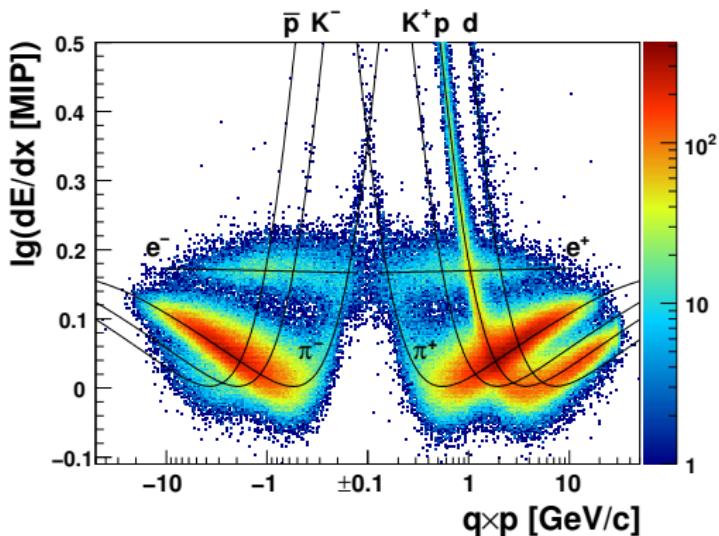
$\pi^- + C$ interaction at 158 GeV/c



- 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: $> 95\%$

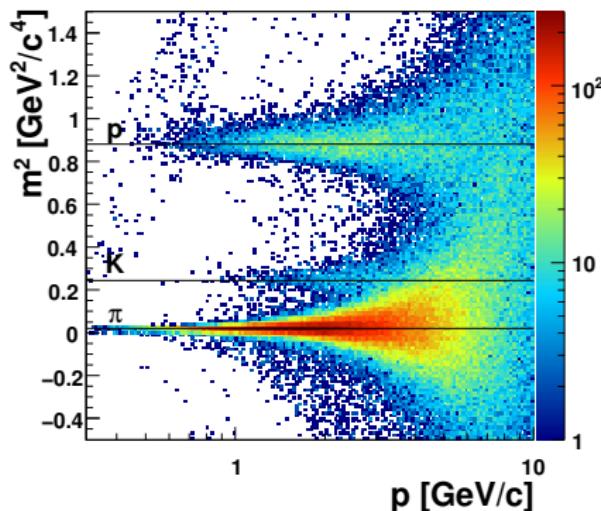
Particle Identification

energy deposit in TPC:



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

time of flight:

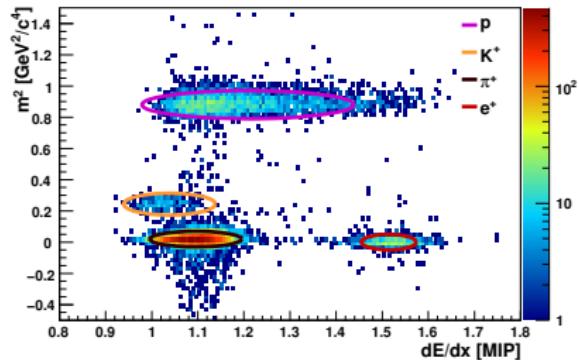


$$\sigma(t) \approx 100 \text{ ps}$$

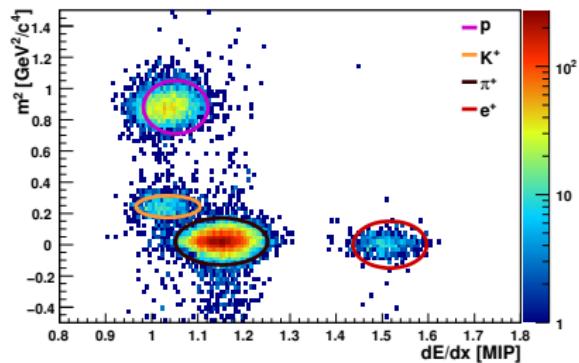
$p + C$ at 31 GeV/c (2007 data)

Particle Identification

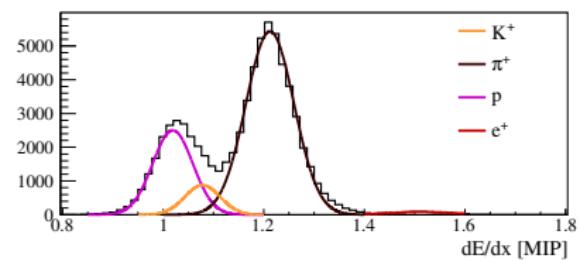
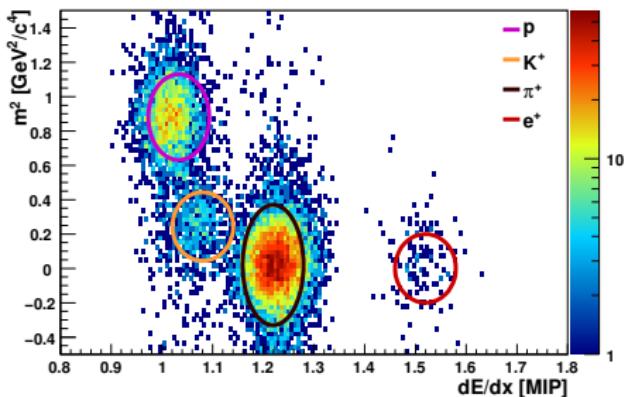
$1 \text{ GeV}/c < p < 2 \text{ GeV}/c$



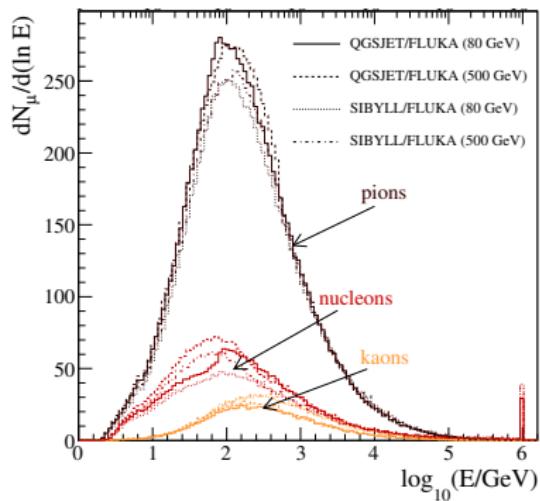
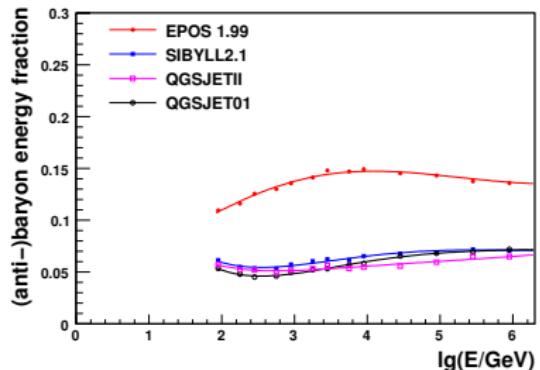
$2 \text{ GeV}/c < p < 3 \text{ GeV}/c$



$4 \text{ GeV}/c < p < 5 \text{ GeV}/c$



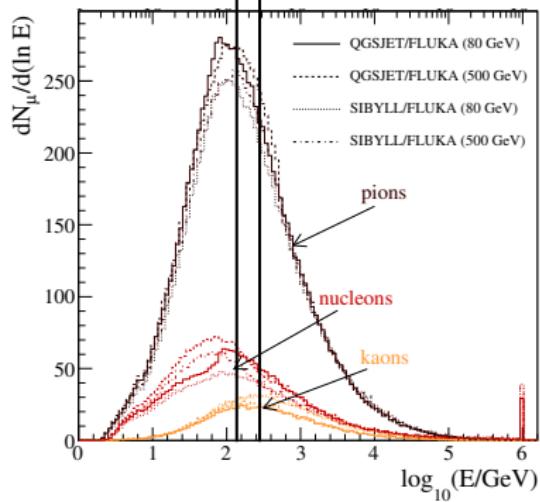
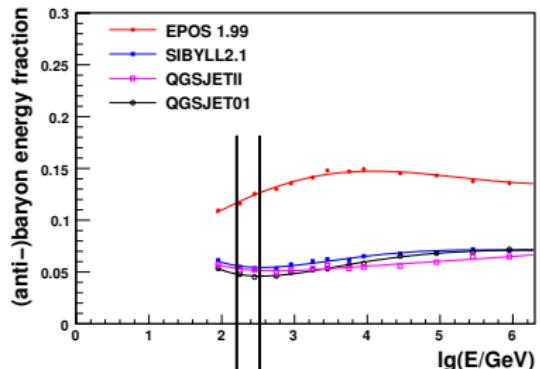
NA61 Hadron Production Data (Hadron-Nucleus)



	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	2014	14

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

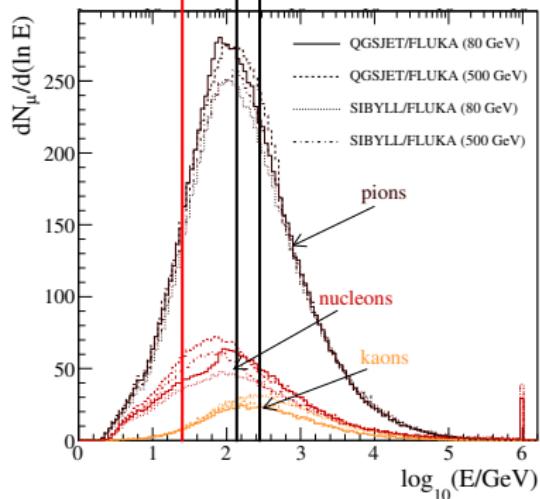
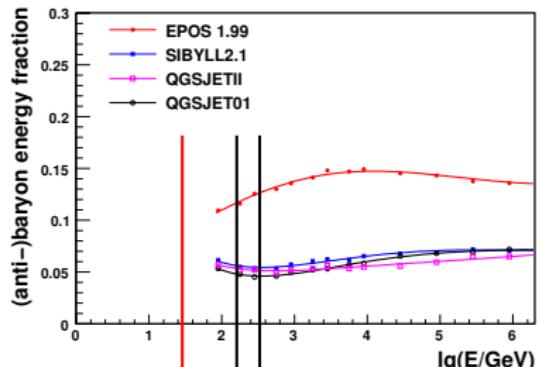
NA61 Hadron Production Data (Hadron-Nucleus)



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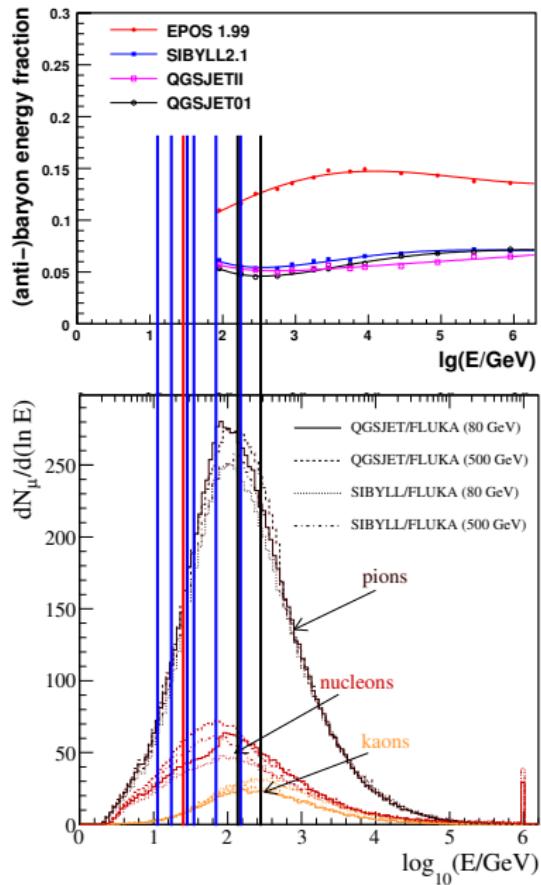
NA61 Hadron Production Data (Hadron-Nucleus)



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- beam momentum p in [GeV/c],
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NA61 Hadron Production Data (Hadron-Nucleus)

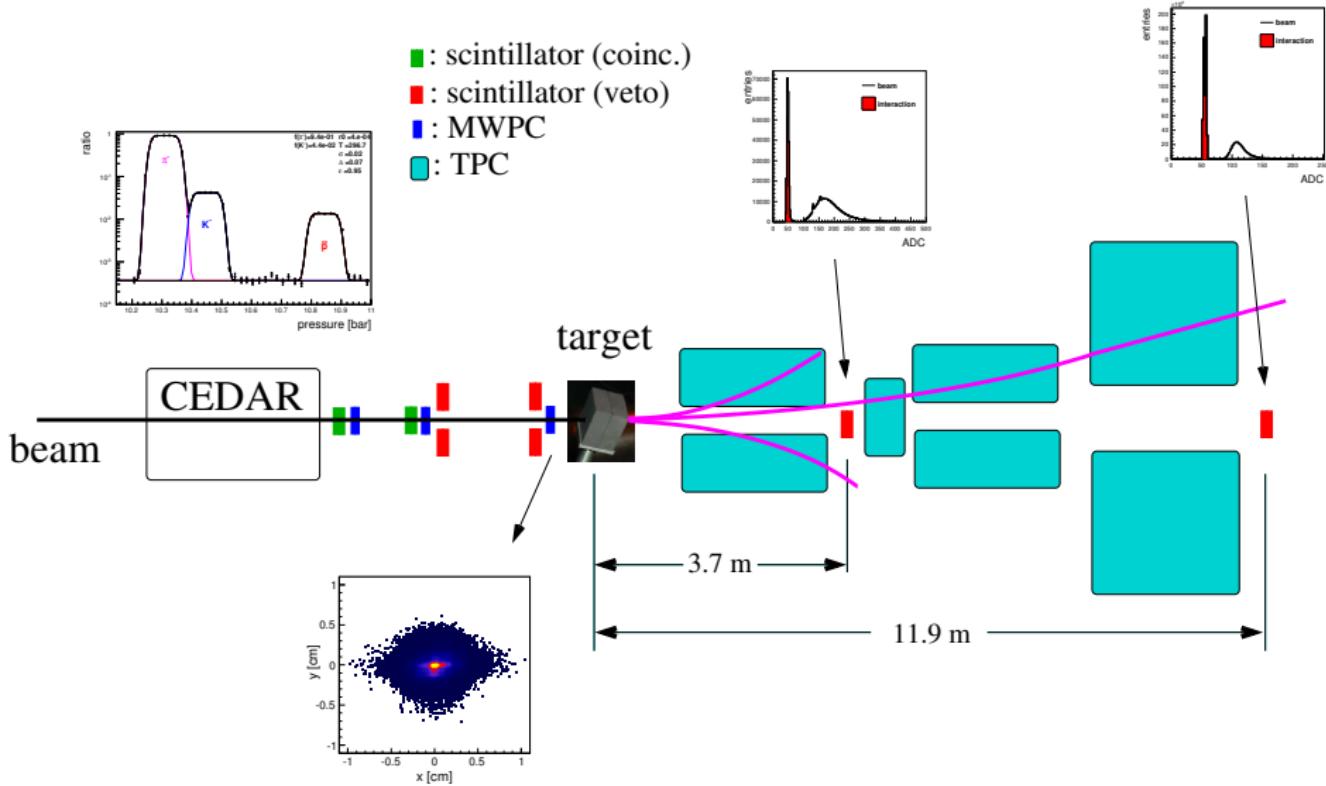


	p	yr	N_{trig}
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$\text{p} + \text{p}$	158	2011	15
$\text{p} + \text{Pb}$	158	2014	14

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

Cross Section Measurements with NA61

Schematic of Beam Line:

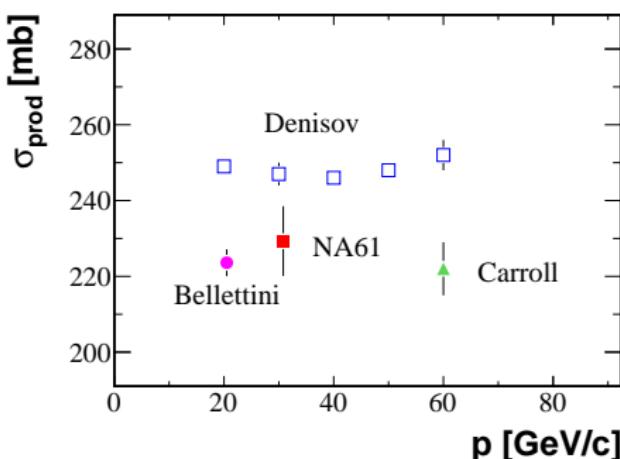


Cross Section Measurements with NA61

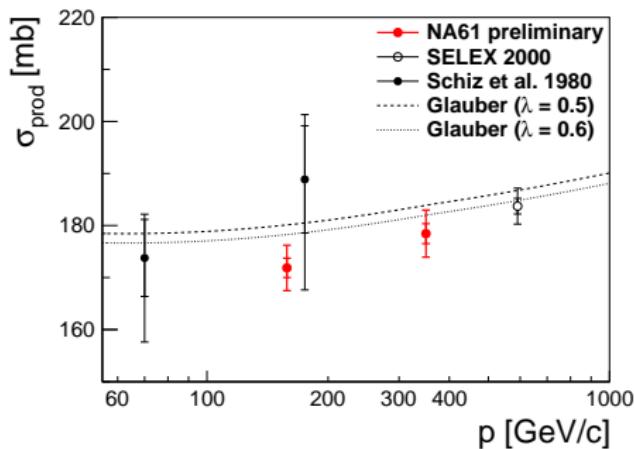
production cross sections:

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

p+C at 31 GeV/c



$\pi^- + C$ at 158 and 350 GeV/c

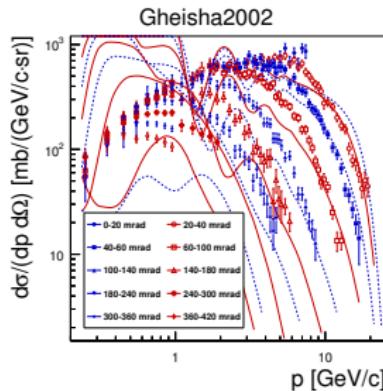
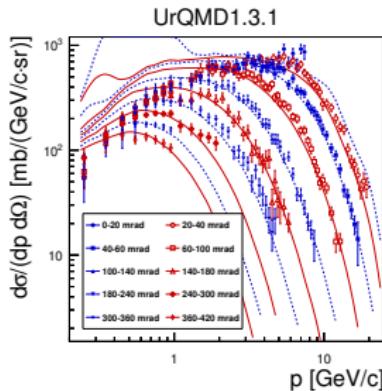
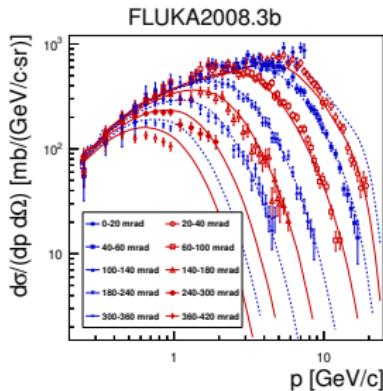


Inclusive π^\pm spectra in p+C at 31 GeV/c

p+C $\rightarrow \pi^+ + X$:

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

data vs. original model

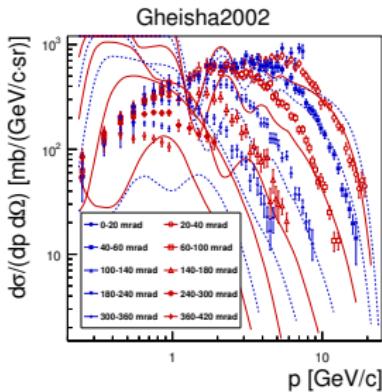
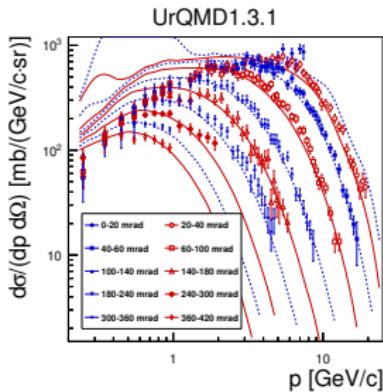
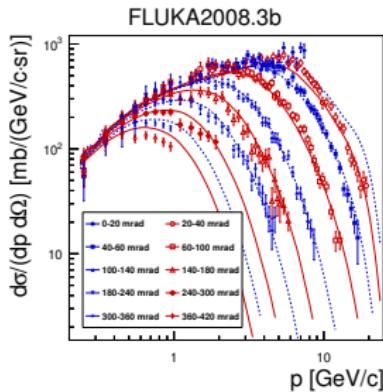


Inclusive π^\pm spectra in p+C at 31 GeV/c

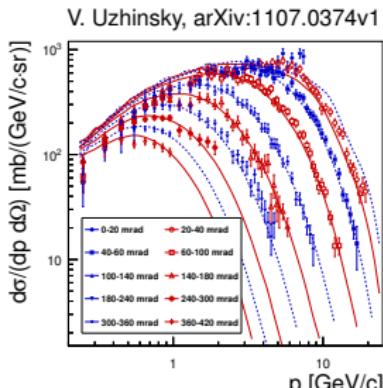
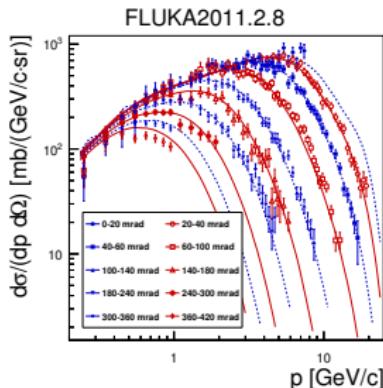
p+C $\rightarrow \pi^+ + X$:

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

data vs. original model

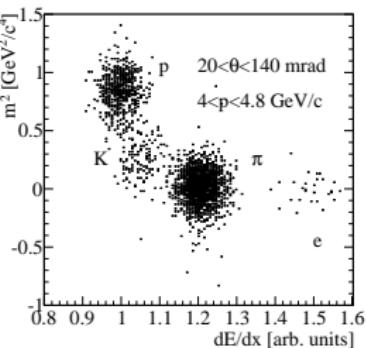
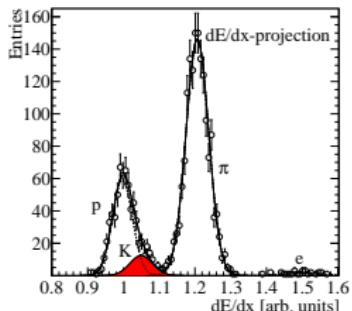


re-tuned model

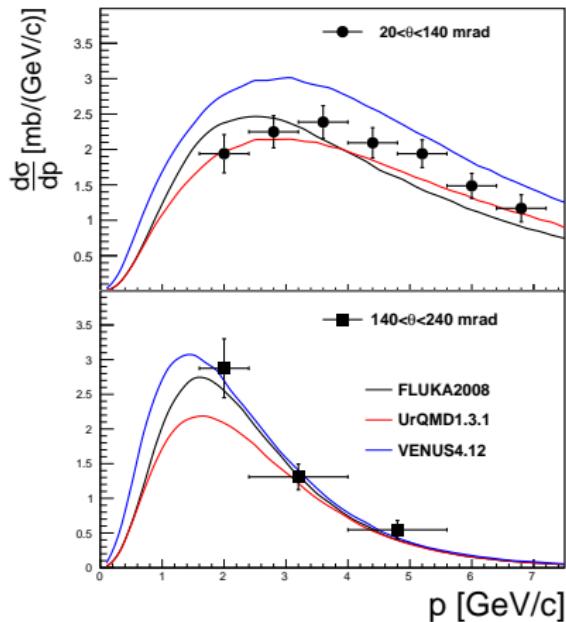


Strange Particle Production in p+C at 31 GeV/c

dE/dx-ToF fit:



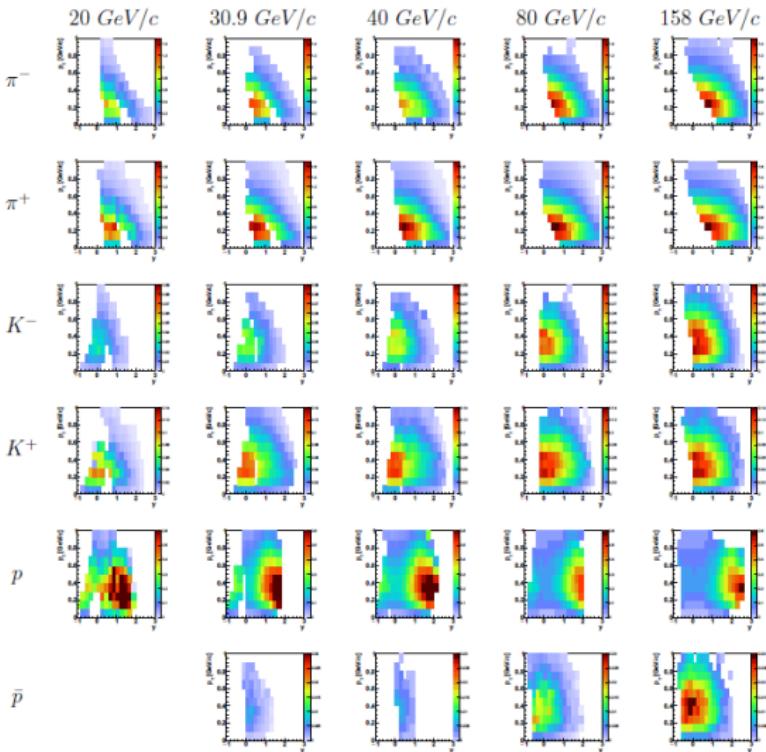
K^+ Yield:



K^+ : NA61/SHINE, Phys. Rev. C85 (2012) 035210

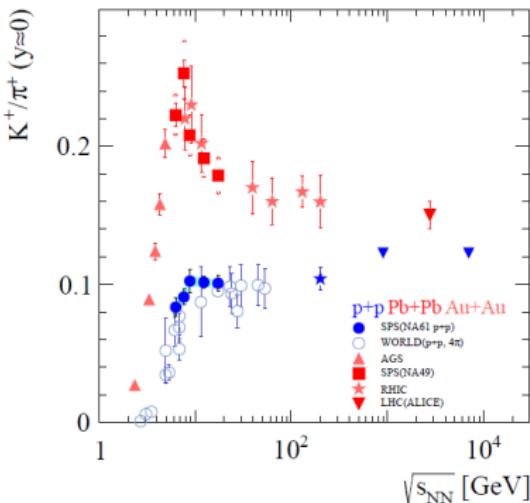
K_S^0 / Λ : NA61/SHINE, Phys. Rev. C89 (2014) 2, 025205

$\pi^\pm, K^\pm, p, \bar{p}$ Spectra in p+p Interactions (prel.)



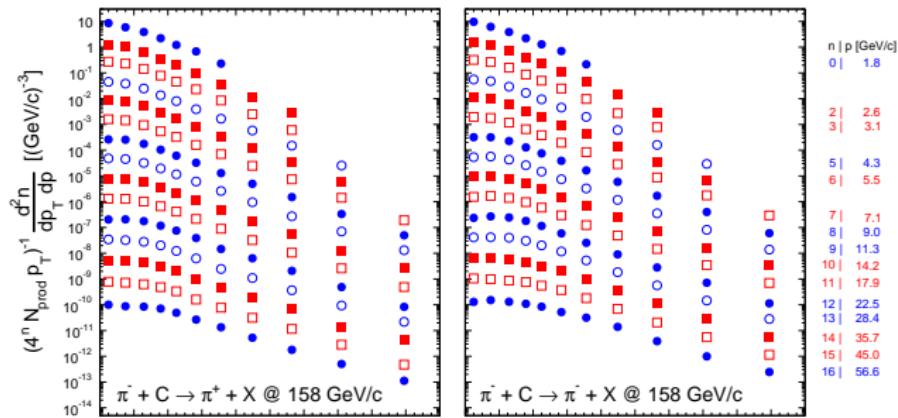
colors: $dn/dy/dp_T$, x-axis: p_T , y-axis: rapidity

- unique extensive data set
- six identified particles
- five beam energies

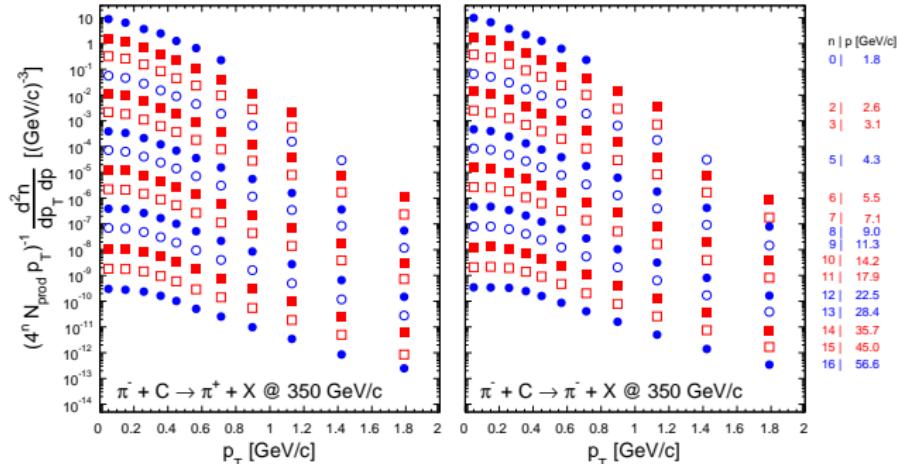


Inclusive π^\pm Spectra in $\pi^- + C$ Interactions (prel.)

158 GeV/c:

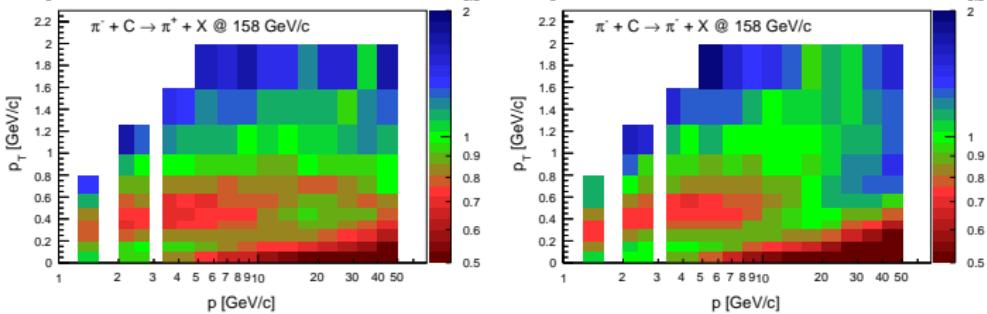
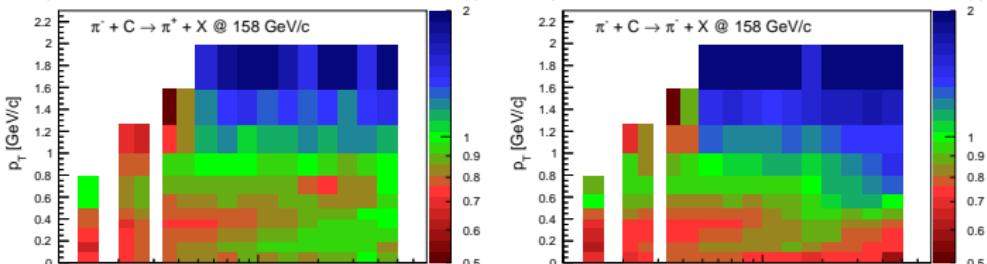
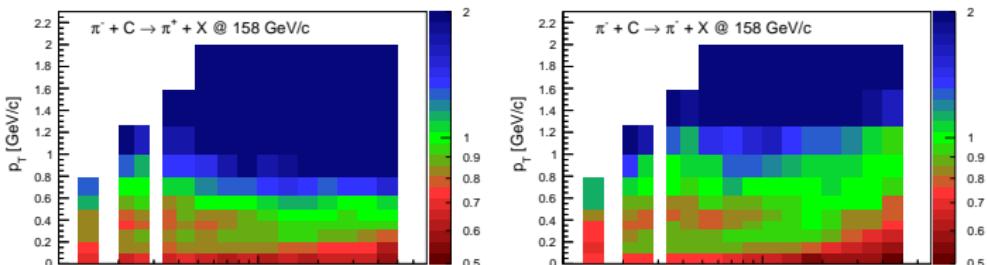
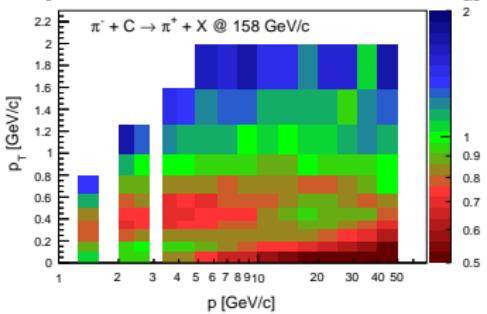
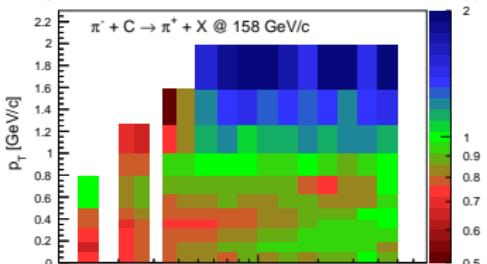
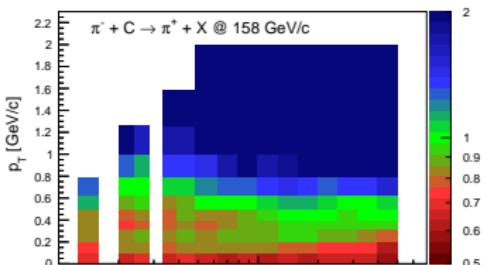


350 GeV/c:



Inclusive π^\pm Spectra in $\pi^- + C$ Interactions (prel.)

Sibyll-2.1:



EPOS-LHC:

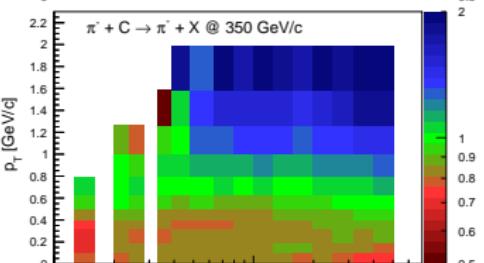
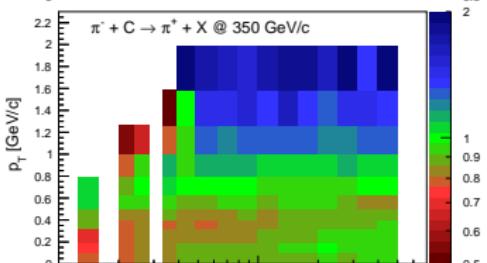
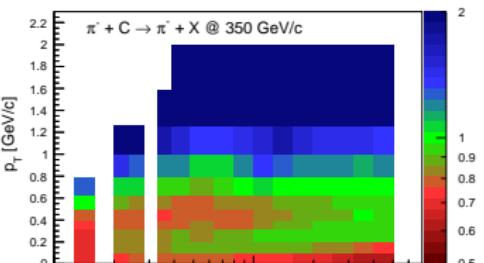
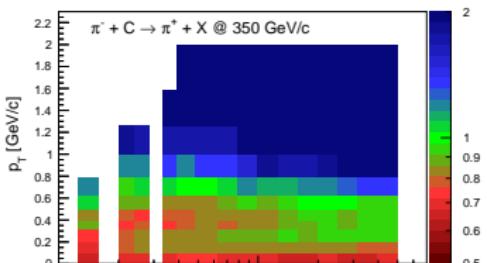
QGSJetII-04:

$p_{\text{beam}} = 350 \text{ GeV}/c$

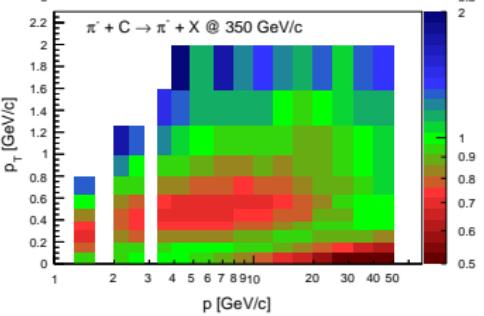
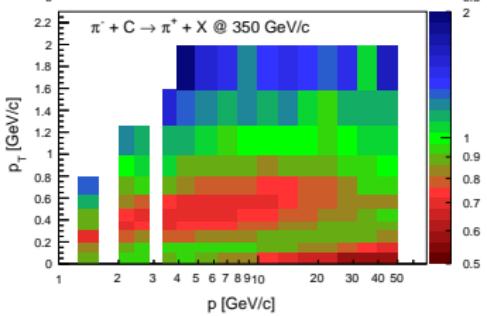
colors: data/MC, dark-red = 0.5, green = 1, dark-blue = 2

Inclusive π^\pm Spectra in $\pi^- + C$ Interactions (prel.)

Sibyll-2.1:



EPOS-LHC:

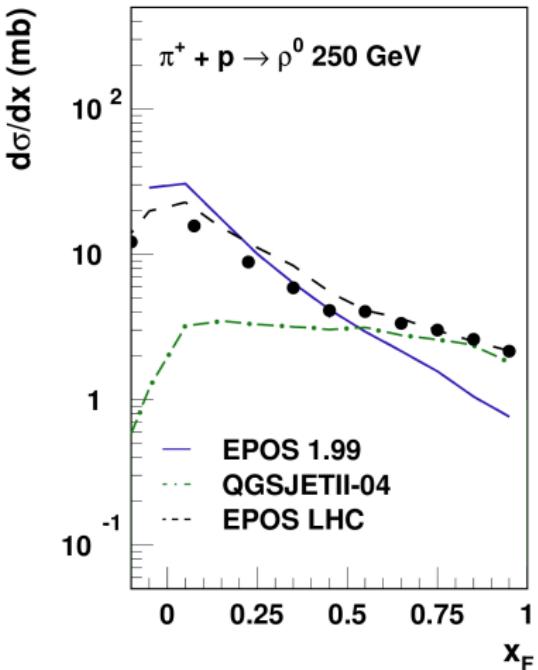
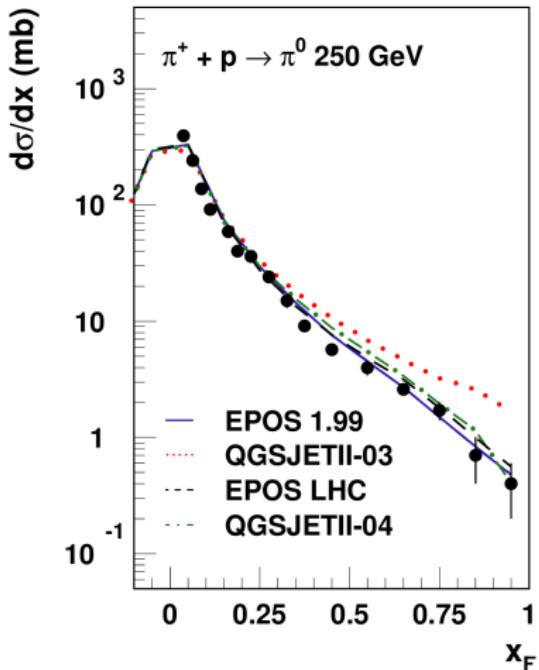


QGSJetII-04:

$p_{\text{beam}} = 350 \text{ GeV}/c$

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

NA22 ρ^0 Data ($\pi^+ + \text{C}$ at 250 GeV/c)

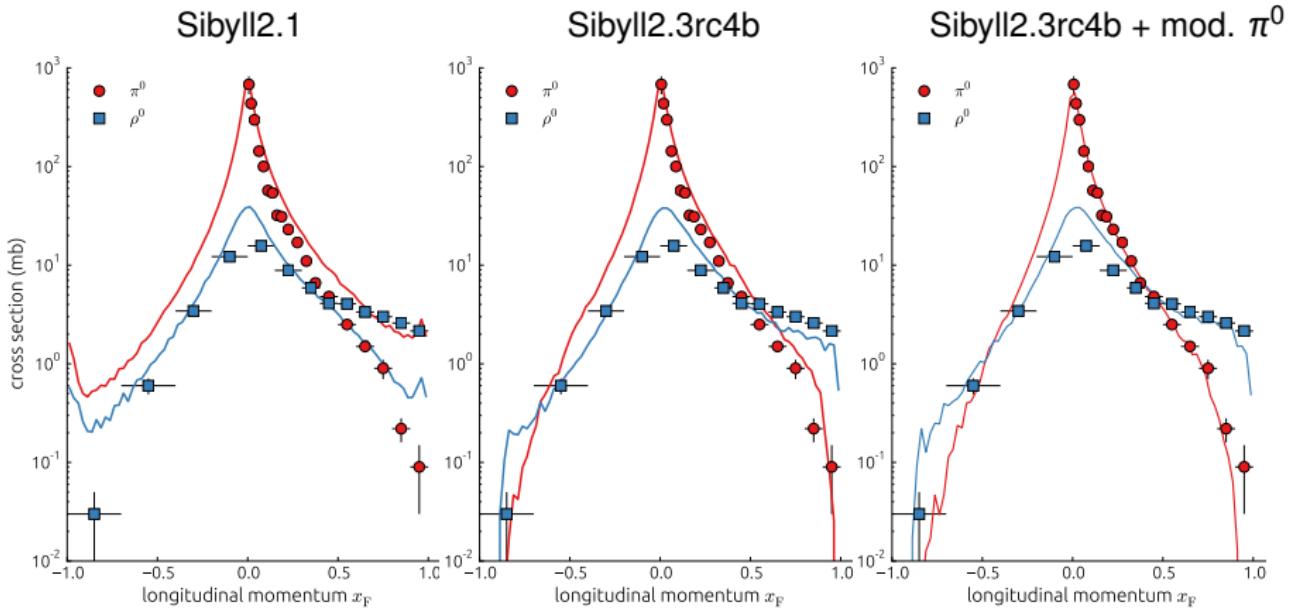


projectile-remnant excitation? (H. Drescher, Phys.Rev. D77 (2008) 056003)

plot by T.Pierog

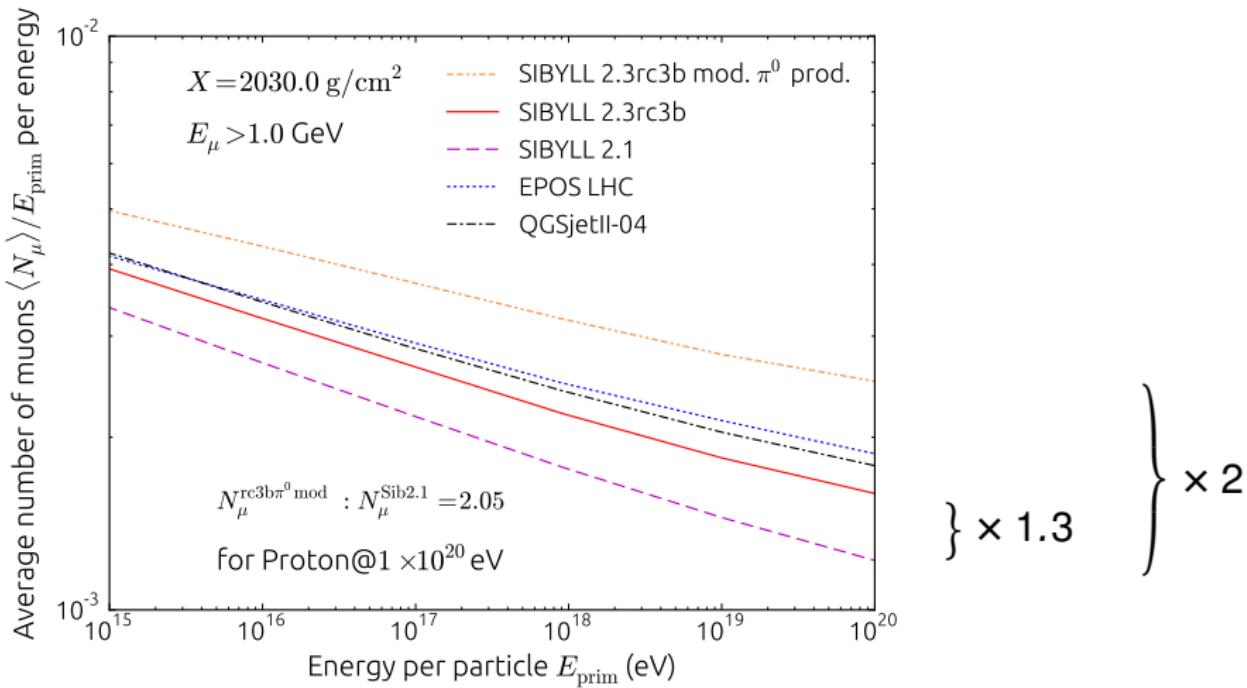
NA22 ρ^0 Data (π^+ +C at 250 GeV/c)

fitting NA22 with Sibyll:

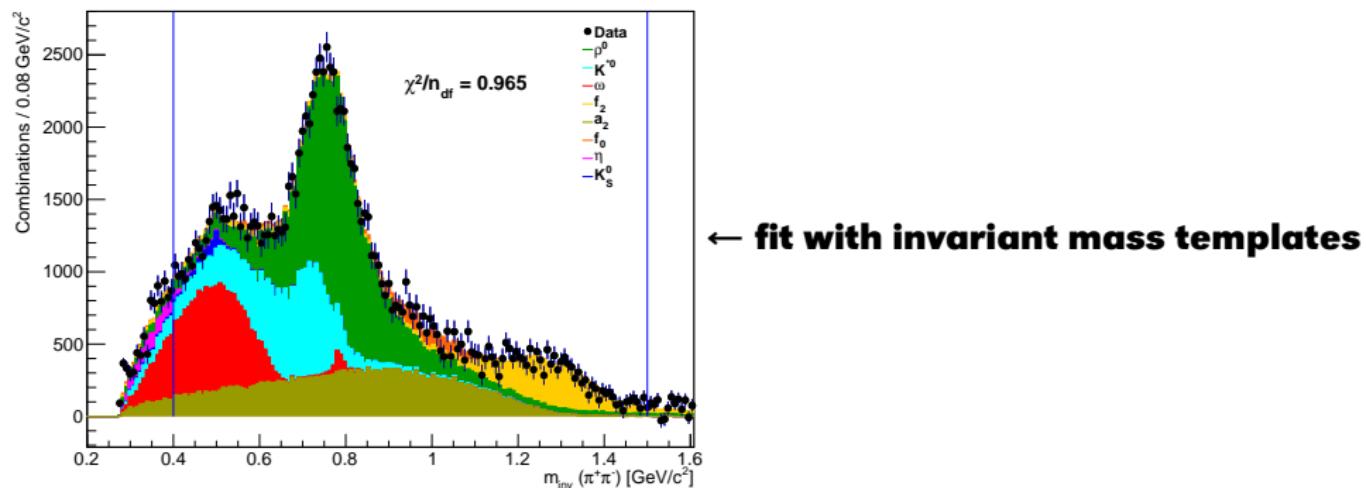


NA22 ρ^0 Data (π^+ +C at 250 GeV/c)

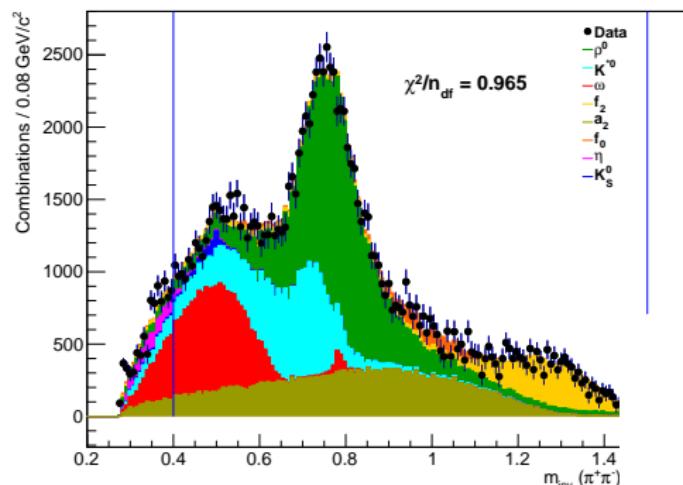
effect on muons in air showers:



NA61: ρ^0 Production in $\pi^- + C$ Interactions (prel.)

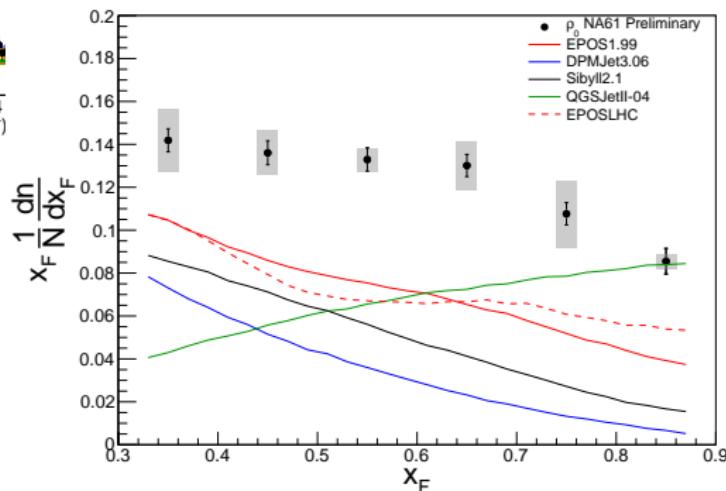


NA61: ρ^0 Production in $\pi^- + C$ Interactions (prel.)



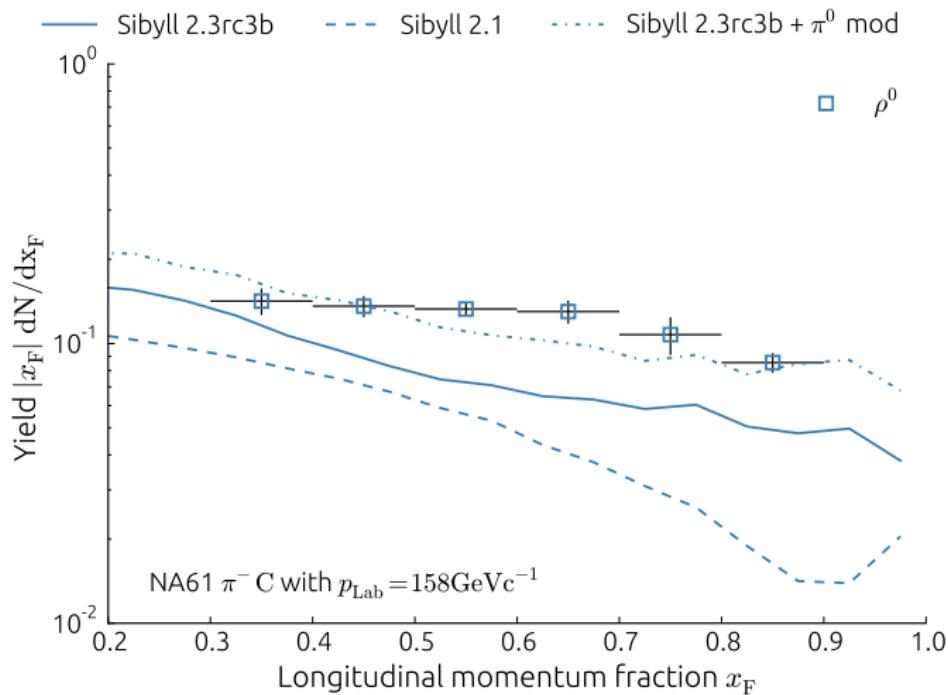
← fit with invariant mass templates

average ρ^0 multiplicity →
at 158 GeV/c



NA61: ρ^0 Production in $\pi^- + C$ Interactions (prel.)

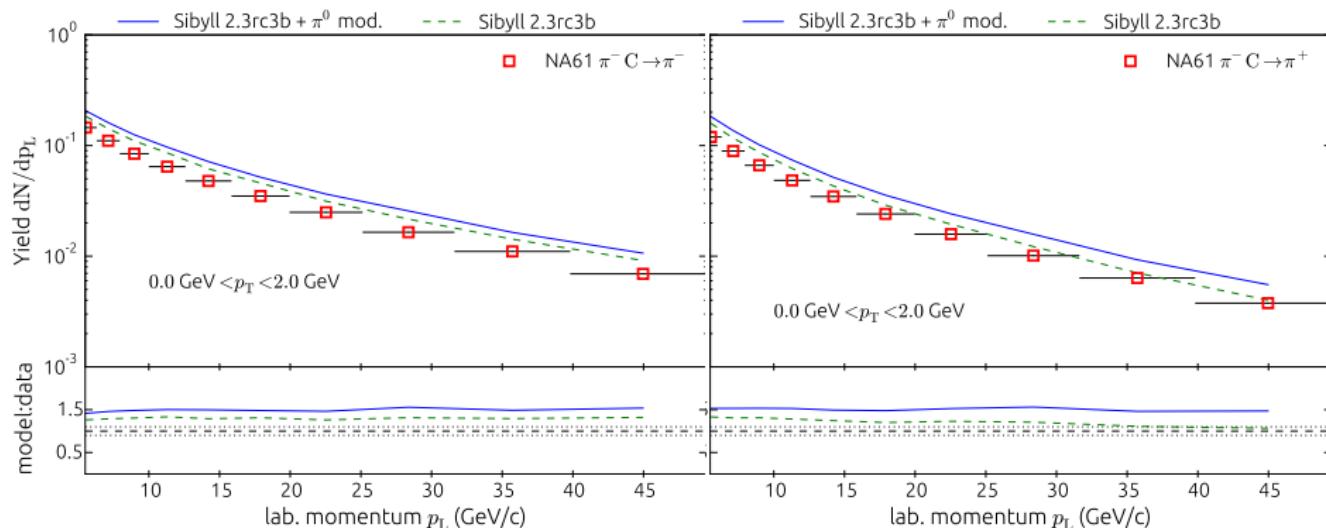
NA22-tune of Sibyll fits ρ^0 data from NA61 well:



NA61: ρ^0 Production in $\pi^- + C$ Interactions (prel.)

NA22-tune of Sibyll fits ρ^0 data from NA61 well:

... but produces too many π^\pm :



Summary and Outlook

- NA61/SHINE: unique facility to study hadronic interactions relevant for air shower physics
- p-p energy scan → reference data set
- p-C at 31 GeV/c → FLUKA ok
- π -C at 158 and 350 GeV/c
 - π^\pm deficit at high p_T (all models)
 - too few ρ^0 's in models
- 2015: p-C and π -C at 60 and 120 GeV/c
- 2016: data taking with new forward TPCs

