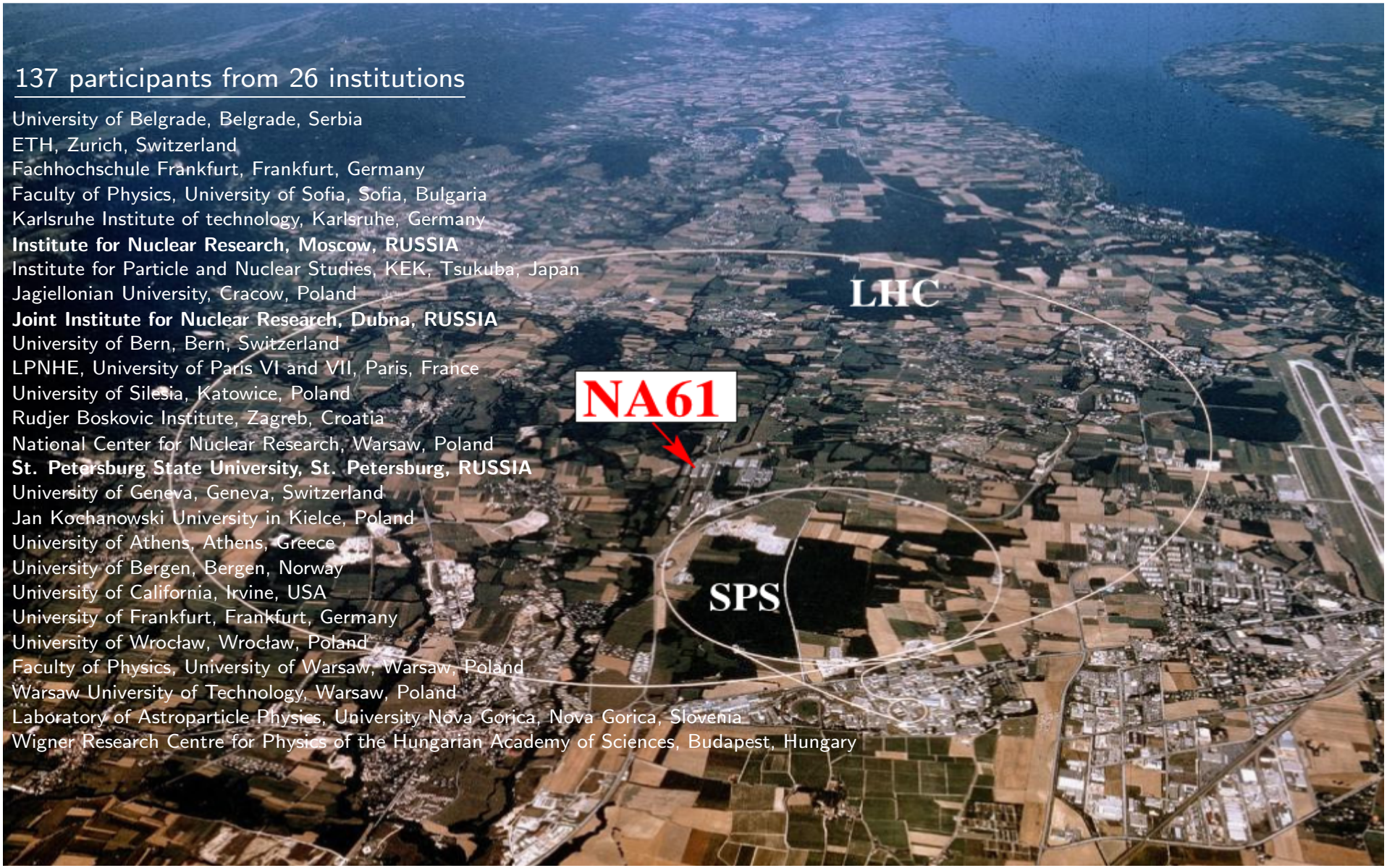
Hadron Production Measurements in NA61/SHINE for the Precise T2K Neutrino Flux Prediction and the Cosmic Ray Physics Program

Alexis Hasler

On Behalf of the NA61/SHINE Collaboration

August 27, 2013

The NA61/SHINE experiment at SPS CERN



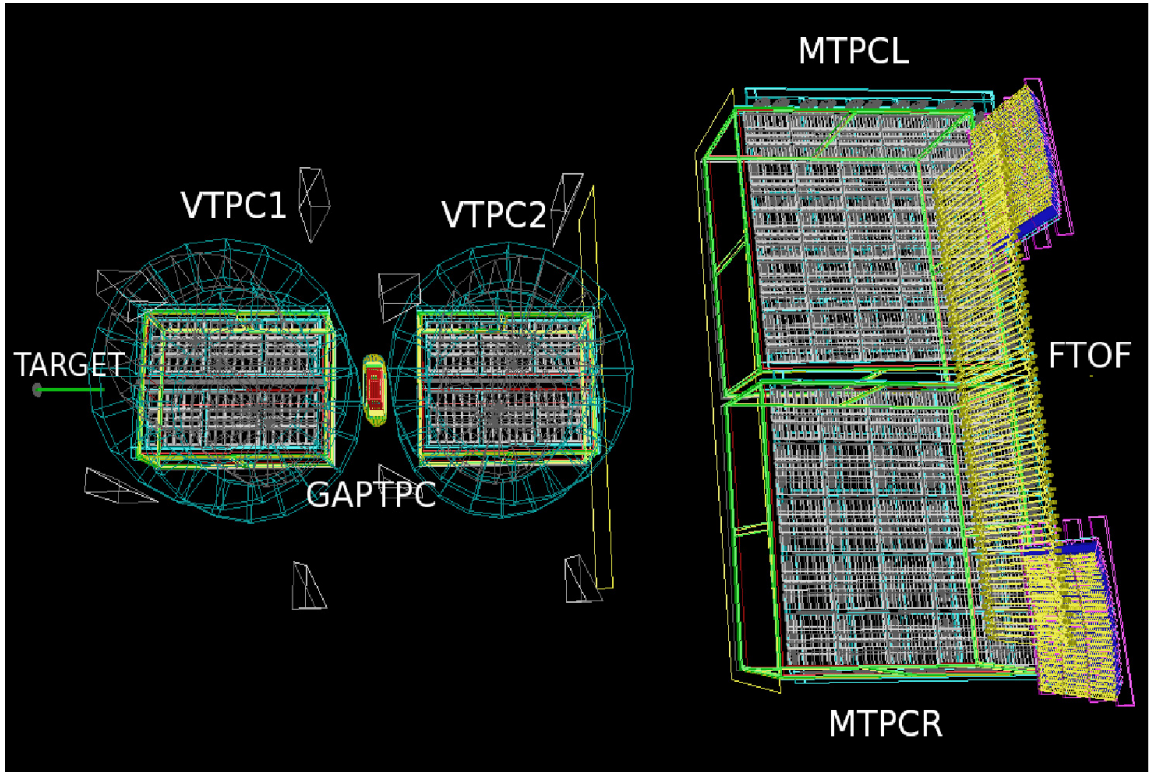
The NA61/SHINE experiment

NA61/SHINE : hadron production experiment at SPS CERN
Rich physics program covering:

- heavy ion physics (presentation from T. Czopowicz)
- hadron-production measurements for cosmic ray experiments
- hadron-production measurements for accelerator neutrino experiments

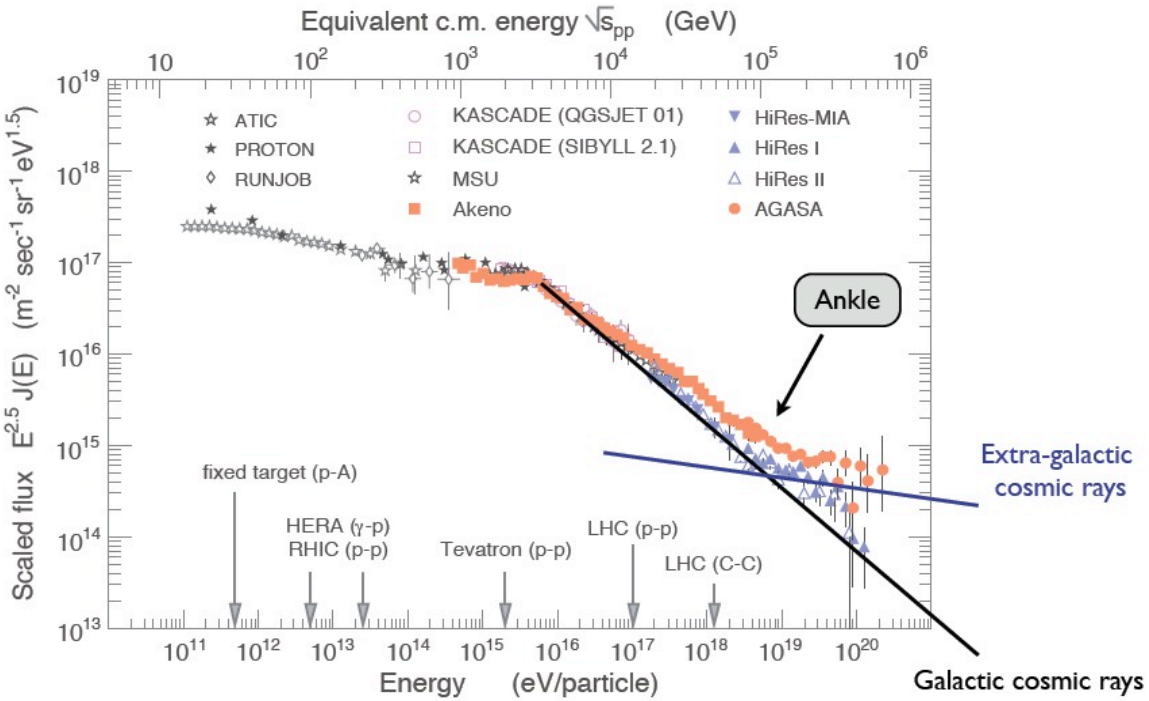
Large acceptance spectrometer:

- 5 TPCs
- 2 dipole magnets
- $\sigma(p)/p^2 \sim 10^{-4}(GeV/c)^{-1}$ (at 9Tm)
- $\sigma(dE/dx)/ < dE/dx > \sim 0.04$
- 3 ToF
- $\sigma(FTOF) \sim 120ps$
- $\sigma(TOF\ L/R) \sim 80ps$



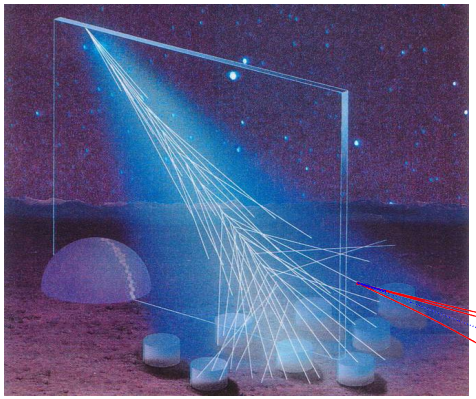
Beam	(GeV/c)	graphite target	year	Nx10^6
π^-	158	2cm	2009	5.5
π^-	350	2cm	2009	4.6
p	31	2cm	2007	0.7
p	31	2cm	2009	5.4
p	31	90cm "T2K replica"	2007	0.2
p	31	90cm "T2K replica"	2009	4
p	31	90cm "T2K replica"	2010	10

Hadron-Production measurements for the Cosmic Ray Program

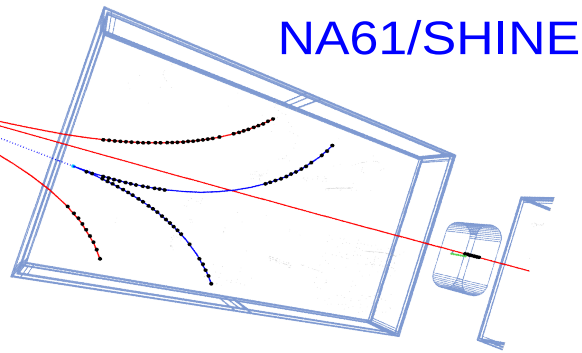


- Cosmic Ray composition of central importance for understanding sources, knee, ankle, ...
- Indirect measurements for Ultra High Energy Cosmic Rays: extensive air showers seen by a surface array detector
- Strong model dependence of the reconstructed primary energy from surface detector signals
- Muon production related to hadronic interaction at fixed target energies

UHECR
air shower



NA61/SHINE



Muons in ultra-high energy air showers

$h + \text{air} \rightarrow \pi/K + X$

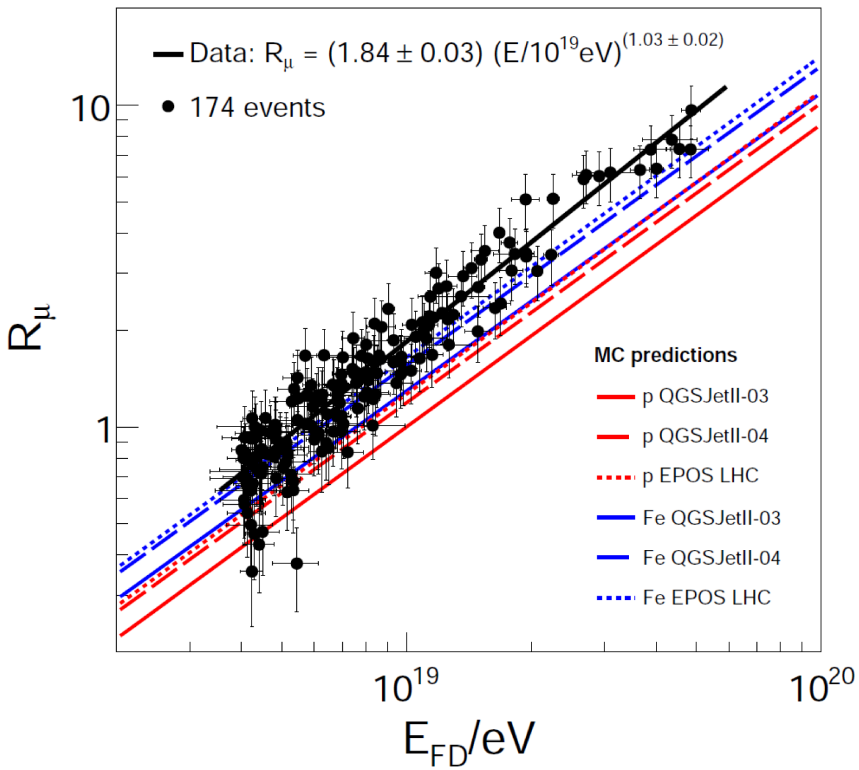
$\mu + \nu_\mu$

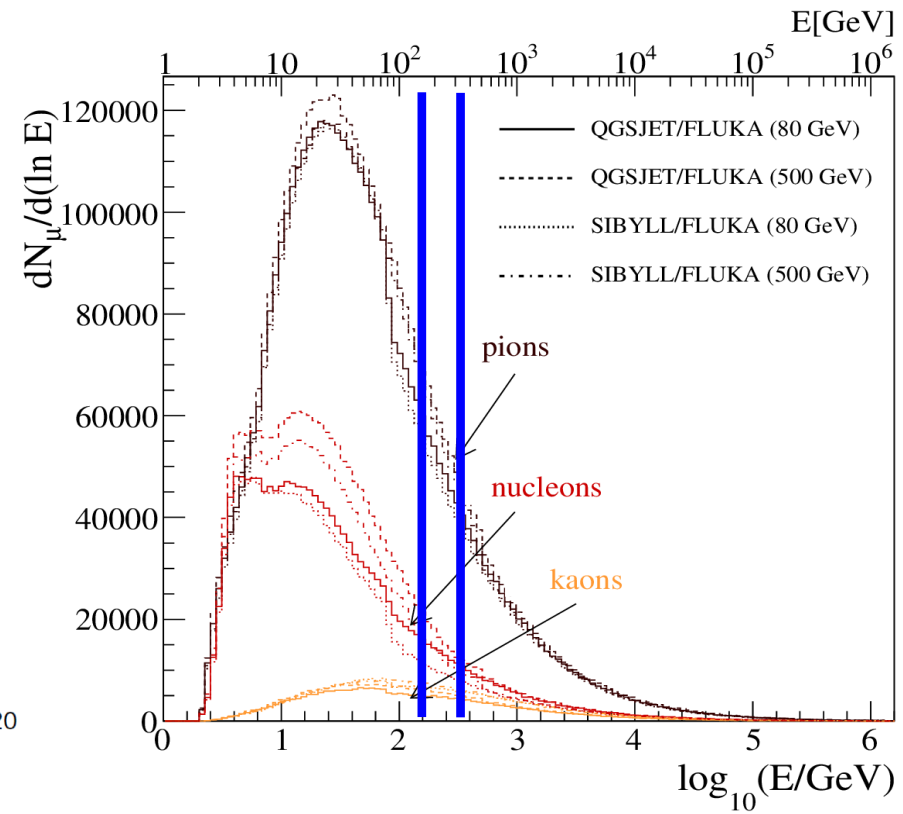
C^{12}

μ at ground mostly depend on π/K produced by π in range of 10-10^3 GeV

Pierre Auger Observatory-like

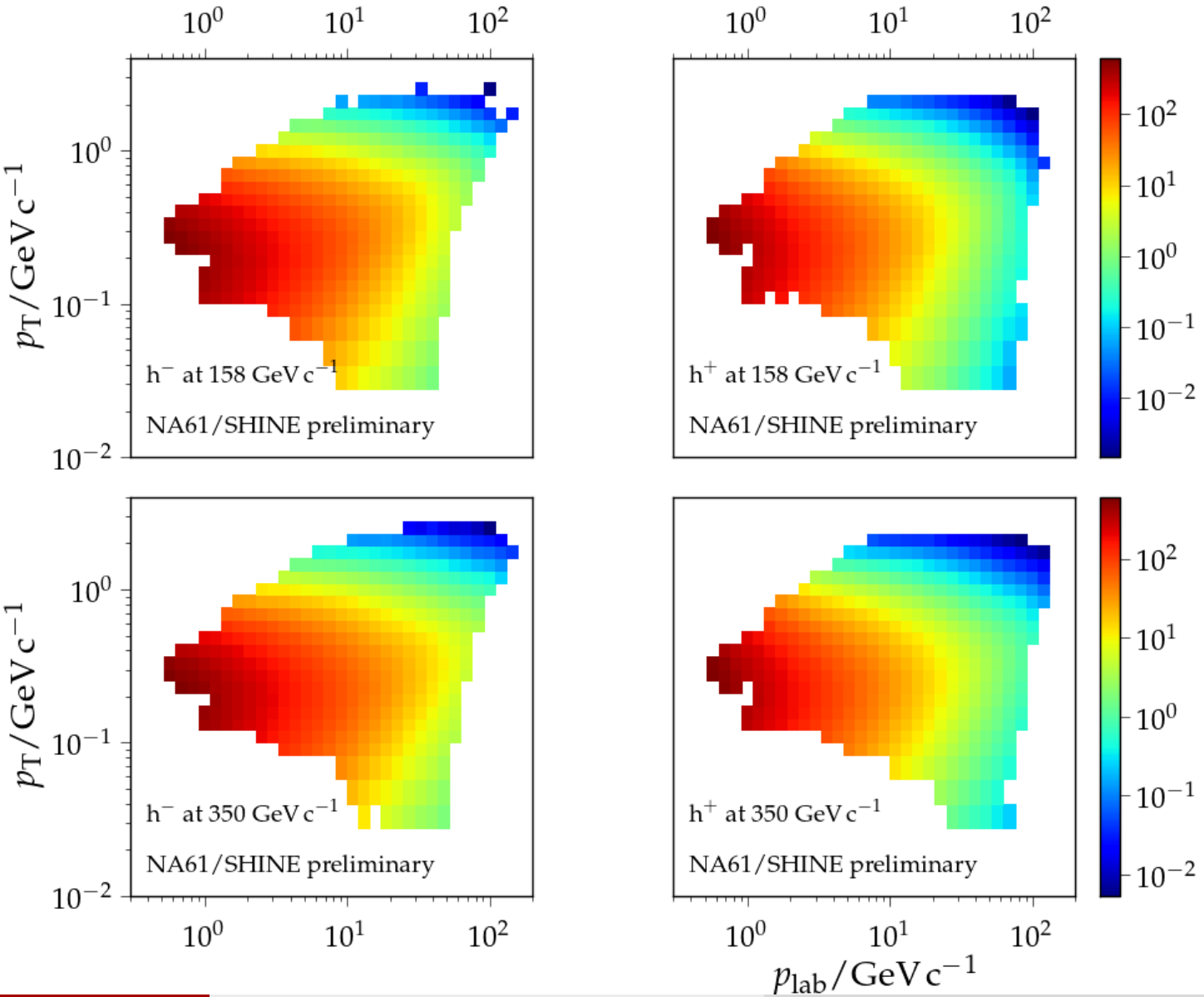
$E_0 = 10^{19}$ eV, r = 1000 m, $E_\mu \geq 150$ MeV



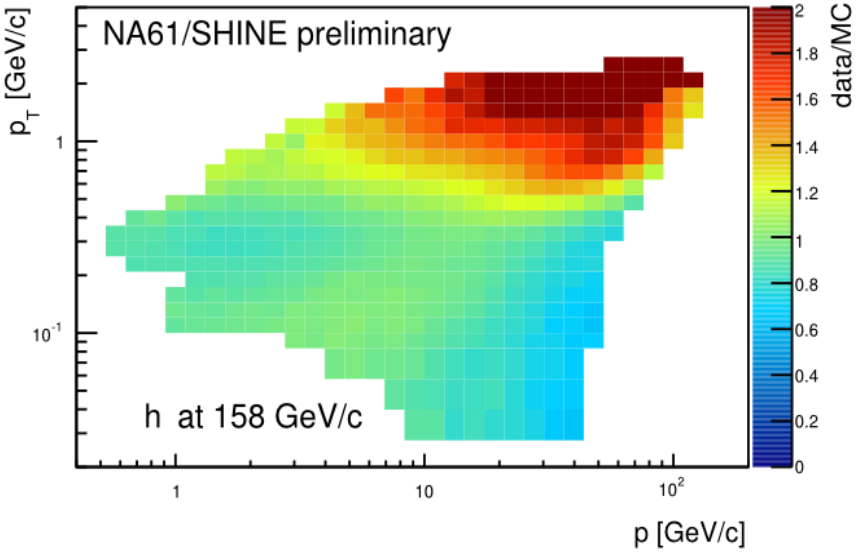


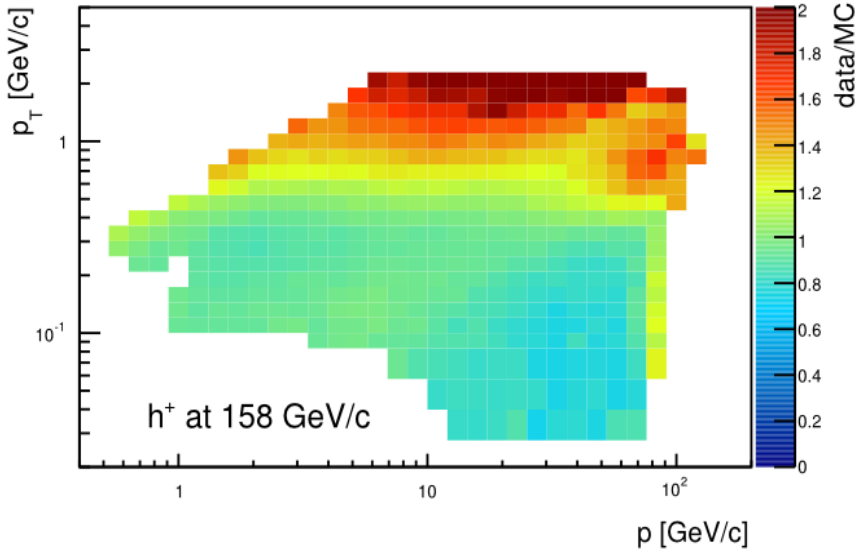
Result: Double differential cross-section $\pi^- + C \to h^\pm + X$

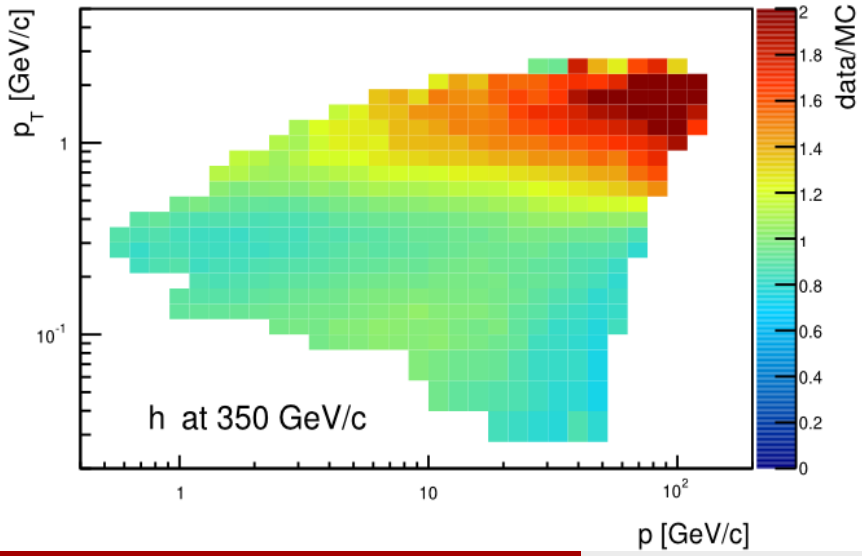
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{lab}}\,\mathrm{d}p_{\mathrm{T}}} \Big/ \mathrm{mb\,GeV^{-2}}\,c^2$$

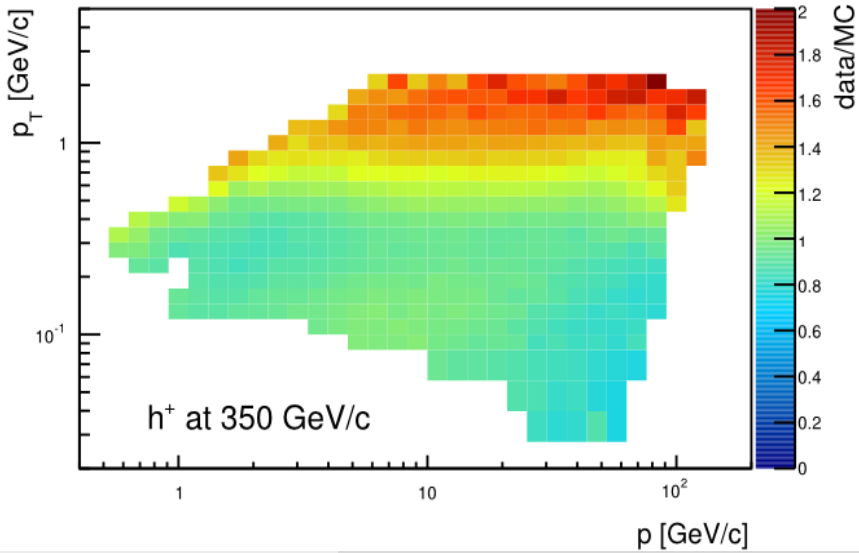


Comparison to models: EPOS 1.99



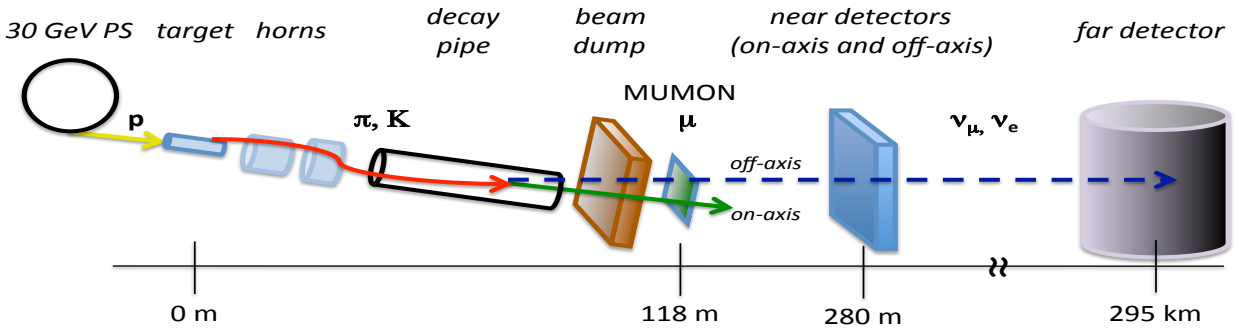






Hadron Production measurements for the T2K neutrino flux prediction

- Conventional ν beam produced by interactions of protons on fixed target
- Neutrino beam predictions rely on modeling the proton interactions and hadron production in the target
- Precise hadron production measurements allow to reduce uncertainties on neutrino flux prediction

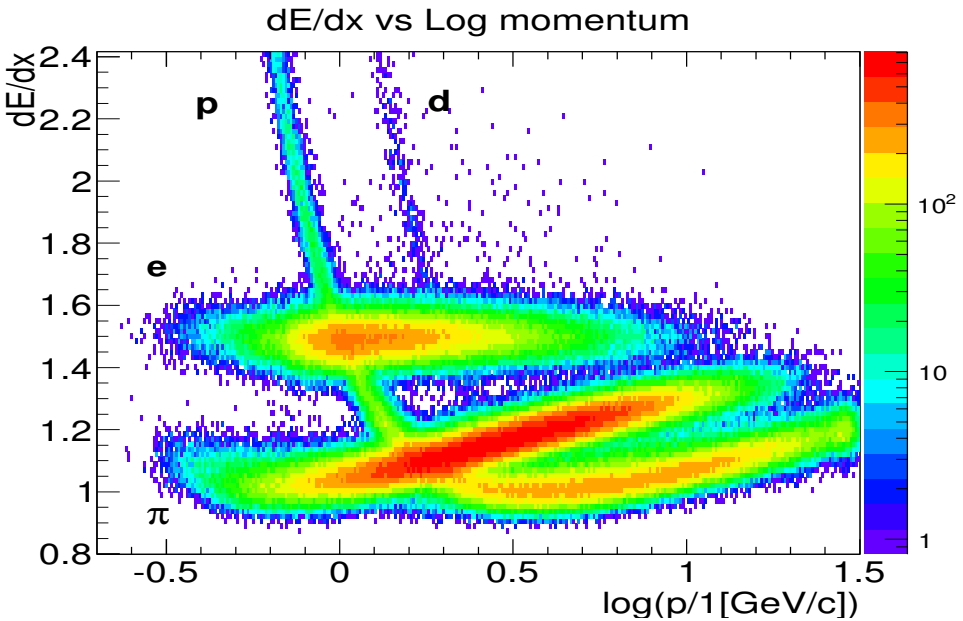


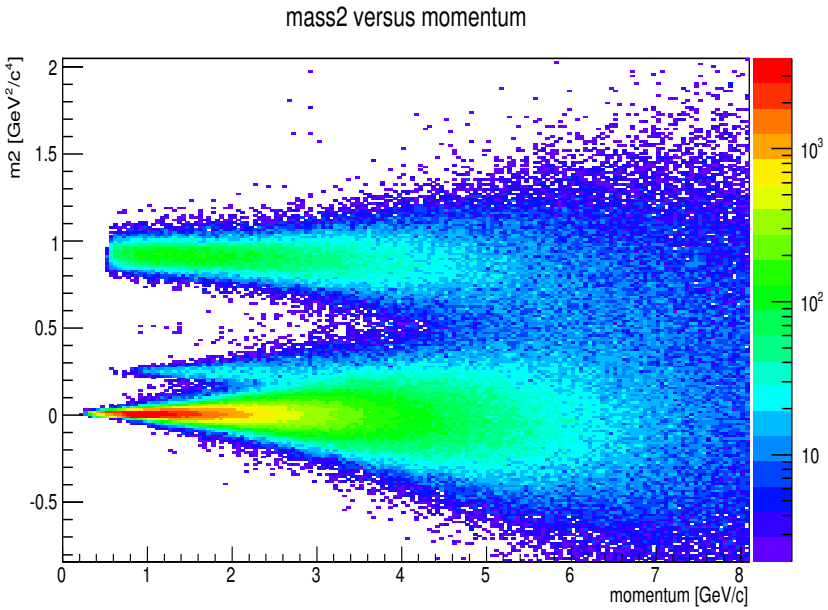
Examples:

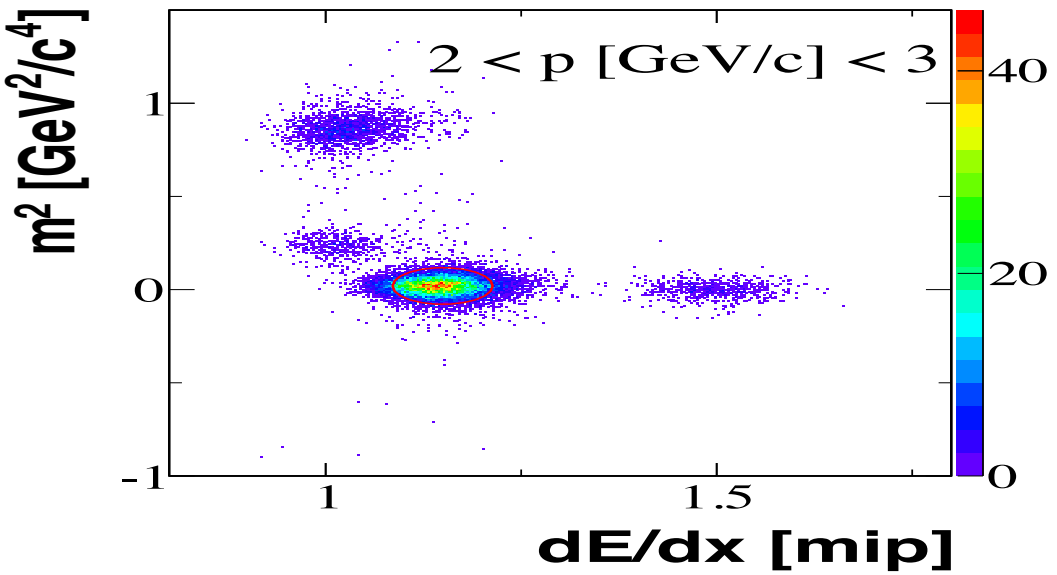
HARP, CERN-PS 1.5 - 15 GeV Beam	Mini- Sci- Micro- BooNE at Fermilab K2K (KEK to Super-Kamiokande)
NA20 & SPY/NA56, SPS 400 - 450 GeV Beam	WANF (NOMAD, CHORUS) CNGS (OPERA, ICARUS)
NA49, CERN-SPS 160 GeV Beam	MINOS (Fermilab to Soudan)
NA61/SHINE, CERN-SPS 30 GeV Beam	T2K (Tokai to Super-Kamiokande) NuMI (Fermilab) LBNE in US, LBNO in Europe

Analysis Techinques

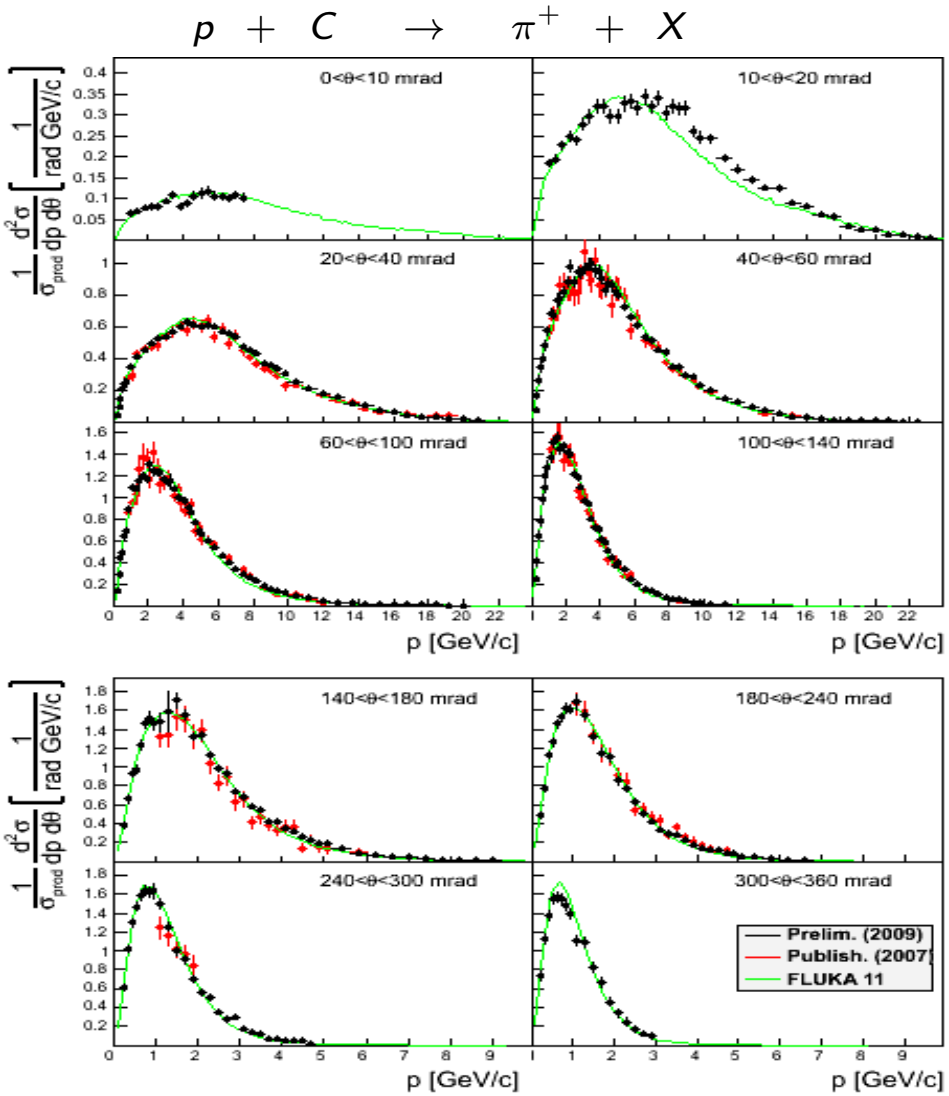
- h^- analysis: analysis of π^- via measurements of negatively charges particles
- dE/dx analysis at $p \leq 1 GeV/c$: $\pi^\pm$ and protons were identified via energy loss in TPC
- $ToF - dE/dx$ analysis at $p \geq 1 GeV/c$: information from dE/dx and ToF is combined to identify $\pi^\pm$, $K^\pm$ and protons

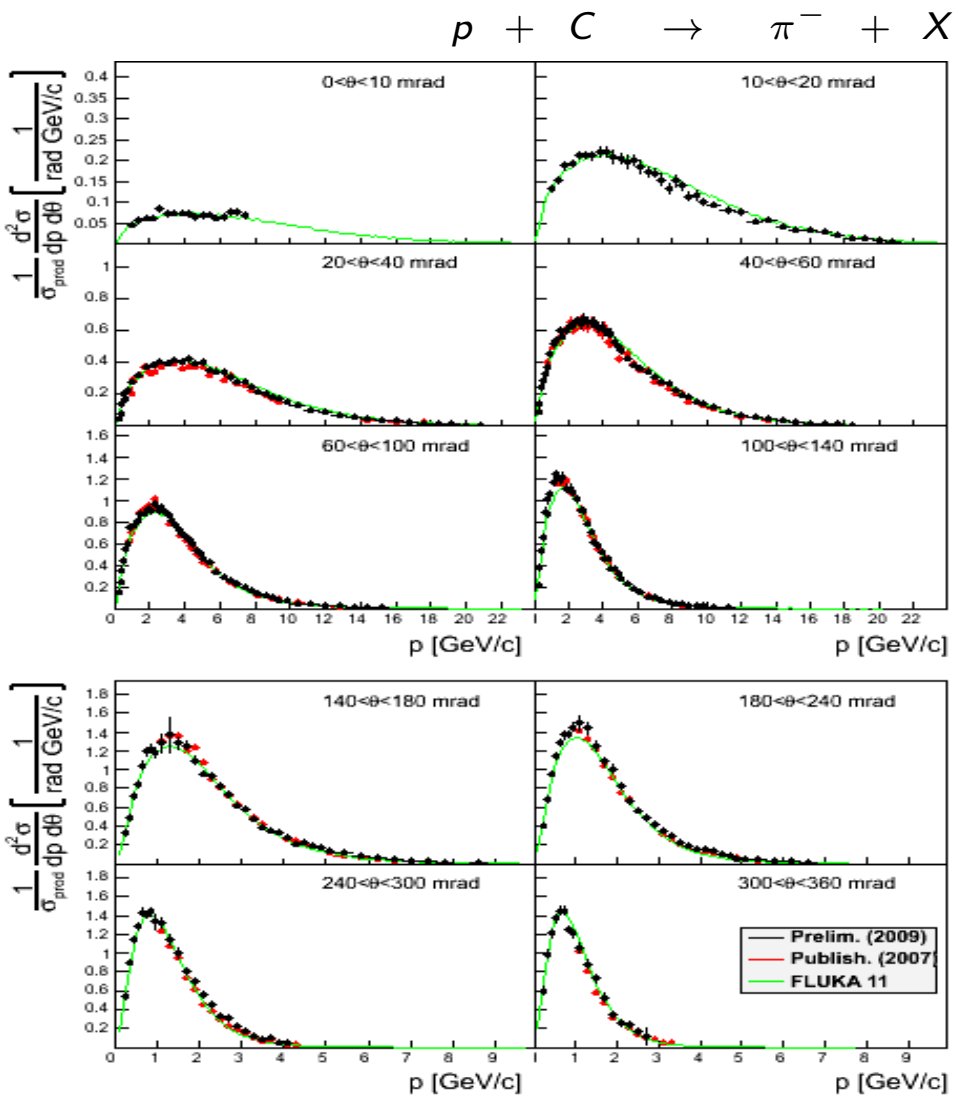






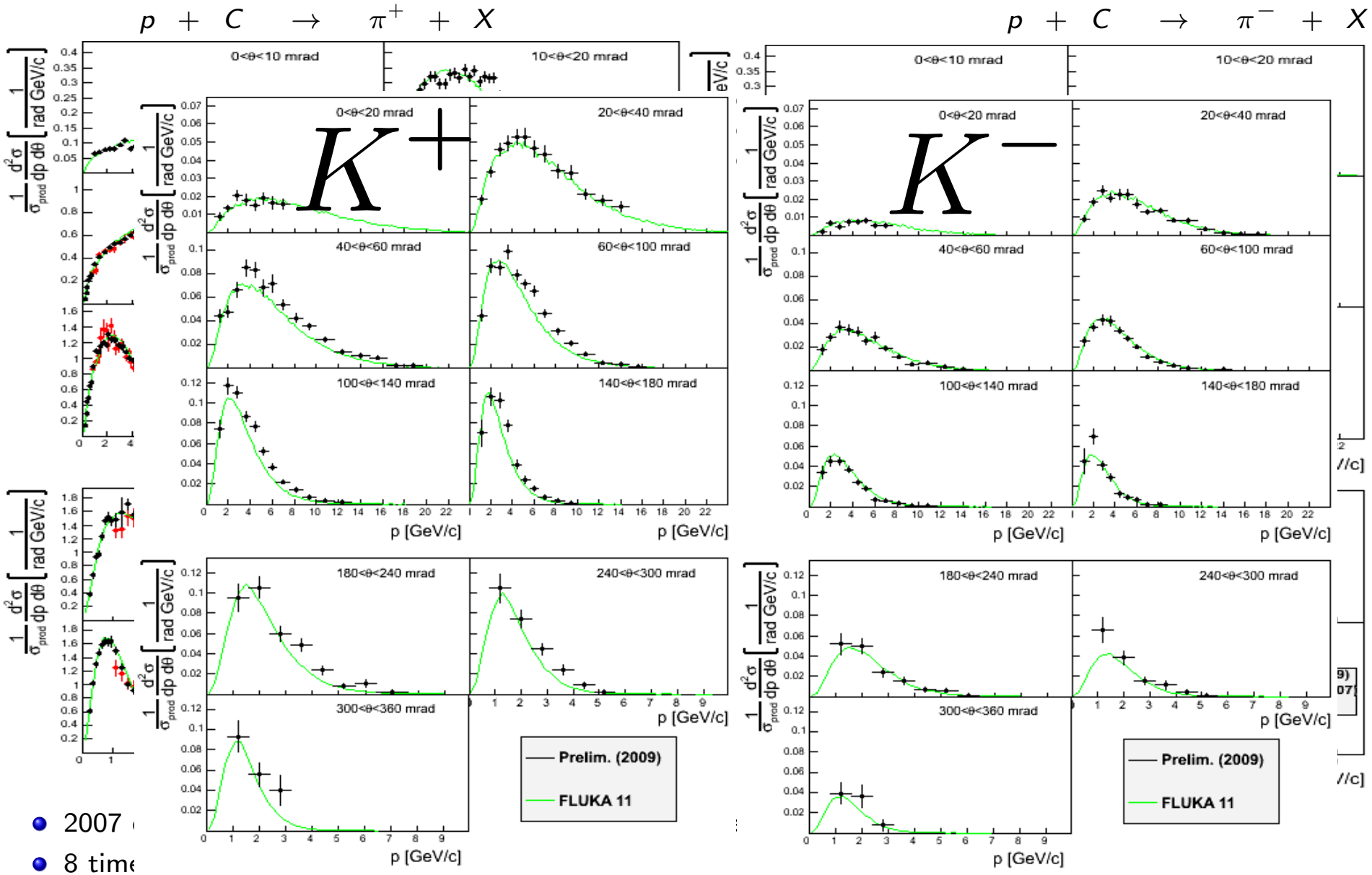
Six Particle Spices Released for p+C at 31 GeV/c





- 2007 data set already published and used by the T2K experiment
- 8 times more statistics for the 2009 data set; preliminary results released

Six Particle Spices Released for p+C at 31 GeV/c



- 2007 (
- 8 time

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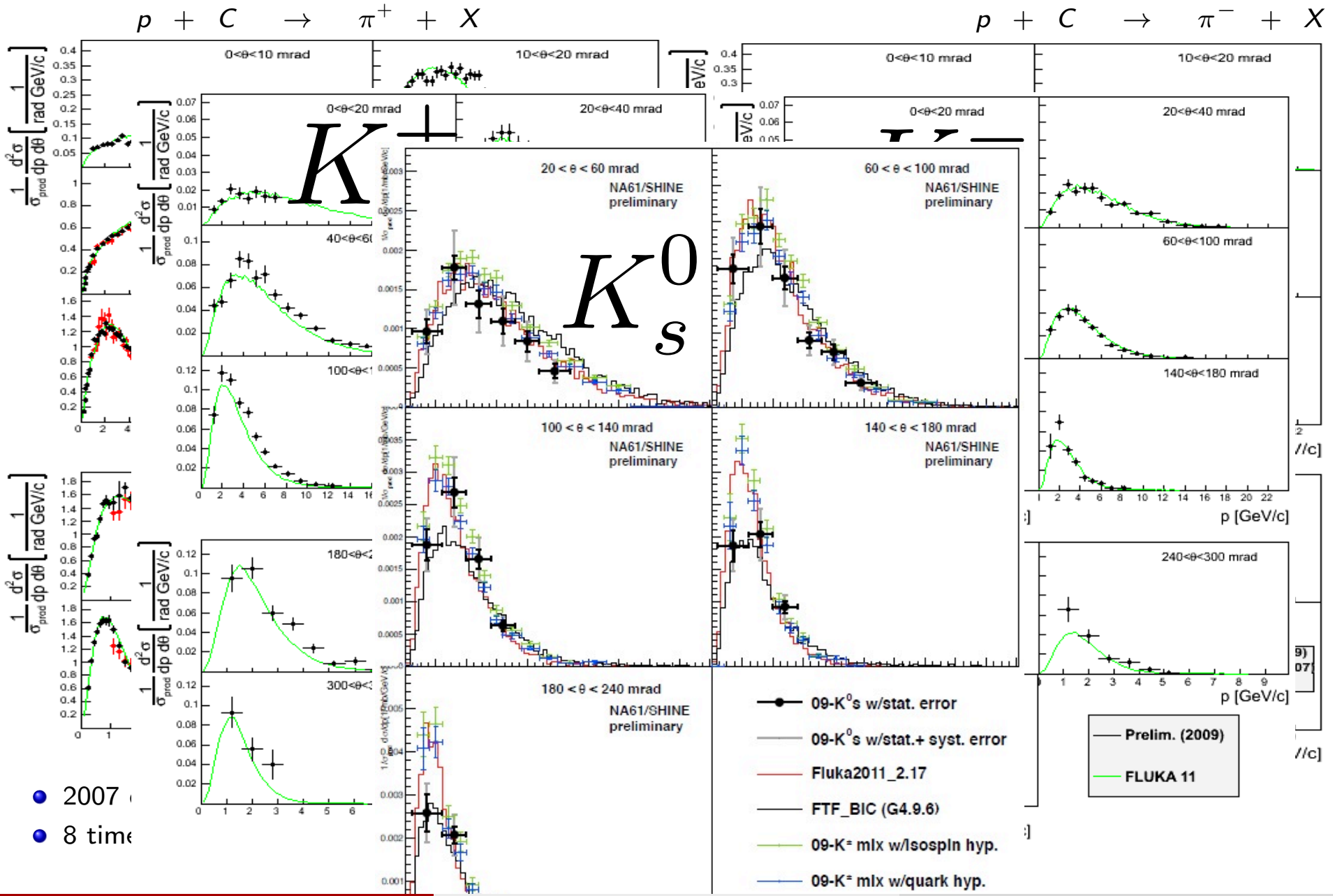

- 2007
- 8 time

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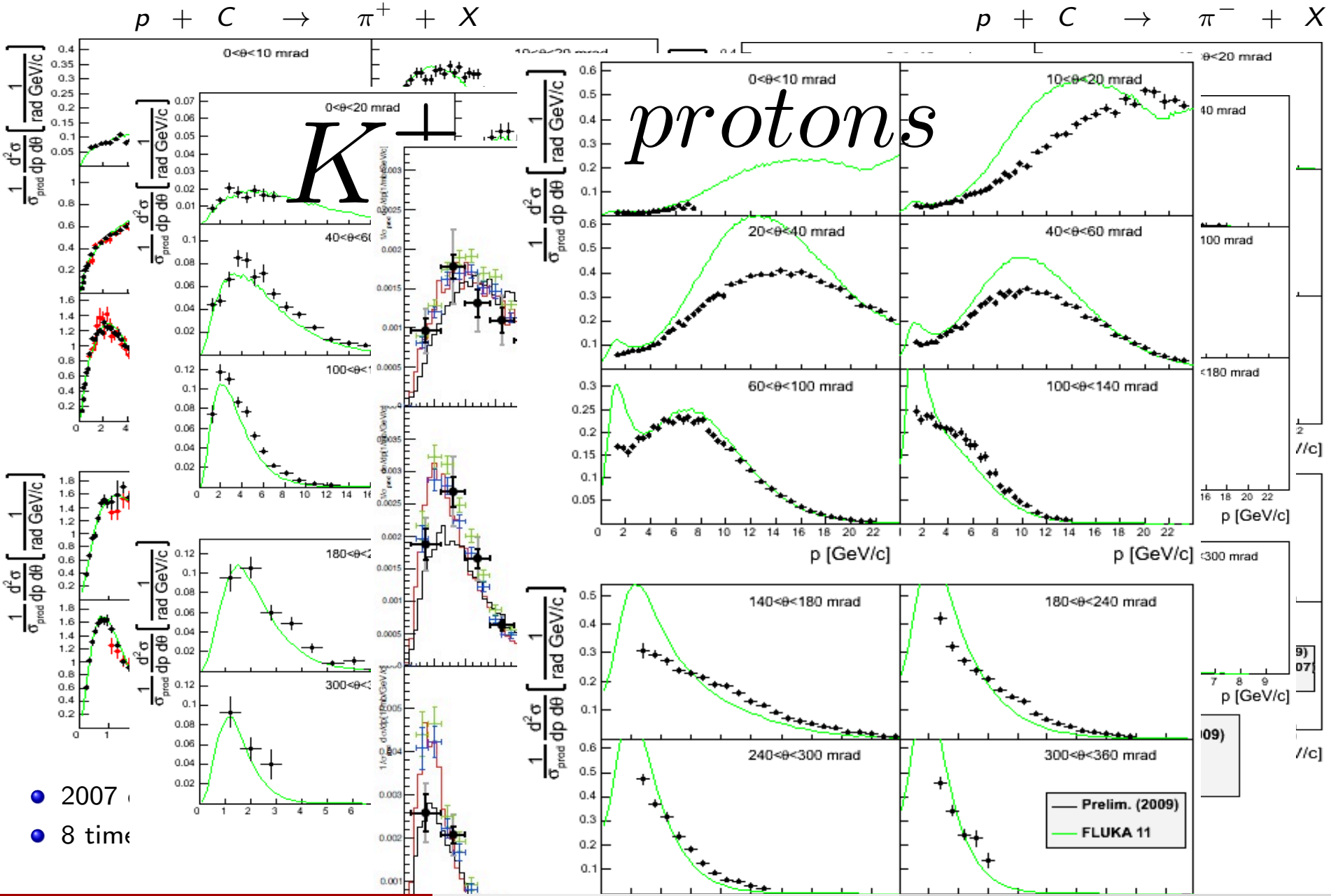
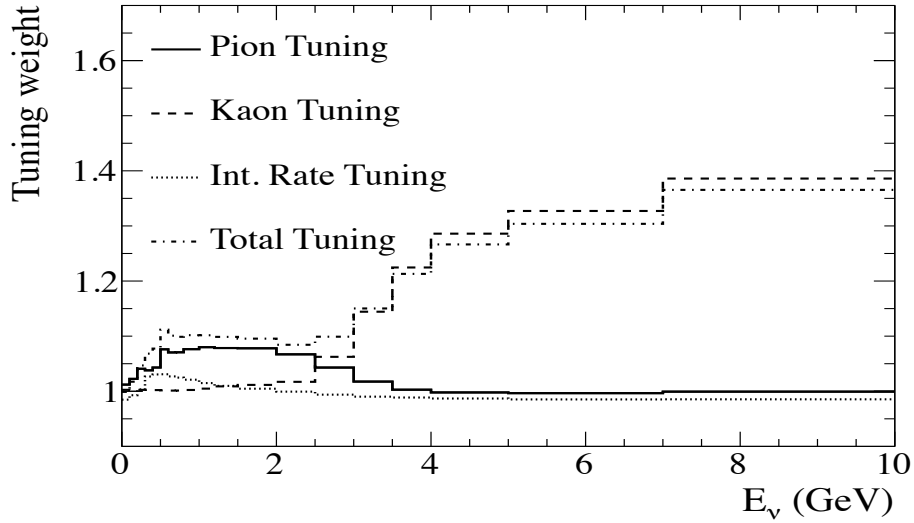


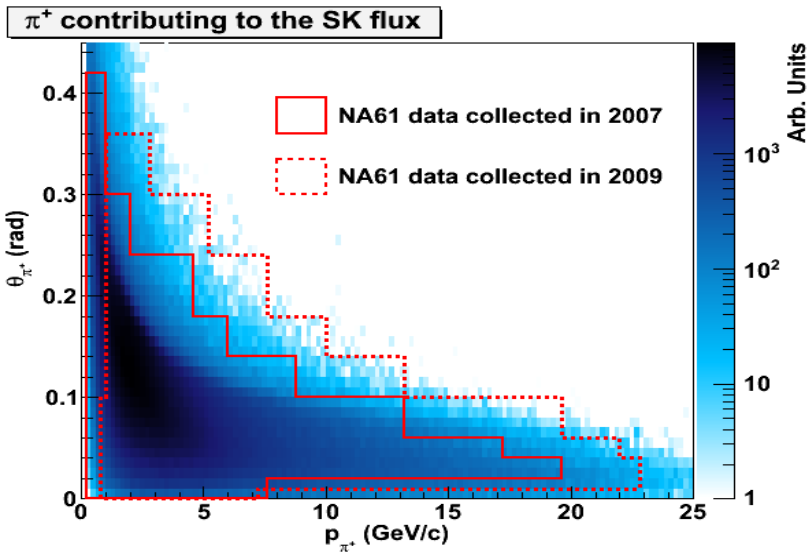
- 2007
- 8 time

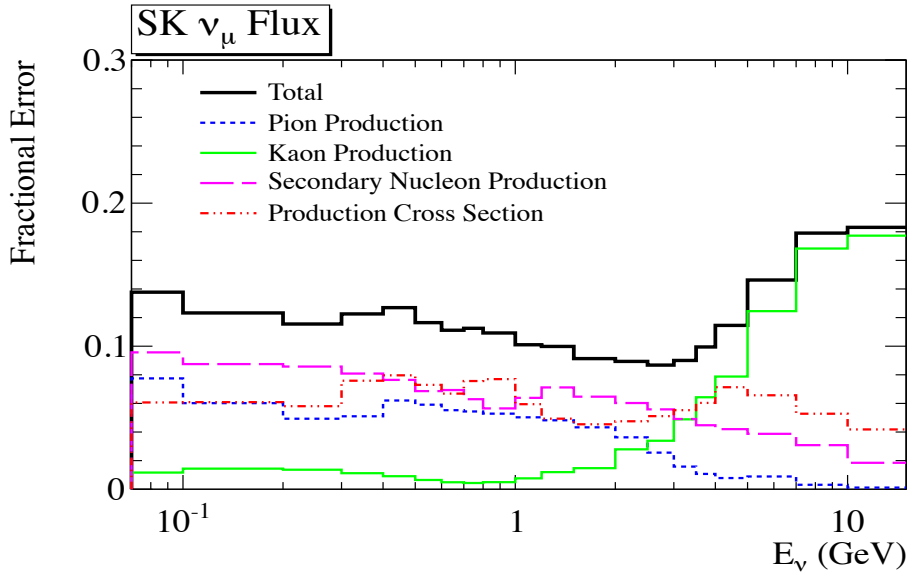
The T2K Beam Tuning with NA61/SHINE Measurements

p+C at 31 GeV/c data in T2K

- Major part of the T2K phase space is covered by NA61/SHINE data
- Interaction chain is stored at the simulation level to be tuned later with measurements
- Tuning of tertiary particles requires extrapolation from NA61/SHINE data:
  - Extrapolation to different incident nucleon momenta
  - Extrapolation to different material (carbon to aluminum)
- Larger uncertainty to the flux due to tertiary particle production





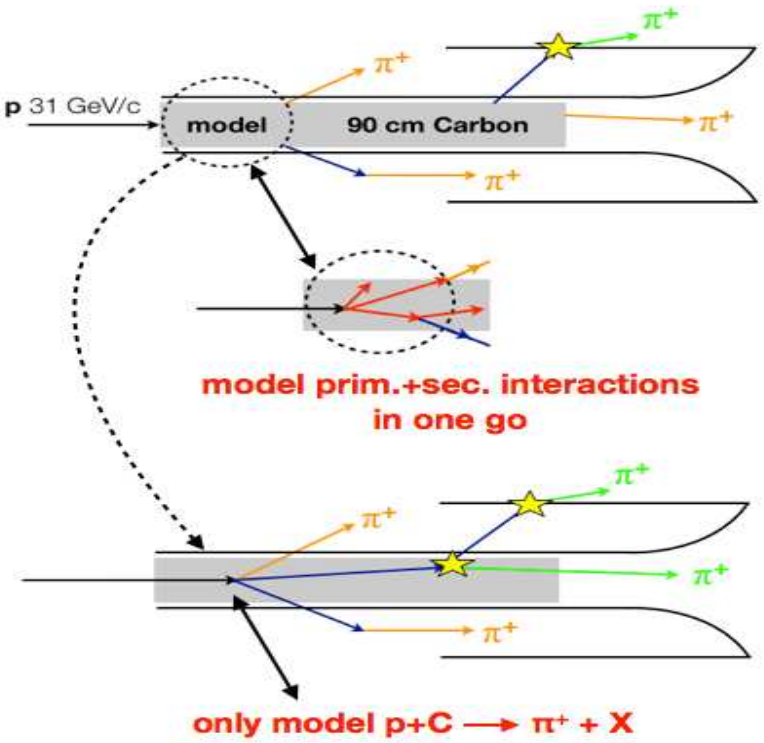


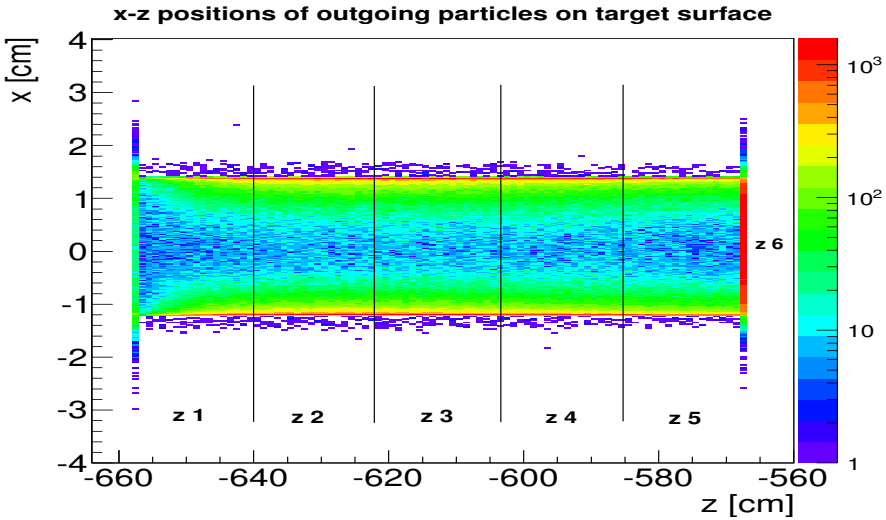
(T2K) K.Abe et al., Phys.Rev.D87 (2013)012001

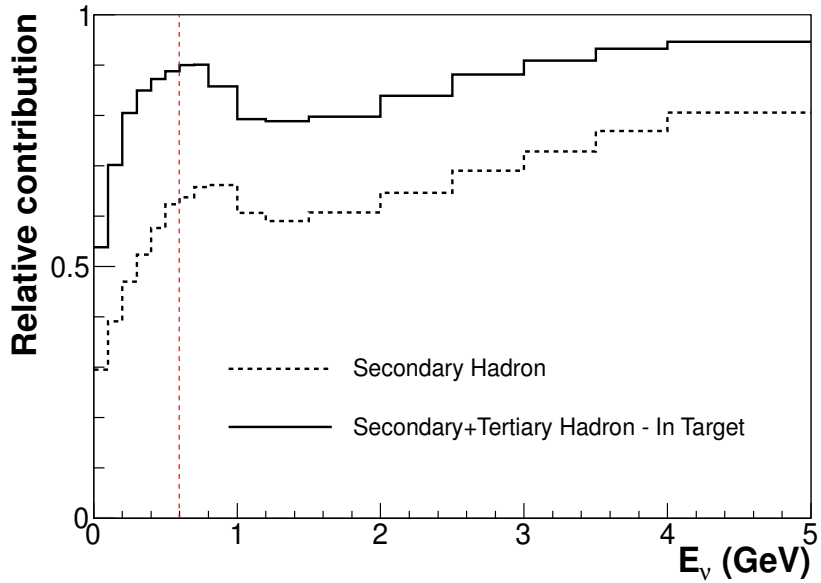
The T2K Beam Tuning with NA61/SHINE Measurements

Alternative approach to the neutrino flux prediction:

- Measurement of hadron multiplicities at the surface of a T2K replica target placed in the NA61/SHINE experimental set-up
- Analysis in (p, θ, z) bins (6 "longitudinal" z bins)
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Re-weighting up to 90% as compared to 60% in the standard approach

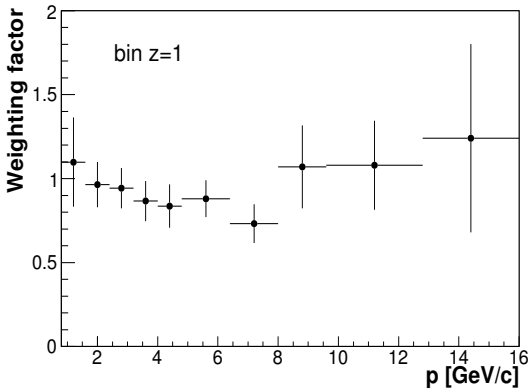


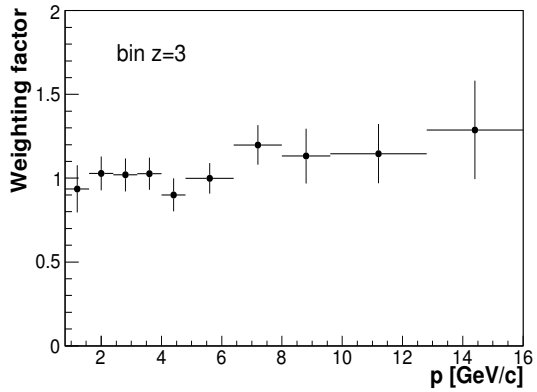


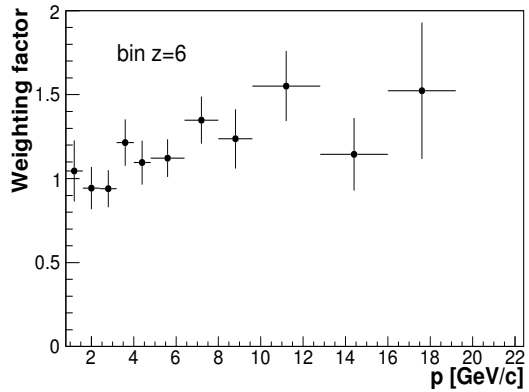


The T2K Beam Tuning with NA61/SHINE Measurements

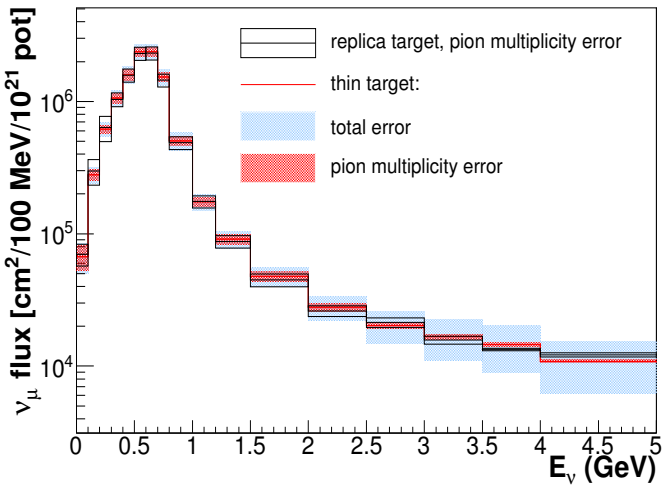
Consider ratios $\omega_{\pi}^{NA61}(p,\theta,z) = n_{\pi\,data}^{NA61} / n_{\pi\,MC}^{NA61}$ for model tuning ($n = numer\ of\ \pi / proton\ on\ target$)

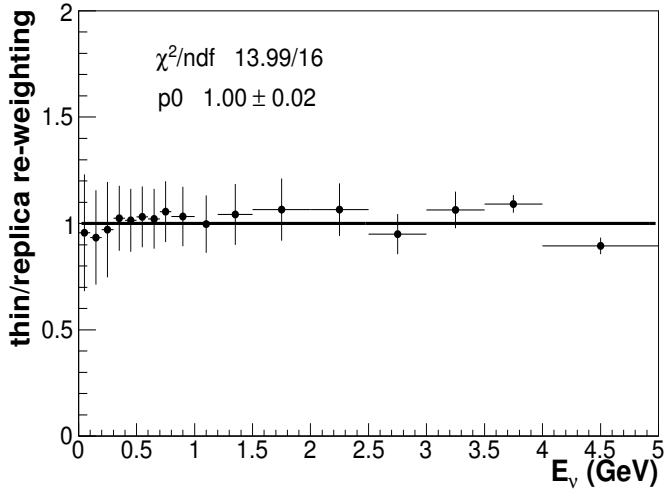






Propagating these results in the T2K beam simulation:





Pilot Analysis based on 2007 low statistics Data set
"Pion emission from the T2K replica target: method, results and application"
Nuclear Inst. and Methods in Physics Research, A (2013) pp. 99-114

Summary

- The NA61/SHINE experiment has proved it's ability to deliver high quality data used for Cosmic Ray physics and Neutrino Physics programs
- Preliminary results of hadrons spectra from pion-carbon interactions at 158 and 350 GeV/c have been released
- All data requested by the T2K long baseline experiment have been recorded
- 8 particle species are extracted for p+C at 31 GeV/c:
  - $\pi^{\pm}$, $K^{\pm}$, K^0_s *and protons* released
  - analysis for Λ and anti-protons is ongoing
- 3 articles have been published from p+C at 31 GeV/c
  - Measurement of Production Properties of Positively Charged Kaons in Proton-Carbon Interactions at 31 GeV/c; Phys.Rev. C85 (2012)
  - Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c; Phys.Rev. C84 (2011)
  - Pion emission from the T2K replica target: method, results and application; Nuclear Inst. and Methods in Physics Research, A (2013)
- NA61/SHINE published results have been extensively used and have contributed to the recent achievements of the T2K experiment. Detailed explanations have been published in an article by the T2K collaboration (T2K neutrino flux prediction; Phys. Rev. D 87,(2013)). Future results with the thin (2cm) and T2K replica graphite target analyses will allow to further improve the T2K neutrino flux prediction.
- NA61/SHINE plans to continue taking hadron production measurements for future neutrino program at Fermilab and for long base line neutrino experiments