ETH
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SHINE NA61

Hadron production measurements at the NA61/SHINE experiment for the T2K Neutrino Flux Prediction

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on behalf of the NA61 collaboration

NuFact 2014, August 26th 2014

The NA61/SHINE experiment

• NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a fixed target experiment at CERN SPS

• Very rich physics program that covers:

- hadron production reference measurements for accelerator neutrino (T2K, Fermilab) and cosmic ray experiments (Pierre Auger Observatory, KASCADE)

- search for the critical point of strongly interacting matter

- study the properties of the onset deconfinement in nucleus-nucleus collisions

• In this talk hadron production measurements used to constrain the T2K neutrino flux will be discussed

Experimental setup

- Large acceptance detector with very good capabilities of momentum, charge and mass measurements
- 2 dipole magnets (max bending power = 9 Tm)
- 5 TPCs with high momentum resolution, $\sigma(p)/p^2 \sim 10^{-4}$ (GeV/c)$^{-1}$
- Good particle identification: $\sigma(dE/dx)$ / <dE/dx> ~ 0.04
- 3 ToF (σ_{ToFF} ~120ps, $\sigma_{ToFL/R}$ ~80ps)
- New ToFF to fully cover the T2K acceptance

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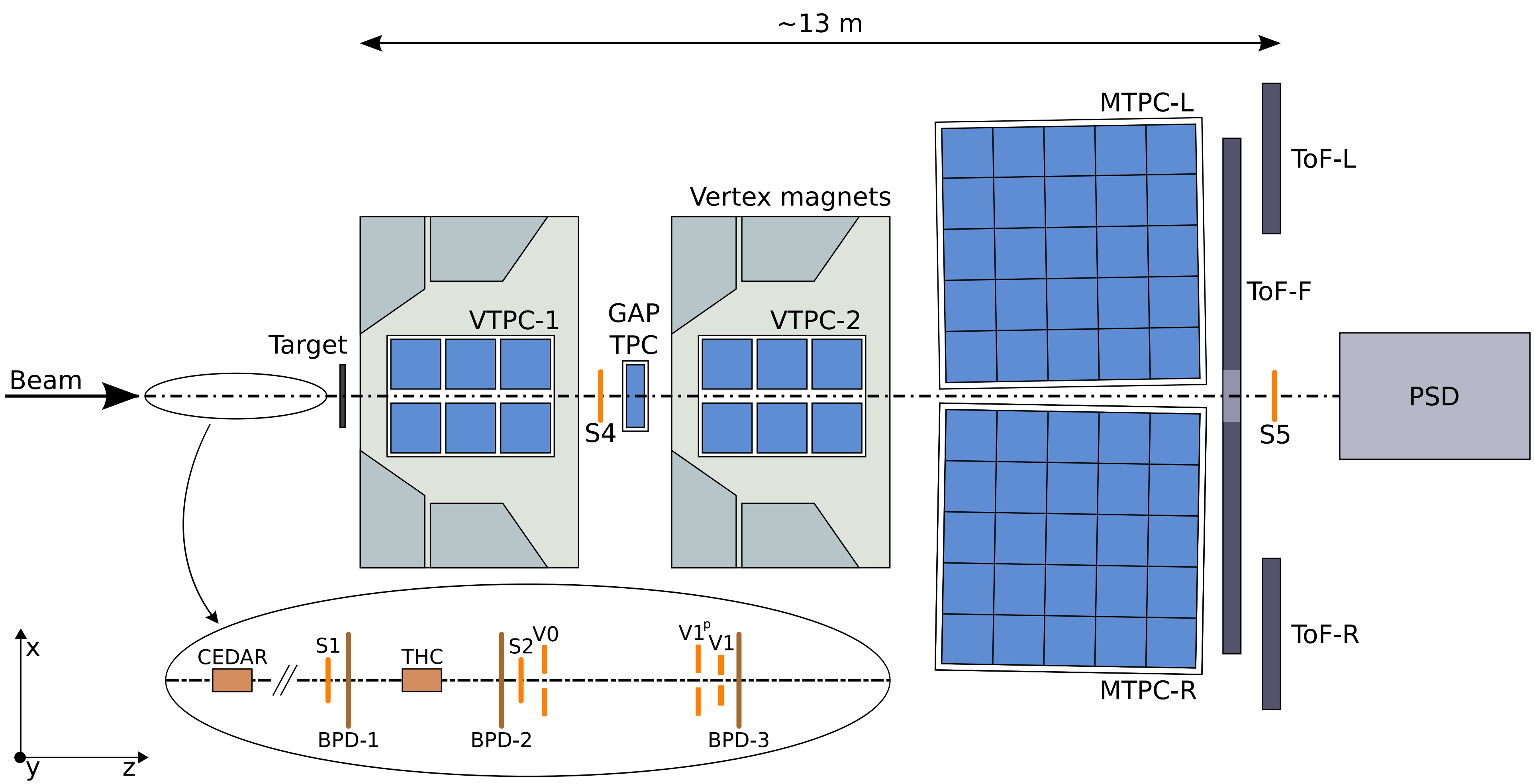
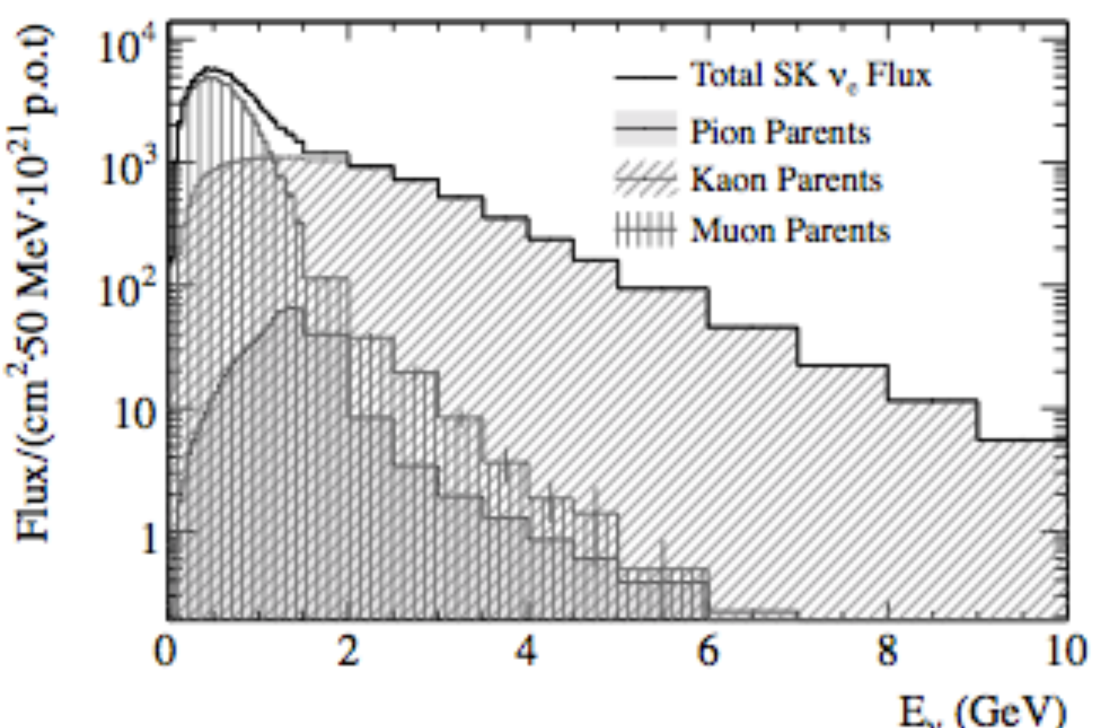


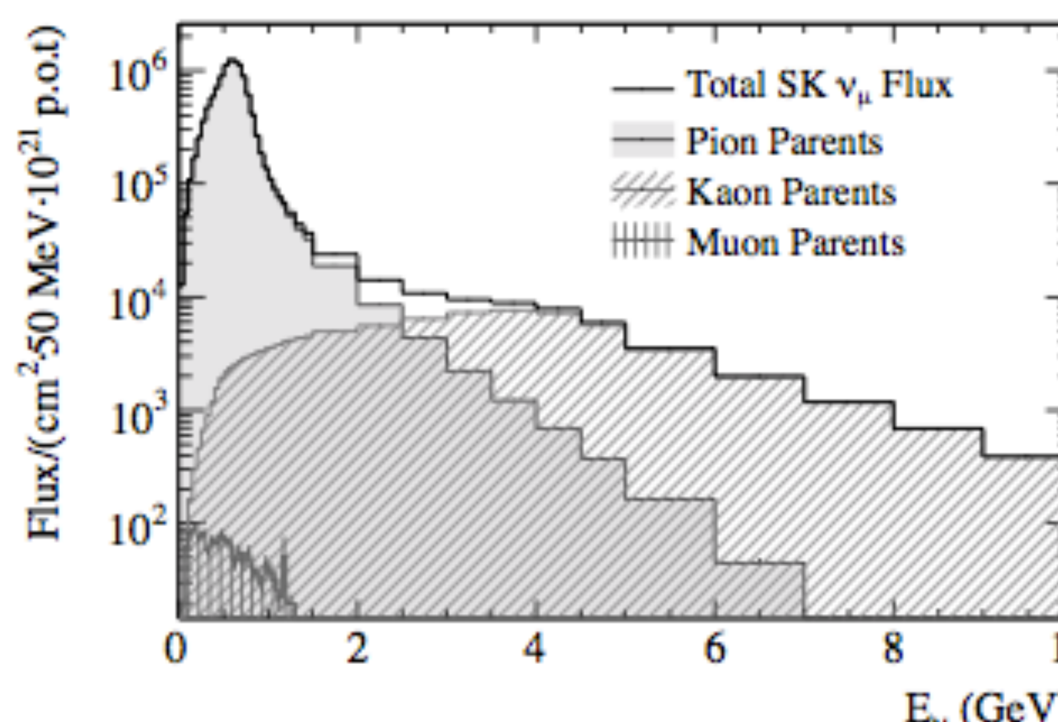
T2K neutrino flux prediction

- T2K is a long baseline experiment that aims to measure the parameters of the PMNS matrix and perform many cross section measurements (see Suzuki-san, Raquel talks)
- Neutrino beam is produced w/ proton-Carbon interactions at 31 GeV/c
- Beam composed by ν_μ with a ν_e contamination of about 1%
- Large flux systematic uncertainties due to the poor knowledge on the hadron production are dominant (difference between models up to 30%)
- T2K requirement is to pull the total flux uncertainty down to ~5%
- Wrong flux estimation would bias oscillation and cross section measurements
- Need to measure hadron production with the NA61/SHINE experiment

ν_e flux @ T2K far detector (MC)



ν_μ flux @ T2K far detector (MC)

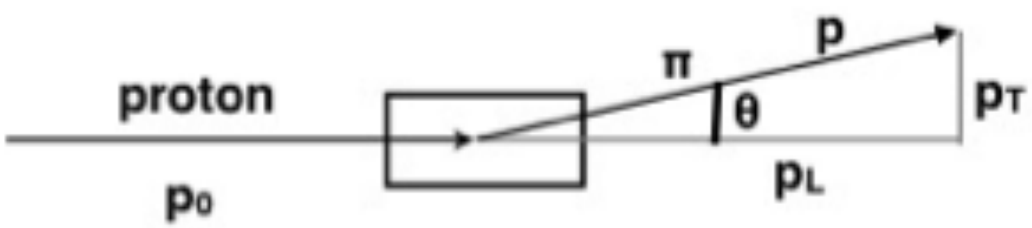


K. Abe et al, Phys. Rev. D 87 (2013), 012001 , arXiv: 1211.0469

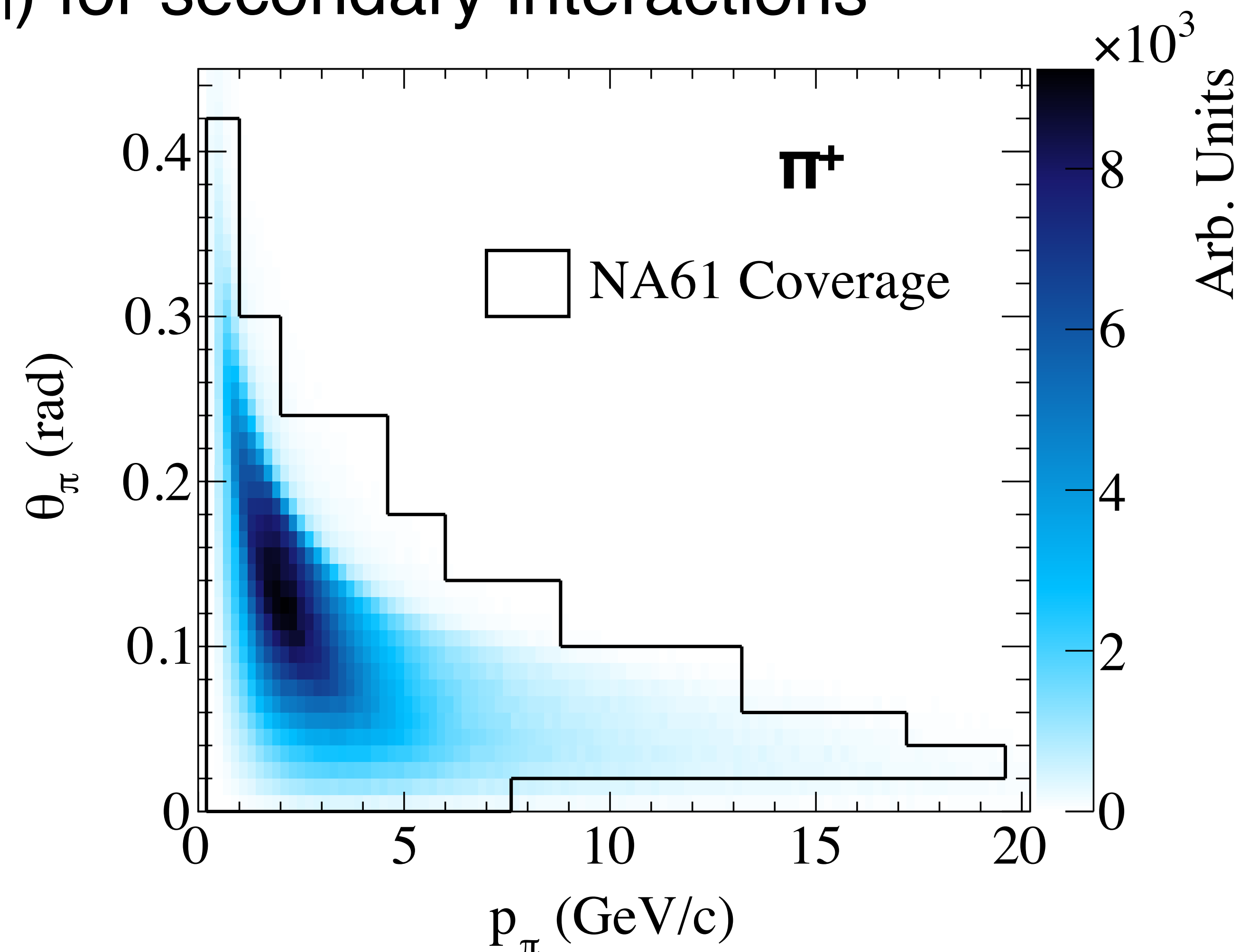
Data set

Hadron production measurements of pC@31 GeV/c

- Thin target (2cm, 4% λ_I) for primary interactions
- T2K replica long target (90cm, 1.9 λ_I) for secondary interactions



T2K phase space is fully covered



target	year	statx10^6	analyzed samples	T2K beam MC
Thin	2007	0.7	published: $\pi^\pm$, K^+, K^0_S, Λ	used
	2009	5.4	prelim: $\pi^\pm$, $K^\pm$, p, K^0_S, Λ	fall 2014
Long	2007	0.2	published: $\pi^\pm$	method proposed
	2009	2.8	to release (2014)	-
	2010	~10	calibration phase	-

N.Abgrall et al., Phys. Rev. C84 (2011) 034604, arXiv:1102.0983
N.Abgrall et al., Phys. Rev. C85 (2012) 035210, arXiv: 1112.0150
N. Abgrall et al., NIM A 701 (2013) 99-114, arXiv:1207.2114
N. Abgrall et al., Phys. Rev C89 (2014) 025205, arXiv: 1309.1997

Derivation of spectra

• The number of particles α in p intervals with the target inserted (Δn_α^I) and target removed (Δn_α^R) are used to compute the differential cross sections:

$$\frac{d\sigma_\alpha}{dp} = \frac{\sigma_{trig}}{1-\epsilon} \cdot \left(\frac{1}{N^I} \frac{\Delta n_\alpha^I}{\Delta p} - \frac{\epsilon}{N^R} \frac{\Delta n_\alpha^R}{\Delta p} \right)$$

• Interactions outside the target estimated with data-set w/o inserted target

• Measure ϵ, i.e. ratio of interaction probability with inserted and removed target (subtract out-of-target interaction background):

$\varepsilon = 0.124 \pm 0.004$

•Measure trigger cross section (σ_{trig}), related to the number of proton on target interactions:

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$\sigma_{trig} = 305.7 \pm 2.7$ (stat) ± 1.0 (det) mb

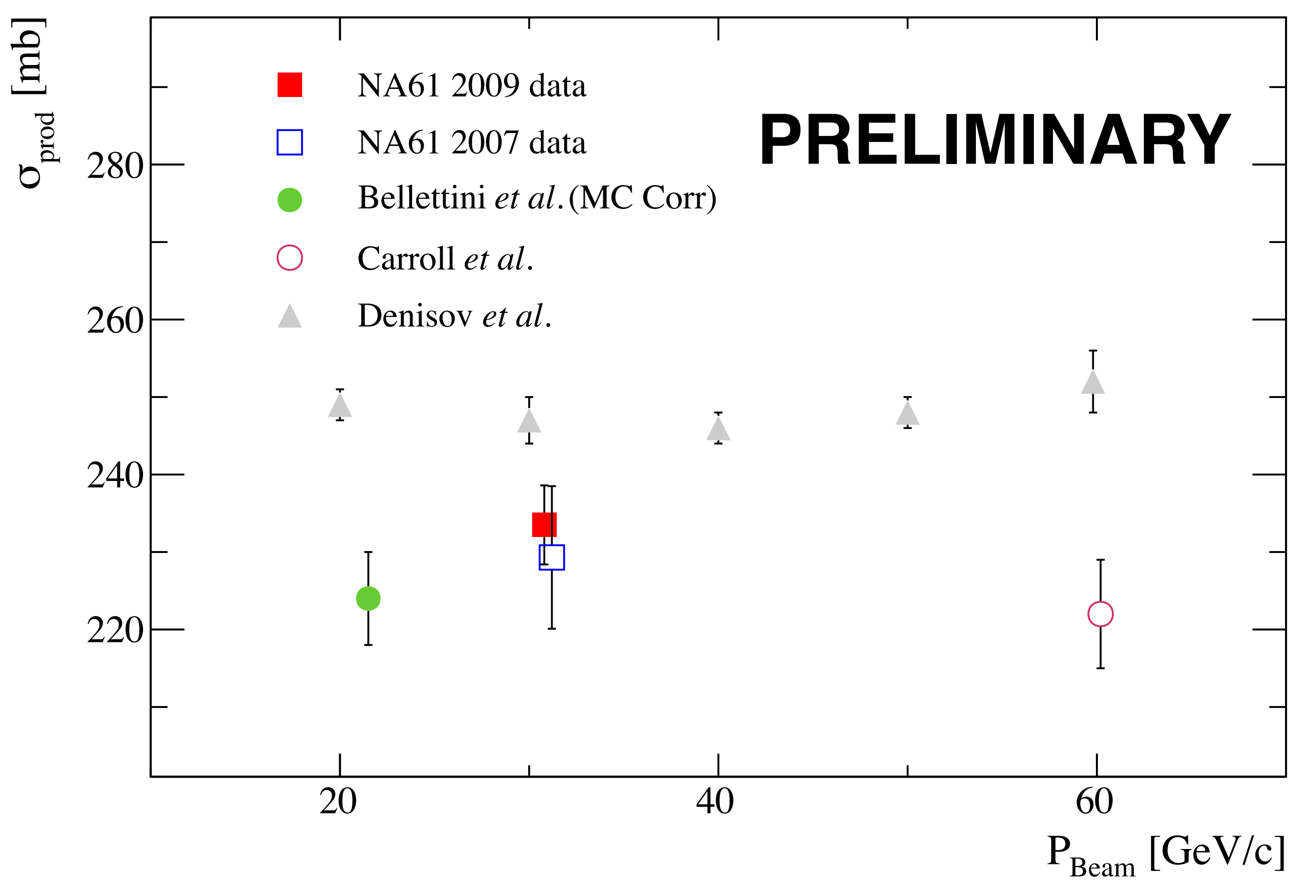
Derivation of spectra

- The particle spectra normalized to the mean particle multiplicity in production interactions was calculated as

$$\frac{dn_\alpha}{dp} = \frac{1}{\sigma_{prod}} \cdot \frac{d\sigma_\alpha}{dp}$$

- Hadron spectra from pC interactions are normalized with the total hadron production cross section
- Subtract elastic and quasi-elastic contributions estimated w/ GEANT4.9.5 (FTF_BIC physics list)

Results w/ 2009 and 2007 data are consistent



σ_{prod} = 233.5 ± 2.8 (stat) ± 2.4 (det) ± 3.6 (mod) mb **(PRELIMINARY)**

Analysis technique for charged hadrons

3 different analysis techniques:

• **h⁻ analysis (0.2-20 GeV):**

- measure π^- spectra by looking at negatively charged particles (~90%)

- no PID is required

- correct contamination with MC

• **dE/dx at low momenta ($\pi^{\pm}$,p):**

- p < 1 GeV/c

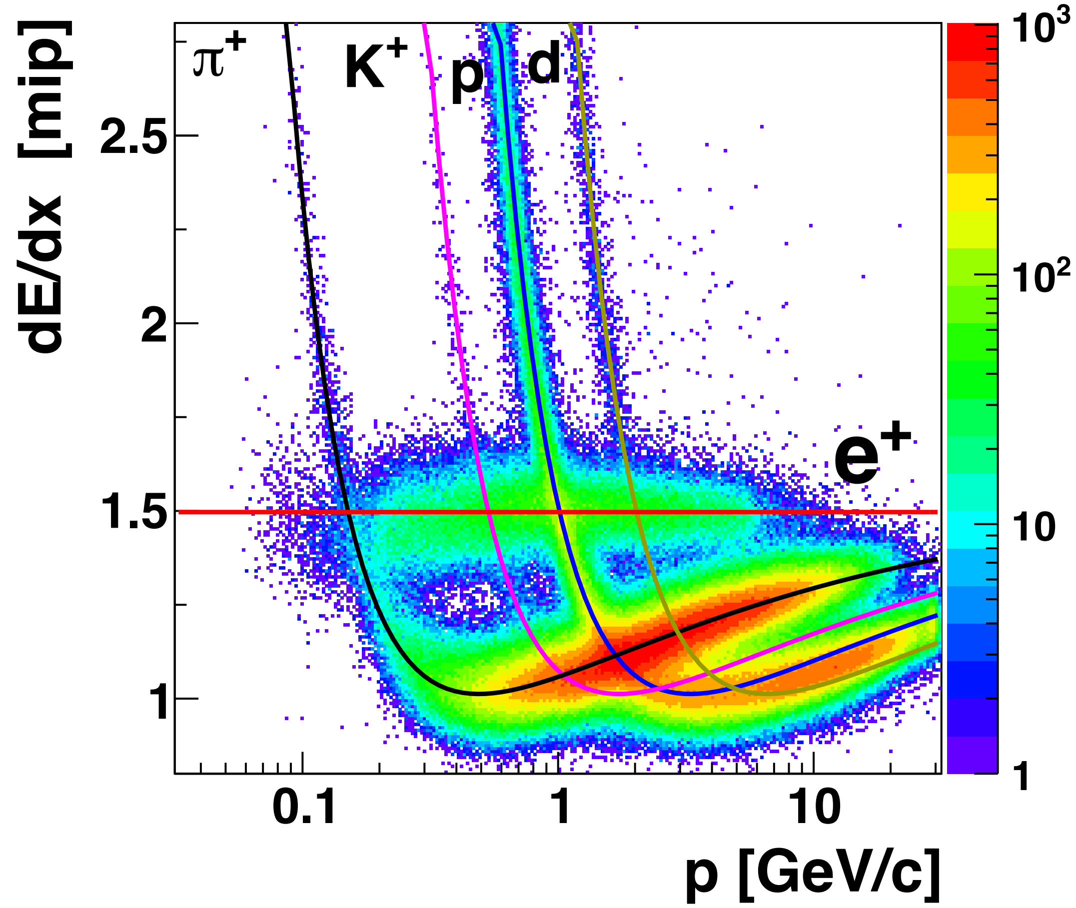
- identify π^- and protons measuring the energy loss in the TPCs

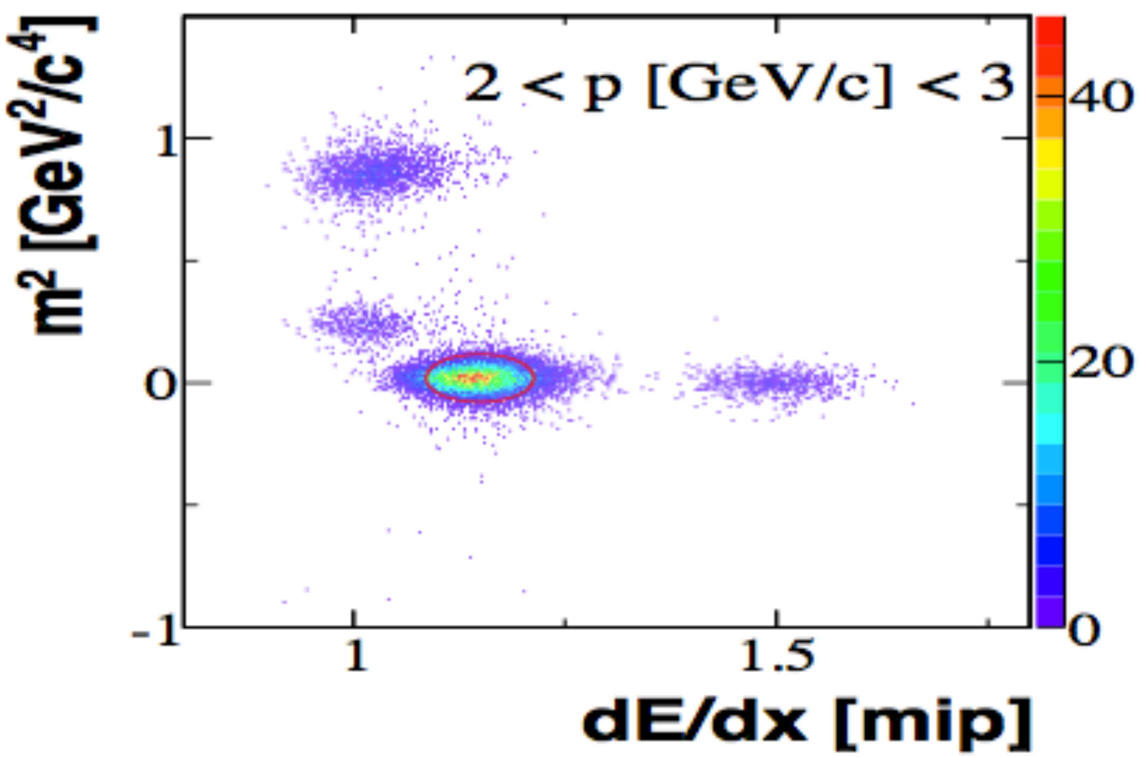
• **combined dE/dx + ToF ($\pi^{\pm}$,p,$K^{\pm}$):**

- p > 1 GeV/c

- combine information from ToF and dE/dx

• MC corrections: correct spectra for geometrical acceptance, reconstruction efficiency, contamination of other particles, secondary interactions and weak decays (“feed-down”)



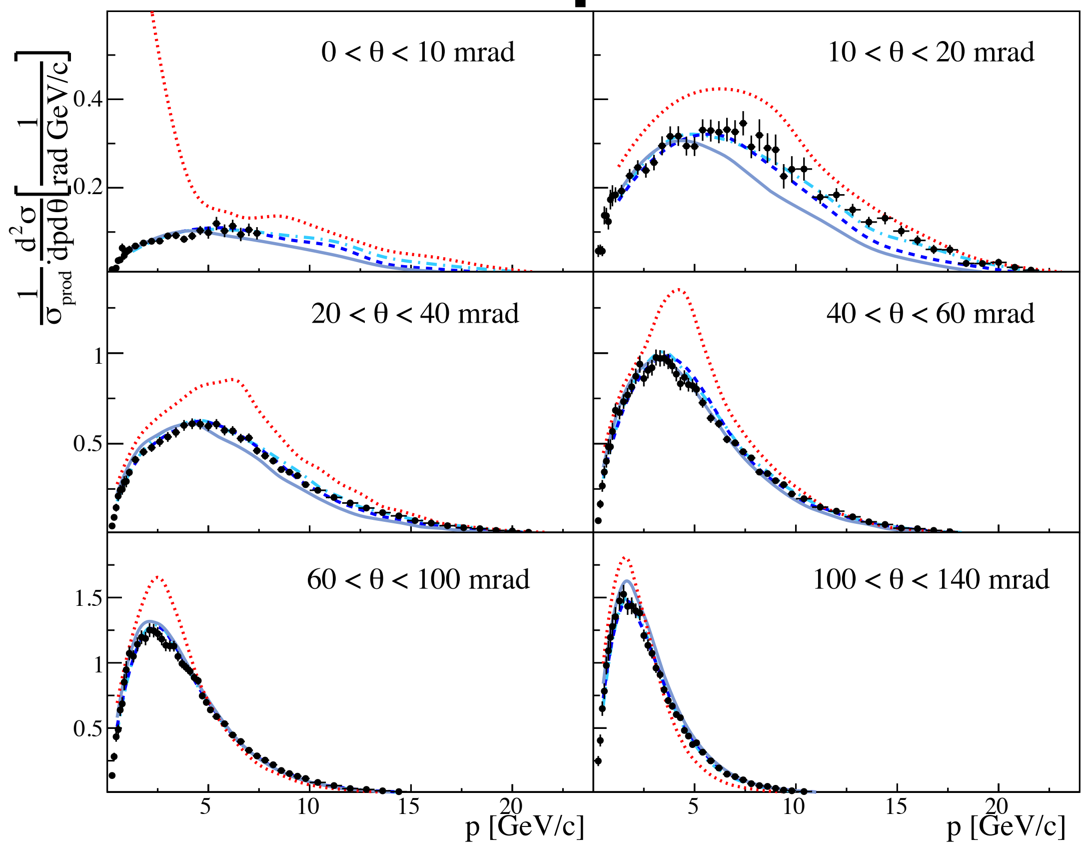


Charged hadron measurements with thin target data

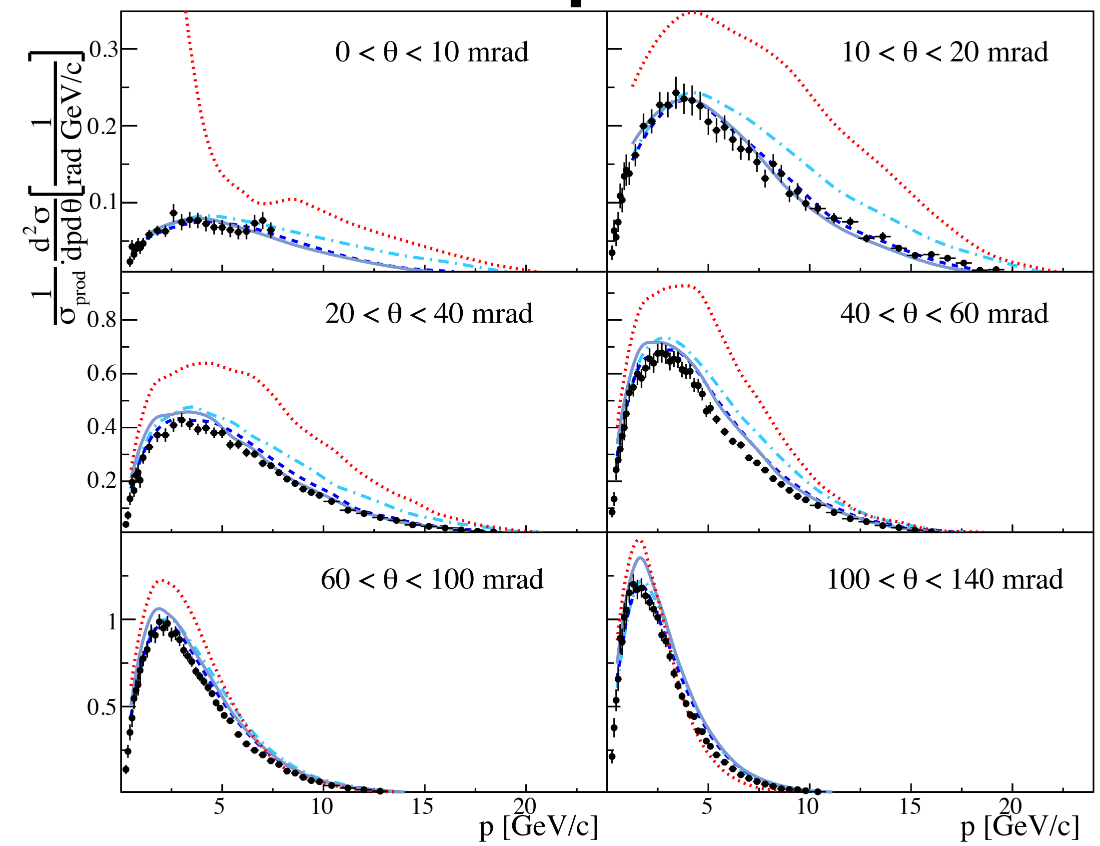
- Combine dE/dx and ToF information to identify $\pi^{\pm}$, $K^{\pm}$, p for p>1GeV/c
- Comparison w/ GEANT4 physics lists
- Typical uncertainty in the T2K region of interest ~ 4%

Current data dominated by 2009 data

π^+ multiplicities



π^- multiplicities



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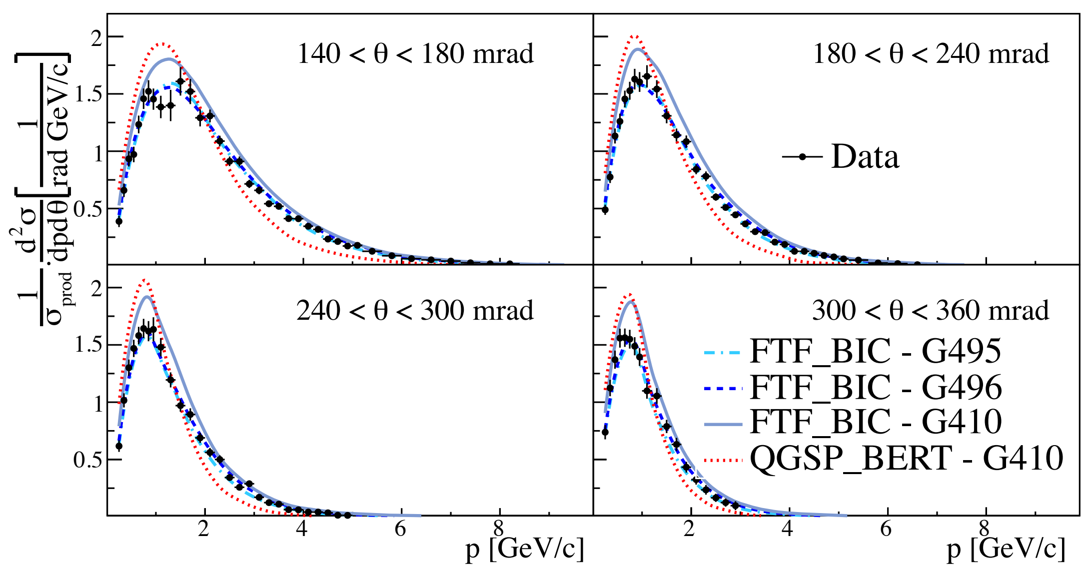
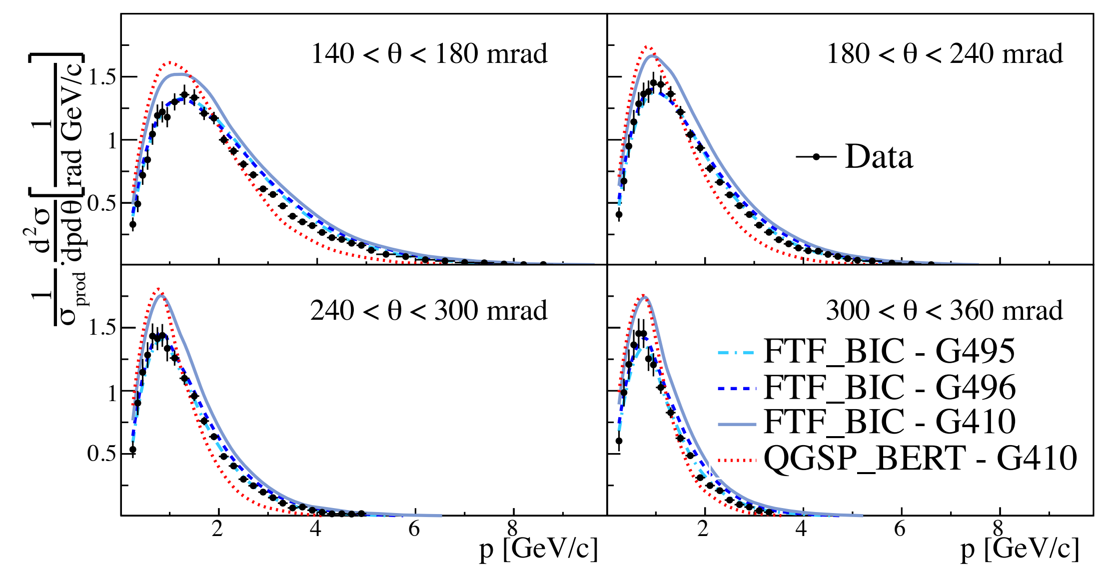
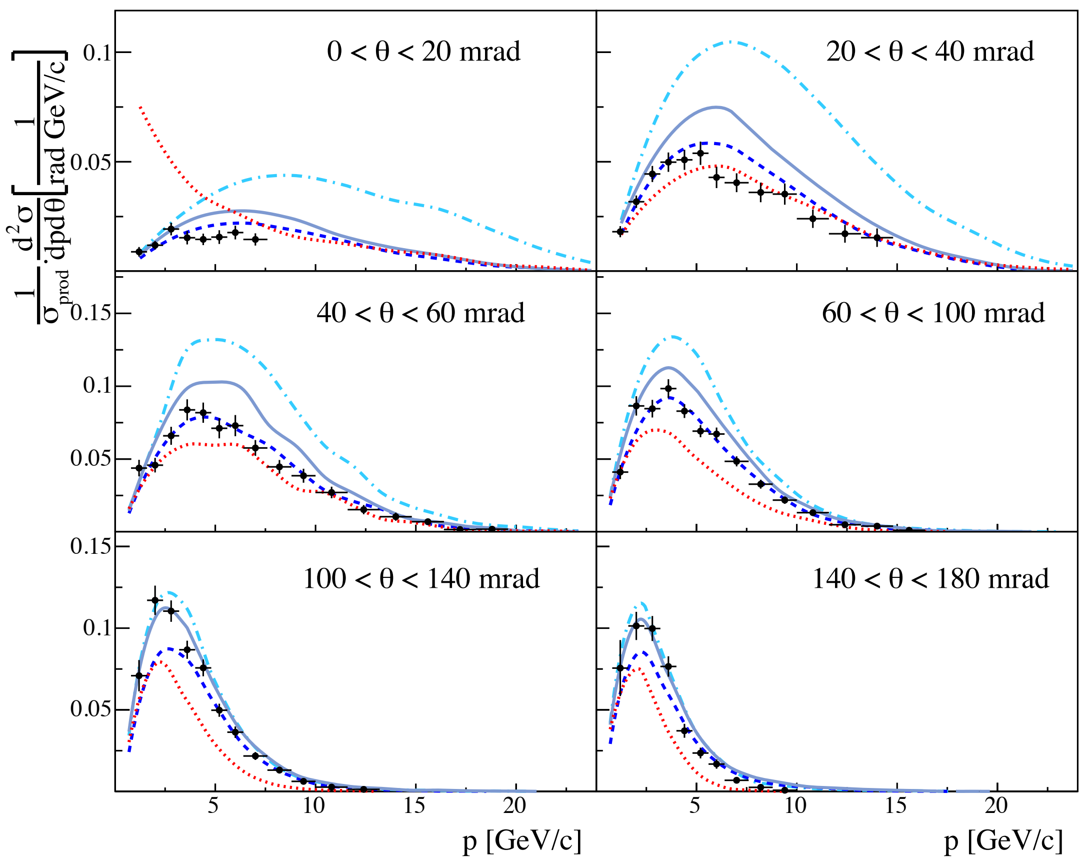




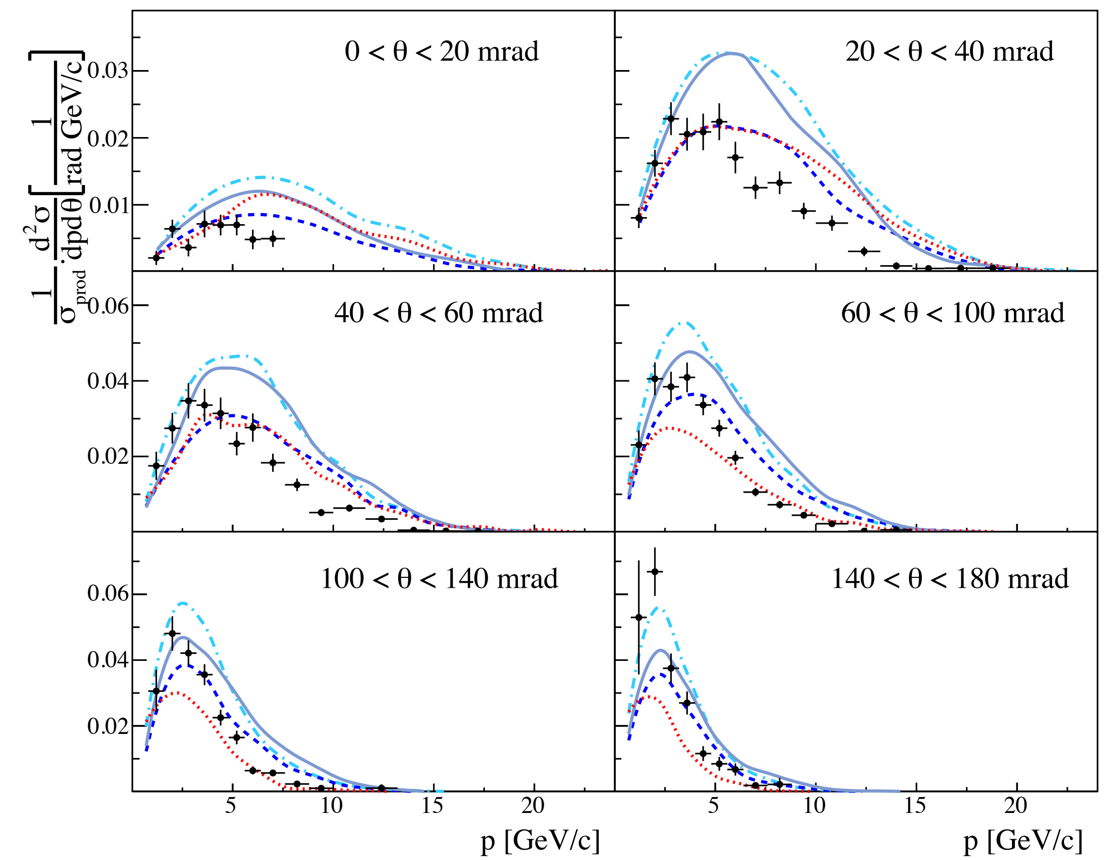
Charged hadron measurements with thin target data

- Combine dE/dx and ToF informations to identify $\pi^{\pm}$, $K^{\pm}$, p for p>1GeV/c
- Comparison w/ GEANT4 physics lists
- Typical uncertainty in the T2K region of interest ~ 15%

K^{+} multiplicities



K^{-} multiplicities



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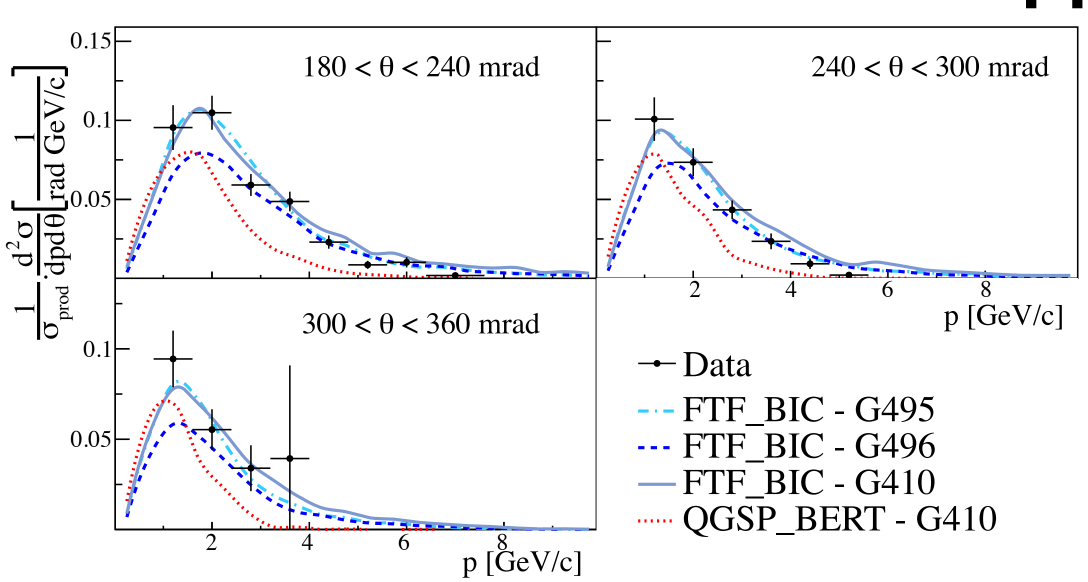

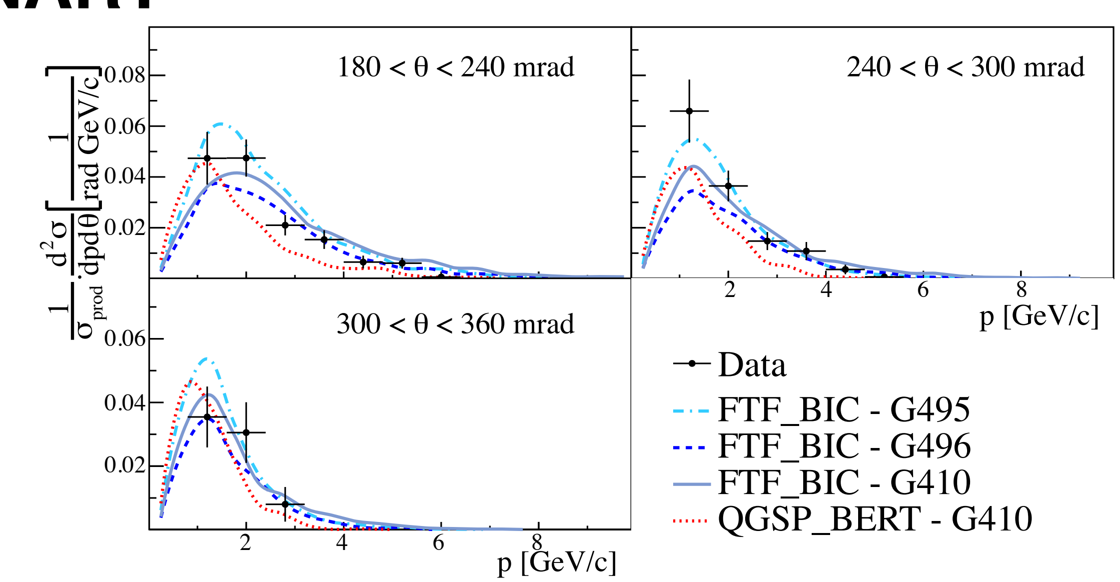

Charged hadron measurements with thin target data

- Combine dE/dx and ToF informations to identify π ±, K±, p for p>1GeV/c
- Comparison w/ GEANT4 physics lists
- Used to tune the secondary nucleon production

proton multiplicities

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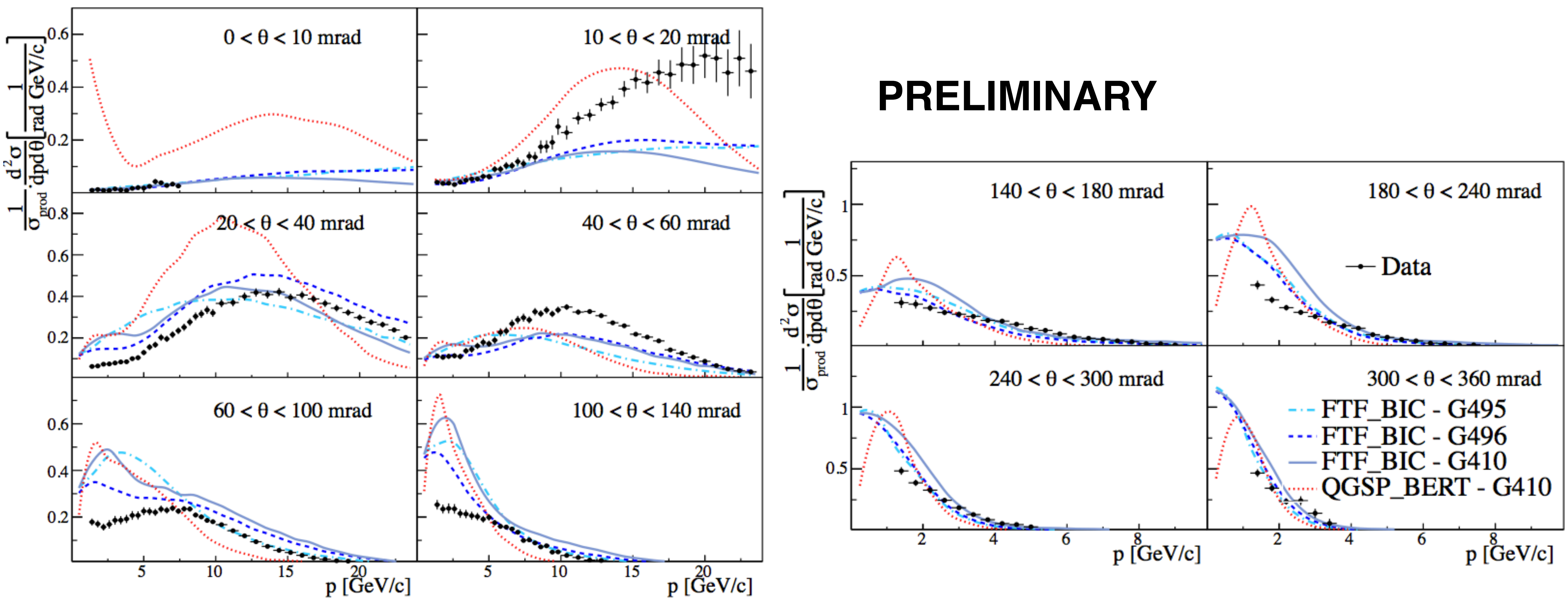
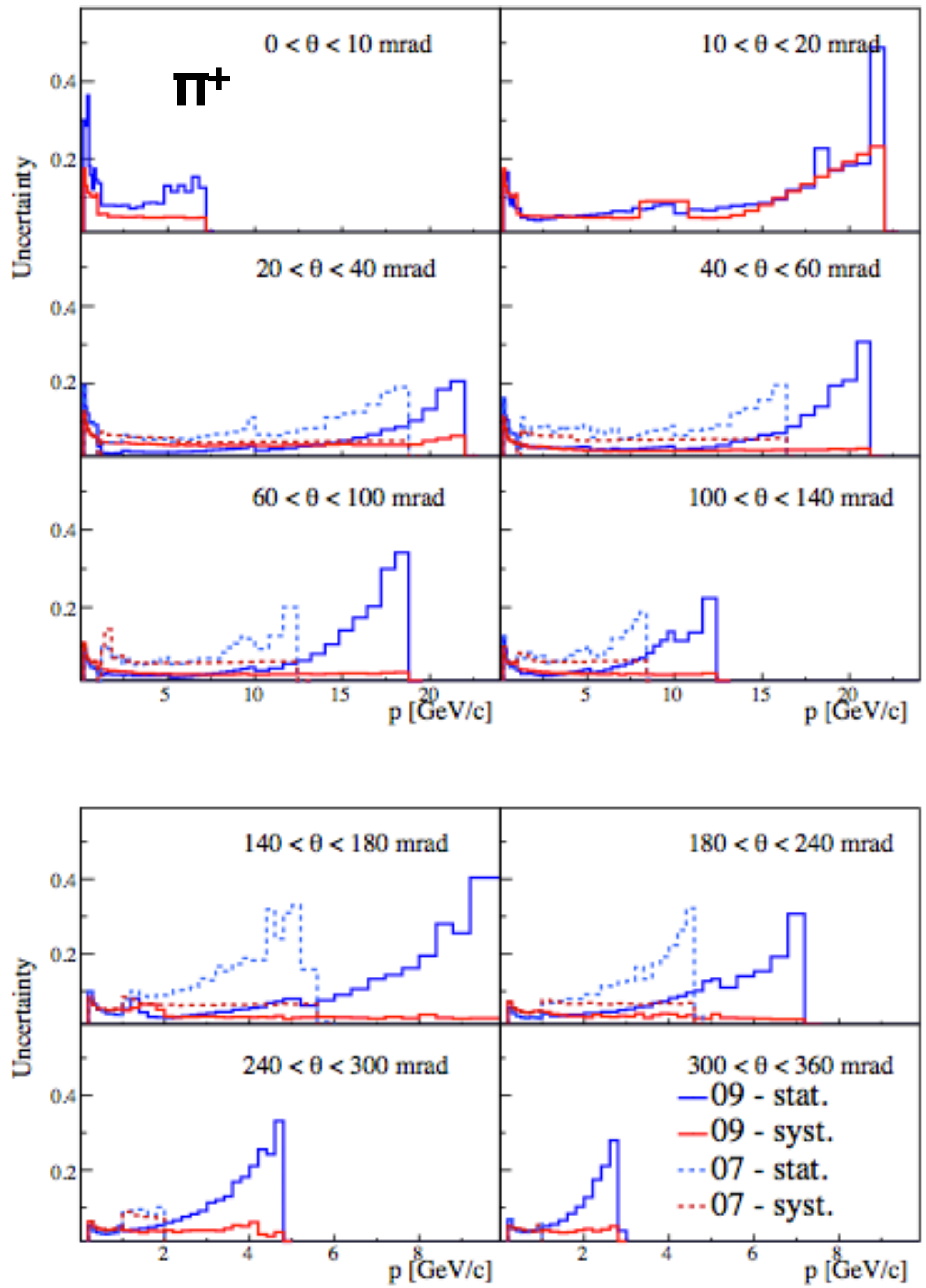


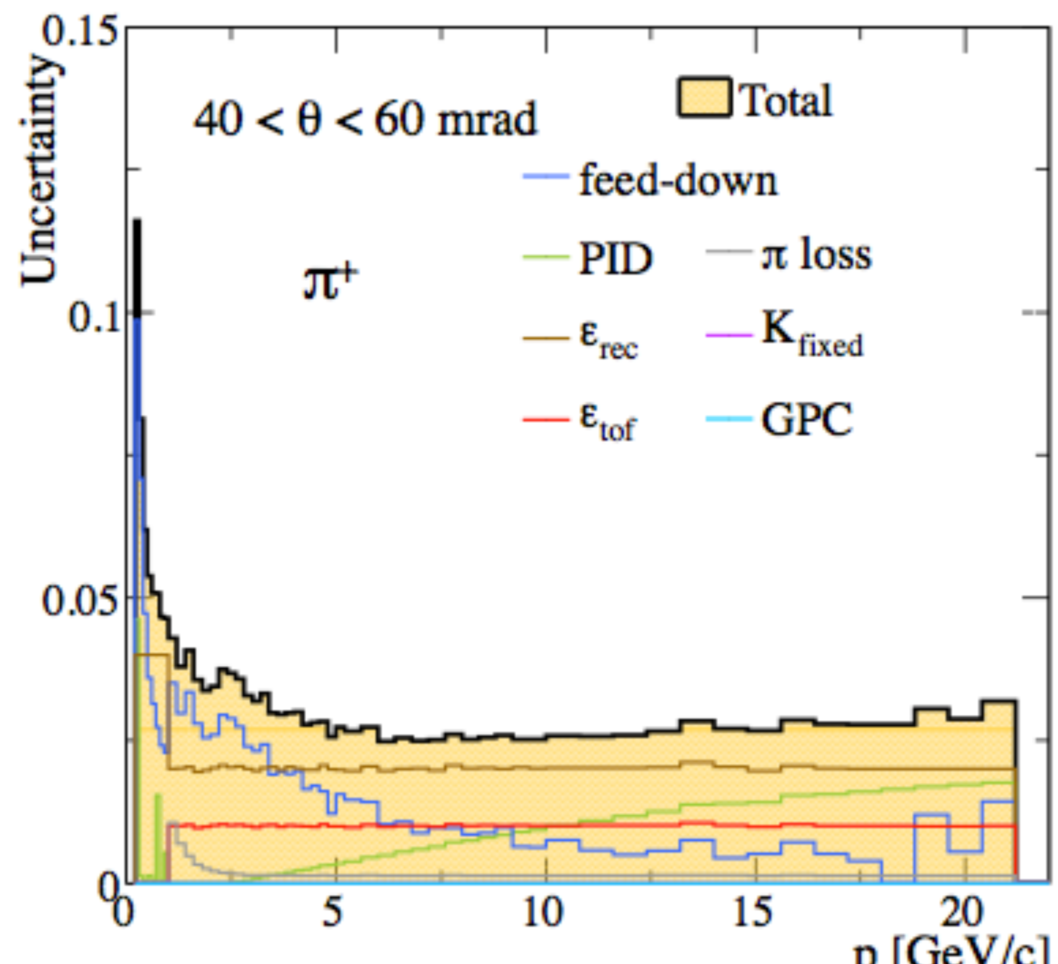
Uncertainty on hadron spectra

- Statistical uncertainties reduced by a factor 2-3
- Systematic uncertainties reduced by a factor 2 thanks to measurement of V^0 spectra



Largest contributions to the total systematic uncertainty is from:

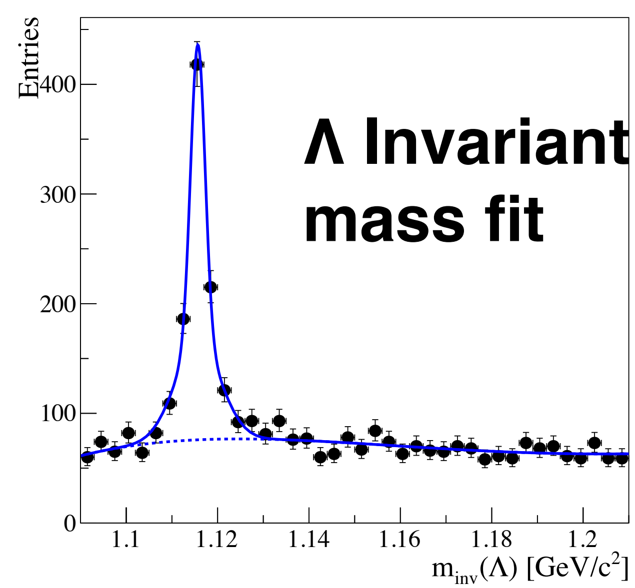
- PID
- feed-down: decay of neutral strange particles V^0, $K^0_S \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow p\, \pi^-$

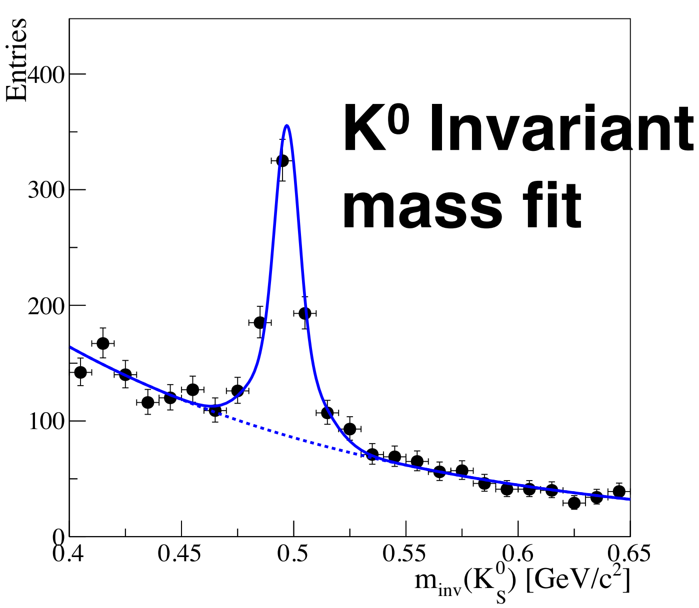


V^0 multiplicities

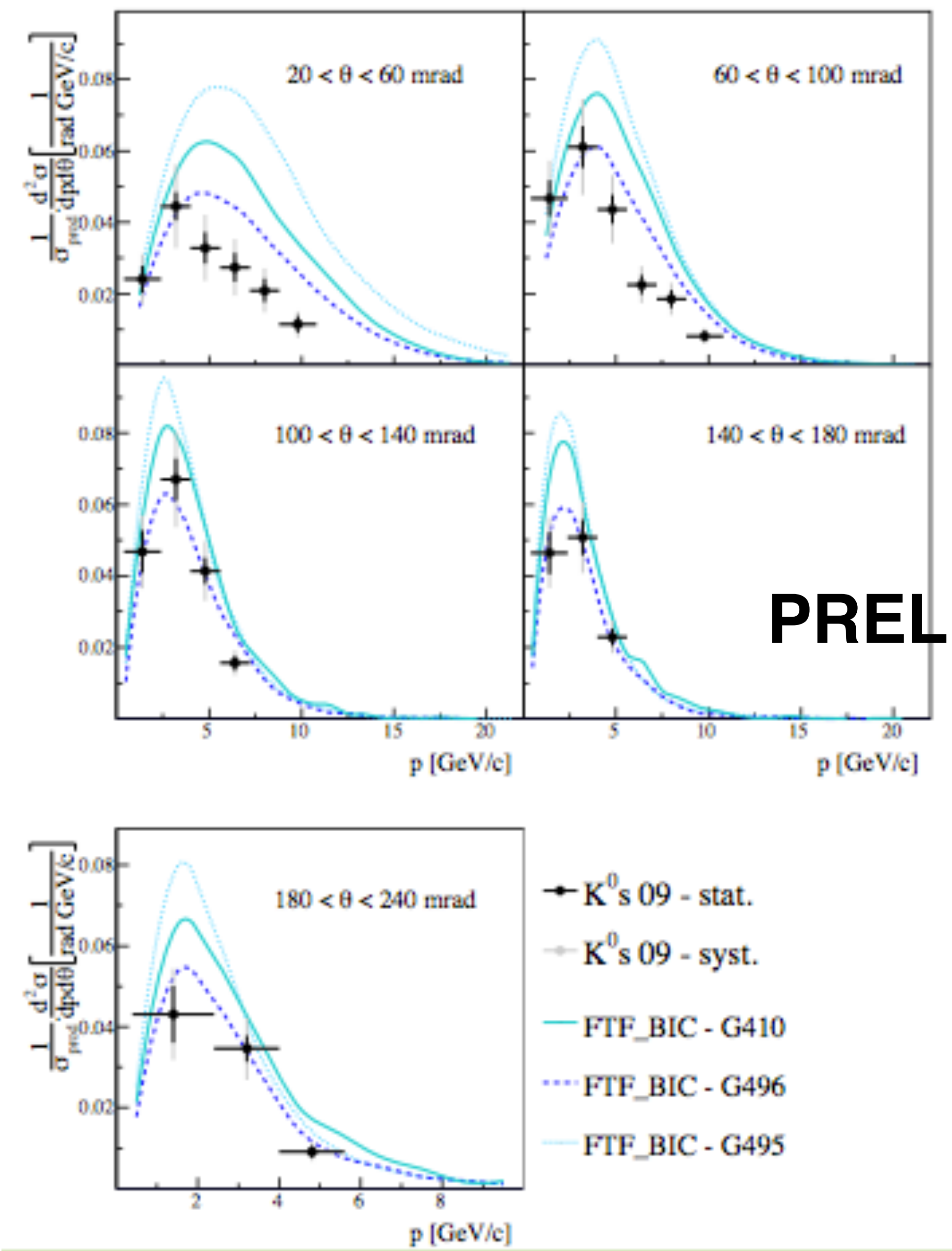
- $K^0_S \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow p\, \pi^-$ are the main source of systematic for $\pi^\pm$ and p multiplicities
- Used to constrain feed-down corrections of charged particle spectra
- $K^0_L \rightarrow \pi^- \nu_e e^+$ is the main source of high energy ν_e at T2K

$$K^0_S \rightarrow \pi^+ + \pi^- \quad \Gamma = (69.20 \pm 0.05)\ \%$$
$$\Lambda \rightarrow p + \pi^- \quad \Gamma = (63.9 \pm 0.5)\ \%$$

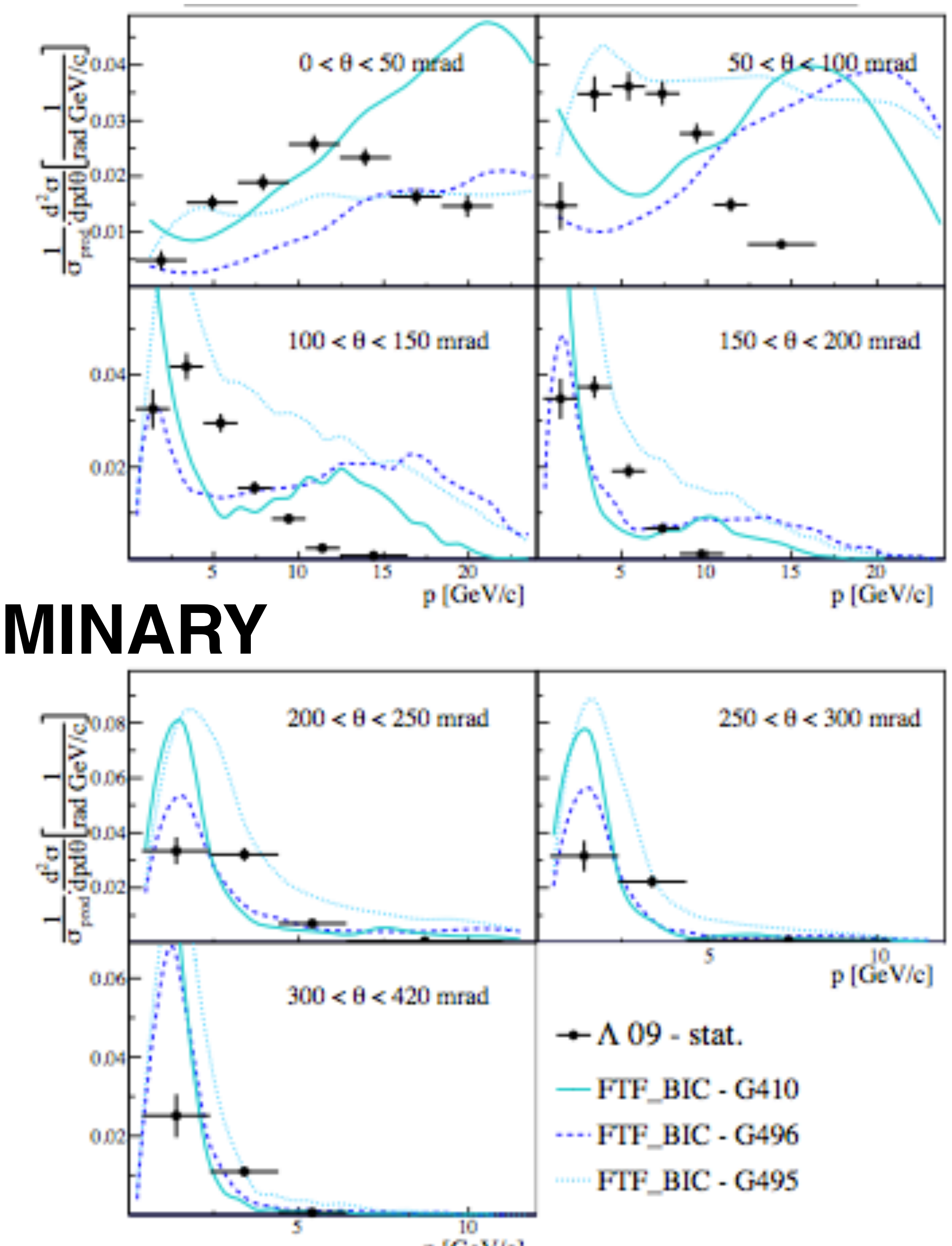




K^0_S multiplicities



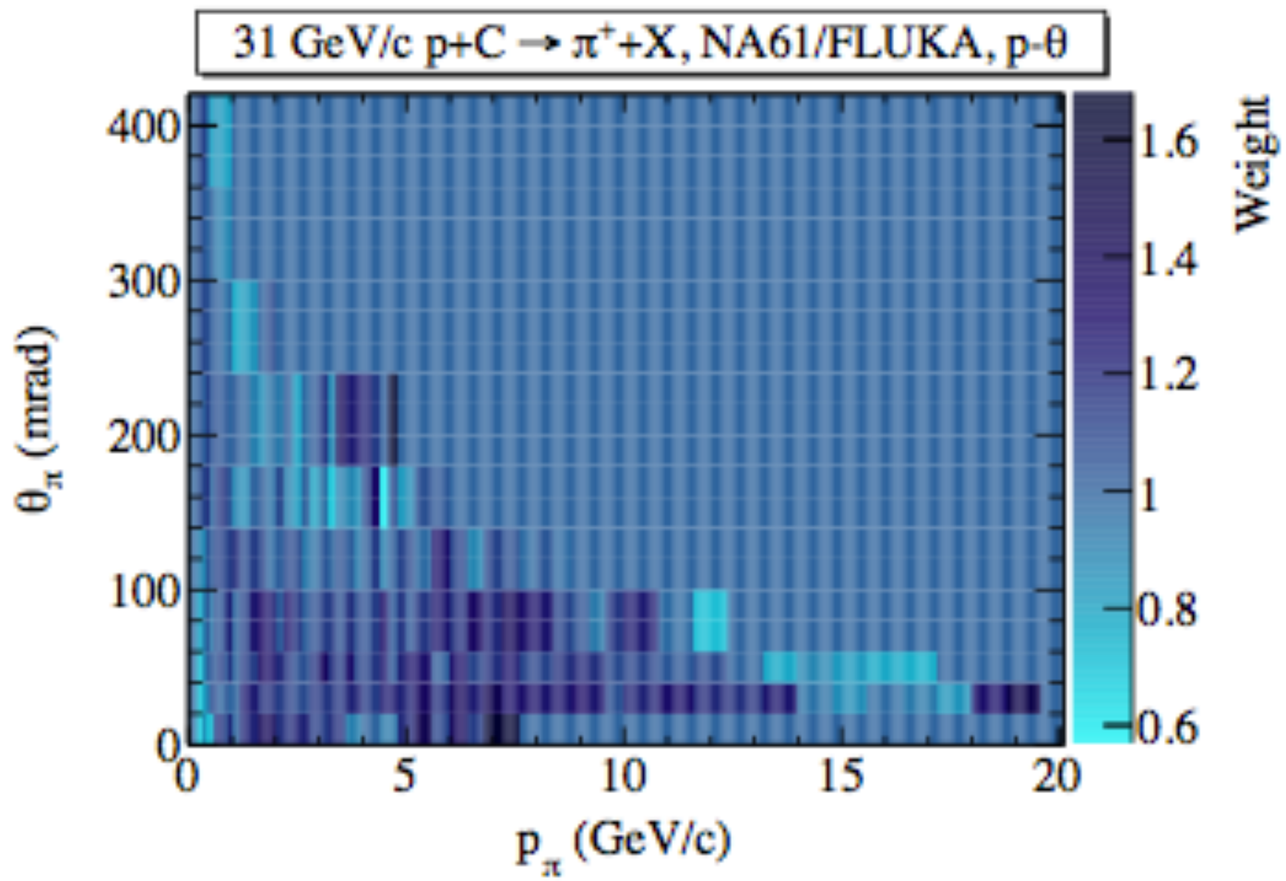
Λ multiplicities



PRELIMINARY

Tuning of the T2K neutrino beam

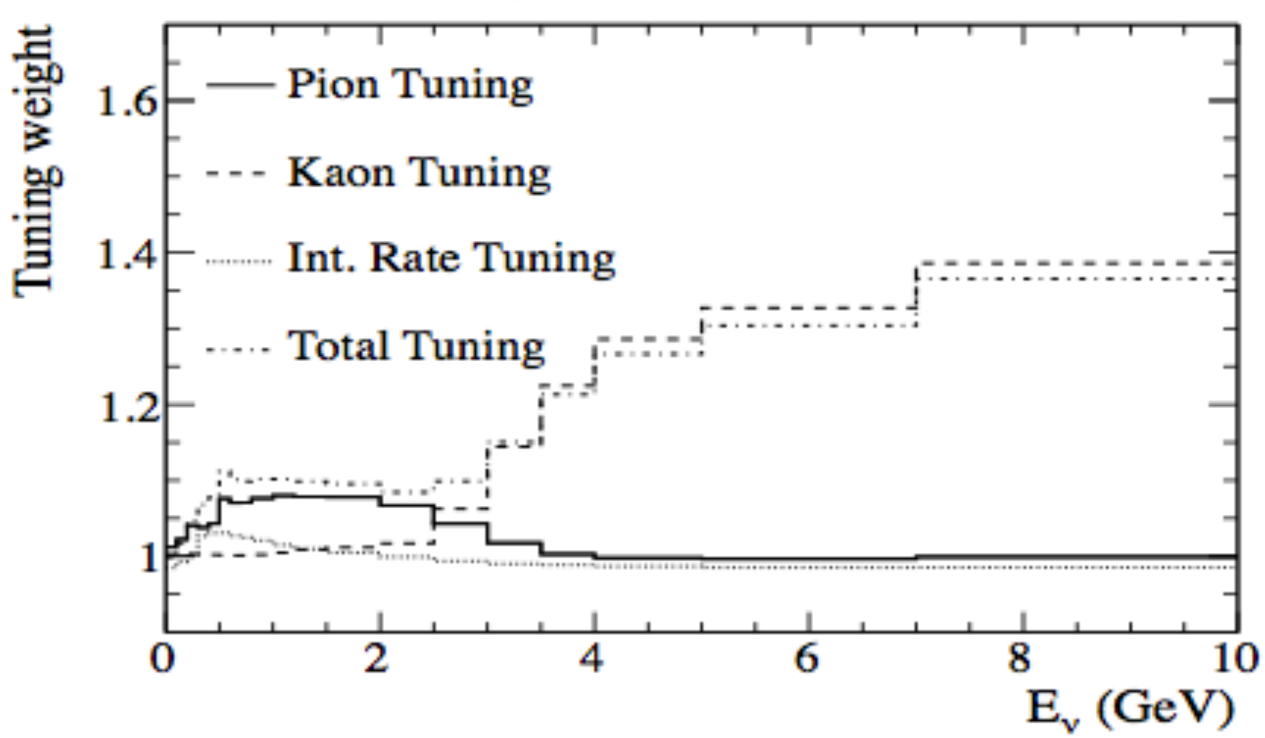
Proton interactions in the target simulated with Fluka
Geant3+CALOR used for the propagation in the beam-line



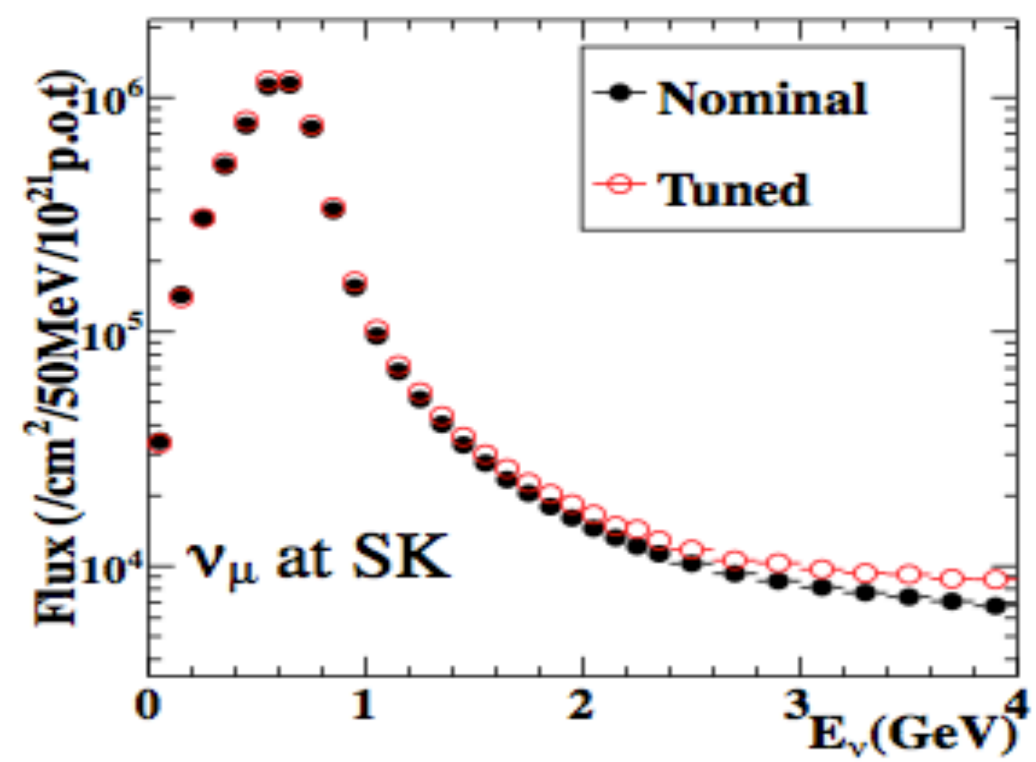
Phys. Rev. D 87 (2013), 012001 arXiv: 1211.0469

Weights computed with external data (priority to NA61/SHINE) are applied to the simulated flux

Procedure successfully tested using the multiplicities of the 2007 pilot run

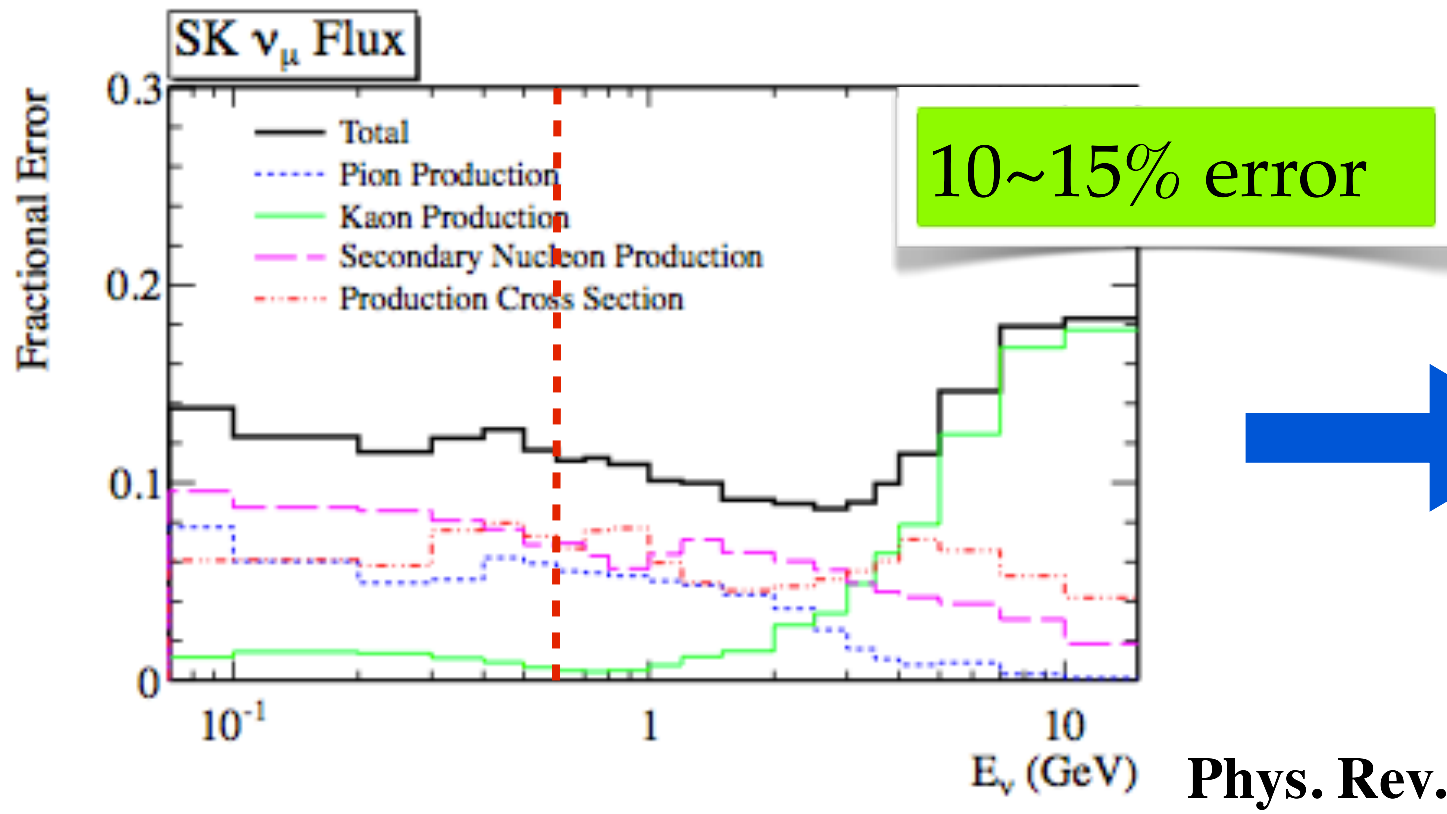


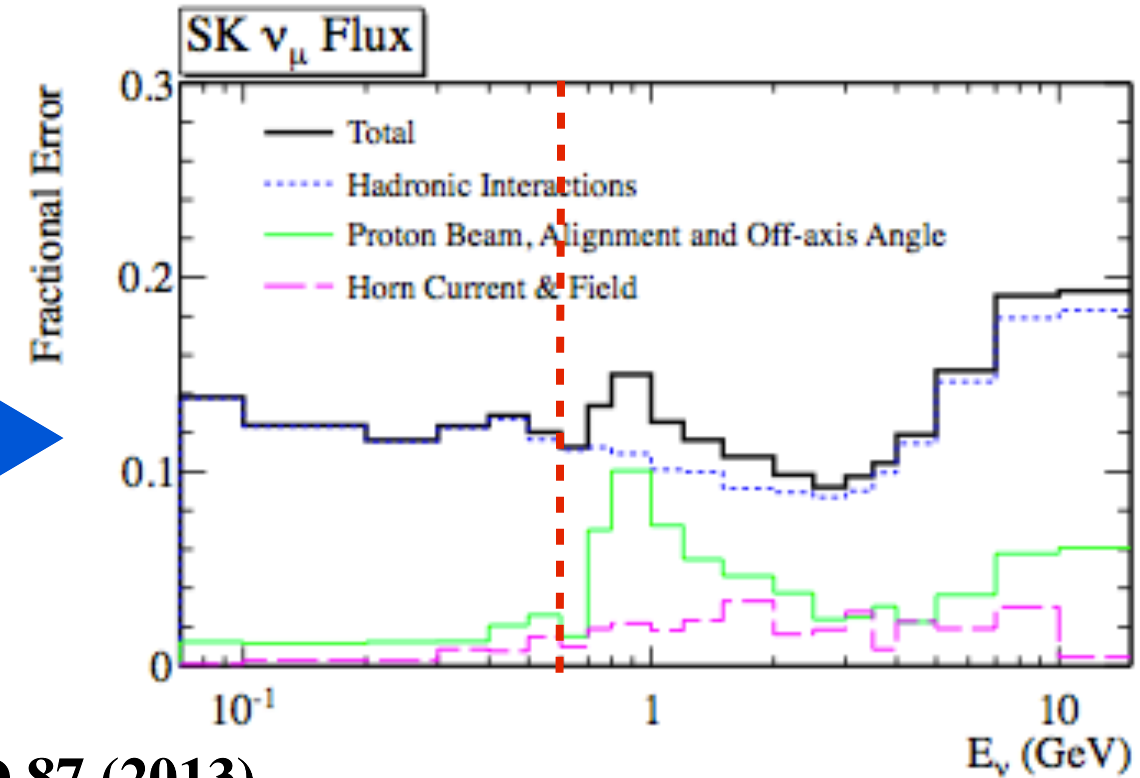
Tuned flux



Hadron production uncertainty

Total flux uncertainty





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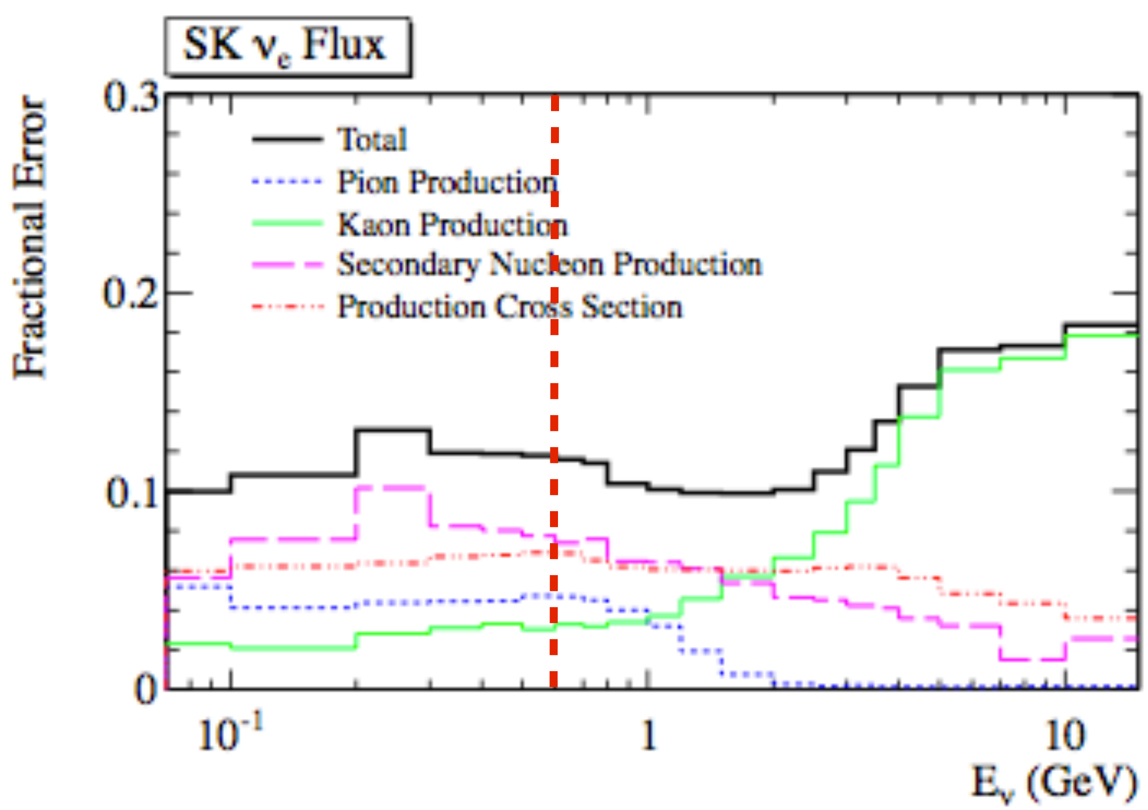
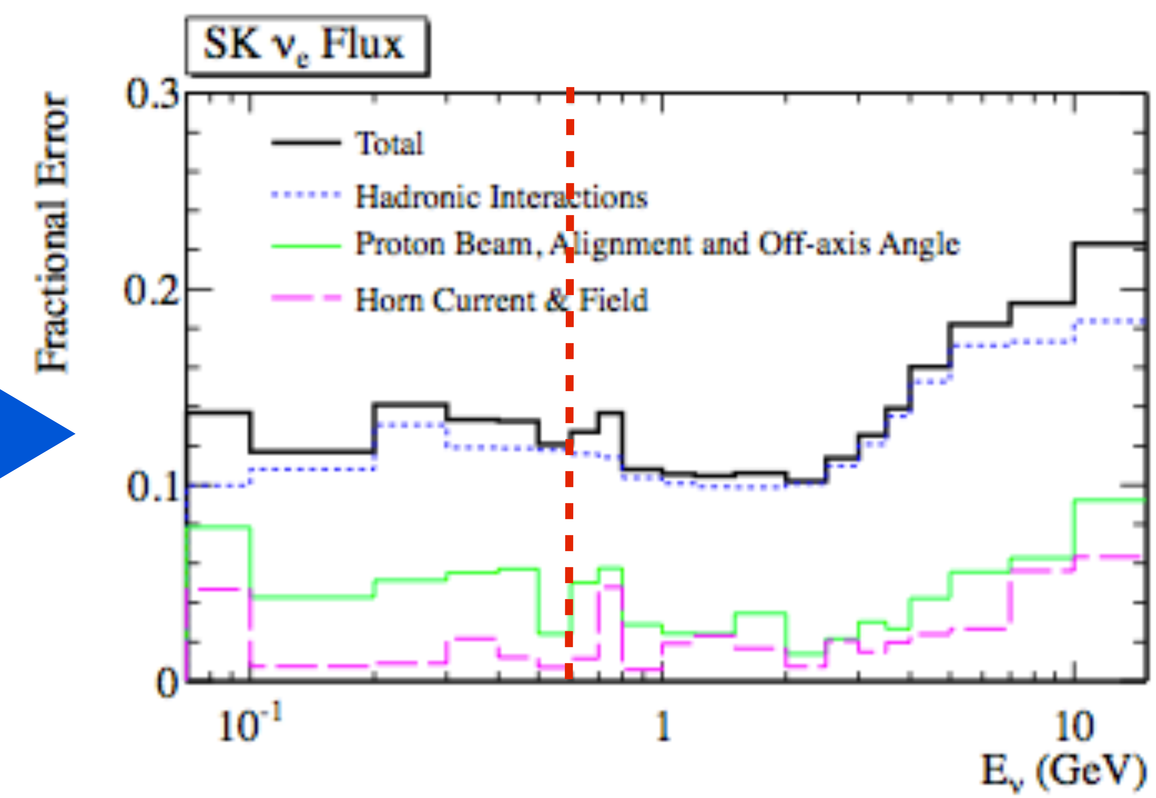
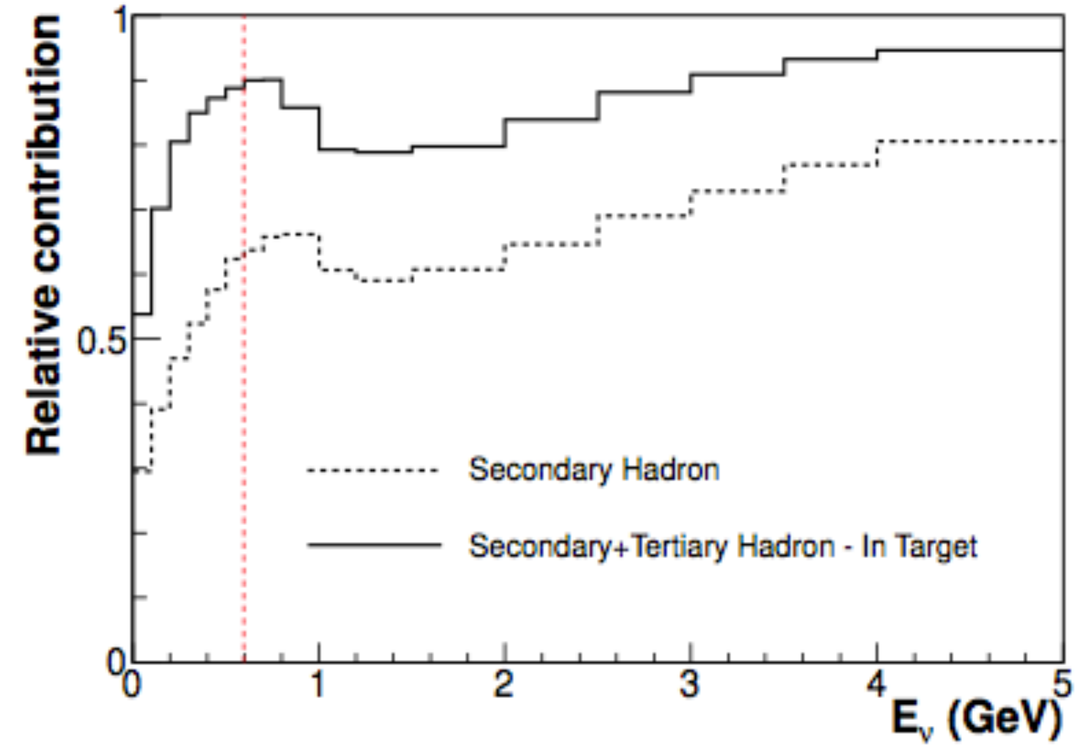




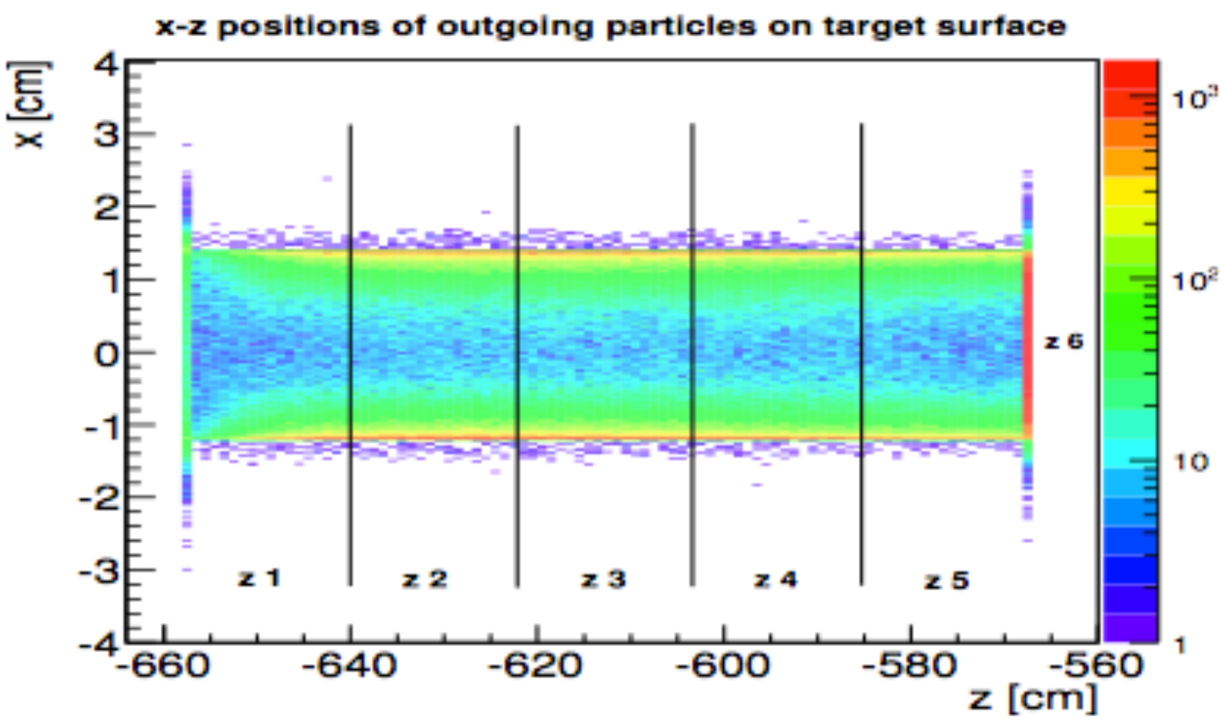
Plan to use multiplicities measured w/ 2009 data in future 2014 T2K analyses

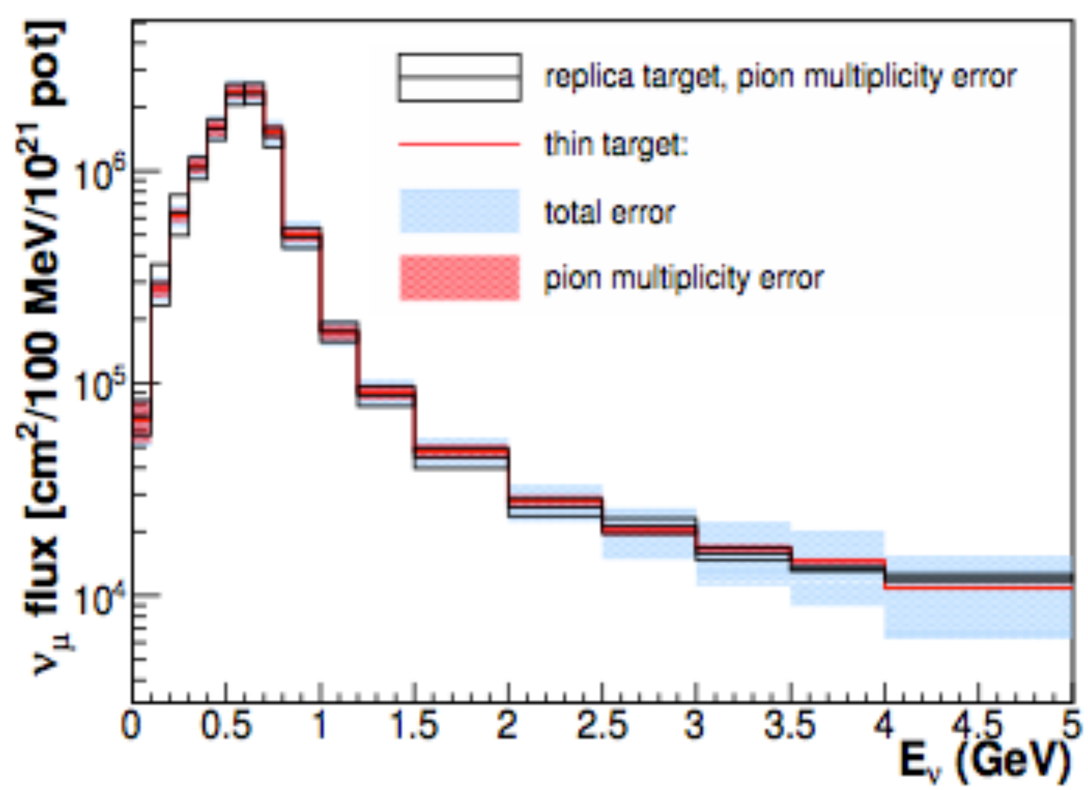
Long target analysis

- Tertiary component (~40%): hadrons produced in interactions of secondary particles in or outside the target (e.g. beam line)



- Measurement of the hadron multiplicities at the surface with the T2K replica long target (pions)
- Backward track extrapolation to the surface
- 5 longitudinal bins of 18 cm each + target downstream face

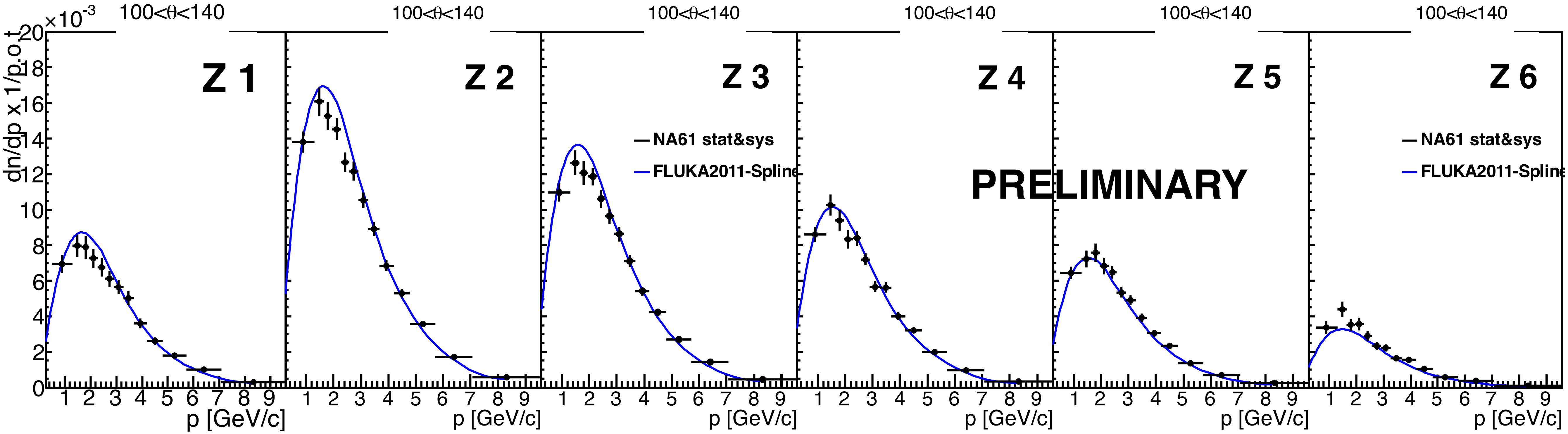




$$w(p,\theta,z) = N^{data}_{NA61}(p,\theta,z)/N^{MC}_{NA61}(p,\theta,z),$$

Nuclear Inst. and Methods in Physics Research, A (2013) pp. 99-114

- The method was successfully tested on the 2007 low statistics pilot run data
- New measurements are performed with high statistics 2009 run data
- Comparison w/ FLUKA prediction
- Example of π+ spectra for the six longitudinal bins and one theta interval as a function of momentum

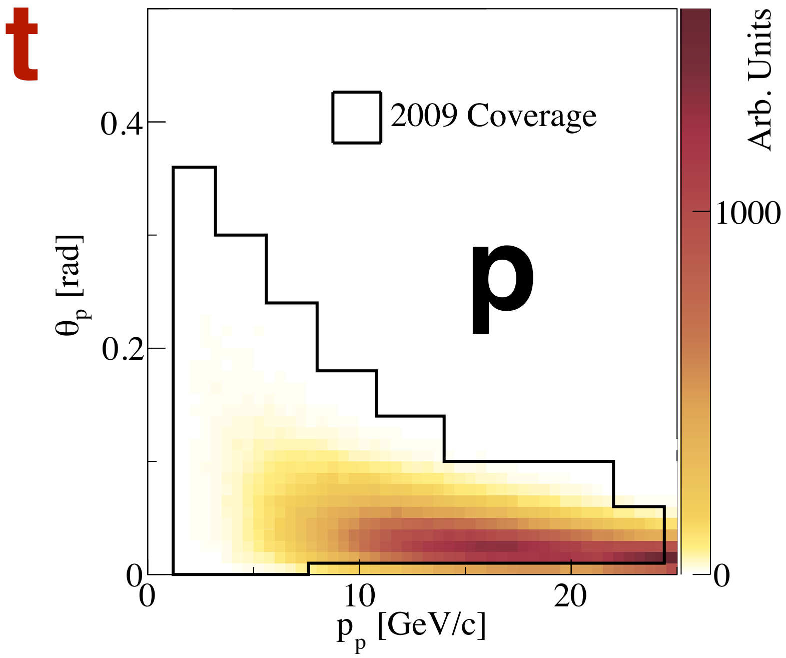


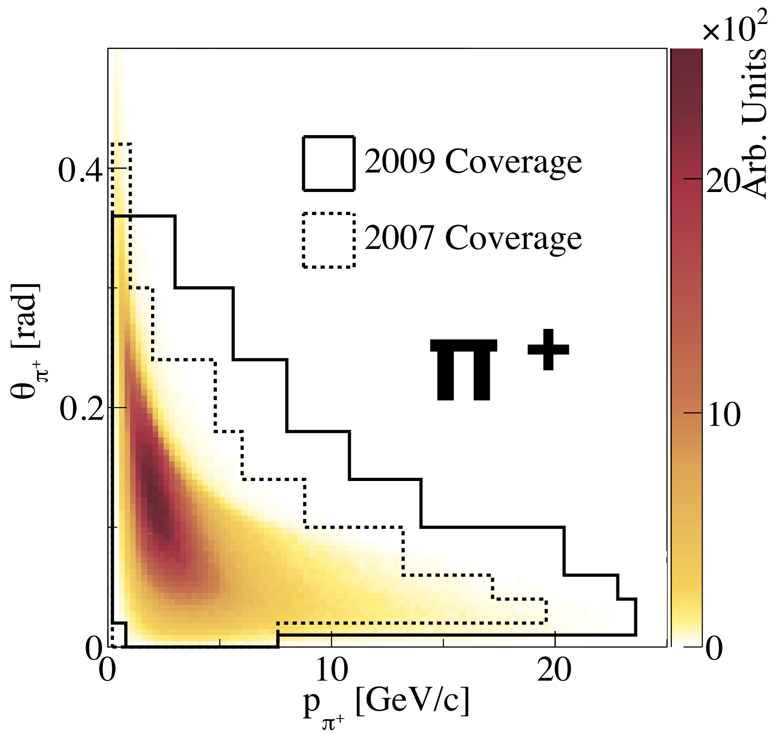
- Statistical uncertainty 5-8%
- Systematic uncertainty ~5% (center of the target) and ~14% (upstream and downstream faces)
- Work ongoing to tune the T2K flux simulation using the pion spectra
- Combination of thin and replica target measurements would allow to better understand re-interactions in long target and normalization of incident protons

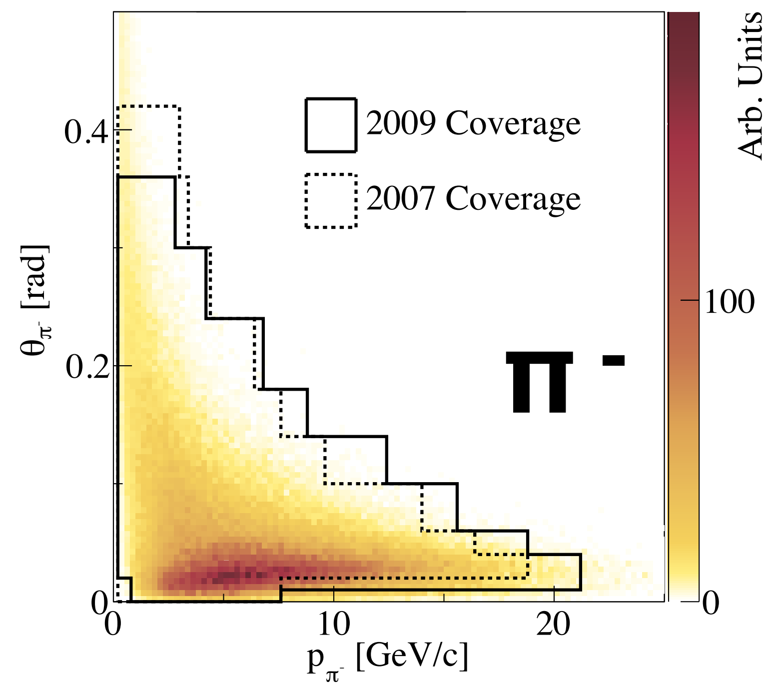
Constrain up to the 90% of the flux

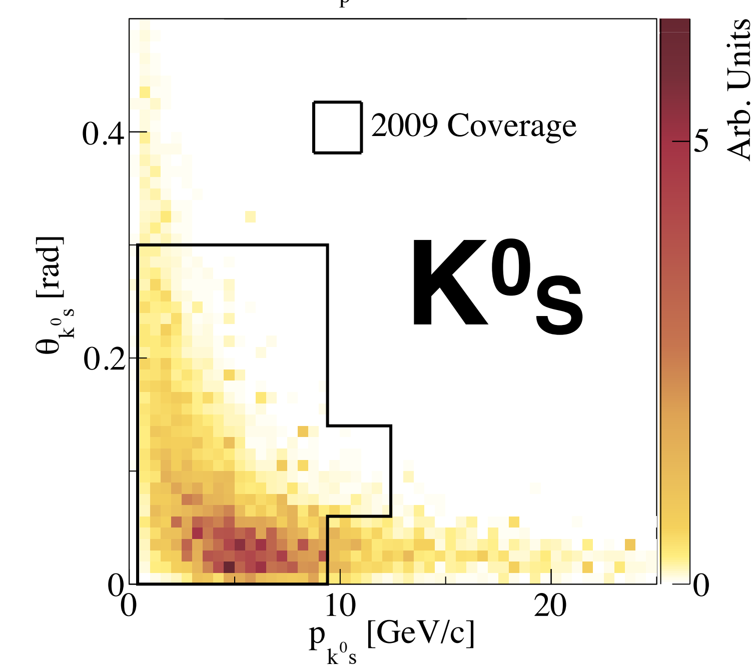
Next future improvement

- Better coverage of $\pi^{\pm}$ and K^{+} spectra
- Measurement of new particles spectra
- T2K neutrino flux estimation will be improved









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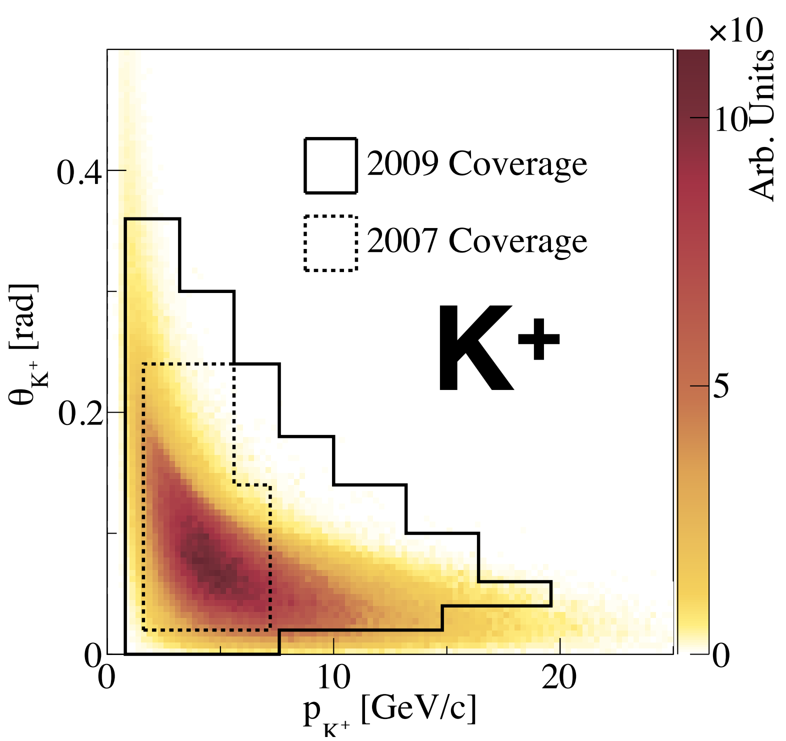

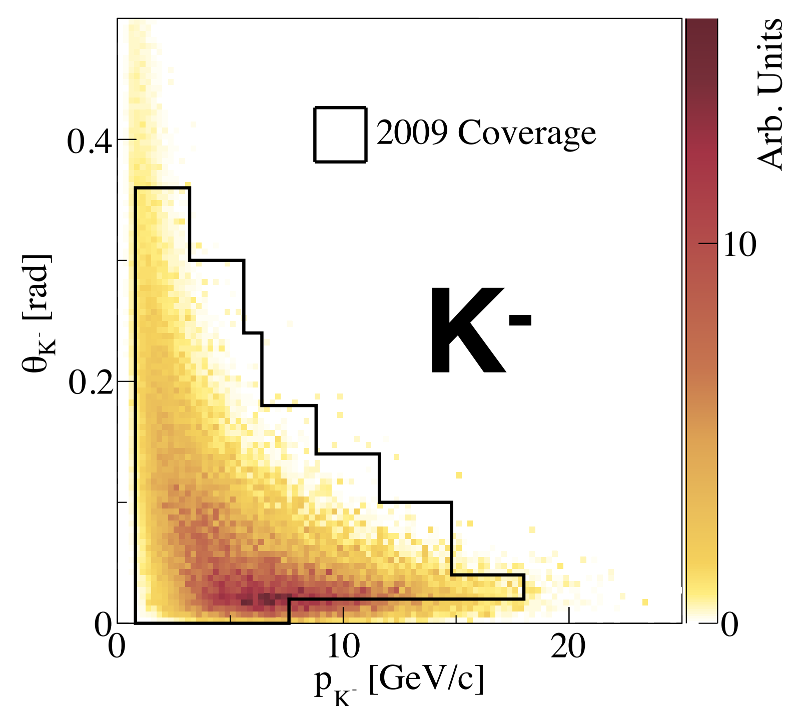

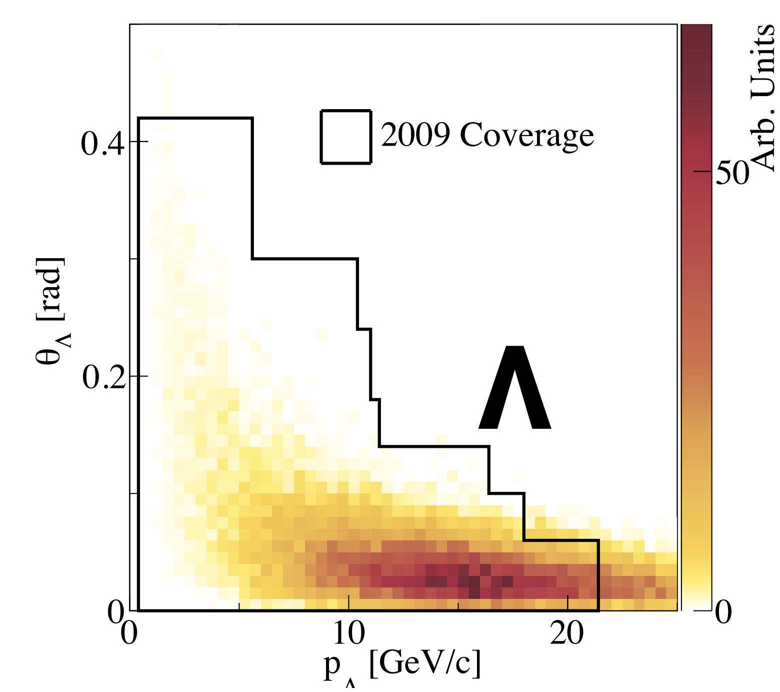

Conclusions

- $\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ spectra have been measured with the full thin target data set

  - Better coverage of the (p,θ) phase space wrt the 2007 pilot run data set and new particle spectra

  - Statistical (systematic) uncertainties reduced by a factor of 3 (2)

- Release of long target pion production measurements based on 2009 data set

- Thin target h^- and dE/dx analyses based on 2009 data set will be finalized soon

- Work to tune the T2K neutrino flux expectation is ongoing. Plan to use it in the next 2014 analyses

- Combining thin and long target data the neutrino flux will be constrained up to 90%

- 5% of precision possible when all the NA61 data are analyzed and included in the re-weighting chain of the expected flux (2010 long target run data)

- Hadron production measurements are very important to reduce the flux uncertainty for cross section and oscillation neutrino measurements

- Mandatory for future neutrino long baseline experiments which require a ~2% uncertainty on the neutrino flux prediction (LBNO-LAGUNA, LBNF, HyperKamiokande)

- Proposal for hadron production measurements at NA61/SHINE for Fermilab neutrino experiments


136 participants from 25 institutions
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Institute for Nuclear Research, Moscow, Russia
Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
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Joint Institute for Nuclear Research, Dubna, Russia
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