

# Hadron production measurements from NA61/SHINE

Alexander Korzenev, Geneva University  
*on behalf of the NA61/SHINE collaboration*



EPS-HEP 2013  
Stockholm, July 19

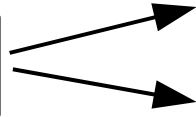


## Outline

- Production cross section
- Multiplicities of  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and  $K_s^0$
- Results on the T2K replica target
- Measurements for the NuMI target

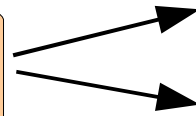
## hadroproduction experiments

HARP, CERN-PS214  
1.5-15 GeV beam



(Mini-, Sci-, Micro-)BooNE at Fermilab  
K2K (KEK to Super-Kamiokande)

NA20 & SPY/NA56, SPS  
400-450 GeV beam



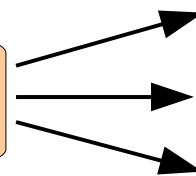
WANF (NOMAD, CHORUS)  
CNGS (OPERA, ICARUS)

NA49, CERN-SPS  
160 GeV beam



MINOS (Fermilab to Soudan)

NA61/SHINE, CERN-SPS  
13-400 GeV beam



T2K (JPARC to Super-Kamiokande)  
NuMI (MINERvA, NovA)  
LBNE in US, LBNO in Europe



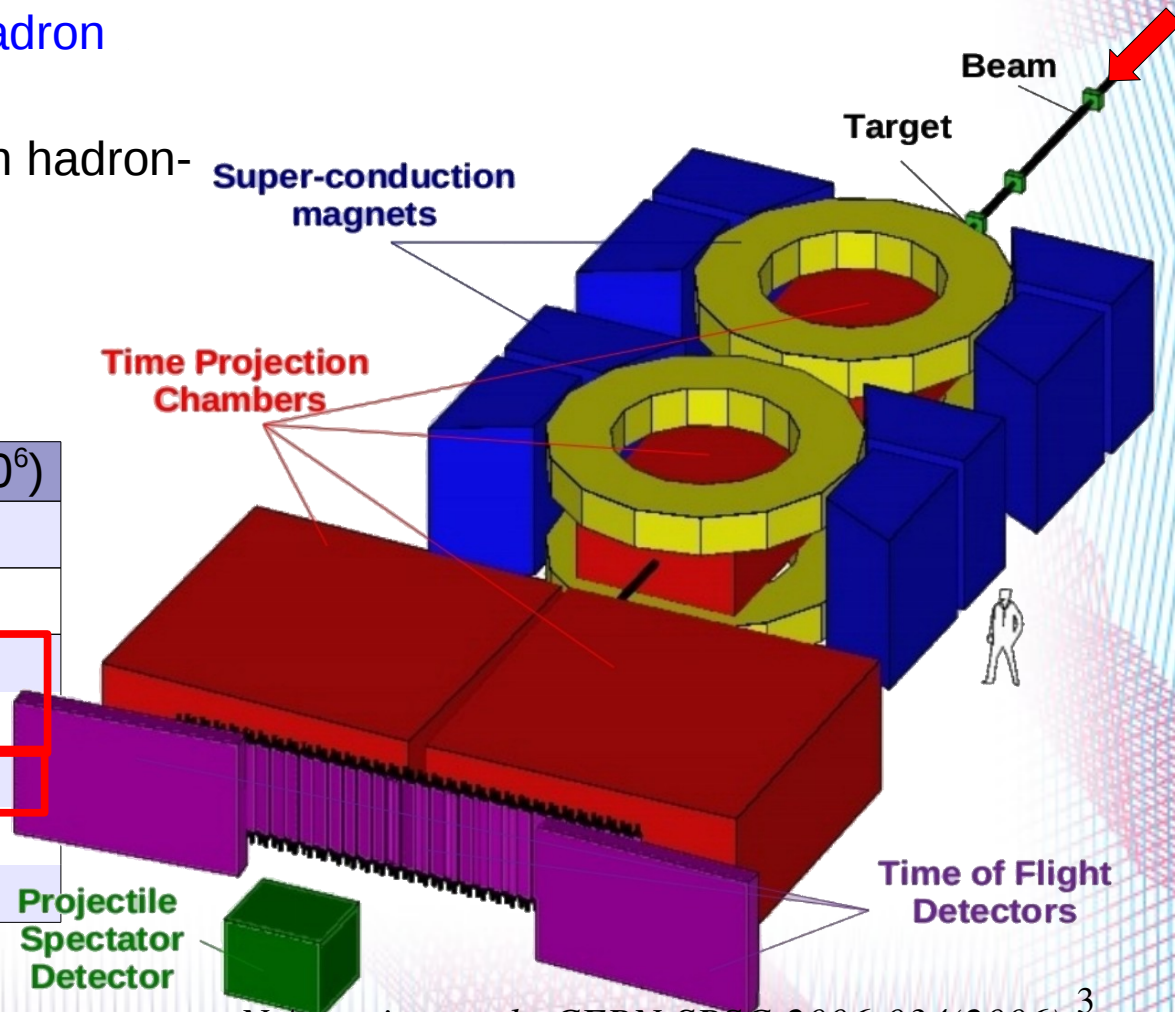
# NA61, SPS Heavy Ion and Neutrino Experiment

- Search for the critical point of strongly interacting matter; onset of deconfinement in nucleus-nucleus collision
- Neutrino physics: measurement of hadron production for the T2K experiment
- Measurement of hadron production in hadron-carbon reactions for the cosmic-ray experiments

- Approved in 2007
- Successor of NA49, H2 beamline of CERN-SPS

Data with the *graphite target*

Beam (GeV/c)	target	year	N(x10 <sup>6</sup> )
$\pi^-$	thin	2009	5.5
$\pi^-$	thin	2009	4.6
$\rho$	thin	2007	0.7
		2009	5.4
$\rho$	T2K replica	2007	0.2
		2009	4
		2010	10

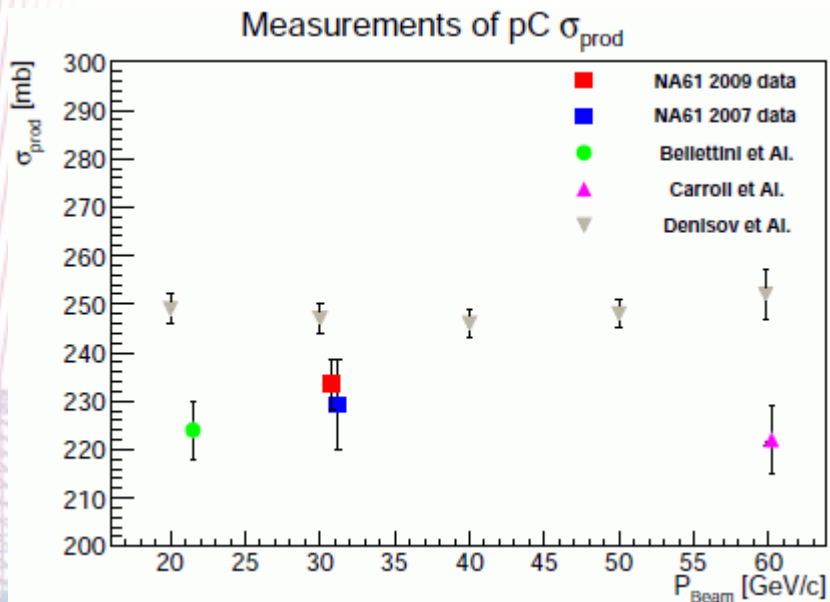


# Production cross section and normalization

- Results obtained in 2007 and 2009 can be considered as two independent experiments
  - Scaler information from special (non-physics) run for 2007
  - Prescaled beam trigger in physics run for 2009

$$\sigma_{prod} = \sigma_{total} - \sigma_{el.} - \sigma_{quasi-el.}$$

- Contributions from  $\sigma_{el.}$  and  $\sigma_{quasi-el.}$  have been estimated with GEANT4



$$\sigma_{prod}^{2007} = 229.3 \pm 1.9 (stat.) \pm 9.0 (syst.) \text{ mb}$$

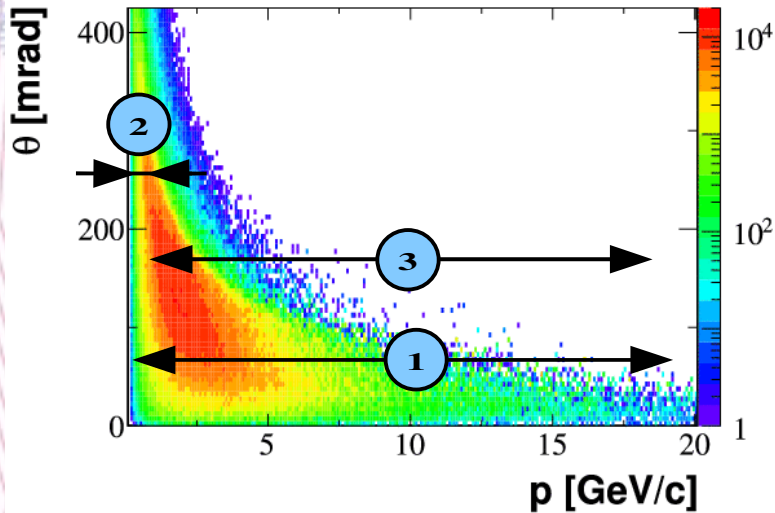
$$\sigma_{prod}^{2009} = 233.5 \pm 2.8 (stat.) \pm 4.2 (model) \pm 1.0 (trigger) \text{ mb}$$

- Total uncertainty decreased 4%  $\rightarrow$  2%
- Used to normalize hadron cross sections to be able to compare to MC models

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

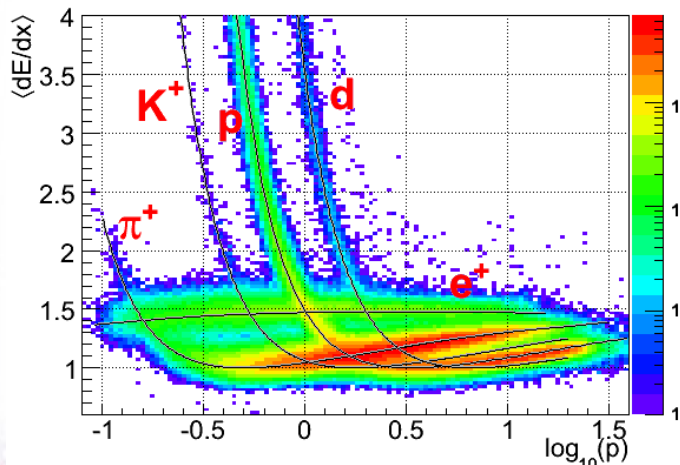


# Analysis techniques (data 2007)

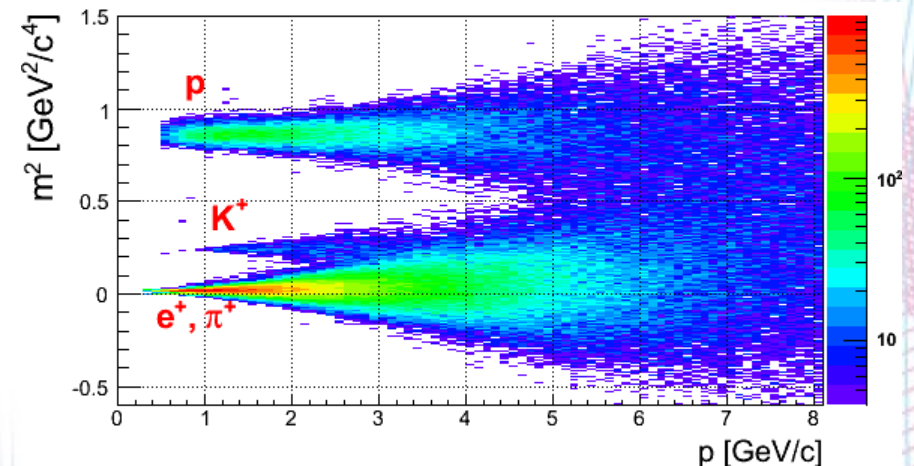


- 1)  **$h^-$  analysis**: analysis of  $\pi^-$  via measurements of negatively charged particles
- 2)  **$dE/dx$  analysis at  $p \lesssim 1 \text{ GeV}/c$** :  $\pi^\pm$  and protons were identified via energy loss in TPC
- 3) **ToF- $dE/dx$  analysis at  $p \gtrsim 1 \text{ GeV}/c$** : information from  $dE/dx$  and ToF is combined to identify  $\pi^\pm$ ,  $K^\pm$  and protons

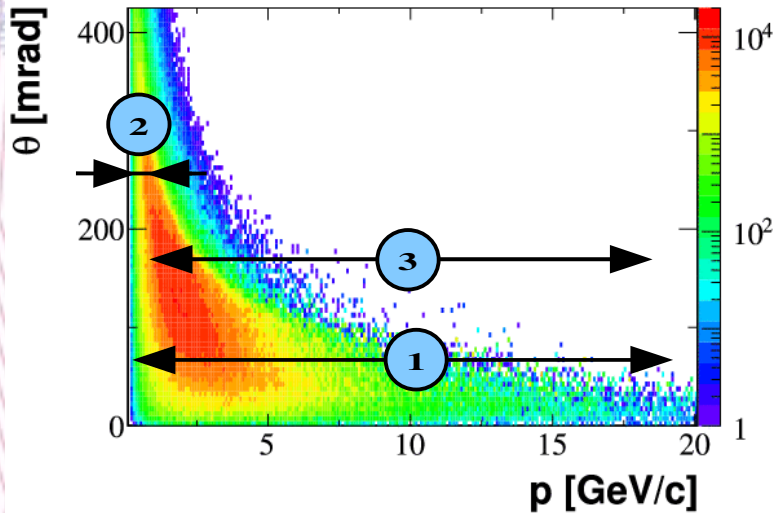
## Energy loss in TPC ( $dE/dx$ )



## Time-of-Flight (ToF)



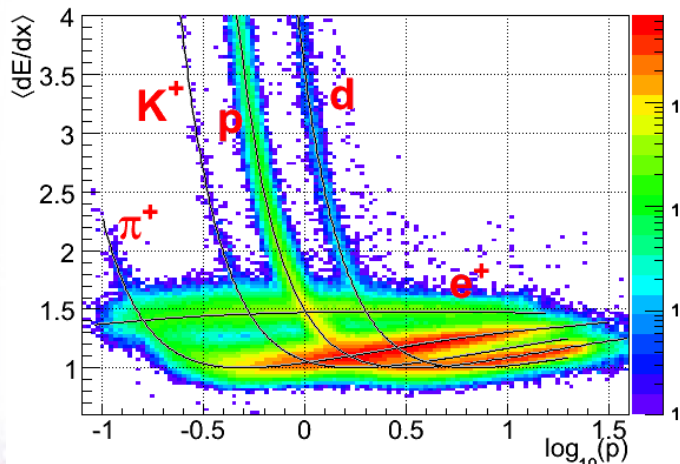
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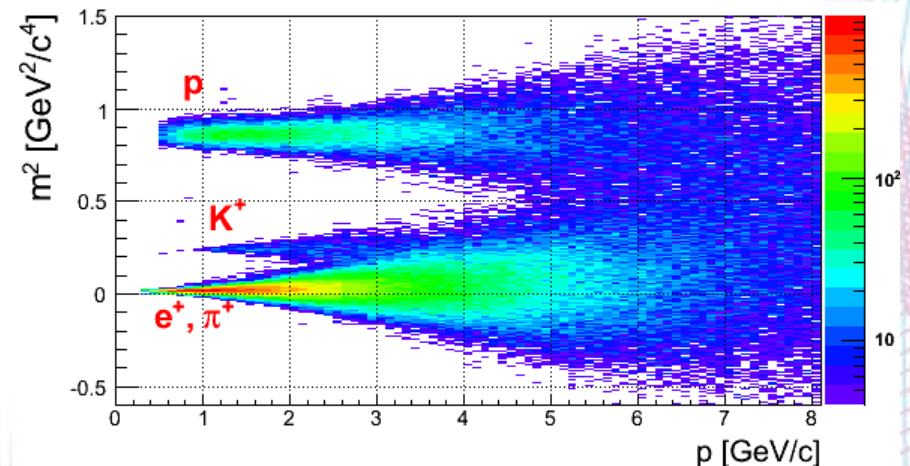
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Data 2009

Energy loss in TPC ( $dE/dx$ )

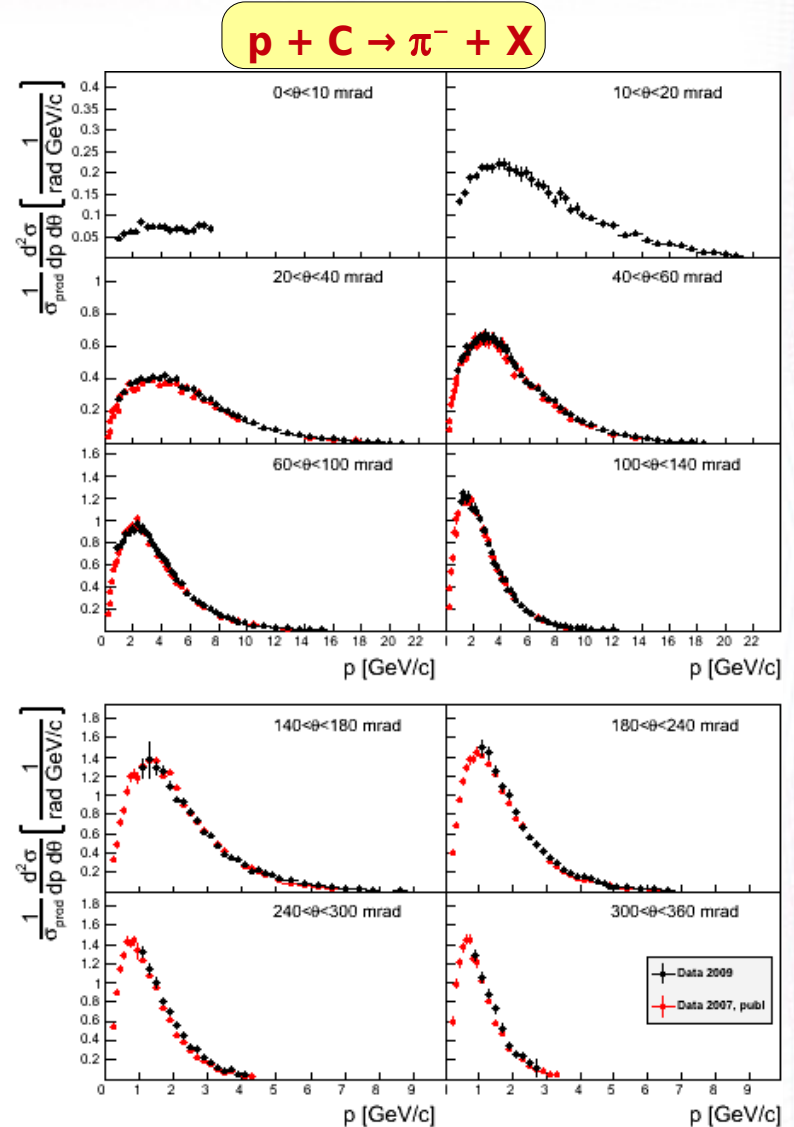
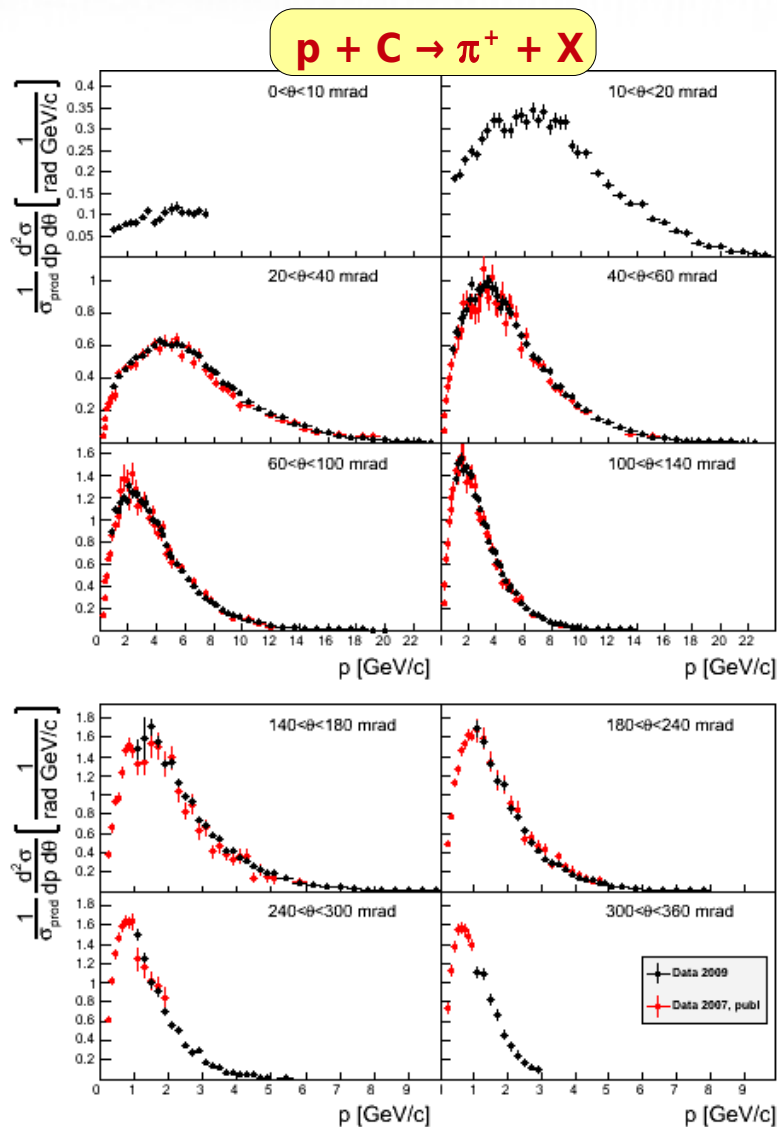


Time-of-Flight (ToF)



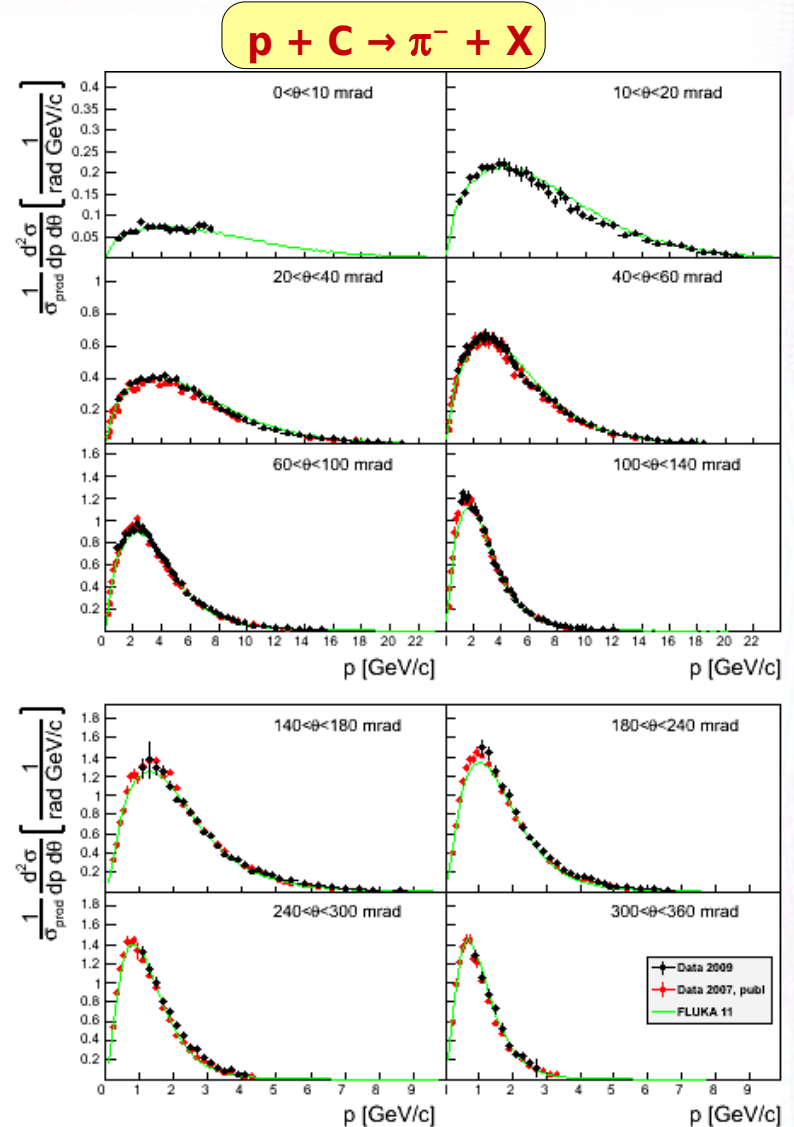
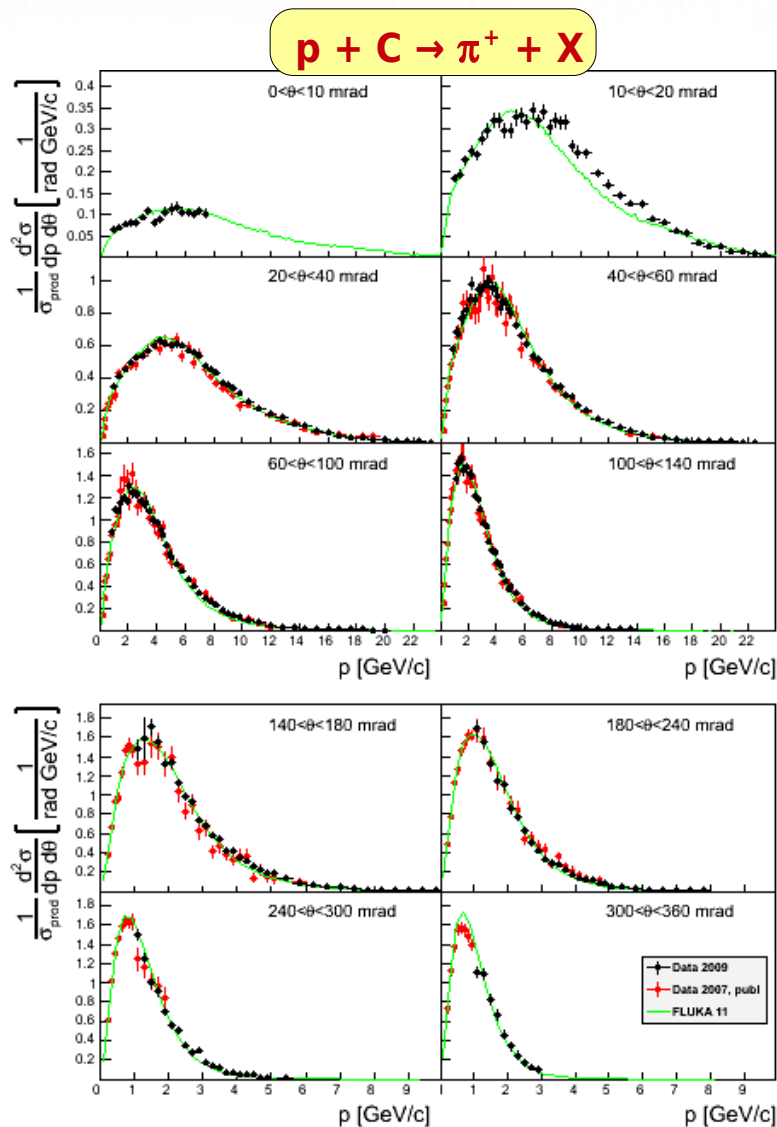


# New results on $\pi^+$ and $\pi^-$ multiplicity in pC @ 31 GeV/c



- Statistical uncertainty of data 2009 vs. 2007 **improved by a factor 2-3**
- Systematic error from analysis of data 2007  $\Rightarrow$  an upper limit. **To be improved**

# New results on $\pi^+$ and $\pi^-$ multiplicity in pC @ 31 GeV/c

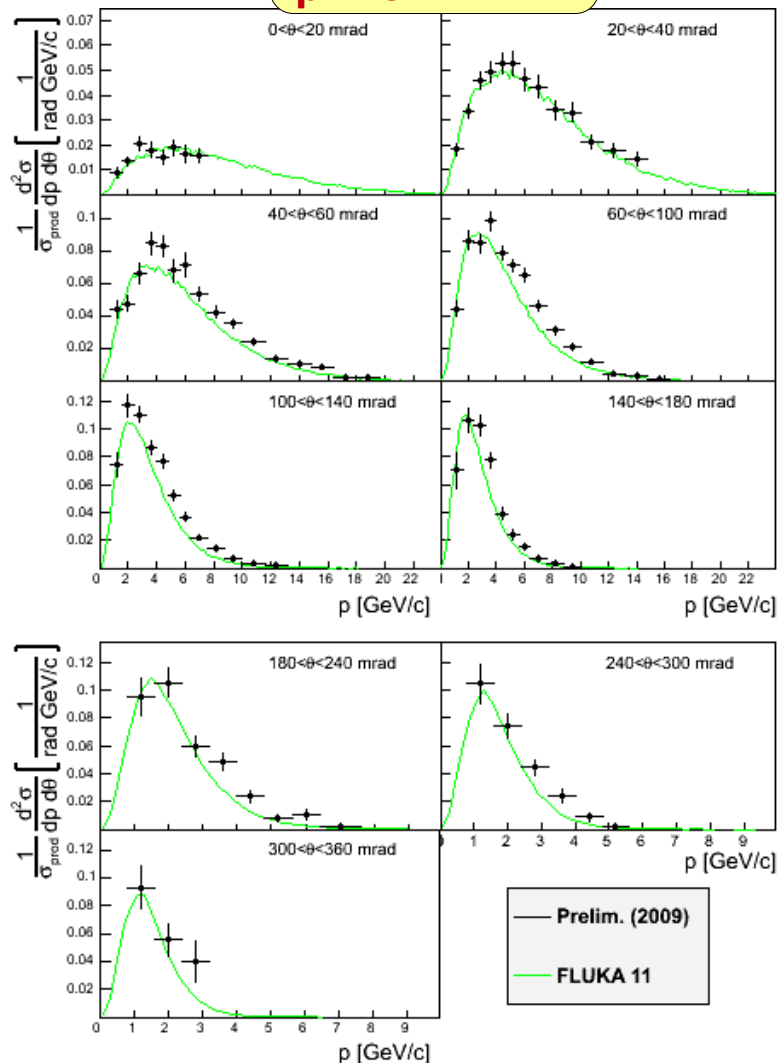


- Statistical uncertainty data of 2009 vs. 2007 **improved by a factor 2-3**
- Systematic error from analysis of data 2007  $\Rightarrow$  an upper limit. **To be improved**
- FLUKA11 describes data reasonably well

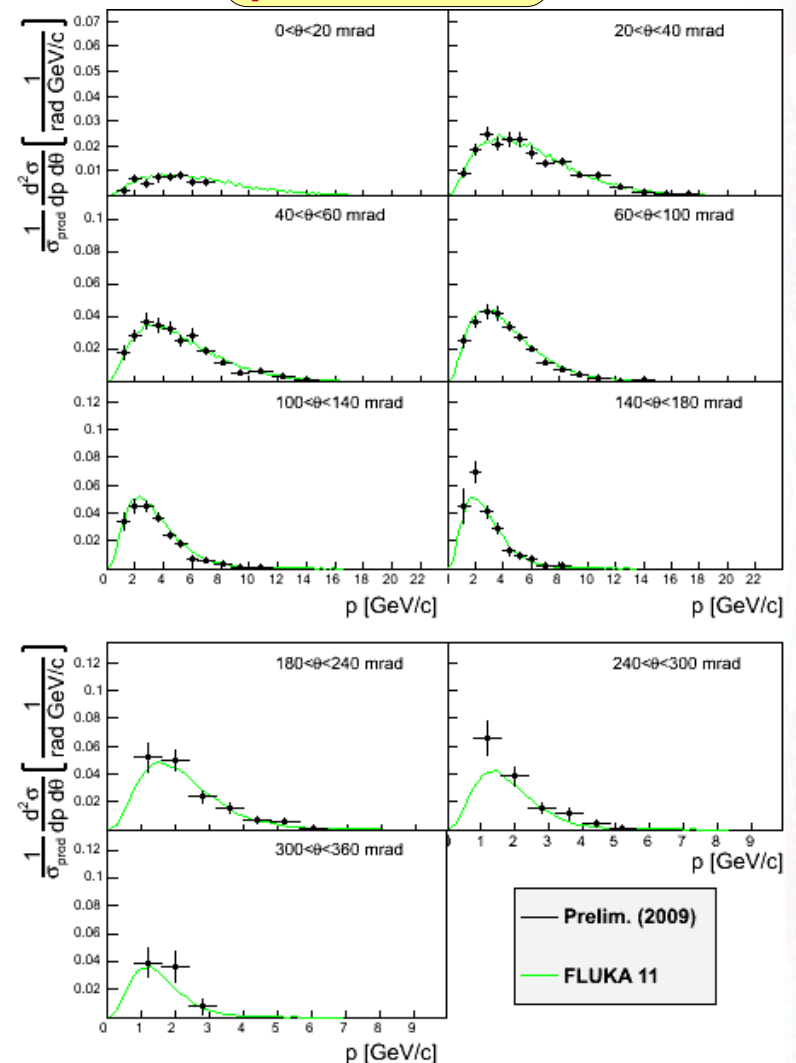


# New results on $K^+$ and $K^-$ multiplicity in pC @ 31 GeV/c

$p + C \rightarrow K^+ + X$

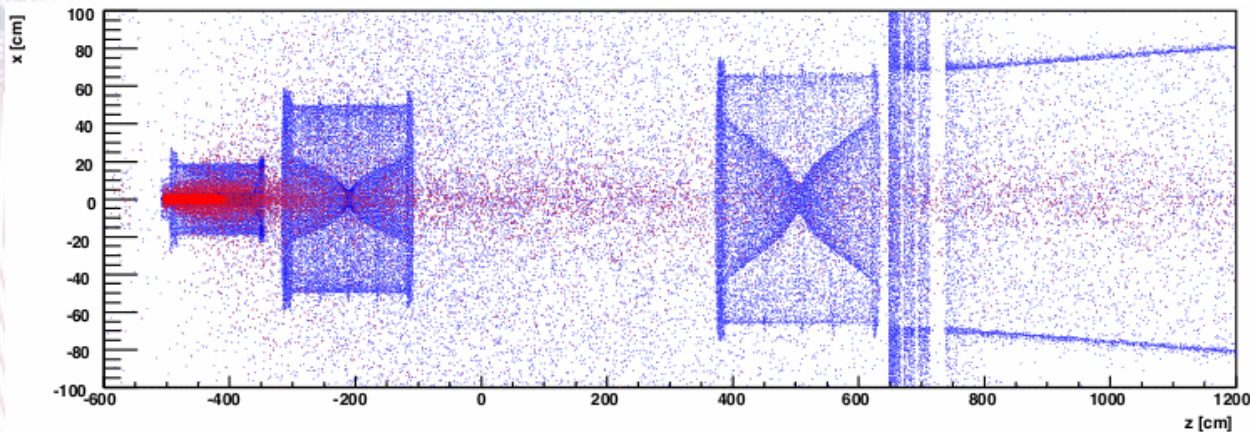


$p + C \rightarrow K^- + X$



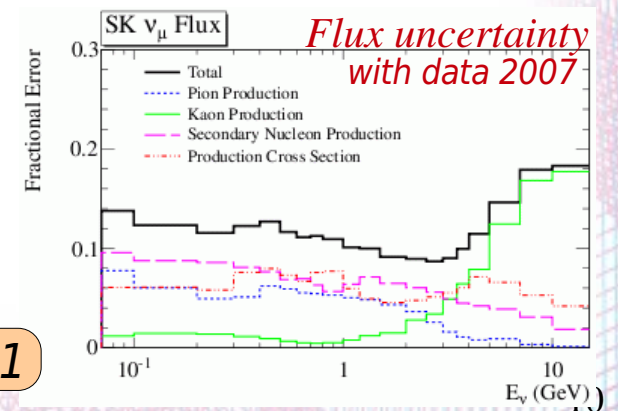
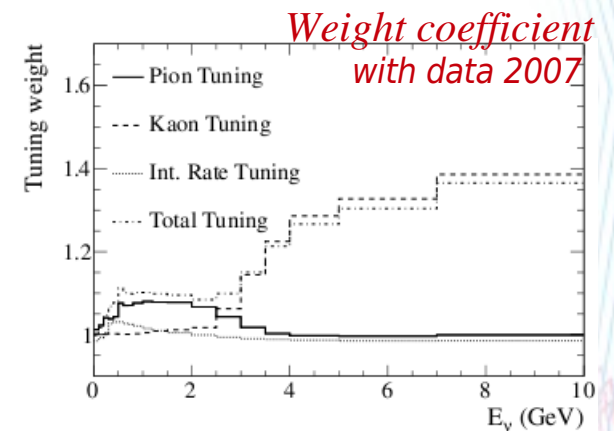
- Statistical uncertainty (and total uncertainty) **improved by a factor 3**
- **$K^-$  are shown for the first time.** Analysis with data 2007 was not possible due to low statistics

# NA61 data in the **T2K** experiment



Hadronic interactions in the target are modeled with FLUKA, outside the target with GEANT3 (GCALOR)

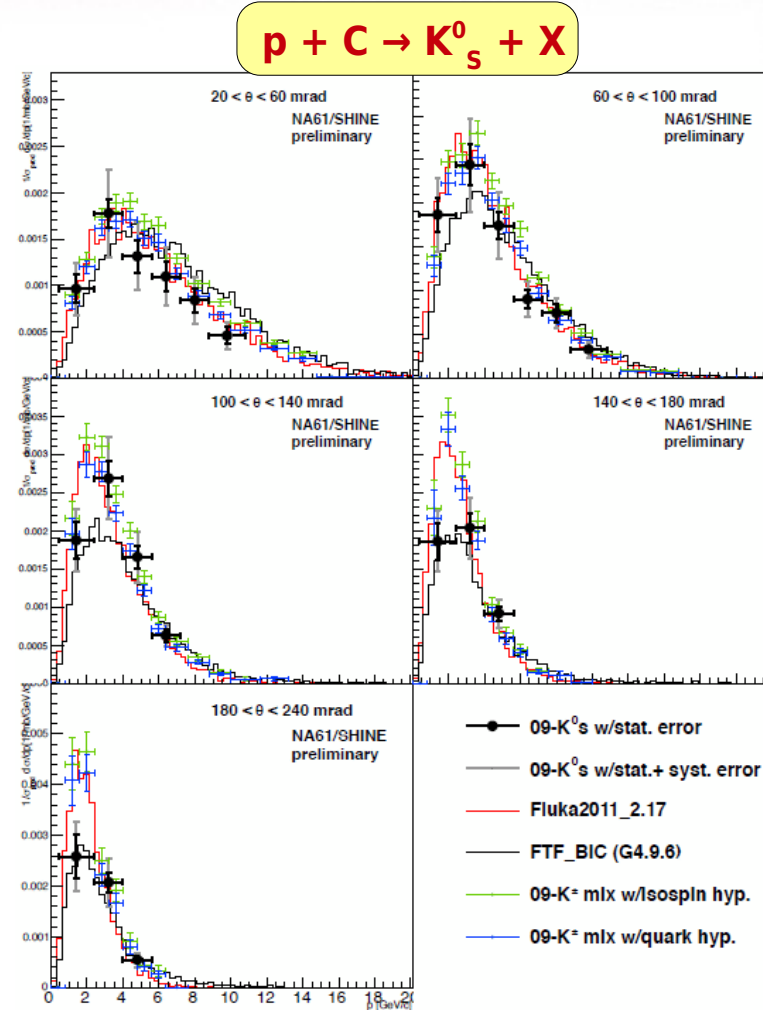
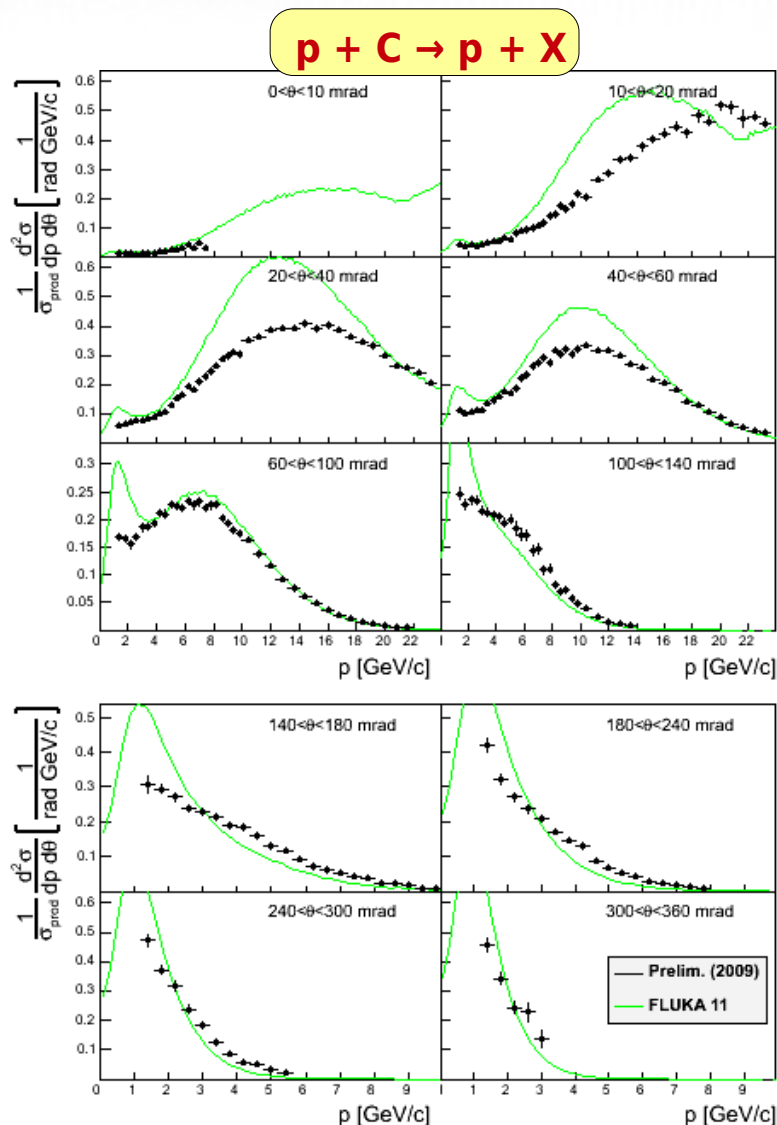
- Major part of the T2K phase space is covered by NA61
- Interaction chain for hadrons is stored, to be **weighted later with real measurements**
- Tuning of tertiary pions requires extrapolation from NA61 data
  - ◆ Extrapolation to different incident nucleon momenta
  - ◆ Extrapolation from carbon to aluminum
- Relative uncertainty on the predicted number of events assuming  $\sin^2 2\theta_{13} = 0$  ( $\nu_e$  appearance paper of T2K arXiv: 1304.0841)
  - ◆ **Due to flux: 8.5%, Total: 13%**



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



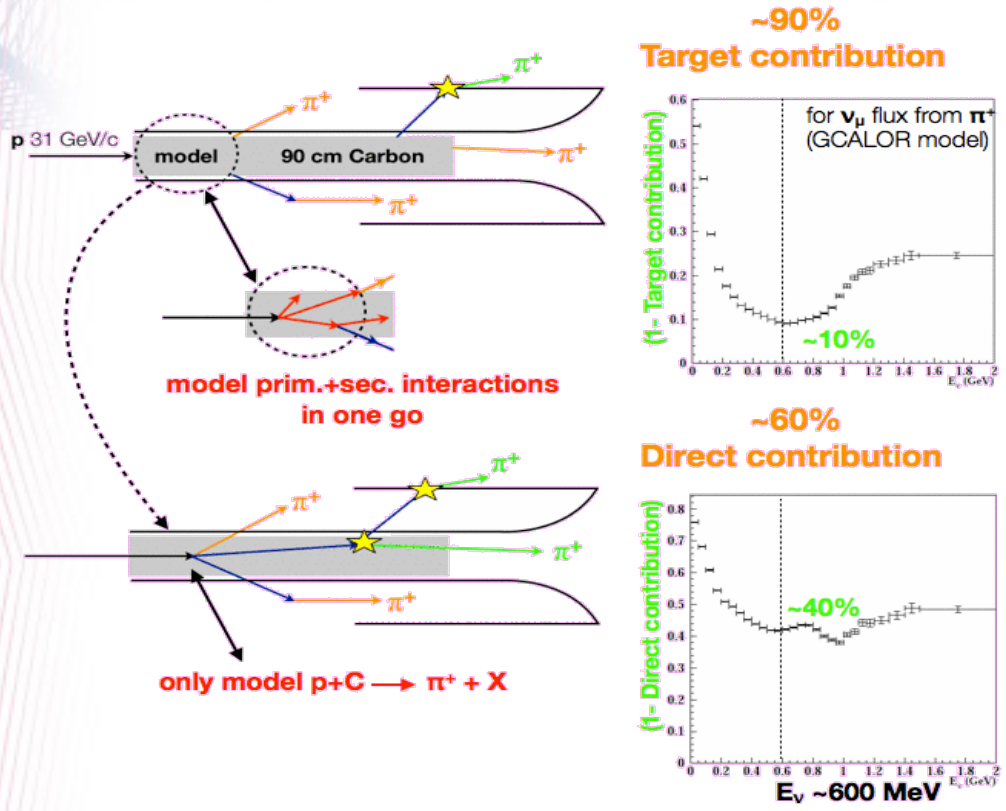
# New results on proton and $K^0_s$ multiplicity in pC @ 31 GeV/c



- To be used in the T2K beam simulation to decrease the systematics due to the secondary nucleon production

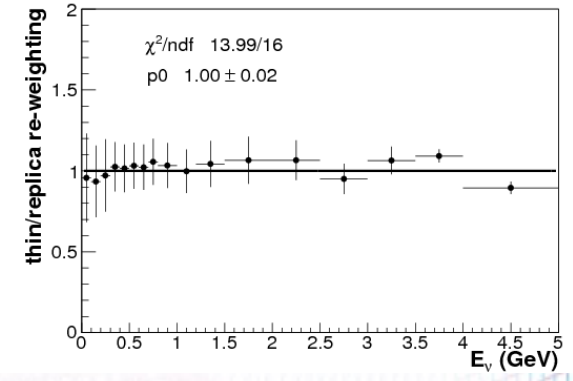
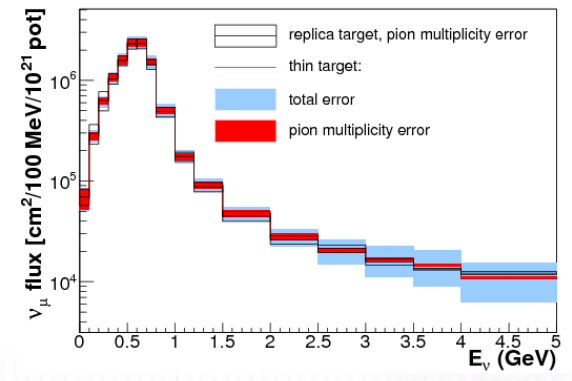
- To be used in the  $\pi$  analysis of NA61 to reduce the feed-down uncertainty. Presently discrepancy between FLUKA and VENUS introduces the error  $\sim 10\%$  at low momenta

# Alternative approach to the $\nu$ flux prediction in T2K



- Hadron multiplicities are parametrized **at the target surface** (no vertex reconstruction)
- Analysis in bins of  $(p, \theta, z)$
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Model dependence is reduced down to 10% as compared to 40% in the standard approach

- Analysis of pilot **data 2007** (method, results and application) is published
- Main statistics is data 2009 (analysis is ongoing) and 2010 (not yet calibrated)



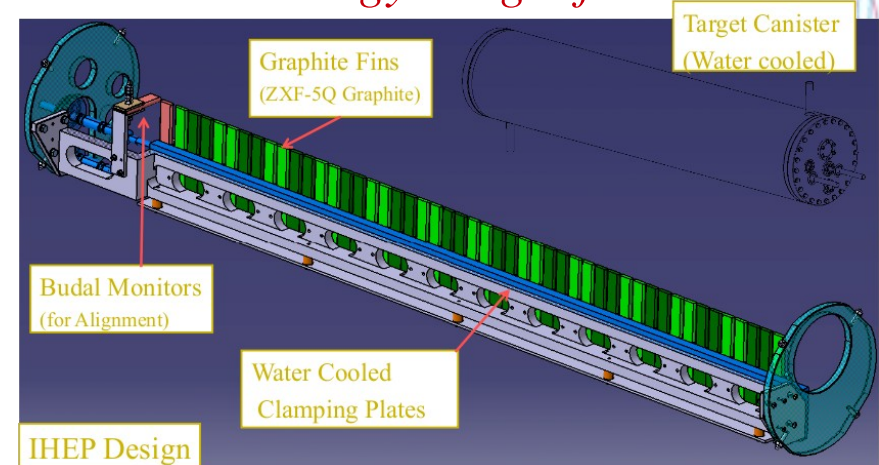
(NA61) N.Abgrall et al., NIM A701(2003)99



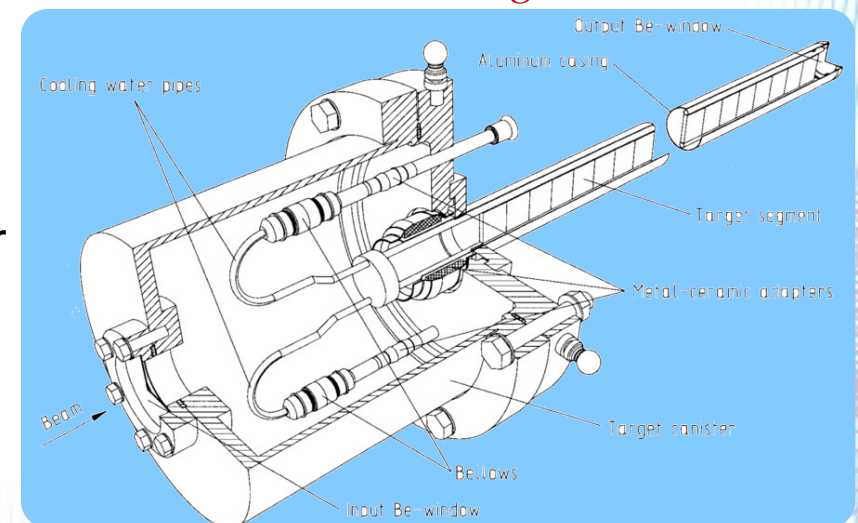
# Measurements for the NuMI target

- The goal is similar to the one for T2K (cross section + replica target)
- LBNE, MINOS(+), NOvA, MINERvA
- US group has been approved for limited membership at the beginning of 2012. Full members in 2014
- 22 physicists from 8 US institutions
- Pilot run in summer 2012
  - ◆ 120 GeV/c proton beam + C target
  - ◆ Non-standard magnet configuration
  - ◆ 3.5 millions triggers recorded
  - ◆ Calibration is in progress
- DOE proposal to be submitted this summer
  - ◆ Upgrade of electronics (Pittsburgh)
  - ◆ Forward tracking (Colorado)
  - ◆ Request for 3-4 weeks of beam time (60, 90, 120 GeV/c, 3-4 targets)

## Medium Energy Target for NOvA



## NuMI target



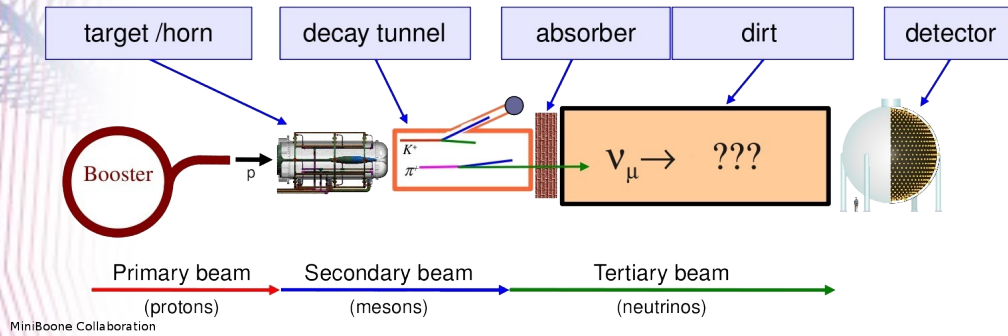
## Summary & conclusion

- First release of results for pC @ 31 GeV/c based on statistics 2009
- Spectra of  $\pi^\pm$ ,  $K^\pm$  and protons have been presented
  - ◆ Statistical precision improved by a factor of 2-3
  - ◆ Reasonable agreement to published data 2007
  - ◆ First results of NA61 for  $K^-$
  - ◆ Upper limit for the systematic uncertainty. To be improved
- Preliminary results of  $K^0_S$  analysis presented
  - To improve the precision of feed down corrections in  $\pi^\pm$  analysis
- Analysis of the T2K replica target data is ongoing
- Good progress in the analysis of the pilot data collected for the NuMI target at 120 GeV/c

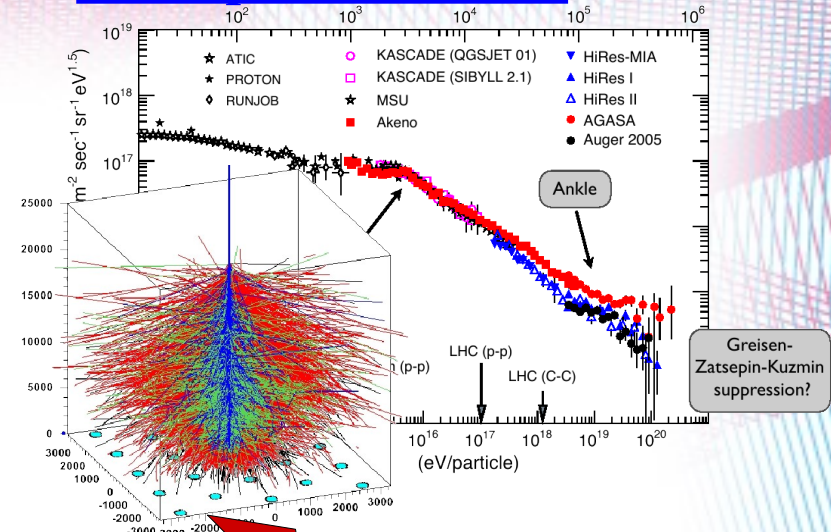


Back up

# Conventional accelerator $\nu$ -beam



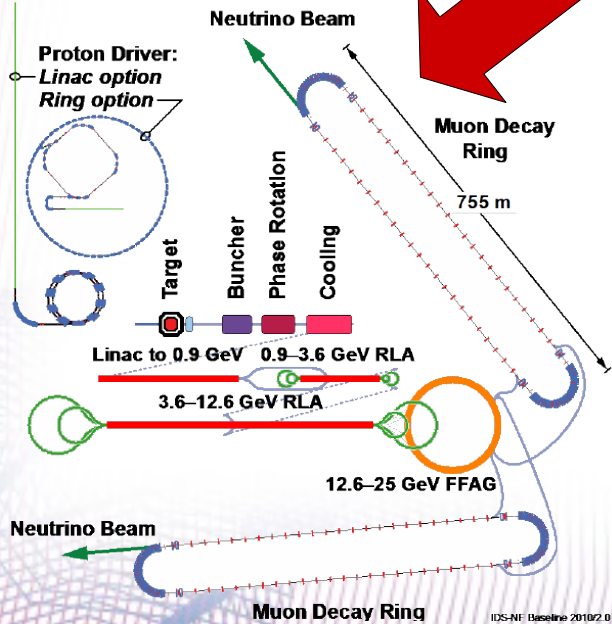
# Atmospheric showers



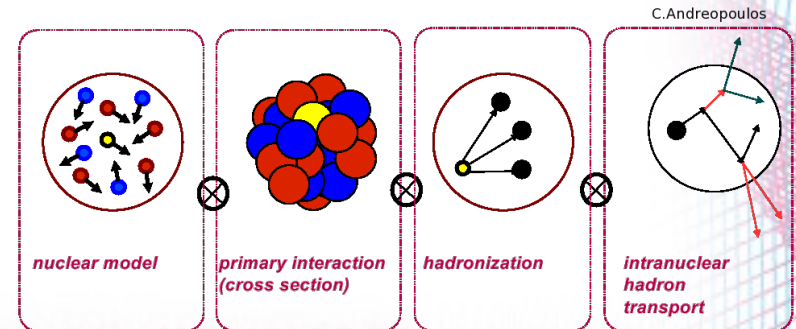
## Hadroproduction measurement

$$p(\pi) + A \rightarrow h + X$$

# Neutrino Factory



# MC generators





## Results

- ◆ Trigger cross section:  
agreement within  $1\sigma$   
with 2007 measurement

$$\sigma_{\text{Trig}} = 305.7 \pm 2.7(\text{stat})_{-1.2}^{+1.0}(\text{syst}) \text{ mb}$$

$$\sigma_{\text{Trig}}^{2007} = 298.1 \pm 1.9(\text{stat}) \pm 7.3(\text{syst}) \text{ mb}$$

- ◆ Inelastic cross section:  $\sigma_{\text{inel}} = \sigma_{\text{trig}} - \sigma_{\text{el-Out of S4}} + \sigma_{\text{loss-p}} + \sigma_{\text{loss-}\pi/K}$

-  $\sigma_{\text{el-Out}}$ : el-scattering outside the acceptance of the interaction trigger counter (S<sub>4</sub>)

-  $\sigma_{\text{loss-x}}$ : forward produced hadrons hitting S<sub>4</sub>

$$\sigma_{\text{inel}} = 261.3 \pm 2.8(\text{stat}) \pm 2.2(\text{model})_{-1.2}^{+1}(\text{trigger}) \text{ mb}$$

- ◆ Production cross section:  $\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}$

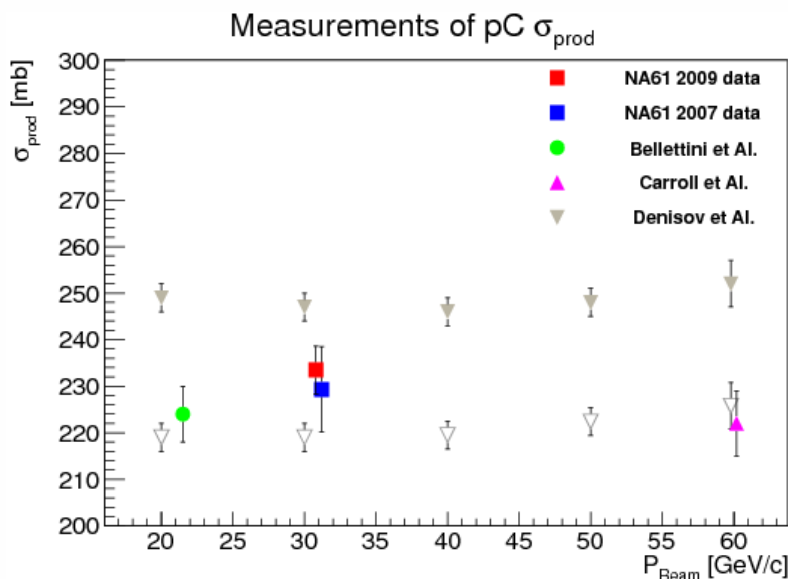
Correction were estimated with GEANT4

$$\sigma_{\text{prod}} = 233.5 \pm 2.8(\text{stat}) \pm 4.2(\text{model})_{-1.2}^{+1}(\text{trigger}) \text{ mb}$$

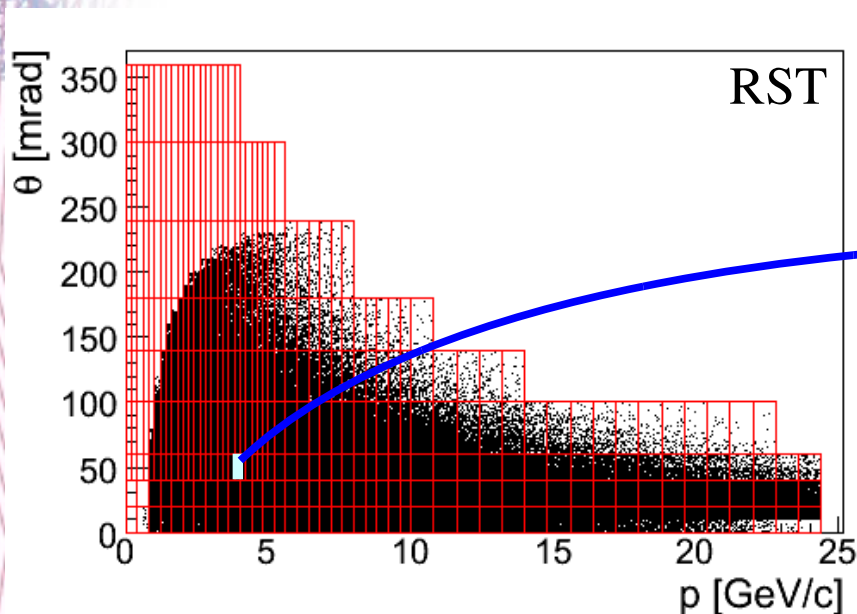
$$\sigma_{\text{prod}}^{2007} = 229.3 \pm 1.9(\text{stat}) \pm 9.0(\text{syst}) \text{ mb}$$

**Normalization analysis is completed**

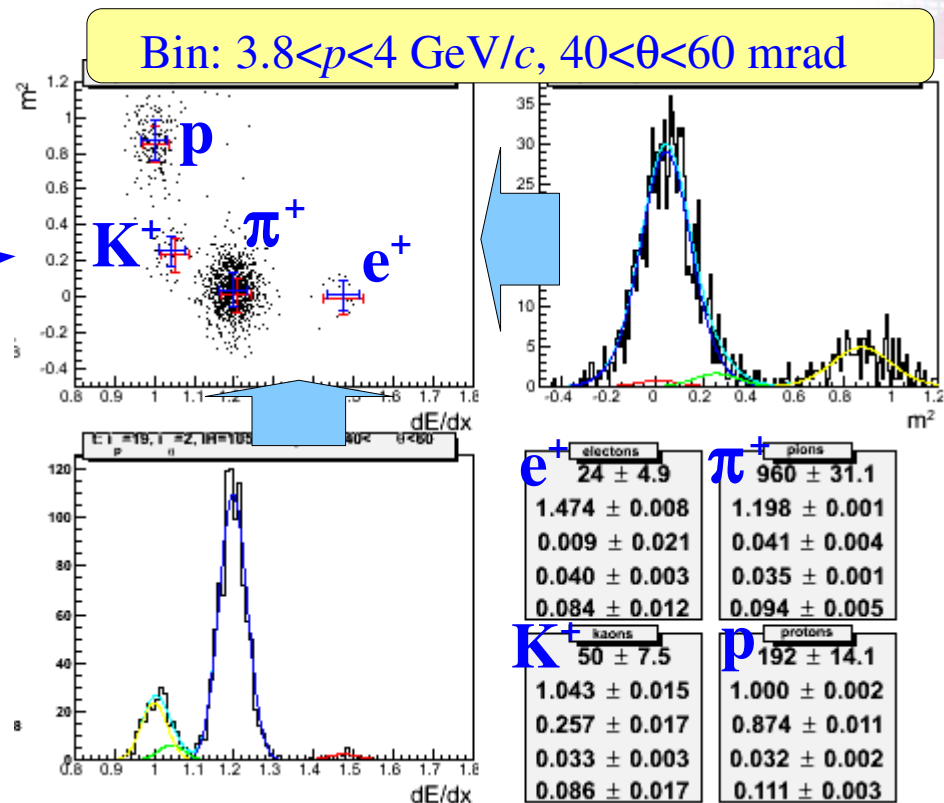
**Total uncertainty from 4% (2007) to 2%**



# Technique of combined ToF- $dE/dx$ analysis



- Signal is parametrized as a product of Gaussian functions in  $m^2$  and  $dE/dx$
- For each  $(p, \theta)$  bin the maximum likelihood method was applied to fit the shape

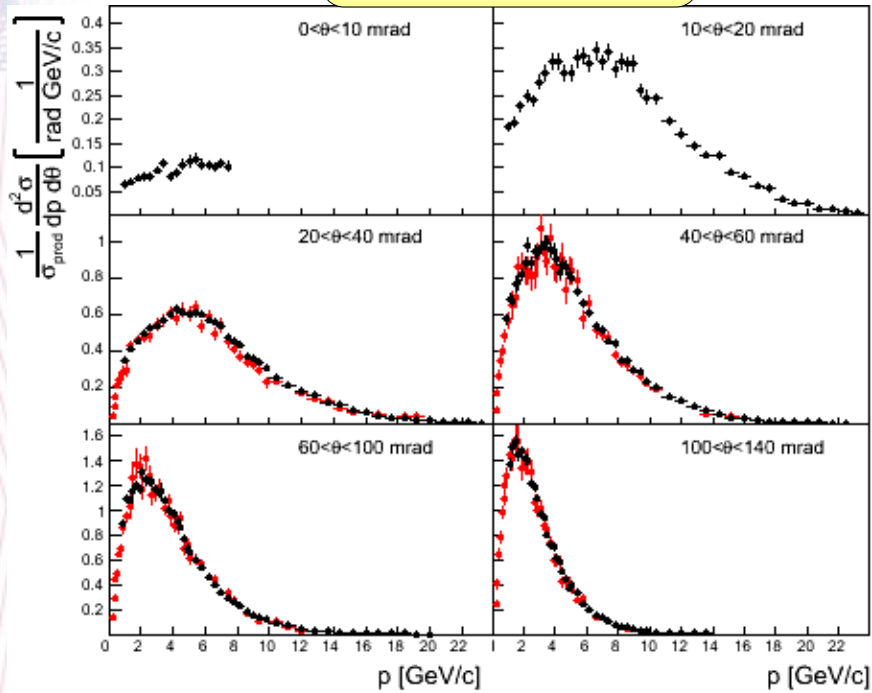


- Uncertainty associated to the unknown functional form is a dominant contribution to the systematic error at  $p \gtrsim 2 \text{ GeV}/c$

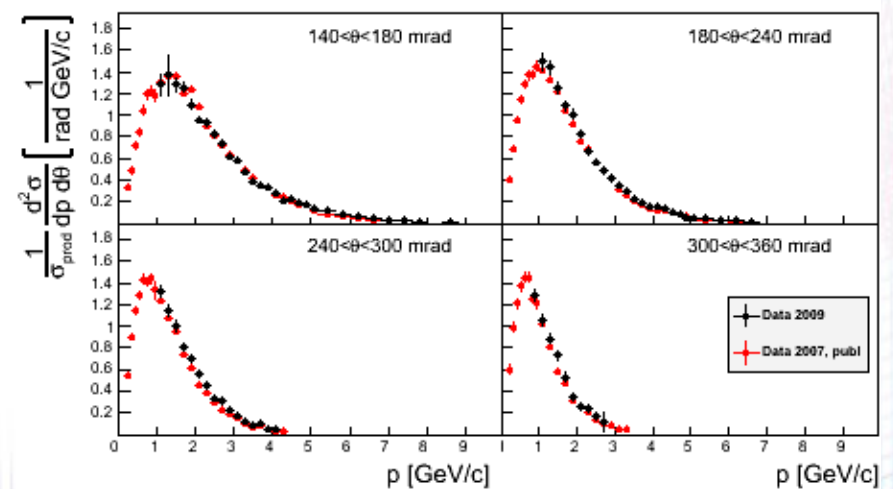
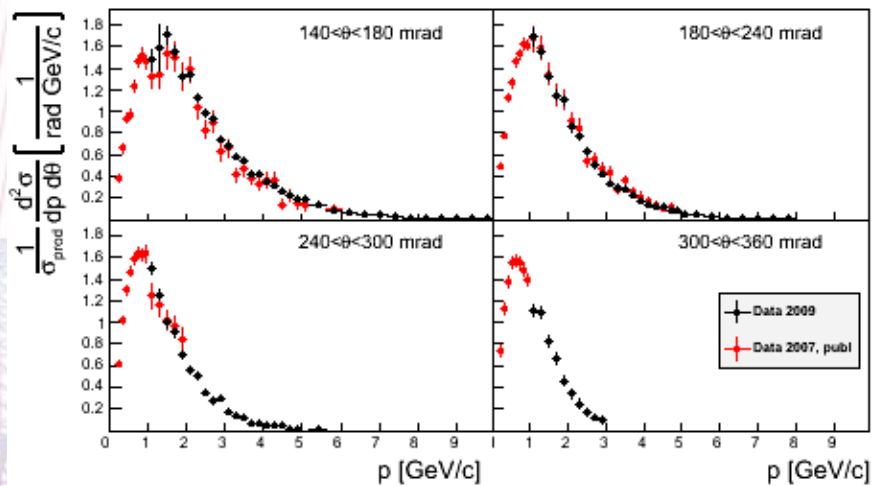
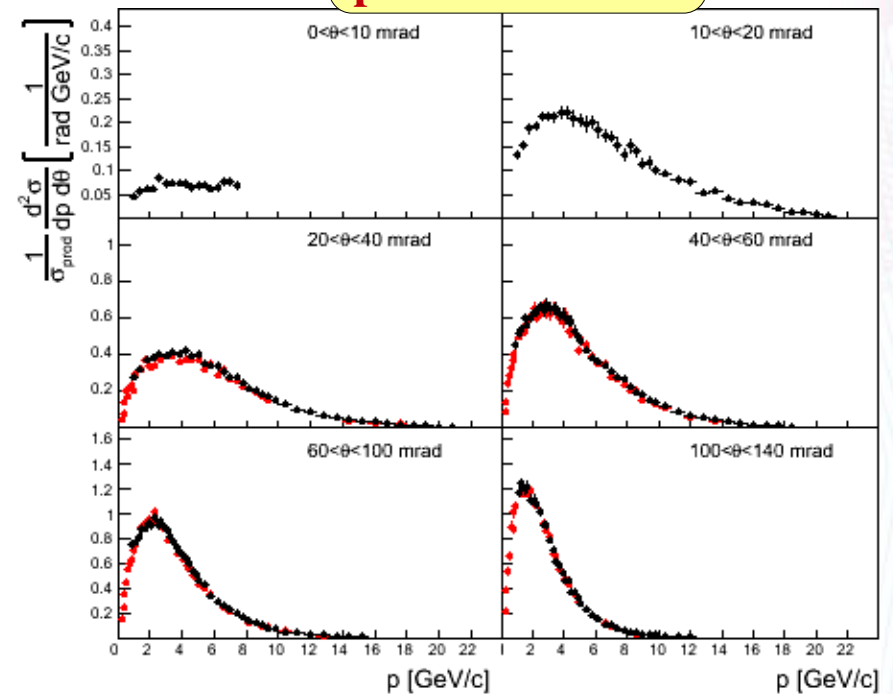


# New results on $\pi^\pm$ multiplicity in pC @ 31 GeV/c

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

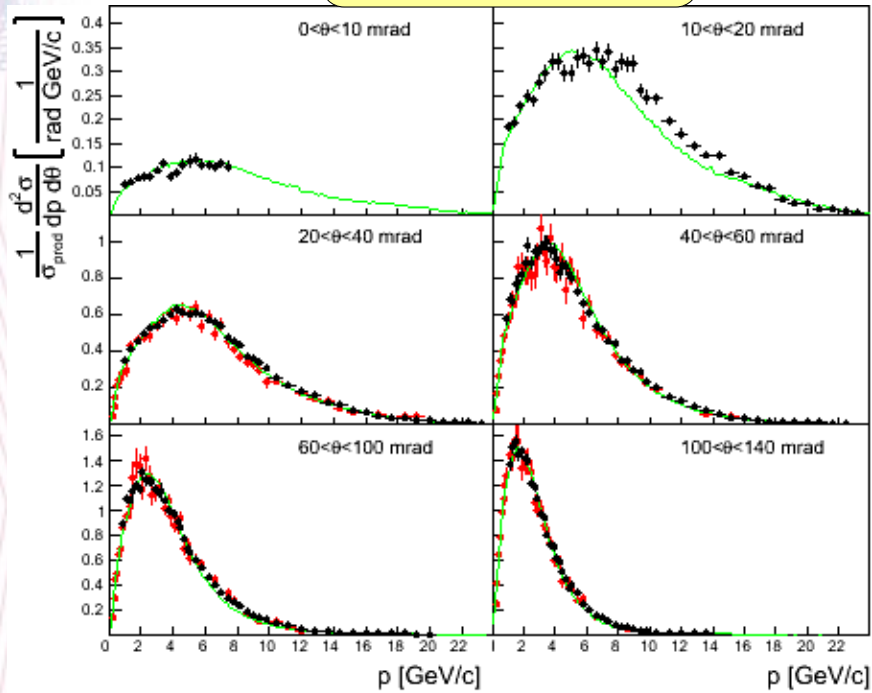


$p + C \rightarrow \pi^- + X$

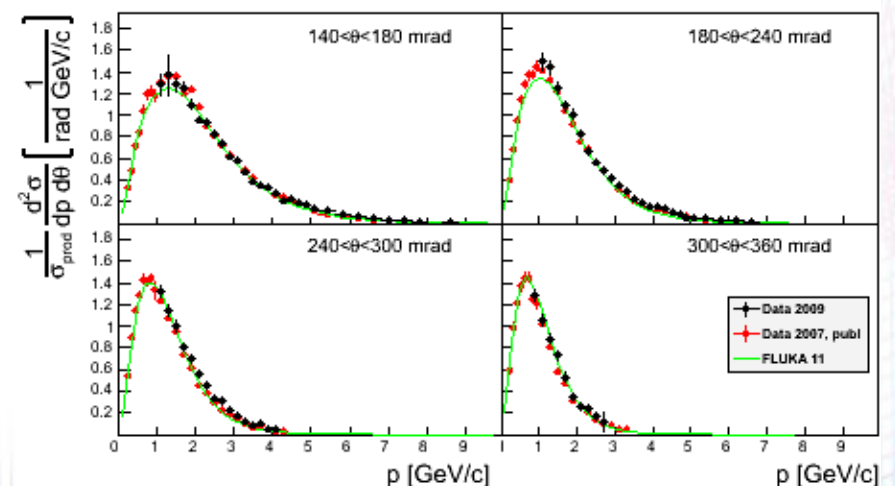
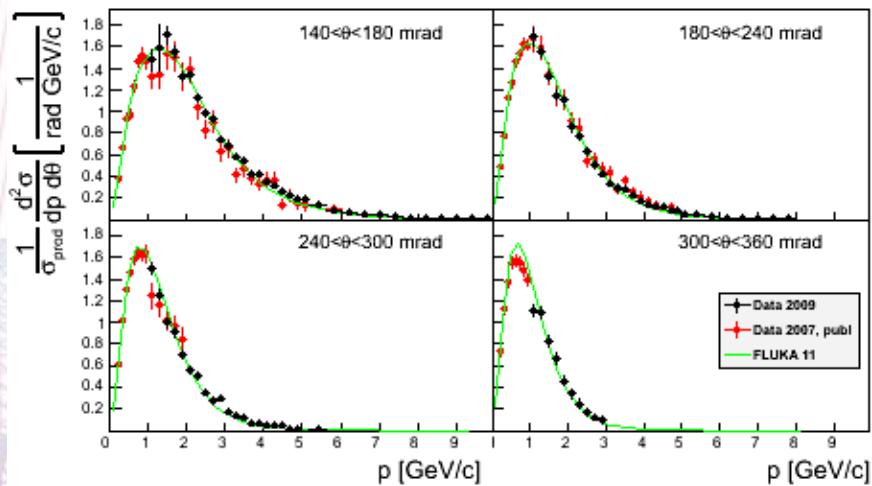
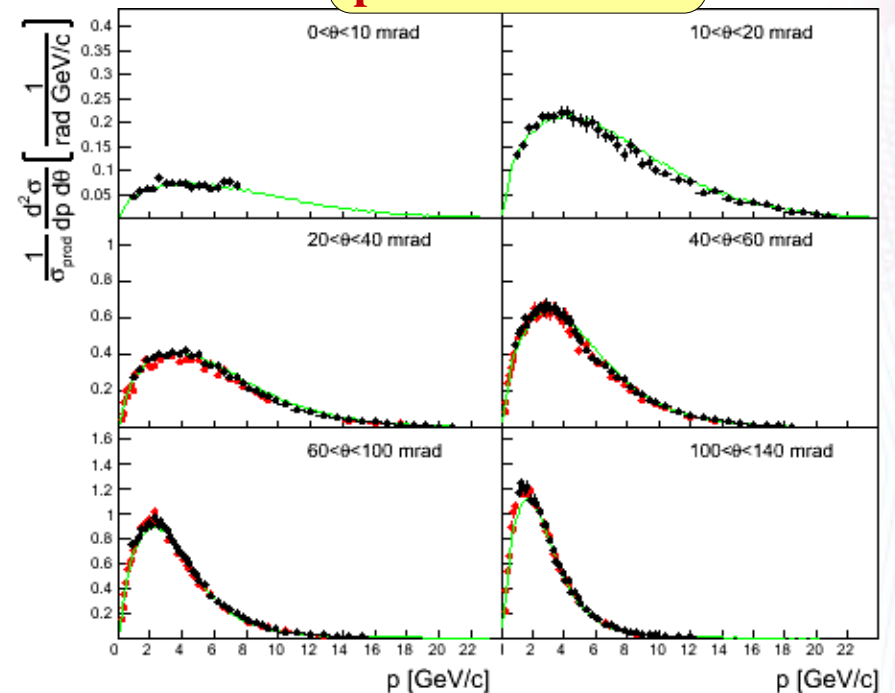


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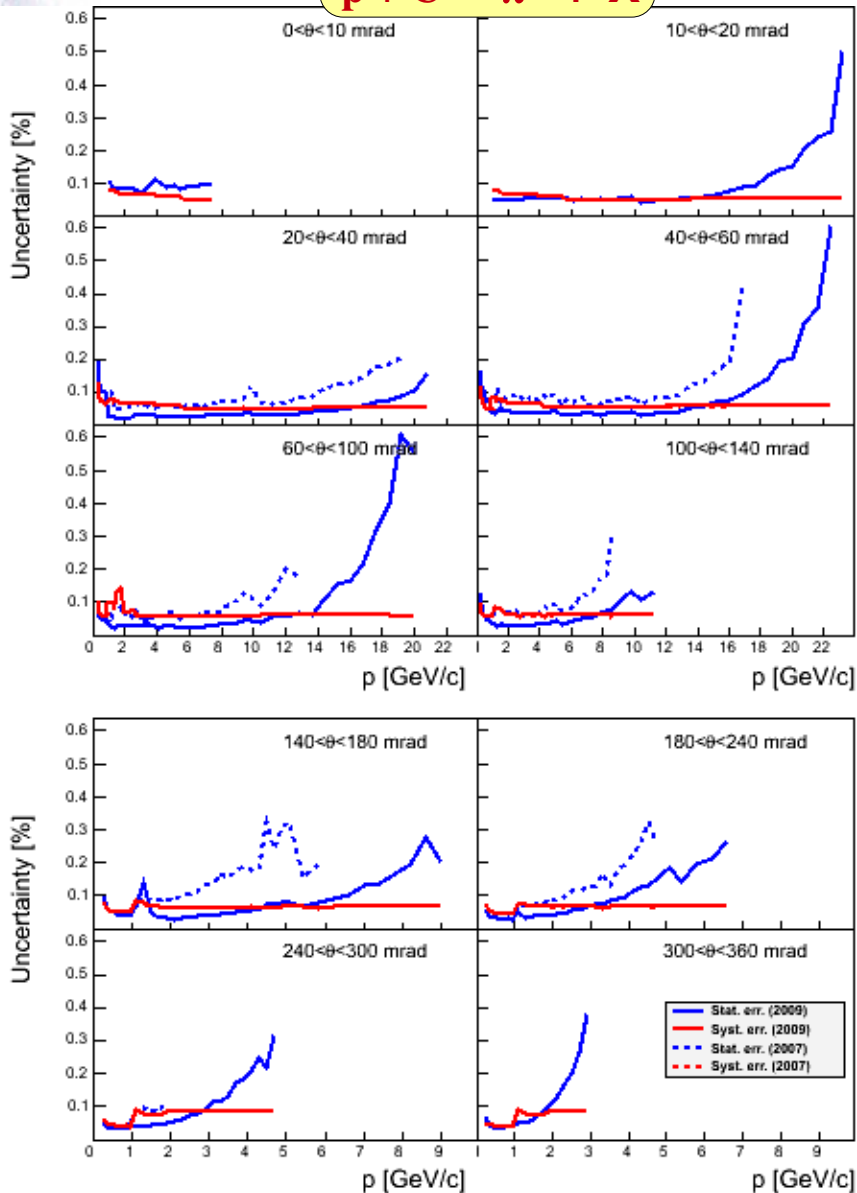
$p + C \rightarrow \pi^- + X$



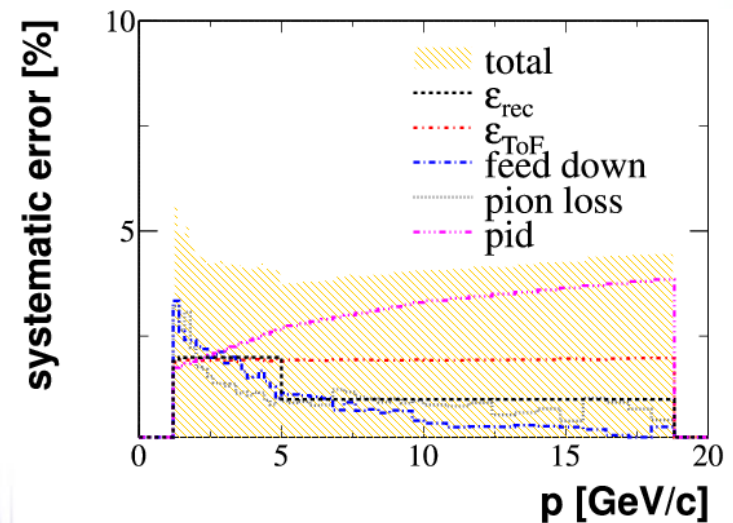


# Statistical and systematic errors

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

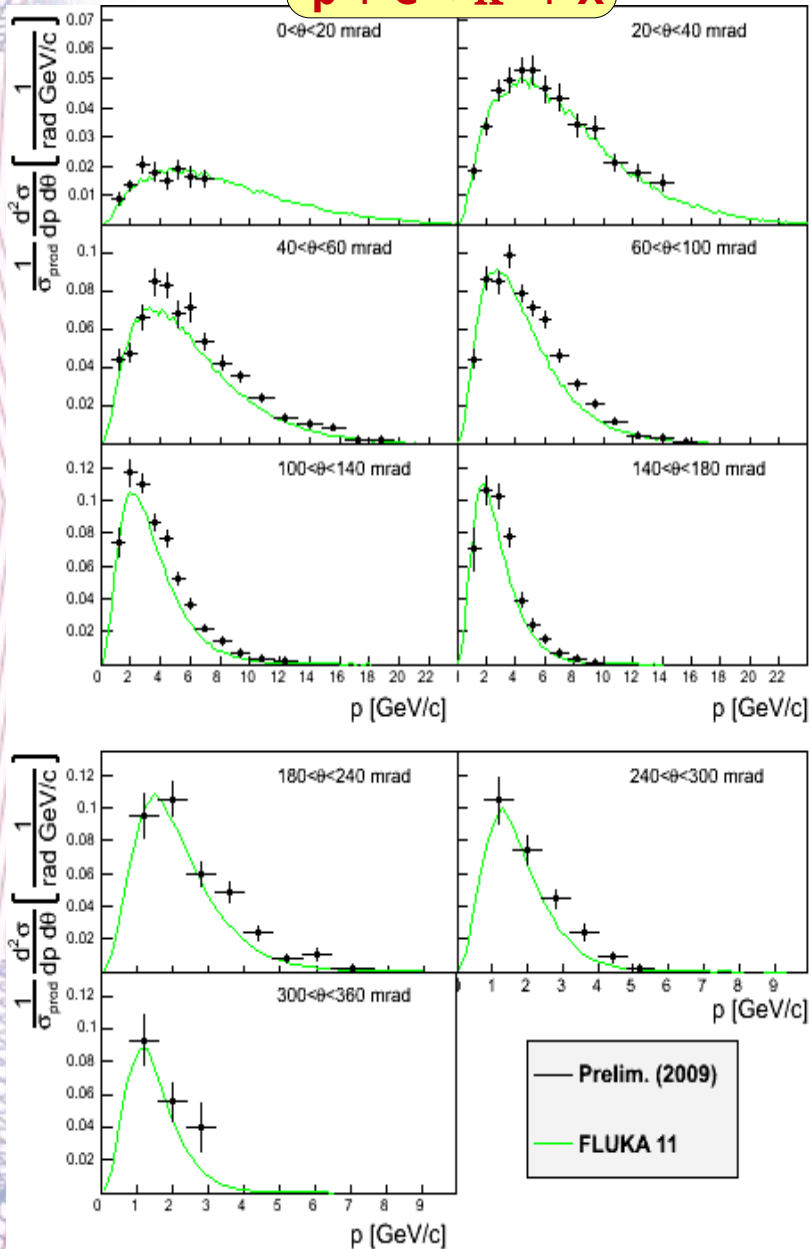


- Statistical uncertainty data 2009 vs. 2007 **improved by a factor 2-3**
- Systematic error from analysis of data 2007  $\Rightarrow$  an upper limit. **To be improved**
- Possible improvement:
  - ◆ PID error can be smaller due to larger statistics
  - ◆ Uncertainty on feed down correction can be smaller once V0 is measured in NA61

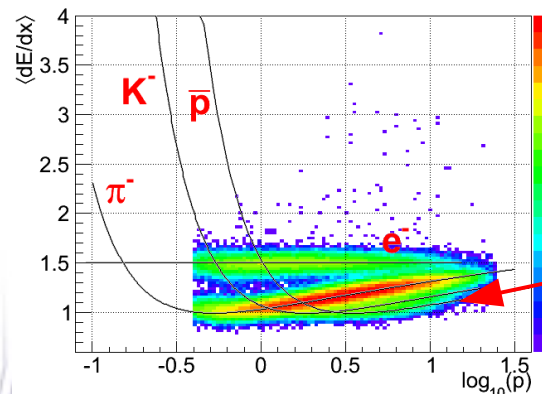
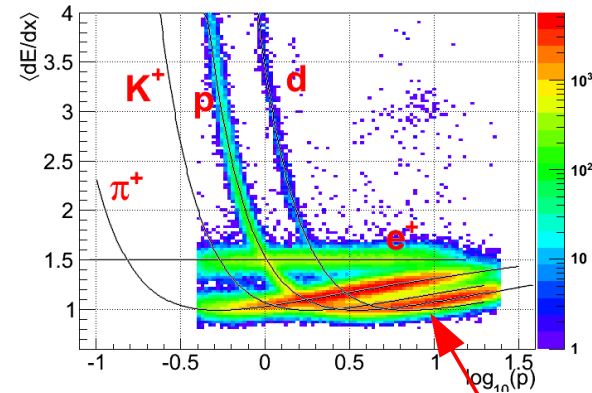


# New results on $K^+$ multiplicity in pC @ 31 GeV/c

$p + C \rightarrow K^+ + X$



- Agreement with published  $K^+$  cross section
  - Statistics (and total error) **improve by a factor 3**
- At large momenta  $K^+$  is totally under the proton peak  $\Rightarrow$  additional systematics
- $K^-$  are shown for the first time. Analysis with data 2007 was not possible due to low statistics

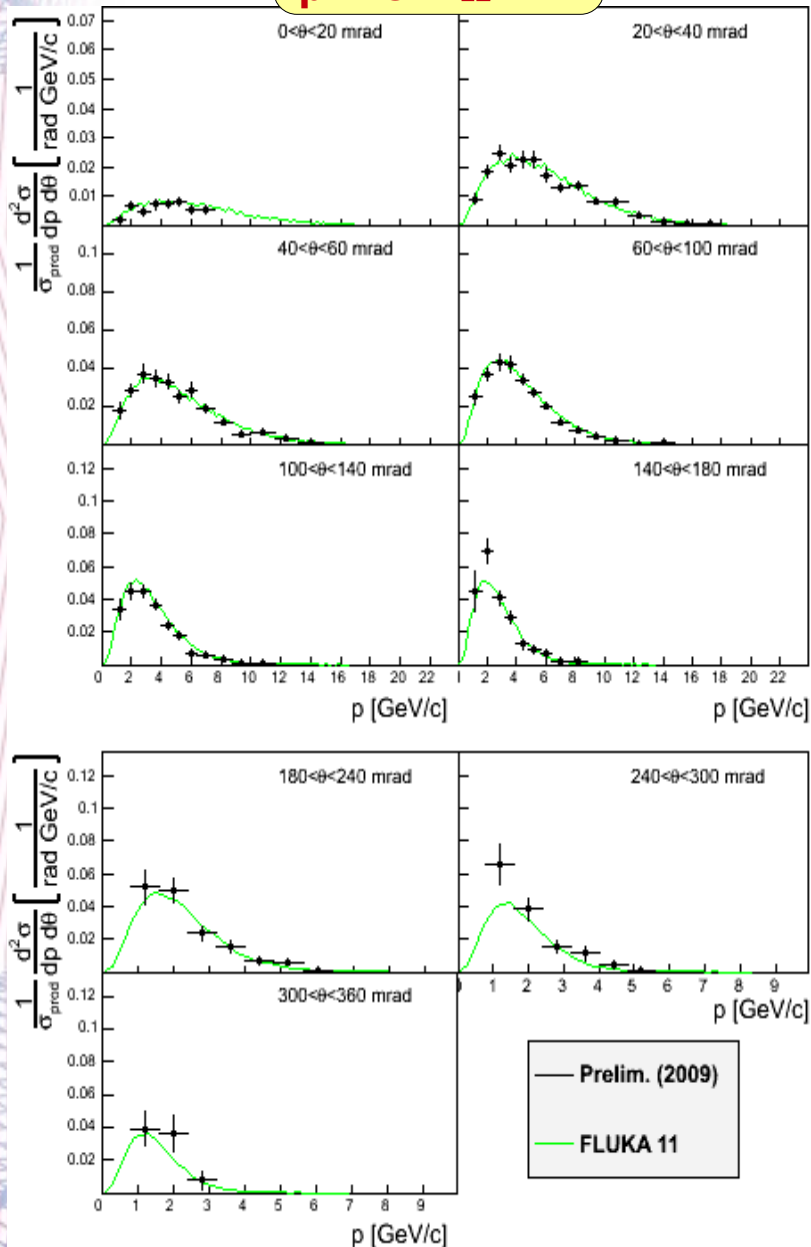


Additional uncertainty on  $K^+$  due to protons

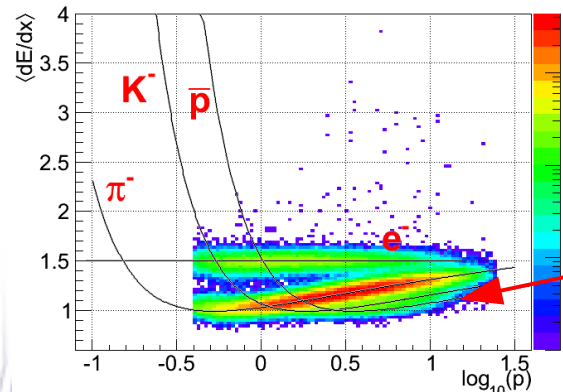
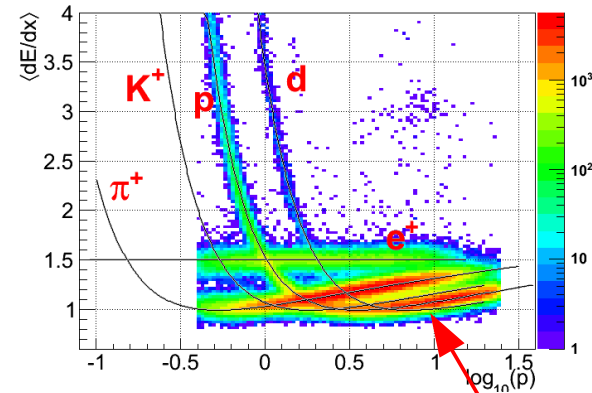


# New results on $K^-$ multiplicity in pC @ 31 GeV/c

$p + C \rightarrow K^- + X$

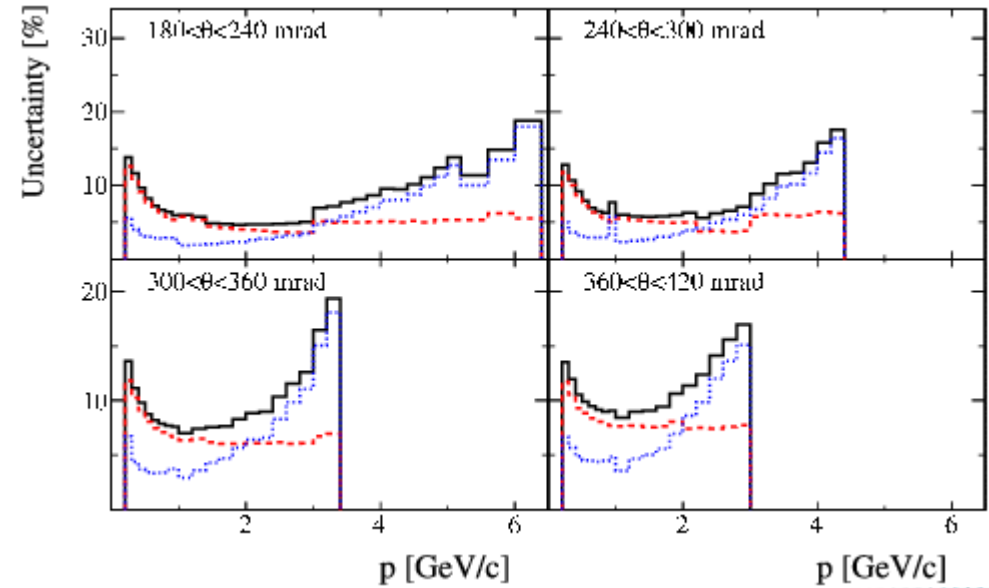
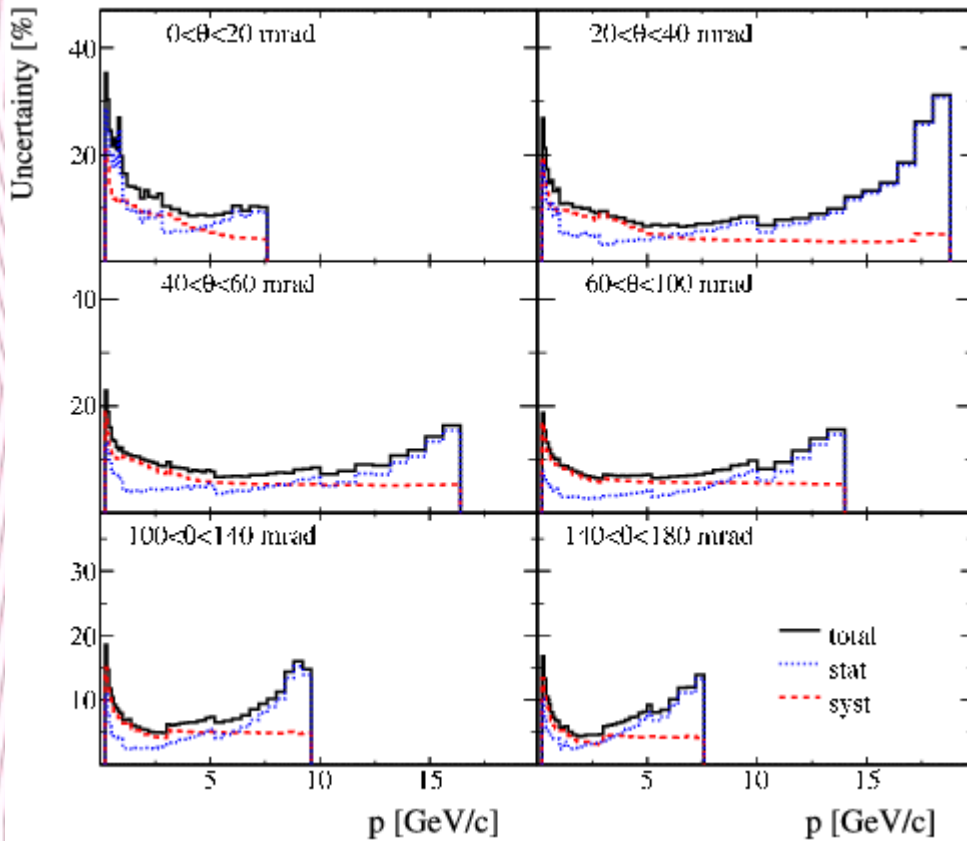


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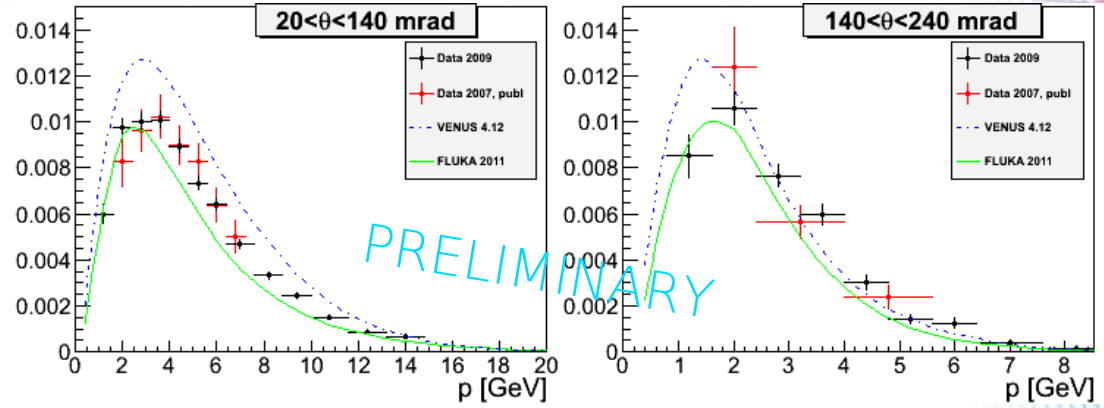
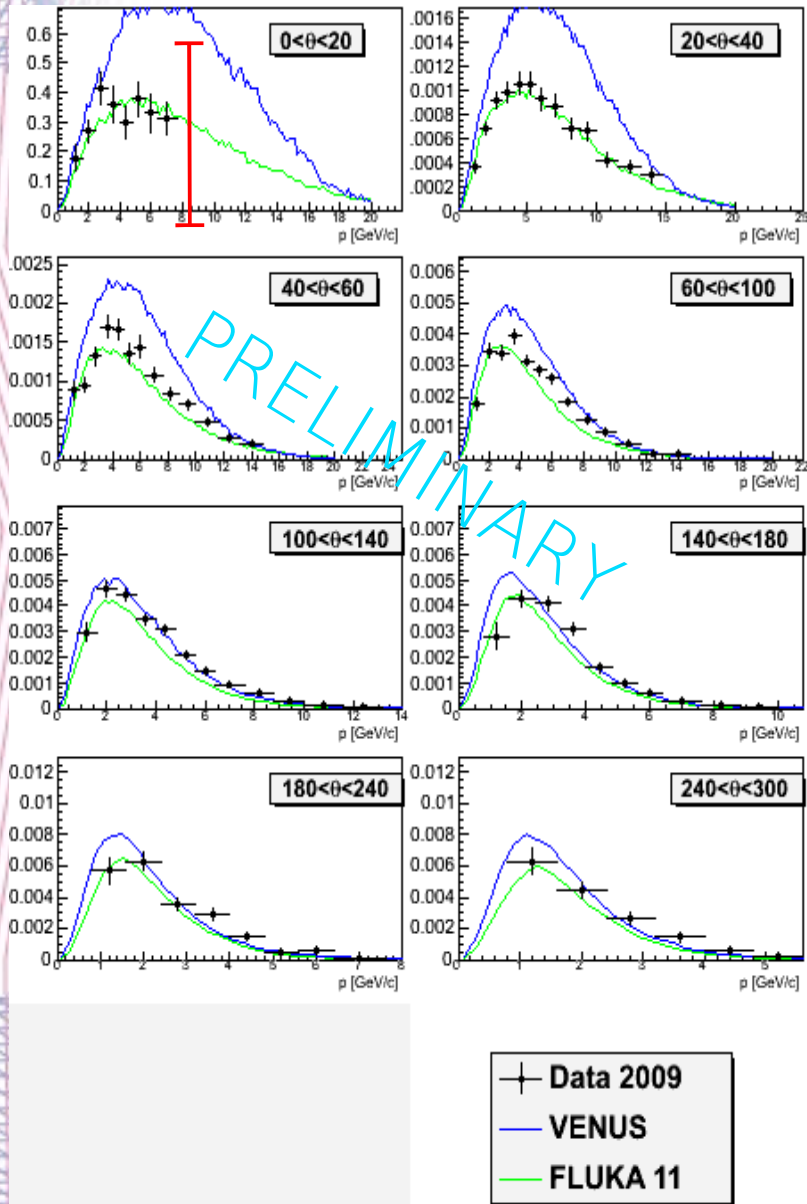
# Relative uncertainties for $\pi^-$ (data 2007)



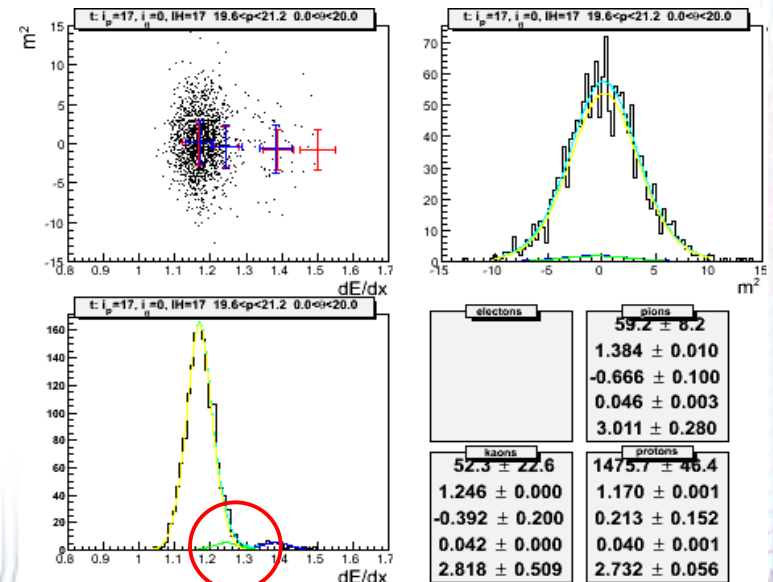
- Among 3 analyzes the one with smaller total error was selected
- Systematic error dominates at lower momenta. At higher momenta stat. error is larger



# Multiplicities for K<sup>+</sup>

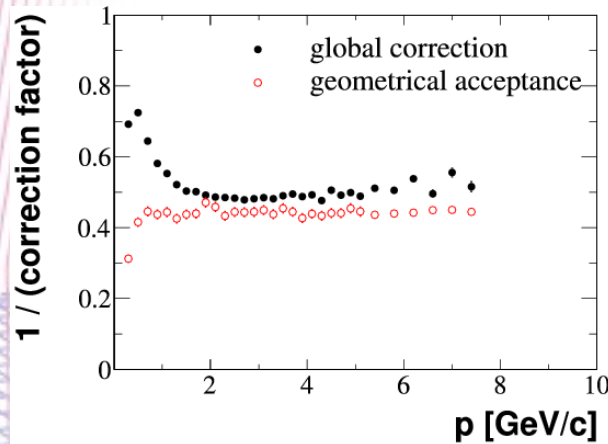
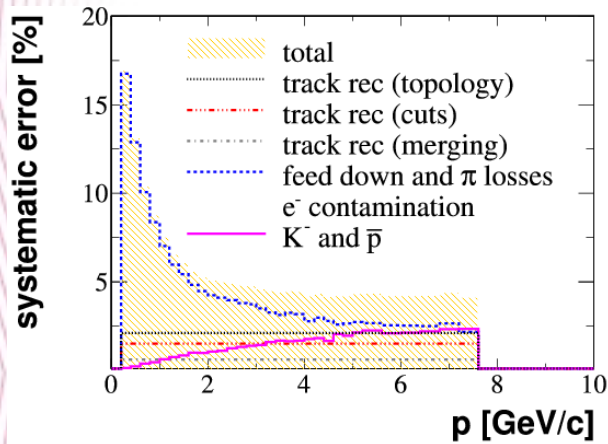


- Agreement with published K<sup>+</sup> cross section
- At large momenta K<sup>+</sup> is totally under the proton peak  $\Rightarrow$  Proper multi-gaussian fit of  $dE/dx$  is needed

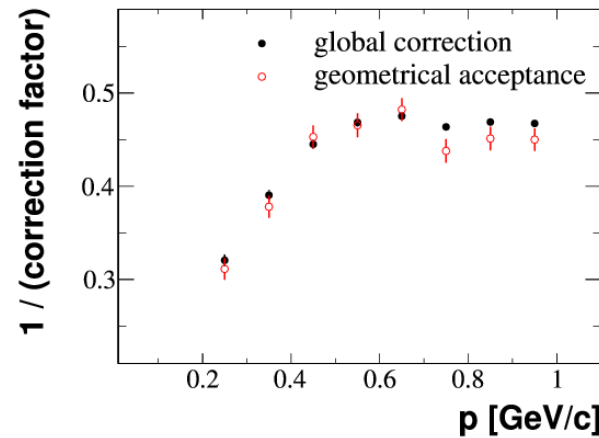
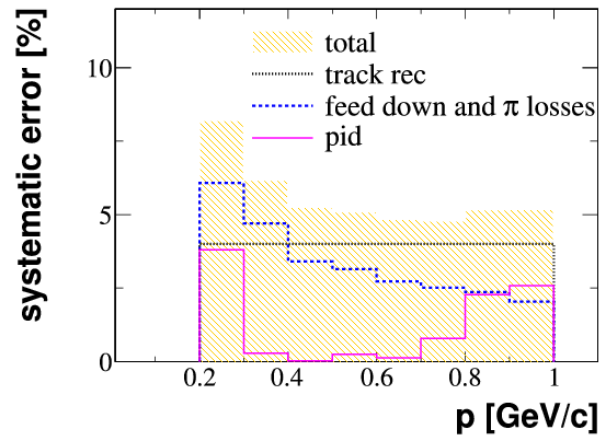


# Syst. error & correction factors for $\pi^-$ analysis (data 2007)

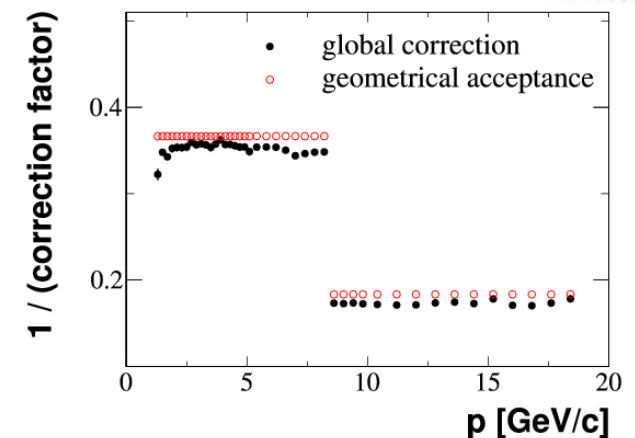
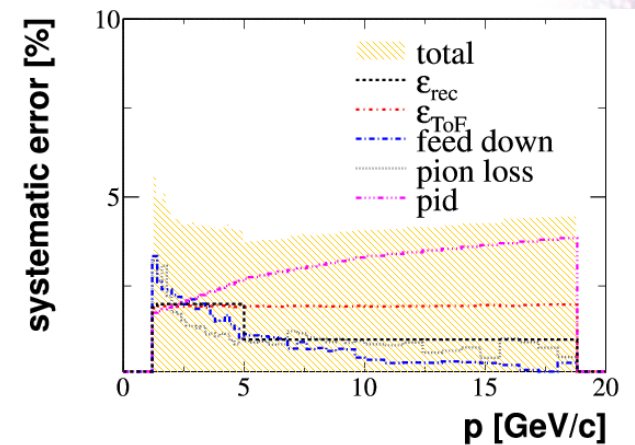
## h- analysis



## $dE/dx$ analysis

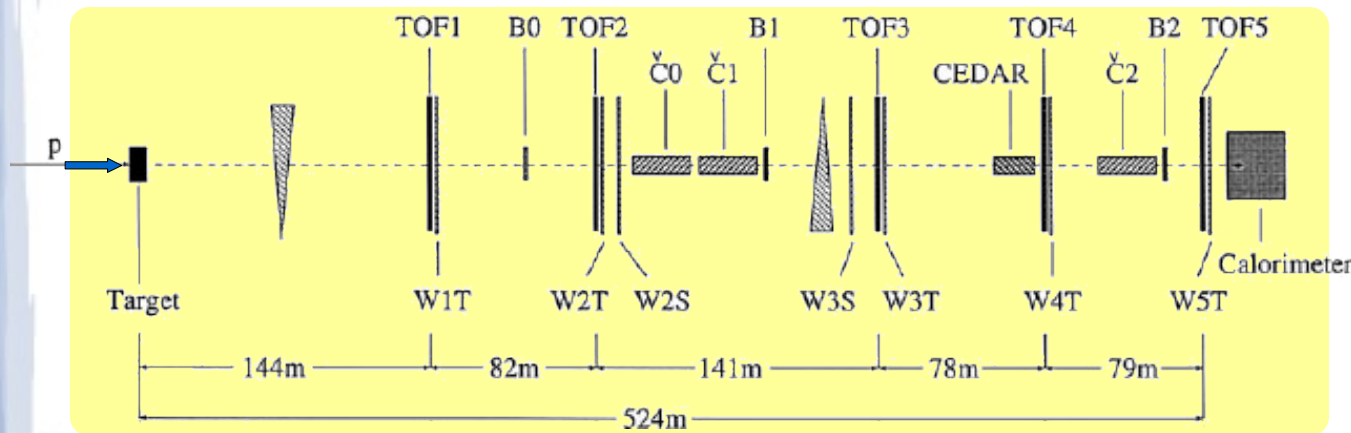


## ToF- $dE/dx$ analysis



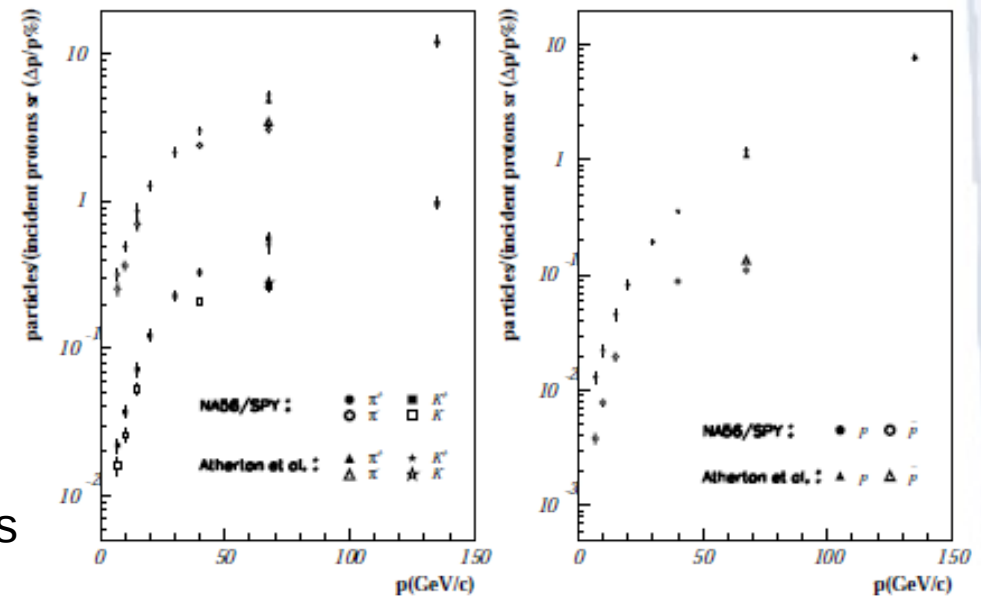


# NA56/SPY, Secondary Particle Yields



- Goal: understanding and planing of  $\nu$  oscillation experiments
- CERN-SPSLC/96-01
- H6 beamline of CERN SPS
- PID by TOF1-5, Cherenkov counters C0-C2 + CEDAR and Hadron Calorimeter

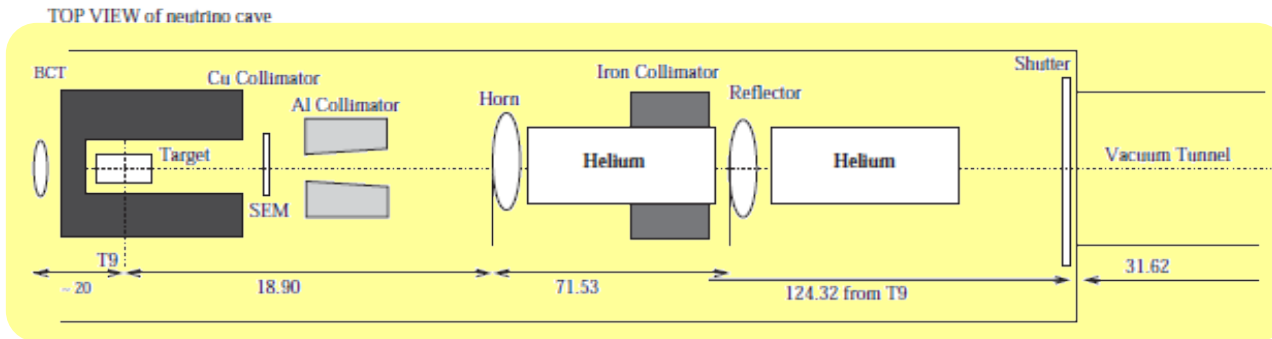
- 450 GeV/c protons interact with Be target
- Production angle up to 30 mrad
- Yields of  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and  $\bar{p}$  have been studied
- Secondary momentum range 7-135 GeV/c ( $0.02 < x_F < 0.3$ ) and  $p_T < 600$  MeV/c
- Experimental accuracy on yields 5-10%, for production ratios 3%
- Dependence of yields on the target thickness and shape have been studied
- Complementary to NA20 (Atherton et al.) measurements at 400 GeV/c and  $0.15 < x_F < 0.75$



*G.Ambrosini et al., Eur.Phys.J.C10(1999)605;  
Phys.Lett.B420(1998)225*

# SPY data in the NOMAD/WANF experiment

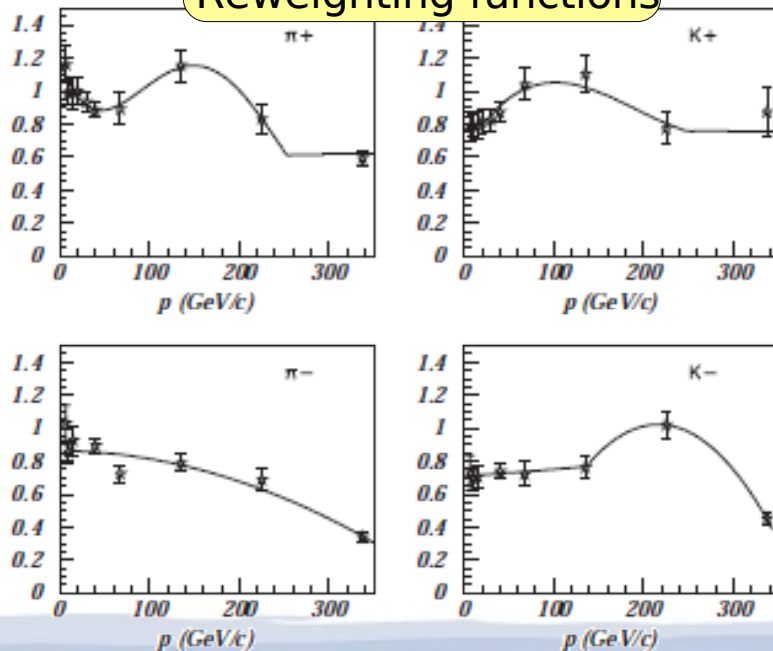
450 GeV/c  
protons  
from SPS



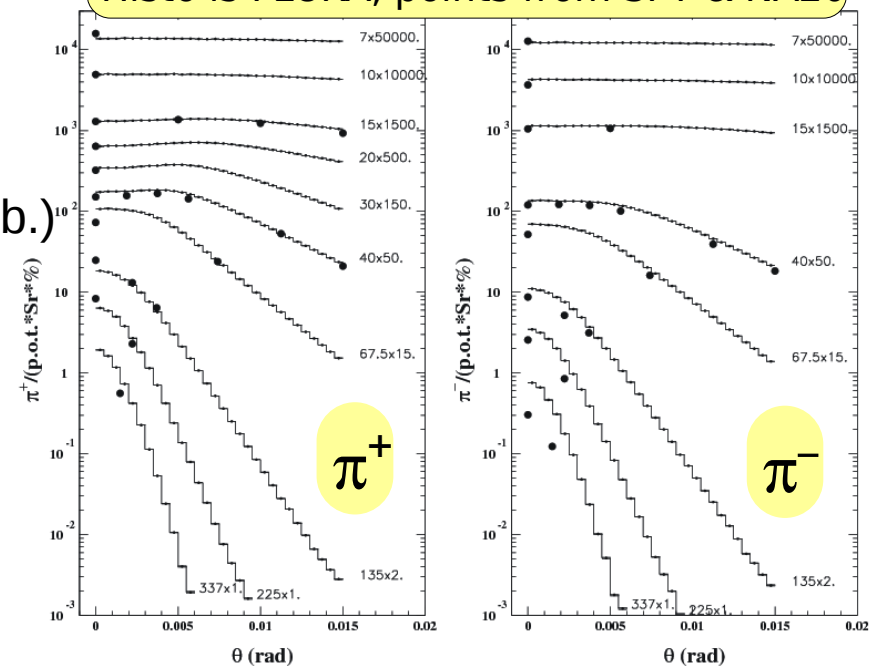
Towards  
CHORUS &  
NOMAD

- FLUKA 2000 was used to calculate rates
- Rates were modified to account for cross-section measured by SPY and NA20
- Weight=Data/FLUKA for bin of  $p$  (and  $\theta$  if posib.)

## Reweighting functions



## Histo is FLUKA, points from SPY & NA20



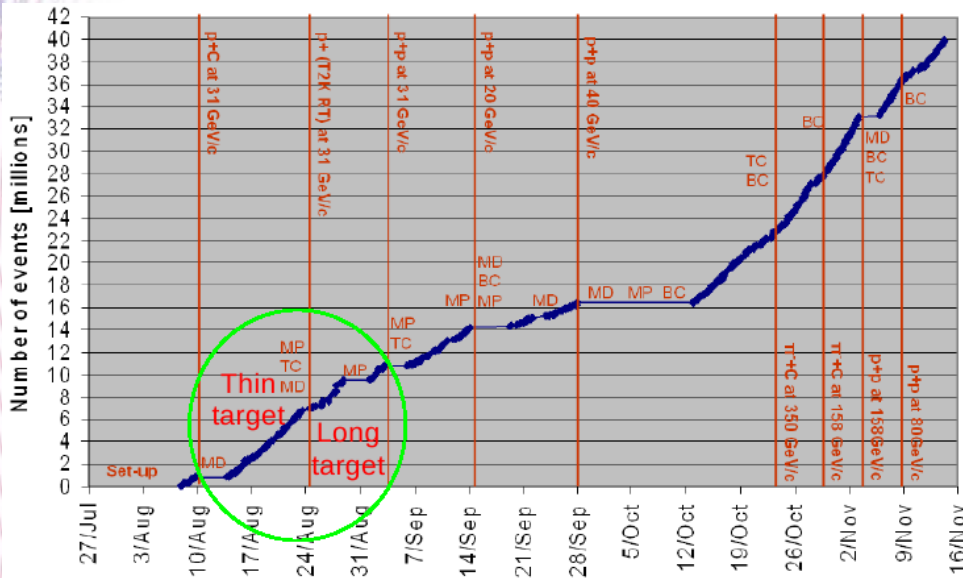
- Overall flux uncertainty 8% for  $\nu_{\mu}$  and  $\nu_e$ ,  
10% for  $\nu_{\mu}^-$  and 12% for  $\nu_e^-$

(NOMAD) P.Astier et al., NIM A515(2003)800

G.Collazuol et al., NIM A449(2000)609

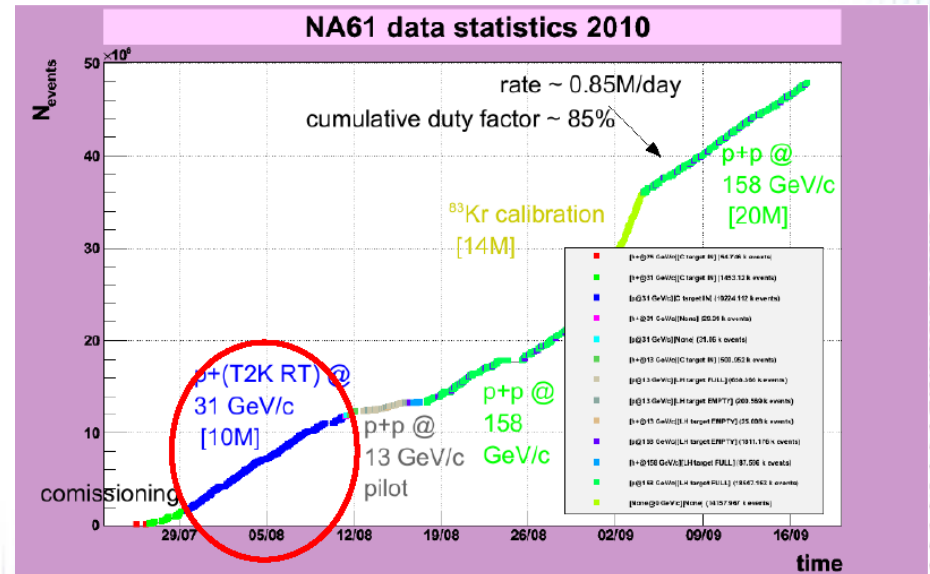


# Prospect for forthcoming results (data 2009 & 2010)

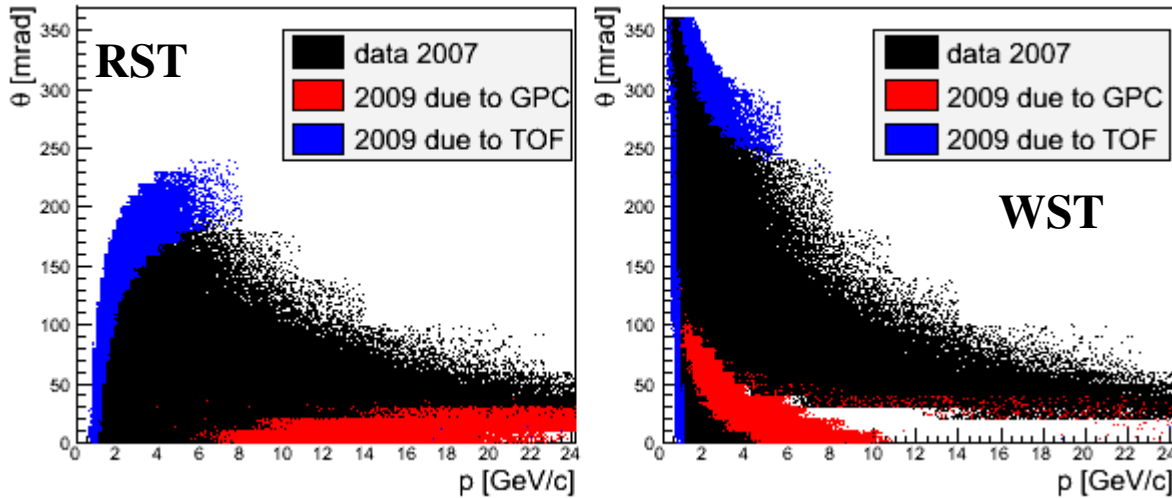


- About 10M events (thin+T2K replica target) collected in 2009
- Simultaneous extraction of  $\pi^\pm$ ,  $K^\pm$ ,  $p$ ,  $\bar{p}$  is possible
- Preliminary results this Autumn

- About 10M events in the T2K replica target configuration collected in 2010
- Alignment and calibration are ongoing
- Statistics should be well enough to get 3% error for the neutrino flux ratio as was requested by T2K



## Data 2009 vs. 2007



- **RST**: tracks which scatter in the direction of bending in the magnetic field
- **WST**: tracks which scatter with an angle opposite to the direction of bending

- Wider TOF-F => wider momentum interval at large scattering angles
- In the published analysis of 2007 the Gap TPC was not used (calibration was not ready at that time). Presently used in combination with MTPC
- Forward region can be *fully* covered by tracks reconstructed in the Gap TPC *only*. However without MTPC hits PID will not be available

## Derivation of spectra

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

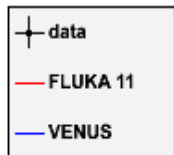
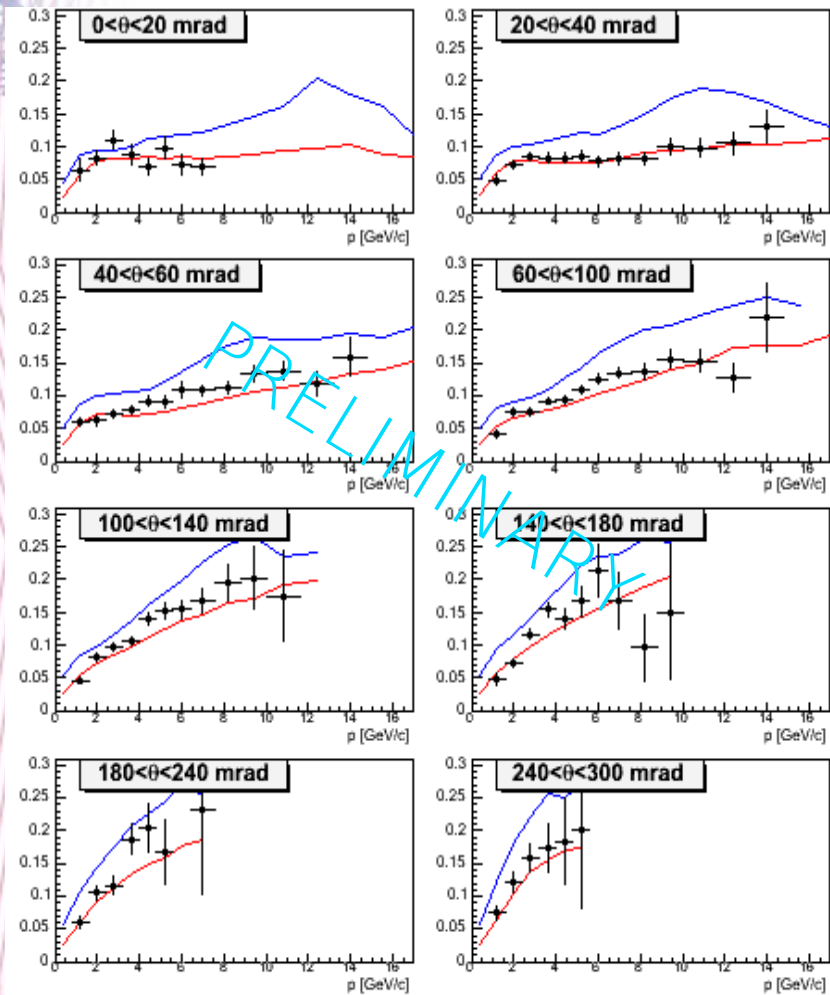
Hadron multiplicity  $\Rightarrow$

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

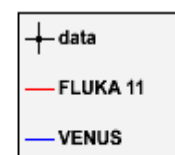
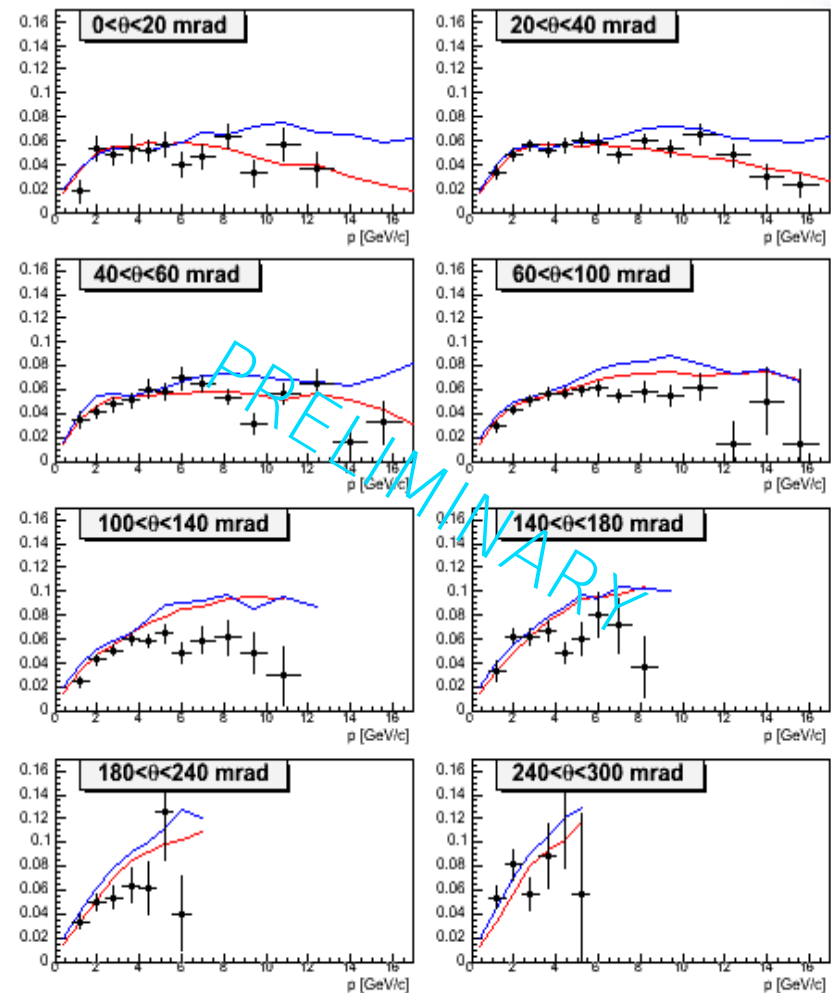
- Statistics for target 'in' and 'out'  
 $N^{in} = 2.5 \cdot 10^6$ ,  $N^{out} = 0.1 \cdot 10^6$
- ◆  $\sigma_{trig} = 305.7 \pm 2.7 \pm 1.2$  mb
- ◆  $\epsilon = P^{out}/P^{in} = 0.123 \pm 0.004$
- ◆  $\sigma_{prod} = 233.5 \pm 2.8 \pm 4.2 \pm 1.2$  mb



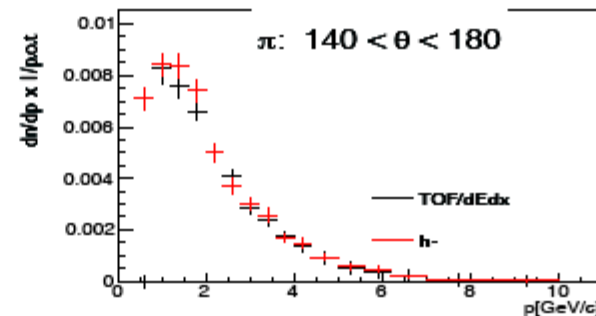
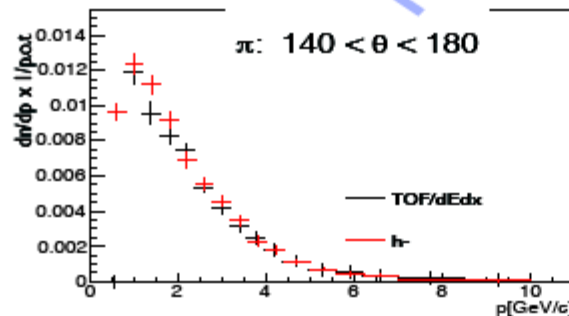
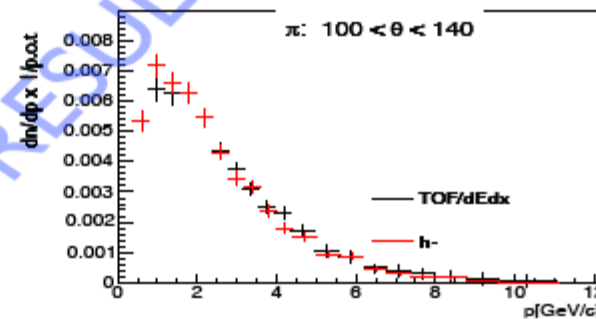
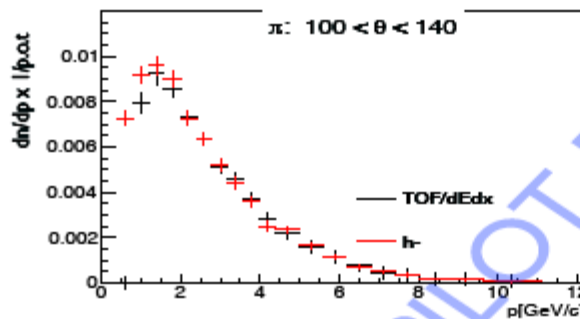
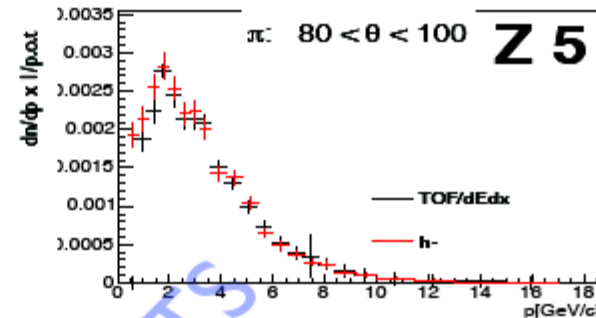
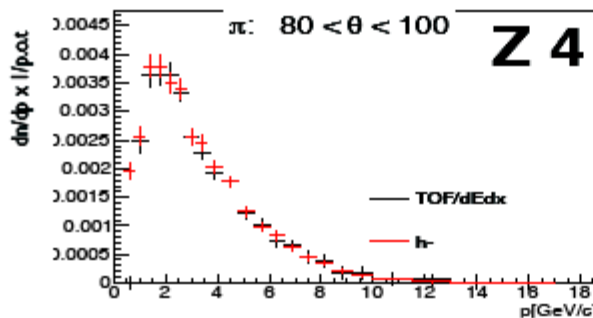
# Ratio $K^+/\pi^+$



# Ratio $K^-/\pi^-$



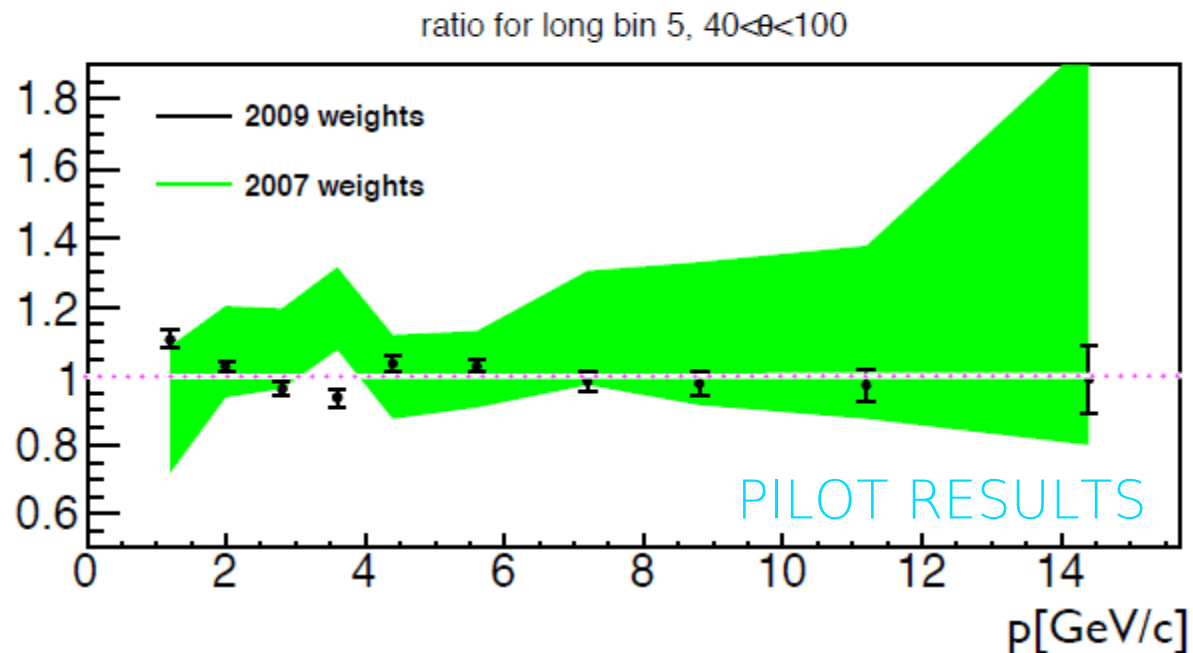
- ▶ two independent analyses for 2009  $\pi^-$  spectra:
  - ▶  $h^-$  analysis: consider all negative hadrons as pions, remove the electrons through dE/dx cut
  - ▶ combined TOF - dE/dx analysis: usual 2D fits for  $m^2$  versus dE/dx
- ▶ both analysis apply bin-by-bin MC corrections
- ▶ corrected spectra normalized to number of protons on target can be compared directly





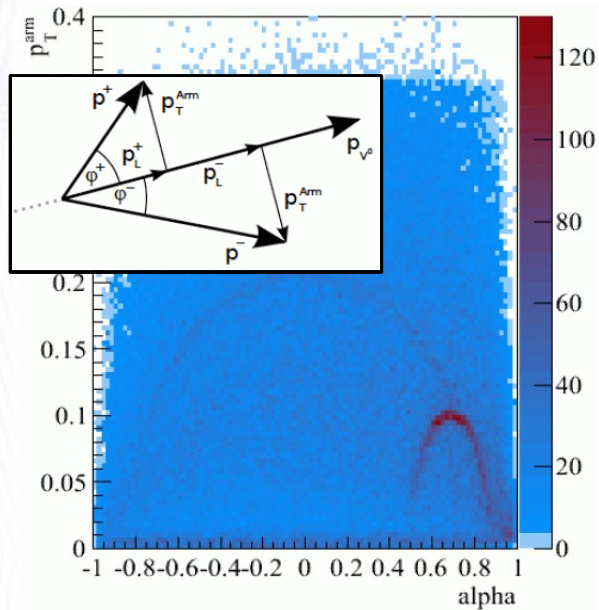
## 2007 - 2009 $\pi^+$ Comparisons

- ▶ no corrections for  $\pi^+$  2007 analysis (bin migration is not taken into account)
- ▶ bin-by-bin MC corrections for 2009 analysis
- ▶ for small  $\theta$  polar angles, longitudinal bin migration becomes large  $\Rightarrow$  comparisons of raw spectra and corrected spectra over model are consistent for large  $\theta$  angles



Ref: Pion emission from the T2K replica target: method, results and application  
Nuclear Inst. and Methods in Physics Research, A 701 (2013) pp. 99-114

# V0 analysis (data 2007)



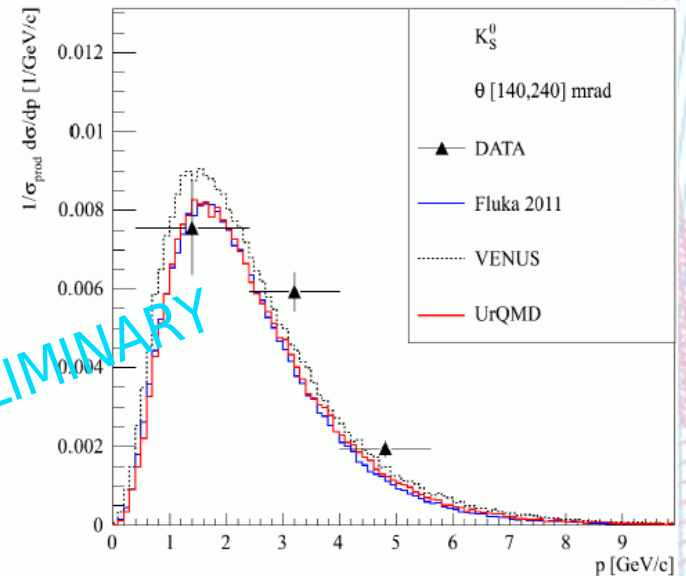
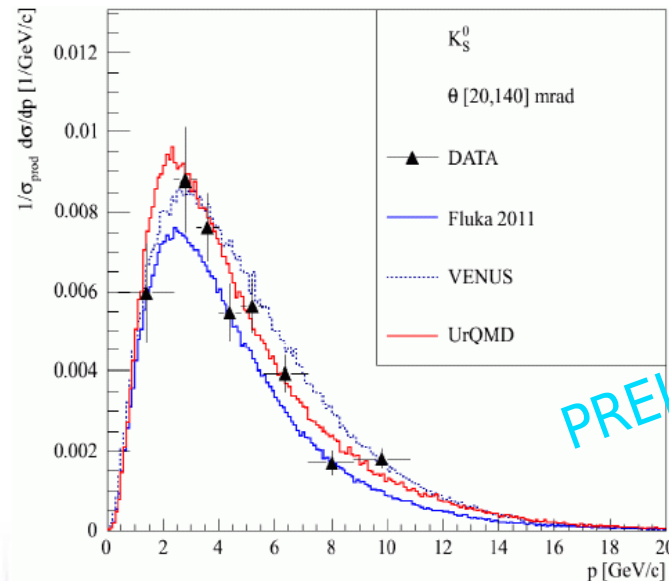
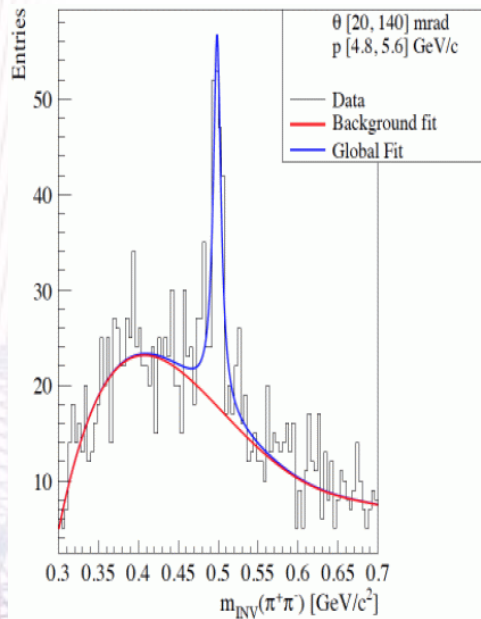
- Constraint on  $K^0$  multiplicity in T2K done (Eichten & Allaby data) assuming isospin symmetry

$$N(K_L^0) = N(K_S^0) = \frac{N(K^+) + 3N(K^-)}{4}$$

- Inclusive cross-section of  $K_S^0$  production corrected to the whole phase space is

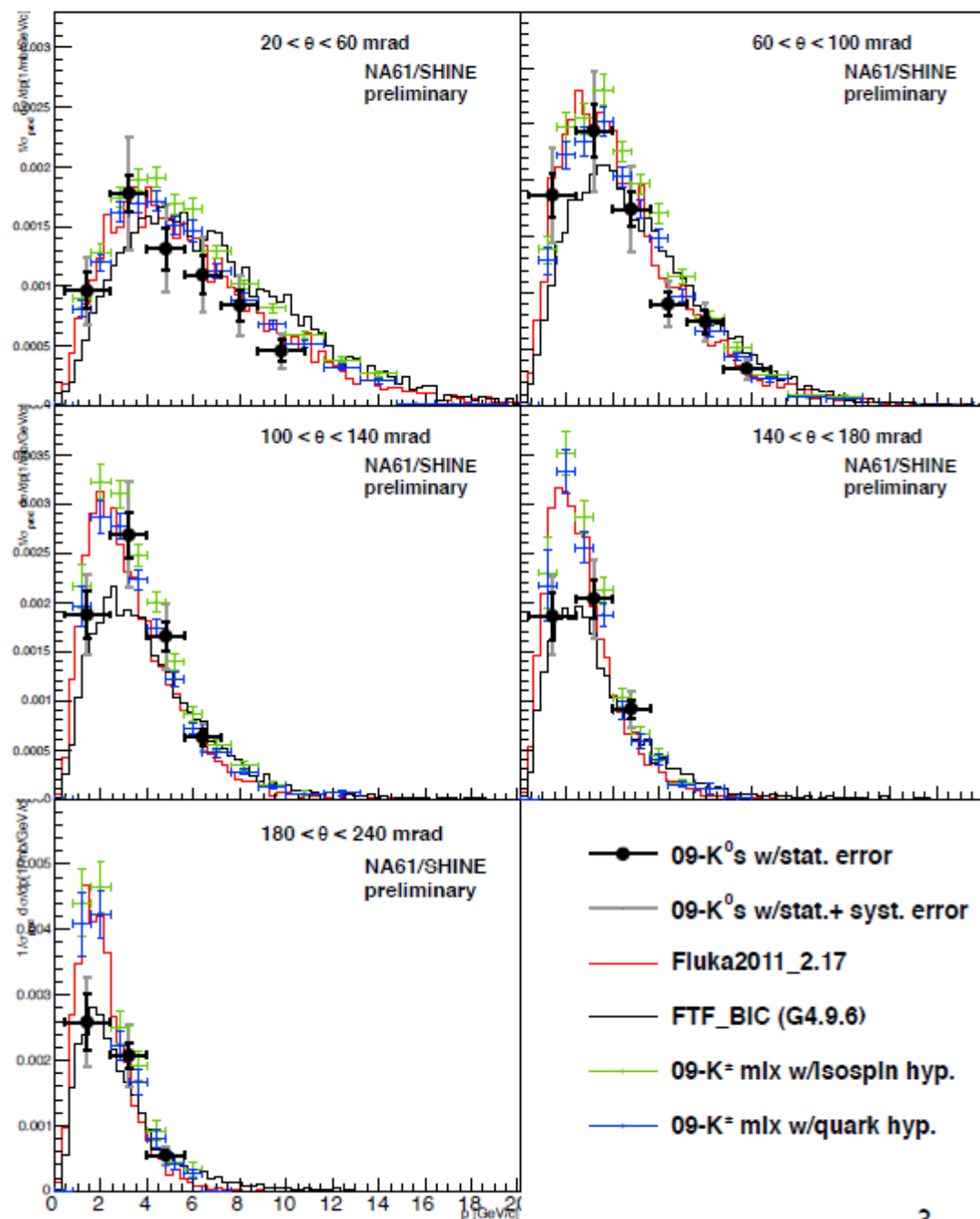
$$\sigma = 28.58 \pm 1.85(\text{stat}) \pm 1.72(\text{sys}) \text{ mb}$$

- T.Palczewski, PhD thesis, NCNR, Warsaw, 2012





# $K_s^0$ Analysis : Differential multiplicities



- The normalization use the standard NA61/SHINE approach

- Influence of short tracks due to electronic noise increase the amount of combinatorial background selected in this analysis. As a result, the statistical error is relatively large.

- Systematical uncertainties have been estimated out of 6 sources: fitting procedure, generator, kinematical and quality cuts, reconstruction algorithm and normalization. The error are at the order of 16 to 25%.

- Comparisons with different generator show are relative good agreement with Fluka and FTF\_BIC hadronic models.

- Comparisons with  $K^\pm$  measurements can be done in two ways:

- using the 'isospin hypothesis':

$$N(K_s^0) = \frac{1}{2}(N(K^+) + N(K^-))$$

- using the 'quark hypothesis':

$$N(K_s^0) = \frac{1}{8}(3 \cdot N(K^+) + 5 \cdot N(K^-))$$