Hadron production measurements from NA61/SHINE

Alexander Korzenev, Geneva University

on behalf of the NA61/SHINE collaboration

NUFACT 2013
Beijing, Aug 23

Outline

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

Few examples

hadroproduction experiments CERN	**neutrino 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

MIPP

In general results of several hadron production experiments are used

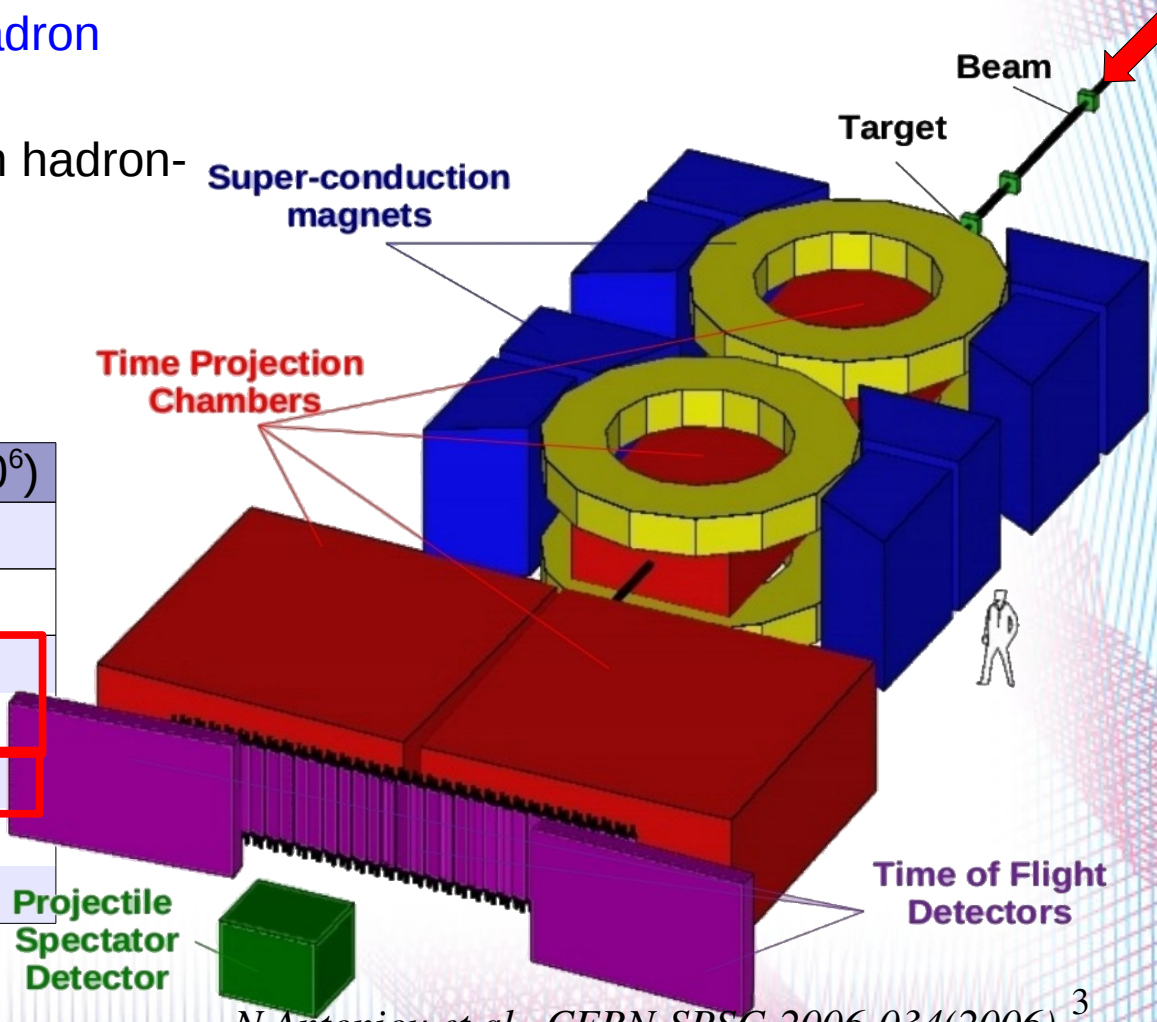
SPS Heavy Ion and Neutrino Experiment

- 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(x10^6)
π-	158	thin	2009	5.5
π-	350	thin	2009	4.6
p	31	thin	2007	0.7
			2009	5.4
p	31	T2K replica	2007	0.2
			2009	4
			2010	10



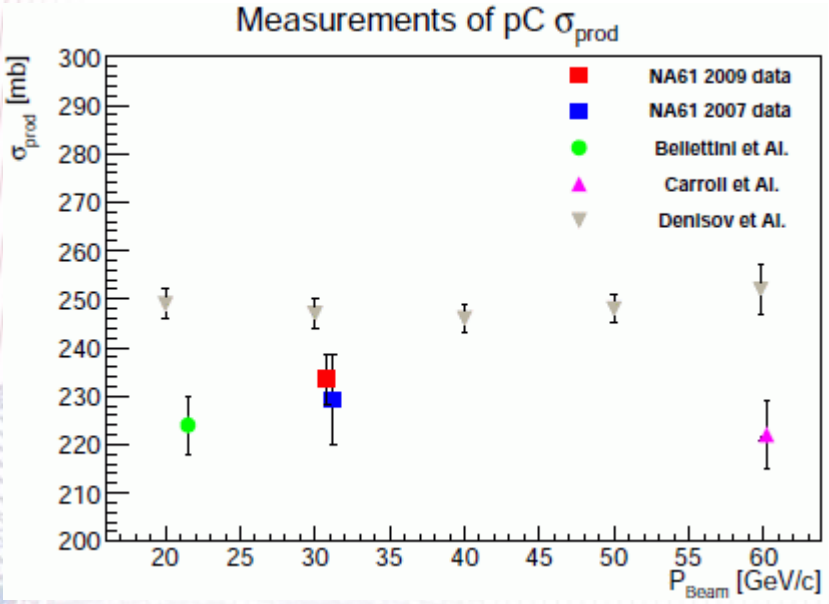
N.Antoniou et al., CERN-SPSC-2006-034(2006)

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 $\sigma_{quasi\text{-}el.}$ have been estimated with GEANT4



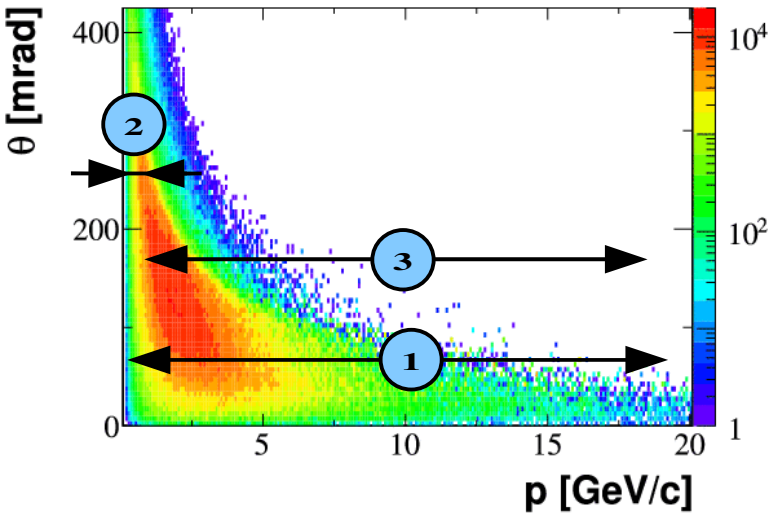
$$\sigma_{prod}^{2007} = 229.3 \pm 1.9\,(stat.) \pm 9.0\,(syst.)\ \ mb$$

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

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

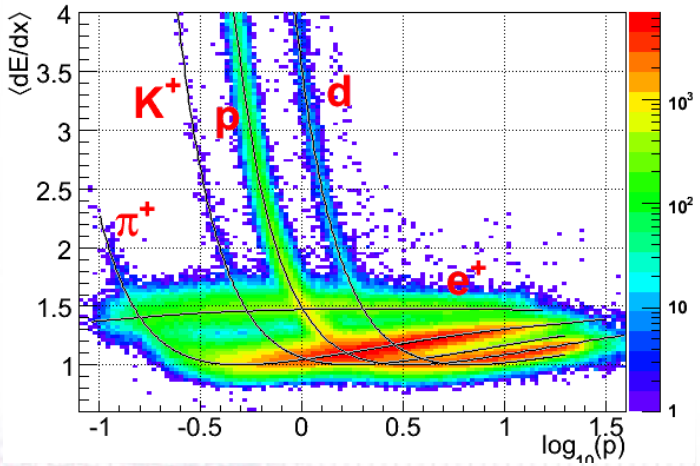
$$\frac{dn_{\alpha}}{dp} = \frac{1}{\sigma_{prod}} \frac{d\sigma_{\alpha}}{dp}$$

Analysis techniques (data 2007)

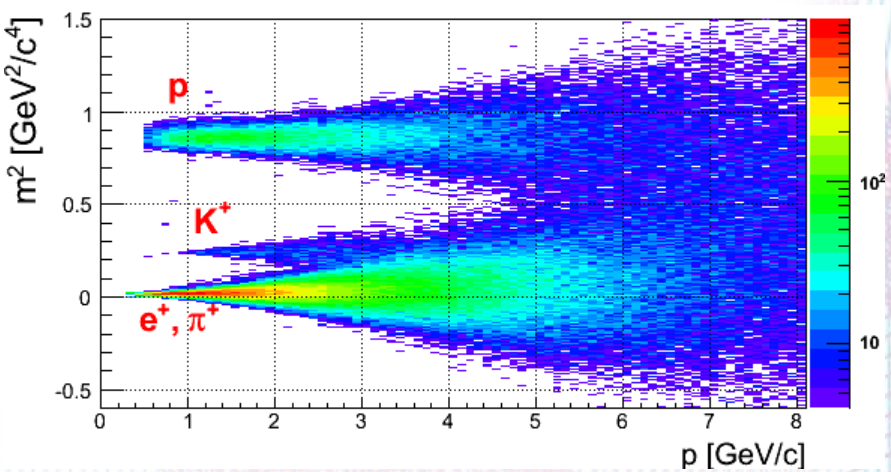


1) **h^- analysis**: analysis of π^- via measurements of negatively charged particles
2) ***dE/dx* analysis at *p*≲1GeV/*c***: $\pi^{\pm}$ and protons were identified via energy loss in TPC
3) **ToF-*dE/dx* analysis at *p*≳1GeV/*c***: information from *dE/dx* and ToF is combined to identify $\pi^{\pm}$,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

Energy loss in TPC (*dE/dx*)



Time-of-Flight (ToF)



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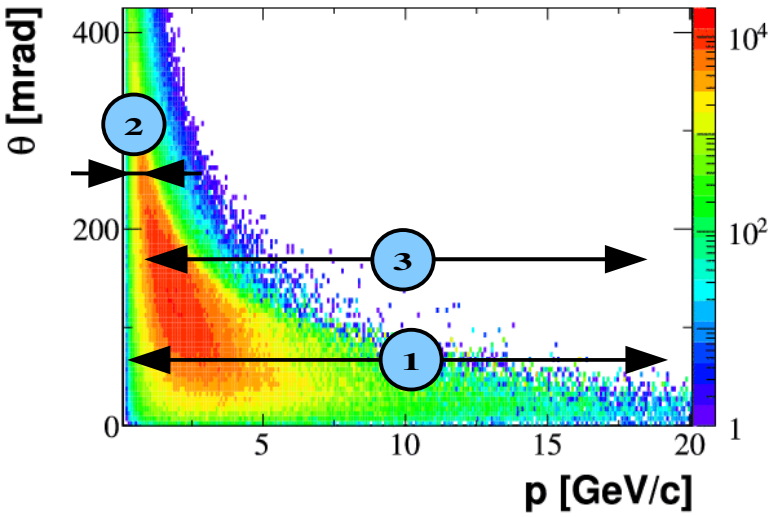

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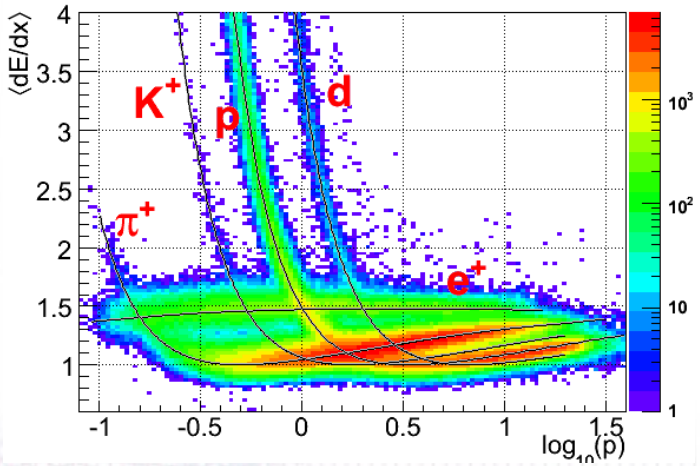
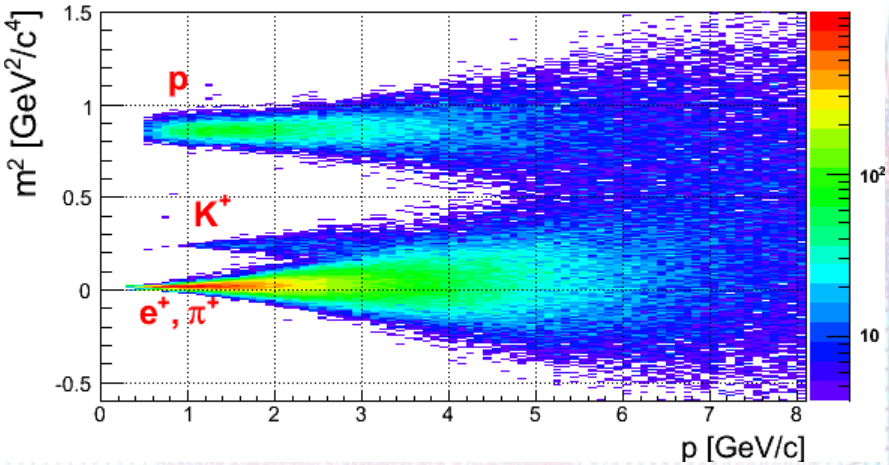
Data 2009

Energy loss in TPC (*dE/dx*)

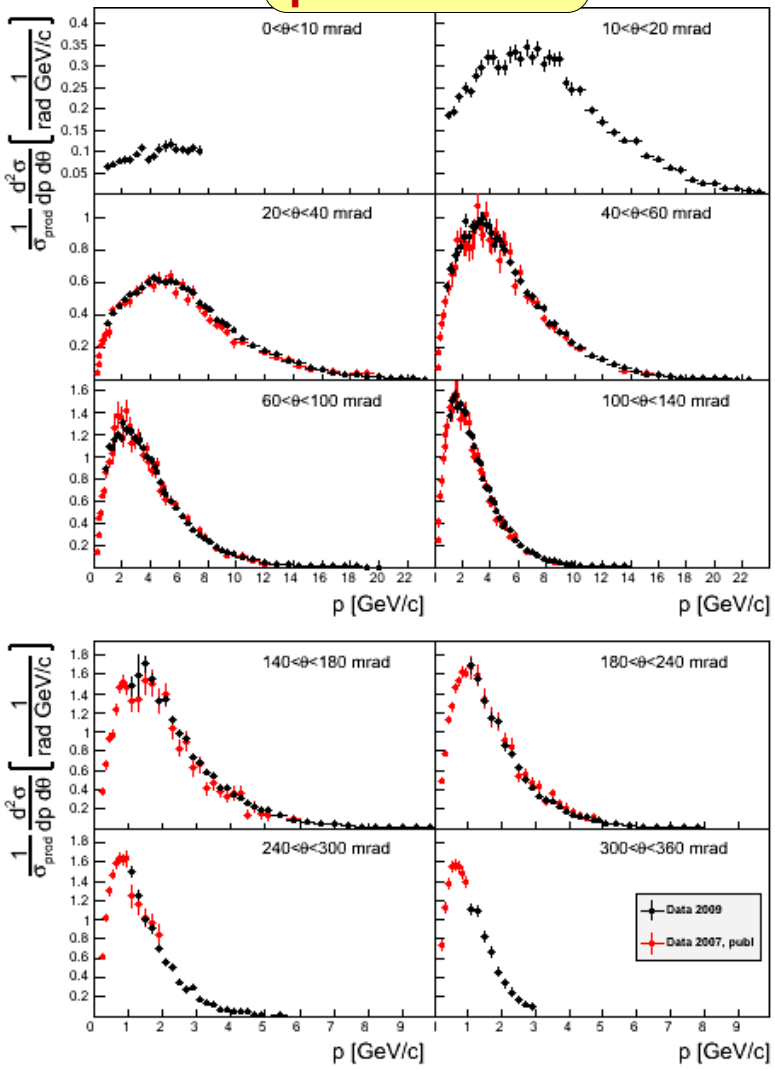


Time-of-Flight (ToF)

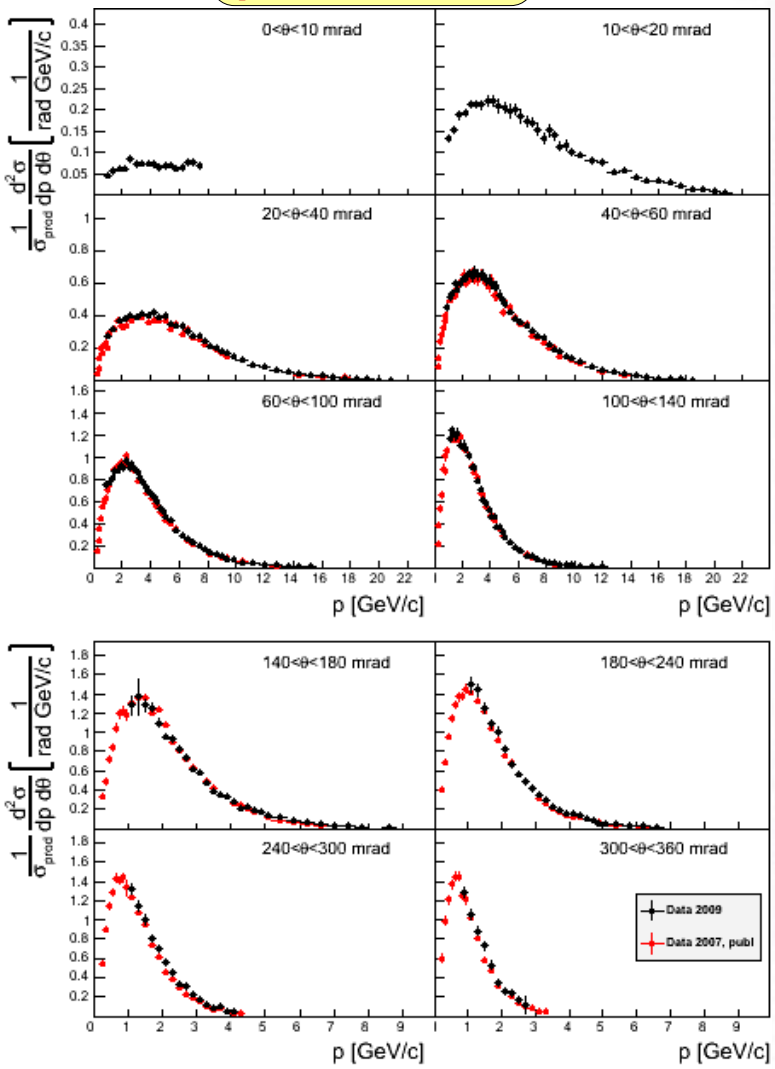


New results on π^+ and π^- multiplicity in pC @ 31 GeV/*c*

p + C → π^+ + X



p + C → π^- + X



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

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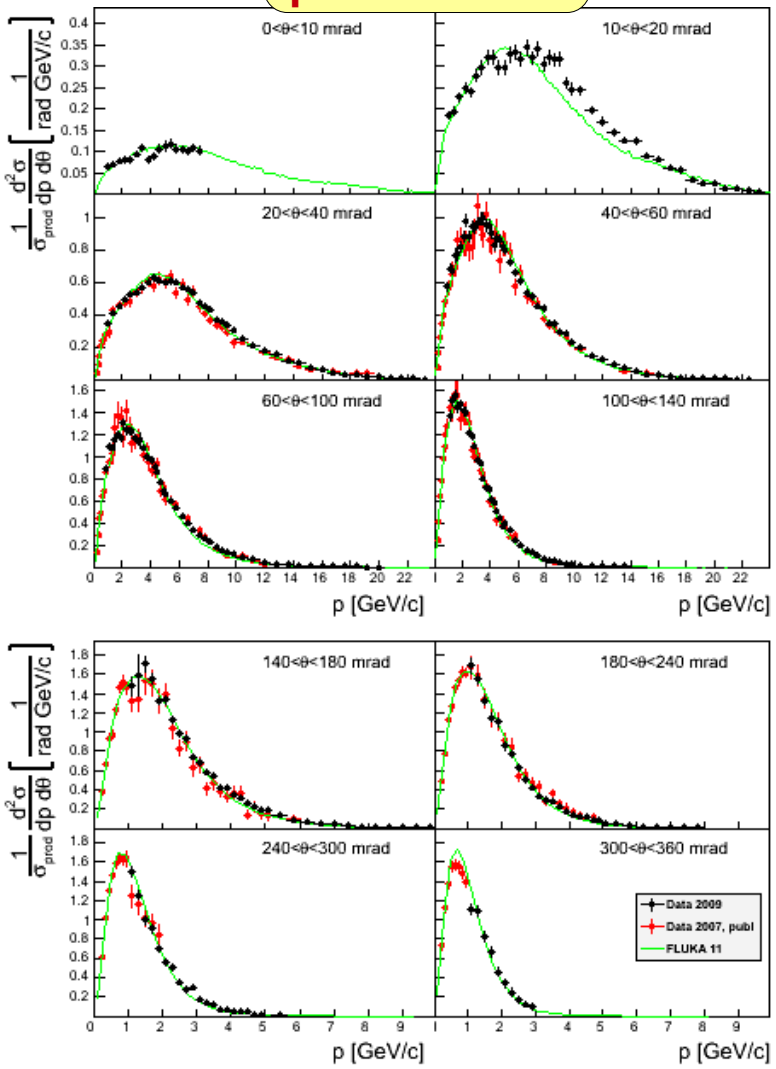
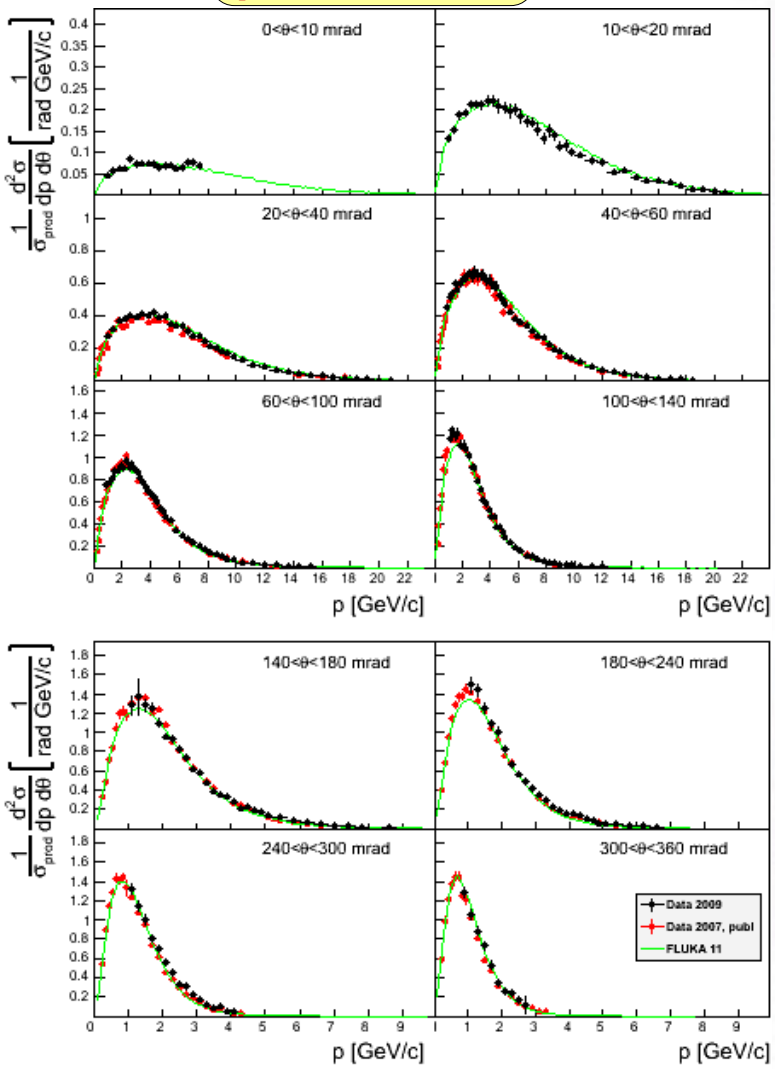
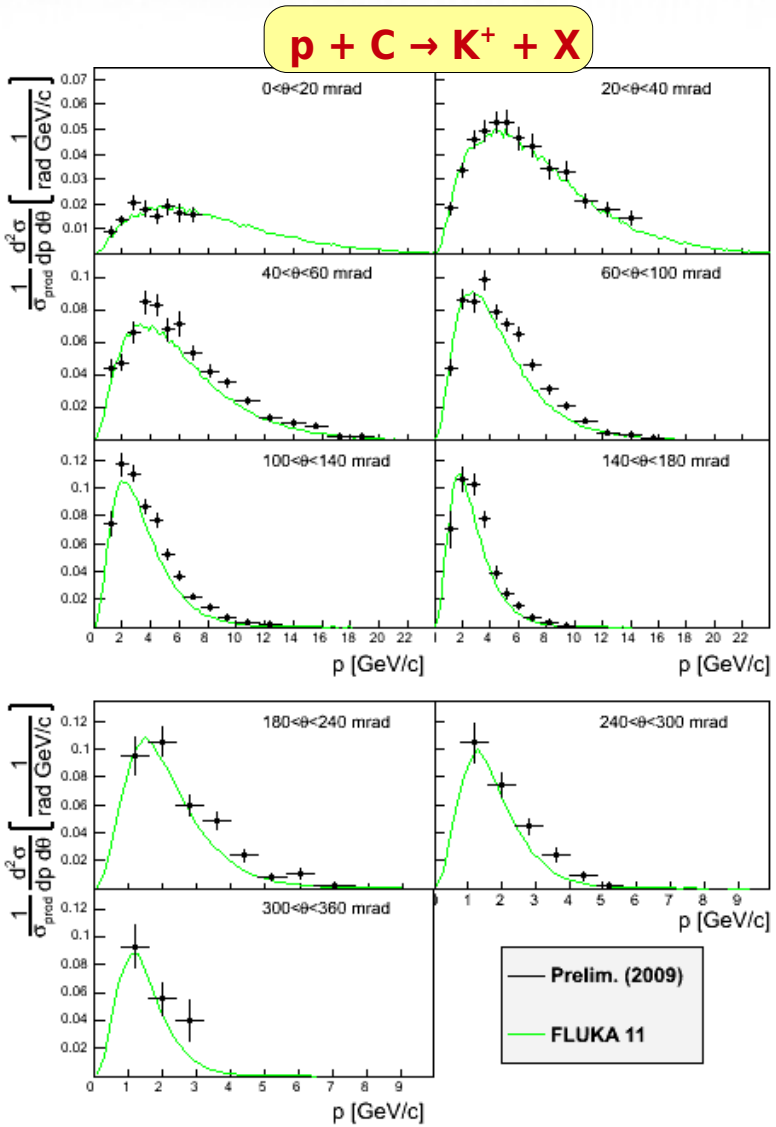


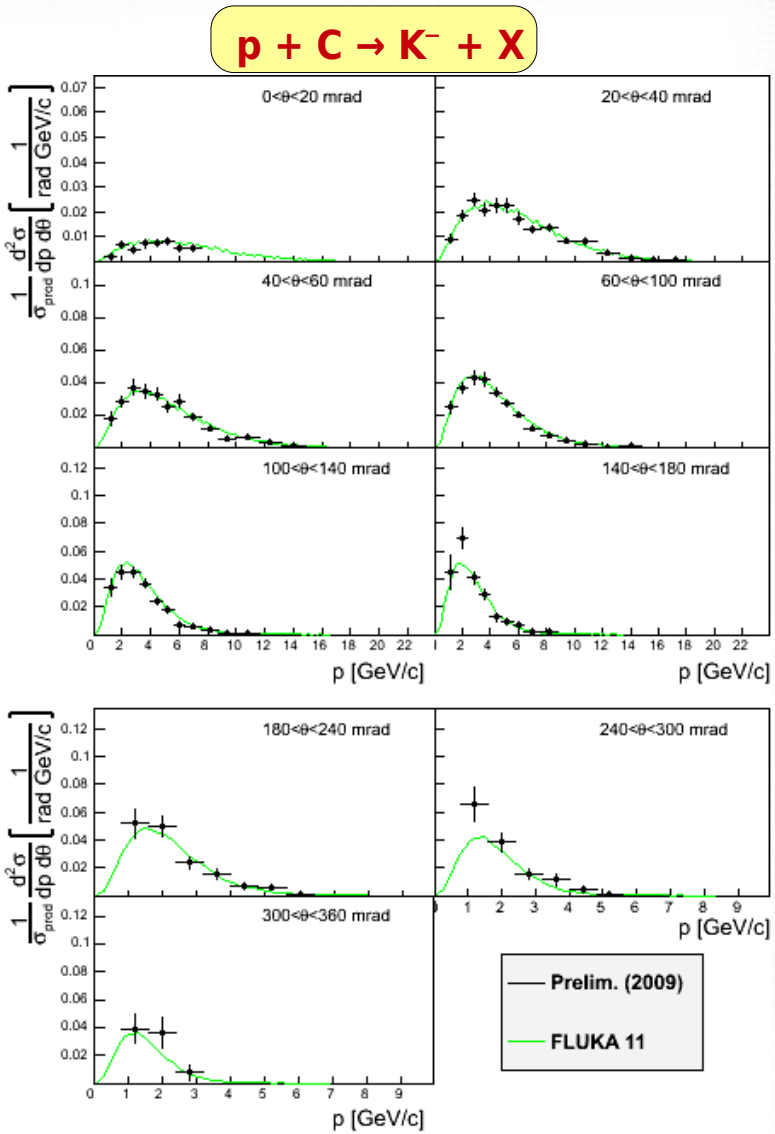
p + C → π^- + X



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

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

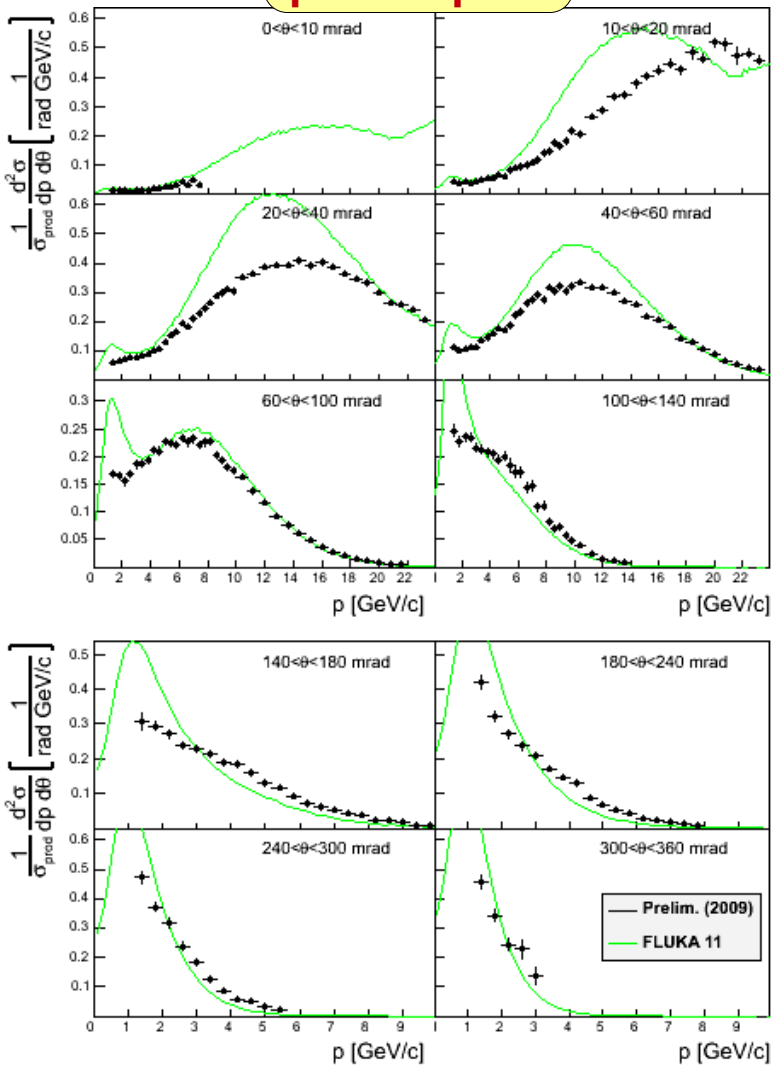




- Statistical uncertainty (and total uncertainty) **improved by a factor 3**
- **K^- are shown for the first time.** Analysis with data 2007 was not possible due to low statistics

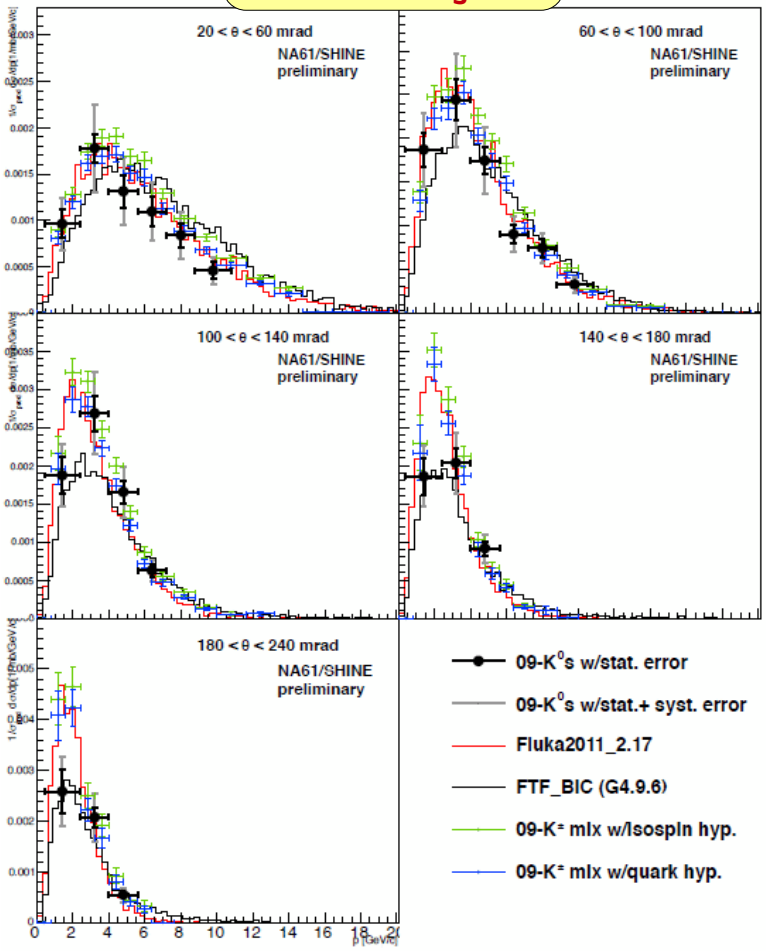
New results on proton and K^0_s multiplicity in pC @ 31 GeV/*c*

p + C → p + X



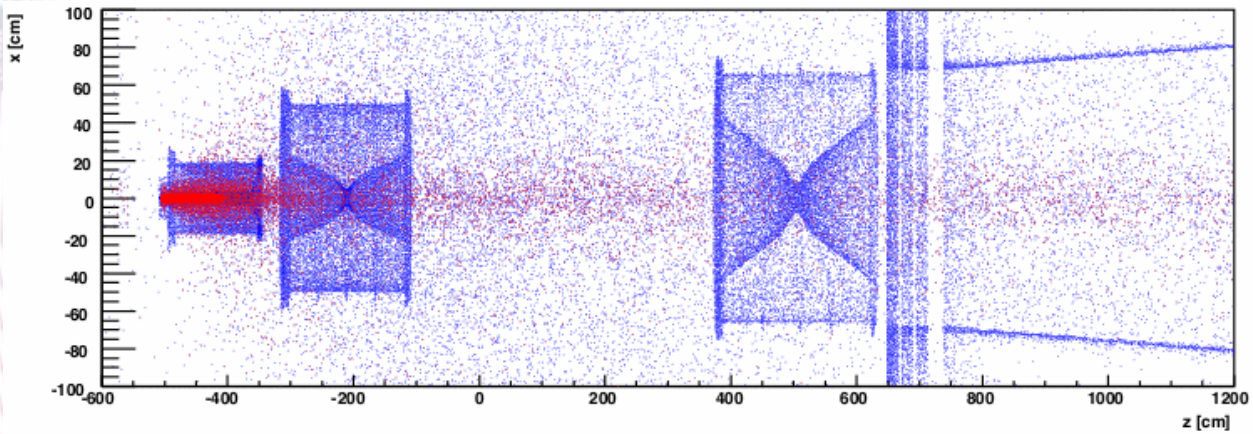
- To be used in the T2K beam simulation to decrease the systematics due to the secondary nucleon production

p + C → K^0_s + X



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

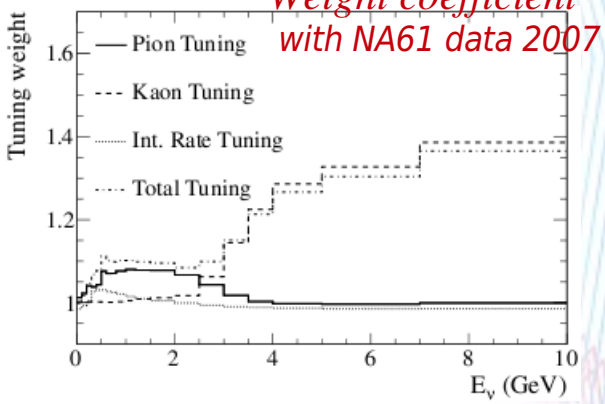
NA61 data in the T2K experiment



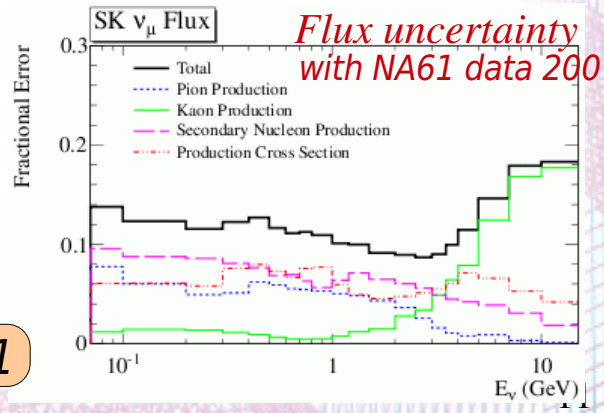
Hadronic interactions in the target are modeled with FLUKA, outside the target with GEANT3 (GCALOR)

- 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 $\sin^2 2\theta_{13}=0$ (ν_e *appearance paper of T2K arXiv: 1304.0841*)
  - **Due to flux: 8.5%, Total: 13%**

Weight coefficient with NA61 data 2007

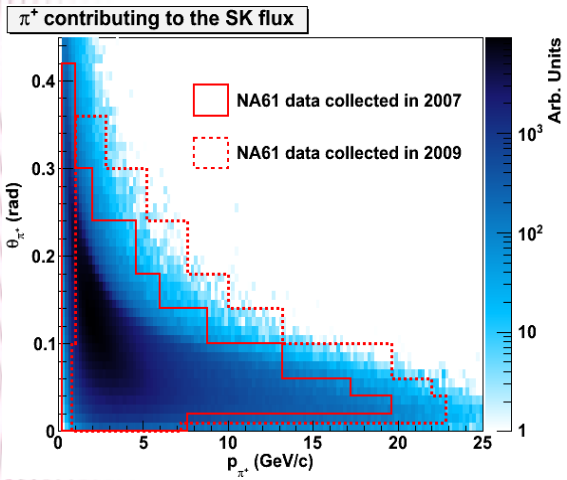


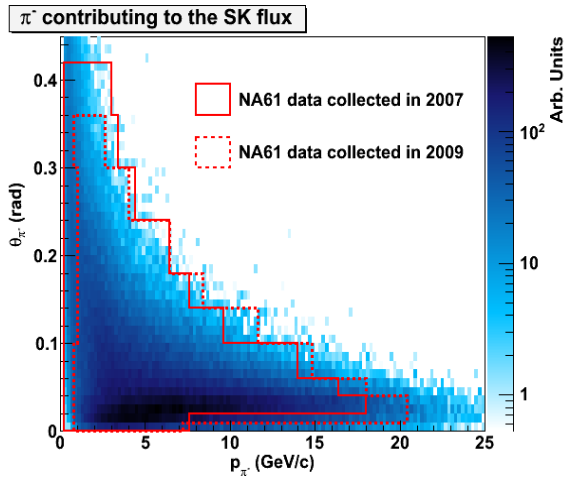
Flux uncertainty with NA61 data 2007



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

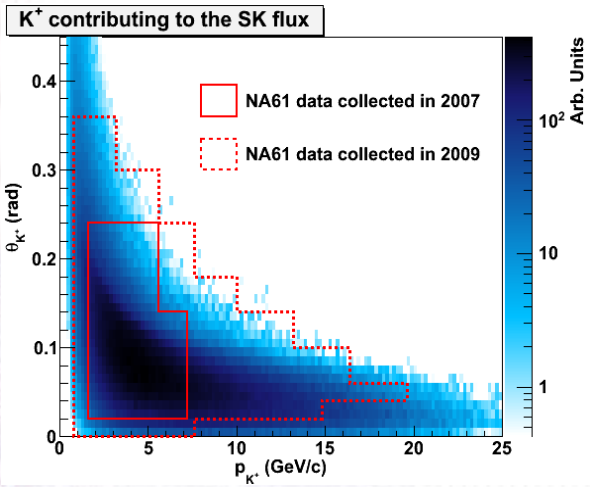
The phase space of hadrons contributing to the predicted ν flux at SK

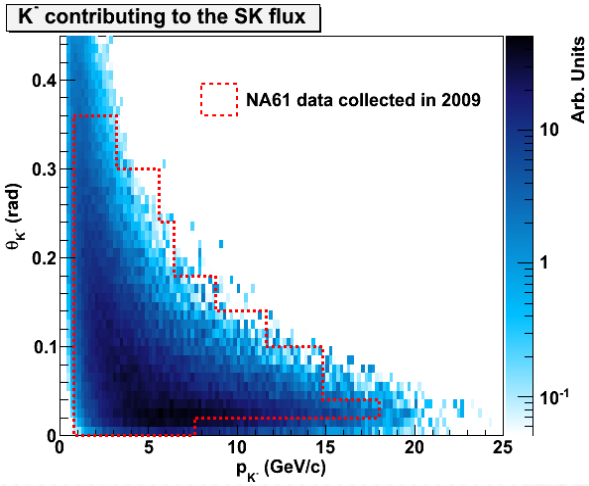


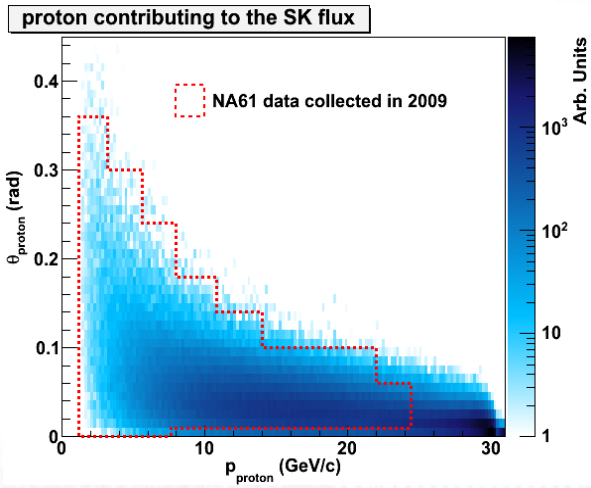


Summary of ν flux uncertainty on N_{SK}^{exp} assuming $\sin^2 2\theta_{13}=0$ (first ν_e analysis)

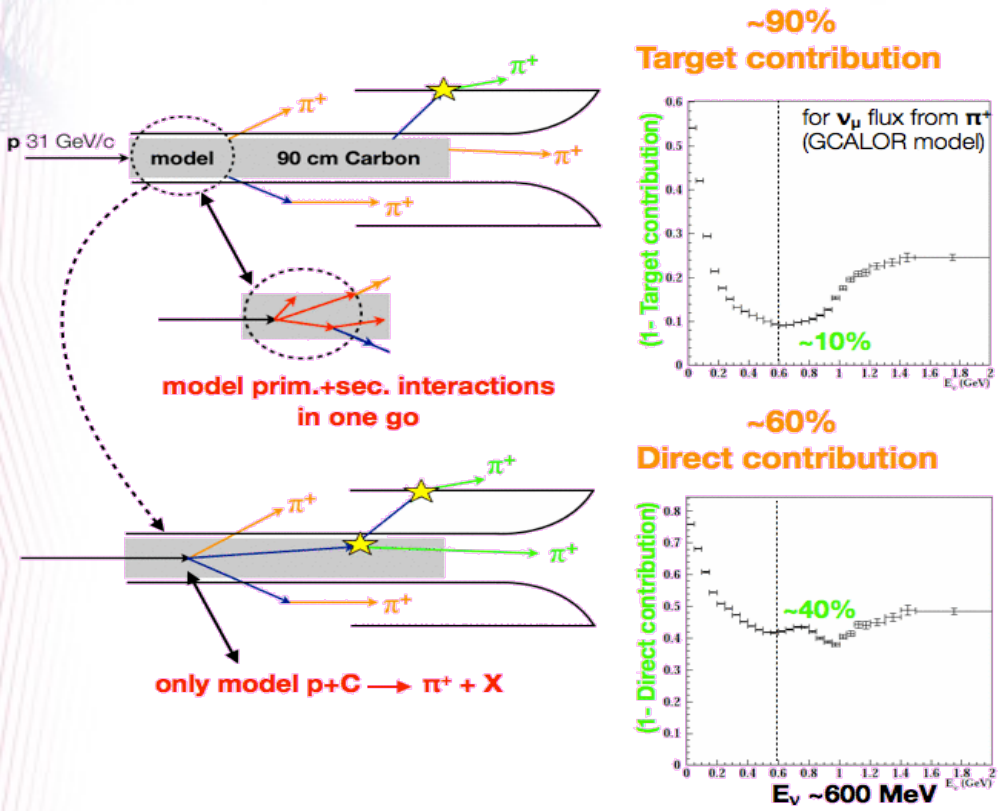
Error source	$N_{SK}^{MC}/R_{ND}^{\mu,MC}$
Pion production	2.5%
Kaon production	7.6%
Nucleon production	1.4%
Production x-section	0.7%
Proton beam posit/profile	2.2%
Beam direction measur.	0.7%
Target alignment	0.2%
Horn alignment	0.7%
Horn abs. current	0.2%
Total	8.5%





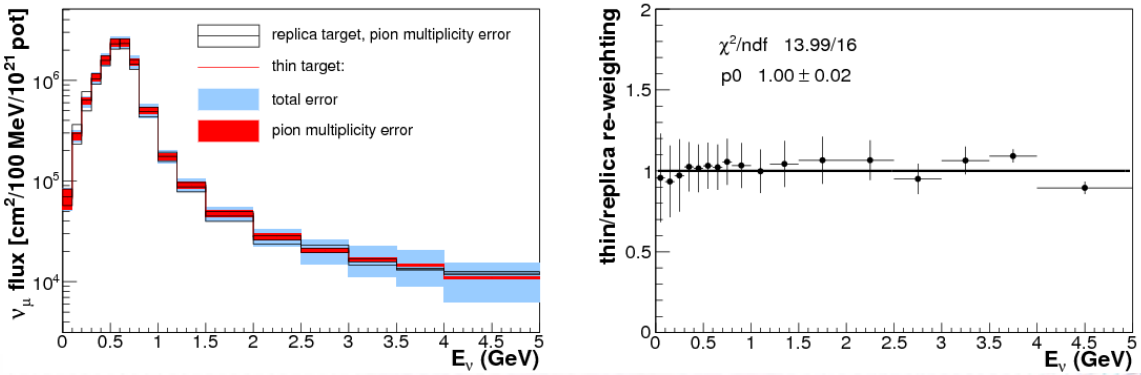


Alternative approach to the ν flux prediction in T2K



- Hadron multiplicities are parametrized **at the target surface** (no vertex reconstruction)
- Analysis in bins of (p, θ, 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)

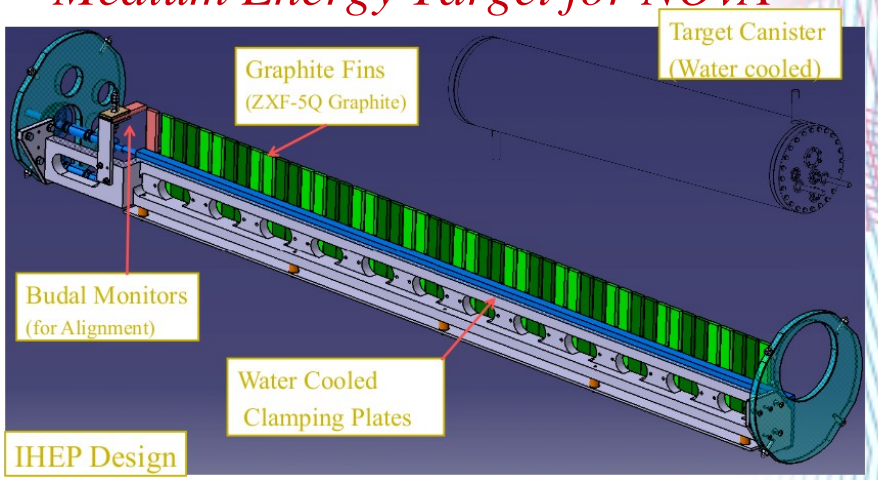


(NA61) N.Abgrall et al., NIM A701(2003)99

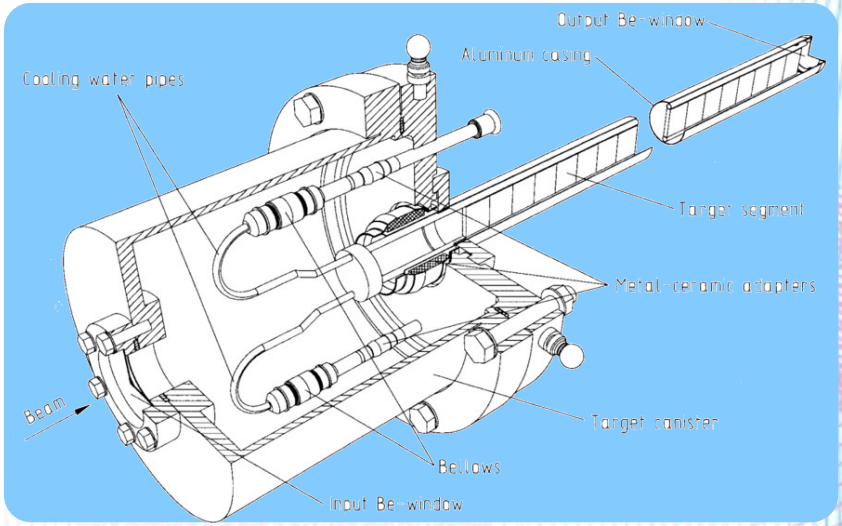
Measurements for the NuMI target

- 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

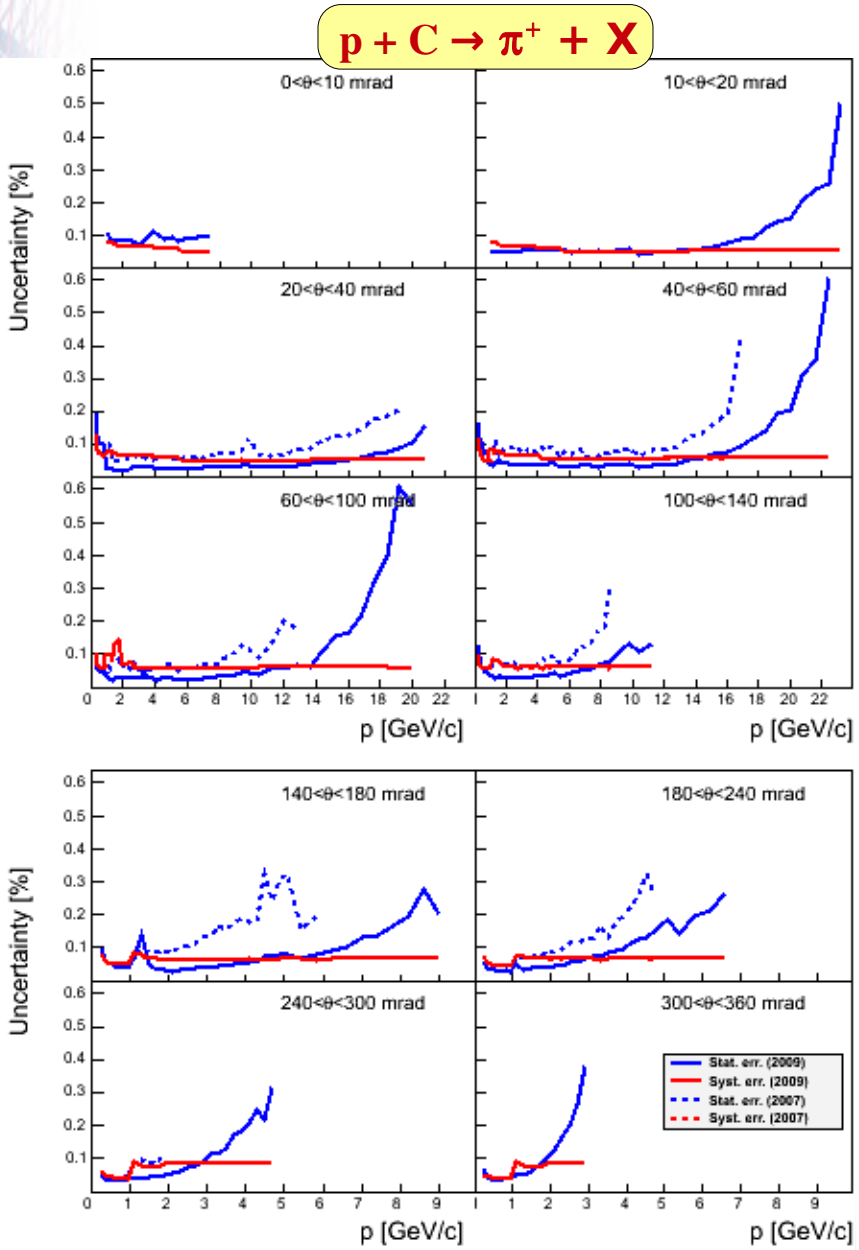
- First release of results for pC @ 31 GeV/*c* based on statistics 2009
- Spectra of $\pi^{\pm}$, $K^{\pm}$, K^{0}_{s} and protons have been presented
  - Statistical precision improved by a factor of 2-3
  - First results of NA61 for K^{-}
  - Upper limit for the systematic uncertainty. To be improved
- 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

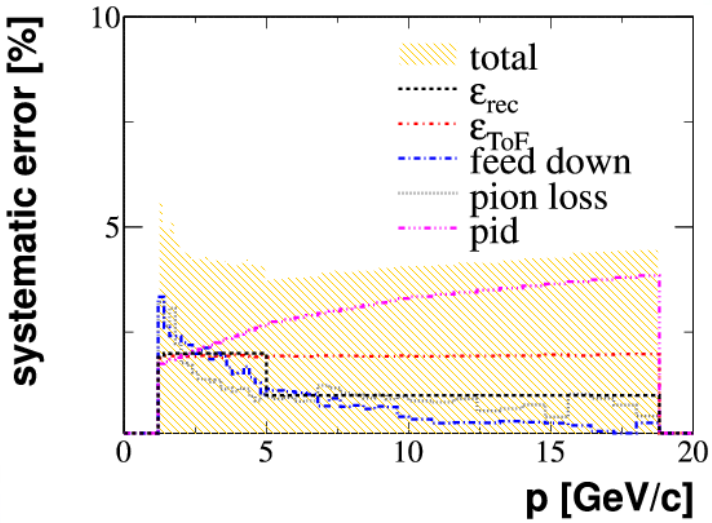
Summary & conclusion

- 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*

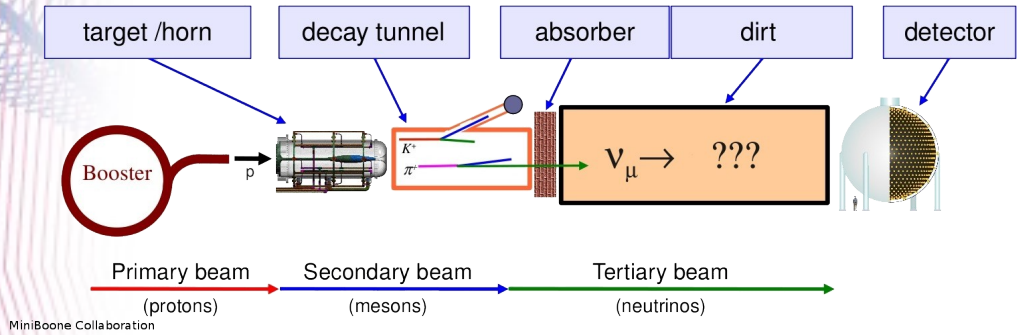
Statistical and systematic errors



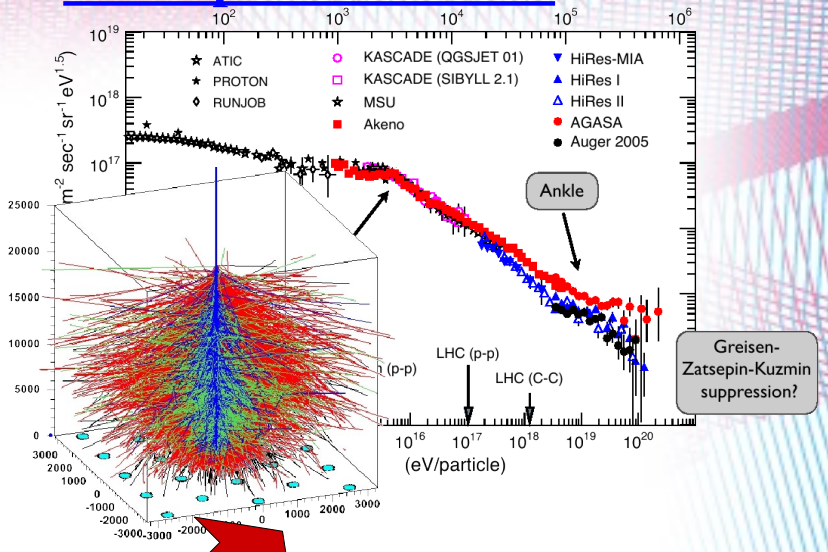
- Statistical uncertainty data 2009 vs. 2007 **improved by a factor 2-3**
- Systematic error from analysis of data 2007 ⇒ an upper limit. **To be improved**
- Possible improvement:
  - PID error can be smaller due to larger statistics
  - Uncertainty on feed down correction can be smaller once V0 is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



Conventional accelerator ν-beam



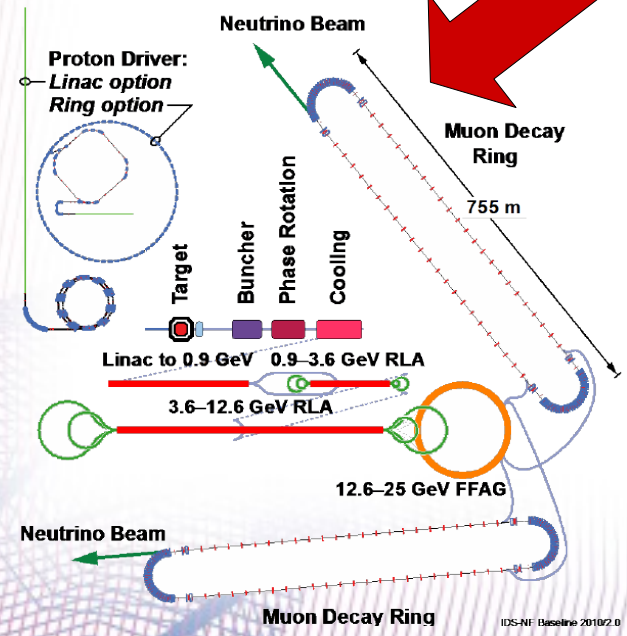
Atmospheric showers



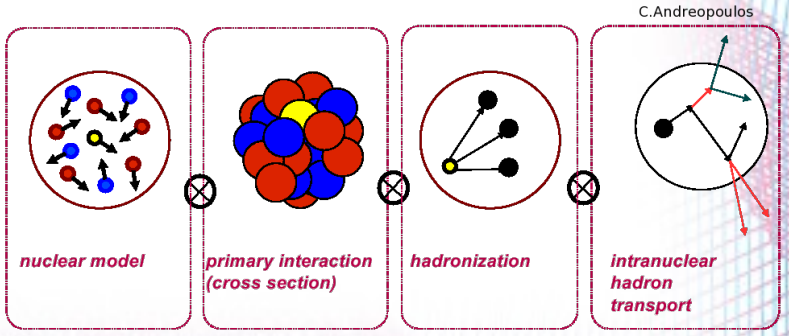
Hadroproduction measurement

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

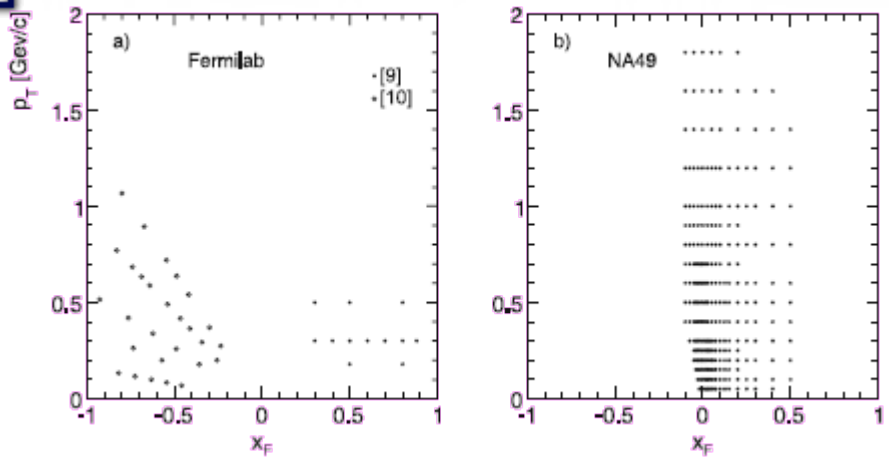
Neutrino Factory



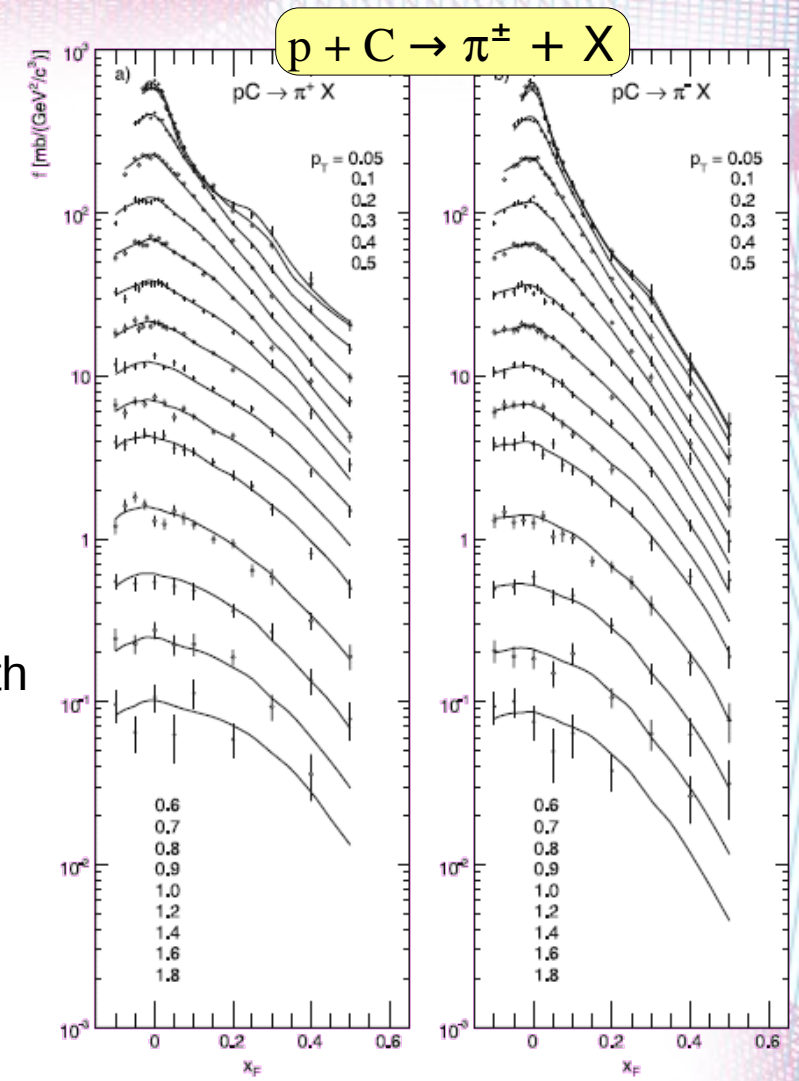
MC generators



Results from NA49



- Dense coverage of the projectile hemisphere
- Sample of 0.37 M inelastic events => only 8% with respect to the p+p sample
- Statistics can be increased by 1-2 orders in NA61



MINOS *Phys.Rev.Lett.107(2011)021801*

- Production of hadrons in NuMI is constrained by fits to the ND data
- π^+/π^- measurements from NA49 are included as constrains in these fits
- No significant effect for the predicted FD energy spectrum

beam	E_{beam}	target	second.	ref
p	158	p	$K^{\pm}$	Eur.Phys.J.C45(2006)343
p	**158**	**C**	$\pi^{\pm}$	**Eur.Phys.J.C49(2007)897**
p	158	p	p,$\bar{p}$,n	Eur.Phys.J.C65(2010)9
p	158	p	$K^{\pm}$	Phys.Rev.C68(2010)1

Normalization and σ_{prod} measurement

Results

Davide Sgalaberna

✦ Trigger cross section:

agreement within 1σ with 2007 measurement

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

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

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

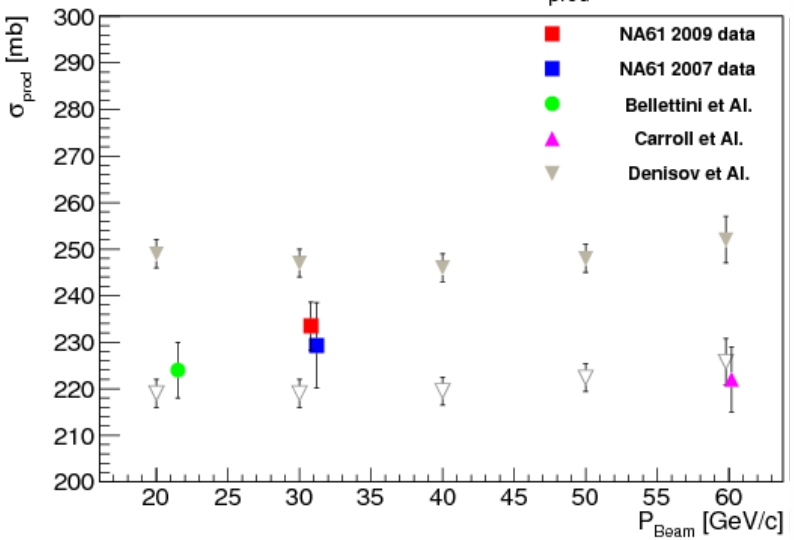
- $\sigma_{el\text{-}Out}$: el-scattering outside the acceptance of the interaction trigger counter (S_4)
- $\sigma_{loss\text{-}x}$: forward produced hadrons hitting S_4

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

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

Correction were estimated with GEANT4

Measurements of pC σ_{prod}



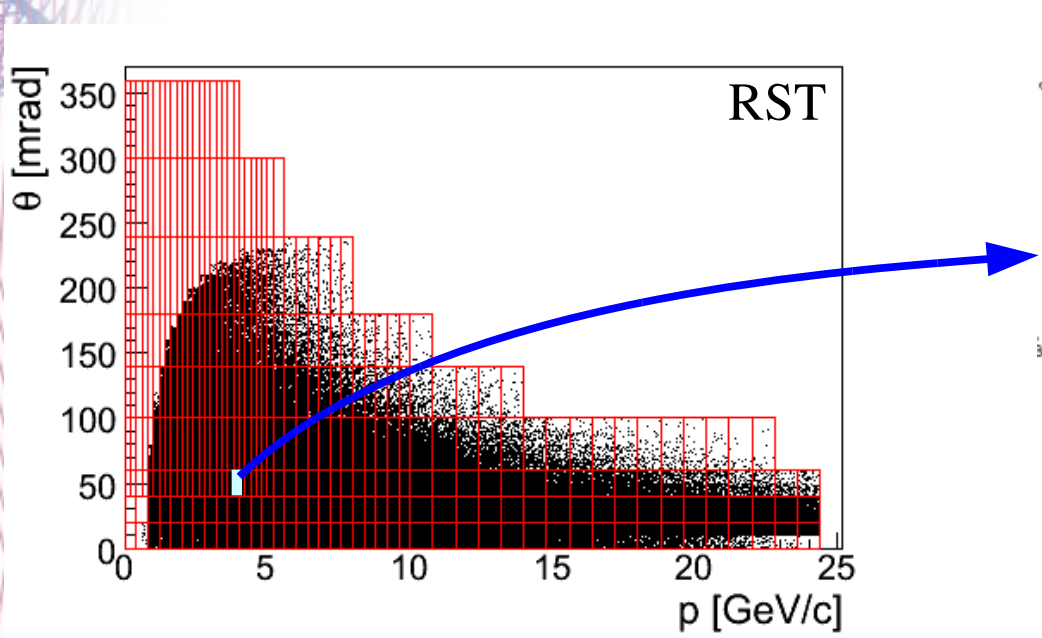
$$\sigma_{prod} = 233.5 \pm 2.8(stat) \pm 4.2(model)^{+1}_{-1.2}(trigger) \text{ mb}$$

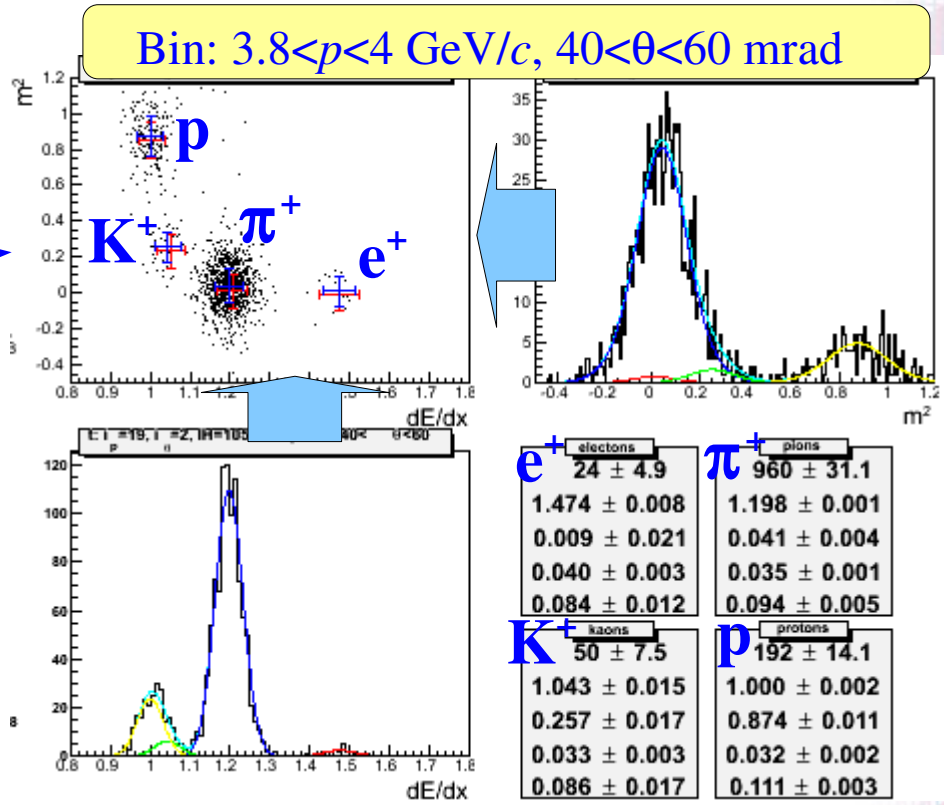
$$\sigma^{2007}_{prod} = 229.3 \pm 1.9(stat) \pm 9.0(syst) \text{ mb}$$

Normalization analysis is completed

Total uncertainty from 4% (2007) to 2%

Technique of combined ToF- *dE/dx* analysis



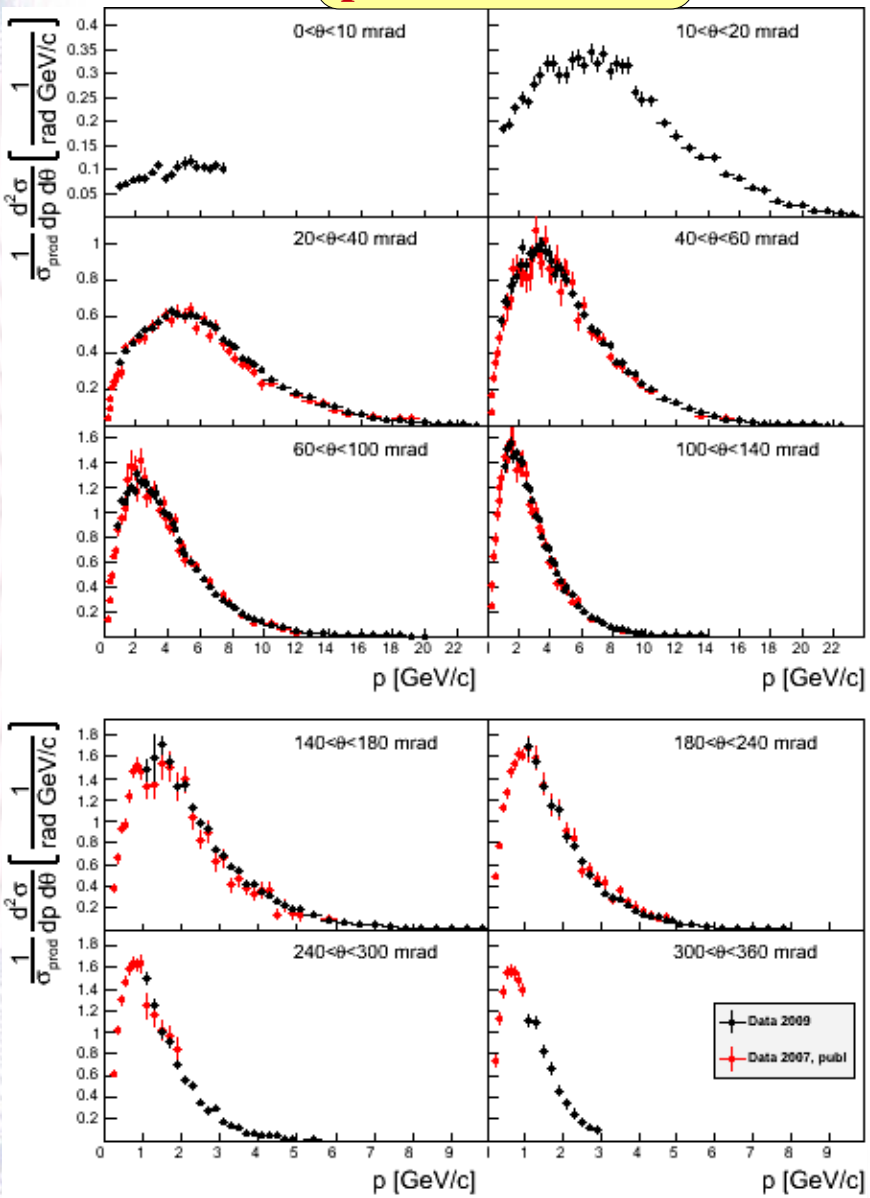


- Signal is parametrized as a product of Gaussian functions in m^2 and *dE/dx*
- For each (p,θ) bin the maximum likelihood method was applied to fit the shape

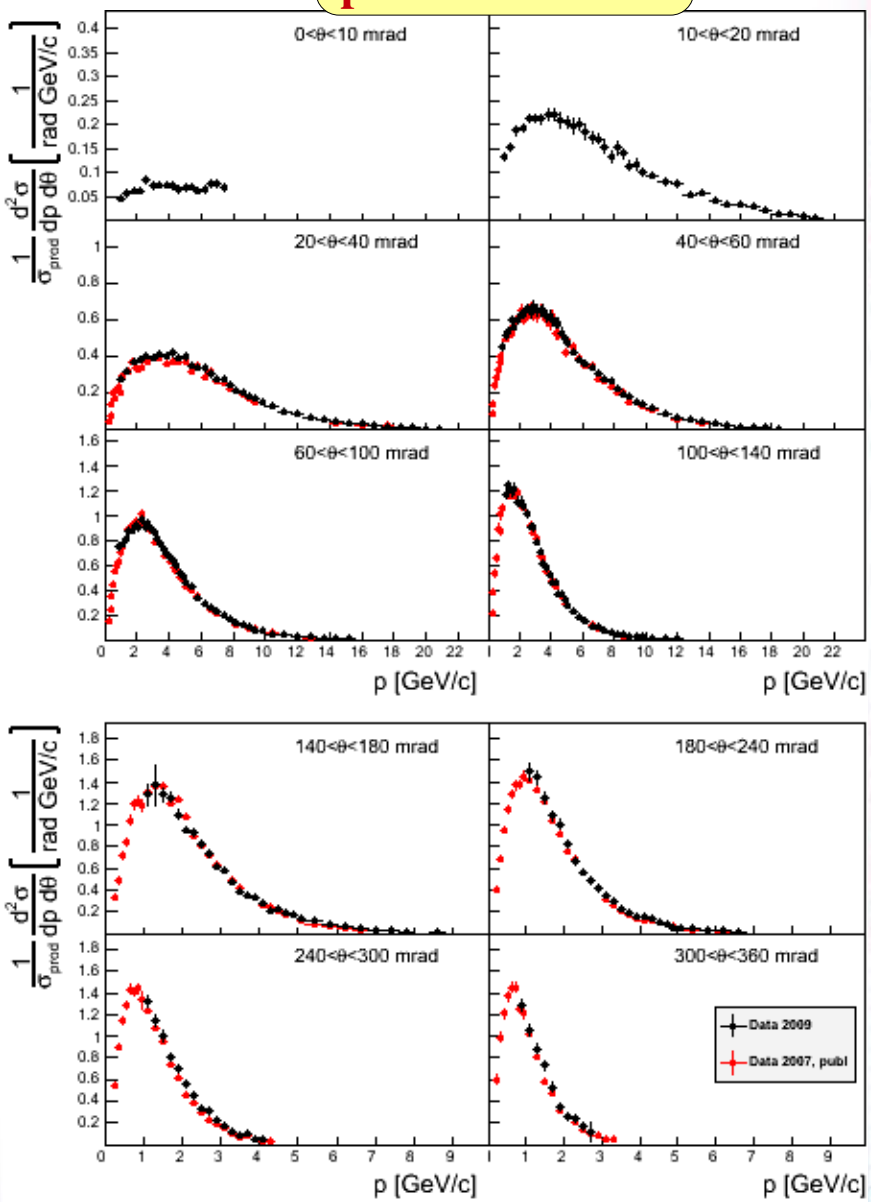
- Uncertainty associated to the unknown functional form is a dominant contribution to the systematic error at $p \gtrsim 2$ GeV/*c*

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

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



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



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

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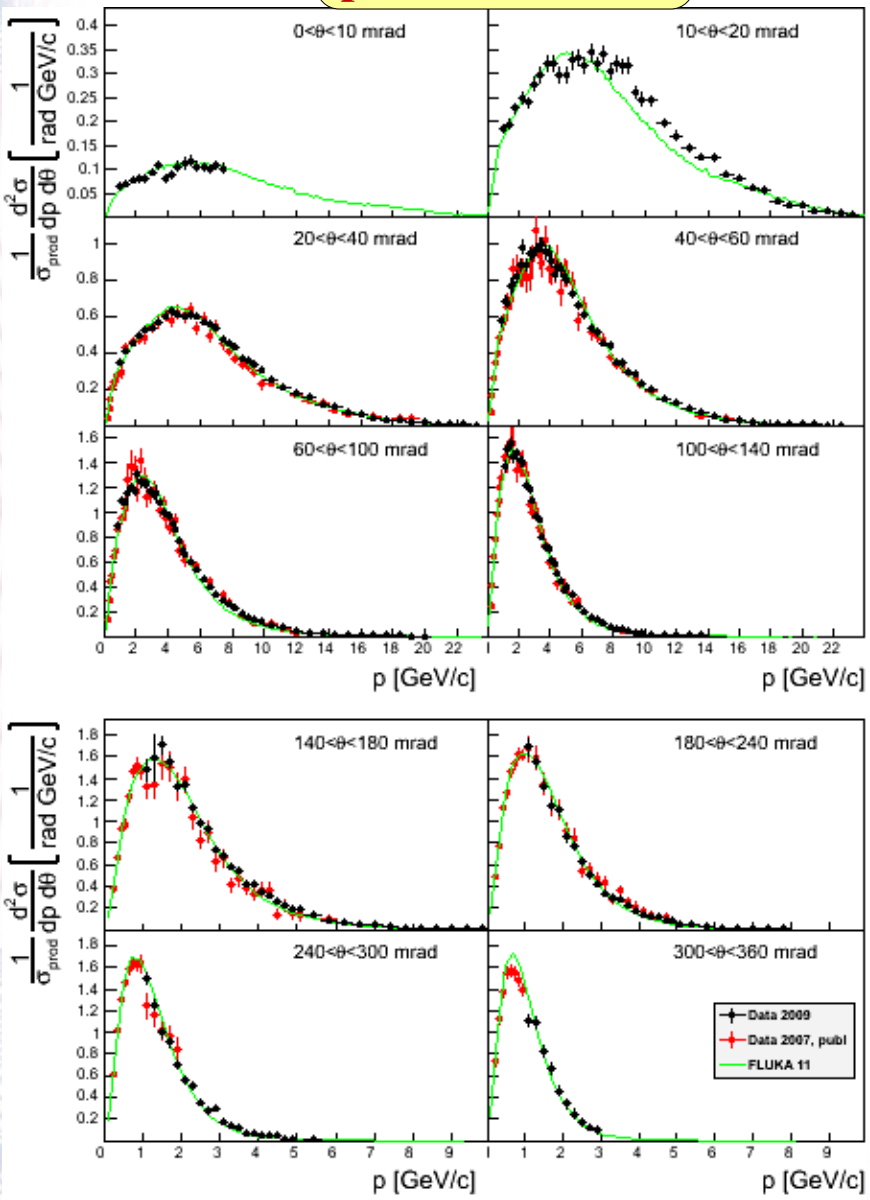
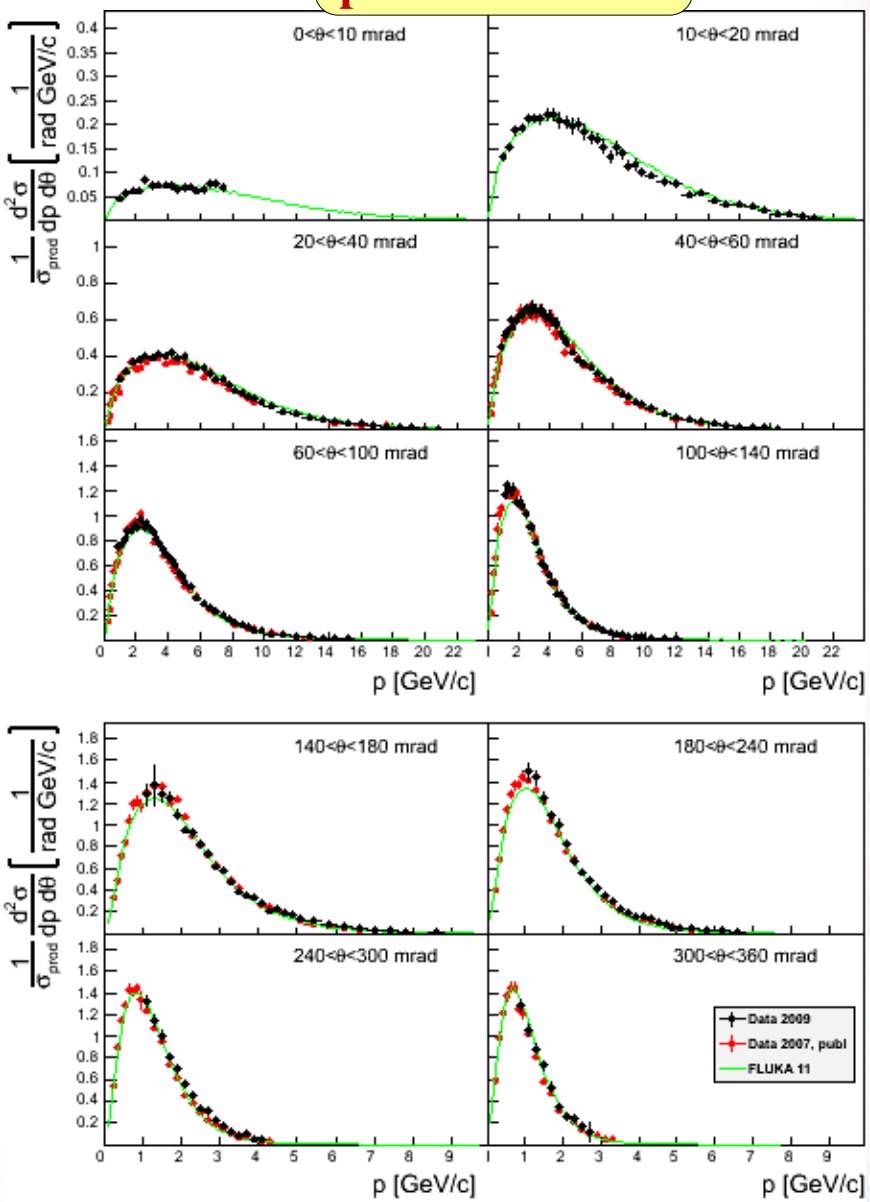
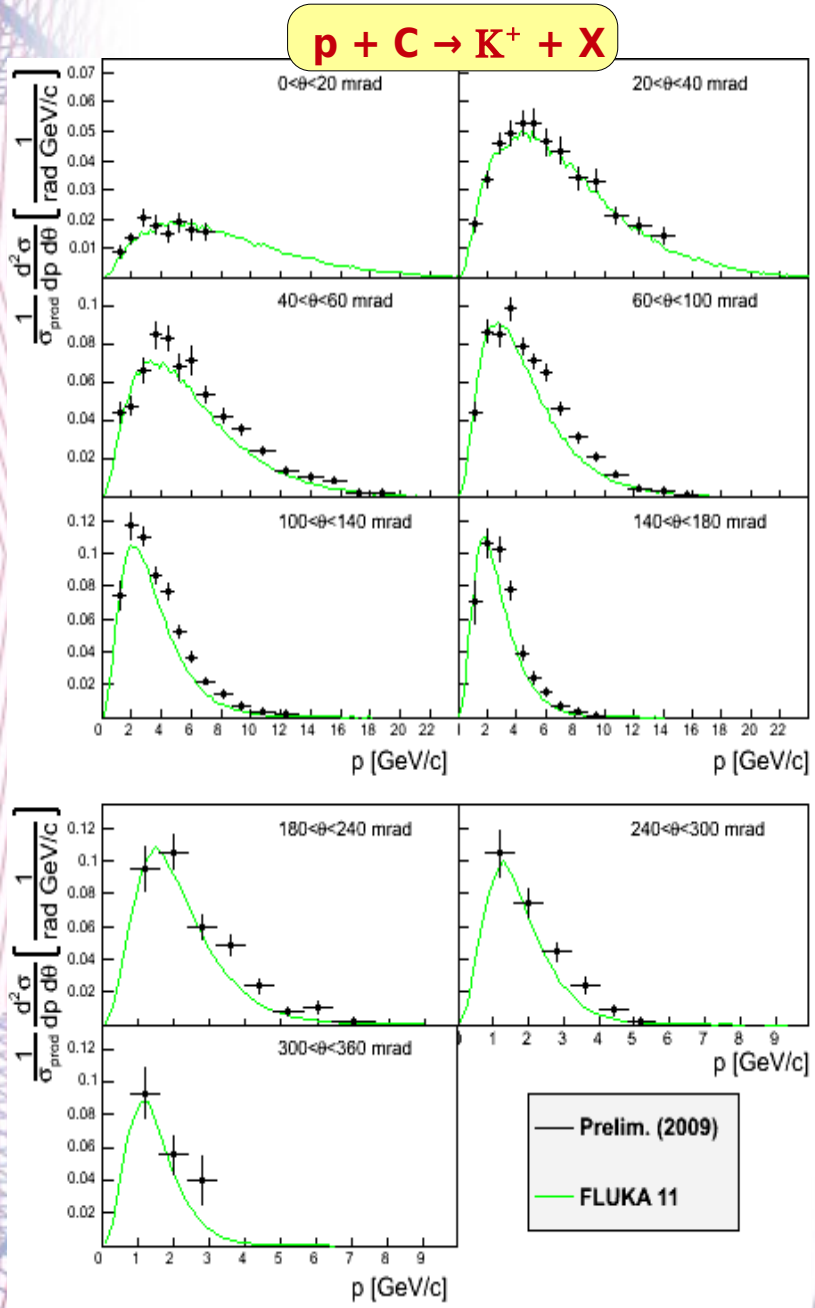


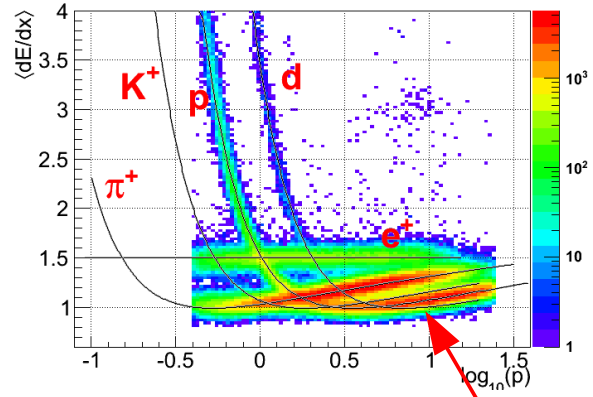
$p + C \rightarrow \pi^{-} + X$

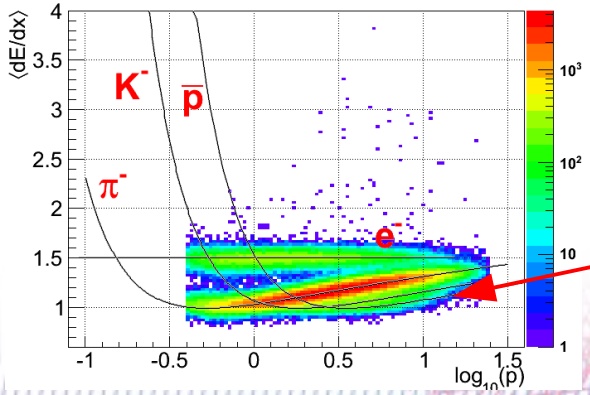


New results on K^+ multiplicity in pC @ 31 GeV/*c*



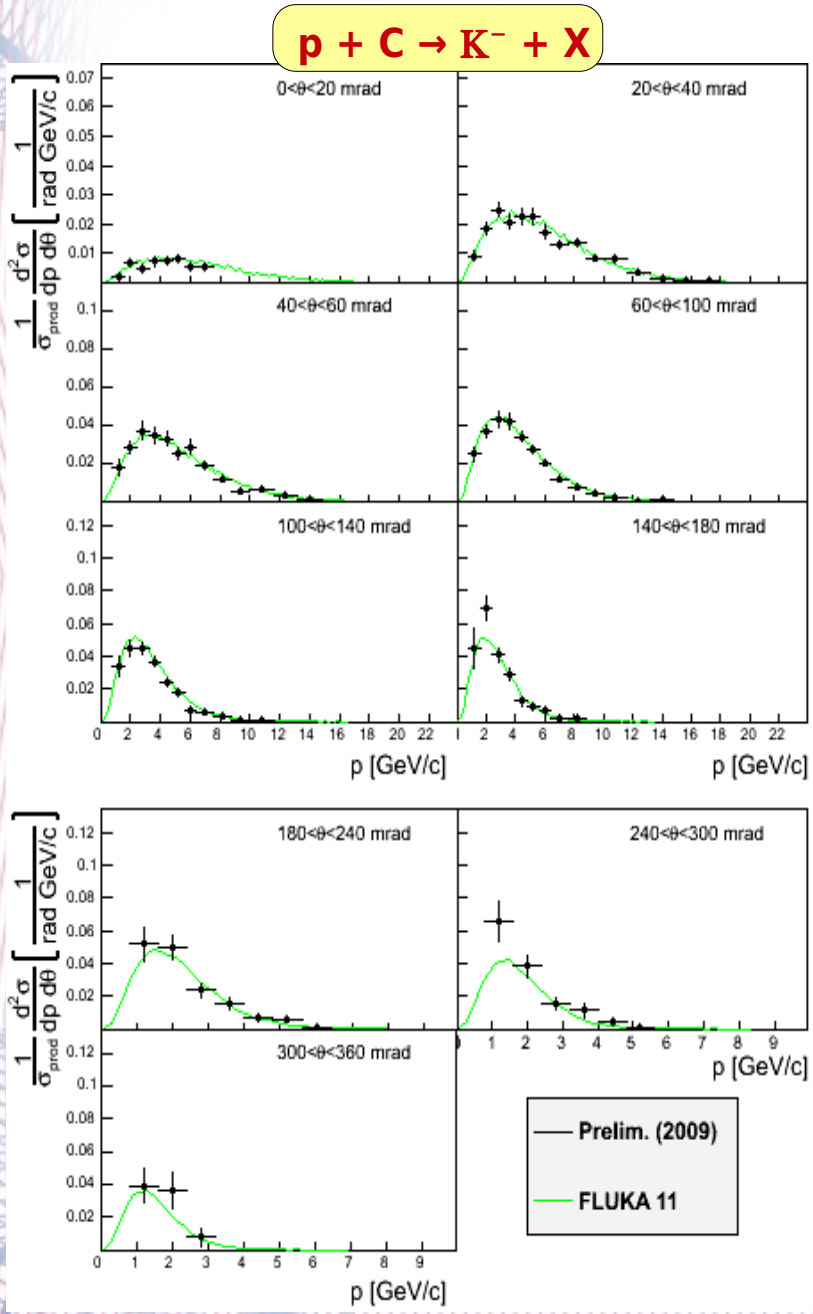
- Agreement with published K^+ cross section
  - Statistics (and total error) **improve by a factor 3**
- At large momenta K^+ is totally under the proton peak ⇨ additional systematics
- K^- are shown for the first time. Analysis with data 2007 was not possible due to low statistics



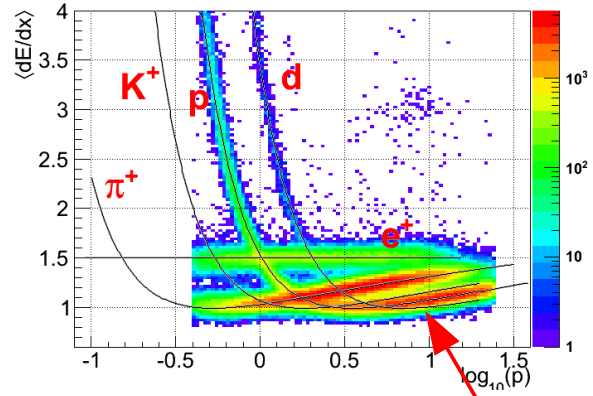


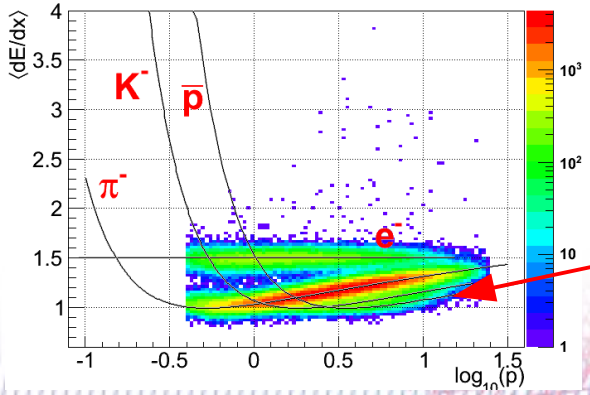
Additional uncertainty on K^+ due to protons

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



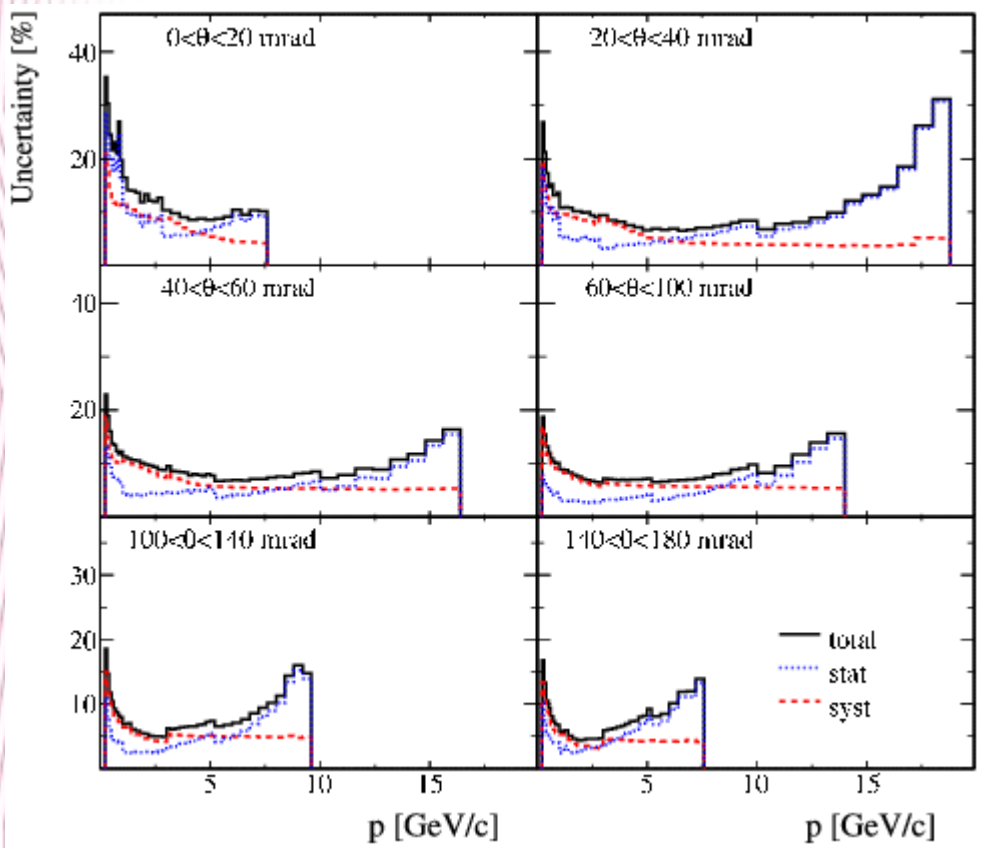
- Agreement with published K^+ cross section
  - Statistics (and total error) **improve by a factor 3**
- At large momenta K^+ is totally under the proton peak ⇨ additional systematics
- **K^- are shown for the first time.** Analysis with data 2007 was not possible due to low statistics

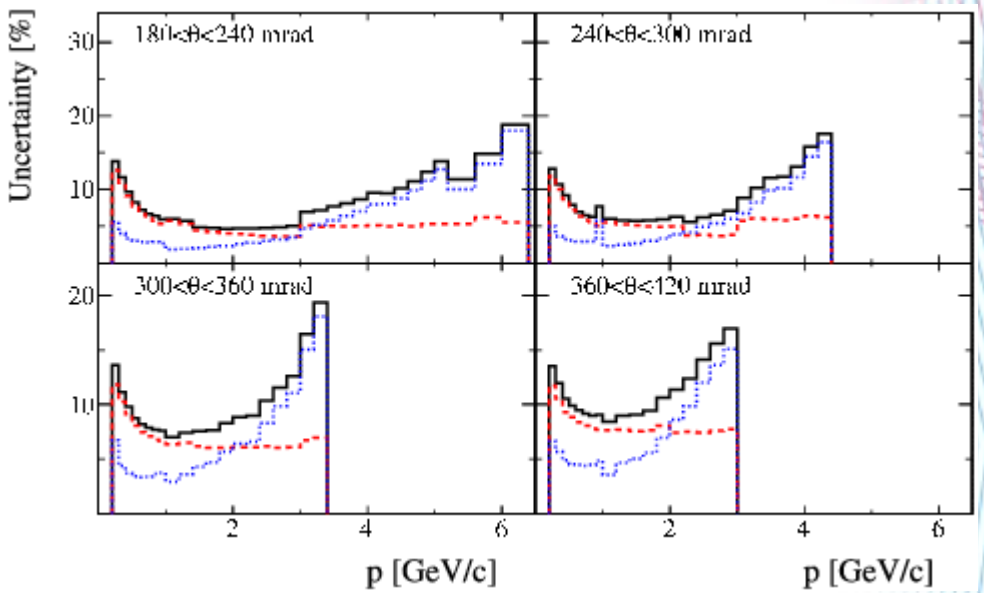




Additional uncertainty on K^+ due to protons

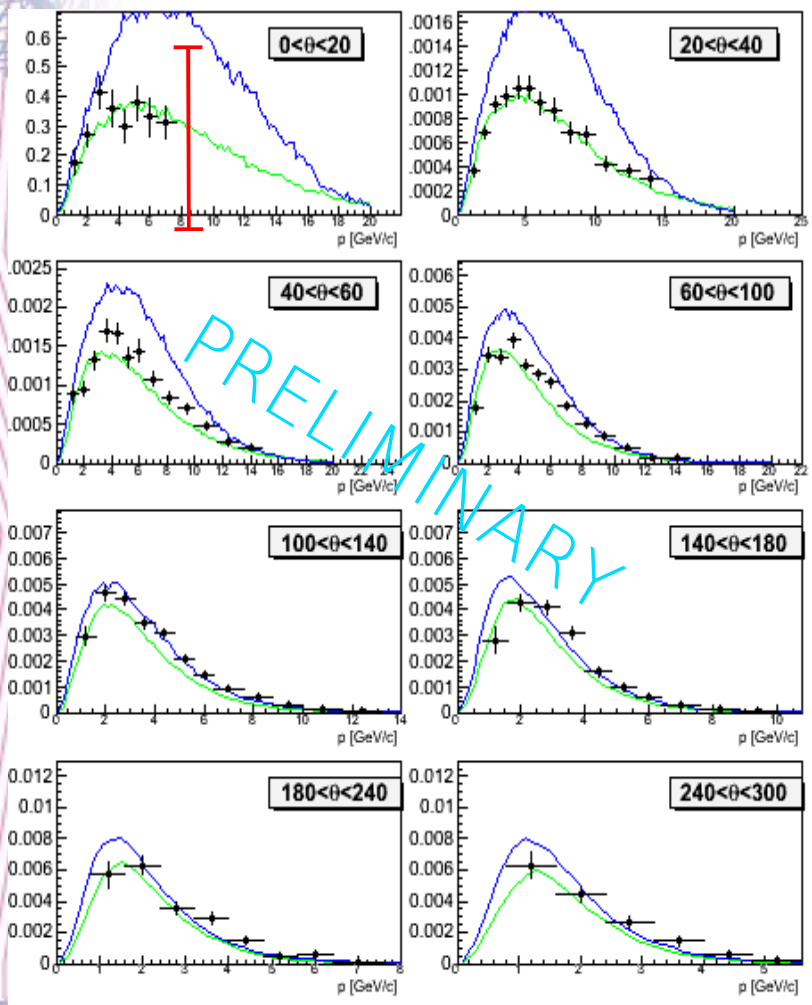
Relative uncertainties for π^- (data 2007)

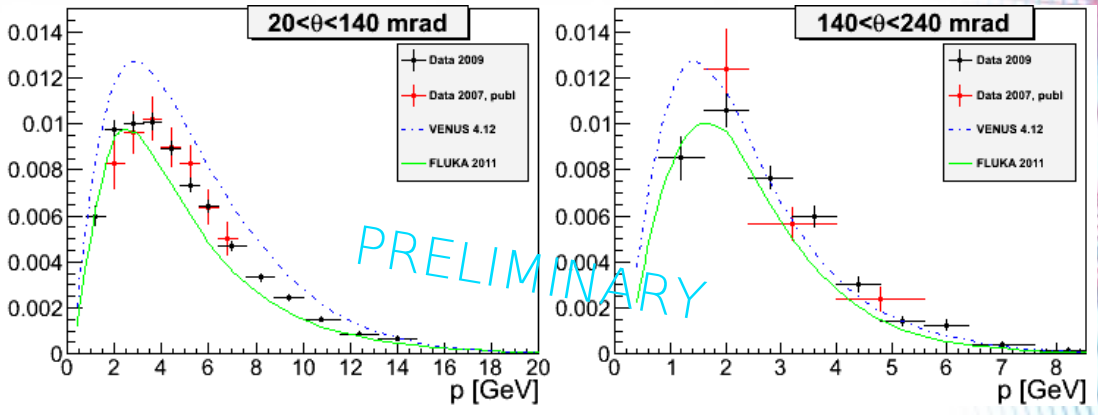


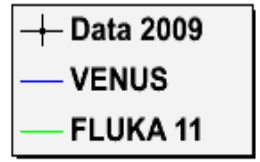


- Among 3 analyzes the one with smaller total error was selected
- Systematic error dominates at lower momenta. At higher momenta stat. error is larger

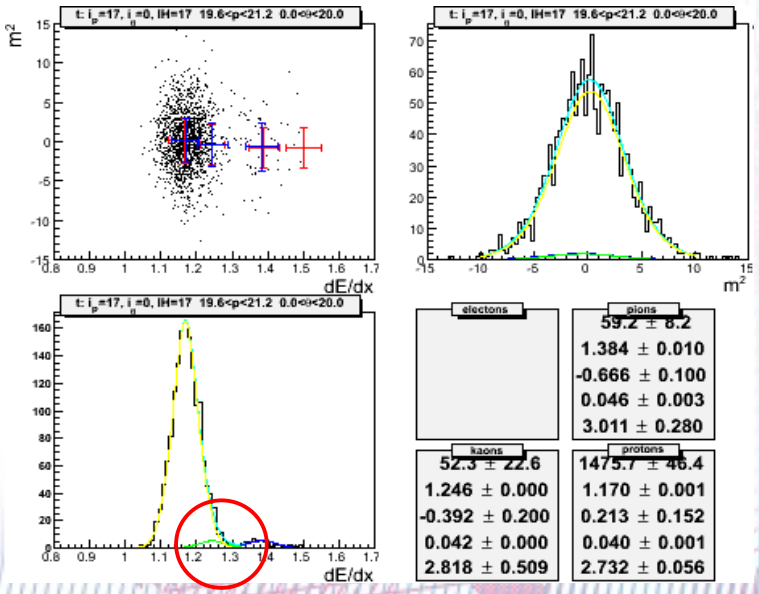
Multiplicities for K+





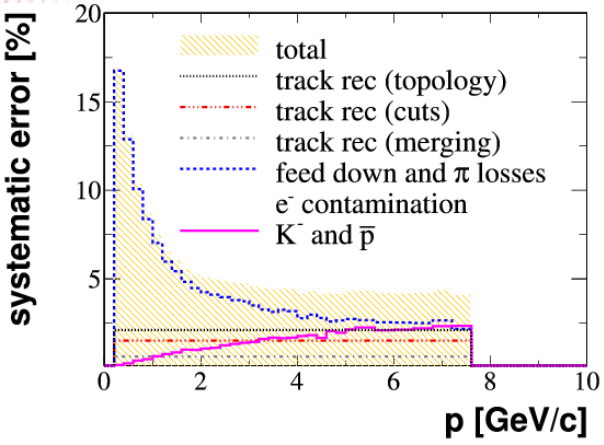


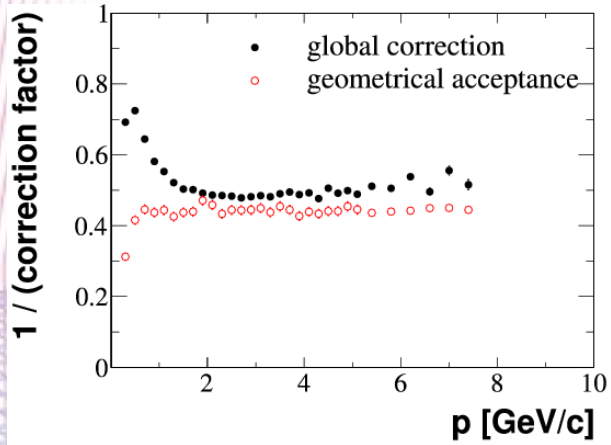
- Agreement with published K^+ cross section
- At large momenta K^+ is totally under the proton peak ⇒ Proper multi-gaussian fit of *dE/dx* is needed



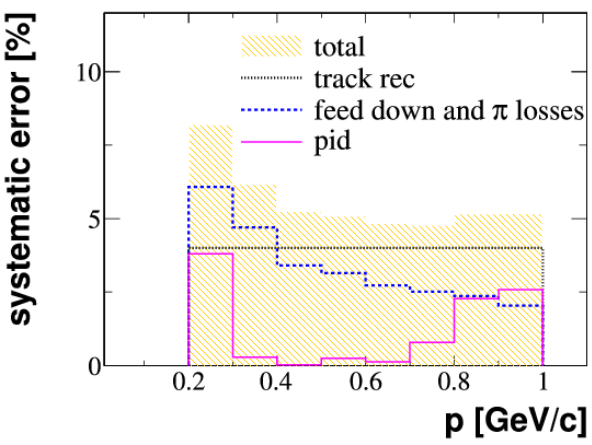
Syst. error & correction factors for π^- analysis (data 2007)

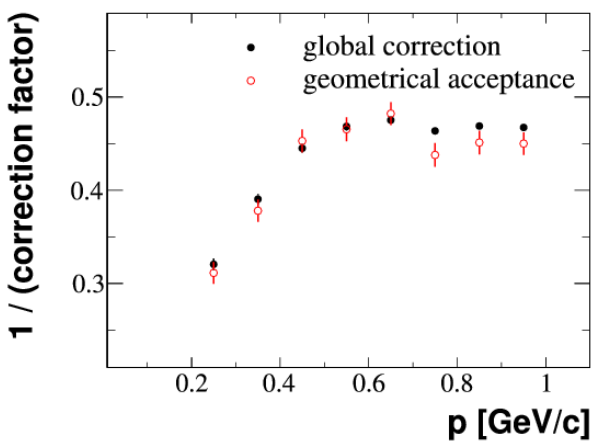
h- analysis



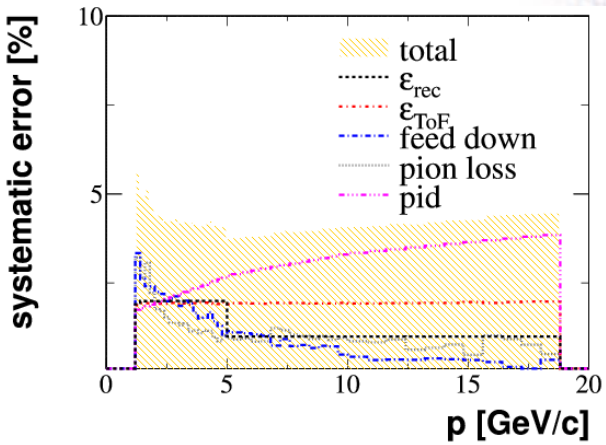


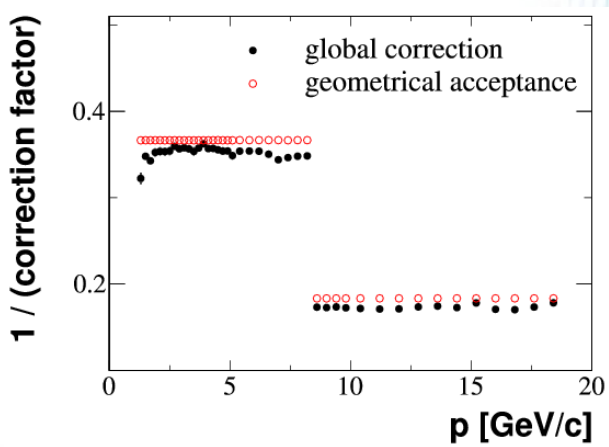
dE/dx analysis



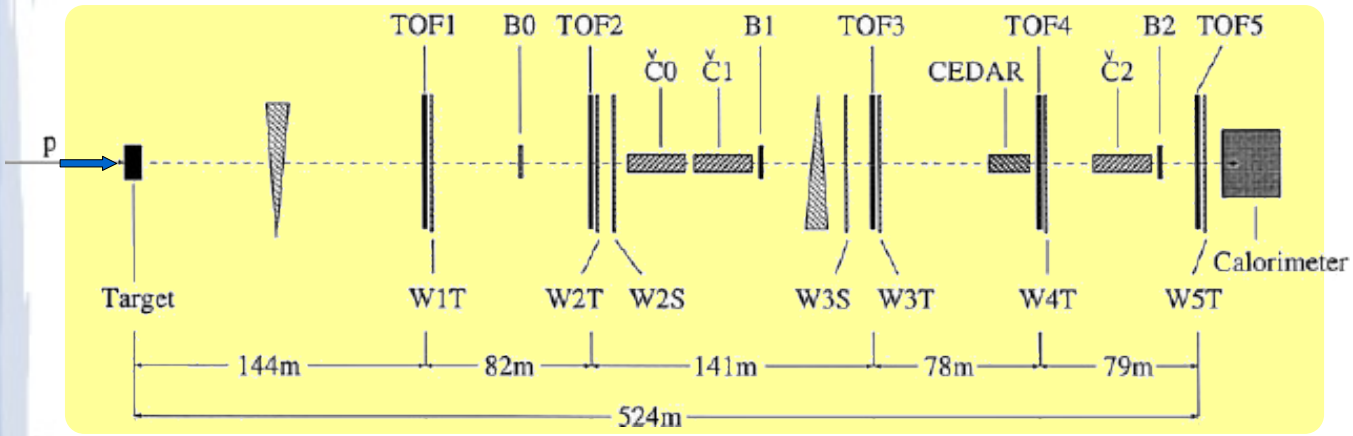


ToF-*dE/dx* analysis



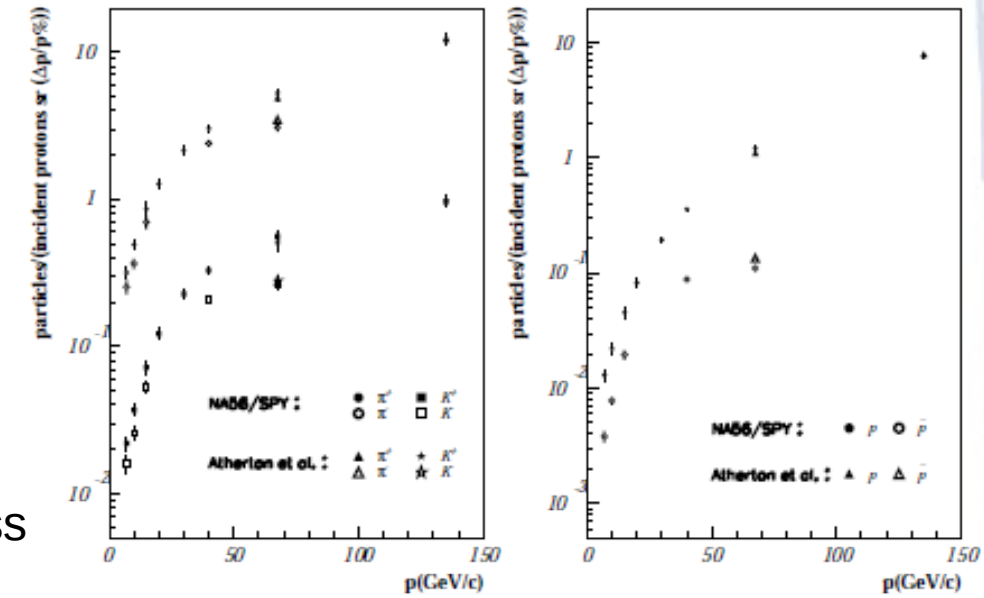


NA56/SPY, Secondary Particle Yields



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

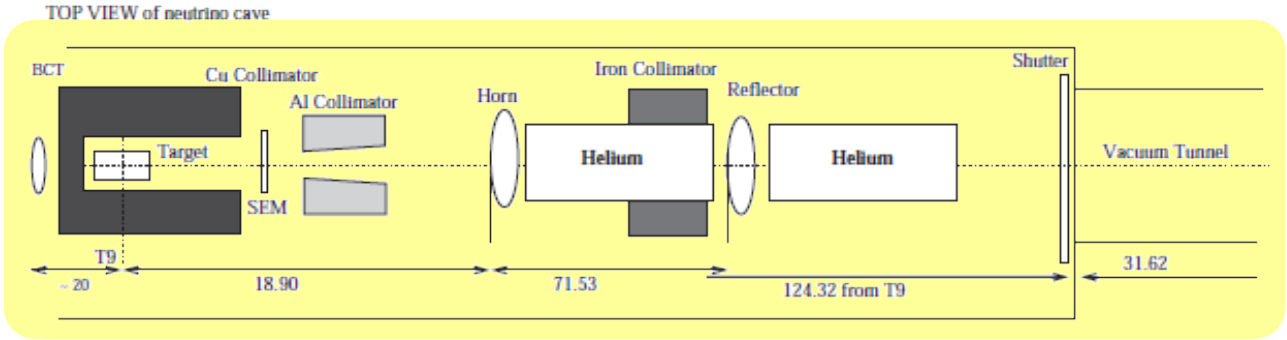
- 450 GeV/*c* protons interact with Be target
- Production angle up to 30 mrad
- Yields of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ have been studied
- Secondary momentum range 7-135 GeV/*c* ($0.02<x_F<0.3$) and $p_T<600$ MeV/*c*
- Experimental accuracy on yields 5-10%, for production ratios 3%
- Dependence 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

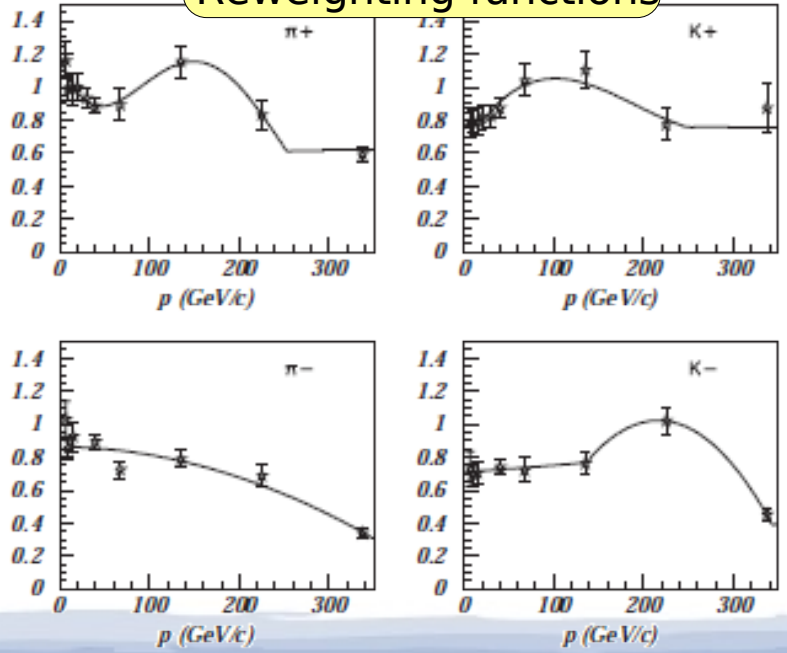
450 GeV/c protons from SPS



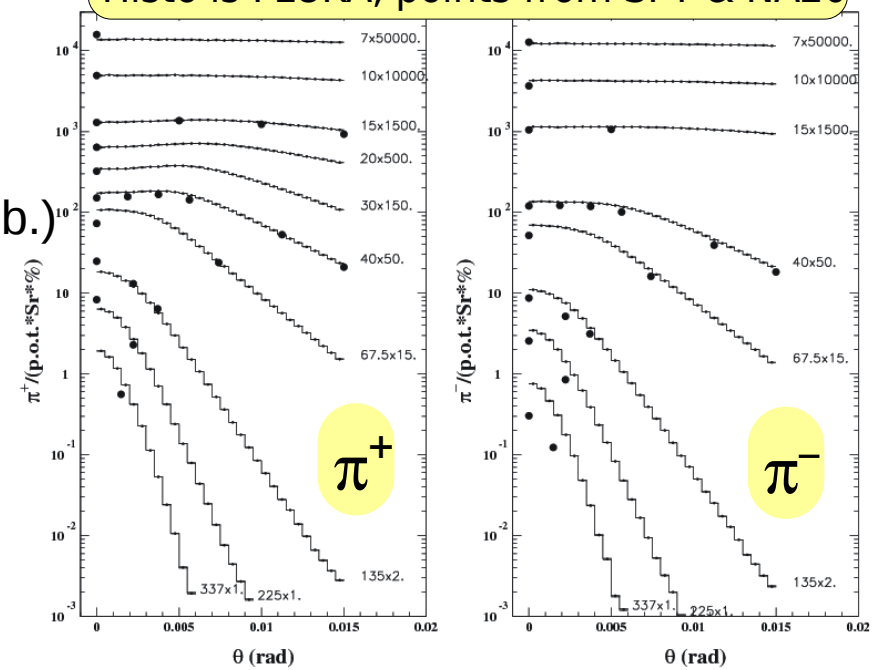
Towards CHORUS & NOMAD

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

Reweighting functions



Histo is FLUKA, points from SPY & NA20

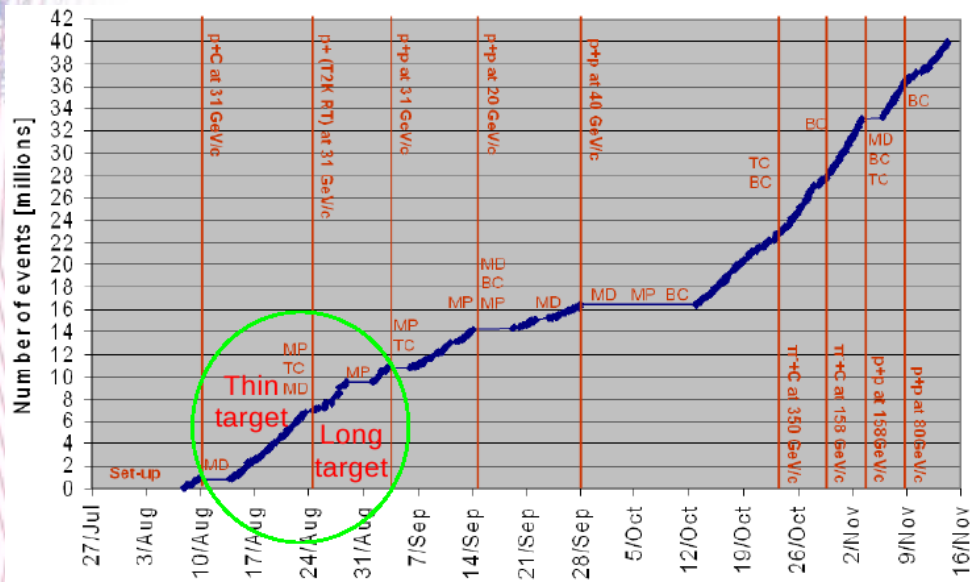


- Overall flux uncertainty 8% for ν_μ and ν_e, 10% for $\nu_{\bar{\mu}}$ and 12% for $\nu_{\bar{e}}$

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

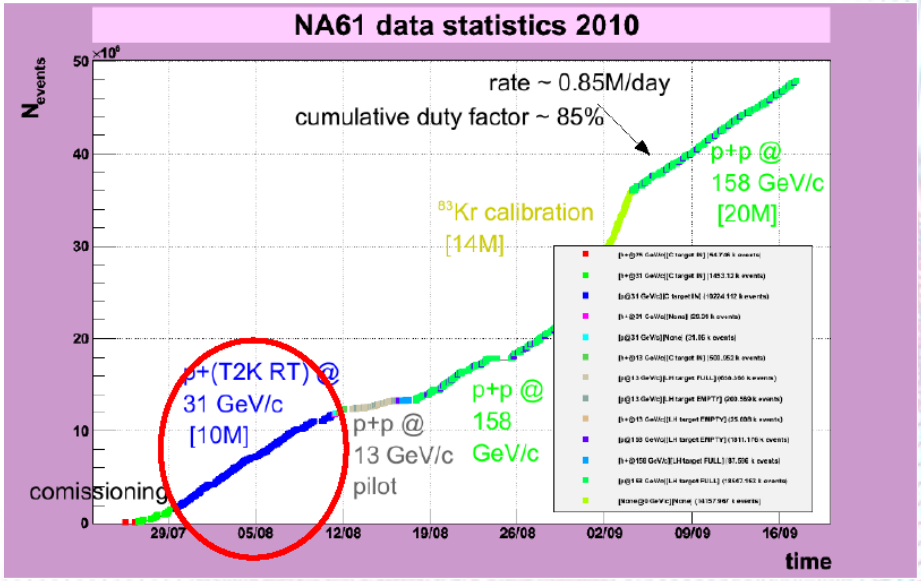
G.Collazuol et al., NIM A449(2000)609

Prospect for forthcoming results (data 2009 & 2010)

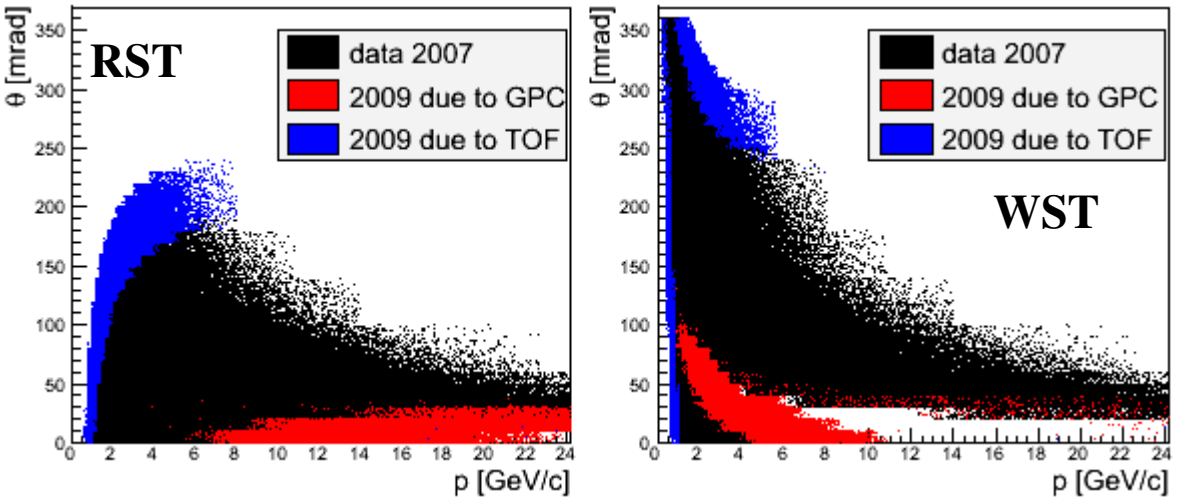


- About 10M events (thin+T2K replica target) collected in 2009
- Simultaneous extraction of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ is possible
- Preliminary results this Autumn

- 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

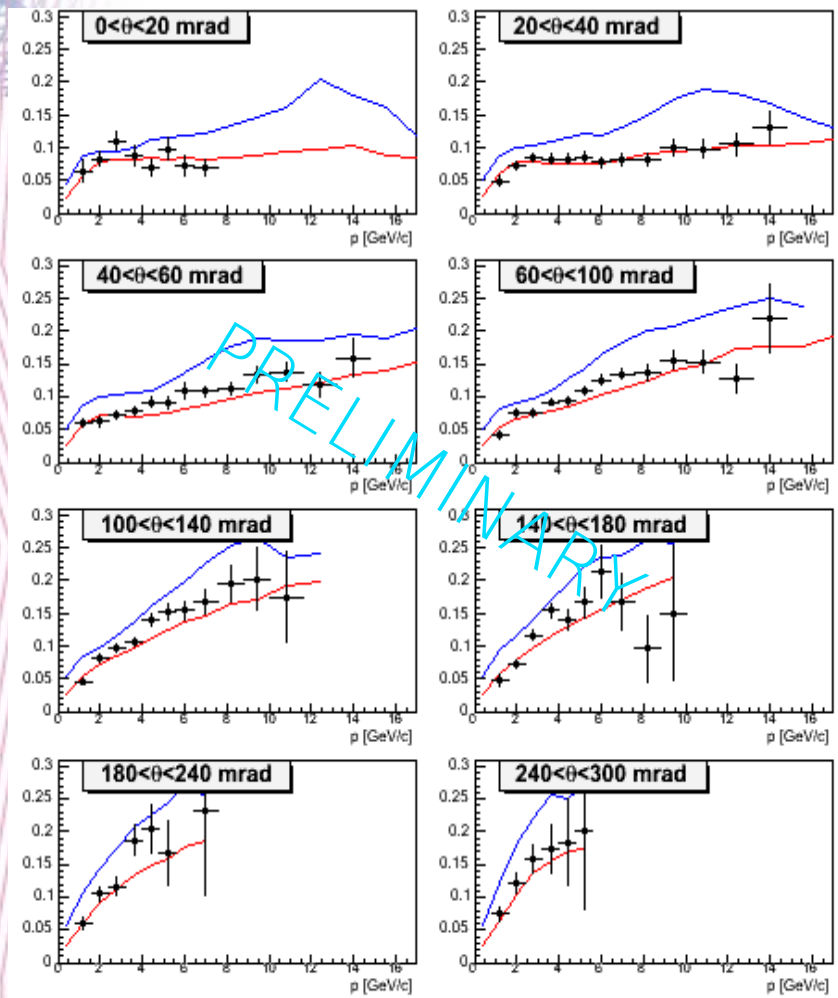
$$\frac{d\sigma_\alpha}{dp} = \frac{\sigma_{trig}}{1-\epsilon}\left(\frac{1}{N^{in}}\frac{\Delta n_\alpha^{in}}{\Delta p} - \frac{\epsilon}{N^{out}}\frac{\Delta n_\alpha^{out}}{\Delta p}\right)$$

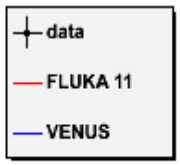
Hadron multiplicity ⇨

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

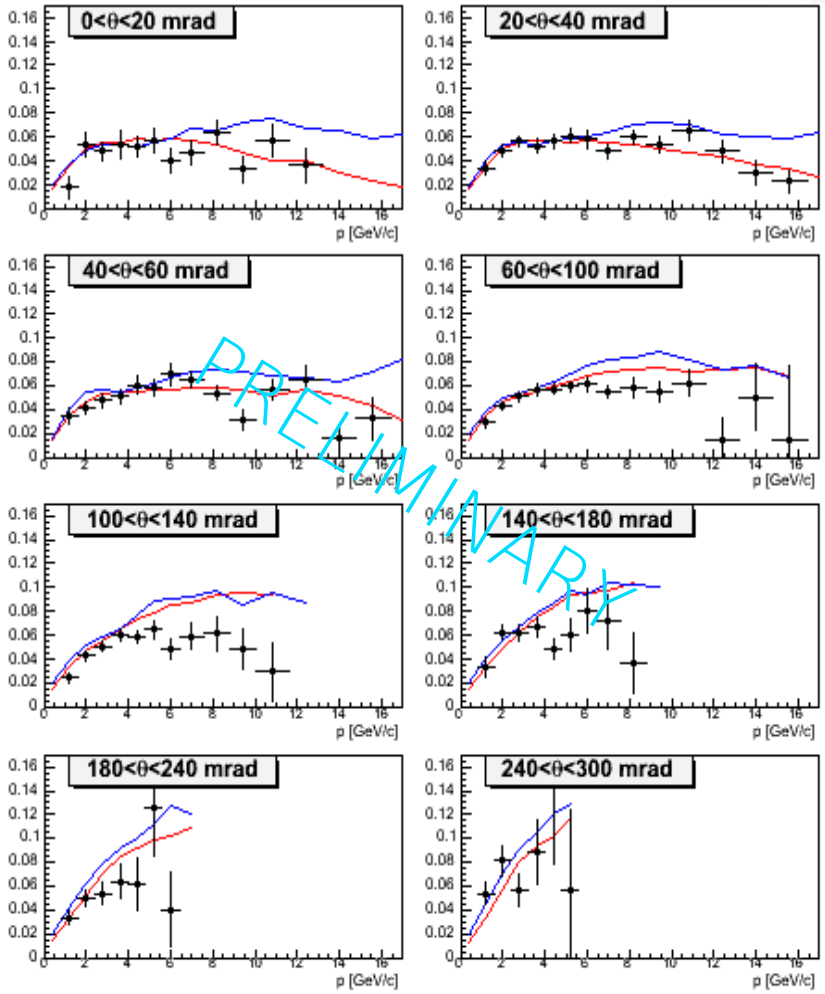
- Statistics for target '*in*' and '*out*'
  $N^{in} = 2.5\cdot10^6$, $N^{out} = 0.1\cdot10^6$
- σ_{trig}=305.7 ± 2.7 ± 1.2 mb
- $\varepsilon = P^{out}/P^{in} = 0.123 \pm 0.004$
- $\sigma_{prod} = 233.5 \pm 2.8 \pm 4.2 \pm 1.2$ mb

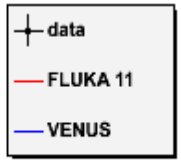
Ratio K^+/π^+



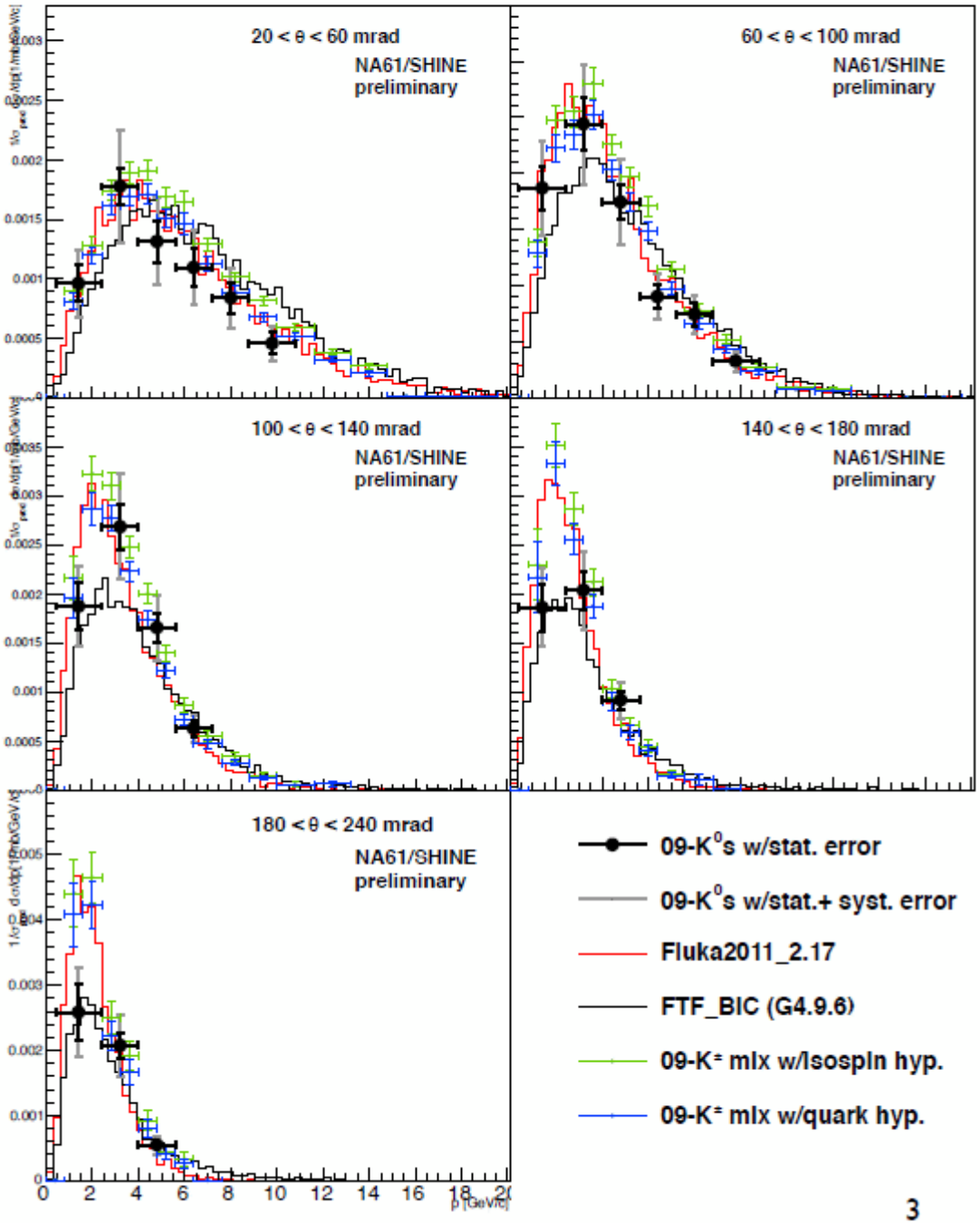


Ratio K^-/π^-





K^0_s 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':

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

Error source	$N_{SK}^{MC}/R_{ND}^{\mu,MC}$
Pion production	2.5%
Kaon production	7.6%
Nucleon production	1.4%
Production x-section	0.7%
Proton beam posit/profile	2.2%
Beam direction measur.	0.7%
Target alignment	0.2%
Horn alignment	0.7%
Horn abs. current	0.2%
Total	8.5%

NA61 data in the T2K experiment

- In MC of T2K the pion production yield at the primary interaction vertex (from FLUKA) was reweighed using NA61 data

$$N_{SK}^{\exp} = R_{ND}^{\mu,data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,MC}}$$

Summary of ν flux uncertainty on N_{SK}^{exp} ($\sin^2 2\theta_{13}=0$ assumed)

Contribution of pions is 2.5% when one uses the NA61 data

Phys.Rev. C84 (2011) 034604

The dominant error (7.6%) is due to the uncertainty on the K^+ flux

Total relative uncertainty

source	error
Neutrino flux	8.5%
Near detector	+5.6/-5.2 %
Near detector stat.	2.7%
Cross-section	10.5%
Far detector	9.4%
Total	+17.6/-17.5%

Contribution from the beam flux to the systematic error is significant (8.5 vs. 17.6 %)

(T2K) Phys.Rev.Lett.107(2011)041801