Hadron production measurements from NA61/SHINE

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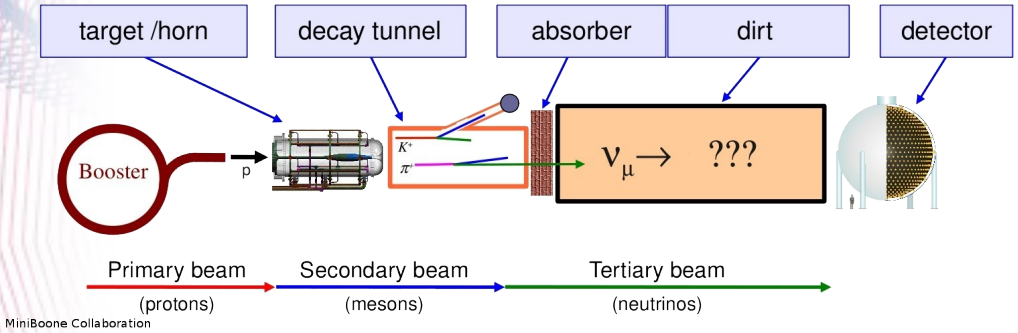
on behalf of the NA61/SHINE collaboration

SPS Annual Meeting
Fribourg, July 2014

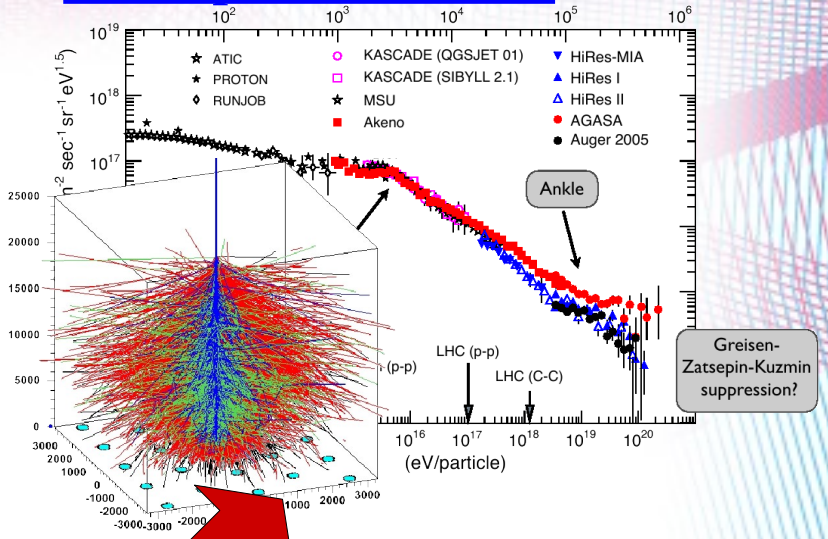
Outline

- Introduction
- Hadron cross section measurements
- Results on the T2K replica target

Conventional accelerator ν-beam



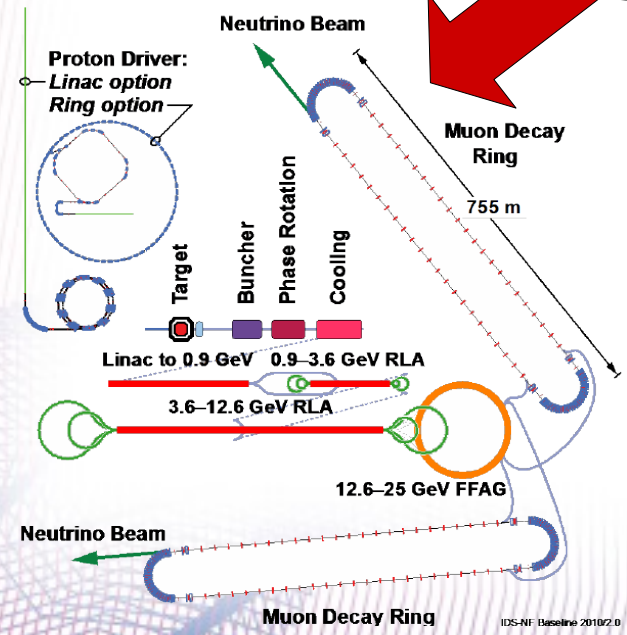
Atmospheric showers



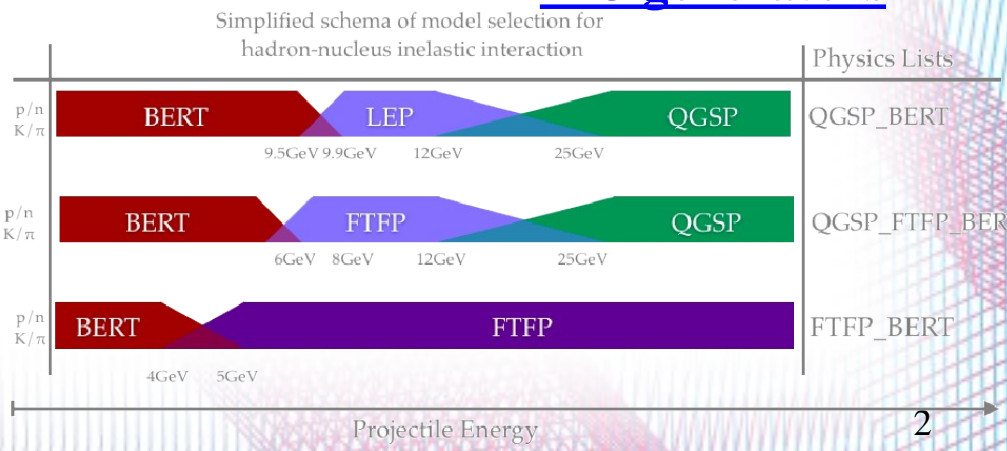
Hadron production measurement

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

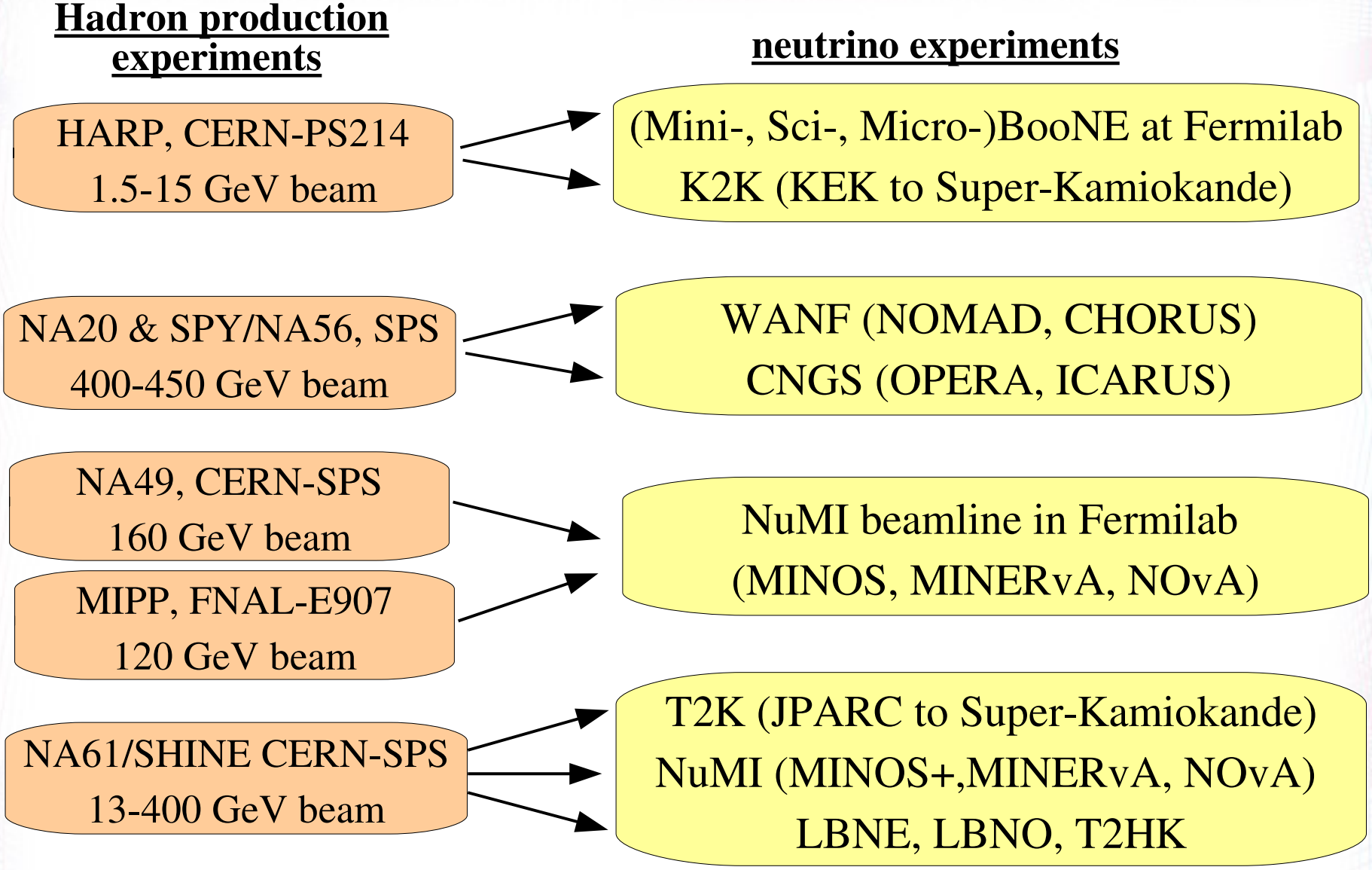
Neutrino Factory



MC generators



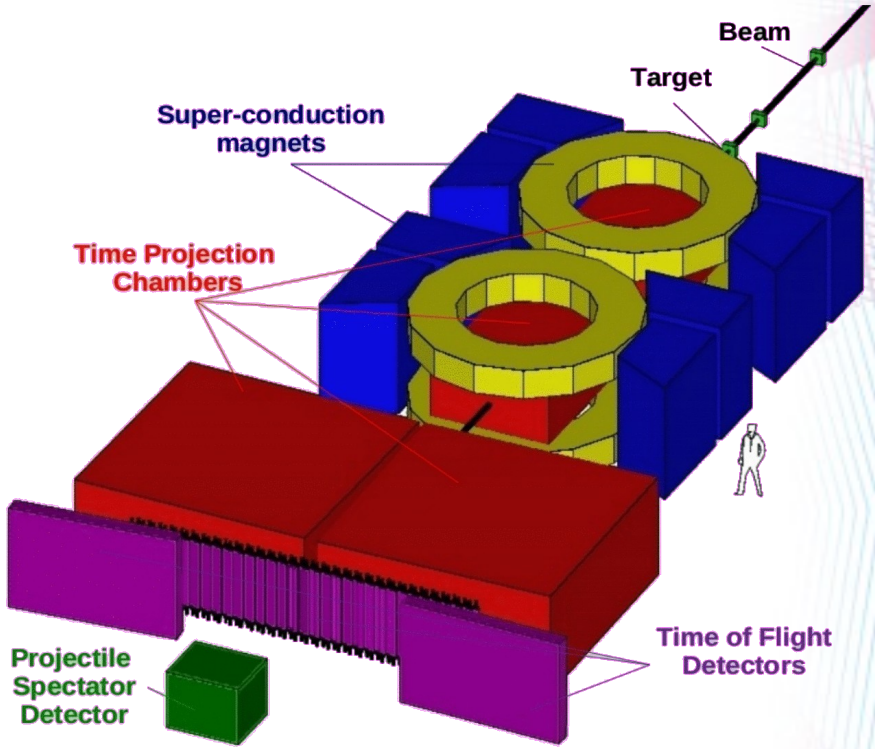
Few examples



Normally results of several hadron production experiments are used

SPS Heavy Ion and Neutrino Experiment

- **NA61/SHINE** has been approved in 2007
- Successor of NA49, situated at H2 beamline of CERN SPS
- Secondary beam particles produced from 400 GeV SPS's protons
  - Momentum range 13-400 GeV/*c*
- PID of beam protons by CEDAR and Cherenkov threshold conter
- 4 large volume TPCs (+1 small TPC) for tracking of secondary particles
- Particle identification by ToF & dE/dx



CERN-SPSC-2006-034(2006)

Summary of data collected by **NA61** for **T2K** (graphite target)

beam	target	year	stat.x10^6	Status of analysis	The T2K beam MC
protons at 31 GeV/c	The thin target 2cm (0.04λ_I)	2007	0.7	published: $\pi^{\pm}$, K^+, K^0_S, Λ	is used
		2009	5.4	prelim: $\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ	to be used in 2014
	the T2K replica target 90 cm (1.9λ_I)	2007	0.2	published: $\pi^{\pm}$	method developed
		2009	2.8	to be released in 2014	-
		2010	~10	under calibration	-

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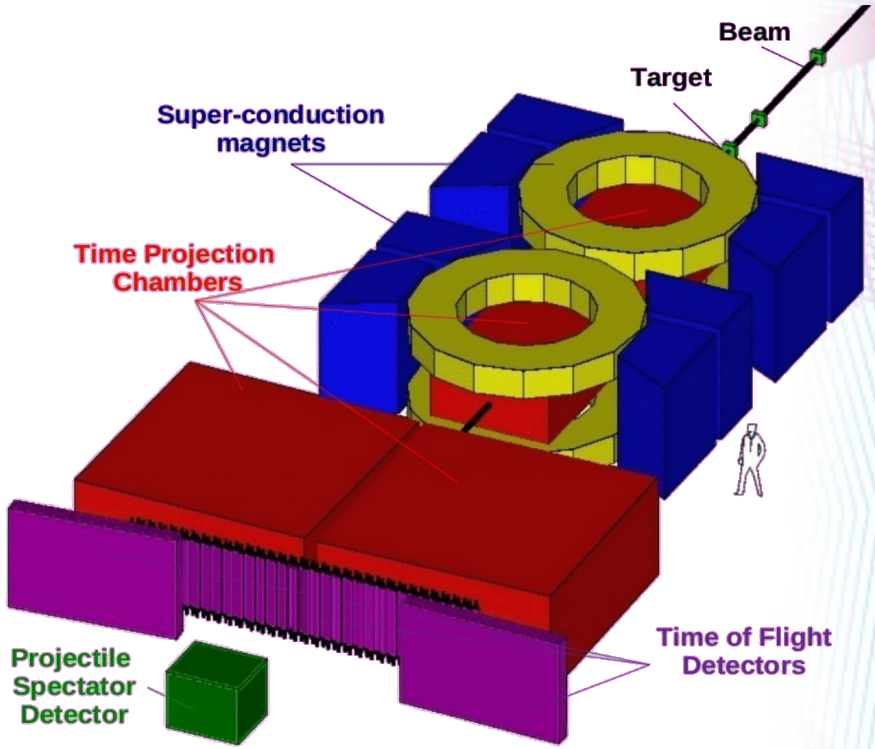

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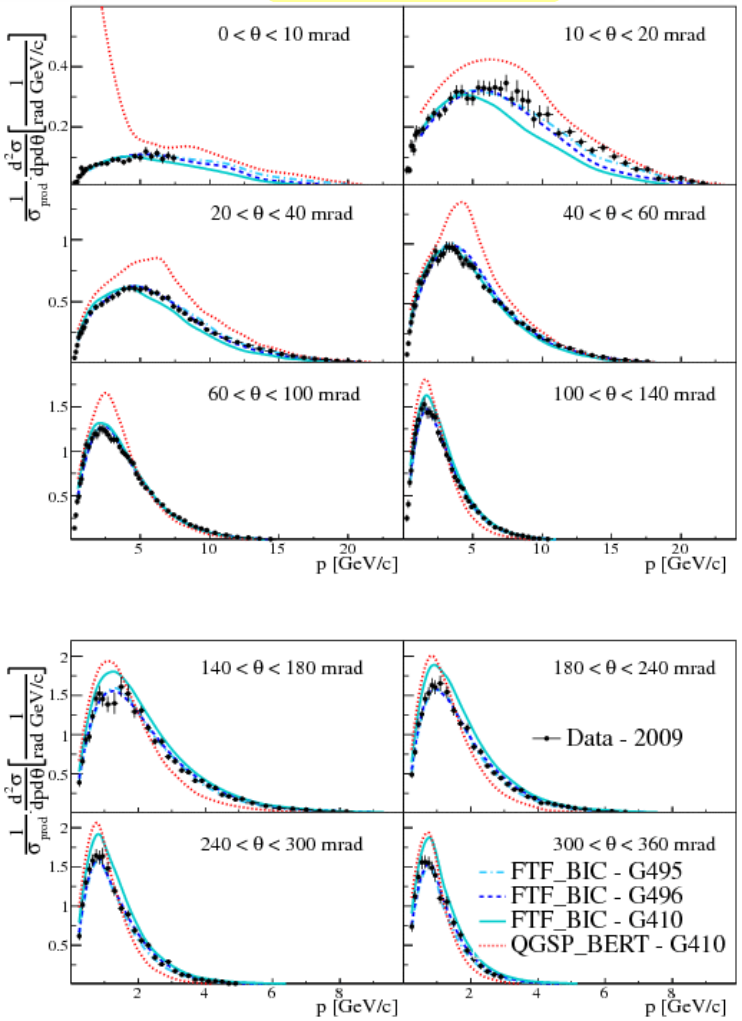
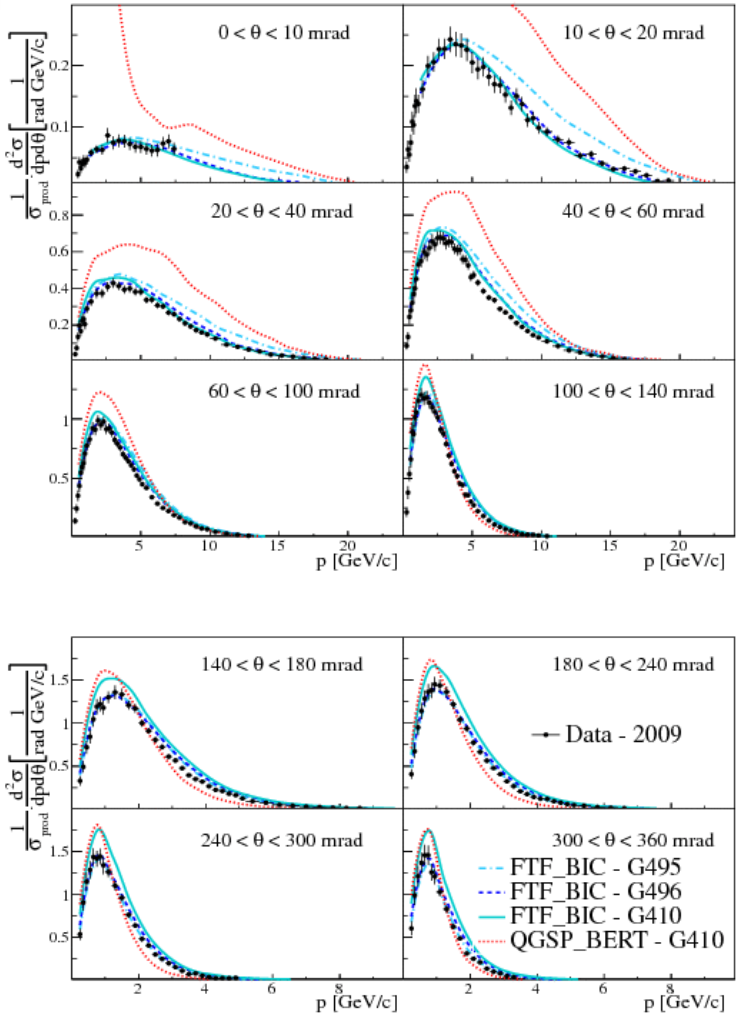
New NA61 measurements for T2K at 31GeV

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



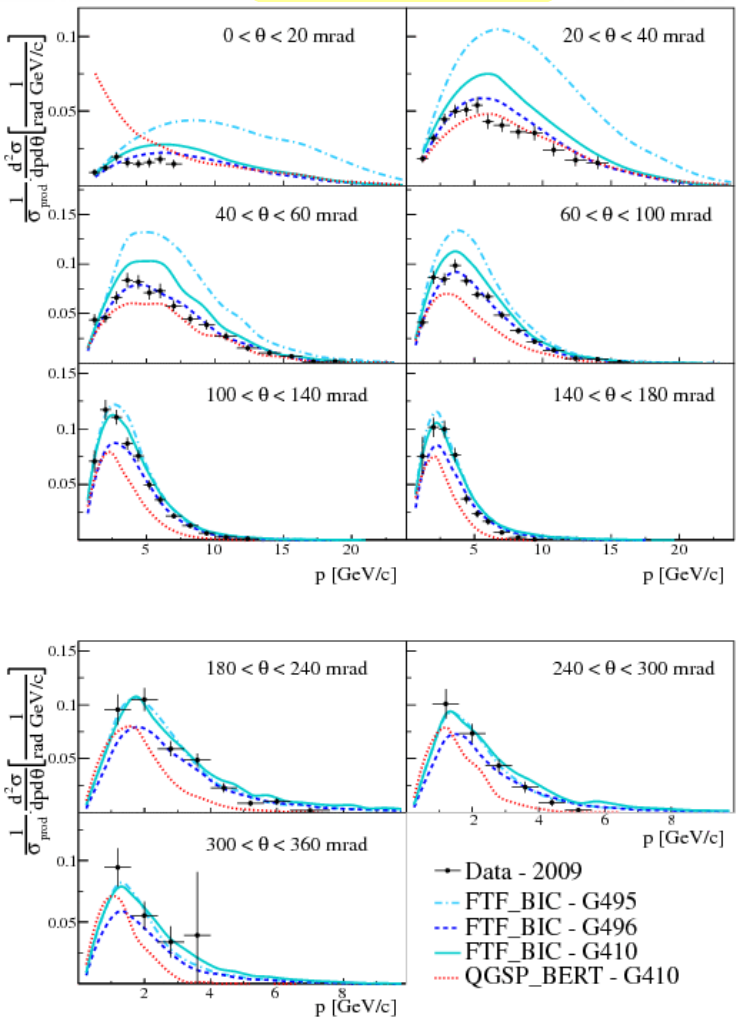
$p + C \rightarrow \pi^- + X$



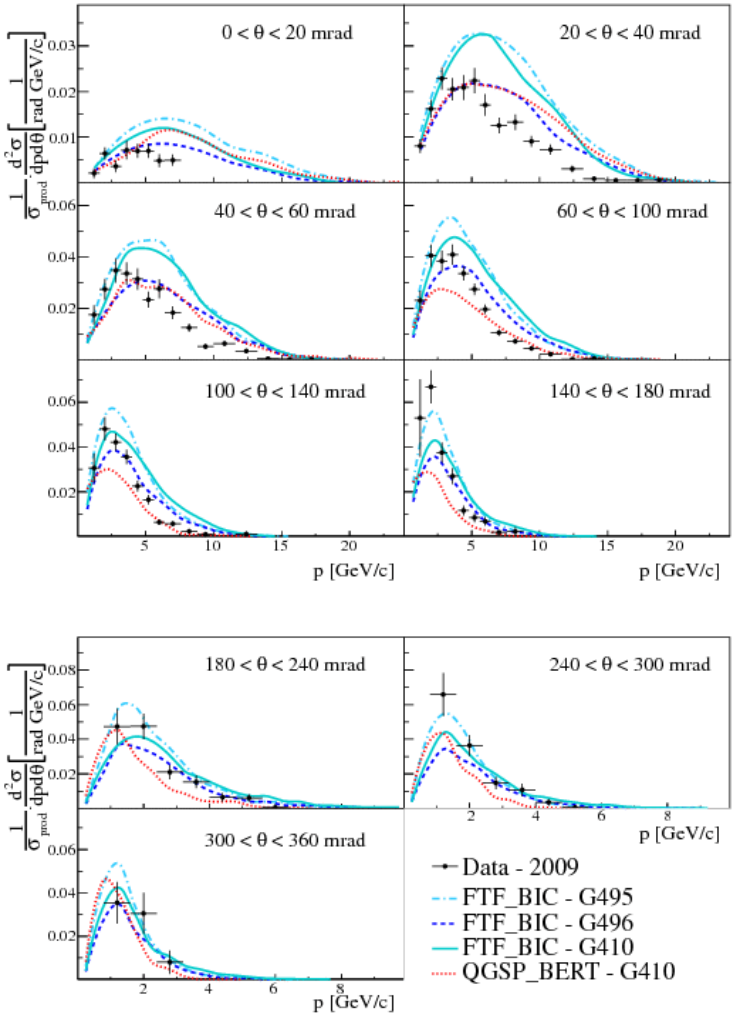
- New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)
- Typical uncertainty for regions which are important for ν flux is ~4%
- Recent versions of FTF_BIC describe data reasonably

New NA61 measurements for T2K at 31GeV

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



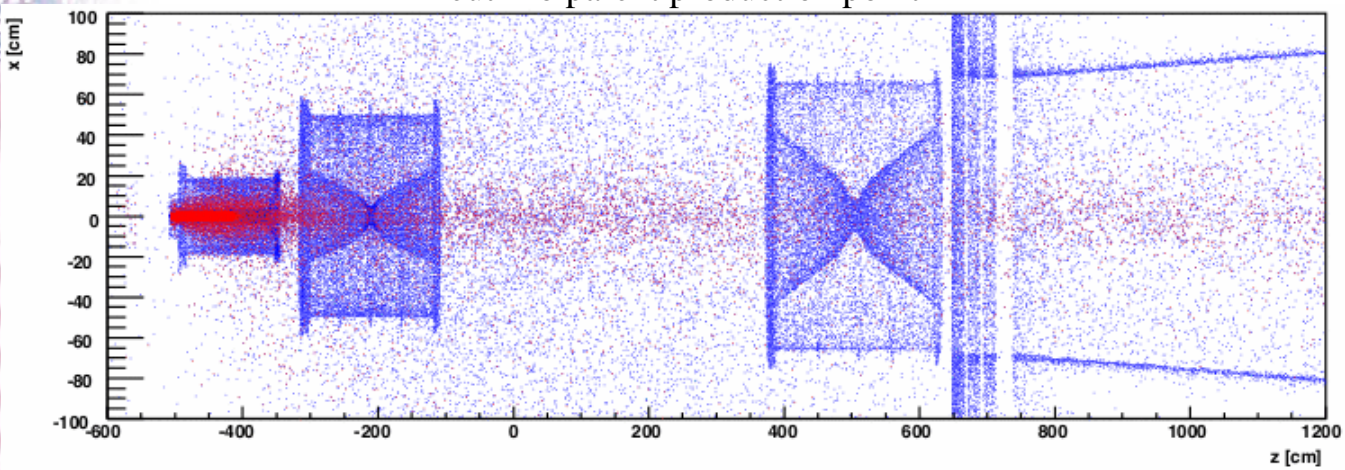
$p + C \rightarrow K^- + X$



- New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)
- Typical uncertainty in a central region is ~15%
- Recent versions of FTF_BIC describe data reasonably

NA61 data in the T2K experiment

neutrino parent production point



Red: parent produced in target
Blue: parent produced outside the target

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

Main set of hadron production data

Experiment	Beam p[GeV/c]	Target	Particle
NA61/SHINE	31	C	$\pi^{\pm}$, $K^{\pm}$, p
Eichten *et al.*	24	Be, Al, ...	p, $\pi^{\pm}$, K^{+}
Allaby *et al.*	19.2	Be, Al, ...	p, $\pi^{\pm}$, $K^{\pm}$
E910	6.4-17.5	Be	$\pi^{\pm}$

Major part of the T2K phase space

For forward kaons

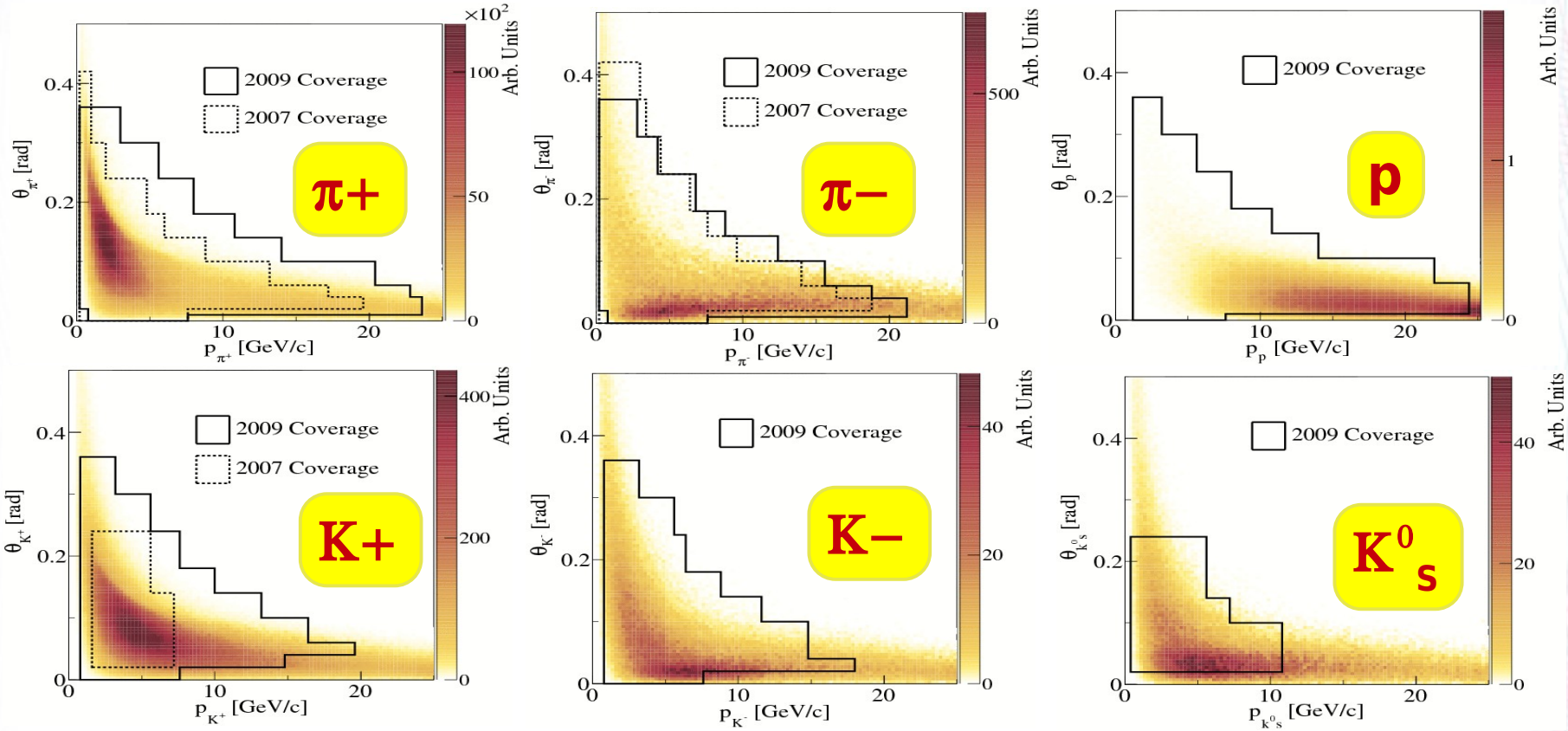
For tertiary pions

- 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 is done assuming Feynman scaling ($x_F=p_L/p_L^{max}$)
  - Extrapolation from carbon to aluminum using

$$E\frac{d^3\sigma(A_1)}{dp^3} = \left[\frac{A_1}{A_0}\right]^{\alpha(x_F,p_T)} E\frac{d^3\sigma(A_0)}{dp^3}$$

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

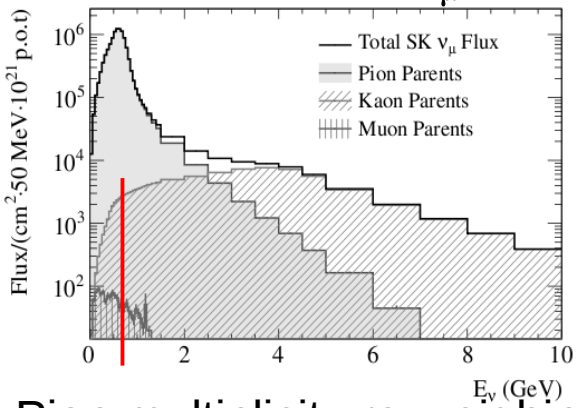
Phase space of hadrons contributing to the predicted ν flux at SK (250 kA)



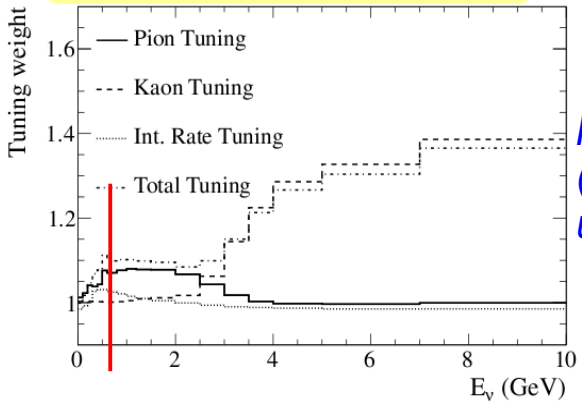
- Two years of datataking with a thin target: 2007 and 2009
- Statistics of 2009 is an order of magnitude higher as compared to 2007
- The phase space of T2K is well covered by NA61

Tuning of ν_μ flux using NA61 spectra

Decomposition of ν_μ flux



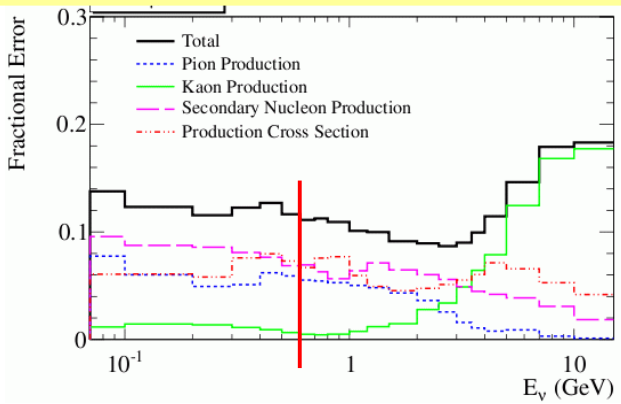
Re-weighting coefficient



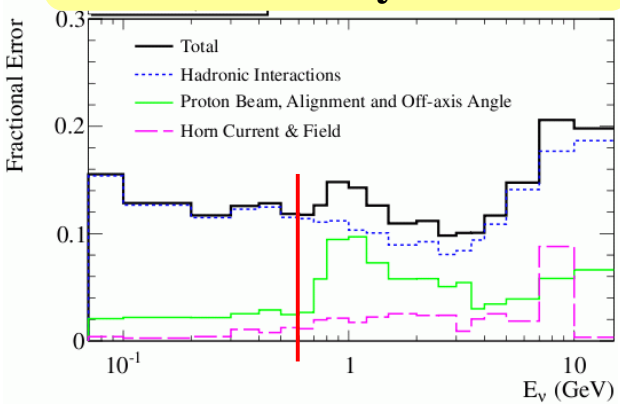
*Pilot data of NA61 (**2007**) have been used*

- Pion multiplicity re-weighing has the largest effect at low energies, while the kaon multiplicity re-weighting is important at high energies.

Error due to hadron production



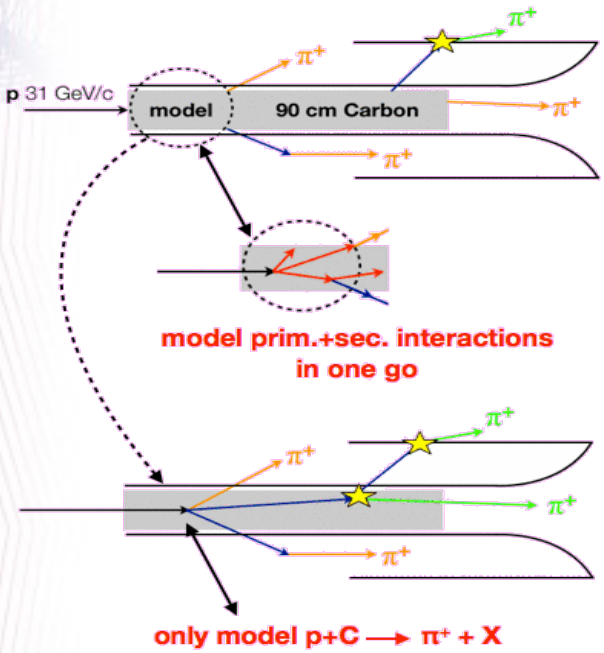
All sources of systematics

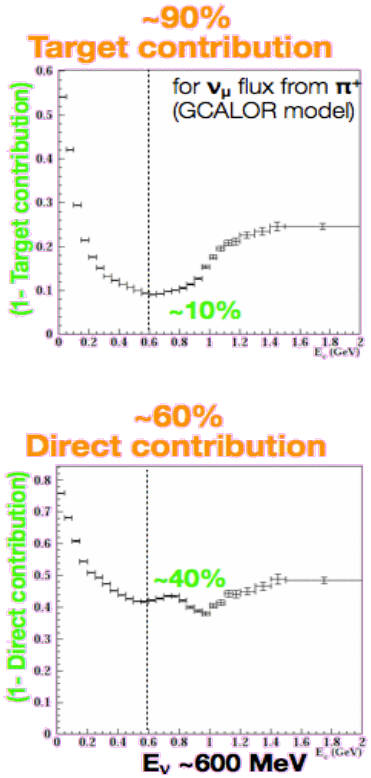


- Total flux uncertainty is dominated by the hadron interaction uncertainties

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

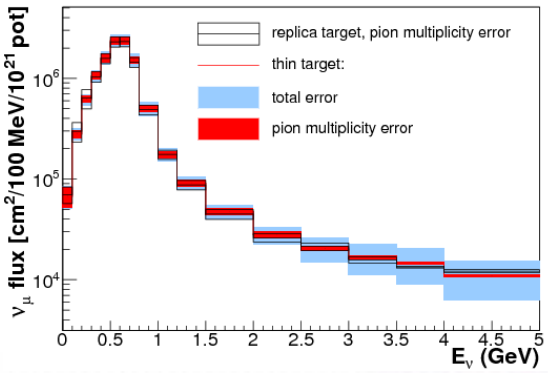
Alternative approach to the ν flux prediction in T2K

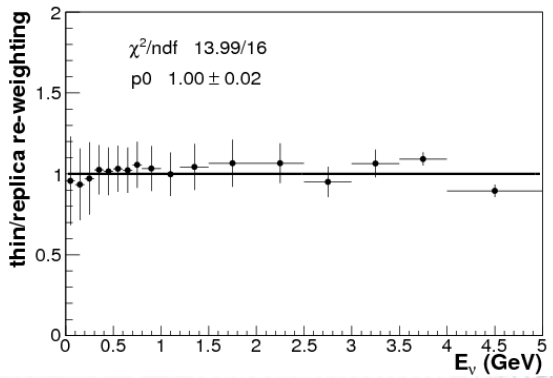




- Hadron multiplicities are parametrized **at the target surface** (no vertex reconstruction)
- Analysis in bins of (p, θ, z)
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Model dependence is reduced down to 10% as compared to 40% in the standard approach

- Analysis of pilot **data 2007** (method, results and application) is published
- Main statistics is data 2009 (analysis is ongoing) and 2010 (under calibration)





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

Conclusion

- Neutrino flux uncertainty is a bottleneck in the analysis of ν data ⇒ precision hadroproduction measurements is a mandatory part of the procedure
- Traditional approach for the ν flux constraint: re-weighting the parent hadron multiplicity at the interaction vertex
  - NA61 data for T2K at 31 GeV/c (datasets 2007, 2009)
  - Present neutrino flux uncertainty in T2K is ~12%
- The T2K replica target measurements:
  - NA61 data for T2K at 31 GeV (dataset 2007)
  - Reduction of model dependent uncertainties

Outlook

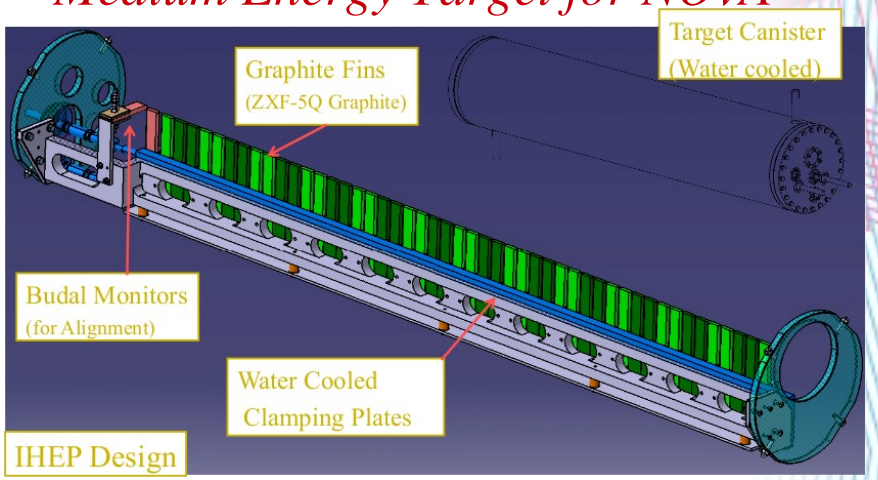
- Completion of the analysis of the T2K replica target data (2009, 2010)
- Extensive physics program is foreseen for NuMI energies (60-120 GeV) starting from the fall of 2015

Back up

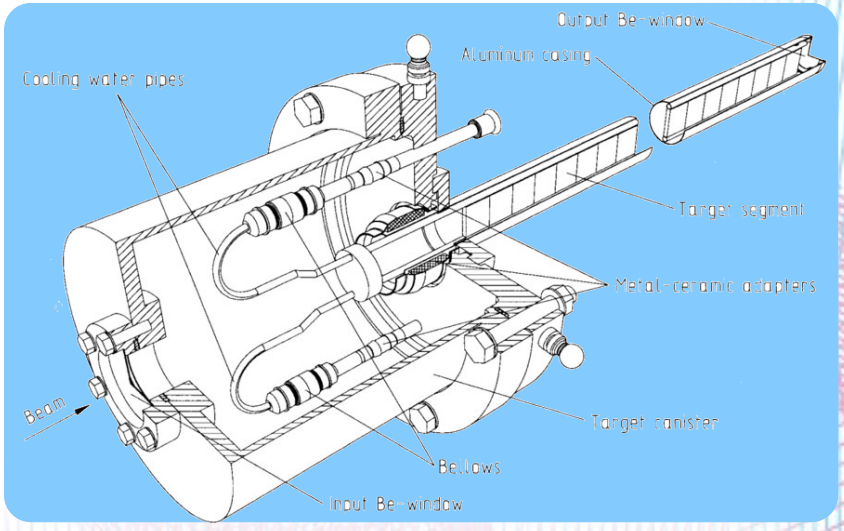
Measurements for the NuMI target

- 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



Assumed systematic uncertainties

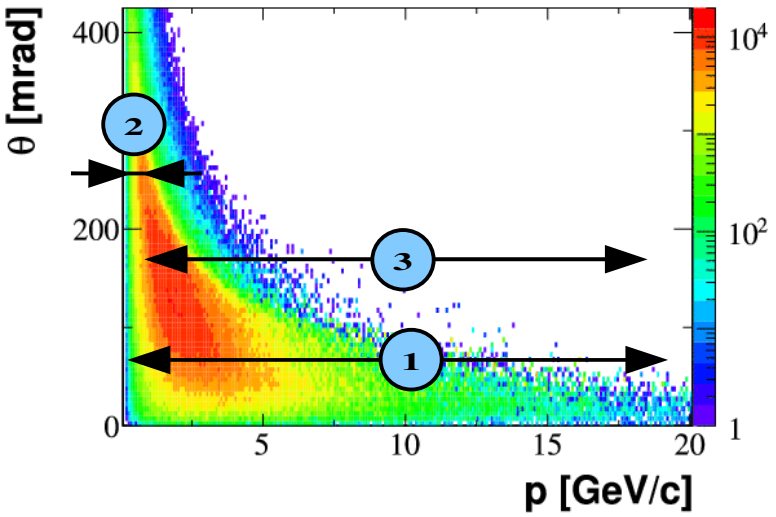
- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
					6.8	7.6

- Further reduction by new near detectors under study

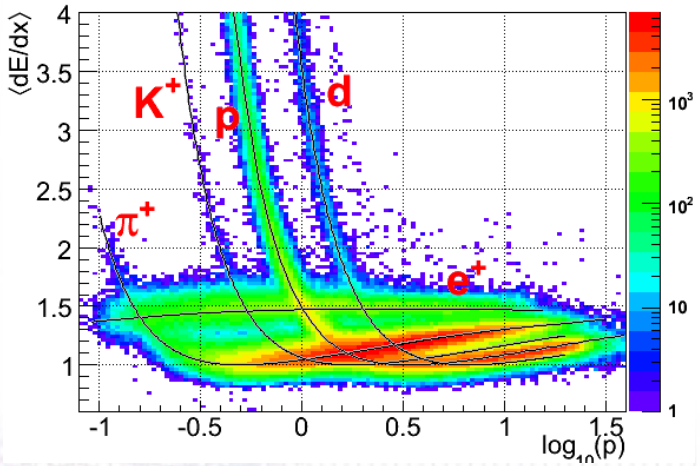
Analysis techniques (data 2007)



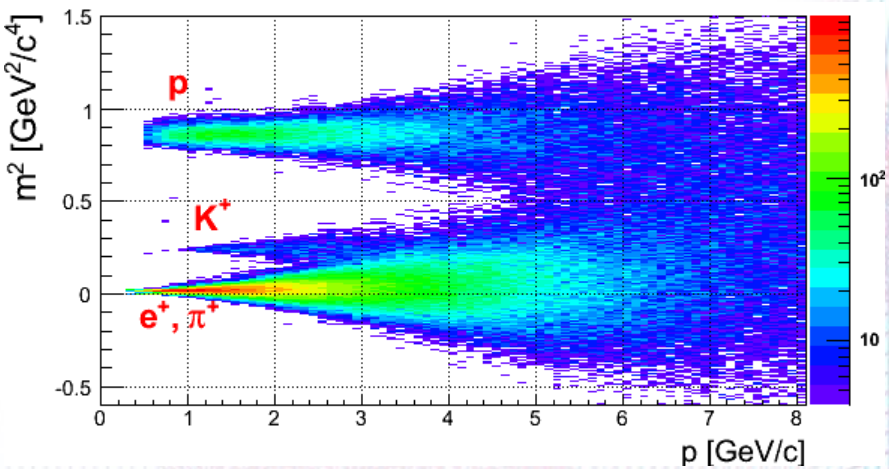
1) **h^- analysis**: analysis of π^- via measurements of negatively charged particles
2) ***dE/dx* analysis at $p \lesssim 1$GeV/*c***: $\pi^{\pm}$ and protons were identified via energy loss in TPC
3) **ToF-*dE/dx* analysis at $p \gtrsim 1$GeV/*c***: information from *dE/dx* and ToF is combined to identify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

Data 2009

Energy loss in TPC (*dE/dx*)



Time-of-Flight (ToF)

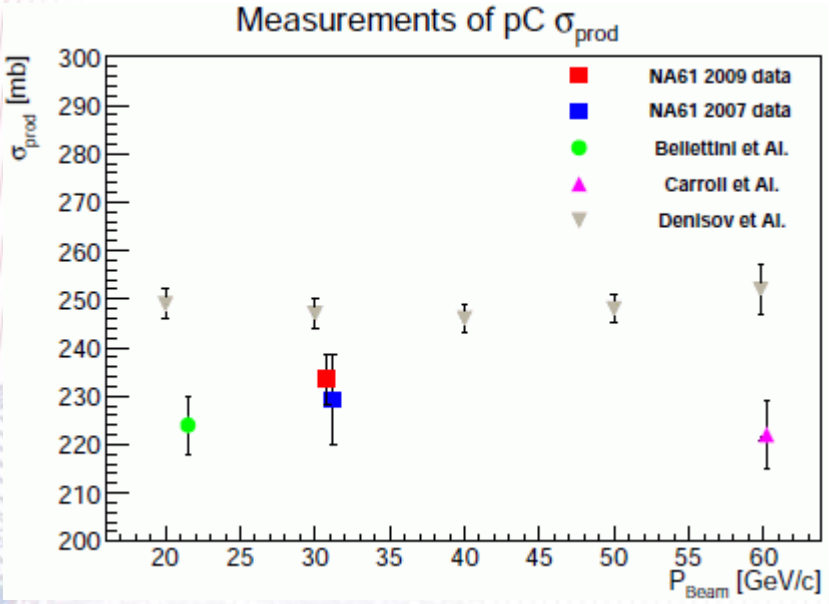


Production cross section and normalization

- 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



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

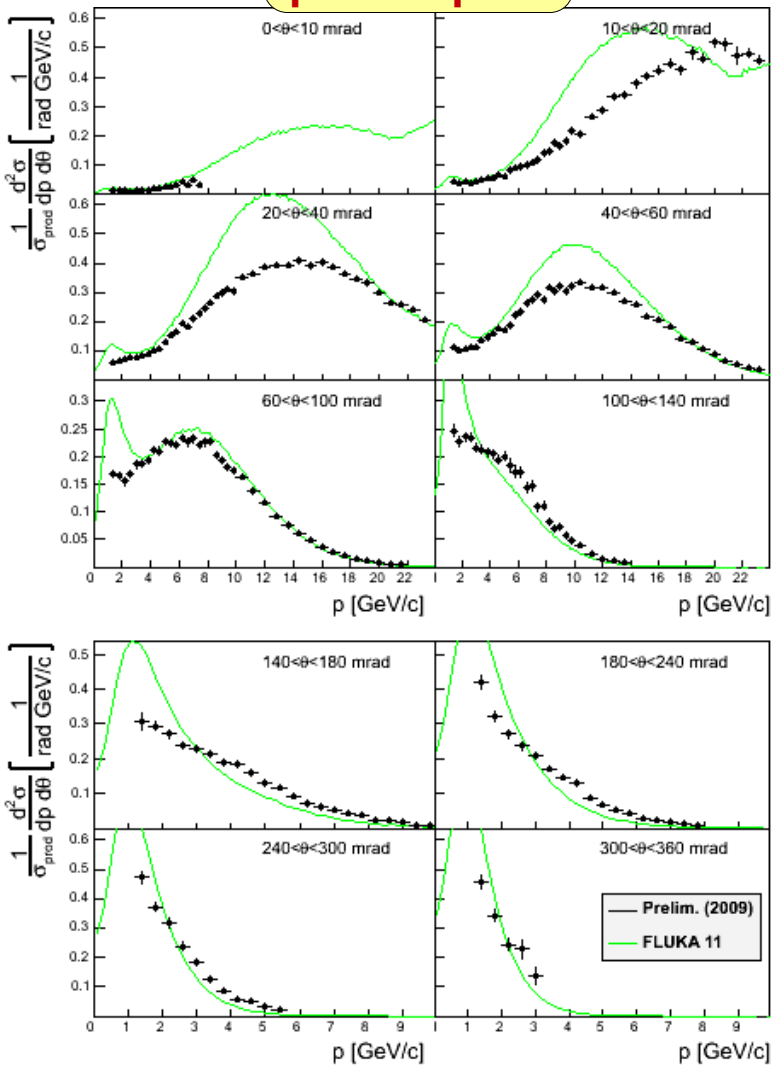
$$\sigma_{prod}^{2009} = 233.5 \pm 2.8\,(stat.) \pm 4.2\,(model) \pm 1.0\,(trigger)\,mb$$

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

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

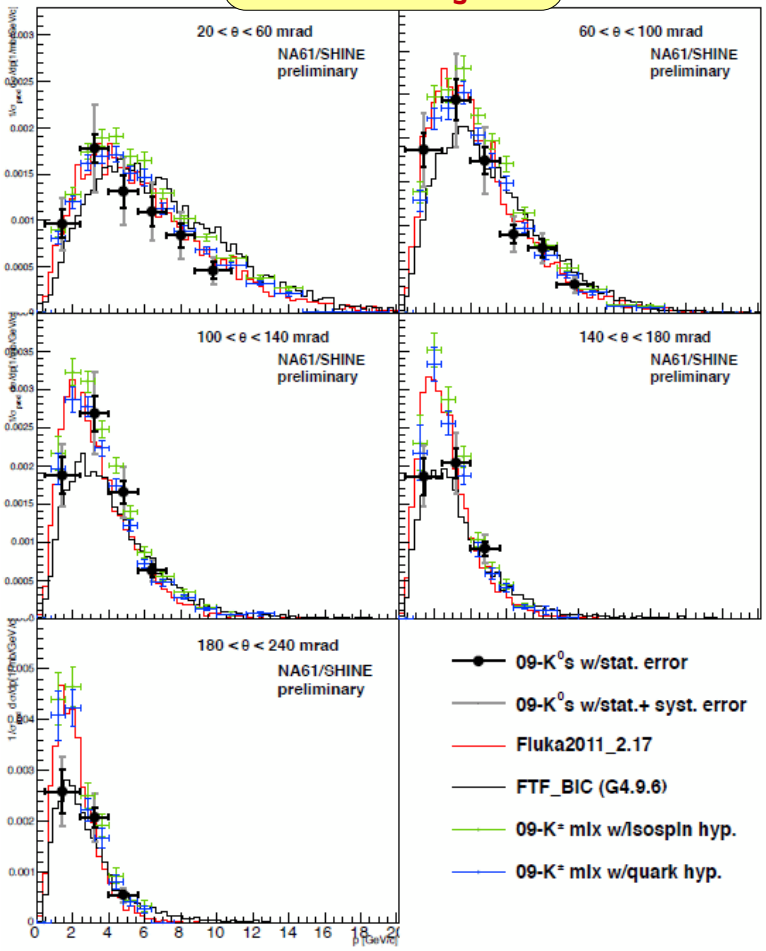
New results on proton and K^0_s multiplicity in pC @ 31 GeV/*c*

p + C → p + X



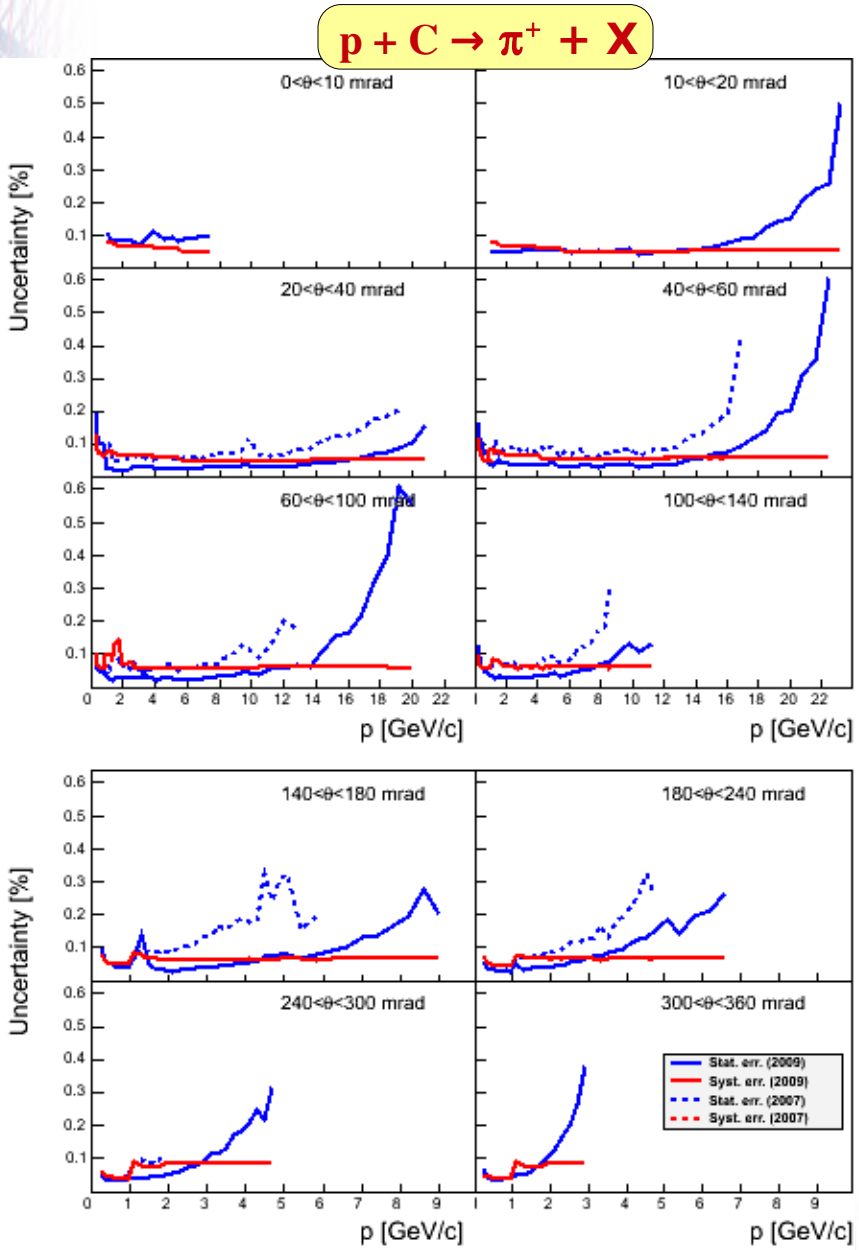
- To be used in the T2K beam simulation to decrease the systematics due to the secondary nucleon production

p + C → K^0_s + X

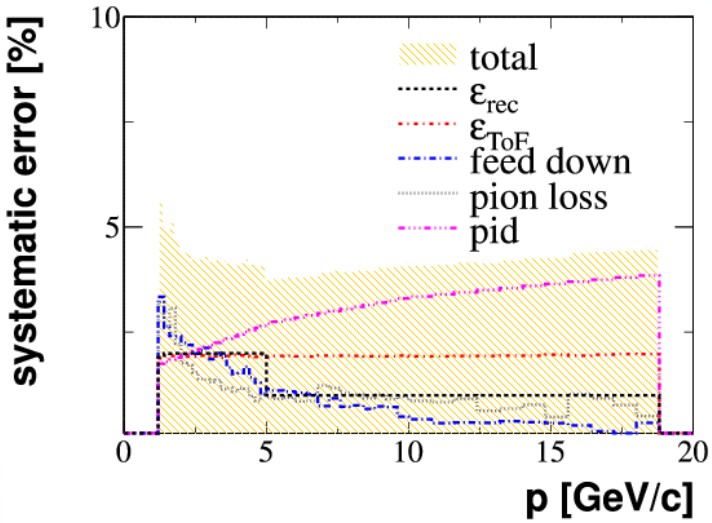


- To be used in the π analysis of NA61 to reduce the feed-down uncertainty. Presently discrepancy between FLUKA and VENUS introduces the error ~10% at low momenta

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



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

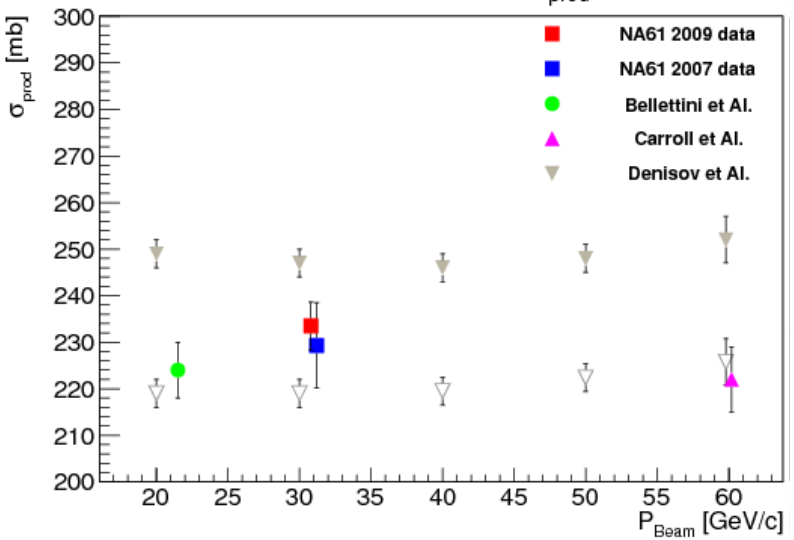
- $\sigma_{el\text{-}Out}$: el-scattering outside the acceptance of the interaction trigger counter (S_4)
- $\sigma_{loss\text{-}x}$: forward produced hadrons hitting S_4

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

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

Correction were estimated with GEANT4

Measurements of pC σ_{prod}



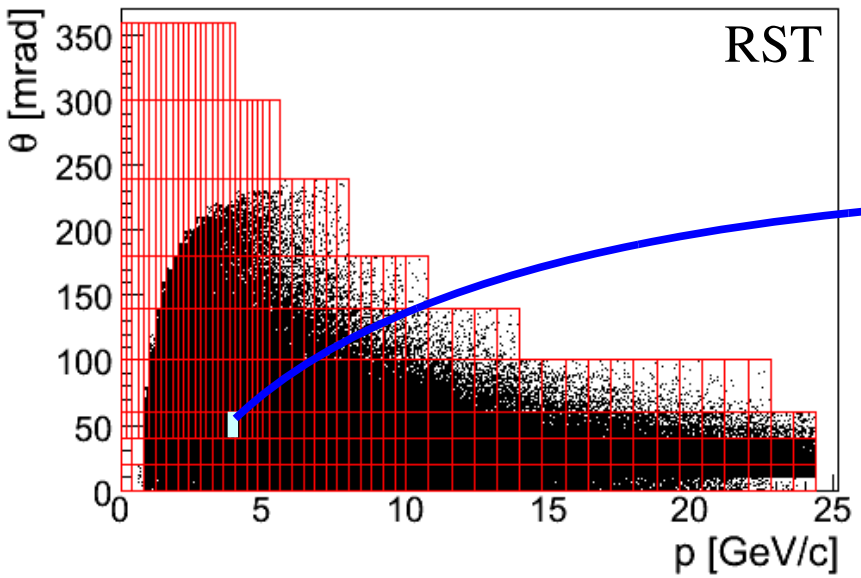
$$\sigma_{prod} = 233.5 \pm 2.8(stat) \pm 4.2(model)^{+1}_{-1.2}(trigger) \text{ mb}$$

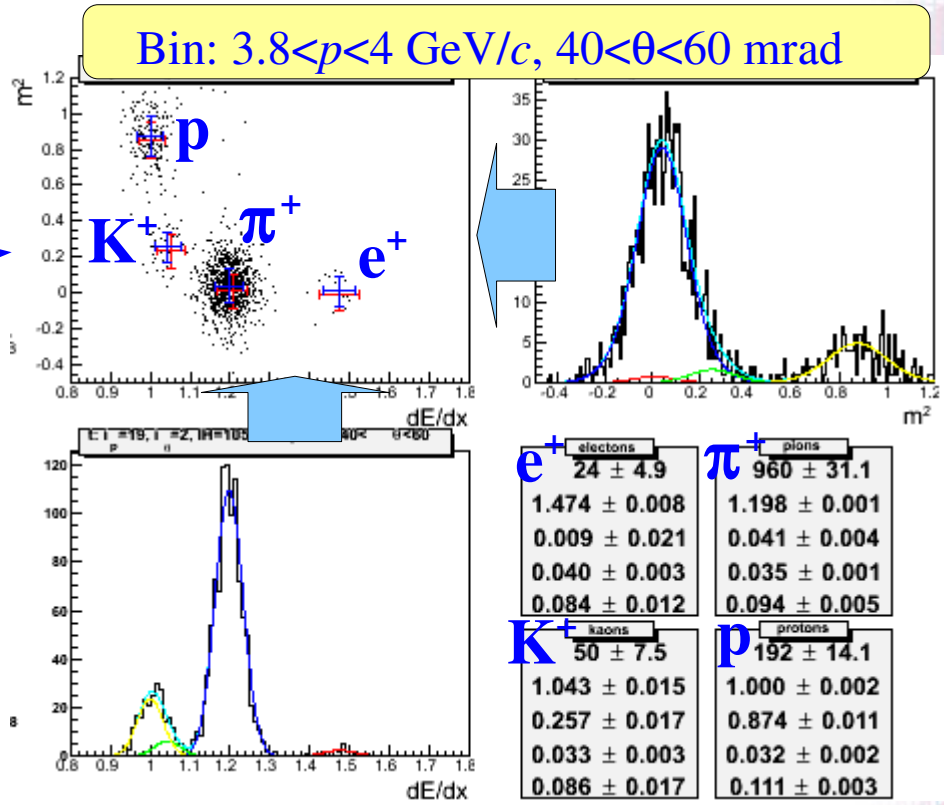
$$\sigma^{2007}_{prod} = 229.3 \pm 1.9(stat) \pm 9.0(syst) \text{ mb}$$

Normalization analysis is completed

Total uncertainty from 4% (2007) to 2%

Technique of combined ToF- *dE/dx* analysis

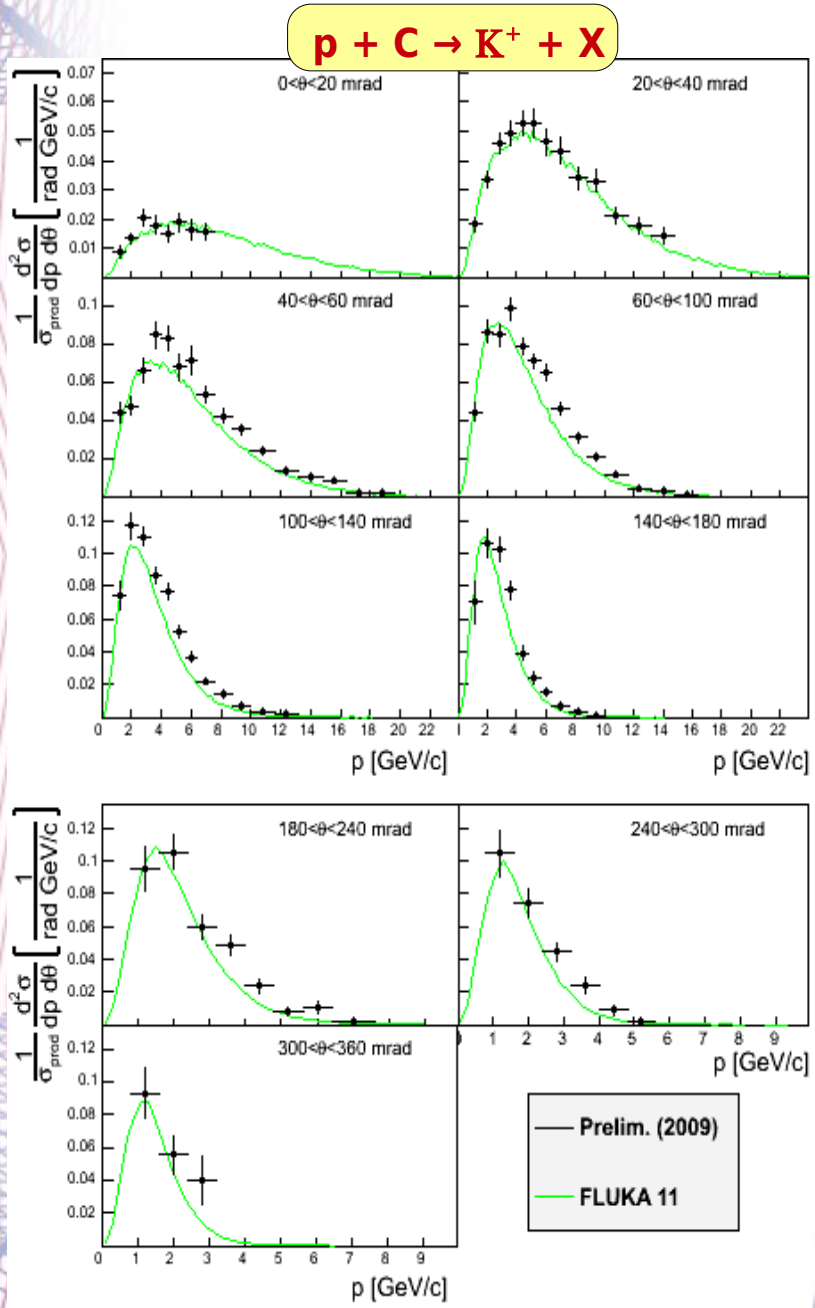




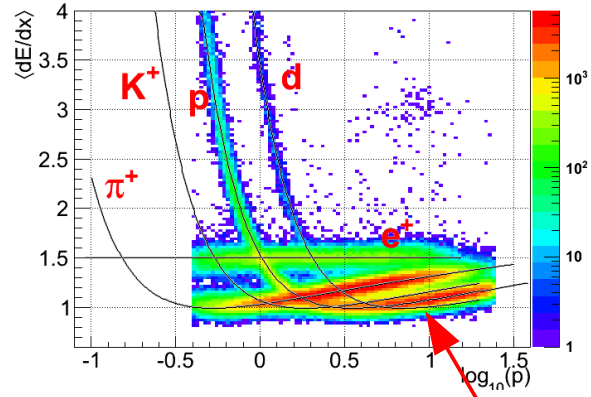
- Signal is parametrized as a product of Gaussian functions in m^2 and *dE/dx*
- For each (p,θ) bin the maximum likelihood method was applied to fit the shape

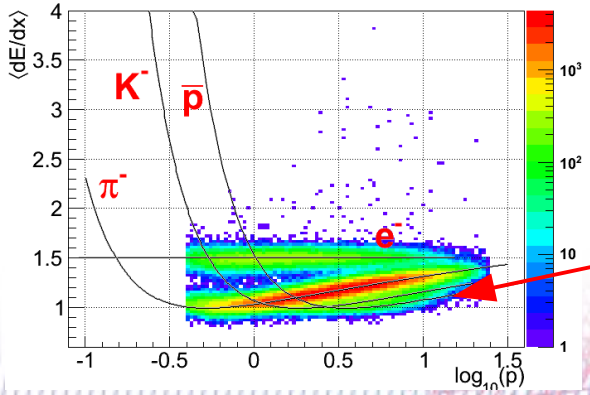
- Uncertainty associated to the unknown functional form is a dominant contribution to the systematic error at $p \gtrsim 2$ GeV/*c*

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



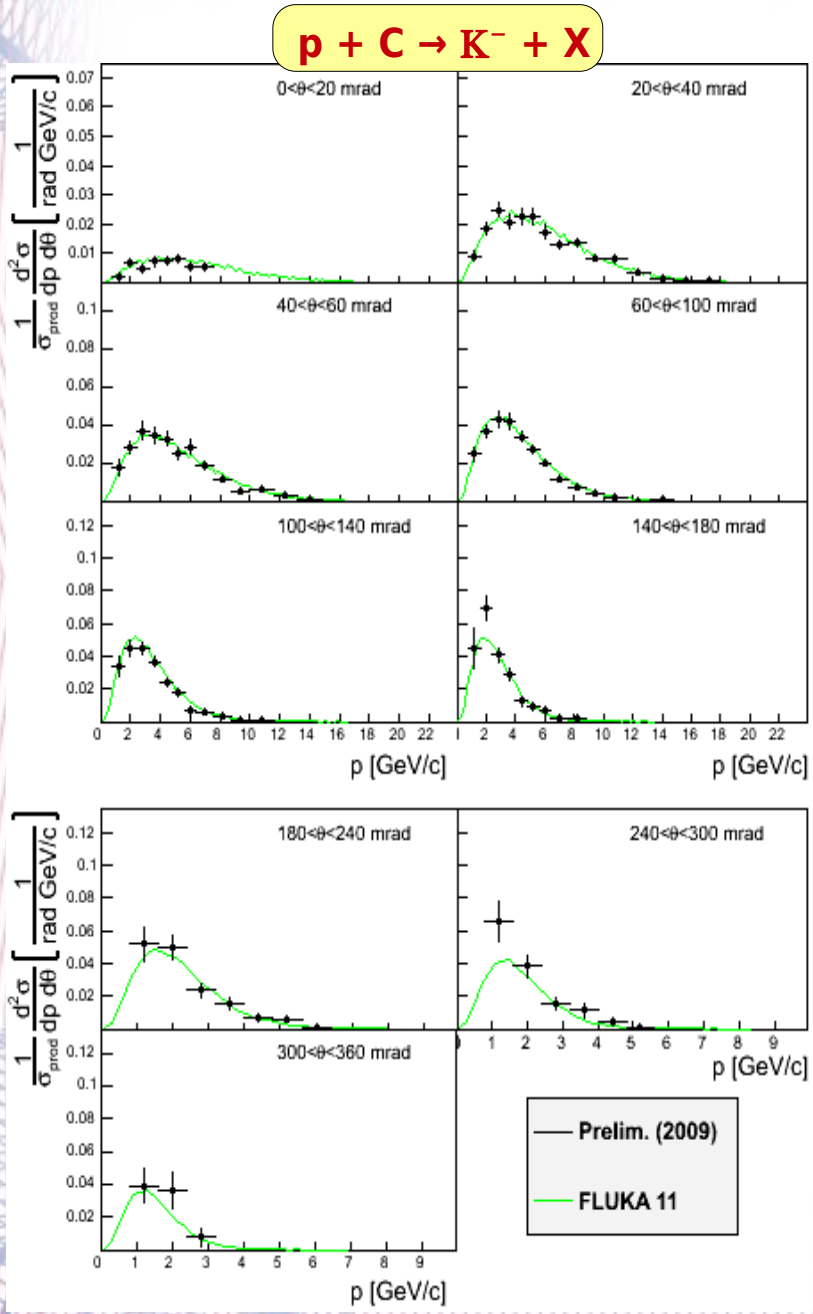
- Agreement with published K^+ cross section
  - Statistics (and total error) **improve by a factor 3**
- At large momenta K^+ is totally under the proton peak ⇨ additional systematics
- K^- are shown for the first time. Analysis with data 2007 was not possible due to low statistics



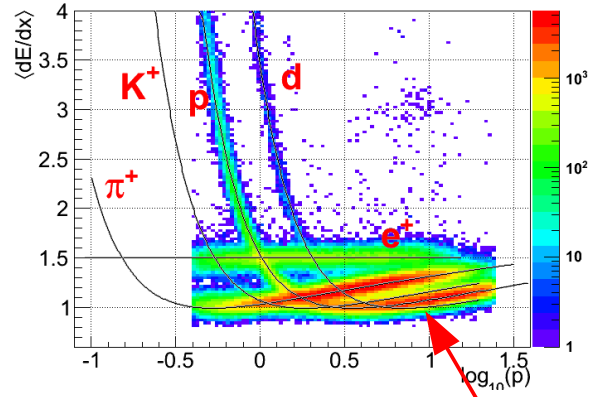


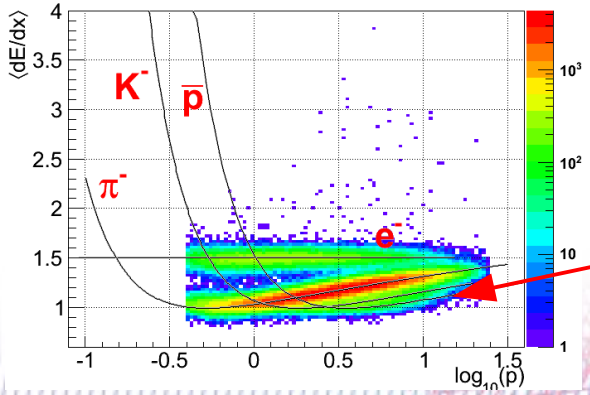
Additional uncertainty on K^+ due to protons

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



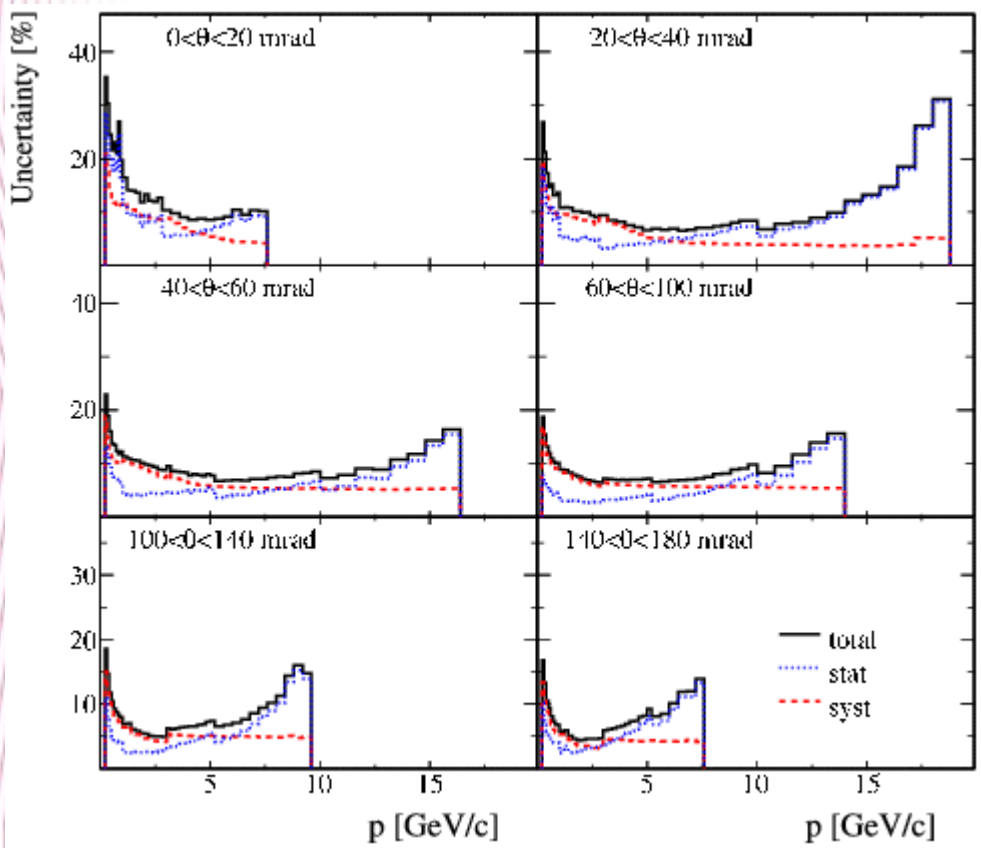
- Agreement with published K^+ cross section
  - Statistics (and total error) **improve by a factor 3**
- At large momenta K^+ is totally under the proton peak ⇨ additional systematics
- **K^- are shown for the first time.** Analysis with data 2007 was not possible due to low statistics

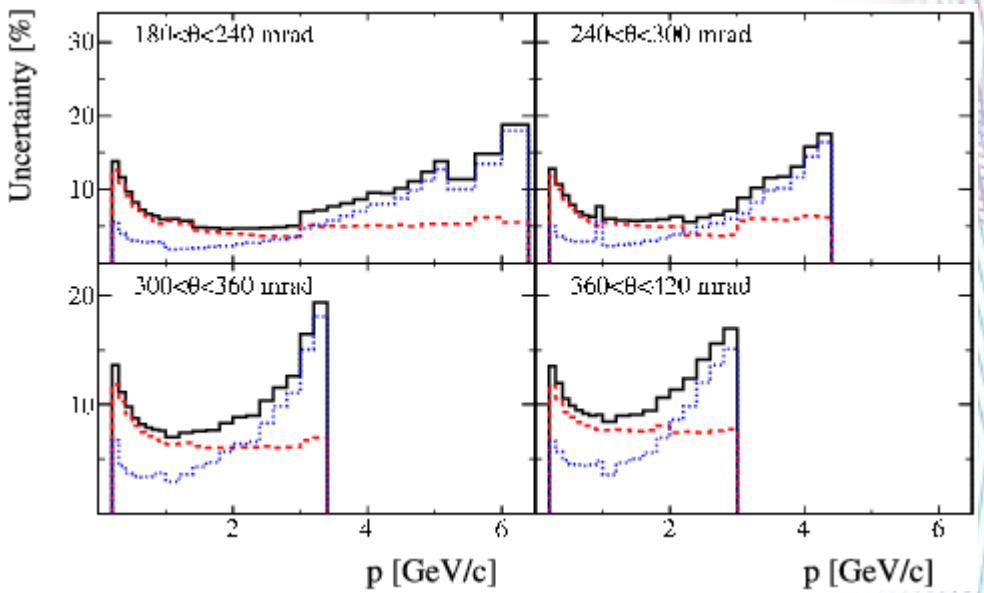




Additional uncertainty on K^+ due to protons

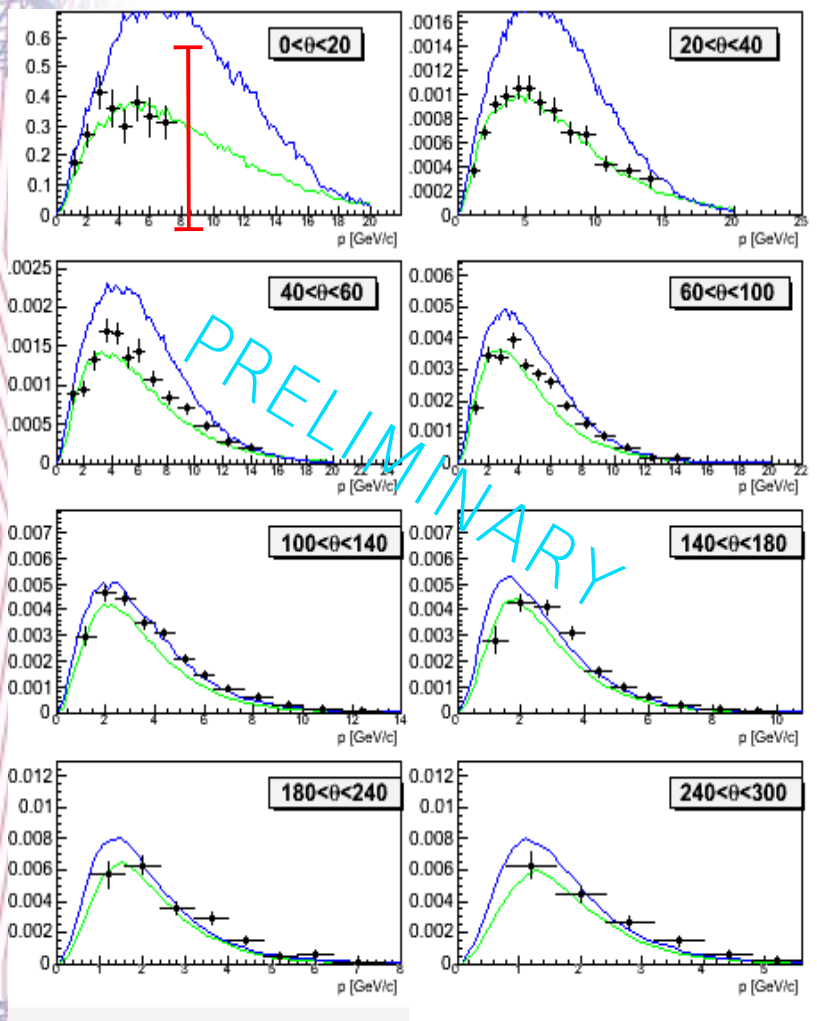
Relative uncertainties for π^- (data 2007)

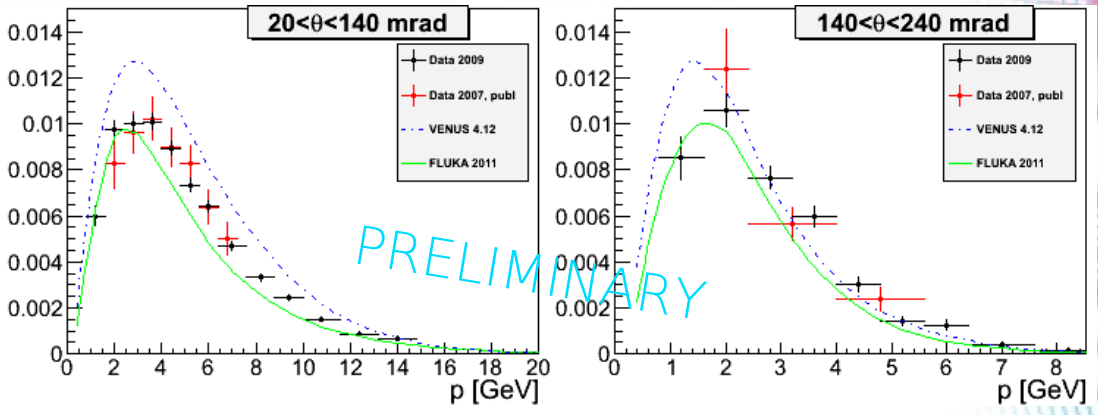


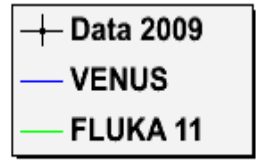


- Among 3 analyzes the one with smaller total error was selected
- Systematic error dominates at lower momenta. At higher momenta stat. error is larger

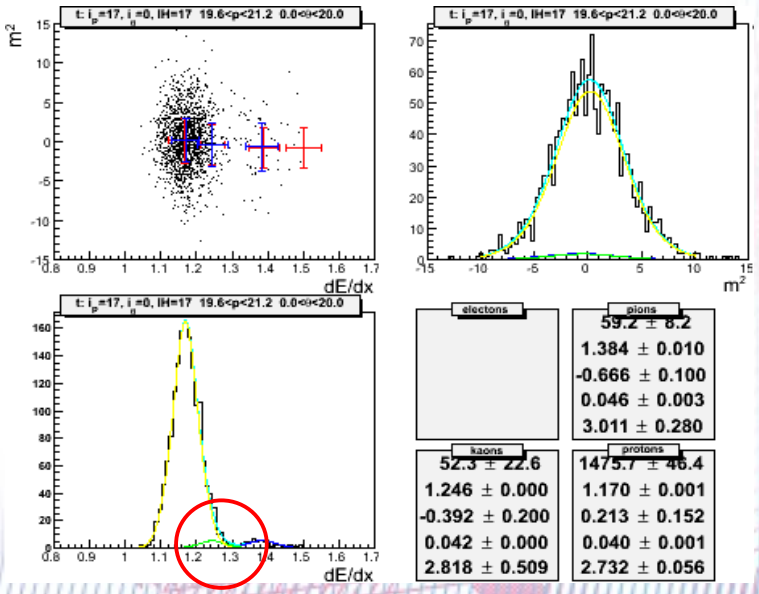
Multiplicities for K+





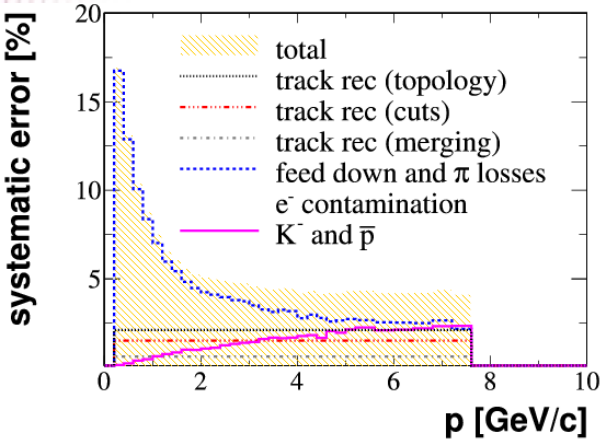


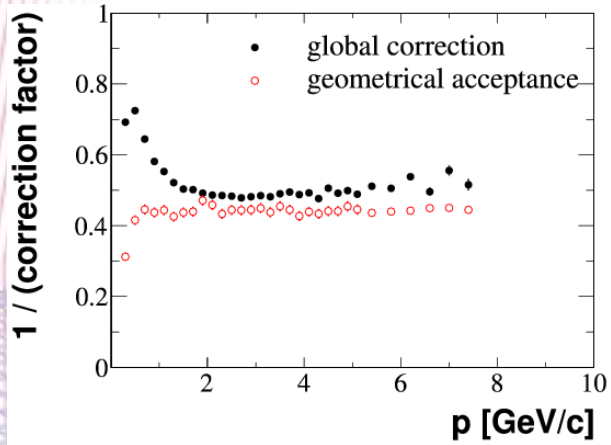
- Agreement with published K^+ cross section
- At large momenta K^+ is totally under the proton peak ⇒ Proper multi-gaussian fit of *dE/dx* is needed



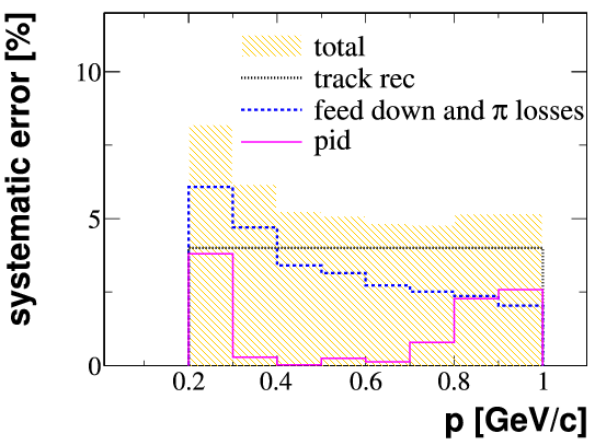
Syst. error & correction factors for π^- analysis (data 2007)

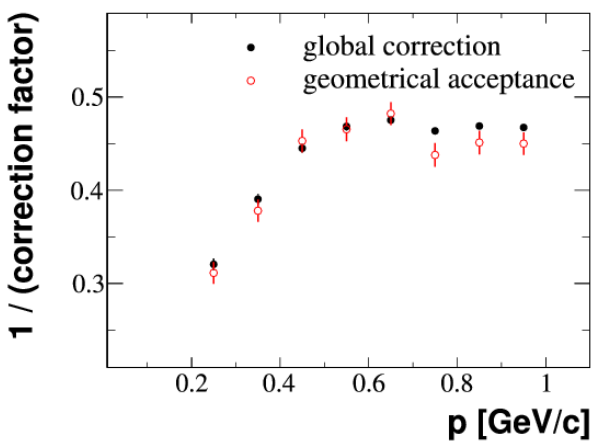
h- analysis



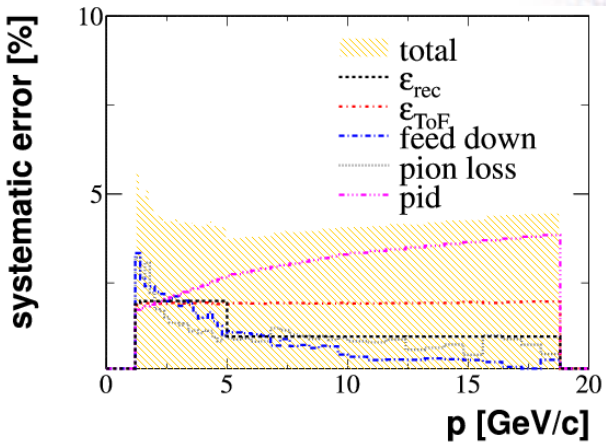


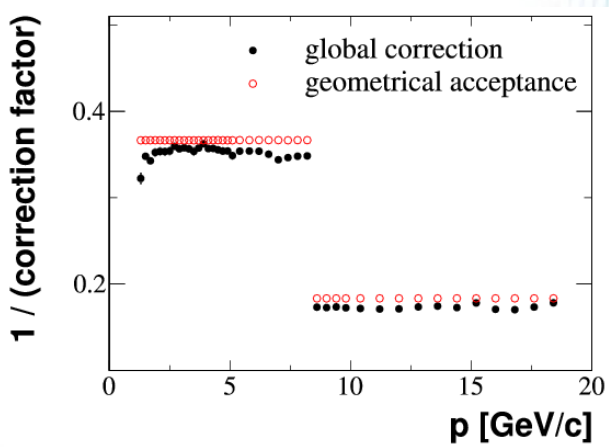
dE/dx analysis



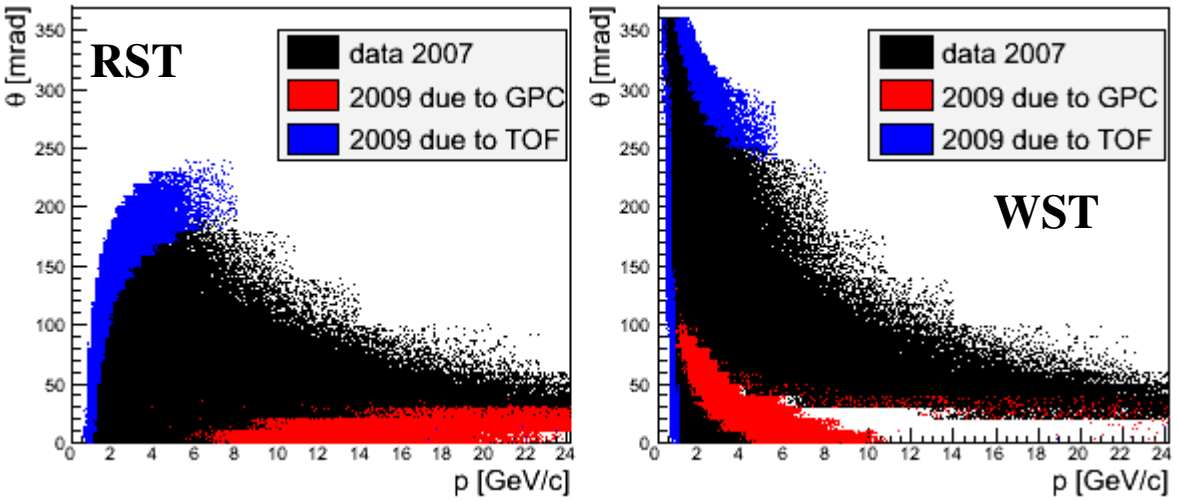


ToF-*dE/dx* analysis





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 ⇨

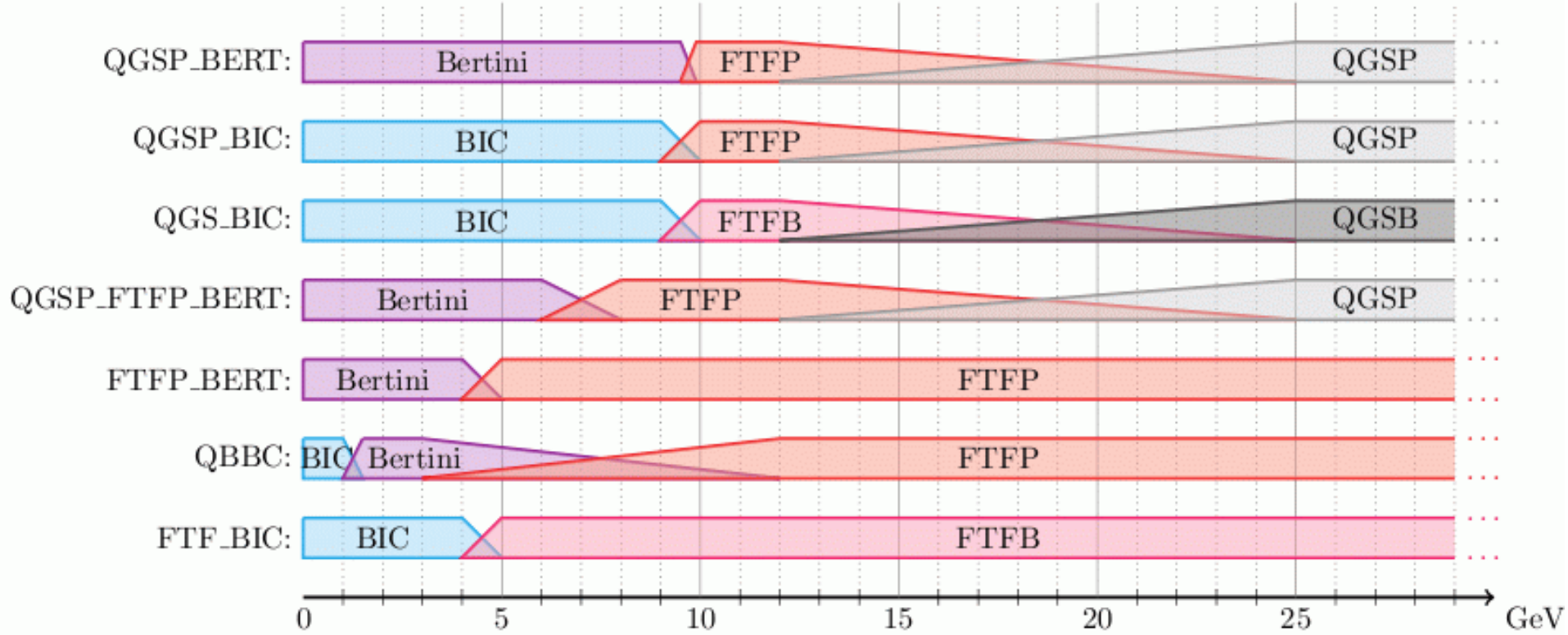
$$\frac{dn_\alpha}{dp} = \frac{1}{\sigma_{prod}}\frac{d\sigma_\alpha}{dp}$$

- 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

Update on physics lists

Composition of physics lists for proton interaction as a function of the energy

Now with **VMC 2.15** (**Geant4.10**)



BIC: Binary Cascade Model
Bertini: Bertini Model
FTF: Fritiof Model
QGS: Quark Gluon String
~~**LHEP**: Low and High Energy Parametrized~~ REMOVED
-**P**: Precoumpound
-**B**: BIC