Hadron production measurements in NA61/SHINE for T2K

Alexander Korzenev, Geneva University

on behalf of the NA61/SHINE collaboration

NOW 2012

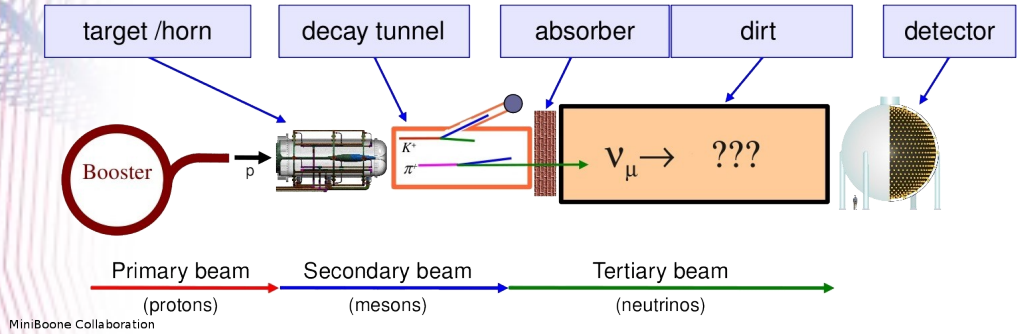
Otranto, Lecce, Italy

September 12, 2012

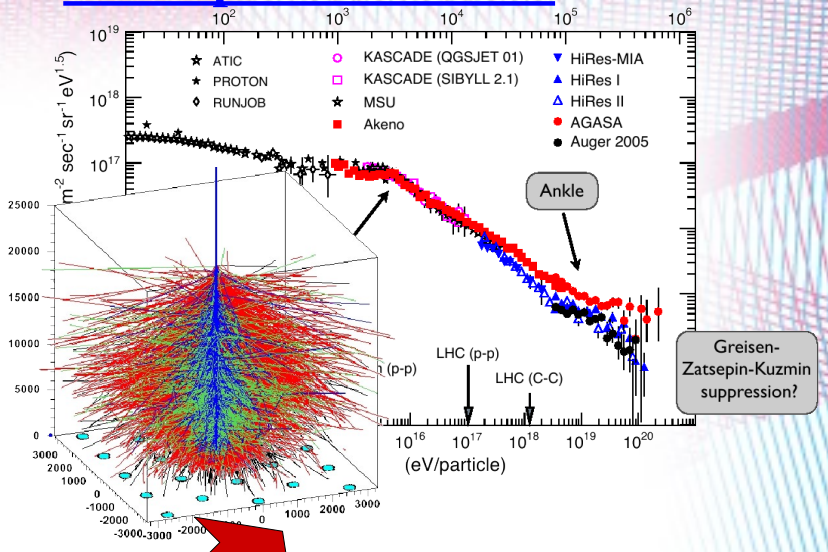
Outline

- Why hadroproduction?
- Results of the pilot run 2007
- Forthcoming results
- Measurements for NuMI

Conventional accelerator ν-beam



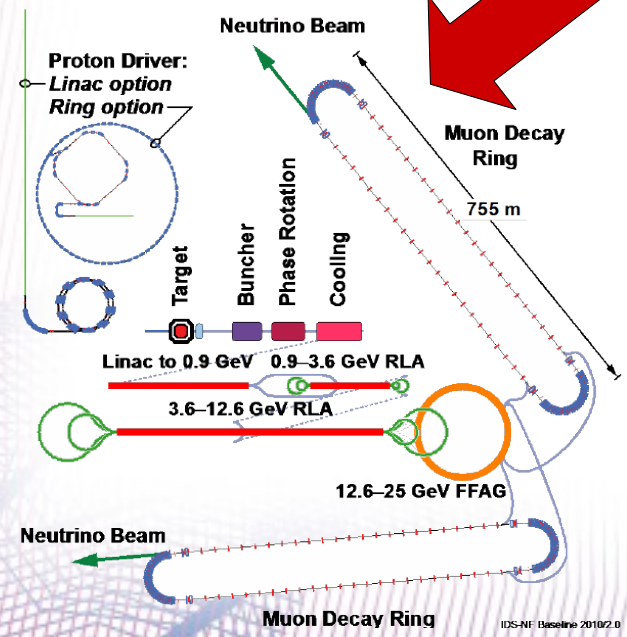
Atmospheric showers



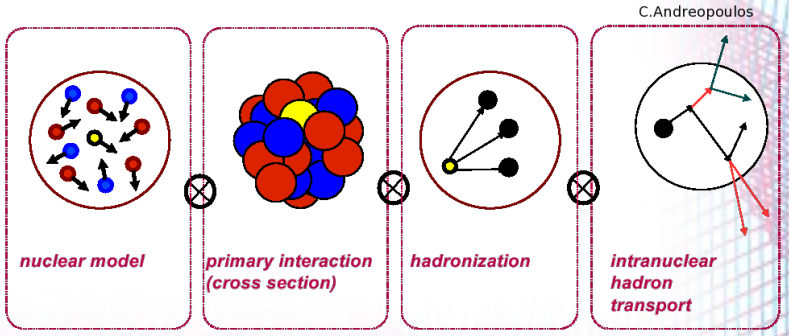
Hadroproduction measurement

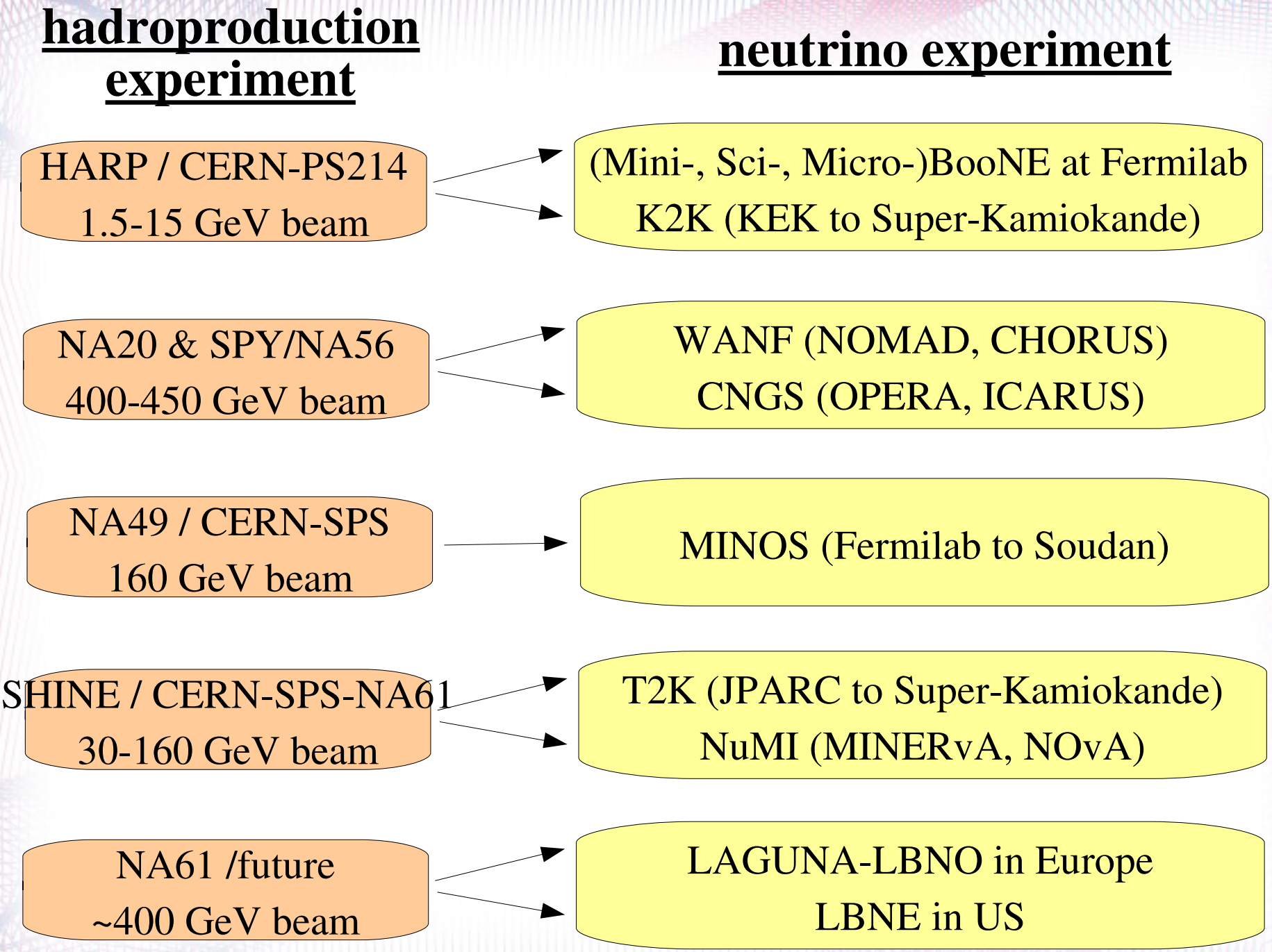
$p(\pi) + A \rightarrow h + X$

Neutrino Factory



MC generators

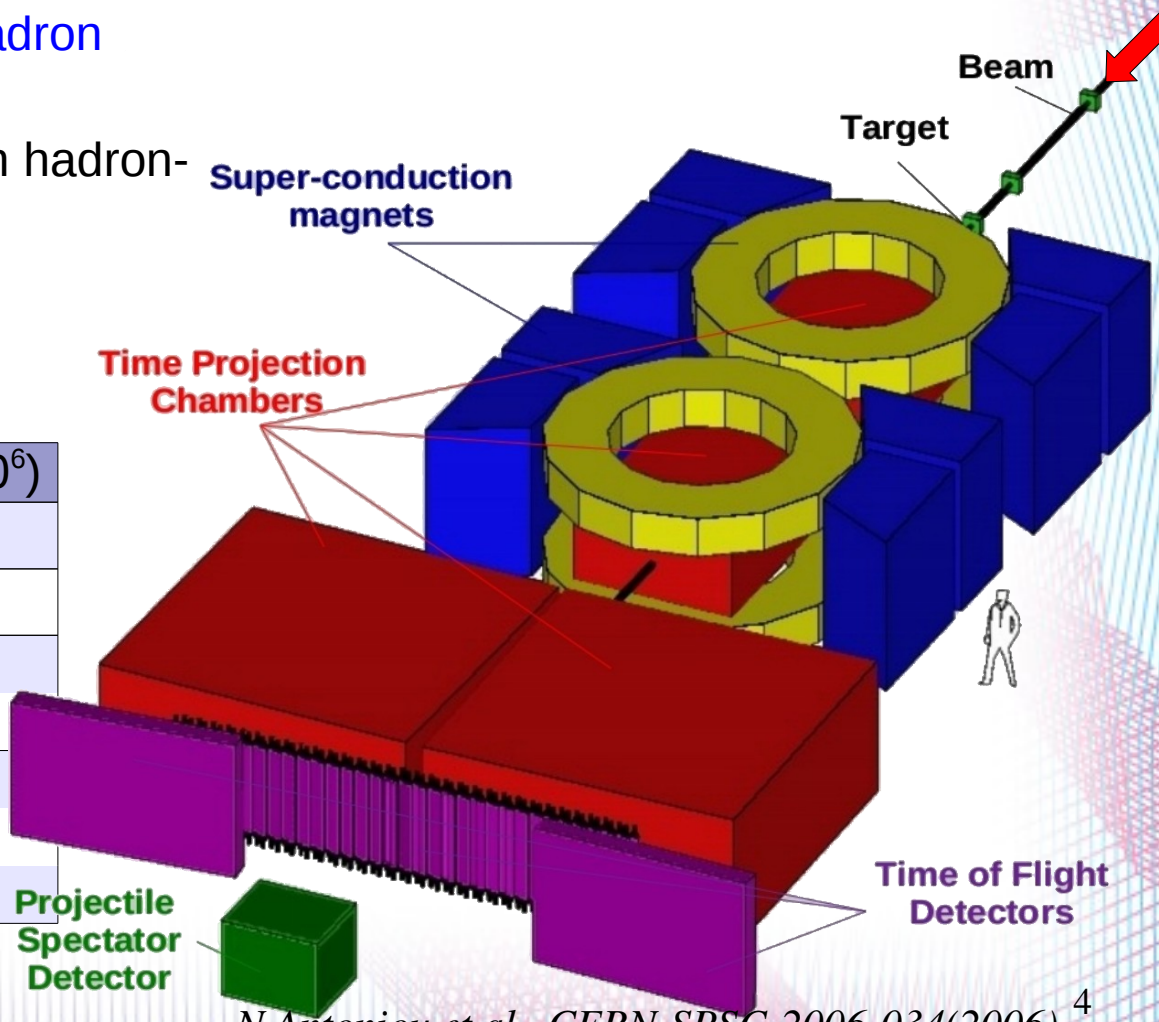



hadroproduction experiment
neutrino experiment
HARP / CERN-PS214
1.5-15 GeV beam
(Mini-, Sci-, Micro-)BooNE at Fermilab
K2K (KEK to Super-Kamiokande)
NA20 & SPY/NA56
400-450 GeV beam
WANF (NOMAD, CHORUS)
CNGS (OPERA, ICARUS)
NA49 / CERN-SPS
160 GeV beam
MINOS (Fermilab to Soudan)
SHINE / CERN-SPS-NA61
30-160 GeV beam
T2K (JPARC to Super-Kamiokande)
NuMI (MINERvA, NOvA)
NA61 /future
~400 GeV beam
LAGUNA-LBNO in Europe
LBNE in US

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
- Pilot run in 2007
- Successor of NA49, H2 beamline of CERN-SPS

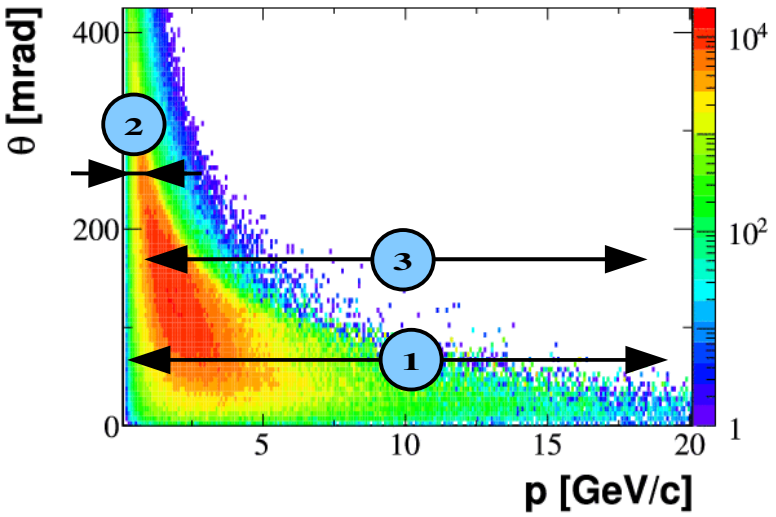


Data with a *carbon target*

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

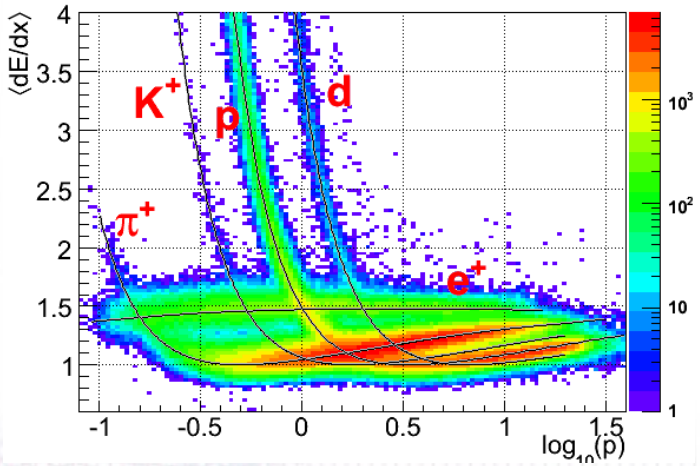
N.Antoniou et al., CERN-SPSC-2006-034(2006)

Analysis techniques (data 2007)

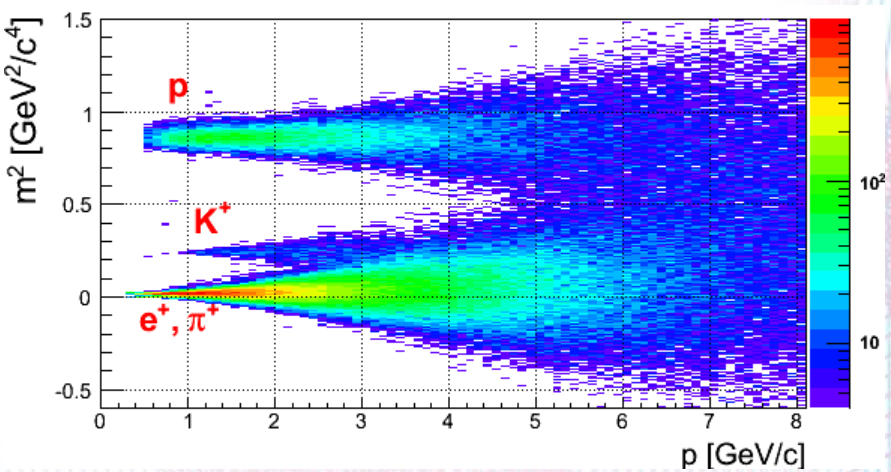


1) **h^- analysis**: analysis of π^- via measurements of negatively charged particles
2) ***dE/dx* analysis**: $\pi^{\pm}$ and p were identified via energy loss in TPC
3) **ToF-*dE/dx* analysis**: information from *dE/dx* and ToF-F is combined to identify $\pi^{\pm}$, $K^{\pm}$ and p

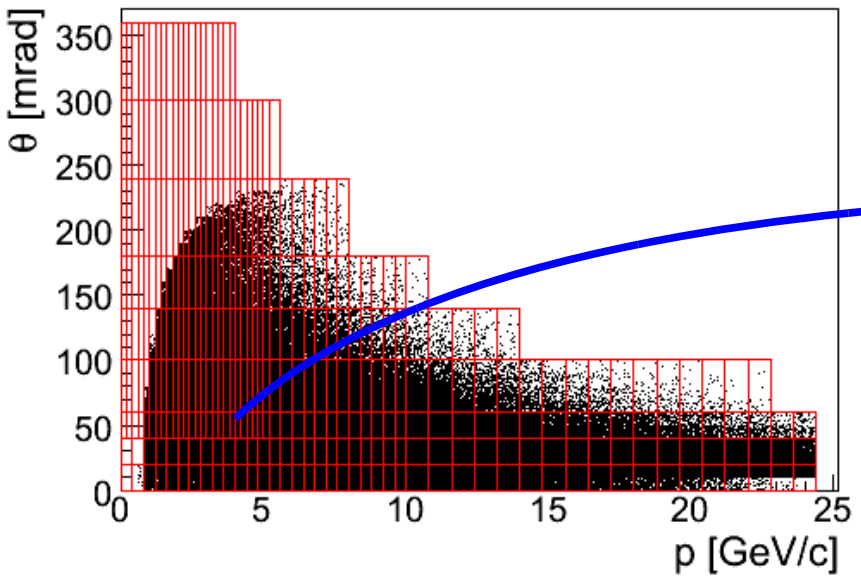
Energy loss in TPC (*dE/dx*)

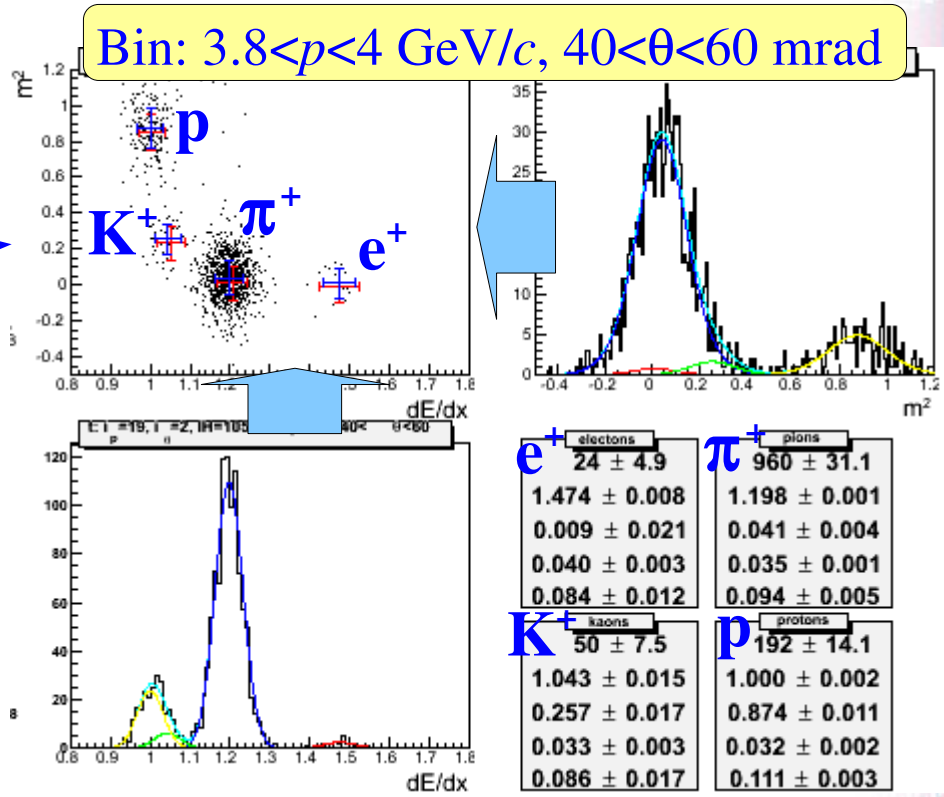


Time-of-Flight (ToF)



Idea of combined ToF-*dE/dx* analysis

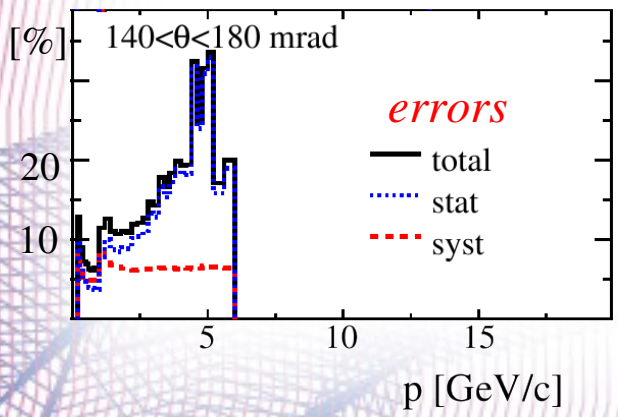




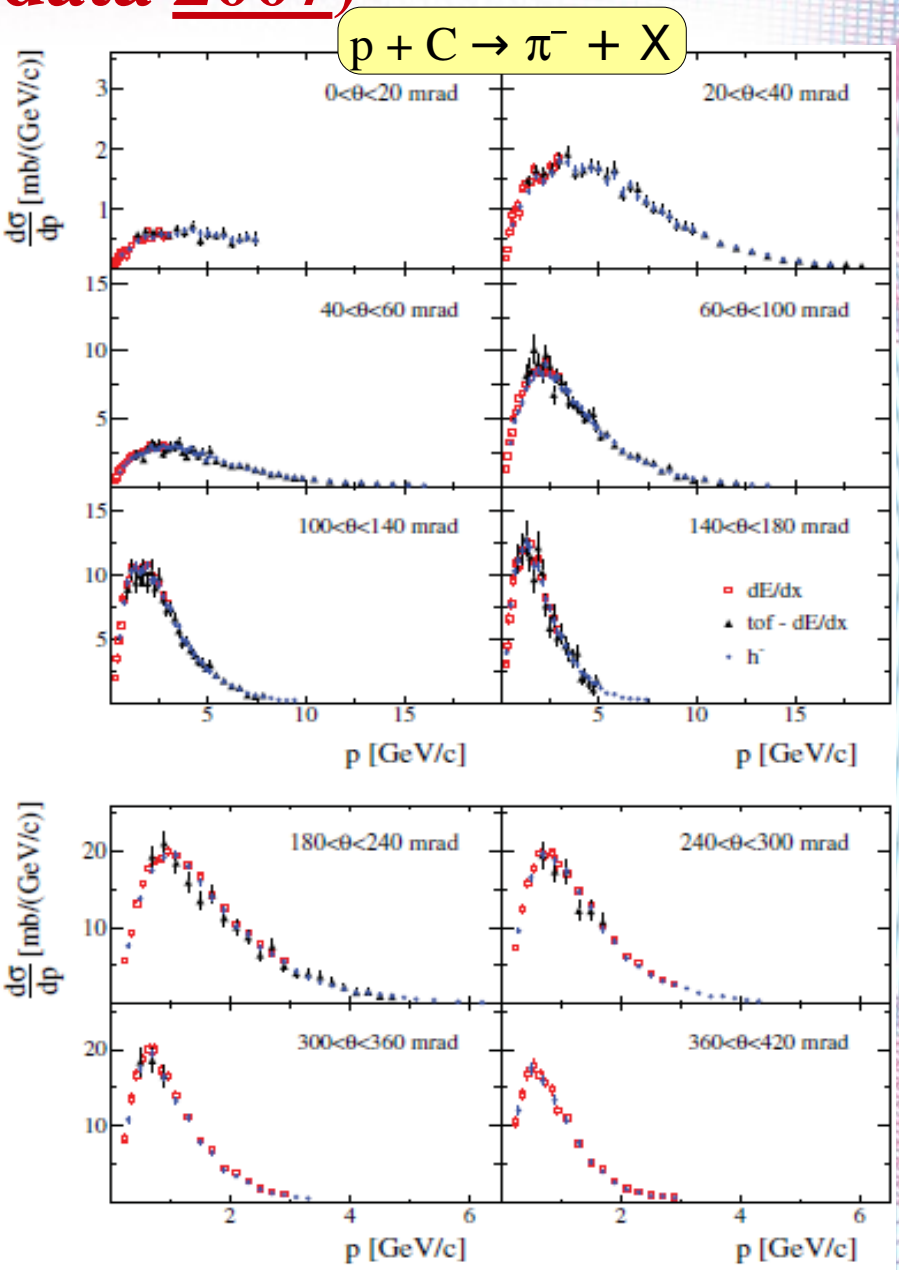
- Signal is parametrized as a product of Gaussian functions in m^2 and *dE/dx*
- For each (p,θ) bin the maximum likelihood method was applied to fit the shape
- Uncertainty associated to the unknown functional form is a dominant contribution to the systematic error at middle and high p

π^+ and π^- results (data 2007)

- Spectra of π^+ and π^- produced in strong and e.-m. processes in p+C interactions at 31 GeV/*c*
- To be used for ν flux prediction in T2K
- Data collected in the pilot run 2007
- Polar angle range: 0<θ<420 mrad
- Tree analysis techniques. Measurement with smaller error was selected for the final value
- At middle and high *p* statistical error is larger than the systematic one => one can profit from higher statistics (factor 10 with data 2009)



Feed down corrections are dominant at low *p*. They are mainly contributions of π produced in week decays of K^0_s and Λ



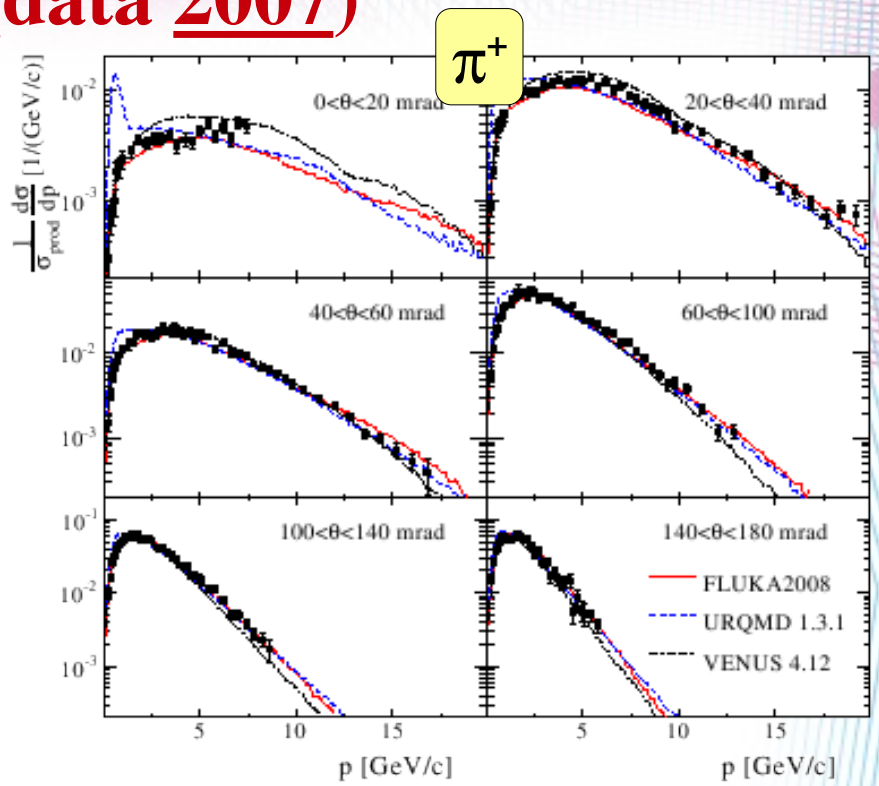
(NA61) N.Abgrall et al., Phys.Rev.C84(2011)034604

π^+ and π^- results (data 2007)

- π spectra normalized to the mean π multiplicity in production interactions are compared to MC

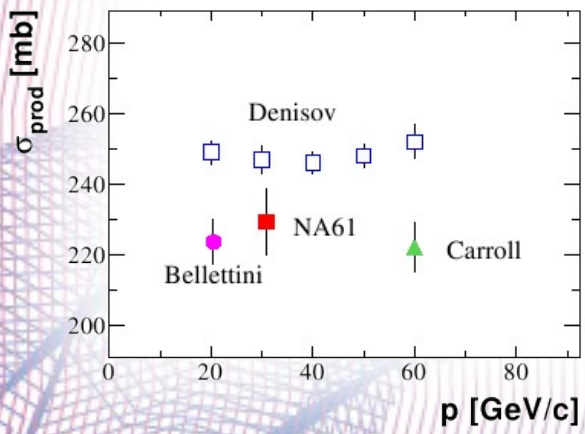
$$dn_\pi/dp = 1/\sigma_{prod} \cdot d\sigma_\pi/dp$$

- In general FLUKA 2008 and VENUS 4.12 give a reasonable description of data
- GHEISHA qualitatively failed to describe data
- UrQMD 1.3.1 model follows the data trend at p>3 GeV/c. Inaccurate treatment of low mass string fragmentation at p<3 GeV/c.
  V.Uzhinsky, arXiv:1107.0374, 1109.6768



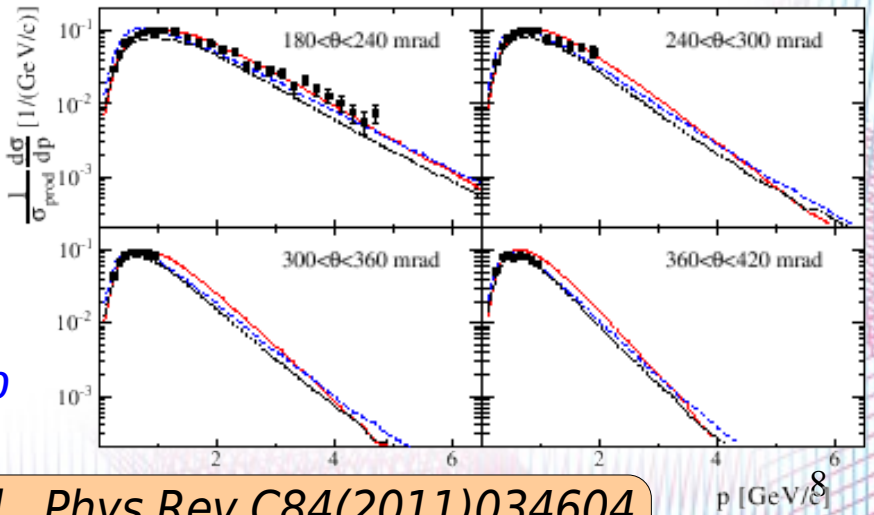
- Corrections for the coherent elastic scattering were calculated using GEANT4

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = 257.2 \pm 1.9 \pm 8.9 \text{ mb}$$



Production cross section is well consistent with previous measurements

$$\sigma_{prod} = \sigma_{inel} - \sigma_{qe} = 229.3 \pm 1.9 \pm 9.0 \text{ mb}$$



(NA61) N.Abgrall et al., Phys.Rev.C84(2011)034604

NA61 data in the T2K experiment

Experiment	Beam p[GeV/c]	Target	Particle
NA61/SHINE	31	C	$\pi^{\pm}$, K^{+}
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	$\pi^{\pm}$

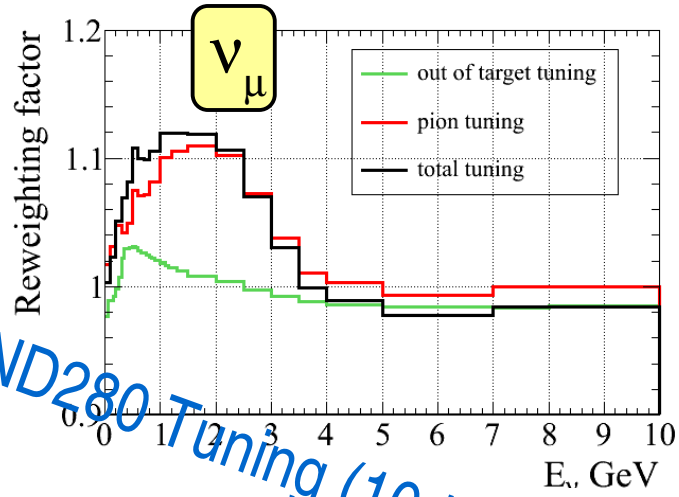
Major part of the T2K phase space

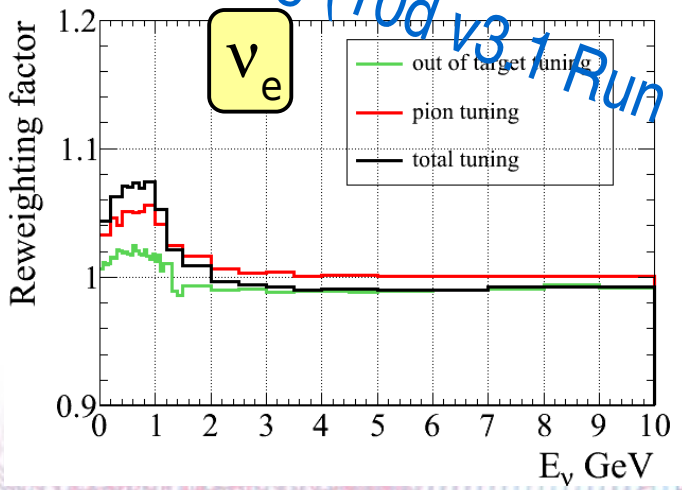
For forward kaons

For tertiary pions

- Hadronic interactions in the target are modeled with FLUKA2008, outside the target with GEANT3 (GCALOR)
- Interaction chain for p, $\pi^{\pm}$, $K^{\pm}$, K^{0}_{L} 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 is done using parametrization

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





ND280 Tuning (10d v3.1 Run 1)

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)

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%

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

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

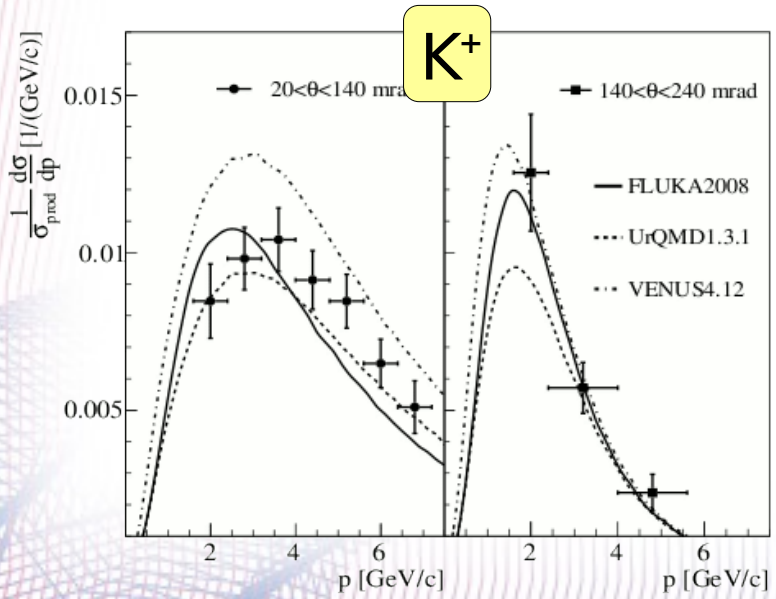
Total relative uncertainty

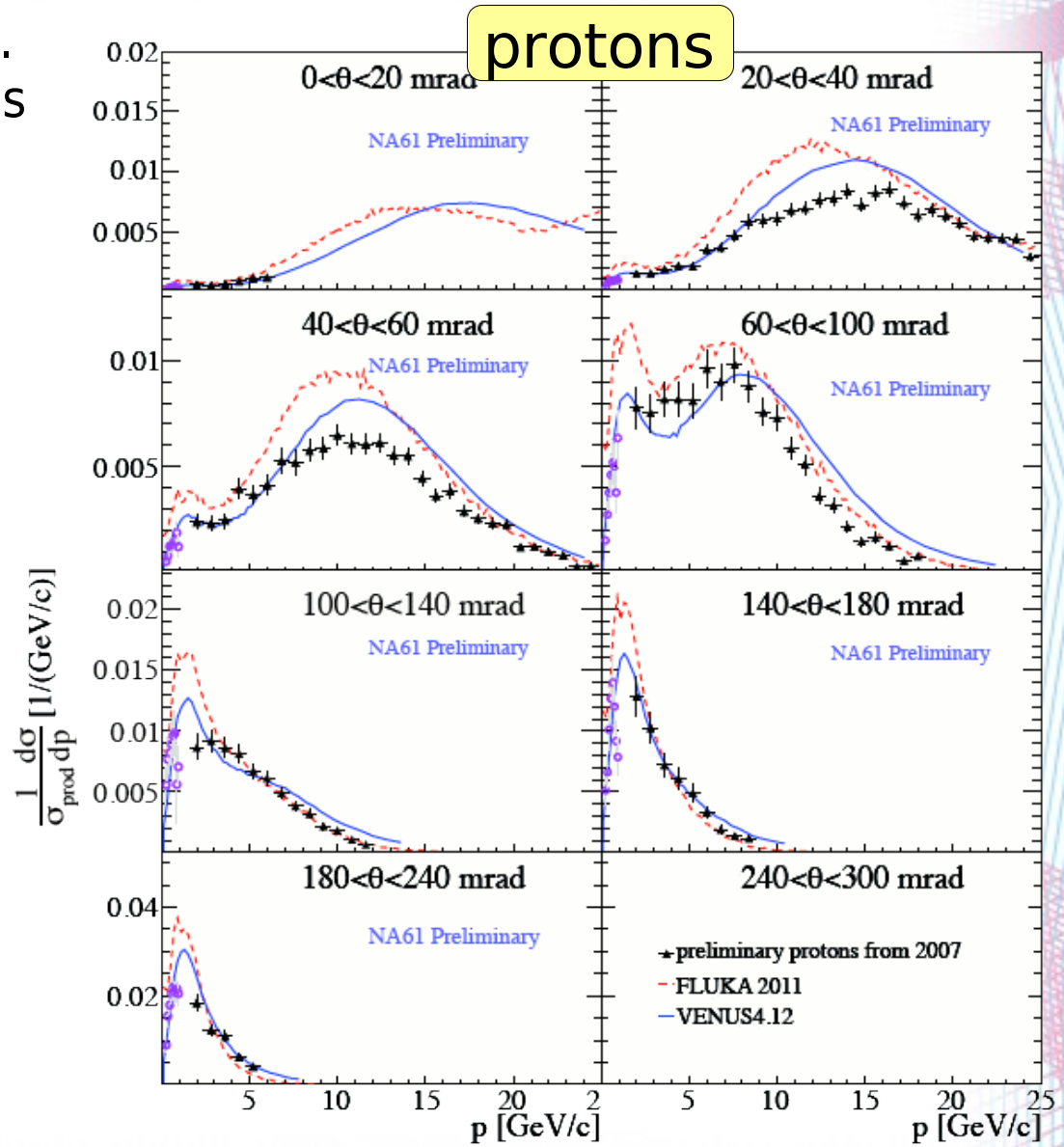
source	error
Neutrino flux	8.5%
Near detector	+5.6/-5.2 %
Near detector stat.	2.7%
Cross-section	10.5%
Far detector	9.4%
Total	+17.6/-17.5%

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

K^+ and proton results (data 2007)

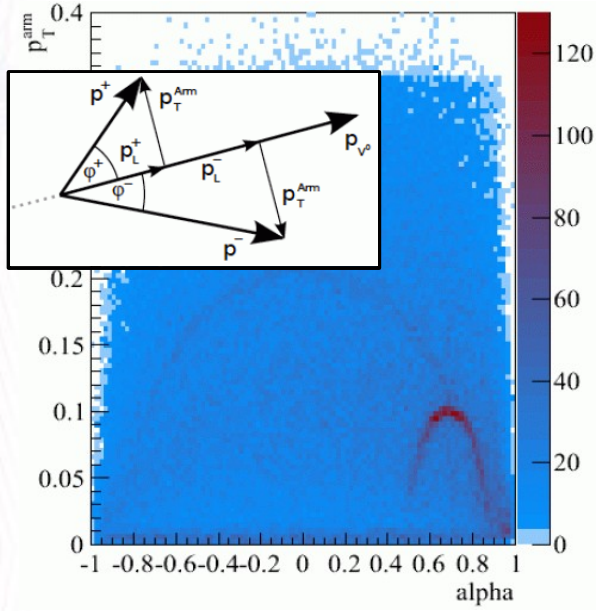
- K^+ cross-section has published. Due to low statistics only 2 bins in θ
- Preliminary result on proton cross-section has been released
- Forward production is important for the μ monitor in T2K (not possible with data 2007)





(NA61) N.Abgrall et al., Phys.Rev.C85(2012)035210

V0 analysis (data 2007)



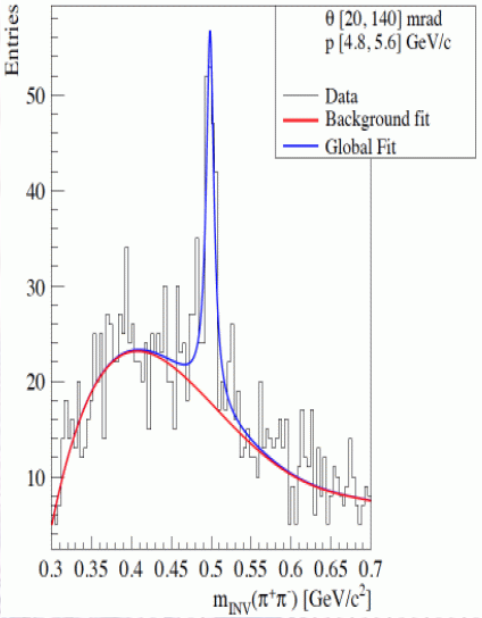
- Constraint on K^0 multiplicity in T2K done (Eichten & Allaby data) assuming isospin symmetry

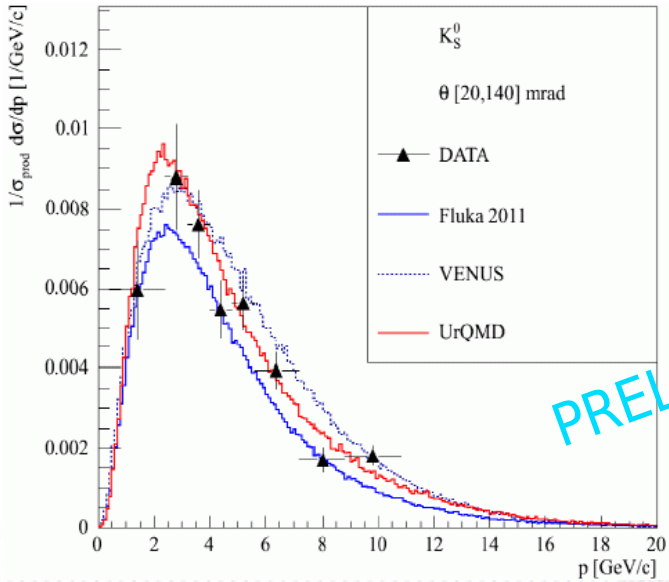
$$N(K_L^0)=N(K_S^0)=\frac{N(K^+)+3N(K^-)}{4}$$

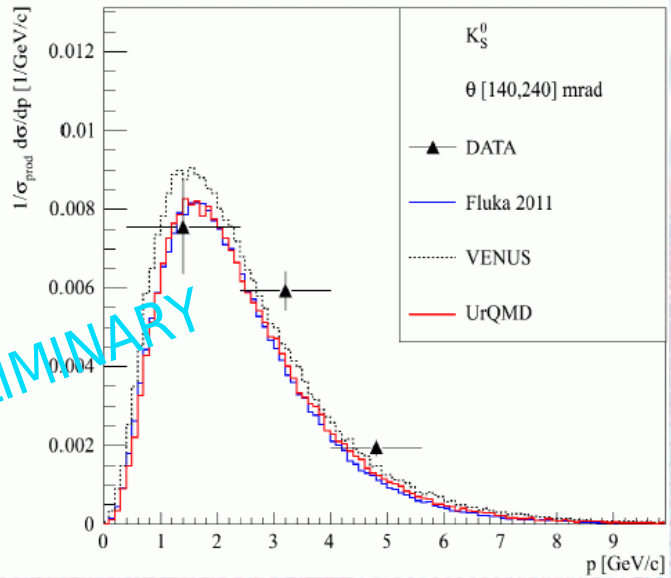
- Inclusive cross-section of K^0_S production corrected to the whole phase space is

$$\sigma=28.58\pm1.85(stat)\pm1.72(sys)\ mb$$

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

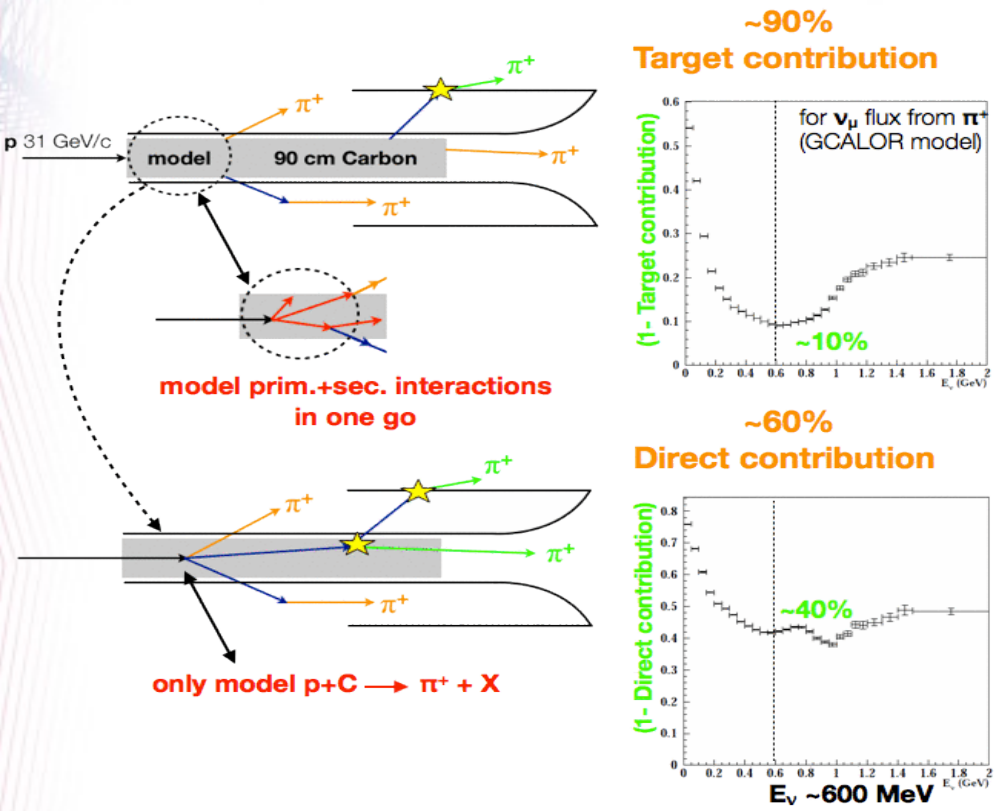






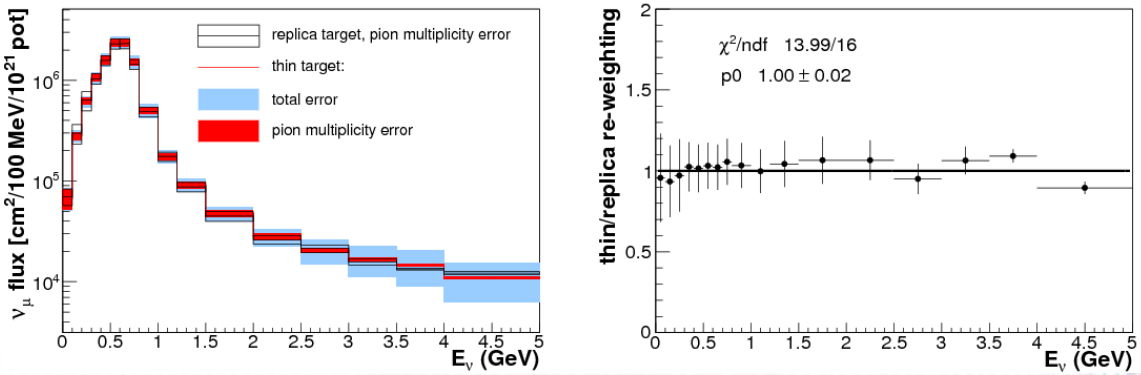
PRELIMINARY

Alternative approach to the ν flux prediction



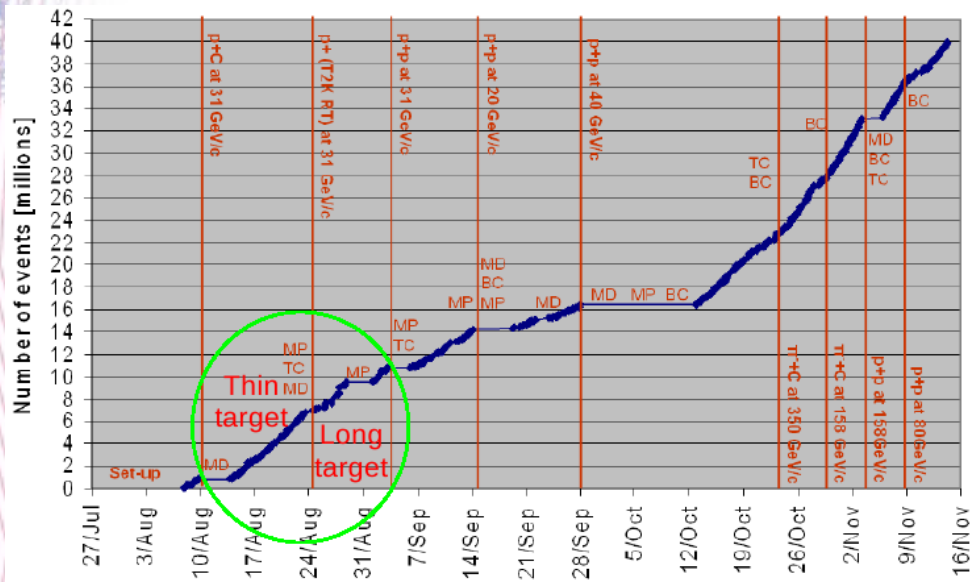
- Hadron multiplicities are parametrized **at the target surface** (no vertex reconstruction)
- Analysis in bins of (p, θ, z)
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Model dependence is reduced down to 10% as compared to 40% in the standard approach

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



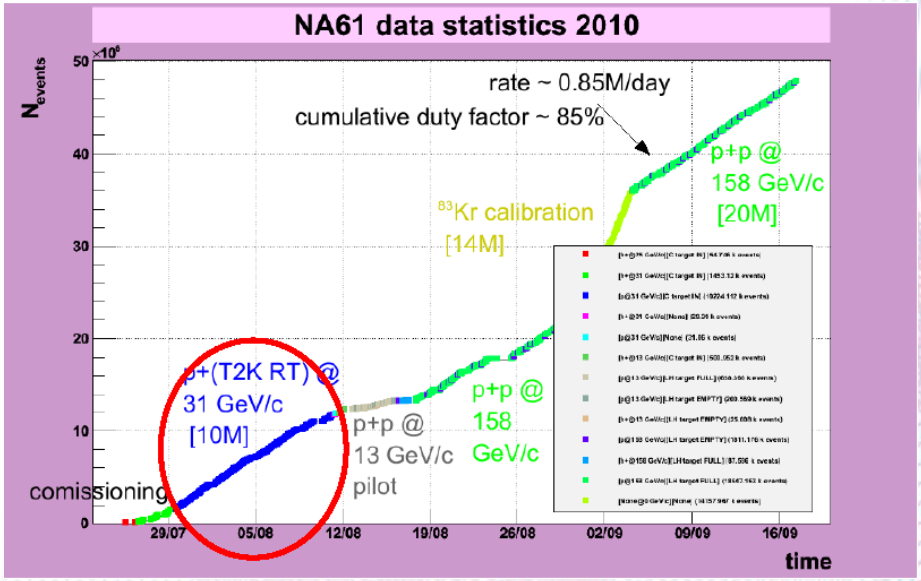
(NA61) N.Abgrall et al., arXiv:1207.2114 [hep-ex]

Prospect for forthcoming results (data 2009 & 2010)



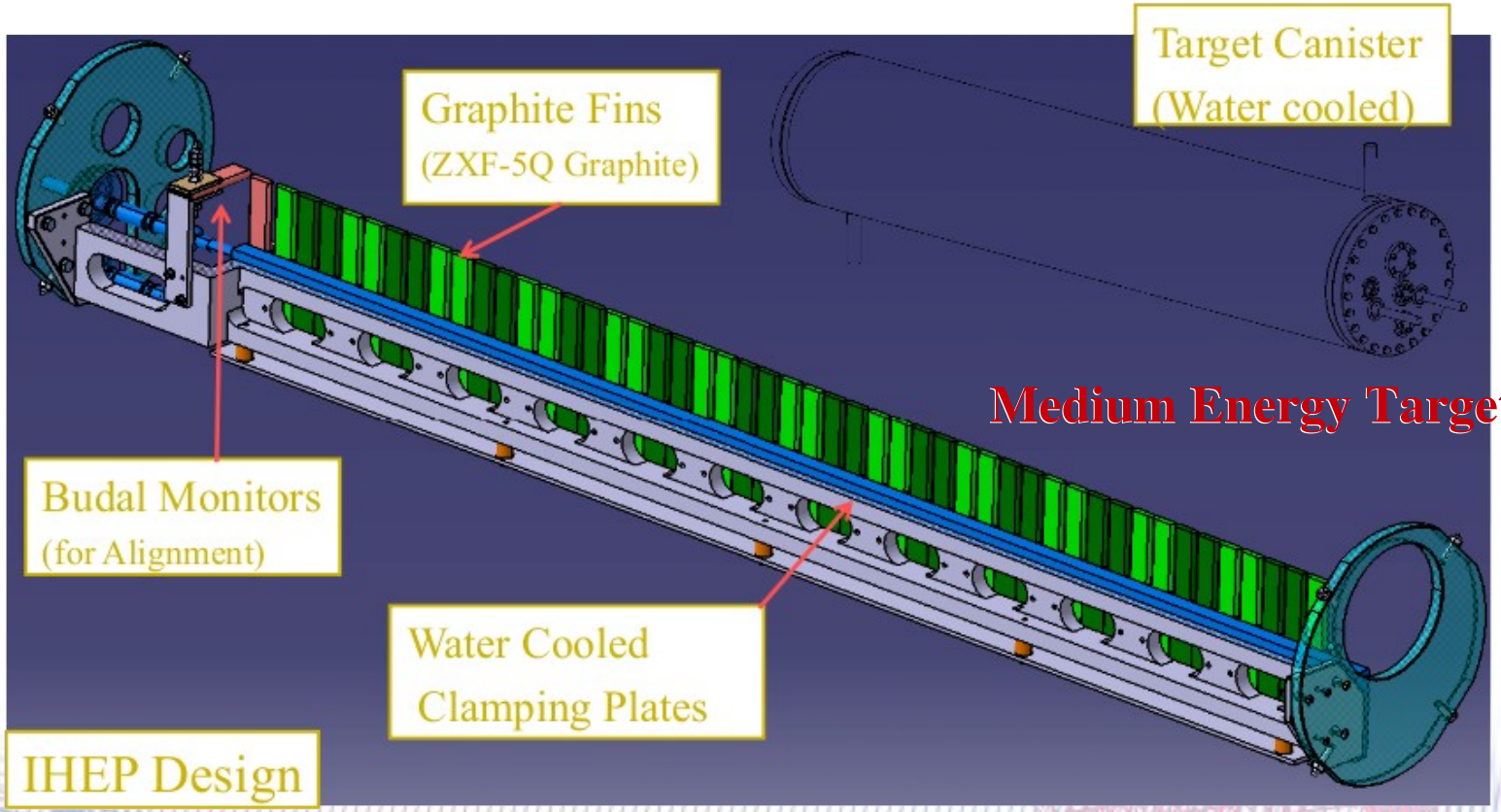
- About 10M events (thin+T2K replica target) collected in 2009
- Simultaneous extraction of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ is possible
- Preliminary results this Autumn

- 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



Measurements for NuMI target

- The goal is similar to the one for T2K (cross section + replica target)
- Letter of Intent for US collaboration on the NA61 experiment has been submitted the US Department of ENSF
- US group has been approved for limited membership by NA61 board
- Primary goal is measurement of hadron multiplicities with a NuMI Replica Target



Medium Energy Target for NOvA

Status of 120 GeV data for this year

- 2 days for datataking with 120 GeV proton beam and carbon target at the beginning of 2012 run were *canceled* due to a failure of VTX-1 dipole (loss of vacuum)
- 1 week for the *test run* with only one magnet on in July
- Problem identified. Expected restart of datataking on 21 of September
- 2 days in normal configuration closer to the end of this year run

Plans for NuMI measurements assuming successful restart of SPS after LS1, no delay of the p+Pb data due to VTX-1 and all necessary approvals for funding

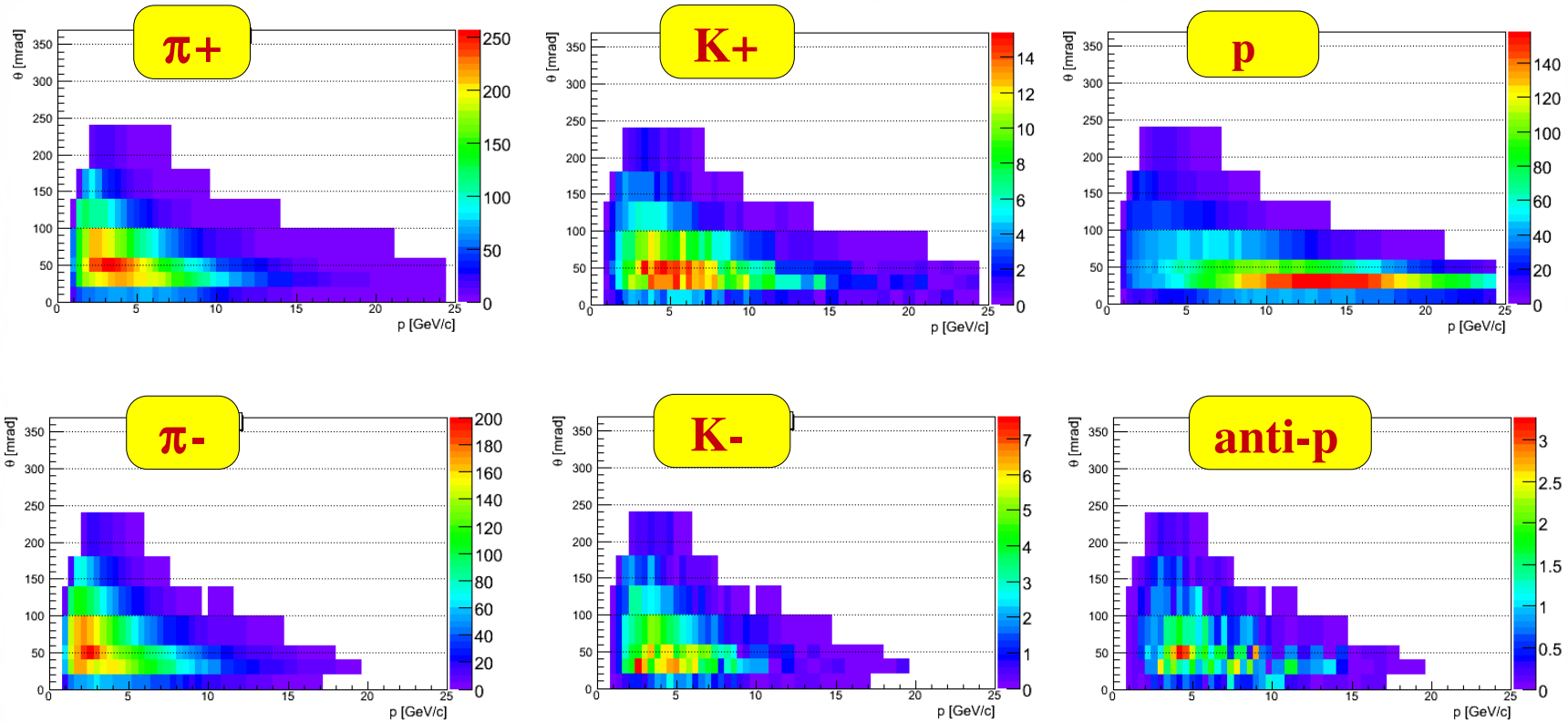
Target	120 GeV/c p	90 GeV/c p	60 GeV/c p	π at ~10-60 GeV/c	8.9 GeV/c
Thin graphite	2012	2014-5?	2014-5?	2014-5?	2014-??
NuMI replica target	2014-5?				
Thin aluminum	2014-5?	2014-5?	2014-??	2014-??	
MiniBooNE target					2014-??

Conclusions

- Hadroproduction measurement is a cornerstone of the modern ν physics: flux prediction for conventional accelerator ν beam, optimization for proton driver of ν factory, improved calculations of atmospheric ν flux, MC generator tuning
- Analysis of the pilot data collected in 2007 is completed
  - 2 publications on $\pi^{\pm}$ and K^{+} cross-sections
  - Preliminary results for K^{0}_{S} and protons
  - Publication on a method for the T2K-RT analysis
  - 5 Ph.D. theses (N.Abgrall, S.Murphy, T.Palczewski, M.Posiadala, C.Strabel)
- Results for cross-sections with a full statistics (data 2009) are expected this year
- Pilot measurement for the Fermilab ν program performed in 2007

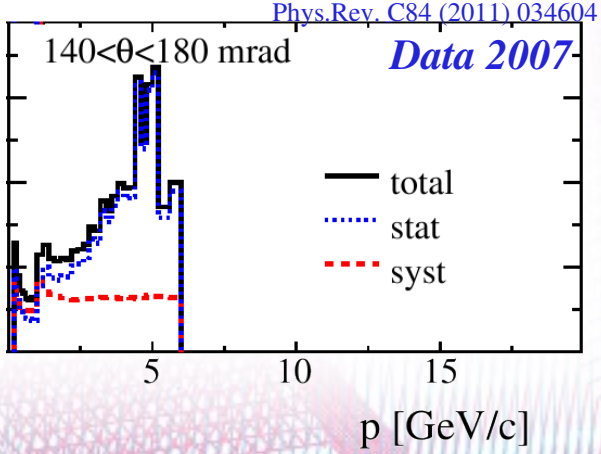
Back up

Raw particle yields normalized to the bin size (Data 2009, RST)

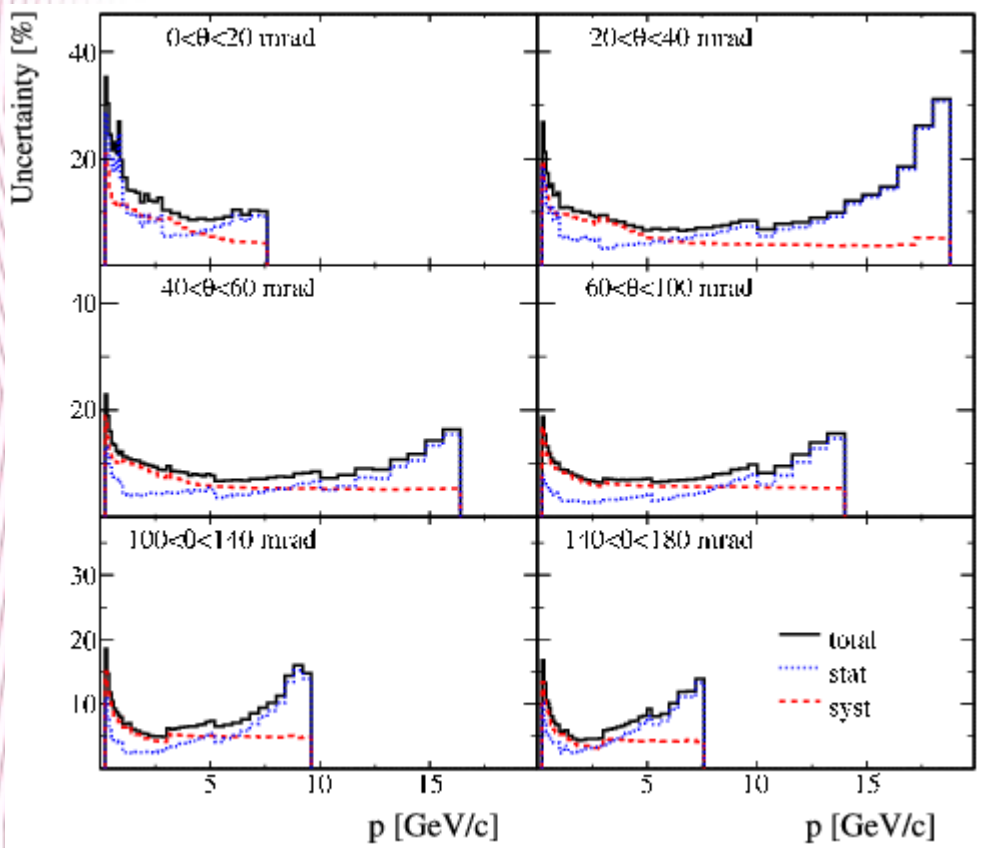


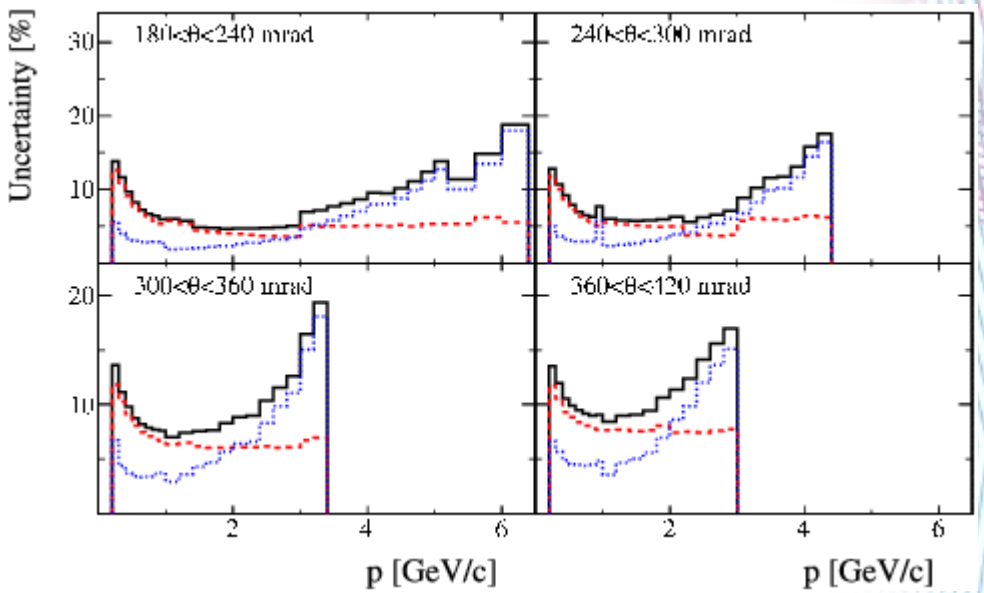
- Stat. error dominates in the analysis of data 2007
- Statistics in 2009 by a factor 10 larger as compared to 2007
- Simultaneous extraction of spectra of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ is possible (only $\pi^{\pm}$, $K^{+}$and p with data 2007)

Phys.Rev. C84 (2011) 034604



Relative uncertainties for π^- (data 2007)

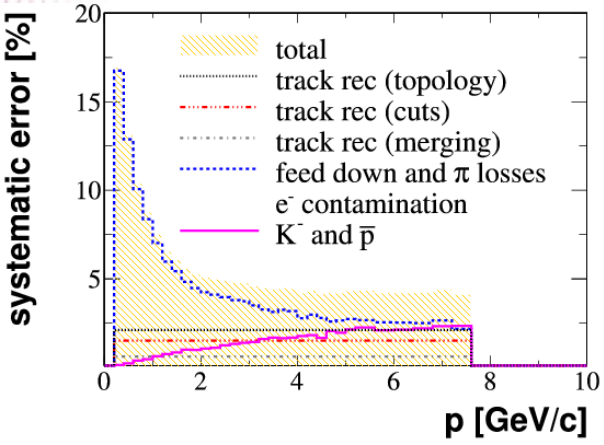


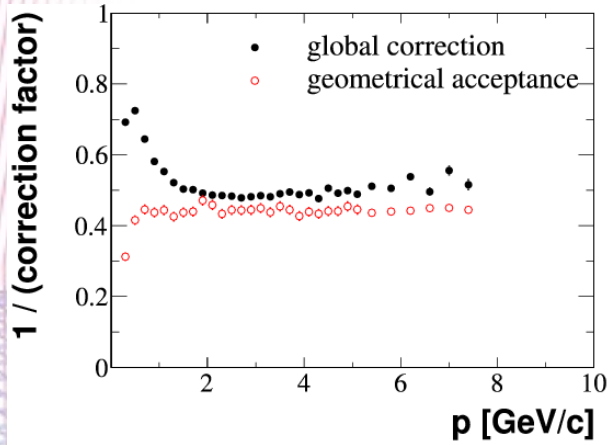


- Among 3 analyzes the one with smaller total error was selected
- Systematic error dominates at lower momenta. At higher momenta stat. error is larger

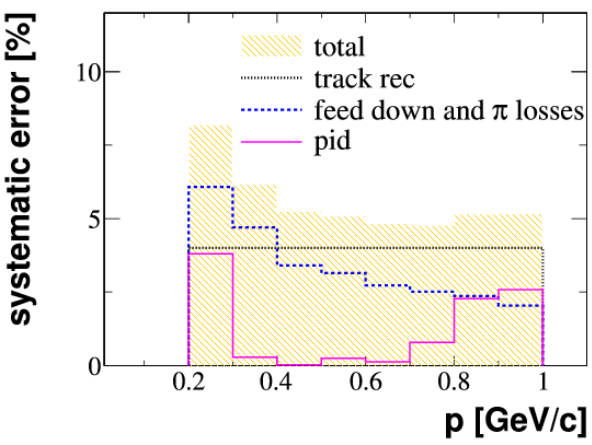
Syst. error & correction factors for π^- analysis (data 2007)

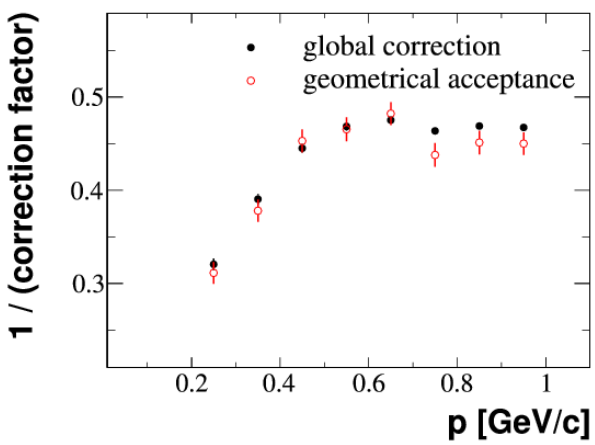
h- analysis



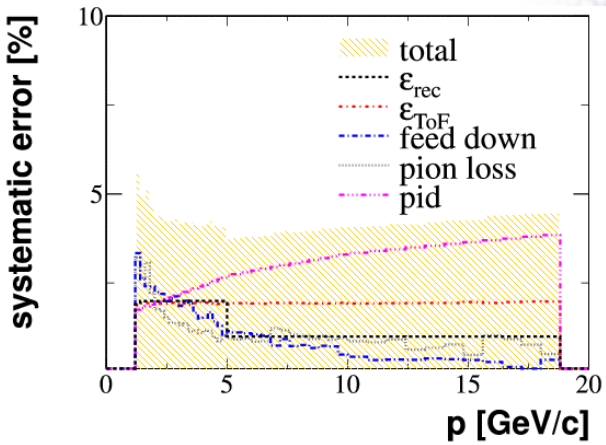


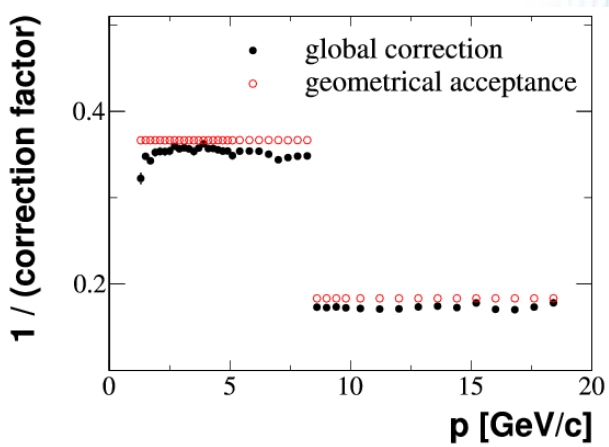
dE/dx analysis



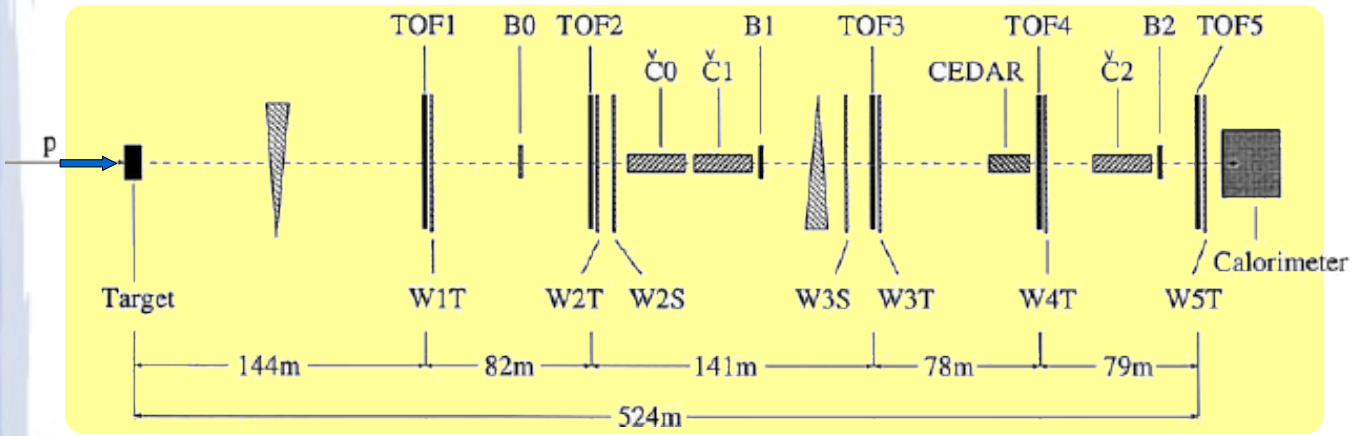


ToF-*dE/dx* analysis



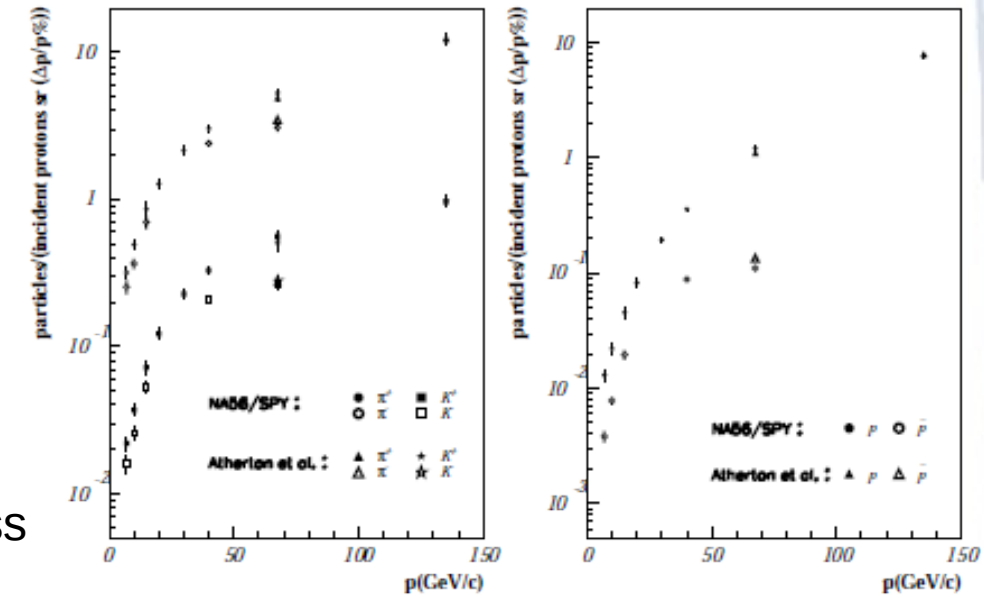


NA56/SPY, Secondary Particle Yields



- 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

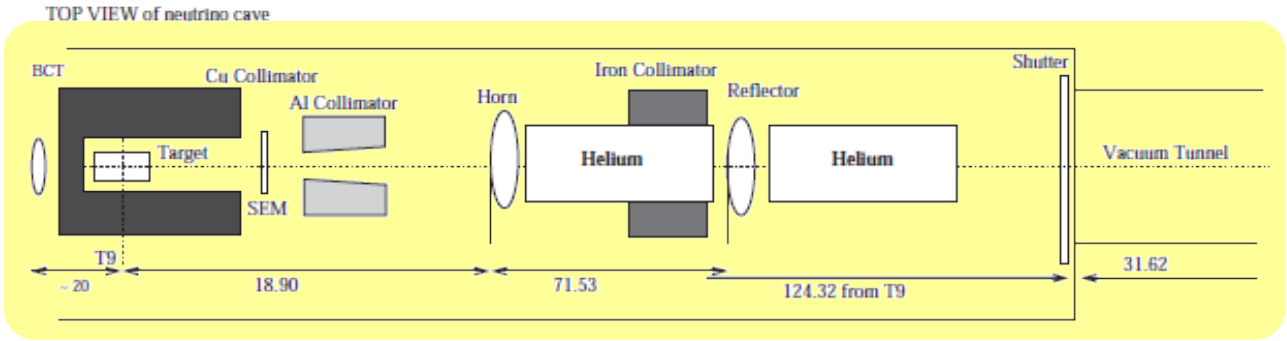
- 450 GeV/*c* protons interact with Be target
- Production angle up to 30 mrad
- Yields of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ have been studied
- Secondary momentum range 7-135 GeV/*c* ($0.02<x_F<0.3$) and $p_T<600$ MeV/*c*
- Experimental accuracy on yields 5-10%, for production ratios 3%
- Dependence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

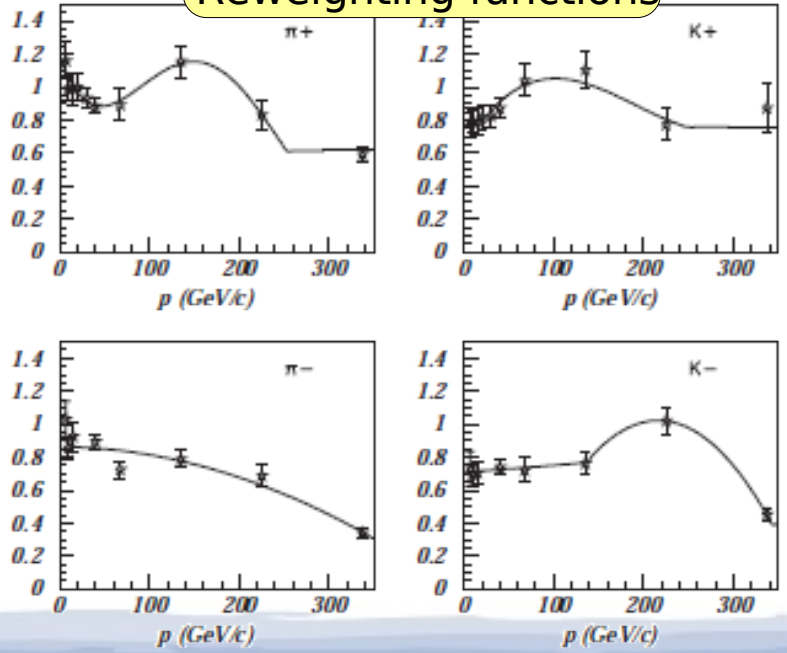
450 GeV/c protons from SPS



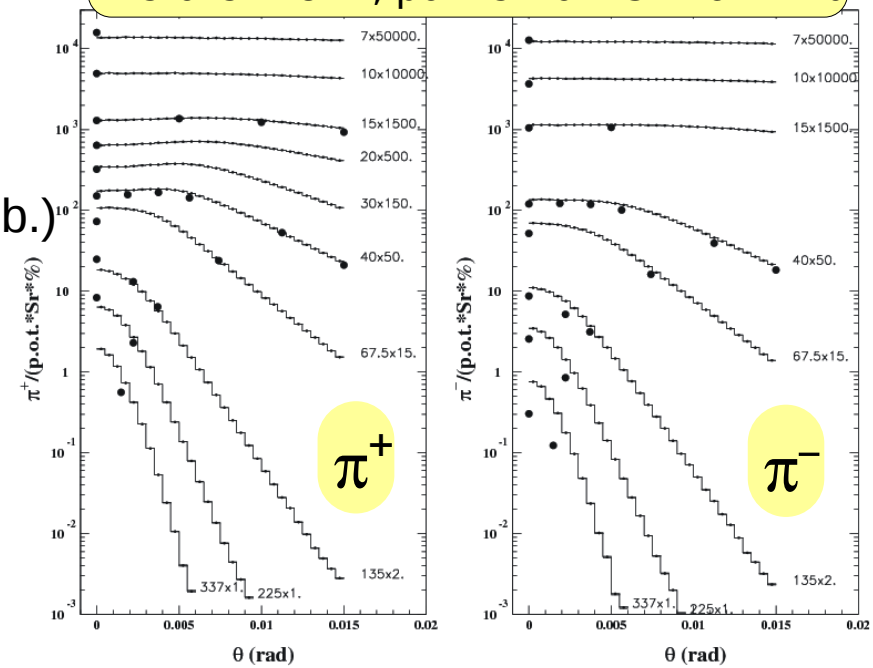
Towards CHORUS & NOMAD

- 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