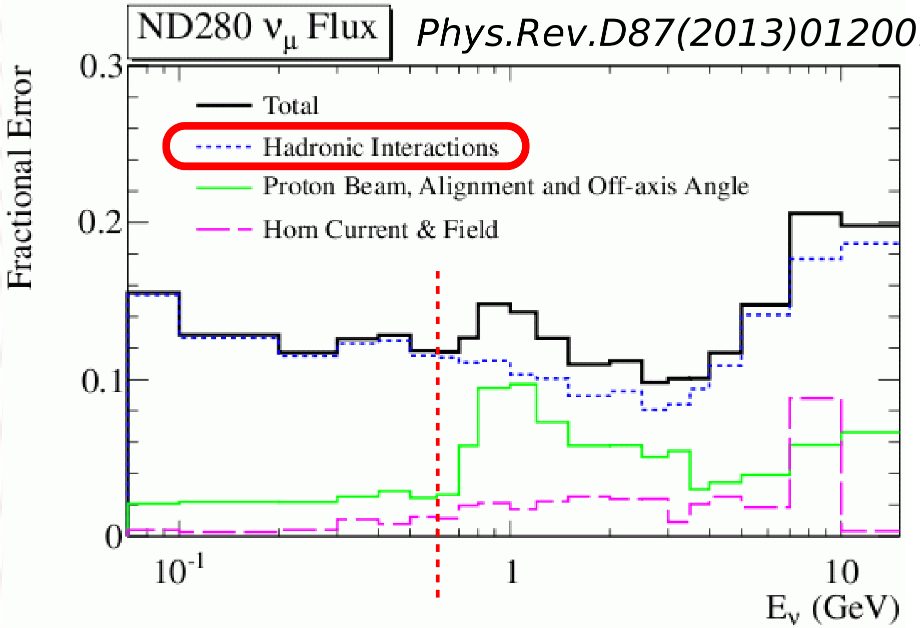
NA61/SHINE –
the present & future

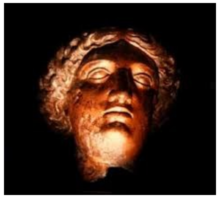
Alexander Korzenev, Geneva University

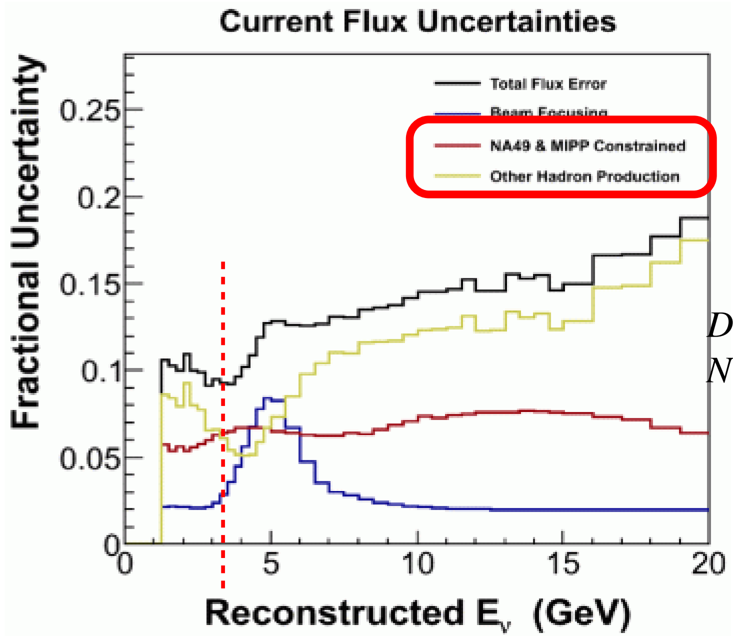
SINERGIA meeting in Bern
July 10, 2014

Motivation for an ancillary hadron production experiment



Phys.Rev.D87(2013)012001





D.Harris NuInt14

- Uncertainty on the neutrino flux is a dominant contribution to systematics of measurements: 10 – 20 %
- Uncertainty on hadronic interactions is dominant contribution to the flux uncertainty

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

Assumed systematic uncertainties

- Beam flux + near detector constraint
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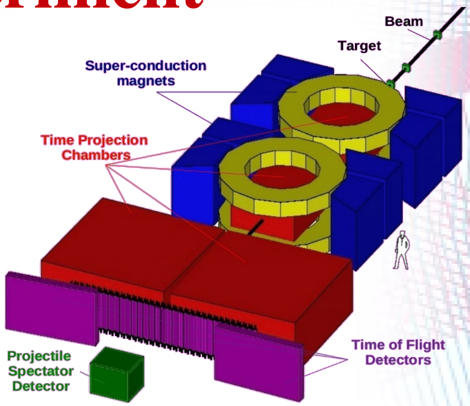
Few examples

Hadron production experiments	**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 MIPP, FNAL-E907 120 GeV beam	NuMI beamline in Fermilab (MINOS, MINERvA, NOvA)
NA61/SHINE CERN-SPS 13-400 GeV beam	T2K (JPARC to Super-Kamiokande) NuMI (MINOS+,MINERvA, NOvA) LBNE, LBNO, T2HK

Normally results of several hadron production experiments are used

SHINE NA61

SPS Heavy Ion and Neutrino Experiment



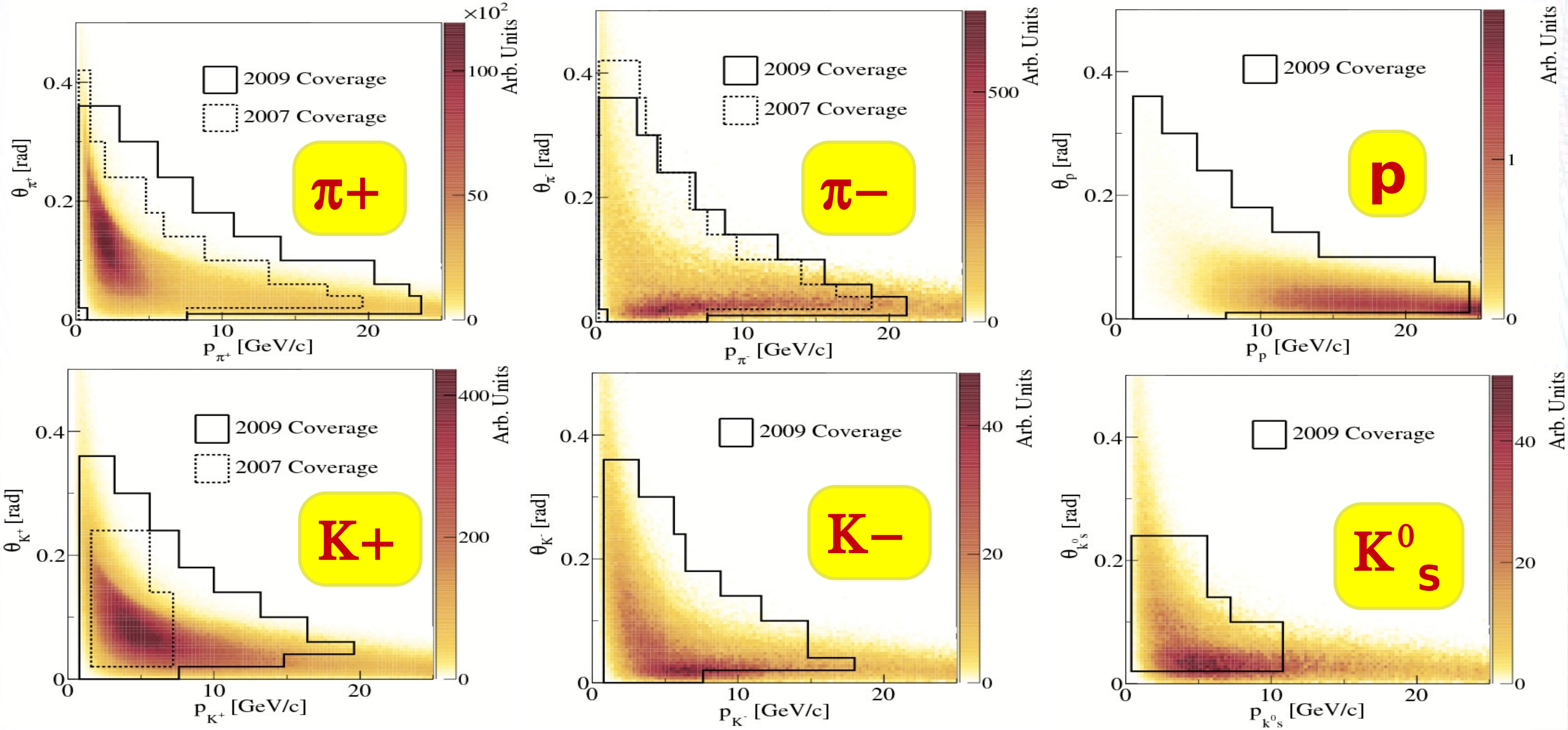
- **NA61/SHINE** has been approved in 2007
- Successor of NA49, situated at H2 beamline of CERN SPS
- Secondary beam particles produced from 400 GeV SPS's protons: momentum range 13-350 GeV/*c*
- Particle identification by ToF and dE/dx in TPC

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 ($0.04\lambda_I$)	2007	0.7	publ: $\pi^{\pm}$[1], K^+[2], K^0_S, Λ[3]	is used [5]
		2009	5.4	**prelim: $\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ**	to be used in 2014
	the T2K replica target 90 cm ($1.9\lambda_I$)	2007	0.2	published: $\pi^{\pm}$ [4]	method developed
		2009	2.8	to be released in 2014	-
		2010	~10	under calibration	-

[1] N.Abgral et al., "Measurement of Cross Sections and Charged Pion Spectra in Proton-Carbon Interaction at 31 GeV/c", Phys. Rev. C84 (2011) 034604
[2] N.Abgrall et al., "Measurement of Production Properties of Positively Charged Kaons in Proton-Carbon Interactions at 31 GeV/c", Phys. Rev. C85 (2012) 035210
[3] N.Abgrall et al., "Measurement of Production Properties of K0S mesons and Lambda hyperons in Proton-Carbon Interactions at 31 GeV/c", Phys. Rev. C89 (2014) 025205
[4] N.Abgrall et al., "Pion emission from the T2K replica target: method, results and application", Nucl. Instrum. Meth. A701 (2013) 99
[5] K.Abe et al., "The T2K Neutrino Flux Prediction", Phys. Rev. D87 (2013) 012001

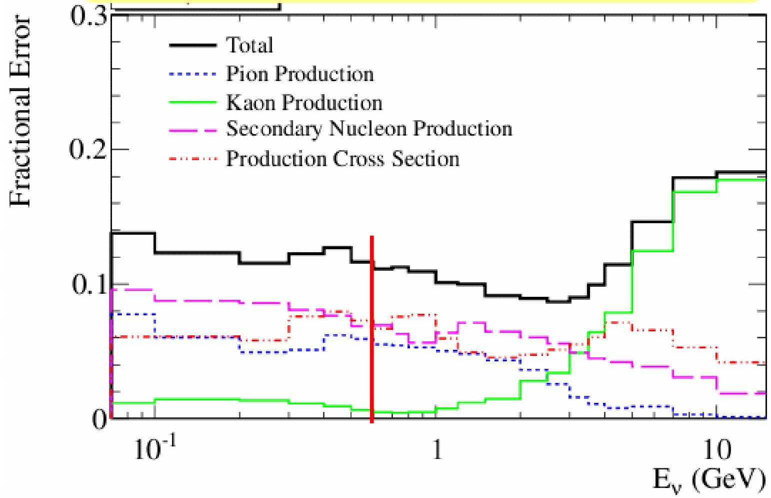
Phase space of hadrons contributing to the predicted ν flux at SK (250 kA)



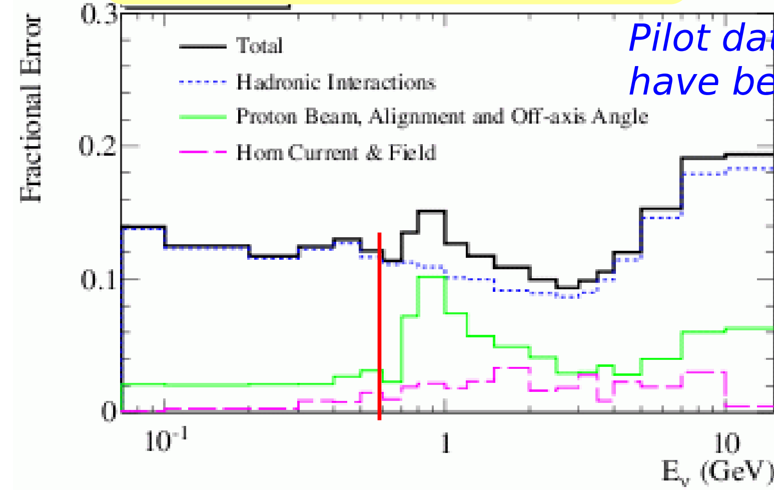
- Two years of datataking with a thin target: 2007 and 2009
- Statistics of 2009 is an order of magnitude higher as compared to 2007
- The phase space of T2K is well covered by NA61

Tuning of ν_μ flux using NA61 spectra

Error due to hadron production



All sources of systematics

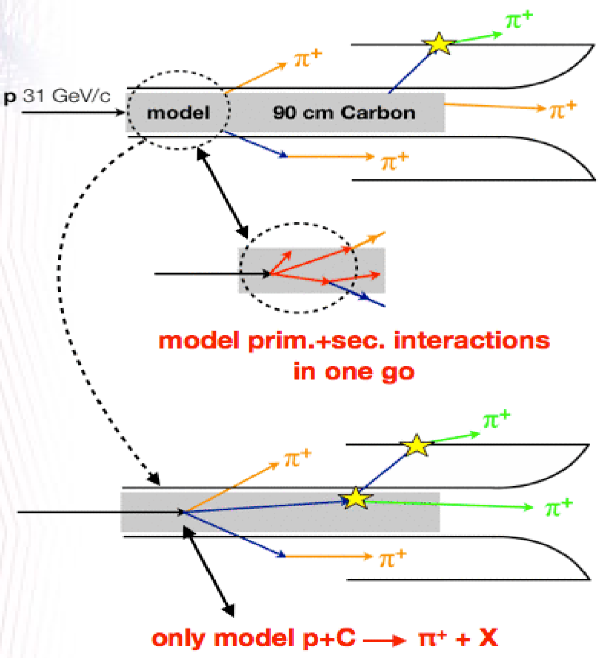


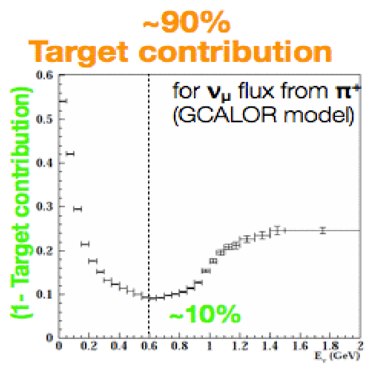
*Pilot data **2007** have been used*

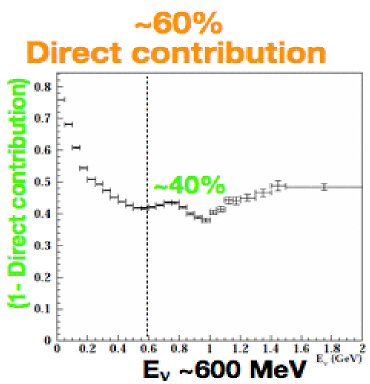
- For every MC event the interaction chain for hadrons is stored, to be weighted later with real measurements
- Pion multiplicity re-weighing has the largest effect at low energies, while the kaon multiplicity re-weighting is important at high energies.
- Total flux uncertainty is dominated by the hadron interaction uncertainties
- Flux uncertainty at the peak energy is ~12%

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

Alternative approach to the ν flux prediction in T2K

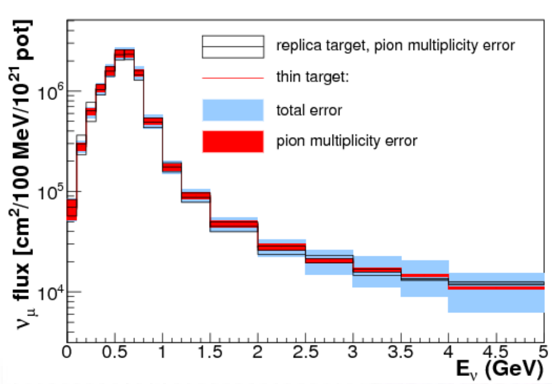


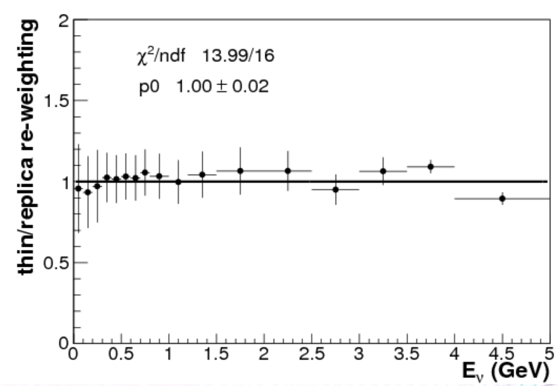




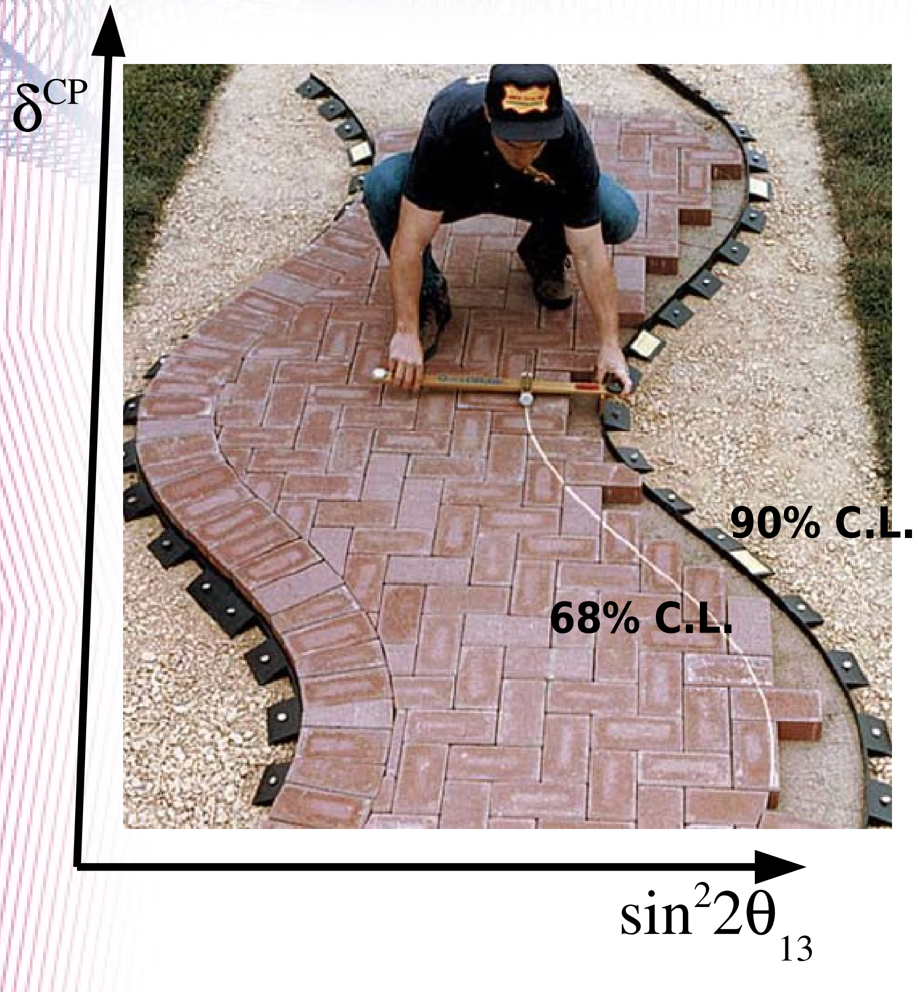
- Hadron multiplicities are parametrized **at the target surface** (no vertex reconstruction)
- Analysis in bins of (p, θ, z)
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Model dependence is reduced down to 10% as compared to 40% in the standard approach

- 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



... to pave the way for ...
long-baseline neutrino projects ...

ECFA / European Strategy for Particle Physics

Plans for Future

- Completion of the T2K RT analysis of 2010
- Special run with high magnetic field
- Upgrade of electronics for the NuMI run

Plans to complete the analysis of T2K data in NA61

- Completion of the analysis of the T2K replica target data (2010)
  - Statistics is about a factor 3 larger as compared to 2009
  - Systematic uncertainty is presently dominated for pions
  - Improvement for the $K^{\pm}$ uncertainty
- No electronics noise in 2010 (the 2009 data pC@31 were the first after upgrade of the TPC electronics in 2008)

- Special run to cover the very forward region of the (p-θ) phase space
  - Dead zone in the forward region in the 'normal field mode'
  - Magnetic field: '20 GeV mode' ⇒ '160 GeV mode'

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		2009	2.8	to be released in 2014	-
		2010	~10	under calibration	-

The US NA61 Collaboration (report to SPSC, Apr-Jun 2014)

*S.R.Johnson, A.Marino, E.D.Zimmerman**
University of Colorado, Boulder, Colorado 80302, USA

D. Harris, A. Marchionni
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

E.Guardincerri, C.Mauger, G.Mills, Z.Pavlovic, K.Yarritu*
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

*N.Graf, B.Messerly, V.Paolone**
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA

S.Manly, K.McFarland
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA

K.Lang
Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA

M.Kordosky, J.Nelson
Department of Physics, College of William & Mary, Williamsburg, Virginia 23187, USA

- US group has been approved for a limited membership at the beginning of 2012. Full members at the end of 2014
- 18 physicists from 7 US institutions

NuMI Fermilab

Measurements for the NuMI target

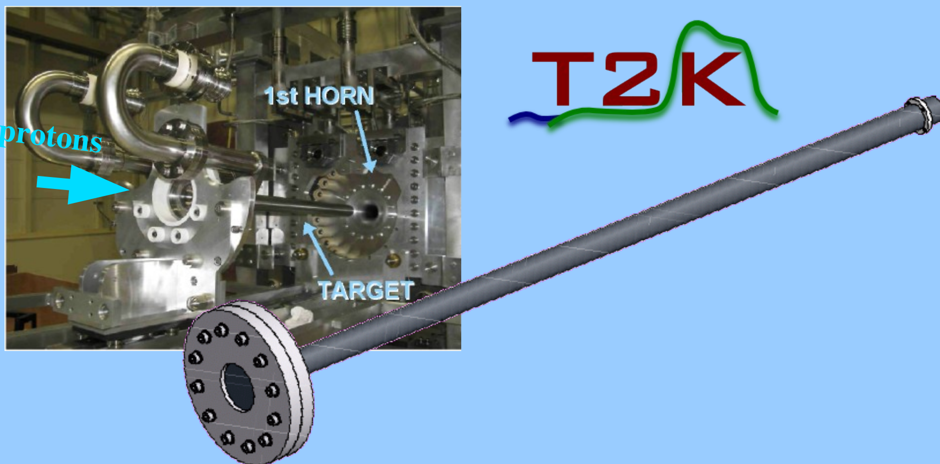
SHINE NA61

- The goal is similar to the one for T2K: cross section + replica target
- LBNE, MINOS(+), NOvA, MINERvA
- Pilot run in summer 2012
  - 120 GeV/c proton beam + C target
  - Non-standard magnet configuration
- DOE proposal & SPSC addendum to be submitted this year
  - Upgrade of electronics (Pittsburgh)
  - Forward tracking (Colorado)

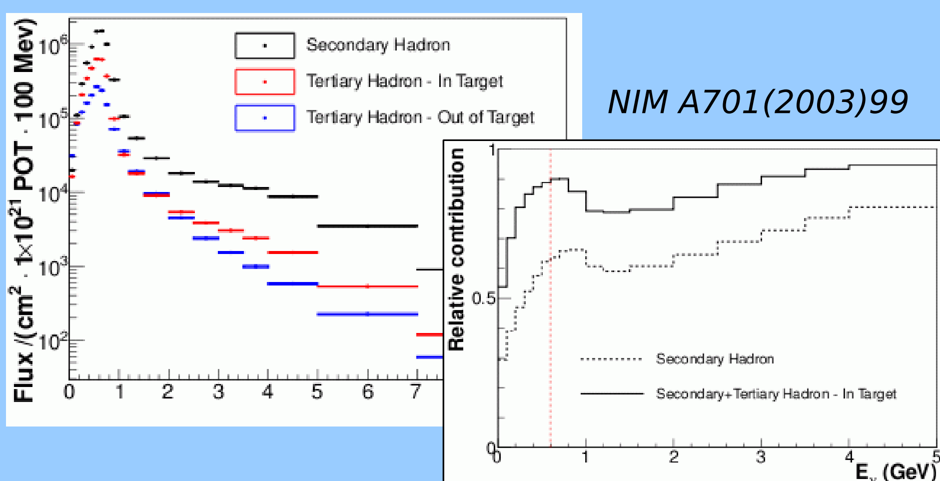
Target	Incident proton/pion beam momentum		
	120 GeV/c	60 GeV/c	30 GeV/c
NuMI (spare) replica	(future)		
LBNE replica	(future)		
Thin graphite (<0.05λ_I)	3M	3M	(T2K data)
Thin Al (<0.05λ_I)		3M	(future)
Thin steel (<0.05λ_I)	(future)	(future)	(future)
Thin Be (<0.05λ_I)	3M	3M	(future)
Thin concrete (<0.05λ_I)	(future)	(future)	(future)

The actual target measurements

Measurement of hadron yields at the target surface (no matter how they are produced)

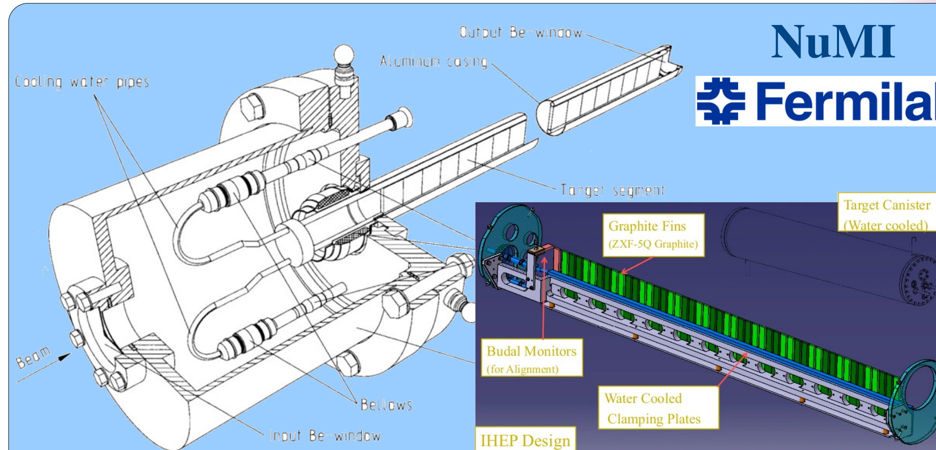


Graphite rod 90 cm long and Ø = 2.6 cm. Replica target was delivered to CERN to be used in NA61



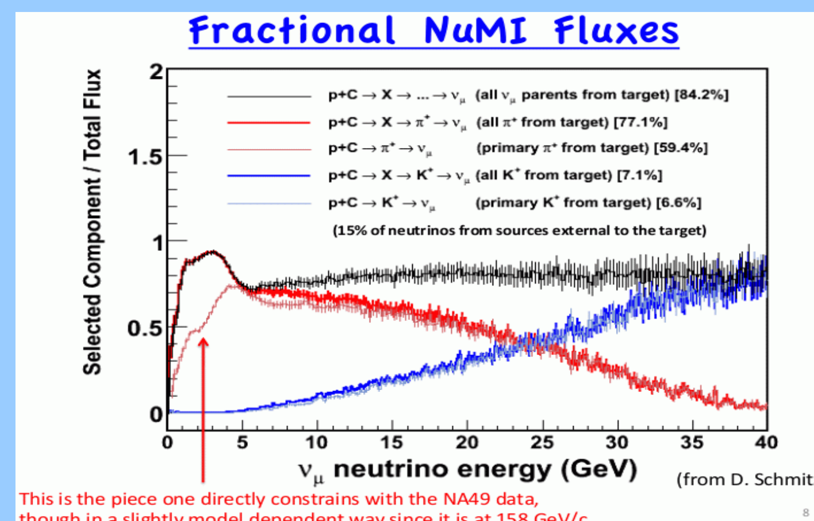
NIM A701(2003)99

Ancillary experiment: NA61/SHINE in CERN



NuMI
Fermilab

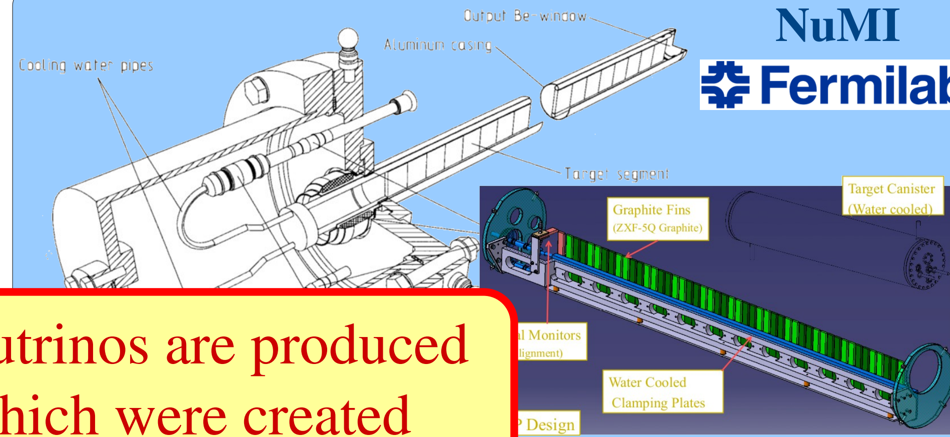
Canister 90 cm long and Ø = 3 cm. 47 graphite segments soldered to water cooling line



Ancillary experiment: MIPP in Fermilab

The actual target measurements

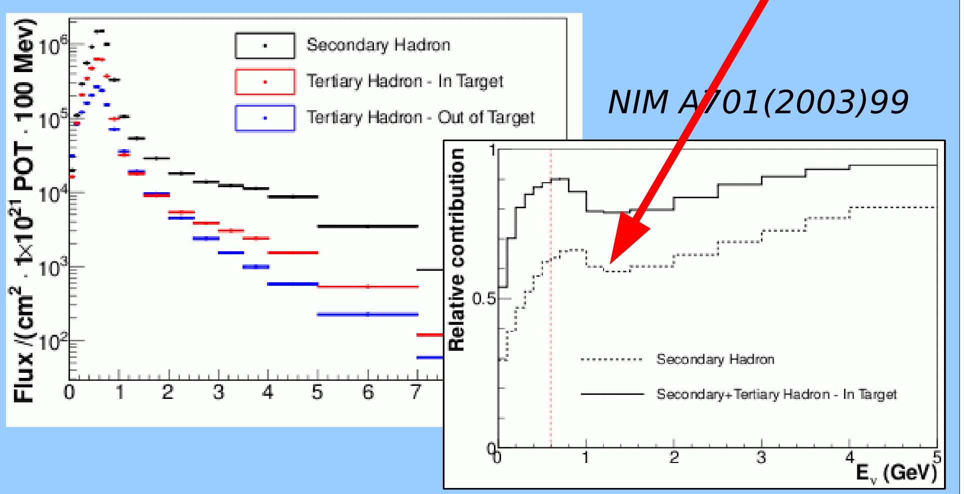
Measurement of hadron yields at the target surface (no matter how they are produced)



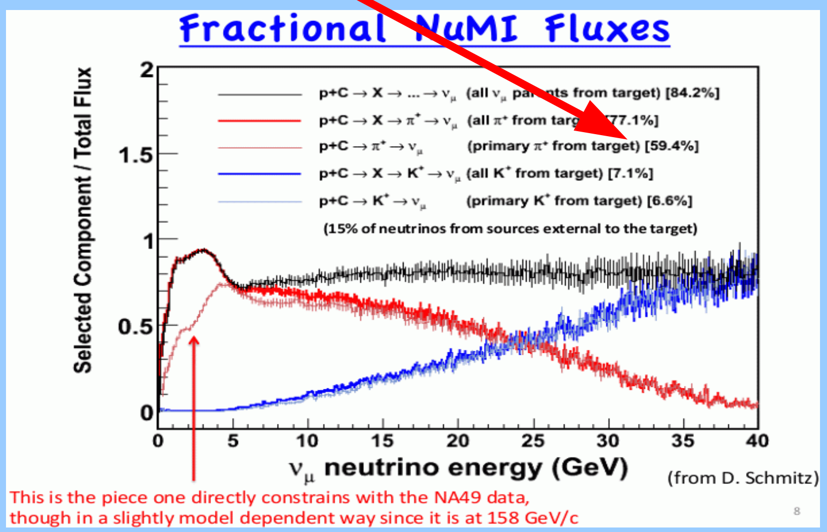
About 40% of neutrinos are produced from hadrons which were created in secondary interactions

Graphite rod 90 cm long and … target was delivered to CERN to be used in NA61

… Ø = 3 cm. 47 graphite segments … water cooling line



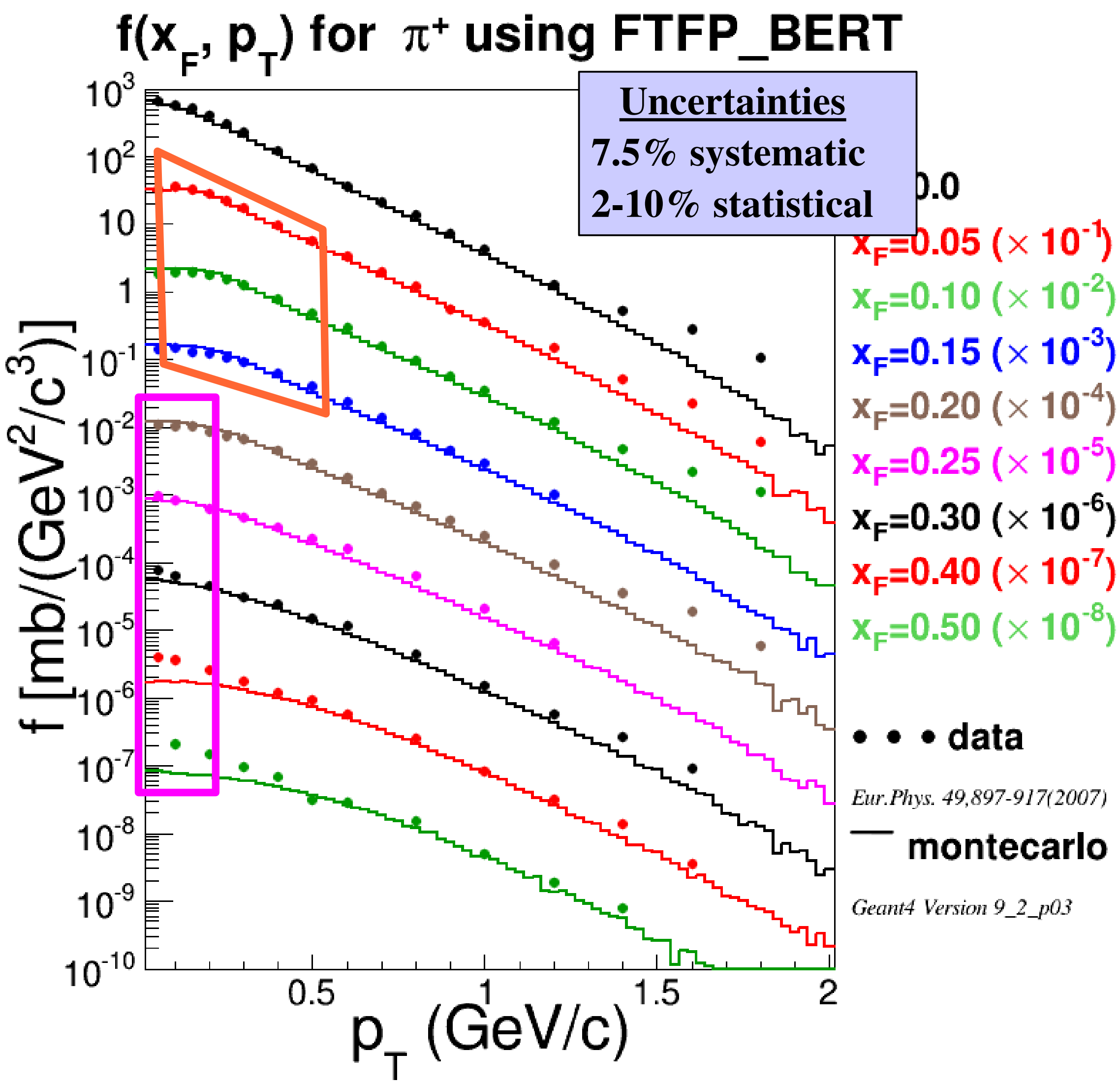
NIM A701(2003)99

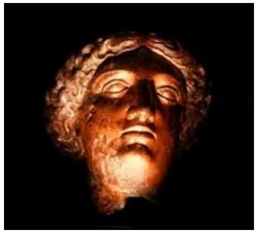


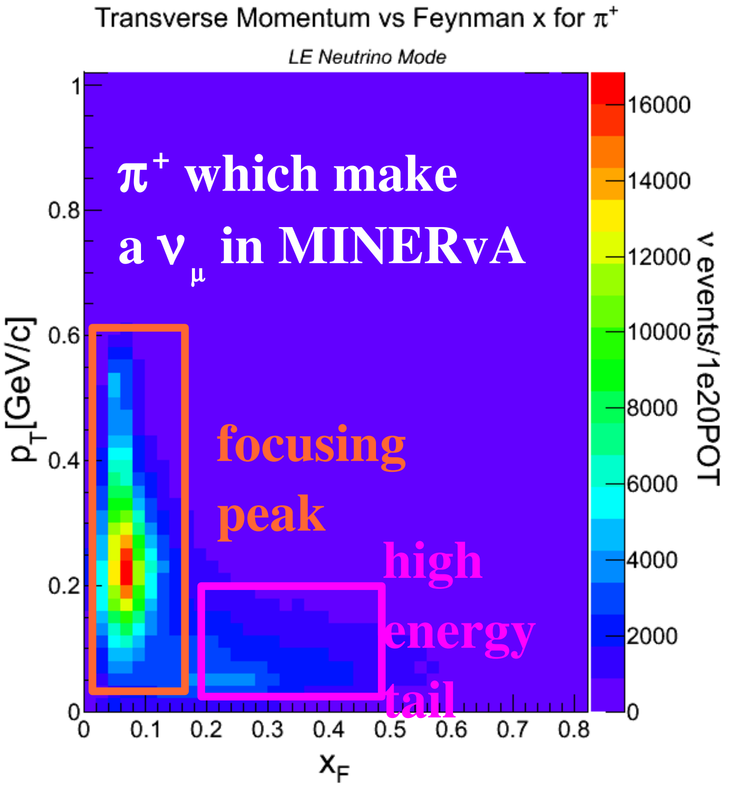
Ancillary experiment: NA61/SHINE in CERN

Ancillary experiment: MIPP in Fermilab

NA49 data for the NuMI simulation





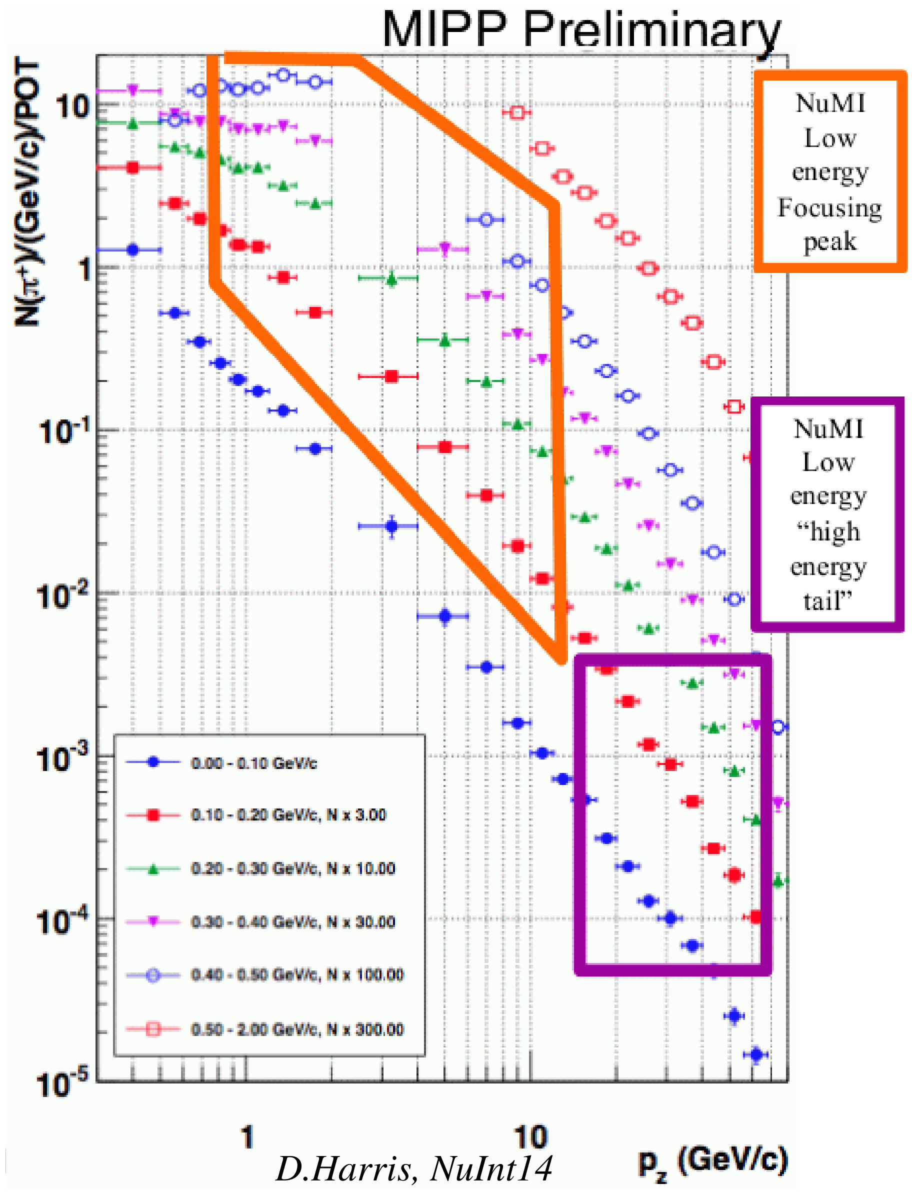


- Cascade leading to ν is tabulated at generation. Save kinematics & material
- In analysis, interactions reweighted as σ(data)/σ(MC)

- NA49 measurements at 158 GeV: p+C → ($\pi^{\pm}$,$K^{\pm}$,p)+X
- MIPP measurements at 120 GeV: ratio of cross sections K/π

MIPP data for the NuMI simulation

- 1.43×10^6 protons at 120 GeV on an actual NuMI target
- Measurement of the $\pi^{\pm}$ yield in ~125 bins of (p_z, p_T) across 2 orders of magnitude in momentum
- There is no binning in *z*
- For PID TPC (*dE/dx*) and RICH have been used
- Combined statistical and systematic errors are <10% in nearly all bins



(MIPP collaboration) J.Paley et al., arXiv:1404.5882, Apr 2014

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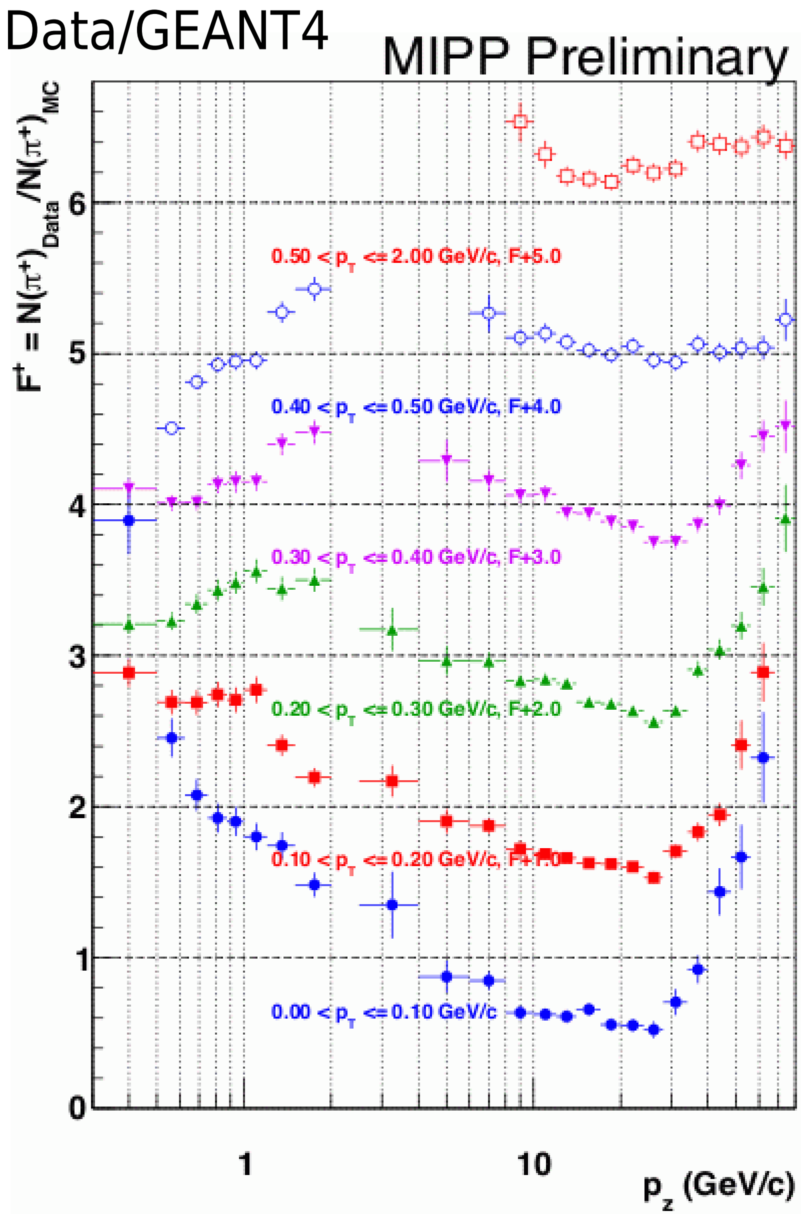
- For PID TPC (*dE/dx*) and RICH have been used
- Combined statistical and systematic errors are <10% in nearly all bins
- Data imply that MCs tend to over-estimate pion yields at higher *p* and under-estimate at the focusing peak
- These data may be used to re-evaluate MC predictions of the NuMI flux and reduce the overall systematic uncertainty



DAQ upgrade using the DRS4v5

- NA61's electronics is obsolete (inherited from NA49): redout of ToF is based on FASTBUS TDC and ADC, beam and trigger detectors based on CAMAC modules
- The project is coordinated by A.Bravar. Plan to finalize the electronics design by the end of 2014 and start production in March 2015. Installation is planned for summer 2015
- The DRS4 chip is based on a circular switched capacitor array, consisting of an array of 1024 capacitors/ch, and samples input analogue signals at a rate up to 5 GHz with a resolution close to 12 bits and a 200 ns deep circular buffer.
- Cost: ~100 CHF/ch. Total: 350 kCHF = 150 k (UniGe) + 150 k (US groups) + 50 k (NA61)

Sub-system	# channels	# DRS channels	# DRS mezzanine boards	# DRS MB	Sampling fr. [MHz]	Buffer depth [ns]
ToF-R	891	891	56	15	5000	200
ToF-L	891	891	56	15	5000	200
ToF-F	160	160	10	3	5000	200
PSD low gain	440	440	28	7	1000	1000
PSD high gain	440	440	28	7	1000	1000
PSD deep buf.	16	128	8	2	1000	8000
Beam (trigger)	32	32	2	1	5000	200
	8	64	4	1	1000	8000
BPD	144	576	36	9	700	6000

Table 2 *Detectors and corresponding number of channels which are planned to upgrade with DRS4.*

Human resources which are going to be provided by UNIGE:

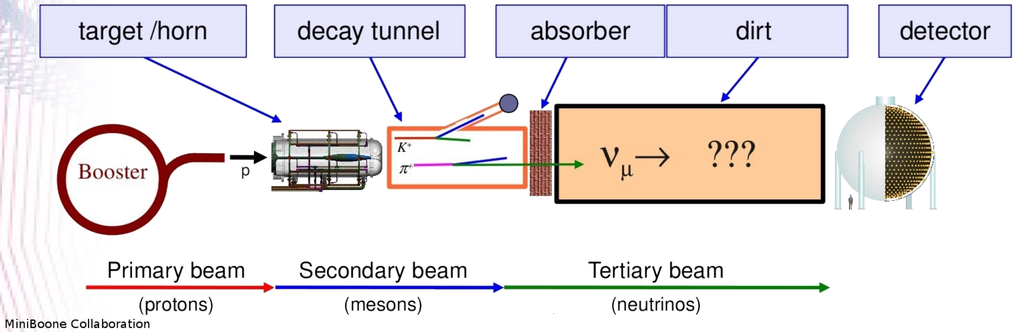
- 1 engineer (1 FTE x 1 year) to develop the DRS mezzanine boards (hardware and firmware): S.Debieux and D.LaMarra (UNIGE) + Pittsburg ?
- 1 engineer / physicist (1 FTE x 1 year) to develop FPGA algos (baseline subtraction and zero suppression, data encoding, waveform processing etc) UNIGE + KFKI + Pittsburg?
- 1 engineer / 1 physicist (1 FTE x 1 year) to develop calibration procedures and FPGA algos (time and energy calibration, synchronization of DRS chips, etc: A.Korzenev + 1 PhD student

Research plans for the UniGe group in NA61

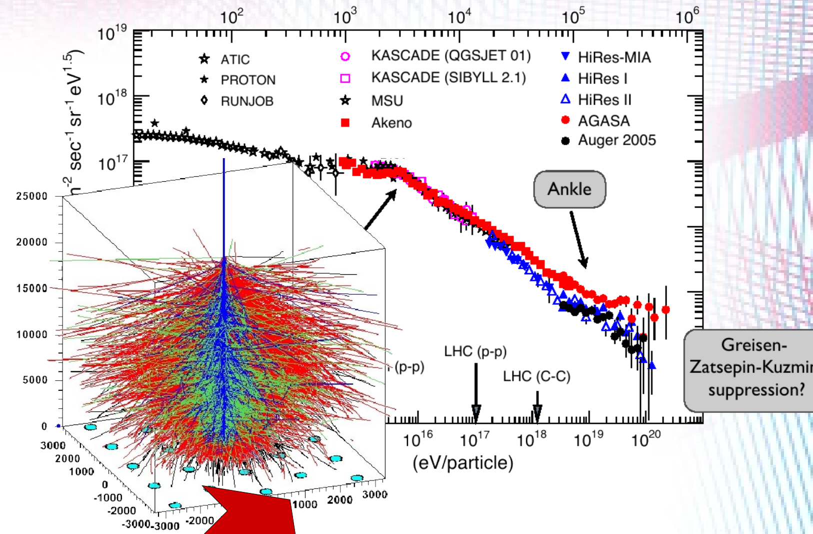
- Completion of the analysis of the T2K replica target data (2010)
  - Statistics is about a factor 3 larger as compared to 2009
  - Improvement for the $K^{\pm}$ uncertainty
  - No electronics noise (data 2009 were affected)
  - Special run to cover the very forward region of the (p-θ) phase space
    - Magnetic field: '20 GeV mode' $\Rightarrow$ '160 GeV mode'
- Extensive physics program is foreseen for NuMI energies (60-120 GeV) starting from the fall of 2015
  - Upgrade of electronics (DRS4)
  - Participation in the analysis of NuMI data
- Manpower to fulfill the program:
  - Alexis Haesler – defense of PhD this winter
  - Alexander Korzenev – contract finishes next autumn
  - At least 1 PhD student and/or PostDoc needed from the beginning of 2015 or better right now to ensure the continuity for the RT analysis
    - Analysis of 2007: N.Abgrall, A.Bravar, S. Di Luise, L.Esposito, A.Korzenev, A.Marchionni, S.Murphy, K.Strabel
    - Analysis of 2009: A.Haesler, A.Korzenev, D.Sgalaberna
    - Analysis of 2010 and NuMI: 1 universal student

Back up

Conventional accelerator ν-beam



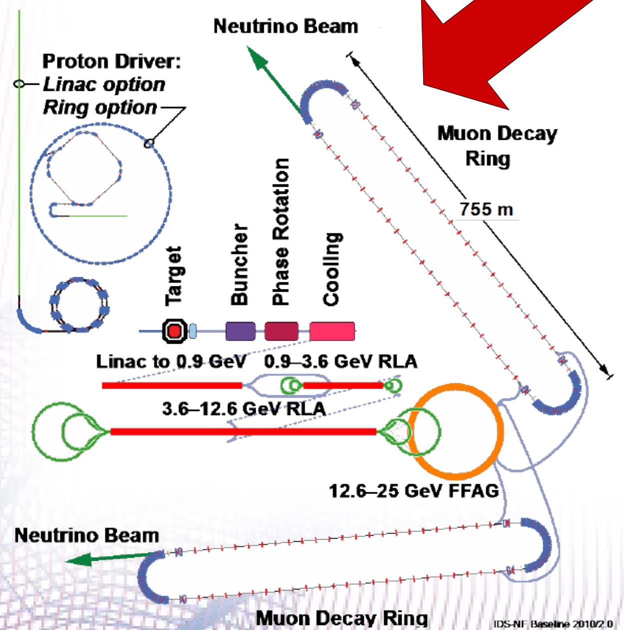
Atmospheric showers



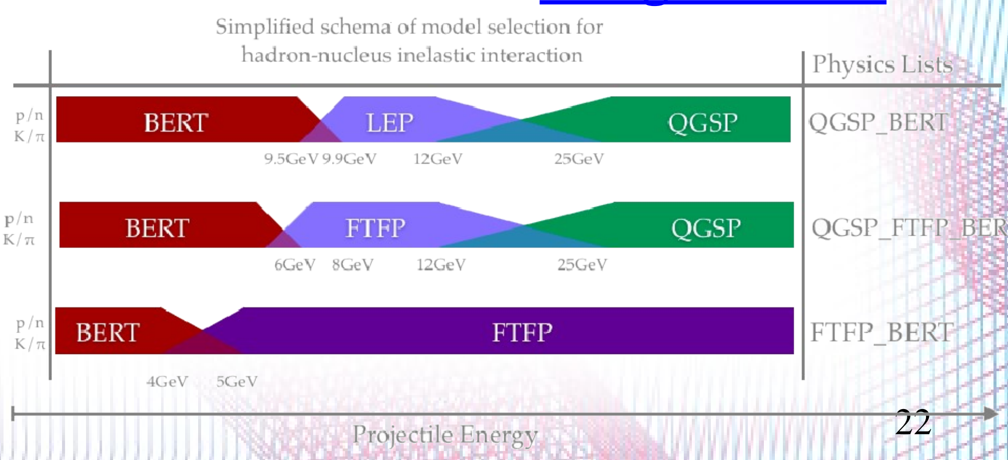
Hadron production measurement

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

Neutrino Factory

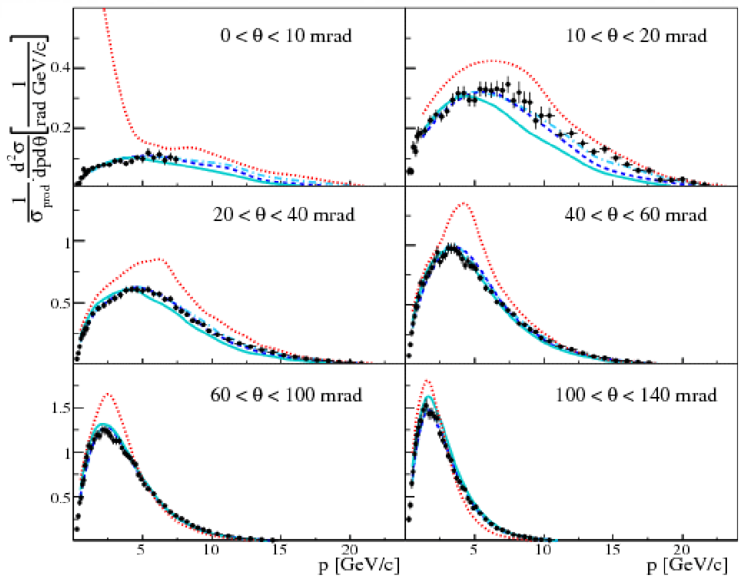


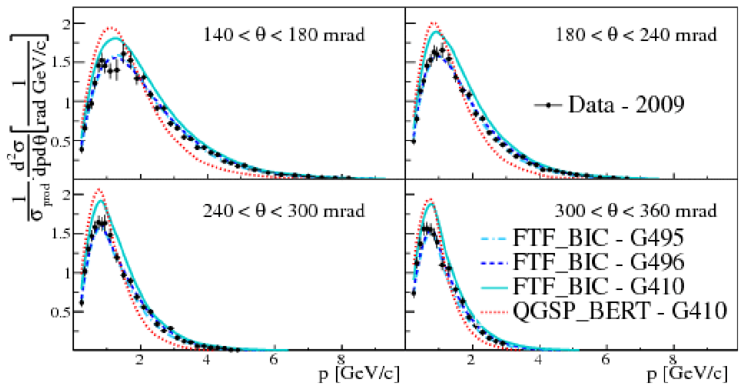
MC generators



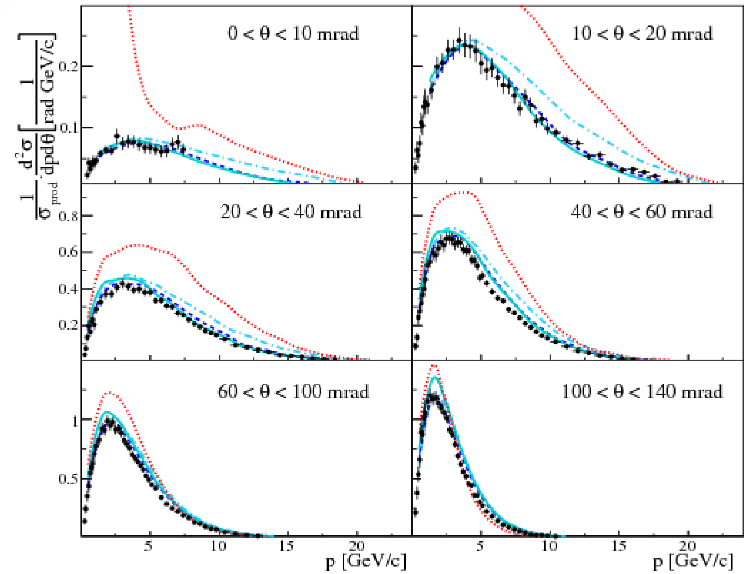
New NA61 measurements for T2K at 31GeV

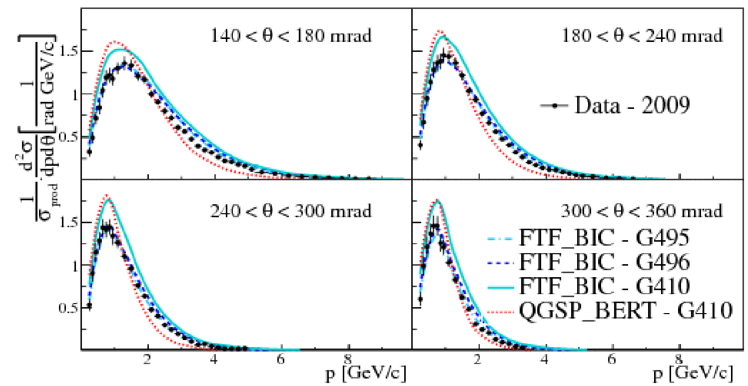
$p + C \rightarrow \pi^+ + X$





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

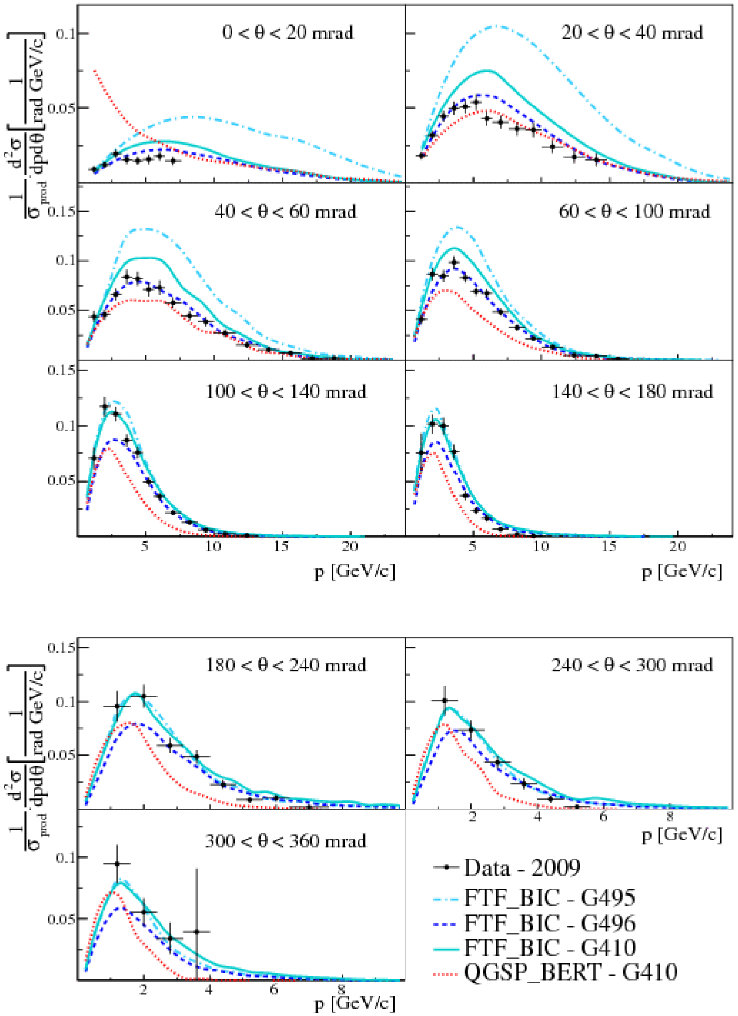




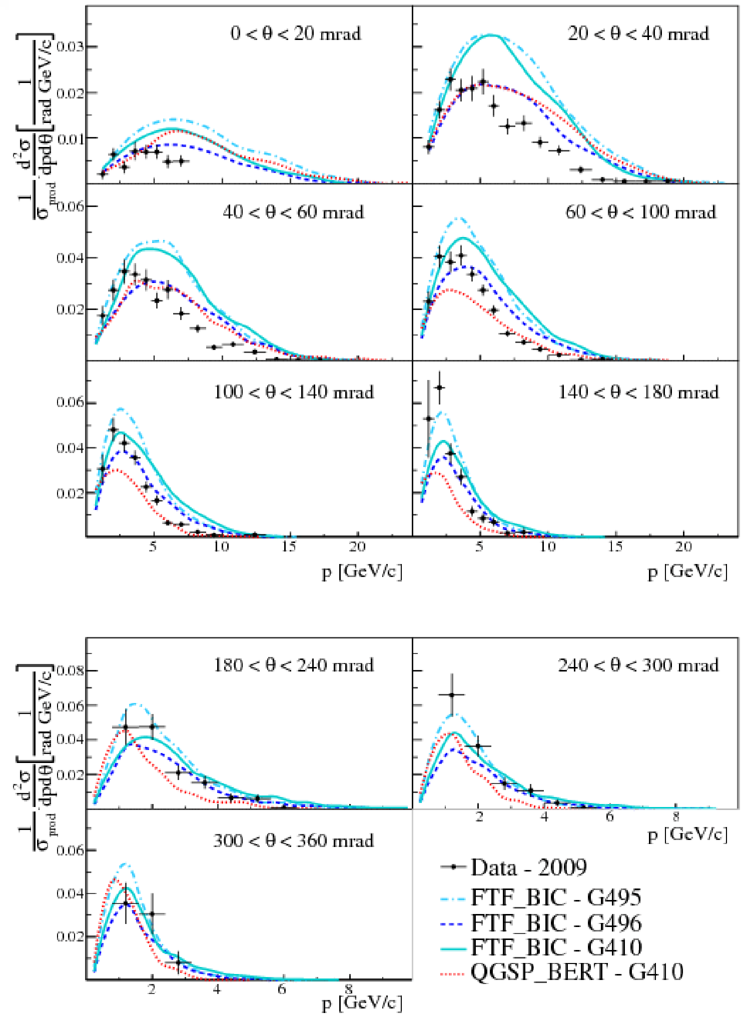
- New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)
- Typical uncertainty for regions which are important for ν flux is ~4%
- Recent versions of FTF_BIC describe data reasonably

New NA61 measurements for T2K at 31GeV

$p + C \rightarrow \mathbf{K}^{+} + X$



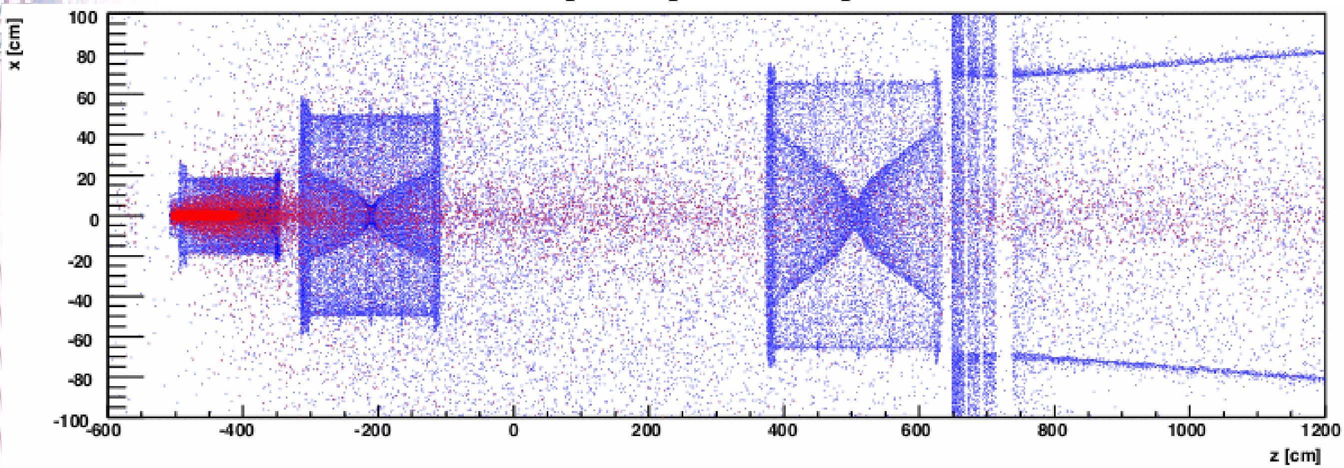
$p + C \rightarrow \mathbf{K}^{-} + X$



- 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 (NA61/SHINE)

For forward kaons (Eichten *et al.*)

For tertiary pions (E910)

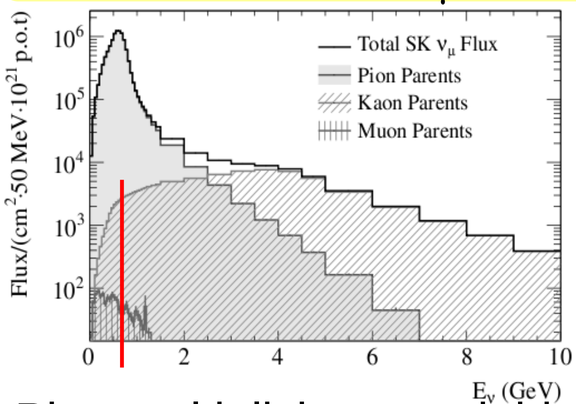
- Interaction chain for hadrons is stored, to be **weighted later with real measurements**
- Tuning of tertiary pions requires extrapolation from NA61 data
  - Extrapolation to different incident nucleon momenta is done assuming Feynman scaling ($x_F = p_L / p_L^{max}$)
  - Extrapolation from carbon to aluminum using

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

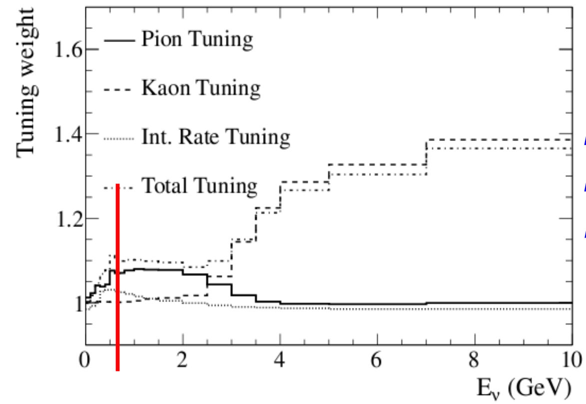
(T2K) K.Abe et al., Phys.Rev.D87(2013)012001

Tuning of ν_μ flux using NA61 spectra

Decomposition of ν_μ flux



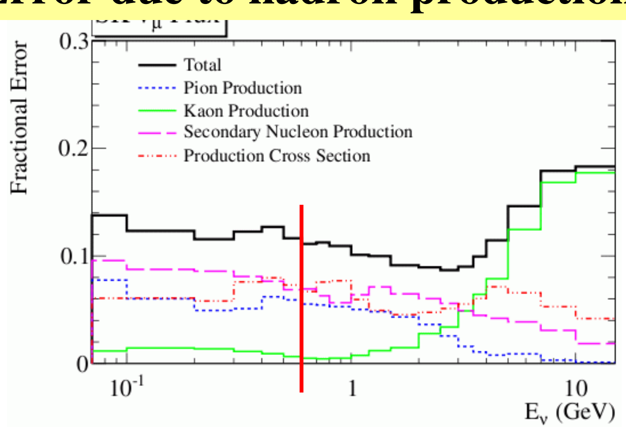
Re-weighting coefficient



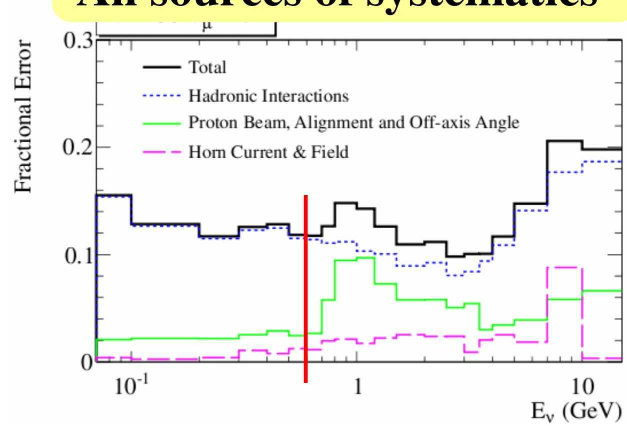
*Pilot data of NA61 (**2007**) have been used*

- 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

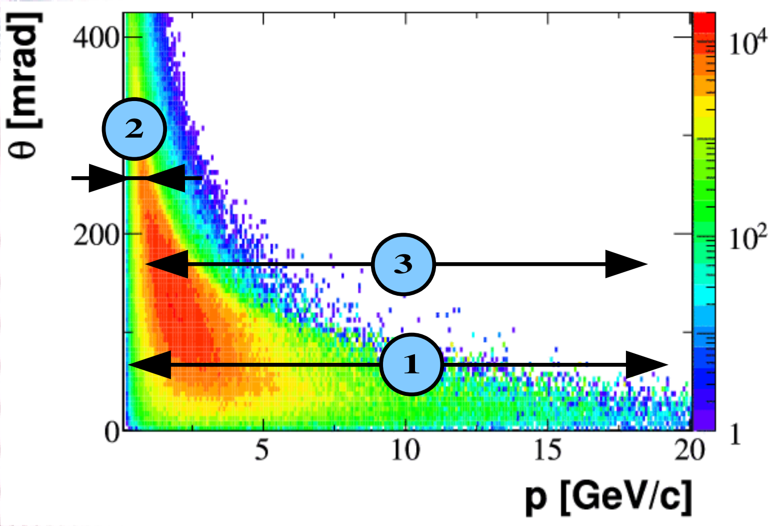
Conclusion

- 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

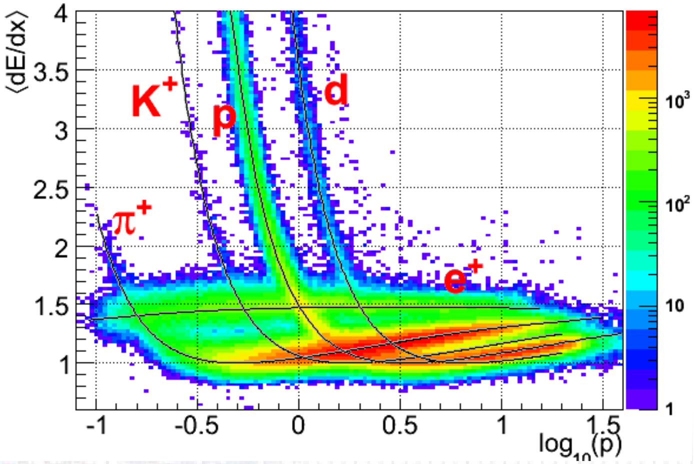
Analysis techniques (data 2007)



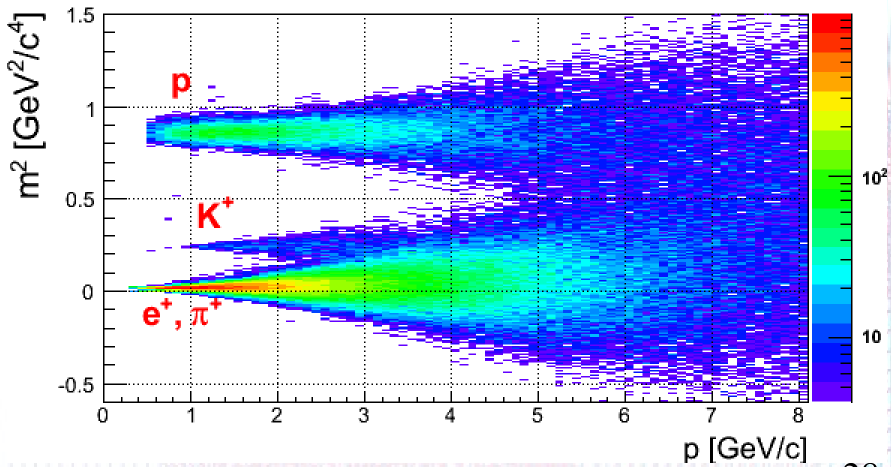
1) **h⁻ analysis**: analysis of π^- via measurements of negatively charged particles
2) ***dE/dx* analysis at *p*≲1GeV/*c***: $\pi^\pm$ and protons were identified via energy loss in TPC
3) **ToF-*dE/dx* analysis at *p*≳1GeV/*c***: information from *dE/dx* and ToF is combined to identify $\pi^\pm$, $K^\pm$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

Data 2009

Energy loss in TPC (*dE/dx*)



Time-of-Flight (ToF)



Normalization and σ_{prod} measurement

Results

Davide Sgalaberna

- Trigger cross section:

  agreement within 1σ with 2007 measurement

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

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

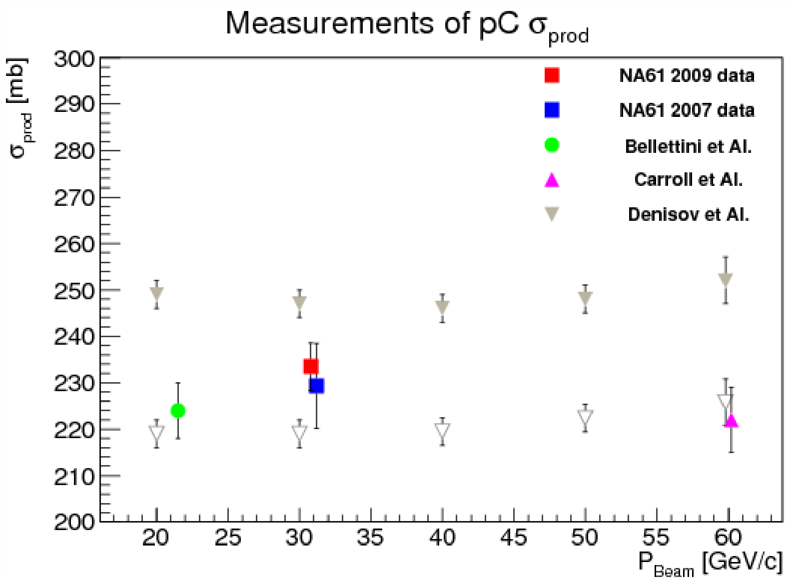
- Inelastic cross section: $\sigma_{inel} = \sigma_{trig} - \sigma_{el-Out\ of\ S4} + \sigma_{loss-p} + \sigma_{loss-\pi/K}$

- σ_{el-Out}: el-scattering outside the acceptance of the interaction trigger counter (S_4)
- σ_{loss-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



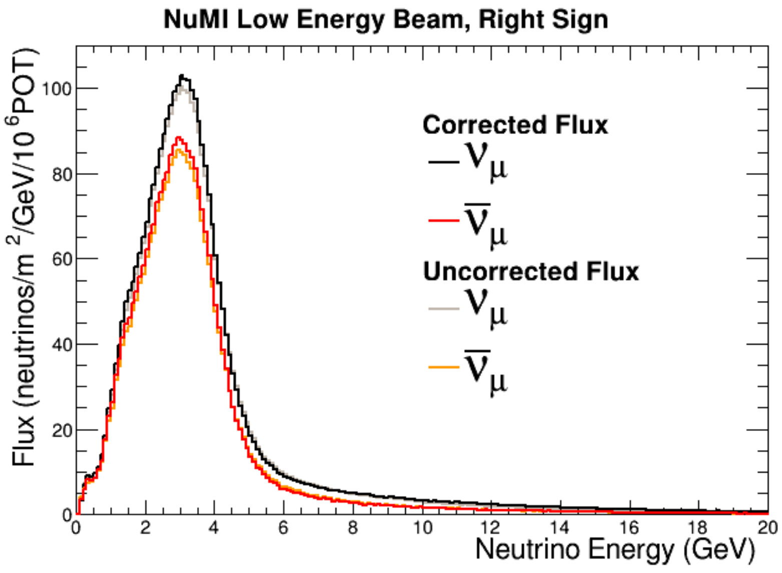
$$\sigma_{prod} = 233.5 \pm 2.8(stat) \pm 4.2(model)^{+1}_{-1.2}(trigger)\ \text{mb}$$

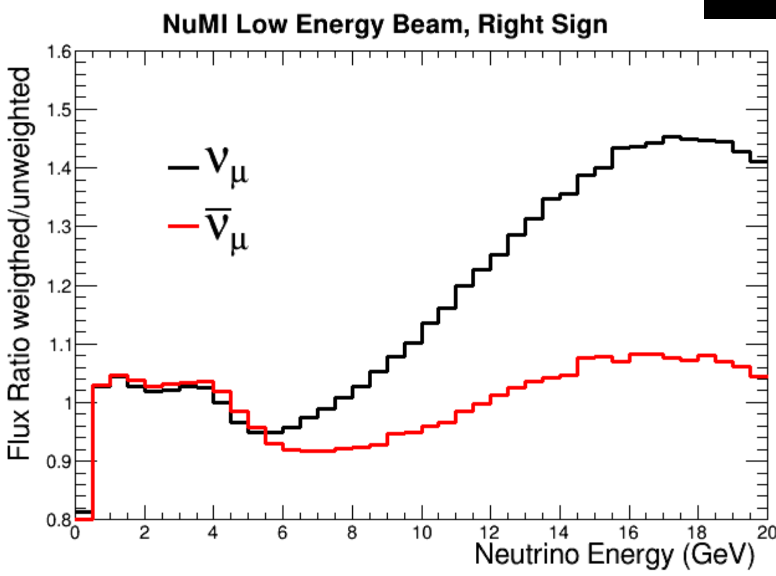
$$\sigma^{2007}_{prod} = 229.3 \pm 1.9(stat) \pm 9.0(syst)\ \text{mb}$$

Normalization analysis is completed

Total uncertainty from 4% (2007) to 2%

NA49 data for the NuMI simulation





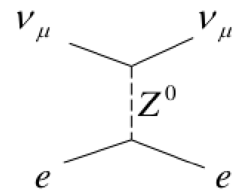
- FLUKA is used to translate NA49 measurements to proton energies between 12 and 120 GeV
- Interactions not constrained by the NA49 data are predicted using FTFP
- Effect of corrections is < 5% at peak energy
- Flux uncertainty is a dominant contribution to the cross section systematics
- Hadron interactions dominates in the systematics of the flux

Direct measurement of ν flux with νe→νe

- Well known reaction

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



- Very small cross section (~1/2000 of ν-nucleon scattering)
- Very forward electron final state
- Background reactions

$$\nu_e + n \rightarrow e^- + p \qquad \nu_\mu A \rightarrow \nu_\mu A \pi^0$$

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad \nu_\mu N \rightarrow \nu_\mu N \pi^0$$

- νe events (LE) after all corrections:
  - **123.8±17.0(stat)±9.1(syst)**
- Prediction from simulation:
  - **147.5±22.9(flux)**
- In both cases precision is **~15%**
- Similar signal/background rate for ME as for LE
  - Expected stat. error ~2%
  - Syst. error 7% → 5%

Very forward single electron final state