NA61-SHINE: Hadron production measurements for neutrino & cosmic rays experiments

N. Abgrall[a]
For the NA61 collaboration

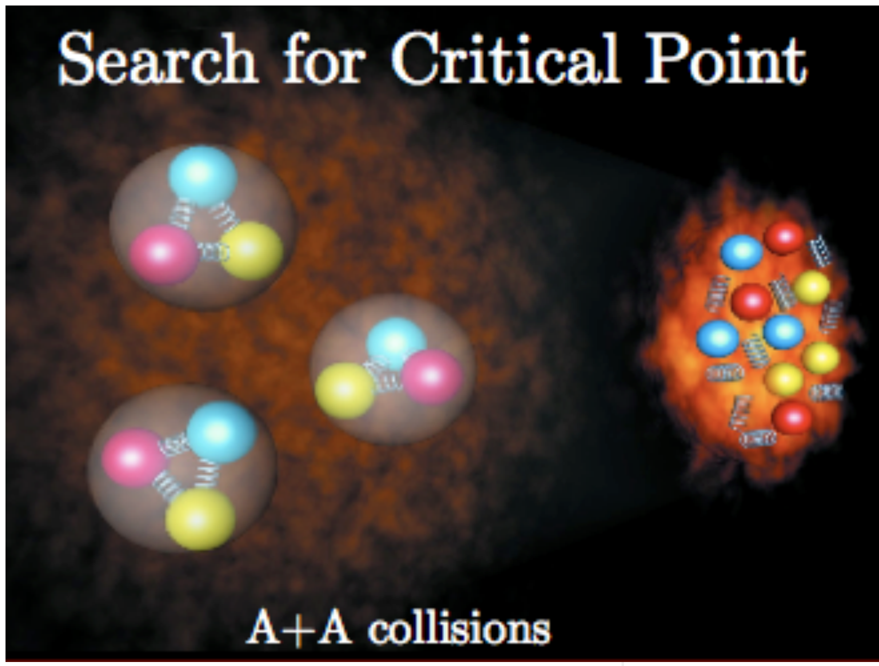
- NA61 hadron production measurements
- What are hadron production data needed for ?
- Neutrino flux prediction studies in T2K: what to measure and how
- NA61 acceptance for T2K flux studies

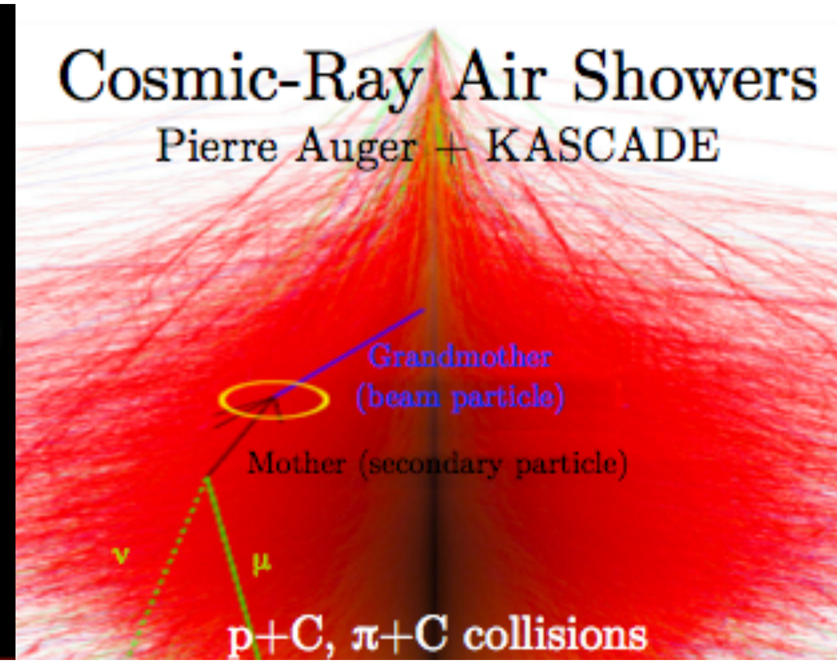
[a] University of Geneva

NA61-SHINE scientific program

SPS Heavy Ions and Neutrino Experiment

- Very broad scientific program !





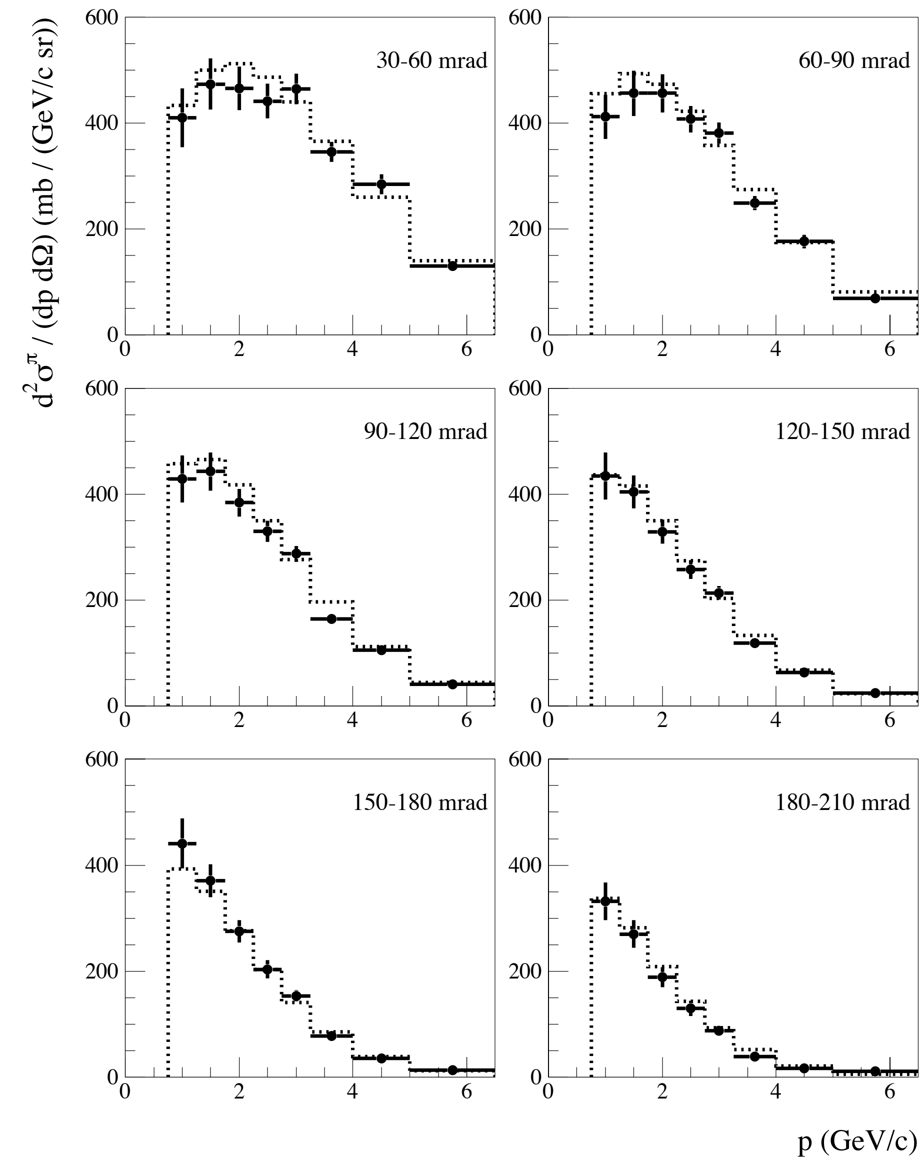
Approved at CERN in 2007
Scientific program approved until 2014.

Collaboration of:
125 scientists
24 institutes
13 countries

What are hadron production data needed for ?

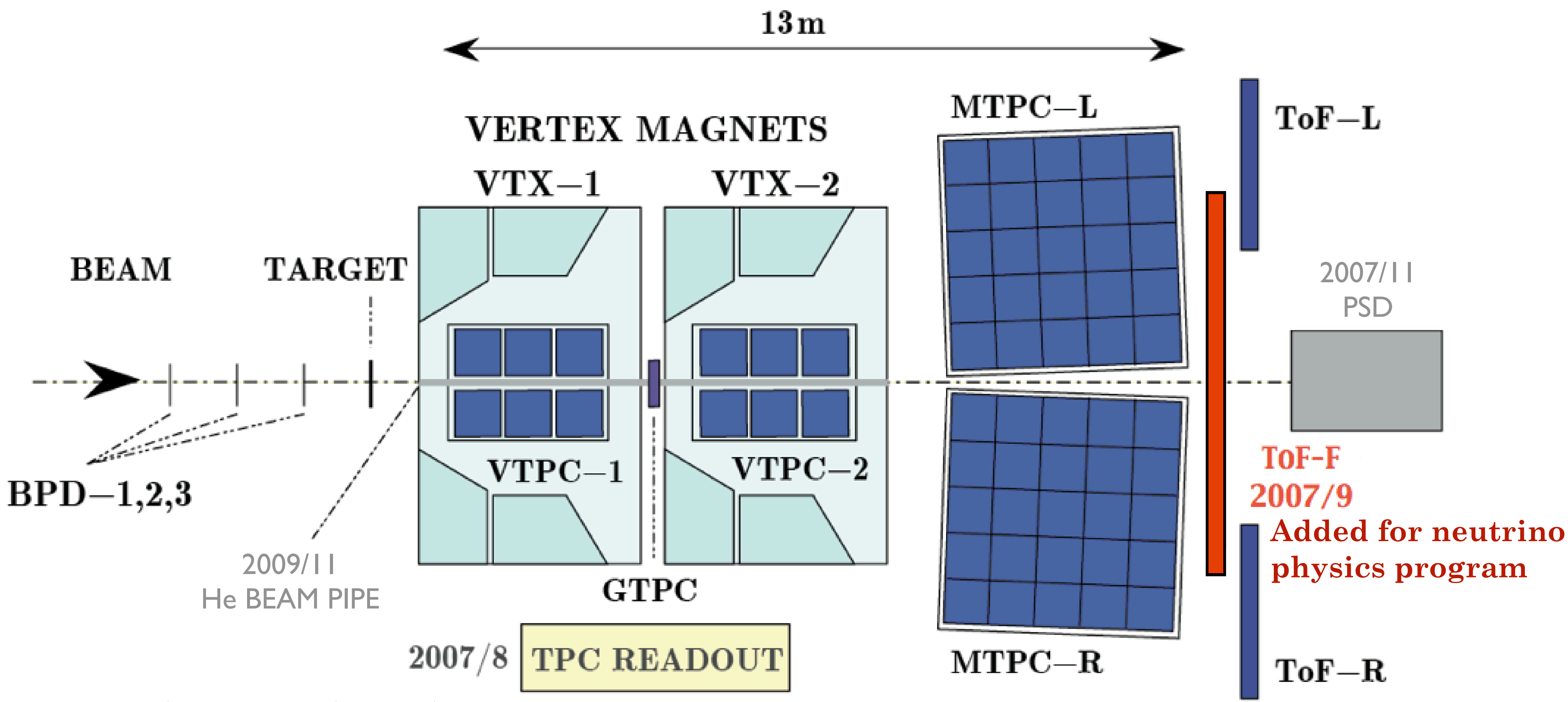
- Several hadron production experiments have been conducted over a range of incident proton momenta from 3 GeV/c to 450 GeV/c. Many cover limited ranges in x_F and p_T.
- Models of secondary production have been derived by fitting and interpolating experimental data on $p + A \rightarrow \pi^{\pm} X$ or $p + A \rightarrow K X$.
  - Shower cascade models: contain all the necessary physics but cannot be modified. (e.g. MARS, FLUKA, DPMJET-III, etc)
  - Parametric models: account for pT scale-breaking, different targets (A scaling), thin/long target parameterizations (e.g. Sanford-Wang, Malensek, BMPT, etc)

e.g. HARP data $p + Al \rightarrow \pi^+ + X$, 12.9 GeV/c
Sanford-Wang fit used for K2K neutrino flux predictions



- The lack of hadron production data implies to rely on models to extrapolate data to conditions of relevance for a given accelerator neutrino beam. This includes:
  - sparse measurements at fixed values of secondary momenta or transverse momenta
  - different target material and target dimensions
  - different projectile momenta on target
- Precise muon & neutrino flux predictions require a good knowledge of hadron production !

NA61-SHINE setup



Large acceptance spectrometer:
- 5 TPCs, $\sigma(p)/p^2 \sim 10^{-4}$ (GeV/c)$^{-1}$
- 3 ToFs, $\sigma_{ToF\text{-}F} \sim 120$ ps, $\sigma_{ToF\text{-}L/R} \sim 70$ ps

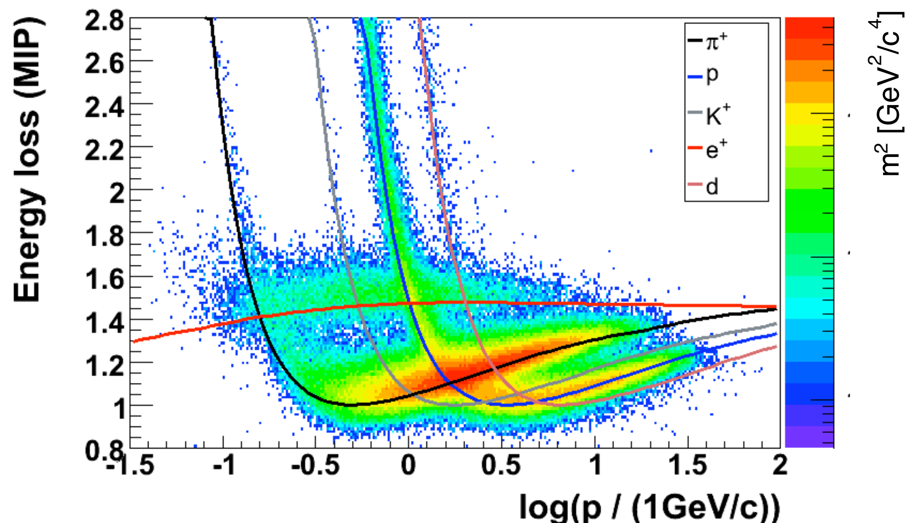
Measurements with thin AND long targets
- Thin Carbon target, (2.5x2.5x2 cm^3, 4% λ_{int}) 600k triggers in 2007
- T2K replica Carbon target (90 cm, 2.6 cm ∅, 1.9 λ_{int}), 250k triggers in 2007

NA61 data quality

- NA61 allows for PID over a large range of momentum

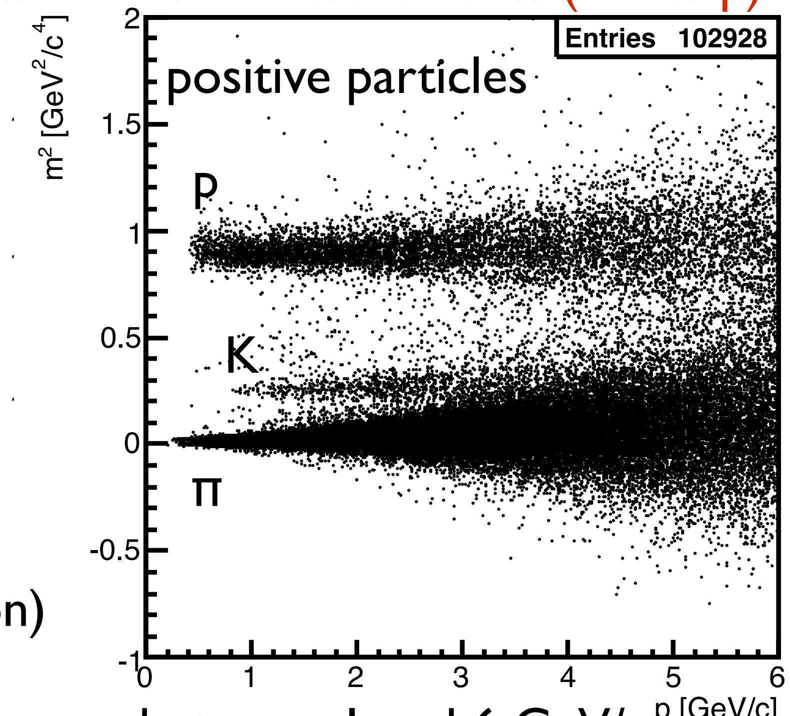
Positive particles

dEdx measurements



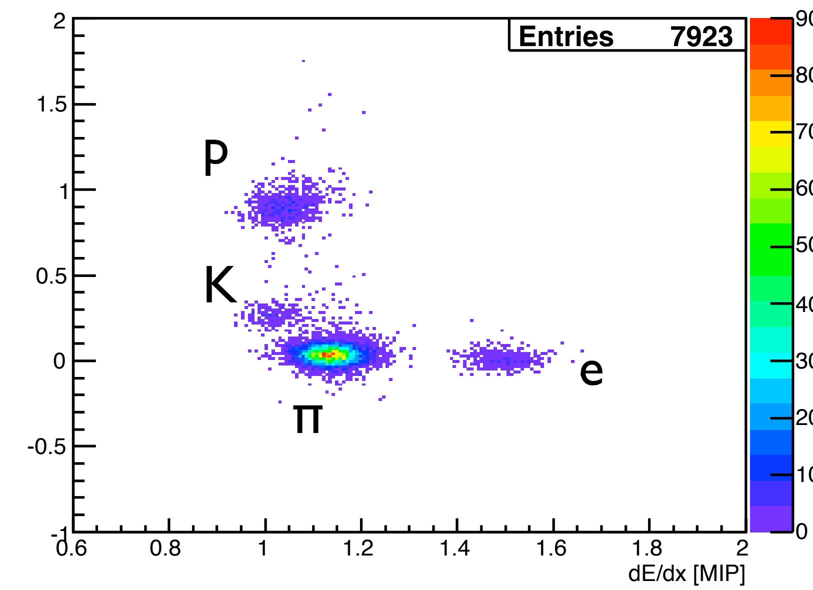
- below 1 GeV/c
- above 4 GeV/c (relativistic rise region)

ToF measurements (m2 vs p)

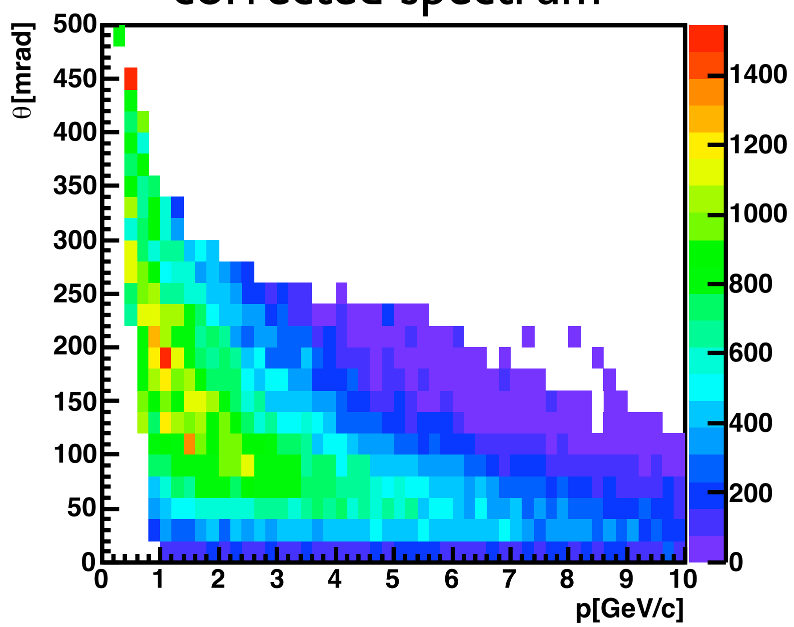


between 1 and 6 GeV/c

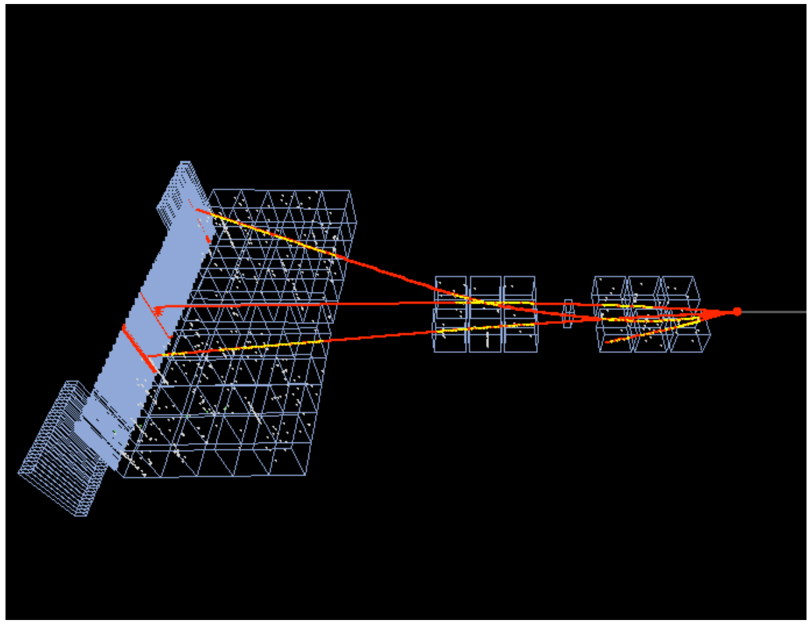
combined ToF/dEdx measurements



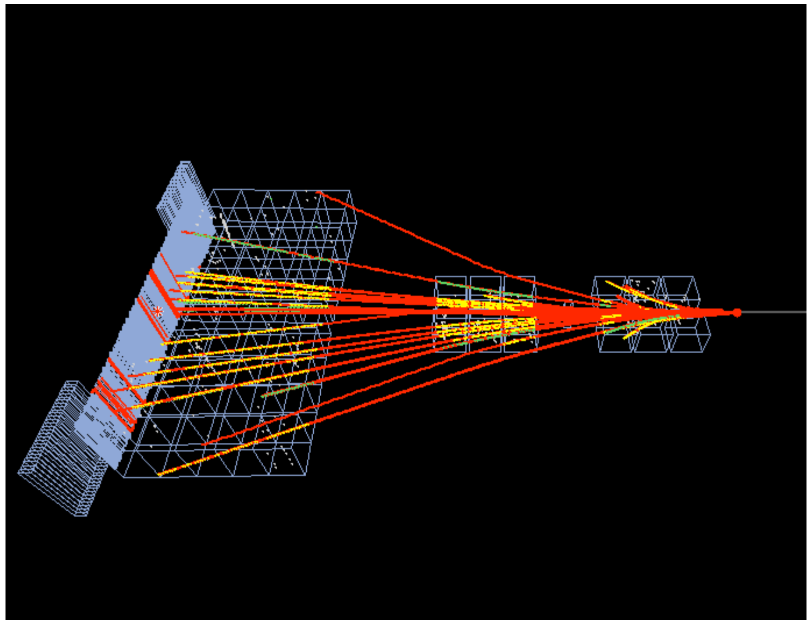
e.g. Phase space covered by π^+
corrected spectrum



- High quality of data reconstruction



p + C (LT) , 31 GeV/c



π^- + C, 350 GeV/c

NA61 hadron production measurements

- The first NA61 preliminary results on 2007 pilot run data are now available for p+C thin target measurements @ 31 GeV/c

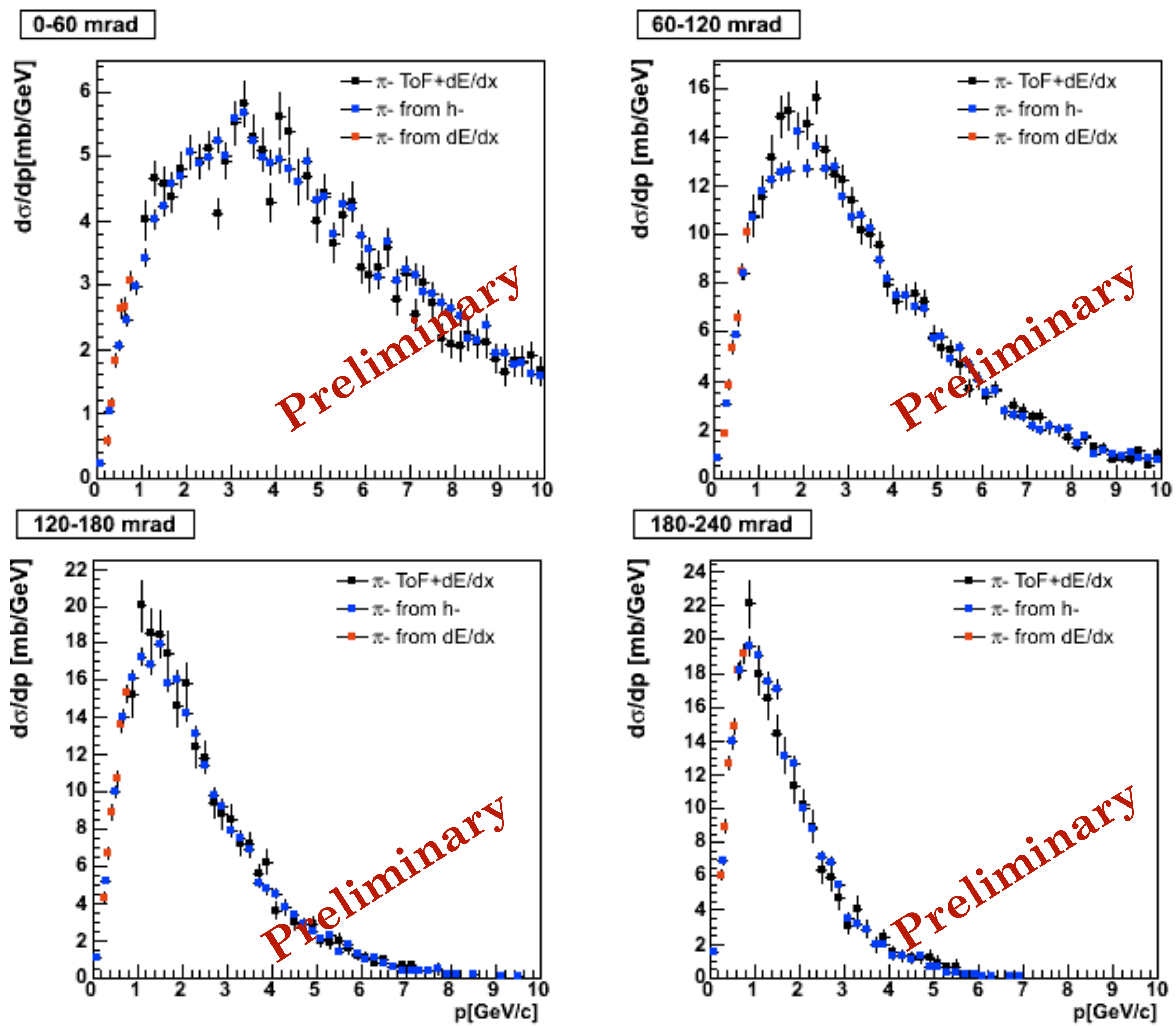
Double differential cross-sections in different bins of ϑ (angle at production point).

Different analysis procedures have been developed [a]:

- dEdx only (< 1GeV/c)
- negative hadrons analysis
- combined ToF-F/dEdx

Results between those different approaches are consistent within 20% systematic errors.

Only statistical errors are shown here. Work is in progress to lower the current systematics.



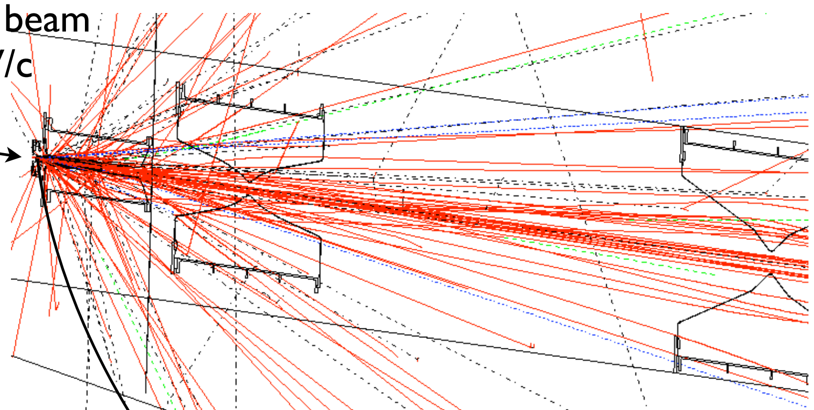
[a] S. Murphy's talk, YSF3

What are hadron production data needed for ?

- Neutrino flux predictions for T2K[a]

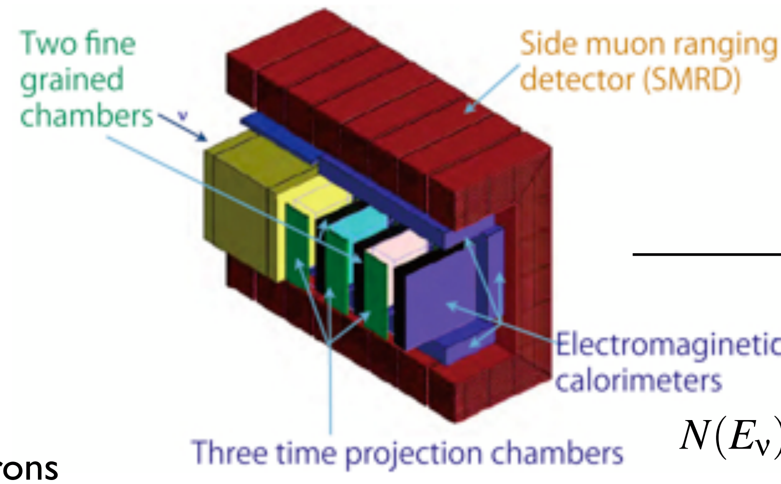
Production source
(Target station T2K beam Monte-Carlo)

proton beam
30 GeV/c



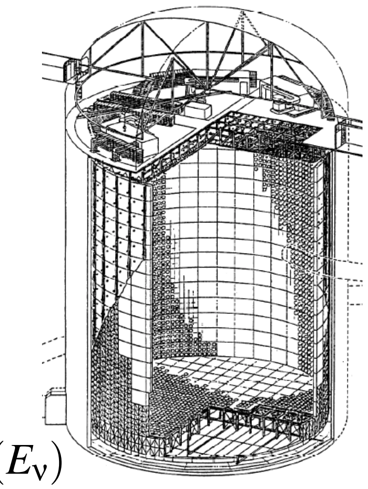
charged π^+, π^-, K^+, K^- and neutral K^0_L hadrons

Near detector



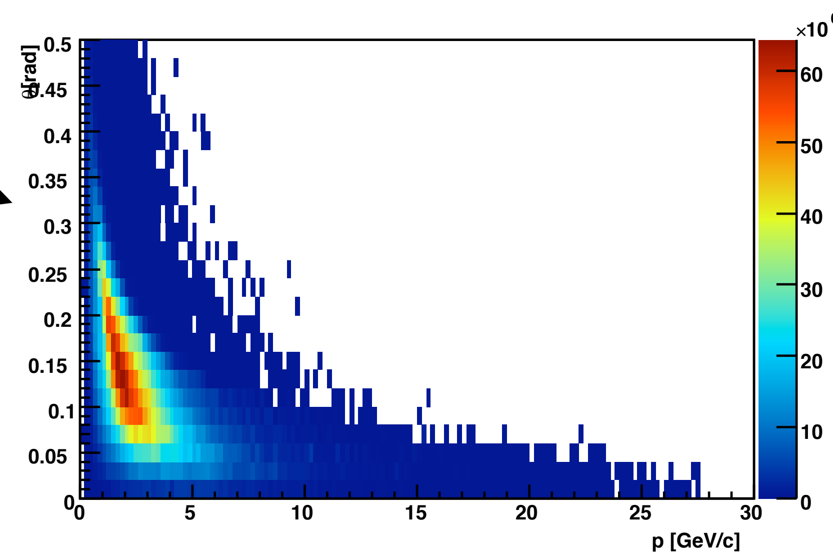
$\nu_\mu \longrightarrow \nu_\mu$ (disappearance)
$\nu_\mu \longrightarrow \nu_e$ (appearance)

Far detector



$$N(E_\nu) = \Phi^{exp}_{FD}(E_\nu) \times \sigma_{react}(E_\nu) \times \varepsilon_{react}(E_\nu)$$
$$= (\Phi_{ND}(E_\nu) \times R_{F/N}(E_\nu)) \times \sigma_{react}(E_\nu) \times \varepsilon_{react}(E_\nu)$$

Phase space (p, ϑ) of π^+ producing neutrinos in the far detector (T2K beam Monte-Carlo, 2.5° off-axis configuration)



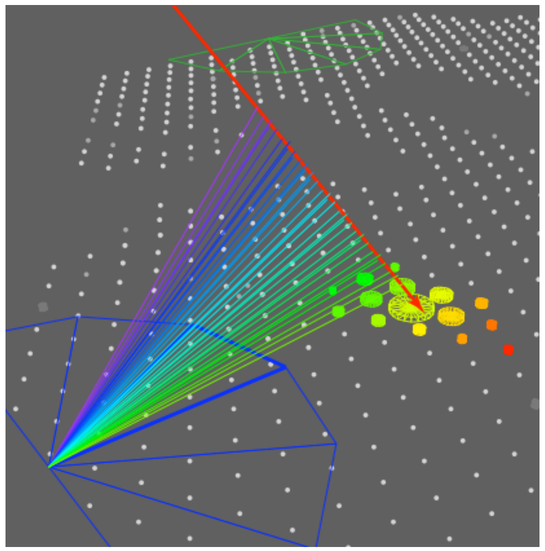
Measure hadron production to constrain uncertainty on the far-to-near extrapolation to $\delta R_{F/N}$ ~ 2-3%

[a] Talk by Matsuoka-san

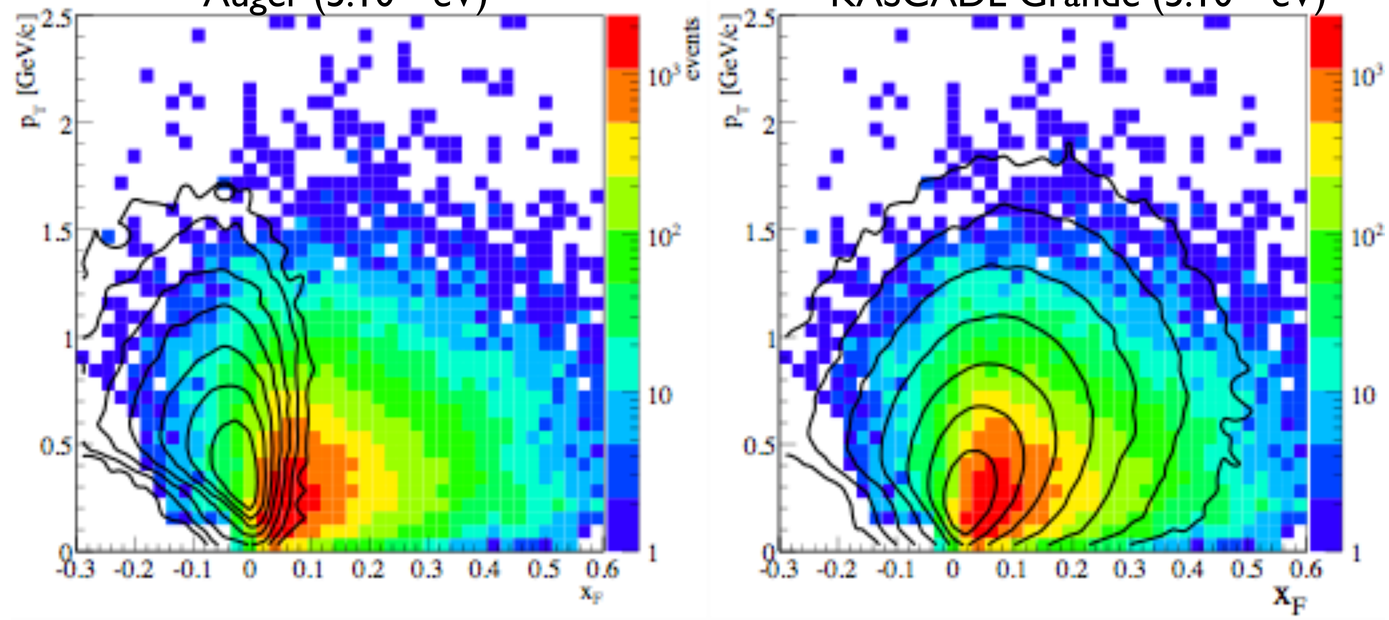
What are hadron production data needed for ?

- Muon flux predictions for cosmic rays

Air shower - Auger event display



Auger (5.10^{18} eV) KASCADE Grande (5.10^{17} eV)



black: simulation
color: 2009 data 158 GeV/c
$\pi^- + C$

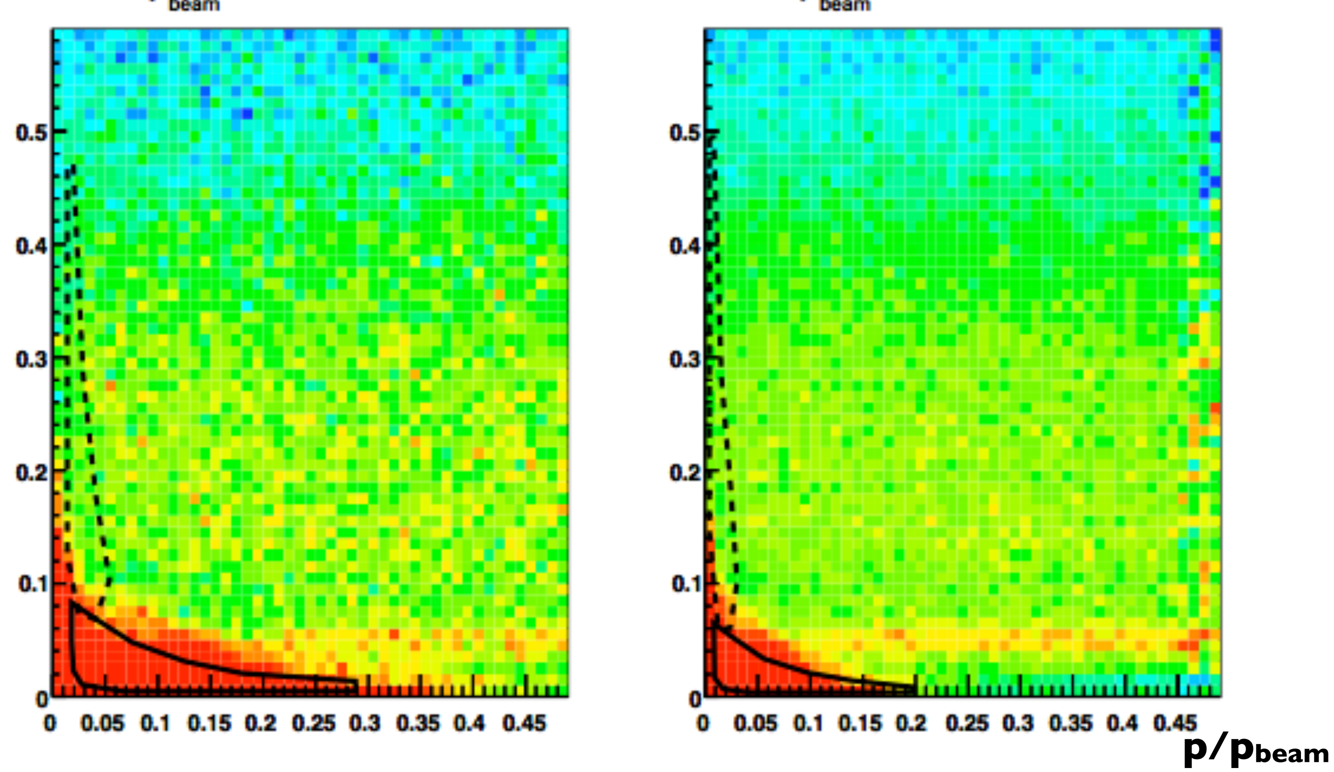
Discrepancy in description of the lateral distribution related to muon density profile.

Measure hadron production to constrain muon density in Monte-Carlo models

---- Auger data
— Knee region

NA61 acceptance specific to cosmic ray data analyis

— > 90%
— 50%
— < 10%



Neutrino flux prediction studies in T2K: what to measure and how

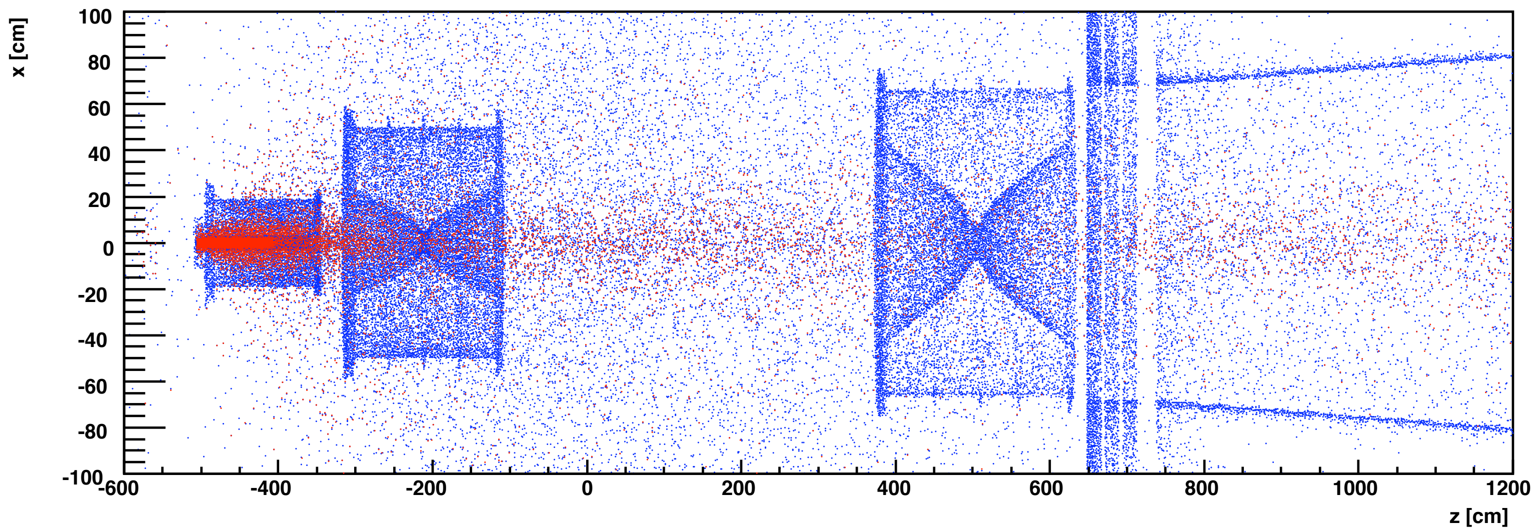
(N. Abgrall, B. Popov, NA61-T2K internal note 01)

- Precise neutrino flux predictions require:
  - study of all species: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
  - study of contributions in terms of parent particles, hadronic interactions and production sources

- We performed studies with the T2K beam Monte-Carlo taking into account the neutrino history back to the primary proton interaction and defining flux contributions in terms of NA61 measurements:
  - direct contribution: neutrino parent particles produced in the primary proton interaction (secondaries), muons or other parent particles from decays of secondaries. This contribution refers to the NA61 thin target measurements (primary interaction).
  - indirect contribution: neutrino parent particles from any higher generation (re-interactions in the target and elements of the beam line).
  - in-target contribution: neutrino parent particles produced in the target, muons and other parent particles from decays of particles produced in the target. This contributions refers to NA61 replica target measurements (primary + secondary interactions).
  - out-of-target contribution: neutrino parent particles produced out of the target.

Neutrino flux prediction studies: what to measure and how

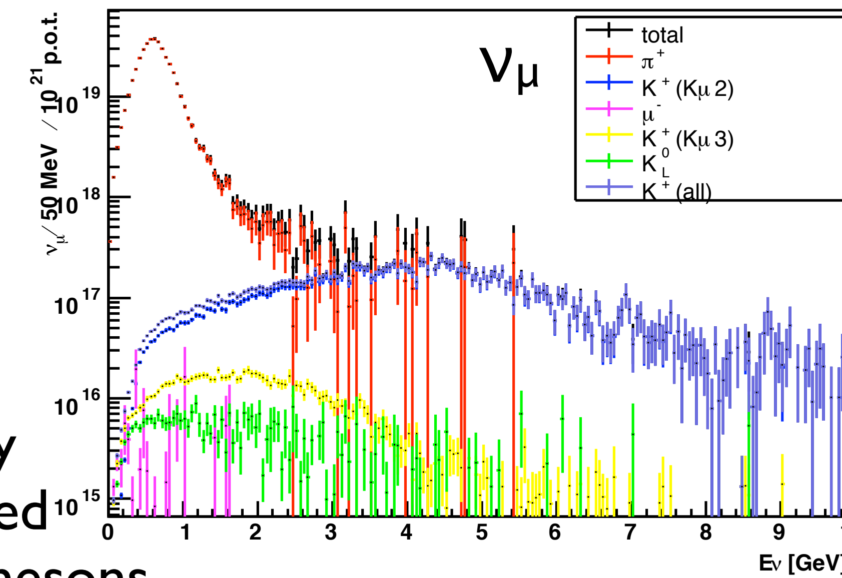
- Neutrino parent production point



Blue: parents produced out of the target volume

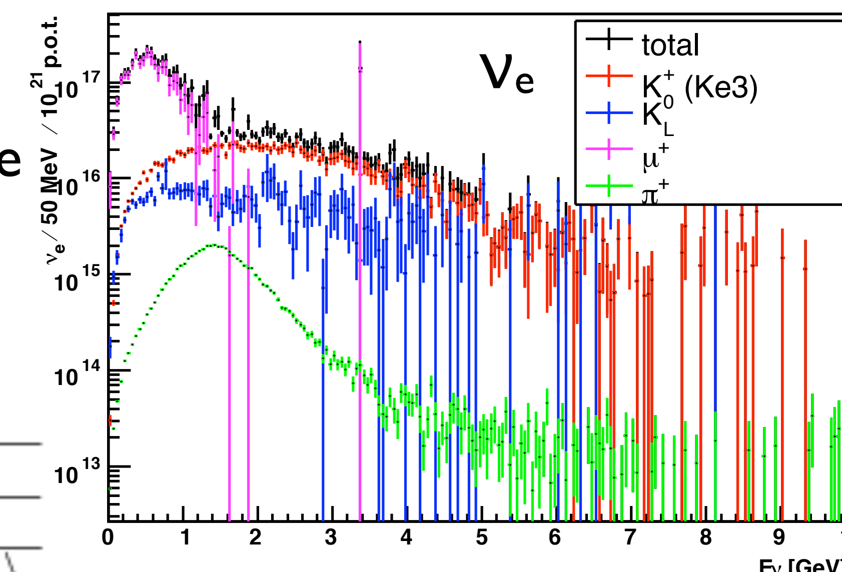
Red: in-target contribution. Most of the dots along the beam line correspond to muons from pion decays

- Parent contributions to ν_μ and ν_e fluxes @ the near detector



Consider all decay channels of charged and neutral π/K mesons

e.g. $\pi^+ \rightarrow e^+\nu_e$ is important in the search for ν_e appearance

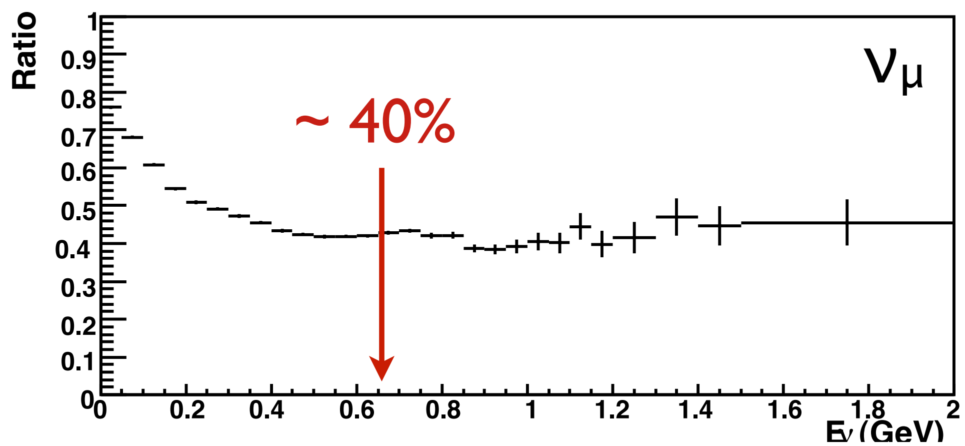


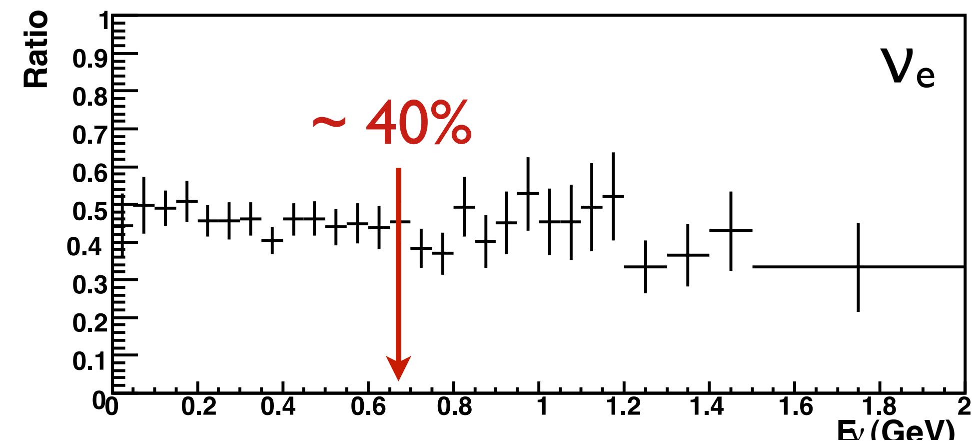
Abundance tables for all species and contributions have been computed, e.g. example for in-target contribution @ the far detector:

ν species	Flux Abund.	Flux $\langle E_\nu \rangle$	π^+ or π^- %	π^+ or π^- $\langle E_\nu \rangle$	K^+ or K^- (K2) %	K^+ or K^- (K2) $\langle E_\nu \rangle$	K^+ or K^- (K3) %	K^+ or K^- (K3) $\langle E_\nu \rangle$	K^0_L %	K^0_L $\langle E_\nu \rangle$	μ^+ or μ^- %	μ^+ or μ^- $\langle E_\nu \rangle$
ν_μ	1.0	0.79	95.1	0.63	4.6	4.03	0.2	1.90	0.1	2.45	< 0.01	0.70
$\bar{\nu}_\mu$	0.0571	1.64	82.2	1.59	5.3	3.93	0.3	1.69	1.7	2.45	10.5	0.71
ν_e	0.0120	1.44	1.0	1.48	–	–	30.3	2.23	12.5	3.01	56.2	0.67
$\bar{\nu}_e$	0.0018	2.80	0.3	3.71	–	–	13.1	2.23	82.1	3.01	4.5	0.52

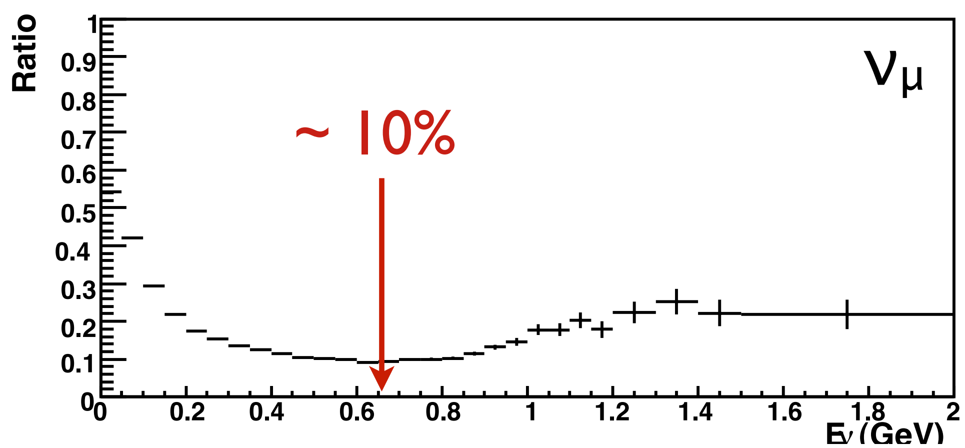
Neutrino flux prediction studies: what to measure and how

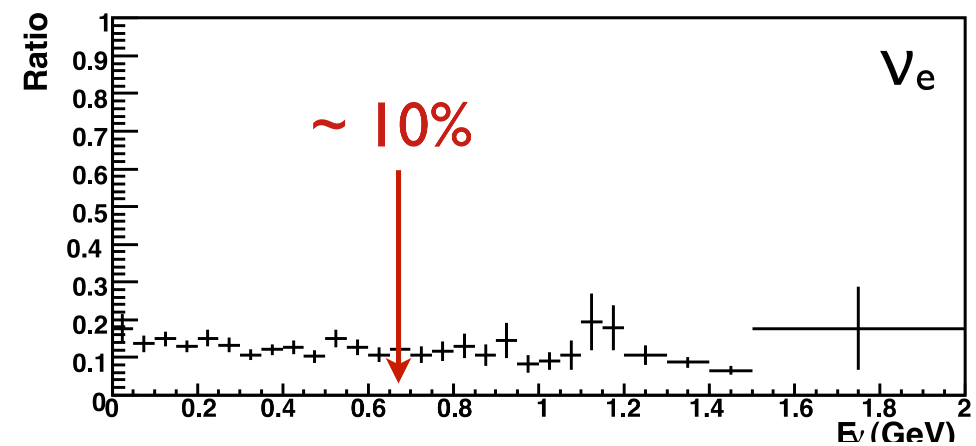
- Ratio of indirect/total contribution for ν_μ, ν_e





- Ratio of out-of-target/total contribution for ν_μ, ν_e



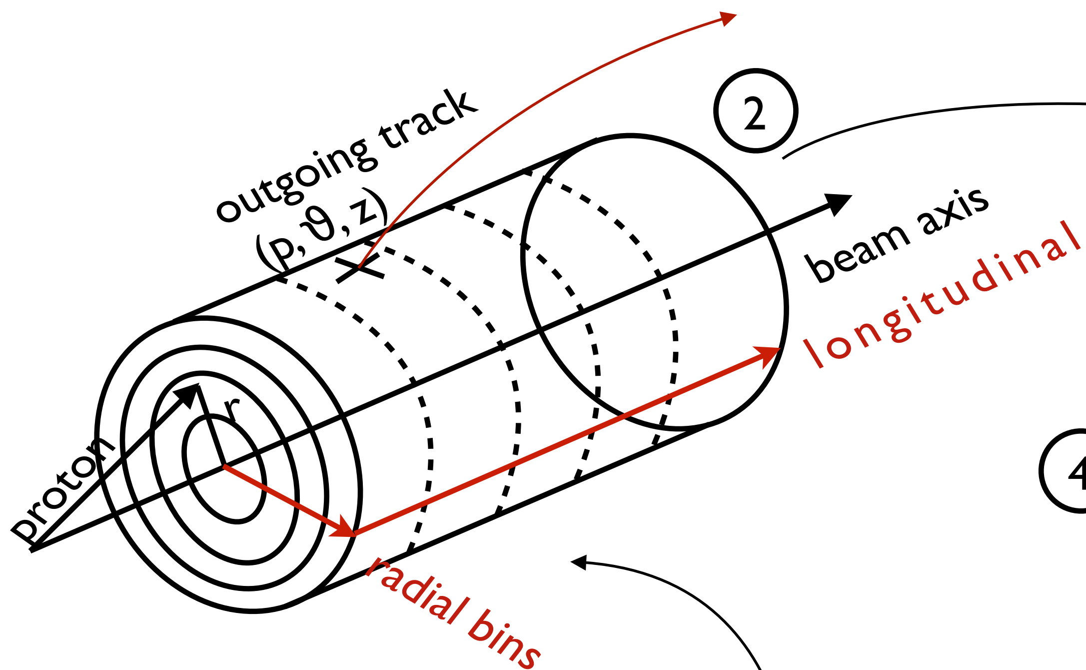


- Thin target data will provide cross-sections as direct input to the T2K beam Monte-Carlo. First point shows however that still 40% of the flux is still to be described by hadronization models. Those models for secondary interactions can be constrained by comparing production spectra on thin and thick targets (Strategy A).

- Second point motivates the use of replica target data (π/K yields off the target skin) as direct input to the beam Monte-Carlo, secondary interaction models are used to correct for remaining interactions out of the target (10% of the neutrino flux) (Strategy B).

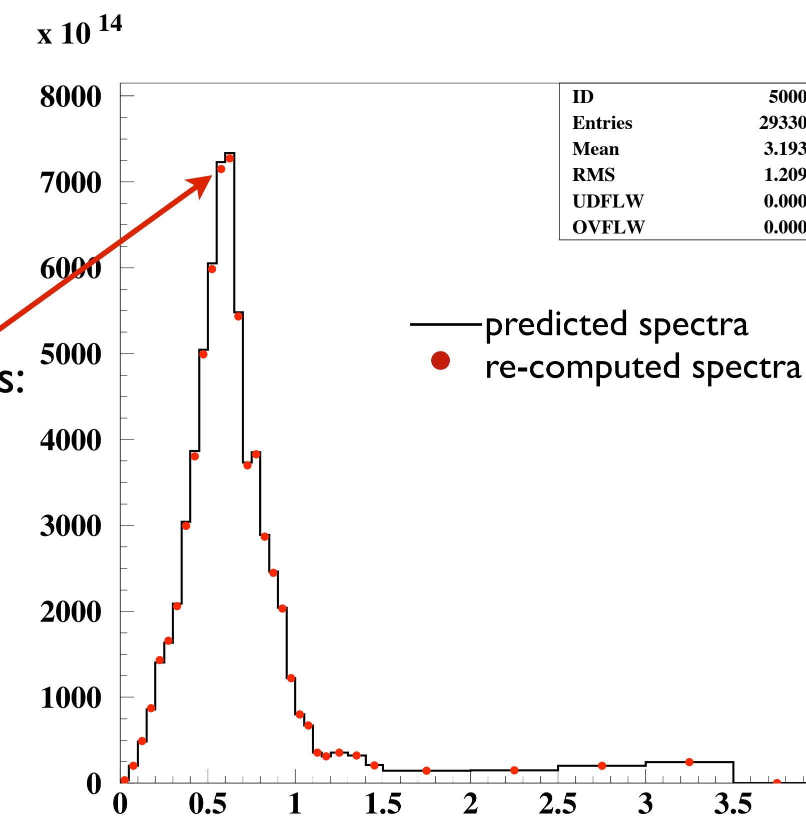
NA61 acceptance for flux studies

- Developed method to implement the NA61 acceptance in the T2K beam Monte-Carlo to account for hadron cross-section measurements uncertainty consistently over the T2K phase space

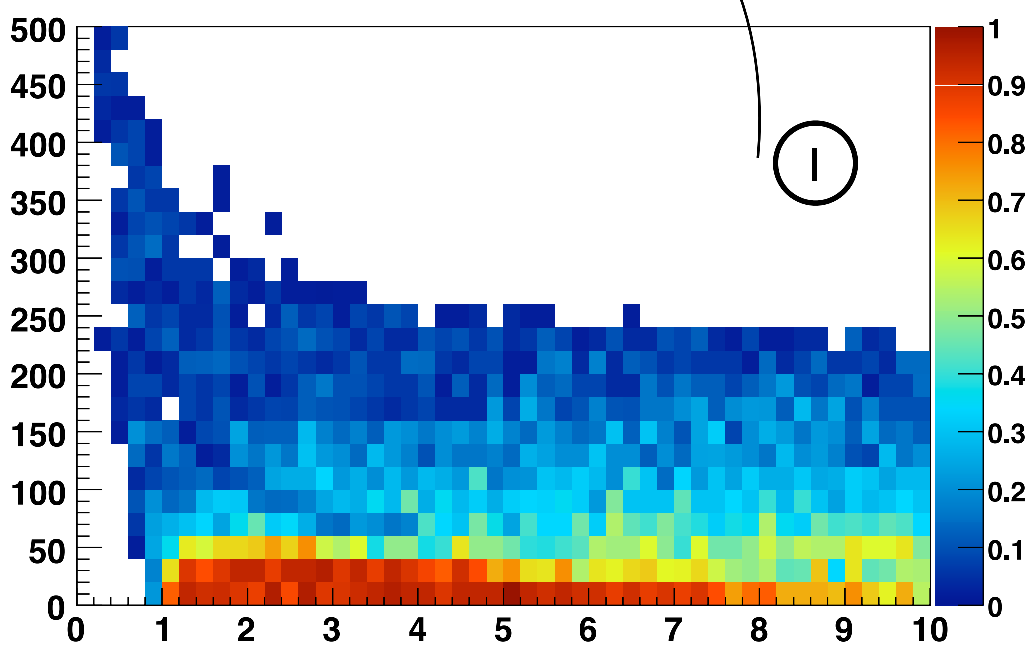


(3) Compute contribution of each bin (p,ϑ,z,r) to different bins of neutrino energy. This contribution is factorized in fraction and normalization weights

(4) Re-compute spectra @ far and near detectors propagating hadron cross-section uncertainties:



$$W = \sum_{i=1}^{N_i} \frac{w_i}{N_i} = \sum_{j=1}^{n} w_{ij}^{f} \sum_{k=1}^{N_j} \frac{w_k}{N_j} = \sum_{j=1}^{n} w_{ij}^{f} w_{ij}^{n} \longrightarrow N(E_\nu)_j = N_i \times w_{ij}^{f} \times w_{ij}^{n}$$



(1)

e.g. Acceptance at target downstream face for track hitting the ToF-F

This method can be used to estimate required statistics of NA61 measurements with respect to the T2K physics goals
e.g. maximal uncertainty on hadron cross-section measurements to get an error less than 2-3% on the far-to-near ratio prediction

Conclusions

- First NA61 preliminary results from the 2007 pilot run have been made public
- Collected much more data in 2009 (currently under calibration): 9 reactions, 40M events !
    - p + C @ 31 GeV/c (6M)
    - p + C (T2K replica target) @ 31 GeV/c (4M)
    - π + C @ 158 GeV/c (5M)
    - π + C @ 350 GeV/c (6M)
    - p + p @ 20, 31, 40, 80, 158 GeV/c (19M)
- The NA61 large acceptance is adequate for hadron production measurements needed by neutrino and cosmic rays experiments.
- NA61 data are important to constrain hadron production models used in the T2K beam Monte-Carlo. Different strategies can be applied.
- Another data taking period for the T2K replica target is under discussion.