Impact of NA61(SHINE) data on T2K experiment

T2K physics goals and requirements **(Report Feb.2007, A.Blondel, T.Kobayashi, K.Sakashita, T.Nakadaira)**

1. ν_e disappearance channel
2. ν_μ appearance channel

T2K motivations for NA61

Requirements on NA61 measurements

1. Relevant phase space
2. Statistical precision required by F/N
3. Statistical precision required by near spectrum prediction
4. Precision of K/π ratio measurement

Review of NA61 2007 data

Strategies to use NA61 data for T2K neutrino flux prediction

1. Strategy A
2. Strategy B

Conclusion

SHINE NA61

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T2K Physics Goals

ν_e disappearance channel

Neutrino oscillations are probed by comparison between near and far sites spectra with and without oscillation hypothesis.
The far site (SK) predictions depend on both ν_μ and ν_e fluxes at SK, $\phi^{SK}{}_\mu$ and $\phi^{SK}{}_e$ resp., which are predicted as the product of the near site (ND) measured spectra by the "Far to Near ratio" as a function of the neutrino energy:

$$\Phi^{SK}_{\mu,e}(E_\nu) = R_{\mu,e}(E_\nu) \times \Phi^{ND}_{\mu,e}(E_\nu)$$

The background predominantly consists of ν_μ NC π^0 interactions and intrinsic ν_e contamination and is predicted at SK by the following equation (integral over ν energy is omitted for simplicity):

$$N_{BG} = N^{\pi^0}_{BG} + N^{e}_{BG} = \Phi^{SK}_{\mu} \cdot \sigma_{NC\pi^0} \cdot \varepsilon^{\pi^0}_{SK} + \Phi^{SK}_{e} \cdot \sigma_e \cdot \varepsilon^{e}_{SK}$$
$$= R_\mu \cdot \Phi^{ND}_{\mu} \cdot \sigma_{NC\pi^0} \cdot \varepsilon^{\pi^0}_{SK} + R_e \cdot \Phi^{ND}_{e} \cdot \sigma_e \cdot \varepsilon^{e}_{SK}$$

- Detection efficiency at SK
- BG process cross-section
- Measured flux at ND
- F/N ratio

} **Sources of systematics for δN_{BG}**

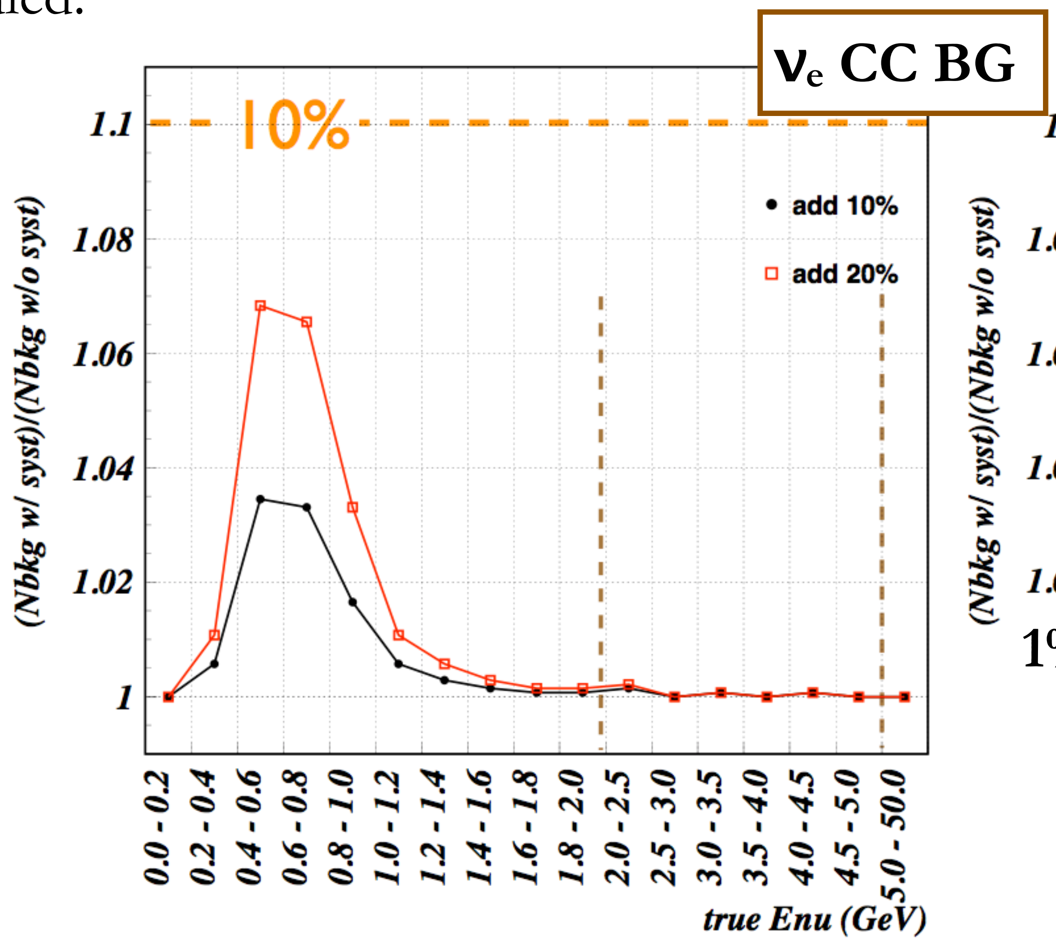
The **T2K goal** is to probe oscillations down to: $\sin^2 2\theta_{13} \sim 0.008$ **(90% CL)**

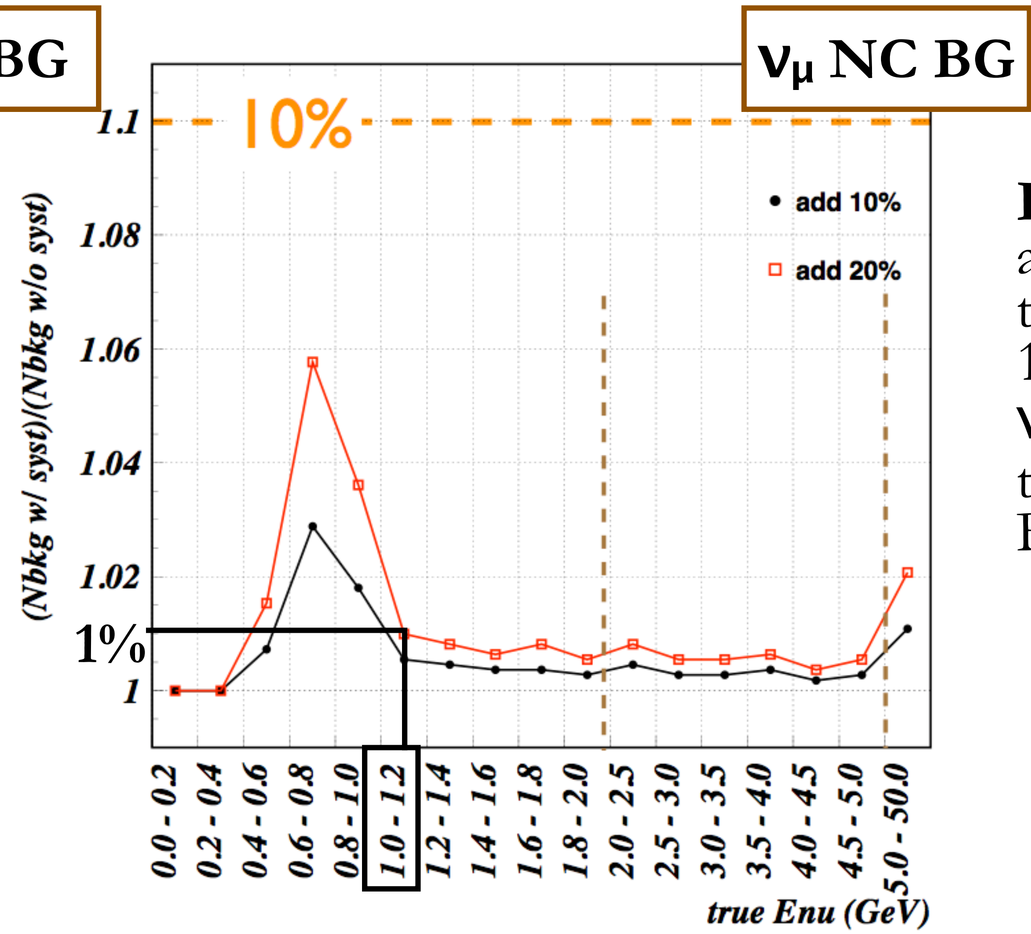
This goal requires a systematic error on the prediction of BG events of: $\delta(N_{BG}) \leq 10\%$ (cf T2K proposal)

T2K Physics Goals

ν_e disappearance channel

Effects of changes in F/N ratio (or equivalently in SK spectrum) on the expected number of BG events have been studied:





For example:
an increase of 20% in the energy bin between 1.0 and 1.2 GeV of the ν_μ spectrum increases the number of ν_μ NC BG by ~1%

- 10% error on R_μ in 0-1 GeV → $\delta N^{\pi^\circ}_{BG} = 5.4\%$
- 10% error on R_μ in 1-10 GeV → $\delta N^{\pi^\circ}_{BG} = 4.6\%$
- 10% error on R_e in 0-1 GeV → $\delta N^{e}_{BG} = 8.9\%$
- 10% error on R_e in 1-10 GeV → $\delta N^{e}_{BG} = 1.2\%$

Goal on F/N precision → **set to $\delta R_{\mu,e}$ ~ 2-3%**

- in 0-1 GeV → $\delta N^{\pi^\circ}_{BG} = 1.6\%$
- in 1-10 GeV → $\delta N^{\pi^\circ}_{BG} = 1.4\%$
- in 0-1 GeV → $\delta N^{e}_{BG} = 2.7\%$
- in 1-10 GeV → δN^{e}_{BG} = negligible

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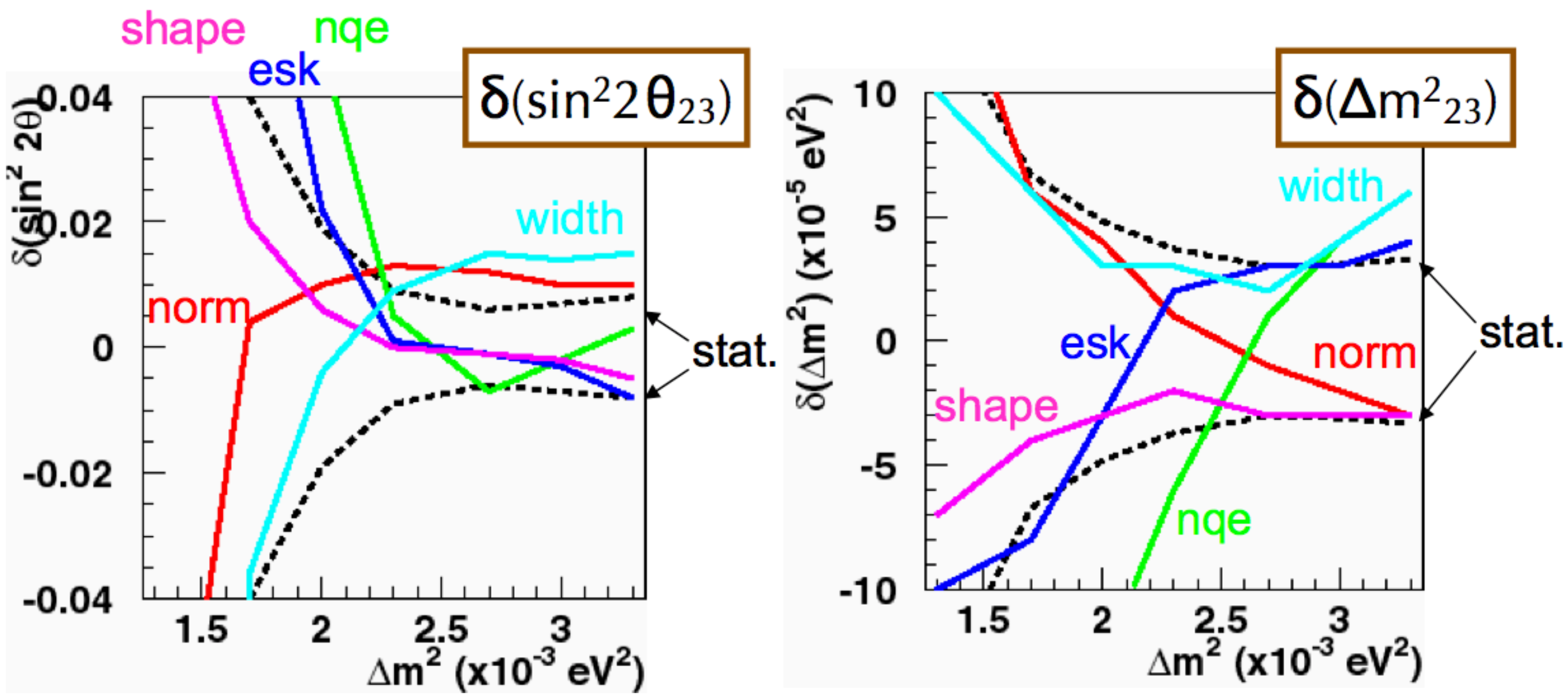
T2K Physics Goals

ν_μ appearance channel

The nominal T2K statistical power (5 years running, 5×10^{21} POT) on the measurement of ν_μ disappearance leads to:

$$\delta(\sin^2 2\theta_{23}) \sim 0.01 \quad \text{and} \quad \delta(\Delta m^2_{23}) <\sim 3\times10^{-5} \quad (\sim1\%)$$



Systematics related to the F/N ratio extrapolation:

- overall SK normalization (change by 10%)
- SK spectrum width (change by 10%)
- energy-dependent bias that roughly reflects uncertainties on hadroproduction models (up to 20%)

In the region of interest of true $\mathbf{\Delta m^2_{23}}$ (E/L ~ 2-3x10^{-3} eV^2), those total contributions add up to:

$$\delta(\sin^2 2\theta_{23}) \sim 0.015 \quad \text{and} \quad \delta(\Delta m^2_{23}) \sim 5\times10^{-5} \quad (\sim 3\text{x}10^{-4}\ \text{eV}^2 \text{ for SK and MINOS})$$

In order not to limit the precision by the F/N extrapolation the goal of F/N ratio precision is set as well to:

$$\delta(R_{\mu,e}) \sim 2-3\ \% \quad \text{which translates to:} \quad \delta(\sin^2 2\theta_{23}) \sim 0.005 \quad \text{and} \quad \delta(\Delta m^2_{23}) \sim 1.5\times10^{-5}$$

Motivations for NA61

Sensitivity w/o NA61 measurements

For T2K, the main goals of the NA61 hadroproduction measurements are:

- Predict the F/N ratio with the required precision
- Predict the near spectrum to be compared with near detector measurements with the required precision

Without the NA61 measurements, the only viable method to constrain the hadroproduction is to purely rely on hadroproduction models fitted to data taken at different energies and materials. This method suffers from 2 major issues: i) nearest data at 12 GeV (HARP) and 159 GeV (NA49), ii) observed K/π ratios are not correctly reproduced by the models.

T2K studies showed that the difference in F/N ratios predicted with different hadroproduction models (FLUKA, MARS, G-FLUKA) are as large as 20% around the peak of the neutrino energy spectrum (0.2-1 GeV). Taking this value as an upper bound on the F/N ratio error leads to:

$$\delta(\sin^2 2\theta_{23}) \sim 1.5 - 3\% \quad \text{and} \quad \delta(\Delta m^2_{23}) \sim (5-10)\times 10^{-5} eV^2$$

Those errors would be: i) much larger than the stat. errors and ii) poorly known ! Moreover, such an error on the F/N ratio would also lead to:

- 20% error on R_μ in 0-1 GeV → $\delta N^{\pi^\circ}_{BG} \sim 10\%$
- 20% error on R_μ in 1-10 GeV → $\delta N^{\pi^\circ}_{BG} \sim 10\%$
- 20% error on R_e in 0-1 GeV → $\delta N^{e}_{BG} \sim 20\%$
- 20% error on R_e in 1-10 GeV → $\delta N^{e}_{BG} \sim 2\%$

Error contribution coming **ONLY** the F/N ratio error is larger than the required 10% error on N_{BG} !

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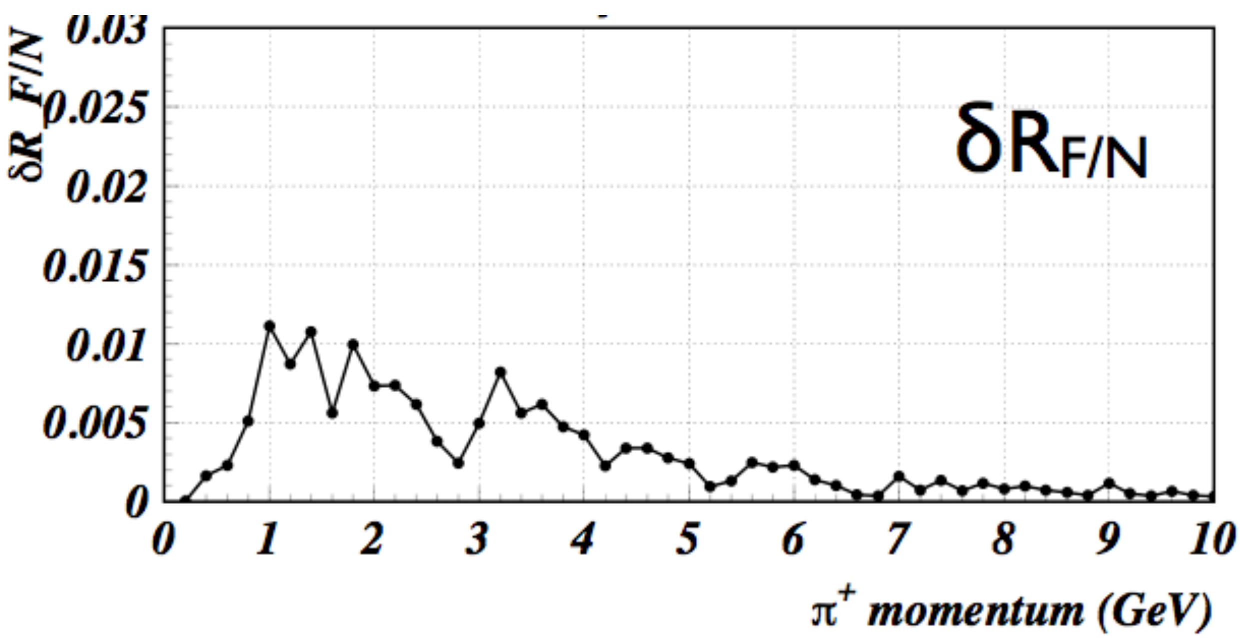
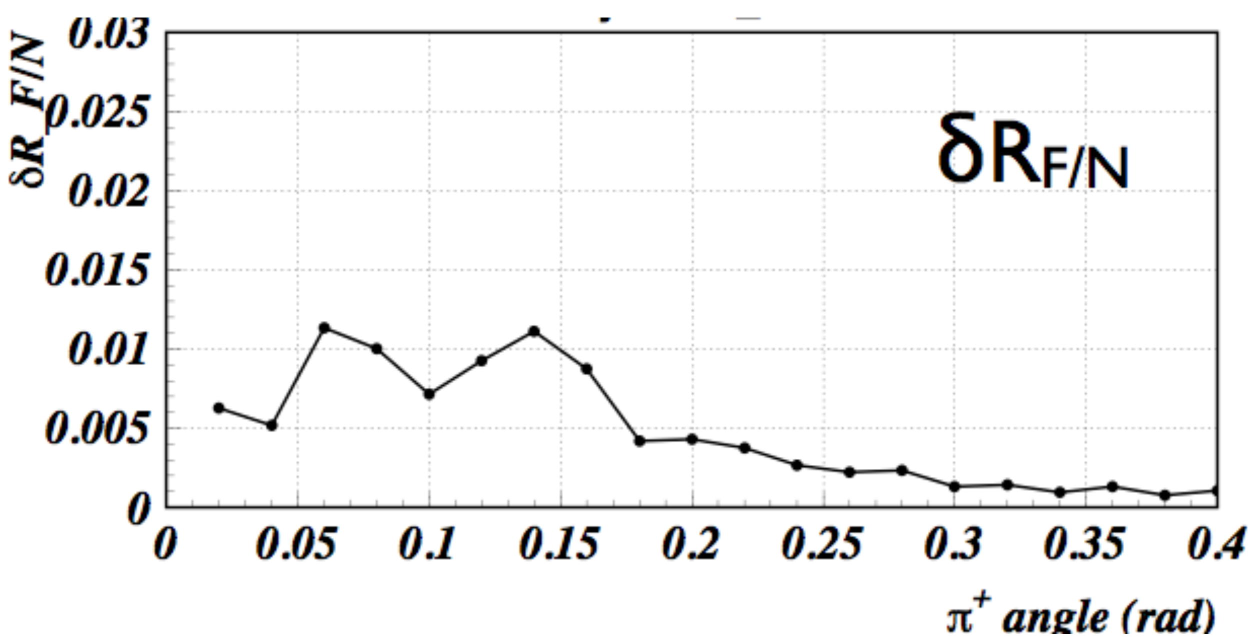
NA61 Measurements

Relevant phase space region

T2K studies have been performed to understand which precision on the NA61 hadroproduction measurements is required to achieve a 2-3% precision on the F/N ratio prediction.

First the sensitivity of the F/N ratio as a function of the phase space region where particles are produced was studied. This was done by dividing the T2K phase space into 10^3 2d bins in p-ϑ and varying each bin content by 30% to estimate the relative change in F/N ratio.





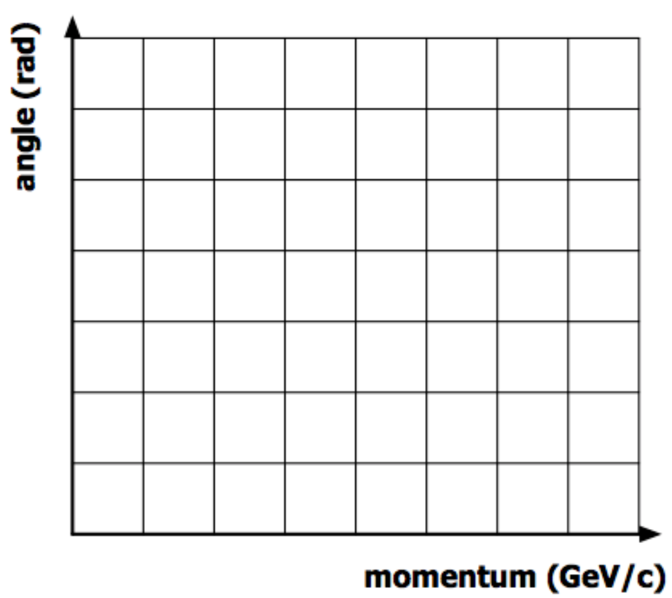
From this study, it was concluded that NA61 should measure the hadroproduction particularly in the region:

$0.3 < p$ [GeV] < 5 and $0 < \vartheta$ [mrad] < 400

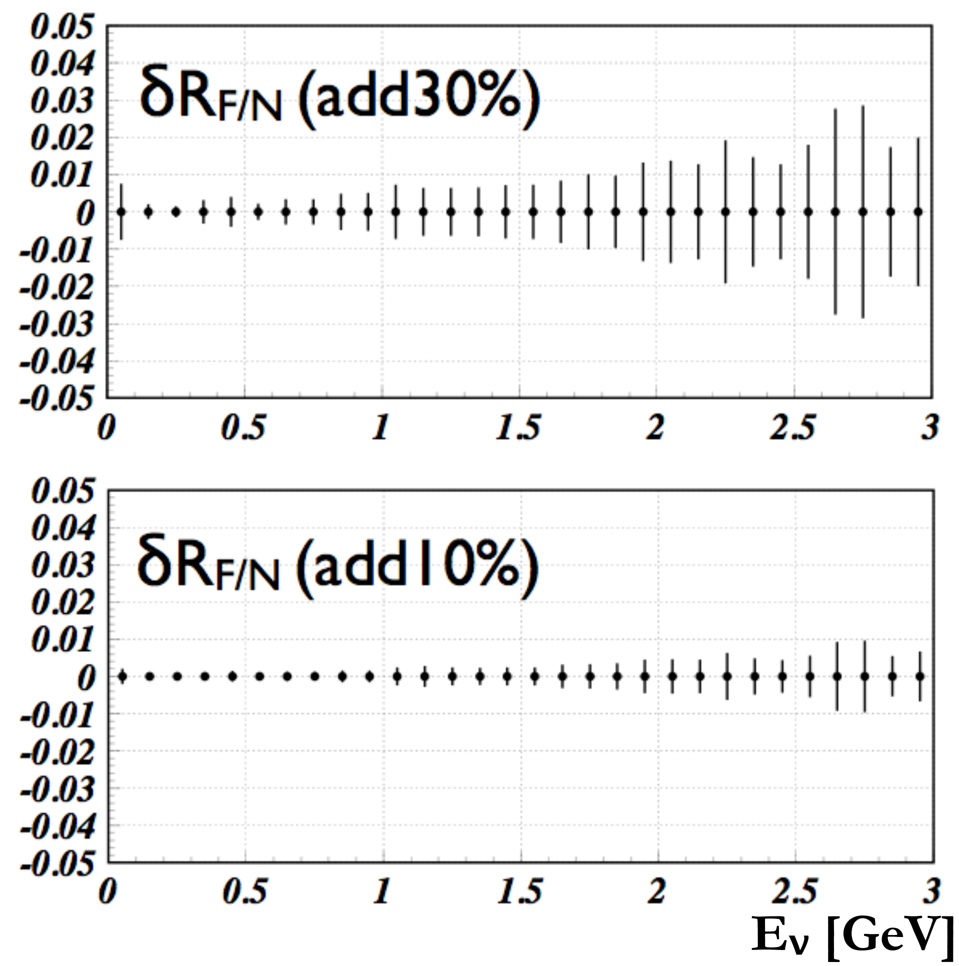
NA61 Measurements

Requirements from T2K F/N ratio precision goal

The required statistical precision of the NA61 measurements has been roughly estimated by dividing the T2K phase space into 10^3 2d bins and adding 10% (30%) uncorrelated uncertainty in all the p-ϑ bins:



P_π 200 MeV/bin x 50 bins
ϑ_π 20 mrad/bin x 20 bins



It was concluded that NA61 needs to measure hadroproduction within a **10% accuracy in each p-ϑ bin.**
For 200k π+ tracks over 0 < p < 10 GeV/c and 0 < ϑ < 400 mrad, the number of events in each p-ϑ bin satisfies this requirement.
N.B.: estimation independent of existing NA61 measurements !!

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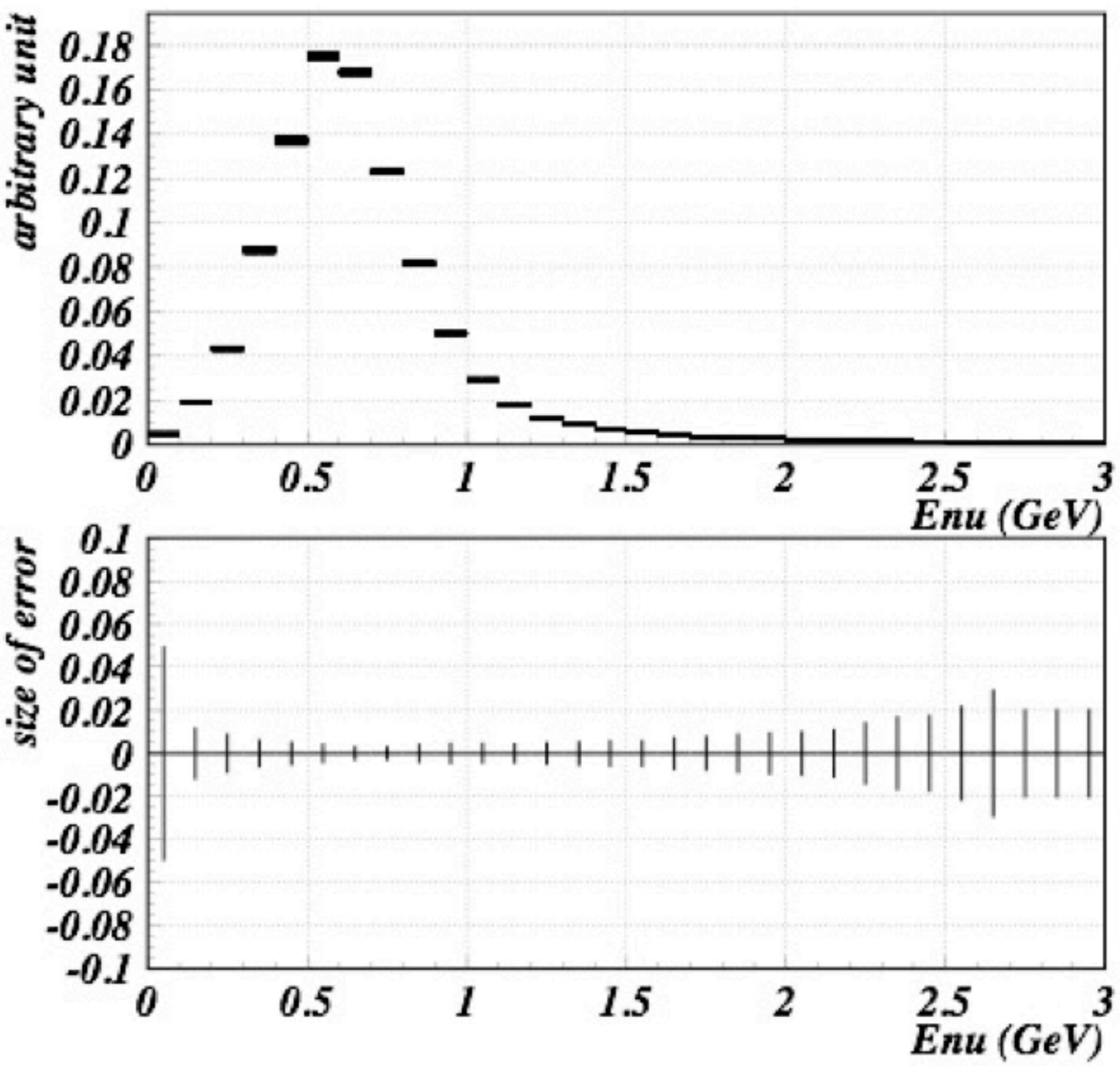
NA61 Measurements

Requirements from near spectrum prediction

Assuming 10% uncertainty on the hadroproduction measurements, the corresponding accuracy on the predicted near spectrum can be estimated:



The size of the errors **(< 5%)** is comparable with the expected systematic uncertainties of T2K from the near detector response (~ 4%) and from the neutrino interaction cross-sections (~ 3-4%).

→Need to measure hadroproduction with better than 10% accuracy.

NA49 measurements have proven to be feasible at the level of typically 3% both in absolute and in the K/π ratio.

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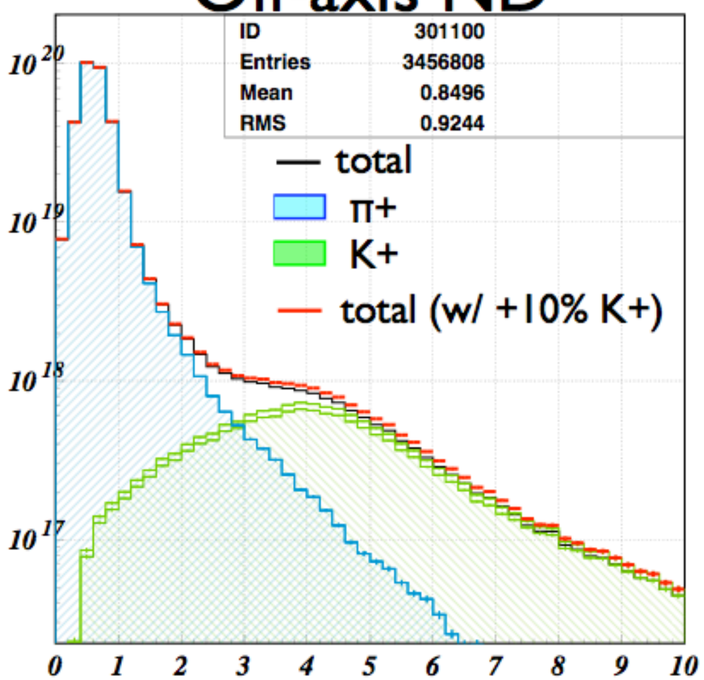
NA61 Measurements

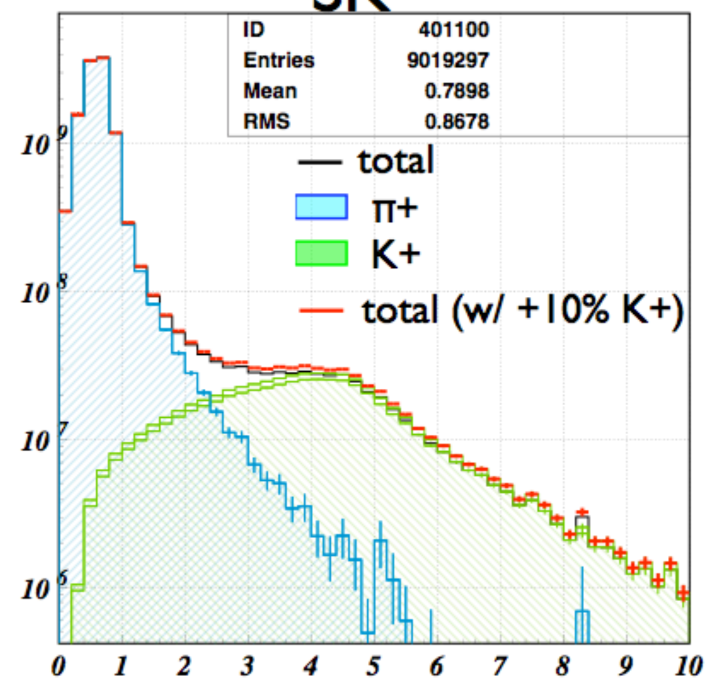
Requirements from K/π ratio precision goal

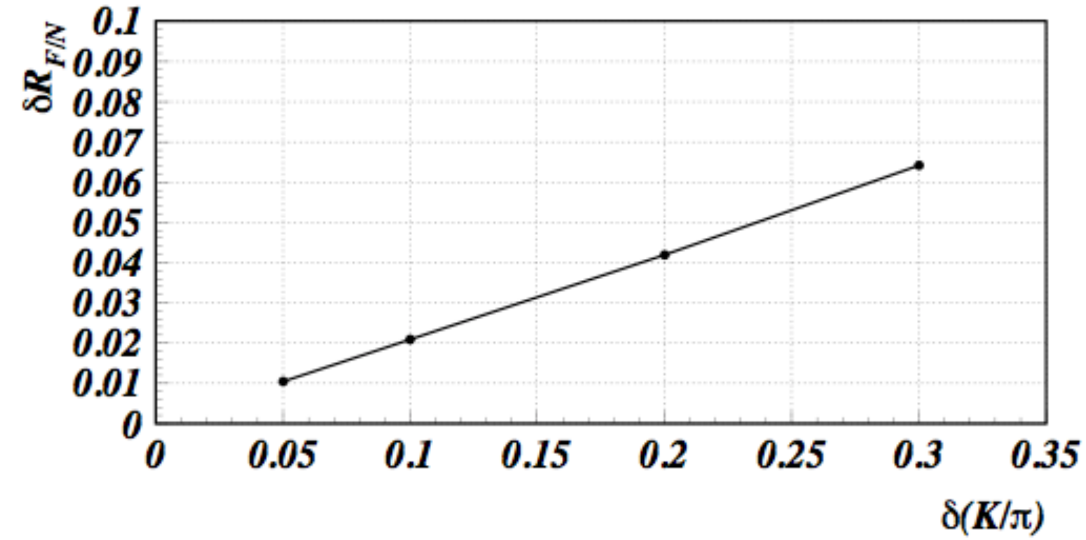
The high energy part of the ν_μ spectrum mainly comes from Kaon decay, thus we need to measure the ratio of K^+ to π^+. The required measurement accuracy has been roughly estimated varying the ratio by 10% and looking at the relative difference in the F/N ratio as a function of energy:

Off-axis ND



SK





From this study, a **10% accuracy on the K/π ratio leads to an uncertainty on the F/N ratio of 2%**. The K/π ratio has to be measured with such an accuracy in the phase space region of T2K that contains the parent Kaons that generate neutrinos in the acceptance of the near and far detectors:

$1 < p\ [\mathrm{GeV}/c] < 20$ and $0 < \vartheta\ [\mathrm{mrad}] < 300$

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NA61 Measurements

Request to NA61 - A.Marchionni, convener of the T2K Beam WG, Jan.09, T2K coll.

❑ The goal is to come up with a ν flux prediction based on experimental measurements

- to be compared with the ν energy distributions measured in ND280
- to be used in the prediction of the $R_{F/N}$

❑ We feel important at this time to have a new look at T2K requirements on hadron production and come up with an updated short document summarizing the T2K requests to NA61

❑ The document will specify:

- Suitable acceptance region to cover full pion and kaon production region giving neutrinos in T2K
- Binning size in (p, θ) plane and necessary statistics
- Definition of targets to be used for the measurements (thin, T2K replica target, intermediate length,...)
- Data format of the measurements (cross sections, raw pion and kaon yields, pion and kaon yields corrected for efficiencies and acceptance,...)
- T2K priorities and desired time frame for data taking and analysis results. In particular will address:
  - Analysis of the NA61 2007 data
  - Definition of NA61 2009 data taking

NA61 Data

2007 Data: 2C (thin) target

Total number of events: 671267
Total number of primary tracks: 1801048

Event quality cuts:

Total number of events after BPD cut: 620601 (92.452184 %)
Total number of events after Vtx cut1: 377651 (56.259432 %) (60.852464 %)
Total number of events after Vtx cut2: 339277 (50.542780 %) (89.838766 %)
Total number of events after Vtx cut3: 292897 (43.633457 %) (86.329754 %)
Number of primary tracks after BPD cut: 1686474 (93.638482 %)
Number of primary tracks after Vtx cut1: 1393683 (77.381780 %) (82.638867 %)
Number of primary tracks after Vtx cut2: 1351003 (75.012049 %) (96.937611 %)
Number of primary tracks after Vtx cut3: 1260161 (69.968207 %) (93.275959 %)

Track quality cuts:

Number of primary tracks after Vtp cut: 1030577 (57.220962 %) (81.781376 %)
Number of primary tracks after Nratio cut: 1017195 (56.477951 %) (98.701504 %)
Number of primary tracks after Bxy cut: 920815 (51.126622 %) (90.524924 %)
Number of primary tracks after Nmax cut: 903557 (50.168402 %) (98.125791 %)
Number of primary (+) tracks after all cuts: 573598 (63.482215 %)
Number of primary (-) tracks after all cuts: 329959 (36.517785 %)
Number of primary tracks in ToF: 193358 (10.735860 %) (21.399646 %)
Number of primary (+) tracks in ToF: 134672 (69.649045 %)
Number of primary (-) tracks in ToF: 58686 (30.350955 %)

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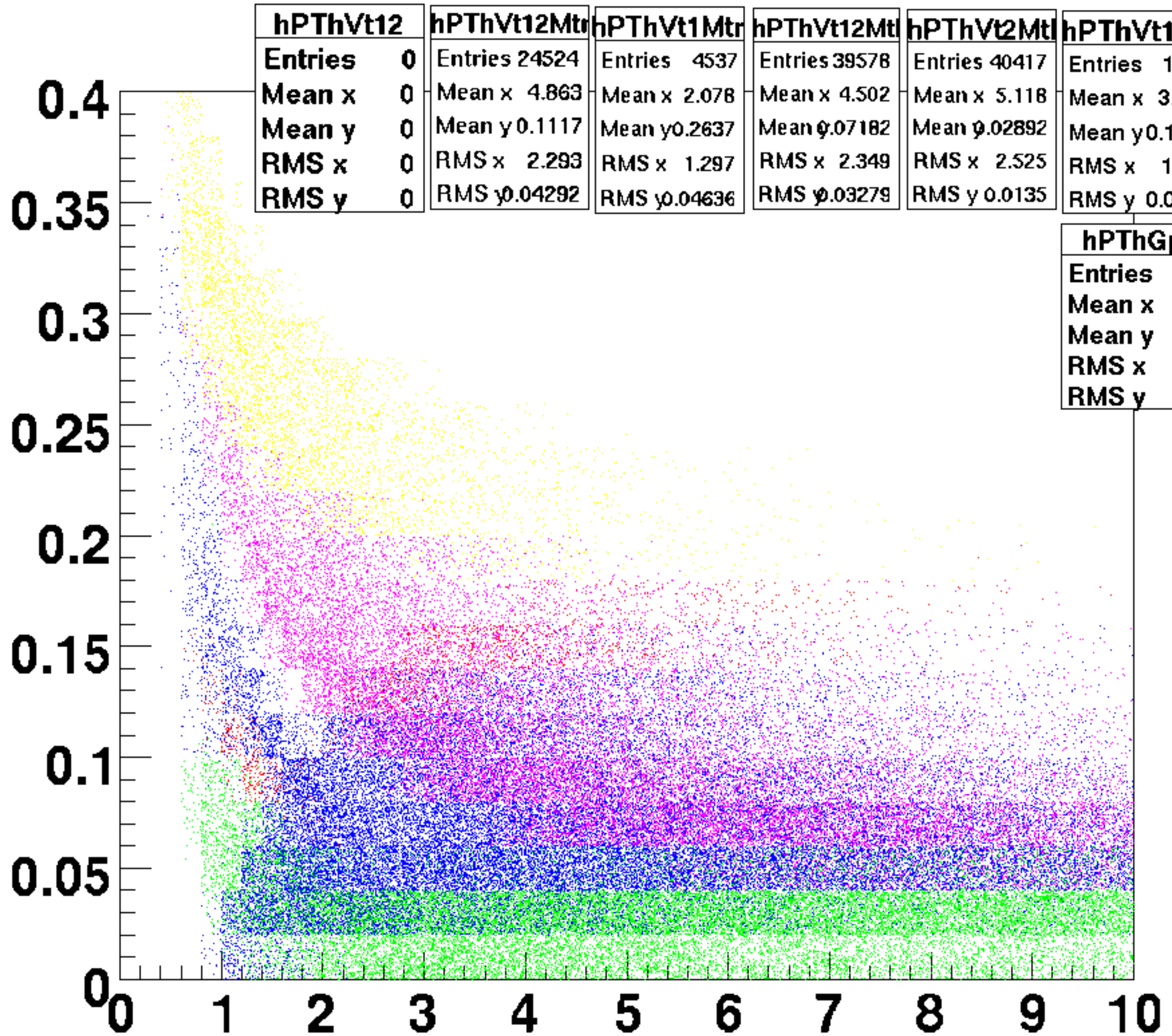
NA61 Data

2007 Data: 2C (thin) target



Production 07A
Includes forward-ToF wall
Does not include GAP TPC

Positive tracks in ToF: 133901 tracks
For those track topologies: 110669 tracks

Covering T2K relevant phase space but large hole due to geometrical acceptance.

This hole can be populated by tracks leaving hits in the side-ToF walls and tracks passing only through VTPCs before reaching the forward-ToF.

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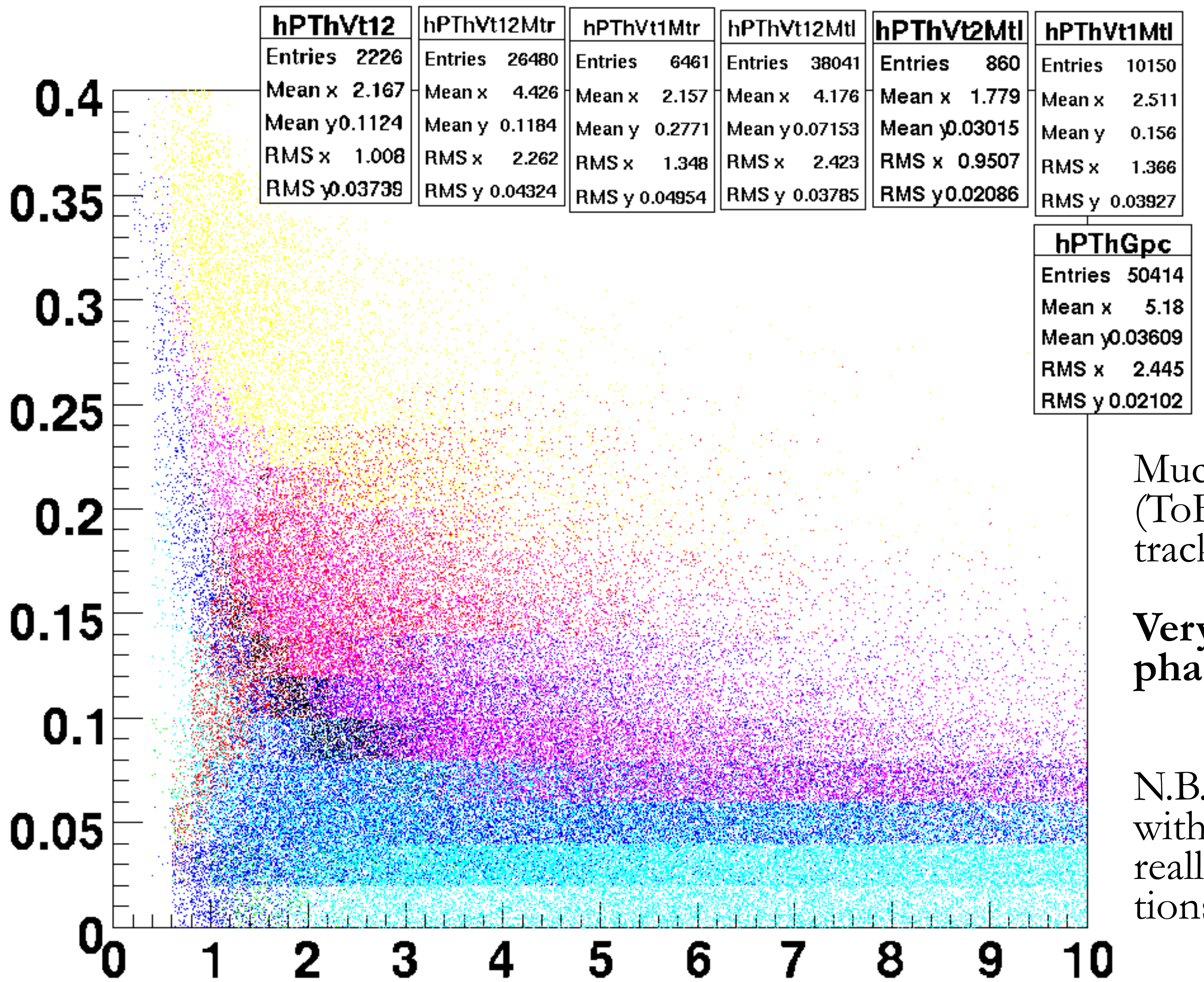
NA61 Data

2007 Data: 2C (thin) target



Production 07B
Includes (forward+side)-ToF walls
Includes GAP TPC
Includes extrapolation of VTPC tracks to the forward-ToF

Positive tracks in ToF: 134672 tracks
For those track topologies: 134632 tracks

Much larger contribution of VT1+MTL tracks (ToF-L) and crucial contribution from VTPC tracks.

Very good coverage of the relevant T2K phase space !

N.B.: previous studies have to be re-estimated with this input. Binning studies for ex. should really take into account the statistical contributions of different track topologies !

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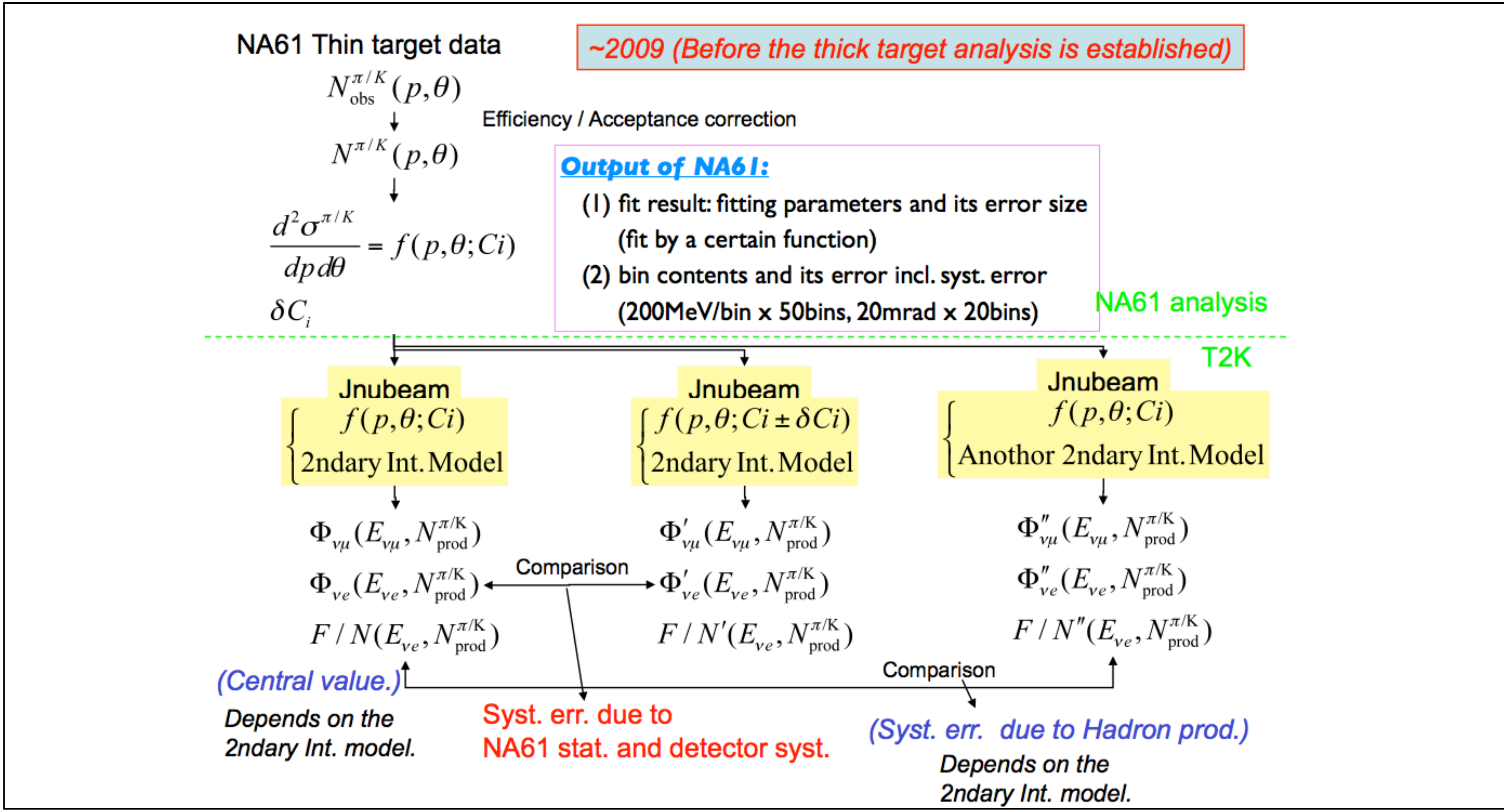
NA61 Data and T2K Flux Prediction

Strategy A



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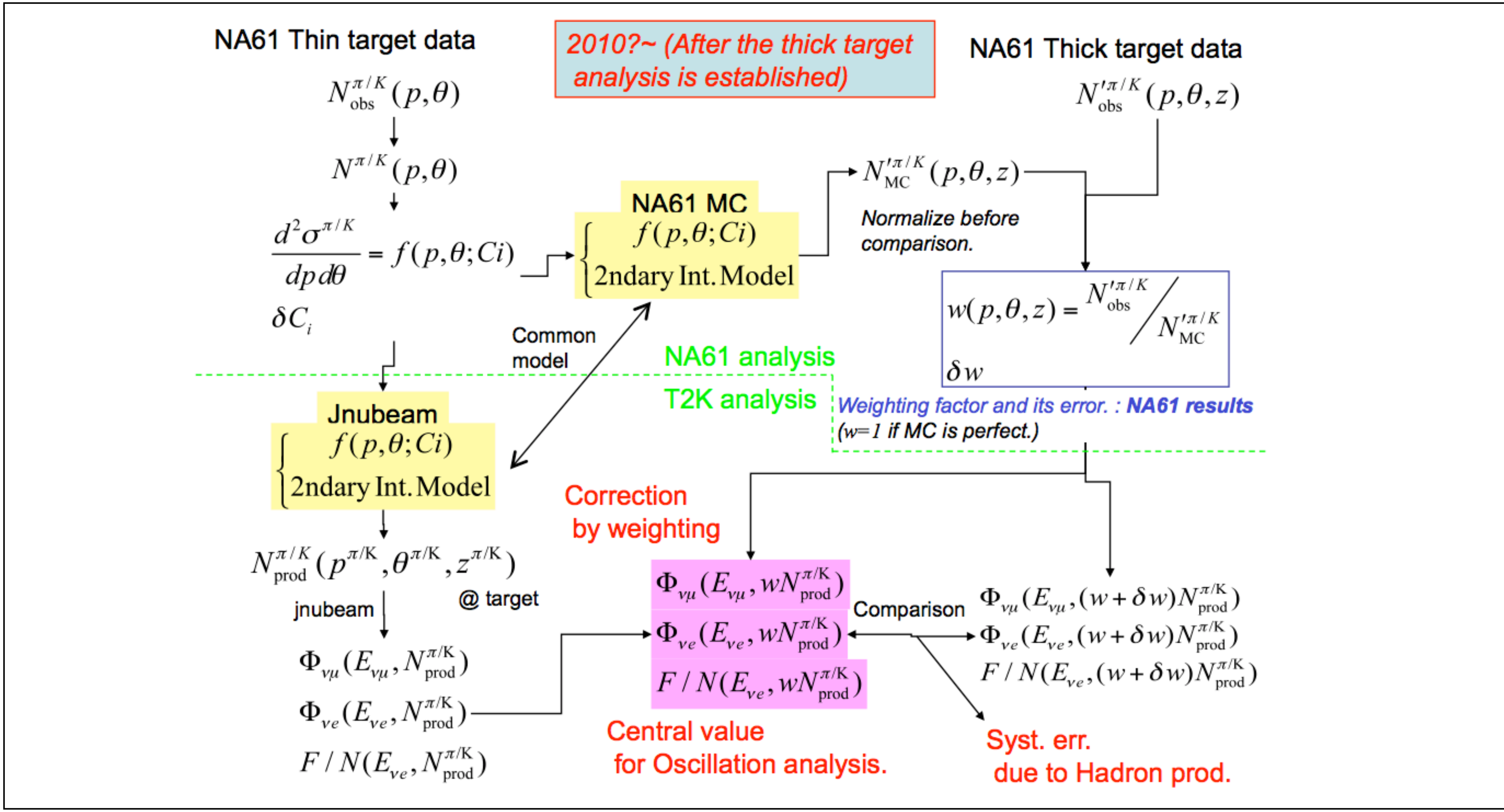
NA61 Data and T2K Flux Prediction

Strategy A



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NA61 Data and T2K Flux Prediction

Strategy B

The NA61 acceptance covers entirely the phase space of hadrons that produce the neutrinos of the T2K experiment (unlike the HARP acceptance which covered only up to 70-80% of the corresponding phase space of the K2K experiment).

Thus, in principle, we can avoid extrapolation to uncovered phase space regions (source of additional syst.) and re-weight T2K beam MC directly with NA61 data for better description of hadroproduction. This requires:
- generation of events within NA61 simulation chain using T2K beam MC event generator
- use identical hadronization model for secondary interactions in both chains

For a given bin **i** in the p-ϑ phase space and a given type **h** of hadron, we consider the ratio (re-weighting factor):

$$R_{hi} = \frac{N_{POT}^{MC}}{N_{POT}^{NA61}} \times \frac{N_{hi}^{NA61}}{N_{hi}^{MC}}$$

NA61 MC

The total neutrino flux in a given energy bin **j** coming from the type of hadron **h** is a sum from contributions from all the p-ϑ bins to this particular energy bin $N_{hi,j}^{MC}$:

$$\Phi_j(E_\nu) = \frac{1}{N_{POT}^{MC}} \sum_{h,i} N_{hi,j}^{MC} \times N_{hi}^{MC}$$

T2K Beam MC (Jnubeam)

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NA61 Data and T2K Flux Prediction

Strategy B

The corrected flux in neutrino energy bin **j** is then corrected by the NA61 re-weighting factor:

$$\Phi_j(E_\nu) = \frac{1}{N_{POT}^{MC}} \sum_{h,i} N_{hi,j}^{MC} \times N_{hi}^{MC} \times R_{hi}$$

The integrated corrected flux is obtained by summing over **j** as well.

This approach allows the estimation of the neutrino flux statistical and systematic errors related to the NA61 measurements in a simple way. Neglecting the MC statistical error (in a first step), the statistical error on the flux due to the NA61 statistics is propagated via the re-weighting factor:

$$\frac{\Delta R_{hi}}{R_{hi}} = \frac{\Delta N_{hi}^{NA61}}{N_{hi}^{NA61}} = \frac{1}{\sqrt{N_{hi}^{NA61}}} \quad \text{or} \quad \Delta^2 R_{hi} = \frac{R_{hi}^2}{N_{hi}^{NA61}}$$

Thus: $$\Delta^2 \Phi_j(E_\nu) = \frac{1}{(N_{POT}^{MC})^2} \sum_{hi} (N_{hi,j}^{MC} \times N_{hi}^{MC})^2 \times \frac{R_{hi}^2}{N_{hi}^{NA61}}$$

The neutrino spectrum mean energy coming from hadron of type h is then given by:

$$< E_\nu >_h = \frac{\sum_j \Phi_j(E_\nu) \times E_{\nu j}}{\sum_j \Phi_j(E_\nu)} = \frac{\sum_{ij} N_{hi,j}^{MC} \times N_{hi}^{MC} \times R_{hi} \times E_{\nu j}}{\sum_{ij} N_{hi,j}^{MC} \times N_{hi}^{MC} \times R_{hi}} \rightarrow \begin{cases} \Delta^2 < E_\nu >_h \\ \sigma_h^2(E_\nu) = < E_\nu >_h^2 - < E_\nu^2 >_h \end{cases}$$

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NA61 Data and T2K Flux Prediction

Strategy B

Systematics errors can be estimated by varying corresponding parameters (if any) in the MC and computing the relative change in the re-weighting factors.
Those variations are then propagated to the neutrino flux predicition described above to estimate the final systematics related to NA61 measurements.

This re-weighting method can be used for both targets if the same target type (thin or replica) is used in both sim. chains.
For the thin target, this method will be use for ex., to give a first estimate of NA61 statistical impact on the neutrino flux prediction.

NA61 Data and T2K Flux Prediction

Conclusion

- Requirements on NA61 measurements have been estimated up to 2 years ago !
- An update of these requirements has been recommended by the T2K beam WG and a new document should be submitted soon.
- NA61 successfully took data for a thin Carbon target and T2K replica target in 2007. Those data, though limited in statistics are of very good quality !
- Strategies are proposed to implement NA61 data into the T2K beam MC for better neutrino flux prediction and work is in progress in this direction in parallel to the NA61 data analysis.

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