NA61-SHINE hadron production results for T2K

N. Abgrall[a]
For the NA61 collaboration

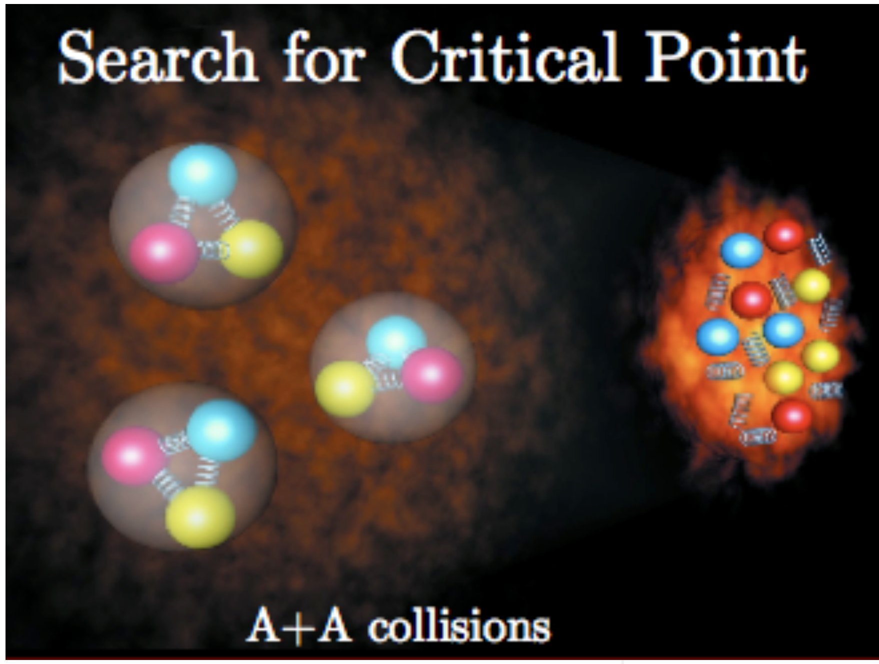
- NA61-SHINE setup and measurements
- Thin target preliminary results and progress
- T2K replica target: motivations and first results
- Using NA61 data for T2K neutrino flux predictions

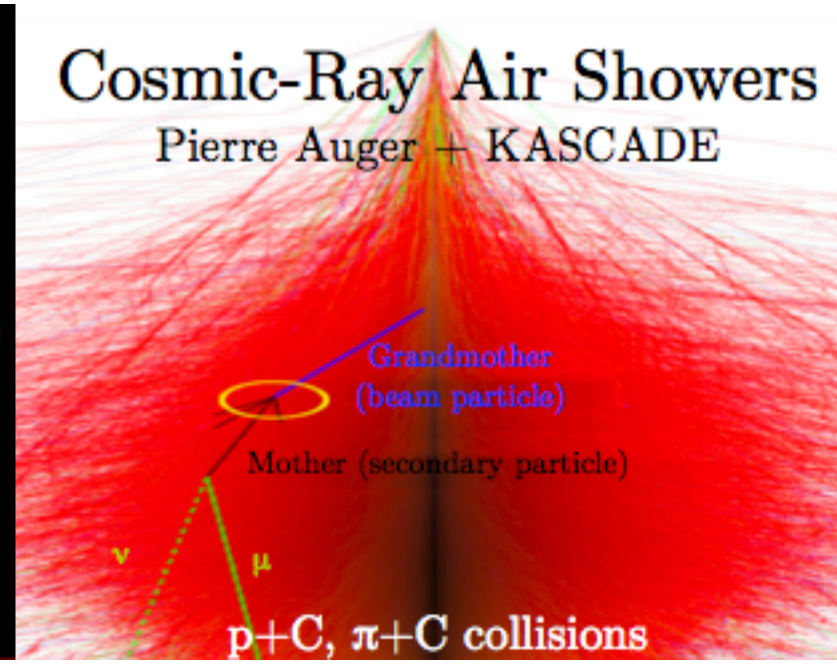
[a] University of Geneva

NA61-SHINE scientific program

SPS Heavy Ions and Neutrino Experiment

- Very broad scientific program !

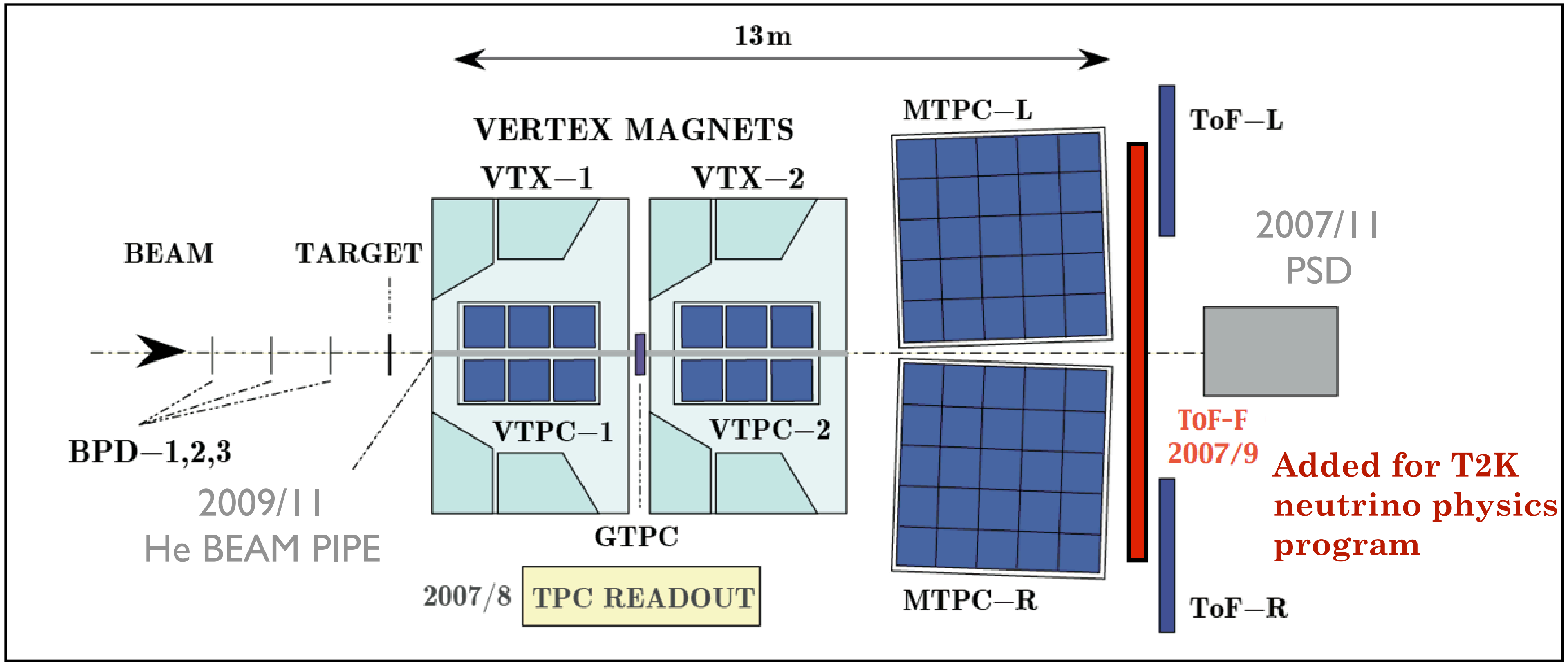




Originally approved at CERN in 2007.
Scientific program is now approved until 2014.

Collaboration of:
125 scientists
24 institutes
13 countries

NA61-SHINE setup



Large acceptance spectrometer:

- 5 TPCs:
  2 dipole magnets with high momentum resolution
- 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, 1.84 g/cm^3, 4% λ_{int})
  - 670k triggers in 2007
  - Set of data used to produce preliminary pion spectra.

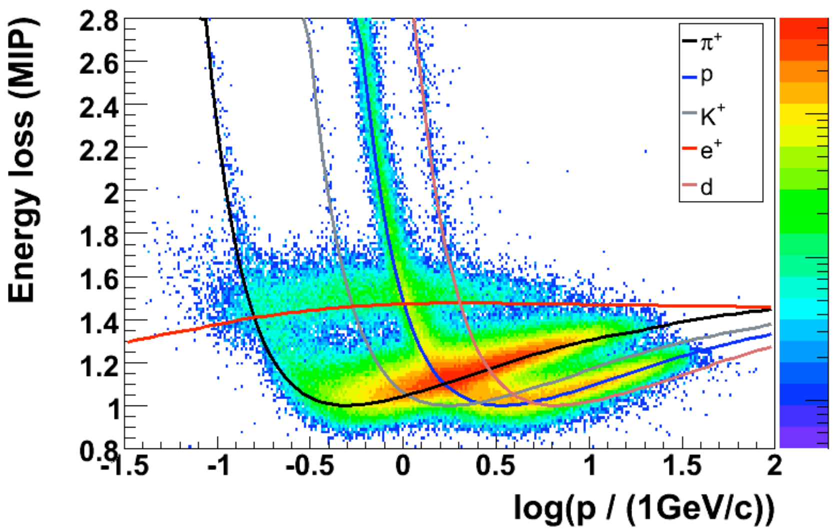
- T2K replica Carbon target (90 cm, 2.6 cm ∅, 1.83 g/cm^3,1.9 λ_{int})
  - 230k triggers in 2007
  - Data under first analysis loop.

- **2009 data under calibration**

NA61 data quality

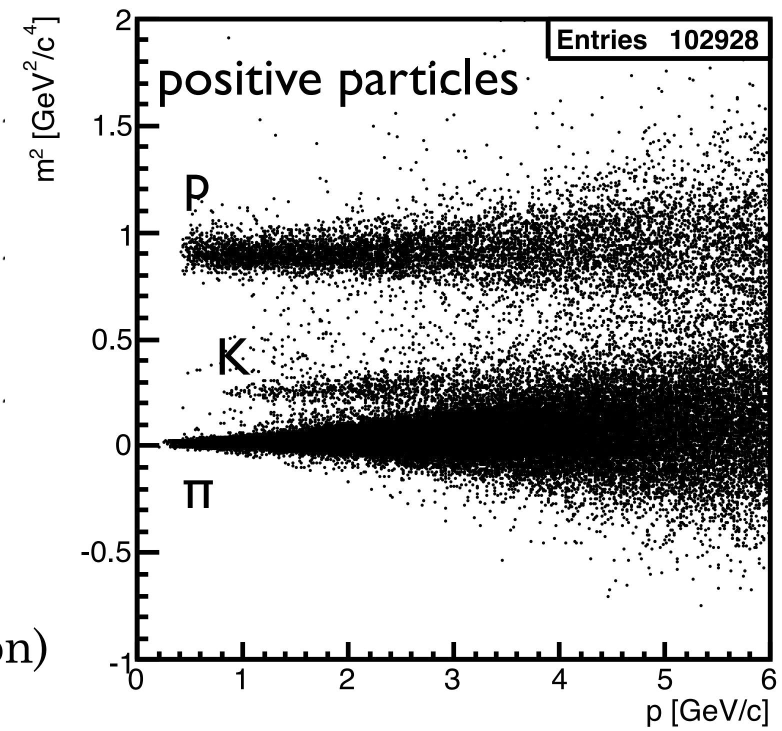
- NA61 allows for PID over a large range of momentum

Positive particles dEdx measurements



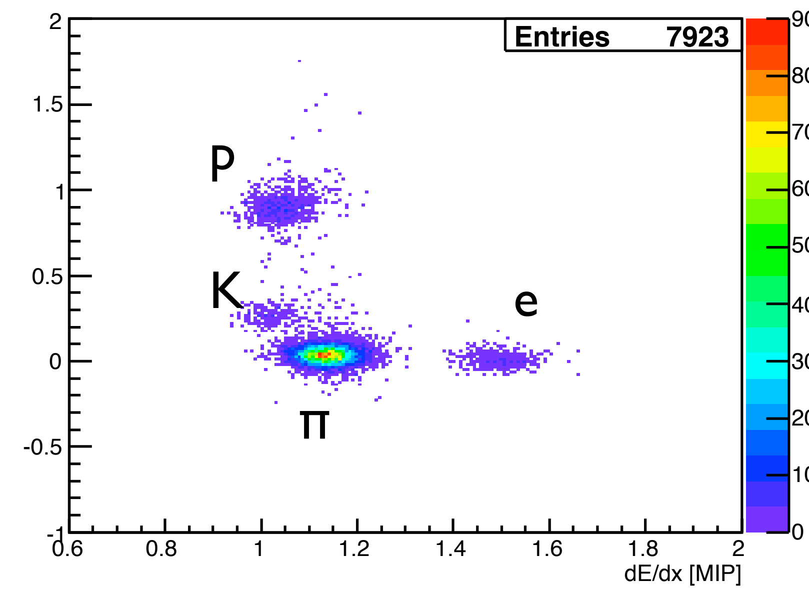
- below 1 GeV/c
- above 4 GeV/c (relativistic rise region)

ToF measurements (m2 vs p)



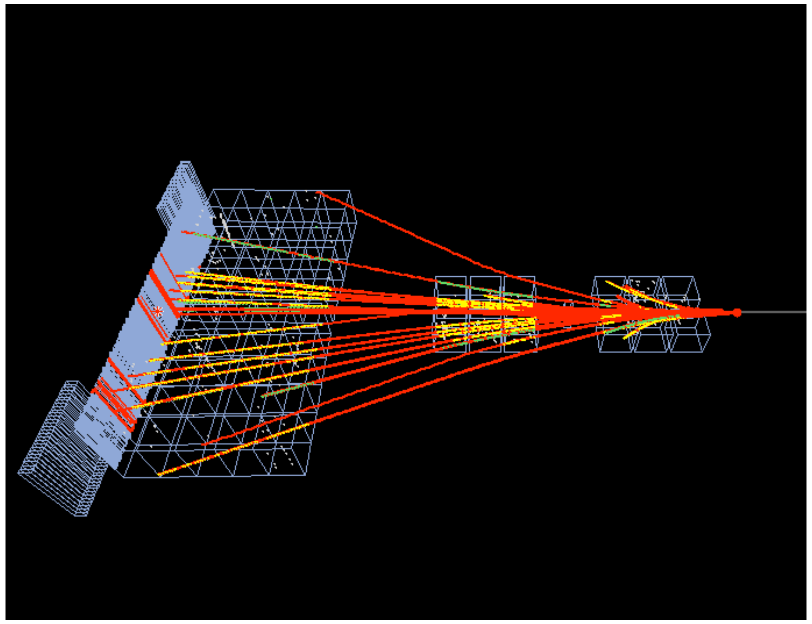
between 1 and 6 GeV/c

Combined ToF/dEdx measurements

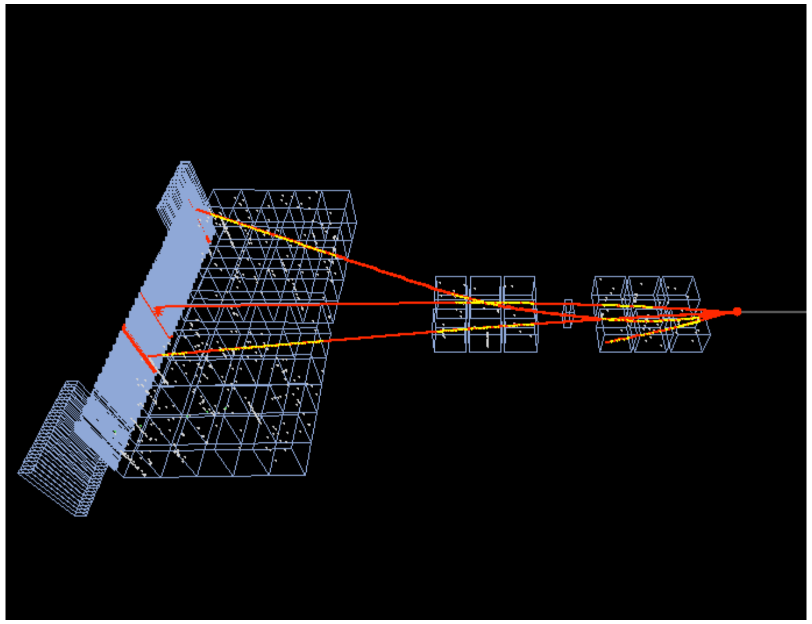


NA61 data quality

- High quality of data reconstruction



$\pi^- + C$, 350 GeV/c

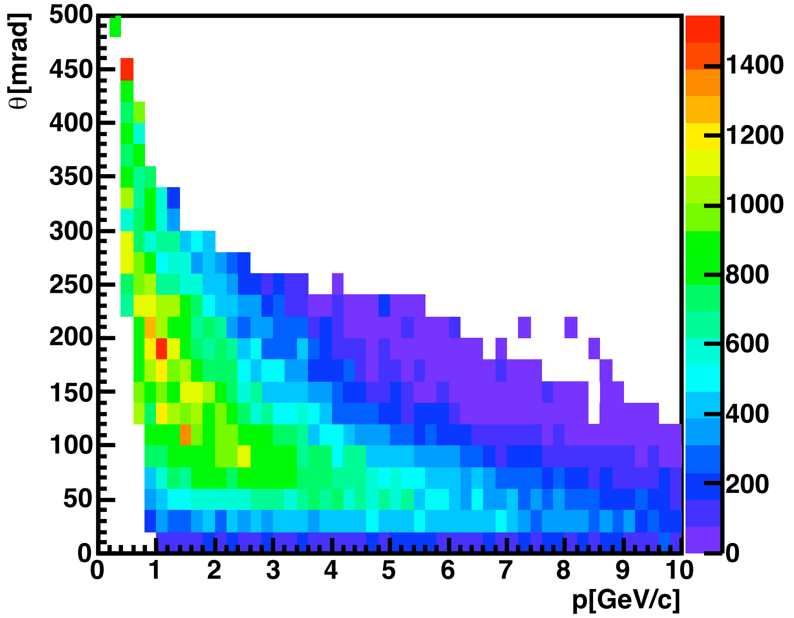


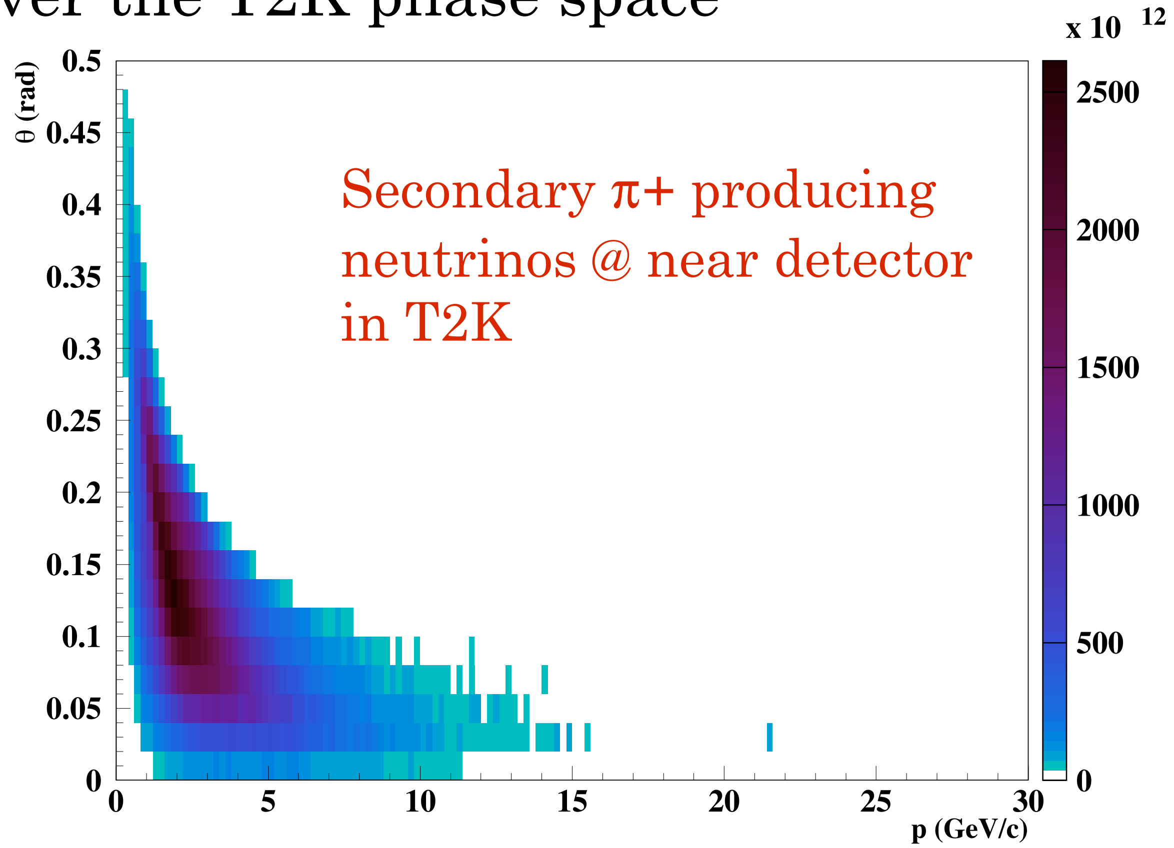
p + C (LT) , 31 GeV/c

- NA61 data covers the region of interest over the T2K phase space

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

NA61





Thin target results

Analyzed p-C data @ 31 GeV/c from 2007 pilot run:

- determination of absolute inelastic cross-section
- π^- up to 15 GeV/c in angular bins of 60 mrad
- π^+ up to 10 GeV/c in angular bins of 60 mrad

20% systematic errors

(Current binning suggested by T2K : 200 MeV/c x 20 mrad (p, ϑ) bins. A coarser binning might be required for the publication of the 2007 data.)

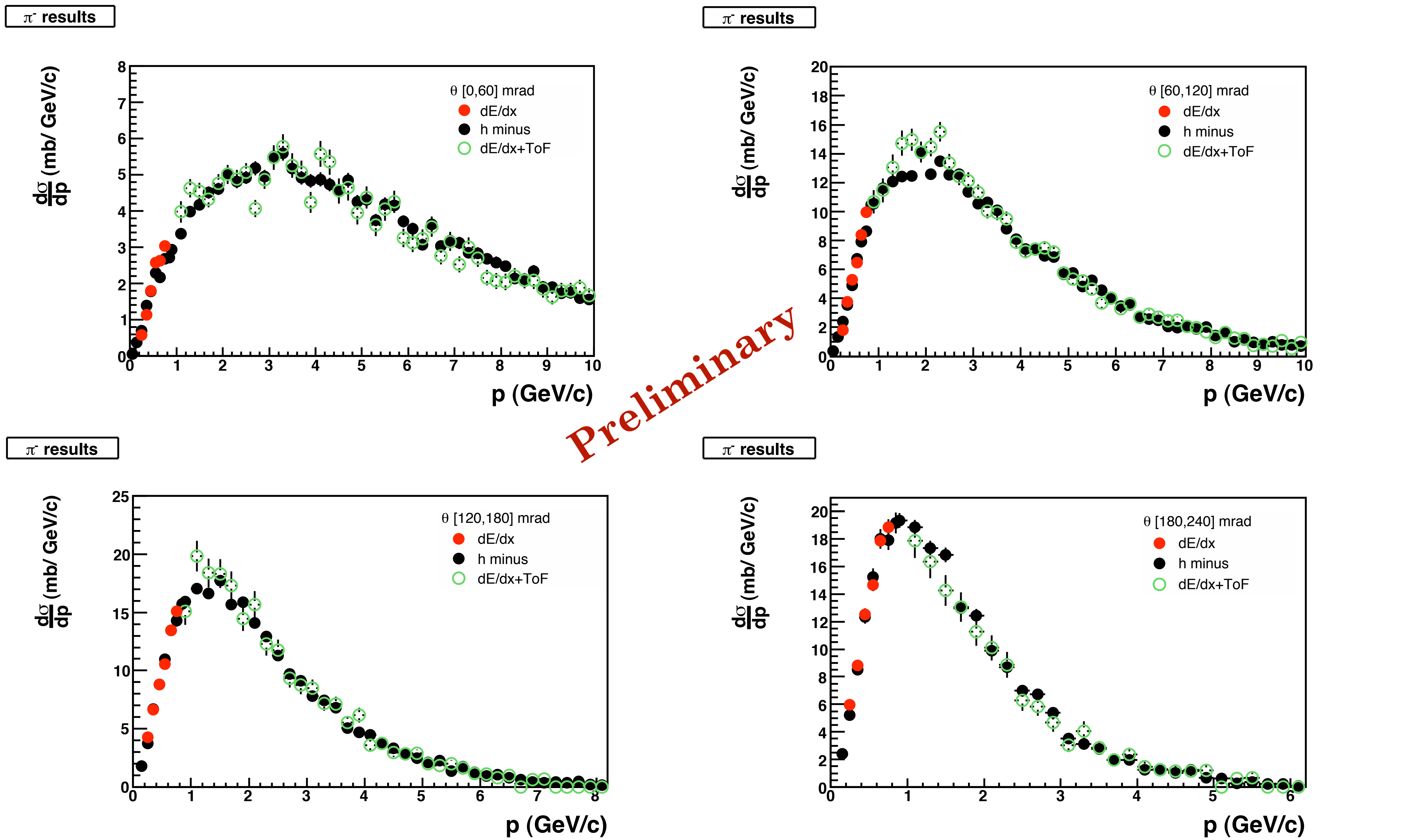
- preliminary comparisons with different models: GiBUU, Geant4, VENUS, GFLUKA and FLUKA-standalone
- no measurements of re-interactions yet: need to analyze long target data.

Those preliminary results have already been shown at international conferences and are currently being used by the T2K beam Monte-Carlo group.

Work on paper preparation started.

Thin target: π^- results

Differential cross-sections in different bins of ϑ (angle at production point):

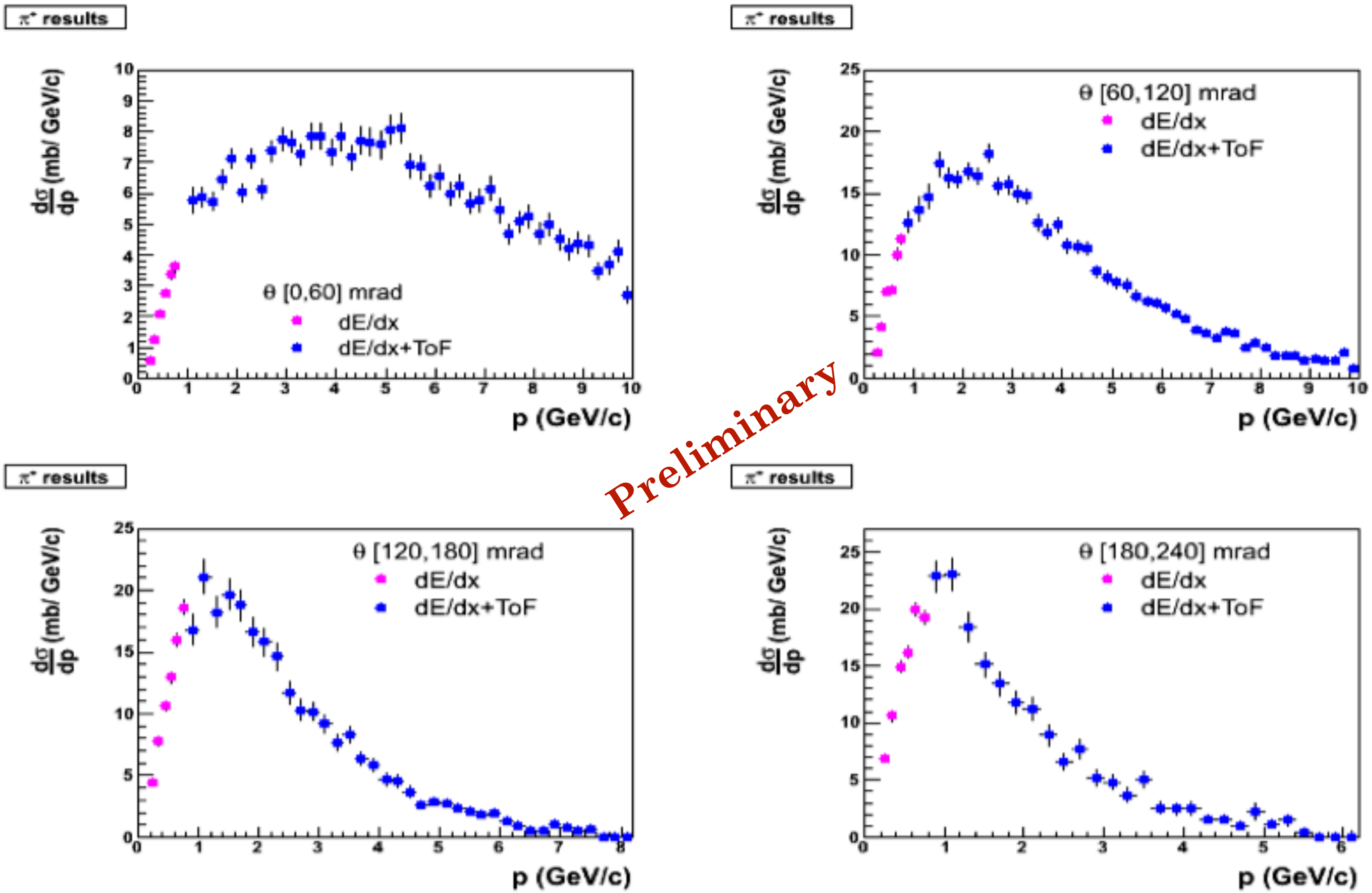


Different analysis procedures have been developed:

- 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.

Thin target: π^+ results



2 different analysis procedures:

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

Continuity observed between the 2 analyses. Only statistical errors are shown here. Work is in progress to lower the current systematics.

Preliminary model comparisons

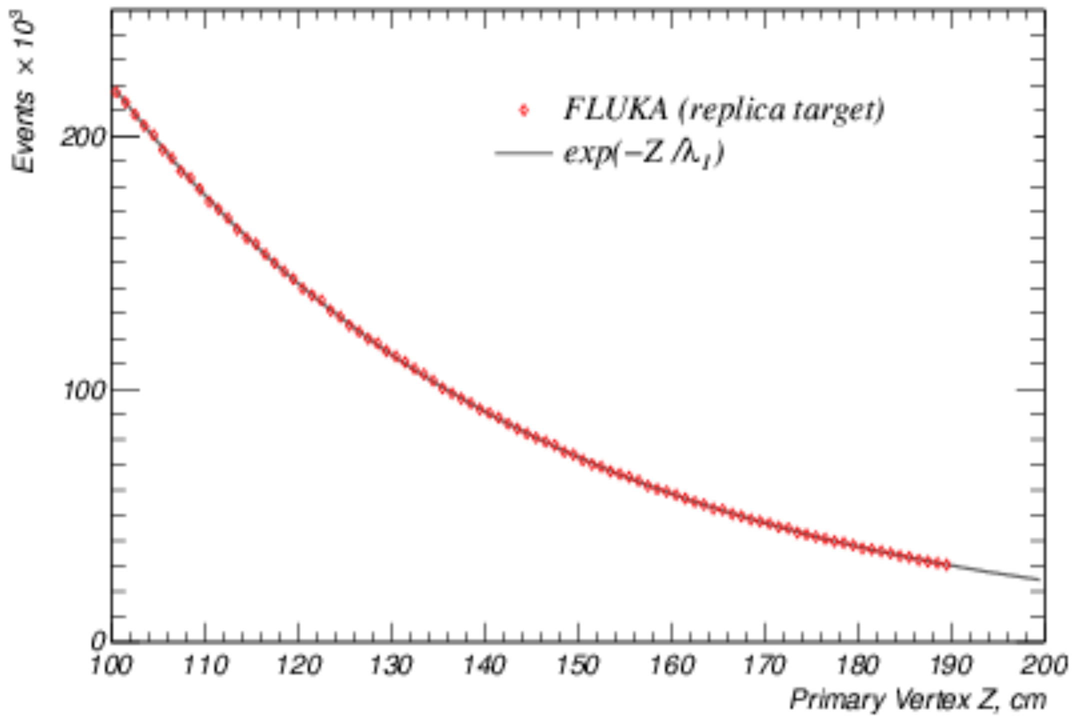
Preliminary

σ_{abs} and λ_{abs} in T2K Replica target

NA61 σ_{inel} = 254.7 ± 0.1 (stat)

σ_{abs} can be measured from:

1. fit the Z coordinate of the primary vertex (inelastic events)



- from fit $\lambda_{abs} = 45.32 \pm 0.03$ cm
- constants:
  replica density $\rho = 1.83$ g/cm^3
  $A = 12.011$ g/mol
  $N_A = 6.022 \cdot 10^{23}$ mol^{-1}
- then, cross section

  $$\sigma_{abs} = \frac{A}{\rho\,\lambda_{abs}\,N_A} = 240.51 \pm 0.16 \text{ mbarn}$$

  (to be compared with 243.6 mbarn reported by Claudia for Geant 4 and 249.7 mbarn by Sakashita-san for GFLUKA)

updated recently **244.6 mbarn**

2. the absolute number of the inelastic events N_{inel}

$$\lambda_{abs} = \frac{-L}{\ln(1 - N_{inel}/N_0)} = 45.41 \text{ cm}; \qquad \sigma_{abs} = 239.99 \text{ mbarn}$$

where $L = 90$ cm is replica length; $N_{inel} = 8.62 \cdot 10^6$ - inelastic interactions for $N_0 = 10^7$ p.o.t.

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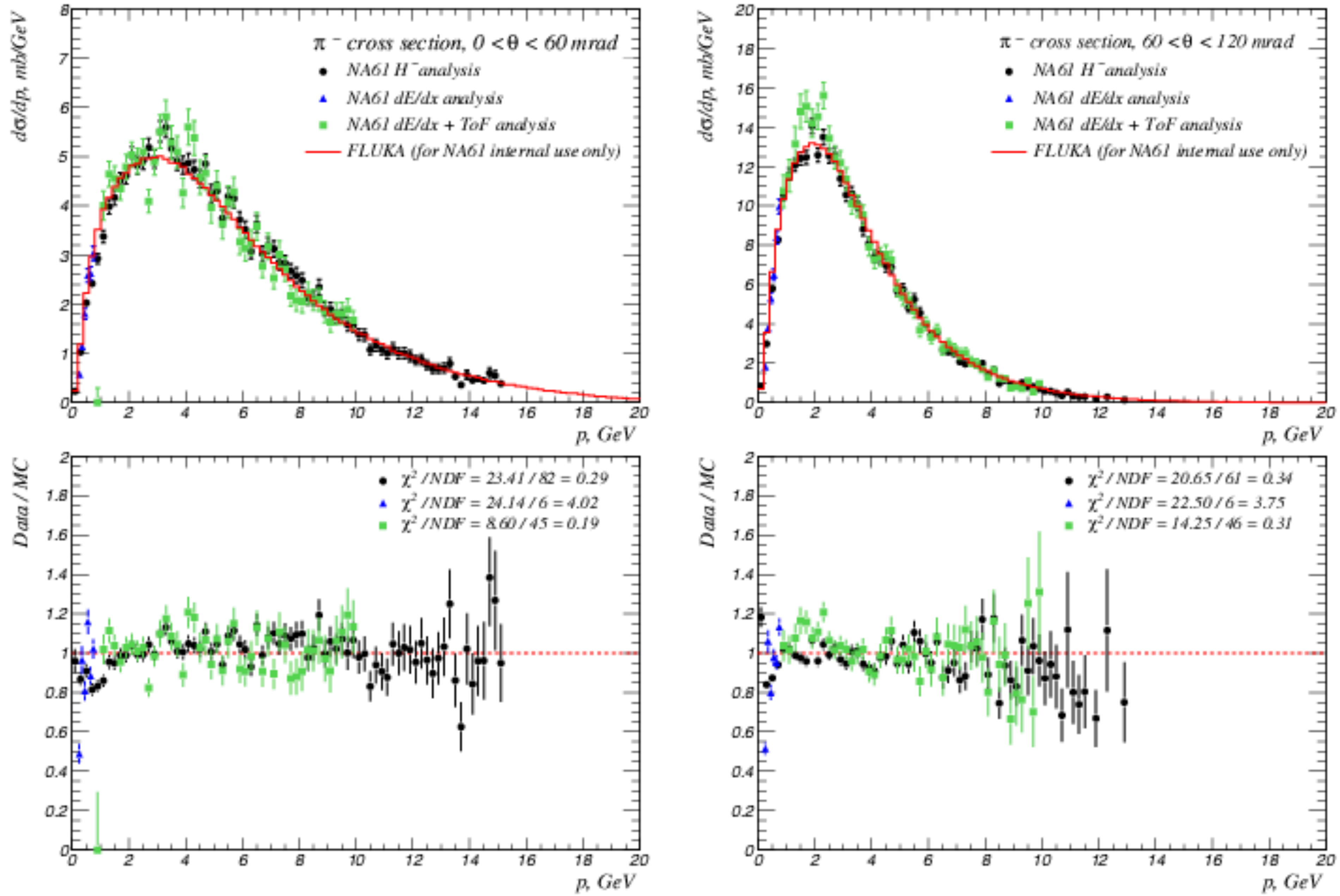
Preliminary model comparisons

π^- cross section & FLUKA predictions

For internal use only



Preliminary model comparisons

π^+ cross section & FLUKA predictions

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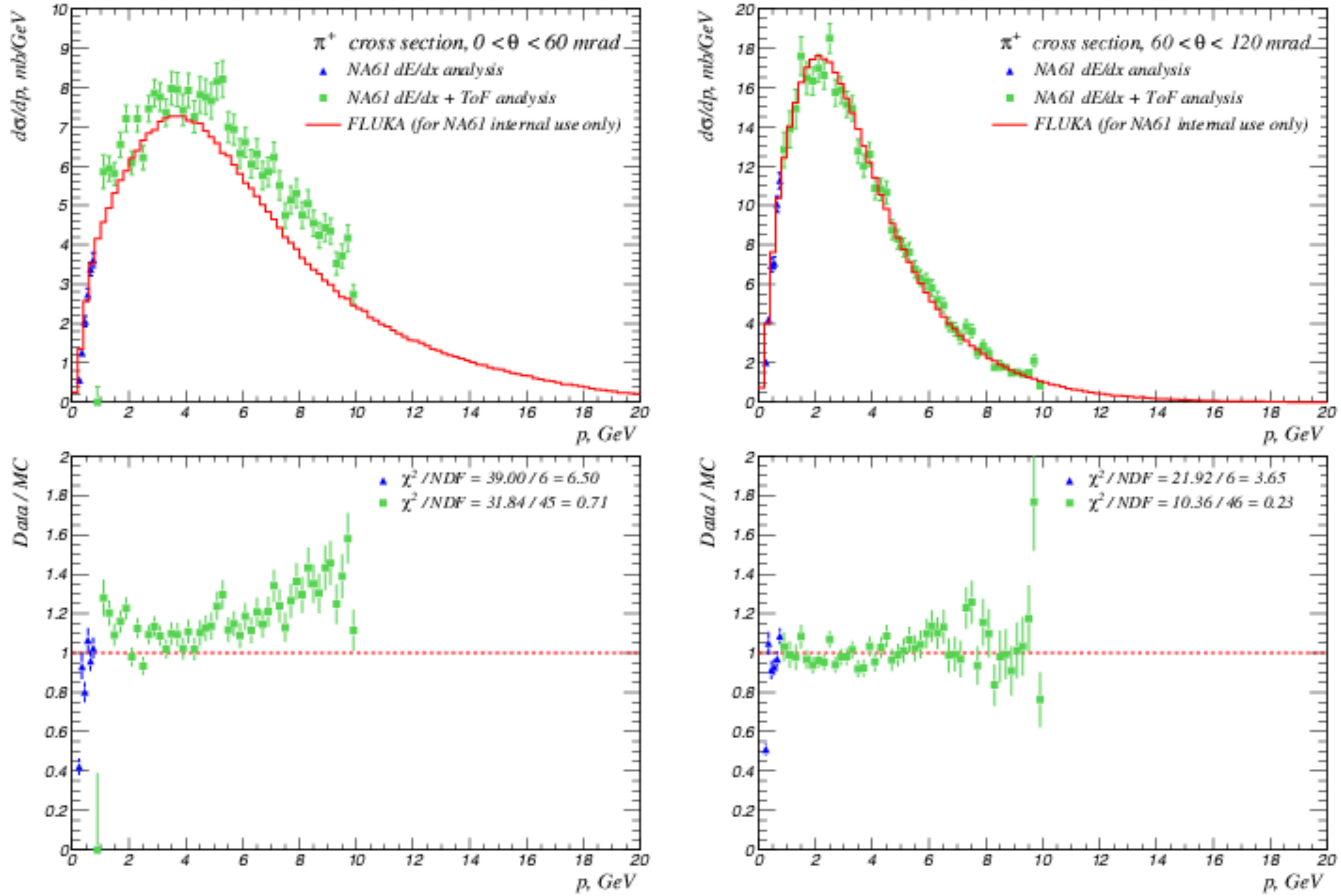


Thin target: work in progress

- improve systematic errors in pion measurements: refine analysis procedures and perform additional cross-checks
- comparison of results between different data productions (e.g. w/ or w/o gap TPC)
- fixed deficiencies in the error propagation and track fitting procedure
- good progressing on improving resolution of the ToF PiD
- started dE/dx analysis in the relativistic rise region
- more careful look into the 0-20 mrad region
- extension of the pion analysis to higher momenta (up to 20 GeV/c)
- proceed with kaon analysis (not enough statistics in 200 MeV/c bins in momentum)

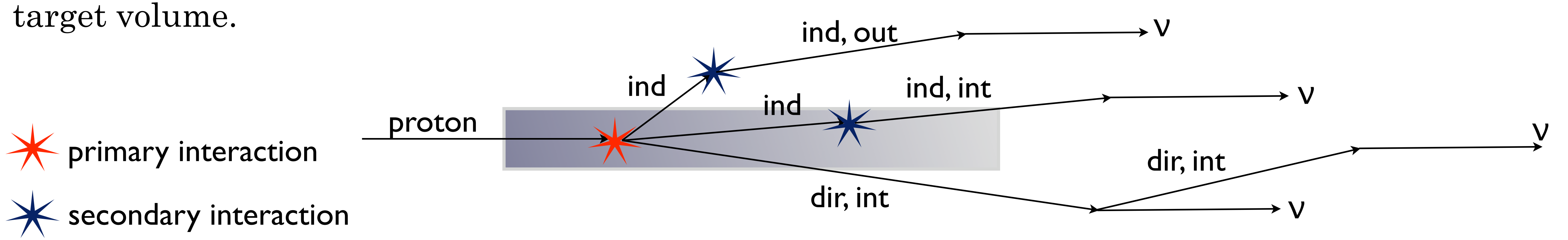
T2K replica target: motivations

- Define a clear and consistent strategy for the NA61 2009-2010 data taking and analysis:
  - understand the flux predictions from different sources;
  - understand the relative contribution of hadron production measurements off a thin Carbon target and the T2K replica target (performed by the NA61 experiment at CERN SPS).
- All results from T2K-NA61 internal note 01: http://www.t2k.org/beam/NuFlux/HadronInt/note-01/view

N. Abgrall (University of Geneva), B. Popov (LPNHE, Paris/JINR, Dubna) and J.-M. Levy (LPNHE, Paris)

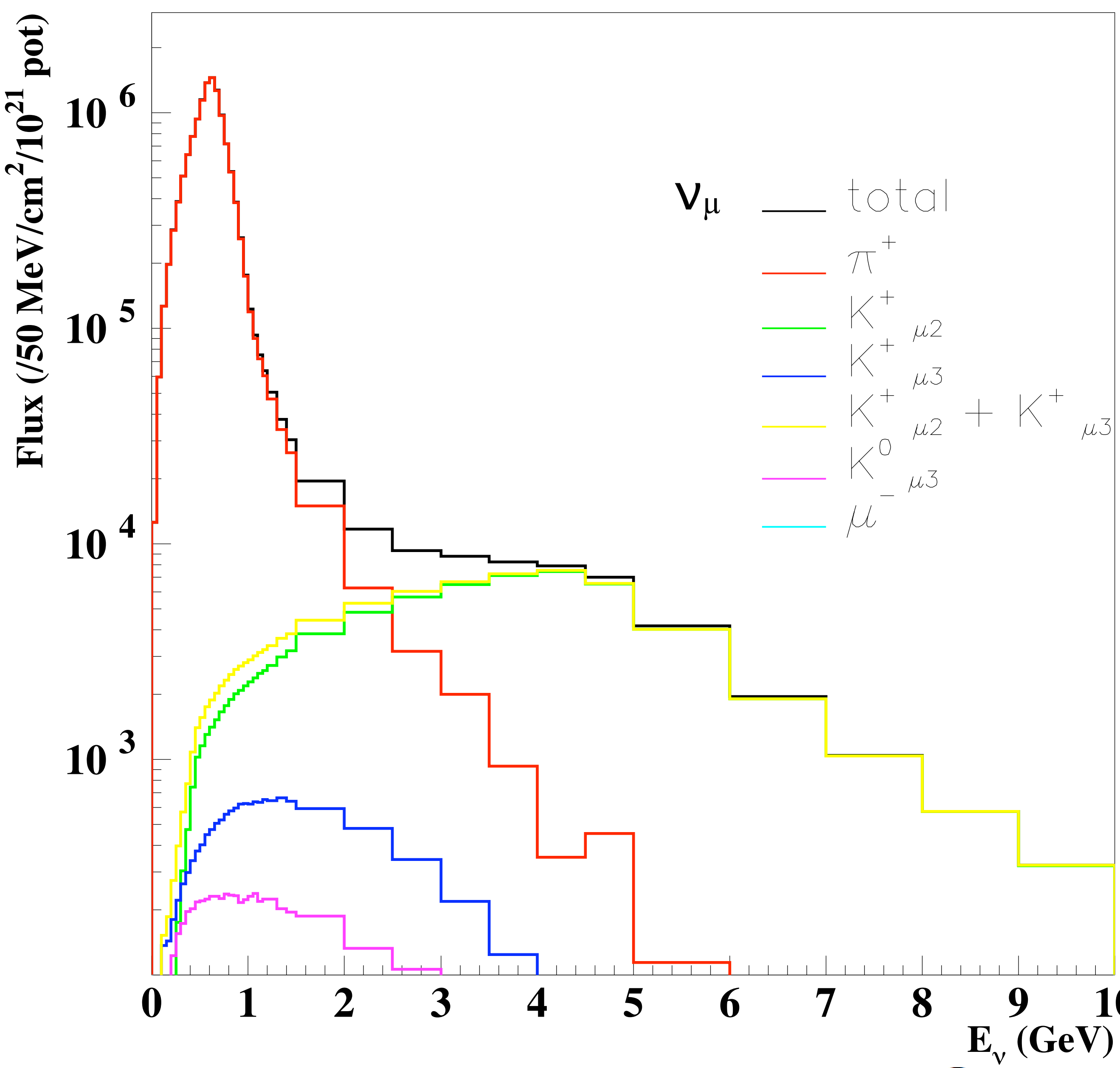
T2K replica target: motivations

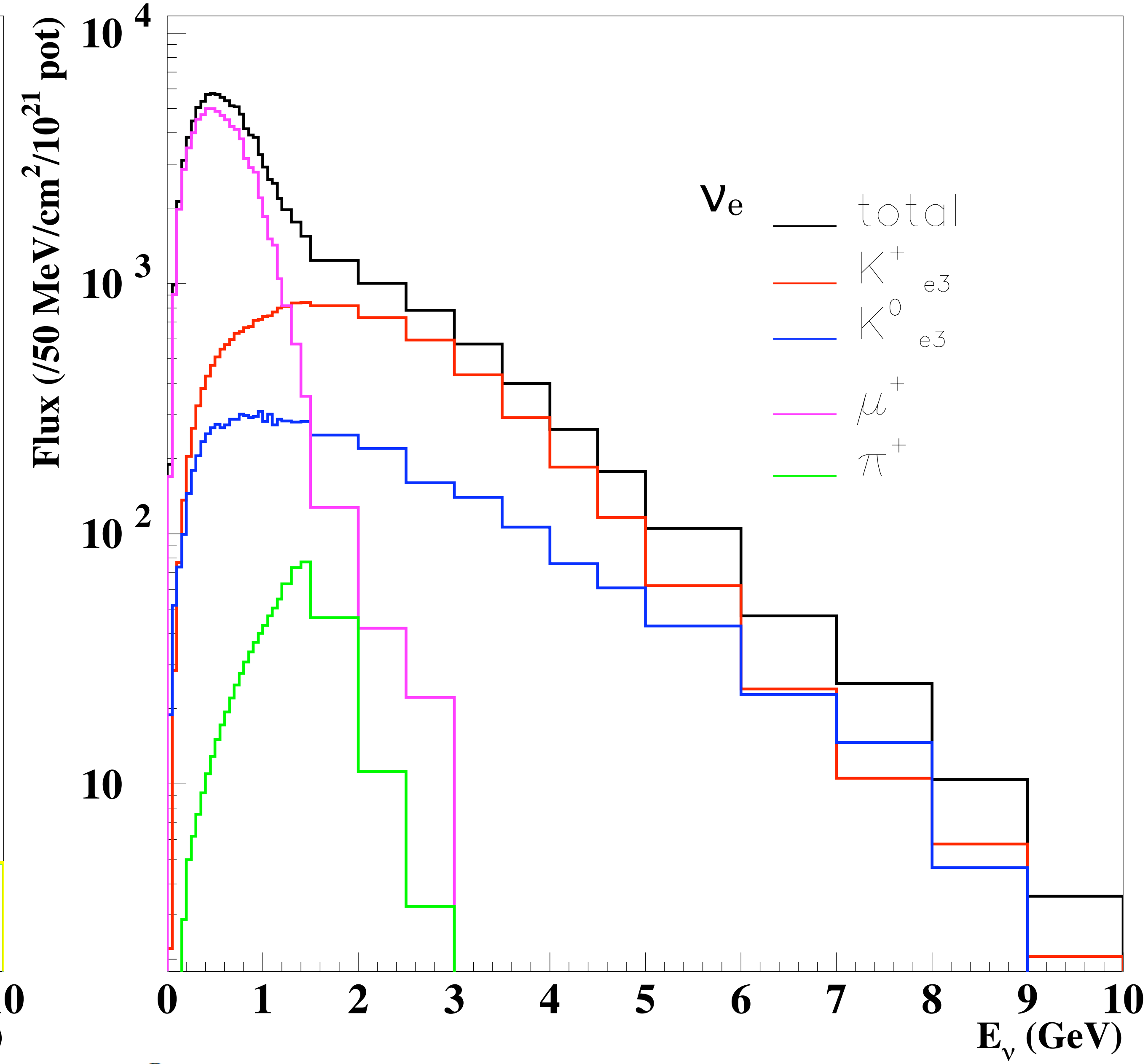
- Modified the T2K beam Monte-Carlo (JNUBEAM 10a) output format to store complete information about the neutrino history back to the primary proton interaction. This allowed us to define flux contributions in terms of the NA61 measurements:
  - direct contribution: a neutrino parent particle contributes directly to the flux if it is produced in the primary interaction (secondaries). This contribution accounts also for neutrino production from muons or any other parent particle that originate from the decay of a secondary particle or which are produced along decay chains of secondary particles. **In terms of NA61 measurements, this corresponds to the thin target measurements (only primary interaction is measured).**
  - indirect contribution: a neutrino parent particle contributes indirectly to the flux if it is of a generation higher than the first generation. This contribution accounts for re-interactions in the target and the elements of the beam line.
  - in-target contribution: accounts for neutrino parent particles produced in the target. This includes also production from muons or any other parent particle that originate from the decay of a particle produced in the target or produced along a decay chain of any ancestor produced in the target. **In terms of NA61 measurements, this corresponds to the replica target measurements (both primary and secondary interactions are measured).**
  - out-of-target contribution: accounts for neutrino parent particles that are produced outside of the target volume.



T2K replica target: motivations

- Neutrino fluxes @ far detector: parent contributions



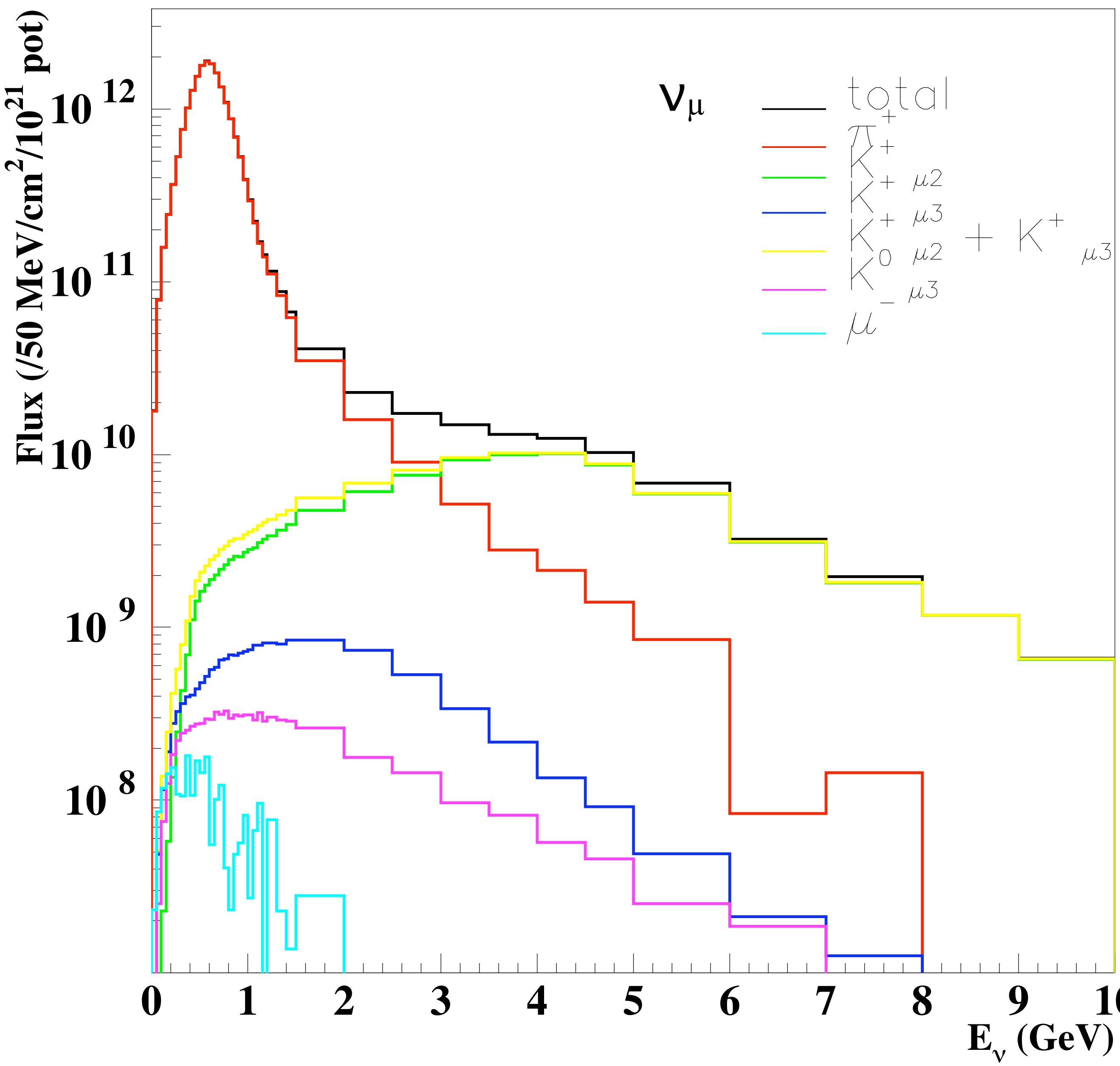


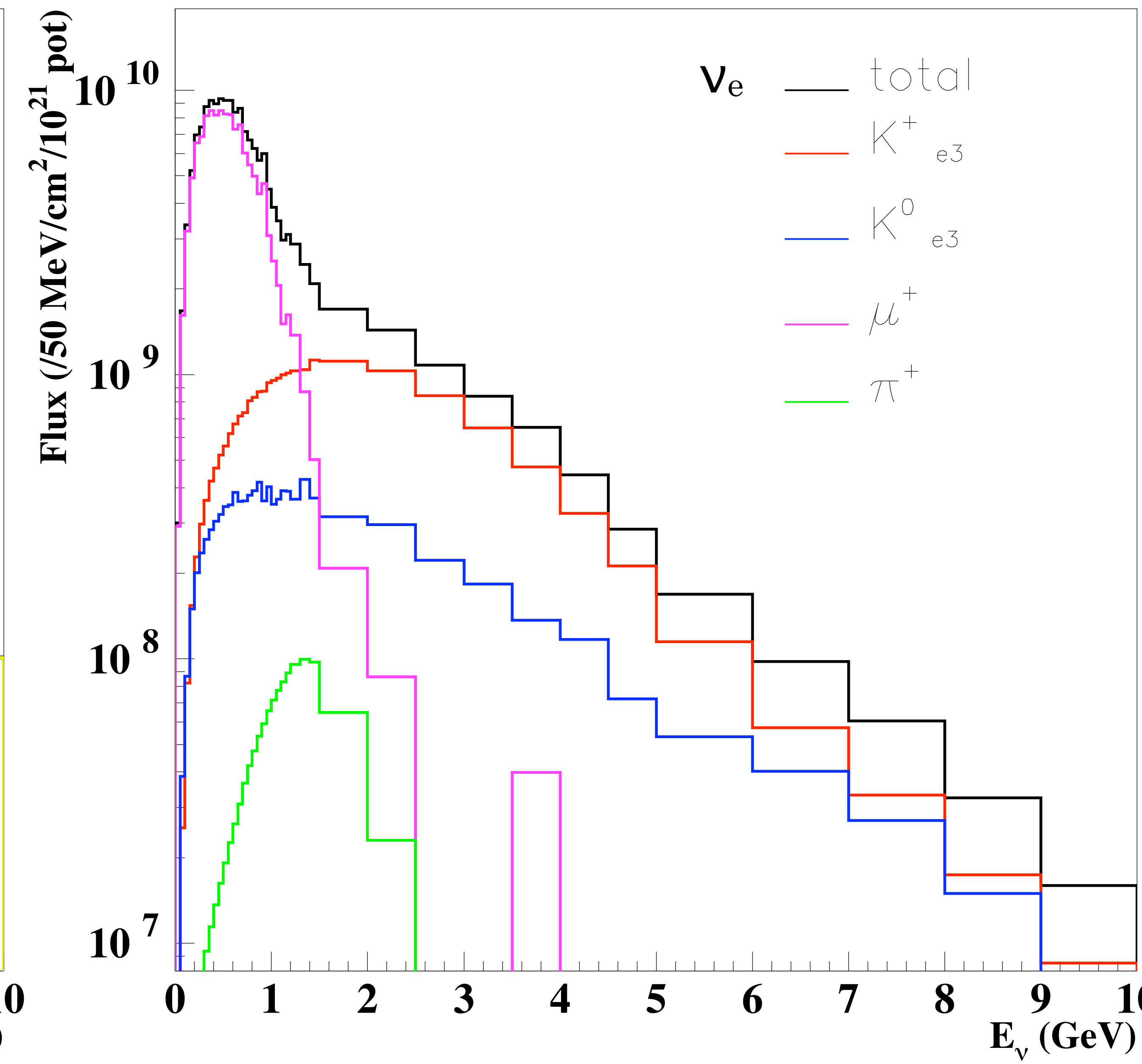
ν species	Flux Abund.	Flux $\langle E_\nu \rangle$	π^+ or π^- %	π^+ or π^- $\langle E_\nu \rangle$	K^+ or K^- (K2) %	K^+ or K^- (K2) $\langle E_\nu \rangle$	K^+ or K^- (K3) %	K^+ or K^- (K3) $\langle E_\nu \rangle$	K^0_L %	K^0_L $\langle E_\nu \rangle$	μ^+ or μ^- %	μ^+ or μ^- $\langle E_\nu \rangle$
ν_μ	1.0	0.79	95.1	0.64	4.5	4.0	0.24	1.93	0.1	2.05	0.01	0.75
$\bar{\nu}_\mu$	0.0701	1.14	85.8	1.05	4.6	3.1	0.2	1.56	1.3	2.05	8.0	0.68
ν_e	0.0110	1.40	1.0	1.48	–	–	33.0	2.25	12.5	2.38	53.3	0.64
$\bar{\nu}_e$	0.0017	2.18	0.4	2.32	–	–	14.7	1.84	77.6	2.38	7.2	0.75

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

T2K replica target: motivations

- Neutrino fluxes @ near detector: parent contributions



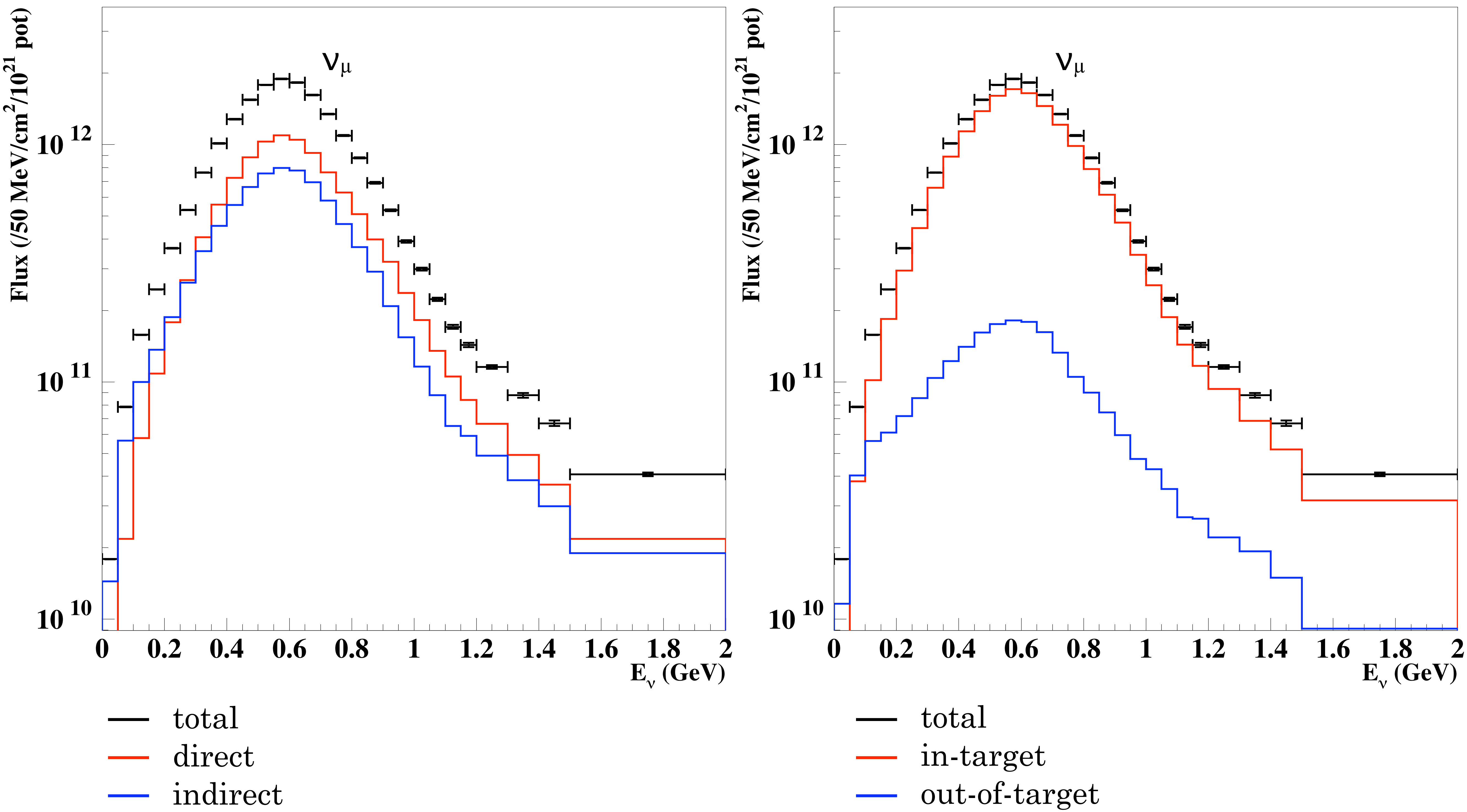


ν species	Flux Abund.	Flux $\langle E_\nu \rangle$	Source: π^+ or π^- %	$\langle E_\nu \rangle$	K^+ or K^- (K2) %	$\langle E_\nu \rangle$	K^+ or K^- (K3) %	$\langle E_\nu \rangle$	K^0_L %	$\langle E_\nu \rangle$	μ^+ or μ^- %	$\langle E_\nu \rangle$
ν_μ	1.0	0.84	95.5	0.69	4.2	4.15	0.2	2.13	0.1	2.10	< 0.01	0.80
$\bar{\nu}_\mu$	0.0692	1.19	85.8	1.13	4.0	3.21	0.2	1.70	1.2	2.12	8.8	0.66
ν_e	0.0110	1.41	1.0	1.58	–	–	30.7	2.48	11.1	2.52	57.2	0.62
$\bar{\nu}_e$	0.0016	2.26	0.4	2.40	–	–	13.6	1.91	76.7	2.49	9.2	0.88

Abundance tables for all species and all contributions have been computed, e.g. example for total contribution @ the near detector

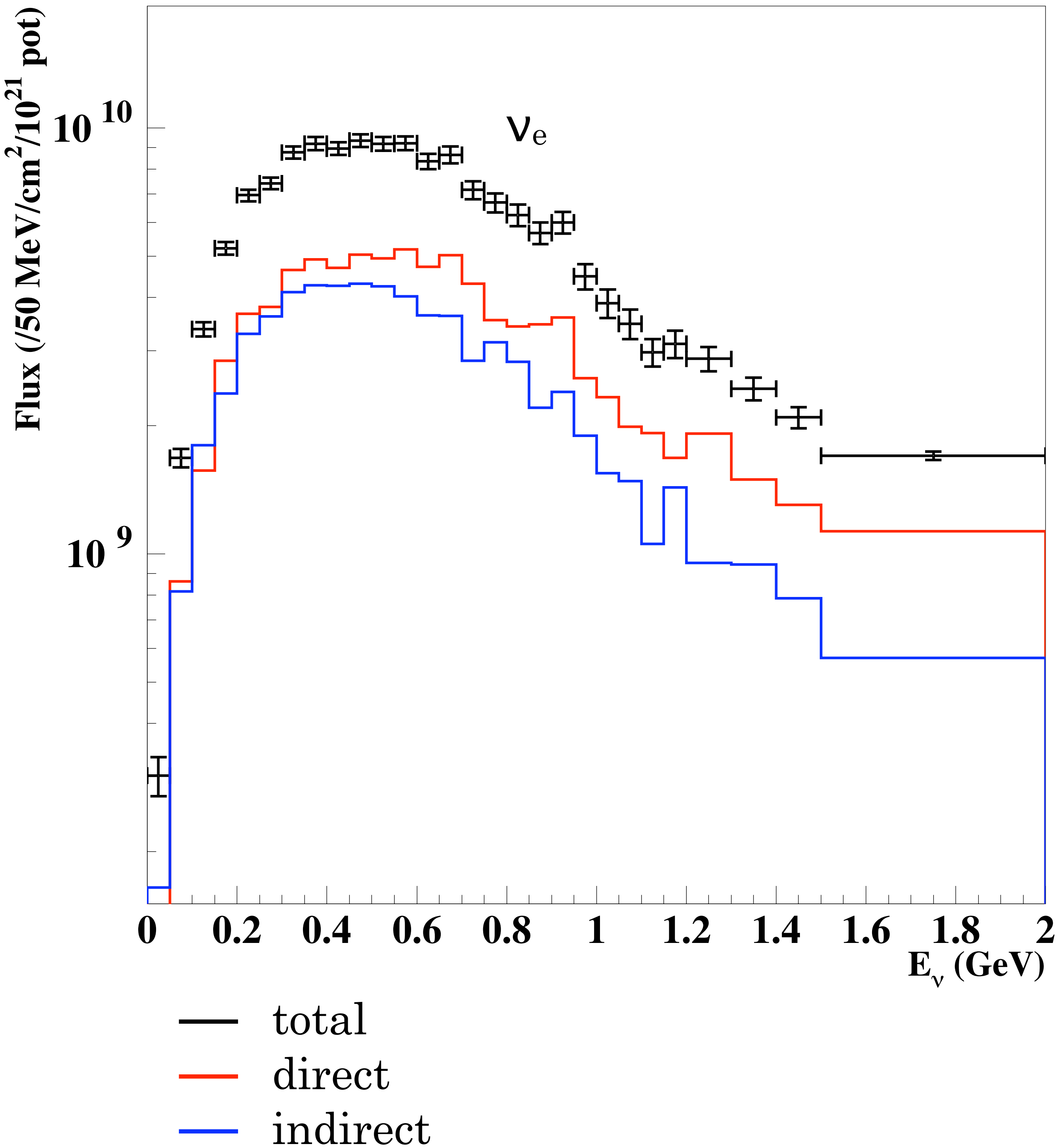
T2K replica target: motivations

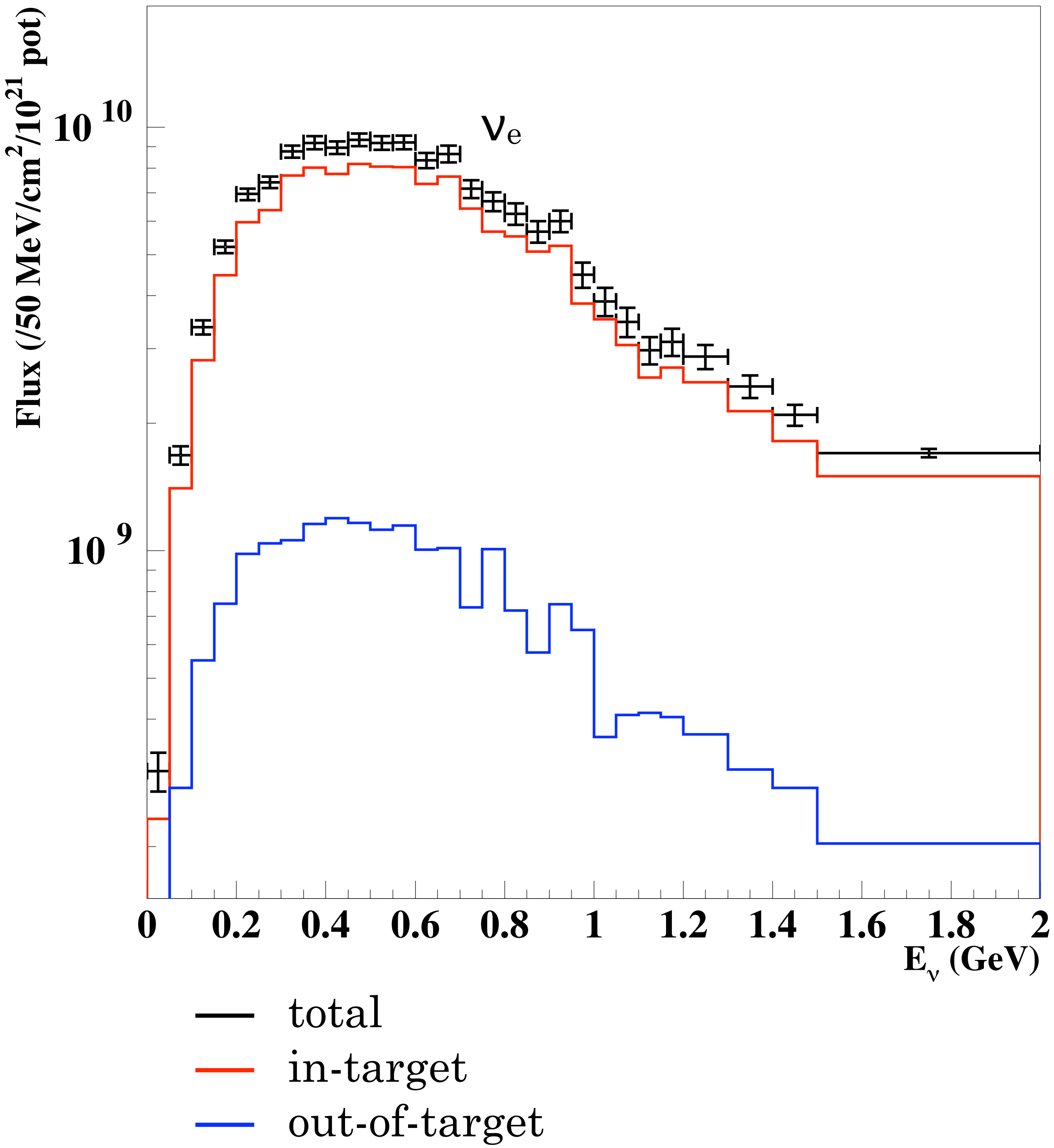
- Direct/indirect, in-target/out-of-target contributions to ν_μ flux @ the near detector



T2K replica target: motivations

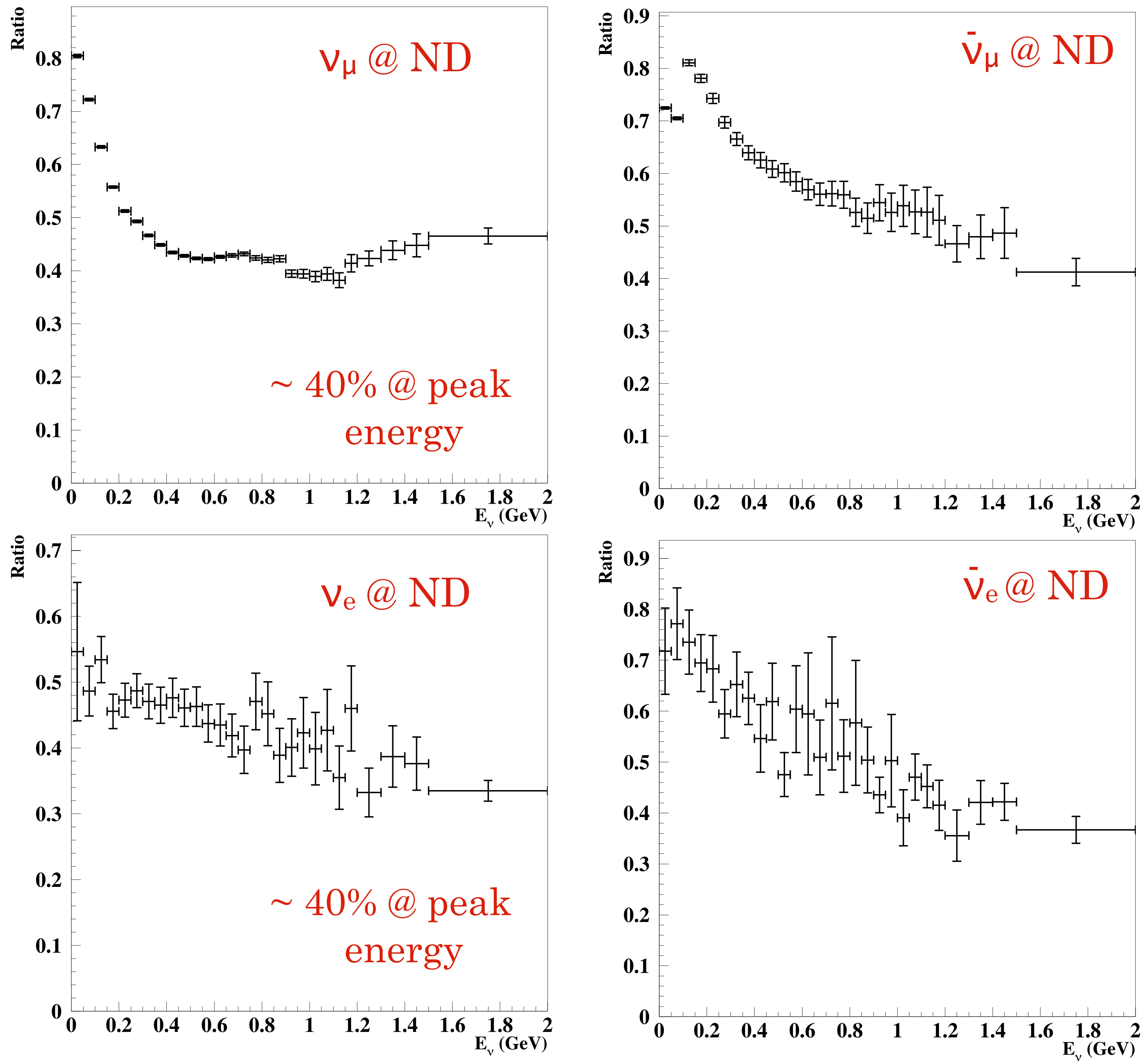
- Direct/indirect, in-target/out-of-target contributions to ν_e flux @ the near detector





T2K replica target: motivations

- Indirect/total contribution for all neutrino species @ the near detector



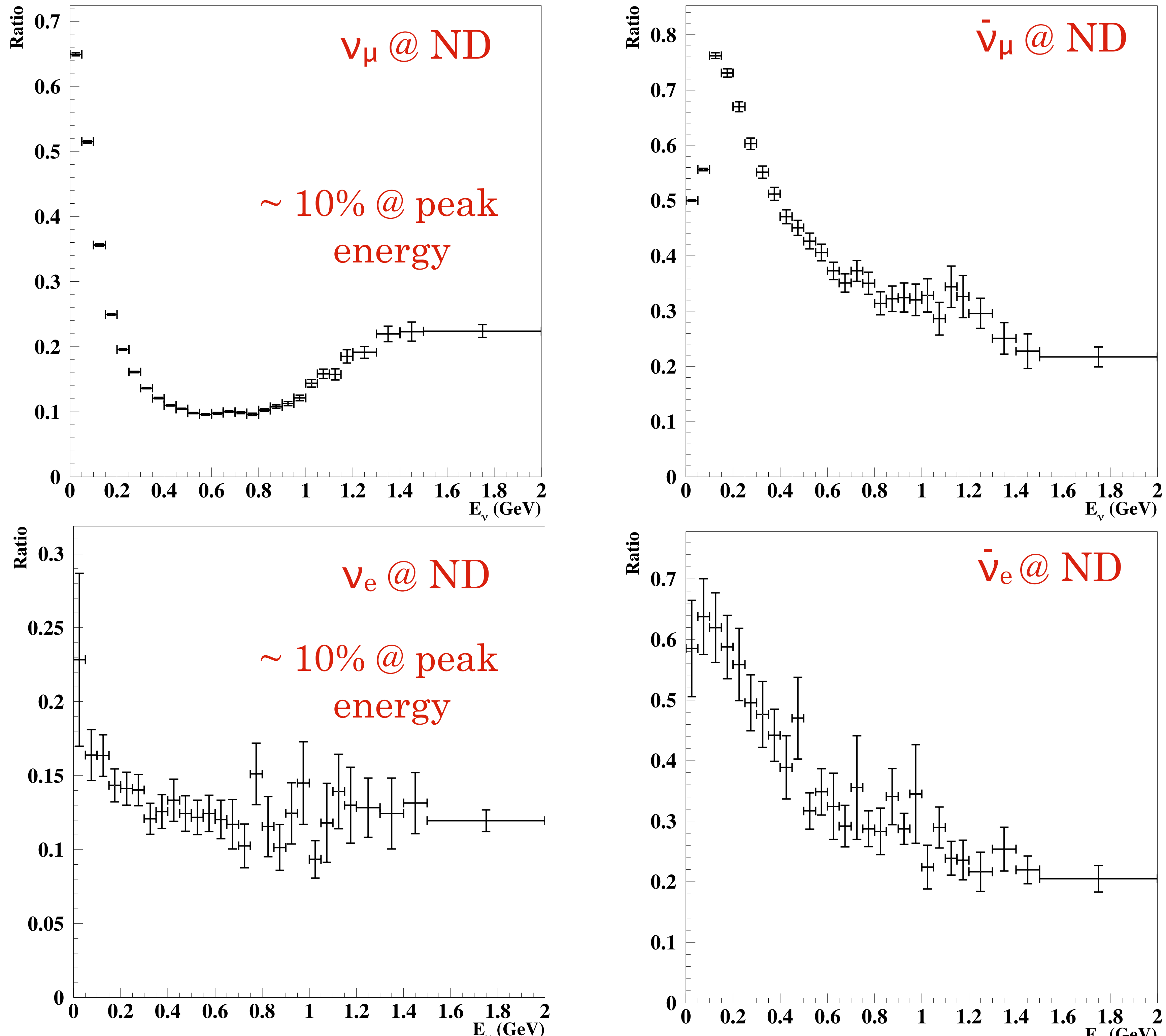
N.B.: clearly need to produce those plots (and following) with more statistics for other species than ν_μ

Thin target measurements

↓

Measurement of the primary int. only would allow us to predict up to ~60% of the fluxes @ peak energy.

- Out-of-target/total contribution for all neutrino species @ the near detector



Replica target measurements

Measurement of both primary and secondary int. in the target would allow us to predict up to ~90% of the fluxes @ peak energy.

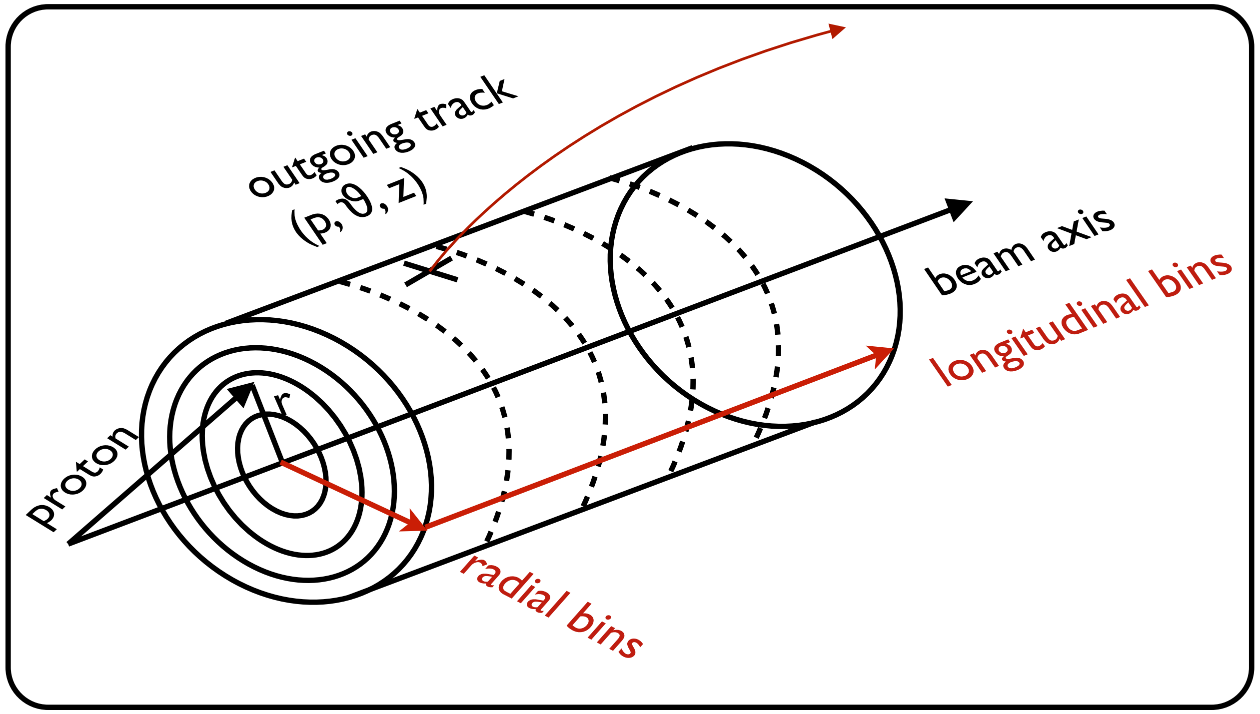
T2K replica target: motivations

- Considering the ratios of indirect and out-of-target contributions over total contribution we may conclude that:
  - Thin target data will provide cross-sections as direct input to the T2K beam Monte-Carlo. However still ~40% of the flux has 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).
  - Measurements with the long target would allow us to predict up to ~90% of the fluxes. The remaining corrections due to interactions out of the target volume would be of the order of 10% and estimated from secondary interactions models (Strategy B).
- This stresses the importance of the replica target data.
- This also naturally defines the analysis method for the replica target: tracks should be reconstructed at the target skin, no need for vertex reconstruction. In this way, we account for both primary and secondary interactions. If we correct for acceptance and reconstruction efficiency, this information can be used as direct input to the T2K beam Monte-Carlo (e.g. re-weighting) to predict 90% of the flux for both ν_μ and ν_e at peak energy.

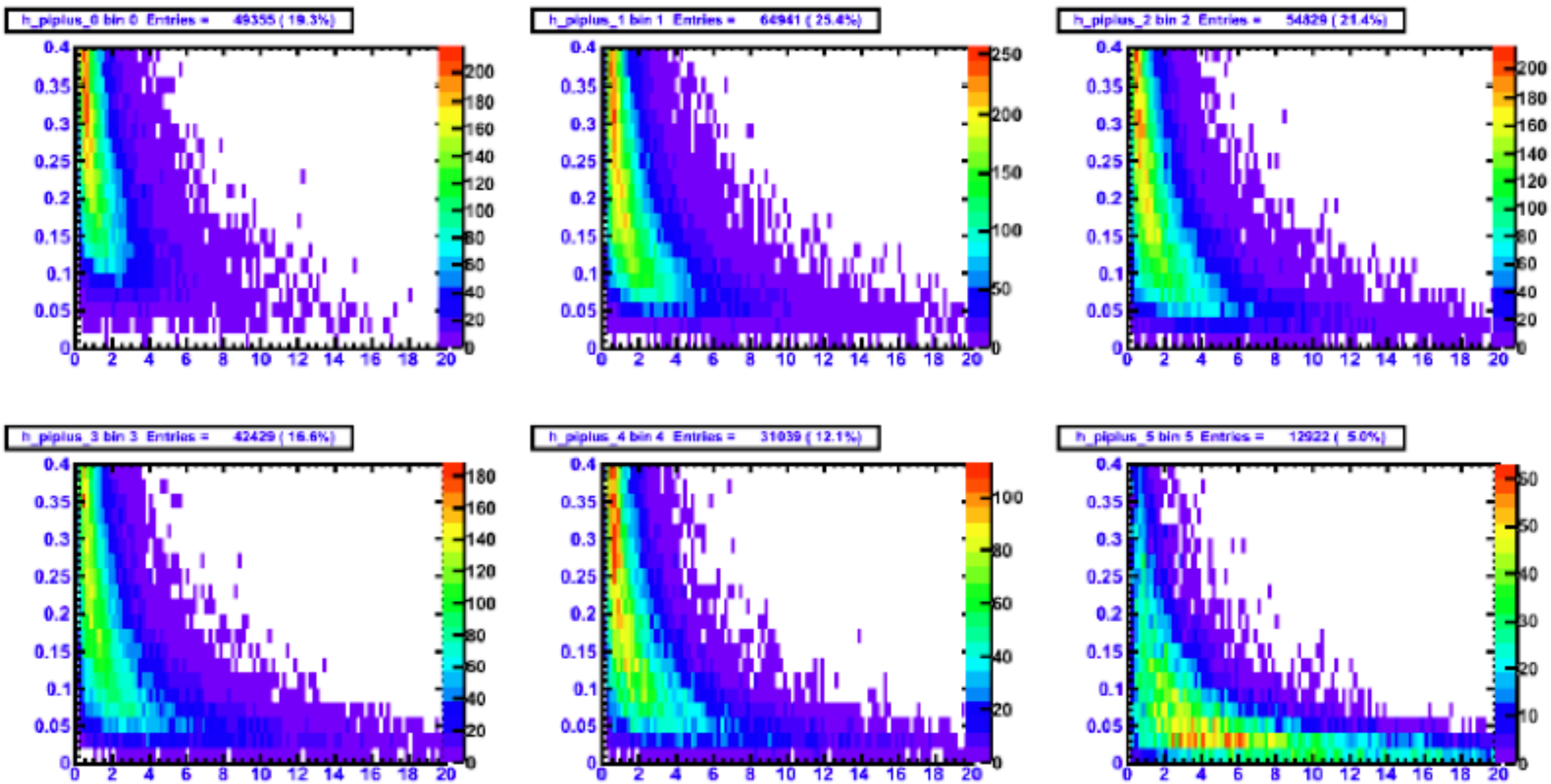
T2K replica target: work in progress

2007 T2K replica target data:

- current analysis strategy is to provide momentum and angle of all tracks at the target skin
- back tracking onto target skin (including error propagation) already implemented
- first results on ToF PID
- analysis chain for negative hadron analysis ready, first distributions with low statistics
- can be used to tune re-interactions
- currently considering 5 longitudinal bins along the target + target downstream face



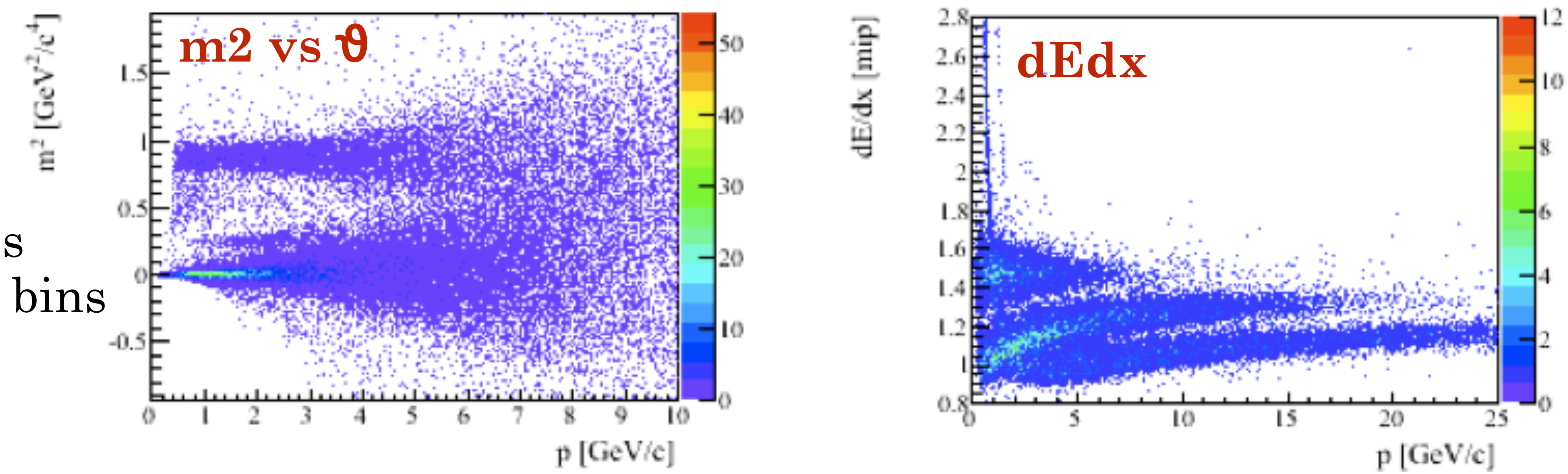
Monte-Carlo π+ (p, ϑ) distributions for 5 longitudinal bins (18 cm) + target downstream face:



Longitudinal distributions sensitive to: re-interactions, beam shape on target and interaction length

T2K replica target: preliminary PID results for 2007 data

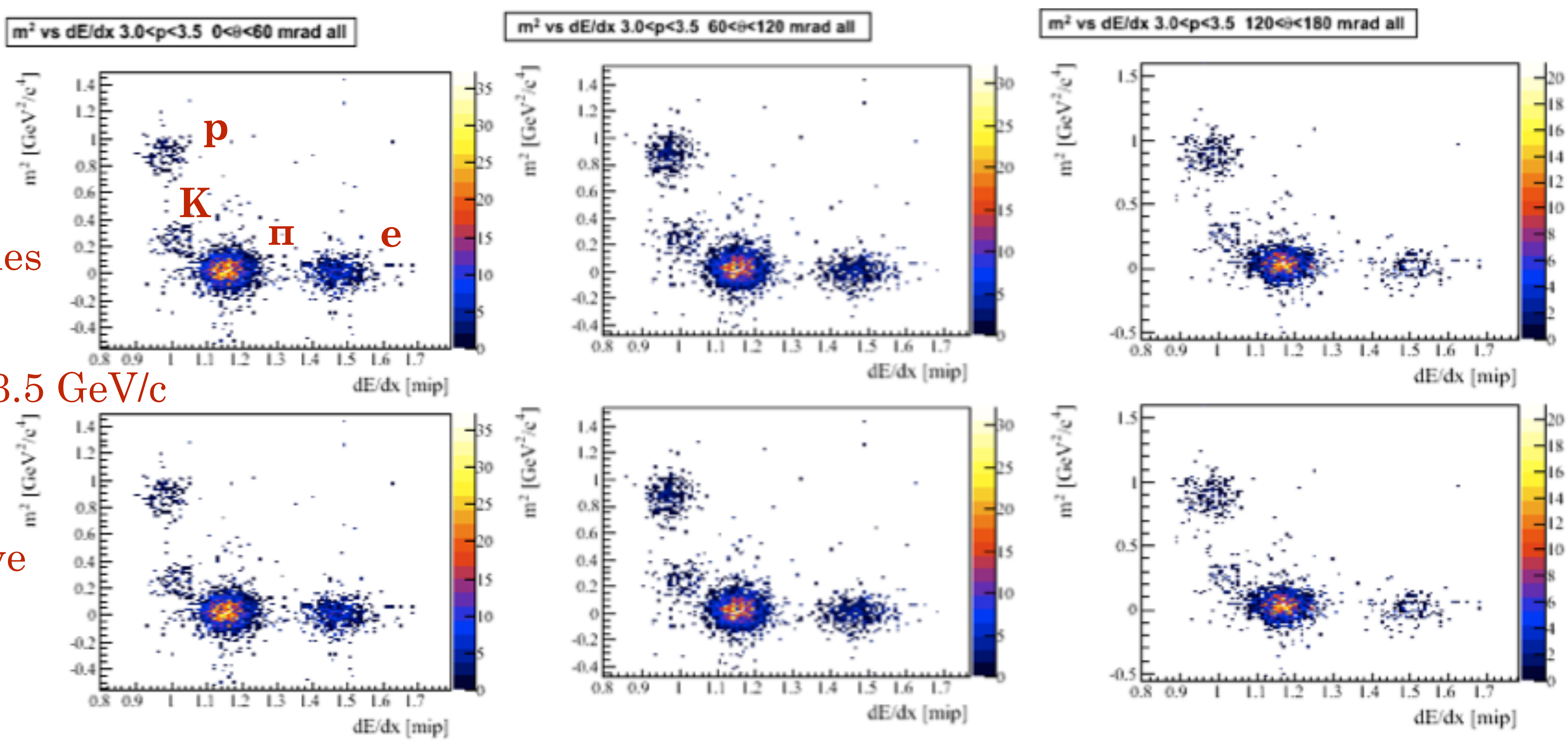
All particles
all angular bins



All particles

3.0 < p < 3.5 GeV/c

All positive particles

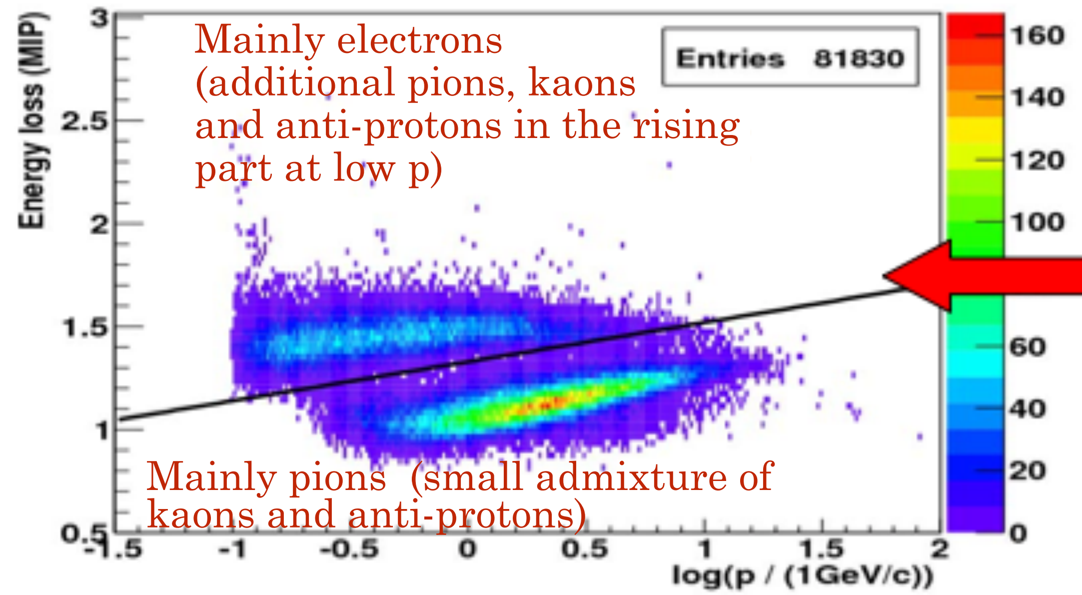


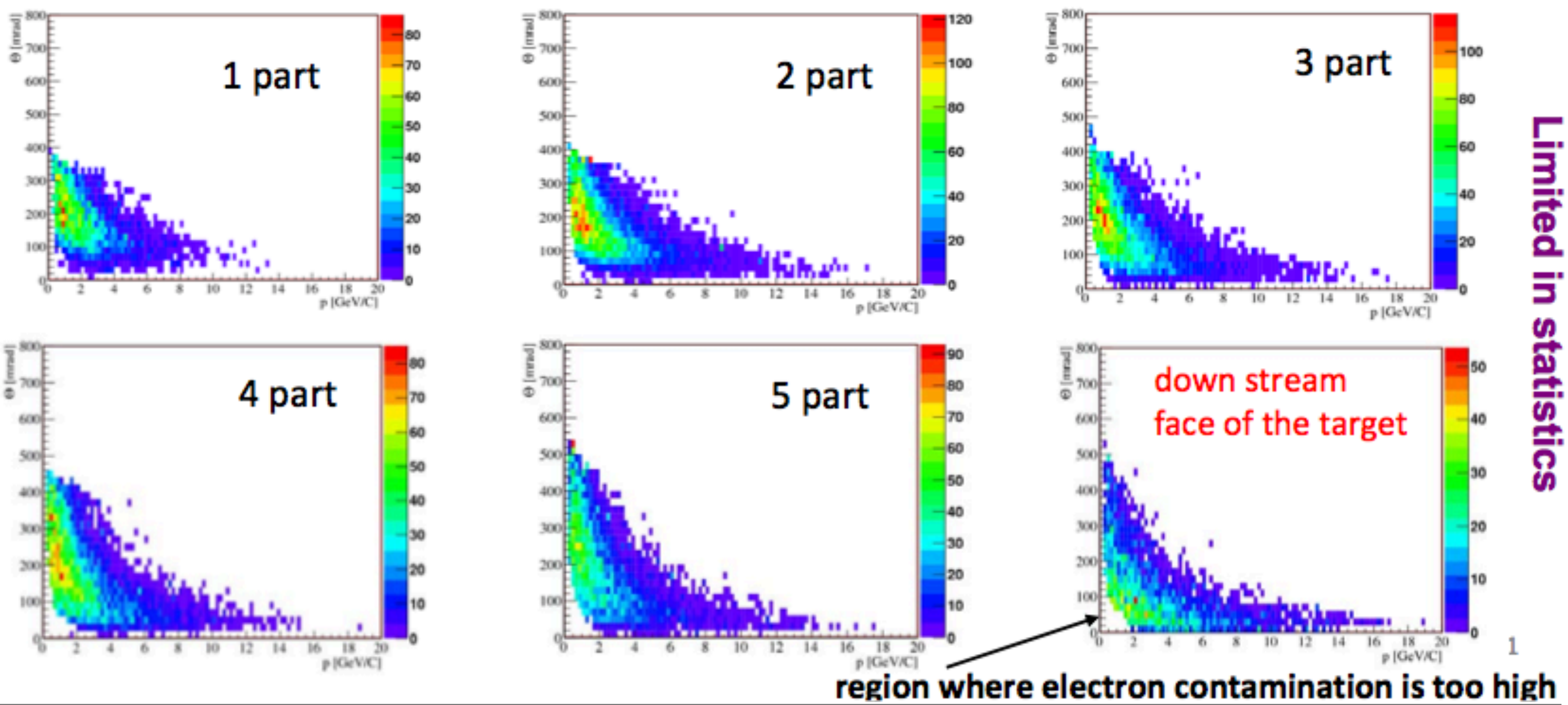
T2K replica target: towards first h- analysis

- **As already done with C thin target data, we analyze all negative tracks in order to extract negative pion distributions**

➡ by applying a global correction using MC, that takes into account geometrical acceptance, reconstruction efficiency, kinematic smearing, and corrects for other particles contamination (kaons, anti-protons, electrons) and feed down from particle weak decays

- given the presence of a large contamination of electrons at low momenta and small angles, we cannot trust the MC electron subtraction in this region
- **since dE/dx provides excellent electron identification, it is being implemented to reject electrons in the data**
- some very preliminary negative pion distributions are shown here, that still do not make use of dE/dx electron rejection (standalone h^- analysis)





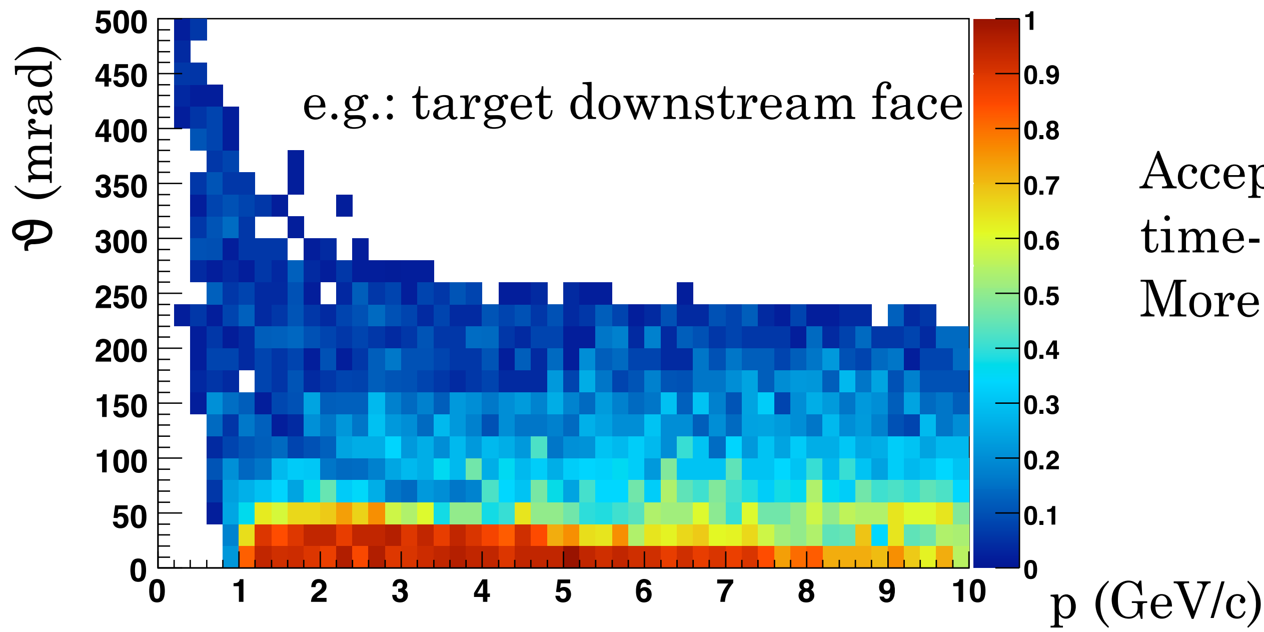
T2K replica target: NA61 data for T2K flux predictions

Considering direct input from the replica target data:

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

- The method assumes analysis based on backward propagation of tracks onto the target skin and tracks described with adequate parameters for re-weighting of the T2K beam M-C:
  - position vector of exit point, (qx, qy, qz)
  - momentum vector at exit point, (px, py, pz)
  - angle wrt beam axis at exit point, ϑ

- Assumes a target binning with:
  - 6 longitudinal bins (18 cm each, last bin corresponds to target downstream face)



Acceptance for tracks hitting the forward time-of-flight + track quality cuts (TPC points). More or less constant along the target.

- All results from T2K-NA61 internal note 03: http://www.t2k.org/beam/NuFlux/HadronInt/note-03/view

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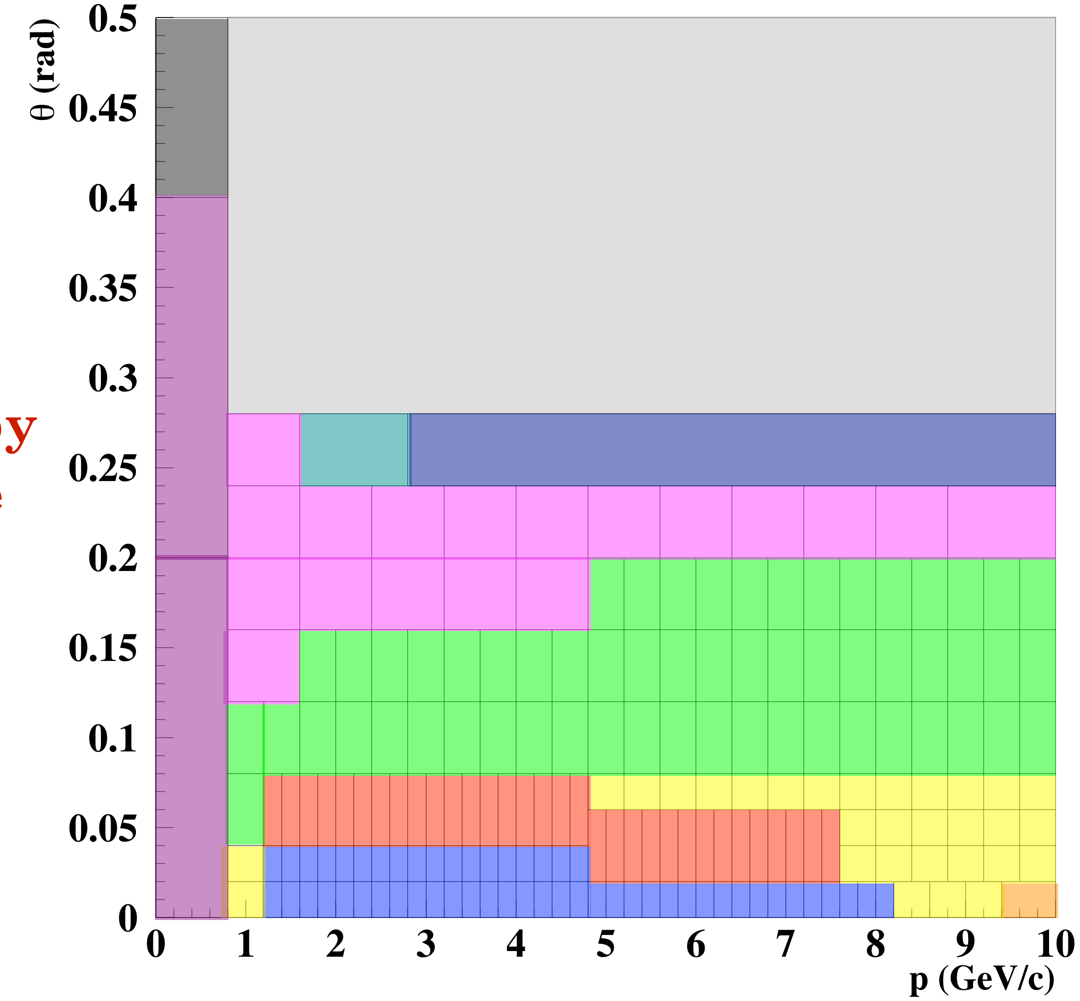
T2K replica target: NA61 data for T2K flux predictions

- Binning template in (p, ϑ) defined over the relevant T2K phase space:
  - regions of maximal acceptance define a default binning of 200 MeV/c bins in momentum and 20 mrad bins in polar angle
  - for regions of lower acceptance an appropriate bin size is increased appropriately to achieve the same statistical accuracy

Binning driven by NA61 acceptance

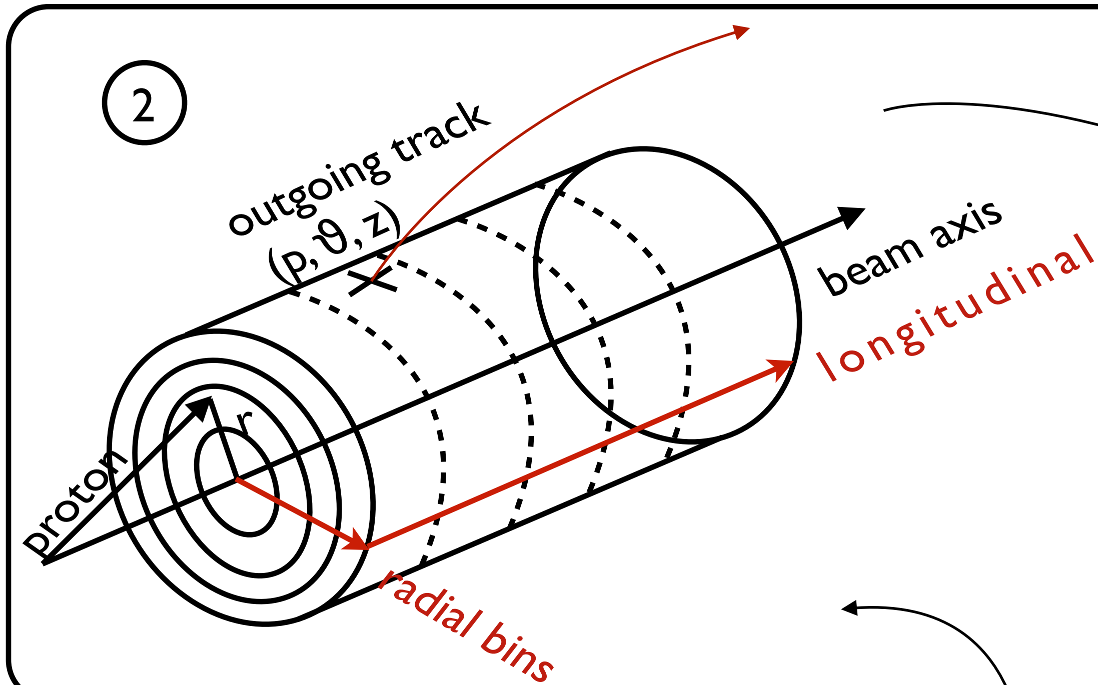


Bin sizes range from:
- 200 to 1200 MeV/c in momentum
- 20 to 200 mrad in polar angle

Bins at the edges of the considered phase space have open boundaries to account for overflows that contribute to the energy spectra.

- This template allows to vary each (p, ϑ) bin content over the T2K phase space by the same amount to account for uncertainties of hadron production cross-section measurements in NA61. Different variation methods are used: purely statistical (random) or variation in the shape of the production cross-section.

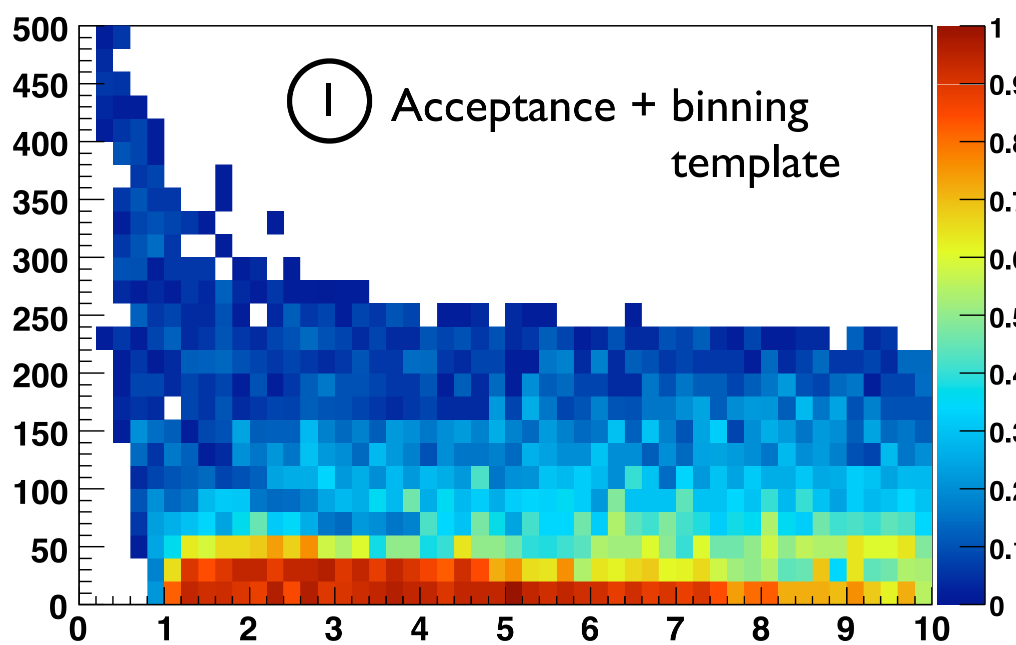
T2K replica target: NA61 data for T2K flux predictions



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:

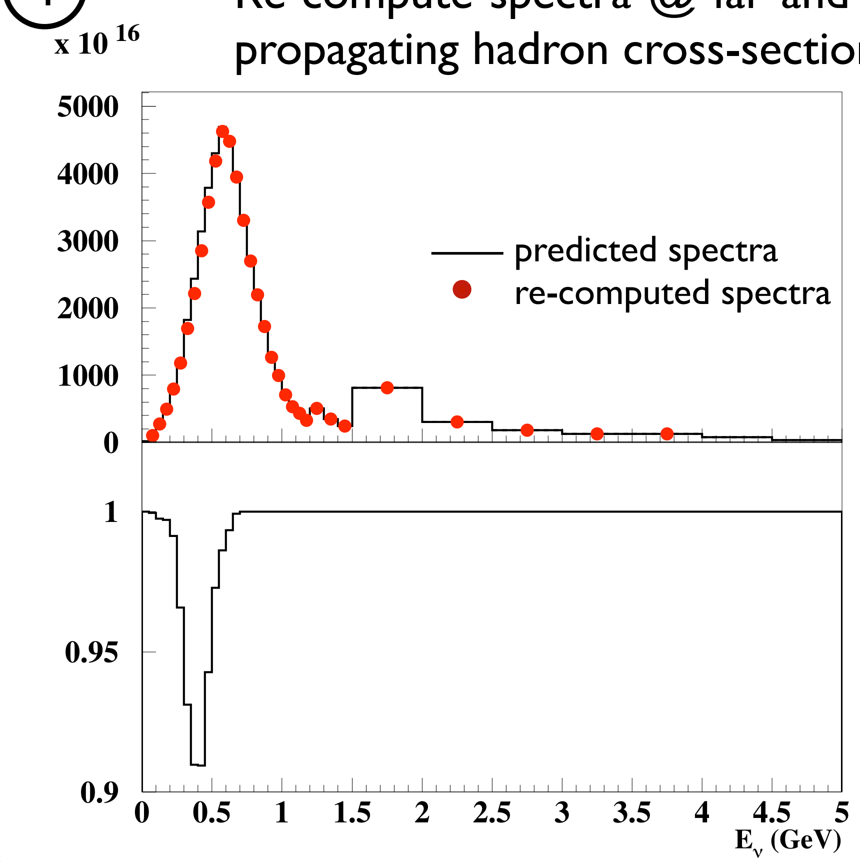
$$\boxed{N'_{ij}(E_\nu) = N'_i(p,\theta) \times w^f_{ij}(E_\nu) \times w^n_{ij}(E_\nu)}$$



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

4

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

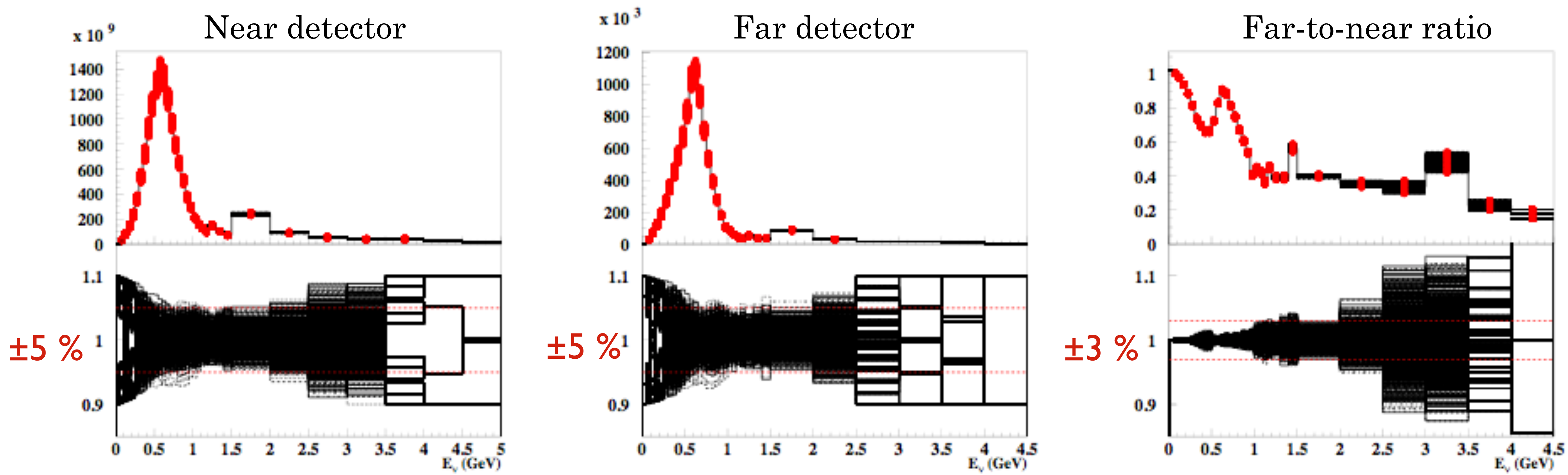


This method can be used to estimate required statistics of NA61 measurements with respect to the T2K physics goals:

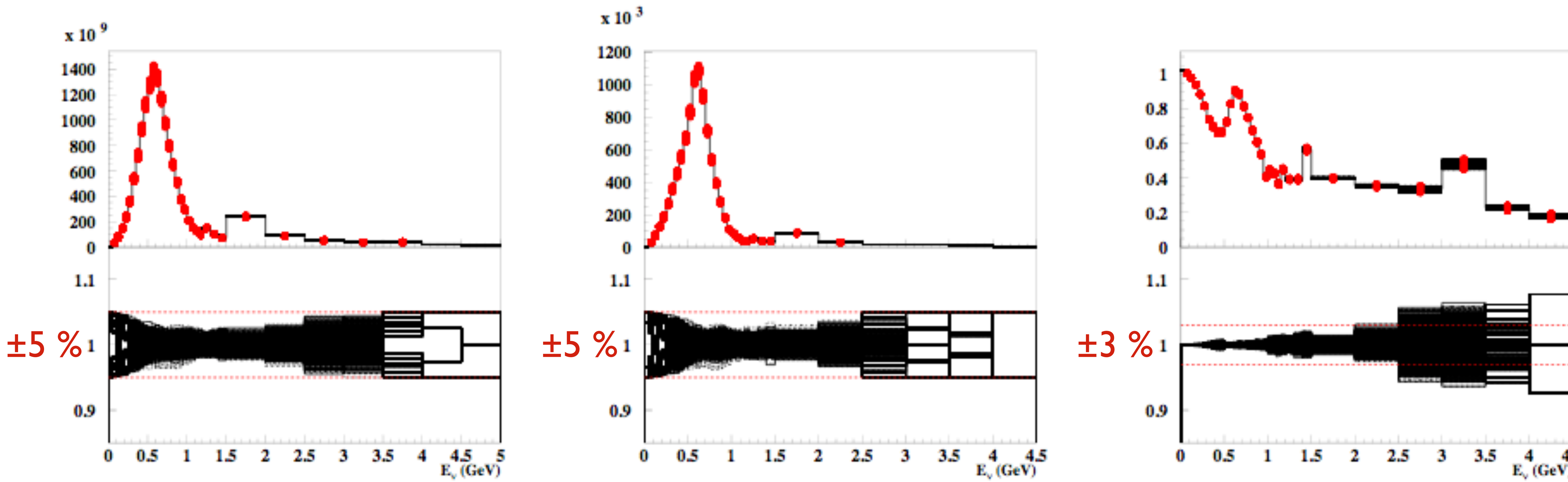
5% on absolute flux prediction

2-3% on far-to-near ration prediction

- 1000 variation templates with 10% variation (random method):



- 1000 variation templates with 5% variation (random method):



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**
  - p + C (thin target) @ 31 GeV/c (4.4M interactions)
    p + C (T2K replica target) @ 31 GeV/c (2M interactions)
  - π + C @ 158 GeV/c (5M triggers)
    π + C @ 350 GeV/c (6M triggers)
    p + p @ 20, 31, 40, 80, 158 GeV/c (19M triggers)
- The NA61 large acceptance is adequate for hadron production measurements needed by neutrino experiments.
- NA61 data are important to constrain hadron production models used in the T2K beam Monte-Carlo. Different strategies can be applied.
- **Goals for this summer:**
  - publish pion distributions from 2007 thin target data
  - preliminary results for protons/kaons from the 2007 thin target data
  - preliminary results for pions/protons from the 2007 replica target data
  - finalize calibration of 2009 data and start analysis
  - finalize statistics estimates for the NA61 long target data (beam allocation within NA61)