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Measuring CP violation: Challenges in Near-Far Extrapolation

F.Sanchez
Université de Genève

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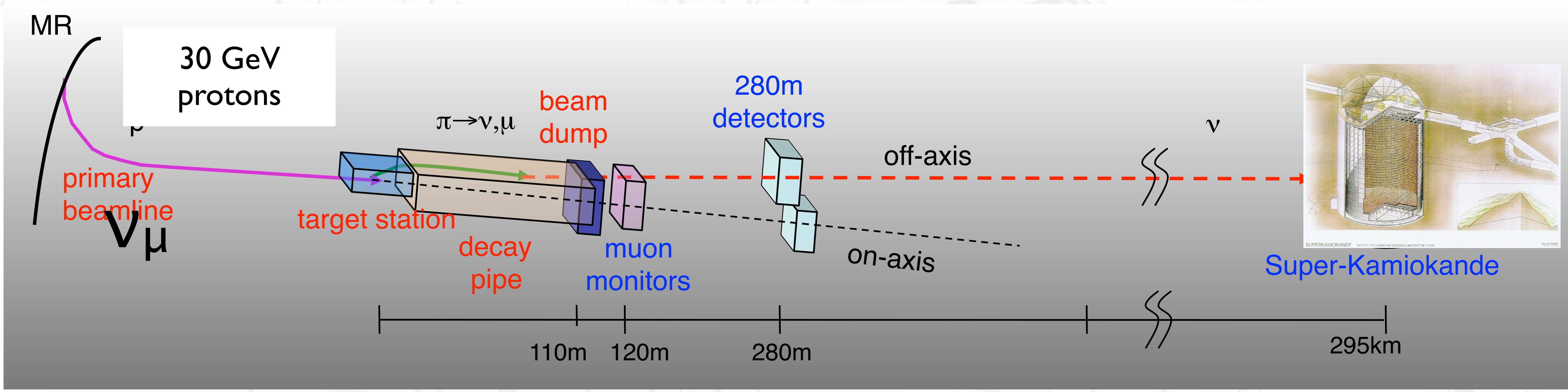
Oscillation experiments

Typical Long Base Line experiment layout

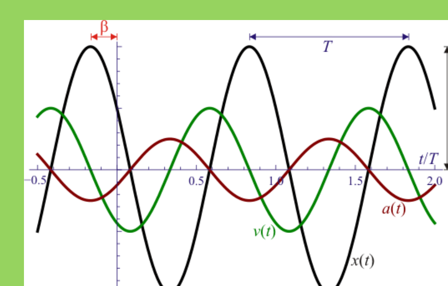


Neutrinos produced in a particle accelerators or nuclear reactors.

–

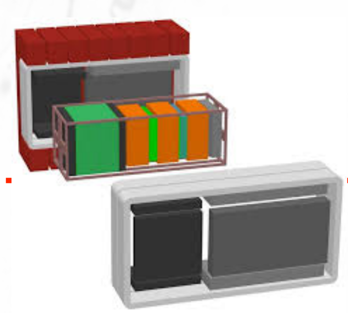
Neutrino flux meas

Oscillations



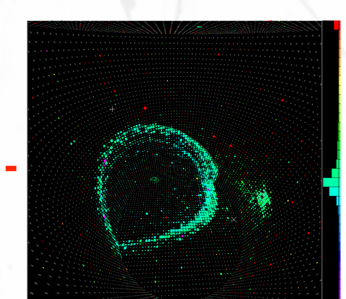
Neutrino flux meas

ν_μ



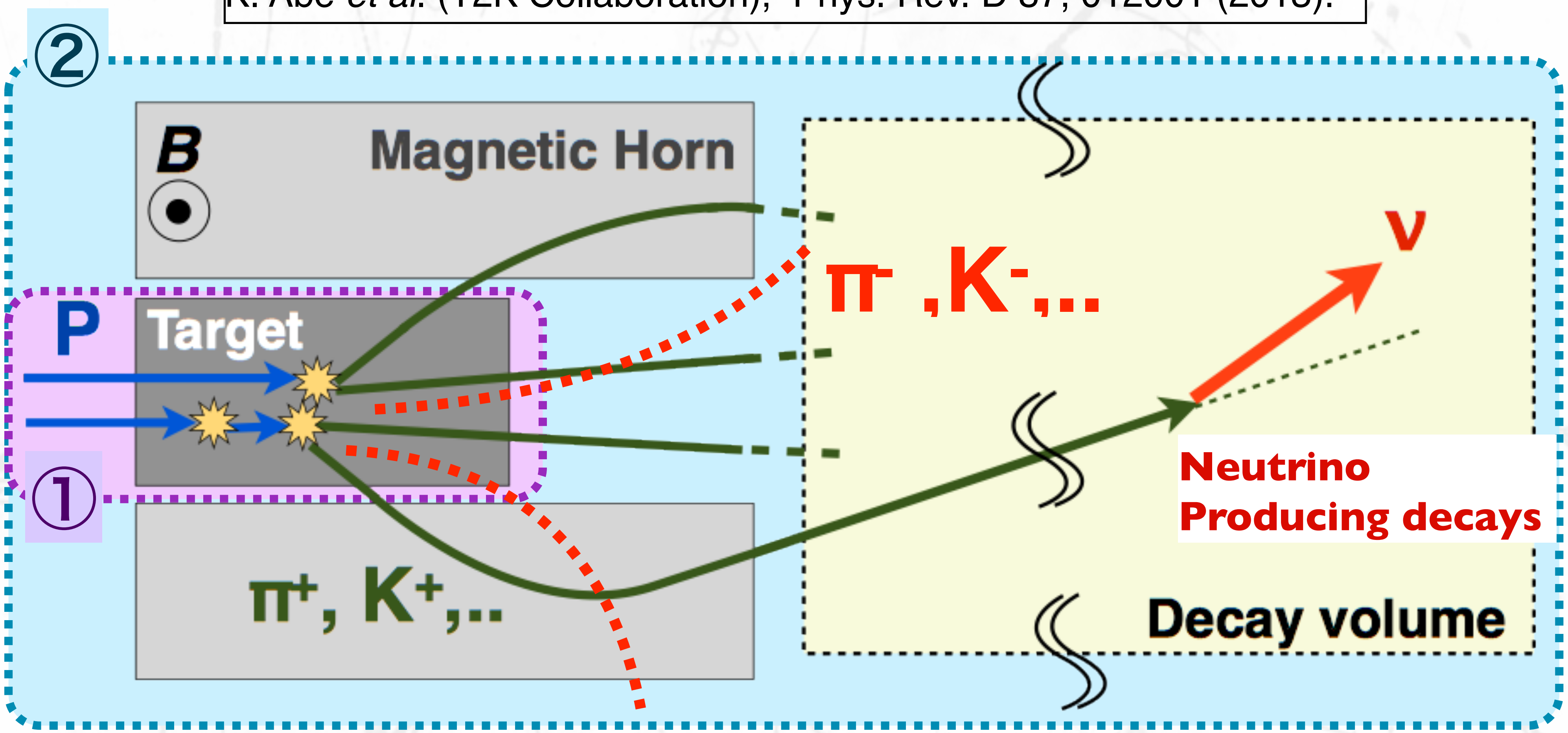
ν_e

ν_μ



Neutrino beam

K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



- Neutrinos and antineutrinos are selected by reversing the B field to focus π^- or π^+.
- Producing π^- is very inefficient starting from matter: antineutrino beams have large neutrino contaminations.

Forward Horn Current vs. Reverse Horn Current

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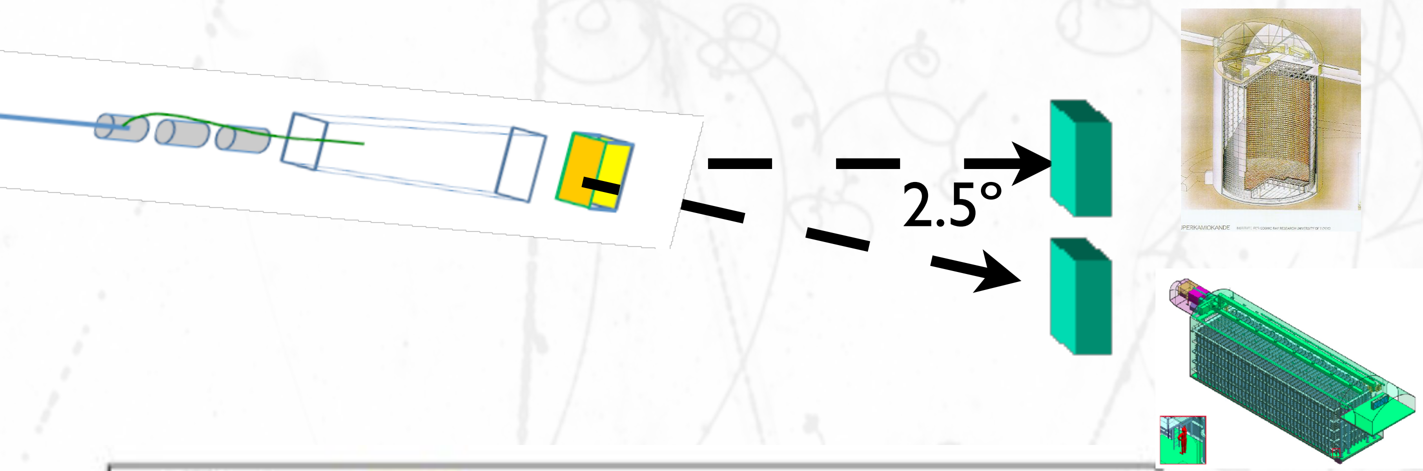
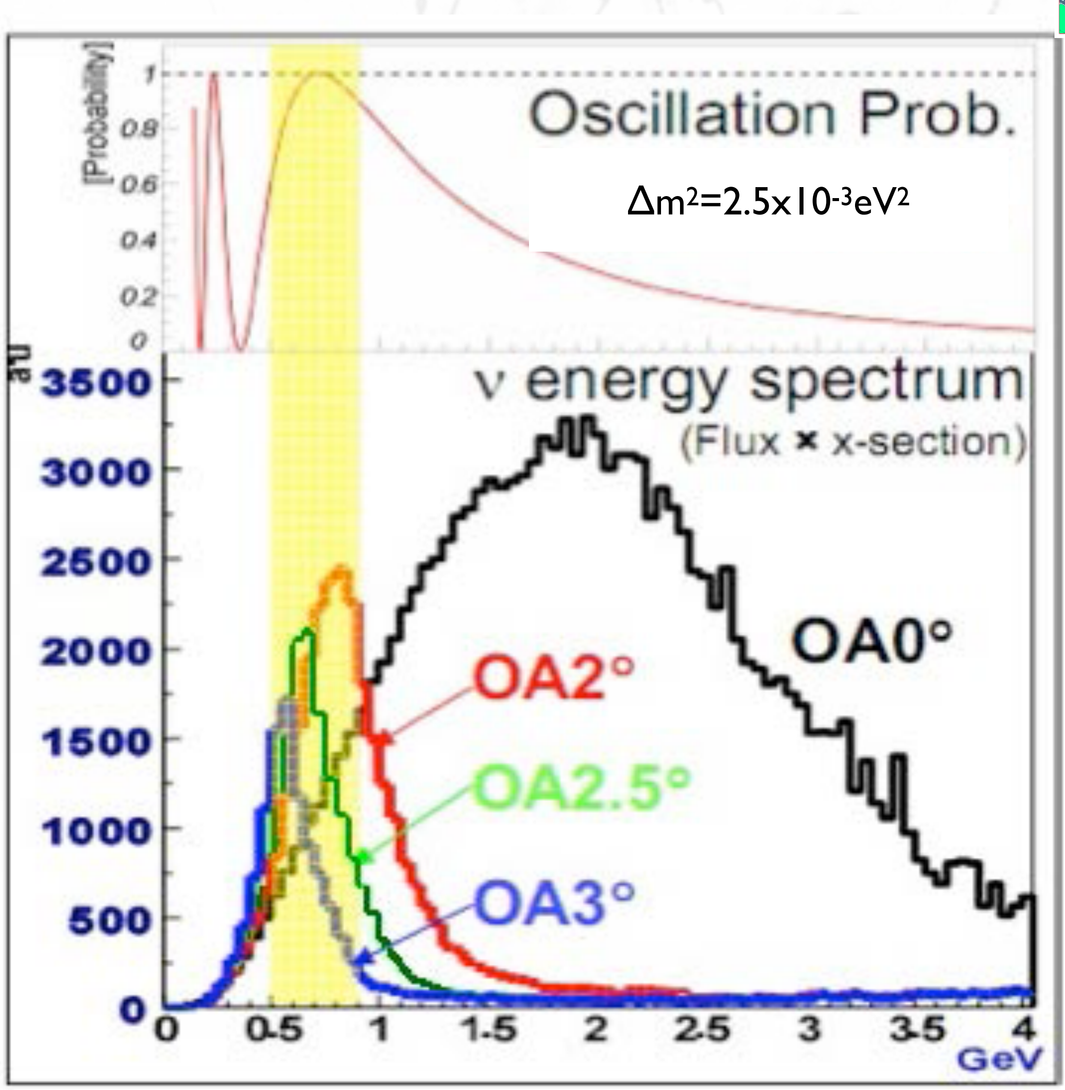
On vs. Off Axis





T2K.T2HK.Nova

Off-axis

- off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.
- Lower energies achieved.

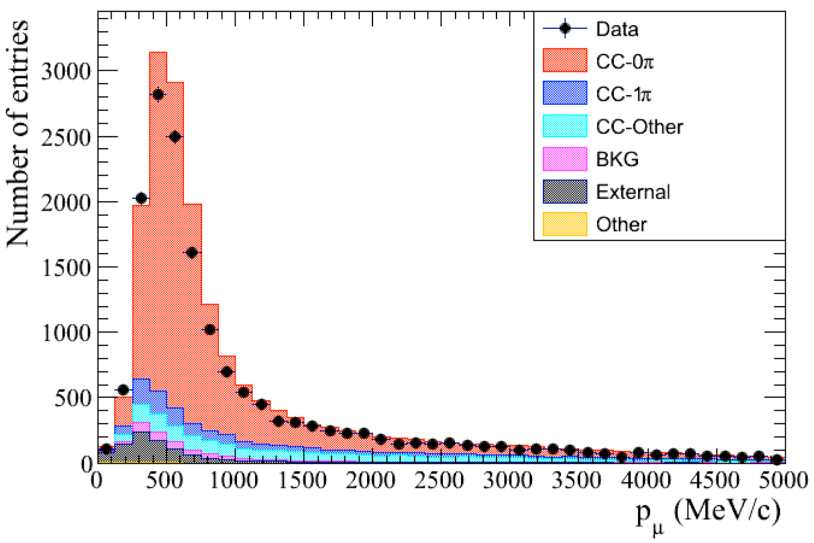
K2K,Minos. Dune

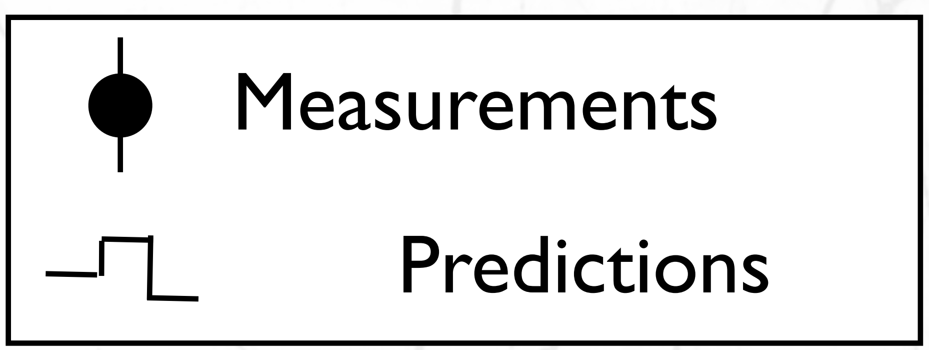
On-axis

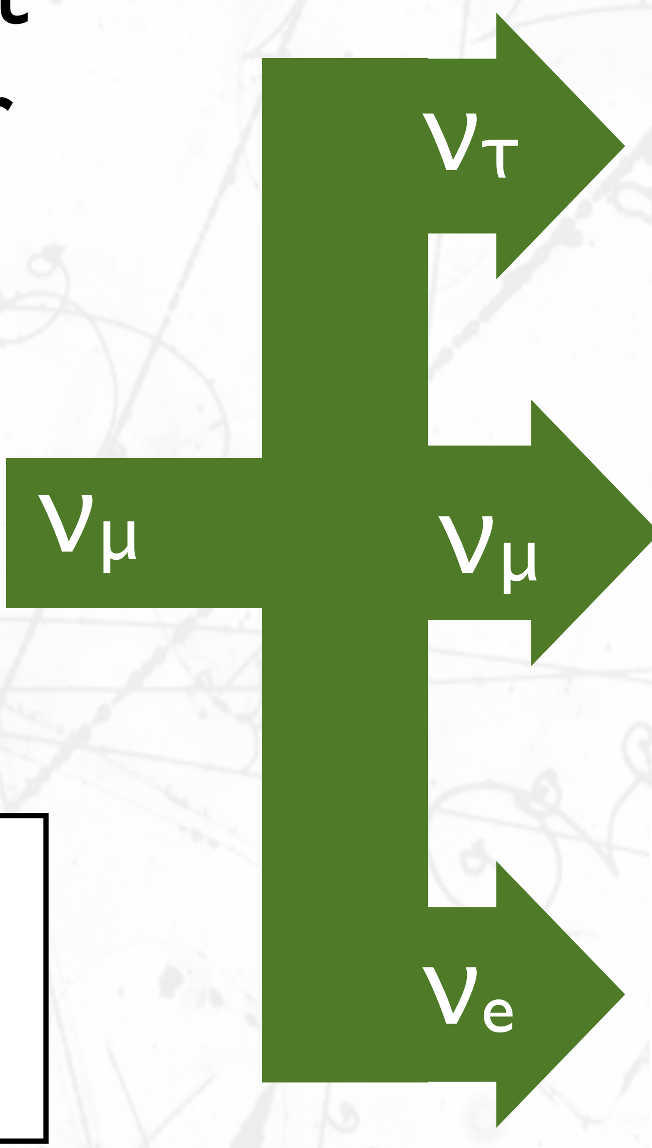
- on-axis optimises the total integrated flux.
- Spectrum with higher neutrino energy (longer oscillation distances)
- More than one oscillation maximum can be measured at a fixed distance.

Measurement

Beam characterisation at the near detector

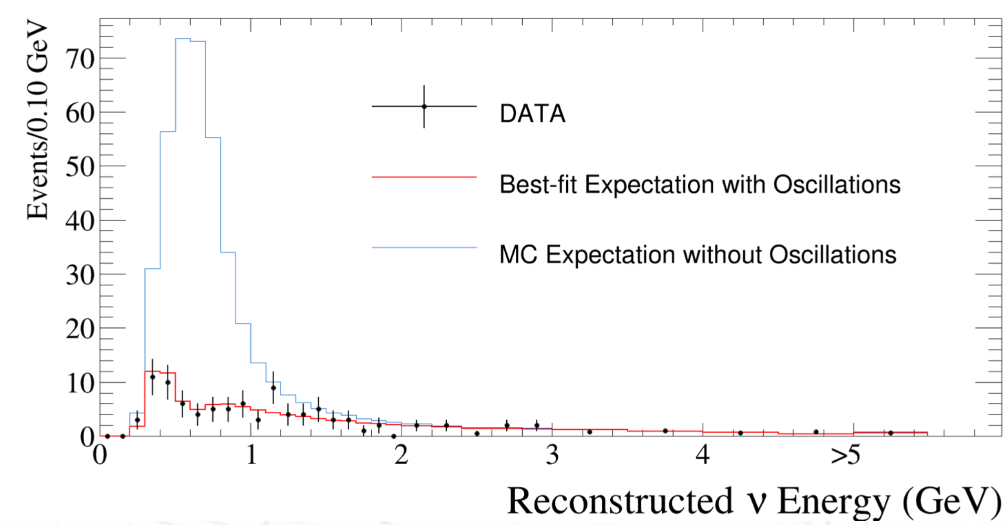


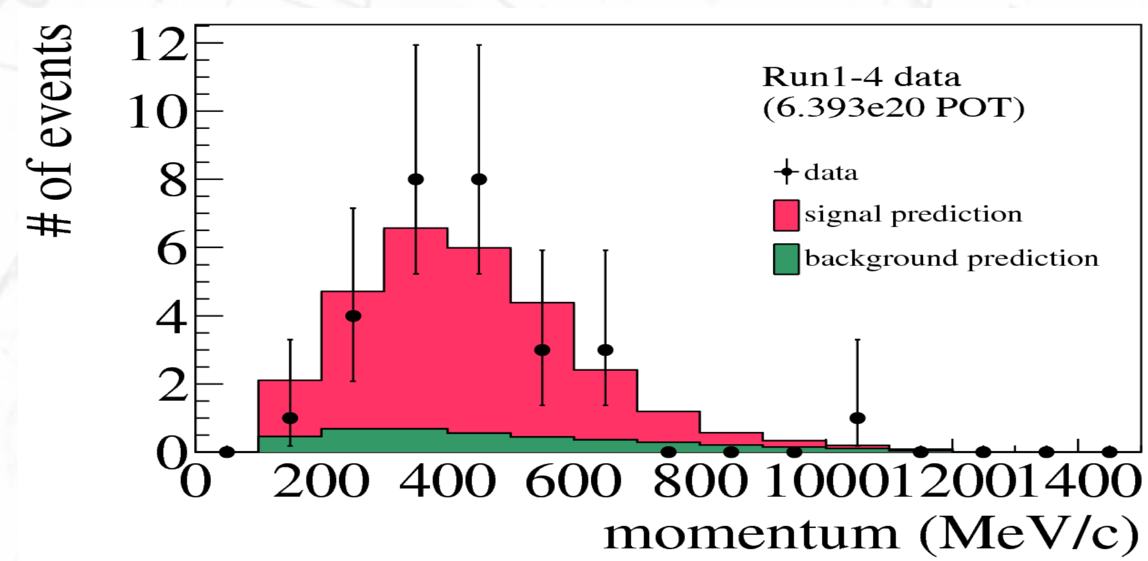




Far detector

Invisible @ T2K
Not enough energy.





Additional measurements done at the near detector to control systematic errors from cross-sections.

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Long base line

- Neutrino oscillation experiments are carried out by comparing neutrino interactions at a near and far sites.

  - The number of events depends on the cross-section & flux:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

  - at the far detector

$$N^{far}_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

- The ratio cancels flux and cross-section:

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

-

Long base line

- Since the neutrino energy is not monochromatic:
  - we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

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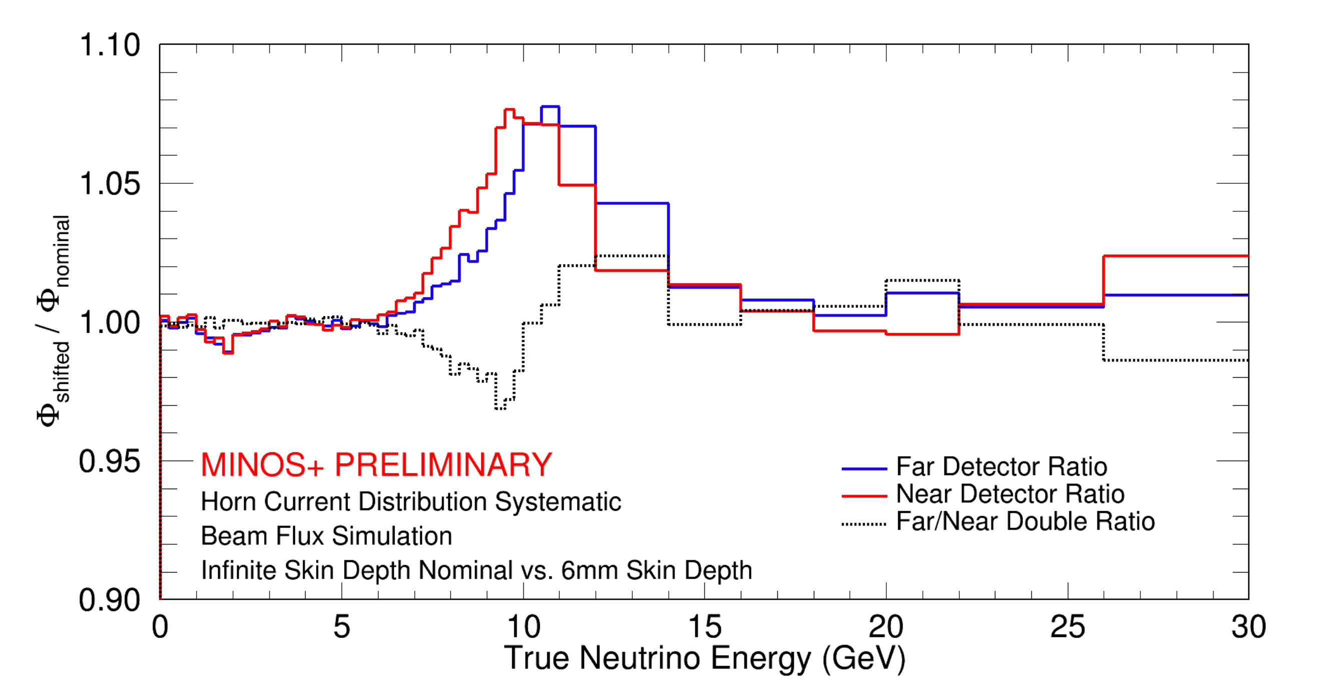
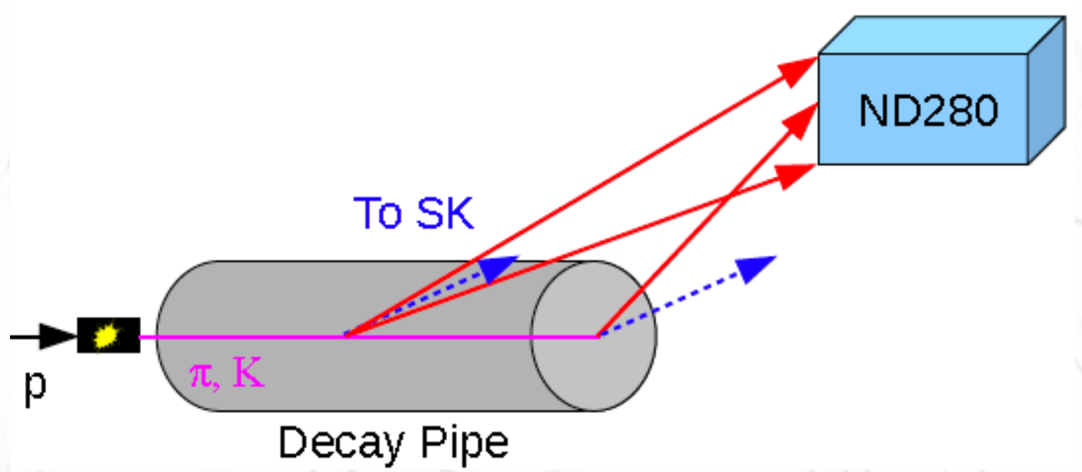
The Flux

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- Flux of near and far sites are not the same:
  - The solid angle sustained by the far detector is minimal wrt the near one.
  - The near detector is sensitive to the length of the decay volume.





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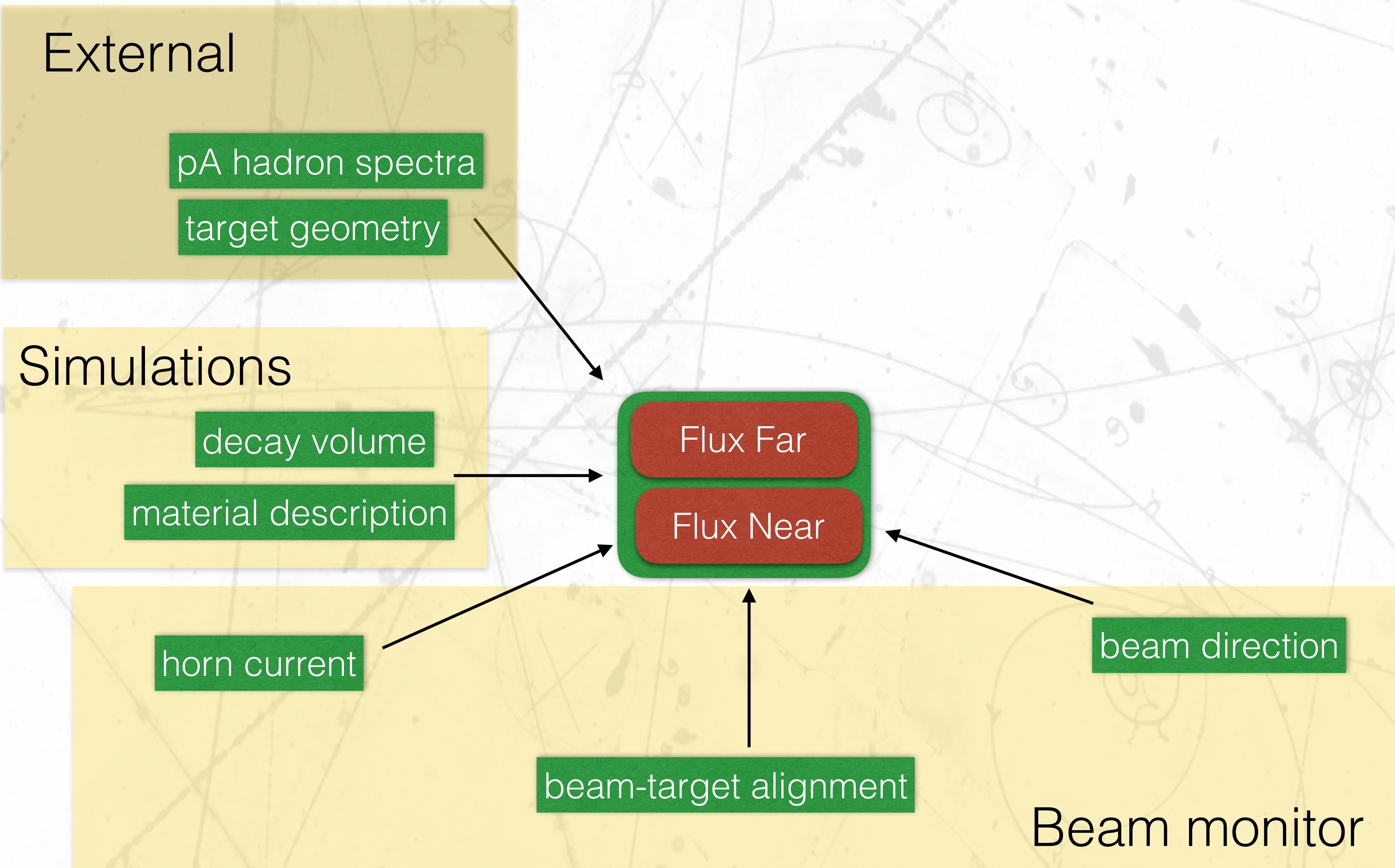
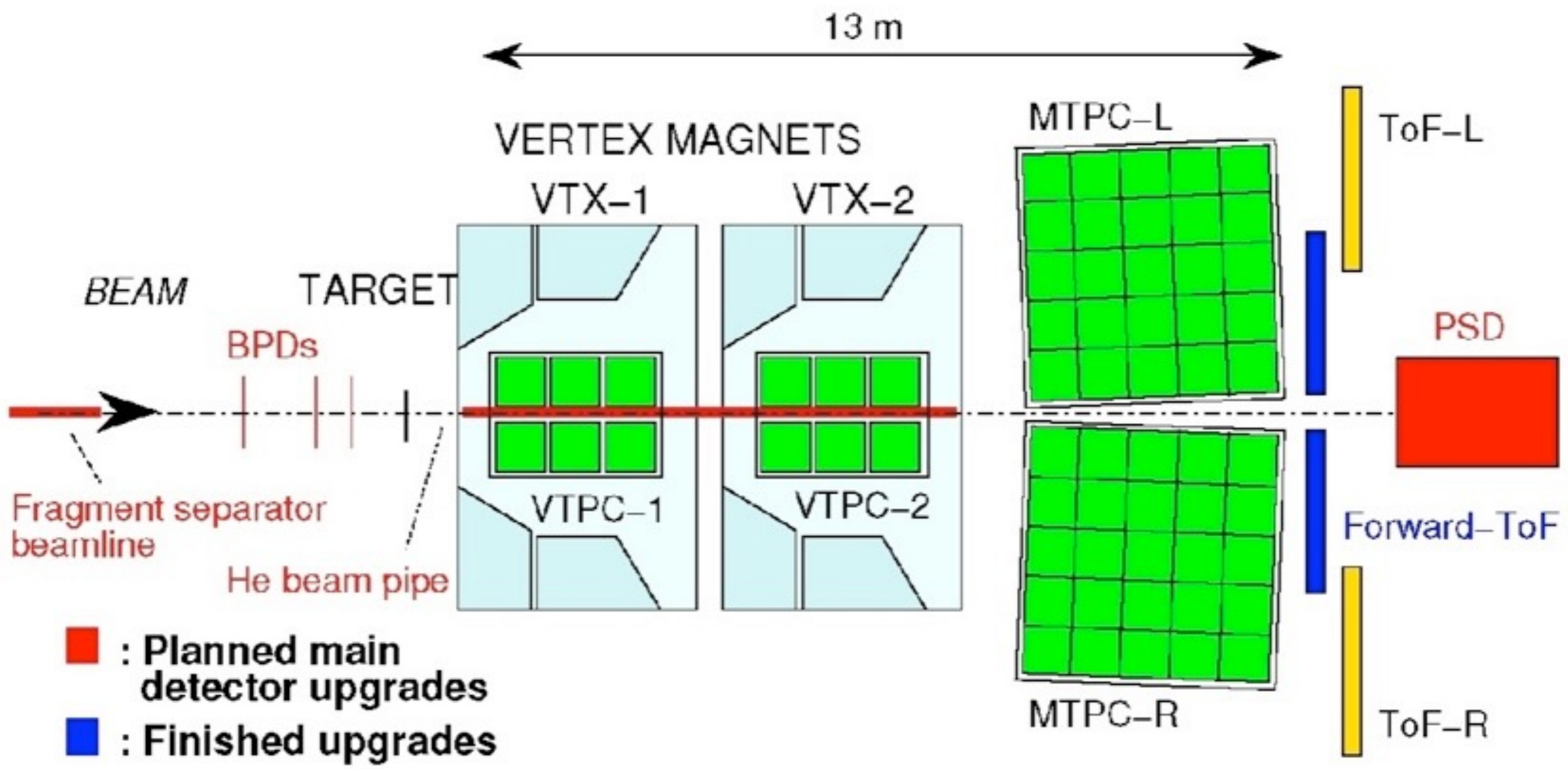
Flux ingredients



Hadro-production

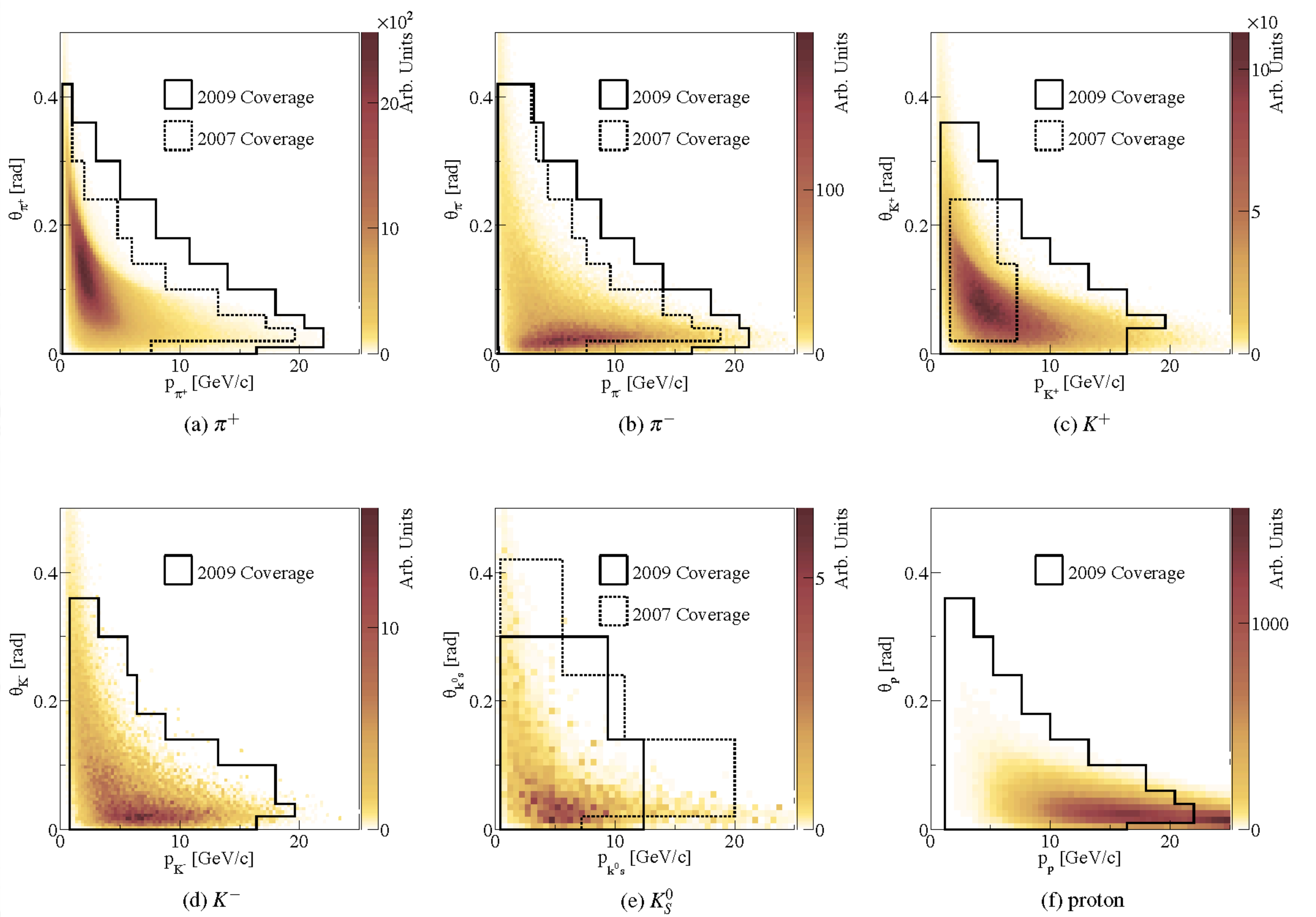
NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

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

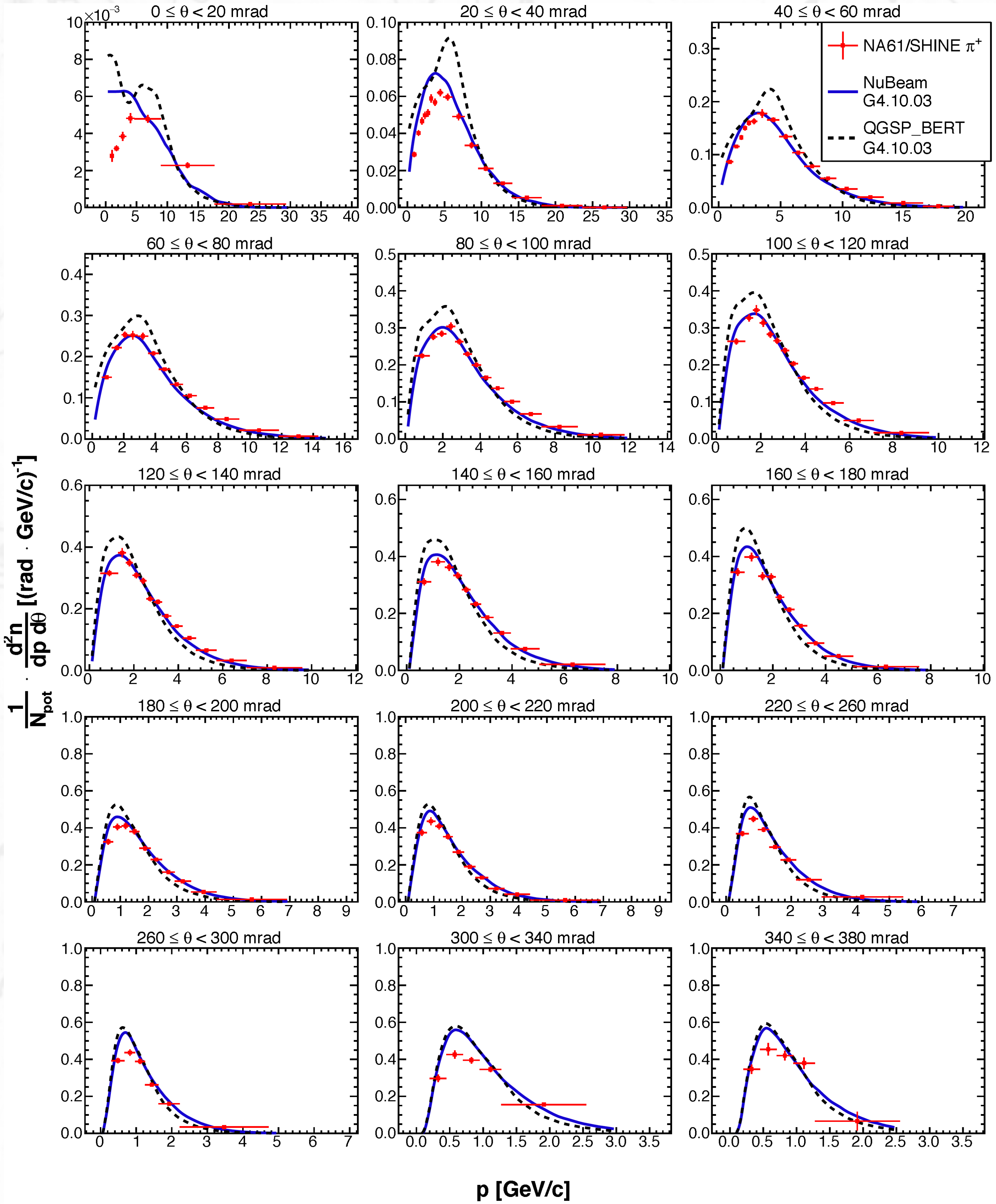


Hadro-production experiments carried in equal conditions to ν beam experiments are critical!

Hadroproduction



Hadroproduction



Models are not precise enough

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Hadro-production

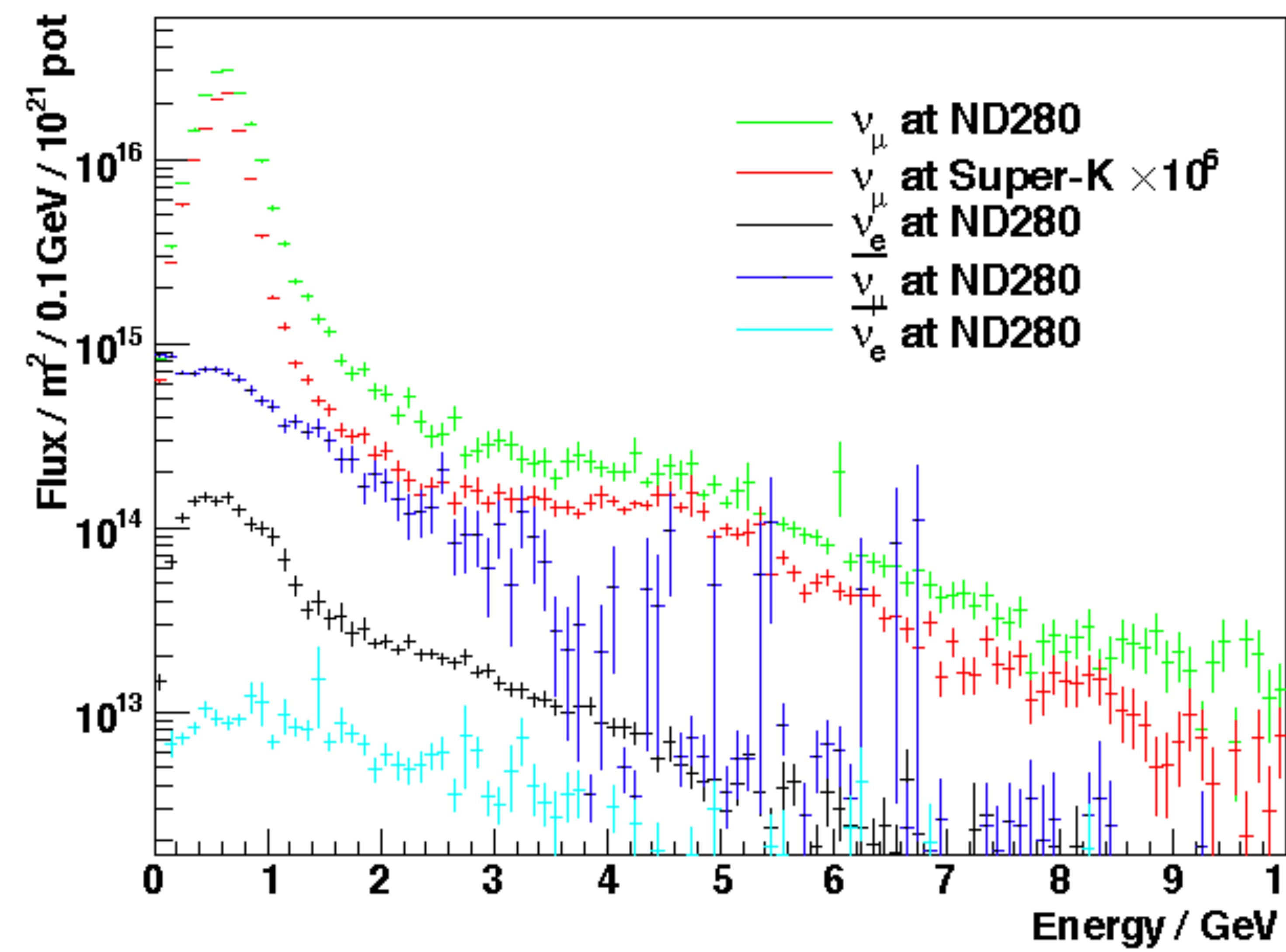
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$K^+ \rightarrow \mu^+ \nu_\mu$$

$$K^+ \rightarrow e^+ \nu_e \pi^0$$

$$K_L^0 \rightarrow e^+ \nu_e \pi^-$$

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

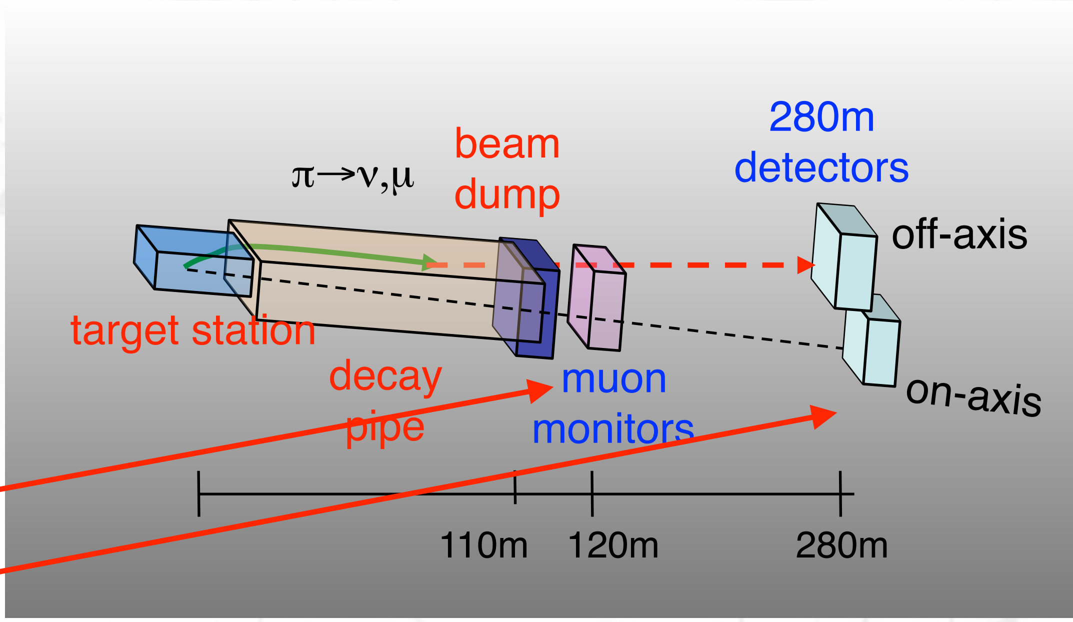


Measuring π^{+-} K^{+-} K^0_L we can determine all beam components.

ν_e are mainly from 3 body decays so the off-axis technique is no affecting them,

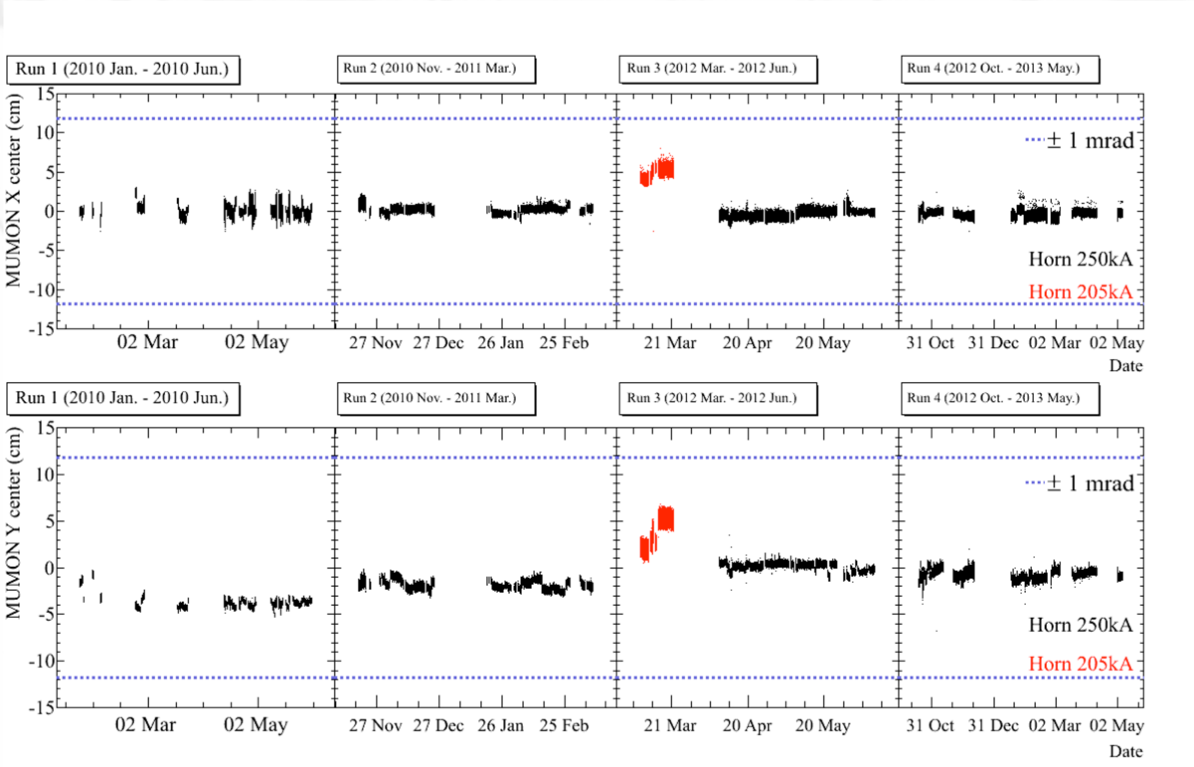
Beam monitoring

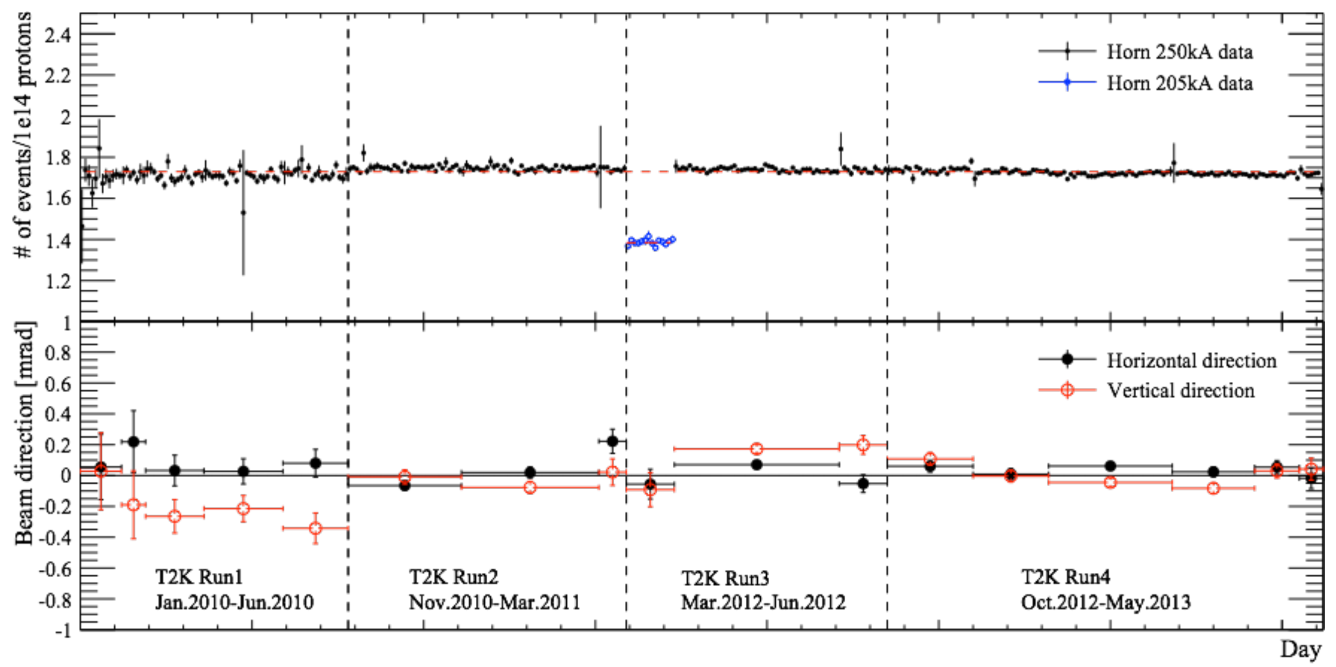
Beam intensity and beam direction are very critical depend on proton beam direction, horn operation and alignment and beam intensity.



Monitoring can be done measuring:

- the muons associated to the pion production.
  - Only high energy muons are possible.
- the neutrinos themselves.





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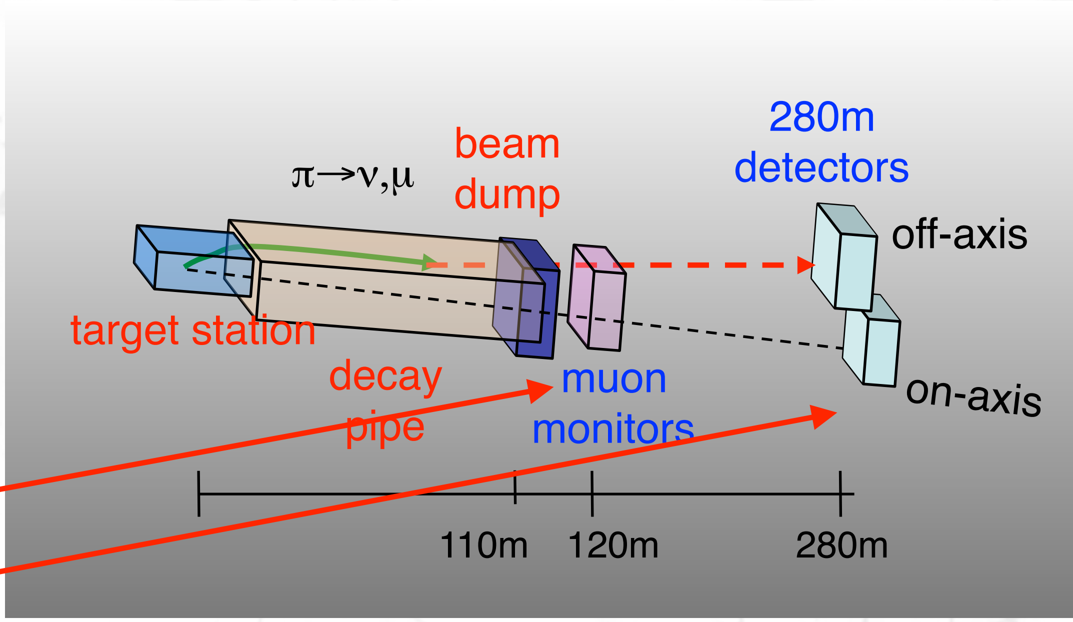

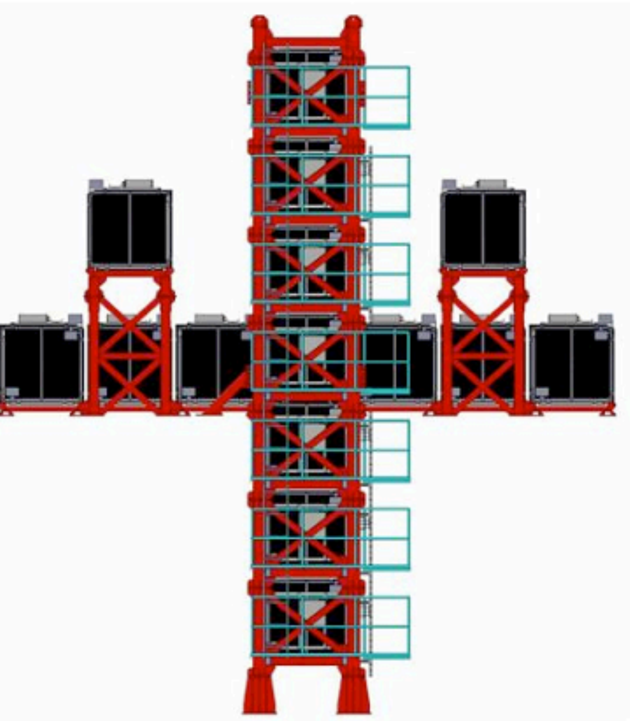

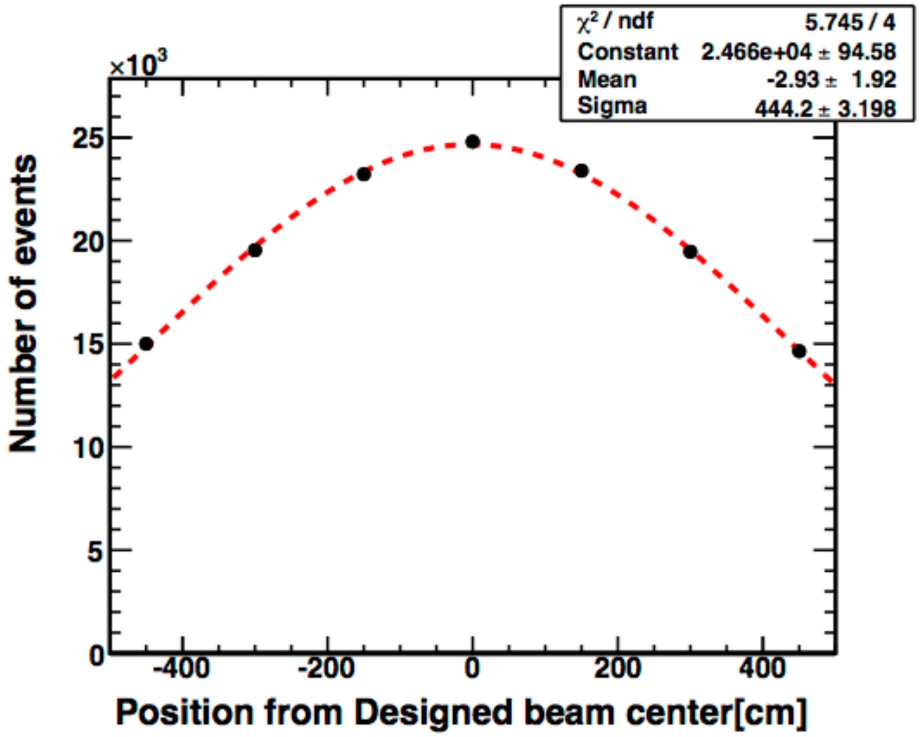

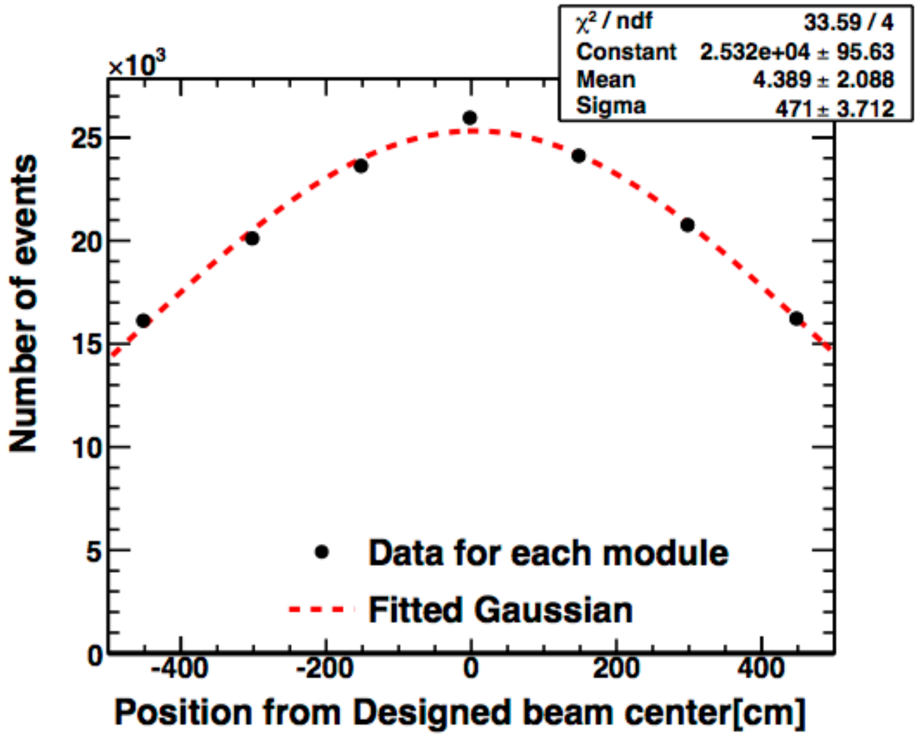

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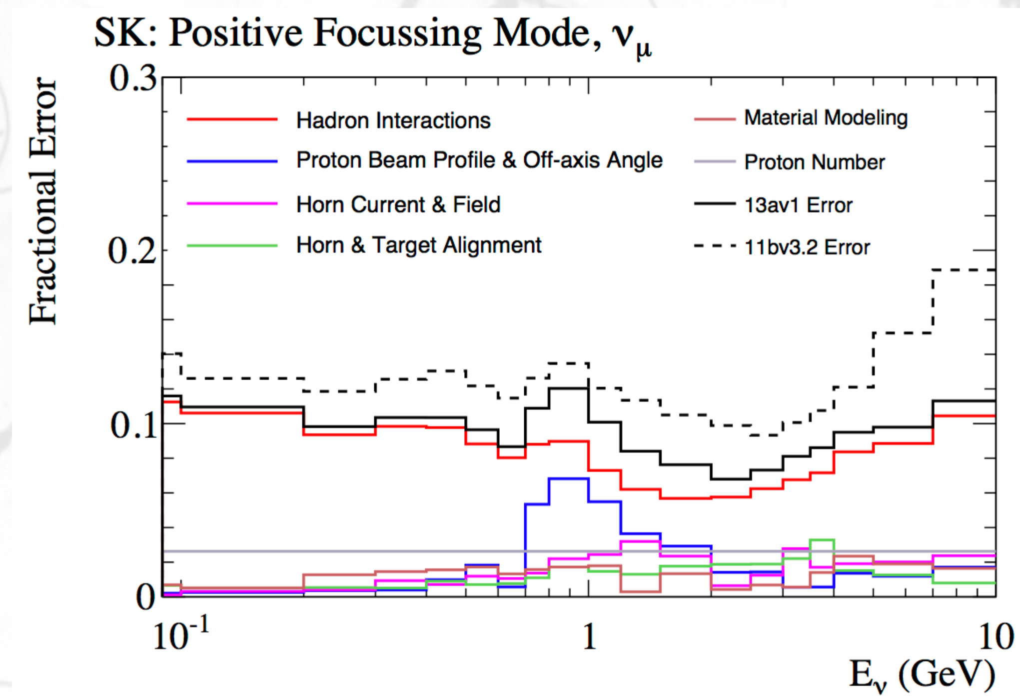
Flux ingredients



External

- pA hadron spectra
- target geometry

Simulations

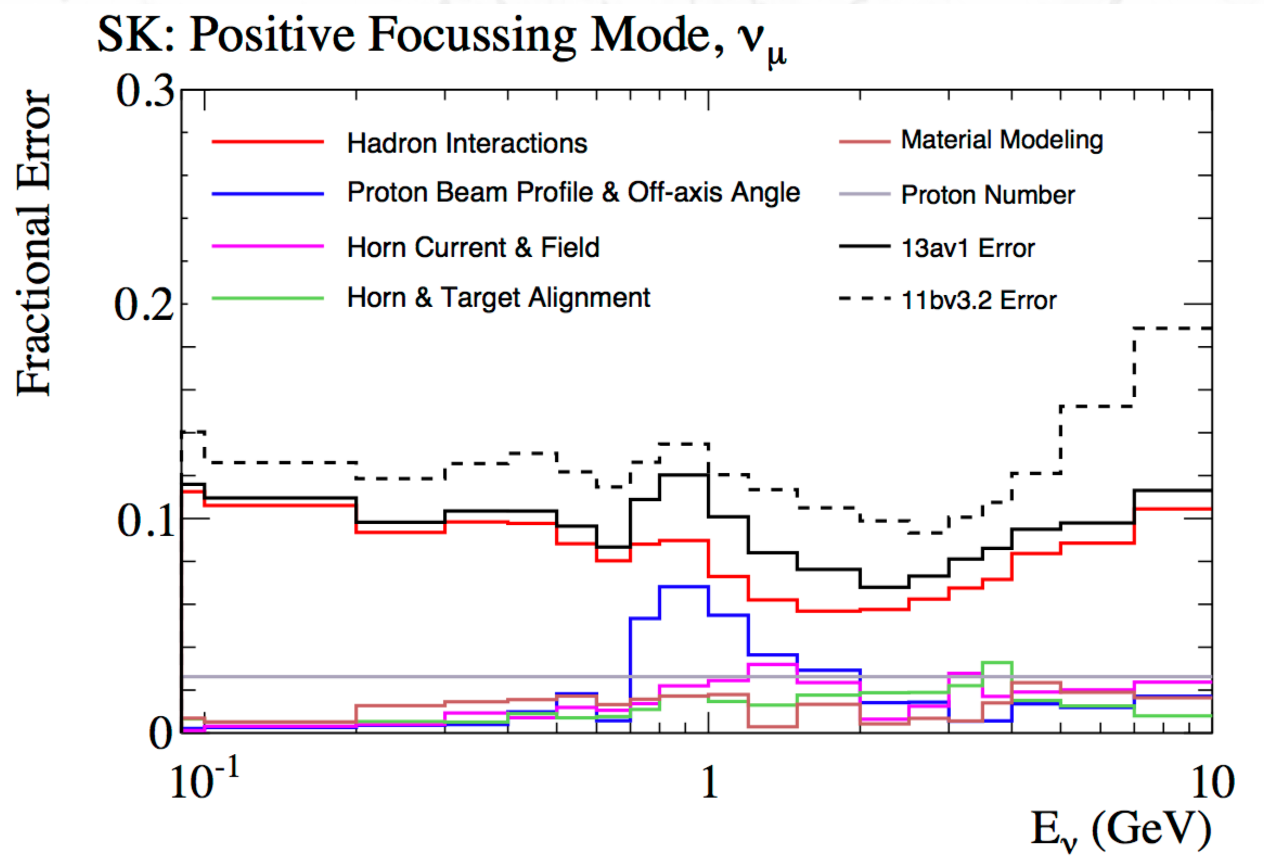
- decay volume
- material description

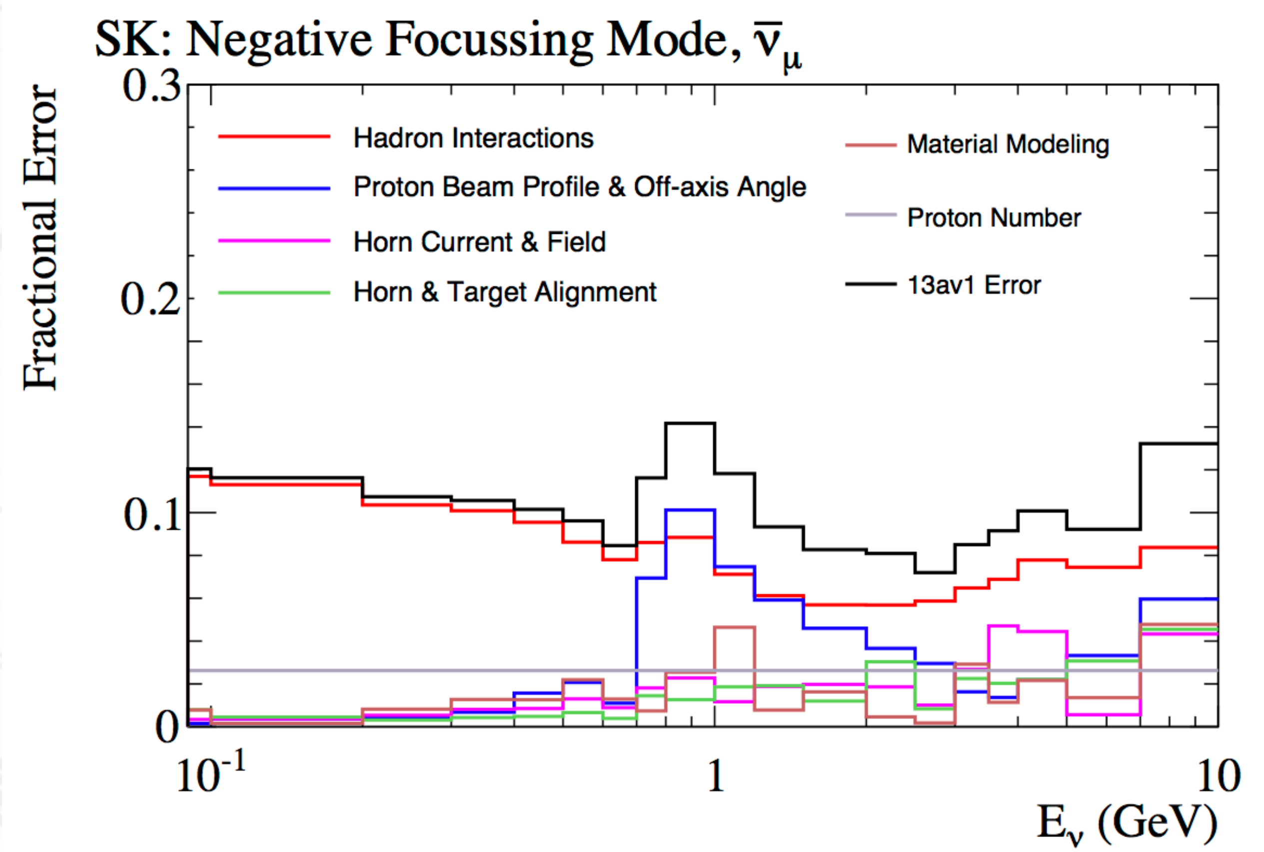
Beam monitor

- horn current
- beam-target alignment
- beam direction

→ Flux Far
→ Flux Near

Flux errors





(10-15% error) Error is dominated by hadro-production :
+ more data
+ more precise data using the replica target.

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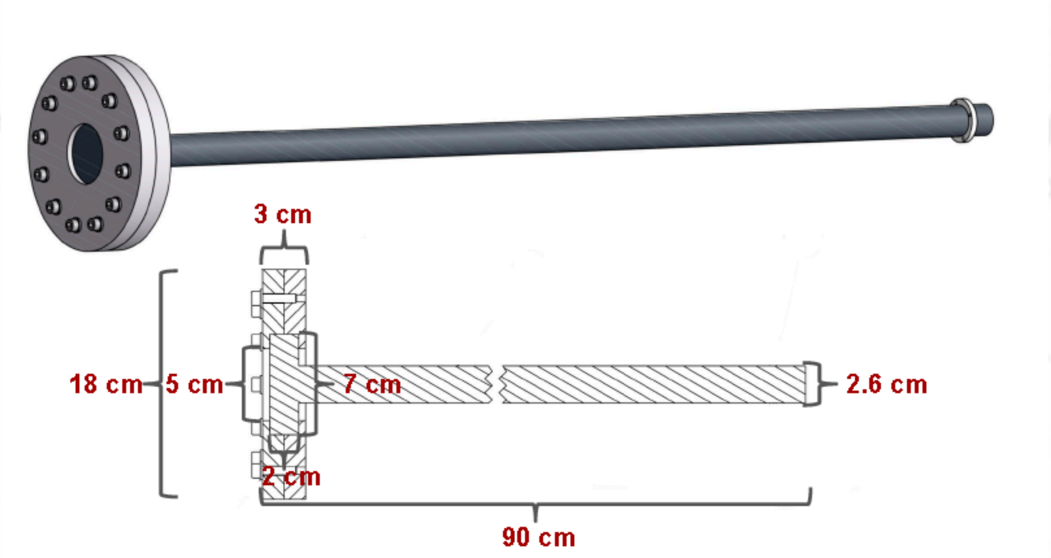
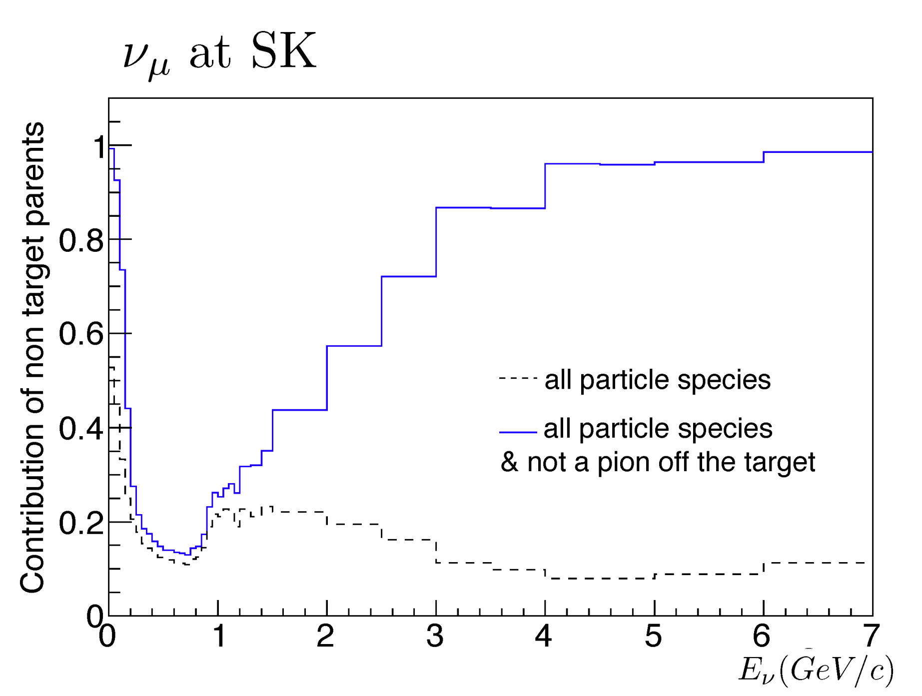
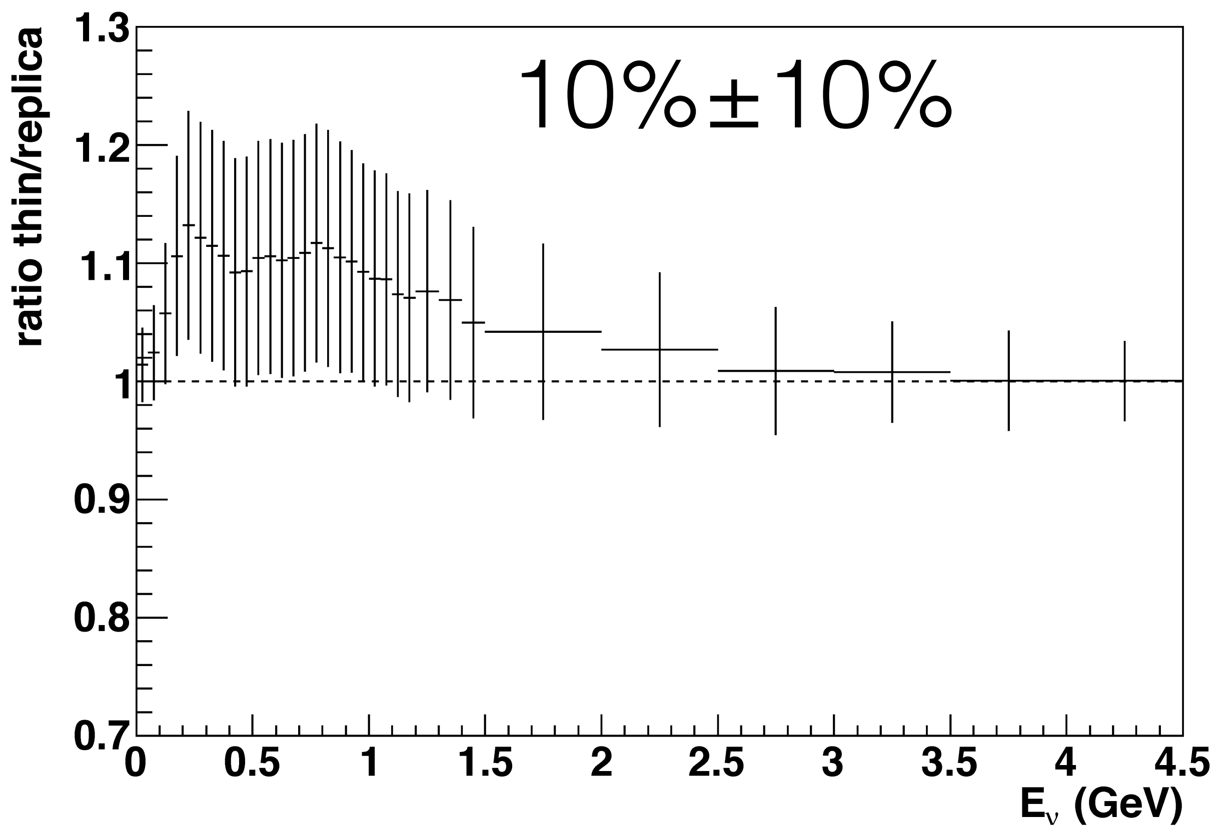
Replica target



- Hadrons can suffer re-scattering before leaving the target.



Fraction of events from the target with no interactions.



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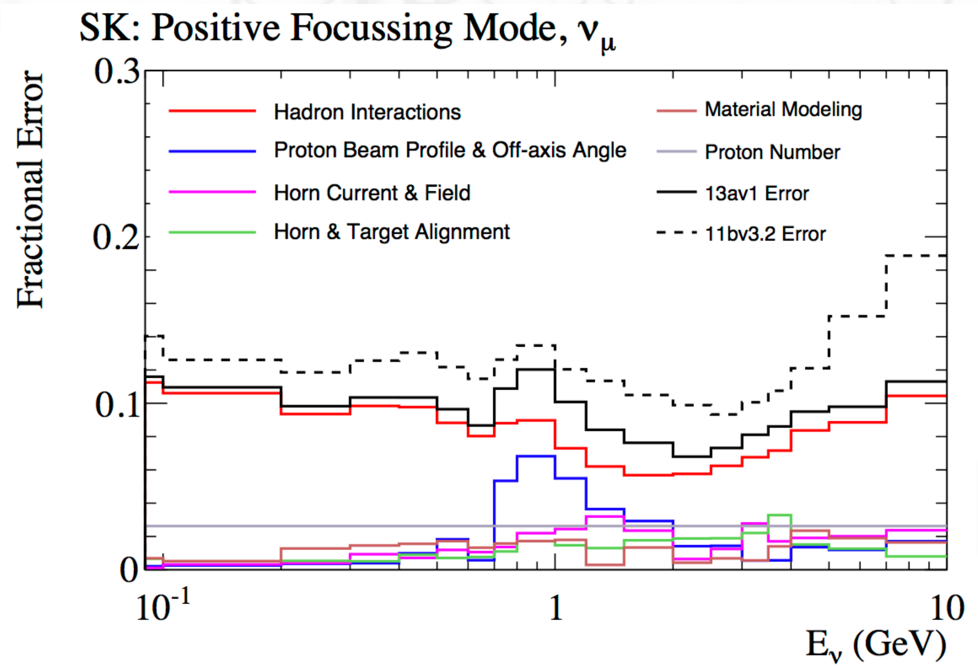
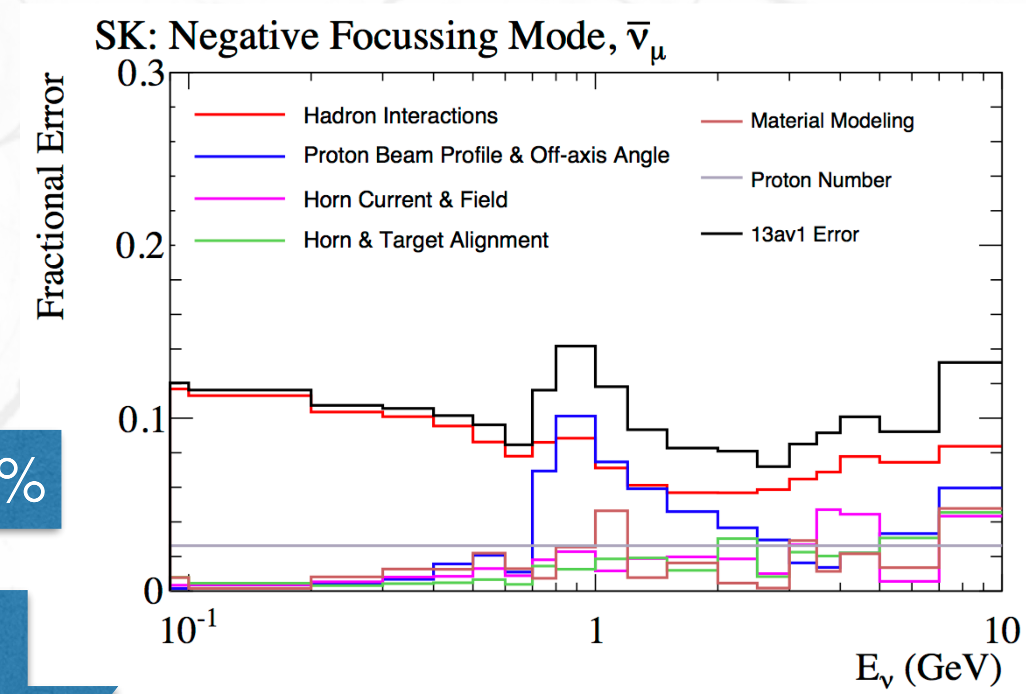
Replica target

Thin

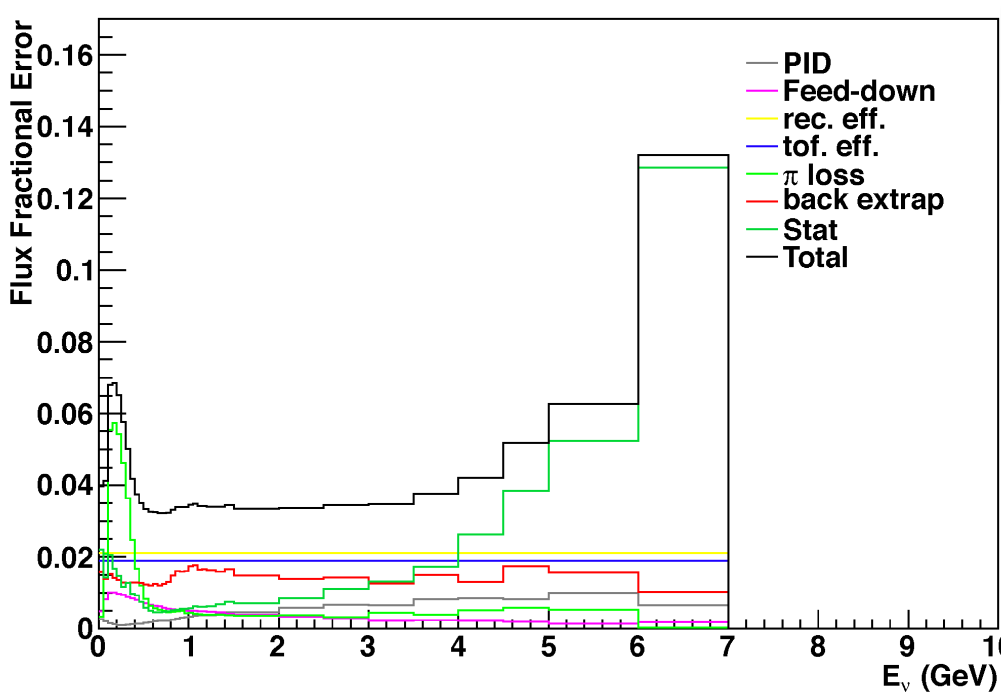


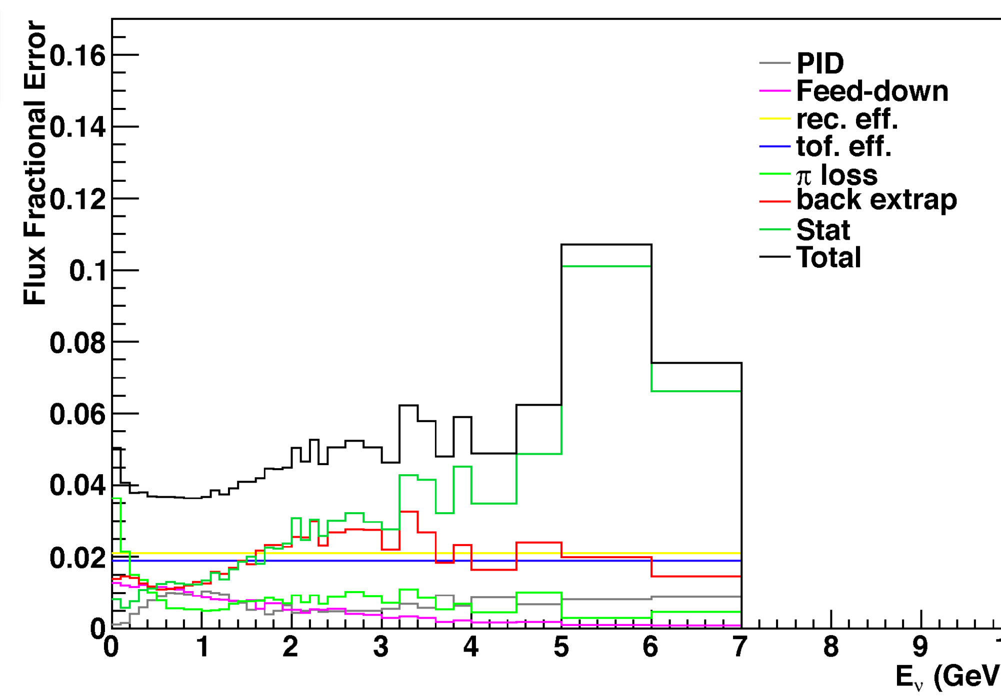


10%

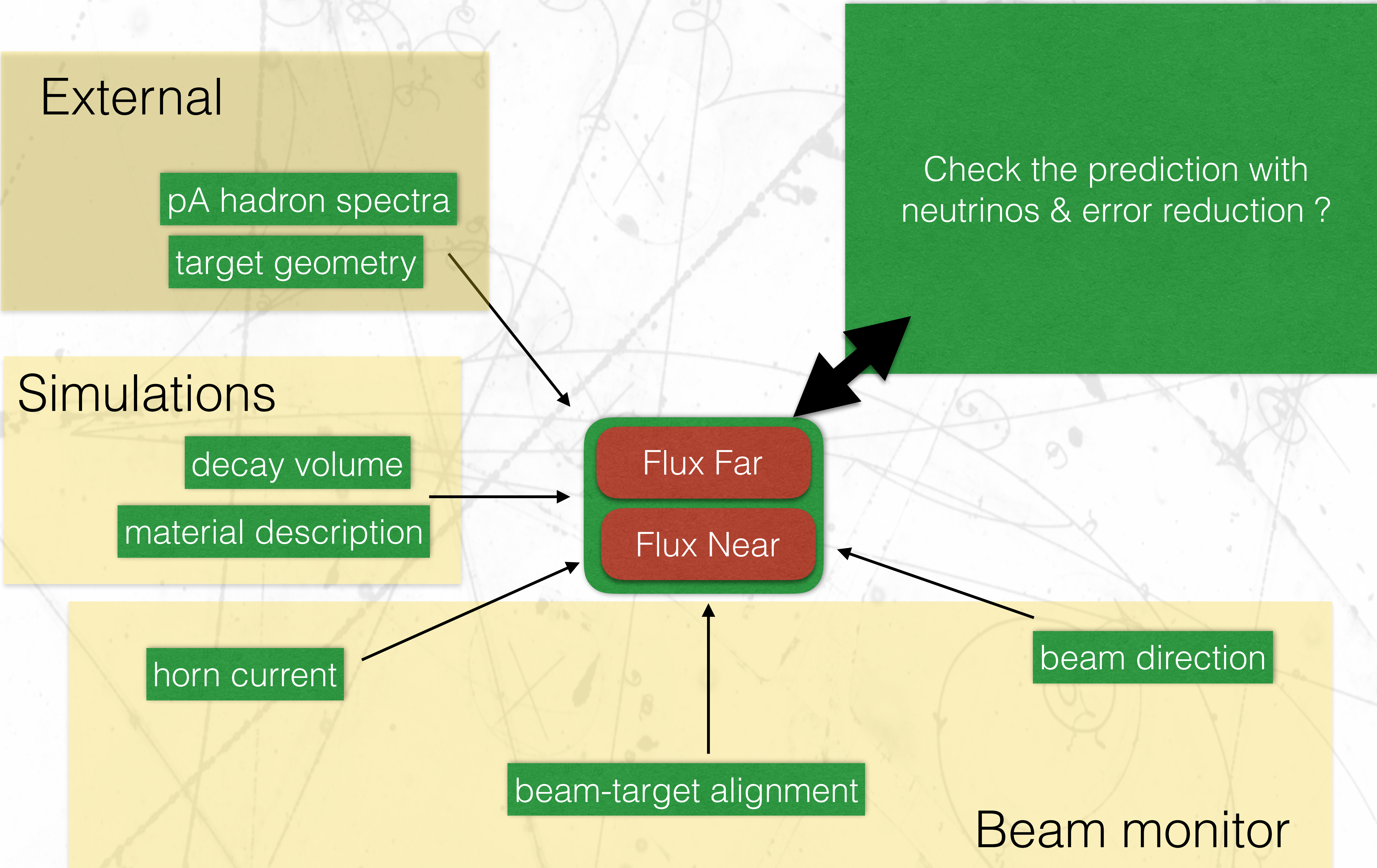
4%

Replica





Flux ingredients



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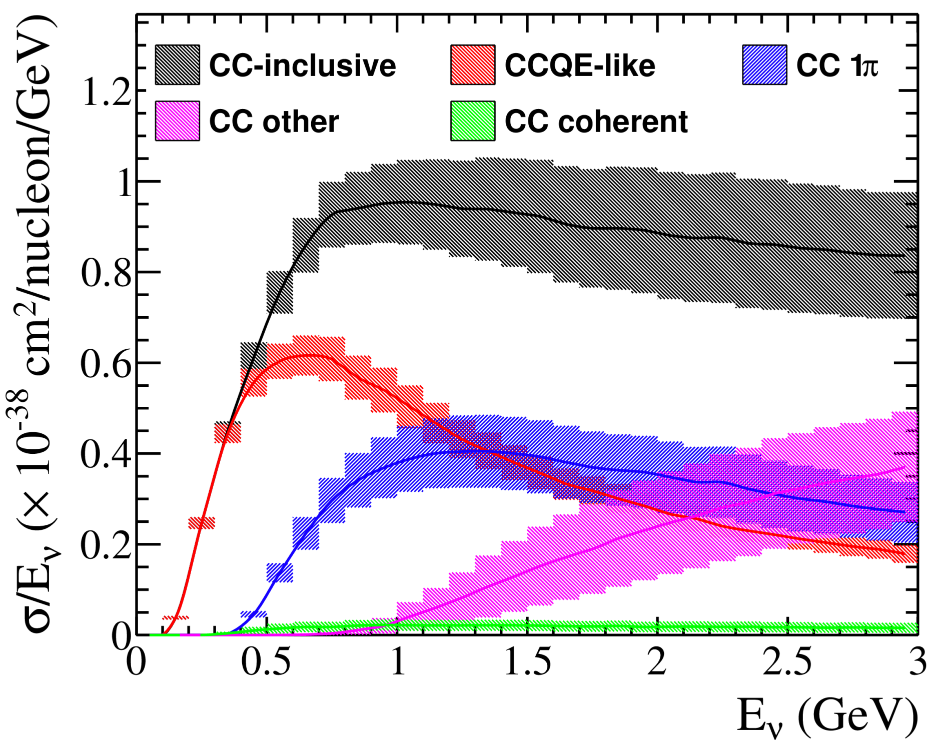
Near detector

- The near detector looks into the neutrino flux through the interaction of neutrinos with matter.
- We measure:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

- The main problem is that the cross-sections are not well known in to aspects:
    - Total cross-section
    - Final states



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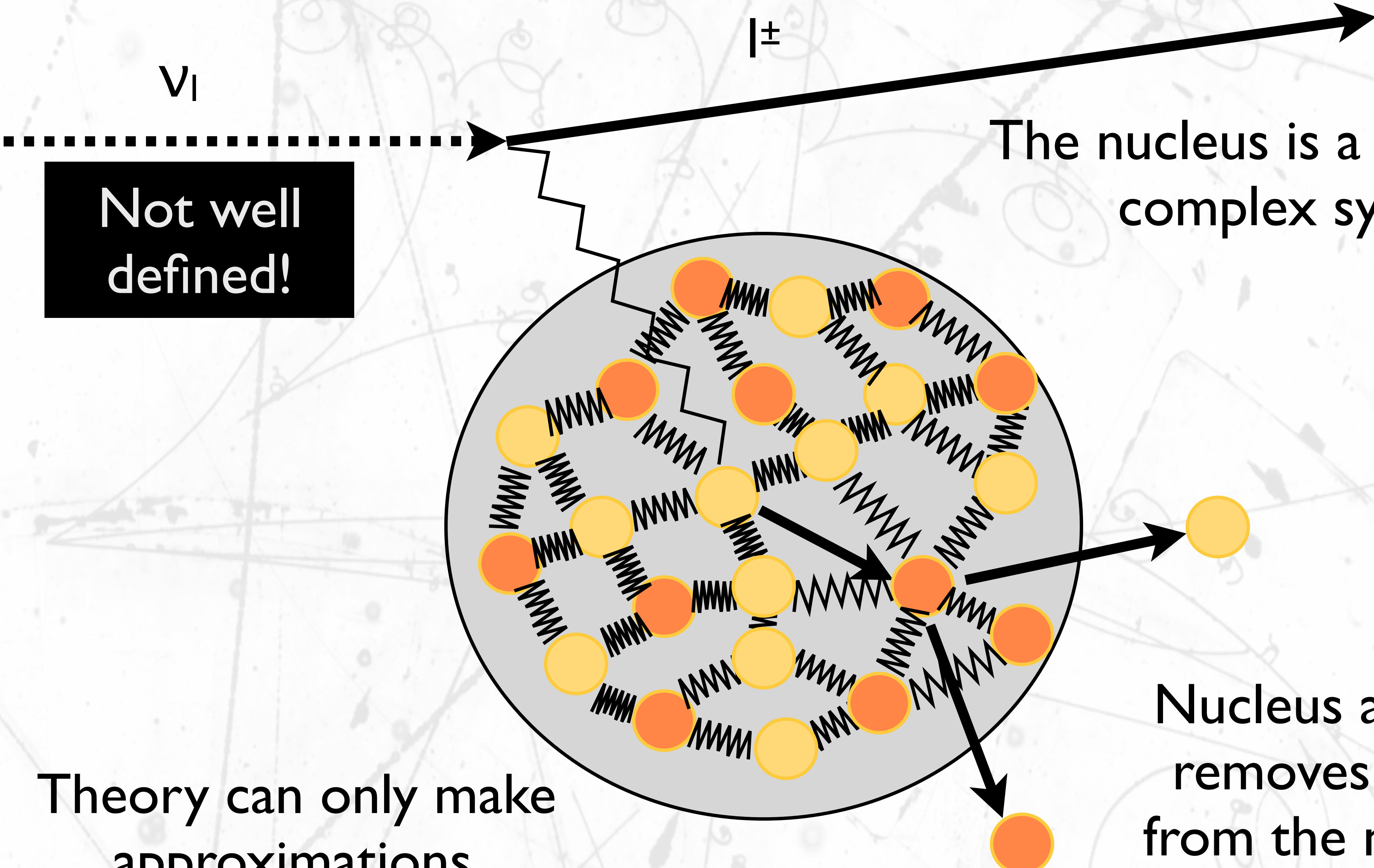
Cross-sections



Not well defined!

The nucleus is a many body complex system.

Theory can only make approximations.

Nucleus adds and removes energy from the neutrino.

The neutrino-nucleon is not well known (form factors)
The nucleus distort both the total cross-section and the products of the interactions.

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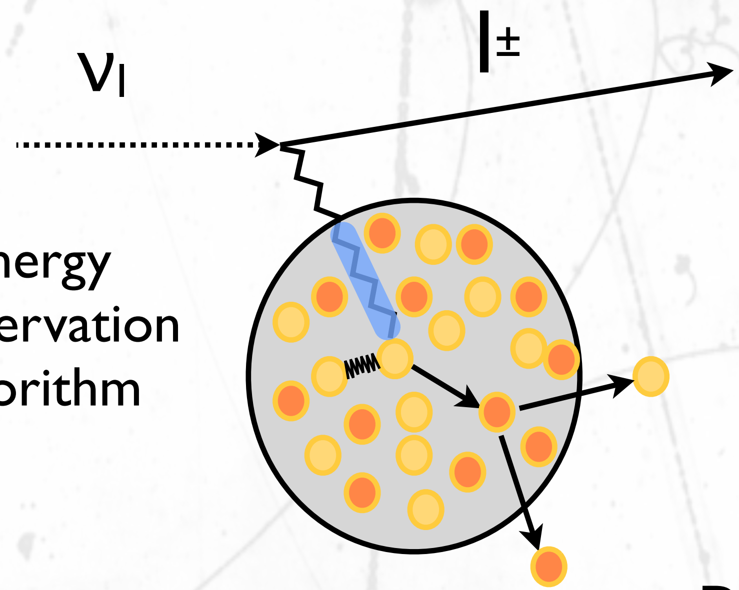
Event selection: topology

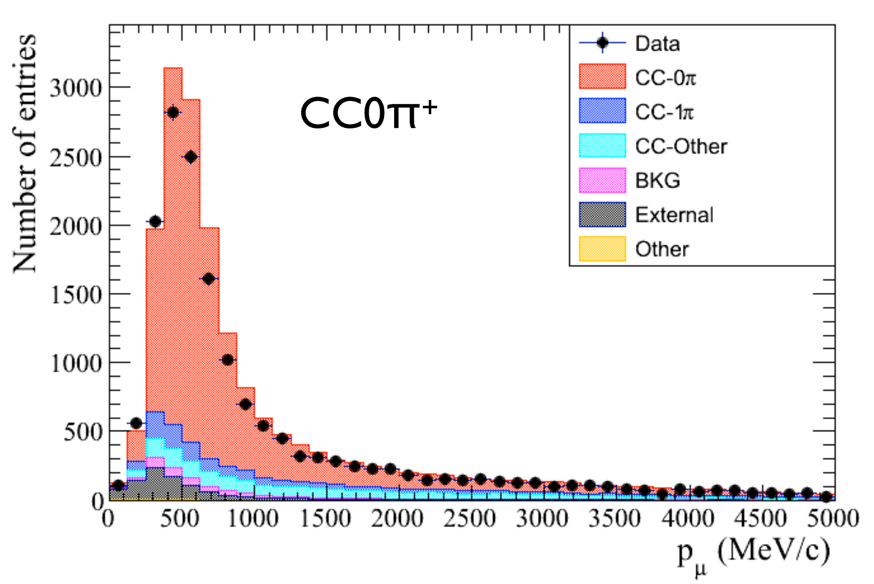


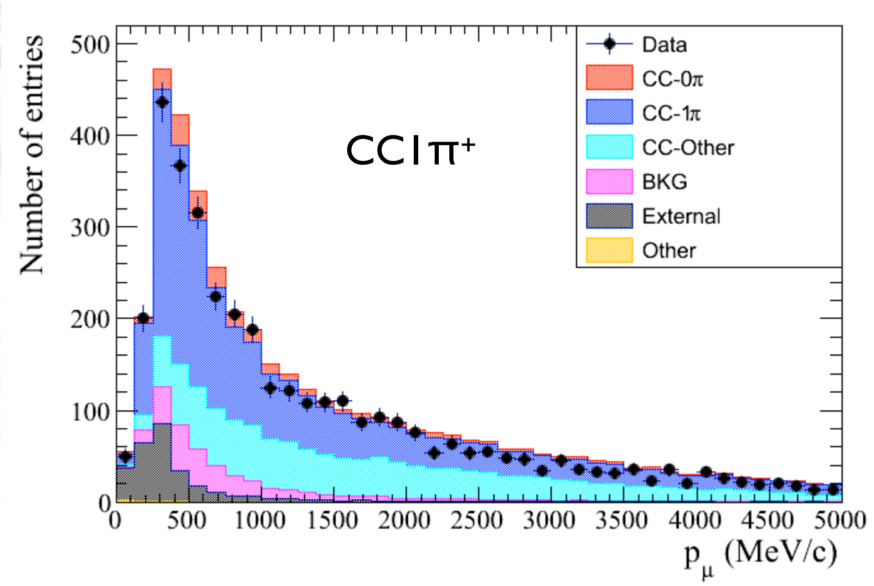
Energy conservation algorithm

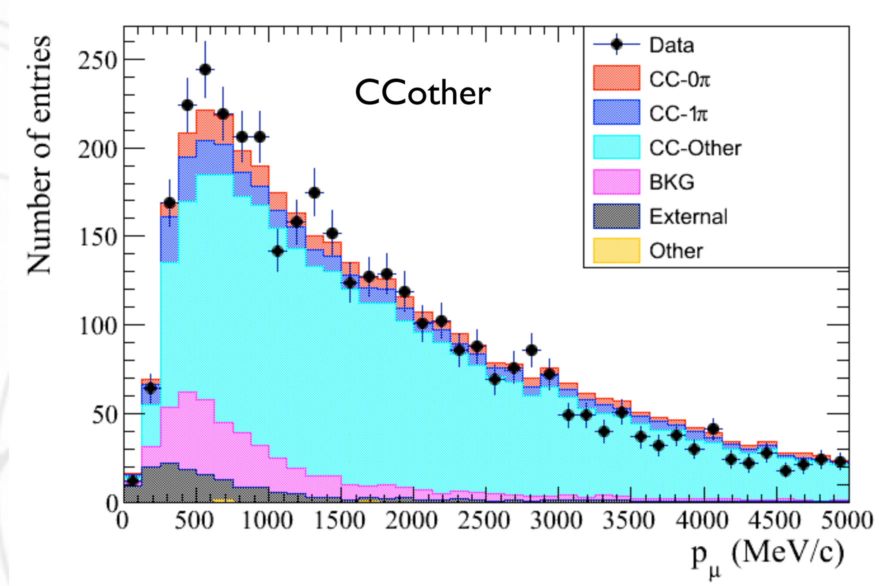
Detector observation: Topologies

- Topologies are based on the presence of pions and or protons in the final state.

- This is an excellent way to unify data releases at different experiments to allow for comparisons.







X 2 (HORN CONF.) X 2 (NEUTRINO-ANTINEUTRINO)+ELECTRONS

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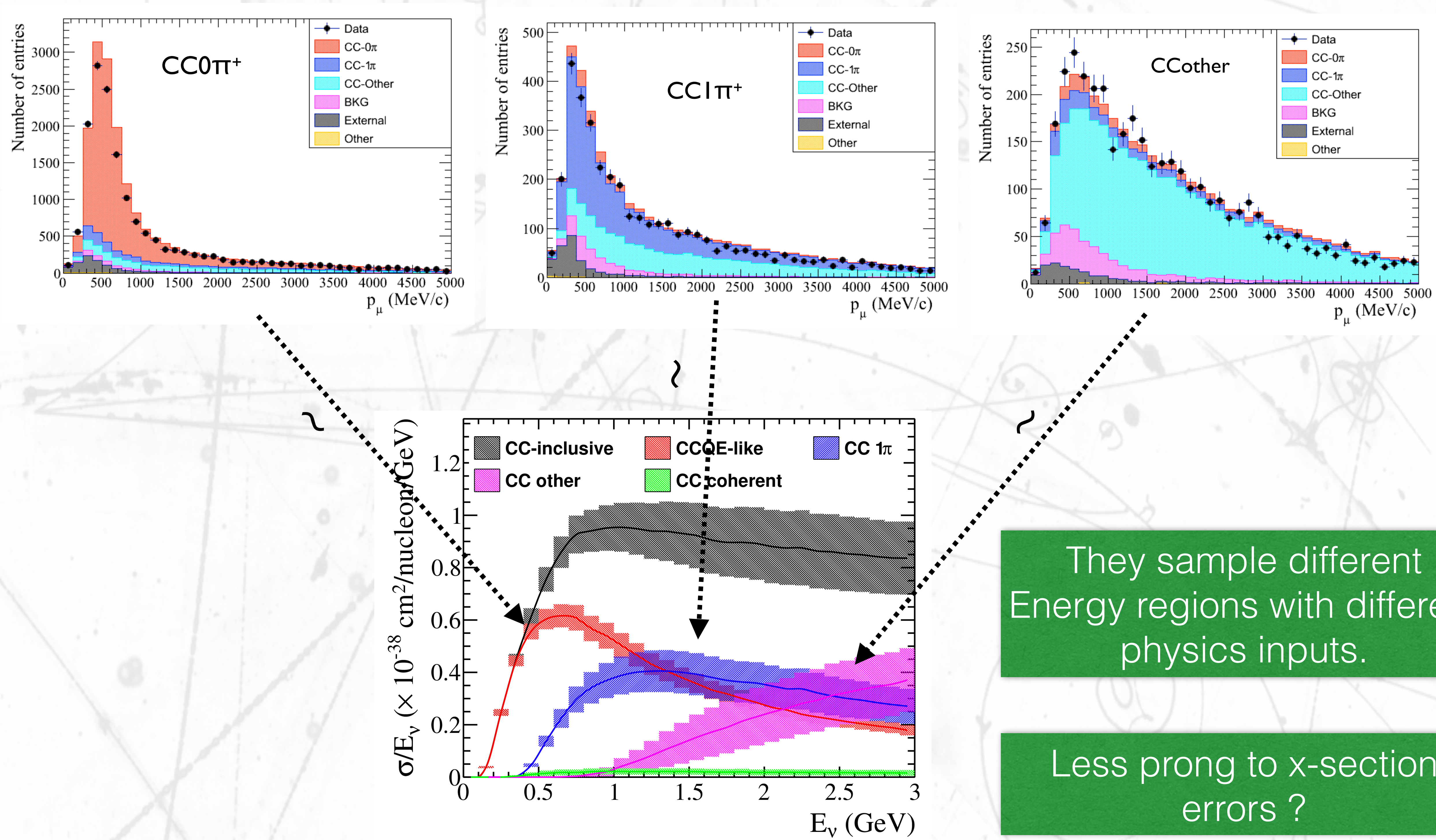
Why topologies?

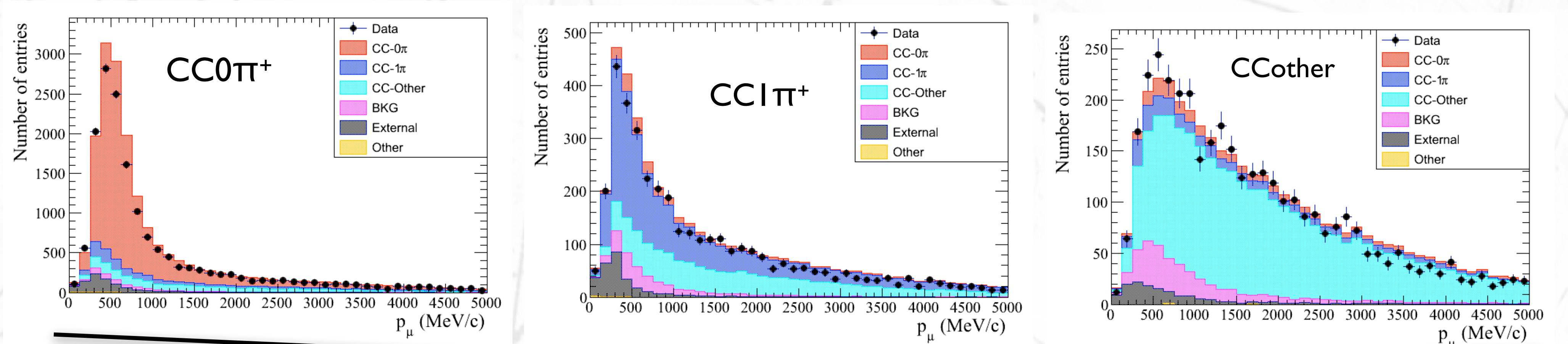


They sample different Energy regions with different physics inputs.

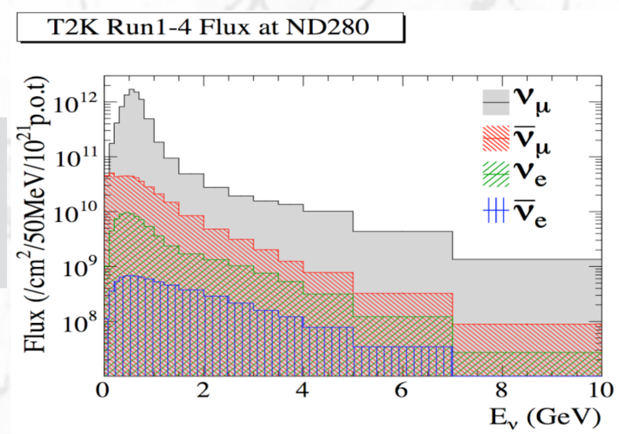
Less prong to x-section errors ?

Role of Near detector

Near detector data

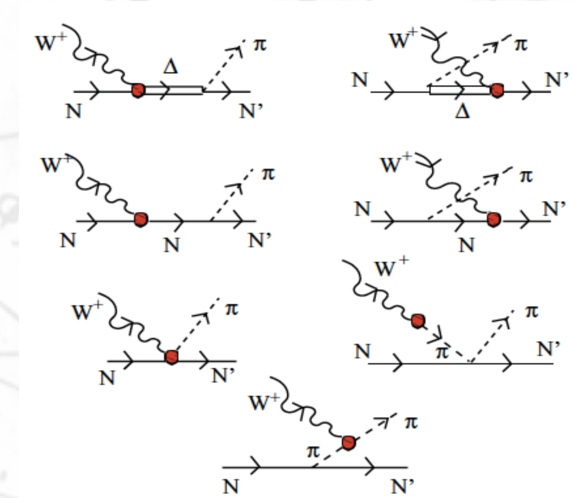


⊕ Hadron production flux prediction

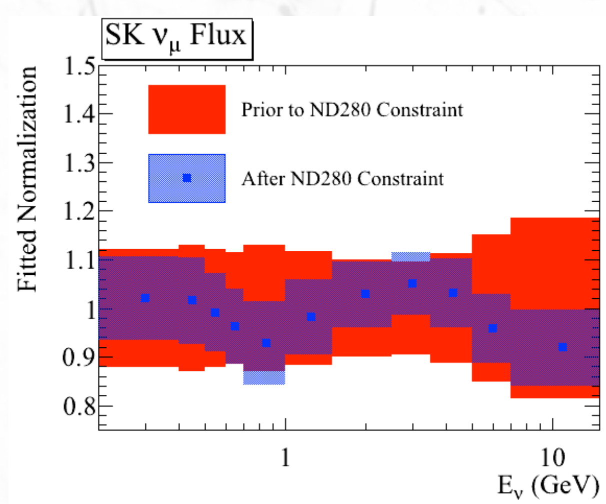


⊕ Cross-section model

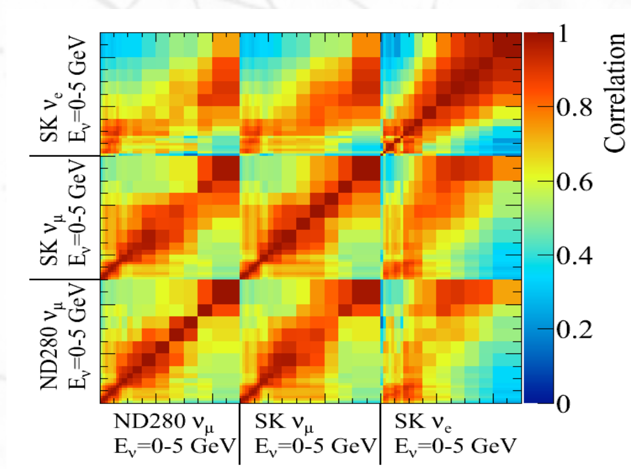
Feed back



= Corrected flux and cross-section model



& correlation



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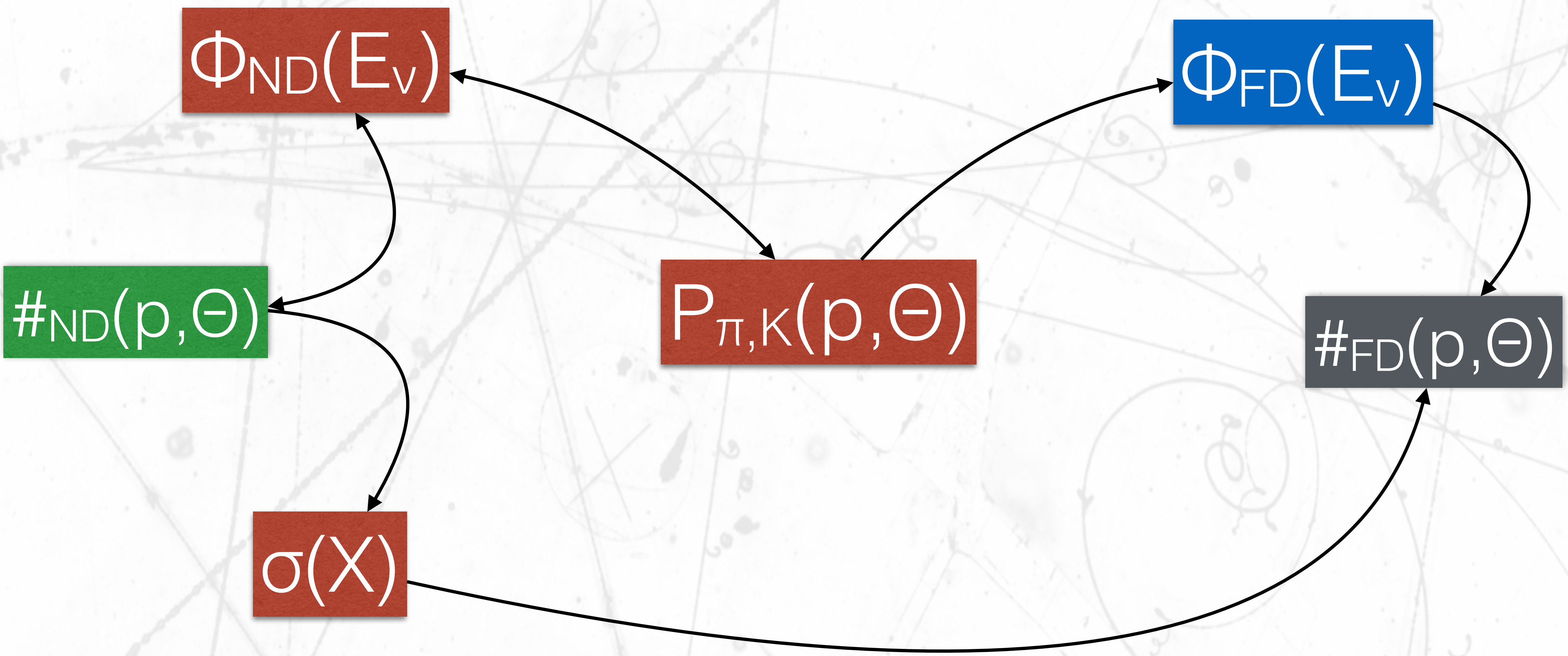
Flux Fit

- The Fit is not fitted but the underlying pion and kaon production probabilities:



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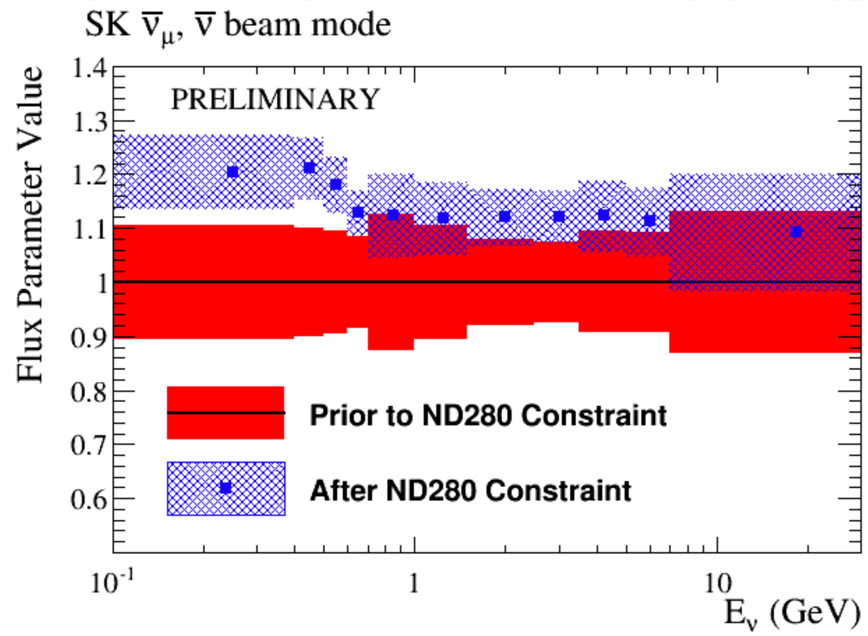
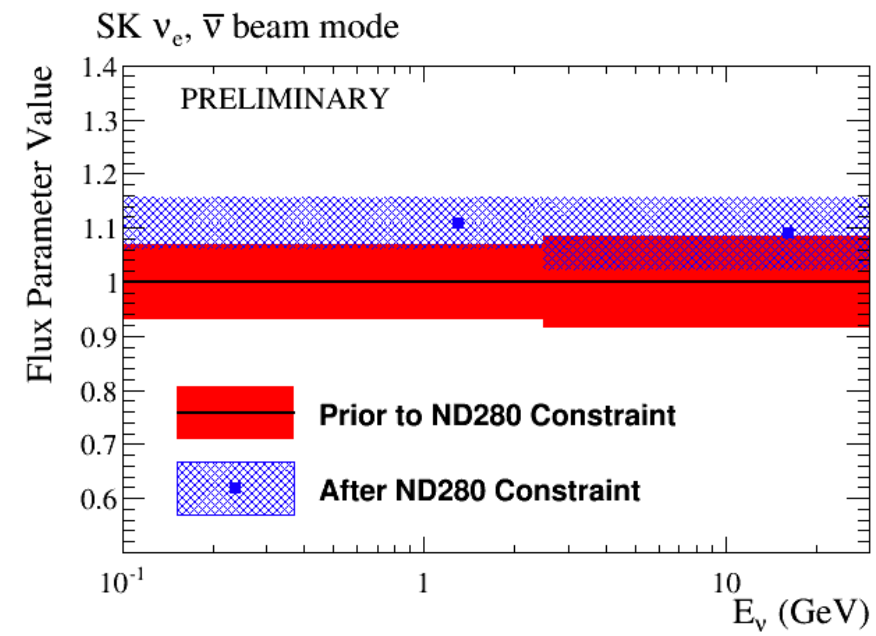
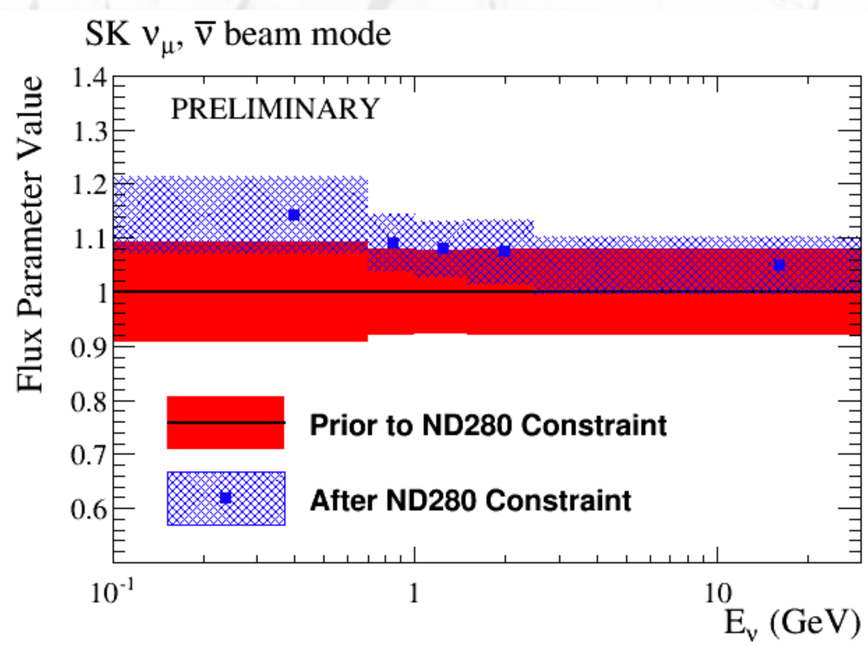
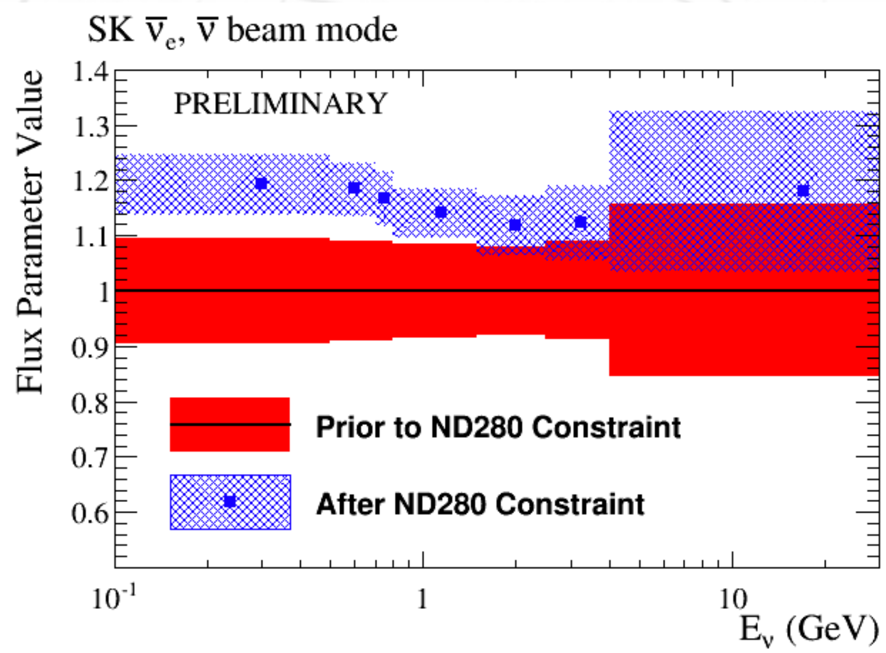
Flux are corrected

We need to obtain the 4 ν species (ν_e & ν_μ + antineutrinos) for the two horn polarizations: forward and reversed.

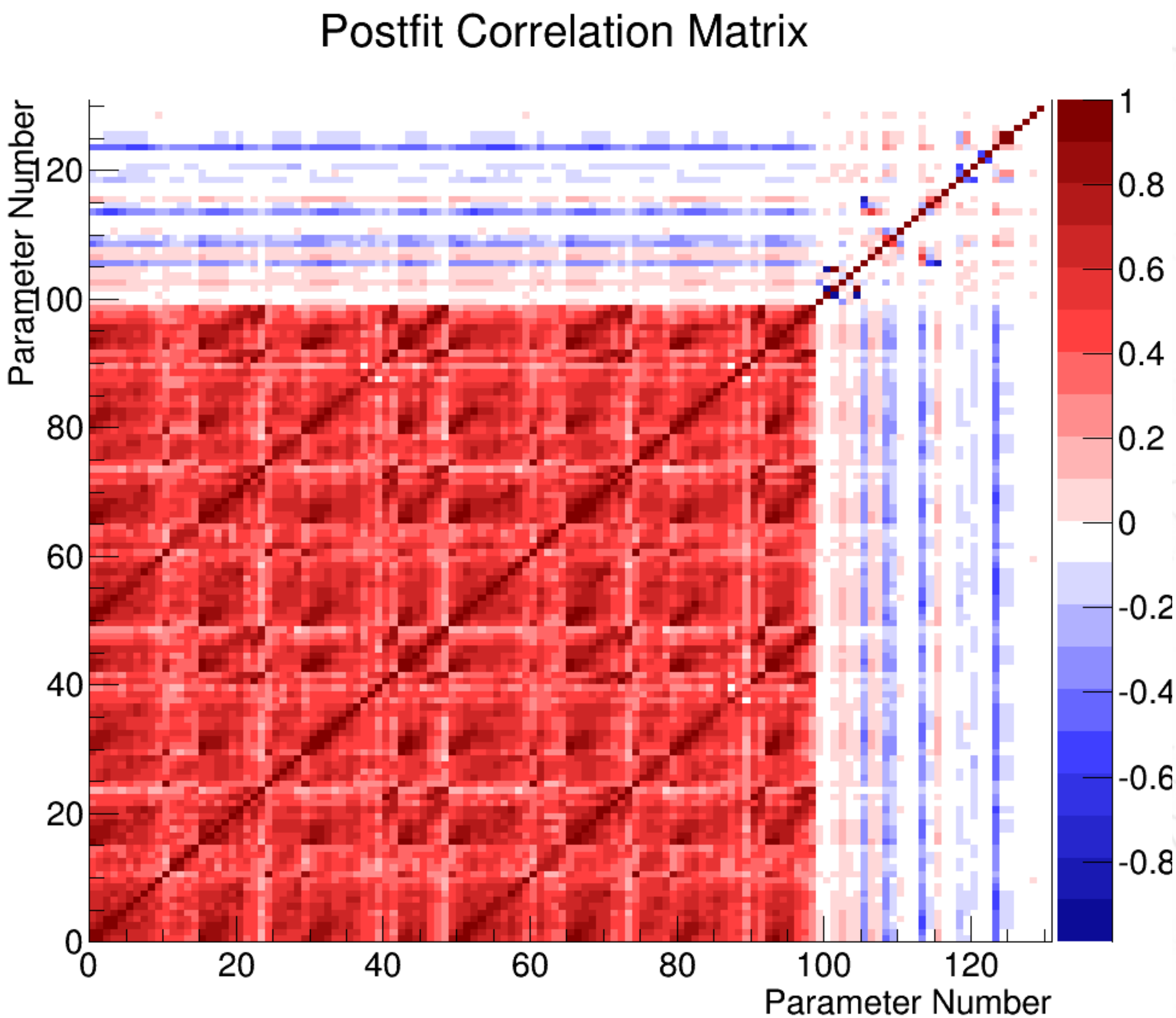








at the expense of correlating flux and cross-sections



This measurement is not taken as a cross-section measurement.
T2K tries to improve on cross-sections with observables that are flux independent.

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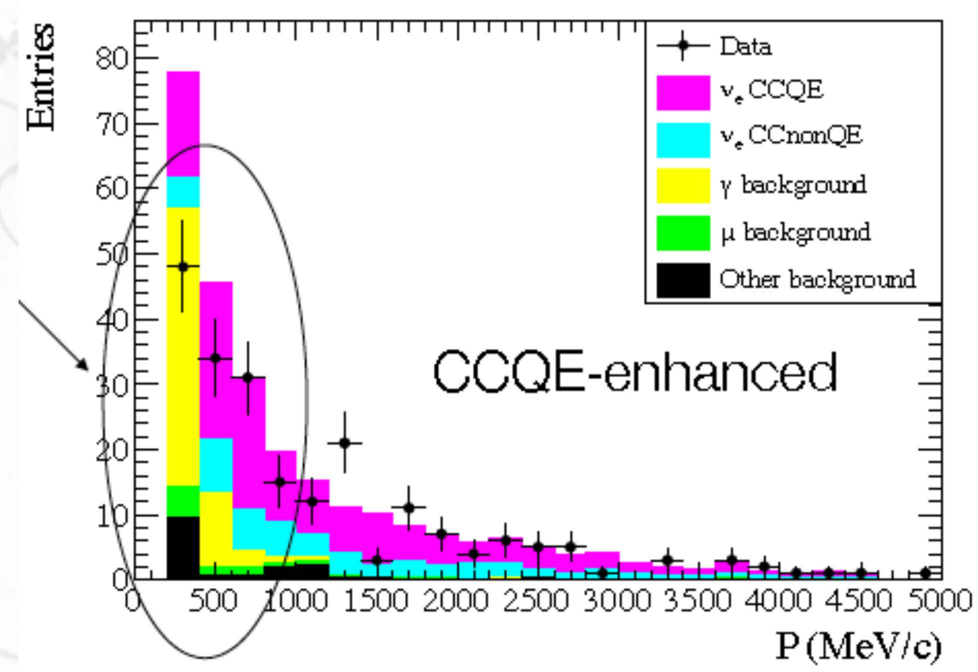
what about ν_e?

- The intrinsic electron neutrino is the main background for ν_e appearance and CP violation measurement.
- But, it is a difficult measurement:
  - Flux is low.
  - Large background of gamma's from ν_μ
- We rely (mainly) on the ν_μ - ν_e relation from the hadroproduction model.



Even more complex for antineutrinos.

As a consequence we do not get a good constrained on ν_eA cross-sections.

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FACULTÉ DES SCIENCES

Final remarks

- Obtention of the neutrino flux is not a trivial task but it is a critical one for CP violation and oscillation experiments.
- It requires:
  - complex hadro-production experiments.
  - cross-section models.
  - near detector neutrino interactions.
  - precise beam monitoring
  - complex fits.

T2K groups

- NA61
- NIWG
- ND280
- BEAM
- BANFF