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Fluxes and systematics reduction with decay monitoring

A. Branca* @ NuFact2021 – ENUBET/nuSTORM Workshop

University & INFN of Milano-Bicocca

*on behalf of the ENUBET Collaboration

Outline

- Systematic uncertainties on neutrino flux:
  - main contributions;
  - current method for systematics assessment;

- Systematics on neutrino flux with lepton monitoring:
  - constraining the flux exploiting leptons observables;
  - fit model for the flux constraint;
  - validation of a toy fit model;

- Conclusions and next steps;

Systematics on ν-flux

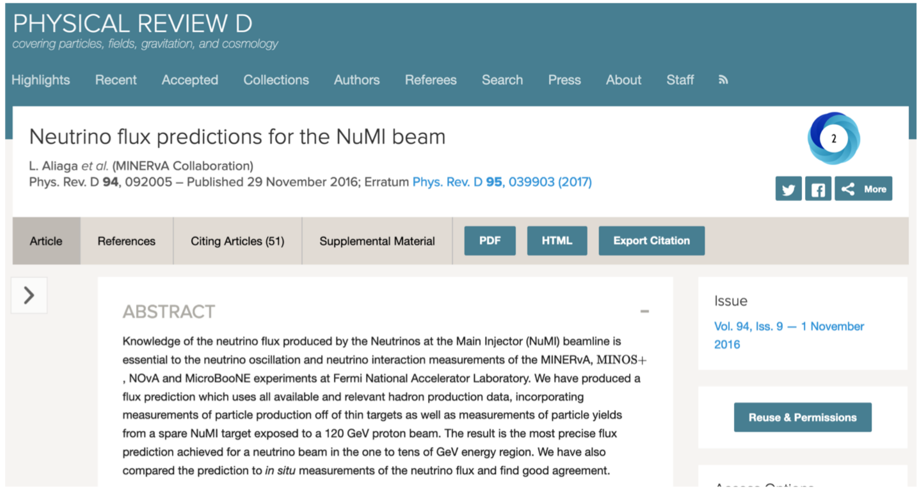
Sources of systematic uncertainties with major impact on neutrino fluxes:

- ➢ hadro-production;
- ➢ beamline geometry & focusing;

For instance, looking at **MINERvA** and **T2K** Collaborations:

- ❖ hadro-production: dominant contribution
  - MINERvA: $\sim 7\%$ around the ν-flux peak & $\sim 9\%$ at high energy ($E_\nu \gtrsim 7\ GeV$);
  - T2K: $\sim 10\%$ around the ν-flux peak & $\sim 15 - 18\%$ in the high energy tail ($E_\nu \gtrsim 5\ GeV$);
- ❖ beamline geometry & focusing: after hadro-production is the main contribution
  - MINERvA: dominant, $\sim 6\%$, in the region where the flux decreases (4-5 GeV);
  - T2K: comparable to hadro-production around the ν-flux peak;

- ➢ MINERvA further improves flux precision ($\sim 4\%$) with $\nu_\mu e^-$ scattering;
- ➢ T2K furrther improves flux precision (~5%) with replica target;



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Neutrino flux predictions for the NuMI beam
L. Aliaga *et al.* (MINERvA Collaboration)
Phys. Rev. D **94**, 092005 – Published 29 November 2016; Erratum Phys. Rev. D **95**, 039903 (2017)

Article | References | Citing Articles (51) | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

Knowledge of the neutrino flux produced by the Neutrinos at the Main Injector (NuMI) beamline is essential to the neutrino oscillation and neutrino interaction measurements of the MINERvA, MINOS+, NOvA and MicroBooNE experiments at Fermi National Accelerator Laboratory. We have produced a flux prediction which uses all available and relevant hadron production data, incorporating measurements of particle production off of thin targets as well as measurements of particle yields from a spare NuMI target exposed to a 120 GeV proton beam. The result is the most precise flux prediction achieved for a neutrino beam in the one to tens of GeV energy region. We have also compared the prediction to *in situ* measurements of the neutrino flux and find good agreement.

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T2K neutrino flux prediction
K. Abe *et al.* (T2K Collaboration)
Phys. Rev. D **87**, 012001 – Published 2 January 2013; Erratum Phys. Rev. D **87**, 019902 (2013)

Article | References | Citing Articles (135) | PDF | HTML | Export Citation

ABSTRACT

The Tokai-to-Kamioka (T2K) experiment studies neutrino oscillations using an off-axis muon neutrino beam with a peak energy of about 0.6 GeV that originates at the Japan Proton Accelerator Research Complex accelerator facility. Interactions of the neutrinos are observed at near detectors placed at 280 m from the production target and at the far detector—Super-Kamiokande—located 295 km away. The flux prediction is an essential part of the successful prediction of neutrino interaction rates at the T2K detectors and is an important input to T2K neutrino oscillation and cross section measurements. A FLUKA and GEANT3-based simulation models the physical processes involved in the neutrino production, from the interaction of primary beam protons in the T2K target, to the decay of hadrons and muons that produce neutrinos. The simulation uses proton beam monitor measurements as inputs. The modeling of hadronic interactions is reweighted using thin target hadron production data, including recent charged pion and kaon measurements from the NA61/SHINE experiment. For the first T2K analyses the uncertainties on the flux prediction are evaluated to be below 15% near the flux peak. The uncertainty on the ratio of the flux predictions at the far and near detectors is less than 2% near the flux peak.

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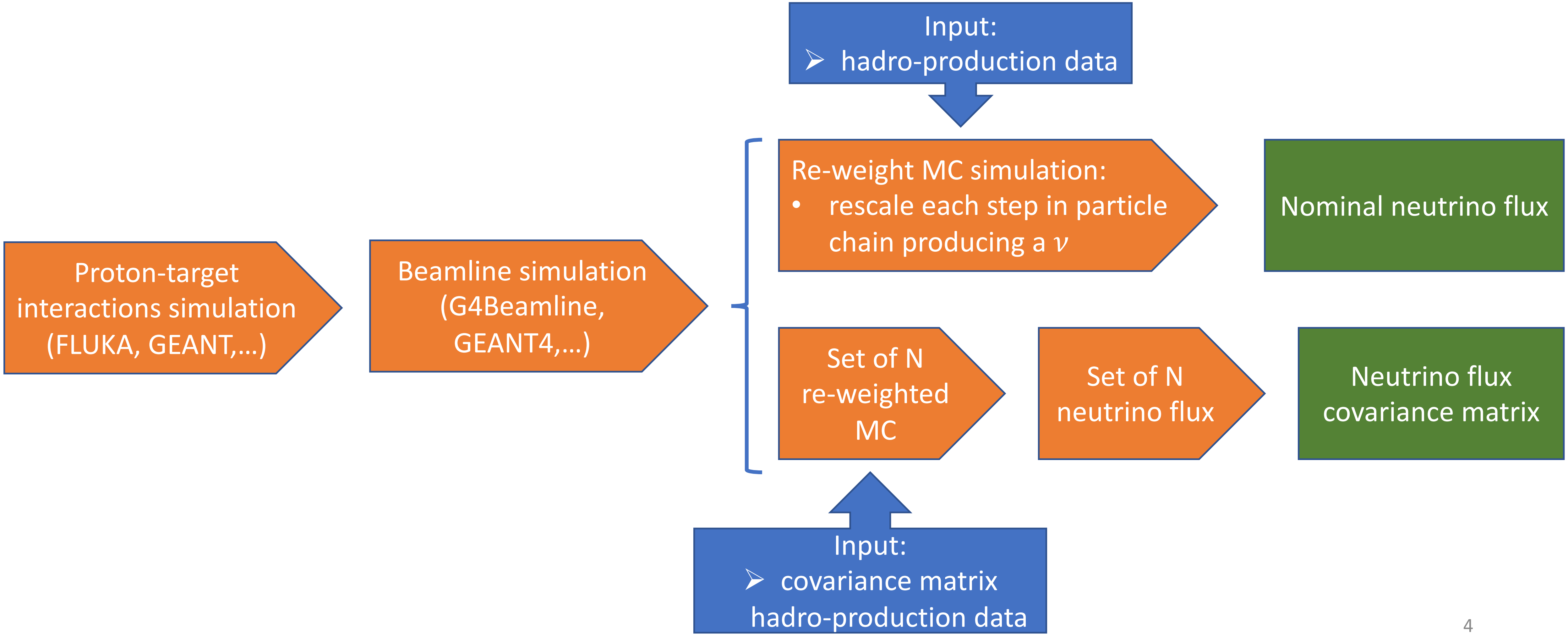
Systematics on ν-flux

In general, how are the systematic contribution treated:

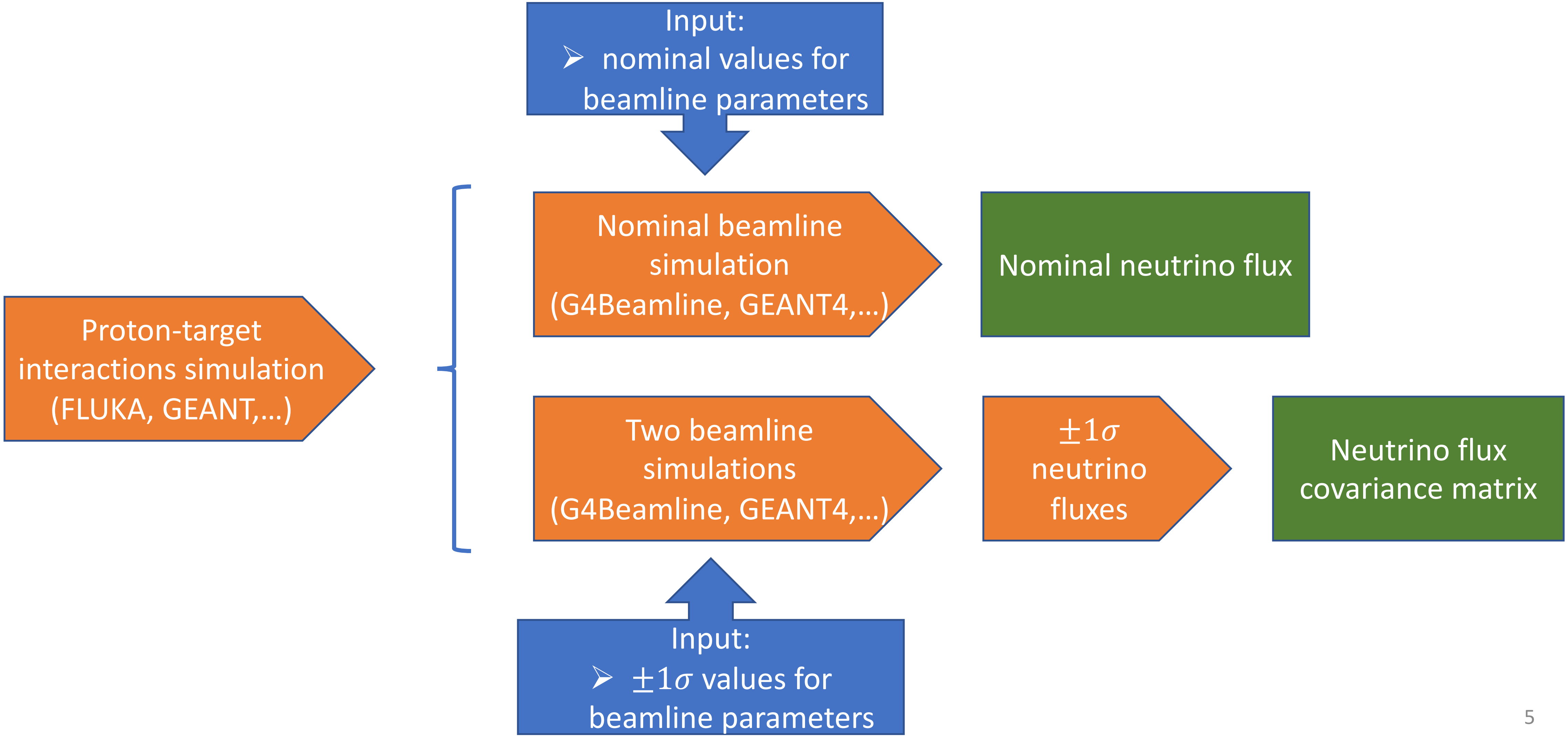
❖ Hadro-production: interaction of protons w/ target & hadrons produced inducing neutrinos



Systematics on ν-flux

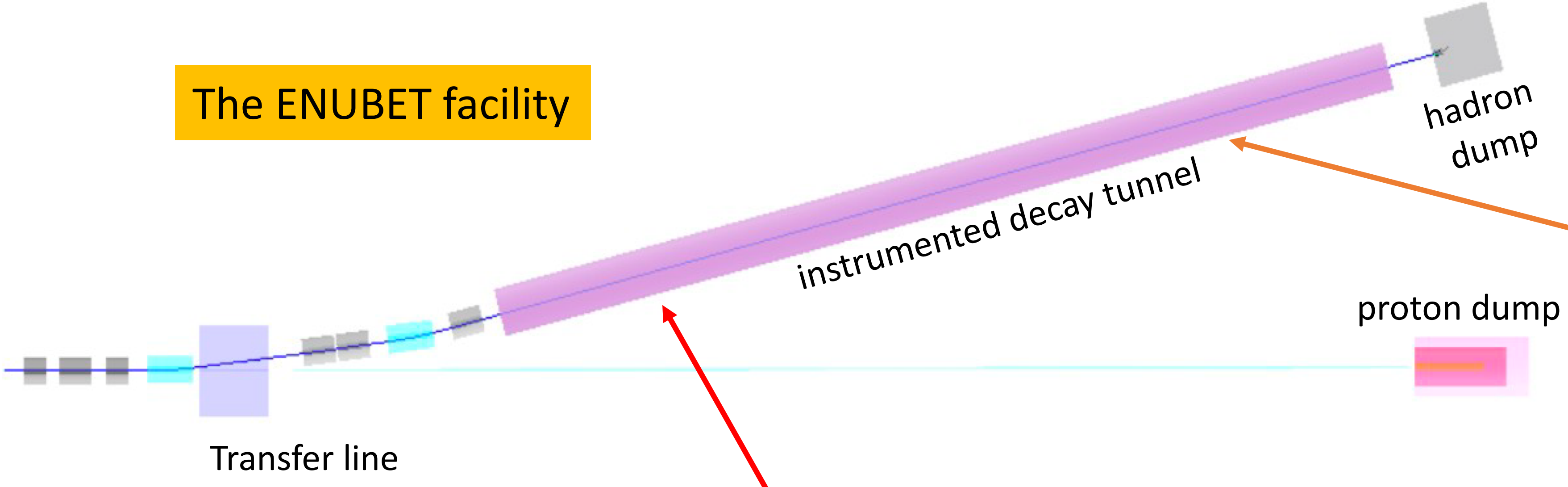
In general, how are the systematic contribution treated:

- beamline geometry & focusing: alignment & shape of magnetic elements, fields



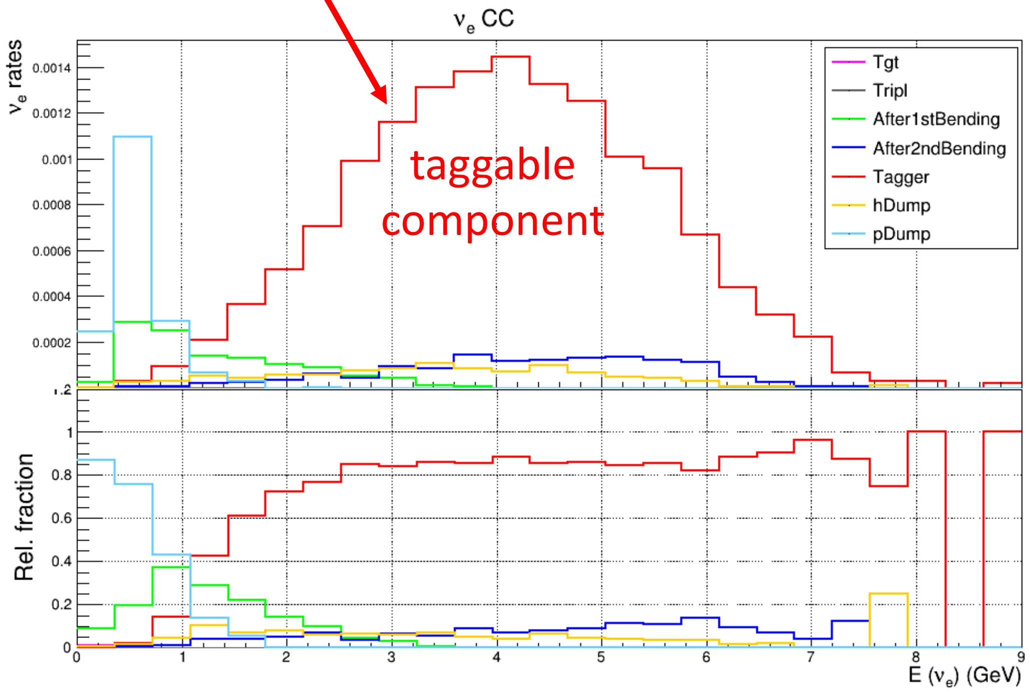
ENUBET: monitoring leptons from K/π decays

The ENUBET facility



In ENUBET we have access to the observables related to the leptons produced together with neutrinos (taggable component)

Constrain on neutrino flux



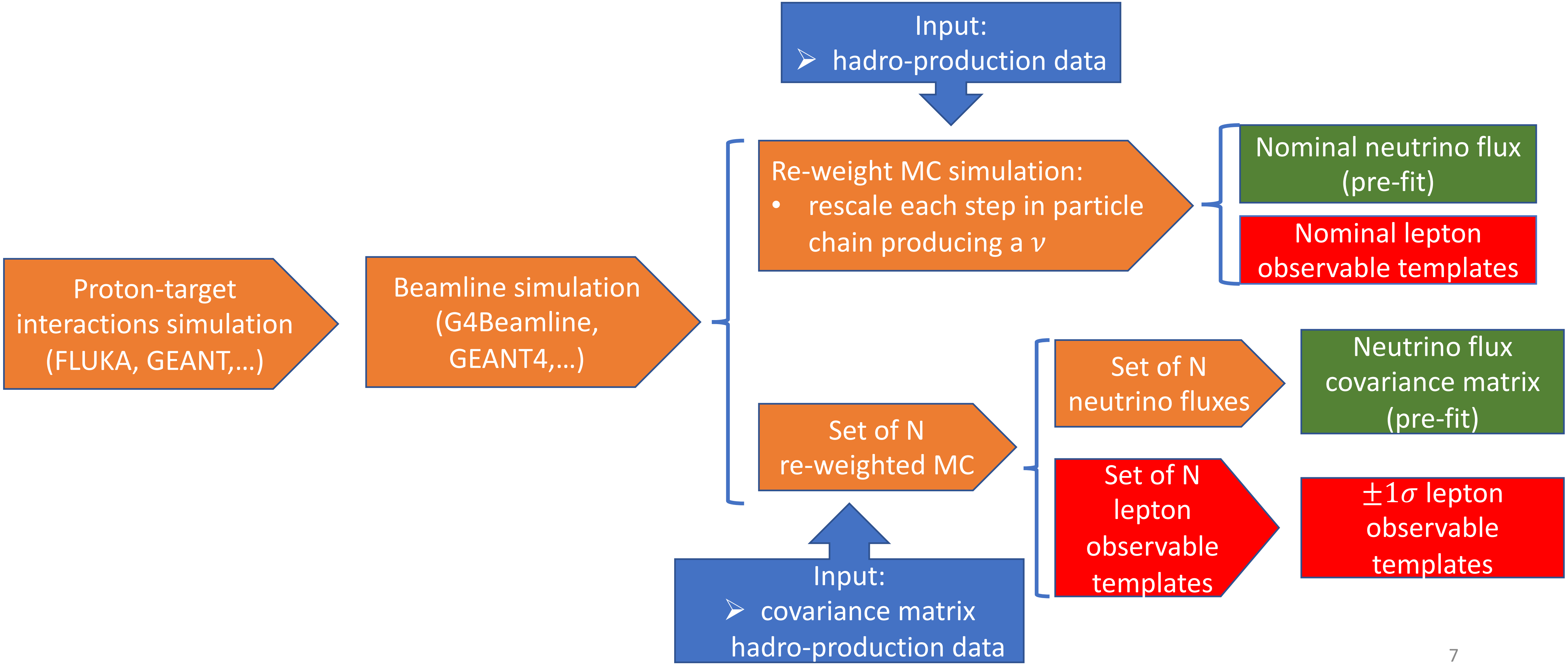
With $4.5{\times}10^{19}$ POT/year => $10^4\ \nu_e^{CC}$ on 500 t @ 100 m from target in ~ 2 years

But how do we actually do this, taking into account also the previous procedure described?

ν-flux with lepton monitoring

Flux systematic treatment including ENUBET information:

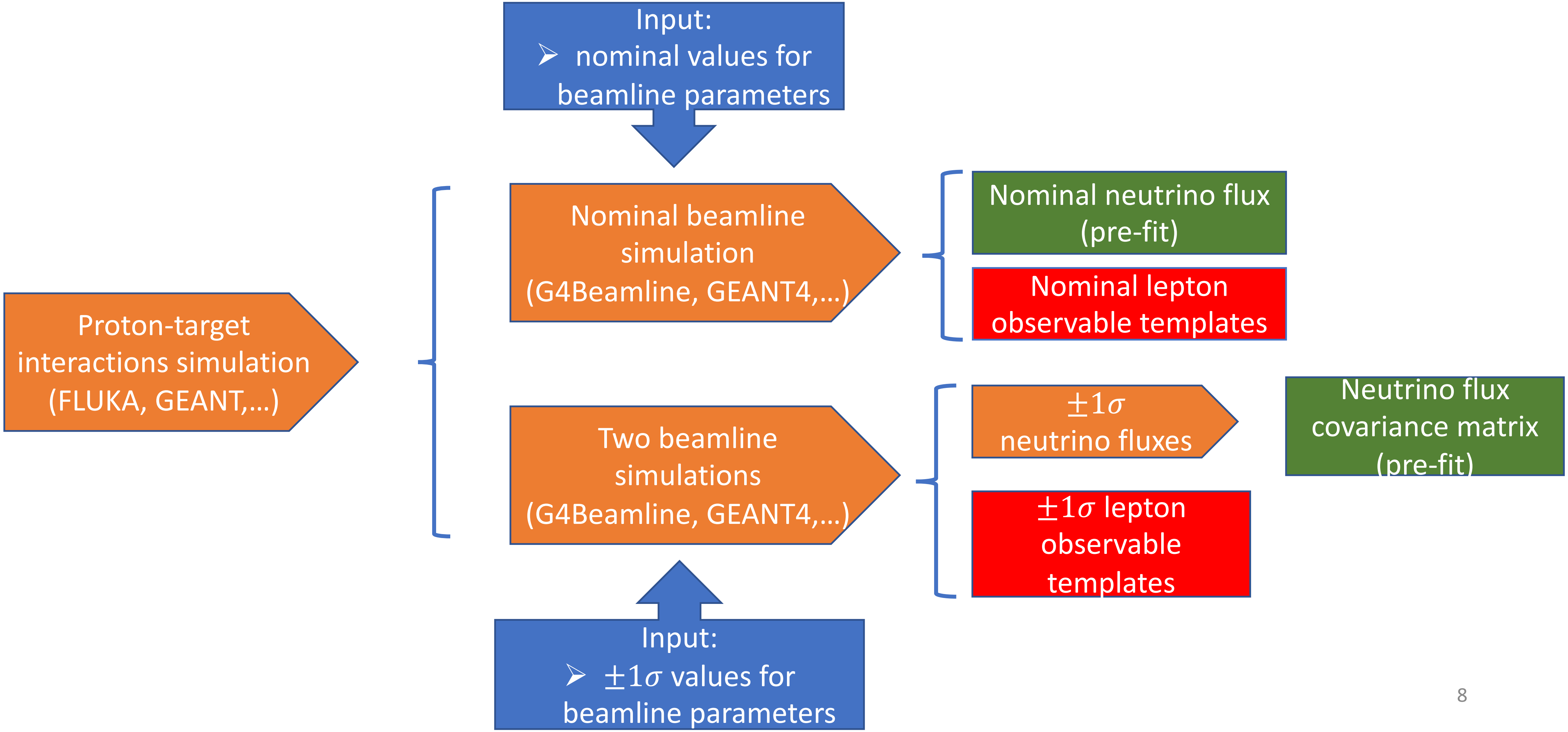
❖ Hadro-production: interaction of protons w/ target & hadrons produced inducing neutrinos



ν-flux with lepton monitoring

Flux systematic treatment including ENUBET information:

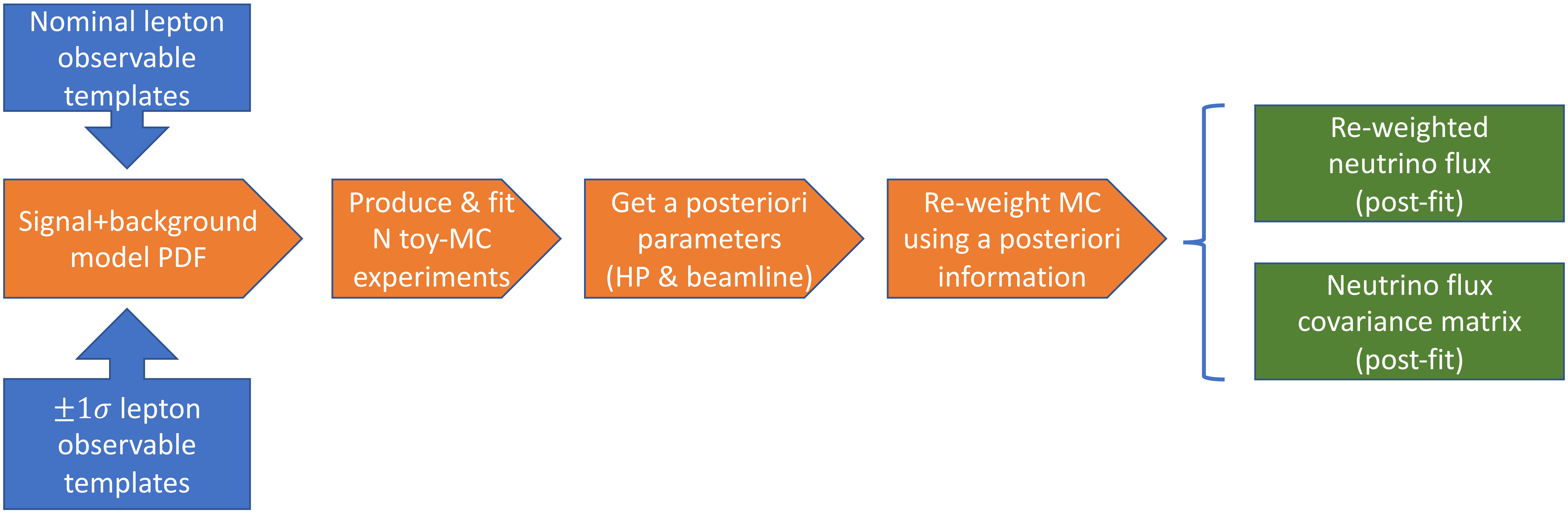
❖ beamline geometry & focusing: alignment & shape of magnetic elements, fields



ν-flux with lepton monitoring

Flux systematic treatment including ENUBET information:

❖ build a model exploiting leptons templates in order to asses the impact on neutrino flux



Fit model for ν-flux constrain

Nominal and $\pm 1\sigma$ templates for the lepton observables are used to build the PDF:

$$\mathrm{PDF}_{\mathrm{Ext.}}(N_{exp}, \vec{\alpha}, \vec{\beta}) = N_S(\vec{\alpha}, \vec{\beta}) \cdot S(\vec{\alpha}, \vec{\beta}) + N_B(\vec{\alpha}, \vec{\beta}) \cdot B(\vec{\alpha}, \vec{\beta})$$

- $\vec{\alpha}$: set of hadro-production nuisance parameters (taking into account their correlations);
- $\vec{\beta}$: set of beamline nuisance parameters (uncorrelated);

Parametrization of signal/background number of events (N) and template shape (T) variations w.r.t. nominal (N_0, T_0):

$$N(\vec{\alpha}, \vec{\beta}) = N_0 \cdot (1 + \vec{r}_\alpha \cdot \vec{\alpha} + \vec{r}_\beta \cdot \vec{\beta})$$

Takes into account normalization systematics

relative variation w.r.t. nominal values due to $\pm 1\sigma$ variation

$$T(\vec{\alpha}, \vec{\beta}) = T_0 \cdot (1 + \vec{\alpha} \cdot \Delta\vec{T}_\alpha + \vec{\beta} \cdot \Delta\vec{T}_\beta)$$

Takes into account shape systematics

EML fit approach:

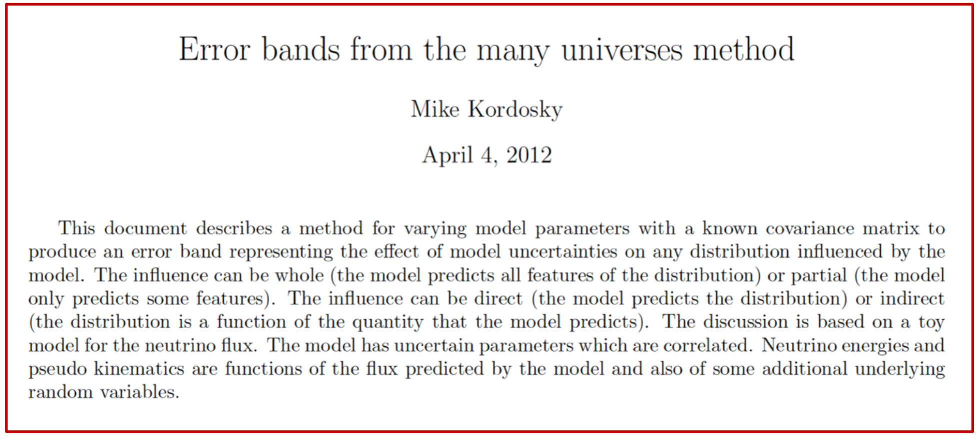
$$L(N|N_{exp}) = P(N \mid N_{exp}) \cdot \prod_{\mathrm{bins}} P(N_i \mid \mathrm{PDF}_{\mathrm{Ext.}}(N_{exp}, \vec{\alpha}, \vec{\beta})_i) \cdot \mathrm{pdf}_\alpha(\vec{\alpha} \mid 0,1) \cdot \mathrm{pdf}_\beta(\vec{\beta} \mid 0,1)$$

parameters are constrained by their pdfs

A toy fit model for $K_{\mu\nu}$ signal

Building the model in practice:

- use RooFit for the building blocks (extensively used and tested by the HE community);
- test on a toy hadro-production model;
- multi universe method to propagate uncertainties from HP parameters to flux/observables;



Error bands from the many universes method

Mike Kordosky

April 4, 2012

This document describes a method for varying model parameters with a known covariance matrix to produce an error band representing the effect of model uncertainties on any distribution influenced by the model. The influence can be whole (the model predicts all features of the distribution) or partial (the model only predicts some features). The influence can be direct (the model predicts the distribution) or indirect (the distribution is a function of the quantity that the model predicts). The discussion is based on a toy model for the neutrino flux. The model has uncertain parameters which are correlated. Neutrino energies and pseudo kinematics are functions of the flux predicted by the model and also of some additional underlying random variables.

The toy HP model

$$E\frac{d^3\sigma}{dp^3} \propto f(x_F, p_T) = \alpha(1 - x_F)^\beta \times p_T^2 e^{\gamma p_T}$$

Nominal parameters

$$\alpha = 1, \beta = 3, \gamma = -6$$

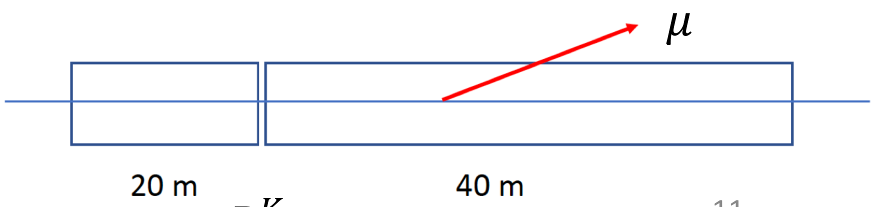
Uncertainty & correlation

$$\sigma = 10\% \qquad C = \begin{bmatrix} +1.0 & -0.1 & 0.0 \\ -0.1 & +1.0 & +0.2 \\ 0.0 & +0.2 & +1.0 \end{bmatrix}$$

Procedure:

- draw events from toy HP model and assign mock kinematic vars:
  - 1 set w/ nominal values from parameters;
  - N sets corresponding to (α, β, γ) drawn from covariance matrix;
- events in each set are re-weighted: $w = f_{new}(x_F, p_T)/f_{nom}(x_F, p_T)$;
- N realizations of flux and observables: $V_{ij} = \frac{1}{N} \cdot \sum_{k=1}^{N} (\phi^i_{nom} - \phi^i_k) \cdot (\phi^j_{nom} - \phi^j_k)$

Mock kinematic vars

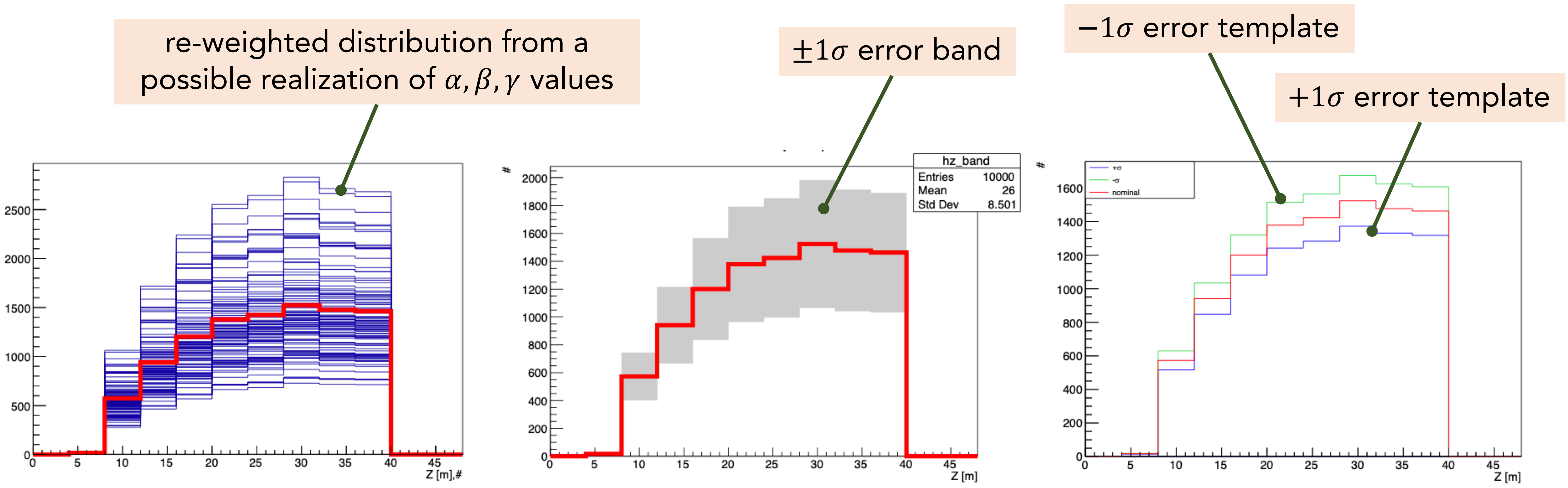


$$P_L^K = x_F \cdot p_{beam}$$

Templates for toy fit model

Example for one observable template: muons impact point in $K \to \mu\nu$ decays

- actual template for model is 2D distribution $(E_\mu^{vis}, Z_\mu^{imp.})$;

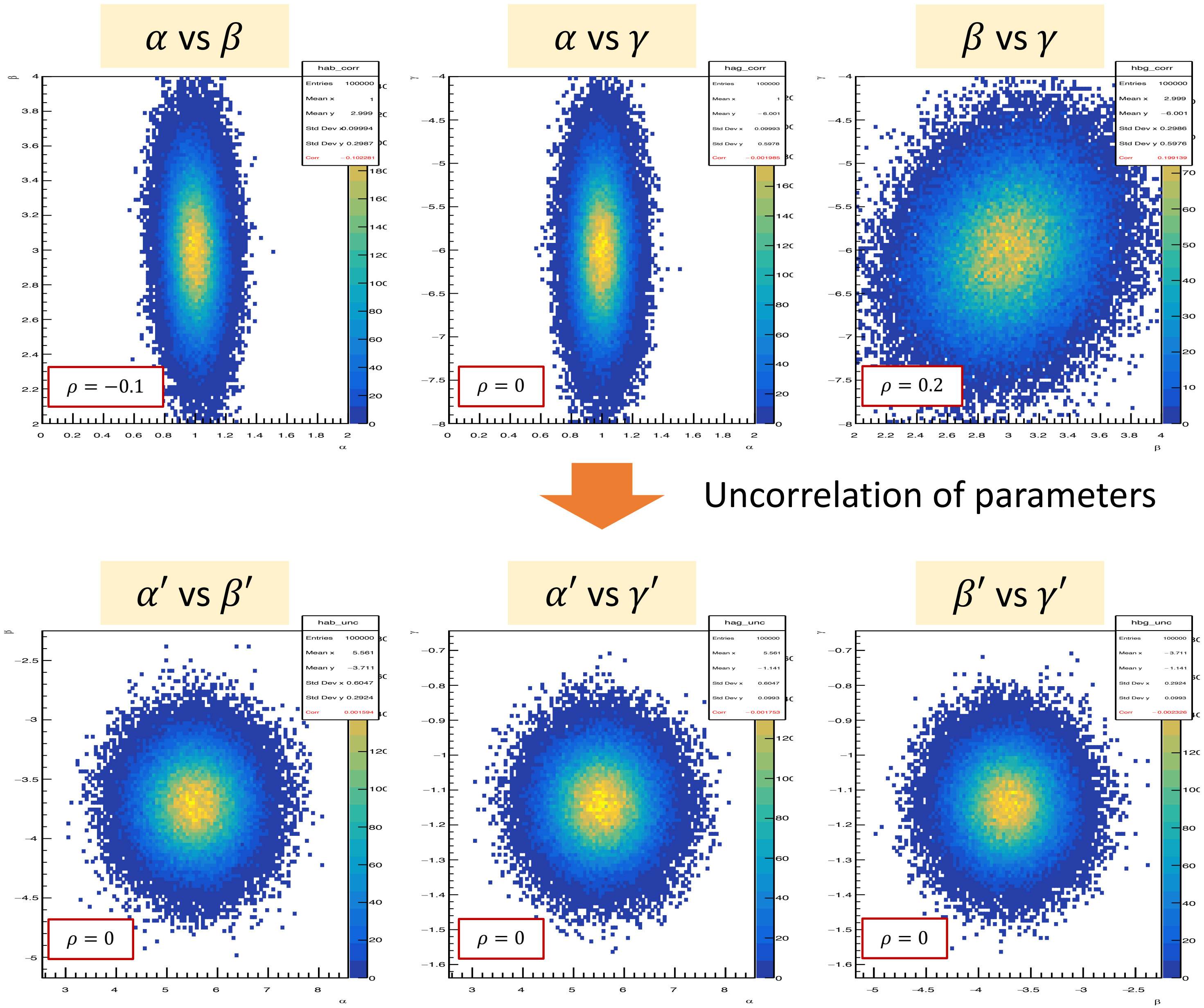


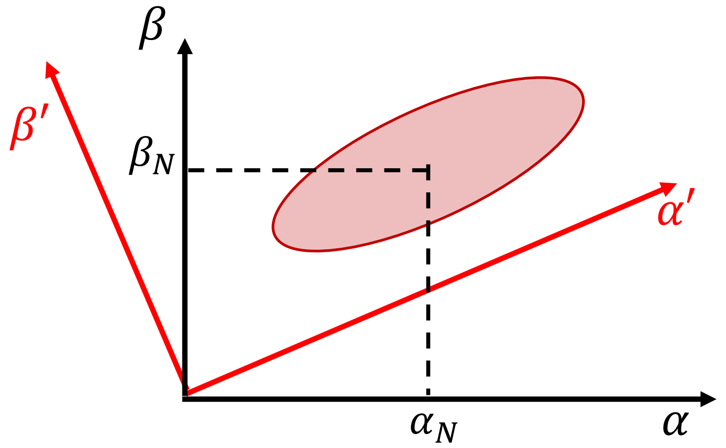
distribution obtained with nominal α, β, γ

Templates for toy fit model

In principle (if needed) given an observable we can build a template distribution for each HP parameter taking into account correlations:

- perform uncorrelation of parameters;
- sample the pdf of each independent parameter to get templates (apply procedure from previous slide);



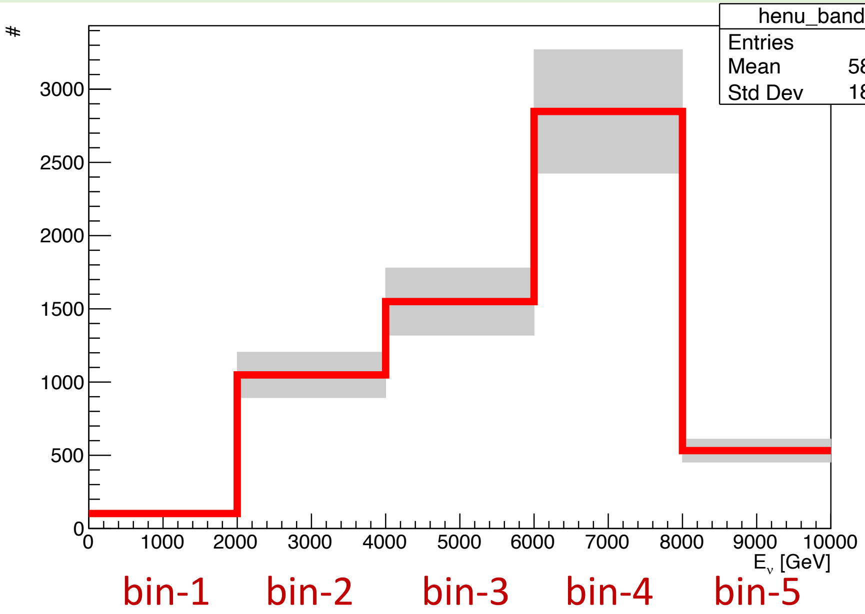


Toy fit model performance

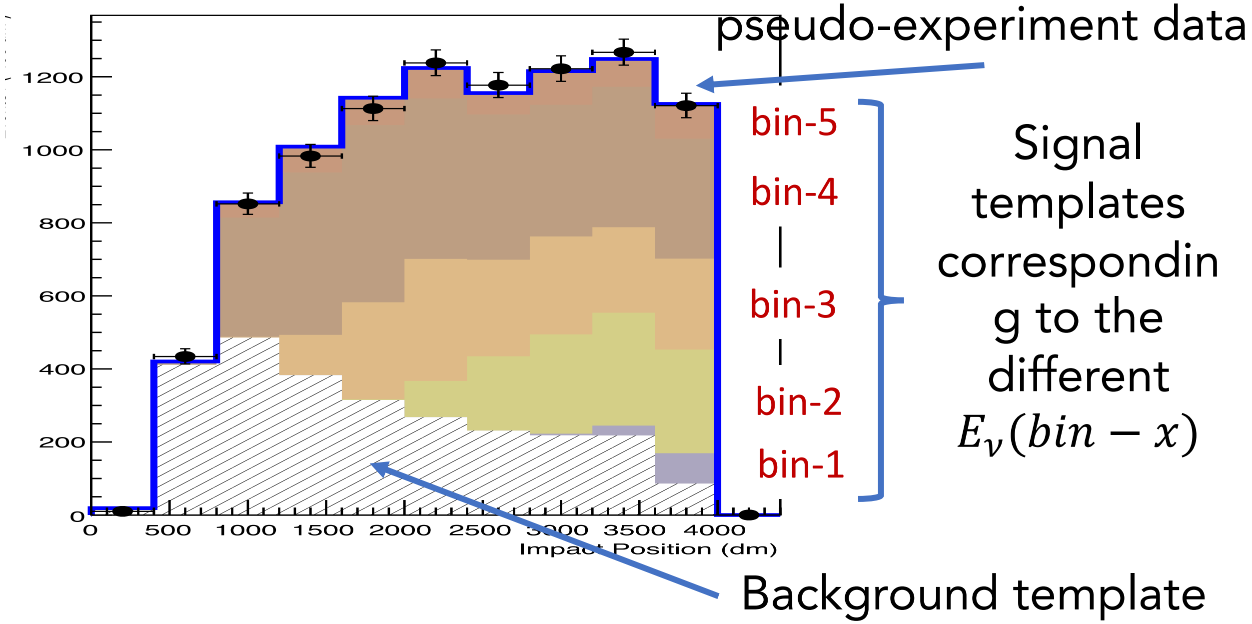
In this test:

- one signal template for each E_ν bin: fitting the number of tagged neutrinos;
- background template: tagged muons not corresponding to neutrinos;

Neutrino energy spectrum: 15% error (pre-fit)



Fit to one toy-MC experiment



Signal templates:

- HP induces a 15% variation in the normalization & negligible change in shape;
- effect correlated (100%) between templates (ν bins);
- 3 HP parameters folded into 1 nuisance in the fit model;

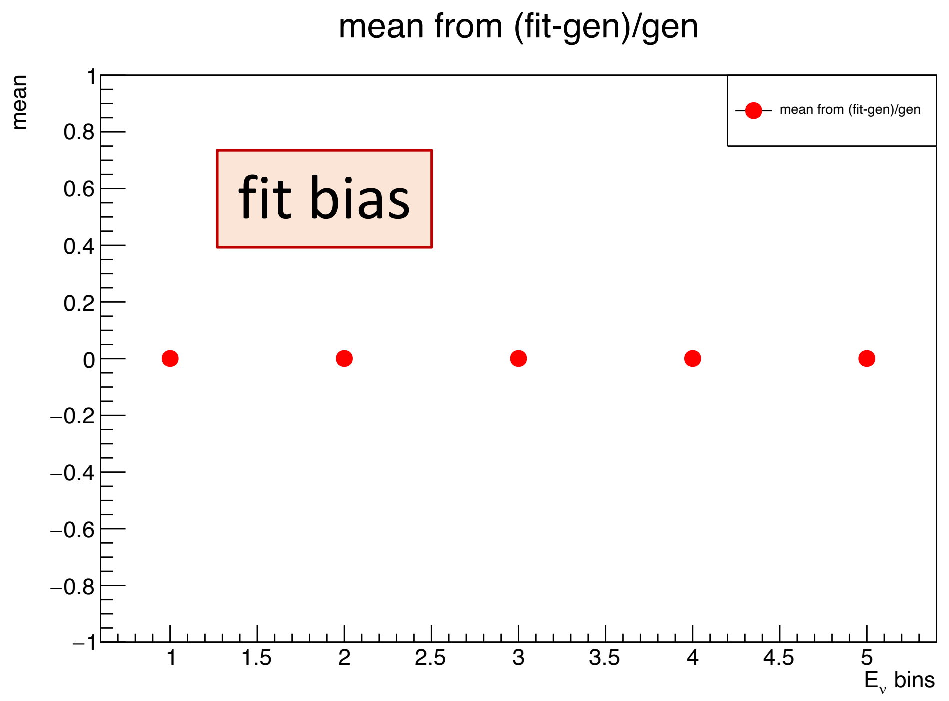
Background template:

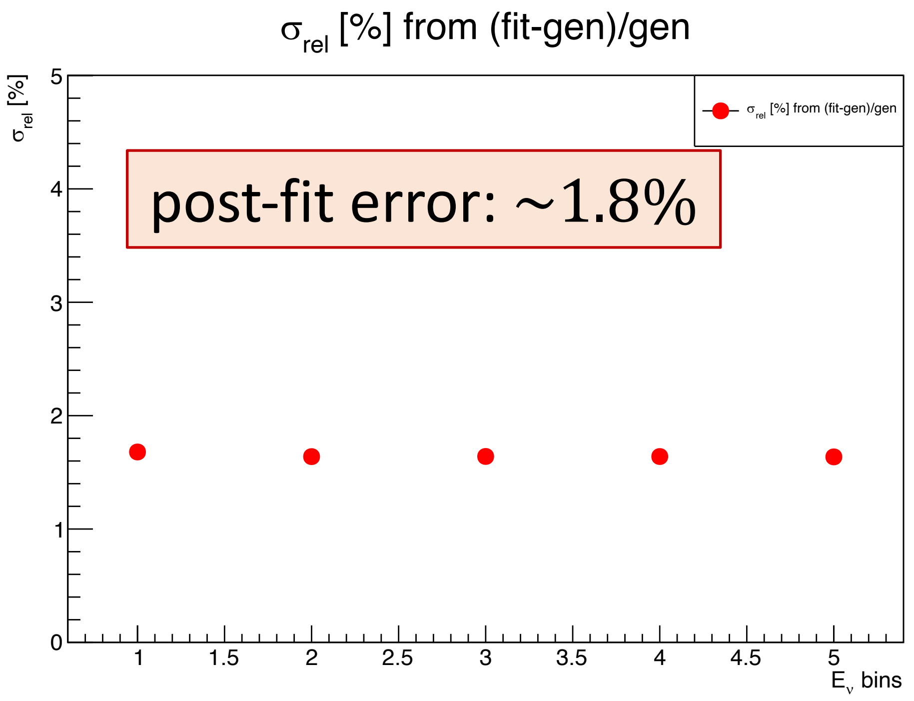
- simulated a 14% variation with some change in shape;
- assuming variation not due to HP: a second nuisance parameter is introduced in the fit model

Toy fit model performance

A sample of N toy-MC experiments are produced to study:

- fit bias/stability;
- performance of the method: precision on the neutrino flux after fit;





With this test performed using a toy hadro-production model:

- ~15% relative error on ν-flux due to the toy hadro-production model;
- ~1.8% error on ν-flux after performing the fit with model built from muon observable templates;

Conclusion and future steps

✓ **Developed procedure for the assessment of ν-flux systematics with lepton monitoring:**

- signal + background model built from templates (RooFit implementation);
- multi universes method for the propagation of the hadro-production uncertainties to observables and ν-flux;
- toy hadro-production model to test procedure and EML fit performance on $K_{\mu\nu}$;

Done!

❖ **Next steps: real model for ENUBET**

- build templates from GEANT4 simulation of facility;
- NA56/SPY hadro production data are being considered:
  - data w/ primary proton beam @ 400 GeV, same as the ENUBET facility;
  - explored phase-space close to the ENUBET one;
- model to constrain both ν_e and ν_μ fllux;

Work is in progress!

❖ **Near future:**

- impact of the beamline parameters will be assessed following the same procedure;
  - some preliminary tests have already been performed studing dipole magnetic field error;