Neutrino Beam at Accelerators

Laura Zambelli
LAPP - CNRS/IN2P3

DUNE-France Workshop
November 15th 2023 - IJCLab

LBL experiments

The goal of long baseline neutrino experiments is to measure the Oscillation Parameters:

$$N_{\nu_\beta}^{FD} = \int dE\ \Phi_{\nu_\alpha}^{FD}(E) \times \sigma_{\nu_\beta}(E) \times \varepsilon_{FD}(E) \times P(\nu_\alpha \rightarrow \nu_\beta)$$

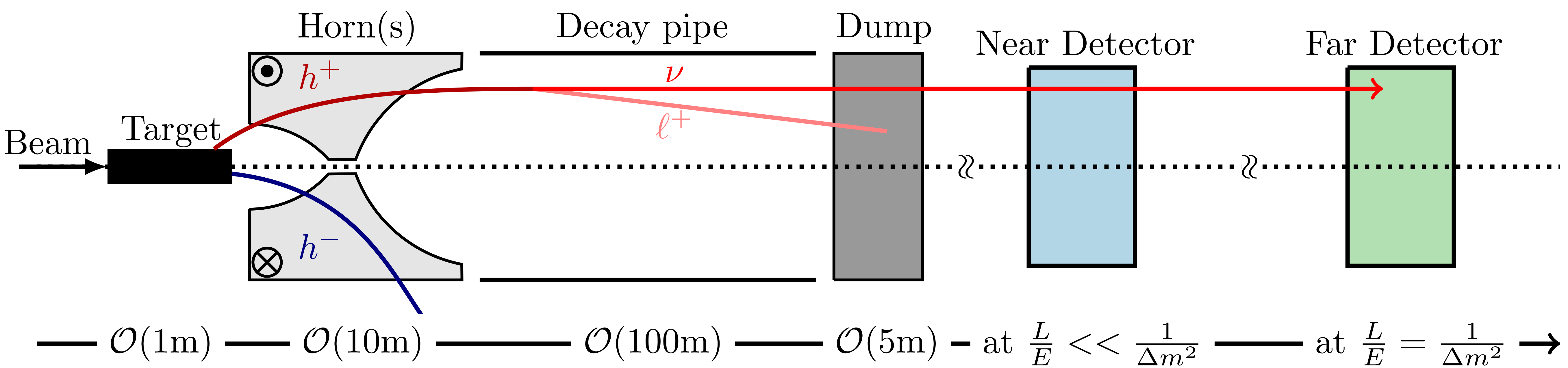
To to access CP/MH (-> Joao, Leila) we need:

- High statistics with a high intensity flux -> This talk!
- Understand the detector -> April's workshop
- Understand the cross section -> Marco's talk

NB : Unless stated, this talk discuss the Forward Horn Current case, *i.e.* neutrino beam creation.
All statement are still valid for Reversed Horn Current case, *i.e.* for anti-neutrino beam.

How To Make a Neutrino Beam with Accelerator

— A general recipe —



1. Direct a proton beam onto a thick target (of a few interaction lengths)
2. Focus secondary hadronic beam with magnetic horns (h+ to get ν flux, h- for ν̄)
3. Let hadrons decay in the decay pipe (mostly $\pi \rightarrow \mu + \nu_\mu$)
4. Absorb remaining particles at the end of the tunnel
5. Place a near detector in a region before the oscillation starts to monitor your ν flux
6. Place a far detector at a L/E maximizing the oscillation phenomena
7. Make discoveries

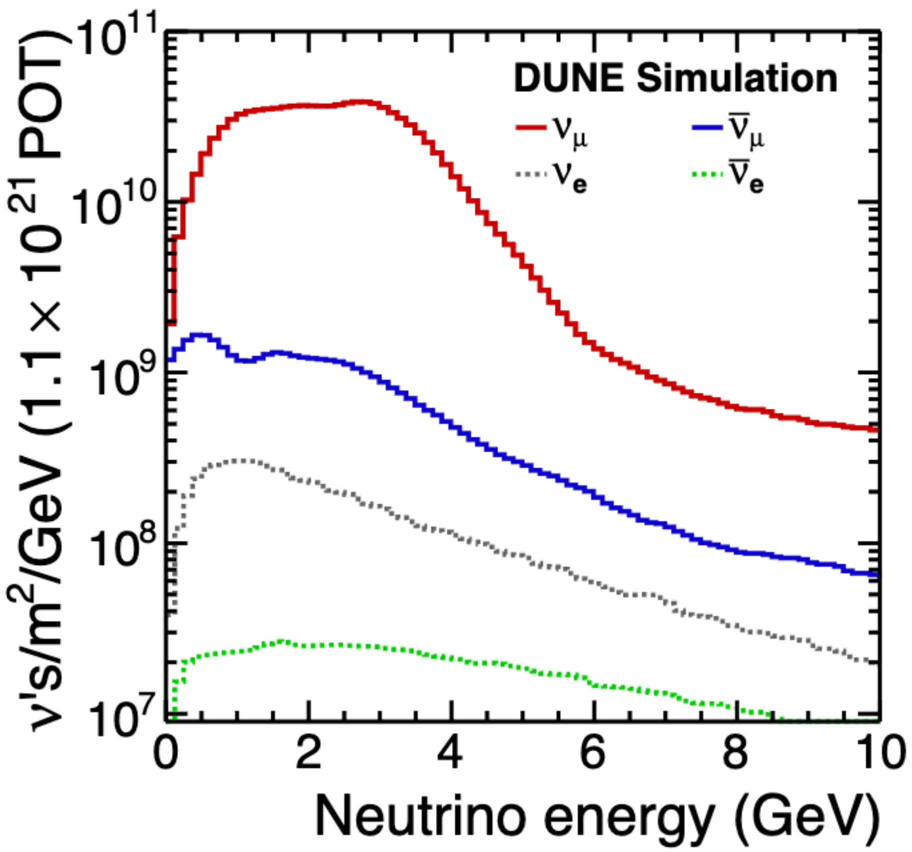
How To Make a Neutrino Beam with Accelerator

What you want :

- A high intensity neutrino beam
- Pure ν_μ content from π^+ decay

What you have :

A high intensity neutrino beam with mostly ν_μ, but also ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ from π^-,$K^{\pm,0}$, $\mu^\pm$, … decays.



Neutrino Parents:

		channel	BR [%]
π	$\rightarrow$	$\mu\ \nu_\mu$	99.9
	$\rightarrow$	$e\ \nu_e$	10^{-4}
K	$\rightarrow$	$\mu\ \nu_\mu$	63.5
	$\rightarrow$	$\pi^0\ e\ \nu_e$	5.1
	$\rightarrow$	$\pi^0\ \mu\ \nu_\mu$	3.3
K_L^0	$\rightarrow$	$\pi\ e\ \nu_e$	40.5
	$\rightarrow$	$\pi\ \mu\ \nu_\mu$	27.0
μ	$\rightarrow$	$e\ \nu_e\ \nu_\mu$	100

Fraction at DUNE FD:

ν_μ : 92 %

$\bar{\nu}_\mu$: 7 %

$\nu_e + \bar{\nu}_e$: 1 %

This talk will discuss :

- How to design a neutrino beamline to have a lot of neutrino with a lot of ν_μ
- How to predict the neutrino flux spectrum and its content

The proton beam

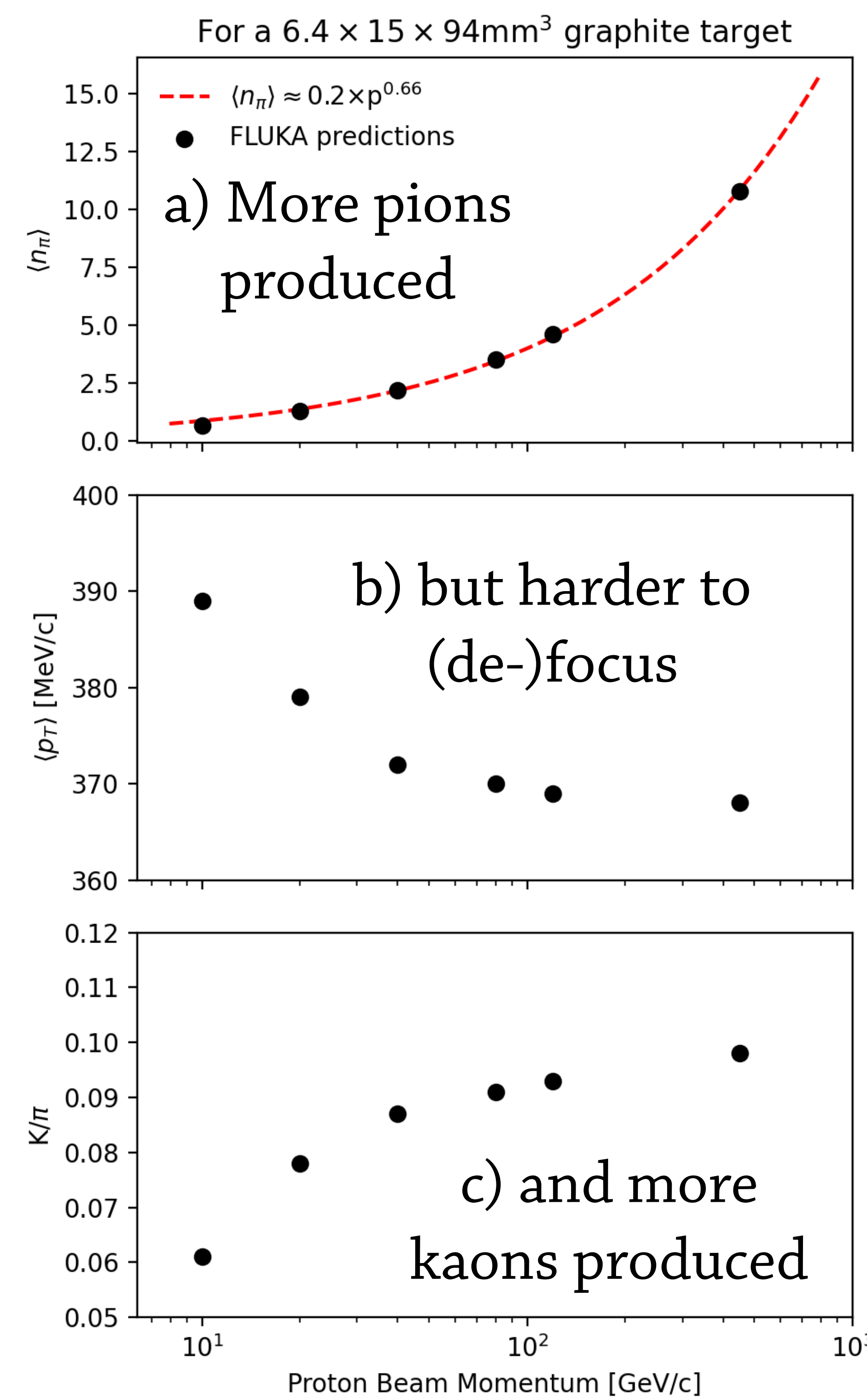
Two figures of merit about the proton beam

Beam power

$$P[\mathrm{W}] = \frac{q_e[\mathrm{C}] \times E[\mathrm{eV}] \times N_{ppp}}{T_{rep}[\mathrm{s}]}$$

Increase beam power with
- Higher beam energy
- More proton per pulse
- Shorter repetition cycle

Beam Energy increase means



S. Kopp 'Accelerator neutrino beams', Phys. Rep., Vol. 439-3, (2007), 101-159

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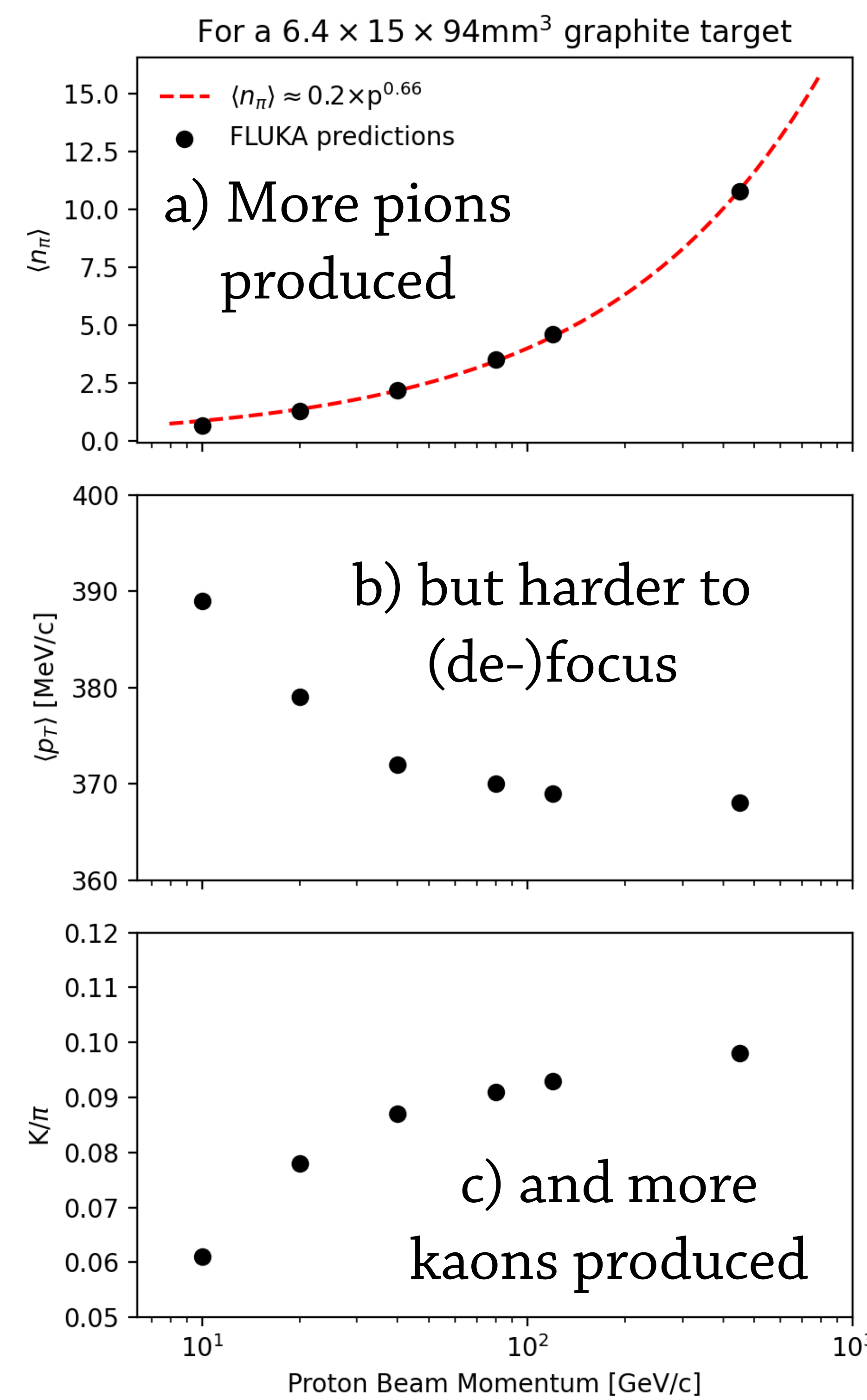
Current & Future neutrino beam powers:

		E_{beam}	N_{ppp}	T_{rep}	**P**
JPARC	T2K	30 GeV	2.5×10^{14}	2.48 s	**500 kW**
	HK	*30 GeV*	3.2×10^{14}	*1.16 s*	***1.3 MW***
NUMI	NOVA	120 GeV	4.9×10^{13}	1.33 s	**700 kW**
	DUNE	*120 GeV*	7.5×10^{13}	*1.2 s [I]* *0.65 s [II]*	***1.2 MW*** ***2.2 MW***

K. Sakashita Neutrino 2020

V. Shiltsev 2017 J. Phys.: Conf. Ser. 888 012043

Beam Energy increase means



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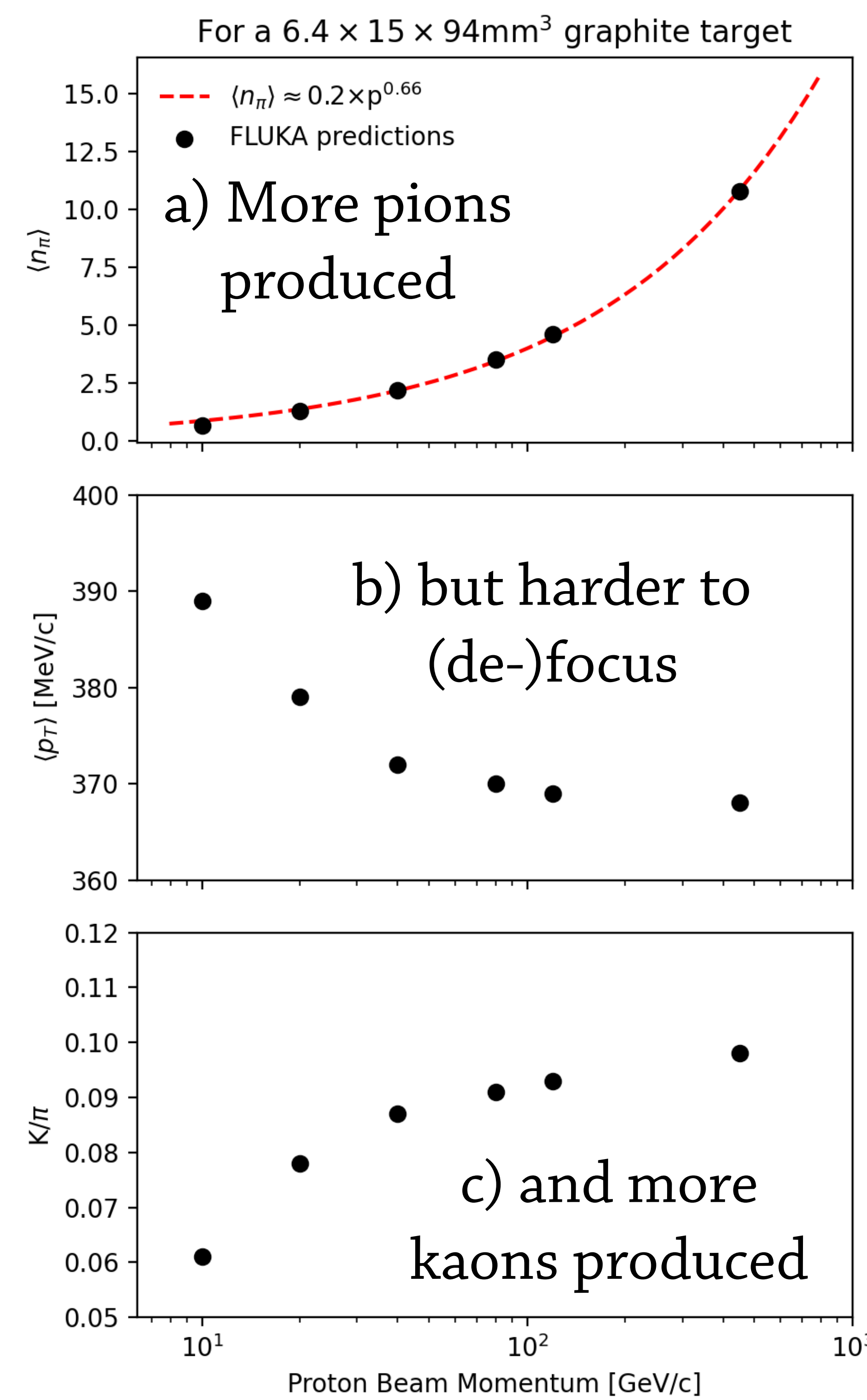
Proton On Target [POT]

Translate the statistics accumulated, equivalent to the luminosity for LHC

T2K	3.5×10^{21} POT collected
HK	*2.7×10^{21} POT/year*
NOVA	3.9×10^{21} POT collected
DUNE	*1.5×10^{21} POT/year*

Beam Energy increase means

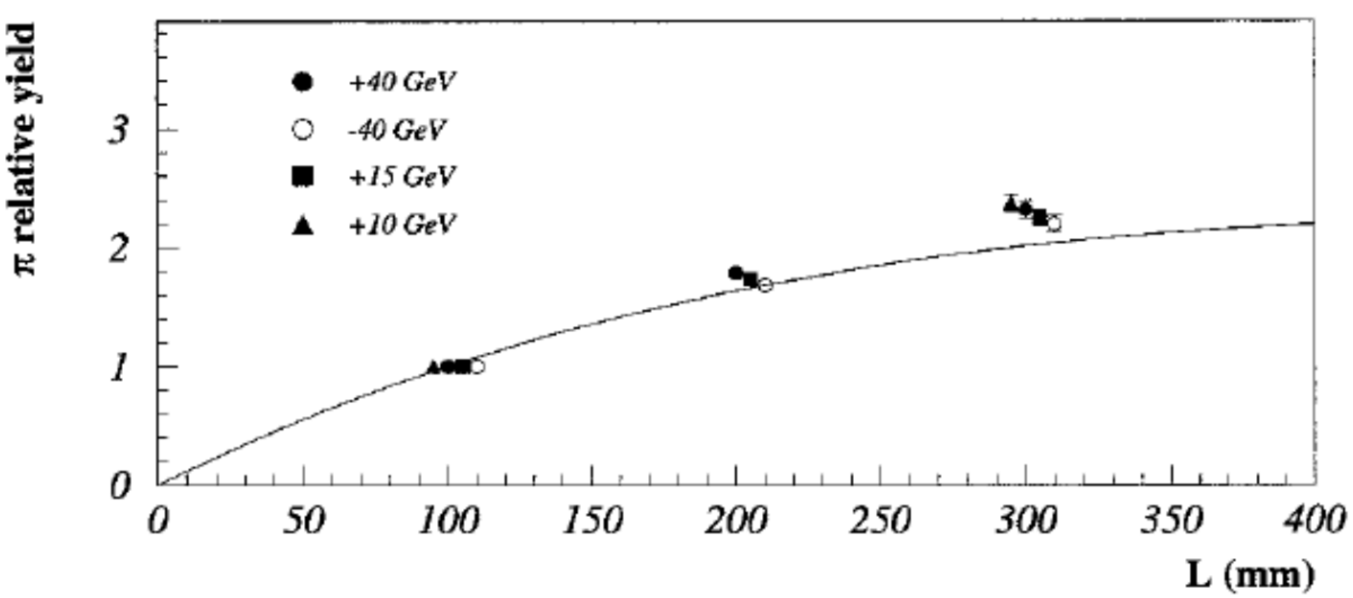


S. Kopp 'Accelerator neutrino beams', Phys. Rep., Vol. 439-3, (2007), 101-159

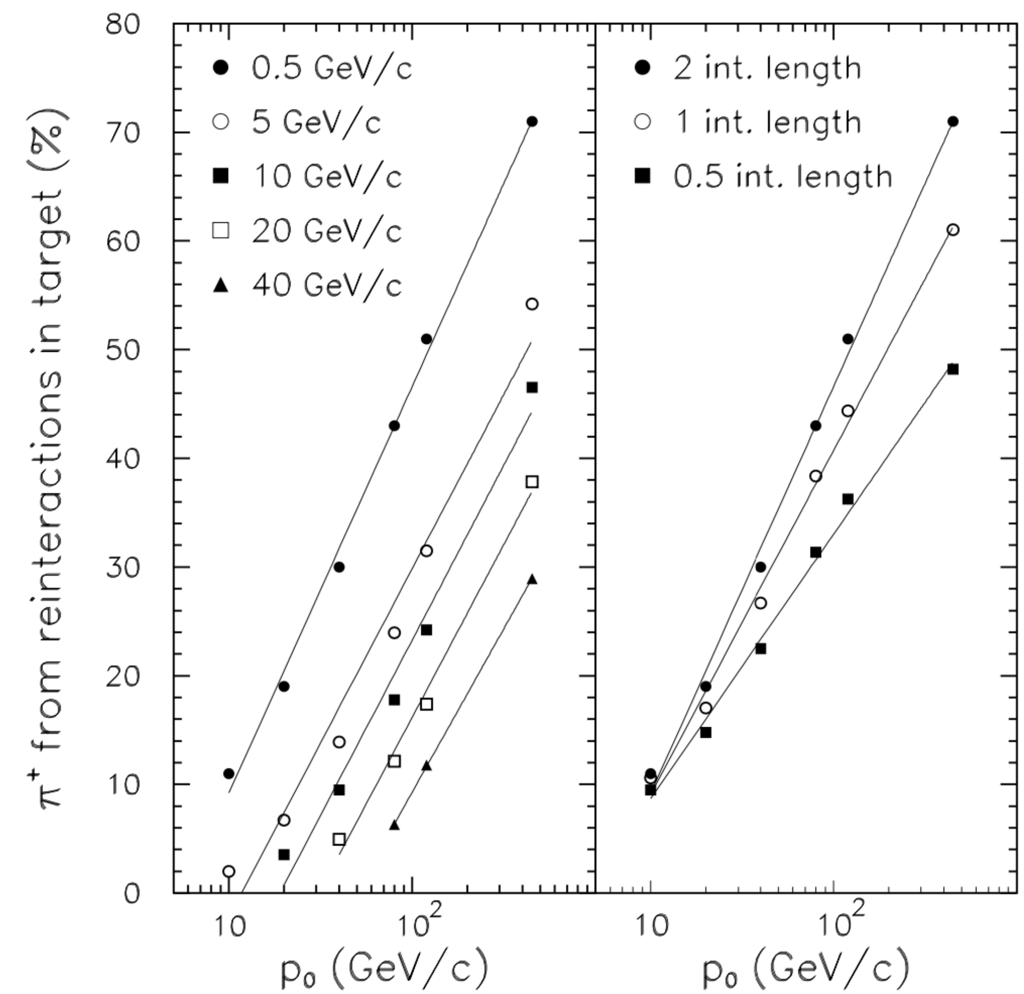
The neutrino beamline

Target
- Should be able to sustain high power, usually graphite or beryllium is used
- Should be long enough (several interaction length) to have hadron production, but not too long to minimize the re-interactions. Some experiment have considered having multiple small targets

π yield in a Beryllium target



Fluka simulation (graphite target)



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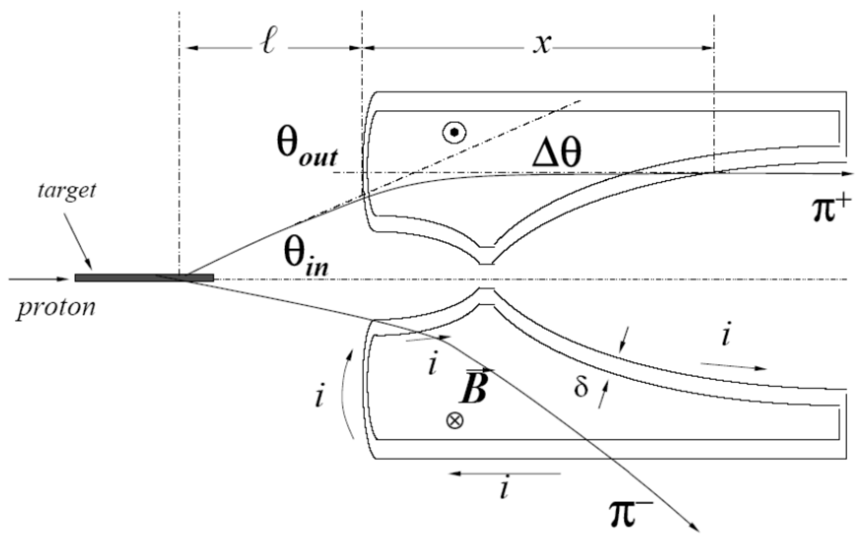
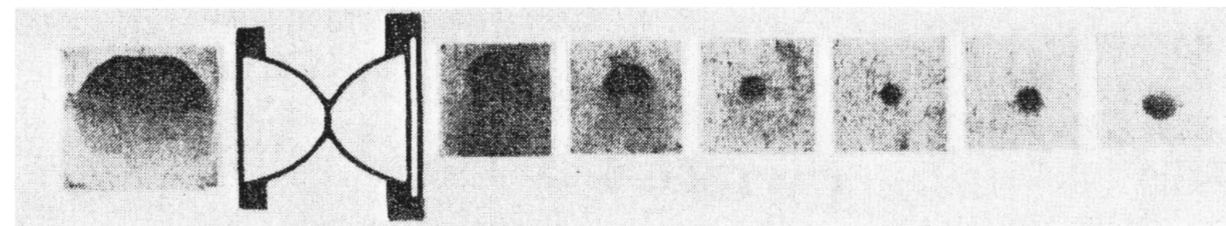
The neutrino beamline

Horns

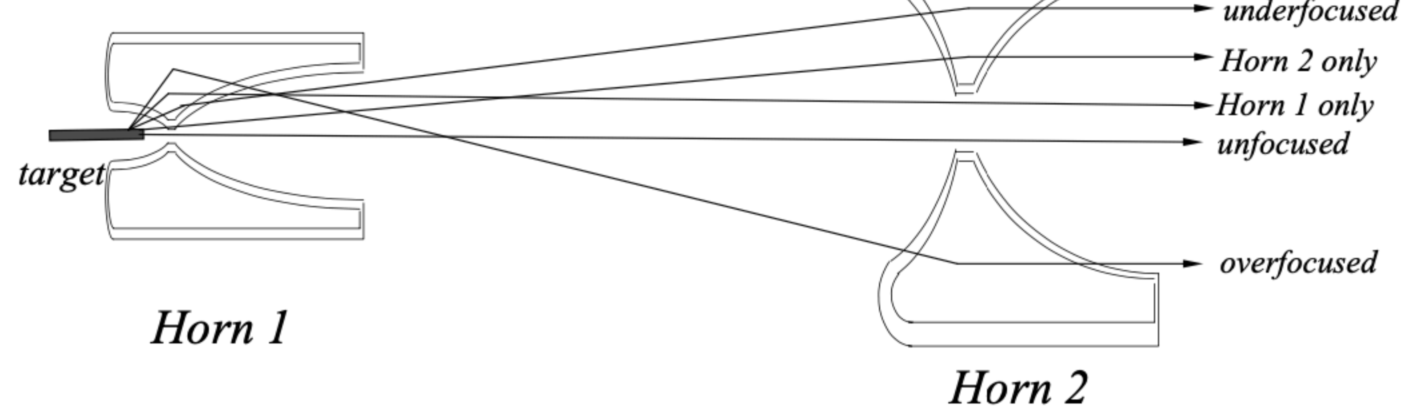


Horns used to focus the charged hadron beam

Effect a beam



NuMI beamline:



Having two (or three) horns improves the focussing efficiency

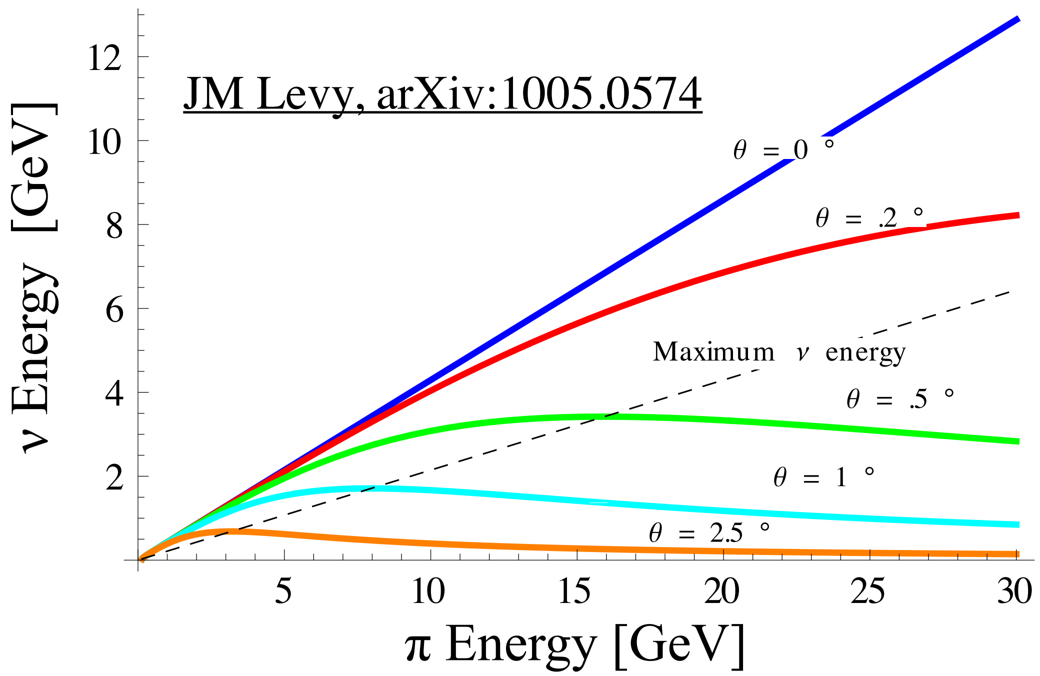
Decay volume

-> Should be long enough to let the pion decay

-> But not too long to minimize the muon decay

S. Kopp 'Accelerator neutrino beams', Phys. Rep., Vol. 439-3, (2007), 101-159

The Off axis technique



In the 2-body decay of charged pions, the neutrino energy depends on the observation angle θ:

$$E_\nu^{\max}(\theta) \approx \frac{E_\nu^*}{\sin\theta} = \frac{30\,\mathrm{MeV}}{\sin\theta}$$

At large θ, all pion energy contribute to the same ν energy

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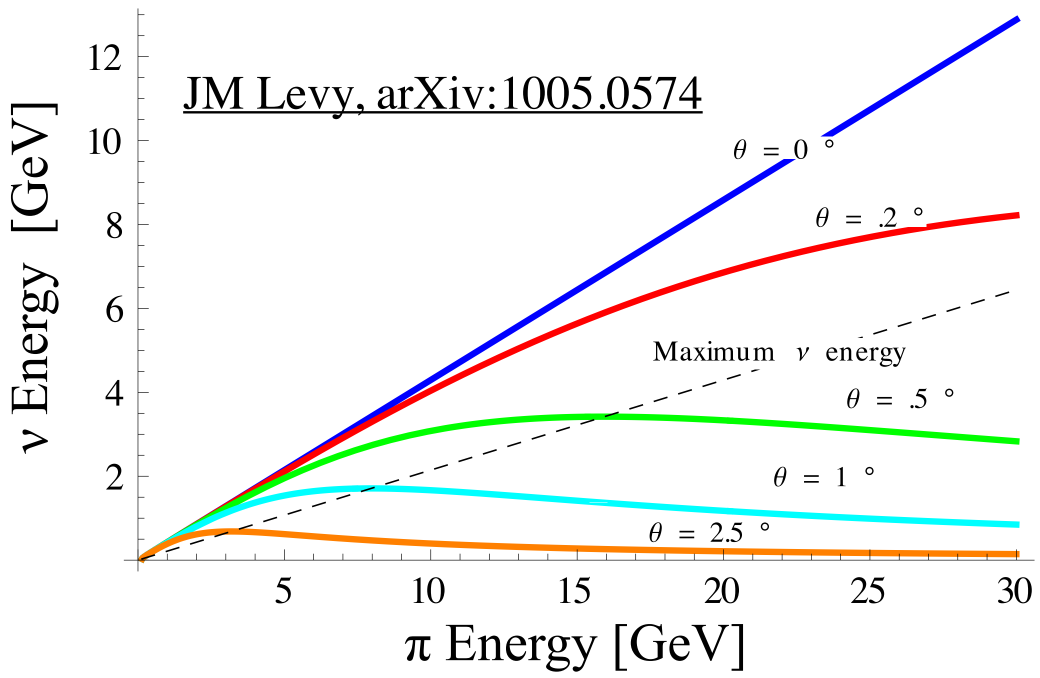

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Off-axis experiments

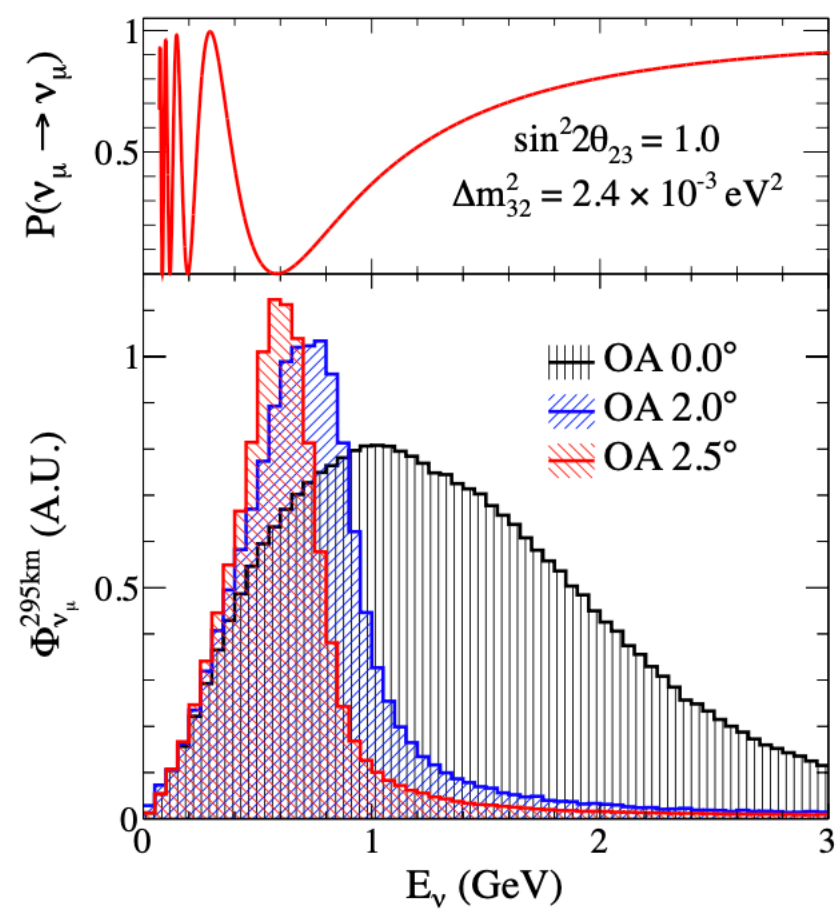
T2K, HK and NOVA are off-axis experiments

They set their off-axis angle such that the ν beam peaks at the oscillation maximum

-> <u>At this energy</u>, the flux is higher than on-axis

-> For T2K & HK the beam peak is where the CCQE interaction is dominant

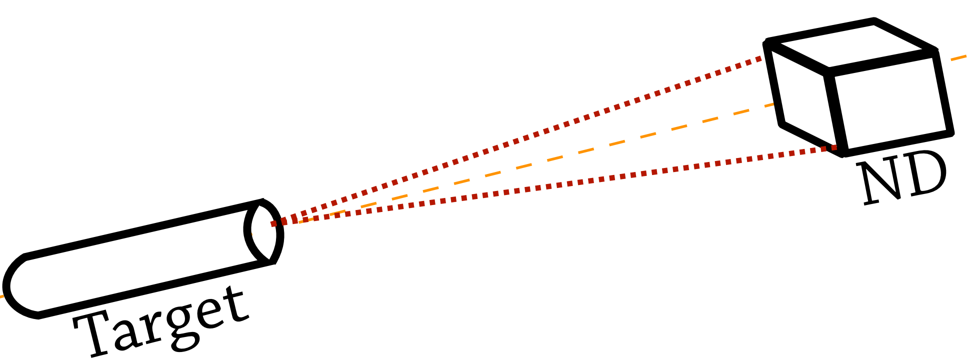
T2K flux



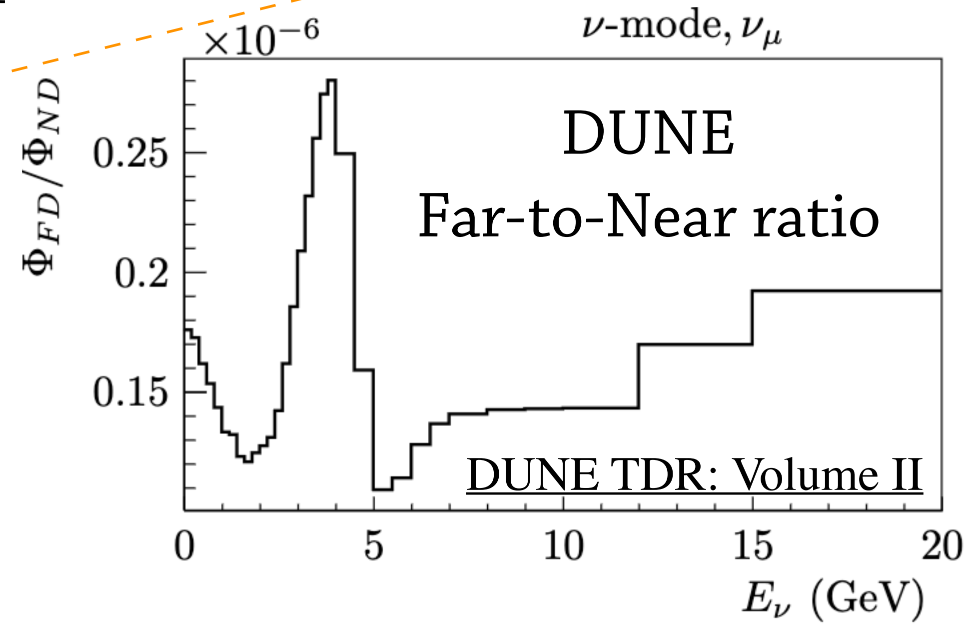
The Off axis technique

The Far-To-Near ratio

For all LBL experiments, the near detector is too close to the target and sees the flux at multiple off-axis angles. On the contrary, the far detector is seen as a point from the target perspective



-> The flux seen at the near and the far detector are different



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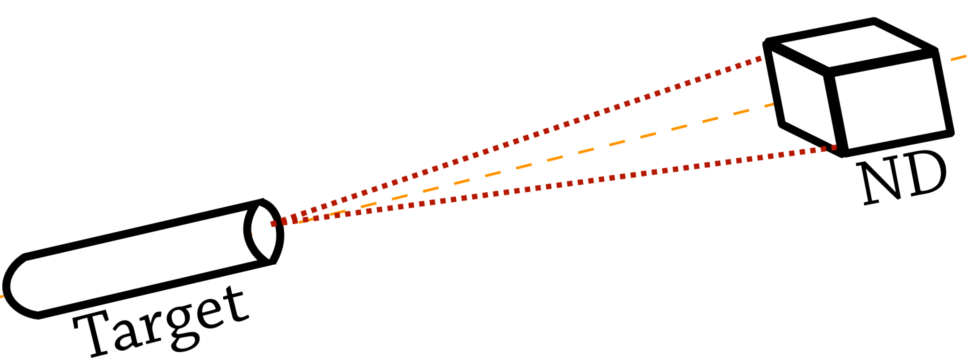

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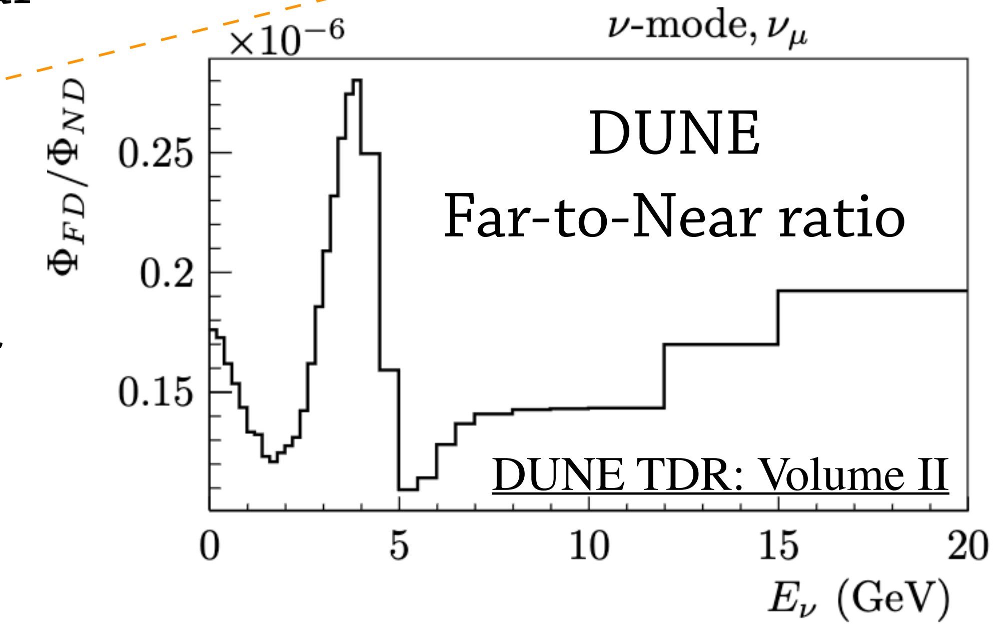
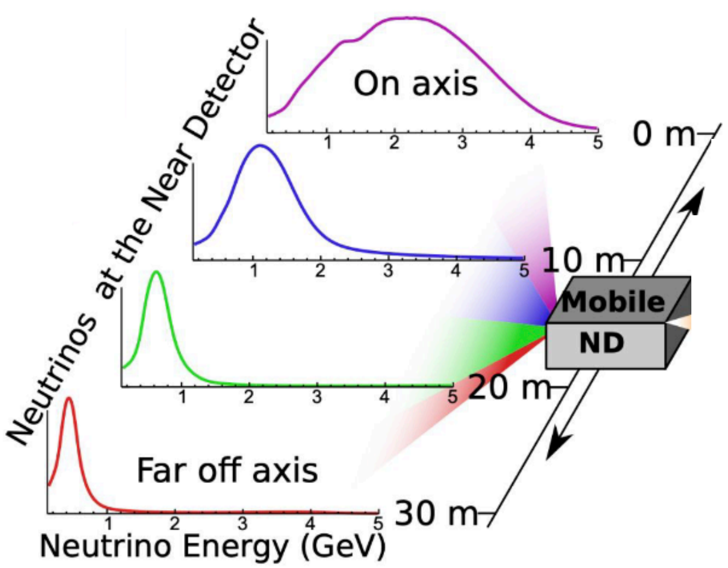
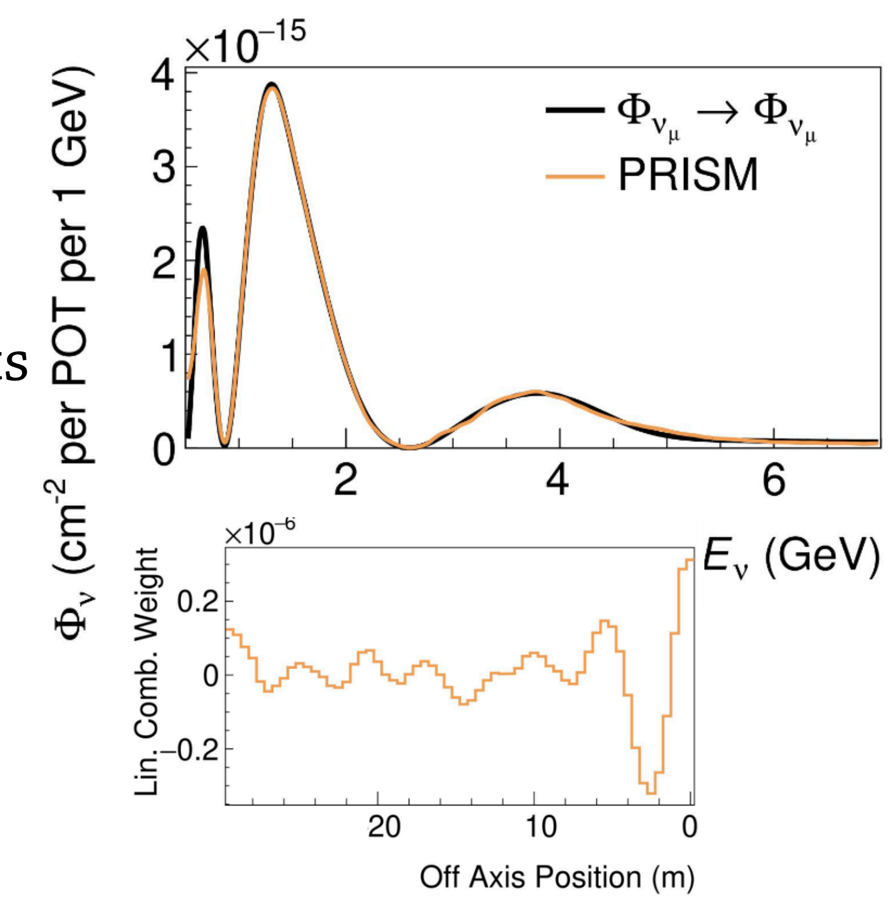


Off-axis detector



PRISM will be a movable near detector at DUNE & HK:
- Make cross-section measurements with ~mono-energetic ν beam
- Reproduce FD spectrum with linear combination of off-axes measured flux



L. Pickering, NUFACT'23

DUNE neutrino beamline optimization

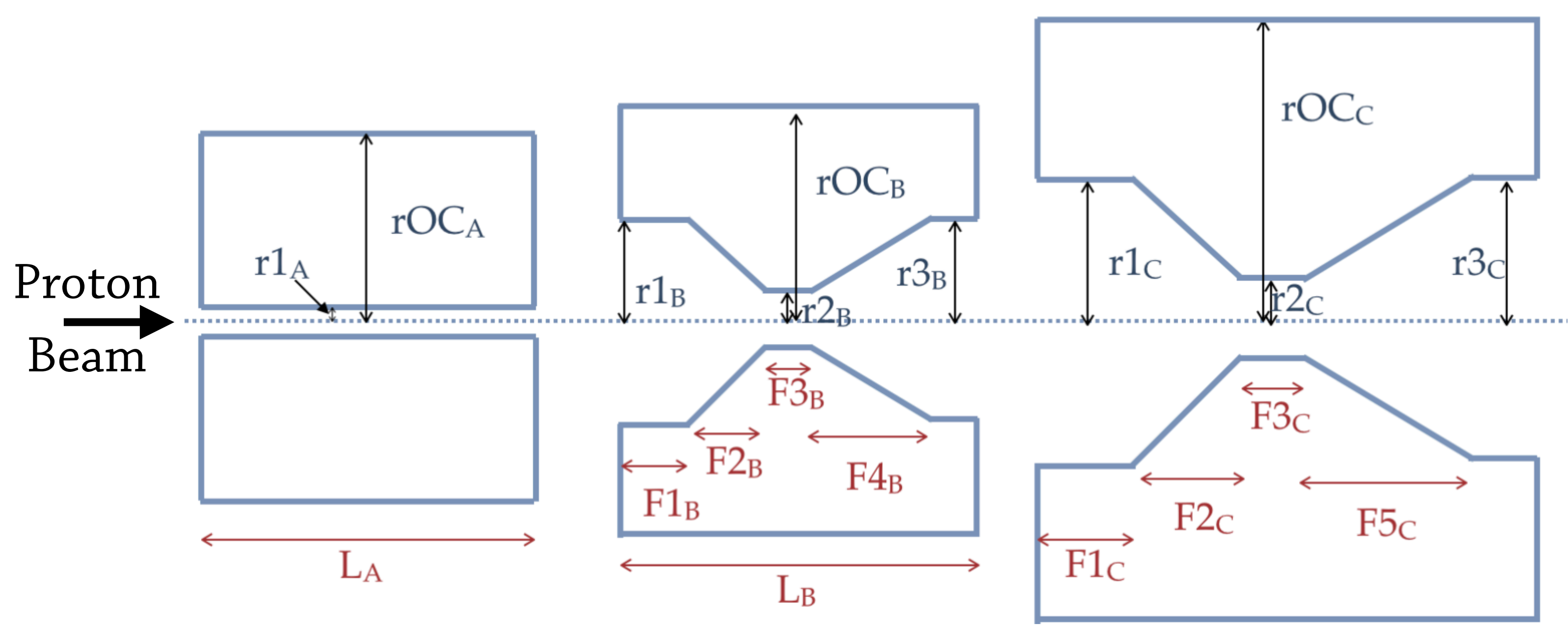
The reference [CDR] beam design was : 80 GeV proton beam ; 1m long graphite ; 2 horns at 230kA
↳ Can the sensitivity to CP/MH be improved with neutrino beamline optimization ?

About 20 beamline parameters of the ν beamline considered for optimization :

- Proton momentum and beam radius
- Graphite target width and length
- Horn shape, current and position
- Decay volume length and radius

For each beamline configuration:

-> Simulate the ν flux + compute CP sensitivity

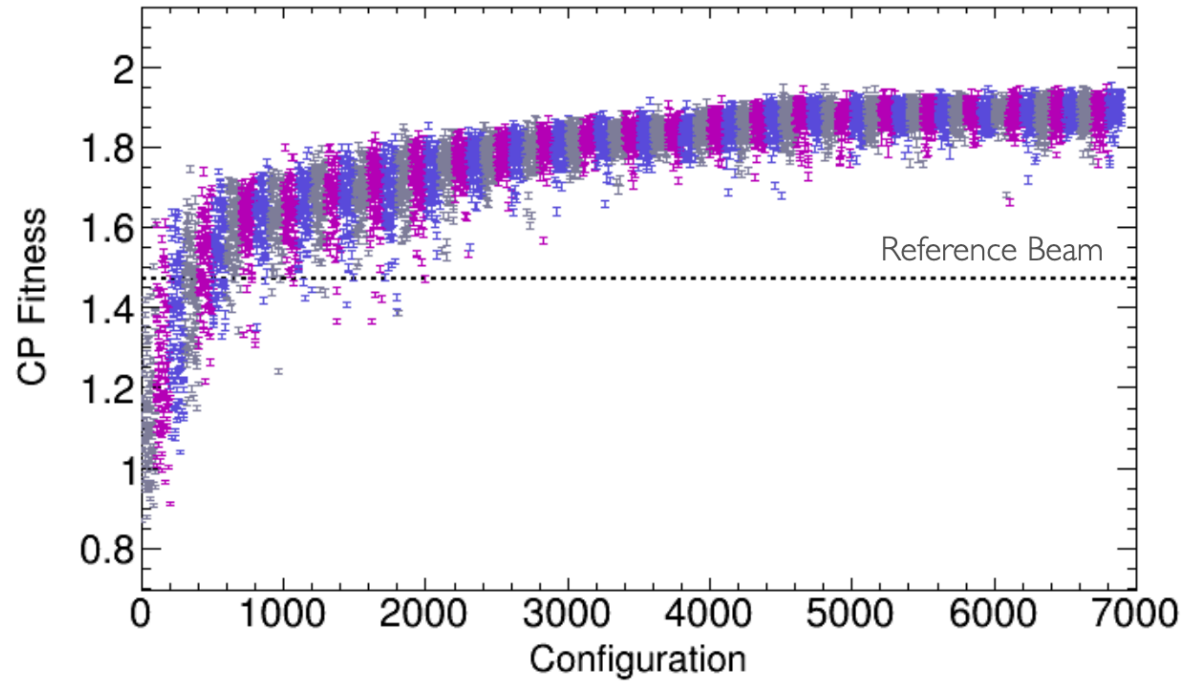


Traditional simulation+CP analysis takes about a week to converge per beamline configuration
-> Would take about a lifetime of the Universe to be complete !

L. Fields, MODE workshop, LBNF optimization

DUNE neutrino beamline optimization

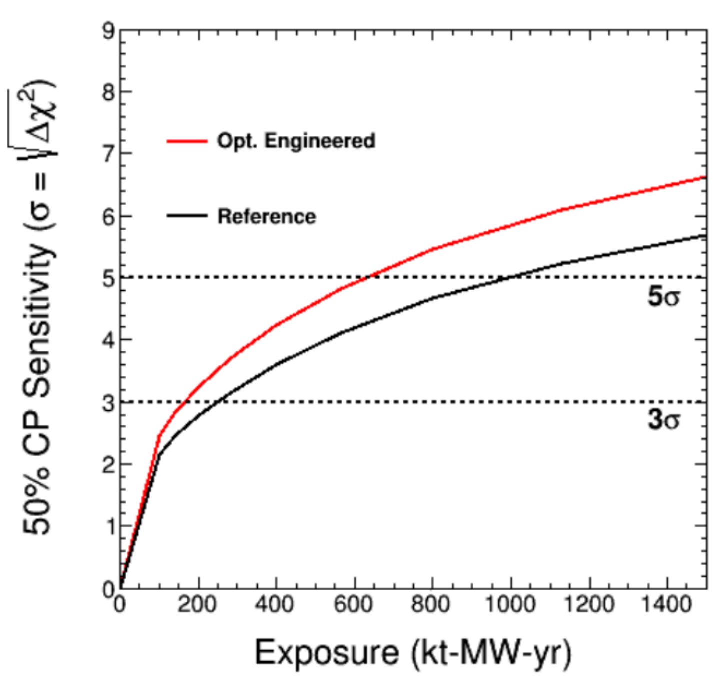
Two methods to speed up the beamline optimization:
- A fast CP sensitivity estimator for a given flux configuration [few seconds to run]
- Use of the genetic algorithm

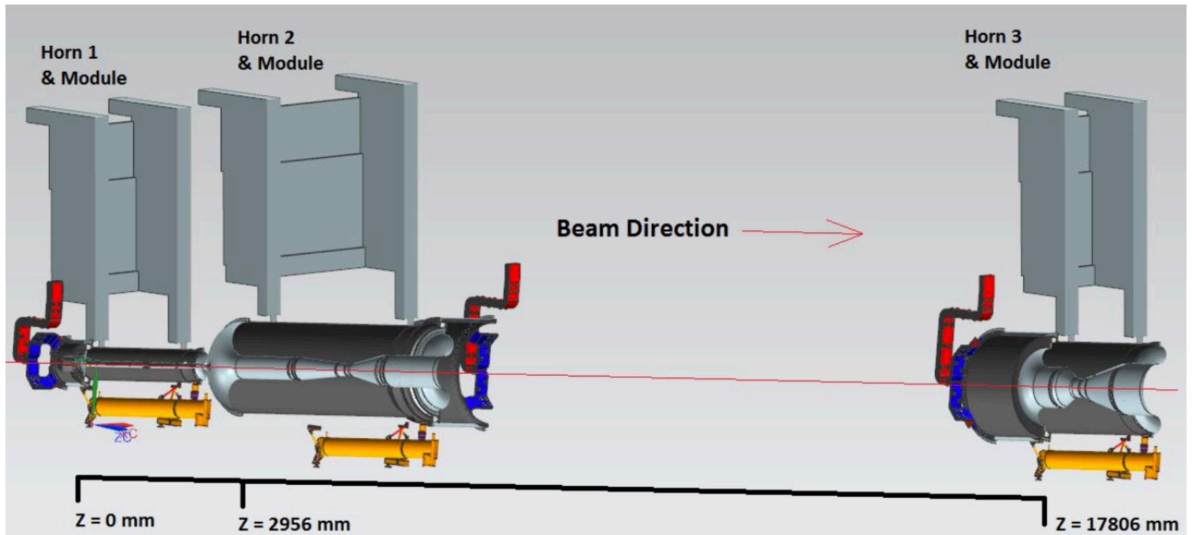


Start with a random set of random configurations
- Best ones (based on CP 'fitness') are mated together to generated new designs
- Redo until convergence

-> It provided an ideal beamline in a few weeks:
- ○ We can't know if this is the best possible design
- ○ Ideal design was then given to the engineers to confront it with reality and add technical things (like support and cooling systems)

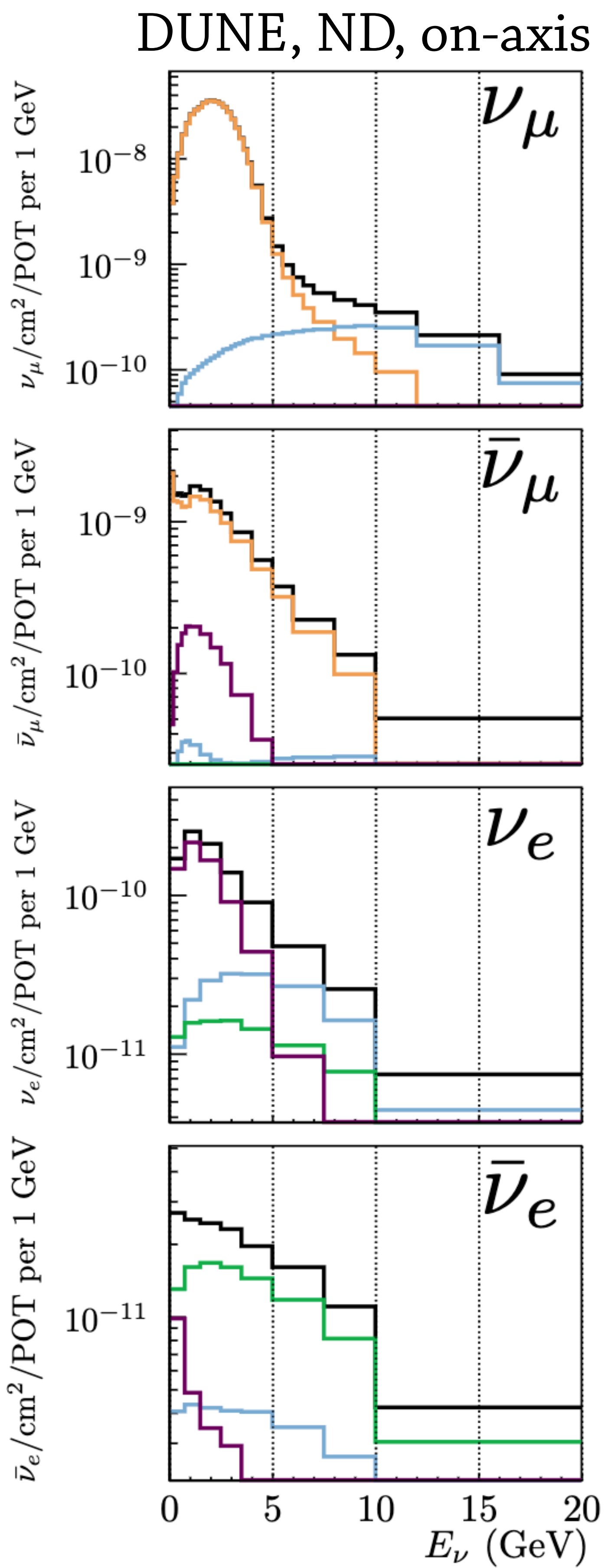
Optimized design increased the CP sensitivity as if we increased the FD mass by 70%





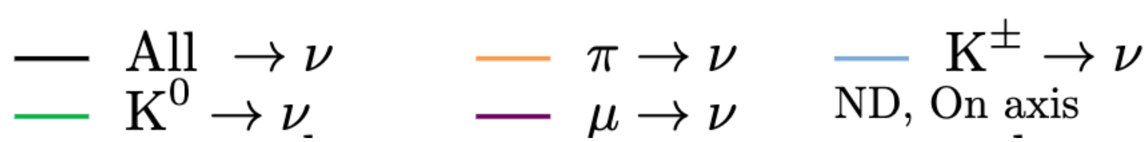
L. Fields, MODE workshop, LBNF optimization

DUNE Neutrino Flux



Beamline Design is :

- ○ Proton beam at 120 GeV/c momentum
- ○ Target : graphite rod of 16mm radius and 1.5~1.8m long
- ○ 3-horns running at 300 kA
- ○ Decay volume Helium filled of 194m long



channel			BR [%]
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	$\to$	$e\ \nu_e$	10^{-4}
K	$\to$	$\mu\ \nu_\mu$	63.5
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K_L^0	$\to$	$\pi\ e\ \nu_e$	40.5
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μ	$\to$	$e\ \nu_e\ \nu_\mu$	100

- ○ ν_μ flux is mainly made of π^+ decay ; the high energy tail comes from K^+
- ○ $\bar{\nu}_\mu$ flux arises from not defocused π^- and μ^+ decay
- ○ ν_e flux comes from μ^+ and K^+ 3-body decay
- ○ $\bar{\nu}_e$ flux mostly comes from K^0 decay

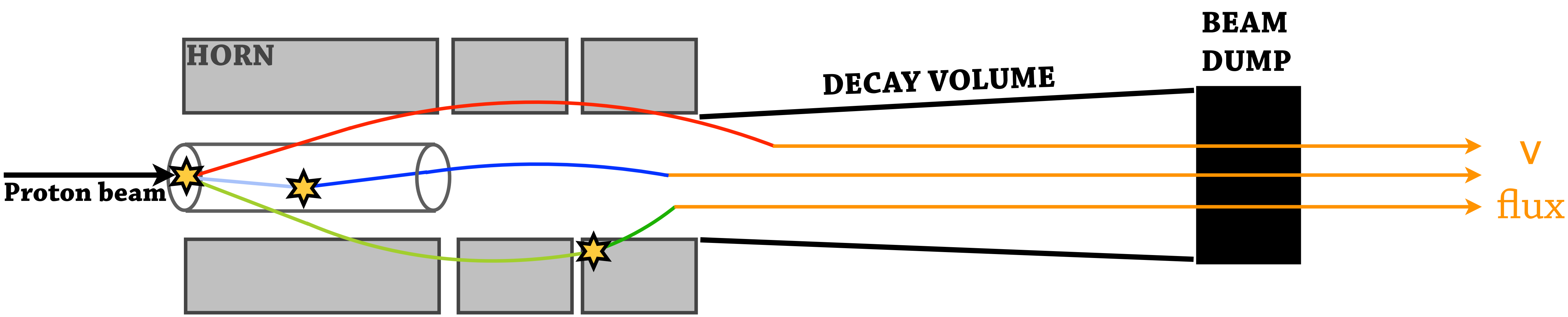
—> *The neutrino flux prediction relies on our knowledge of the hadron production in the neutrino beamline*

Neutrino Parents Production Point

The neutrino parent can be produced [values for T2K, but should be similar for DUNE]:

NIM A**701** (2013) 99-114 [1207.2114]

- By the proton interaction in the target -> 60% of neutrinos
- By subsequent re-interactions in the target -> 30% of neutrinos
- By interactions in the beamline elements -> 10% of neutrinos



These hadronic interactions (p/π/K/… + C/Al/Be/Ti/… at various energies) leading to the production of the neutrino parent are not well known nor well modeled

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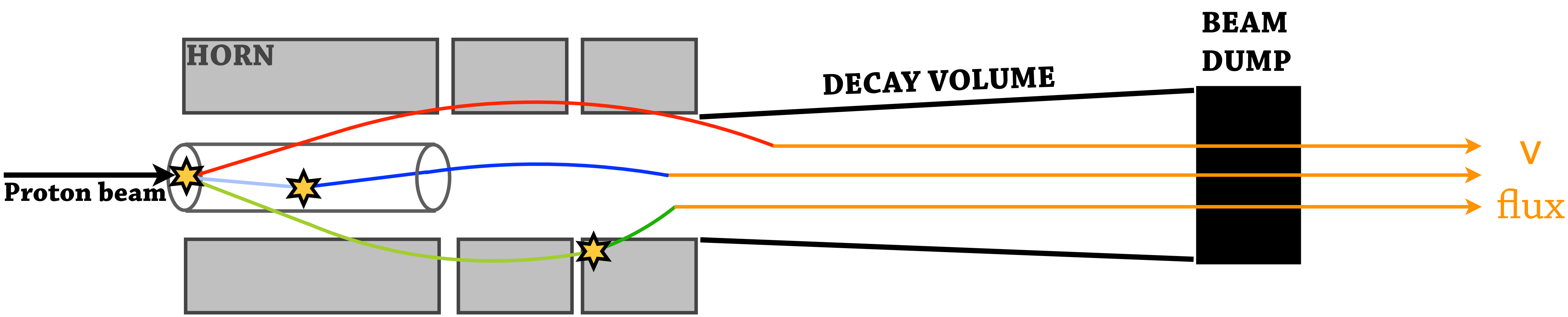

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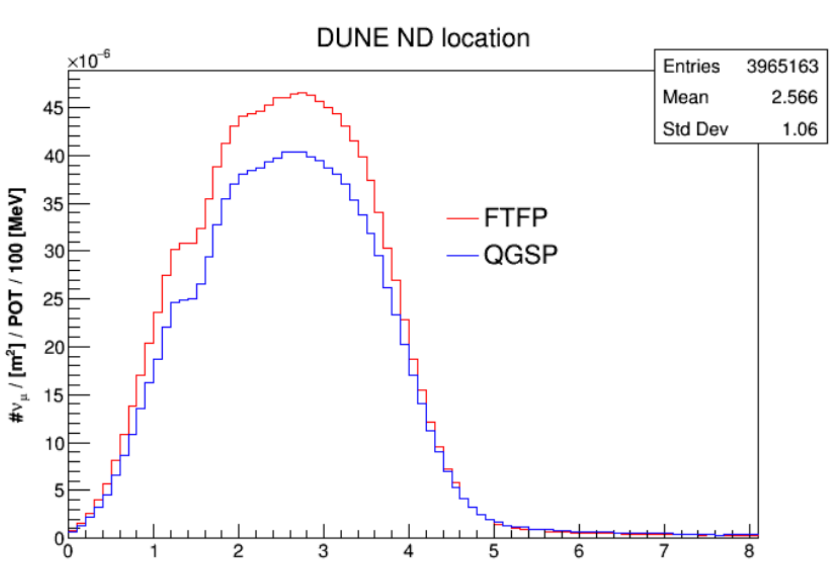
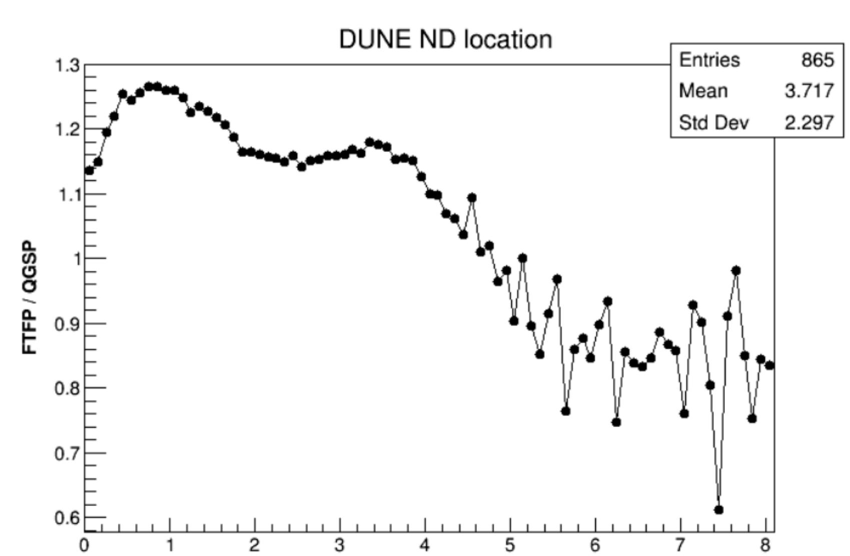




N. Bostan BIWG meeting

Example of the predictions from 2 physics lists of Geant4 [QGSP_BERT and FTFP_BERT] for the ν_μ flux at ND generated by the secondary pion decay :

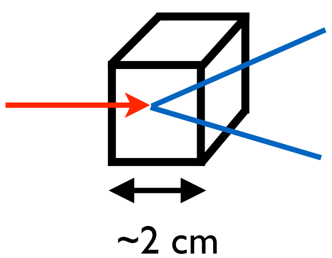
$p+C \rightarrow \pi^+ \rightarrow \nu_\mu$

Targets in hadroproduction experiments

In order to measure and understand these (re-)interactions, LBL ν experiments uses ***hadroproduction experiments***.

Two types of measurements are needed:

Thin target -> Study the total cross section (σ_{prod}) & differential yield ($d^2n/dpd\theta$) of specific interaction channels



NA61 p+C->charged hadronss
NA61 p+C->neutral hadrons
NA61 π+C/Be -> hadrons

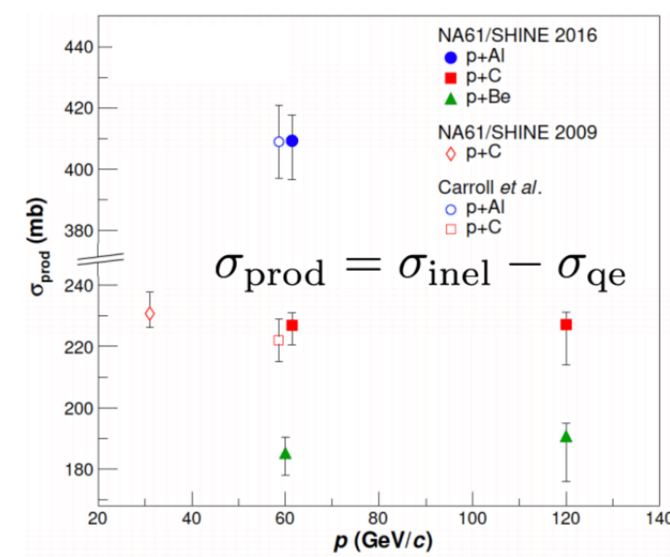
Example of data already taken and analyzed for DUNE:

p [120 GeV] + C -> $\pi^\pm$, $K^\pm$, p, $\bar{p}$, K^0_S, Λ^0, $\bar{\Lambda}^0$

↳ Used to tune the primary interaction [60%]

$\pi^\pm$[60 GeV]+C/Be ->$\pi^\pm$, $K^\pm$, K^0_S, Λ^0, $\bar{\Lambda}^0$

↳ Used to tune the target re-interaction [30%] and out-of-target interactions [10%]



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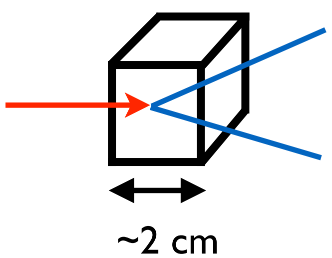

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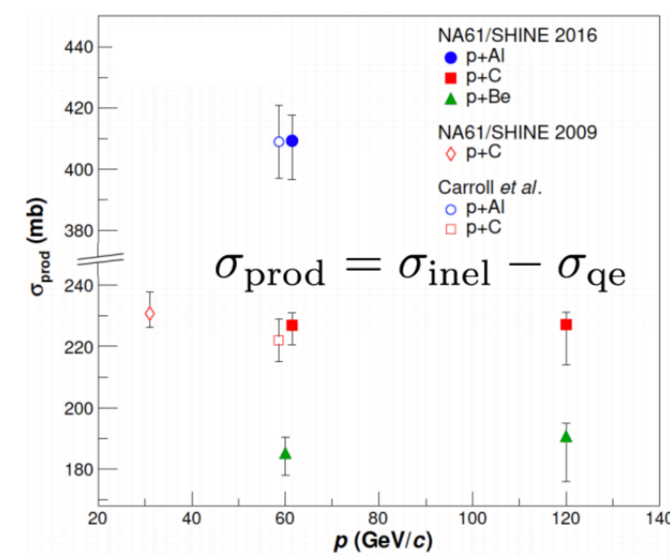
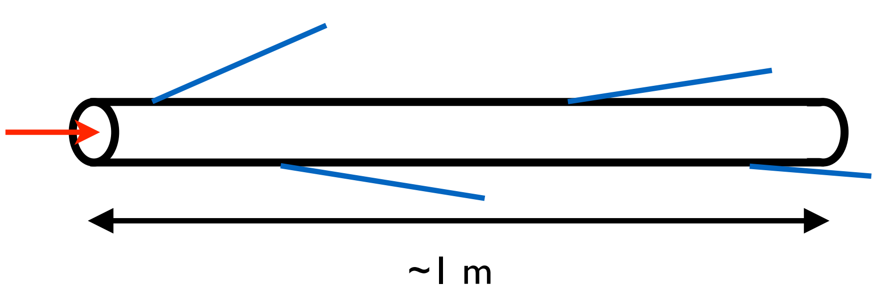


Replica target



-> Study the differential yield ($d^3n/dpd\theta dz$) of escaping hadrons along the same target as the LBL experiment

↳ Used to tune all in-target interactions [60%+30%]

Hadroproduction experiments

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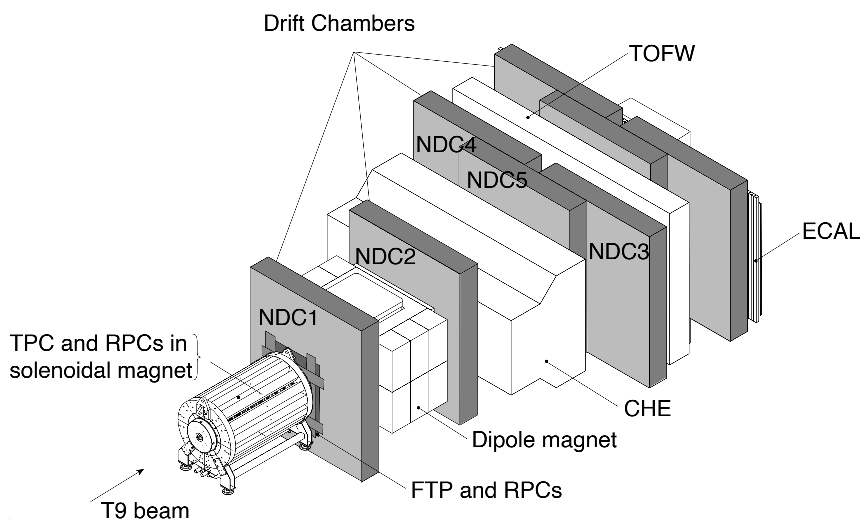
Some hadroproduction experiments :

HARP at CERN [2001~2002]

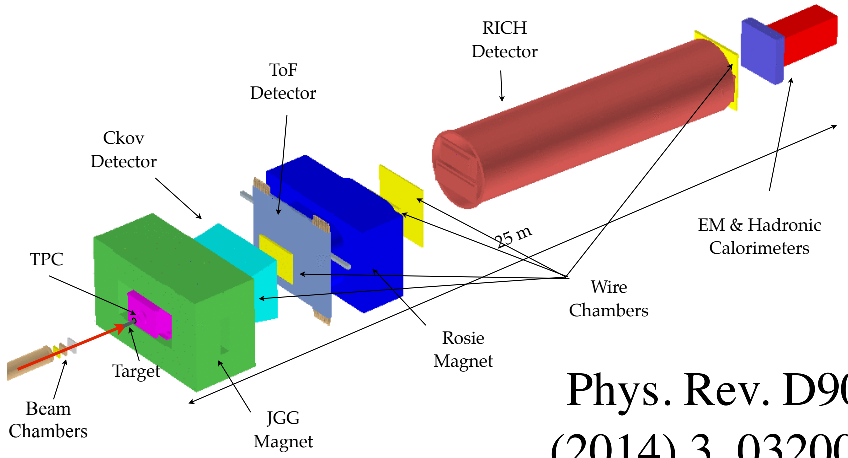


Data for K2K, miniBooNE and LSND experiments (thin and replica targets)
$p/\pi^{\pm}$ + Be/C/Al/Cu/... -> $\pi^{\pm}/K^{\pm}/p$
With p_{beam} : 1.5~15 GeV/c
-> About ~300 different settings taken, 17 papers

NIM **A571** (2007) 524

MIPP at Fermilab

Data for NuMI experiments

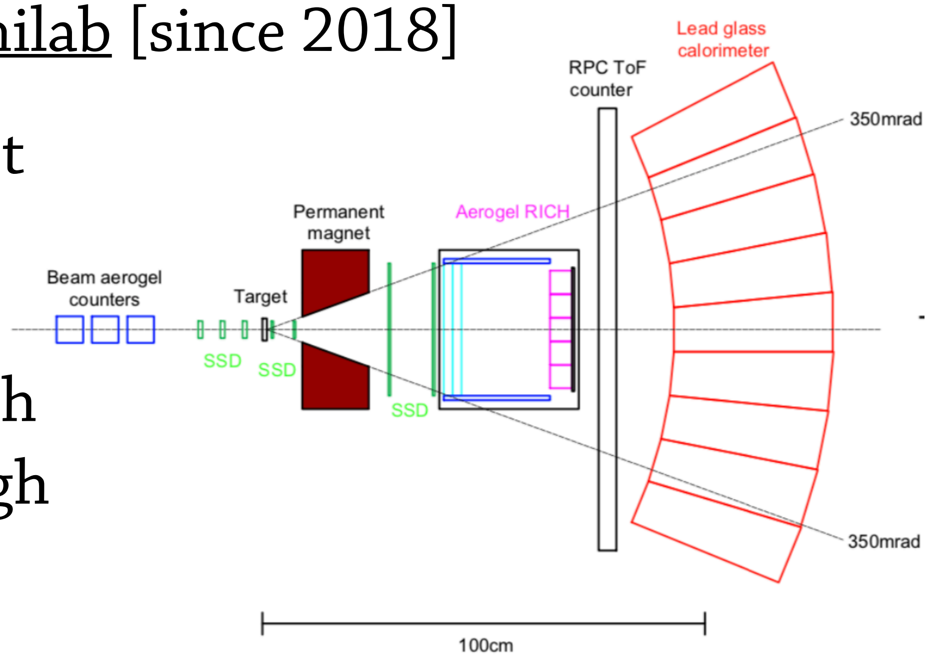


Phys. Rev. D90 (2014) 3, 032001

Measured p[120 GeV/c] + NuMI target -> $\pi^{\pm}$

<u>EMPHATIC at Fermilab</u> [since 2018]

Compact experiment to measure hadron production cross section at low to high momentum with high precision



-> Plans to measure the hadron yield after the first focusing horn of NUMI in the next data taking

Hadroproduction experiments

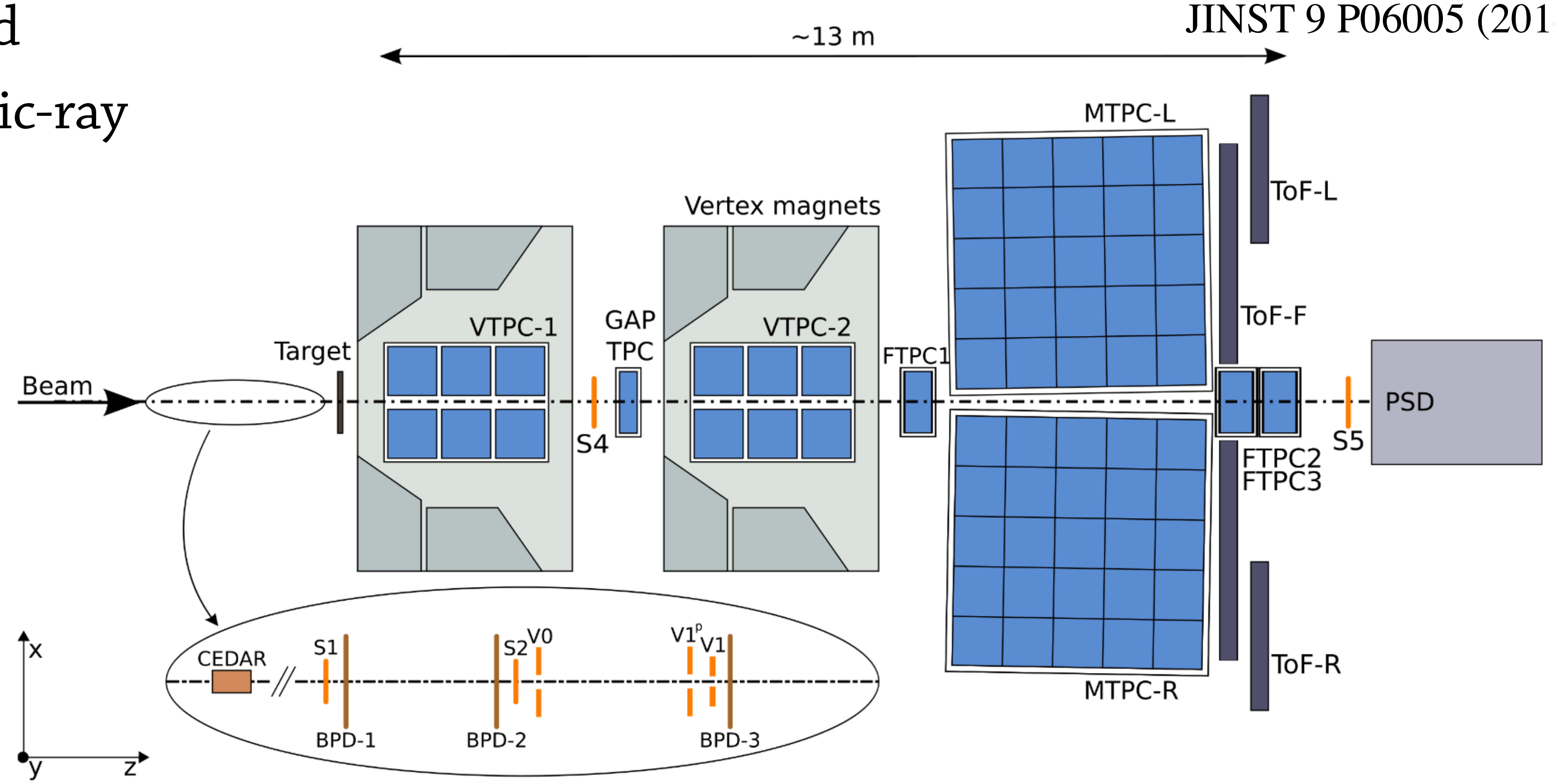
In order to measure and understand these (re-)interactions, LBL ν experiments uses ***hadroproduction experiments***.

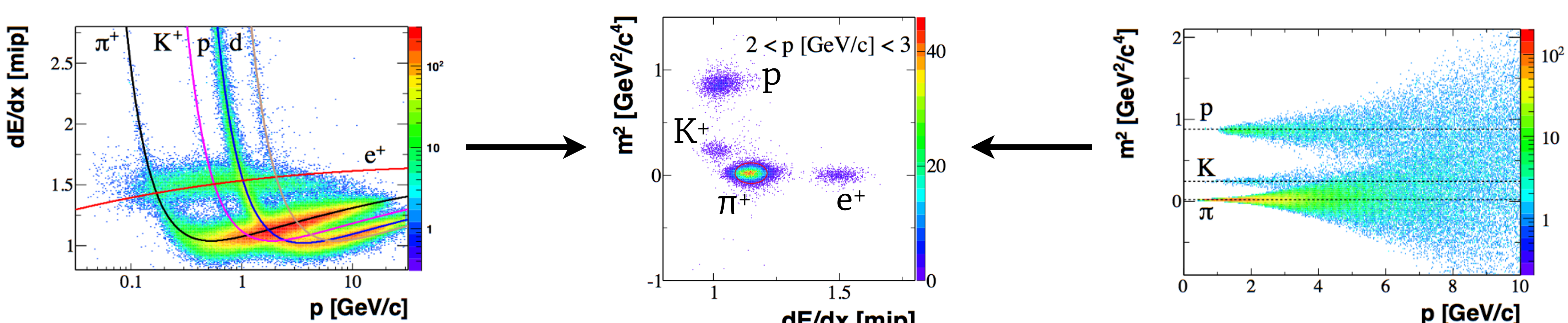
NA61/SHINE is a large acceptance spectrometer at CERN in EHN1 (successor of NA49)

↳ study quark-gluon plasma and collects data for LBL ν and cosmic-ray experiments.

- Made of 8 TPCs (2 in a 1.5T magnetic field) for tracking and dE/dx and 4 downstream ToF walls
- Particle identification made by the combination of dE/dx and ToF

JINST 9 P06005 (2014)

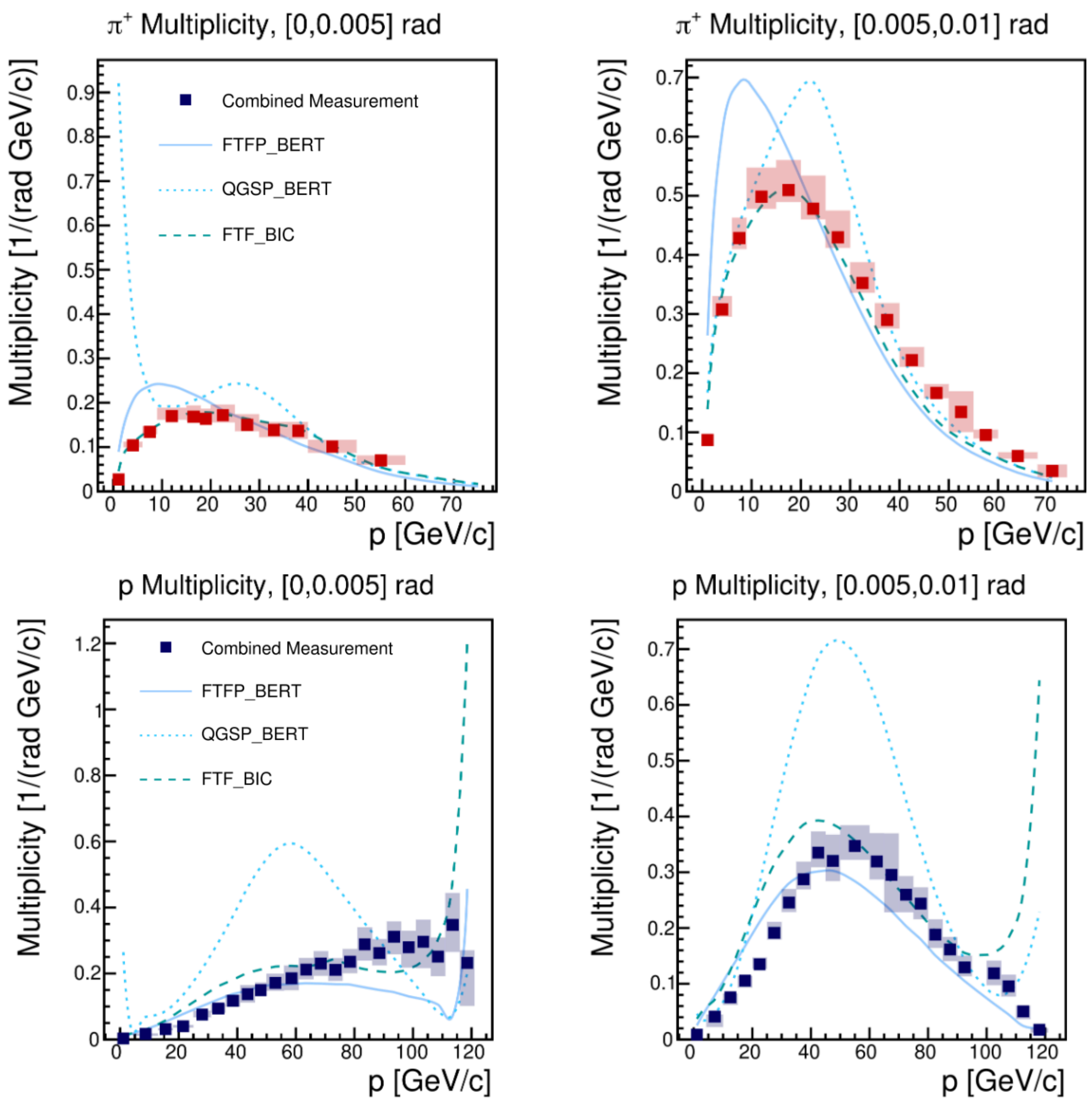




NA61/SHINE data

NA61 p[120 GeV/c] + C thin target data

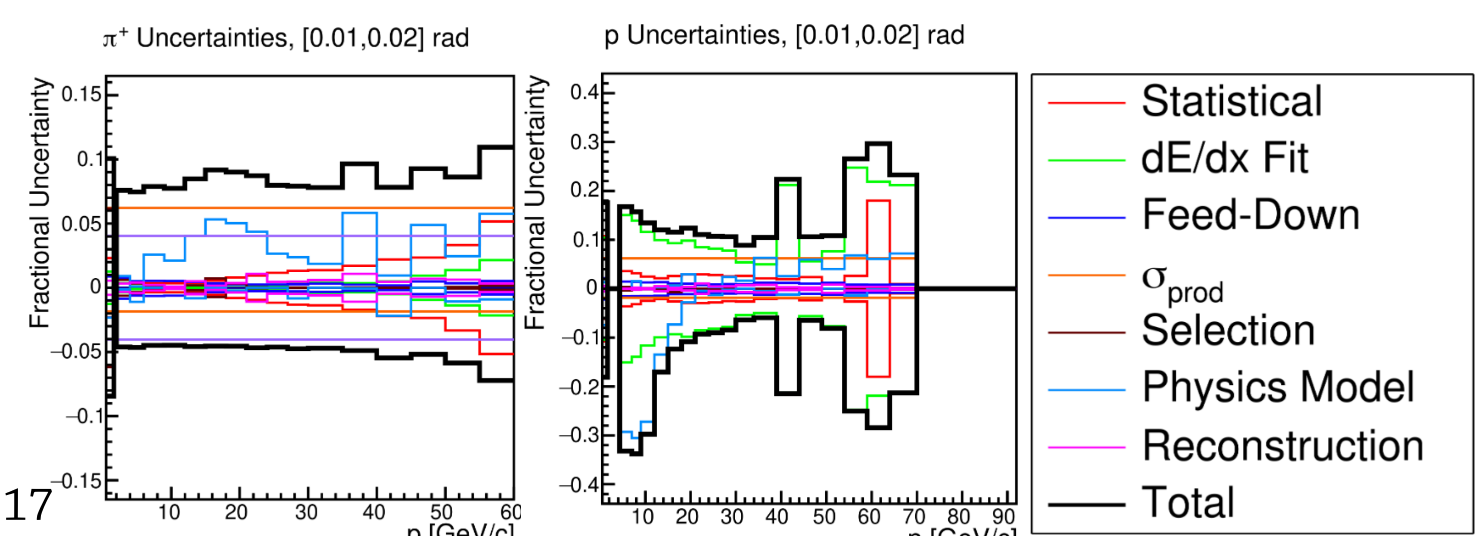
NA61 p+C->charged hadrons



The hadronic yields are binned in p-θ and compared to hadronic model predictions

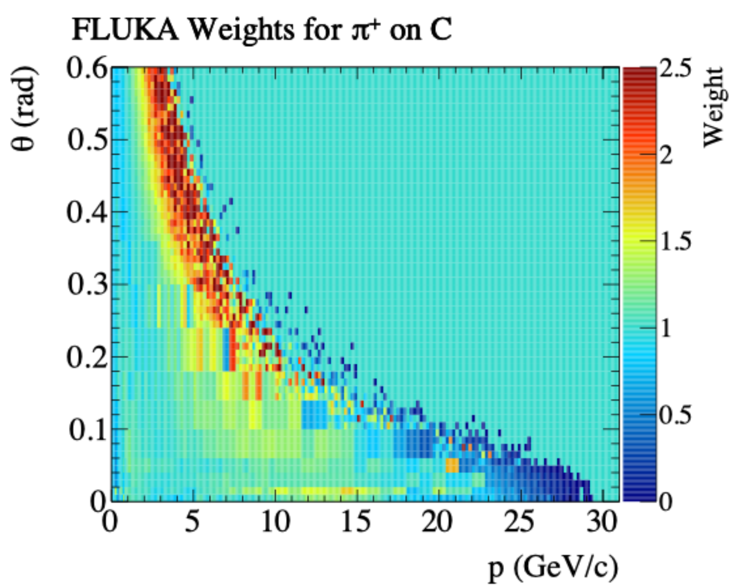
↳ Hard to find one model that reproduces well all datasets

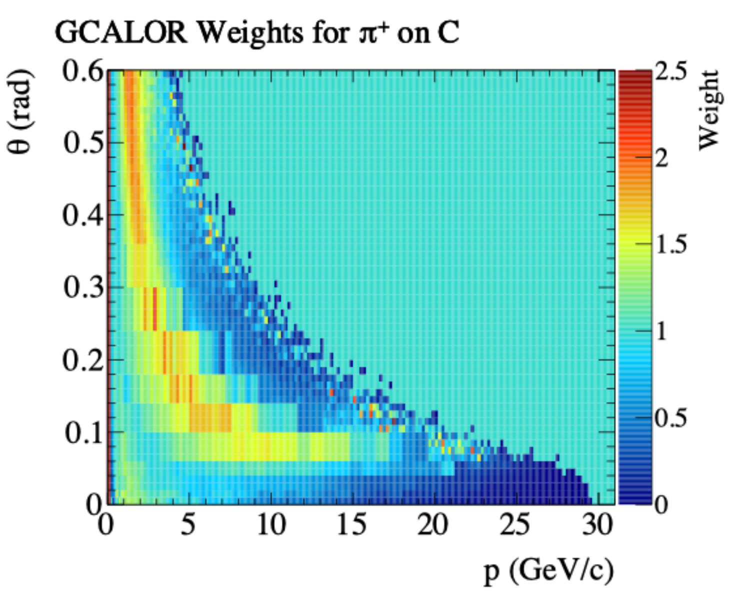
->In general Fritriof-based ones [FTF*] are in better agreement for many interactions

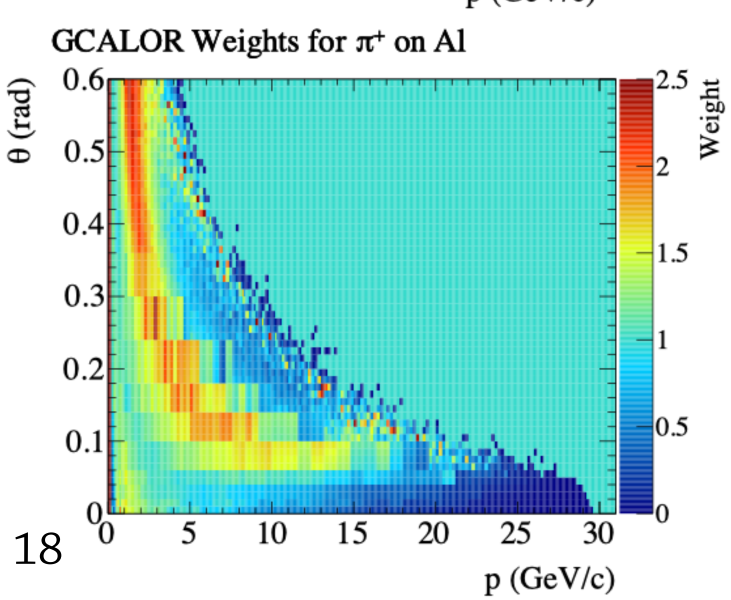


The dominant uncertainty of NA61/SHINE measurements depends with the particle and the phase-space

Flux prediction re-weight with thin targets





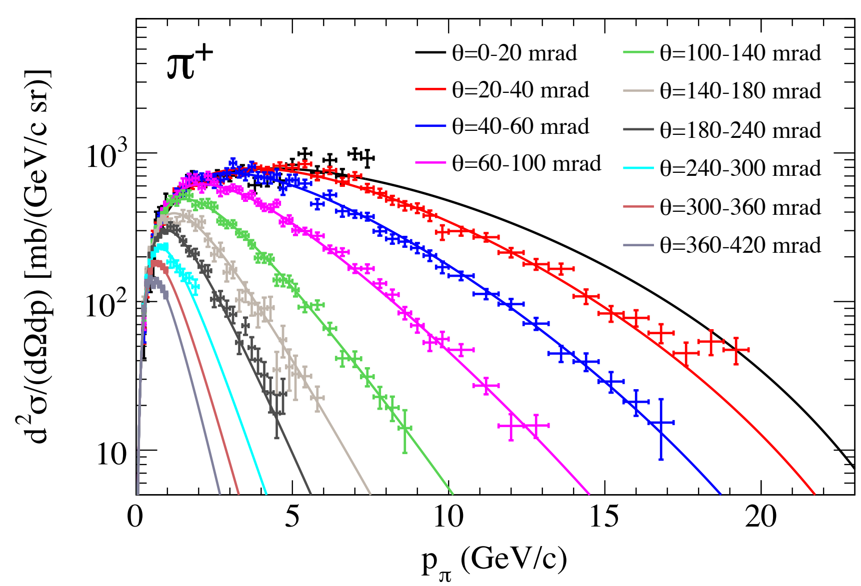


The hadroproduction measurements will be directly used to constrain the neutrino flux predictions.

An hadronic model is chosen for the neutrino flux simulation. First, yield ratios data/MC are computed for all relevant differential hadron production cross section available:

$$W = \frac{\left(\frac{d^2 n}{dp d\theta}\right)_{data}}{\left(\frac{d^2 n}{dp d\theta}\right)_{MC}}$$

The kinematic coverage of the data can be extended with a parametrization of the differential cross section:



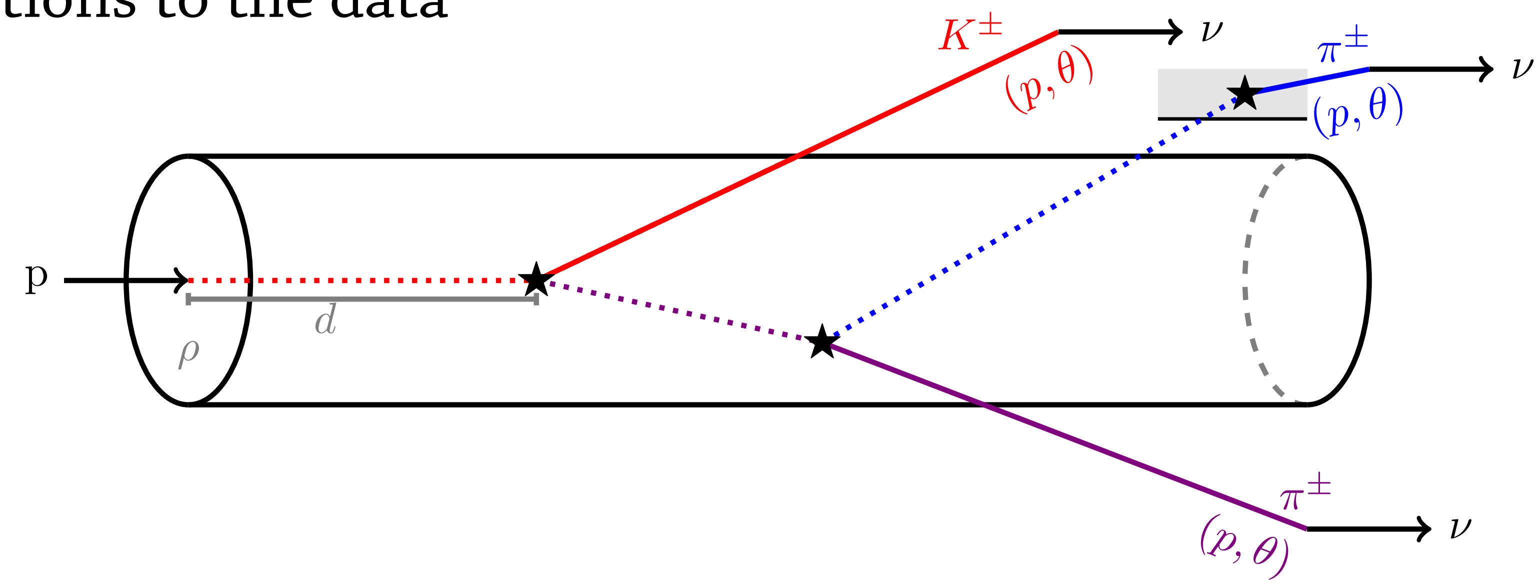
BMPT fits to NA61/SHINE 2007 p+C thin target data

Eur. Phys. J. C20 13-27 (2001)

[NB: Plots are from slightly outdated T2K case]

Flux prediction re-weight with thin targets

In the neutrino flux simulation, using the same hadronic model, look at the ν history and correct the MC predictions to the data



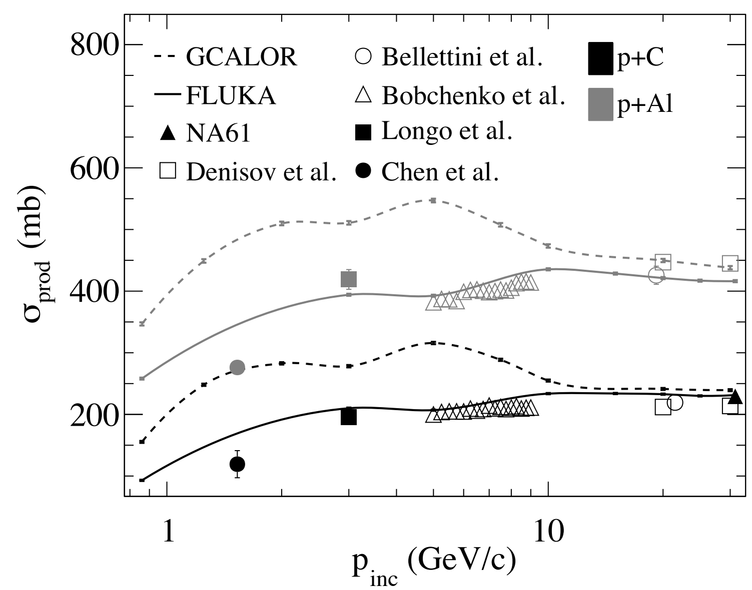
If the interaction is directly covered by hadroproduction data :

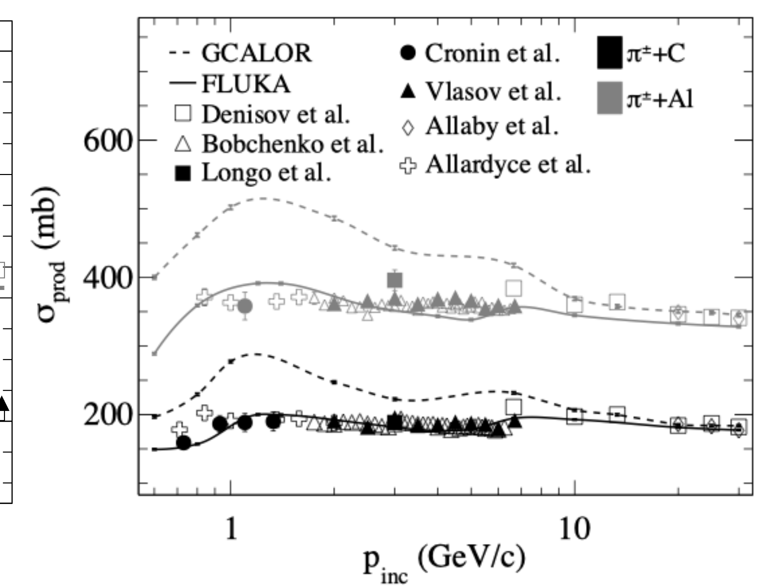
- Correct the MC multiplicity $:W = \frac{\left(\frac{d^2n}{dpd\theta}\right)_{data}}{\left(\frac{d^2n}{dpd\theta}\right)_{MC}}$

- Correct the MC interaction cross section :

$$w_{\text{int.}} = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}} \times \exp(-\rho d(\sigma_{\text{data}} - \sigma_{\text{MC}}))$$

NB : one should be careful with the chosen hadronic model





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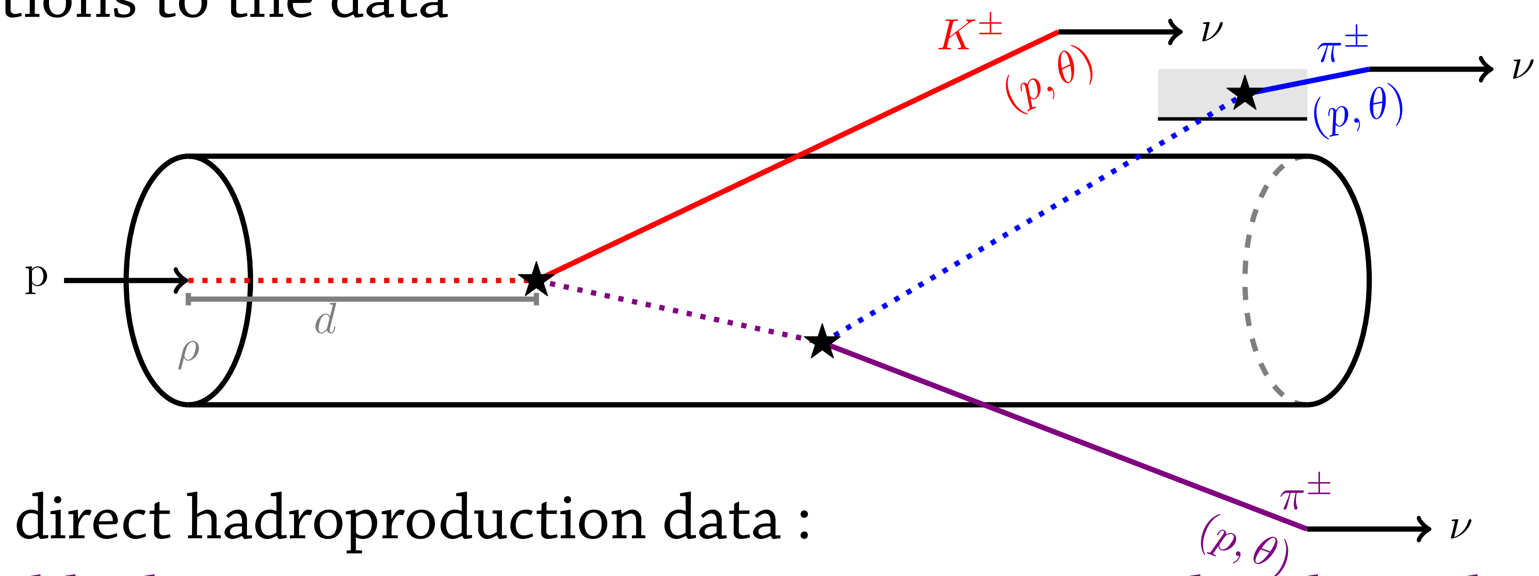


If there is no direct hadroproduction data :

-> Scale available data in momentum using Feynman-scaling hypothesis

When expressed in x_F-p_T kinematics, differential hadroproduction cross section becomes invariant

Phys. Rev. Lett. 23, 1415 (1969)

x_F : $p^*_L/p^*_{L,max}$

P_T = transverse mom

-> Scale available data in target

Target dependency of differential hadroproduction cross section is parametrized by a function expressed in x_F-p_T $\frac{d^2\sigma}{dpd\theta}(A_1) = \left[\frac{A_1}{A_0}\right]^{\alpha(x_F,p_T)} \frac{d^2\sigma}{dpd\theta}(A_0)$

Eur. Phys. J. C20 13-27 (2001)

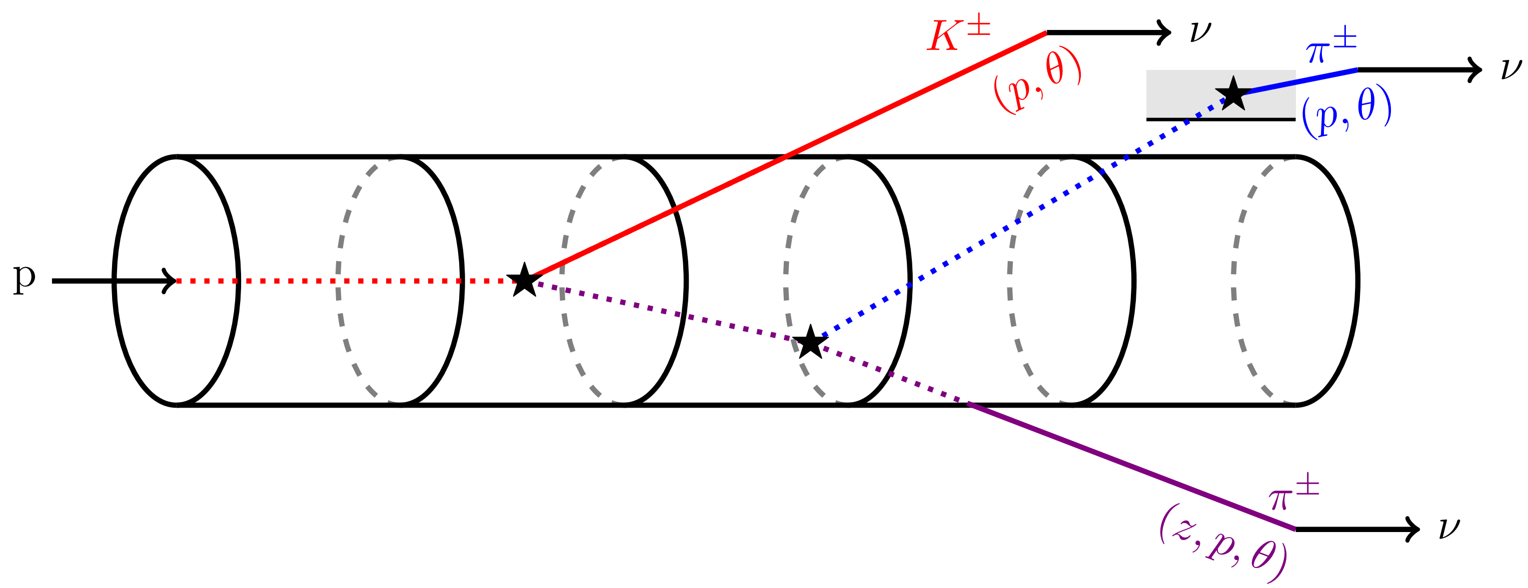
->Make an educated guess

E.g. K^0_L yield can be expressed as a mixture of $K^{\pm}$

 ->Trust the MC prediction

Flux prediction re-weight with replica targets

When replica target hadroproduction data is available



○ If the hadron is a pion produced in the target and if there is corresponding hadroproduction data :

Tune the MC yield at the surface of the target according to data :

$$w_{\mathrm{mult}}(z,p,\theta) = \frac{[\frac{dN}{dp}(z,p,\theta)]_{\mathrm{data}}}{[\frac{dN}{dp}(z,p,\theta)]_{\mathrm{MC}}}$$

-> Corrects the amount of hadrons produced in the target ; interaction tuning is no longer needed

○ Any other case

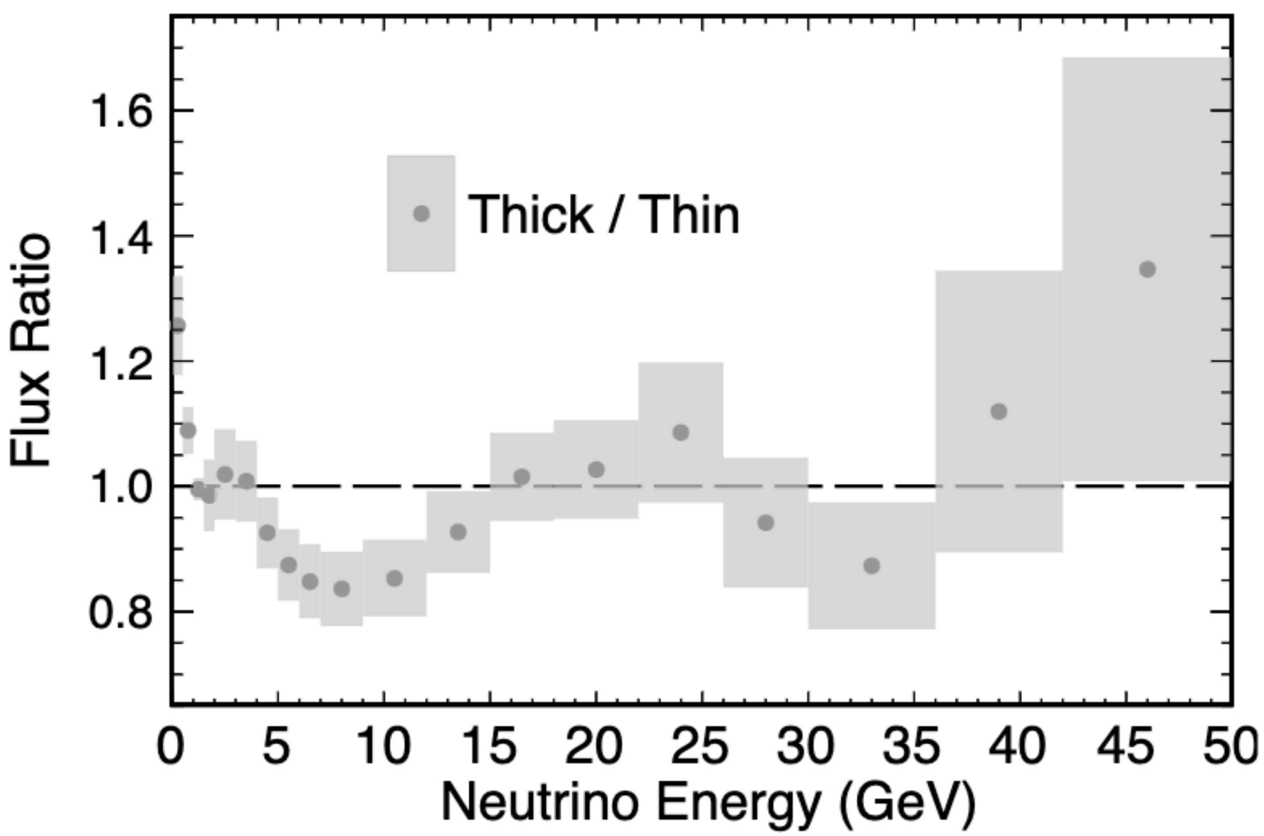
Apply the thin target tuning method

-> Thin and thick target data are important !

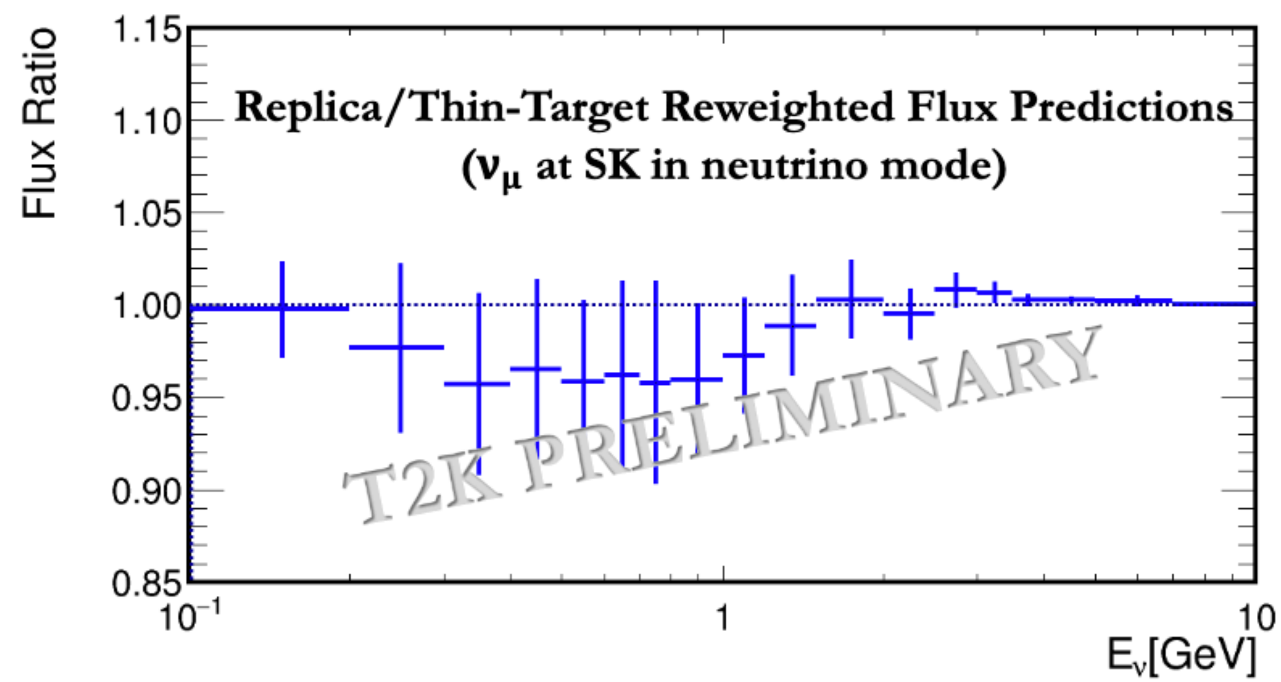
NB: with the replica target tuning method, the proton beam and target design are fixed!

Flux prediction : thin vs replica re-weight

NuMI Flux

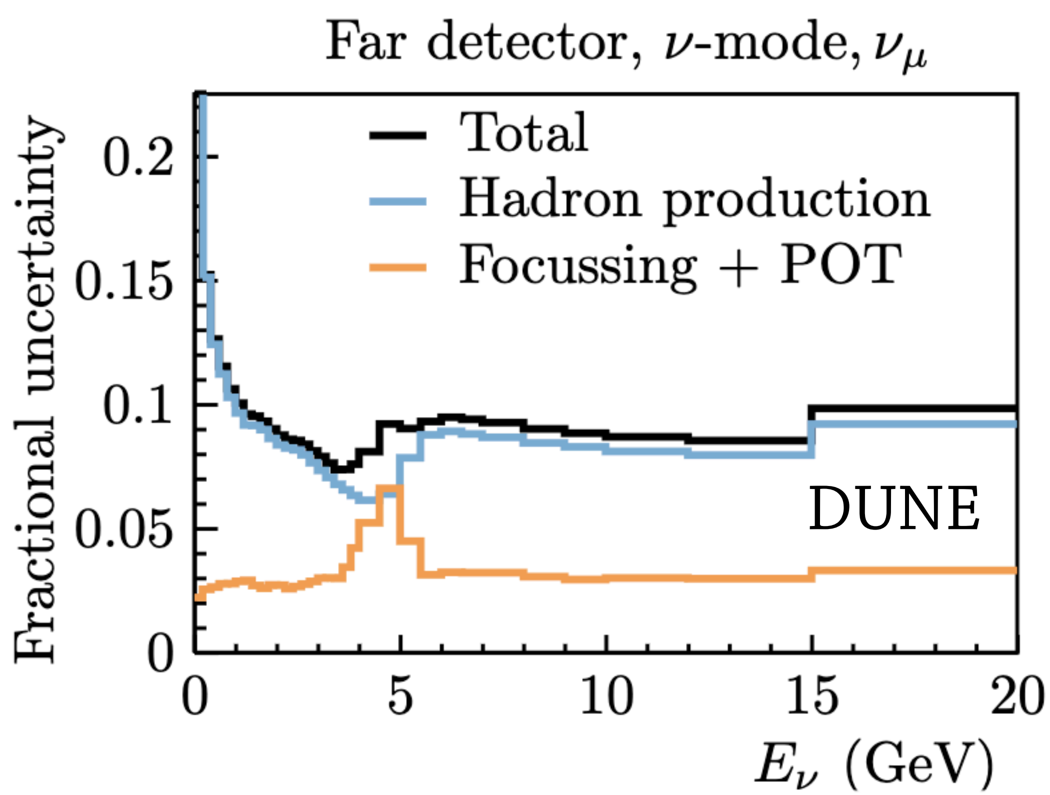


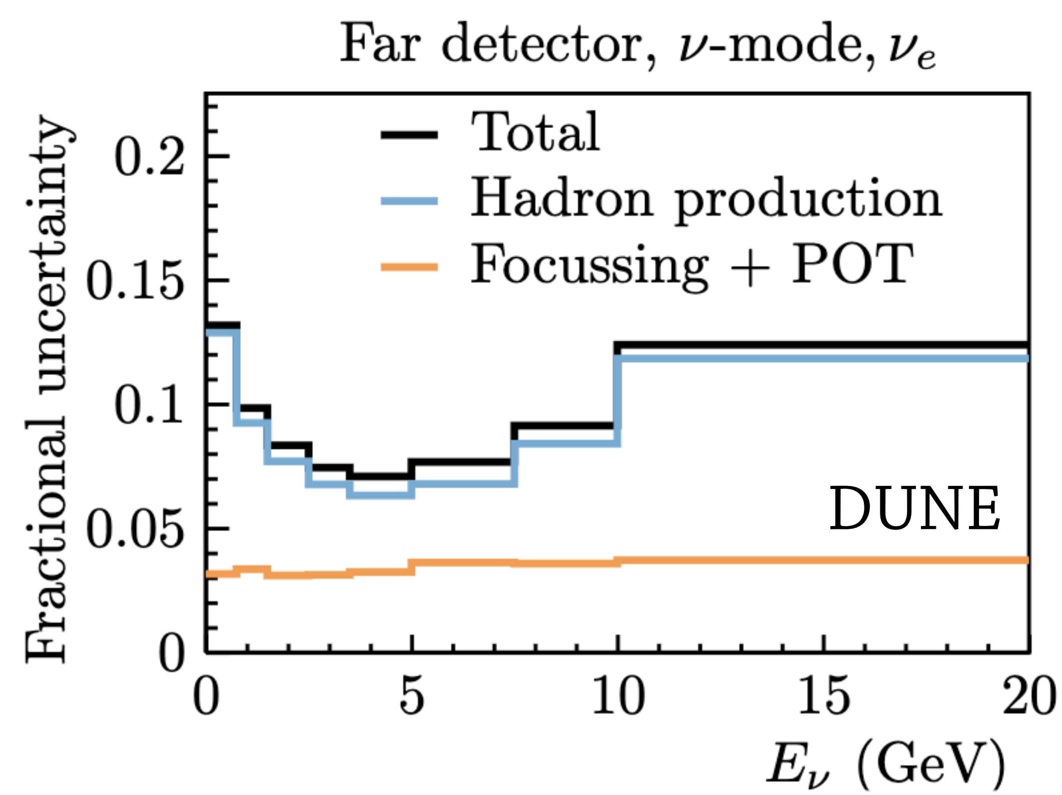
T2K Flux



In both cases, the flux tuning with the replica target predicts less neutrinos wrt to the thin target tuning -> Still ongoing working to understand this effect

Flux uncertainties

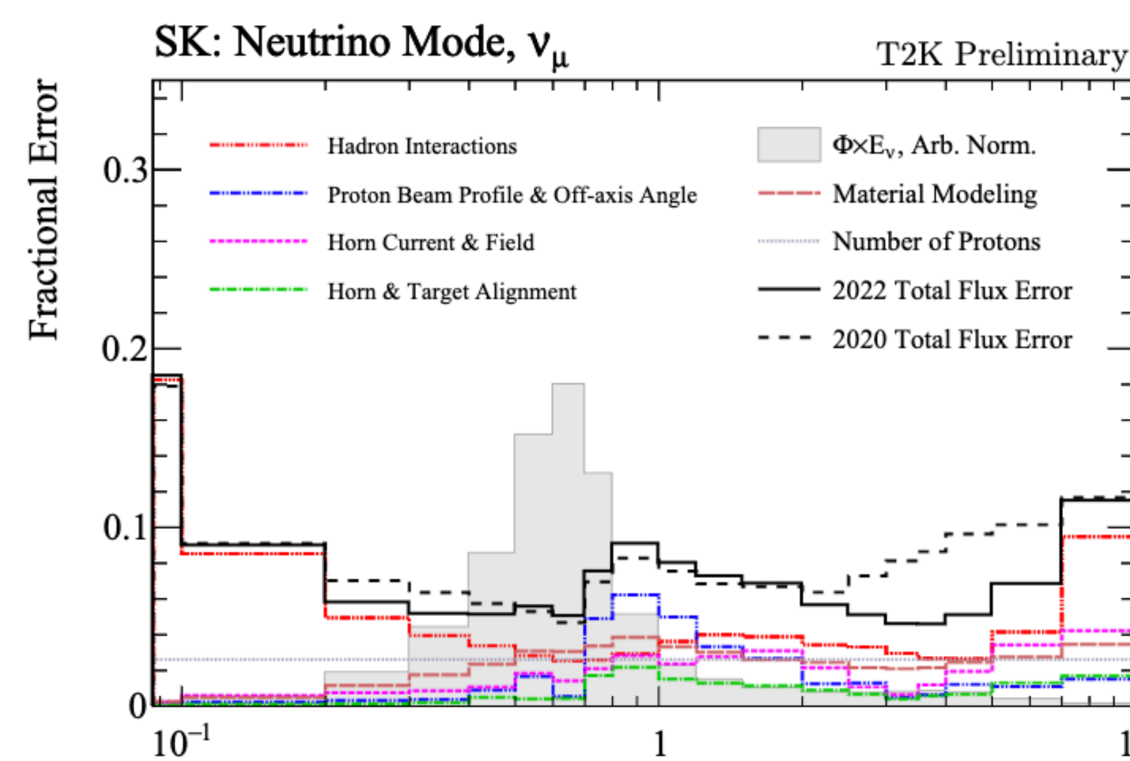




The DUNE flux errors are dominated by the hadronic interactions

-> Expect to decrease as new hadroproduction data (thin and replica) will be taken

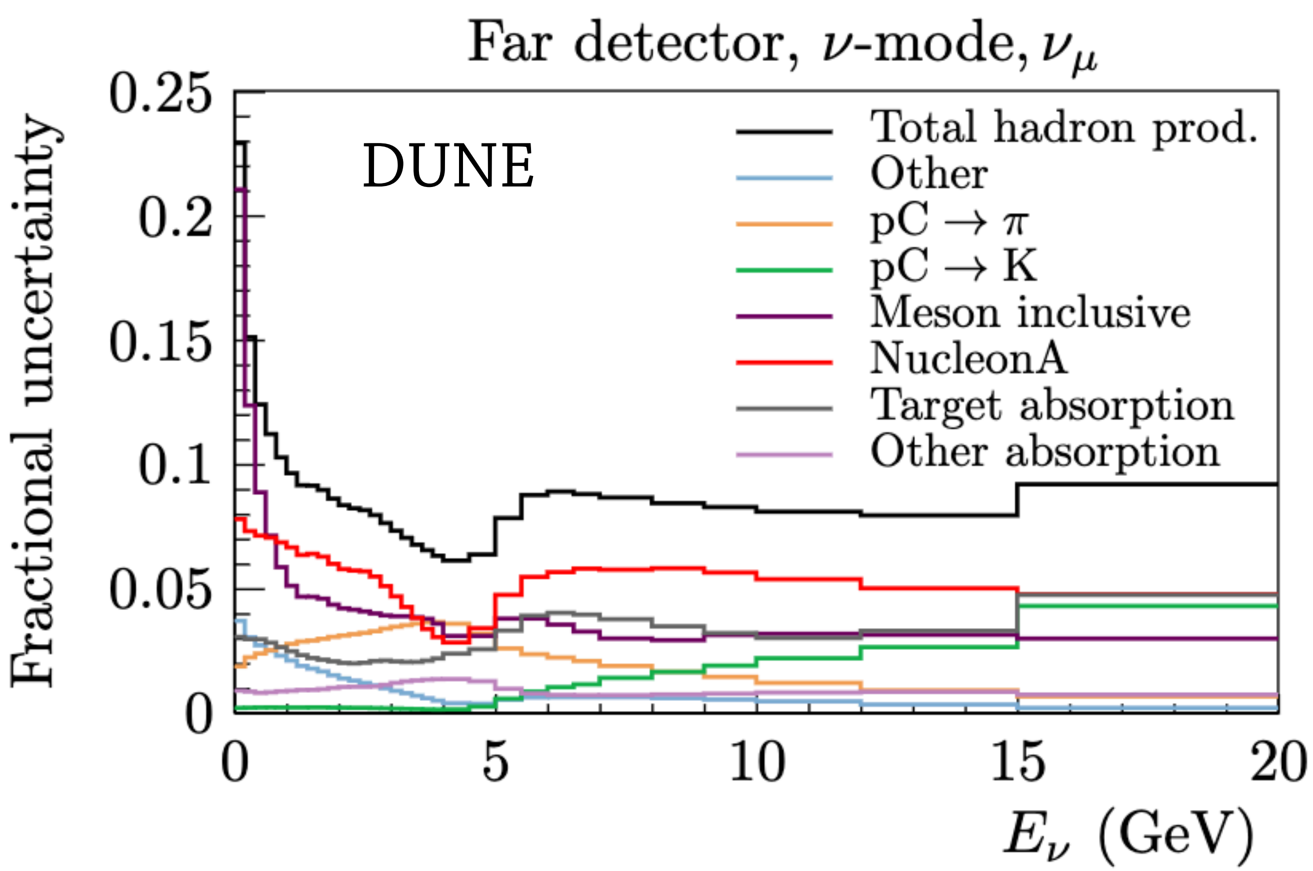
-> in T2K, hadron and beamline related errors are now equivalent

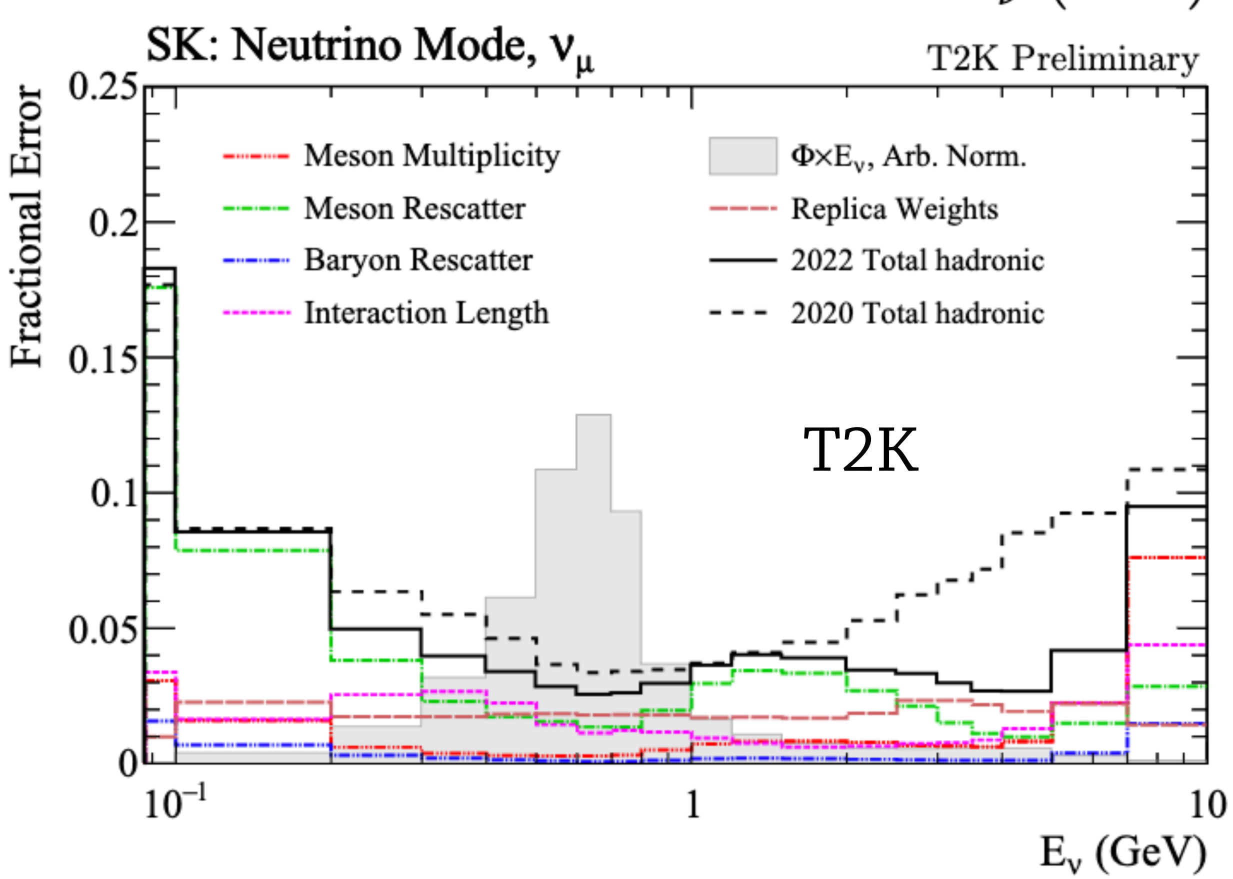


E_ν (GeV)

M. Friend NUFACT 23

Flux uncertainties : hadronic part





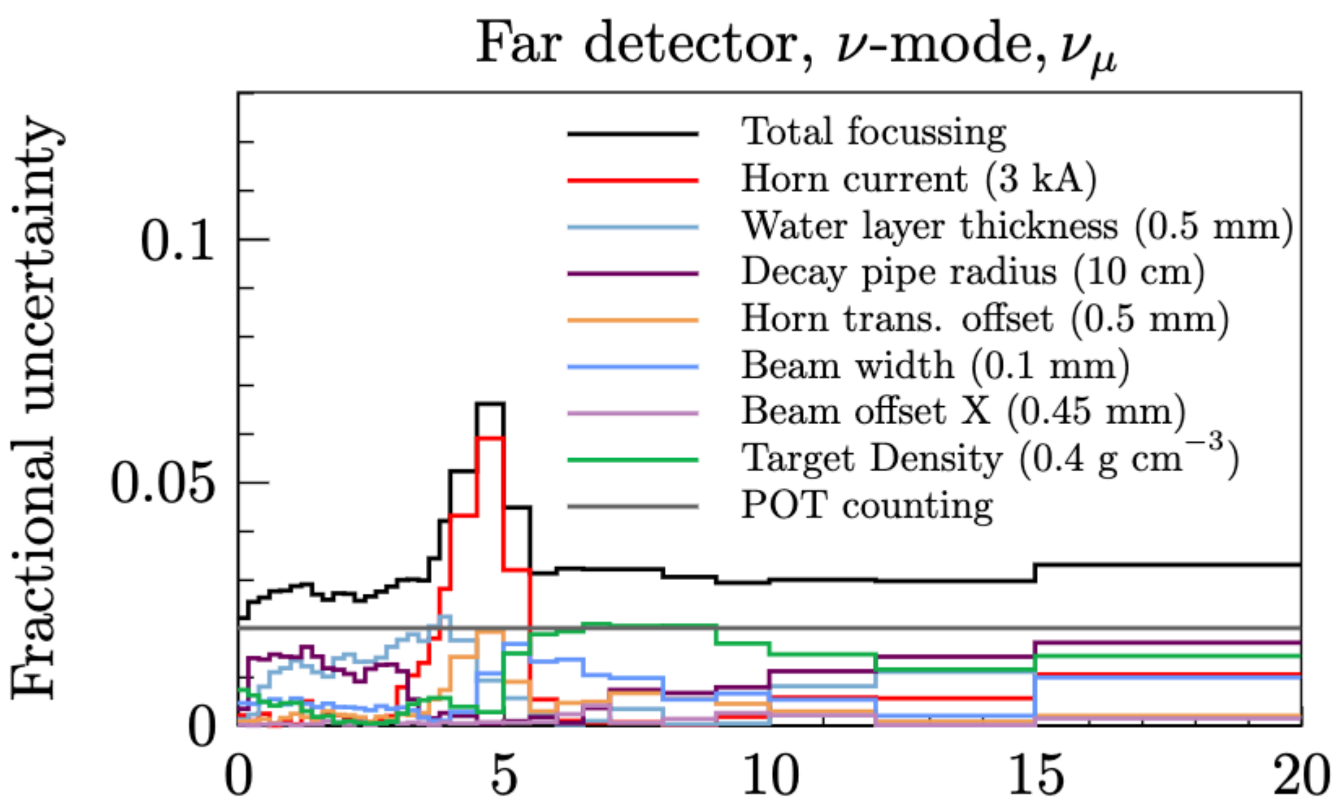
For the hadronic errors, DUNE is currently dominated by :

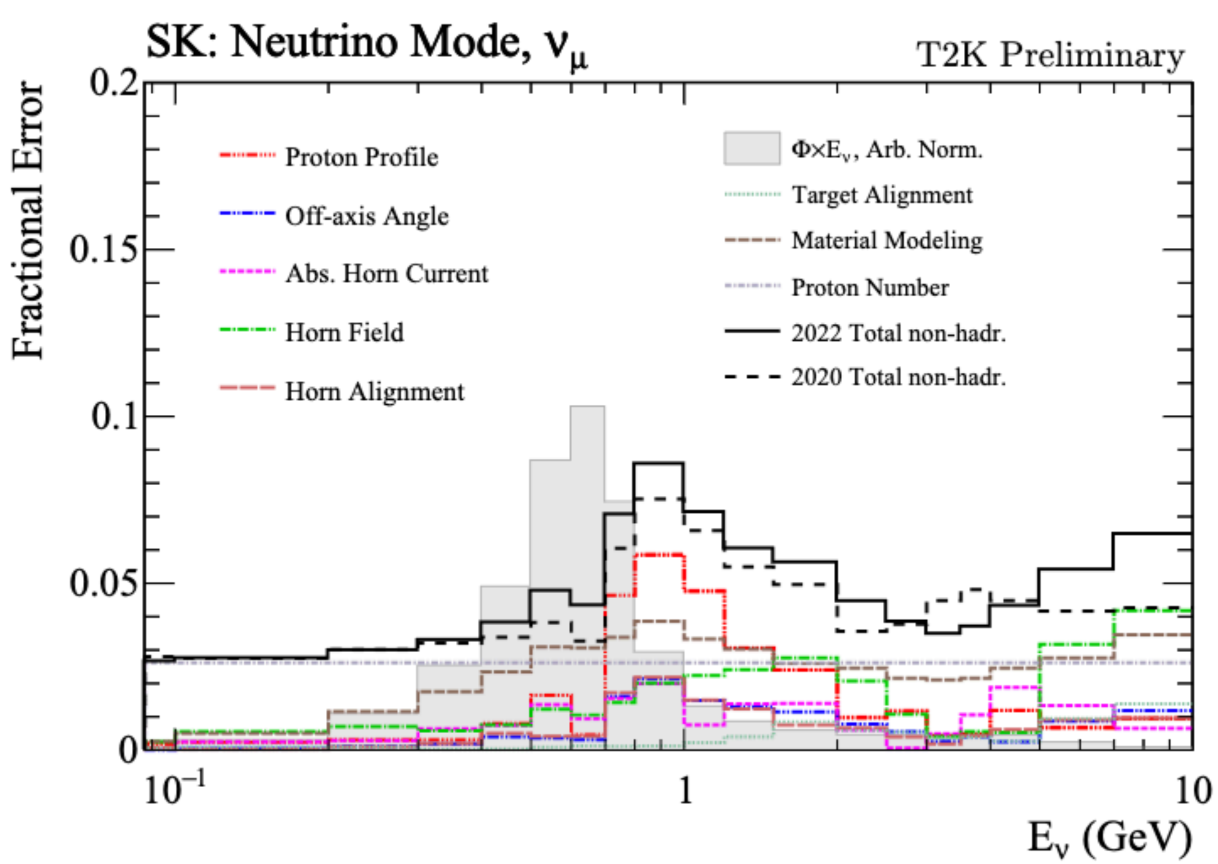
- 'NucleonA' : p and n (re-)interactions not covered by external data
- 'Meson Inclusive' : pion re-interaction not covered by external data

For T2K, the hadronic errors account for ~ 4% at the flux peak, dominated by the pion re-interaction

-> More data from hadroproduction are needed!

Flux uncertainties : non-hadronic part





For the non-hadronic errors, DUNE is currently dominated by :

- Horn Current : 1% uncertainty
- POT counting : 2% on the number of proton on the target

For T2K, the non-hadronic errors are dominant on the high energy tail:

- Proton Profile : proton beam shape and radius on the target

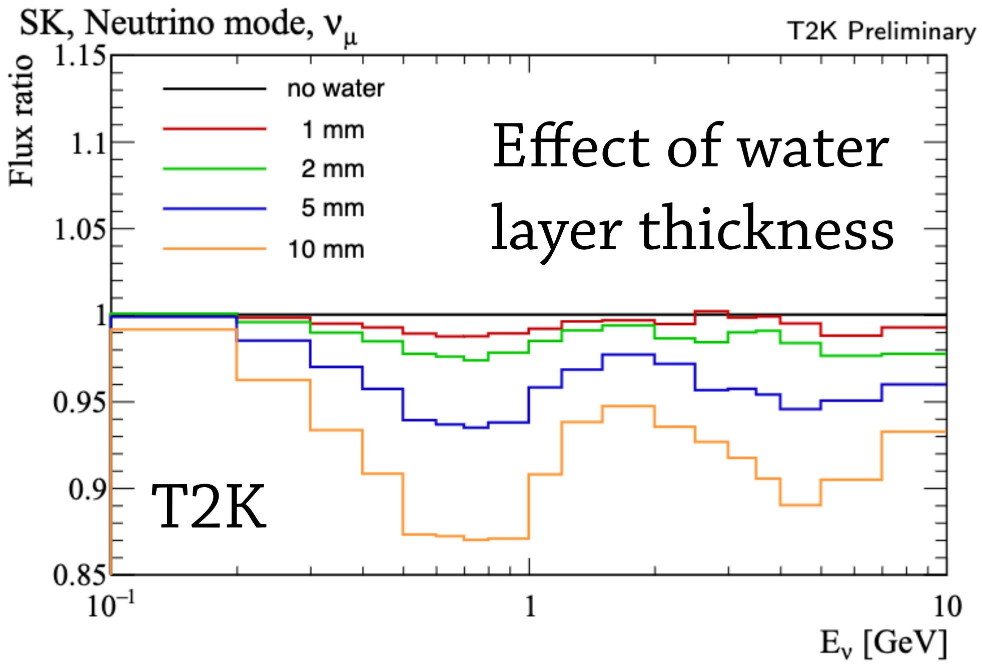
Flux uncertainties : non-hadronic part

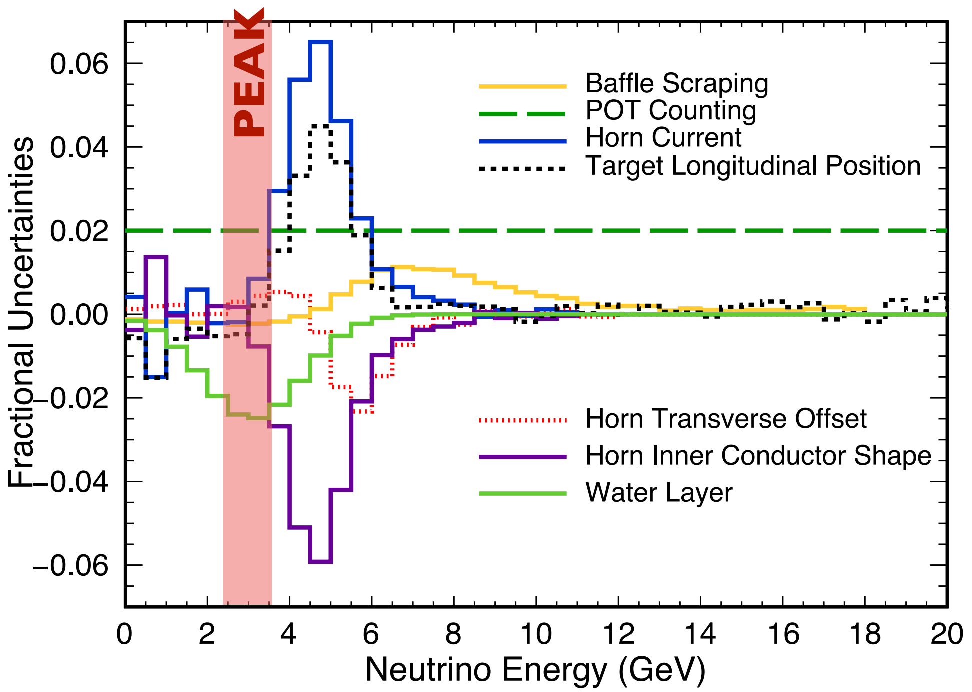
The knowledge of the neutrino beamline is very important for the flux prediction & errors :

Example of the horn cooling water effect on the flux:

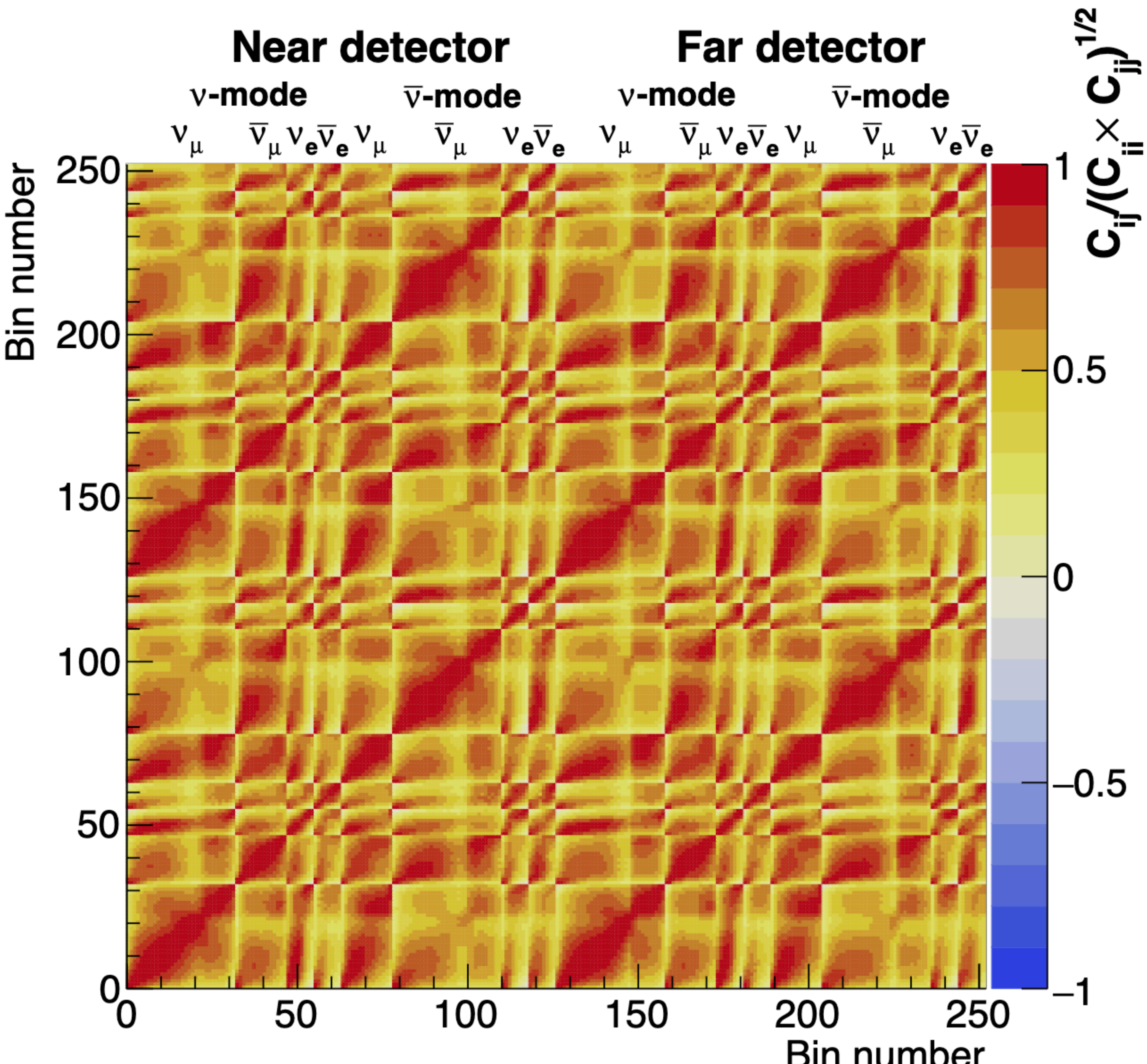
Focusing horns are cooled by water spray between the inner and outer conductors
-> Difficult to measure the thickness of the water layer

For T2K, that layer was 0 ± 1 mm, and has recently been re-estimated to 3 ± 2 mm
-> Same effect seen in Minerva flux at NuMI





Flux uncertainty correlations



In general flux errors are correlated across energy bins and across detectors

-> High energy tail (from K) not so correlated with the peak (from π)

-> Horn focusing uncertainty do not affect the wrong sign background such the νμ/ν̄μ are not so correlated

Other methods to constrain the ν flux

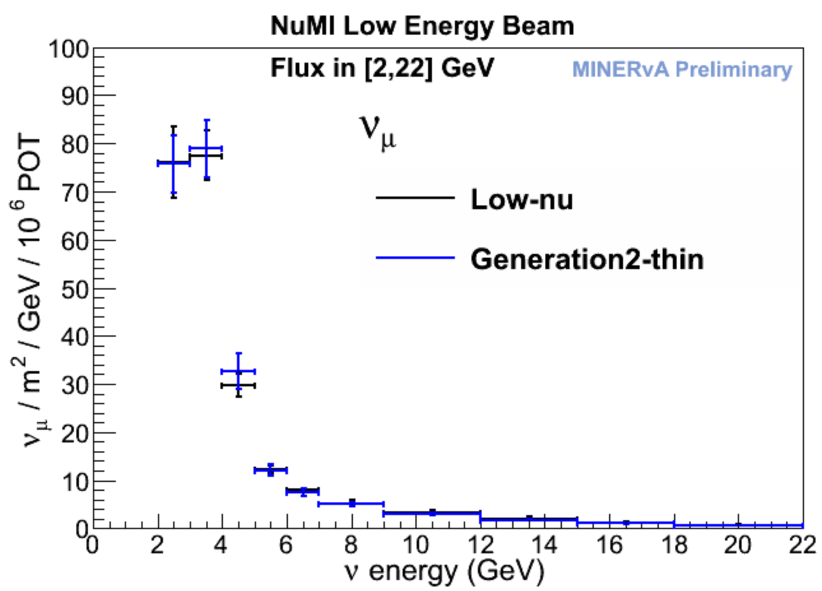
Low-ν technique

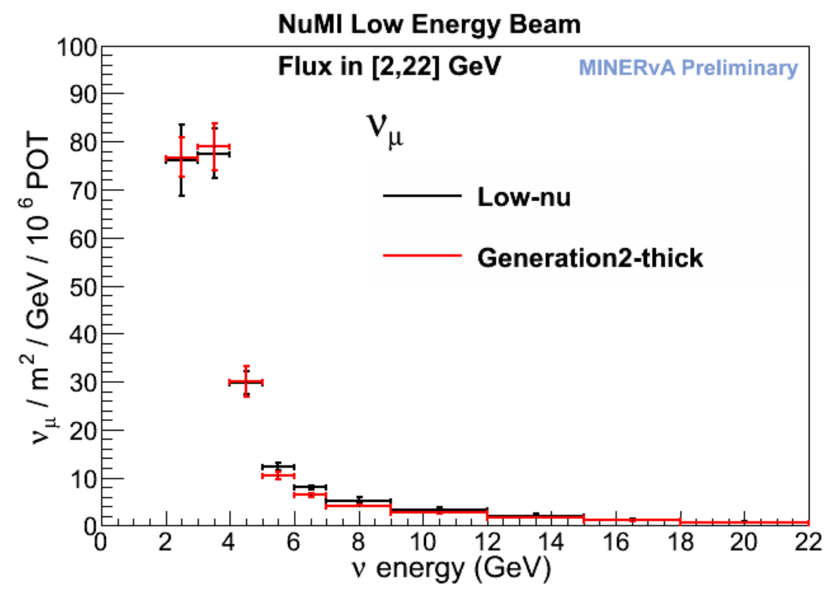
The differential ν-CC interaction at low nucleon recoil energy (ν) is almost constant ; therefore its measurement approximates the flux shape.

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E_\nu} - \frac{C}{A}\frac{\nu^2}{E_\nu^2}\right)$$

A,B,C : integral over structure functions

ν : recoil energy, E_ν neutrino energy





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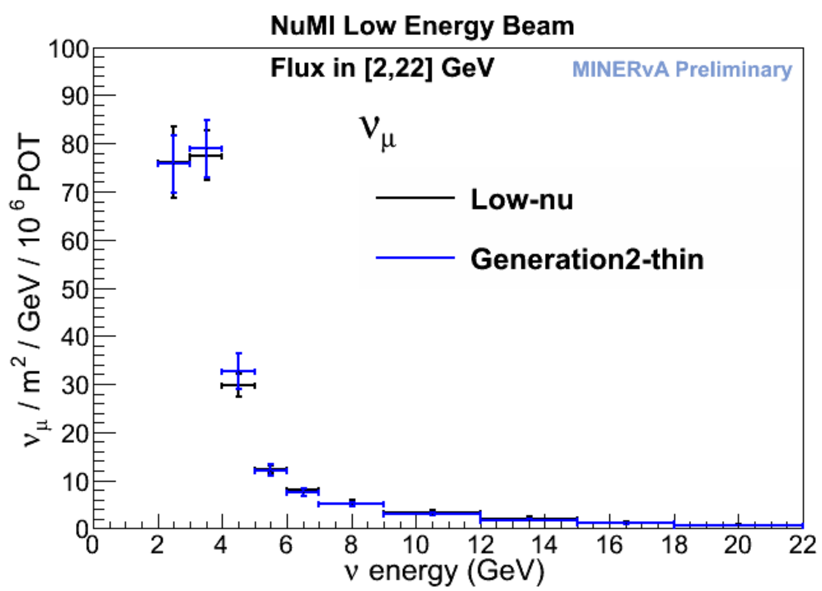
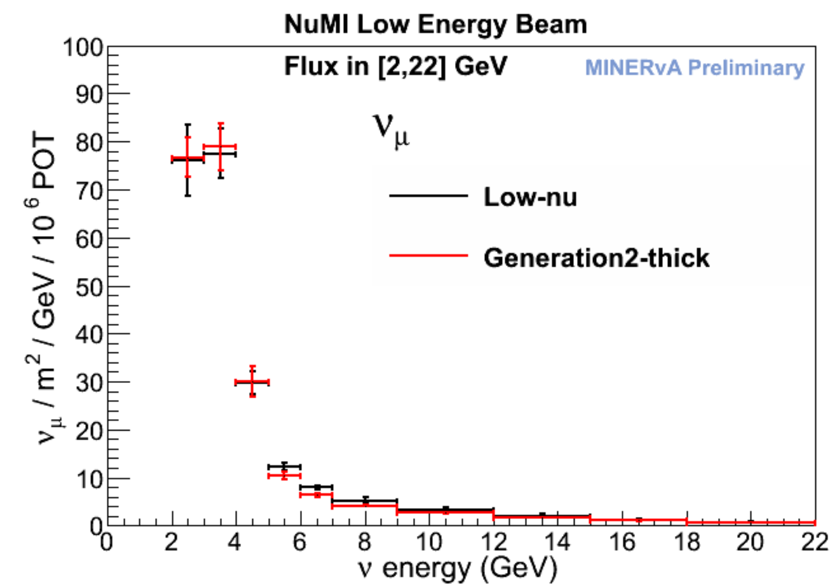
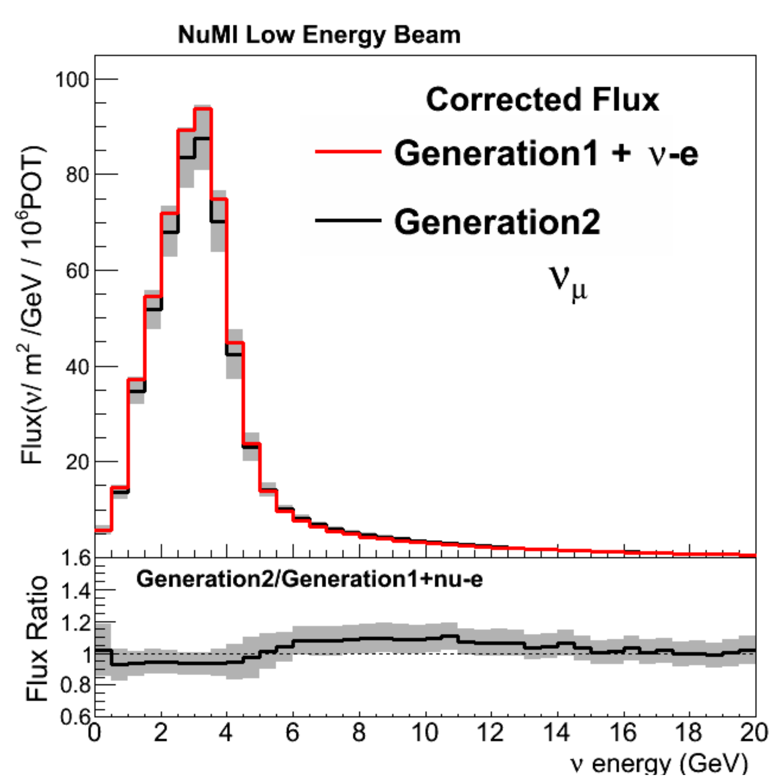
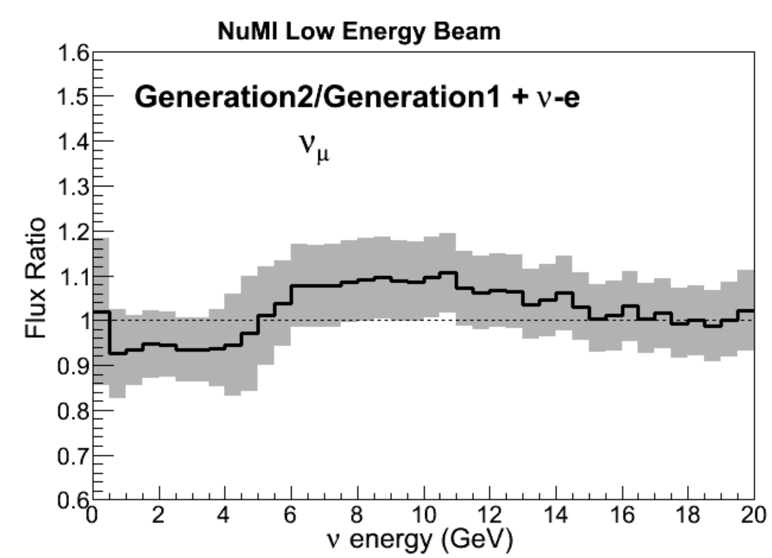




ν-e scattering constrain

$\nu e \rightarrow \nu e$ cross section is very well predicted by the standard model and can help to constrain the flux prediction

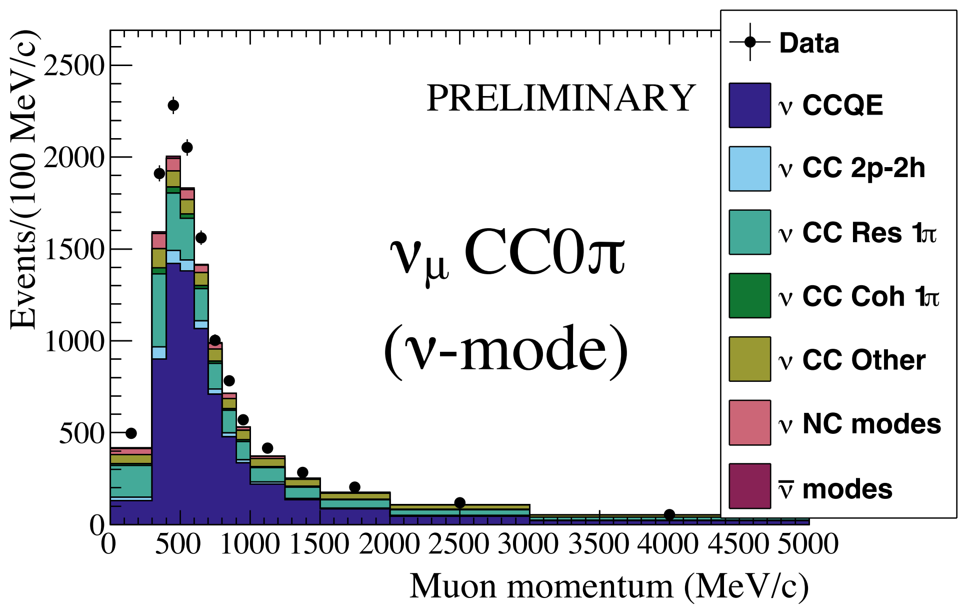




<u>Sensitivity to DUNE</u>

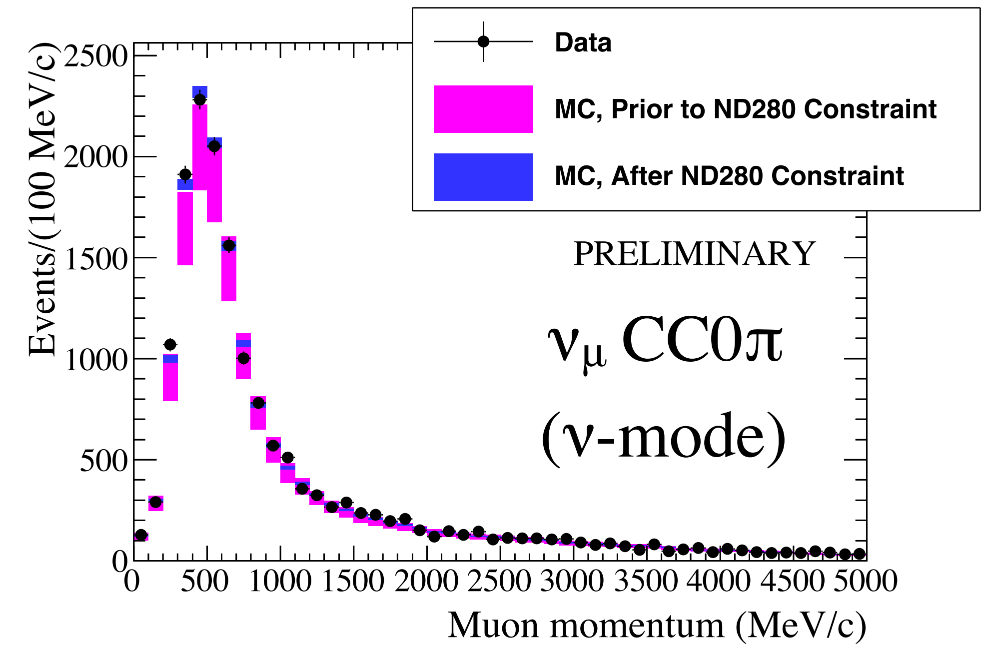
Near Detector Data & Fit - old T2K case

Use the ND data to measure flux × cross section
-> The more sample the better



And fit the spectrum with :

- one per flux bin
- cross section parameters like $M_A^{QE/RES}$, Fermi momentum, MEC normalization,...



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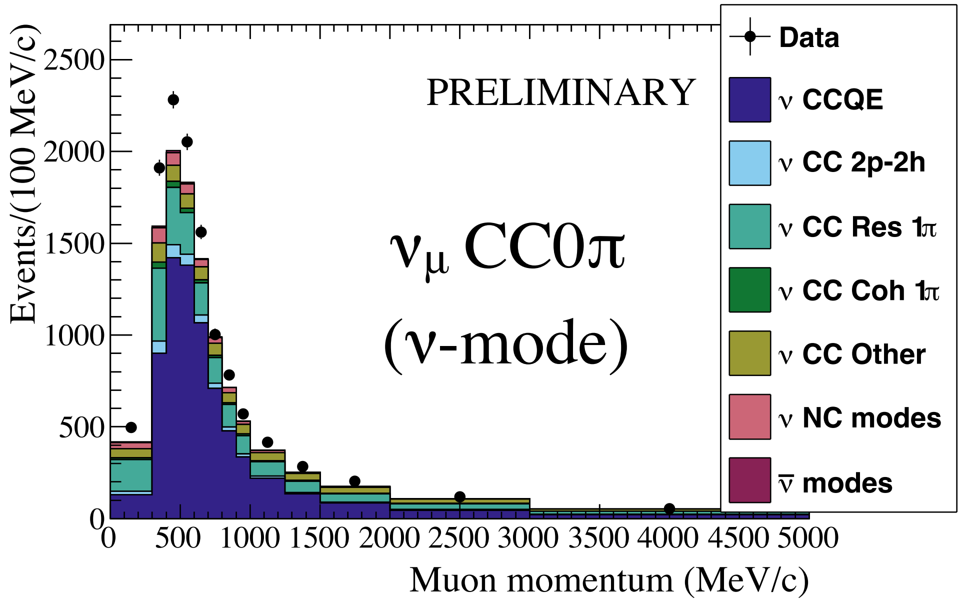

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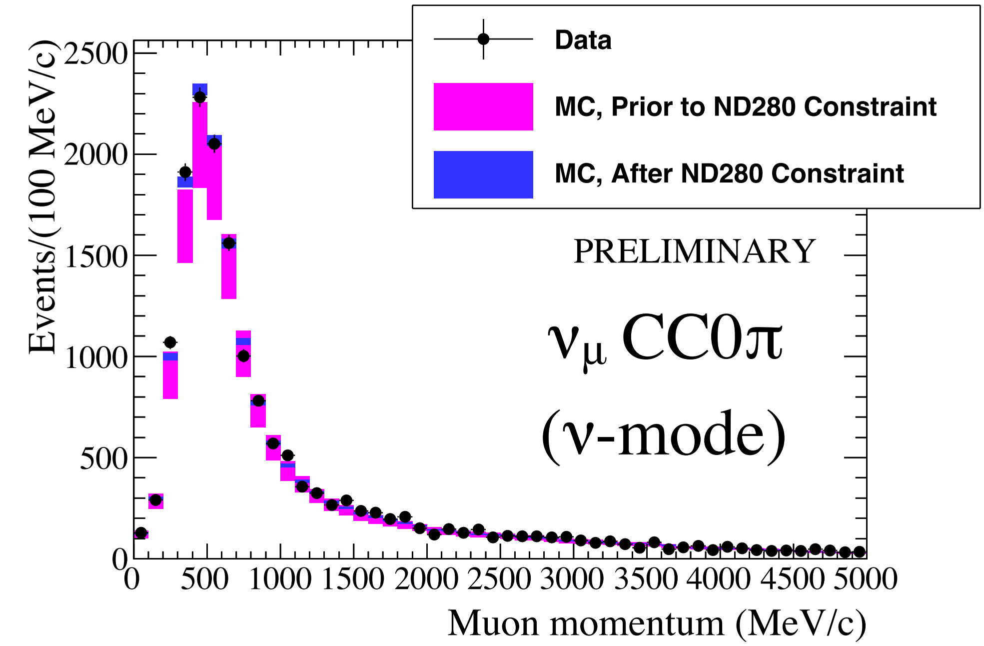
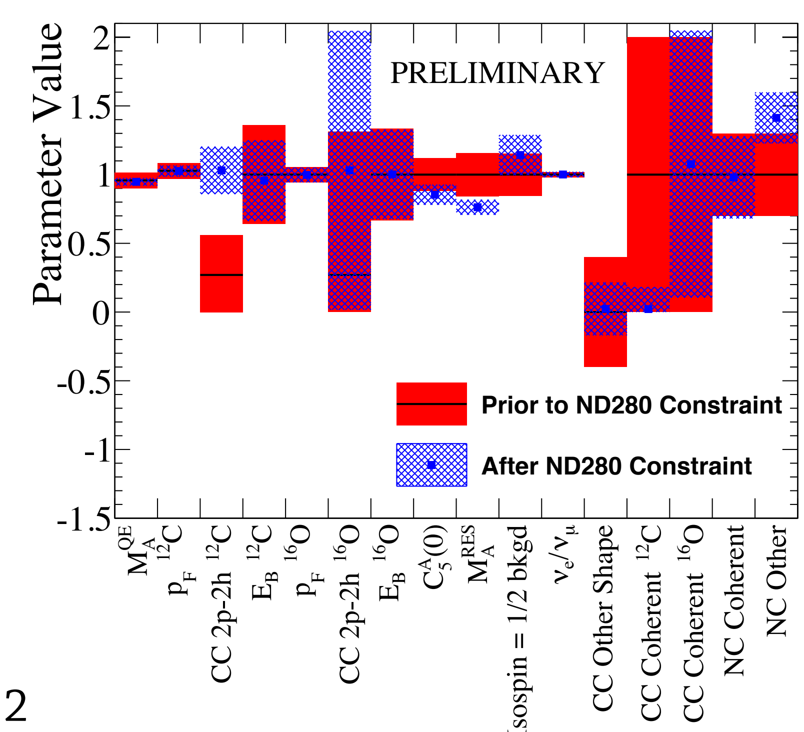
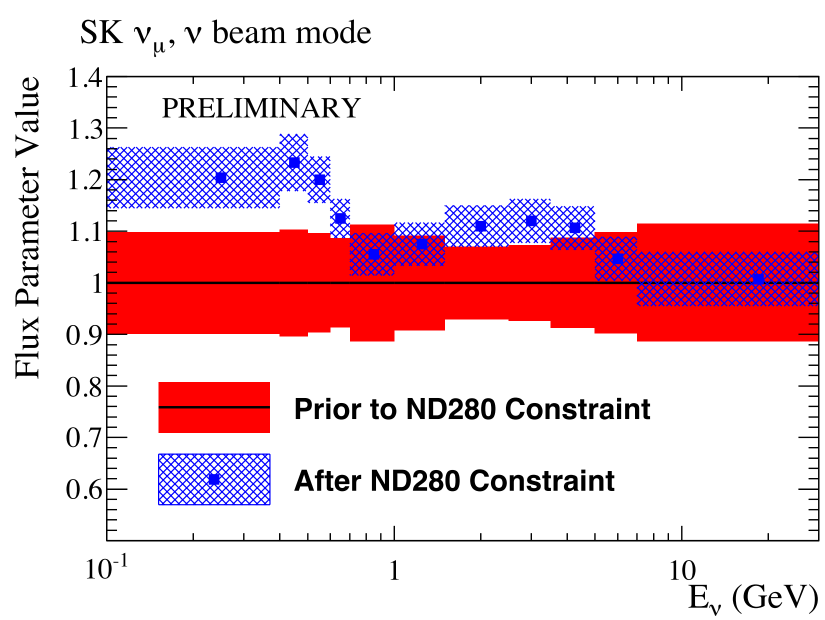
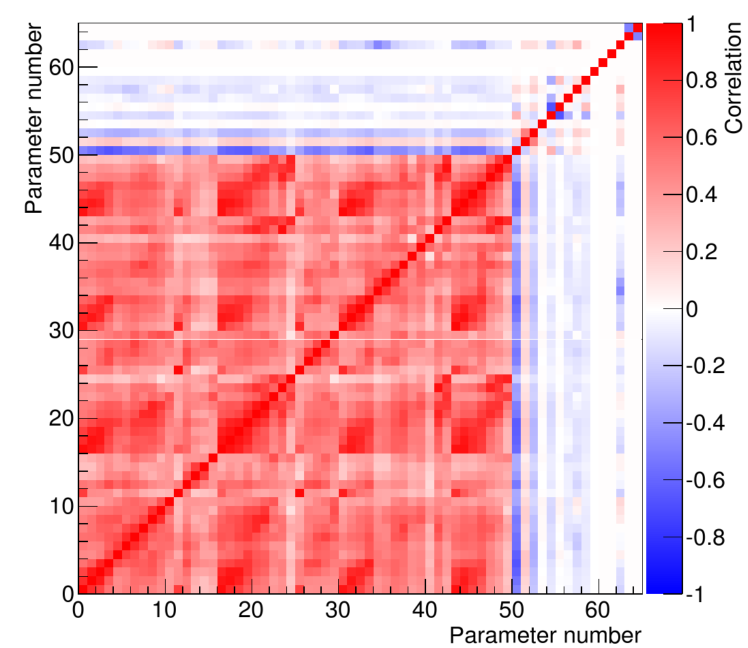


With multiple sample, one can get a data-derived weights for the flux and the cross section parameters and the correlation matrix







[NB: Plots are from slightly outdated T2K case]

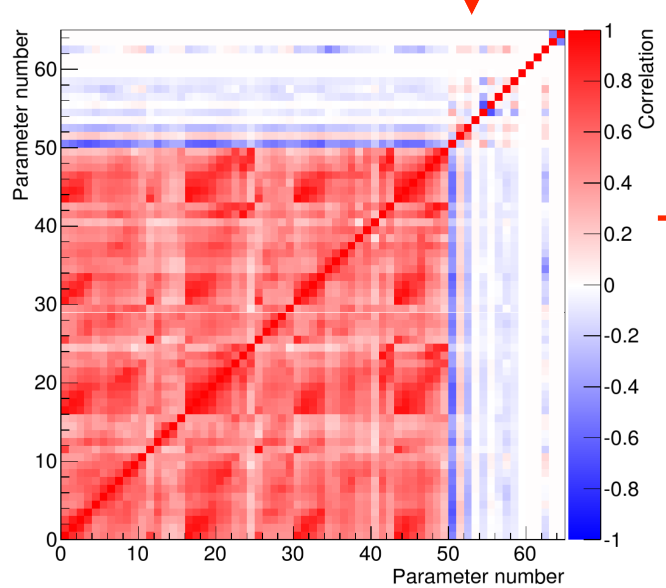
ν flux in the oscillation fit - old T2K case

Flux model constrained by NA61/SHINE

Cross section model constrained by external data

ND Data → Near detector Fit

Systematic error source	$\Delta N_{SK}/N_{SK}$ before ND fit	$\Delta N_{SK}/N_{SK}$ after ND fit
Flux	7,9 %	3,94 %
Cross section	10,6 %	4,85 %
Flux and cross section	12,4 %	3,19 %
Final state / secondary interactions at SK	1,93 %	
SK detector	2,22 %	
Total	***13,92 %***	***4,25 %***



SK Data → Oscillation fit → Oscillation parameters

$$N_{SK} = \int dE\, \Phi(E) \times \sigma(E) \times \varepsilon_{SK} \times P(\nu_\alpha \to \nu_\beta)$$

# of events; $\Phi(E) \times \sigma(E)$: constrained by ND fit; ε_{SK}: det. efficiency

[NB: Values are from slightly outdated T2K case

Conclusions

Neutrino flux is an important part of any long baseline neutrino oscillation experiment !

The errors are dominated by our understanding of the hadronic interactions in the target and in the beamline
-> Hadroproduction are taking data with thin and replica target to constrain the flux prediction

-> T2K has reached a flux uncertainty at the level of 5% , DUNE error is still large but is foreseen to be reduced with new data at NA61/SHINE and EMPHATIC

The precise knowledge of the beamline elements is very important
-> Some parameters cannot be measured once the experiment has started

There are other ways to constrain the flux, with specific channels
-> Small statistics and hard to tag events