Neutrino beams and fluxes and neutrino cross sections

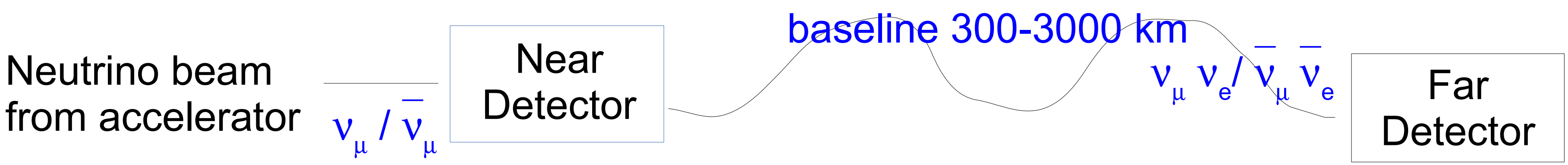
- Introduction: oscillation measurements and impact of flux and cross-section
- Neutrino beams and neutrino flux prediction and tuning
- Neutrino cross-sections and near detector constraints

CAVEAT: strong bias toward **accelerator long baseline experiments**
(and some bias toward T2K)

QUESTIONS at any time (also in one year from now... at sara.bolognesi@cern.ch)

Sara Bolognesi (CEA Saclay)

Long baseline experiments



Oscillation probability estimated by comparing ν_μ and ν_e rate between near and far detectors:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2\left(\underbrace{1.27\frac{\Delta m^2_{ji}[\text{eV}^2]L[\text{km}]}{E_\nu[\text{GeV}]}}_{\text{frequency}}\right)$$

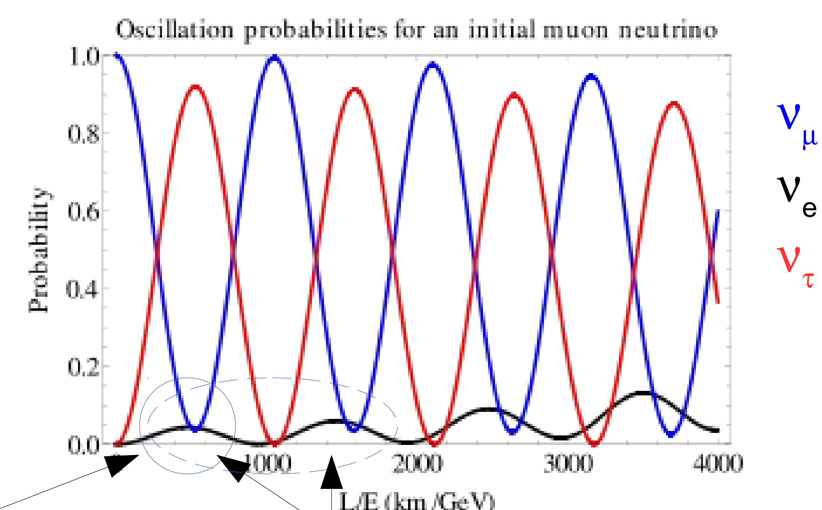
(simplified 2-flavors approximation)

In the atmospheric sector

$$\Delta m^2_{32} = 2.5 \times 10^{-3}\,\text{eV}^2$$

Experiment	Energy	Baseline
T2K (T2HK)	0.6 GeV	295 km
Nova	2 GeV	810 km
DUNE	1-3 GeV	1300 km

(to exploit ν_τ need $E_\nu > m_\tau$ 1.78 GeV)



T2K (T2HK) and NOVA working point

DUNE wideband beam covers (at low energy) also the second oscillation maximum

Introduction

Why should we care about neutrino flux and cross-section when we measure neutrino oscillations ???

Oscillation analysis: the basics

$$N^{FD}_{\nu_{\alpha'}} \approx P_{\nu_\alpha \to \nu_{\alpha'}} \times N^{ND}_{\nu_\alpha}$$

Number of neutrinos at the Far Detector (FD) of a given flavour α' (α=e,μ,τ)

Number of neutrinos at the Near detector (ND)

The **oscillation probability** $\nu_\alpha \to \nu_{\alpha'}$ which you want to estimate: it depends on the parameters you want to measure (long baseline experiments: θ_{13}, θ_{23} Δm^2_{32} δ_{CP})

Real measurement:
background subtraction and efficiency corrections

$$N_{\nu_{\alpha'}}^{FD} = \frac{N_{\nu_{\alpha'}}^{measured-at-FD} \times p^{FD}}{\epsilon^{FD}} \qquad N_{\nu_{\alpha}}^{ND} = \frac{N_{\nu_{\alpha}}^{measured-at-ND} \times p^{ND}}{\epsilon^{ND}}$$

$$\epsilon = \frac{N_{\nu_{\alpha}}^{signal-measured}}{N_{\nu_{\alpha}}^{signal}}$$

efficiency corrects for events which escape the detection
(threshold, acceptance, containment...)

$$p = \frac{N_{\nu_{\alpha}}^{measured} - N^{background}}{N_{\nu_{\alpha}}^{measured}} = \frac{N_{\nu_{\alpha}}^{signal-measured}}{N_{\nu_{\alpha}}^{measured}}$$

purity corrects for background
(events wrongly identified as ν_{α})

Need to know efficiency and purity in order to correct for them → any possible mis-modeling of them causes a **systematic uncertainty in the oscillation analysis**

$$P_{\nu_{\alpha} \to \nu_{\alpha'}} \approx \frac{N_{\nu_{\alpha'}}^{measured-at-FD}}{N_{\nu_{\alpha}}^{measured-at-ND}} \times \frac{\epsilon^{ND}}{\epsilon^{FD}} \times \frac{p^{FD}}{p^{ND}}$$

What really matter is the difference between ND and FD, common systematics cancel out (to first order...)

Then... let's just build identical near and far detectors
and we are done!!!

We can forget of flux and cross-section uncertainties... right?

Well... No! … Because I cheated!!!

Dependence on neutrino energy

To extract the oscillation parameters, the oscillation probability must be evaluated **as a function of neutrino energy,** since the neutrino beams are not monochromatic:

$$P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m_{21}^2 L}{4 E_\nu}\right)$$

→ we need to know the **number of neutrinos as a function of E_ν** at near and far detectors

$$N_{\nu_\alpha}^{ND}(E_\nu) = \varphi(E_\nu) \times \sigma(E_\nu)\, dE_\nu$$

flux= number of neutrinos produced by the accelerator per cm^2, per bin of energy, for a given number of protons on target

$$\left[\int \varphi(E_\nu)\, dE_\nu\right] \equiv [\Phi] = [cm^{-2} POT^{-1}]$$

cross-section = probability of interaction of the neutrinos in the material of the detector

$$[\sigma] = [cm^2]$$

Flux and cross-section

- So the oscillation probability becomes:

predicted number of neutrino interactions at the FD (w/o oscillations)

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_{\alpha}}(E_\nu)} \approx P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) \times \frac{\varphi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\varphi^{ND}_{\nu_{\alpha}}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_{\alpha}}(E_\nu)} \times \frac{\epsilon^{ND}}{\epsilon^{FD}} \times \frac{p^{FD}}{p^{ND}}$$

measured number of neutrino interactions at the ND

We measure flux and xsec for ν_α (and $\nu_{\alpha'}$) at the ND and *we use our models to extrapolate* at the far detector (like a ratio measurement...)
→ systematic minimized if same flux (eg, same off-axis angle) and same target material

- But the most complicated part is :

1) the neutrino energy spectrum is different at ND (before oscillation) and at the FD (after oscillation)
→ so we measure the xsec and flux at a given energy and we need to extrapolate to a different energy

2) flux and xsec extrapolation from ND to FD are different → we need to separately estimate flux and xsec at the ND

But we measure only the product of the two (strong anti-correlation between them)

The hard stuff...

The following issues induce an ***unavoidable model dependency in any oscillation analysis*** and make the evaluation of systematics in oscillation measurements a difficult task:

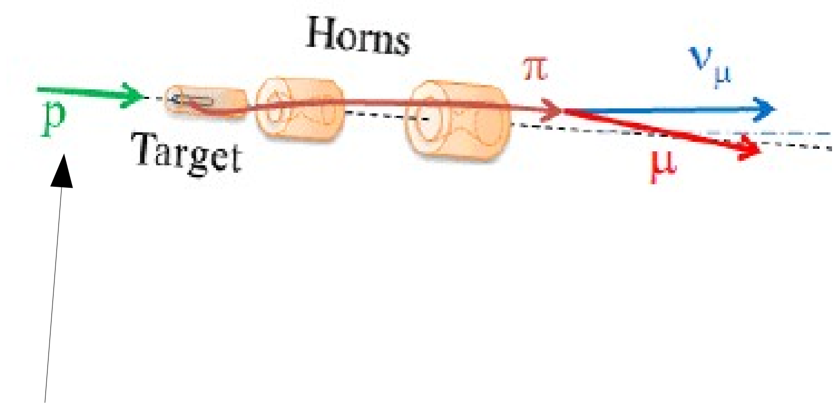
- extrapolation of xsec to different energy spectrum
- separate flux and xsec evaluation from ND data

There is one more issue we will address later...
how do we estimate the neutrino energy?
Different detectors have different strategies with different advantages and drawbacks

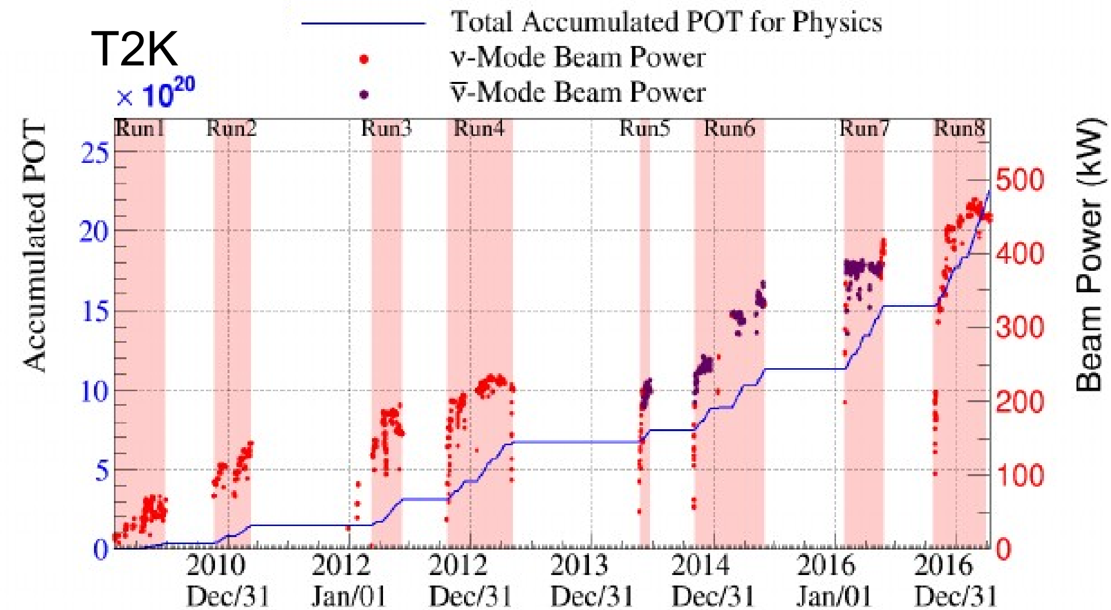
Neutrino beam

Very complete reference (2006) arXiv:physics/0609129

Proton beam

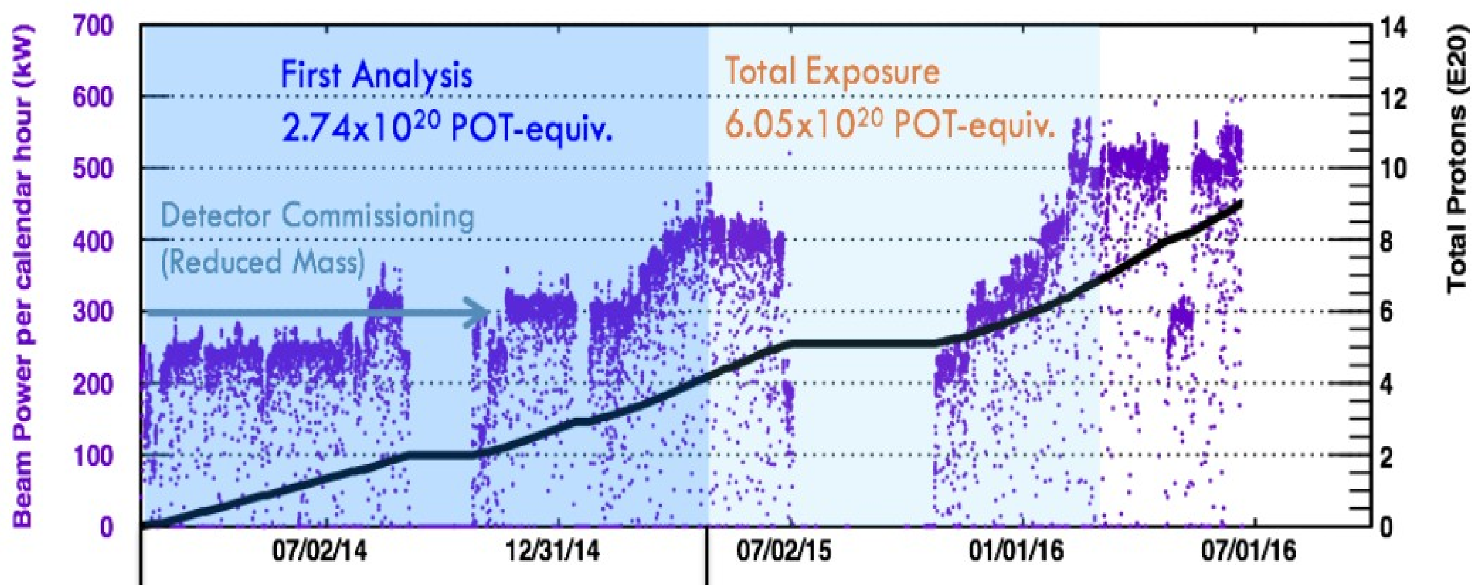


Proton beam (30 GeV T2K, 120 GeV NuMi)



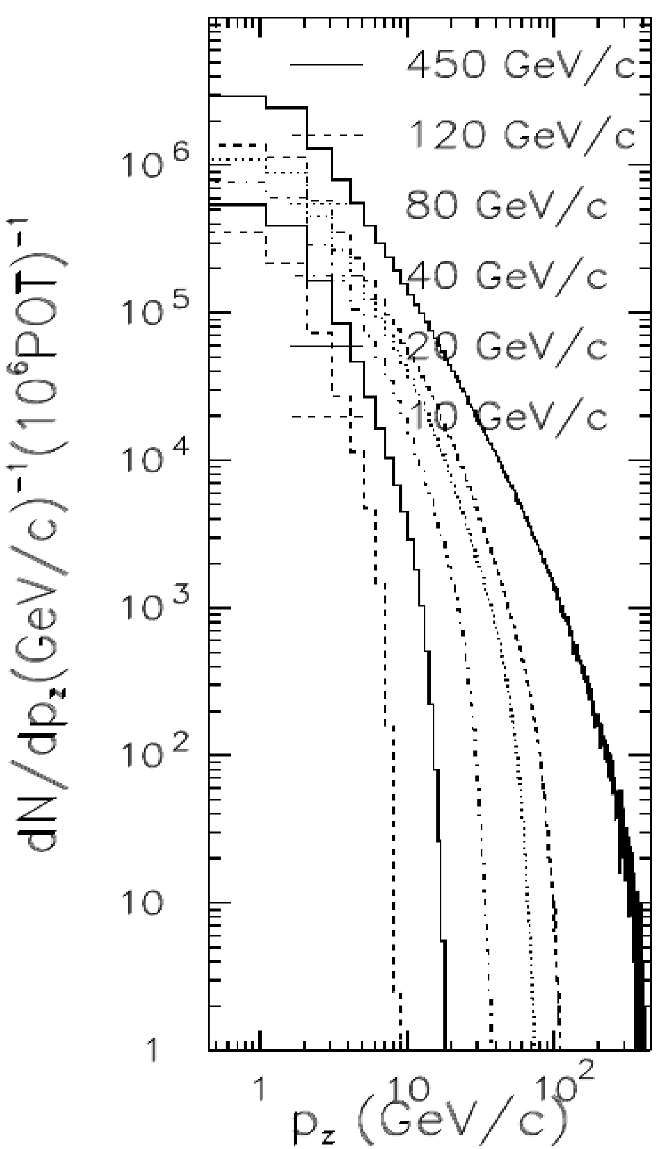
$$P(kW) \propto POT\ (10^{20}) \times E_p\ (GeV)/T\ (10^7\ s)$$

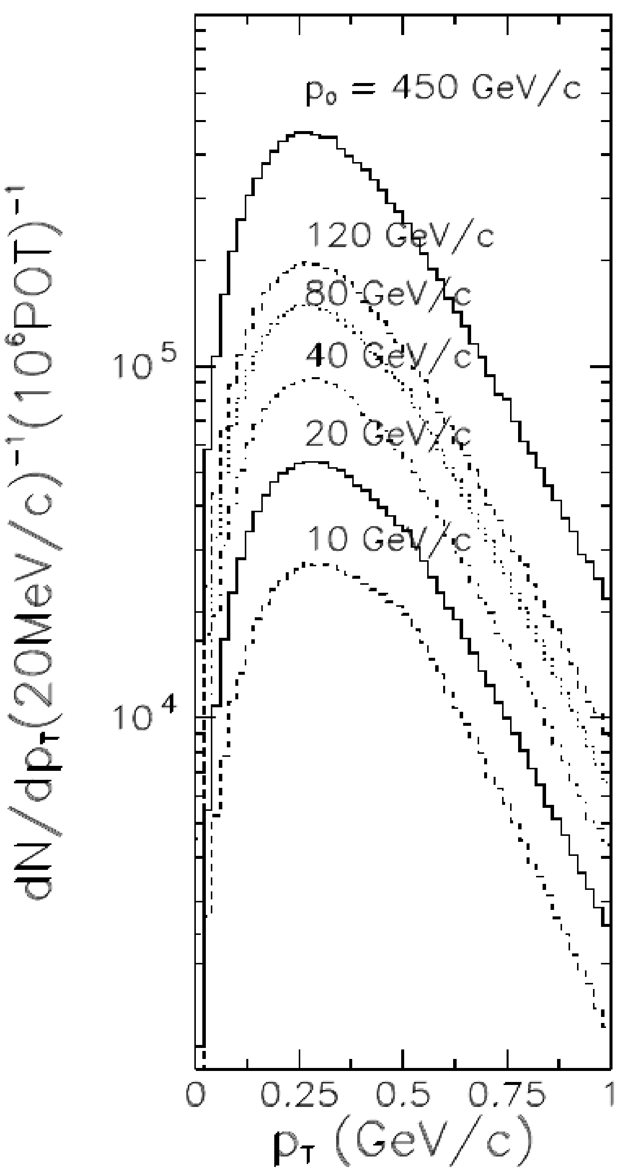
NOVA



Next generation of experiments: 1-2 MW

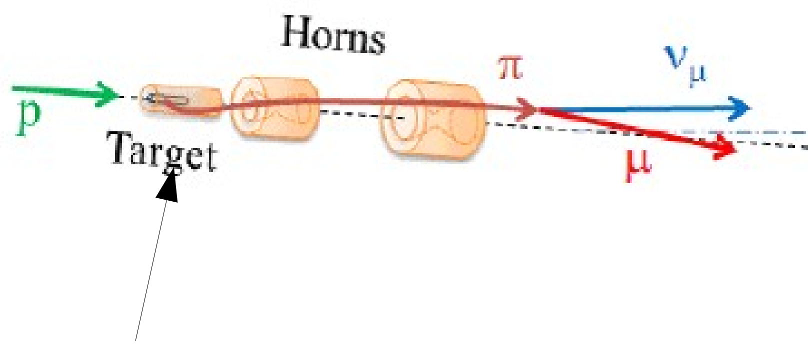
Pion spectra for different proton momenta





p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

Target



- **Shape**: cylindrical (or ruler) along proton beam direction to maximize the probability of protons to interact (~50-100cm)

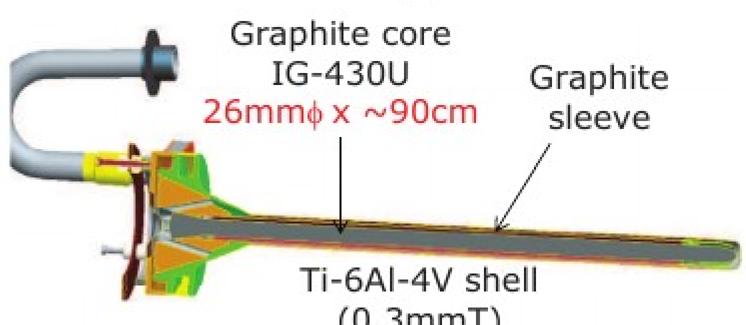
  (but re-interactions of hadrons inside the target are an additional complication)

  Transversal section should be ~3σ of proton beam width (~5-10mm)

- **Low Z** (Aluminium, Berillium, Carbon, …) high probability of proton interacting and low probability of radiating (loosing energy in the target)

- **Need cooling** (air or water): larger the beam intensity → hotter the target

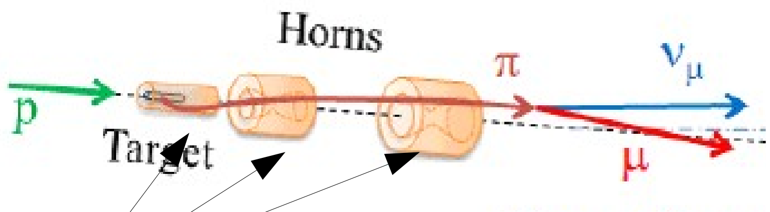
T2K



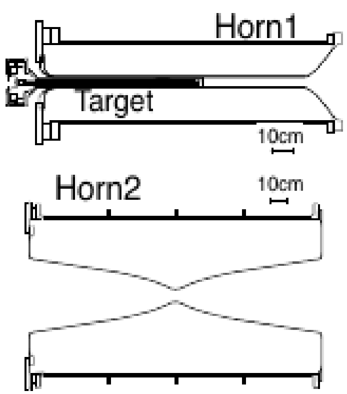
~2 interaction lenght

gas cooling

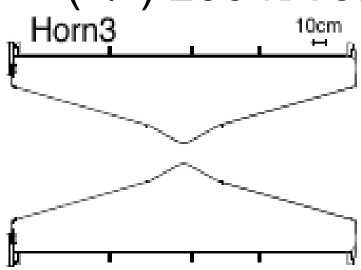
Horns

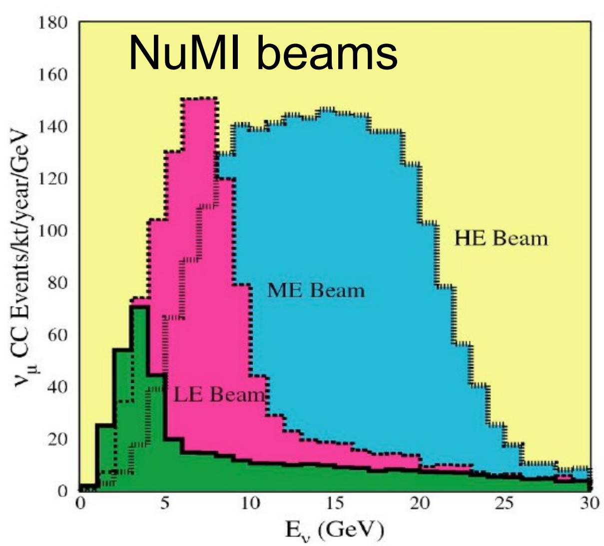


Horns to focus $\pi^{+/-}$ parallel to beam axis $\rightarrow \nu_\mu$ or $\bar{\nu}_\mu$ beam



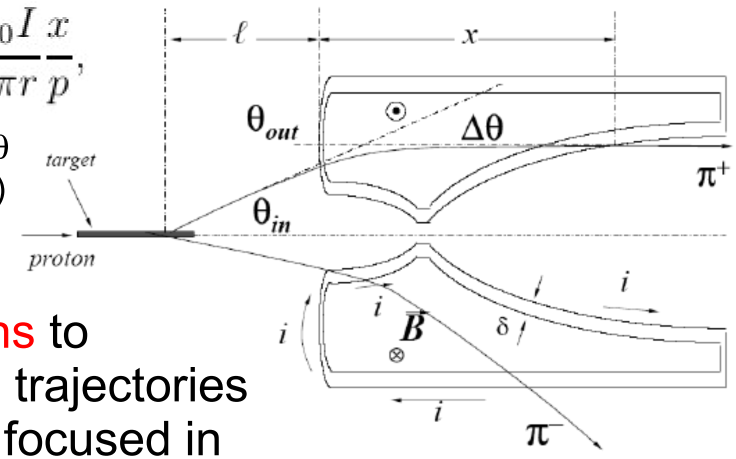
T2K-horns
(+/-) 250 kA current



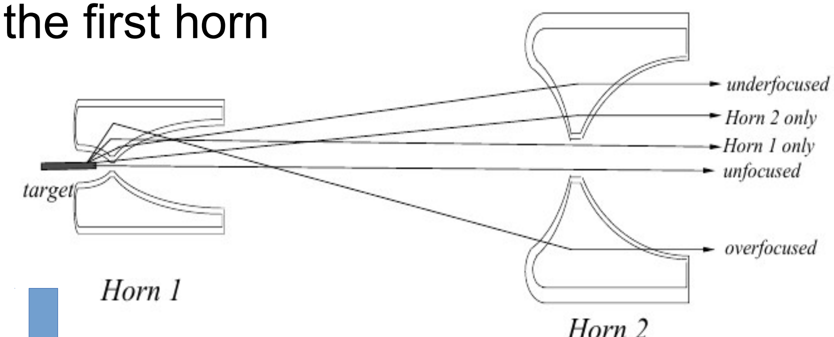


- $\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$,

(parabolic: same θ kink for all angles)

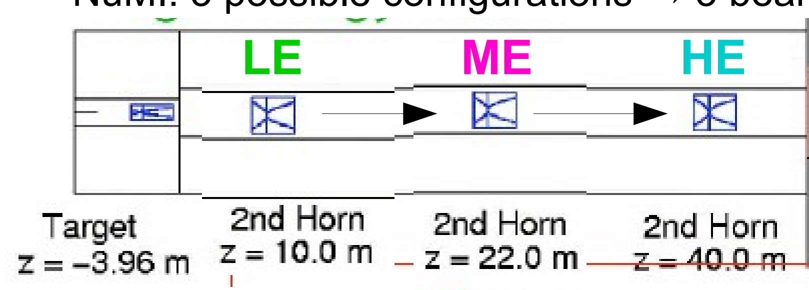


- multiple horns to recover pion trajectories not properly focused in the first horn



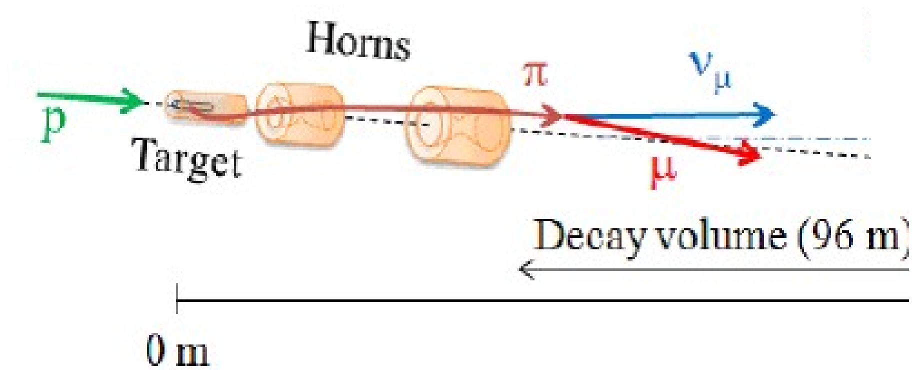
- the pions with smallest angle are the most energetic → to focus them need to move the horns

NuMI: 3 possible configurations → 3 beam energies



Decay volume

- **Let the hadrons to decay in (μ and) ν:**



Decay volume (T2K: He filled):

- longer to let most of the pion decaying
- not too long to avoid muon decay (ν_e pollution)

- most ν_μ's from 2-body decays:

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

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

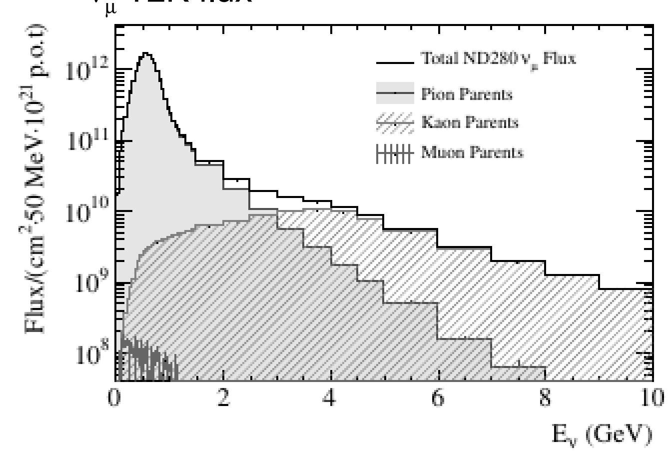
- most ν_e's from 3-body decays:

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

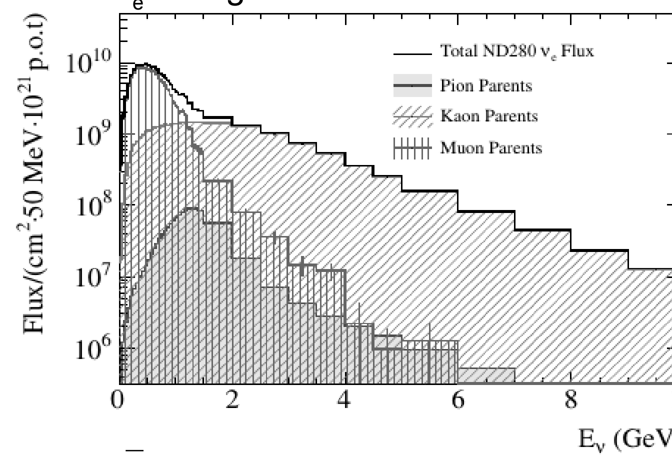
$K^+ \rightarrow \pi^0 e^+ \nu_e$

- $\bar{\nu}_\mu / \nu_\mu$ larger at high energy due to high p_L π- which cannot be (de-) focused

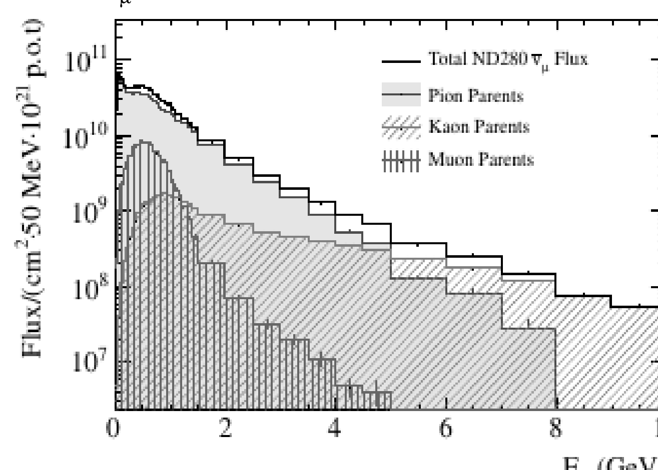
ν_μ T2K flux



ν_e background in T2K flux

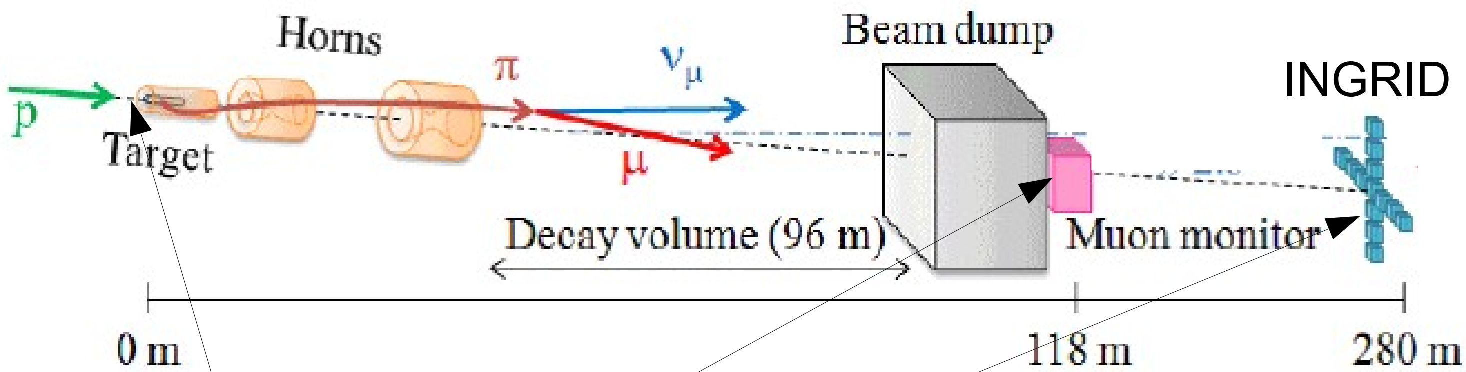


$\bar{\nu}_\mu$ background in T2K flux

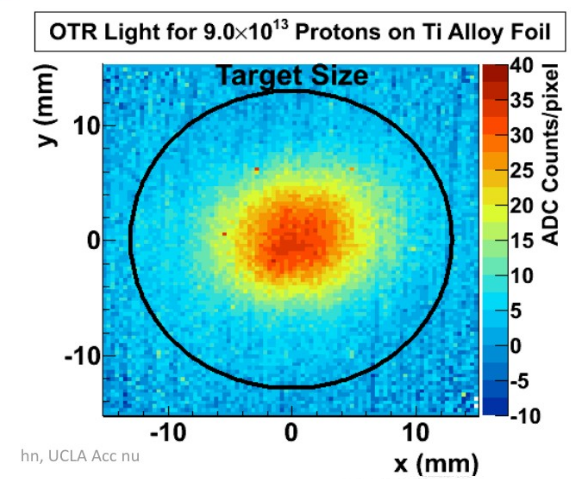


Beam monitoring

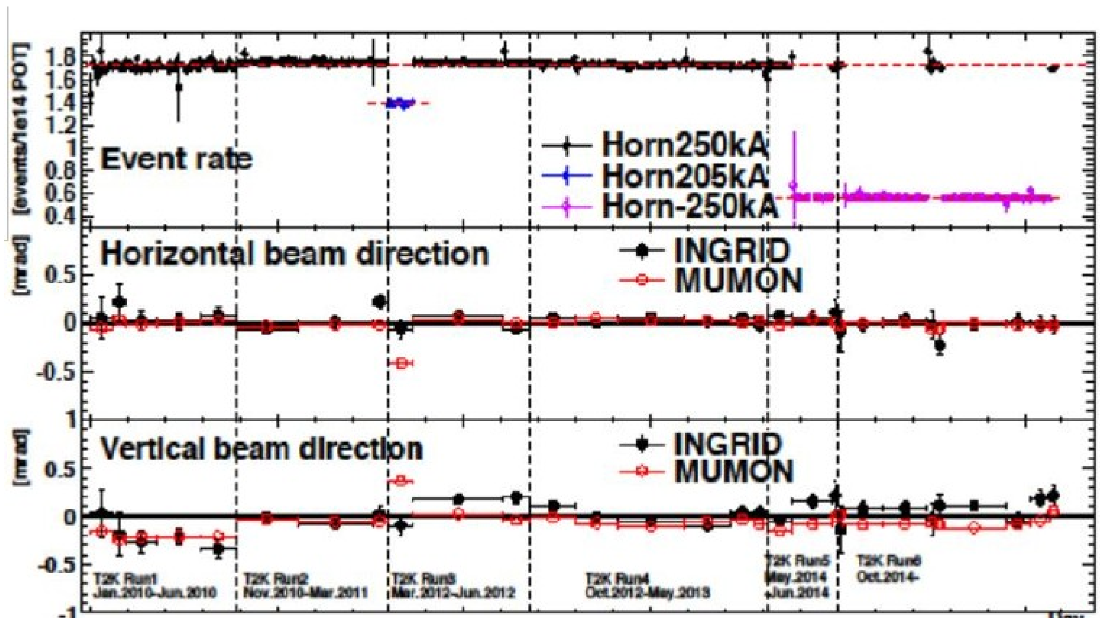
- **Monitoring of the beam:** intensity, position, direction



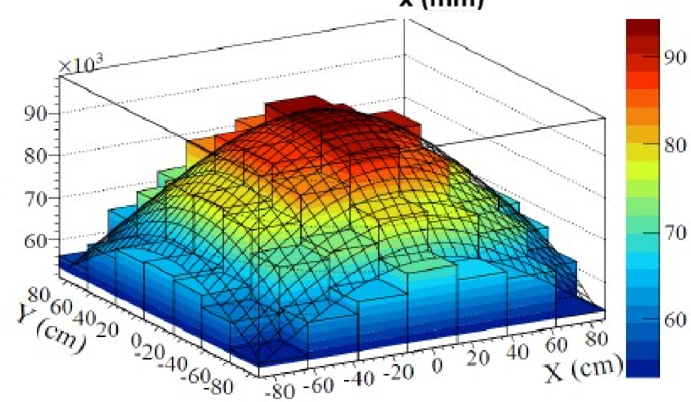
- looking at **protons**
- looking at **muons**
- looking at **neutrinos**



Protons

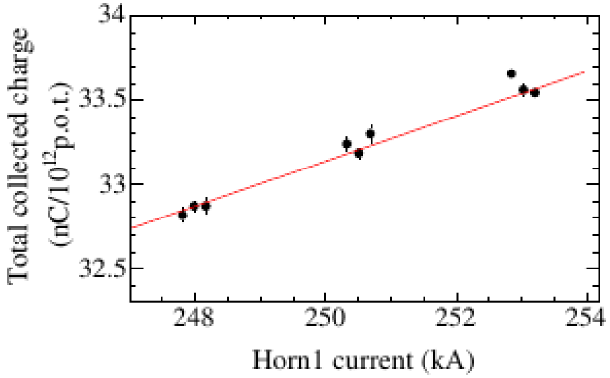


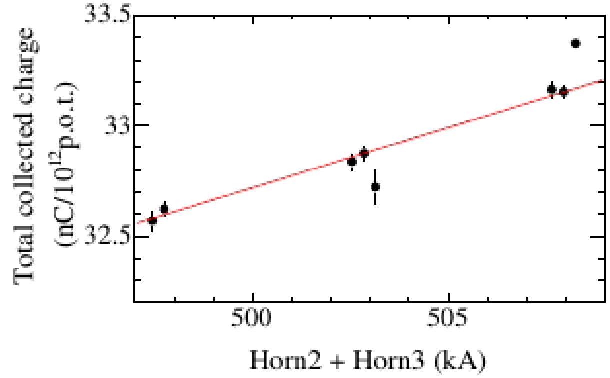
Muons

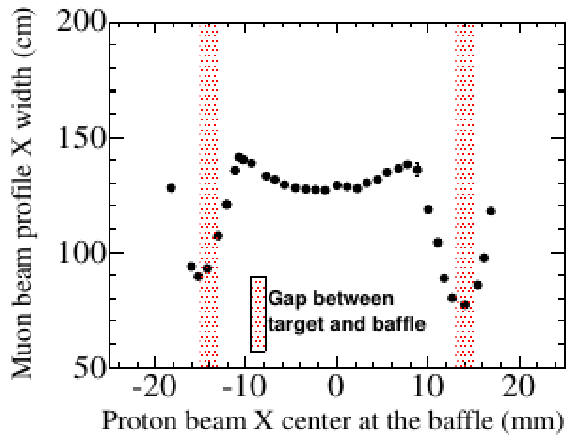


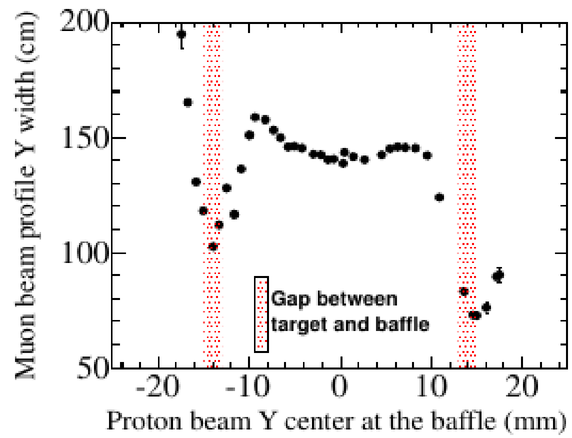
Playing around with the muon monitor

- Example from T2K: sensitivity to horn current and proton beam position

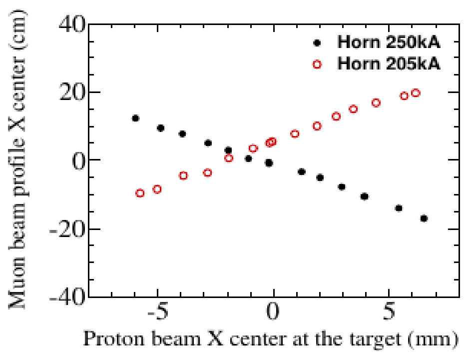


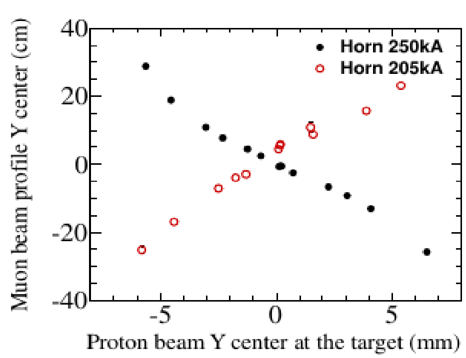


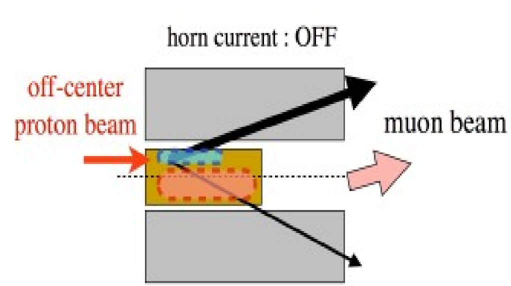


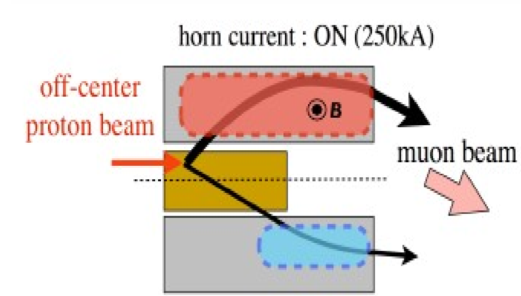


- Correlation between current and beam position

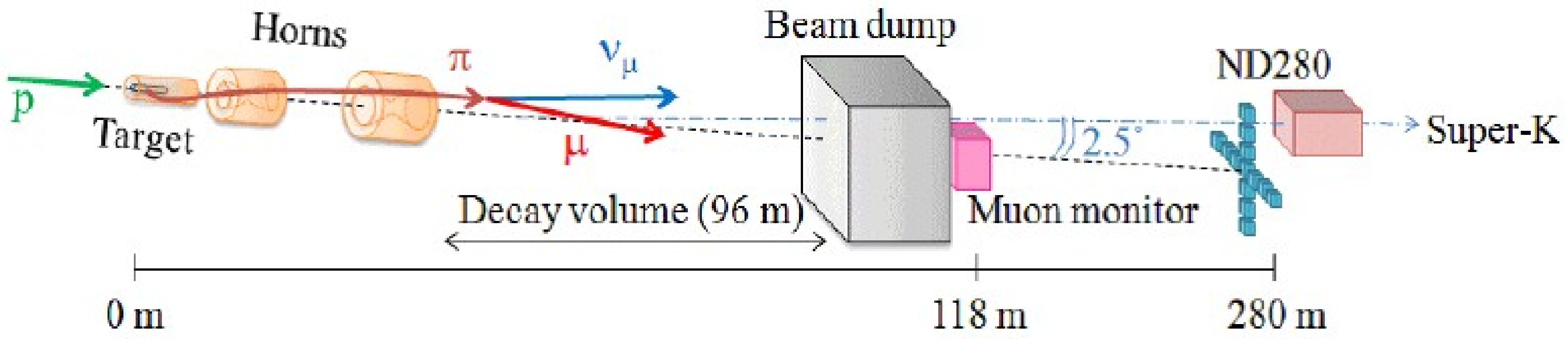






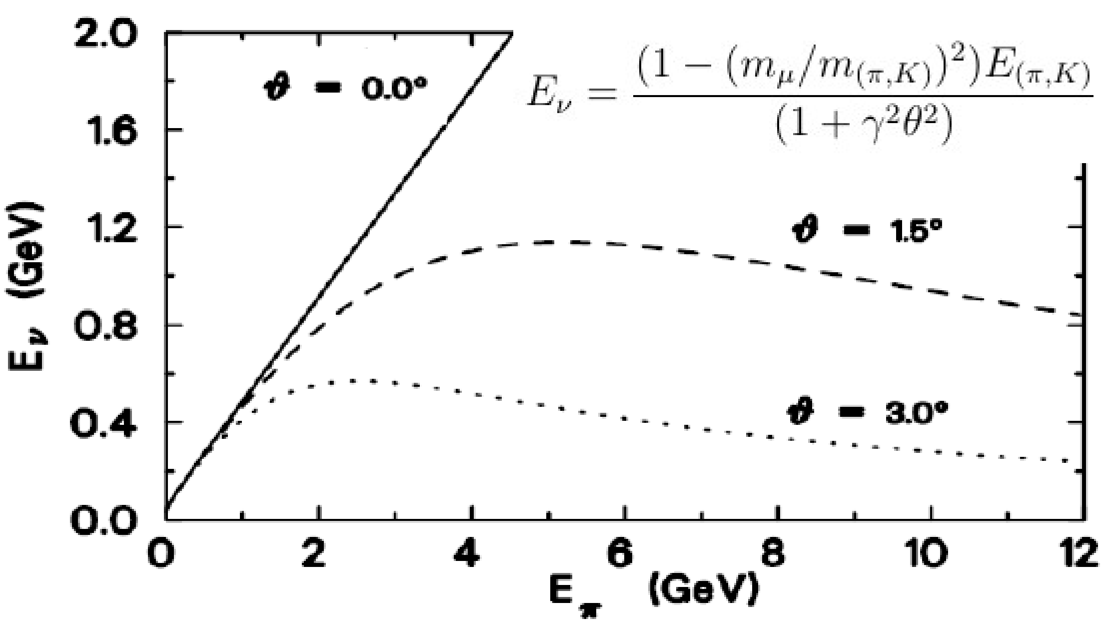


Tuning the neutrino energy

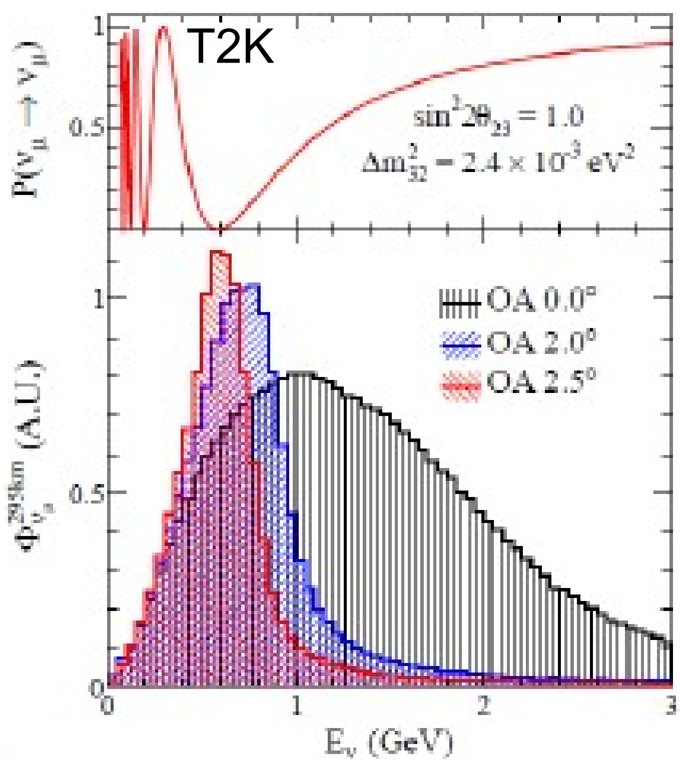


Energy of ν emitted in 2-body decay at an angle relative to π (K) direction is only weakly dependent on parent's momentum

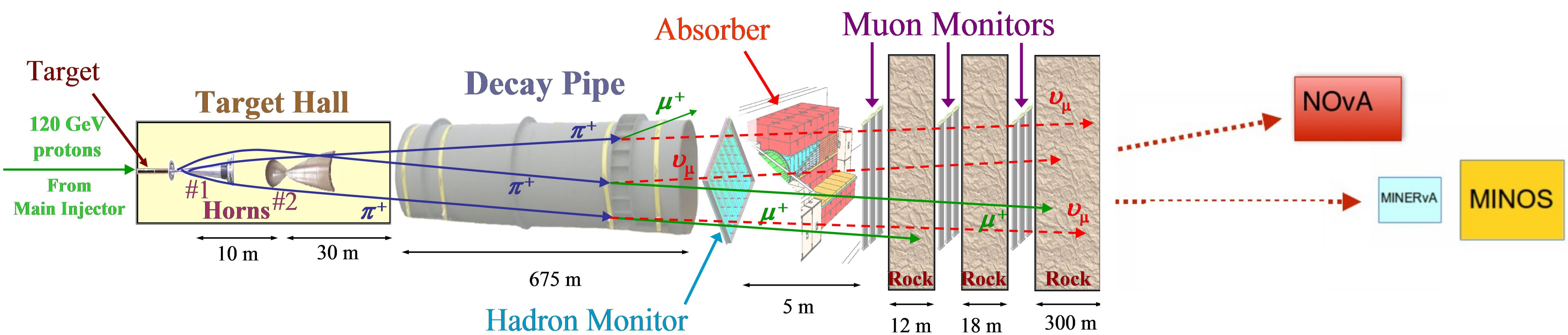
Off-axis → narrow flux at the maximum of the neutrino oscillation

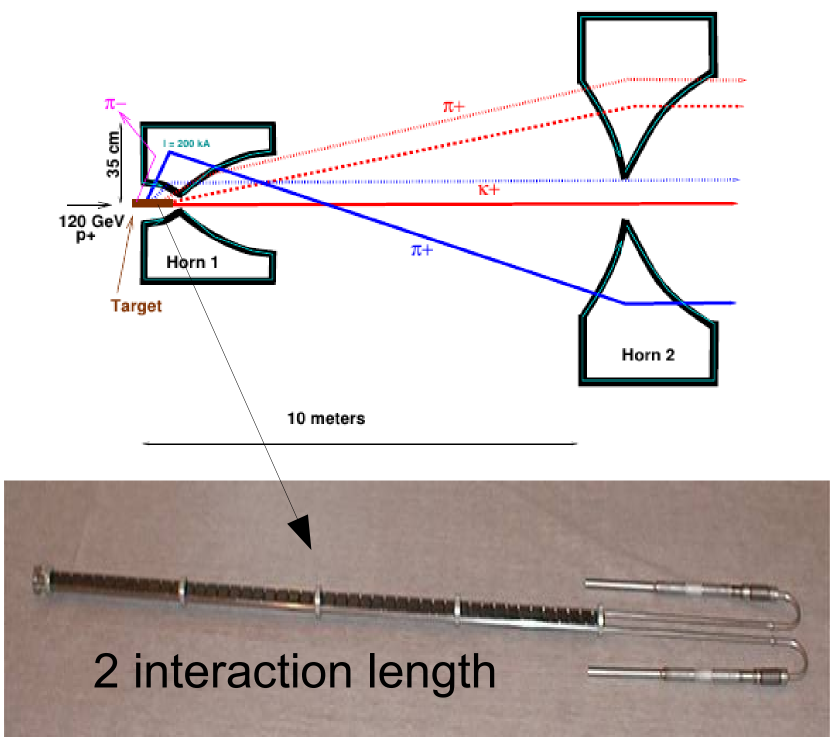


$$E_\nu = \frac{(1-(m_\mu/m_{(\pi,K)})^2)E_{(\pi,K)}}{(1+\gamma^2\theta^2)}$$



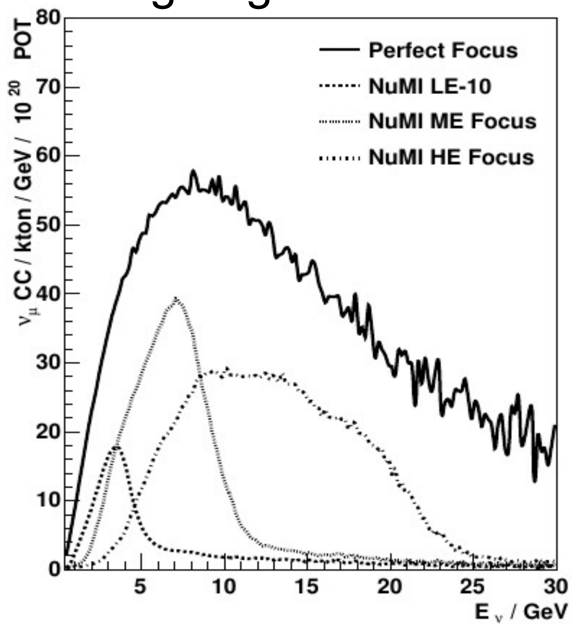
NuMI beam



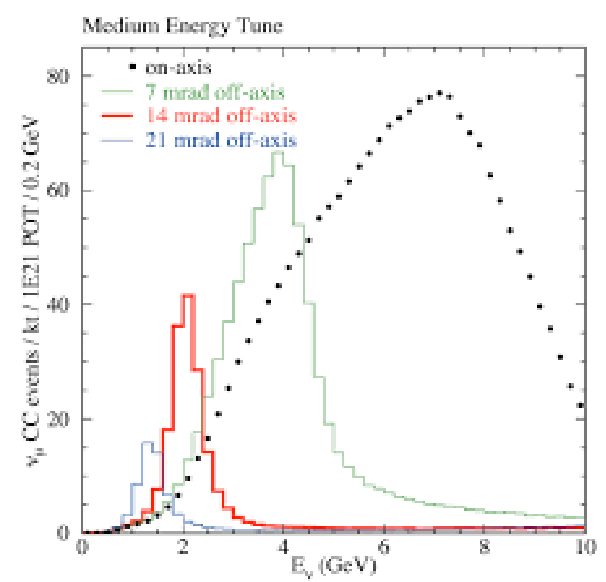


2 interaction length

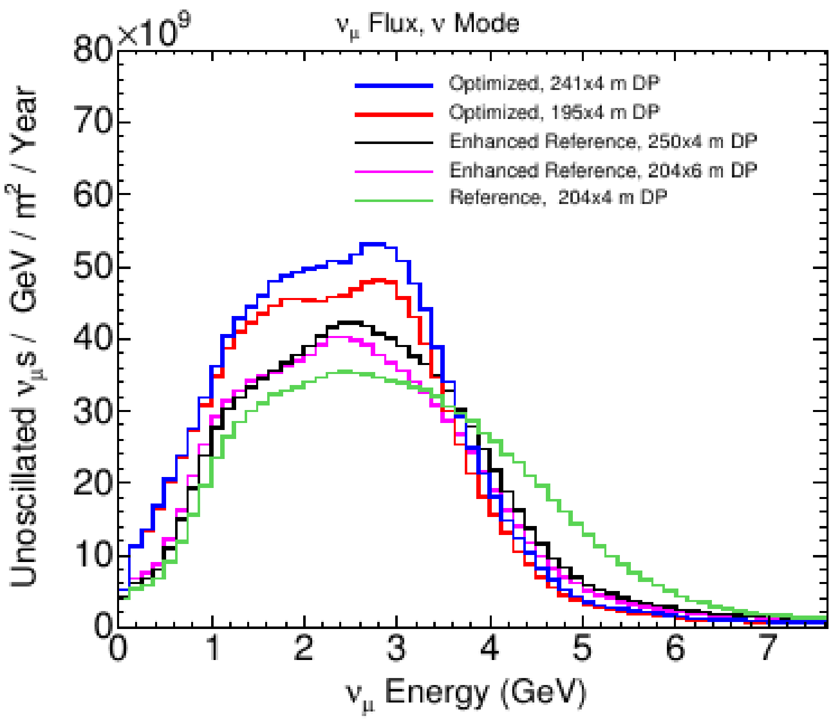
Change energy by moving target and horns



Off-axis technique



The importance of beam optimization (DUNE)

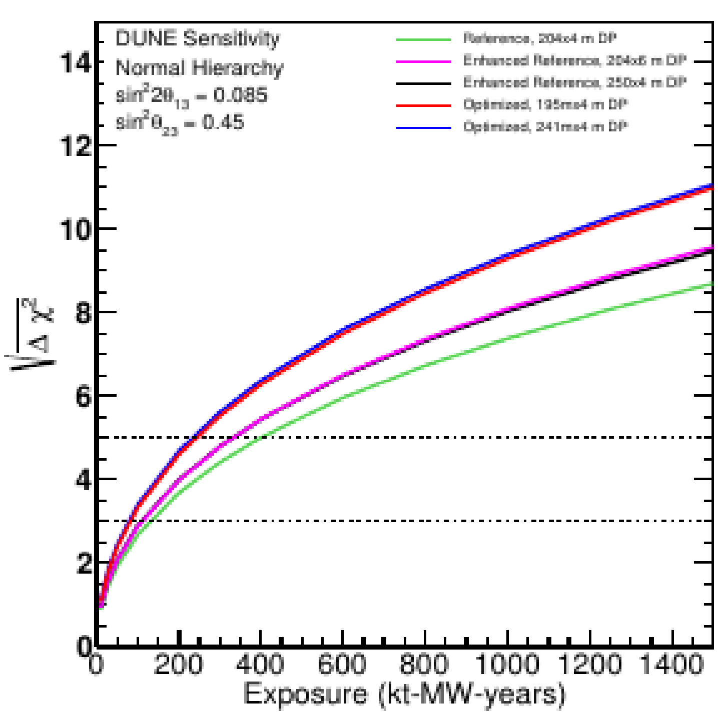


Reference = NuMI-like with larger beam power

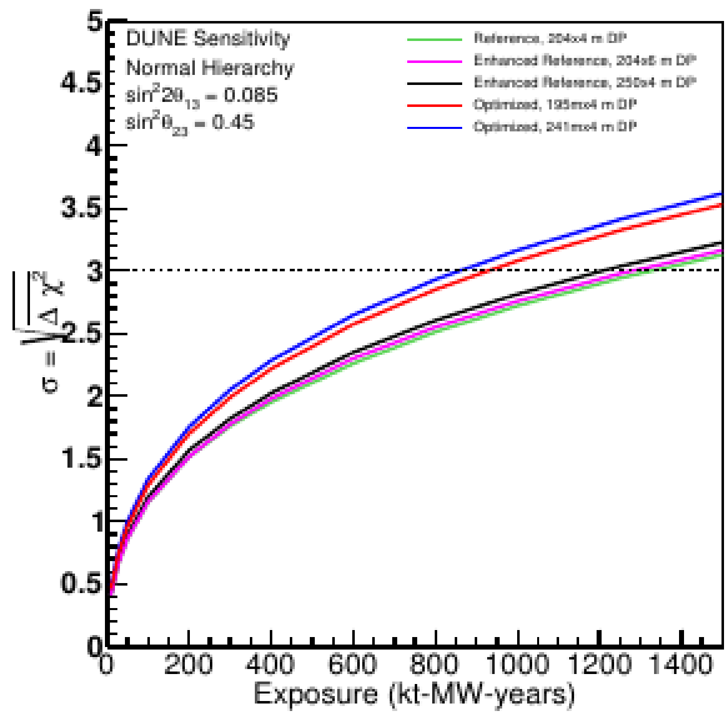
Enhanced = 80 GeV protons, different target (possibly with longer decay volume)

Optimized = 80 GeV protons and complete re-design of focusing (possibly with longer decay volume)

MH sensitivity



75% CP Violation Sensitivity



Flux simulation and tuning

Flux simulation

Proton interactions in the target → production of **'secondary hadrons' on Carbon**

Re-interactions of hadrons with target, horns, vessel, beam dump... → production of **'tertiary hadrons' on other materials**

T2K

	Flux percentage of each(all) flavor(s)			
Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K^0_L	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K^0_L	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

NuMI low energy

	Material						
Projectile	C	Fe	Al	Air	He	H_2O	Be
p	117.5	2.9	1.0	1.1	1.5	0.1	0.1
π^+	8.1	1.3	1.8	0.2	...	0.4	...
π^-	1.3	0.2	0.2	...	...	...	...
$K^\pm$	0.6	0.1	0.1	...	...	...	...
K^0	0.6	...	...	...	...	...	...
Λ/Σ	1.0	...	...	...	...	...	...

(average hadron interaction x 100 for each ν_μ)

Simulation of hadron interactions with the target and all the beamline with **GEANT and FLUKA**

Flux tuning

The simulations are tuned using external measurement from hadro-production experiments

T2K

Experiment	Beam Mom. (GeV/c)	Target	Particles
NA61/SHINE [11][12]	31	C	$\pi^{\pm}$, K^{+}
Eichten *et al.* [27]	24	Be, Al, ...	p, $\pi^{\pm}$, $K^{\pm}$
Allaby *et al.* [28]	19.2	Be, Al, ...	p, $\pi^{\pm}$, $K^{\pm}$
BNL-E910 [29]	6.4 – 17.5	Be	$\pi^{\pm}$

NuMI

- NA49 pC @ 158 GeV
- MIPP pC @ 120 GeV
- Barton et Al *[Phys. Rev. D 27, 2580 (1983)]*

(need scaling to different proton energy and different targets)

Total probability of hadron interactions and outgoing hadron multiplicity
as a function of **incoming proton momentum and outgoing hadron momentum and angle**
are tuned to match the hadro-production measurements:

$$P(x;\sigma_{prod}) = \Delta x \sigma_{prod} \rho e^{-x\sigma_{prod}\rho}$$

$$W = \frac{P(x;\sigma'_{prod})}{P(x;\sigma_{prod})}$$

probability of proton to travel a path x in the target and interact in Δx

$$\frac{dn}{dp}(\theta, p_{in}, A) = \frac{1}{\sigma_{prod}(p_{in}, A)} \frac{d\sigma}{dp}(\theta, p_{in}, A).$$

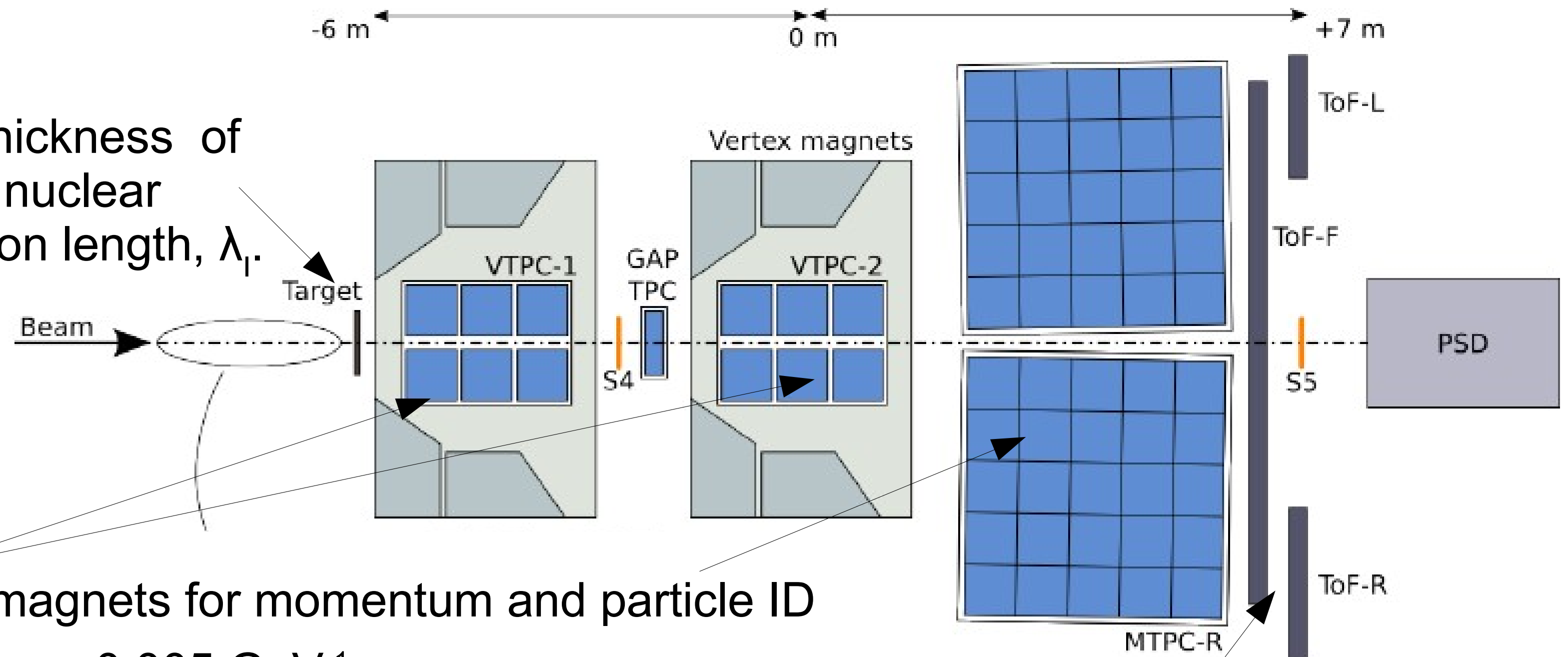
$$W(p_{in}, A) = \frac{[\frac{dn}{dp}(\theta, p_{in}, A)]_{data}}{[\frac{dn}{dp}(\theta, p_{in}, A)]_{MC}}$$

hadron multiplicity (with a certain angle and momentum) for each proton interaction

NA61/SHINE

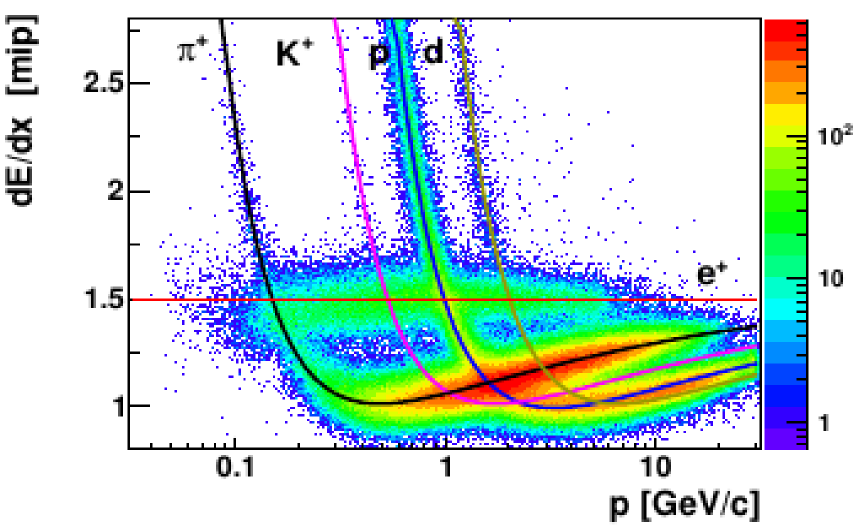
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS

- Target thickness of 4% of a nuclear interaction length, λ_I.

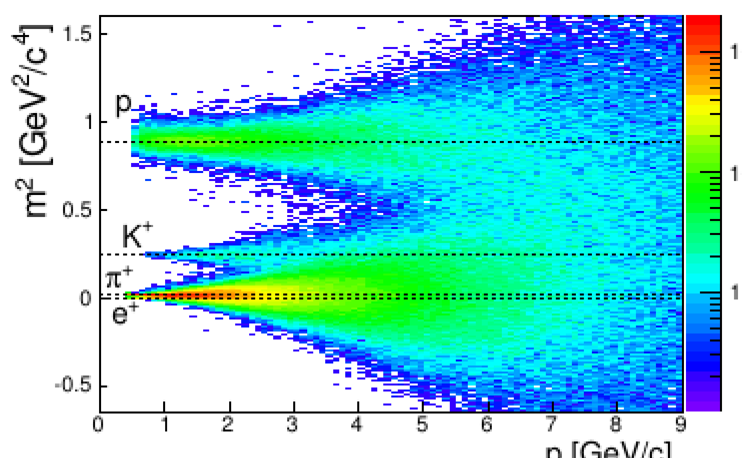


TPC in magnets for momentum and particle ID

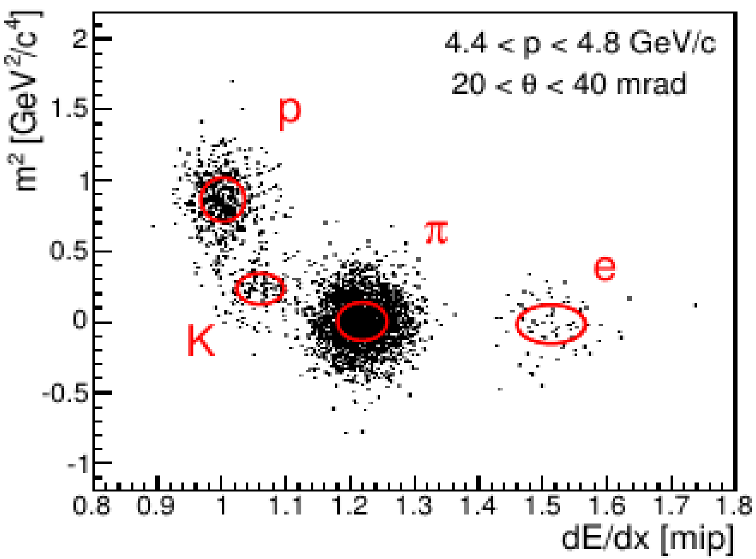
$\sigma(p)/p \sim p \times 0.005\ \mathrm{GeV}^{-1}$

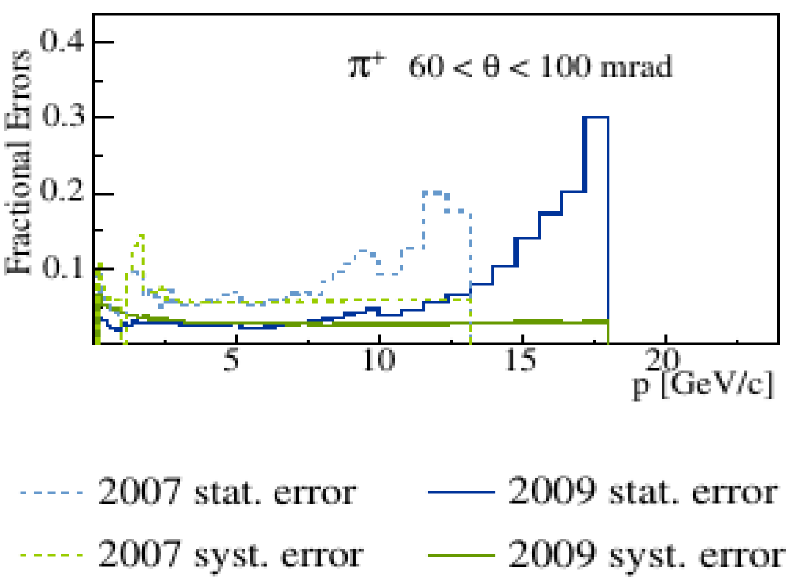


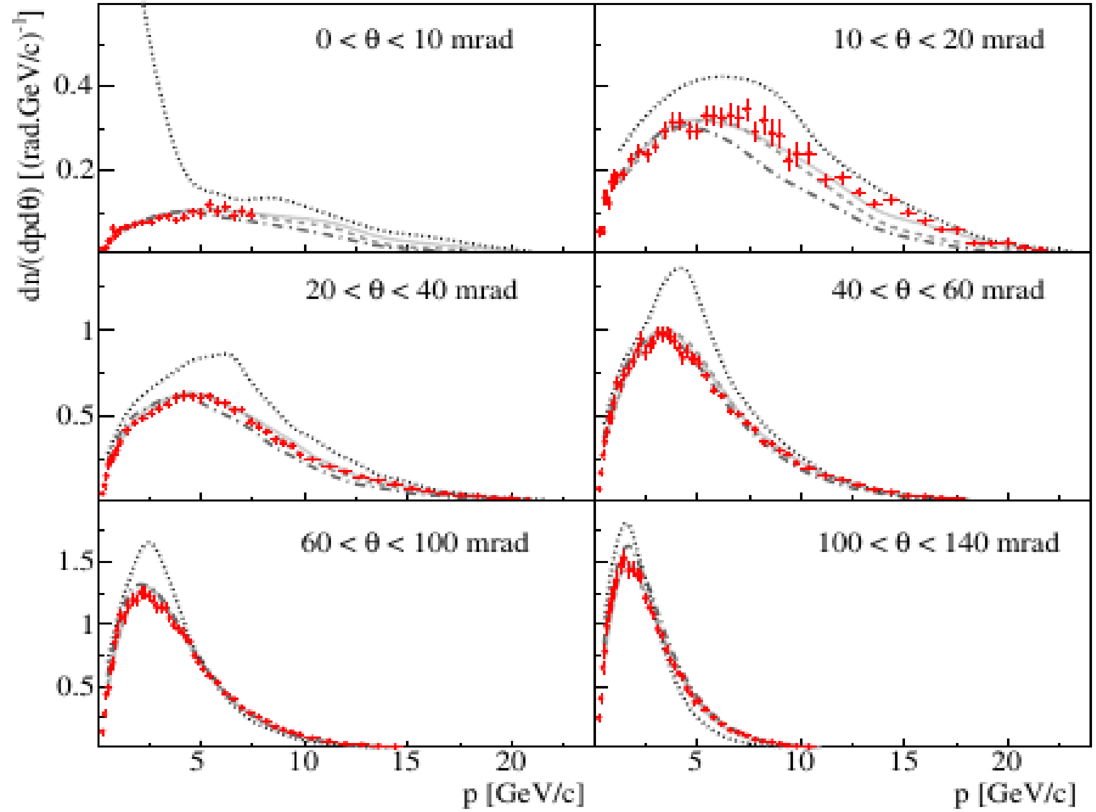
ToF for particle ID

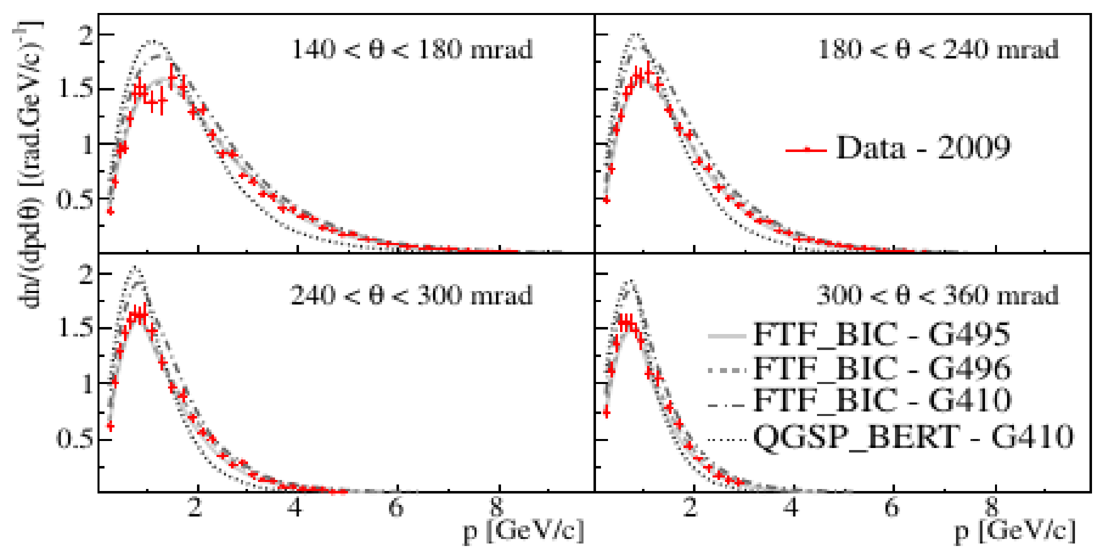


Results

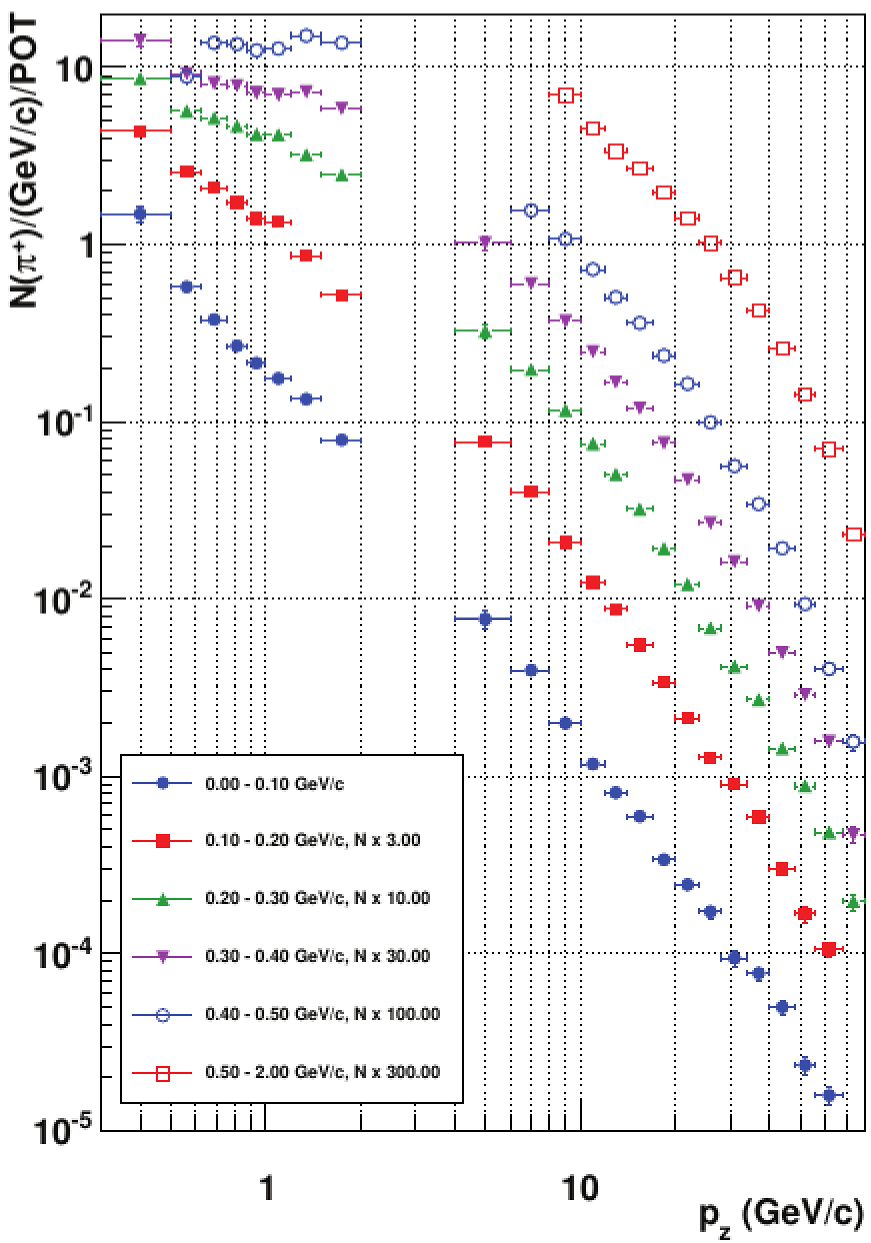

4.4 < p < 4.8 GeV/c
20 < θ < 40 mrad
p
π
e
K
m² [GeV²/c⁴]
dE/dx [mip]

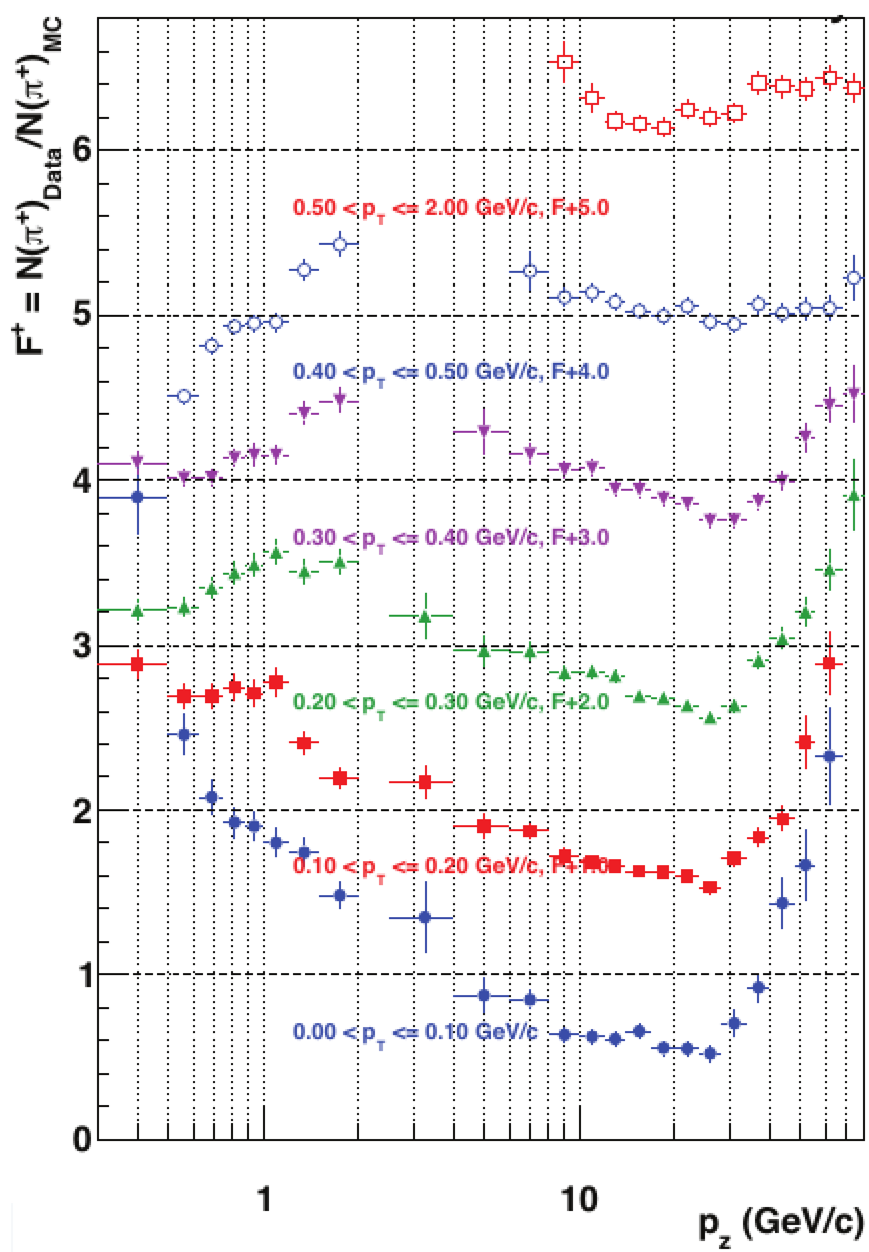

π⁺ 60 < θ < 100 mrad
Fractional Errors
p [GeV/c]
2007 stat. error
2009 stat. error
2007 syst. error
2009 syst. error


0 < θ < 10 mrad
10 < θ < 20 mrad
20 < θ < 40 mrad
40 < θ < 60 mrad
60 < θ < 100 mrad
100 < θ < 140 mrad
dn/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]


140 < θ < 180 mrad
180 < θ < 240 mrad
240 < θ < 300 mrad
300 < θ < 360 mrad
Data - 2009
FTF_BIC - G495
FTF_BIC - G496
FTF_BIC - G410
QGSP_BERT - G410
dn/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]

MIPP results for NuMI



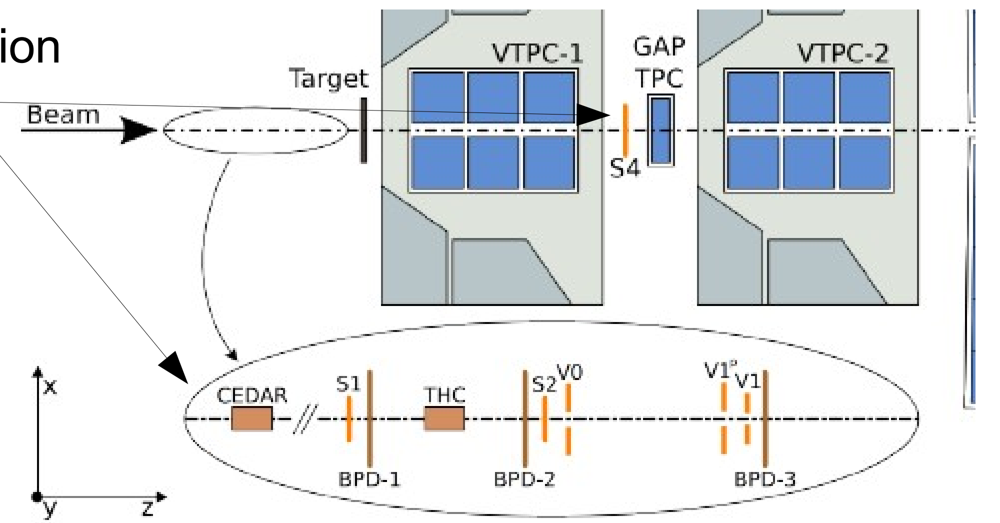


Cross-section normalization

$$\sigma_{hadroprod} = \sigma_{tot} - \sigma_{el} - \sigma_{qe}$$

σ_{tot} can be extracted from beam instrumentation in anti-coincidence with S4 (normalized to number of carbon nuclei in the target)

Need to correct for events with actual interactions in S4 using model



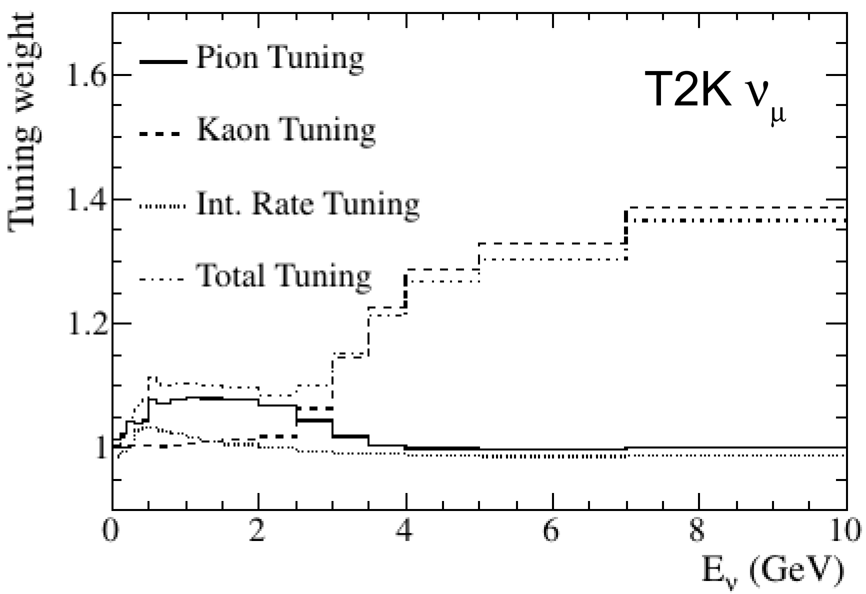
σ_{el} elastic scattering on carbon nucleus (from previous measurements compared to GEANT → largest uncertainty)

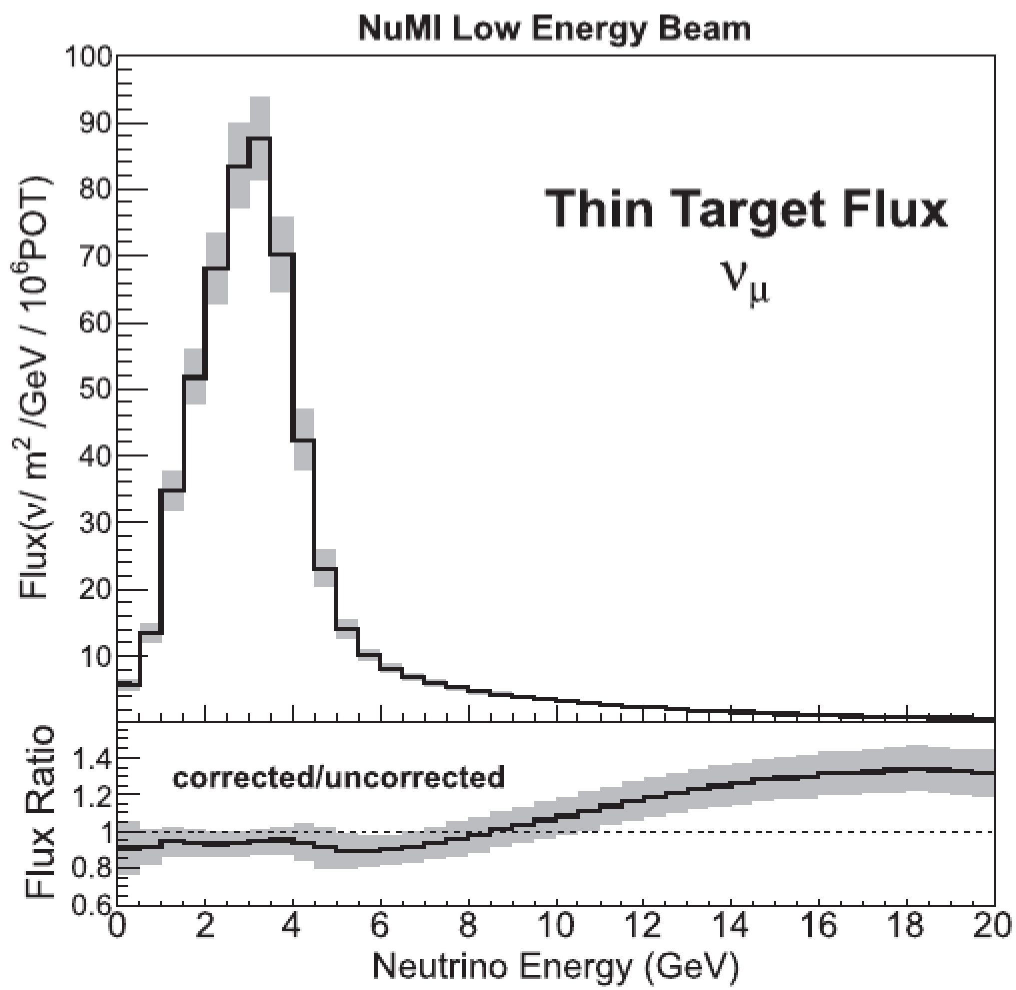
σ_{qe} quasi-elastic scattering on single nucleon in the carbon nucleus which get ejected (from GEANT)

$$\sigma_{\mathrm{prod}} = 230.7 \pm 2.8(\mathrm{stat}) \pm 1.2(\mathrm{det})\,^{+6.3}_{-3.5}(\mathrm{mod})\,\mathrm{mb}$$

Tuning factors

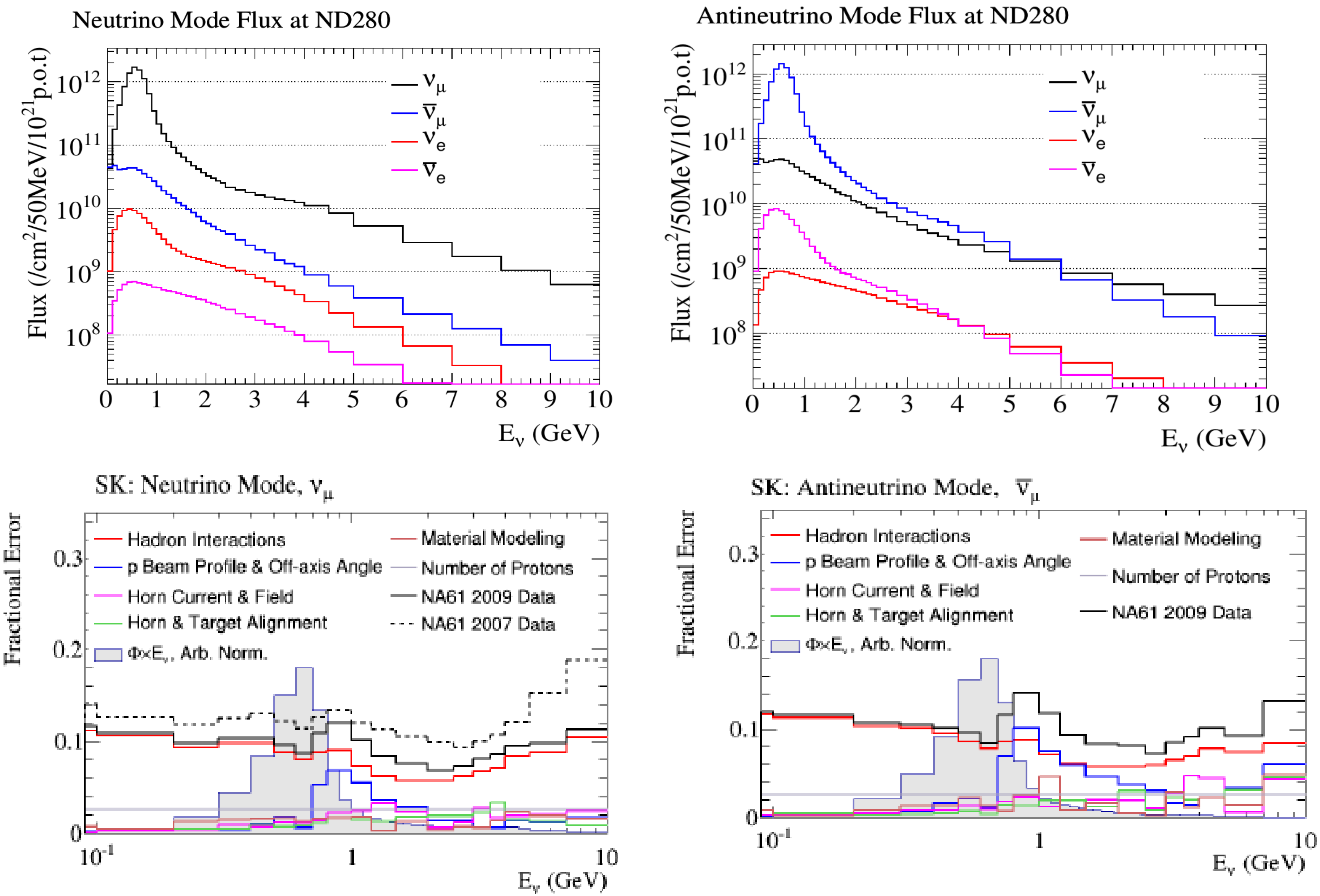
$$\frac{\text{flux tuned}}{\text{flux simulated}}$$





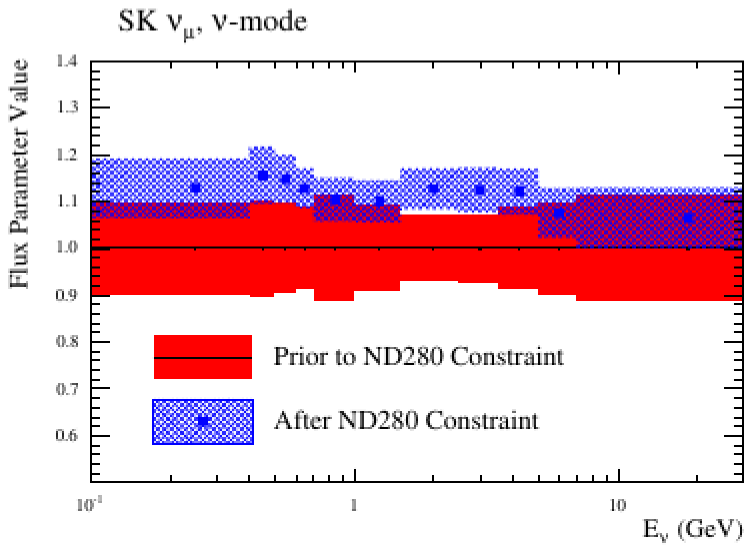
Uncertainties from theory corrections (scaling to different proton energies, targets, not covered phase space…) and from hadro-production data (statistics and systematics uncertainty)

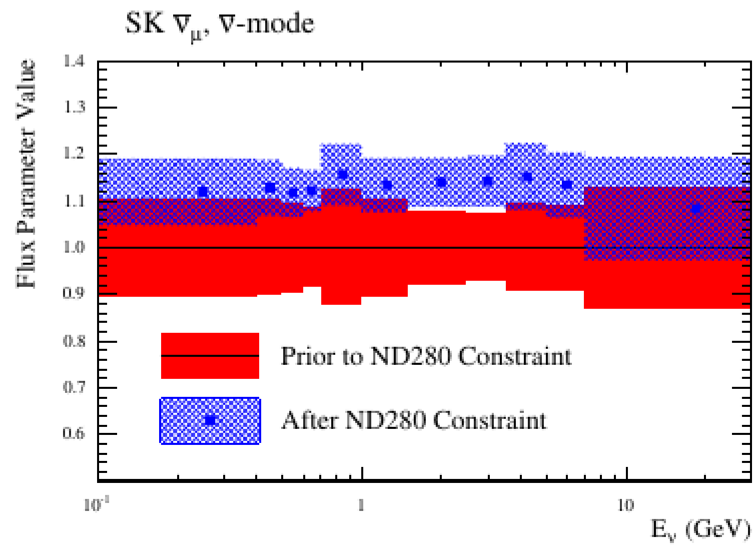
Flux prediction and uncertainties



Flux constraint from the ND

The ND measures the rate of neutrinos therefore it further constrain the flux





$$N^{ND}_{\nu_\alpha}(E_\nu) = \varphi(E_\nu) \times \sigma(E_\nu)\, dE_\nu$$

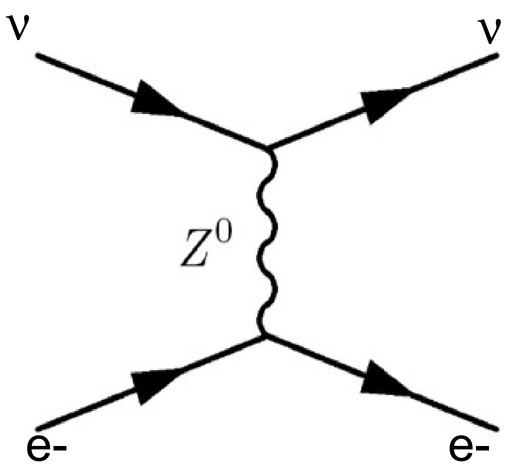
Uncertainties before and after ND constrain

Flux+XSec (Pre ND280)	10.90%
Flux+XSec	2.90%
Flux	3.54%

Strong anticorrelation between flux and cross-section (see also the dedicated exercise)
Today xsec uncertainties similar or larger than flux uncertainty

Further constraint from the ND (2)

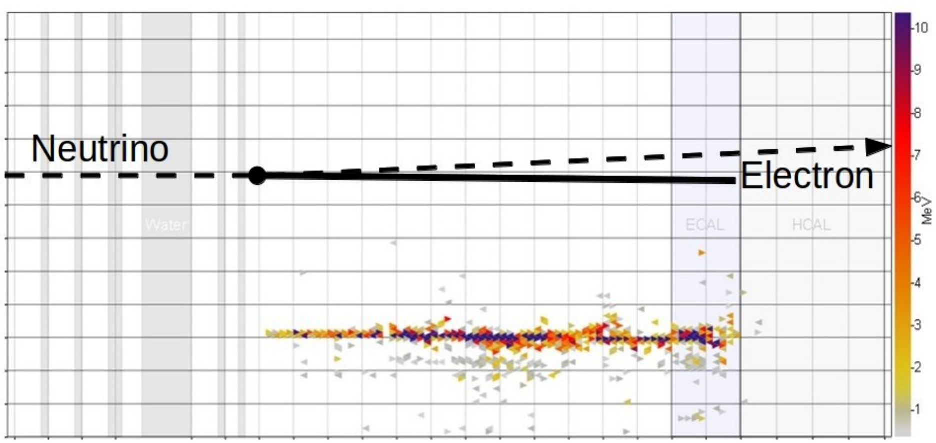
One nice exception: a cross-section which we know very well (no nuclear effects!)

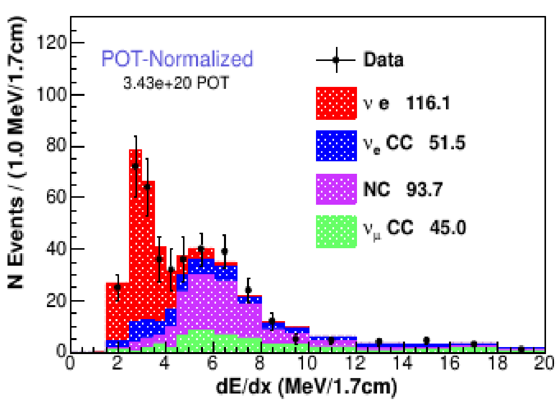


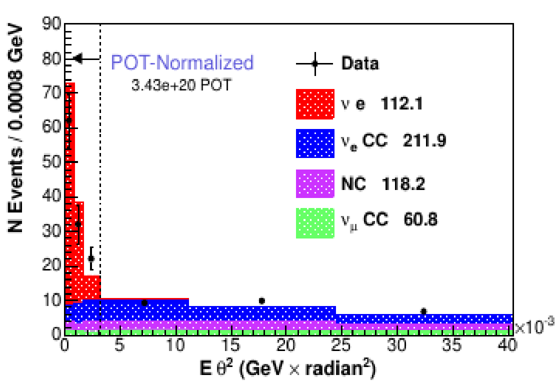
Neutrino scattering on electrons:
simple electroweak Neutral Current process for ν_μ and ν_τ,
(some Neutral Current – Charged Current interference for ν_e)

Difficulties: **very small xsec** (10^{-4} wrt to total CC ν interaction)
large backgrounds from $\pi^0 \to \gamma\gamma$ and ν_e CC

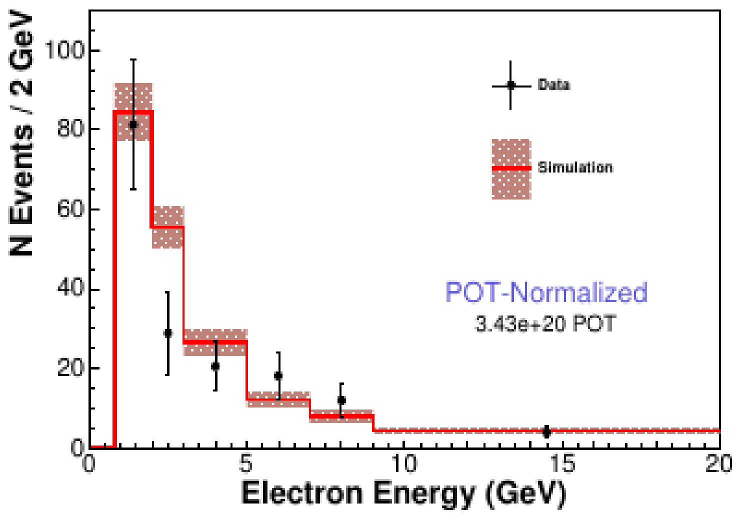
Minerva: clever cuts on electron ID and kinematics (forward electrons)





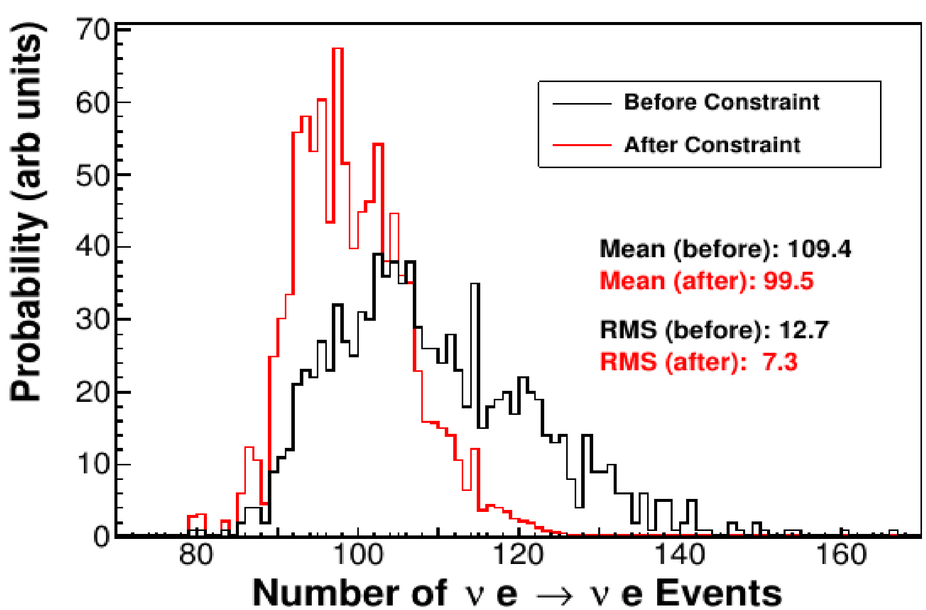


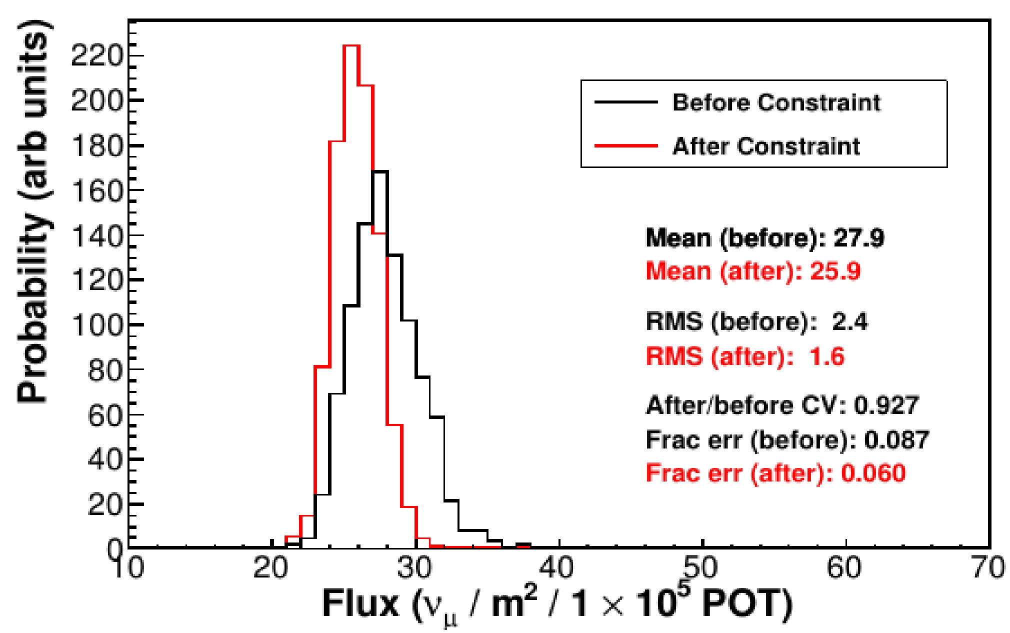
Constraints from ν-e scattering



Flux uncertainty is larger than the uncertainty on the measurement (stat.+syst) → can be used to constrain the flux

10% stat + 5-10% syst → prospects for high precision with future high intensity beams and large near detectors





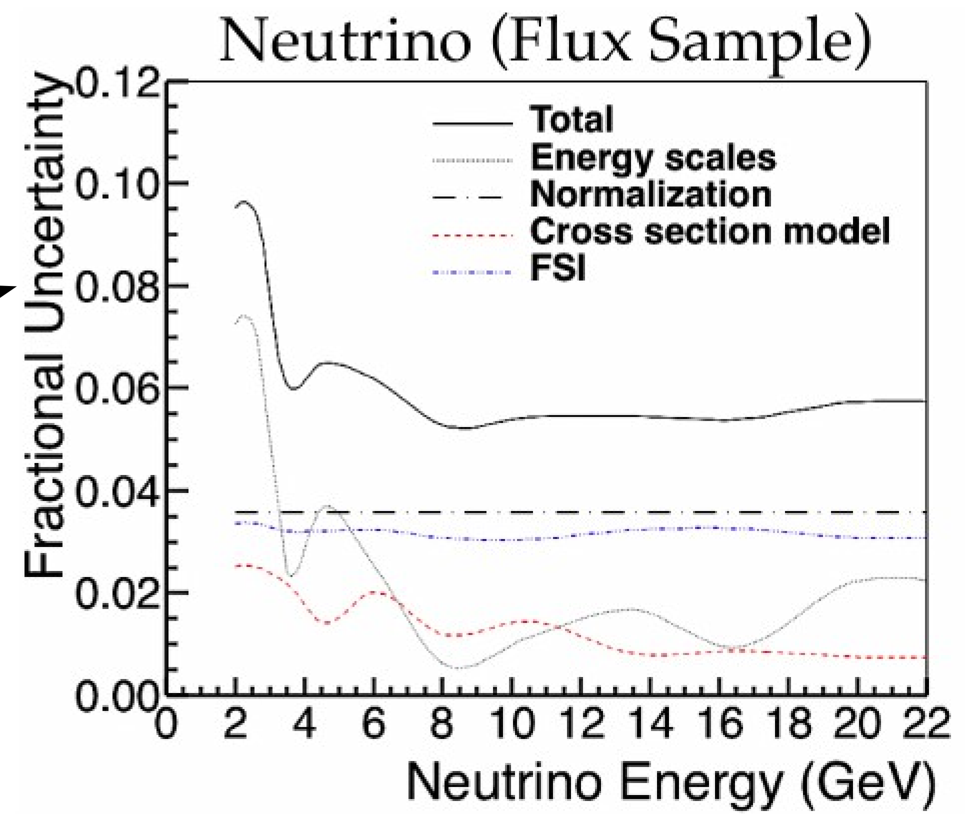
Constraints from low-ν method

$$\frac{d\sigma^{\nu,\bar{\nu}}}{d\nu} = A(1 + \frac{B^{\nu,\bar{\nu}}}{A}\frac{\nu}{E} - \frac{C^{\nu,\bar{\nu}}}{A}\frac{\nu^2}{2E^2})$$

ν= energy transferred to the nucleus

In the limit of ν->0 the xsec does not depend on Eν

→ **event rate at low ν can be used to constraint the flux shape as a function of Eν**

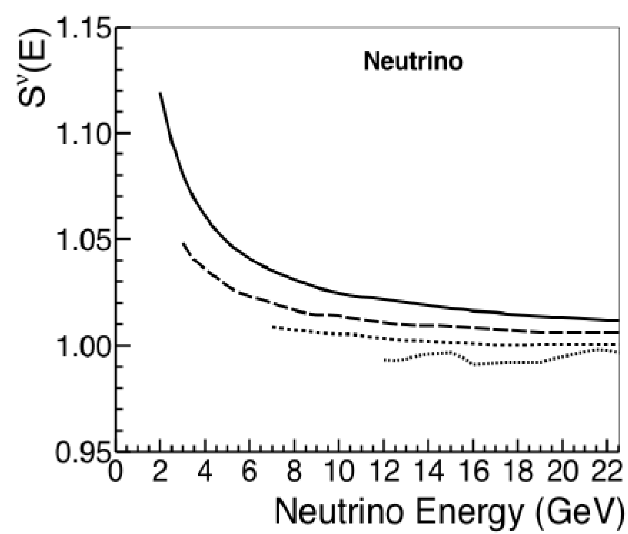


Limitations:

- difficult to reconstruct the energy transferred to the nucleus: look at energy deposits around the vertex (vertex activity) → correct for neutrons and invisible energy (nuclear excitation, binding energy) below threshold
- flux normalization cannot be constrained
- independence on Eν is an approximation

→ need to correct with xsec models:

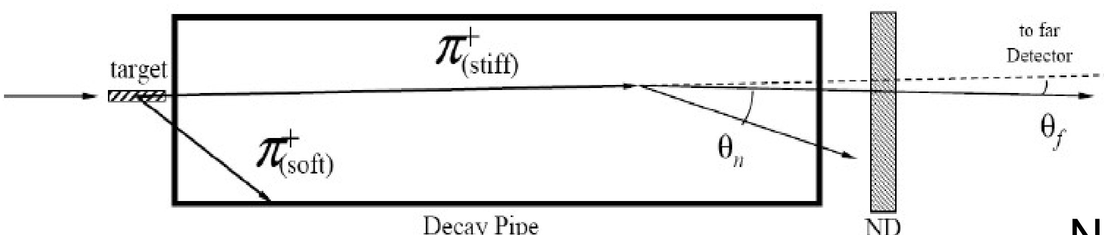
$$S^{\nu}(\bar{\nu})(\nu_0, E) = \frac{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E)}{\sigma^{\nu}(\bar{\nu})(\nu < \nu_0, E \to \infty)}$$

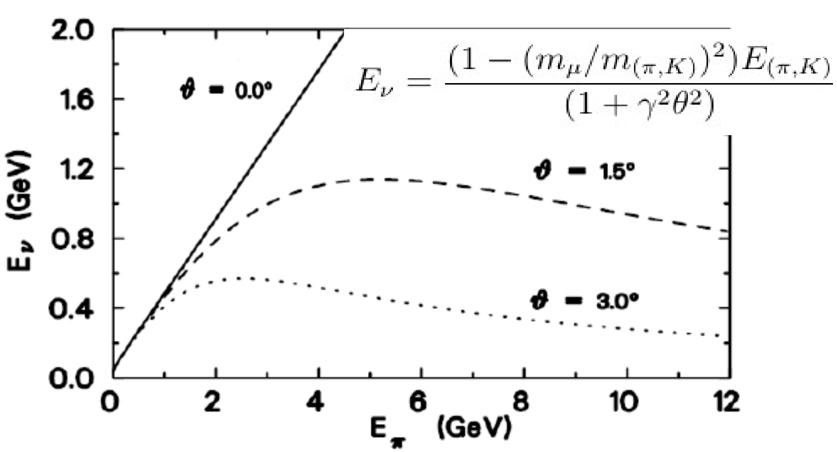


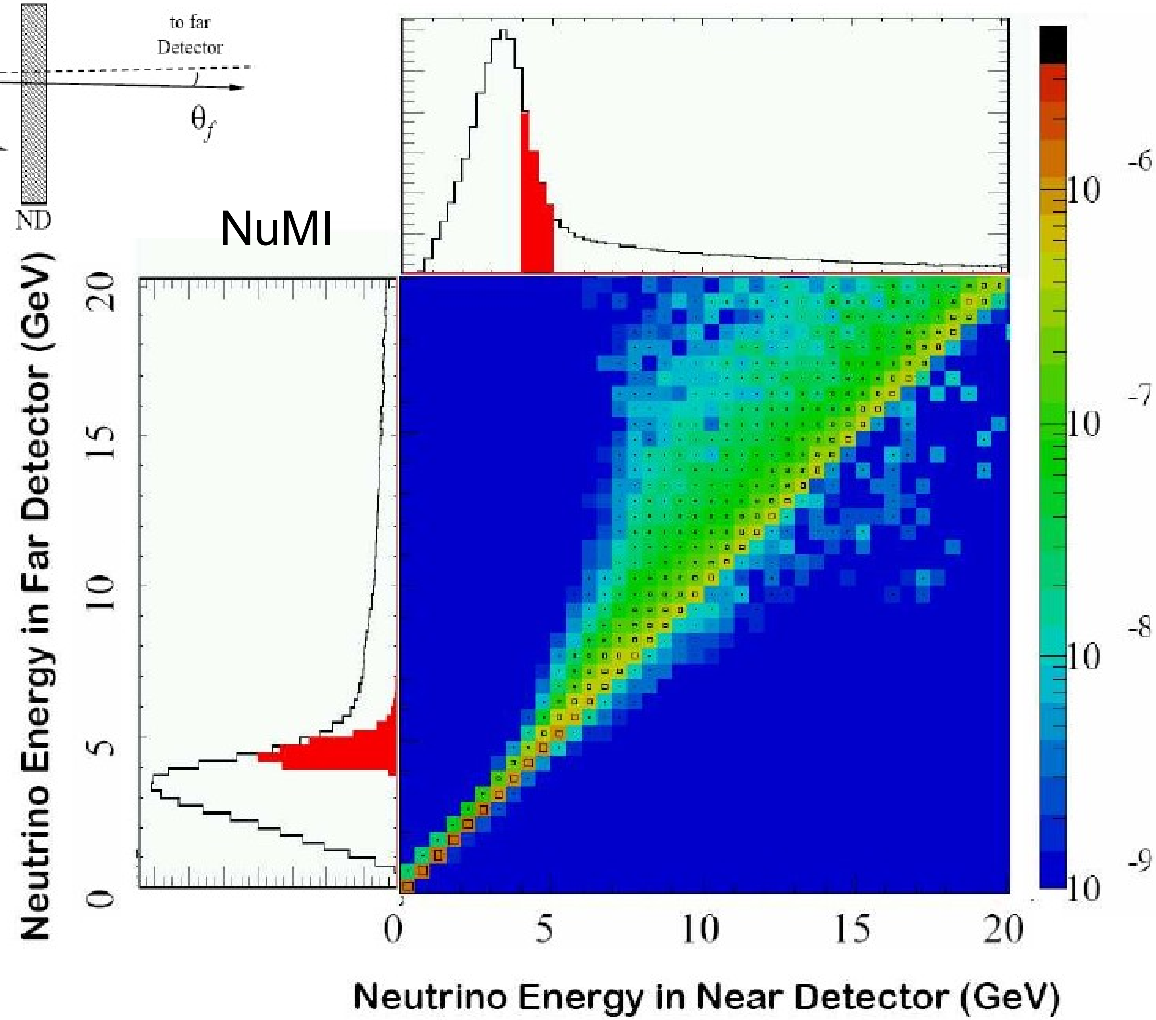
From ND to FD flux extrapolation

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) \times \frac{\varphi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\varphi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

Different acceptance of pion angles → different neutrino energies for same pion kinematics



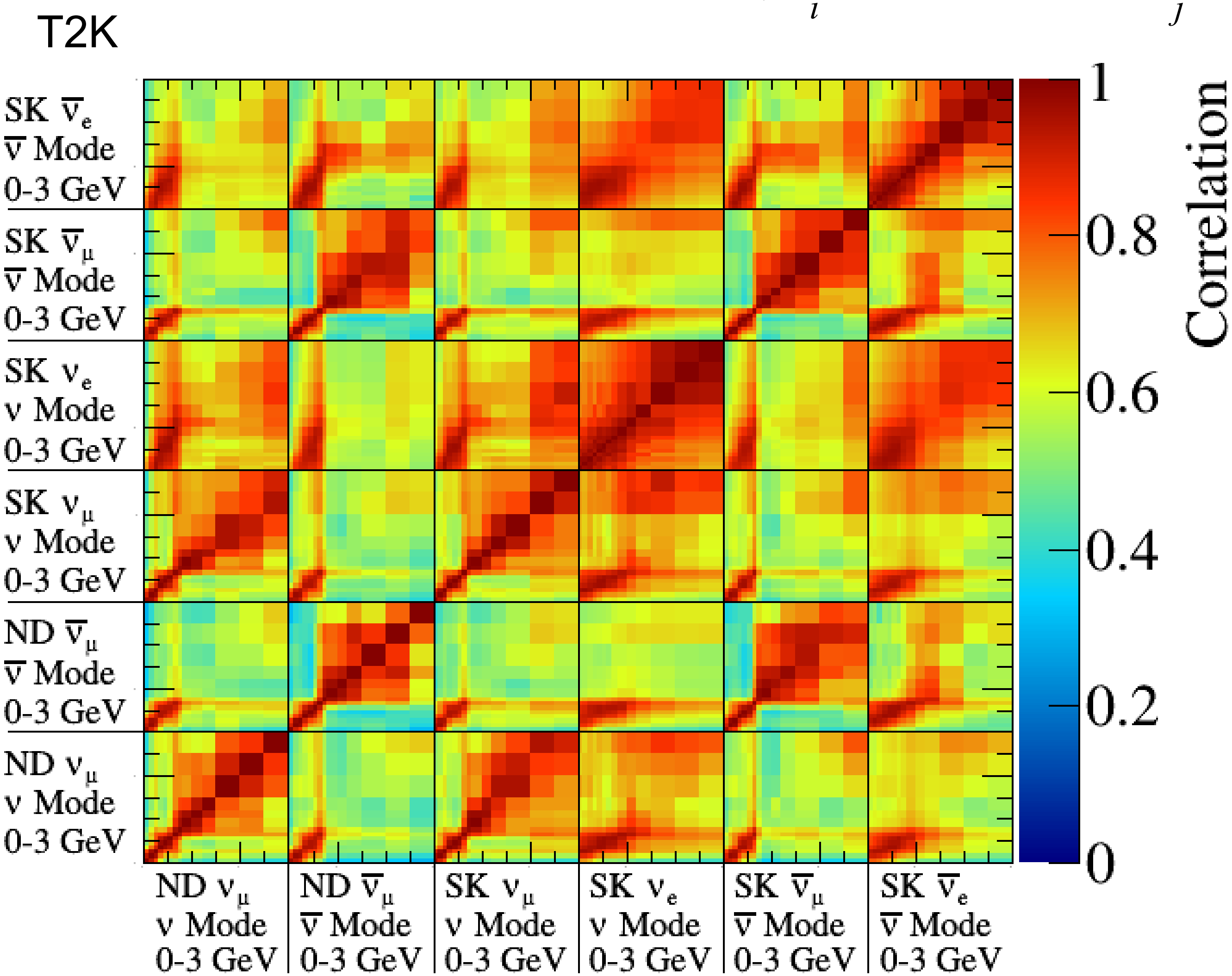




Extrapolation ND->FD uncertainties smaller (~1%) than overall flux uncertainties (10% → 5%)

From ND to FD flux extrapolation

Flux Correlations $$\rho = \frac{\sigma^2_{cov.ij}}{\sigma_i \sigma_j} = \frac{\sum_{i,j} (f_i - \langle f_i \rangle)(f_j - \langle f_j \rangle)}{\sqrt{\sum_i (f_i - \langle f_i \rangle)^2 \sum_j (f_j - \langle f_j \rangle)^2}}$$



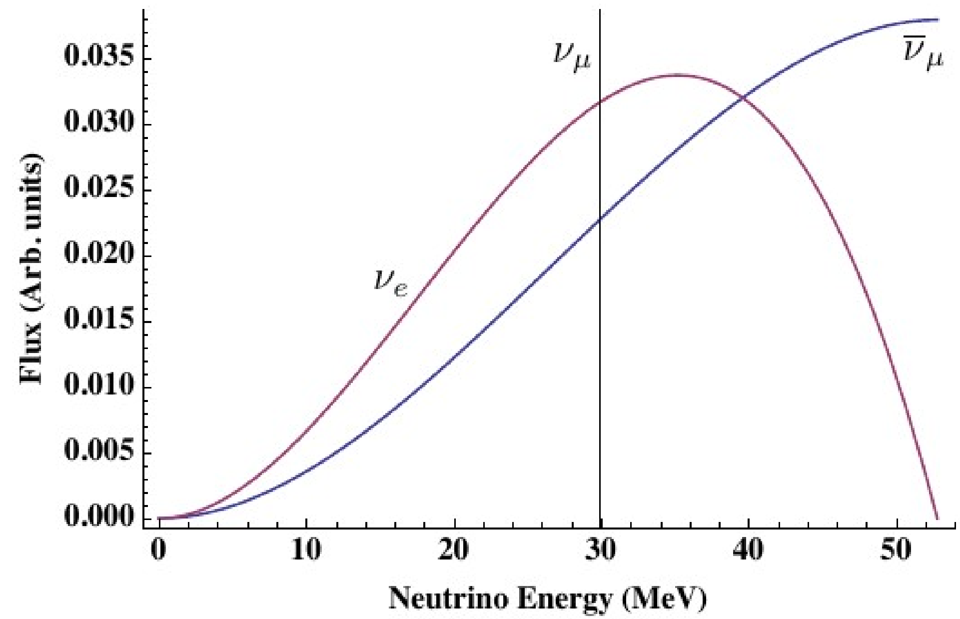
- **~100% correlation between ND and SK fluxes**
- Large correlations between different bins in the same 'mode' → **flux uncertainty is to large extent an overall normalization** (shape uncertainties are smaller)
- **Correlations between different modes and neutrino flavors:** (to a certain extent) we can use ν_μ data to constrain $\bar{\nu}_\mu$ or ν_e fluxes

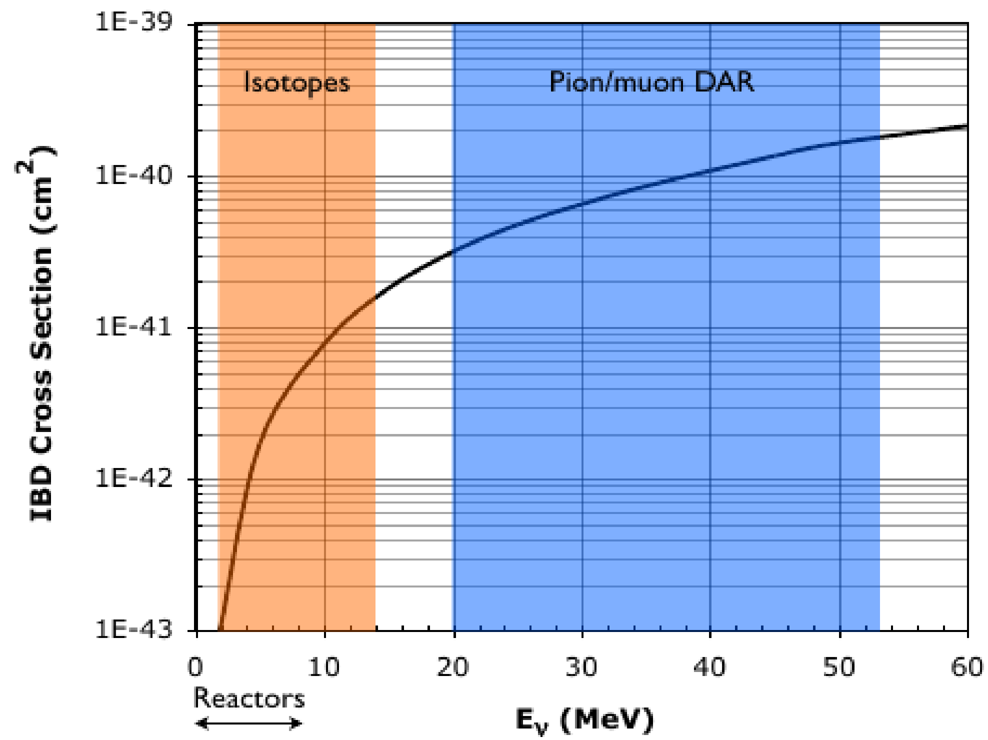
Non standard beams and fluxes

Pion decay at rest (DAR) in contrast to standard pion decay in flight (DIF)

- well known energy of neutrinos
- low energy → well known cross-section: IBD ($\bar{\nu}_e + p \to e^+ n$) and ν-e elastic scattering
- low energy → very low xsec need VERY intense sources

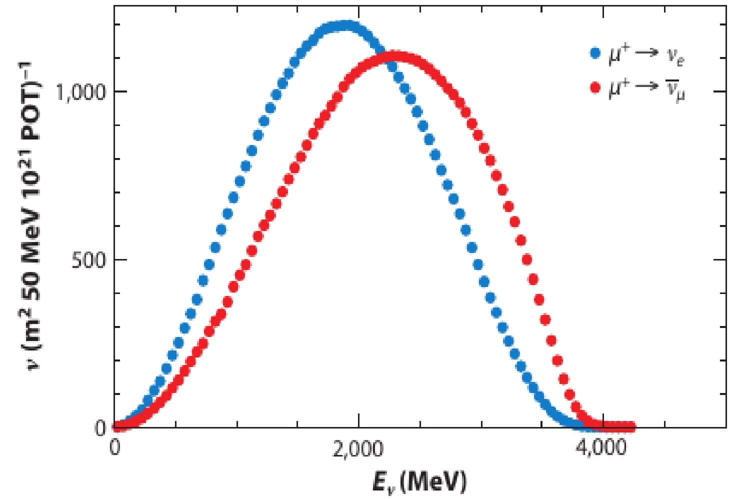
Low energy protons (eg from cyclotron) impinging on target surrounded by absorber to avoid DIF





Non standard beams and fluxes

- Neutrinos from Stored Muons (**nuSTORM**): beams from the decay of 3.8 GeV muons confined within a storage ring

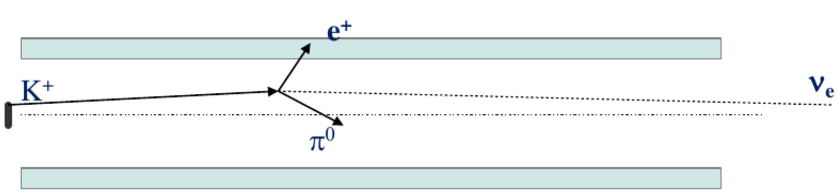


well known energy of neutrinos

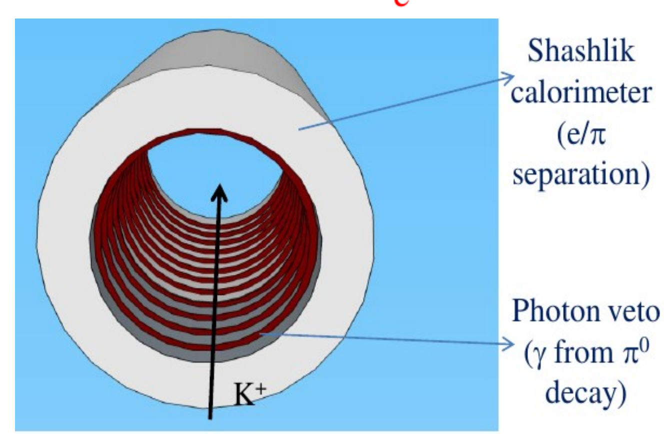
large ν_e statistics

- Monitor the production of electrons in standard ν beam: uncertainty on ν_e flux improved by one order of magnitude

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

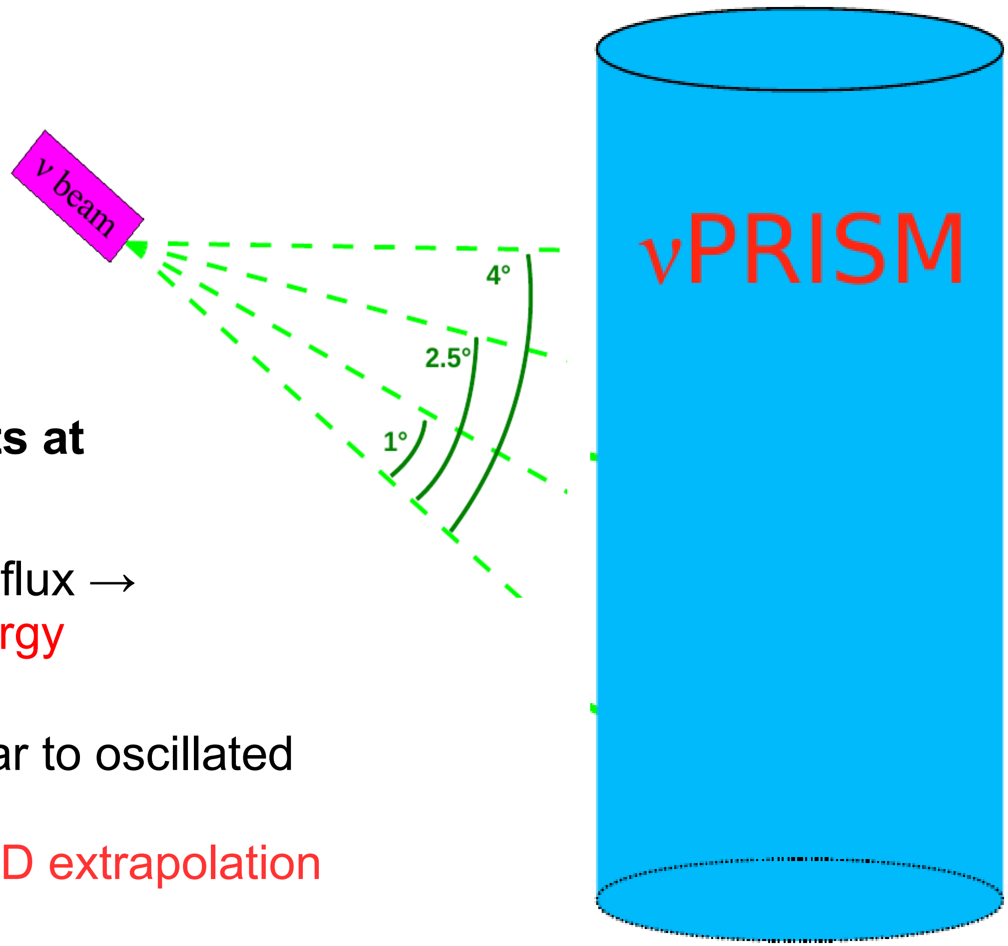


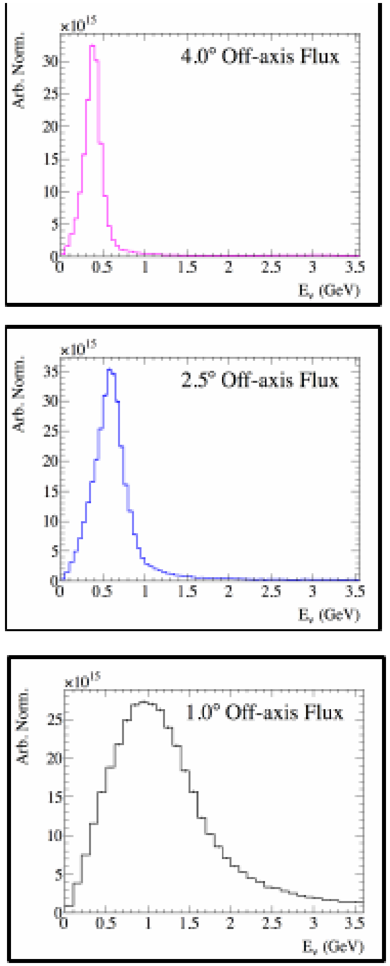
A. Longhin, L. Ludovici, F. Terranova EPJC 75 (2015) 155



Alternative concept: NuPRISM

Flux at different off-axis angle = different E_ν spectra





Combine measurements at different angles to

- build monochromatic flux → measure xsec vs energy
- build flux shape similar to oscillated flux at far detector → decrease the ND → FD extrapolation uncertainty