Systematics on (long-baseline) neutrino oscillation measurements

- **Introduction on oscillation measurements:** present results from T2K and NOVA and precision needed for next generation HyperKamiokande, DUNE

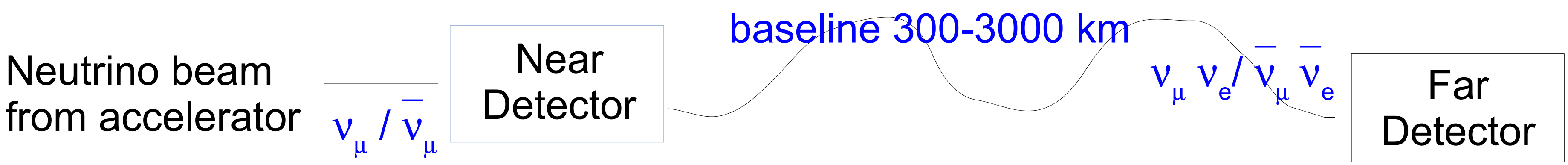
- Overview of the systematics:
  - How **neutrino flux and cross-section** affect neutrino oscillation measurements ?
  - **Flux** simulation and tuning
  - Main neutrino **cross-section uncertainties** (from an experimentalist point of view)

- Neutrino oscillation analyses and xsec systematics in details: **the T2K and NOVA examples**

S.Bolognesi (CEA Saclay) - T2K

Introduction on oscillation measurements: results and precision

Long baseline experiments



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

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

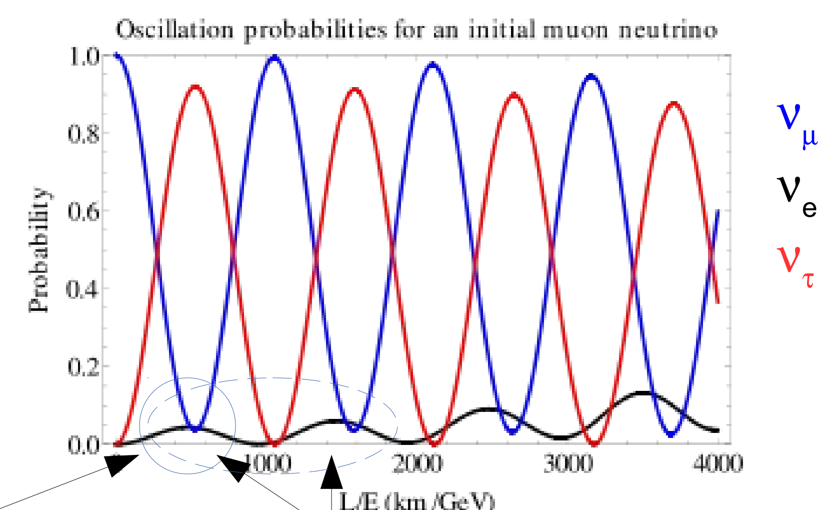
(simplified 2-flavors approximation)

In the atmospheric sector

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

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)

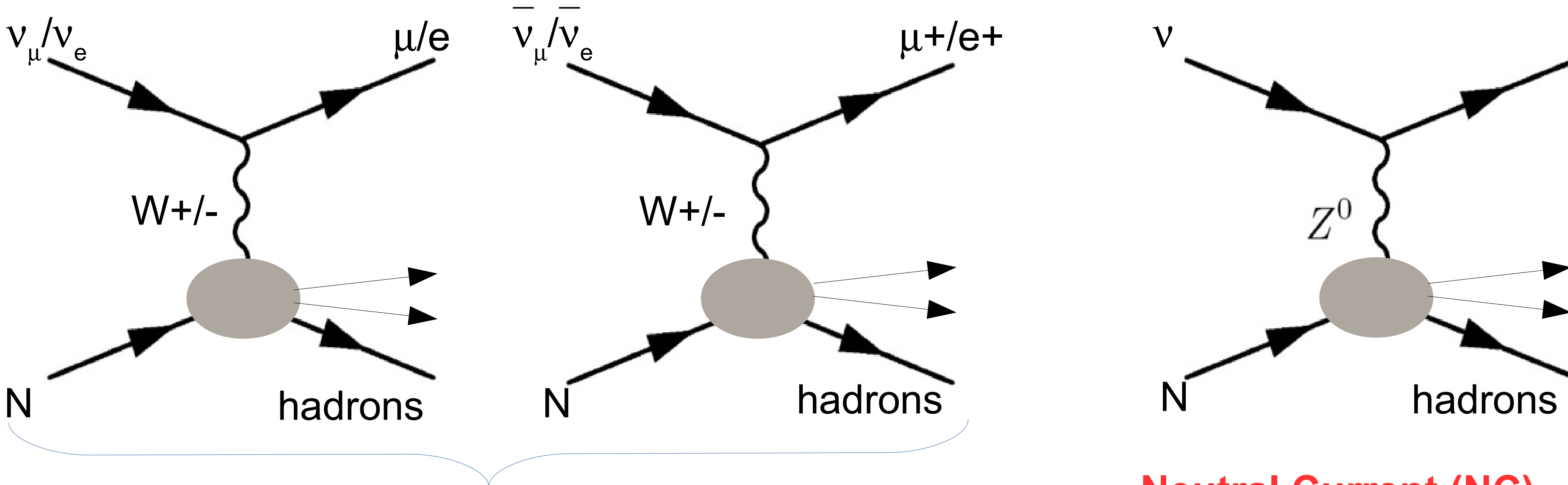


T2K (T2HK) and NOVA working point

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

Neutrino “signal” and “background”

Neutrino can interact with target nucleons in our detector materials with



Charged Current (CC) main signal:

- outgoing lepton well visible in the detector to tag interactions → allow to **identify the incoming neutrino flavour and 'charge'**
- full final state can be reconstructed in the detector → allow to **estimate the incoming neutrino energy**

(in realistic detectors this actually relies on various approximations)

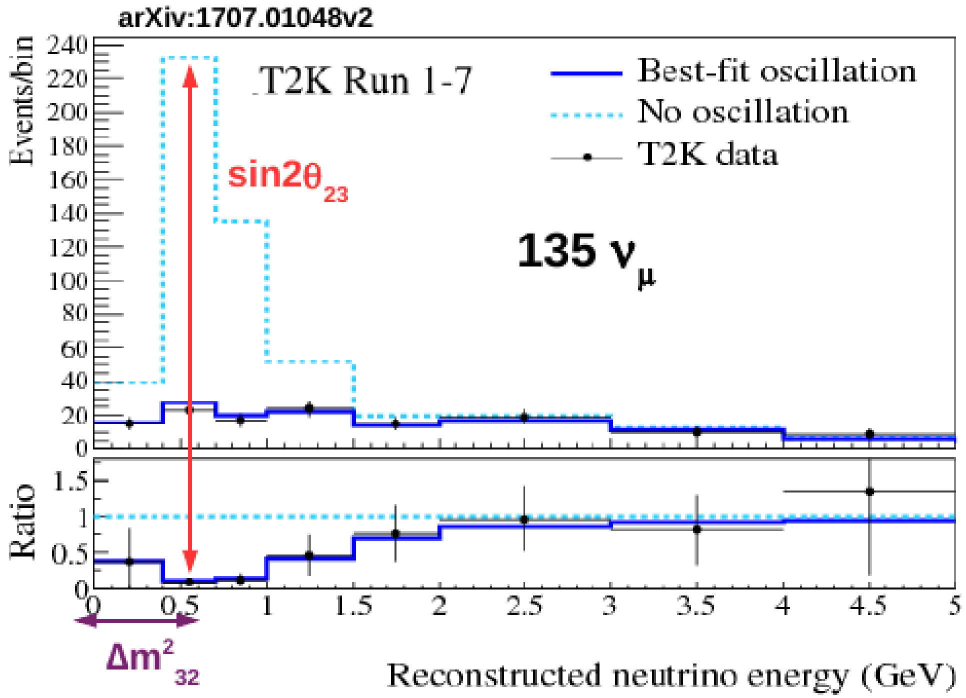
Neutral Current (NC) background

Sometimes the outgoing hadrons can be misidentified as lepton in the detector → background that need to be estimated and subtracted from data distributions

(I will discuss CC but everything can be 'easily' extended to NC)

T2K oscillation analyses

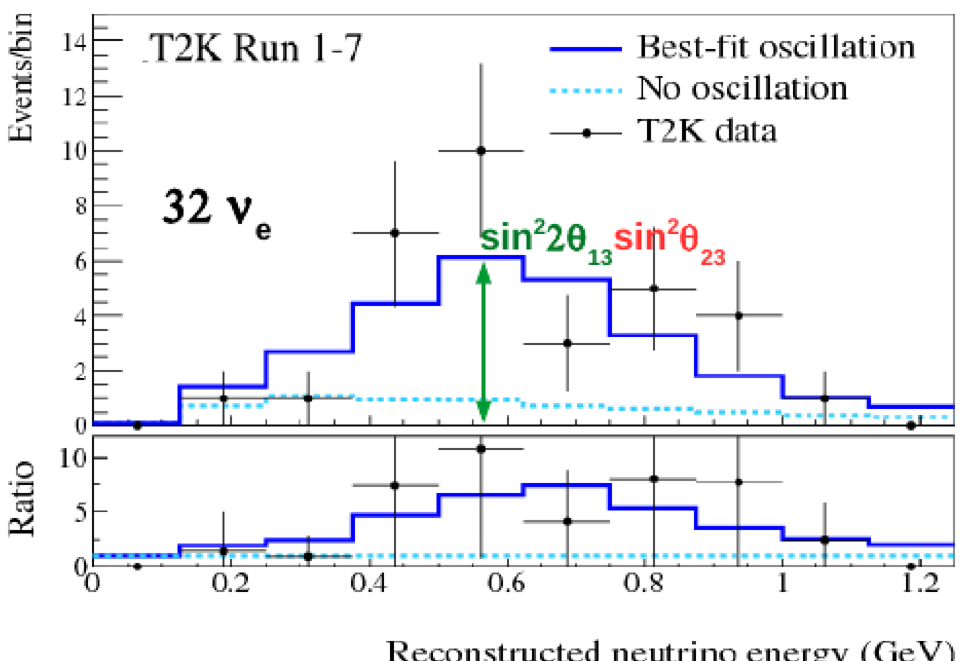
(F.Gizzarelli thesis defence)



Disappearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- $\sin 2\theta_{23}$ proportional to the depth of the dip
- Δm^2_{32} position of the dip



Appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \mathbf{x}$$

$$\left(\sin^2\theta_{23} \mp \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\left(\frac{\Delta m^2_{21} L}{4E}\right)\right)$$

- $\sin^2 2\theta_{13} \sin^2\theta_{23}$ proportional to the oscillation maximum
- δ_{CP} flip sign for ν (-) and $\bar{\nu}$ (+)

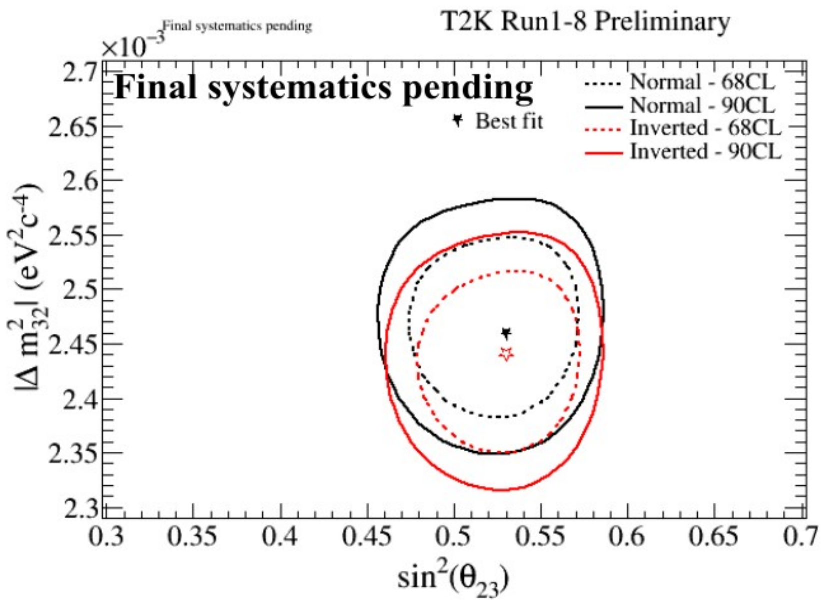
Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
e-like ν	28.8	24.2	19.7	24.2	32
e-like $\bar{\nu}$	6.0	6.9	7.7	6.8	4

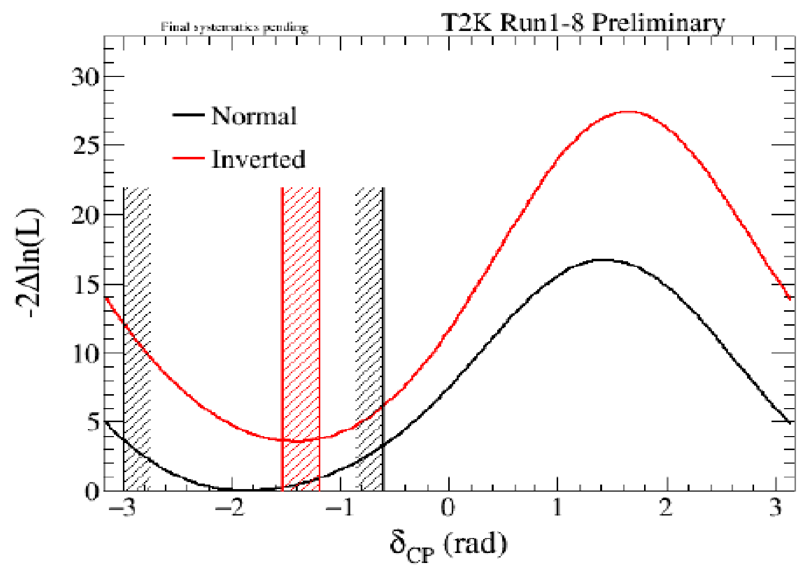
T2K: systematics and results

Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	$\overline{\nu}_e$ CCQE-like $\delta N/N$	$\overline{\nu}_\mu$ $\delta N/N$
Flux+cross-section				
(w/o ND280 constraint)	11.3%	10.8%	12.9%	11.3%
(w/ ND280 constraint)	4.2%	2.9%	4.7%	3.5%
Flux (w/ ND280 constraint)	3.7%	3.6%	3.8%	3.8%
Cross section (w/ ND280 constraint)	5.1%	4.0%	5.5%	4.2%
FSI+SI+PN at SK	2.5%	1.5%	3.0%	2.1%
SK detector	2.4%	3.9%	2.5%	3.4%
All				
(w/o ND280 constraint)	12.7%	12.0%	14.5%	12.5%
(w/ ND280 constraint)	5.5%	5.1%	6.5%	5.3%

2016 systematics (similar in 2017):

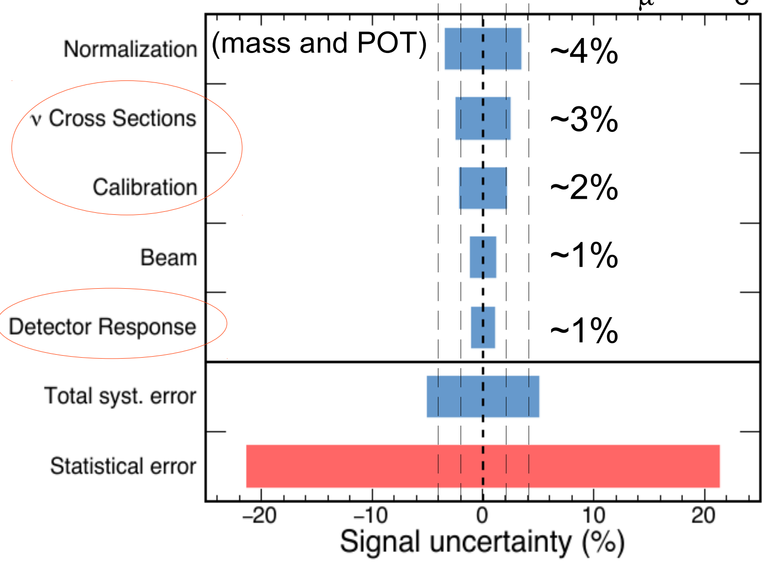
total systematics on number of events **~ 5-6%**
Still fully dominated by statistics

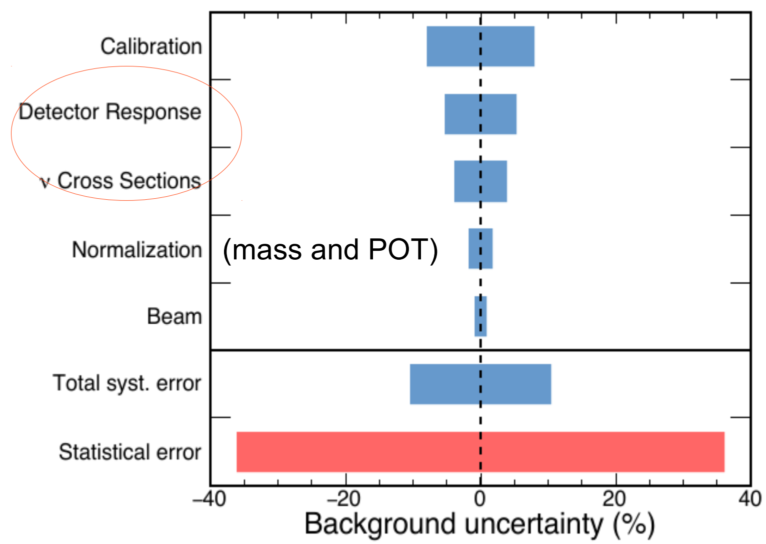




NOVA: systematics and results

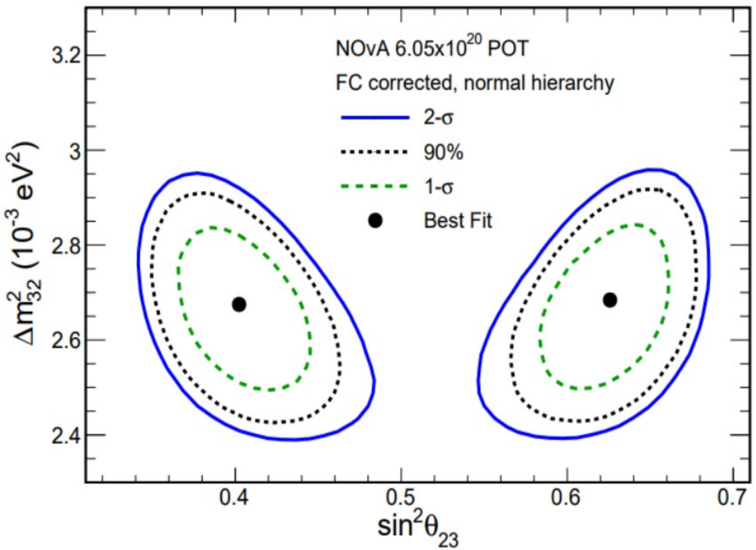
Systematics on combined $\nu_\mu + \nu_e$ analysis:

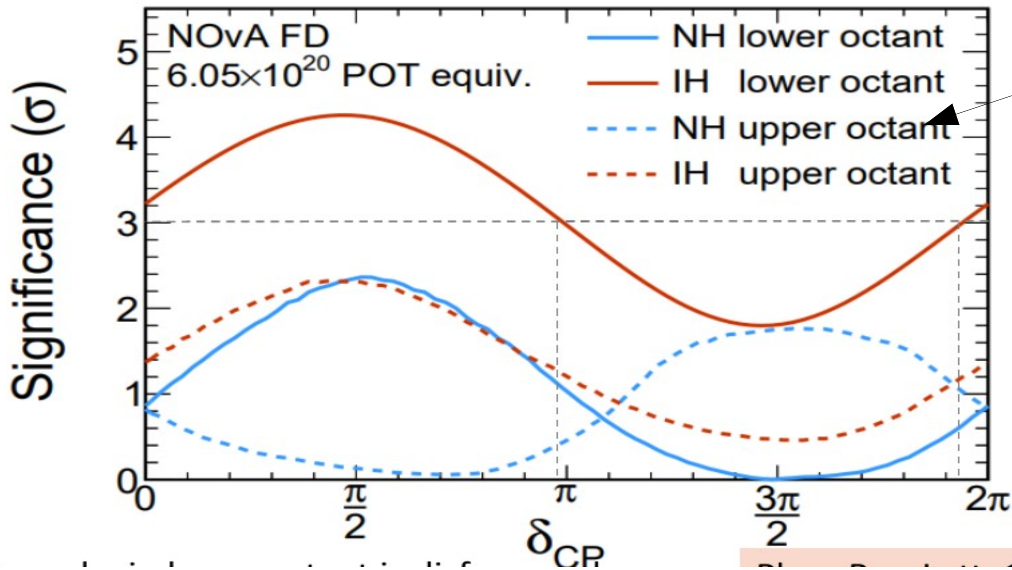




total systematics on number of **signal events ~ 5-6% (~10% on background) Still fully dominated by statistics**

Results:





Degeneracy can be solved with antinu data

Statistics

D.Hadley NuFact2017

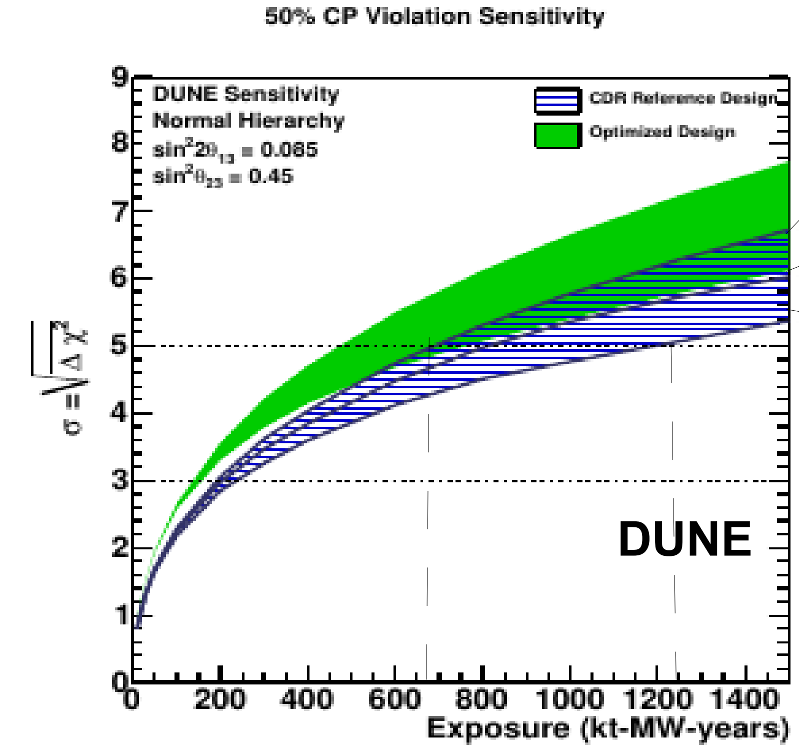
Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 9%	20×10^{21} POT, arXiv1607.08004 [hep-ex]
T2HK	2900 + 2700	2% + 2%	10 yrs 2-tank staged KEK Preprint 2016-21
DUNE	1200 + 350	3% + 5%	3.5+3.5 yrs x 40kt @ 1.07 MW arXiv:1512.06148 [physics.ins-det]

Today stat error ~ 15%

Next generation experiments ~ few 10^3 events → need systematics <2%

The targeted precision

- Oscillation measurements in future long baseline experiments aim to **~1-3% systematic uncertainty on signal normalization**

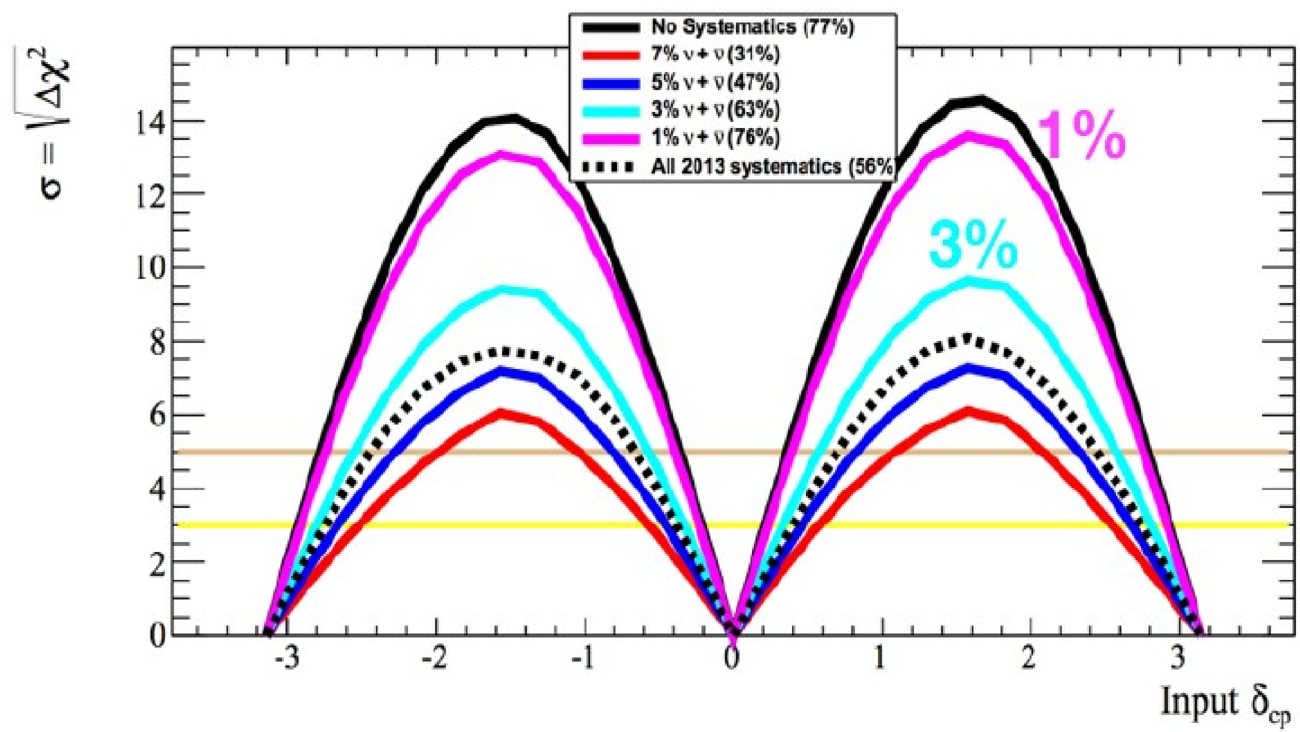


5% ± 1%

5% ± 2%

5% ± 3%

→ equivalent to factor 2 in exposure!



DUNE and HK talks @ NuFact 2015

How neutrino flux and cross-section affect neutrino oscillation measurements ?

Oscillation analysis: the basics

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

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** $\nu_\alpha \rightarrow \nu_{\alpha'}$ 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

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

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

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

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

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**

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

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:

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

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

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

flux= number of neutrinos produced by the accelerator per cm², per bin of energy, for a given number of protons on target

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

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 *<u>we use our models to extrapolate</u>* 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:

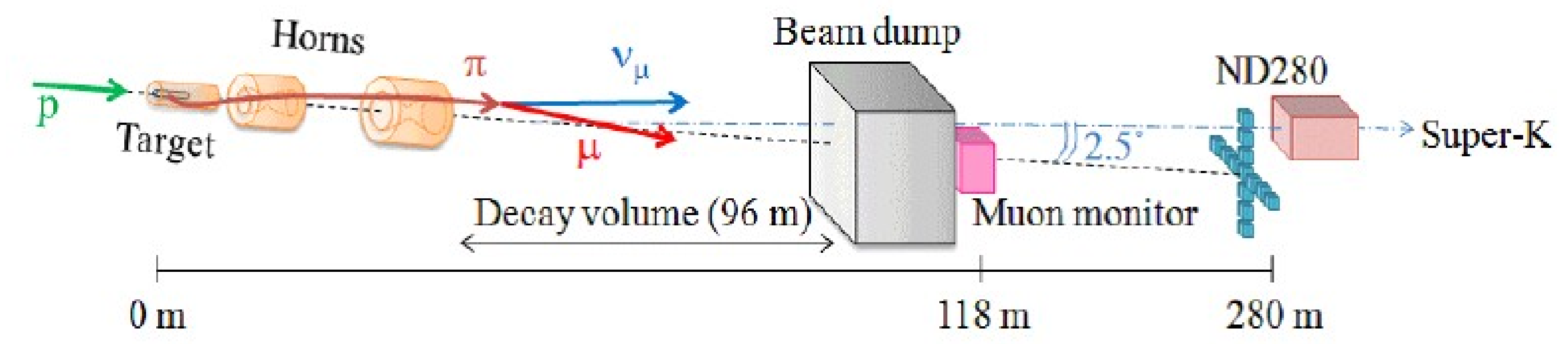
- extrapolation of xsec to different energy spectrum

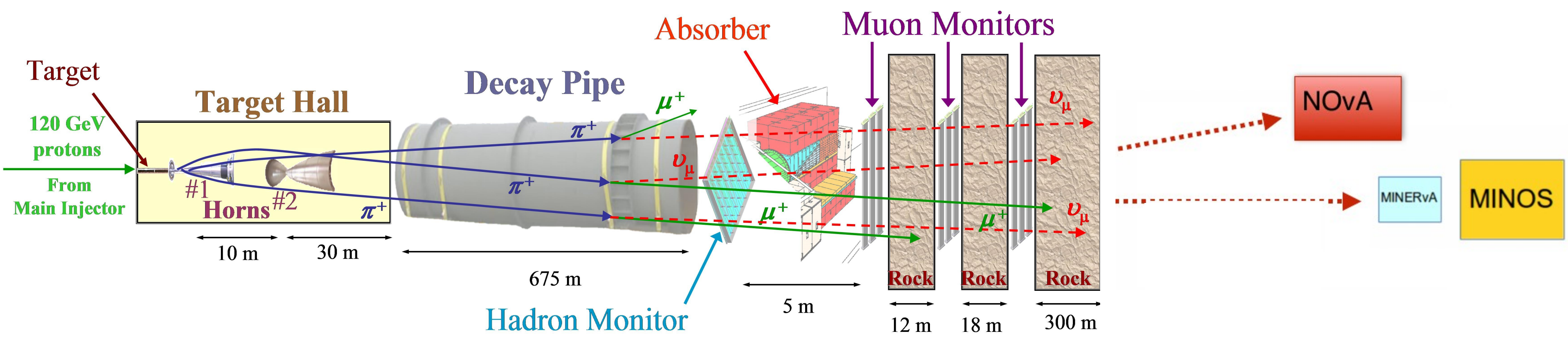
- separate flux and xsec evaluation from ND data

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

Flux simulation and tuning

Neutrino 'beams'





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

Parent	Flux percentage of each(all) flavor(s) 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

Projectile	Material 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

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

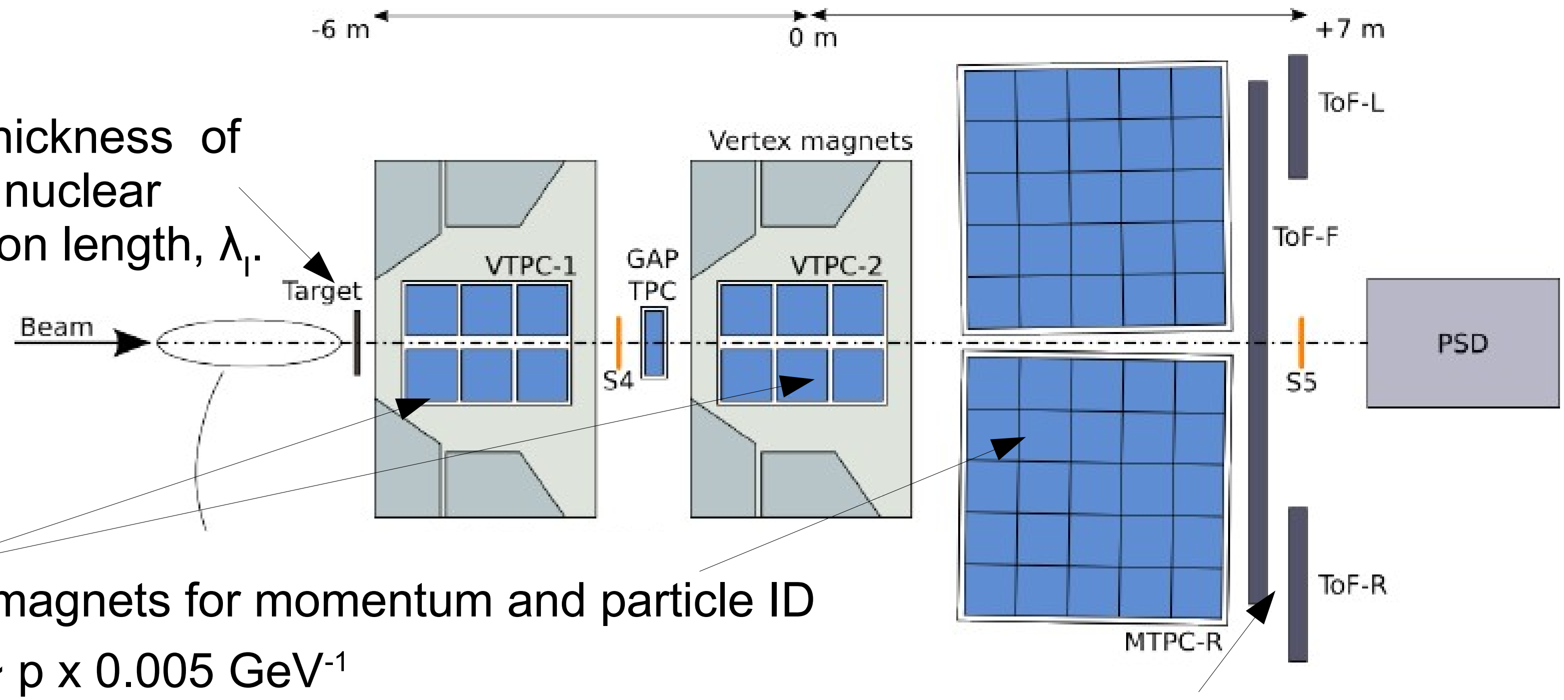
$$W(p_{in}, A) = \frac{[\frac{dn}{dp}(\theta, p_{in}, A)]_{data}}{[\frac{dn}{dp}(\theta, p_{in}, A)]_{MC}}$$

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

NA61/SHINE

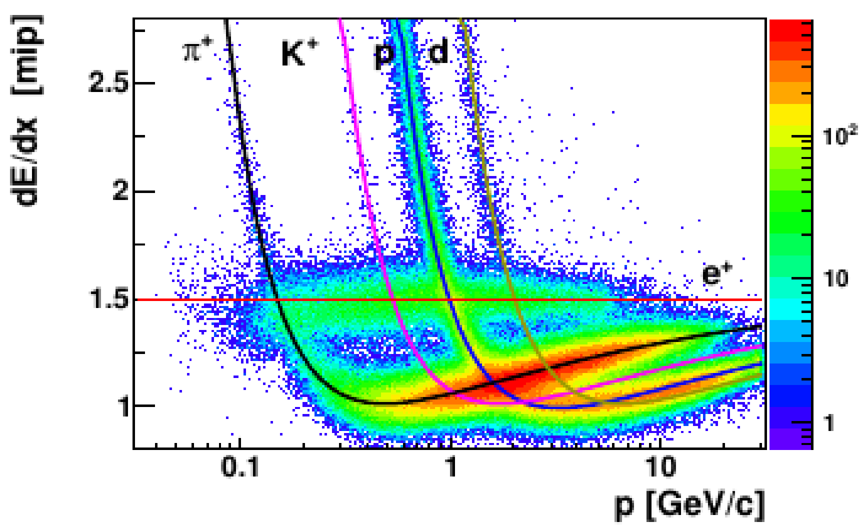
SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS

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

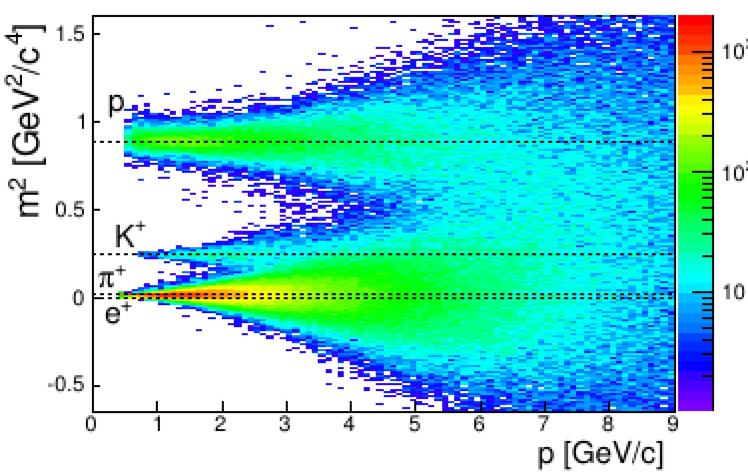


TPC in magnets for momentum and particle ID

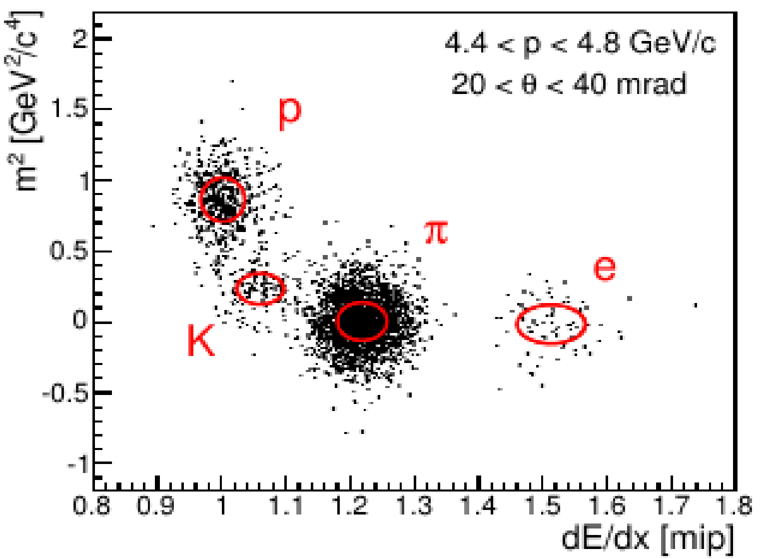
$\sigma(p)/p \sim p \times 0.005\ \mathrm{GeV}^{-1}$



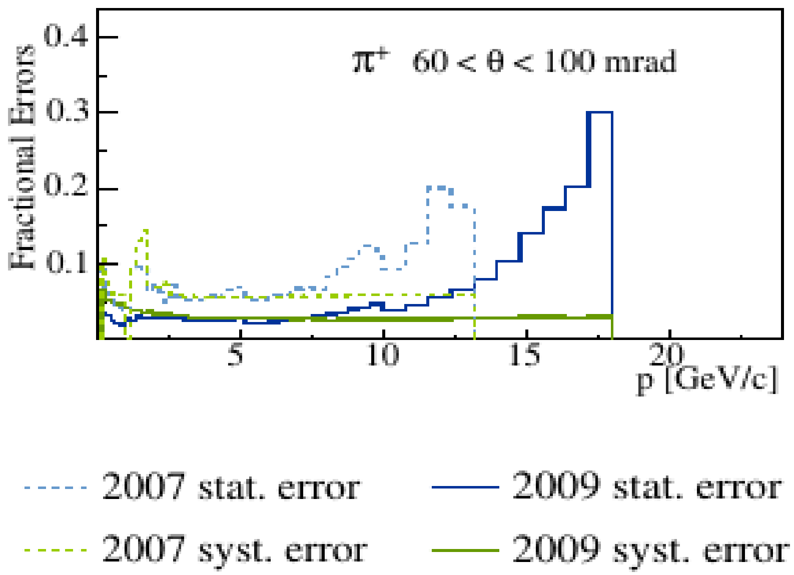
ToF for particle ID



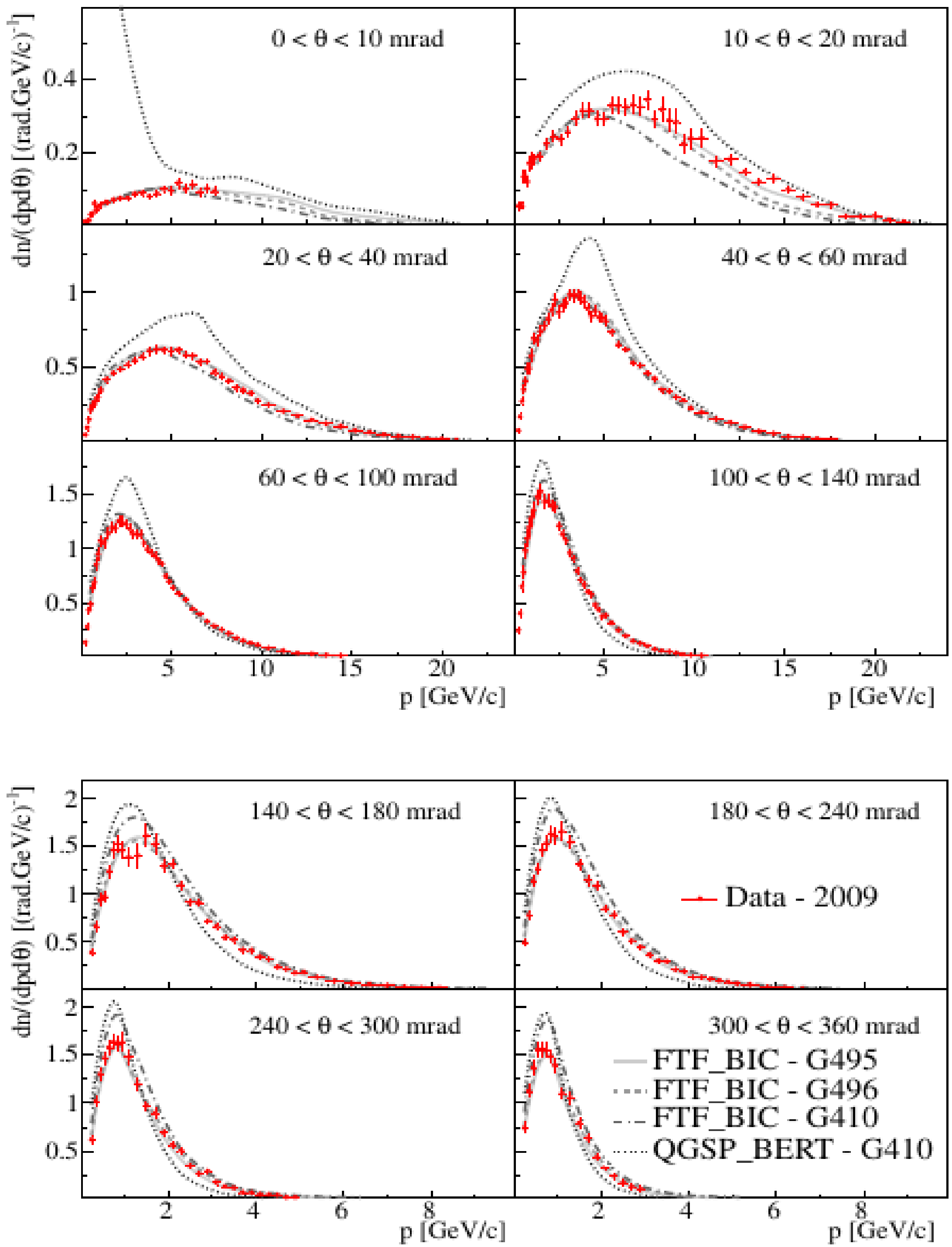
Results



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

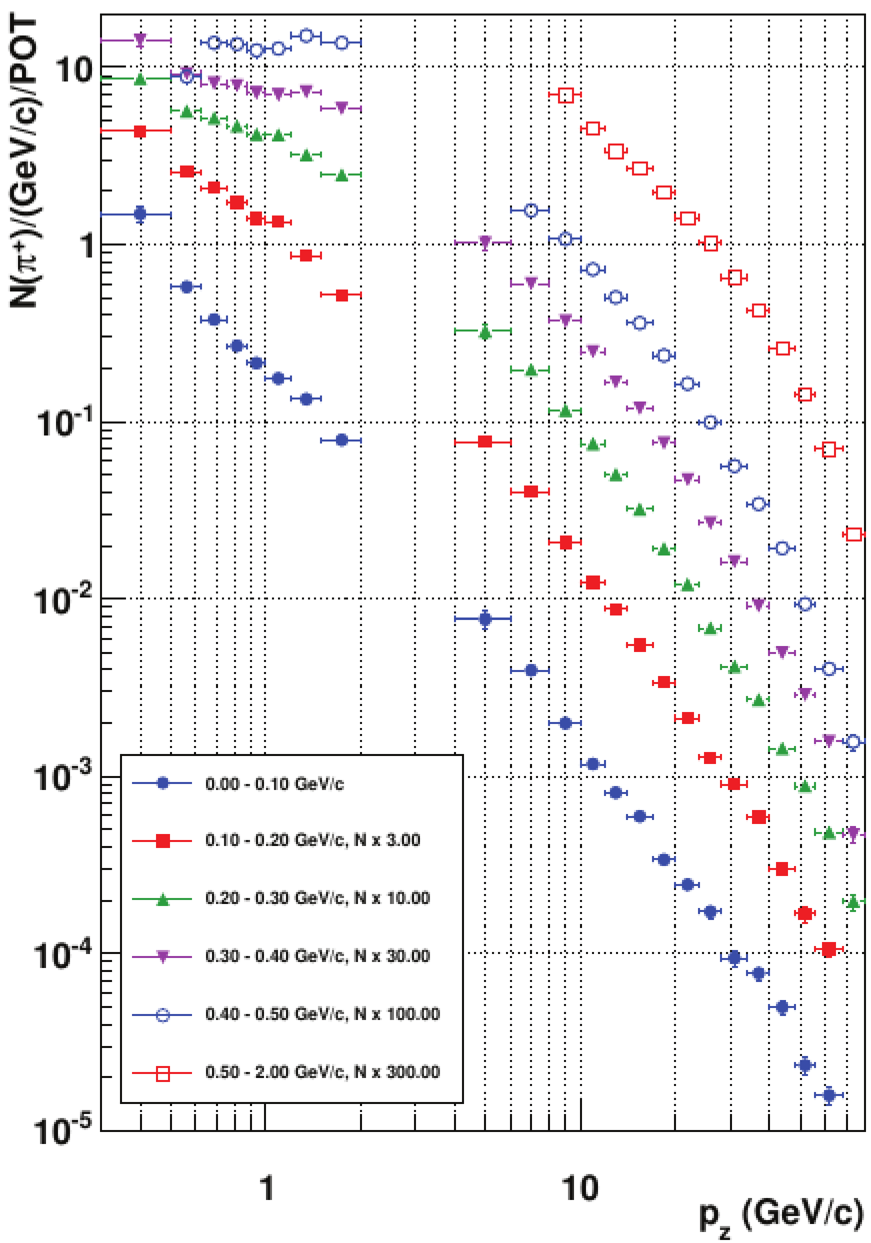


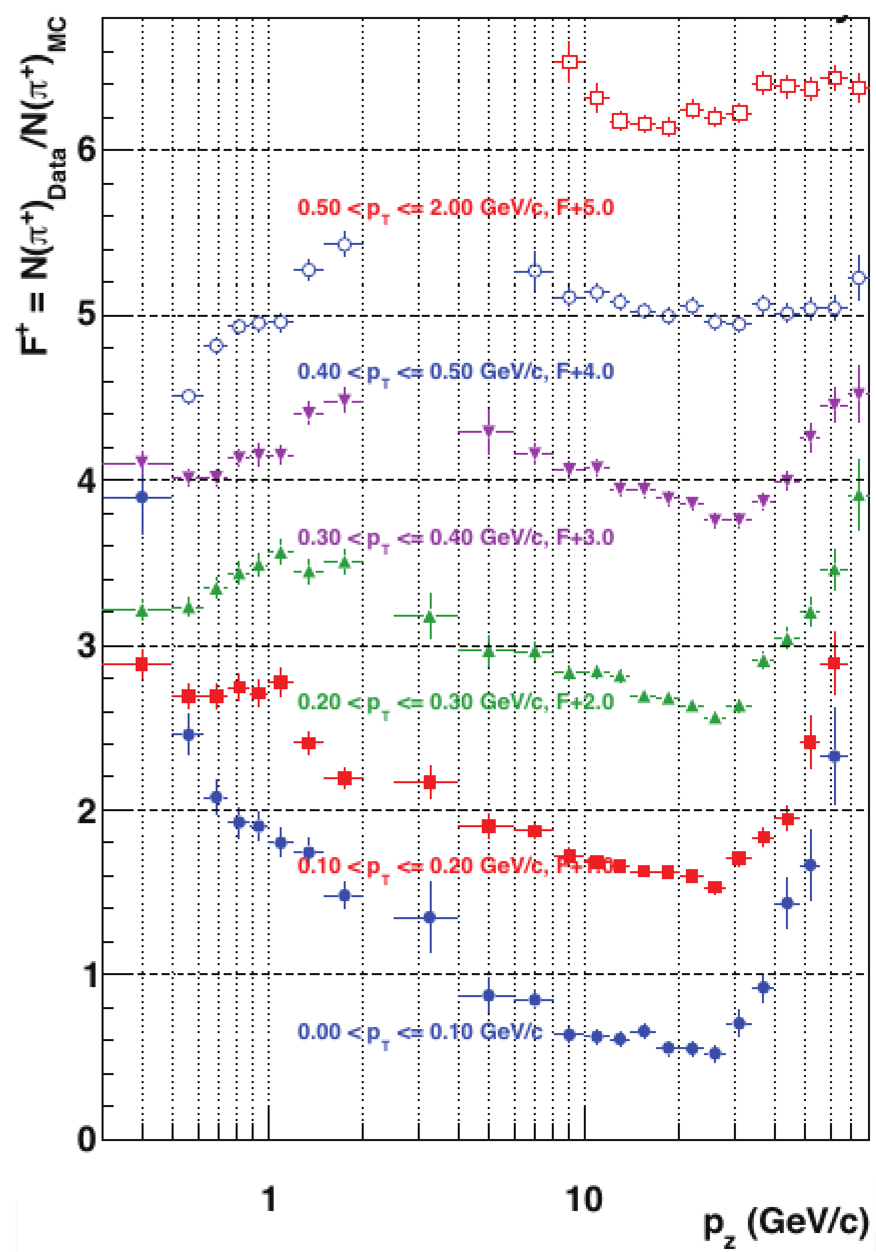
π⁺ 60 < θ < 100 mrad
Fractional Errors
p [GeV/c]
2007 stat. error
2009 stat. error
2007 syst. error
2009 syst. error



0 < θ < 10 mrad
10 < θ < 20 mrad
20 < θ < 40 mrad
40 < θ < 60 mrad
60 < θ < 100 mrad
100 < θ < 140 mrad
140 < θ < 180 mrad
180 < θ < 240 mrad
240 < θ < 300 mrad
300 < θ < 360 mrad
dn/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
Data - 2009
FTF_BIC - G495
FTF_BIC - G496
FTF_BIC - G410
QGSP_BERT - G410

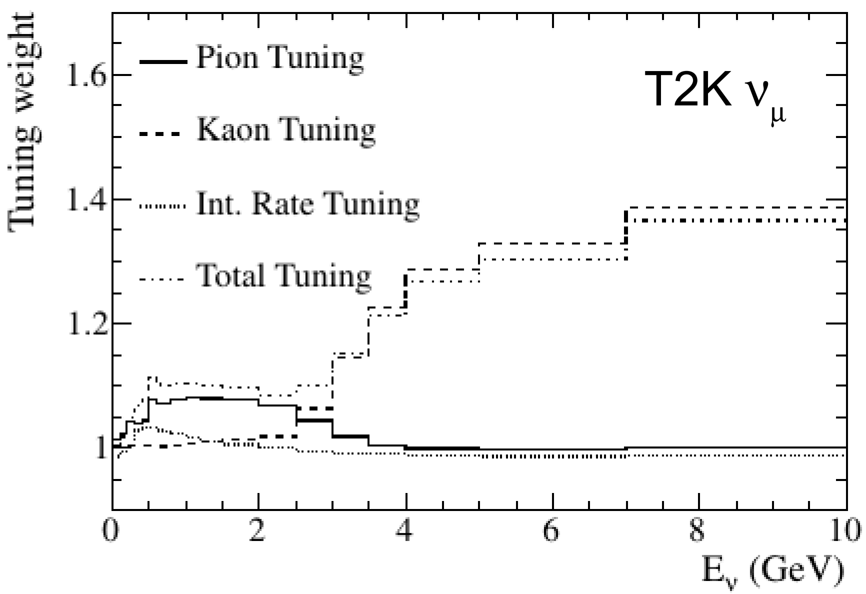
MIPP results for NuMI

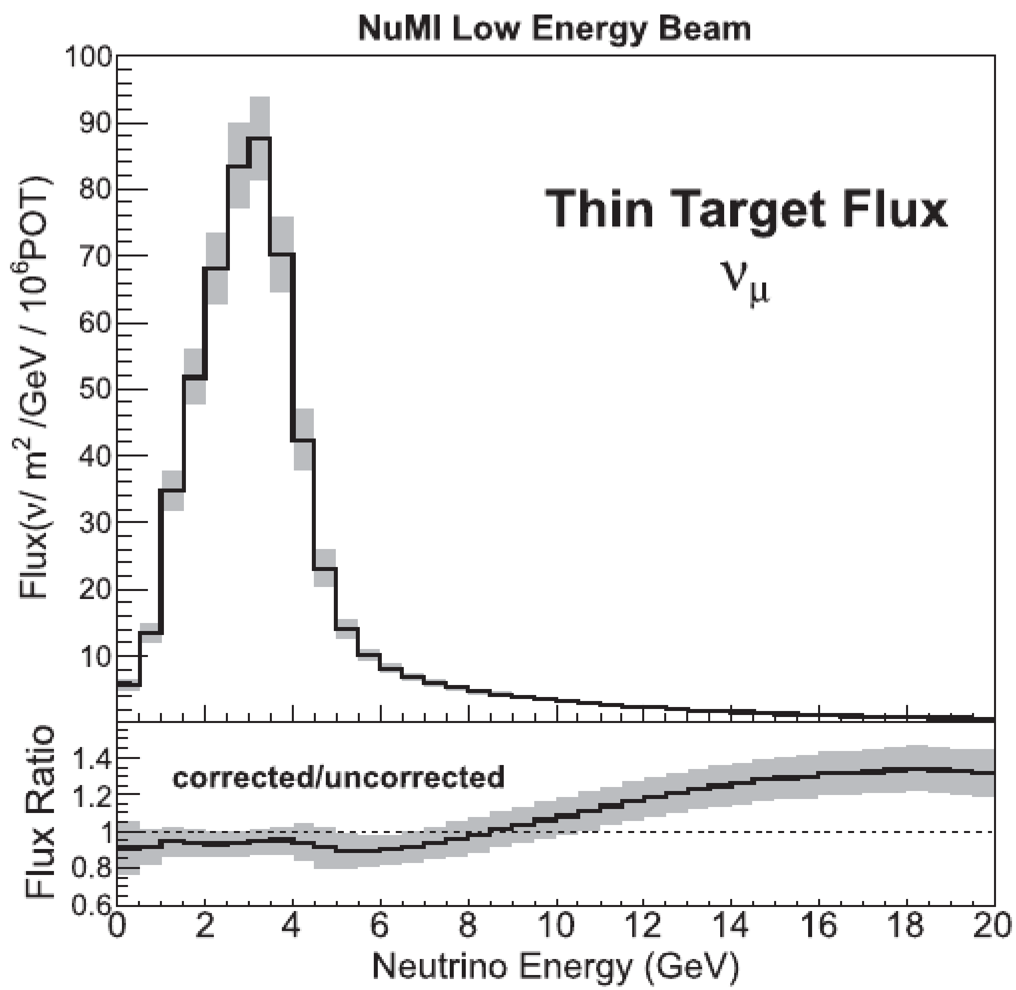




Tuning factors

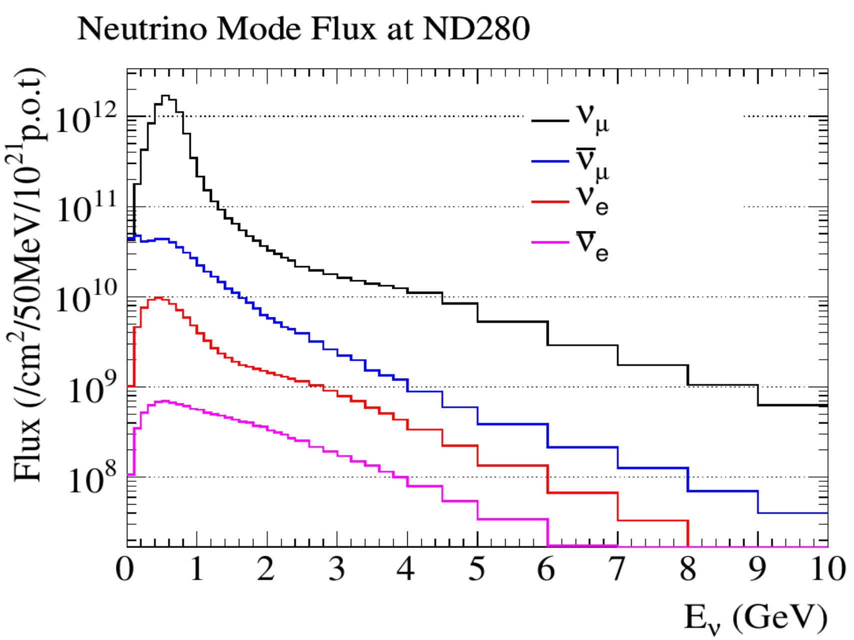
$$\frac{\text{flux tuned}}{\text{flux simulated}}$$

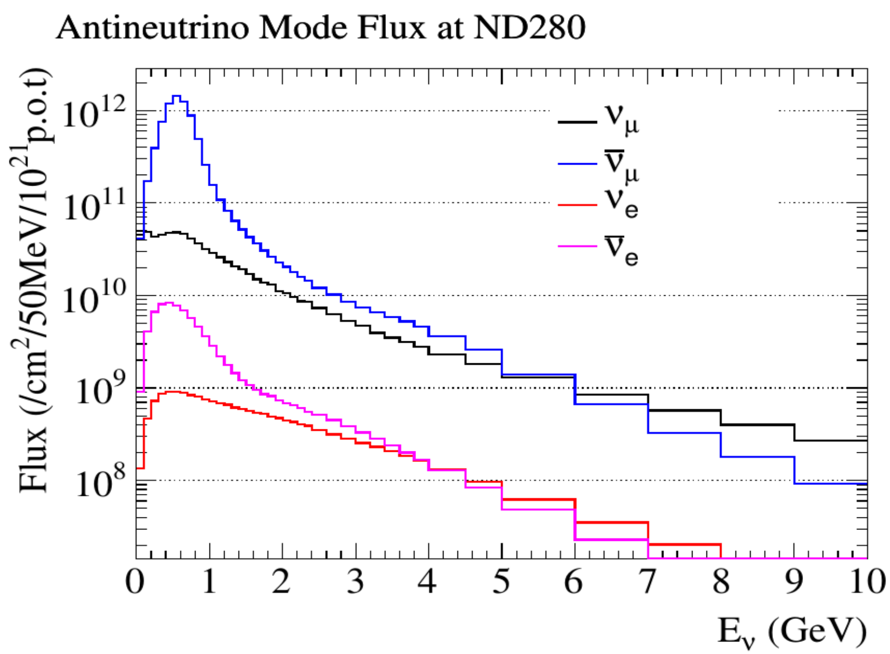


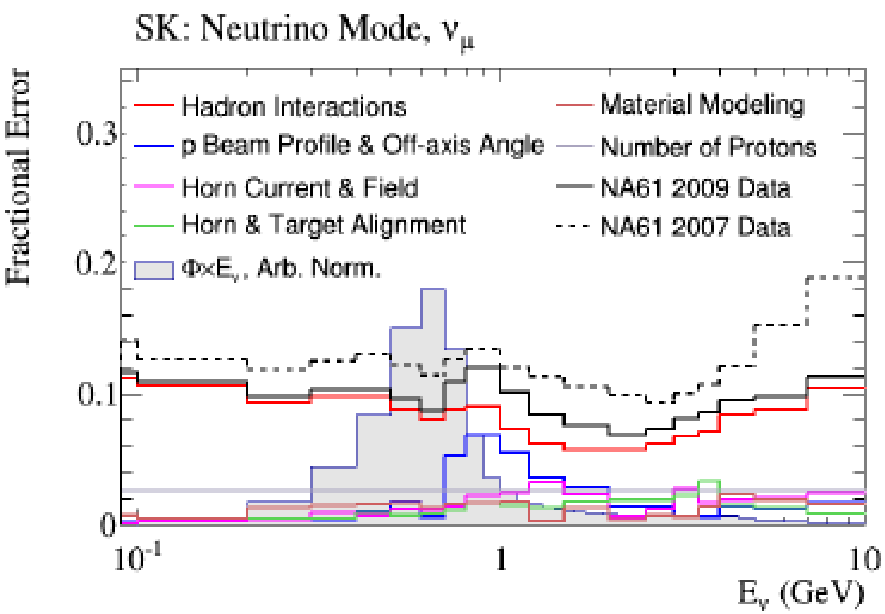


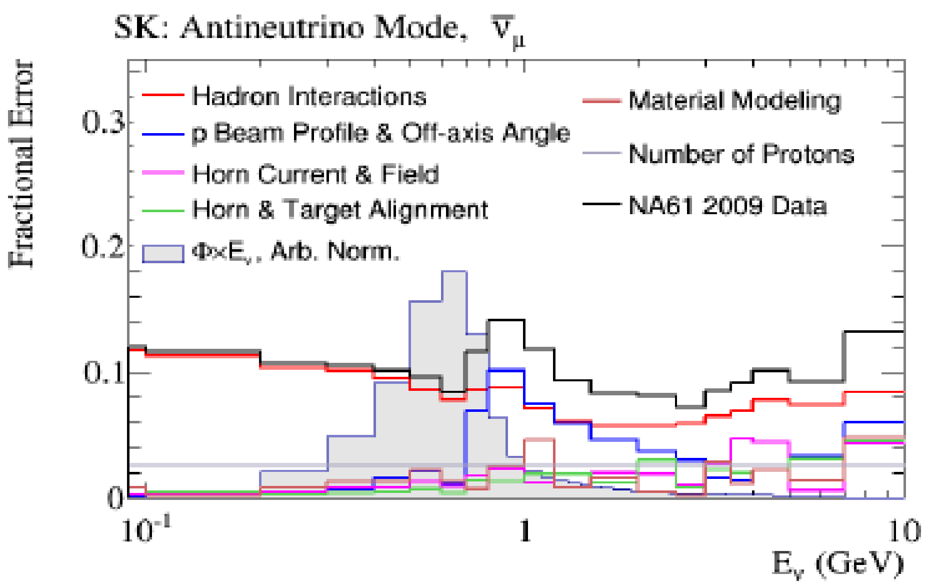
Uncertainties from theory corrections (scaling to different proton energies, targets, not covered phase space…) and from hadro-production data (statistics and systematics uncertainty)

Flux prediction and uncertainties



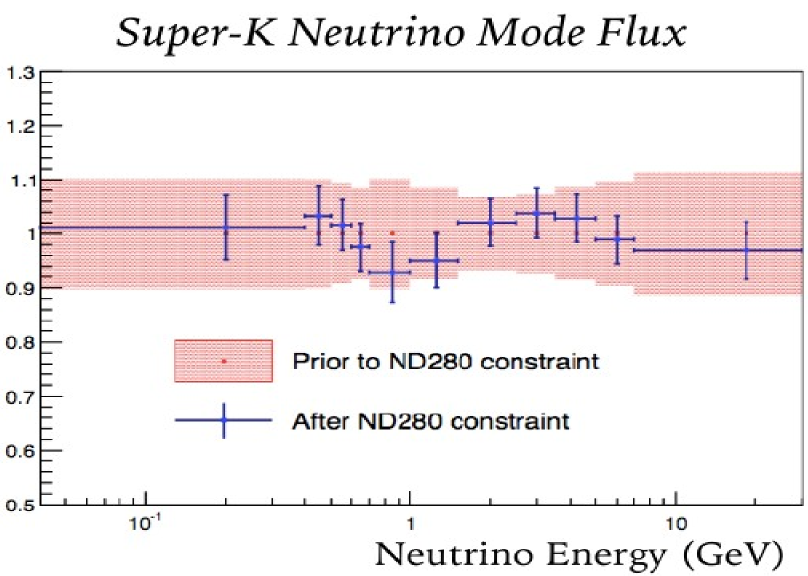


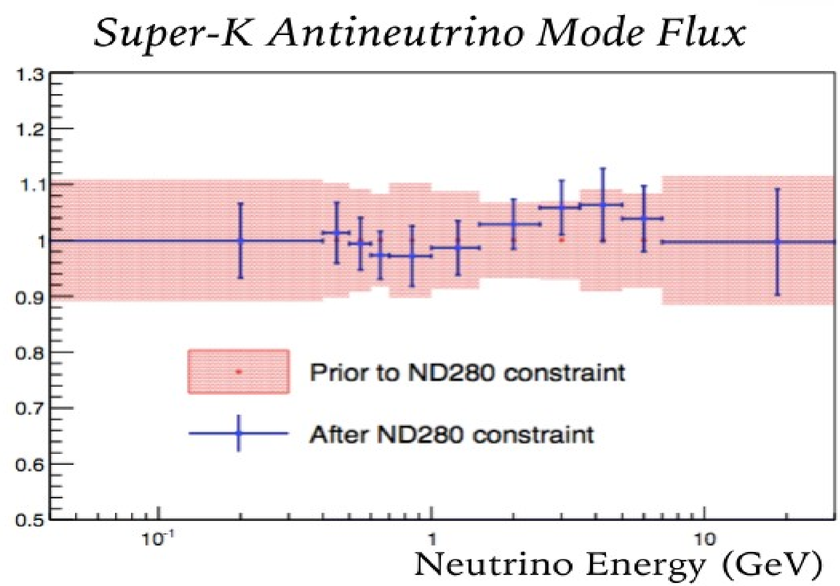




Flux constraint from the ND

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

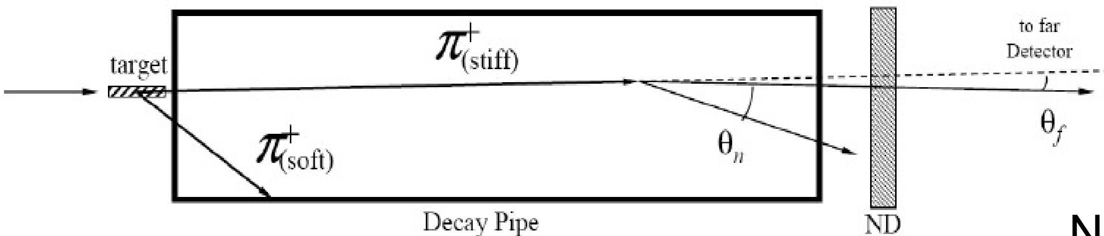
Flux+XSec (Pre ND280)	10.90%
Flux+XSec	2.90%
Flux	3.54%

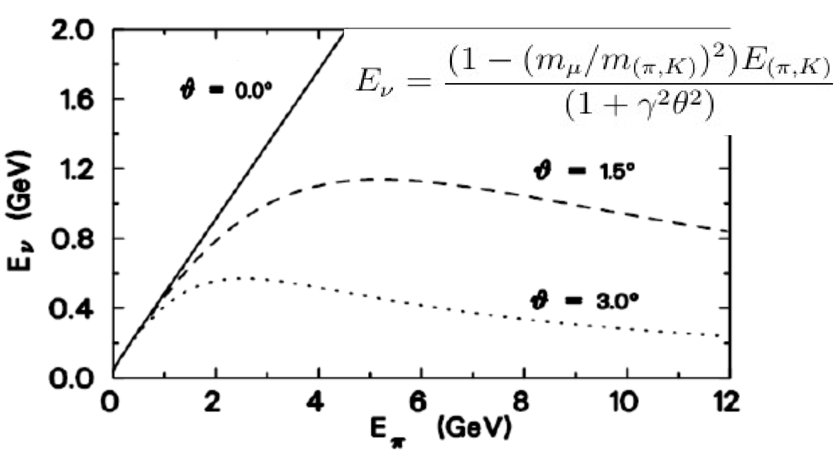
Strong anticorrelation between flux and cross-section
Today xsec uncertainties similar or larger than flux uncertainty

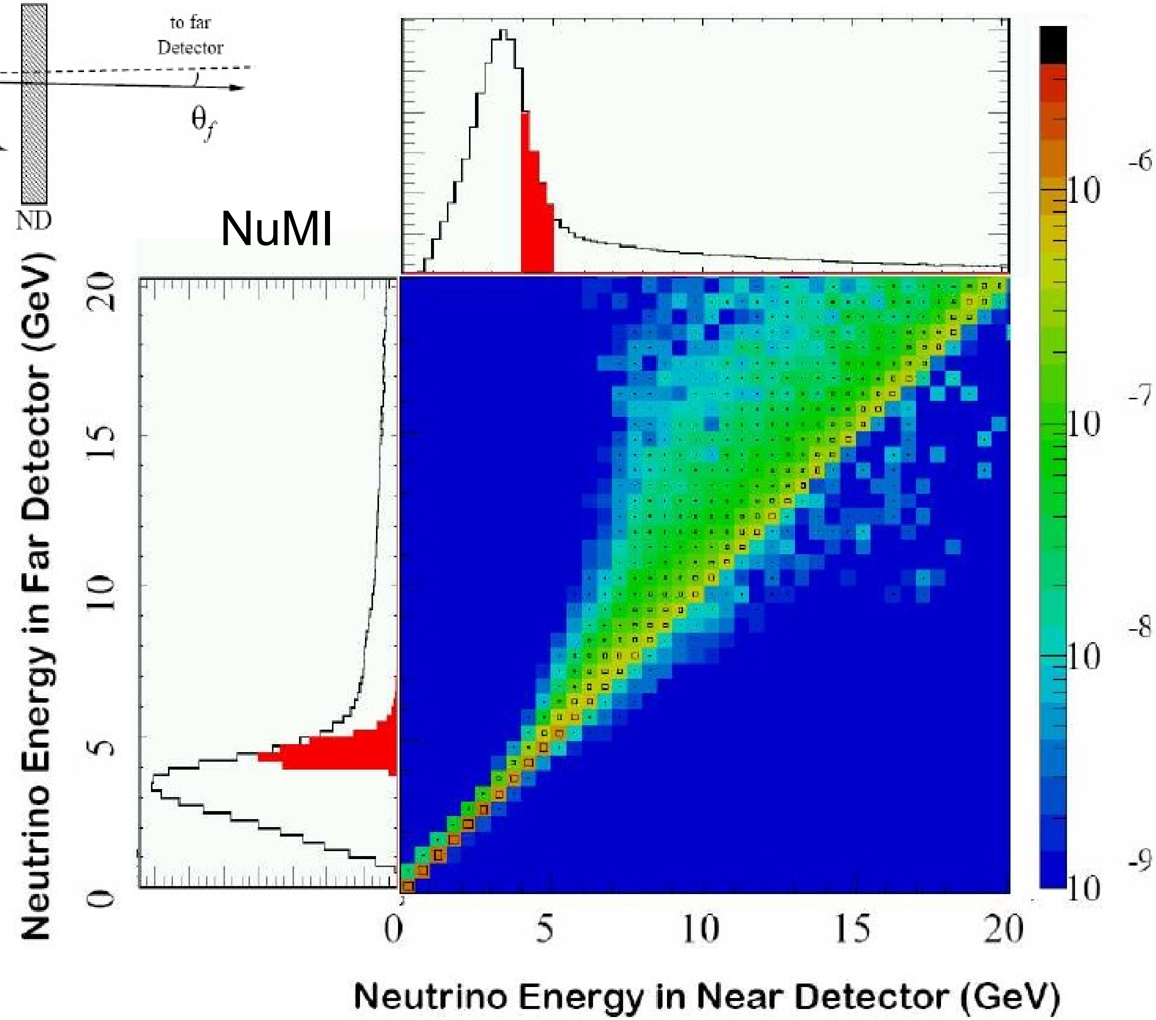
From ND to FD flux extrapolation

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

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



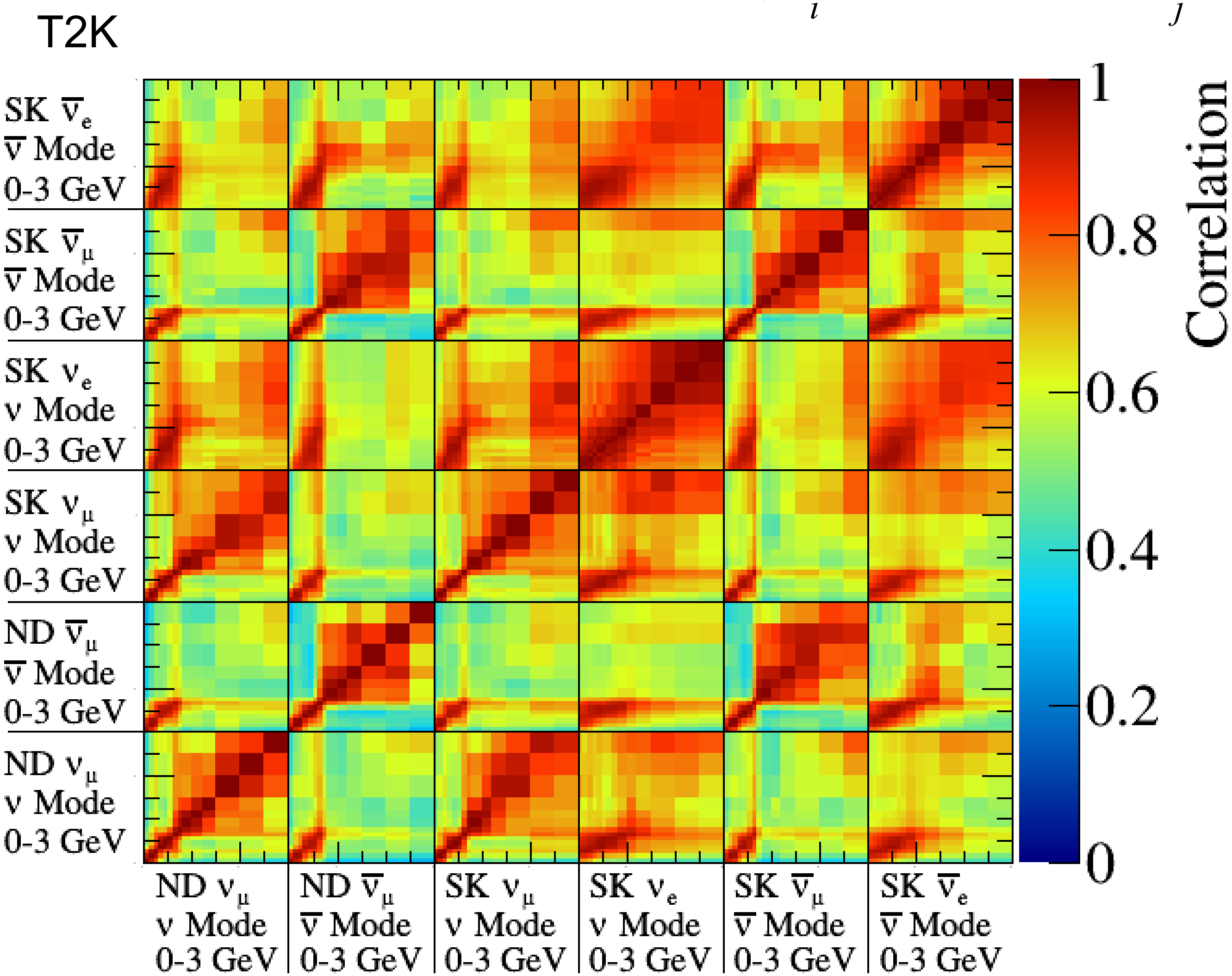




Extrapolation ND->FD uncertainties smaller (~1%) than overall flux uncertainties (10% → 5%)

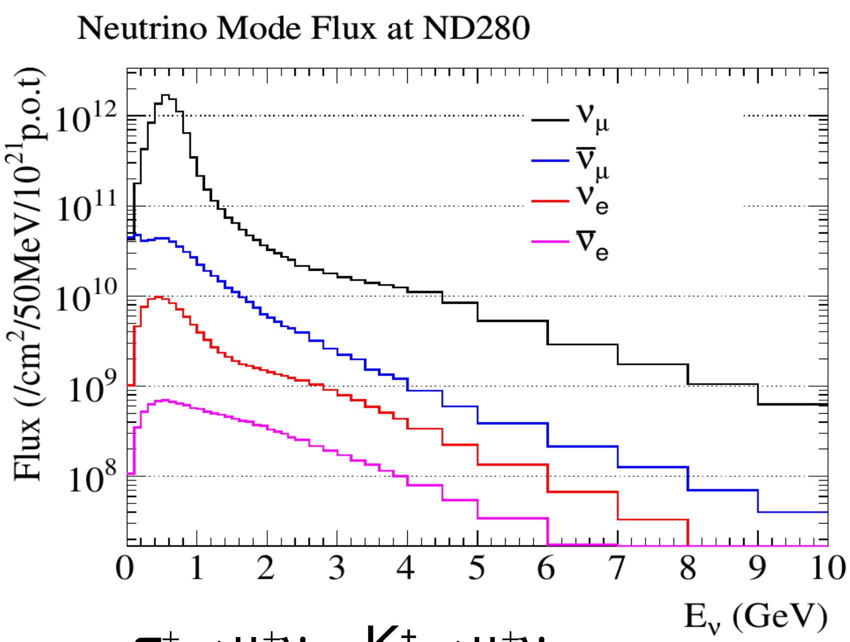
From ND to FD flux extrapolation

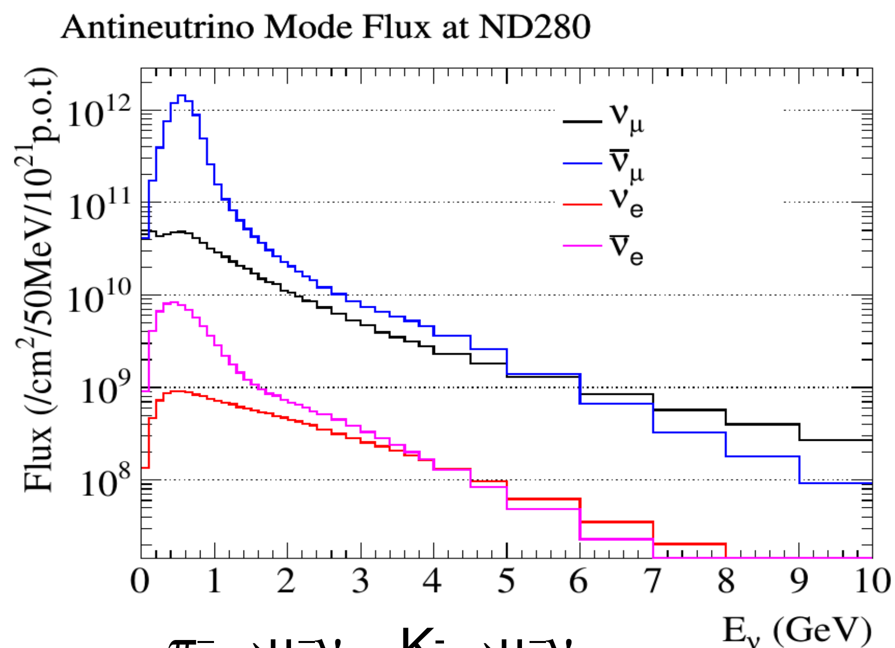
Flux Correlations $$\rho = \frac{\sigma^2_{cov.ij}}{\sigma_i \sigma_j} = \frac{\sum_{i,j} (f_i - \langle f_i \rangle)(f_j - \langle f_j \rangle)}{\sqrt{\sum_i (f_i - \langle f_i \rangle)^2 \sum_j (f_j - \langle f_j \rangle)^2}}$$



- **~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

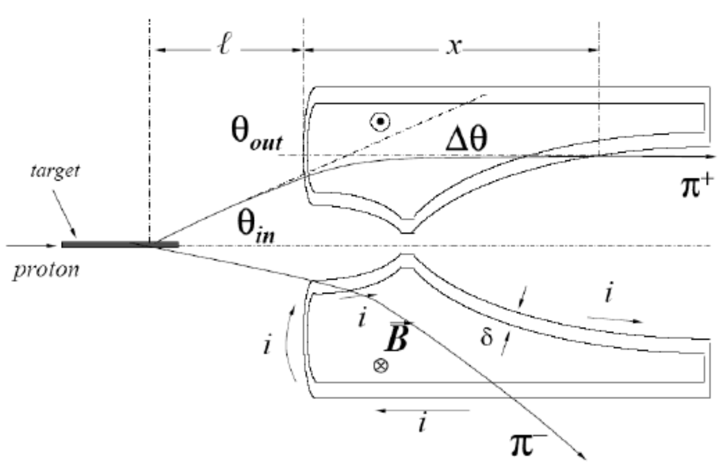
BACK-UP

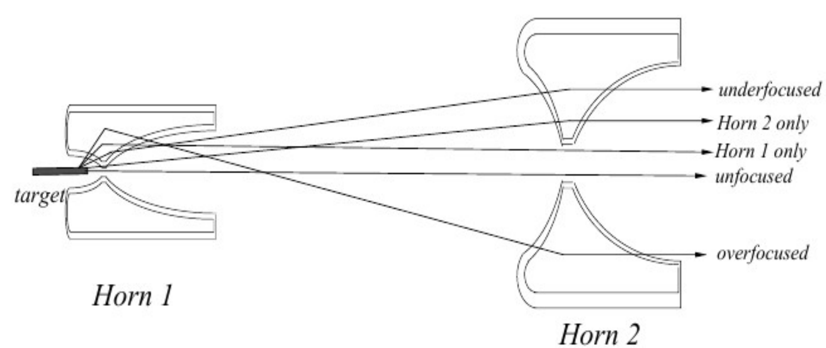


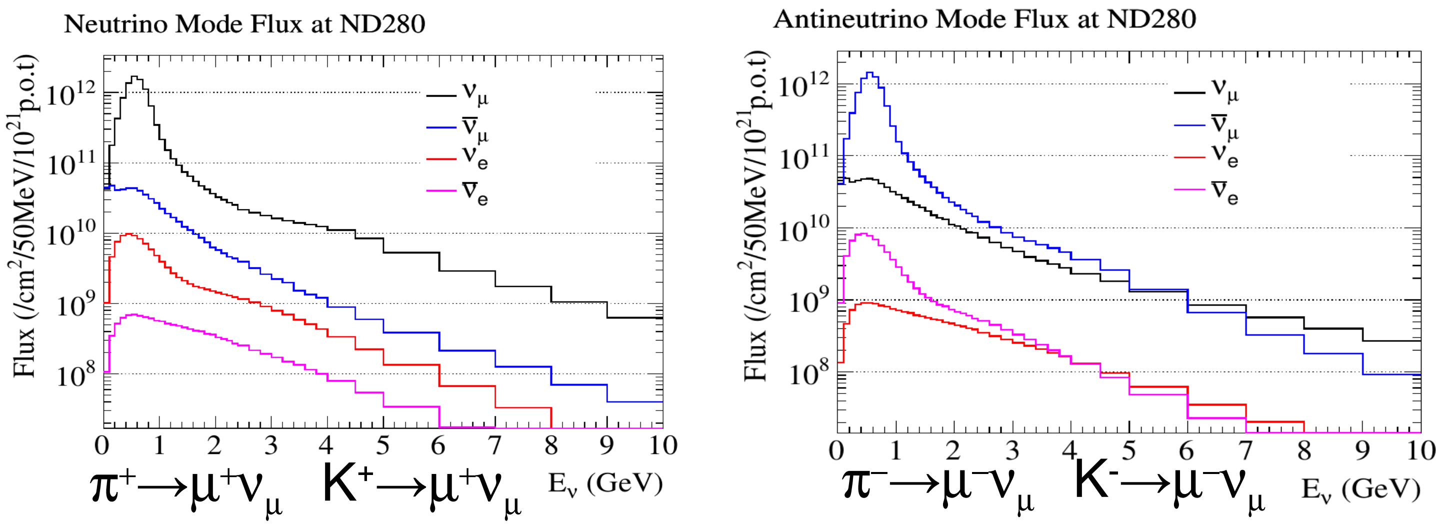


$\pi^+ \to \mu^+ \nu_\mu$ $K^+ \to \mu^+ \nu_\mu$ $\pi^- \to \mu^- \nu_\mu$ $K^- \to \mu^- \nu_\mu$

The 'wrong sign' background comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns







When proton hits the target it is more probable to create positive charged hadrons than negative ones