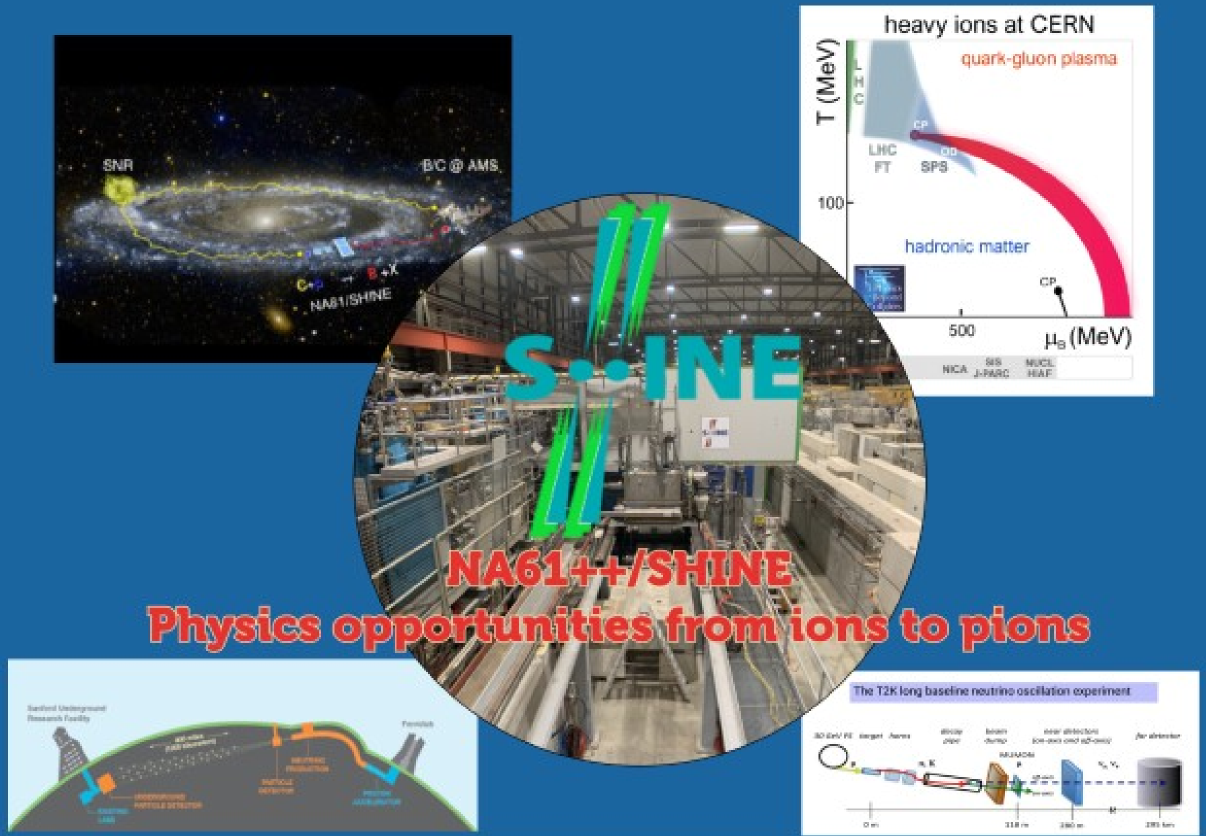


NA61++/SHINE: Physics opportunities from ions to pions

Neutrino long baseline physics: general considerations

December 15-17, 2022, CERN

S.Bolognesi (CEA, IRFU)

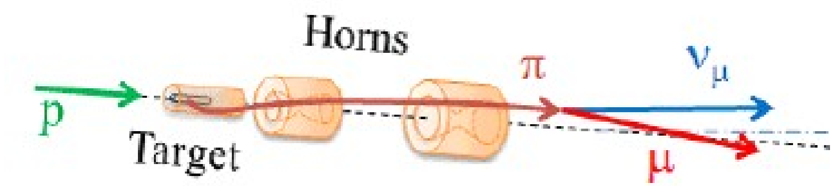
INTRODUCTION:

- Beamlines and fluxes of present and future LBL experiments

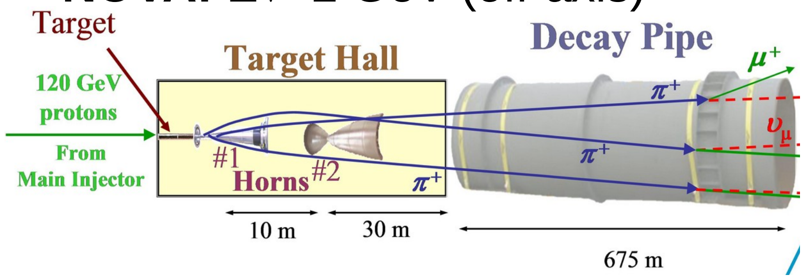
- **Lesson learned** from present generation of LBL and hadro-production experiments

Accelerator experiments

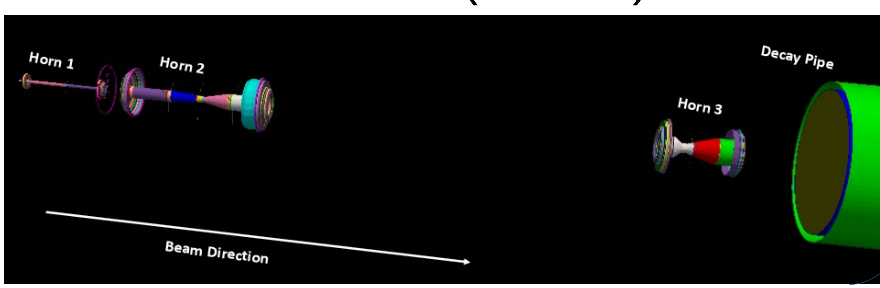
T2K and HK: Eν~600 MeV (off-axis)



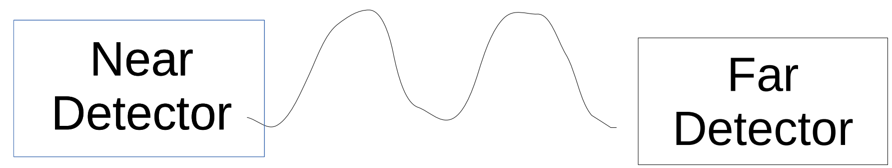
NOVA: Eν~2 GeV (off-axis)



DUNE: ~0.4-4 GeV (on-axis)



neutrino oscillations



$\phi(E_\nu)\times\sigma(E_\nu)$

$\phi(E_\nu)\times\sigma(E_\nu)\times P_{osc}(E_\nu)$

- Different proton energy (30 GeV, 120 GeV)

- Different focusing of hadrons

- Different on/off-axis angle (selection of most relevant hadrons)

→ different neutrino energy flux at Near Detectors

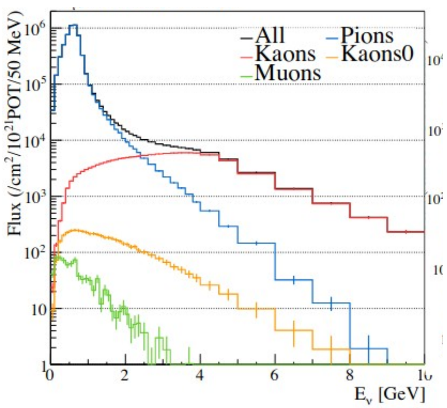
- Different baseline length → different oscillated neutrino energy spectrum

Despite all these differences: general common needs for hadroproduction tuning: the topic of this talk

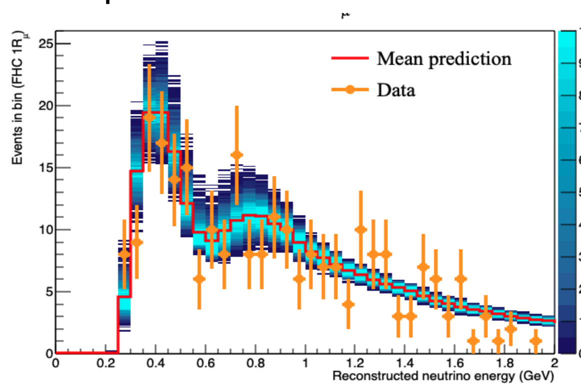
Accelerator experiments: nm fluxes and spectra

T2K: ~600 MeV

Flux before oscillations

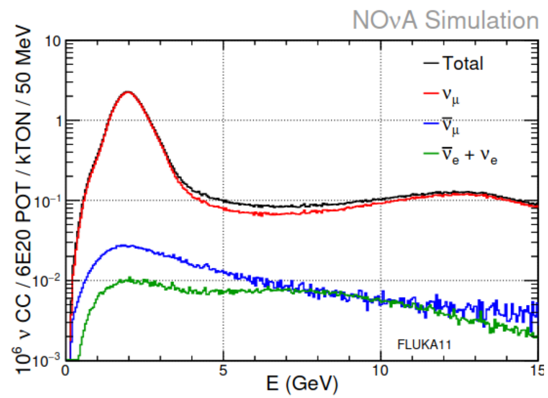


Spectrum after oscillation

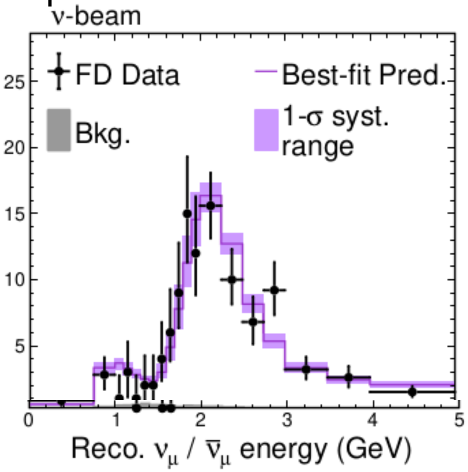


NOVA: ~2 GeV

Flux before oscillations



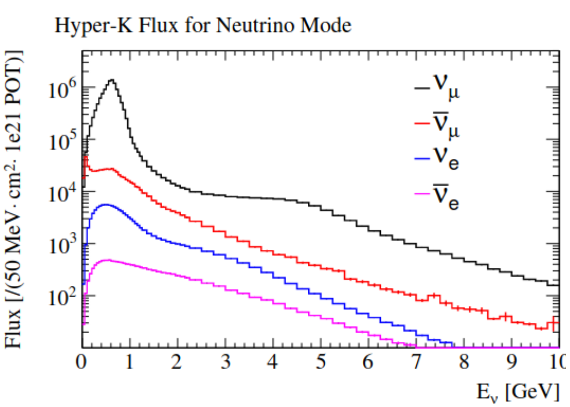
Spectrum after oscillation



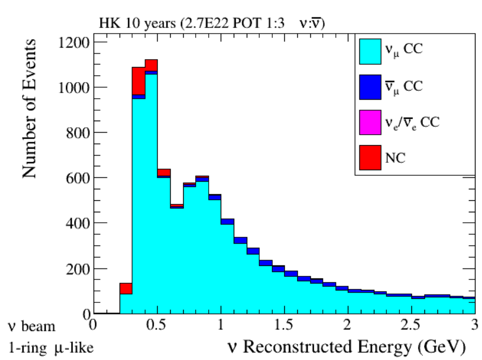
DUNE: ~0.4-4 GeV

HK: ~600 MeV (slightly higher horn current than T2K)

Flux before oscillations

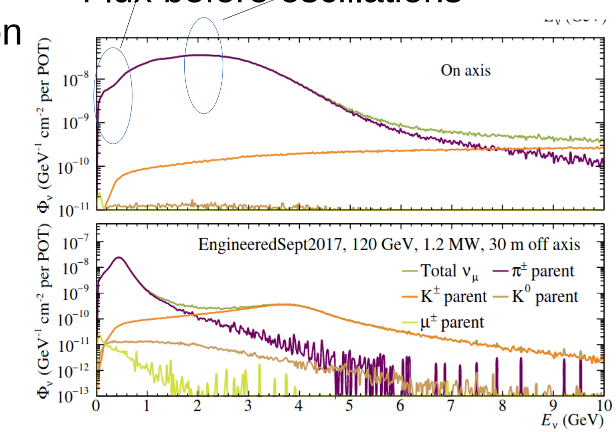


Spectrum after oscillation

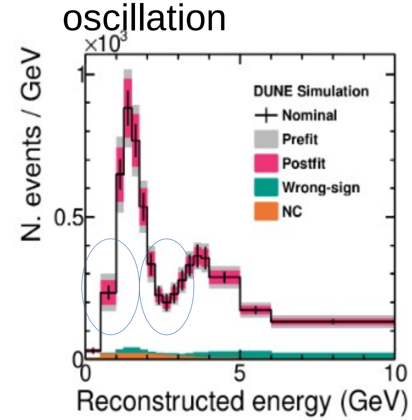


Second (~0.8GeV) and first (~2.5GeV) oscillations maxima

Flux before oscillations

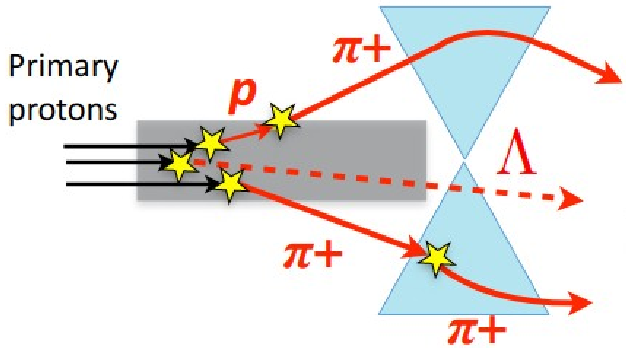


Spectrum after oscillation



Flux tuning

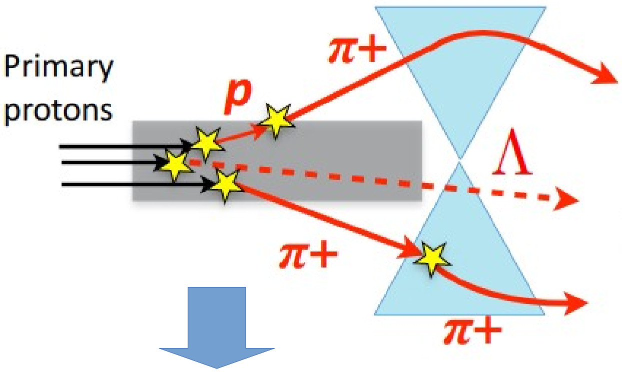
Yoshikazu Nagai
WANP 2022 @Nagoya, Japan



	Interaction length tune σ_{prod}(p+C) to NA61 measurement	**Multiplicity** Mostly 30 GeV p+C data by NA61
At interaction	"Vertex" weight $\sigma_{\mathrm{DATA}}/\sigma_{\mathrm{MC}}$	$\left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{DATA}} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{MC}}$ p, θ: outgoing particle kinematics
For distance L traversed in matter	"Attenuation" weight $e^{-(\sigma_{\mathrm{DATA}}-\sigma_{\mathrm{MC}})\rho L}$	N.A.

Flux tuning

Yoshikazu Nagai
WANP 2022 @Nagoya, Japan



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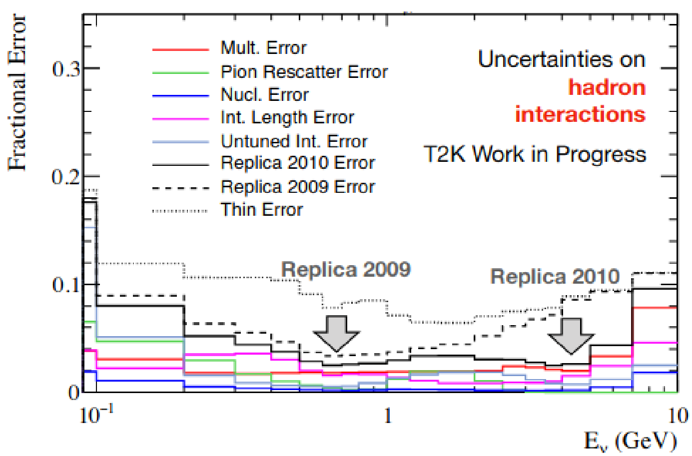
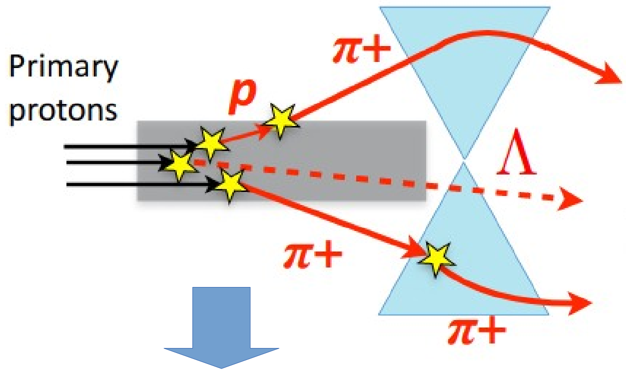
Error on $\phi(E_\nu)$



Flux tuning

Yoshikazu Nagai
WANP 2022 @Nagoya, Japan



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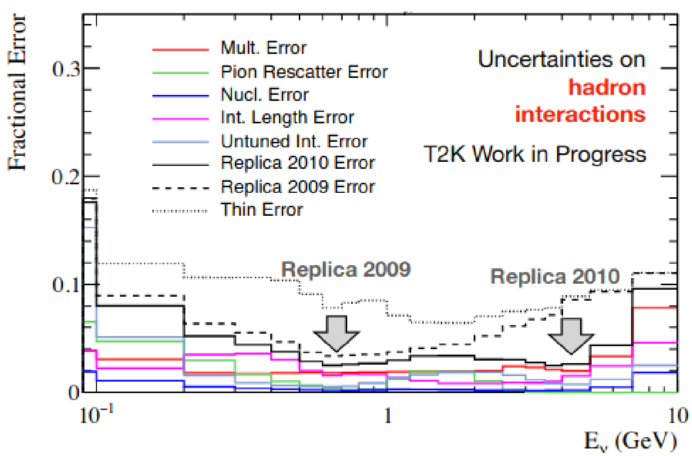
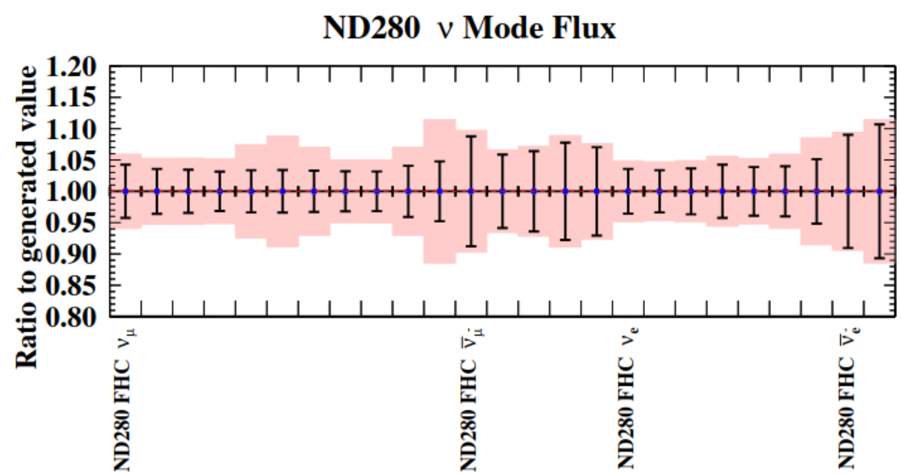
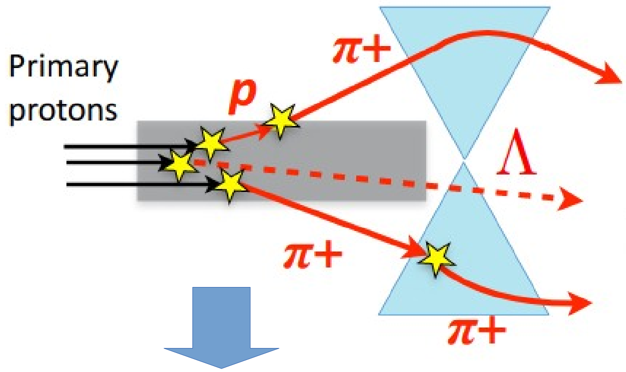


Fit of ND data : $N_{\nu_\alpha}^{ND}(E_\nu) = \phi(E_\nu)\times\sigma(E_\nu)\,dE_\nu$



Flux tuning

Yoshikazu Nagai
WANP 2022 @Nagoya, Japan



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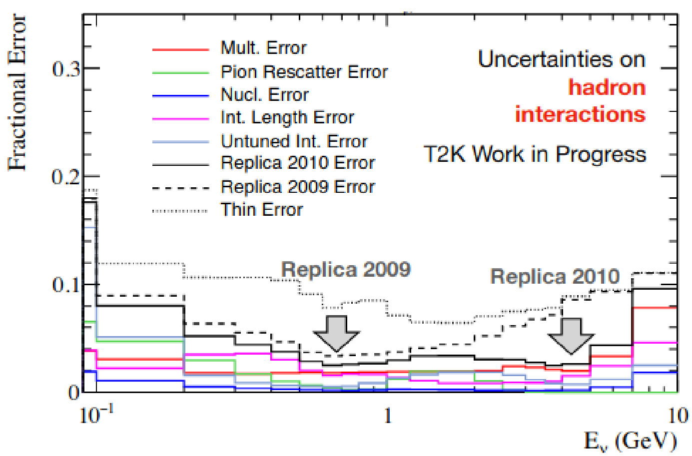
Error on $\phi(E_\nu)$



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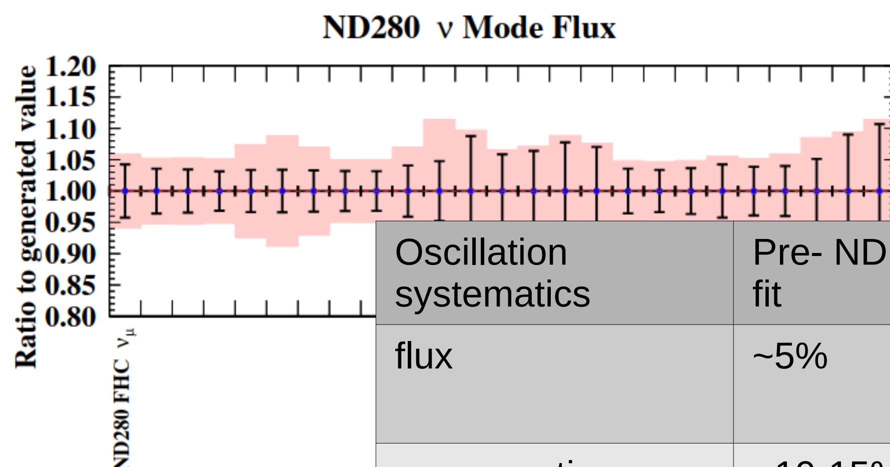


Oscillation systematics	Pre- ND fit	Post- ND fit
flux	~5%	~2.8-3.0%
cross-section	~10-15%	~3.5-3.8%
flux+xsec		~2.6-2.8%
Total (+ xsec not accessible at ND, SK detector)	~17%	~3.5-5%

- Today xsec uncertainties dominate before the fit
- strong anticorrelation between flux and xsec (would be 5-10% if uncorrelated)
- flux*xsec constitutes ~50% of the final systematic error budget

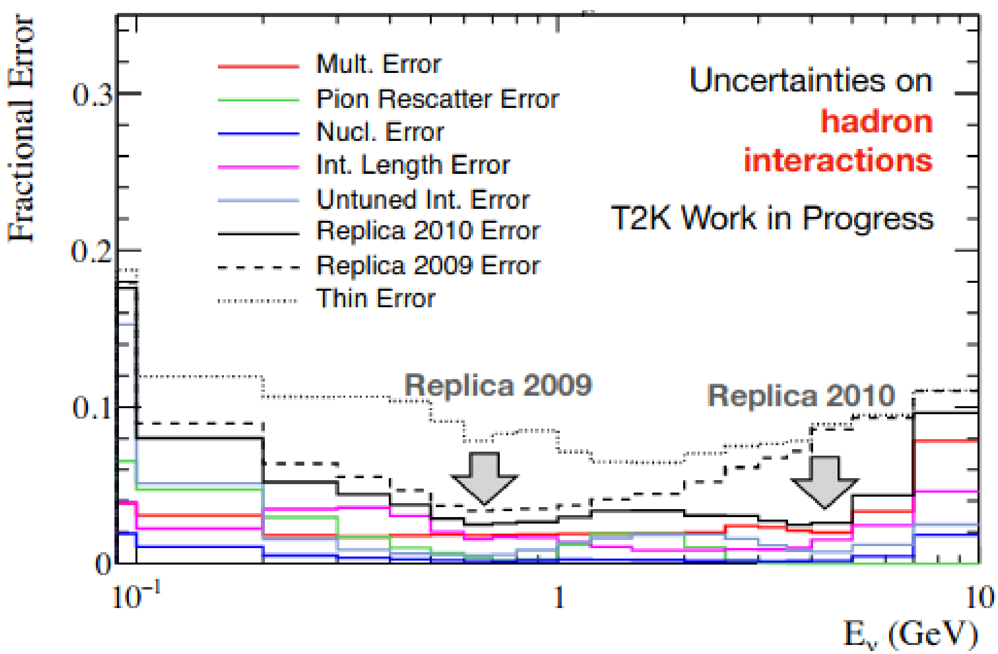
Lessons learned

- **First order:** pC→ π, K multiplicity and kinematics

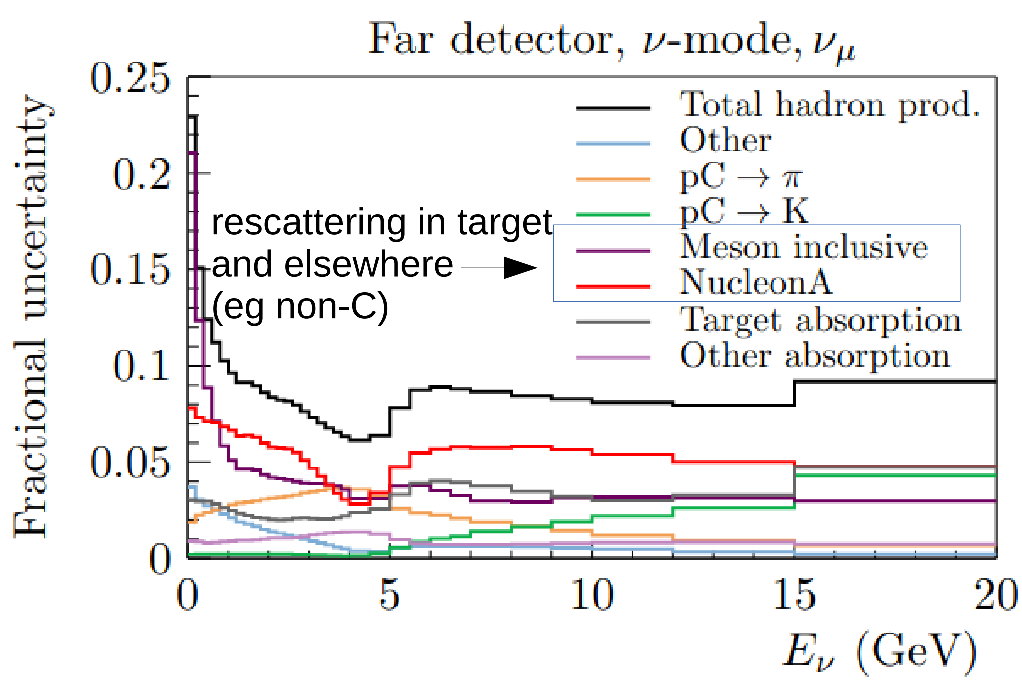
- With **replica target:** able to tune also re-interactions in target + minimize the impact of total proton cross-section uncertainty
(important to define exactly what do we measure for proton xsec: see Y.Nagai@WAMP)

- **Next:** re-interactions in the other elements of the beamline (not C) + hadrons outside the present NA61 acceptance

T2K (with intensive tuning from NA61 data-taking!)



Example for next LBL (DUNE): clear need of measurements on replica of future targets



FUTURE NEEDS:

- Precision prospects for future LBL generation

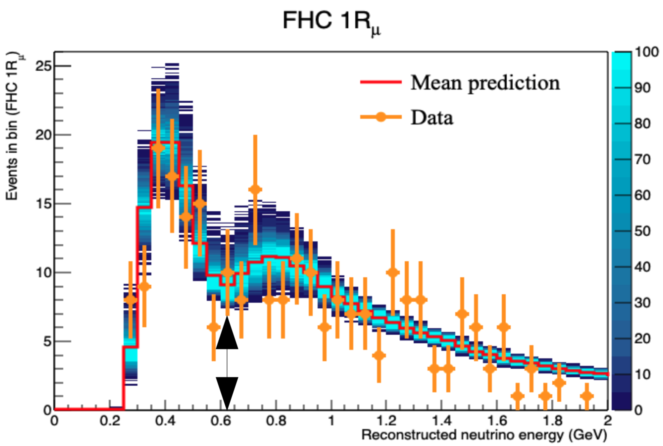
→ Implication on precision for hadro-production measurements

Very rough evaluation!
Detailed studies for next generation LBL on-going ...

ν_μ disappearance: $\sin^2\theta_{23}$

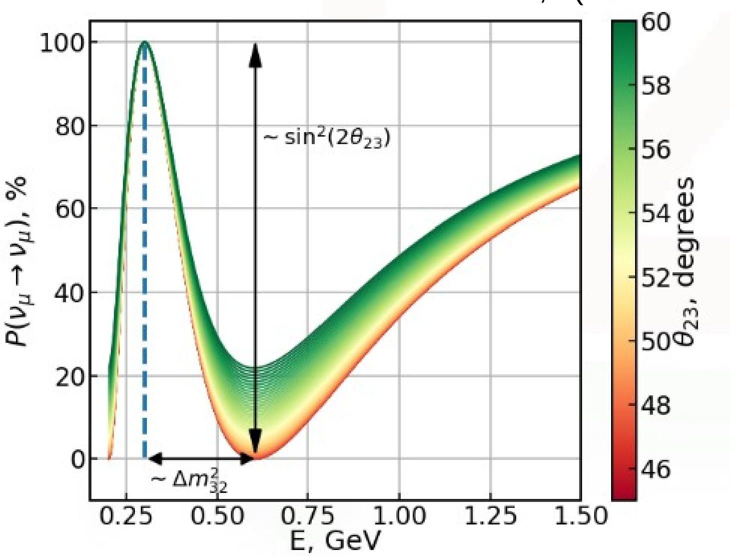
$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2\left(\underbrace{1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}}_{\text{frequency}}\right)$$

(simplified 2-flavors approximation)



- **$\sin^2 2\theta_{23}$ ~ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance (neutrino rate normalization)**

Full 3-flavour formula at T2K E,L (D.Carabadjac)



Best global fit (NH)
NuFit 5.1

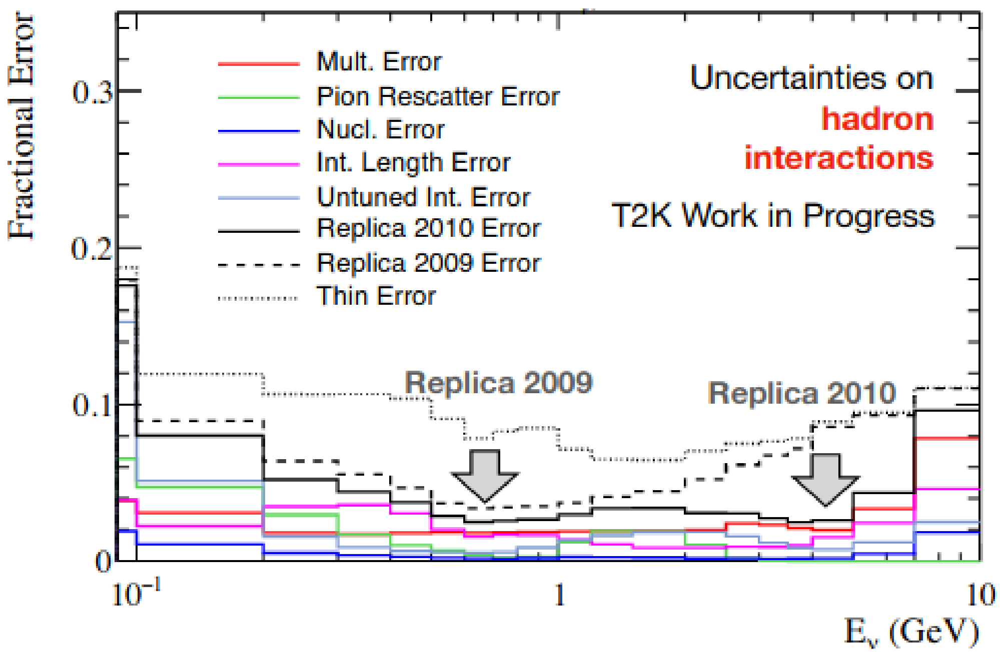
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$
$\theta_{23}/°$	$42.1^{+1.1}_{-0.9}$

Control of overall neutrino rate (flux normalization before oscillation):
for 1 degree precision → few % on normalization

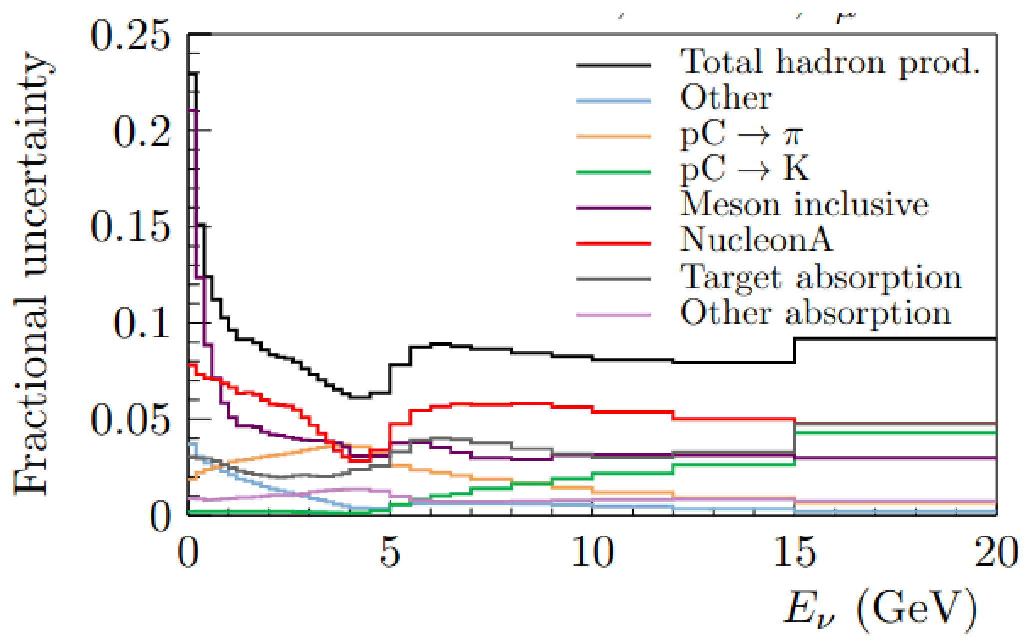
Prospects

Prospects for DUNE and HK: factor 2-3 better $\sin^2\theta_{23}$ measurement than today for each single experiment → **need control at ~<1% on flux normalization**

T2K (as an example for HK)



DUNE



A systematics with leading impact on total flux rate is the total proton cross-section (aka interaction length): today ~2%

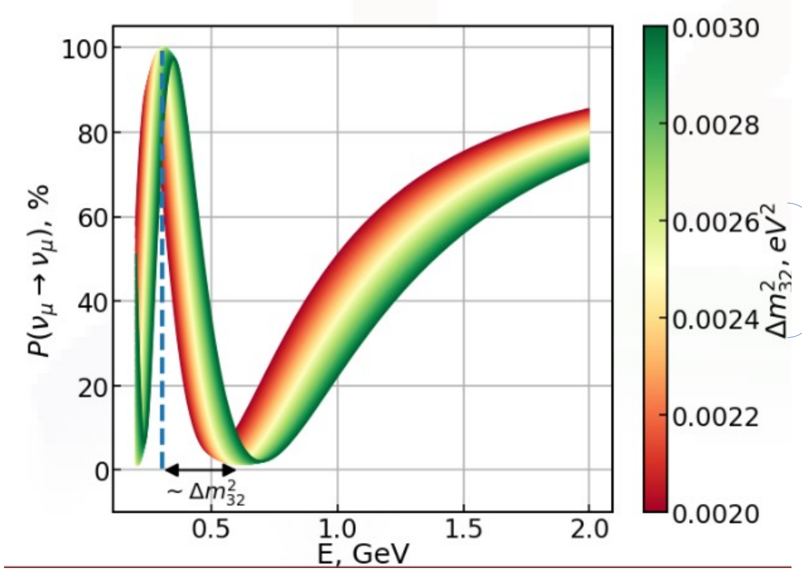
ν_μ disappearance: $|\Delta m^2_{32}|$

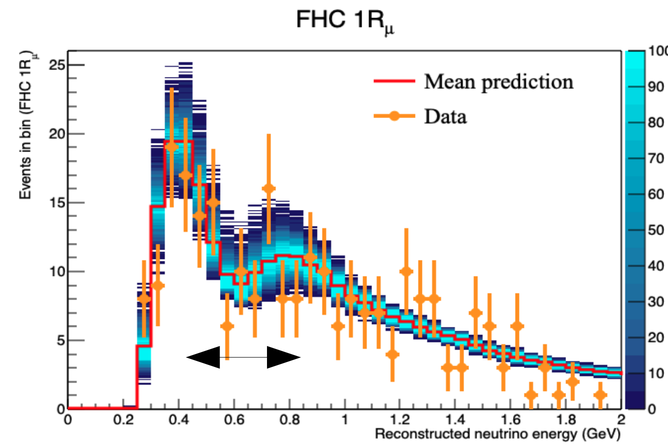
$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2\left(\underbrace{1.27\frac{\Delta m^2_{ji}[\text{eV}^2]L[\text{km}]}{E_\nu[\text{GeV}]}}_{\text{frequency}}\right)$$

(simplified 2-flavors approximation)

- **$\Delta m^2_{31(32)}$ ~ frequency of the disappearance (neutrino spectral shape)**

Full 3-flavour formula at T2K E,L (D.Carabadjac)





	Best fit (NH)	3σ range
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$

(NuFit 5.1)

Today ~2% by each experiment → 1% in joint fit
(IMHO, very fragile against systematics)

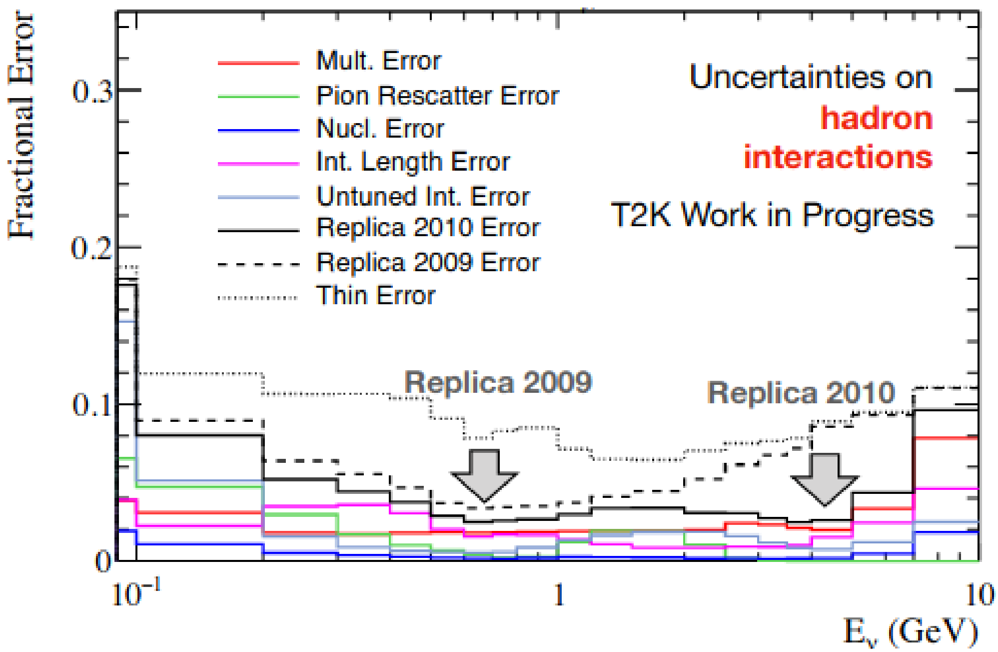
- Need control on neutrino energy: avoid bias in energy scale + precise flux peak/shape before oscillation + precise treatment of nuclear effects like binding energy

Roughly linear: relative Eν precision ~ relative **Δm²** error (eg, few MeV at T2K for 2% on **Δm²**)

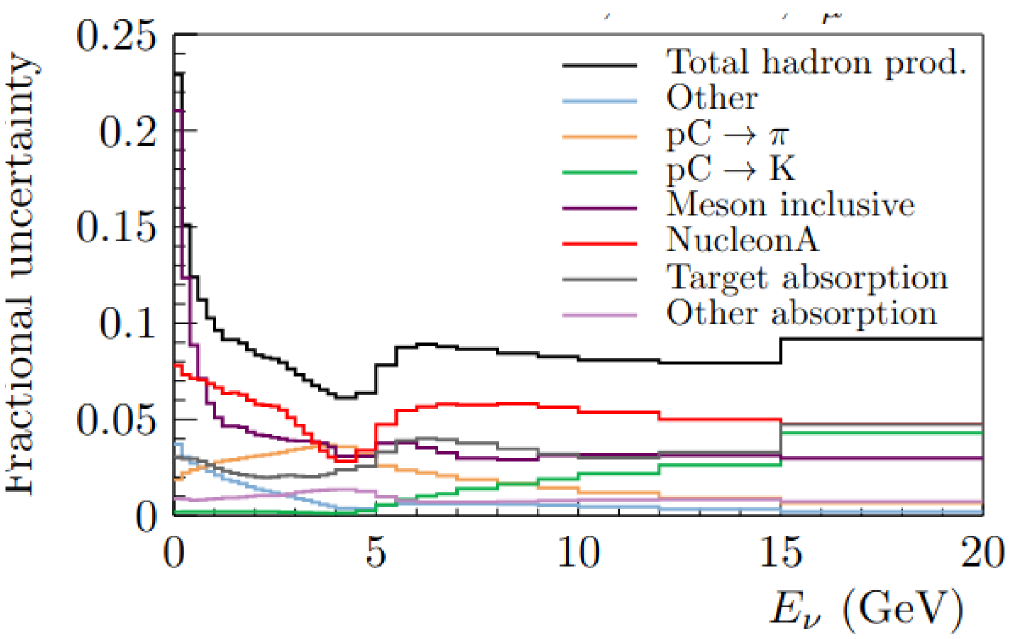
Prospects

Prospects for DUNE and HK: for each single experiment factor 2-3 better **Δm²** measurement then global fit today → **control at ~<0.5% on "energy scale"**

T2K (as an example for HK)



DUNE

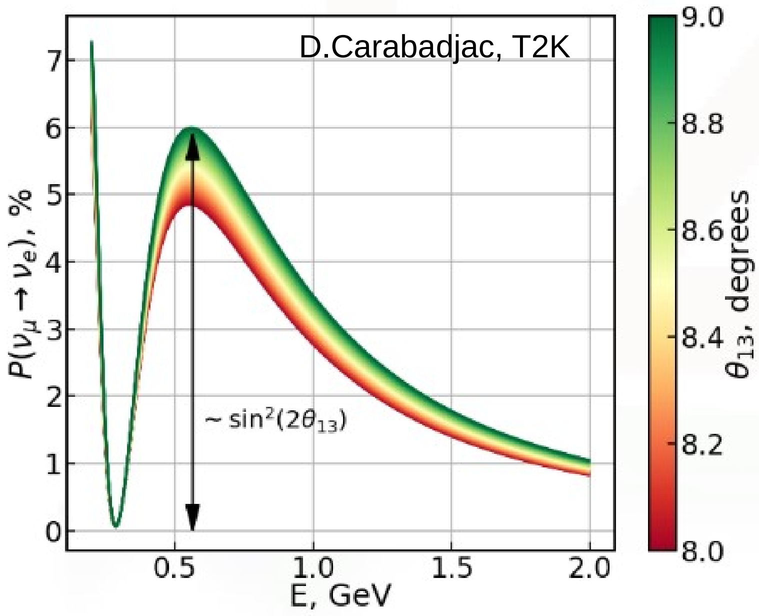


Most challenging systematics on flux shape comes from hadron rescattering error and untuned interactions (outside NA61 phase space)

Thanks to replica target in T2K: ~ 30% reinteractions in target now under control → still 10% of re-interactions in beamline. New measurements on other target material

ν_e appearance: θ_{23} octant

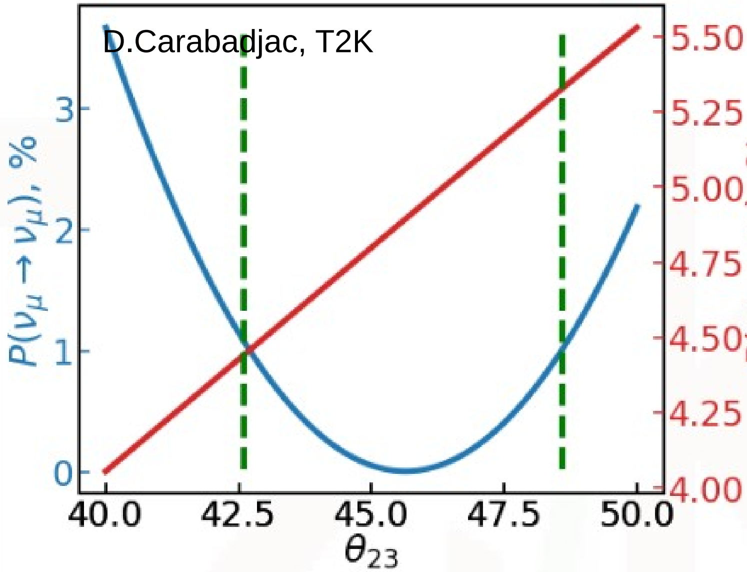
Full 3-flavour formula at T2K E,L (D.Carabadjac)

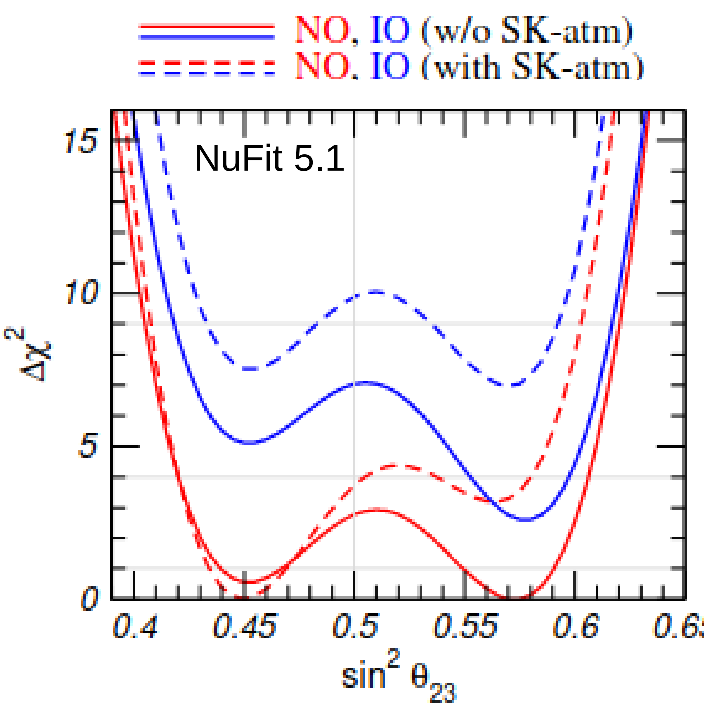


$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

- Dominated by large uncertainty on θ_{23}, since $\boldsymbol{\theta_{13}}$ well measured by reactor experiments

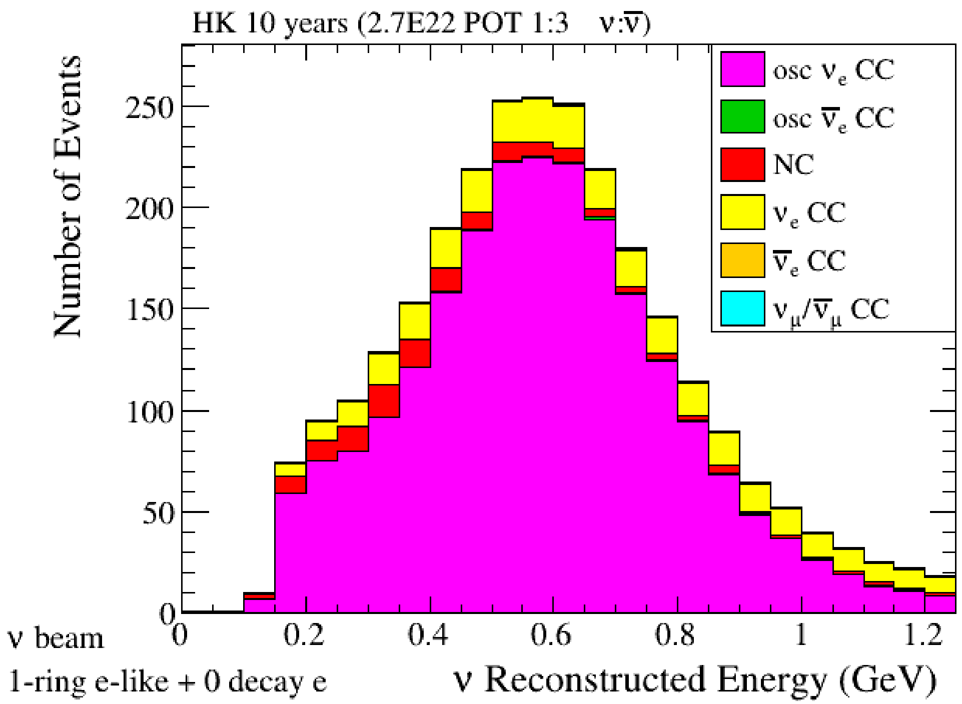
→ break degeneracy in θ_{23} octant (~1% effect on ν_e normalization at present best θ_{23} fit)

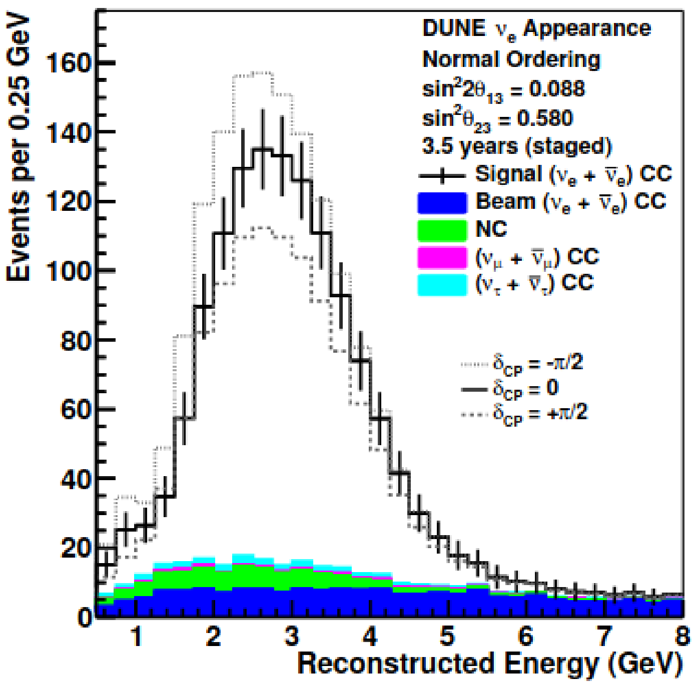




Prospects

For today best fit values of θ_{23} we expect both HK and DUNE to reach ~4-5 sigma sensitivity to reject the wrong octant: huge increase in statistics of ν_e sample



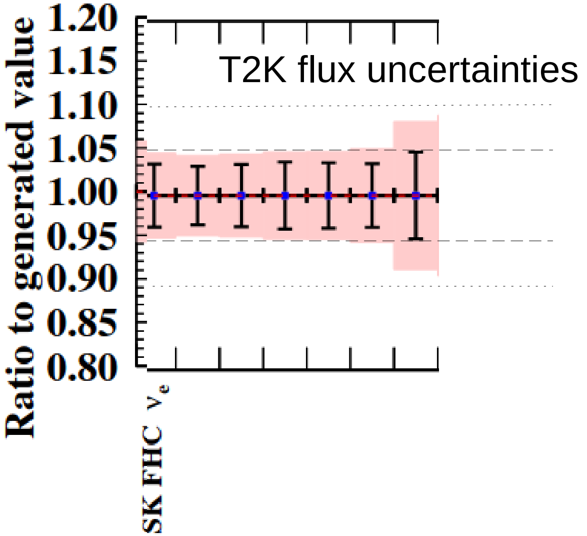


The most important background is the **intrinsic ν_e component inside the flux** (already present before oscillation): ~10%

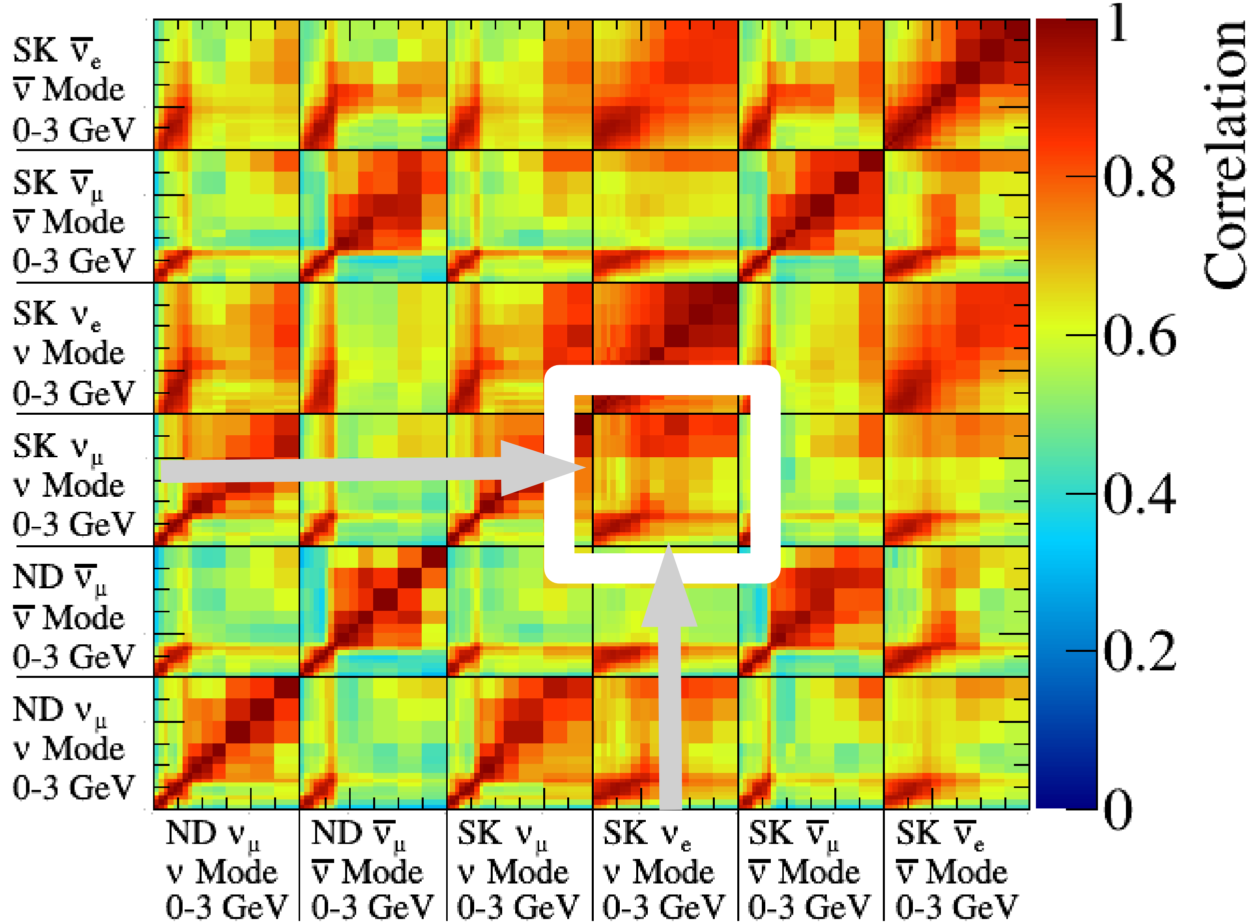
To measure ν_e oscillated signal normalization at ~1% (octant degeneracy breaking) need to have a **relative precision on the ν_e intrinsic background <5 %**

ν_e flux today

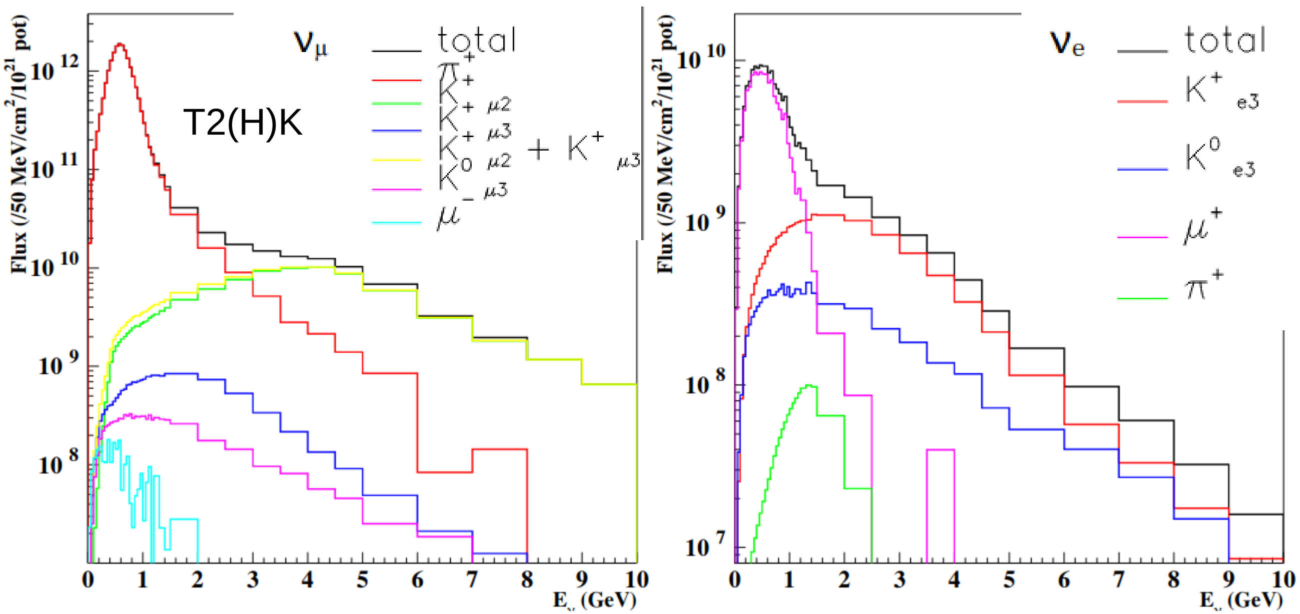
Today uncertainty on ν_e flux already at 5% level before ND constraints and **strong correlation between ν_μ and ν_e flux uncertainties:**



Correlations of T2K flux uncertainties

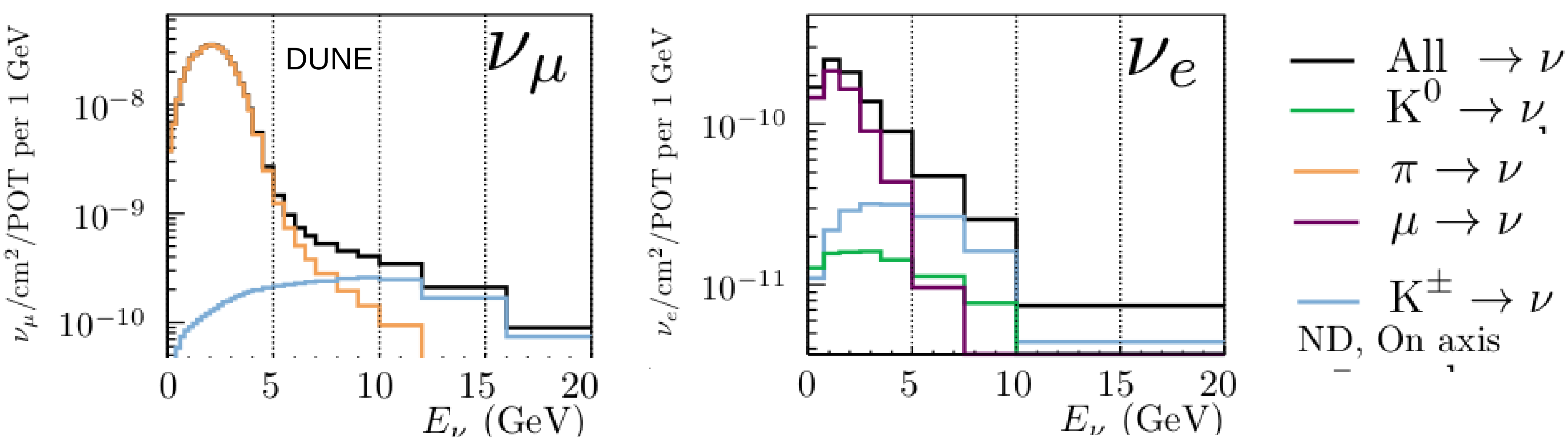


ν_e flux vs ν_μ flux



ν_e flux at the oscillation peak energy is dominated by μ decay coming from from π,K decays → correlation with **ν_μ**

(+ direct K decays into **ν_e** at higher energy,
K0 subdominant)



$\nu_e/\overline{\nu}_e$ appearance: CPV and MH

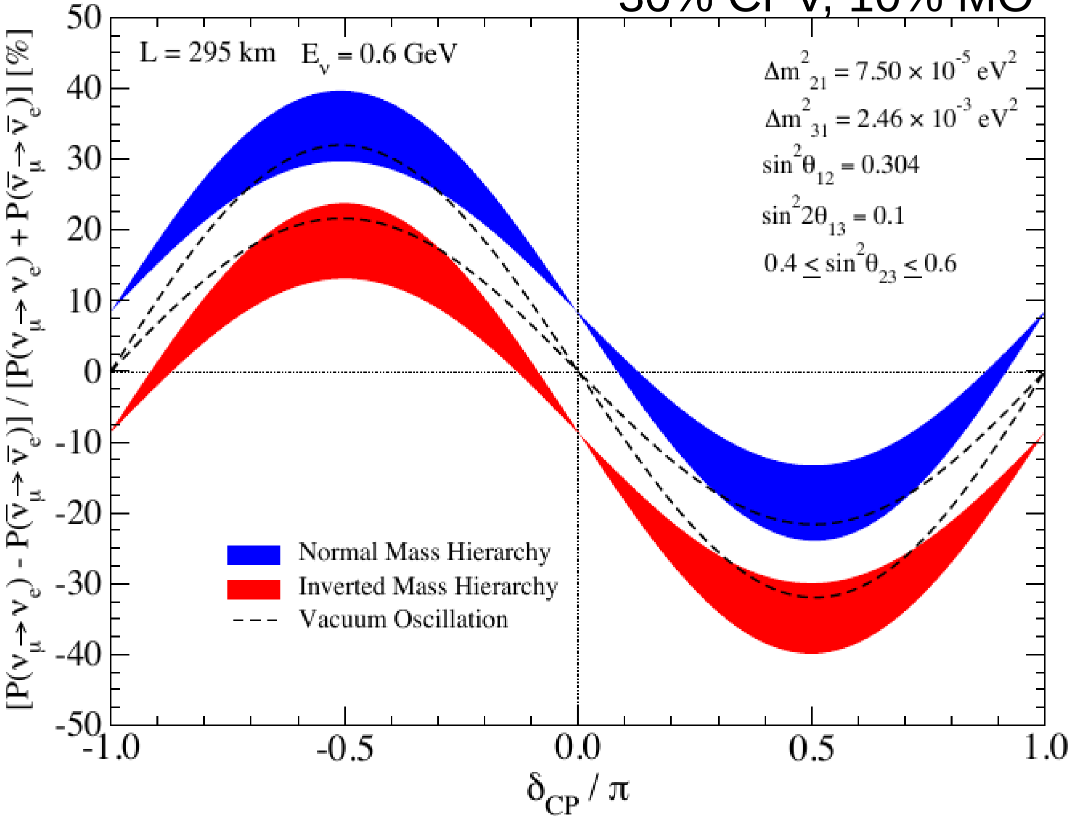
$$\mathcal{A}_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects},$$

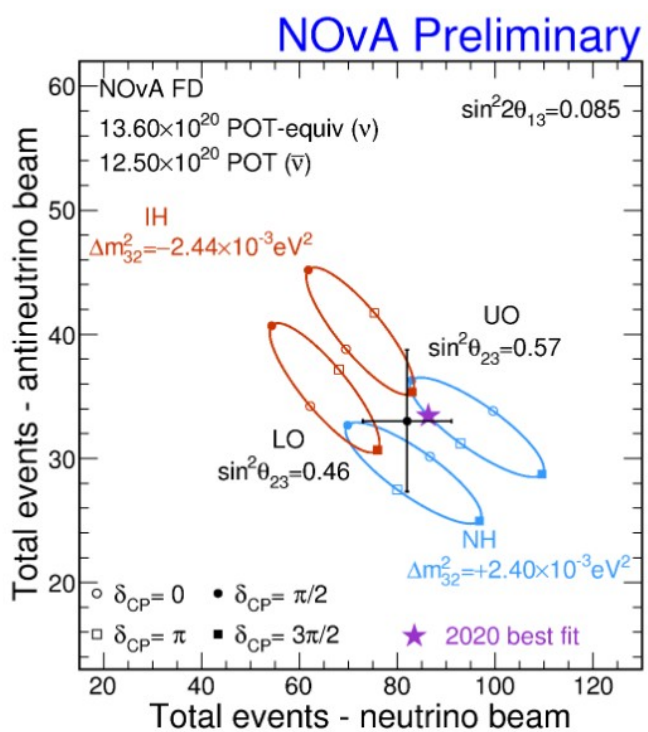
Different matter effects $\overline{\nu}/\nu$, since due to CC interaction with the Earth matter

- **larger neutrino energy and longer baseline → larger the matter effect**

T2K baseline and energy

~30% CPV, 10% MO





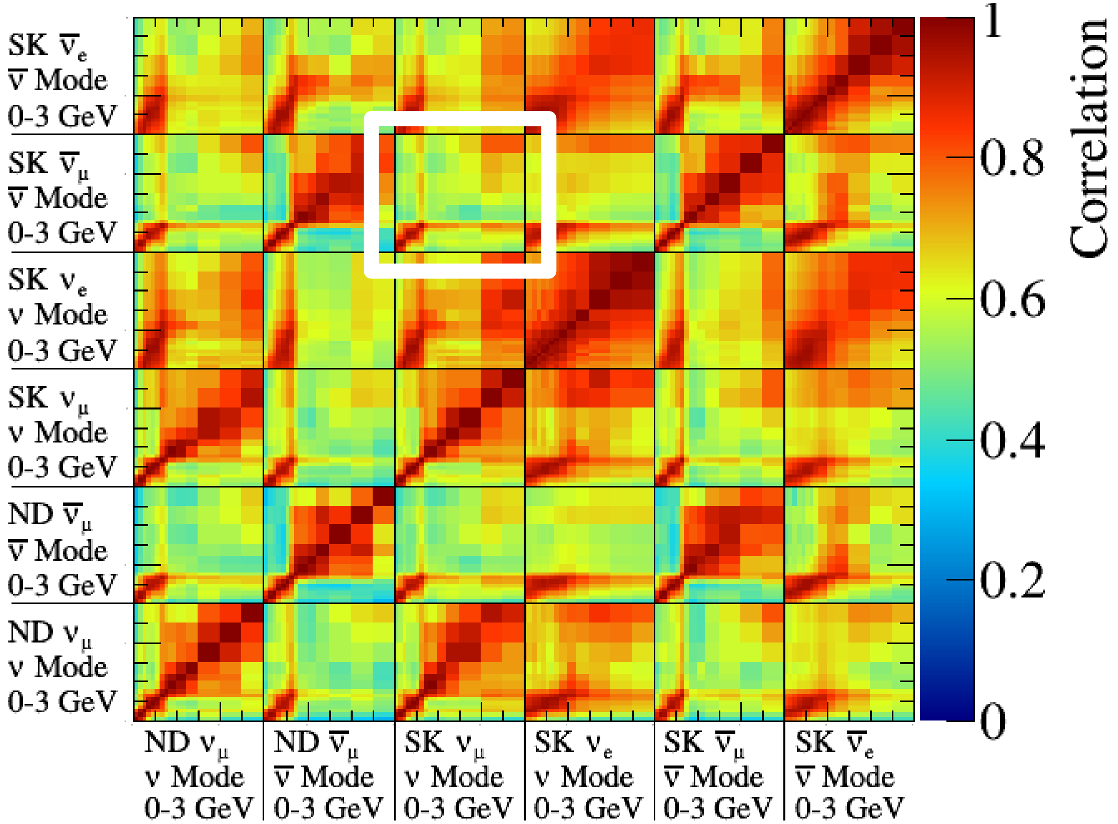
Prospects

Prospects for next generation: 5σ on CPV and MH

What is really important are $\nu_e/\bar{\nu}_e$ anticorrelations, they must be below 2% (the lower, the better → direct impact on sensitivity and ultimate limitation to it)

No direct anticorrelation from flux uncertainties (but need to constrain ν contamination into $\bar{\nu}$ [aka wrong sign])

Correlations of T2K flux uncertainties



$\nu_e/\overline{\nu}_e$ appearance: δ_{CP} measurement

Search for CPV and measuring dCP are two very different experimental targets.
Prospects for dCP precision ~10-15 degrees from each experiment of next generation

$$\mathcal{A}_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects},$$

Actually at second order:

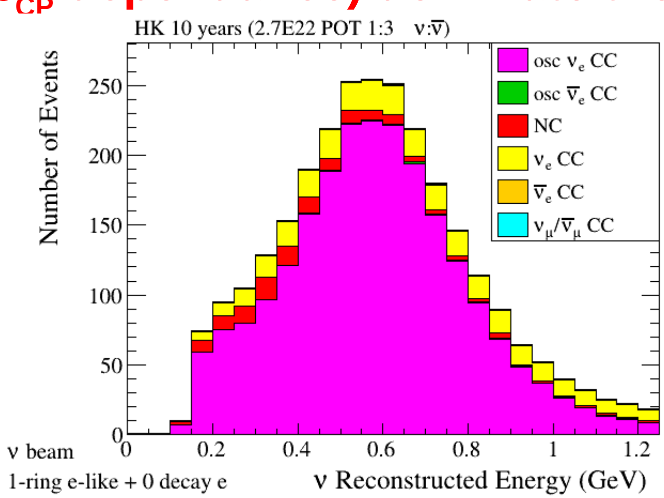
$P_{apperarance}$ ~ +/- A sinδ + Bcosδ + ...

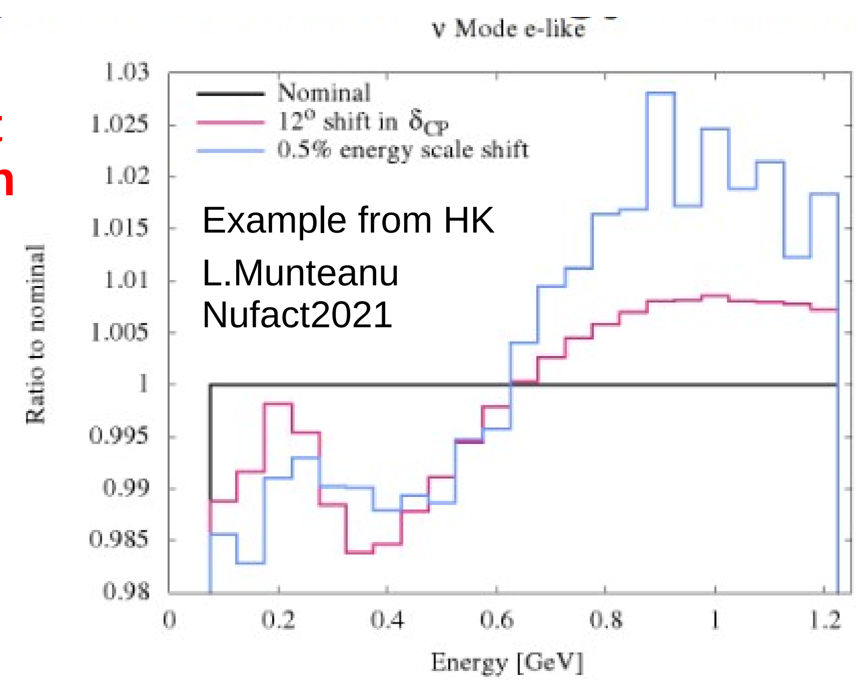
detailed formula →

$$\begin{aligned} P_{long-baseline} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta \\ & \mp \alpha \sin 2\theta_{13} \sin\delta_{CP} \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\Delta \\ & + \alpha \sin 2\theta_{13} \cos\delta_{CP} \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\sin^2\Delta \\ & + \alpha^2 \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta \end{aligned}$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$.

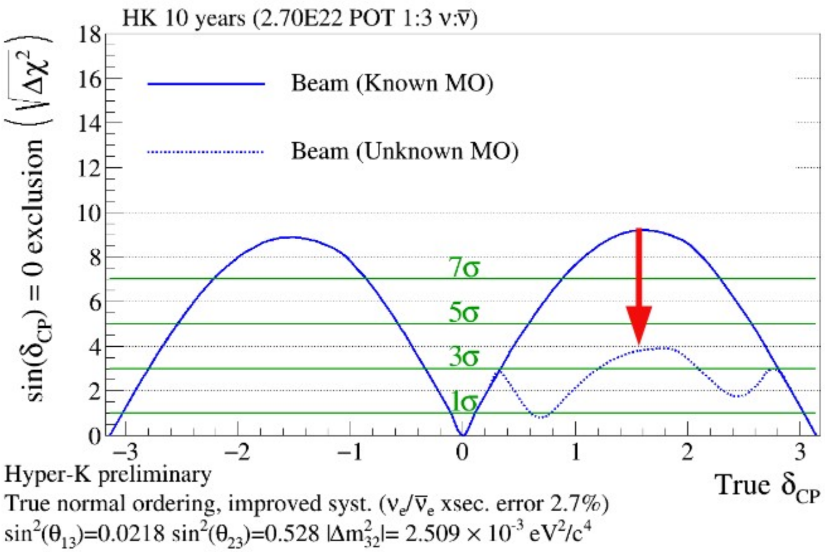
- **At δ_{CP}~ +/-π/2** the precision on δ_{CP} (~P_{app} derivative vs δ_{CP}) is dominated by the second term: **precise energy spectrum measurement ($\cos\delta_{CP}$ dependance) dominate the resolution**





Beam + atmospherics combination

Important to enhance MH sensitivity



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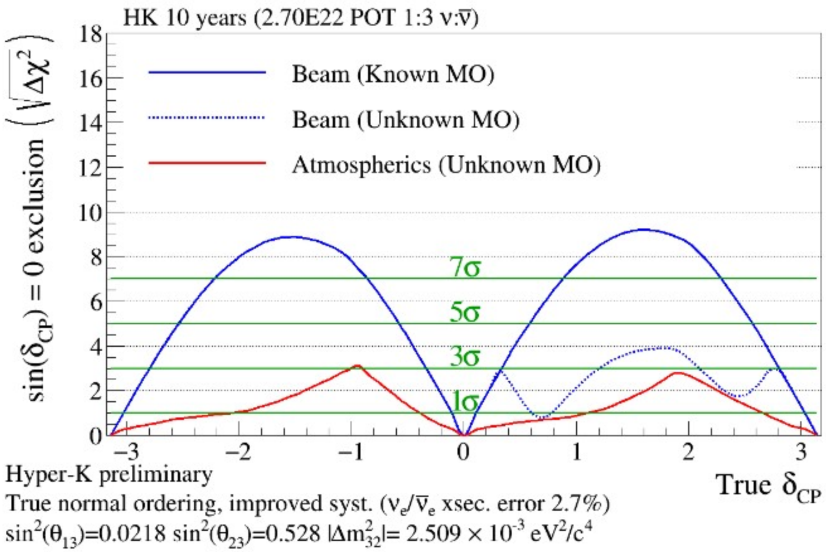

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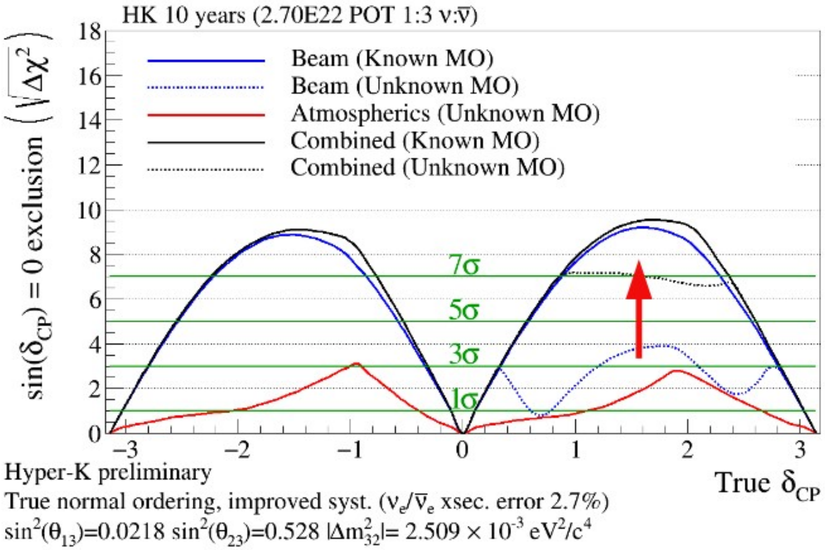
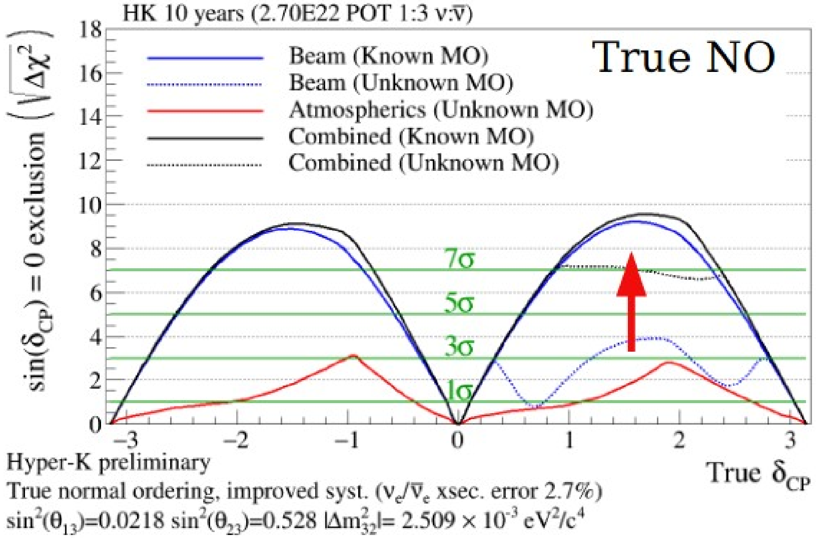
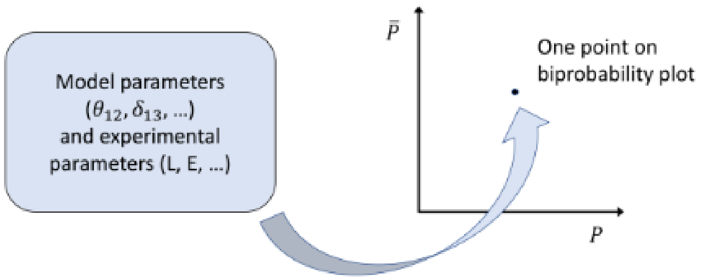


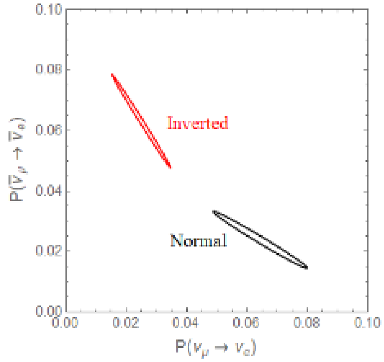
Beam + atmospherics combination

Important to enhance MH sensitivity + disentangle BSM effects (NSI, model-independent CPV, …)
thanks to much broader range of L/E



DUNE





CIPANP 2018,
Print:1809.11128 [hep-ph]

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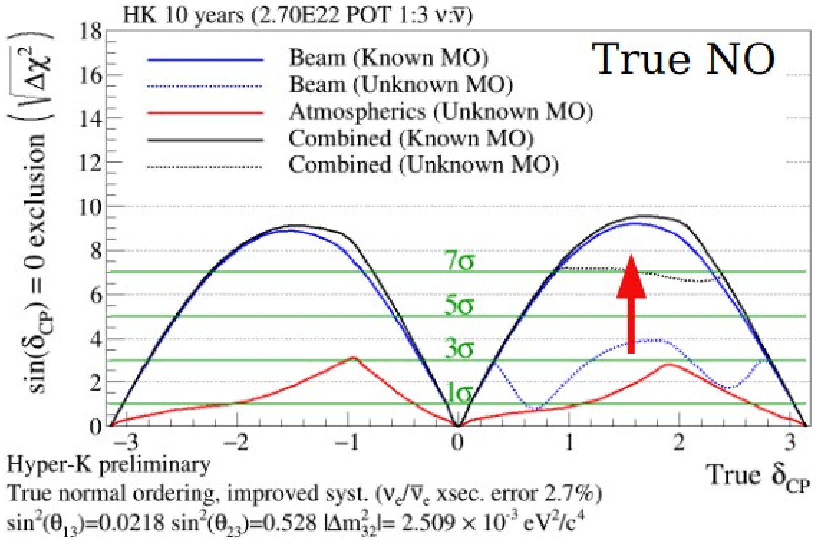
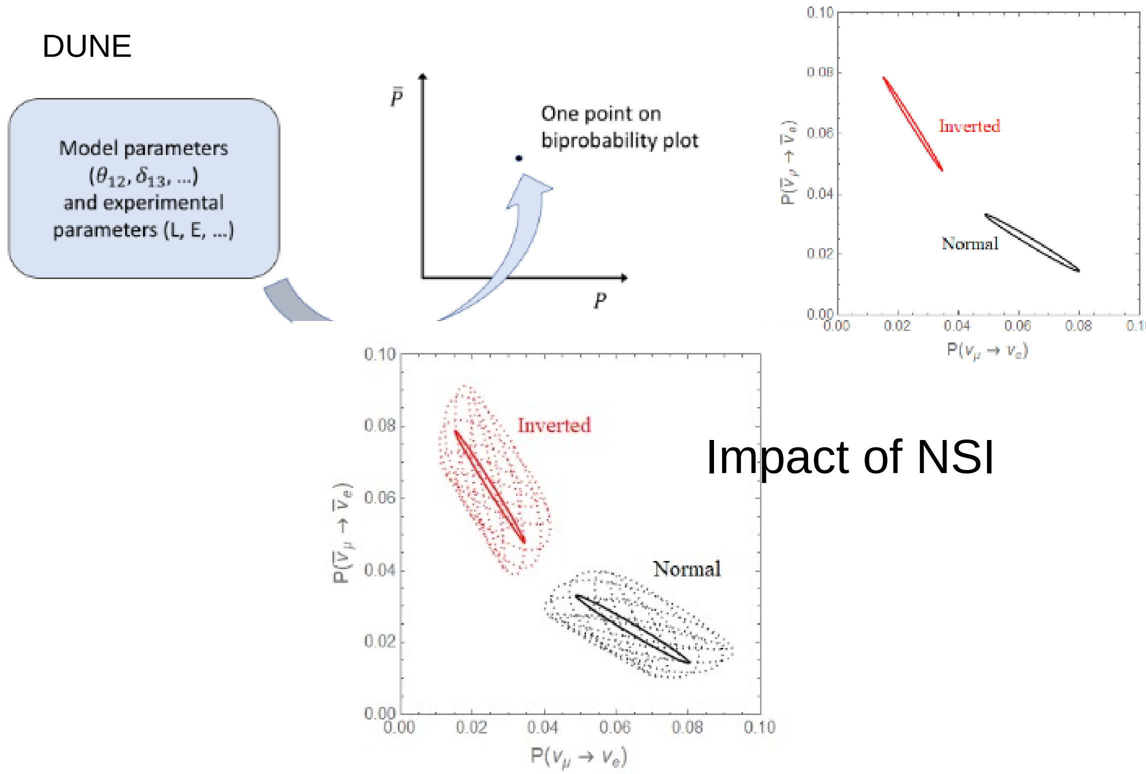


DUNE



Impact of NSI

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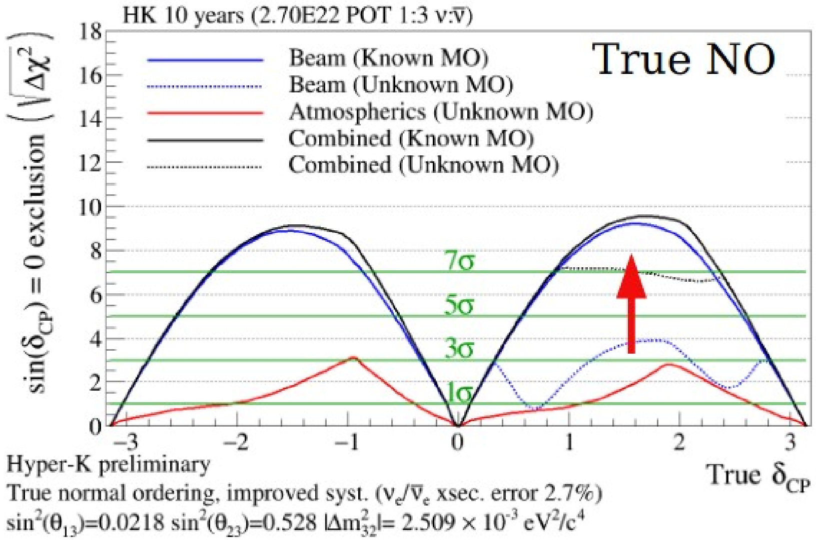

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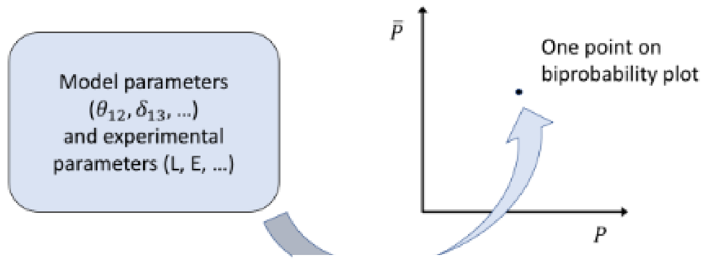
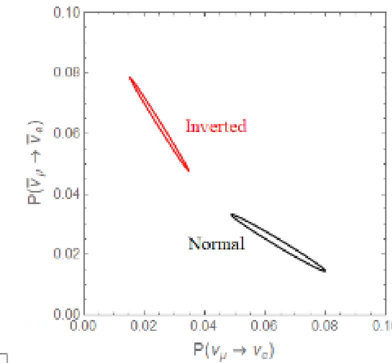
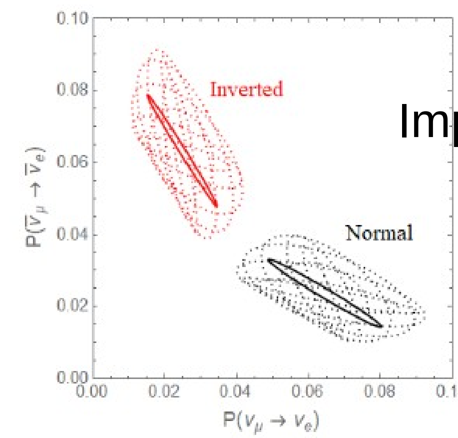
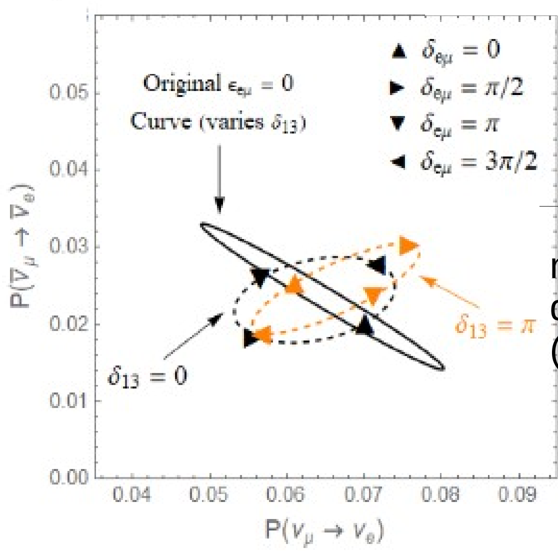


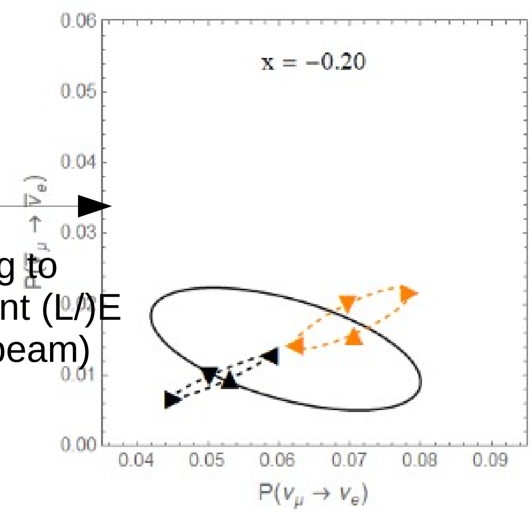




Impact of NSI



moving to different (L/)E (with beam)



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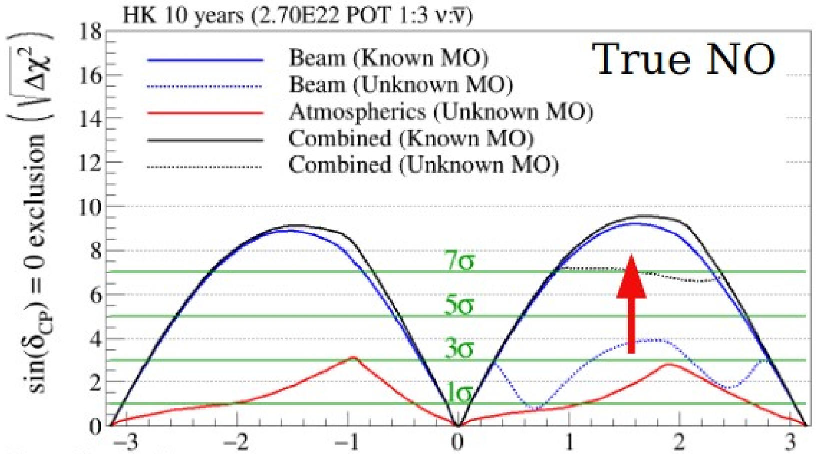
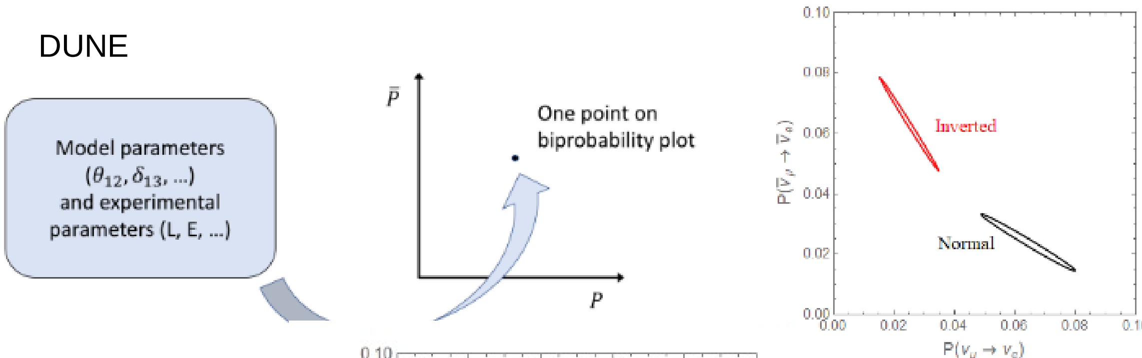
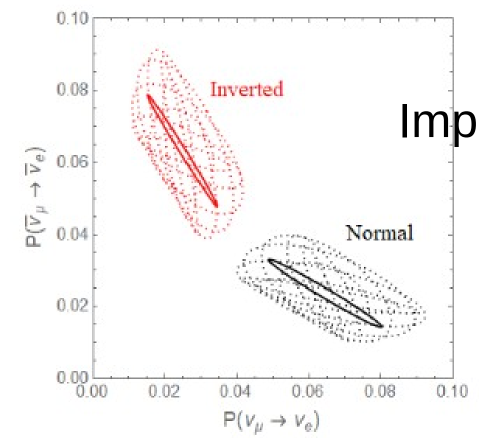


Hyper-K preliminary
True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}$ eV^2/c^4

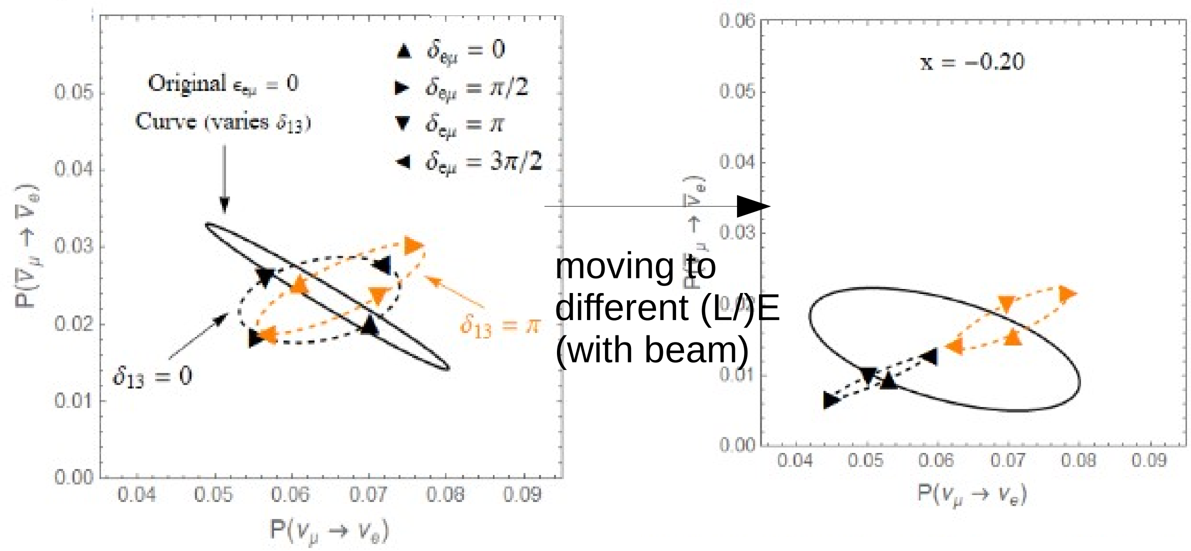
DUNE





Impact of NSI

Correlations between beam and atmospheric fluxes?
In **physics models** + (in future) from common hadroproduction measurements



moving to different (L/)E (with beam)

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Summary of needs for future

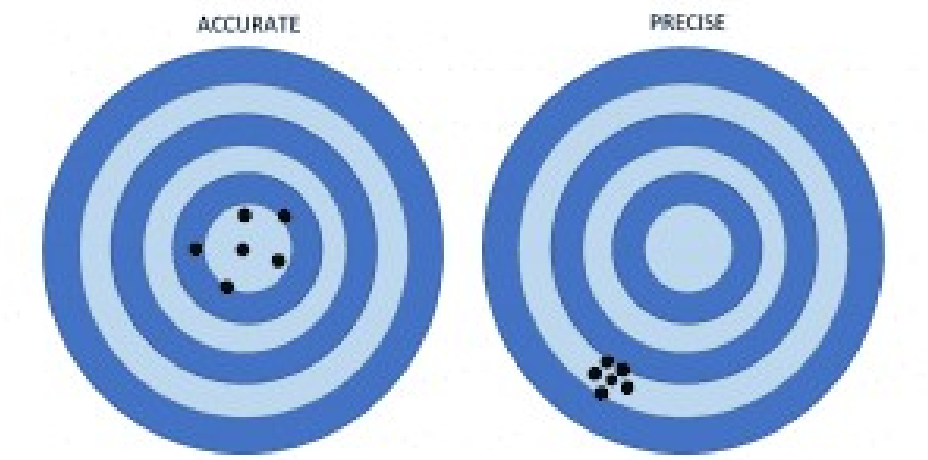
Δm^2: few % ‘energy scale’ of the flux → 0.5% for future

$\sin^2\theta_{23}$: few % on normalization of the flux → 1% for future

θ_{23} octant: ~1% on ν_e normalization of the flux

CPV and MH (for future): <2% on $\nu_e/\bar{\nu}_e$ anticorrelated uncertainties

δ_{CP} precision: similar needs as Δm^2



But it is more then just better precision: the challenge is better accuracy!

The precision we require for next generation is even beyond today accuracy

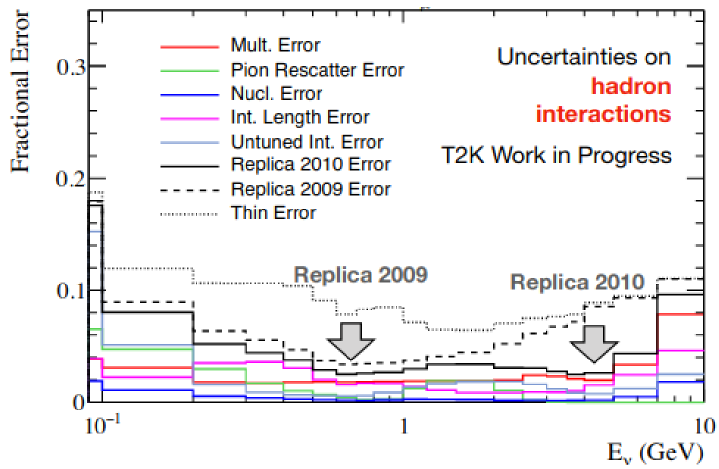
The way to face the accuracy challenge is to improve the model of our systematic uncertainties, including hadroproduction uncertainties:

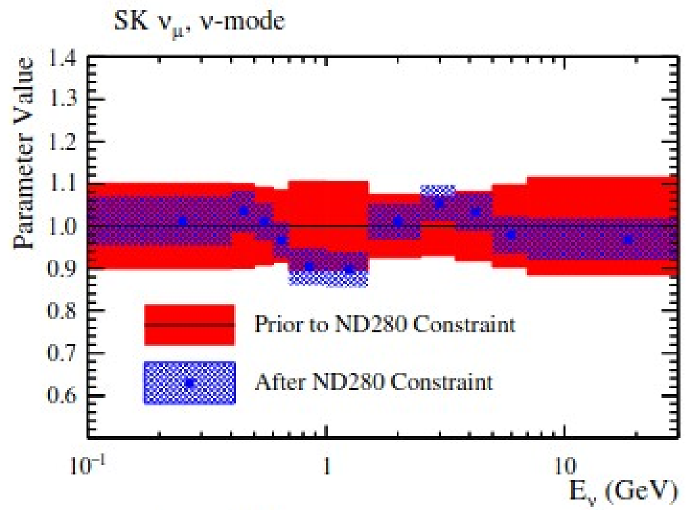
i.e. complete and detailed parametrization of the uncertainties as a function of neutrino energy and flavour (as of today) but also as a function of parent particle type, angle, rescattering etc. → all this encoded into our LBL analyses

The challenge

The statistics will be huge: **to accurately constrain systematics uncertainties we need the correct model of them**

→ having a **full parametrization depending on all the fundamental physics** degrees of freedom will allow to control the physics meaningfullness of ND postfit constraints

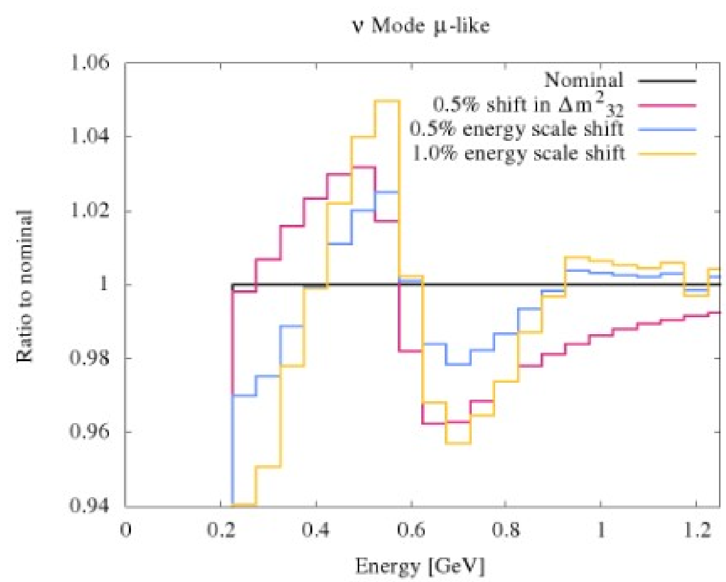




→ even FD statistics is so large to constrain systematics together with oscillation parameters by exploiting the fact that **they are not completely degenerate** between them

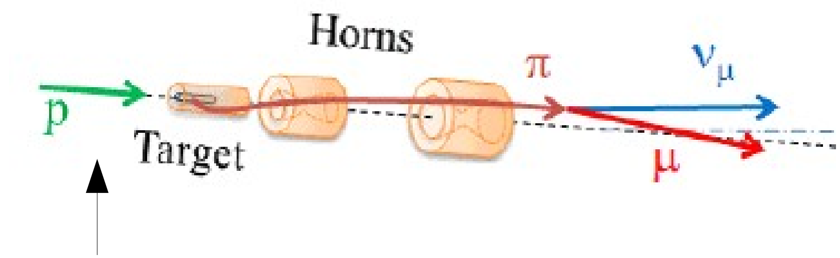
Example of “energy scale”: ν_μ can constrain it for ν_e.

Correlations between ν_μ and ν_e (and $\nu/\bar{\nu}$) uncertainties needs to be well modeled



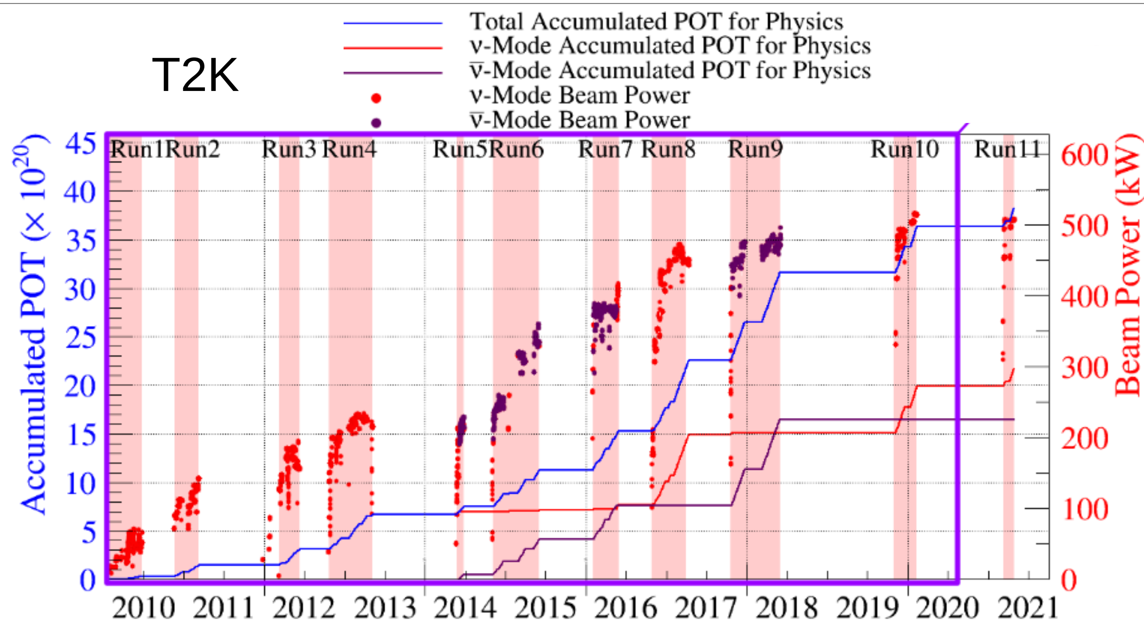
BACK-UP

Proton beam



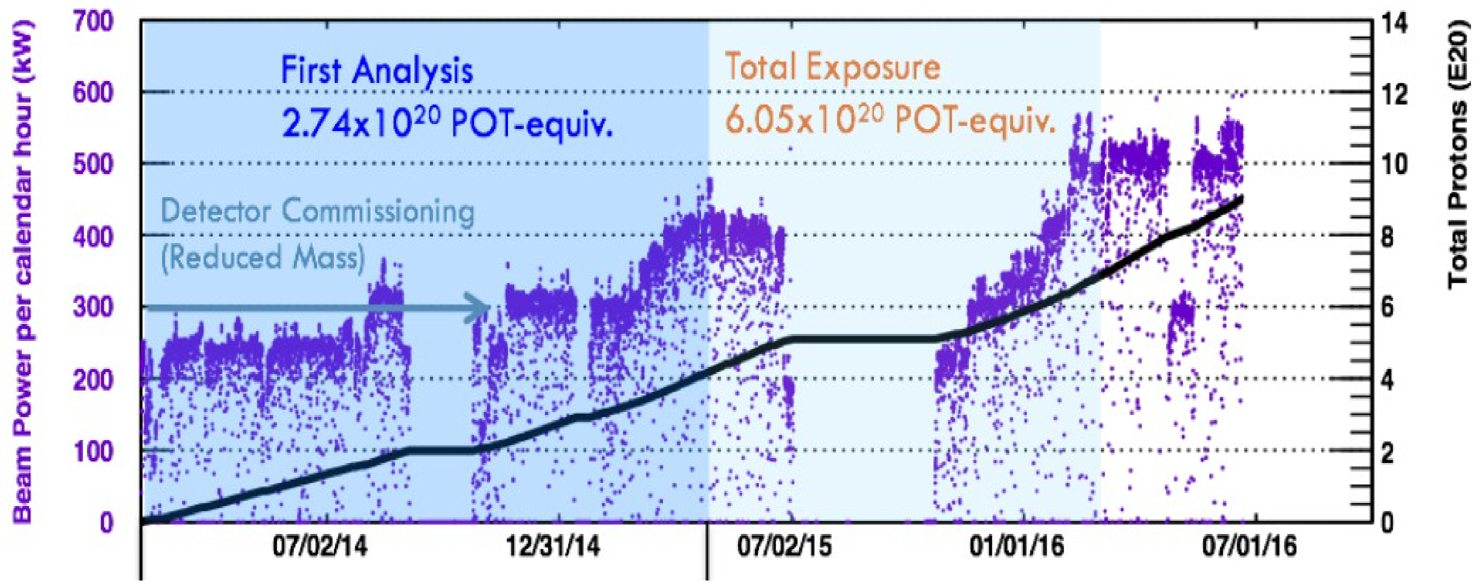
Proton beam
(30 GeV JPARC, 120 GeV NuMi FNAL)

T2K



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

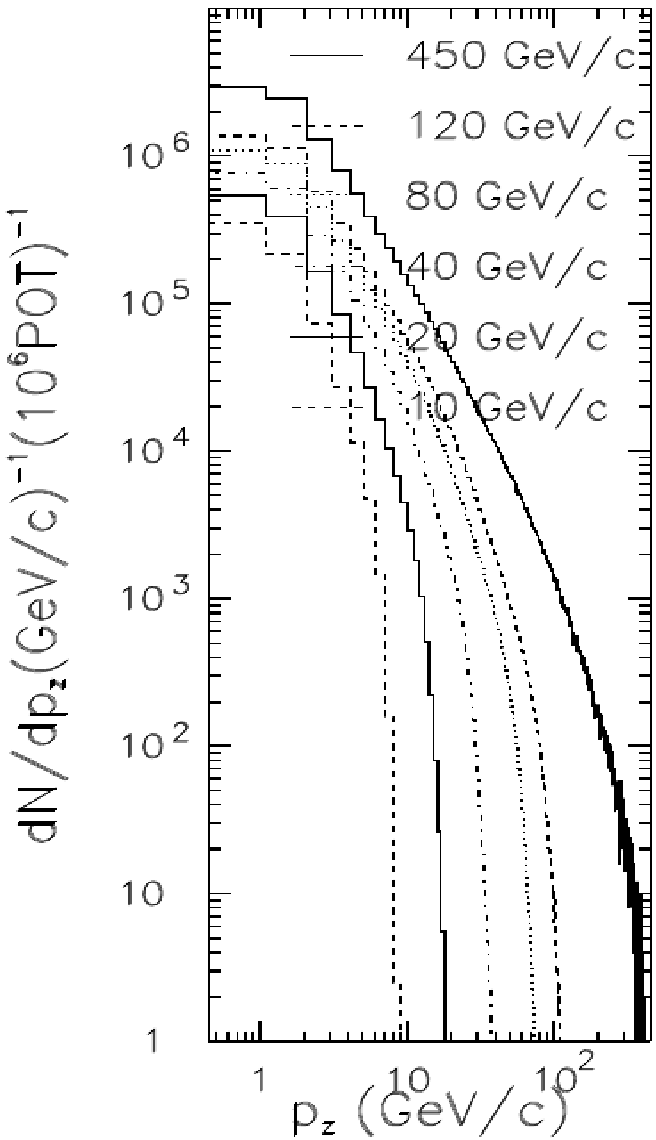
NOVA (old)

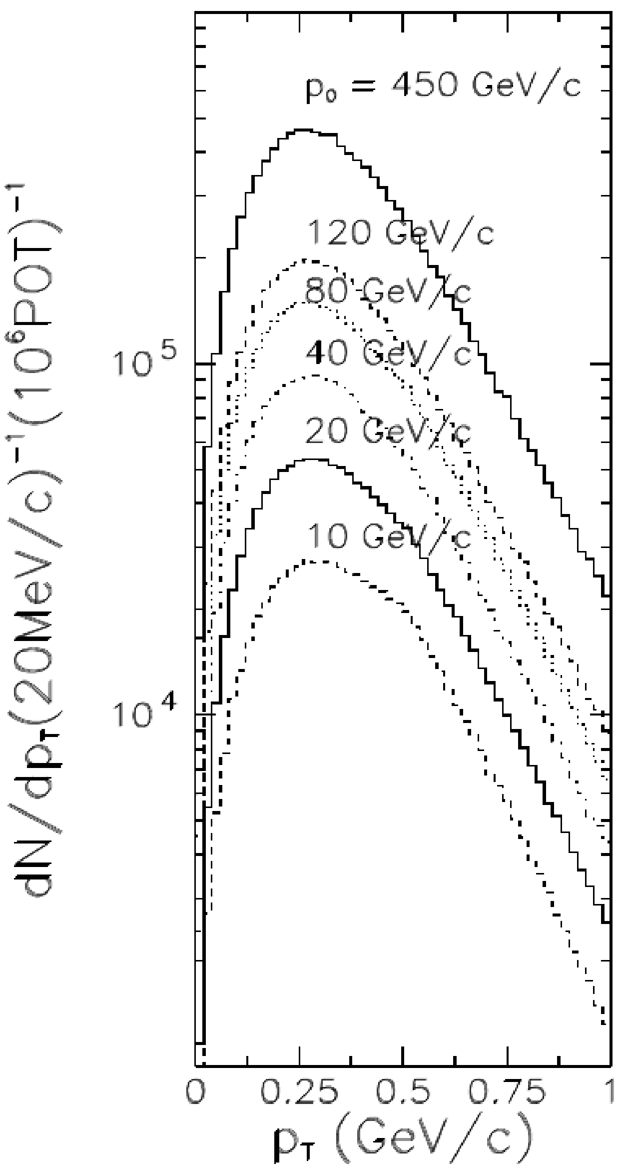


Next generation of experiments: 1-2 MW (larger POT and/or E)

Proton beam

Pion spectra for different proton momenta



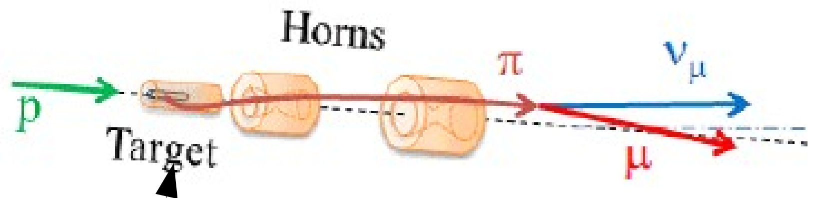


p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

Roughly speaking: higher proton energy produce more pions without increasing much their transverse momentum

(but lower energy typically allows larger repetition rate)

Target



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

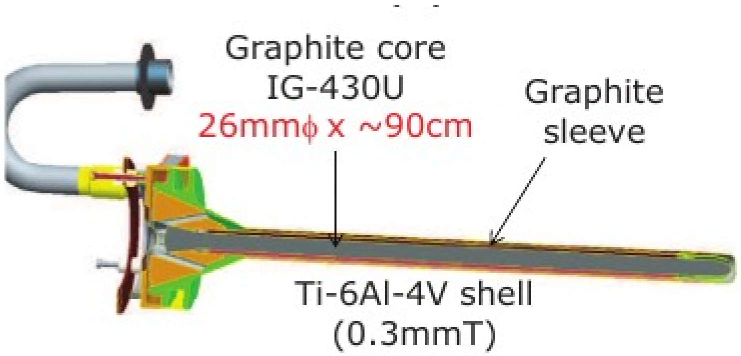
  (but re-interactions of hadrons inside the target are an additional complication)

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

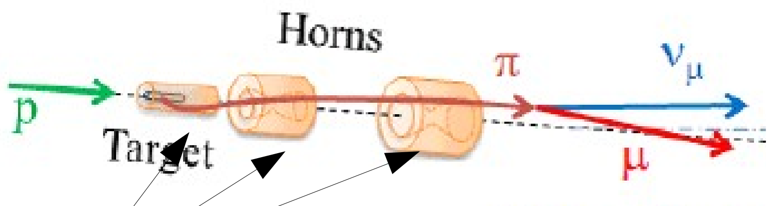
- **Low Z** (Aluminium, Berillium, Carbon, …) high probability of proton interacting and low probability of radiating (loosing energy in the target)

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

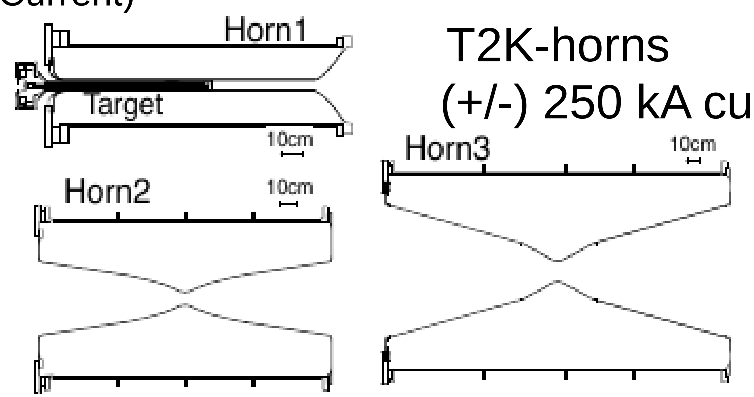
T2K



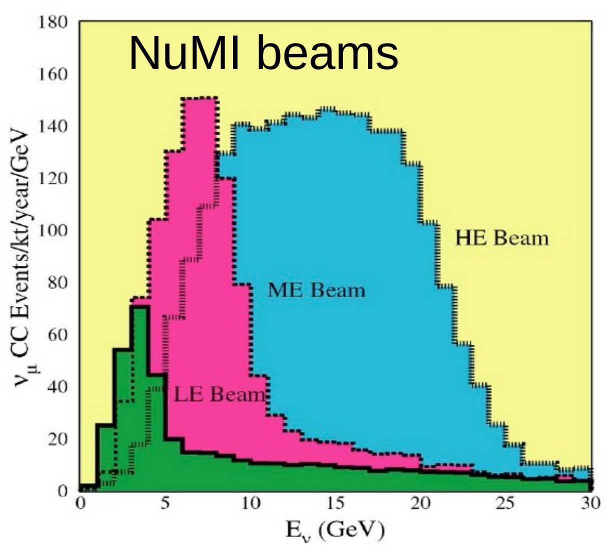
Horns



Horns to focus $\pi^{+/-}$ parallel to beam axis → ν_μ or $\bar{\nu}_\mu$ beam (aka Forward/Reverse Horn Current)

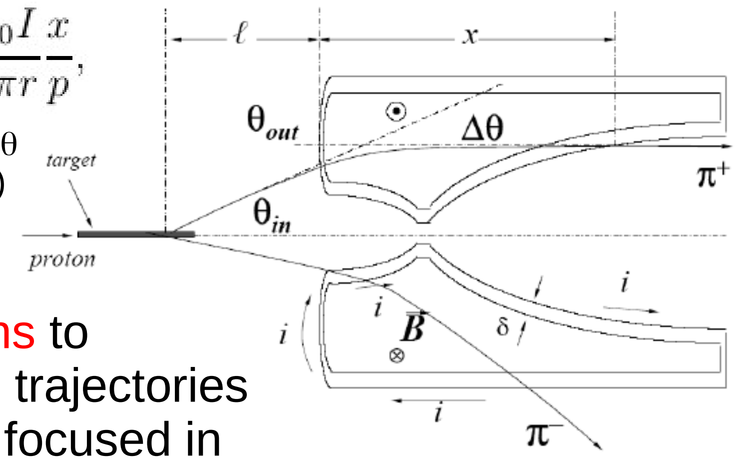


T2K-horns
(+/-) 250 kA current

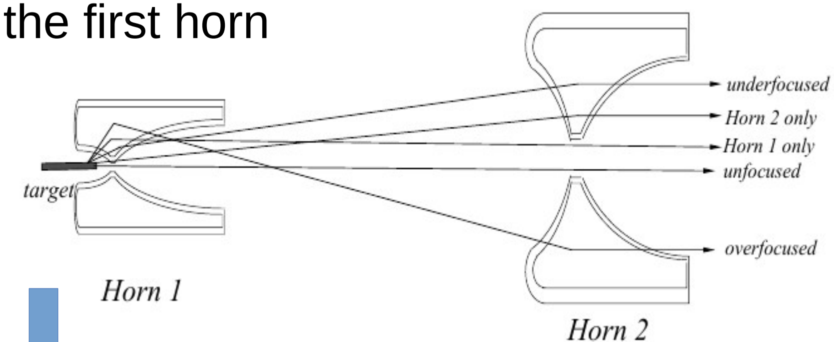


- $\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$,

(parabolic: same θ kink for all angles)

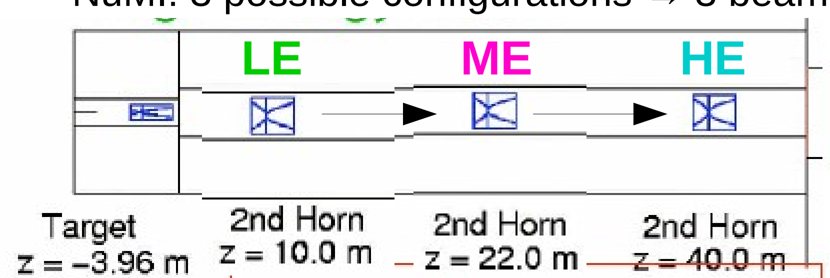


- multiple horns to recover pion trajectories not properly focused in the first horn



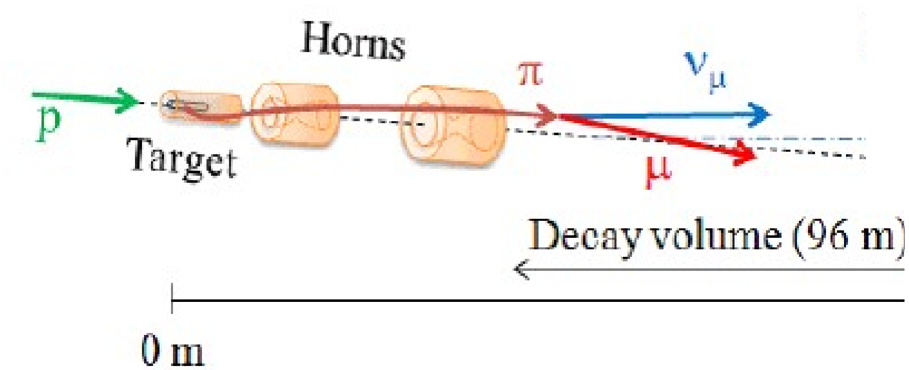
- the pions with smallest angle are the most energetic → to focus them need to move the horns

NuMI: 3 possible configurations → 3 beam energies



Decay volume

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



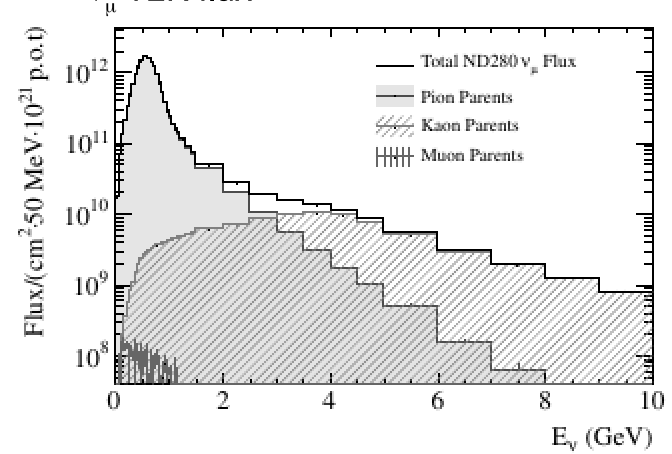
- most ν_μ's from 2-body decays:
$\pi^+ \to \mu^+\nu_\mu$
$K^+ \to \mu^+\nu_\mu$

- most ν_e's from 3-body decays:
$\mu^+ \to e^+\nu_e\nu_\mu$
$K^+ \to \pi^0 e^+\nu_e$

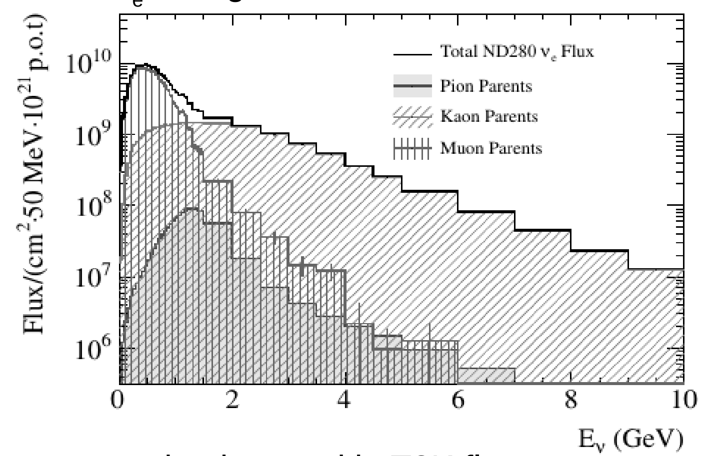
Decay volume (T2K: He filled):

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

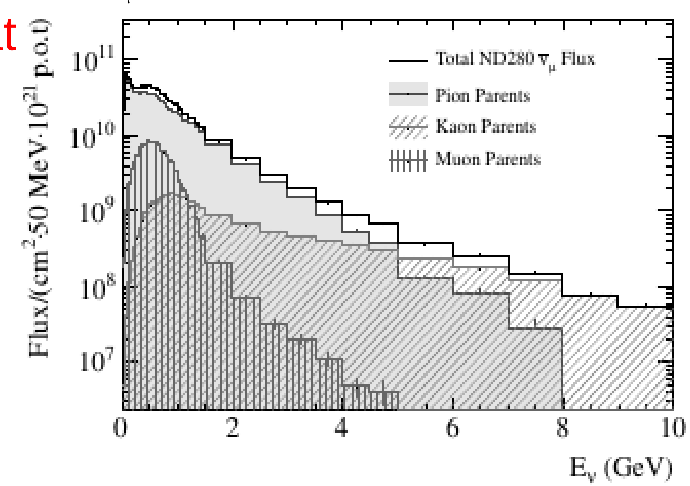
ν_μ T2K flux



ν_e background in T2K flux



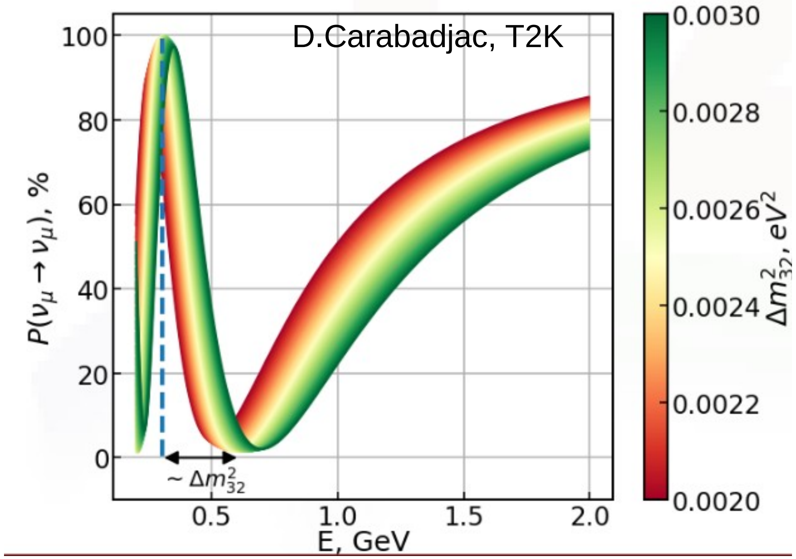
$\bar{\nu}_\mu$ background in T2K flux



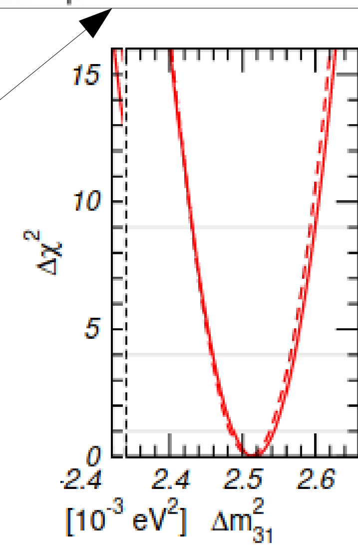
- $\bar{\nu}_\mu$ / ν_μ larger at high energy due to high p_L π- which cannot be (de-) focused

Atmospheric parameters: ν_μ disapp

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



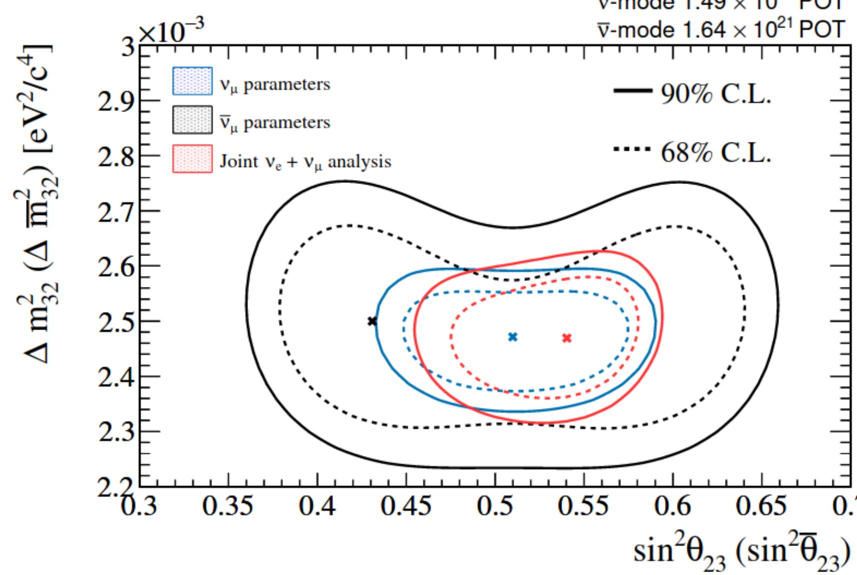
	Best fit (NH)	3σ range
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$



(joint fit results from
T. Schweitz talk
at Neutrino 2022,
NuFit 5.1)

- Precise measurement of neutrino energy event by event is crucial: good resolution on neutrino energy reconstruction + avoid bias in energy scale
Precision at few % level (→ few MeV)

- Correlated effects in neutrino and antineutrino (assuming CPT invariance)



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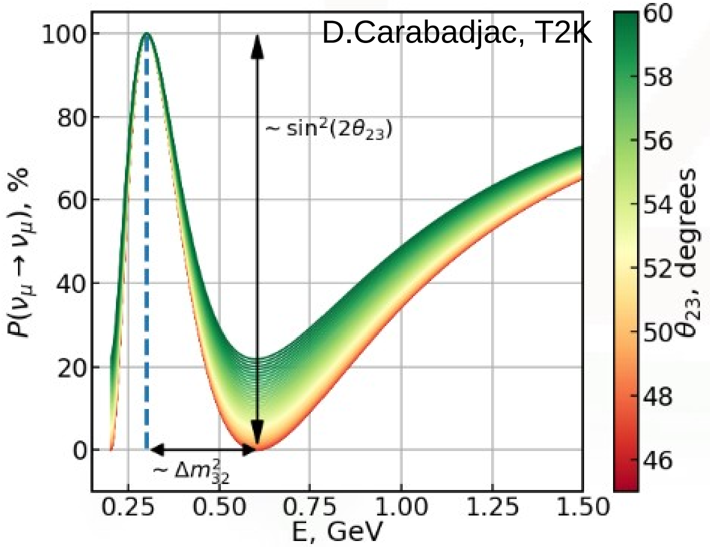

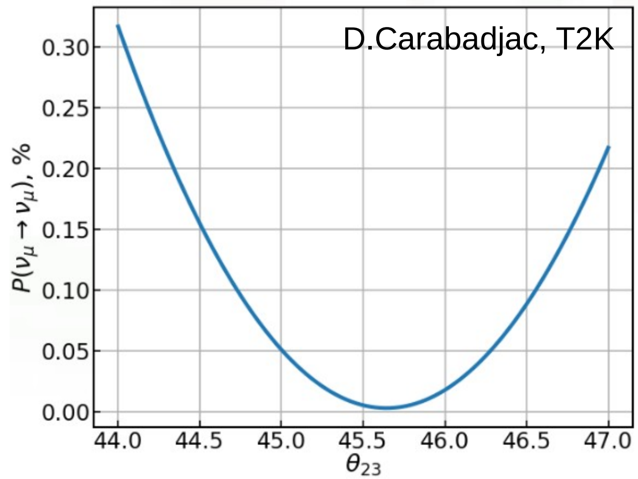

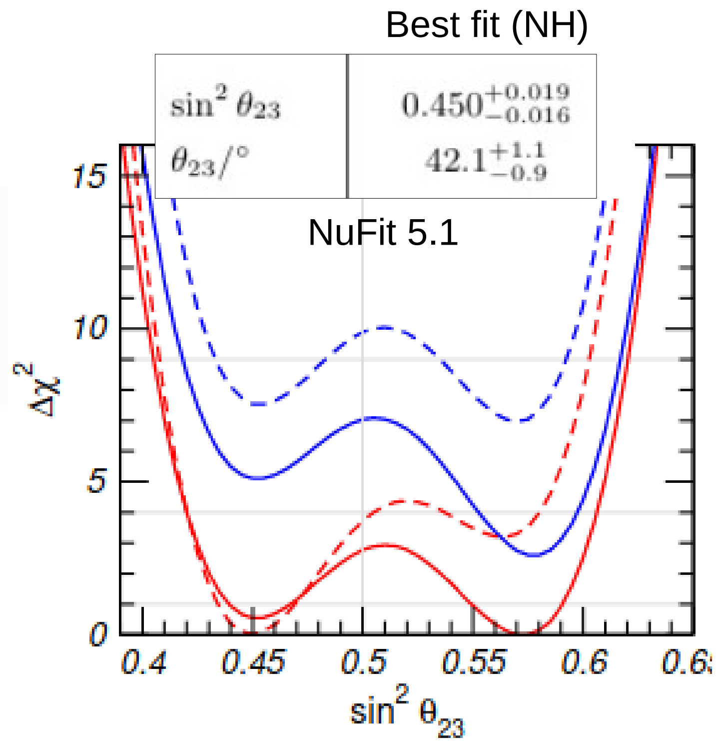

- Measurement proportional to number of observed muon neutrino at oscillation maximum
→ need control of ν_μ overall normalization at few %
(again correlated between nu and nubar)

- Maximal mixing **θ_{23}~π/4** would be a very interesting symmetry.
Away from that, octant degeneracy due to quadratic dependence on $\sin^2 2\theta$

1. $\theta_{23} \in [0\,;\,\pi/4]$ - lower octant
2. $\theta_{23} \in [\pi/4,\ \pi/2]$ - upper octant