Synergies with Neutrinos

Patrick Huber

Center for Neutrino Physics at Virginia Tech

Inaugural U.S. Muon Collider Collaboration Meeting
August 7–9, 2024

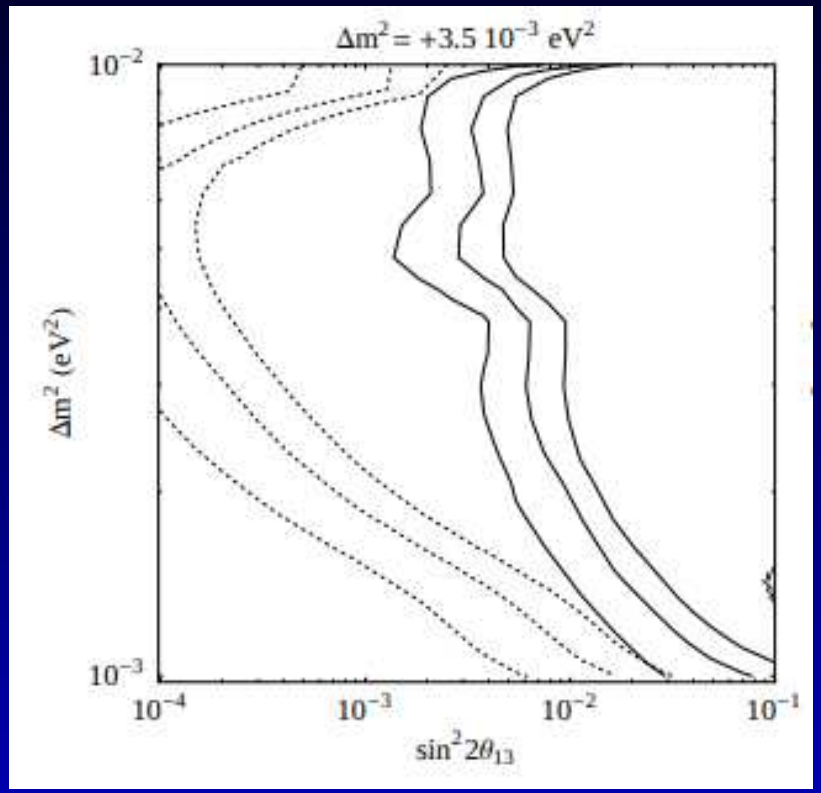
Nuclear Physics B
Volume 585, Issues 1–2, 2 October 2000, Pages 105-123

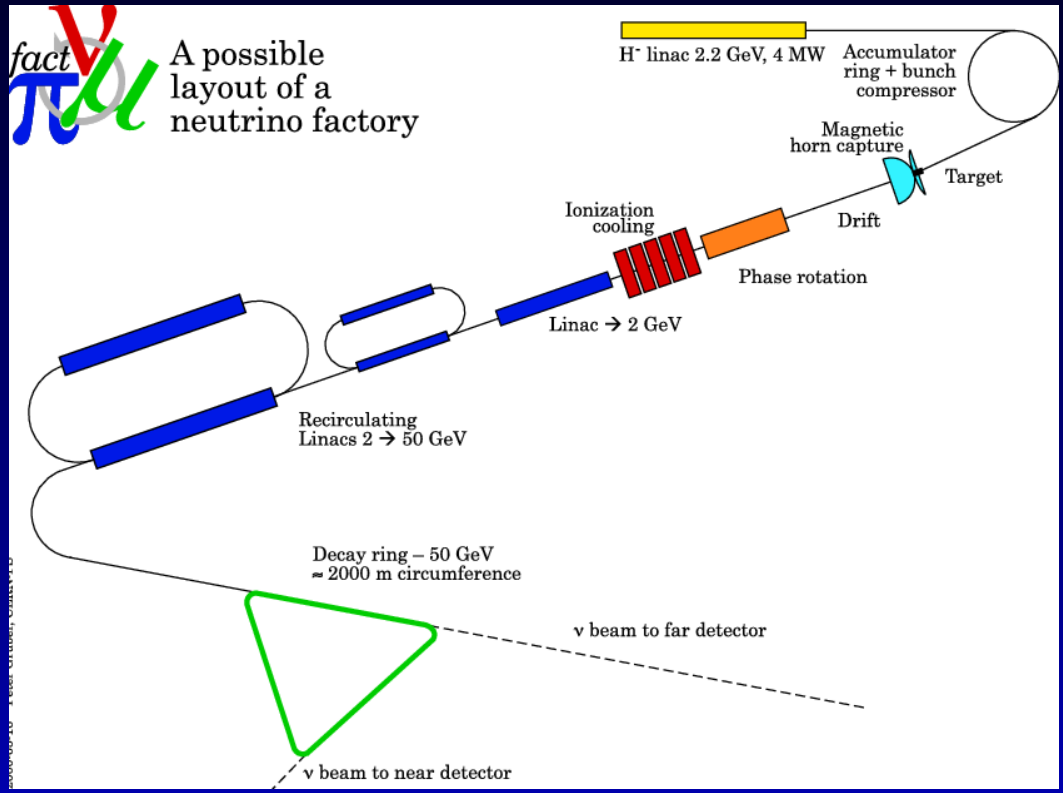
Extracting matter effects, masses and mixings at a neutrino factory ☆

M. Freund ✉, P. Huber ✉, M. Lindner ✉

Back to the Future. . .

Neutrino factories in 2000



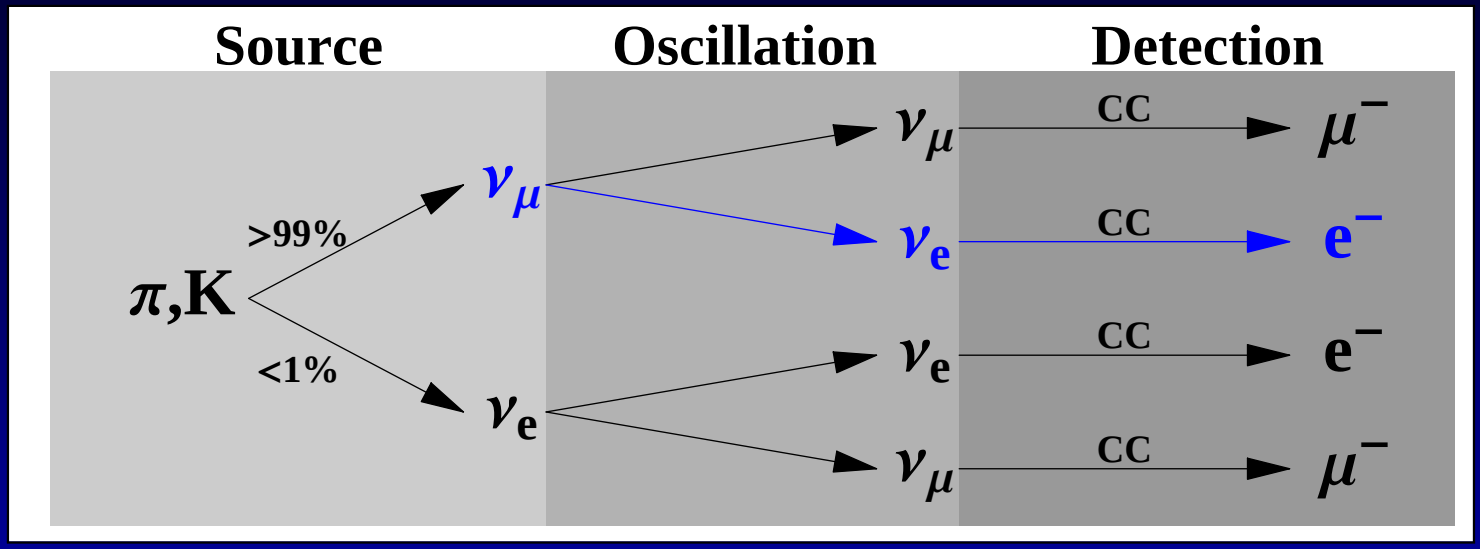


Freund, PH, Lindner, 2000

and we knew that $\sin^2 2\theta_{13}$ is small...

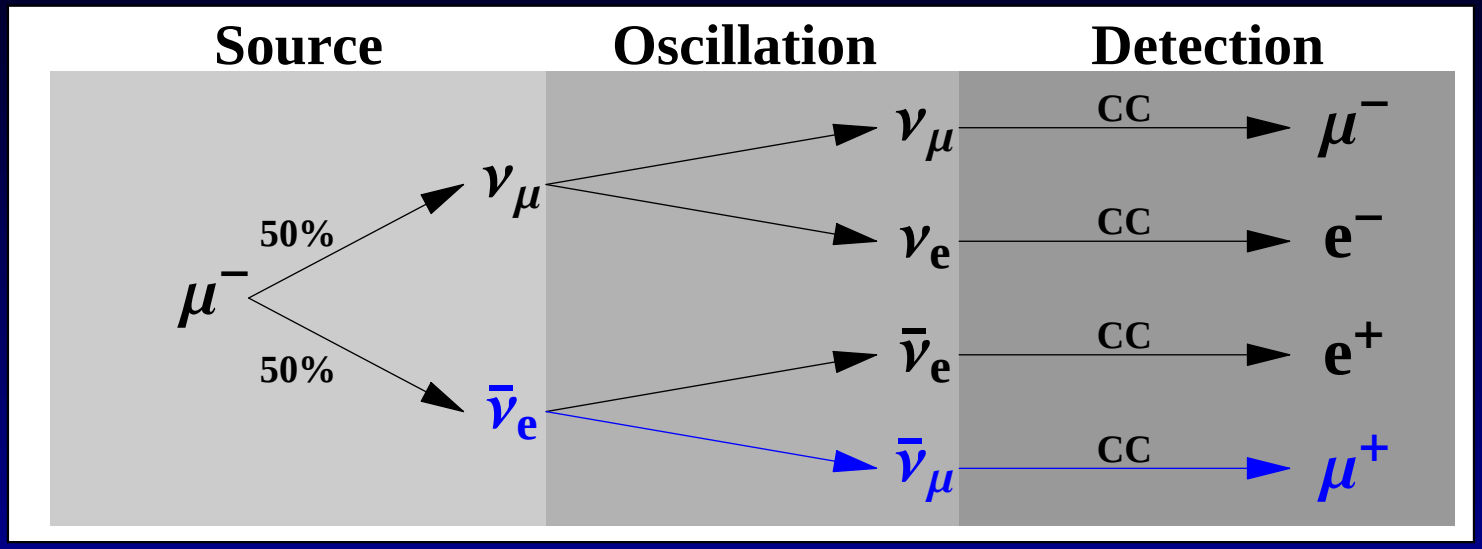
Traditional beam

Neutrino beam from π-decay



- primary ν_μ flux constrained to 5-15%
- ν_e component known to about 20%
- anti-neutrino beam systematically different – large wrong sign contamination
- ν_e difficult to distinguish from NC events

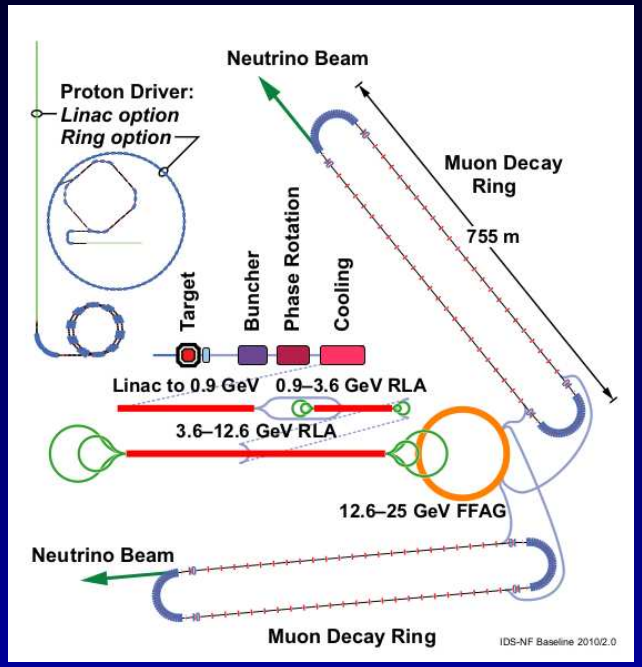
Neutrino factory beam



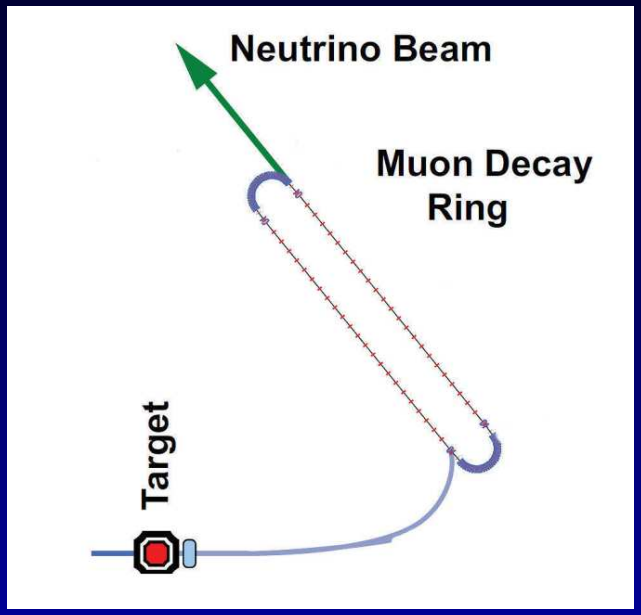
This requires a detector which can distinguish μ^+ from $\mu^- \Rightarrow$ magnetic field of around 1T

- beam known to %-level or better
- muon detection very clean
- multitude of channels available, including ν_τ
- Event rate scales $\propto E_\mu^3 \Rightarrow$ very long baselines

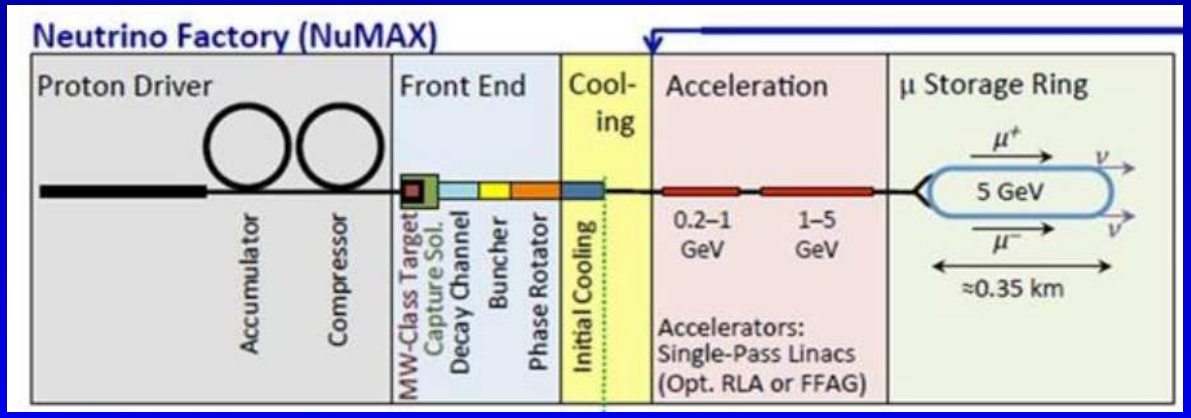
Neutrino factories a decade ago



IDS, 2010



nuSTORM, 2012

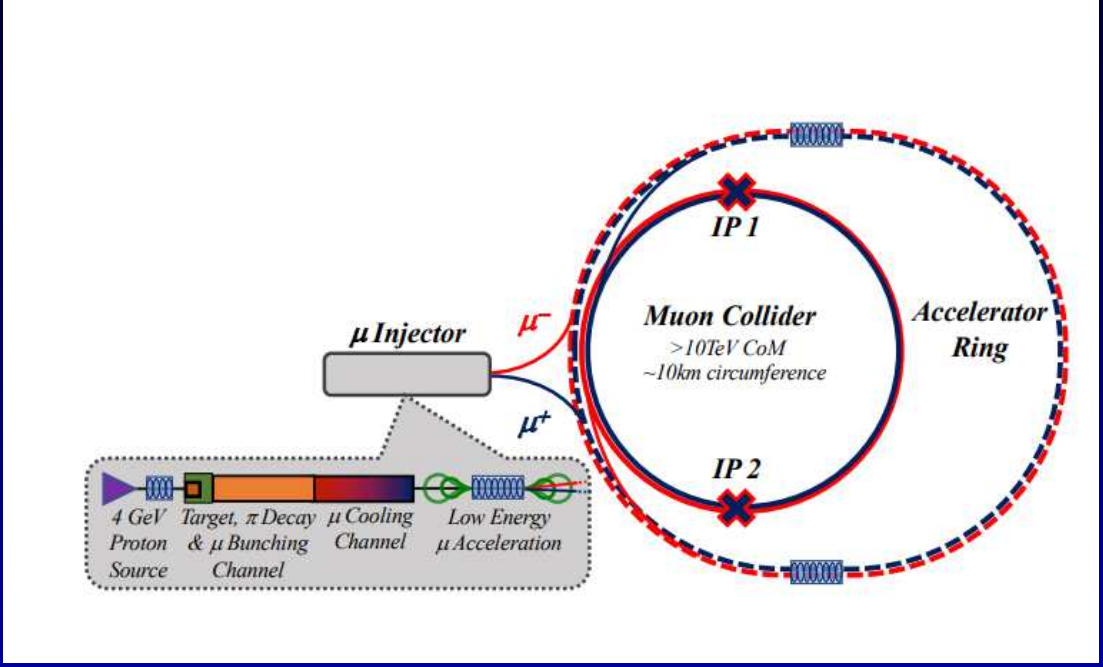


MAP/MASS, 2013

muon cooling for high luminosity

high energy for BSM physics

MC concept 2024



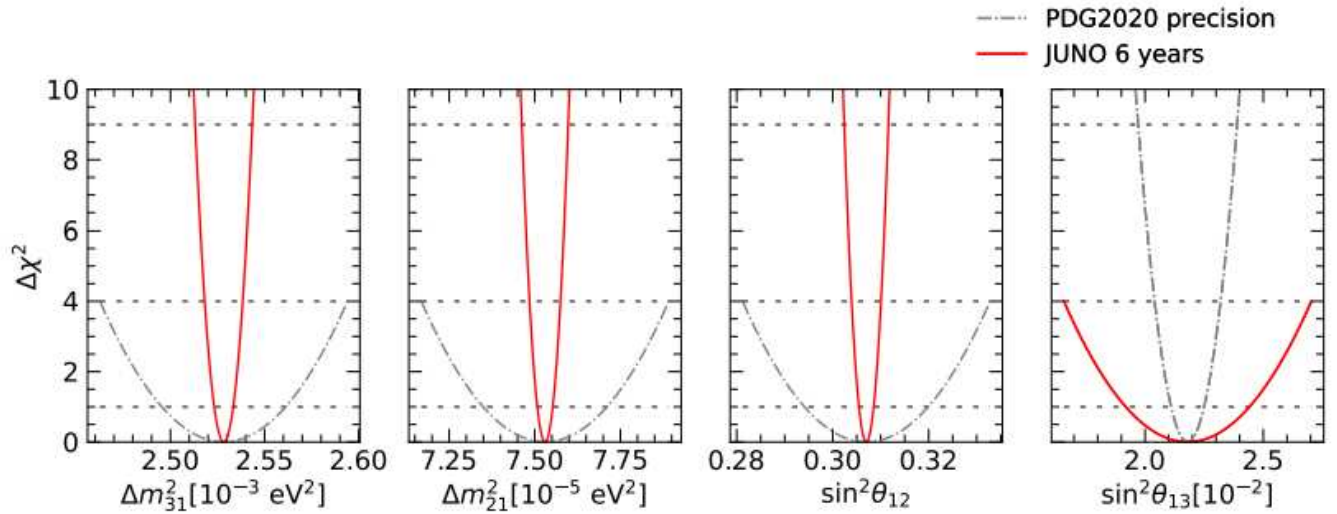
Intrinsic ν beams:
TeV at the interaction point
1-60 GeV after the RLAs
0.5 GeV at the end of cooling

Interim Report IMCC 2024

When will what beam be available?
Are there other places to pick off?
Can we add dedicated straights/storage rings?
10-100 GeV fixed target program for nuclear physics?

Reactor neutrinos JUNO

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)

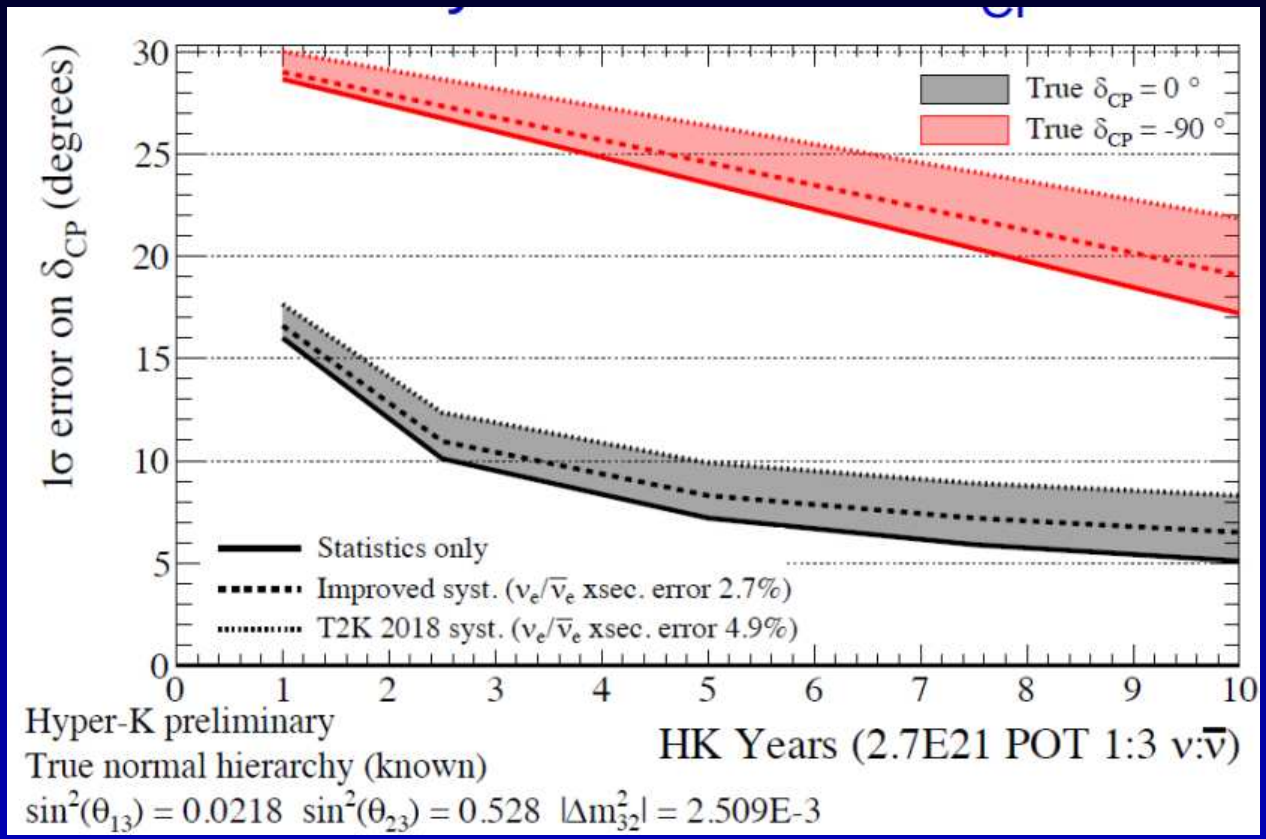


JUNO 2022

Electron antineutrinos, 6 year nominal run.

We will get there around early 2030s

Long-baseline oscillation T2HK

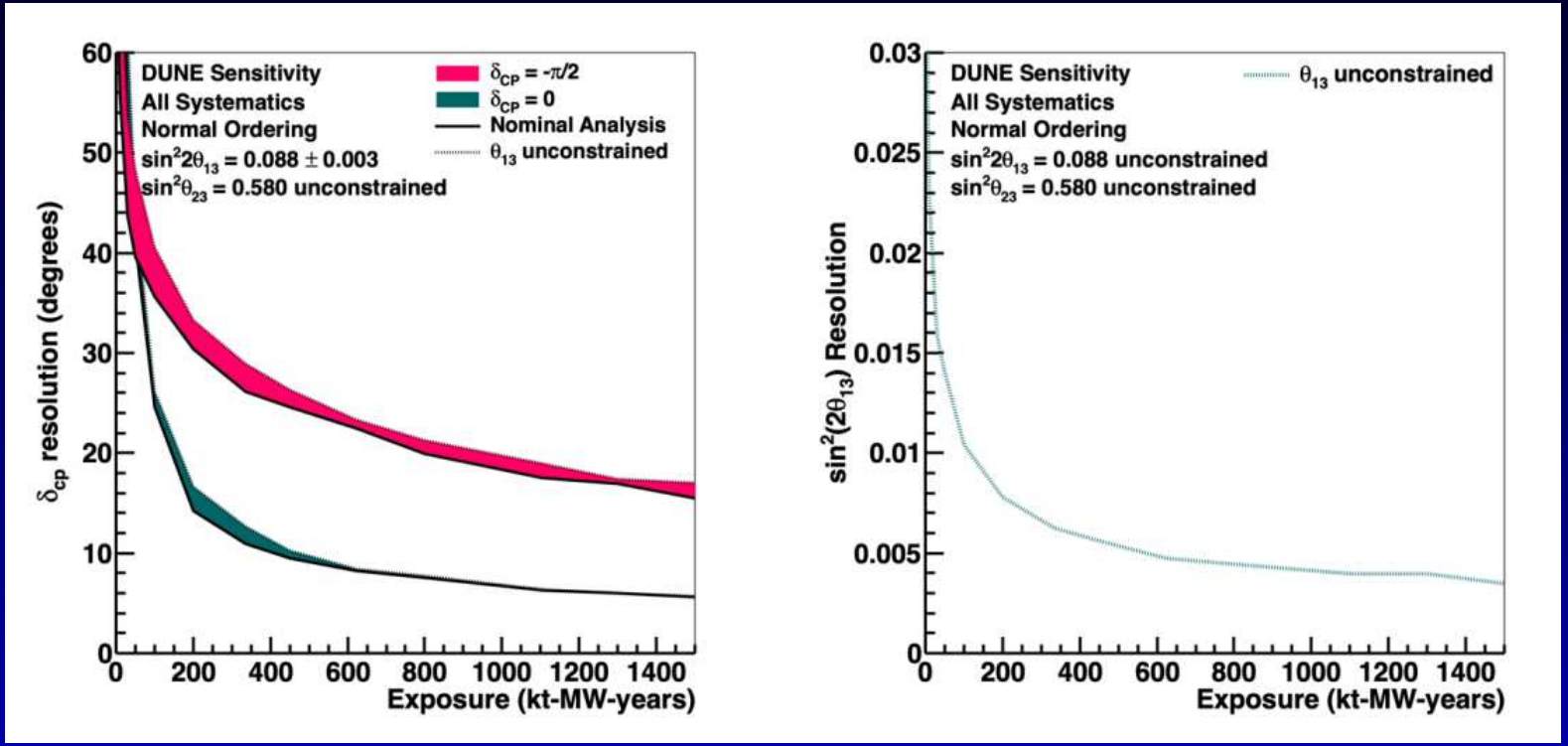


T2HK 2022

Muon neutrinos, 10 year nominal run.

We will get there around late 2030s/early 2040s

Long-baseline oscillation DUNE



DUNE TDR 2020

Muon neutrinos, 600 MW kt yr nominal run

We will get there around early 2040s

15-20 years from now

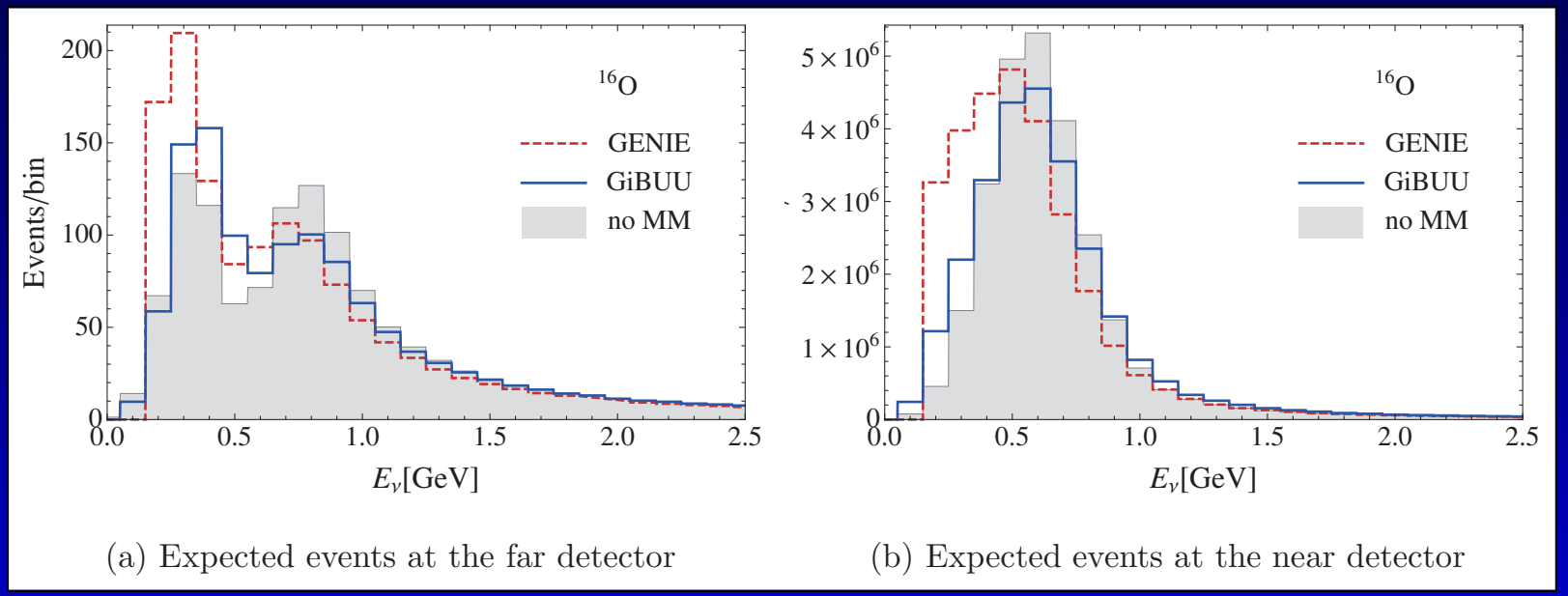
- JUNO will have determined Δm^2_{21} and $\sin^2\theta_{12}$ to better than 0.5%
- T2HK/DUNE will have determined δ to 5–10°
- Global fits will constrain the 3-flavor oscillation framework at the %-level
- Very little information on ν_τ

T2HK and DUNE detectors are NOT suitable for muon decay beams

T2HK and DUNE are enourmous facilities and the neutrino community likely would want to keep using them – BUT systematics will have to improve.

Quasi-elastic scattering

Nuclear effects will make some non-QE events appear to be like QE events $\Rightarrow$ the neutrino energy will not be correctly reconstructed.



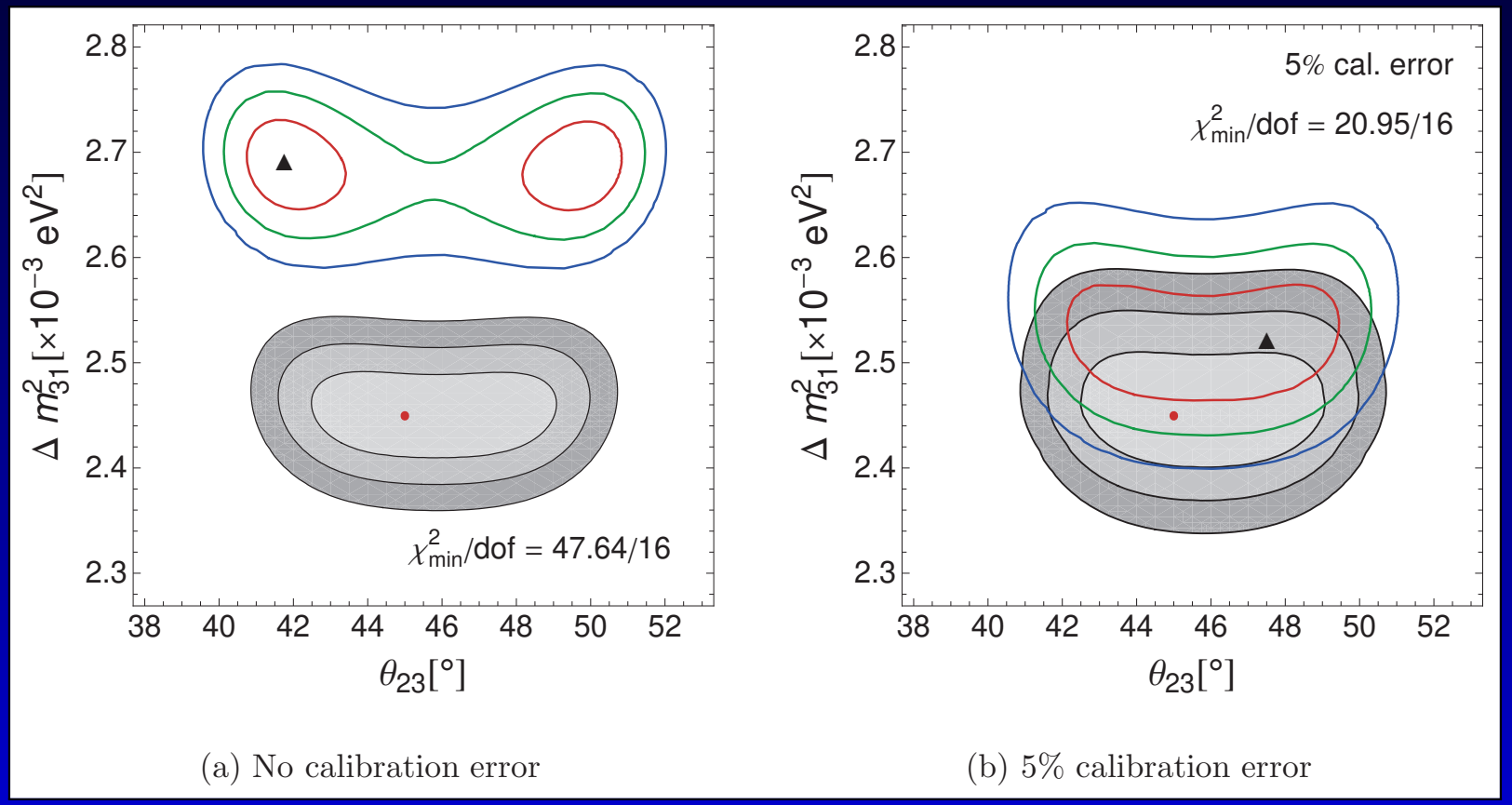
(a) Expected events at the far detector

(b) Expected events at the near detector

Coloma *et al.* 2013

Impact on oscillation

$\nu_\mu \to \nu_\mu$ in a T2K-like setup with near detector.

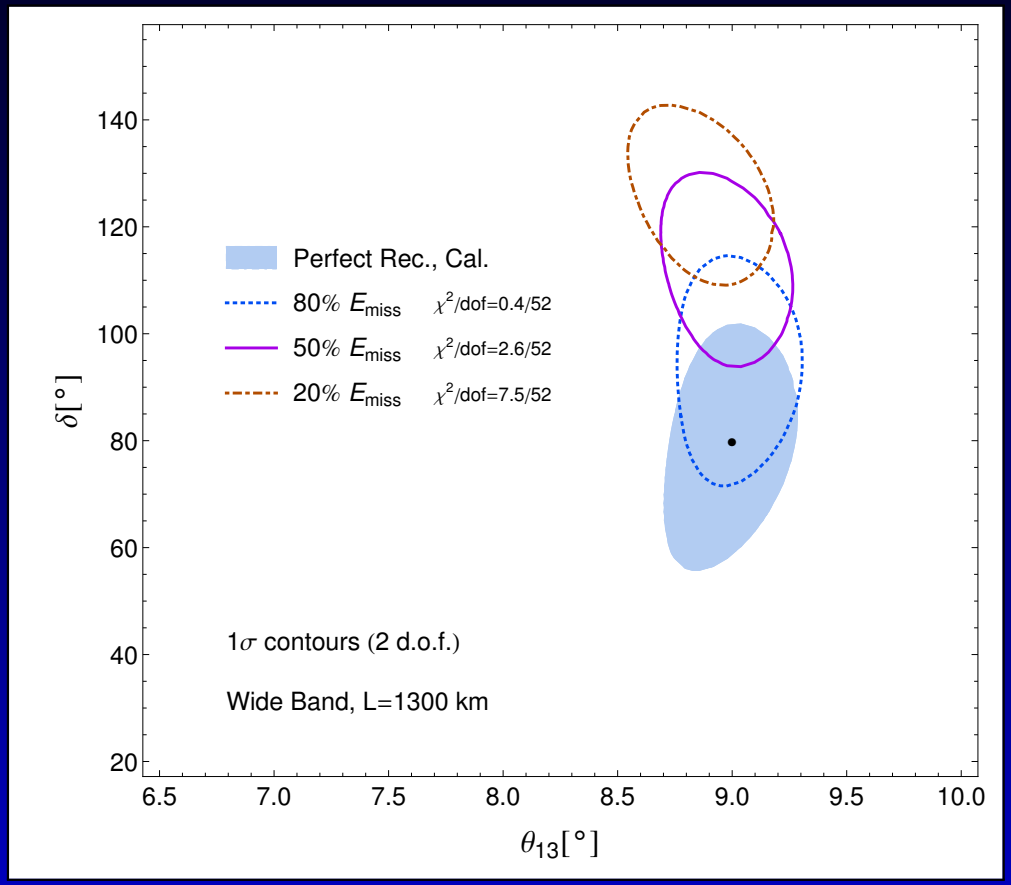


(a) No calibration error

(b) 5% calibration error

Coloma *et al.* 2013

Missing energy



Ankowski *et al.*, 2015

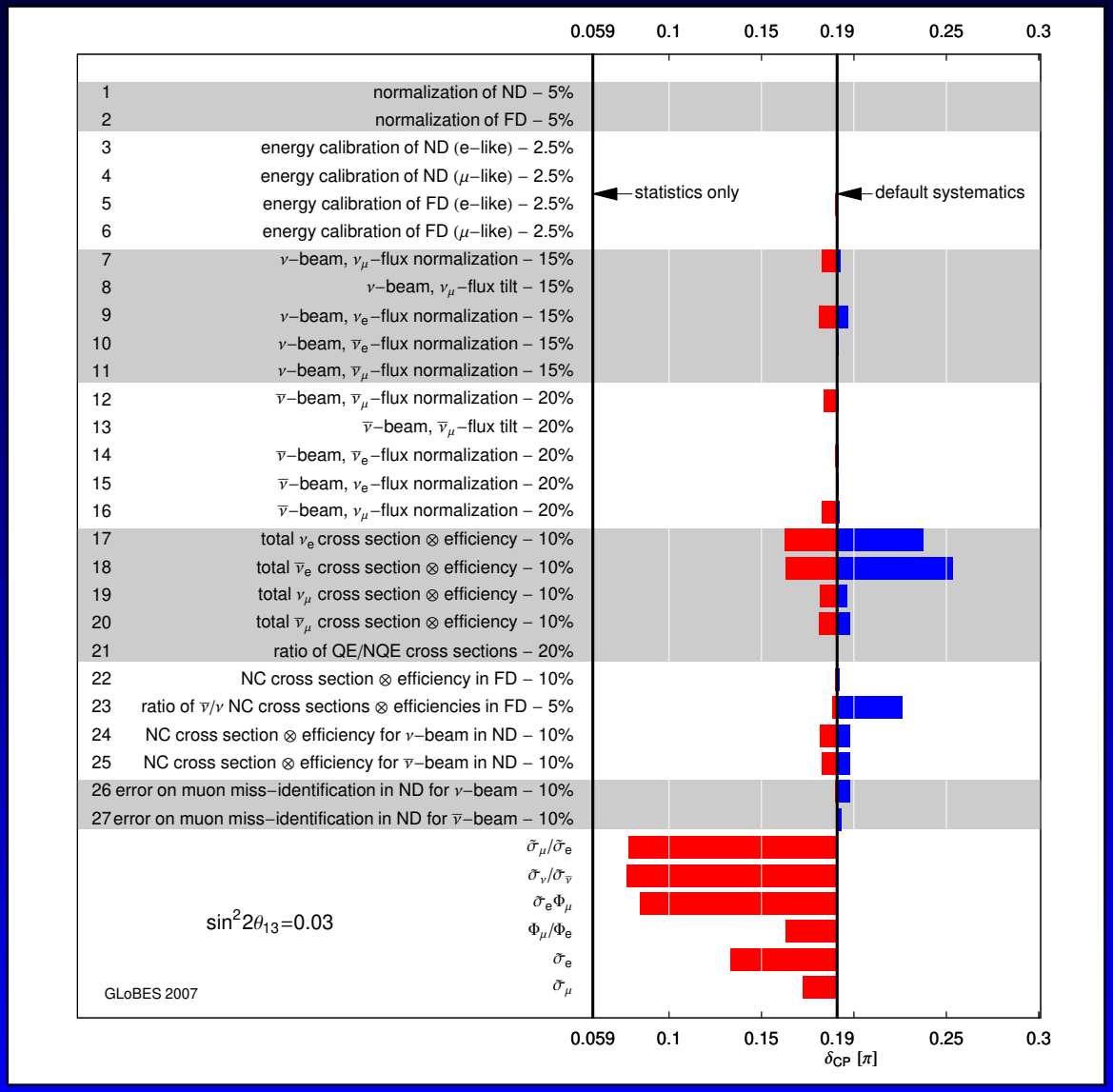
In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

Known unknowns

All studies somehow use a table like this



Two great philosophers

"[...] that is to say we know there are some things we do not know. But there are also unknown unknowns — there are things we do not know we don't know."

Donald Rumsfeld

"In theory there is no difference between theory and practice. In practice there is."

Yogi Berra

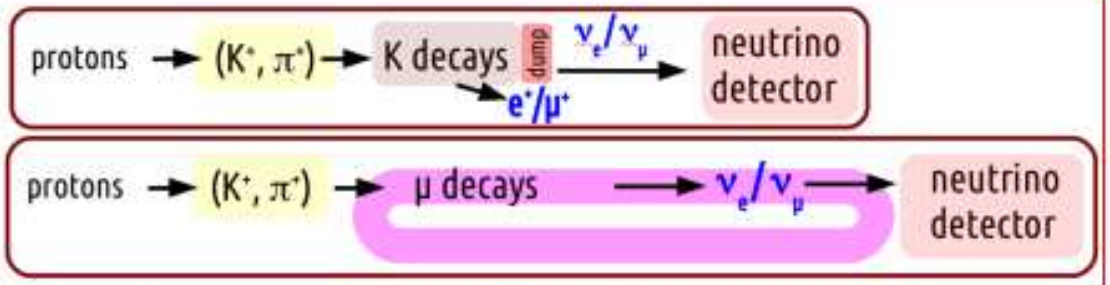
Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people working on this. . .

Without being anchored by data, any result will be based on assumptions and uncontrolled approximations.

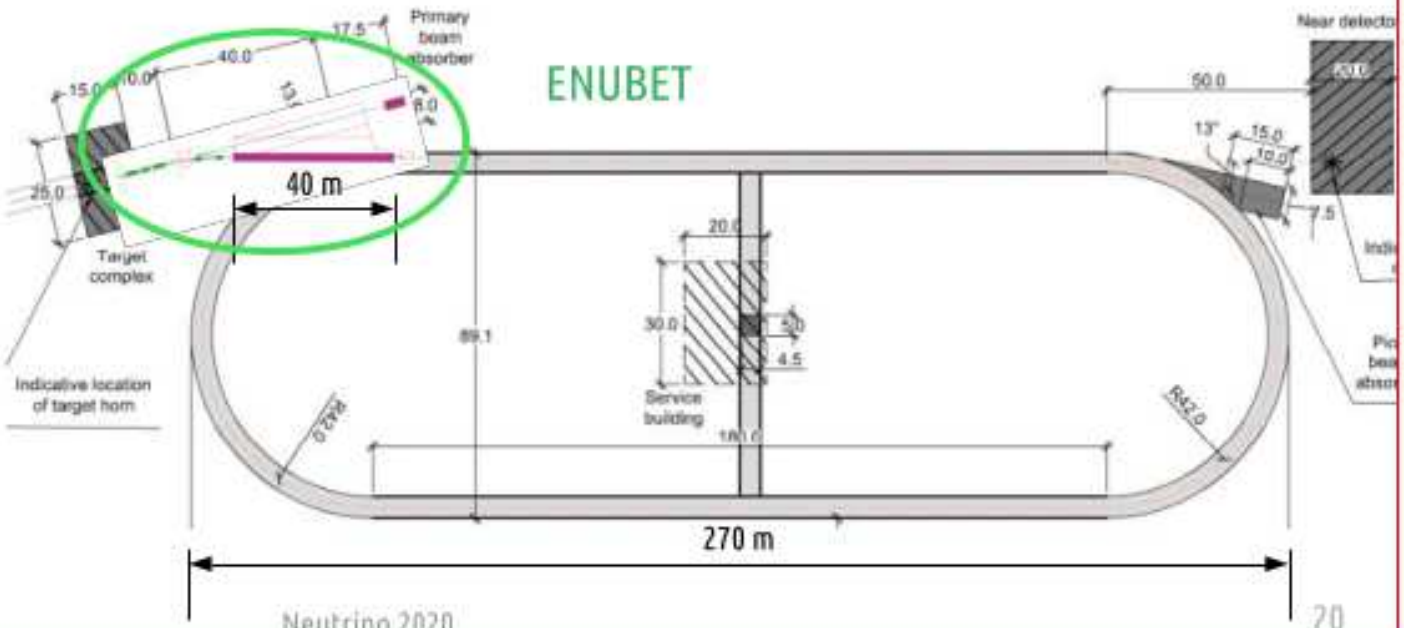
Requires a novel precision, high-luminosity neutrino source $\Rightarrow$ muon decay at a few GeV

nuSTORM & ENUBET



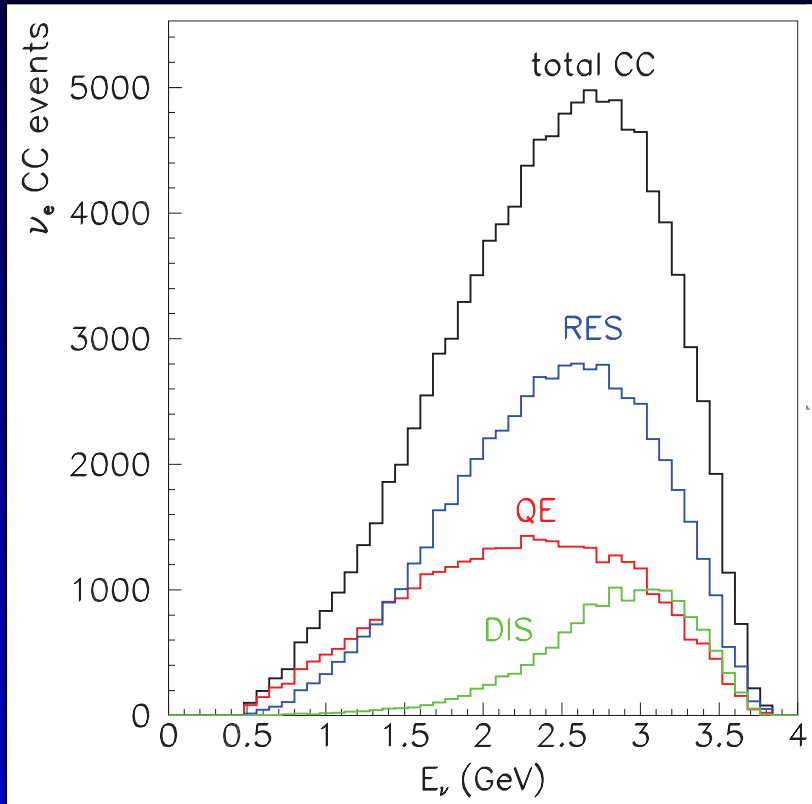
	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. Muons are kept: the most interesting flux parents.	Fast, 100 GeV	Yes, similar	> 300 m from target (ring straight section)

- Different concepts, budget, geometry.
- Main synergy: target facility, 1st stage of meson focusing, proton dump.



nuSTORM in numbers

Beam flux known to better than 1%, 5 GeV muons

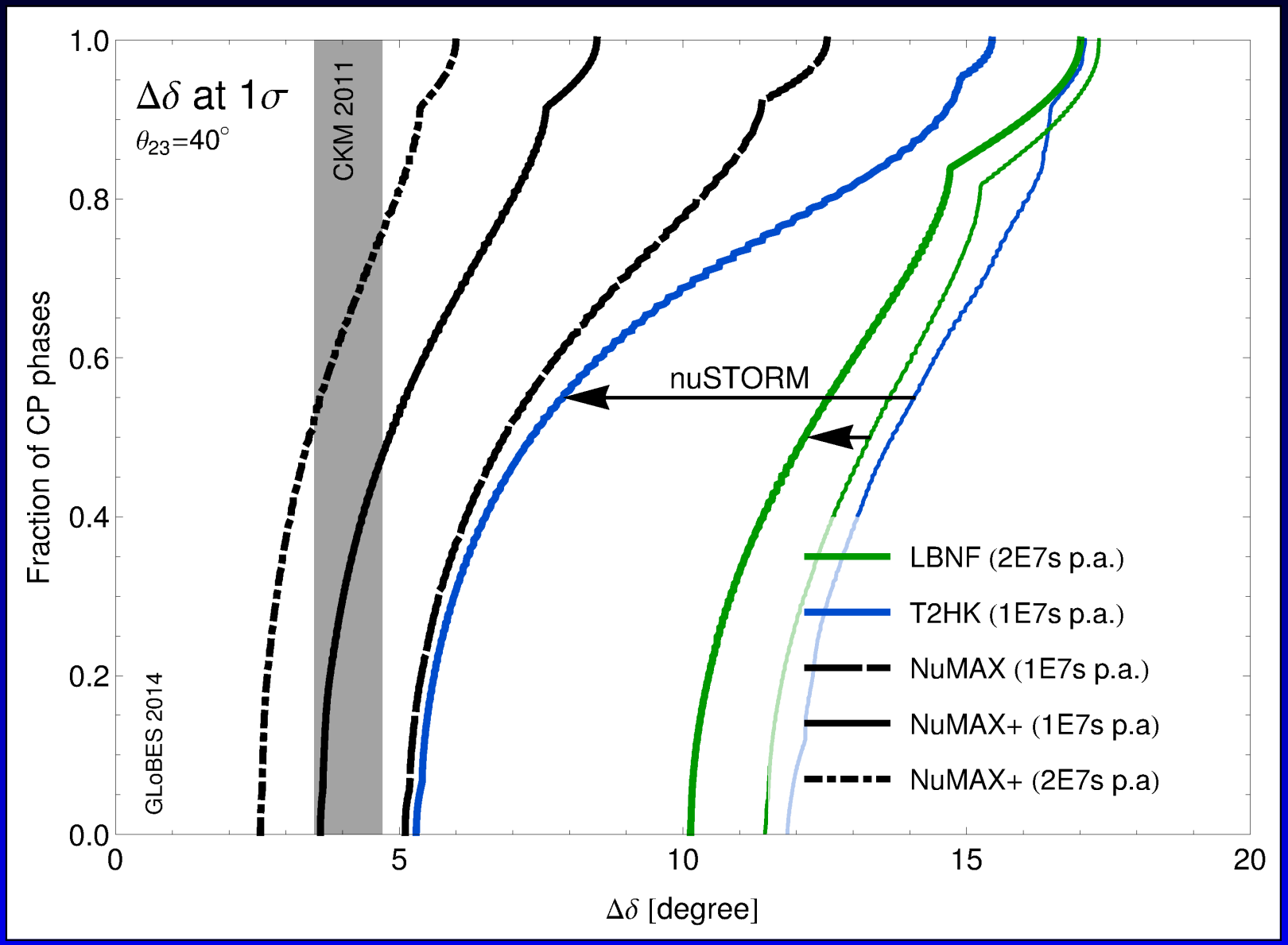


μ^+		μ^-	
Channel	N_{evts}	Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

nuSTORM collab. 2013

DUNE's NDGAr could be an excellent detector.

What this buys you



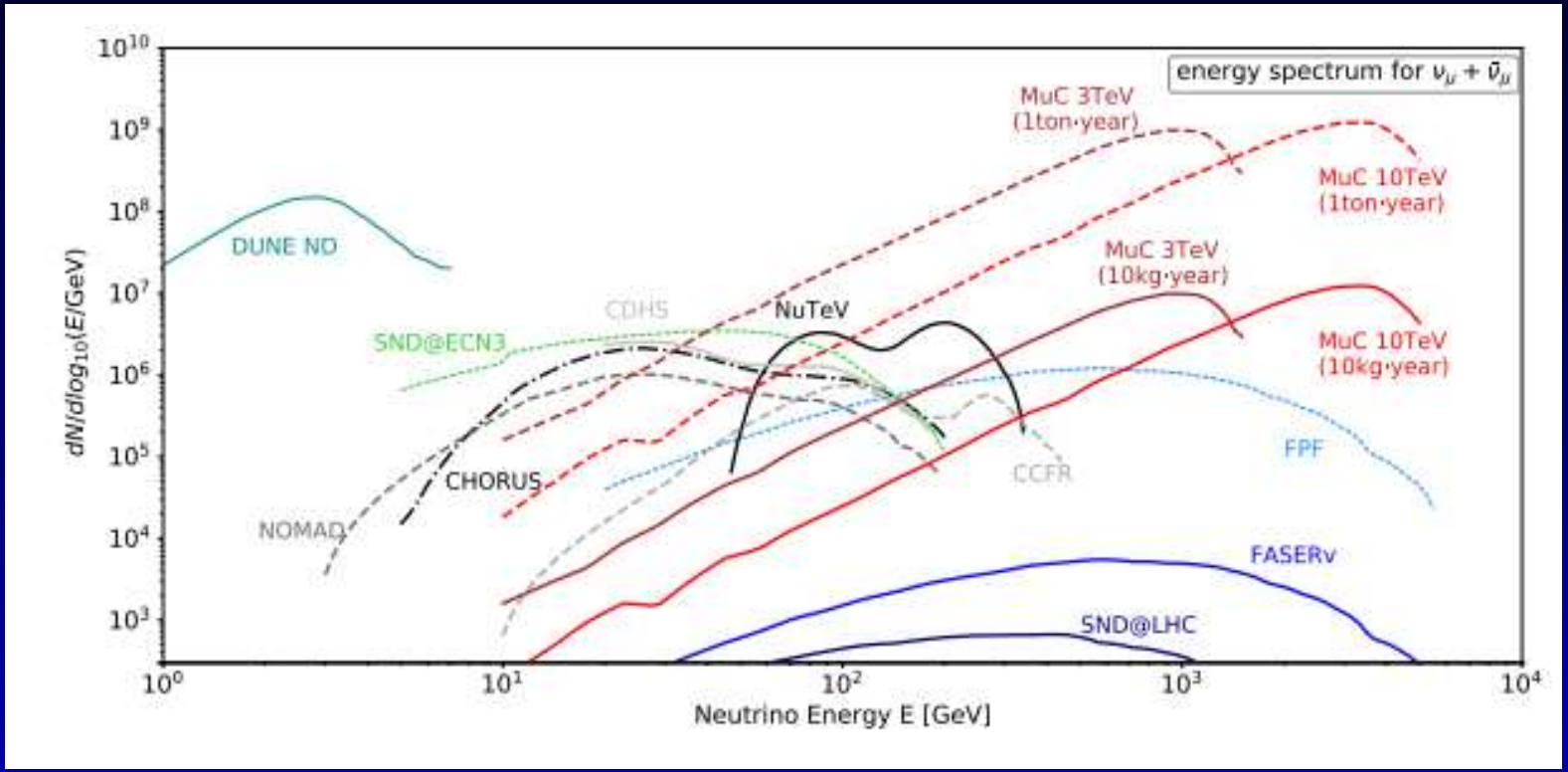
PH, Bross, Palmer, arXiv:1411.0629

Oscillations and the MC

A full-scale neutrino factory is about the same level of effort as DUNE and would improve error bars by a factor of few relative to the current program.

- Neutrino community is focused on DUNE/T2HK for the next 1-2 decades.
- Current detectors can not easily accept a muon based beam.
- Low-energy muon storage ring for cross section precision program to control systematics is needed.
- Time-scale is right: MC demonstrator $\sim$ end of current oscillation program

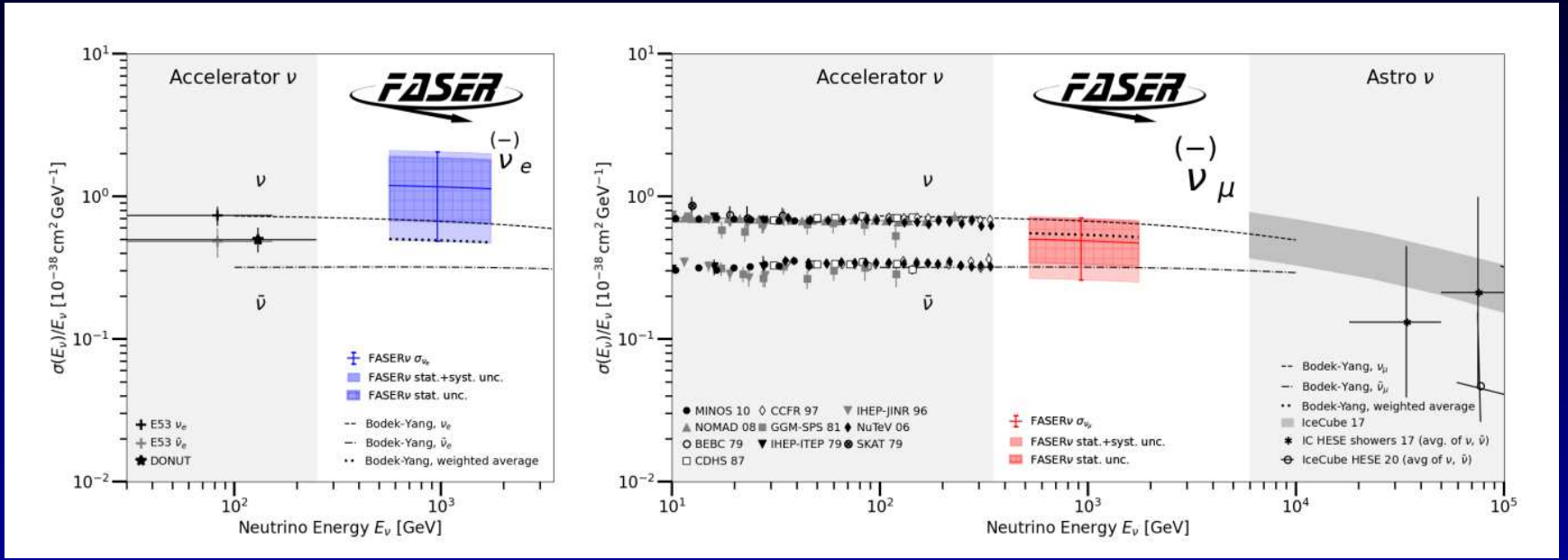
High energy neutrinos



Interim Report IMCC 2024

Fantastic high energy neutrino source
Straightfoward very small detector
Can this sustain 2500 neutrino phycisists?

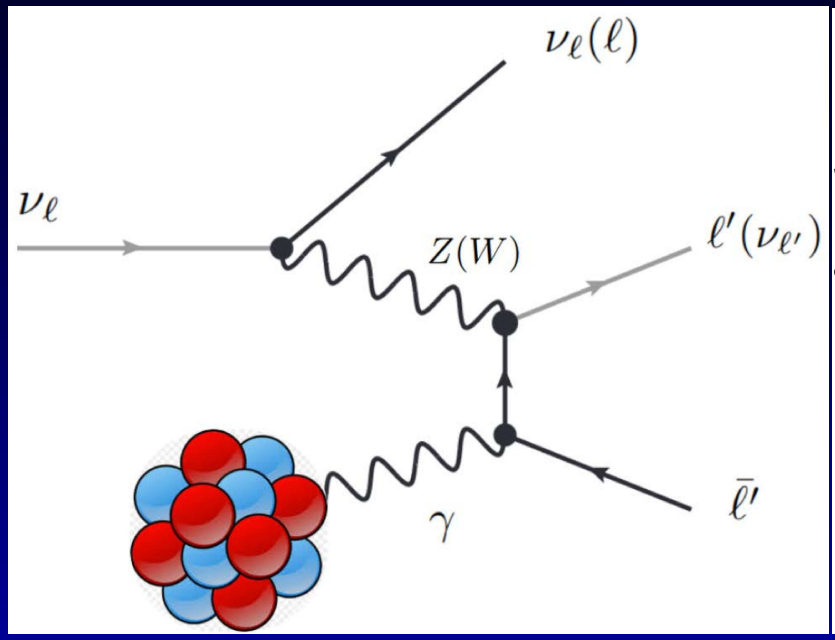
High-energy cross sections

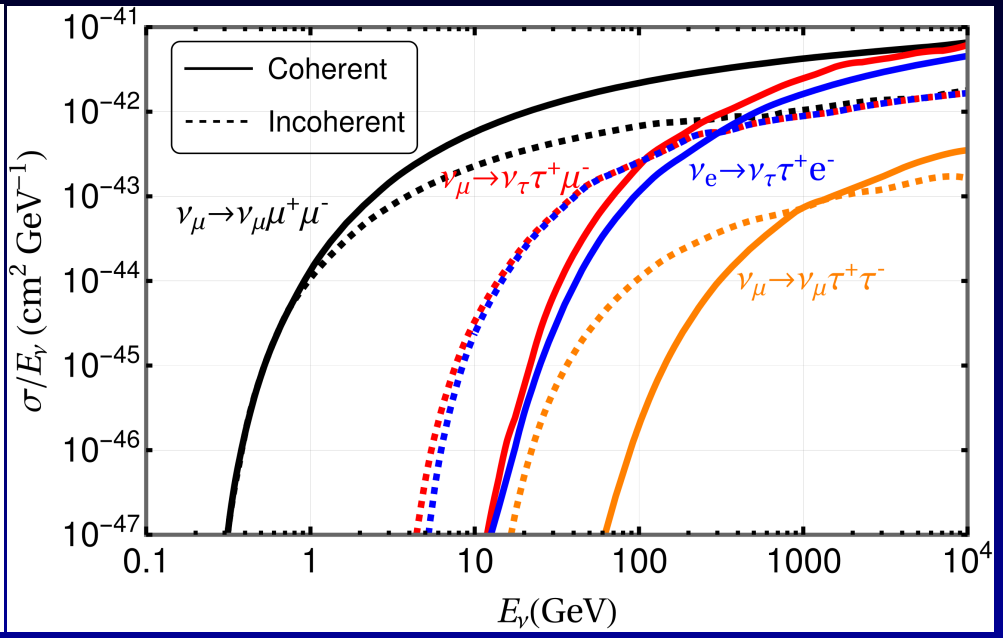


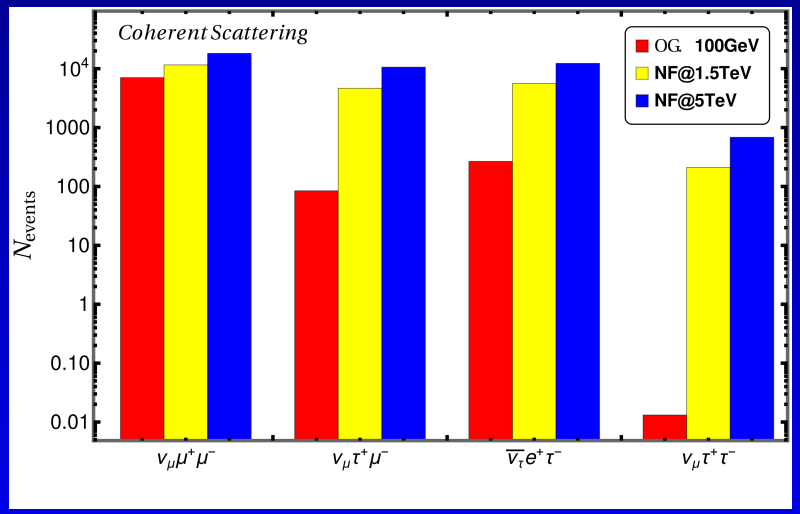
Faserν 2024

Based on a few thousand events.

Tridents







τ tridents not accessible with DUNE

G. Chauhan, PH, in progress

Summary

- Long-baseline oscillation will be done using conventional beams for the next 20 years
- Currently, no obvious upgrade path for DUNE/T2HK to use muon-decay beams.
- Muon storage ring at few GeV to improve neutrino cross sections for DUNE/T2HK. Fits timeline of both communities.
- TeV neutrino fixed-target program very well motivated, but overall small-scale.

Way forward

Muons at all energies are great neutrino sources — number of useful muon decays matters greatly!

Potential synergies are large — to realize them both communities need to talk with each other on a regular basis.

What is the best format for these interactions?