Low Energy neutrino cross sections with muon beams

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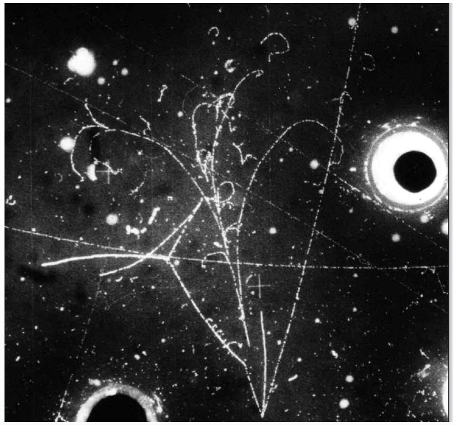
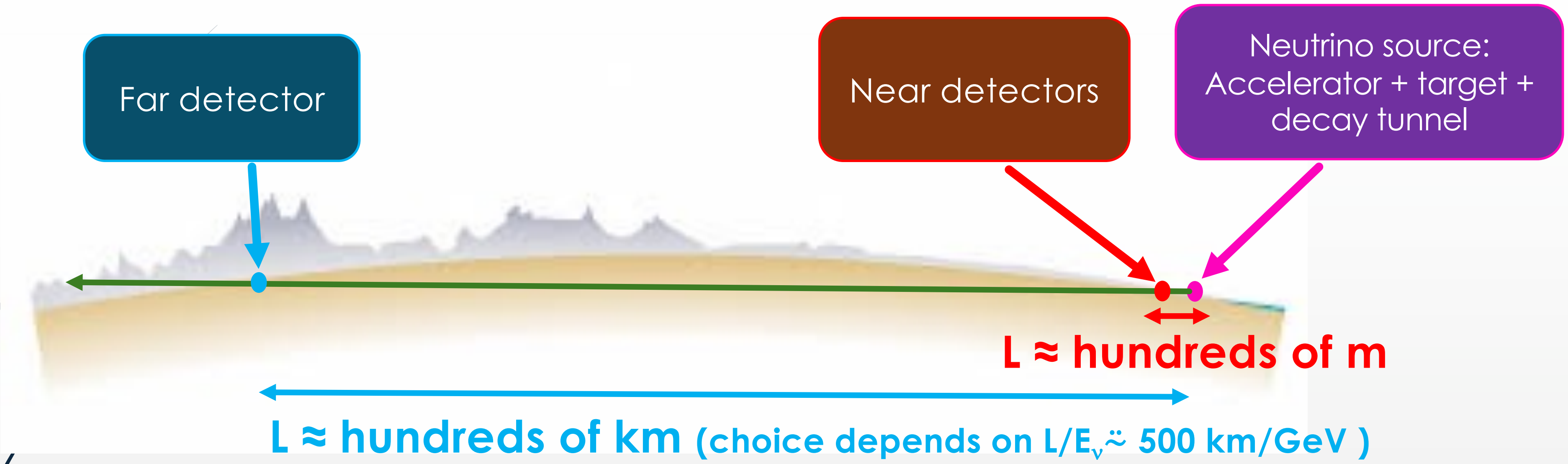
INFN Bari
Venezia 26-30 Maggio 2025

Introduction



- **Neutrino cross-sections first measured in bubble chambers in the 1960's and 70's (ANL, BNL, FNAL, CERN, IHEP)**
  - Very successful experiments; observation of neutral currents
  - Some low Z targets, deuterium x-sec measurements suffered small statistics and poor knowledge of neutrino fluxes
- **Data have large uncertainties (20-100%) or show discrepancies that we would like to understand**
- **Discovery of neutrino oscillations in the last decades has meant two things for neutrino cross-section physics:**
  - Suddenly we really care about neutrino cross-sections in the 0.5-10 GeV range where they are not well measured and the channels are complicated
  - Suddenly there are high intensity (almost pure) muon neutrino beams around the world in the 0.5-10 GeV range for making some of these measurements (but not all ...)

LBNO Concept (experimental point of view)



- Huge masses (10s of kT)
- Often underground
- Oscillated neutrino spectrum

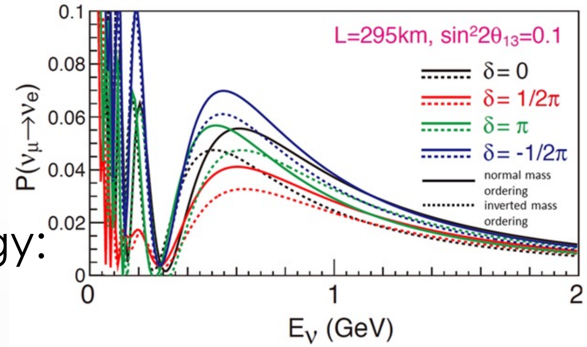
- Constraints on neutrino flux before oscillation
- **Neutrino cross sections**
- Direction of neutrino beam

- High Intensity Proton synchrotron (30-120 GeV)
- Target to produce mesons
- Magnetic horns to select polarity
- Decay tunnel to let mesons decay and produce neutrinos

LBNO experiments enable the unique possibility to compare oscillation in controlled beams of neutrinos and antineutrinos separately

LBNO Concept

Detectors provide event rates in bins of reconstructed neutrino energy:



ND: $$\frac{dN_\beta^{ND}}{\Delta E_\upsilon^{reco}} = N_{target}^{ND} \sum_i \phi^{ND}(E_\upsilon)\sigma_i^{ND}(E_\upsilon)T_i^{ND}(E_\upsilon, E_\upsilon^{reco})\epsilon_i^{ND}(E_\upsilon, E_\upsilon^{reco})dE_\upsilon$$

FD: $$\frac{dN_\beta^{FD}}{\Delta E_\upsilon^{reco}} = N_{target}^{FD} \sum_i \phi^{FD}(E_\upsilon)\sigma_i^{FD}(E_\upsilon)T_i^{FD}(E_\upsilon, E_\upsilon^{reco})\epsilon_i^{FD}(E_\upsilon, E_\upsilon^{reco})P_{\upsilon_\alpha \to \upsilon_\beta}(E_\upsilon)dE_\upsilon$$

Neutrino flux | **Cross-sections for interaction mode** | **Energy migration tensor** | **Efficiency/ acceptance** | **Oscillation probability**

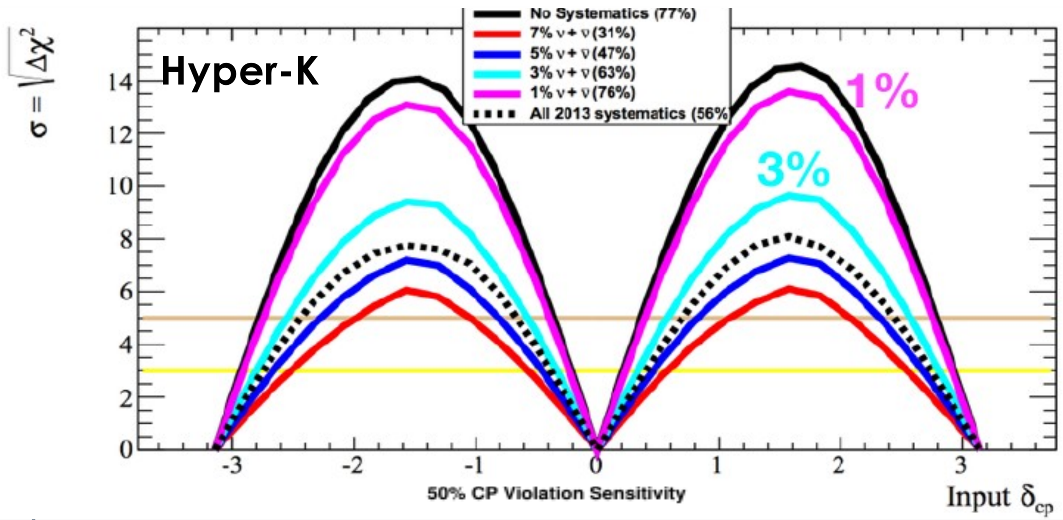
We need to measure with high precision the **oscillation probability** from event rates and then from the **oscillation probability** we extract the oscillation parameters

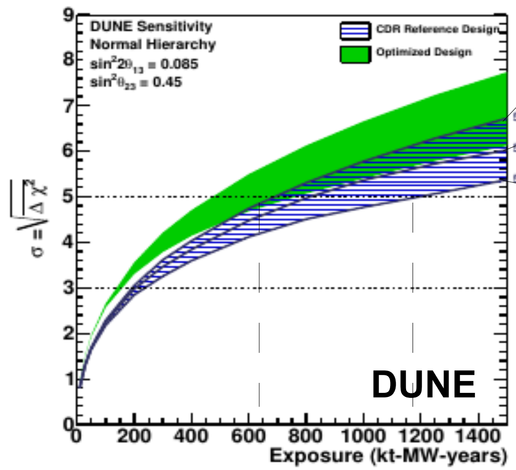
Understand Neutrino Flux and neutrino x-sections is fundamental in LBNO !

ν_μ → ν_μ ν_e

$\bar{\nu}_\mu$ → $\bar{\nu}_\mu$ $\bar{\nu}_e$

Sensitivity of future Neutrino Oscillation Experiments

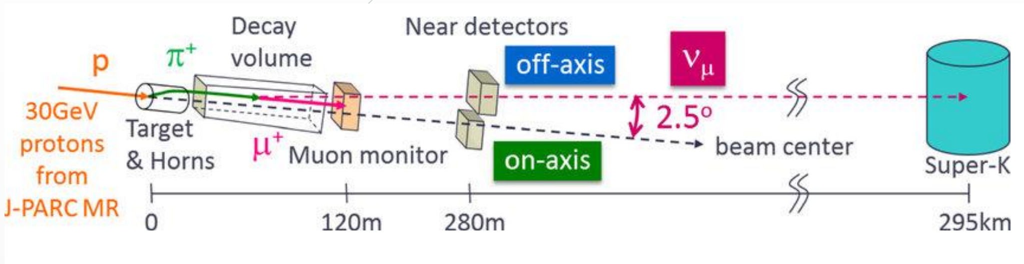




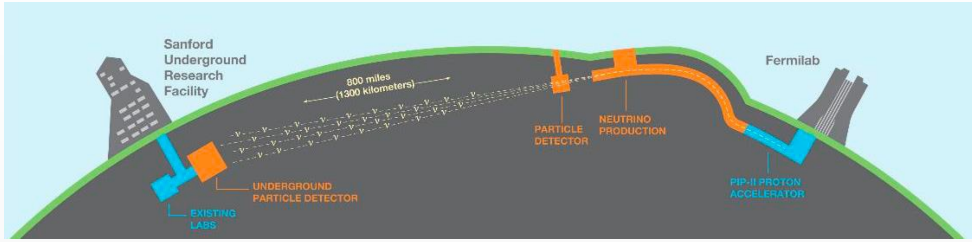
- *Up to now the precision was limited by statistics but once DUNE and Hyper-Kamiokande will begin data collection, their unprecedented beam power and large detector mass will drastically reduce statistical uncertainties, making systematic errors the dominant constraint on their physics potential.*
- The sensitivity of future neutrino oscillation experiments strongly depends on the ability to reduce the impact of systematic errors to the percent level.
- Uncertainties in low-energy cross-section measurements (0.2–5 GeV/c) and Monte Carlo models affect the extrapolation of fluxes from Near Detectors (ND) to Far Detectors (FD), limiting the precision of the results.

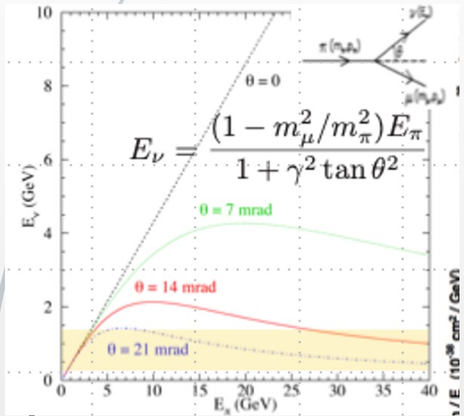
Neutrino Beams (0.2-5.0 GeV)

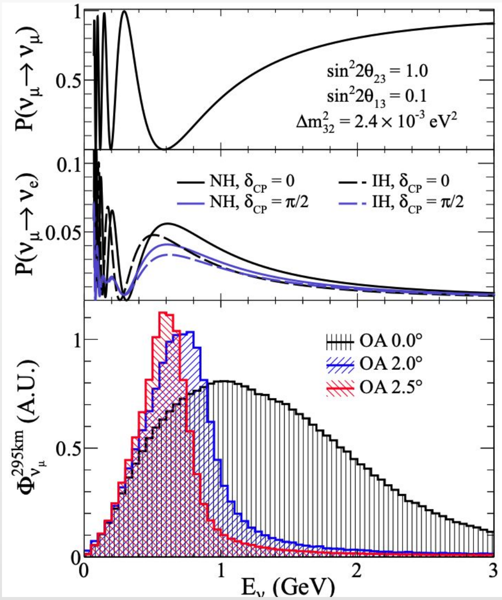
T2K/Hyper-K



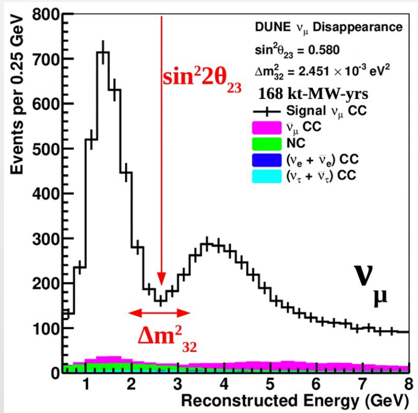
Dune

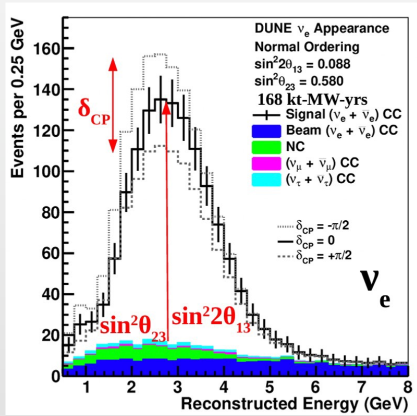






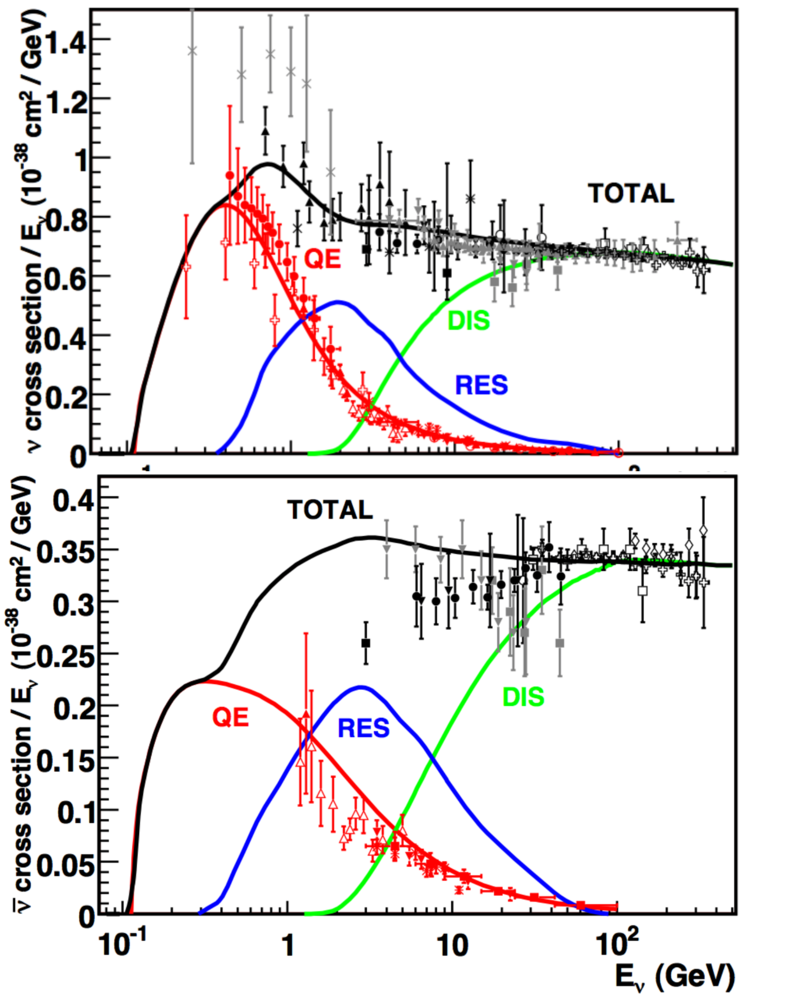
60-120 GeV protons
L=1300 Km
E_{peak} = 2-4 GeV/c
Wide on Axis



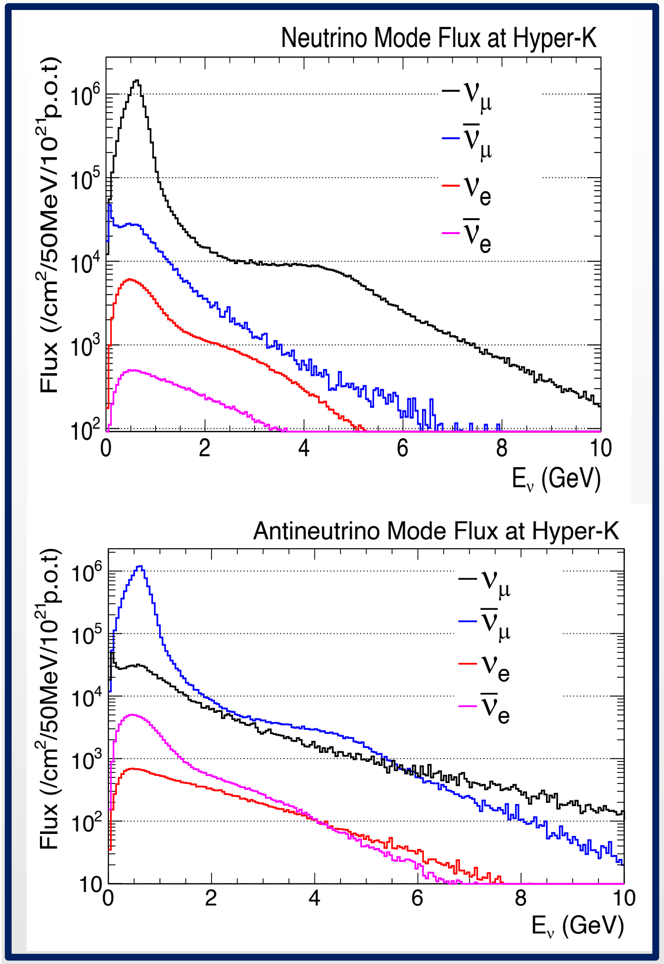


30 GeV protons
L=300 Km
E_{peak} = 600 MeV/c
Off-axis

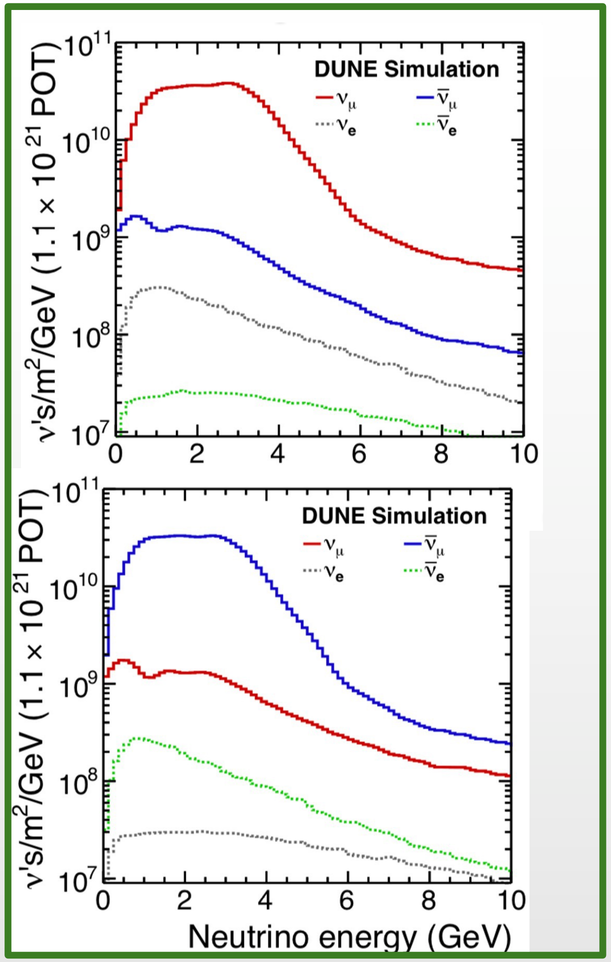
X-Sections & beam composition



Hyper-K



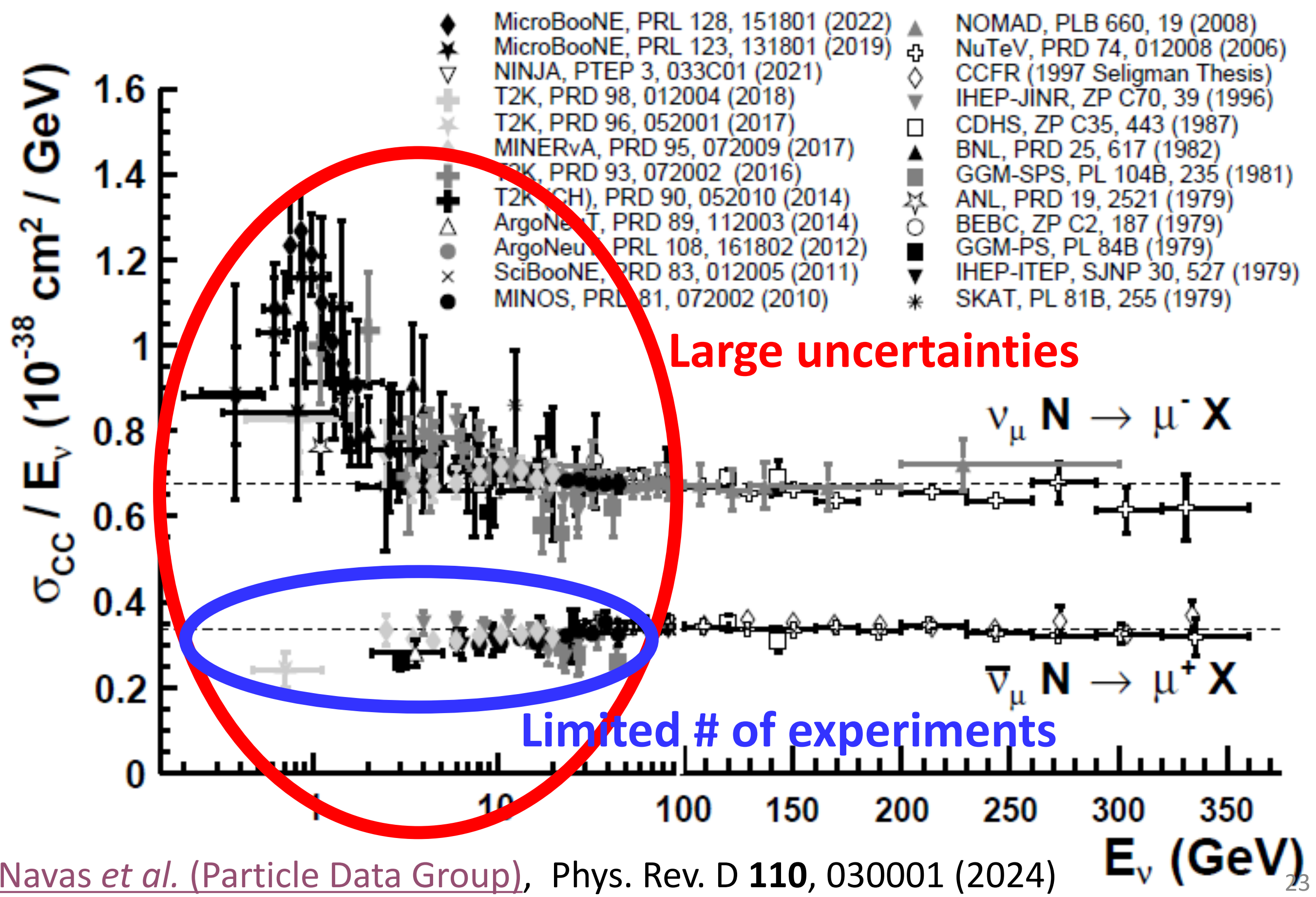
DUNE



Current status of "neutrino cross-section" measurements

Inclusive charged current total cross-section

(G.P. Zeller's review)

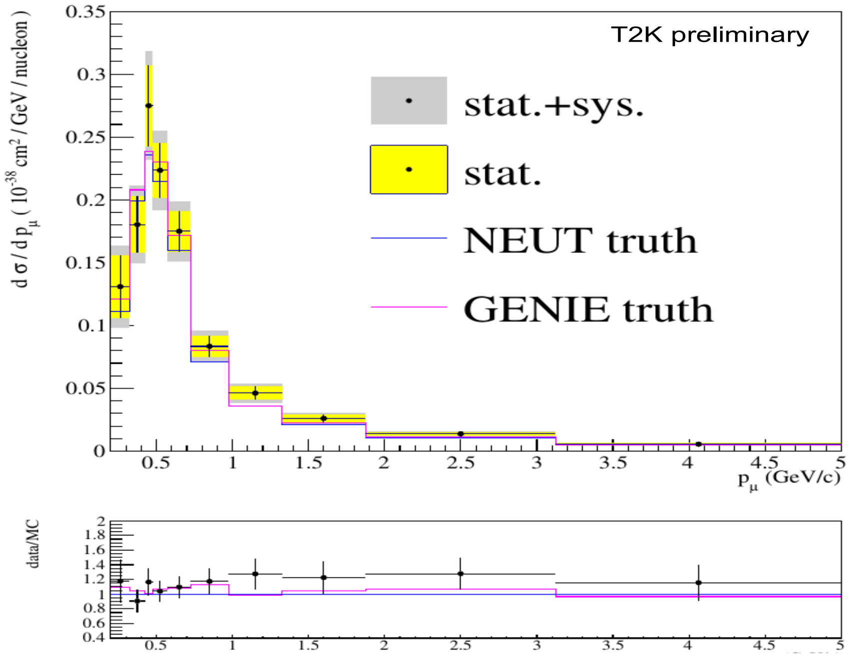


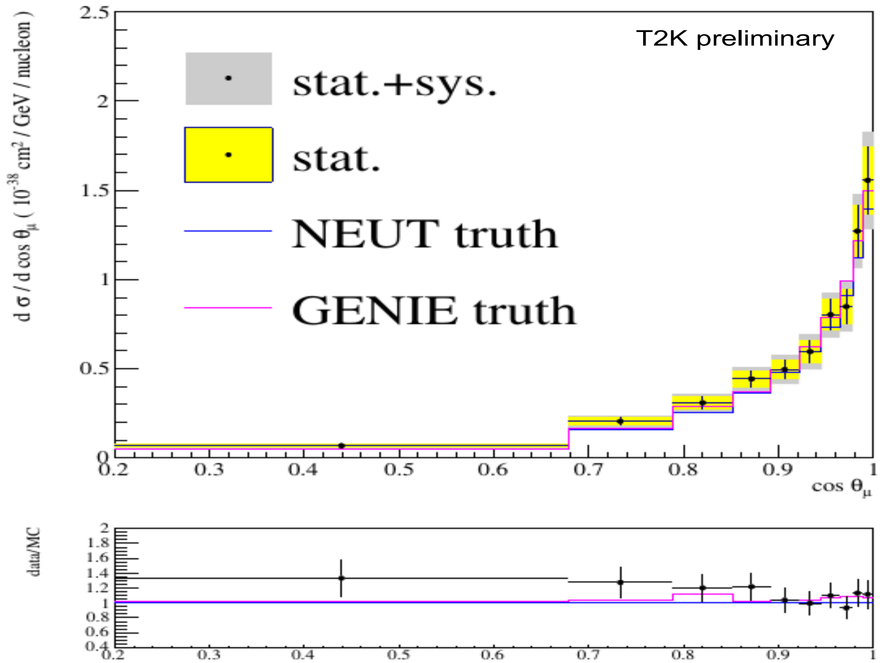
S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

$\bar{\nu}$ cross section measurement

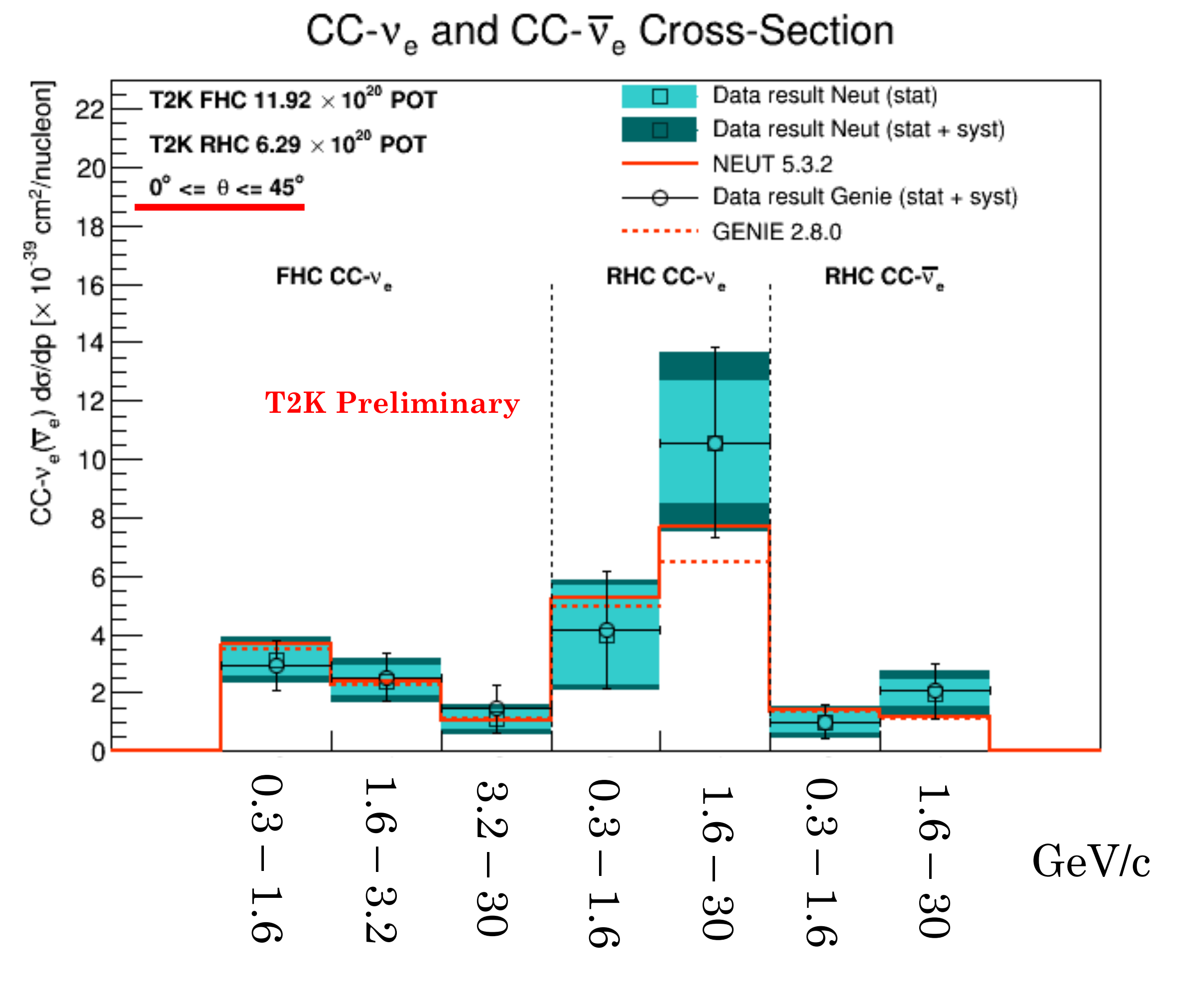
The measurement of δ_{CP} crucially depends on the comparison of ν vs $\bar{\nu}$ oscillation

$\rightarrow$ **bias on ν vs $\bar{\nu}$ cross section direct reflect in bias on δ_{CP} measurement**



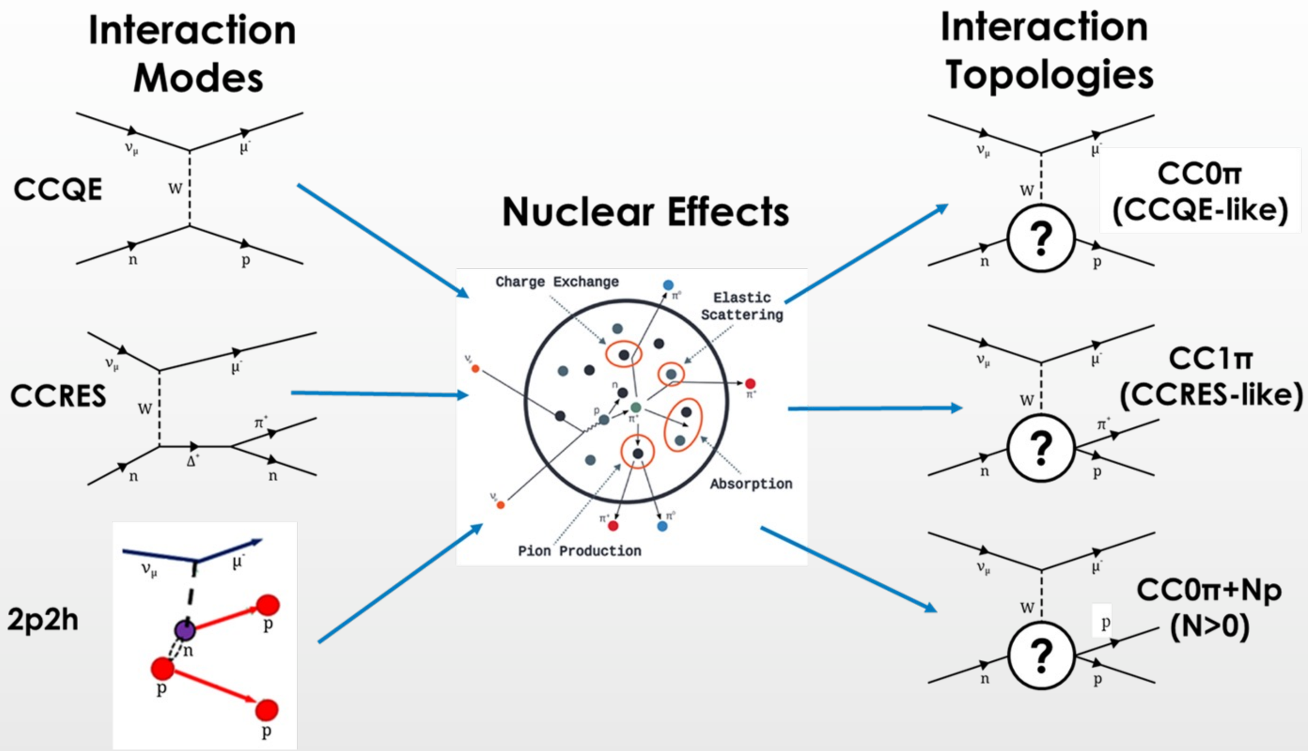


ν_e X-section



What do we measure?

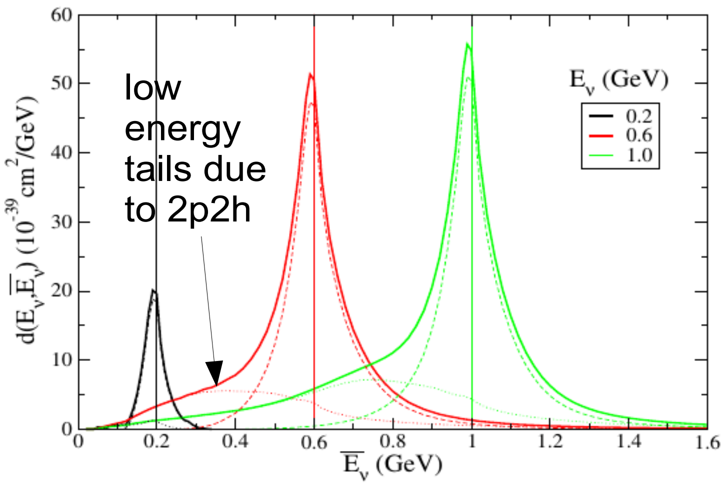
- Interaction not on free nucleons
- Nuclear effects / Final State Interactions (FSI) can alter the event observables
- Effects depend on target material
- More relevant for low neutrino energies



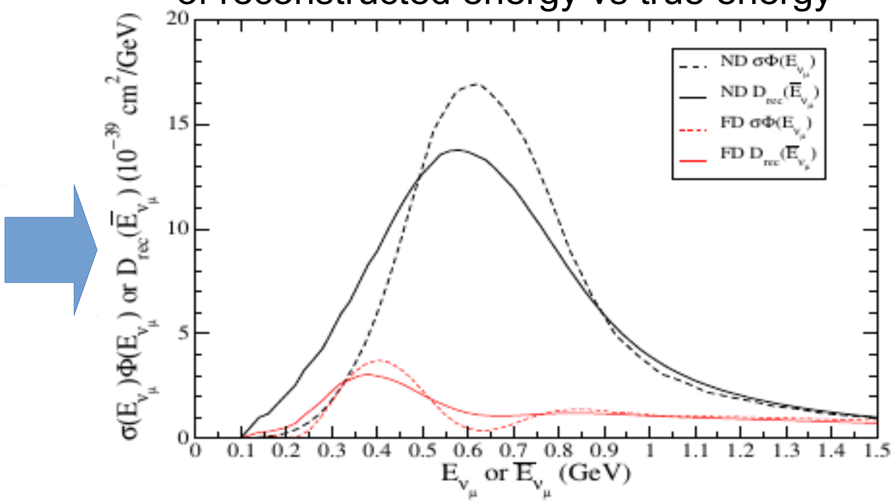
Why do we need good models ?

Neutrino oscillation goes like ~L/E_ν but we do not measure E_ν ! We measure the outgoing muon at SuperKamiokande and we infer the neutrino energy on the base of available models

Distribution of true energy for a given reconstructed energy



Near Detector and Far Detector spectra of reconstructed energy vs true energy



2p2h events fill the "dip" region sensitive to neutrino oscillation → **wrong modelling would cause bias on oscillation parameters**

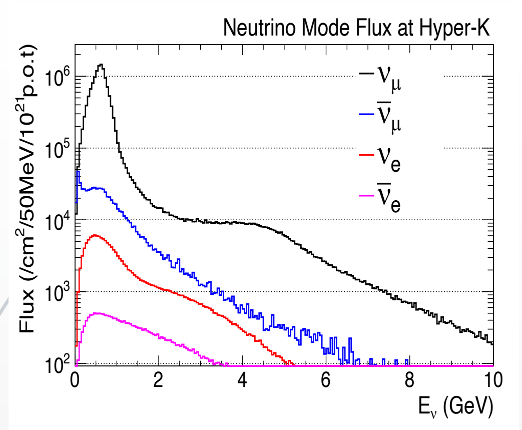
What do we need to measure?

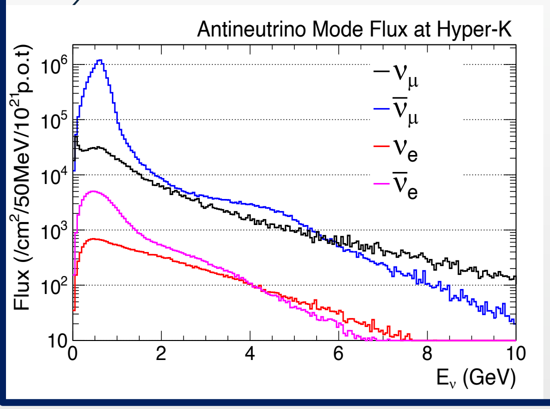
Uncertainties in ND→FD extrapolation :

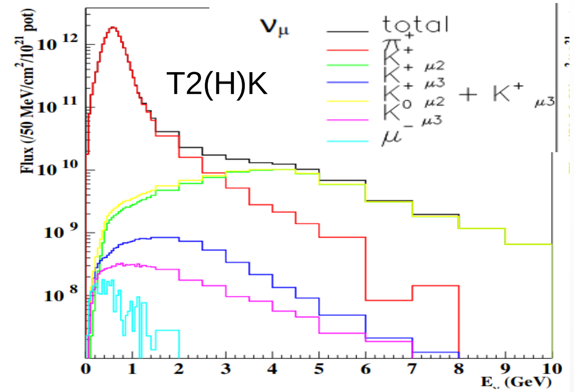
✔ • different E_ν distribution (because of oscillation)	need to reconstruct the neutrino energy from the final state particles
✔ • different target	A-scaling: measure cross-sections on different targets (and/or on the same target of FD)
➔ • different acceptance	measurement of cross-section in the larger possible phase-space: increase angular acceptance of ND
➔ • different neutrino flavor (because of oscillation) ν ($\bar{\nu}$) flux has typically a wrong sign component	measure cross-section asymmetries between different neutrino species (eg ν vs $\bar{\nu}$ important for δ_{CP})

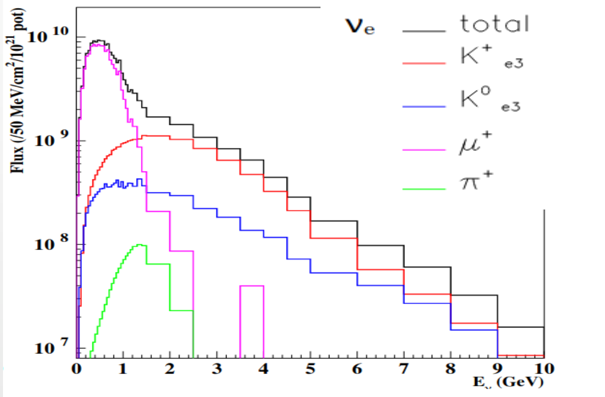
The new generation of ND detectors will help a lot in reducing the systematic errors ... but it's not enough ...

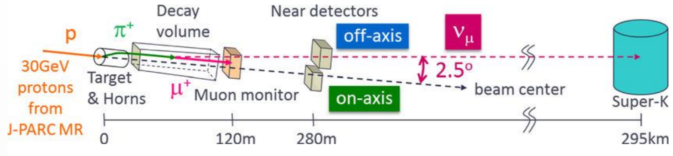
Neutrino beam composition: (T2K/Hyper-K)











- Almost pure ν_μ beam
- Only 1% ν_e contamination (from muon decay) => Minimise ν_e to observe appearance
- The ν_e flux is an intrinsic background
- The low ν_e flux makes it difficult to perform precise measurements of the ν_e cross-section.

external measurements !

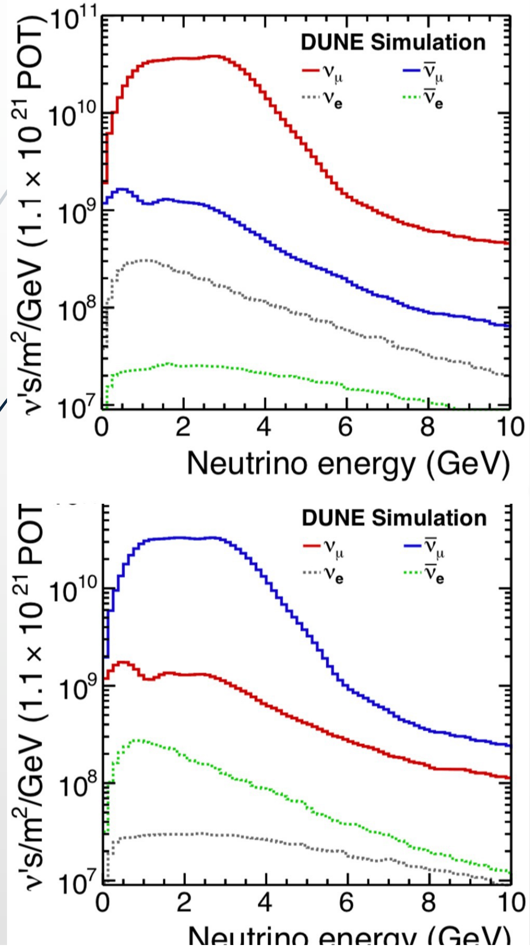
$\nu_\mu \longrightarrow \nu_\mu \quad \nu_e$

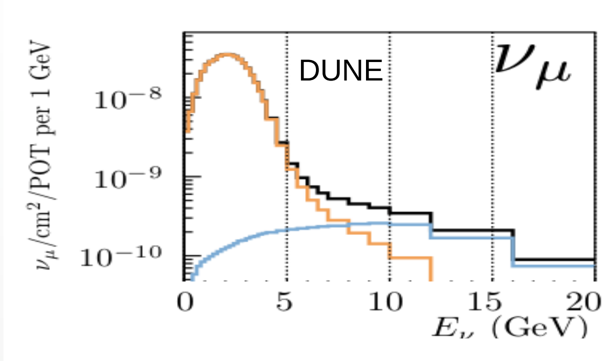
$\bar{\nu}_\mu \longrightarrow \bar{\nu}_\mu \quad \bar{\nu}_e$

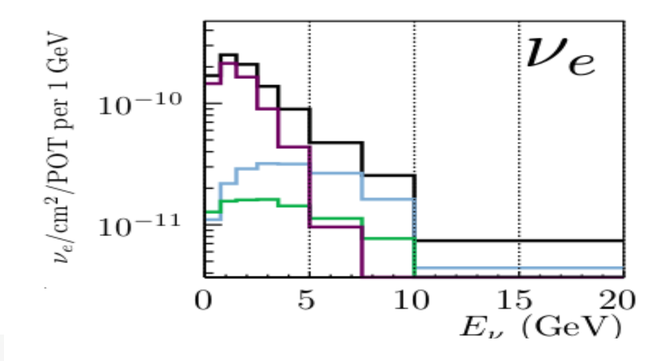
oscilllated samples at LBL far detectors

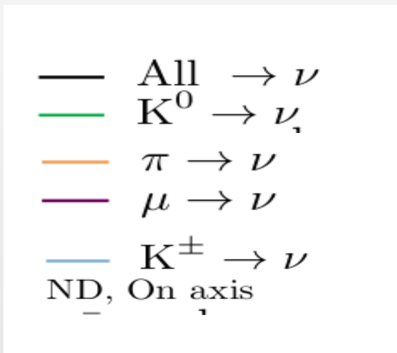
Neutrino beam composition (DUNE)

DUNE









Similar to T2K but higher energy and broader spectrum and a larger fraction of ν_e comes from K_0.

The problem can be partially mitigated by using tagging techniques in an ancillary experiment

Can we do something more ?

Neutrino beam from muons

- *The limitations can be overcome by producing neutrino beams via muon decay in the straight section of a storage ring.*
- The key advantages of generating neutrino beams from muon decays rather than meson decays are:
  - The absolute neutrino flux can be accurately determined, provided the stored muon current, momentum, and polarization are carefully measured.
  - The beam contains only one type of neutrino and one type of antineutrino, with their identities controllable by selecting the charge of the stored muons.
  - This enables precise measurements of ν_e, ν_μ, (anti)ν_e, and (anti) ν_μ.

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

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

Advantages

Beam Composition
=> 50% of $\nu_{e,}$

Excellent ratio ν/proton
=> running cost

No background

Simple and more compact detectors

First intense ν_e and $\bar{\nu}_e$ Beam in the word !!

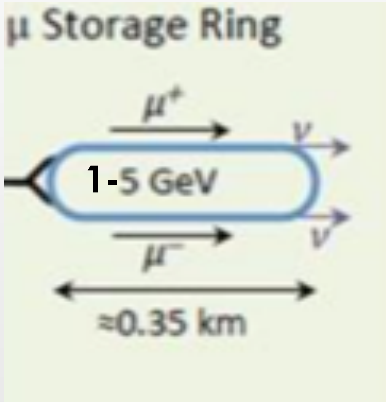
Storage muon rings for neutrinos

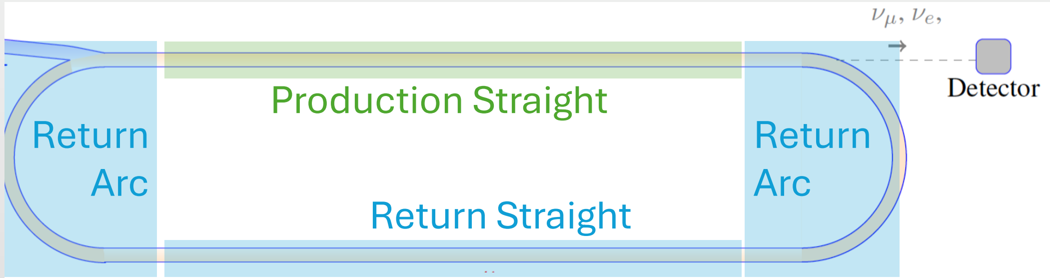
- **Why we need a storage muon ring**
  - The muon lifetime is about 100 times longer than the corresponding charged pion lifetime. A linear decay channel of the type used to produce conventional neutrino beams would in practice be too short to use efficiently as a muon decay channel.
  - This problem can be overcome by using a muon storage ring with a straight section pointing towards the desired experimental area.

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

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- **This method yields a beam with a well-defined and precisely known composition:**
  - a stored μ−beam produces 50% muon neutrinos and 50% electron antineutrinos, while a stored μ+ beam results in 50% muon antineutrinos and 50% electron neutrinos.
  - In the energy region of interest 0.2 muons/p.o.t can be produced
  - We assume 25% of the decay in the straight section

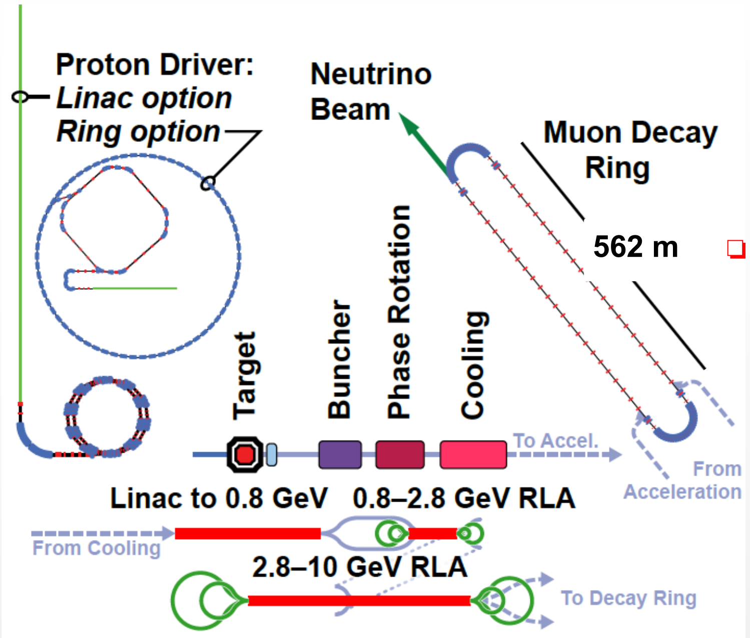




Neutrino Factories: a first stage of a Muon Collider (past)

- *Requirements*
  - High intensity Proton driver – Proton beam ~10 GeV on target > 10^{22}/year
  - Target, capture and decay
  - Bunching and phase rotation
  - Ionization Cooling (MICE)
  - Acceleration - 120 MeV →→ 10 GeV with RLAs
  - Decay ring
    - Store for ~100 turns
    - Long straight sections
- *Results :* 10^{21} muons/year

Investments in R&D and High Cost



Baseline: 10 GeV muons, one storage ring with detector at ~2000 km, due to large θ_{13}

Magnetised Iron Neutrino Detector (MIND):
- 100 kton at ~2000 km

An example from the literature (Rev. D 57 (1998) 6989-6997)

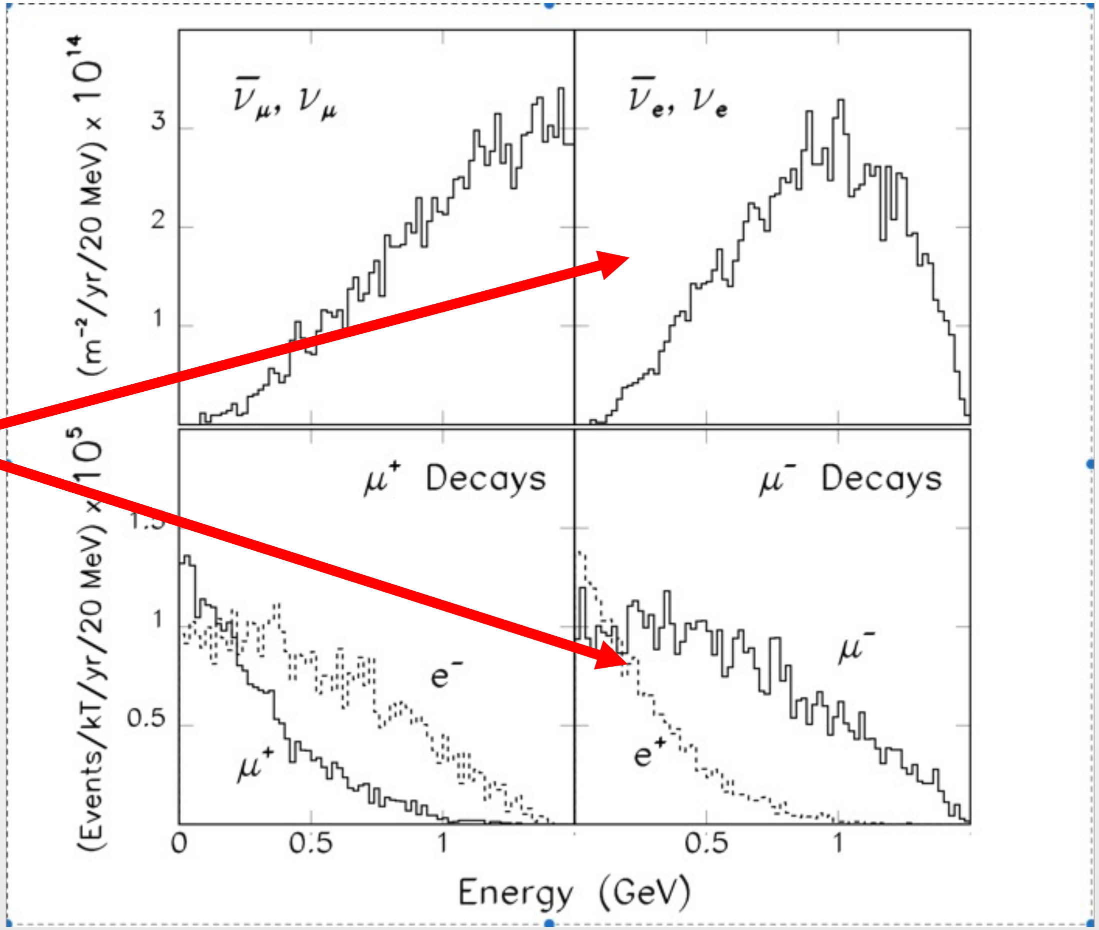
- $5*10^{13}$ proton/burst (2 bursts x cycle) => $1.5*10^{21}$ p.o.t/year
- 25% decays in the straight section
- $5*10^{19}$ (ν_e + anti-ν_μ + anti-ν_e + ν_μ)

- $5*10^6$ CC interactions (ν_e + anti-ν_μ + anti-ν_e + ν_μ)

High intensity required by the N.F. and muon collider parameters

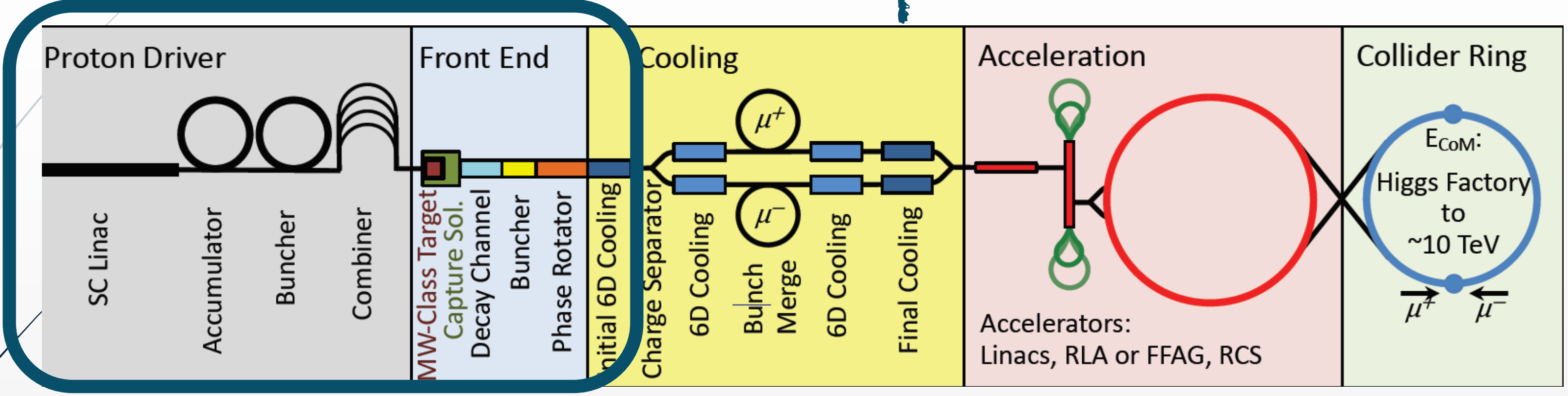
Very good potential as ν_e beam

p (GeV/c)	m_{DET} (kT)	L (km)	$< E_\nu >$ (GeV)	L/$< E_\nu >$ (km/GeV)	ν_e CC interactions/yr
20	10	9900	13	744	1×10^3
20	10	732	13	57	2×10^5
10	10	732	6.6	111	3×10^4
1.5	1	1	1	1	5×10^6



Calculated fluxes and spectra from a detector of 1 KTon , 1 km downstream of a muon source of 1.5 GeV/c for 10^{21} p.o.t..

Neutrino beam as first stage of a muon collider (present)



The R&D required at the initial stage has so far delayed the realization of the first neutrino beam from muons

However, new opportunities are now emerging to initiate a promising neutrino physics program !

Key Feasibility Issues

- Proton Driver
- Target
- Front End
- Cooling

High Power Target Station

Capture Solenoid

Energy Deposition

RF in Magnetic Fields

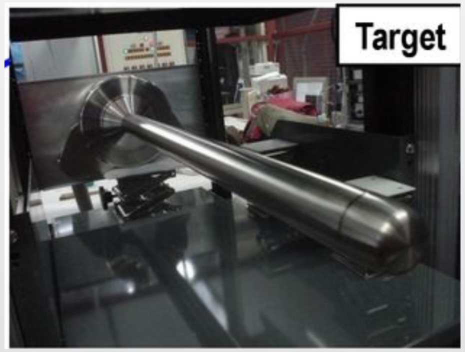
Magnet Needs (Nb_3Sn vs H

Performance

To make the first neutrino experiment using a muon-derived beam we dont need high intensity from day 1.....

- For example, in a CERN-based scenario, we could start with the currently available SPS intensity (10^{12}–10^{13} protons per burst), with the possibility of a gradual upgrade to higher intensities.
- There are no critical issues related to the proton target or horn technology up to 10^{14} protons per burst, as standard solutions can be adopted.
- Even with a proton intensity 100 times lower than in typical Neutrino Factory scenarios, we can already achieve meaningful results.
- at least $5 \cdot 10^4$ CC interactions of ν_e /year

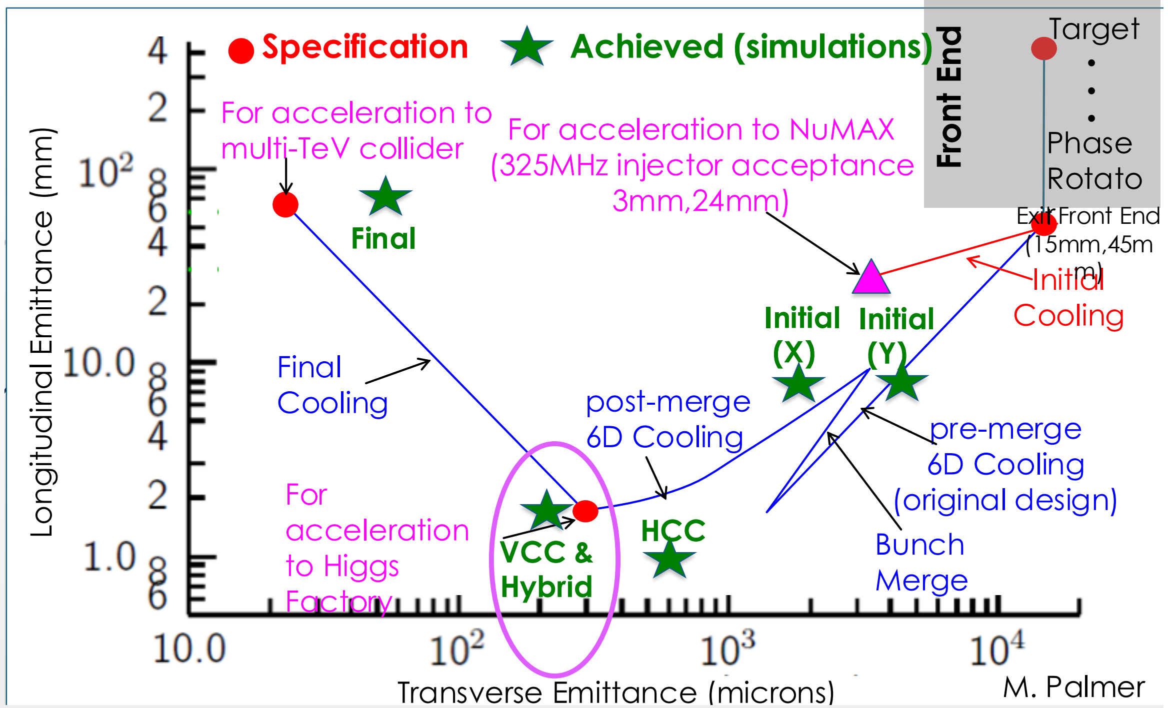
  (but also anti-ν_μ + anti-ν_e + ν_μ)



To make the first neutrino experiment using a muon-derived beam we dont need final cooling from day 1.....

Cooling: The Emittance Path

- For example, at CERN, a fantastic opportunity will arise with the construction of the 6D cooling demonstrator.
- This facility, combined with the available SPS intensity, could enable the production of the first cooled muon beam at an energy of 200 MeV/c.



However, we still need an initial acceleration stage to ramp up the muons from 200 MeV/c to 1.5 GeV/c (for Hyper-K) and up to 5 GeV/c (for DUNE).

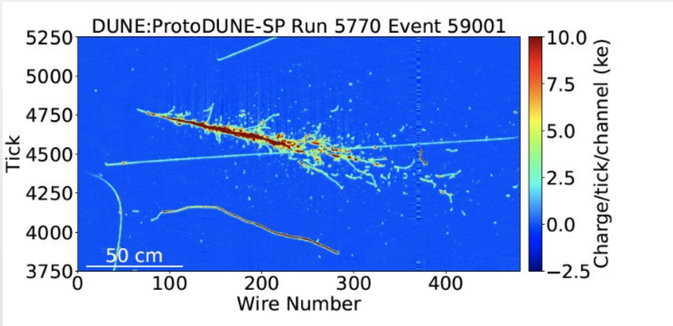
- ➢ not very difficult
- ➢ not very expensive

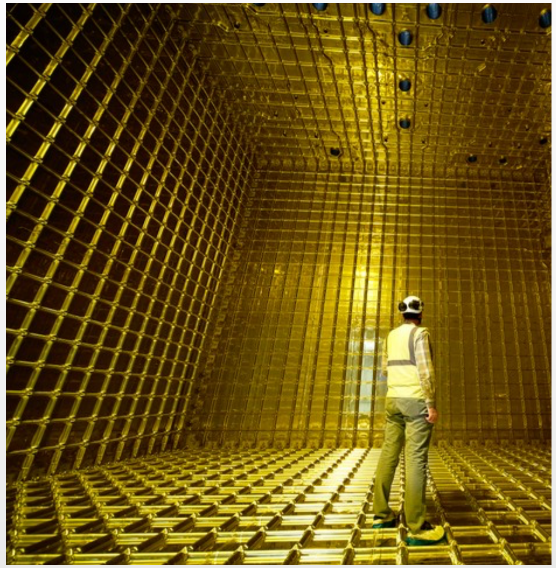
To make the first neutrino experiment using a muon-derived beam we dont need to build expensive detectors from day 1.....

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

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

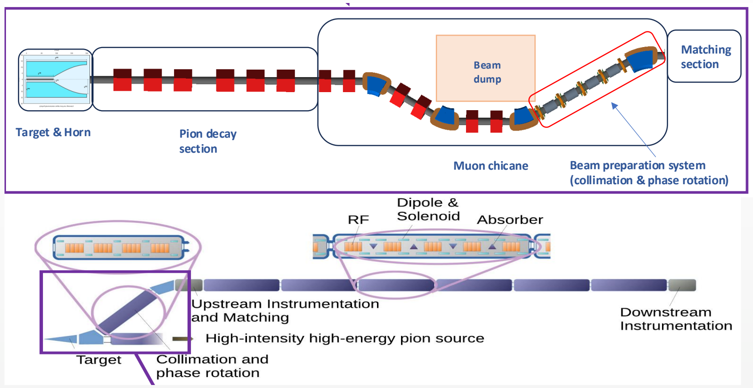
- As an example, at CERN 2 beautiful ProtoDune detectors (total mass 1Kton liquid argon) are available at the Neutrino platform
- This kind of beam does not t require a magnetized setup.
- A detector with good PID capabilities (able to distinguish muons from electrons with high efficiency) will be OK (WC are also OK)
- You can complement measurements in liquid argon by adding (as an example) a High pressure TPC allowing topologies and A dependence studies to discriminate between nuclear models (prototypes are already available)
- No background in the beam will maximize achievable physics results





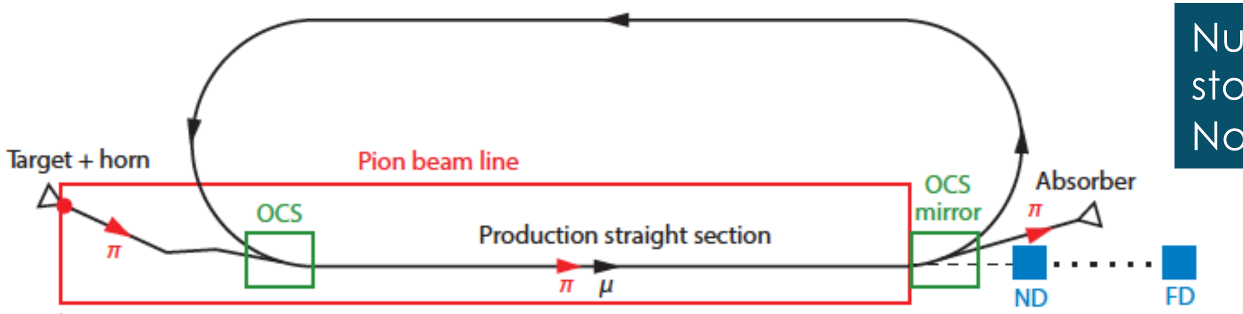
Recipe for a neutrino experiment using a muon-derived beam @CERN

- BEAM = 10^{19} protons/year from SPS
- Target & Pion capture
- Pion transport & decay
- Muon transport, collimation & phase rotation
- Matching to cooling channel
- Cooling 6D (initial)
- Acceleration up to 5 GeV
- Storage muon ring (synergy with NUSTORM)
- Detectors : Proto DUNE + High Pressure TPC +...



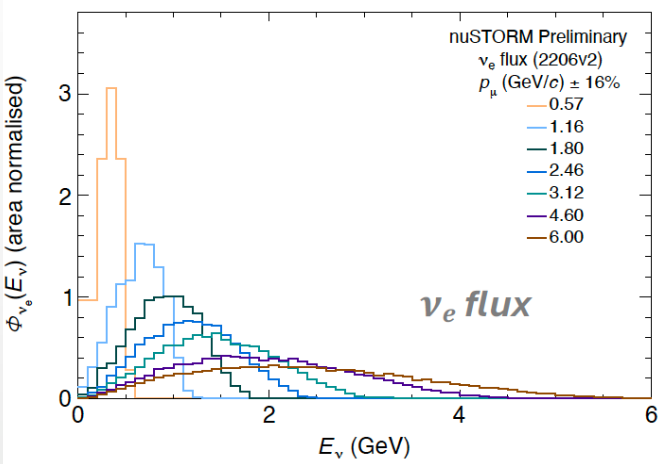
6D Demonstrator as first step

Synergies with NuStorm (ν from STORed Muons)



Nustorm as testbed for a stored muon ring
No Cooling required

T. Alves, M. Pfaff

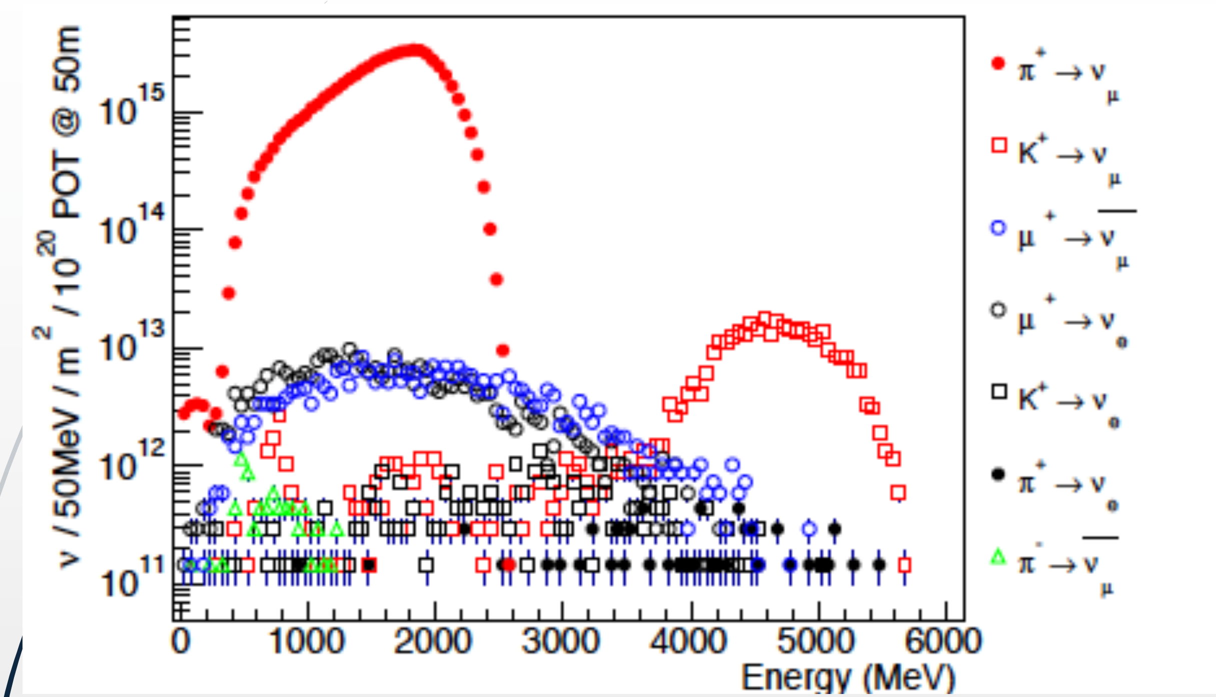


- ***ν beam facility based on a stored muon beam***
- Production Straight (example w/ π^+ injection)
- ν_μ flux from $\pi^+ \to \mu^+ \nu_\mu$ ("pion flash")
- $\nu_\mu + \nu_e$ flux from $\mu^+ \to e^+ \nu_e$ (anti)ν_μ
- μ momentum tunable between 1 and 6 GeV/c, spread ±16%

> - Complete implementation for large acceptance (inc. injection and extraction sections)
> - R&D for very precise determination of stored-muon energy and spread

See Stefania Ricciardi talk

Nustorm is a hybrid solution



ν_μ from pion decay $\pi^+ \to \mu^+ + \nu_\mu$ flux: 6.3×10^{16} ν/m^2 at 50 m

ν_e from muon decay $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ flux: 3.0×10^{14} ν/m^2 at 50 m

ν_μ from kaon decay $K^+ \to \mu^+ + \nu_\mu$ flux: 3.8×10^{14} ν/m^2 at 50 m

10^{21} p.o.t./year

P. Soler

In Summary ....

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

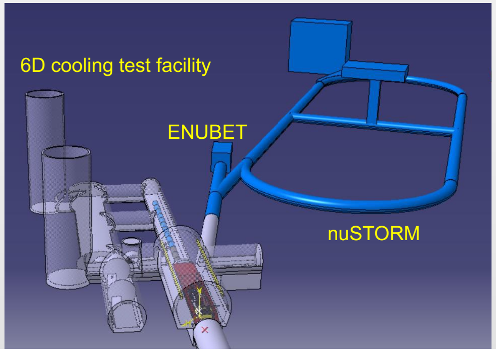
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

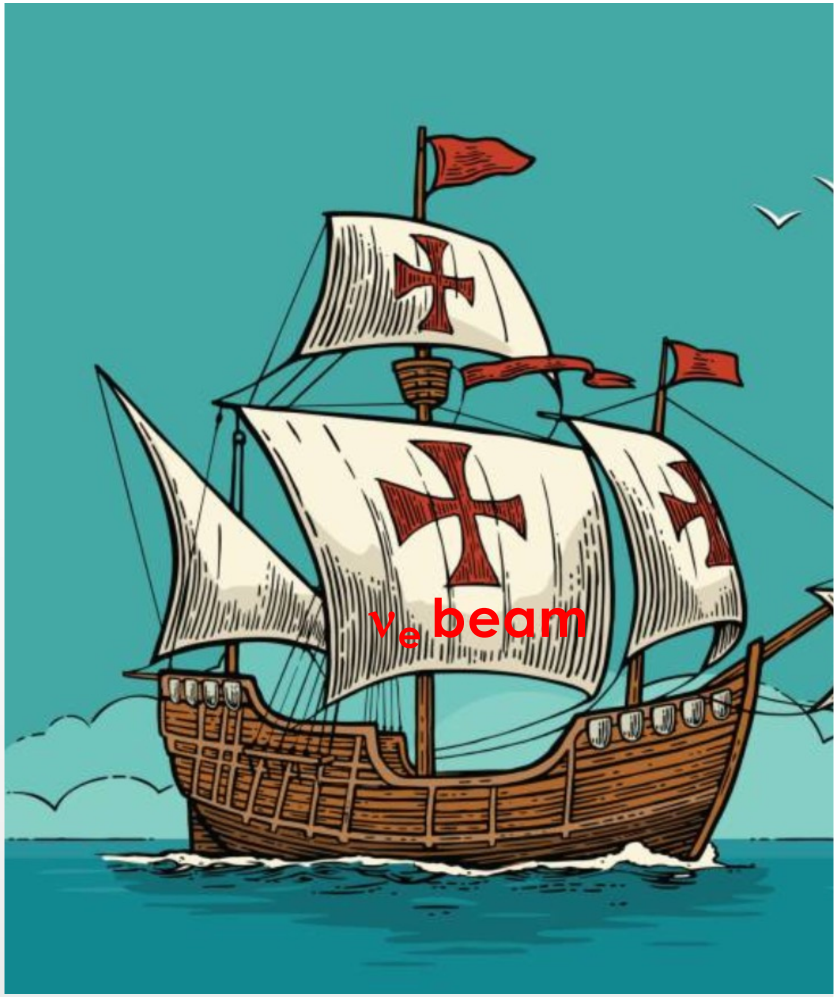
- The possibility of producing neutrino beams from muons was first proposed in 1986. In particular, it would allow for the generation of electron neutrino beams — something never achieved before.
- Initially, such beams were envisioned as the first stage of a muon collider, a crucial starting point for creating an ultra-intense neutrino source for long-baseline oscillation physics. However, despite the clear advantages and strong physics potential, realization of such a facility proved impossible due to major technical challenges and the high costs associated with building such an infrastructure.
- Today, however, the growing interest in — and importance of — low-energy neutrino cross-section measurements (especially for ν_e), combined with the exciting opportunity to produce a cooled muon beam at CERN for the first time, opens the door to a new and promising scenario.

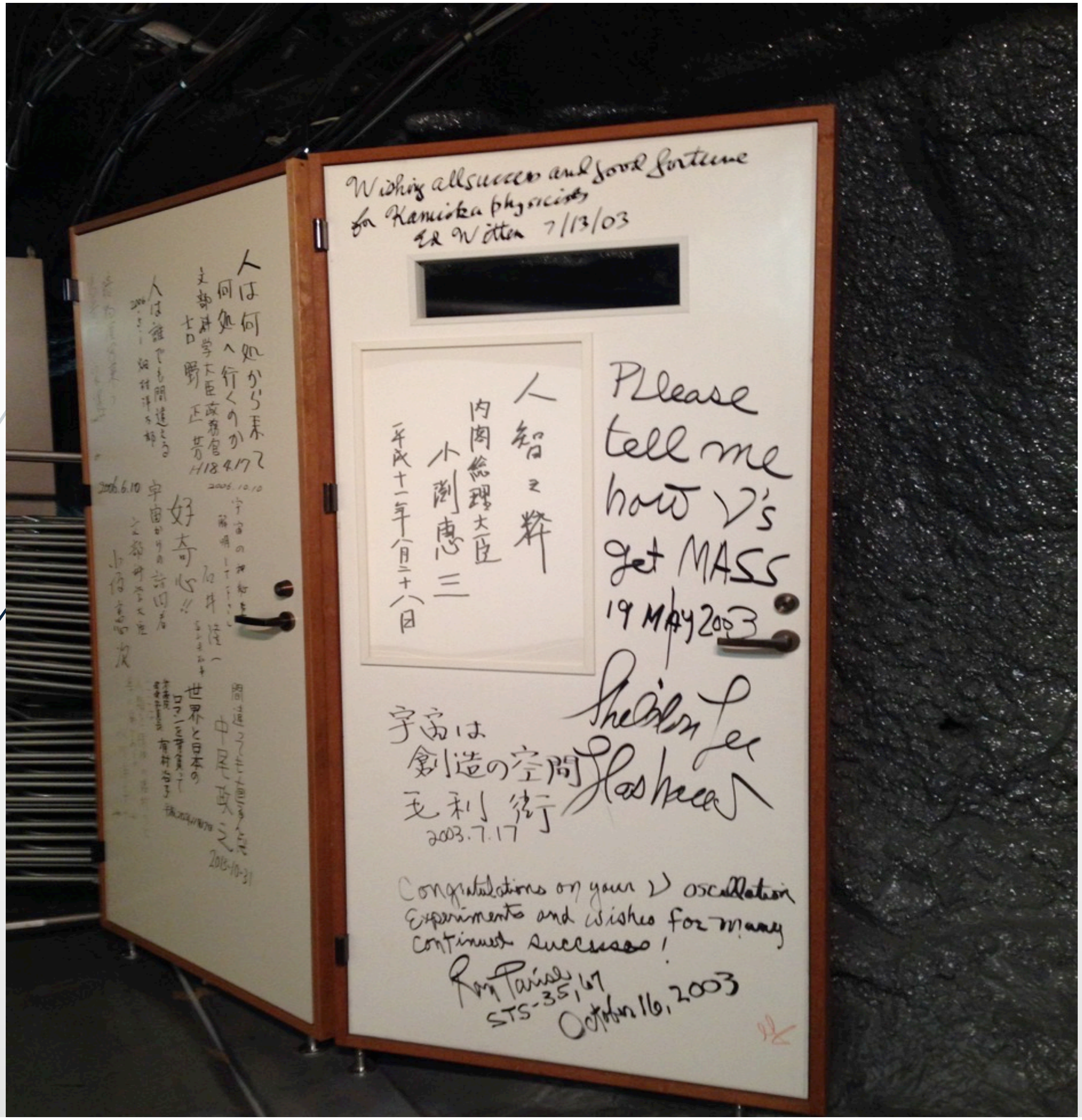
I hope that I convinced you that:

- Low-energy cross-section measurements do not require proton budgets beyond what a laboratory like CERN can provide.
- If the cooling channel can deliver a sufficiently intense muon beam, it could serve not only for validating the beam generation concept, but also as a valuable source for meaningful physics.
- Equipping the laboratory with a muon storage ring for the first time would make it possible to begin testing — and even doing physics — before the cooling channel interface is fully operational.
- The presence of appropriately sized neutrino detectors at the lab would allow for immediate neutrino measurements.
- At the same time, the availability of a neutrino beam would enable the development of new instruments to measure all relevant parameters, including interaction types and validation of nuclear models.

- To set sail, a ship needs more than just resources — it requires those resources to be used in a synergistic and optimized way.
- *For example, creating a neutrino infrastructure that concentrates in one area the development of pure muon-neutrino beams, the nuSTORM approach for the ring, and new neutrino tagging systems is essential for advancing this field.*
- This talk was made to show the great potentialities of these ideas I think it is important to share with you.
- We are working hard to have soon realistic simulations allowing us a more quantitative assessment about the physics reach. Stay tuned !







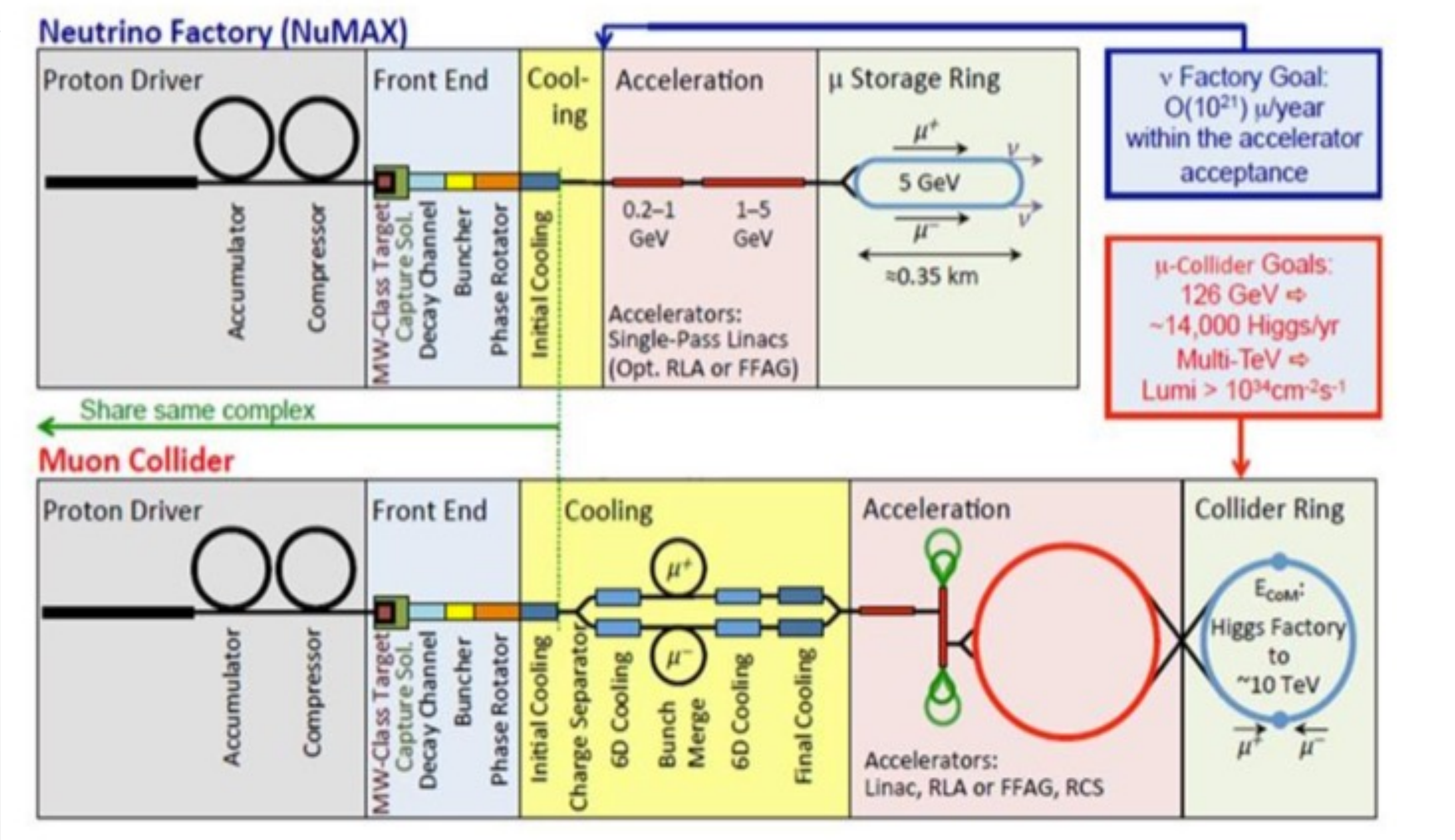
Please tell me how νs get mass !

19/05/2003
Sheldon Lee Glashow
Nobel Prize in Physics 1979

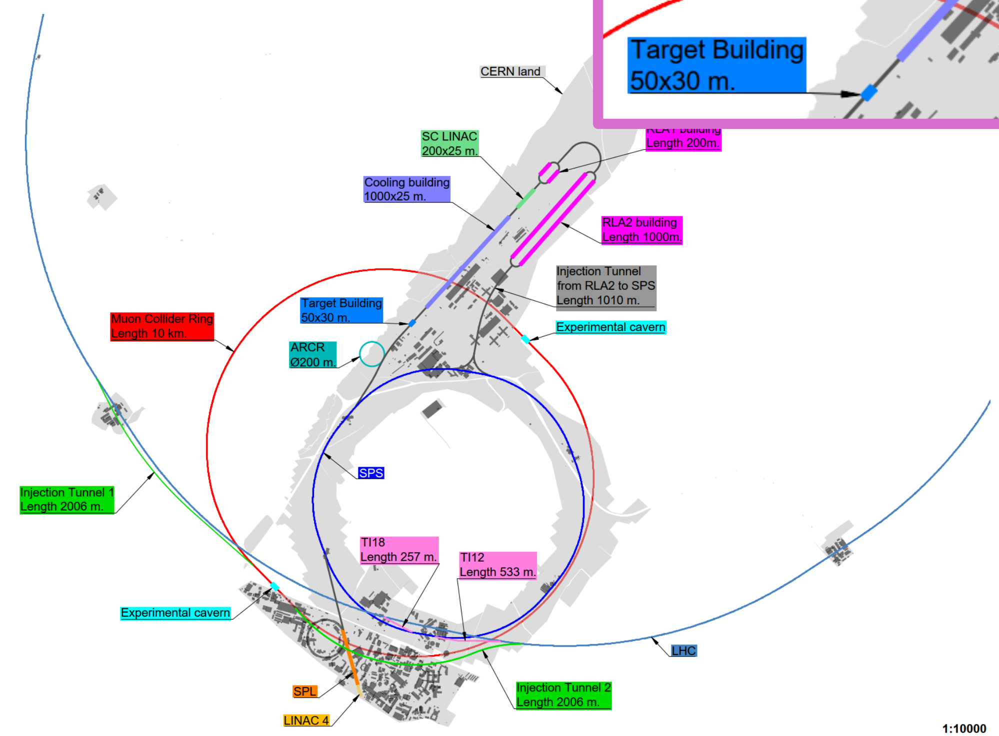
Thanks !

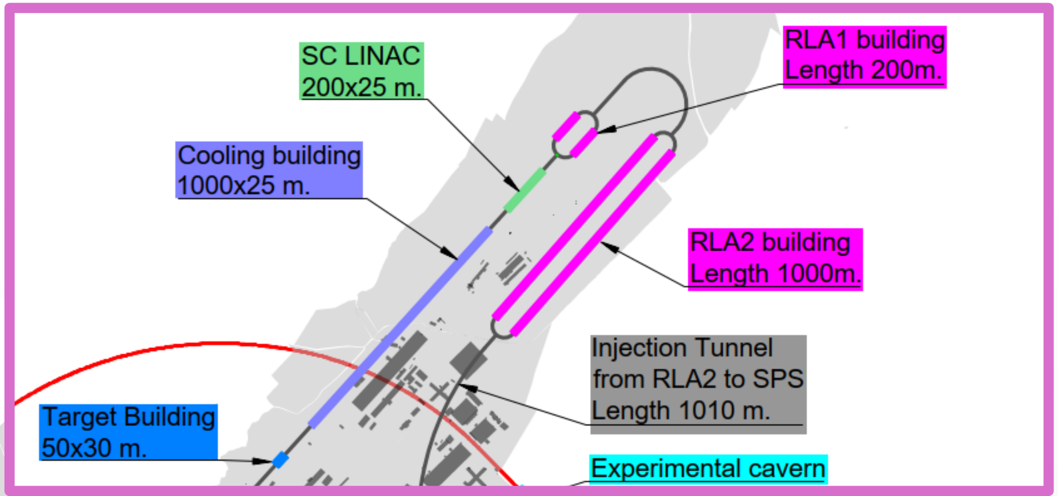
backup

Numax (High Intensity) at Fermilab



Mu_Col. @ cern


CERN land
SC LINAC
200x25 m.
Cooling building
1000x25 m.
RLA1 building
Length 200m.
RLA2 building
Length 1000m.
Injection Tunnel
from RLA2 to SPS
Length 1010 m.
Target Building
50x30 m.
Experimental cavern
Muon Collider Ring
Length 10 km.
ARCR
Ø200 m.
SPS
Injection Tunnel 1
Length 2006 m.
TI18
Length 257 m.
TI12
Length 533 m.
Experimental cavern
LHC
SPL
LINAC 4
Injection Tunnel 2
Length 2006 m.
1:10000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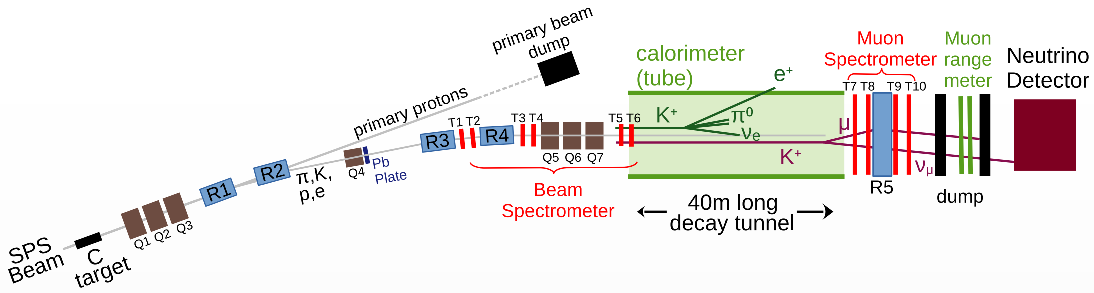
SBN@CERN



Parameter	Value
Primary proton momentum (GeV/c)	400
Beamline meson momentum (GeV/c)	max. 8.5
Proton-beam spill duration	slow (4.8 s to 9.6 s)
Spill intensity (protons/spill)	$1.0 \cdot 10^{13}$
Event rate (THz)	1 – 2
Instantaneous power on target (W)	170 – 340
(K^+, π^+) yield per proton	$(1.3 \cdot 10^{-3}, 1.9 \cdot 10^{-2})$
(K^+, π^+) rate (GHz)	max. (2.7, 40)
Annual proton yield (protons/year)	$2.1–3.2 \cdot 10^{18}$
Total proton requirement (protons)	$1.4 \cdot 10^{19}$