Accelerator neutrino beams and precision measurements of the PMNS matrix

Beyond the van der Meer paradigm: monitored and tagged neutrinos, neutrinos from stored muons

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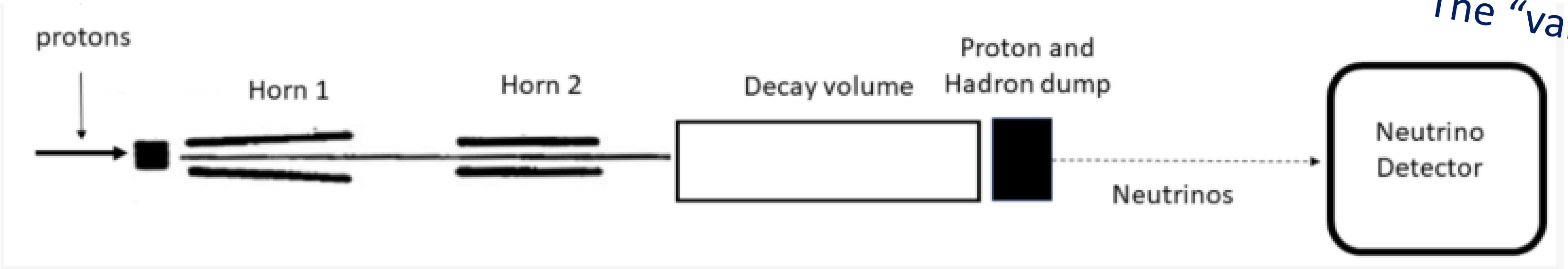
Re-thinking artificial neutrino beams

The "van der Meer paradigm"



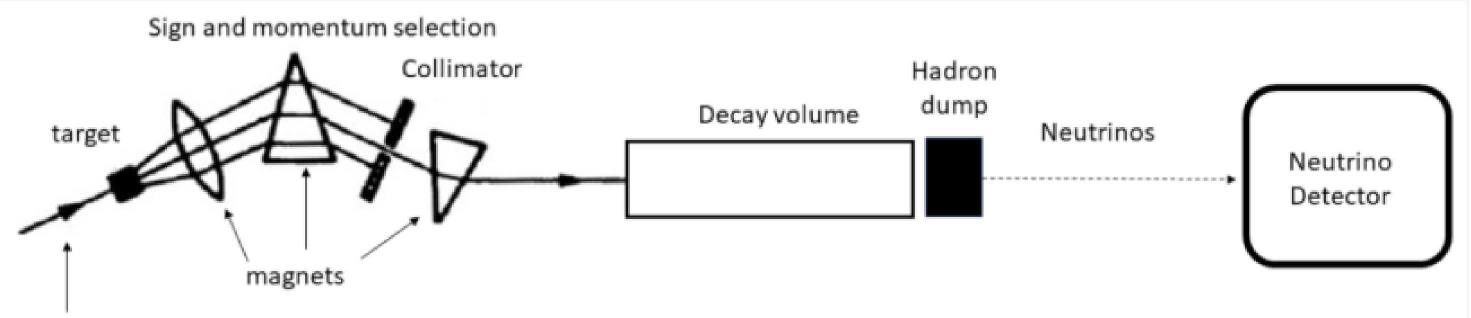
	"Employ the most intense proton accelerator at your disposal"	"Focus as many pions/kaons as possible"	"Eliminate any material along the beamline in the decay tunnel"	"Build the largest possible neutrino detector"
Pros:		Large yield of pions per proton-on-target (pot)	Large number of neutrinos from pion decay	Large statistics of neutrino interaction events (CC and NC)
Drawbacks:		Lack of control on neutrino energy	Coarse beam diagnostics	Limited precision in the final state reconstruction

LBNF/DUNE is.... the FCC of the van der Meer paradigm ☺

But we don't need such an intense (and coarse) source to measure cross sections!

In addition, we must find a way to have potential sources of ν_e to test PMNS unitarity ($\nu_e \rightarrow \nu_\tau$) oscillation and, in general, to understand oscillations beyond ν_μ appearance/disappearance

A new paradigm for high-precision beams



protons over a long extraction (2-10 s)	horn-less static focusing system based on dipole/quadrupoles	instrumented decay tunnel	high granularity, fast, neutrino detectors
Pros: We select secondaries in a narrow energy band We can track pions at single particle level using fast silicon tracker (tagging)		We can measure charged leptons associated with the neutrino decay (direct monitoring of flux)	Exquisite reconstruction of interaction vertex (NBOA – see later) and final state particles Time correlation with parent pion and daughter muon (tagging)
Drawbacks: Limited neutrino beam intensity		Need for fast, rad-hard detectors	Limited statistics

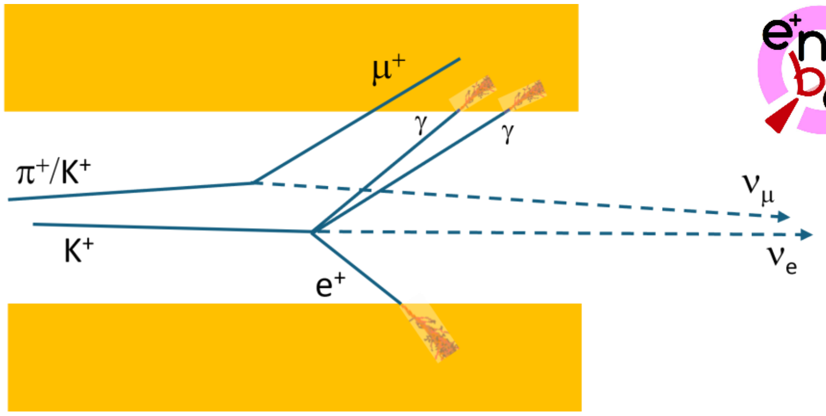
This approach is ideally suited for **cross section measurements** and precision/BSM physics (NSI, sterile neutrinos, dark photons, etc.)

Neutrino monitoring and tagging

"Monitored neutrino beams are beams where diagnostic can directly measure the flux of neutrinos because the experimenters monitor the production of the lepton associated with the neutrino at the single-particle level. " (Wikipedia)

Monitoring: effective removal of systematic uncertainties associated with neutrino flux modelling

Pioneered in the 1980s, proposed with modern technologies in 2015 , R&D from the CERN NP06/**ENUBET** Collaboration

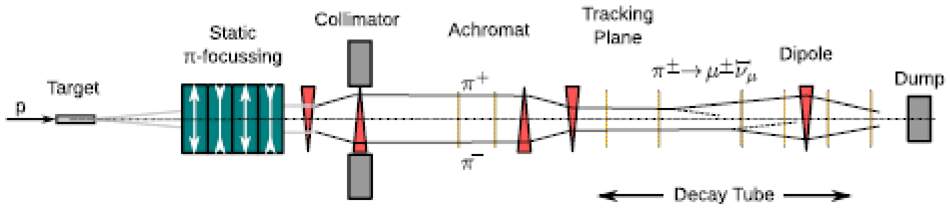


A. Longhin. L. Ludovici, F. Terranova, Eur. Phys. J.C 75 (2015) 155

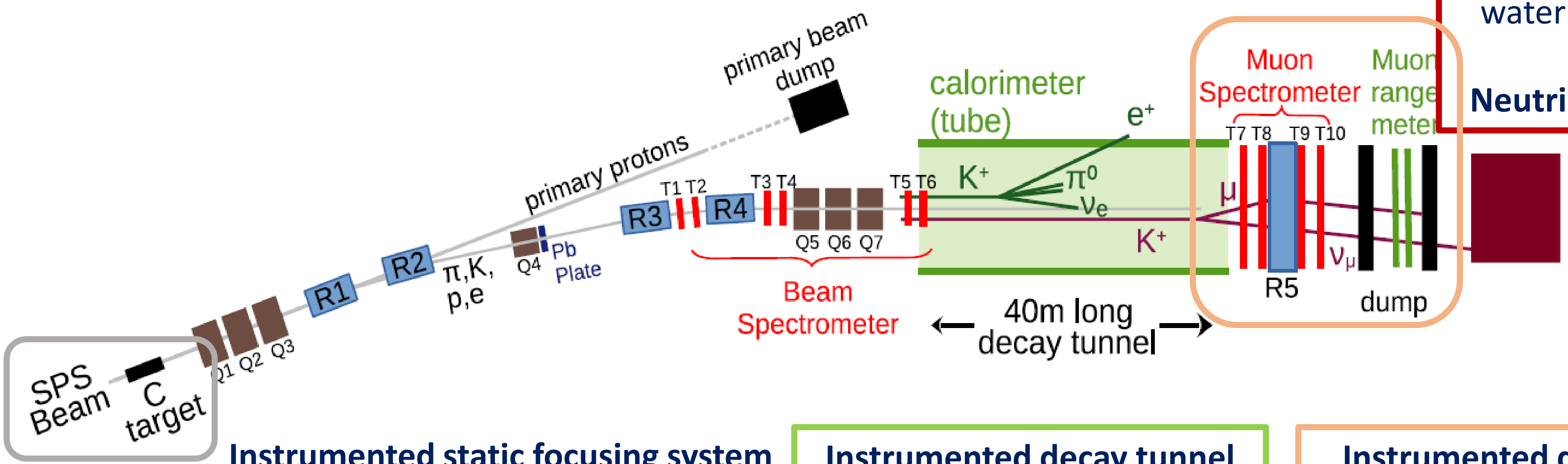
"If the time resolution of the particle detector in the tunnel and the neutrino detector outside the tunnel is very good (below 1 ns), the experimenters can associate unambiguously the neutrino observed in the detector with the charged lepton recorded in the tunnel." (Wikipedia)

Tagging: Event-by-event knowledge of incoming neutrino energy

Proposed in the 1970s, developed in USSR in the 1980s, proposed with modern techniques in 2022, R&D from the NP06 and **NuTAG** Collaborations



The nuSCOPE implementation



Liquid argon and water Cherenkov/ WBLS

Neutrino detectors

Proton accelerator:
CERN SPS (400 GeV/c)
Carbon target

Instrumented static focusing system
Two quadrupole triplet, four dipoles, six silicon trackers for momentum measurement and tagging

Instrumented decay tunnel
Segmented Fe-scint calorimeter for lepton monitoring in the tunnel wall

Instrumented dump
Muon spectrometer and muon range-meter

The CERN implementation exploits

- An instrumented decay tunnel and muon range-meter to monitor the number of $K \to \pi^0 e \nu_e$, $\pi \to \mu \nu_\mu$, and $K \to \mu \nu_\mu$ decays, and to directly measure the ν_e and ν_μ fluxes from pions and kaons (**monitoring**).
- A static focusing system and muon spectrometer to tag pions/kaons and the muons from $\pi \to \mu \nu_\mu$ and $K \to \mu \nu_\mu$ decays. These are time-associated with the ν_μ observed in the detector, allowing reconstruction of the neutrino energy from the two-body kinematics of the parent K and π (**tagging**).

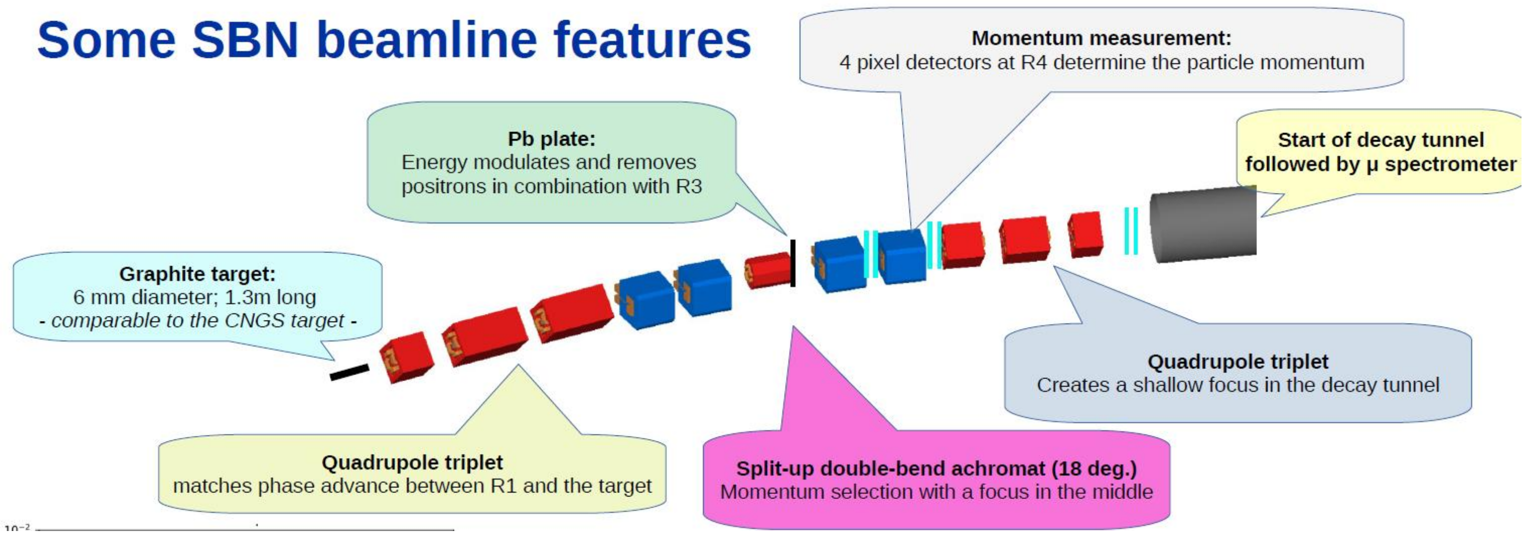
Beam parameters and optimization

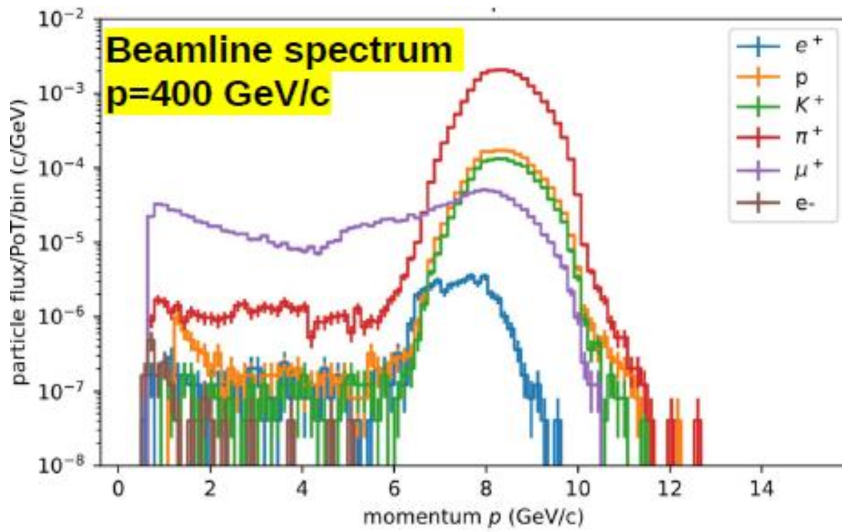
The beamline design originates from the ENUBET design but has been re-optimized to:

- achieve the original ENUBET physics goals with a number of protons compatible with the CERN fixed target program, including SHiP
- reduce the instantaneous meson rate in the final dipoles to a level compatible with particle tracking (silicon trackers)
- Suppress intrinsic backgrounds, such as neutrinos originating outside the decay tunnel that hit the detector, and positrons produced by tertiary interactions.
- Enable a realistic implementation within the CERN accelerator complex.

Parameter	Value
Primary proton energy	400 GeV/c
Beamline momentum (mesons)	up to 8.5 GeV/c
Extraction type	slow: 4.8s or 9.6s from the SPS
Spill intensity	1.0E13 protons/spill
Event rate	1 – 2 THz
Instantaneous power	170 – 340 W
K^+ / π^+ per proton	1.3E-3 / 1.9E-2
K^+ / π^+ rate	up to 2.7 GHz / 40 GHz
Annualized proton requirement	2E18 – 3E18 protons/year
Total proton requirement (1% stat. error on ν_e x-section)	1.4E19 protons
Beamline length to decay tube	23 m
Bending magnet strength	1.8 T

Some SBN beamline features

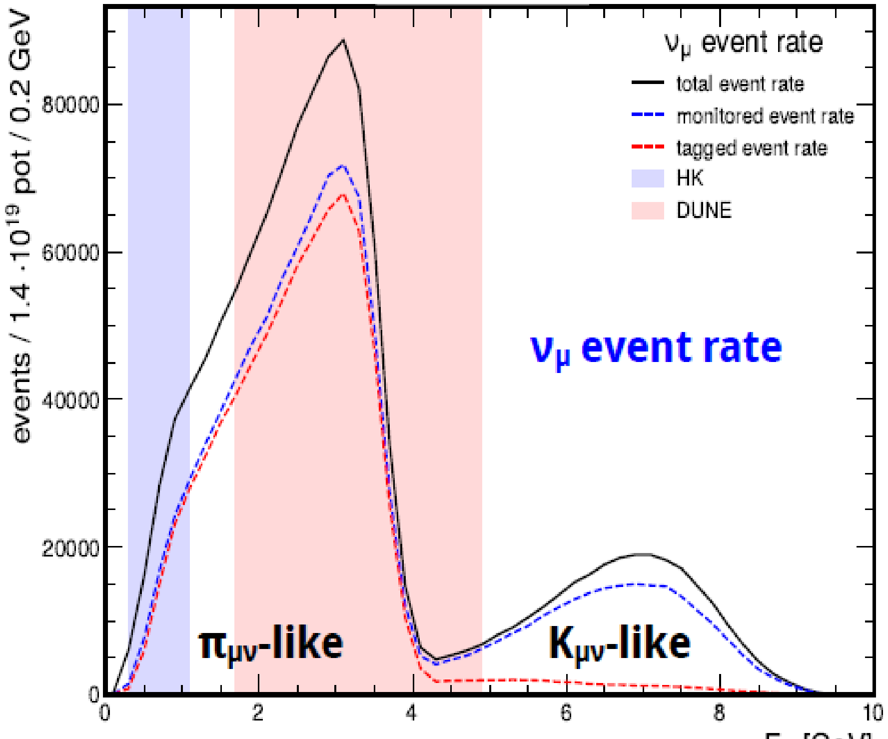


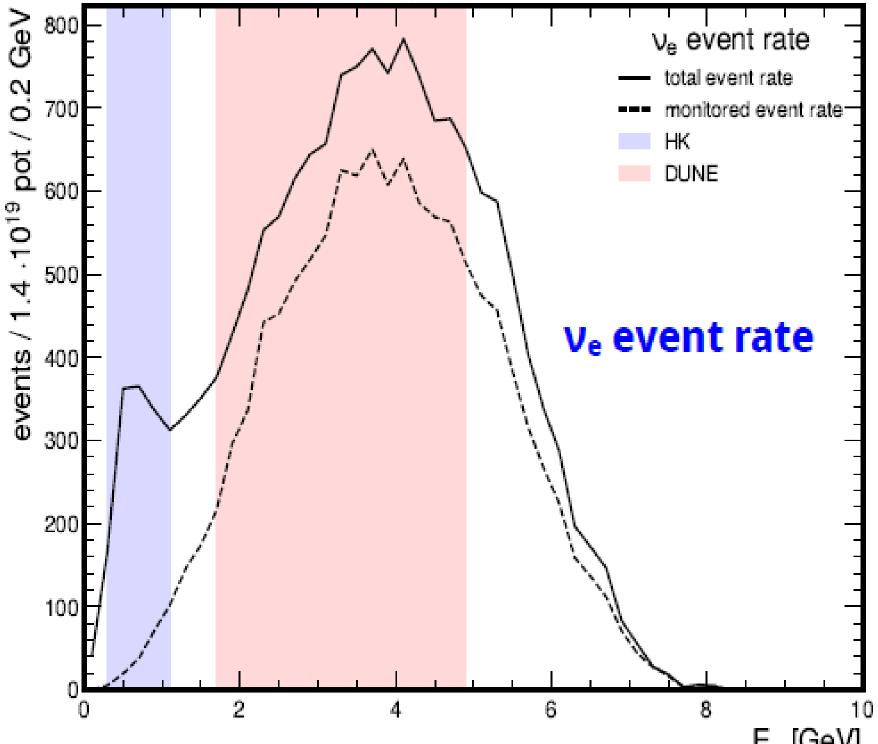


Beam performance and expected statistics

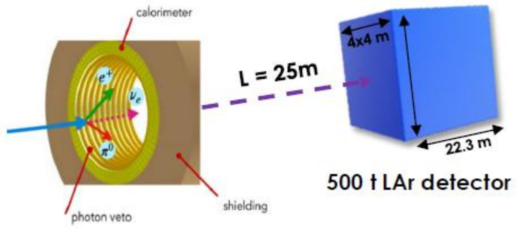
Reference setup:

- A 5-y neutrino run mode with 8.5 GeV momentum secondaries [dedicated low energy runs and anti-neutrino modes under evaluation]
- A 500 ton liquid argon detector 4x4 m^2 face; length: 22.3 m, distance: 25 meter from the hadron dump
- Collected statistics: 10^6 ν_μ CC events, 12000 ν_e CC events
- Projected event spectra estimated with GENIE from the output flux of the nuSCOPE BDSIM simulation. Flux systematics from the ENUBET analysis. Tagging efficiency from tracker simulations.





	events / $1.4 \cdot 10^{19}$ PoT
total ν_μ	1.3×10^6
total ν_e	1.7×10^4
total monitored ν_μ	1.0×10^6
total monitored ν_e	1.2×10^4
total tagged ν_μ	7.6×10^5

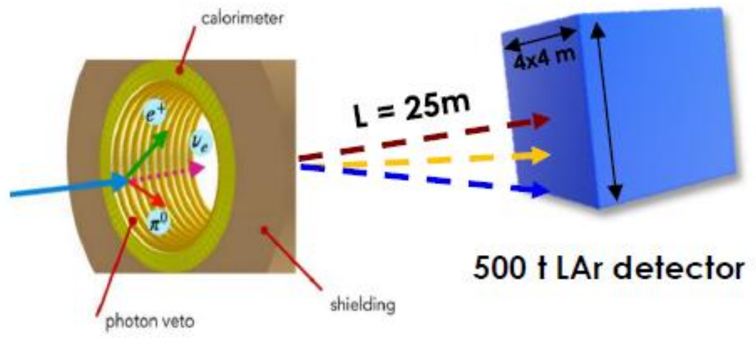


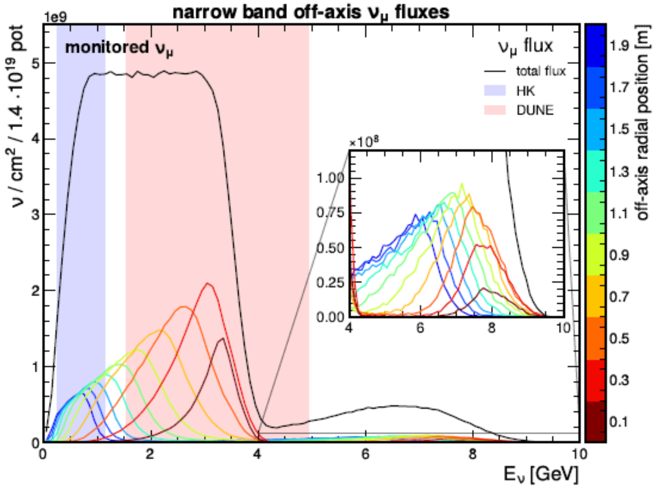
Physics performance

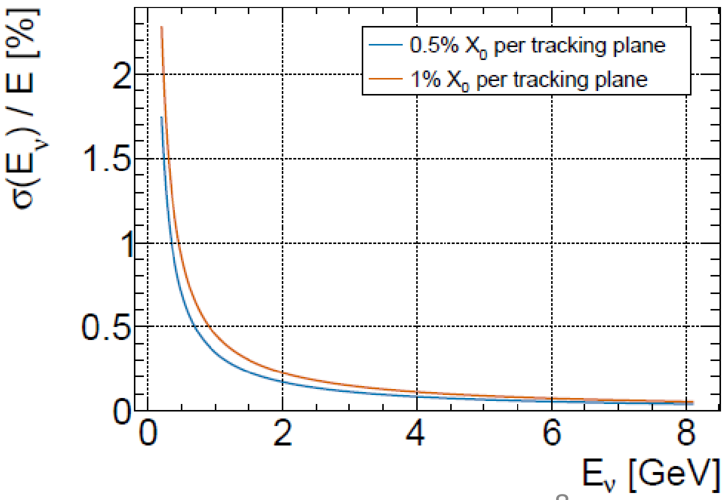
This facility addresses the most relevant issues for a full understanding of neutrino cross sections, especially for oscillation experiments. Monitoring provides **unprecedented control of the flux and a moderate precision on the initial neutrino energy** through the "Narrow band off axis" technique. Tagging, although technically more challenging, offer **superior energy resolution** for the incoming neutrino energy.

The "Narrow-band off-axis" technique exploits the observed neutrino interaction vertex, since its distance from the beam axis correlates with the neutrino energy—provided the parent meson momentum has a small spread (10% in nuSCOPE).

"Neutrino tagging" (≈80% of the full ν_μ CC sample from π decay for a 300ps detector time resolution): the energy is reconstructed from the parent kinematics. It thus offers a golden sample of tagged neutrino with **sub-percent energy resolution**

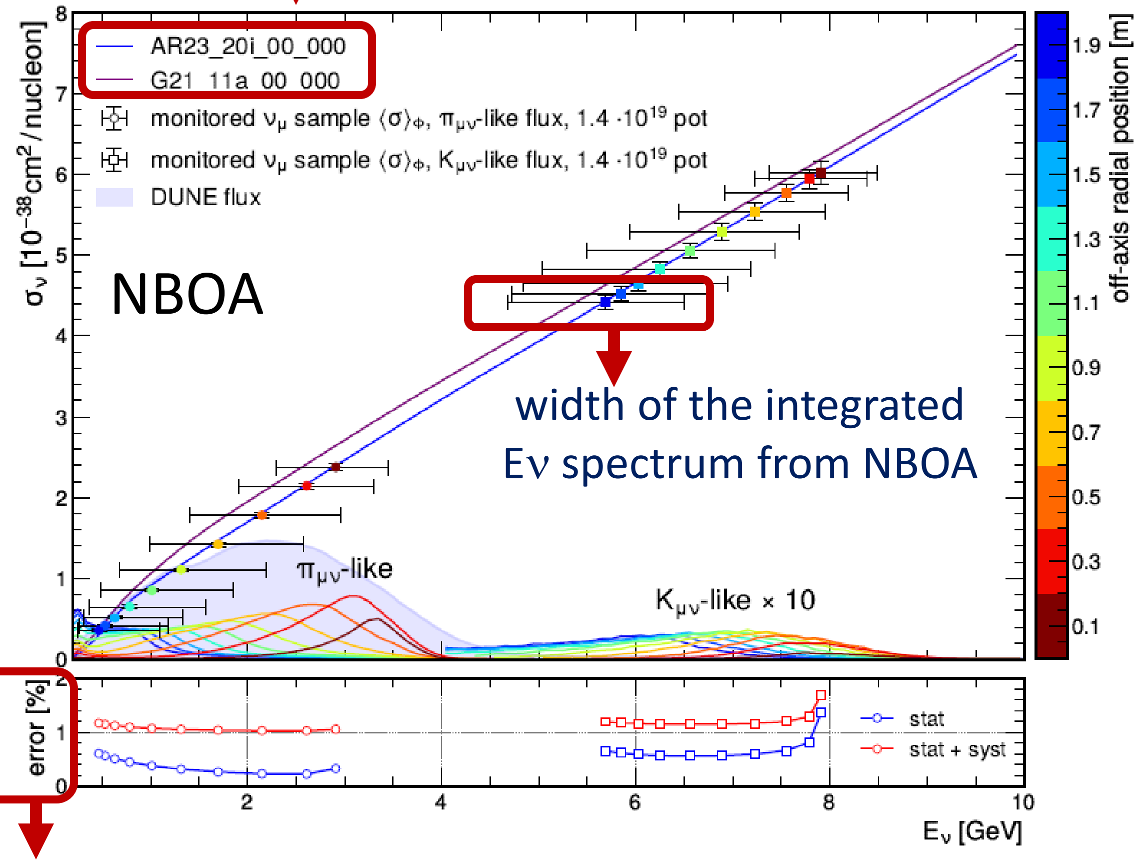






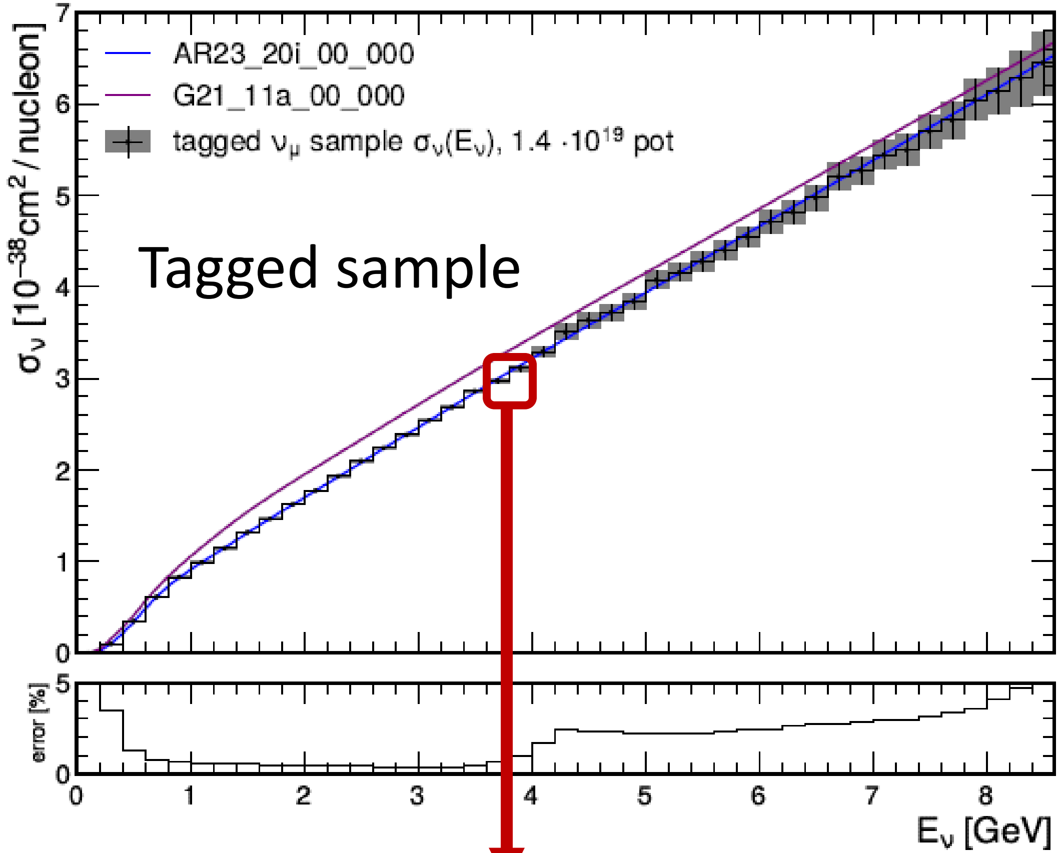
The energy dependence of ν_μ cross section

it illustrates sensitivity to theory models



width of the integrated Eν spectrum from NBOA

stat.+sys. error

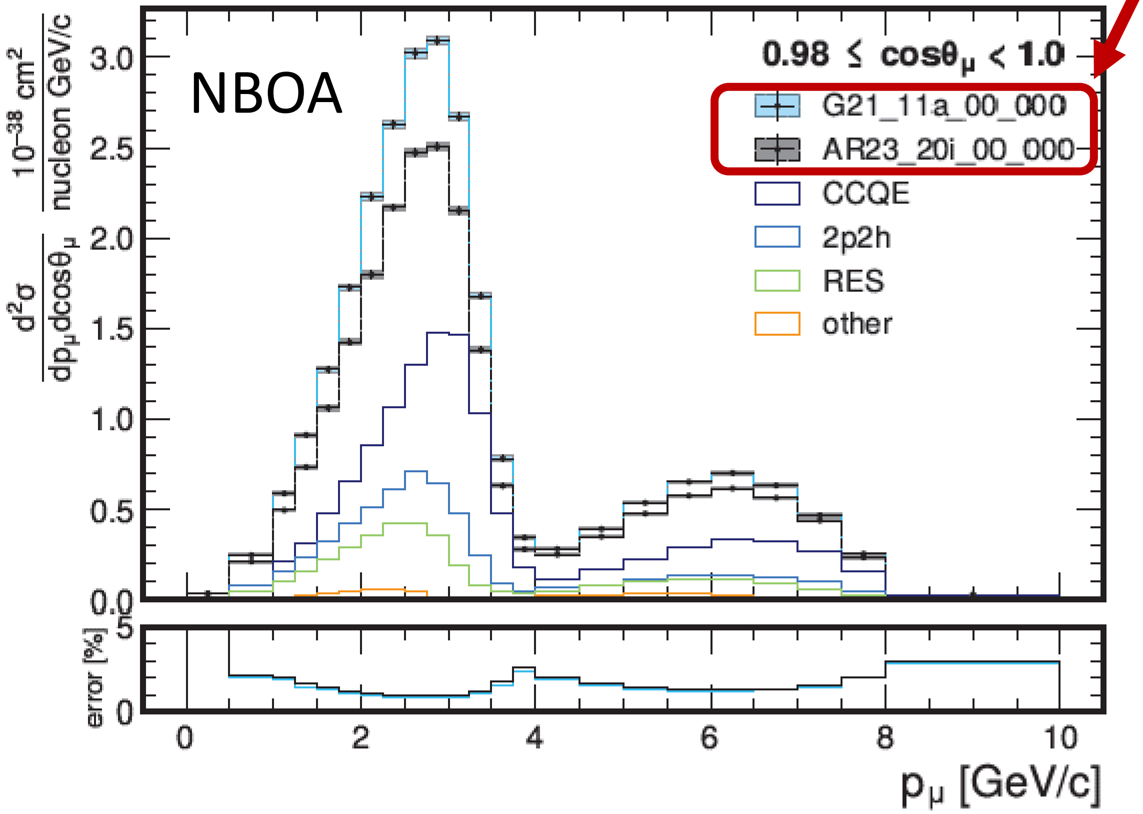


in the golden tagged sample, the integration width is no more driven by the energy uncertainty (<1% !!) but just by statistics

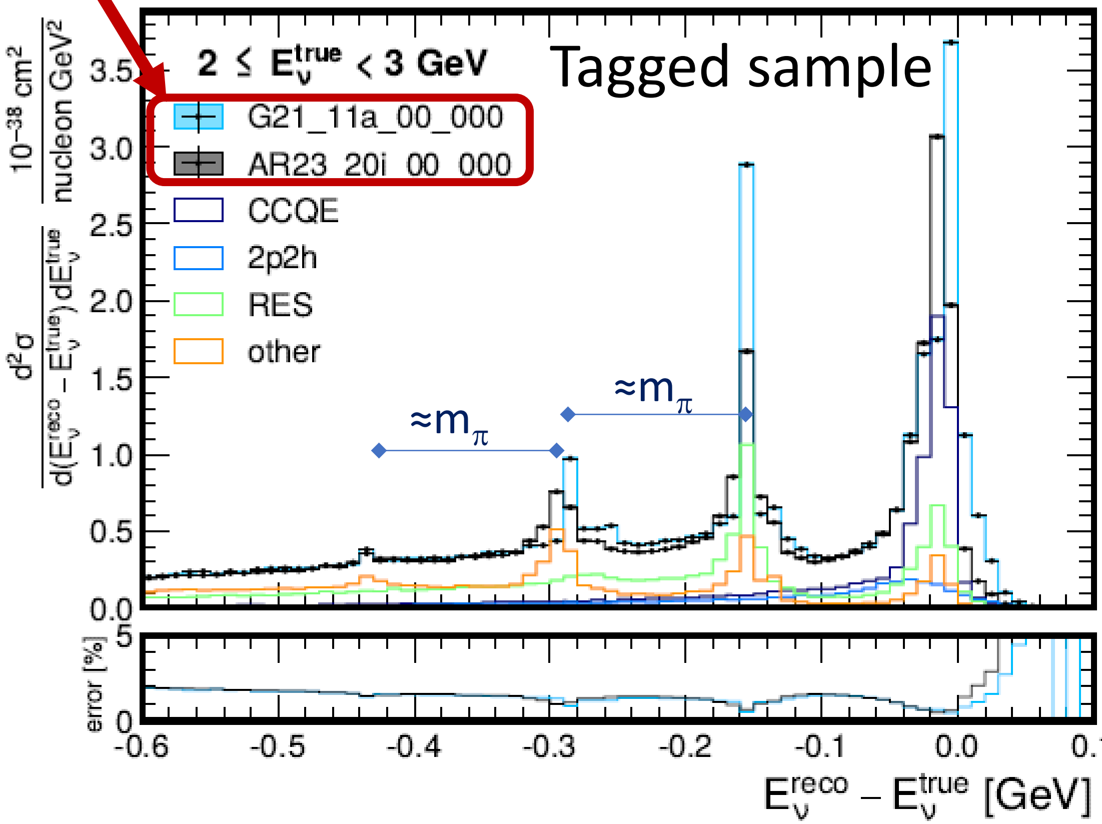
The smearing of reconstructed neutrino energy due to nuclear effects

We can address this key issue by performing high-precision measurements of double differential cross sections using the NBOA technique or by directly measuring the energy bias from the tagged neutrino sample.

it illustrates sensitivity to theory models



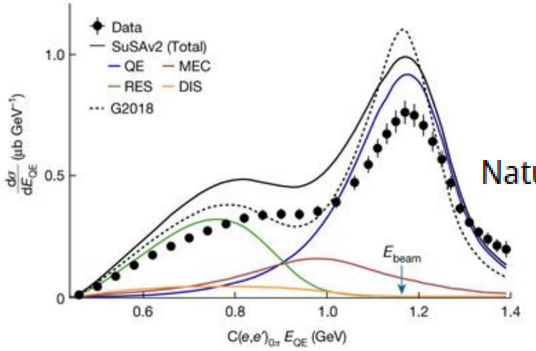
Without **monitoring**, the double differential cross section for “quasi elastic” (CC0π) would be systematic limited



The **tagged** sample employs the knowledge of the “true” neutrino energy to directly measure the energy bias in bins of E_{true}

Electron-scattering-like measurements with tagged neutrinos

Electron-nucleon scattering experiments provide the primary experimental input for understanding nuclear effects and developing robust theoretical models. However, they only access vector currents since the probe is electromagnetic. Tagged ν_μ–nucleus interaction events exhibit the same features, but with a neutrino probe, which also provides access to the axial component. For example, the exploitation of the "true" energy transfer ω to probe:

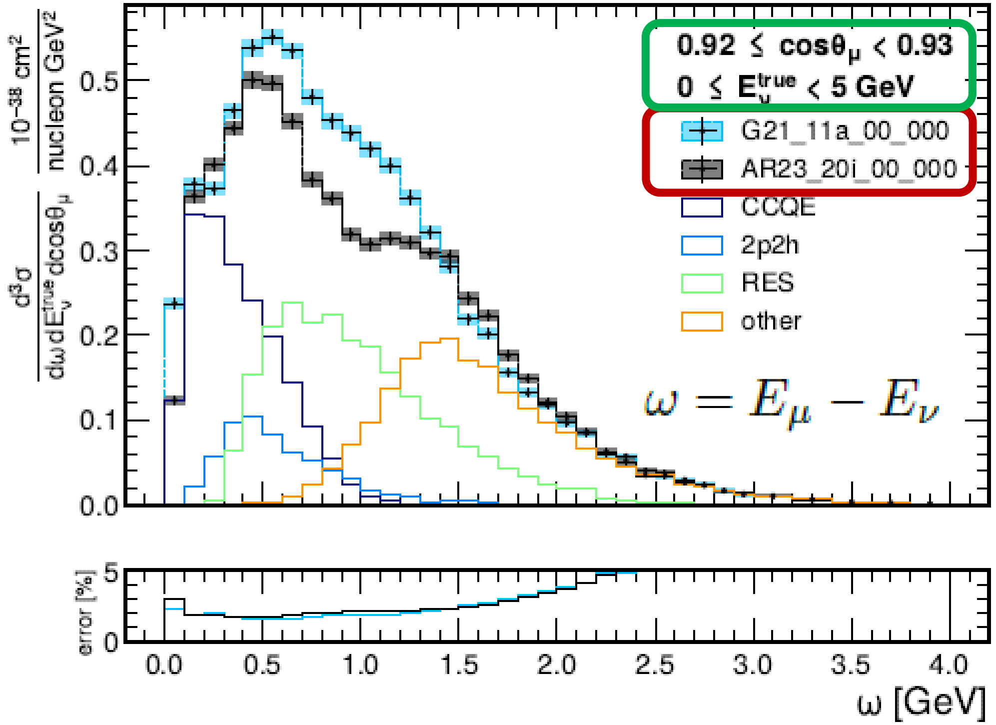


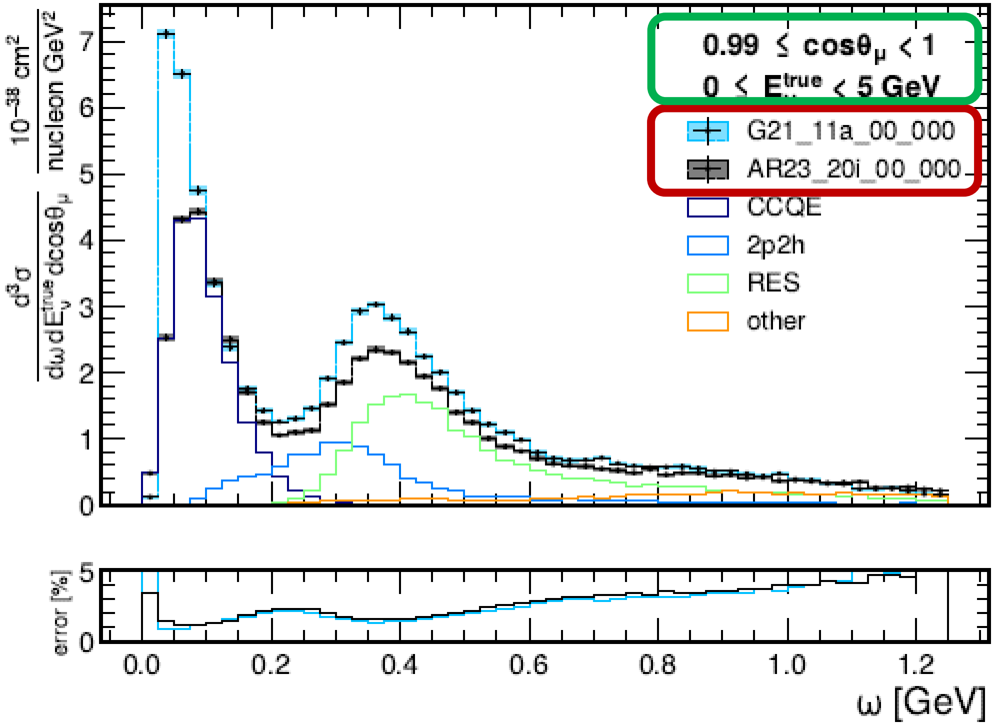
e4v

Nature 599, 565–570 (2021)

regions sensitive to nuclear-level form factors

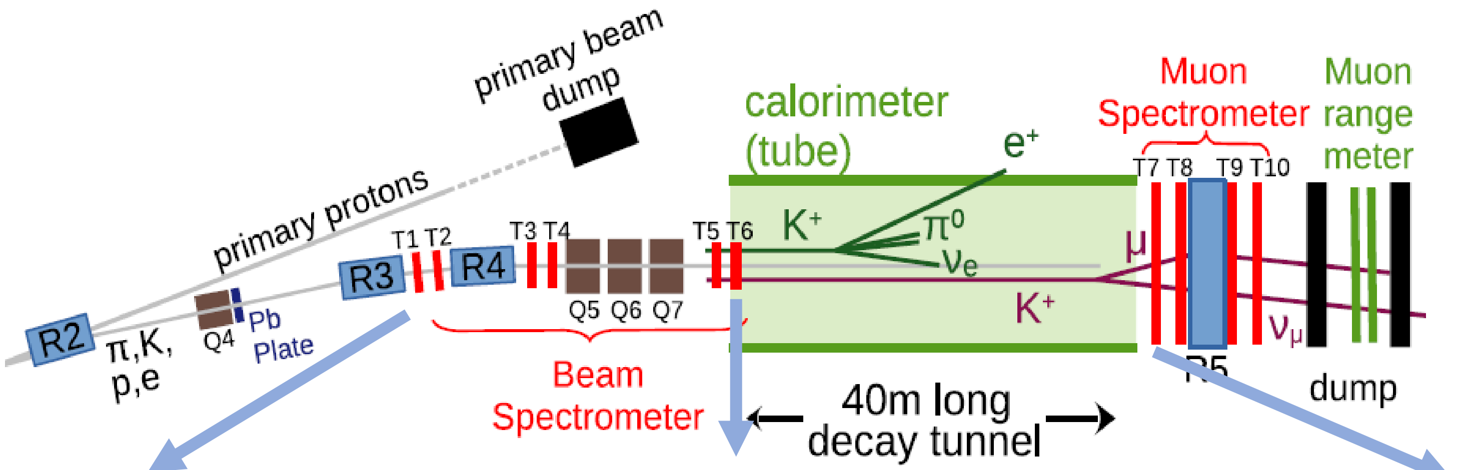
regions sensitive to collective nuclear effects



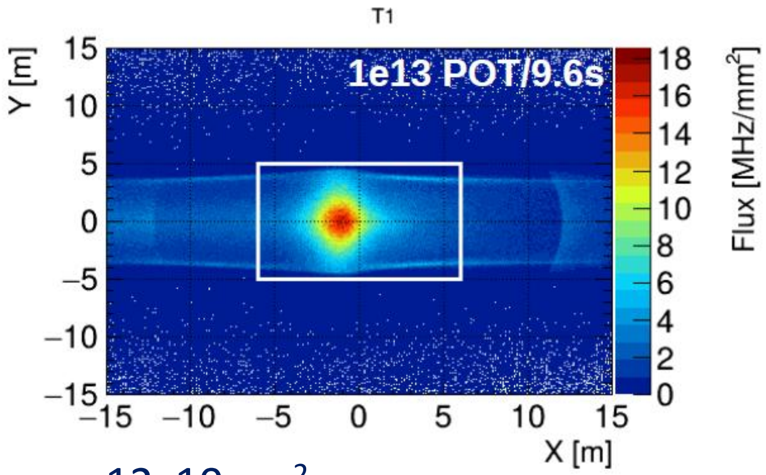


the dominant T2K systematics for Δm^2_{32}

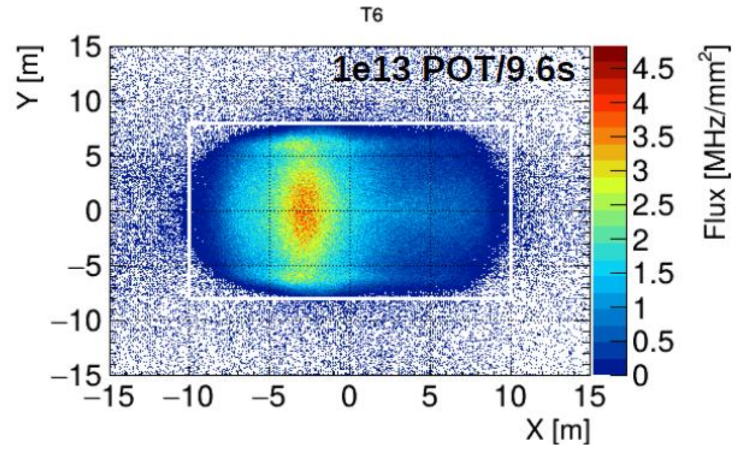
Meson and muon tracking (I)



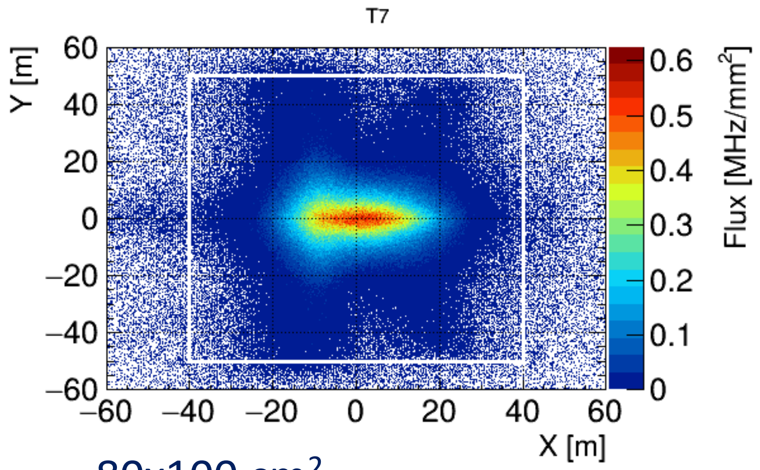
Silicon detectors are needed only at the core of the tracking planes. Scintillating fiber planes are sufficient to instrument the outer radii



$12x10\ cm^2$



$20x16\ cm^2$



$80x100\ cm^2$

Parent and muon tracking requires a time resolution of O(100 ps) and a detector granularity of 300 μm. Particle rates in the hottest (central) planes are 20 MHz/mm^2 for 10^{13} pot in 9.6 s. The peak fluence (non-ionizing dose) is 10^{16} $MeVn_{eq}/cm^2$ **We thus benefit from the technology currently being developed for the LHCb velo upgrade and pioneered at the 2 MHz/mm^2 level by NA62**

Accelerator neutrinos from muons

Produce, accelerate and collect muons in a storage ring is the holy grail of Collider Physics because

- a Muon Collider accelerates muons, which have negligible radiation losses inside a ring (multi-TeV lepton colliders)
- Muons are elementary leptons and offer the same clean environment as an electron-positron collider

but poses tremendous technical challenges because

- the muon lifetime is quite short (10^{-6} s) and acceleration to high Lorentz gamma must occur nearly instantaneously to prevent early decays
- The muon emittance must be small enough to be collected in the storage ring (challenging) or provide high-luminosity collisions inside the muon collider (very challenging)

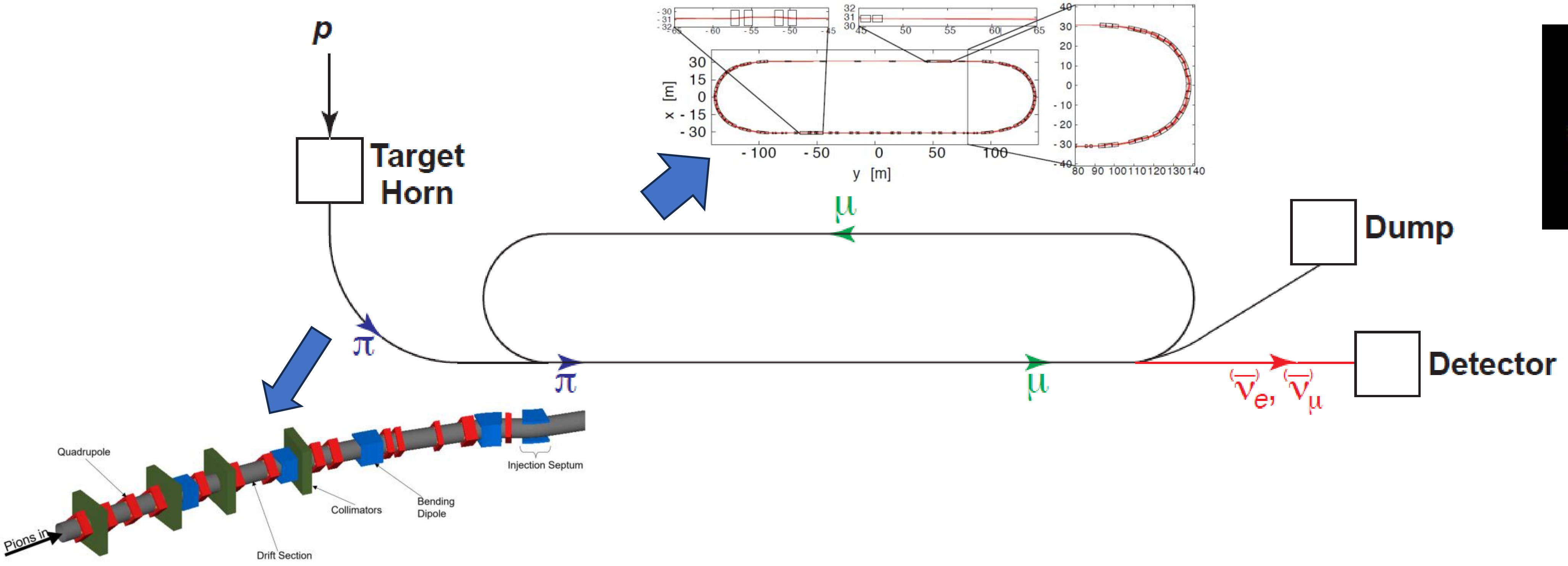
Classical (1990-2012) approach:

- First stage: muon are stored in a ring without acceleration and cooling to have a new source of neutrino for cross-section experiments and high-precision physics - **NuSTORM**
- Second stage: muons are cooled (emittance reduction) and accelerated at moderate energies to produce a Neutrino Factory – **IDS-NF**
- Third stage: muons are cooled and accelerated to a level adequate for a **multi-TeV muon collider**

This strategy has been updated after the discovery of θ_{13} and I will briefly present the perspectives for muon-based neutrino sources.

NuSTORM

Pions are injected at one end of the production straight. Only 50% of the pions decay in the production straight. Since the arcs are set for the central muon momentum lower than the momentum of the injected pion beam, pions remaining at the end of the straight will not be transported through the arc and the undecayed pion beam are dumped into an appropriate absorber.



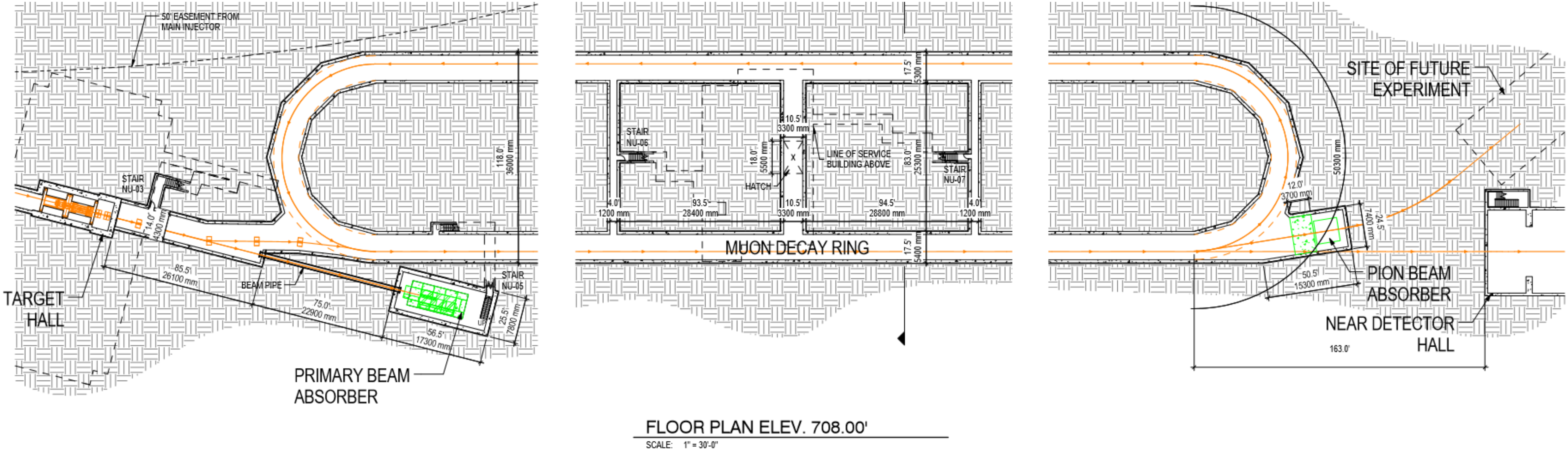
Muons that decay along the straight section produces $\mu^+ \rightarrow e^+ \nu_e$ anti-ν_μ if we store μ^+ and $\mu^- \rightarrow e^-$ anti-$\nu_e\ \nu_\mu$ if we store μ^-. **This source produces as many ν_e as ν_μ - unlike conventional beams!**

Accelerator challenges

Target → Horns → Quadruples → Storage ring → ν → Neutrino detector

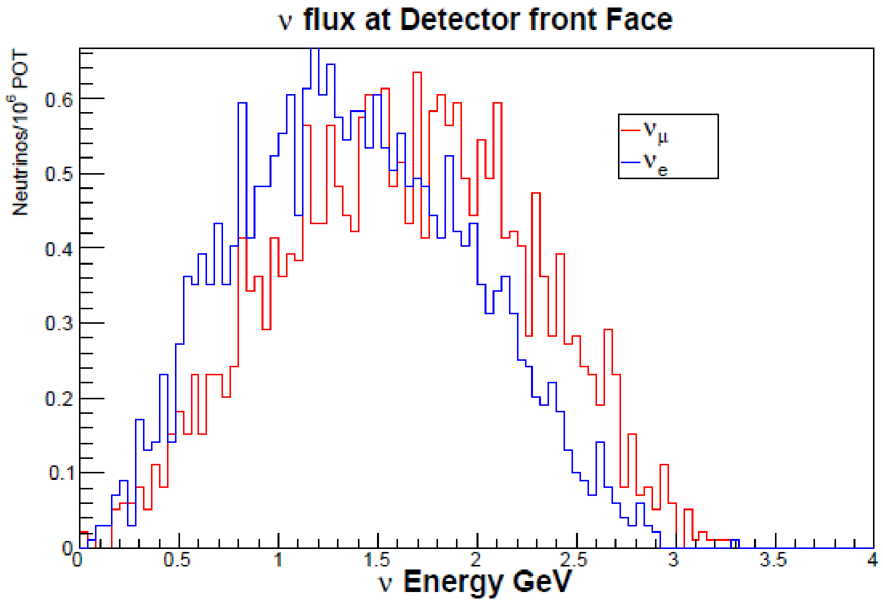
Pion absorber

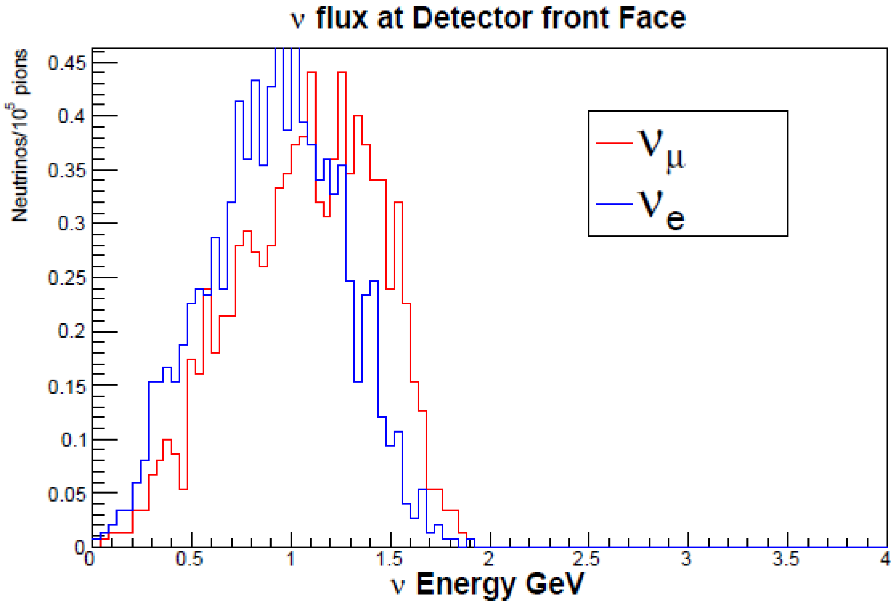
Here is where complexity and cost resides

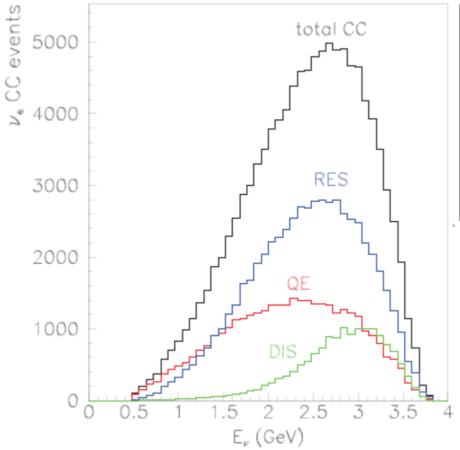


The ring has a very large aperture since we are not tightly focusing the pions (just a magnetic horn) and muons have an intrinsic emittance that originate from their decay from pions ($p_T \approx 100$ MeV)

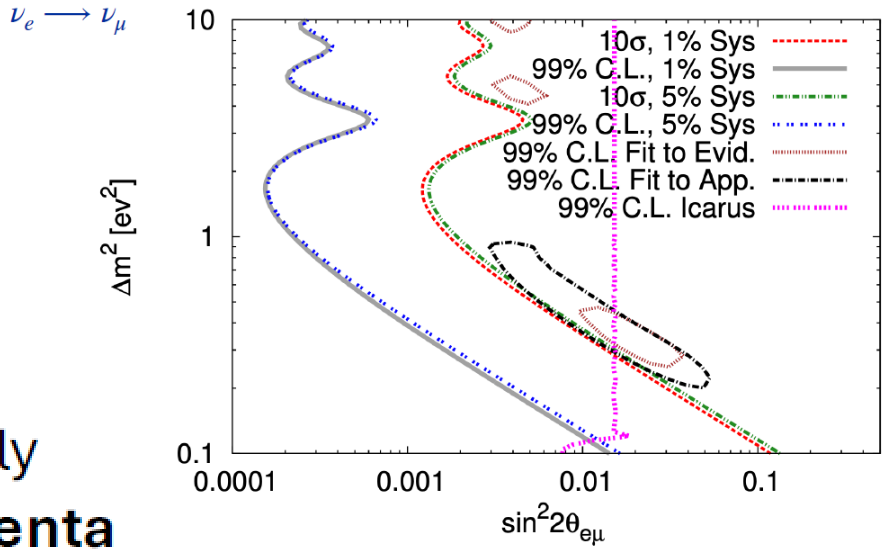
Neutrinos from NuSTORM







Channel (μ^+)	N_{evts}	Channel (μ^-)	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: detector **always on-axis**, but can linearly combine fluxes from **different stored-muon momenta**

Neutrino Factories

The concept originates from two seminal papers:

PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Neutrino beams from muon storage rings: Characteristics and physics potential

S. Geer
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
(Received 4 December 1997; published 13 April 1998)

Geer understood the enormous potential of muons stored in a decay ring to provide intense source of ν_μ and ν_e

Neutrino oscillation physics with a neutrino factory

A. De Rújula [a,1], M.B. Gavela [b,2], P. Hernández [a,3]
[a] *Theory Division, CERN, 1211 Geneva 23, Switzerland*
[b] *Dept. de Física Teórica, Univ. Autónoma de Madrid, Spain*

Received 20 November 1998; accepted 1 February 1999

They understood the unique features of this source to address the lepton Yukawa Sector of the SM **if the baseline matches the oscillation peak at Δm^2_{23}**

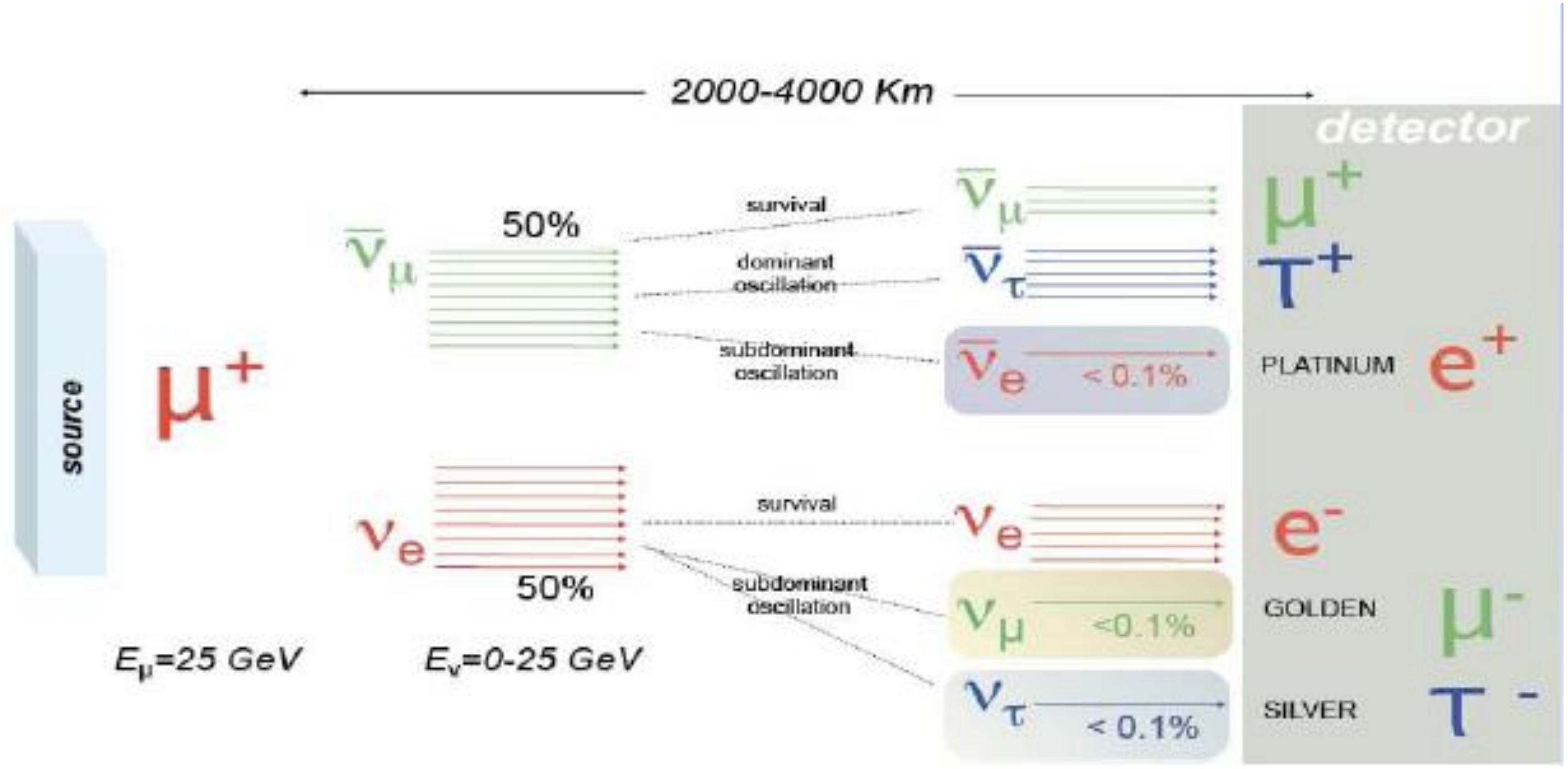
Features:

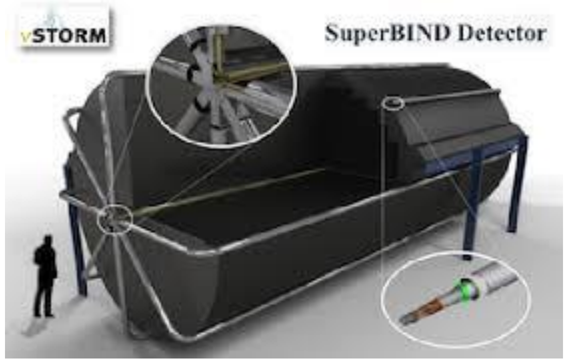
- Ultra-high neutrino fluxes (10^{21} useful muon decays per year with E_μ =20-50 GeV))
- Possibility to study $\nu_e \rightarrow \nu_\mu$ oscillations
- Background from "right sign muons" originating from anti- ν_μ

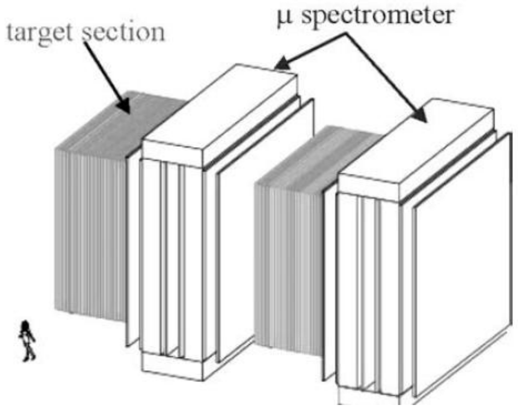
The type of detectors are much simpler than DUNE and HyperKamiokande. Moderate mass detector with high density and capability to measure the muon sign (magnetized iron)

Neutrino Factories: detectors

They look quite similar to MINOS, a magnetized iron detector aimed at observing the ν_μ oscillation pattern. However, they should be able to look at wrong sign muons ("golden channel" - $\nu_e \rightarrow \nu_\mu$ oscillations and its CP conjugate), $\nu_e \rightarrow \nu_\tau$ oscillations ("silver channel" - nuclear emulsions) and, possibly, $\nu_\mu \rightarrow \nu_e$ oscillations (low density)

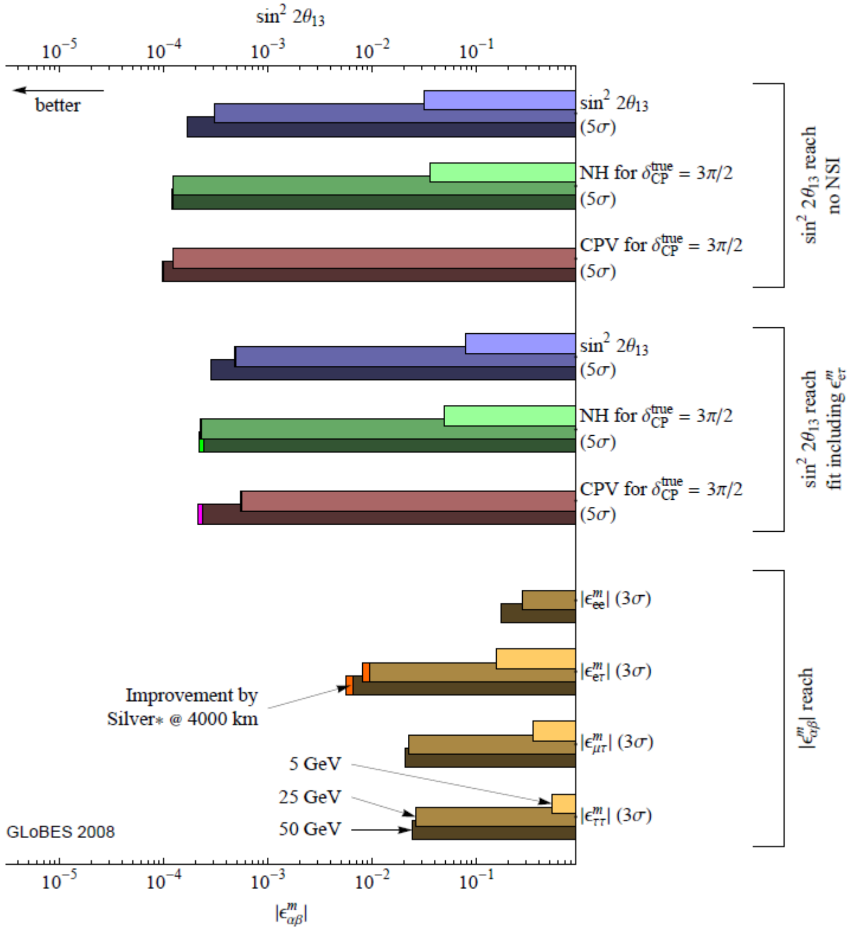


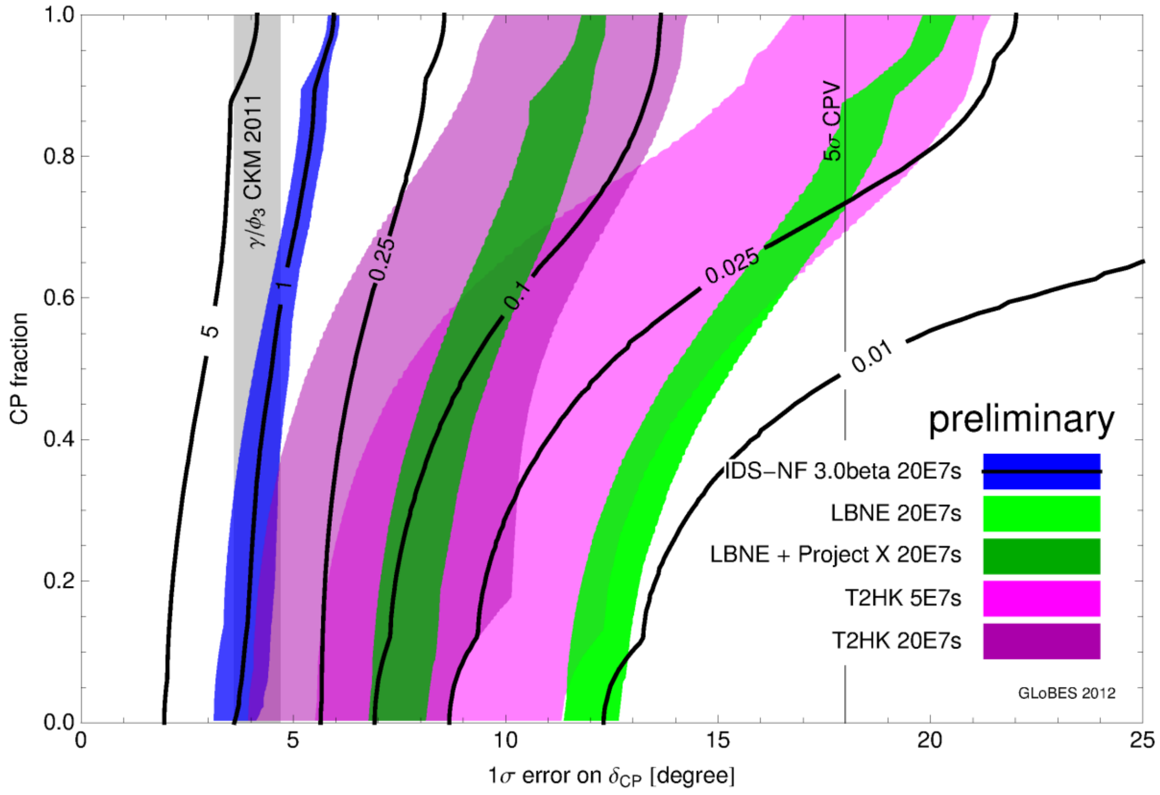




Neutrino Factories: “ultimate precision” ?

The discovery of a large θ_{13} has reduced interest in ultimate facilities, as superbeams are considered 'good enough' to study the PMNS matrix at the O(1–10%) level. However, achieving a precision comparable to that of the CKM matrix will still require a new paradigm shift.





A final thought: these lectures in 10 years from now

Goal	Timescale	Facility	Notes
Determine the missing parameters of the lepton Yukawa sector (except m_1)	Today–2035	T2K, NoVA, DUNE, HyperKamiokande	Very likely – at least with 5–10% precision. In particular, I expect the CP phase to be measured with a precision of about 10°.
Study eV-scale sterile neutrinos	Today–2035	SBN, DUNE, HyperKamiokande	By definition, this will never be conclusive, but it's likely that current anomaly tests will be completed.
Unitarity tests	>2030	DUNE, HyperKamiokande, Neutrino Factory	Unfortunately, we lack a crucial facility: an intense source of electron neutrinos to study $\nu_e \rightarrow \nu_\mu$ oscillations. A future muon collider could radically change this.
Measure standard neutrino interactions	Today–2035	Near detectors of DUNE and HyperK, ENUBET, nuSTORM	Significant room for improvement compared to current precision (10–30%). Target: 1%.
Constrain non-standard interactions (NSI) significantly	>2030	DUNE, HyperKamiokande, Neutrino Factory	Wide room for improvement, but we lack benchmarks as there are no robust models predicting large NSIs without LHC signals.

Backup slides

What will we be measuring?

The energy dependence of the neutrino cross section

↓

So we know how to extrapolate from our near to far detectors in oscillation experiments

The smearing of our neutrino energy reconstruction

↓

So we can infer the shape of the oscillated spectrum in DUNE/HyperKamiokande

The differences in the cross section for ν_e and ν_μ

↓

So we can reliably use ν_e appearance to probe CP-violation

The interaction channels that constitute backgrounds in DUNE/HyperKamiokande (e.g. NC π^0 production)

↓

So we know how to interpret far detector event rates

ν-N elastic scattering with tagged ν_μ

↓

The axial counterpart of e-N elastic scattering

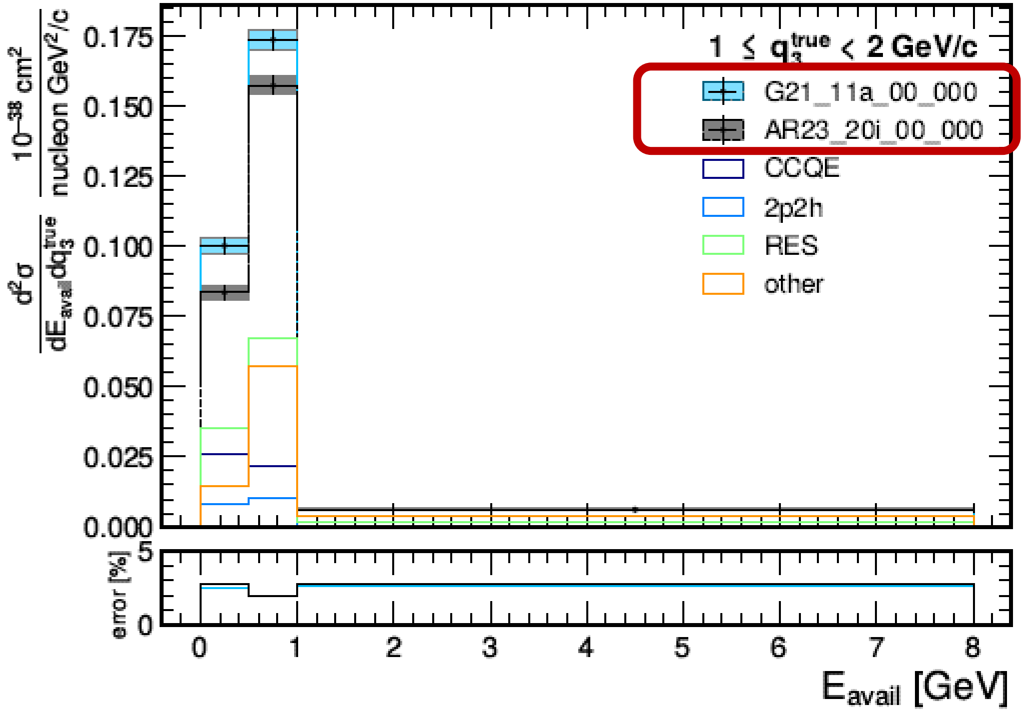
Many other channels not covered in this seminar because they are work in progress

↓

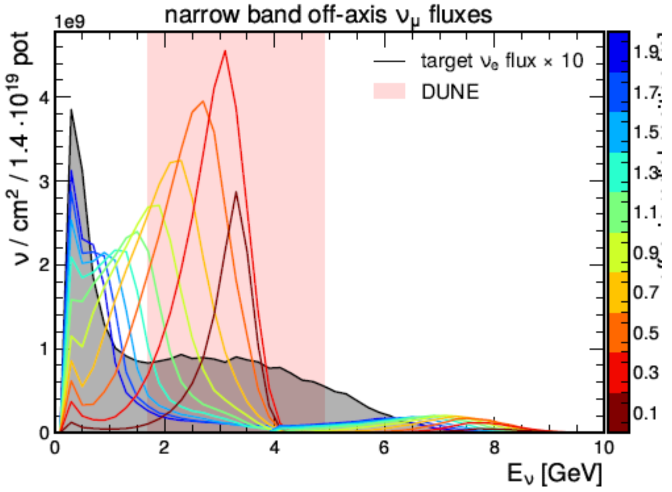
exclusive channels, non-standard interactions, dark sector probes, sterile neutrinos, etc.

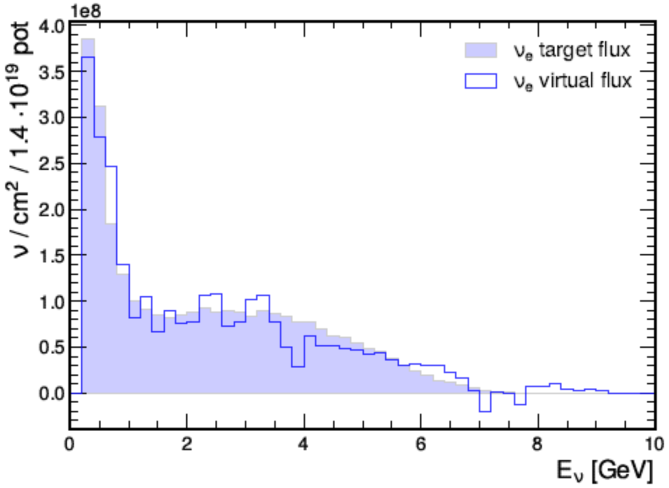
ν_e cross sections and ν_e / ν_μ ratio

Oscillation experiments cannot fully rely on lepton universality to account for the ν_e cross sections due to phase-space-induced effects. Electron neutrino cross sections are therefore particularly valuable and, in nuSCOPE, mainly originate from kaon decays. These can be monitored with a precision at the 1% level. Additionally, a 2% level measurement of the ν_e/ν_μ ratio can be performed using the PRISM technique.



$$E_{\text{avail}} = \sum_{i=\pi^{\pm},p} T_i + \sum_{i=\pi^0,\gamma} E_i$$





Since we cannot use either NBOA or tagging for ν_e, we measure the flux integrated ν_e cross section and compare it with the corresponding ν_μ cross section, which is built from narrow-width ν_μ fluxes obtained from the NBOA or tagged sample.

Lepton monitoring the decay tunnel

Shielding

- 30 cm of borated polyethylene;
- SiPMs installed on top → factor 18 reduction in neutron fluence;

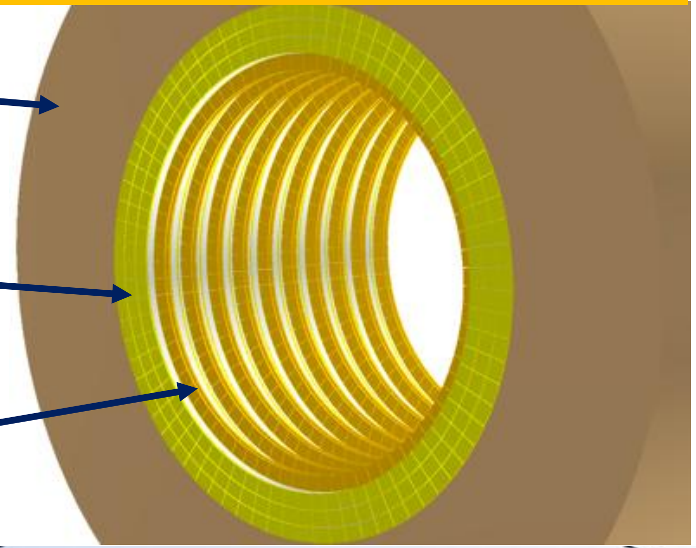
Calorimeter with $e/\pi/\mu$ separation capabilities:

- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of modules / longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout;

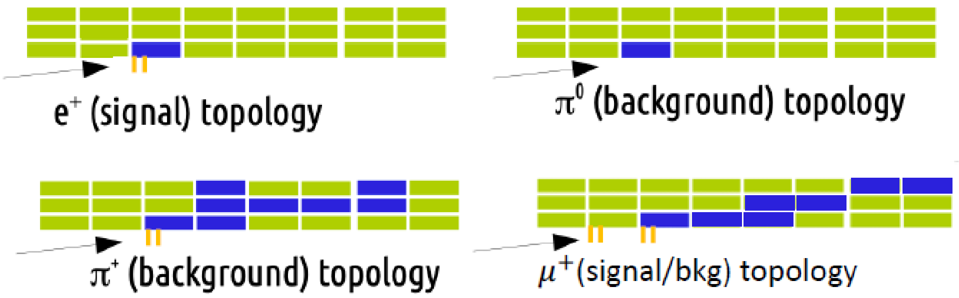
Photon-Veto allows π^0 rejection and timing:

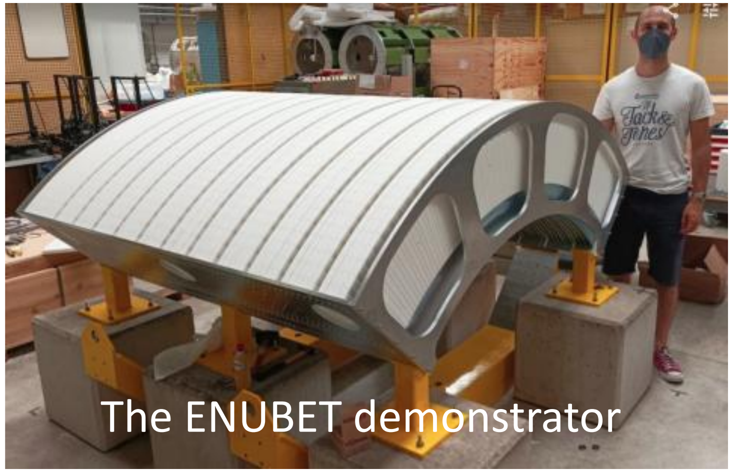
- plastic scintillator tiles arranged in doublets forming inner rings with a time resolution of $\sim$400 ps;

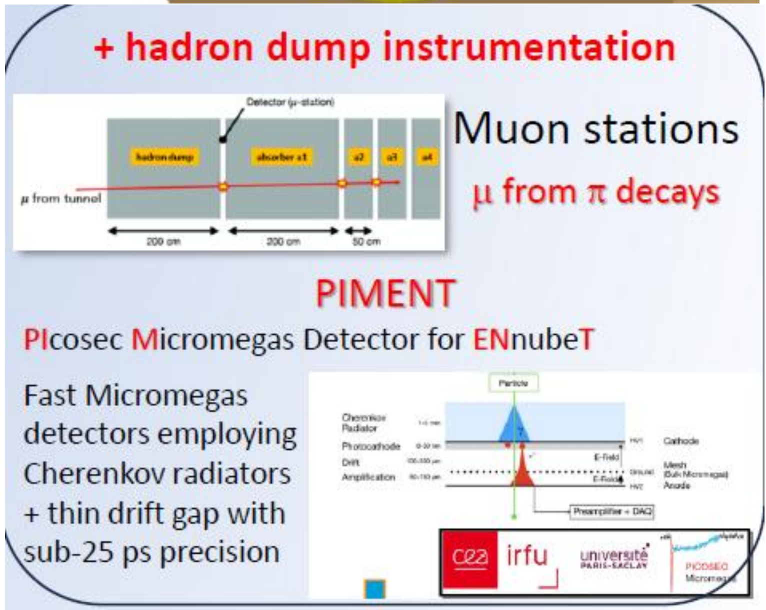
Layout of the instrumented tunnel



Pattern identification based on the pattern of energy deposit in the calorimeter modules



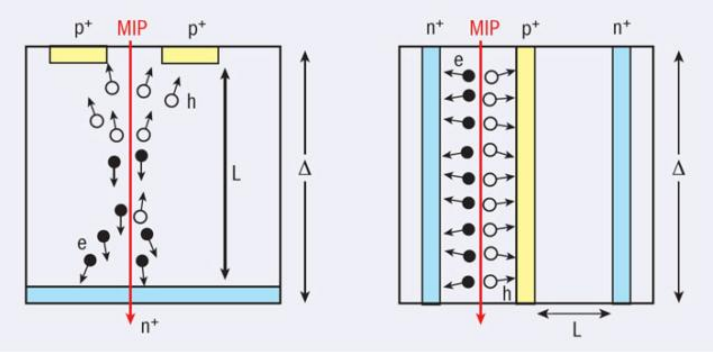


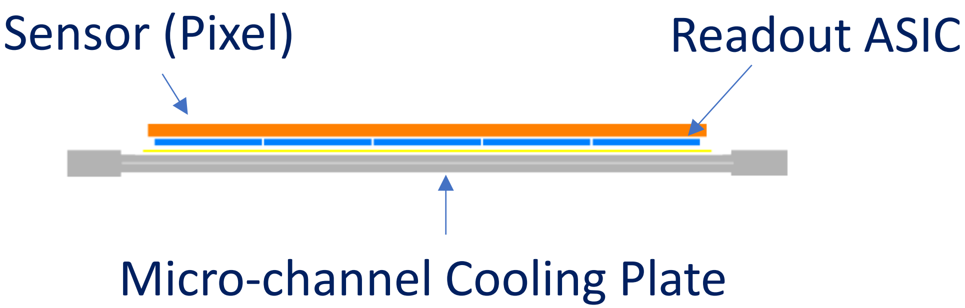


Meson and muon tracking (II)

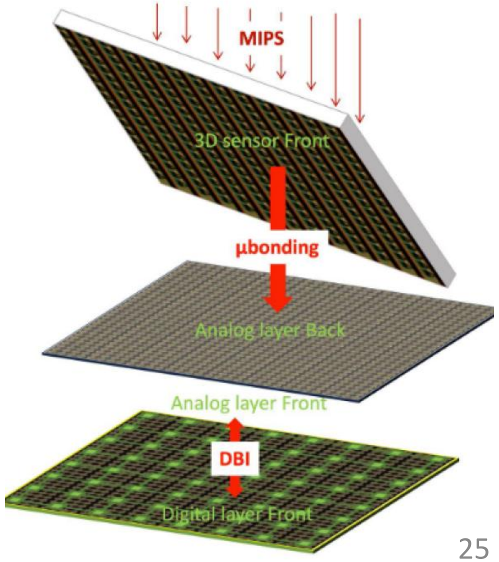
Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [$1MeVn_{eq}/cm^2$]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [MHz/mm^2]	20	0.6	$10 - 100$	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300		45	300
Material Budget [X_0]	$< 1\%$		0.8%	0.5%

3D trench sensors
(FBK through INFN TimeSpot)





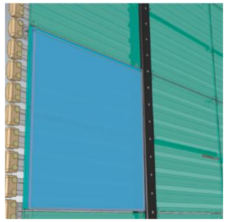
Readout ASIC
Three developments ongoing, all with 28nm CMOS technology
Timespot v2 and IGNITE (3D stacked) by INFN
PicoPix by CERN, Nikhef



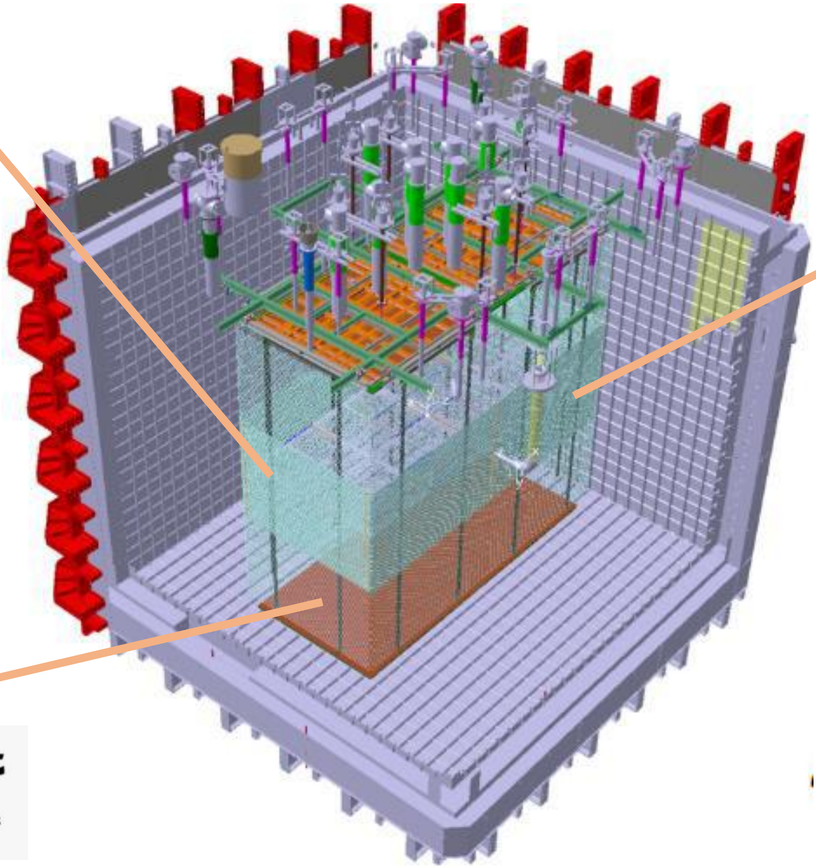
Liquid argon detector

The Liquid Argon TPC technology developed by DUNE, in both its "Horizontal Drift" and "Vertical Drift" configurations, meets all the specifications of nuSCOPE except for the time resolution in tagging mode, which should be in the 200-500 ps range. It is limited by the light collection efficiency due to poor coverage. This limitation will be overcome by the third and fourth DUNE modules, which anticipate full 4π photon coverage.

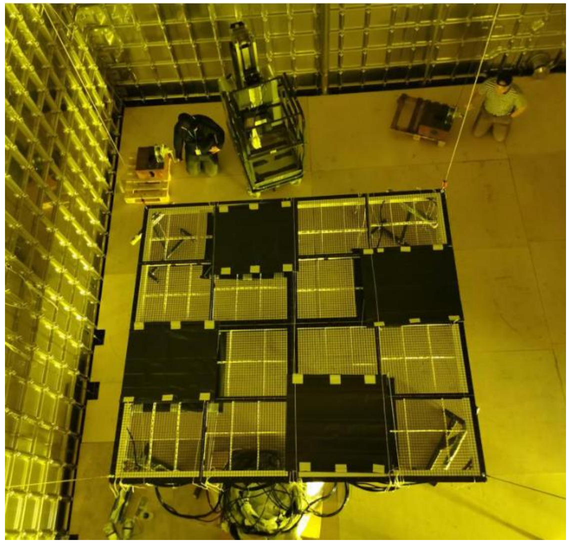
Field cage equipped with Photon Detectors (128 nm)



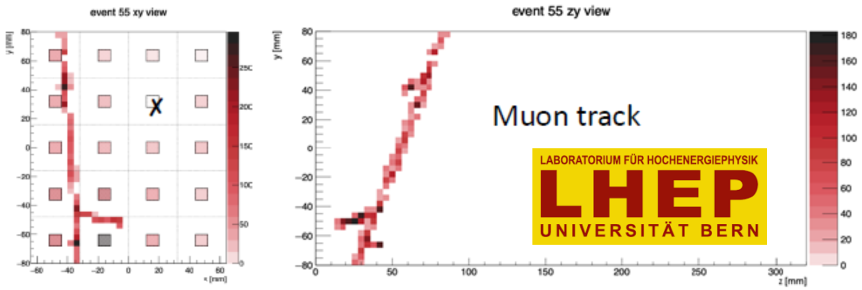
ProtoDUNE-VD Run III (2027-28)



Cathode equipped with Photon Detectors (128 nm) as in DUNE Vertical Drift, validated in ProtoDUNE-VD (2025)



Anode equipped with VUV (128 nm) SiPMs



SoLAr

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