Neutrinos from Stored Muons, nuSTORM:
A Unique GeV Electron-(Anti)Neutrino Machine

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On behalf of the nuSTORM Collaboration

Workshop on Neutrinos@CERN
2025 January 24, CERN

Outline

1. Problems and opportunities with neutrino masses

2. Call for a GeV ν_e and $\bar{\nu}_\mathrm{e}$ machine
    - ❑ Accelerator neutrino experiments vs. nuSTORM

3. nuSTORM physics programs
    a. Neutrino cross section
    b. BSM

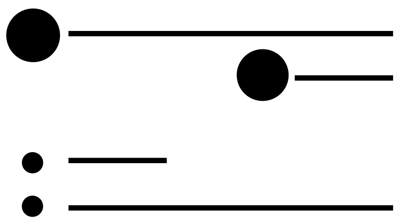
Neutrino Mass and Mixing

Standard Model

Beyond Standard Model

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \boxed{\begin{array}{c}\text{Pontecorvo–Maki–Nakagawa–Sakata}\\ \text{PMNS matrix}\end{array}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass Ordering



Δm^2 leads to neutrino oscillations

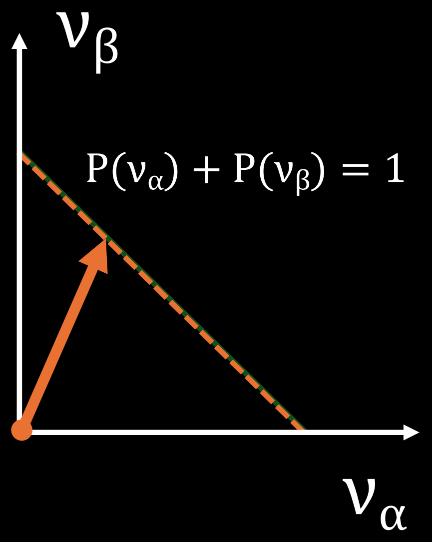
Problems

- ❑ What are the neutrino masses?
  - ❖ Mass gaps, Δm^2_{21}, $|\Delta m^2_{32}|$, and ordering, sgn(Δm^2_{32})?
- ❑ What are the mixing parameters?
  - ❖ Mixing angles, θ_{12}, θ_{23} , θ_{13}, and CP-phase, δ_{CP}?
- ❑ Are there more than three types of neutrinos?

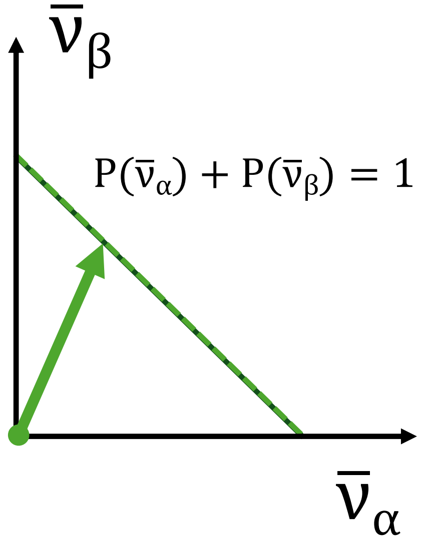
Neutrinos

$\theta_{13} = 0$

2-flavor oscillation



Antineutrinos

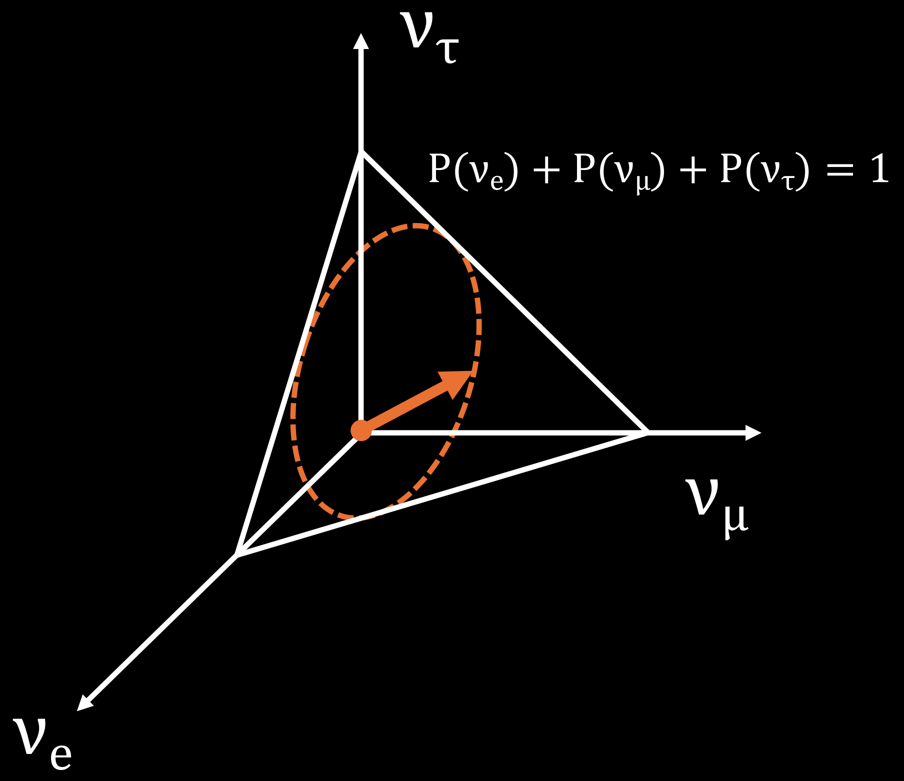


- 2-flavor oscillation: CP not observable

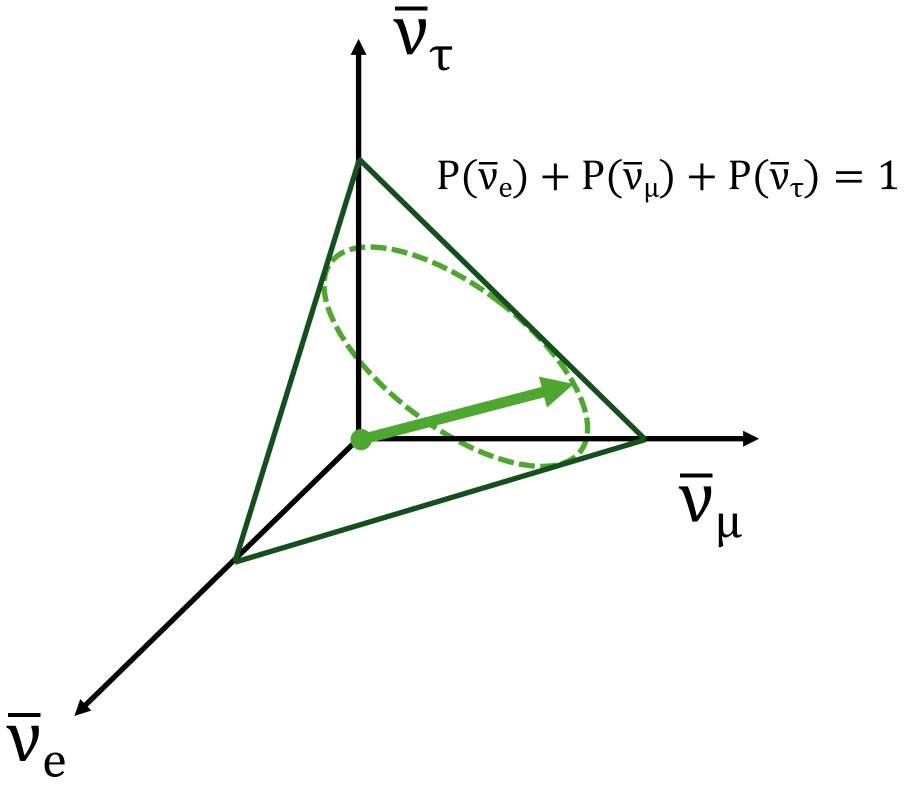
Neutrinos

$\theta_{13} \neq 0$

3-flavor oscillation



Antineutrinos



Opportunities

- ❑ 3-flavor oscillation: CP-violation possible
- ❑ Short-baseline anomalies: sterile neutrinos?

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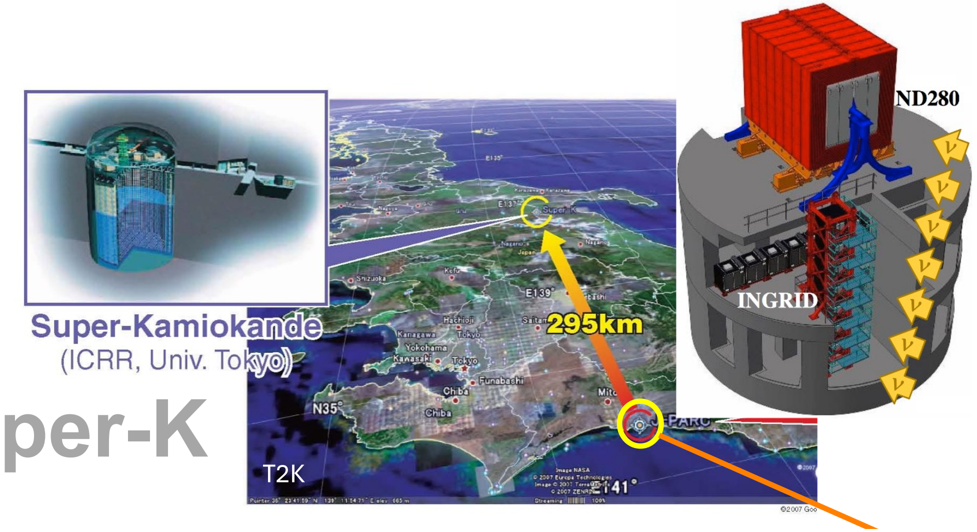
Accelerator Neutrino Experiments

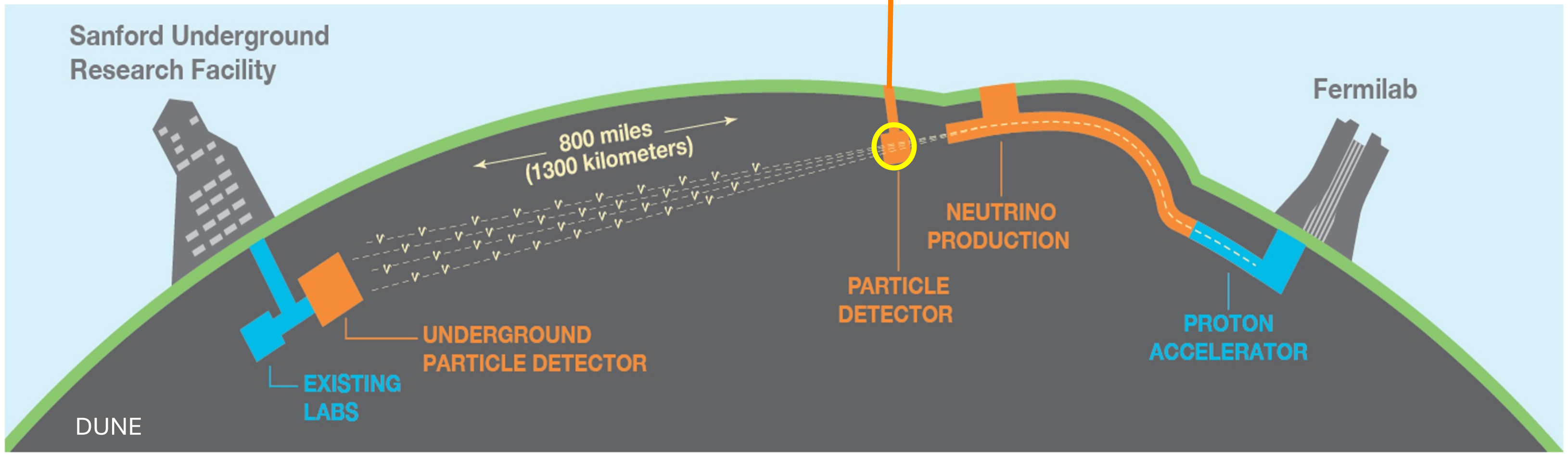
T2K / Hyper-K



NOvA

ν beams via hadron decay

DUNE



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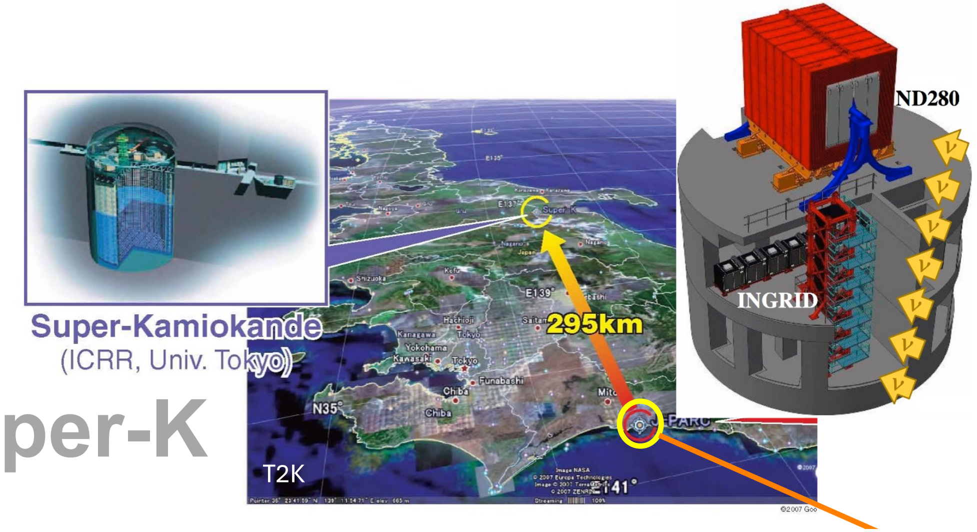
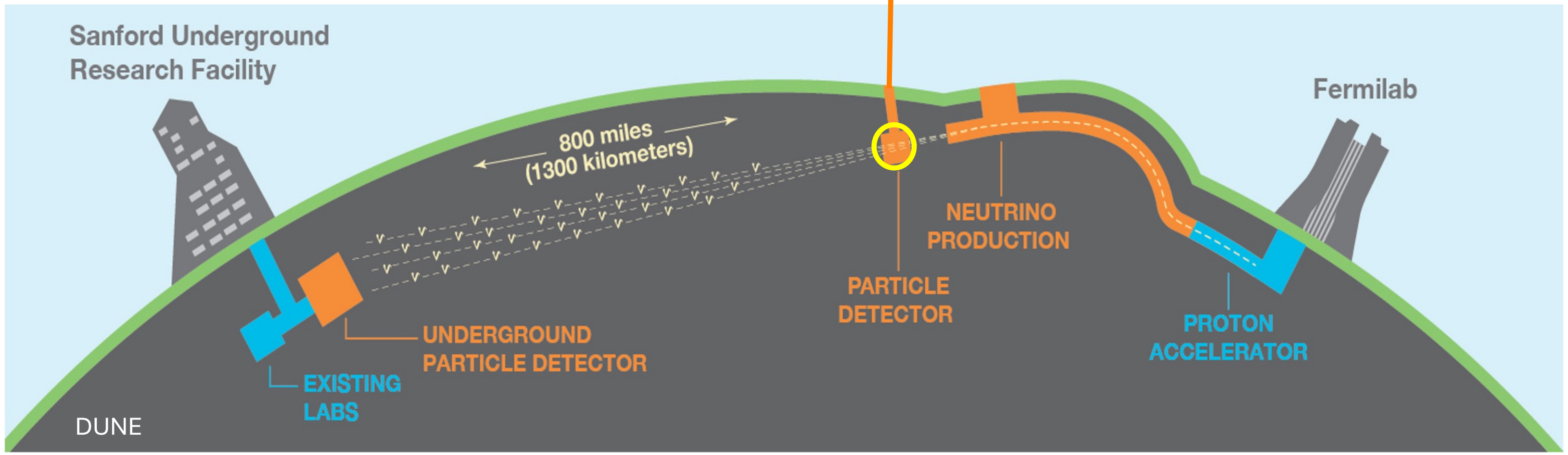


NOvA

Near Detectors to constrain ν flux ***and*** cross section ***together*** (no oscillation)

DUNE



Accelerator Neutrino Experiments

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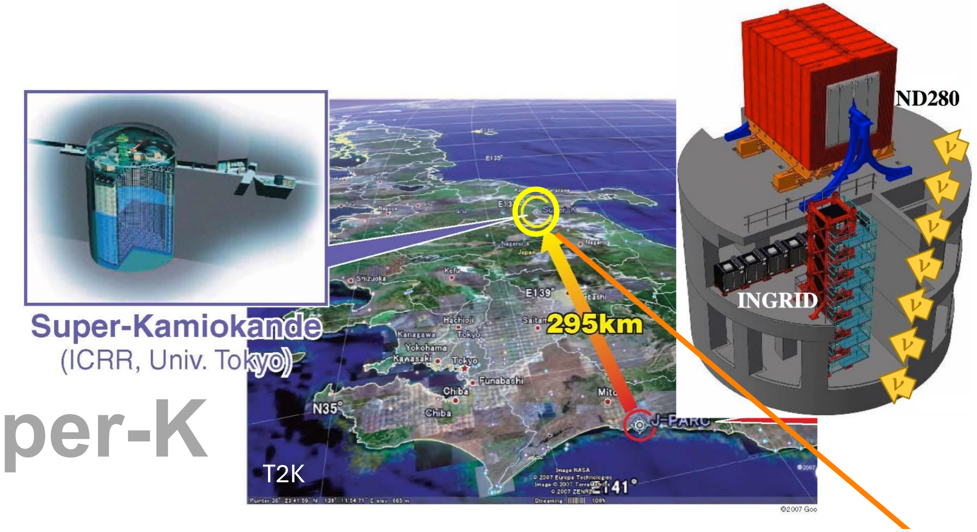
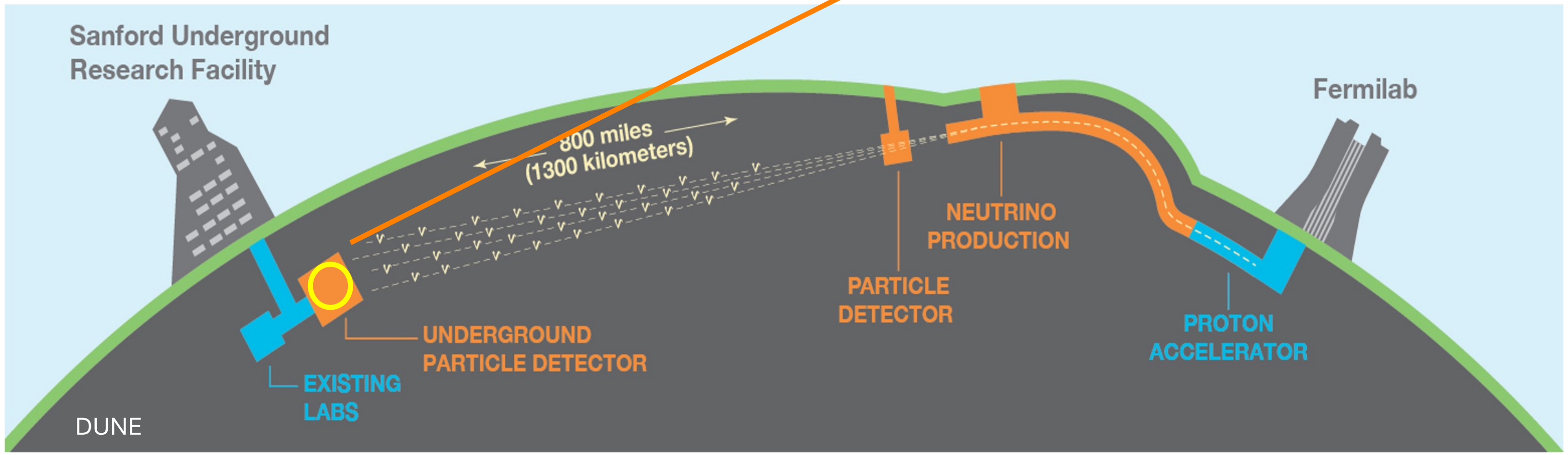


NOvA

Far Detectors to measure ν oscillation

DUNE



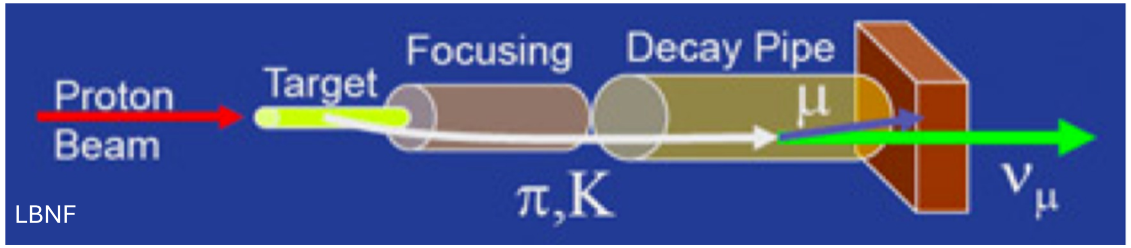
Accelerator Neutrino Experiments

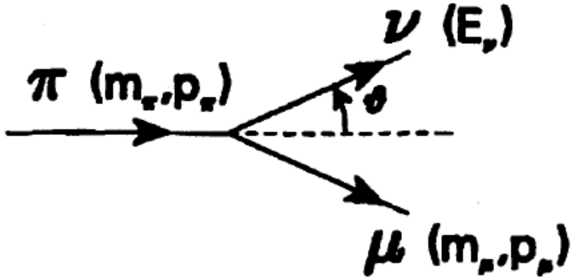
Accelerator ν Experiment	E_ν/GeV @ Flux Peak	Far Detector Technology	Target Nuclei
T2K / Hyper-K	0.6	Water Cherenkov	H_2O
NOvA	2	Liquid Scintillator	CH
DUNE	2.4	LAr TPC	Ar

Signal = (**Beam flux** · **Oscillation probability** · Cross section) ⊕ Detector effects

- ❑ Beam: ν_μ and $\bar{\nu}_\mu$
- ❑ Oscillation
  - ❖ ν_μ and $\bar{\nu}_\mu$ disappearance (most oscillated to ν_τ and $\bar{\nu}_\tau$)
  - ❖ **ν_e and $\bar{\nu}_e$ appearance, then CP violation**

Accelerator Neutrino Experiments





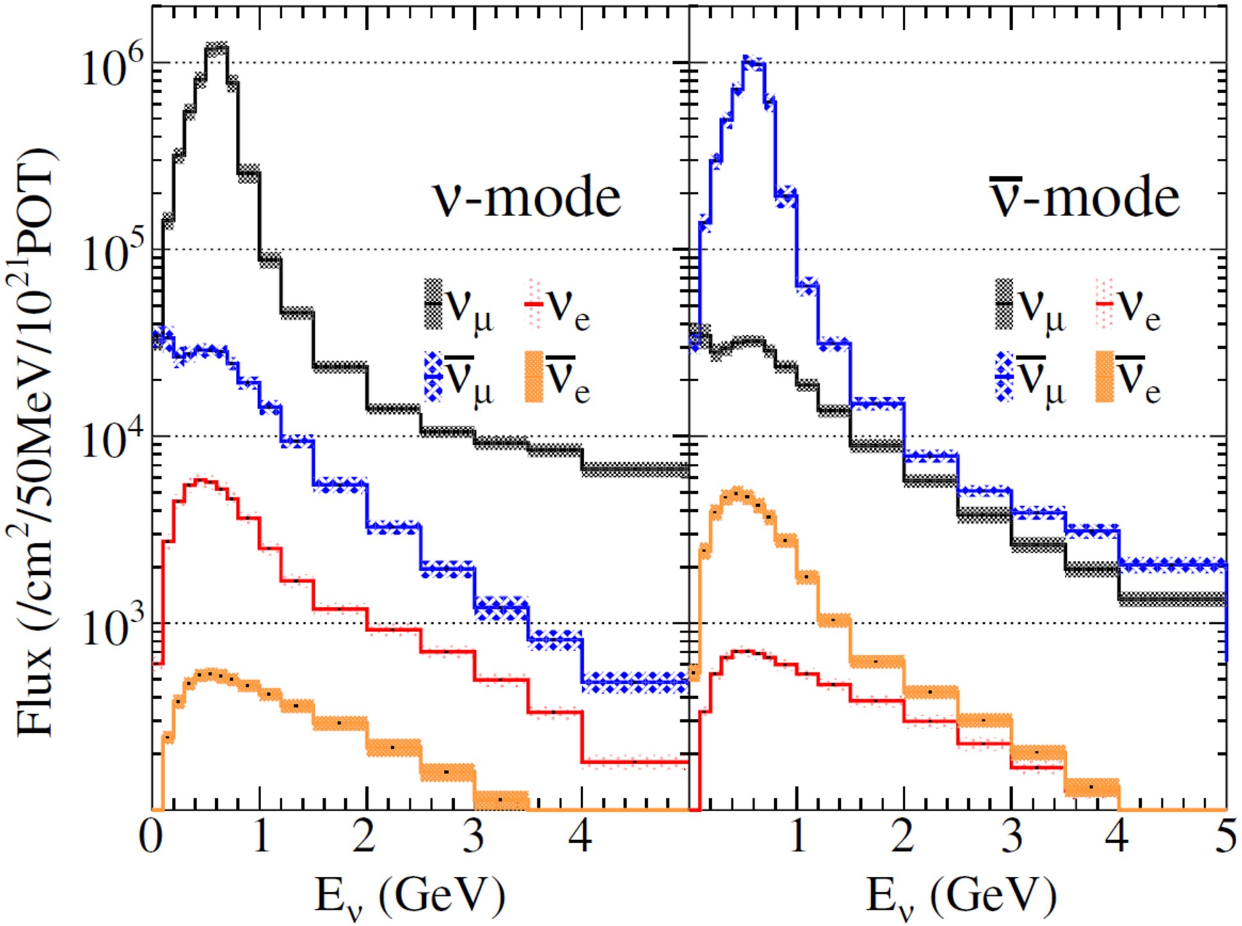
"β decay" of collision products
(ν_μ from π, ν_e from K)

Neutrino beams from accelerators
→ Directional

Charge selection on π
→ High purity ν or $\bar{\nu}$ beams

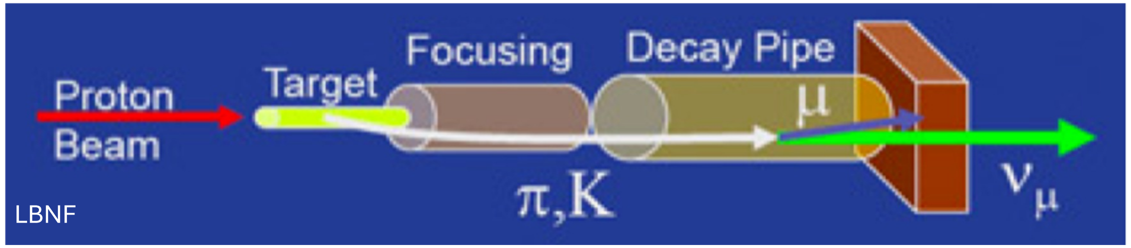
T2K flux

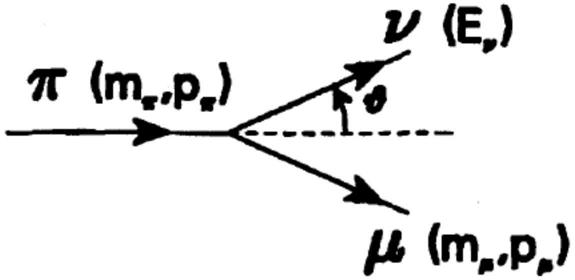
T2K, Phys.Rev.Lett. 116, 181801 (2016)



❑ Maximise ν_μ and $\bar{\nu}_\mu$ flux

Accelerator Neutrino Experiments





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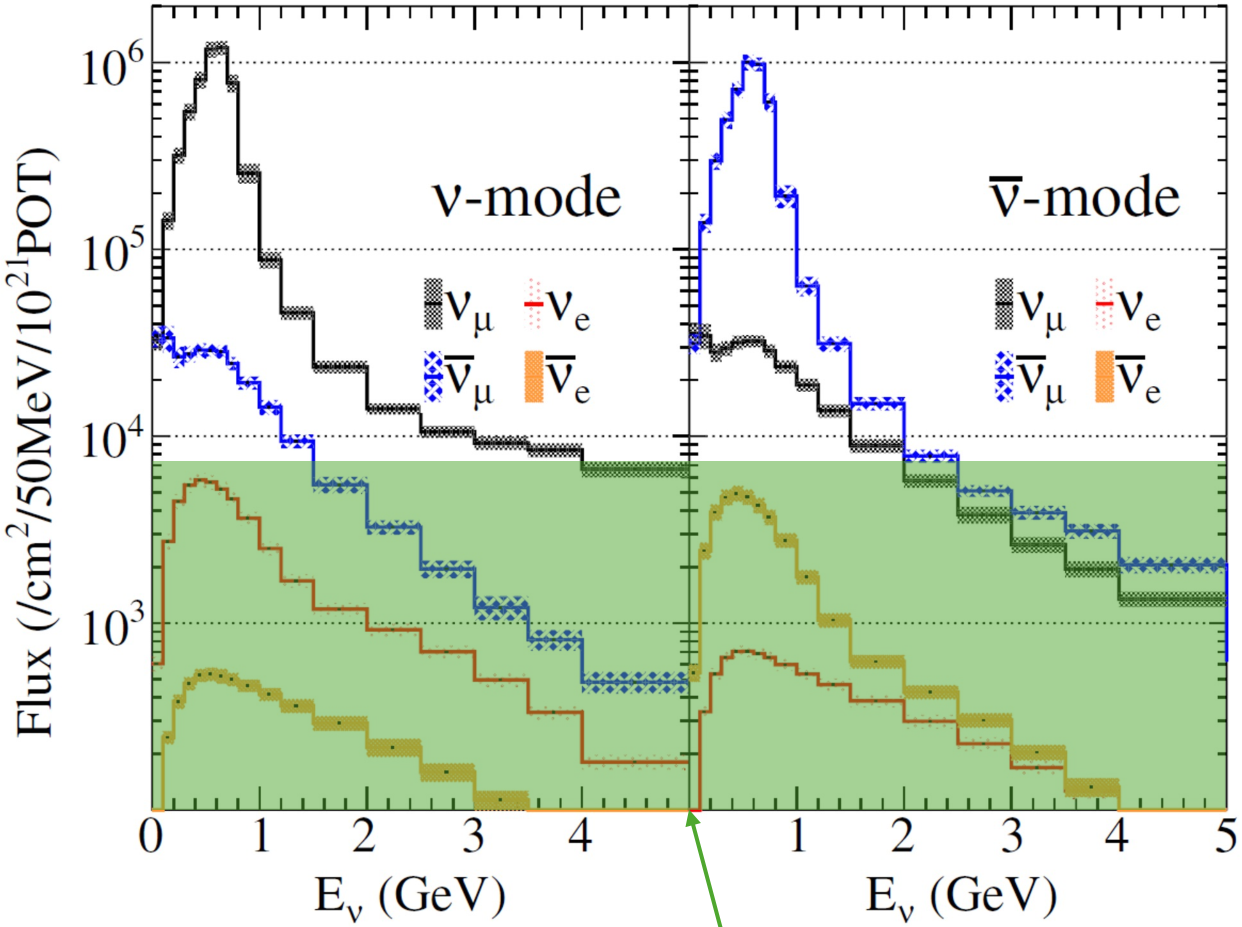


- ☐ Maximise ν_μ and $\bar{\nu}_\mu$ flux
- ☐ **Minimise ν_e and $\bar{\nu}_e$ to observe appearance**
  - ☐ **ν_e and $\bar{\nu}_e$ flux are background**

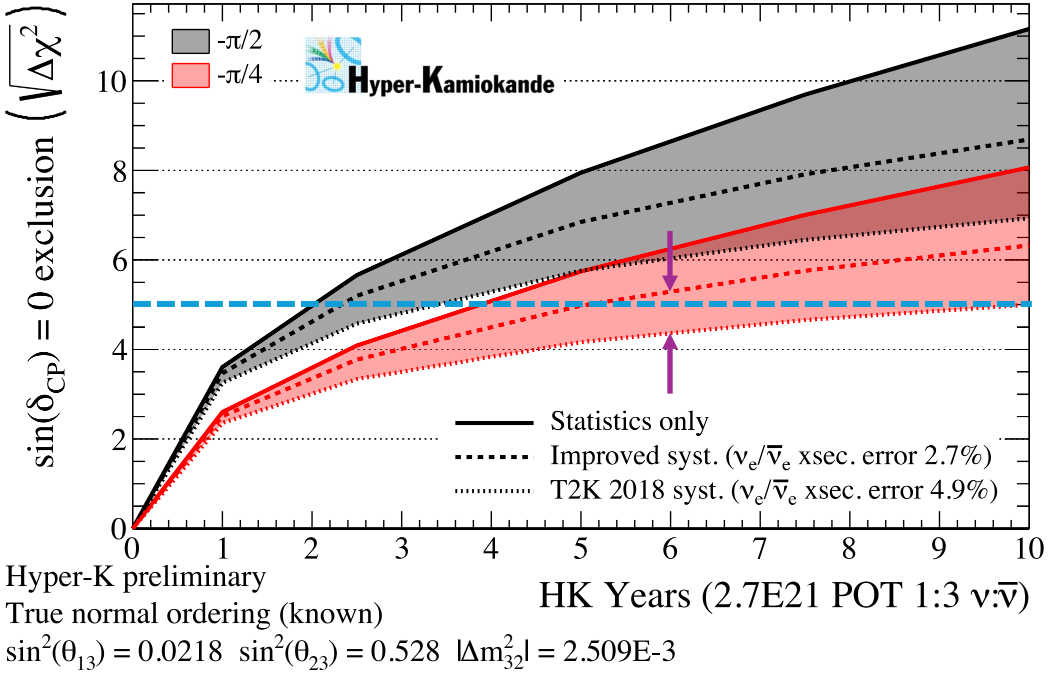
Call for a GeV ν_e and $\bar{\nu}_e$ Machine

Oscillation Signal = (Beam flux · Oscillation probability · **Cross section**) ⊕ **Detector effects**

ν_e ($\bar{\nu}_e$) cross sections: major δ_{CP} systematics

- ☐ $\delta_{\mathrm{CP}} \sim \nu_e$ appearance ~ no ν_e in beams
  - ❖ No *in situ* ν_e measurements
- ☐ ν_μ for ν_e via lepton universality, but higher precision needed for δ_{CP}

Jeanne Wilson, Neutrino2022



Hyper-K example

Improving error of $\nu_e/\bar{\nu}_e$ xsec ratio 4.9% → 2.7%

- ☐ Improve δ_{CP} sensitivity by ~ 1 σ for 6 year
- ☐ **Significantly shorten running time to reach 5 σ**

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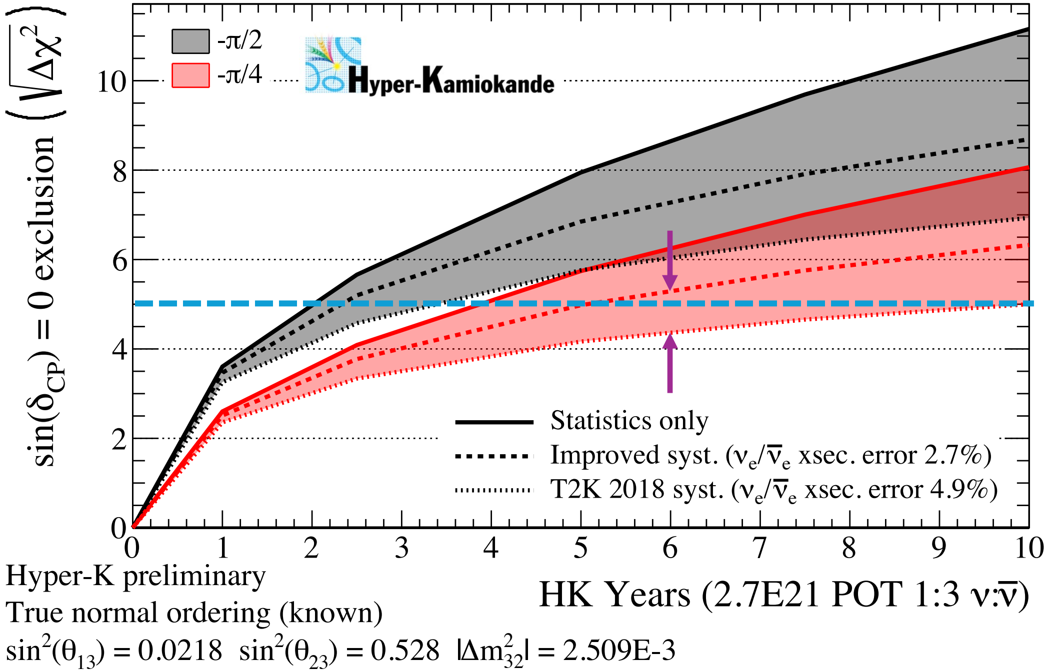

Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\mathrm{E}{-3}$

Host

Cost

Co-Host

Cost

Time

Call for a GeV ν_e and $\bar{\nu}_e$ Machine

Oscillation Signal = (Beam flux · Oscillation probability · **Cross section**) ⨁ **Detector effects**

ν_e ($\bar{\nu}_e$) cross sections: major δ_{CP} systematics

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✓ Dedicated ν_e measurements

1. **Better-understood fluxes**
2. **Correct settings for oscillations: beam energy, final-state acceptance, etc.**
3. **Higher statistics**
4. **Lower ν_μ background**
5. **Optimised detection for ν_e**

❖ **Shorten running time = ~~reduce~~ share cost**

Host

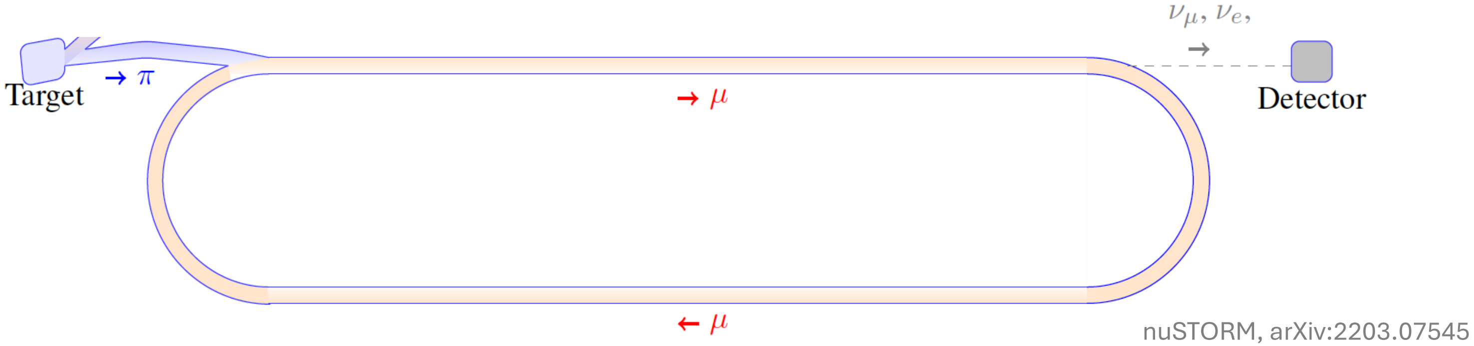
Cost

Co-Host

Cost

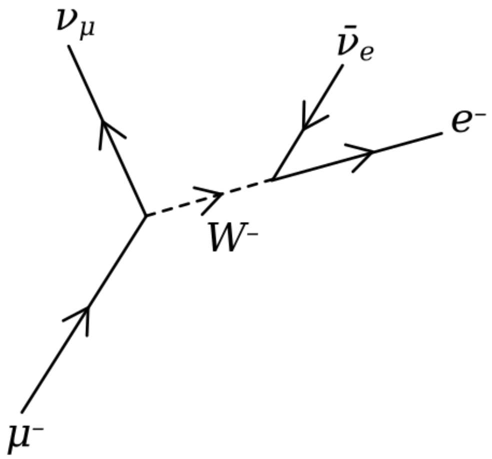
Time

ν *from STORed Muons (nuSTORM)*



nuSTORM, arXiv:2203.07545

- ☐ $\bar{\nu}_\mu + \nu_e$ and $\nu_\mu + \bar{\nu}_e$ fluxes from $\mu^\pm$ decays
  - ❖ **Optimisable ν_e and $\bar{\nu}_e$ fluxes**
  - ❖ **Perfect understanding of flux shape and normalisation**
- ☐ Scientific objectives
  - ❖ %-level ν cross sections
  - ❖ BSM searches, e.g. steriles beyond FNAL SBN
  - ❖ Muon collider demonstrator



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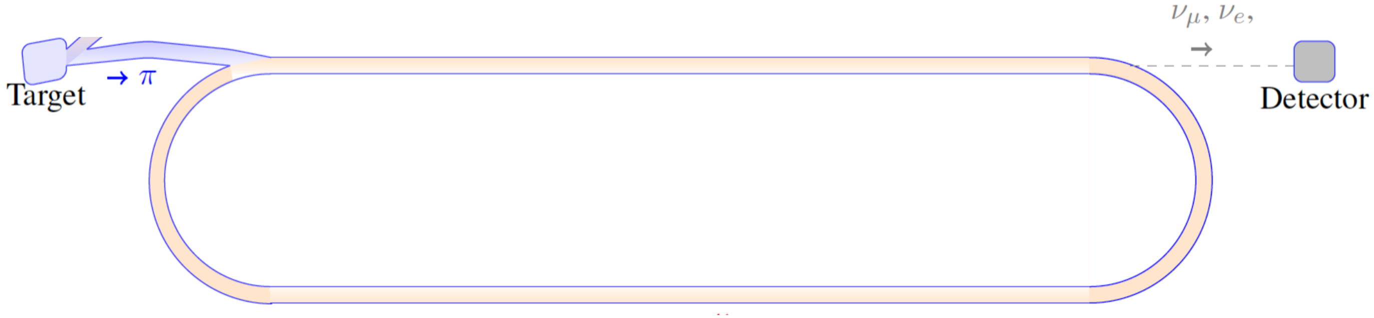
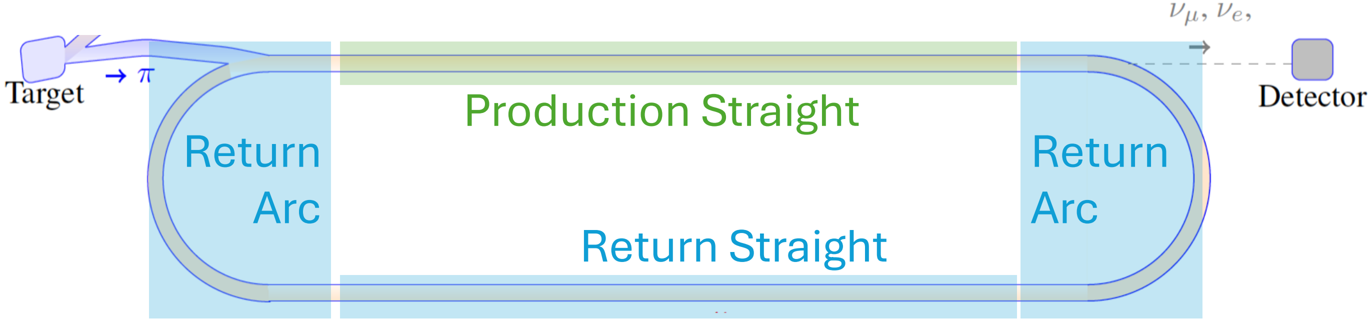


- **1^{st} ν beam facility based on a stored muon beam**
- **Highest ever stored-muon beam power**
- ν flux deduced by μ beam monitoring

ν from STORed Muons (nuSTORM)



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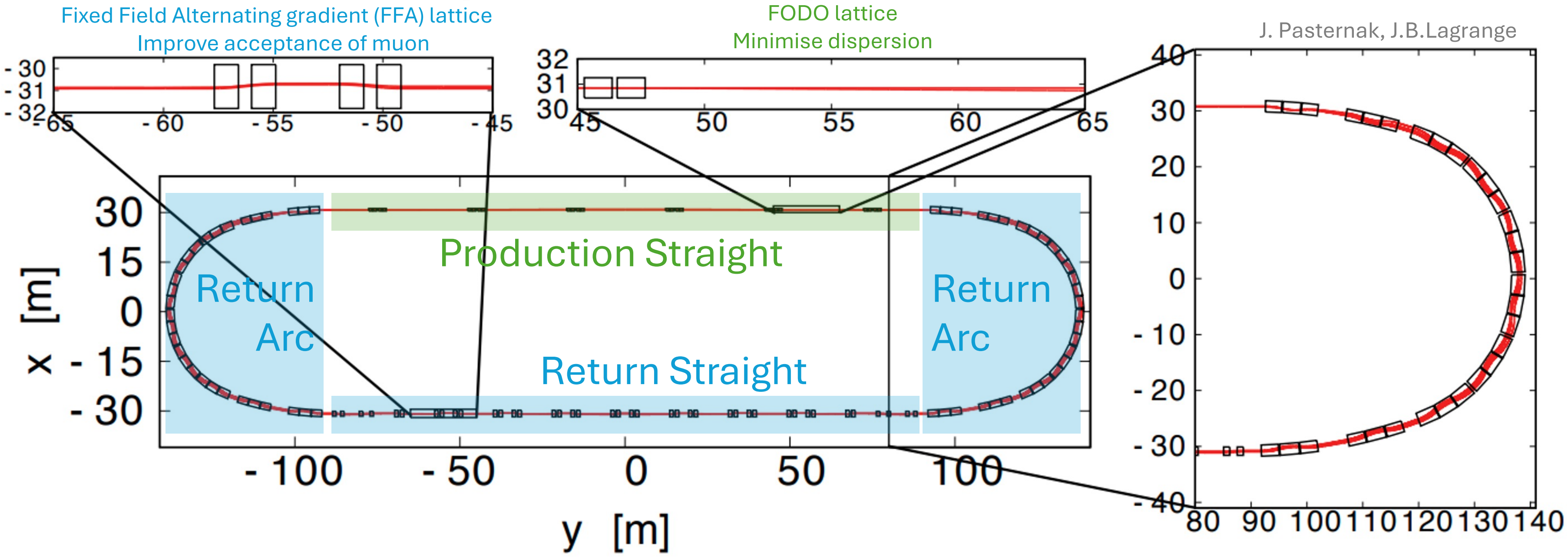


Fixed Field Alternating gradient (FFA) lattice
Improve acceptance of muon

FODO lattice
Minimise dispersion

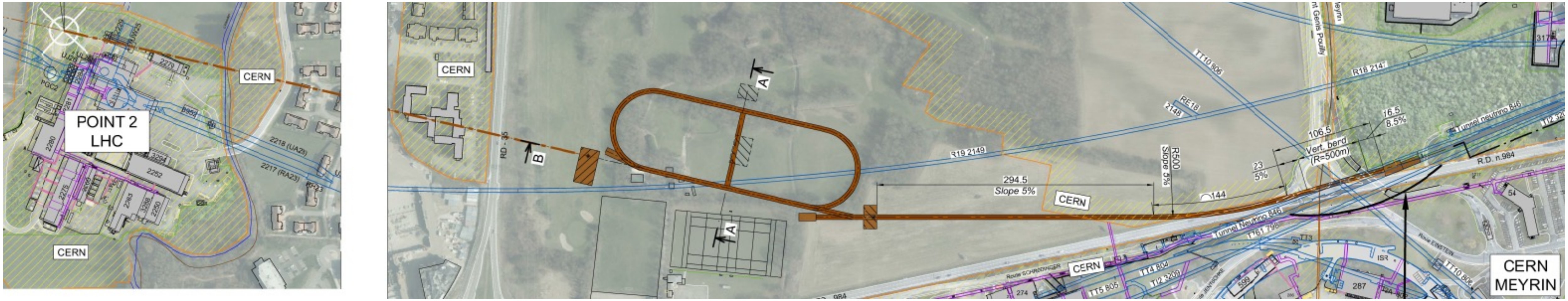
J. Pasternak, J.B.Lagrange

- **1st ν beam facility based on a stored muon beam**
- **Highest ever stored-muon beam power**
- ν flux deduced by μ beam monitoring

- Production Straight (example w/ π^+ injection)
  - ν_μ flux from $\pi^+ \rightarrow \mu^+\nu_\mu$ ("pion flash")
  - $\nu_e + \bar{\nu}_\mu$ flux from $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$
  - Maximise μ capture efficiency
- Arcs and Return Straight
  - μ momentum tunable between 1 and 6 GeV/c, spread ±16%

A Brief History of nuSTORM

CERN-PBC-REPORT-2019-003
DOI:10.17181/CERN.FQTB.O8QN



2012-2013	LoI and Proposal to FNAL PAC [arXiv:1206.0294, arXiv:1308.6822], EoI to CERN [arXiv:1305.1419]
	➢ Sterile neutrinos
	➢ Neutrino-nucleus scattering
	➢ Technology test-bed for muon accelerators
2014	Steriles sensitivity [Phys.Rev.D 89, 071301 (2014)]
	➢ nuSTORM at FNAL
2019	Feasibility of nuSTORM at CERN [CERN-PBC-REPORT-2019-003]
	➢ SPS 100 GeV proton beam
	➢ Optimised for neutrino-nucleus scattering, maintaining sensitivity to BSM (steriles + non-unitarity, NSI, Lorentz-invariance/CPT violation)
2022	Snowmass 2021 [arXiv:2203.07545]
	➢ Advocating synergy with ENUBET and Muon Collider Demonstrator

nuSTORM at CERN

- ✓ Muon Collider demonstrator
  - ☐ 6-D cooling

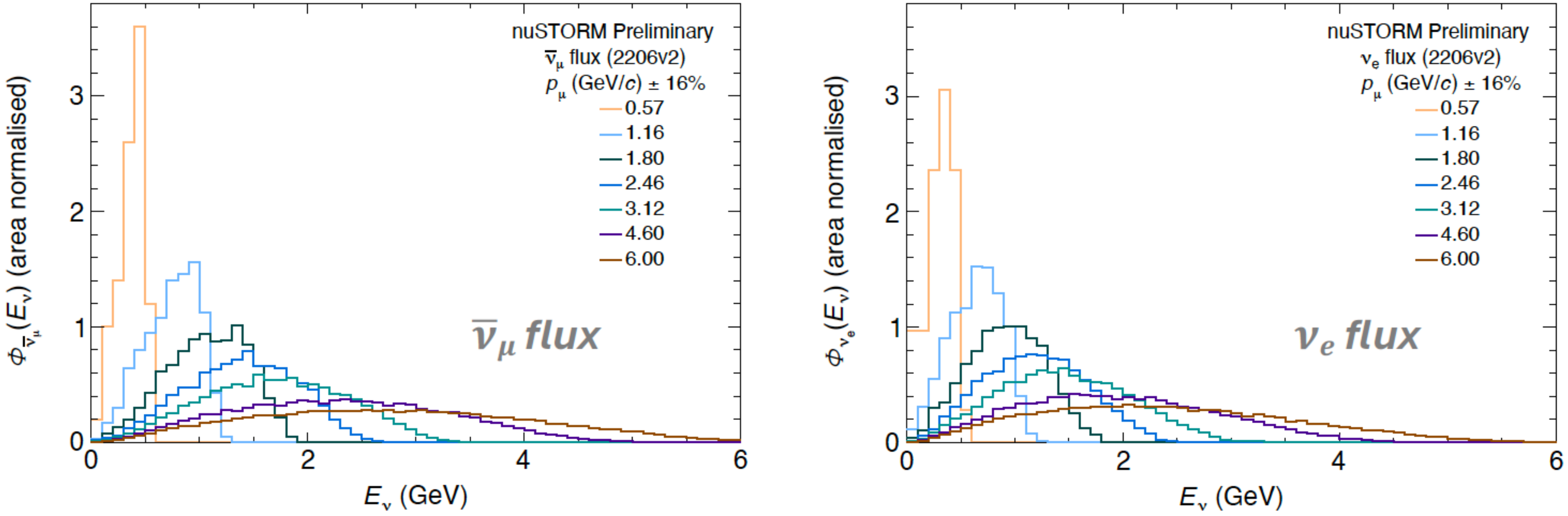
- ✓ ENUBET (see talks yesterday)
  - ☐ ν_e from e^+ tagging for $K^+ \rightarrow \pi^0 e^+ \nu_e$
  - ☐ ν_μ from μ^+ tagging
  - ☐ Flux uncertainty ~ 1%

- ✓ nuSTORM as testbed for muon storage ring
  - ➢ Complete implementation for large acceptance (inc. injection and extraction sections)
  - ➢ R&D for very precise determination of stored-muon energy and spread

nuSTORM Fluxes

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

T. Alves, M. Pfaff



Beam properties

- Oscillation-relevant energy regime
  - Hyper-K: 0.6 GeV
  - DUNE: 2.4 GeV
- Neutral lepton
- 100% polarized
- Isospin sensitive

- Accelerator "tune" gives fine control
  - E.g. optimise flux shape (or spread) by adjusting the ring acceptance
- **Unique opportunity**
  - **E_ν-scan measurements**

nuSTORM Fluxes

PRISM concept: Combine multiple fluxes to synthesise a statistically equivalent flux to the desired one

- ☐ **nuSTORM synthetic flux**: beam energy tune, **no detector moving**
- ☐ PRISM at Hyper-K or DUNE: sample fluxes at different detector locations

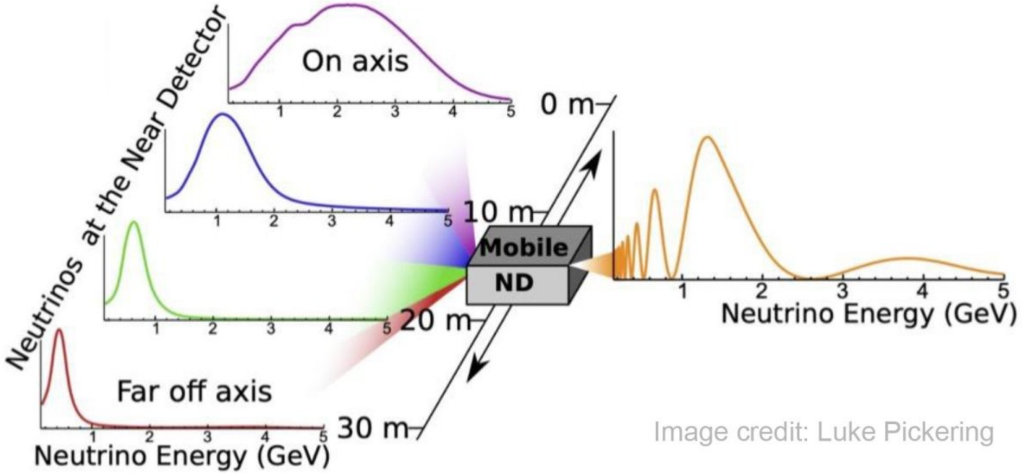
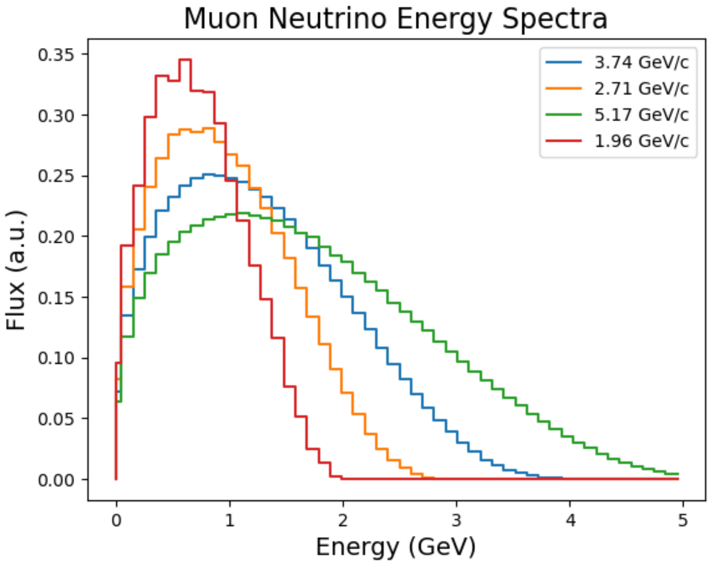
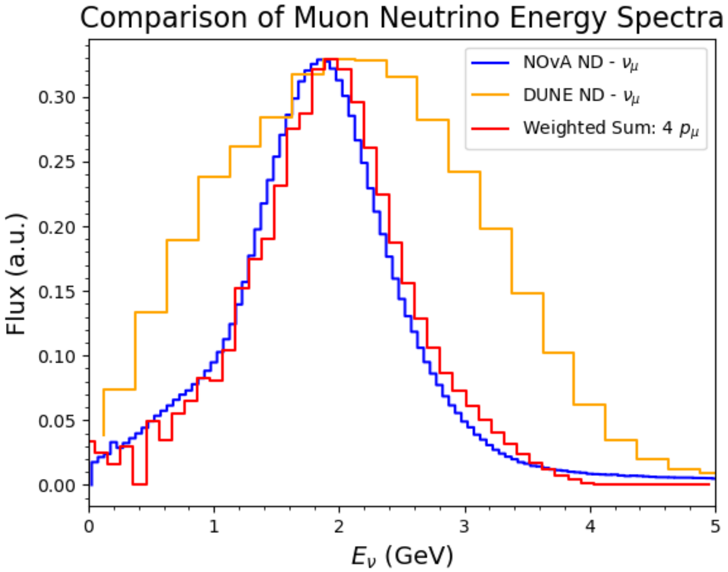


Image credit: Luke Pickering



R. Kamath



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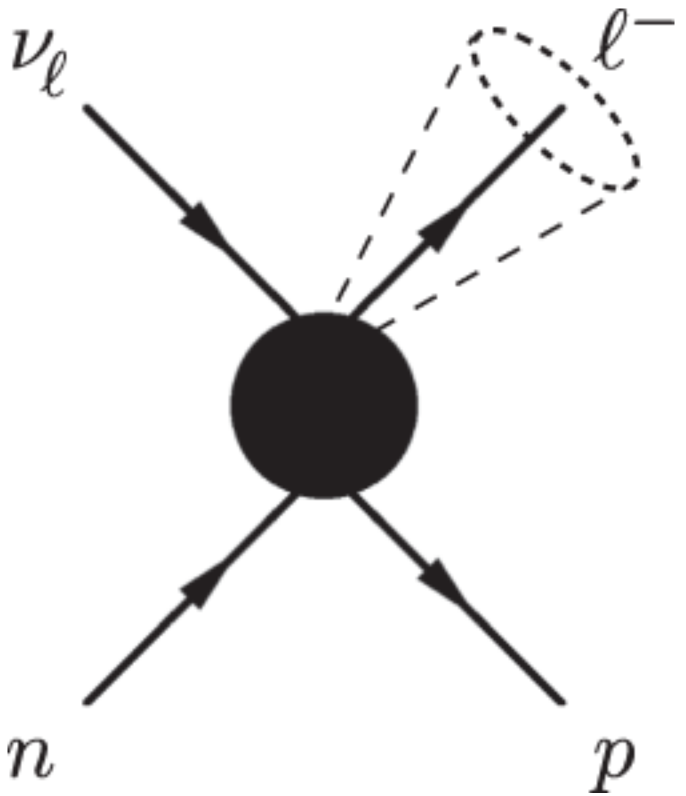
Neutrino interactions at nuSTORM

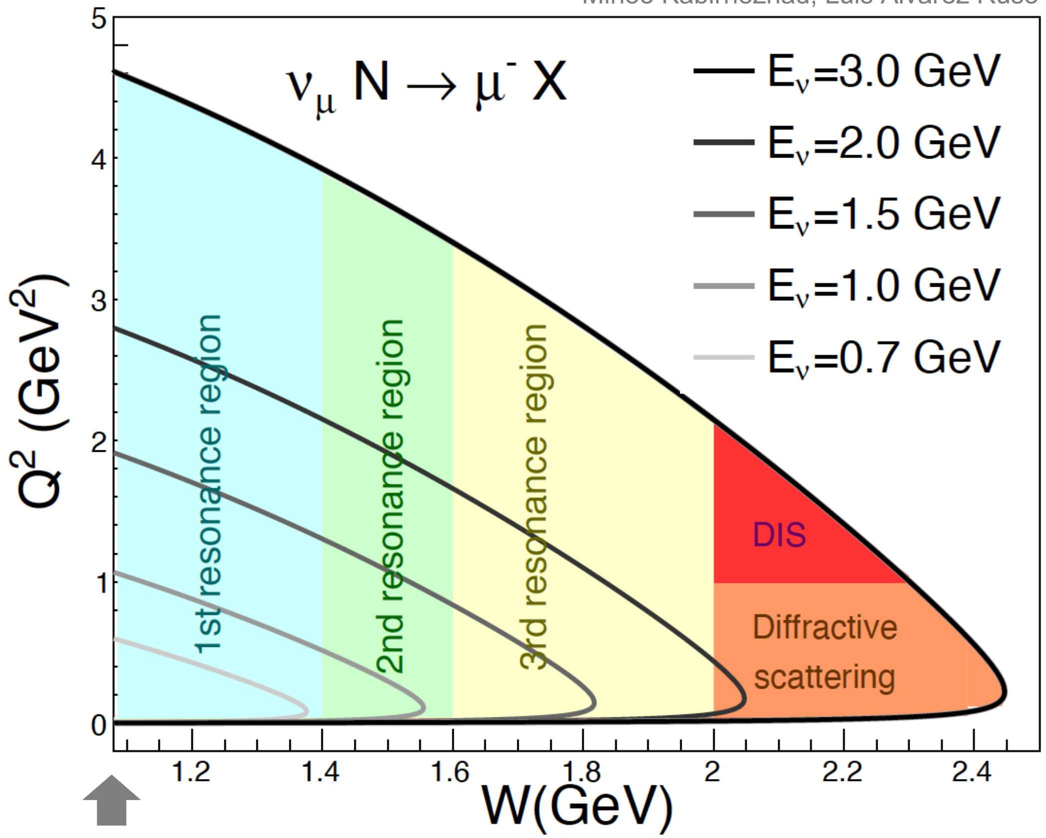
- ☐ Flavour-dependent effects
  - ❖ Radiative corrections



Tomalak *et al.*, Nature Commun. 13, 5286 (2022)

- ☐ Various elementary processes

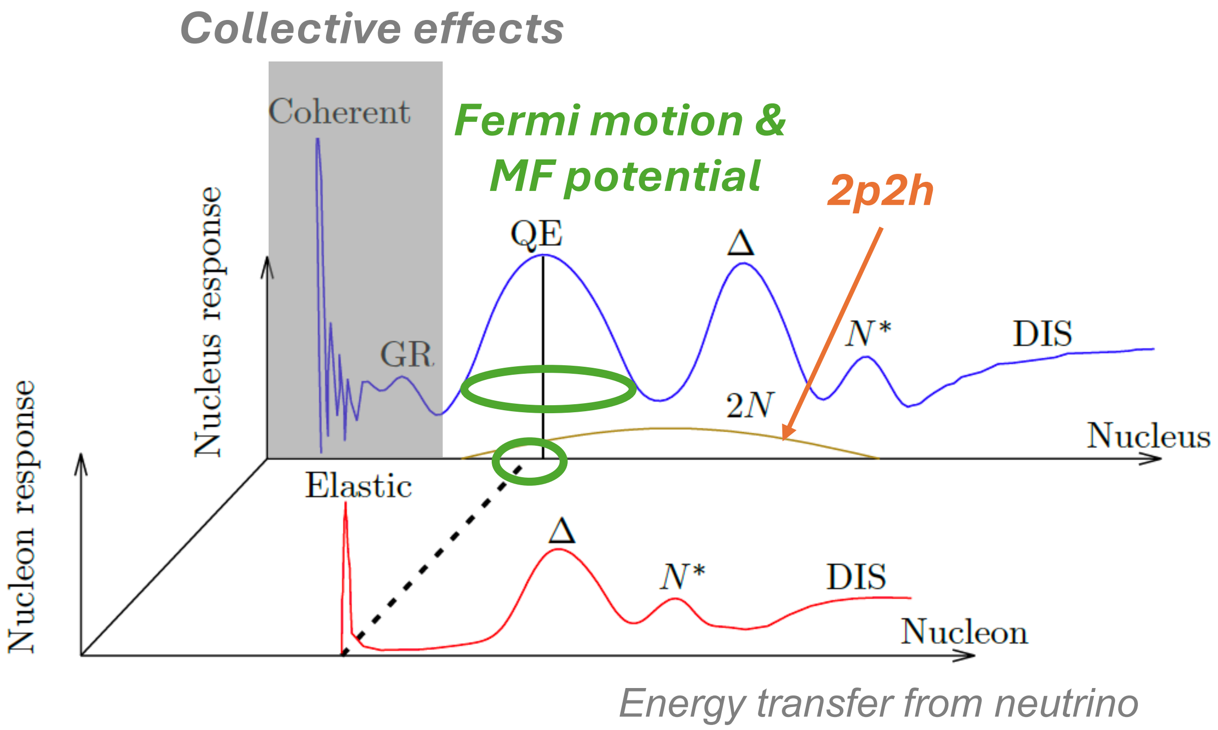
Minoo Kabirnezhad, Luis Alvarez Ruso



Quasi-elastic

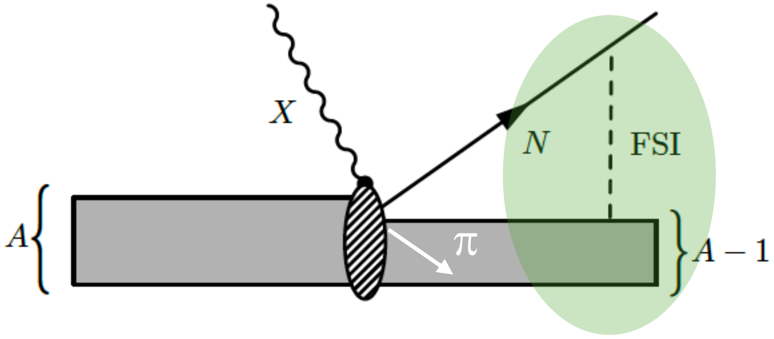
Neutrino interactions at nuSTORM

- ❑ Nuclear medium dynamics



Van Cuyck, PhD Thesis, Ghent University (2017)

- ❑ (Hadronic) Final-State Interactions



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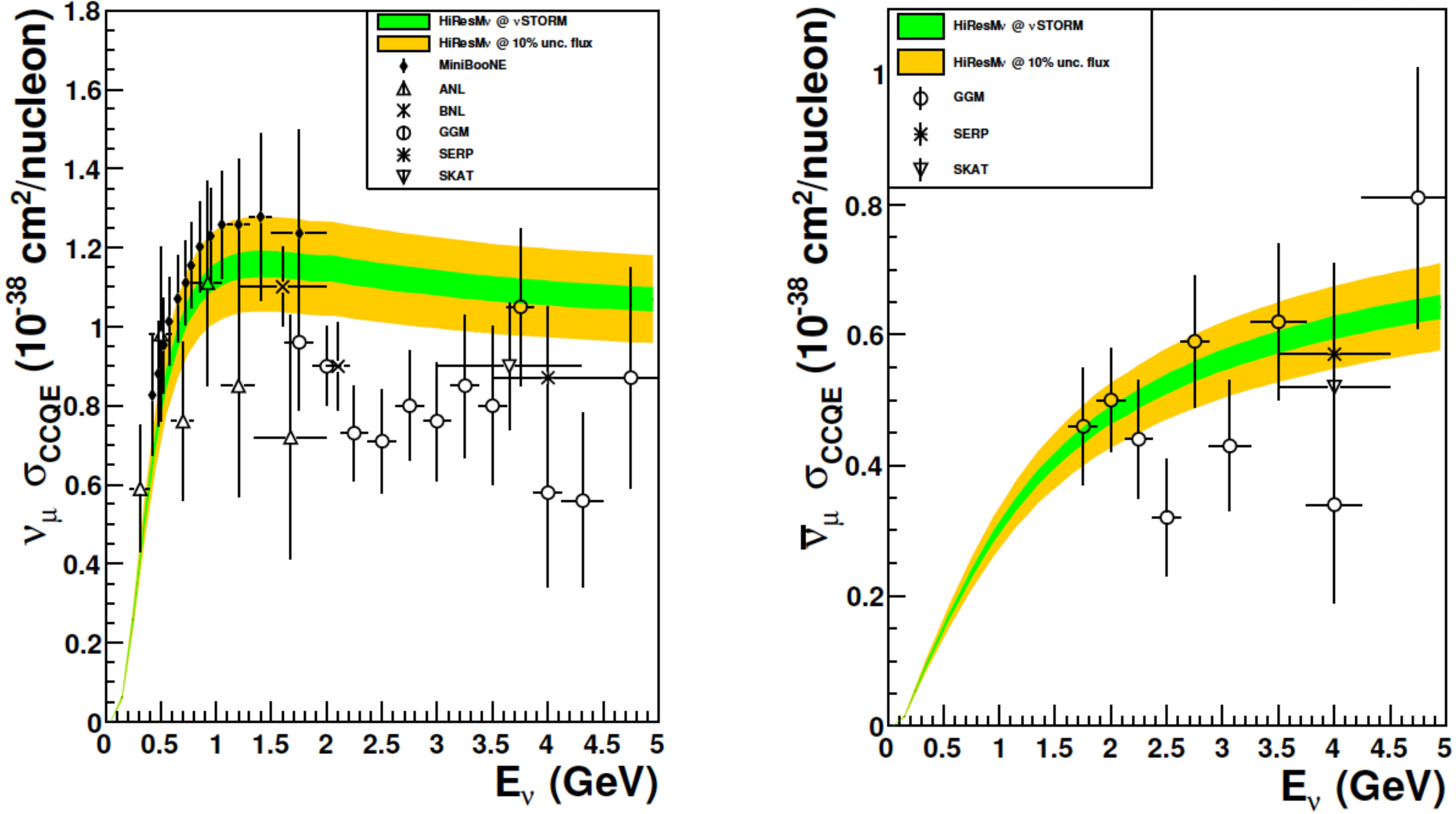
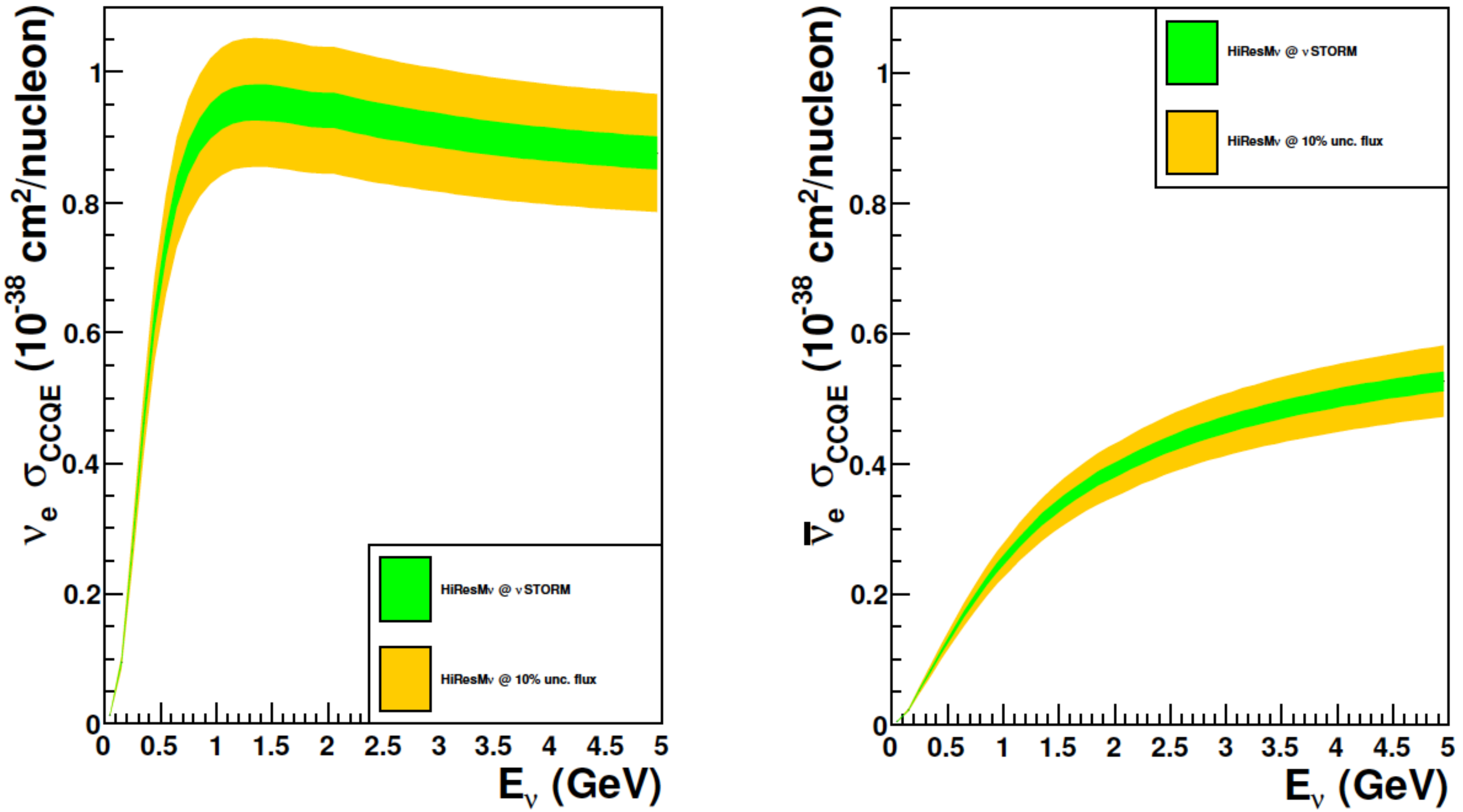
nuSTORM ν_μ and $\bar{\nu}_\mu$ Cross Section Measurements



arXiv:1308.6822

- 100-ton fiducial mass (carbon) detector, 50 m from end of Production Straight, 10^{21} POT (5 years)
- 1% (green) and 10% (yellow) flux uncertainty + detector systematics

nuSTORM ν_e and $\bar{\nu}_e$ Cross Section Measurements



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- 100-ton fiducial mass (carbon) detector, 50 m from end of Production Straight, 10^{21} POT (5 years)
- 1% (green) and 10% (yellow) flux uncertainty + detector systematics
- **Very sparse existing data (mainly from MINERvA and T2K from last decade)**

nuSTORM TKI Measurements

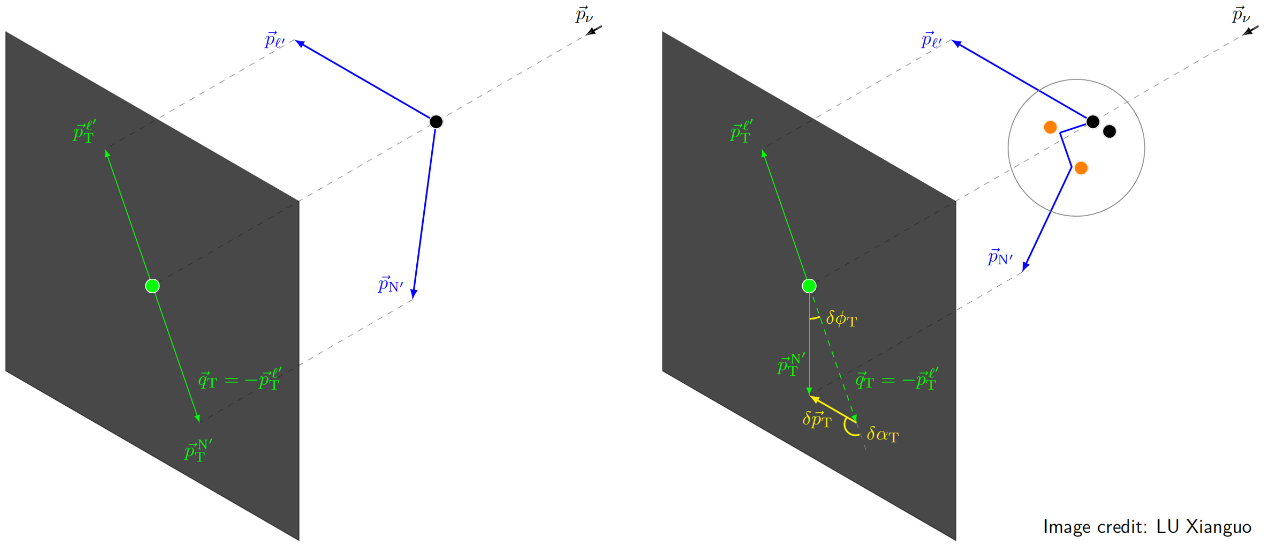
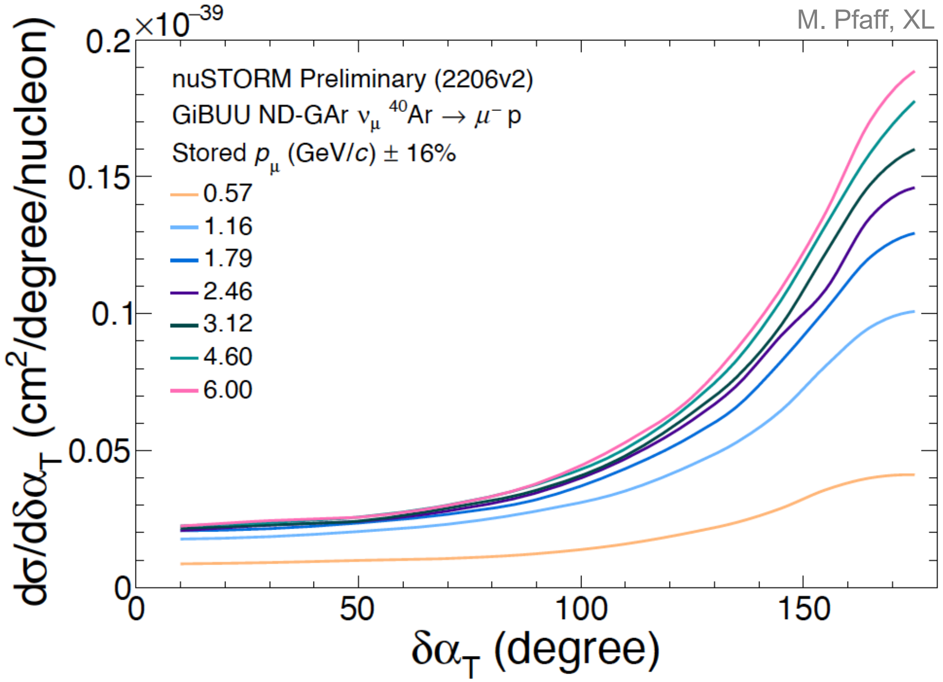


Image credit: LU Xianguo

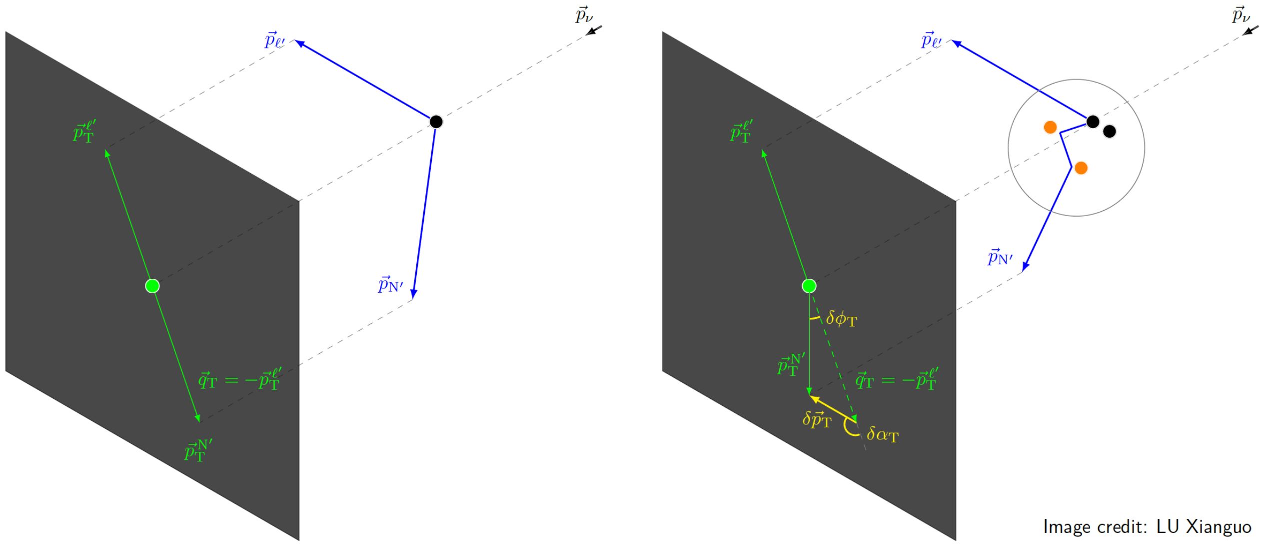


Transverse Kinematic Imbalance (TKI) [Phys.Rev.C 94, 015503 (2016)]

Measurement of nuclear effects with minimal dependence on neutrino energy

- Measured at T2K, MINERvA, MicroBooNE
- E_ν scan to extract dynamical evolution of nuclear medium effects

nuSTORM TKI Measurements



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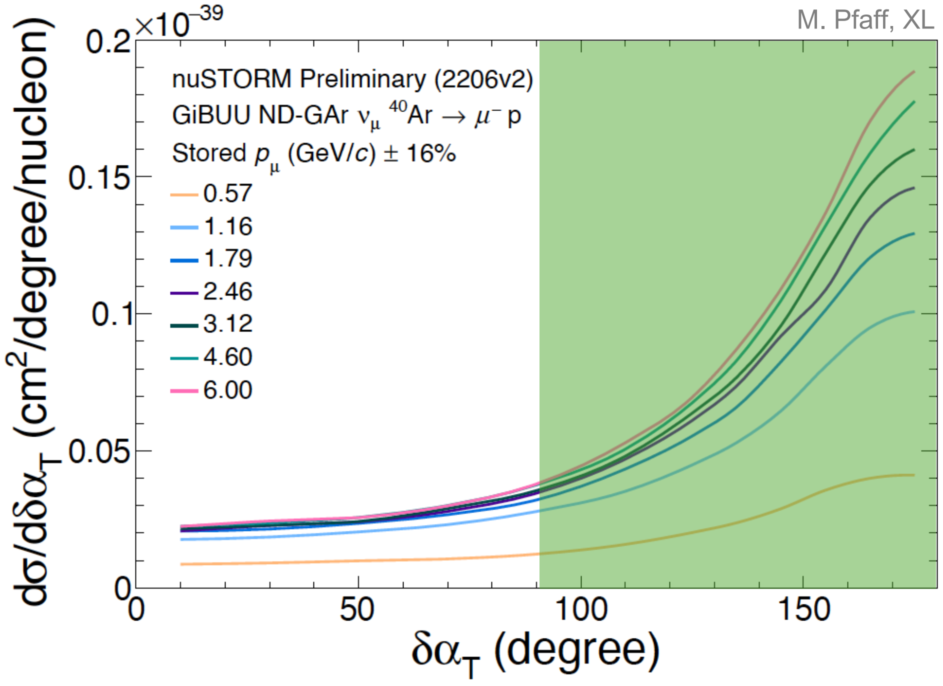

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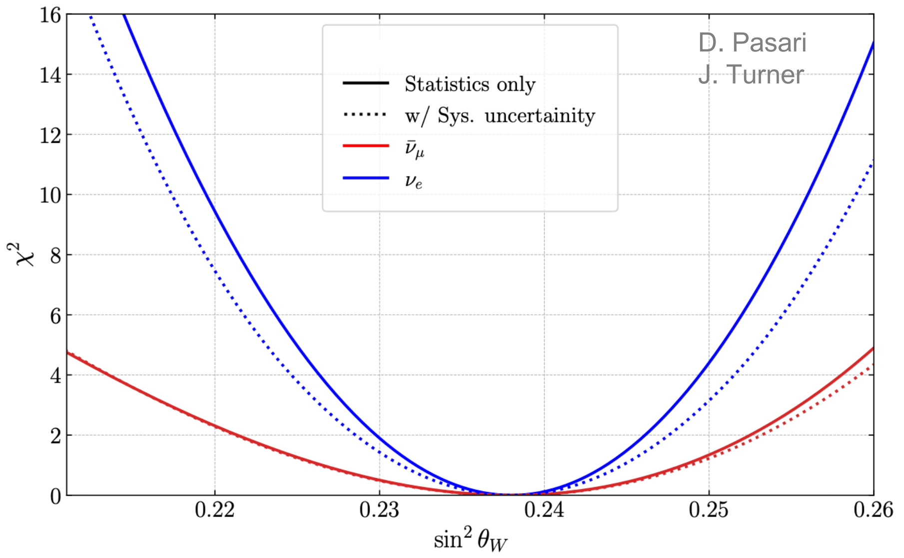
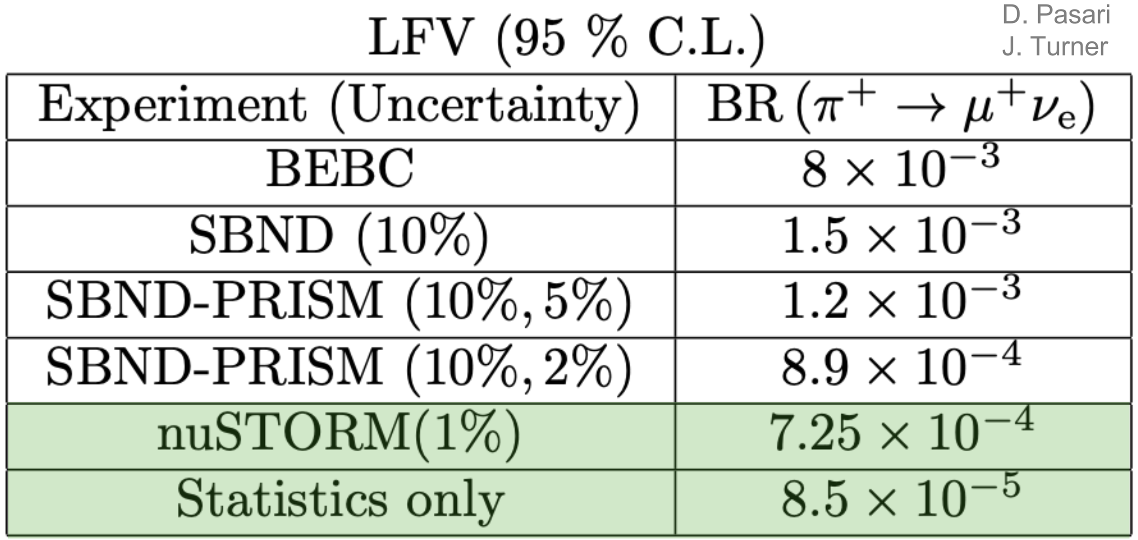
- Dissipative processes: 2p2h, FSI
- Dynamical evolution mapped out via E_ν scan

nuSTORM BSM Physics

- ❑ nuSTORM has sensitivity to the **weak mixing angle** with protoDUNE-like detector
- ❑ nuSTORM high competitive in constraining **lepton flavour violation** (LFV) & **neutrino tridents**



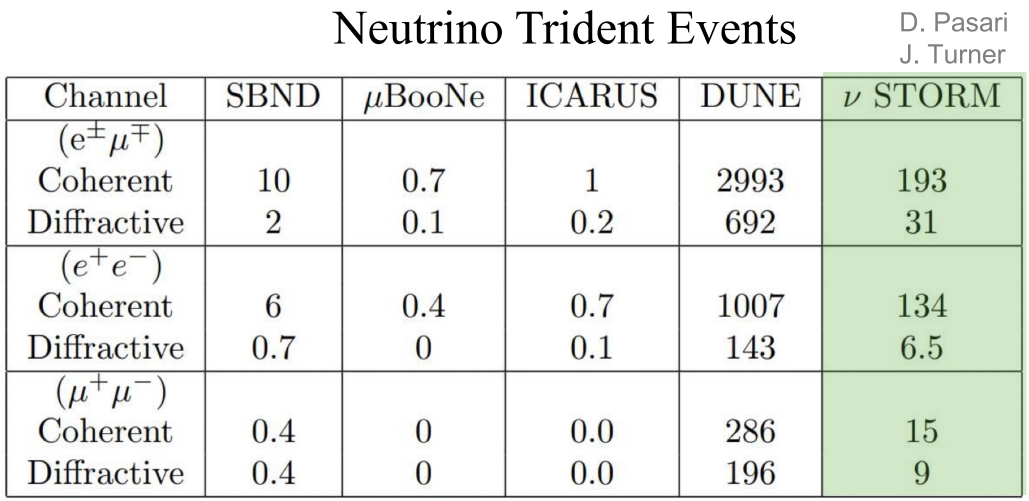
D. Pasari
J. Turner



LFV (95 % C.L.)

D. Pasari
J. Turner

Experiment (Uncertainty)	$BR(\pi^+ \to \mu^+\nu_e)$
BEBC	8×10^{-3}
SBND (10%)	1.5×10^{-3}
SBND-PRISM (10%, 5%)	1.2×10^{-3}
SBND-PRISM (10%, 2%)	8.9×10^{-4}
nuSTORM(1%)	7.25×10^{-4}
Statistics only	8.5×10^{-5}



Neutrino Trident Events

D. Pasari
J. Turner

Channel	SBND	μBooNe	ICARUS	DUNE	ν STORM
$(e^\pm\mu^\mp)$					
Coherent	10	0.7	1	2993	193
Diffractive	2	0.1	0.2	692	31
(e^+e^-)					
Coherent	6	0.4	0.7	1007	134
Diffractive	0.7	0	0.1	143	6.5
$(\mu^+\mu^-)$					
Coherent	0.4	0	0.0	286	15
Diffractive	0.4	0	0.0	196	9

nuSTORM BSM Physics

- Large Extra dimension (LED) can explain the lightness of neutrino masses
  - Using protoDUNE like detector with 50 m baseline, nuSTORM has sensitivity to μm LED length scales
  - nuSTORM can set very competitive limits on LED length scale for inverted ordering

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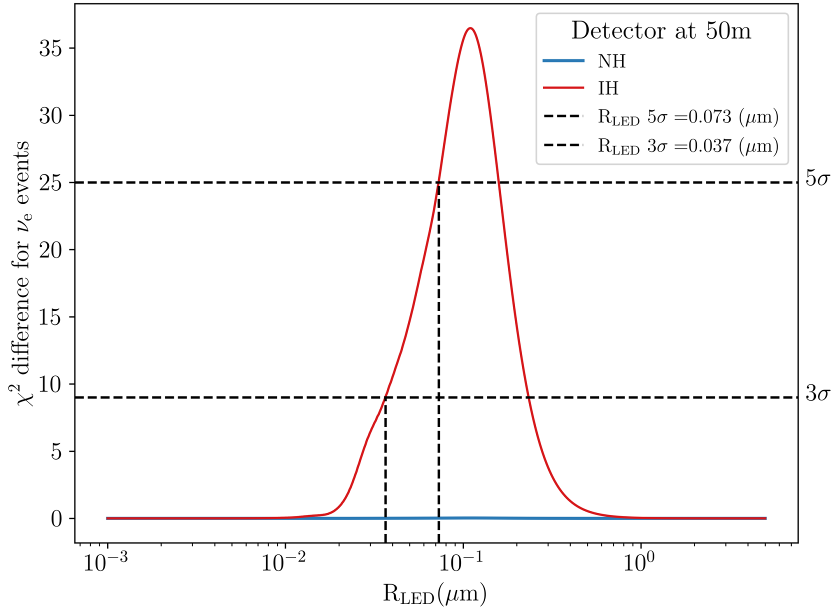

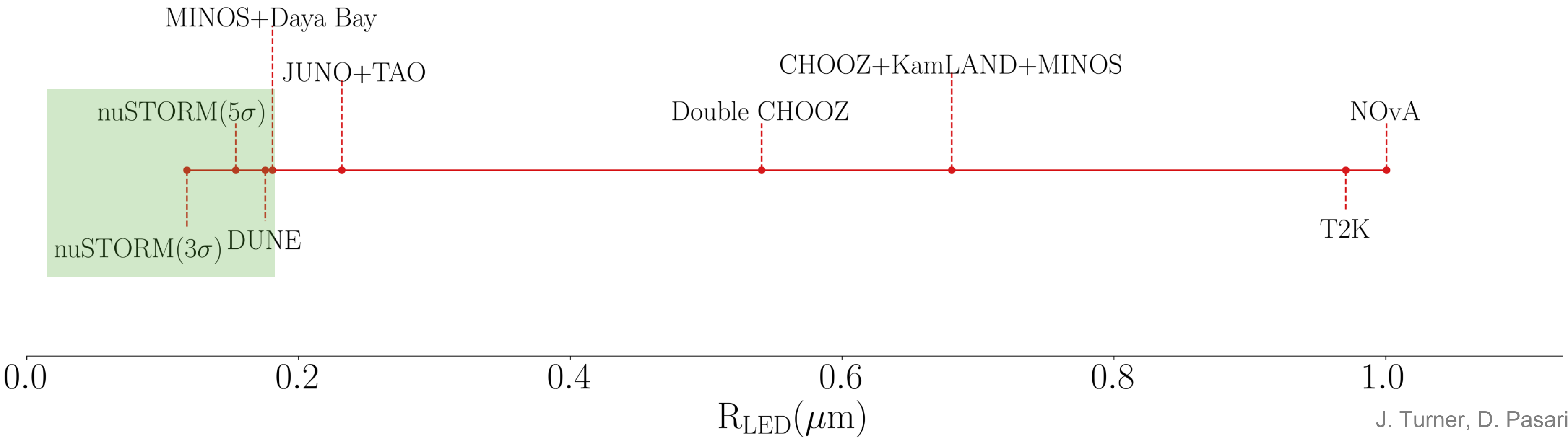

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Summary, Outlook, and Discussions

1. Problems and opportunities with neutrino masses

- ➢ Future accelerator neutrino experiments will be systematics dominated. We need a community plan after Hyper-K and DUNE.
- ➢ ***How to position the neutrino community for ESPPU?***

2. Call for a GeV ν_e and $\bar{\nu}_e$ machine
    - ❑ Accelerator neutrino experiments vs. nuSTORM

- ➢ Synergies with other future machines (ENUBET, Muon Collider)
- ➢ Advanced detector R&D for near-future experiments will guide nuSTORM's choice of detector technology

3. nuSTORM physics programs
    a. Neutrino cross section
    b. BSM

- ➢ Opportunities with perfectly understood ν_e and $\bar{\nu}_e$ flux (shape and normalisation) in the few GeV regime

BACKUP

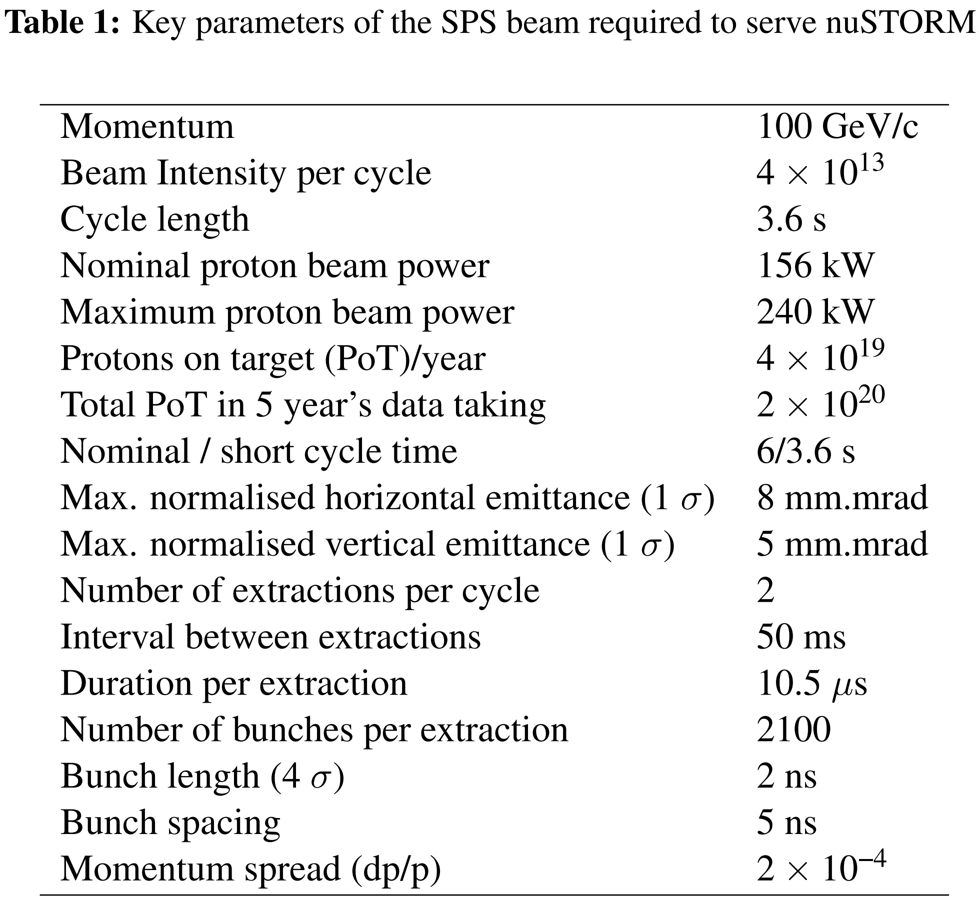

Table 1: Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c
Beam Intensity per cycle	4×10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1 σ)	8 mm.mrad
Max. normalised vertical emittance (1 σ)	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	10.5 μs
Number of bunches per extraction	2100
Bunch length (4 σ)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2×10^{-4}

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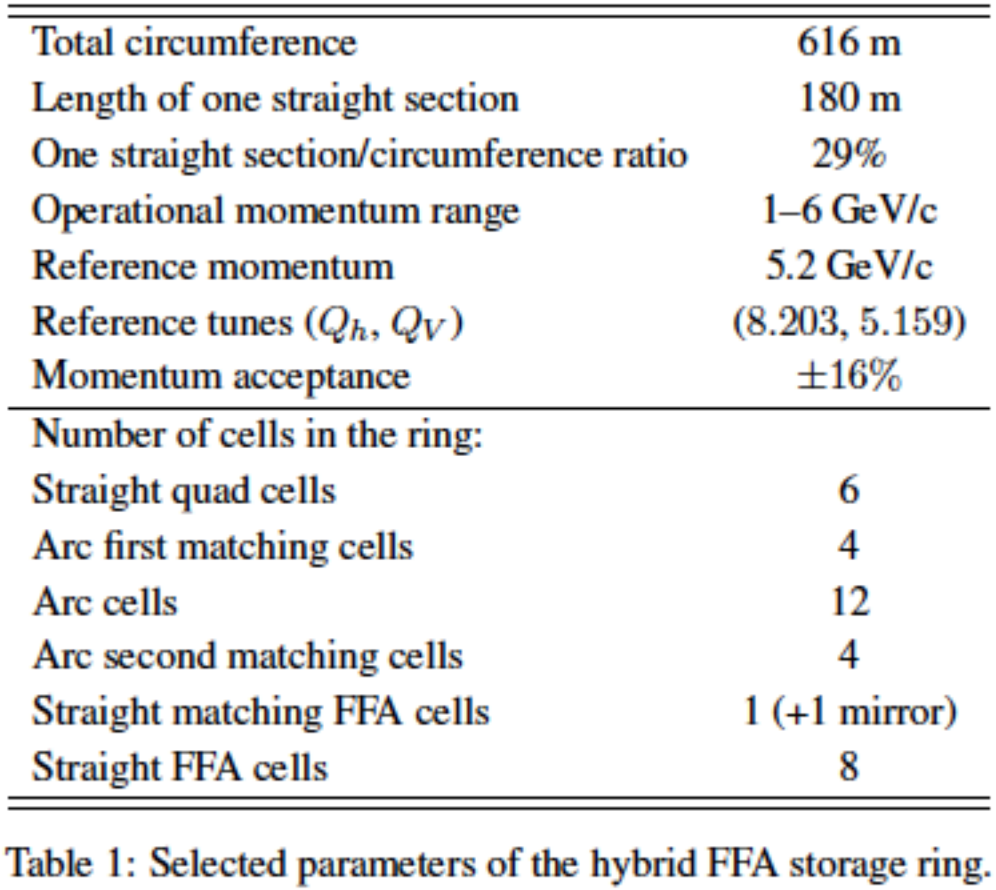

Total circumference	616 m
Length of one straight section	180 m
One straight section/circumference ratio	29%
Operational momentum range	1–6 GeV/c
Reference momentum	5.2 GeV/c
Reference tunes (Q_h, Q_V)	(8.203, 5.159)
Momentum acceptance	±16%
Number of cells in the ring:	
Straight quad cells	6
Arc first matching cells	4
Arc cells	12
Arc second matching cells	4
Straight matching FFA cells	1 (+1 mirror)
Straight FFA cells	8

Table 1: Selected parameters of the hybrid FFA storage ring.

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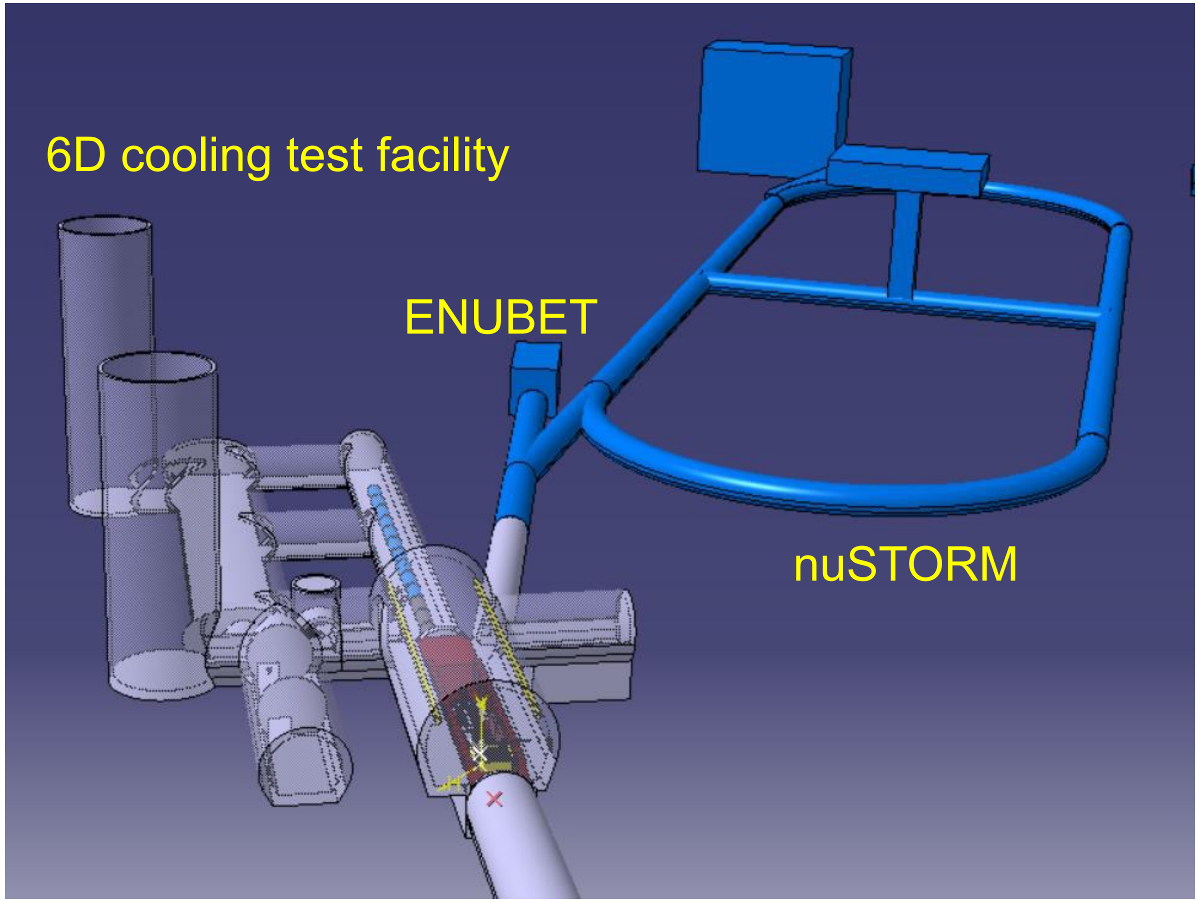
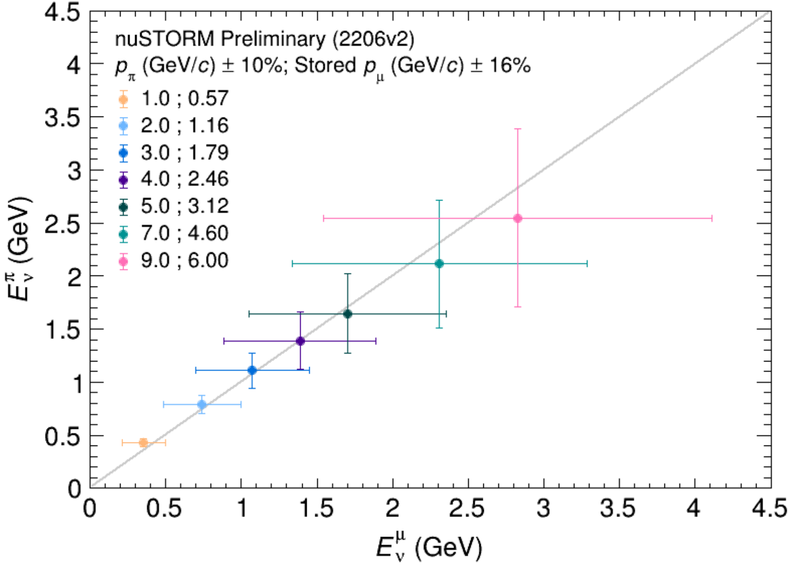


w/ CERN PS 26 GeV proton beam

T. Alves, M. Pfaff



- nuSTORM can constrain the presence of an additional light sterile & is complementary to other current SBN programmes