Neutrino physics: what's our plan after DUNE and HK

Years of ISIS Neutron and Muon Source

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Neutrinos

- Long baseline neutrino programme looks very strong
- DUNE phase 1 is under construction
  - Supported by Fermilab as a neutrino source
- DUNE phase 2 is considered
  - P5 report
- T2HK is under construction
  - Beam upgrade
  - Detector upgrade
- Its crazy to talk about future after DUNE & T2HK
  - 20+ years away with good science in the meantime
  - Saturated physics community delivering existing facilities
- But:
  - Not clear there is a path for superbeams beyond next generation
  - Time required to deploy a major new facility is ~25 years

DUNE – plans (potential)

Experiment Stage	Physics Milestone	Exposure (kt-MW-years)	Years (Staged)
Phase I	5σ MO ($\delta_{\mathrm{CP}} = -\pi/2$)	16	1-2
	5σ MO (100% of δ_{CP} values)	66	3-5
	3σ CPV ($\delta_{\mathrm{CP}} = -\pi/2$)	100	4-6
Phase II	5σ CPV ($\delta_{\mathrm{CP}} = -\pi/2$)	334	7-8
	δ_{CP} resolution of 10 degrees ($\delta_{\mathrm{CP}} = 0$)	400	8-9
	5σ CPV (50% of δ_{CP} values)	646	11
	3σ CPV (75% of δ_{CP} values)	936	14
	$\sin^2 2\theta_{13}$ resolution of 0.004	1079	16

Neutrino beam available in 2032

Snowmass Neutrino Frontier: DUNE Physics Summary, Dune Collaboration, https://arxiv.org/abs/2203.06100

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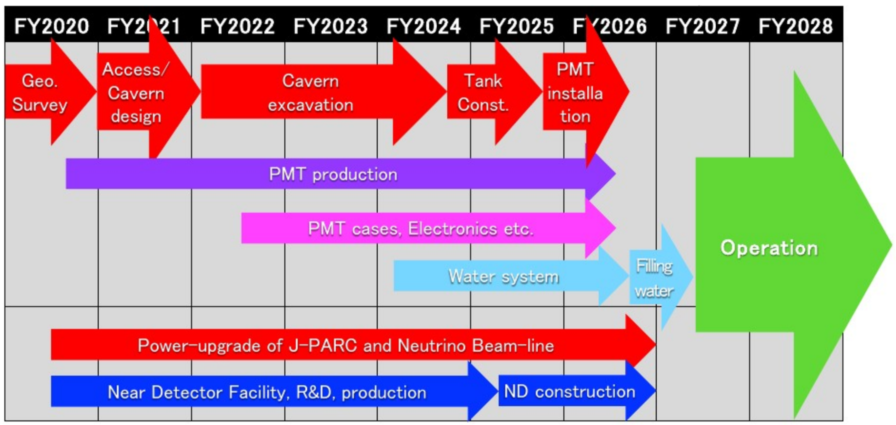
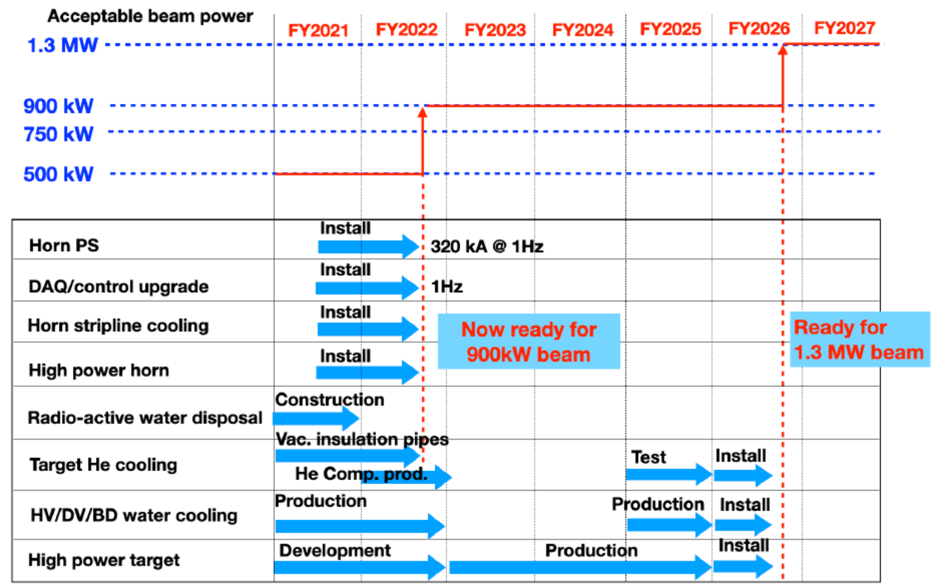
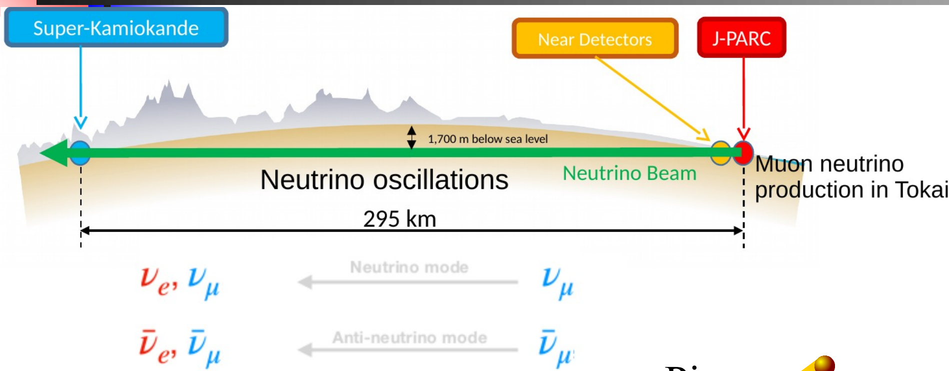
T2HK

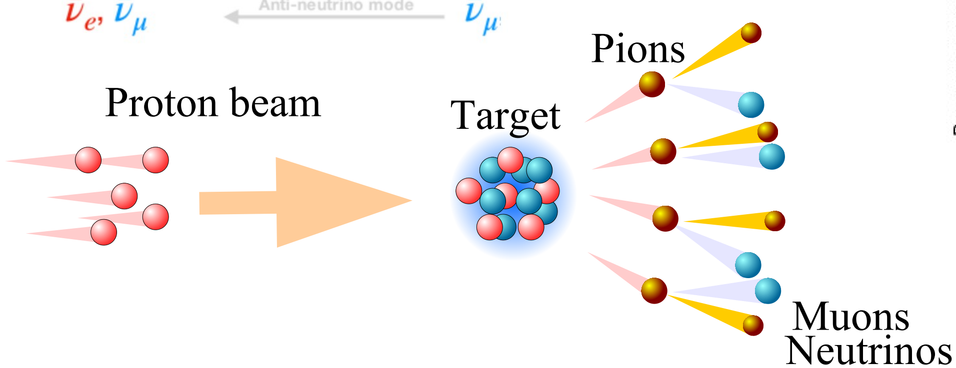


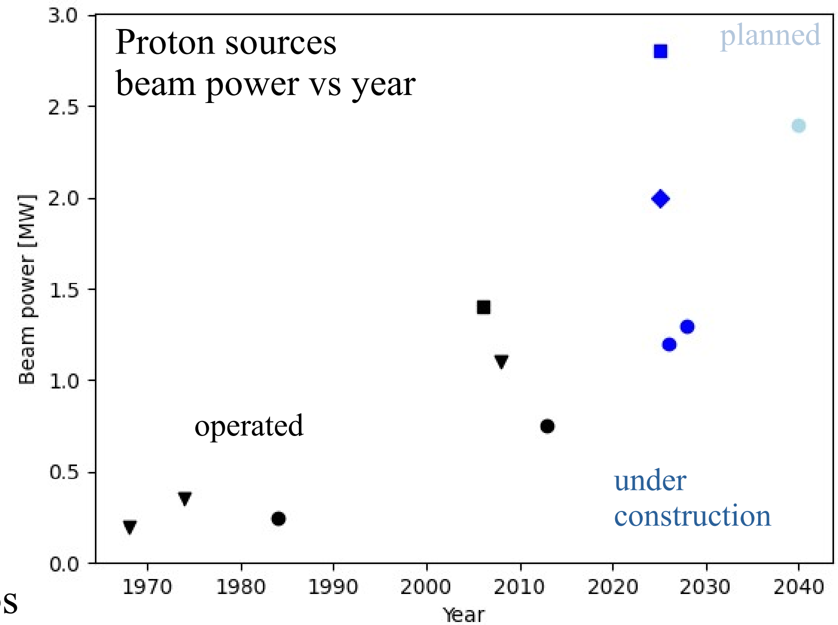


- T2HK
  - Accelerator upgrade to 1.3 MW
  - Far Detector upgrade
  - Near Detector upgrade

Direct Production







- Direct production → event rate follows

*beam power on target * detector mass*

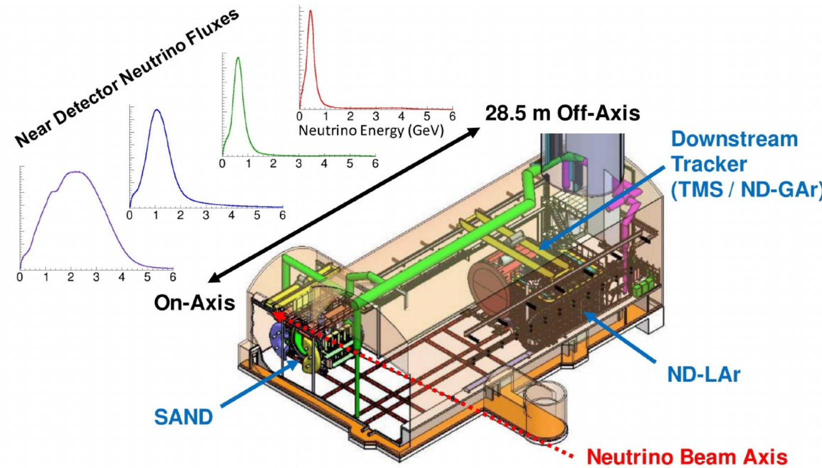
- Detector mass proportional to budget (linear with time)
- Beam power historically rises rather slowly with time
  - What is the limit?

Limits on proton beam power

- Beam loss
  - Rule of thumb – allow 1 W/m of uncontrolled loss
  - As beam power increases, fractional loss decreases
  - 0.25 MW ISIS → O(1) % losses
  - Increasing beam current makes things harder
    - Space charge
    - Instabilities
  - Losses need to be better controlled
    - 2.5 MW → O(0.1) % losses
- Technology limits
  - Heat load on target
    - Moving targets
    - Liquid metal targets
  - Heat load on injection foil
    - Foil "strips" H^- into H^+
    - Laser stripping is an R&D topic

Beam quality & systematics

- Need to consider systematic errors
  - Ratio of number/species of neutrinos at source vs energy
- Improve knowledge of ν source composition & energy
- Measure pion distribution from target
  - E.g. HARP, NA61/SHINE
- Measure flux before oscillation
  - E.g. Near detector
  - E.g. DUNE-PRISM
    - Move ND off-axis(!)
    - Scan the neutrino energy distribution
    - Check reconstruction matches expected energy distribution
  - Will T2HK and DUNE be systematics limited?
- Improve physics models → improve detector resolution
  - Enubet
  - nuSTORM



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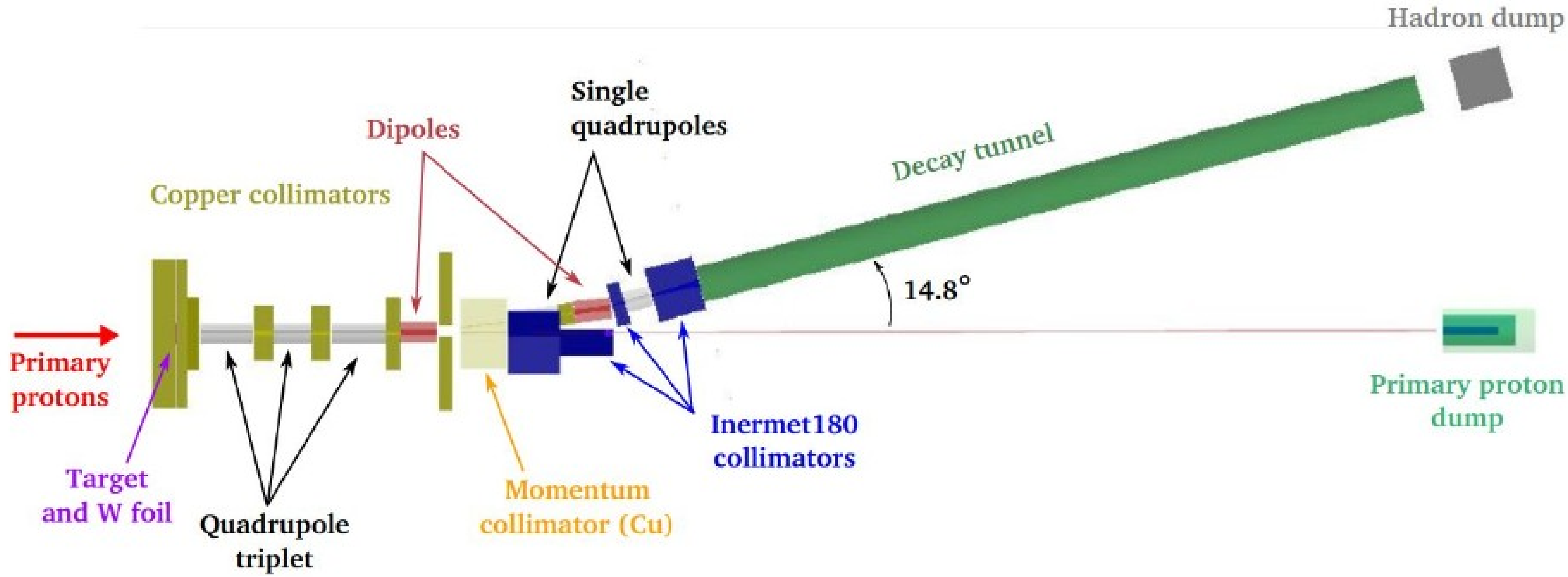
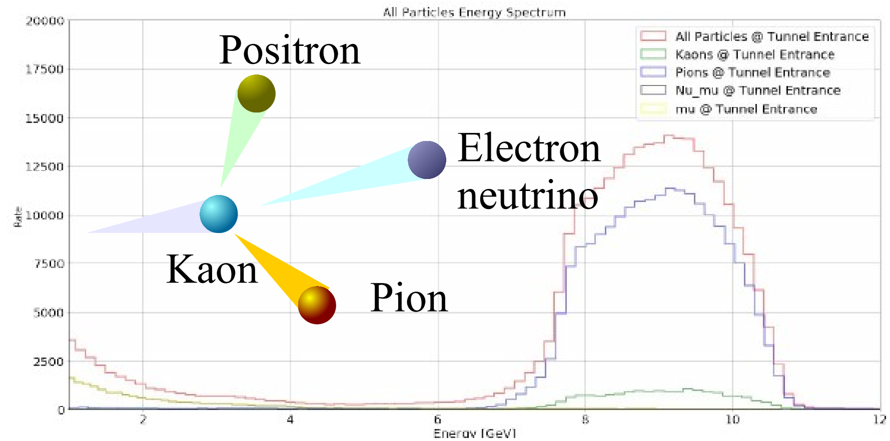
ENUBET (1)

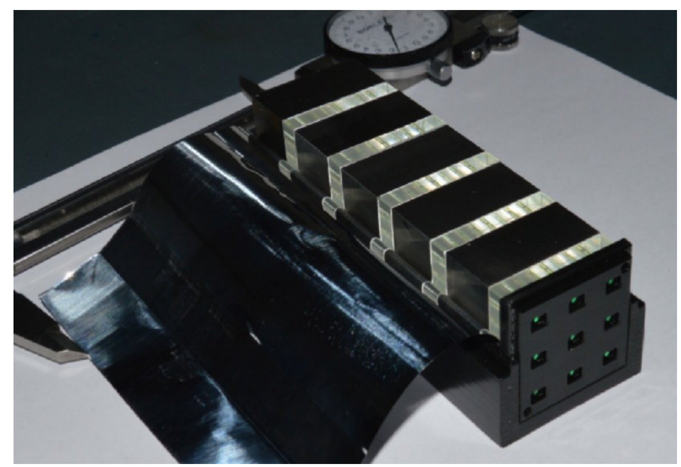


- Slowly extract protons to a target
- Produce pions and kaons
- Monitor decays of kaons in the decay tunnel
- Either pulsed extraction or CW extraction
  - 1 kaon every 70 ps or every 1 ns

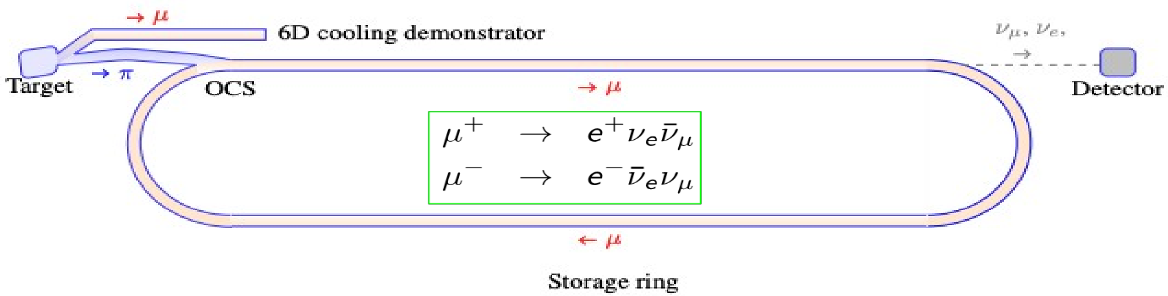
ENUBET (2)

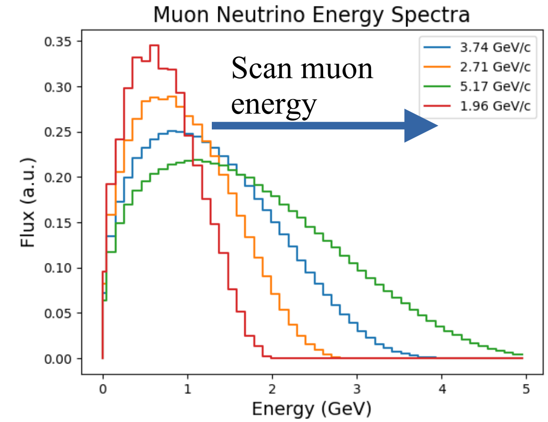
- Identify positrons from kaon decay
  - Understand ν_e rate and beam kinematics
  - Estimate pion rate → ν_μ
- Map individual kaons to neutrinos using time coincidence
  - Understand individual neutrino kinematics





Neutrinos from Muons - nuSTORM





- NuSTORM
  - Lifetime of muons is "long" → store muons while they decay
    - Very pure, well characterised beam
    - Very good knowledge of neutrino distribution from muon decay
  - Measure number of neutrino interactions in different materials
  - Seek to understand neutrino cross-sections
    - Drill down systematic uncertainty in the neutrino distribution
- Also BSM physics
- Also nuclear physics

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Alternative sources

- Neutrinos arise from radioactive decay
  - Pions
  - Kaons
  - Etc

  Lifetime < 30 ns (8 m) – "direct production"

  - Muons

  Lifetime 2200 ns (660 m) – "neutrino factories" "nuSTORM"

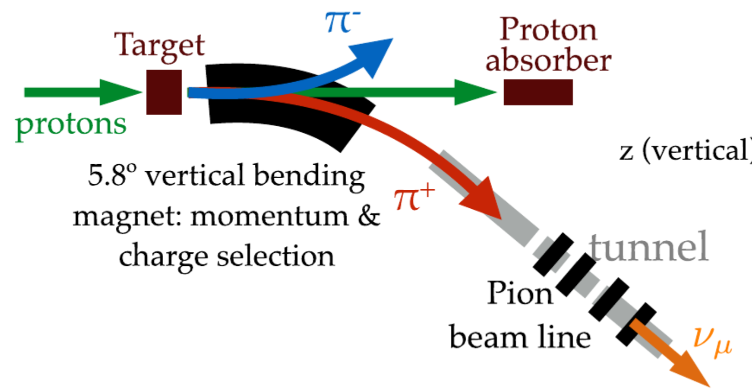
  - Nuclear decay

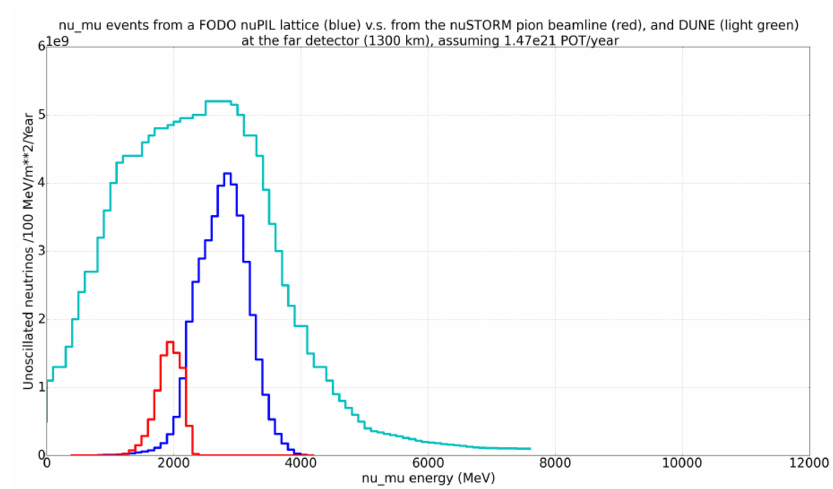
  Flexible lifetime – "beta beams"

- Note lifetimes are time dilated in the lab frame
- Alternative sources can be chosen to improve beam quality

nuPIL

- Upgrade to production beam
- Add momentum selection chicane after the target
  - Most kaons decay
  - Pion charge/momentum selection
  - Pion beam line instrumentation





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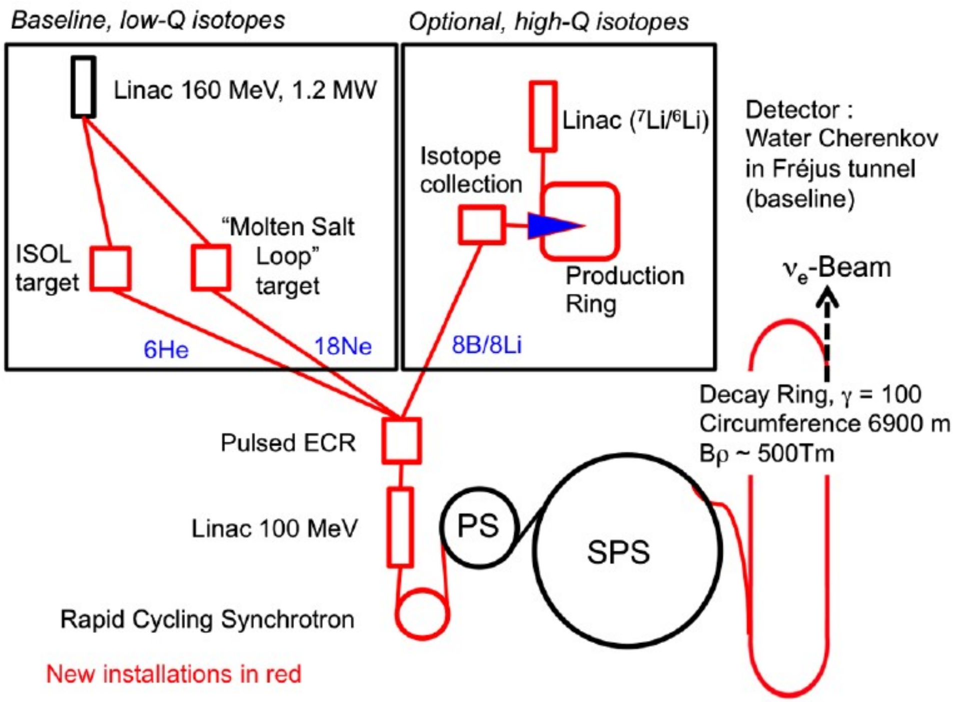
Beta beams



- Beta decay produces electron + electron neutrino
  - Generate (anti-)ν from (inverse)β decay
  - E.g. accelerated ^{6}He and ^{18}Ne

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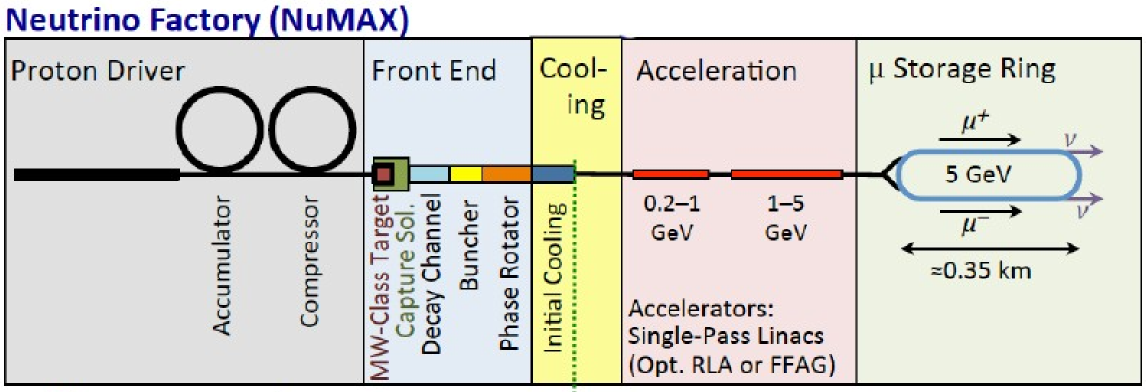
Neutrino Factory



- How to improve precision further?
- Take the nuSTORM concept further
  - Enhanced muon capture
    - Use solenoid and beam cooling
  - Accelerate muons in a linac
  - Storage ring
- Much improved source
  - Tunable neutrino energy (with appropriate baseline)

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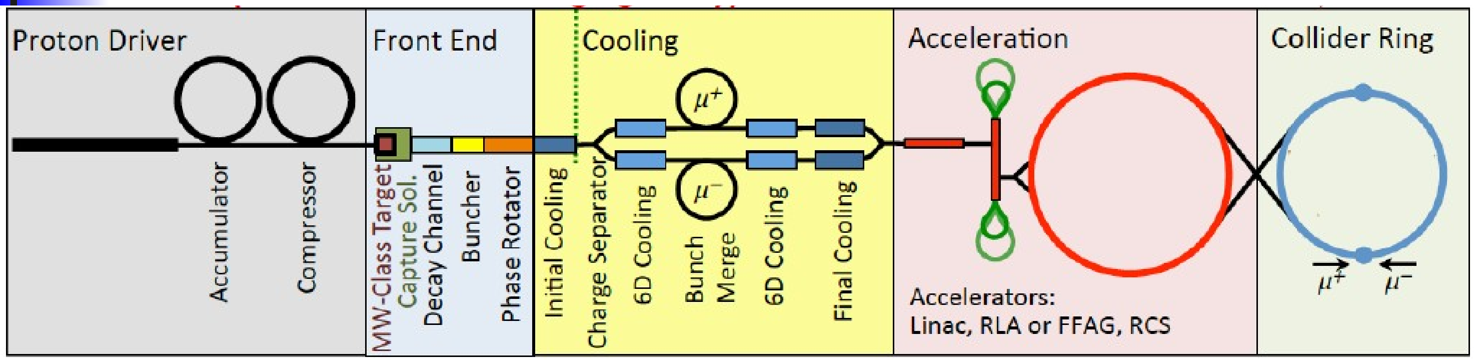
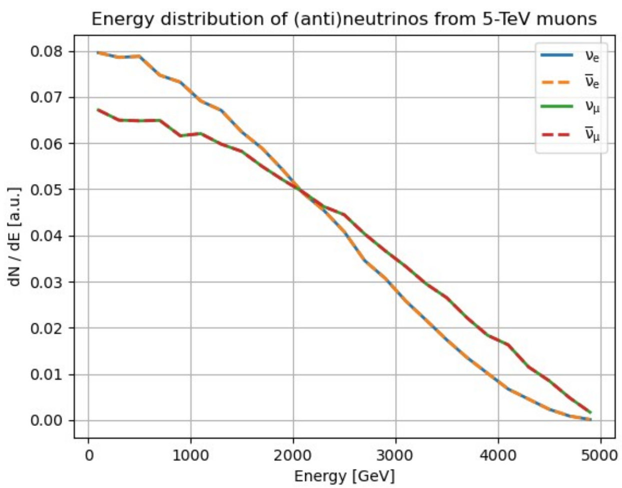
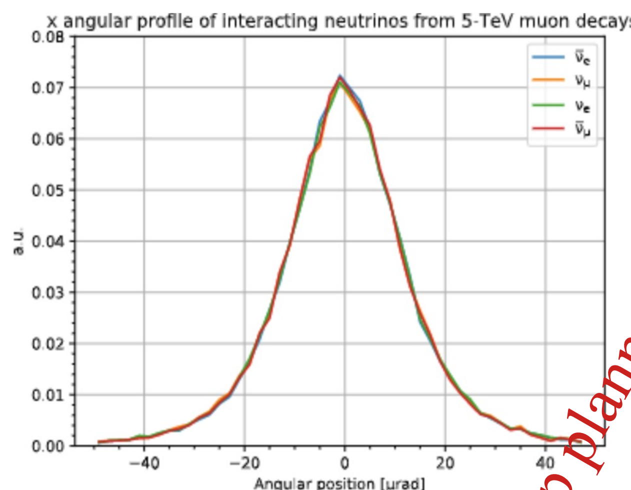
Neutrinos from Muon Collider







- Muon collider **is** a neutrino factory
  - O(1e13) muons per second
  - “Decay” straight O(1e-3) of the ring
  - Neutrino beam is narrow and very high energy → pile up

Workshop planned for Spring 2025

Timeline

- For intermediate complexity facility e.g. nuSTORM
  - Establish project – physics reach, funding, etc
  - Magnet prototypes – complicated SC dipoles
  - Magnet production
  - Excavate tunnel
  - Install equipment
  - Commission
- Need to establish a plan in this ESPPU “cycle”
  - Opportunities will start disappearing through inaction

Conclusion

- Not clear there is a path for superbeams beyond next generation
- Time required to deploy a new facility is ~25 years
- Need to establish a plan in this ESPPU "cycle"
  - Opportunities will start disappearing through inaction