Future of neutrino physics in Europe

A proposal for the Croatian national input to ESPP from the RBI neutrino group

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CROHEP meeting
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Some facts about neutrinos

- Weak interactions only
- Three standard flavours: ν_e, ν_μ, ν_τ
  - each a superposition of three neutrino mass states: m_1, m_2, m_3
- They oscillate: effectively change flavour while propagating
  - implies that they have non-zero mass (except perhaps one state)
  - oscillations described by PMNS matrix and mass-square differences
  - six free parametes: 2 mass-square differences, 3 mixing angles, 1 CP-violating phase

Neutrino parameters in 2024

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

Octant problem

$\sin^2(\theta_{23}) = 0.553^{+0.016}_{-0.024}$ (S = 1.1) (Inverted order)

$\sin^2(\theta_{23}) = 0.558^{+0.015}_{-0.021}$ (Normal order)

Mass hierarchy problem

$\Delta m^2_{32} = (-2.529 \pm 0.029) \times 10^{-3}$ eV^2 (Inverted order)

$\Delta m^2_{32} = (2.455 \pm 0.028) \times 10^{-3}$ eV^2 (Normal order)

$\sin^2(\theta_{13}) = (2.19 \pm 0.07) \times 10^{-2}$ (S = 1.2)

CP phase unknown

δ, *CP* violating phase $= 1.19 \pm 0.22\ \pi$ rad (S = 1.2)

$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL = 99.7%

$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2

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

Measuring the CP-violation

- Neutrinos oscillate different than antineutrinos

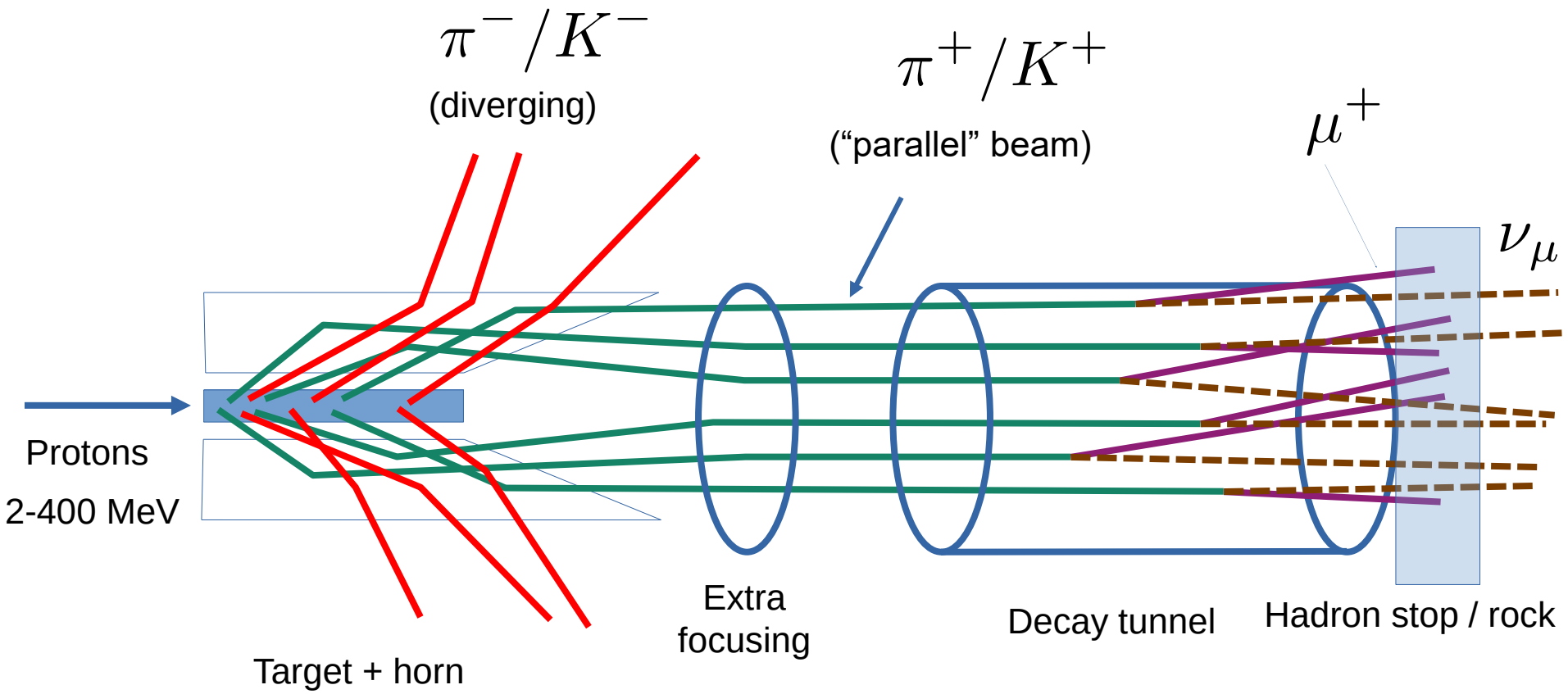
$$P_{\nu_\alpha \to \nu_\beta} \neq P_{\overline{\nu}_\alpha \to \overline{\nu}_\beta}$$

- All long-baseline neutrino beams are muon (anti)neutrino, so CPV is going to be (first) measured by (hopefully) observing

$$P_{\nu_\mu \to \nu_e} \neq P_{\overline{\nu}_\mu \to \overline{\nu}_e}$$

- Experiments under construction for CPV measurement:
  - Hyper-Kamiokande (Japan)
  - DUNE (US)

Conventional neutrino beam production



ESSnuSB – 2.5 GeV kinetic (ESS)
T2K – 30 GeV (J-Parc)
NUMI – 120 GeV (Fermilab)
CNGS – 400 GeV (SPS)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

All long baseline beams are (mostly) ν_μ beams.

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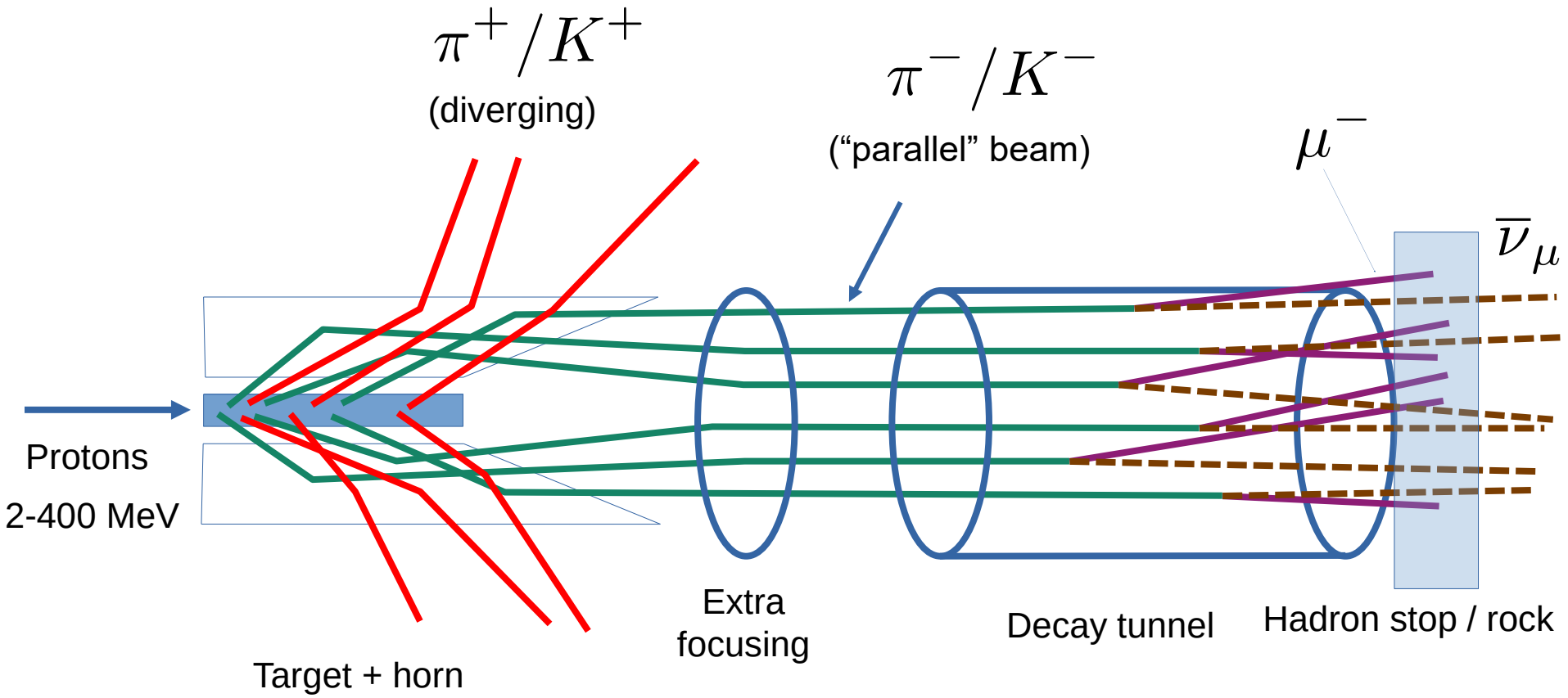

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ESSnuSB

ESSnuSB

A design study for a next-to-next generation neutrino oscillation experiment in Europe for precise measurement of CPV in the lepton sector at second oscillation maximum.

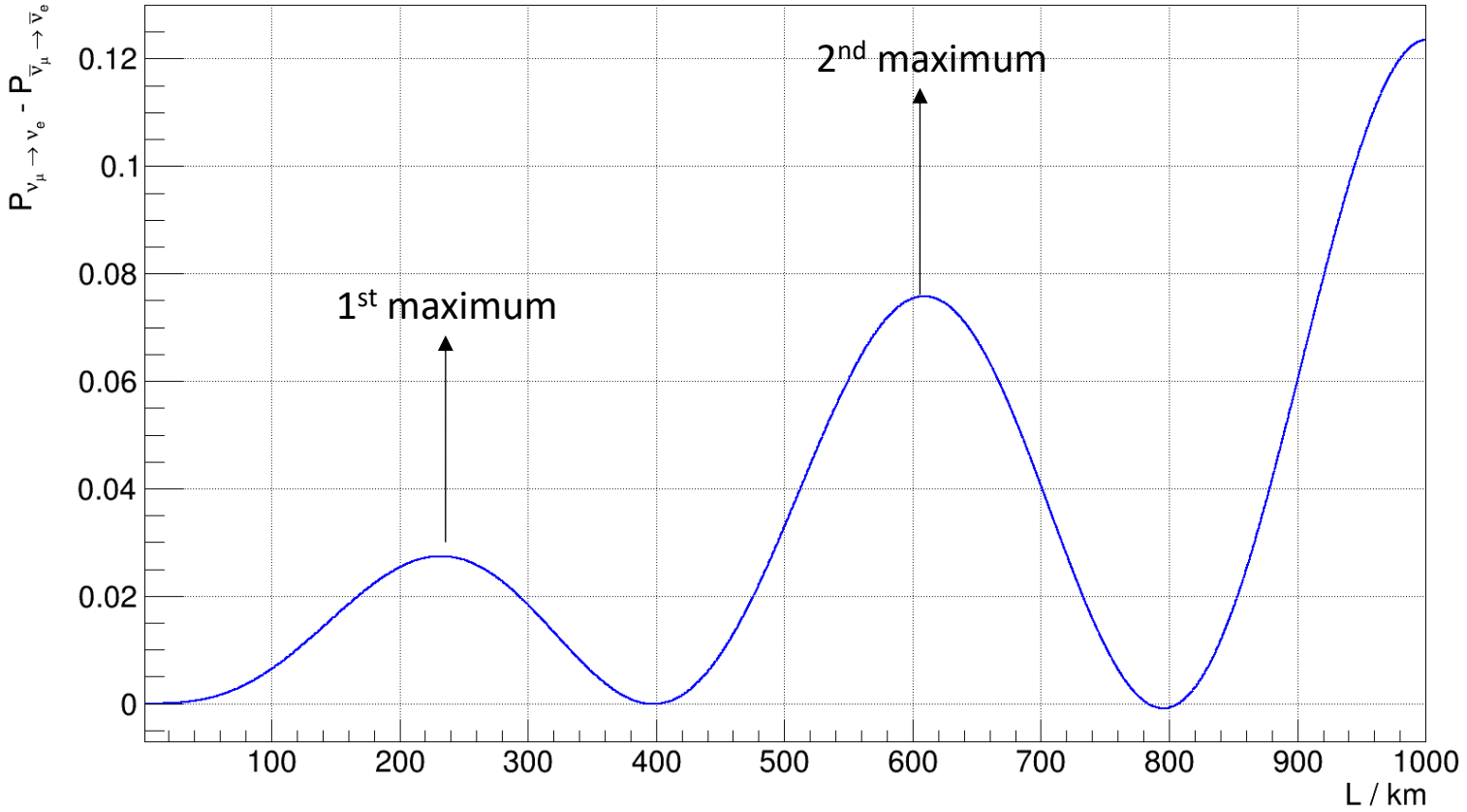
$$P_{\nu_\mu \to \nu_e} \neq P_{\overline{\nu}_\mu \to \overline{\nu}_e}$$

CP violation in ESSnuSB

$$A_{CP} \equiv P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e} = -16J \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

$$s_{ij} \equiv \sin \theta_{ij}$$
$$c_{ij} \equiv \cos \theta_{ij}$$
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$
$$A^{\alpha\beta}_{ij} \equiv U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}$$

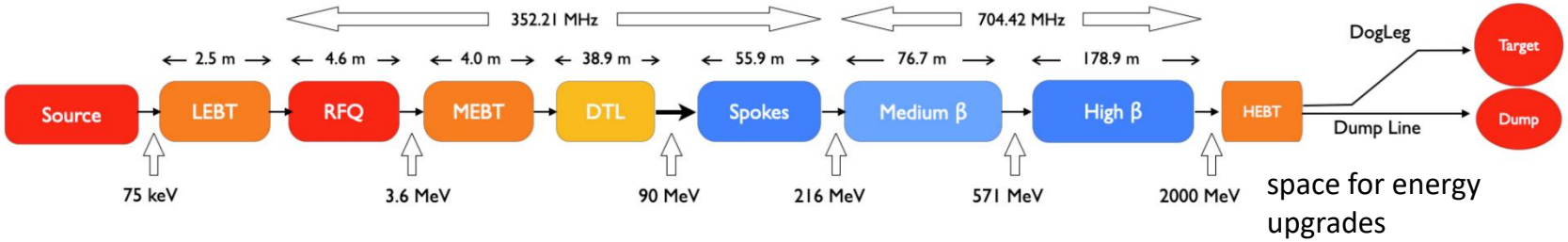
E = 400 MeV



$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

- Does not depend on *J*, i.e. PMNS matrix elements
- Depends only on mass splittings

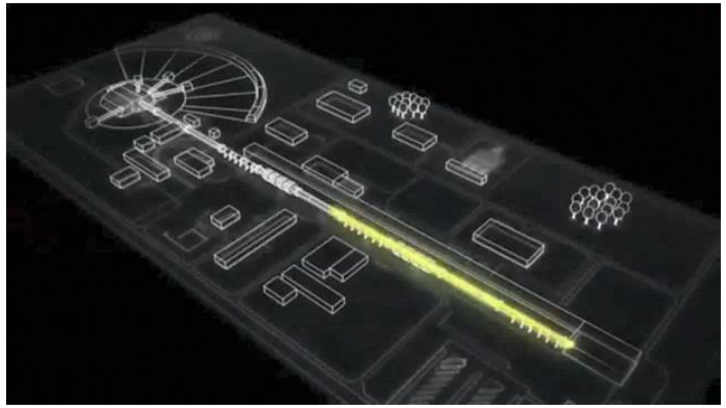
ESS proton linac



- The ESS will be a copious source of spallation neutrons.
- **5 MW average beam power.**
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

First beam on target expected in 2026.

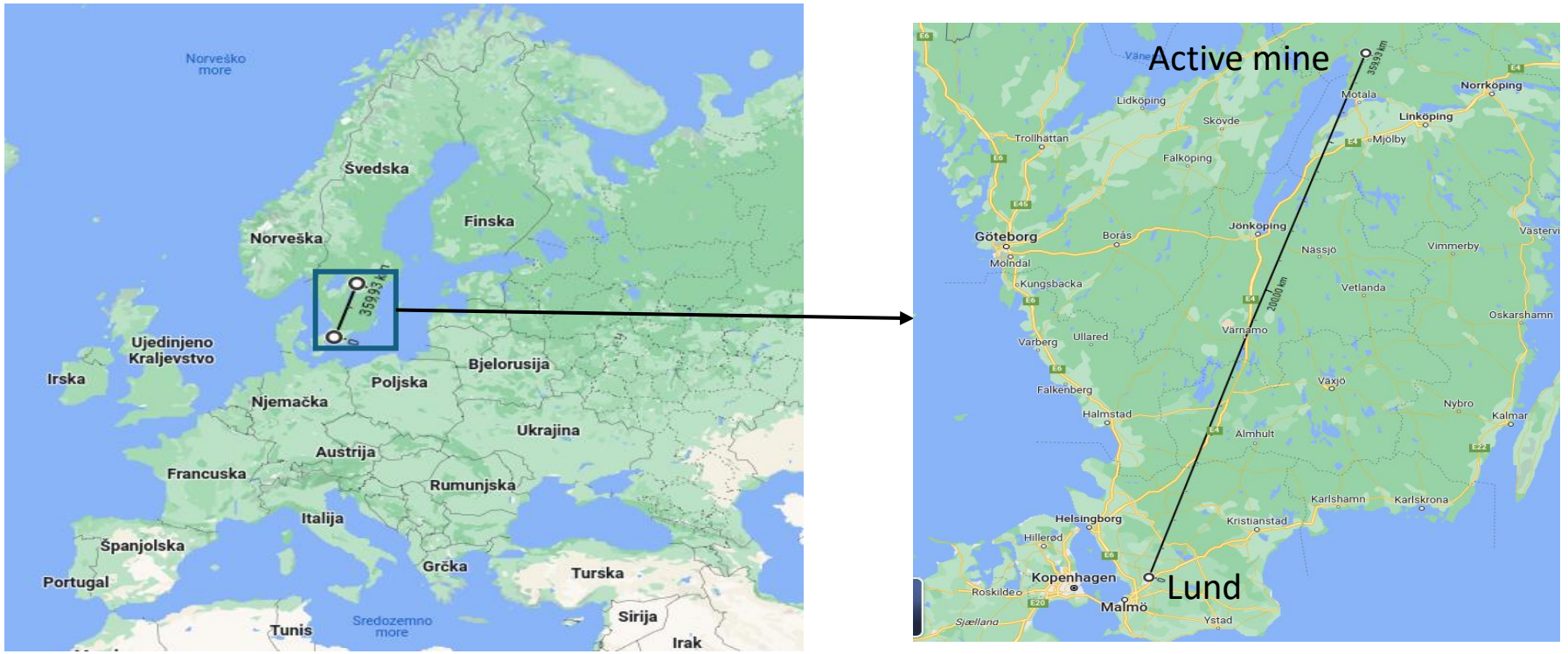
450 mg of protons/year
at 95% speed of light!



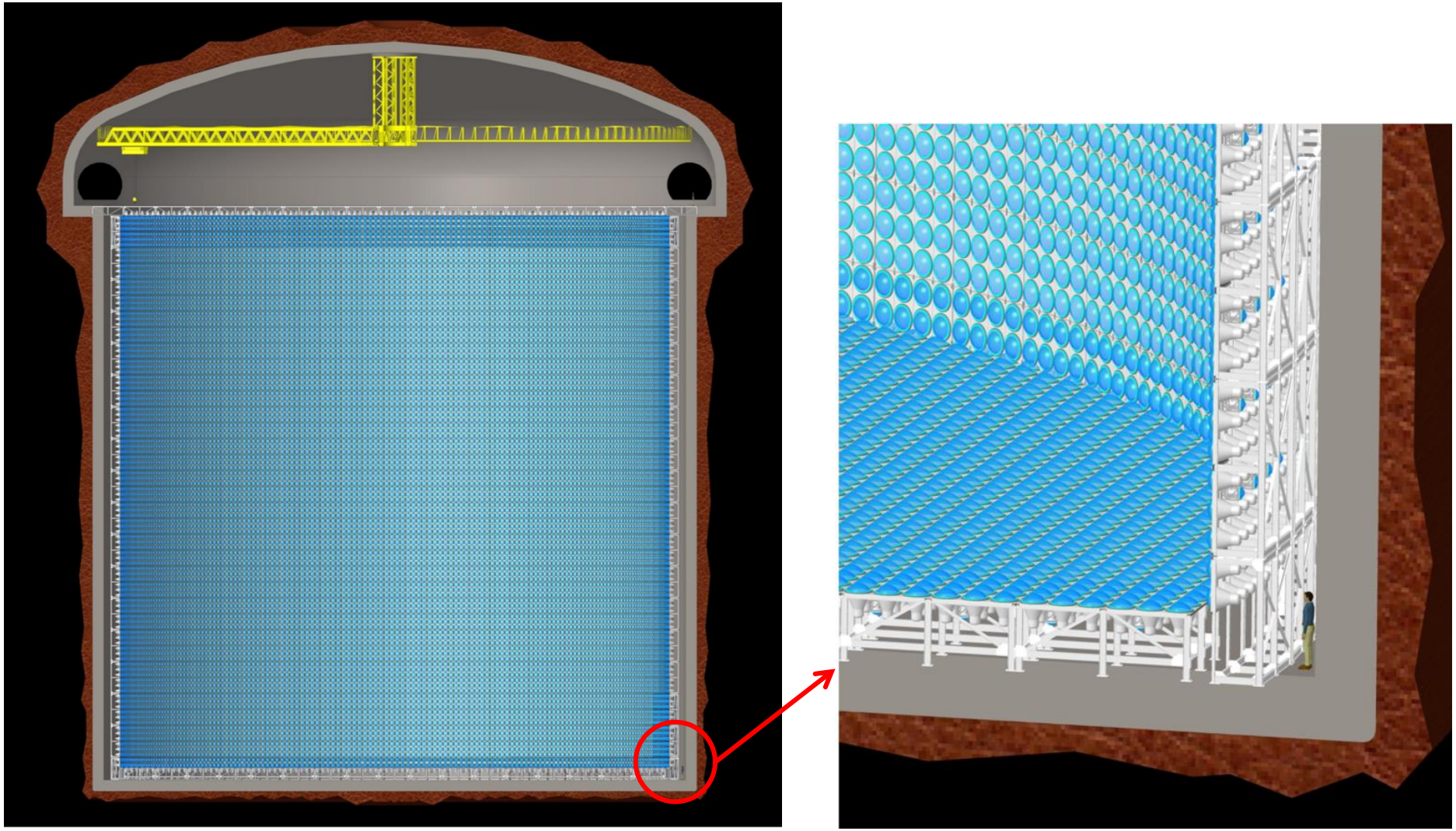
UNDER CONSTRUCTION

ESSnuSB neutrino baseline

Active mine, 360 km from the source, partly covernig 1st and 2nd maximum

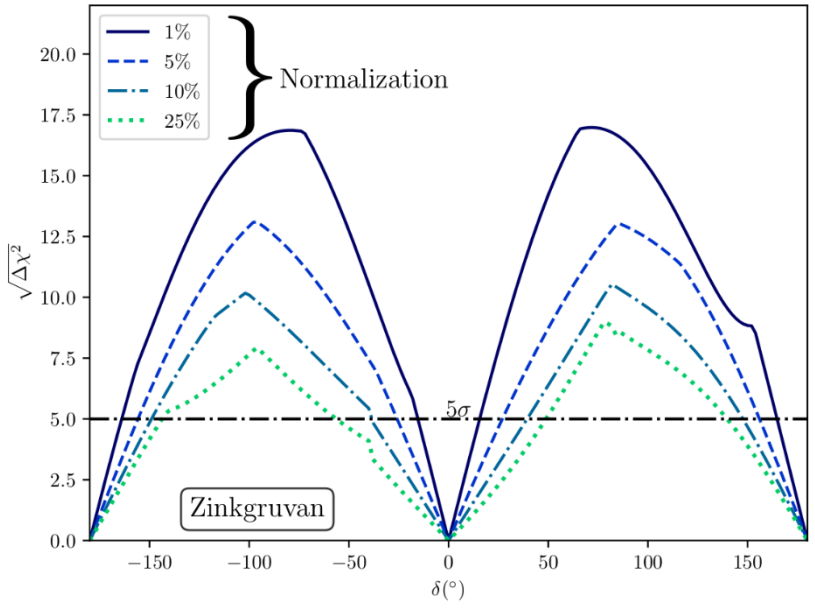


Far detectors

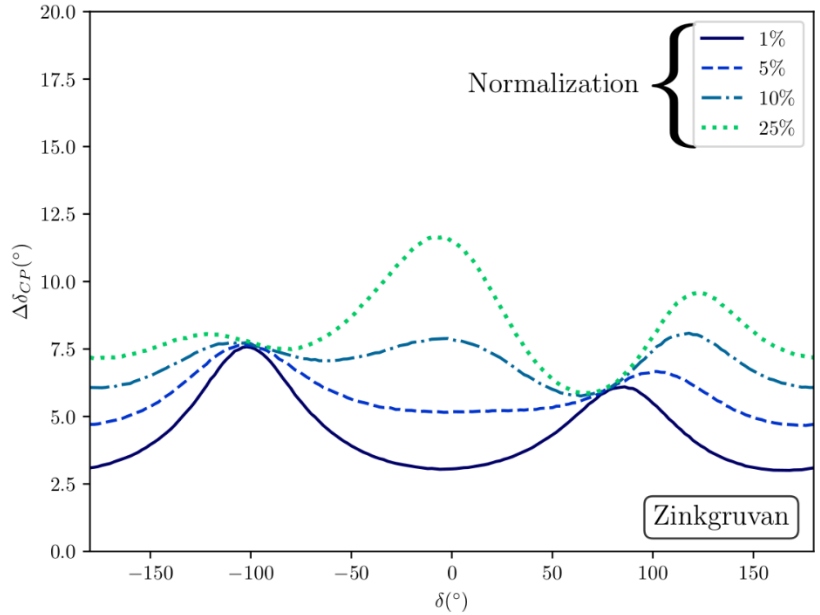


Discovery potential and precision

Sensitivity



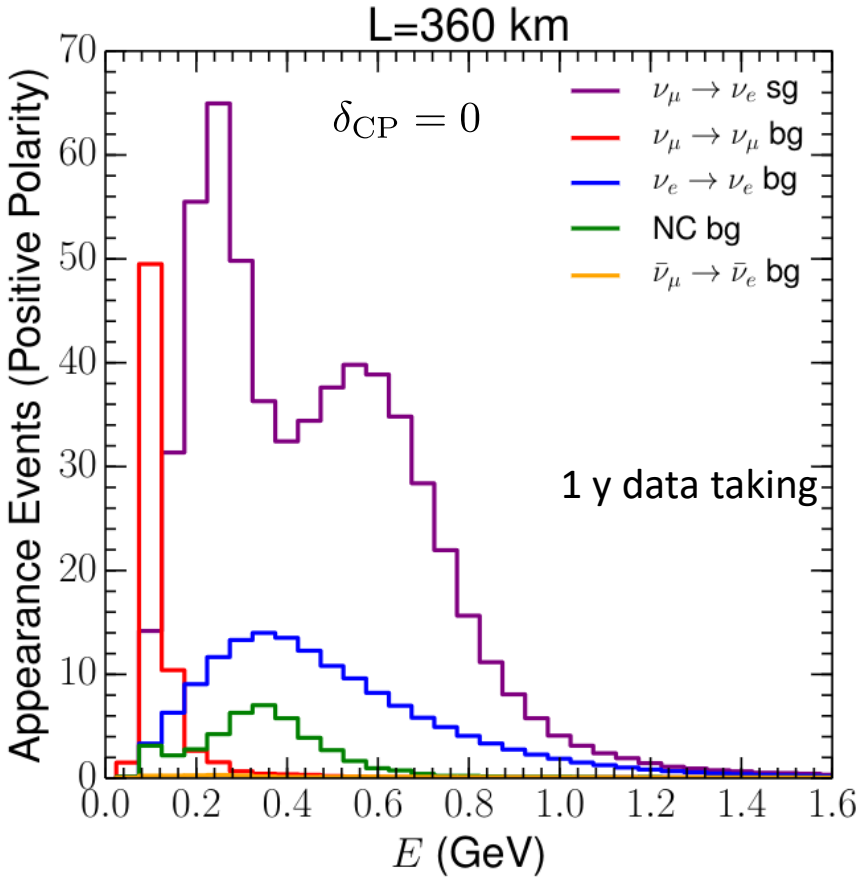
Precision

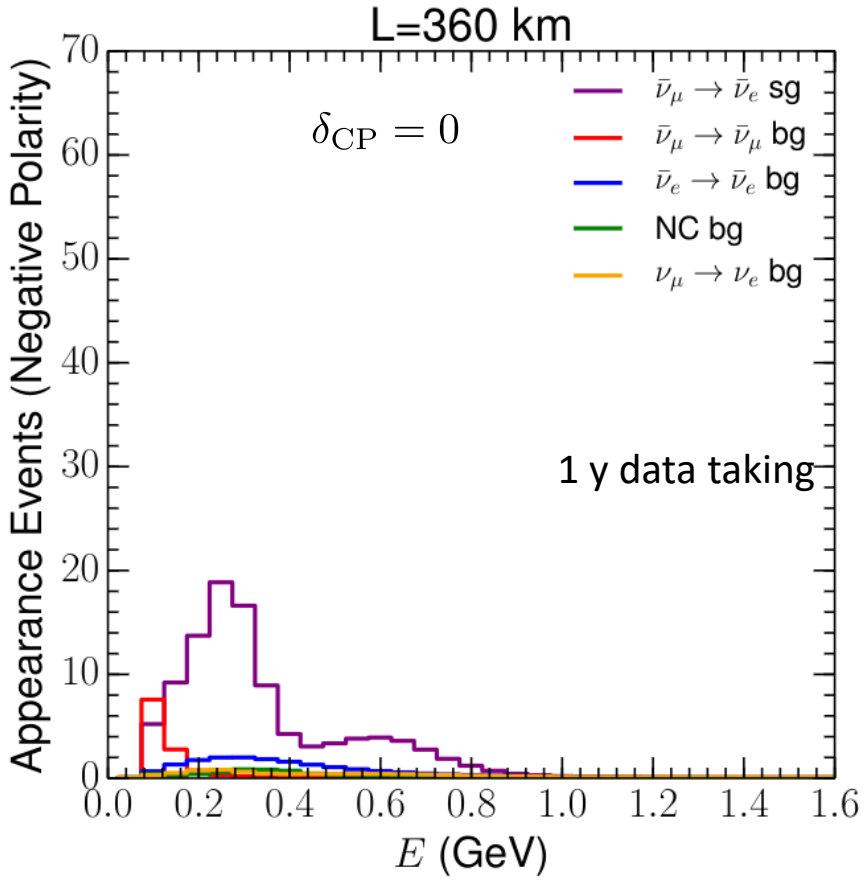


Precision for δ_{CP}:
ESSnuSB < 8°
HyperK < 22°
DUNE < 19°

From the ESSnuSB CDR: https://doi.org/10.1140/epjs/s11734-022-00664-w &
https://arxiv.org/abs/2203.08803

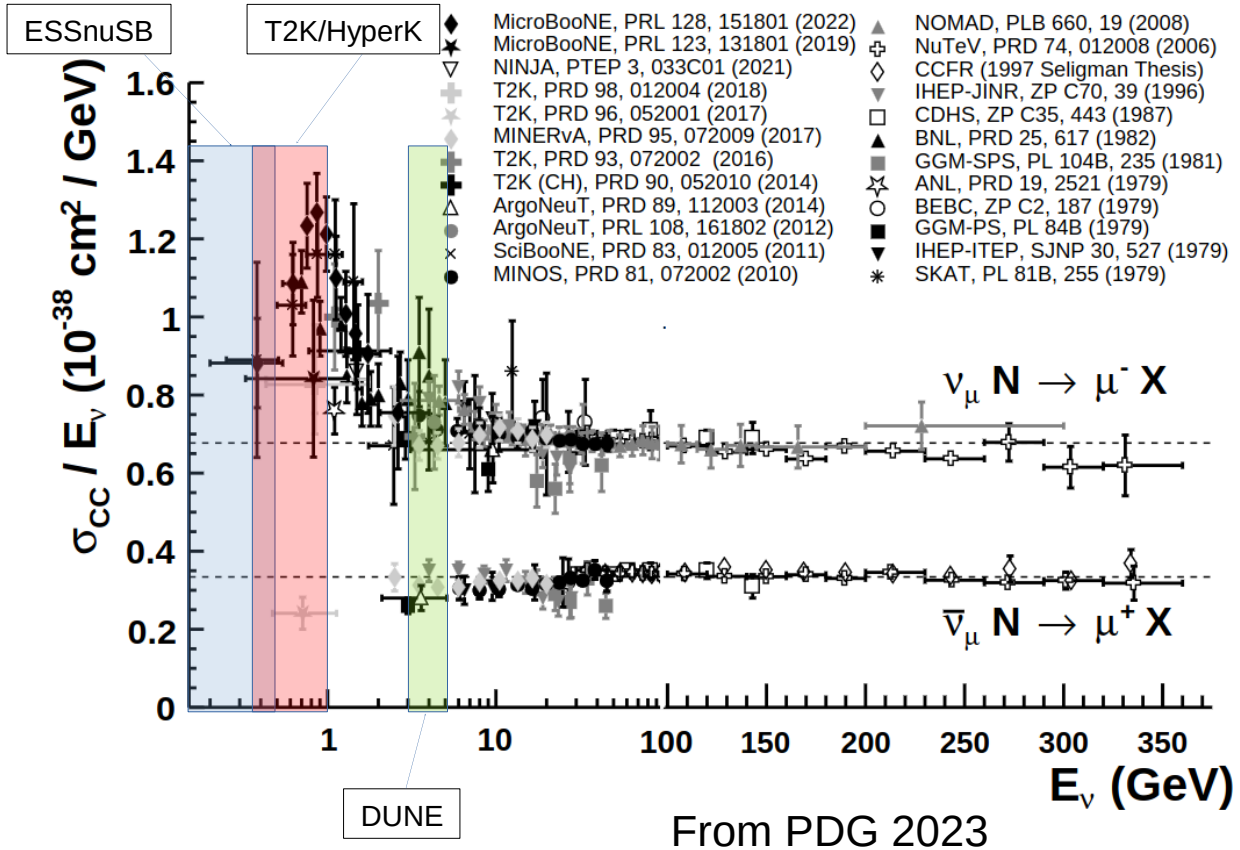
Neutrino interaction xsec problem (CPV signal)





Shapes and amplitudes of this depend on neutrino–water xsec which we don't know well.

Neutrino interaction xsec problem (current xsec measurements)

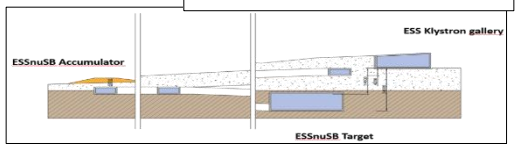


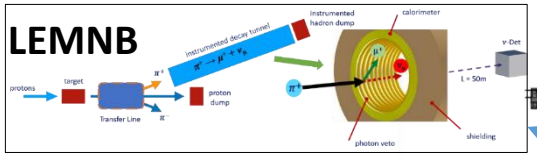
From PDG 2023

We must measure neutrino interaction cross-sections for CPV programme!

ESSnuSB+ design study

Civil engineering

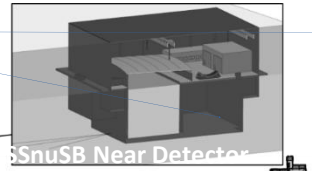


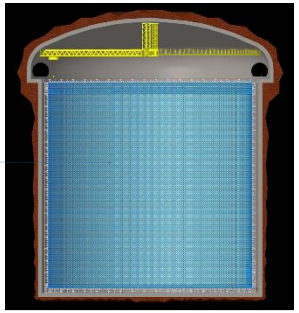


Low Energy Monitored neutrino Beam

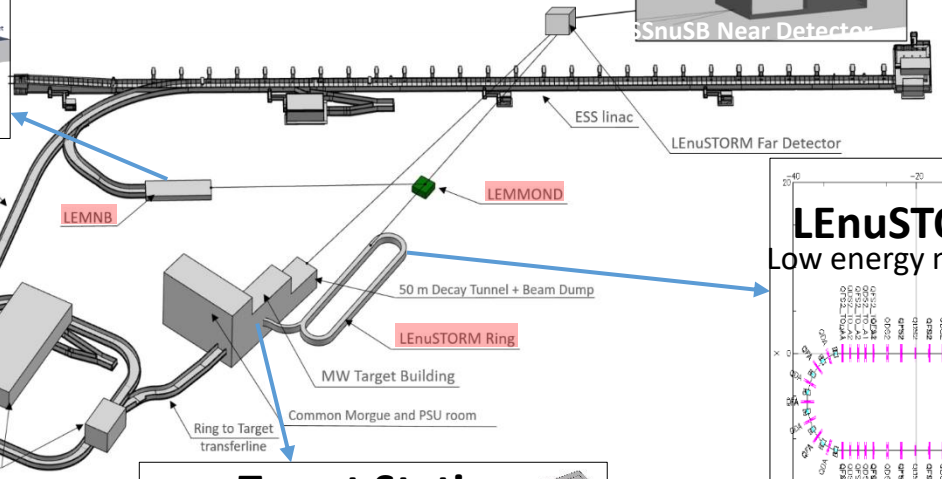
ENUBET

Gd doping



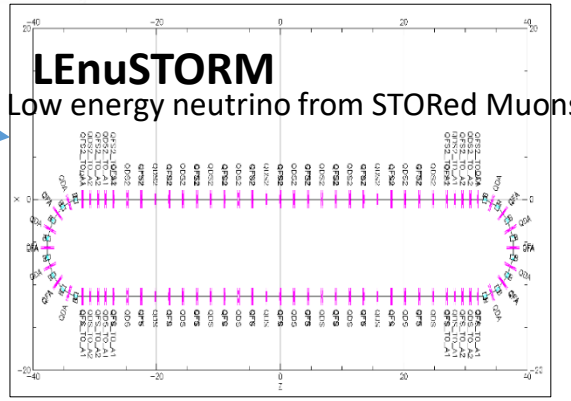


Mining

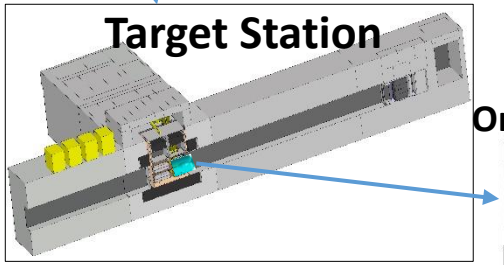


LEnuSTORM

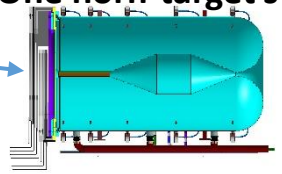
Low energy neutrino from STORed Muons

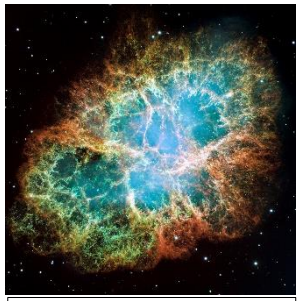


Target Station



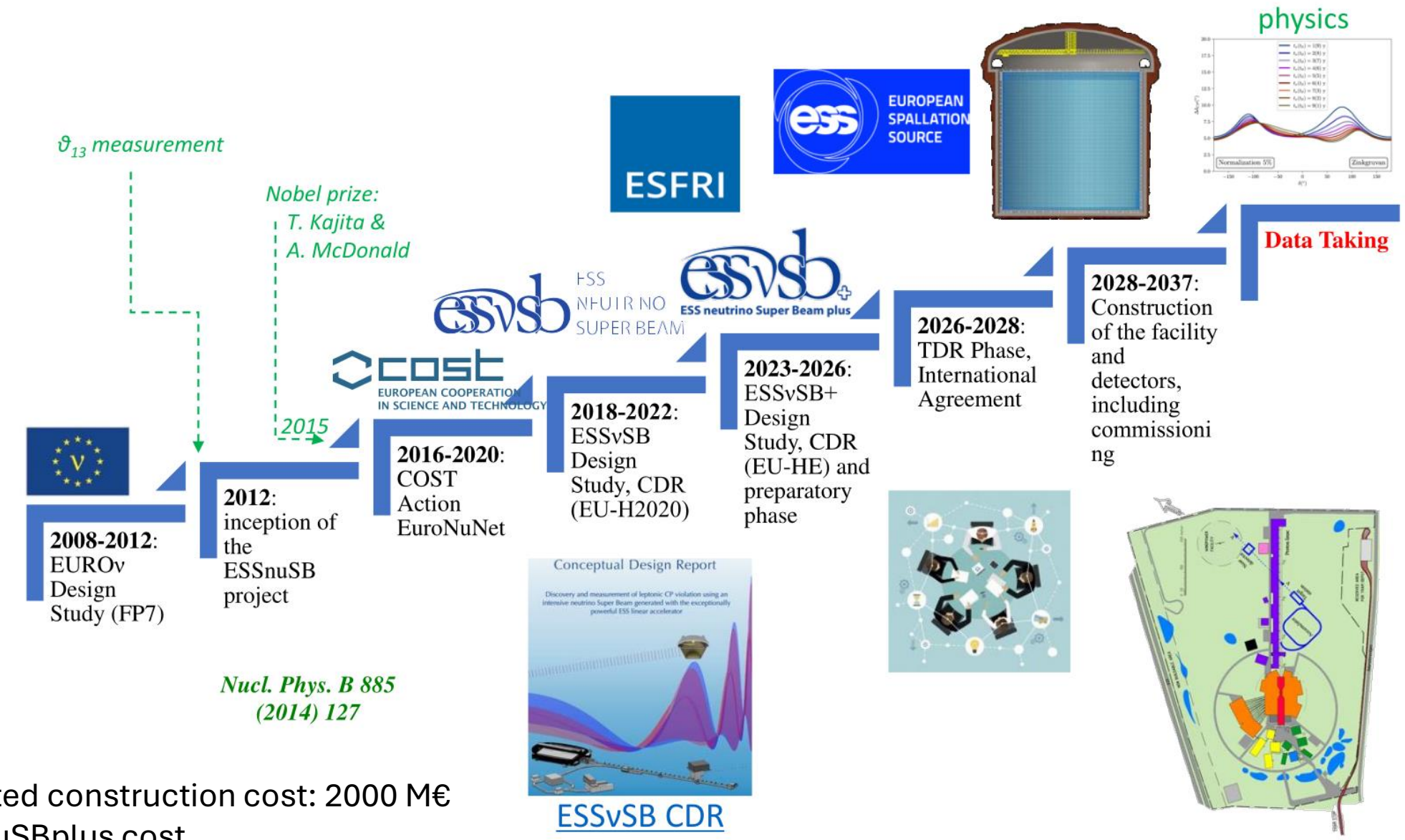
One horn-target system





Additional physics

ESSnuSB timeline



Estimated construction cost: 2000 M€
+ ESSnuSBplus cost

SBN@PBC

SBN@PBC

- **Short-Baseline Neutrinos at Physics Beyond Colliders**
- Proposal to have ENUBET+NuTAG beamline to produce a neutrino beam
  - Allows for <1% error on the neutrino flux
- Use an existing ProtoDUNE detector at CERN to detect neutrinos

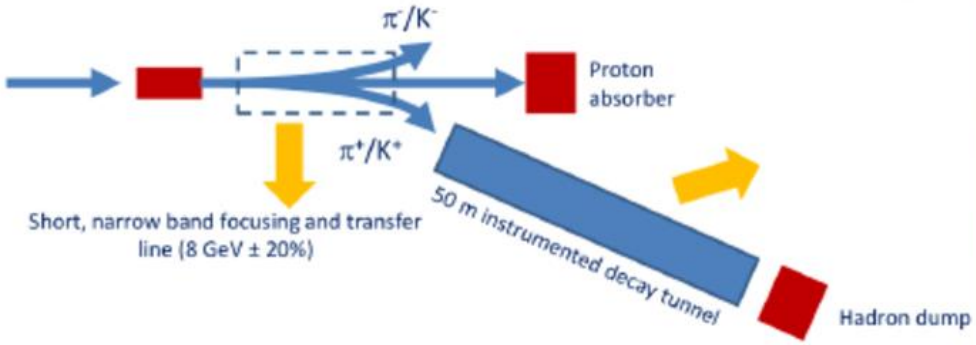
- Very precise neutrino interaction cross-section measurement since $\sigma \sim N_{int}/L_{\nu}$, could go down to 1% error

- **There seems to be a consensus among the CERN neutrino community that this is the neutrino beam program we want at CERN**

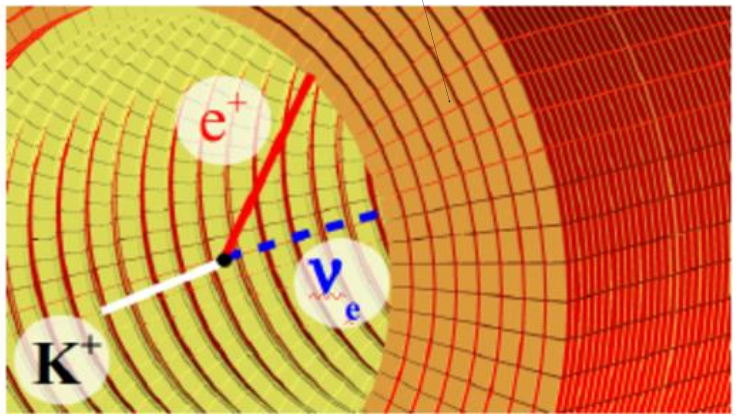
ENUBET

Measurement of ν_e component of a neutrino beam by instrumentizing the decay tunnel

- CP violation will be masured by observing $\nu_\mu \rightarrow \nu_e$ oscillations
  - prompt elecrton neutrinos are dangerous background to be kept under control



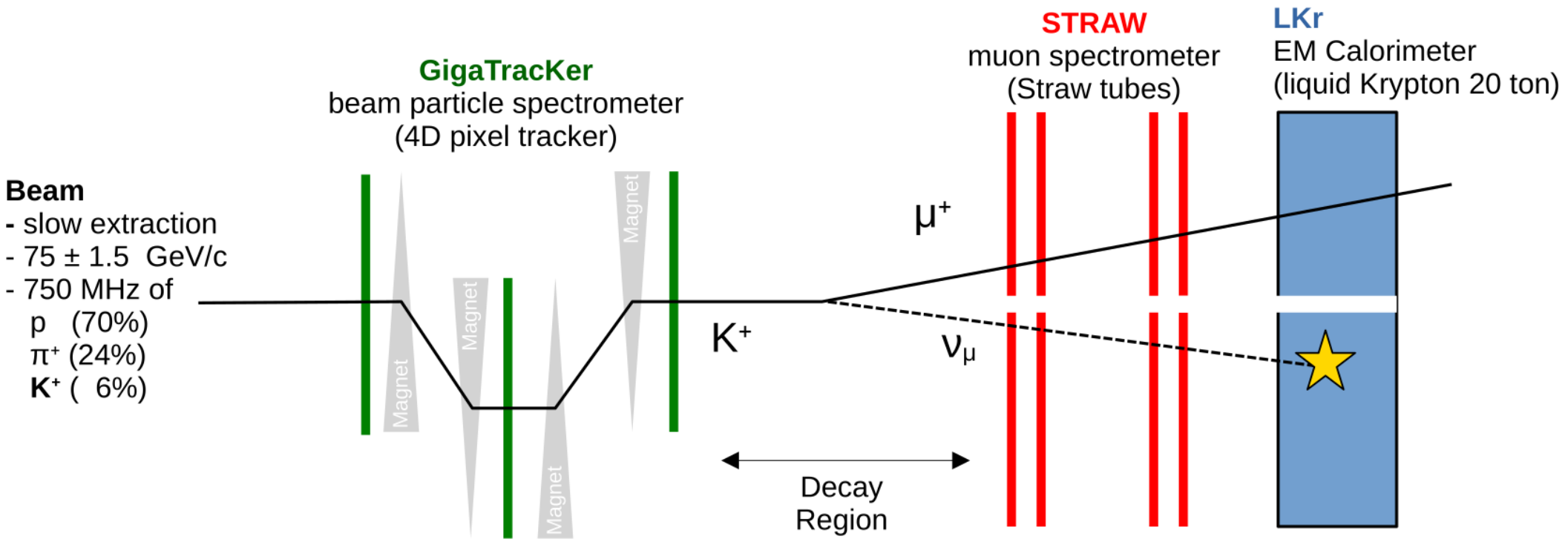
Scintillators with SiPM readout + iron



OK — $\pi^+ \rightarrow \mu^+ + \nu_\mu$

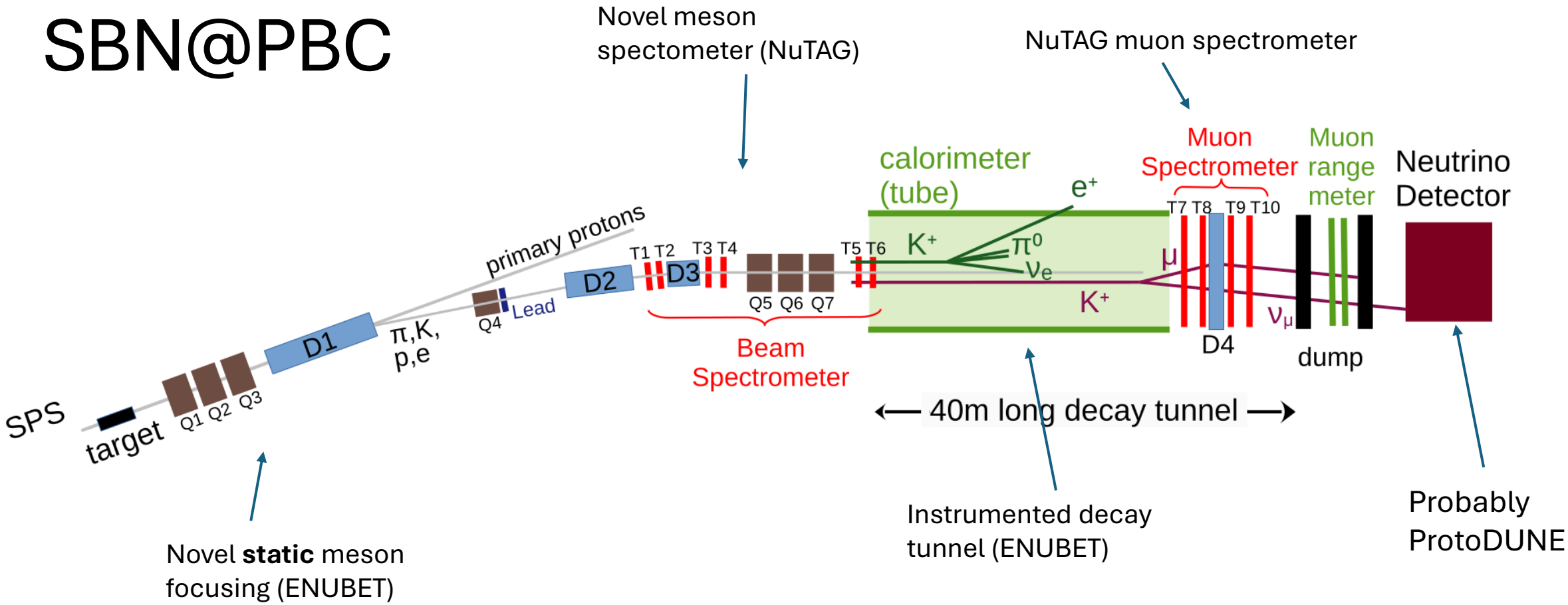
$K^+ \rightarrow \pi^0 + e^+ + \nu_e$ — Background to CPV measurements

NuTAG



Reconstruction and spectrometry of meson tracks.

SBN@PBC



The detector is already there, the accelerator is there (we can use SPS in semi-parasitic mode), the technology is there. Can be used for electron neutrino cross-section measurement.

Let's build it!

Conclusions

- Neutrino physics is at the very frontier of science
  - The only part of (extended) Standard Model where there are known unknowns: we can measure them
- Europe is lagging behind in the experimental neutrino beam physics
  - We are mostly active in big neutrino projects in Japan and US
- Smaller CERN neutrino projects are quite successful: FAZER, SND, …
- Let's go big time!
  - Having an active neutrino beam is also a sign of technological and economic power

- We propose that Croatia strongly supports the following two neutrino projects in the upcoming ESPP update:
  - **ESSnuSB as the flagship European long baseline neutrino project**
    - Precise CPV measurement in the lepton sector + rich additional physics programme
  - **Short Neutrino Baseline at Physics Beyond Colliders at CERN (SBN@PBC)**
    - a novel approach to precise neutrino beam production
    - precise neutrino cross-section measurement required for CPV measurements
    - a lot of infrastructure already exists at CERN