Neutrino Beams

12^{th} Beam Telescopes and Test Beams Workshop

Johannes Bernhard (CERN)

15.04.2024

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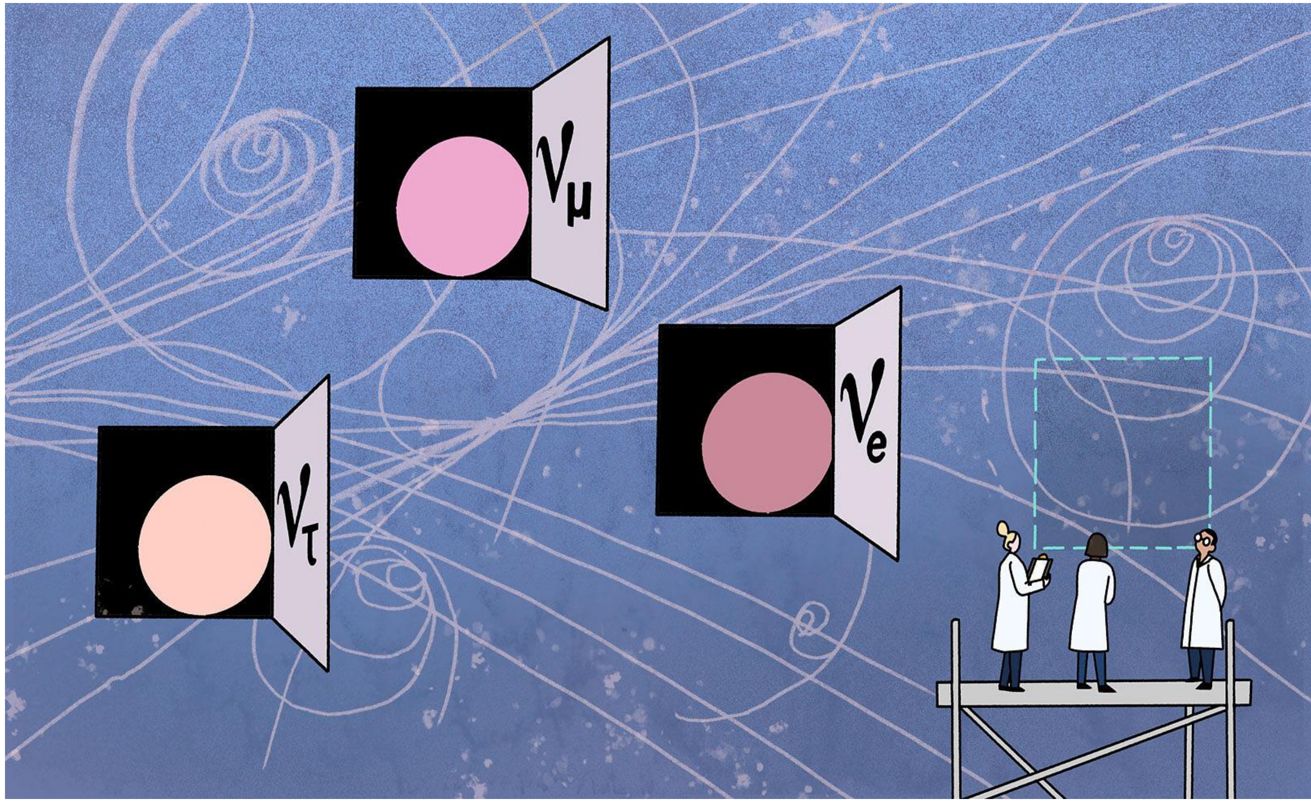
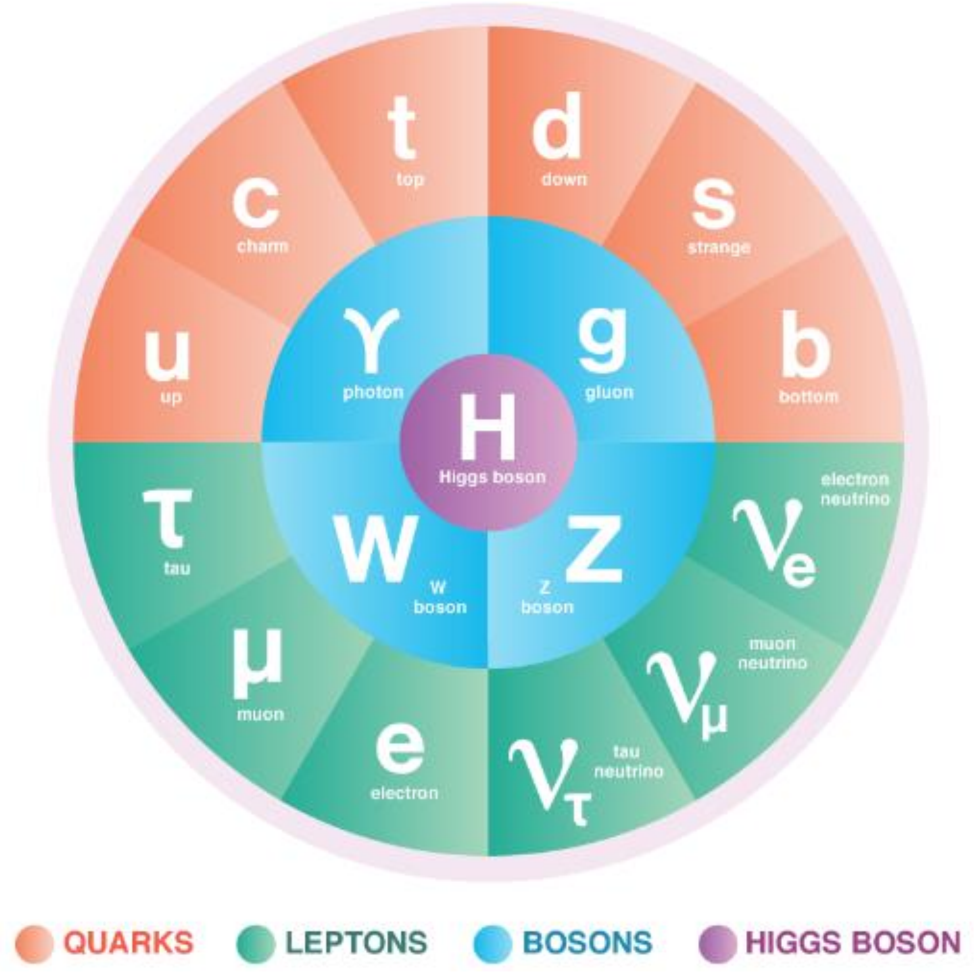


Image courtesy of Symmetry magazine, a joint Fermilab/SLAC publication. Illustration by Sandbox Studio, Chicago.

Neutrinos – Factsheet

- Three types of neutrinos (ν_e | ν_μ | ν_τ)
- Only weakly interacting
- Left-handed
- Have mass and oscillate → Only clear observation of Beyond Standard Model (BSM) effects in particle physics
- Neutrinos are the most abundant matter particles in the universe (about 350 per cm^3)



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Neutrinos – Why are we interested?

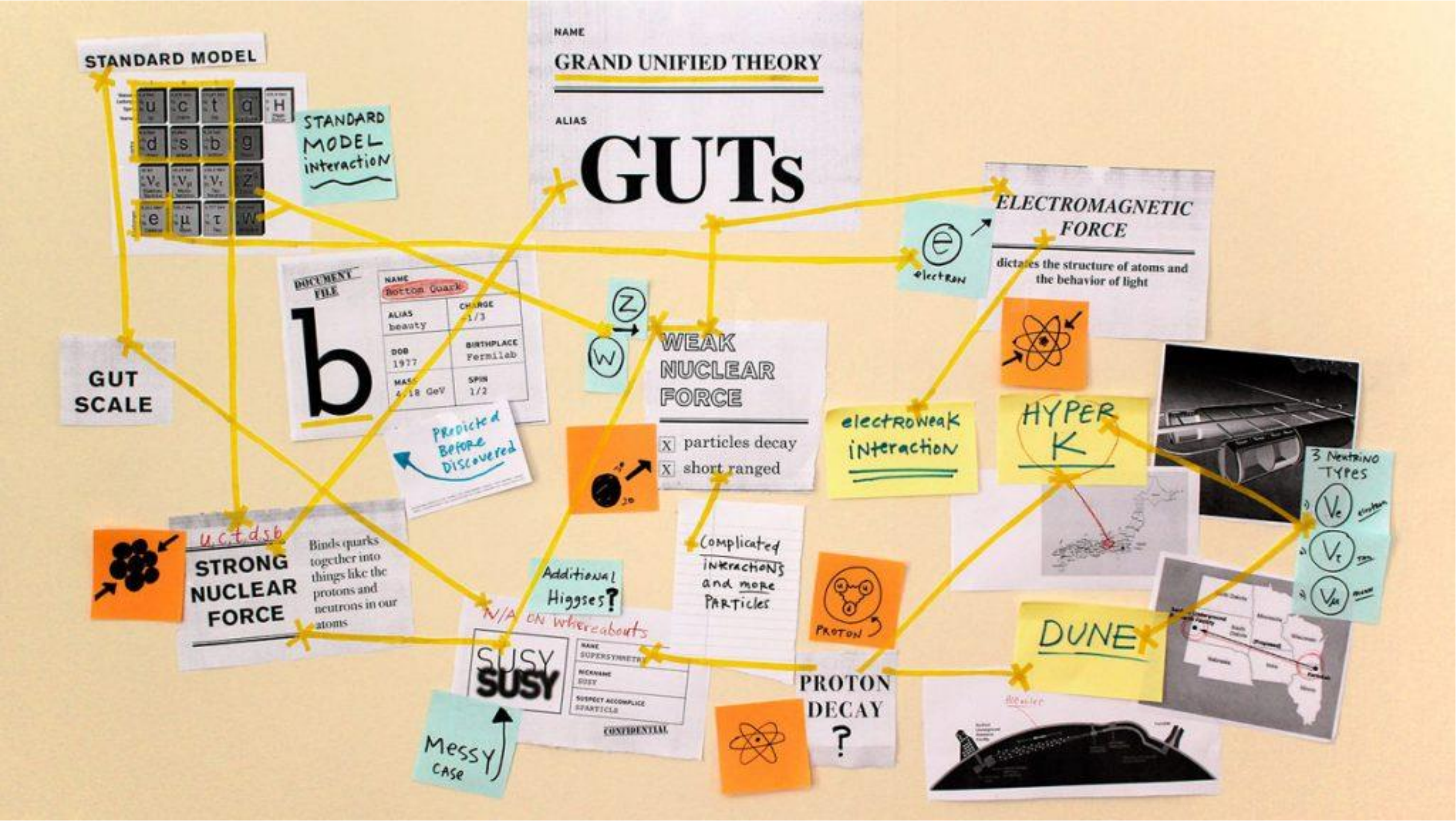


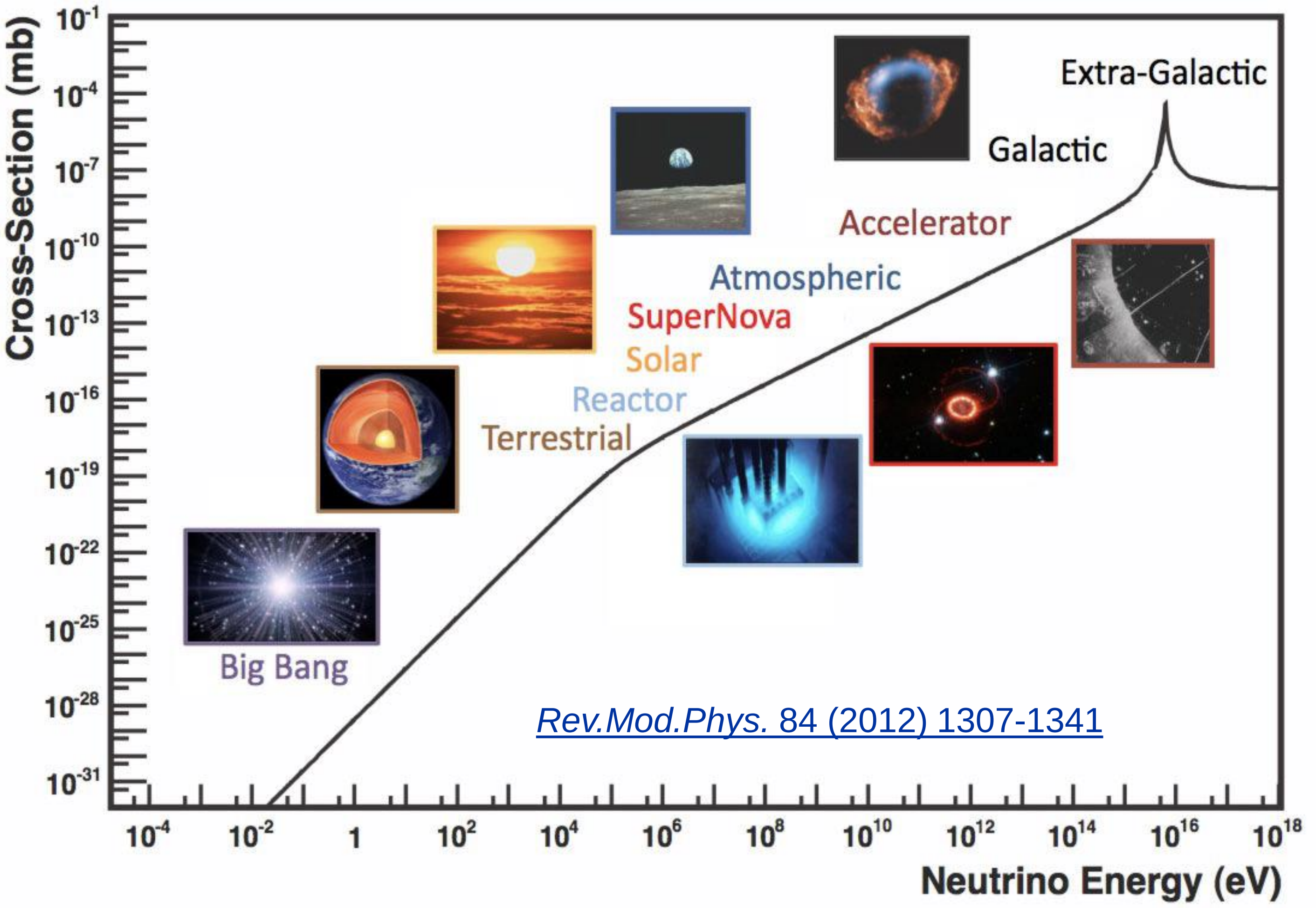
Image courtesy of Symmetry magazine, a joint Fermilab/SLAC publication. Illustration by Sandbox Studio, Chicago.

More questions than answers…

- What is the origin of neutrino mass?
- What is the mass hierarchy?
- Do neutrinos and antineutrinos behave differently, more specifically do they oscillate differently?
- Are they their own antiparticles?
- Are there only three neutrinos?

Sources of Neutrinos

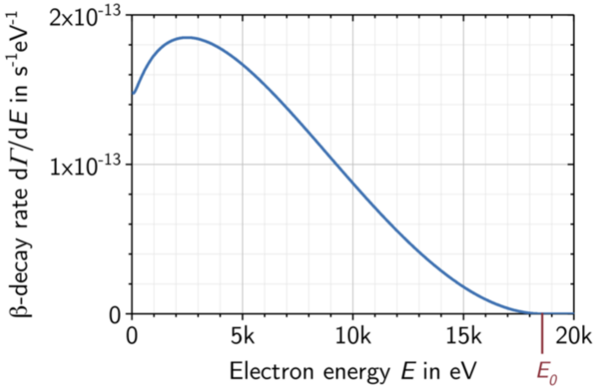
- There are many sources of neutrinos, such as
  - Relics from the Big Bang
  - Nuclear fusion in the sun and stars
  - Core collapse of supernovae
  - Atmospheric interactions of cosmic rays
  - Radioactive decays (β)
- The cross section is also measure of how likely a neutrino is to be stopped by normal matter. A 1 MeV neutrino is only stopped by 10 lightyears of lead

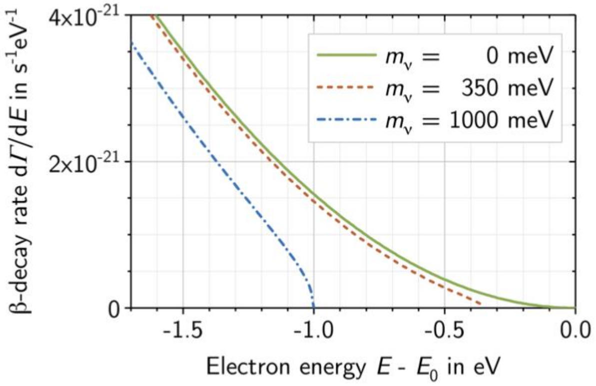


Rev.Mod.Phys. 84 (2012) 1307-1341

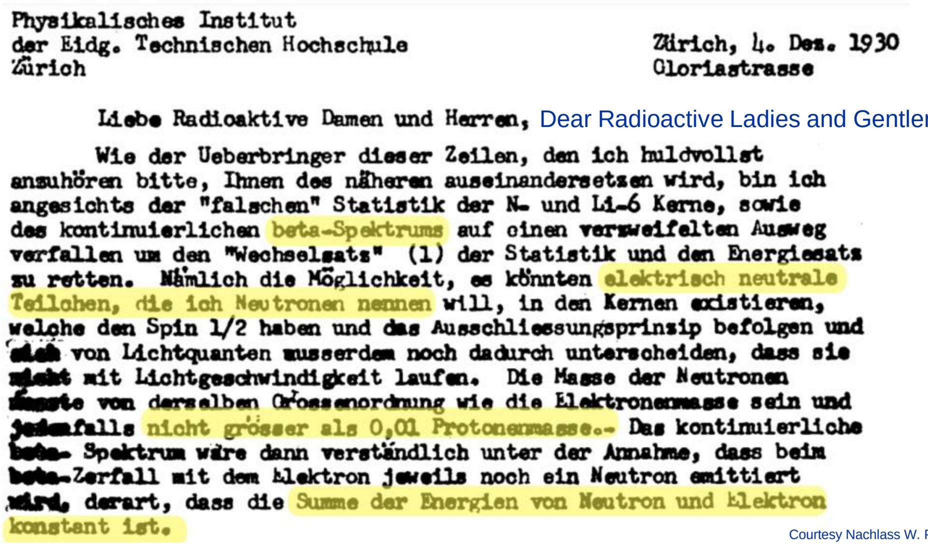
Neutrino Masses

- In 1930, Pauli proposes a new particle to explain the violation of the β decay energy conservation with either a very small or zero mass
- In 1934, Fermi develops a theory of the β decay and shows that the mass can be determined by the slope of the spectrum near its endpoint
- In fact, still one of the go-to methods to determine the neutrino mass nowadays (e.g. KATRIN experiment)





[Eur. Phys. J. C 79, 204 (2019)]



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren, Dear Radioactive Ladies and Gentlemen

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse. - Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Courtesy Nachlass W. Pauli

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di ENRICO FERMI

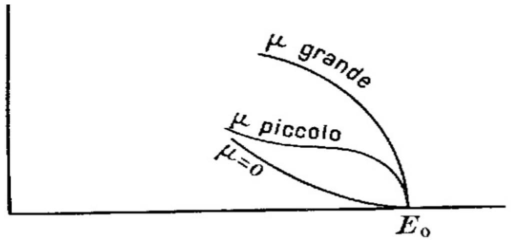


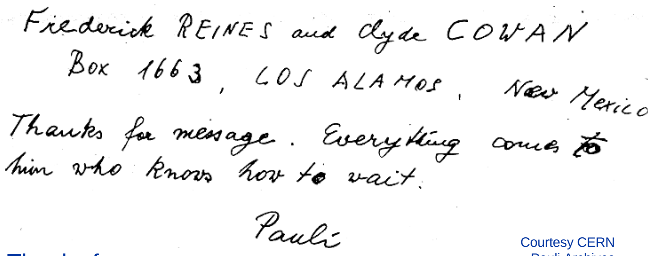
Fig. 1

[Nuovo Cim **11**, 1–19 (1934)]

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

[Science 124, 124 (1956)]

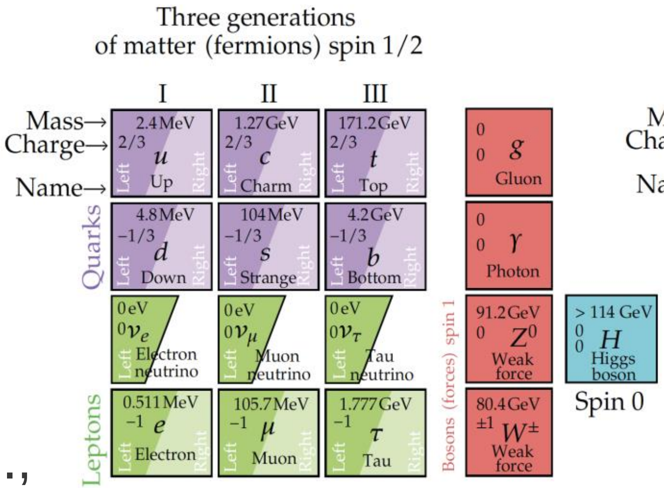


Thanks for message.
Everything comes to him who knows to wait.

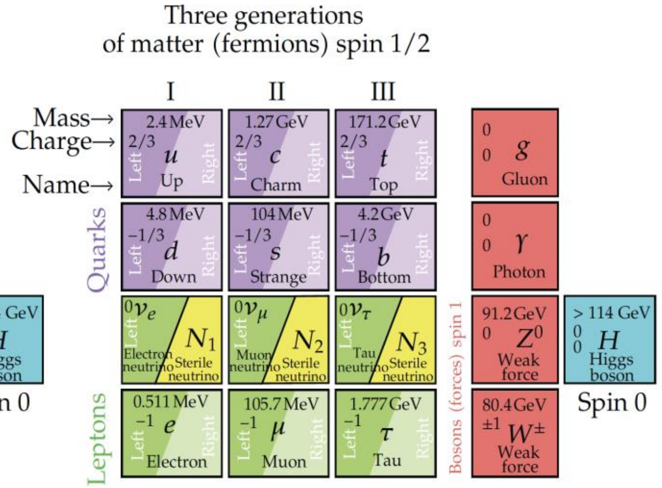
Courtesy CERN
Pauli Archives

Neutrino Masses

- There is no explanation of neutrino mass in SM
- If it would arrive through the Higgs-Mechanism, then right-handed (sterile) neutrinos exist
- It is possible to add terms to extend the SM, e.g.,
  - Dirac-like (conserves total lepton number but can break lepton flavour number symmetries)
  - Majorana-like (singlet of the SM gauge group, breaks lepton number by two units, neutrino = antineutrino)

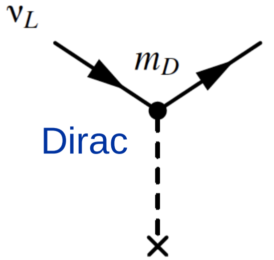


SM

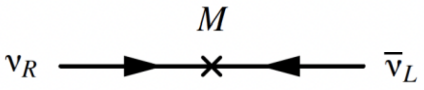


One possibility to extend: νMSM
Phys.Lett.B 620 (2005) 17-26

$$-\mathcal{L}_{M_\nu} = M_{D ij}\bar{\nu}_{si}\nu_{Lj} + \frac{1}{2}M_{N ij}\bar{\nu}_{si}\nu^c_{sj} + \text{h.c.}$$



Dirac



Majorana

  - If both are present, possibility of a "seesaw mechanism", i.e. with small left-handed mass $m_\nu \approx \dfrac{m_D^2}{M}$ one would expect a very high right-handed mass $m_N \approx M$ in the order of $10^{12} - 10^{16}$ GeV/c^2

$$\mathcal{L} \sim -\frac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{\nu^c_R} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

  - Side note: Models like νMSM account for baryon asymmetry of the universe through leptogenesis and include a candidate for dark matter, i.e. one of the sterile neutrinos

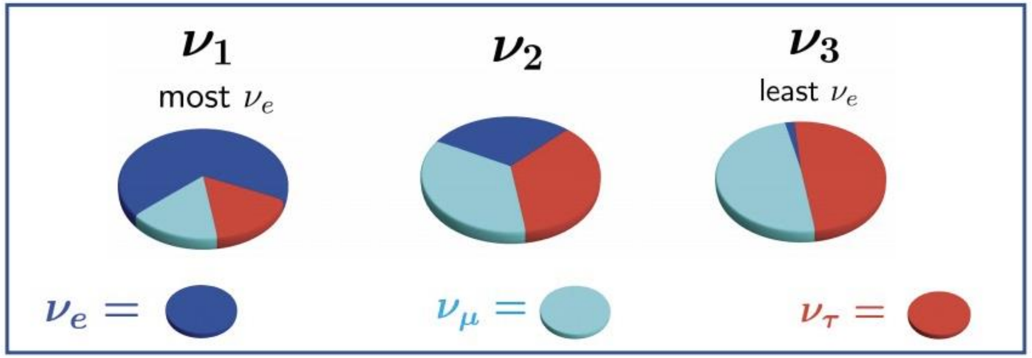
Neutrino Masses

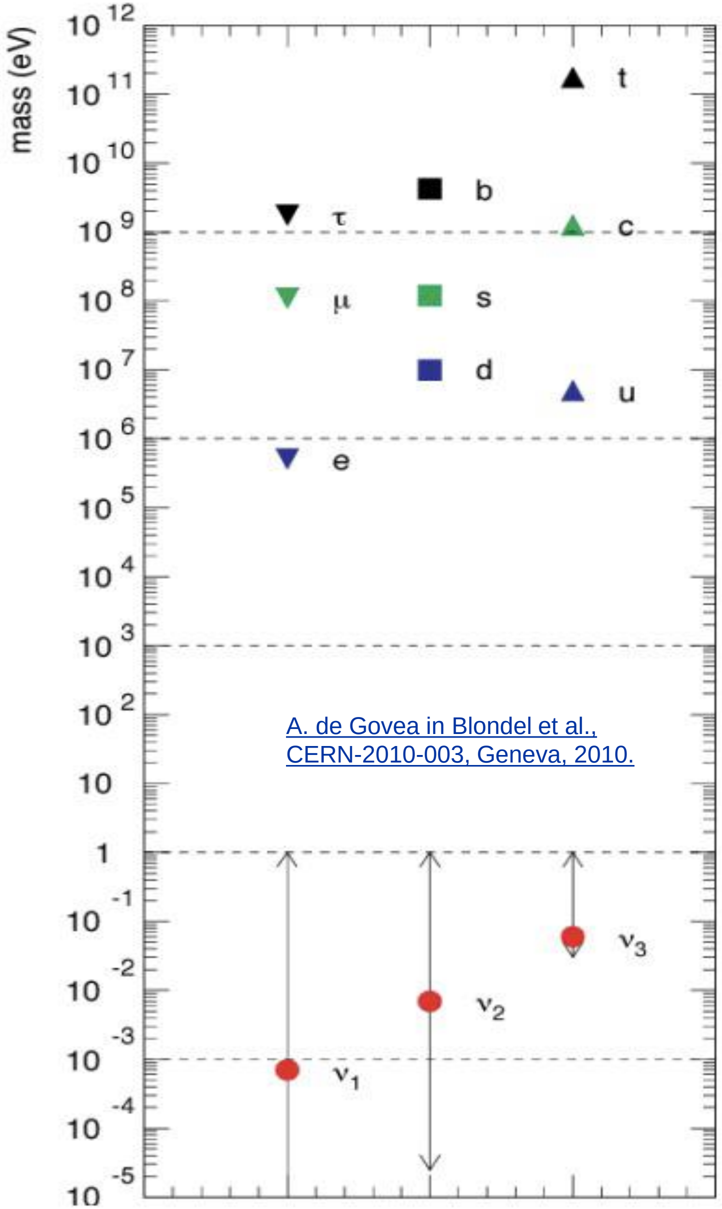
- Neutrino interactions are described in their flavour-eigenstates, but they propagate in their mass eigenstates

$$|\,\nu_j(t)\,\rangle = e^{-i\left(E_j t - \vec{p}_j \cdot \vec{x}\right)}\,|\,\nu_j(0)\,\rangle$$

- Both are connected via a unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



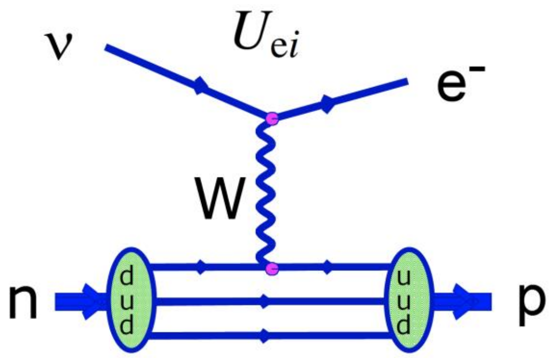


A. de Govea in Blondel et al., CERN-2010-003, Geneva, 2010.

Neutrino Oscillations

- Probability to find an electron neutrino

$$P(\nu_e \to \nu_e) = |U_{e1}^* U_{e1} e^{-i\phi_1} + U_{e2}^* U_{e2} e^{-i\phi_2} + U_{e3}^* U_{e3} e^{-i\phi_3}|^2$$



- With phases $\phi_i = p_i x$

$$= E_i t - \mathbf{p}_i \cdot \mathbf{x}$$

- Phase differences between ν_1, ν_2, ν_3 drive oscillations

$$P(\nu_e \to \nu_e) = 1 + 2|U_{e1}|^2|U_{e2}|^2\,\Re\{[e^{i(\phi_2-\phi_1)} - 1]\}$$
$$+ 2|U_{e1}|^2|U_{e3}|^2\,\Re\{[e^{i(\phi_3-\phi_1)} - 1]\}$$
$$+ 2|U_{e2}|^2|U_{e3}|^2\,\Re\{[e^{i(\phi_3-\phi_2)} - 1]\}$$

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\left(\frac{m_2^2 - m_1^2}{4}\frac{L}{E}\right)$$
$$- 4|U_{e1}|^2|U_{e3}|^2 \sin^2\left(\frac{m_3^2 - m_1^2}{4}\frac{L}{E}\right)$$
$$- 4|U_{e2}|^2|U_{e3}|^2 \sin^2\left(\frac{m_3^2 - m_2^2}{4}\frac{L}{E}\right)$$

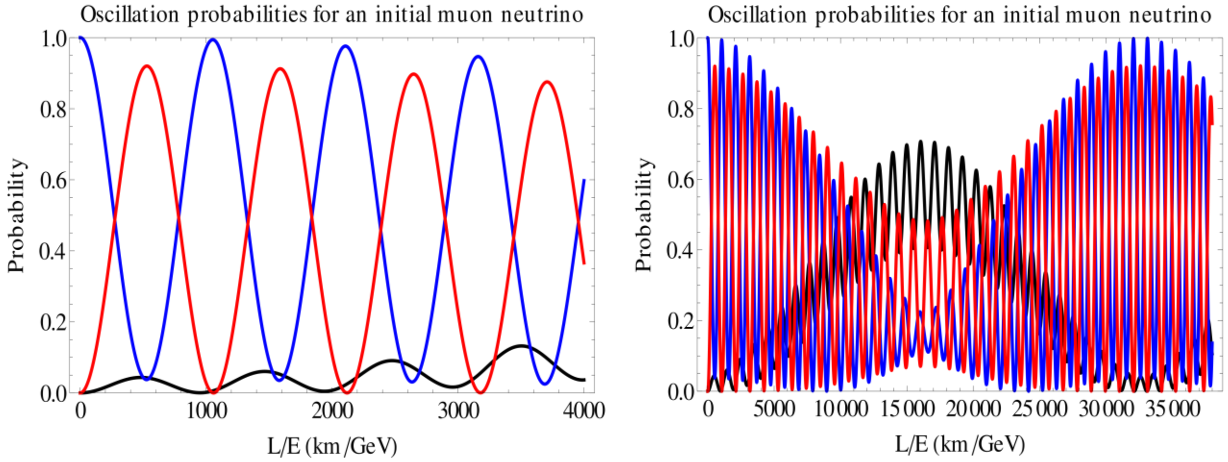
Use $\Re\{[e^{i(\phi_j-\phi_i)} - 1]\} = \cos\Delta\phi_{ji} - 1 = -2\sin^2\frac{\Delta\phi_{ji}}{2}$

and $\Delta\phi_{ji} = (E_j - E_i)T \underset{p \gg m}{=} \left[p\left(1 + \frac{m_j^2}{p^2}\right)^{\frac{1}{2}} - p\left(1 + \frac{m_i^2}{p^2}\right)^{\frac{1}{2}}\right]T$

$$\approx \left[p\left(1 + \frac{m_j^2}{2p^2}\right)^{\frac{1}{2}} - p\left(1 + \frac{m_i^2}{2p^2}\right)^{\frac{1}{2}}\right]T$$

$$= \frac{(m_j^2 - m_i^2)}{2p}L \underset{p \approx E}{=} \Delta m^2 \frac{L}{E}$$

Neutrino Oscillations



Wolfram demonstration on Neutrino oscillations

- Typical wavelength of neutrino oscillation

$$\lambda_{\text{osc}}(\text{km}) = 2.47 \frac{E(\text{GeV})}{\Delta m^2(\text{eV}^2)}$$

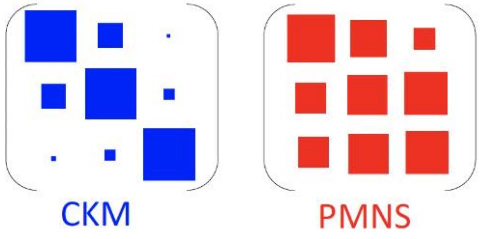
- And for e.g. muon neutrino to electron neutrino

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\text{eV}^2]L[\text{km}]}{E_\nu[\text{GeV}]}\right)$$

- With that one can rewrite the unitary matrix from p.8 to take the form of the PMNS matrix

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{bmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.779 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{bmatrix}$$

- Analogue to the CKM matrix in the quark sector, but a lot more mixing



- Why is this important?
  - It's one of the few sources of information on BSM physics and neutrino characteristics
  - Defines **how and where to build experiments** and with that the **neutrino beam design**

Neutrino Detection

- Detection typically via **charged** and neutral **weak currents**
- Several detection techniques exist, such as
  - Bubble chambers (e.g. liquid Hydrogen/BEBC, liquid Freon/Gargamelle)
  - Scintillators (e.g. liquid/KamLAND)
  - Radiochemical, e.g. neutrino capture and conversion of ^{37}Cl to ^{37}Ar, then chemically detect Ar → see Homestake experiment that detected the first solar neutrinos
  - Cherenkov (e.g. water/Kamiokande, oil/MiniBooNE)
  - Calorimeters (e.g. steel-scintillator sandwich/MINOS)
  - TPCs (e.g. lAr/ICARUS)
  - Emulsions (e.g. AgBr/OPERA), also often in the form of emulsion cloud chambers
  - Semiconductors and crystal detectors (e.g. CaWO4/CRESST)

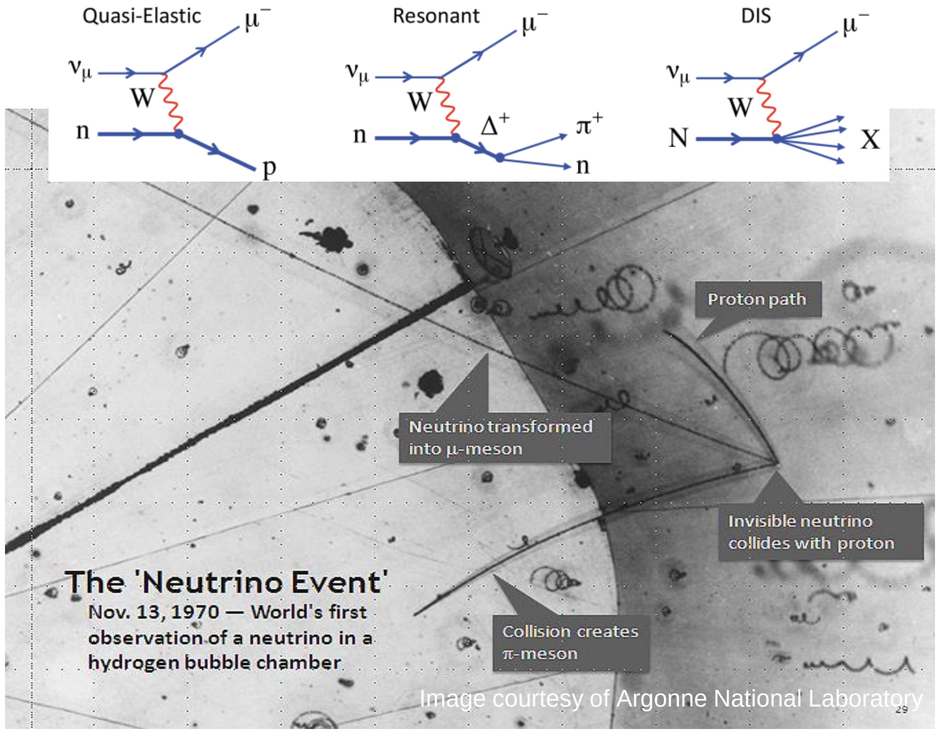
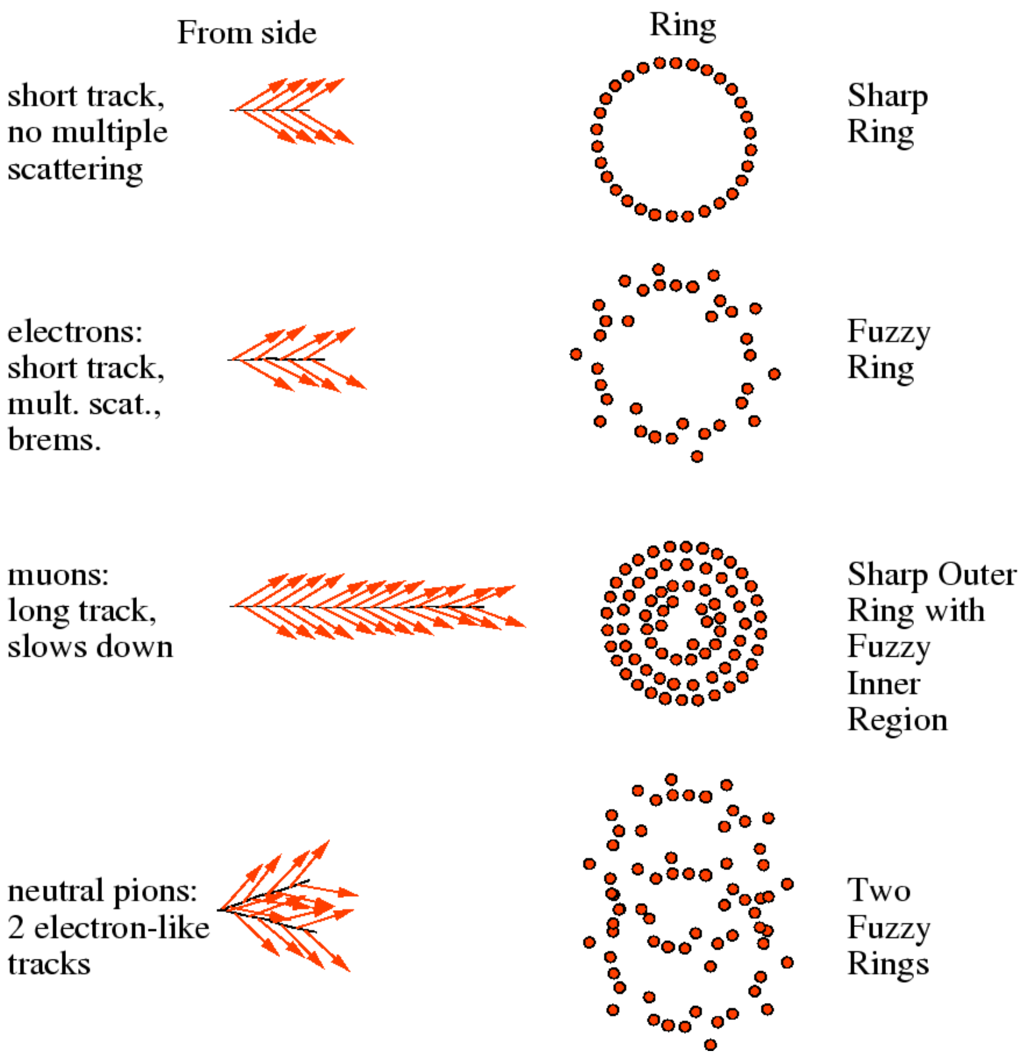


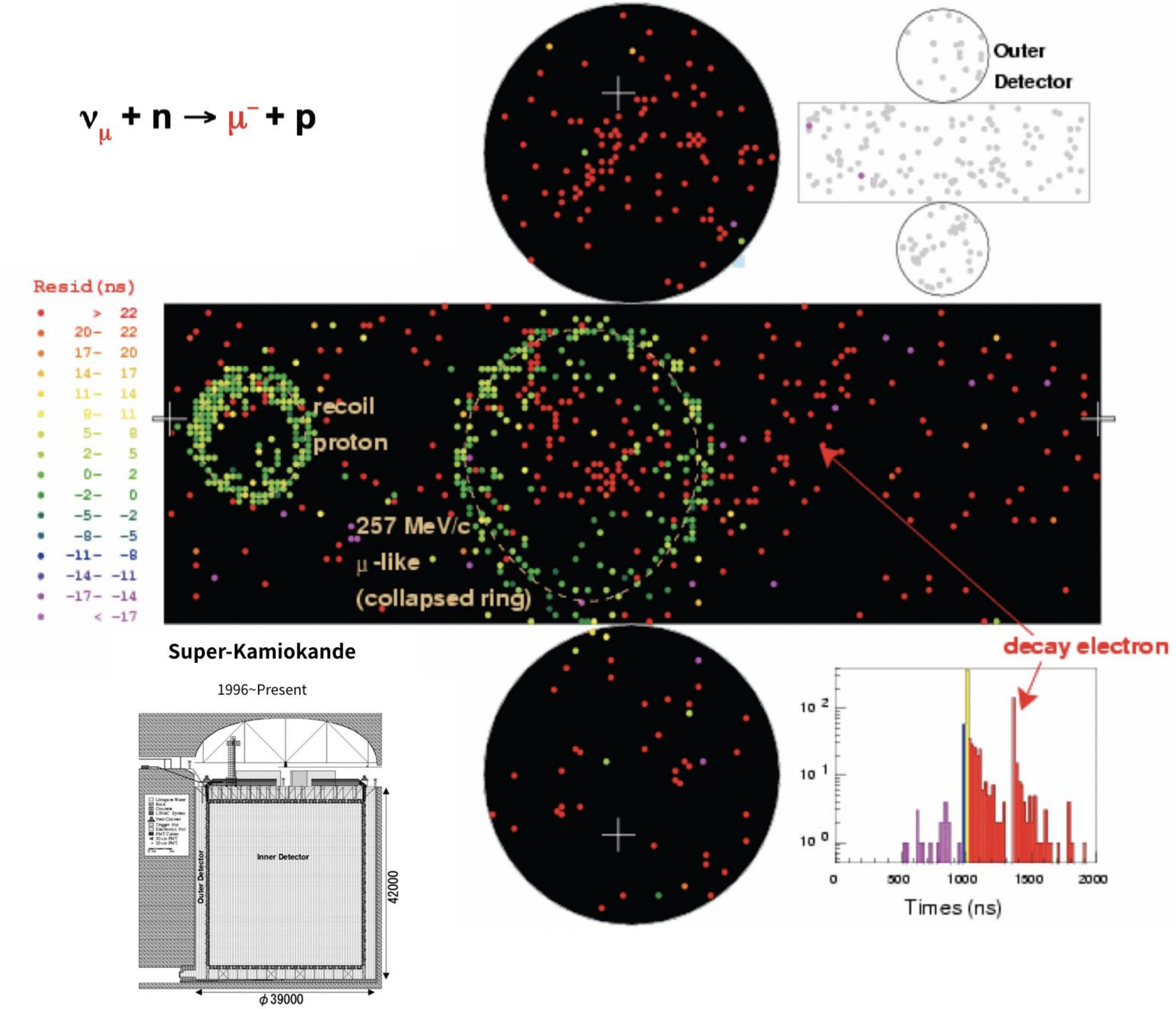
Image courtesy of Argonne National Laboratory


Gargamelle / CERN


BEBC / CERN

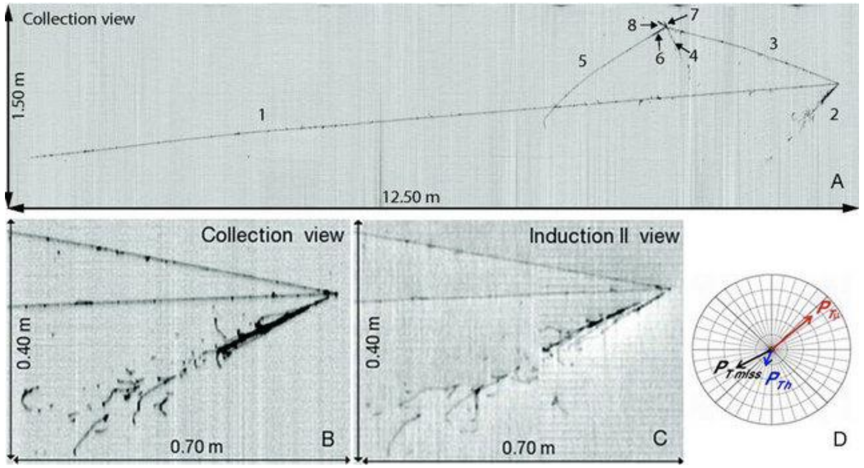
Water Cherenkov Detectors

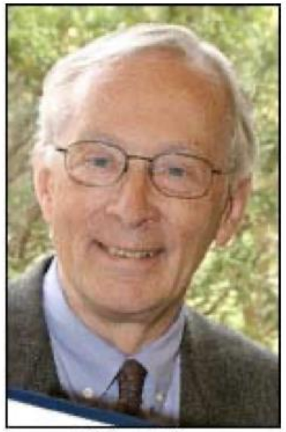


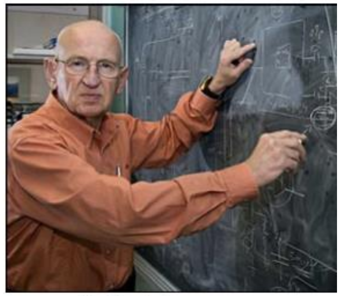


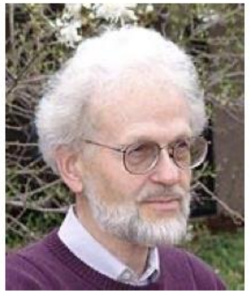
Liquid Argon TPCs

- W. Willis and V.Radeka, Liquid argon ionization chambers as total absorption detector, Nucl.Instr.&Meth. 120 (1974) 221
- D.R. Nygren, The Time projection Chamber: A new 4π Detector for Charged Particles, eConf C740805 (1974) 58
- H.H. Chen et al., A Neutrino detector sensitive to rare process. A study of neutrino electron reactions, FNAL-Proposal-0496 (1976)
- C. Rubbia, The liquid argon time projection chamber: a new concept for neutrino detector, CERN-EP/77-08 (1977)
- Proposal for a Massive LArTPC ICARUS T600, INFN/AE-85/7 (1985)
- 2010: ICARUS at Gran Sasso laboratory with CERN CNGS beam




William Willis


V. Radeka


D. R. Nygren

H. H. Chen


C. Rubbia

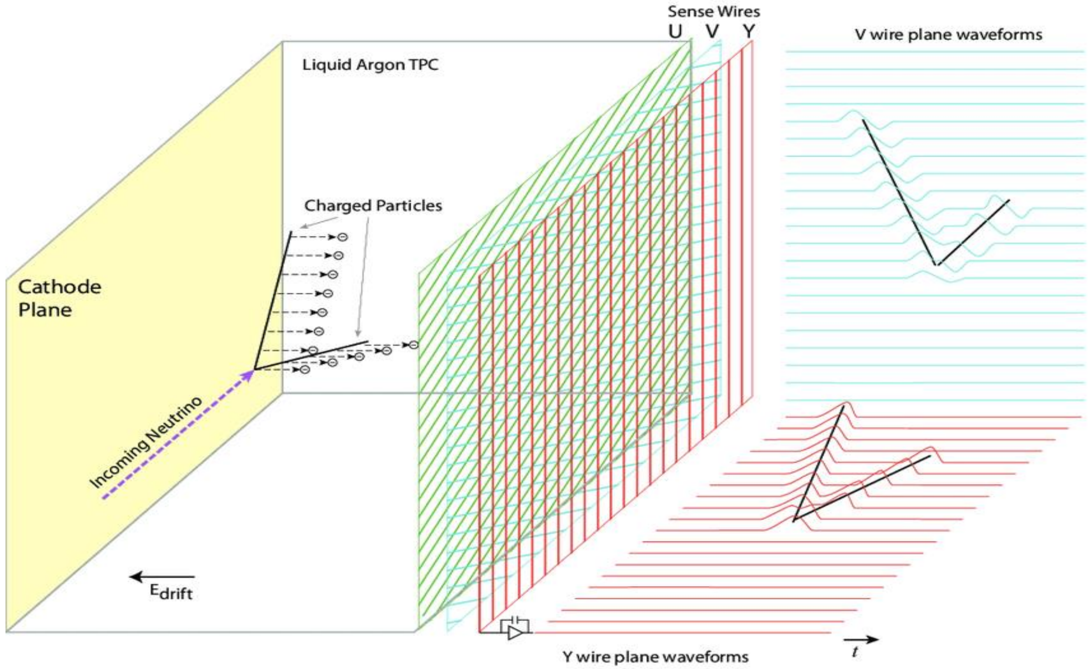
Liquid Argon TPCs

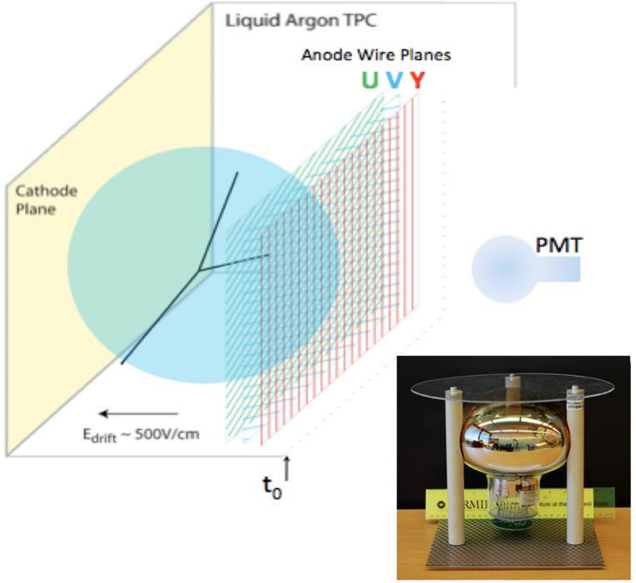
Charge Readout

- Neutrino interactions produced charged particles that ionise the Argon
- Applying a high electrical field lets ions and ionisation electrons towards segmented wire planes → electrical current
- Reduces 3D readout cost to 2D (surfaces instrumented only)

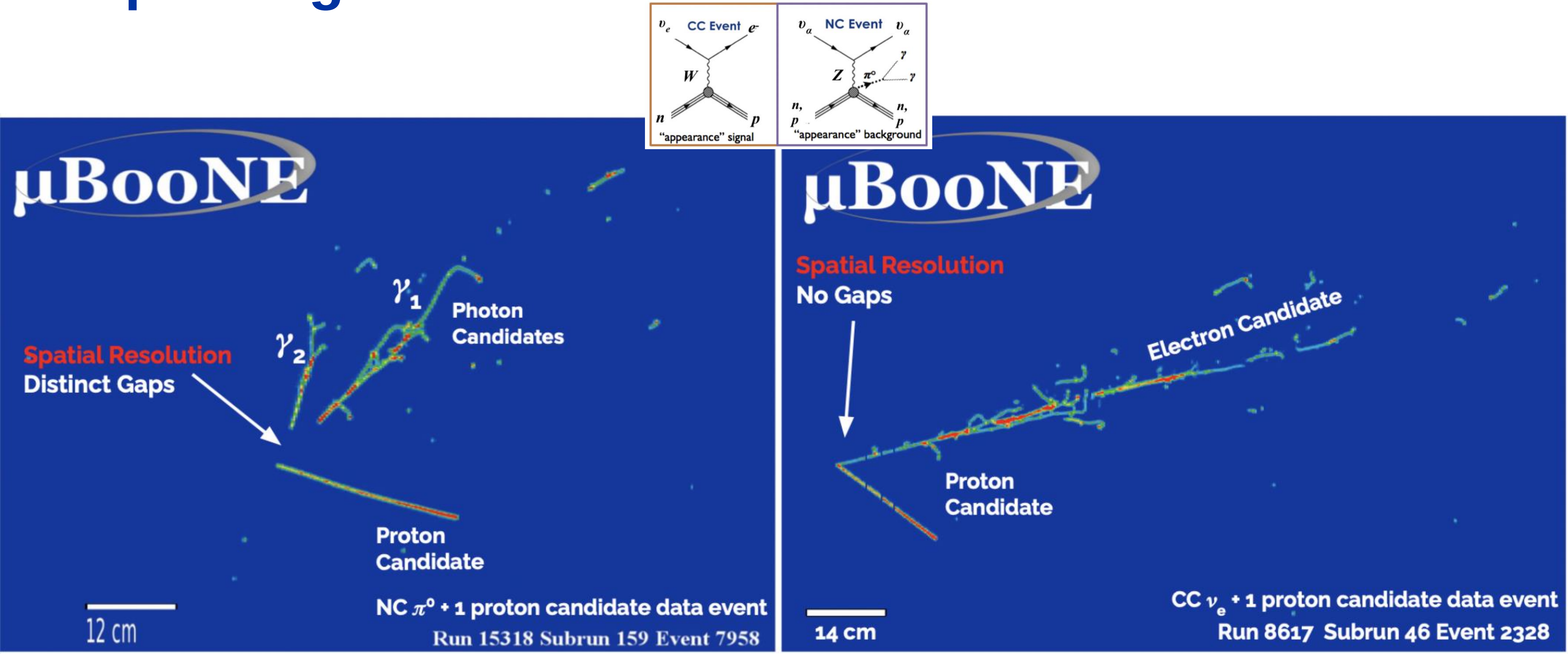
Scintillating light readout

- Neutrino interactions produced charged particles that cause Argon to scintillate
- Argon emits light at 128 nm in the VUV range → wavelength shifting mechanism needed to make it visible, then photodetector readout

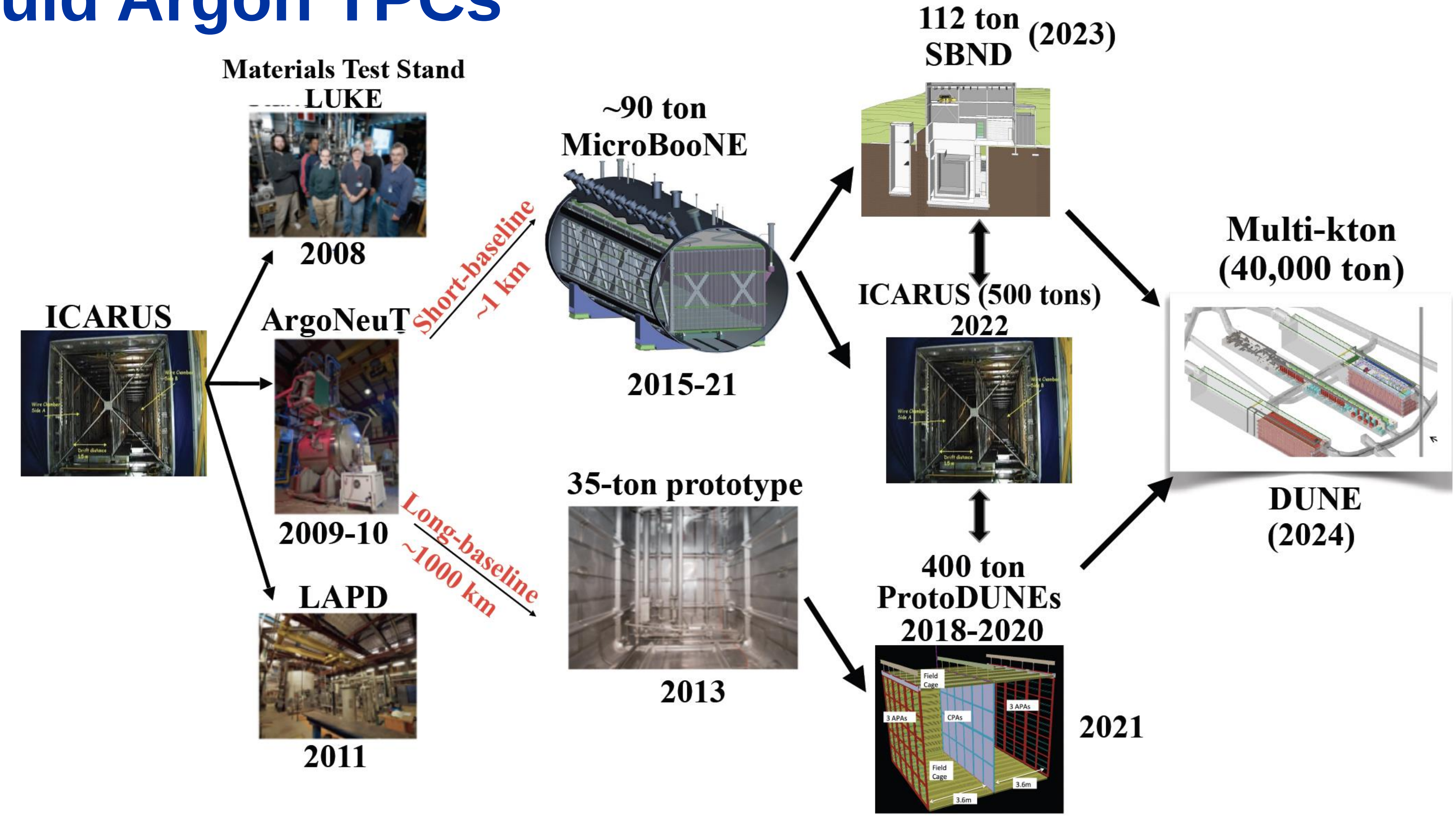




Liquid Argon TPCs



Liquid Argon TPCs



Oscillation Experiments – Principle

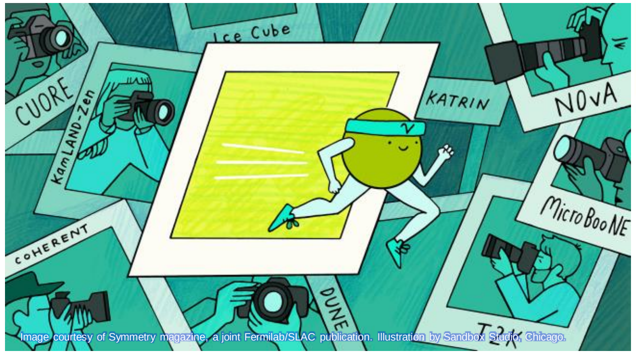
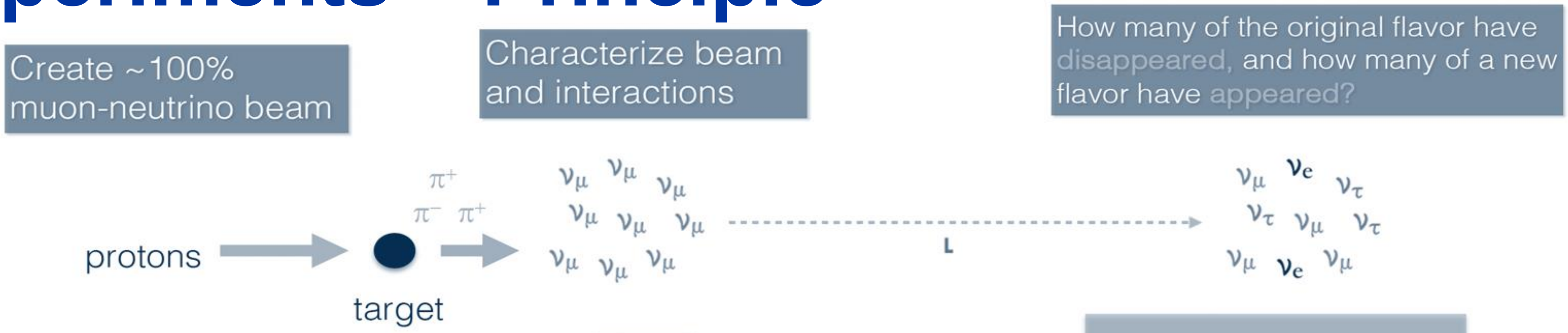
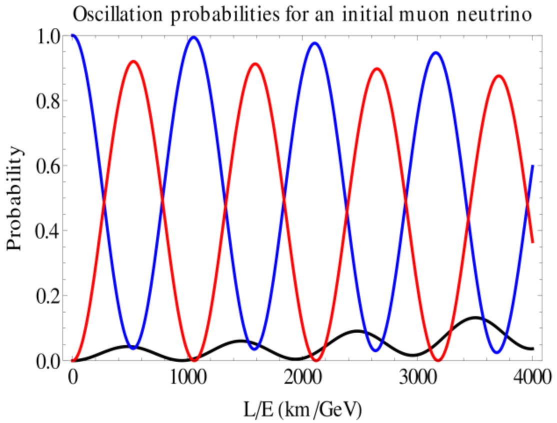


Image courtesy of Symmetry magazine, a joint Fermilab/SLAC publication. Illustration by Sandbox Studio, Chicago.



How do I design a neutrino oscillation experiment?

- First question: what is my neutrino source?
  - Solar, reactor and atmospheric neutrinos have been key to establishing SM of neutrinos, but no control of source (even on/off is difficult with commercially run reactors)
  - Beam neutrino oscillations experiments give control, but need intense beams (hundreds of kW) and long baselines (hundreds of km)
- Second question: Where do I put my detector(s)?
  - Basic idea for beam-based searches: Sample the not yet oscillated beam near the source and the oscillated beam far away from the source
  - Oscillations observed through either appearance or disappearance of neutrino species



Oscillation Experiments – Matter Effects

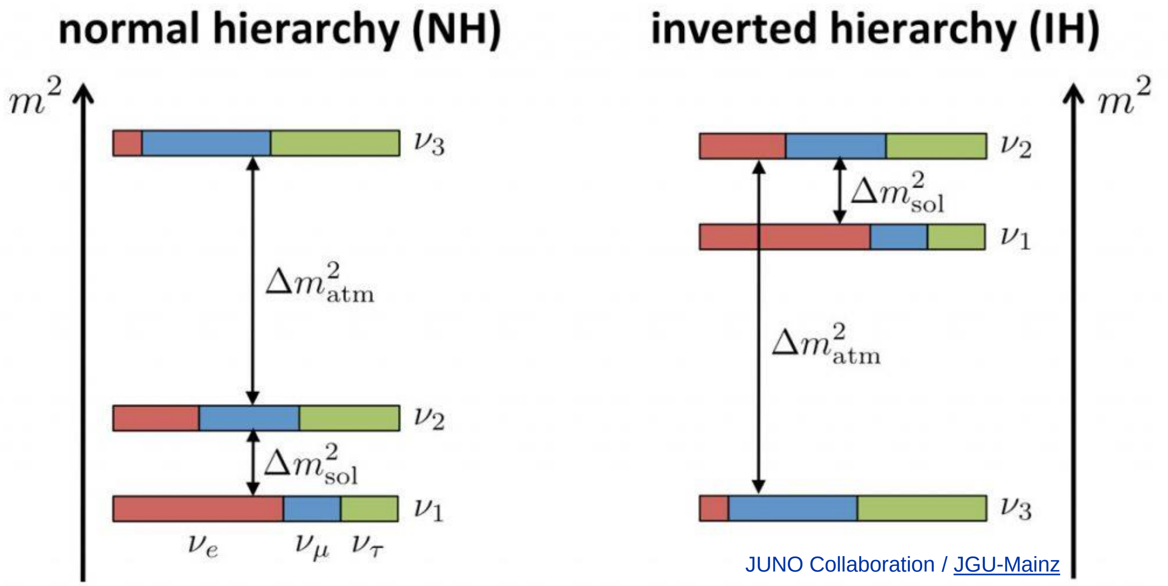
- With long baselines, neutrinos travel typically though the Earth due to its curvature → need to take into account modifications due to Mikheyev-Smirnov-Wolfenstein (MSW) effect
- When neutrinos travel through a medium, they interact weakly with electrons in matter → process is coherent when neutrinos scatter off electrons without absorbing or emitting any particles
- Affects all neutrino types, but with a stronger impact on electron neutrinos due to charged current interactions
- Modified probabilities make life complicated, but yield a nice surprise → **sensitivity to mass differences**

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha\tilde{J}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$
$$\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$
$$\Delta = \Delta m^2_{31}L_\nu/4E_\nu$$
$$A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{13}$$

- As we don't know the absolute mass of neutrinos, we have now at least access to their relative differences Δm_{32} and Δm_{21}

Neutrino Mass Ordering



JUNO Collaboration / JGU-Mainz

Image courtesy of Symmetry magazine, a joint Fermilab/SLAC publication. Illustration by Sandbox Studio, Chicago.

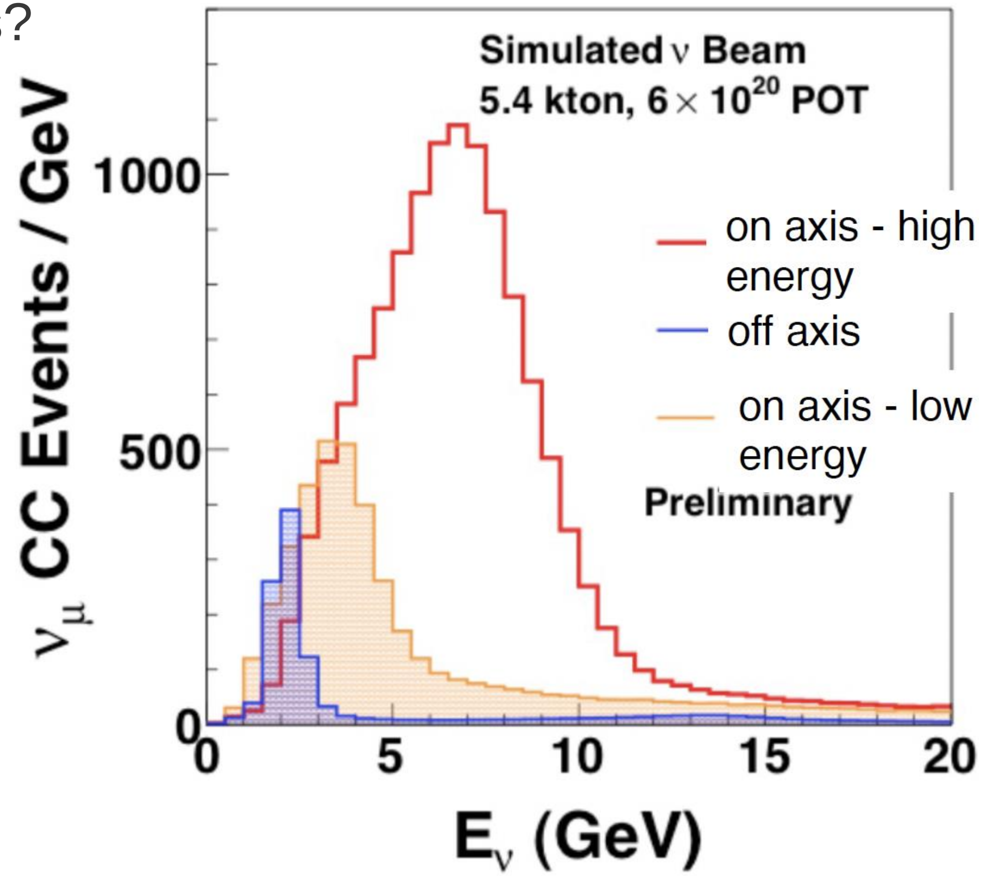
- Neutrino oscillations in vacuum only determine $|\Delta m^2_{ji}| = |m_j^2 - m_i^2|$
- Two distinct and very different mass scales
  - Atmospheric neutrino oscillations $|\Delta m^2|_{\mathrm{atmos}} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$
  - Solar neutrino oscillations $|\Delta m^2|_{\mathrm{solar}} \sim 8 \times 10^{-5}\,\mathrm{eV}^2$
- Currently, there are two possible mass orderings, the normal hierarchy and the inverted hierarchy
- Matter effects helps understanding which one is real

Oscillation Experiments – Choices I

Third question: Do I want to place the detector on- or off-axis?

- Rule of thumb: on-axis $E_\nu = 0.43 E_\pi$

  off-axis $E_\nu/\mathrm{GeV} = \dfrac{0.03}{\theta}$
- Older detectors have a relatively poor energy resolution
- Production yield of hadrons in the GeV region is surprisingly not precisely known → hadron flux and thus, neutrino flux precision suffers (bad for both appearance and disappearance experiments)
- Off-axis has been favoured by many experiments, but there were also experiments that measured on/off-axis with the same detector



- Nowadays prominent proposals for on-axis measurments, e.g., DUNE with better energy resolution
- Lots of investments in service measurements to understand better production of hadrons at GeV scale (e.g. NA61 at CERN)

Oscillation Experiments – Choices II

Fourth question: Do I want to suppress or enhance matter effects?

1. Supress: keep L small (order 200 km)
   - Need high flux at the first oscillation maximum: $\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2}$ with $E_\nu < 1\,\mathrm{GeV}$
   - Off-axis beam: narrow range of neutrino energies

T2K Hyper-Kamiokande

295 km

2. Enhance: make L large (>1000 km) and measure matter effects
   - First oscillation maximum: $\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2}$ with $E_\nu > 2\,\mathrm{GeV}$
   - On-axis beam: wide range of neutrino energies

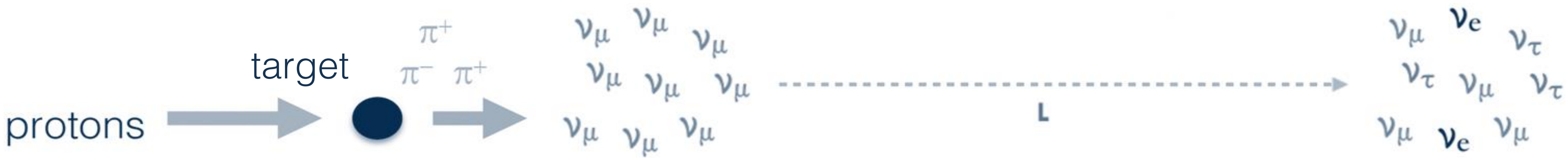
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

1300 km

Oscillation Experiments – Beam Requirements

Appearance vs. disappearance

- Typical experiments search for disappearance of neutrino species, hence need well defined muon species to start from
- Similar to atmospheric neutrinos, accelerator neutrinos are produced conventionally by a high energy proton drive beam that interacts with a target and produces mainly low energy pions, which then decay into (anti-)muons and (anti-)muon neutrinos



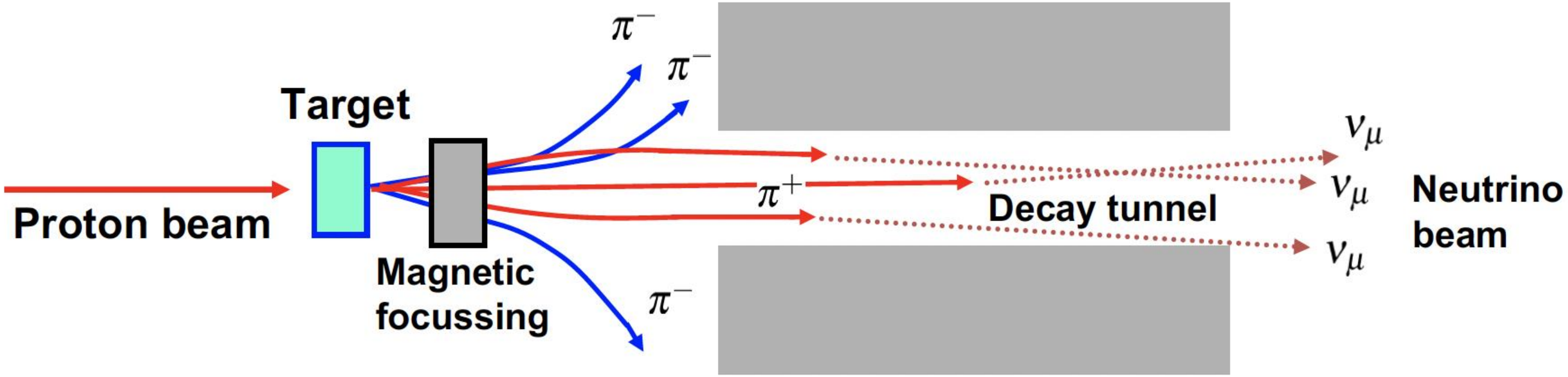
Threshold considerations for beam energy

- For charged current interactions with atomic electrons
  $E_{\nu_e} > 0$ $E_{\nu_\mu} > 11\,\mathrm{GeV}$ $E_{\nu_\tau} > 3090\,\mathrm{GeV}$
- For charged current interactions with nucleons
  $E_{\nu_e} > 0$ $E_{\nu_\mu} > 110\,\mathrm{MeV}$ $E_{\nu_\tau} > 3.5\,\mathrm{GeV}$
- Defines typical beam energies around $0.5\,\mathrm{GeV}$ if one wants to observe muons in final state

Neutrino Beams

Beam Design Principle

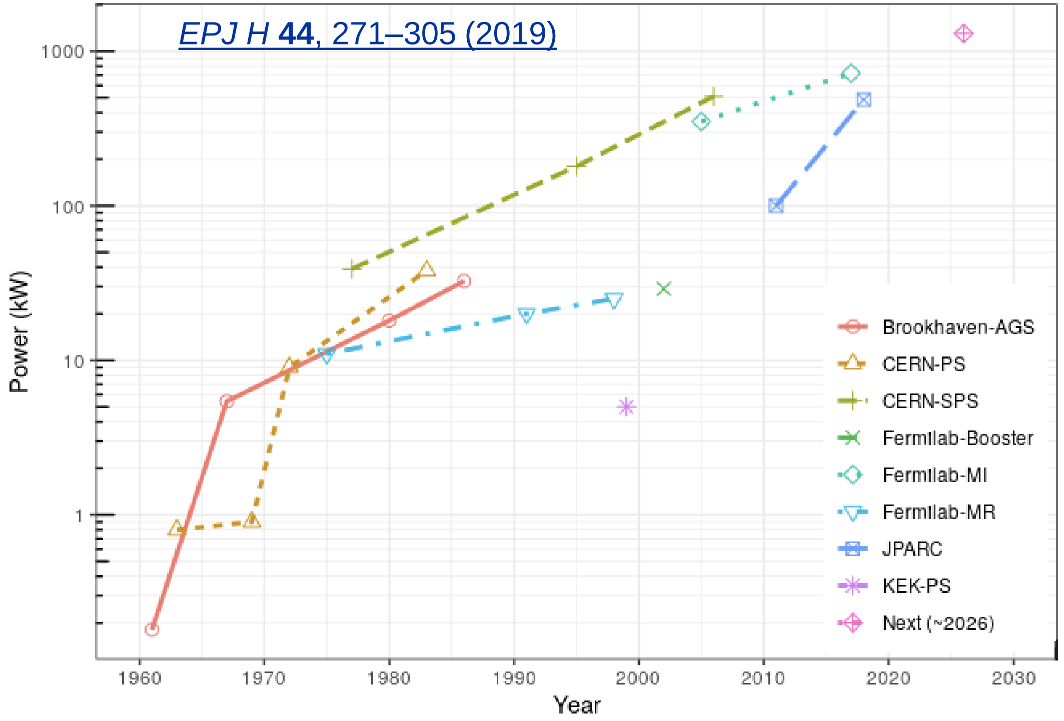
- Use high energy high intensity proton beam to hit a solid target → Need of high power targetry
- Focus beam in forward direction (mostly point to parallel) → Need of magnetic horns
- Let produced pions decay → Need of decay region
- Detect hadrons and decay muons (measure of systematics) → Need of hadron / muon detectors
- Neutrino energy spectrum determined by decay kinematics and beam optics
- Impurities through production and decay of muons themselves and other hadrons, which is mostly kaon decay channels with electron neutrinos in the final state



Proton Drivers

Main points for modern proton drivers

- High beam intensity for more neutrino interactions
- High beam energy (see energy threshold)
- Energy-efficient acceleration technologies
- Adjustable energy ranges for diverse experiments
- Upgradeable power capacity for future research



Proton Source	Experiment	Proton Energy (GeV)	Protons per year (p/yr)	Power (MW)	Neutrino Energy (GeV)
KEK	K2K	12	1×10^{20} / 4	0.0052	1 - 1.4
FNAL Booster	MiniBooNE	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS and NOvA	120	2.5×10^{20}	0.7	2 - 17
CERN SPS/CNGS	OPERA	400	0.45×10^{20}	0.12	17 - 25
J-PARC	T2K	40-50	1.1×10^{21}	0.75	0.77
FNAL Main Injector Upgrade PIP-II	DUNE	60 - 120	1.1×10^{21} - 1.6×10^{21}	1.2 (planned upgrade to 2.4)	Main: 2.5GeV (range: few hundred MeV to a few GeV)

Non-exhaustive overview on proton drivers with experiments

Proton Drivers

Main points for modern proton drivers

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- High beam energy (see energy threshold)
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- Adjustable energy ranges for diverse experiments
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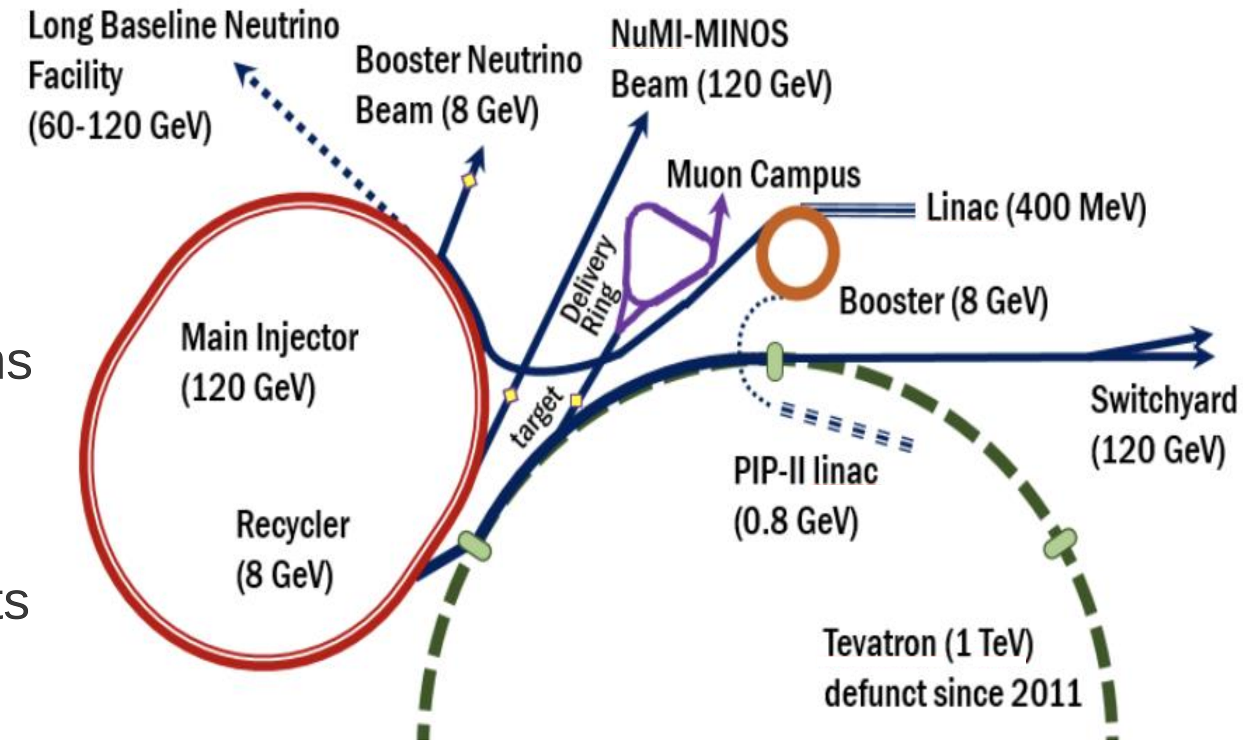

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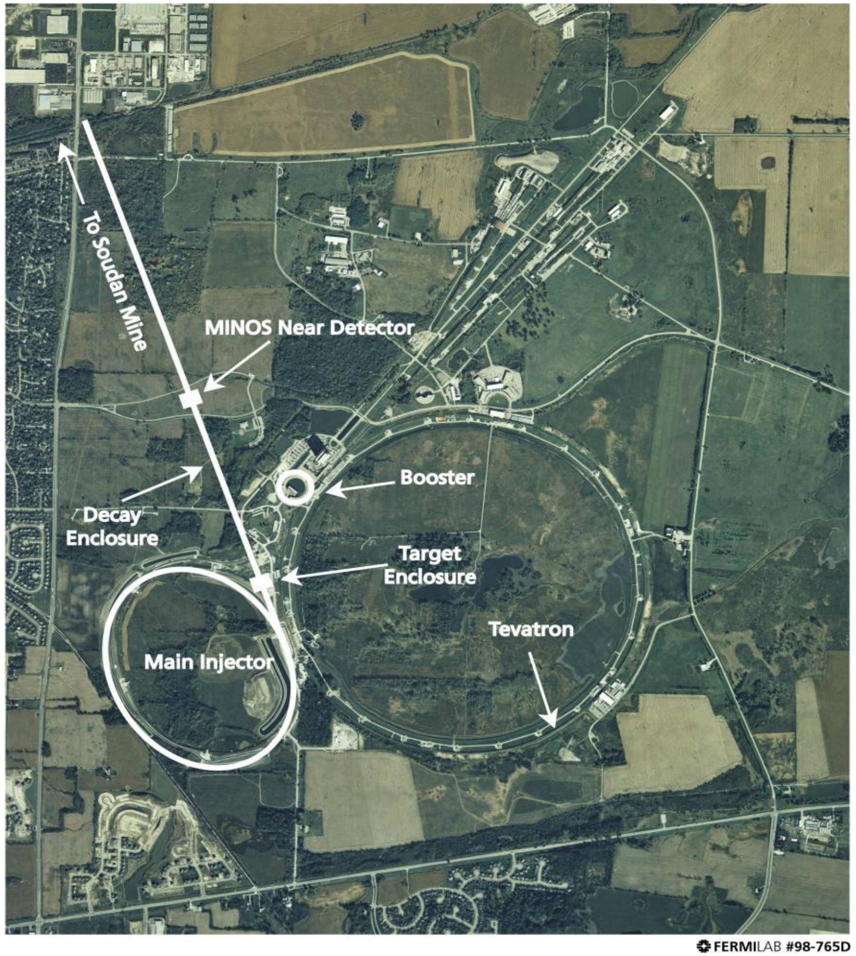
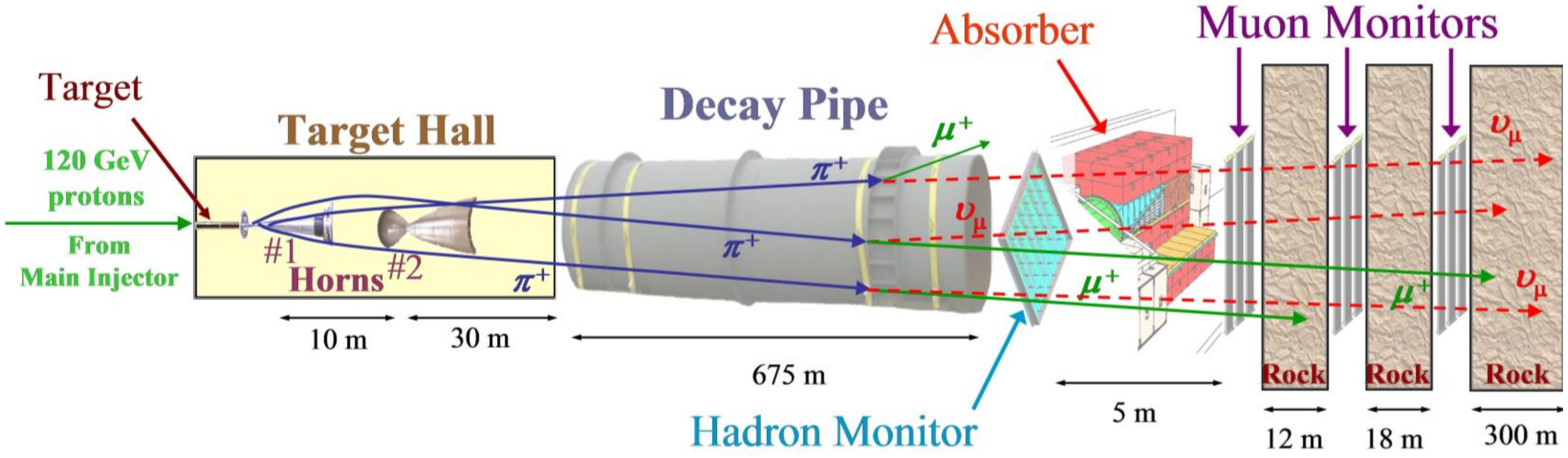
Non-exhaustive overview on proton drivers with experiments

NuMI Beam Design



- 120 GeV proton beam from FNAL Main Injector
- 8.7 µs pulse every 2 s
- Beam power 700 kW



- Main components: target, magnetic horn, decay pipe, hadron monitor, absorber, muon monitors

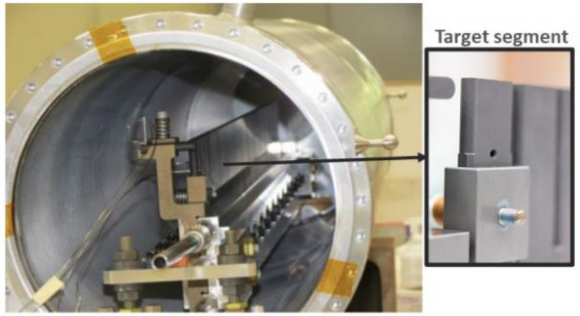
Targets

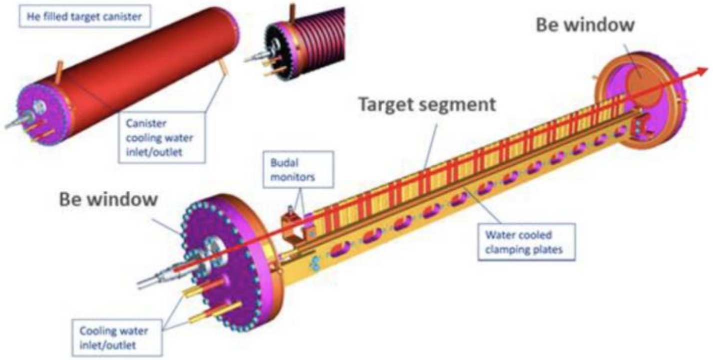
Main Considerations

- Use a long target to optimise hadron yield
- Use not too long target to minimise multiple scattering

} Best compromise typically long target with low-Z material, e.g., Be, C

- Make sure target can withstand pulsed MW beams inducing high-stresses and high temperatures

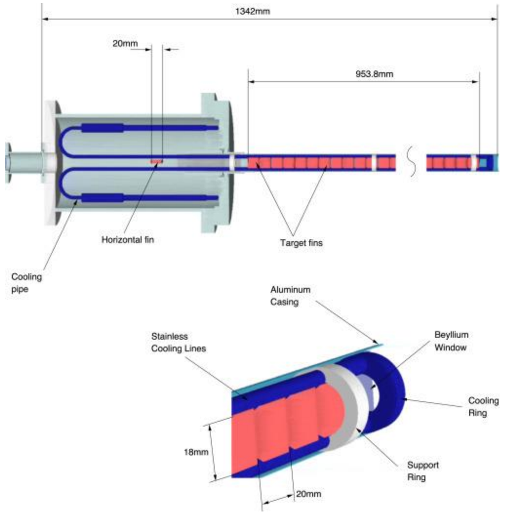


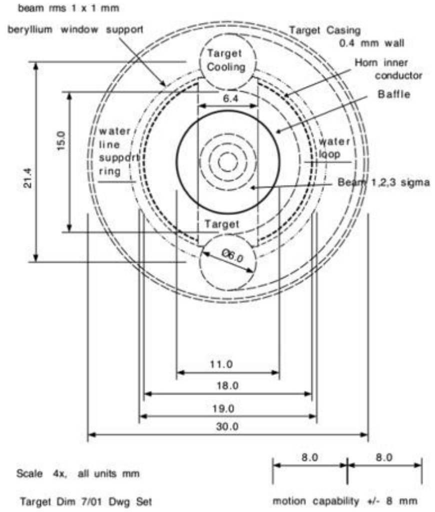


	NOvA	AIP
Graphite fins	50 x 24 mm x 7.4 mm	50 x 24 mm x 9 mm
Beam energy [GeV]	120	120
p/pulse	4.90E+13	6.50E+13
Power [kW]	700	1000
σ [mm]	1.3	1.5
Peak Temp. [°C]	670	1000
QS Temp [°C]	390	890
POT	1.10E+21	1.28E+21
Peak dpa	1.10	0.96
Peak He [appm]	5580	3600

- Helium atmosphere
- Beryllium windows
- Water cooled aluminum pressing plates
- Graphite core

Frederique Pellemoine





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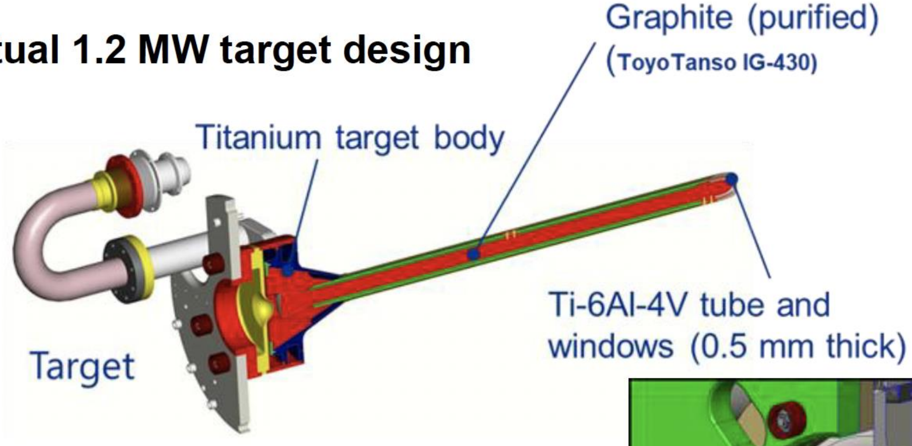
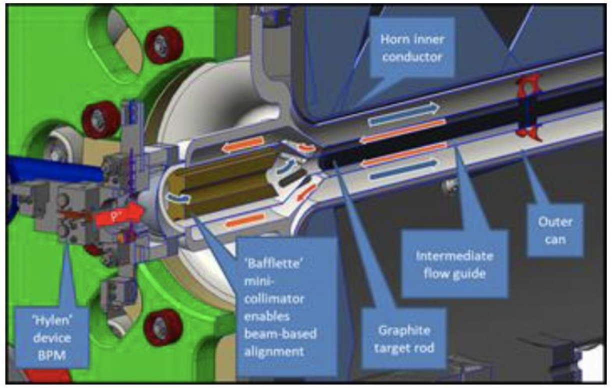
- Make sure target can withstand pulsed MW beams inducing high-stresses and high temperatures

Conceptual 1.2 MW target design



- Helium atmosphere
- Titanium target containment windows
- Helium gas cooled graphite core

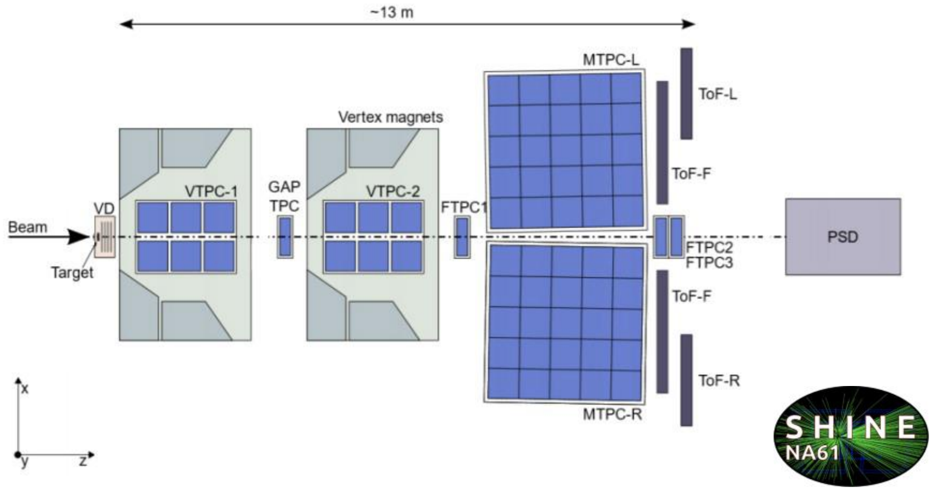


	DUNE
Graphite fins	TBD
Beam energy [GeV]	60-120
p/pulse	7.50E+13
Power [kW]	1200-2400
σ [mm]	2.67
Peak Temp. [°C]	TBD
QS Temp [°C]	TBD
POT	2.54E+21
Peak dpa	0.73
Peak He [appm]	400

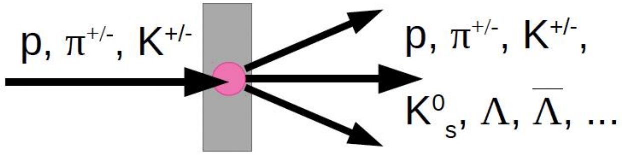
Frederique Pellemoine

Replica Targets

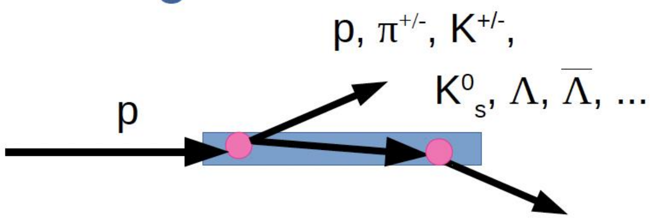
- Hadron production occurs in both target and magnetic horn
- Important to measure the hadron yield with a replica target in a test beam, e.g., NA61 / CERN with 120 GeV/c protons
- Fed into simulation codes → important benchmarking



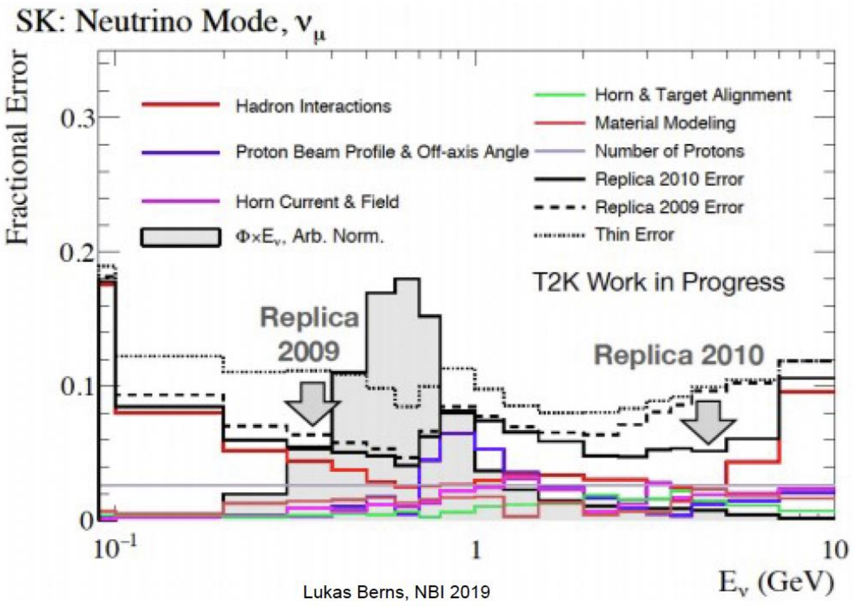
Thin-Target Measurements

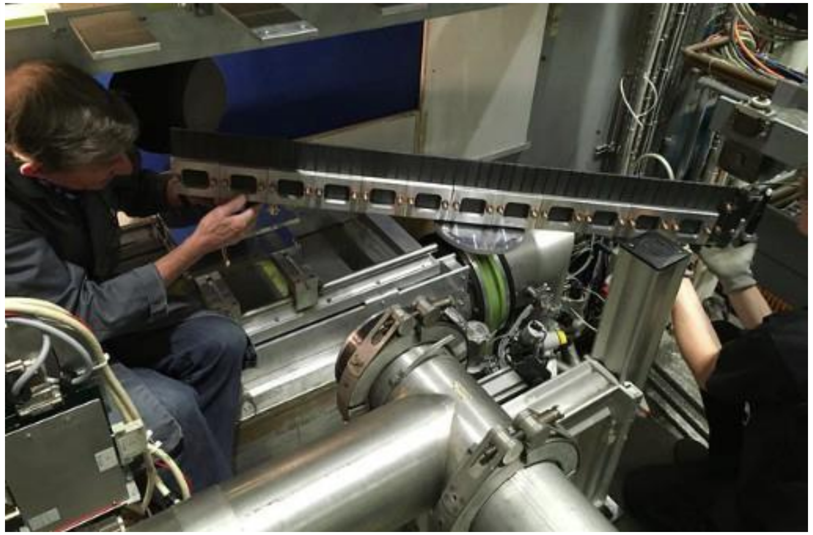


Replica-Target Measurements



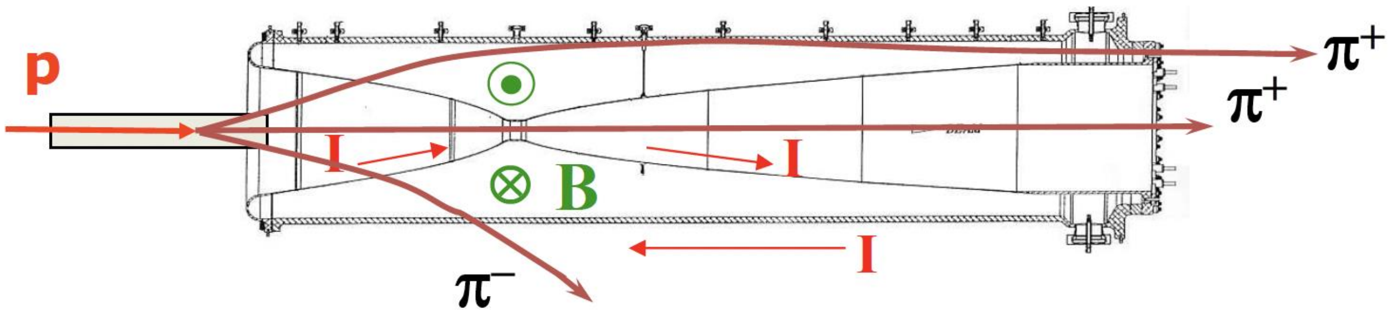
Brant Rumberger, ICHEP 2020





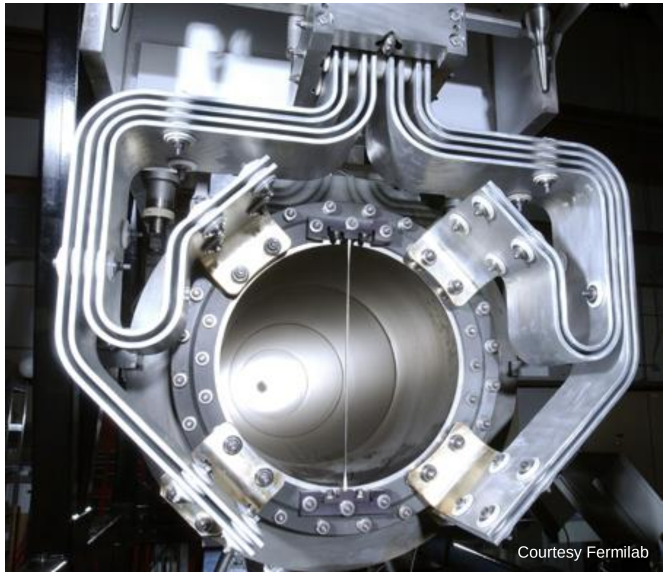
Magnetic Horns

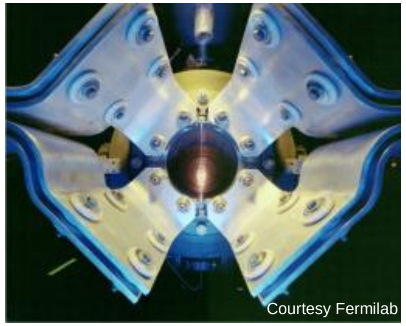
- Pions produced from the target come with finite transverse momentum, so they need to be focused in the beam direction
- In 1961, Simon van der Meer proposed to use parabolic magnetic horns to focus in both planes

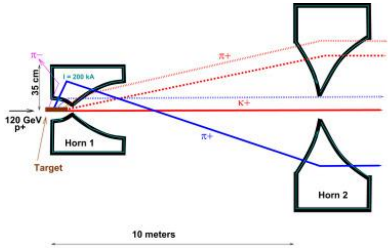


- Magnetic horns have an azimuthal magnetic field between inner and outer conductors
- The field strength needs to be very high to achieve the intended effect, e.g. at NuMI about 3T
  → need very high current (200 kA) and need to be pulsed (order of ms)

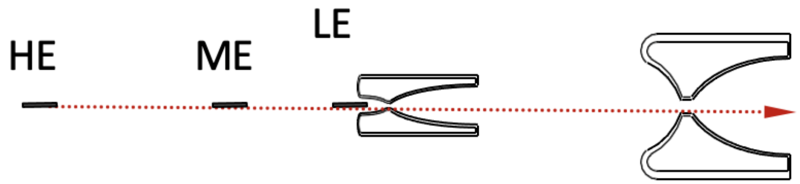

Courtesy CERN

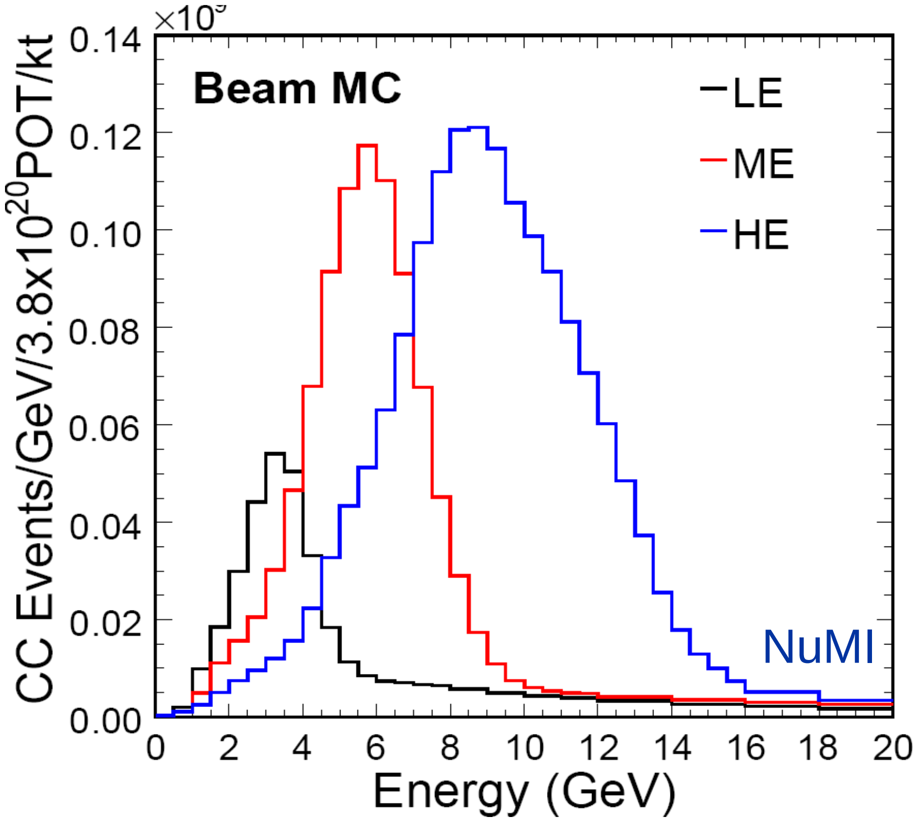

Courtesy Fermilab


Courtesy Fermilab

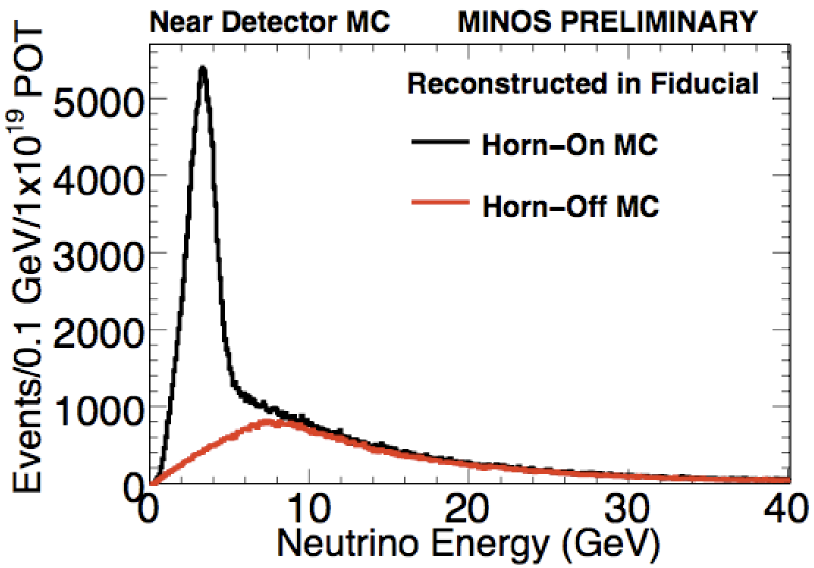


Magnetic Horns





- Often more than one horn is used
- Changing the target position in a two-horn set-up changes the energy spectrum → effectively this is a change of optics
- Horn has very high efficiency but only in limited energy range → there is always a high-energy tail



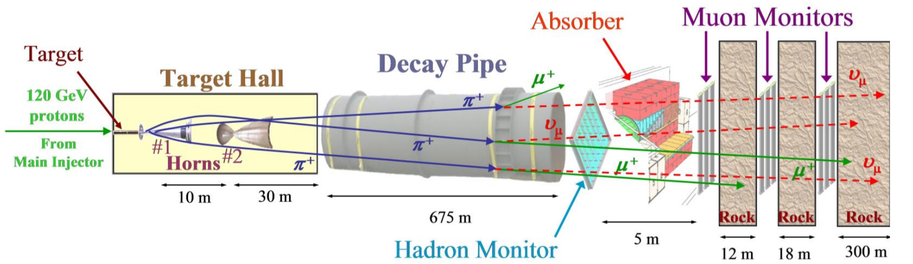
Decay Region

- Length and width of decay region given by secondary (pion) beam characteristics
- For length, need to find optimum between maximising pion decays while keeping muon decays under control, otherwise ν_e contamination
- For width, dominated by energy and focusing but also by choice on-axis vs. off-axis experiment
- Choice also needs to take into account
  - Multiple scattering $\vartheta_{rms} = \frac{0.1}{\gamma}\sqrt{\frac{x}{X_0}}$
  - Neutrino Beam divergence $\theta = \frac{0.07}{\gamma}$

- In general, trade-off needed between
  - Air, no beam windows
  - Helium, thin beam windows
  - Vacuum, thick vacuum windows

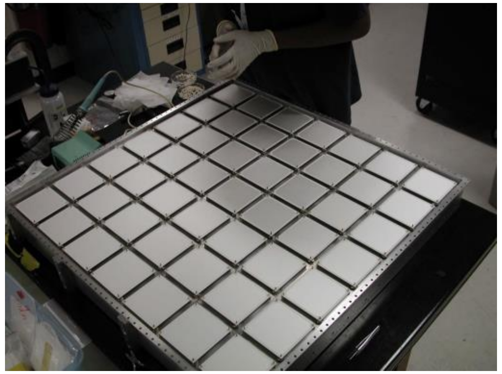
	Length (m)	Width (m)	Energy (GeV)	Filled with
MiniBoone	50	1.8	2.5	air
K2K	200	Up to 3	3.5	He
MINOS	675	2	9	vacuum
CNGS	1000	2.45	50	vacuum
T2K	130	Up to 5.4	9	He

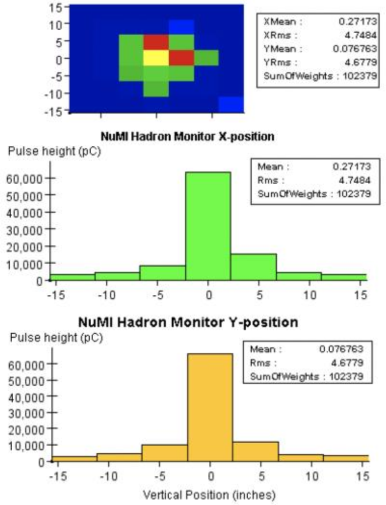
The End (of the NuMI Beam Line)



Hadron monitor

- Measure primary and secondary beam
- Used also for beam alignment
- Must withstand high flux, typically ionisation chamber(s)
- NuMI: Max flux $10^9/cm^2/spill$



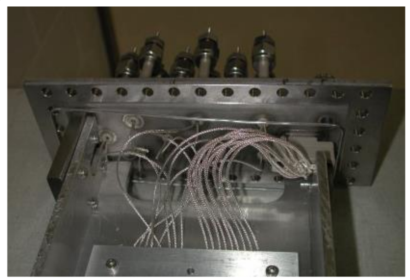


Hadron absorber

- Beam dump for non-interacting protons
- With high power beams normally actively cooled
- NuMI: Al core and Fe housing

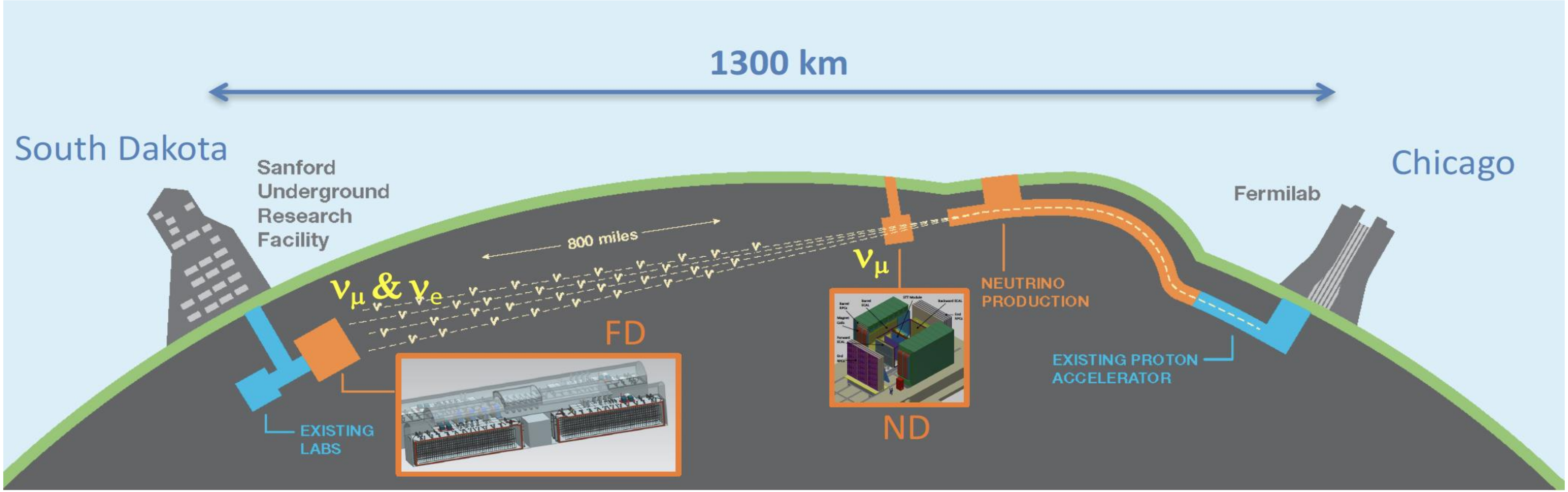
Muon monitors

- Several detectors with interleaved absorber material (rock) to sample muon spectra
- Typically used to tune beam (e.g. magnetic horn) and as stability checks
- NuMI: Max flux 4 10^7 $/cm^2/spill$



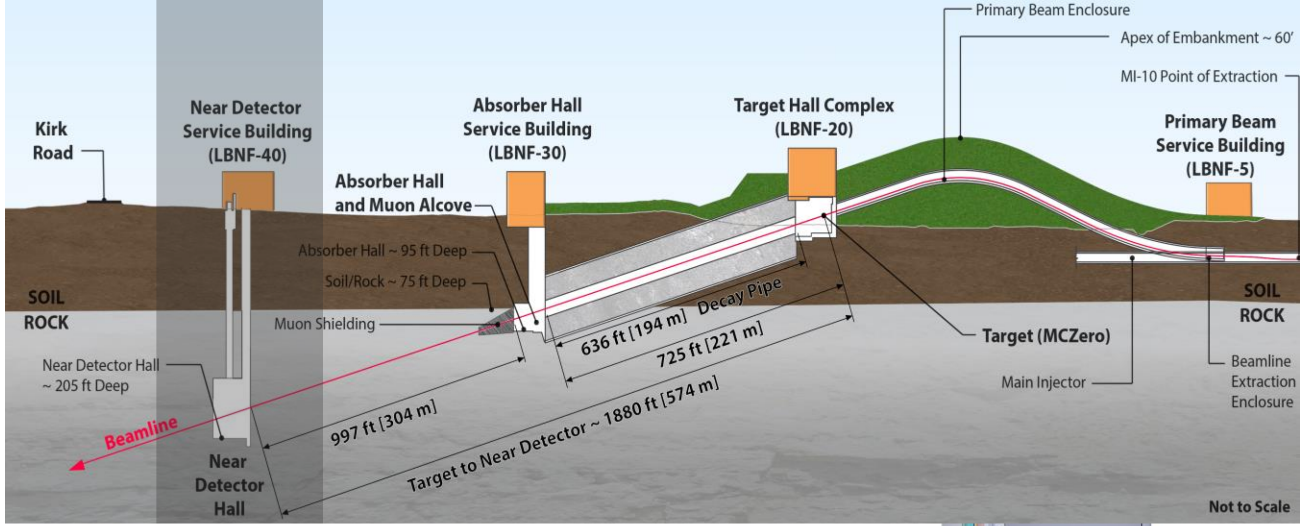
Example: LBNF / DUNE

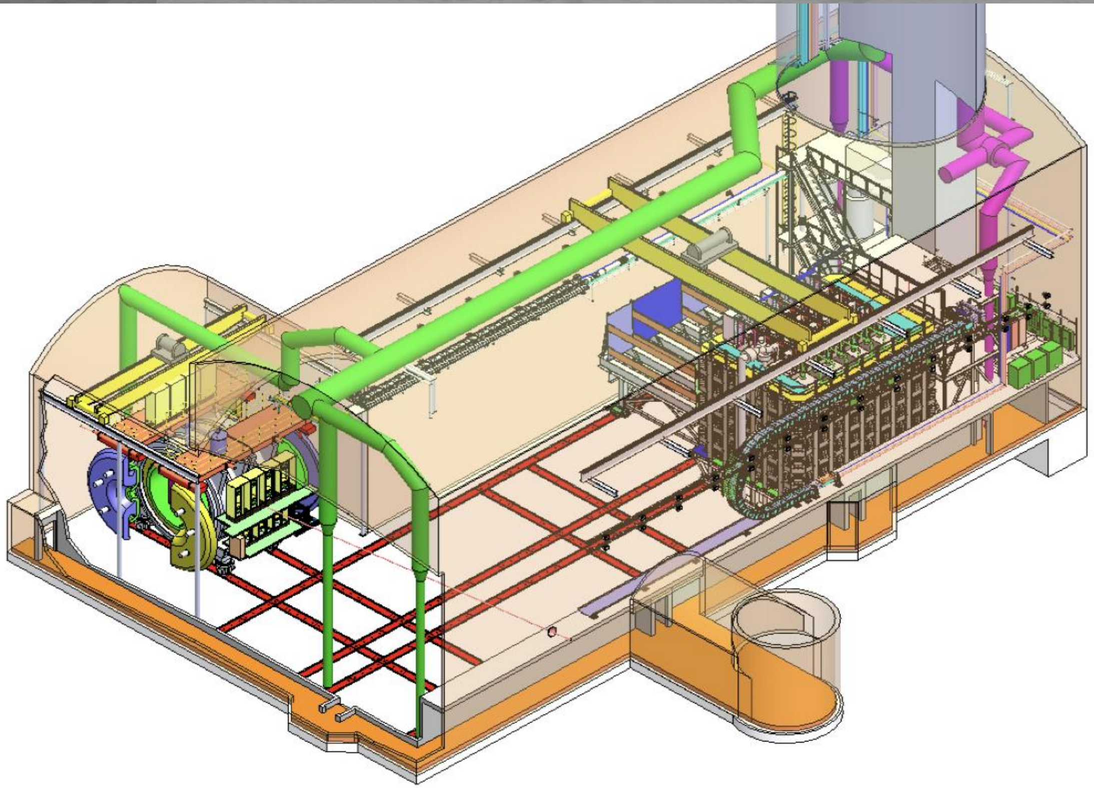
- Muon neutrinos/antineutrinos from high-power proton beam: PIP-II upgrade for FNAL accelerator complex to deliver 1.2 MW proton beams at 60 to 120 GeV/c
- New set of underground caverns at SURF to host LArTPCs with 4 x 17 kt fiducial mass
- Near detector for beam characterisation



DUNE Near Detector

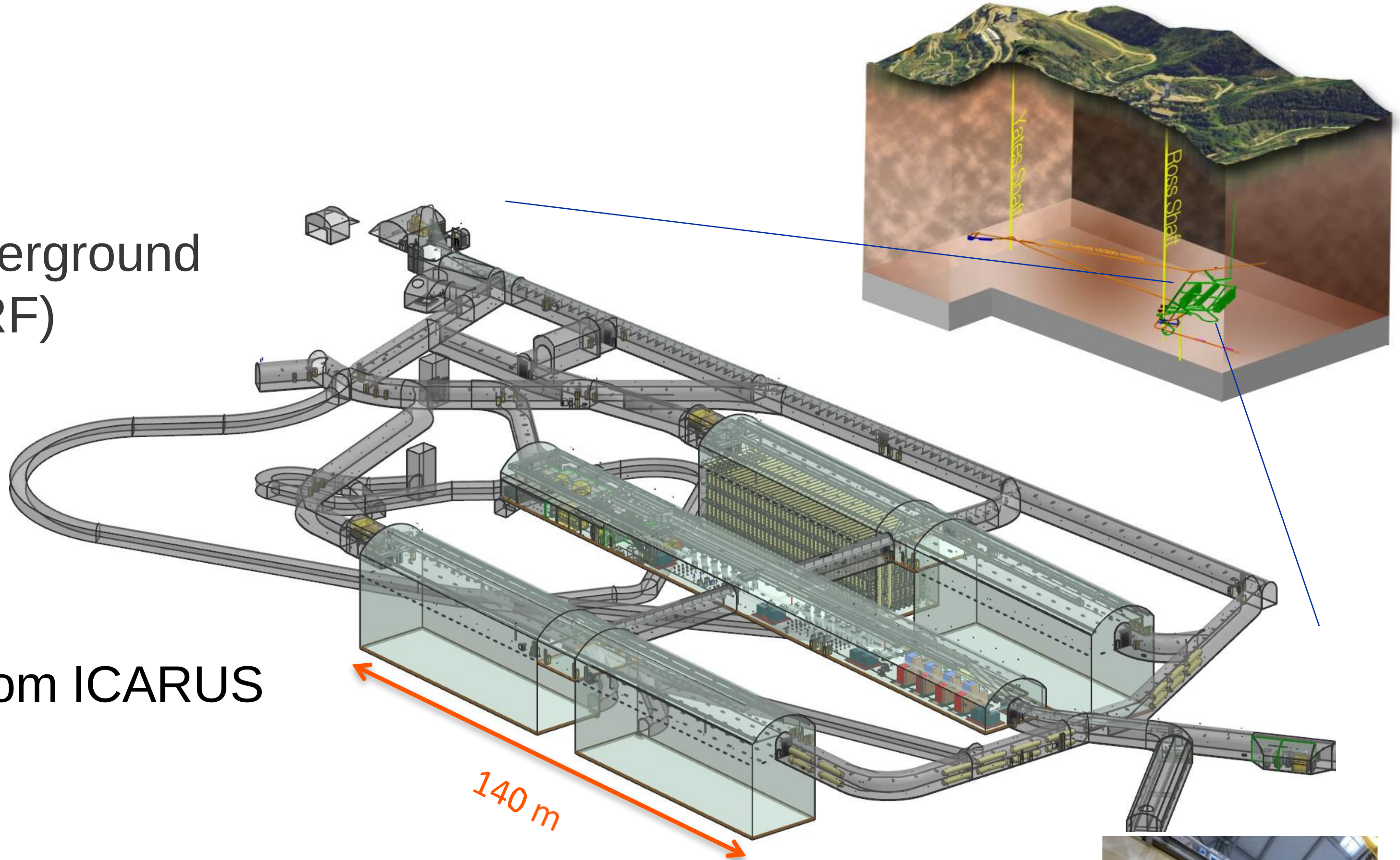
- Main motivation is to **control systematic errors** in the long baseline analysis
- Concept: moveable LArTPC system
  - *ND-LAr*: 7x5 array of modular 1x1x3 m^3 LArTPCs with pixel readout
  - *TMS*: magnetized range stack to measure μ momentum/sign from ν_μ CC interactions in *ND-LAr*
  - *DUNE-PRISM*: *ND-LAr* + *TMS* move up to 28.5 m off-axis
- *SAND*: Multi-purpose, on-axis, magnetized detector
  - *KLOE* superconducting solenoid and calorimeter
  - *GRAIN*: Optical LAr target

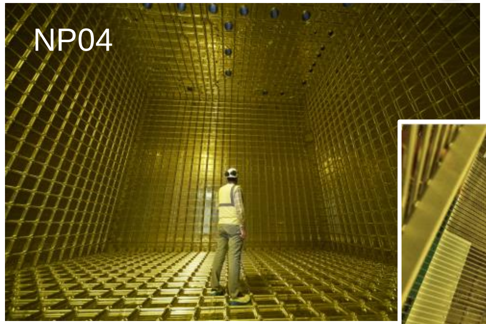




DUNE Far Detector

- Far detector will be built at Sanford Underground Research Facility in South Dakota (SURF)
- **Space for four 17 kt detectors**
- Technology for LArTPCs being investigated, main proponents
- Single Phase
  - Known technology with experience from ICARUS
  - Being tested at CERN / NP04
- Dual Phase
  - New technology with amplification in a gas layer on top of LAr, basically given up
- Vertical Drift (single phase, but rotated readout)
  - Latest technology
  - Will be tested at CERN / NP02





Overview of Neutrino Beams

PDG Neutrino Beamlines at High-Energy Proton Synchrotrons

	PS (CERN)				SPS (CERN)			PS (KEK)	Main Ring (JPARC)	
Date	1963	1969	1972	1983	1977	1995	2006	1999	2023	(2028)
Proton Kinetic Energy (GeV)	20.6	20.6	26	19	350	450	400	12	30	(30)
Protons per Cycle (10^{12})	0.7	0.6	5	5	10	36	48	6	153	(330)
Cycle Time (s)	3	2.3	-	-	-	14.4	6	2.2	1.36	(1.16)
Beam Power (kW)	0.8	0.9	-	-	-	180	510	5	540	(1300)
Target	-	-	-	-	-	Be	Graphite	Al	Graphite	(Graphite)
Target Length (cm)	-	-	-	-	-	290	130	66	91	(91)
Secondary Focussing	1-horn WBB	3-horn WBB	2-horn WBB	bare target	2-horn WBB	2-horn WBB	2-horn WBB	2-horn WBB	3-horn off-axis	(3-horn off-axis)
Decay Pipe Length (m)	-	-	-	-	-	110	1090	200	96	(96)
$\langle E_\nu \rangle$ (GeV)	1.5	1.5	1.5	1	20	24.3	17	1.3	0.6	(0.6)
Experiments	HLBC, Spark Ch.	HLBC, Spark Ch.	GGM, Aachen-Padova	CDHS, CHARM	GGM,CDHS, CHARM, BEBC	NOMAD, CHORUS	OPERA, ICARUS	K2K	T2K	Hyper-K

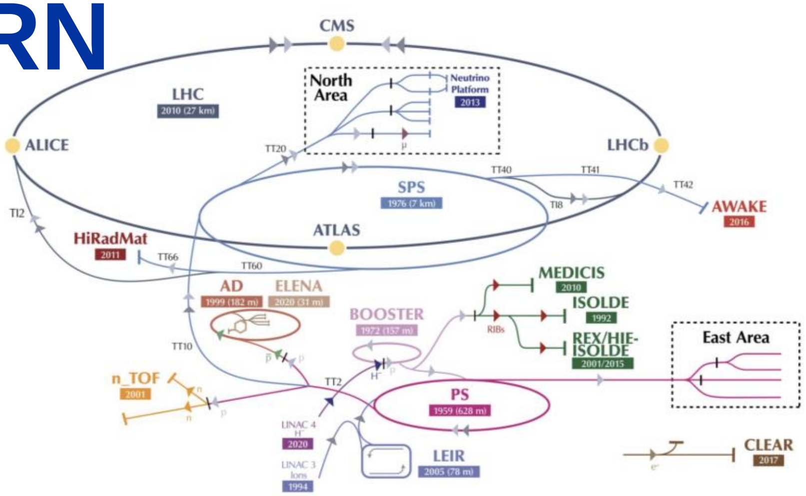
Overview of Neutrino Beams

PDG Neutrino Beamlines at High-Energy Proton Synchrotrons

	Main Ring (Fermilab)					Booster (Fermilab)	Main Injector (Fermilab)			
Date	1974	1979	1976	1991	1998	2002, (2022)	2005	2017	2021	(2031)
Proton Kinetic Energy (GeV)	300	400	350	800	800	8	120	120	120	(60 – 120)
Protons per Cycle (10^{12})	10	10	13	10	12	4.5	37	54	55 (65)	(75)
Cycle Time (s)	-	-	-	60	60	0.2	2	1.333	1.2	(1.2)
Beam Power (kW)	-	-	-	20	25	29	350	720	840 (1000)	(1200)
Target	-	-	-	-	BeO	Be	Graphite	Graphite	Graphite	(Graphite)
Target Length (cm)	-	-	-	-	31	71	95	120	120	(150-180)
Secondary Focussing	dichromatic NBB	2-horn WBB	1-horn WBB	quad trip.	SSQT WBB	1-horn WBB	2-horn WBB	2-horn off-axis	2-horn off-axis	(3-horn WBB)
Decay Pipe Length (m)	400	400	400	400	400	50	675	675	675	(220)
$\langle E_\nu \rangle$ (GeV)	50,180†	25	100	90,260	70,180	1	3-20‡	2	2	(2.5)
Experiments	CITF, HPWF, 15' BC	15' BC	HPWF 15' BC	15' BC, CCFRR	NuTeV	MiniBooNE, SciBooNE, MicroBooNE, (SBND,ICARUS)	MINOS, MINERνA	NOνA, MINERνA, MINOS+	NOνA	DUNE

Excursus: Secondary Beams at CERN

- CERN houses two main facilities for secondary beams and fixed-target experiments, see F. Metzger’s talk!
  - **North Area**, one of the most diverse experimental facilities, serving proton, hadron, electron, muon, and ion beams to yearly over 200 user teams for detector R&D and to the NA61, NA62, NA64, and NA66/AMBER experiments, the **two large neutrino platform cryostats**, and to the GIF++ and CERF irradiation facilities, with combined more than 2000 users
  - The renovated **East Area** serves the CLOUD experiment, both IRRAD and CHARM irradiation facilities, and soon even a **water Cherenkov test detector (WCTE)**



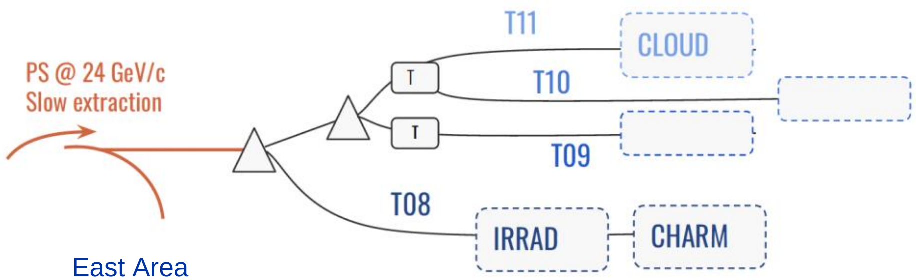
Significant consolidation efforts:

East Area Renovation

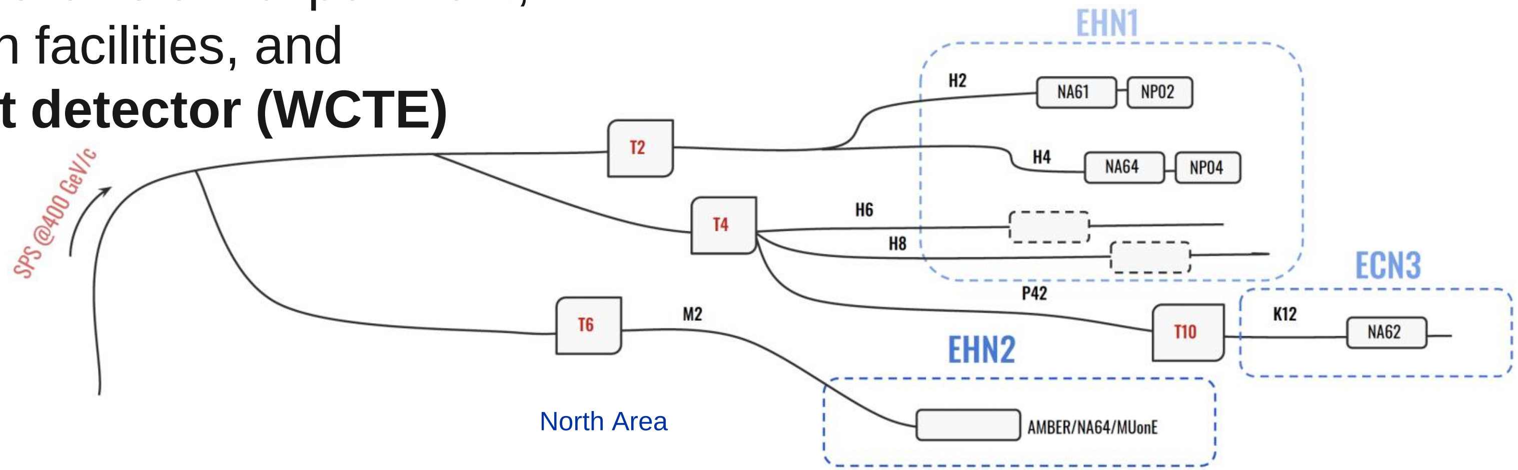
2018 - 2021

NA cons

2021 - 2032



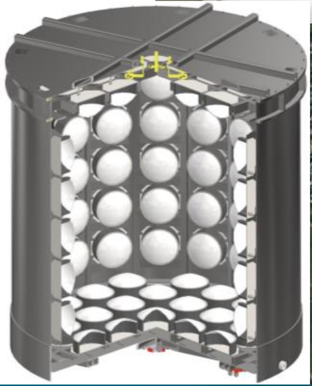
East Area

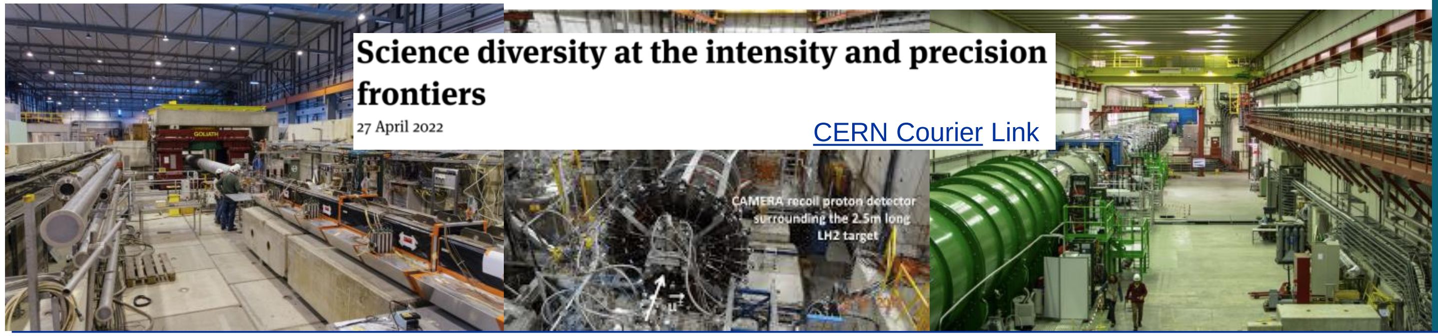


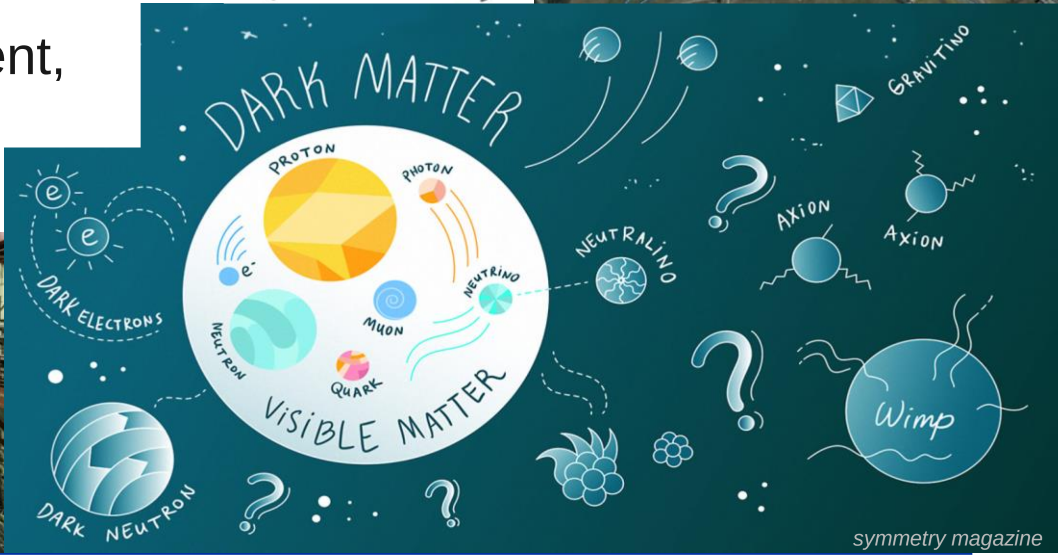
North Area

Excursus: Secondary Beams at CERN

- CERN houses two main facilities for secondary beams and fixed-target experiments, see F. Metzger's talk!
  - **North Area**, one of the most diverse experimental facilities, serving proton, hadron, electron, muon, and ion beams to yearly over 200 user teams for detector R&D and to the NA61, NA62, NA64, and NA66/AMBER experiments, the **two large neutrino platform cryostats**, and to the GIF++ and CERF irradiation facilities, with combined more than 2000 users
  - The renovated **East Area** serves the CLOUD experiment, both IRRAD and CHARM irradiation facilities, and soon even a **water Cherenkov test detector (WCTE)**

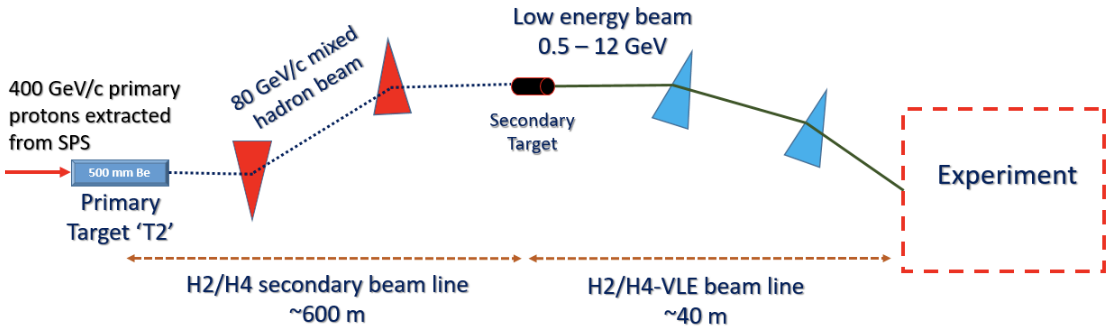






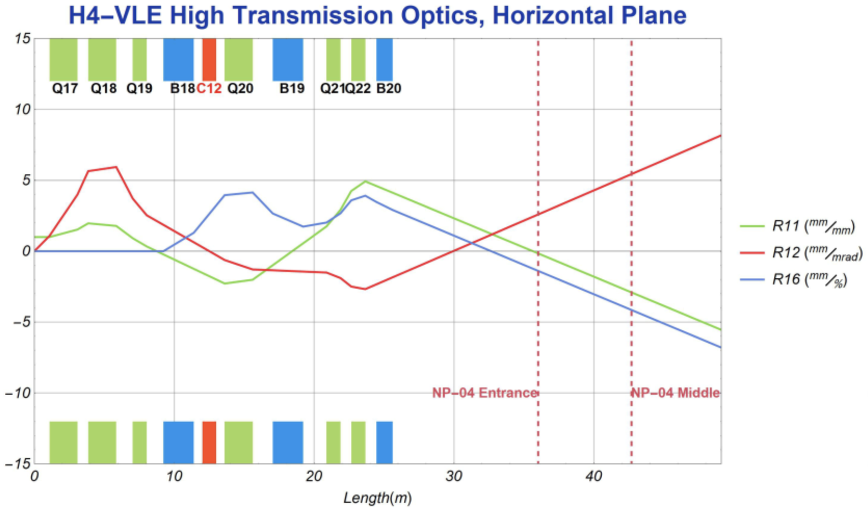
symmetry magazine

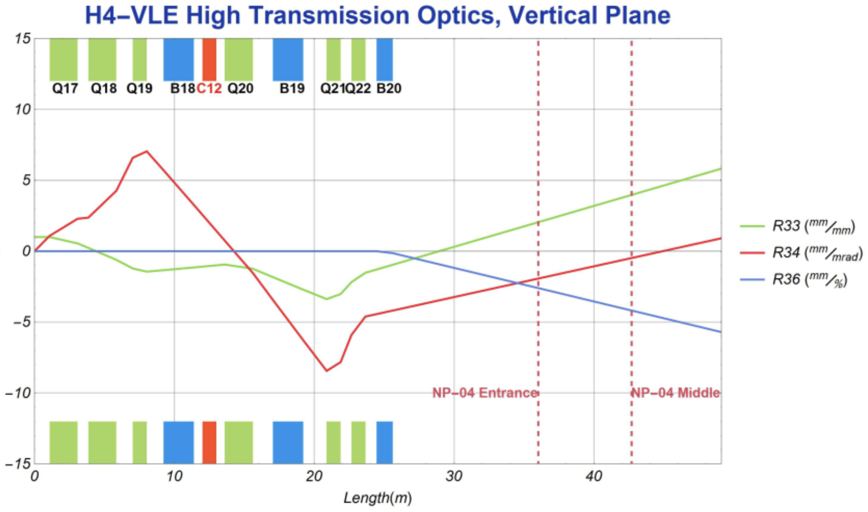
Test Beams for Neutrino Detector R&D – H2/H4

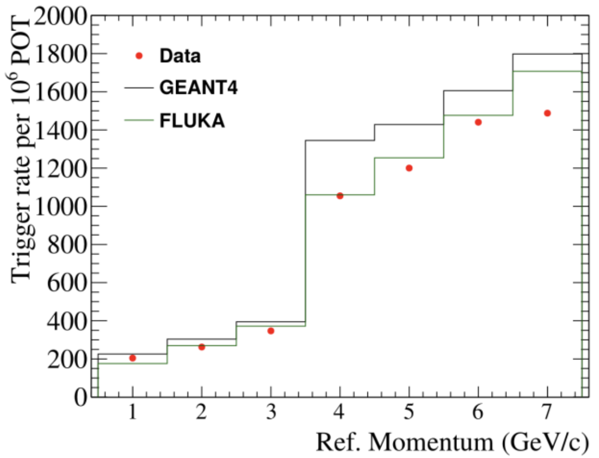


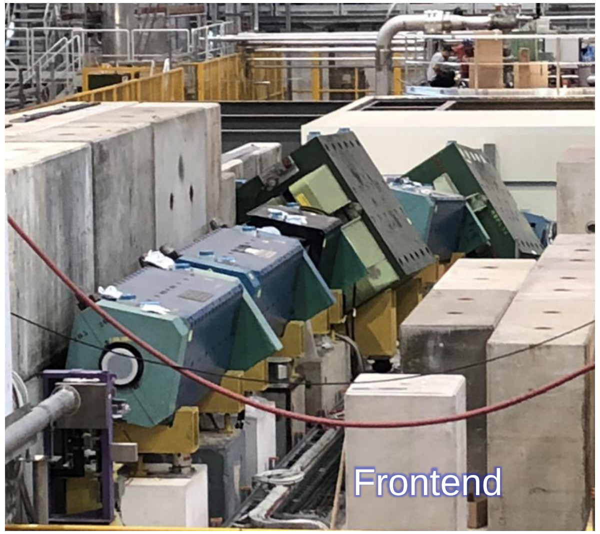
- Primary 400 GeV/c SPS proton beam produces a secondary hadron beam of 80 GeV/c (North Area)
- Secondary beam is used to produce a tertiary very low energy beam (VLE) beam in the range of about 0.3 to 7 respectively 12 GeV/c
- Low intensity of about 100 particles per s in 4.8 s spills
- Tertiary beams are composed of pions, protons, kaons, electrons, muons → ideal to check detector response for a wide range of particles
- Different target materials to optimize total particle rate vs. pion-positron-ratio: copper for p > 3 GeV/c, tungsten for p ≤ 3 GeV/c, lead for pure electron beams
- Main users are the two large-sized ProtoDUNE detectors (LArTPC) in the framework of the CERN Neutrino Platform

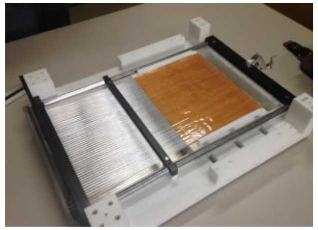
Test Beams for Neutrino Detector R&D – H2/H4





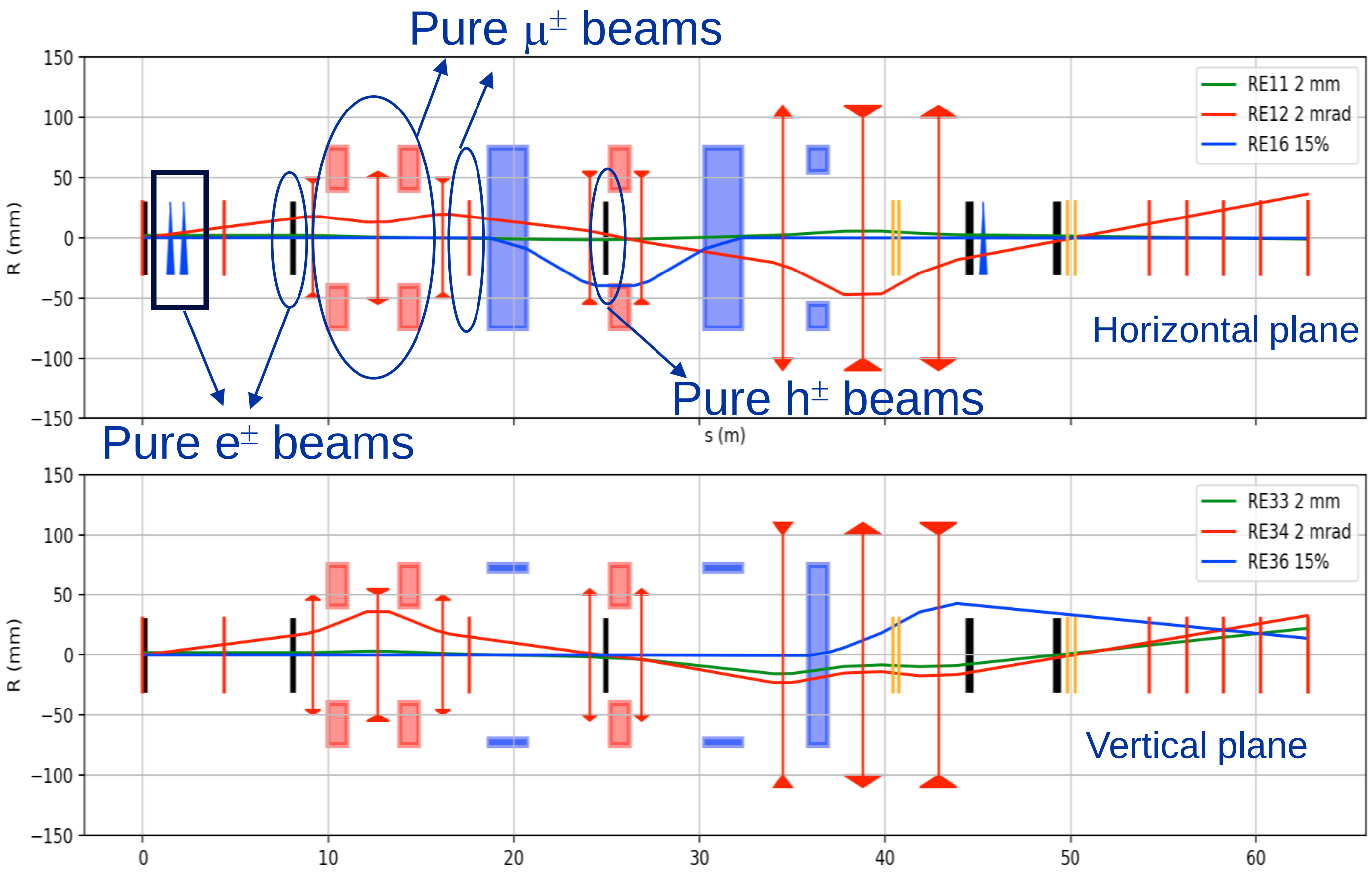






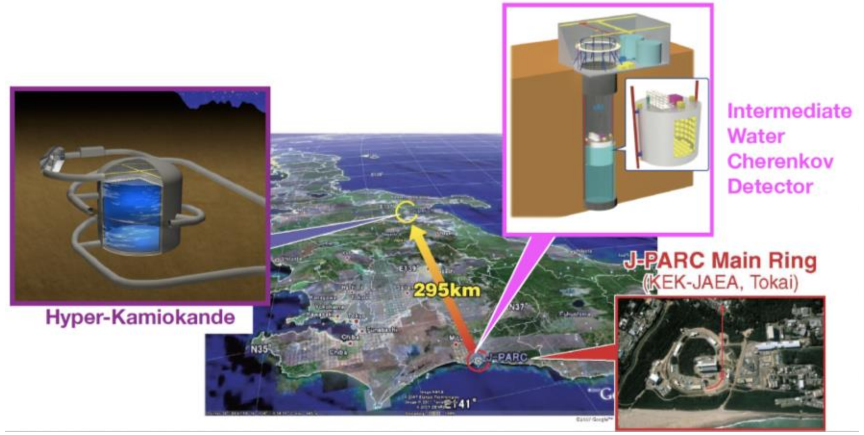
Test Beams for Neutrino Detector R&D – T09/T10

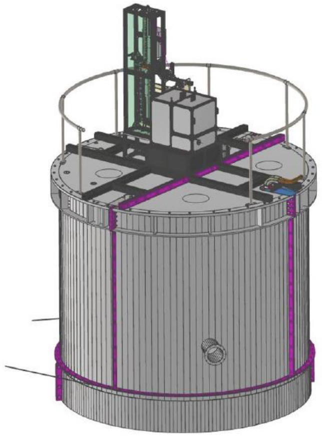
- Primary 24 GeV/c PS proton beam produces directly secondary beams in the relevant momentum range (East Area) → much better efficiency and rates than VLE beams
- All important particle species available (pions, protons, kaons, electrons, muons) in a range from 0.1 GeV/c to 16 GeV/c
- Intensities of up to 10^7 particles per s in 0.4 s spills
- Very pure beams available
  - Electron/positron beams via $\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-$ conversion (T09 only)
  - Lead absorbers to filter out electrons
  - Thick absorbers to filter all hadrons and electrons → muon beams

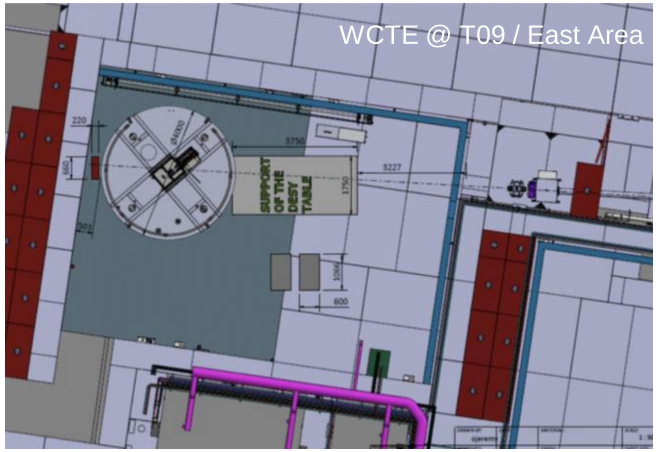


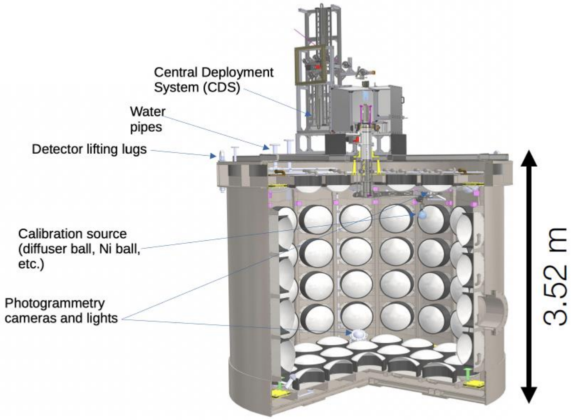
Test Beams for Neutrino Detector R&D – T09/T10

- Users included several TPCs (e.g. high pressure TPC with optical readout, ARIADNE, …)
- Next: Water Chrenkov Test Experiment (WCTE)







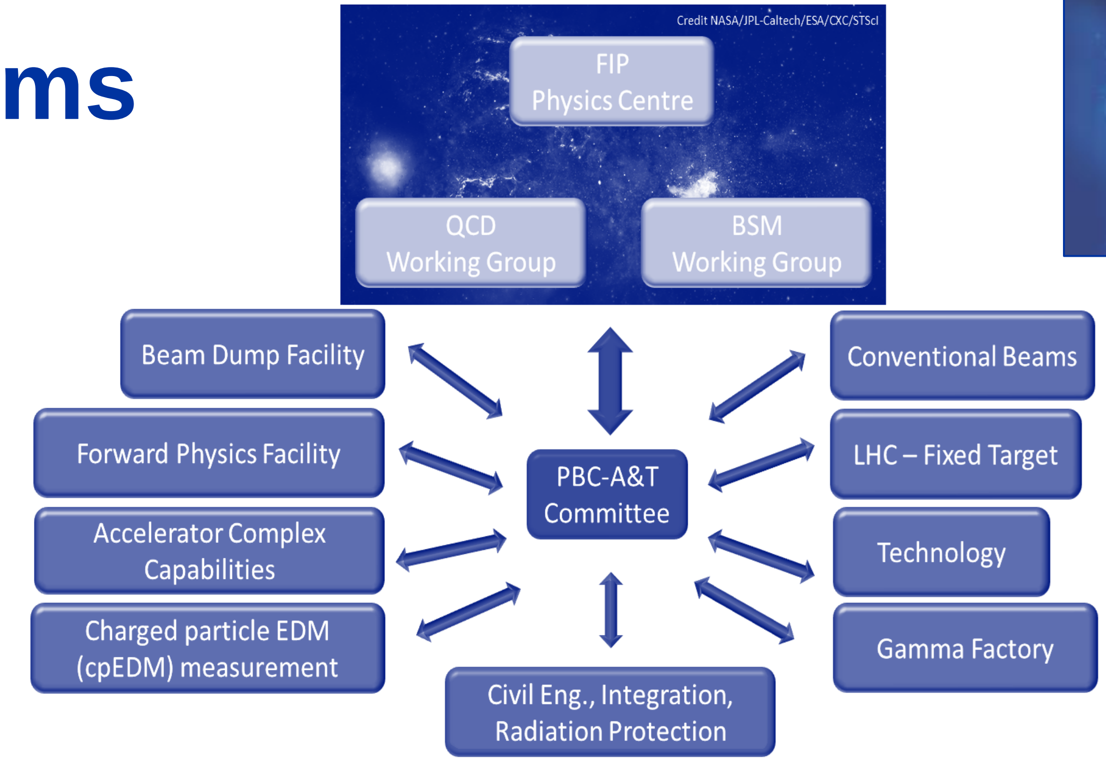


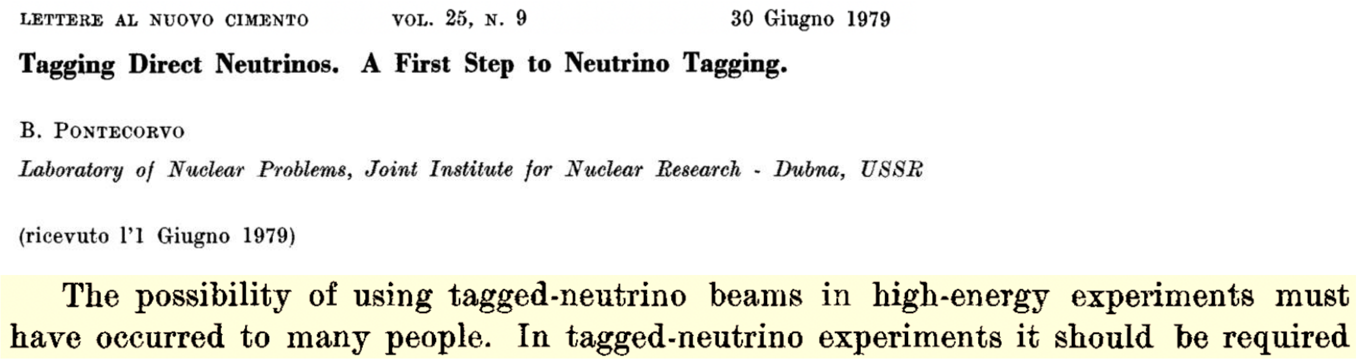
- A 40-ton water Cherenkov Detector
- Operate in the T9 beam line in East Hall
- Particle fluxes of $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ and p in the 200 MeV/c to 1000 MeV/c range
- Operating phase with $Gd_2(SO_4)_3$ loading to allow for neutron detection
- Primary photon detection system is 100 multi-PMT photosensors mounted on inside of detector
- Proposal document: SPSC-P-365

M. Hartz

Monitored Neutrino Beams

- CERN launched an initiative for Physics Beyond Colliders, broad spectrum of ideas for fixed-target and other facilities
- Within the Conventional Beams Working Group, there is also a specialised team for monitored neutrino beams
- Neutrino tagging is not exactly a new idea, but with modern detectors in reach
- Three ideas to tag specific hadron decays and thus the neutrino flavour
  - ENUBET
  - NuTAG
  - SBN (ENUBET + NuTAG + optimised)





LETTERE AL NUOVO CIMENTO VOL. 25, N. 9 30 Giugno 1979

Tagging Direct Neutrinos. A First Step to Neutrino Tagging.

B. PONTECORVO

Laboratory of Nuclear Problems, Joint Institute for Nuclear Research - Dubna, USSR

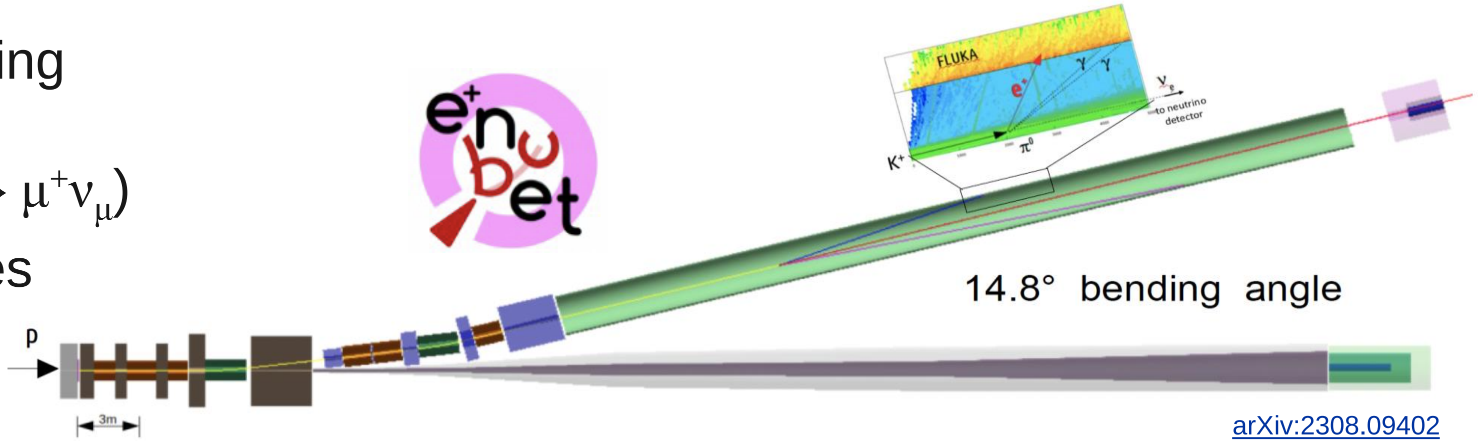
(ricevuto l'1 Giugno 1979)

The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required

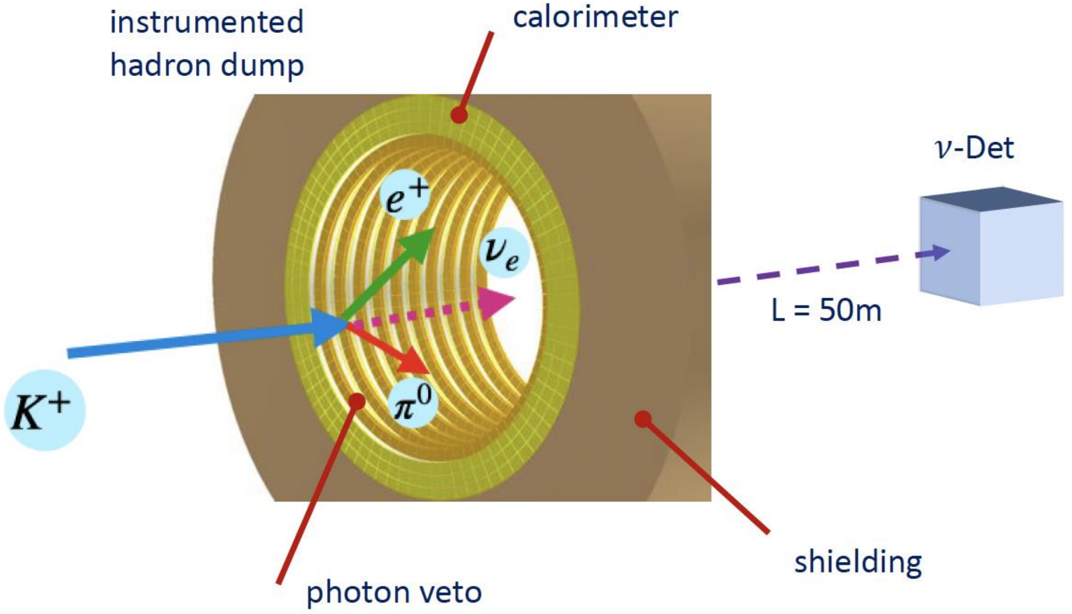
Lett. Nuovo Cimento 25, 257–259 (1979)

ENUBET

- Idea: monitored neutrino beam employing mainly the K_{e3} decay ($K^+ \rightarrow \pi^0 e^+ \nu_e$) and $K_{\mu3}$ decay ($K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$) / K decay ($K^+ \rightarrow \mu^+ \nu_\mu$)
- ν_e and ν_μ flux prediction from e^+ / μ^+ rates
- Momentum-selected hadron beam
- Final goal: A tagged beam of about 10^{10} K^+ per spill, slowly extracted, decaying inside an instrumented tunnel
- Tunnel detector:
  - Sampling calorimeter with $e/\pi/\mu$ separation capabilities (SiPM readout)
  - Photon-Veto for π^0 rejection and timing

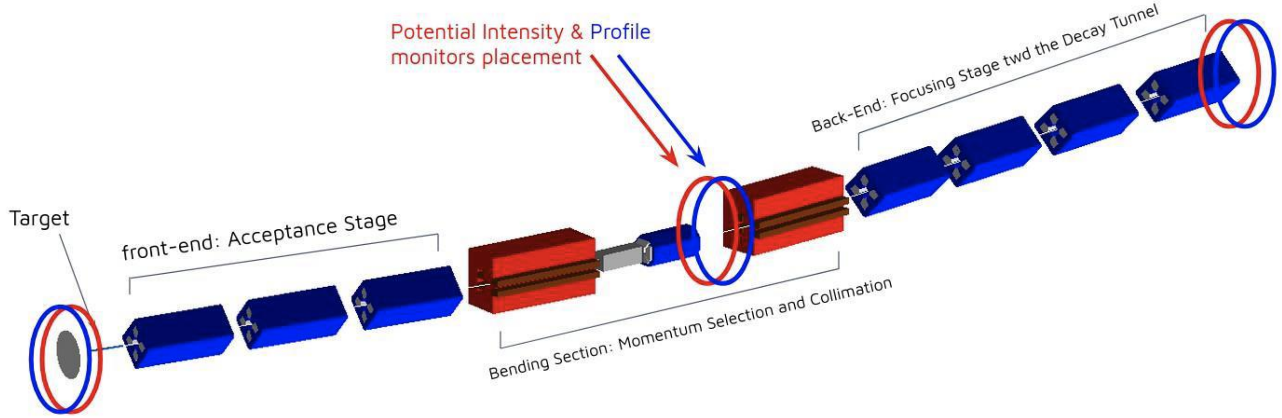


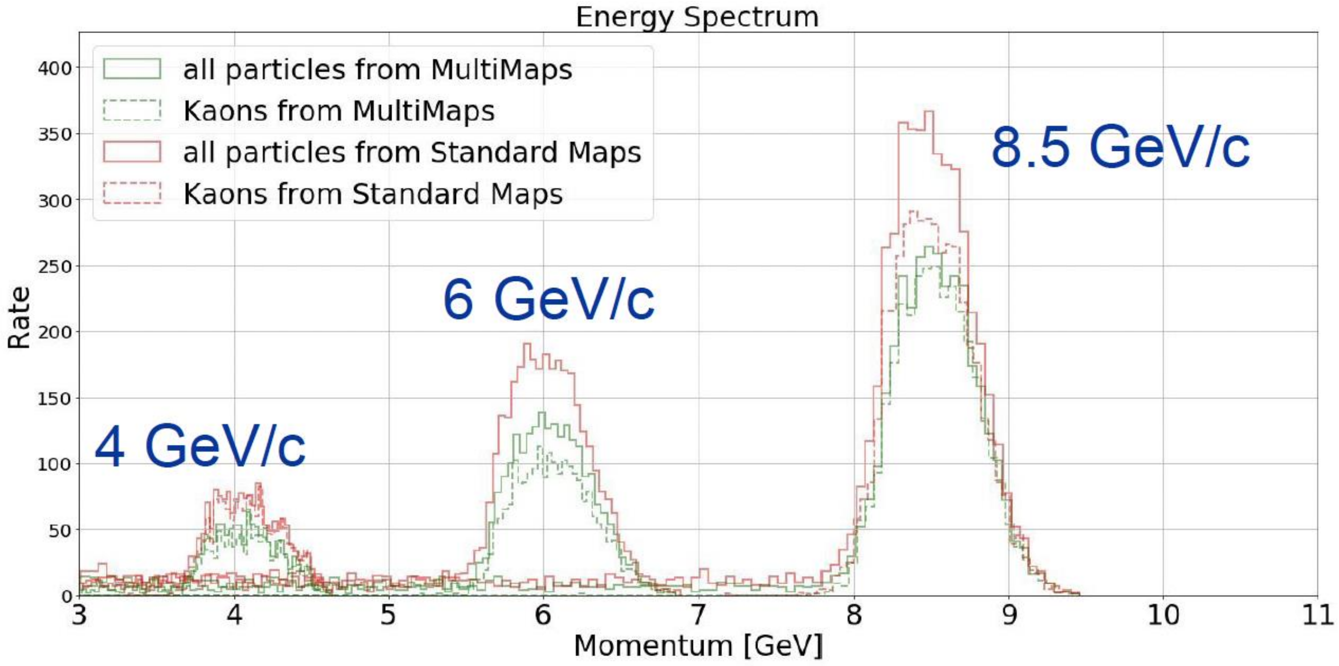
arXiv:2308.09402



ENUBET

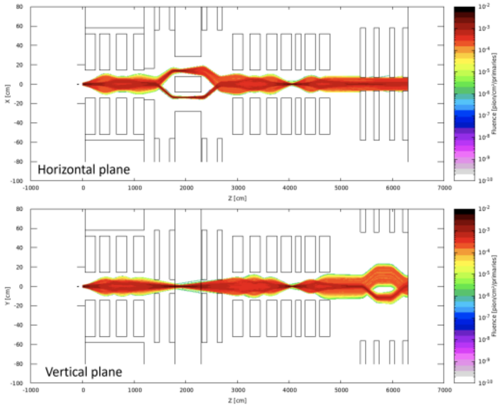
- Version 2 with variable beam energy (PhD thesis E. Parozzi)
- Based on existing CERN magnet designs
- Operate with secondary momenta from 4 to 8.5 GeV to cover both the DUNE and HyperKamiokande region of interest
- Double bend achromat in the middle assures first-order zero dispersion optics and reasonable spot-size at the decay tunnel
- More efficient than baseline design (more kaons per primary proton)

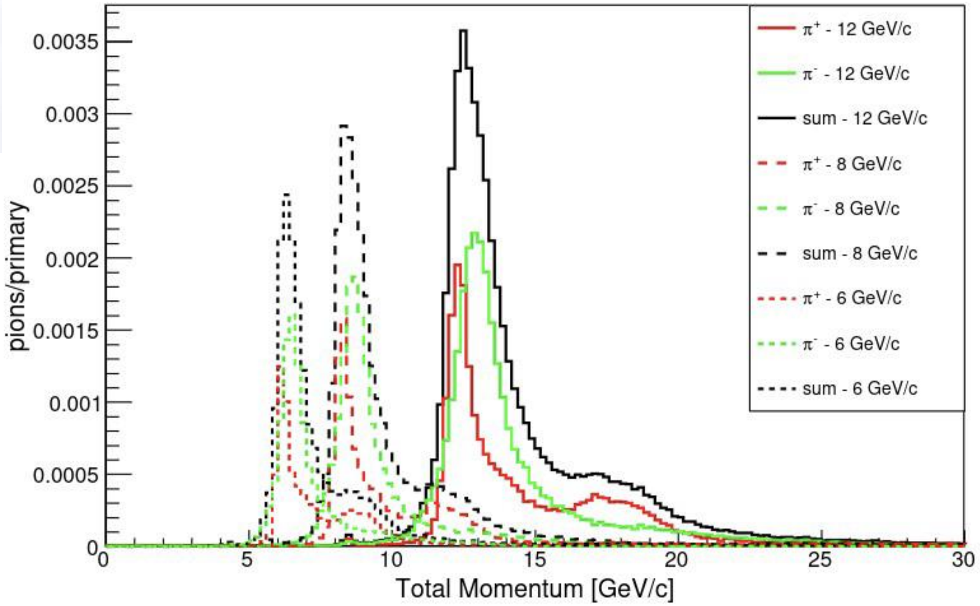


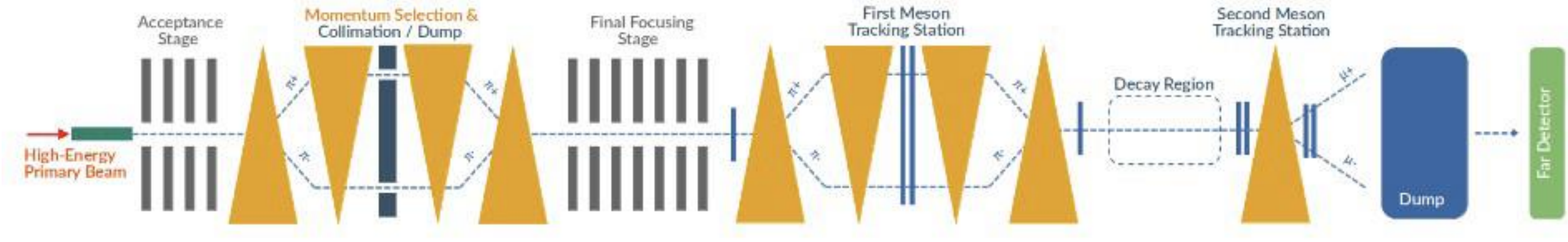


NuTAG

- Idea is to build a conventional neutrino beam, but with trackers to reconstruct neutrino from π and μ kinematics → **tagged neutrino beam**
- Simultaneous transport of π^+ and π^-
- Develop new generation of trackers on well-known NA62 GTK technology
- Beam line conceptional design completed (arXiv:2401.17068)



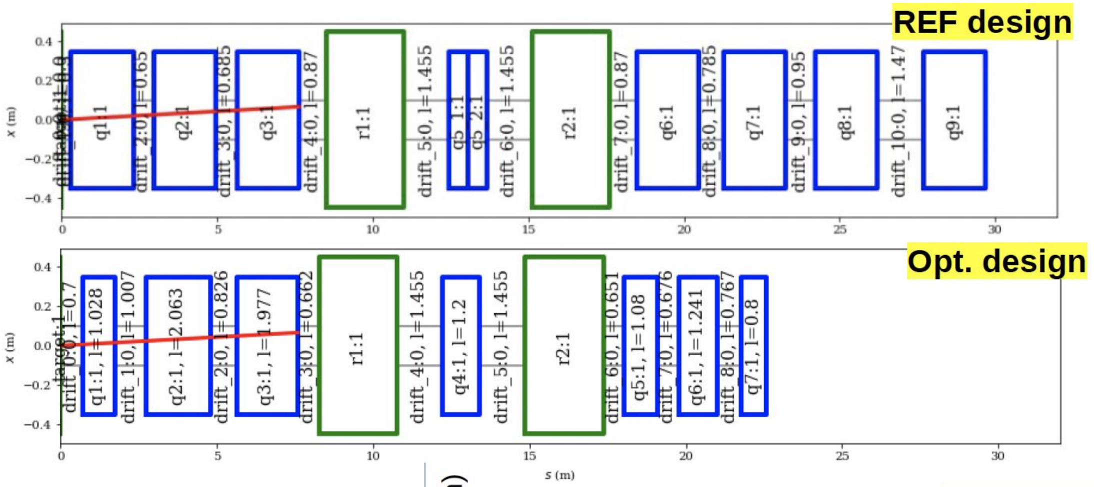




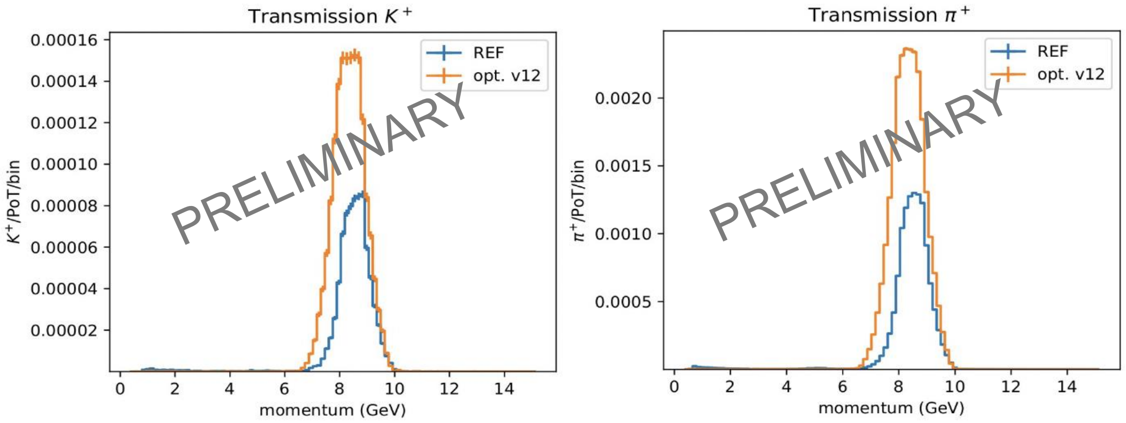
A. Baratto Roldan

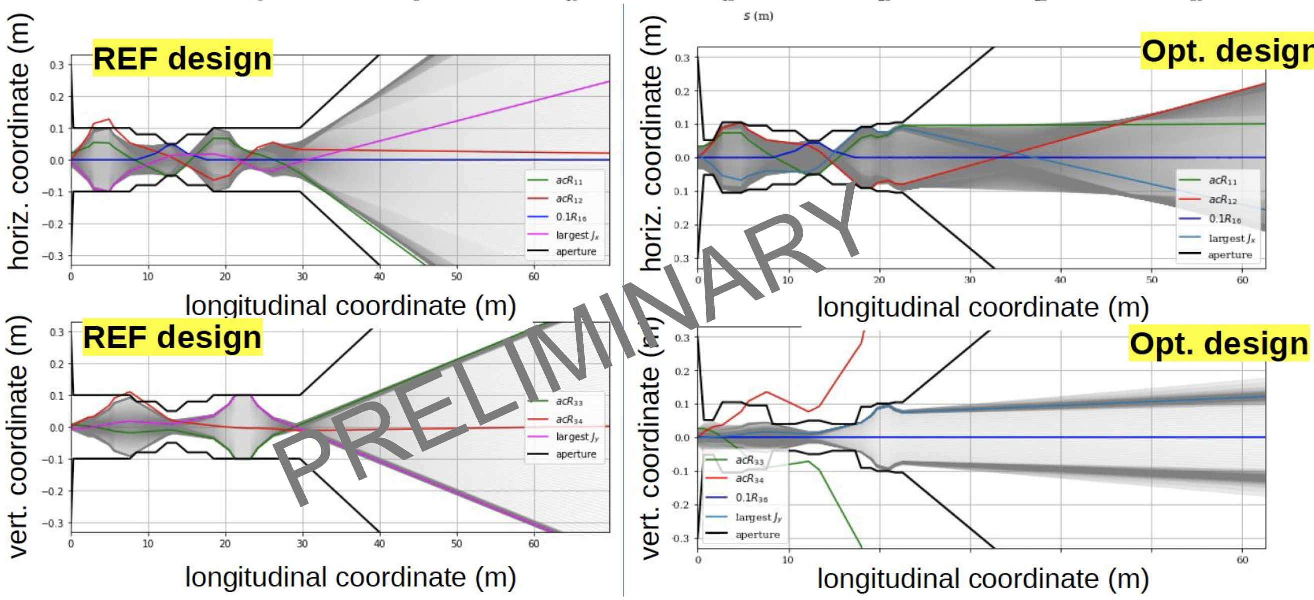
SBN

- Combine ideas of ENUBET and NuTAG plus optimize for less needed protons per tagged neutrino
- Based on ENUBET version 2 beam design but with CNGS-like target and quadrupole triplets
- Use a Multi-Objective Genetic Algorithm (MOGA) to optimize without restrictions to existing magnets
- Next: Investigate possible implementation sites



Name	*baseline*	REF	optimized REF V12
K^+/PoT	3.6×10^{-4}	7.0×10^{-4}	14.1×10^{-4} (+102%)
π^+/PoT	4.0×10^{-3}	1.1×10^{-2}	2.15×10^{-2} (+101%)





M. Jebramcik

Summary and Outlook

- Neutrino Beams derived from powerful proton synchrotrons will fuel the next generation of long baseline neutrino experiments with excellent opportunities to research physics beyond the Standard Model.
- The new experiments will be able to tackle long-standing questions, such as CP violation, mass hierarchy, potentially even proton decay.
- Besides the conventional neutrino beams, new ideas for monitored and even tagged neutrino beams look feasible that would open a new precision era. At the moment, neutrino cross sections are stuck around at the 10-30% level, whereas experiments would aim for 1% to eliminate leading systematic uncertainties.
- Beyond these possibilities, also collider neutrinos (e.g. FASER, SND as well as FPF proposal at CERN) and beam dump neutrinos (SHiP at CERN) will access other interesting phenomena in the heavy flavour domain, for instance physics with tau and anti-tau neutrinos.
- In the future, also whole neutrino facilities could be built, such as ESSνSB in LUND or NuSTORM.

Thank you very much for your attention!

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