Neutrino Oscillations and 0νββ

Dan Pershey (Florida State University) – Jul 19, 2024

Second school on neutrino and dark matter detection
South American Institute for Fundamental Research

Remaining questions in the standard model

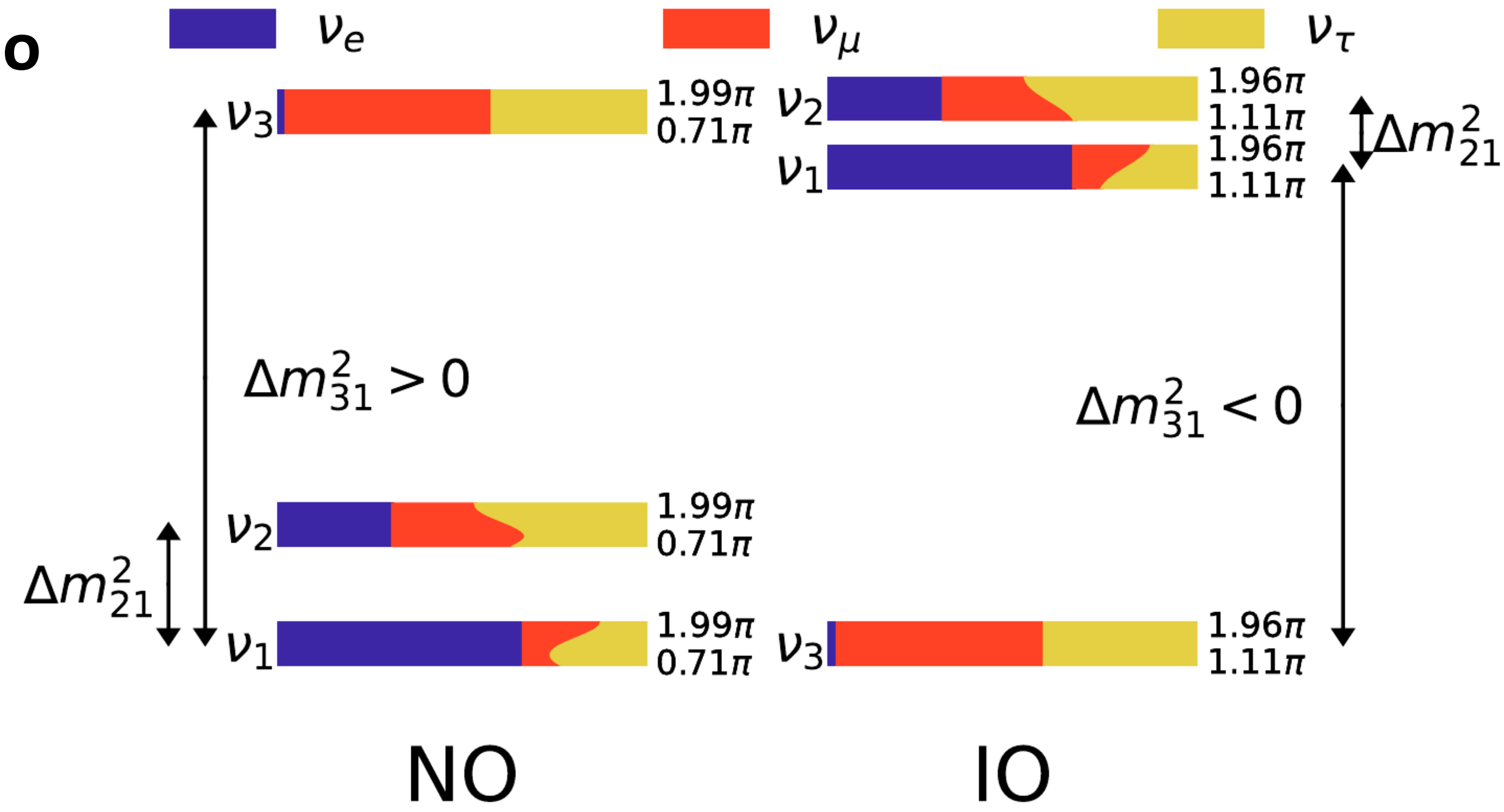
Spoiler alert: they're all in the neutrino sector

1: which is the heaviest neutrino mass eigenstate?

2: what is the θ_{23} octant?

3: is there CP violation in neutrinos?

4: what is the absolute neutrino mass scale?



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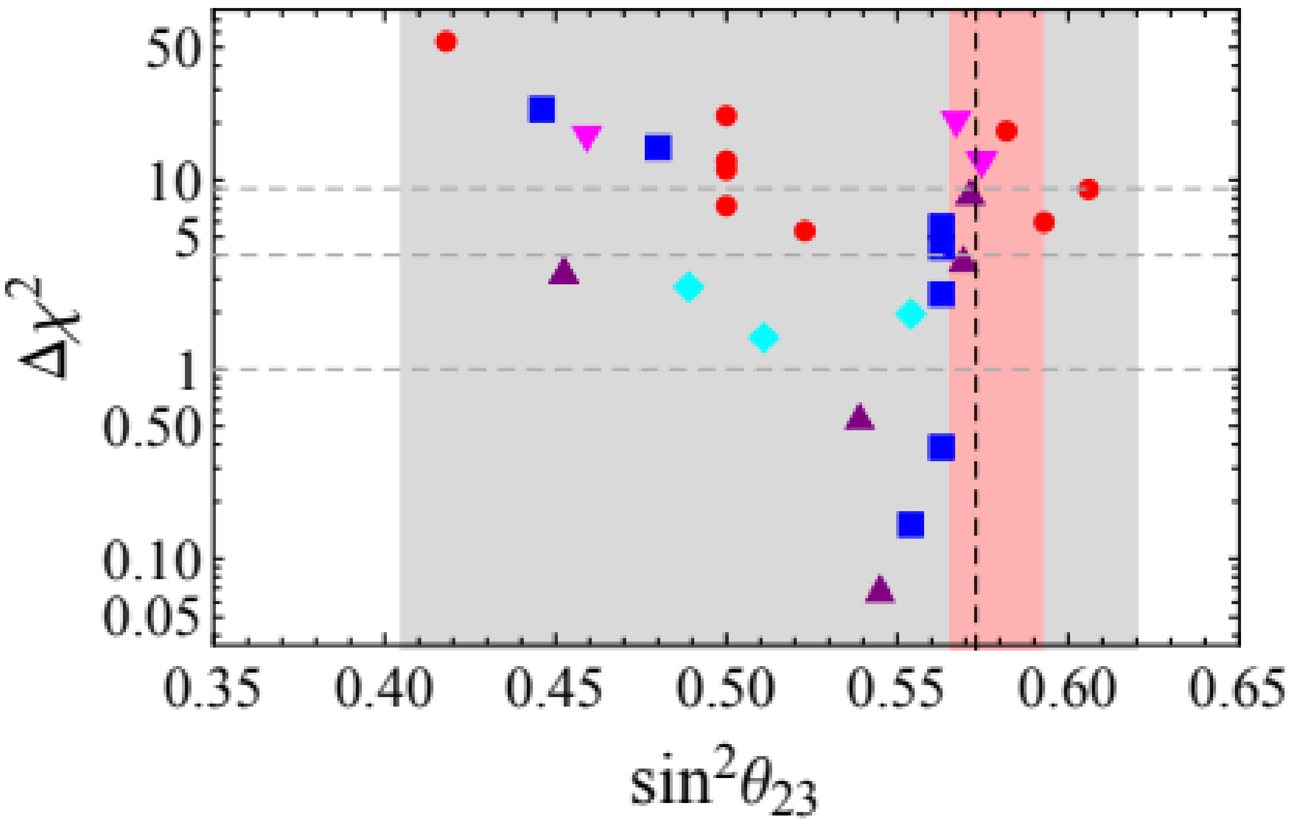

Gehrlein, Petcov, Spinrath, Titov, arXiv:2203.06219 (2024)

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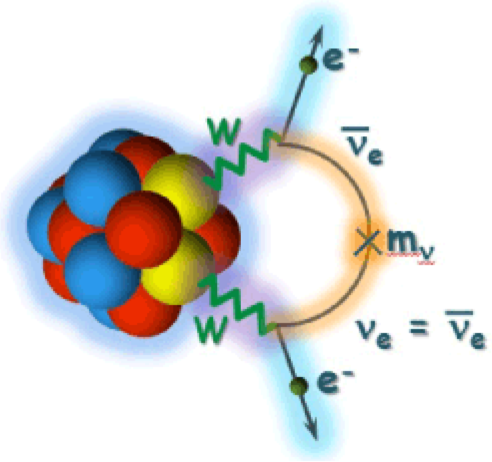

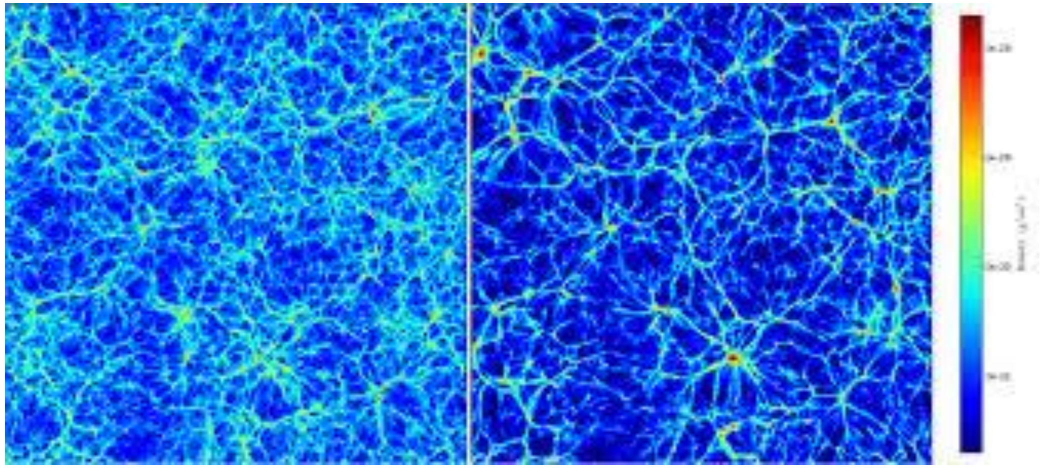

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Long-baseline oscillation experiments

4: what is the absolute neutrino mass scale?

0νββ, tritium spectrometers, cosmology

Long-baseline accelerator experiments

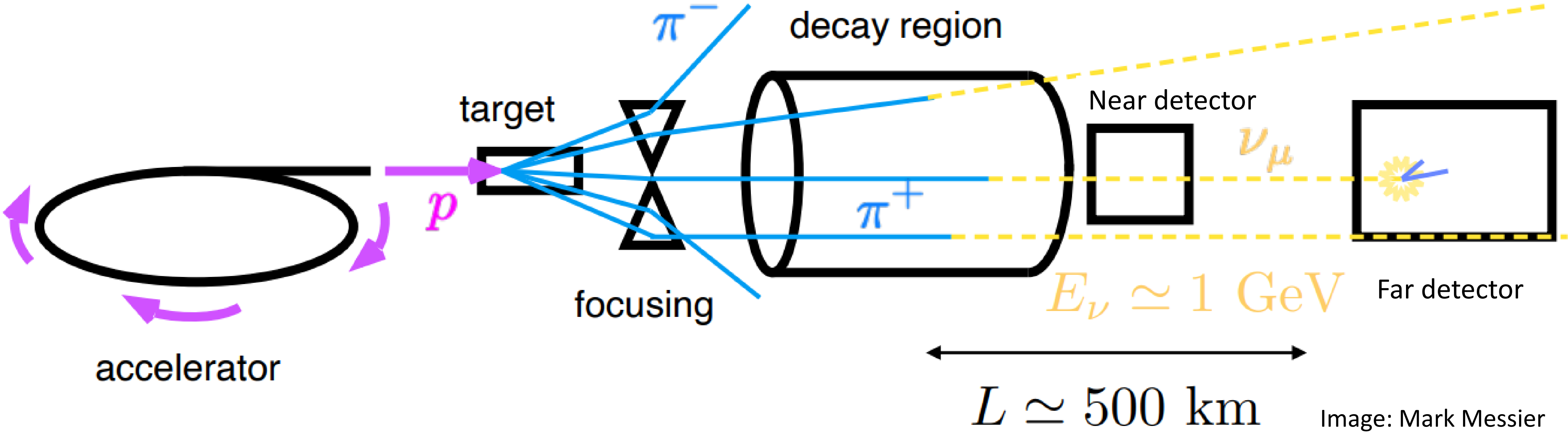


Image: Mark Messier

Accelerator produces beam of GeV-scale neutrinos

Can focus either π^+ or π^- giving ν_μ or $\bar{\nu}_\mu$ neutrino flux

Near detector – constrain uncertainties on flux, cross section, etc.

Far detector – measure oscillated spectrum

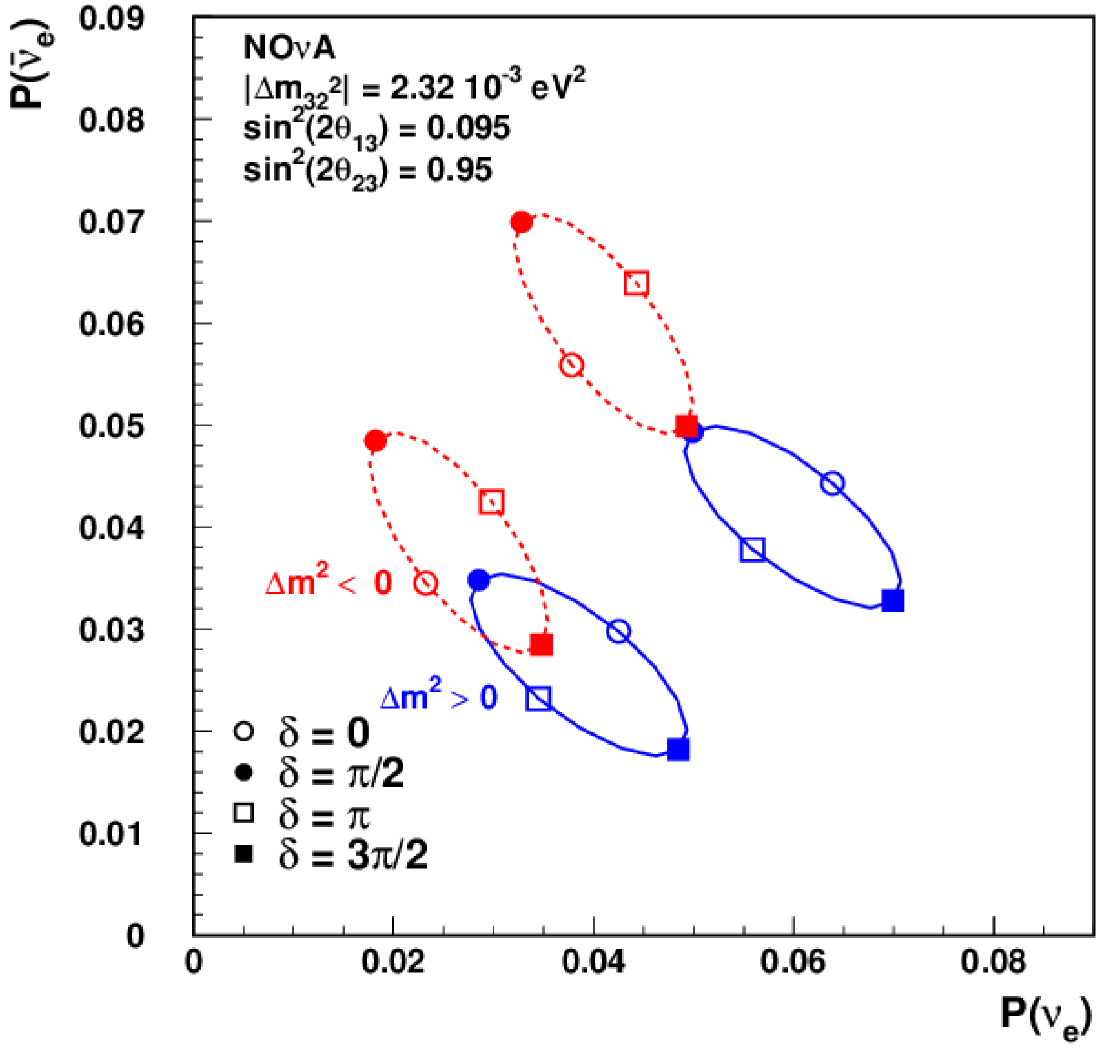
Oscillation channels: $\nu_\mu \to \nu_\mu$ // $\bar{\nu}_\mu \to \bar{\nu}_\mu$ and $\nu_\mu \to \nu_e$ // $\bar{\nu}_\mu \to \bar{\nu}_e$

Disappearance Appearance

ν_e appearance probability

$\nu_\mu \to \nu_e$

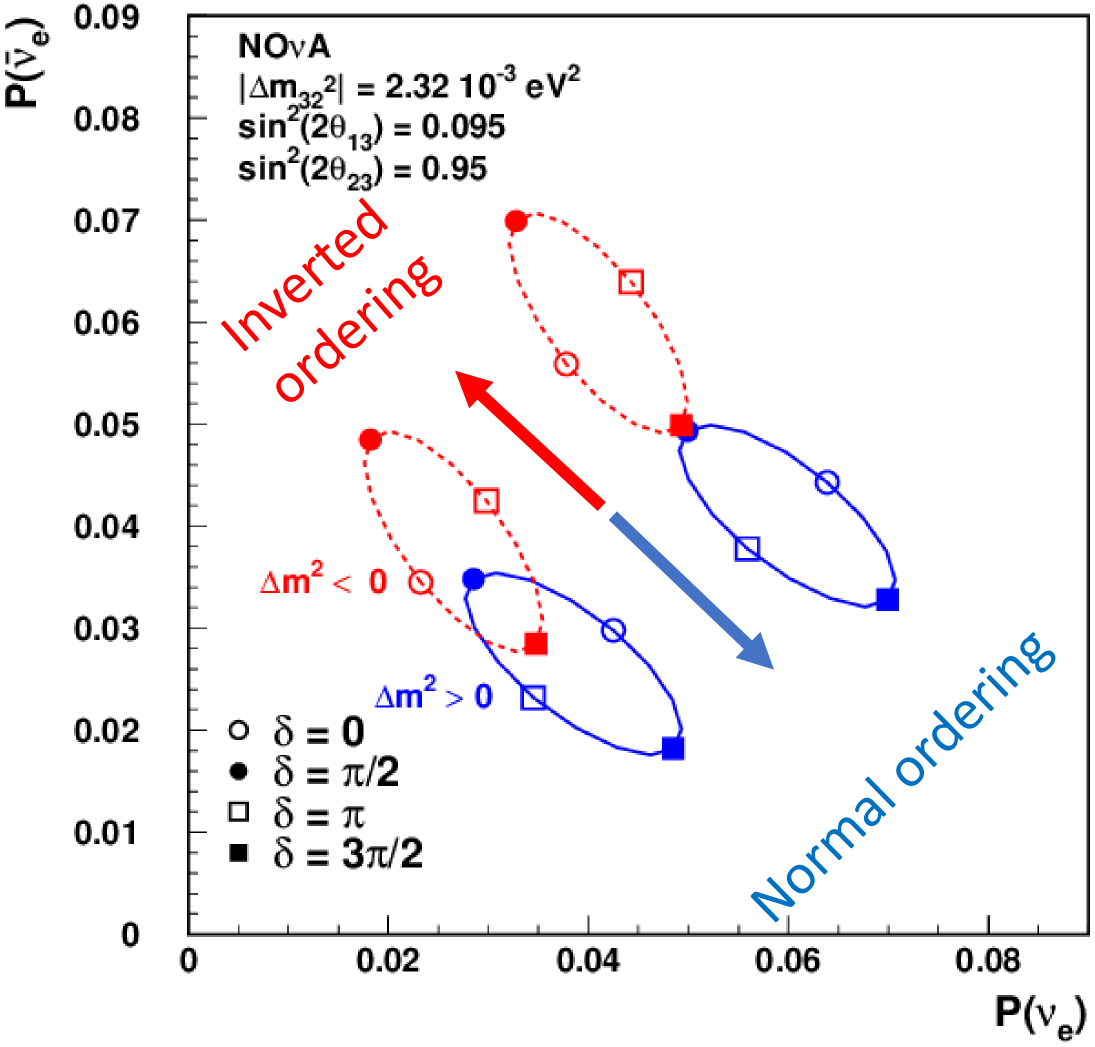
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \; = \; & \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\ \Delta_{31}^2 \\
& + \sin 2\theta_{23}\ \sin 2\theta_{13} \sin 2\theta_{12}\ \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\ \Delta_{31}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}\ \cos(\Delta_{31}+\delta) \\
& + \cos^2\theta_{23}\ \sin^2 2\theta_{12}\ \frac{\sin^2(aL)}{(aL)^2}\ \Delta_{21}^2,
\end{aligned}
$$



Neutrino mass ordering

$$\nu_\mu \rightarrow \nu_e$$

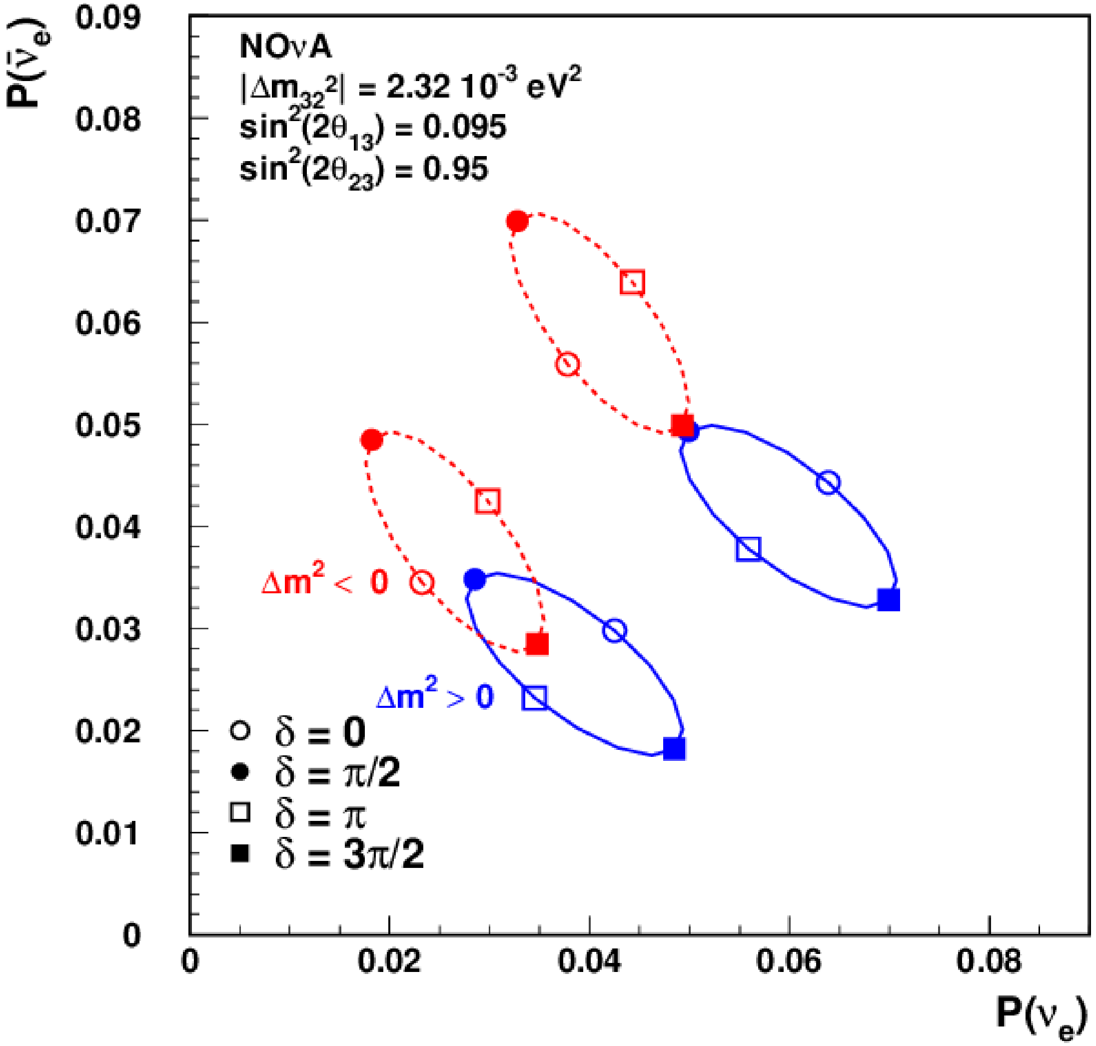
$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \; = \; & \sin^2\theta_{23}\; \sin^2 2\theta_{13}\; \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\, \Delta_{31}^2 \\ & + \sin 2\theta_{23}\; \sin 2\theta_{13} \sin 2\theta_{12}\; \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\, \boxed{\Delta_{31}}\, \frac{\sin(aL)}{(aL)}\, \Delta_{21}\; \cos(\Delta_{31} + \delta) \\ & + \; \cos^2\theta_{23}\; \sin^2 2\theta_{12}\; \frac{\sin^2(aL)}{(aL)^2}\, \Delta_{21}^2, \end{aligned}$$



CP violation

$\nu_\mu \rightarrow \nu_e$

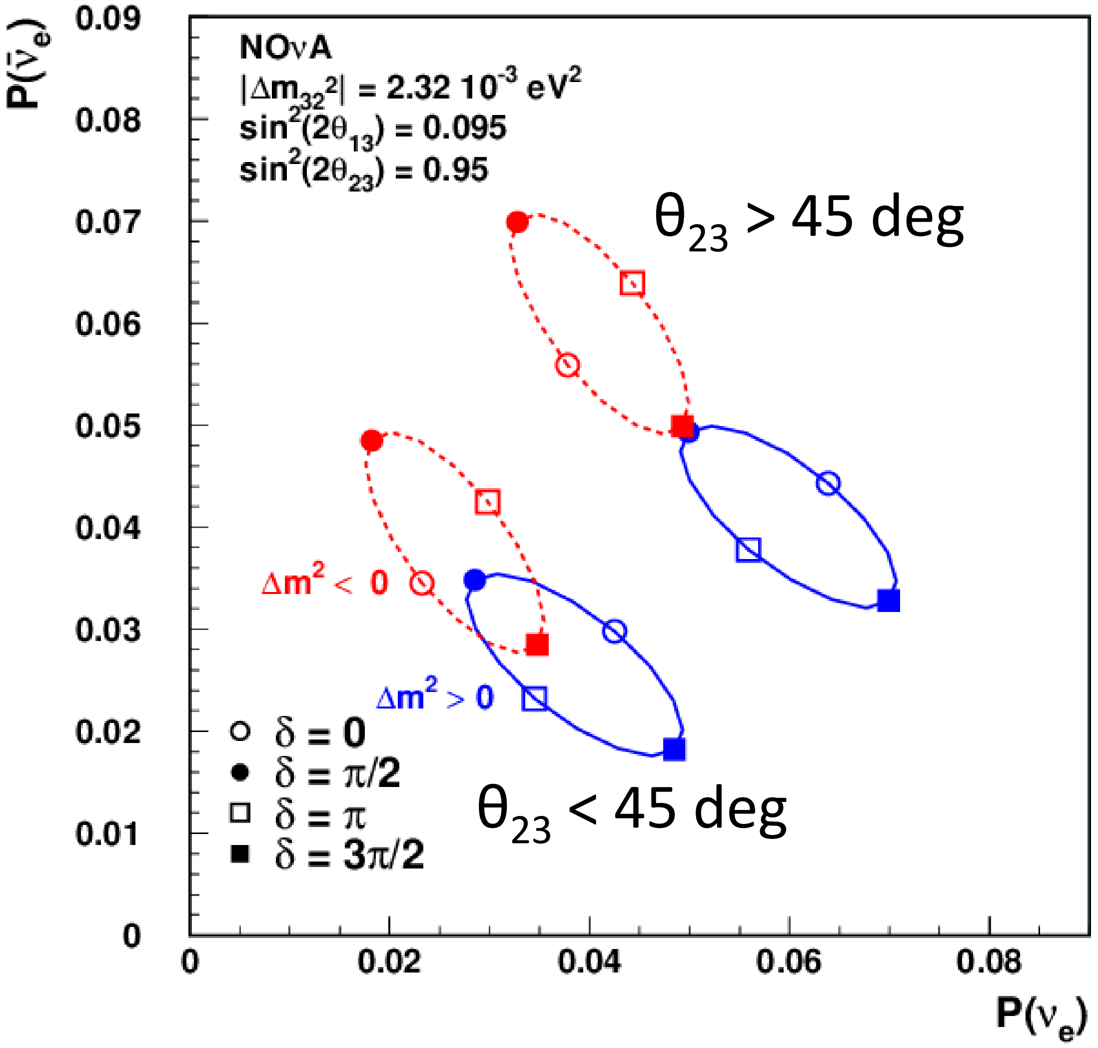
$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \; = \; & \sin^2\theta_{23} \; \sin^2 2\theta_{13} \; \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \; \Delta_{31}^2 \\ & + \sin 2\theta_{23} \; \sin 2\theta_{13} \sin 2\theta_{12} \; \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \; \Delta_{31} \; \frac{\sin(aL)}{(aL)} \; \Delta_{21} \; \cos\left(\Delta_{31} + \delta\right) \\ & + \; \cos^2\theta_{23} \; \sin^2 2\theta_{12} \; \frac{\sin^2(aL)}{(aL)^2} \; \Delta_{21}^2, \end{aligned}$$



θ_{23} octant

$\nu_\mu \rightarrow \nu_e$

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = & \boxed{\sin^2\theta_{23}} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\ & + \sin 2\theta_{23} \ \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \ \cos(\Delta_{31} + \delta) \\ & + \cos^2\theta_{23} \ \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2, \end{aligned}$$



Maximal ν_μ-ν_τ mixing

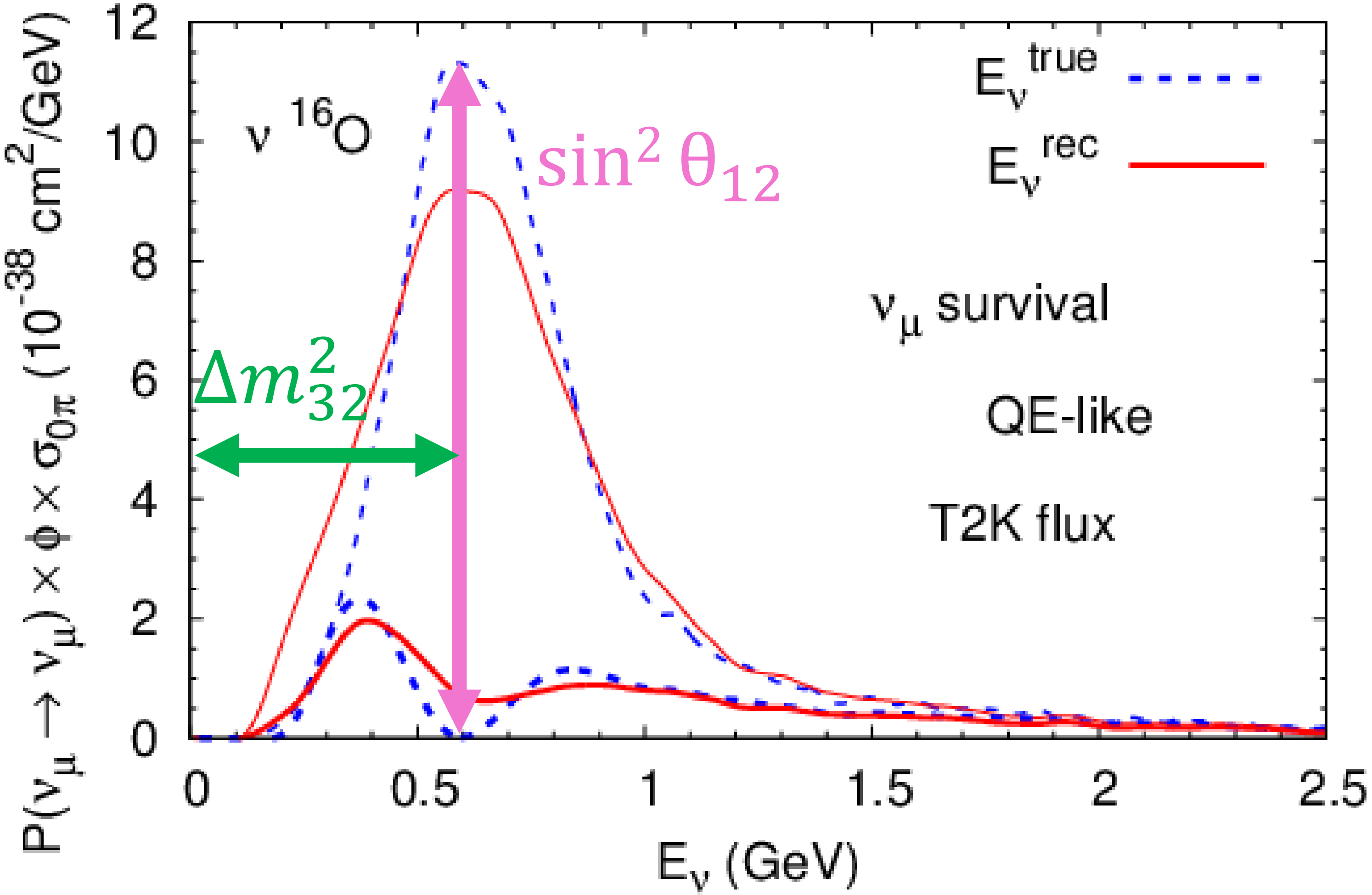
$$\nu_\mu \rightarrow \nu_\mu$$

$$P_{\mu\mu} = 1 - \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}$$

Is there “maximal mixing” between ν_μ and ν_τ?

Would expect complete disappearance of ν_μ beam at the oscillation maximum

Need to worry about smearing and backgrounds!



The NOvA experiment

Long baseline neutrino oscillation experiment in NuMI neutrino beam at Fermilab

High-purity and configurable $\nu_\mu/\bar{\nu}_\mu$ beam

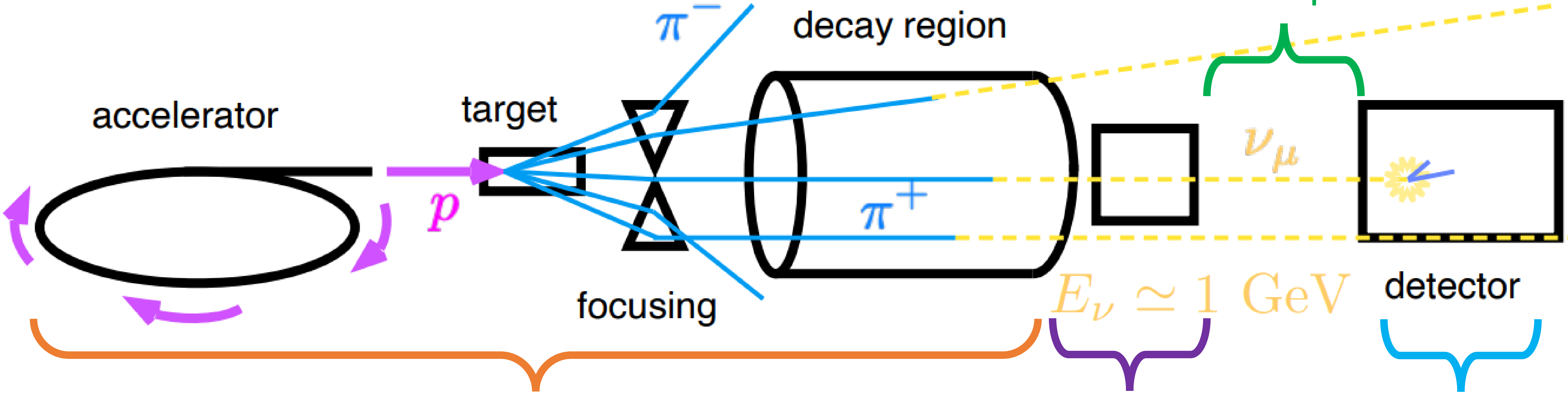
Peak energy = 1.8 GeV // baseline = 810 km

Functionally identical near and far detectors for optimal cancelation of systematic uncertainties

– Liquid scintillator detector
– Low-Z: good imaging of electromagnetic showers necessary for ν_μ/ν_e channel tagging
– FD(ND) is 14(0.3) kt

Long-baseline oscillation measurements

Step 3: Oscillate and extrapolate



Step 1: make a neutrino beam

Step 2: Measure in near detector

Step 4: Measure in far detector

Make a neutrino beam: the target

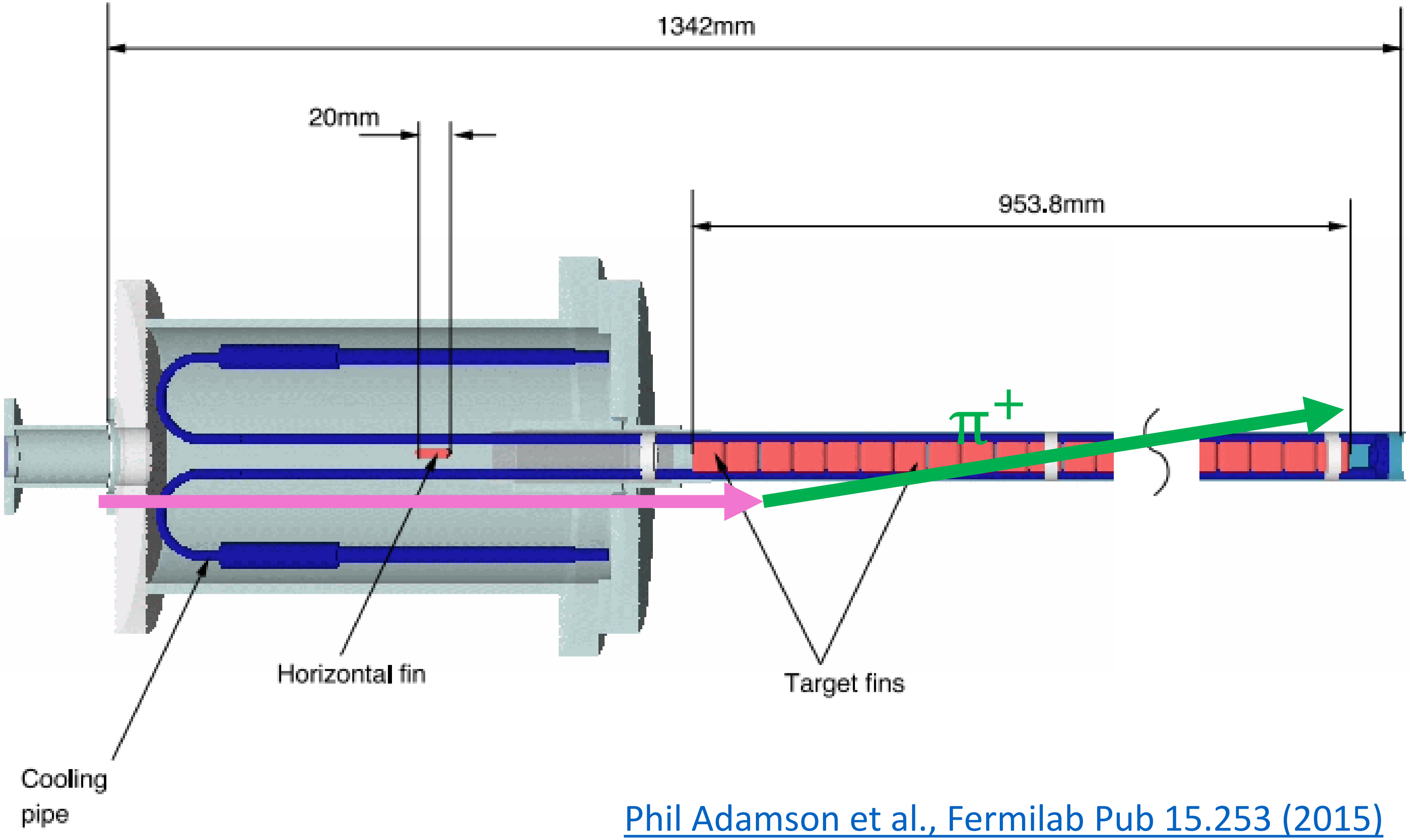
~ 1 MW primary proton beam incident on target of 48 2-cm long and 1.5-cm wide cylindrical graphite fins

Fins held in vacuum and cooled with water

344 C maximum temp in each of the fins after beam spill

Beam spill rate of 0.53 Hz

Produces secondary meson beam



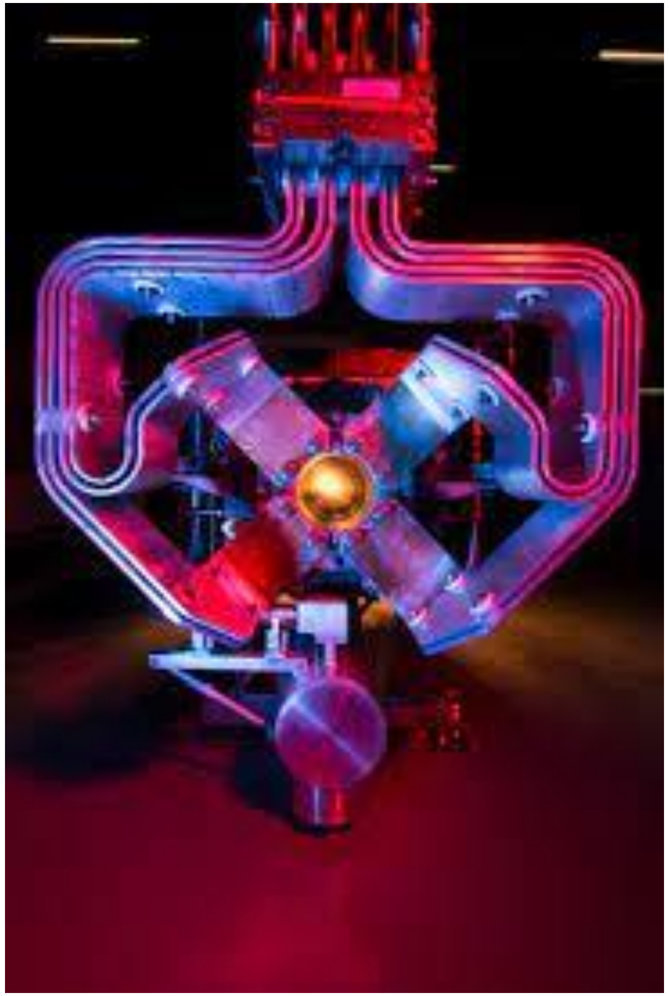
Phil Adamson et al., Fermilab Pub 15.253 (2015)

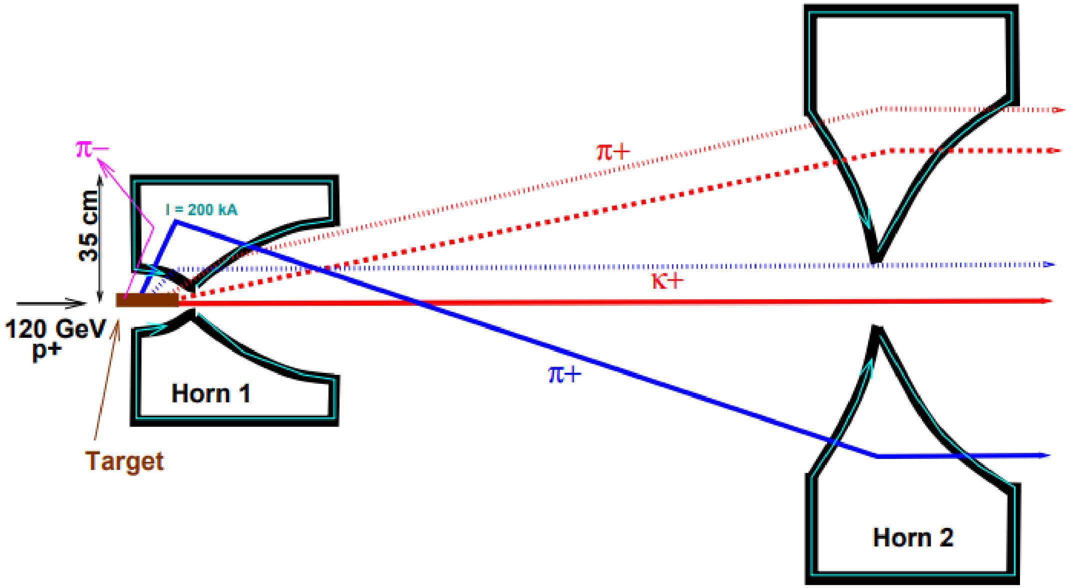
Make a neutrino beam: the horns

Horn = giant electromagnet that acts like a lens

Pulse current up to 207 kA through the horn for 2.3 ms each beam spill

Produces magnetic field which deflects charged particles. Series of two horns together *focuses mesons of one charge sign while deflecting those of opposite sign*





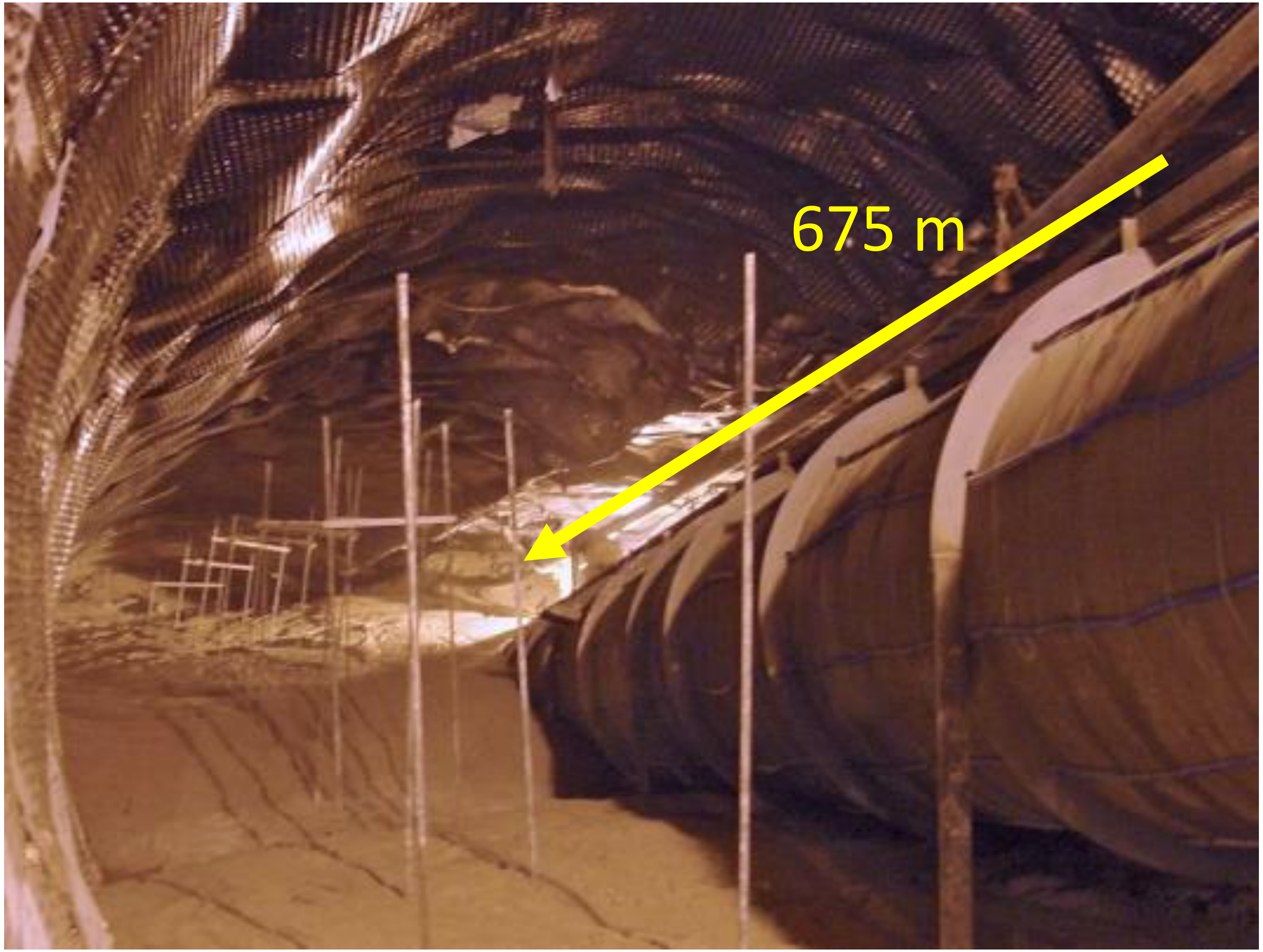
Make a neutrino beam: the decay pipe

Mesons produced in target need opportunity to decay

Steel cylander evacuated to 0.0006 atm of pressure allowing mesons to decay in vacuum

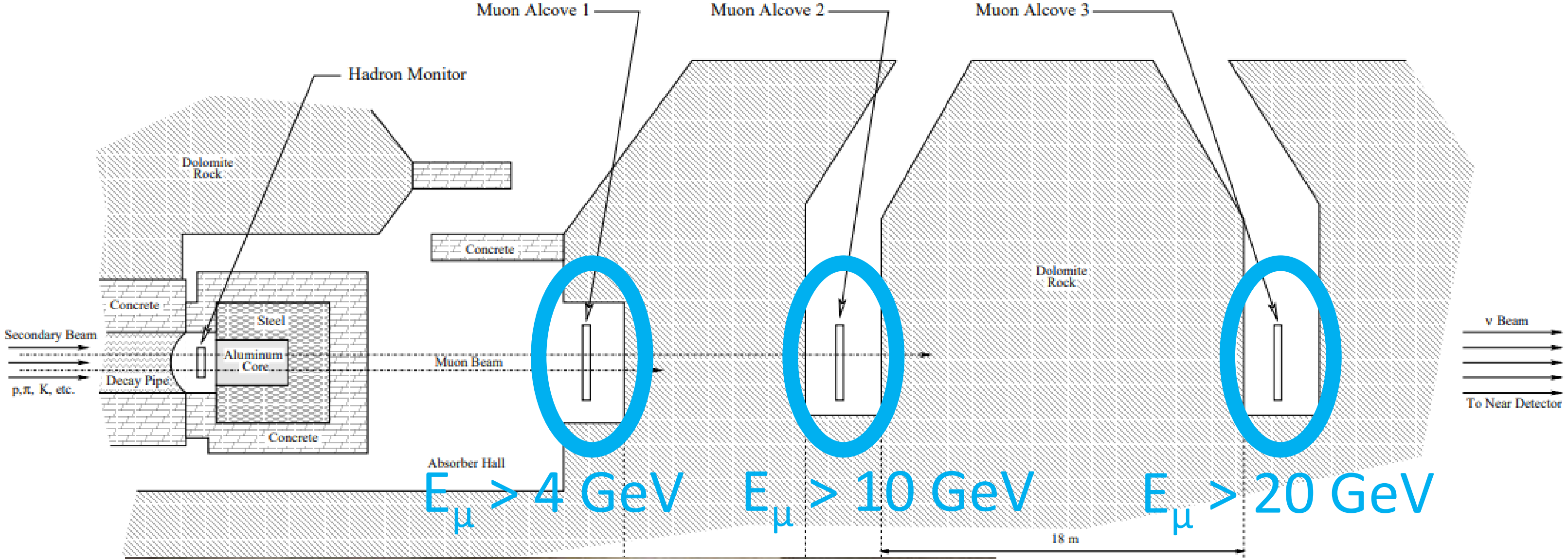
How long should the pipe be?
Beam peaks at 2 GeV -> comes from pions of about 4 GeV
$L = \gamma\tau c = (E/m)\tau c$
= (4 GeV / 140 MeV)(26 ns)c
= 220 m

Finally, terciary neutrino beam!



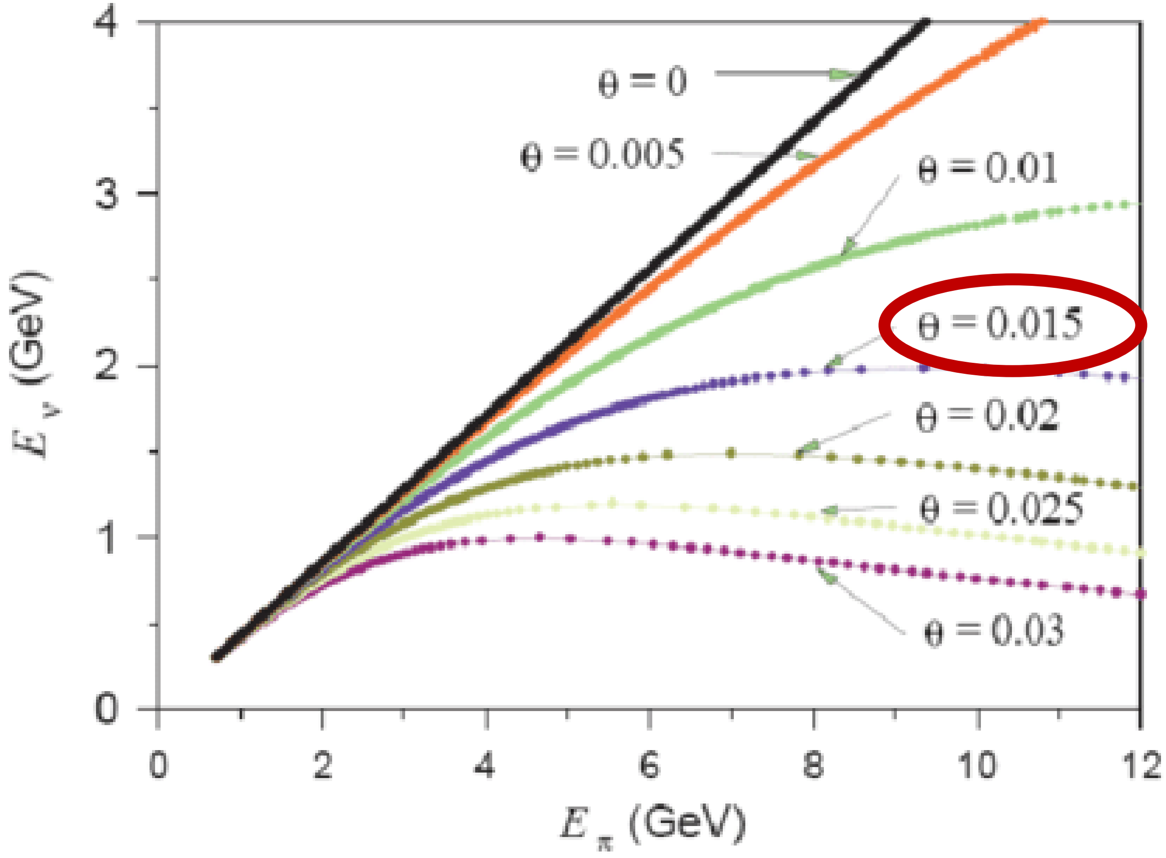
Make a neutrino beam: the absorber

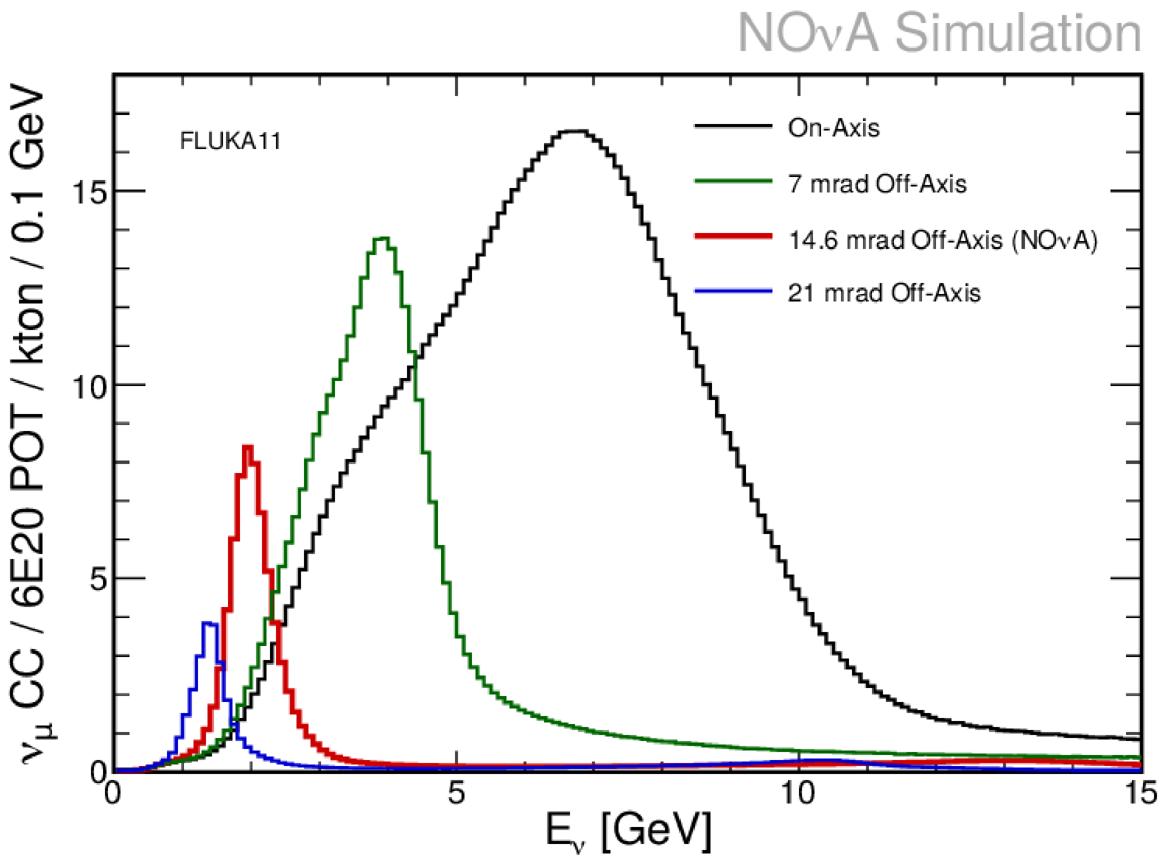
At end of decay: sequence of concrete slabs and undisturbed rock to absorb all charged particles produced in the target



Includes muon counters to beam rate position

Make a neutrino beam: off-axis angle



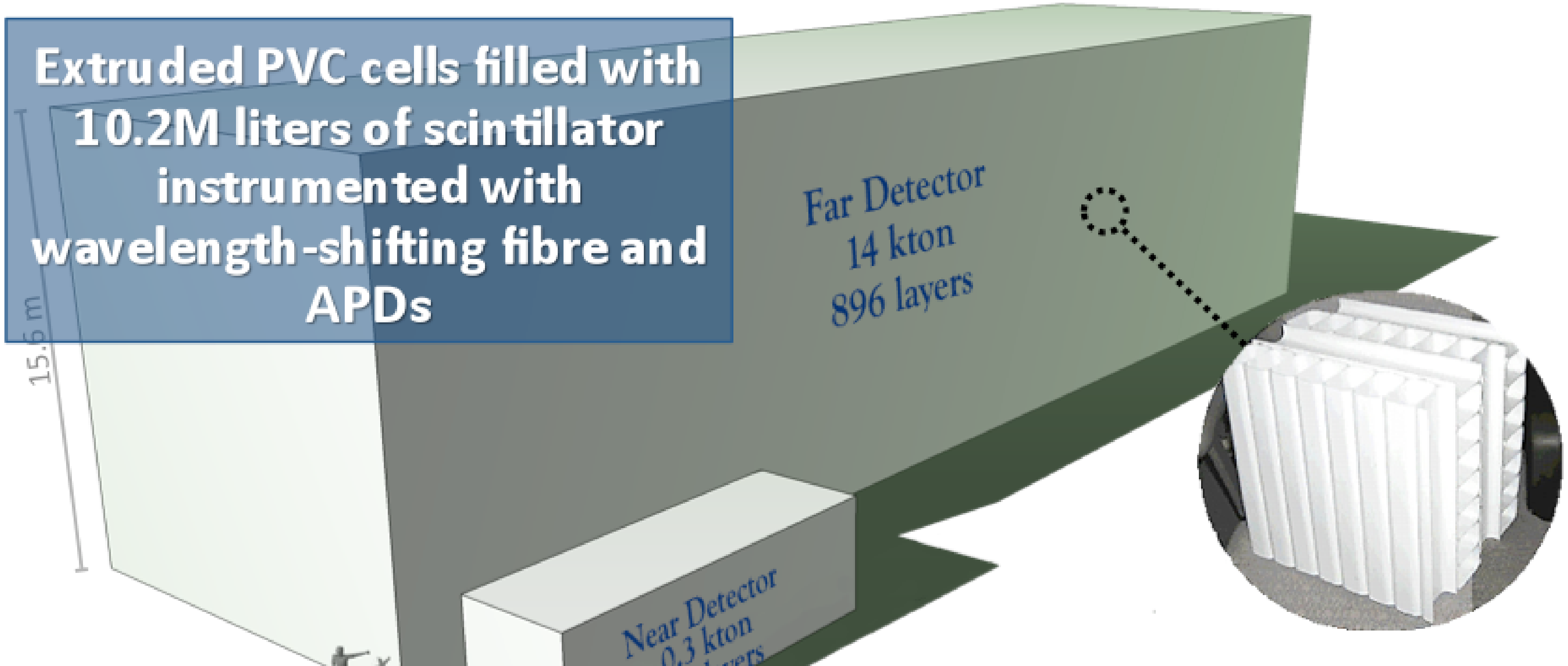


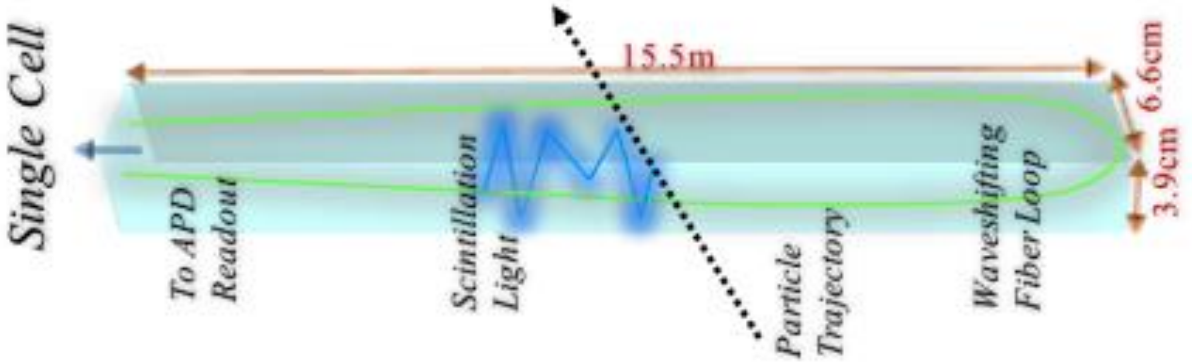
Off-axis, kinematics of meson decays limits the maximum energy of neutrinos produced
-> induces a narrow-band beam.

NOvA placed 14.6 mrad off-axis with peak beam energy of 1.8 MeV

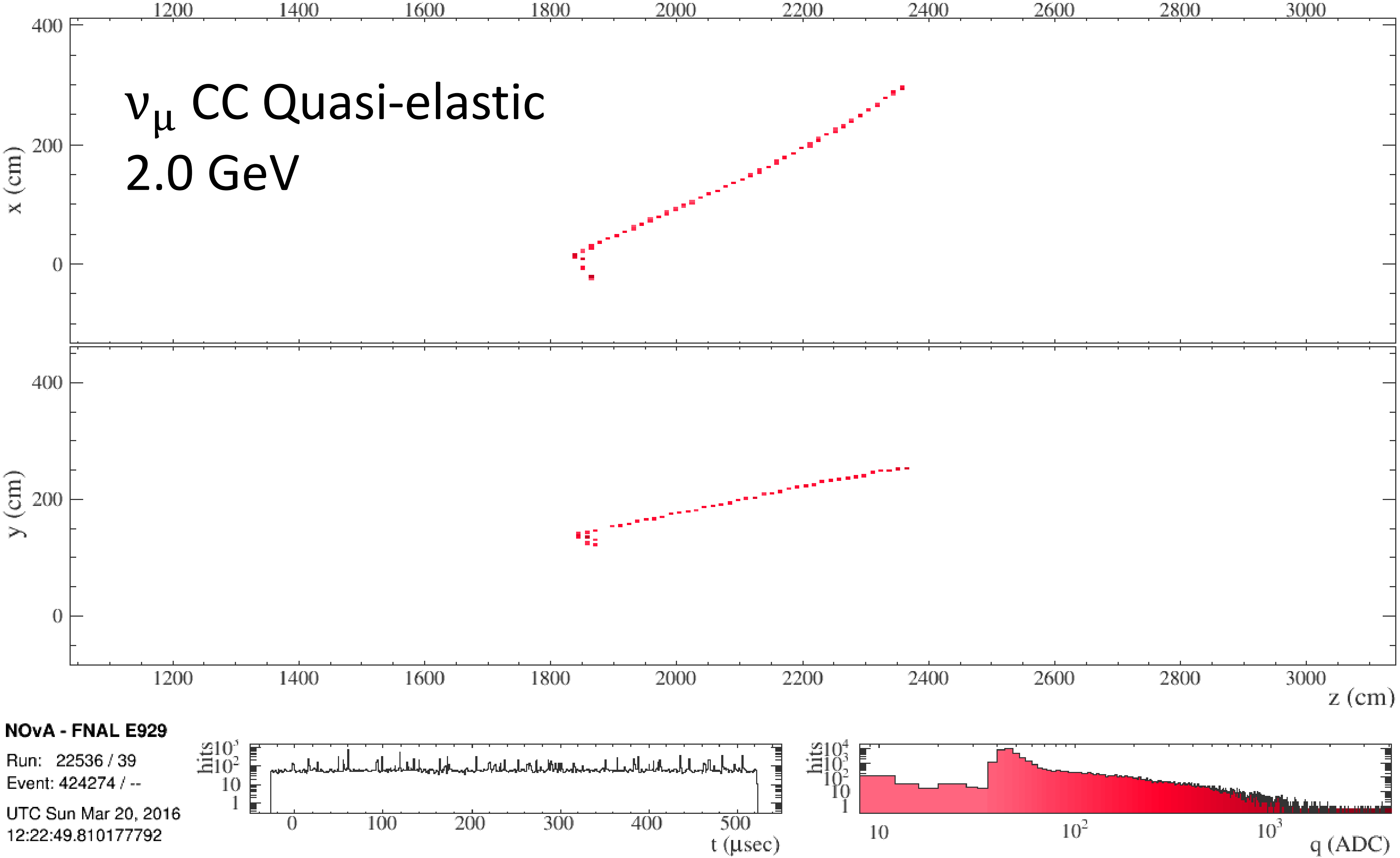
NOvA detectors

Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs



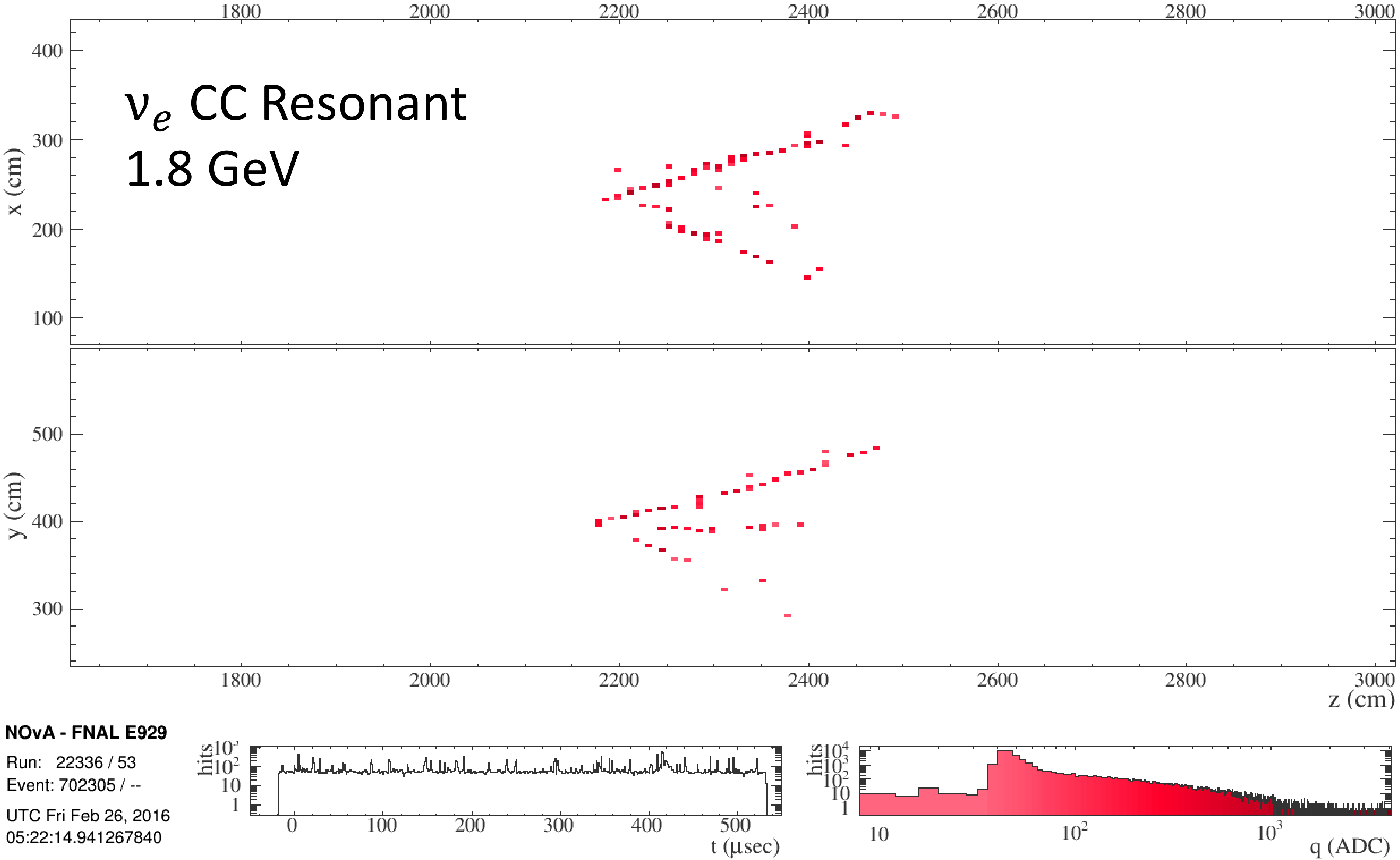


Neutrino interactions in NOvA



ν_μ CC Quasi-elastic
2.0 GeV

Neutrino interactions in NOvA



ν_e CC Resonant
1.8 GeV

NOvA - FNAL E929

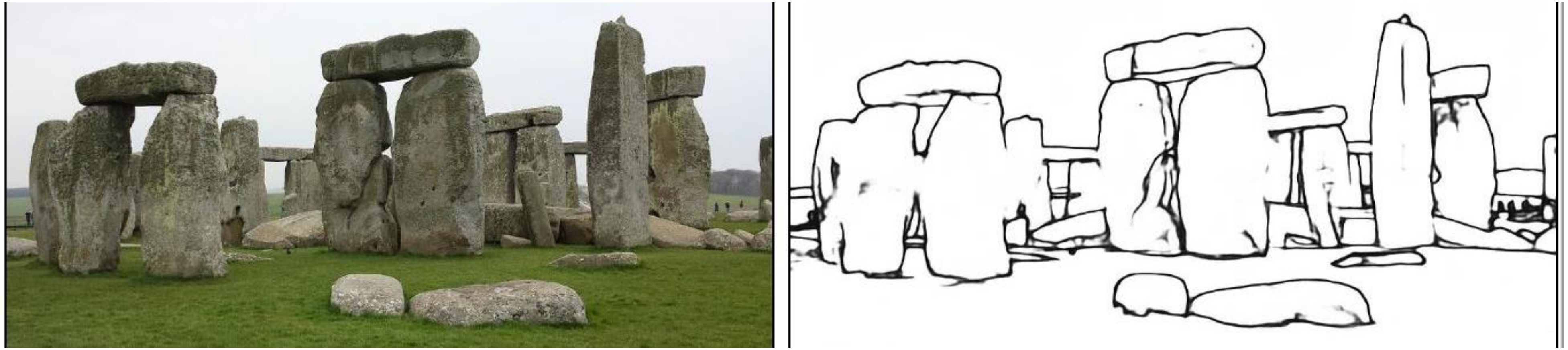
Run: 22336 / 53
Event: 702305 / --

UTC Fri Feb 26, 2016
05:22:14.941267840

Event identification with convolutional neural networks

Edge detection kernel

$$\frac{1}{8}\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$



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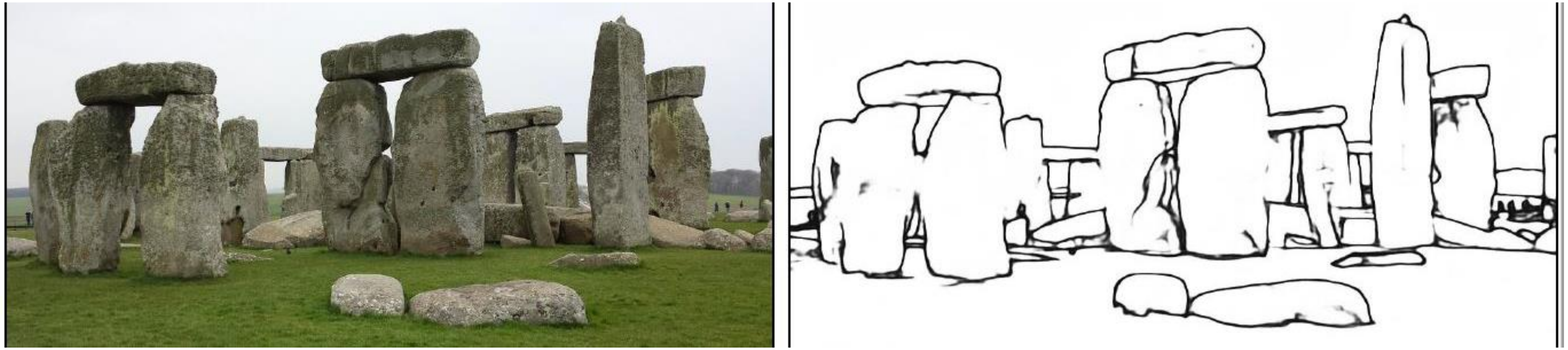
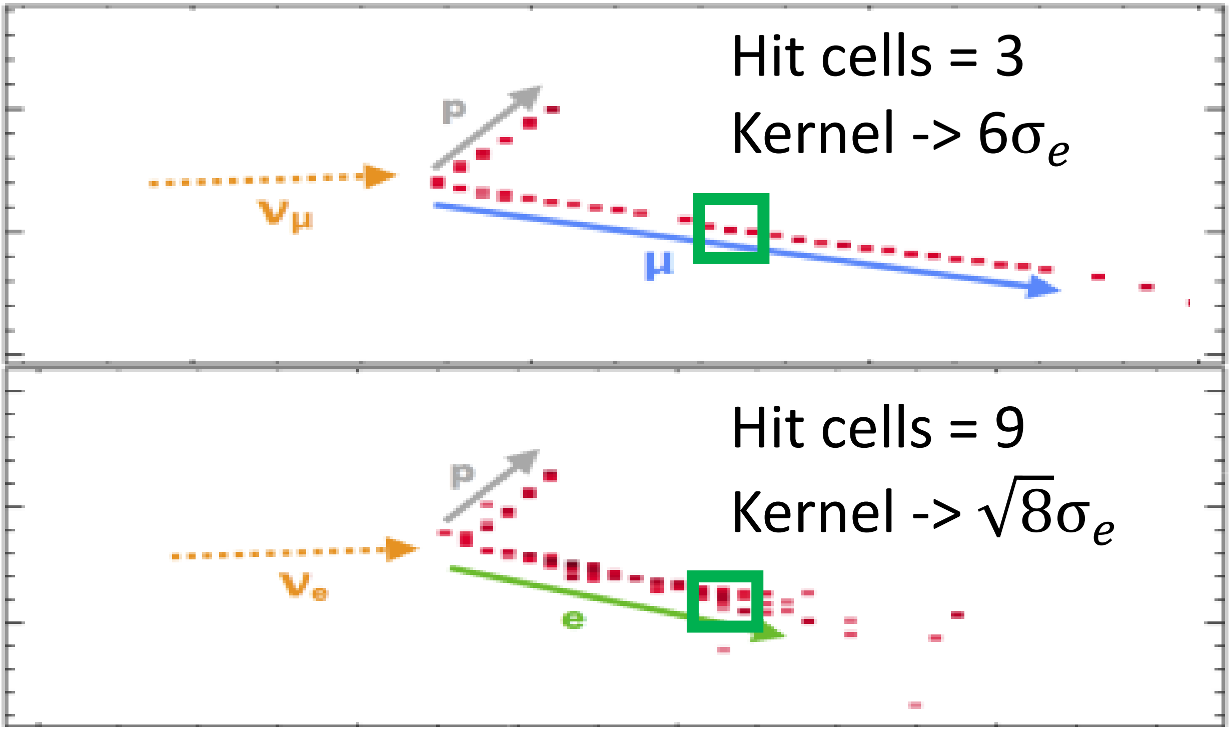




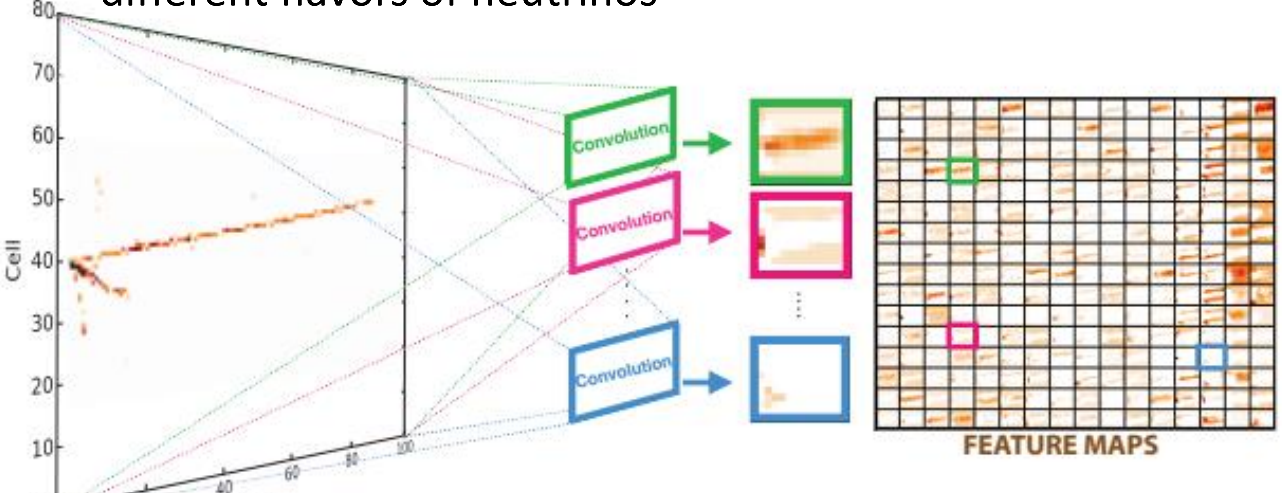
Hit cells = 3

Kernel -> $6\sigma_e$

Hit cells = 9

Kernel -> $\sqrt{8}\sigma_e$

CNN – train multiple kernels at different degrees of down-sampling which produce feature maps distinctive for different flavors of neutrinos



Aurisano et al., JINST 11 P09001 (2016)

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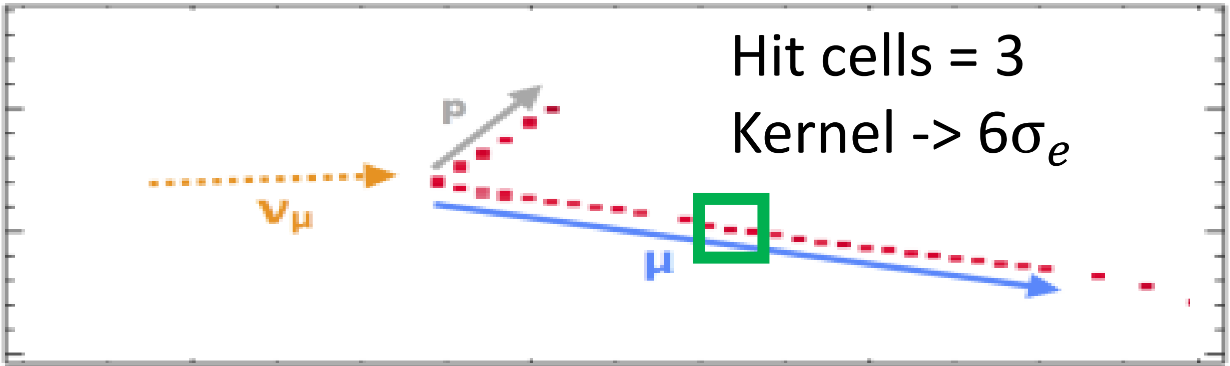

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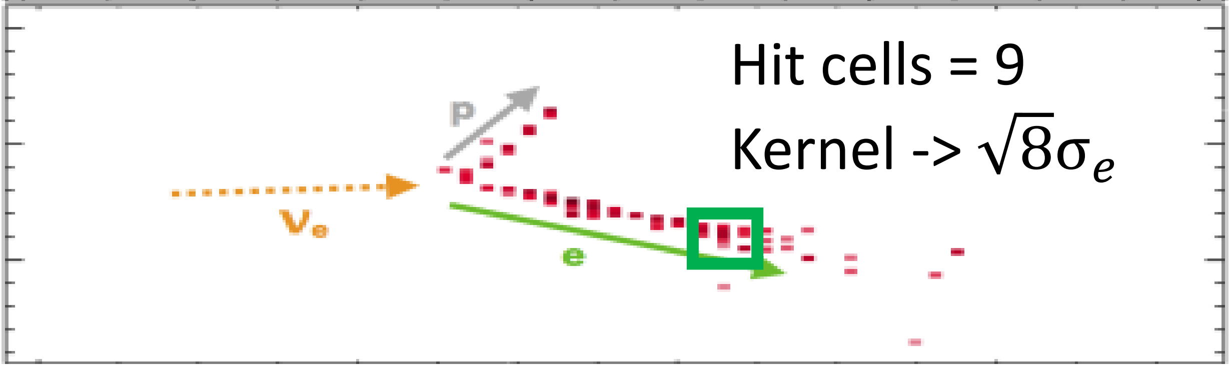
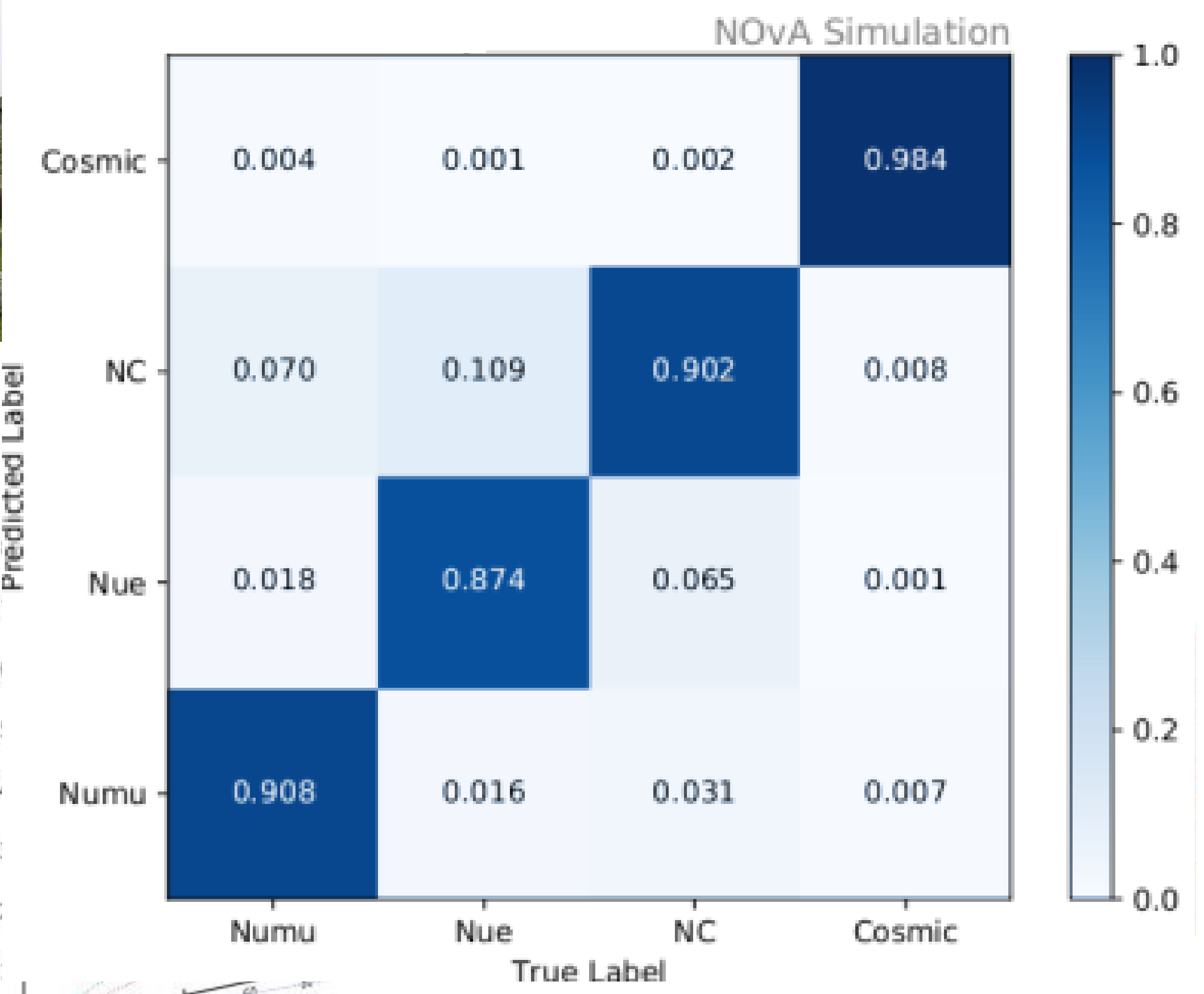


Hit cells = 9

Kernel -> $\sqrt{8}\sigma_e$

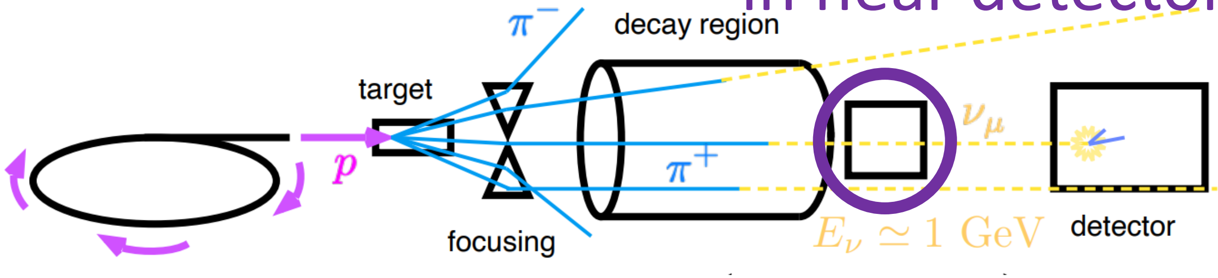


Predicted Label \ True Label	Numu	Nue	NC	Cosmic
Cosmic	0.004	0.001	0.002	0.984
NC	0.070	0.109	0.902	0.008
Nue	0.018	0.874	0.065	0.001
Numu	0.908	0.016	0.031	0.007

Aurisano et al., JINST 11 P09001 (2016)

Near detector data

Step 2: Measure in near detector

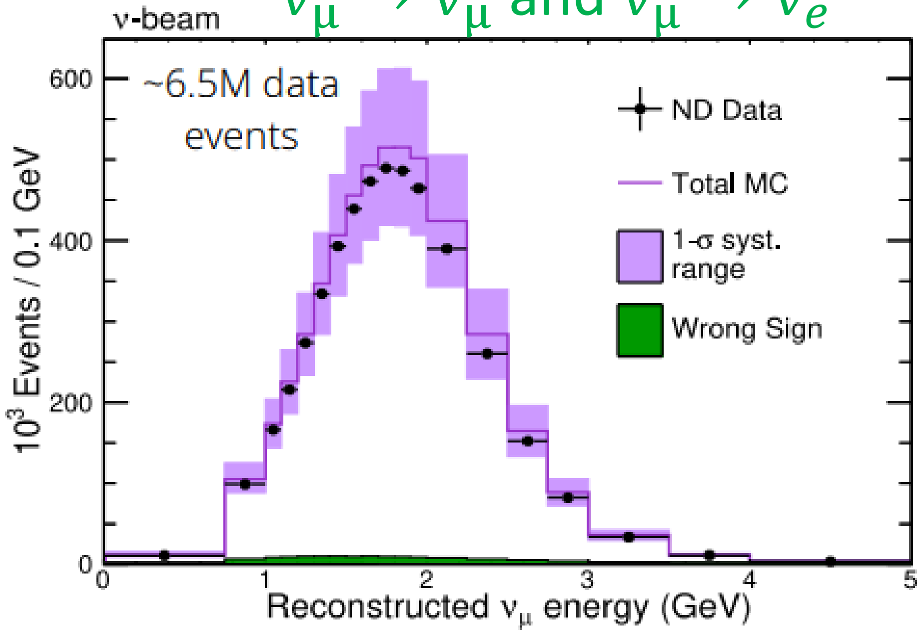


Apply CNN classifier to data to select events believed to be ν_μ or ν_e CC

Degree of mismatch with simulation must be propagated to the far detectors

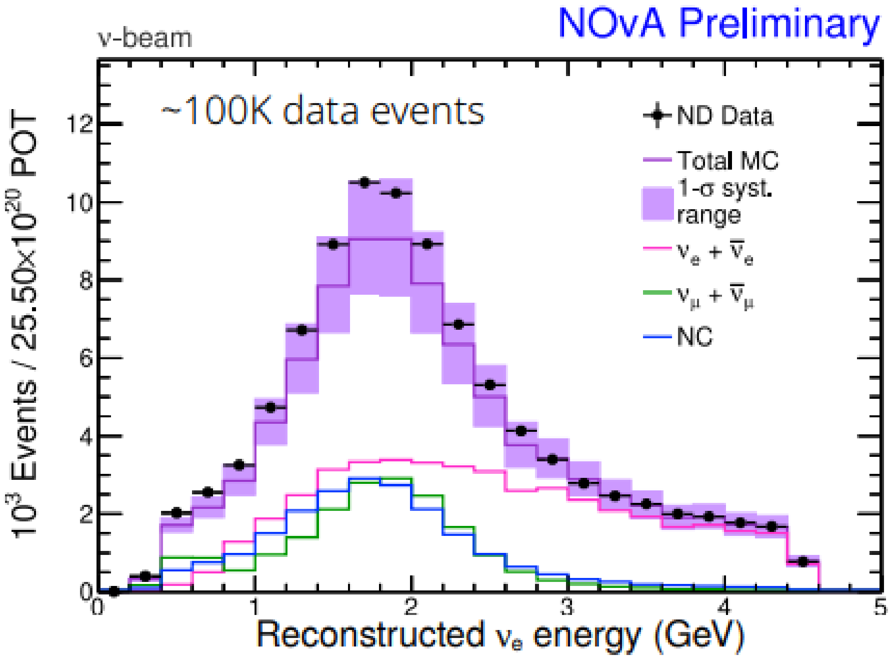
ν_μ CC-selected

Signal for channels $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$



ν_e CC-selected

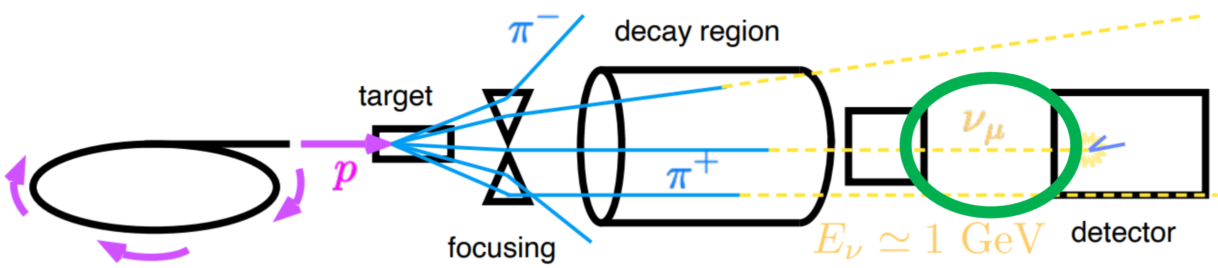
Background for $\nu_\mu \to \nu_e$



Constraining the far detector prediction – extrapolation

Apply simulated acceptance differences and oscillation probabilities channel-by-channel

Result: a data-driven constraint of the far detector signal prediction!



Step 3: extrapolate

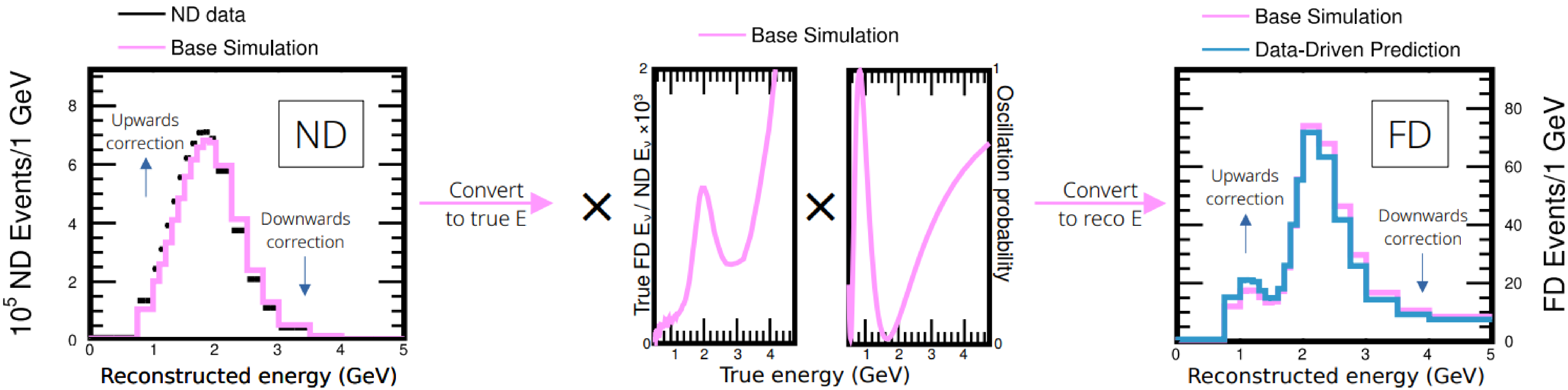
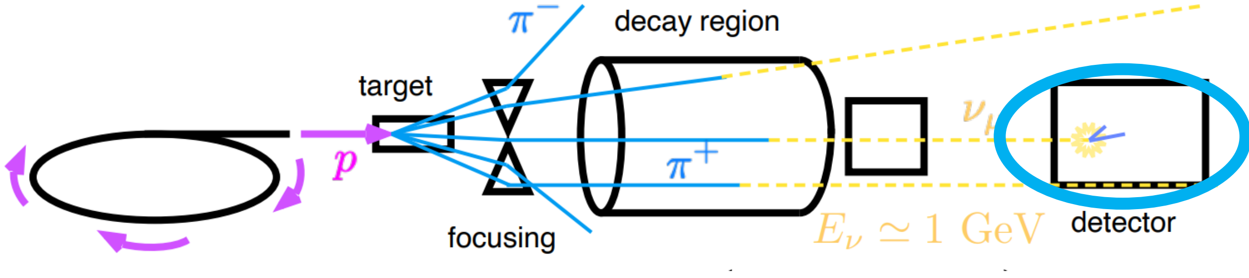


Image: Jeremy Wolcott

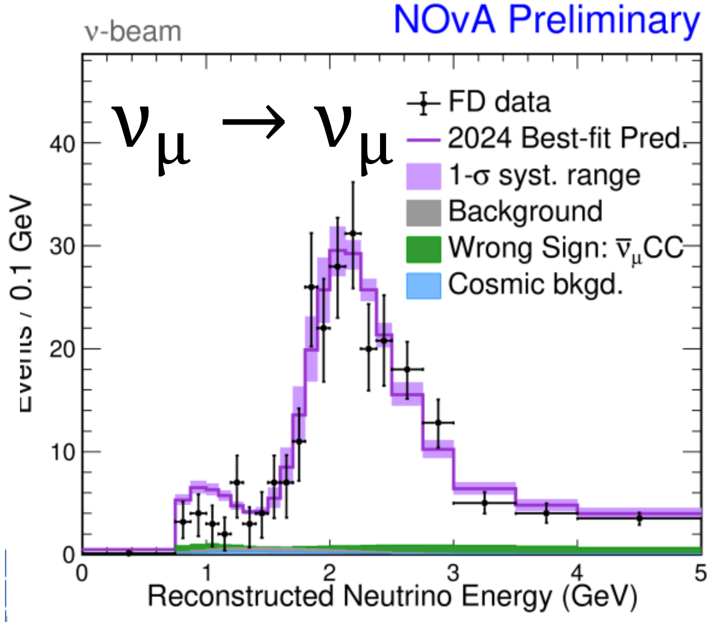
ν_μ disappearance data

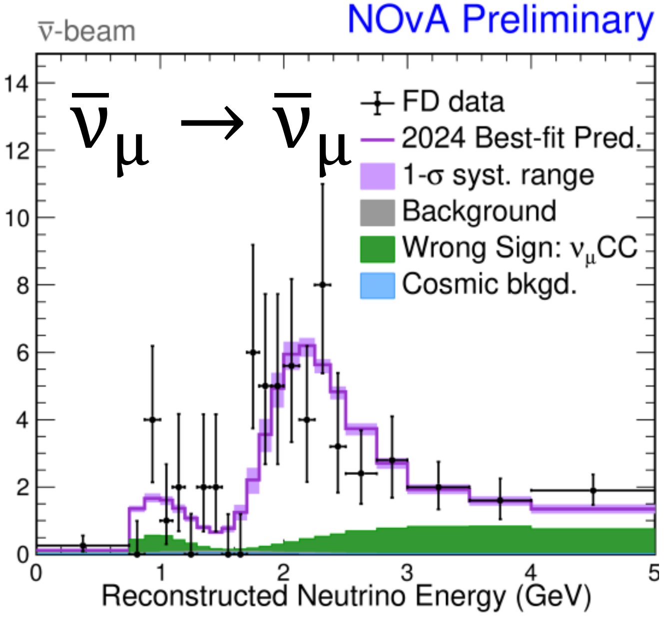
Step 4: far detector



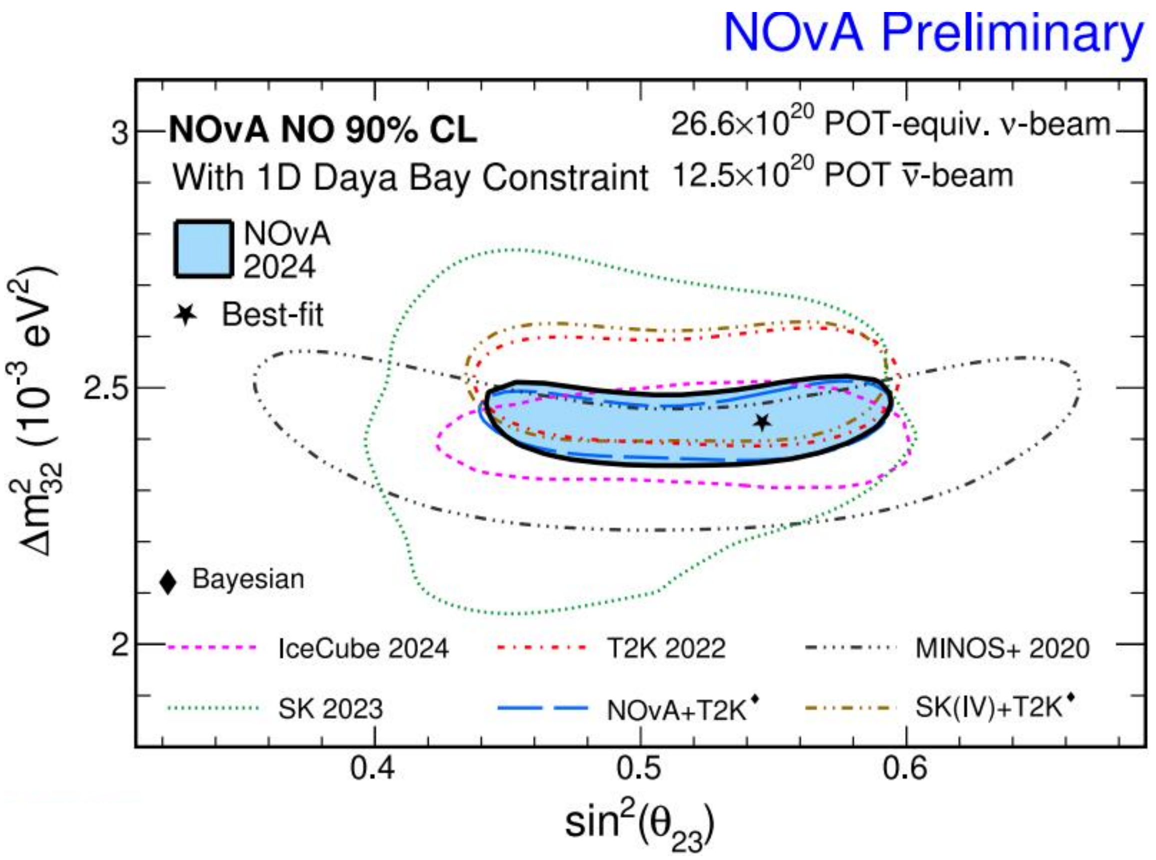
Simple oscillation formula, can check if θ_{23} is maximal

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



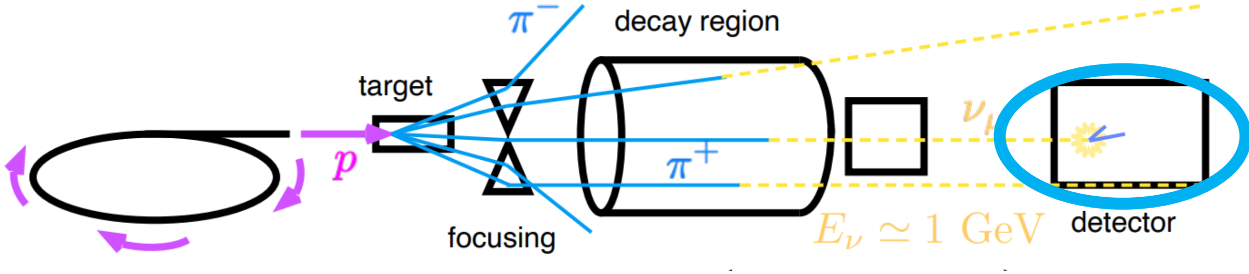


Jeremy Wolcott, Neutrino 2024

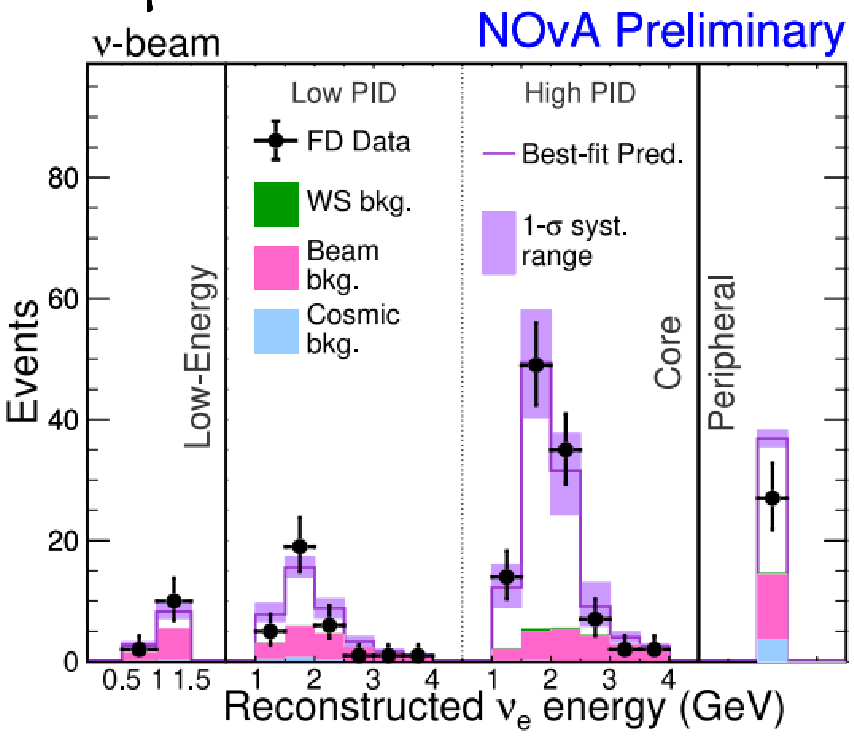


ν_e appearance data

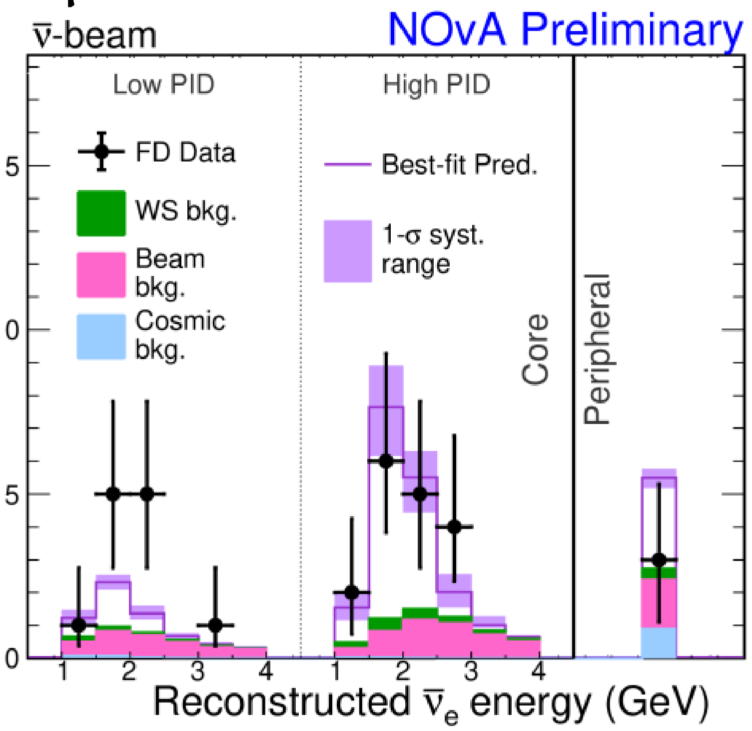
Step 4: far detector



$$\nu_\mu \rightarrow \nu_e$$



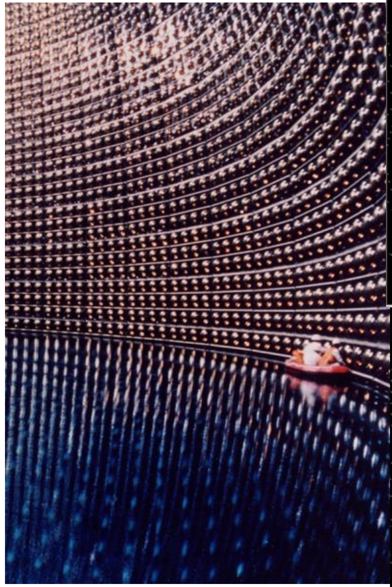
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

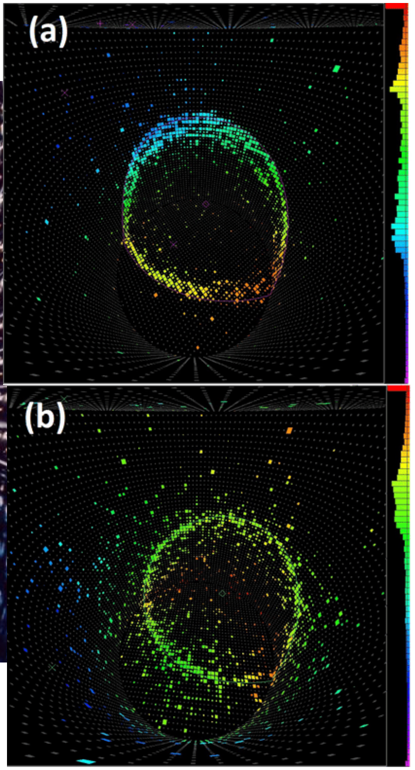


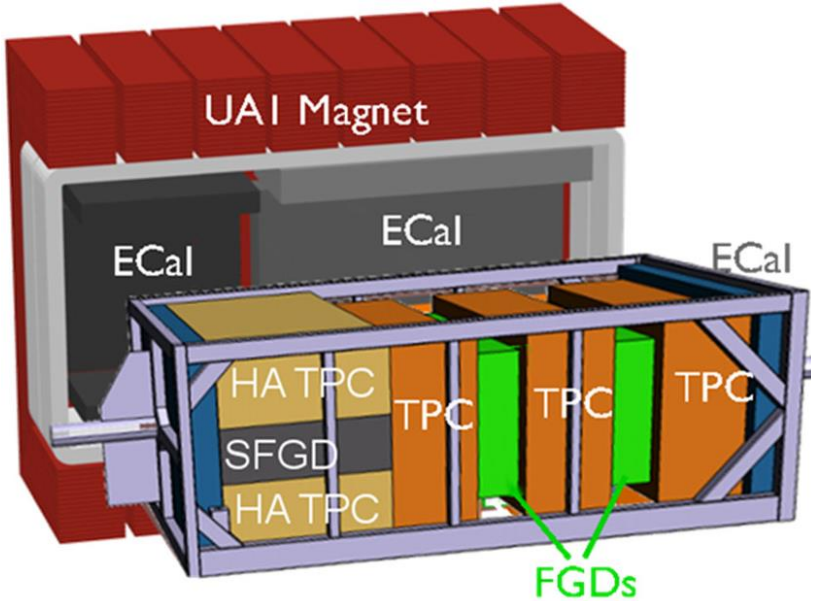
Jeremy Wolcott, Neutrino 2024

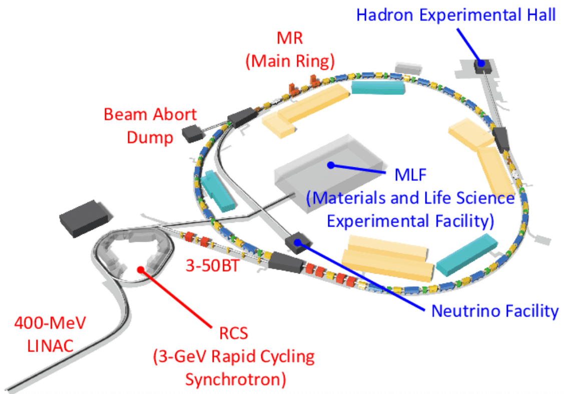
The T2K experiment

0.6 GeV beam from J-PARC
295-km baseline
Composite near detector
  with tracking capabilities
Far detector = SK

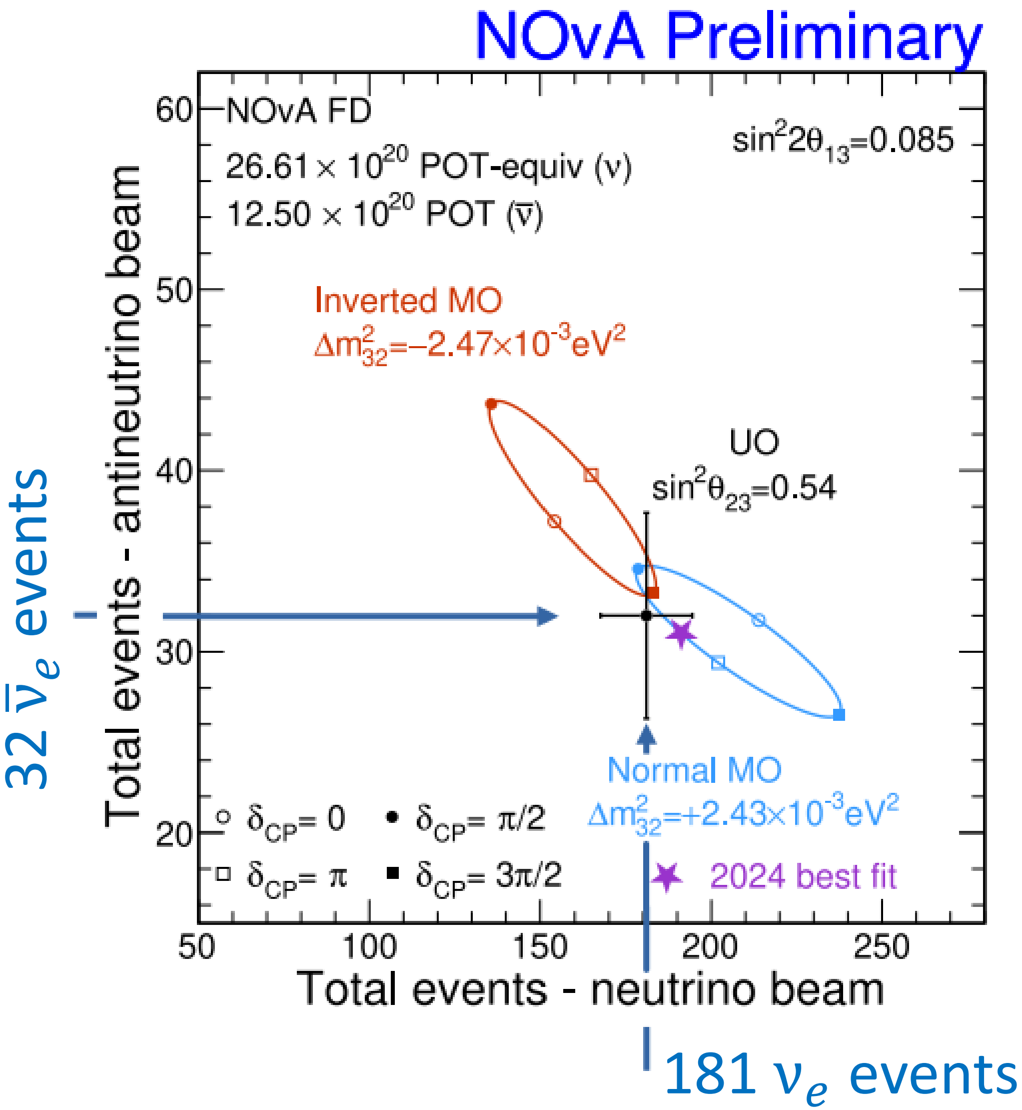






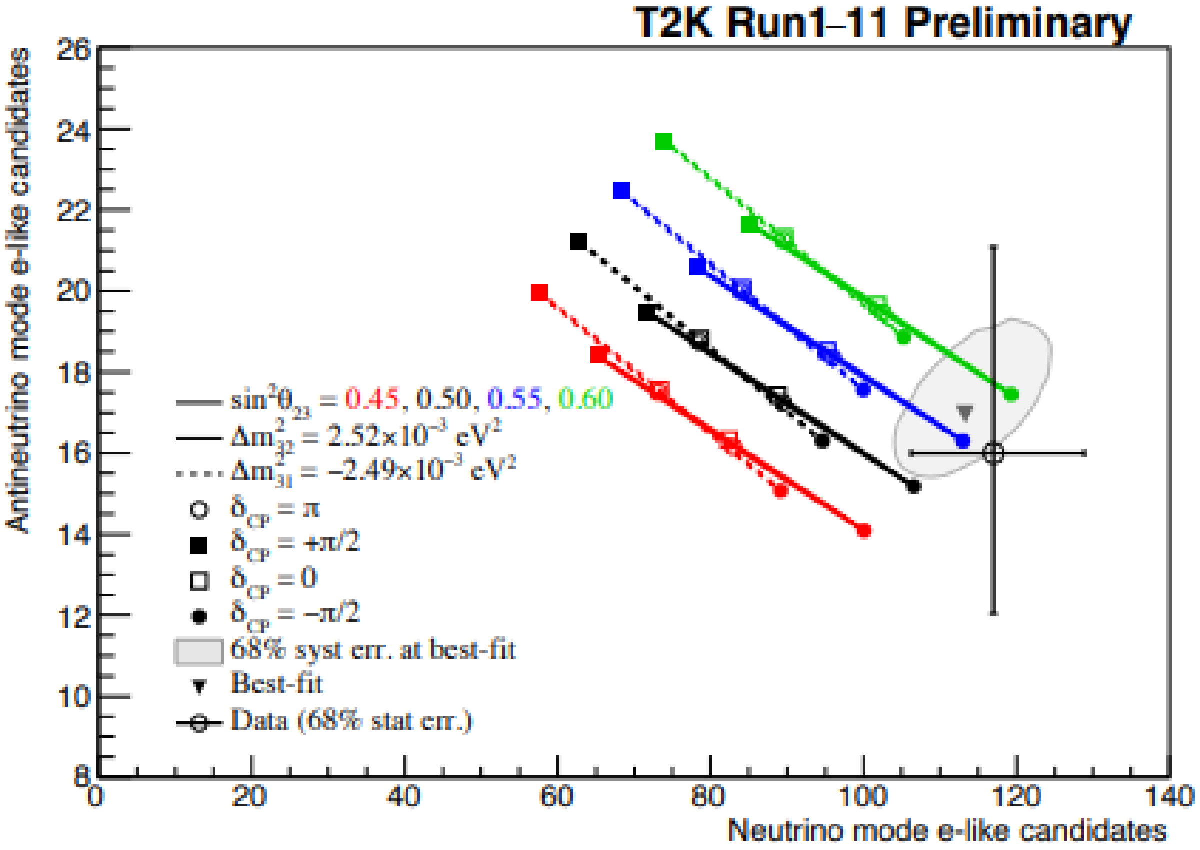


Summary of appearance data



$32\ \bar{\nu}_e$ events

$181\ \nu_e$ events

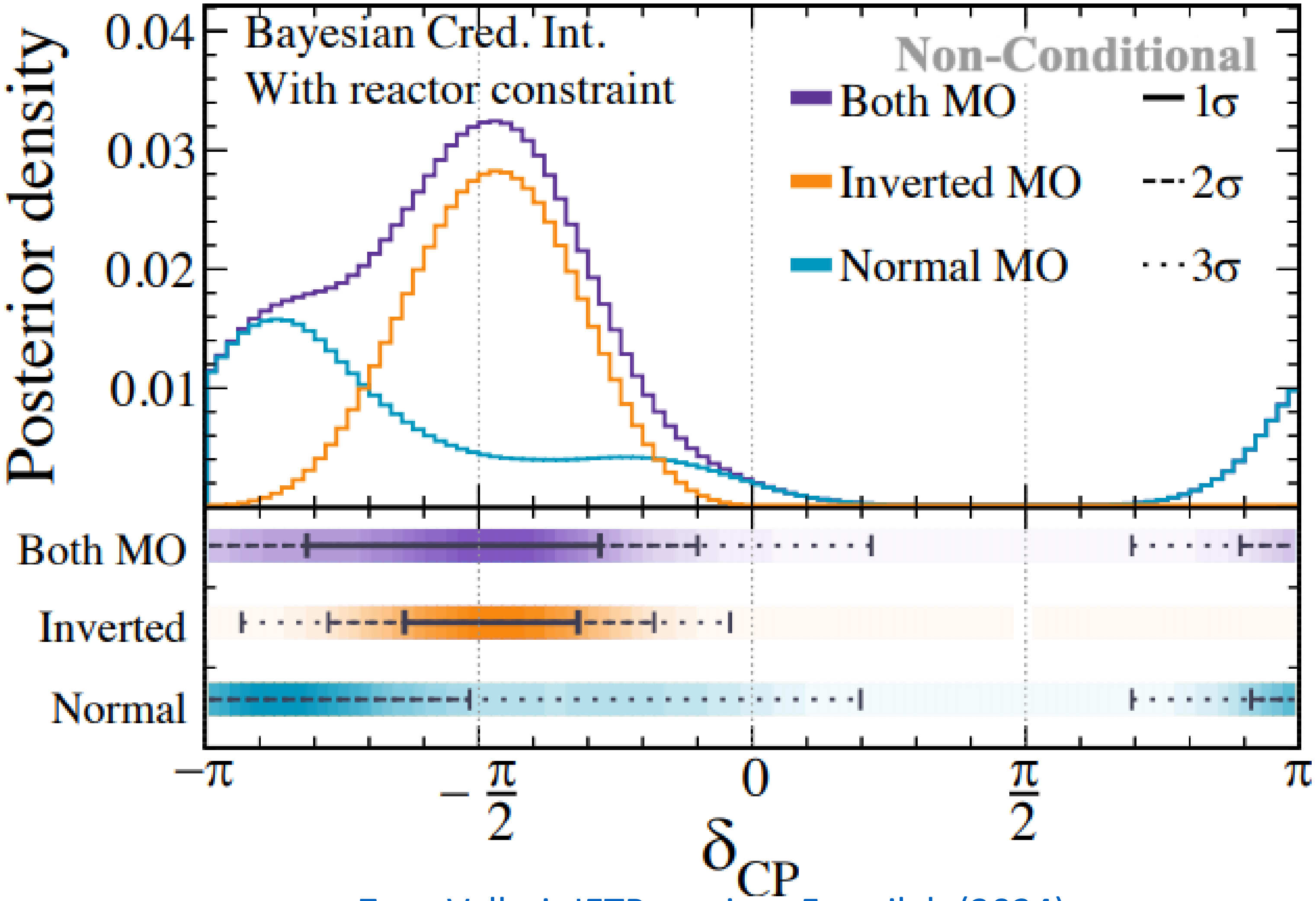


Joint NOvA/T2K data: CP violation and mass ordering

Slight overall preference for the inverted mass ordering

If mass ordering is inverted: $\delta_{CP} = 3\pi/2$ – to give more appearance in neutrino mode

Marginalizing over mass ordering and θ_{23}, we can say $\delta_{CP} = \pi/2$ is ruled out at > 3σ

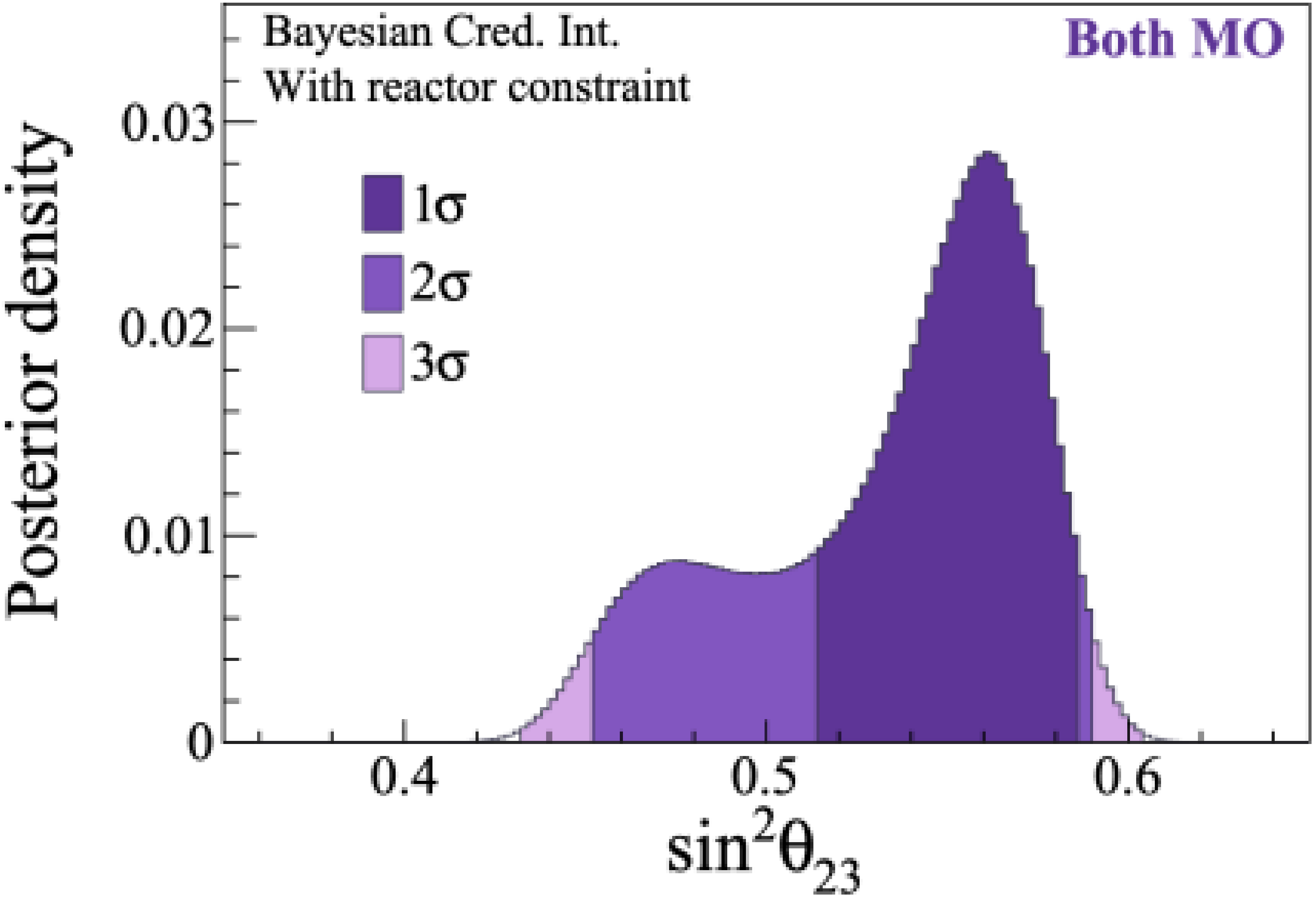


Zoya Vallari, JETP seminar Fermilab (2024)

Joint NOvA/T2K data: θ_{23} octant

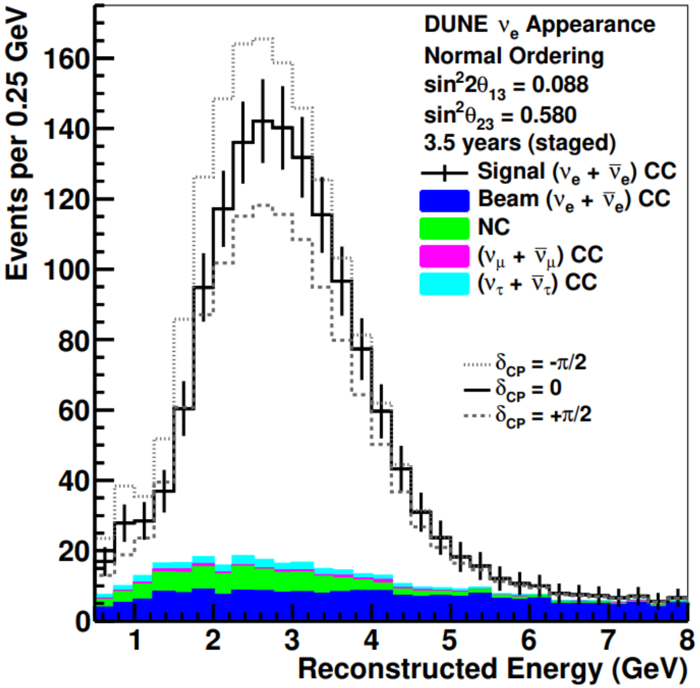
Slight preference for upper octant: $\theta_{23} > \pi/4$

Indication $\nu_e/\bar{\nu}_e$ appearance both more likely than expected in maximal mixing scenario



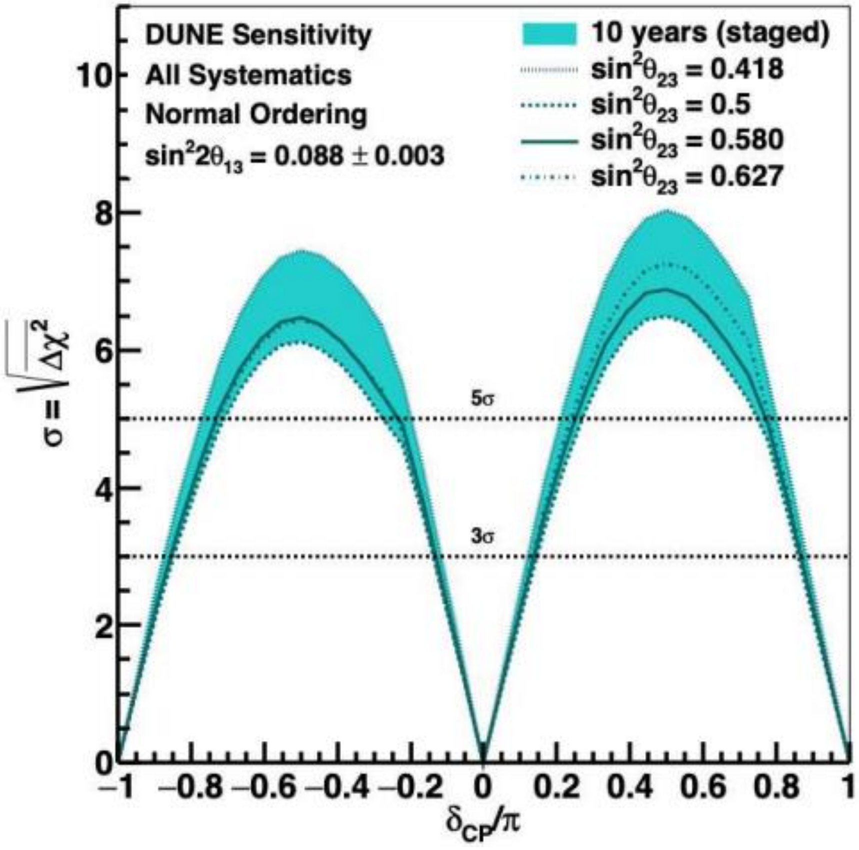
Zoya Vallari, JETP seminar Fermilab (2024)

Sensitivity of the future DUNE experiment

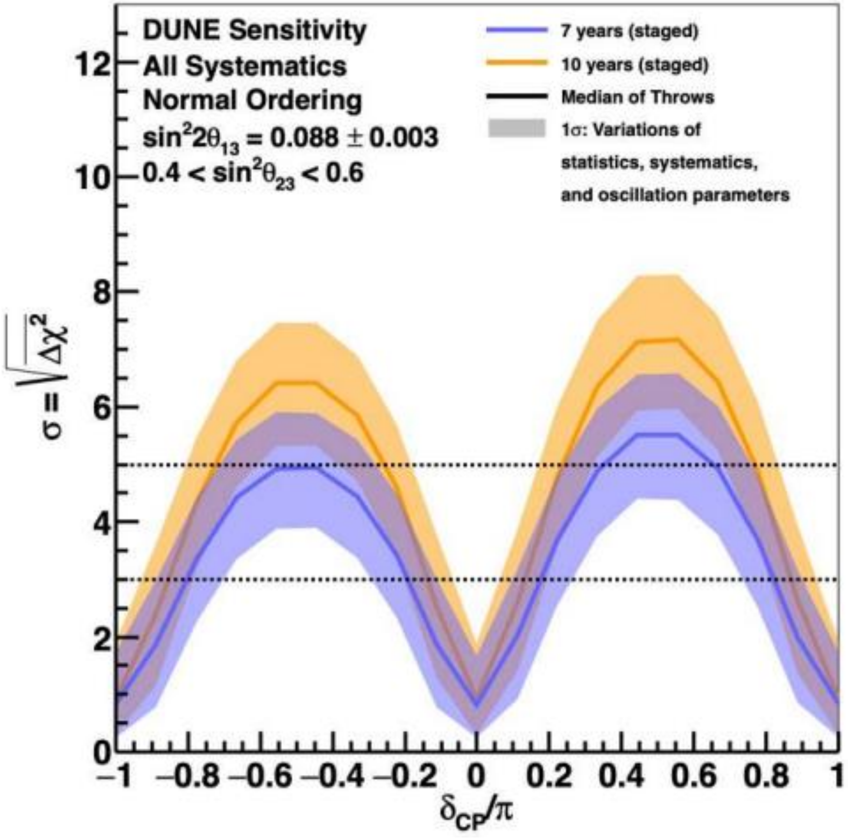


DUNE experiment will massively improve the datasets for appearance

Mass ordering



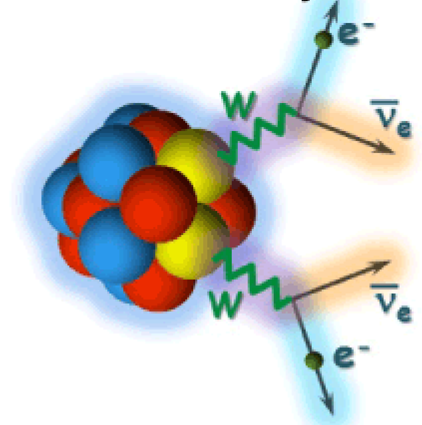
CP violation



Direct mass measurements

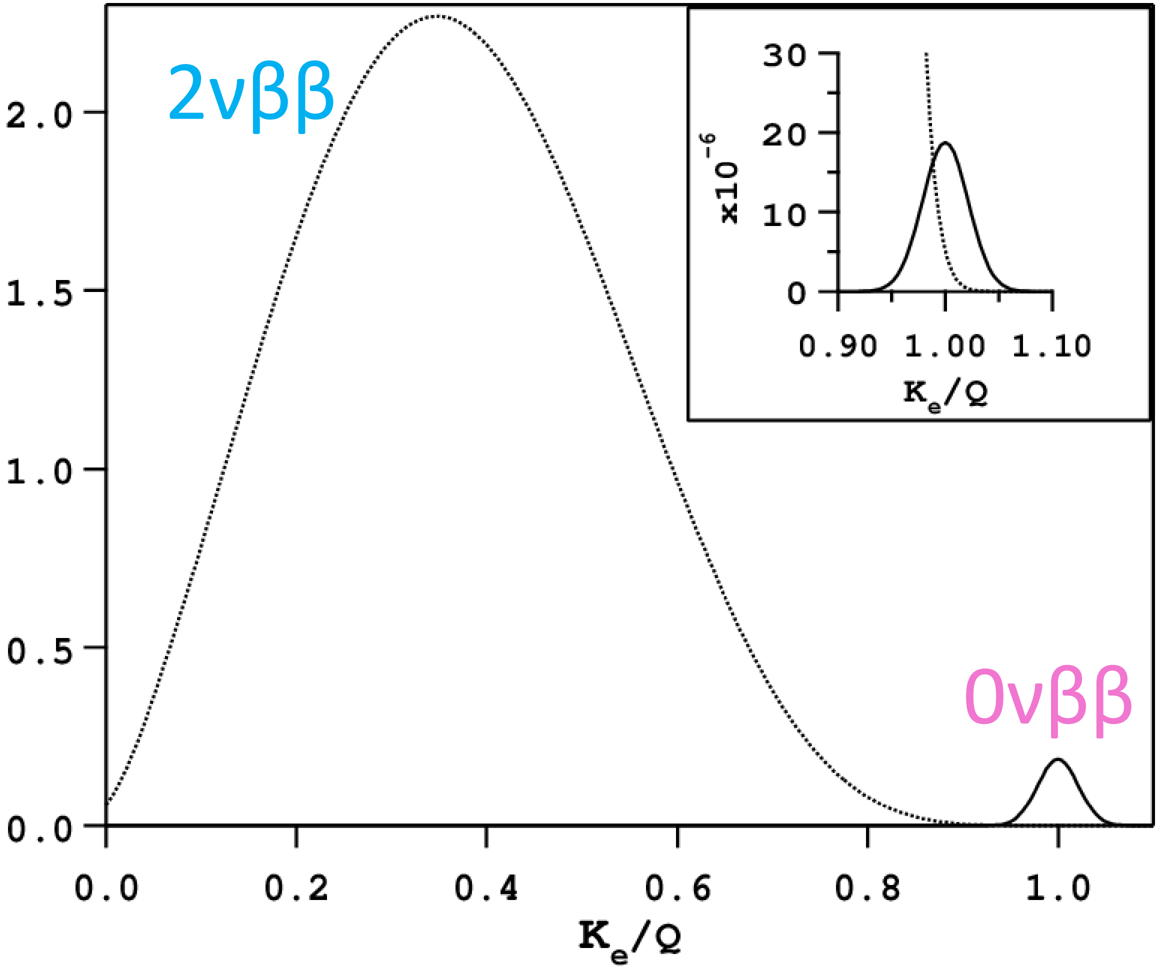
Double beta decay

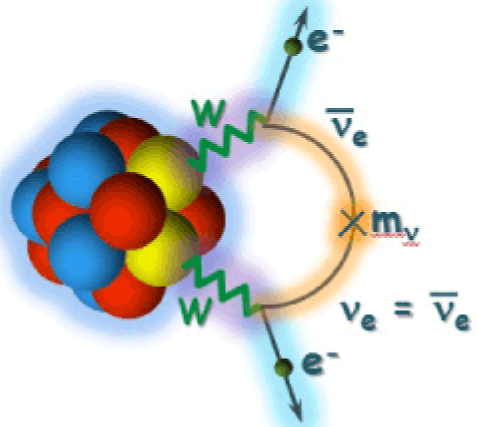
【Double beta decay】



Double beta decay
which emits anti-neutrinos

ΔL = 0





Neutrinoless
double beta decay

ΔL = 2

What we measure

$$\left[\underline{T^{0\nu}_{1/2}\left(0^+ \to 0^+\right)}\right]^{-1} = G^{0\nu}(E_0, Z)\left|M^{0\nu}\right|^2 \underline{\langle m_{\nu_e}\rangle^2}$$

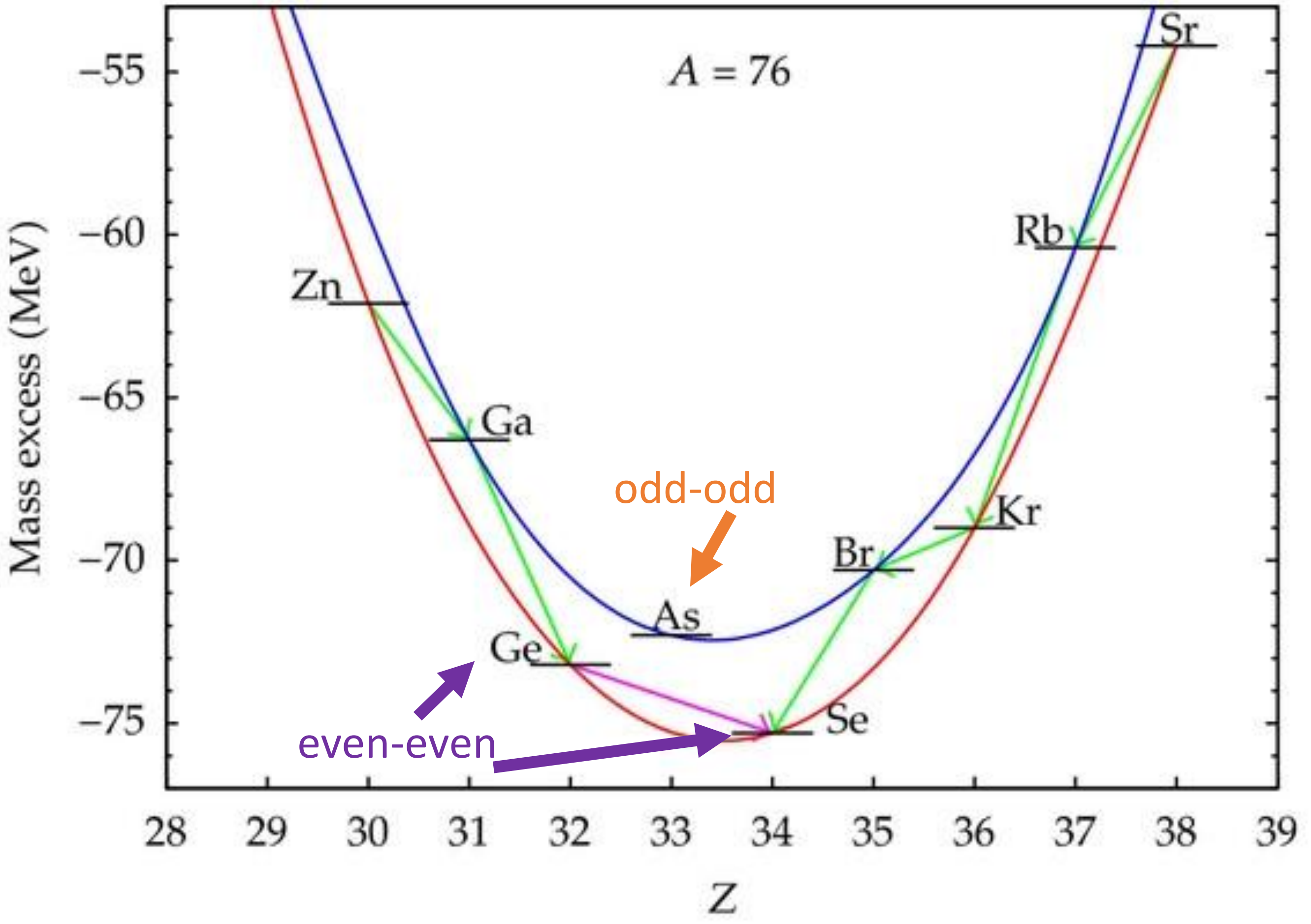
What we want

Finding candidate nuclei

Consider nuclei whose 1β decay is kinematically forbidden!

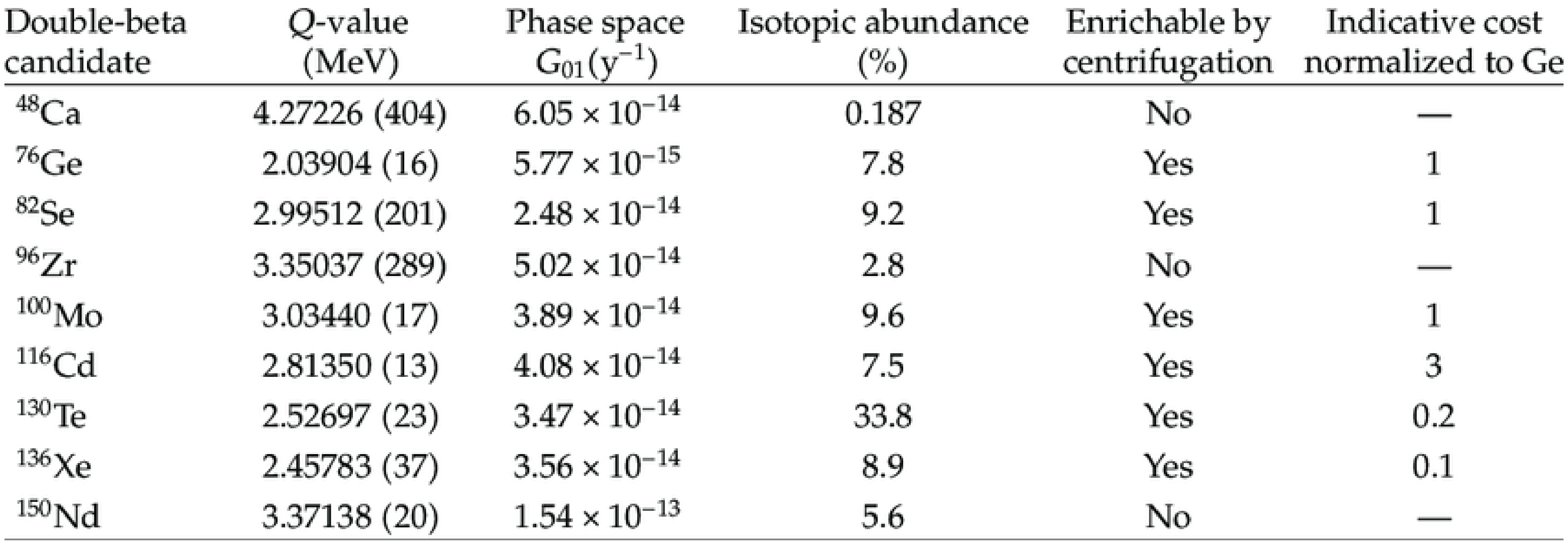
General trends in binding energy for nuclei as a function of proton number for a given atomic mass

– Due to unpaired nucleons, odd-odd nuclei have higher binding energy than typical
– Look for most stable even-even for a given atomic mass



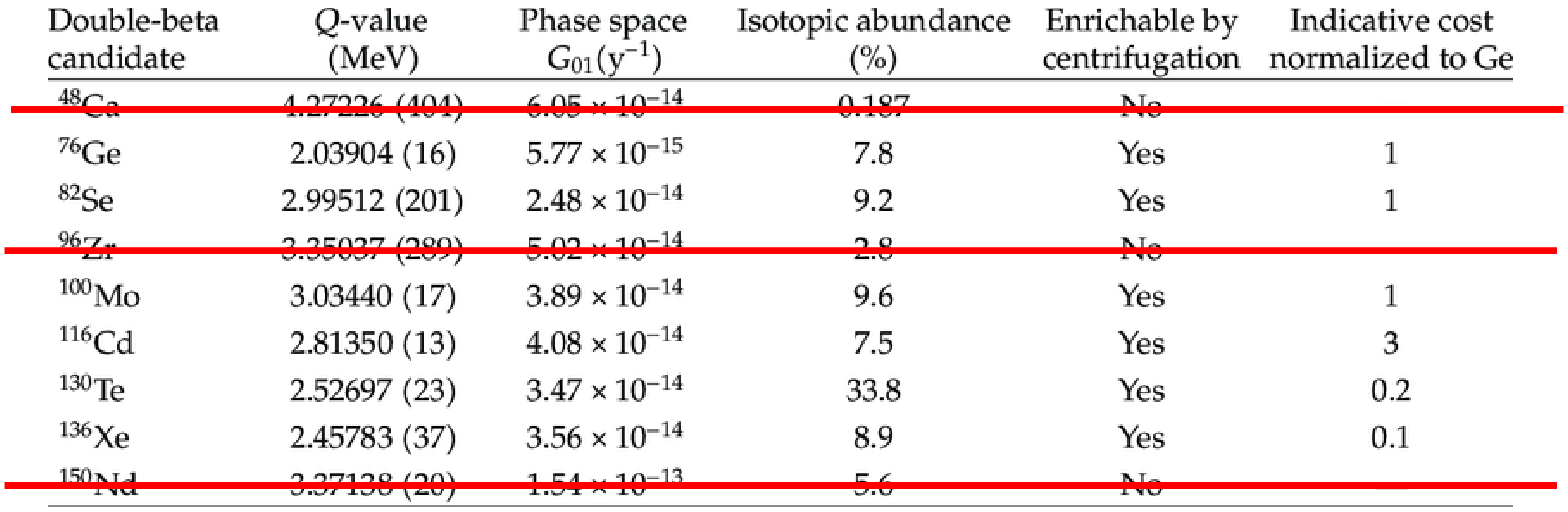
^{48}Ca	^{76}Ge	^{82}Se	^{96}Zr	^{100}Mo	^{116}Cd	^{130}Te	^{136}Xe	^{150}Nd	^{238}U

Choosing your target



Double-beta candidate	*Q*-value (MeV)	Phase space $G_{01}(y^{-1})$	Isotopic abundance (%)	Enrichable by centrifugation	Indicative cost normalized to Ge
^{48}Ca	4.27226 (404)	6.05×10^{-14}	0.187	No	—
^{76}Ge	2.03904 (16)	5.77×10^{-15}	7.8	Yes	1
^{82}Se	2.99512 (201)	2.48×10^{-14}	9.2	Yes	1
^{96}Zr	3.35037 (289)	5.02×10^{-14}	2.8	No	—
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes	1
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes	3
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes	0.2
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes	0.1
^{150}Nd	3.37138 (20)	1.54×10^{-13}	5.6	No	—

Choosing your target



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Choosing your target

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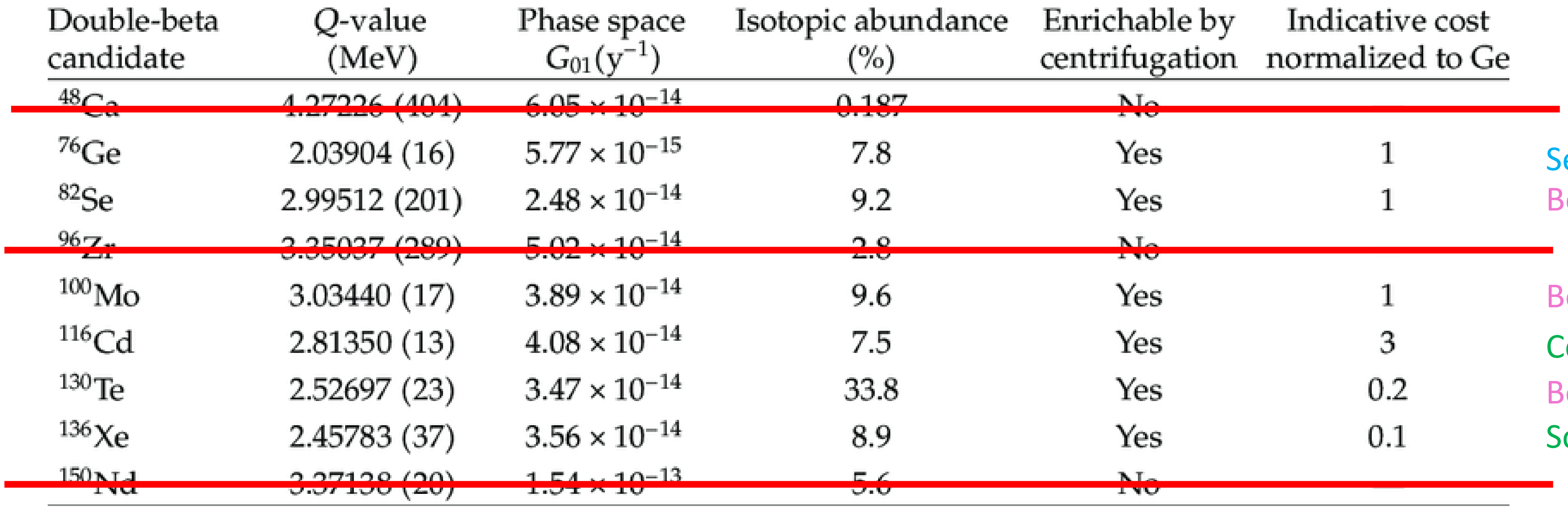
~~^{96}Zr~~	~~3.35037 (289)~~	~~5.02×10^{-14}~~	~~2.8~~	~~No~~		
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes	1	Bolometer
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes	3	$CdWO_4$ scintillator
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes	0.2	Bolometer
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes	0.1	Scintillator
~~^{150}Nd~~	~~3.37138 (20)~~	~~1.54×10^{-13}~~	~~5.6~~	~~No~~	~~—~~	

Choosing your target



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~~^{150}Nd~~	~~3.37138 (20)~~	~~1.54×10^{-13}~~	~~5.6~~	~~No~~		

Focus on one example of each technology

Semiconductor
^{76}Ge – LEGEND-200

Bolometer
^{130}Te – CUORE

Scintillator
^{136}Xe – KamLAND-Xen

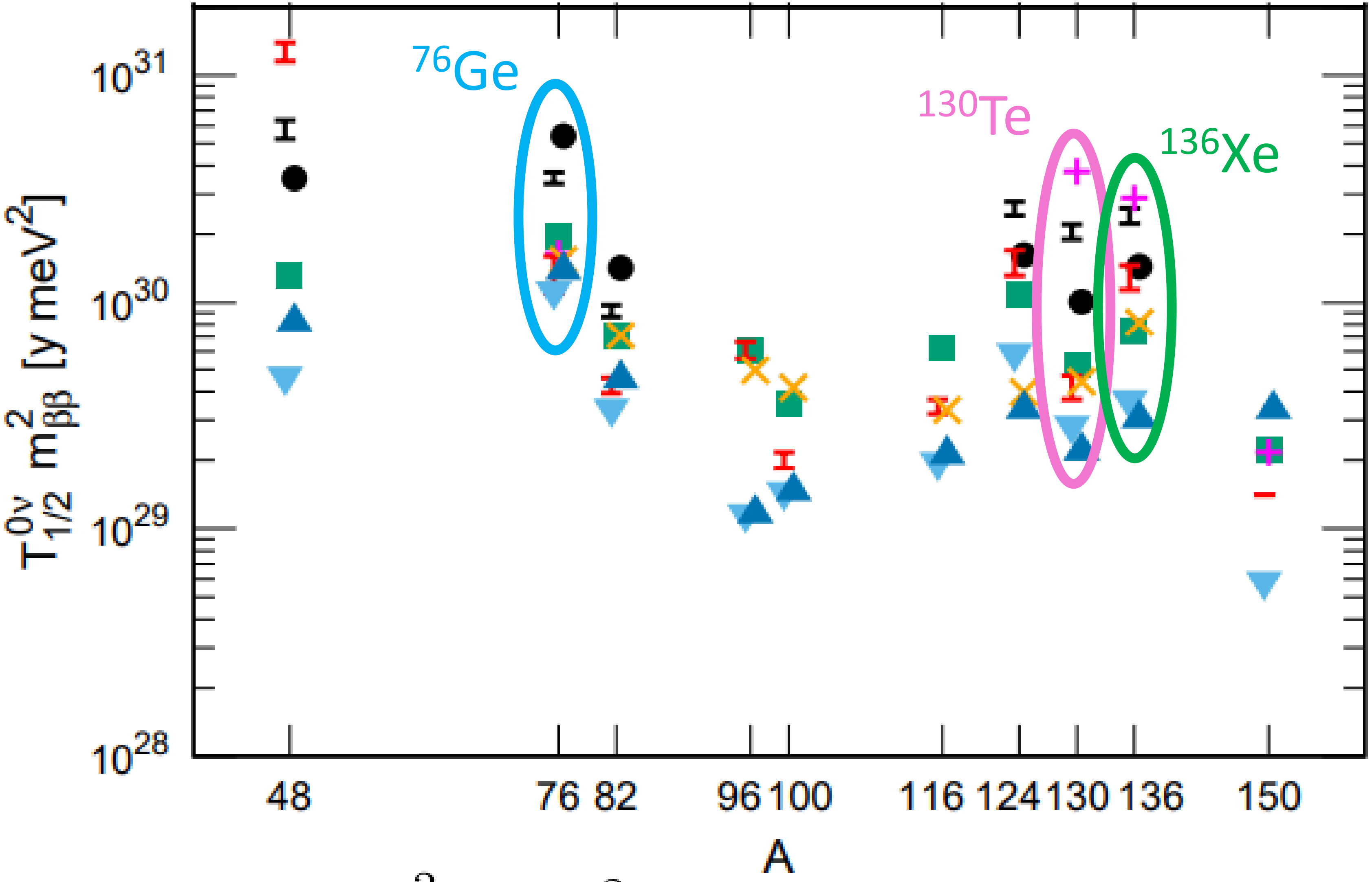
Translating to neutrino mass: nuclear theory

Relies on "nuclear matrix element"

$\langle {}^{76}\mathrm{Ge}|0\nu\beta\beta|{}^{76}\mathrm{Se}\rangle$

Depends on neutrino mass: needs helicity flip!

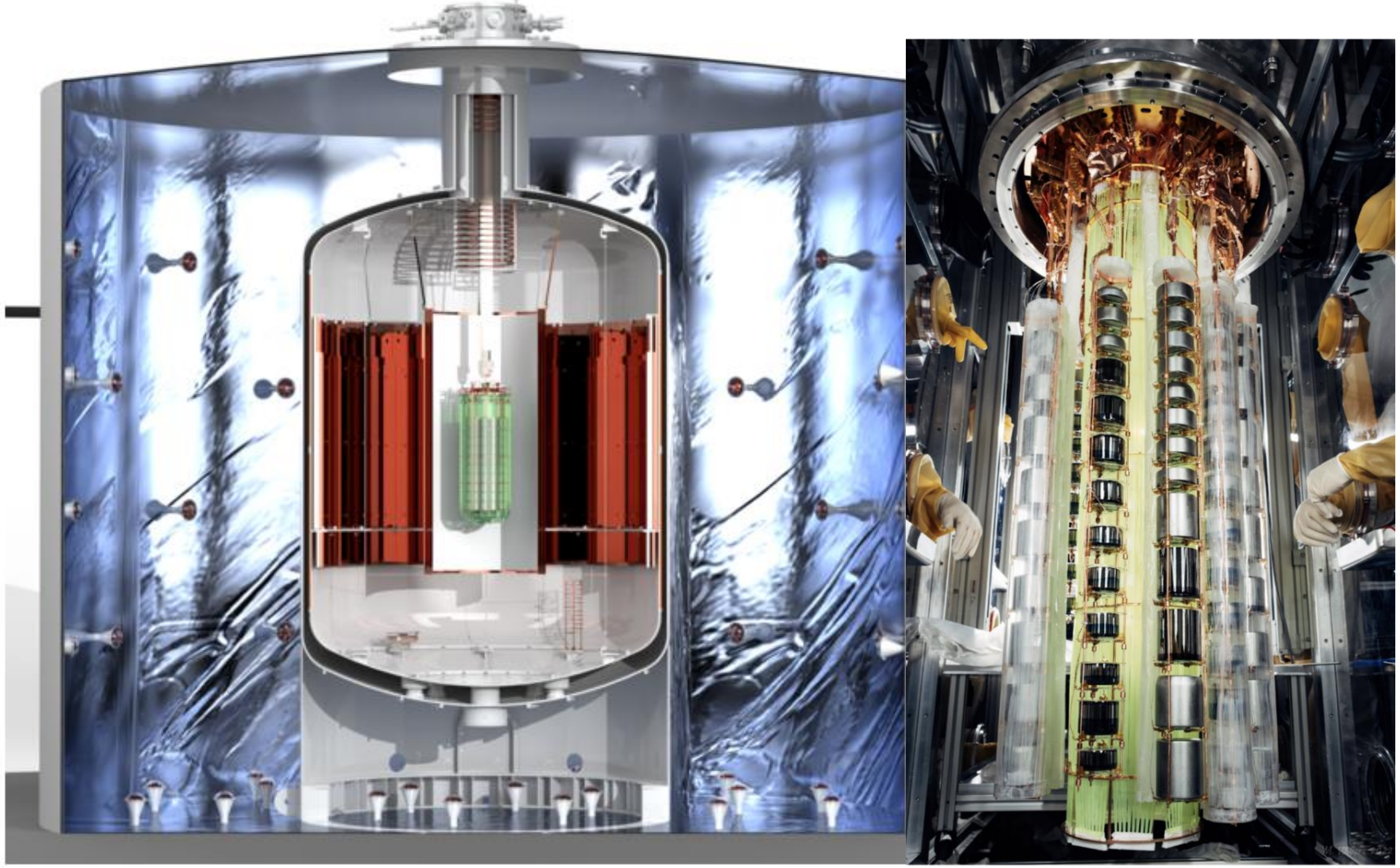
Some nuclei intrinsically more efficient at probing neutrino mass



$$\left[T^{0\nu}_{1/2}\left(0^+ \to 0^+\right)\right]^{-1} = G^{0\nu}(E_0, Z)\underline{|M^{0\nu}|}^2 \langle m_{\nu_e}\rangle^2$$

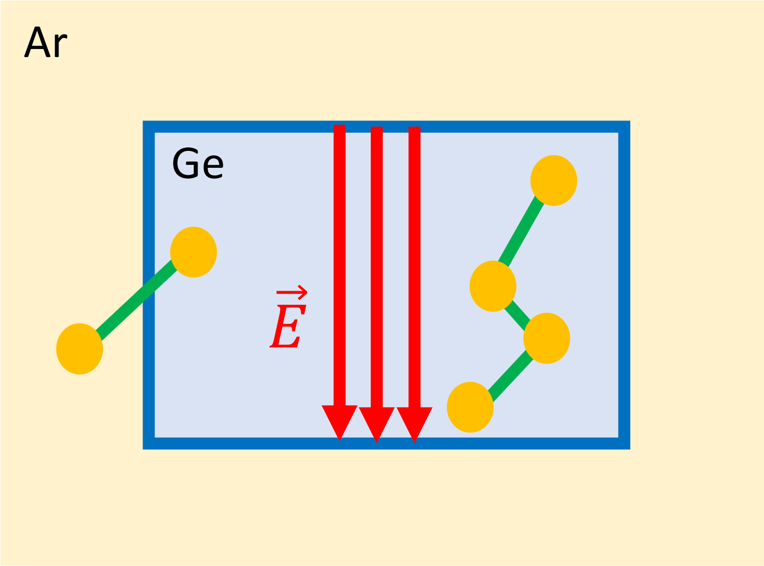
Ge: the LEGEND-200 experiment

Mass: 200 kg
Enrichment: up to 92%
Energy resolution: ~ 0.1%
Background: 5.3e-4 /keV/kg/yr



200 Ge semiconductor ionizing detectors
Inner liquid argon scintillating veto
Outer water Cherenkov veto

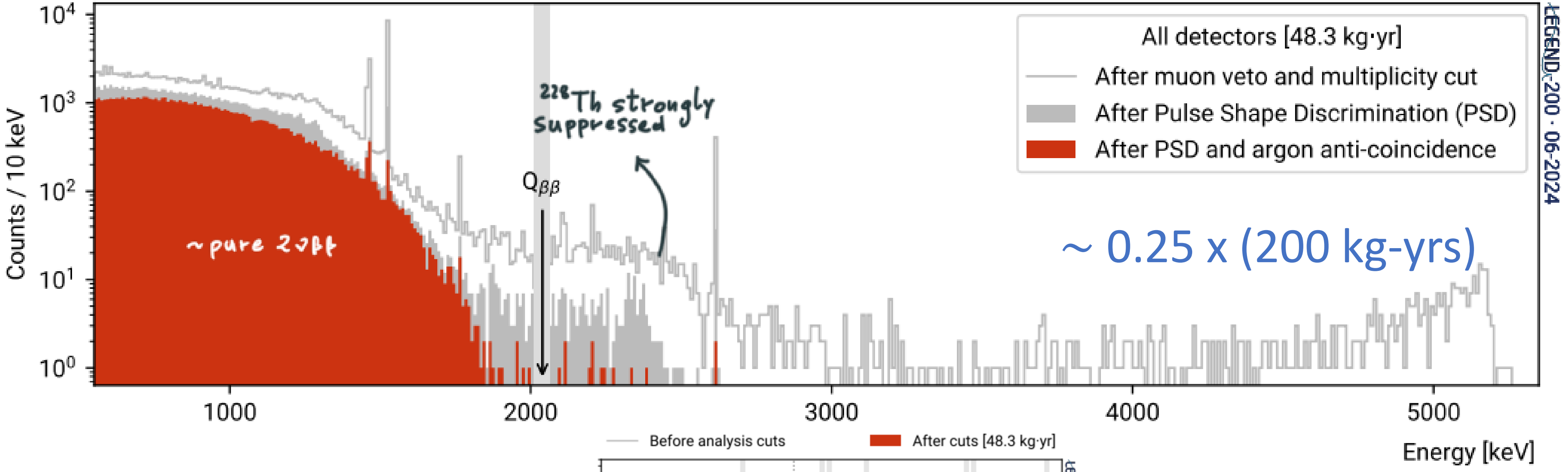
Controlling backgrounds
with multi-site rejection



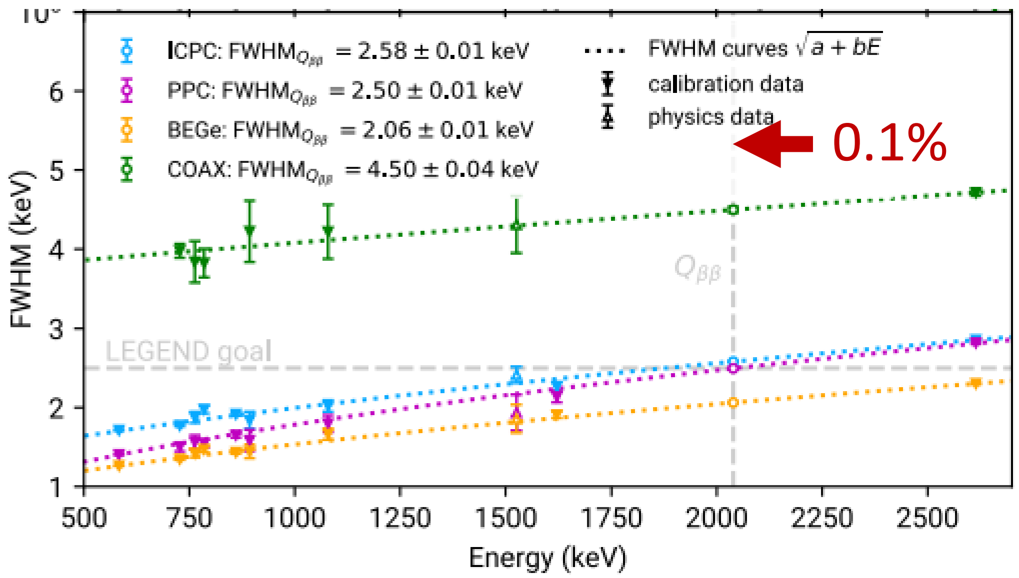
1: Pulse shape discrimination
2: Argon anti-coincidence

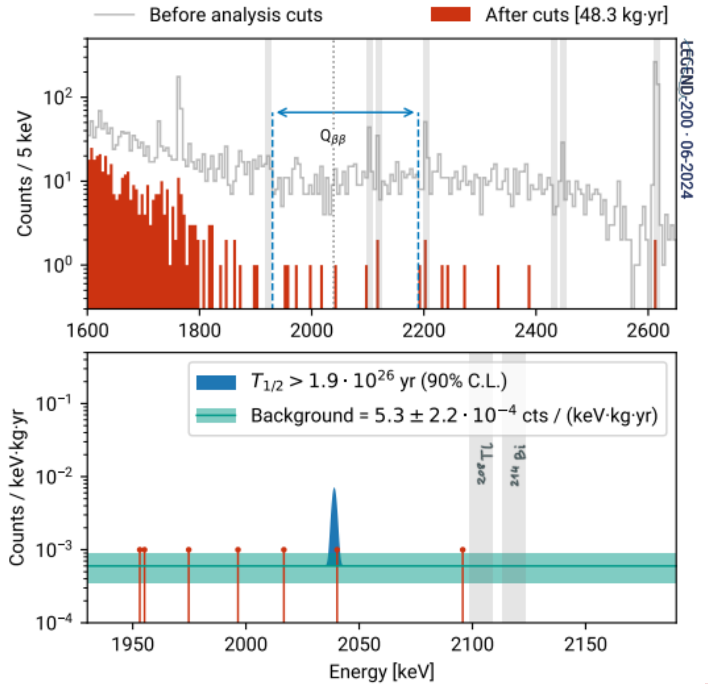
First results

Two-stage strategy for background mitigation reduces by 100x



~ 0.25 x (200 kg-yrs)





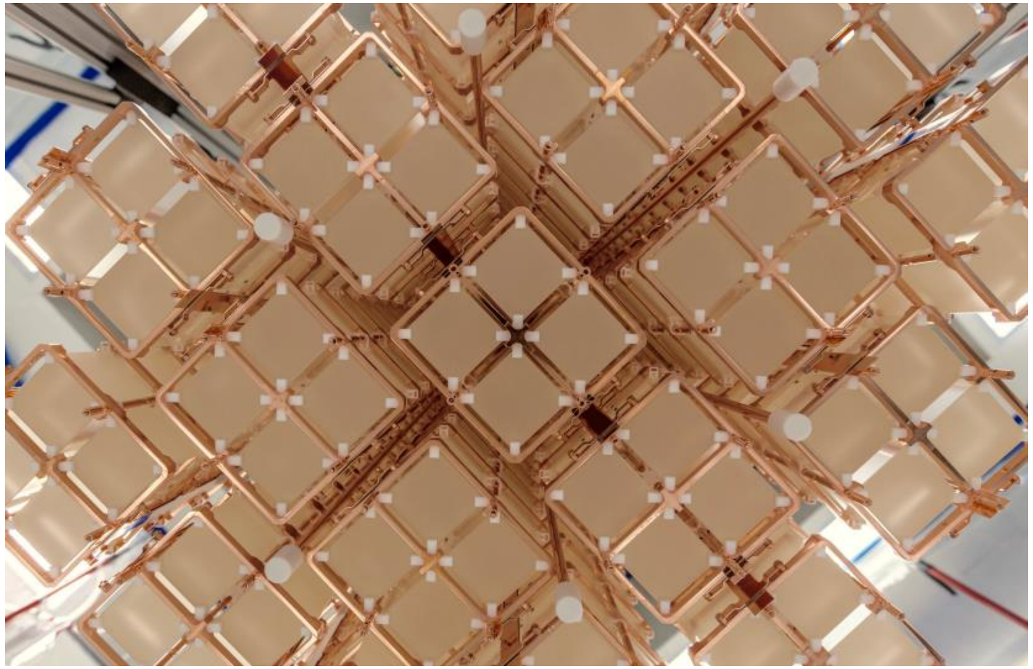
First results –
7 events in ROI
$T_{1/2}$ > 1.9e26 yr

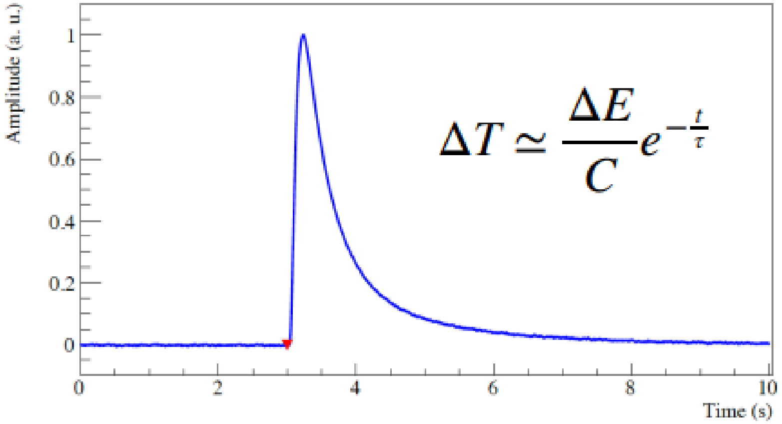
Preliminary

Luigi Pertoldi, Neutrino 2024

Te: the CUORE experiment

Mass: 742 kg
Natural abundance: 34%
Energy resolution: ~ 0.1%
Background: 1.4e-2 /keV/kg/yr



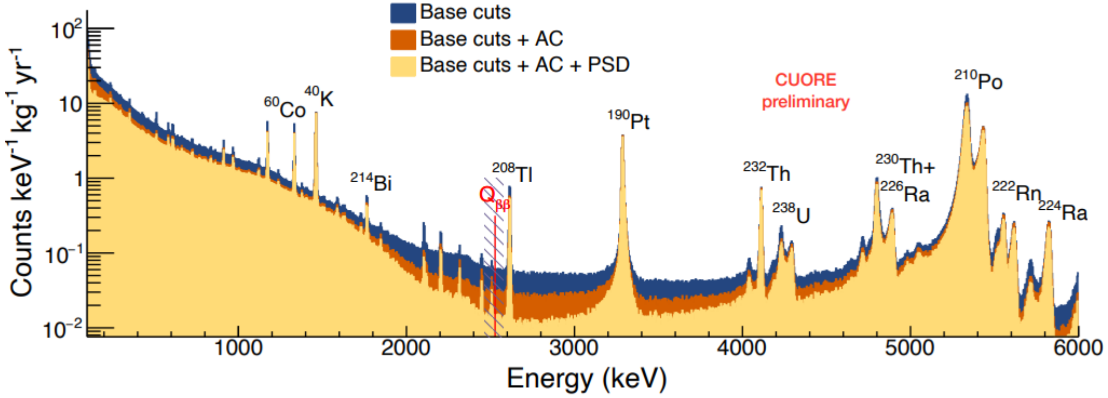


988 TeO_2 bolometers in 10 mK cryostat
No active veto – but passive shielding

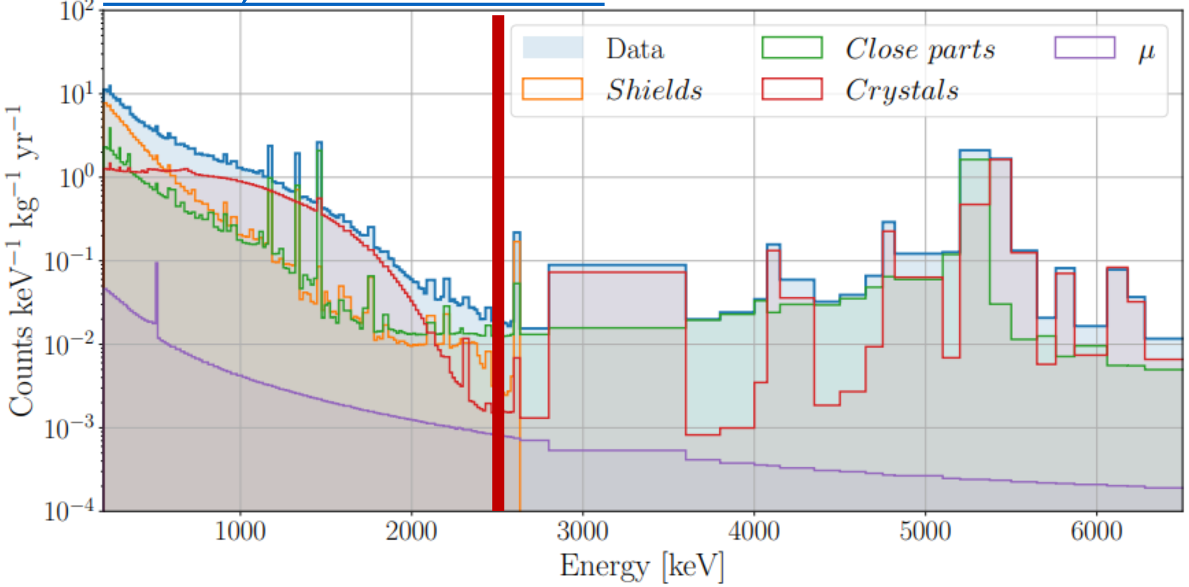
Slow pulses – background rejection is difficult
Veto for coincidence activity in multiple detectors

Te: the CUORE experiment

Full background characterization in response to larger background rate
Natural radioactive shielding in tower structure and shielding dominate background

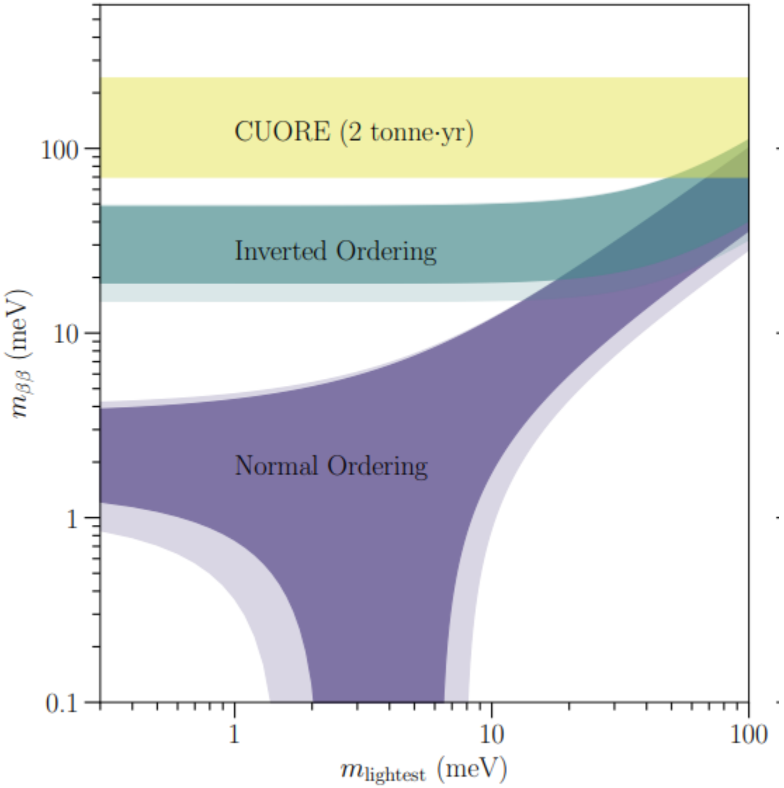


CUORE, arXiv:2405.17937



CUORE, arXiv:2404.04453

$T_{1/2}$ > 3.8e26 yrs
$\langle m_{\beta\beta}\rangle$ constraint
70-240 meV

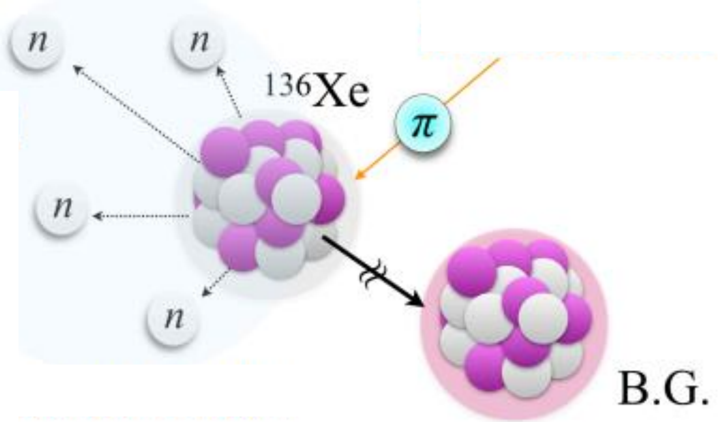


Xe: the KamLAND-Zen experiment

745 kg Xe-loaded liquid scintillator in nylon balloon
Radiopure liquid scintillator veto in detector
Outer water Cherenkov veto

Mass: 745 kg
Enrichment: 91%
Energy resolution: ~ 4-5%
Background: 1.1e-4 /keV/kg/yr

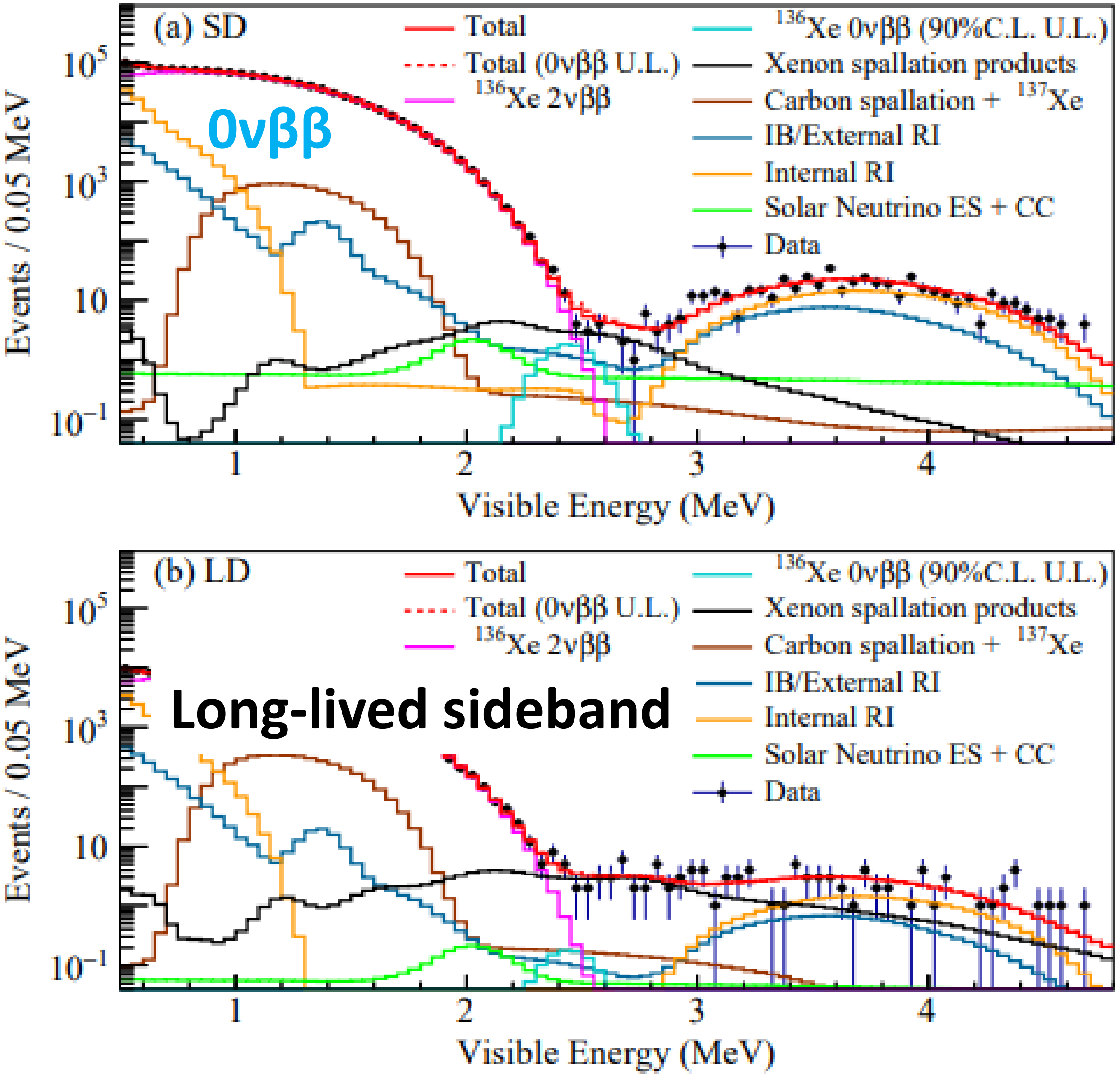
Itaru Shimizu, Neutrino 2024



Dominant background:
Xe spallation – a long-lived nuclei activated by cosmics

Position + time coincidence

Double beta decay results



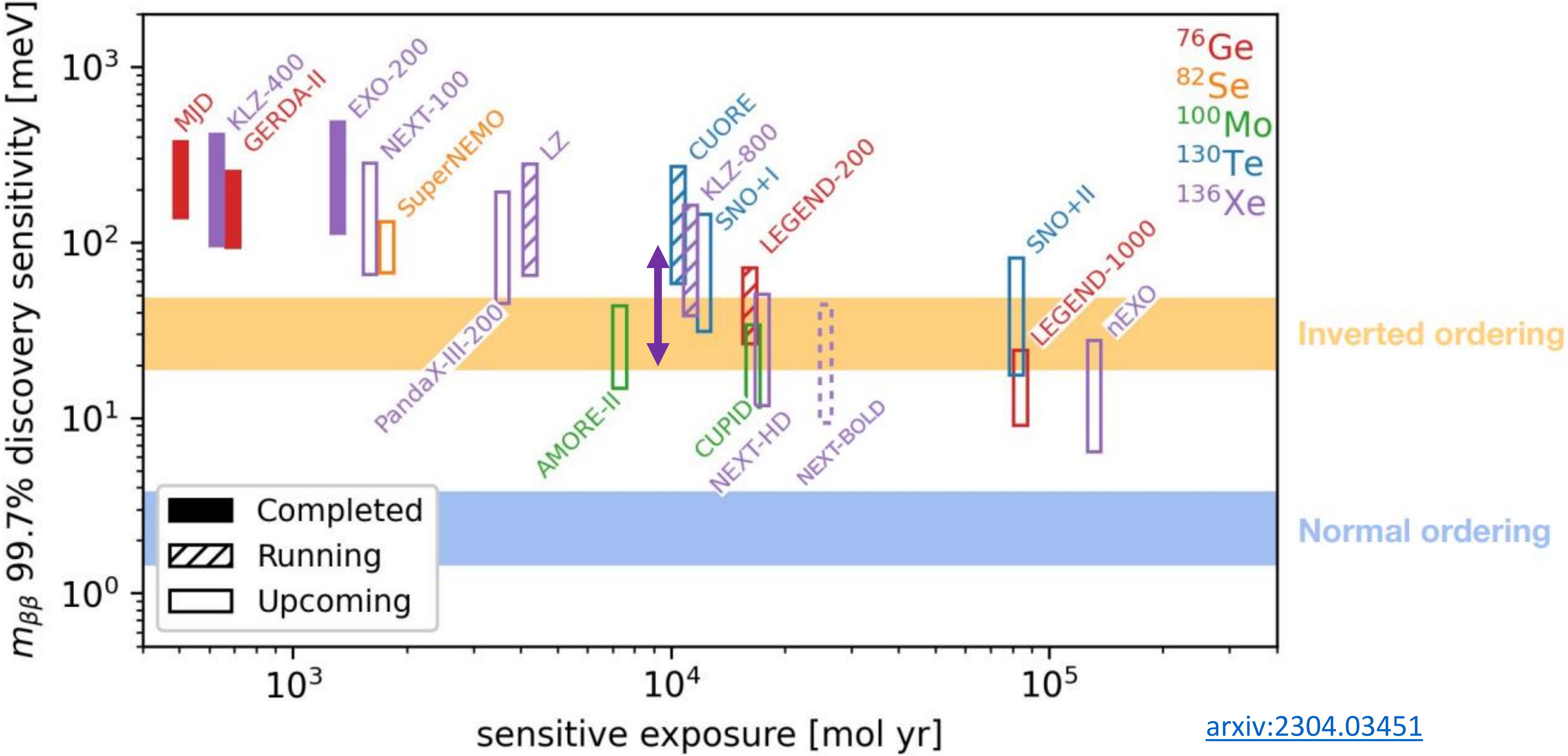
KamLAND-Zen, arXiv:2406.11438

– Tag long-lived spallation background:
– Time correlated to multi-neutron interaction using $N_{neutron}$, dR, dT info
– Tags 47% of background giving sideband to estimate background in region of interest

57 events on 32 background in 1.13 t-yrs
$T_{1/2}$ > 3.8e26 yrs
Translates to $\langle m_{\beta\beta} \rangle$ less than 28-122 meV

Current run completed, upgrading light collection to improve energy resolution

Experimental outlook



arxiv:2304.03451

Summary

– Plenty of fundamental physics questions remain for neutrino physics!

– Many unknowns in oscillation frameworks which are currently known at the $\sim 1\sigma$ level from NOvA/T2K experiments

– Current data demonstrates validity of accelerator approach which will be advanced by future experiments such as DUNE

– Beyond oscillations, $0\nu\beta\beta$ experiments can determine direct mass scale which would resolve last SM question