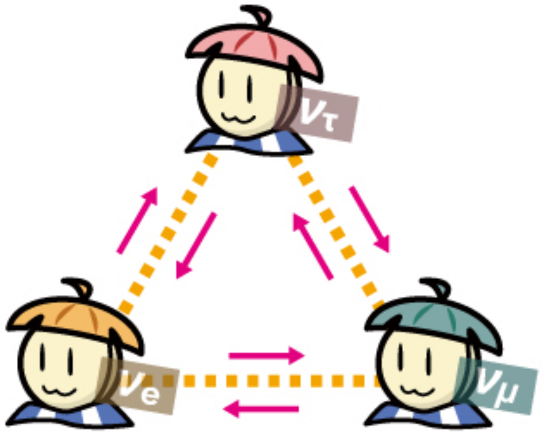
Low-energy physics overview

Yusuke Koshio (Okayama university, Japan)

December 9, 2020, Workshop 'NA61/SHINE at Low Energy', Online

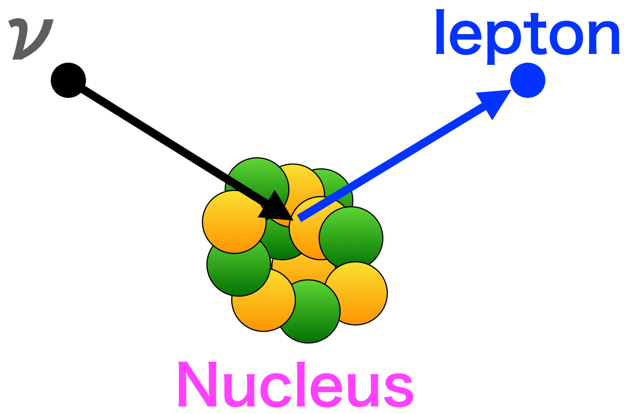
Why low energy beam?

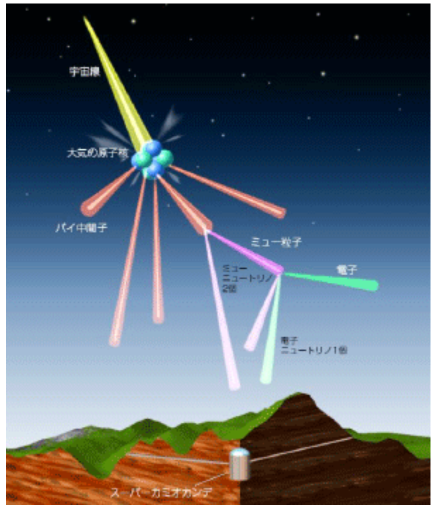
Need for various types of neutrino experiments



Neutrino oscillation

Neutrino interaction



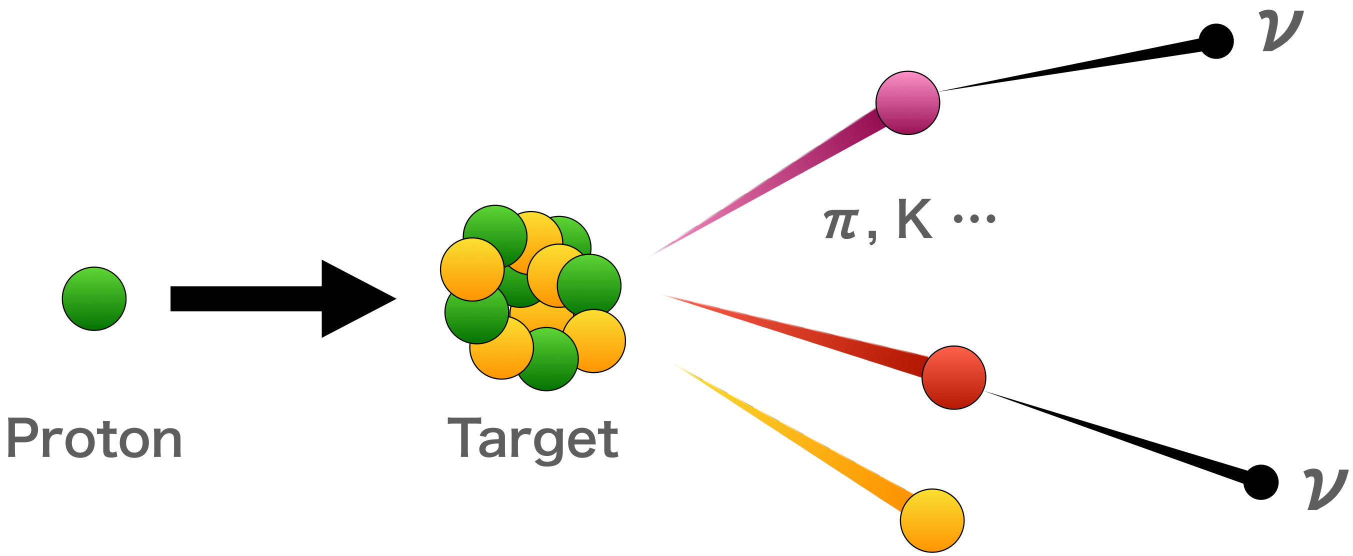


Neutrino flux

Neutrino flux determination is critical

Why low energy beam?

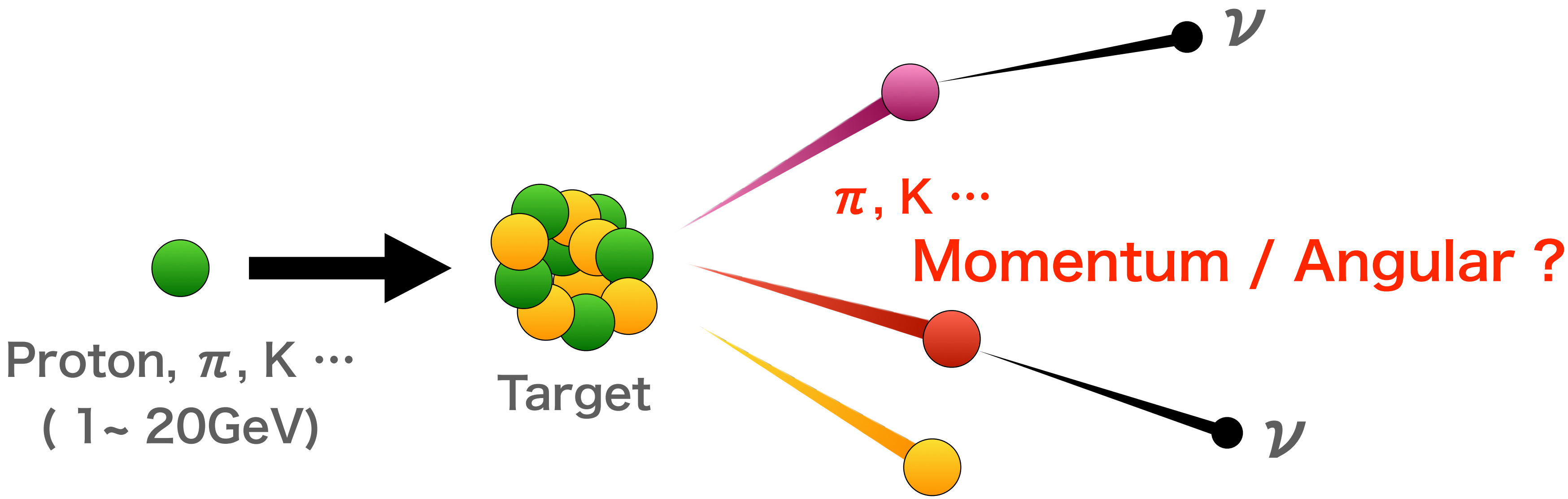
How to make neutrinos?



Neutrino flux determination is critical

Why low energy beam?

Hadron production uncertainty is serious problem



Precise hadron interaction data of low energy hadron beam with wide acceptance detector is not enough!

Brief introduction of physics program

JSNS^2 experiment

(J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

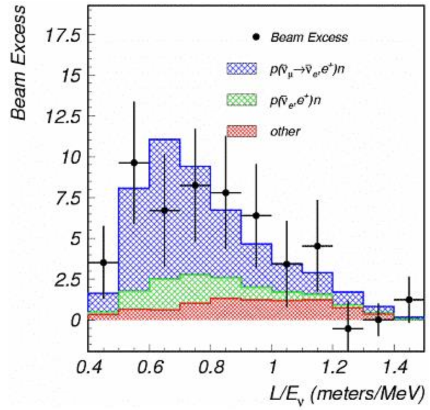
Search for sterile neutrino

Several anomalies,
indication of a sterile neutrino (Δm^2~1eV^2)?

Experiment	Neutrino source	signal	Significance	E(MeV) / L (m)
LSND	μ DAR	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40 / 30
MiniBooNE	π Decay in Flight	$\nu_\mu \rightarrow \nu_e$	4.7σ	800 / 600
		combined	4.8σ	
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3 / 10
Reactor	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3 / 10~100

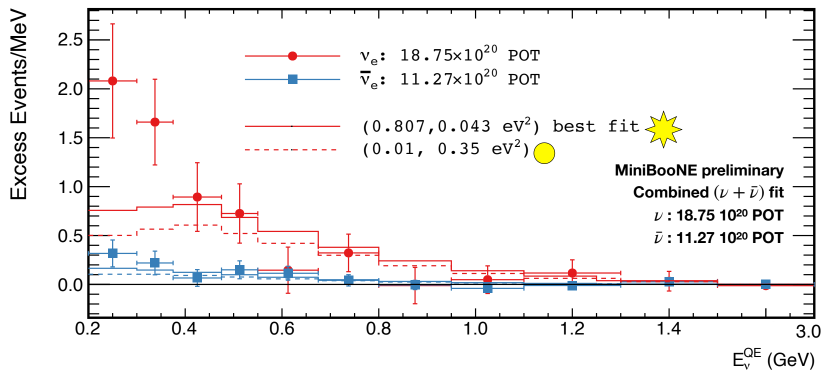
Finally, solve the long standing problem

LSND

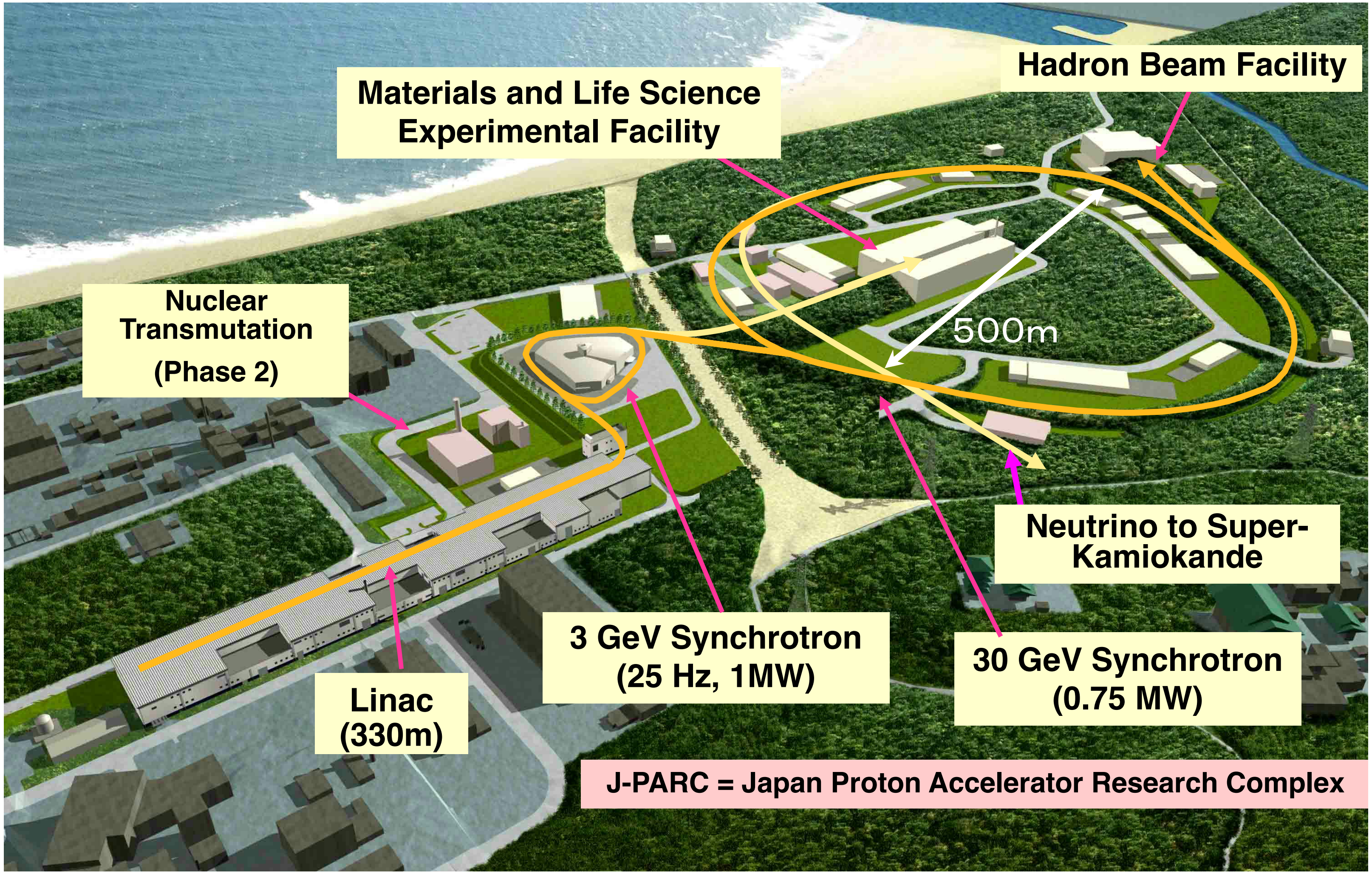


MiniBooNE

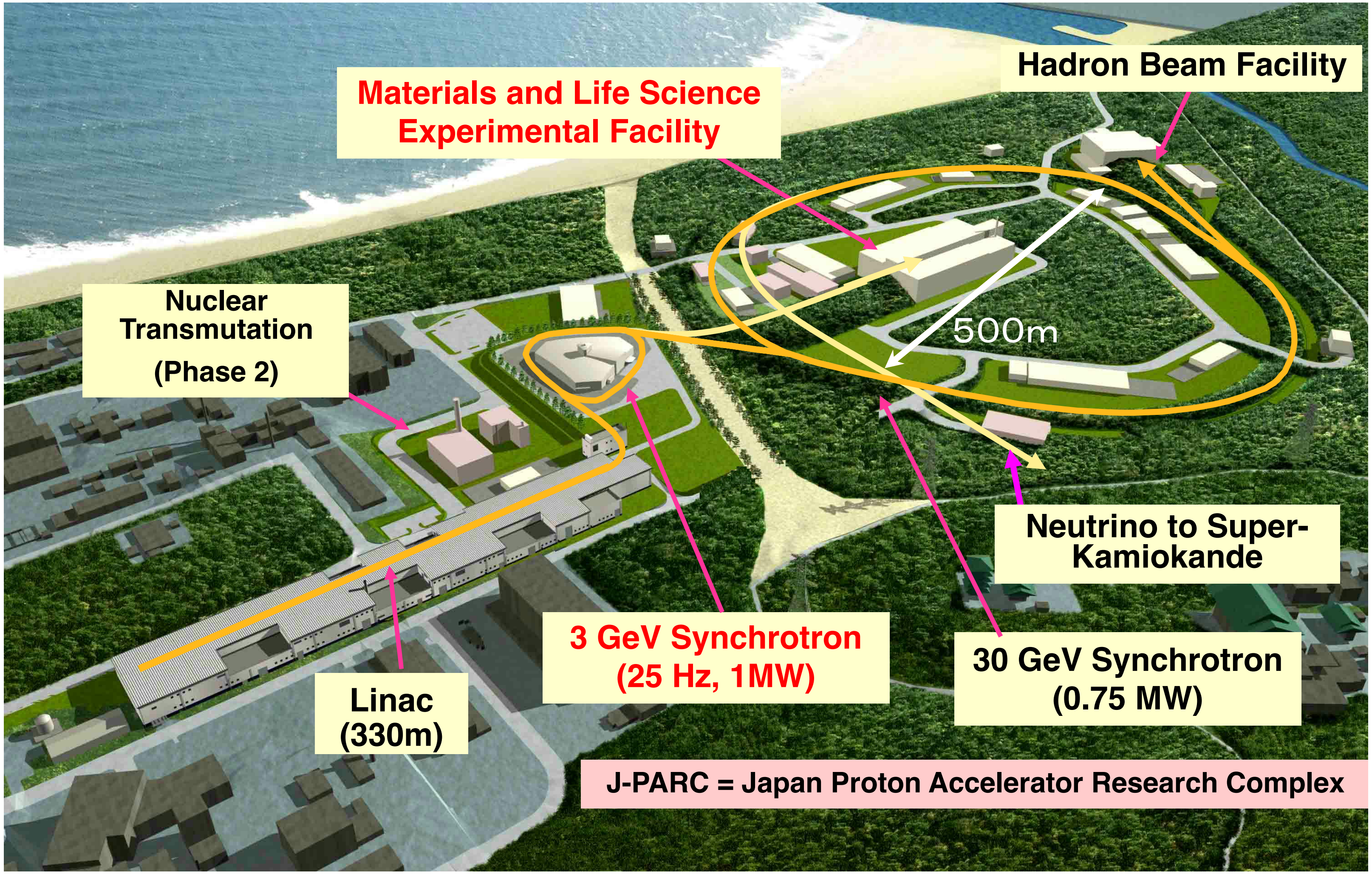
- Neutrino mode excess 4.7σ,
- **Neutrino+Anti-neutrino modes excess : 4.8σ**



J-PARC Facility



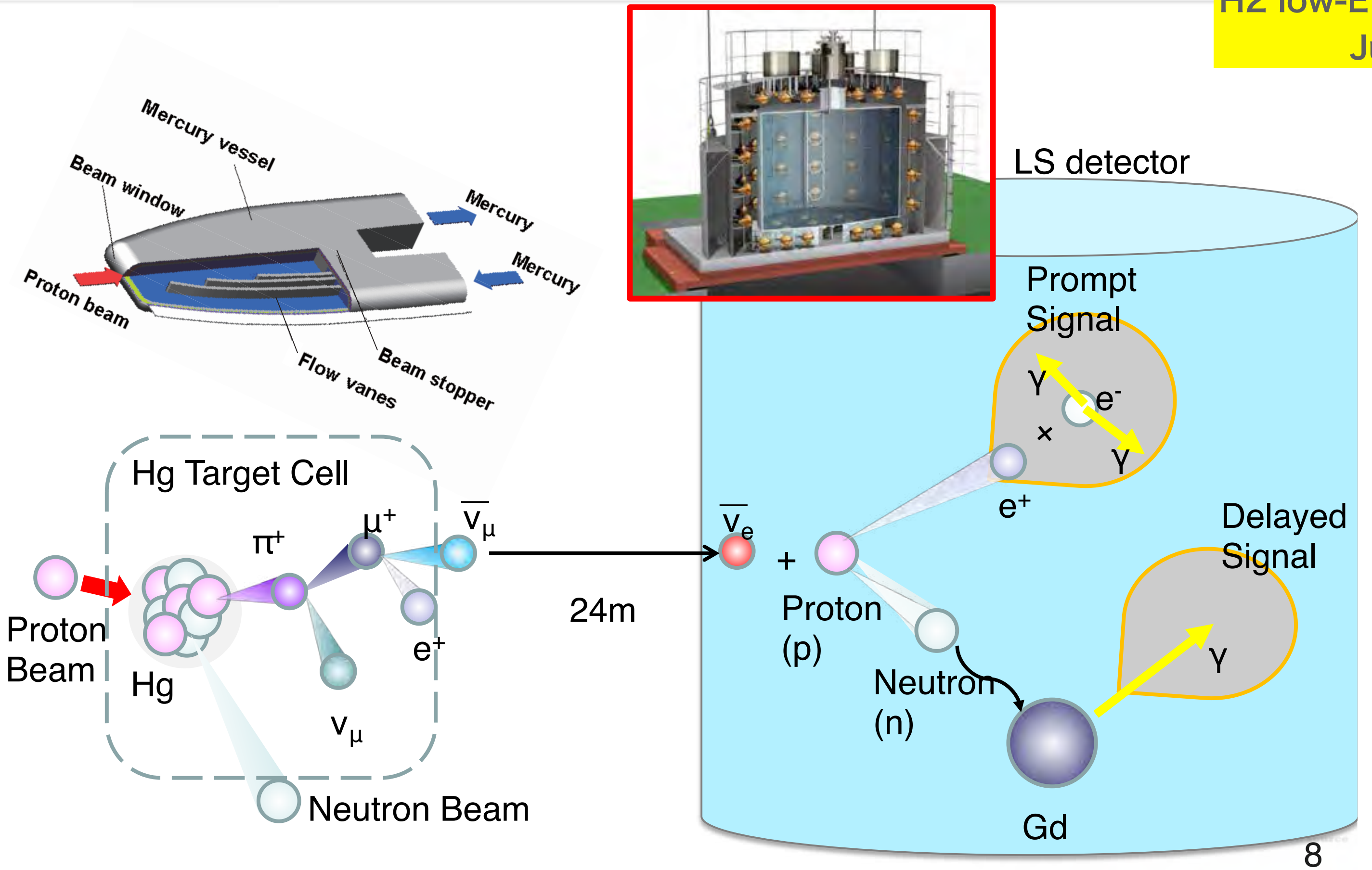
JSNS^2 experiment



JSNS² experiment

Neutrino source and detection

S. Hasegawa
H2 low-E beam line meeting
July 9, 2020



JSNS^2 experiment

Neutrino source and detection

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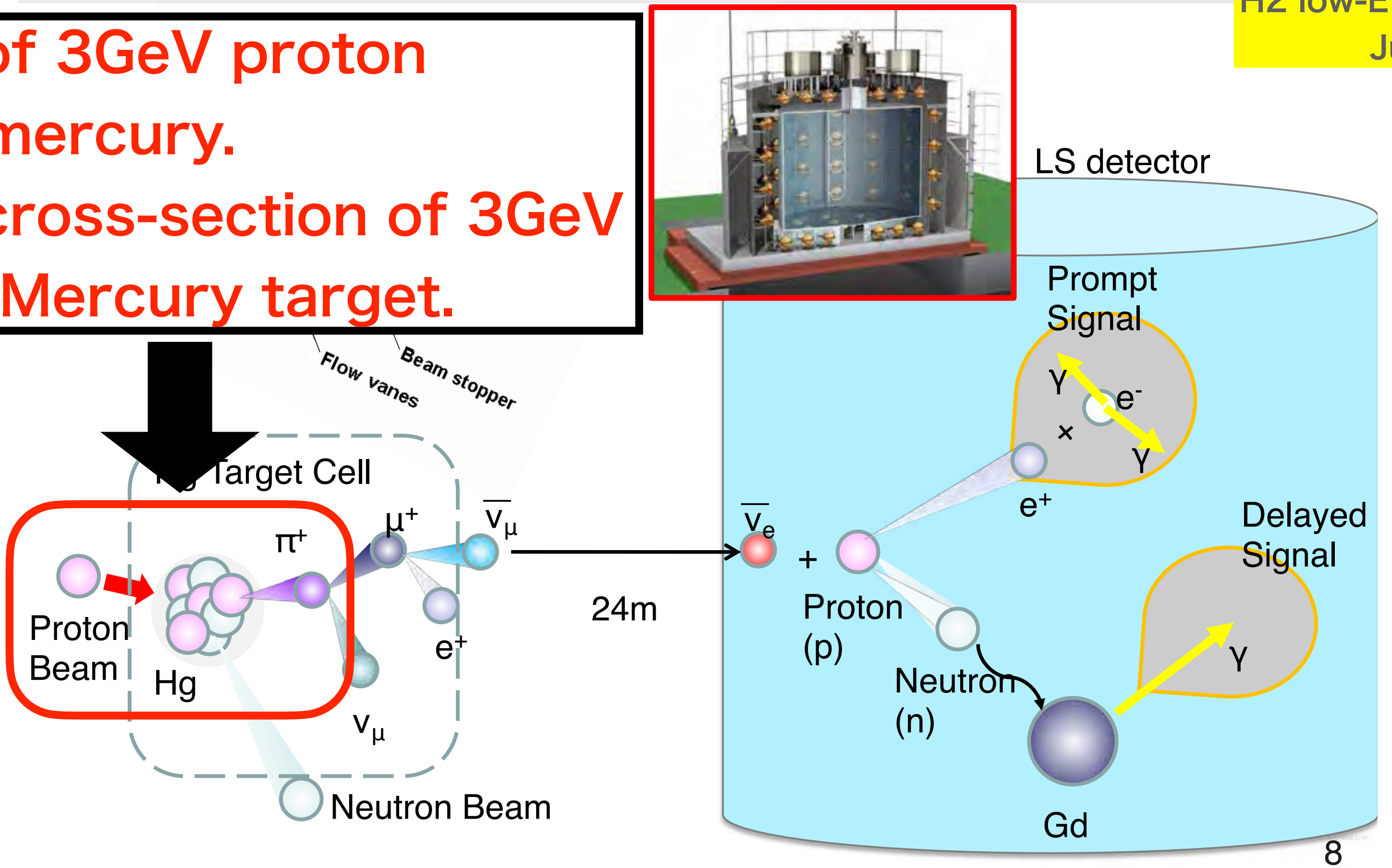
No data of 3GeV proton injected mercury.
Need to cross-section of 3GeV Proton + Mercury target.



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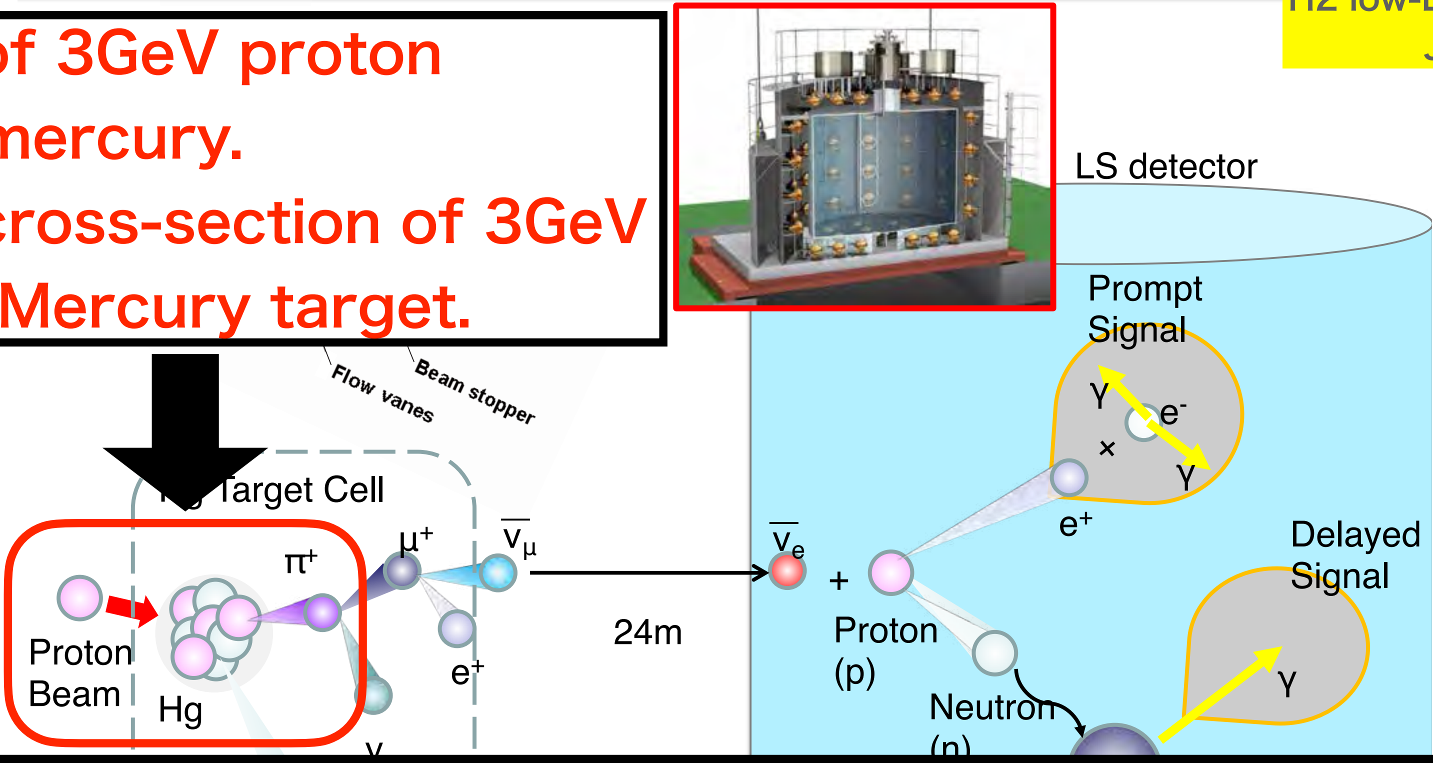


The 1st physics run just started in this year!
Need the data as soon as possible.

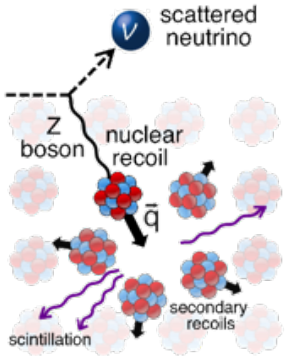
COHERENT experiment

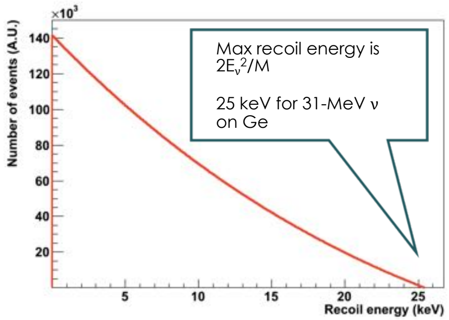
First Experiment Observation of CEvNS

J. Newby
Neutrino 2020
June 23, 2020

Coherent elastic neutrino-nucleus scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV





CEvNS cross section is well calculable in the Standard Model

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2)$$

CEvNS cross section is large! $\propto N^2$

- Predicted in 1974 by D. Freedman
- Interesting test of the standard model
  - Sensitive to **non-standard interactions**
  - Largest cross section in **supernovae** dynamics
  - Background for future **dark matter** experiments
  - Sensitive to nuclear physics, **neutron skin** (neutron star radius)

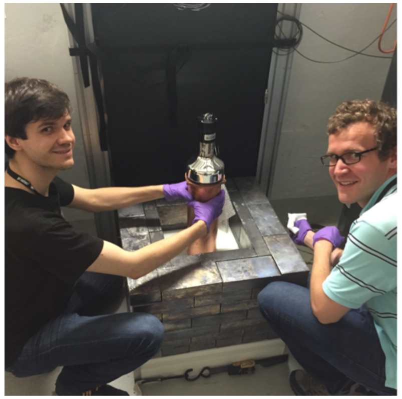
- "act of hubris" - D. Freedman
  - Need a low threshold detector
  - Need an intense neutrino source

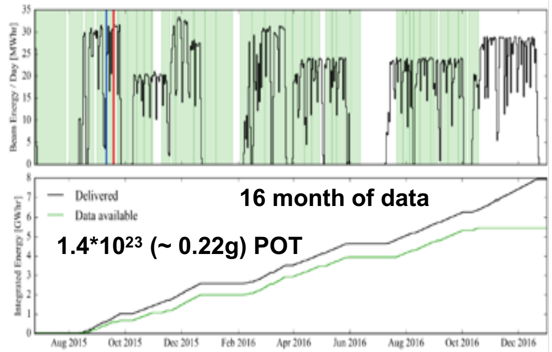
COHERENT experiment

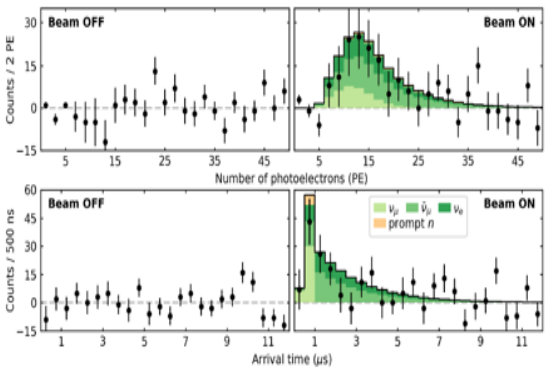
First Detection!

J. Newby
Neutrino 2020
June 23, 2020

First Detection of CEvNS with CsI detector



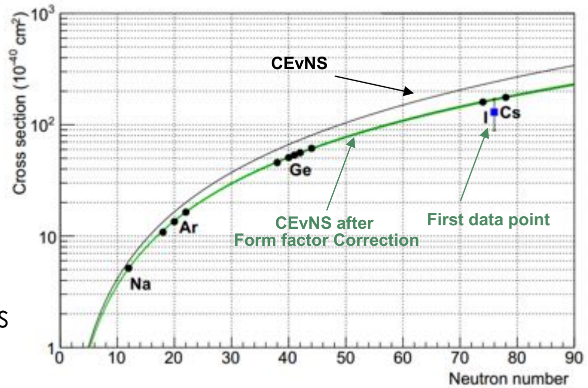




First working, hand held neutrino detector -14kg!!!

After 40 years, all the pieces have finally come together

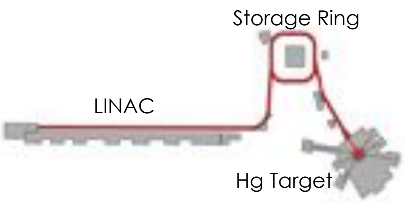
- ✓ Intense Neutrino Source
- ✓ Sensitive Detectors
- ✓ Mitigation of Backgrounds



COHERENT experiment
Spallation Neutron Source at ORNL

J. Newby
Neutrino 2020
June 23, 2020

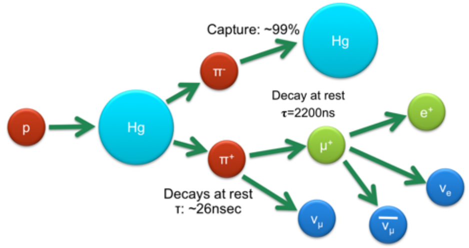
Spallation Neutron Source at ORNL



"Jet-flow" Target

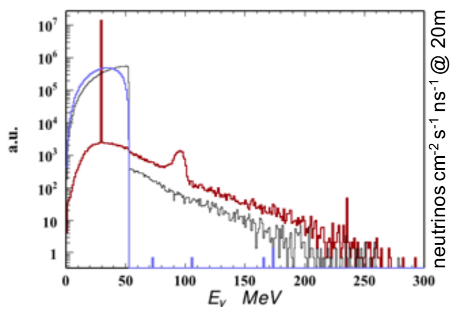
- Superconducting H⁻ LINAC: 1 GeV @ 1.4MW @ 60 Hz
- Storage Ring: 1200 pulses, 1us Period, 350ns FWHM
- Liquid Mercury Target: circulates 20 tons with He gas injection to mitigate cavitation
- Operation ~5000 hours per year: 25 Terajoules/year

Neutrinos via Pion Decay-at-Rest

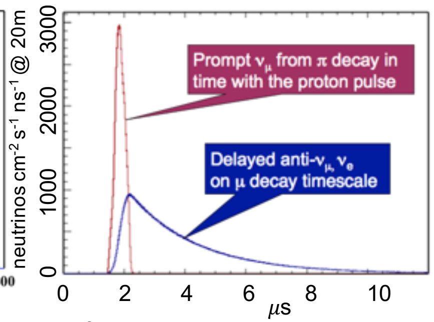


2.81×10^{14} ν/cm^2/flavor/SNSYear @ 20m

Neutrino Energy



Neutrino Timing



- SNS timing preserves DAR flavor structure
- Mono-energetic ν_μ separated from ν_e, $\bar{\nu}_\mu$

COHERENT experiment

What is the uncertainty?

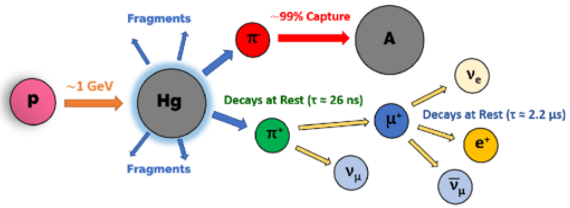
J. Newby
Neutrino 2020
June 23, 2020

Beyond First Light Measurements … CEvNS as quantitative probe

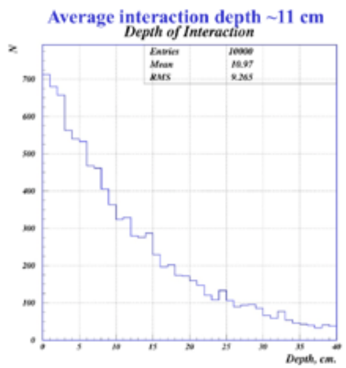
Dominant Uncertainties on CsI signal	
Event selection (signal acceptance)	5%
Form Factor	5%
Neutrino Flux	10%
Quenching factor	25%
Total uncertainty on signal	**28%**

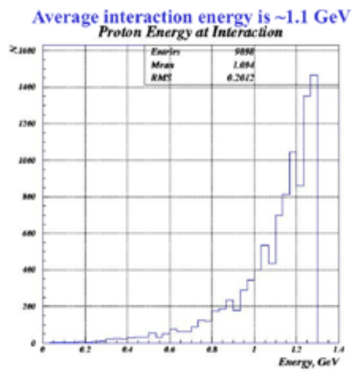
Dominant Uncertainties on Ar CEvNS Rate	
Detector Model (includes QF)	2%
Fiducial Mass	2.5%
Prompt Light Fraction (Pulse Shape)	8%
Neutrino Flux	10%
Total uncertainty on signal	**13.4%**

All uncertainties except neutrino flux are detector specific and could be much less for other technologies



- Largest uncertainty is pion production from p+Hg
- 10% discrepancy between Bertini and LAHET calculations





To unlock high precision CEvNS program, we need to calibrate the SNS neutrino flux.

COHERENT experiment

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J. Newby
Neutrino 2020
June 23, 2020

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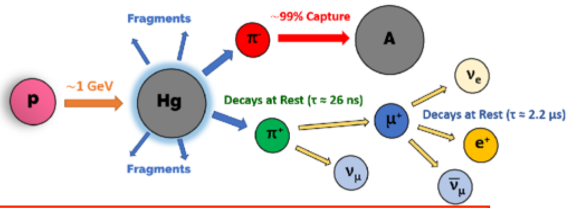

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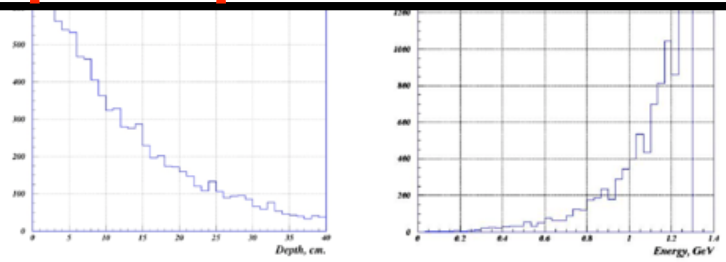

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COHERENT experiment

Future plan

J. Newby
Neutrino 2020
June 23, 2020

Power Upgrade and STS Facility create new opportunities …

FTS 2021	2022	2024	2028 **STS Neutrino Hall**
1.4 MW	1.7 MW	2.0 MW	FTS: 2.0 MW @ 45 Hz STS: 0.7 MW @ 15 Hz

Calorimetry

COHERENT "First Light" Program
- CEvNS with HPGe, NaI
- Heavy Water Flux Normalization of FTS

Ton-Scale Argon Calorimetry
- CEvNS studies
- Dark Matter searches
- Limits on quark-lepton couplings for DUNE mass ordering degeneracy
- Low Threshold Detector R&D: Quantum Enhanced Light Collection, Xenon Doping, SiPM
- Supernovae neutrino cross sections for DUNE

Directionality

Ton-Scale Directionality with Low Threshold Detector R&D

Heavy Water Ring Imaging Design
- Improved Flux Normalization
- ν_e-oxygen Interactions for Super-K, Hyper-K

Argon Detector R&D for STS
- Scalable Low threshold Light Collection
- Advanced Techniques for Position/Direction Reconstruction
- Direction reconstruction for CC-leptons
- Multi-site reconstruction for coherent inelastic interactions

Discovery Scale

Neutrino Program at STS

10-ton Liquid Argon
- Dark Matter searches
- Precision CEvNS studies
- Precision Ar cross sections for DUNE
- Weak Mixing Angle
- Neutrino EM properties

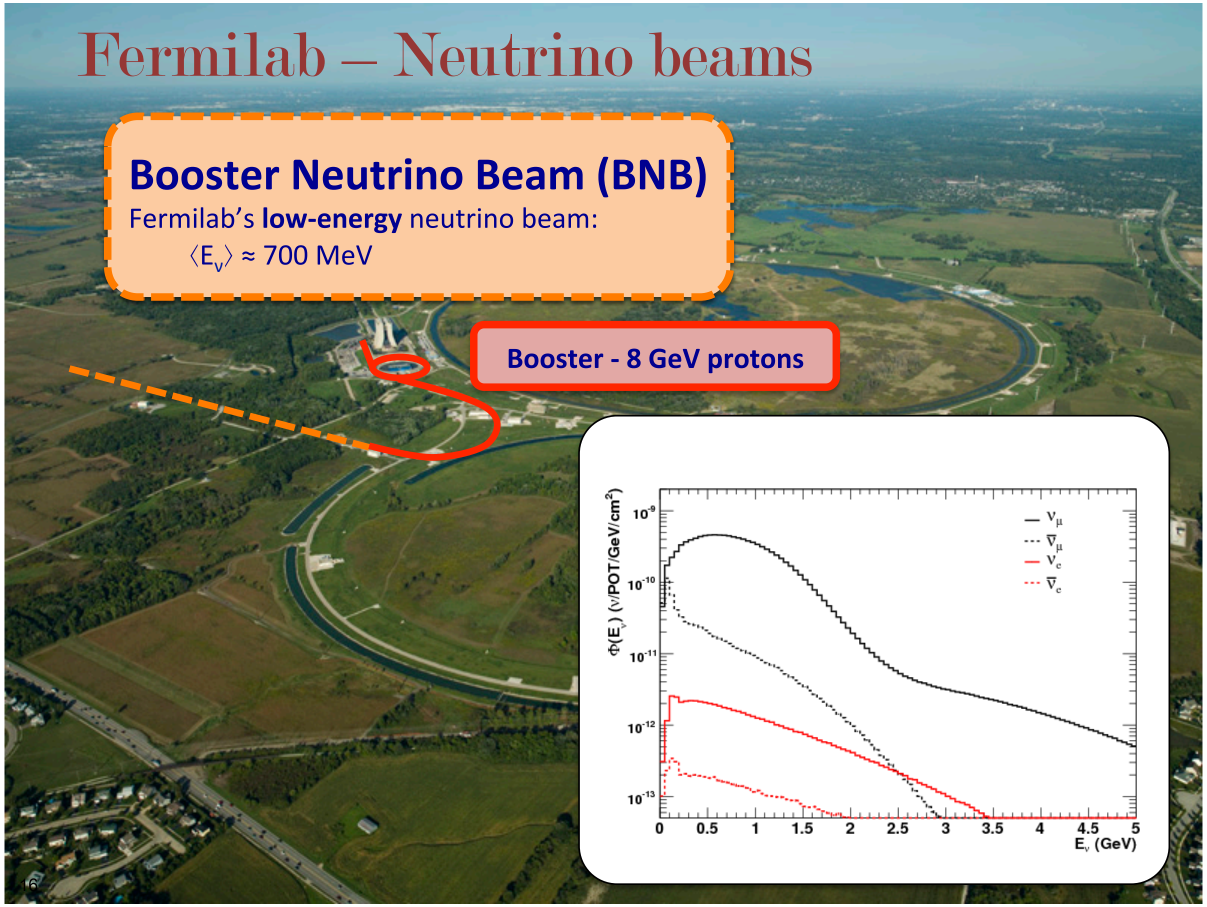
Heavy Water Ring Imaging
- Flux Normalization of STS
- Precision ν_e-oxygen for Super-K, Hyper-K

We are just getting started!

Exact time evolution of program to be determined by the collaboration

Fermilab Booster Neutrino Beam

Short baseline neutrino experiment / neutrino interaction



- Several experiments are on going and planned. (ANNIE, MicroBooNE, MiniBooNE, MITPC, SciBath, ICARUS, SBND)
- Neutrino interaction cross section with Argon is important for DUNE.

<u>Precise neutrino flux measurement is critical</u>

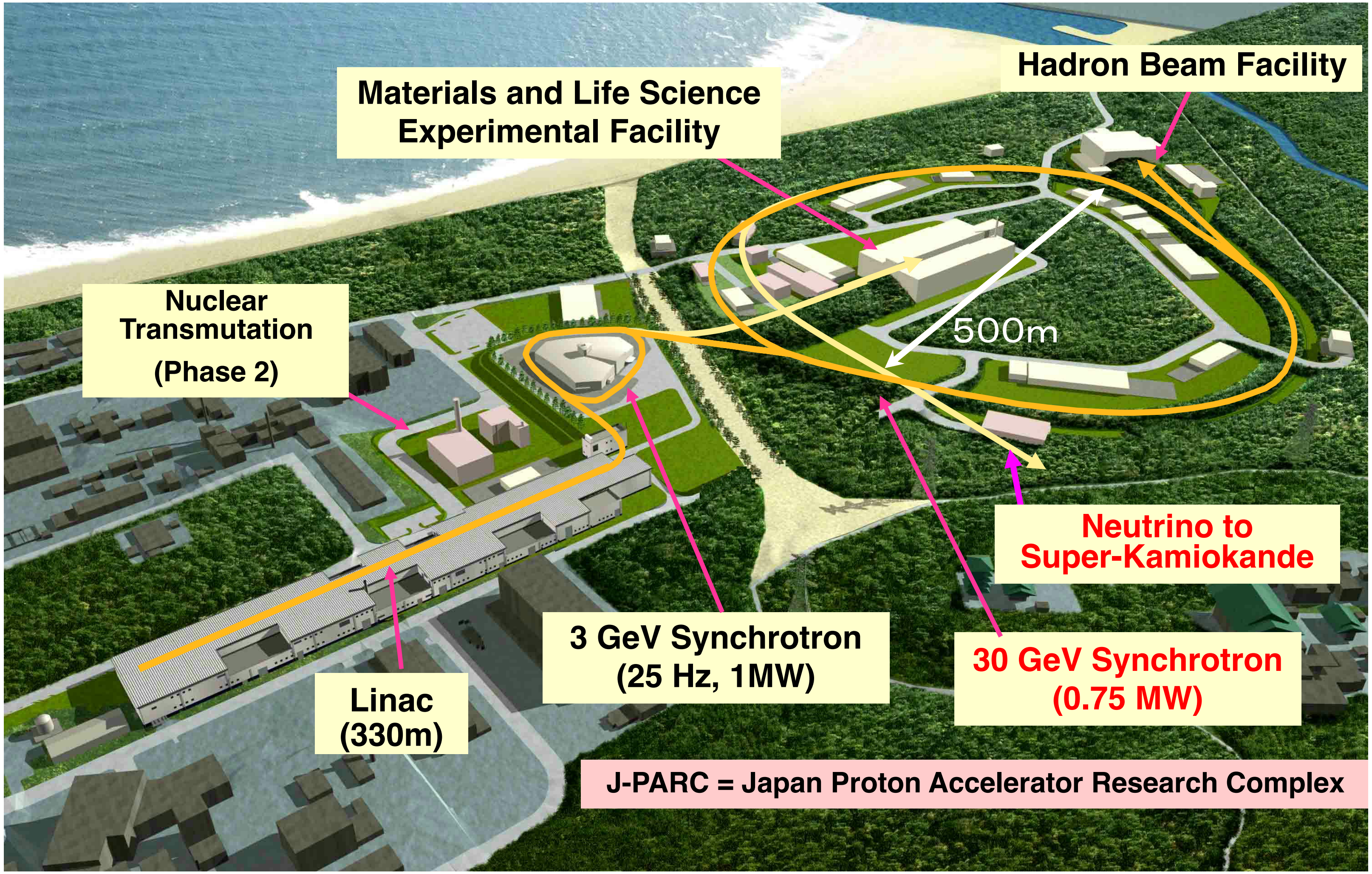
T2K

Long baseline neutrino experiment in Japan

P. Dunne
Neutrino 2020
July 2, 2020

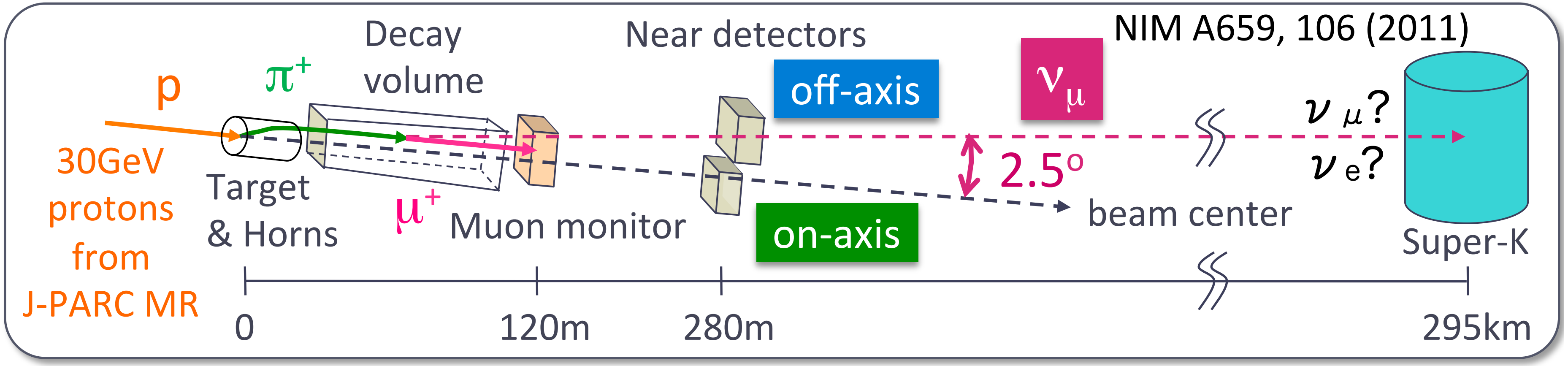
- Muon (anti) neutrino beam generated at J-PARC
- Beam travels 295 km to large SK far detector to be measured after oscillations
- Near detector complex, ND280 constrains beam flux and interaction cross-section before oscillation
- Important to constrain non-oscillation parts of model to avoid bias

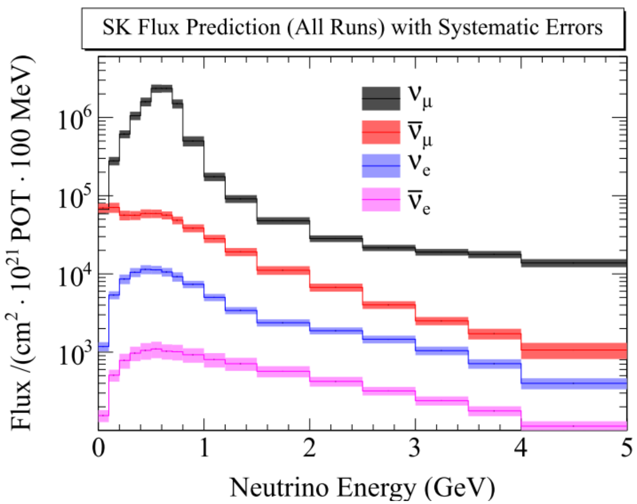
T2K

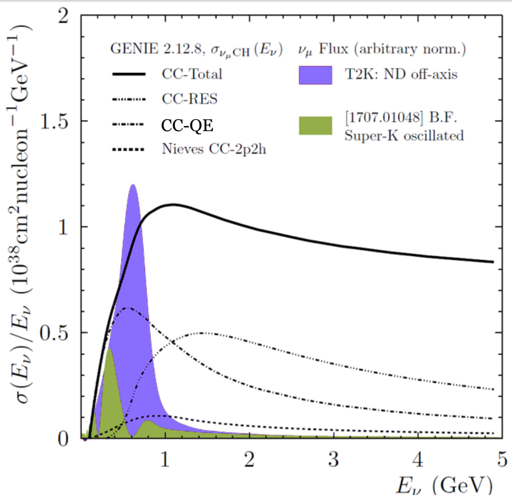

Hadron Beam Facility
Materials and Life Science
Experimental Facility
Nuclear
Transmutation
(Phase 2)
500m
Neutrino to
Super-Kamiokande
3 GeV Synchrotron
(25 Hz, 1MW)
30 GeV Synchrotron
(0.75 MW)
Linac
(330m)
J-PARC = Japan Proton Accelerator Research Complex

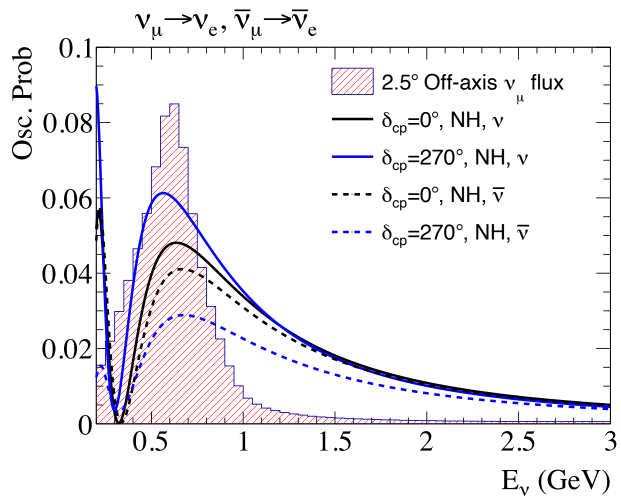
T2K

Neutrino oscillation / interaction measurement





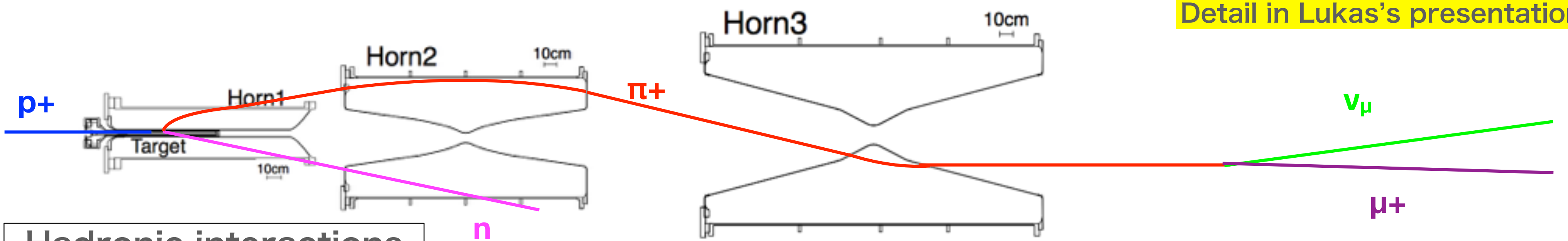




T2K

Neutrino flux prediction

Detail in Lukas's presentation



Hadronic interactions in target are simulated with FLUKA

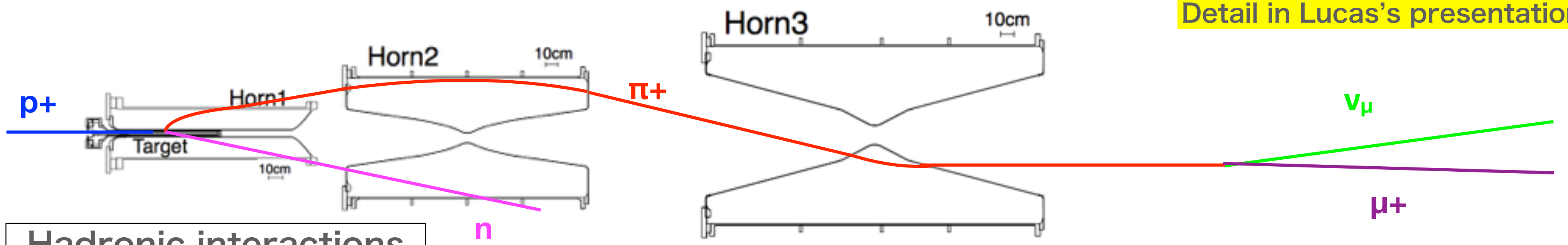
Propagation and horn focusing outside target with GEANT3

Tune multiplicities and production cross section using NA61/SHINE data

- Previous analyses used NA61/SHINE data taken with a thin graphite target
  - Initial pion production reweighted in momentum and angle to match data then subsequent propagation through target was simulated
- New for this year we use NA61/SHINE data with a replica of T2K's target [EPJC 76, 84 (2016)]
  - MC spectrum now reweighted to match data in momentum, angle and target exit point
- Allows significant reduction in input flux uncertainty on SK rate from ~8% to ~5%

T2K
Neutrino flux prediction

Detail in Lucas's presentation



Hadronic interactions in target are simulated with FLUKA

Tune multiplicities and production cross section using NA61/SHINE data

Propagation and horn focusing outside target with GEANT3

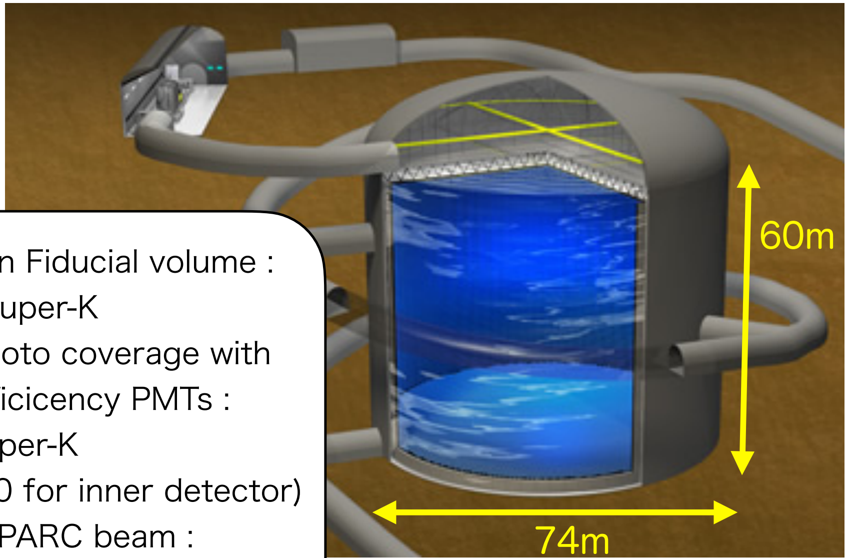
Fraction of tuned hadronic interaction

Dataset	Tuned Hadronic Interactions in Neutrino Ancestry							
	SK ν-mode				SK $\bar{\nu}$-mode			
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
NA61 2009 Thin	85.8%	80.0%	83.8%	76.9%	80.9%	85.3%	77.6%	83.2%
+ NA61 2009 Replica	94.0%	83.6%	89.2%	77.3%	84.4%	93.6%	77.9%	89.5%
+ HARP	96.5%	87.6%	90.5%	77.8%	87.8%	96.2%	78.3%	91.1%

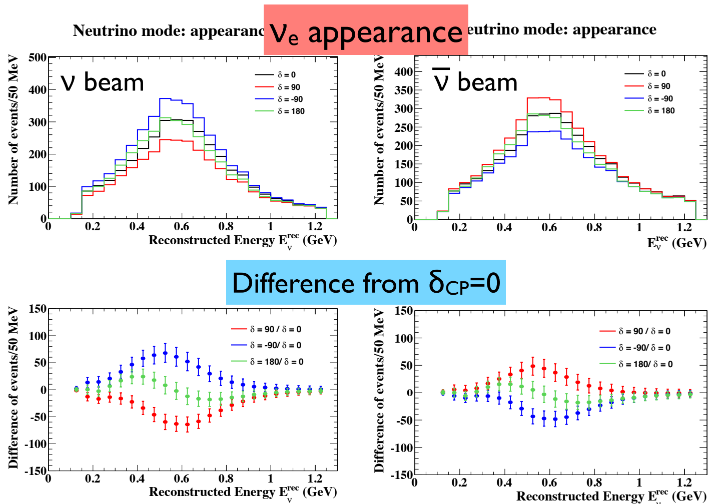
Still ~10% untuned from target C and exiting, decay pipe Fe, Horn Al.

Hyper-Kamiokande

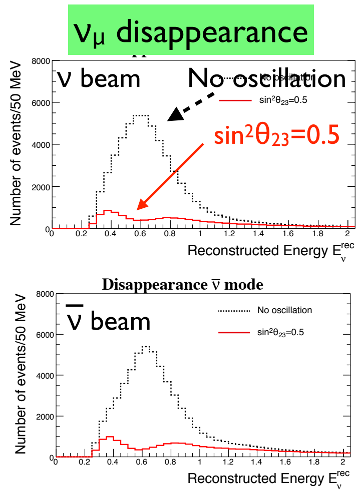
Next generation experiment (2027~)



- 190kton Fiducial volume : ~10 x Super-K
- 40% photo coverage with high-efficicency PMTs : ~2 x Super-K (~40000 for inner detector)
- >MW J-PARC beam : ~3 x current power.



for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	1,643	15	7	159	134
ν beam	1,183	206	4	317	196



	$\nu_\mu+\bar{\nu}_\mu$ CCQE	νμCC nonQE	Others
ν beam	6,391	3175	515
ν beam	8,798	4315	614

10 years (10yrs×1.3MW×10⁷s), ν : νbar = 2.5yrs : 7.5yrs

Control of systematics (neutrino flux, interaction, detector) is crucial.

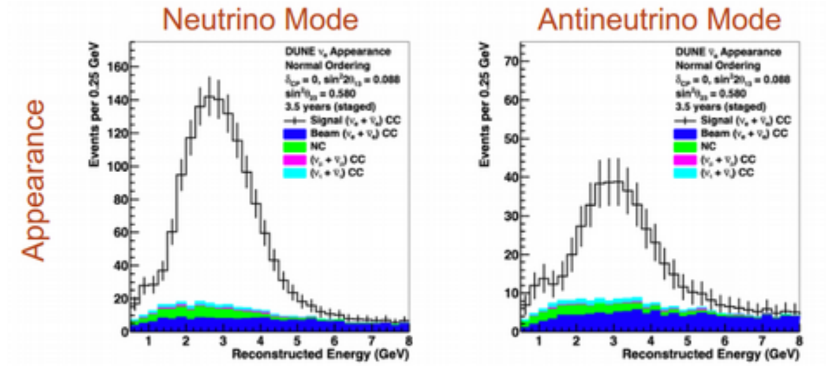
M. Mooney
Neutrino 2020
June 29, 2020

DUNE

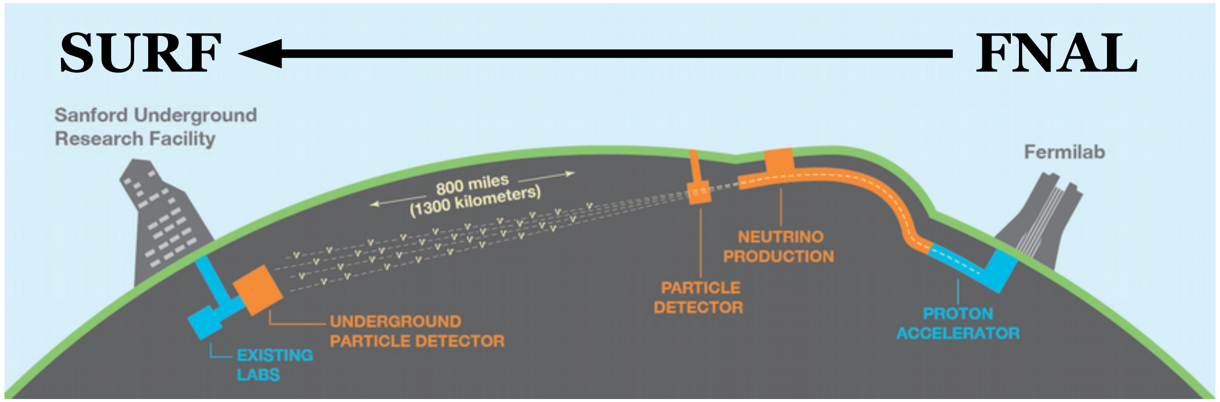
Long baseline neutrino experiment in US

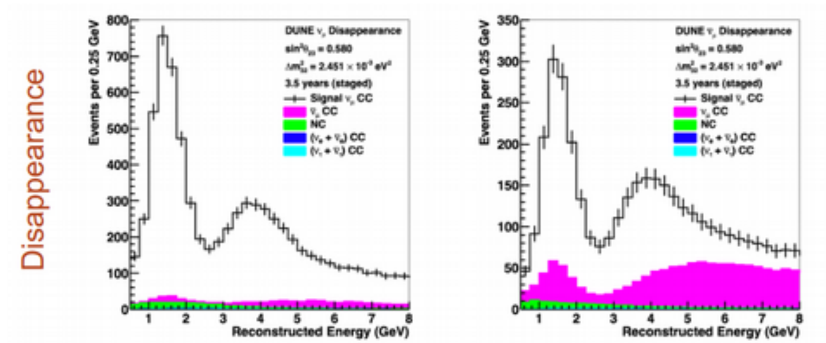
- "Deep Underground Neutrino Experiment"
  - 1300 km baseline
  - Large (70 kt) LArTPC **far detector** 1.5 km underground
  - **Near detector** w/ LAr component

- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - $\boldsymbol{\delta_{CP}}$, θ_{23}, θ_{13}
    - **Ordering of ν masses**
  - Supernova burst neutrinos
  - BSM processes (baryon number violation, NSI, etc.)



~1,000 ν_e events in 7 years (staged)



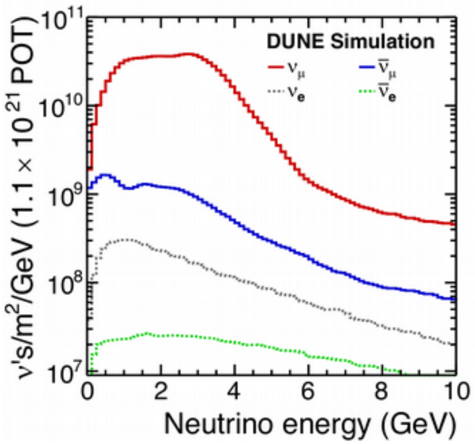


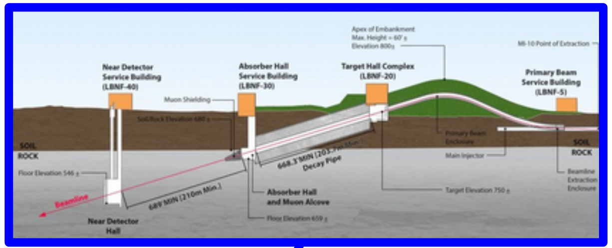
~10,000 ν_μ events in 7 years (staged)

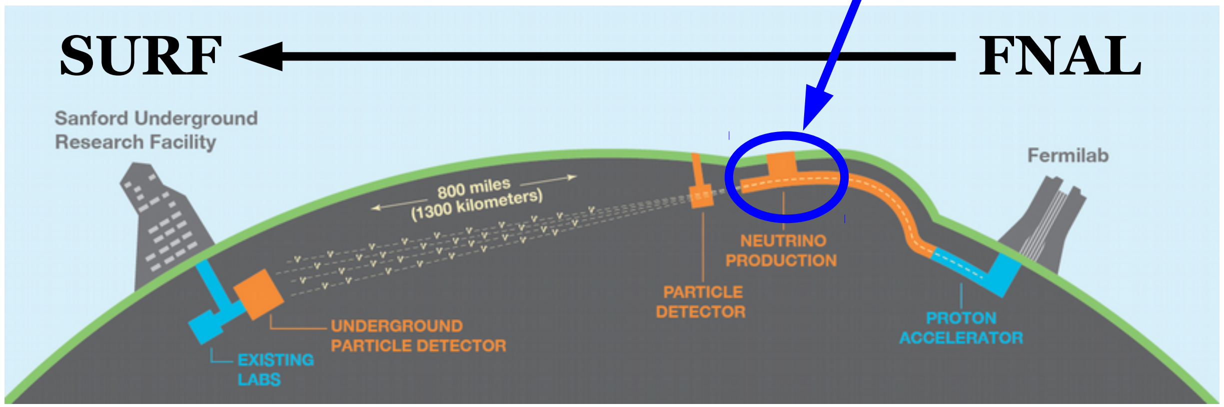
M. Mooney
Neutrino 2020
June 29, 2020

DUNE

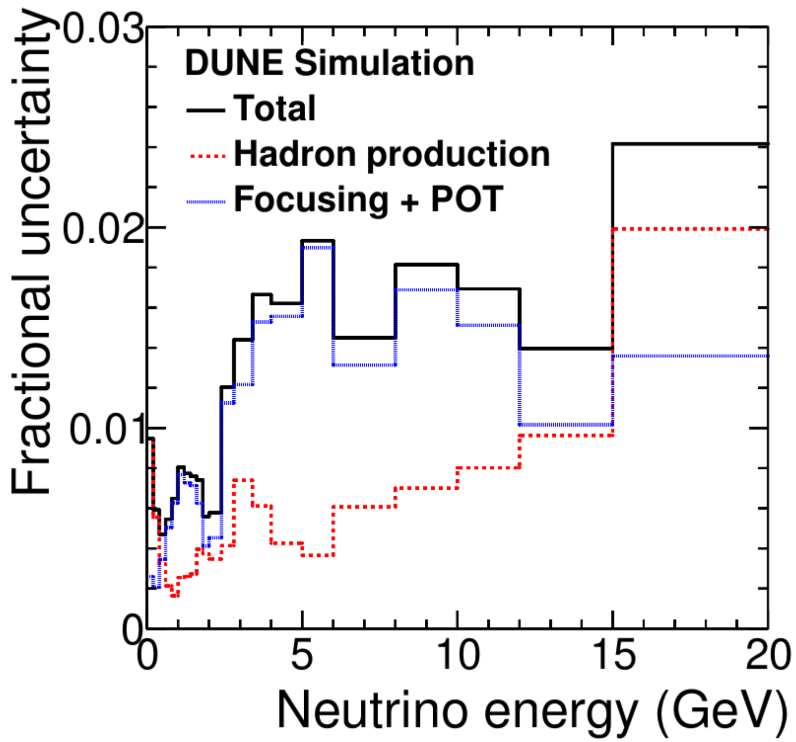
Neutrino source: LBNF Beam





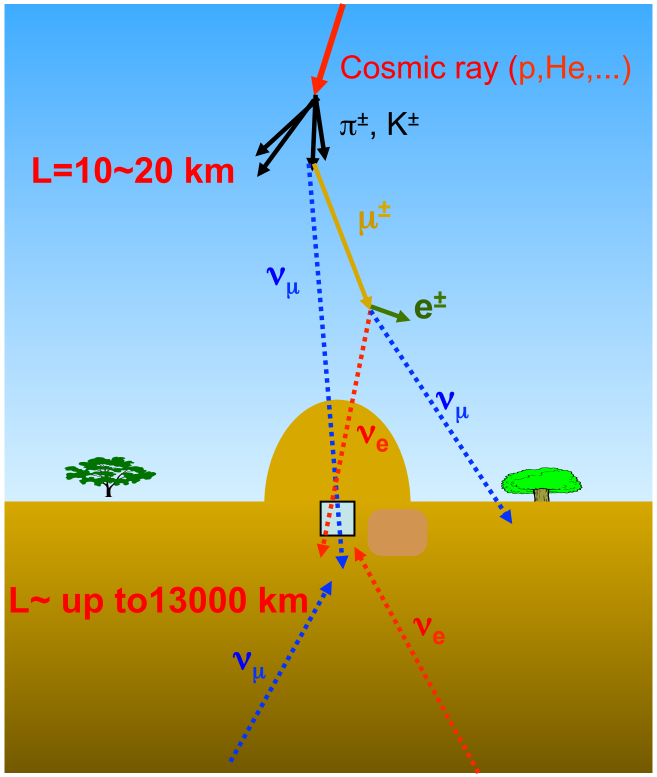


Uncertainties on the FHC muon neutrino ratio (arXiv. 2006.16043)



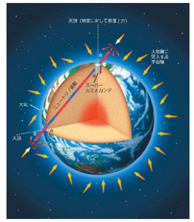
Atmospheric neutrino

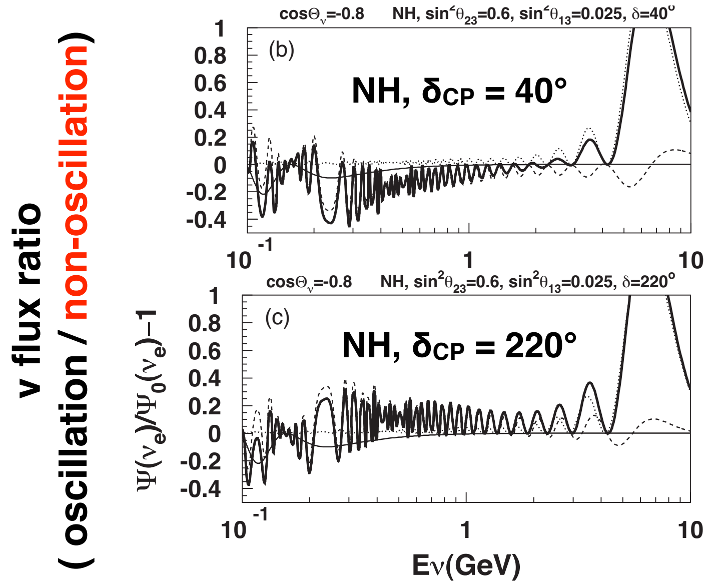
Flux measurement



- Develop hadronic shower, and the decay of the pions and muons give neutrinos.
- Energy of neutrinos O(10)MeV to O(10)TeV, and the flight length before detection is 10-10,000 km. It makes wide ranges of L/E.
- Both neutrinos and anti-neutrinos in the flux.

Neutrino oscillation in the earth

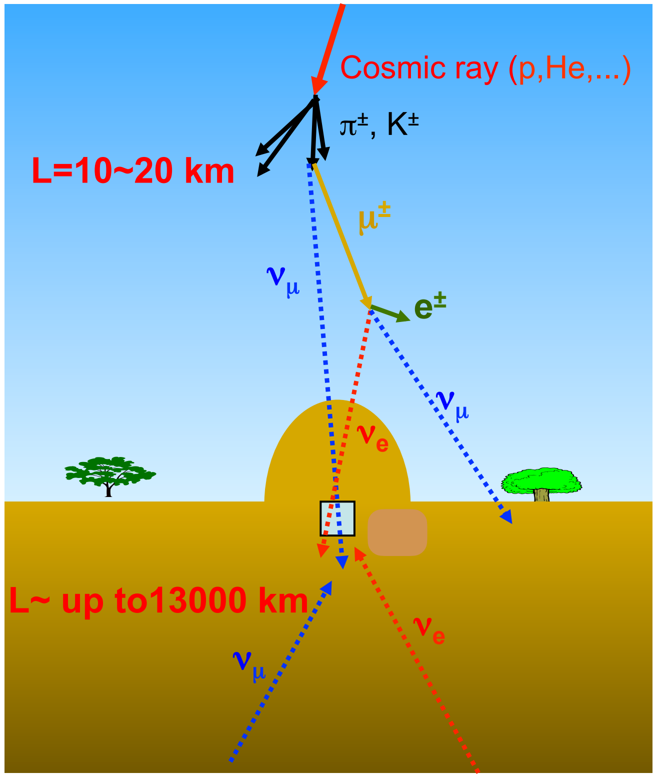




Predicted atmospheric neutrino flux is important for neutrino oscillation and other physics as a background for Dark Matter, Supernova neutrinos, etc.

Atmospheric neutrino

Why hadronic interaction?



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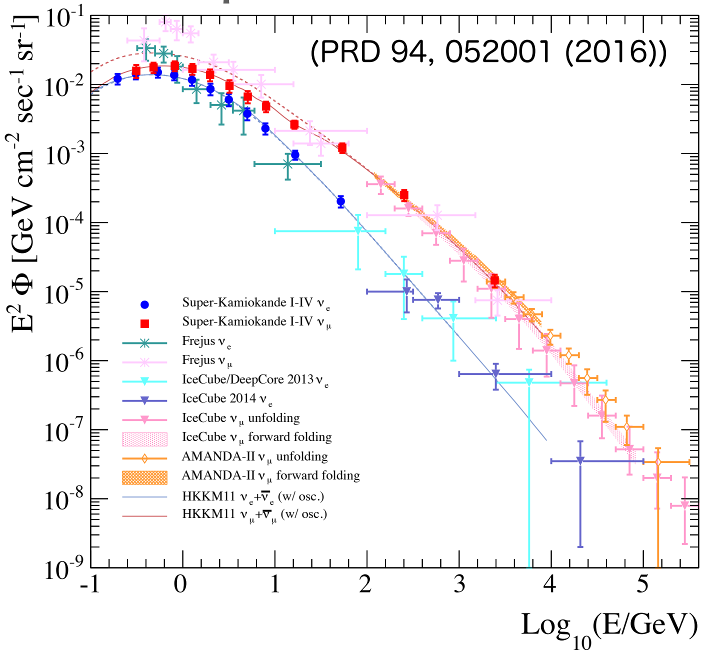
Atmospheric neutrino flux



The predicted flux uncertainty of π and K in the air is a dominant error sources

K. Sato
H2 low-E beam line meeting
October 30, 2020

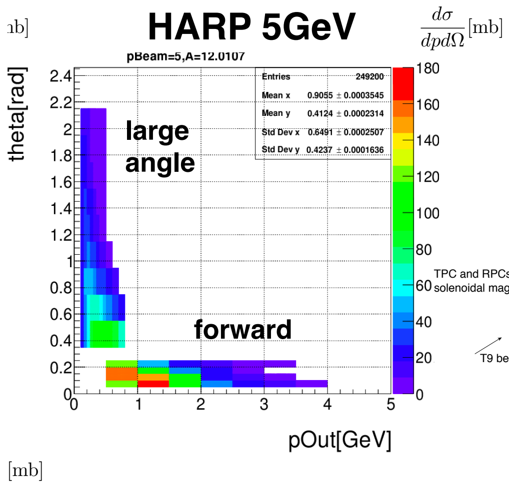
Atmospheric neutrino
Available beam data for input

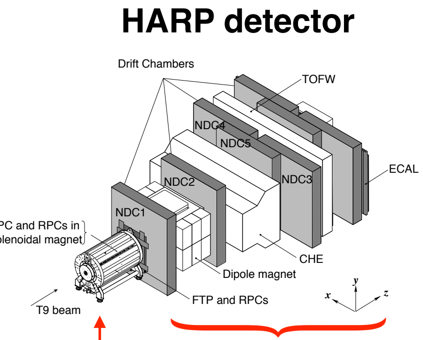
p_{beam} [GeV/c]	3	5	6.4	8	12	12.3	17.5	31
p+Be	HARP $\pi^\pm$	HARP $\pi^\pm$	E910 $\pi^\pm$	HARP $\pi^\pm$	HARP $\pi^\pm$	E910 $\pi^\pm$	E910 $\pi^\pm$	
p+C	HARP $\pi^\pm$	HARP $\pi^\pm$		HARP $\pi^\pm$	HARP $\pi^\pm$			NA61 **$\pi^\pm$,$K^\pm$,p**
p+Al	HARP $\pi^\pm$	HARP $\pi^\pm$		HARP $\pi^\pm$	HARP $\pi^\pm$			

HARP : **3,5,8,12 GeV, p+ (Be,C,Al,Cu) → π^{+-} + X**
(Forward) Phys.Rev.C80, 035208 (2009)
(Large Angle) Eur. Phys. J. C 53, 177–204 (2008)
(Large Angle) Eur. Phys. J. C 54, 37–60 (2008)

BNL E910 : **6.4, 12.3, 17.5 GeV, p+ (Be,Cu,Au) → π^{+-} + X**
(Forward) Phys. Rev. C 77, 015209 (2008)
(Large Angle) Phys. Rev. C 65, 024904 (2002)

NA61/SHINE : **31 GeV, p + C → π, K, p + X**
Eur. Phys. J. C 76, 84 (2016)





for forward
Acc : 0 ~ 0.25 rad

large-angle
Acc: 0.35 ~ 2.5 rad

HARP coverage in p-θ plane:
- forward: p > 0.5 GeV/c, θ < 0.25 rad
  - binning is rough
- large-angle: p < 0.8 GeV/c, θ > 0.35 rad

Need low energy proton data with wide acceptance

Summary

- Various neutrino physics programs seriously need for data of low energy hadron beam with several targets.
- In a timely manner seems to be important:
  - On going projects (~middle of 2020's) need it as soon as possible.
  - Data after long shutdown 3 is also important for long term projects
- Promising new discovery for neutrino physics coming next decade, but precise hadron interaction data is crucial.