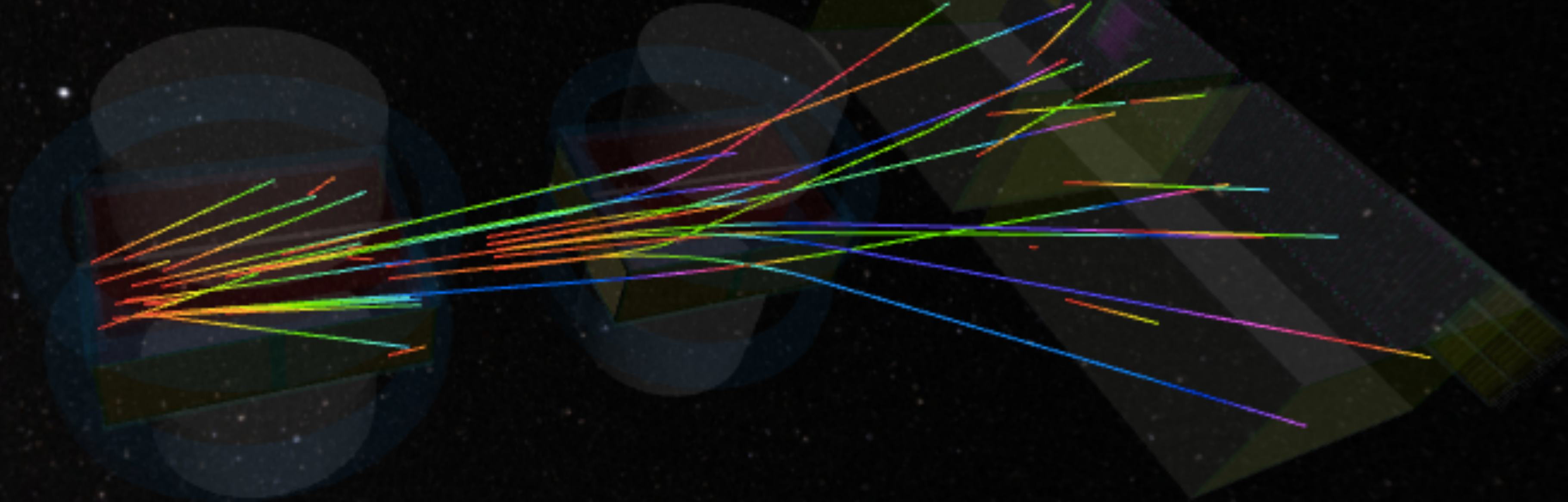
Hadron production Measurements for Long-Baseline Neutrino Beams



Alysia Marino, University of Colorado Boulder

October 28, 2020

Outline

- Neutrino oscillations
- Accelerator-generated neutrino beams
- Why hadron production measurements?
  - Measurement Strategies
  - Brief overview of external data

Neutrino Oscillations

Standard Model of Particles

	Quarks		Leptons	
charge → / mass →	+2/3 u 3 MeV	-1/3 d 7 MeV	-1 e 0.5 MeV	0 ν_e ~0 eV
	+2/3 c 1.2 GeV	-1/3 s 120 MeV	-1 μ 105 MeV	0 ν_μ ~0 eV
	+2/3 t 174 GeV	-1/3 b 4.3 GeV	-1 τ 1.8 GeV	0 ν_τ ~0 eV
	Strong, EM, Weak forces		EM, Weak forces	Weak force

Force carriers not included

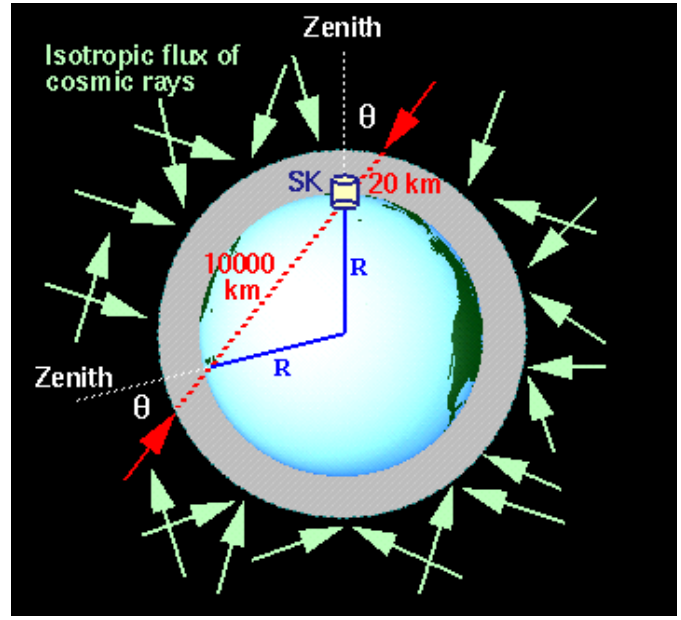
Heavier Masses (?)

- Each particle also has a corresponding anti-particle, eg e^+ and $\bar{\nu}$

Evidence for Oscillations

- **Atmospheric neutrinos** should be symmetric about the horizon
- **Super-Kamiokande** reported same number of electron neutrinos, but **fewer muon neutrinos** from below than above

hep.bu.edu/~superk/atmnu/



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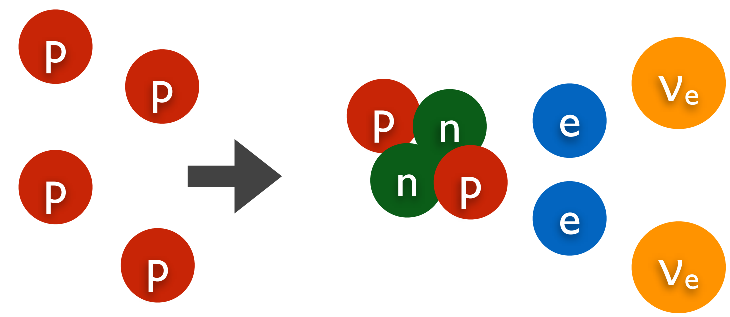
- **Sudbury Neutrino Observatory** showed that solar ν_e **turn into other flavors**.

$$4p \rightarrow {}^4_2\,\mathrm{He} + 2e^- + 2\nu_e$$



- ν_e flux:

$$1.68^{+0.06}_{-0.06}(\mathrm{stat})^{+0.08}_{-0.09}(\mathrm{syst}) \times 10^6 cm^{-2}s^{-1}$$

- ν_X flux:

$$4.94^{+0.21}_{-0.21}(\mathrm{stat})^{+0.38}_{-0.34}(\mathrm{syst}) \times 10^6 cm^{-2}s^{-1}$$

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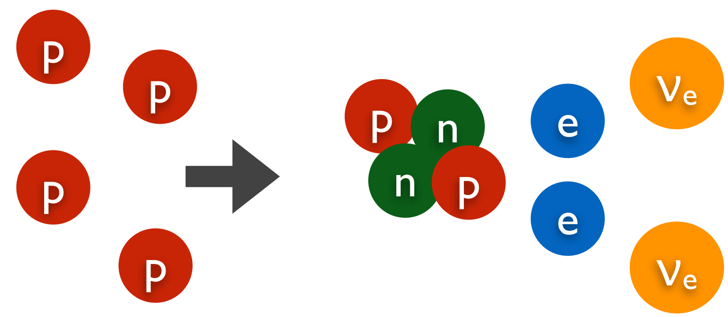

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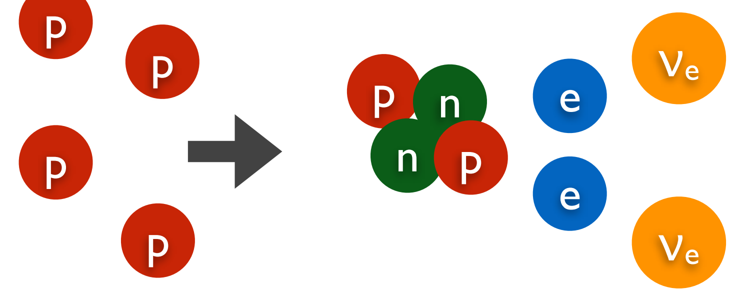

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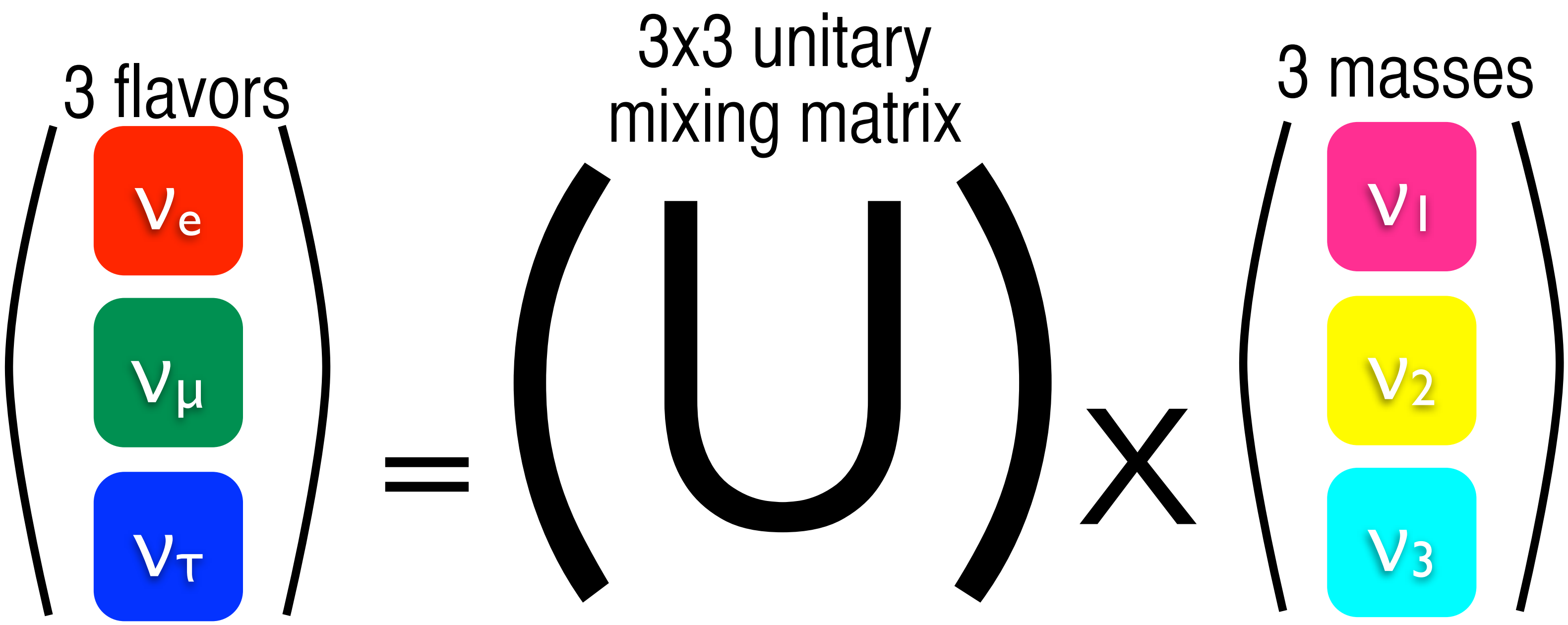
- Now making more precise measurements **with accelerator-generated neutrino** beams and **reactor anti-neutrinos**.

Neutrino Mixing

- Neutrino flavor states are a mixture of neutrino mass states.



- Neutrinos are produced in pure flavor states.
- Interference between the **flavor eigenstates** and the **mass eigenstates** causes the observed flavor to oscillate over time.

Two-Flavor Mixing

- For 2 neutrino mixing this mixing matrix can be expressed as a rotation matrix, with a single **mixing angle** θ_{12}

Flavor States | Mixing Matrix | Mass States

$$\begin{bmatrix} \nu_\alpha \\ \nu_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{bmatrix} \times \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

Example: Two-flavor Oscillations

- A neutrino produced with a given **flavor α** is a mixture of neutrino mass eigenstates (1 and 2)

$$|\psi(t=0)\rangle = |\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle$$

- These evolve over time with slightly different frequencies

$$|\nu_\alpha(t)\rangle = U^*_{\alpha 1}|\nu_1\rangle e^{-i(E_1 t - \vec{p}\cdot\vec{x})} + U^*_{\alpha 2}|\nu_2\rangle e^{-i(E_2 t - \vec{p}\cdot\vec{x})}$$

- Since L~t for neutrinos, probability of starting with **flavor α** and later **observing flavor β** is

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta(L)|\nu_\alpha\rangle|^2$$

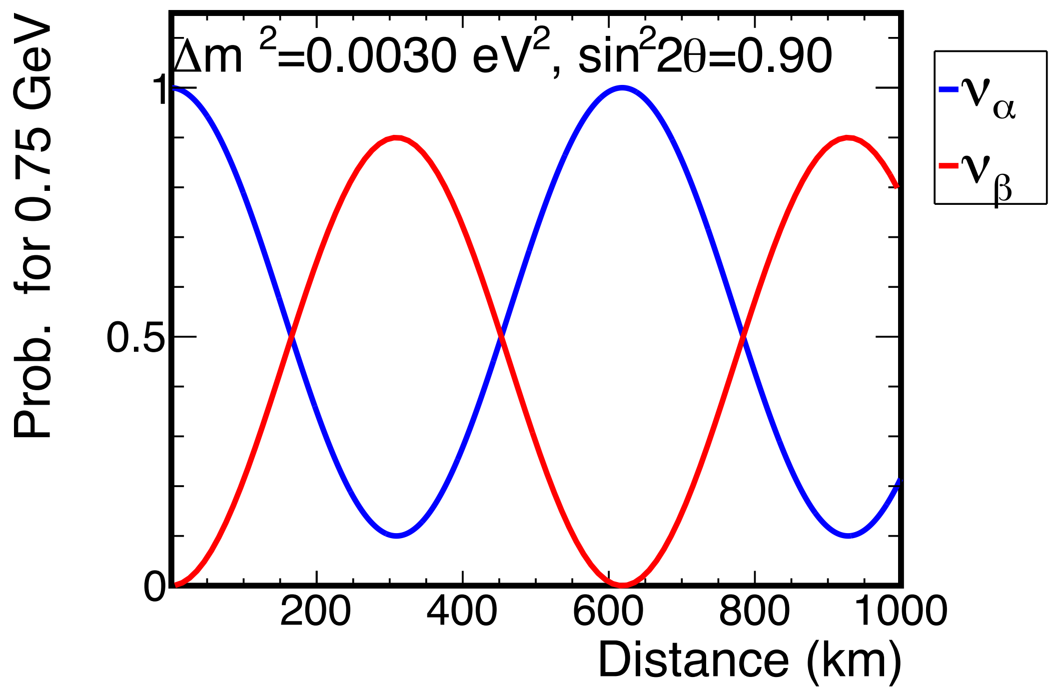
Two-Flavor Oscillations

- For 2 flavors, the survival probability simplifies to:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{12} \sin^2\left(\Delta m^2_{12} \frac{L}{4E}\right)$$

Matrix Elements

$\Delta m_{ij}^2 = m_i^2 - m_j^2$



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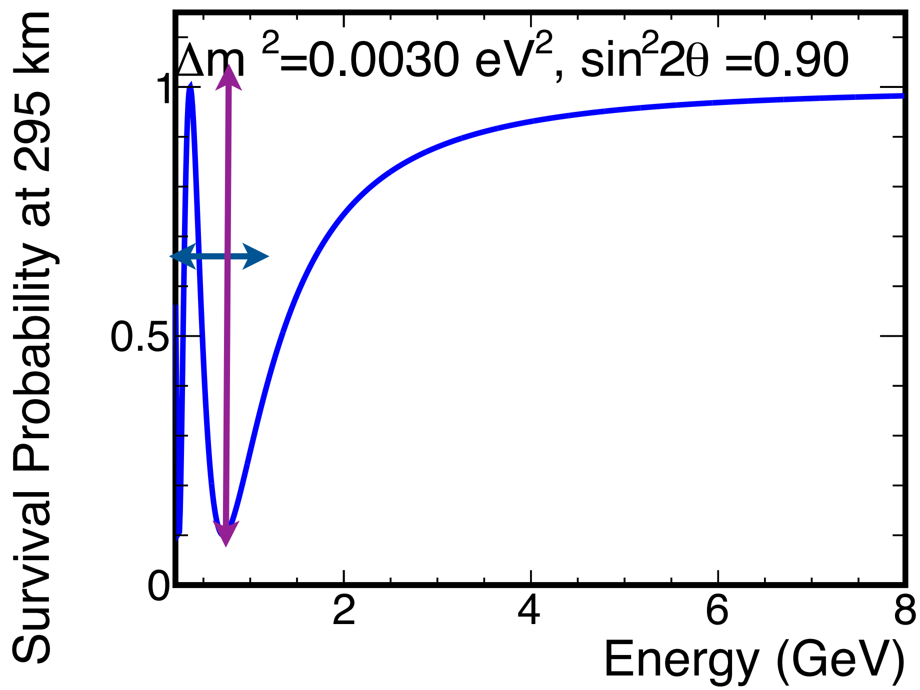


3 Flavor Neutrino Mixing

- For 3 flavors, can be described by 3 angles and a phase in the PMNS matrix

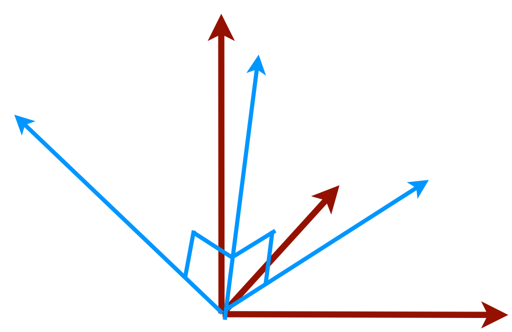
θ_{23} and Δm^2_{32}
Atmospheric/ Accelerator neutrinos
θ_{23}~45°

δ, θ_{13} and Δm^2_{31}
reactor anti-neutrinos and accelerator neutrinos
θ_{13}~9°

θ_{12} and Δm^2_{21}
Solar neutrinos/ reactor anti-neutrinos
θ_{12}~34°

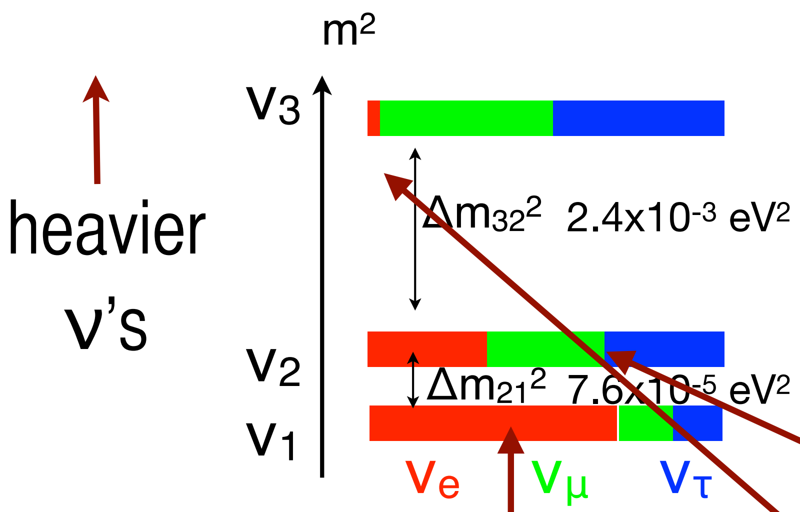
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $s_{ij} = sin(\theta_{ij})$ and $c_{ij} = cos(\theta_{ij})$



- Anti-ν depend on U*

What We Know about Neutrino Masses and Mixings



We know that atmospheric ν oscillate with a much a smaller L/E than solar ν.
→**Two different Δm^2 scales**

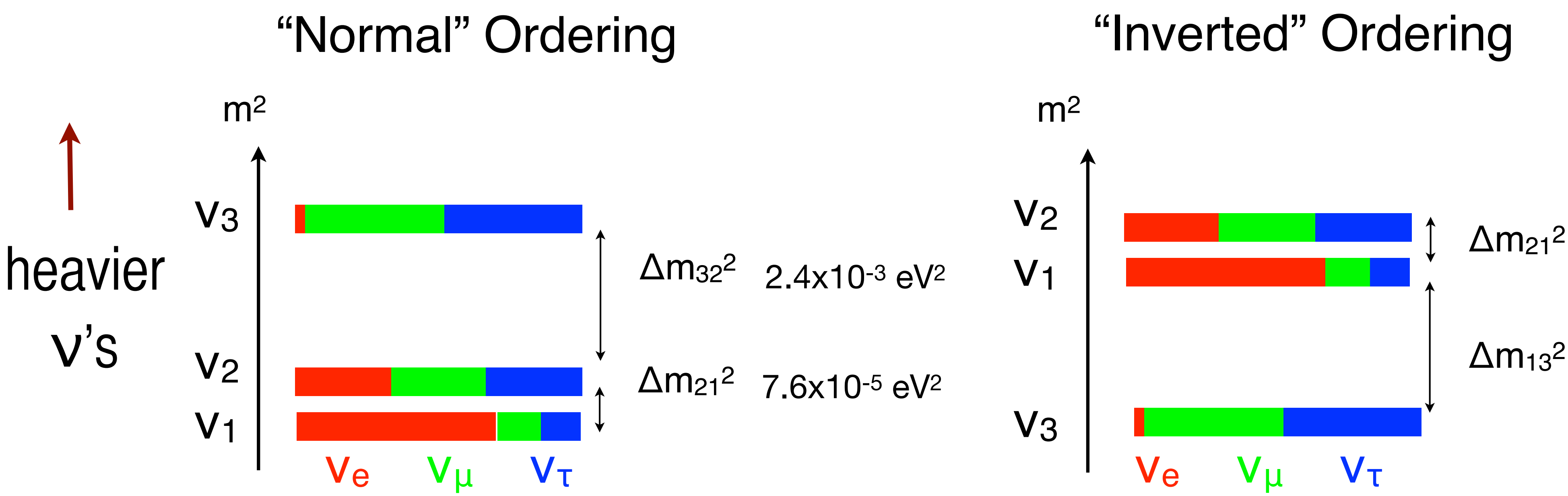
From atmospheric and accelerator ν_μ we know that ν_2 and ν_3 have significant ν_μ and ν_τ fractions. Mixing large, so $\boldsymbol{\theta_{23}}$ **nearly 45°**.

From solar and long-distance reactor ν, we know that the ν_1 and ν_2 have significant ν_e fractions so large mixing, but angle is less than 45°

From short-distance reactor ν we know that ν_3 has a small ν_e fraction. **$\boldsymbol{\theta_{13}}$ angle is only ~9°**

Neutrino Masses

- Two different mass difference orders are possible



- Sign of Δm_{21}^2 is known due to effects in the Sun, but sign of Δm_{32}^2 isn't, so two possible orderings of masses

Three-Flavor Mixing in Vacuum with δ=0

- L/E scale relevant for recent accelerator beams oscillation effects are dominated by $m_3 \leftrightarrow m_2$ and $m_3 \leftrightarrow m_1$ mixing

- ν_μ Disappearance in a ν_μ Beam

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \cdot \sin^2 (\Delta m^2_{32} L/4E)$$

- ν_e Appearance in a ν_μ Beam

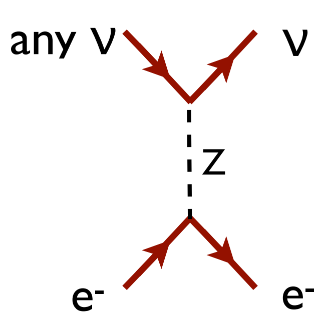
$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 (\Delta m^2_{31} L/4E)$$

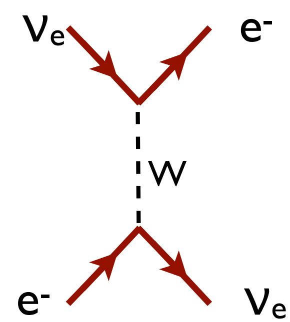
- Precision measurements require 3 flavor fits

Neutrino Oscillations in Matter

- Matter has e^-, and few μ^- or τ^-
- Additional processes for ν_e and anti-ν_e scattering on e^-

All ν





νe only

- Modifies apparent oscillation probabilities

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \frac{\sin^2\theta_{23}}{(A-1)^2} \cdot \sin^2\left((A-1)\Delta m^2_{31} L/4E\right)$$

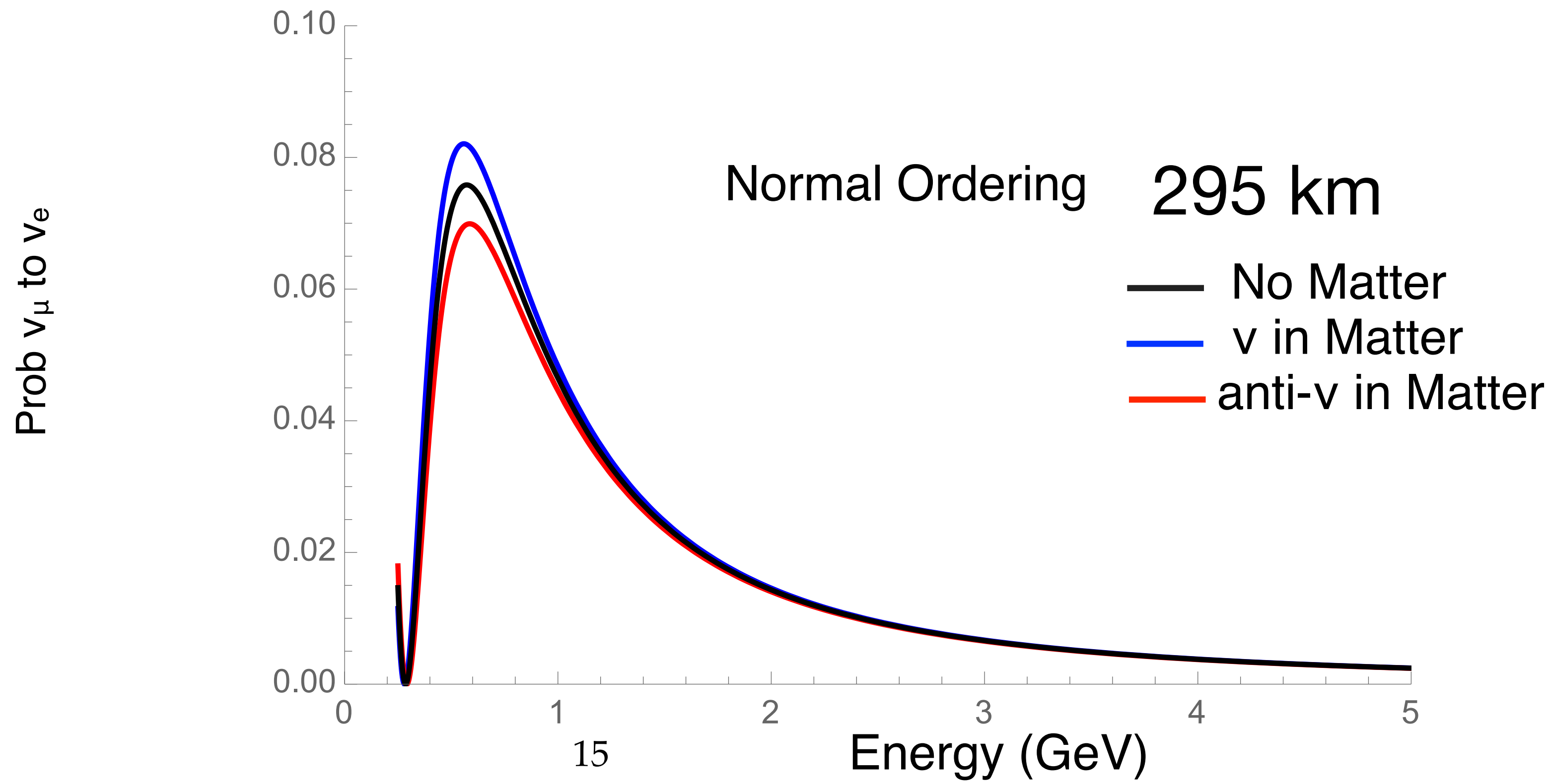
where $A = \sqrt{2} G_F N_e \frac{2E}{\Delta m^2_{31}}$

- Effect increases with E and N_e

Depends on mass ordering

Matter Effects

- Additionally matter effects change sign for anti-neutrinos
- So in the normal ordering the appearance probability increases for neutrinos and decreases for anti-neutrinos.



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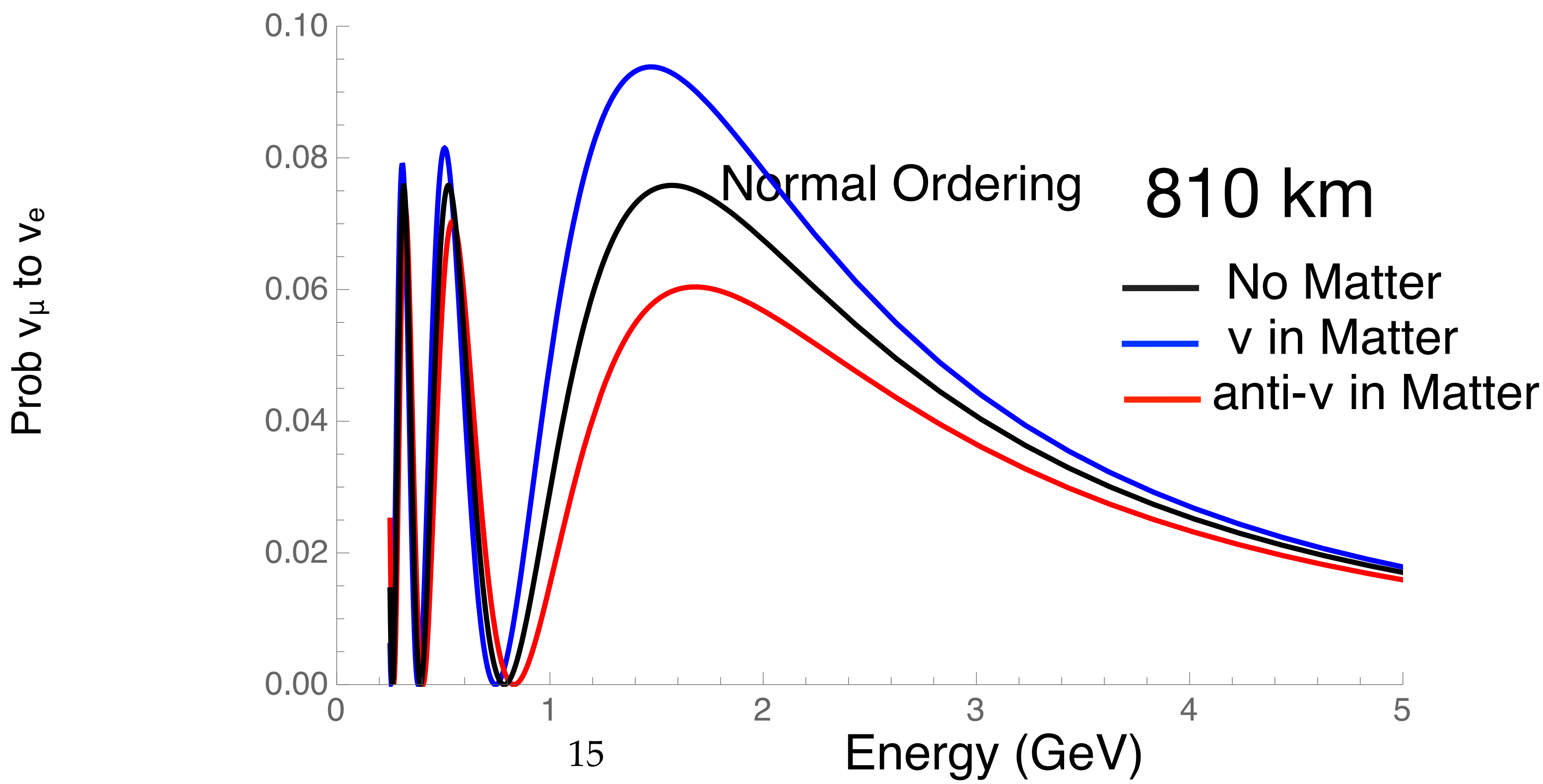
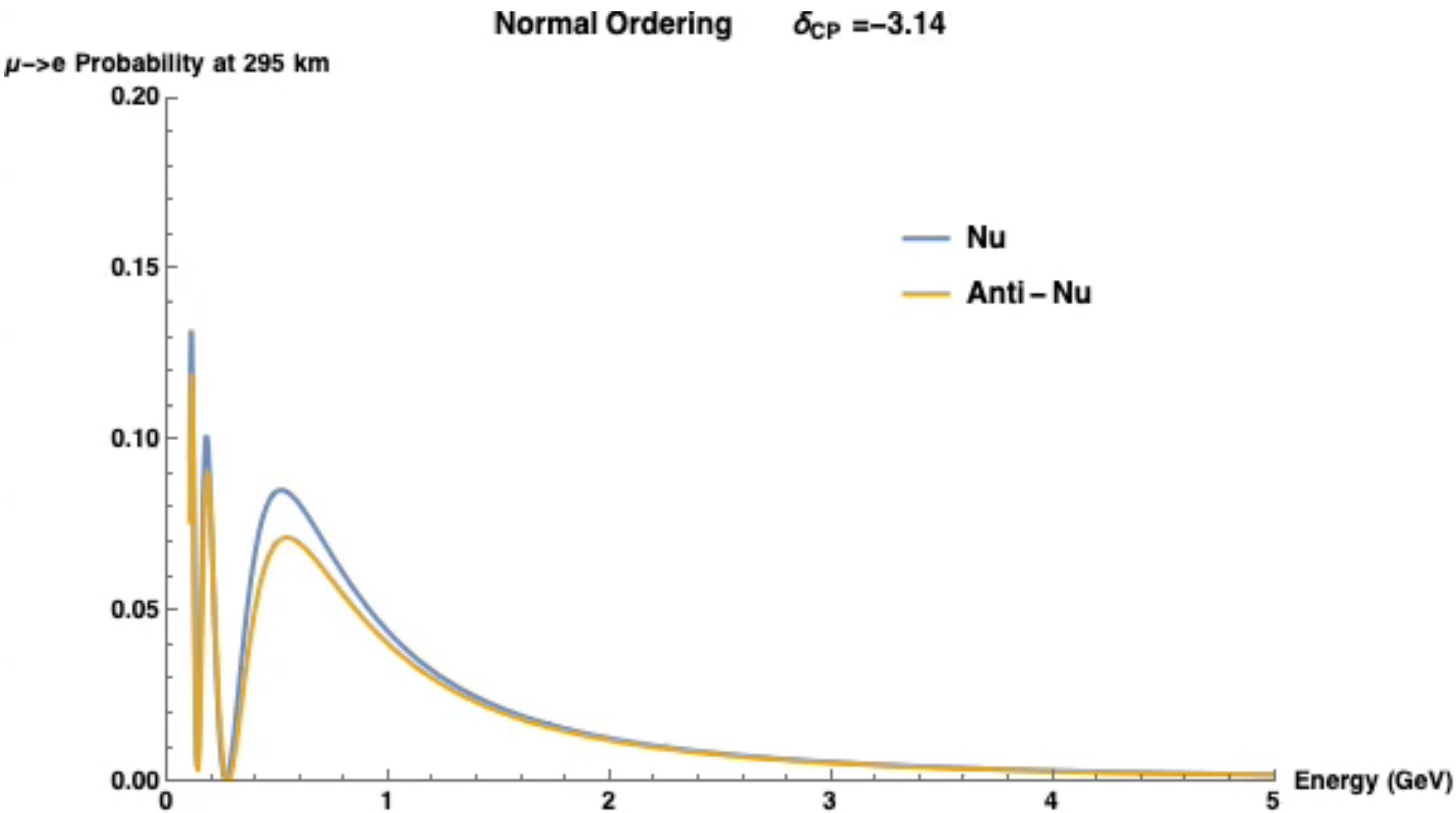


Impact of δ

- There are additional terms in the oscillation probability that depend on -sin(δ) for neutrinos and sin(δ) for anti-neutrinos.
- This will lead to **differences** in $P(\nu_\mu \to \nu_e)$compared to even in vacuum $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

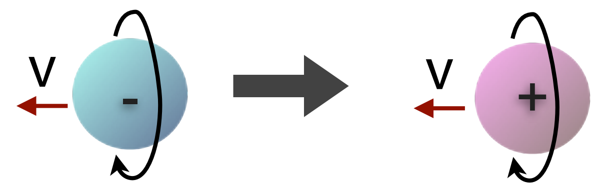
Effect of value of δ



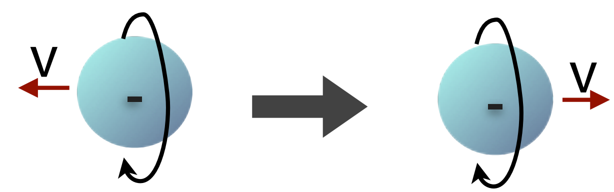
CP Symmetry

- **C:** Charge conjugation
  - Replace all particles with anti-particles
- **P:** Parity
  - Invert all spatial coords ($x \rightarrow -x$, etc)
  - Converts right-handed particles to left-handed particles
- Weak interaction violates **C and P symmetry**, but if **CP** is a good symmetry left-handed neutrinos and right-handed anti-neutrinos should have identical physics

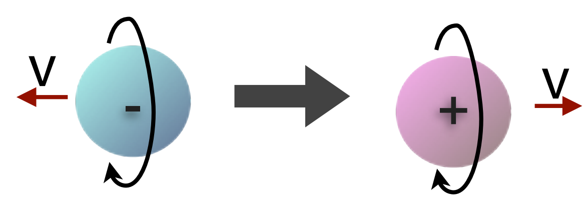
C transformation



P transformation



CP transformation



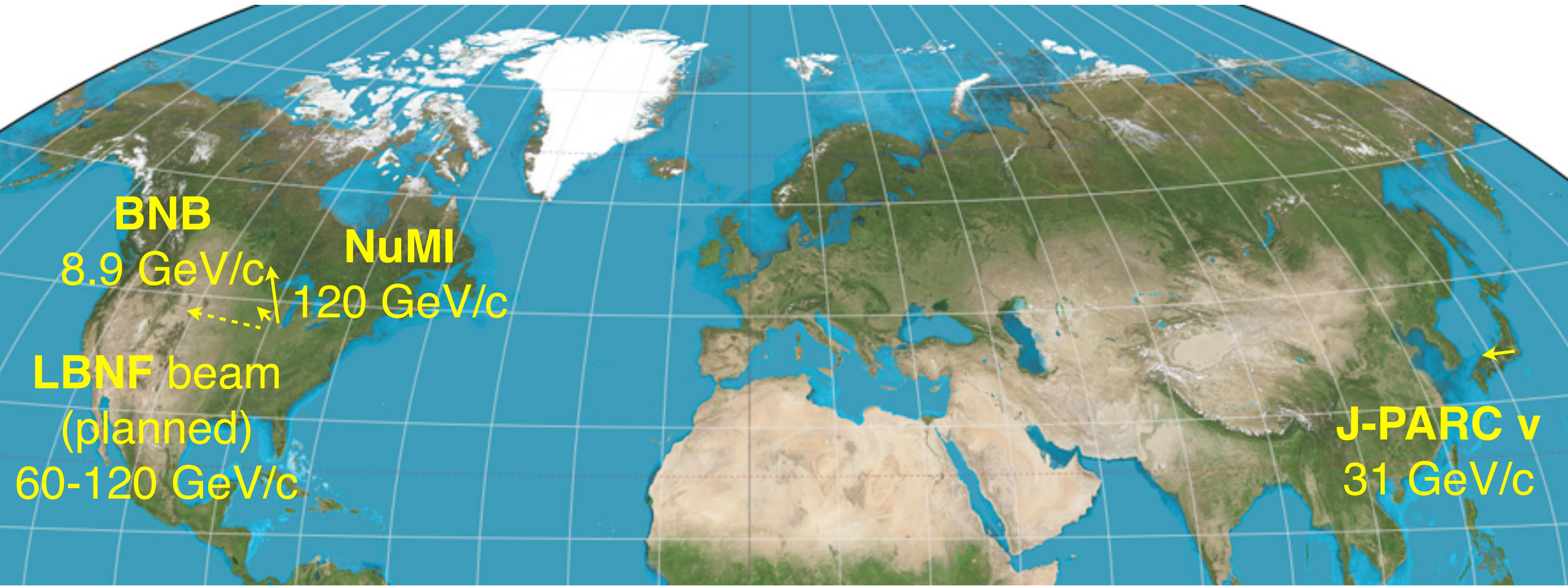
Big Questions to Answer with Long-Baseline Neutrino Beams

- Is the **mass ordering** normal or inverted?
- Is θ_{23} exactly 45 degrees?
- Is the mixing matrix different for neutrinos and anti-neutrinos?
  - Is **sin(δ)=0**?
  - CP Violation w leptons?
- Is the mixing matrix unitary?

Neutrino Experiments

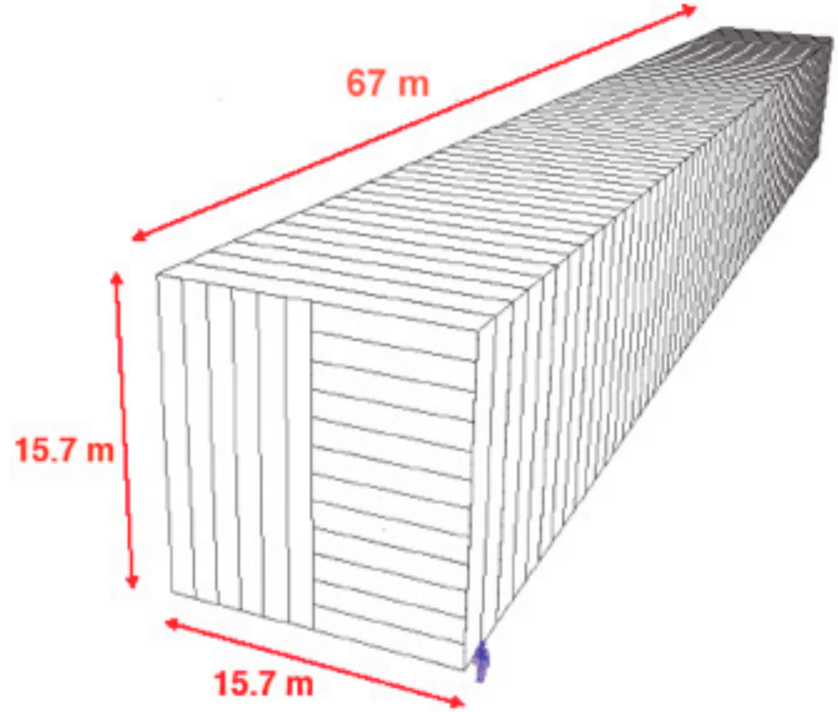
Current Neutrino Beams

- Current long-baseline experiments:
  - T2K using J-PARC neutrino beam
  - NOvA using NuMI beam
- Future long-baseline experiments:
  - Hyper-Kamiokande using J-PARC neutrino beam
  - DUNE using the LBNF beam

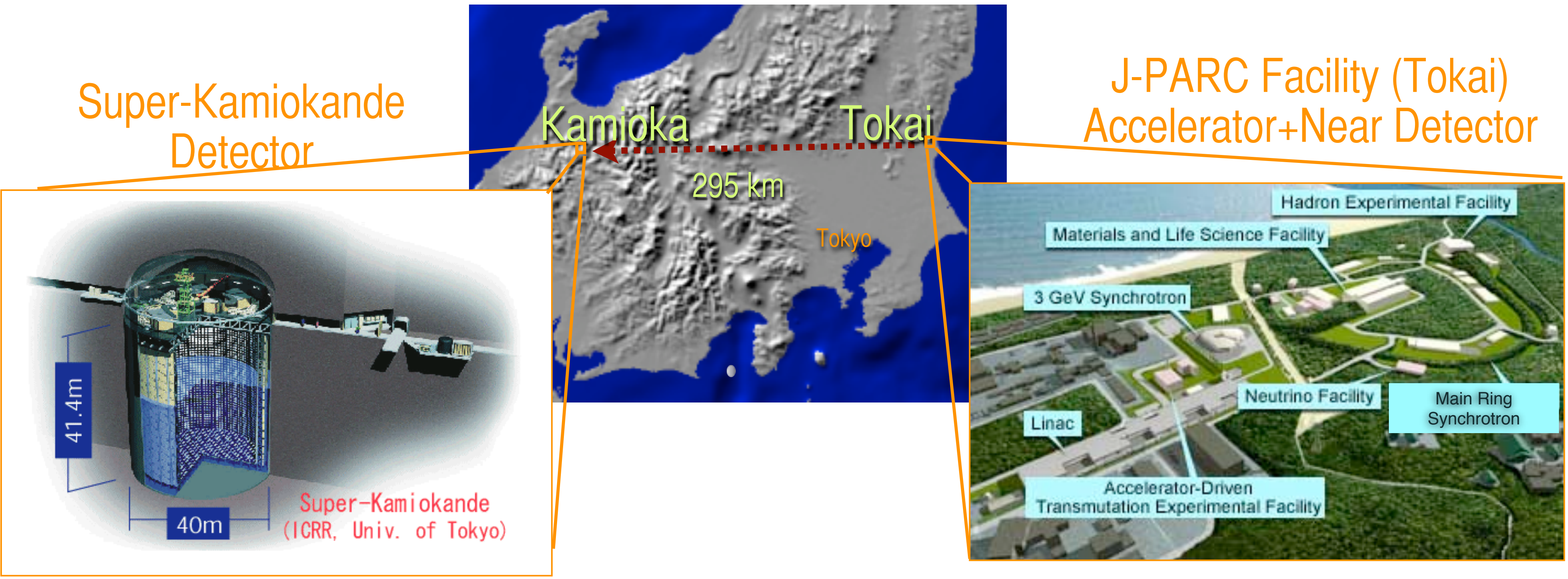


NOνA

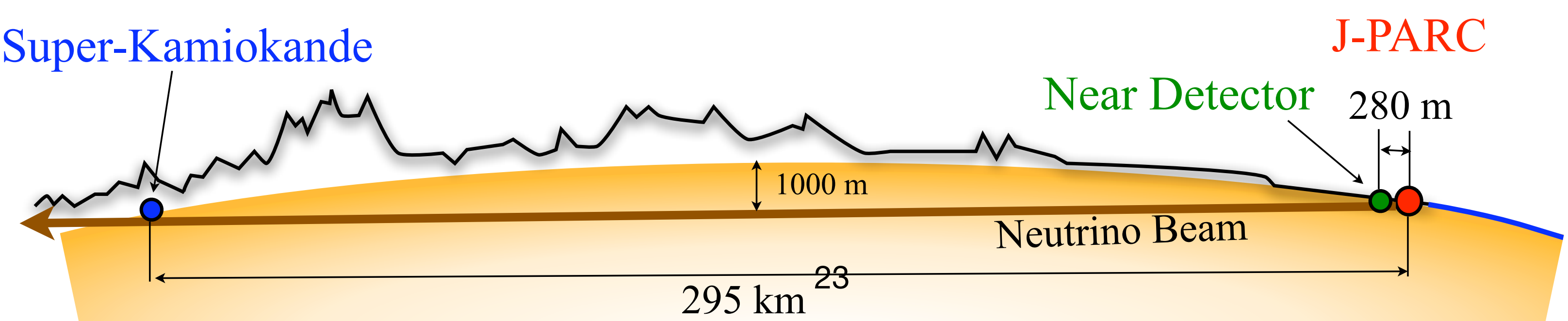
- Off-axis from NuMI beam
- 810 km baseline
- Active liquid scintillator detectors, 14 kton far det



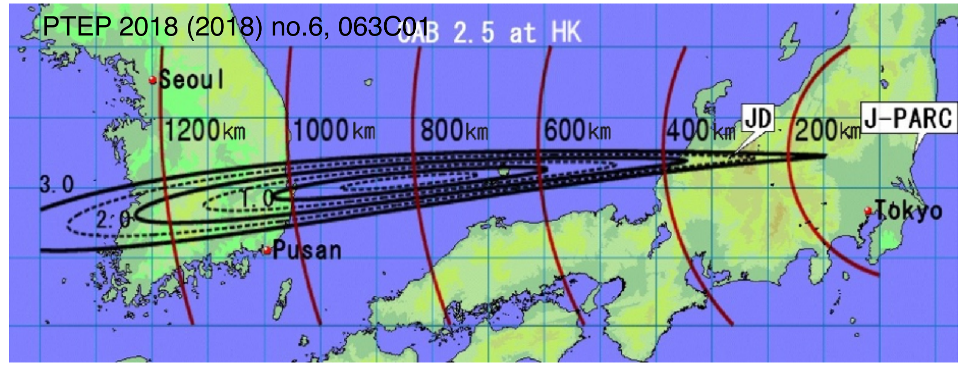
T2K: Tokai-to-Kamioka



- Long-baseline neutrino experiment in Japan with 295 km baseline

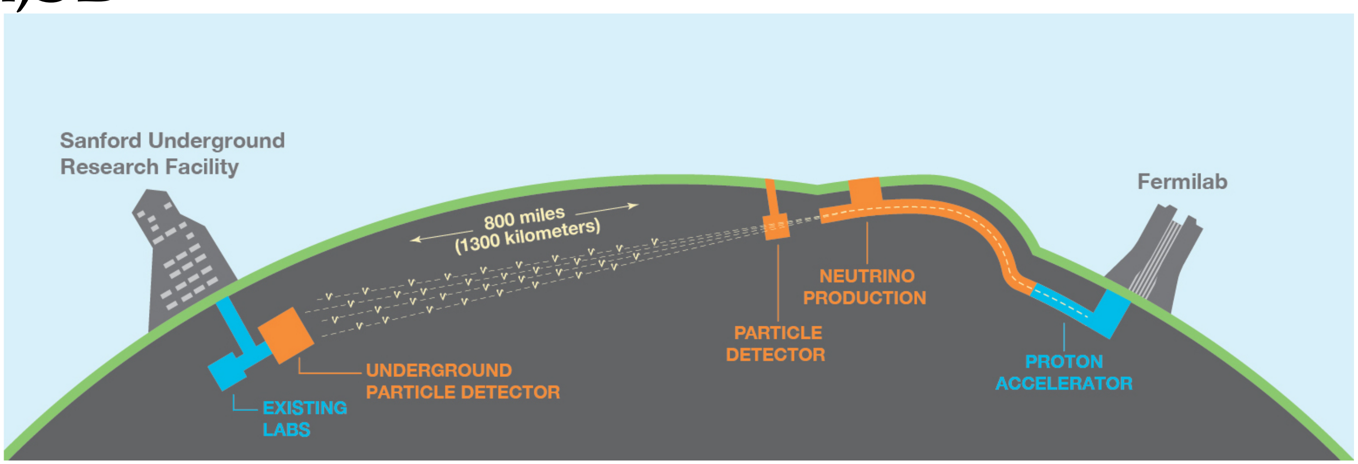


Future Long-Baseline Neutrino Experiments



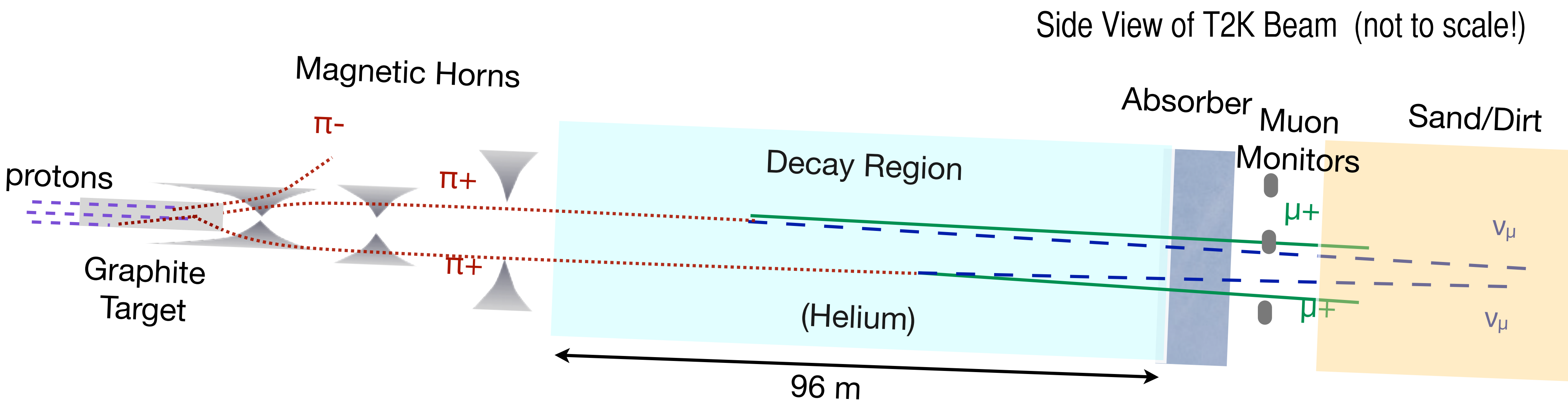
- **Hyper-Kamiokande**:
  - New far detector in Japan
  - Possibility for other detectors at longer-baselines

- Deep Underground Neutrino Experiment (**DUNE**)
  - New LBNF beamline from Fermilab to SURF in Lead,SD



Neutrino Production
(Using T2K as an example)

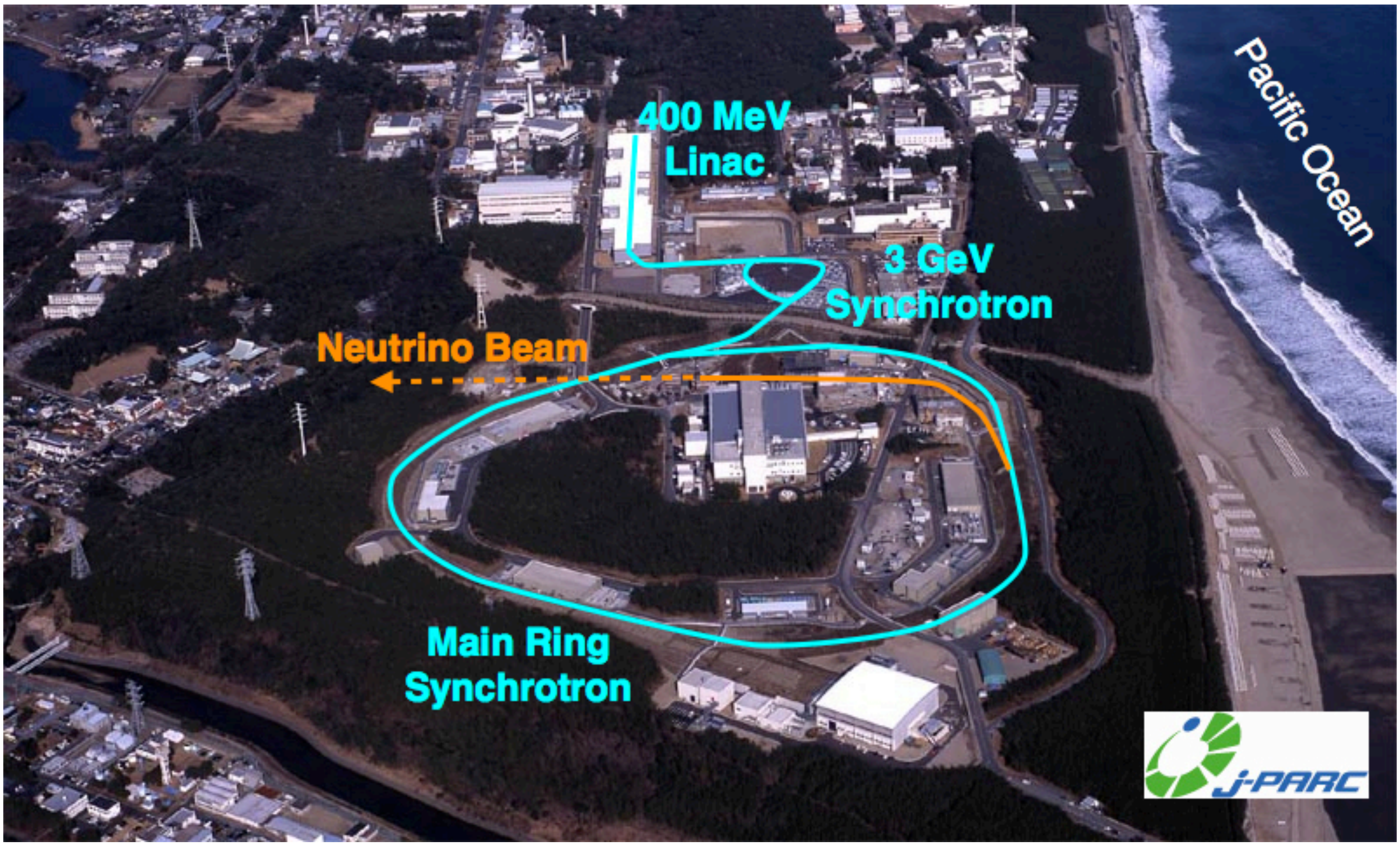
How to Make a Beam of ν: T2K Beam



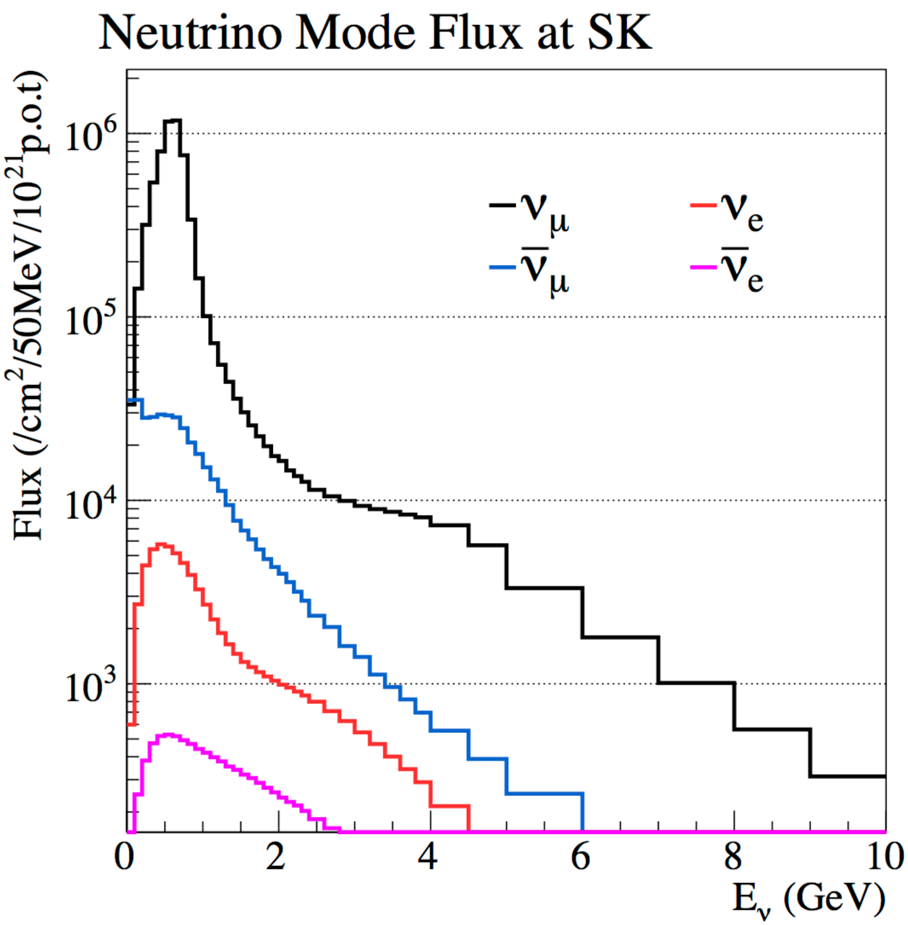
- 30 GeV p's strike graphite target, producing π's and K's
- 3 magnetic horns focus π^+ and K^+ in desired direction
- π's and K's to decay to μ's and ν's
- Dirt will stop μs; νs continue through the earth
- T2K Beam is ~95% ν_μ, 4% $\bar{\nu}_\mu$, 1% ν_e
- Can make a $\bar{\nu}_\mu$ beam by changing sign of horn current

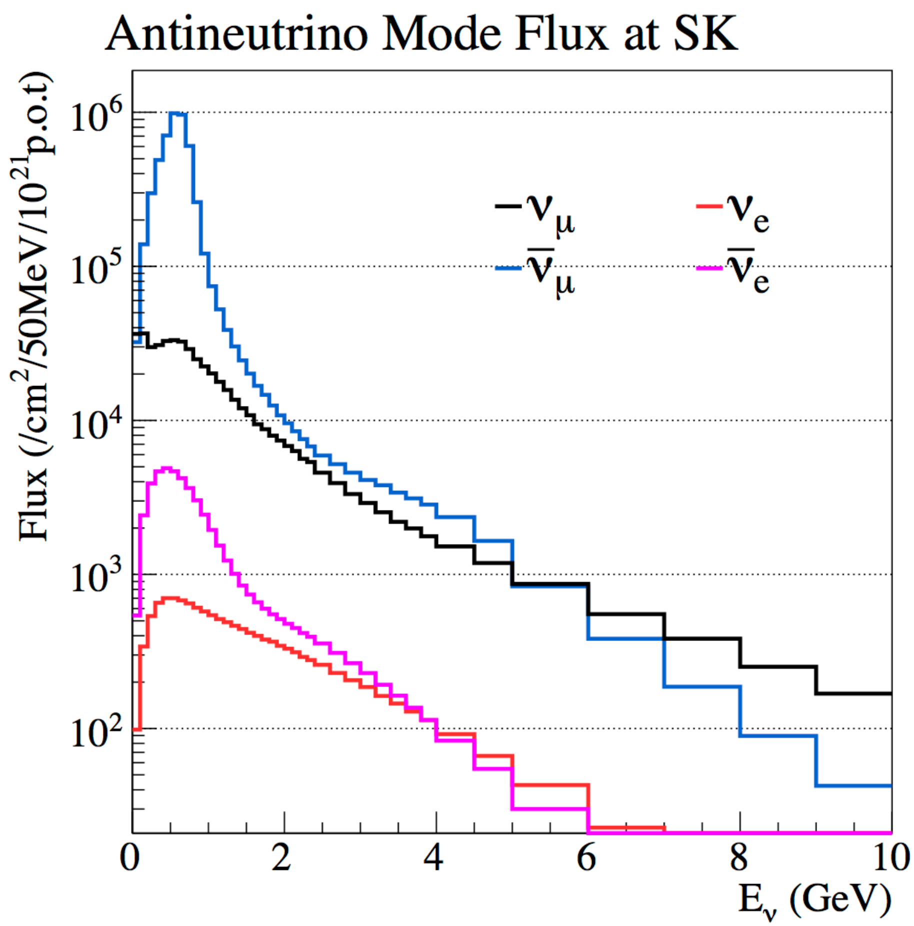
Accelerator used by T2K

- Protons accelerated to 30 GeV at J-PARC
- Designed for 3.3×10^{14} protons per pulse
- Pulse is 5.2 μsec, 1 pulse every ~2.5 sec



Neutrino Flux Example: T2K

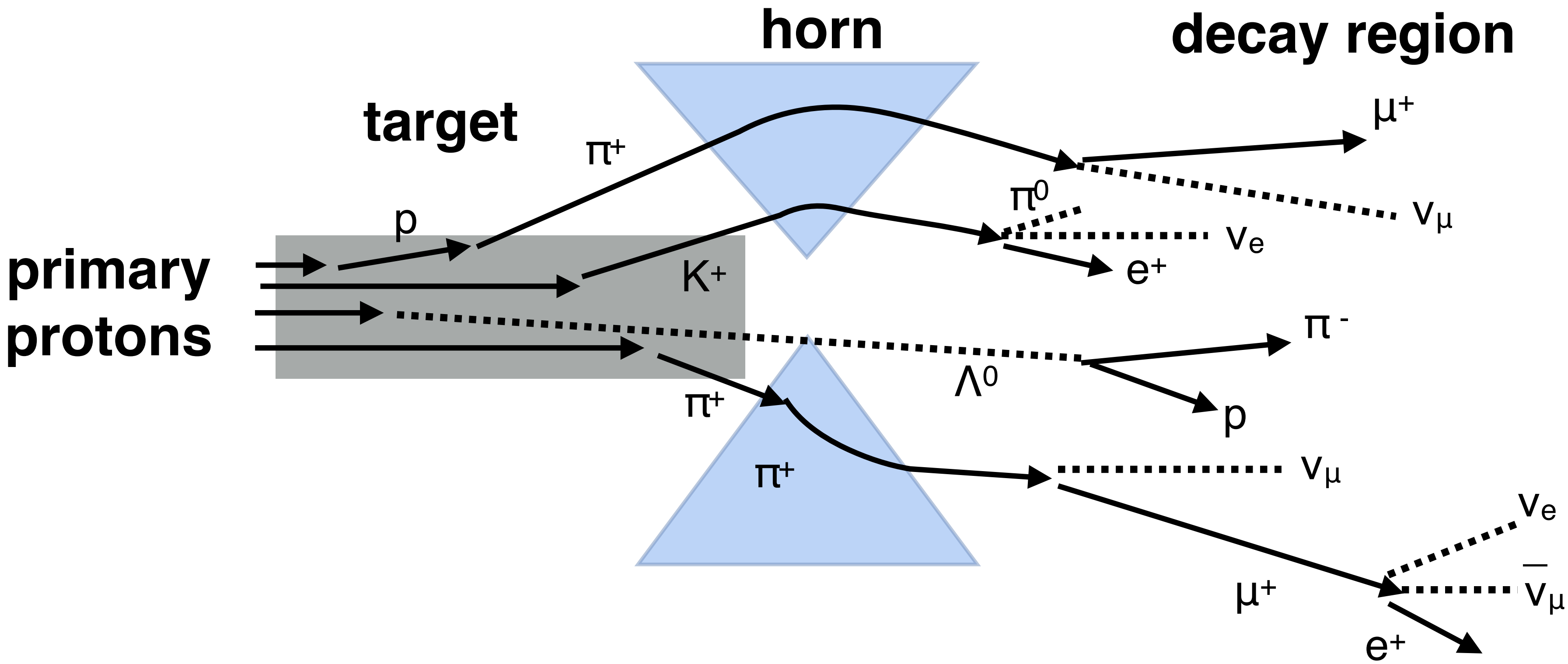




Pause for Questions

Hadron Production Measurements for Neutrino Experiments

Neutrino Production



- For **accelerator-based** and **atmospheric neutrino sources** neutrino production processes are complex.
  - Hadron production in beamline interactions typically dominates the flux uncertainty

Why Hadron Production Measurements?

- Neutrino flux not well-modeled by Monte Carlo simulations
  - But with more measurements the model predictions keep improving
- Important to **understand neutrino source** when making measurements of **flavor oscillation**
- **Neutrino interaction** measurements and other **near detector physics** require precise independent flux constraints

Hadron Production Measurement Strategies

- **In Situ** measurements:
  - Direct hadron production measurements in beamline
  - Muon monitors
  - Very challenging detector environment!
- **External hadron production** measurements:
  - **Thin targets** (few %of λ)
  - **Thick or replica targets** (>~λ)

2 cm C target

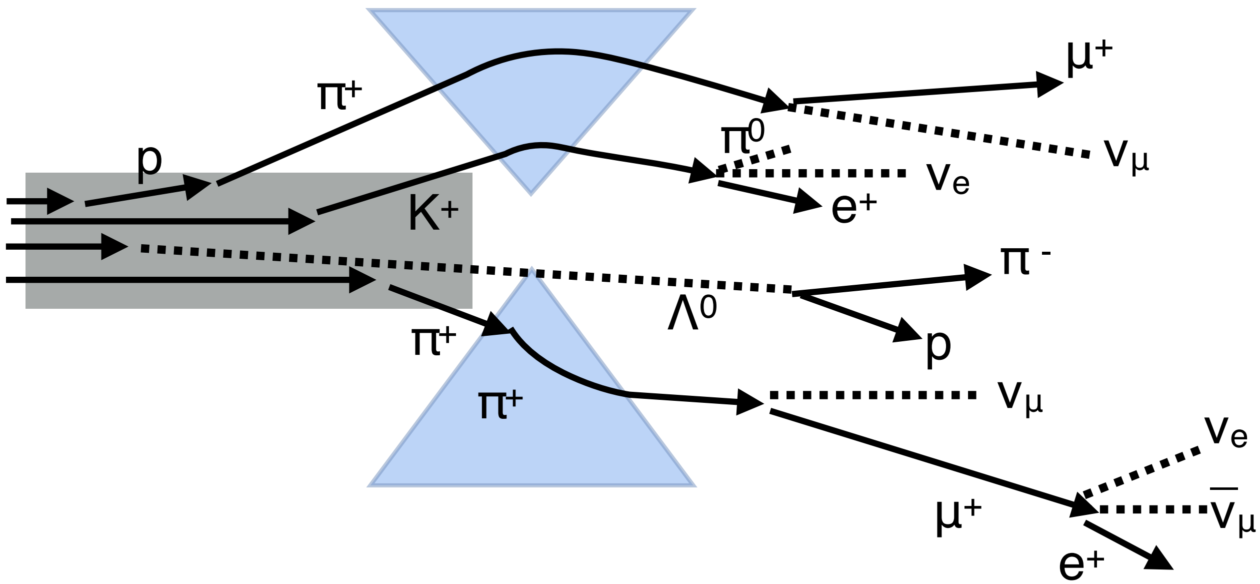
T2K replica target

External Measurement Needs

- Total **cross section** measurements help to model the interaction probabilities in the beamline materials
- Also need **particle production spectra**
  - Often reported in bins of hadron (p,θ) or (x_F, p_T) where $x_F = 2p_L^*/\sqrt{s}$
- Some existing single-arm spectrometer measurements
- More recently there are **dedicated hadron production experiments** using large acceptance tracking detectors

Secondary Interactions and Beyond

- Secondary and tertiary interactions often significant, so want **not just primary proton** data, but also **thick target** data and l**ower energy hadron data** to constrain reinteractions



- In T2K ~1.4 hadronic interactions per ν_μ in neutrino mode
- In NOvA, ~1.5-1.6 hadronic interactions per ν_μ in neutrino mode for $E_\nu > 1$ GeV, even more at lower energies

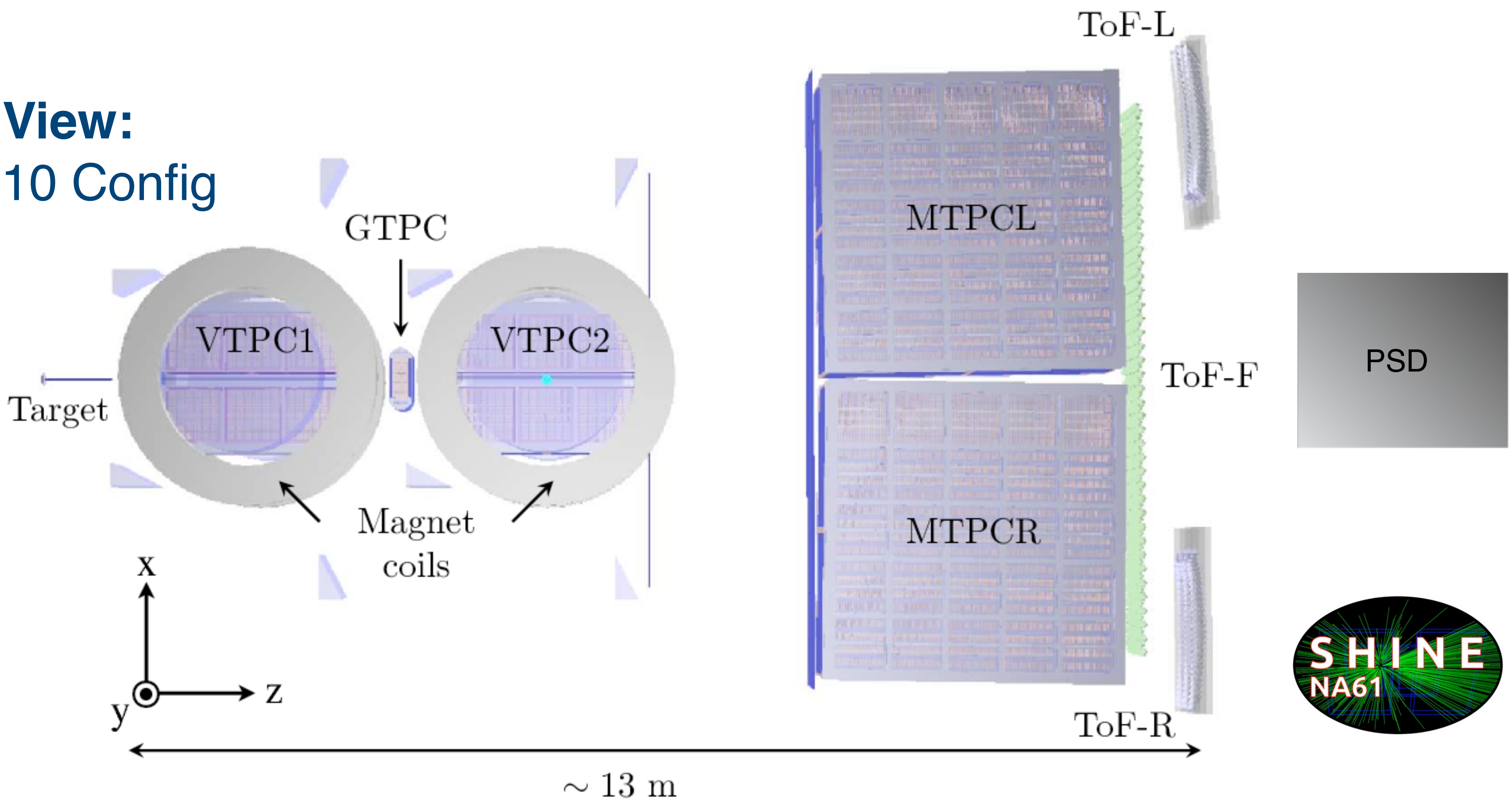
Key Thin Target Data below 25 GeV/c

Reaction	Experiment	Particles Measured	Reference
8.9 GeV/c p + thin Be	HARP	π^+	Eur. Phys J C **52** (2007) 29
6.4, 12.3, and 17.5 GeV/c p + thin Be	BNL E910	$\pi^\pm$	Phys. Rev. C **77** (2008) 015209
12.9 GeV/c p + thin Al	HARP	π^+	Nucl. Phys. B **732** (2006) 1
12 GeV/c p and $\pi^\pm$ + C	HARP	$\pi^\pm$	Astr. Phys. **29** (2008) 257
19.2 GeV/c p on p,Be, Al, Cu, Pb	Allaby et al	p,pbar, $\pi^\pm$, $K^\pm$	Tech. Rep. 70-12 (CERN, 1970)
24 GeV/c p on Be, Al, Cu, Pb	Eichten et al (CERN-Rome)	p,pbar, $\pi^\pm$, $K^\pm$	Nucl. Phys. B**44**, 333 (1972)

NA61/SHINE Experiment

- SPS Heavy Ion and Neutrino Experiment: Fixed target experiment at CERN SPS
- Primary 400 GeV/c p beam, Secondary hadron beams ~26 to 160 GeV/c

Top View:
2009-2010 Config



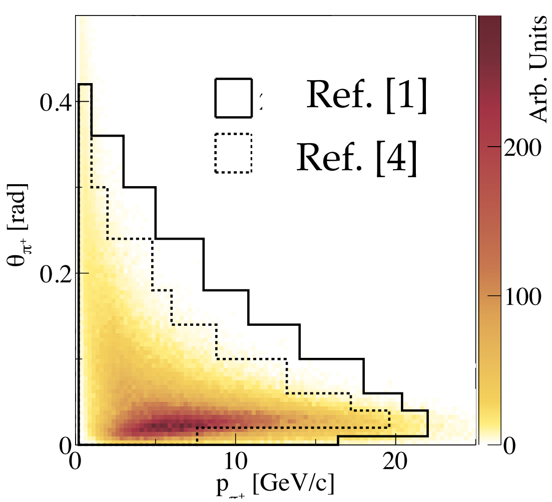
- Comprises several large acceptance TPCs, Two inside magnets

JINST **9** (2014) P06005

NA61/SHINE Thin Target Data 31-60 GeV

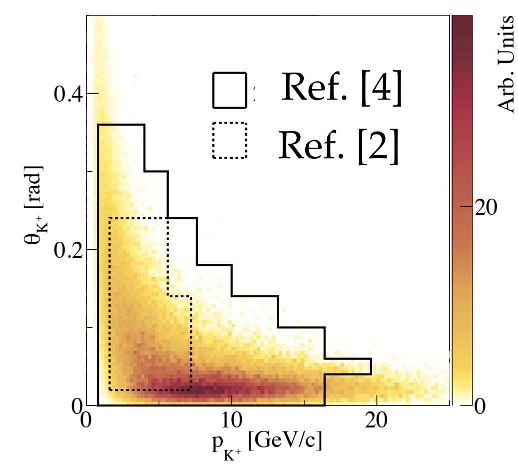
Reaction	Particles Measured	Reference
31 GeV/c p + C	$\pi^{\pm}$	[1] Phys. Rev. **C84** (2011) 034604
31 GeV/c p + C	K^{+}	[2] Phys. Rev. **C85** (2012) 035210
31 GeV/c p + C	K^{0}_{s}, Λ	[3] Phys.Rev. **C89** (2014) 025205
31 GeV/c p + C	$\pi^{\pm}$, $K^{\pm}$,K^{0}_{s}, Λ,p	[4] Eur.Phys.J. **C76** (2016) 84
60 GeV/c π^{+}+C, p+Be	$\pi^{\pm}$, $K^{\pm}$,K^{0}_{s}, Λ,p	[5] Phys.Rev.D 100 (2019) 11, 112004
60 GeV/c p+C, p+Be, p+Al	$\pi^{\pm}$, $K^{\pm}$,K^{0}_{s}, Λ,p	in progress

π+ Coverage



Colors indicate relative contribution to T2K neutrino flux at SK in neutrino mode

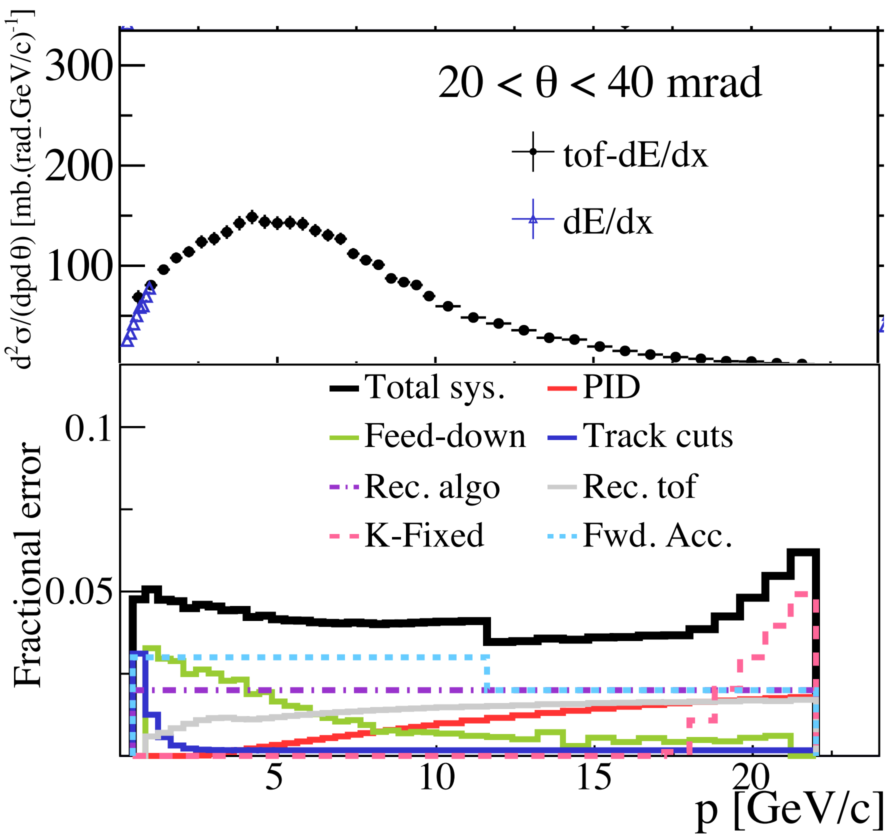
K+ Coverage



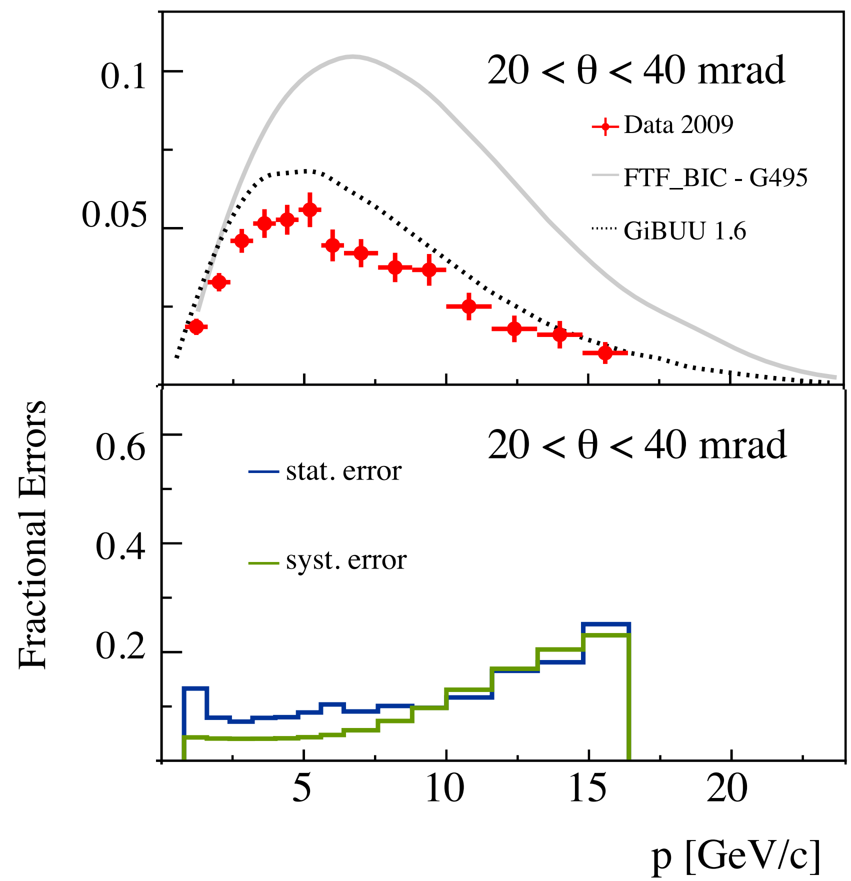
Thin Target Results

- Sample slices for π^+ and K^+ for 20-40 mrad

π^+



K^+



Eur.Phys.J. C**76** (2016) 84

Key data at 120-160 GeV/c

Reaction	Experiment	Particles Measured	Reference
58, 84, 120 GeV/c p + various thin targets	E907/MIPP	n	Phys.Rev. D**83** (2011) 012002
120 GeV/c p + NuMI low energy target	E907/MIPP	$\pi^{\pm}$	Phys.Rev. D**90** (2014) 032001
158 GeV/c p +C	NA49	$\pi^{\pm}$	Eur.Phys.J. C**49** (2007) 897
158 GeV/c p +C	NA49	p, pbar, n, d, t	Eur.Phys.J. C**73** (2013) 2364
120 GeV/c p +C	NA61		in progress

Key Data at 400-450 GeV/c

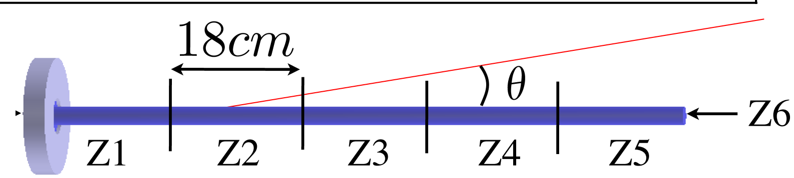
Reaction	Experiment	Particles Measured	Reference
400 GeV/c p + 10-50 cm Be target	NA20	$\pi^{\pm}$, $K^{\pm}$,p,pbar	CERN Tech. Rept. 80-70 (1980)
450 GeV/c p + 10 cm Be target	NA56/SPY	K/π ratio	Phys. Lett. B**420** (1998) 225
450 GeV/c p + 10 cm Be target	NA56/SPY	$\pi^{\pm}$	Phys. Lett. B**425** (1998) 208
450 GeV/c p + Be target	NA56/SPY	$\pi^{\pm}$, $K^{\pm}$,p,pbar	Eur. Jour. Phys. C**10** (1999) 605

- Most of existing data just covers the interactions of protons, and not re-interactions of pions, kaons, etc.

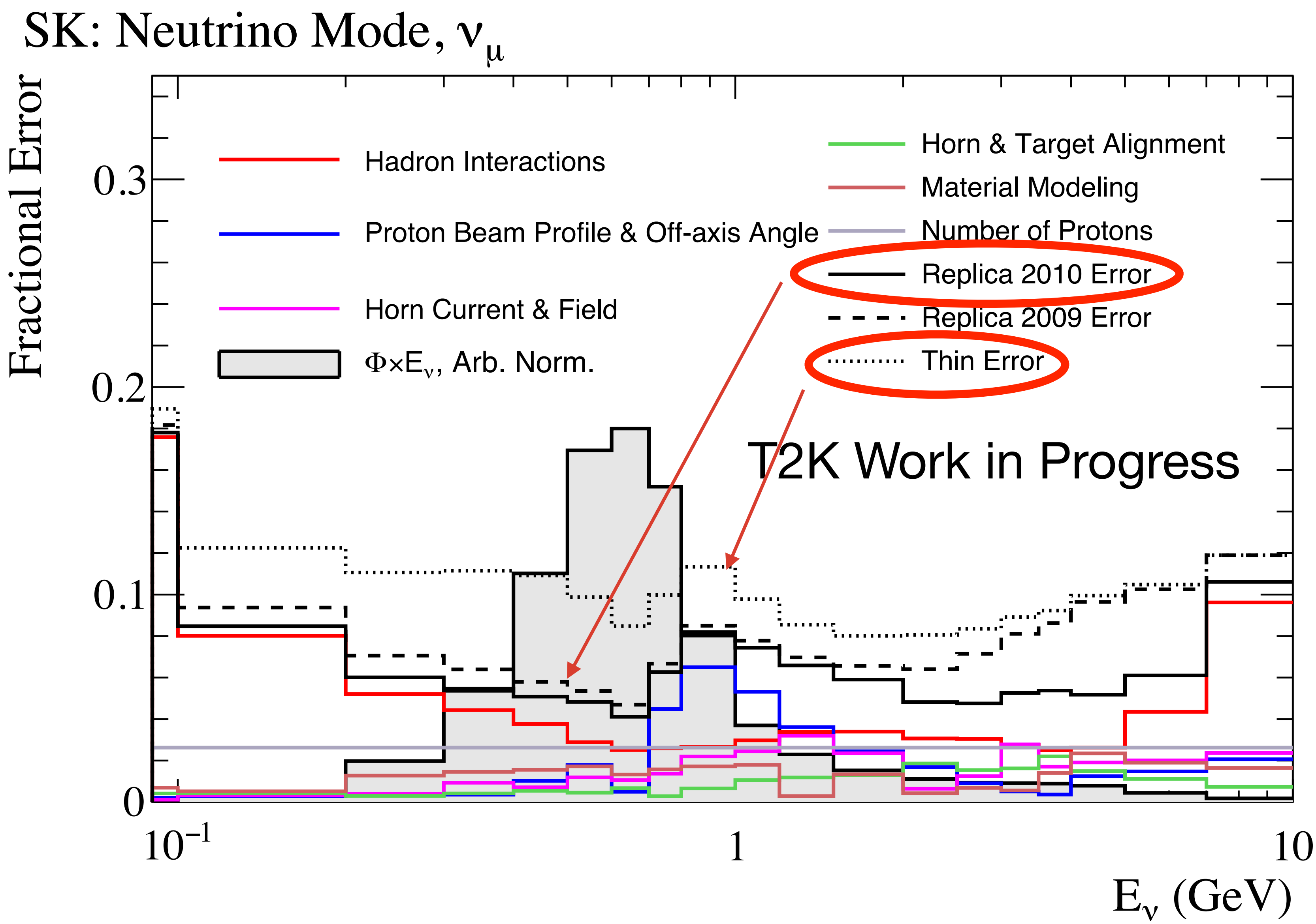
Thick Target Data at 31 GeV/c

Reaction	Particles Measured	Reference
31 GeV/c p + T2K replica target	π^+	Nucl.Instrum.Meth. A701 (2013) 99-114
31 GeV/c p + T2K replica target	$\pi^\pm$	Eur.Phys.J. C76 (2016) no.11, 617
31 GeV/c p + T2K replica target	$\pi^\pm$,$K^\pm$,p	Eur.Phys.J.C 79 (2019)2, 100
31 GeV/c p + T2K replica target	p total cross section	CERN-EP-DRAFT-NA61-2020-007

- Differential yields in (p,θ,z_{target})



Improvements with Replica Data



Application of NA61data to T2K

- Thin target weights: Where available reweight each interaction by $$W(p,\theta) = \frac{N(p,\theta)_{Data}}{N(p,\theta)_{MC}}$$
  - Can apply scaling for different materials and momenta
- Replica target data: Reweight particles exiting the target by
$$W(p,\theta,z) = \frac{N(p,\theta,z)_{Data}}{N(p,\theta,z)_{MC}}$$

Sanford-Wang Parameterization

- J. R. Sanford and C. L. Wang, "Empirical formulas for particle production in p–Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967), *unpublished*
- Depends on p_{beam}, p,θ of hadron

Reproduced from Phys.Rev. C80 (2009) 035208

- 8 free parameters for π

$$\frac{d^2\sigma(\mathrm{pA} \to \pi^\pm X)}{dp d\Omega} = c_1 \exp[B] p^{c_2} (1 - \frac{p}{p_{\mathrm{beam}}})$$

where:

$$B = -c_3 \frac{p^{c_4}}{p_{\mathrm{beam}}^{c_5}} - c_6 \theta (p - c_7 p_{\mathrm{beam}} \cos^{c_8} \theta)$$

BMPT Parameterization

- From M. Bonesini, A. Marchionni, F. Pietropaolo, T. Tabarelli de Fatis, Eur. Phys. J. C **20**, 13 (2001)
- Fits include data from 400 GeV and 450 GeV data.

For π^+ and K^+

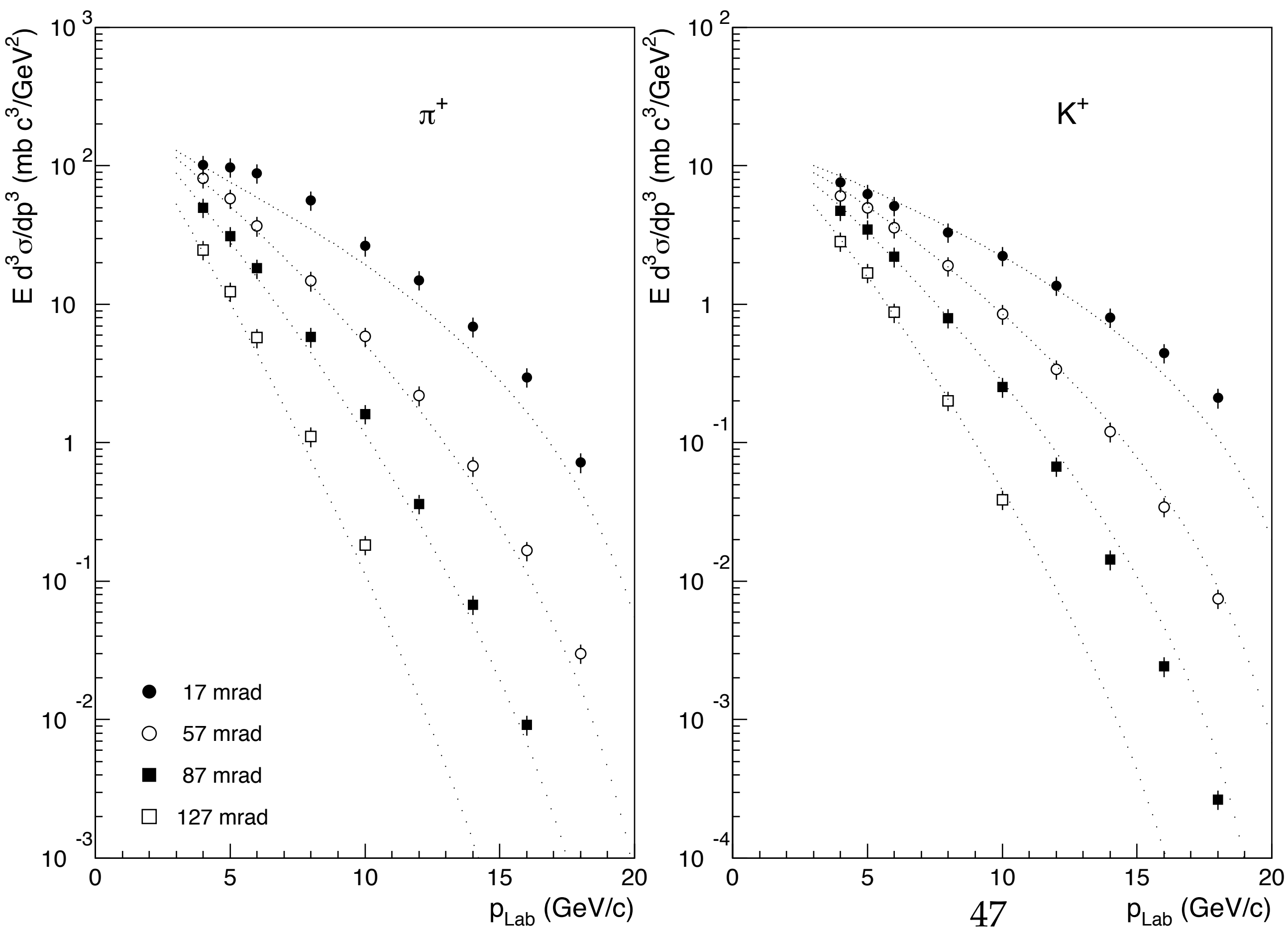
$$(E \times \frac{d^3\sigma}{dp^3}) = A(1 - x_R)^\alpha (1 + Bx_R) x_R^{-\beta} \times$$
$$(1 + a'(x_R)p_T + b'(x_R)p_T^2) e^{-a'(x_R)p_T}$$

where $a'(x_R) = a/x_R^\gamma$ and $b'(x_R) = a^2/2x_R^\delta$.

- Paper also discusses p/pbar/π^-/K^-/K^0 production, A scaling, momentum scaling, long targets

Scaling of Hadron Production Above ~30 GeV

- Feynman argued that invariant cross section ($E\frac{d^3\sigma}{d^3p}$) should be more or less constant with p_T and x_F, where $x_F = 2p_L^*/\sqrt{s}$
- Others have scaled by $x_R = E^*/E^*_{max}$



From Eur. Phys. J. C **20**, 13 (2001)

Dashed = fit to 400 and 450 GeV p + Be data scaled in p_T and x_R

Points = data for 24 GeV p + Be interactions

Scaling for A of materials

- From BMPT:

$$E\frac{d^3\sigma^{hA_1}}{dp^3} = \left(\frac{A_1}{A_2}\right)^\alpha \cdot E\frac{d^3\sigma^{hA_2}}{dp^3}.$$

- Scales as a power law of degree α which depends on x_F, p_T

$$\alpha(x_F) = (0.74 - 0.55 \cdot x_F + 0.26 \cdot x_F^2) \cdot (0.98 + 0.21 \cdot p_T^2) \quad (10)$$

- At lower energies HARP data (Phys.Rev. C80 (2009) 035208) has shown that for the Sanford-Wang parameterization a correction of $corr = (A/A_{Be})^\alpha$ where $\alpha = \alpha_0 + \alpha_1 \times x_F + \alpha_2 \times x_F^2$

	π^+	π^-
α_0	(0.69 ± 0.04)	(0.72 ± 0.04)
α_1	(-0.91 ± 0.21)	(-1.36 ± 0.20)
α_2	(0.34 ± 0.21)	(2.18 ± 0.21)

Summary

- Lots of progress over the past 5 years in understanding hadron production uncertainties and their impact on neutrino flux uncertainties.
- Increasingly measurements are available with uncertainties at the few % level
- More measurements that can have a major impact on the T2K, NuMI, and LBNF fluxes expected over the next few years
- These experiments are **crucial for reaching the scientific goals** of next-generation neutrino beam experiments

Thanks!

- Supported in part by

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