H. A. TANAKA

ACCELERATOR-BASED NEUTRINO EXPERIMENTS

WHAT AM I TALKING ABOUT?

- “Neutrino beams”
- “Physics with neutrino beams”

OVERVIEW OF LECTURES:

- These lectures are about accelerator-based neutrino experiments
  - **Lecture 1: Producing neutrinos with accelerators**
  - **Lecture 2: Detecting neutrinos produced with accelerators**
  - **Lecture 3: Neutrino oscillation studies with accelerator-based beams**
- relation to other lectures:
  - Boris: neutrino theory
    - We'll just do a quick review later
  - Jon: sterile neutrinos
    - Some of these experiments use accelerator-based neutrinos. I won't cover these topics
  - Dave: neutrino detectors
    - Will focus here on two particular technologies in Lecture 2 for ~GeV neutrinos
  - Minerba: neutrino interactions
    - accelerator-based beams are used in dedicated study of neutrino interactions. Won't cover this.
    - very important relation to how we detect the neutrinos. Will cover basics, Minerba will cover in detail
  - Patrick: reactor neutrinos
    - Important interplay between reactor and accelerator-based measurements.

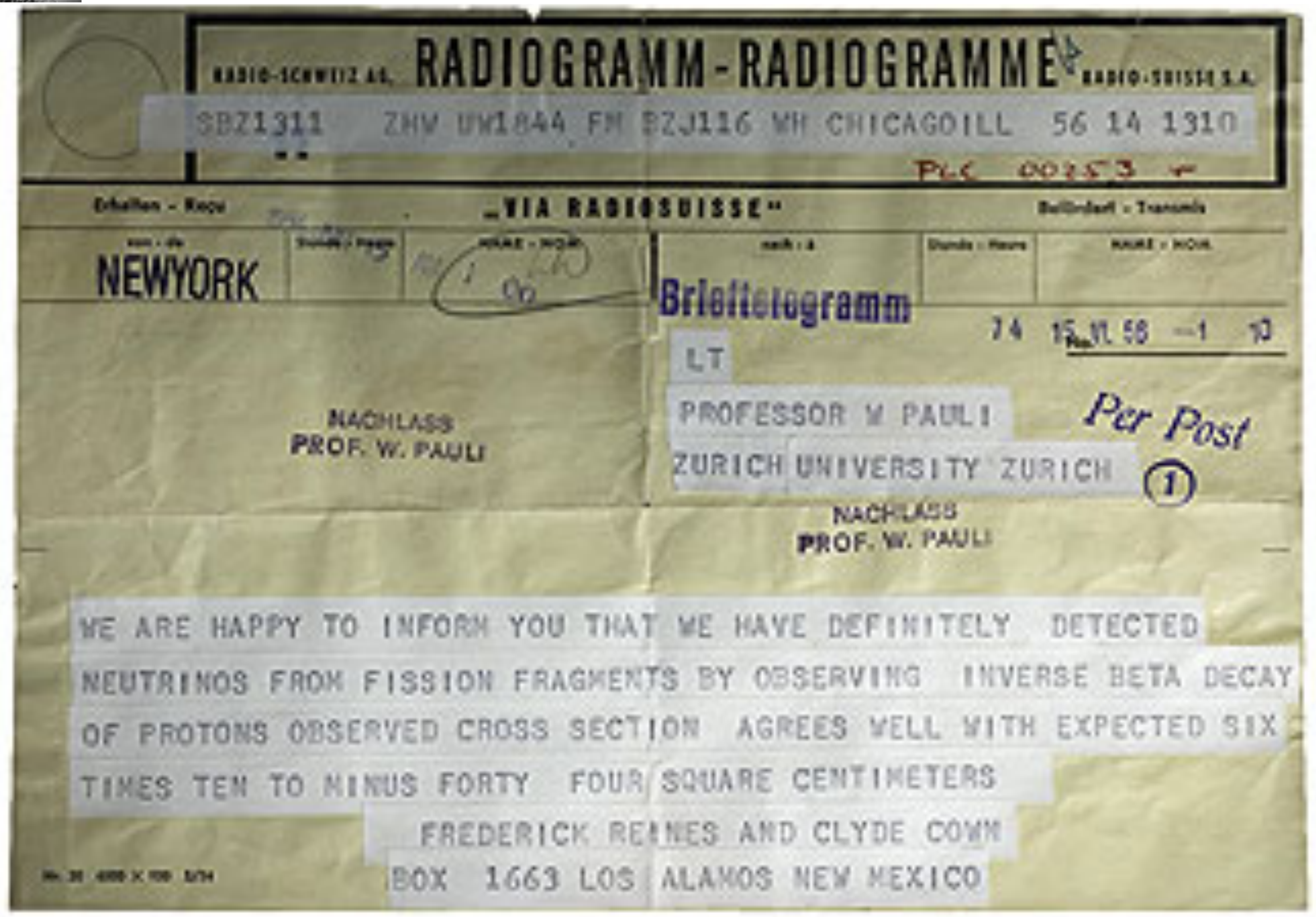
NEUTRINO CROSS SECTIONS

- Neutrino cross sections are tiny!
  - H. Bethe and R. Peirels: “there is no practically possible way of observing neutrinos”

did we hear something like this?

- Typical cross section for 1 GeV neutrinos on a nucleon: $\sigma(\nu\text{-N}) = 10^{-38}$ cm^2

Fred Reines
1 day ago near Los Alamos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PROFESSOR W PAULI
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Per Post
NACHLASS PROF. W. PAULI
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

Like · Comment · Share

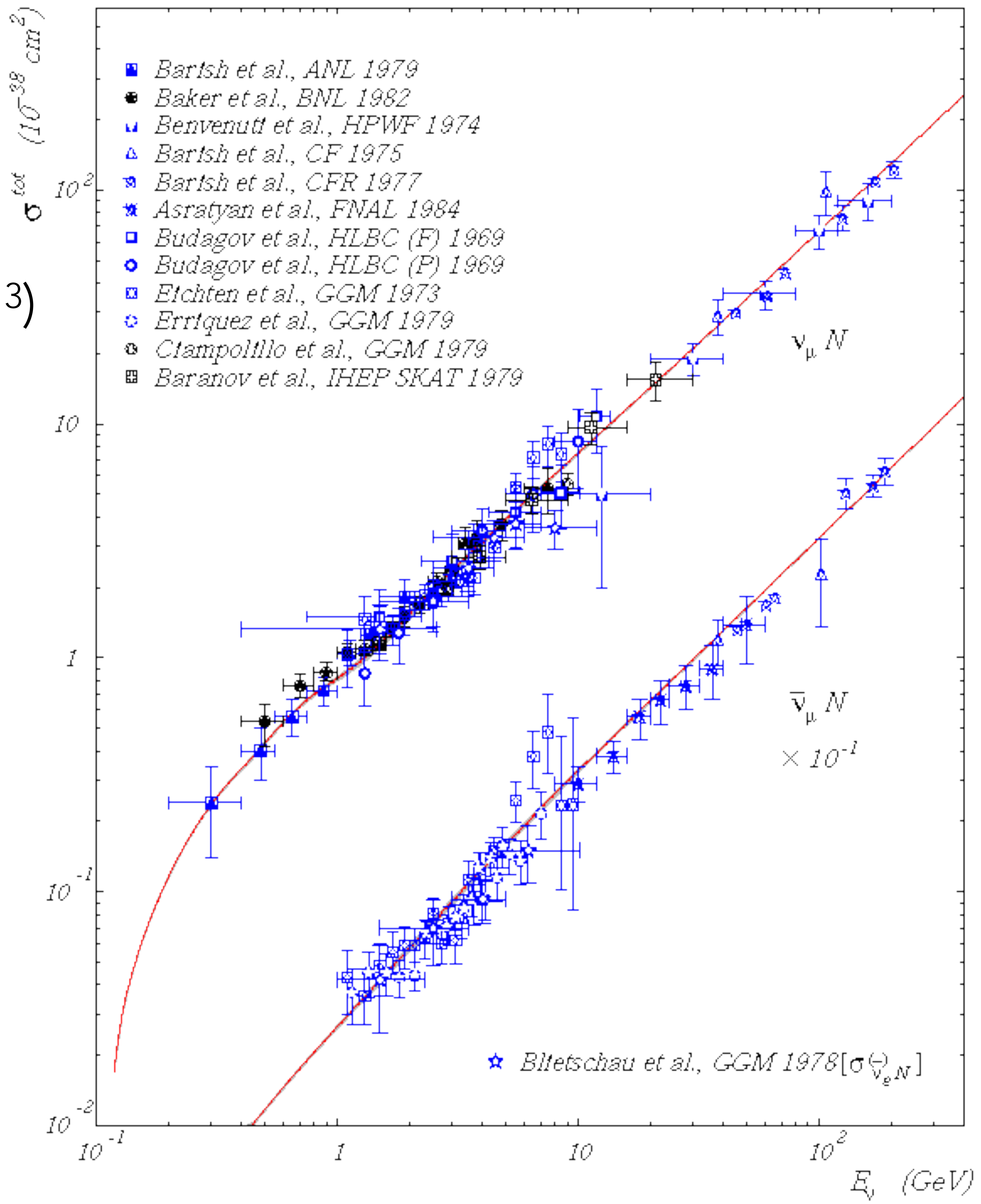
Wolfgang Pauli likes this

Fred Reines: “no practically possible way”, eh?
30 min · Like

Hans Bethe: well, you shouldn’t believe everything you read in papers
1 min · Like

Write a comment . . .

- For normal matter (ρ~1 gm/cm^3)
  - $1/L = \sigma \times n \rightarrow L = 10^{14}$ cm
- Alternatively
  - 1 in 10^{12} neutrinos passing through a meter of matter will interact
  - note $\sigma(\nu\text{-N}) \sim (3\text{-}4) \times \sigma(\bar{\nu}\text{-N})$



NEUTRINO ECONOMICS:

- The ability to precisely study neutrino interactions depends heavily on statistics
  - i.e. how many neutrino interactions you observe

$$N = \varphi \times \sigma \times V \times n \times \varepsilon$$

- N = number of neutrino interactions
- φ = flux of neutrinos (neutrinos/cm^2)
- σ = neutrino interaction cross section on target (e.g. electron, nucleon, nucleus)
- V = volume of detector (cm^3)
- n = number of density of targets
- ε = detection efficiency

Lecture 1: how do we produce large number of neutrinos with accelerators

Thanks, Minerba!

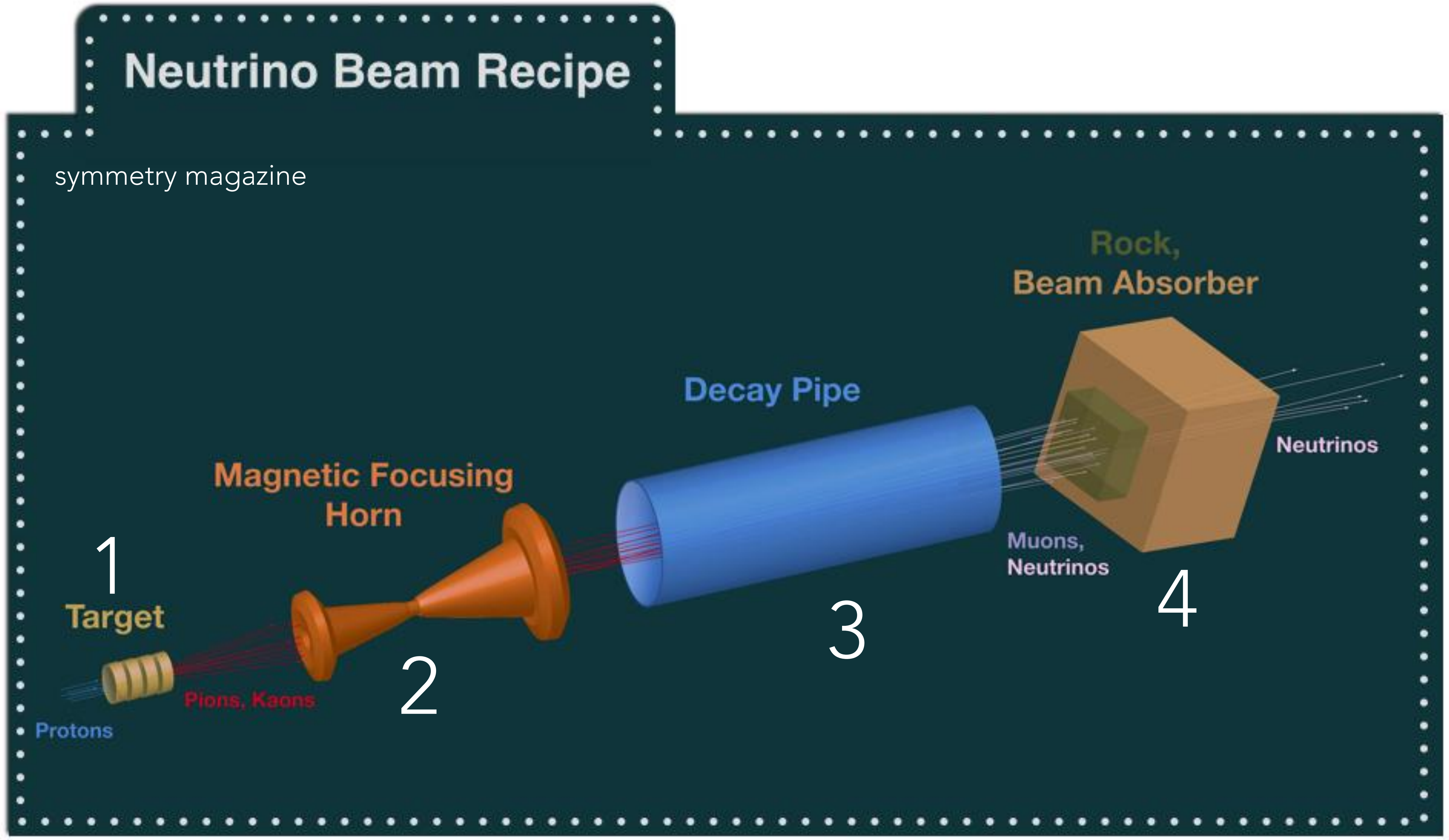
Lecture 2: How do we make massive detectors that can efficiently detect neutrino interactions

LECTURE 1:
ACCELERATOR-BASED NEUTRINO BEAMS

in memoriam G.B. Mills (LANL)

IN A NUTSHELL:

- Good news:
  - To first order, existing accelerator-based neutrino beams operate on the same basic principles and components



1. High energy protons impinge on a target
   - pions are produced
2. Electromagnets focus pions into a decay region
   - one sign is focussed, the other defocussed
3. The pions decay in a decay pile
   - muon (anti)neutrinos are produced
4. Beam absorber stops all other remaining particles
   - some muons penetrate and can be monitored.
   - neutrinos go on to the detector

- "Bad" news:
  - Each step represents an enormous technical challenge
  - Methods and results vary

SANITY CHECK 1: WHY PIONS? WHY ν_μ?

- Pions are mesons
  - they interact strongly . . . and therefore are produced copiously by proton-nucleus interactions
- They are the lightest hadron
  - they cannot decay into other hadrons
  - only lighter particles are leptons (e, μ, ν)
  - Each pion must decay weakly and produce neutrinos
- They decay 99.9877% of the time to $\mu + \nu_\mu$
  - helicity suppression resulting from chiral structure of weak interaction

Decay Modes ▸ Expand all decays

π^- modes are charge conjugates of the modes below.
For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

Mode			*Fraction* (Γ_i/Γ)	*Scale Factor/ Conf. Level*	*P (MeV/c)*
Γ_1	$\mu^+\nu_\mu$	[1]	$(99.98770 \pm 0.00004)\%$		30
Γ_2	$\mu^+\nu_\mu\gamma$	[2]	$(2.00 \pm 0.25) \times 10^{-4}$		30
Γ_3	$e^+\nu_e$	[1]	$(1.230 \pm 0.004) \times 10^{-4}$		70
Γ_4	$e^+\nu_e\gamma$	[2]	$(7.39 \pm 0.05) \times 10^{-7}$		70
Γ_5	$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
Γ_6	$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
Γ_7	$e^+\nu_e\nu\bar{\nu}$		$< 5 \times 10^{-6}$	CL=90%	70

particle data group

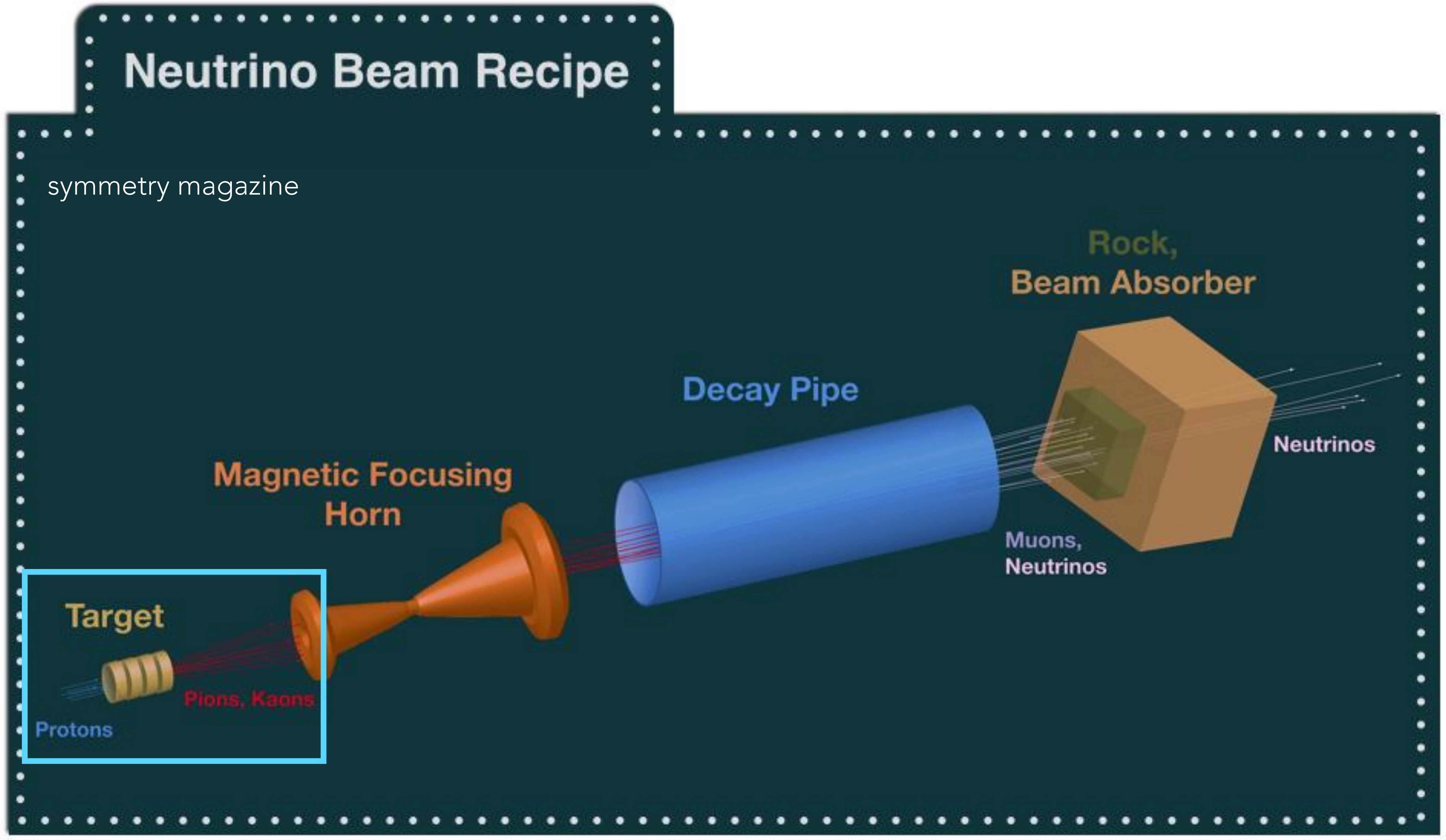
SANITY CHECK 2: ARE ν_e, ν_τ PRODUCED?

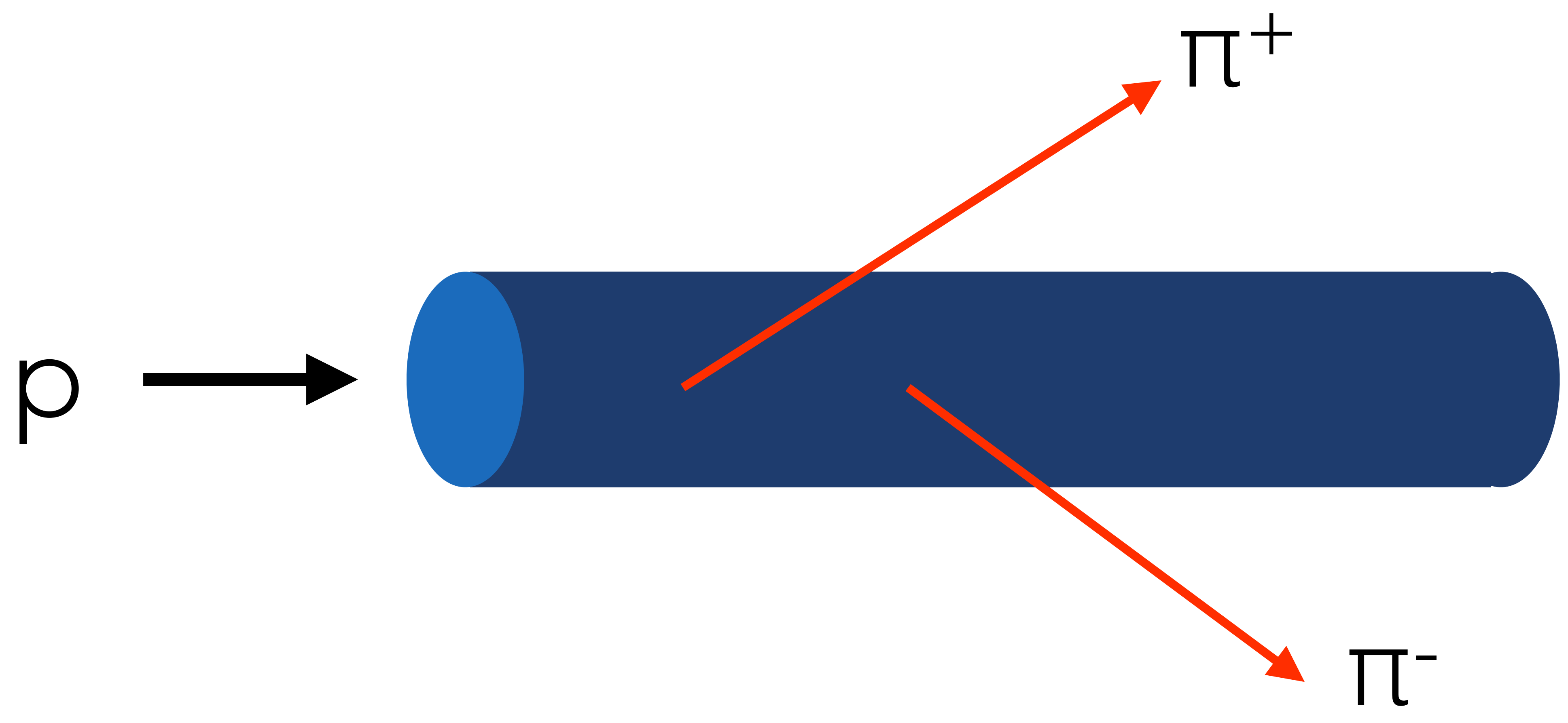
- Recall that every time a pion decays to produce a ν_μ, a muon is also produced
  - muon decays produce

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad\qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

  - an electron (anti)neutrino
  - a muon neutrino that is the charge conjugate of the muon neutrino produced in the pion decay
    - “wrong sign” muon neutrinos
  - Note: $\tau(\mu^\pm)$= 2.2x10^{-6} sec $\gg$ $\tau(\pi^\pm)$ = 2.6x10^{-8} sec
- Consider the kaon
  - the lightest strange hadron . . . it must decay weakly
  - as with pions, $\Gamma(K^+ \to \mu^+ + \nu_\mu) \gg \Gamma(K^+ \to e^+ + \nu_e)$ (63.6% vs. 0.0016%)
  - but . . . . because pions are lighter than kaons, we also have “Ke3” and “Km3” which escape helicity suppression
    - $K^+ \to \pi^0 + \mu^+ + \nu_\mu$ (5.1%) , $K^+ \to \pi^0 + e^+ + \nu_e$ (3.4%)
    - likewise for neutral kaons
- Consider the the τ with mass is 1.777 GeV
  - D mesons are the lightest mesons that have enough mass, but can decay to many hadronic states
  - In practice D_s mesons give the largest source of ν_τ

THE TARGET





- Considerations: We want
  - a large fraction of the incident protons to interact: Length > λ_{int} (~50 cm)
  - minimize pion reinteraction/absorption in the target: Diameter should be small, possibly limits length of target
  - minimize scattering of the pions: low Z materials have lower λ/X

TARGET CHALLENGE

	NuMI	T2K	LBNF
PRIMARY ENERGY	**120 GeV**	**30 GeV**	**60-120 GeV**
SPILL CYCLE	**1.87 s**	**2.5 (1.2) s**	**0.7-1.2 s**
BUNCH LENGTH	3-8 ns	80 ns (3σ)	
BUNCHES/BATCH	84	8	84
BATCHES/SPILL	5-6	1	6
EMITTANCE	40 π mm-mr	60 π mm-mr	
SPILL LENGTH	**8-10 μs**	**4.7 μs**	**10 μs**
PROTONS/SPILL	**4×10^{13}**	**$2.4(3.2) \times 10^{14}$**	**$7.5(15) \times 10^{13}$**
	6.4x10 μC	38(51) μC	12(25) μC
BEAM SIZE	**1 mm**	**4 mm**	**~2.7 mm**
BEAM POWER (KW)	**404 (900)**	**470 (1300)**	**1200 (2400)**

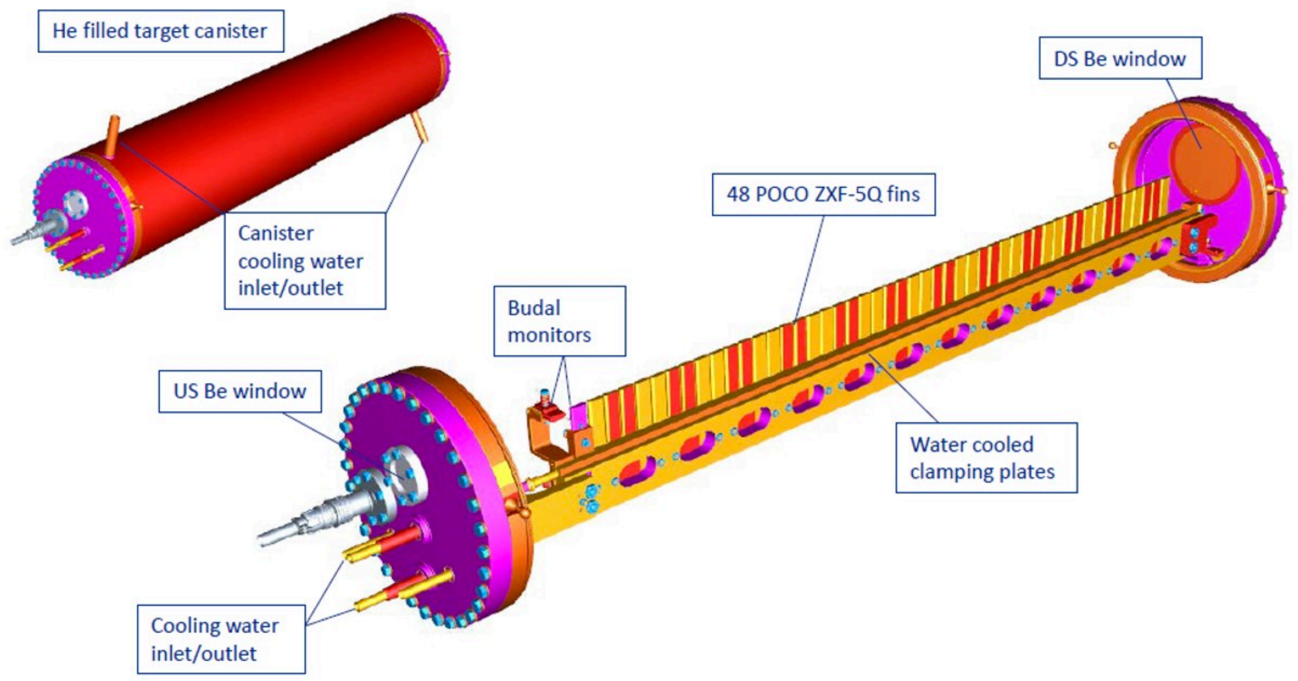
- More protons → more pions → more neutrinos
  - we want as intense a proton beam as possible
- Energy in current beam pulse:
  - 10^2 GeV/proton
  - 10^{14} protons-per-spill
  - 1.6×10^{-19} J/eV =
  - 10^6 Joules/spill
  - Equivalent to ~200 grams of TNT
    - delivered in ~10 μsec to an area a few mm wide
    - every few seconds . . .
- Target must withstand
  - thermal shock
  - heating

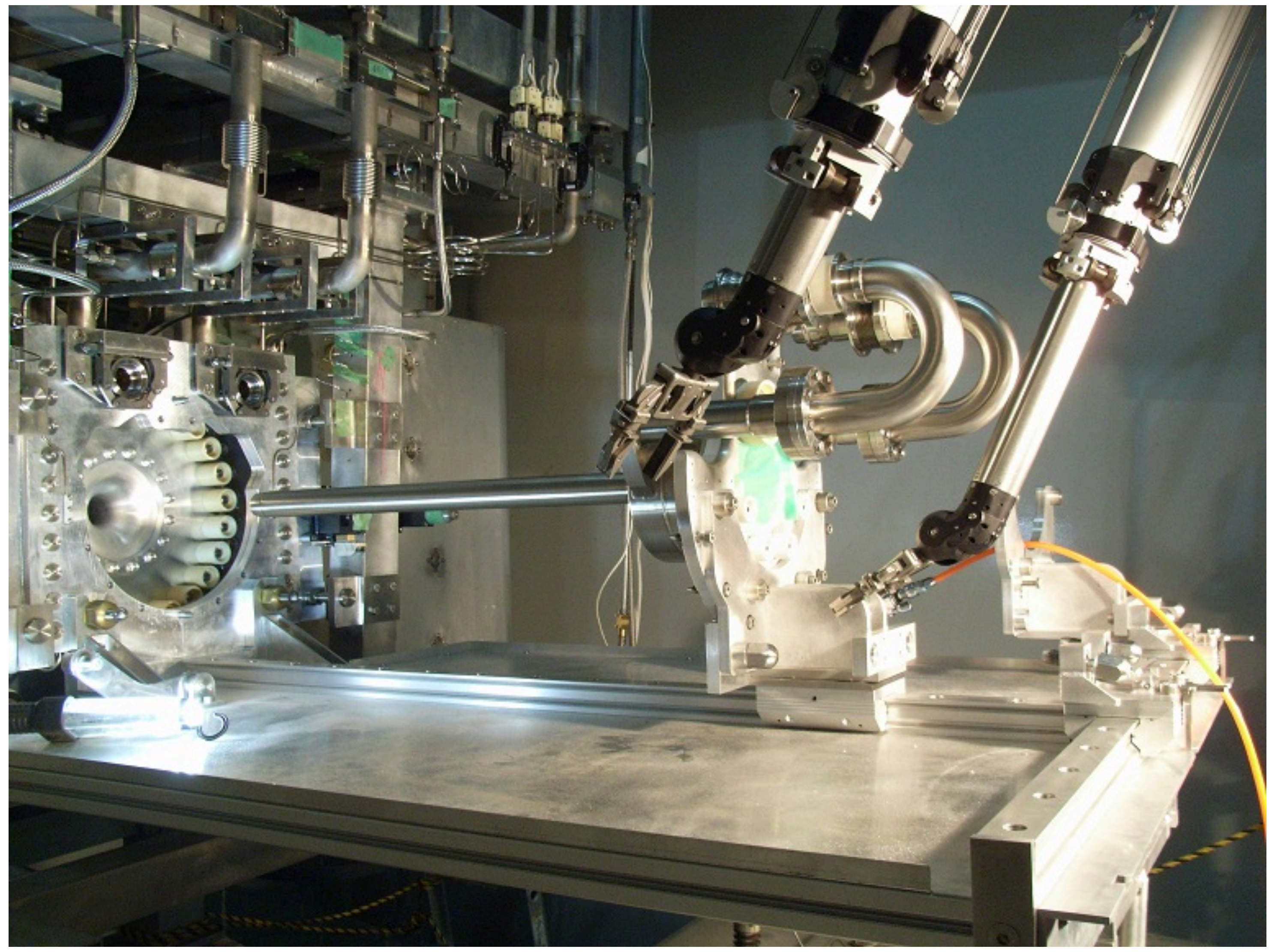
TARGET EXAMPLES

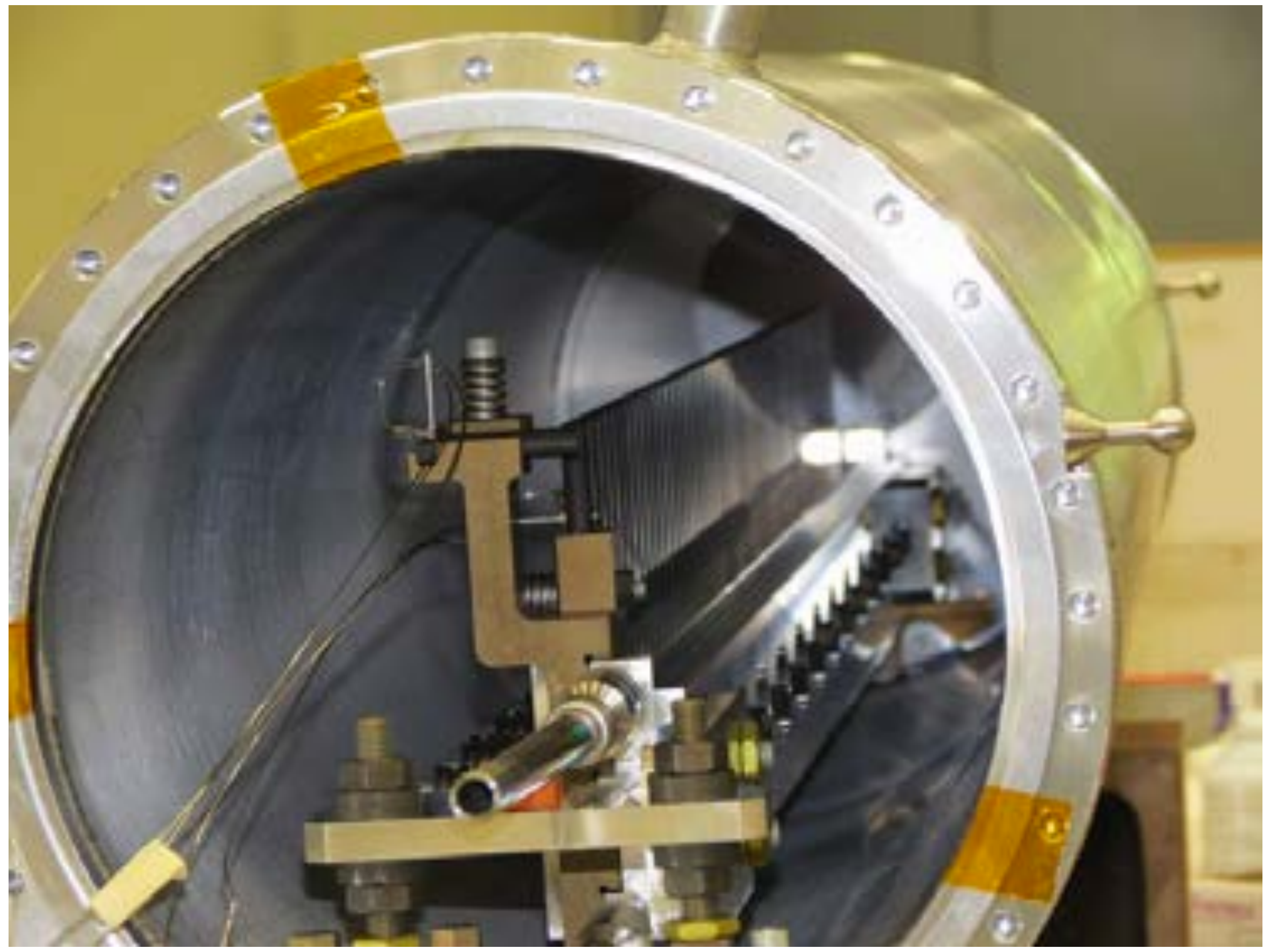
NuMI

T2K

MiniBooNE

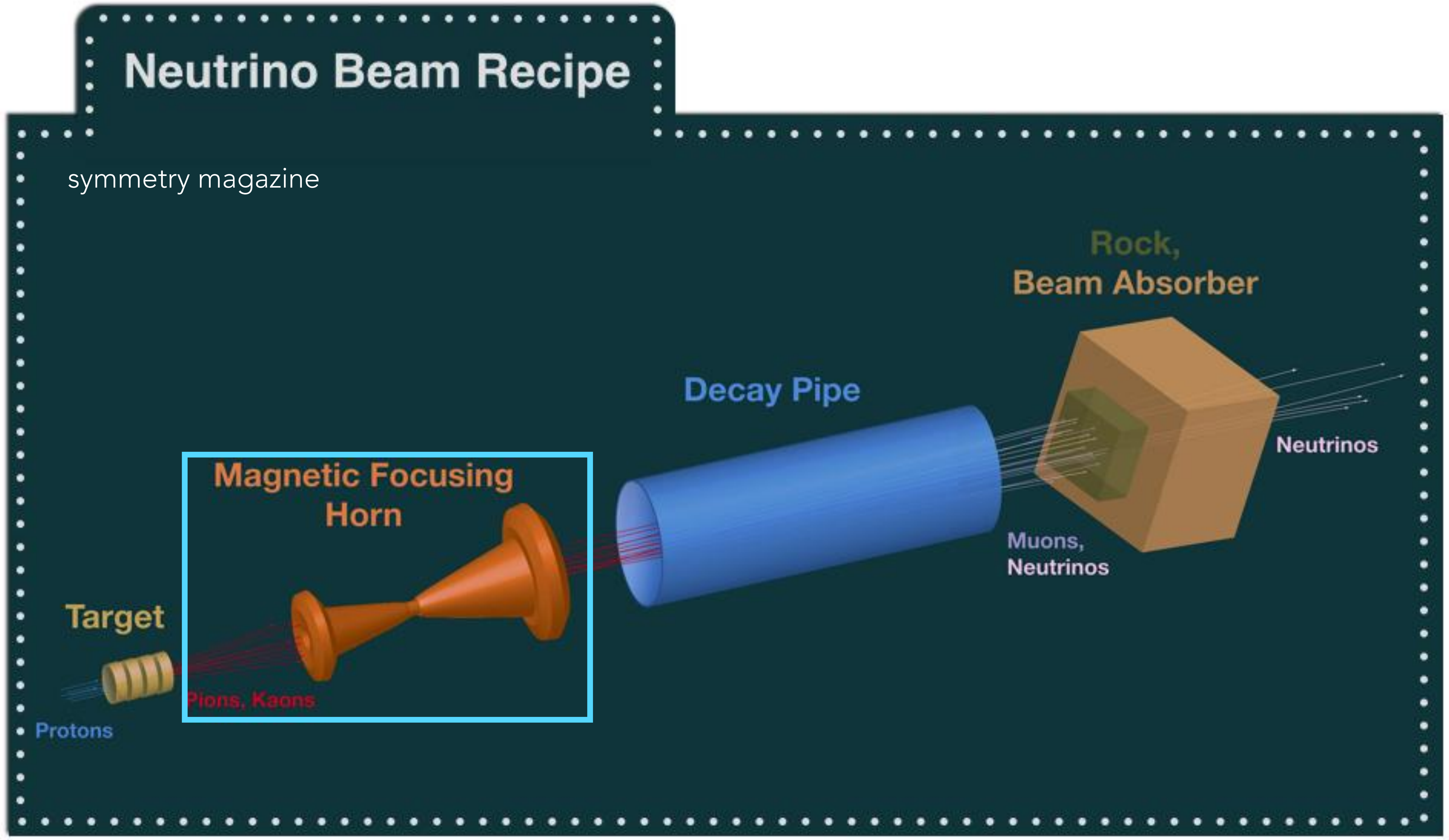


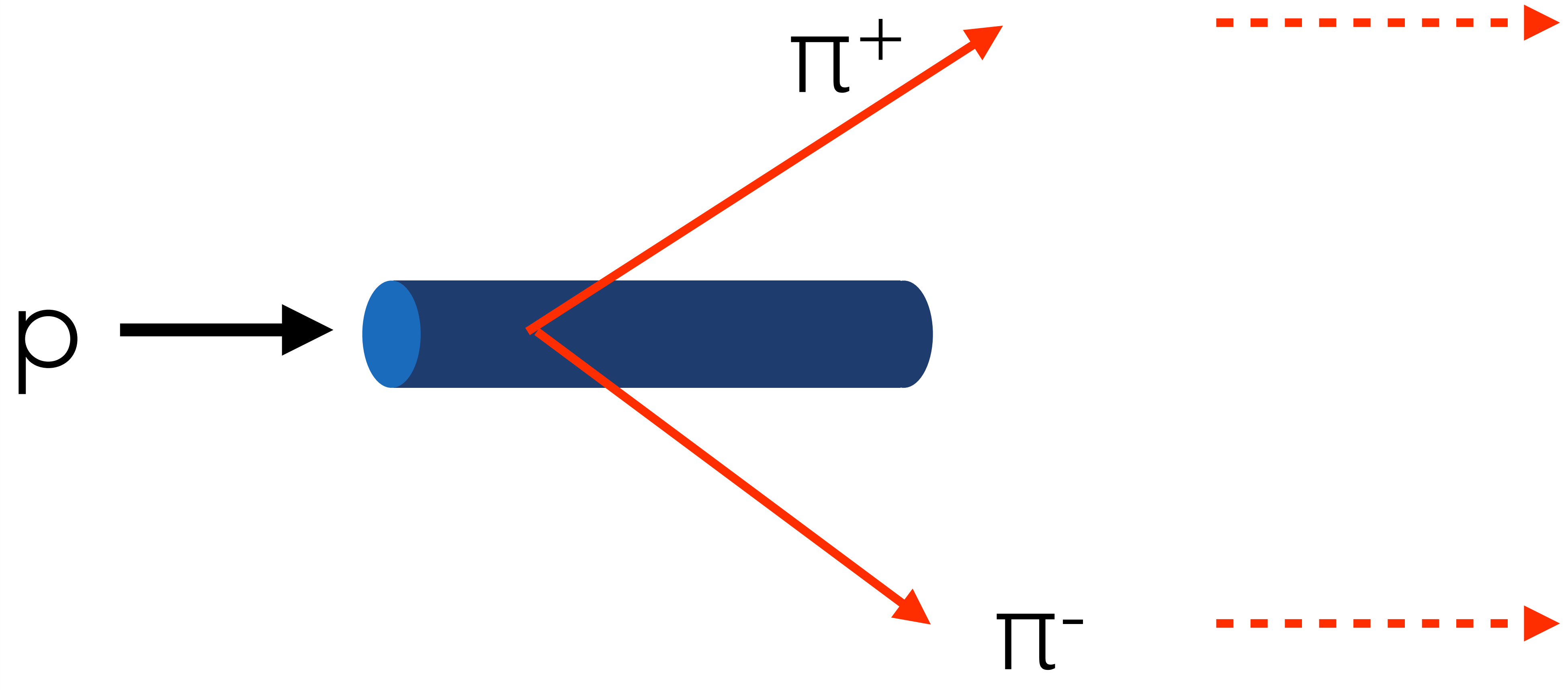




- Beryllium/Carbon core, sometimes segmented
- Helium and/or water cooled, with outer sleeve for circulation
- Replaceable in case of target failure

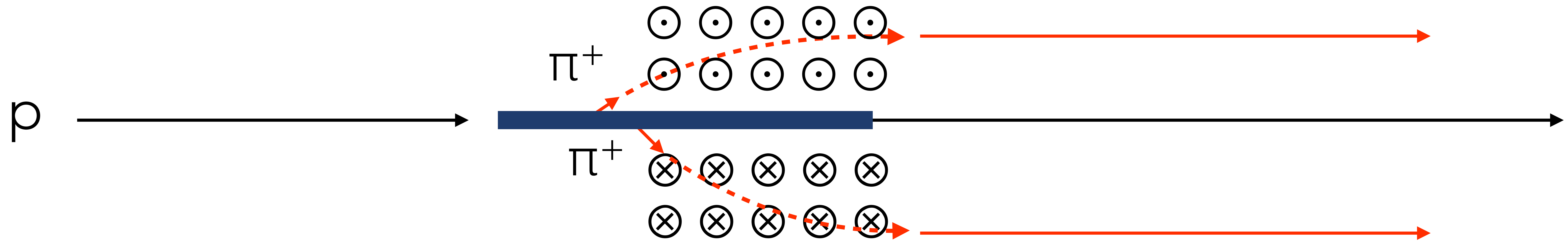
MAGENTIC FOCUSING





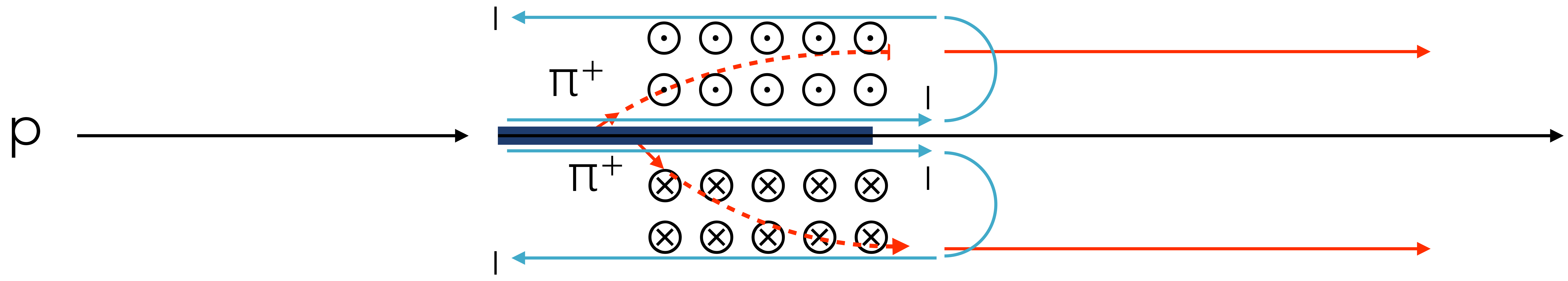
- Considerations:
  - particles emitted from the target may have significant transverse momentum
    - we want to focus a pions of a particular charge into the decay pipe, defocus the other sign
  - Otherwise:
    - they may not decay before they hit the periphery of the target station/decay pipe
    - the resulting neutrinos will tend to decay away from the axis of the beam .. . and away from the detector.

WHAT MAGNETIC FIELD DO WE WANT?



- A toroidal field along the primary beam axis will bend particles towards the axis
- The amount of bending depends on the momentum transverse to the axis (p_T)
  - we want to minimize this component of moment to have particles fly "forward"
  - the optimum magnetic field depends on the p_T distribution of the pions
- One can see:
  - the field that focusses positive particles will defocus negative particles
  - reversing the field will focus negative particles and focus positive particles
  - we can separately make "neutrino" and "antineutrino" beams

HOW TO MAKE THE FIELD

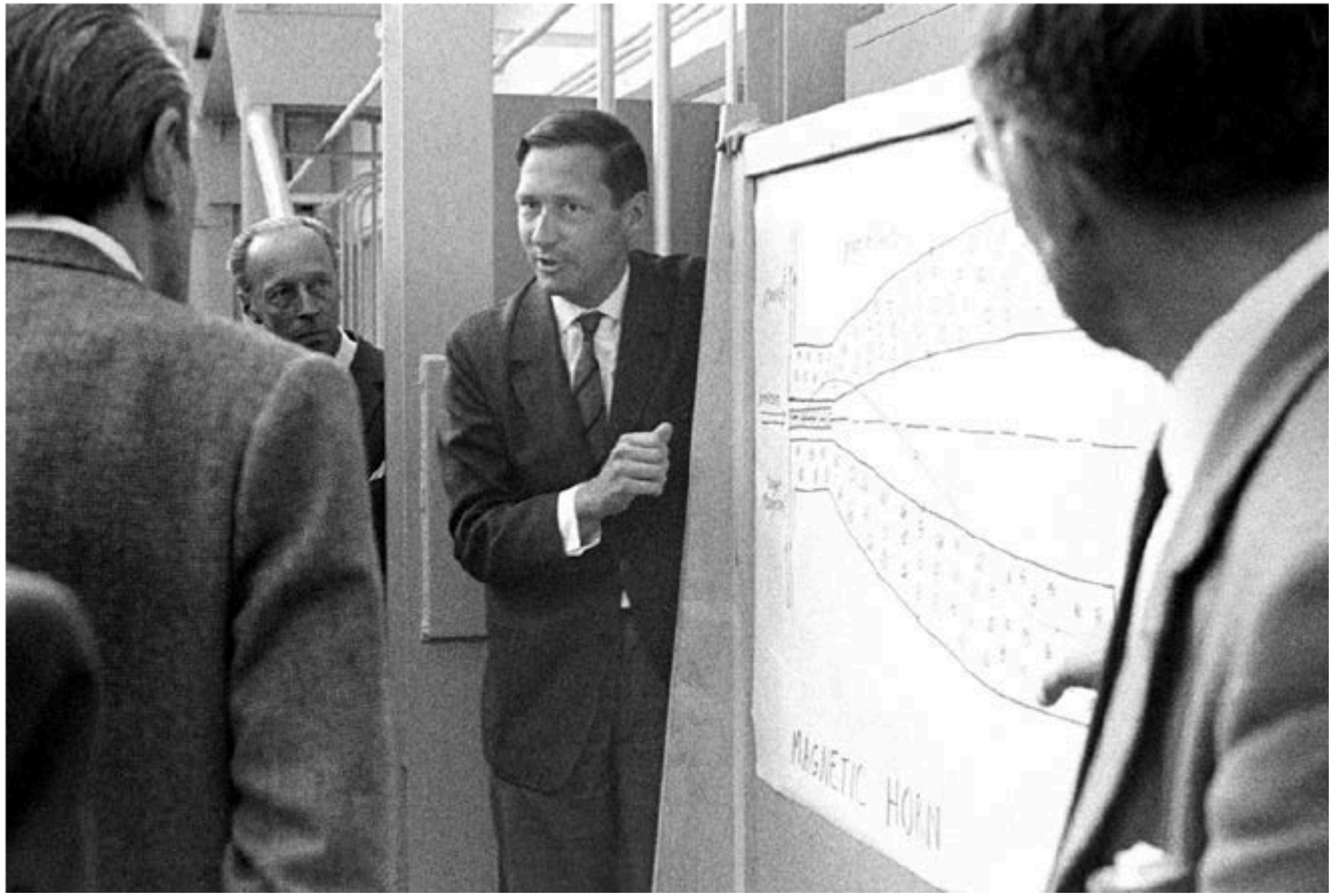


- How much current is needed?
  - Consider p_T ~1 GeV/c: we want to produce enough transverse "kick" to zero out this component
  - Assume:
    - v ~ c
    - magnetic field runs from R = 1 cm to 100 cm
  - Requires $10^{5\text{-}6}$ A of current!
- Consequences:
  - current must be pulsed (no way to support DC at this level)
  - enormous striplings to handle this current

$$F = qvB \rightarrow \Delta p_T = \int dt\ qvB \qquad B = \frac{\mu_0 I}{2\pi R}$$

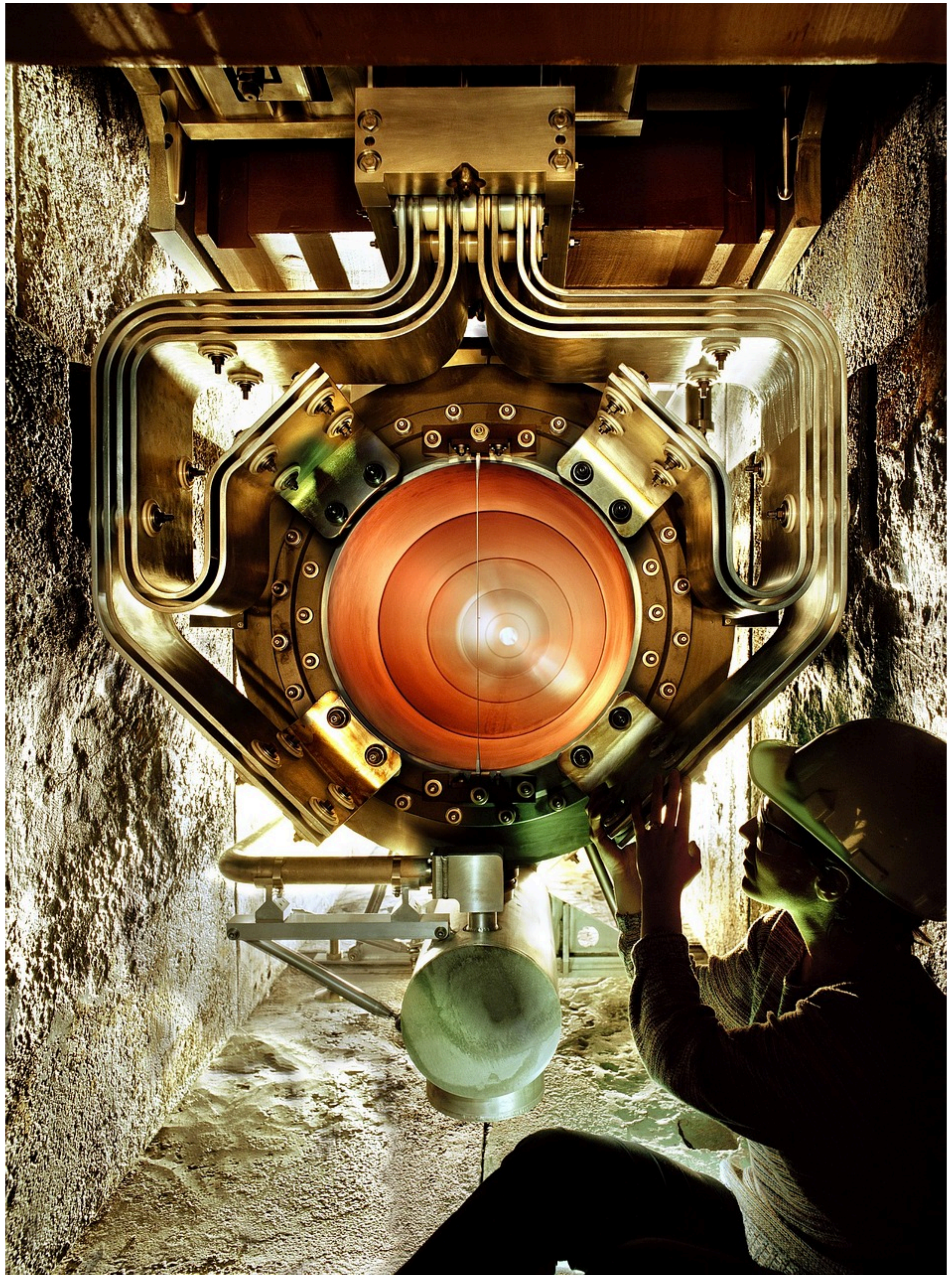
$$= \frac{q\mu_0 I}{2\pi} \int_{in}^{out} dR \frac{1}{R}$$

THE HORN



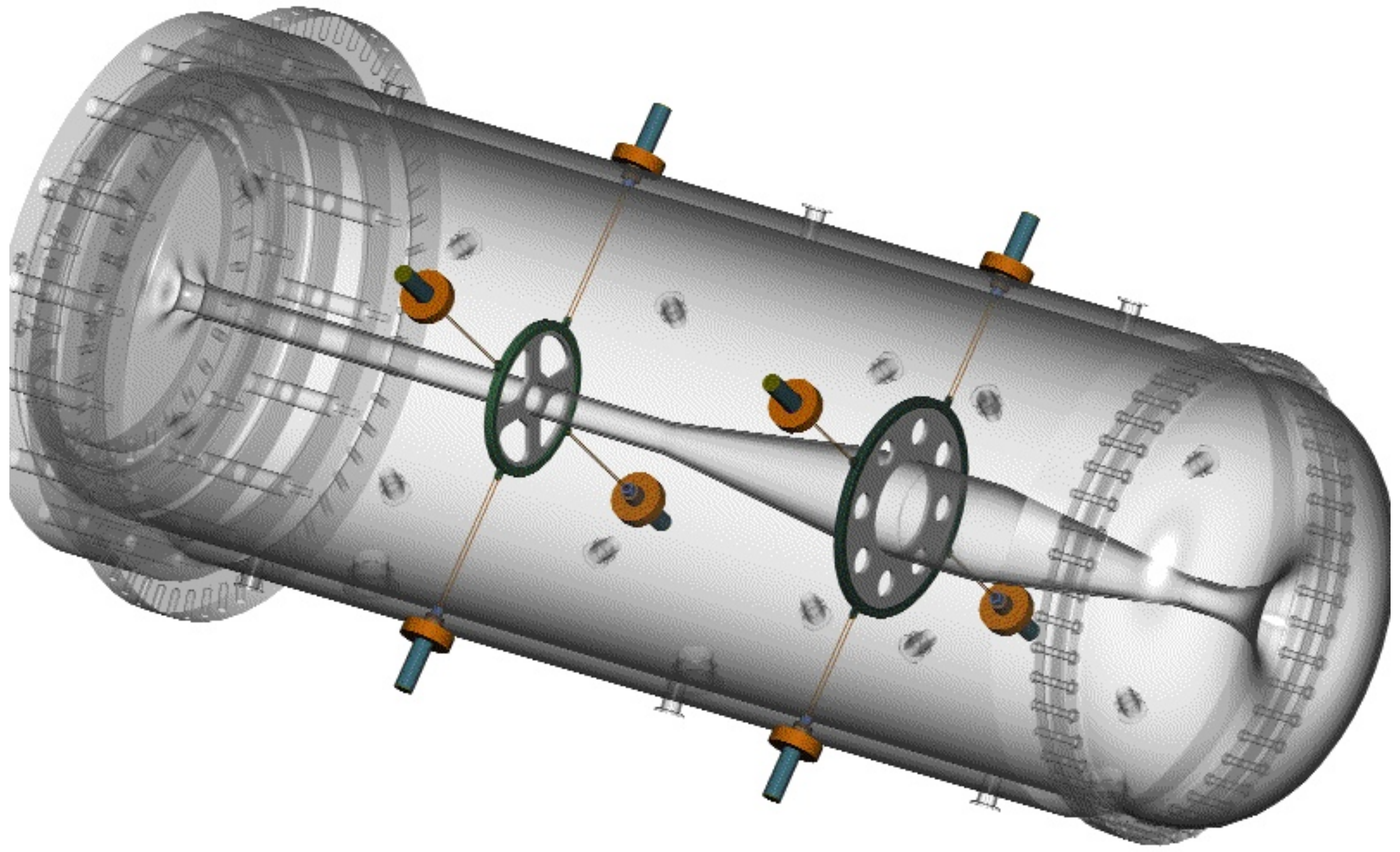
- Invented by Simon van de Meer in 1961
  - "quiet giant of engineering and physics"
  - 1984 Nobel Prize winner for invention of stochastic cooling

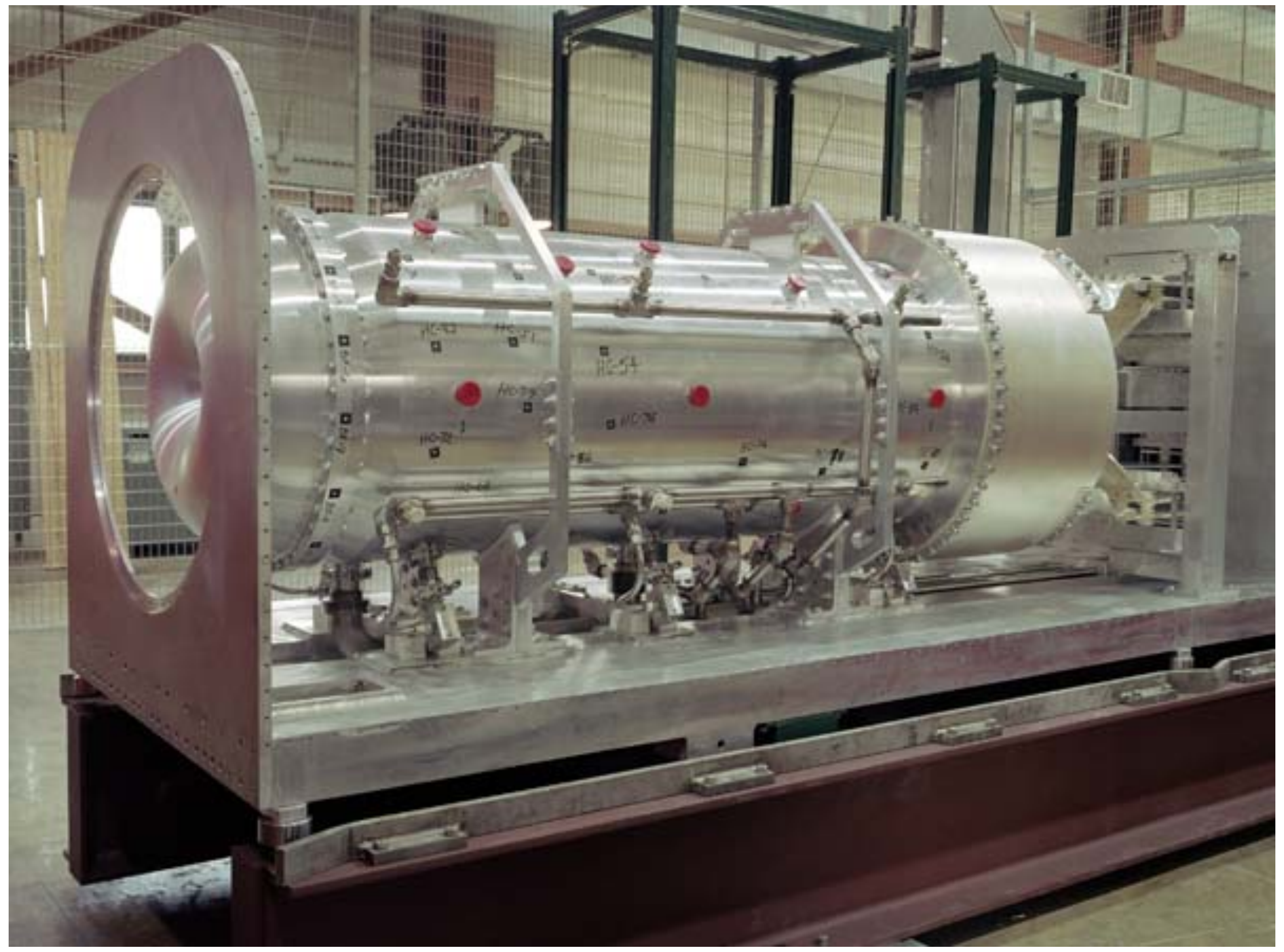
STRIPLINES FOR CURRENT

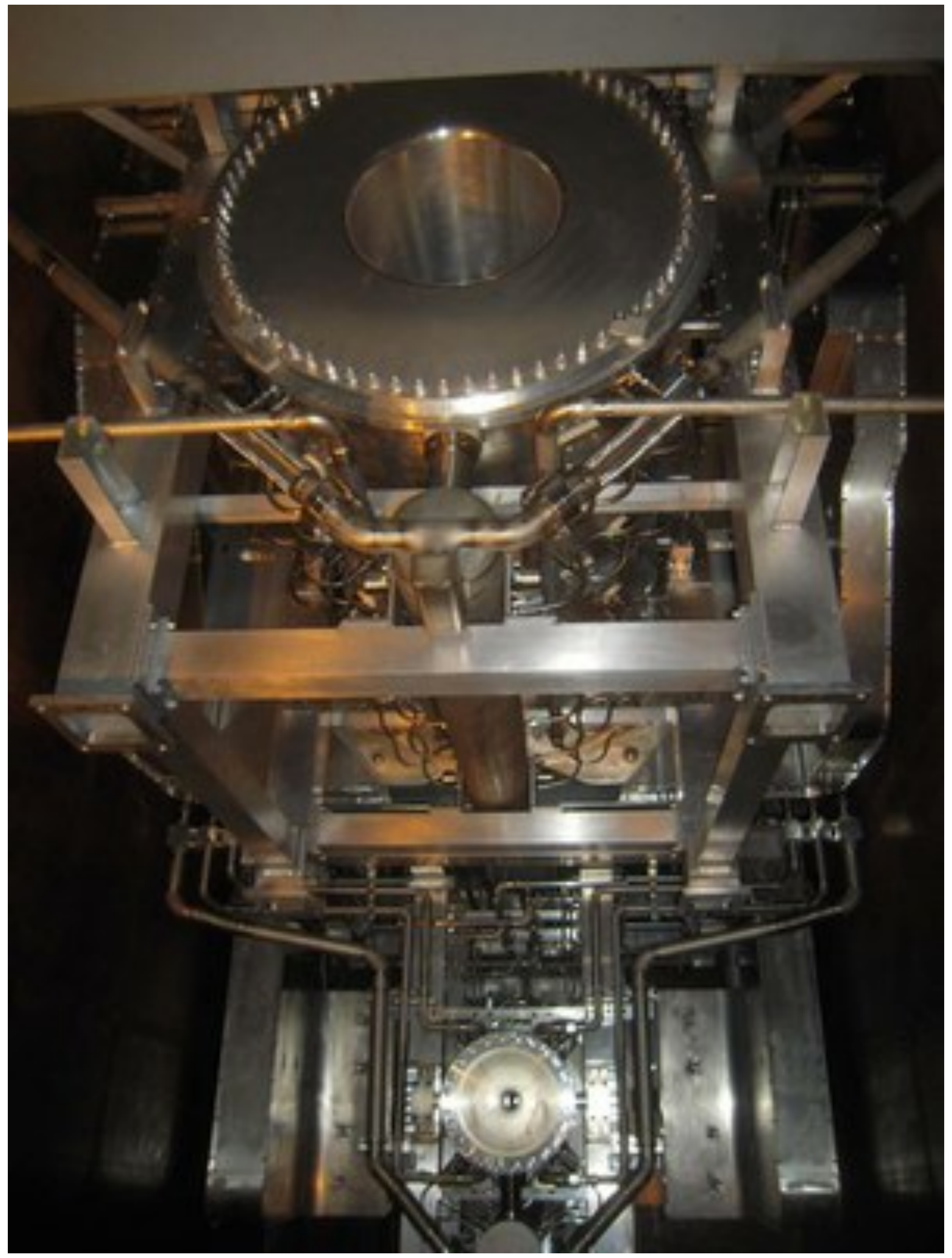


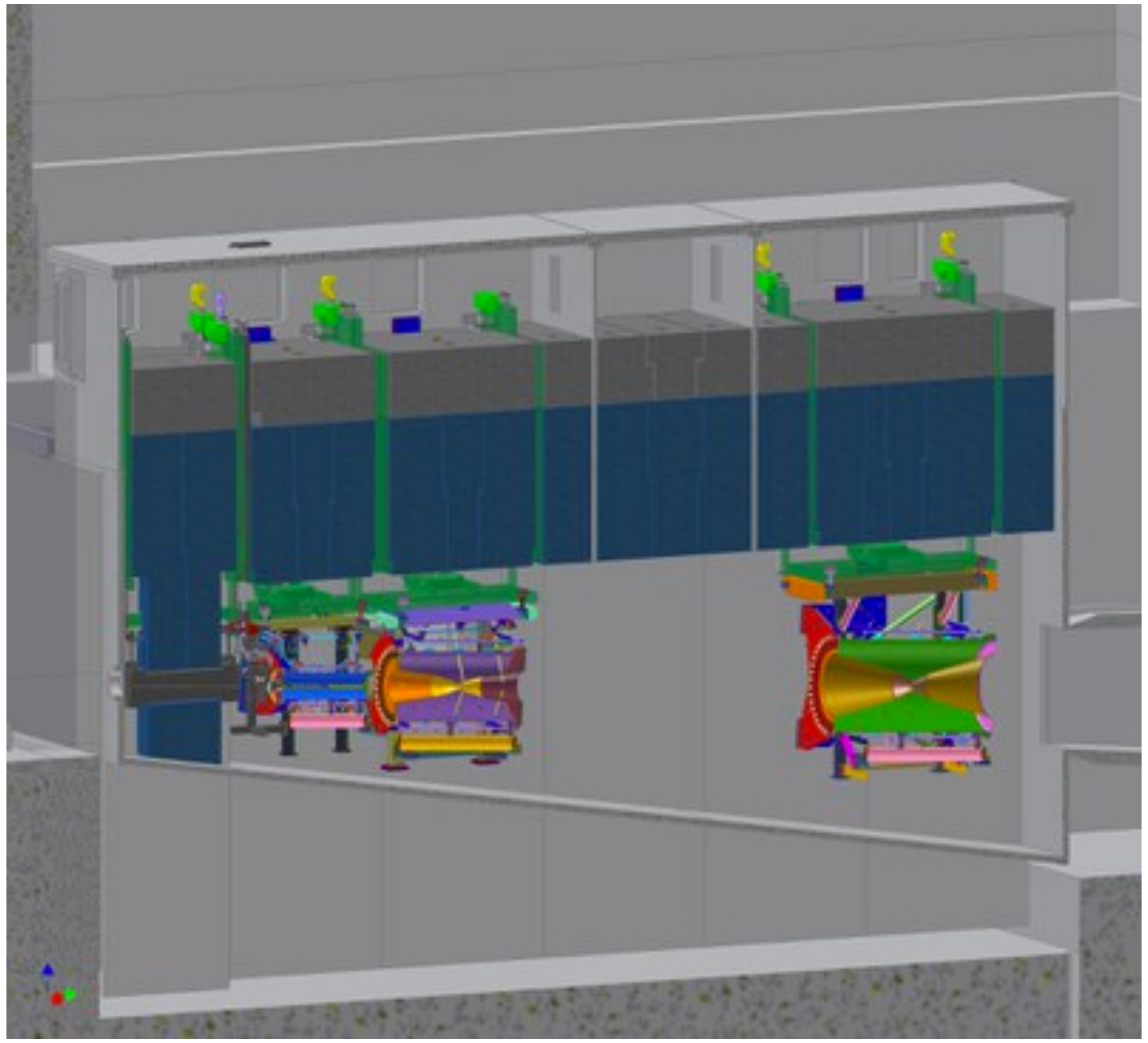
- Left: T2K, Right: NuMI
- Must handle hundreds of kiloamps of current!

HORN SYSTEMS



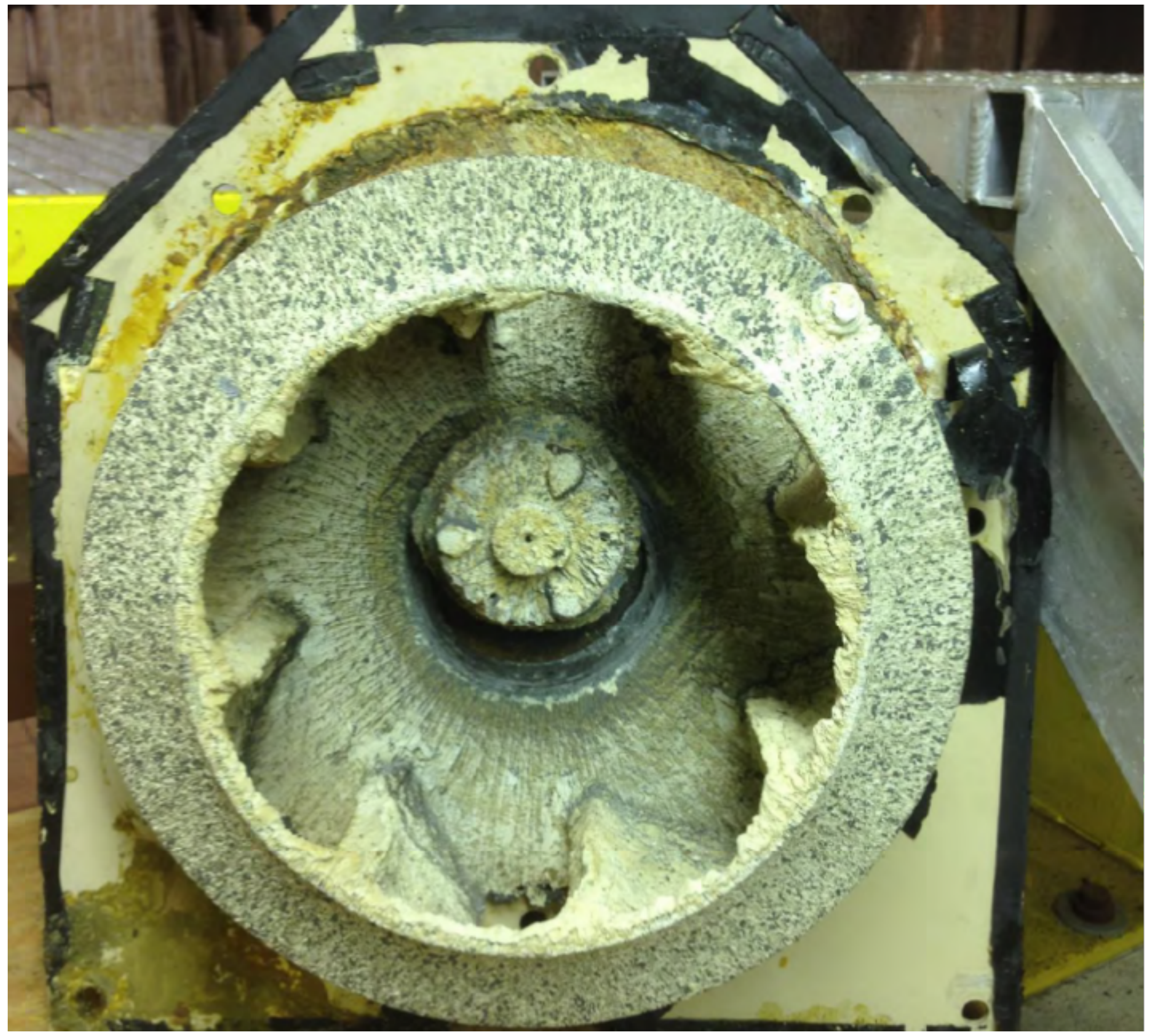


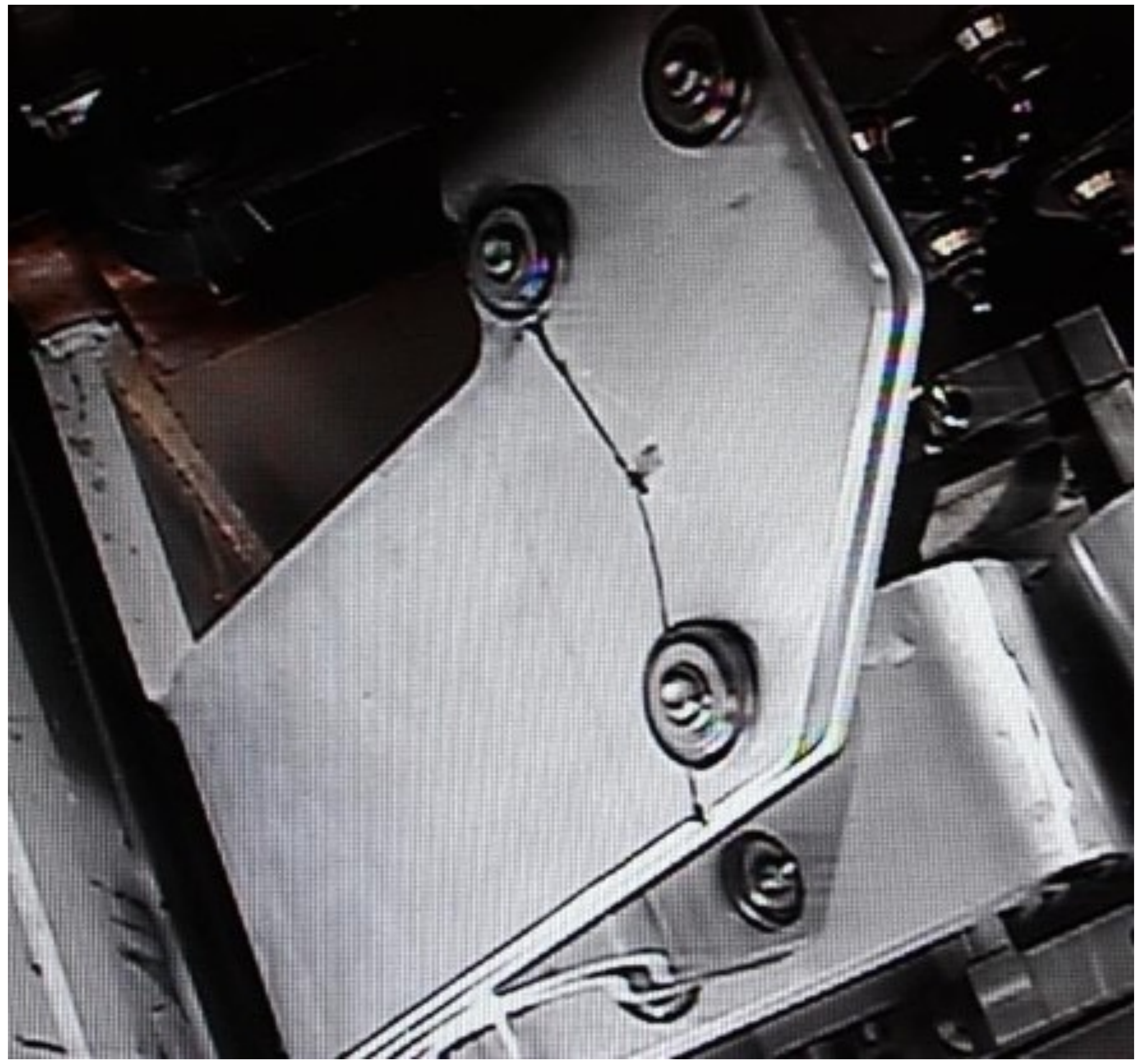


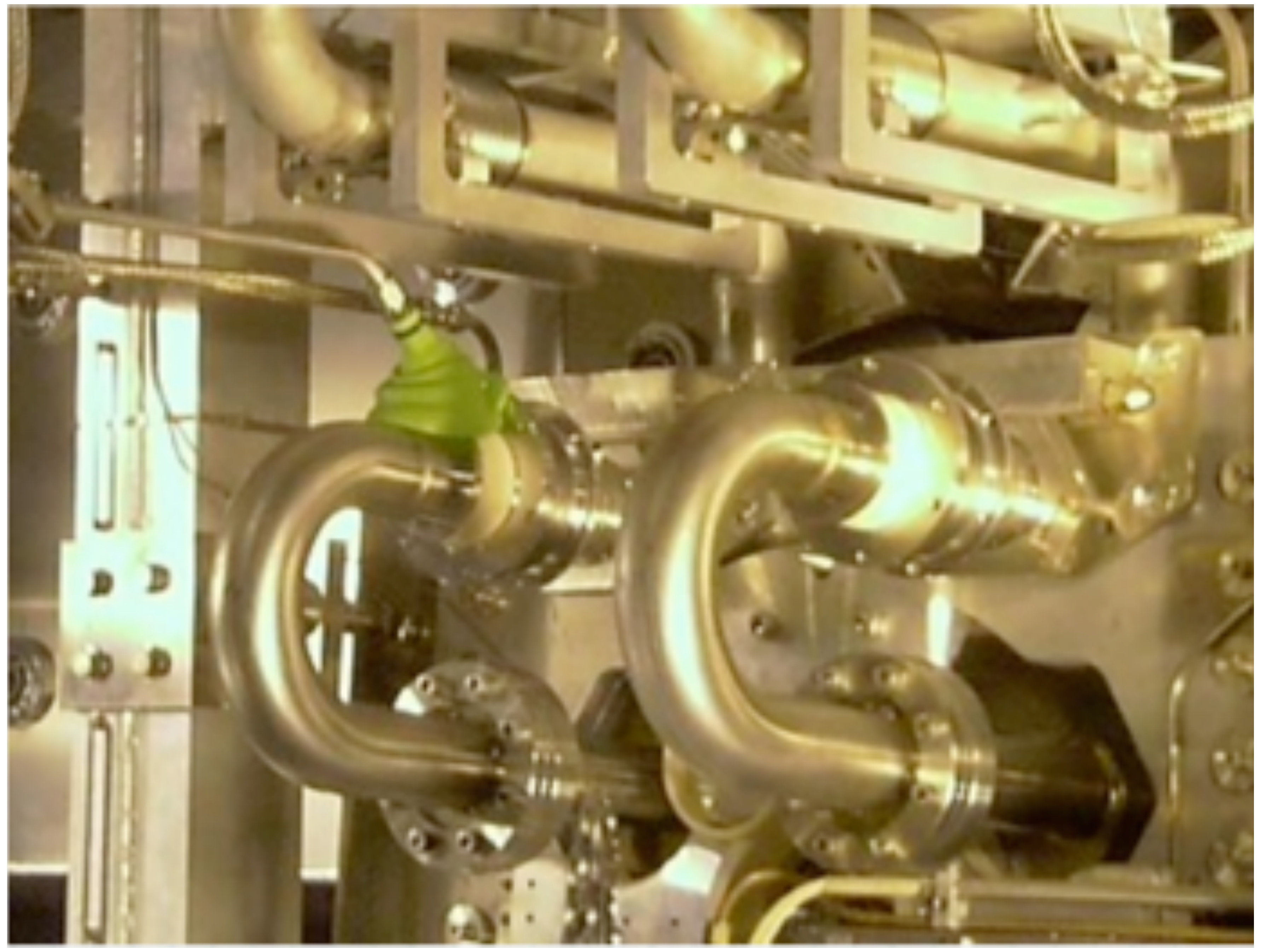


- Left: single horn FNAL Booster Neutrino Beam system
- Top: three horn T2K neutrino beam system
  - (left shows first two horns)
- Aluminum conductor, water cooled

CHALLENGES


corrosion

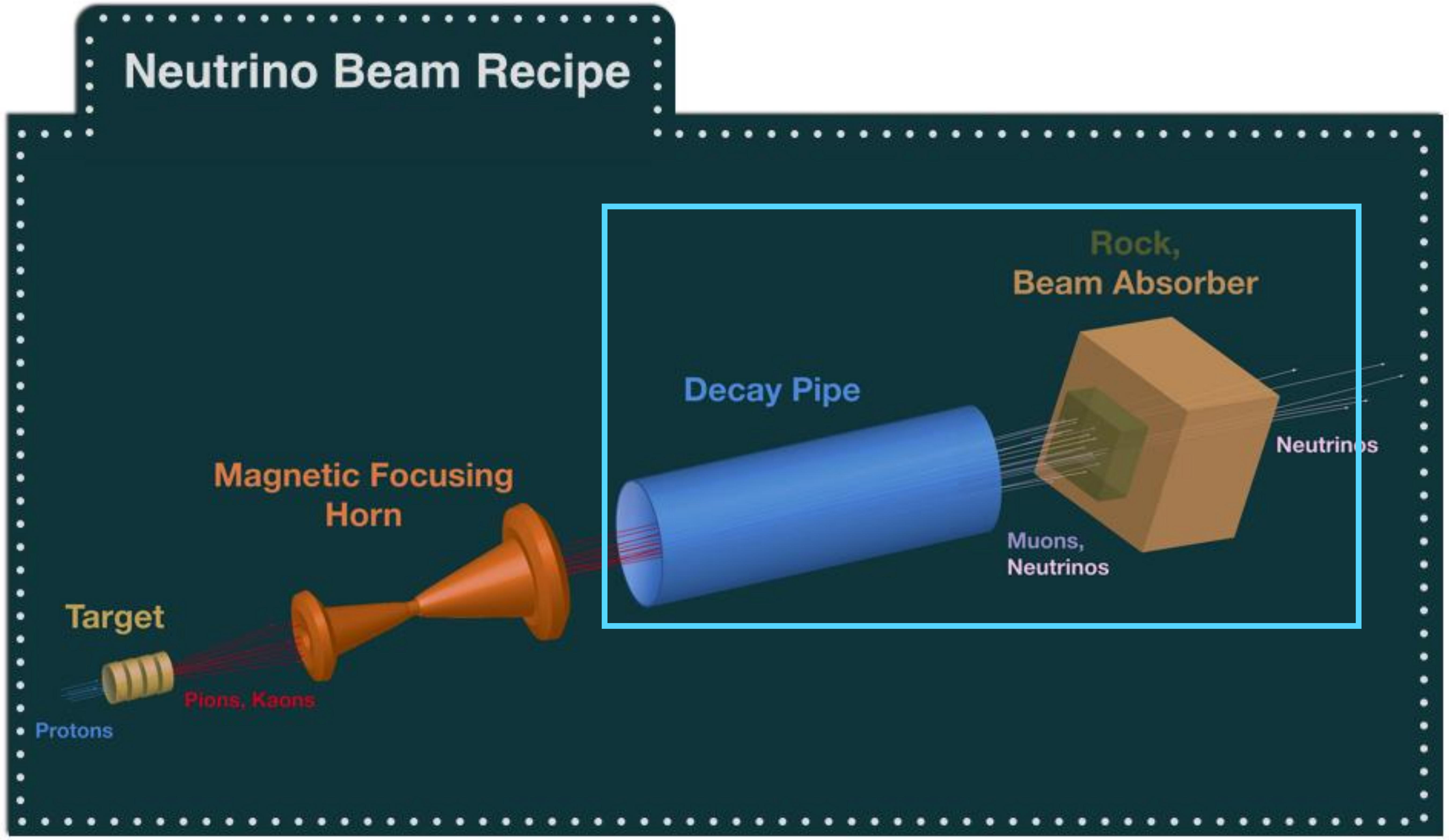

mechanical failure

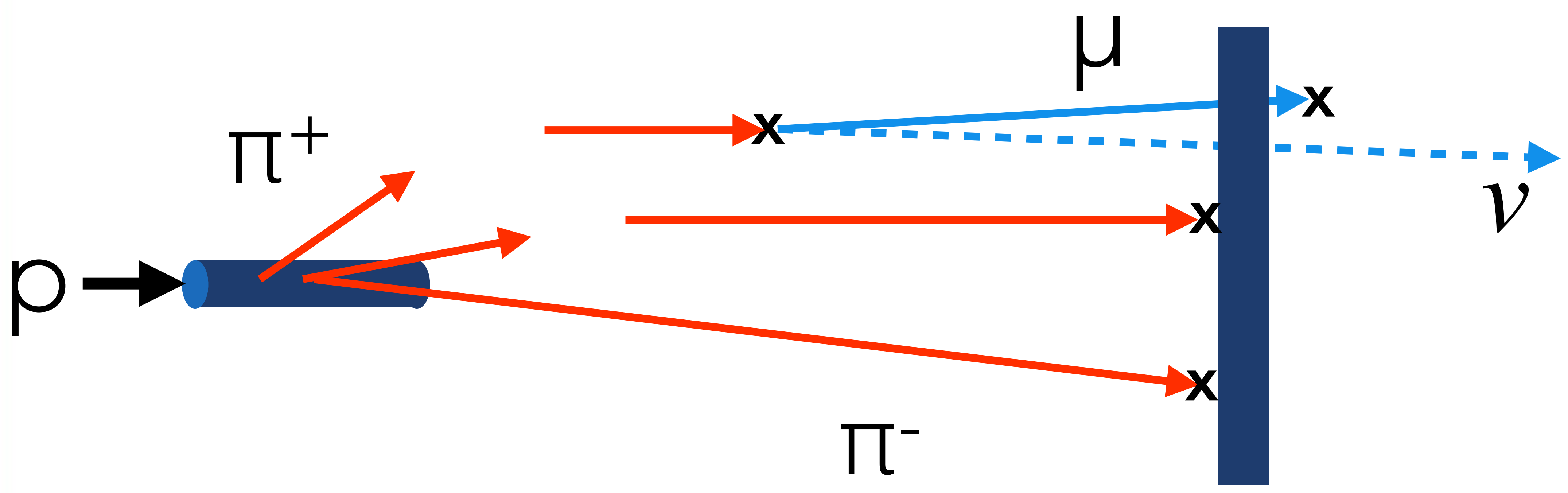

leaks

https://youtu.be/VWGXz5QHFH4

- A neutrino target station is a hostile environment!
- Many things can break
- Careful engineering/design for longevity and repair in ultra high radiation

DECAY AND ABSORPTION

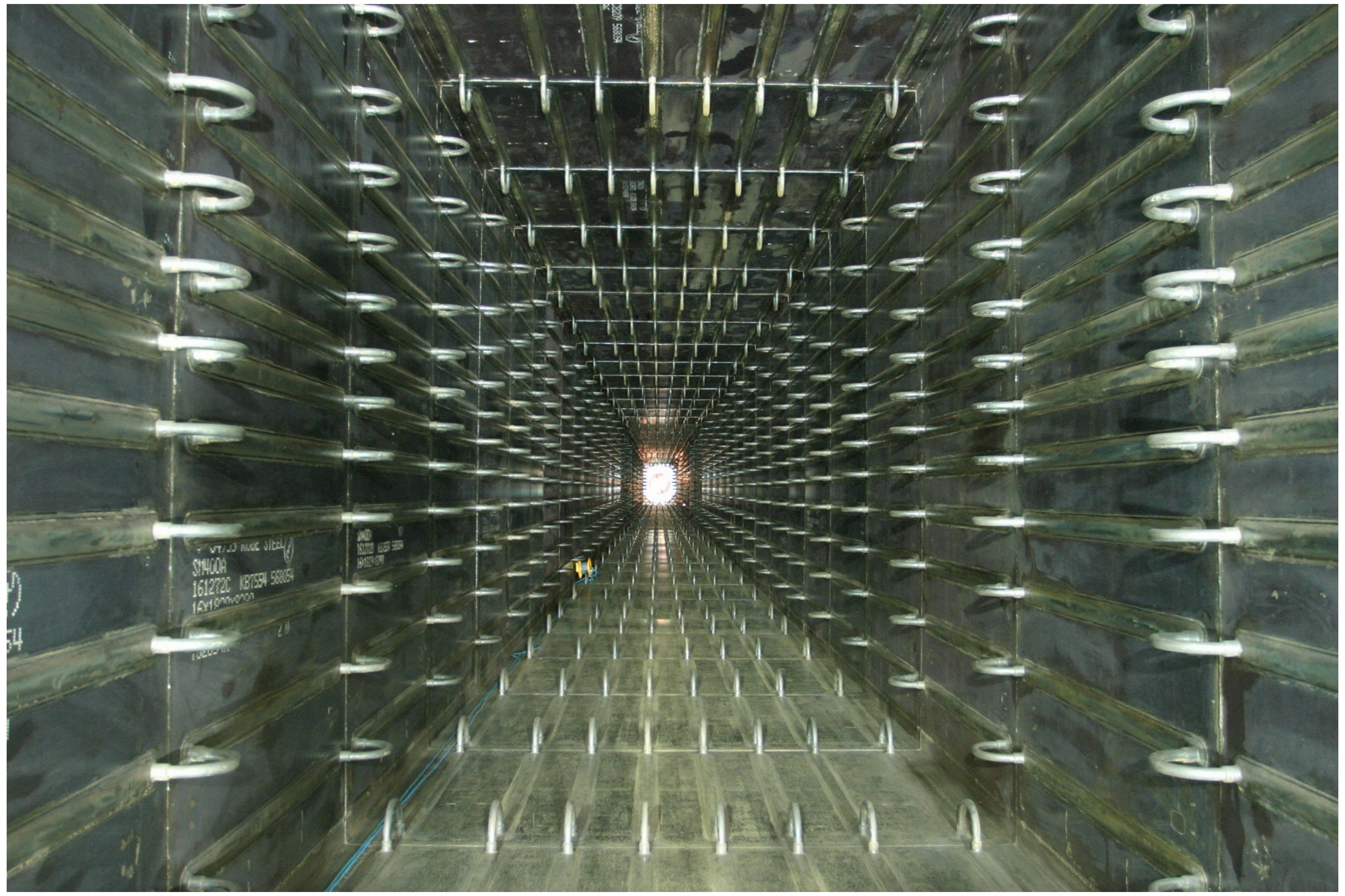


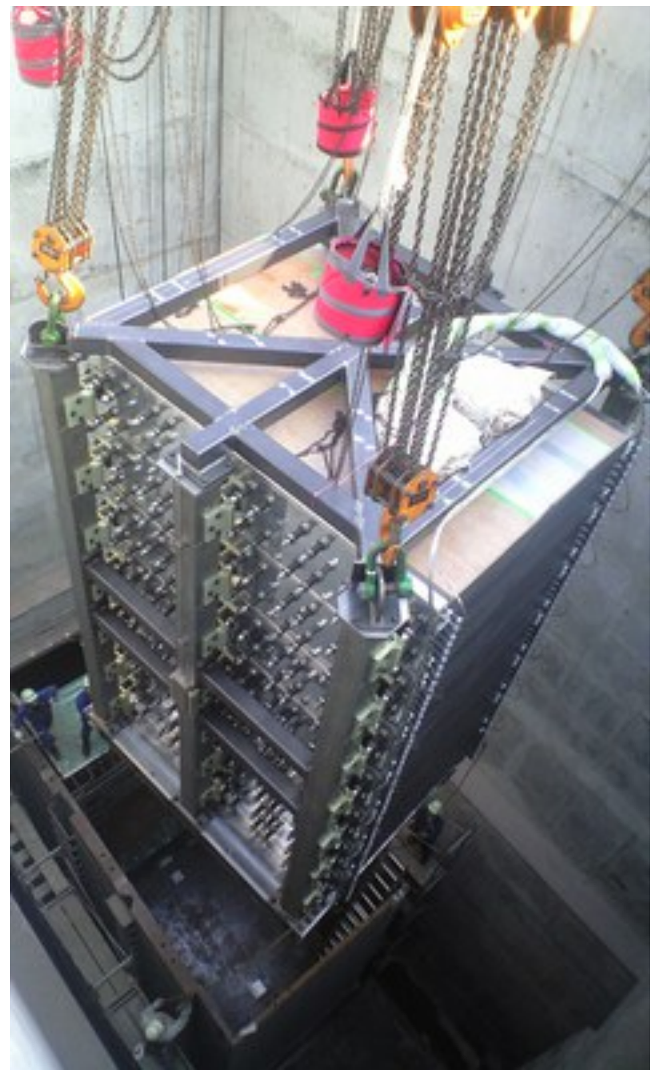


- Considerations:
  - we want a beam of neutrinos!
  - allow pions to decay to produce neutrinos
    - minimum amount of interactions
  - stop all other particles

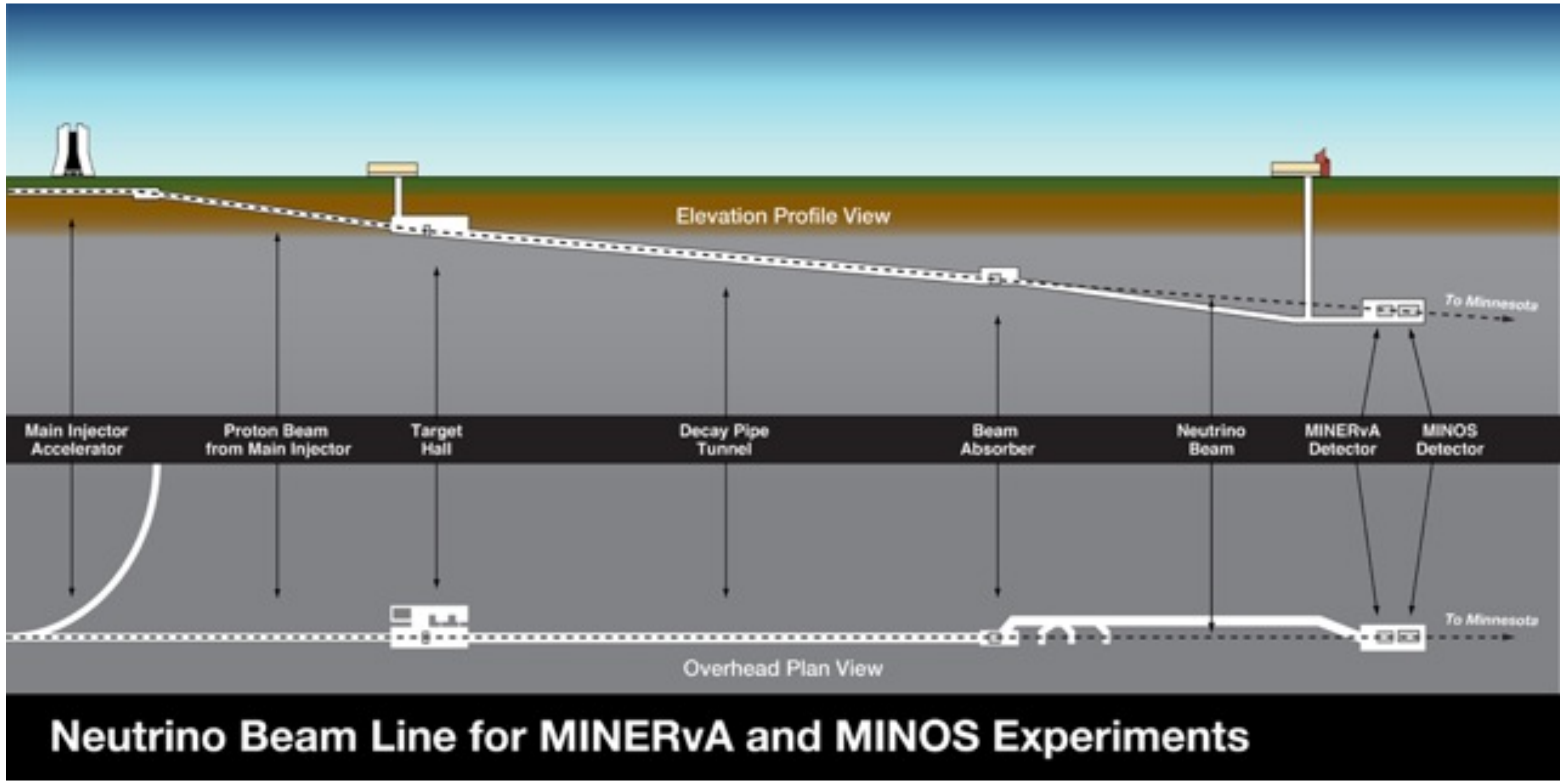
EXAMPLES

- Left: View down the 100 m-long T2K decay pipe
- Bottom: 675 m-long NuMI decay pipe



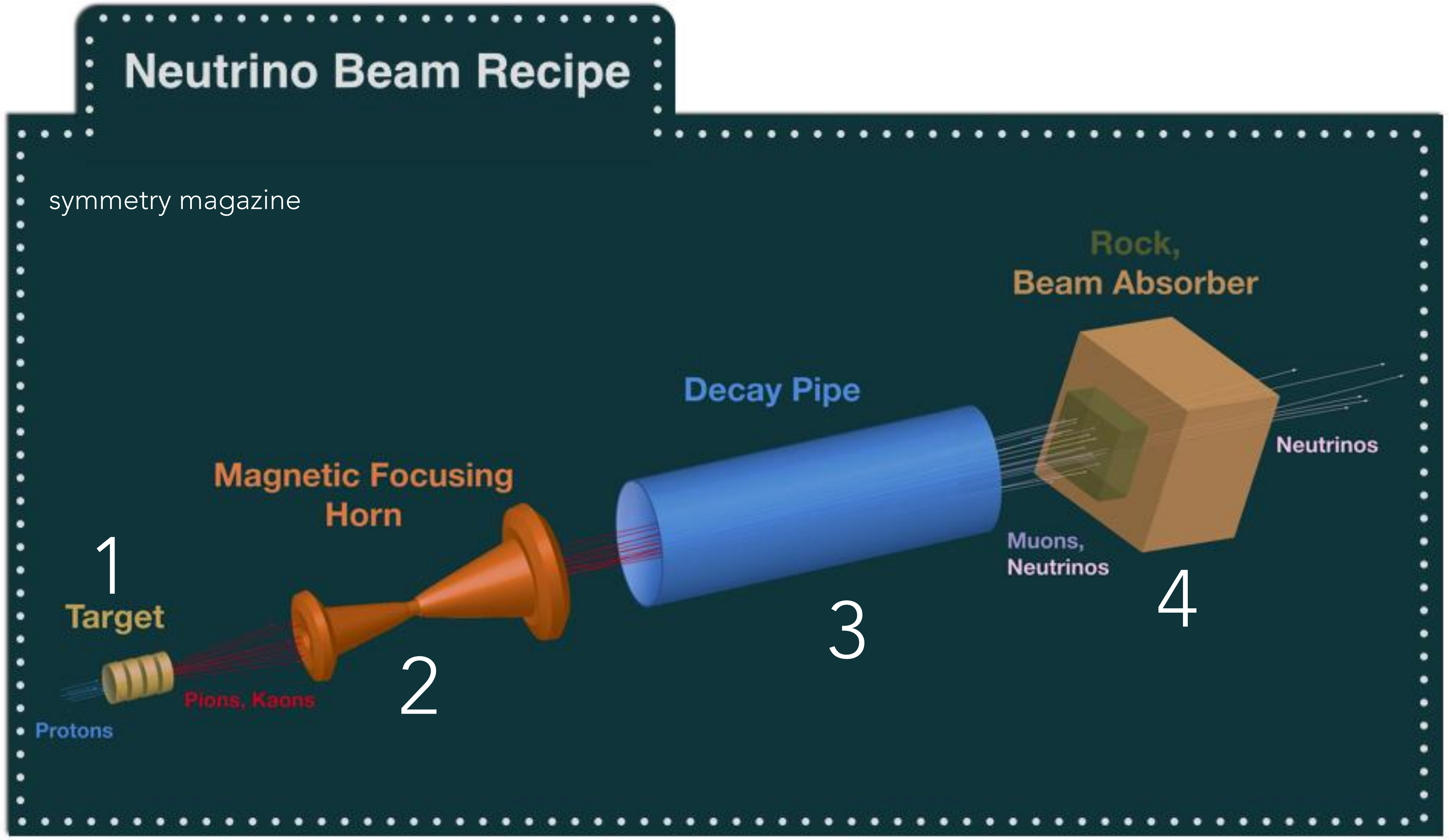


- Helium filled volume to minimize interactions
- Water cooled walls to prevent heat damage



PREDICTING NEUTRINO FLUXES

- What kind of neutrino result from the beam?
- We perform a Monte Carlo simulation accounting for each stage of the process



1. High energy protons impinge on a target
   - pions are produced
2. Electromagnets focus pions into a decay region
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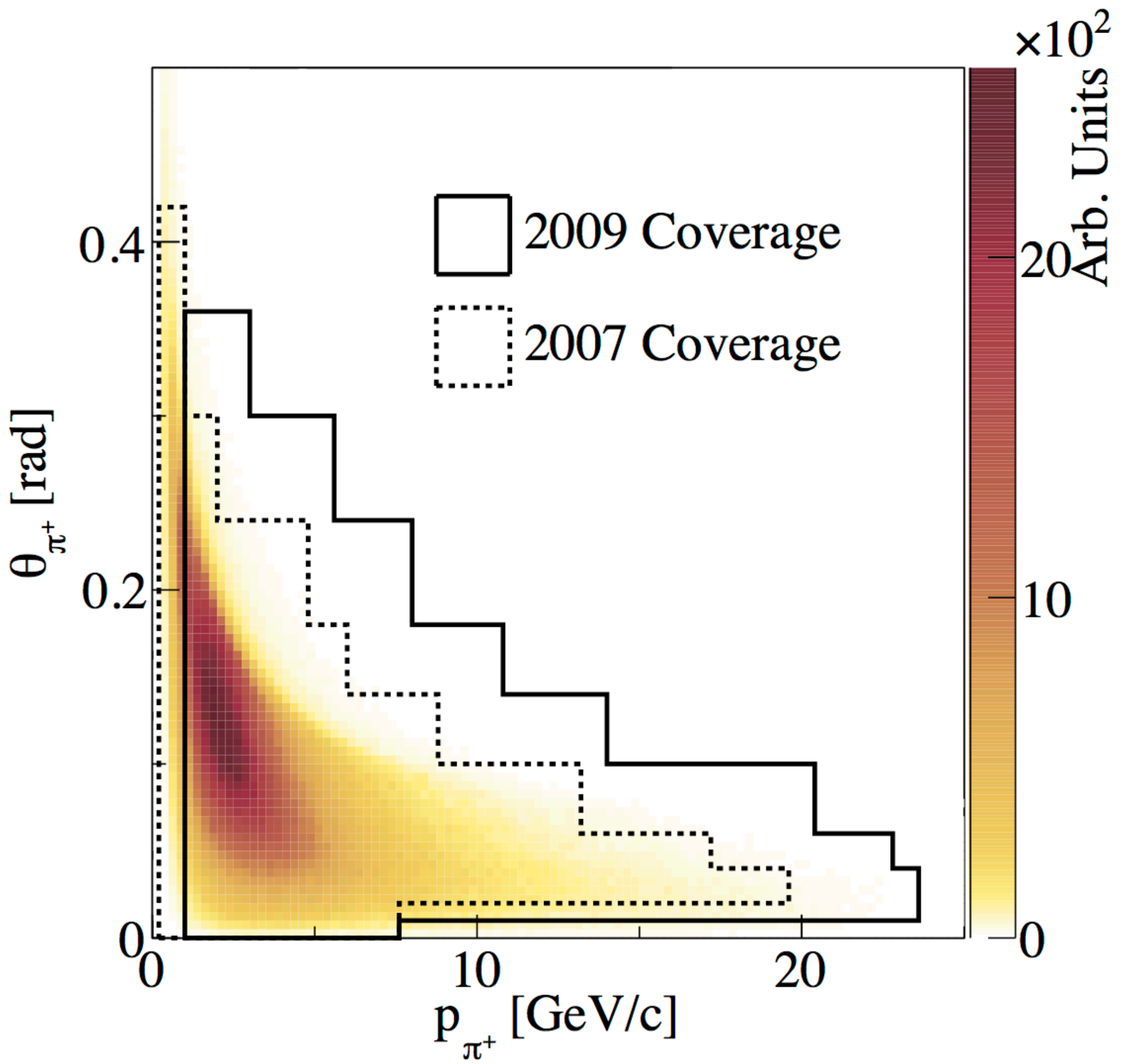
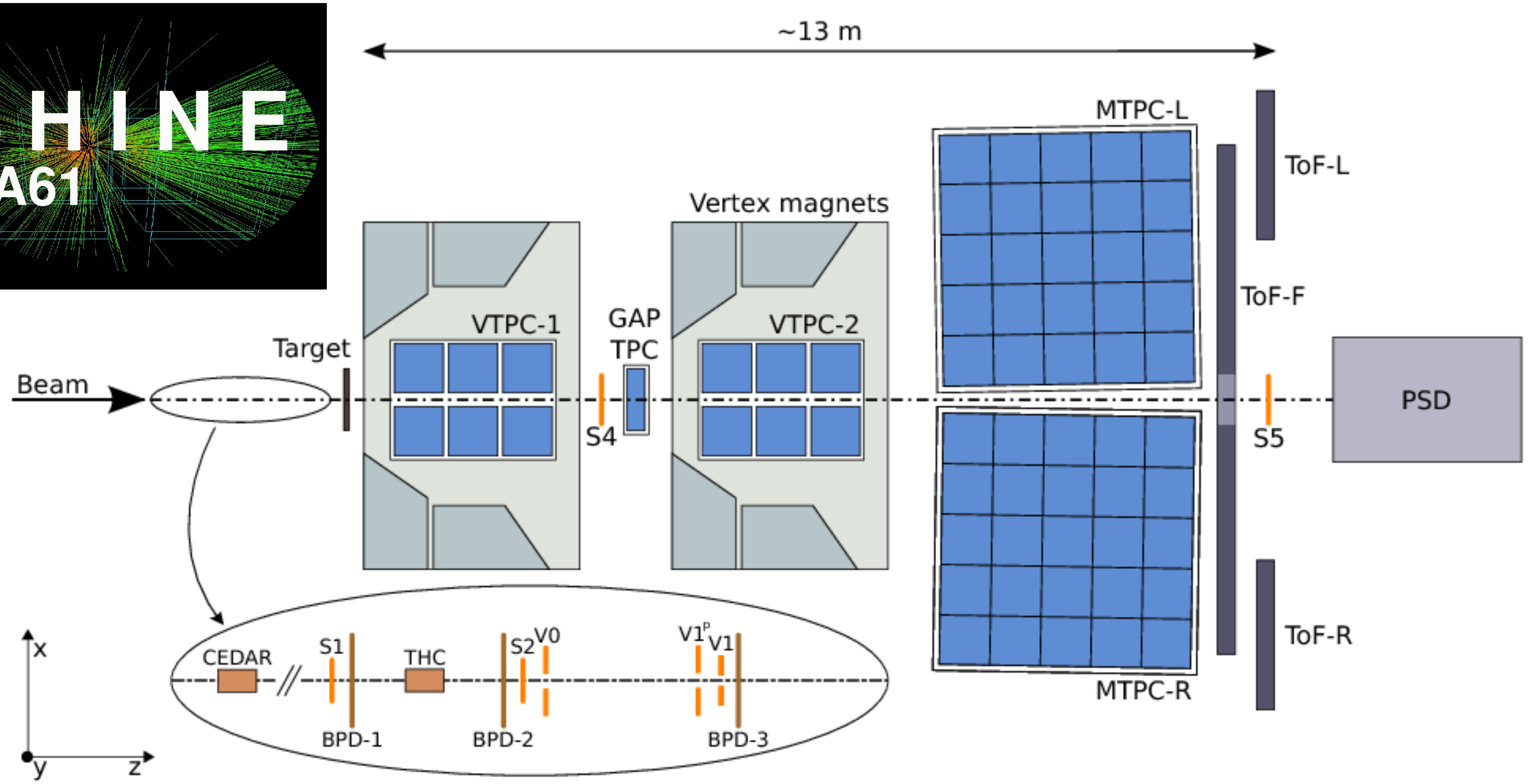
3. The pions decay in a decay pile
   - muon (anti)neutrinos are produced
4. Beam absorber stops all other remaining particles
   - some muons penetrate and can be monitored.
   - neutrinos go on to the detector

- Until they decay to produce neutrinos, track for each particle
  - potential particle interaction with materials (target, horn, gas, etc.)
  - track additional particles (e.g. muons from pion decay) to see if they produce neutrinos

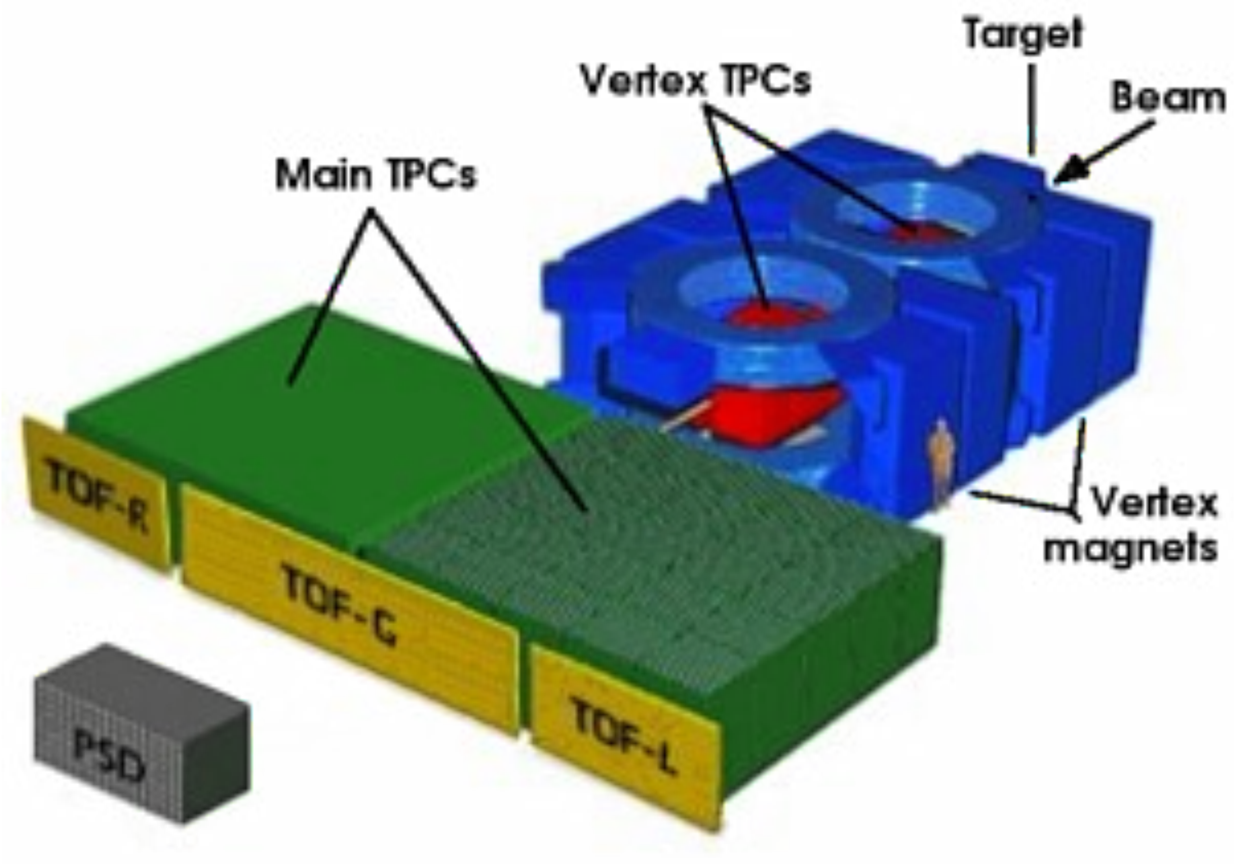
PARTICLE PRODUCTION OFF TARGET

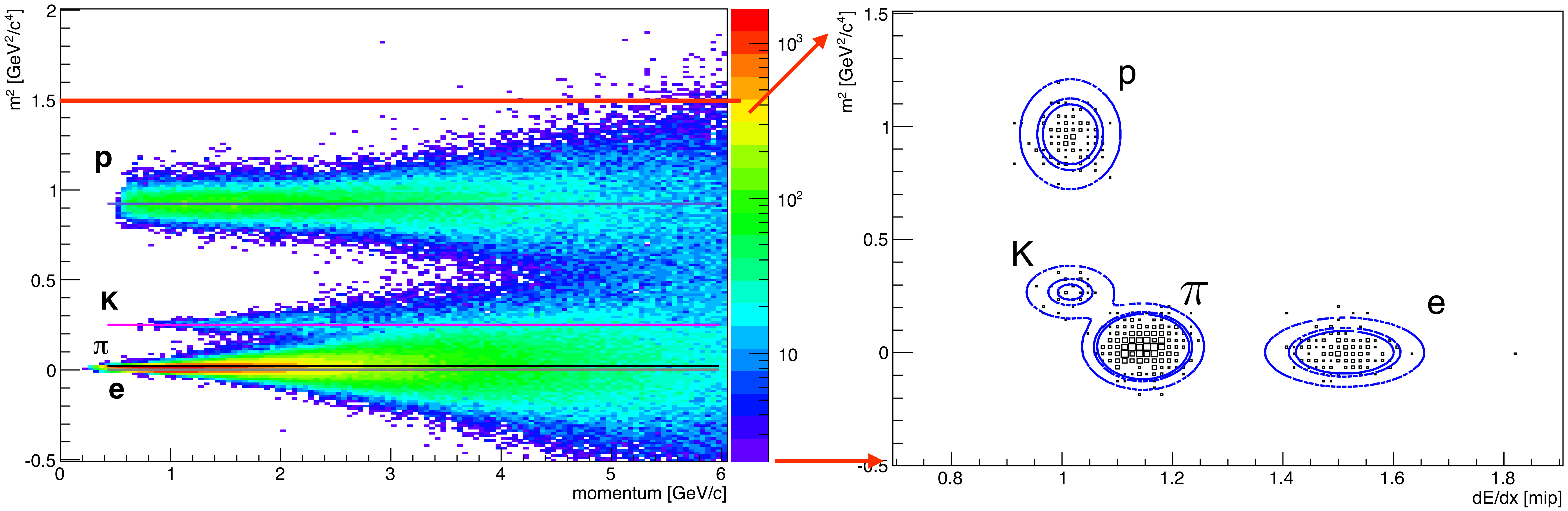
- While particle production is “known” physics, it is difficult to predict ab initial
  - strong interaction physics is difficult to model
  - “off-the-shelf” models such as GCALOR, Geant4 (FTFP, Binary Cascade, etc.) can vary in their predictions by O(1)
    - without further constraints, this would introduce a large into the flux prediction
  - Dedicated experiments measure the species/spectrum of particles coming off of proton-nucleus interactions
  - I’ll talk about one here . . . .



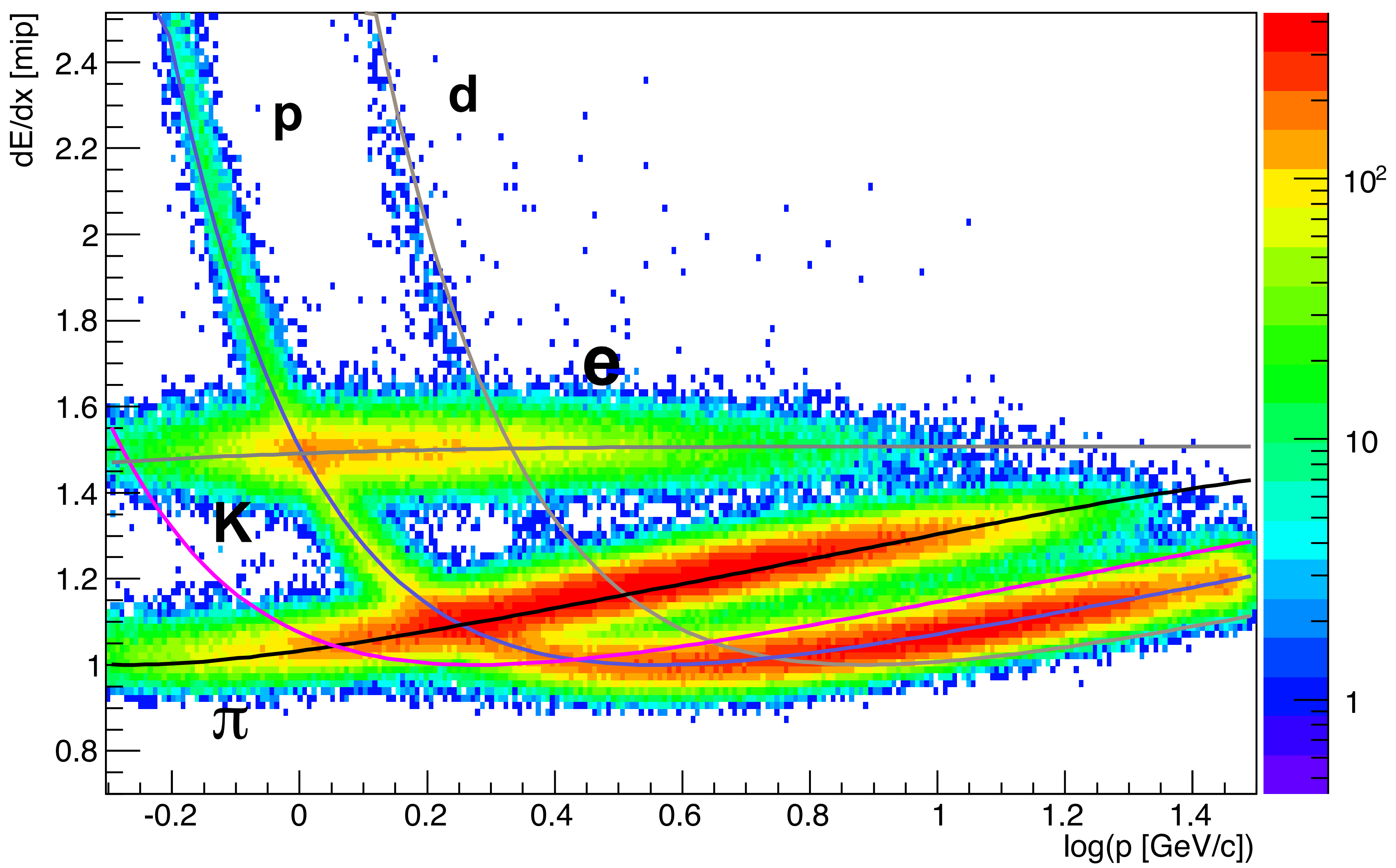


PARTICLE IDENTIFICATION

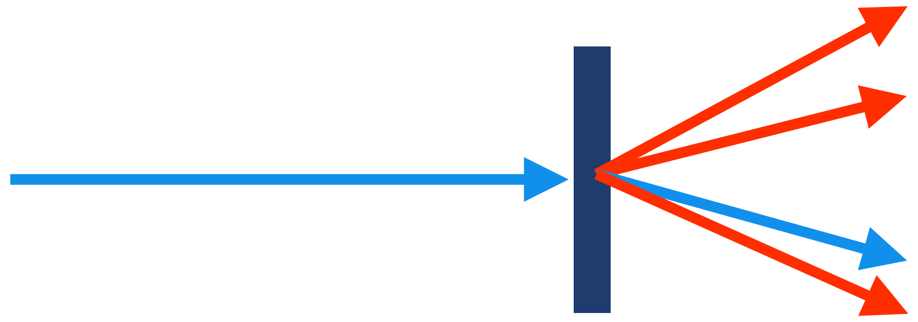


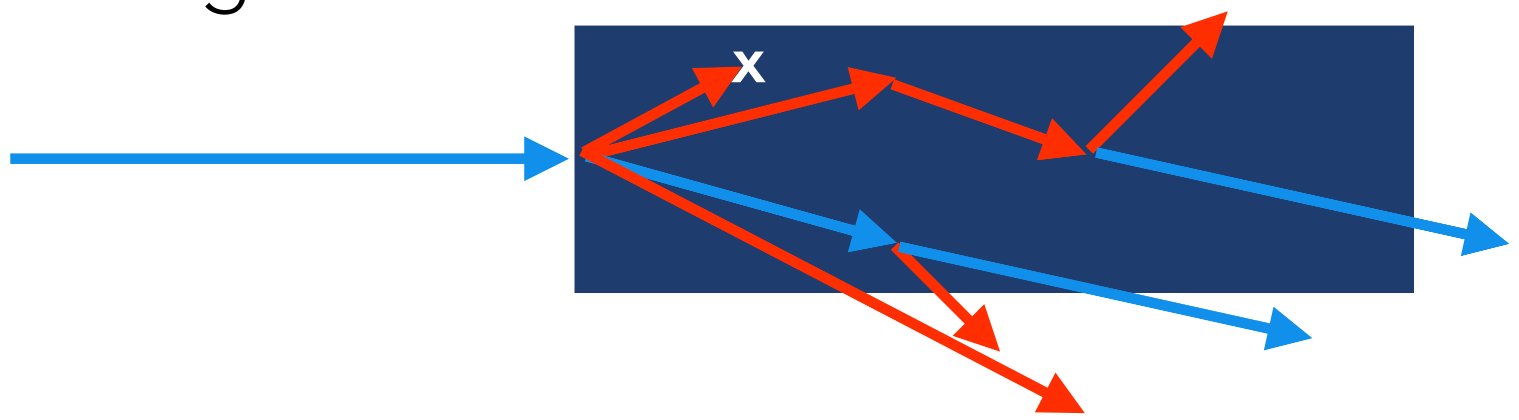


- In addition to particle momentum, particle identification is very important
  - we need to know what kind of particle is produced!
- In NA61, two systems provide complementary information
  - time-of-flight system
  - dE/dx (ionization density) in the time projection TPCs

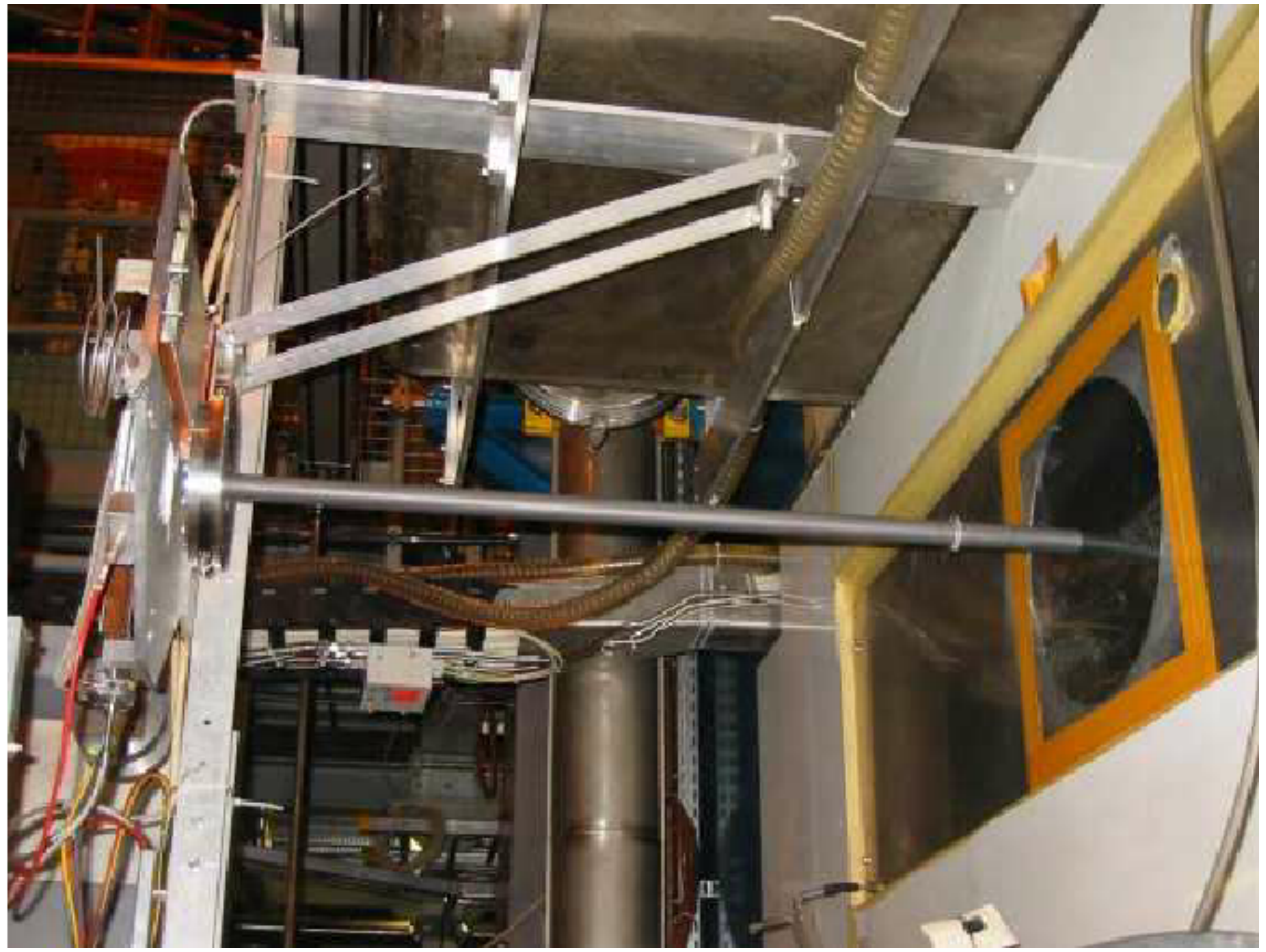


THIN VS REPLICA TARGET



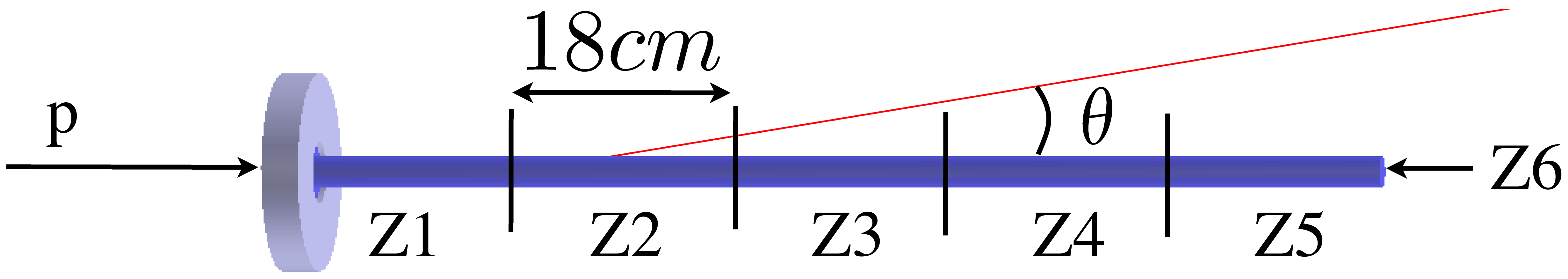


- Two separate measurements (assume target is carbon)
  - what comes out of a proton-carbon interaction?
  - what comes out of a proton interacting with an (extended) carbon target
- "Thin target" measurement
  - minimize reinteraction of outgoing particles
  - aimed at measuring "primordial" proton-carbon interaction
- "Thick" target measurement
  - allow outgoing particles (including proton) to reinteract
    - scattering, absorption, additional particle production
    - see what comes out after all this . . . . .
  - use a target as similar as possible to the one we use
    - "replica target"
- If we model reinteractions correctly, the two should agree



T2K replica target at NA61/SHINE

RESULTS:



- Thin target: "double differential cross sections"

$$\frac{d^2\sigma}{dp\ d\theta}$$

- Thick/replica target: "differential multiplicity"

$$\frac{d^2 n}{dp\ d\theta\ dz}$$

  - longitudinal position (z) where particle emerges

θ=[0,20] mrad

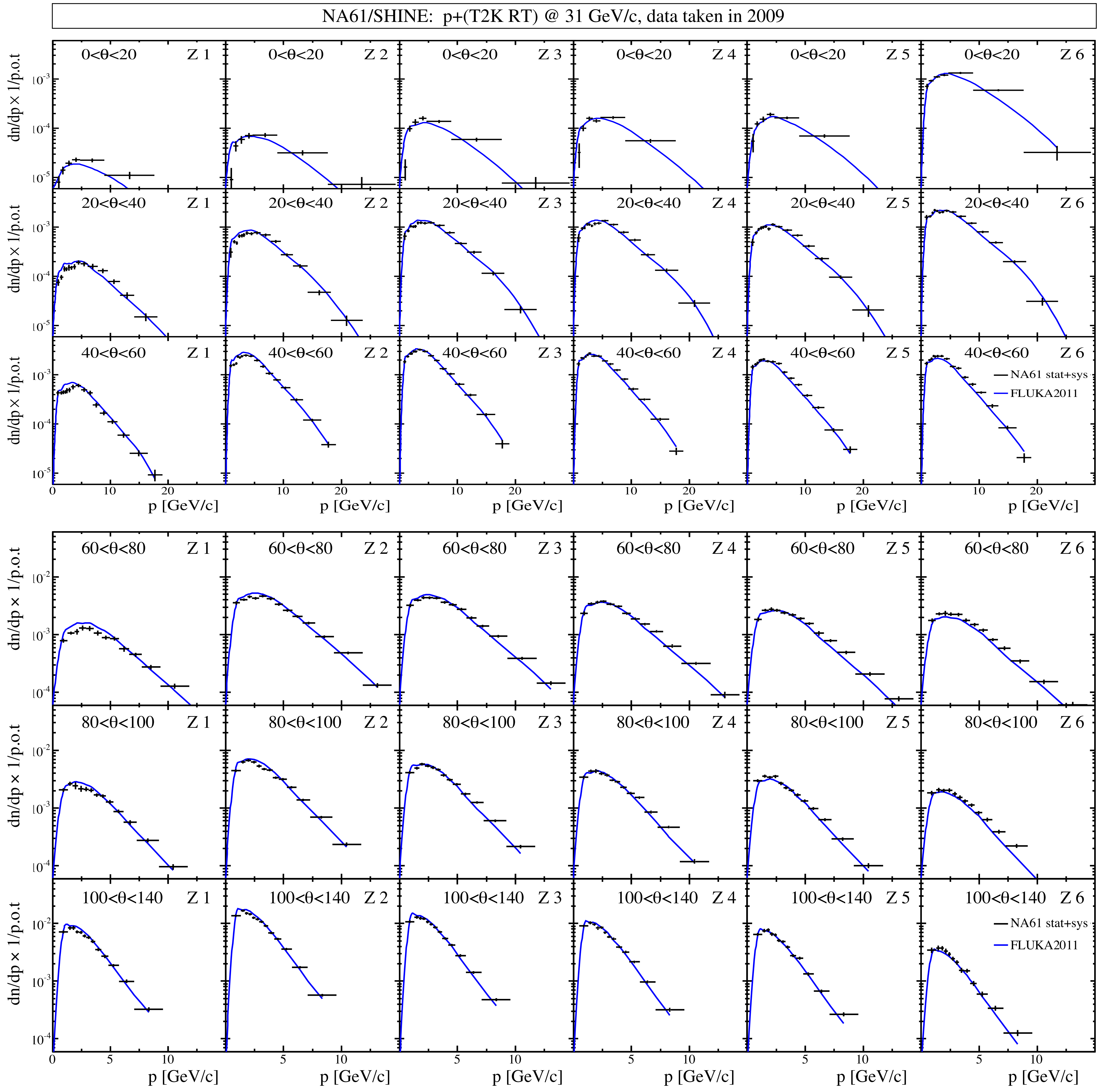
θ=[20,40] mrad

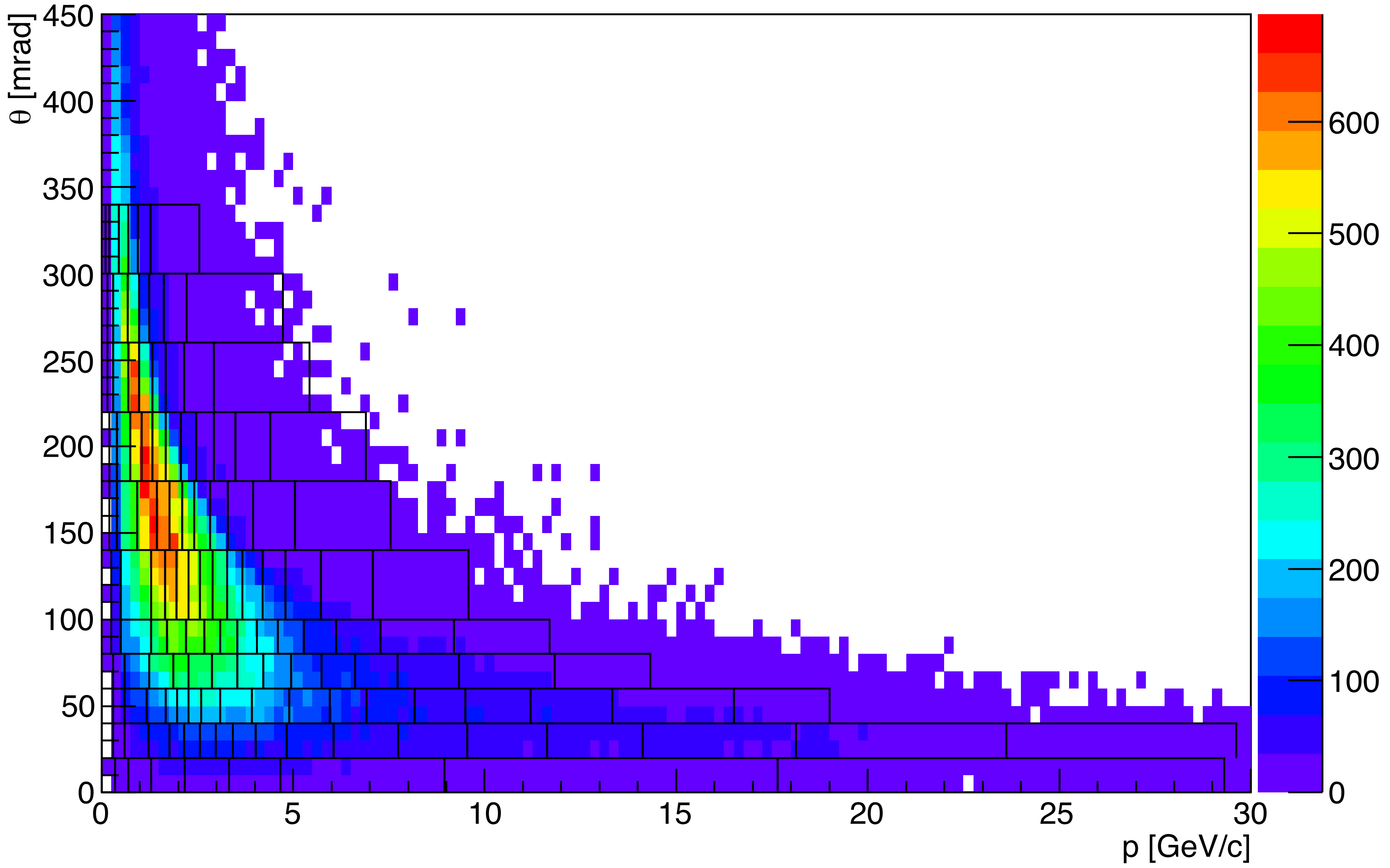
θ=[40,60] mrad

θ=[60,80] mrad

θ=[80,100] mrad

θ=[100,140] mrad

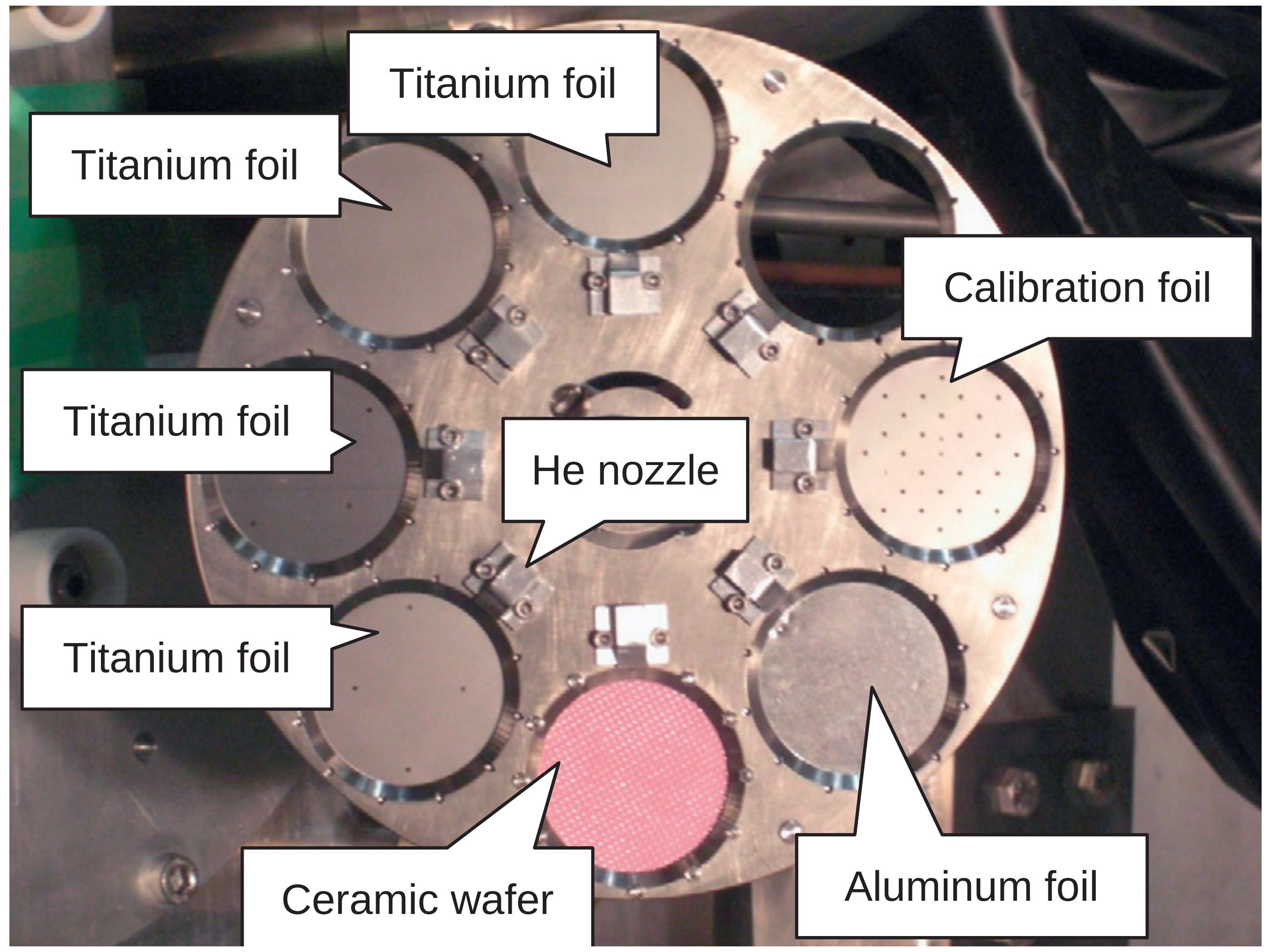


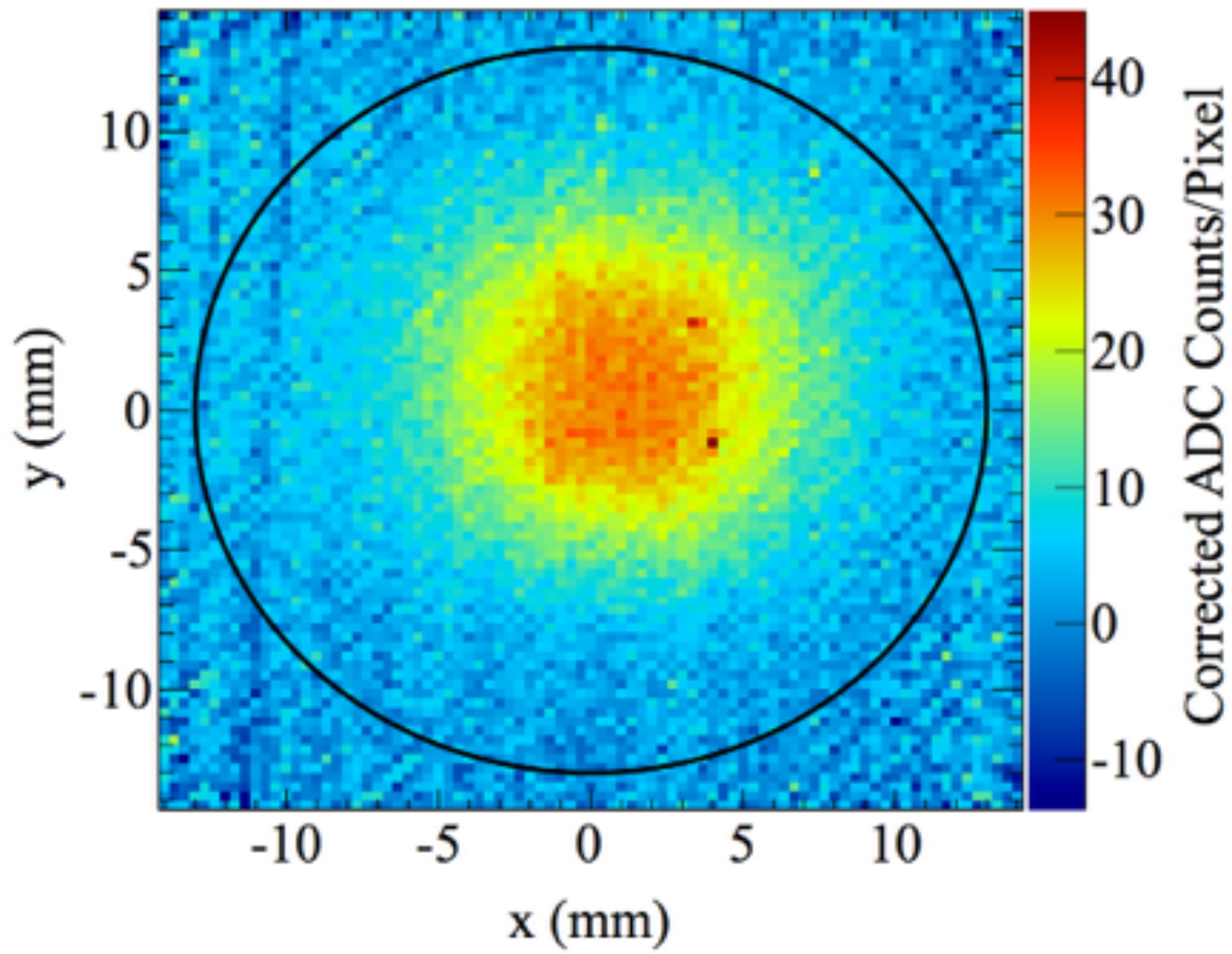


phase space of π^+ contributing to ν flux to SK vs. measured phase space

BEAM CONDITIONS

- uncertainties result from understanding of the beam line itself
  - optics of the proton beam
    - what is the location, spread, and emittance of the beam?
  - alignment and geometry?
    - are the components where we think they are and aligned correctly?
    - is the modelling of the material correct?
    - requires precise surveying and detailed materials accounting.
  - horn current
    - how much current is actually passing through the horns?
    - where does the current actually pass?

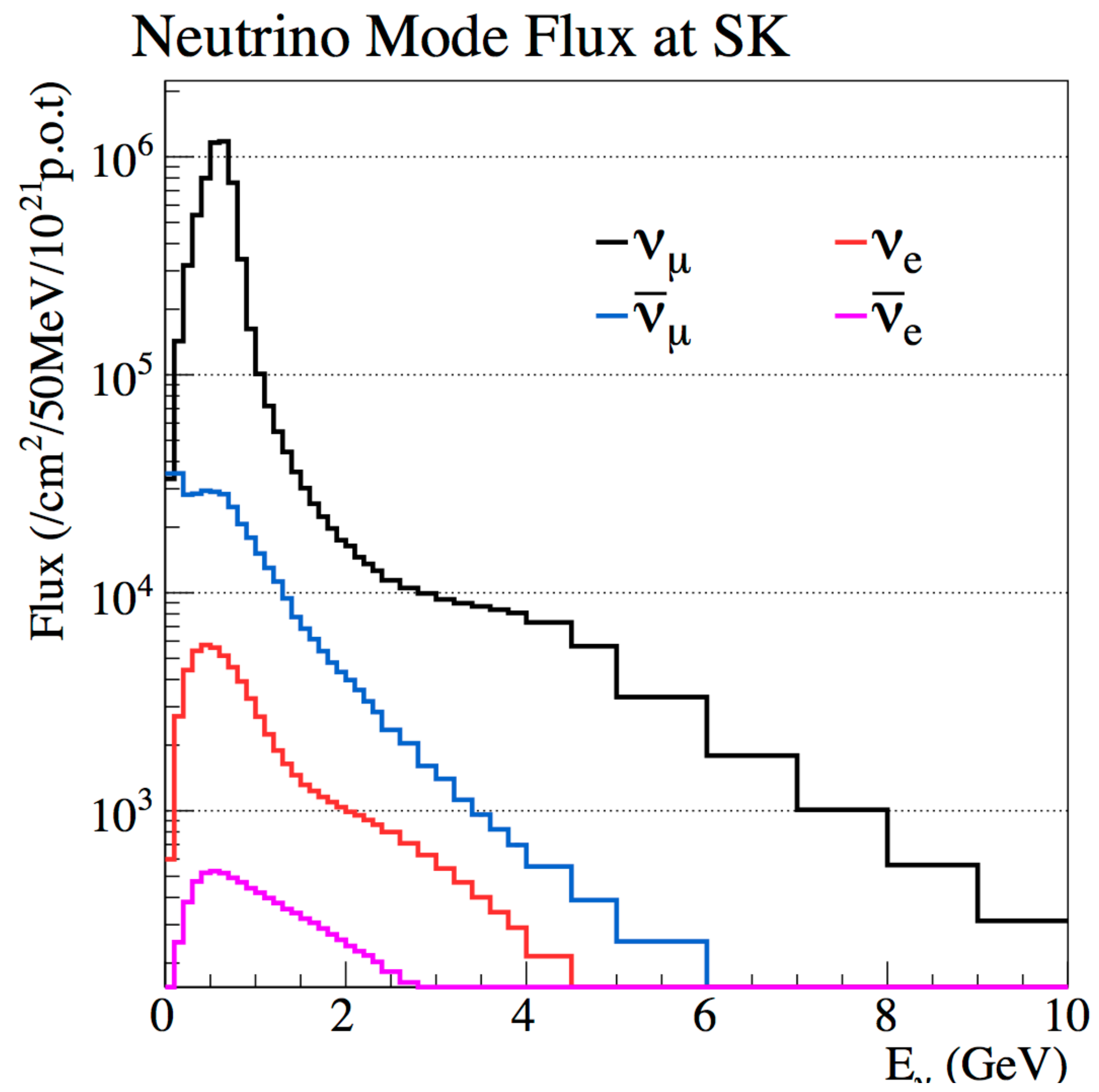


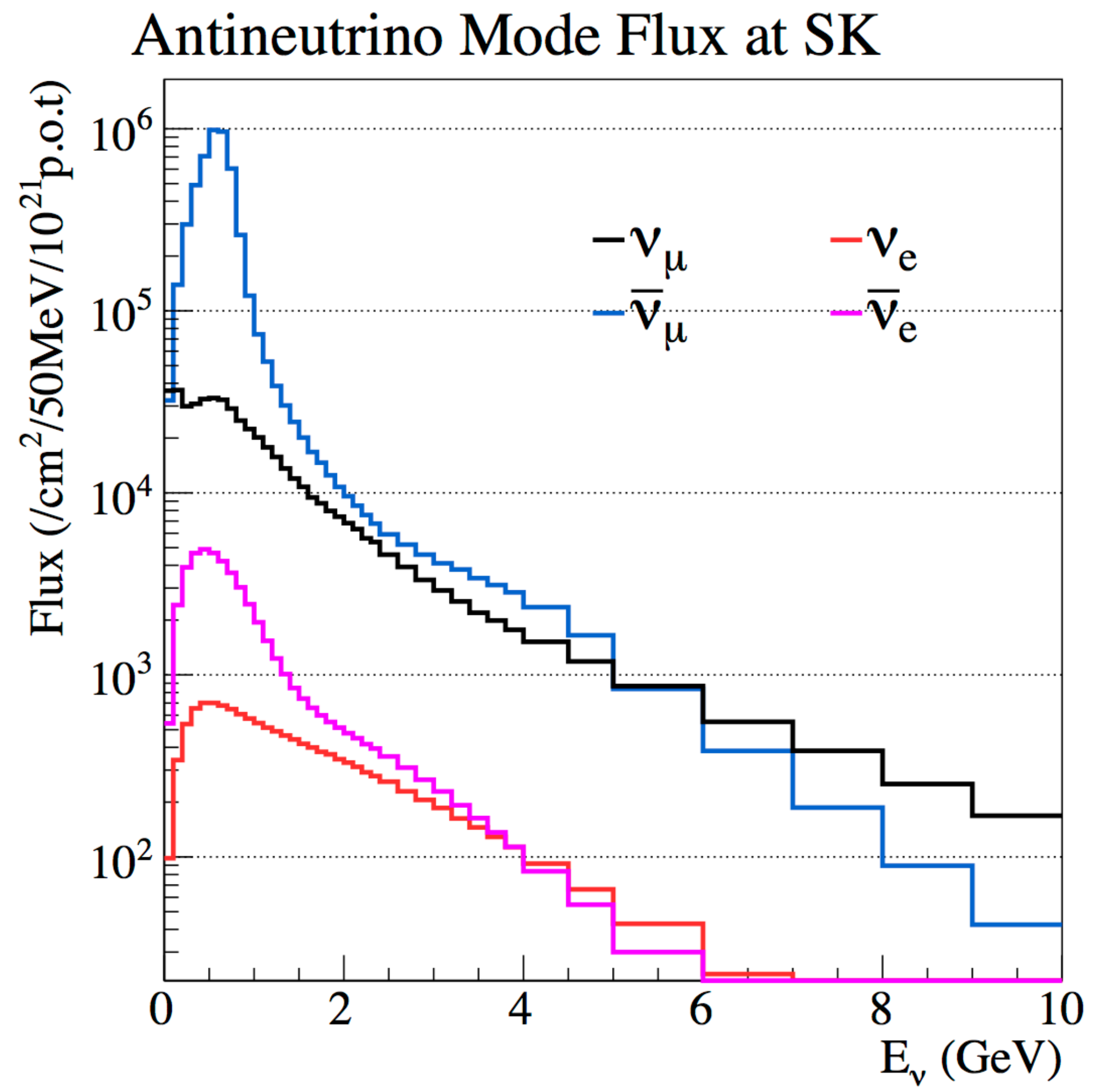


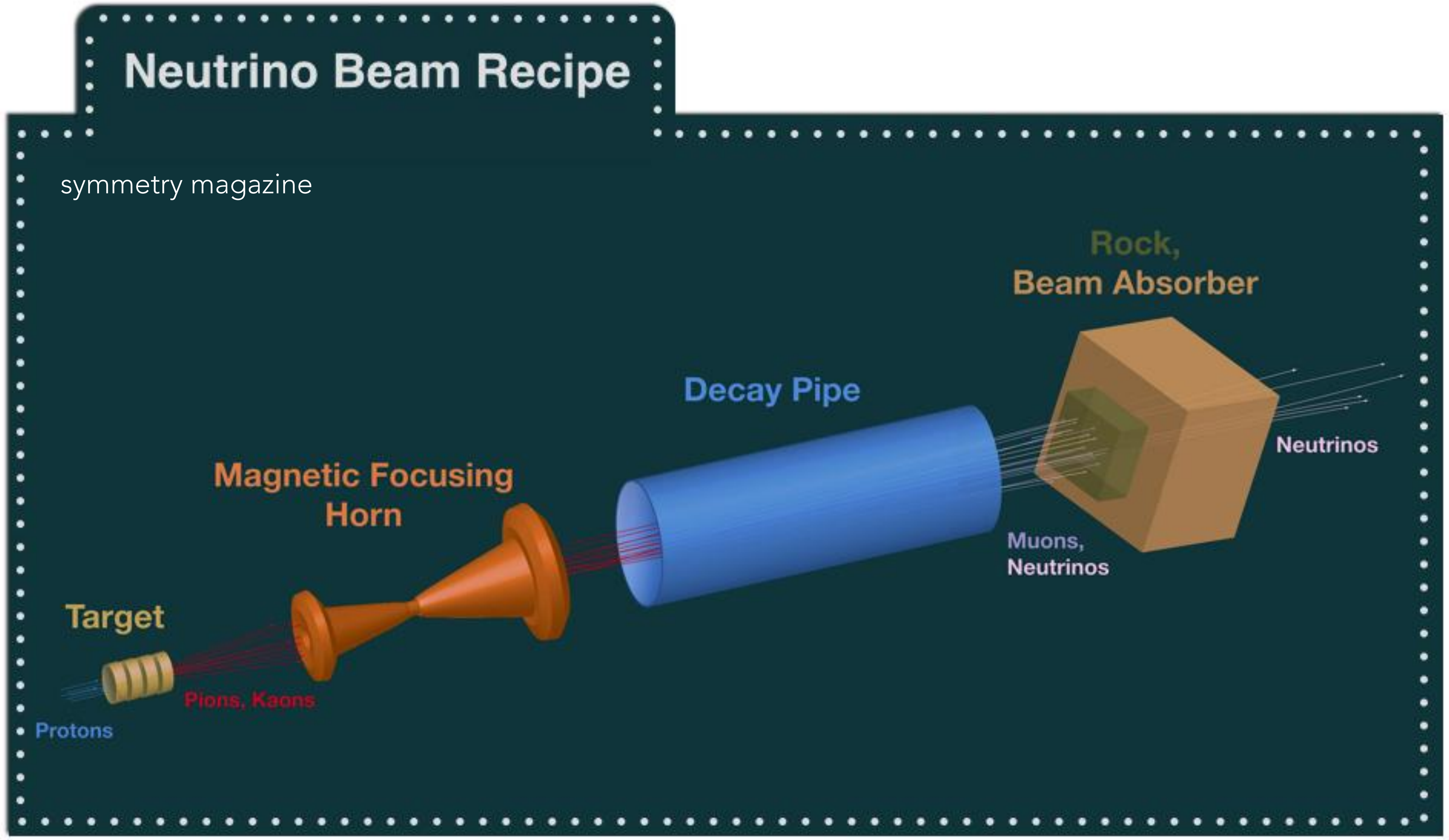
T2K optical transition radiation monitor images primary proton beam just upstream of the target

PREDICTION

predicted neutrino flux at SK from the T2K beam

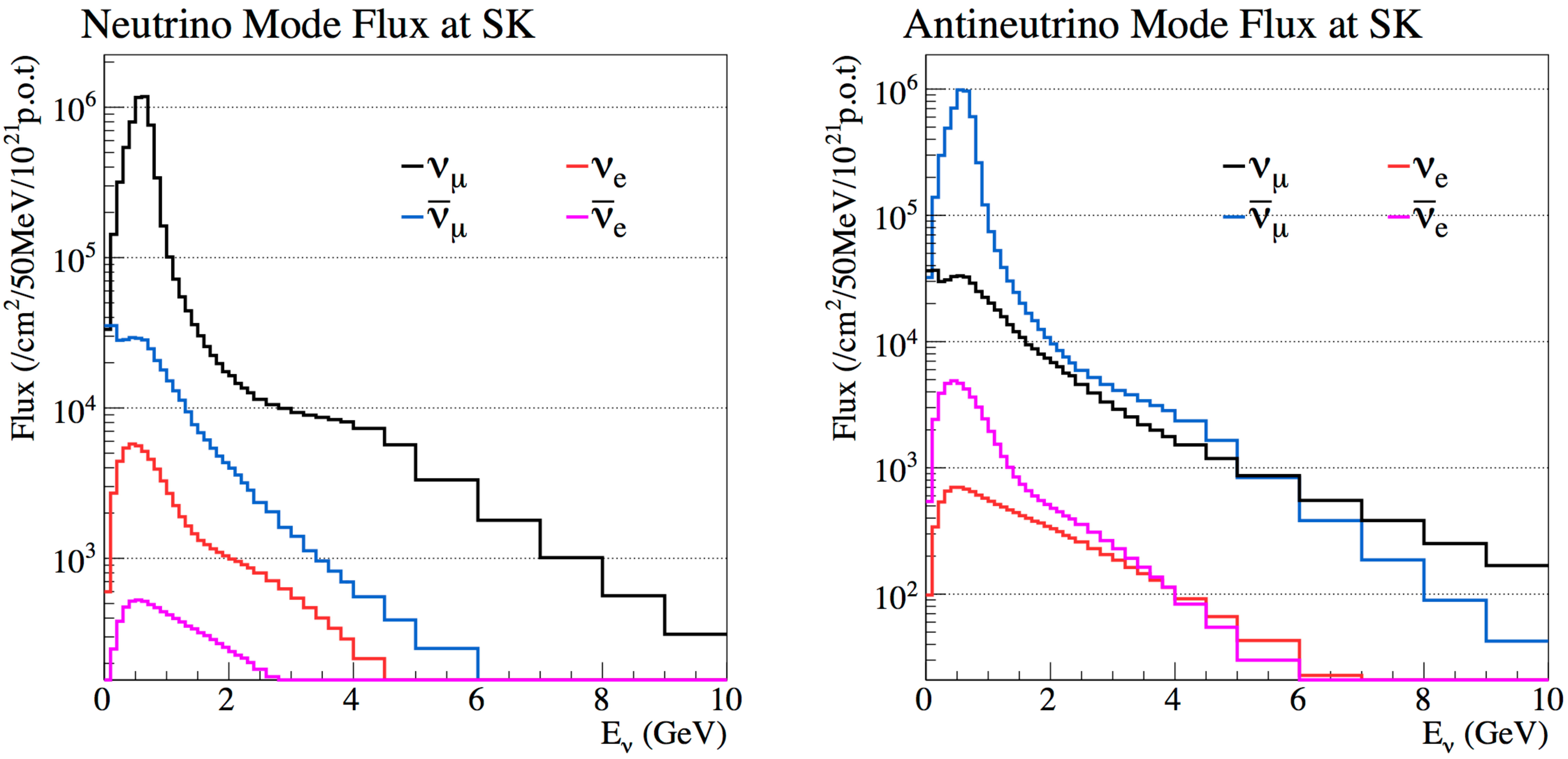




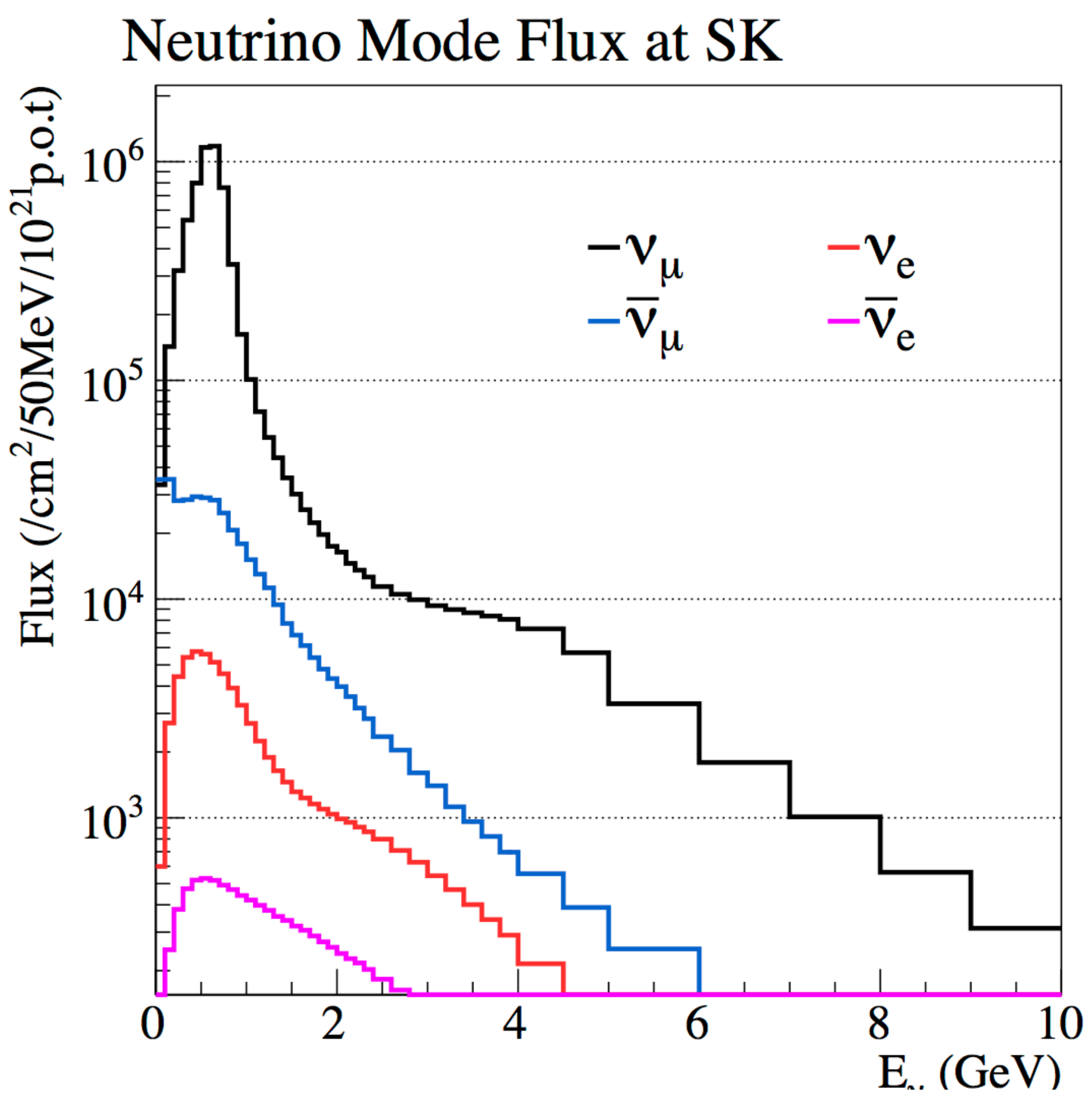


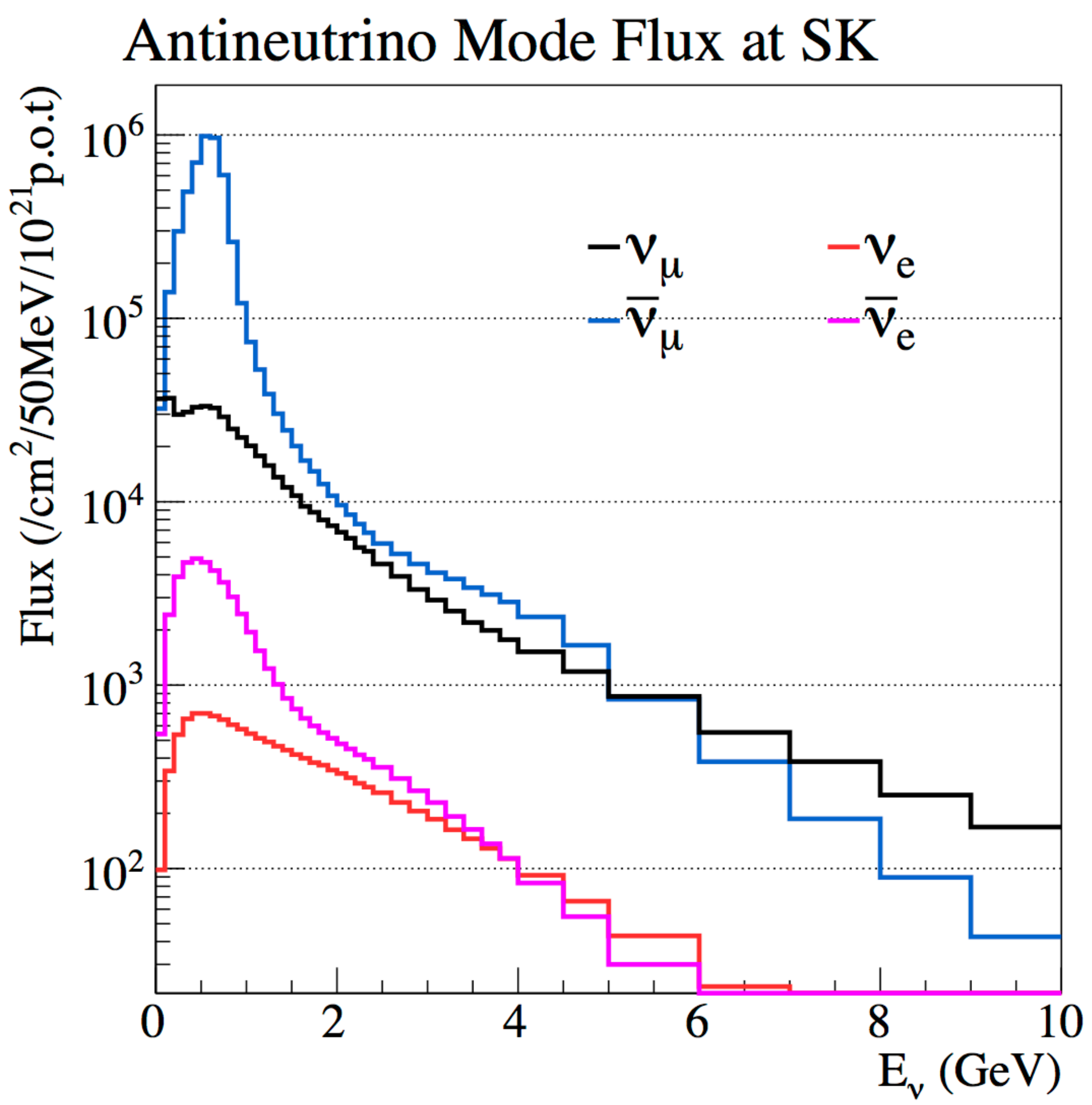
- The simulation follows the whole process
  - a proton generated according to the beam parameters hits the target
  - if it interacts, particles are produced based on measurements
  - particles are tracked out of the target,
    - through the horn (or any other material) until they decay
    - any additional particles that are produced are tracked
  - neutrinos that are produced at any point are recorded

PREDICTED NEUTRINO FLUXES



SANITY CHECK:

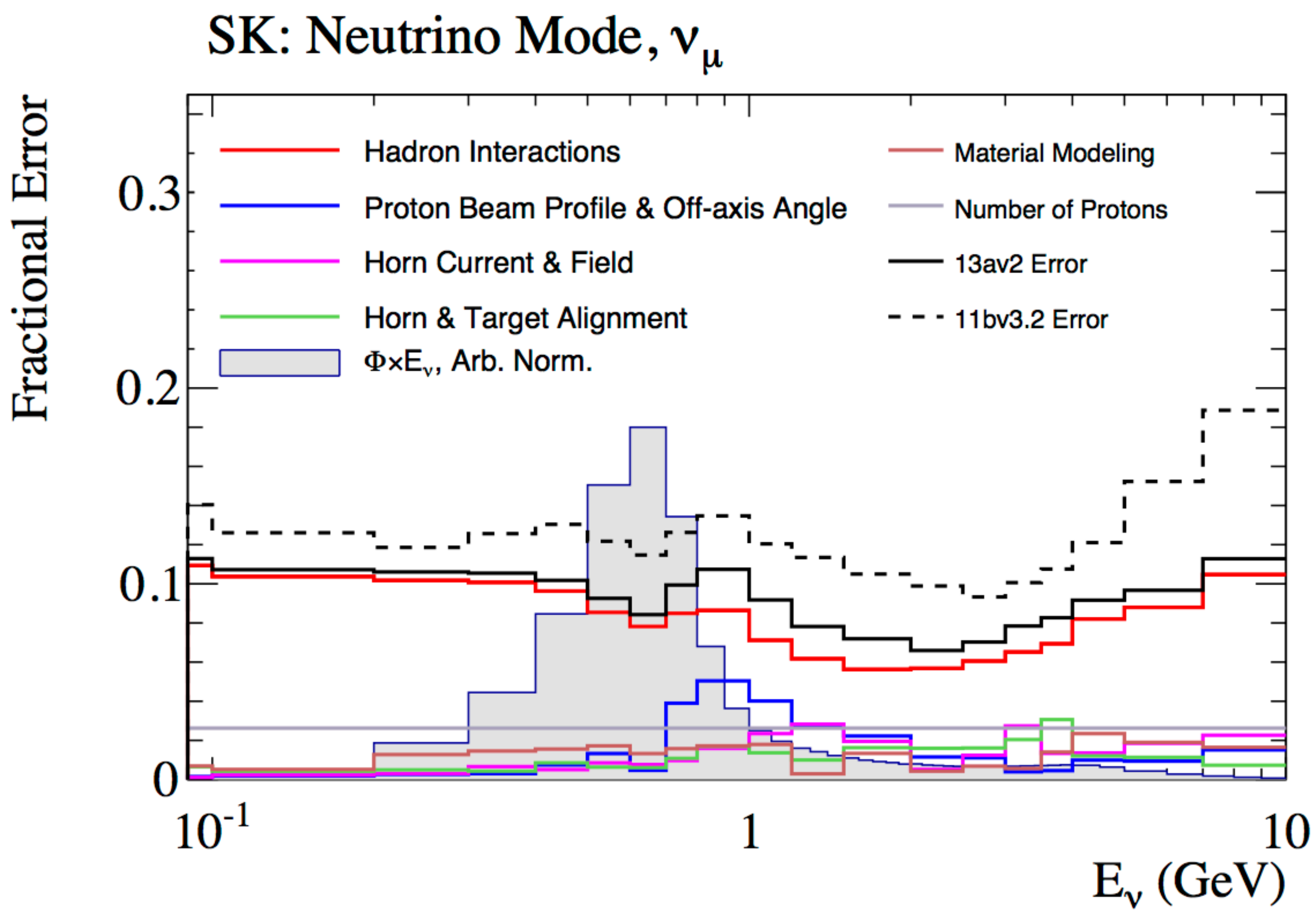


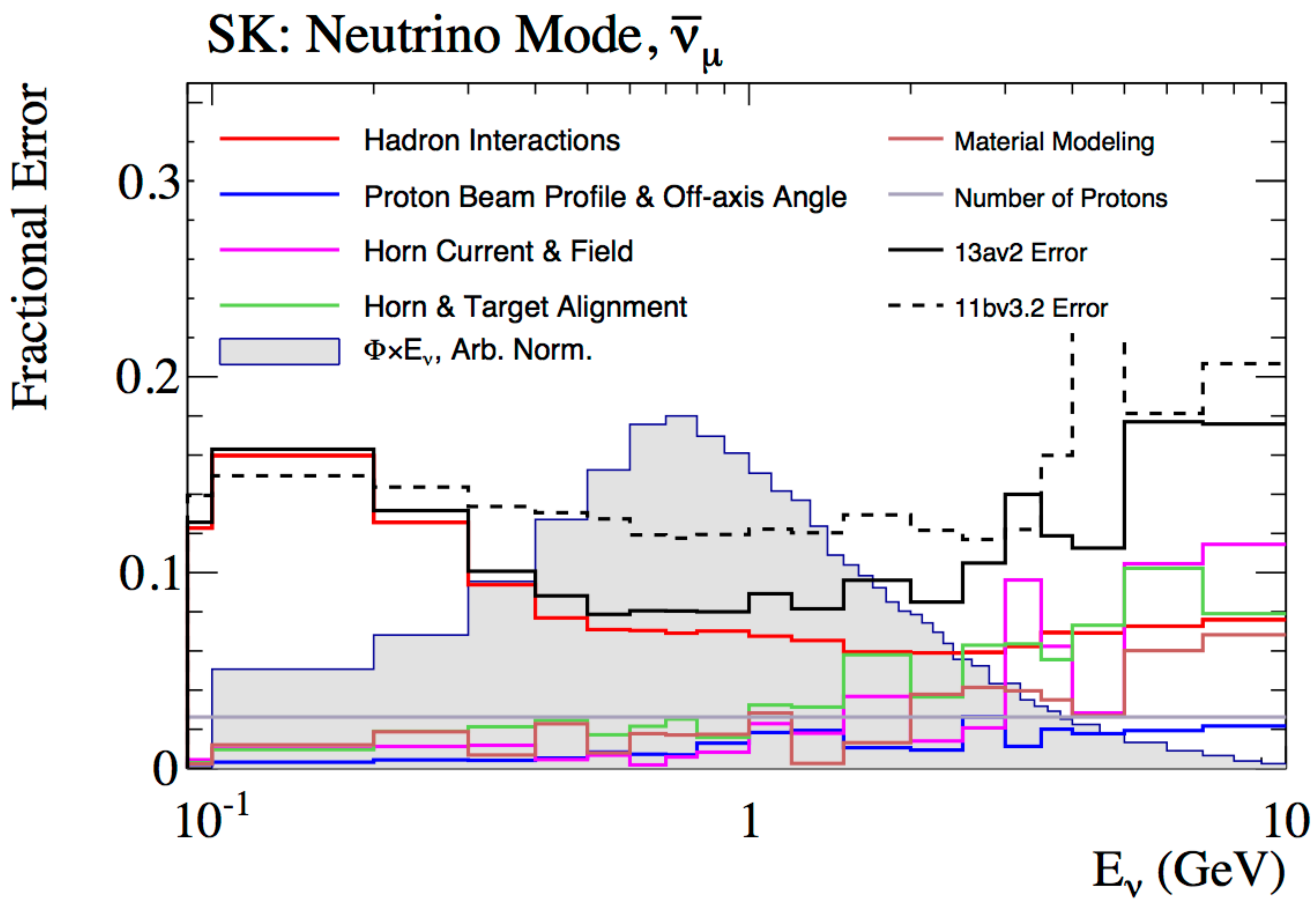


- While the $\nu_\mu/\bar{\nu}_\mu$ "wrong sign" flux contamination is about the same in neutrino and antineutrino mode, it is much more of a problem for antineutrino mode.
- Why?

- The wrong sign ν_e contamination in antineutrino mode looks larger than the corresponding $\bar{\nu}_e$ contamination in neutrino mode.
- Why?

UNCERTAINTIES:





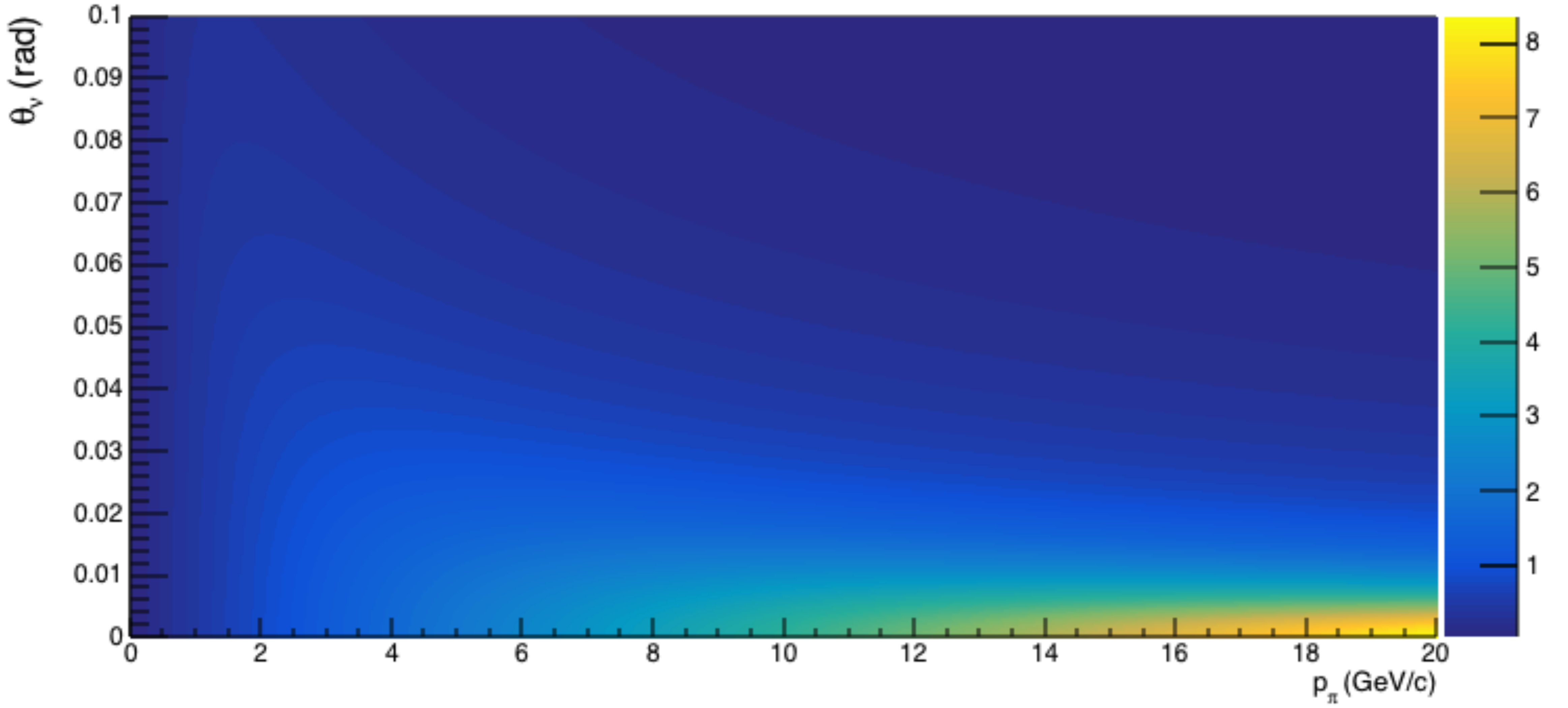
- Dominant uncertainty is still hadron interactions
  - these results use "thin target" measurements.
  - Expect large reduction in uncertainty once replica target data is incorporated
- Next largest uncertainty from primary beam and geometric uncertainties
- wrong sign flux also has large uncertainty at high energies from forward particle production

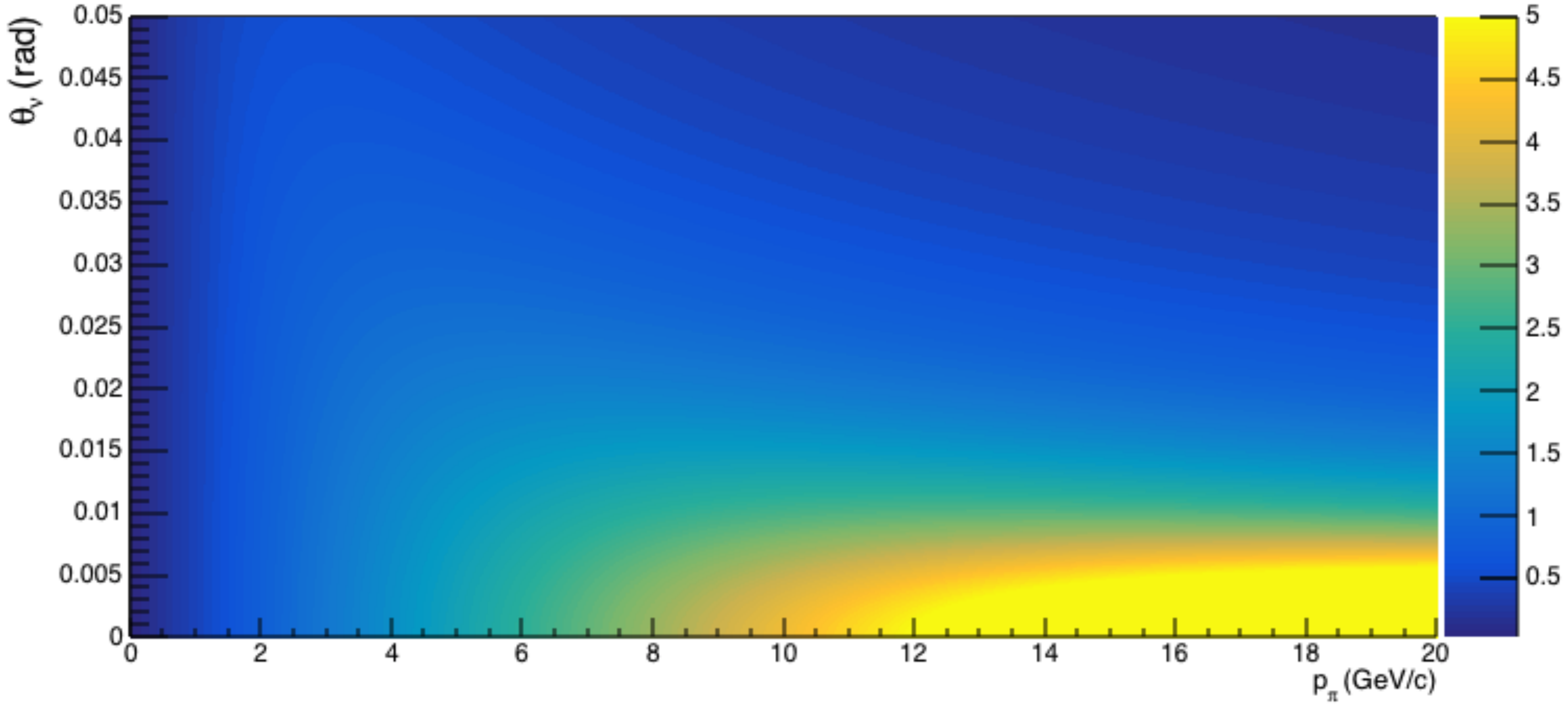
VARIATIONS

OFF-AXIS BEAM:

- For forward decays (e.g. neutrinos directed in the same direction as the pion), E_ν scales with E_π
  - These are the neutrinos that are directed down the axis of the neutrino beam
  - broad pion spectrum → broad neutrino energy spectrum
- 1990s: neutrinos directed away from the initial pion momentum lose this correlation
  - E_ν becomes uncorrelated with E_π
  - at an "off-axis" angle, neutrinos pile up at a particular E_ν despite broad E_π spectrum
  - larger off-axis angles result in lower E_ν
- To take advantage of this, one paradoxically points the neutrino beam away from the detector
  - "off-axis beam"

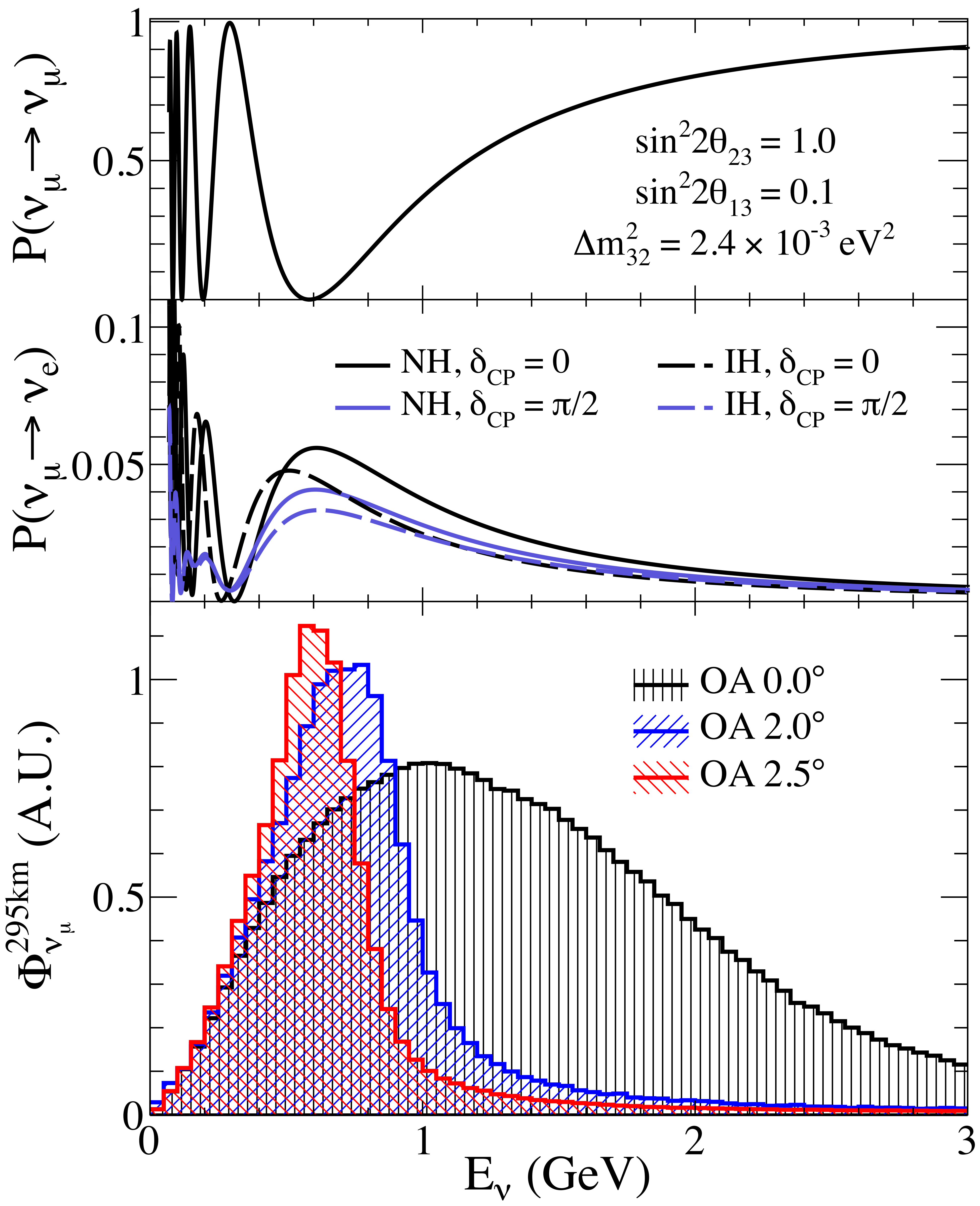
z scale is the E_ν resulting from a neutrino emitted at angle θ_ν relative to the decay of pion of momentum p_π





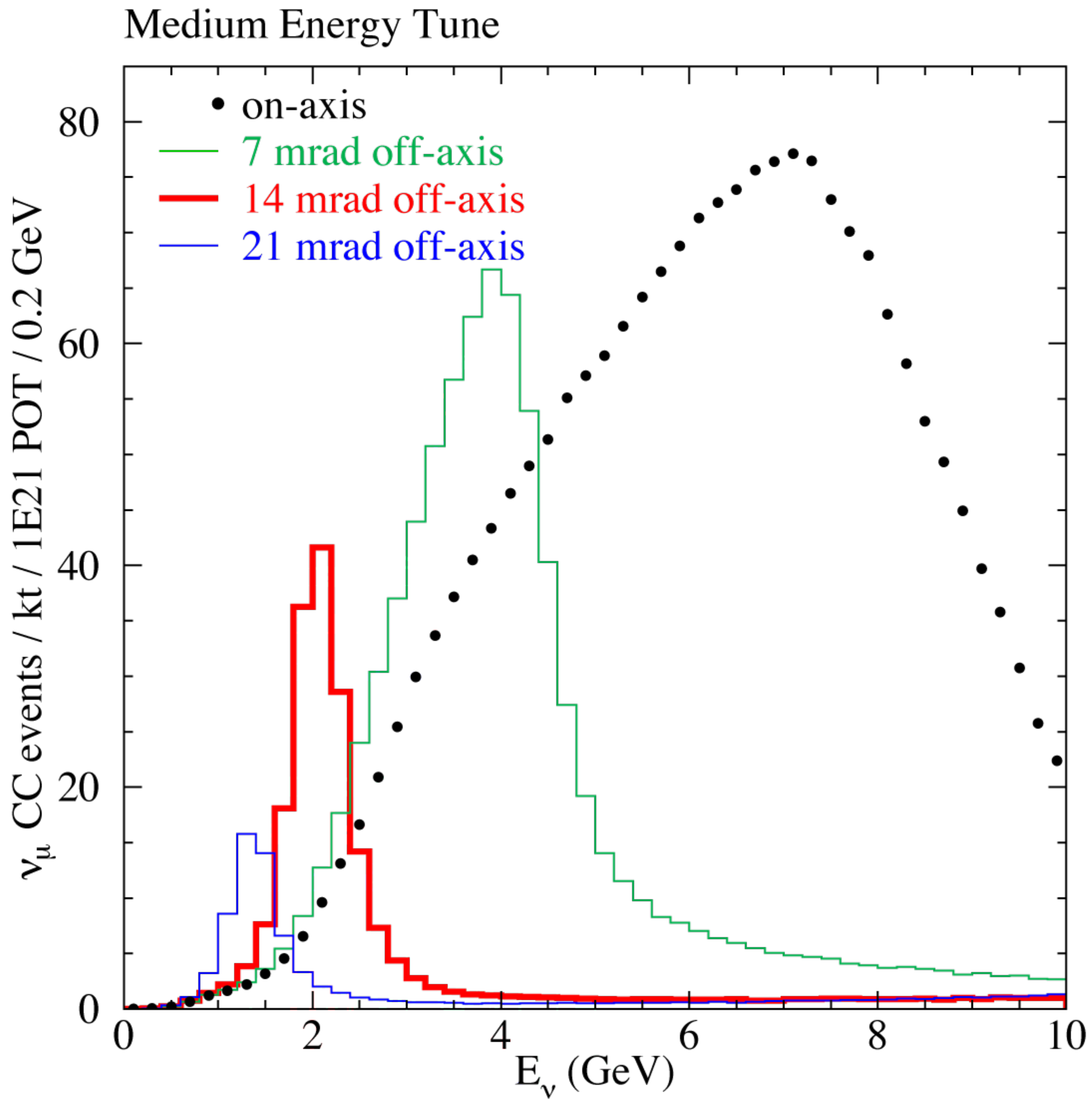
bottom plot has restricted θ_ν, E_ν scale

T2K AND NOVA



Left: off-axis beam at T2K:

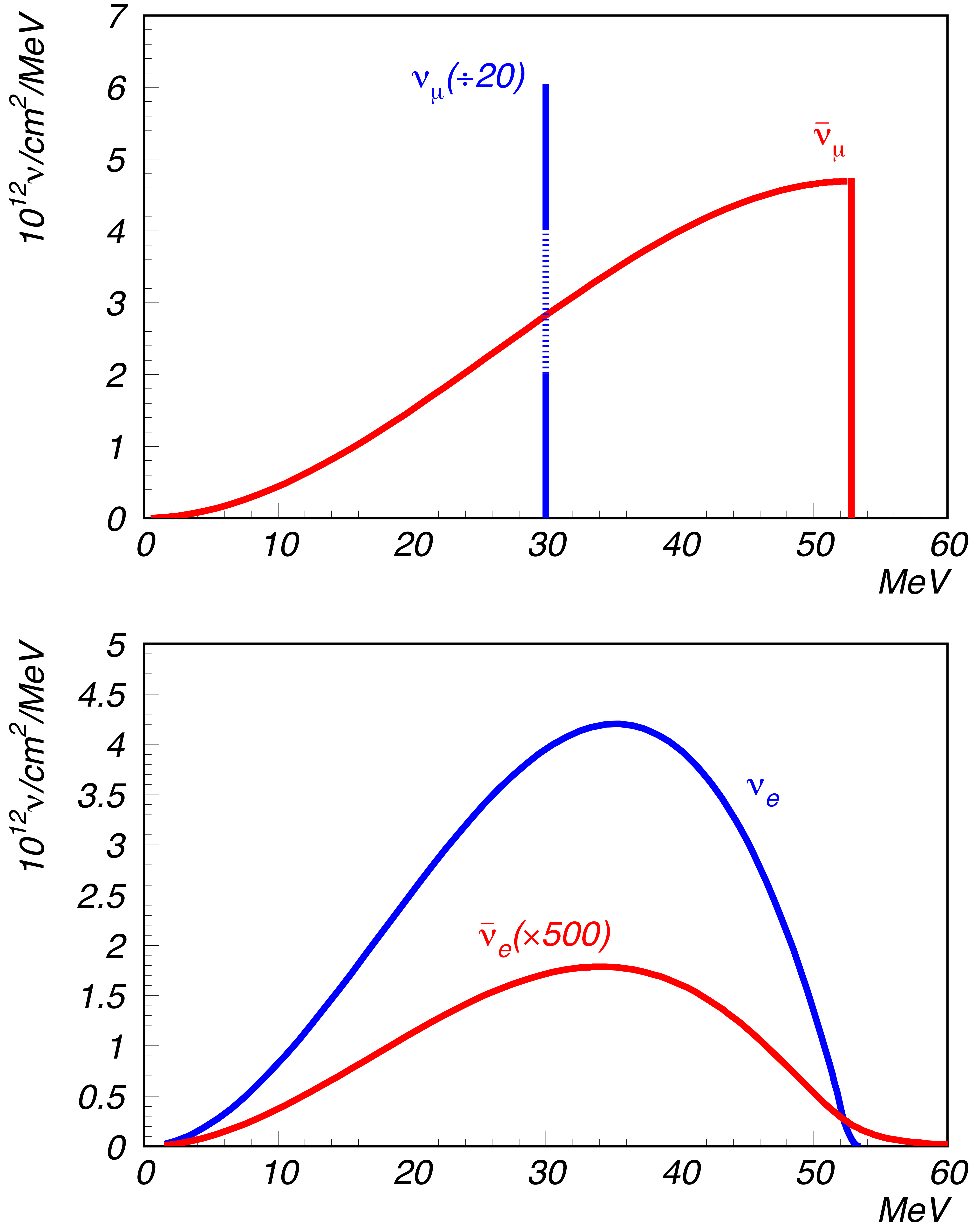
Right: off-axis beam at NOvA



- off-axis: maximize flux of neutrinos at the oscillation maximum for a particular baseline (and Δm^2)
  - e.g. for T2K, at 295 km ($\Delta m^2 = 2.5 \times 10^{-3}$ eV), E_ν ~600 MeV.
- Reduce backgrounds from "feed down" of high energy neutrinos

STOPPED PION BEAM

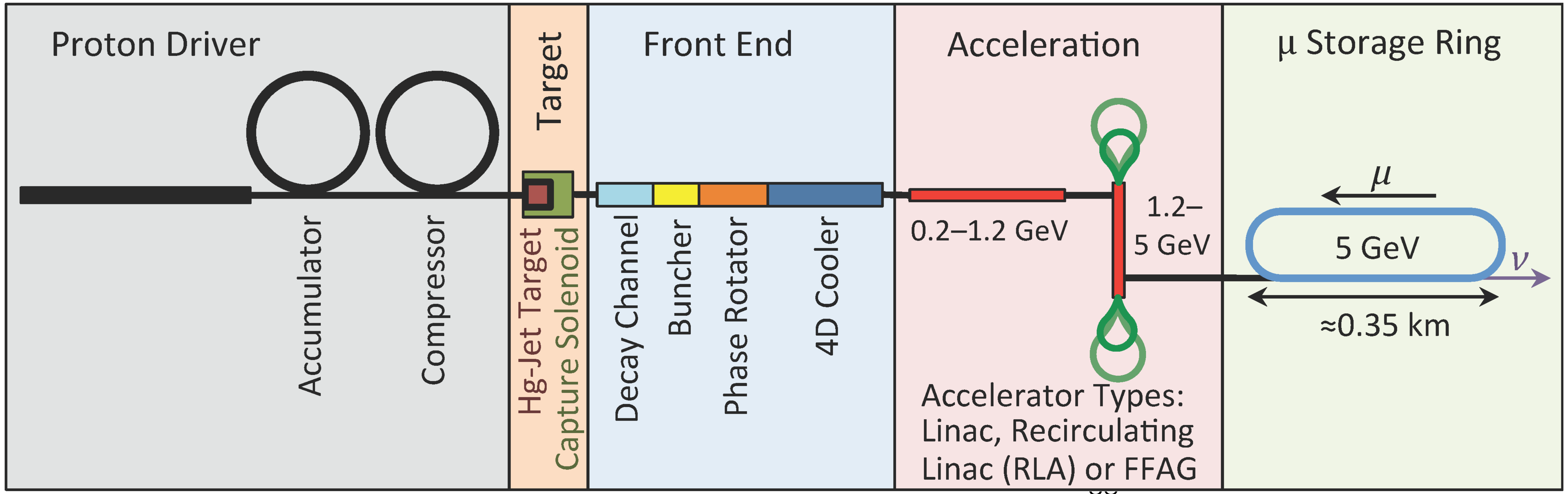
- Instead of allowing pions "fly" into a decay region, they can be stopped in a thick target
- Positive pions can then decay at rest
  - monoenergetic ν_μ
  - emitted μ^+ also stops and decays to $e^+ + \nu_e + \bar{\nu}_\mu$
  - very well understood spectrum
- Stopped negative pions are captured with high efficiency by the target and don't decay
  - some may decay in flight
  - depending on target, for μ^- that do get produced, there is a large chance that these will capture as well

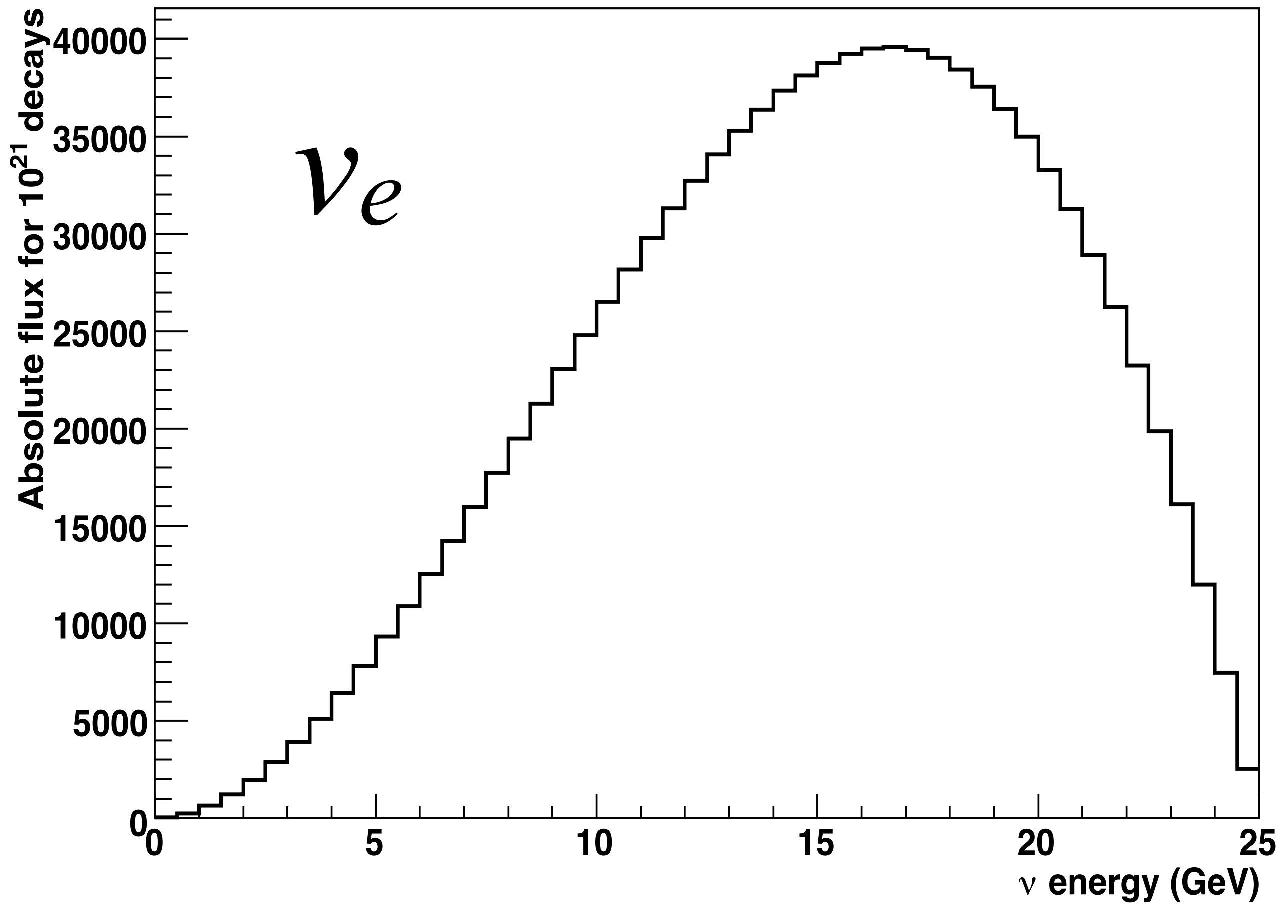


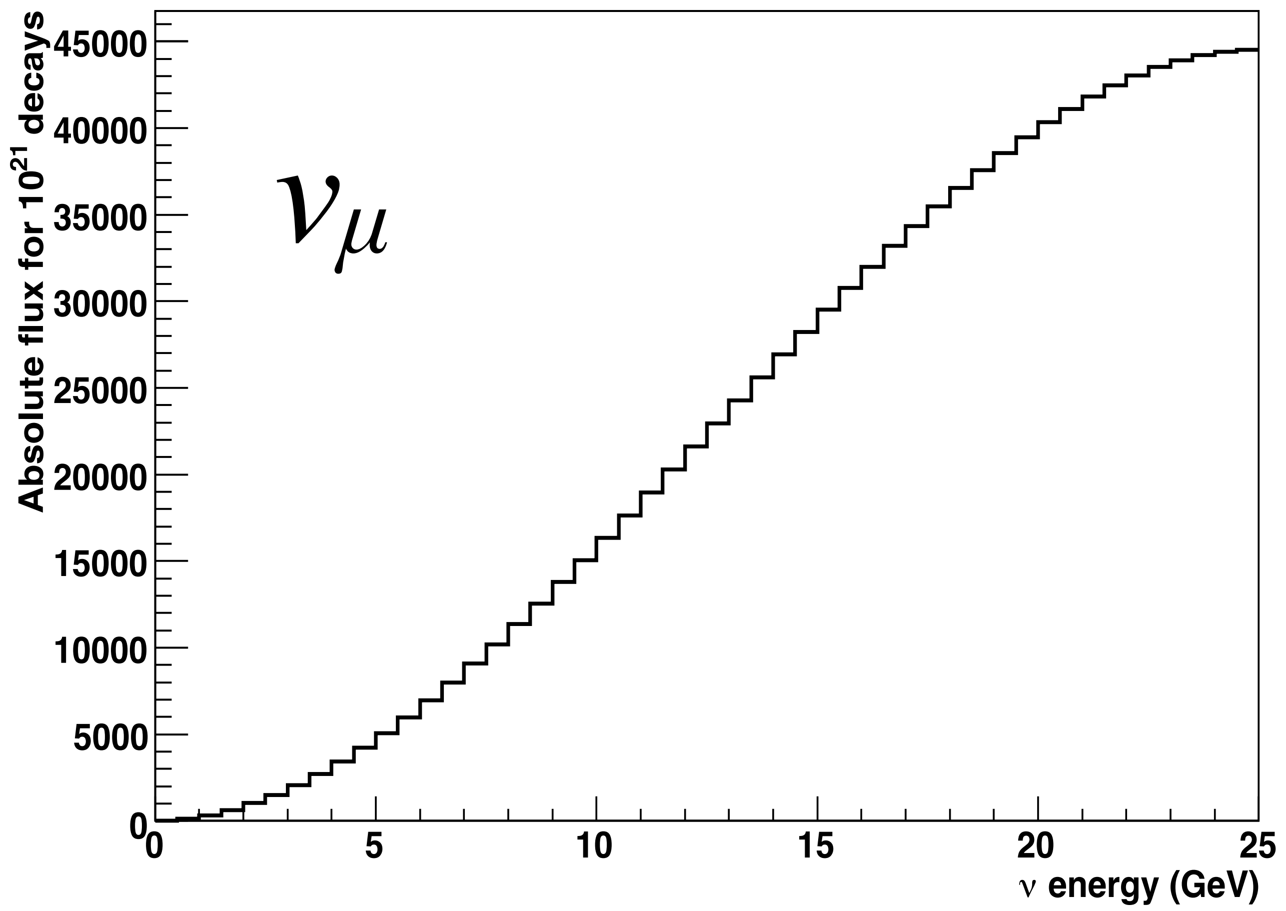
Right: Spectra from the LSND experiment at Los Alamos

STORED MUON RING (NEUTRINO FACTORY)

- "Conventional" neutrino beams produce mainly ν_μ
- If we could use muons instead, we could get ν_μ and ν_e
- "Neutrino Factory"
  - capture muons, accelerate them, and store them in a storage ring
  - muons decay in "straight" sections to produce a beam of $\bar{\nu}_\mu$ and ν_e (for μ^+)
  - allows us to study more neutrino oscillation channels
    - storing μ^- vs. μ^+ allows us to study CP conjugate channels
- Ambitions that this could be a set towards a muon collider . . . .



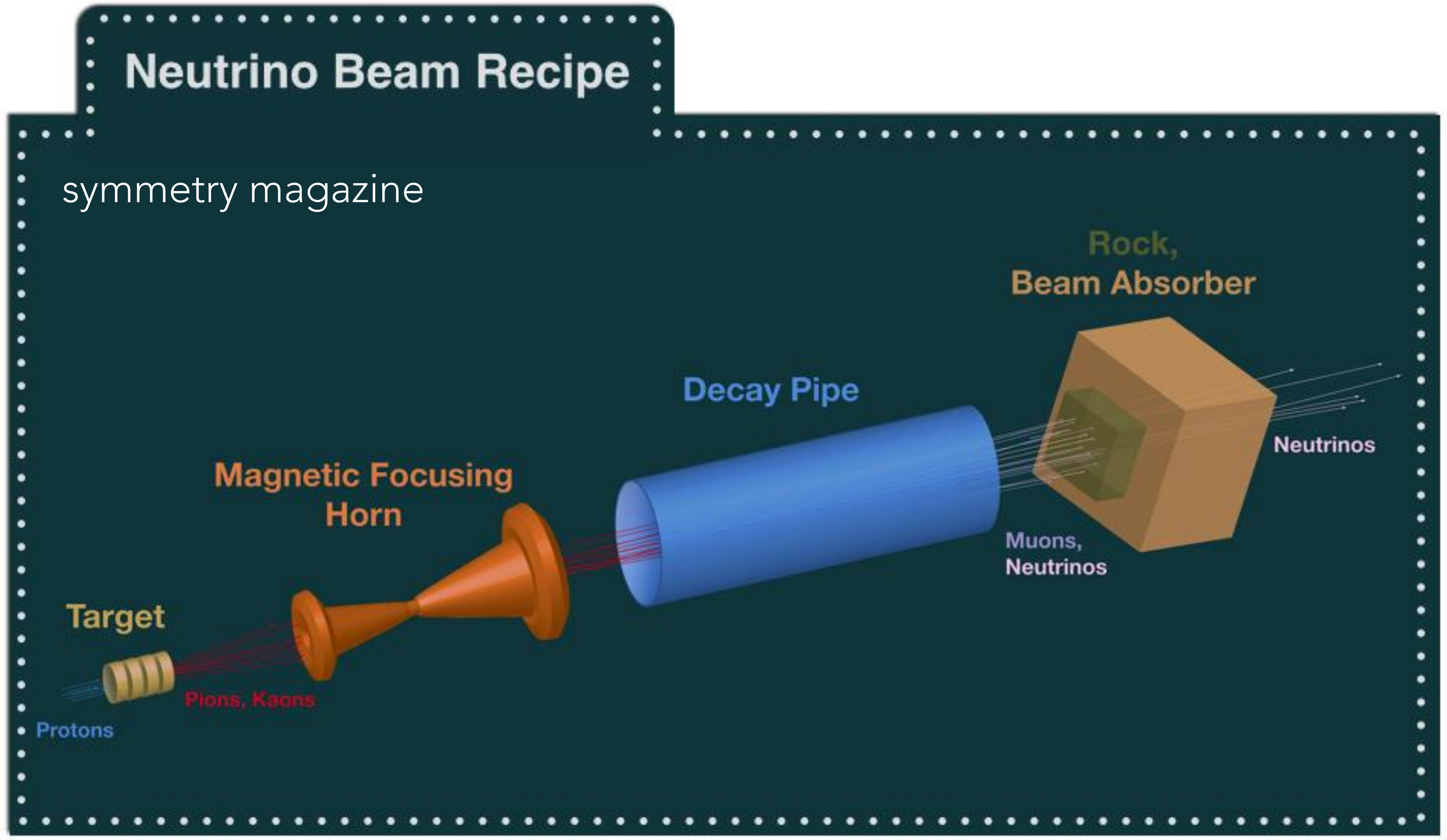




Flux produced by 25 GeV stored muon

CONCLUSIONS

- We covered basics of "conventional neutrino beam"
  - neutrino beams made from pions produced by protons interacting on a target
  - electromagnetic focussing allows muon neutrino or muon antineutrino beams to be made
- Each step of this "recipe" is an enormous technical challenge
  - enormous radiation, heat, currents, shock, etc.
  - magnified as we go to even higher intensities: 1 MW and beyond . ..
- A few variations on the theme
  - off-axis beams
  - pion-decay-at-rest
  - "neutrino factories"



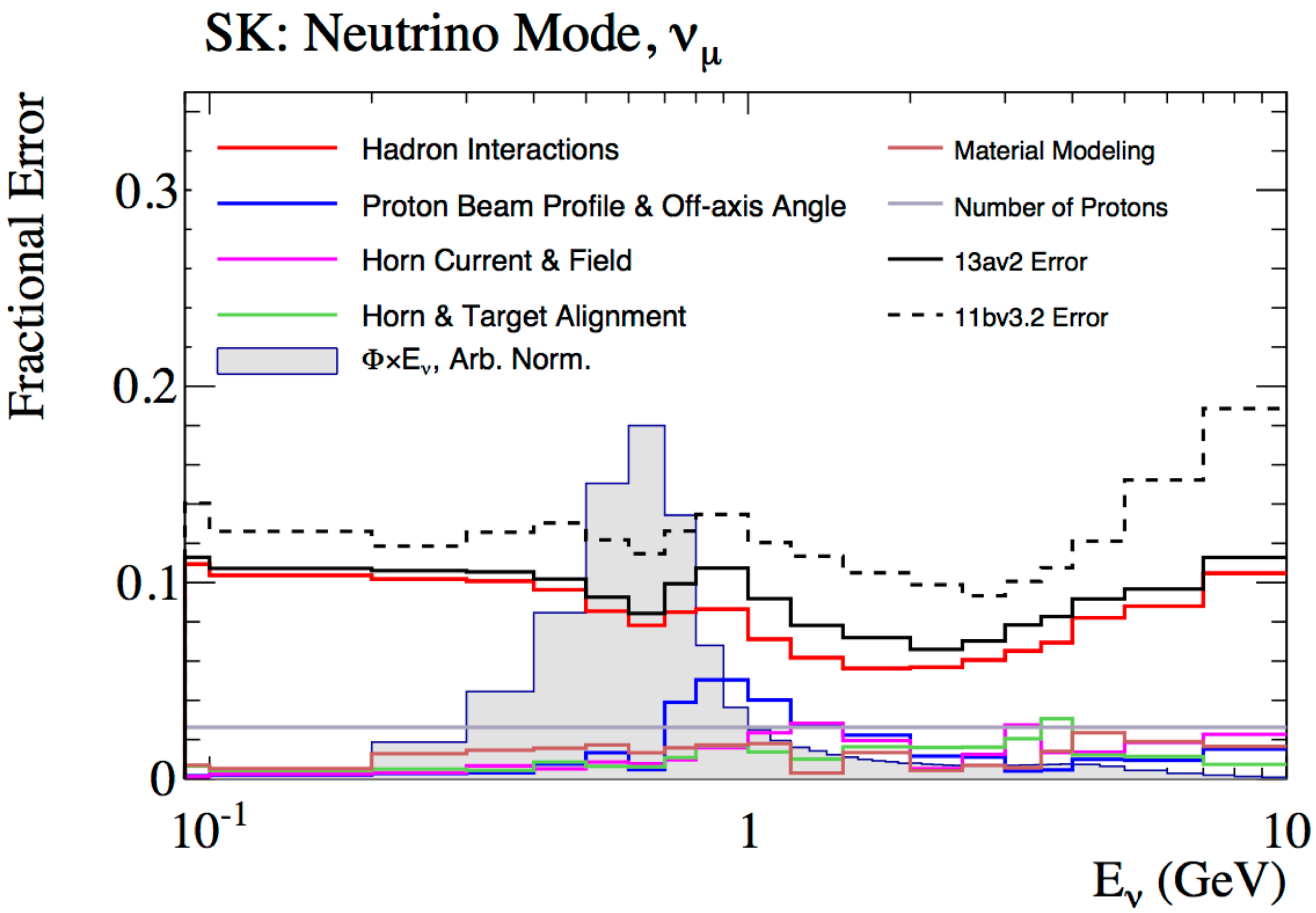
EPILOGUE
NEAR DETECTORS

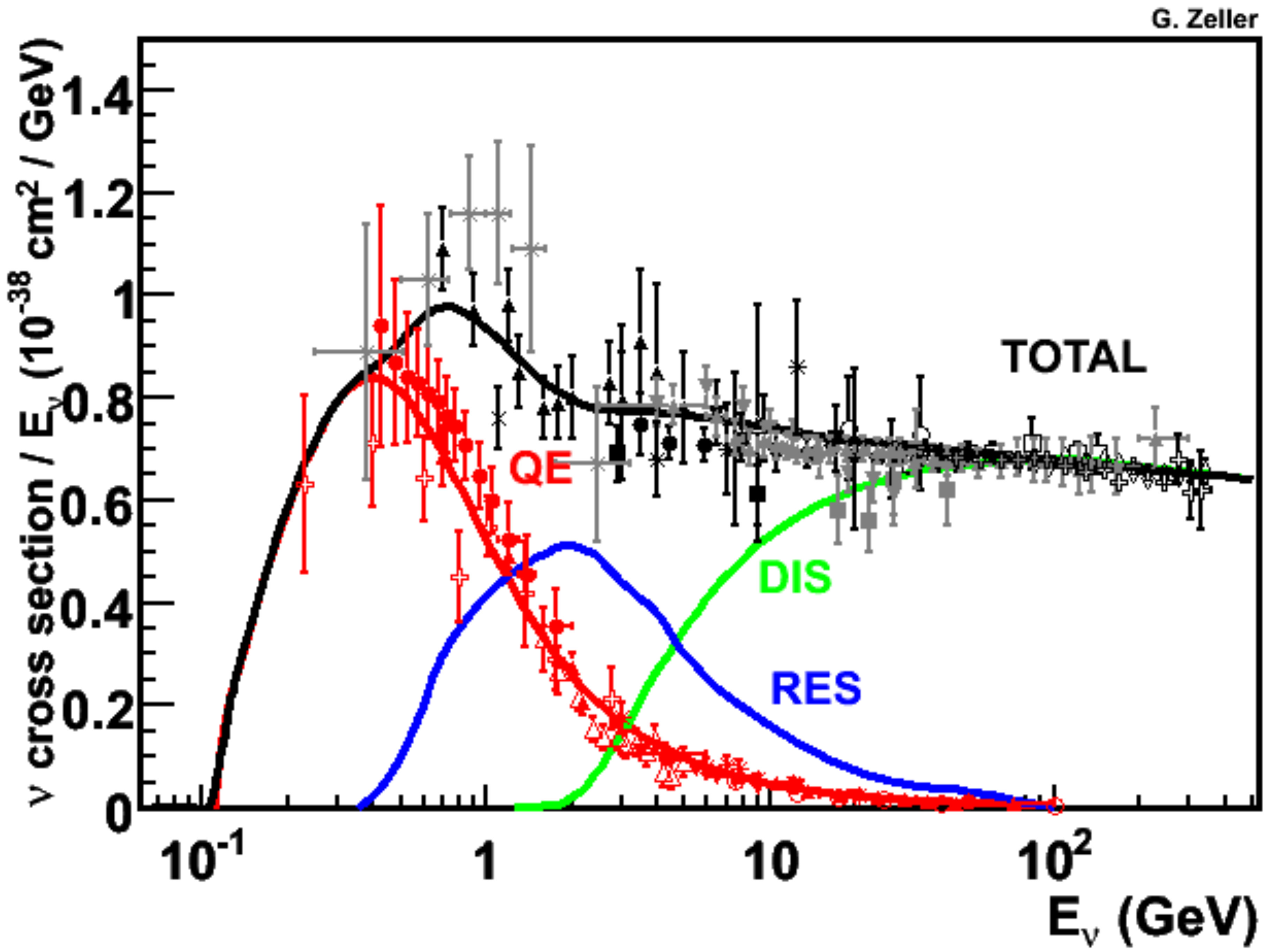
NEUTRINO OSCILLATON MEAUREMENT

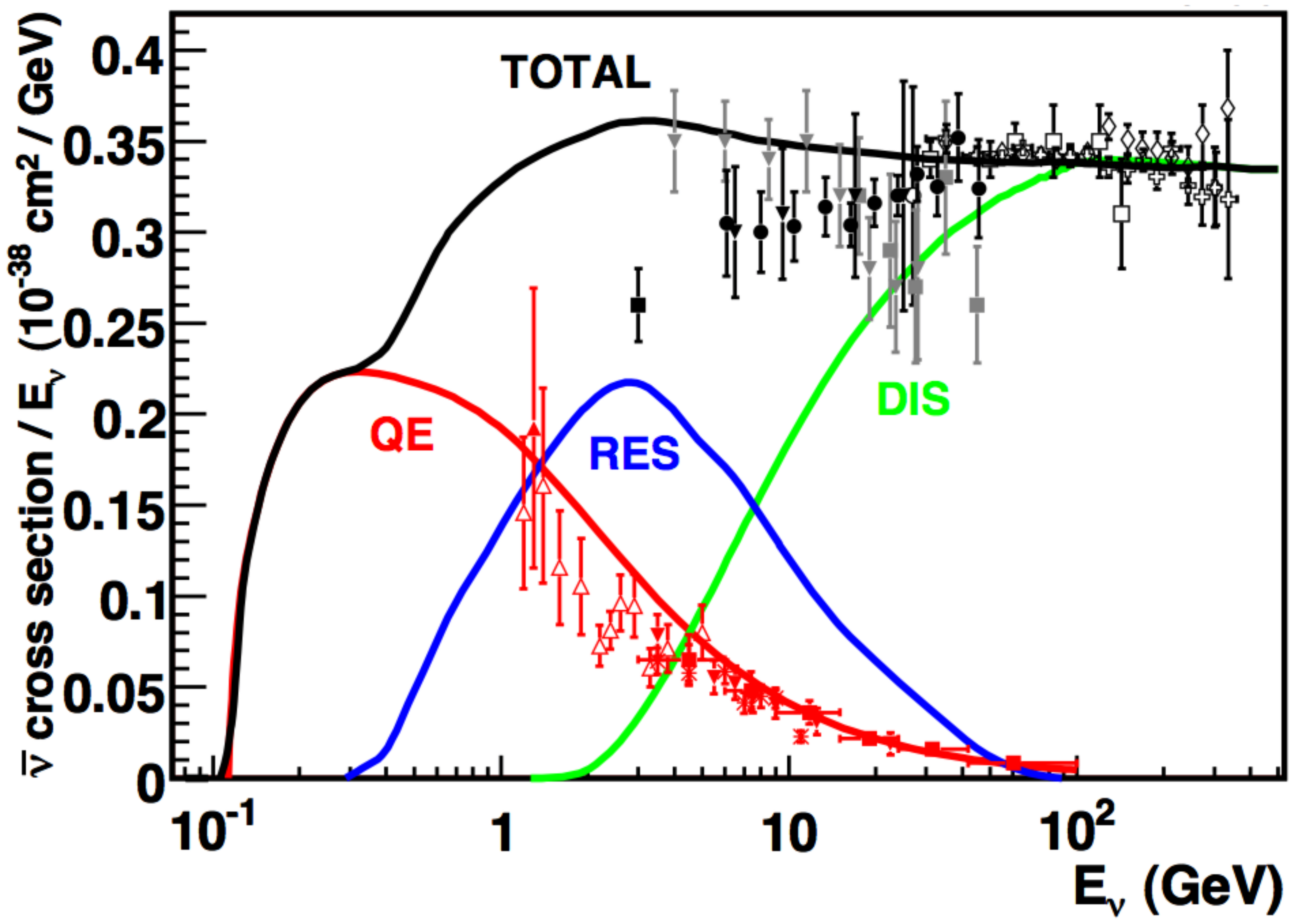
$$N(\nu_\alpha \rightarrow \nu_\beta, L/E_\nu) = \varphi_\alpha \times \sigma \times V \times n \times \varepsilon \times P(\nu_\alpha \rightarrow \nu_\beta, L/E_\nu)$$

- Measure how many ν_β interactions there are in the detector at distance L as a function E_ν
- If we want to measure the oscillation parameters:
  - we have to be able to compute $N(\nu_\alpha \rightarrow \nu_\beta)$ as a function of the parameters
  - compare this to the observed number na->nb candidates we have vs. energy via likelihood function to obtain estimates of the oscillation parameters
- We need precise estimates of φ, σ, V, n, ε
  - i.e. small systematic errors

SYSTEMATIC ERRORS







- Large systematic errors in neutrino flux and neutrino cross sections.

NEAR DETECTOR

$$N(\nu_\alpha \rightarrow \nu_\beta, L/E_\nu) = \boxed{\varphi_\alpha \times \sigma \times V \times n \times \varepsilon}$$

$$\times P(\nu_\alpha \rightarrow \nu_\beta, L/E_\nu)$$

$$\downarrow$$

$$N(\nu_\alpha, L=0) = \boxed{\varphi_\alpha \times \sigma \times V \times n \times \varepsilon} (\times \delta_{\alpha\beta})$$

- Sufficiently close to the neutrino source, the oscillation probability is ~0
  - we can study φ, σ, V, n, ε prior to neutrino oscillations and constrain the uncertainties
  - "near detector"
- In practice (for an accelerator-based detector)
  - near detector measurements usually do not constrain φ, σ separately
  - ideally, V, n, ε would be the same (identical detector), but in practice, we usually need a different detector

NAIVE PICTURE

- Far

$$N(\nu_\alpha \to \nu_\beta, L/E_\nu) = \varphi_\alpha \times \sigma \times V \times n \times \varepsilon \times P(\nu_\alpha \to \nu_\beta, L/E_\nu)$$

- Near:

$$N(\nu_\alpha, L=0) = \varphi_\alpha \times \sigma \times V \times n \times \varepsilon$$

- Can't we just divide the two and obtain $P(\nu_\alpha \to \nu_\beta)$?
- That's a zeroth order way to think about it . ..
  - as you might guess, it gets much more complicated very quickly!