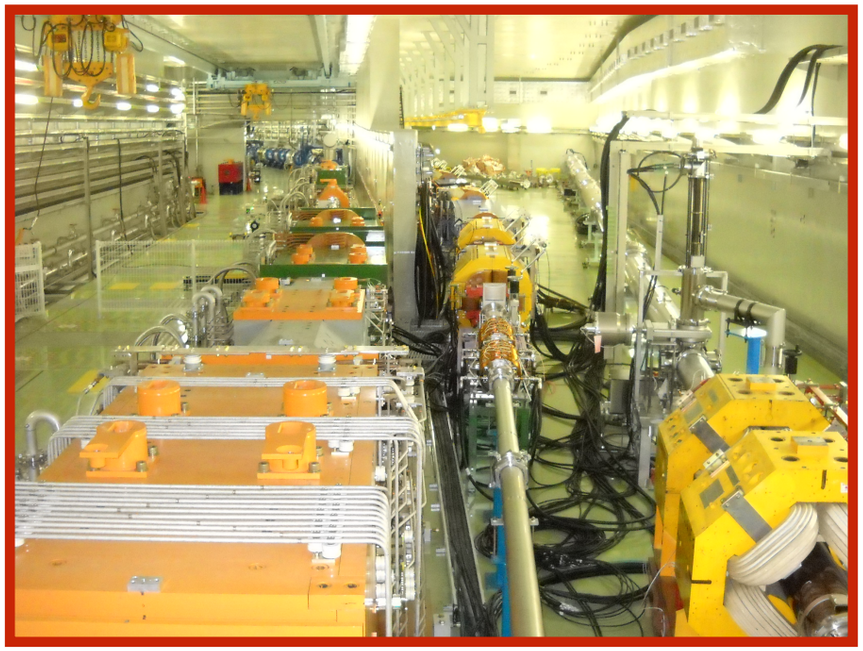
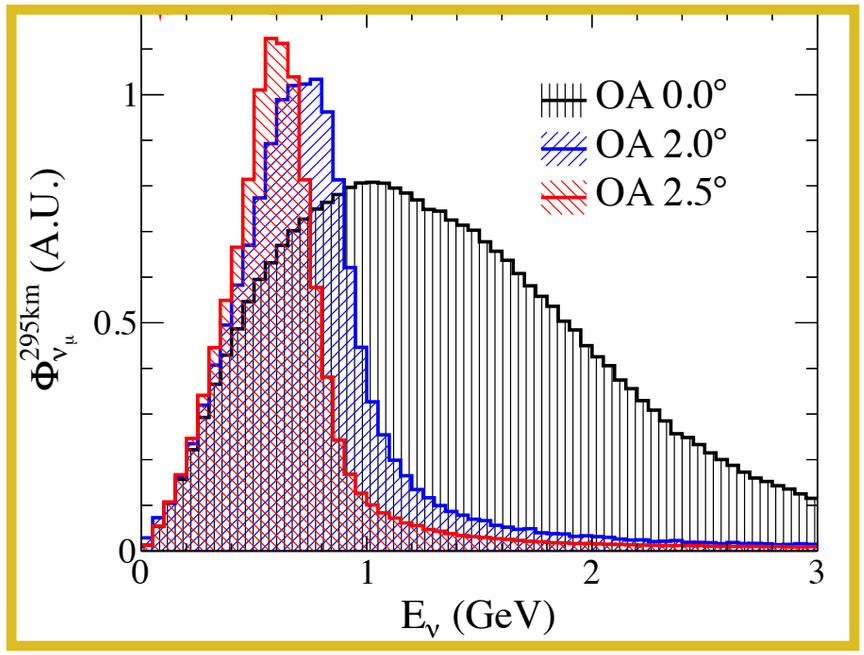
Neutrino Beams and Fluxes





Kendall Mahn
Michigan State University

International Neutrino Summer School
Fermilab
Aug 12th 2019

Office of Science
U.S. Department of Energy

Disclaimer

- I speak (too) fast in English… sorry…
- Please! ask me to repeat or slow down
- It is OK to raise your hand or interrupt with a question

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Feedback? Comments? mahn@pa.msu.edu

Outline

Key features of a neutrino beam

The parts, pieces of a successful neutrino beam

Challenges of operating neutrino beams

Future neutrino beam ideas

Outline

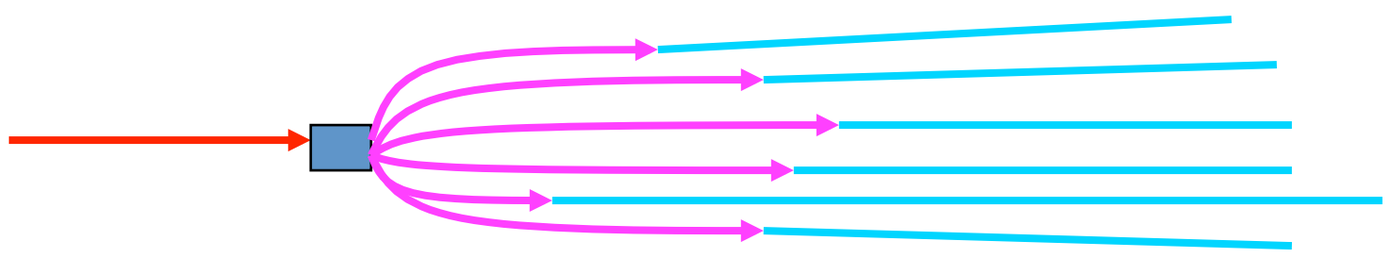
Key features of a neutrino beam

Accelerator-produced neutrino beams

Credit: 123RF.com

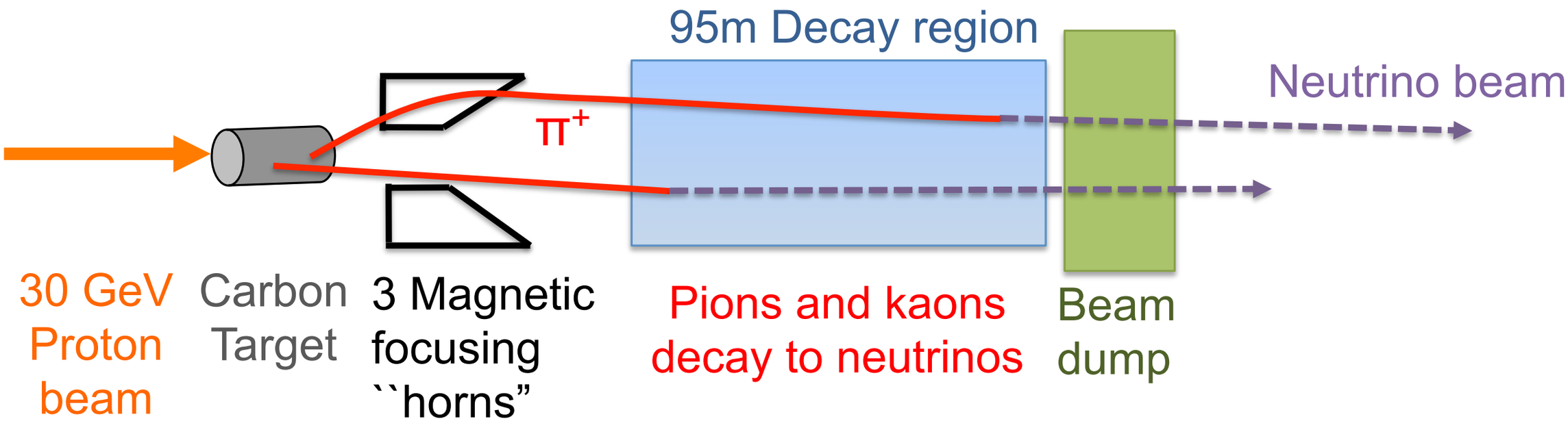
Accelerator-produced neutrino beams

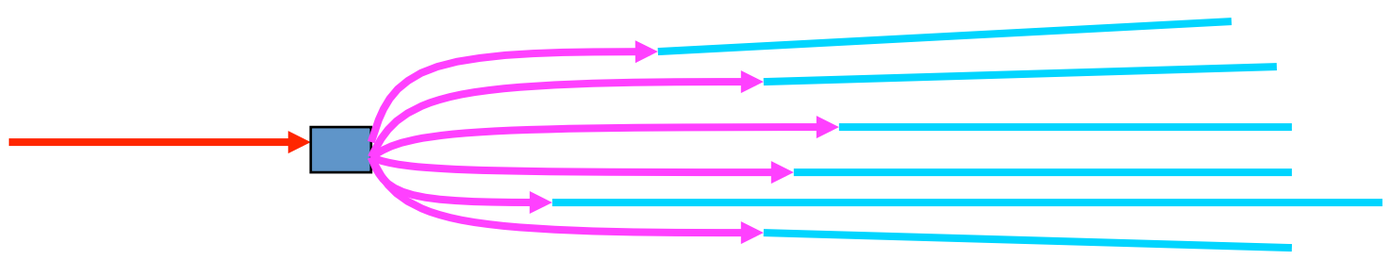
Electrical current hits a filament producing light focused into a beam



protons→carbon target→unstable particles→neutrinos

Accelerator-produced neutrino beams





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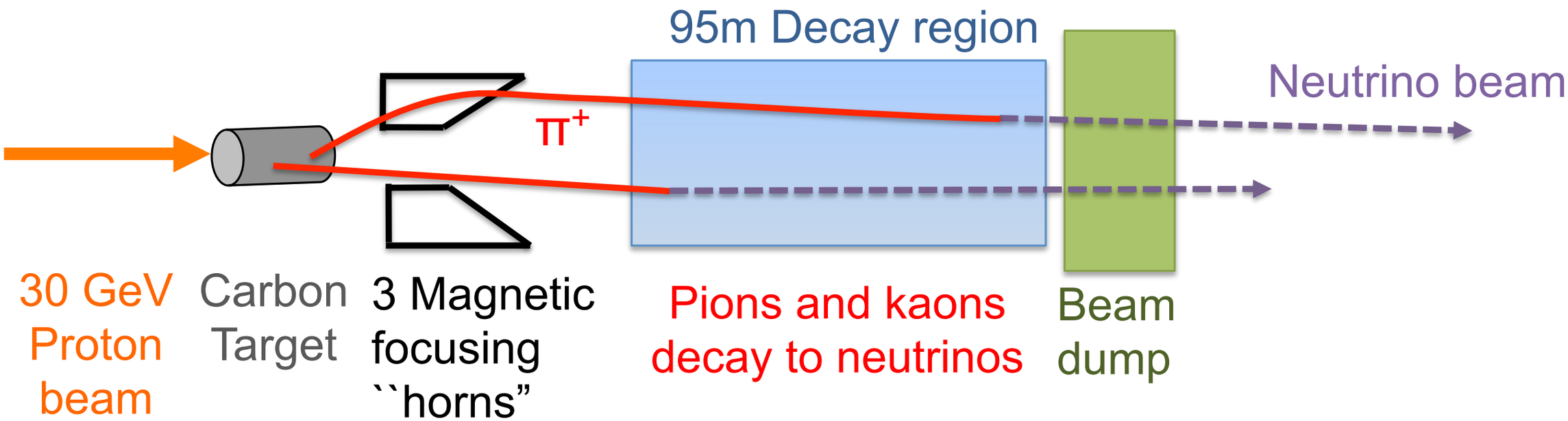
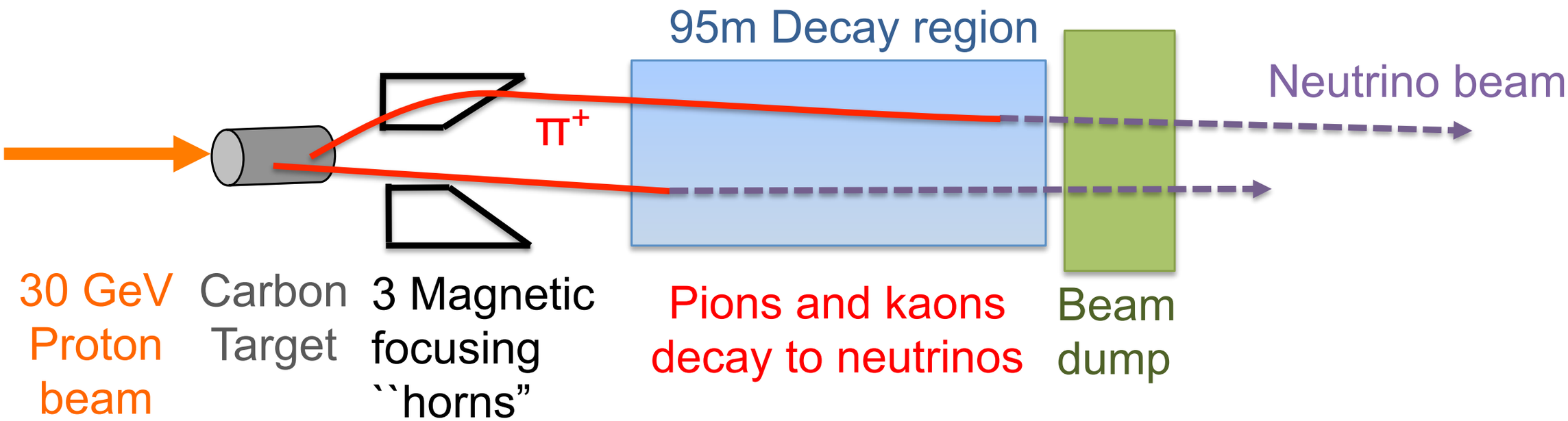


Tunable energy!

Can be neutrino or antineutrino!

99% pure muon neutrino beam!

How do we tune the energy?



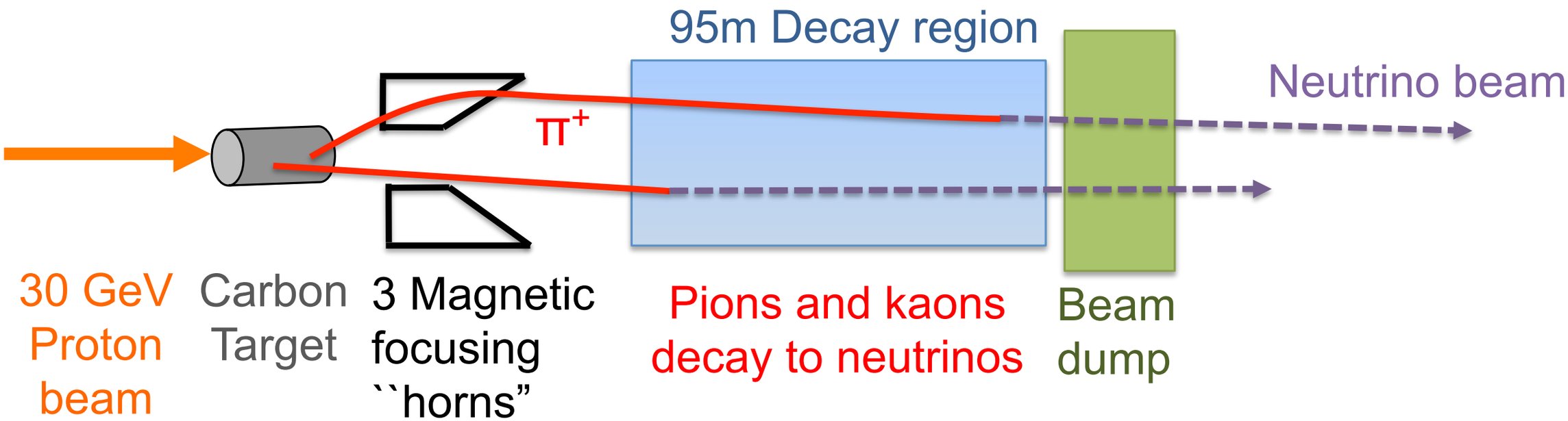
Change focusing elements

Change target position

Change proton beam energy

Will discuss these in the beam line elements section

How do we tune the energy?



Change focusing elements

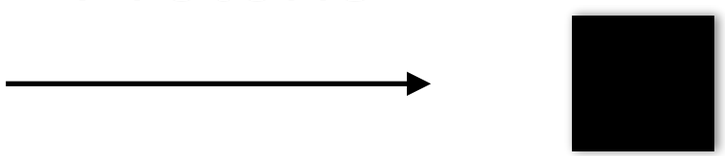
Change target position

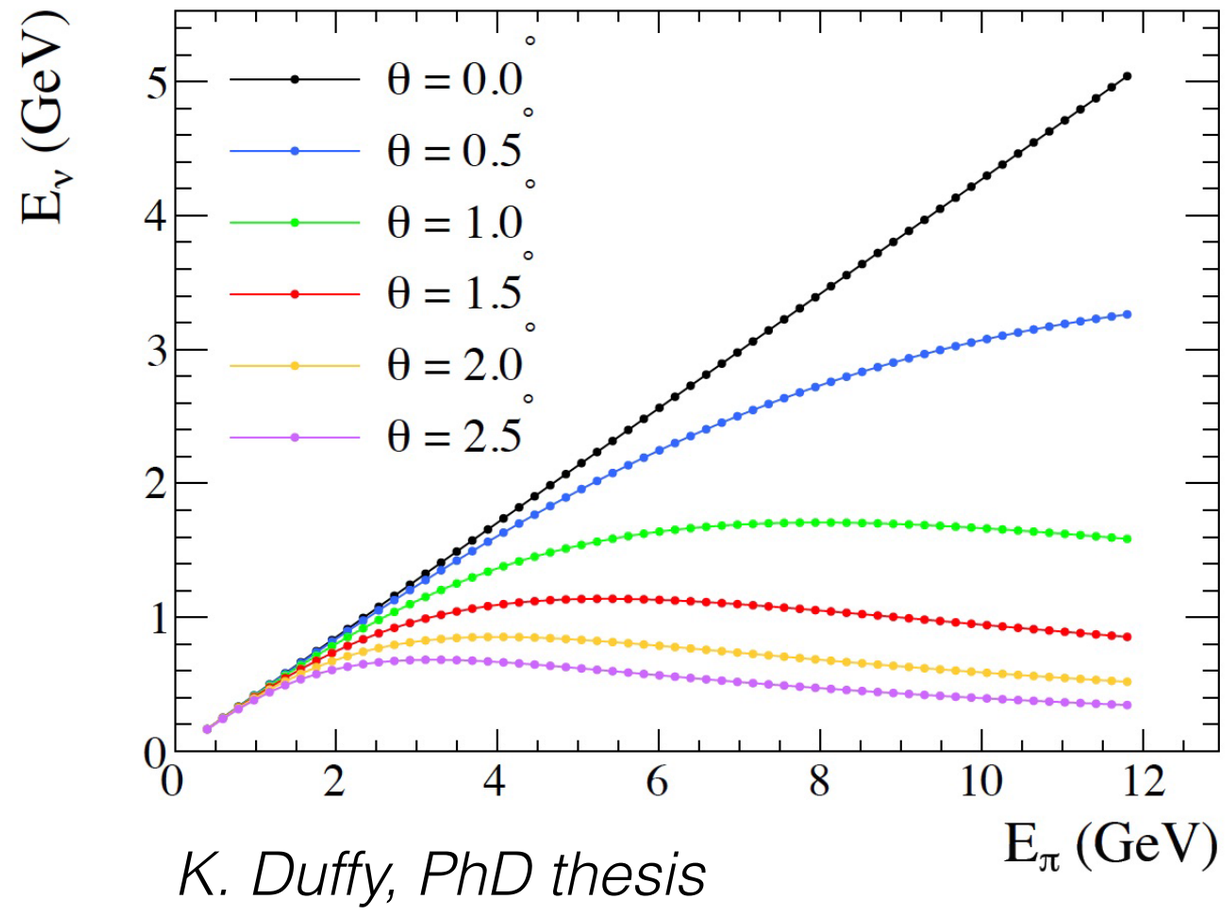
Change proton beam energy

Or just decide to sit 'off-axis'

Off-axis vs. on-axis

Protons

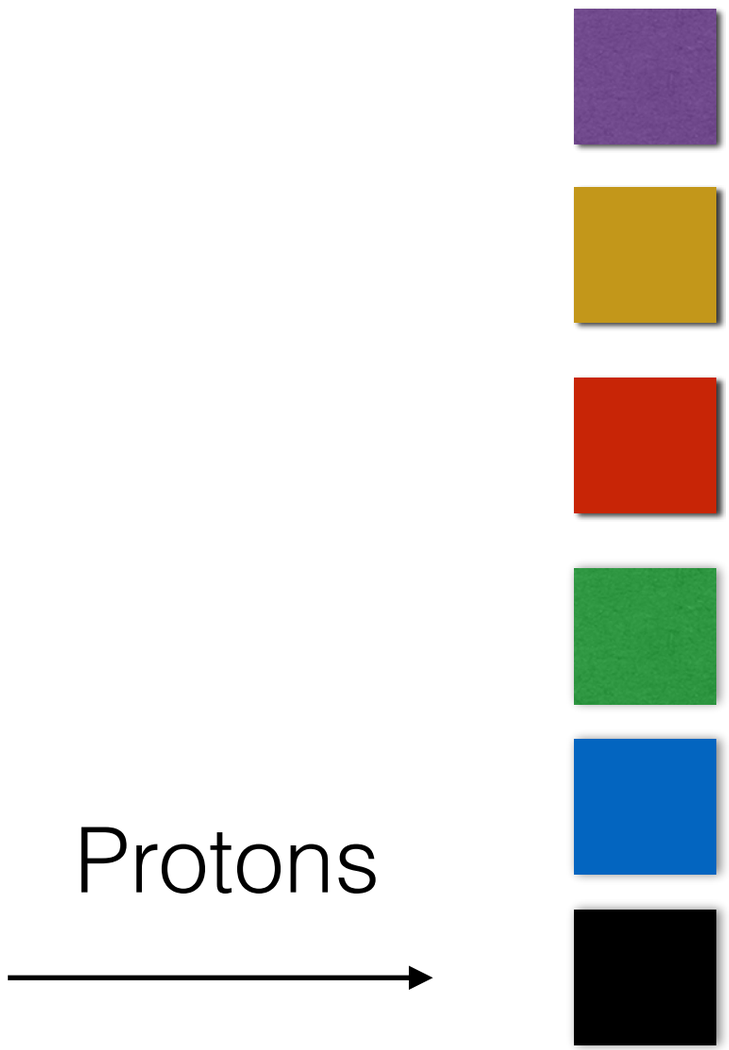


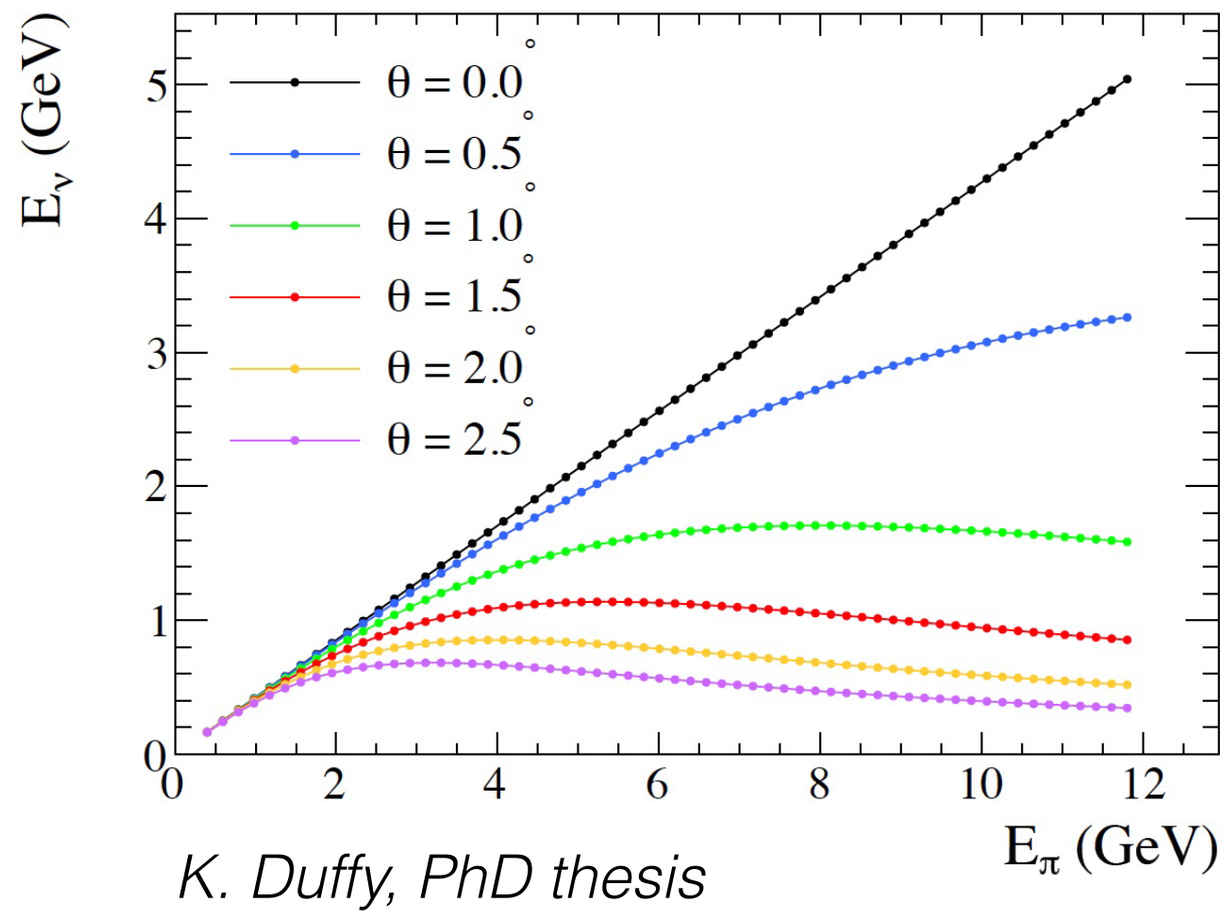


K. Duffy, PhD thesis

"On-axis" of the proton beam, the neutrino energy increases linearly with the proton-> pion energy

Off-axis vs. on-axis



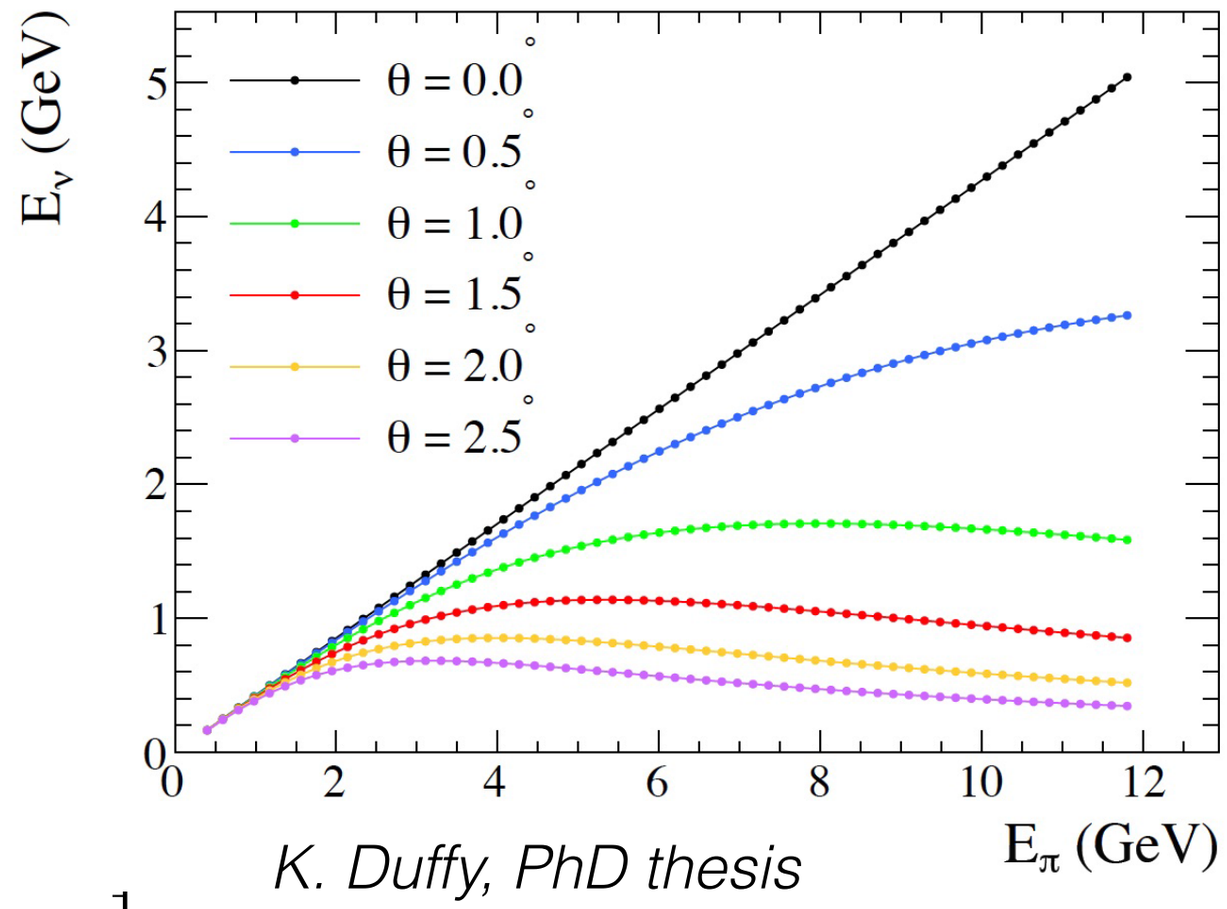


K. Duffy, PhD thesis

Neutrino energy spectrum changes in transverse direction to (proton) beam

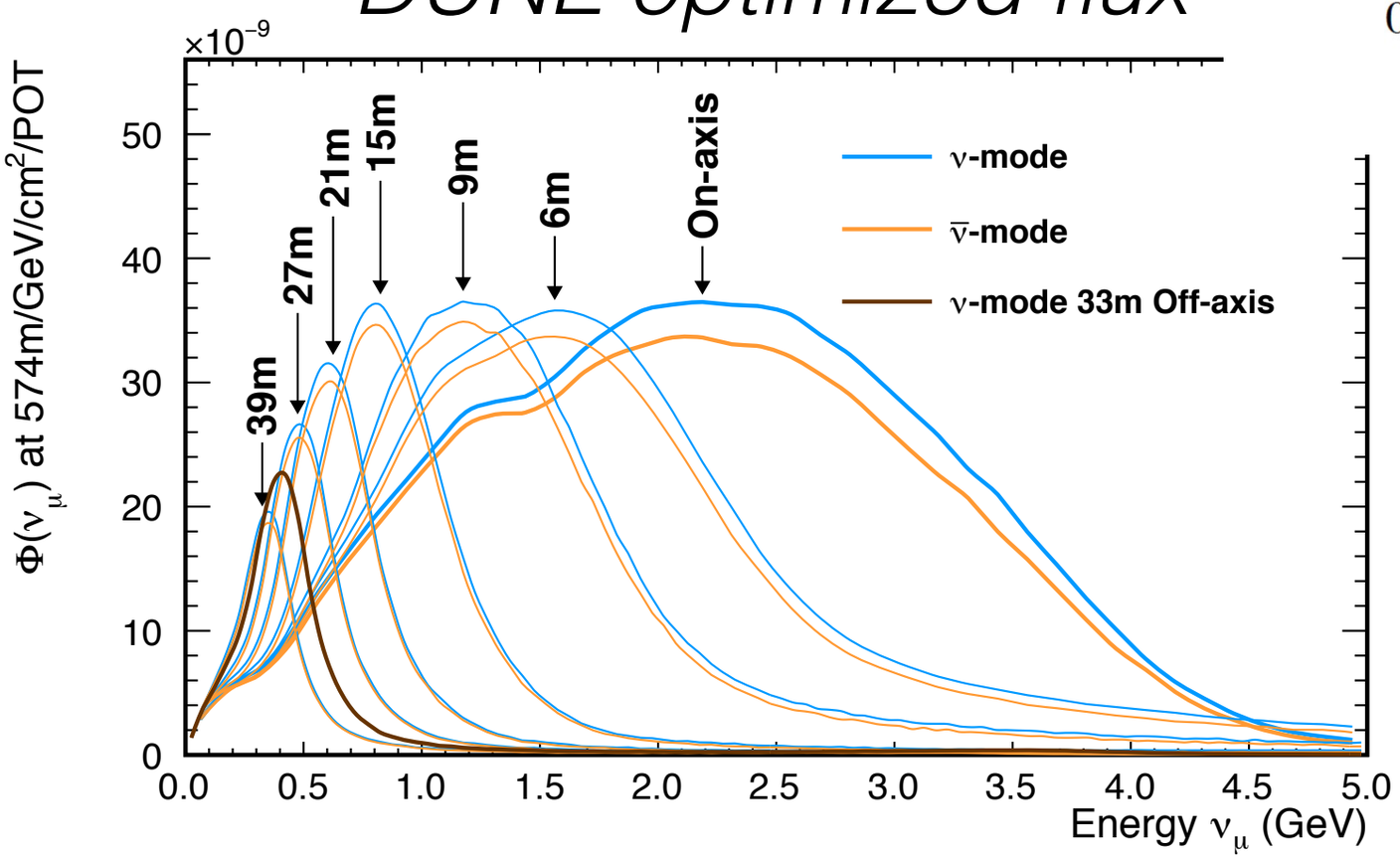
Off-axis vs. on-axis

"Off-axis", the beam becomes narrower and the peak shifts down

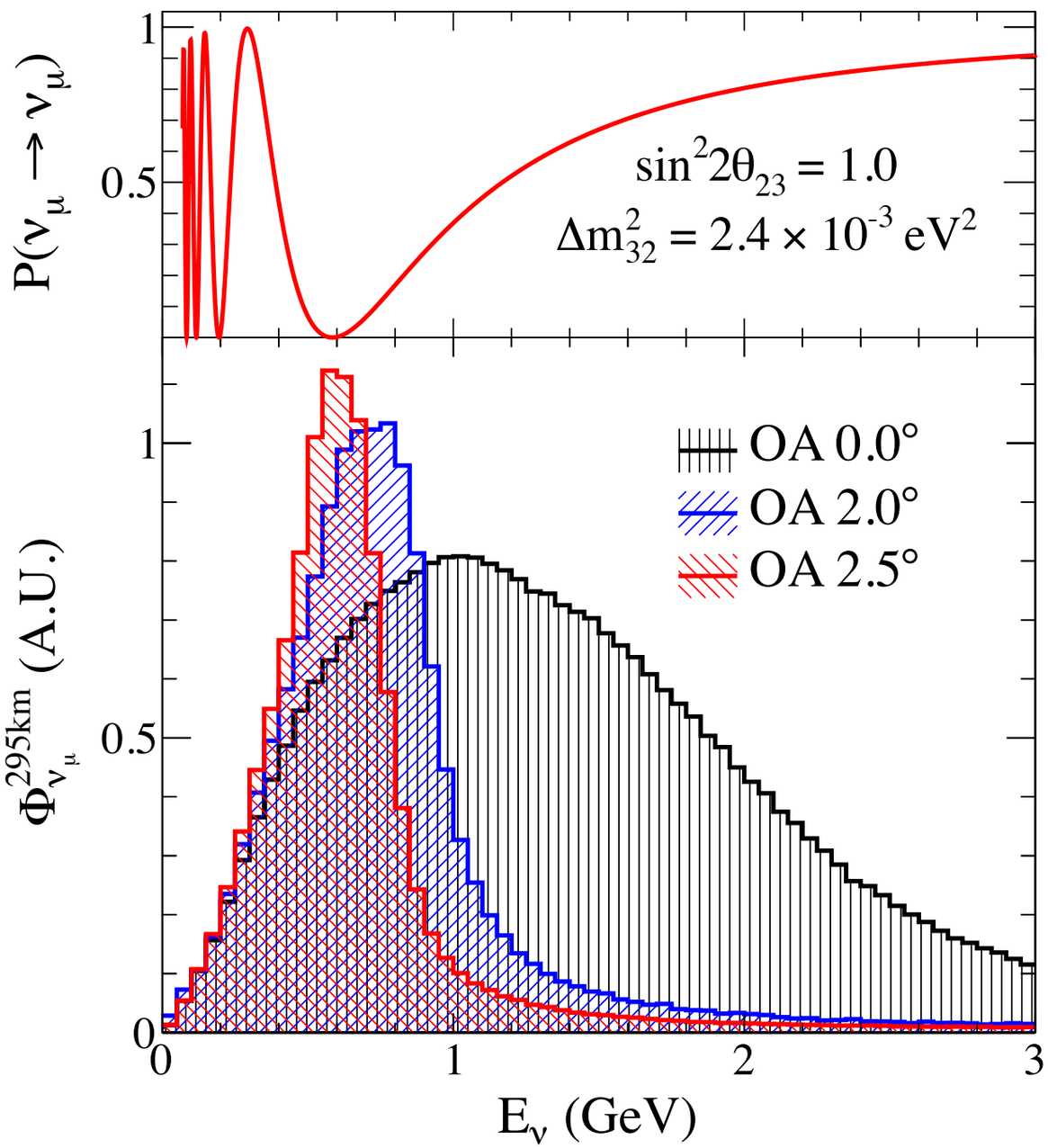


K. Duffy, PhD thesis

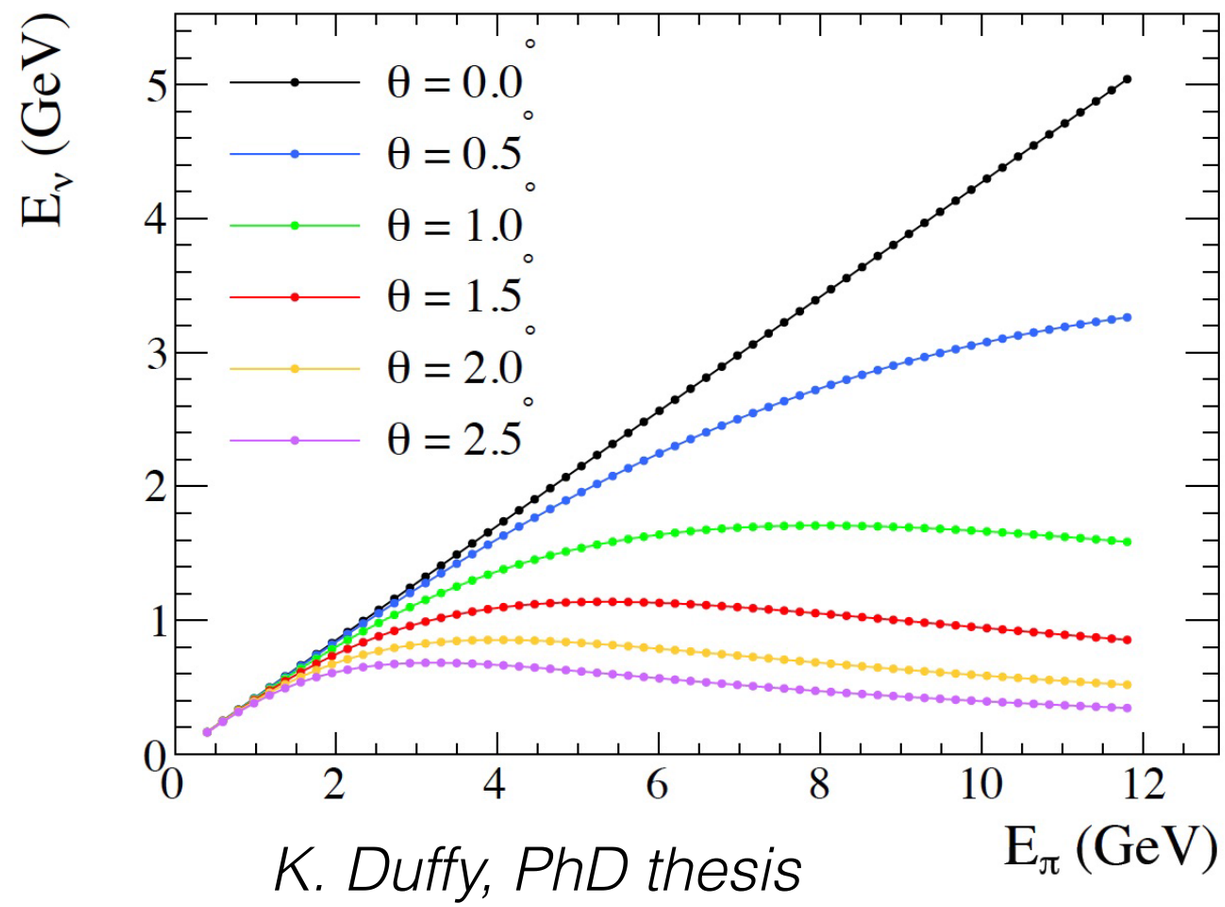
DUNE optimized flux



Off-axis vs. on-axis



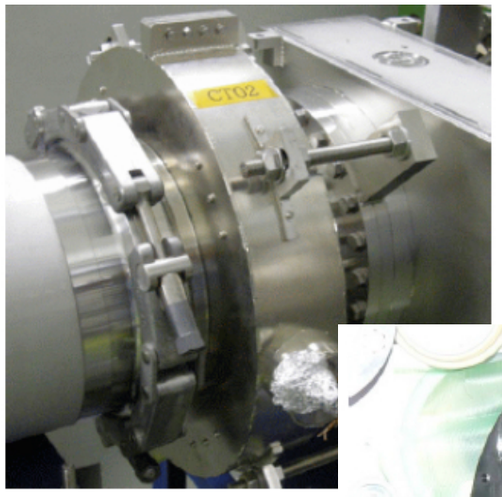
PRD 88, 032002 (2013)

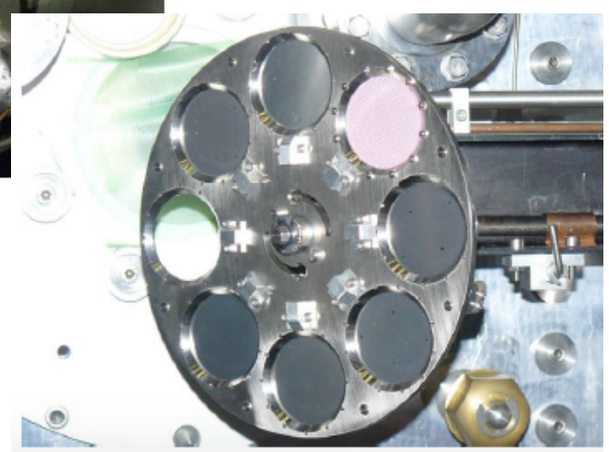


K. Duffy, PhD thesis

Technique used by NOvA and T2K experiments

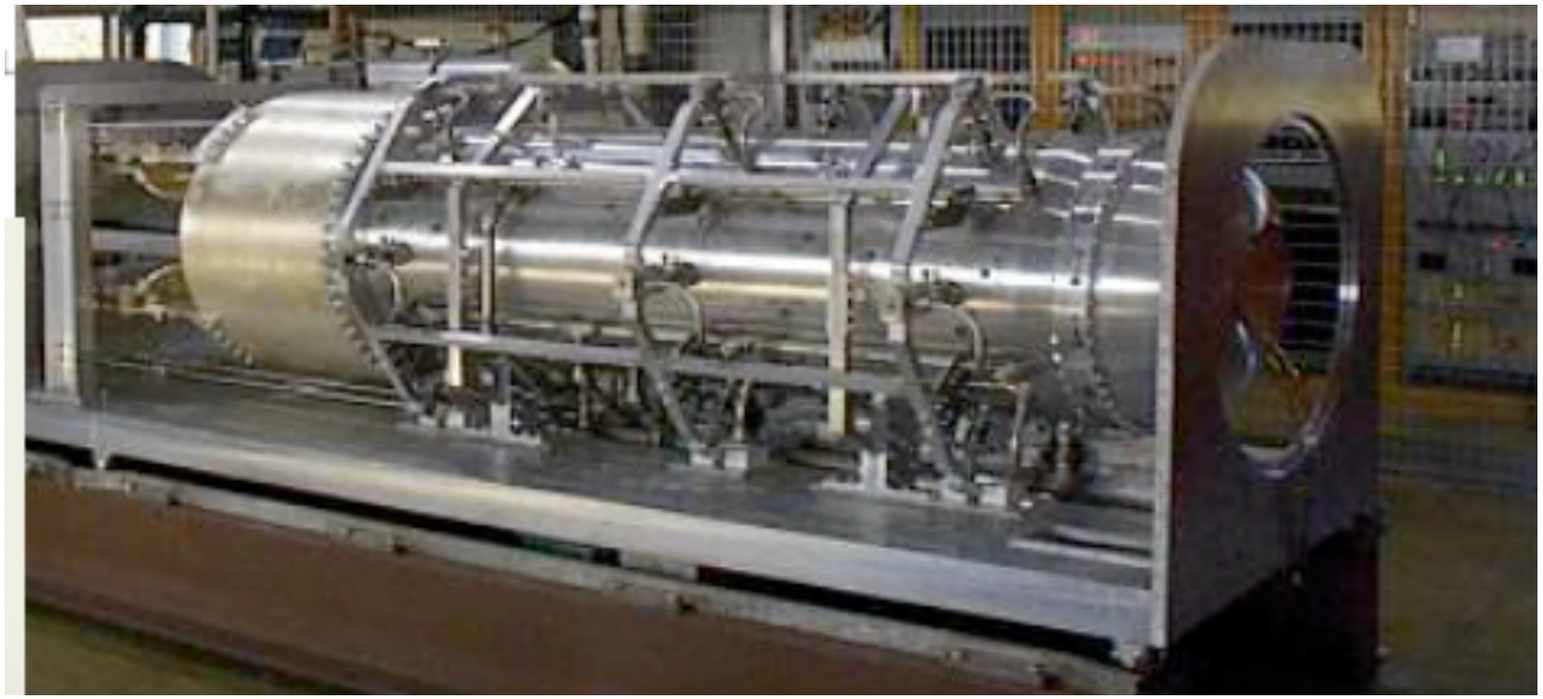
Outline



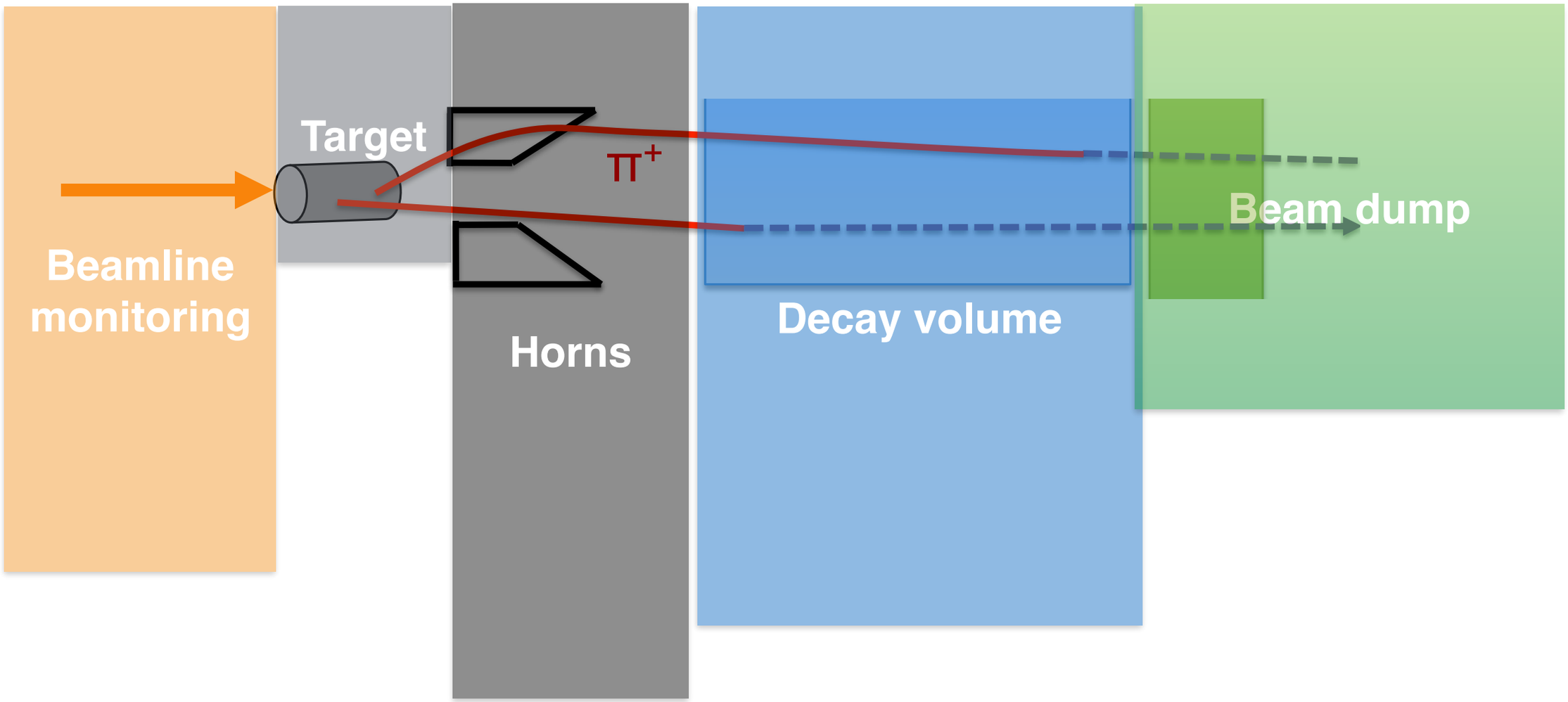


Examples from Neutrino Beams and Instrumentation workshop series (NBI)

The parts, pieces of a successful neutrino beam



All the pieces



Hadron production measurements

Muon monitors, neutrino profile detectors, and near detectors

Beamline monitoring (T2K)

Types of proton beam monitors:

- Beam intensity (number of protons on target)
- Beam position (is beam ON target? monitor activation)
- Beam profile (direction)
- Beam losses (monitor activation, necessary for high power operation)

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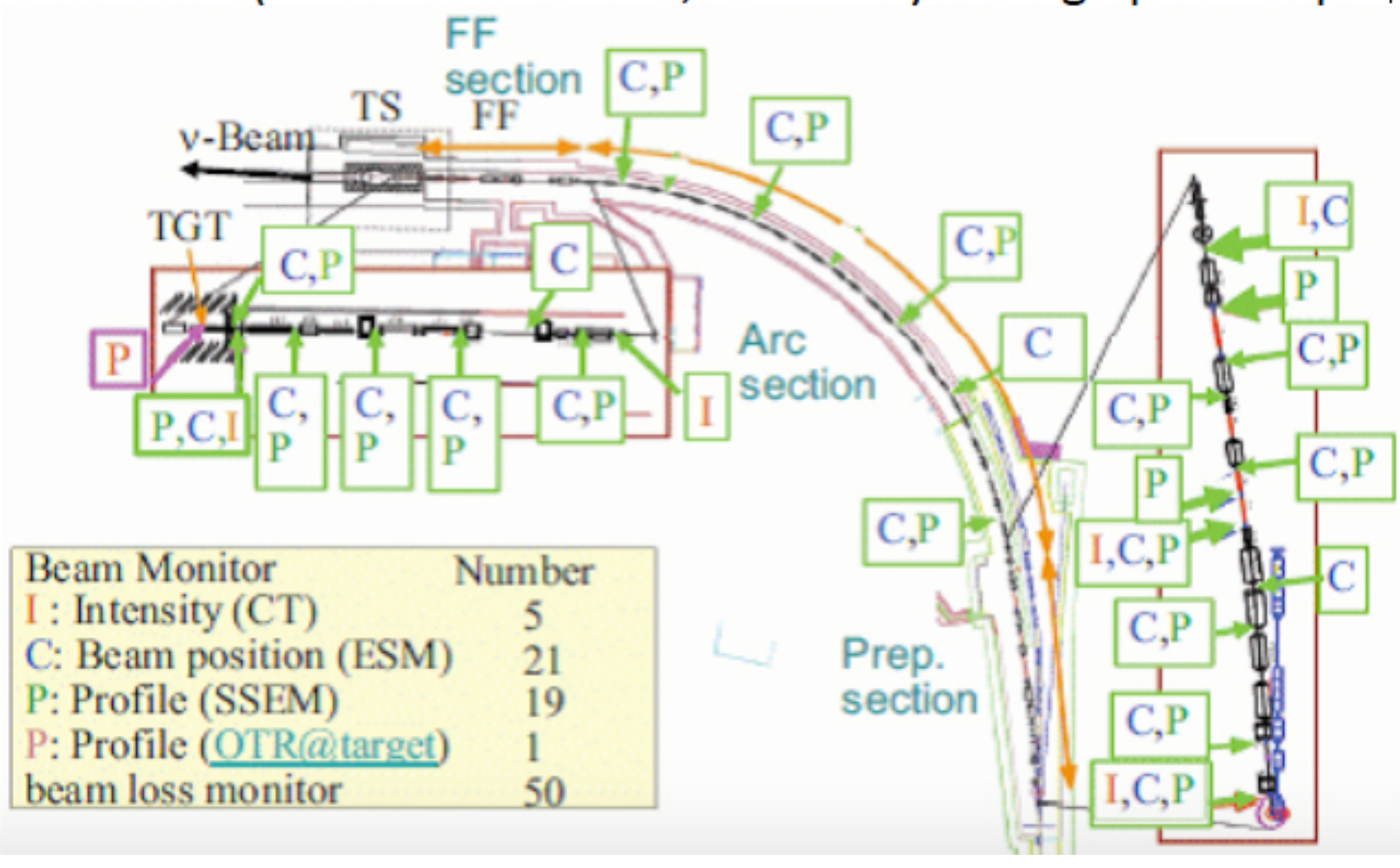
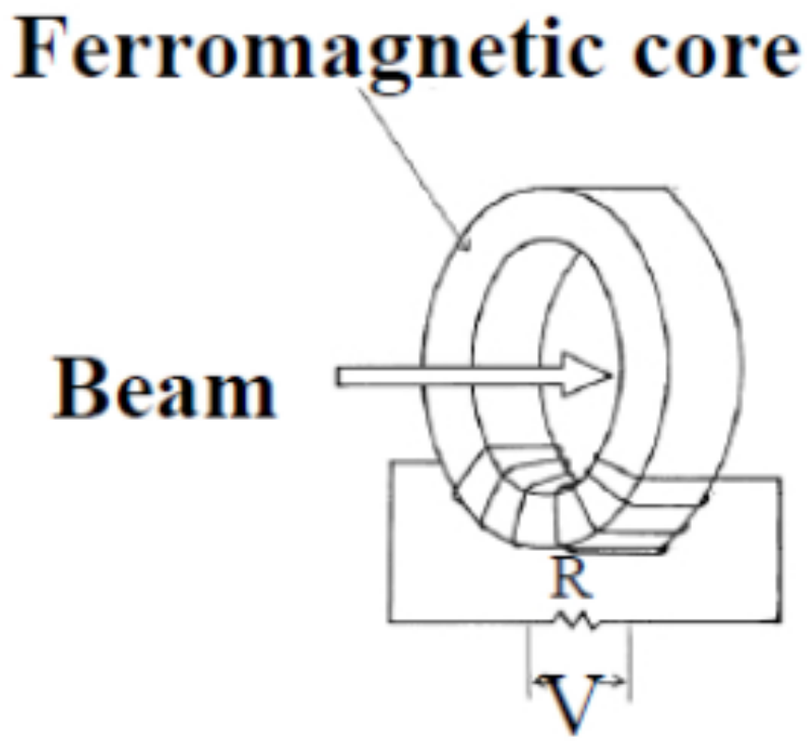


Beam Monitor	Number
I : Intensity (CT)	5
C: Beam position (ESM)	21
P: Profile (SSEM)	19
P: Profile (OTR@target)	1
beam loss monitor	50

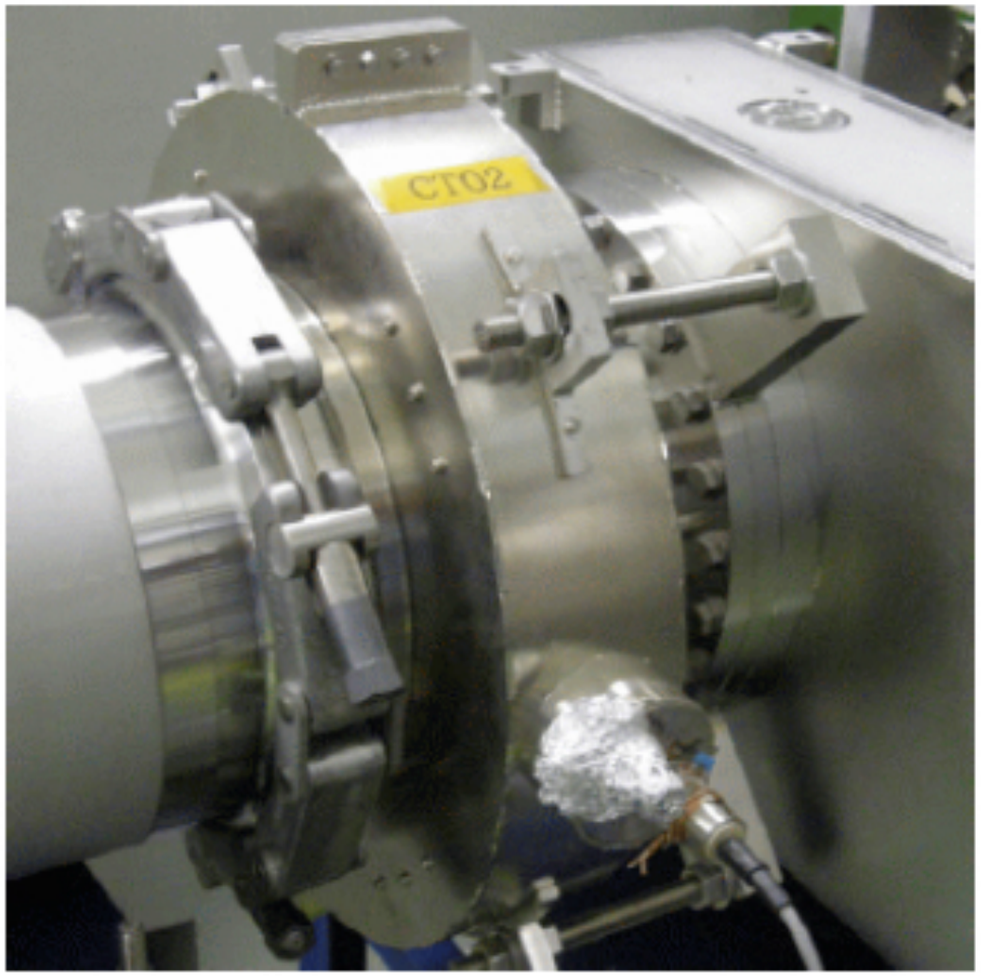
Beamline intensity monitors (T2K)

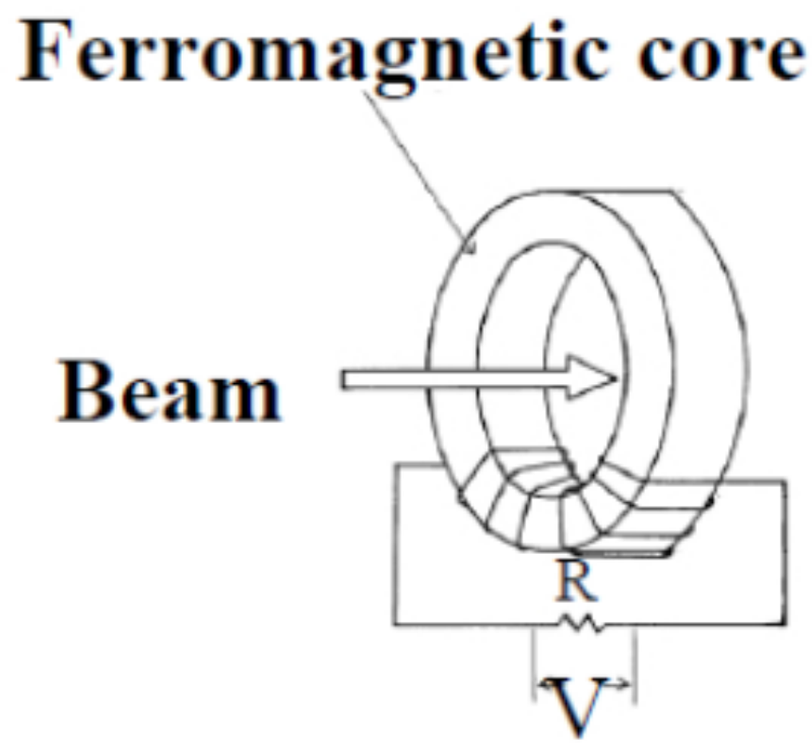


$$|V = \frac{IR}{N}$$

N is number of turns in the coil

Beamline intensity monitors (T2K)





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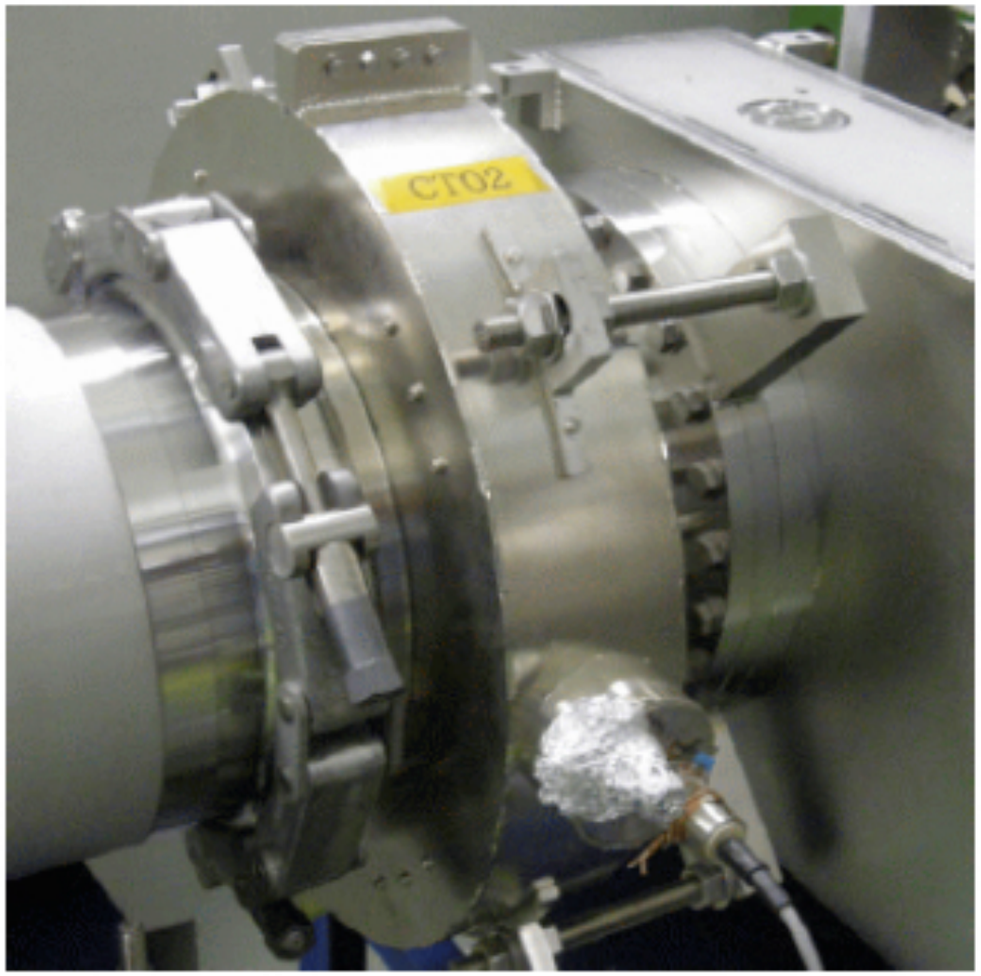
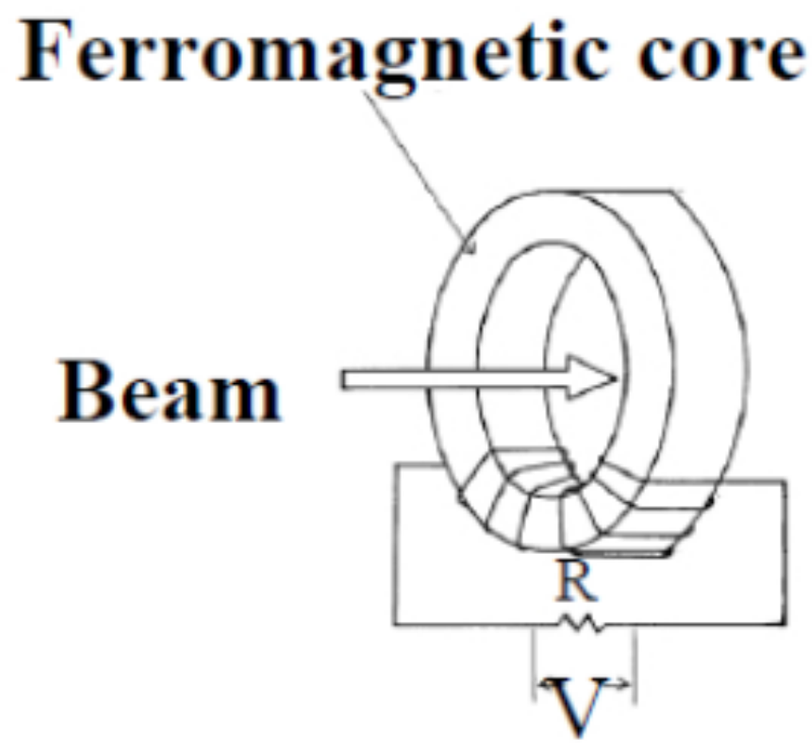
CT "Current transformer"

- Use voltage to determine current of protons
- No material in beam

Beamline intensity monitors (T2K)





$$V = \frac{IR}{N}$$

N is number of turns in the coil

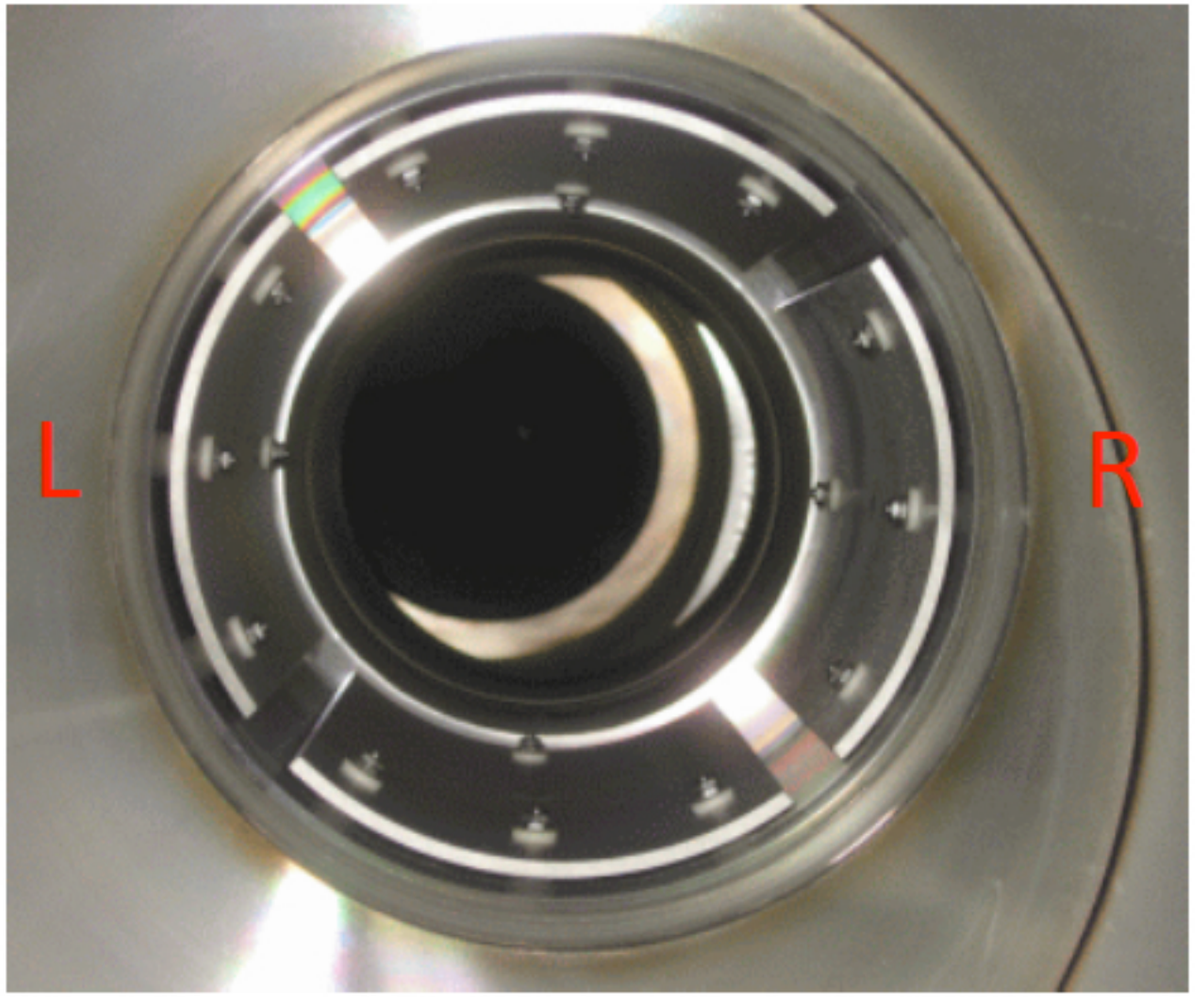
CT "Current transformer"

- Use voltage to determine current of protons
- No material in beam

"Absolute proton beam intensity with a 2% uncertainty and the relative intensity with a 0.5% fluctuation. Beam timing precision better than 10 ns."

T2K NIM, arxiv.org/1106.1238

Beamline position monitors (T2K)



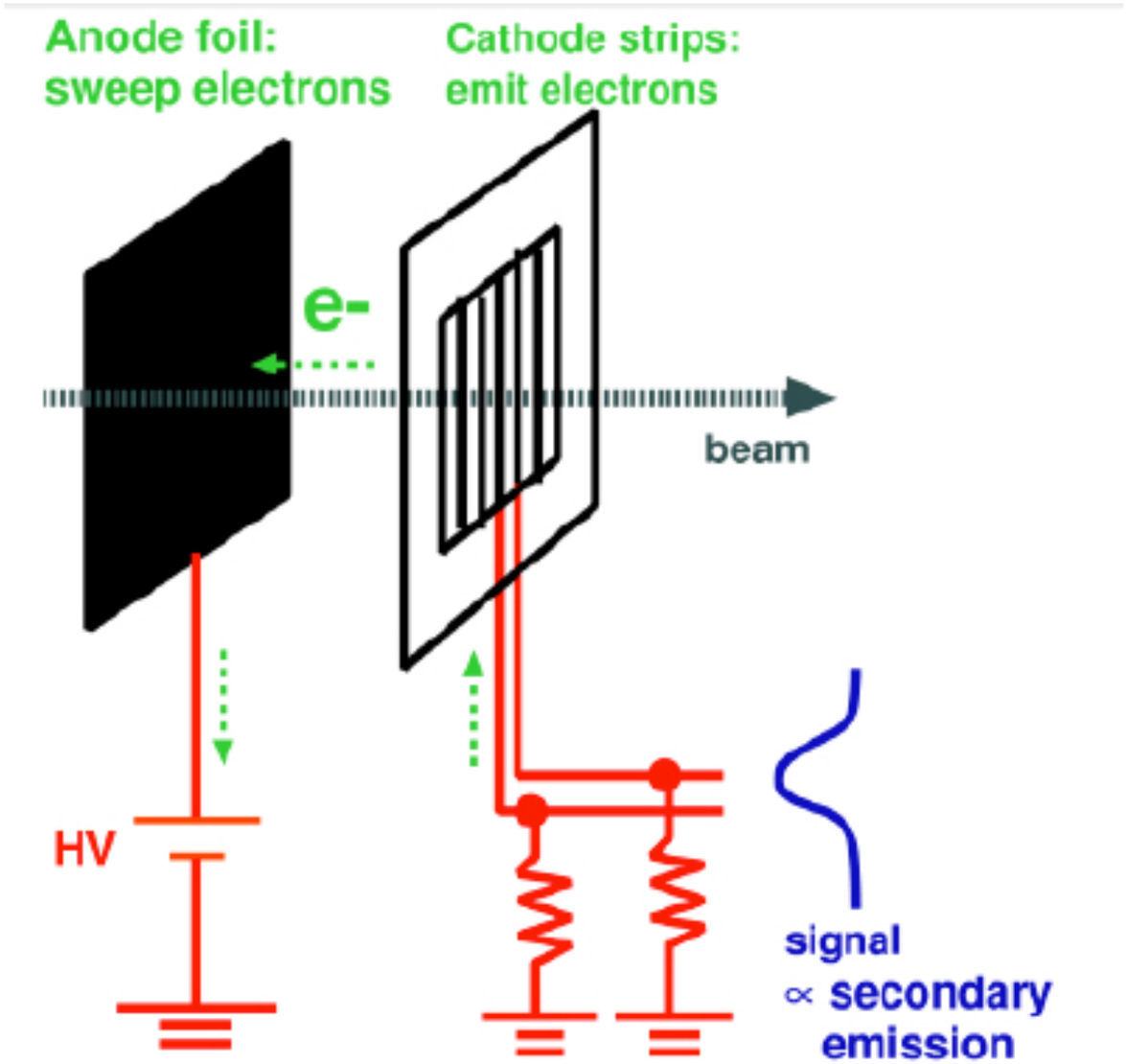
$$center \propto \frac{L-R}{L+R}$$

"Precision of the beam position < 450μm"

ESM "Electro static monitor"

- Charged particles presence induces a current on the wall
- Compare current on opposite sides to determine position

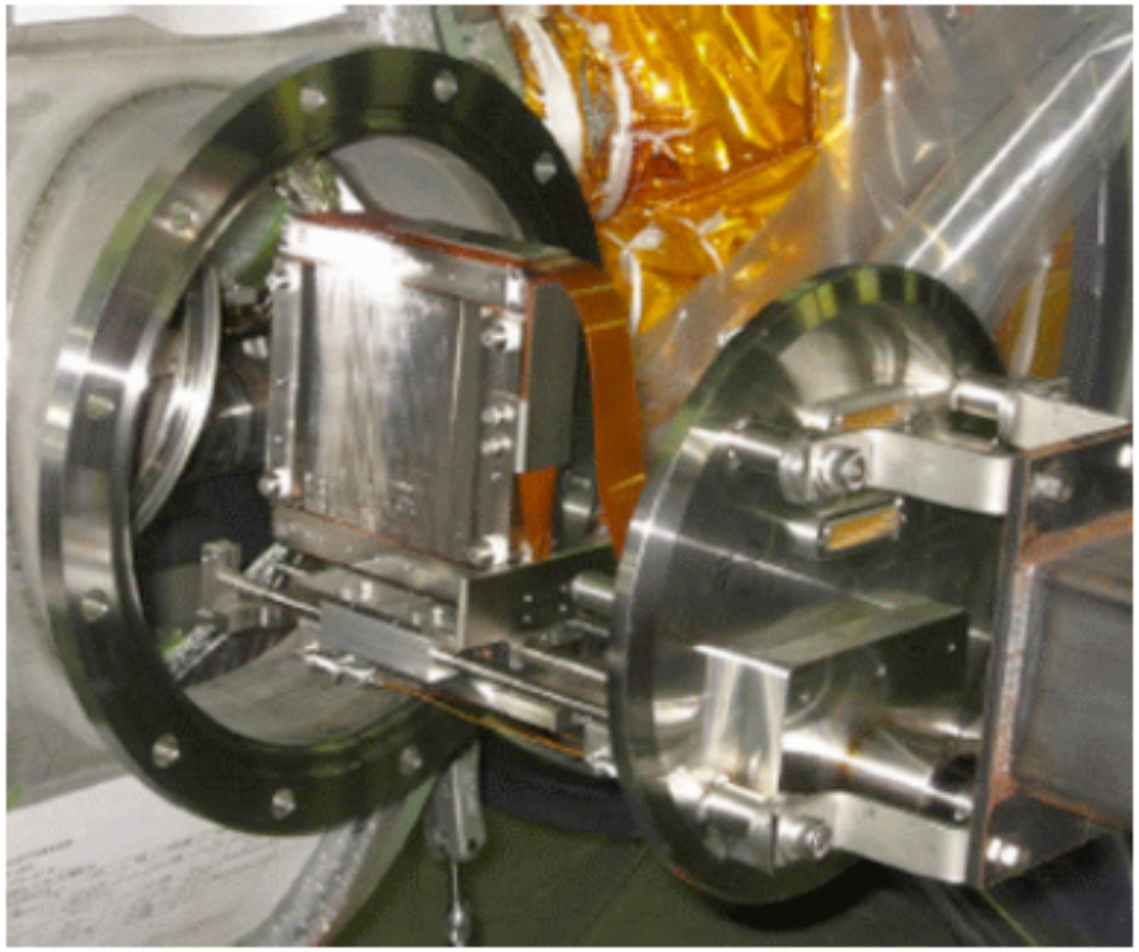
Beamline profile monitor (T2K)

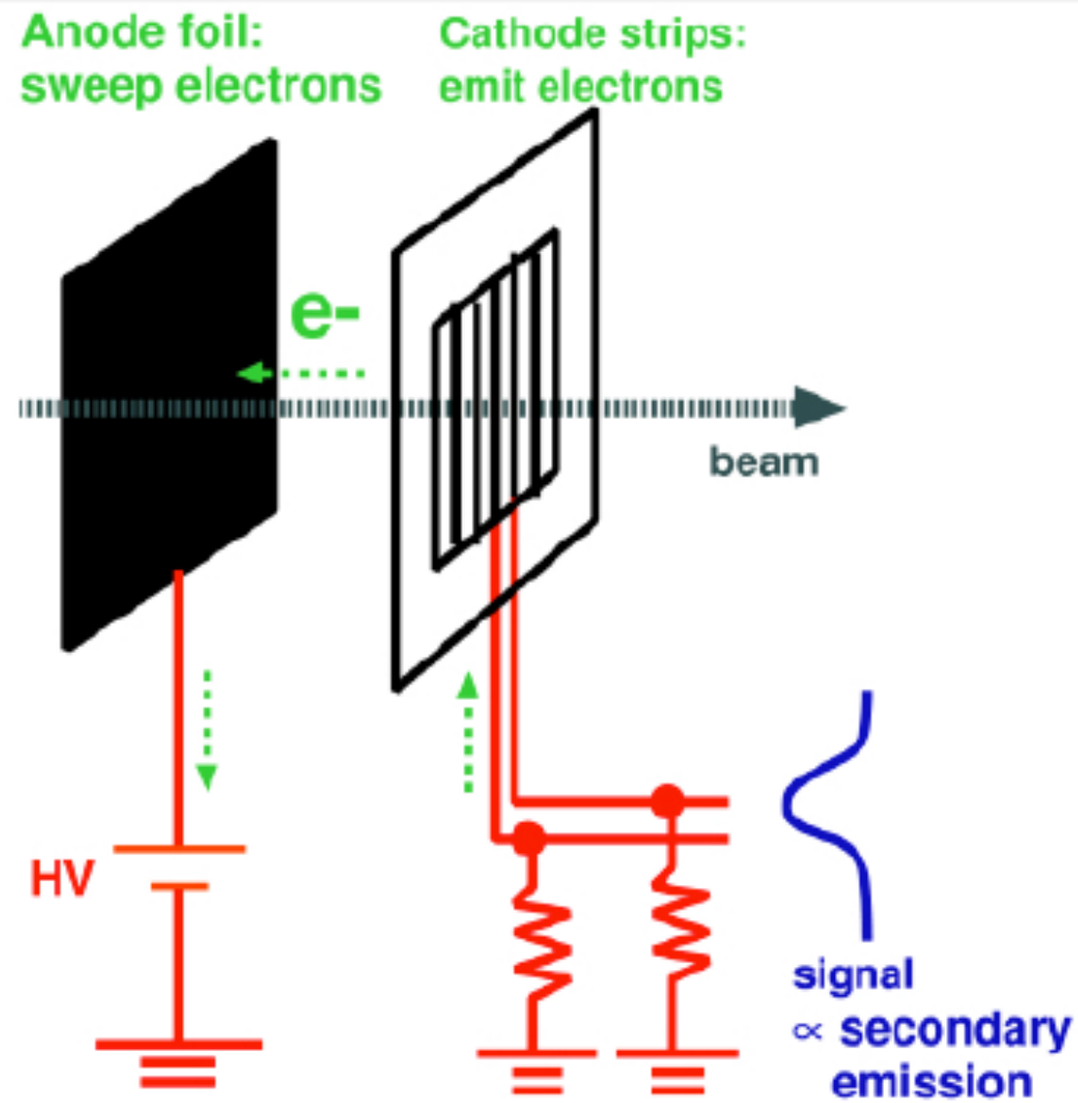


SSEM "Segmented Secondary Emission Monitor"

- Proton beam ejects electrons from thin foil
- Apply electric field to collect electrons

Beamline profile monitor (T2K)





SSEM "Segmented Secondary Emission Monitor"

- Proton beam ejects electrons from thin foil
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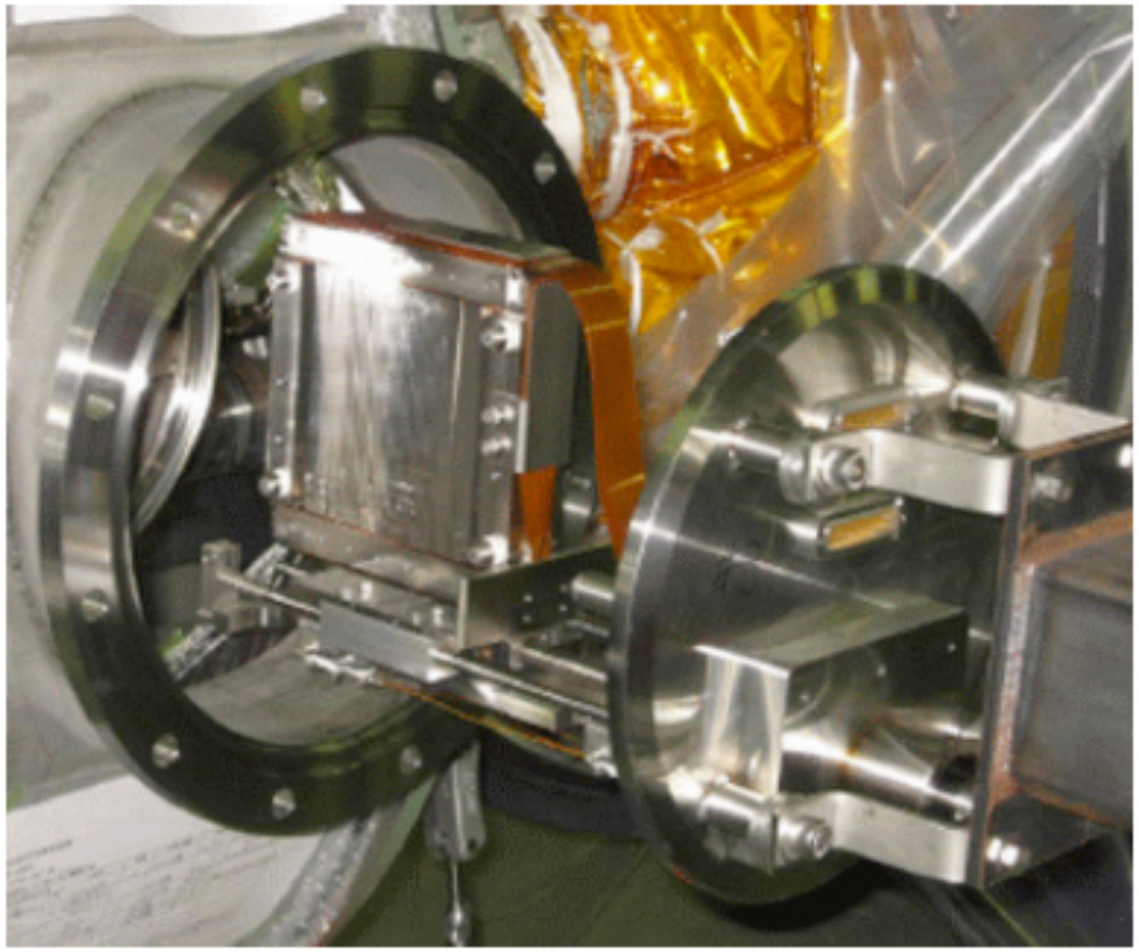
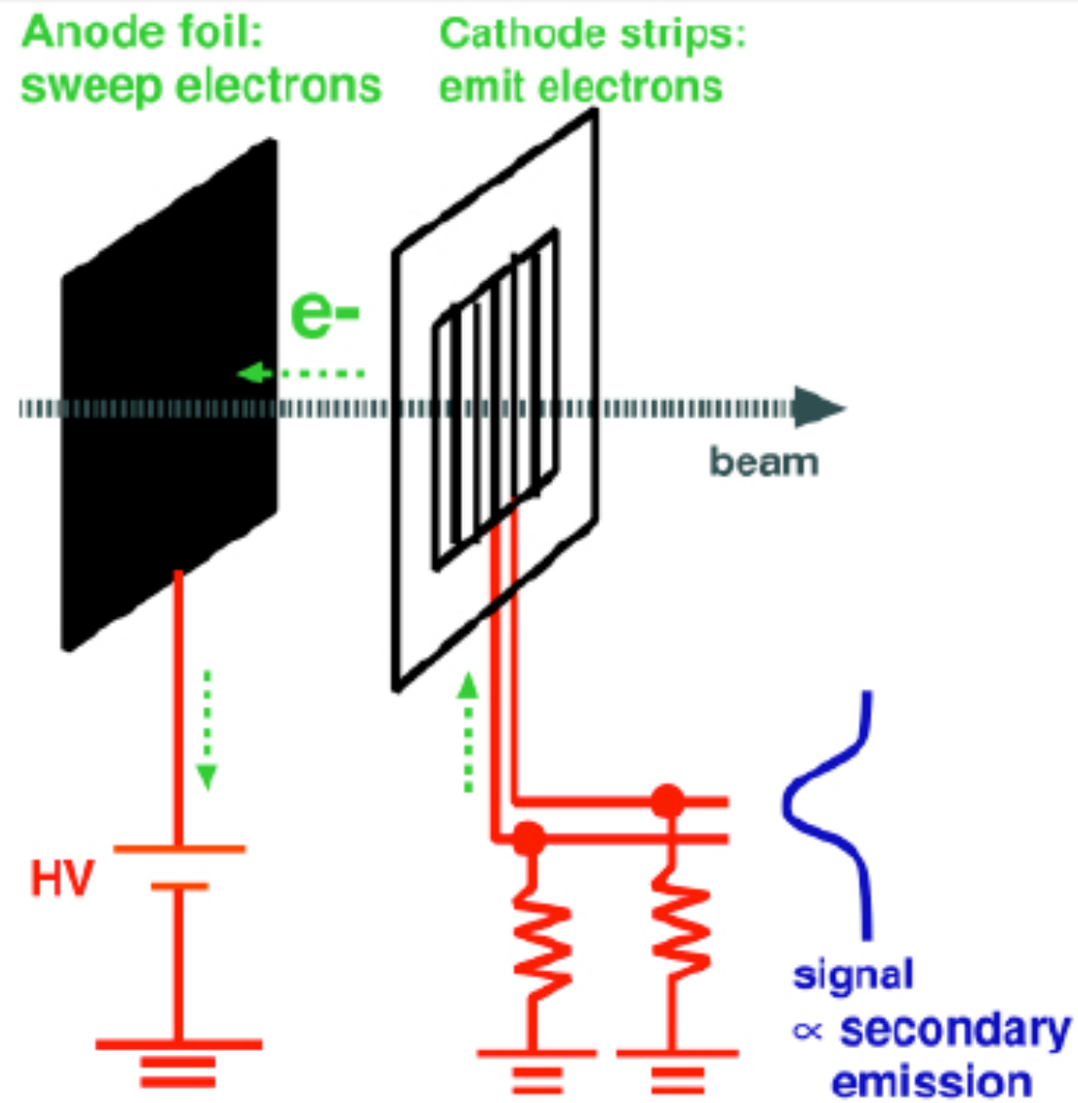
Beamline profile monitor (T2K)





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- Proton beam ejects electrons from thin foil
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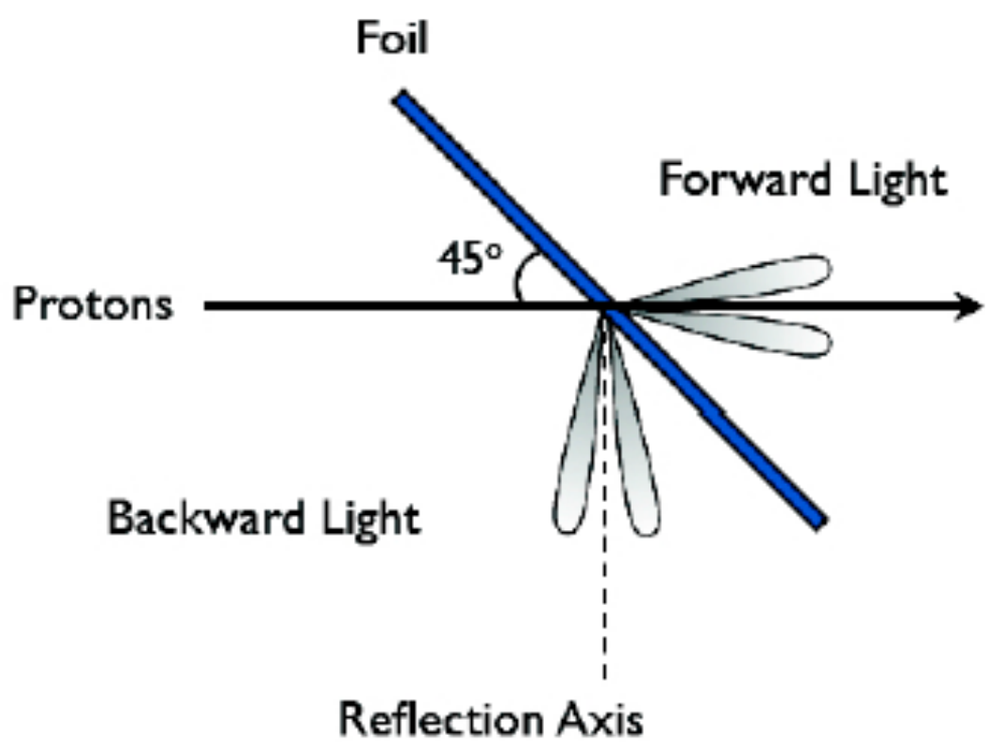
Beam width measurement is ~200μm

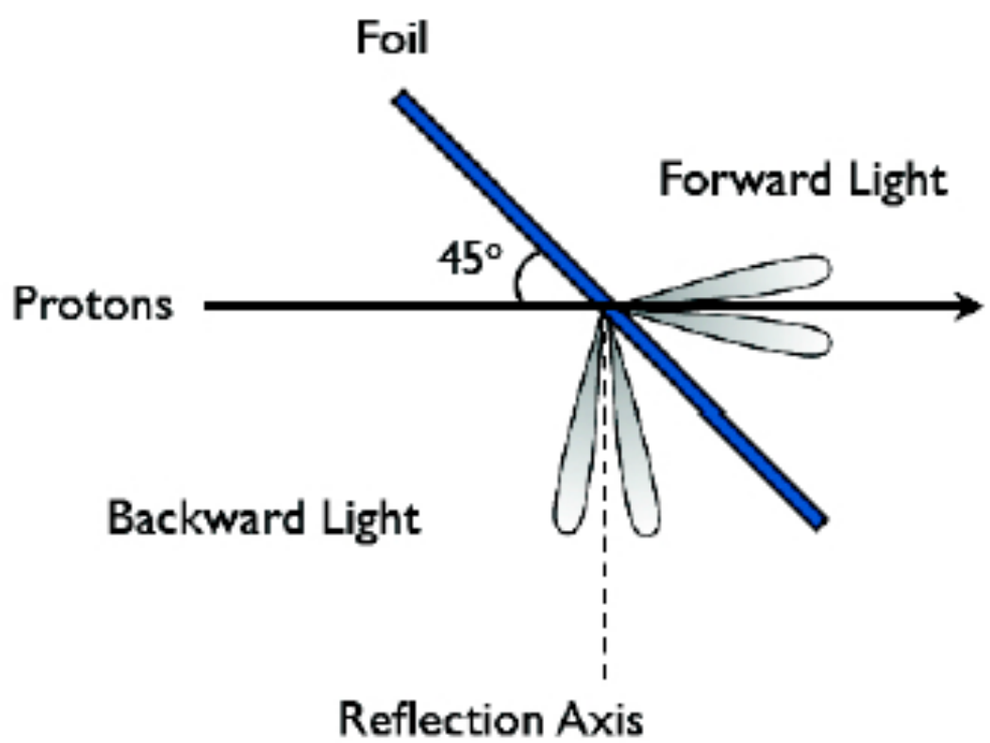
Beamline profile monitor at the target (T2K)

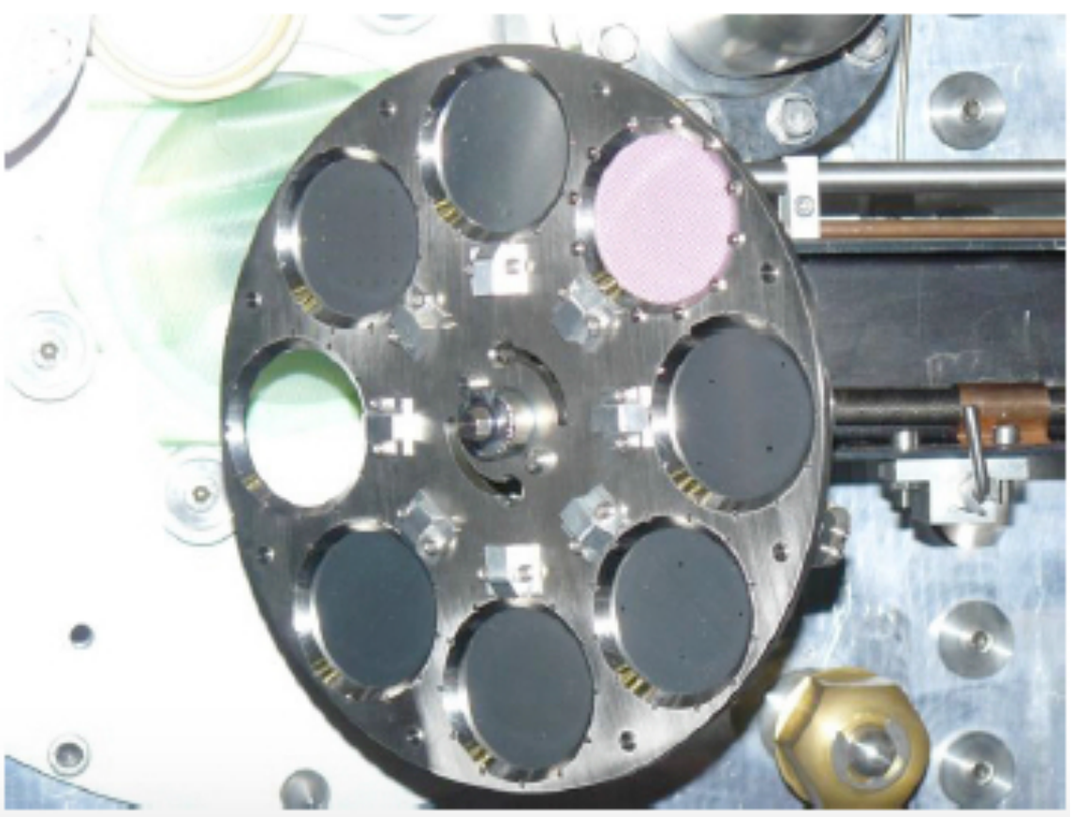


OTR "Optical Transition Radiation"

- Produced by the the protons as they pass through a thin Ti foil in front of the neutrino target
- The light is emitted perpendicular to the beam and reflected via parabolic mirrors to a CID camera
- OTR light is used to determine the beam profile and position on the target

Beamline profile monitor at the target (T2K)





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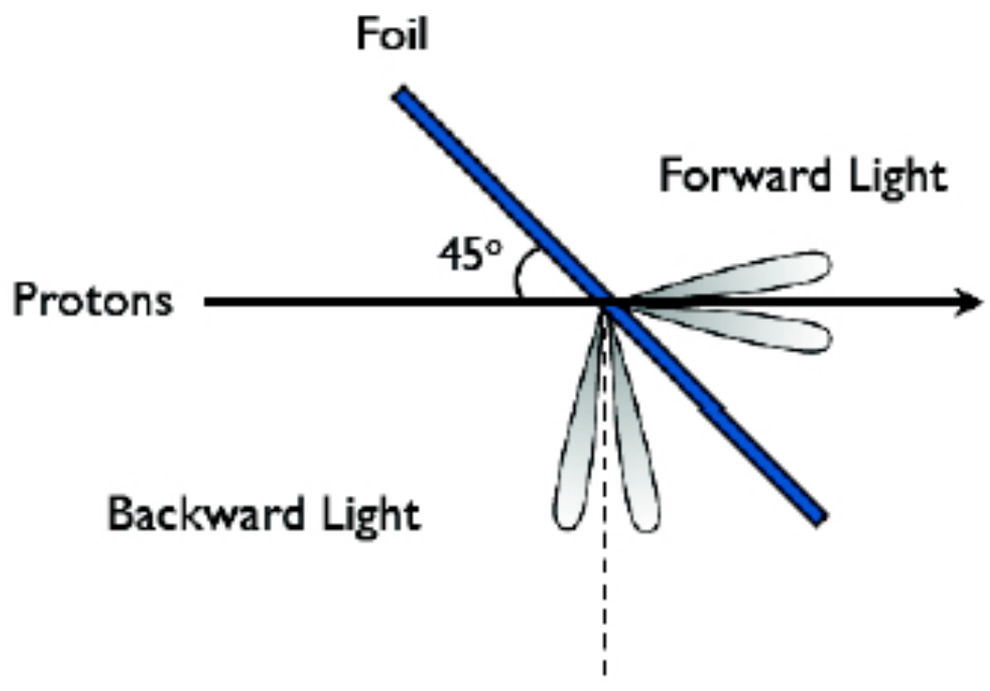

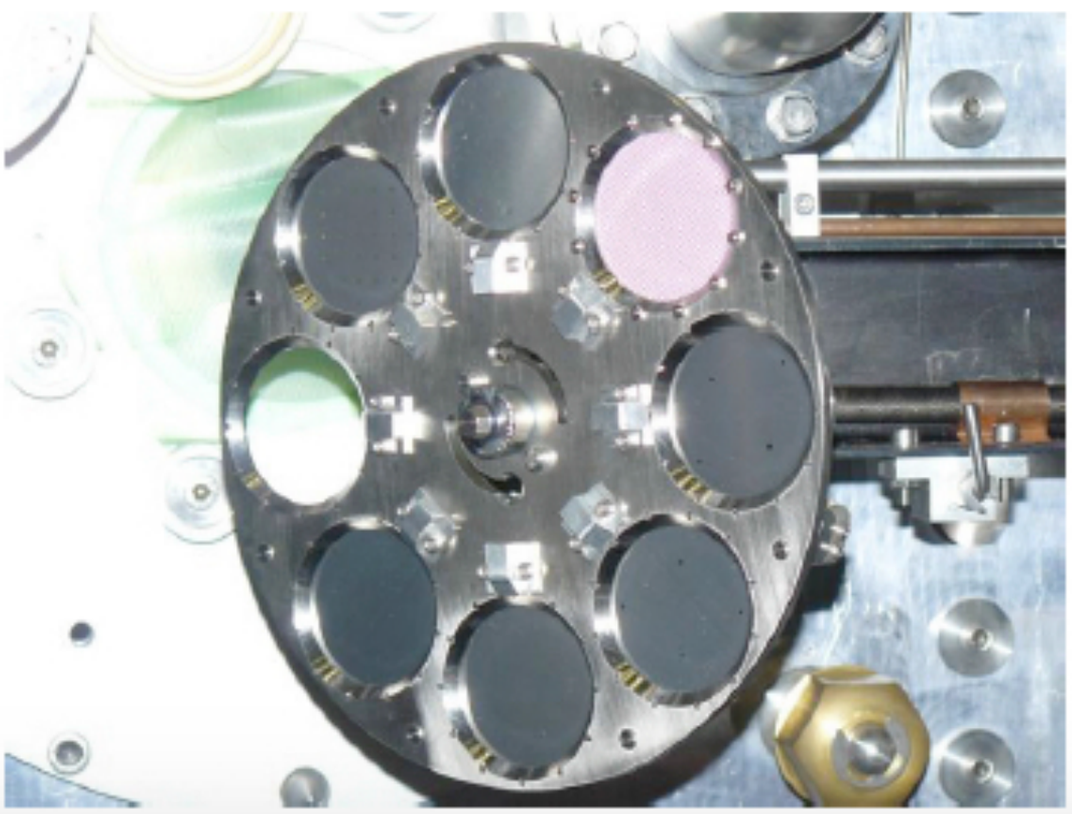

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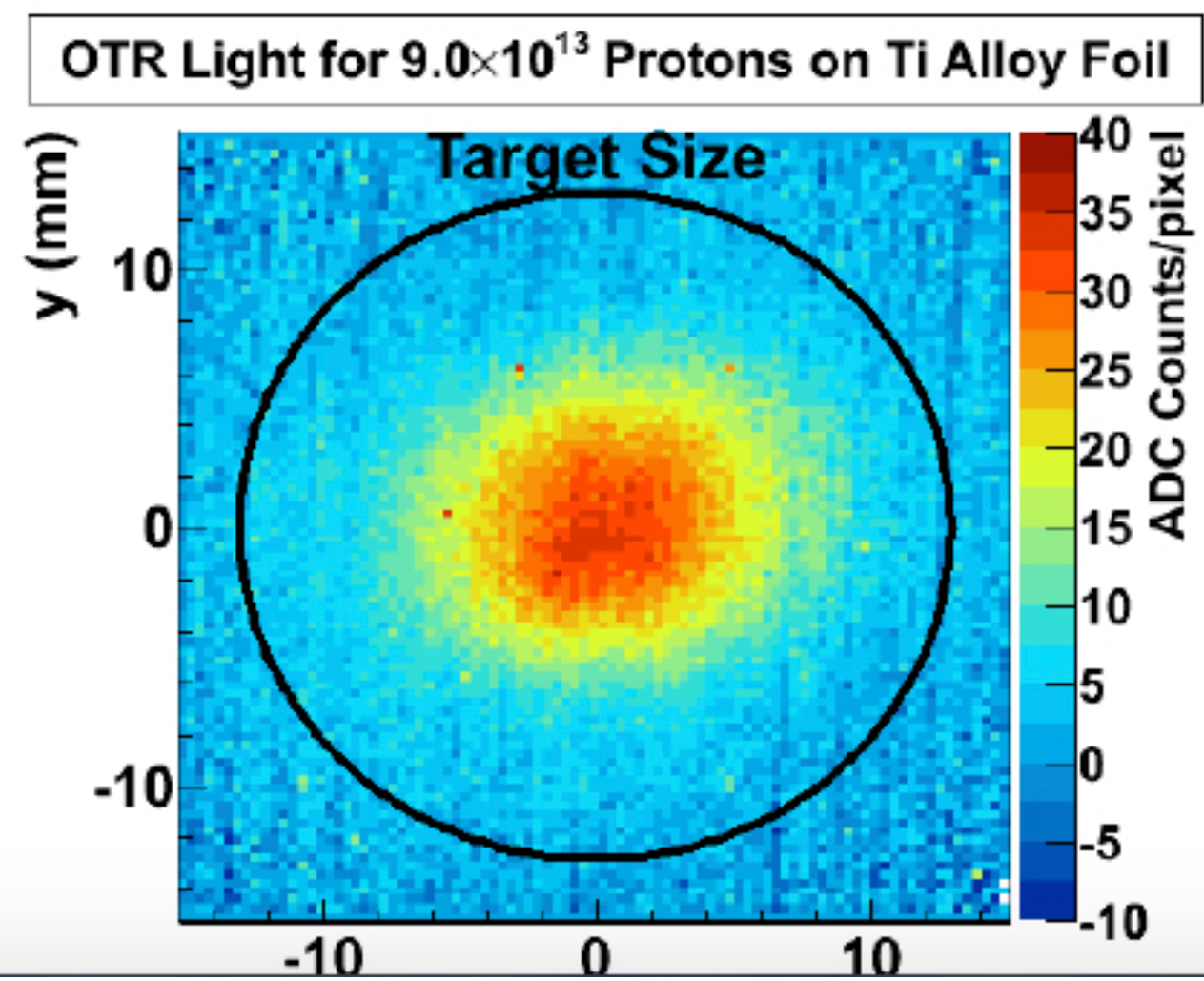
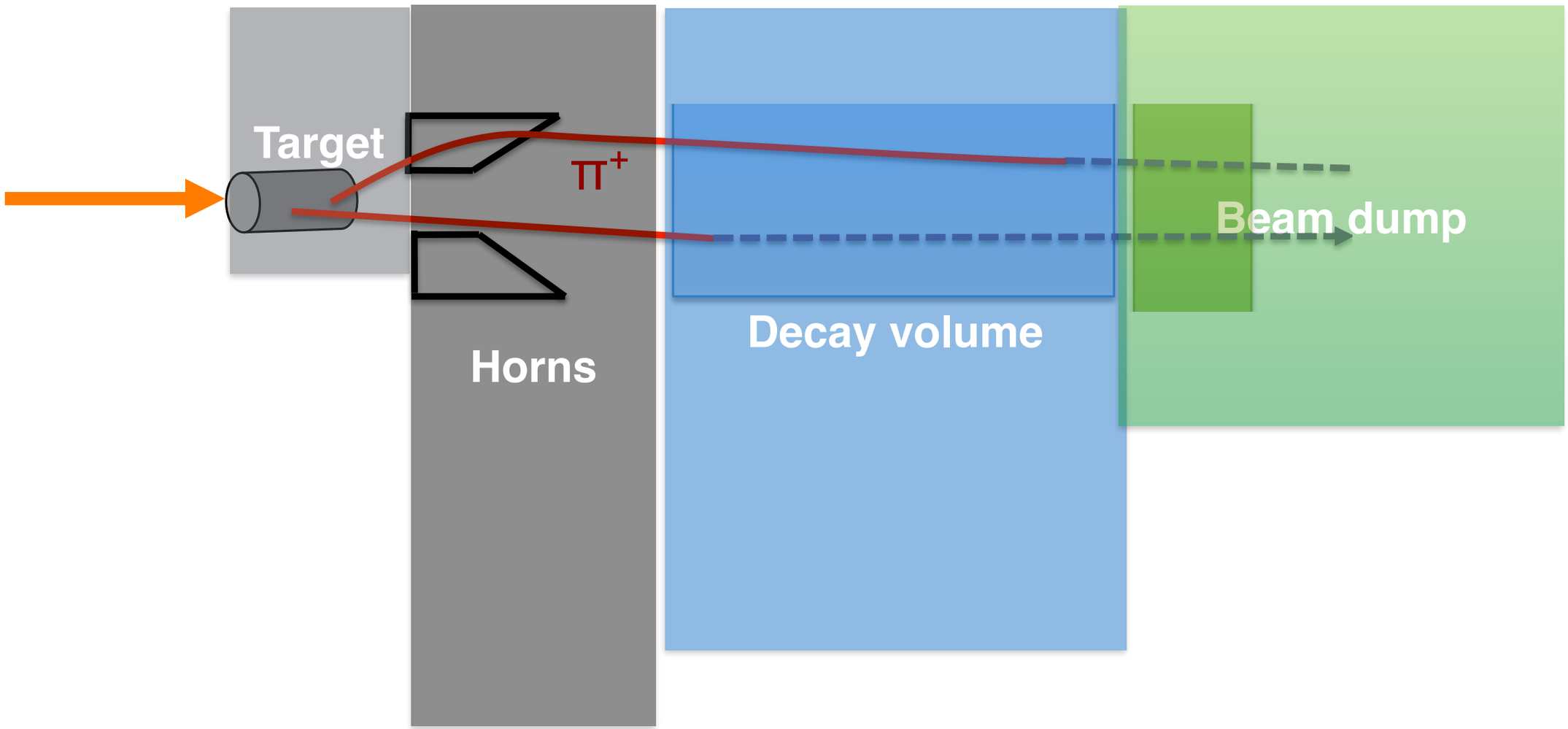


All the pieces



Hadron production measurements

Muon monitors, neutrino profile detectors, and near detectors

Targets

Material:

- Low Z: protons interact without losing too much energy
- Interaction length > radiation length

Shape:

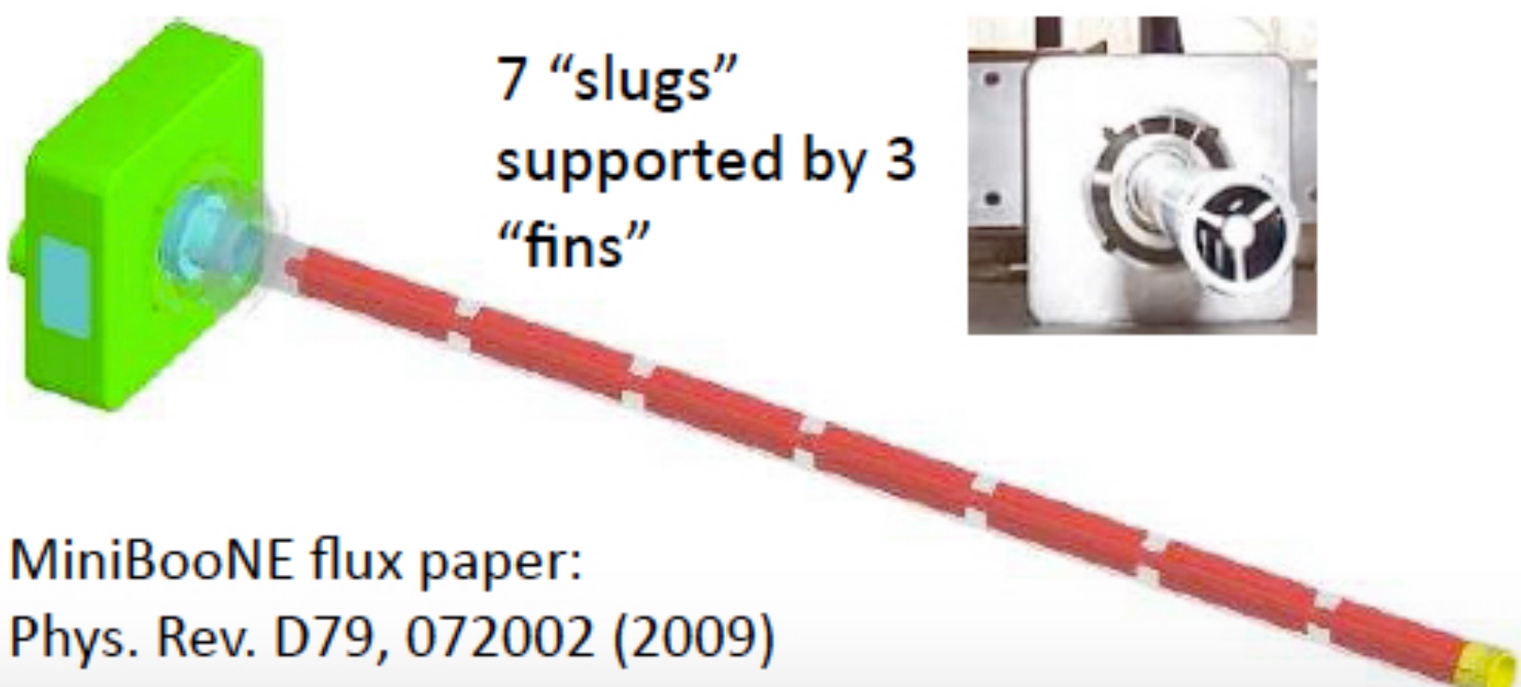
- Ruler or cylinder (longest dimension along beam direction, for protons to interact, and produce more neutrinos)

Cooling:

- Target has to withstand the proton beam (shock and heating)
- Air cooling or water cooling depending on beam energy

Targets

Example: NuMI (MINOS) target
Material: Graphite with Al casing
Shape: ruler 6.4 mm x 15 mm x 20 mm) x 47 (2 interaction lengths)

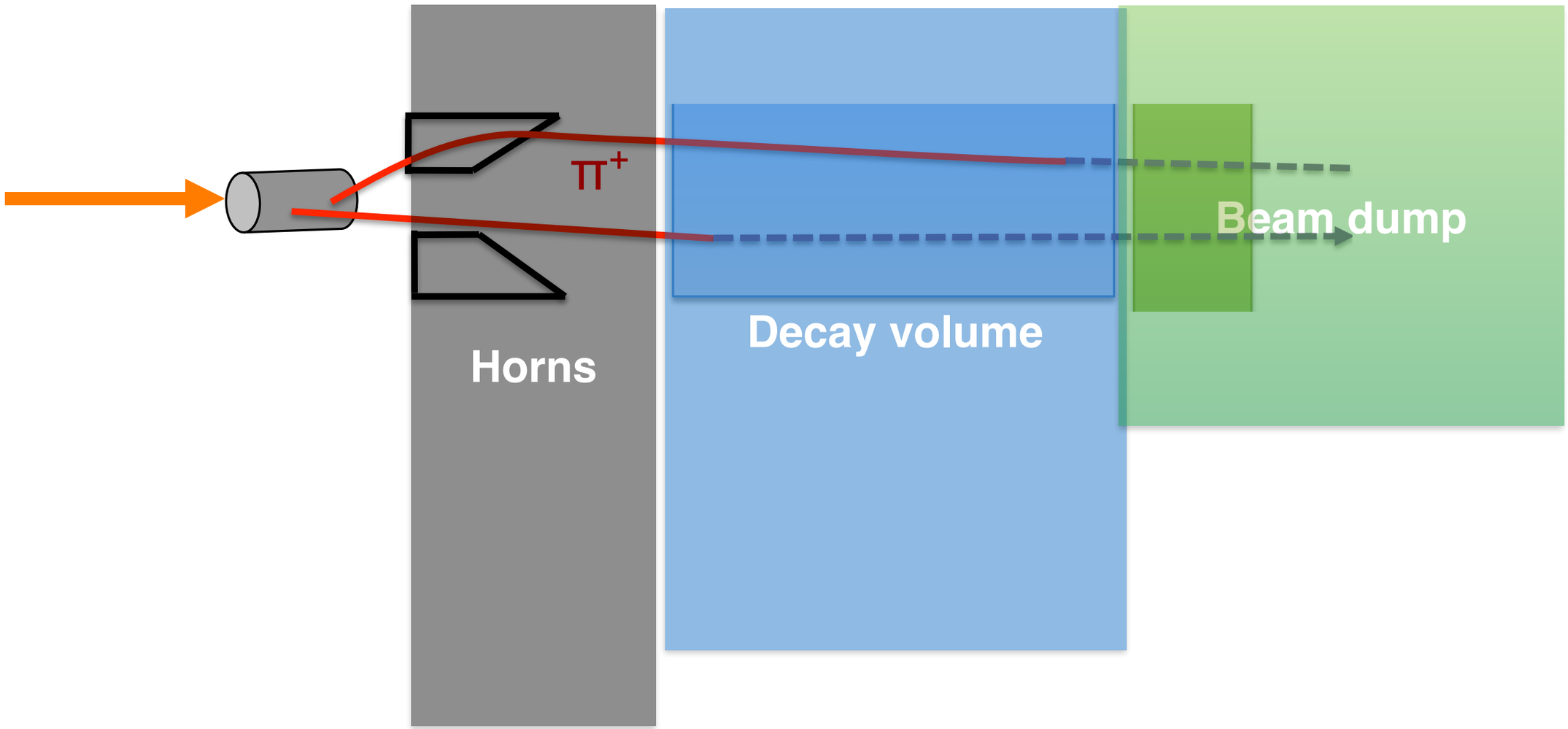


MiniBooNE flux paper:
Phys. Rev. D79, 072002 (2009)

Example: MiniBooNE target
Material: Beryllium

Shape: cylinder
Length: 1.7 interaction lengths for 8 GeV/c protons (71cm)
Diameter: 1cm
Air cooled

All the pieces



Hadron production measurements

Muon monitors, neutrino profile detectors, and near detectors

How horns work

Want to remove transverse momentum of pions out of the target

$$\theta_\pi \sim p_T/p_\pi \sim 280\ MeV/p_\pi \sim 2/\gamma$$

How horns work

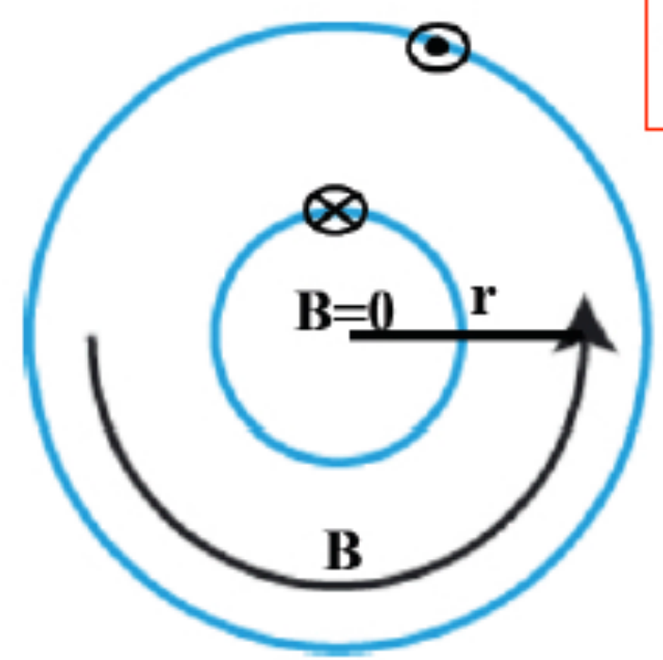
Want to remove transverse momentum of pions out of the target

$$\theta_\pi \sim p_T/p_\pi \sim 280\ MeV/p_\pi \sim 2/\gamma$$

S. Gilardoni
INSS09

Apply a force in the radial direction to overcome θ_π with a magnetic field in the azimuthal direction:

$$B = \frac{\mu_0 I}{2\pi r}\hat{\theta}$$



⊗ Current OUT
⊙ Current IN

How horns work

Complication: Need to overcome non-constant p_T~r

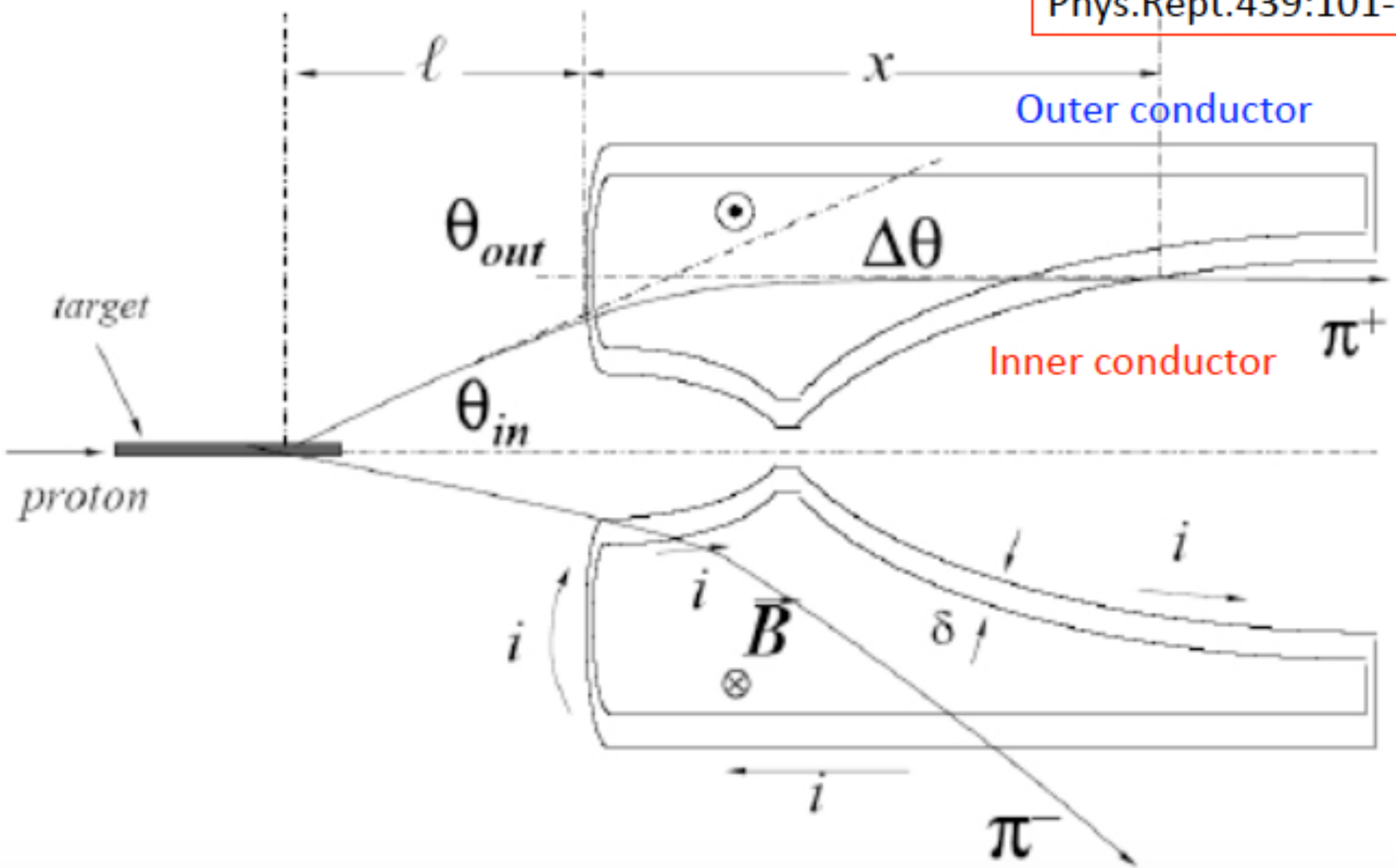
$$\theta_\pi \sim p_T/p_\pi \sim 280\ MeV/p_\pi \sim 2/\gamma$$

How horns work

Complication: Need to overcome non-constant p_T~r

Solution: Modify shape of conductor so that particles produced at larger angles travel through more of the magnetic field:

Phys.Rept.439:101-159,2007

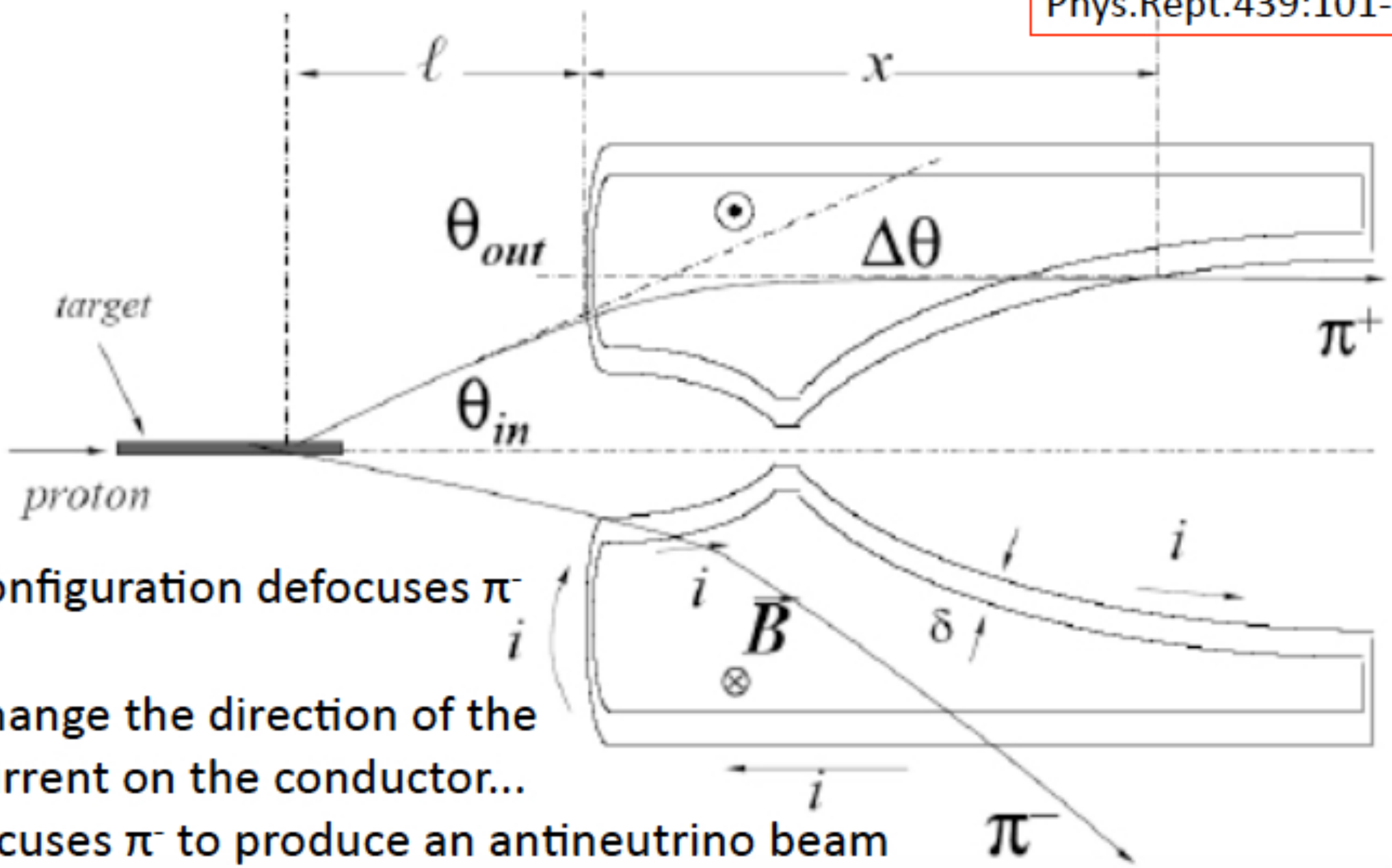


How horns work

Complication: Need to overcome non-constant p_T~r

Solution: Modify shape of conductor so that particles produced at larger angles travel through more of the magnetic field:

Phys.Rept.439:101-159,2007



Configuration defocuses π^-

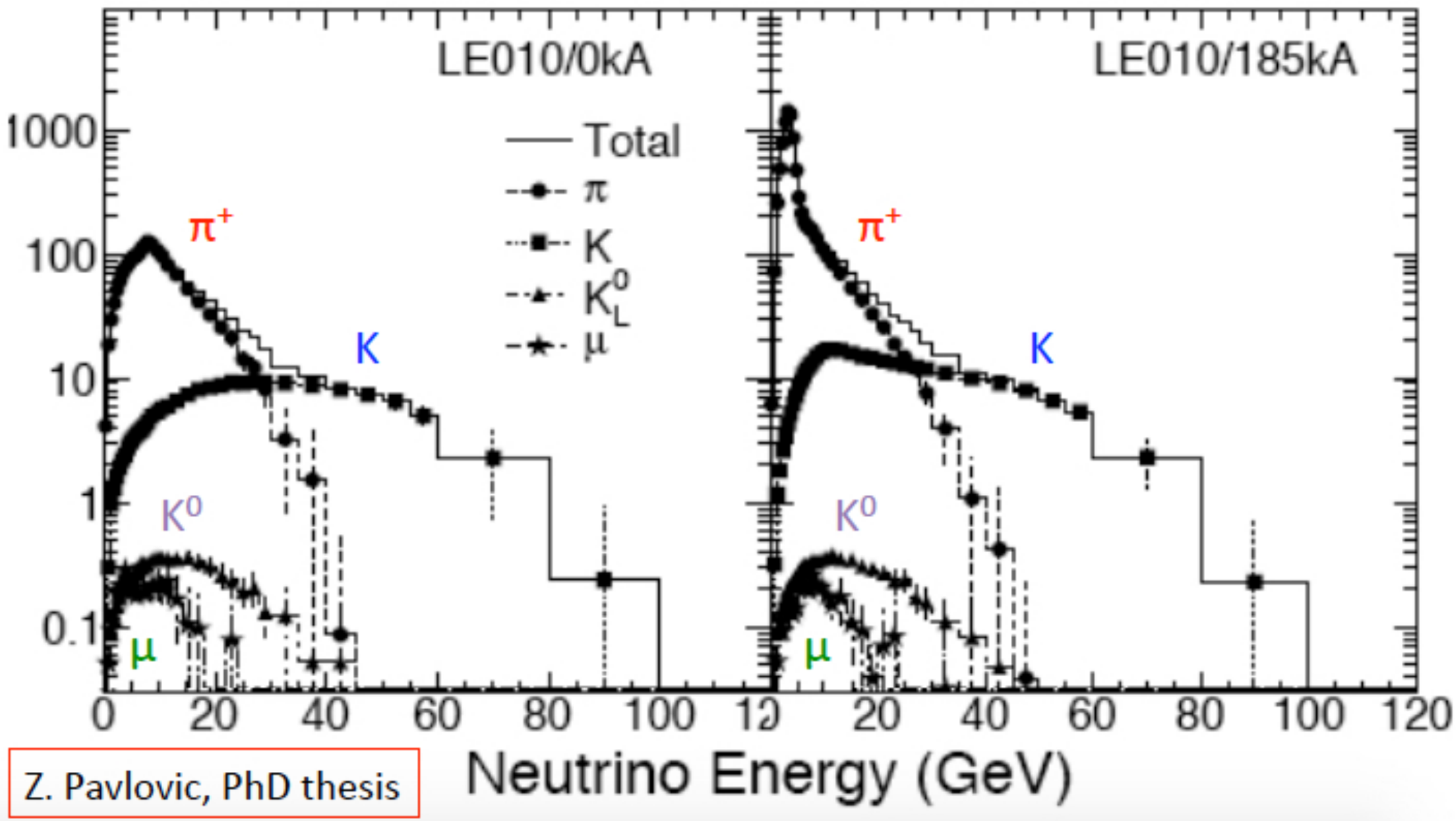
Change the direction of the current on the conductor...

focuses π^- to produce an antineutrino beam

Why we need horns

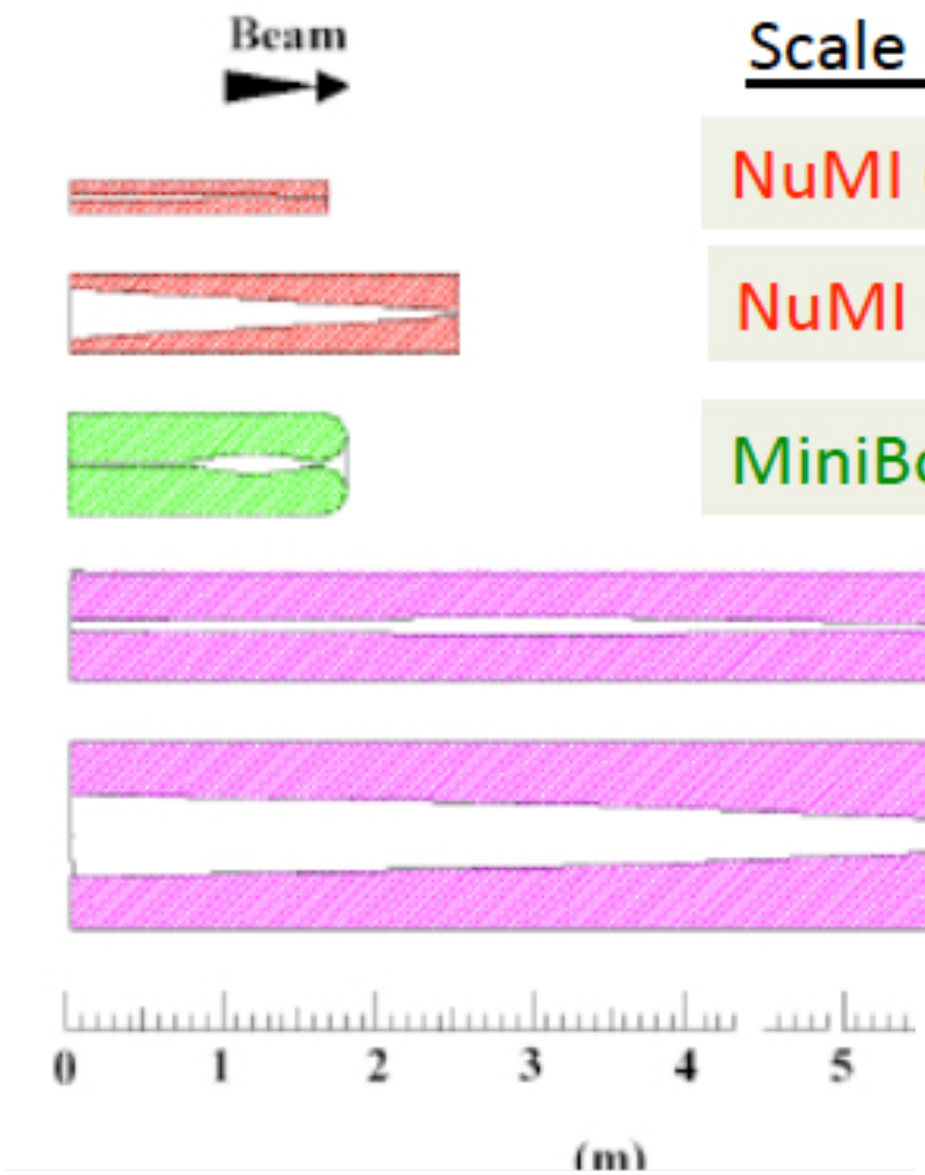
Use of a horn system increases the neutrino flux substantially

- Increases peak of neutrino energy distribution
- Doesn't increase HE tail (mesons which went through centre of horn)
- Depends on pion momentum (MiniBooNE flux increase is ~x6)



Z. Pavlovic, PhD thesis

Example horns



Scale drawings of various horns

NuMI (MINOS) horn 1

NuMI (MINOS) horn 2

Phys.Rept.439:101-159,2007

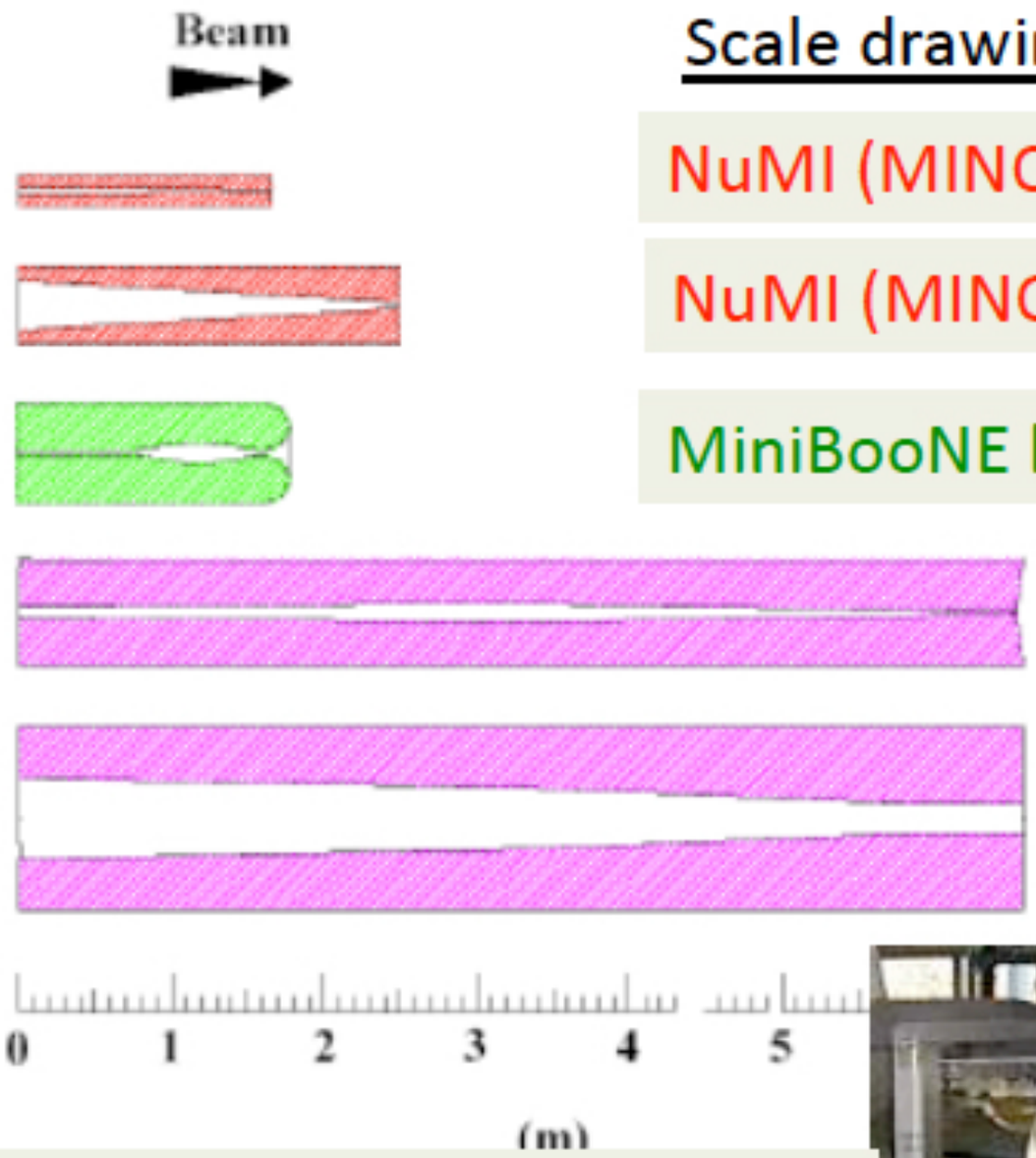
MiniBooNE horn

CNGS (OPERA) horn 1

CNGS (OPERA) horn 2

D. Harris
INSS'05

Example horns



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MiniBooNE horn

CNGS (OPERA) horn 1

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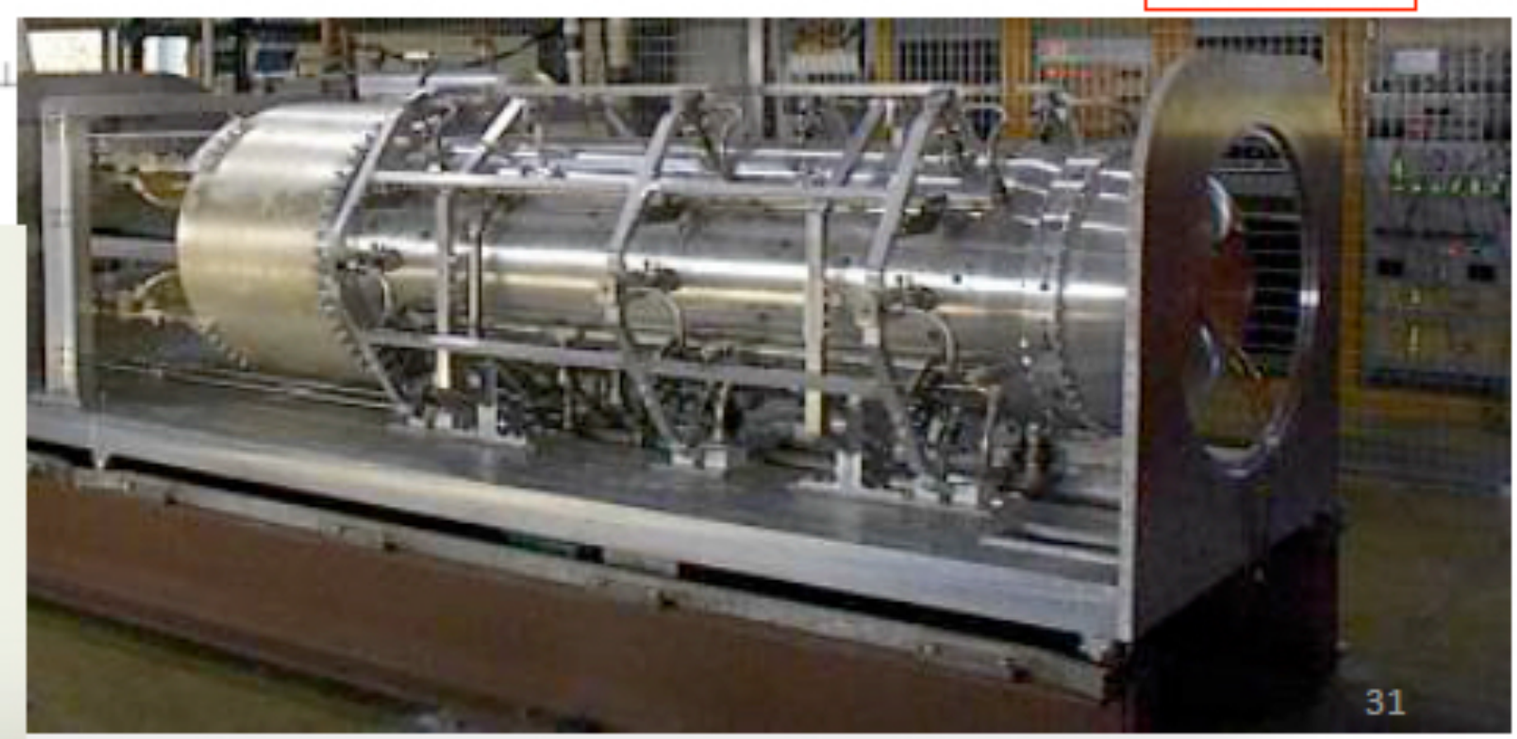
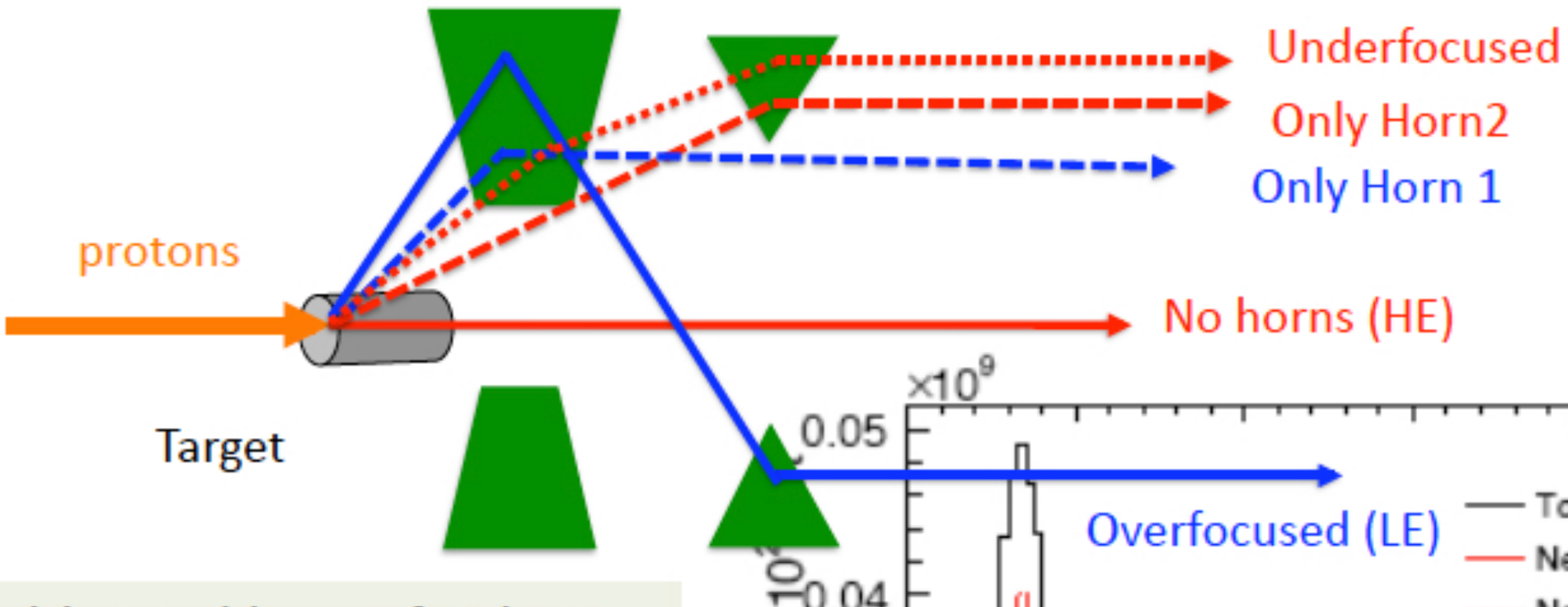
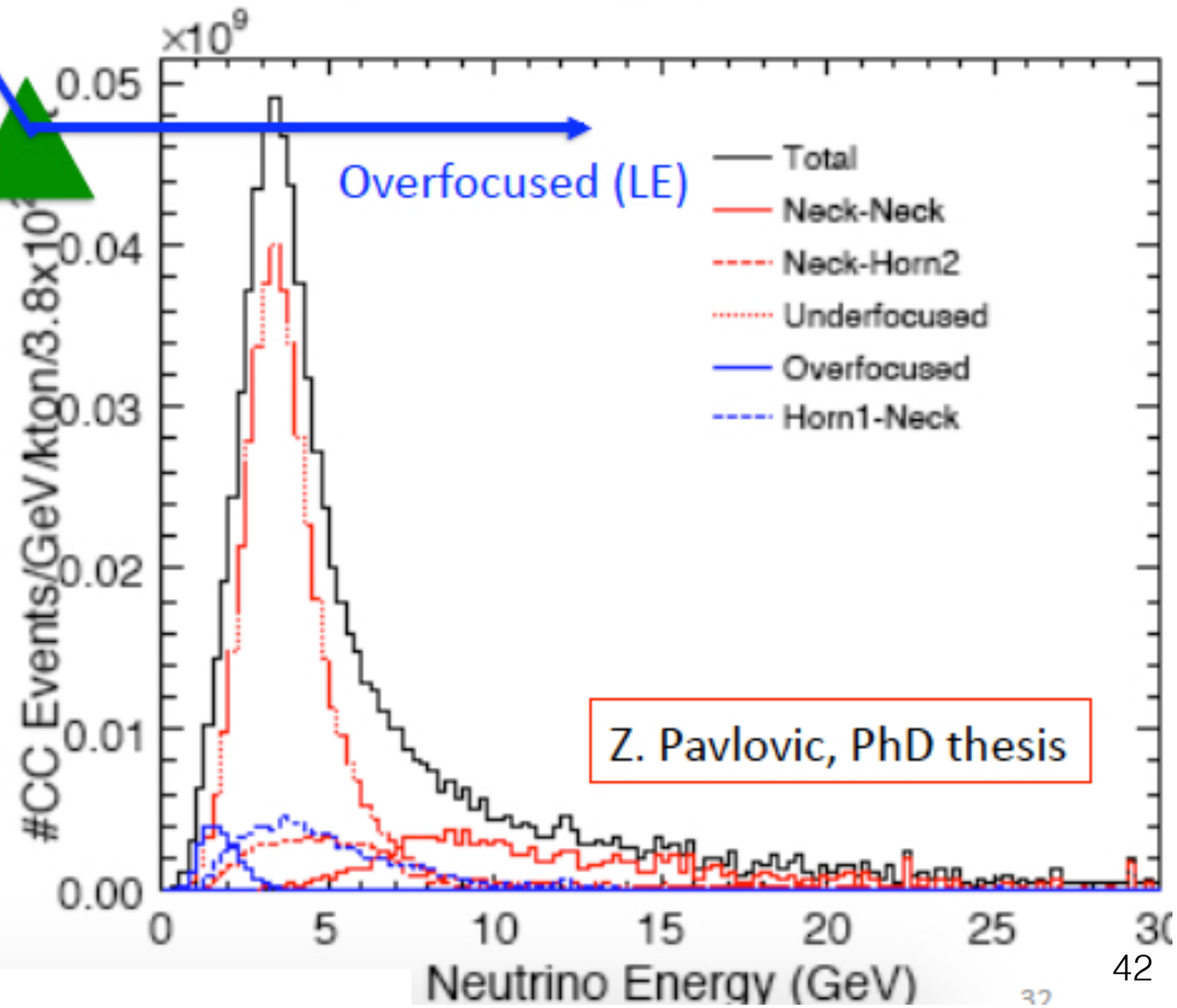
D. Harris
INSS'05

MiniBooNE horn outer conductor with water cooling system pipes
Aluminum is thin and low mass to reduce scattering



MORE horns





Additional horns further focus the beam, like series of lenses

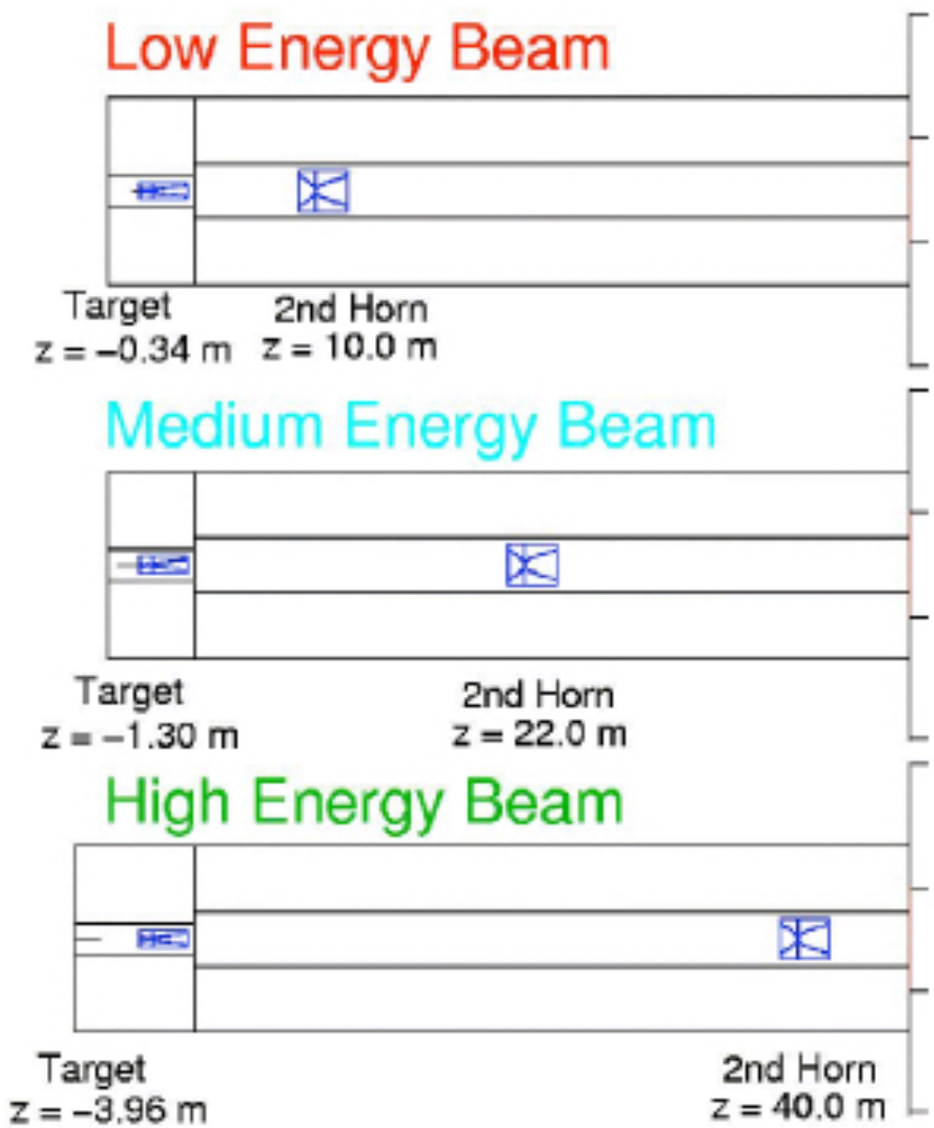
Largest flux component would have been underfocused by just the first horn

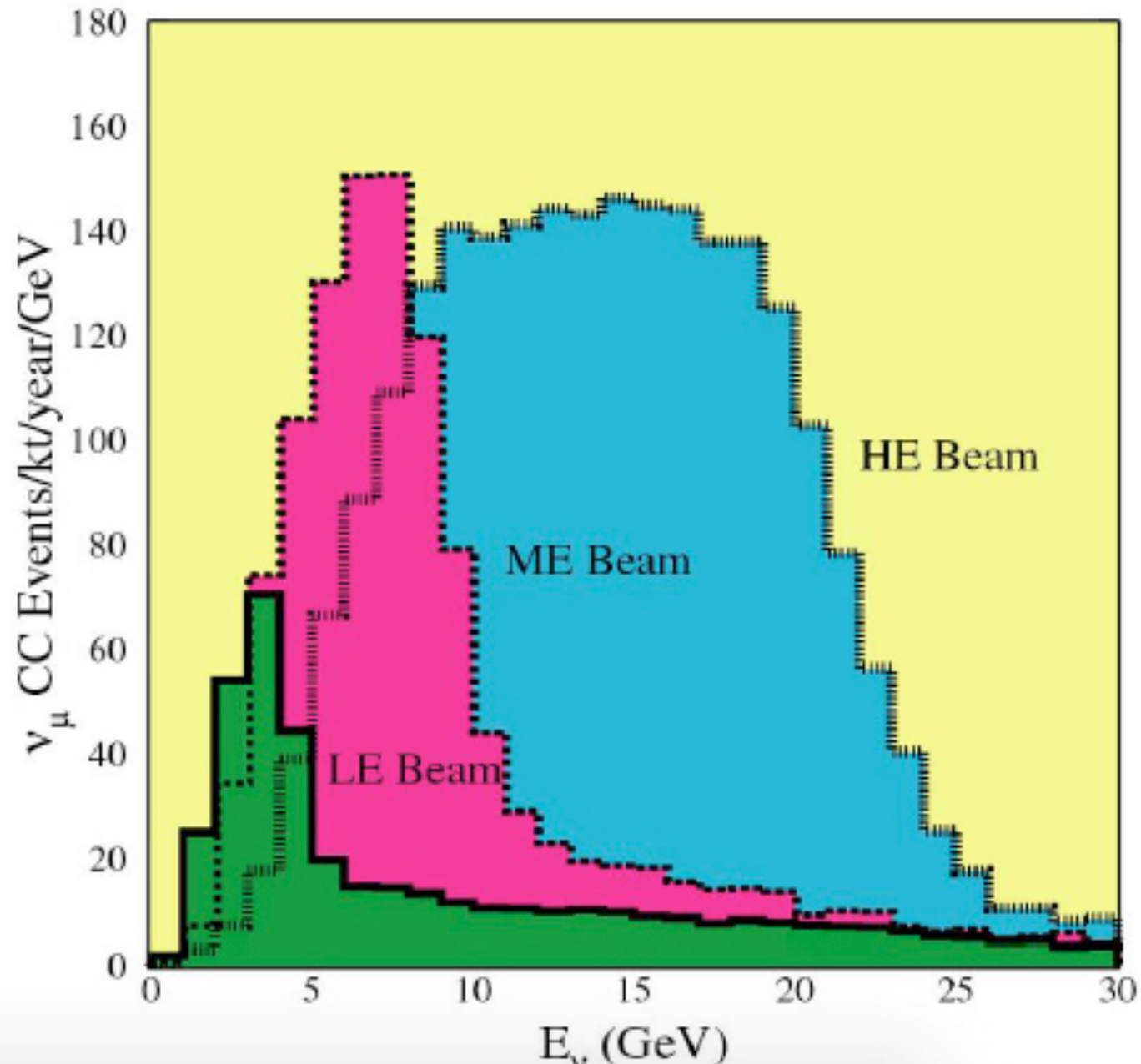
Horn position also matters

NuMI beam was designed to create a range of neutrino beams

For high energy (HE) to low energy (LE) beam configurations

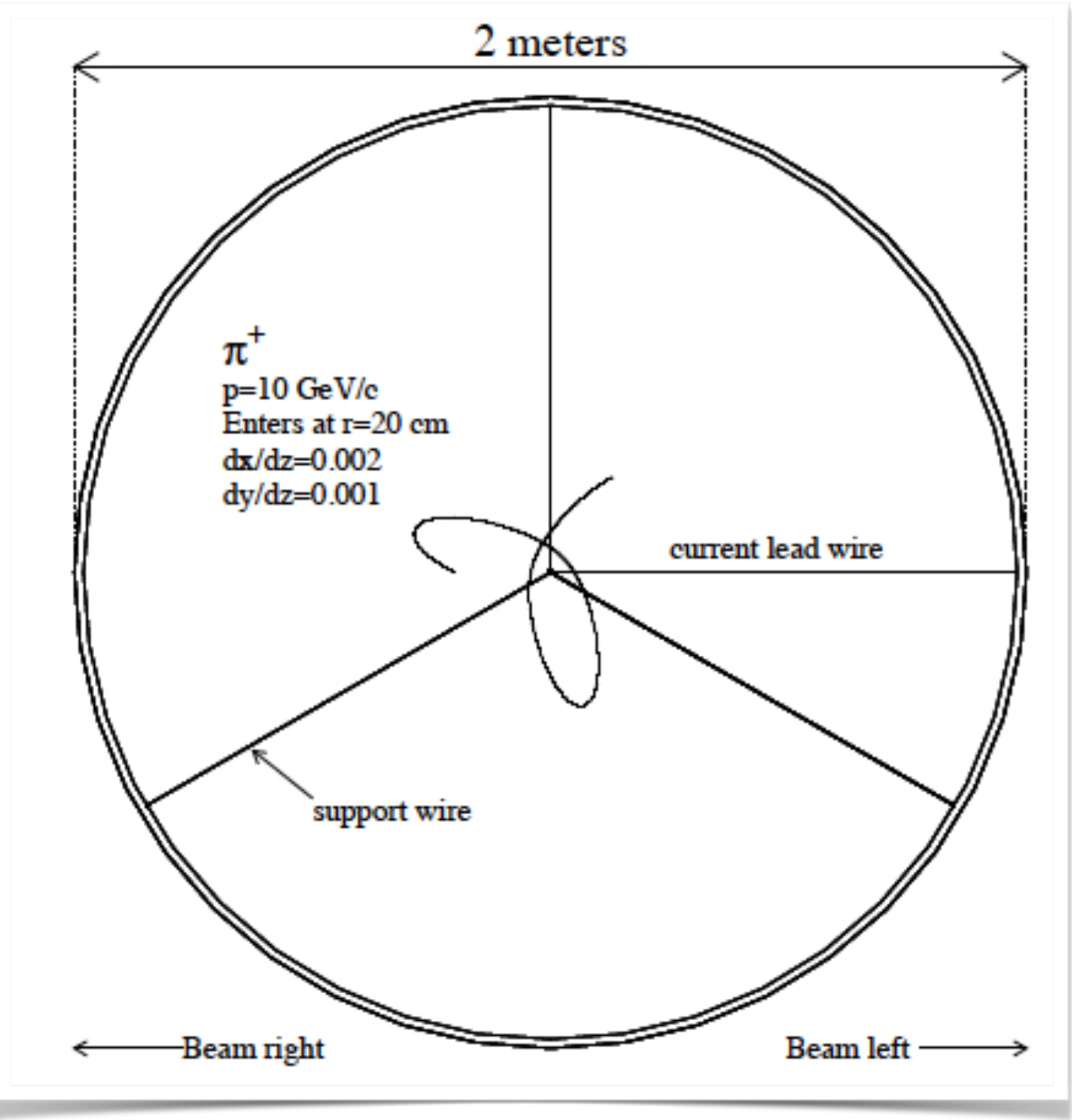
1) Target position relative to first horn decreases
2) Second horn position relative to first horn decreases





A. Marchionni, NBI2005

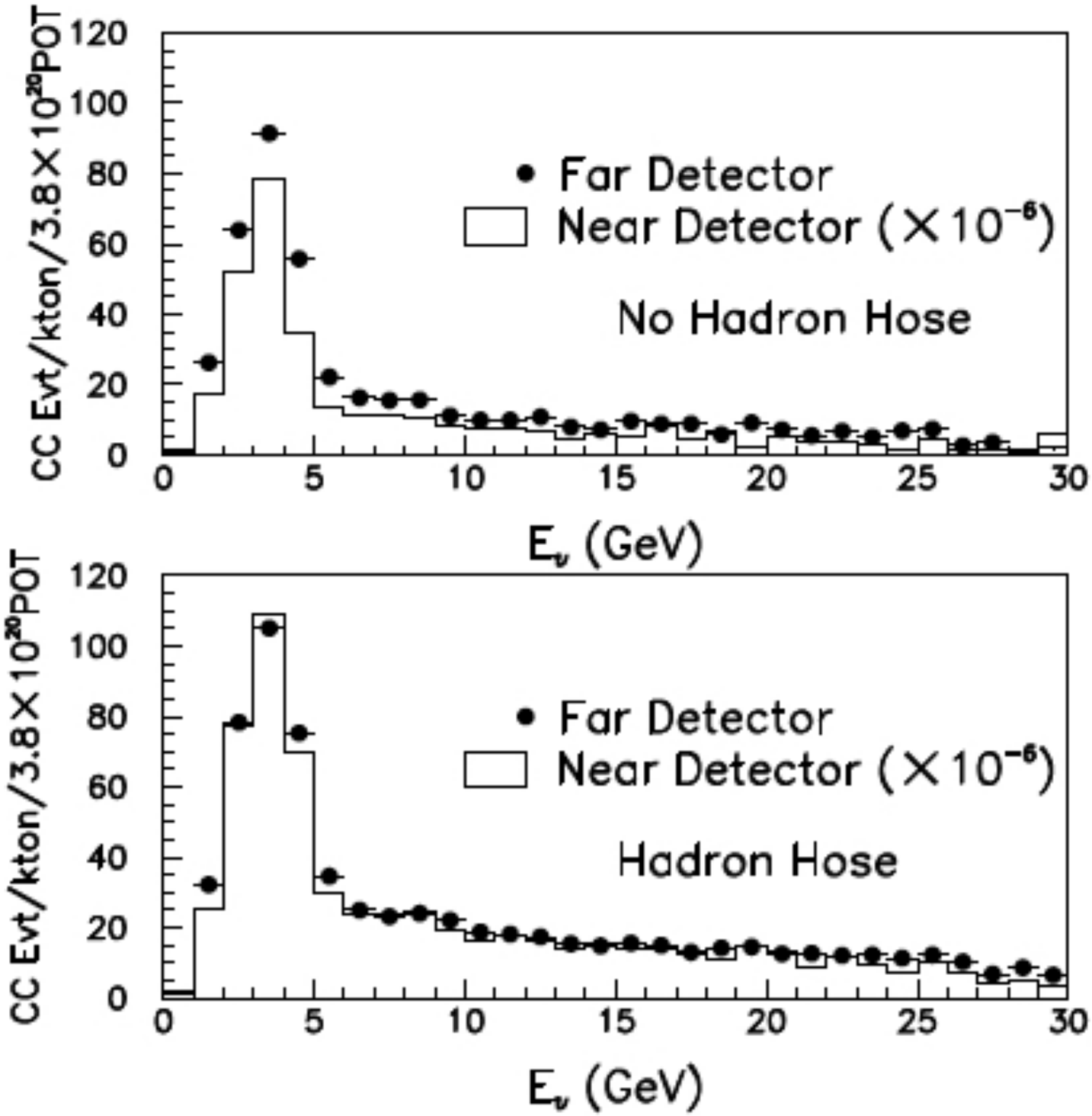
Another boost: Hadron Hose



Nucl.Instrum.Meth. A498 (2003) 29-51

"Mesons spiral around the hose wire and are drawn away from the decay volume walls"

Another boost: Hadron Hose

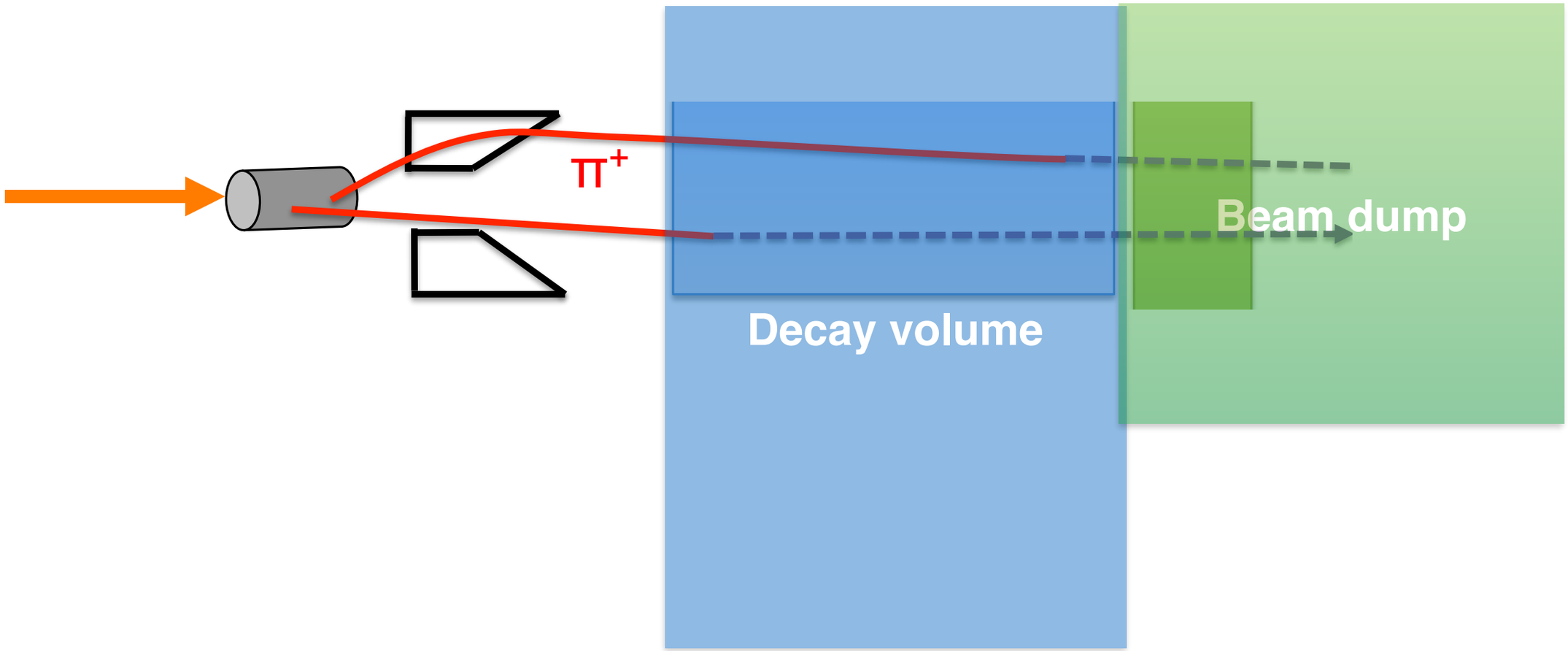


Nucl.Instrum.Meth. A498 (2003) 29-51

Boosts flux, but

"This randomization washes out the kinematic correlation between neutrino energy and decay angle"

All the pieces



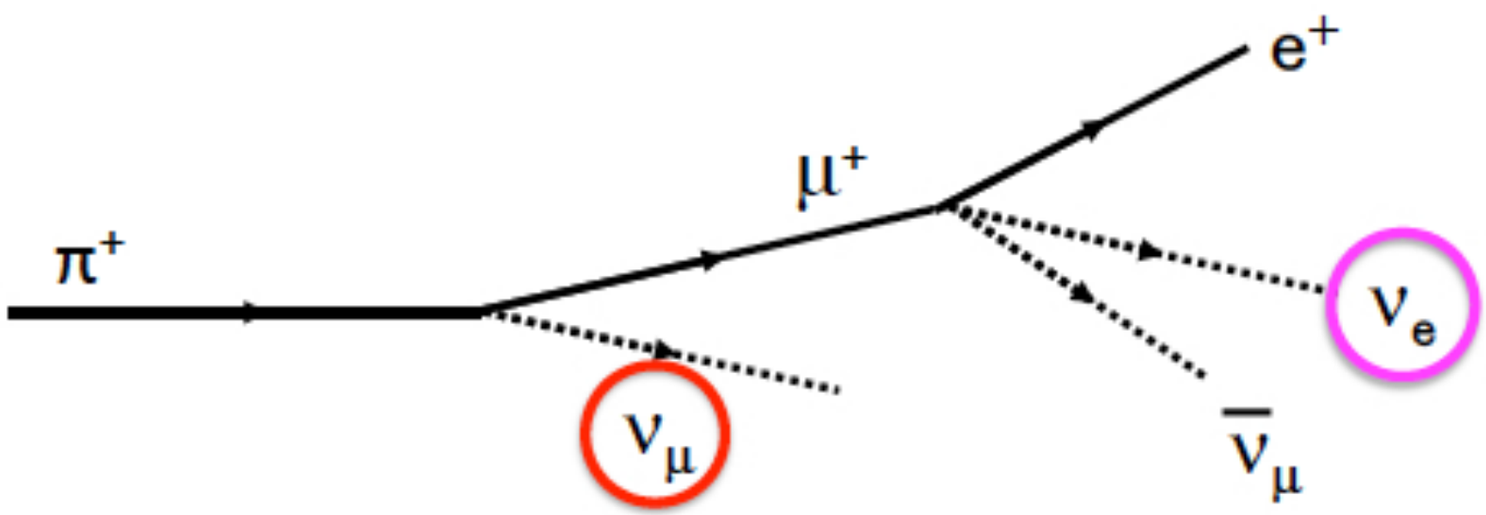
Hadron production measurements

Muon monitors, neutrino profile detectors, and near detectors

Decay volume

Shape considerations:

- Longer distance to maximize pion decay
  - For a 5 GeV pion, $\gamma \approx 35$, and $\gamma\beta c\tau \approx 280$ m
  - Consider width/diameter too: low E pions may hit walls
- Shorter distance reduces the number of muons which decay



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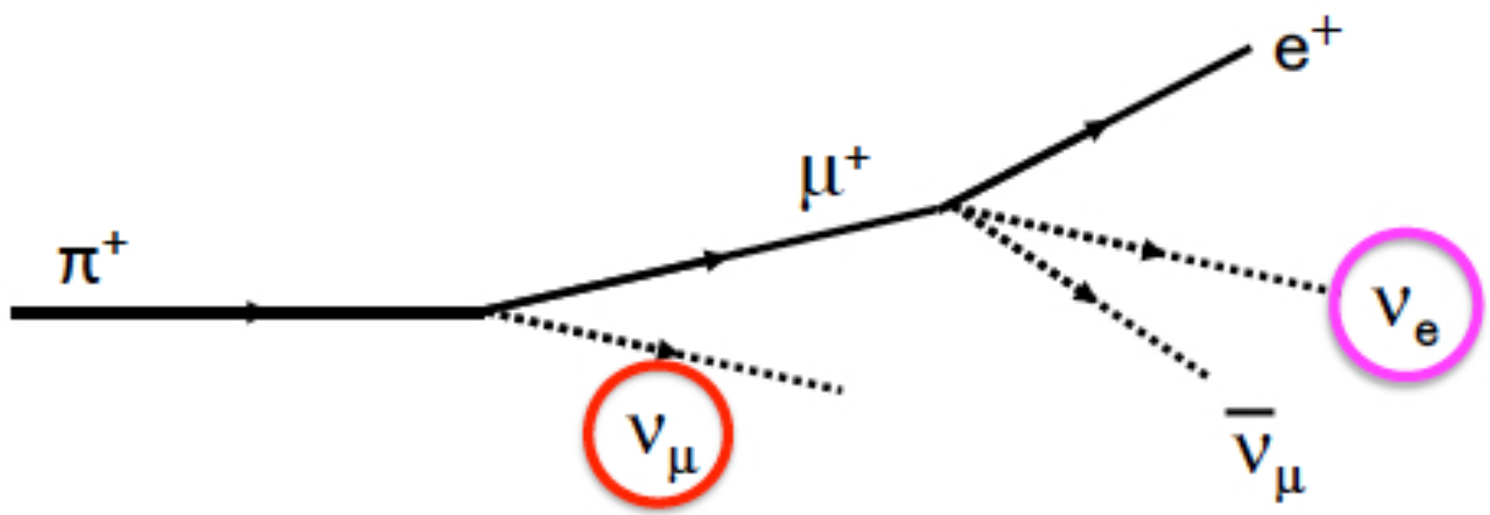


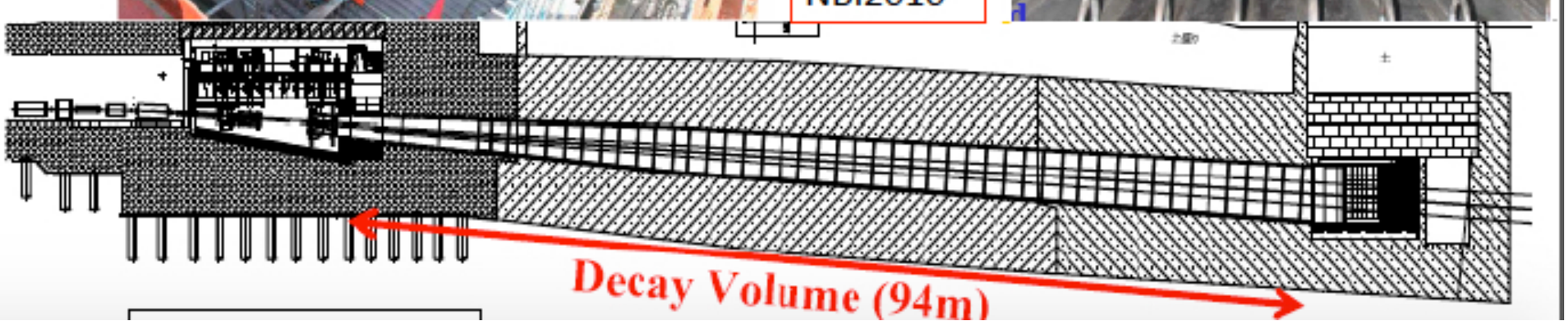
Filler choice:

- Depends on energy of pions and distance
  - 280m in air is 0.26 interaction lengths (26% chance to interact)
- Volume often separated from target region with window to maintain pressure

Decay volume (T2K)

- Iron plating with water cooling
- Flared structure
- Filled with 1atm He (same volume as target)
  - He replaces air which causes nitric acid and tritium production

Y. Yamada
NBI2010



Decay volume (NuMI)

- Copper pipes provide water cooling in surrounding concrete
- Cylinder structure (2m diameter, 677m long)
- Held at vacuum
  - Entrance window is 1.5mm stainless steel

Impressive energy deposition warrants cooling:

- 63 kW in 1 cm thick steel decay pipe
- 52 kW in shielding concrete

J. Hylen
NBI02

Beam dumps

Need a dedicated absorber of uniteracted protons from the beam, and undecayed beam (pi,K,mu) particles

<u>NuMI absorber</u>

1kton Al core

water cooled

Surrounded with steel, concrete

Of 10^{20} protons on target per year, roughly 10^{19} per year hit the absorber

<u>T2K absorber</u>

75 ton graphite core (~3m L x 2m W x 4.5 m H)

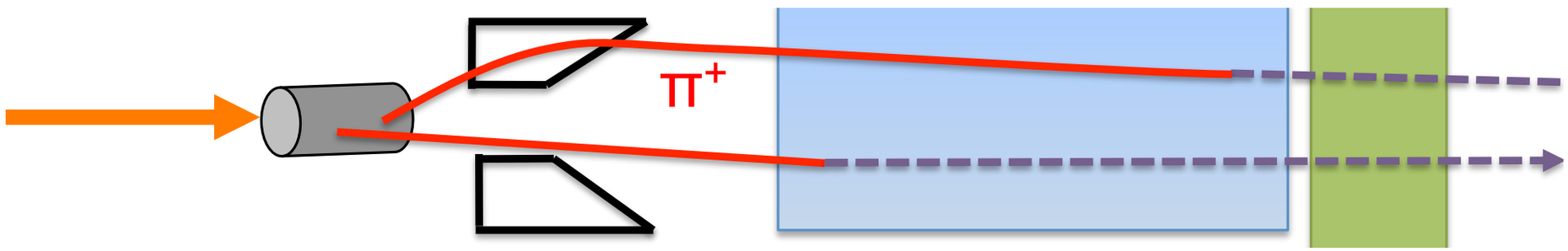
Also within He vessel of decay region

150deg C at 750kW operation

Designed for ~MW beam

D. Harris, INSS05

All the pieces



Hadron production measurements

Muon monitors, neutrino profile detectors, and near detectors

Hadron production measurements

The rate and kinematics of pions (and kaons) exiting the target is one of the most important systematic errors for neutrino beams

- Uncertainty in production cross section of 10% becomes a 10% neutrino beam uncertainty

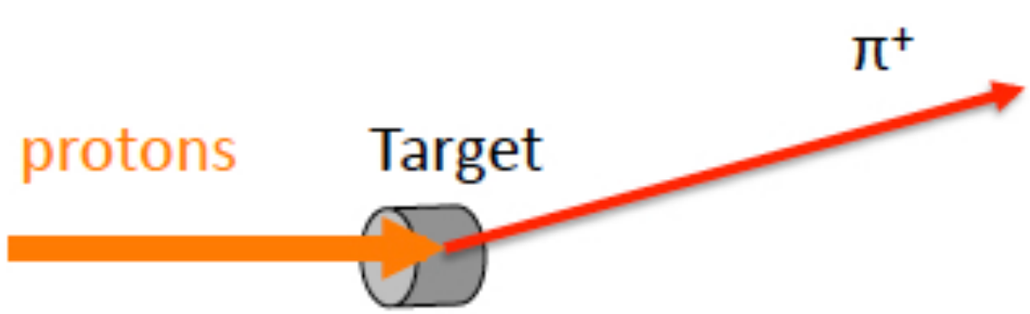
Hadron production measurements

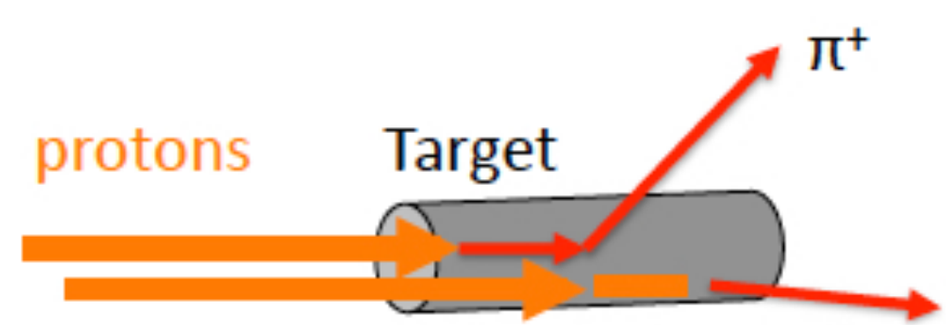
The rate and kinematics of pions (and kaons) exiting the target is one of the most important systematic errors for neutrino beams

- Uncertainty in production cross section of 10% becomes a 10% neutrino beam uncertainty

Modern neutrino experiments rely on dedicated hadroproduction experiments which use the same target and proton energy

- "Thin target": Use a small portion of the target to determine pion production cross section
- "Thick target": Use replica target from experiment. Also includes energy loss and reinteractions of the protons, pions within the target





Hadron production measurements

NA61/SHINE

North Area 61 / SPS Heavy Ion and Neutrino Experiment

Enhanced NeUtrino BEams from kaon Tagging

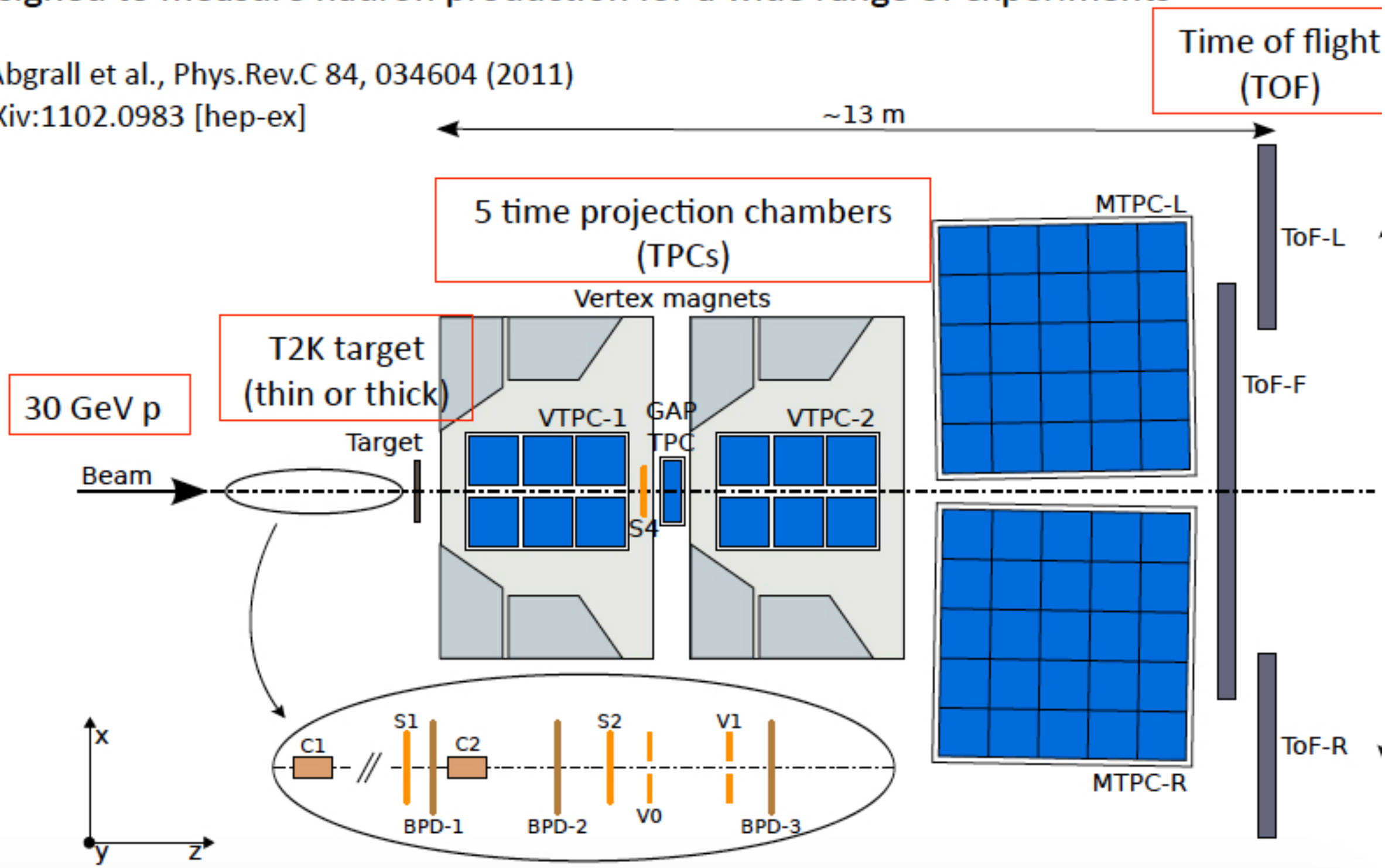
CERN-SPSC-2016-036 ;
SPSC-EOI-014

Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland

Example: NA61/SHINE experiment

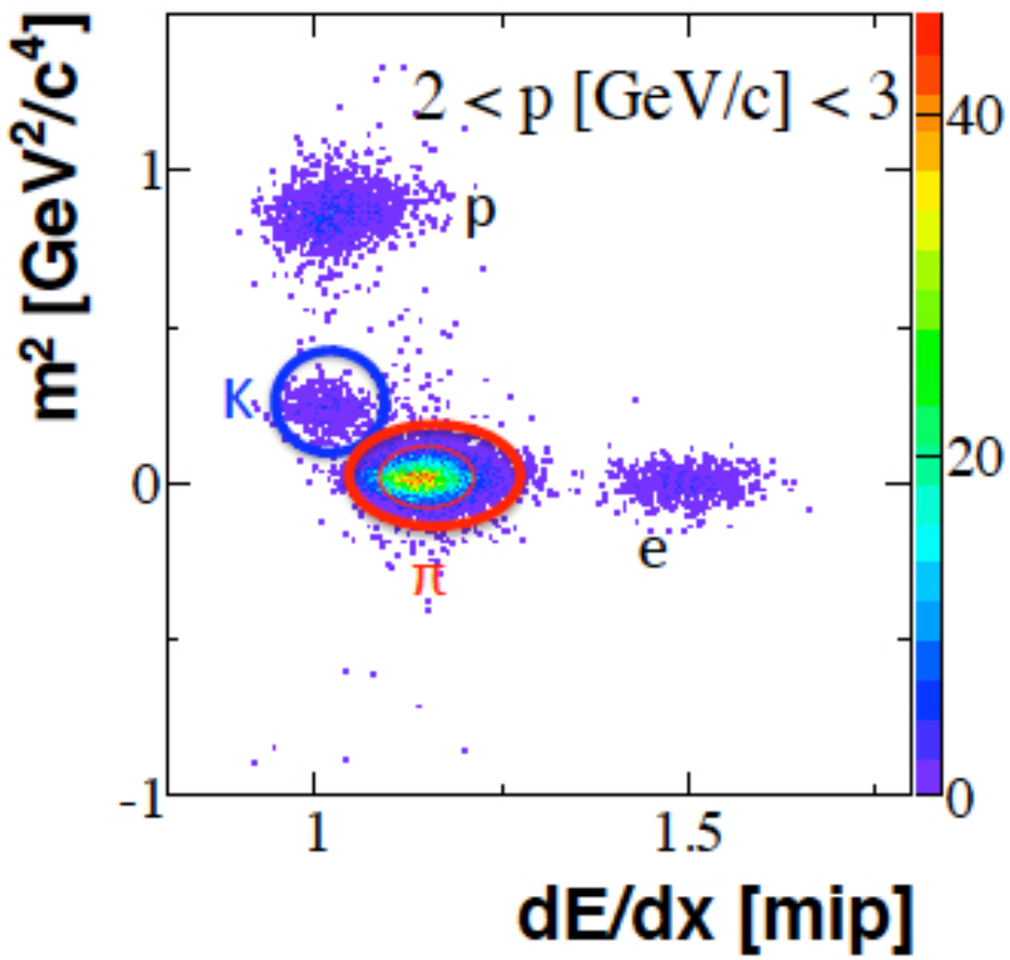
Designed to measure hadron production for a wide range of experiments

N.Abgrall et al., Phys.Rev.C 84, 034604 (2011)
arXiv:1102.0983 [hep-ex]



Example: NA61/SHINE experiment

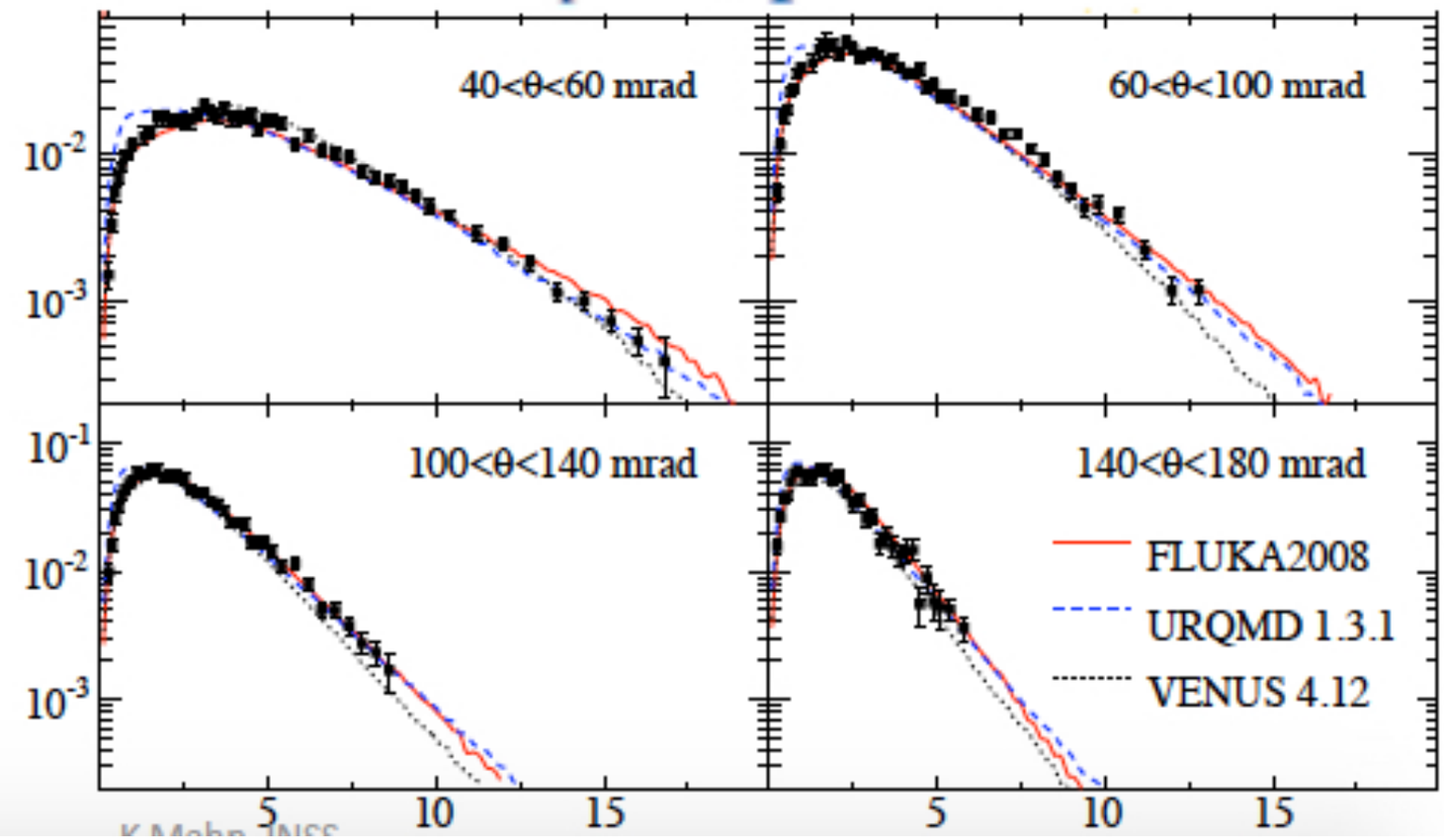
First, select pions using TOF and dE/dx:



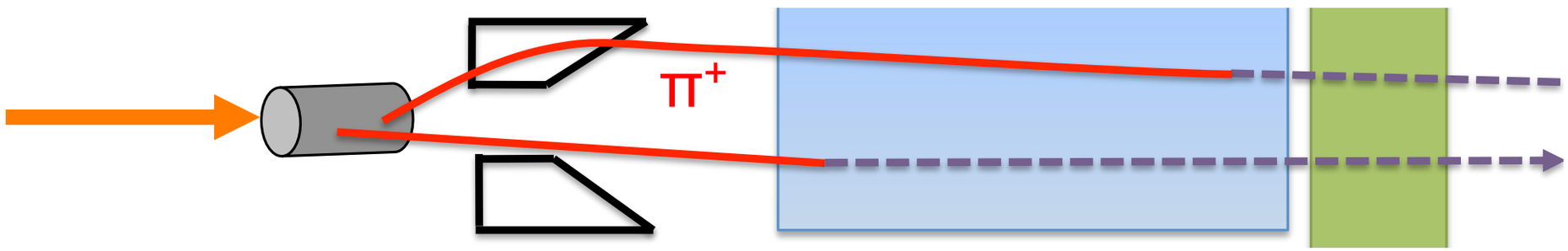
- Reasonable agreement with simulation used for T2K
- Used to determine uncertainties on pion, kaon production

Then, determine the pion production differential cross section:

$$\frac{1}{\sigma_{prod}}\frac{d\sigma}{dp}\,[1/\mathrm{GeV}/c]$$



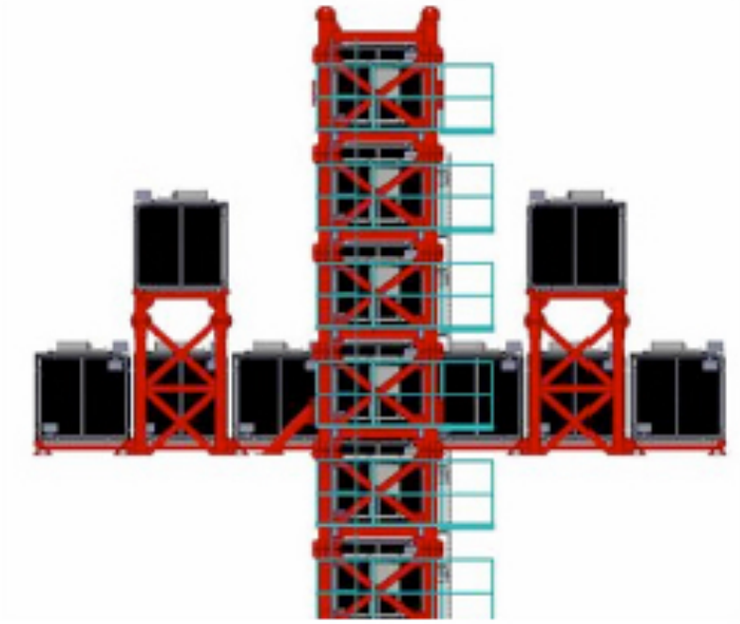
All the pieces



More on near detectors tomorrow

Muon monitors, neutrino profile detectors, and near detectors

Beam direction monitors (T2K)

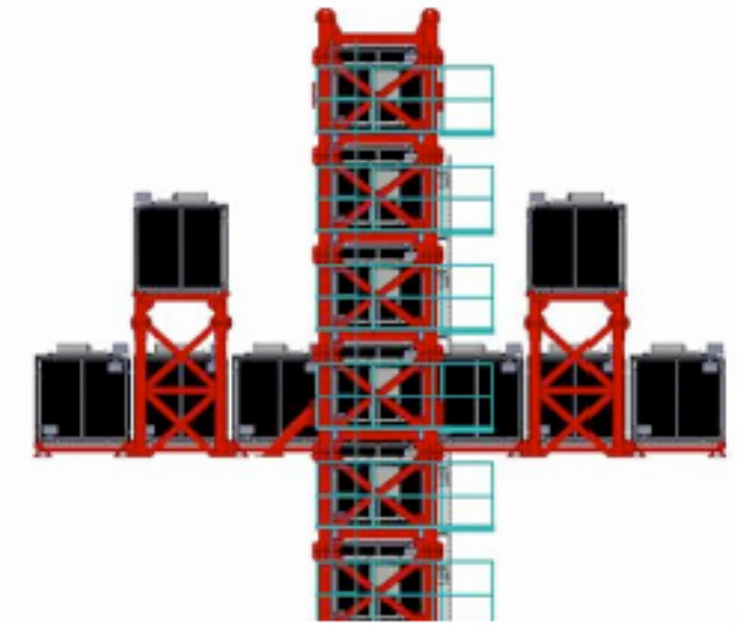


T2K's Interactive Neutrino GRID

- Offaxis beam direction alters ν energy spectrum
- Beamline and detector position known from surve but may vary with time

  Constrain beam direction with dedicated detector

Beam direction monitors (T2K)

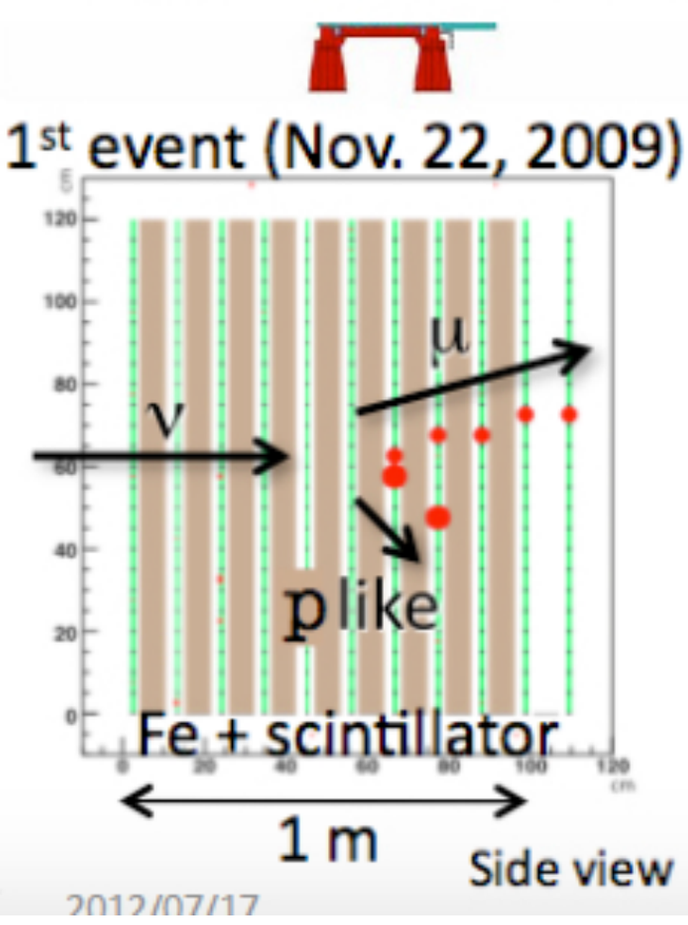


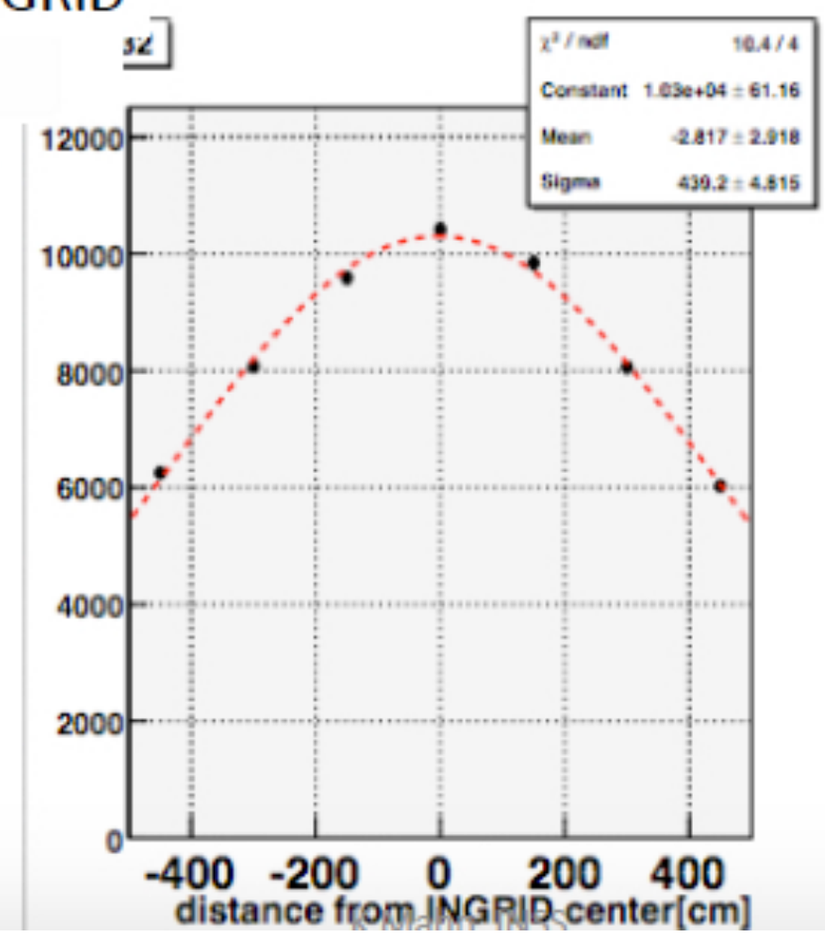
T2K's Interactive Neutrino GRID

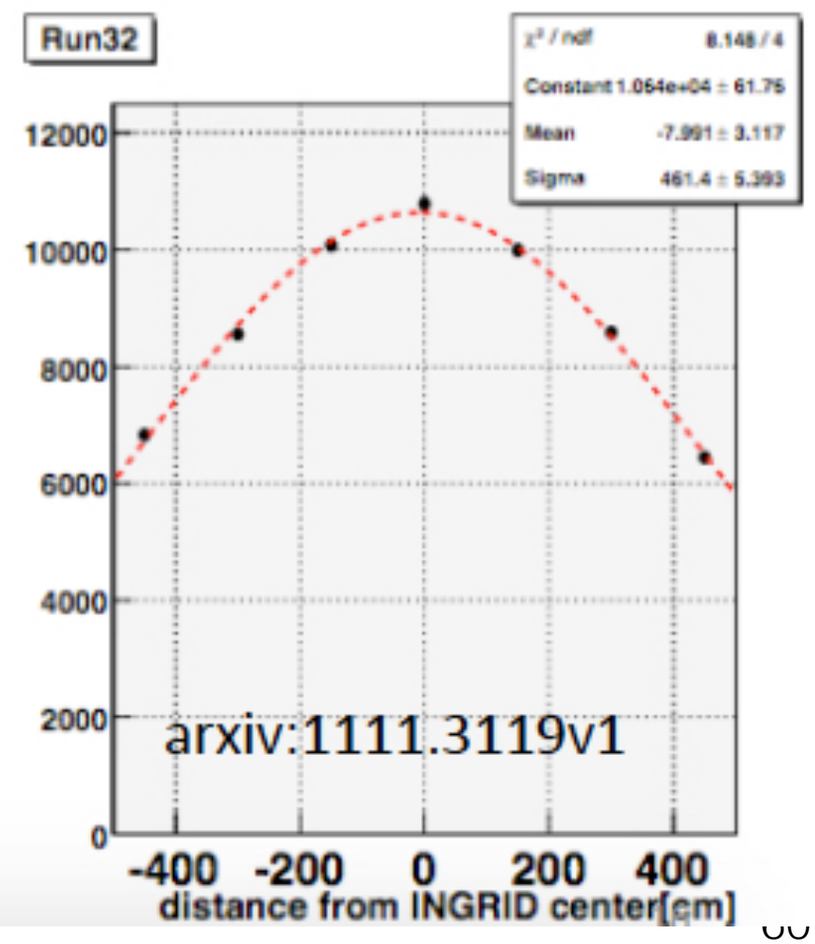
- Offaxis beam direction alters ν energy spectrum
- Beamline and detector position known from survey, but may vary with time

  Constrain beam direction with dedicated detector

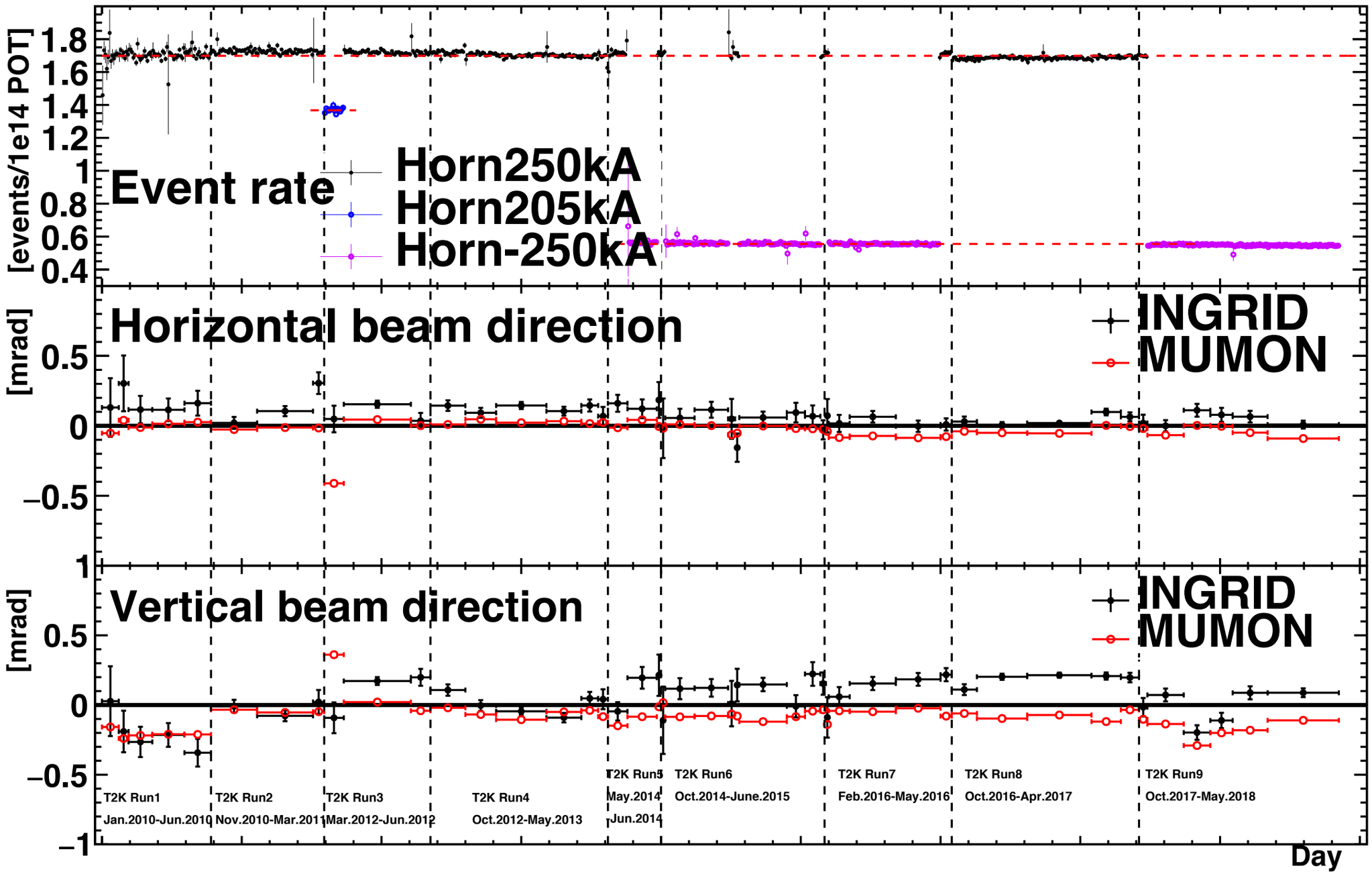
- Count neutrino interactions in each module to determine neutrino rate vs. position
- Extract beam direction better than 0.5 mrad







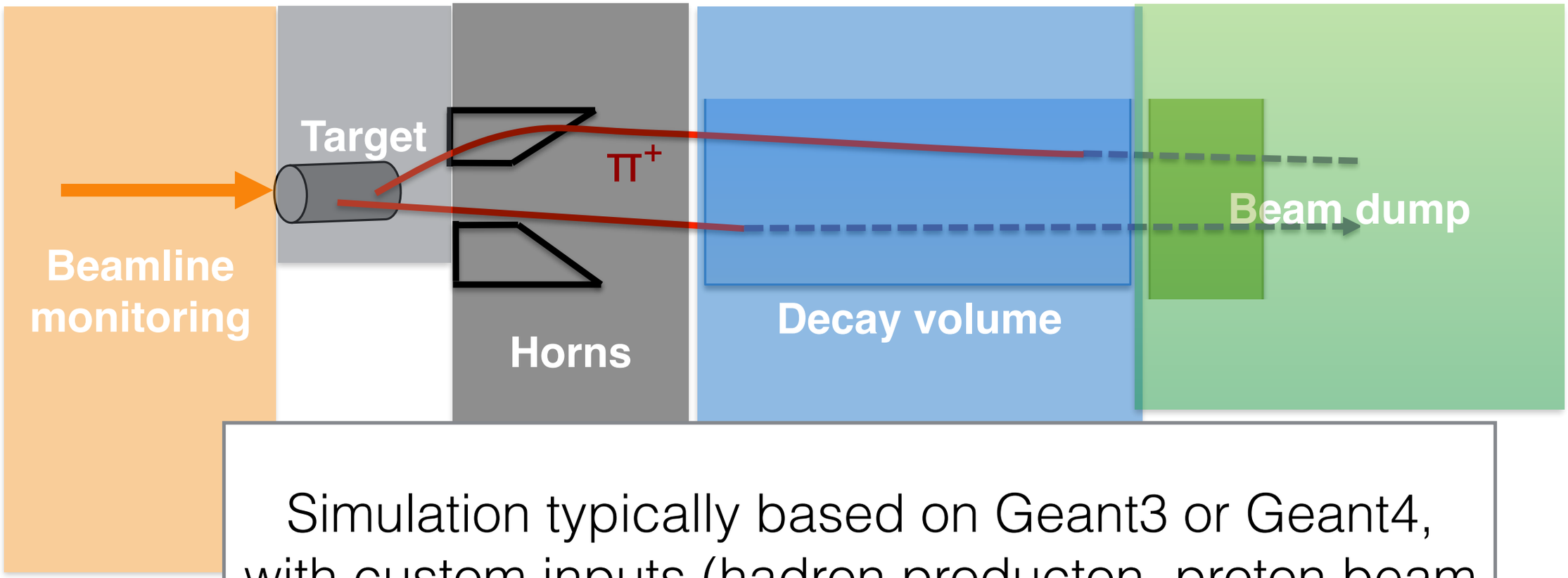
Beam direction monitors (T2K)



High energy part of the flux sampled by a muon monitor

Nucl.Instrum.Meth.A624:591-600,2010

Simulate All the pieces

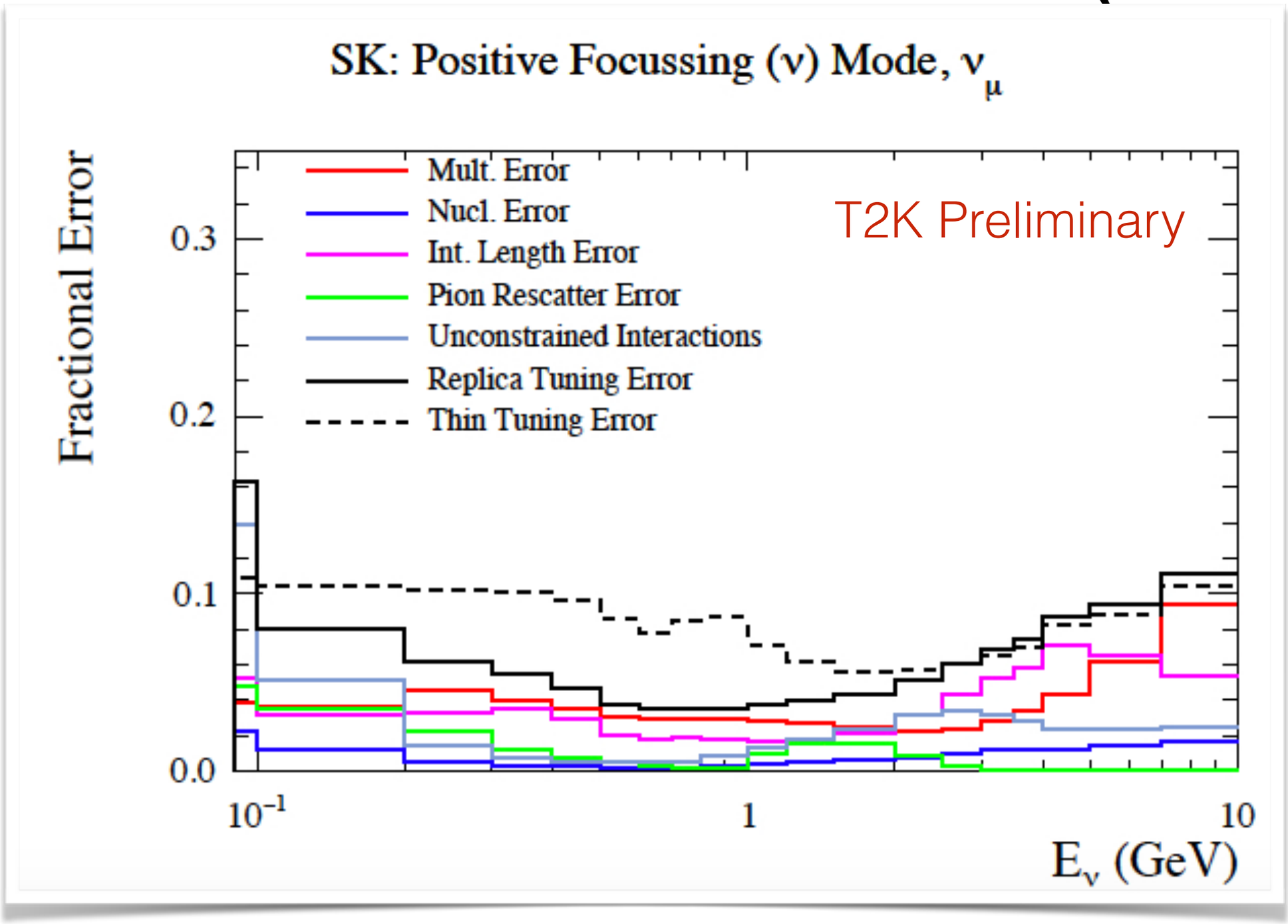


Simulation typically based on Geant3 or Geant4, with custom inputs (hadron producton, proton beam conditions, etc)

Hadron production measurements

Muon monitors, neutrino profile detectors, and near detectors

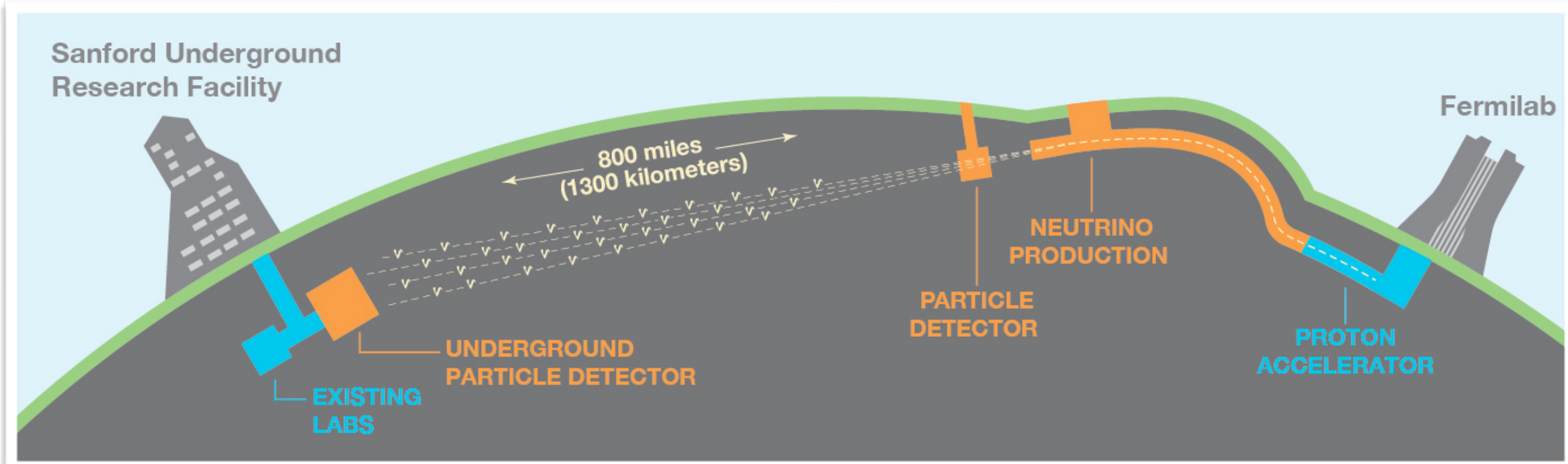
Latest flux uncertainties (T2K)



Outline

Challenges of operating neutrino beams

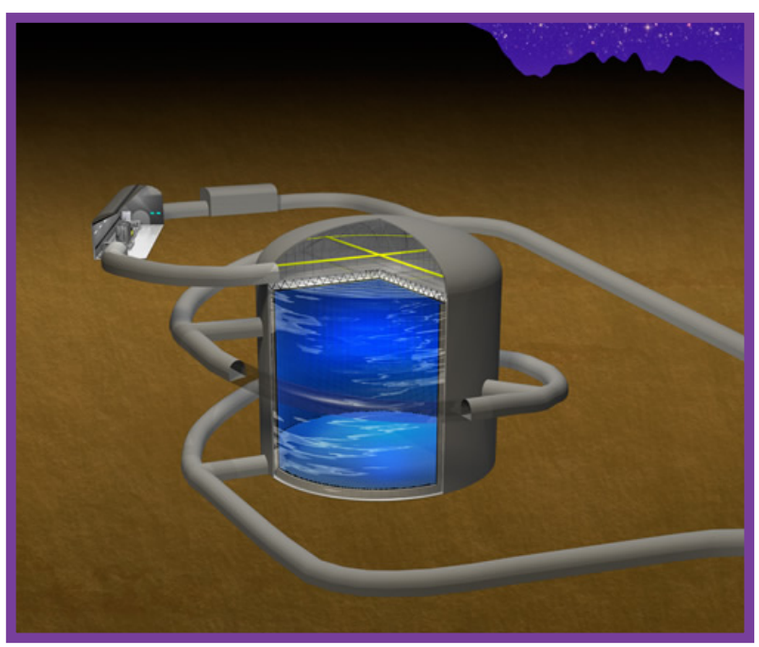
Next generation: DUNE and Hyper-Kamiokande

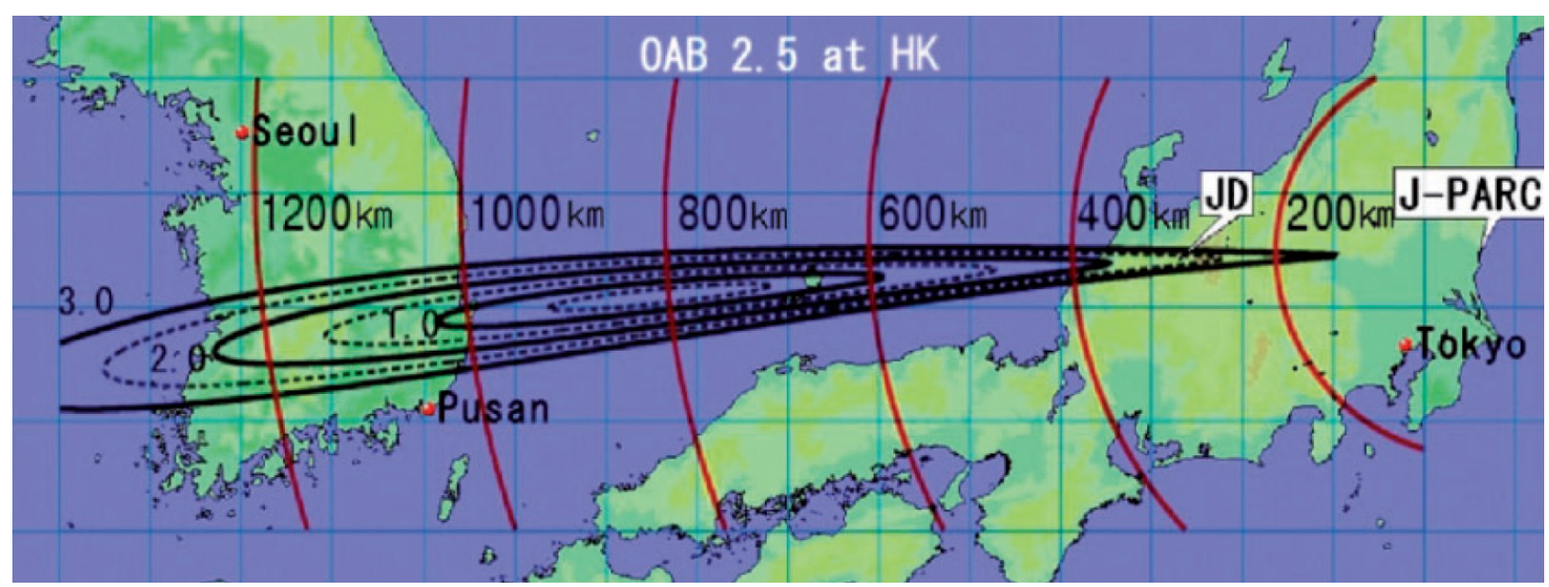


dunescience.org

arxiv.org/1807.10334

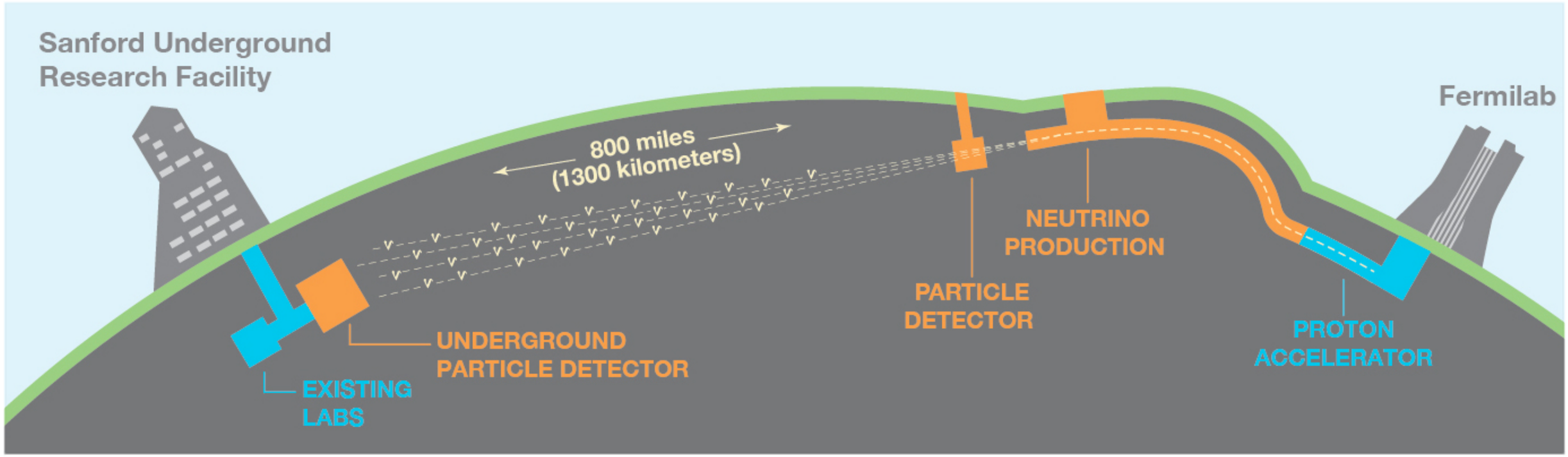
Next generation oscillation experiments will use ~MW scale beams





Prog. Theor. Exp. Phys. 2018 , 063C01

Next generation: DUNE and Hyper-Kamiokande



dunescience.org

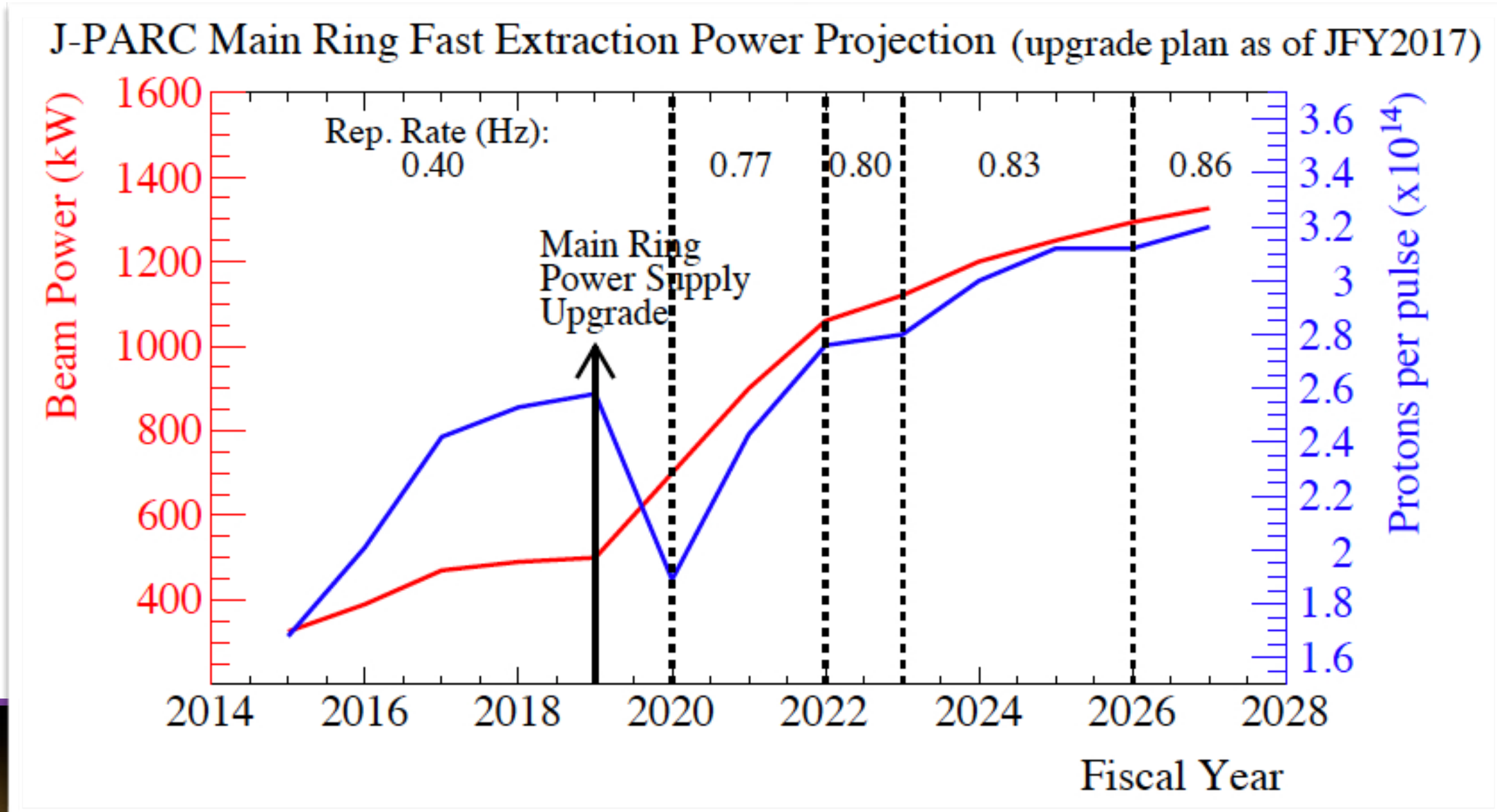
arxiv.org/1807.10334

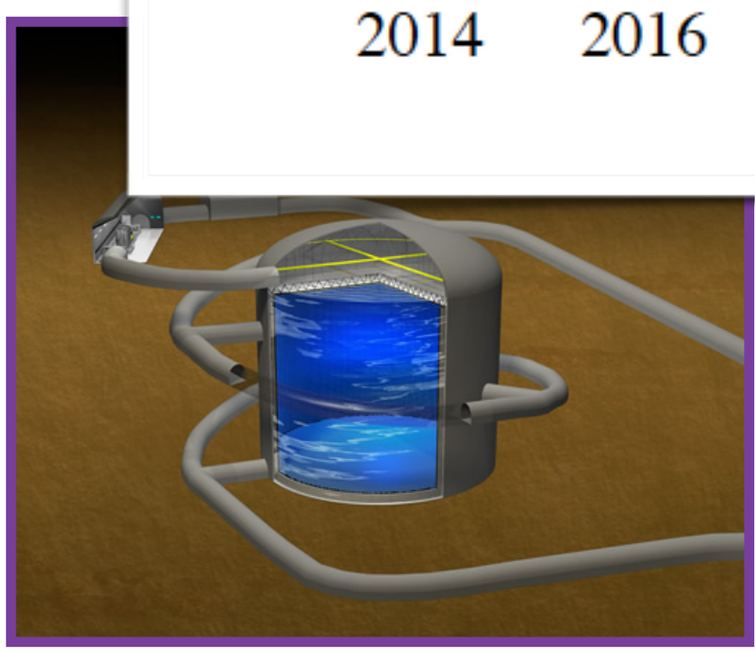
Next generation oscillation experiments will use ~MW scale beams

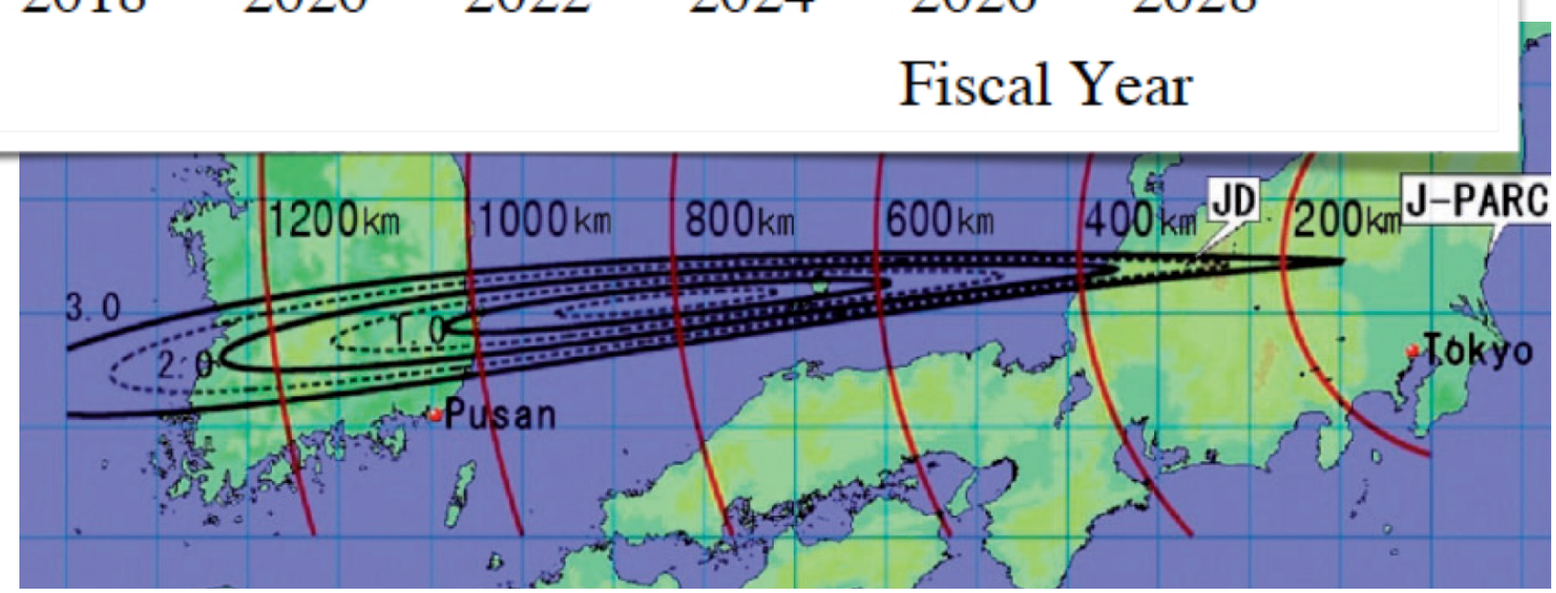
Specifically, the Long-Baseline Neutrino Facility (LBNF) provides

- the technical and conventional facilities for a powerful 1.2 MW neutrino beam utilizing the PIP-II upgrade of the Fermilab accelerator complex, to become operational by 2026 at the latest, and to be upgradable to 2.4 MW with the proposed PIP-III upgrade;

Next generation: DUNE and Hyper-Kamiokande

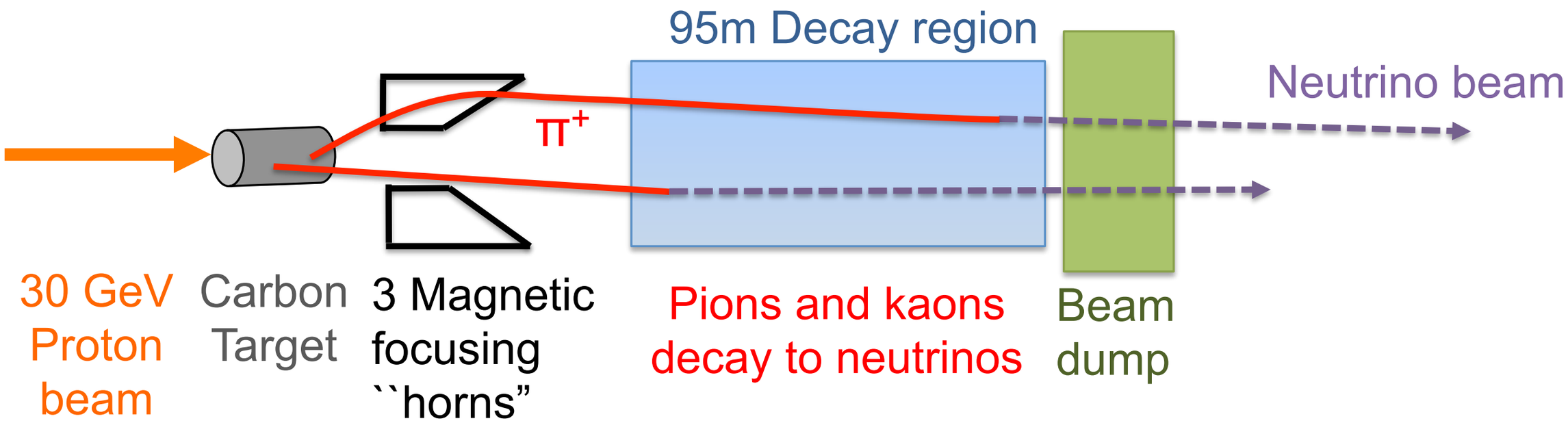






Prog. Theor. Exp. Phys. 2018 , 063C01

Towards high powered (conventional) beams



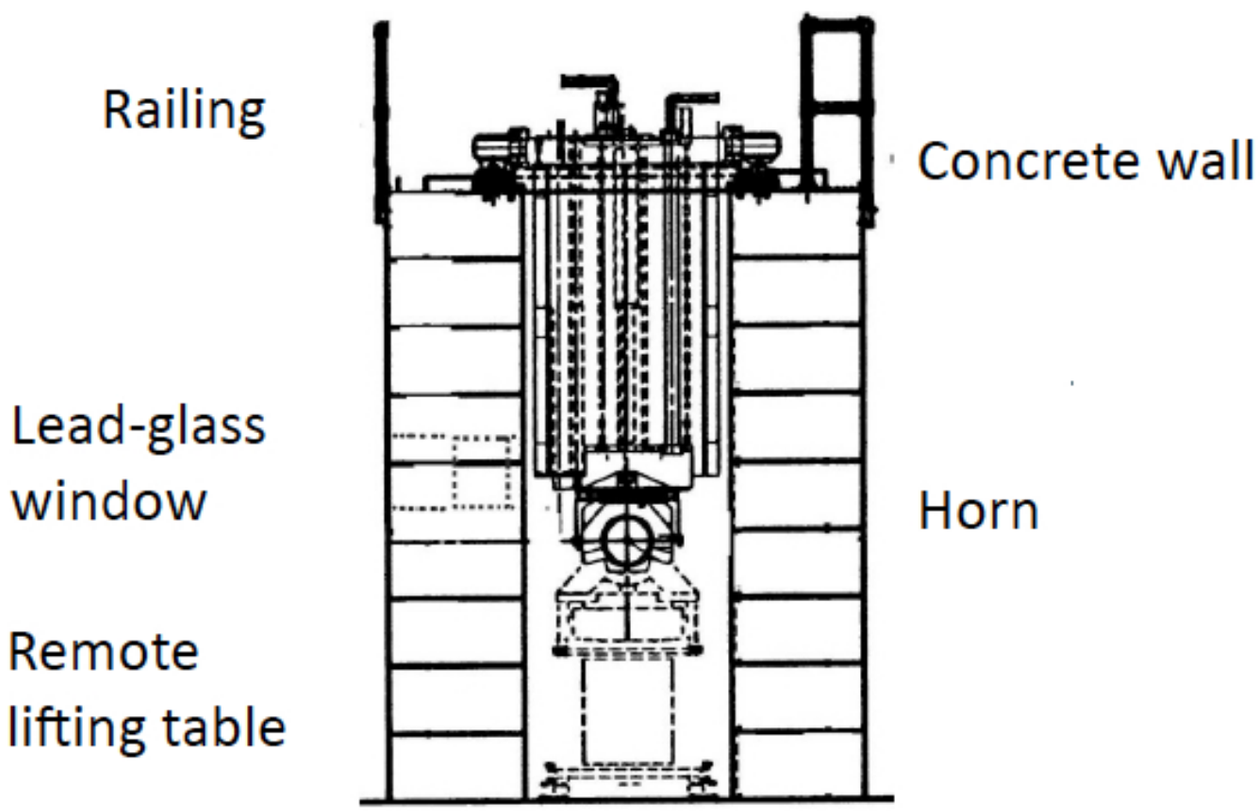
Next generation oscillation experiments will use ~MW scale beams

Considerations:

- Direct or indirect contact with high intensity proton beam?
- What materials are used, and how long will they last?
- How can components be replaced or disposed of?

Examples of neutrino beam line failures: Targets

NuMI
E. Gschwendtner, NuFact08



☑ Remote access to target + backups

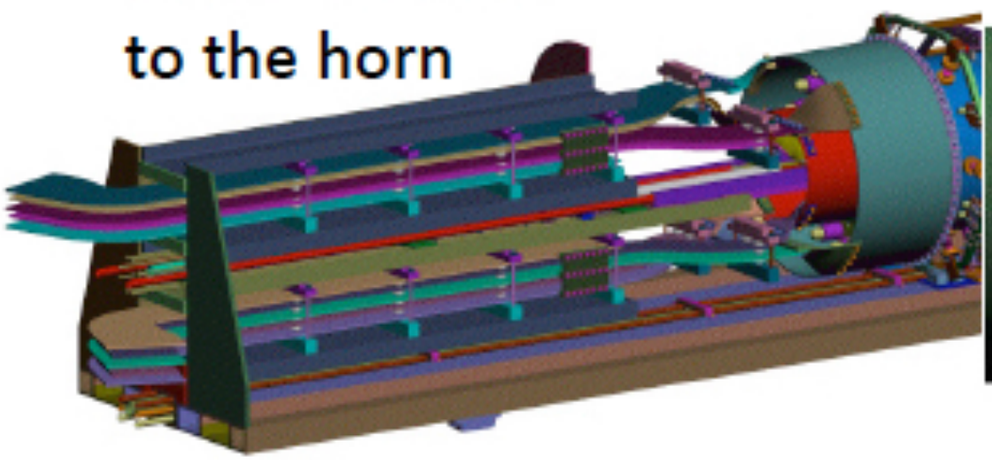
Replaced target when motor drive shaft failed, repair/replaced longitudinal drive failure
Used He gas to mitigate the water cooling system leak

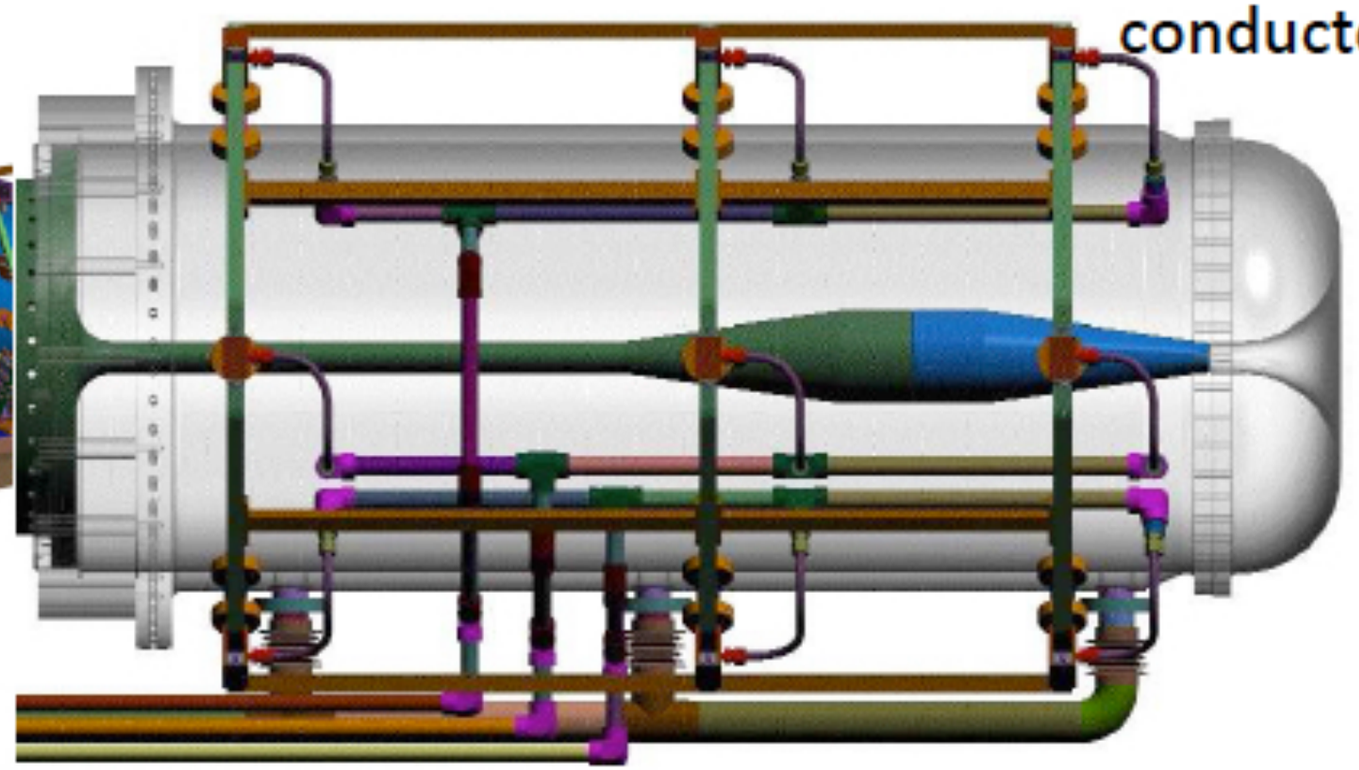
Horns are complex devices

Power supply and striplines which connect to the horn

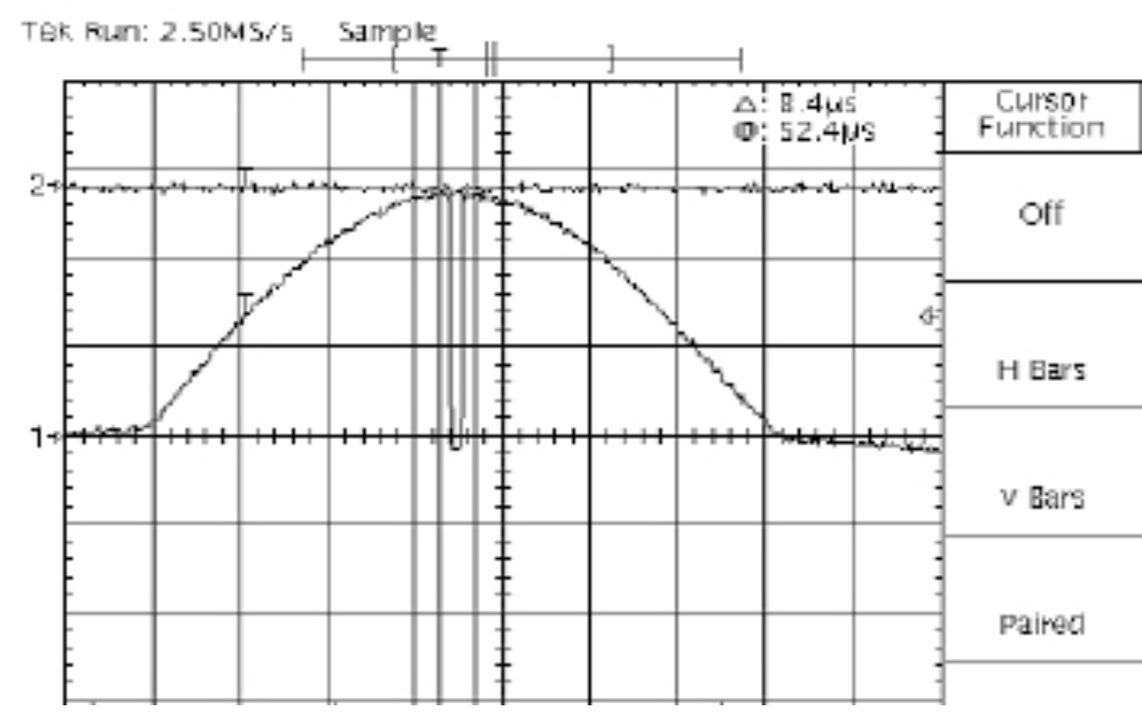
Cooling system

Inner and outer conductors





MiniBooNE horn design drawings (Bartoszek Engineering)



"Pulsed": maximum current goes across conductor for small period of beam

Example: MiniBooNE 170kA at 5Hz

Examples of neutrino beam line failures: Horns

K2K: *Replace horns before too radioactive*

- Final (4th) horn inner conductor failed close to end-of-run, too radioactive

MiniBooNE: *Prepared dedicated remote removal system*

- First horn failed due to water corroding the stripline from cooling system
- Second horn cooling system bellows modified, never failed

NuMI: *Prepared dedicated remote removal system and remote handling cell*

- Multiple issues: ground fault, material in water cooling system (resin), water system ceramic seal leaks
- Initially problems were repairable, but later had to replace the first horn

T2K: *Prepared dedicated remote removal system and remote handling cell*

- Neutrino beamline recovered from severe earthquake
- Power supply component failed, reused older power supply

☑ Learn from previous experiments

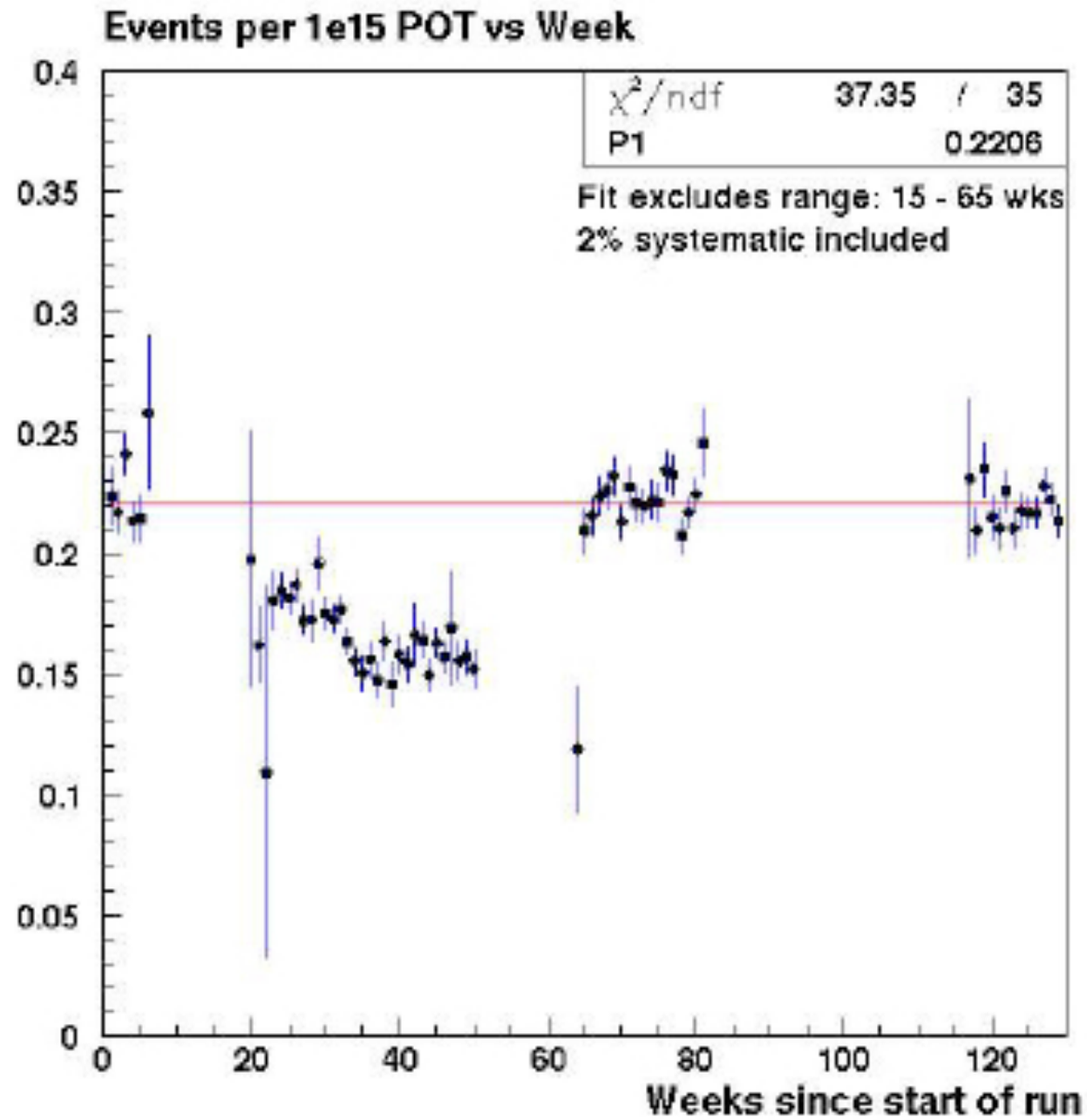
Examples of neutrino beam line failures: decay region?!

MiniBooNE's 50m decay region was designed with extra absorbers at 25m which could be placed into the beam

- Shortens decay region, alters beam ν_e composition

In 2006, two of the 10 absorber plates fell into the beamline, and were later removed

E. Gschwendtner, NuFact08



The hardened steel supports for the suspended plates had weakened in the high radiation environment

- Softer steel was used to suspend the plates
- Many experiments now fill decay region with He

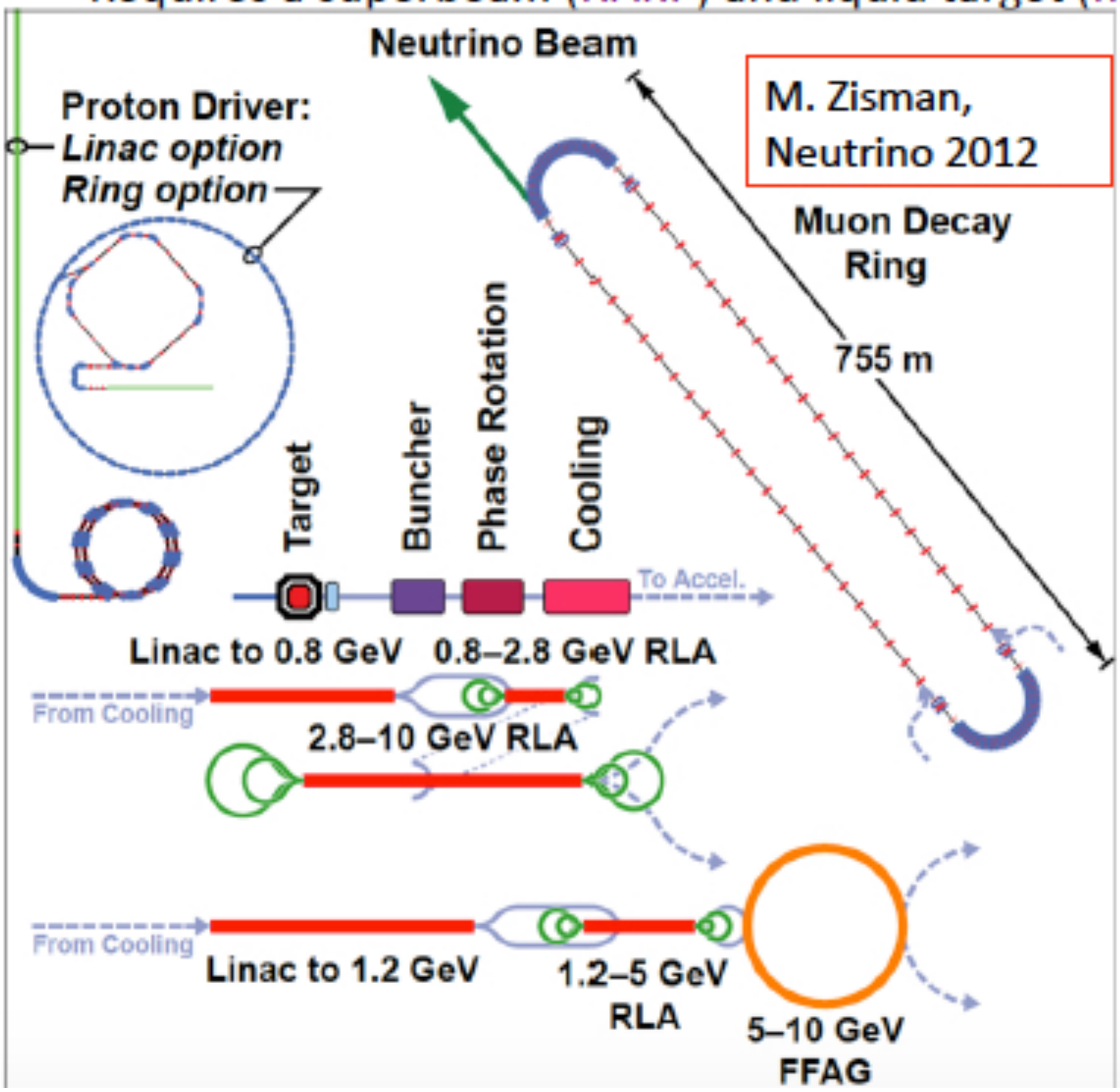
☑ The unexpected is possible

Outline

Future neutrino beam ideas

Neutrino factory

Requires a superbeam (HARP) and liquid target (MERIT, mercury)



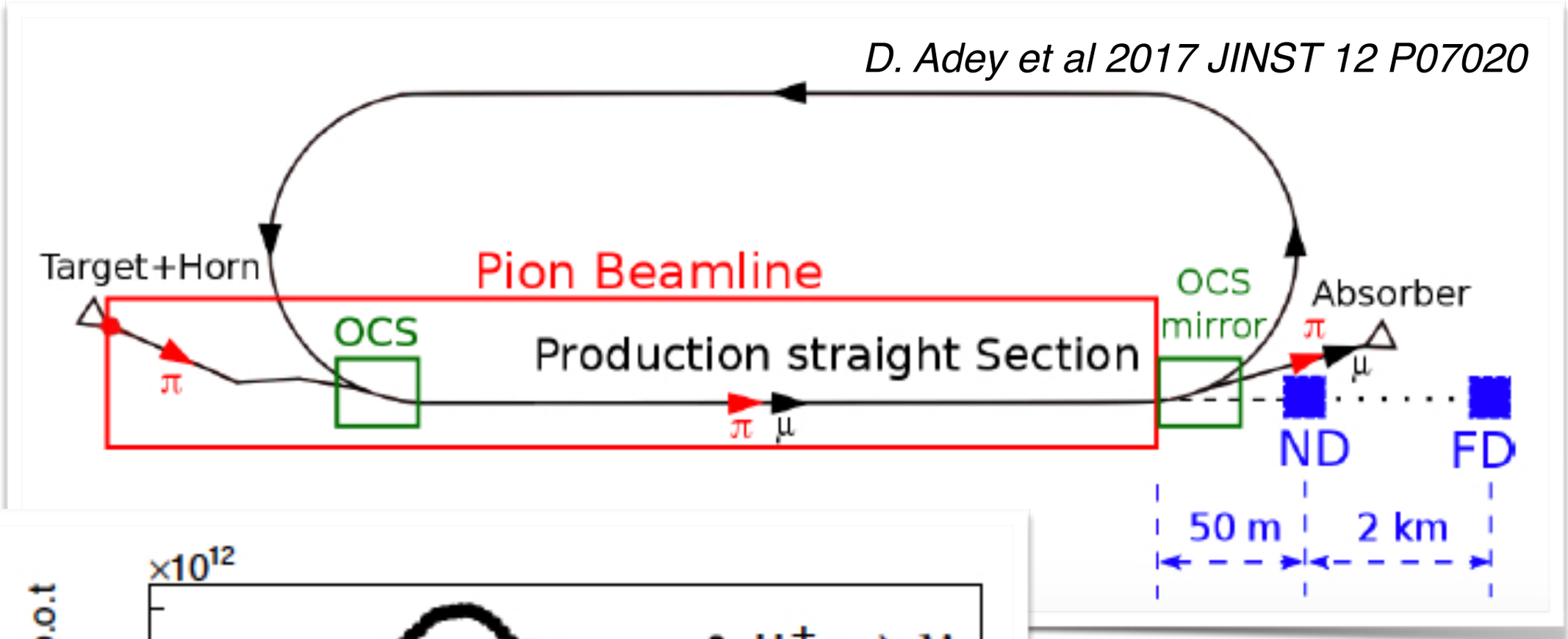
M. Zisman, Neutrino 2012

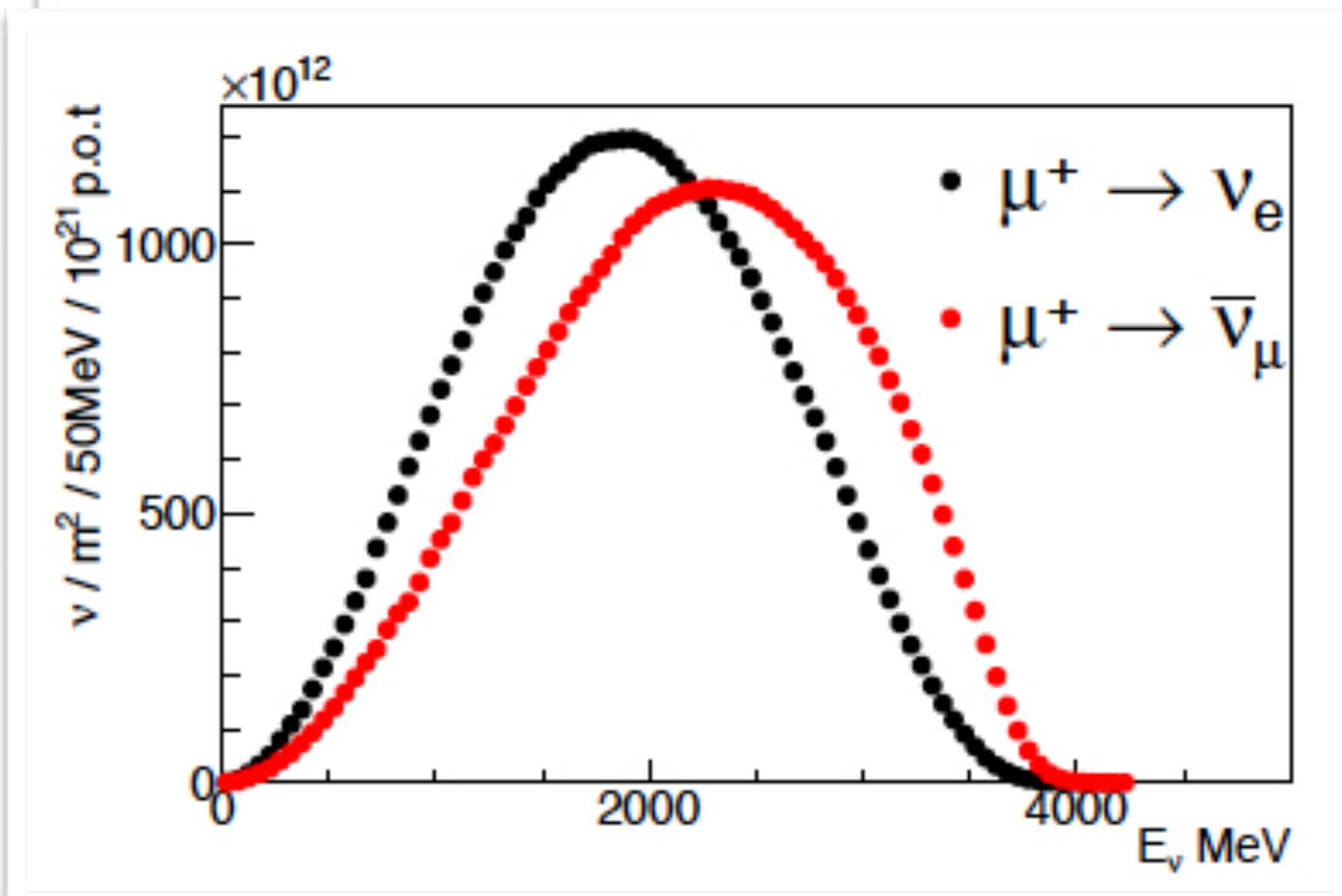
Bunch and phase rotate them
Cool them (MICE)
Accelerate them (EMMA)
Store them, and let them decay to produce a neutrino beam

Dedicated R&D projects to produce each of the steps:

1) Large energy spread, transverse phase space of the muons
2) Short lifetime before decay requires rapid beam manipulations

vSTORM



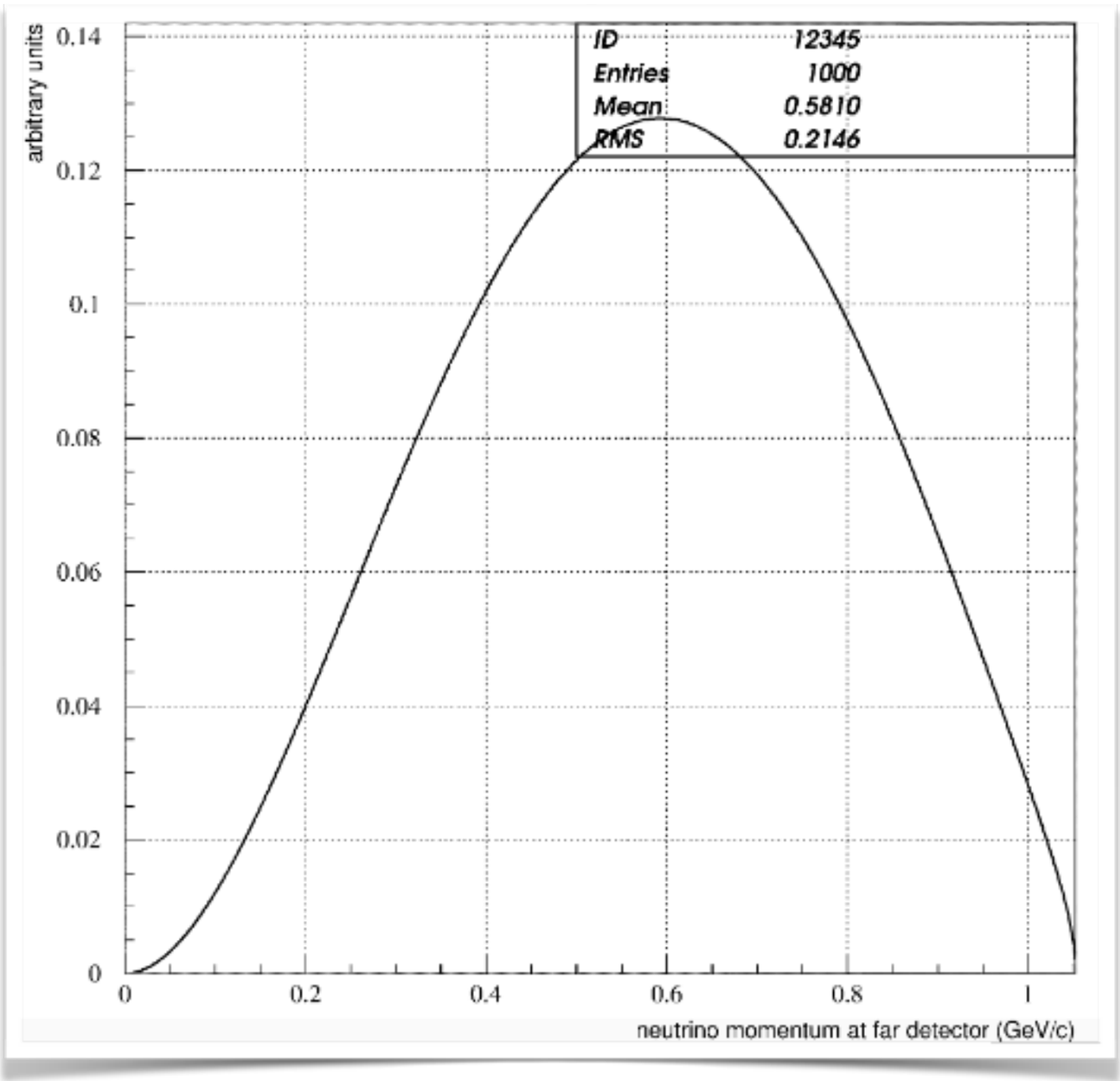


Uses 'conventional' beam technology

Extremely pure beam

“beta” beam

$$\boxed{{}^{6}_{2}He^{++} \rightarrow {}^{6}_{3}Li^{+++} + e^{-} + \overline{\nu}_{e}}$$



Pure (low energy) beam from beta decay

P. Zucchelli, Phys. Lett. B 532, 166 (2002).

“beta” beam

$$\boxed{{}^{6}_{2}He^{++} \rightarrow {}^{6}_{3}Li^{+++} + e^{-} + \overline{\nu}_{e}}$$

Additional advantages:

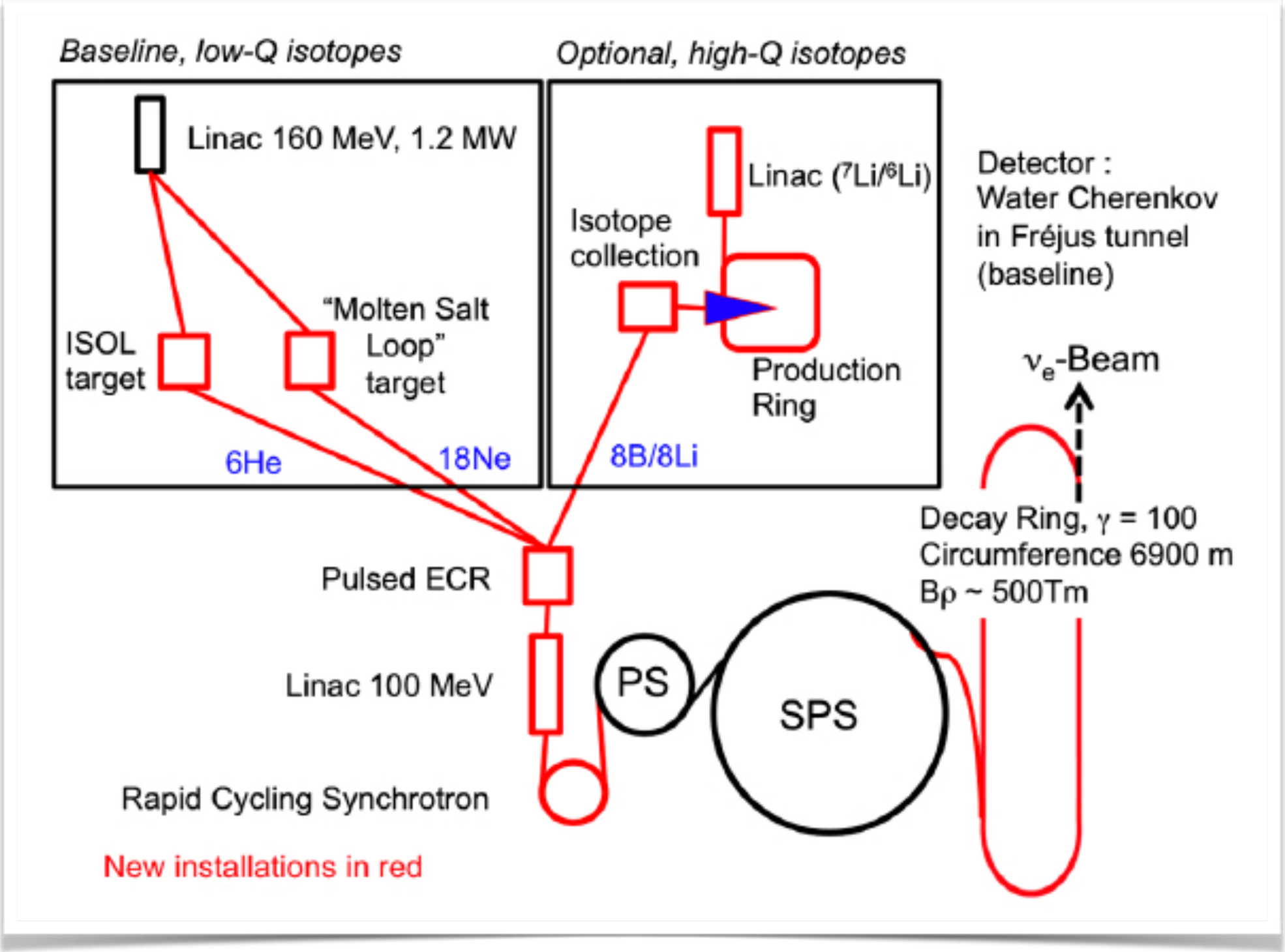
- No need for a magnetized detector
- Energy spectrum determined from electrons emitted from decay at rest, and boost: Assuming γ~100, get E_ν~0.4 GeV

$$\boxed{E_\nu \leq 2Q\gamma}$$

- “Free” focusing of ν beam comes from boost:

$$\boxed{\theta \leq \frac{1}{\gamma}}$$

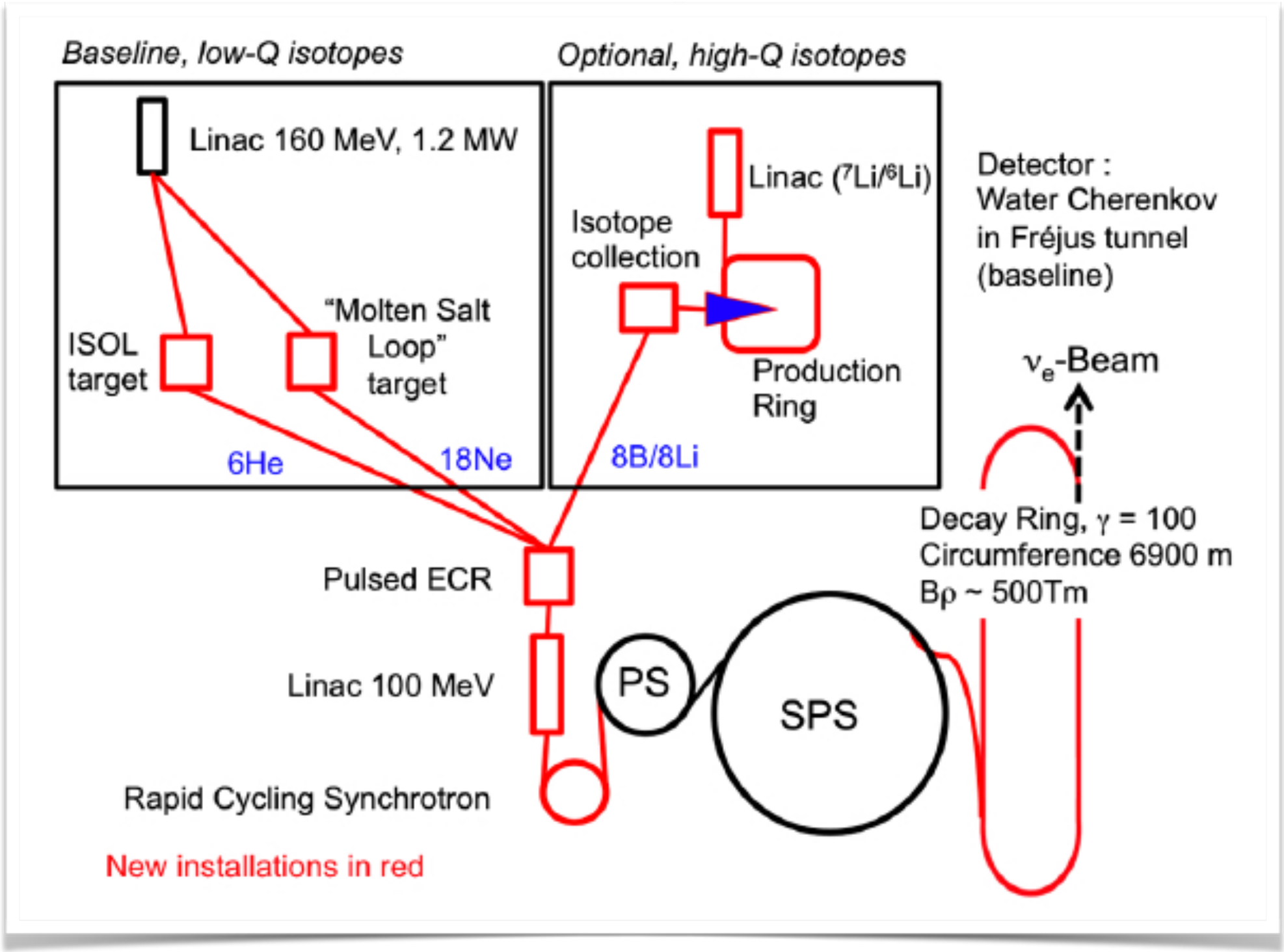
“beta” beam



Phys.Rev. Special Topics: Accelerators and Beams **17**, *071002 (2014)*

Additional reading: *Lindroos and Mezzetto, Ann. Rev. Volume 60, 2010*

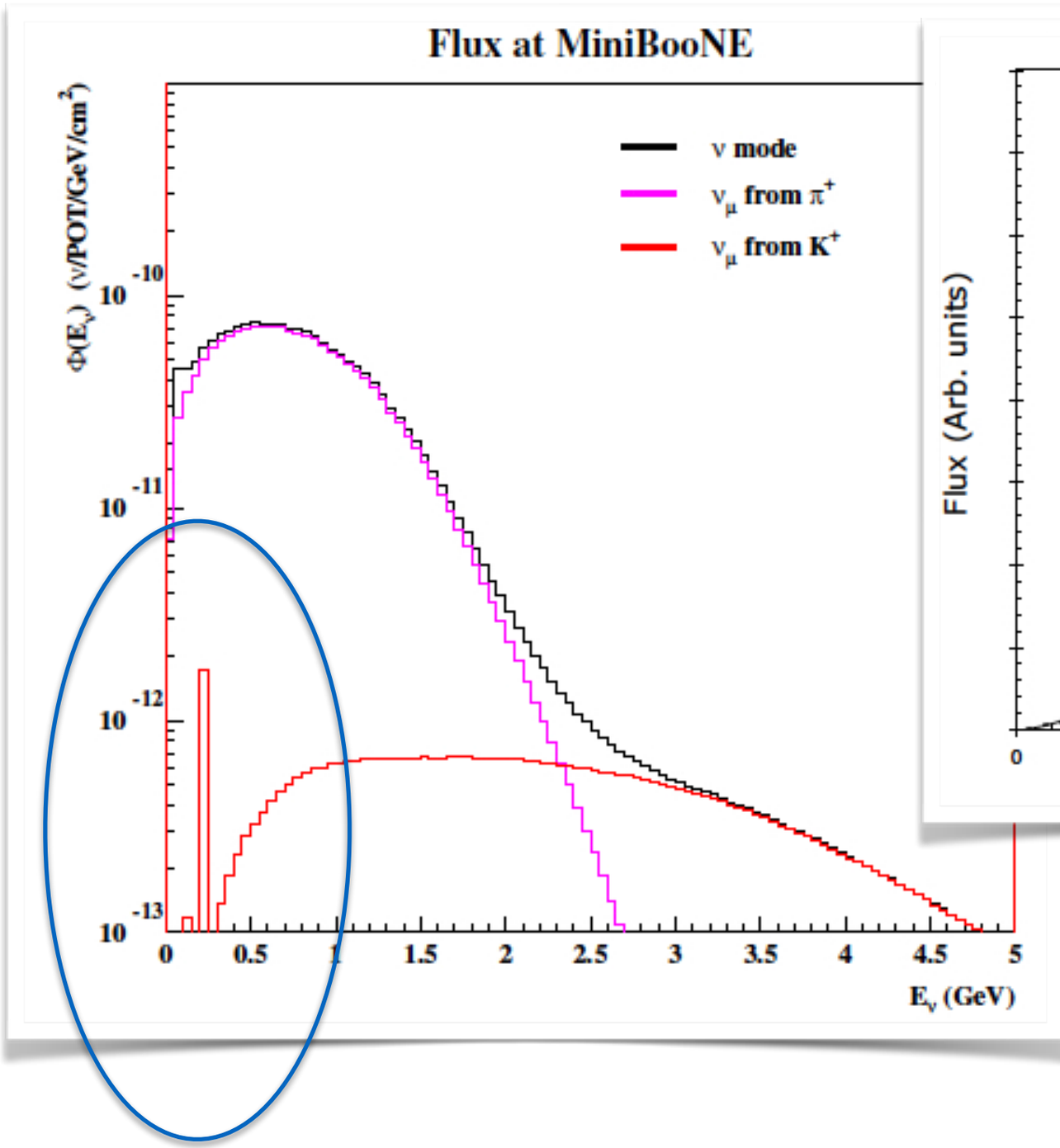
“beta” beam

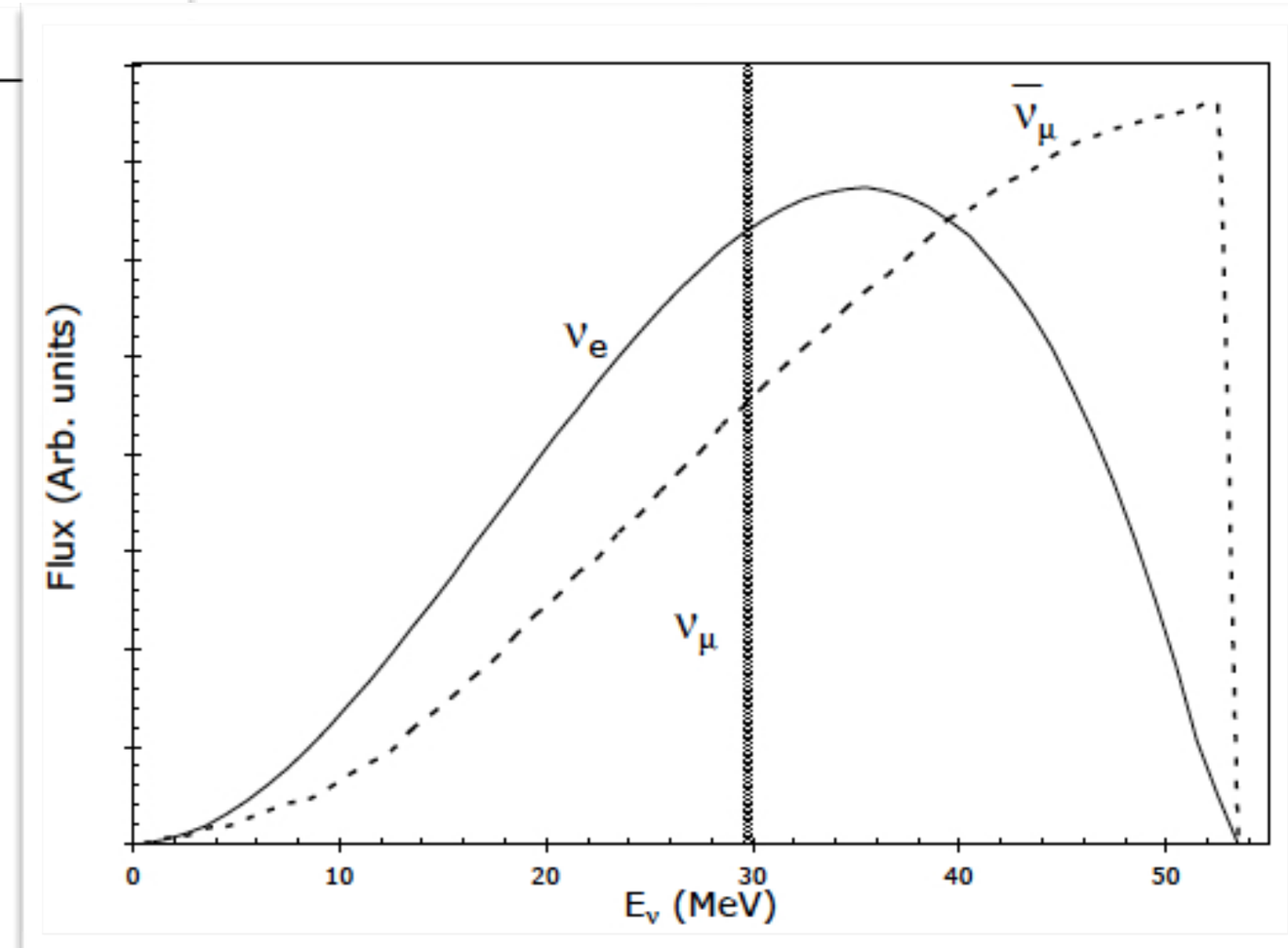


Phys.Rev. Special Topics: Accelerators and Beams **17**, *071002 (2014)*

Challenge: Long isotope lifetime to avoid decays during acceleration but short isotope lifetime or issues in decay ring

Decay at Rest (DAR) beams



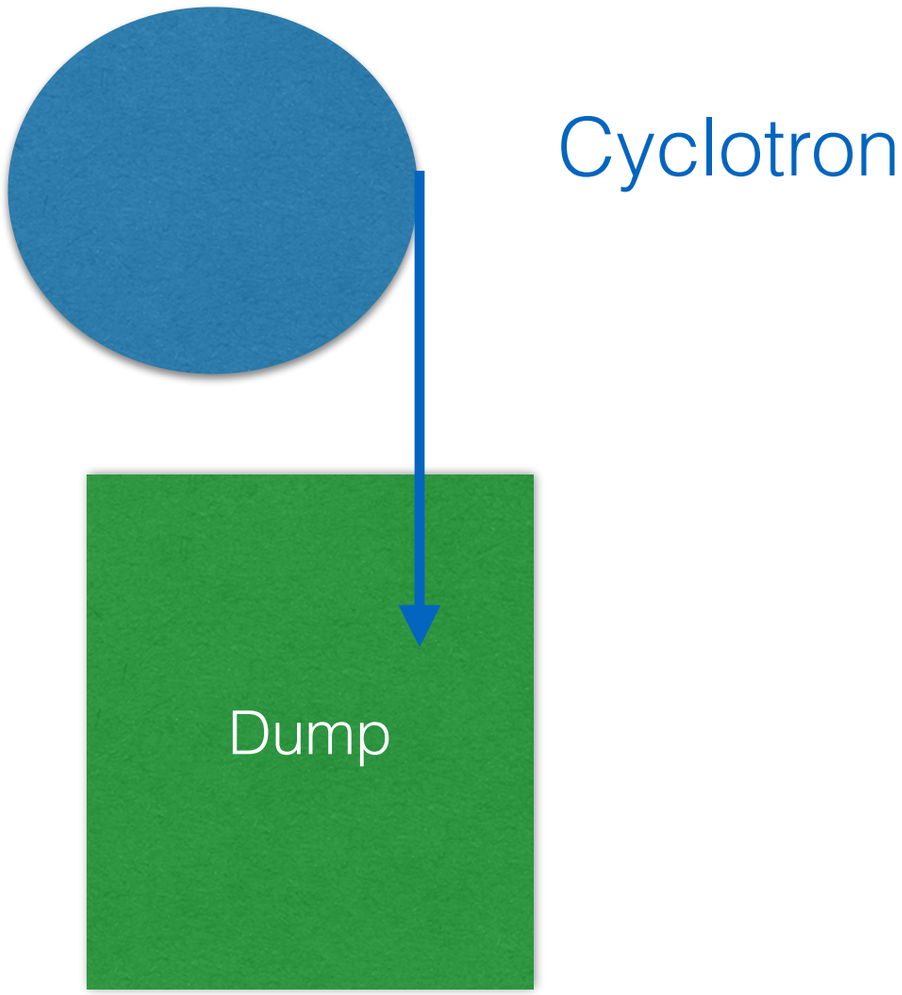


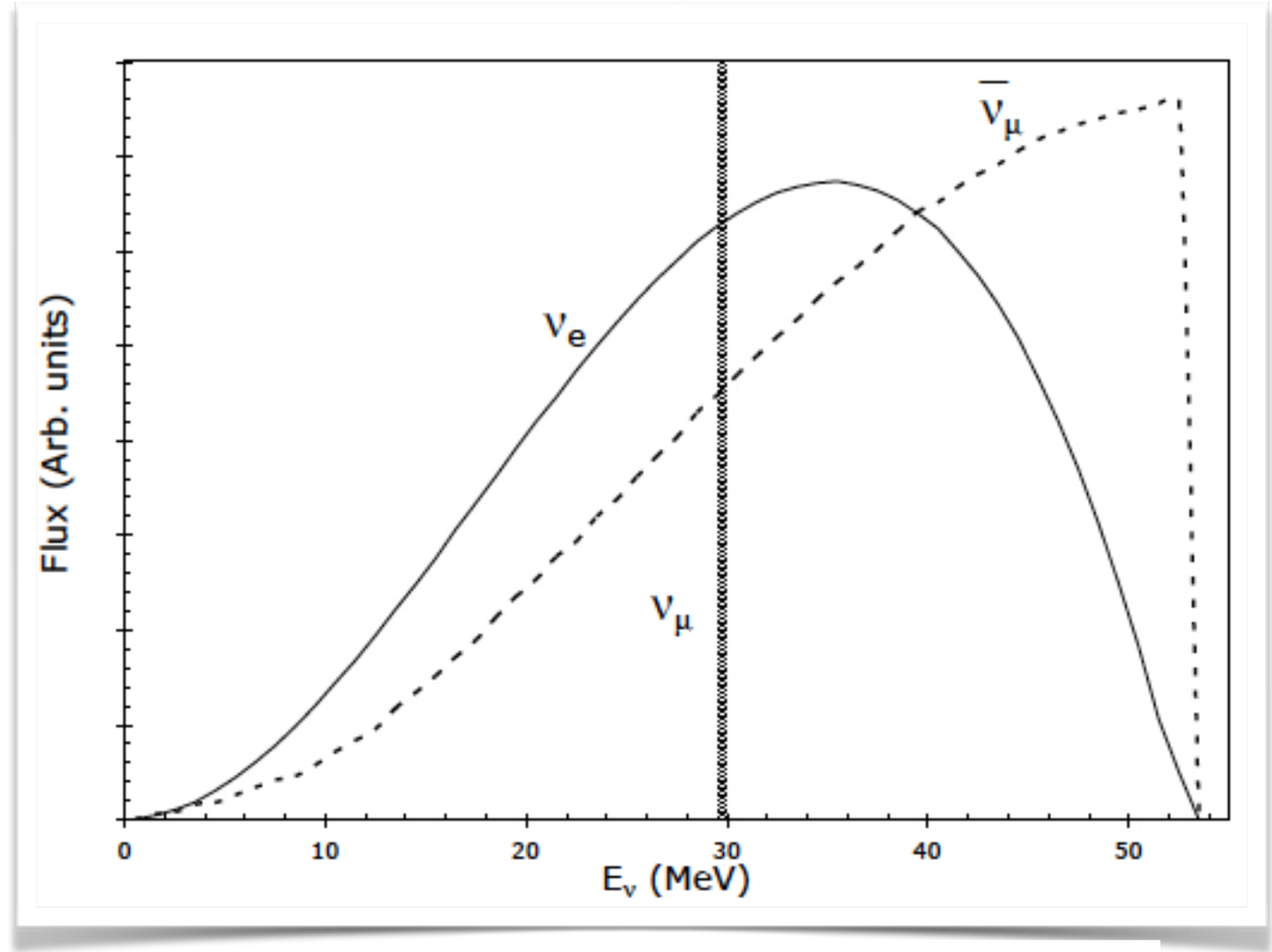
arxiv.org/1207.4895

Monoenergetic (236 MeV) peak from stopped kaon decay

Pion decay at rest

Decay at Rest (DAR) beams



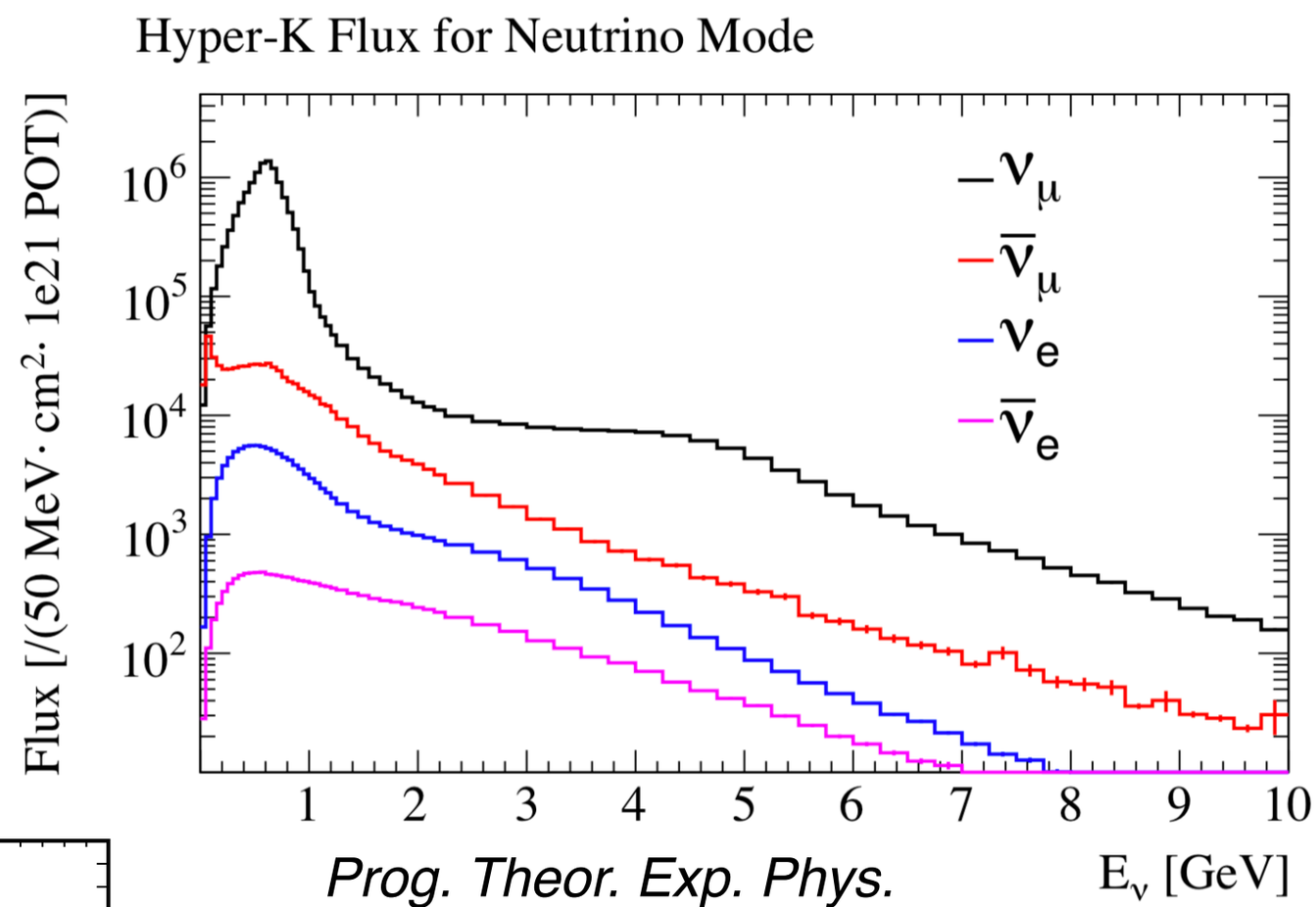


arxiv.org/1207.4895

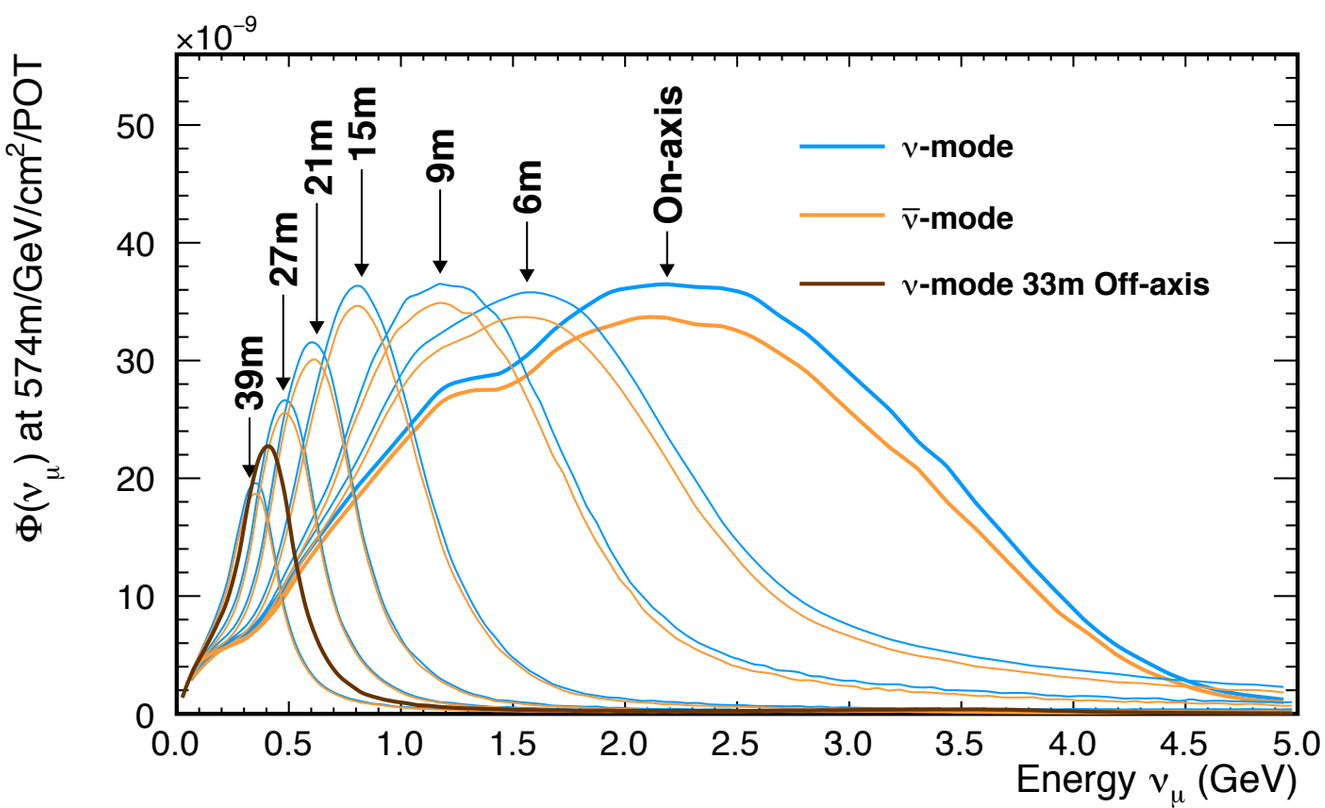
Proton source directly into dump
Cyclotron example: DAEδALUS

Summary

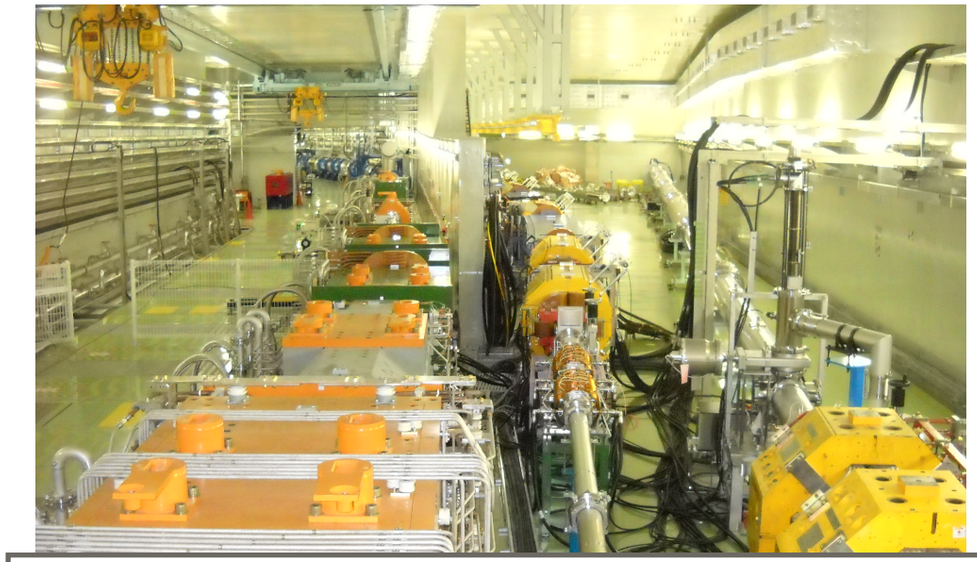
Neutrino physics has been enabled by **tunable energy**, **flavor selected** beams

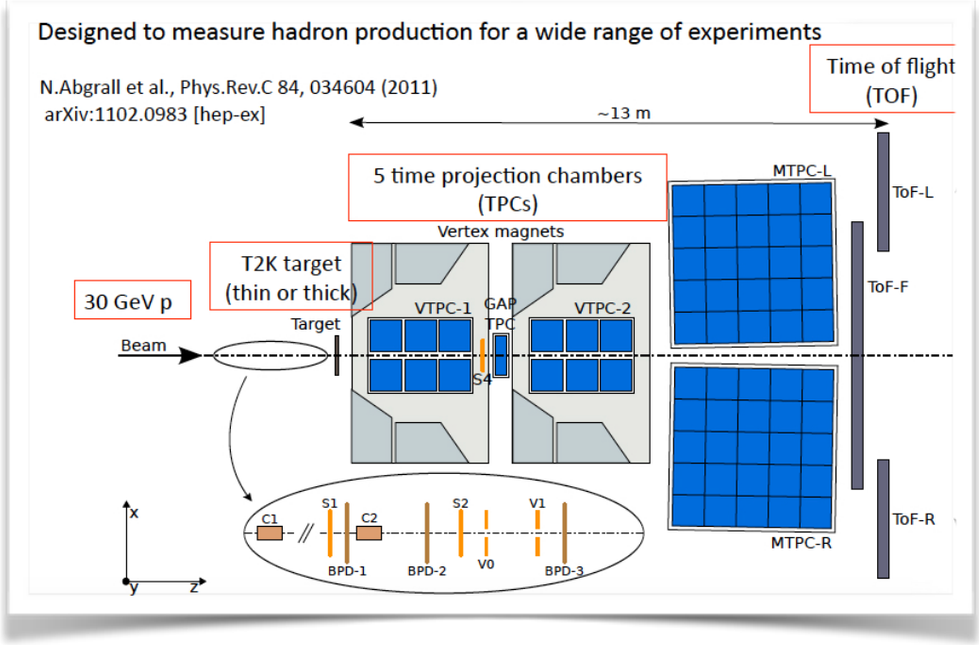


Prog. Theor. Exp. Phys. 2018 , 063C01

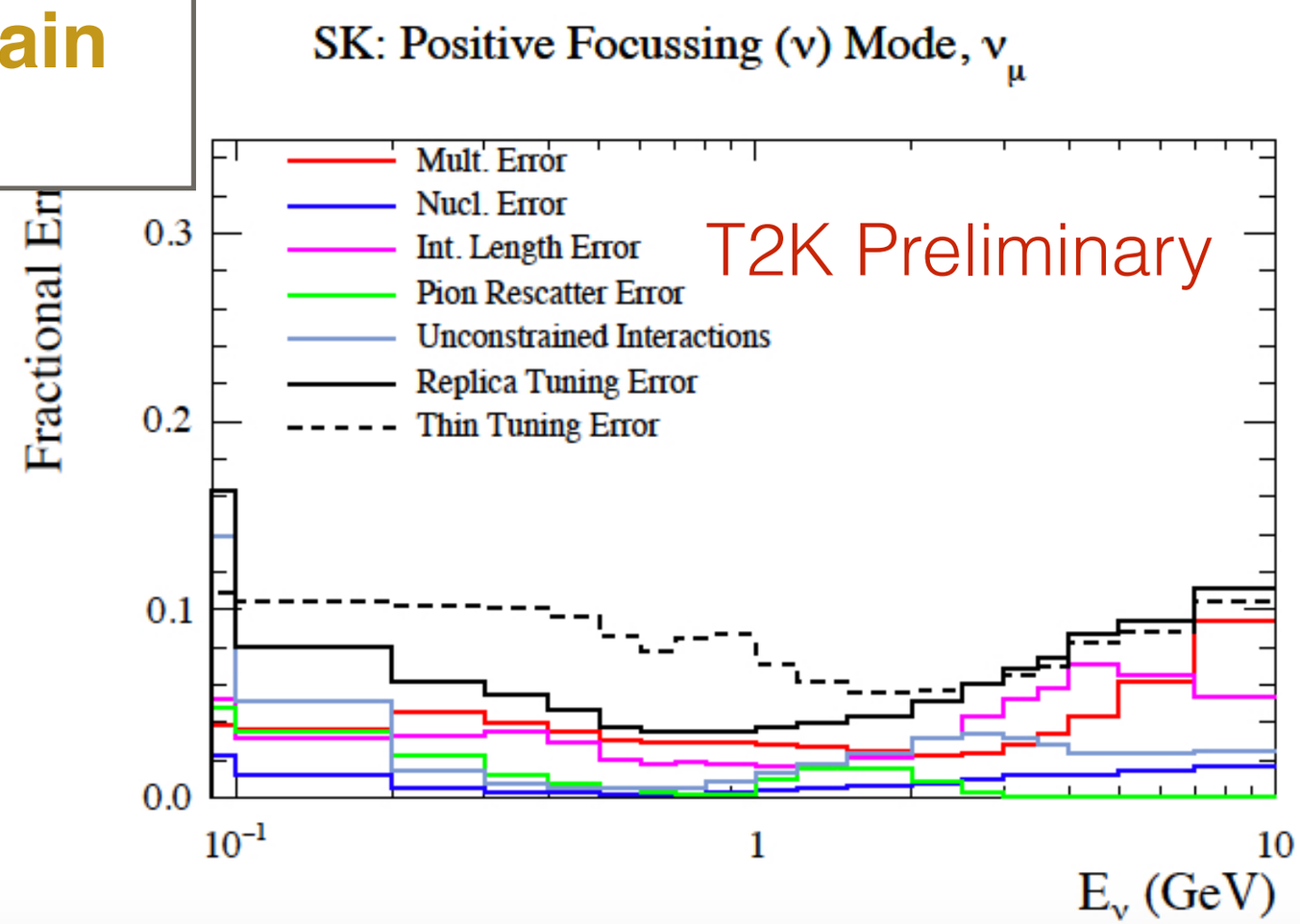


Summary

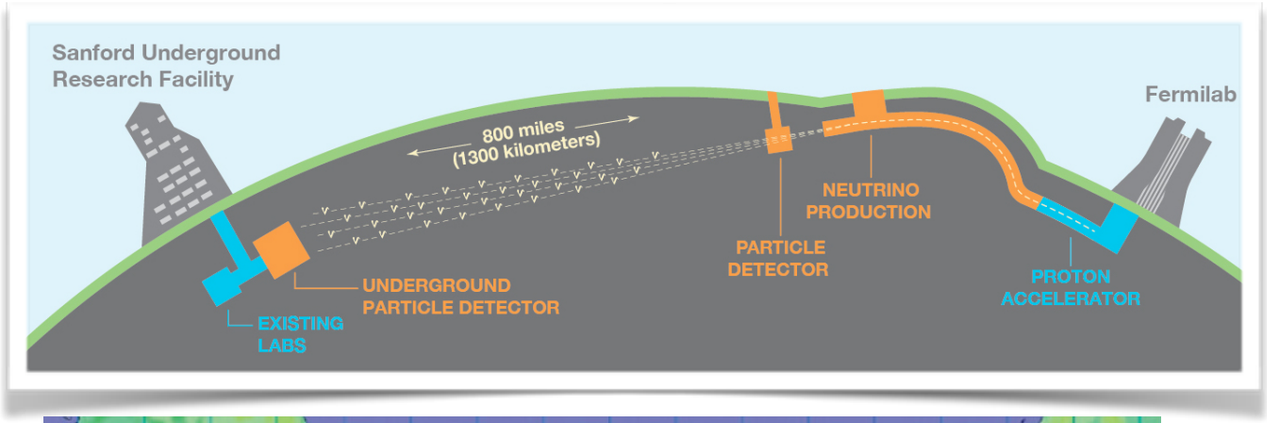


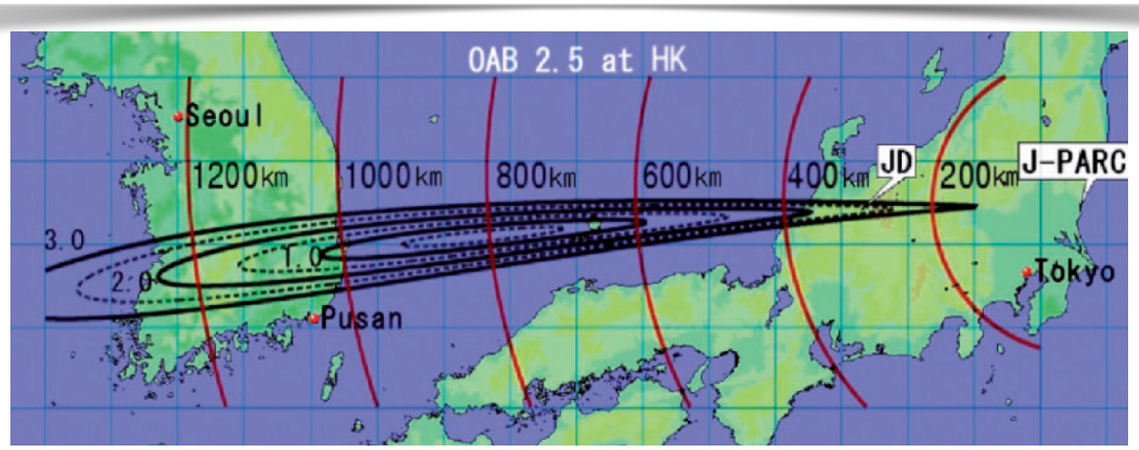


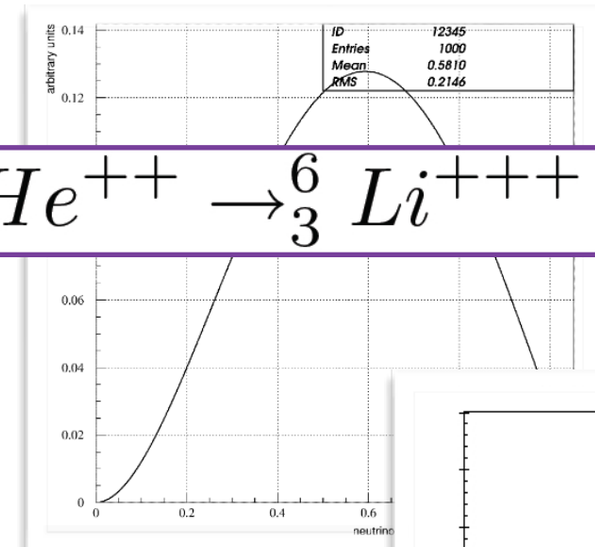
Neutrino beams are complex devices to **operate**, **maintain** and **characterize**



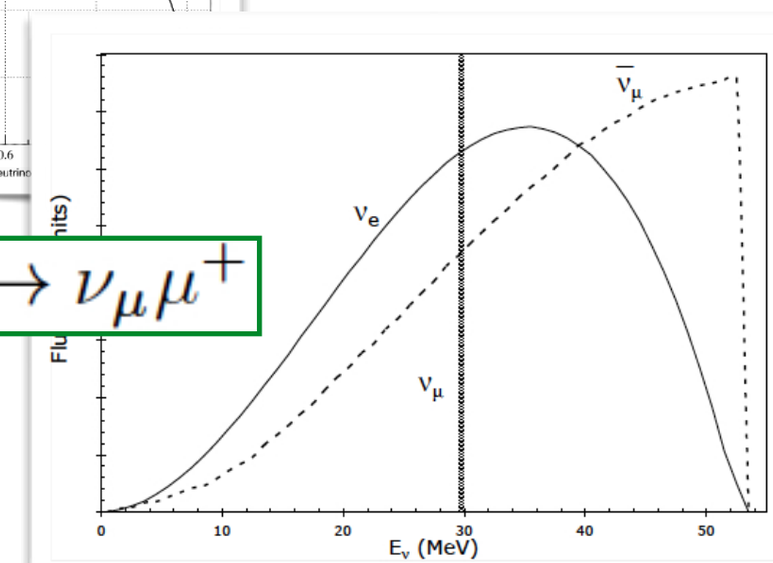
Summary



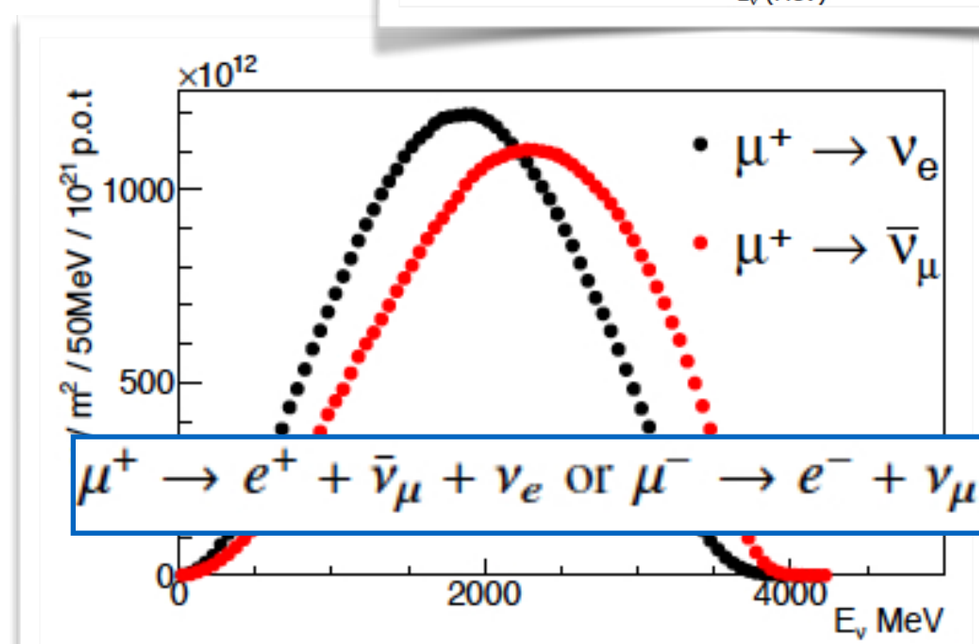




$$^{6}_{2}He^{++} \rightarrow ^{6}_{3}Li^{+++} + e^{-} + \overline{\nu}_e$$



$$\pi^{+} \rightarrow \nu_\mu \mu^{+}$$



$$\mu^{+} \rightarrow e^{+} + \bar{\nu}_\mu + \nu_e \text{ or } \mu^{-} \rightarrow e^{-} + \nu_\mu + \bar{\nu}_e$$

Neutrino beams are a **critical part** of the future program, as are creative **new ideas** for future neutrino sources

Thank you for the invitation and your attention!

Support from:

Department of Energy

Michigan State University

Backup