Accelerator-based neutrinos
Lecture 2

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Outline

Last lecture:

- Physics of modern neutrino beams

This lecture:

- The first neutrino beam
- Conventional neutrino beams
- Experimental challenges of neutrino experiments

The first accelerator based neutrino beam

Is there more than one flavor of neutrino?

Start with a pure source of neutrinos from pion decay

$$\pi^+ \rightarrow \mu^+ + \nu$$

Do we see one, or both of these interactions?

$$\nu + n \rightarrow p + \mu^-$$

$$\nu + n \rightarrow p + e^-$$

Experiment: Detect leptons from pion decay
Determine flavor from identifying the muon or electron

Need a pion beam to do this experiment

The first accelerator based neutrino beam

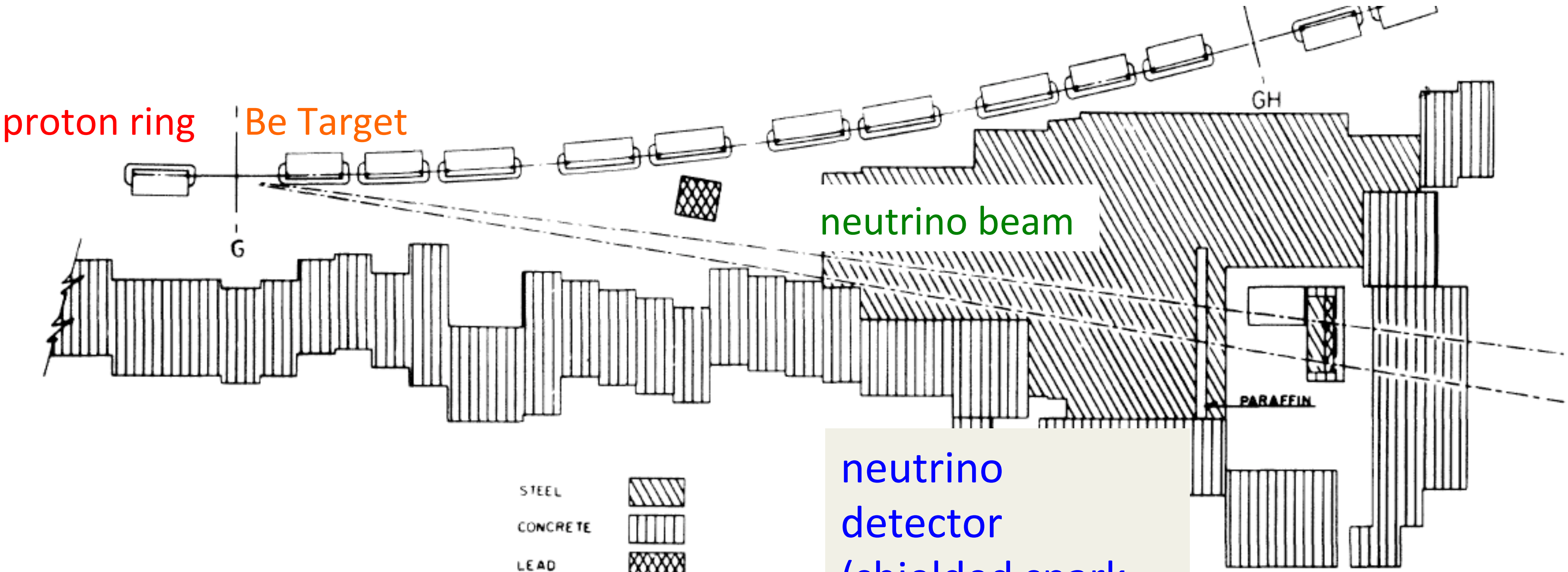
Produce a pion beam using 15 BeV (GeV) proton beam at BNL

Smash the proton beam into a beryllium target

Produce pions

Pions decay to neutrinos

Neutrinos interact in detector to produce electrons or muons



Phys. Rev. Lett., 9(1):36-44, Jul 1962

The first accelerator based neutrino beam

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Produce pions

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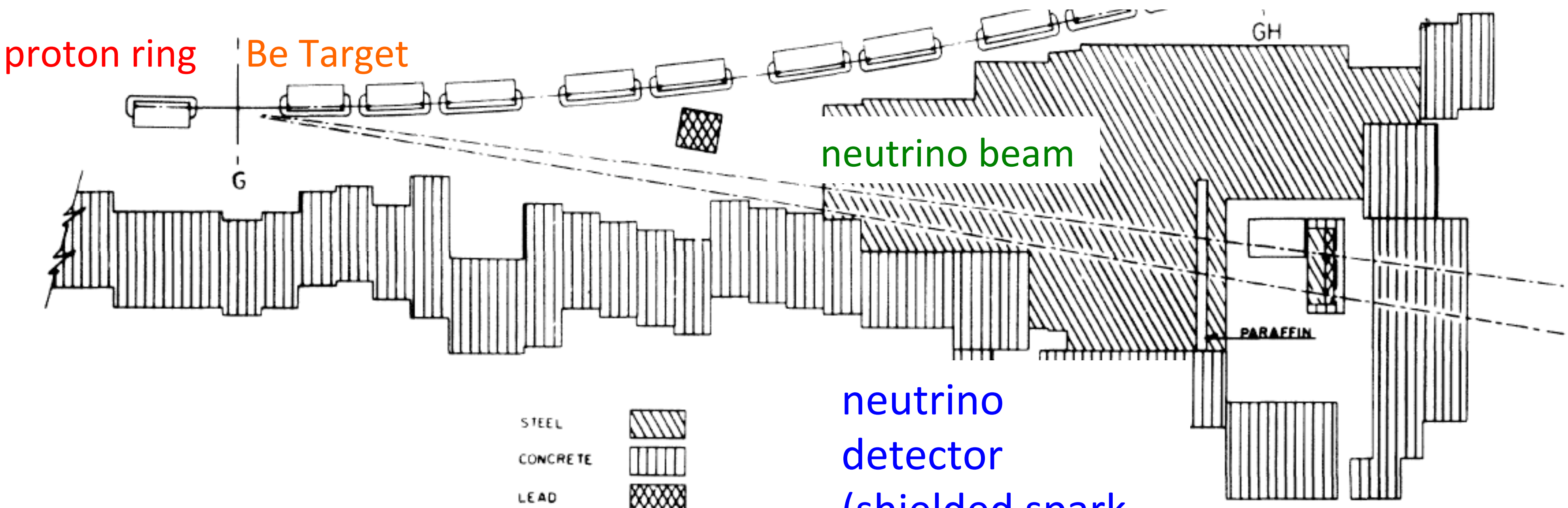
Neutrinos interact in detector to produce ~~electrons or~~ muons

So, electron neutrinos are distinct from muon neutrinos

Nobel Prize in 1988
Mel Schwartz, Leon Lederman, Jack Steinberger

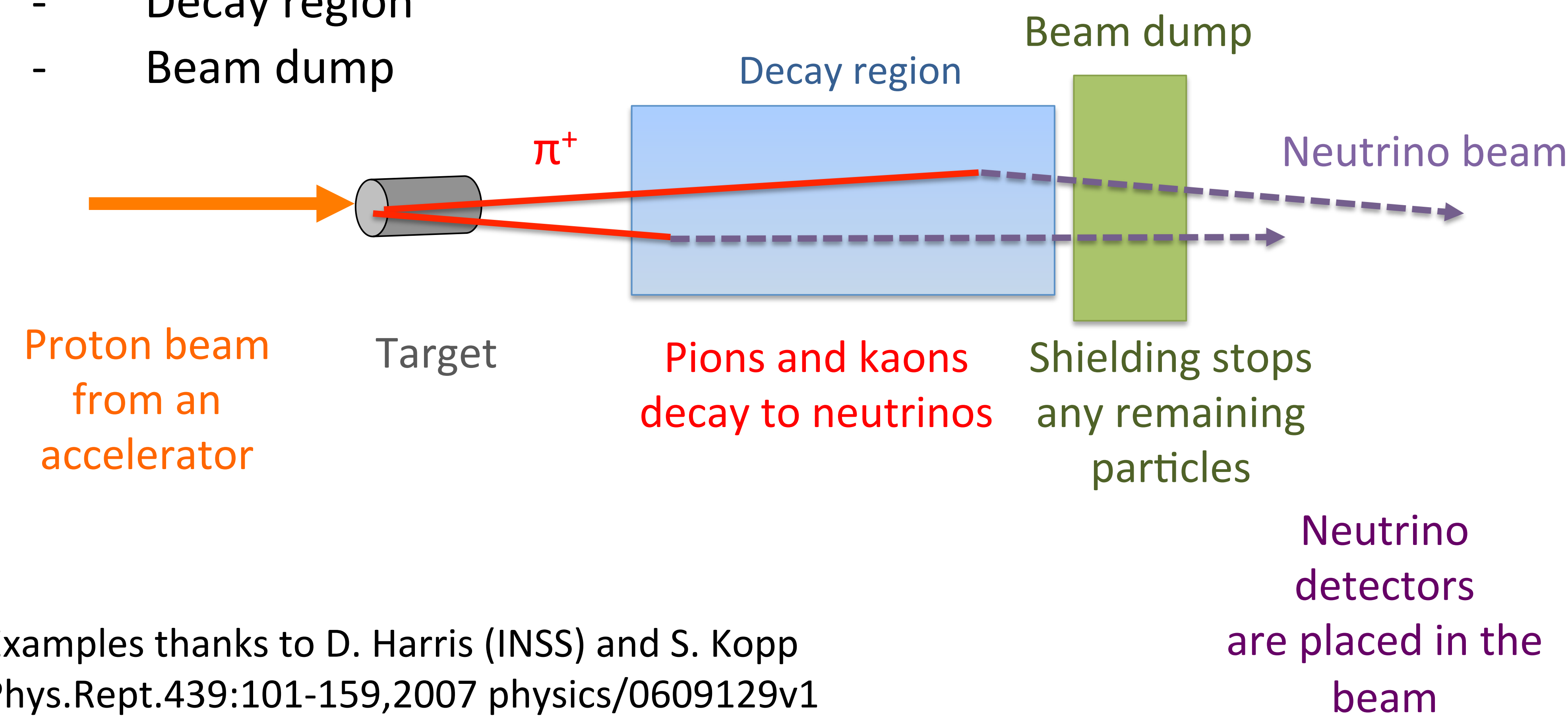


Phys. Rev. Lett., 9(1):36-44, Jul 1962

Conventional neutrino beam

Ingredients:

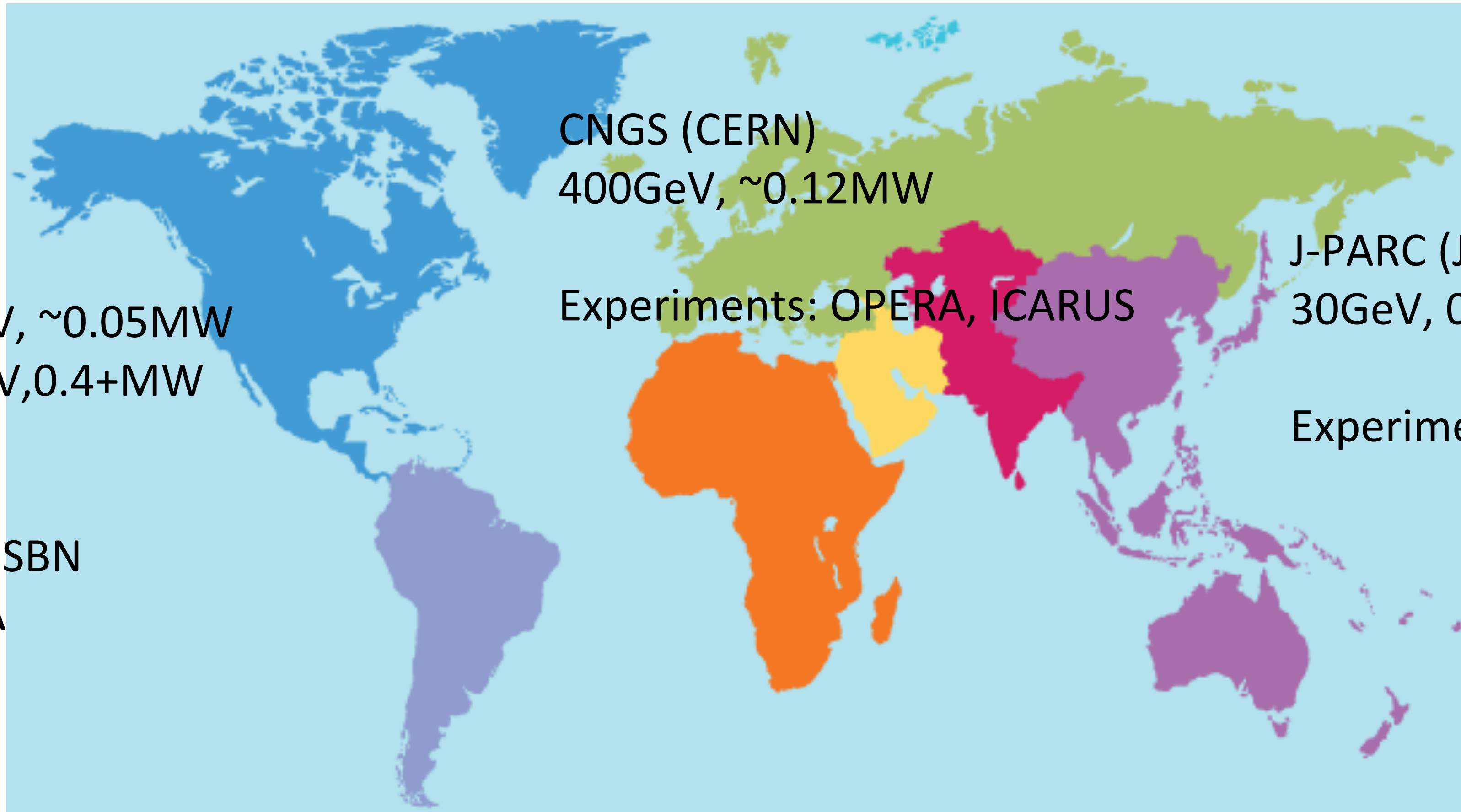
- Proton beam
- Target
- Decay region
- Beam dump



Examples thanks to D. Harris (INSS) and S. Kopp Phys.Rept.439:101-159,2007 physics/0609129v1

Accelerators around the world

Colorful map from Amazon.com



FNAL (Illinois)
Booster: 8GeV, ~0.05MW
NuMI: 120GeV,0.4+MW

Experiments:
MiniBooNE-> SBN
MINOS, NOvA

CNGS (CERN)
400GeV, ~0.12MW

Experiments: OPERA, ICARUS

J-PARC (Japan)
30GeV, 0.3+MW

Experiment: T2K

Proton energy scales neutrino energy (higher proton E, higher π E)
More protons usually also means more pions, neutrinos
Proton ``beam power" is proportional to protons on target (POT) and proton energy:

$$P(kW) \propto POT\ (10^{20}) \times E_p\ (GeV)/T\ (10^7\ s)$$

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

7 “slugs” supported by 3 “fins”

Example: MiniBooNE target
Material: Beryllium

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

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

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Cooling:

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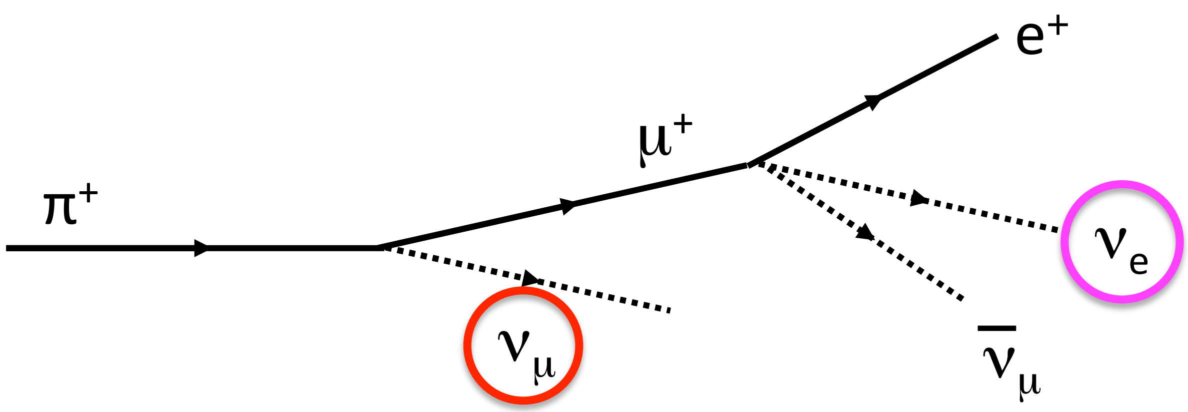
Example: NuMI (MINOS) target
Material: Graphite with Al casing
Shape: ruler 6.4 mm x 15 mm x 20 mm) x 47 (2 interaction lengths)

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



Kaons also contribute to both ν_μ and ν_e flux

Decay volume

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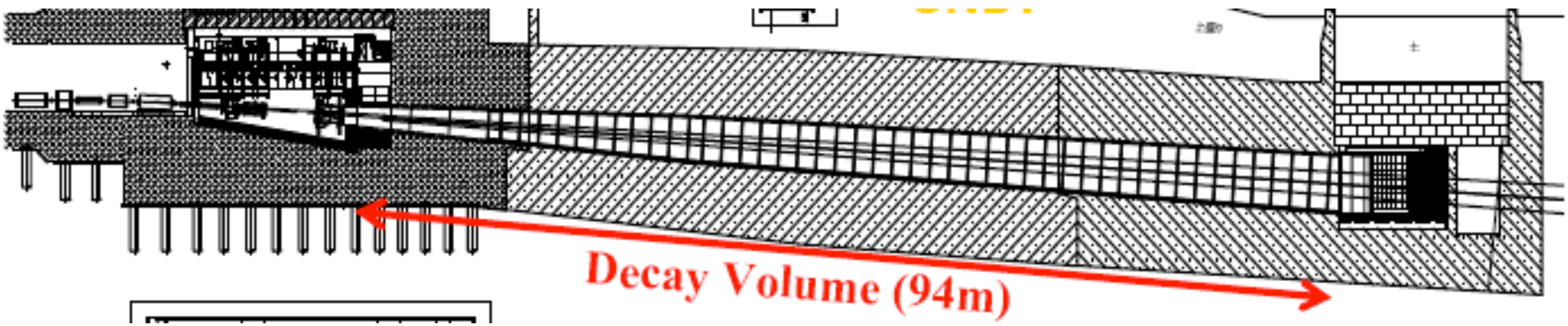
Filler choice:

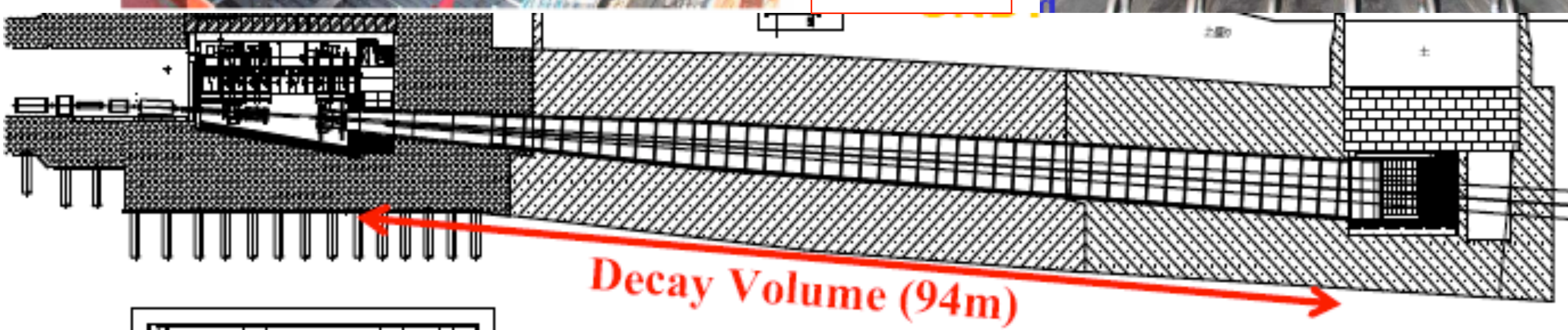
- Depends on energy of pions and distance
  - 280m in air is 0.26 interaction lengths (26% chance to interact)
- Volume often separated from target region with window to maintain pressure



T2K decay volume

- 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



NuMI decay volume

- 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 dump

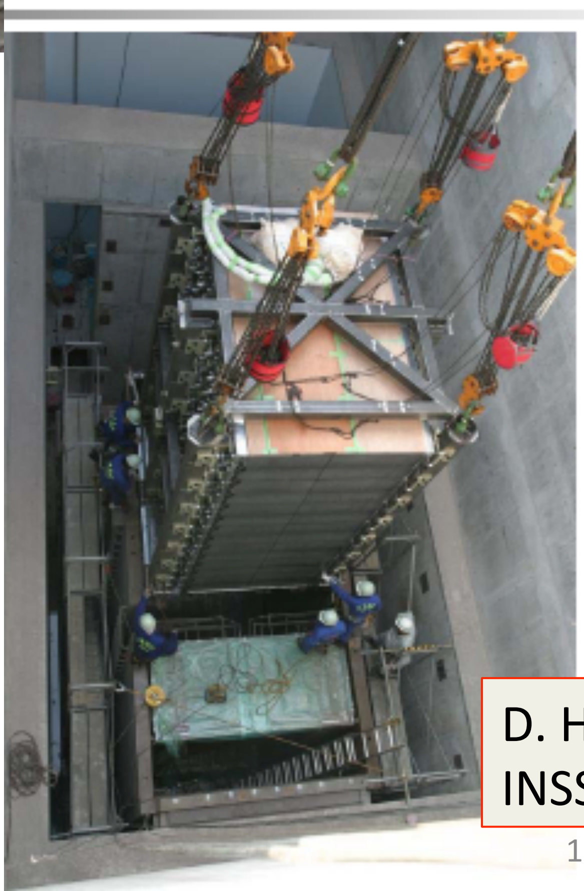
Need a dedicated absorber of uniteracted protons from the beam, and undecayed beam (pi,K,mu) particles

<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

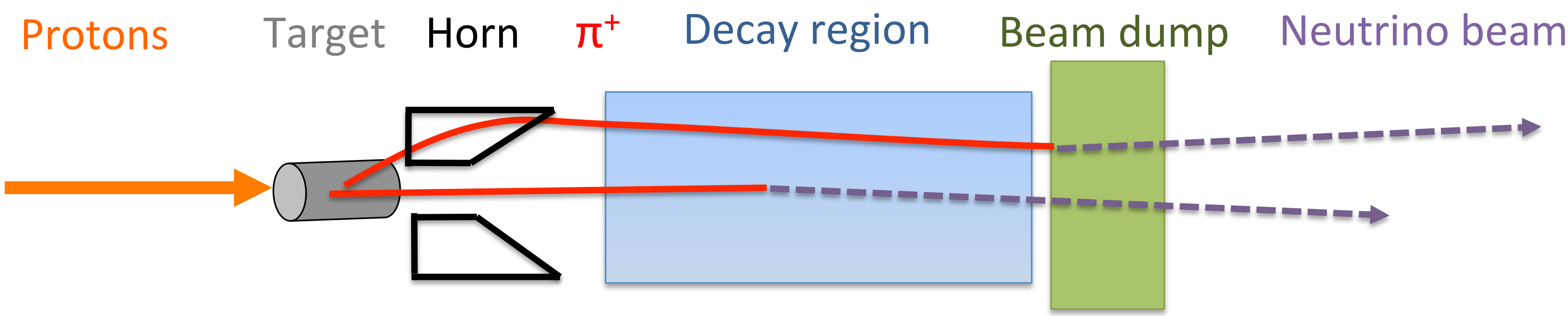


D. Harris, INSS05

How to get the most from your neutrino beam

Ingredients:

- Proton beam
- Target
- Add a Magnetic focusing ``horn''
- Decay region
- Beam dump



Can't focus neutral neutrinos

Increase flux of neutrino beam by first focusing parent mesons

How horns work

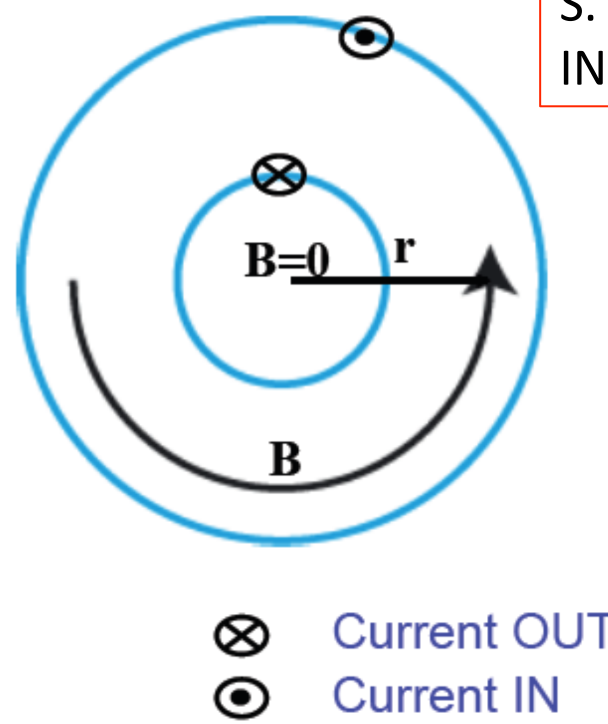
Want to remove transverse momentum of pions out of the target

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

S. Gilardoni
INSS09

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

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

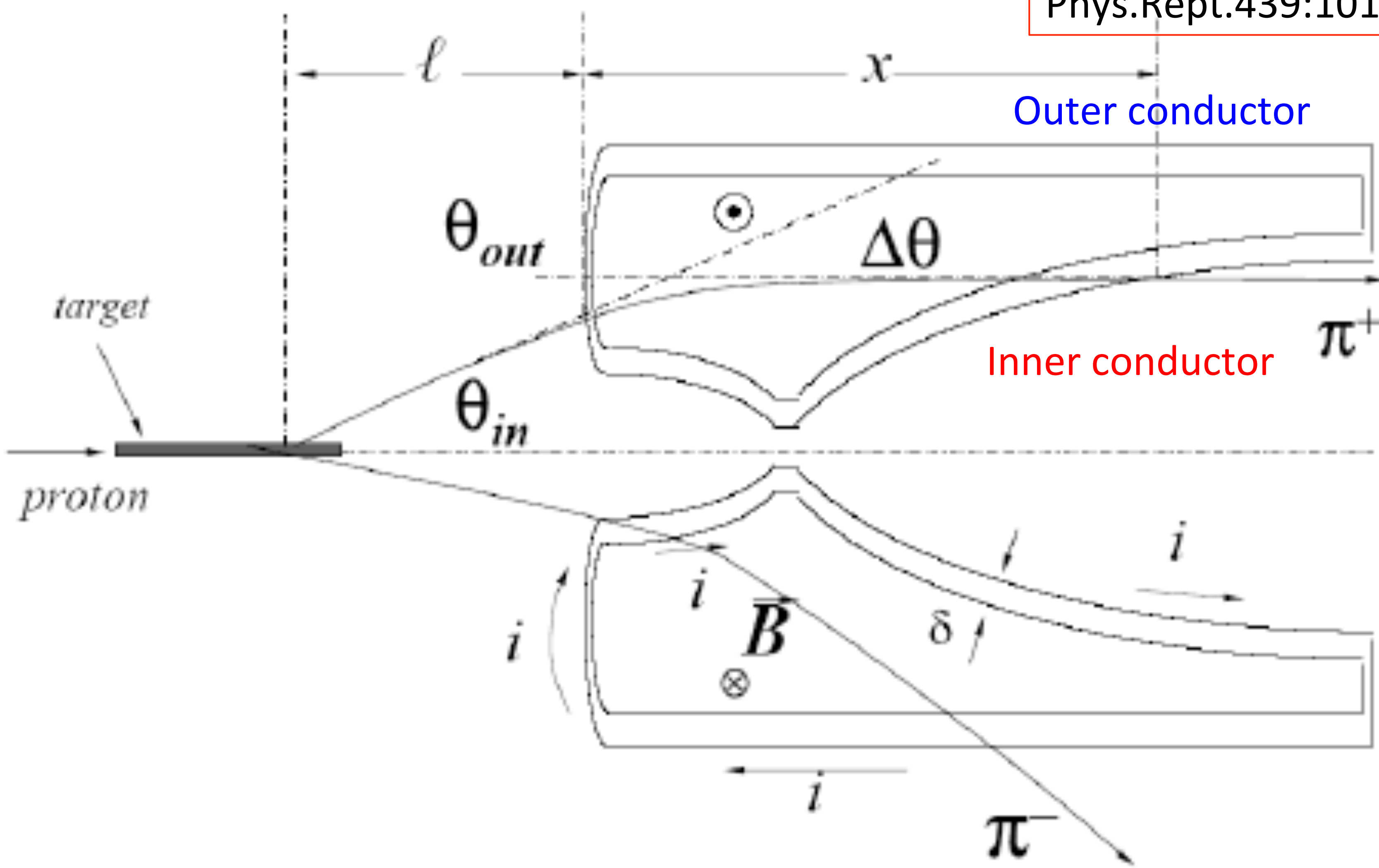


How horns work

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



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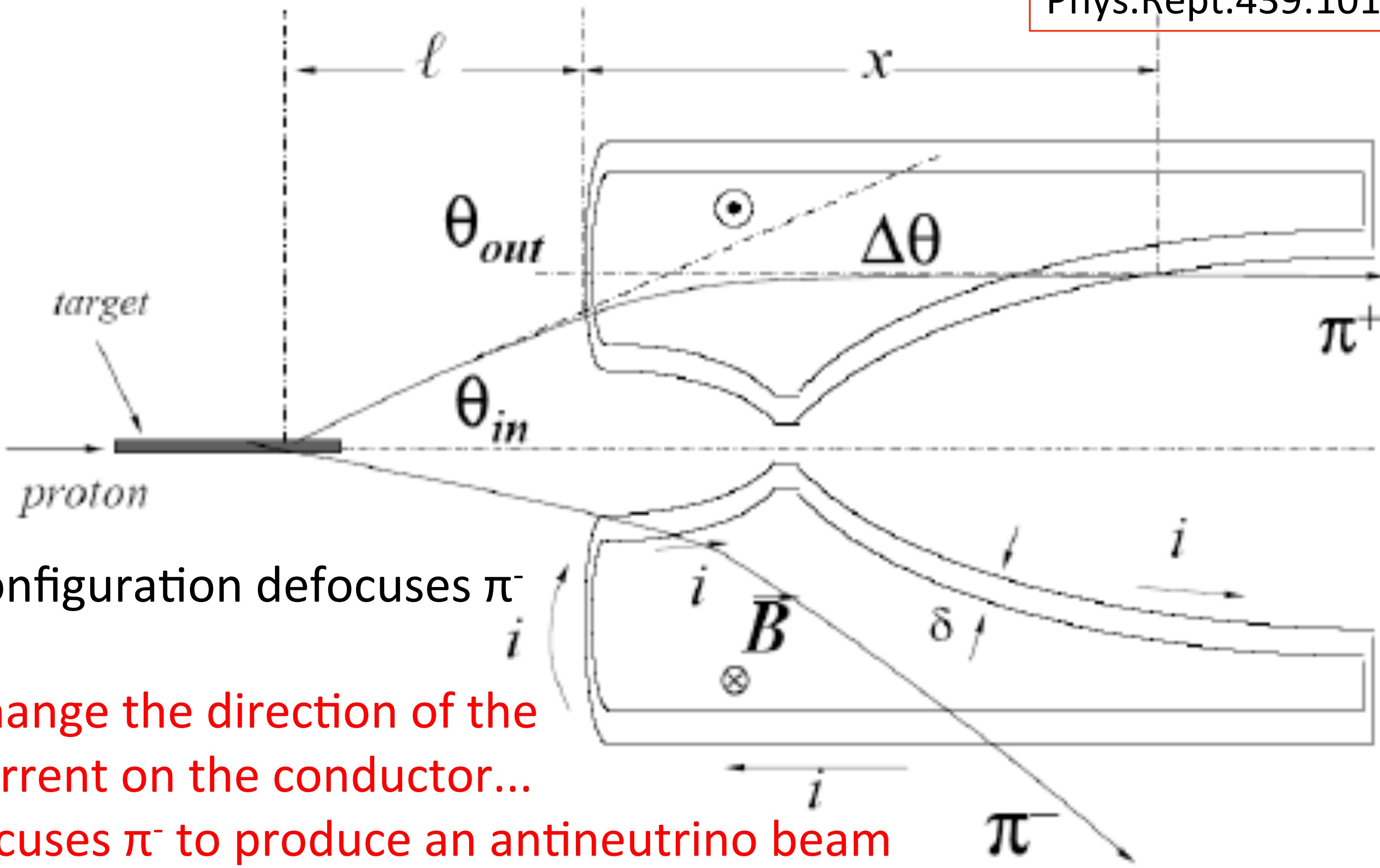


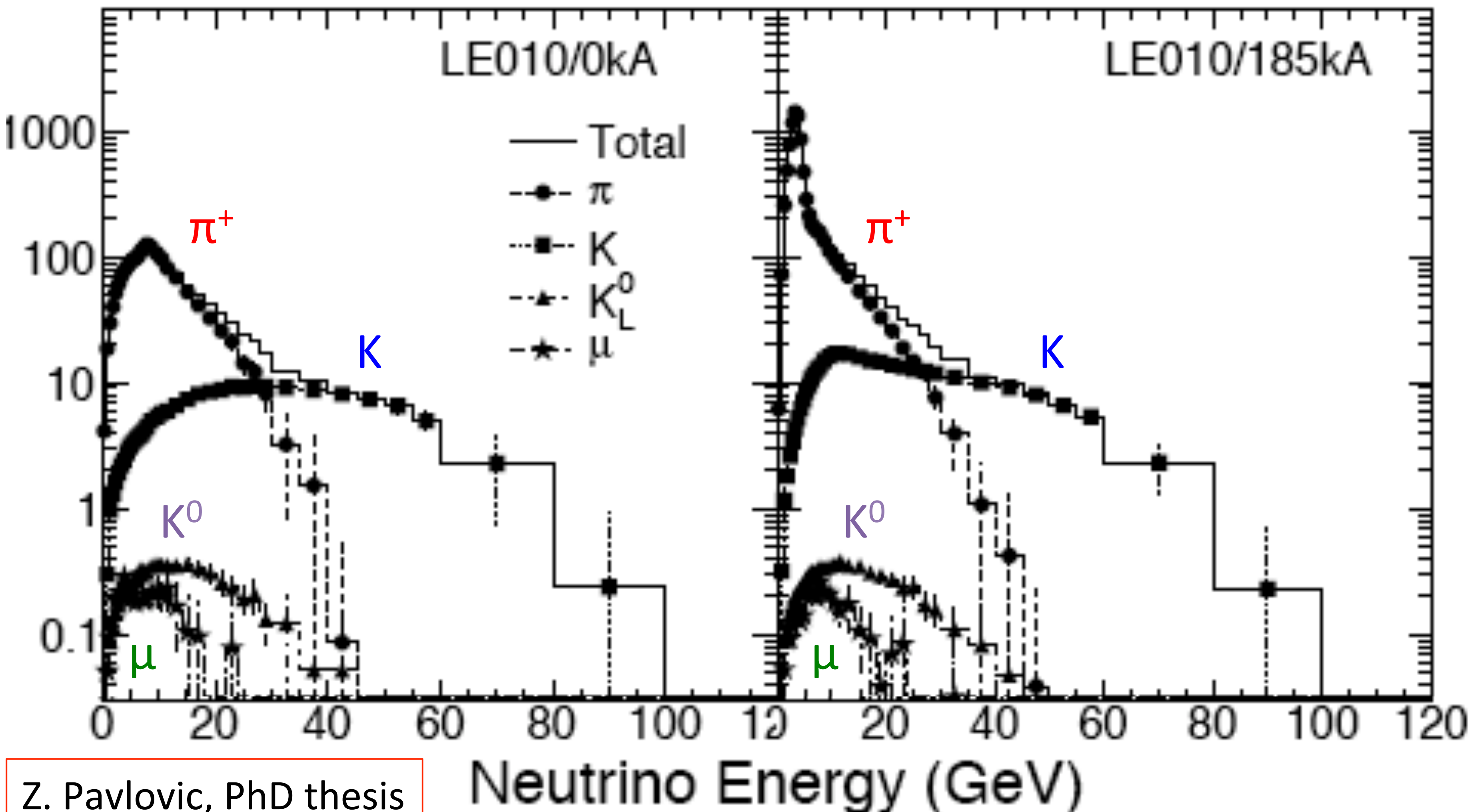
Configuration defocuses π⁻

Change the direction of the current on the conductor...
focuses π⁻ to produce an antineutrino beam

How much do horns help?

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)

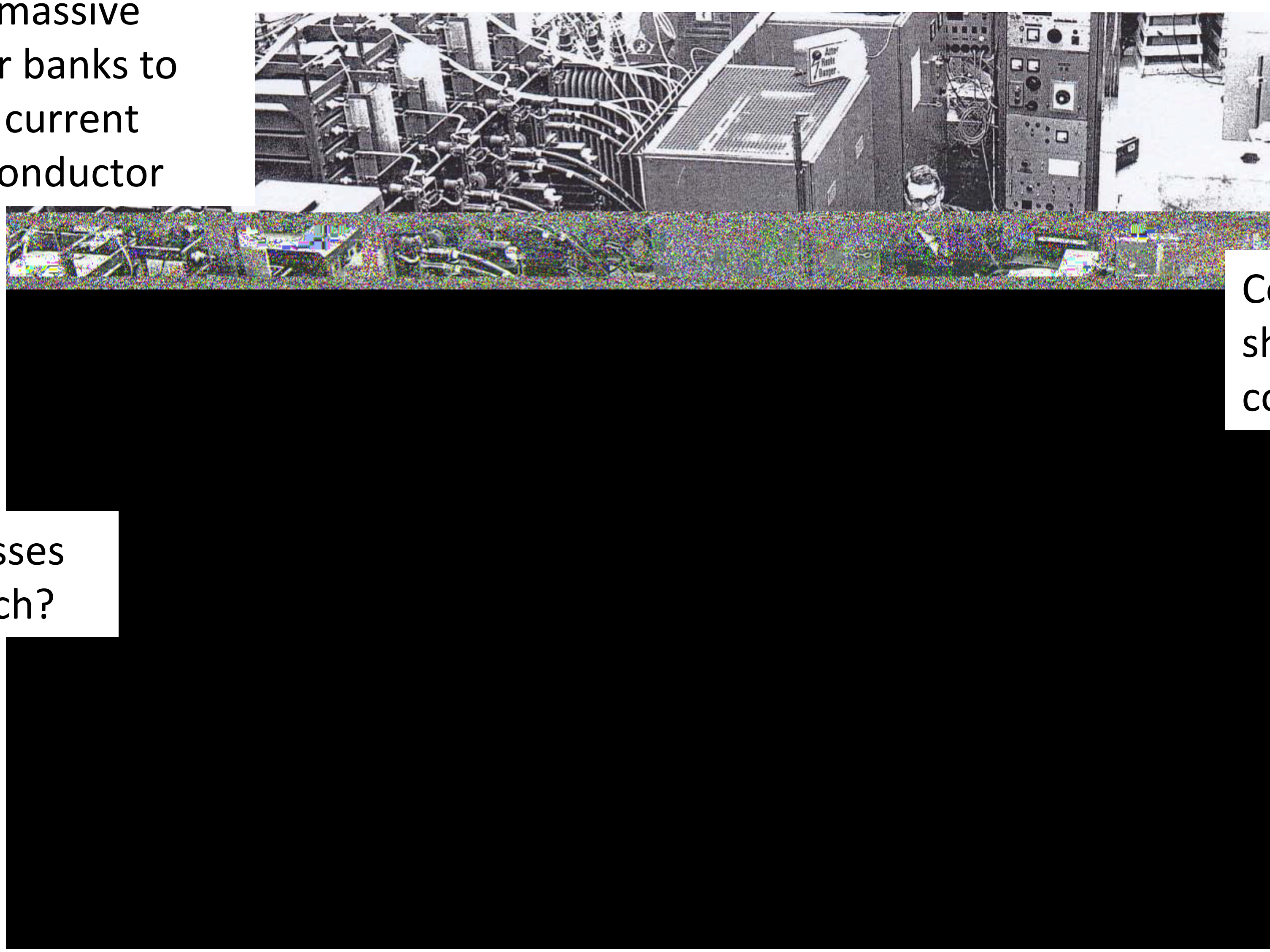


Z. Pavlovic, PhD thesis

Example horns

First horn invented by Simon van der Meer

Require massive capacitor banks to produce current for the conductor



Conical shape of the conductor

Any guesses how much?

J. Steinberger Neutrino2012

How much current, exactly?

- Given two horns that are each 3m long and 16cm diameter, what kind of current would you need to give a ~200MeV kick to produced secondary particles?
- For pion going through "sweet spot" of focusing assume r/r_{max}=1/2

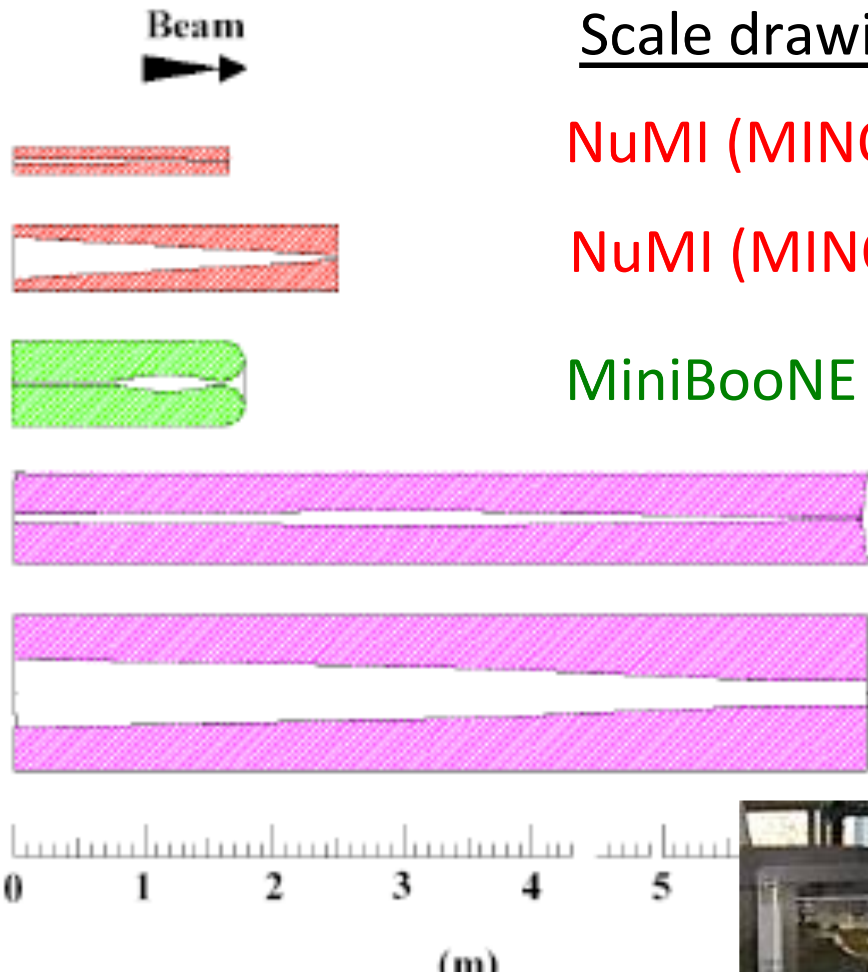
$$dp_t(GeV) = 0.3B(T)l(m)$$

$$B(T) = \frac{\mu_0 I}{2\pi r} = 2\times 10^{-7}\frac{I(Amps)}{r(m)}\left(\frac{r}{r_{\max}}\right)^2$$

$$I(Amps) = \frac{dp_t(GeV)}{0.3}\frac{2r_{\max}}{l}\frac{1}{2\times 10^{-7}}$$

For MINOS: 180kA!
For T2K: 250kA!

Example horns



Scale drawings of various horns

NuMI (MINOS) horn 1

NuMI (MINOS) horn 2

Phys.Rept.439:101-159,2007

MiniBooNE horn

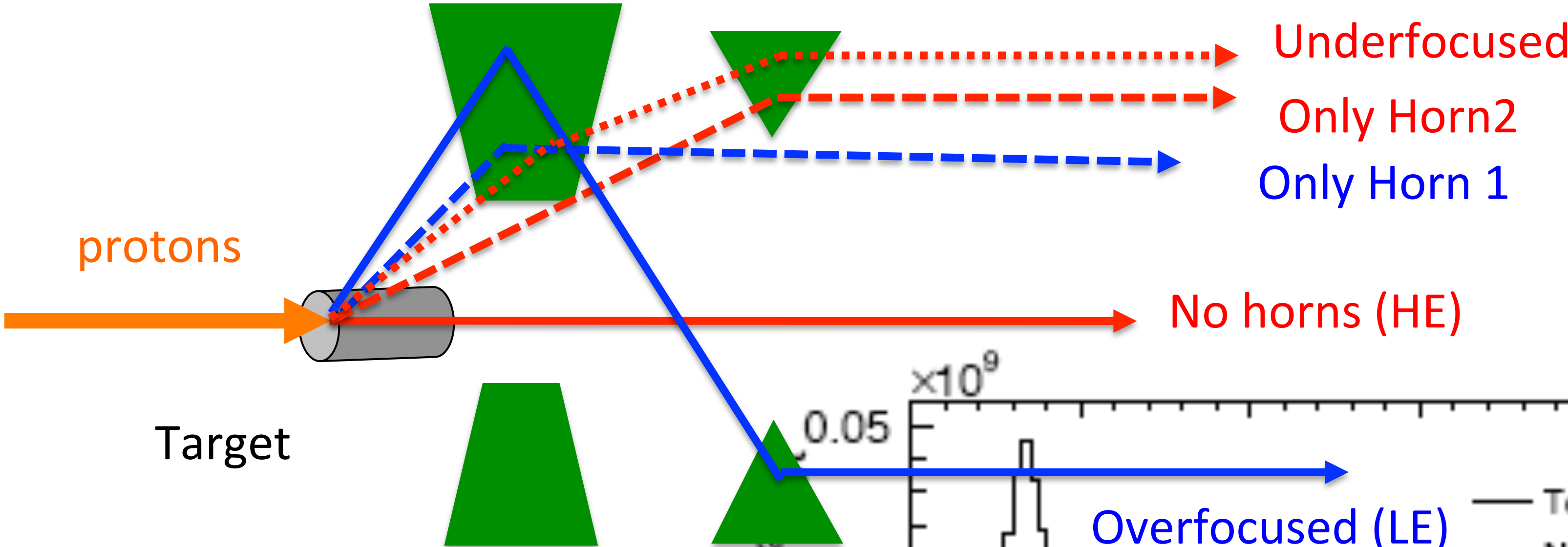
CNGS (OPERA) horn 1

CNGS (OPERA) horn 2

D. Harris
INSS'05

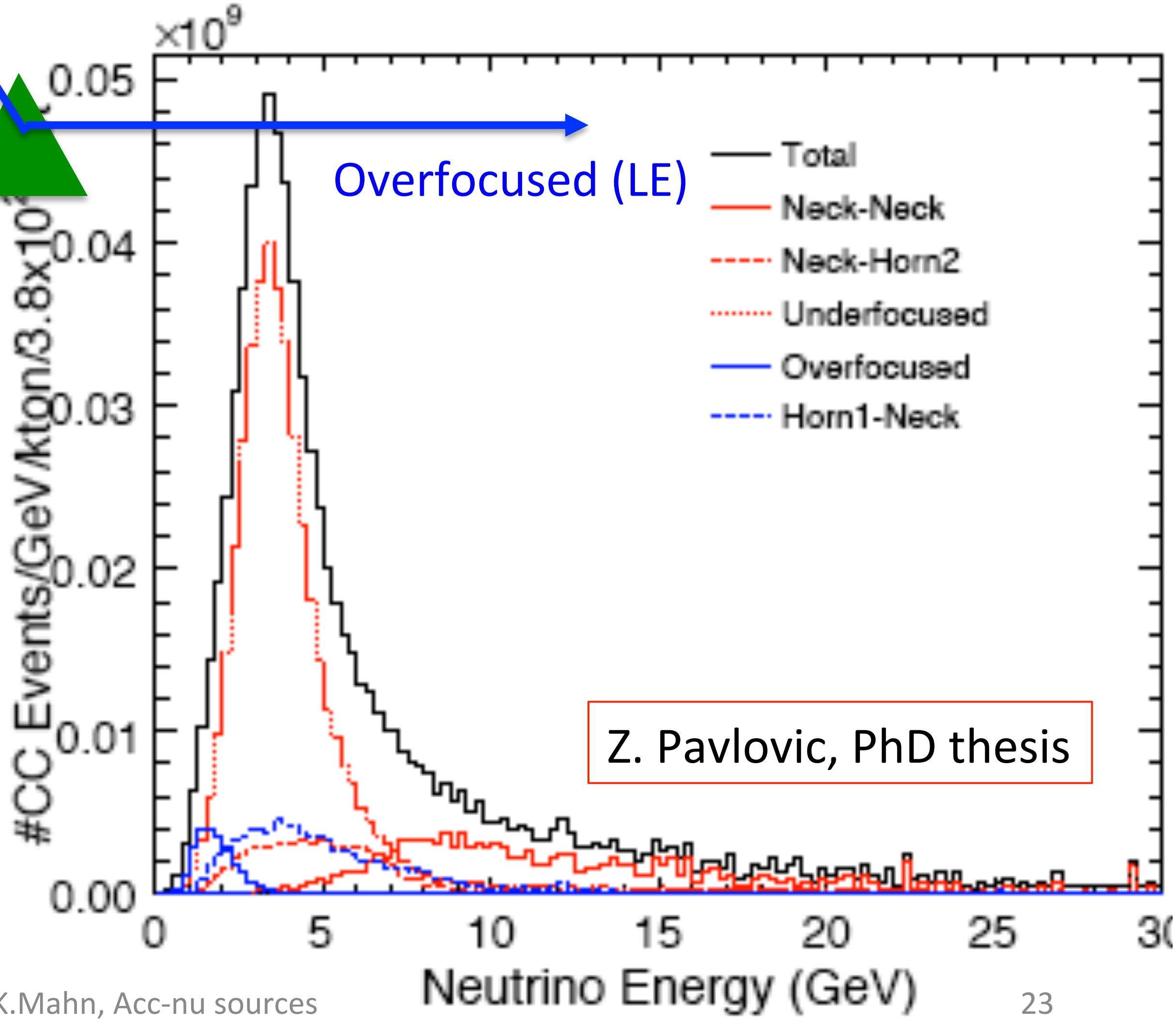
MiniBooNE horn outer conductor with water cooling system pipes
Aluminum is thin and low mass to reduce scattering

Multiple horns



Additional horns further focus the beam, like series of lenses

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

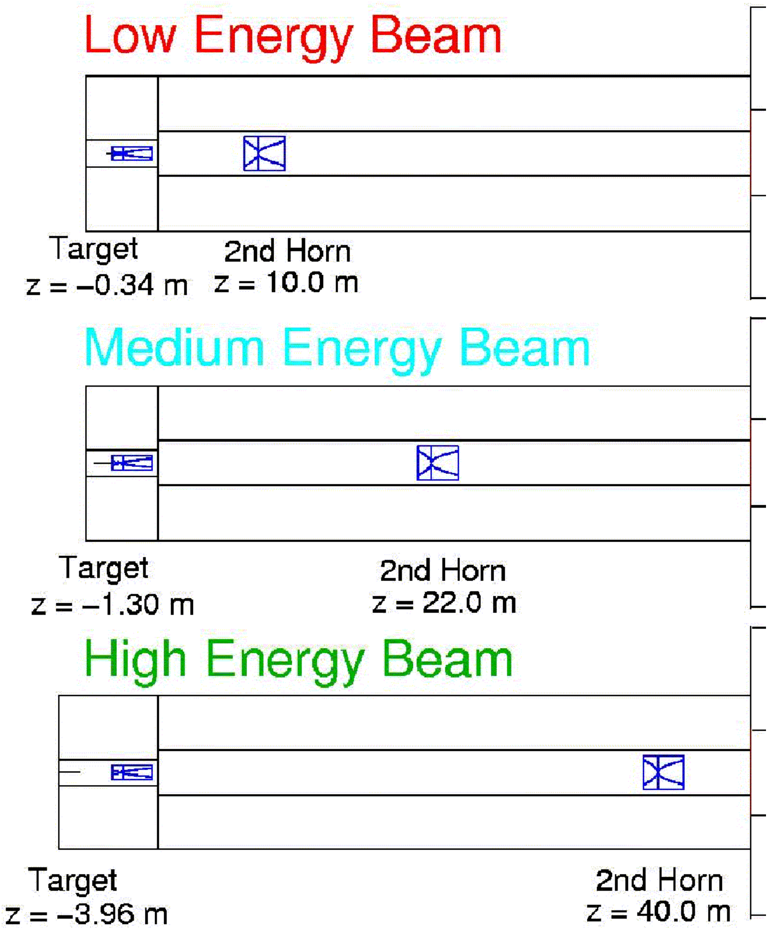


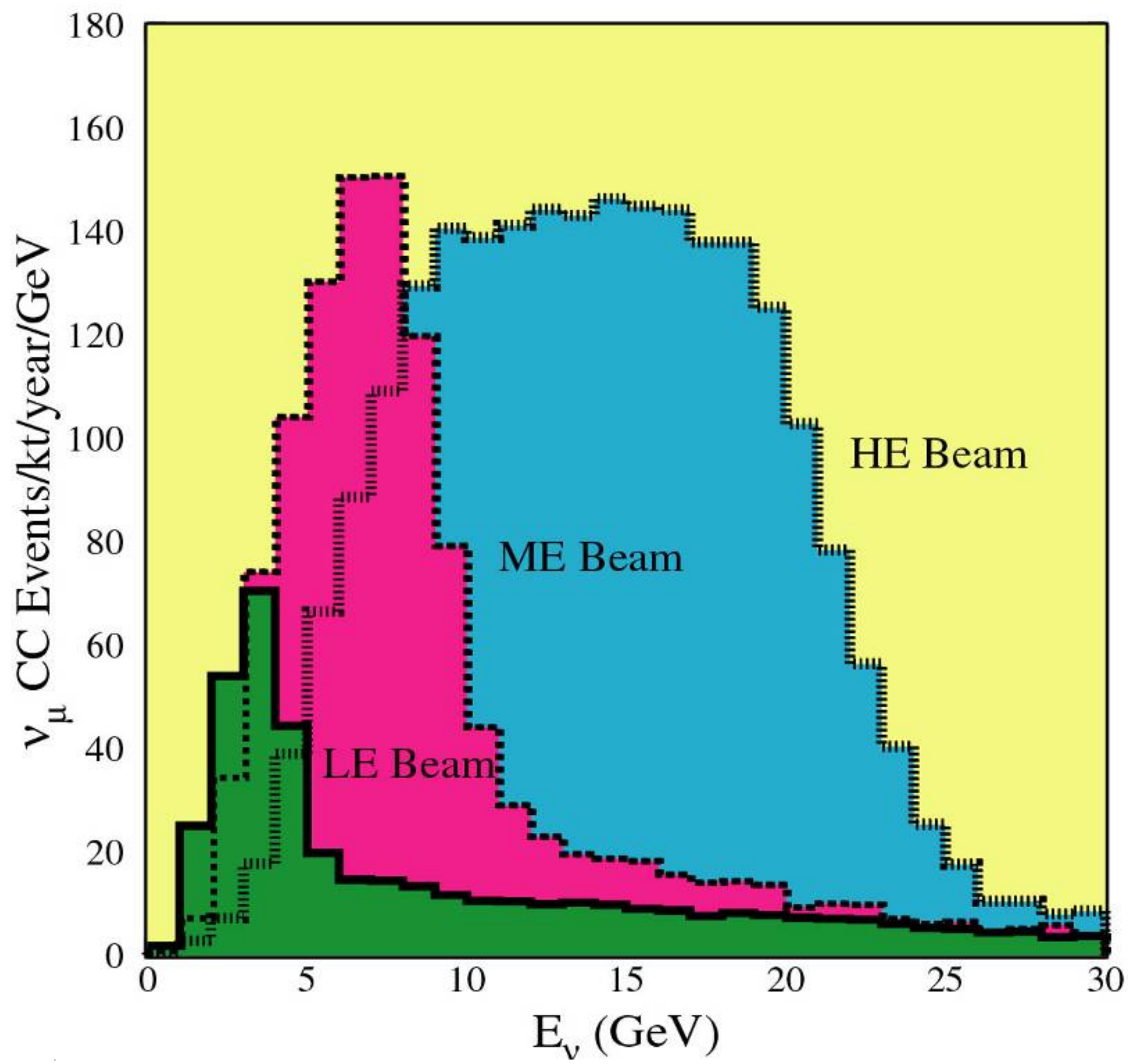
What happens if we change the horn positions?

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





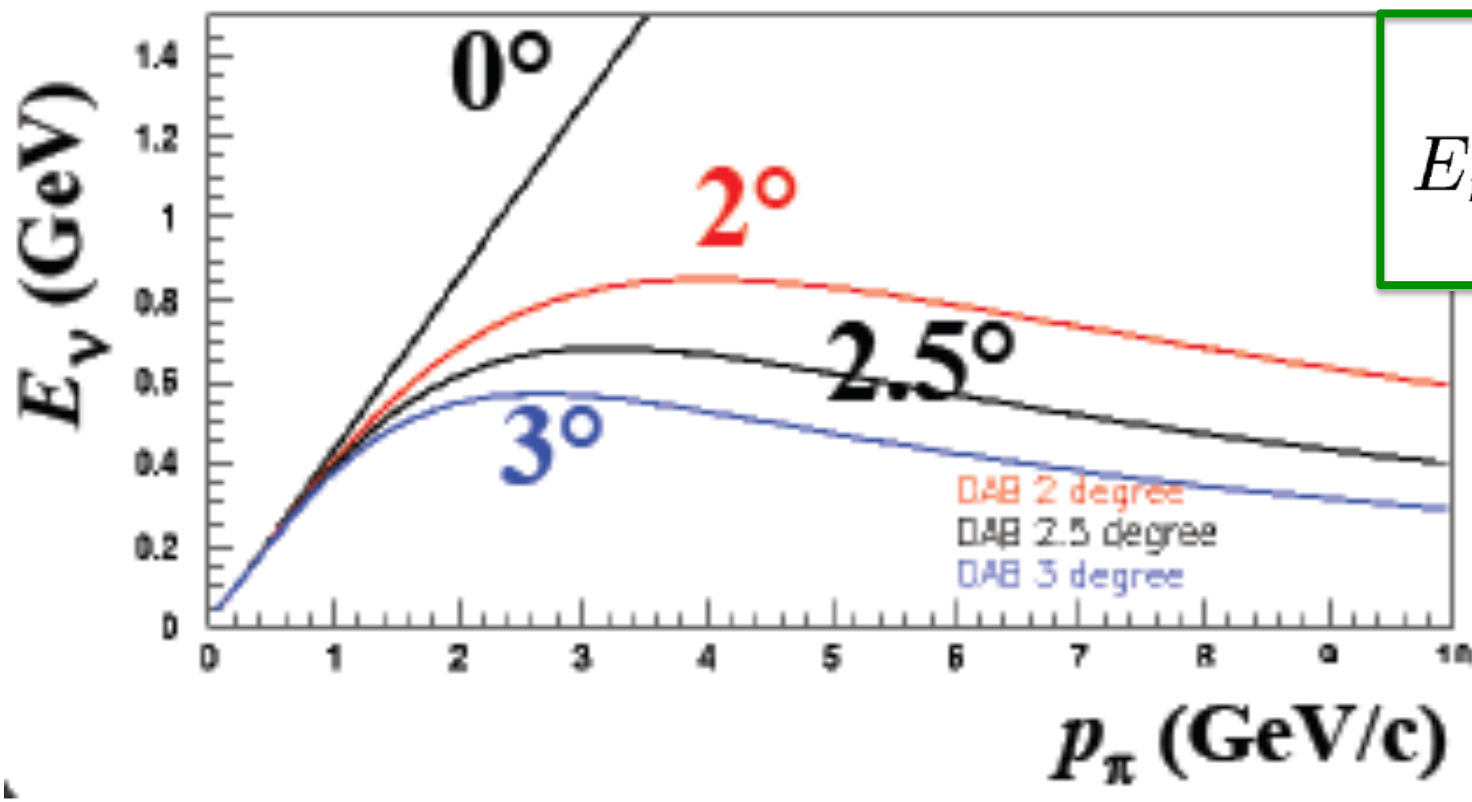
A. Marchionni, NBI2005

Tuning the energy of the neutrino beam

Oscillations depend on L/E. How do we change E of our neutrino beam?

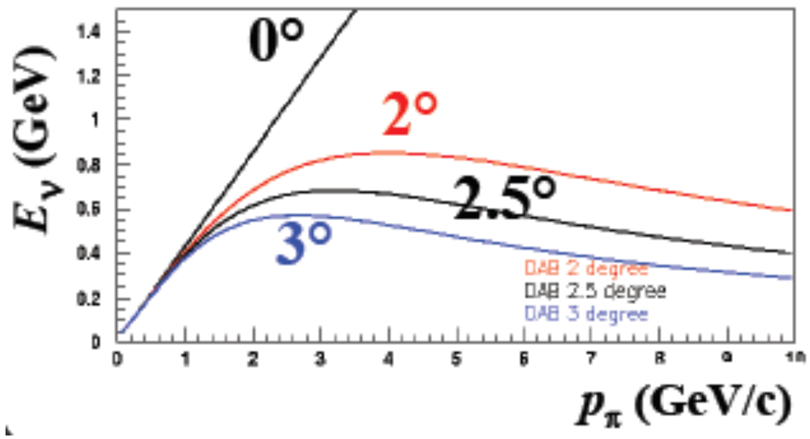
1) Target position relative to the horn? Lower limit: target is within horn
2) Horn current? Reduces flux at the peak of the spectrum
3) Reduce or increase pion energy?

Pion decay is 2 body, so apply pion's boost to center of mass frame to get neutrino energy



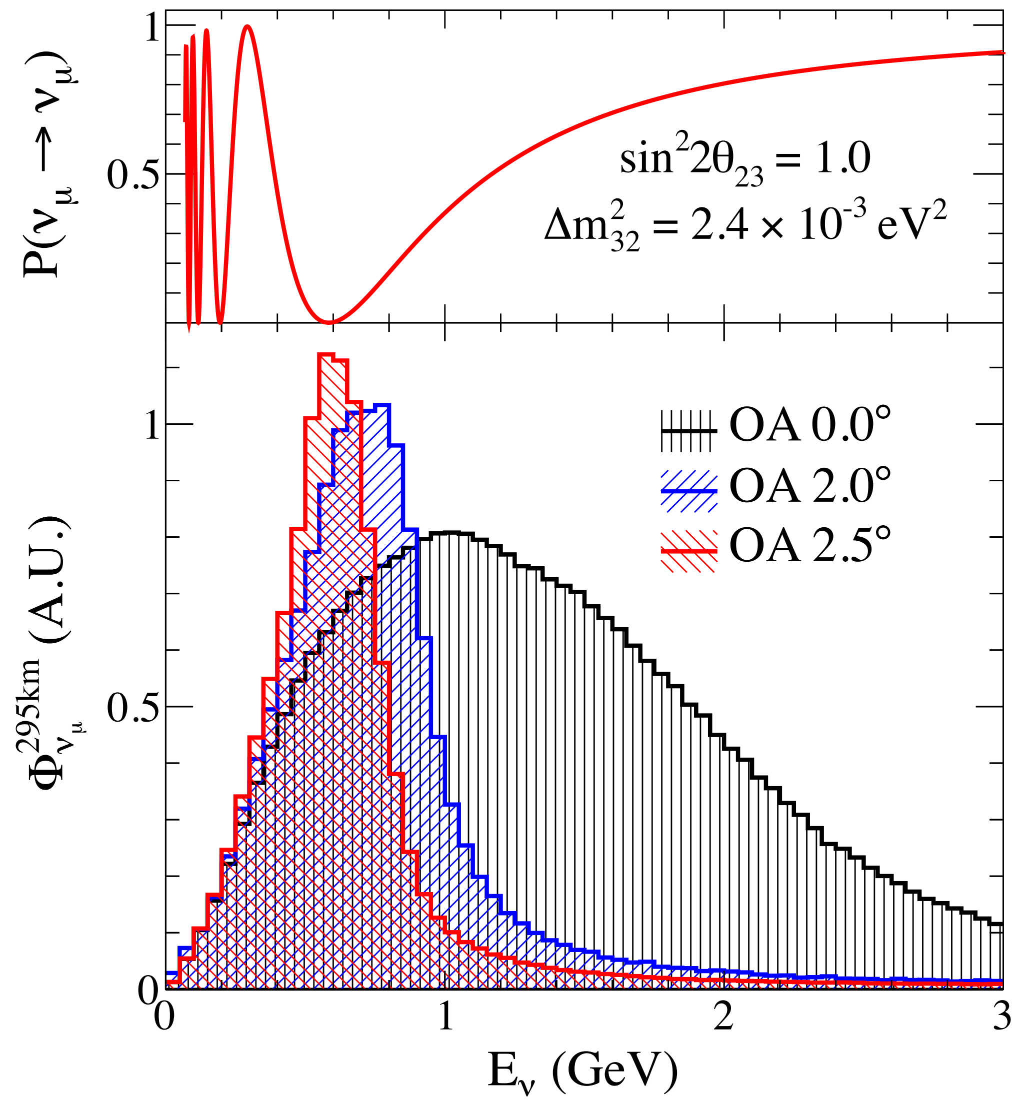
$$E_\nu = E_\pi \frac{1 - \frac{m_\mu^2}{m_\pi^2}}{1 + \gamma^2\theta^2}$$

Off-axis neutrino beams



At angles away from the parent pion's direction, the neutrino energy is independent of pion momentum

- Narrower neutrino spectrum
  - Reduces HE backgrounds
  - Recall: NC backgrounds for T2K, NOvA
- Select peak energy
  - Tune to oscillation physics



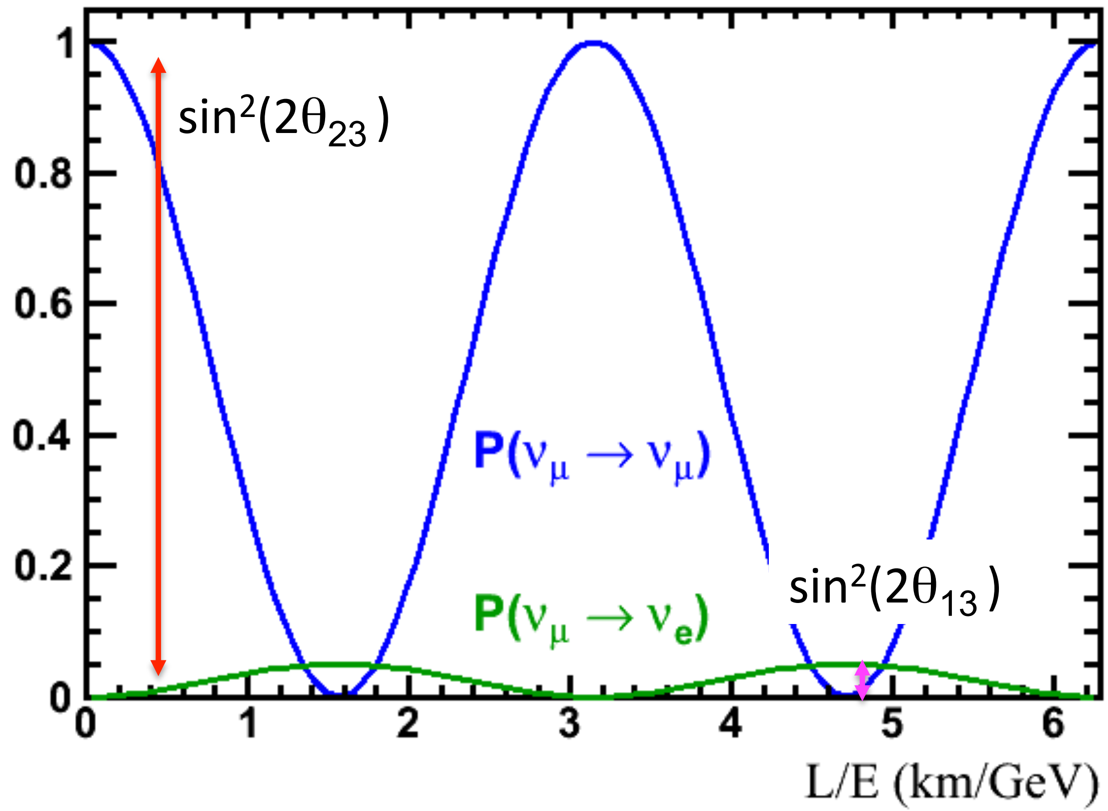
PRD 88, 032002 (2013)

First proposed for BNL E889, and part of T2K, NOvA experiments

The details of oscillation measurements

Recall: we infer the values of oscillation parameters from:

- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)



Requires knowledge of:

- The source of neutrinos (neutrino flux prediction)
- How neutrinos interact (neutrino cross section) and are detected
- Rate modified by external or in-situ measurements (near detectors)

Rest of this lecture will describe how we predict our neutrino flux and uncertainties, and how we use near detector(s)

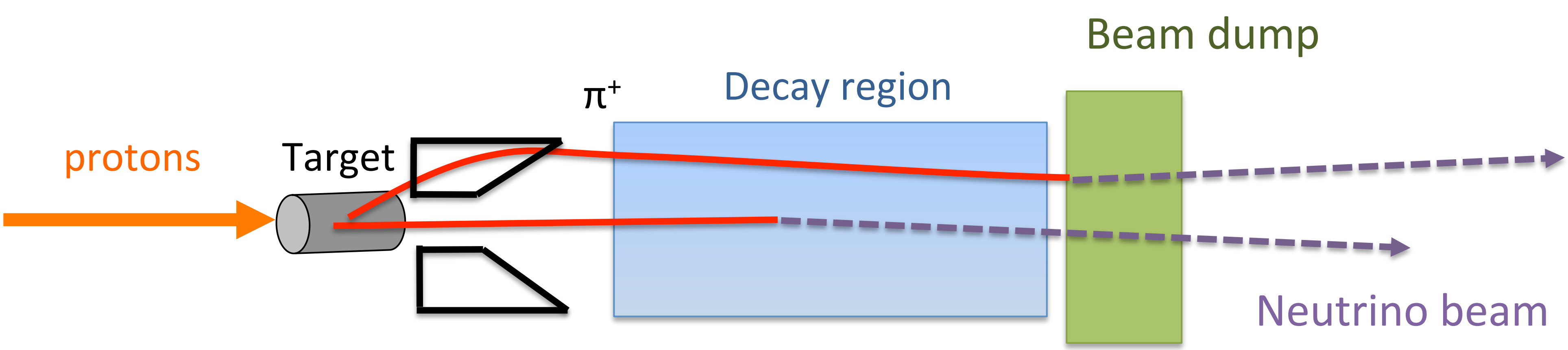
Predicting the neutrino flux

To predict the unoscillated event rate, we need to know the neutrino flux

- Relative rate may use near detectors, still require a flux prediction
- Need absolute flux: single detector (sterile neutrino searches)
- Need absolute flux: neutrino cross sections

Typically predicted with a beamline simulation (Geant3 or Geant4)

- Proton beam position, profile, divergence as it hits the target
- π, K production off of the target
- Focusing of the mesons with the horns
- Decay to neutrinos (in decay volume or in beam dump)



Predicting the neutrino flux

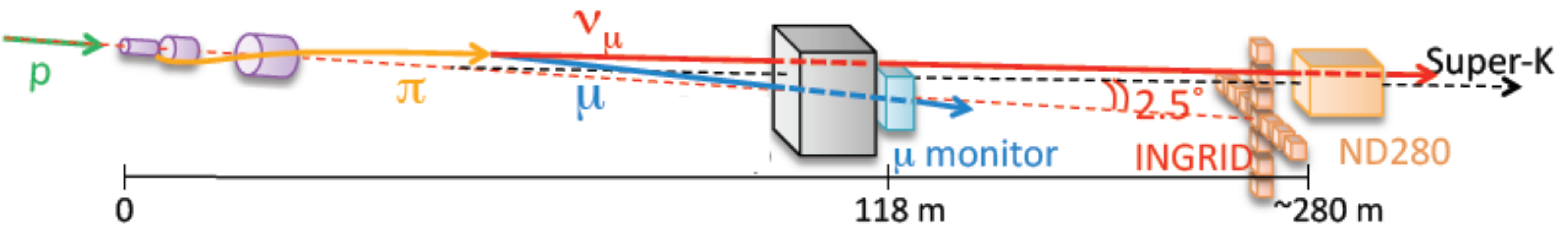
Geant3 and Geant4 use models tuned to data

- Confirm what model, data is used (and what assumptions are made)
- Collect necessary data, and tune to model directly

Monitoring is essential to find problems or changes in the beamline

Continuing the T2K example, data used to understand the beam:

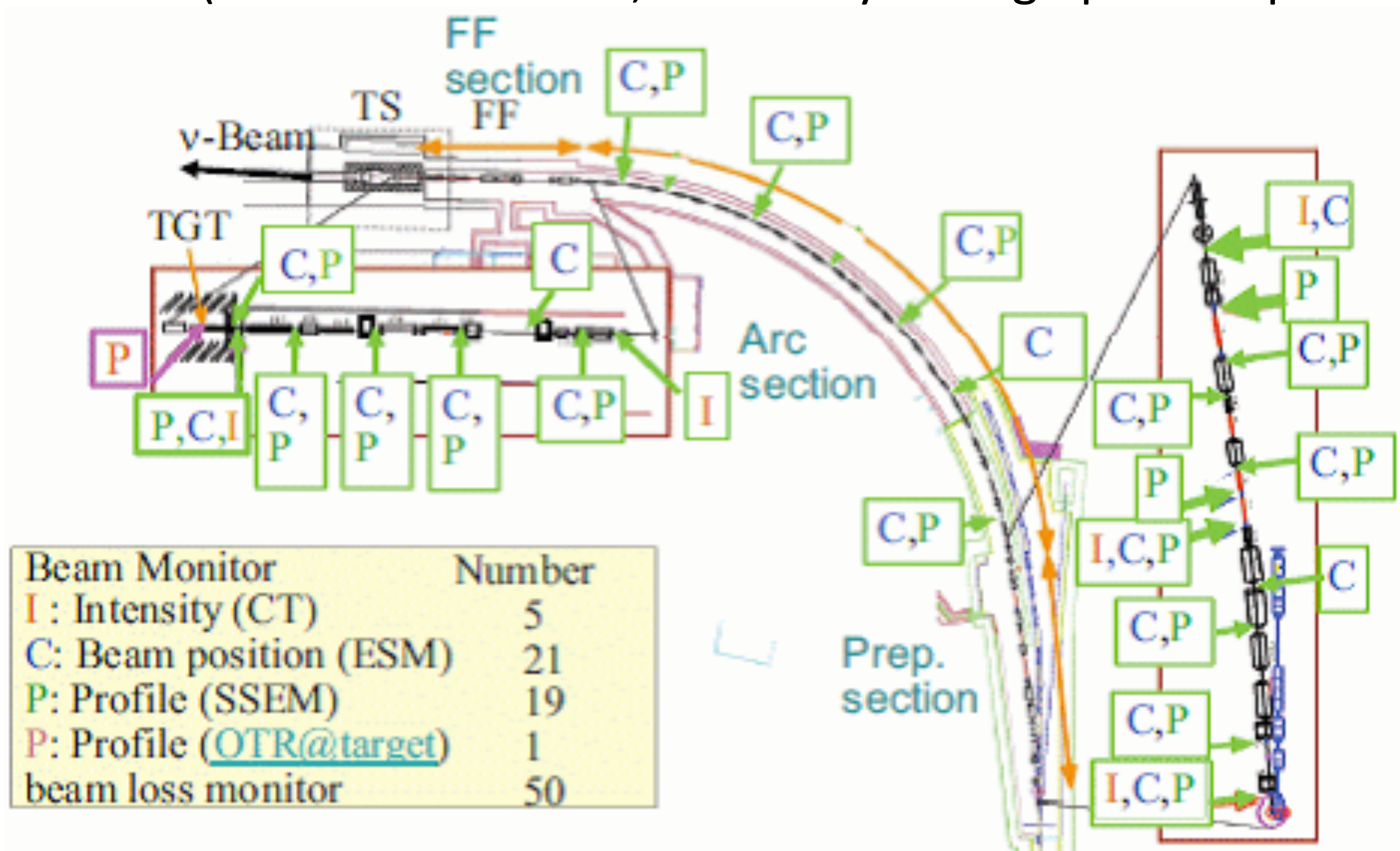
- "Primary beam" (proton) monitors
- "Secondary beam" π, K production dedicated experiments
- Indirect muon monitors (infer neutrino beam properties from μ
- produced at same time, determine beam stability)
- Neutrino detectors (on and off-axis)



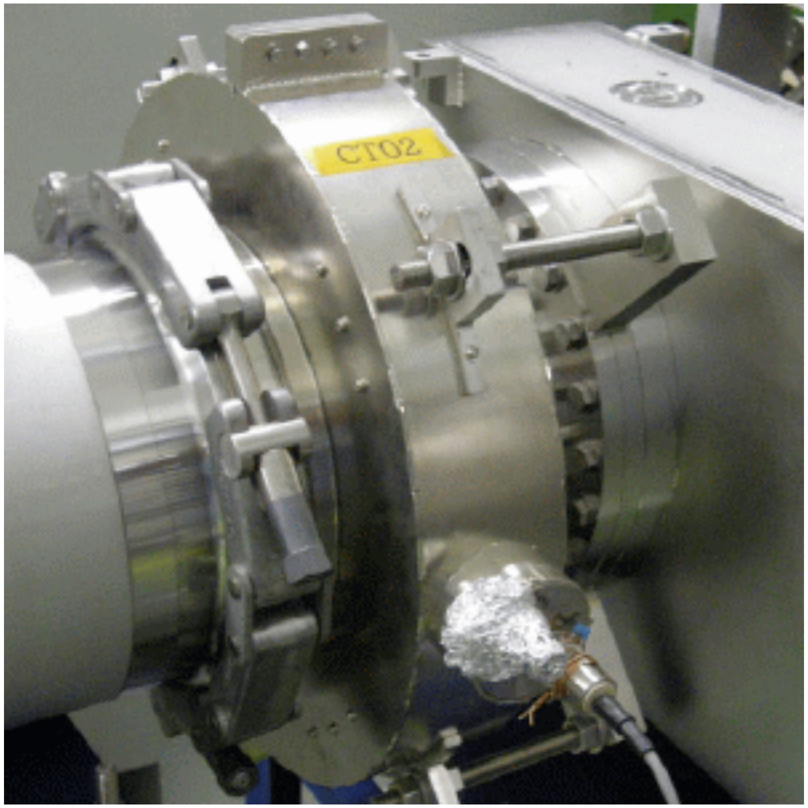
Proton beam monitoring

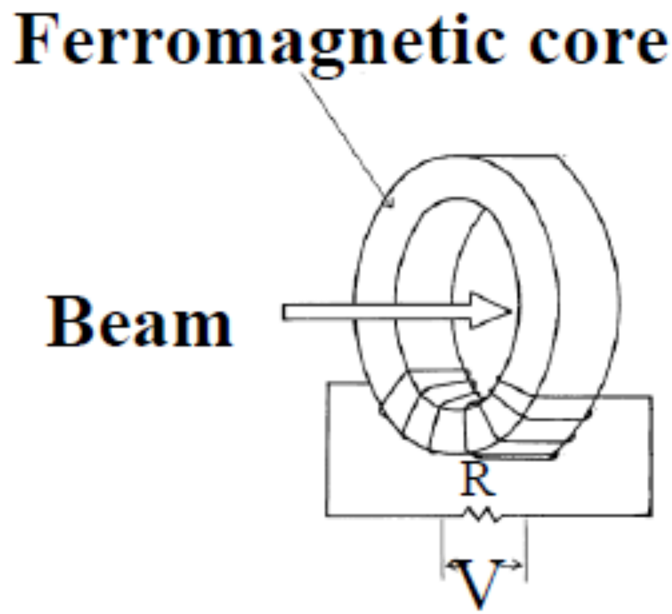
Types of proton beam monitors:

- 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)



Beam intensity monitors





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

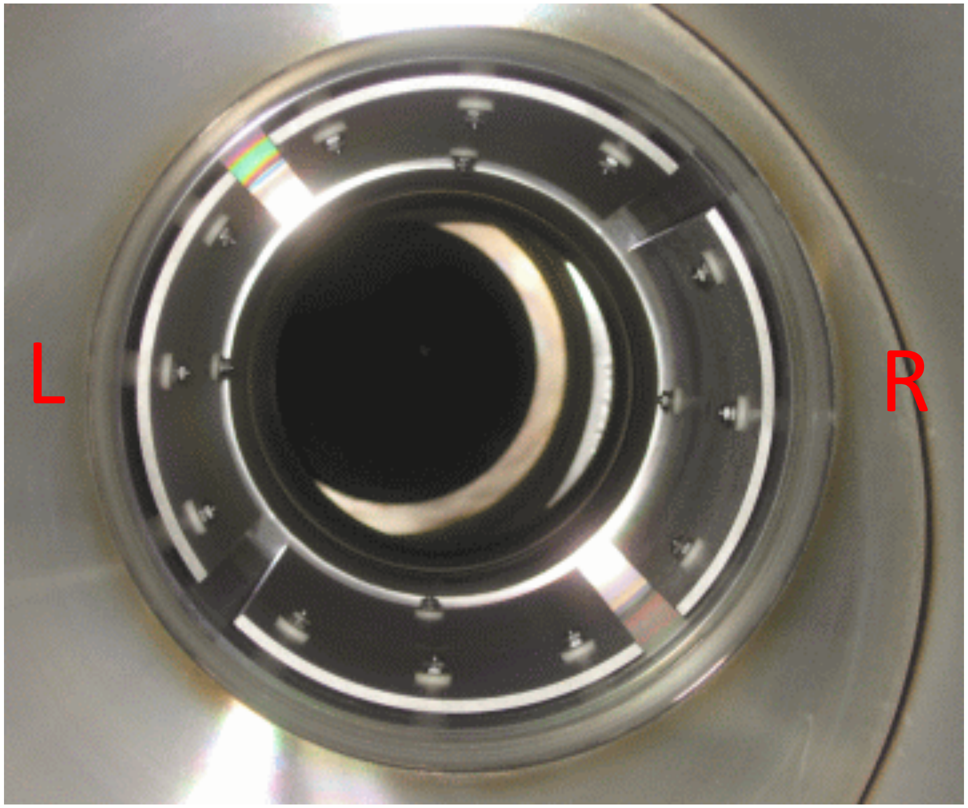
N is number of turns in the coil

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

Beam position monitor



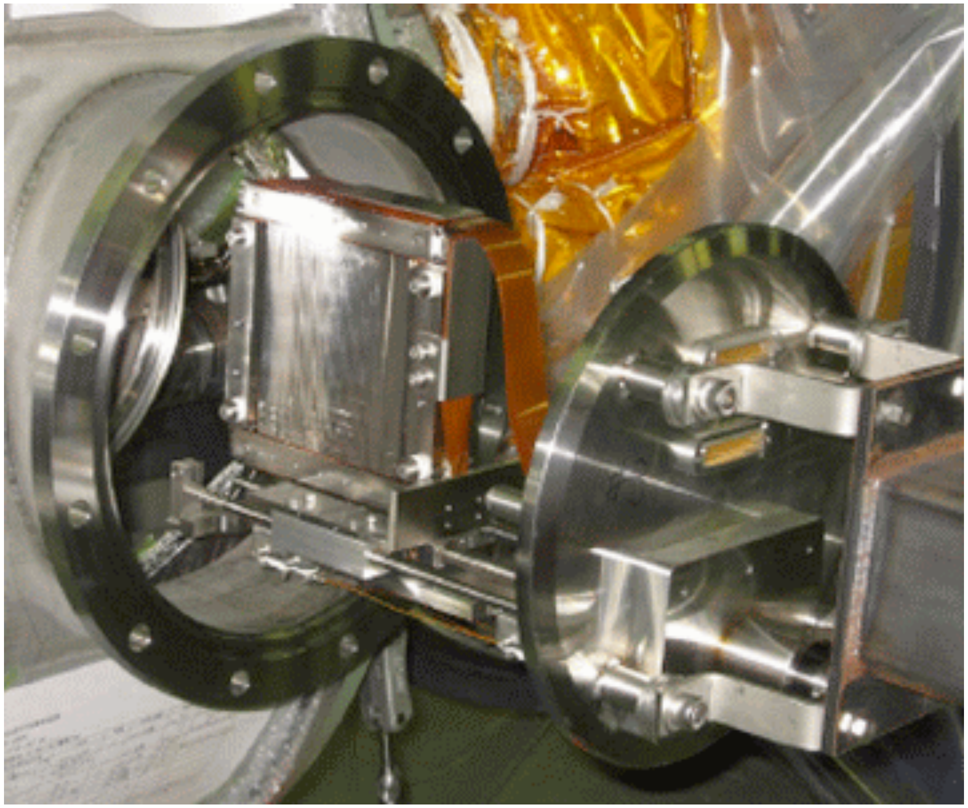
$$center \propto \frac{L-R}{L+R}$$

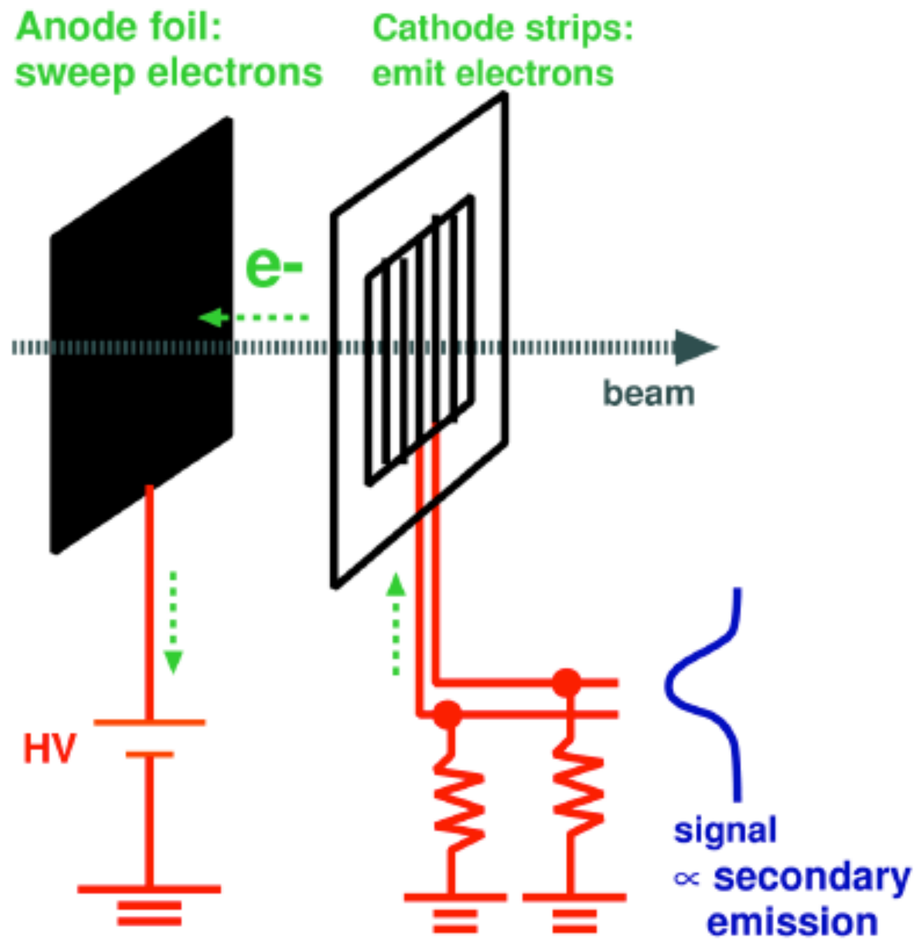
"Precision of the beam position < 450μm"

ESM "Electro static monitor"

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

Beam profile monitor



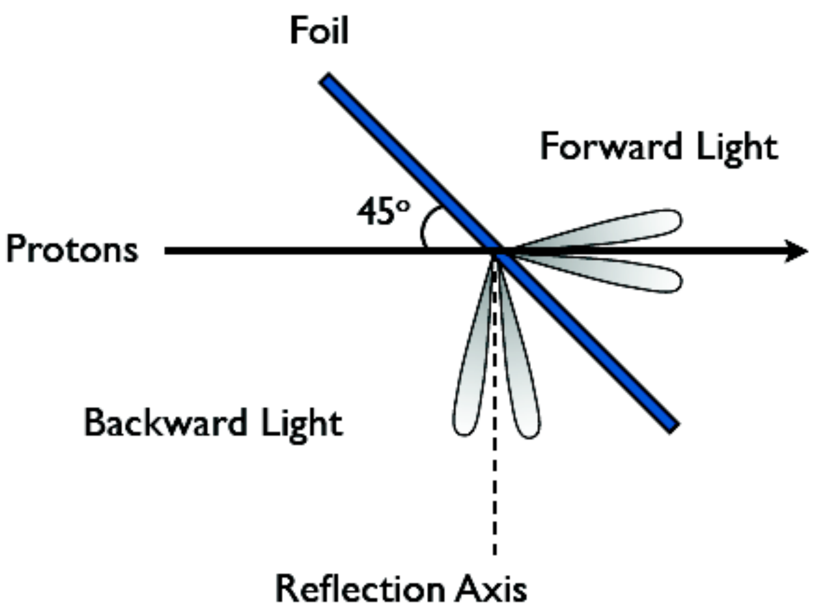


SSEM "Segmented Secondary Emission Monitor"

- Proton beam ejects electrons from thin foil
- Apply electric field to collect electrons
- Multiple planes of foil allow the profile to be determined
- Retractable with stepping motor (minimize time in beam, beam losses)

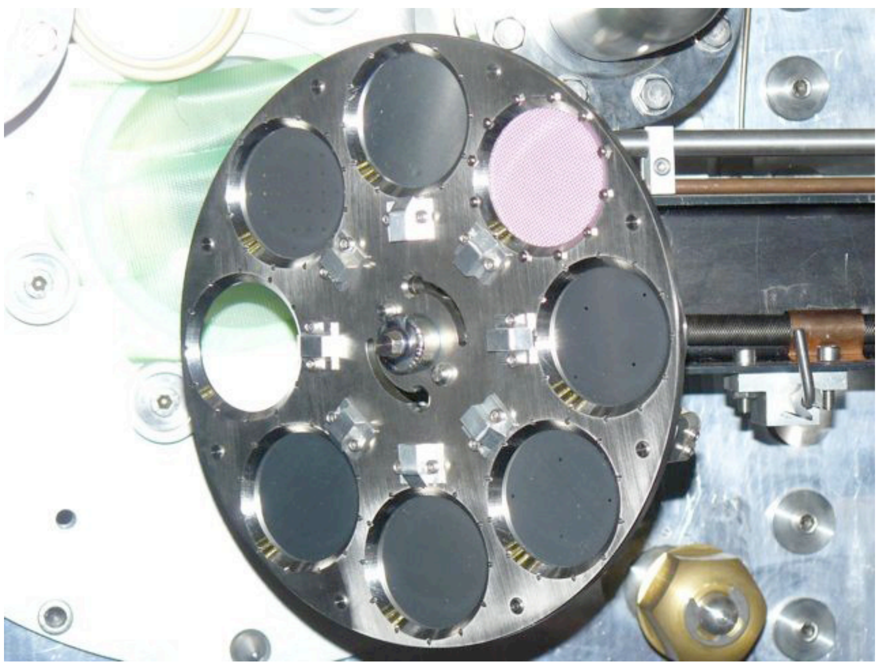
Beam width measurement is ~200μm

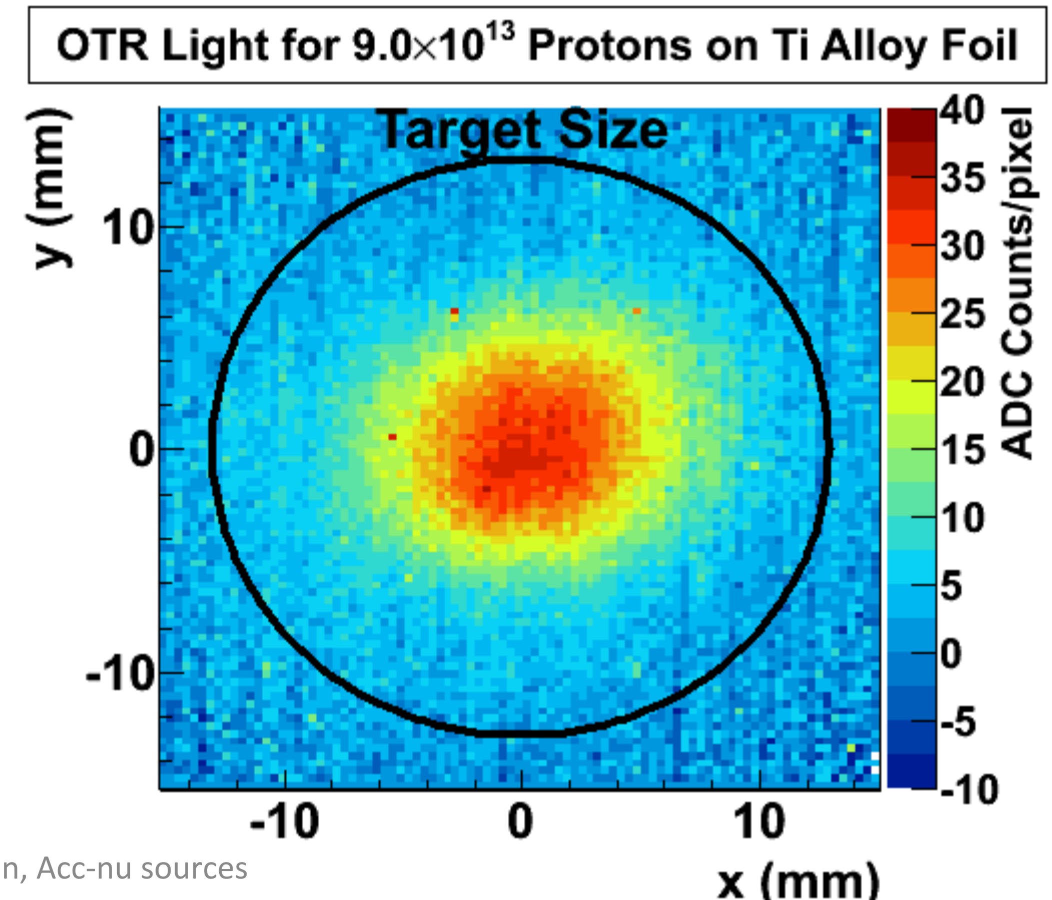
Beam profile monitor at the target



OTR "Optical Transition Radiation"

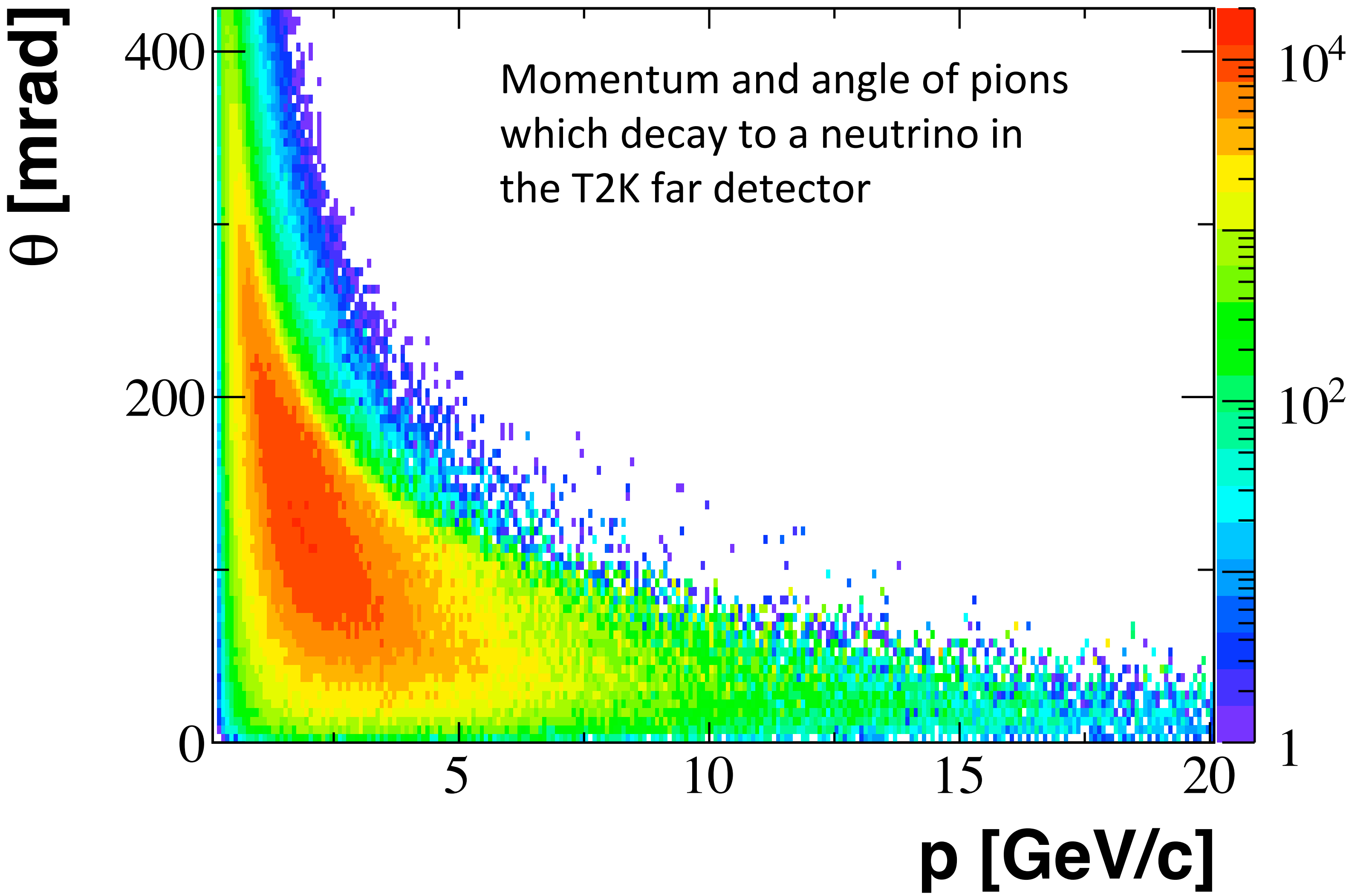
- Produced by the the protons as they pass through a thin Ti foil in front of the neutrino target
- The light is emitted perpendicular to the beam and reflected via parabolic mirrors to a CID camera
- OTR light is used to determine the beam profile and position on the target





Pion and kaon production

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



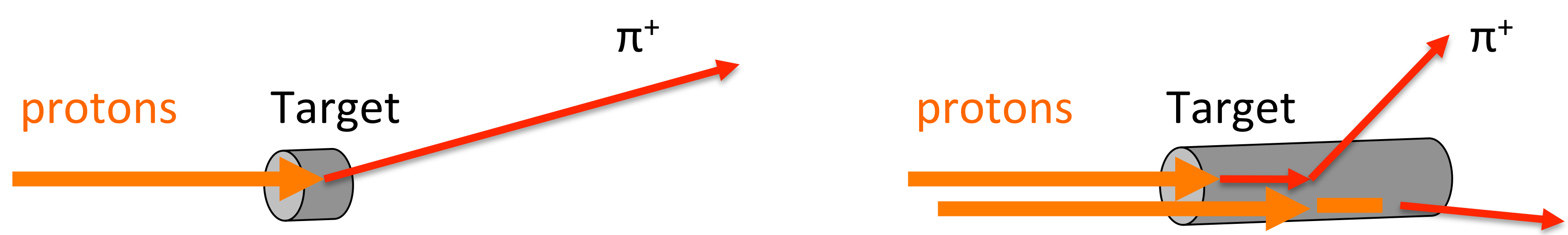
Pion and kaon production

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

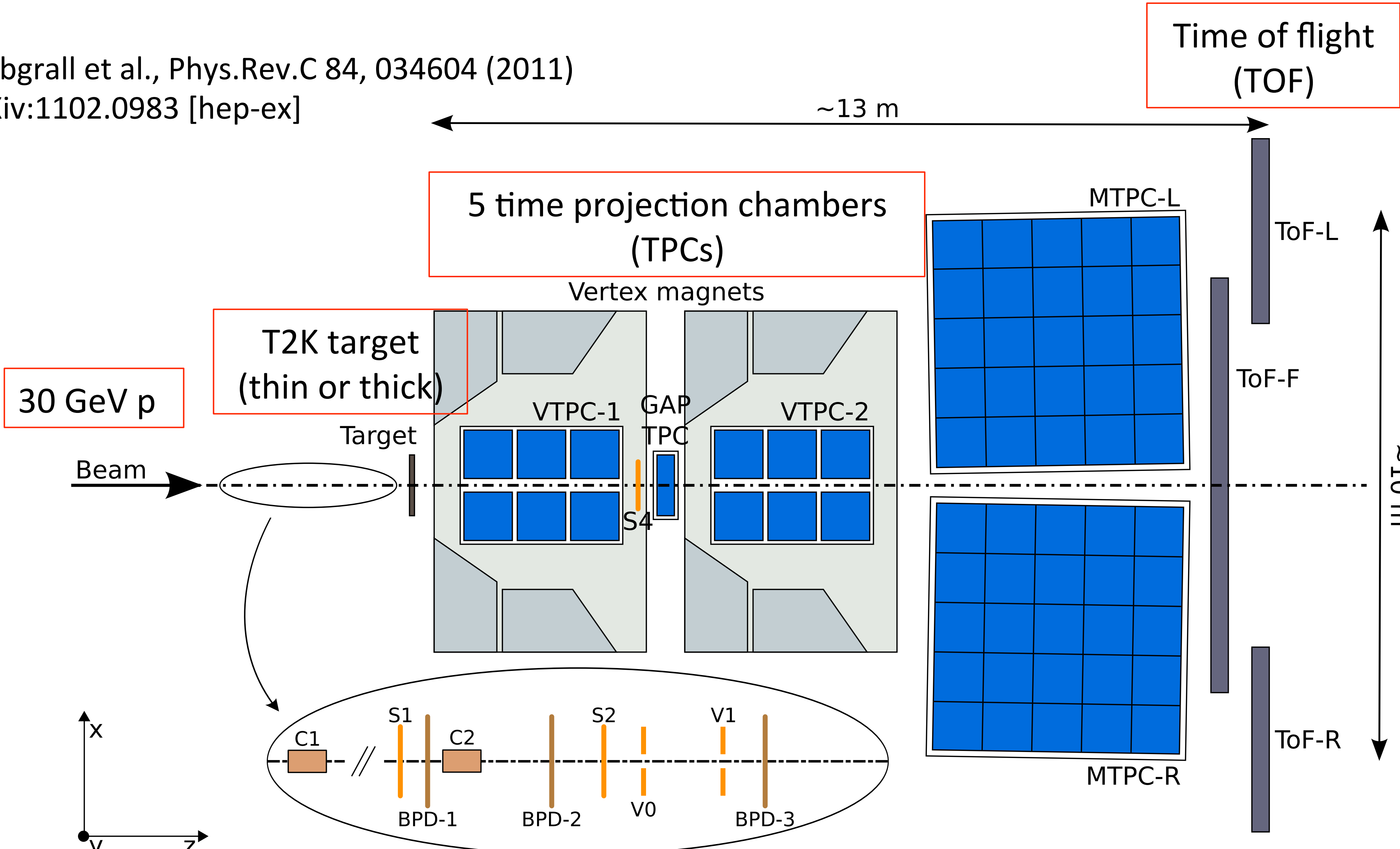


NA61 experiment

NA61/SHINE experiment at CERN

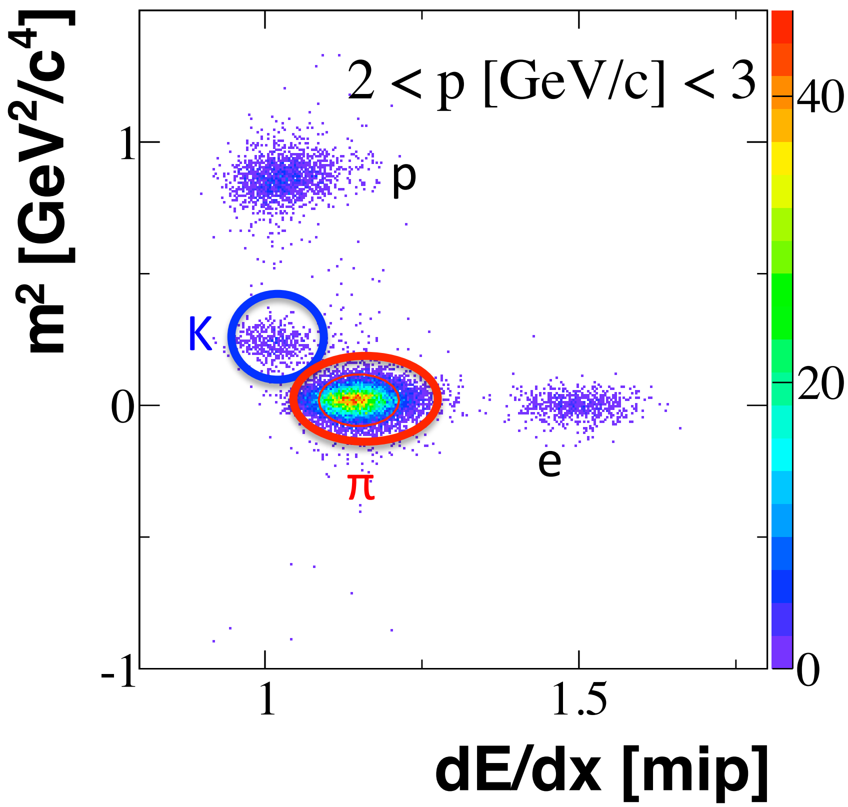
Designed to measure hadron production for a wide range of experiments

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



NA61 analysis and results

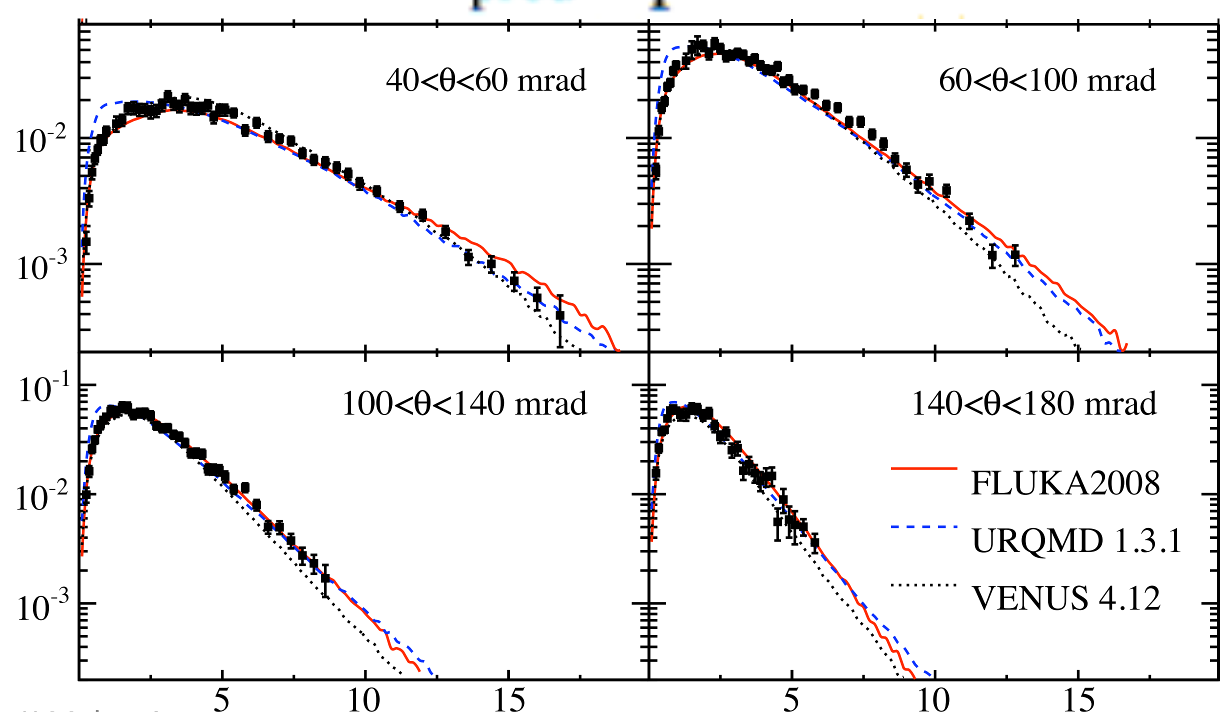
First, select pions using TOF and dE/dx:



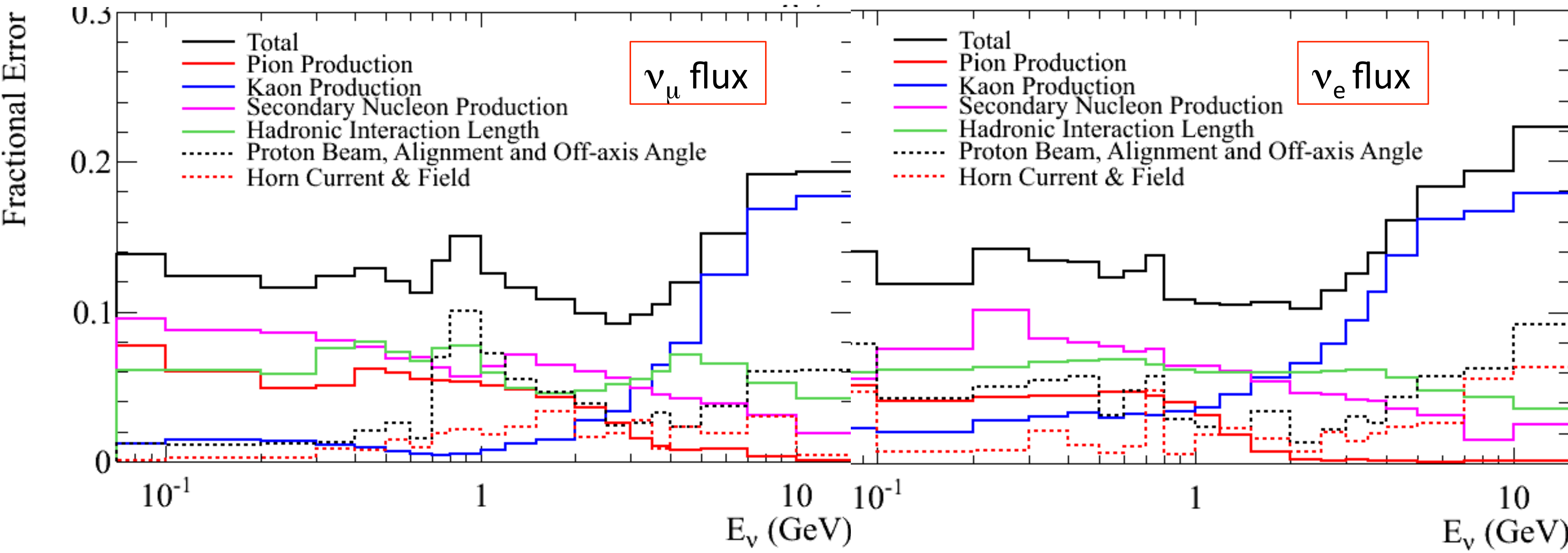
- Reasonable agreement with simulation used for T2K
- Used to determine uncertainties on pion, kaon production

Then, determine the pion production differential cross section:

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



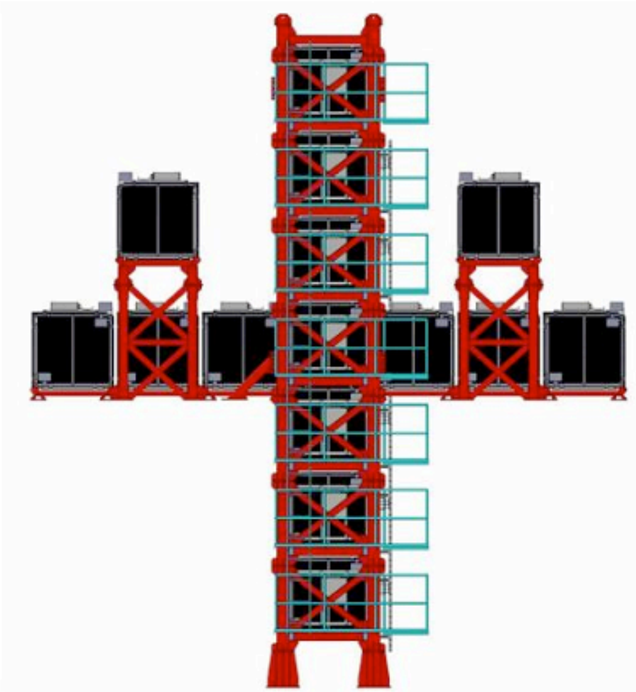
Summary of T2K flux uncertainties



These plots show the effect of the different systematic errors vs. neutrino energy

- Pion production and kaon production were reduced due to NA61 data
- Proton beam, alignment and offaxis angle uncertainties are constrained from beam monitors, survey data and INGRID
- Secondary nucleon production (reinteractions of protons, pions within the target which compose ~30% of the flux) will be constrained with new thick target NA61 data

On-axis beam direction detector

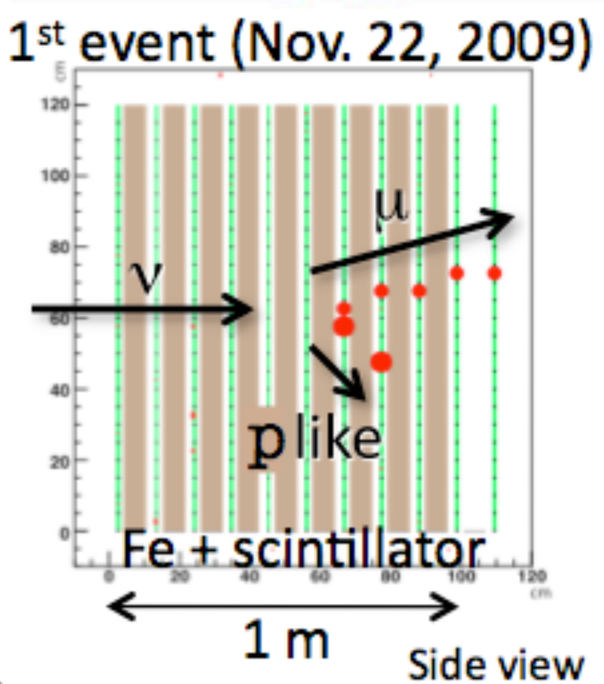


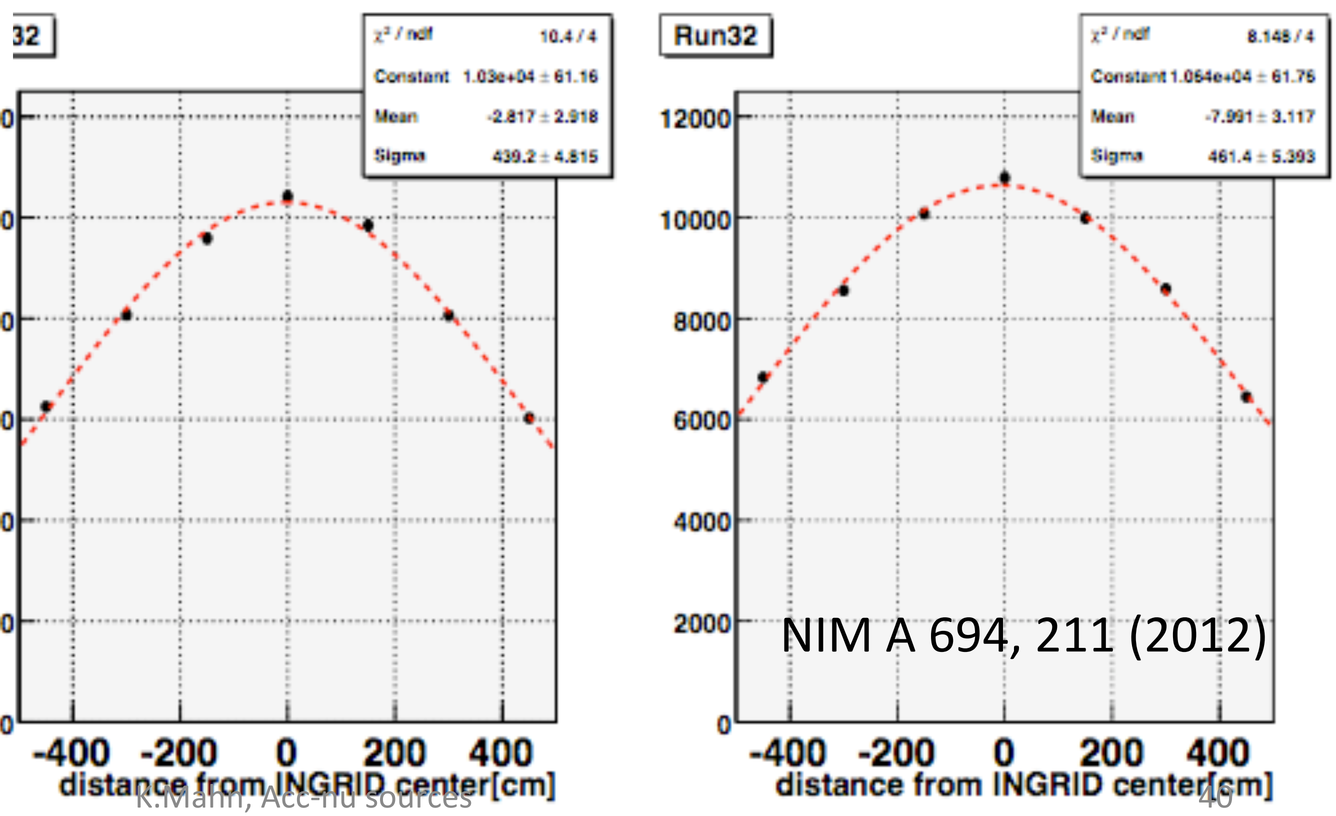
- Offaxis beam direction alters ν energy spectrum
- Beamline and detector position known from survey, but may vary with time

  Constrain beam direction with dedicated detector

- Count neutrino interactions in each module to determine neutrino rate vs. position

T2K's Interactive Neutrino GRID = INGRID





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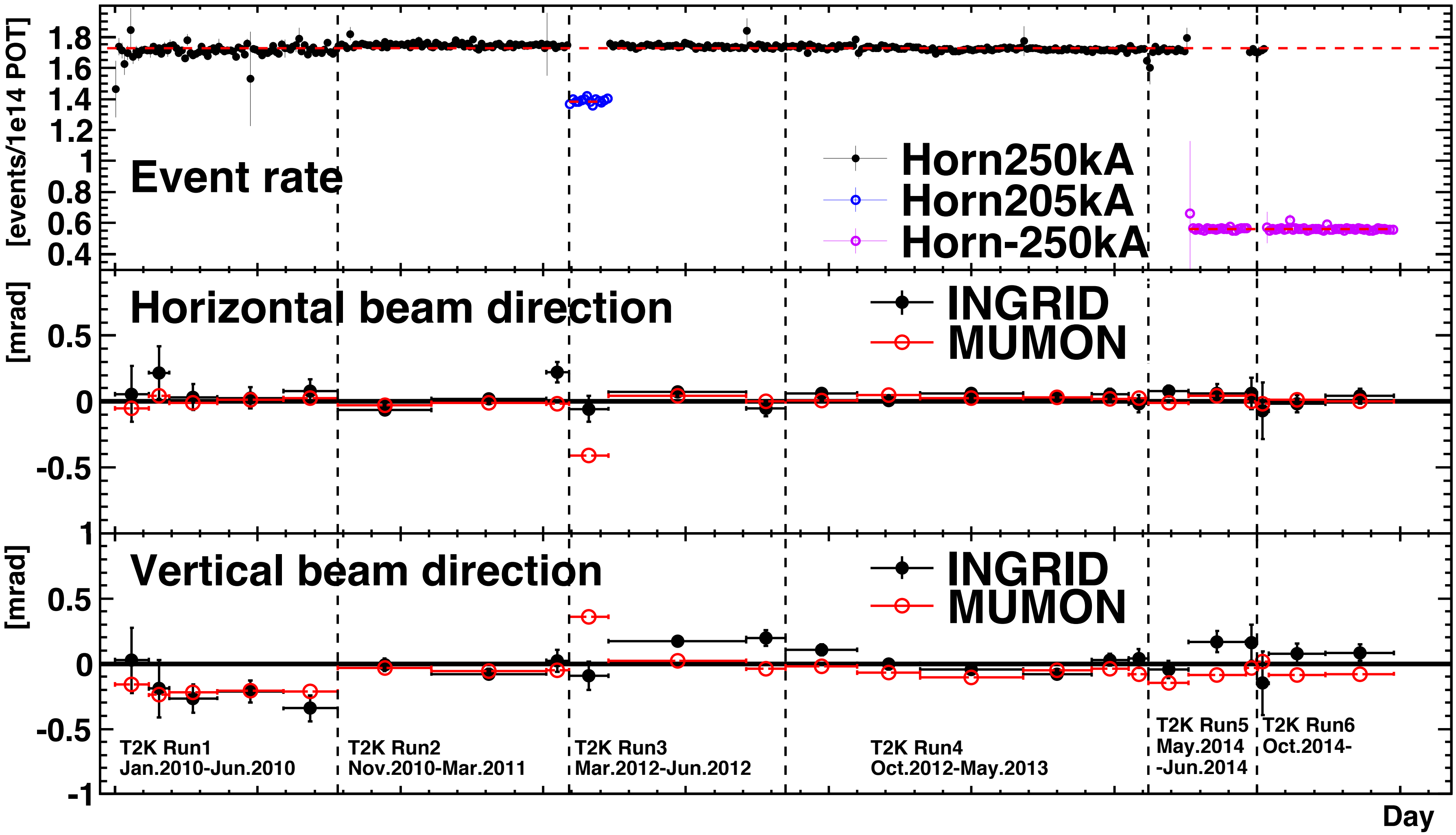
Off-axis beam direction



Profile of neutrino beam measured with scintillator/iron detectors placed from 0-0.9 degrees off-axis (INGRID)

- Confirms POT normalized event rate stable (better than 1%)
- Beam direction is stable to within 1mrad; 1mrad corresponds to a 2% shift to peak of the off-axis neutrino energy distribution

Near neutrino detectors

Many long baseline neutrino experiments have a "near" detector at a short distance from the neutrino beam to measure the unoscillated neutrino rate:

$$\boxed{N'_{FD} = R^{data}_{ND}(CC\ \nu_\mu) \times \frac{N_{FD}}{R^{exp}_{ND}(CC\ \nu_\mu)}}$$

One can reduce the systematics on the oscillation measurement (based on rate) with a "near to far ratio", where flux and cross section cancel:

$$\frac{N_{FD}}{R^{exp}_{ND}} = \frac{\int \boxed{\Phi^{FD}_{\nu_\mu}} \times \boxed{\sigma} \times \boxed{\epsilon_{FD}} \times P(\nu_\mu \rightarrow \nu_x)\ dE_\nu}{\int \boxed{\Phi^{ND}_{\nu_\mu}} \times \boxed{\sigma} \times \boxed{\epsilon_{ND}} dE_\nu}$$

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This cancellation isn't perfect! Note the integral.
Inherent dependence on energy dependence of cross section
(and assumed background contributions)

Requires a robust cross section and flux model

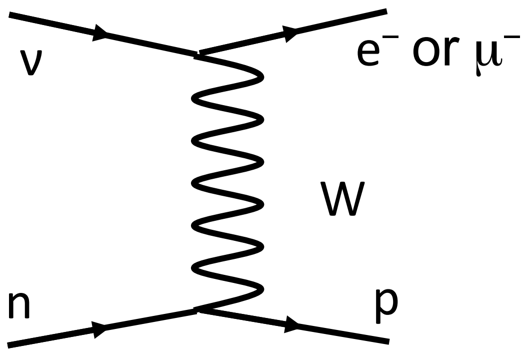
Accelerator-based experiment example: T2K

$$\boxed{P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) + \ldots}$$

Oscillation probability depends on neutrino energy)same for appearance)

For T2K's neutrino spectrum, dominant process is Charged Current Quasi-Elastic:

CCQE

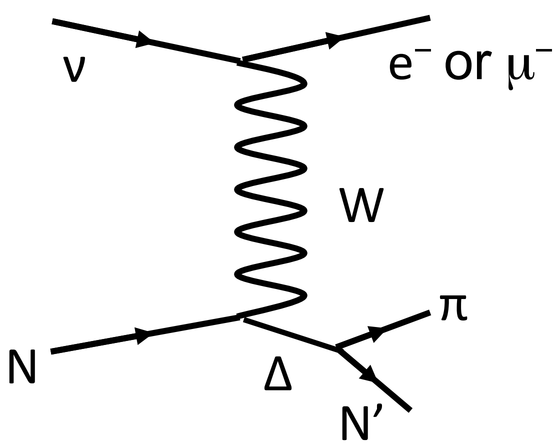


Infer neutrino properties from the lepton momentum and angle:

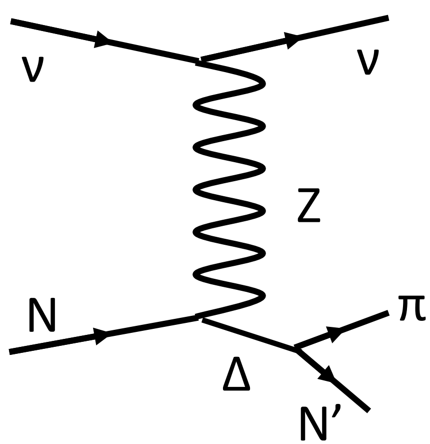
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



NCπ



Additional significant processes:

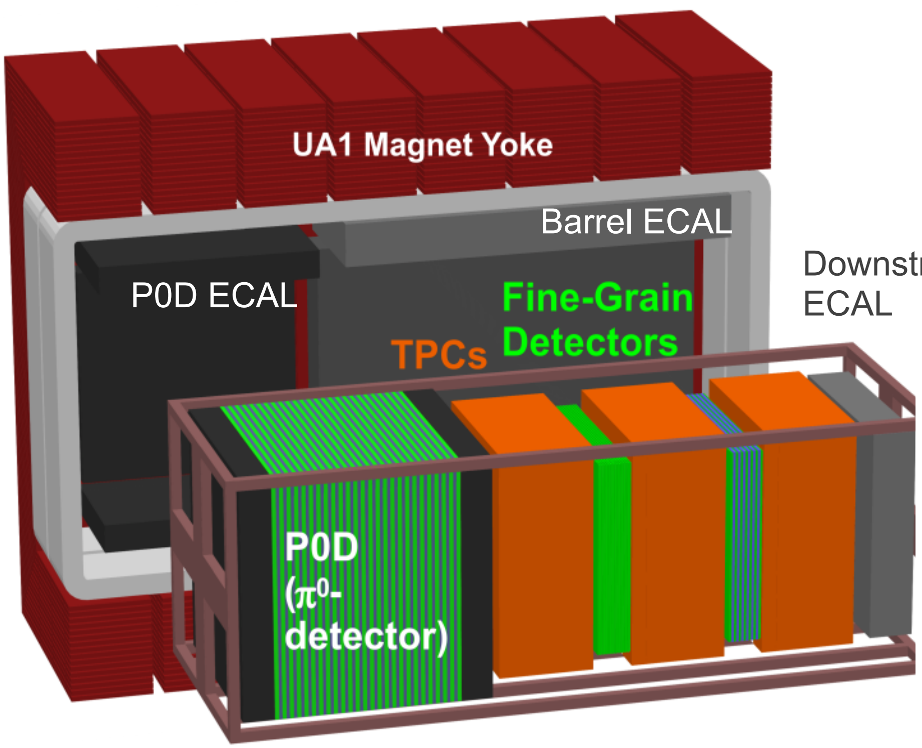
- CCQE-like multinucleon interaction
- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ)

Off-axis near detectors: ND280 (ND)

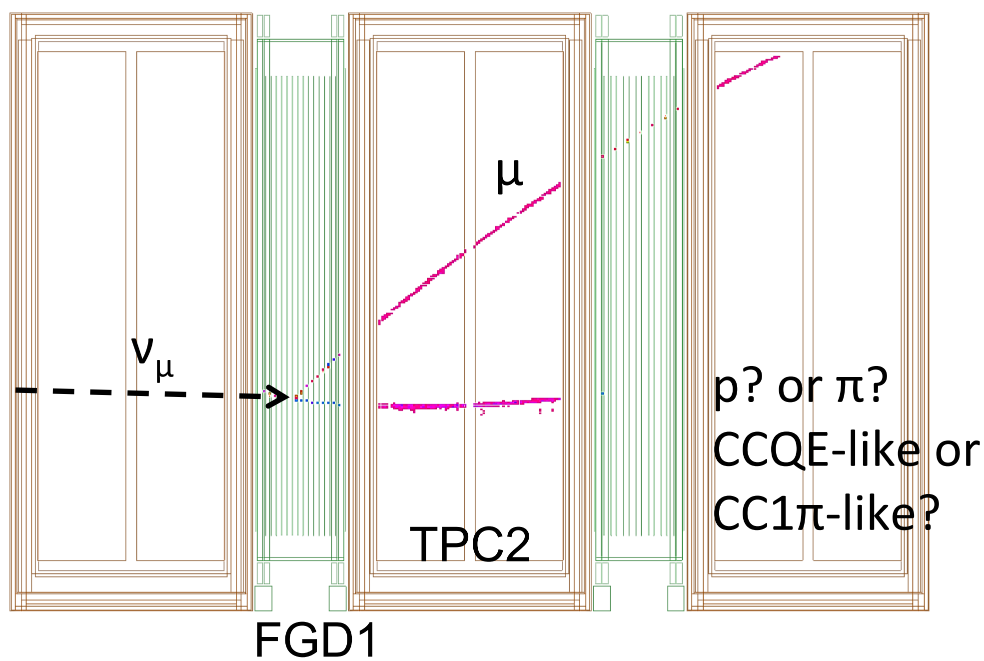
Suite of near detectors sit within UA1 (B=0.2T, 850 tons) magnet

Measure unoscillated CC ν_μ rate in Tracker:

- Neutrinos interact on FGDs (carbon target)
- Measure lepton angle, momentum and flavor with TPCs
- Separate selection into CCQE-like (CCQE) and all other CC (CCnQE, now CC1π, CCother) using energy loss, track multiplicity and calorimetry



NIM A 624, 591 (2010)

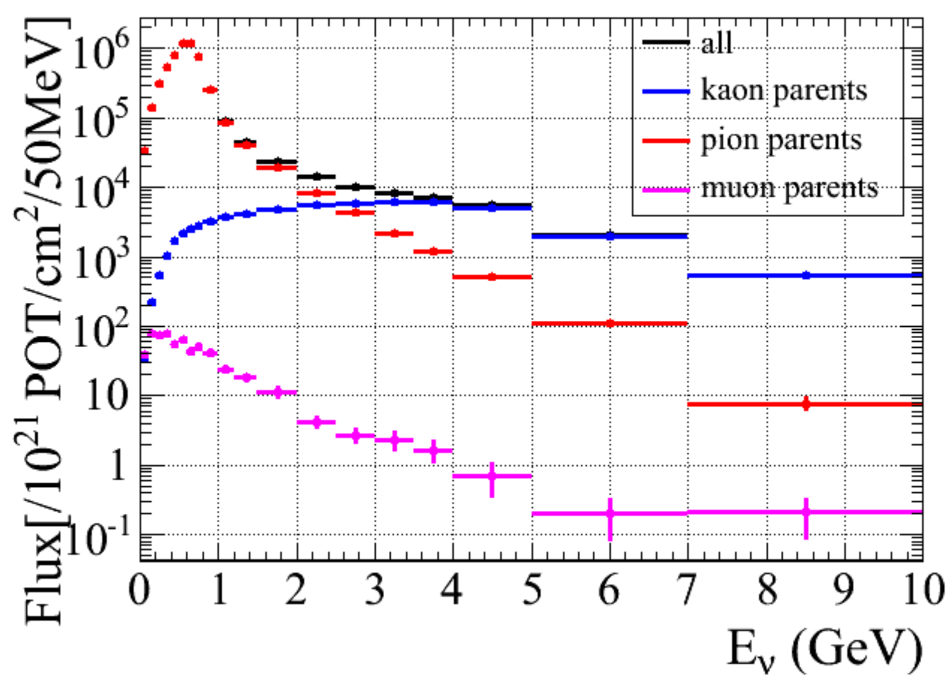


Neutrino flux at ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu_\mu}$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

ND samples represent ν_μ flux

- ν_μ from π decay: CCQE, CCnQE samples
- ν_μ from K decay: CCnQE sample



Neutrino flux at ND and SK

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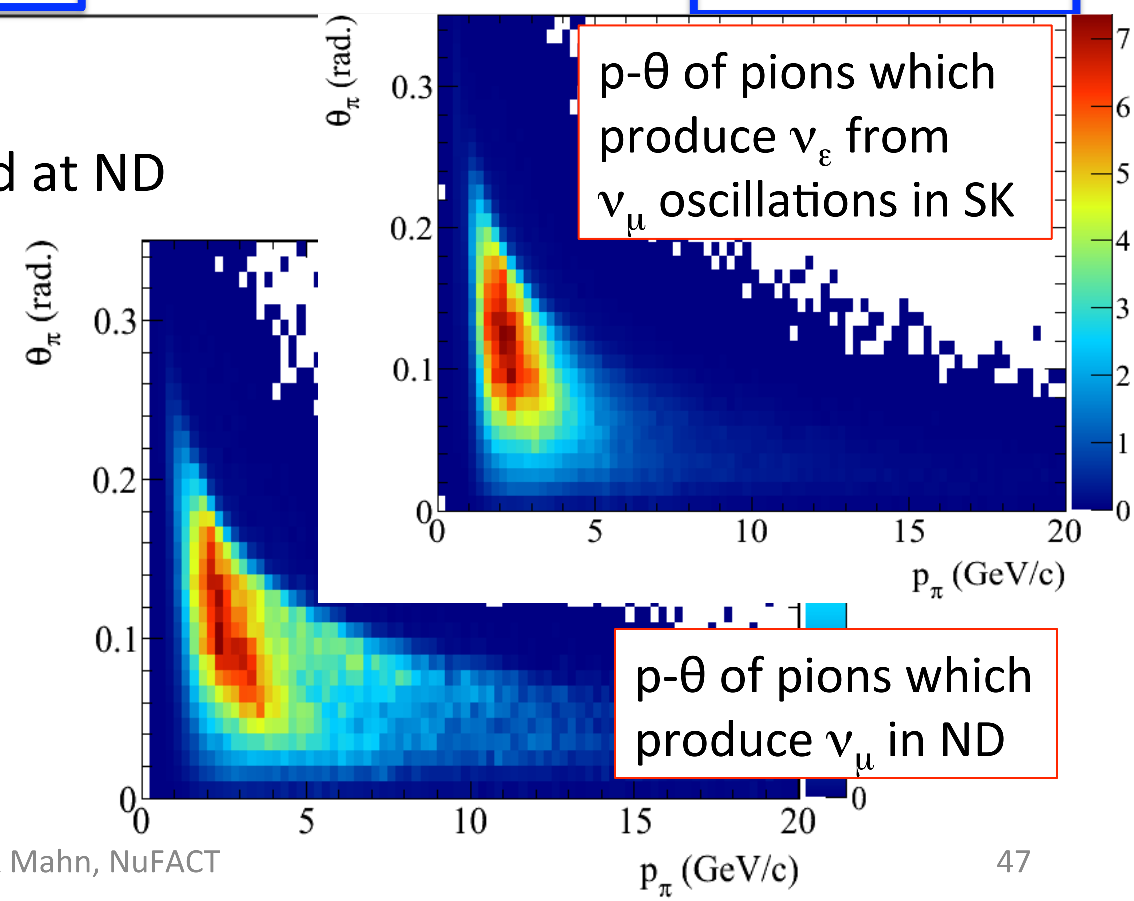
SK signal and NC background events come from ν_μ flux directly measured at ND



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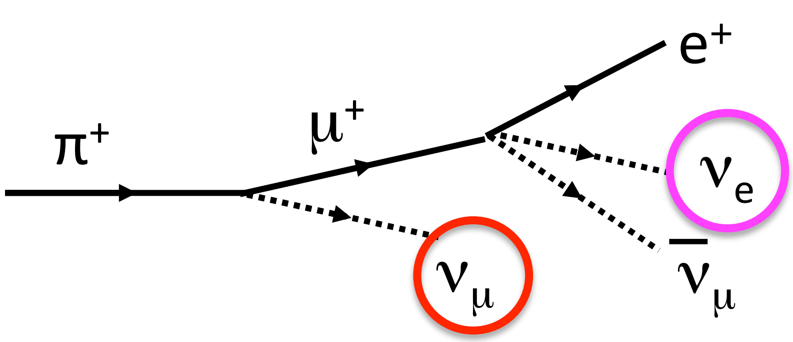
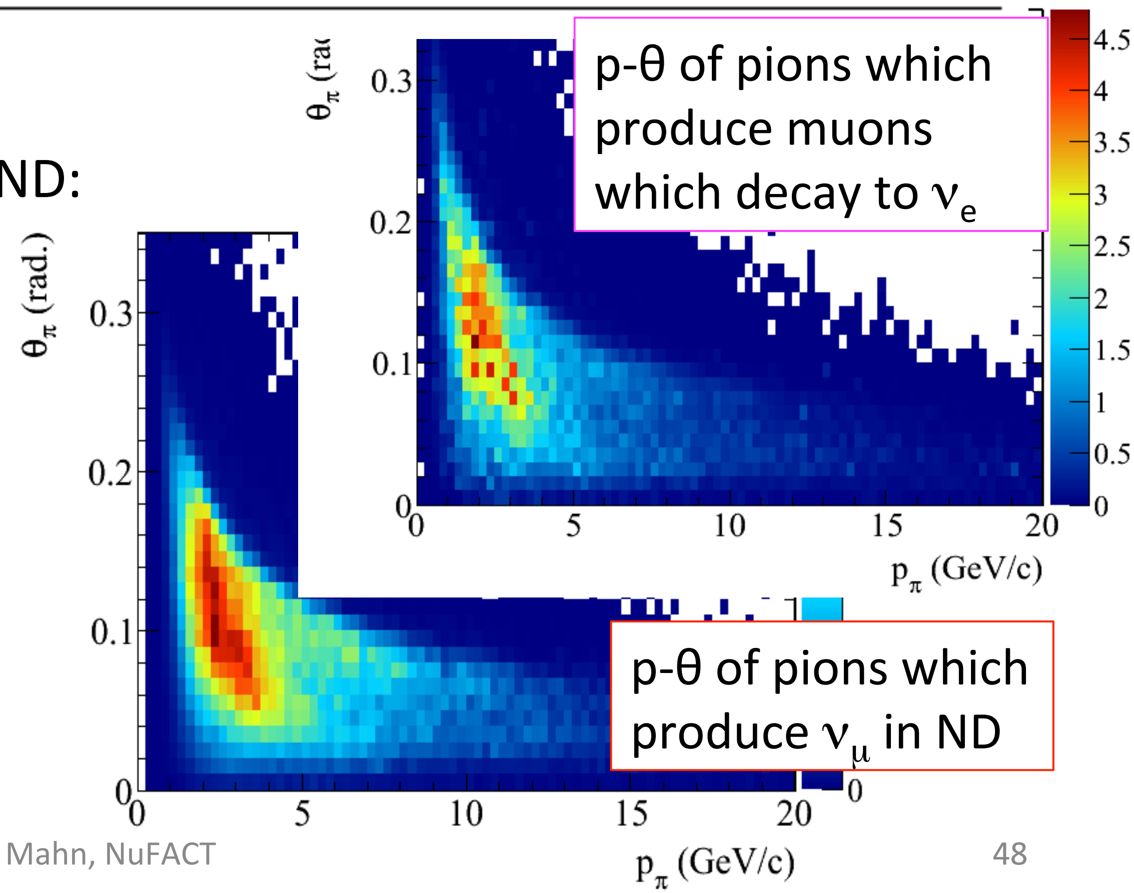
CC background from beam ν_e is strongly correlated with ν_μ flux at ND:

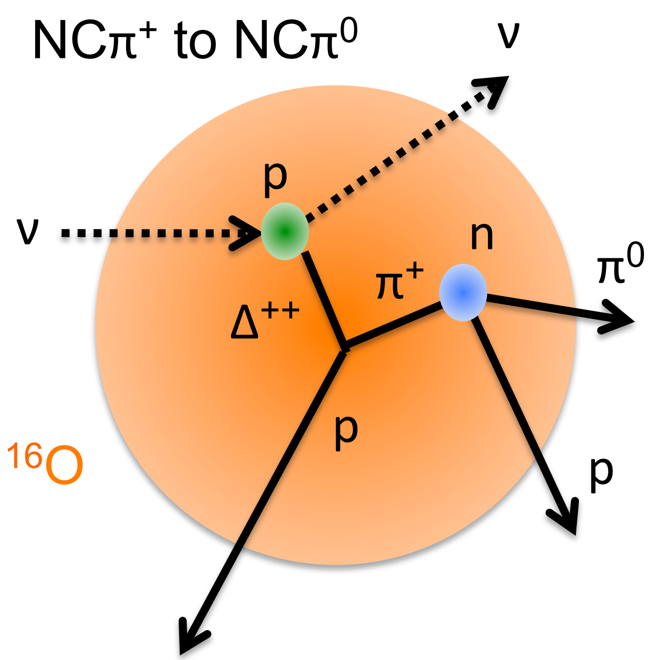


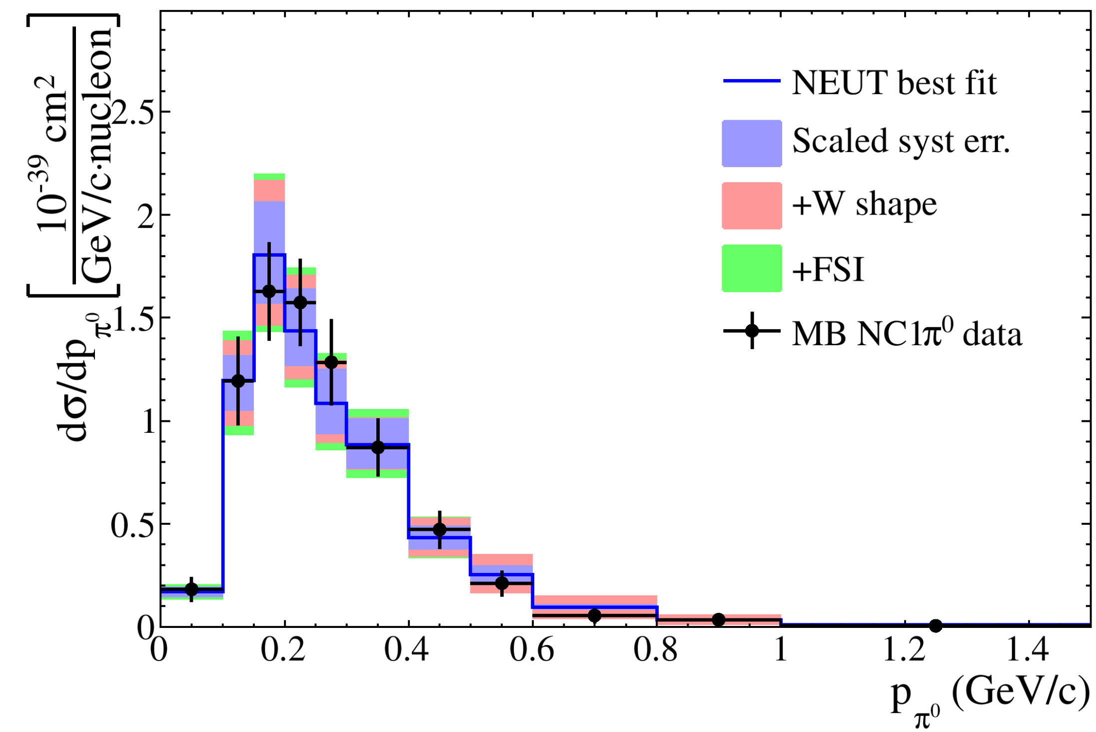


Neutrino interaction uncertainties

Cross section model (NEUT, GENIE) composed of:

- Base model prediction
- Final state interaction model (FSI)





Cross section model uncertainties set from fits to MiniBooNE (and now MINERvA) data (E_ν ~ 1, 3 GeV) for signal and background (CCQE, $CC1\pi$ and $NC\pi^0$) interactions:

- Inherent reliance on model – test it against as much available data as possible
- Currently, no single model appears to represent all data

Neutrino interactions at ND and SK

Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

CCQE and CC1π are the largest interaction mode in ND, SK samples

Caveats:

- Acceptance: ND sample is forward going (small angle, low Q^2)
    - External data covers larger Q^2 (MiniBooNE, 4π Cherenkov detector)
- Target: ND selection is C, SK is O
    - C-O model dependent uncertainties included
    - Upcoming analyses will use ND water-target sample

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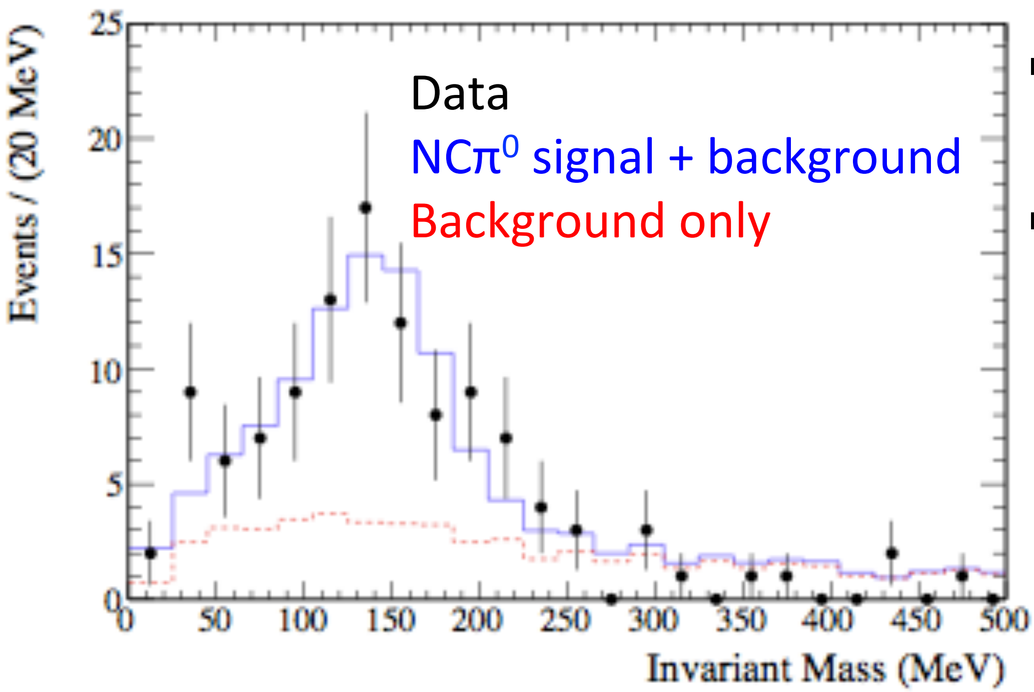


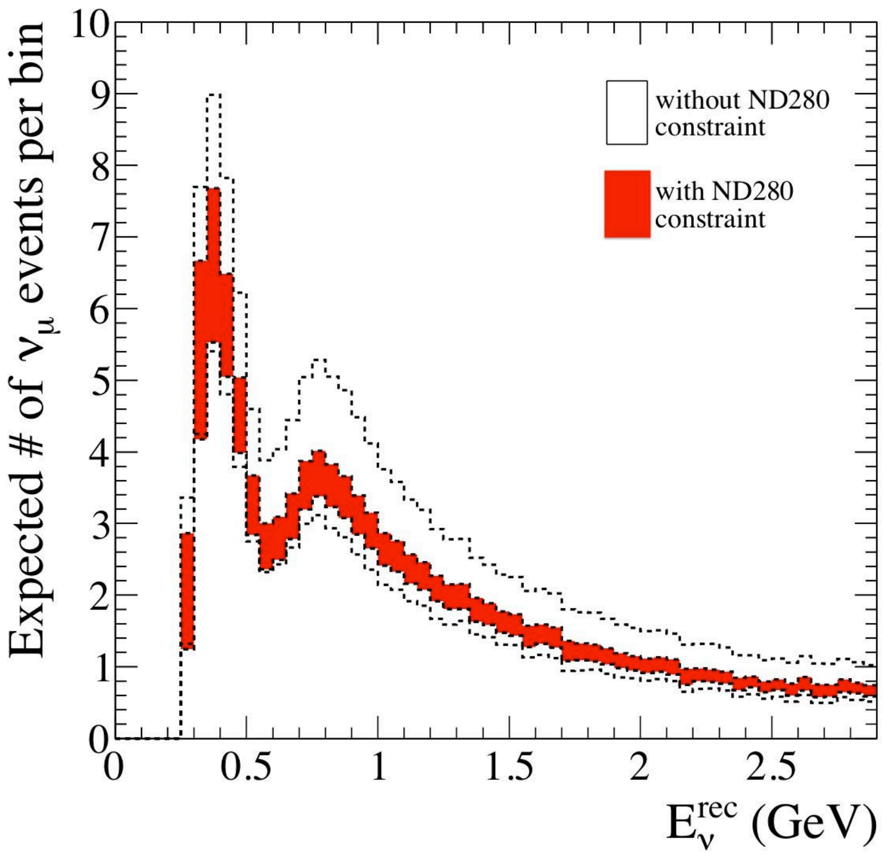
- Indirect constraint on NC ($1\pi^0$) through CC1π in ND measurement
- Additional ND selection of NCπ^0 with P0D detector

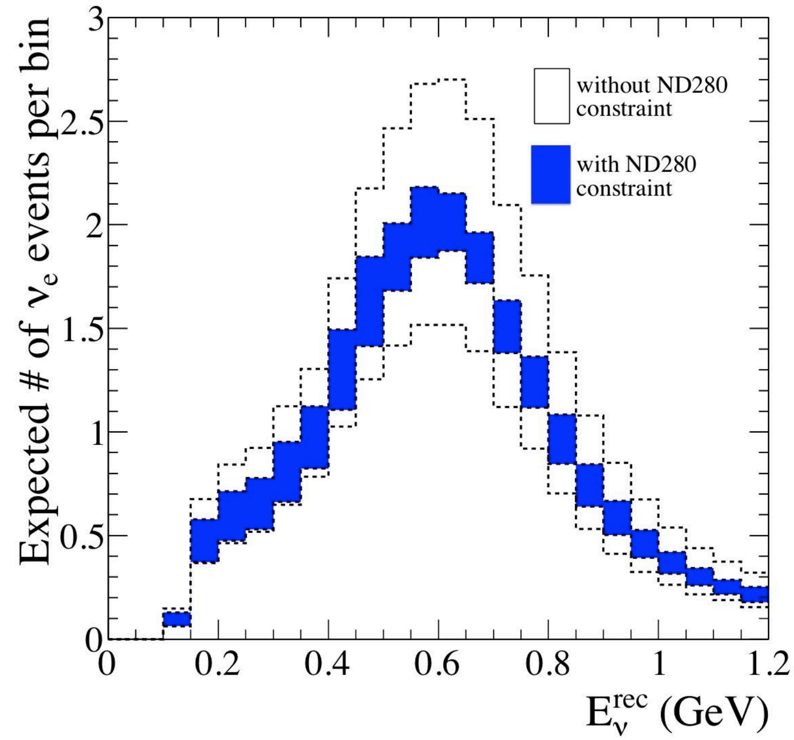
Systematic errors for T2K analyses

Table summarizes normalization (overall) uncertainty

- Substantial reduction to systematic uncertainties due to ND data
- Shape is also important to discriminate signal from backgrounds or between osc models

uncertainties	ν_μ disap.	ν_e app
ν flux+xsec (before) after ND constraint	(21.7%) ±2.7%	(26.0%) ±3.2%
ν unconstrained xsec	±5.0%	±4.7%
Far detector	±4.0%	±2.7%
Total	(23.5%) ±7.7%	(26.8%) ±6.8%





Systematic errors for T2K analyses

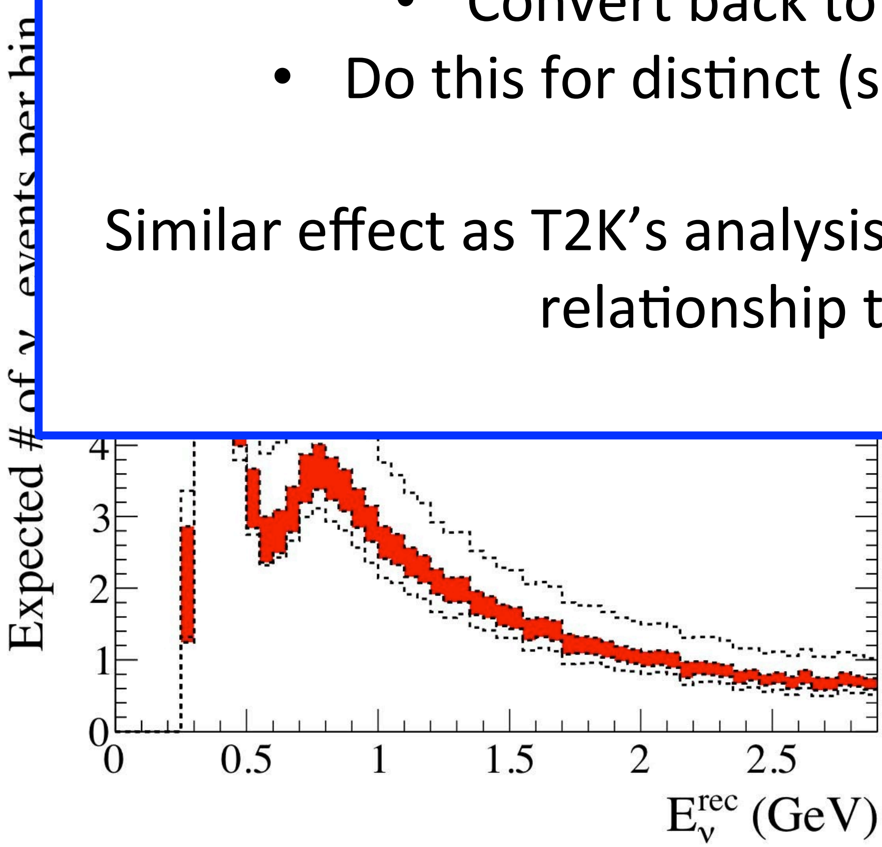
Table summarizes normalization (overall) uncertainty

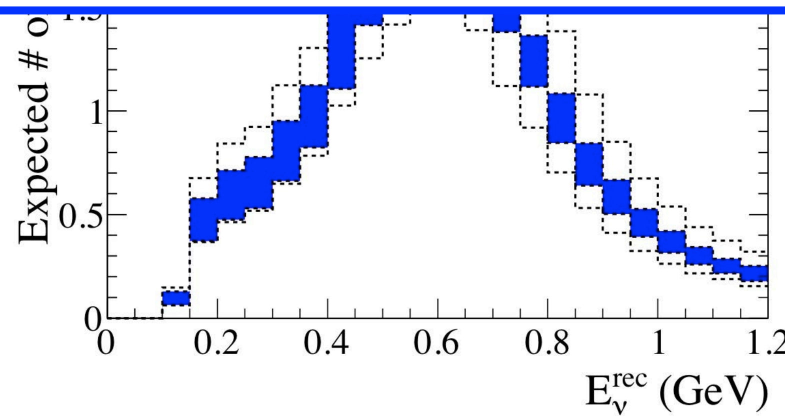
uncertainties	ν_μ disap.	ν_e app
ν_μ flux+xsec (before)	(21.7%)	(26.0%)

Different approach used by MINOS, NOvA extrapolations:

- Estimate true neutrino energy from ND events reconstructed energy,
  - then multiply the true distribution by the oscillation probability.
    - Convert back to a reconstructed distribution
  - Do this for distinct (signal and background) categories

Similar effect as T2K's analysis, model dependence enters in assumed relationship to true neutrino energy





Second lecture summary

Conventional neutrino beams are complicated machines

- Enormous progress from factor of 2 to 10% uncertainties on neutrino, antineutrino fluxes

Oscillation experiments rely on a lot of data to estimate the far detector rate

- Measurements of the beamline (horn current, proton beam monitors)
- Measurements of dedicated hadron production experiments
- Measurements from other neutrino beams of relevant neutrino cross section processes
- On-axis near detectors measure direction of the beam
- Off-axis near detectors provide additional constraint on predicted event rate

Next lecture: the future!

- Future neutrino beam proposals for search for δ_{CP} and sterile neutrinos

Backup slides