The T2K Beamline and Beamline Simulation

M. Friend

KEK

September 22, 2014

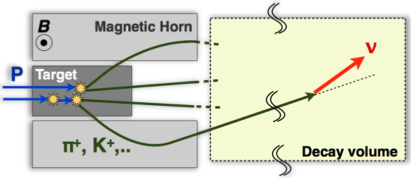
Outline

- T2K Experiment and Neutrino Facility at J-PARC
  - Primary Beamline
  - Secondary Beamline
- Modeling the Neutrino Flux
  - Flux MC
  - Hadron Production Reweighting

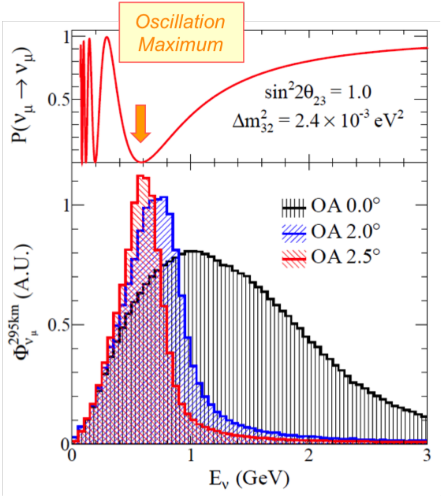
The T2K Experiment (Tokai to Kamioka Long Baseline Neutrino Experiment)

- Primarily ν_μ, 2.5° off axis neutrino beam produced at J-PARC
- ND280 Near Detector at J-PARC – 280 m from ν source
  - Constrains neutrino flux/systematic errors
  - ν cross sections, beam backgrounds, sterile search, etc.
- Neutrino interactions detected at the Super-Kamiokande (SK) far detector – 295 km from ν source
  - $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_\mu$ disappearance ν oscillation information from SK

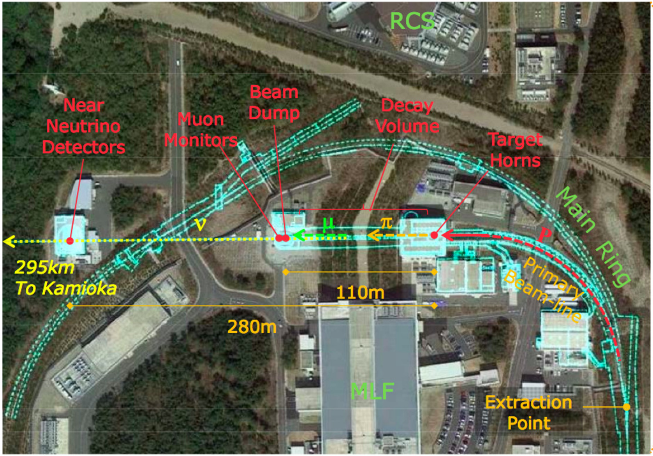
Neutrino Production with a Conventional Neutrino Beam



- Protons hit carbon target, produce hadrons (π^+, K^+, etc)
- Hadrons are focused in series of magnetic horns
- Hadrons then decay into μ, ν_μ, etc in long decay volume
- An off axis neutrino beam has a more sharply peaked energy spectrum



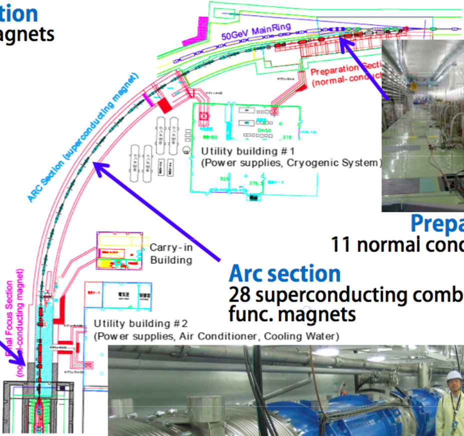
The Neutrino Facility at J-PARC



- 30 GeV protons from the J-PARC Main Ring (MR) used to generate conventional, off axis neutrino beam
- Primary beamline transports protons extracted from MR
- Secondary beamline consists of carbon target, horns to focus outgoing hadrons, and a decay volume

T2K Primary Beamline

Final focusing (FF) section
10 normal conducting magnets



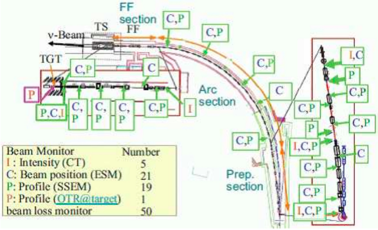
Preparation section
11 normal conducting magnets

Arc section
28 superconducting combined func. magnets

- Beam orbit (and beam loss) should be firmly controlled anytime.

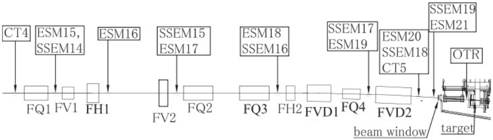
T2K Primary Beam Monitors

Primary Beamline Monitors



Final Focusing Section

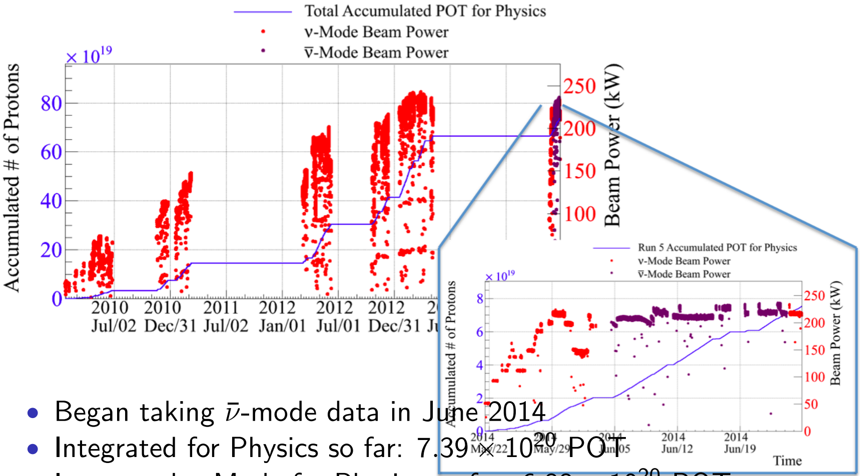
Beam Direction $\longrightarrow$



- Use information from beam monitors for input into neutrino flux simulation
  - 21 ESMs (Electrostatic Monitors): measure beam position
  - 19 SSEMs (Segmented Secondary Emission Monitors): measure beam profile
  - 5 CTs (Current Transformers): measure beam current
    - See beam monitor talk on Wednesday by me
  - 1 OTR (Optical Transition Radiation) Monitor: measures beam position at target
    - See OTR talk on Wednesday by M. Hartz
  - MUMON (Muon Monitor): measures muon yield/profile
    - See MUMON talk on Friday by T. Hiraki

T2K Protons on Target

Use information from CTs to calculate number of protons on target

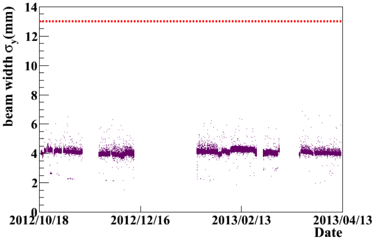


- Began taking $\bar{\nu}$-mode data in June 2014
- Integrated for Physics so far: 7.39×10^{20} POT
- Integrated ν-Mode for Physics so far: 6.88×10^{20} POT
- Integrated $\bar{\nu}$-Mode for Physics so far: 0.51×10^{20} POT
  $\rightarrow$ ~9.5% of T2K approved full statistics (7.8×10^{21} POT)

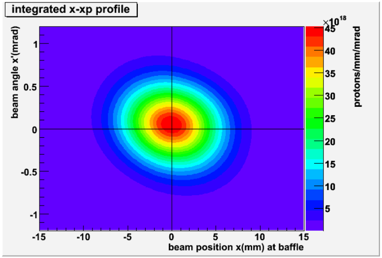
T2K Proton Beam Parameters

Use information from beam position and profile monitors to calculate the beam profile at the baffle (upstream of the target)

Y Width at Target vs. Time



Integrated X Profile at Baffle

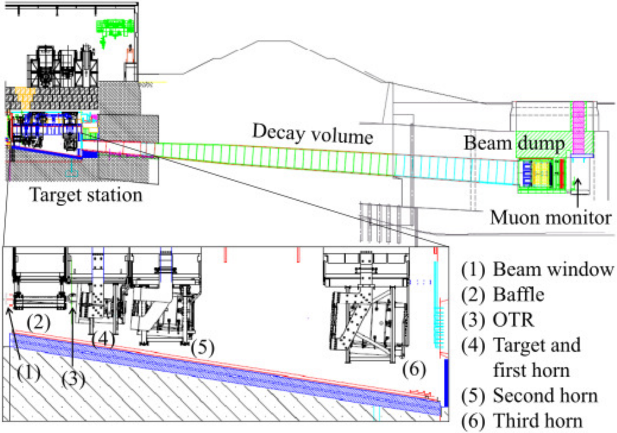


T2K Run 4	X Profile		Y Profile	
Parameter	Central value	Error	Central value	Error
X, Y (mm)	0.03	0.34	-0.87	0.58
X', Y' (mrad)	0.04	0.07	0.18	0.28
σ (mm)	3.76	0.13	4.15	0.15
ϵ (π mm mrad)	5.00	0.49	6.14	2.88
Twiss α	0.15	0.10	0.19	0.35

T2K Proton Beam Parameter Errors

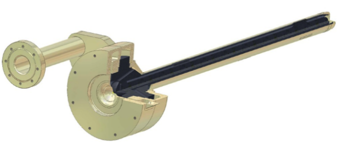
- Systematic errors on the proton beam properties and off-axis angle are the major contributions to the flux errors that don't come from hadron production
- Errors on the proton beam properties come mainly from uncertainties on the beam monitor positions and calibrations
  - These are estimated by including these position and calibration uncertainties when fitting for proton beam parameter information using the beam monitor data
  - Uncertainties on proton beam width, emittance, and Twiss α are also estimated by varying the proton beam momentum and the primary beamline magnet lengths and B fields within uncertainties and calculating the resulting change in the measured beam parameters
    - However, these errors are relatively small
- Uncertainties on the off-axis angle are also constrained by near detector data (see later slide)

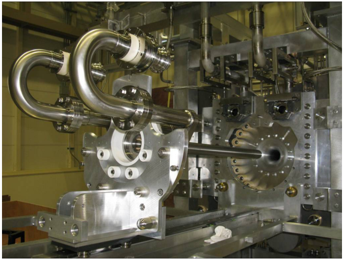
T2K Secondary Beamline



- $\pi^{\pm}$, $K^{\pm}$, K_L^0, re-scattered protons, produced in carbon target
- Focused in three magnetic horns
- Decay in 96-m-long decay volume
- Muons with energy below 5 MeV and other hadrons stopped in beam dump; neutrinos and high energy muons continue

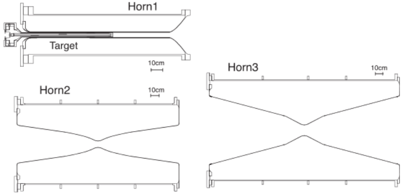
Long Carbon Target

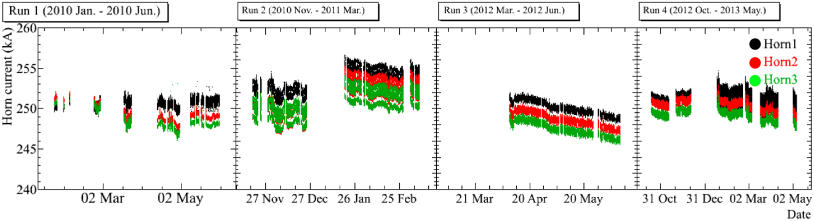




- Long (1.9 interaction length, 91.4 cm long), 2.6 cm diameter and 1.8 g/cm3 graphite
- Proton interactions in the target are simulated using FLUKA 2011 using the true target geometry
- Interaction cross sections and multiplicities are then reweighted (see following slides for method)
- Particles exiting the target are then tracked through horn field and decay volume by GEANT3 simulation using GCALOR package

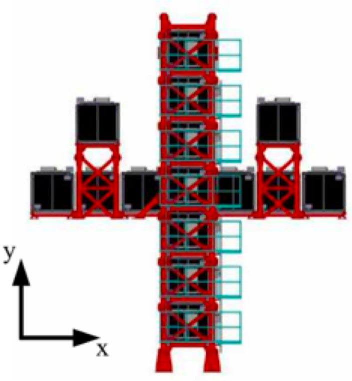
Horns





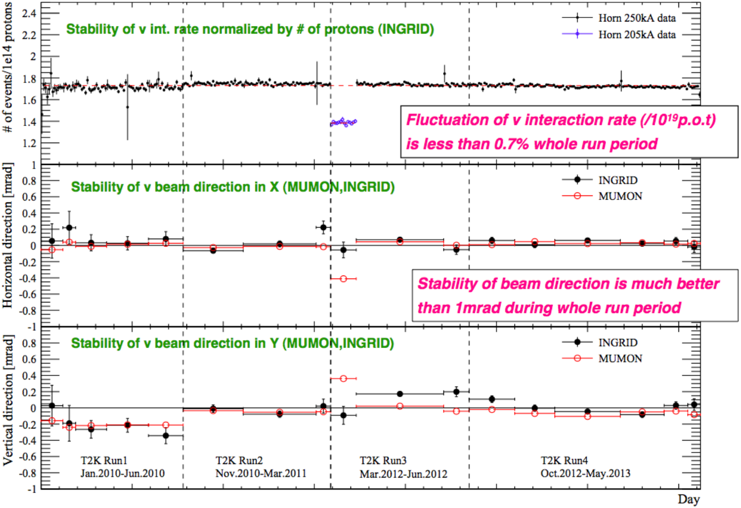
- 3 electromagnetic horns generally run at 250 kA
  - Took brief period of 205 kA data
  - Also took first -250 kA data earlier this year!
- Continuously monitor horn current and use this information in simulation

ND280 – On-Axis INGRID Detector



- Modules with iron and scintillator bar layers
- 14 identical modules in a cross configuration centered on beam axis
- Monitors the neutrino event rate and beam direction

ν Beam Stability Measured by On-Axis MUMON and Near Detector



Measurement from INGRID on-axis near detector is used to constrain the neutrino beam position/angle uncertainty

Modeling the T2K Neutrino Beamline

- Proton interactions in the target are simulated using FLUKA 2011 with a set of nominal proton beam parameters
  - Switched from (unsupported) FLUKA 2008 last year
- Particles exiting the target are then tracked through the horn field and decay volume, where surveyed geometries are modeled by a GEANT3 simulation using GCALOR package
  - Determine which decays produce neutrinos
  - Estimate flux at near and far detectors
- Simulated particle cross sections and multiplicities are re-weighted using external hadron production data
  - From NA61/SHINE experiment, etc
  - See talk by M. Hartz later today for details about external constraints, as well as constraints by the near detectors

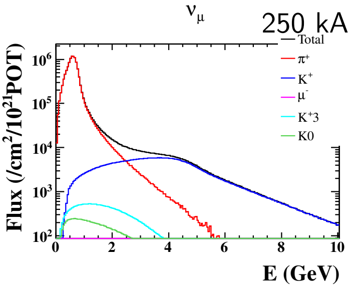
Flux Prediction

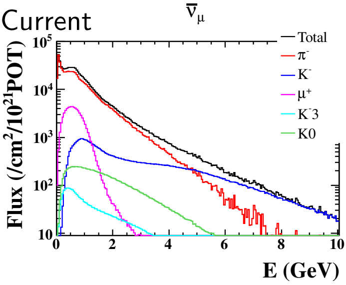
- Generate nominal flux prediction at near and far detectors
  - Including several different separate regions of the near detector hall
- Generate realistic flux prediction using measured proton beam parameters, horn currents
  - Ratios of realistic to nominal fluxes are used to re-weight MC samples for the near and far detectors
- Also re-weight nominal fluxes based on external data
- Simulate for both 250 kA and -250 kA horn current
  - Out-of-target interactions, neutrinos produced from wrong-sign parent particles become more important at -250 kA – need to understand this information well

Flux Components at SK

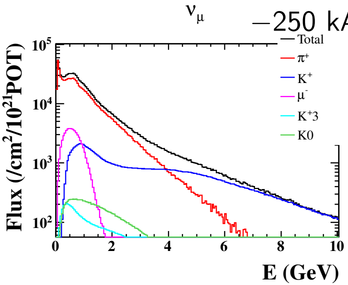
Nominal flux, before re-weighting

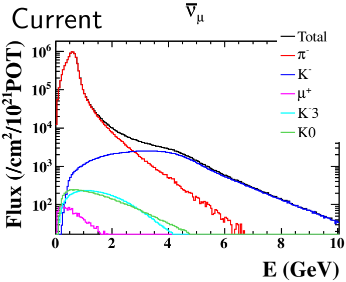
250 kA Horn Current



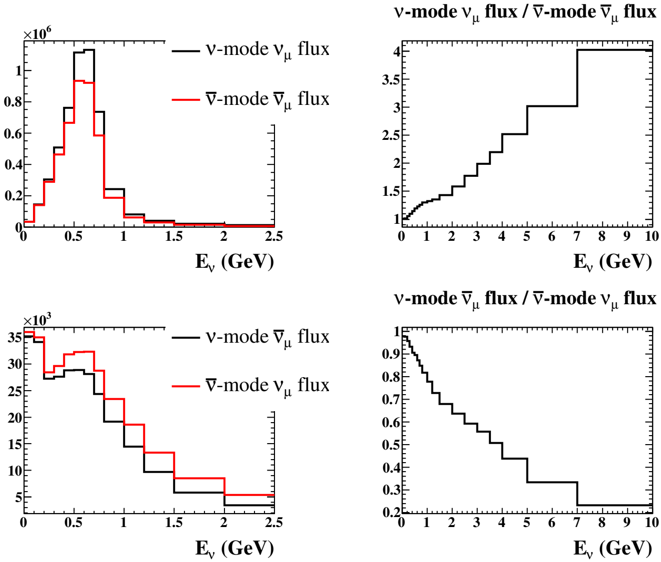


−250 kA Horn Current





SK Fluxes – Comparison of ν-Mode and $\bar{\nu}$-Mode Fluxes



Fraction of the Neutrino Flux Coming from Each Parent Particle at 250 kA

After re-weighting

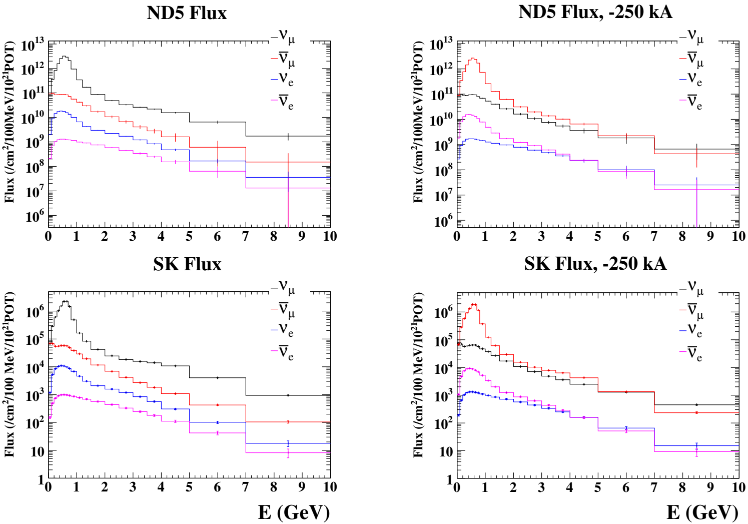
Parent	Flux percentage of each(all) flavor(s)			
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K^0_L	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K^0_L	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

For ν_μ flux at ND280/Super-K, the pion contribution is dominant (95%)

Predicted Total Flux at SK and ND280 Off-Axis Detector

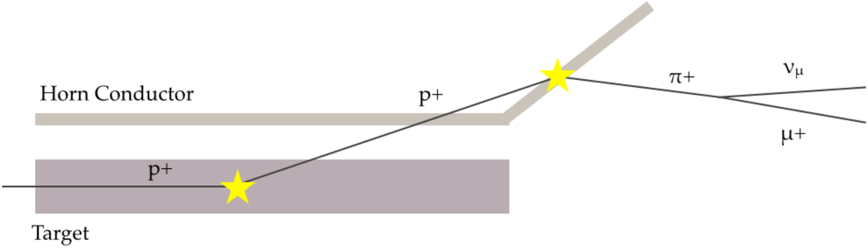
Nominal flux, before re-weighting

ν-Mode $\bar{\nu}$-Mode



Hadron Interaction Tuning (1)

- For each neutrino produced, we save the information of its ancestor particles and their hadronic interactions

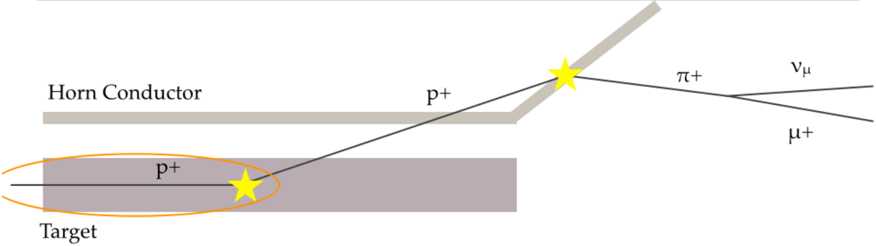


- 4 momentum of each ancestor particle is saved.
- Distance traveled through each material by each ancestor particle is saved
- Interaction type (elastic or inelastic) producing the particle is saved

Hadron Interaction Tuning (2)

- Tuning is done by reweighting the probability of:
  - The particle being produced - weighting the multiplicity distribution
  - The particle surviving for the simulated distance and then re-interacting - weighting the interaction length (production cross section)

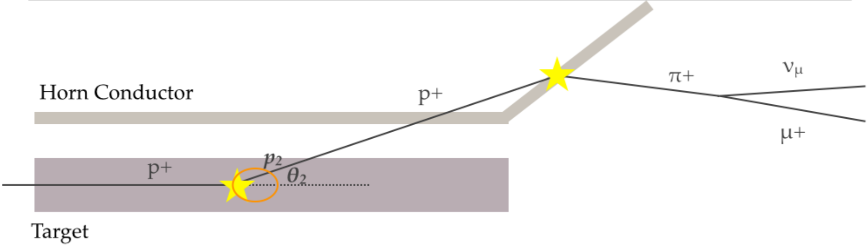
Tuning Example in Steps (1)



Reweight the probability that a proton with momentum p_1 travels a distance $d_{1,C}$ before interacting, assuming the production cross section is tuned from $\sigma_C(p_1)$ to $\sigma'_C(p_1)$ to agree with data

$$W = e^{-\rho_C[\sigma'_C(p_1) - \sigma_C(p_1)]d_{1,C}} * \frac{\sigma'_C(p_1)}{\sigma_C(p_1)}$$

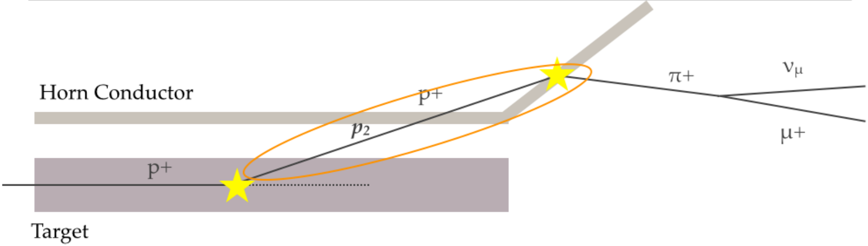
Tuning Example in Steps (2)



Reweight the probability to produce a secondary proton with momentum $\boldsymbol{p_2}$ and scattering angle $\boldsymbol{\theta_2}$ based on the ratio of the multiplicity in data over MC

$$W = e^{-\rho_C[\sigma'_C(p_1) - \sigma_C(p_1)] d_{1,C}} * \frac{\sigma'_C(p_1)}{\sigma_C(p_1)} * \frac{\frac{dn'_C(p_2, \theta_2 | p_1)}{dp d\theta}}{\frac{dn_C(p_2, \theta_2 | p_1)}{dp d\theta}}$$

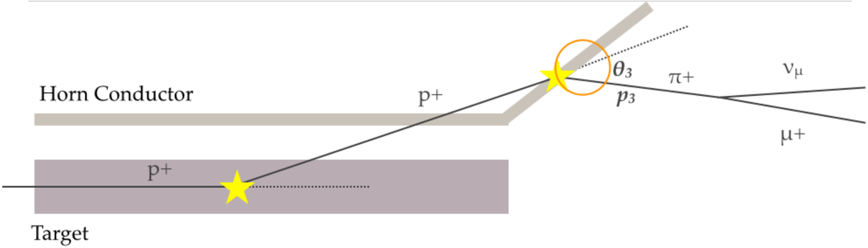
Tuning Example in Steps (3)



Reweight the probability that the secondary proton survives through the target and part of the horn before interacting

$$W = e^{-\rho_C[\sigma'_C(p_1)-\sigma_C(p_1)]d_{1,C}} * \frac{\sigma'_C(p_1)}{\sigma_C(p_1)} * \frac{\frac{dn'_C(p_2,\theta_2|p_1)}{dpd\theta}}{\frac{dn_C(p_2,\theta_2|p_1)}{dpd\theta}} * e^{-\rho_C[\sigma'_C(p_2)-\sigma_C(p_2)]d_{2,C}} * e^{-\rho_{Al}[\sigma'_{Al}(p_2)-\sigma_{Al}(p_2)]d_{2,Al}} * \frac{\sigma'_{Al}(p_2)}{\sigma_{Al}(p_2)}$$

Tuning Example in Steps (4)

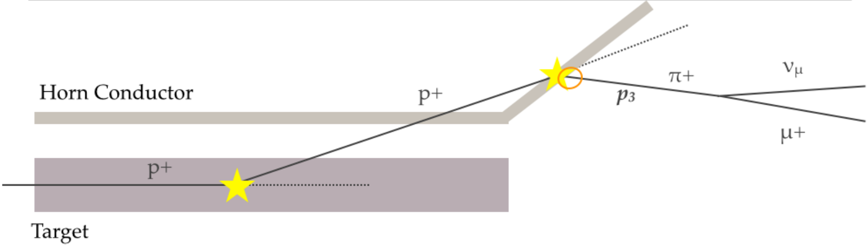


Reweight the probability to produce a tertiary pion with momentum $\boldsymbol{p_3}$ and scattering angle $\boldsymbol{\theta_3}$ based on the ratio of the multiplicity in data over MC

$$W = e^{-\rho_C[\sigma'_C(p_1)-\sigma_C(p_1)]d_{1,C}} * \frac{\sigma'_C(p_1)}{\sigma_C(p_1)} * \frac{\frac{dn'_C(p_2,\theta_2|p_1)}{dpd\theta}}{\frac{dn_C(p_2,\theta_2|p_1)}{dpd\theta}} * e^{-\rho_C[\sigma'_C(p_2)-\sigma_C(p_2)]d_{2,C}} * e^{-\rho_{Al}[\sigma'_{Al}(p_2)-\sigma_{Al}(p_2)]d_{2,Al}} * \frac{\sigma'_{Al}(p_2)}{\sigma_{Al}(p_2)}$$

$$* \frac{\frac{dn'_{Al}(p_3,\theta_3|p_2)}{dpd\theta}}{\frac{dn_{Al}(p_3,\theta_3|p_2)}{dpd\theta}}$$

Tuning Example in Steps (5)



Reweight the probability that the pion with momentum p_3 survives traversing the horn Al without interacting

$$W = e^{-\rho_C[\sigma'_C(p_1)-\sigma_C(p_1)]d_{1,C}} * \frac{\sigma'_C(p_1)}{\sigma_C(p_1)} * \frac{\frac{dn'_C(p_2,\theta_2|p_1)}{dpd\theta}}{\frac{dn_C(p_2,\theta_2|p_1)}{dpd\theta}} * e^{-\rho_C[\sigma'_C(p_2)-\sigma_C(p_2)]d_{2,C}} * e^{-\rho_{Al}[\sigma'_{Al}(p_2)-\sigma_{Al}(p_2)]d_{2,Al}} * \frac{\sigma'_{Al}(p_2)}{\sigma_{Al}(p_2)}$$

$$* \frac{\frac{dn'_{Al}(p_3,\theta_3|p_2)}{dpd\theta}}{\frac{dn_{Al}(p_3,\theta_3|p_2)}{dpd\theta}} * e^{-\rho_{Al}[\sigma'_{Al}(p_3)-\sigma_{Al}(p_3)]d_{3,Al}}$$

Errors on the Flux

Summary of errors on the flux given as a percent of the number of events at SK

Error source	% Error on number of events at SK	
	ν_μ	ν_e
Proton beam properties	2.7	2.3
Off axis angle	2.9	1.8
Horn current	0.1	1.2
Horn field	0.8	0.1
Horn misalignment	0.8	0.6
Target misalignment	0.3	0.0
MC statistics	0.1	0.0
Hadron production		
Pion multiplicities	3.5	5.1
Kaon multiplicities	2.0	1.1
Secondary nucleon multiplicities	6.2	6.7
Hadronic interaction lengths	5.5	6.6
Total hadron production	9.2	10.8
Total including cross section errors	10.1	11.2
Total after ND fit	2.7	3.2

Assuming $\sin^2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2, $\sin^2\theta_{12} = 0.306$, $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2

Conclusion

- Hadronic interactions are simulated inside the target using FLUKA 2011
- Particles are tracked through horns and decay volume by the GEANT3 GCALOR package
- Inputs from measured proton beam parameters, horn currents, etc. are used
- Flux prediction is then tuned using external data

- See talk by M. Hartz later today for details about:
  - The external hadron production data used for re-weighting
  - Final tuned fluxes
  - Detailed description of errors on the flux
  - Constraining the flux with a near detector