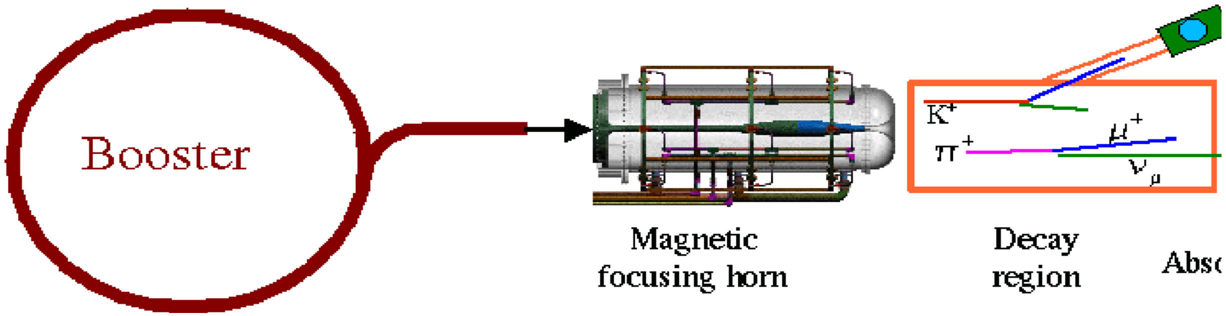
MiniBooNE beam simulation

Kendall Mahn
on behalf of those who did all this work



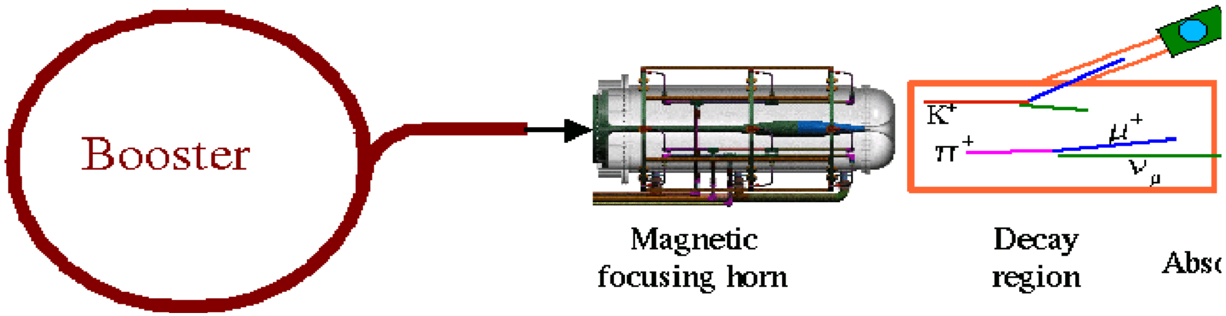
primary p+Be interactions

$\pi^{+/-}$, $K^{+/-}$, K^0 production

horn, magnetic field modeling

secondary interactions

neutrino production



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Primary (p+Be) interactions
Proton beam and target

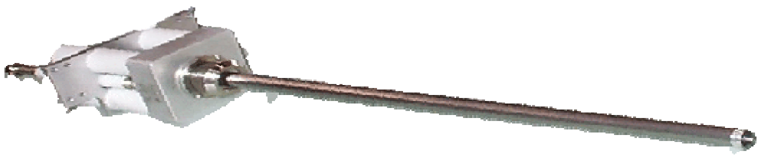
Beam protons produced around a mean position, angle, with gaussian smearing

central values of position, angle and spread (positional and directional) based on beam position monitor information

Be target

7 "slugs" make a total of 1.7 interaction lengths

Target material, shape (including cooling fins) included in simulation



Primary (p+Be) interactions
Beam Optics

Varying spread of beam in target changes the relative efficiency of an interaction by 1%

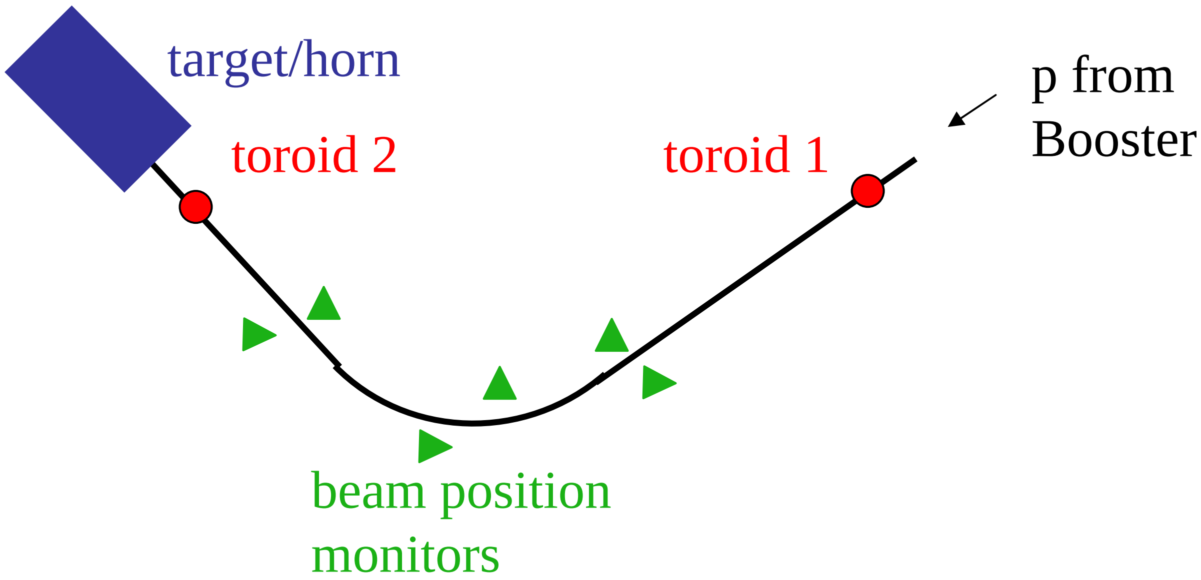
relative efficiency is how often a proton will or won't interact, roughly corresponds to how much the flux can change

Considered "pin" beam (no divergence or spread), perfectly focused beam, and different focus points

Primary (p+Be) interactions

Proton beam

- Absolute proton on target (p.o.t.) measured by two toroids upstream of the target
  - Two toroids measurements track each other well
  - Toroid drift main contributor to error
  - 3% total error on delivered p.o.t before March 2003, since then 1.7%



Primary (p+Be) interactions
p+Be cross sections

Protons then interact with the target, and either scatter or react to produce a meson

$$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$$

$$\sigma_{\text{inelastic}} = \sigma_{\text{quasi-elastic}} + \sigma_{\text{reaction}}$$

p+Be-> p+... (→ σ_{elastic}, $\sigma_{\text{quasi-elastic}}$)

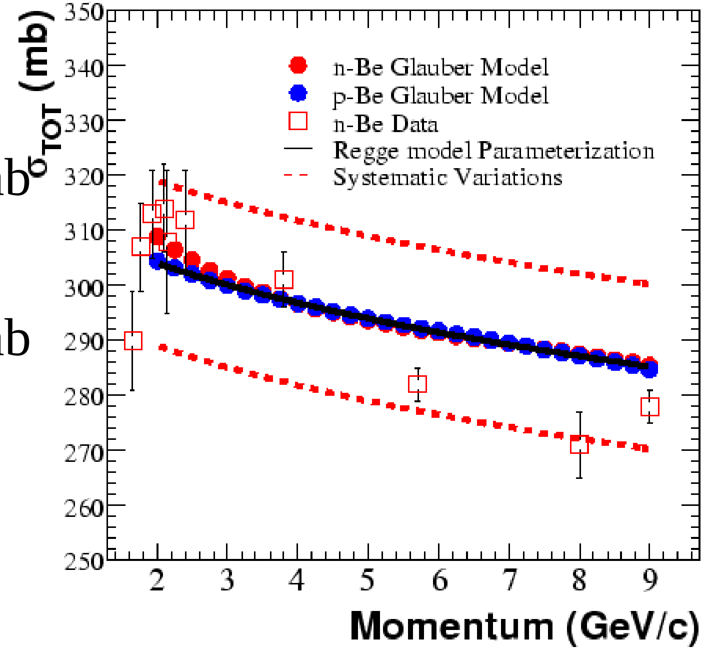
p+Be-> π,K+.... (→ σ_{reaction})

Primary (p+Be) interactions
p+Be cross sections

Measurements for σ_{total} , $\sigma_{inelastic}$

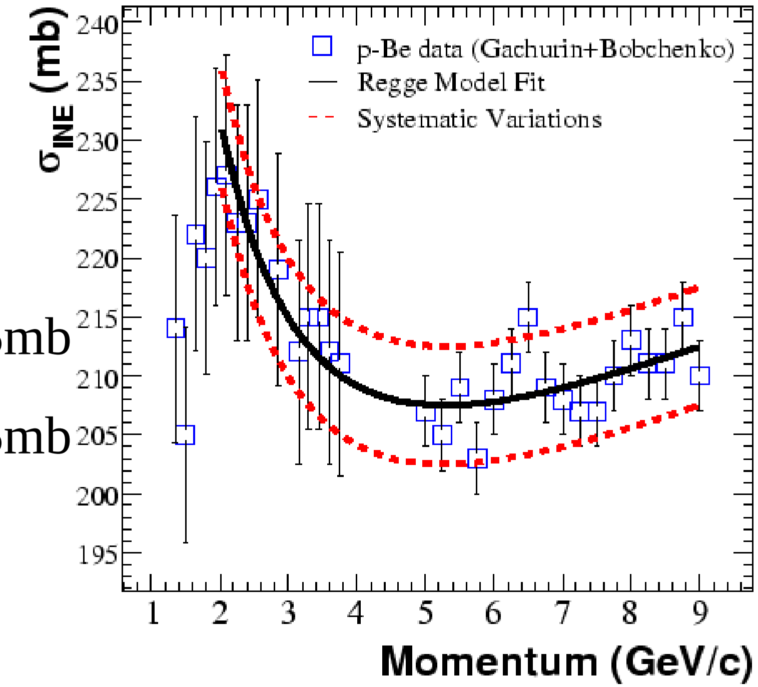
320mb

290mb



215mb

205mb



σ_{total} = 285+/-15mb

$\sigma_{inelastic}$ = 212.4+/-5mb

⇒1% change in reaction efficiency

Primary (p+Be) interactions

p+Be cross sections

$\sigma_{total} = \sigma_{elastic} + \sigma_{inelastic}$

$\sigma_{inelastic} = \sigma_{quasi\text{-}elastic} + \sigma_{reaction}$

Model dependent quantities:

$\sigma_{elastic}$ range constrained by σ_{total} and $\sigma_{inelastic}$ => 1%

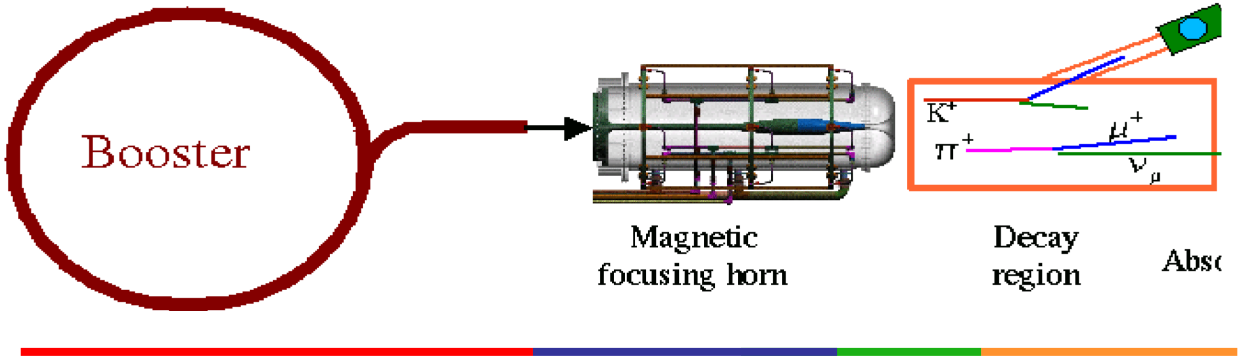
Variation of 30 mb for $\sigma_{quasi\text{-}elastic}$ => 2.5%

Kinematic variation in model

More forward going events see more target, material

=> <1% change for $\sigma_{elastic}$, 2% for $\sigma_{quasi\text{-}elastic}$

Measure $\sigma_{reaction}$ with differential cross sections



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Primary (p+Be) interactions

Differential cross sections of π,K

Various experiments have measured how often protons react to produce π,K

However, such data sets vary across proton beam energy, meson angle and momentum, as well as incident targets

=> Fit the differential cross section data sets with a parameterization function

Use of a parameterization allows for comparisons between data sets, as well as combining different data sets into one

Primary (p+Be) interactions

Sanford-Wang (S-W) Parametrization

MiniBooNE uses Sanford-Wang parametrization for the π,K fits

- Given the proton beam momentum (p_{beam}) and meson lab frame momentum (p) and angle (θ), can fit to data using c_1-c_9
- Function based on Feynman scaling

$$\frac{d^2\sigma(p+A\to\pi^++X)}{dp\, d\Omega}(p,\theta) = c_1 p^{c2}(c_9 - p/p_{beam}) \exp[-c_3 (p^{c4}/p_{beam}{}^{c5}) - c_6\theta(p - c_7 p_{beam} \cos^{c8}\theta)]$$

- c_9 represents mass threshold for kaons (=1 for pions)

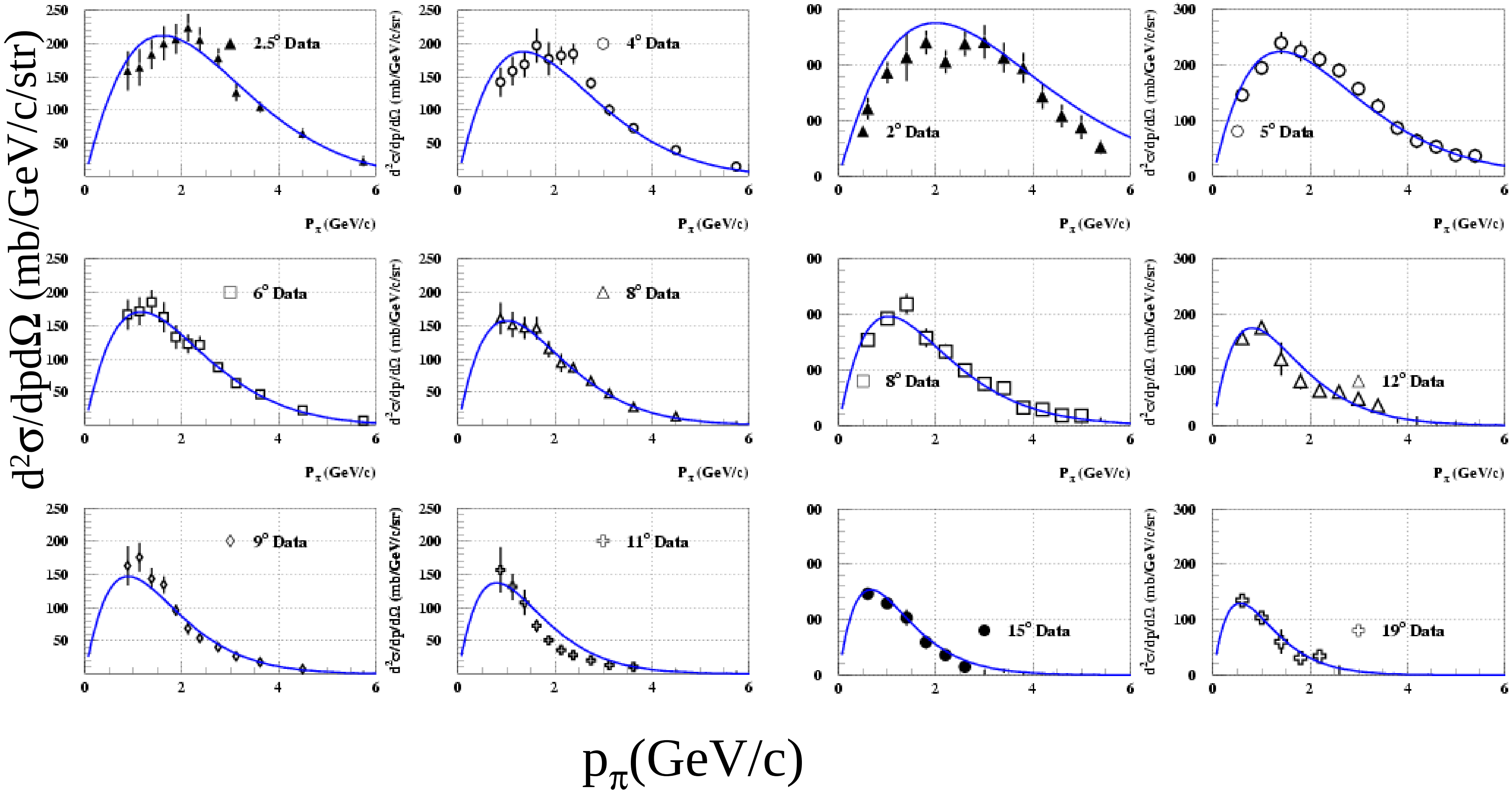
Errors are calculated based on the allowed 1σ variations in the c_i ; c_i correlations are included

π^+ external data

- Combined S-W fit to preliminary HARP 8.9 GeV and E910 6.4,12.3 GeV datasets
  - HARP is at correct beam energy, E910 provides some of the smallest angular bins
- E910 and HARP have similar normalization, some difference in shape of fits
- Fit pre-HARP is consistent with current fit including HARP

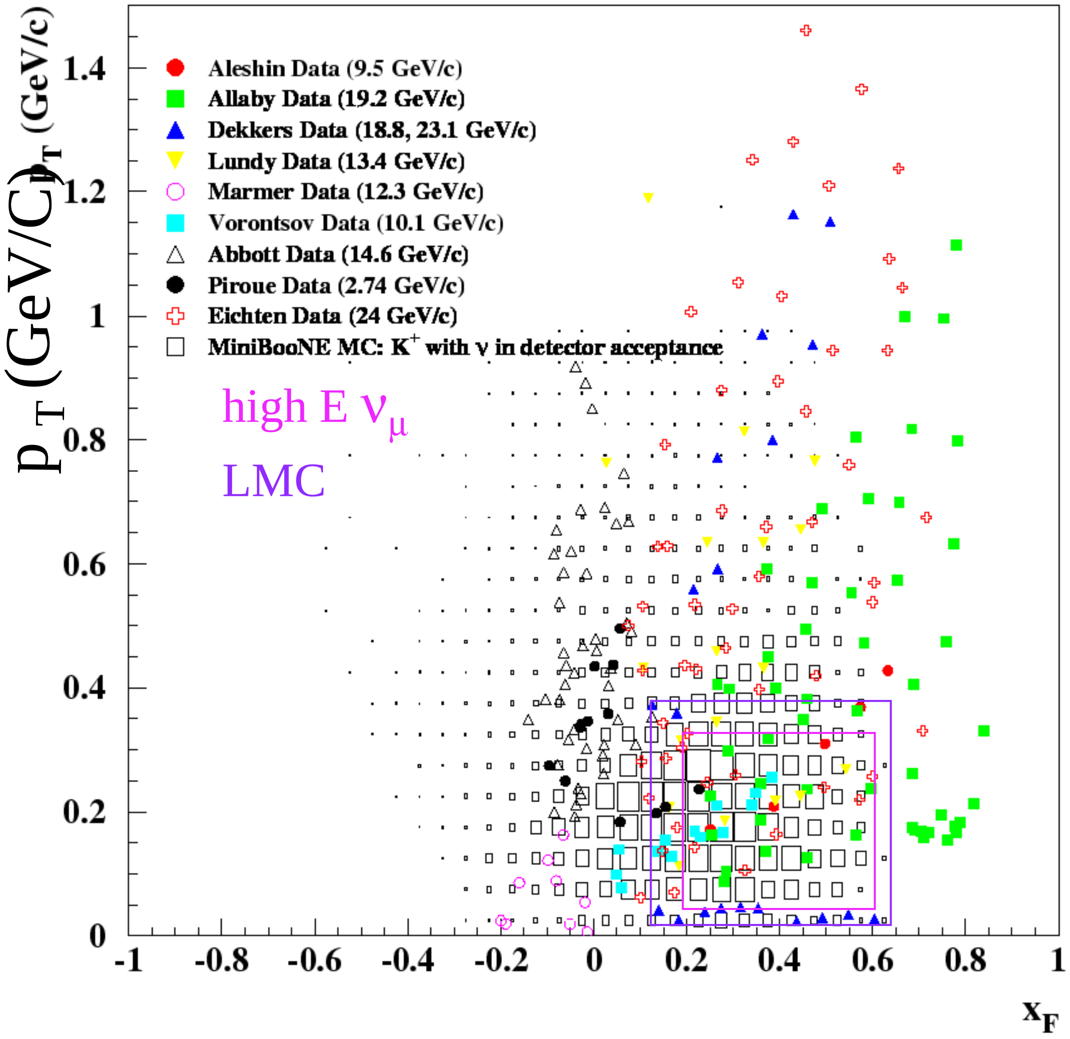
π^+ external data

HARP (preliminary) 8.9 GeV   Combined S-W fit   E910 12.3 GeV



K^+ external data

- Currently use Aleshin, Abbot, Eichten and Vorontsov data
- K+ flux shape fixed by fit, normalization determined by beam data
  - LMC, high E ν_μ
- HARP will make a measurement of kaon production on Be in the next year

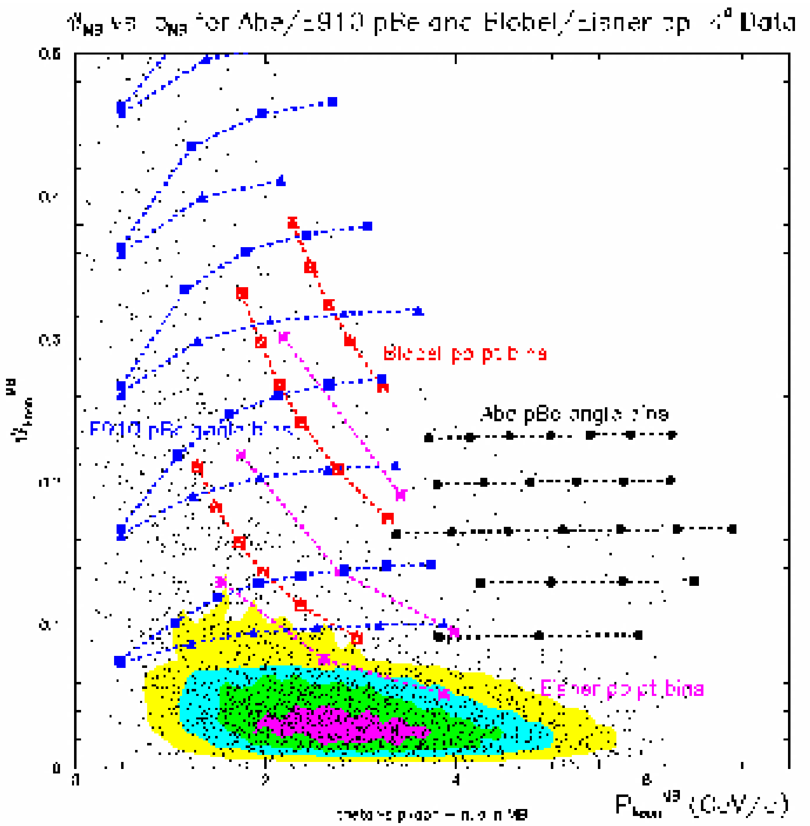


X F

K^0 external data

- K^0 data sets: E910 12.3,17.6, Abe 12 GeV/c
  - Other data sets exist (Eisner, 6.0 GeV/c, Blobel, 12,24 GeV/c) but p-p not p-Be

θ_{kaon} (rad)



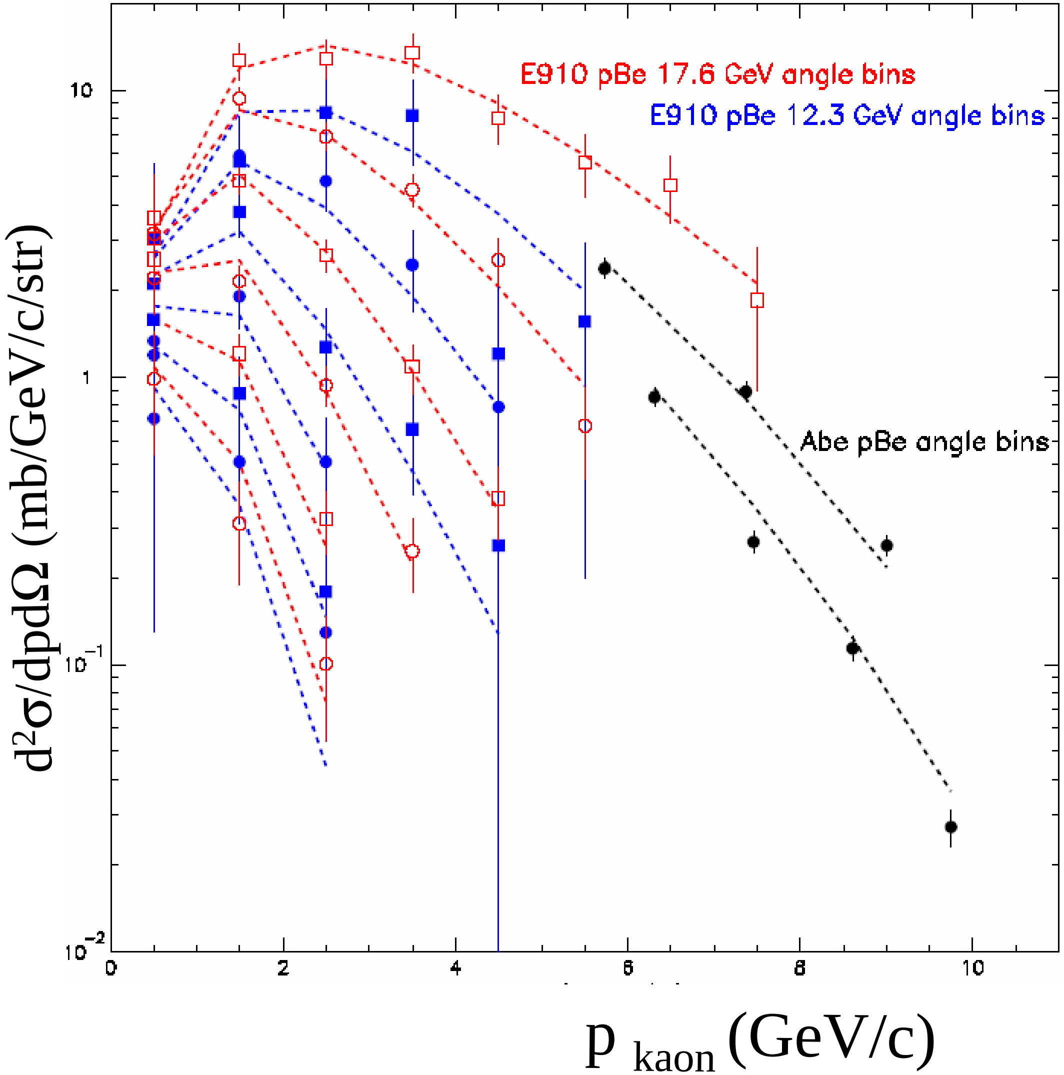
p_{kaon} (GeV/C)

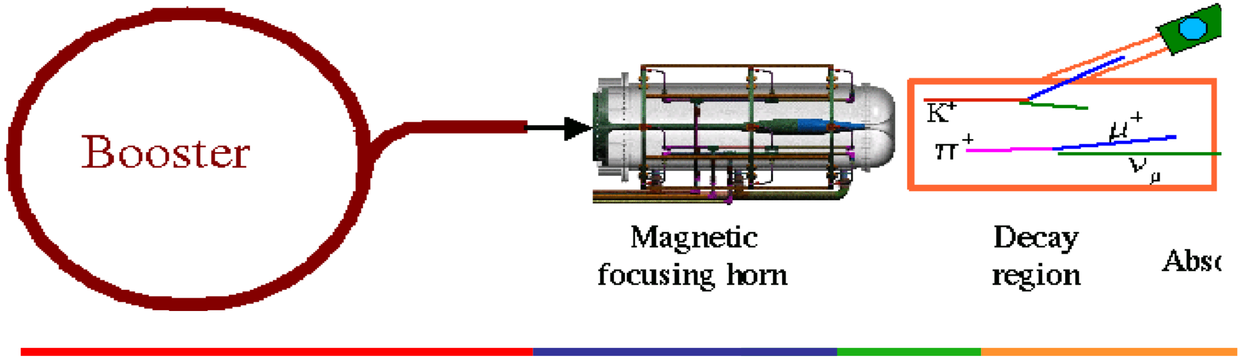
K^0 external data

S-W fit -------

E910 12.3, 17.6, Abe

- S-W fit constrains K^0 to 26% level
- K^0 normalization and shape are set by this fit
  - K^0 ν_e s only compose <10% of c_1 sample





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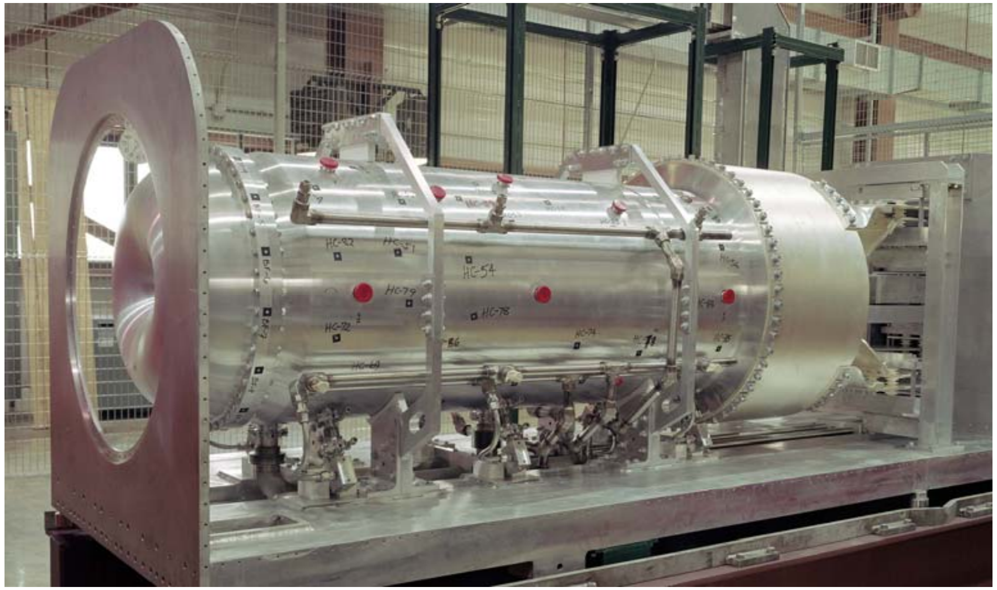
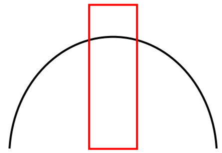
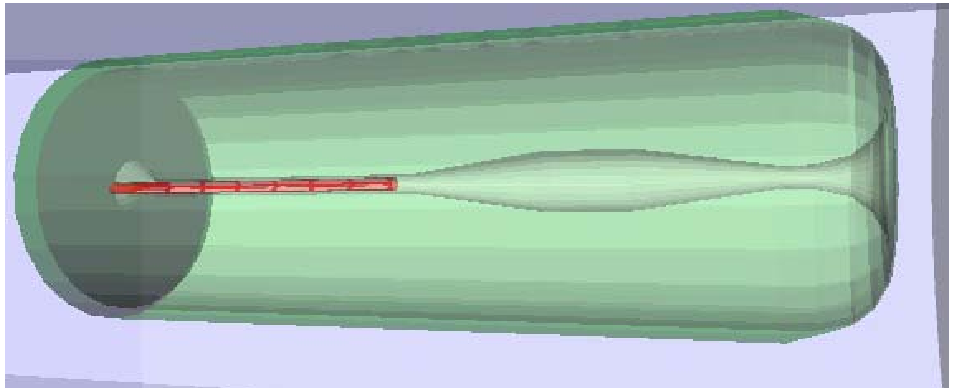
Magnetic horn



Horn is
pulsed at
174 kA
for 141μs

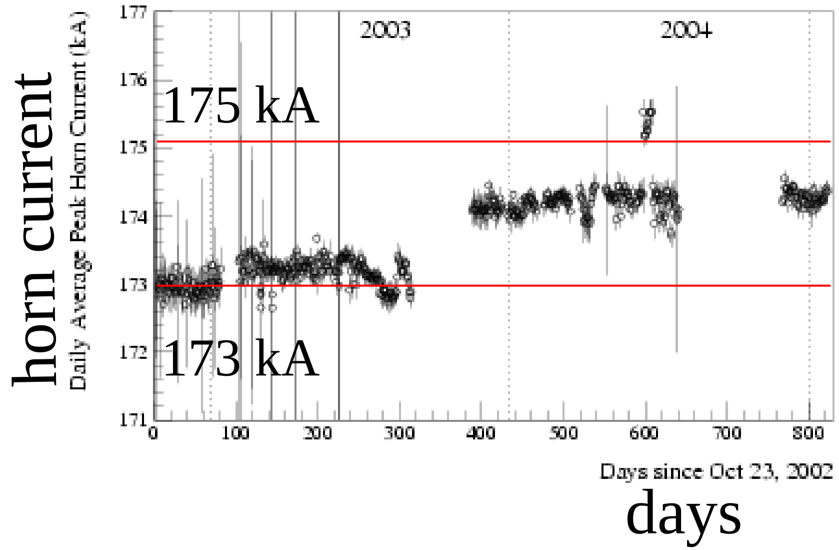


Geometry in Geant3
(converted to Geant4)



Horn current

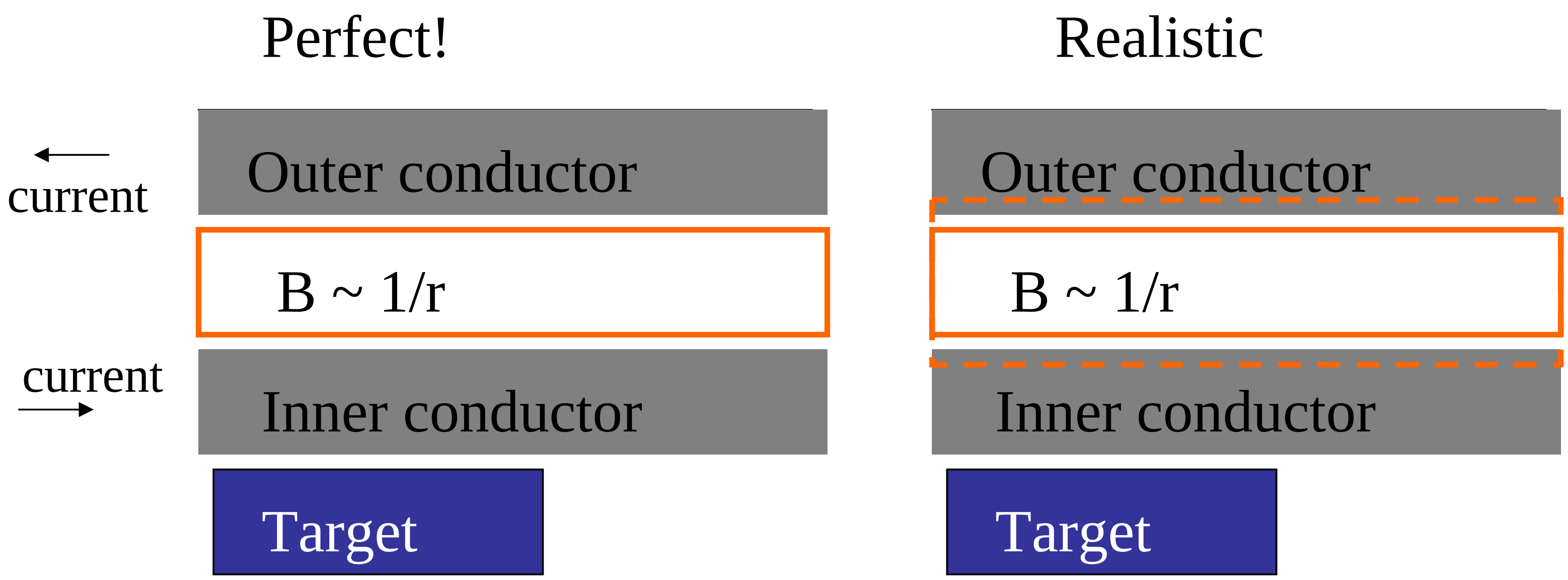
- Absolute current measurement of 174 kA
  - value measured by current transformers to 0.5% level
  - => consider variations of +/- 1kA
  - Most effect at high energy



- Horn current pulse timing
  - Horn pulse peak arrives when protons do
  - Current delivery timing is stable over time

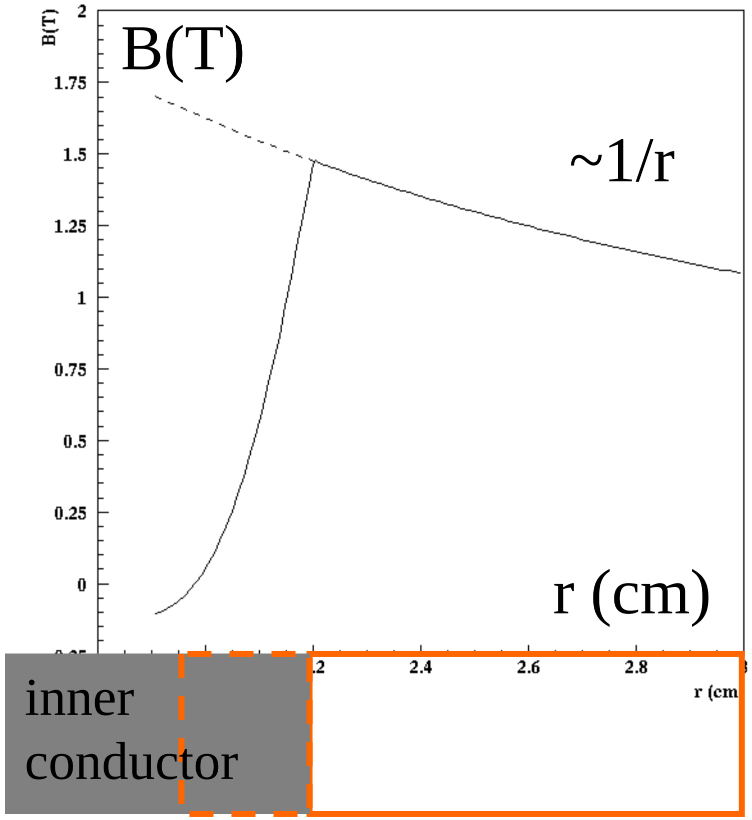
Horn
Electromagnetic field model

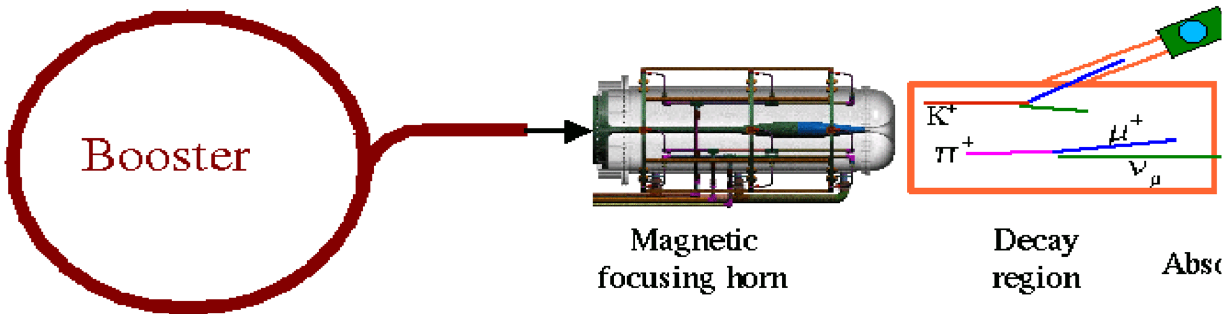
- In a perfect conductor, the magnetic field does not enter the conductor
- In reality, the field can be nonzero into the surface of the conductor, this is called "the skin depth effect"



Horn
Electromagnetic field model

- Measurements of MiniBooNE horn across voltage, radius consistent w/ 1/r
- Measured field on the inner surface of conductor on NuMI horn to be small
- Field penetration (modeled as an exponential decay) in conductor has no substantial effect on normalization





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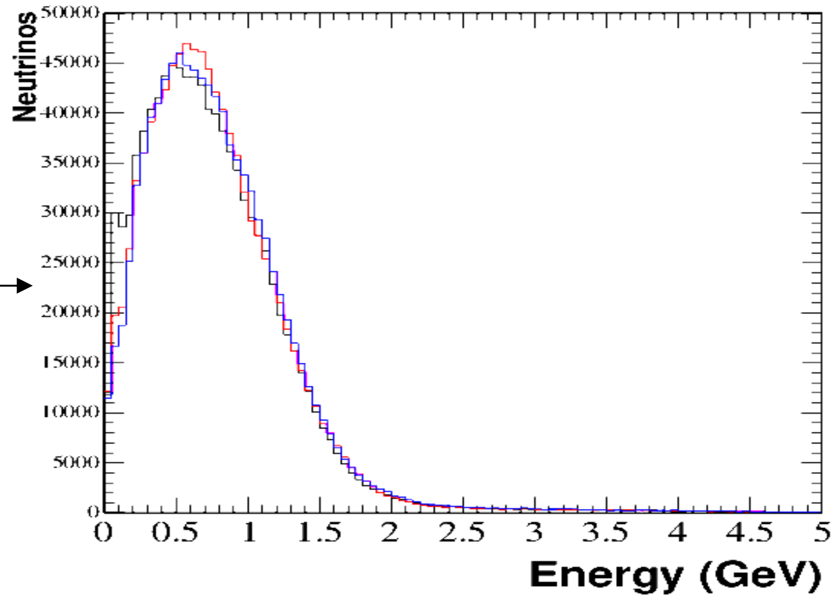
Secondary Interactions

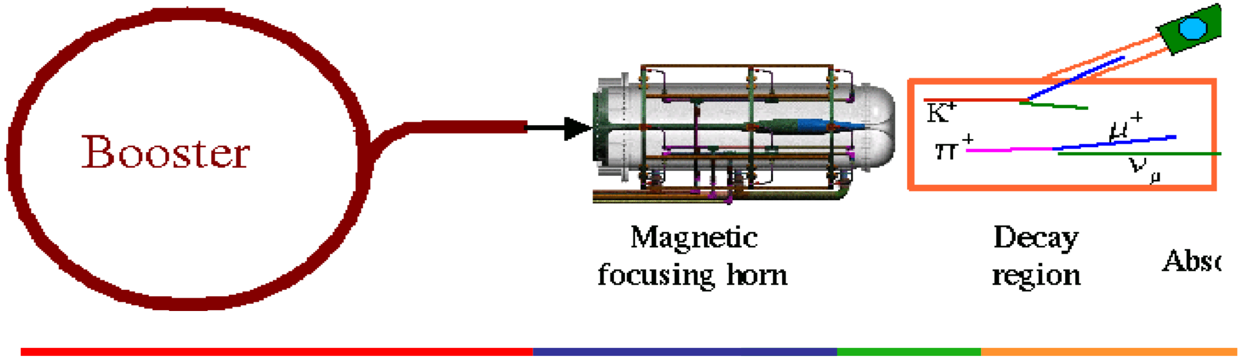
17% of all protons interact twice

7% of ν_μ come from p-> p -> π

Additionally, pions and kaons can interact with the horn, target or concrete

- Changing the secondary production models has a minimal effect on the neutrino flux
  - GHEISHA, Bertini, Binary cascade models similar
- HARP has the ability to measure both proton and meson interactions on Be
- Thick target data will check current model as well





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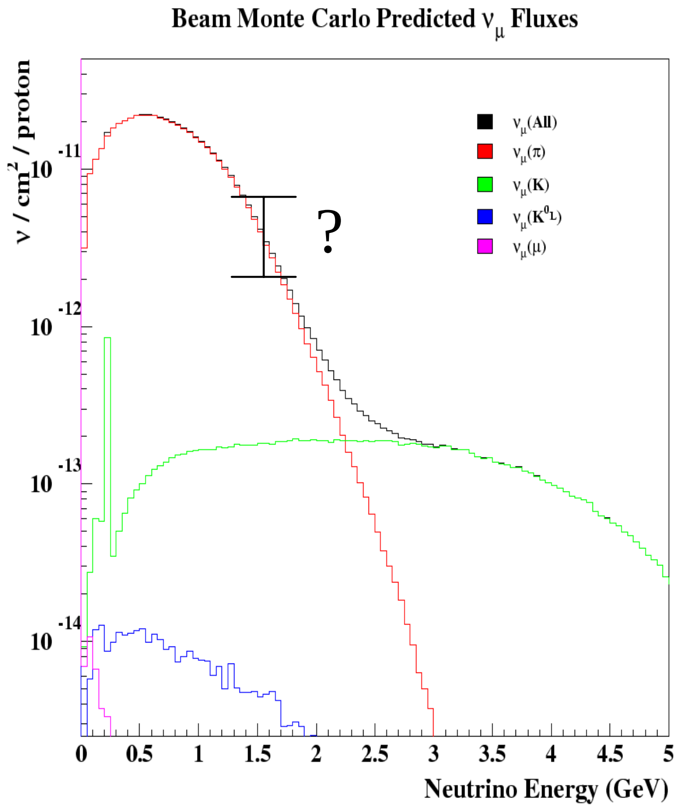
Meson decay to neutrinos

- Mesons don't always decay to neutrinos (absorption, scattering); neutrinos don't always hit our detector
- To help boost statistics, we use "redecay"
  - Every meson that decays to a neutrino is saved
  - It is decayed ~1000s of times with the same meson momentum, position and decay mode
    - Muon polarization is taken into account
    - Neutrino's position, direction is maintained when it interacts at detector
- More events are produced for sparse kinematic regions, but with a corresponding lower weight
  - Statistics can cause fluctuations which redecay can amplify
    - One pion producing a neutrino at 7 GeV, but no neutrinos from pions of slightly different momentum, angle, now there's 1000 of them
  - Deweight events after redecay to produce a smooth flux



Lots of work put into understanding the primary parts of neutrino production

- –Hadron production by HARP extremely valuable

A neutrino flux only has meaning with an associated error and scale of that error

- – absolute p.o.t, beam optics, p+Be cross sections, Sanford-Wang parametrization, horn current, skin depth, secondary interactions and geometry all considered
- –Still working!

Geometry of beamline

- Distance from target/horn to detector verified by:
  - surveyors
  - walking
  - driving
  - Google Maps
- Only "large" (noticable) shifts would produce a significant effect on the flux
  - Shifting the target by 23 cm -> 8% change in flux
  - Shifting collimator by 1 m further down -> 1% change in flux
  - Increasing decay pipe diameter by 4 inches -> 4% change in flux
  - Increasing the length of the horn by 10cm -> 1% change in flux

References

- Toroid calibration/checks: J. Monroe thesis
- Sanford-Wang parameterization: J. R. Sanford and C.L.Wang “Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c”, Brookhaven National Laboratory, AGS internal report, (1967) (unpublished)
- p+Be cross sections (total)
  - Bellettini et al., Nucl. Phys. 79 (1966) 609-624
- p+Be cross sections (inelastic)
  - V. V. Gachurin et al., ITEP-59-1985
  - B.M. Bobchenko et al., Sov. J. Nucl. Phys. 30, 805 (1979) [Yad. Fiz. 30, 1553 (1979)].
- E910, HARP: publications in progress