Hadron Production Measurements for Fermilab Neutrino Experiments at NA61/SHINE

Workshop on Future Short-Baseline Neutrino Experiments

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Fermilab

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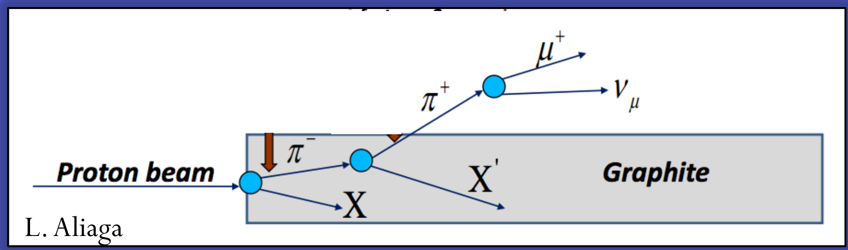
Calculating Neutrino Fluxes

- Though the details and size of the impact may vary, accurate neutrino flux predictions are an important issue for both long and short-baseline neutrino experiments (see S. Zeller's talk from this morning)
  - Note also: Improved flux predictions -> improved ν cross section measurements, another important input for oscillation experiments
- Traditionally a very difficult problem in DIF neutrino experiments
  - Early wide-band beams limited to >30% uncertainty in flux calculations
- Largest uncertainty comes from primary hadron production in the beamline target by incident proton beam
  - Impact of secondary interactions in the target varies depending on the proton beam energy and target design



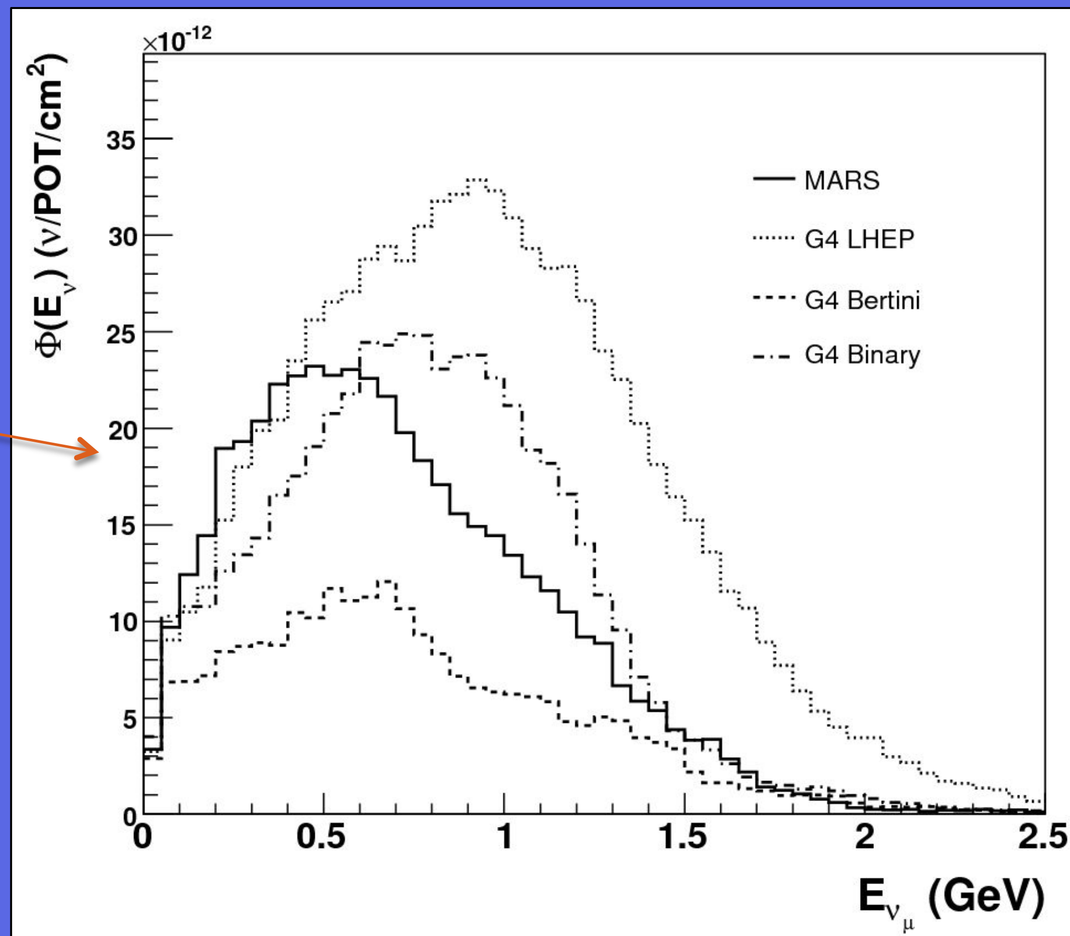
Hadron Production for Neutrino Beams

- A quick look at two case studies of experiments which have collected dedicated hadron production data
  - MiniBooNE and HARP
  - T2K and NA61
- Then will describe an on-going effort to explore possible collection of new hadron production data at the NA61/SHINE experiment at CERN with relevance for Fermilab neutrino beams
  - Provide external constraints for precise neutrino flux calculations for NuMI experiments (MINERvA, NOvA, MINOS+) and a future LBNE beamline
  - Perhaps also an opportunity to expand on measurements of pion production and measure kaon production for the Booster Neutrino Beam (MiniBooNE, MicroBooNE), though the low-energy beam introduces additional challenges

Case Study 1: MiniBooNE and HARP

- Booster Neutrino Beamline (BNB) impinges 8.9 GeV/c protons on a 1.7λ beryllium target

Example of predicted fluxes at MiniBooNE detector location using four different hadron interaction models available in Geant4 (circa 2003)

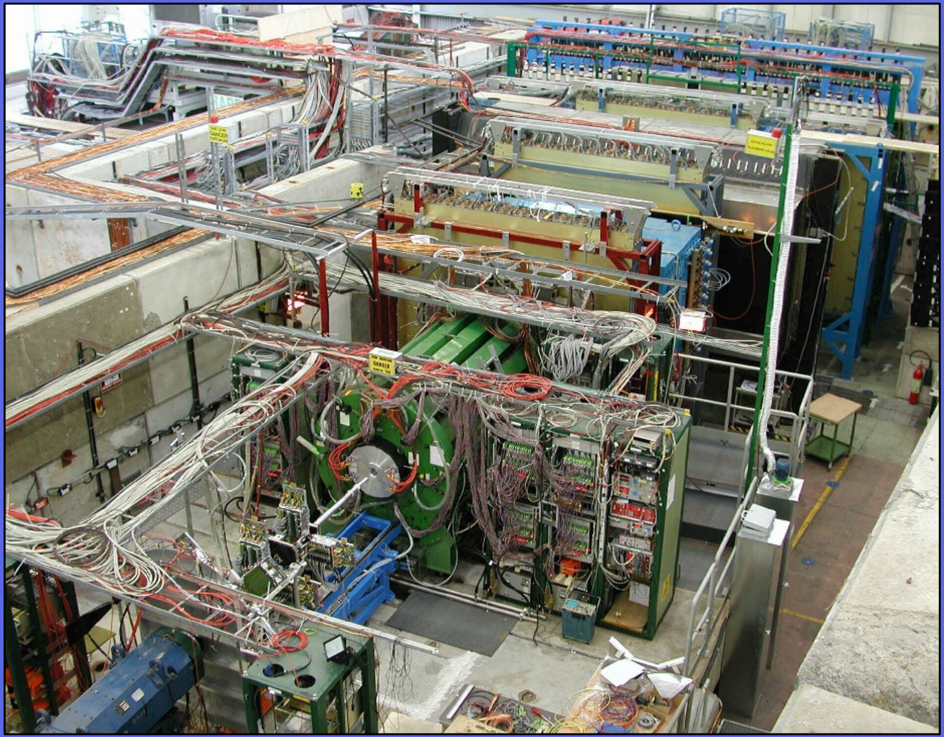


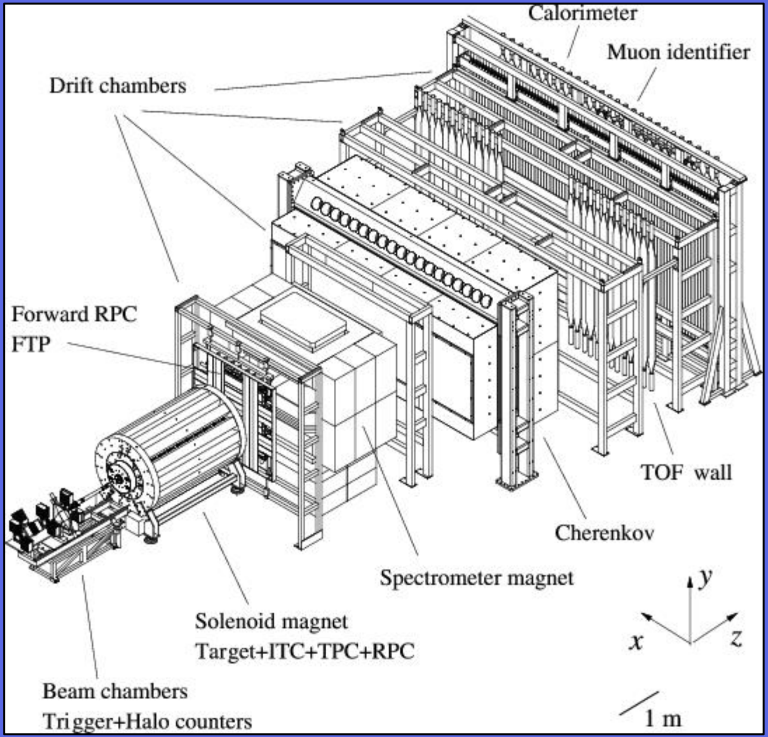
Of course, with hard work one can do much better than this

Phys.Rev.D79, 072002 (2009)

Case Study 1: MiniBooNE and HARP

- HARP Hadron Production Experiment at CERN PS (ran in 2003)
  - 8.9 GeV/c protons
  - Thin (5%λ) and thick BNB replica (0.5λ, 1.0λ) beryllium targets

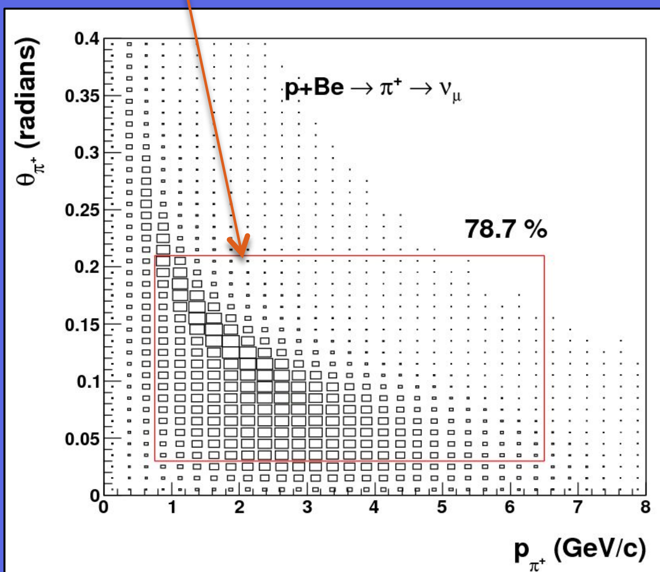




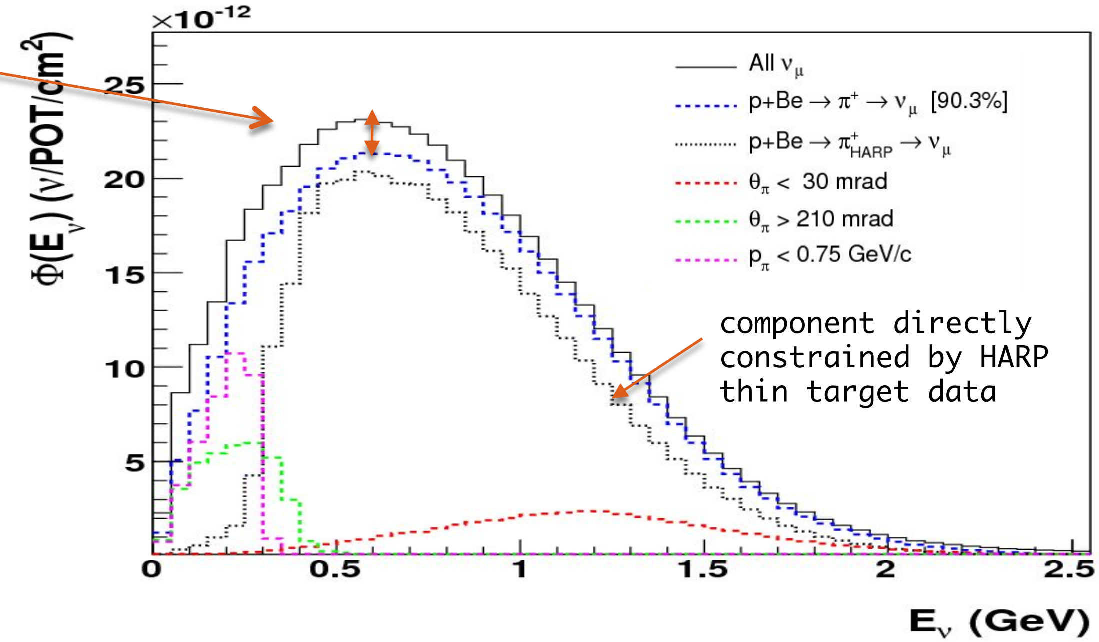
Case Study 1: MiniBooNE and HARP

Secondary interactions relatively small effect in BNB

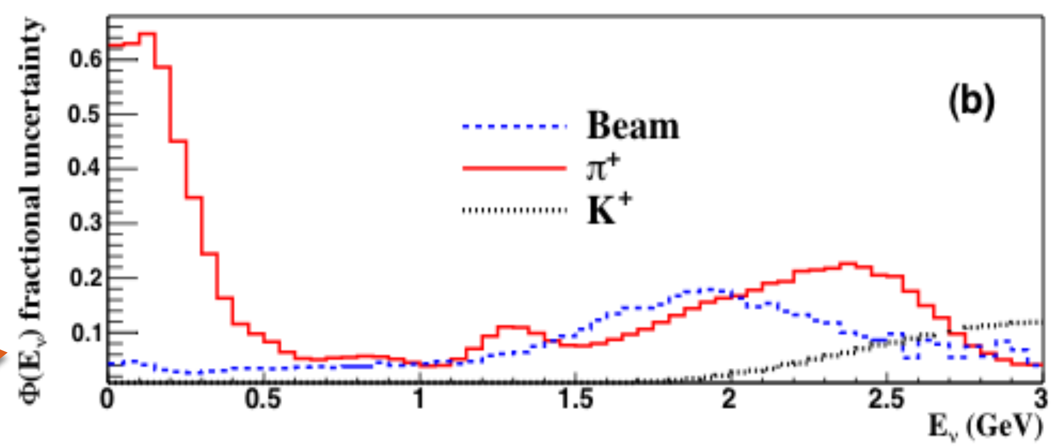
Kinematic coverage of thin target data set at HARP



Errors on production cross sections can be propagated to neutrino flux prediction



component directly constrained by HARP thin target data



Case Study 2: T2K and NA61/SHINE

- T2K interested in both absolute flux predictions at their near detector for making cross section measurements <u>and</u> event rate ratios, Far/Near, for oscillation measurements

- T2K has collaborated with NA61/SHINE experiment to perform new hadron production measurements in p+C collisions at 31 GeV/c

- In 2011, published total production cross section and differential cross sections (p_h,θ_h) for π^+, π^- (arXiv:1102.0983) and K^+ (arXiv:1112.0150) production using initial lower statistics, thin-target data set collected in 2007

- T2K example is relevant for looking at impact of dedicated hadron production data, but also as demonstration of capabilities of NA61/SHINE detector for making these measurements

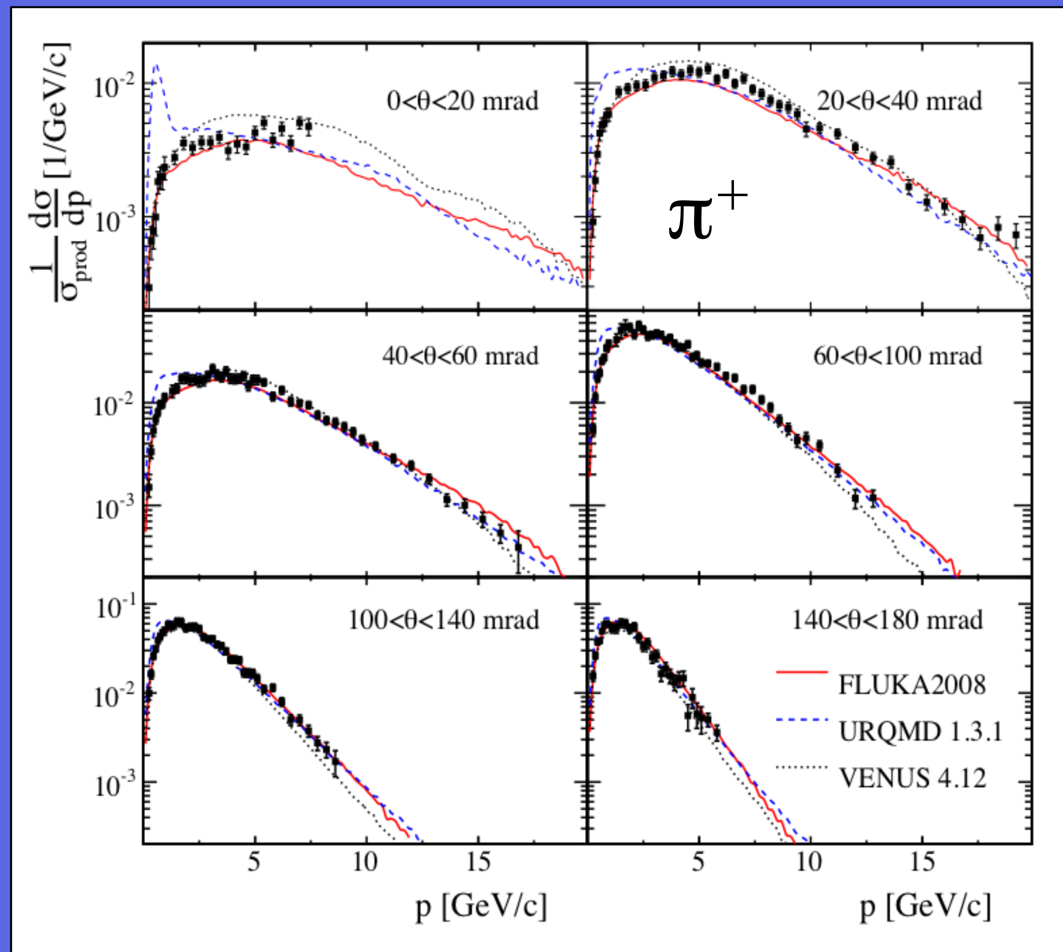
Case Study 2: T2K and NA61/SHINE

- Measurement of total production cross section for 31 GeV/c p+C

$$\sigma_{prod} = 229.3 \pm 9.2\ mb$$

- Systematic uncertainties on differential cross section points 5-10%
- 2.3% overall normalization uncertainty
- Uncertainties on hadron spectra propagated directly into xsec and oscillation analyses

arXiv:1102.0983



Case Study 2: T2K and NA61/SHINE

Conclusions from the pion production paper, arXiv:1102.0983:

> The data presented in this paper already provide important information for calculating the T2K neutrino flux. Meanwhile, a much larger data set with both the thin (4% λ_I) and the T2K replica carbon targets was recorded in 2009 and 2010 and is presently being analyzed. This will lead to results of higher precision for pions and extend the measurements to other hadron species such as charged kaons, protons, K^0_S and Λ. The new data will allow a further significant reduction of the uncertainties in the prediction of the neutrino flux in the T2K experiment.

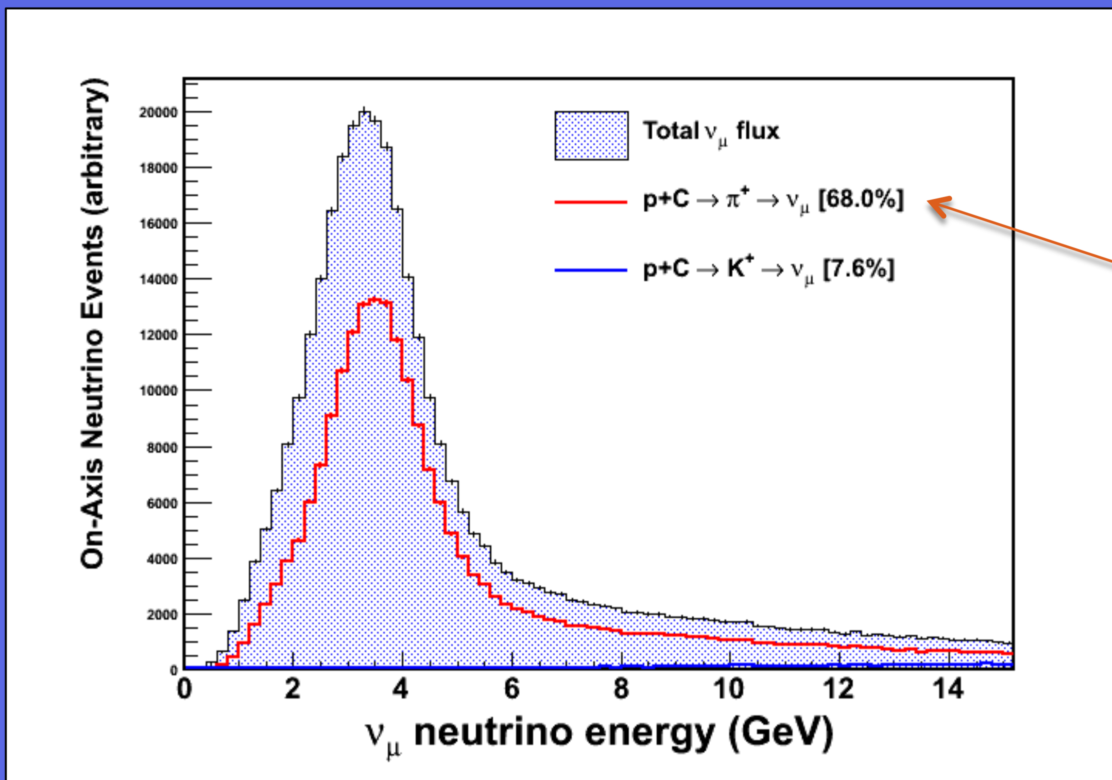
The Good and Bad of Higher Energies

- At higher beam energies (order 100 GeV):
  - The Good: Invariant cross section scaling laws seem to work pretty well

- On-going analysis effort within MINERvA to make use of existing hadron production data to constrain primary and secondary interactions in NuMI beam Monte Carlo wherever possible
  - NA49 measurements of pion production in p+C at 158 GeV/c (Eur.Phys.J.C49:897-917,2007)
  - Use scaling laws to "predict" invariant cross sections at 31 GeV/c and compare to NA61 measurements. Such studies help determine systematic uncertainty in scaling from 158 GeV to 120 GeV
  - Available cross section data from HARP, Barton et. al., NA61, etc. for incident proton/π at energies from 10-100 GeV very valuable for constraining secondary interactions in the beamline
  - π/K ratio measurements from MIPP at 120 GeV to provide kaon constraint

The Good and Bad of Higher Energies

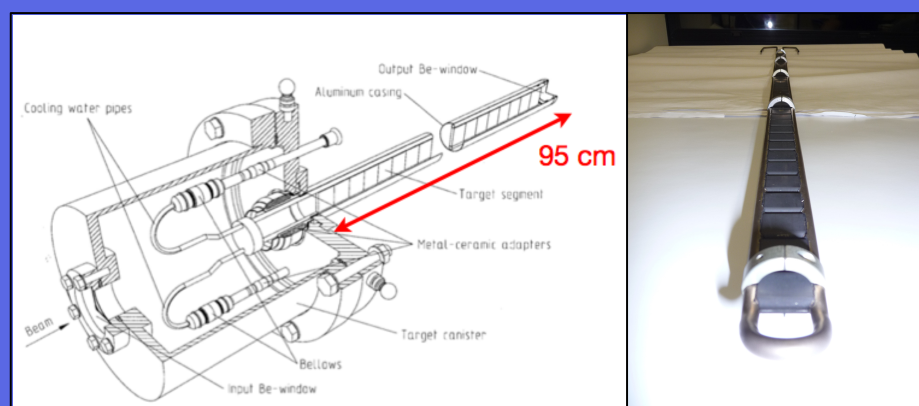
- At higher beam energies (order 100 GeV):
  - The Good: Invariant cross section scaling laws seem to work pretty well
  - The Bad: Secondary interactions are much bigger effect at high energy



Secondary interactions in the NuMI target much larger effect than for Booster experiments [<10% in BNB]

New Hadron Production Data at NA61

- Combination of thin target cross section measurements and production off replica targets best constraint on flux Monte Carlos
- Group exploring possibility of collecting new hadron production data for Fermilab neutrino experiments at the NA61/SHINE experiment at CERN
  - Now assembling LOI including sketch of physics case and run plan
  - Opportunity to collect test data set with 120 GeV beam on thin graphite target this June (~2 days)
    - These data will already be useful for constraining primary production and further testing scaling approaches
  - More complete run would come in 2014 after CERN shutdown



Possible NA61 Data Sets

	Incident proton/pion beam momentum			
Target	120 GeV/c	90 GeV/c	60 GeV/c	8.9 GeV/c
NuMI replica	201X			
BNB replica				201X
LBNE replica	201X			
thin graphite ($< 0.05\lambda_I$)	**2012**	201X	201X	
thick graphite ($\sim 1\lambda_I$)	201X	201X	201X	

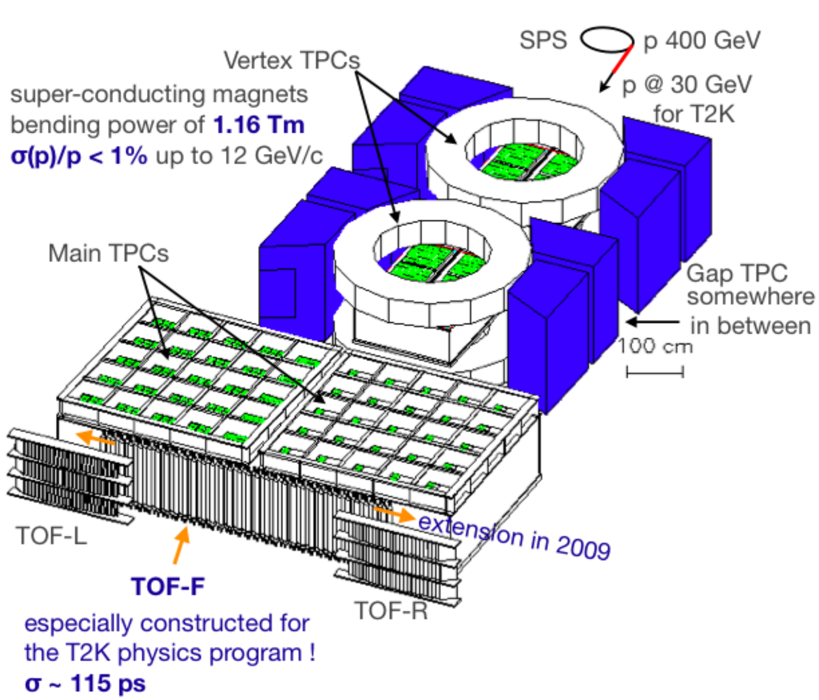
Table 1: Target and beam settings which could be relevant to US neutrino experiments. The **2012** entries are settings that might be run in 2012, while the 201X entries correspond to settings that could be run after the CERN 2013-14 shutdown.

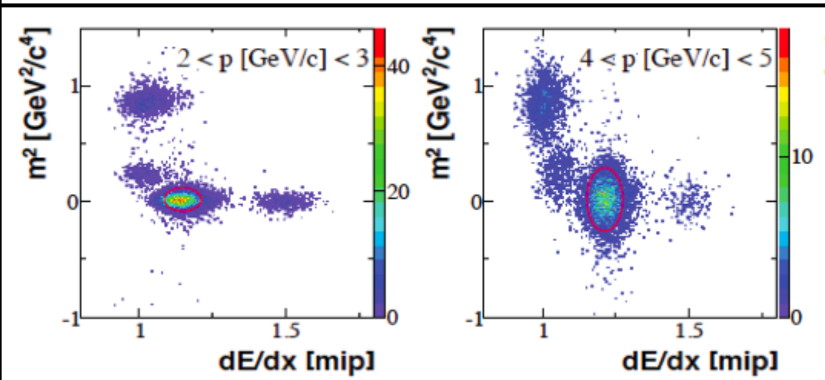
Participating Institutions (so far)

- Multiple experiments and beamlines represented:
  - MINERvA, MINOS, NOvA, LBNE, MiniBooNE, MicroBooNE
  - NuMI, BNB, LBNE
- Participating institutions:
  - FNAL
  - LANL
  - University of Texas at Austin
  - University of Colorado
  - Columbia University
  - University of Florida
  - Northwestern University
  - University of Pittsburgh
  - University of Rochester
  - William and Mary

NA61/SHINE Spectrometer

- Large spectrometer on the H2 beamline of the SPS at CERN:



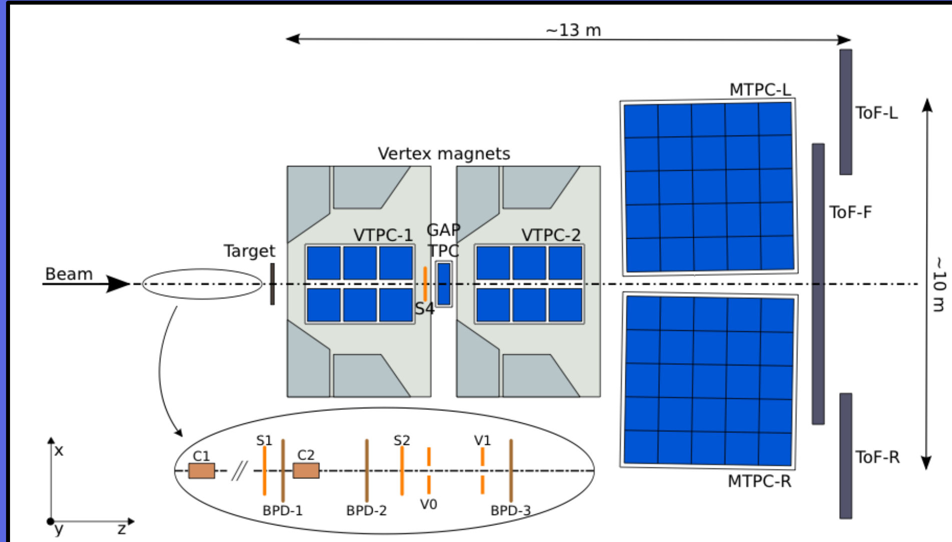


Incident beam is mixed p/π produced by 400 GeV primary SPS beam (NA61 physics run plan includes 13-158 GeV/c)

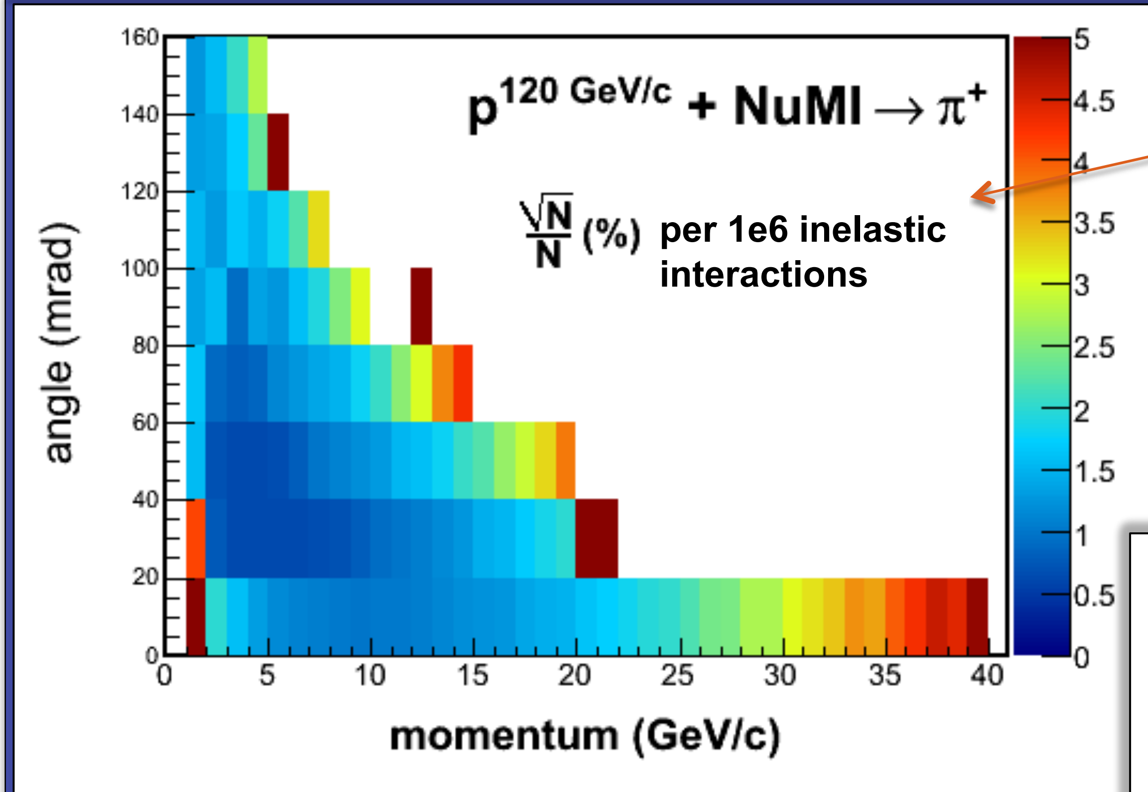
Particle Tracking performed in 4 TPCs

Adjustable magnetic field settings allow tuning of kinematic acceptance (up to 9 Tm bending power)

Particle separation performed through dE/dx and ToF

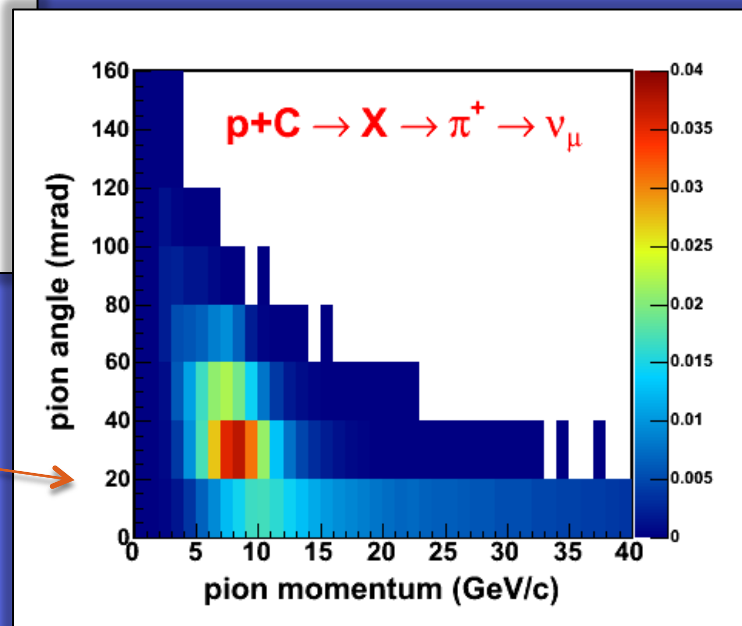


Example NA61 Acceptance for NuMI



Pions accepted in NA61

Currently working on studies for the different beamlines, configurations, on/off-axis, etc.



Pions that make a ν_μ in an on-axis experiment at NuMI

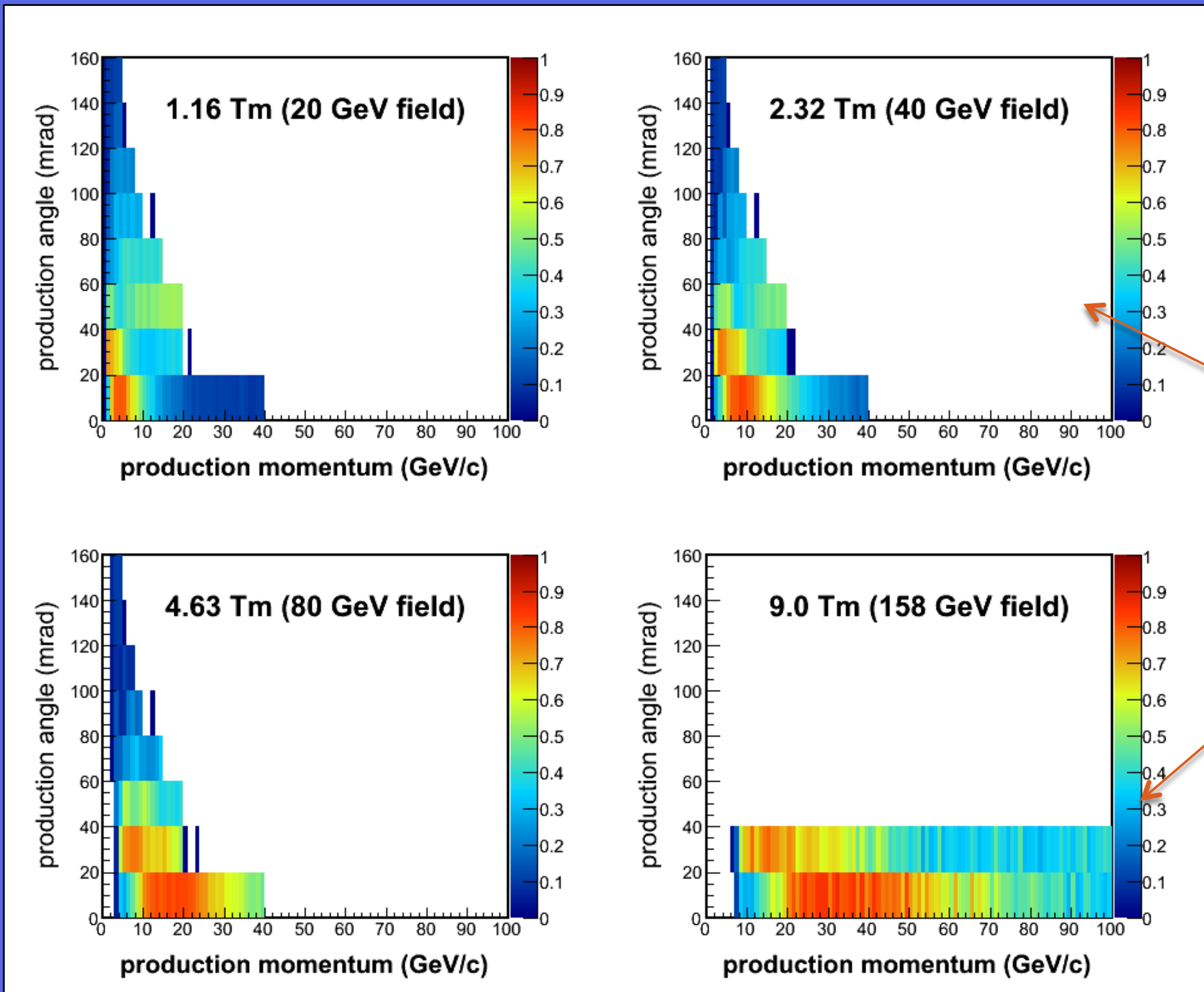
['low-energy' beam tune]

Summary

- Accurate neutrino flux calculations at super beam facilities are challenging but are increasingly important as we aim to make more and more precise measurements in neutrino physics (both cross sections and oscillations)
- Dedicated hadron production measurements a key ingredient to achieving precise flux calculations
- Group from 10 US institutions (so far) exploring possibility of collecting new data relevant for NuMI experiments (MINERvA, NOvA, MINOS+), Booster experiments (MiniBooNE, MicroBooNE) and LBNE at NA61/SHINE experiment at CERN
- Lower energy (~8 GeV) running is challenging, but could be worth the effort, especially for SBL program using the BNB (in particular, for measuring kaons and pions making low energy neutrinos)
- Important thin target test run (but with real physics potential) being planned for June, 2012
- More complete data run could begin after CERN shutdown in 2014

Backups...

NA61 Acceptance



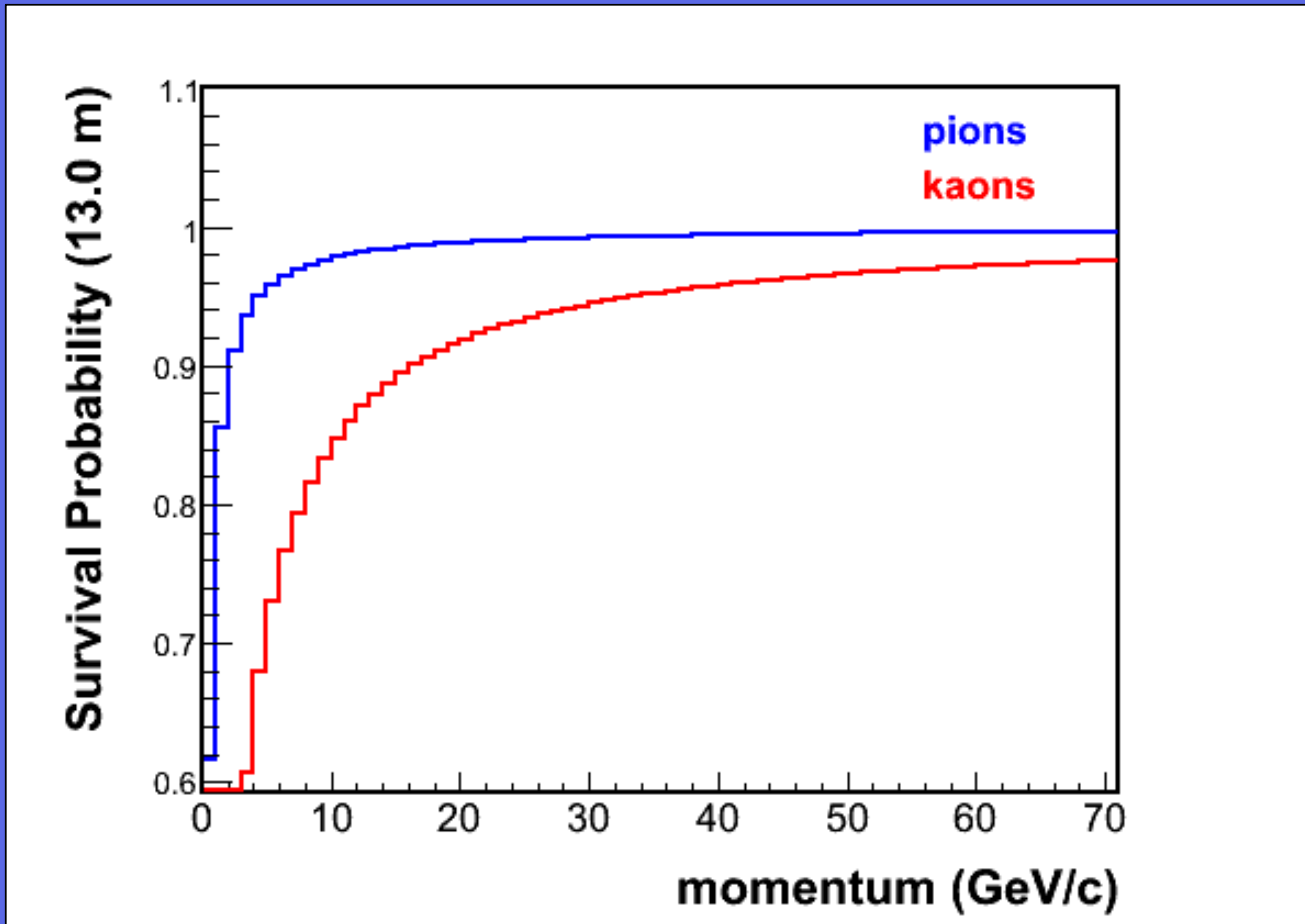
Will require taking data in multiple field settings to get coverage of:

low momentum/ high angle

&

forward production

NA61 Acceptance



NA61 Particle ID

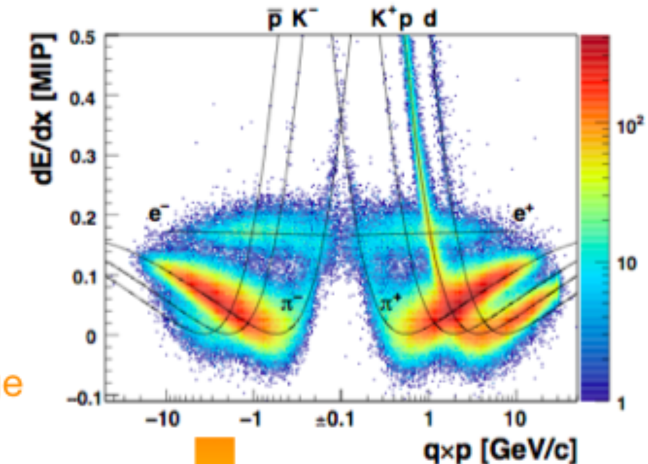
- How do we identify particles in NA61/SHINE ?

TPCs: energy loss measurement

TOFs: time of flight → m^2

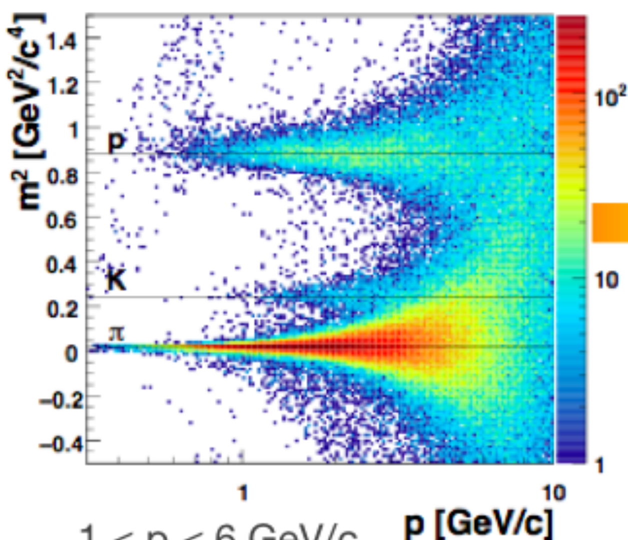
Combined measurement of ToF & dEdx

powerful PID over large momentum range

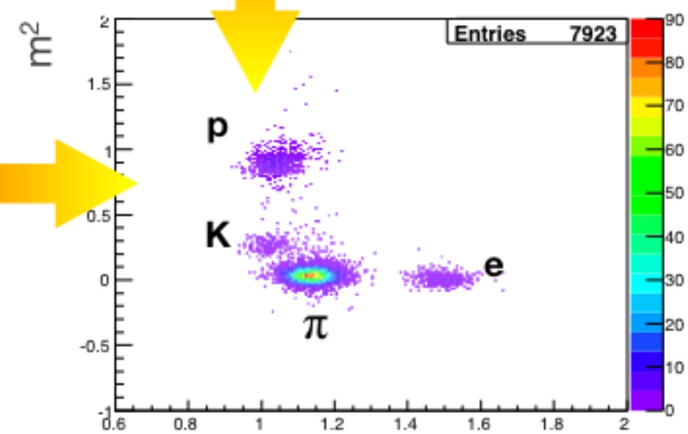


p < 1 GeV/c

p > 3 GeV/c

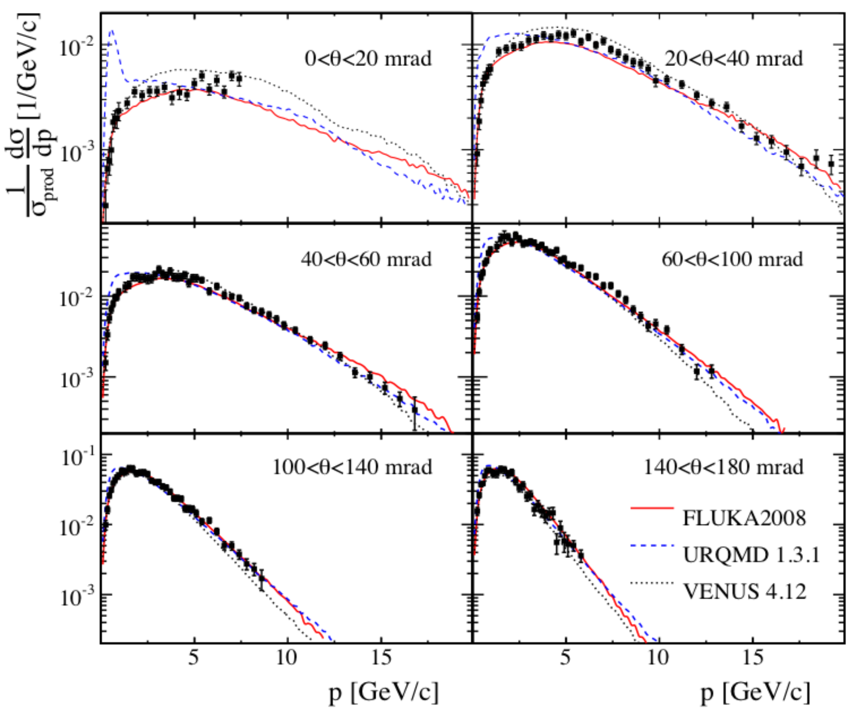


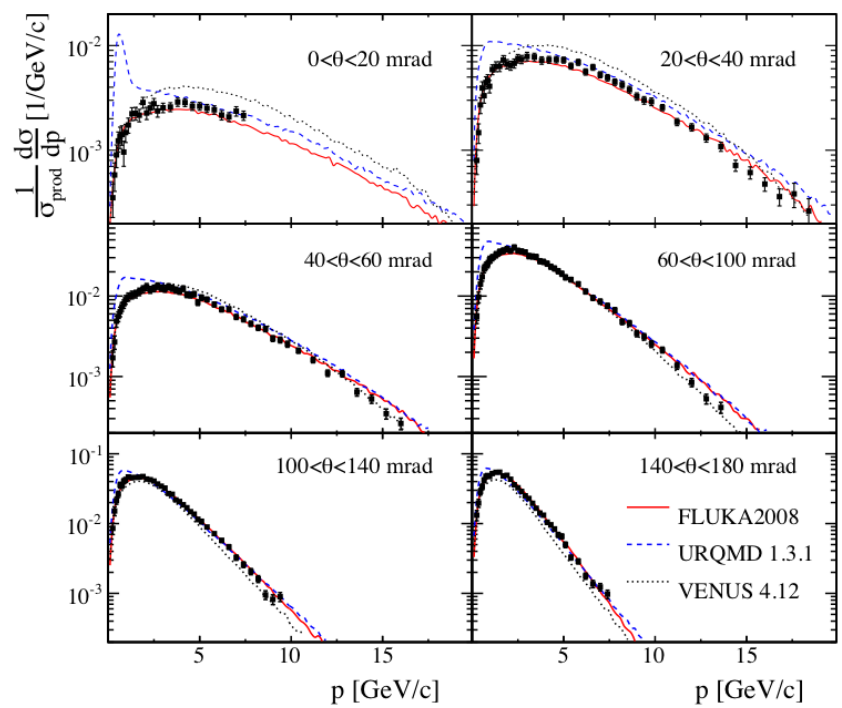
1 < p < 6 GeV/c

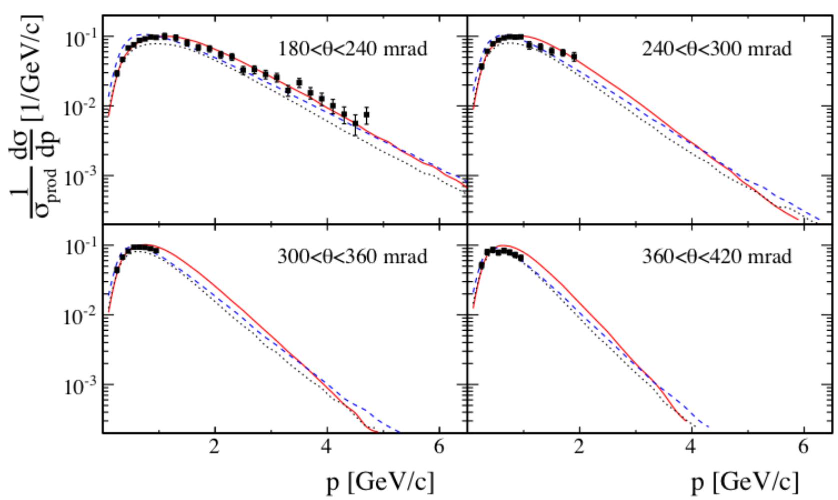


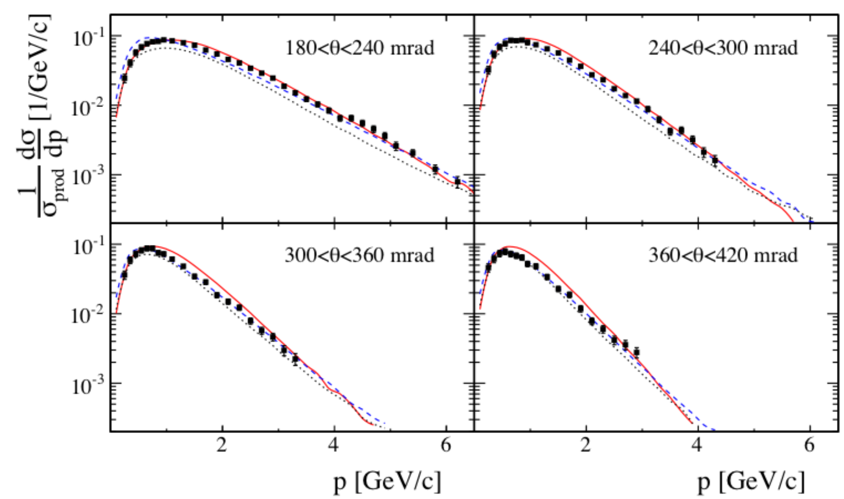
dE/dx

π^+ Ex: T2K and NA61 π^-



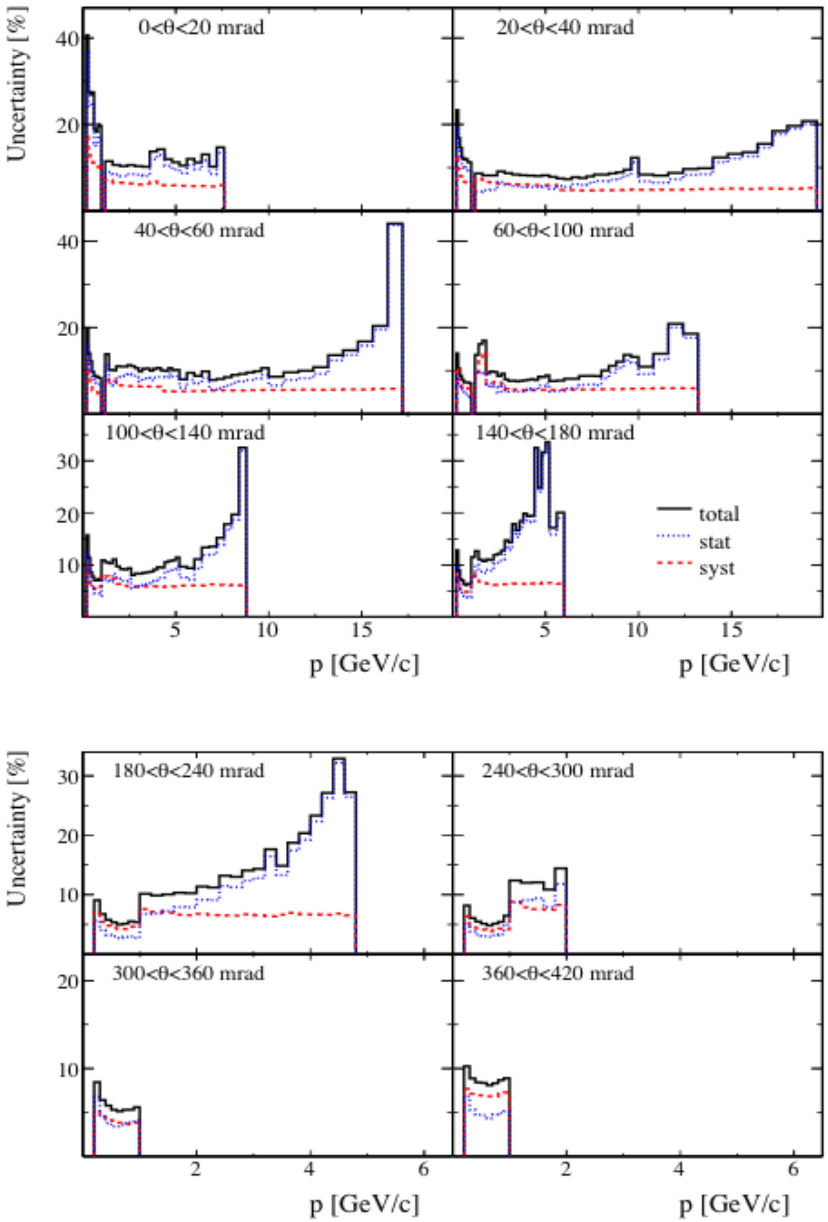




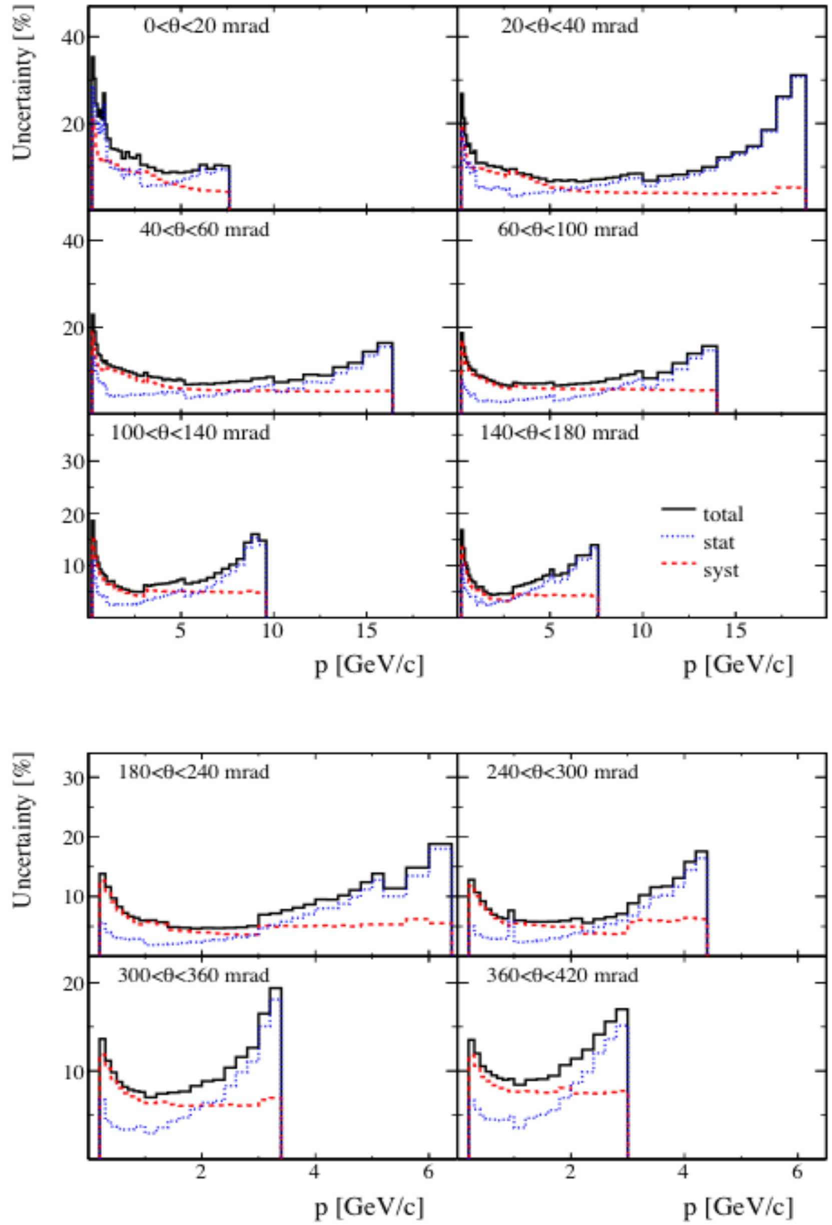


NA61 Systematics

π^+



π^-



T2K and NA61

- First measurements of K+ production from 2007 thin target 31 GeV/c data now also available

- Of course, important for determining electron neutrino beam content and high-energy muon neutrino spectrum

- Statistical errors large, but as with pions this is only 2007 data set (2009 = 10 x 2007)

arXiv:1112.0150

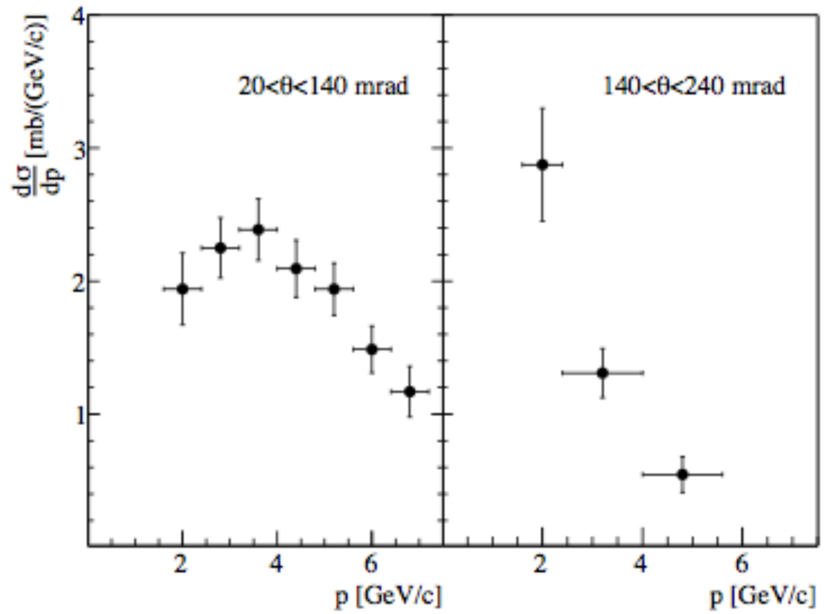
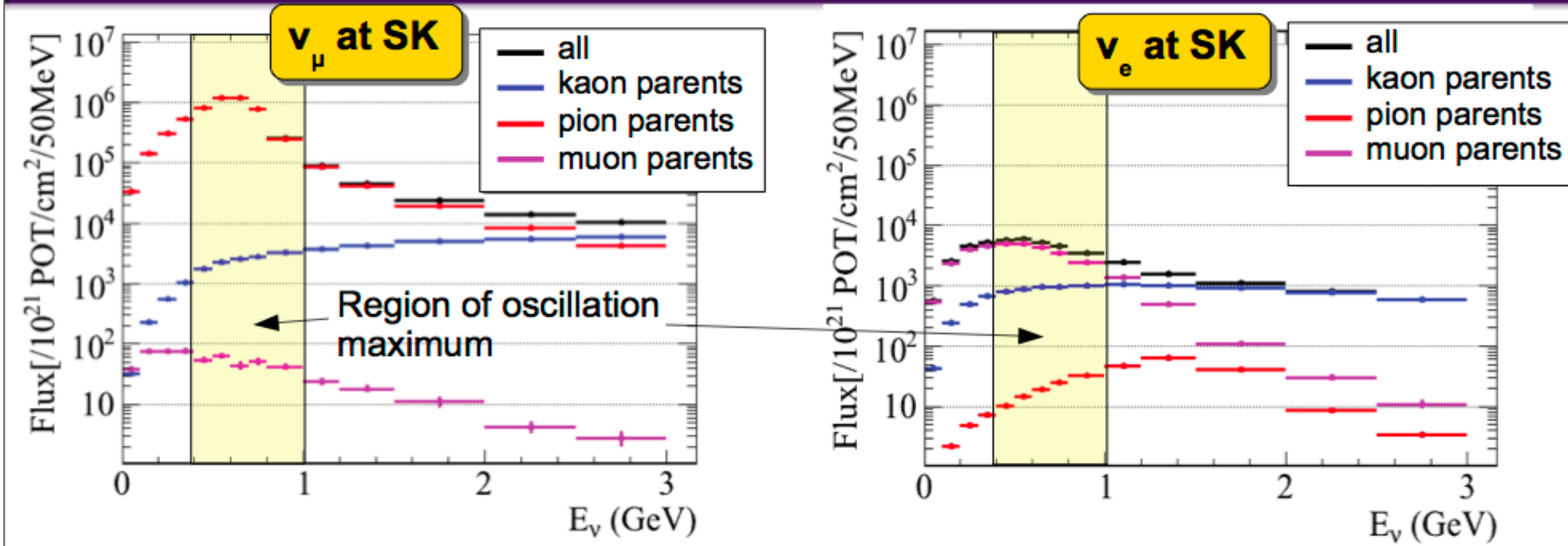


Figure 9: Differential cross sections for K^+ production in p+C interactions at 31 GeV/c. The spectra are presented as a function of laboratory momentum, p, in two intervals of polar angle, θ. Error bars indicate statistical and systematic uncertainties added in quadrature. The overall uncertainty (2.5%) due to the normalization procedure is not included.

Neutrino Flux Prediction



- Muon neutrino flux around oscillation maximum predominantly from pion decays
- Intrinsic electron neutrino flux in beam from muon and kaon decays ~1% of total flux below 1 GeV
  - Dominant source around oscillation maximum is from muon decays

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

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Flux depends on pion production

Flux Uncertainty

Uncertainties on hadronic interactions dominate:

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu)\cdot P_{osc}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{SK}(E_\nu)\,dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{ND}(E_\nu)\,dE_\nu}$$

1. Pion production: systematic uncertainties from NA61
2. Kaon production: from comparison of FLUKA to external data
3. Secondary nucleon production: comparison of FLUKA to external data
4. Hadron interaction probabilities: from external measurements of π, p, K cross sections

Percent Errors from Flux Uncertainties (θ_{13}=0)

Error Sources	$R_{ND}^{\mu,MC}$	N_{SK}^{MC}	$N_{SK}^{MC}/R_{ND}^{\mu,MC}$
Pion Production	5.7%	6.2%	2.5%
Kaon Production	10.0%	11.1%	7.6%
Other Hadron Int.	9.7%	9.5%	1.5%
Beam Direction, Alignment, Horn Current	3.6%	2.2%	2.3%
Total	15.4%	16.1%	8.5%

Cancellation works best for neutrinos from pion production

Example: T2K ν_e Appearance

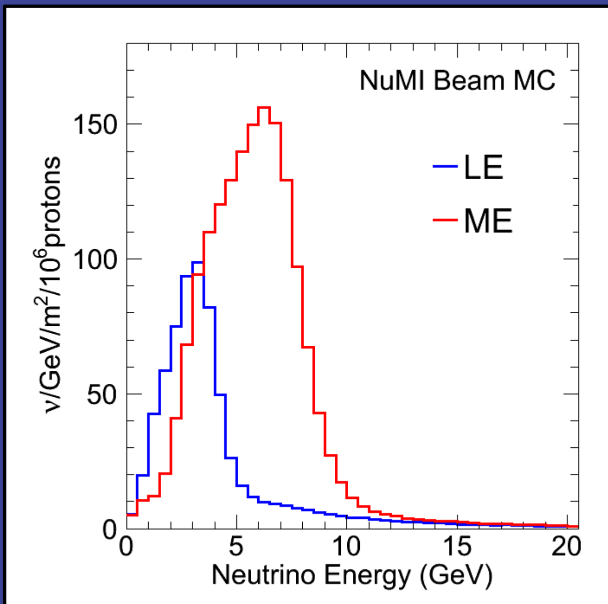
- T2K ν_e appearance PRL
  - Neutrino cross-section models contribute significant systematics; Important for both signal and background
  - Followed by detector systematics and flux

arXiv::1106.2822

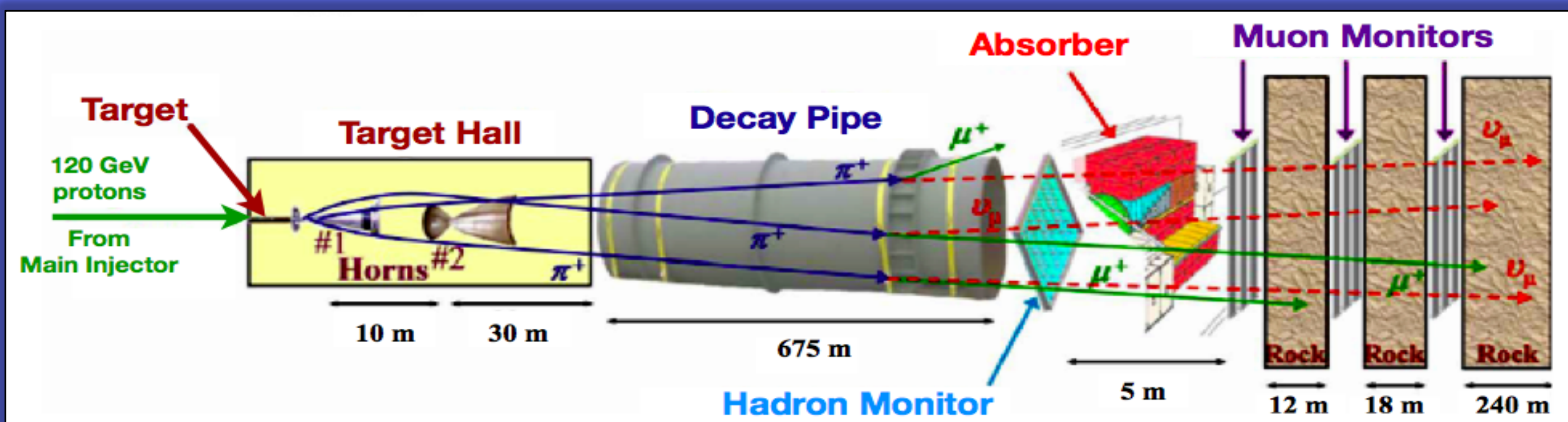
TABLE III. Contributions from various sources and the total relative uncertainty for $\sin^2 2\theta_{13} = 0$ and 0.1, and $\delta_{CP} = 0$.

Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}$%	$^{+5.6}_{-5.2}$%
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}$%	$^{+17.6}_{-17.5}$%

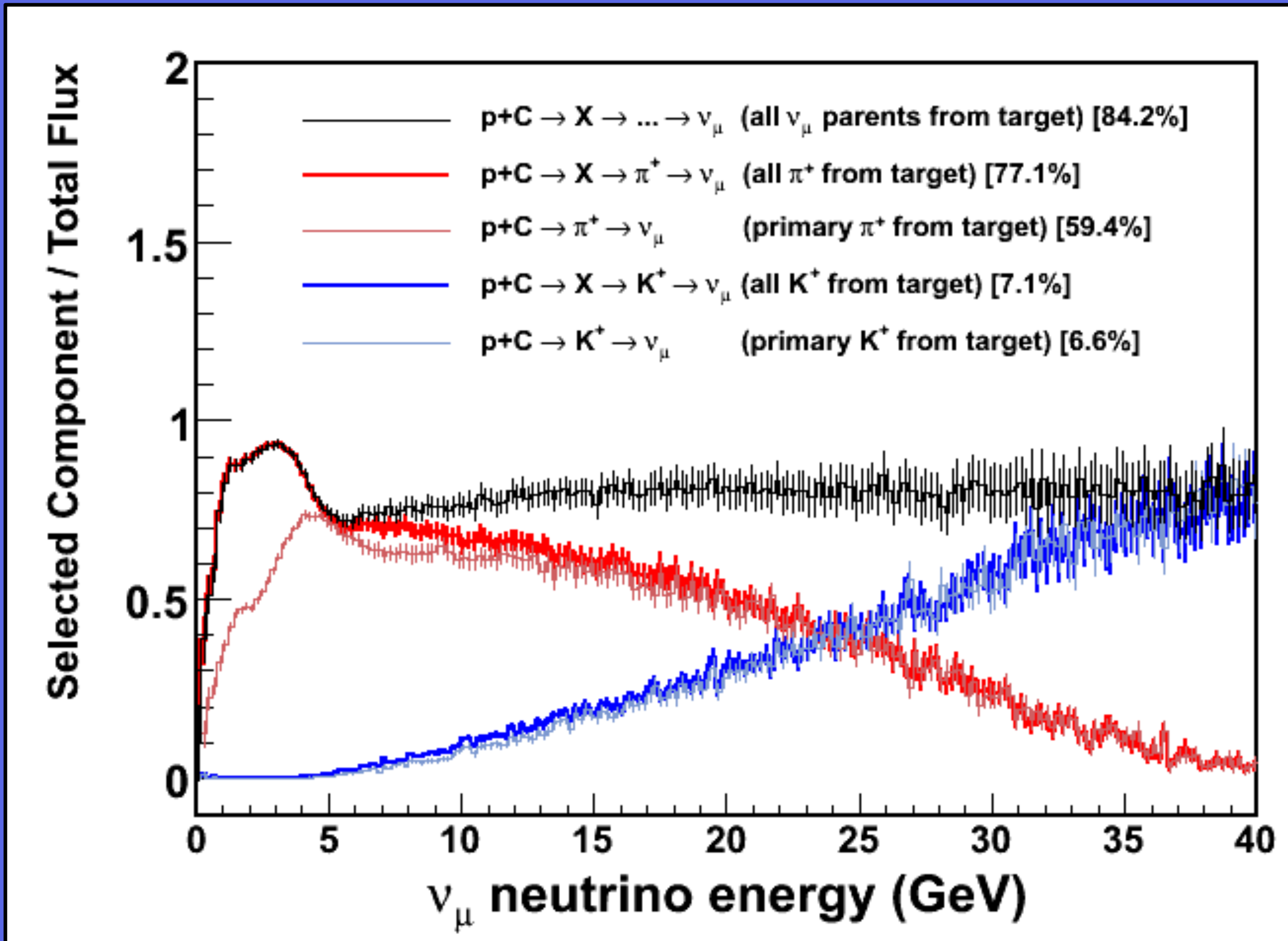
NuMI Beam



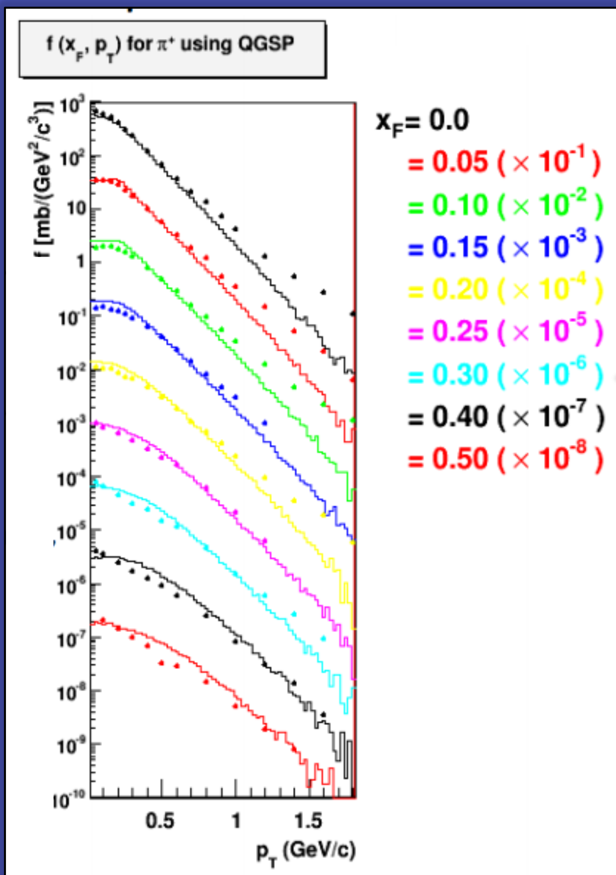
- Intensity: ~35e12 P.O.T per spill
  - about 1 ν event and a few rock muons in MINERνA per spill
- Spill length/frequency: 10ms / ~0.5 Hz.
- Beam power: 300 – 350 kW
- Mean energy of NuMI ν beam tuned by changing longitudinal positions of the target and horns
- Reversing current in focusing horns changes beam from mostly neutrinos to mostly antineutrinos



NuMI Flux Components



Constraining NuMI Flux with NA49 Data

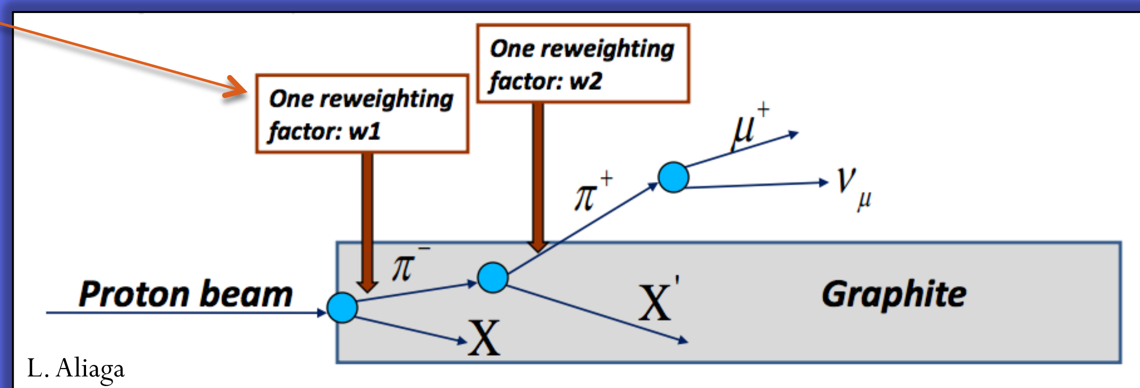


Eur.Phys.J.C49:897-917,2007

CERN experiment NA49 published measurements on thin carbon targets:

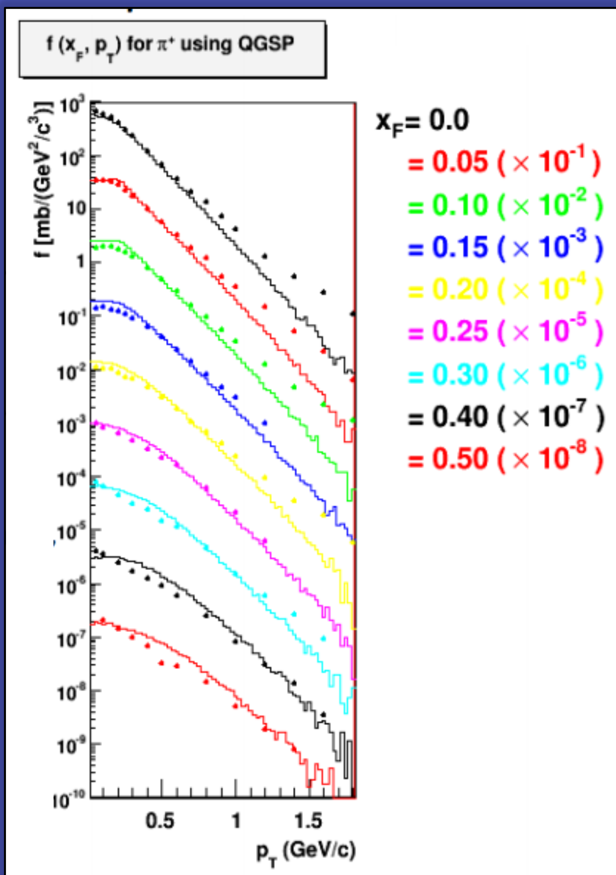
p(158 GeV/c) + C -> π^+ + X

p(158 GeV/c) + C -> π- + X (not shown)



Also looking at lower energy data to cross-check secondary interaction models

Constraining NuMI Flux with NA49 Data



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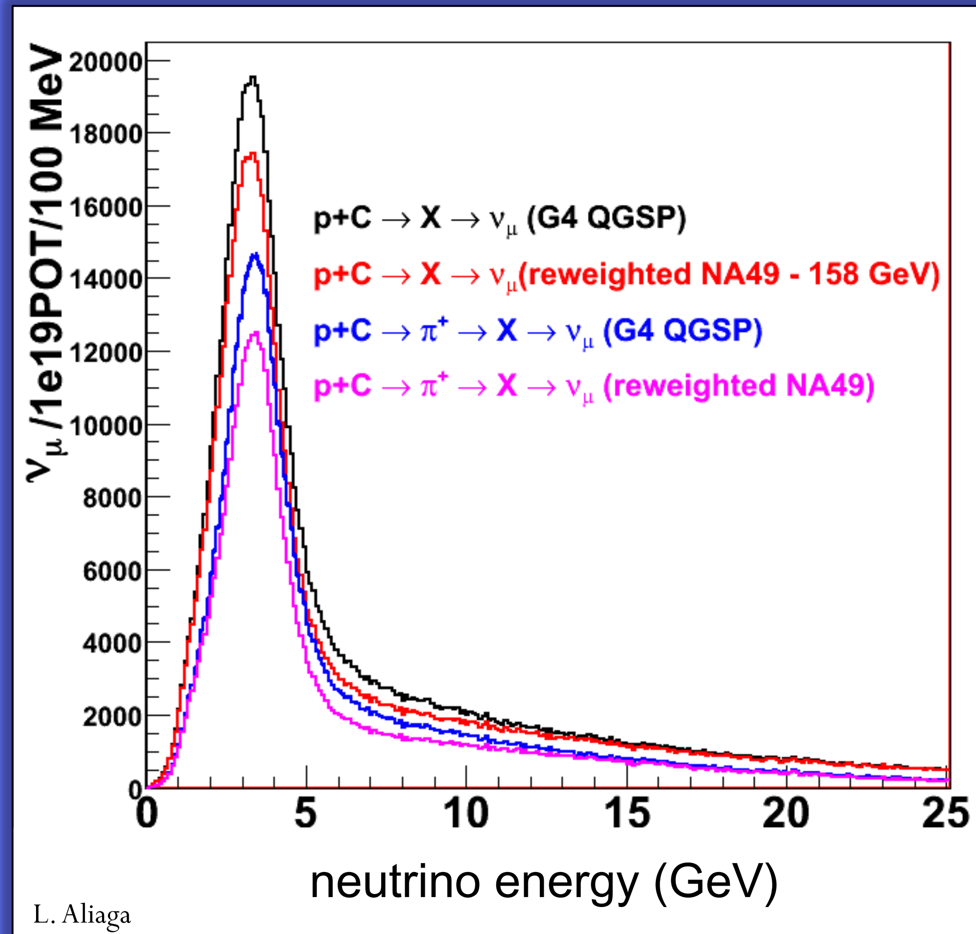
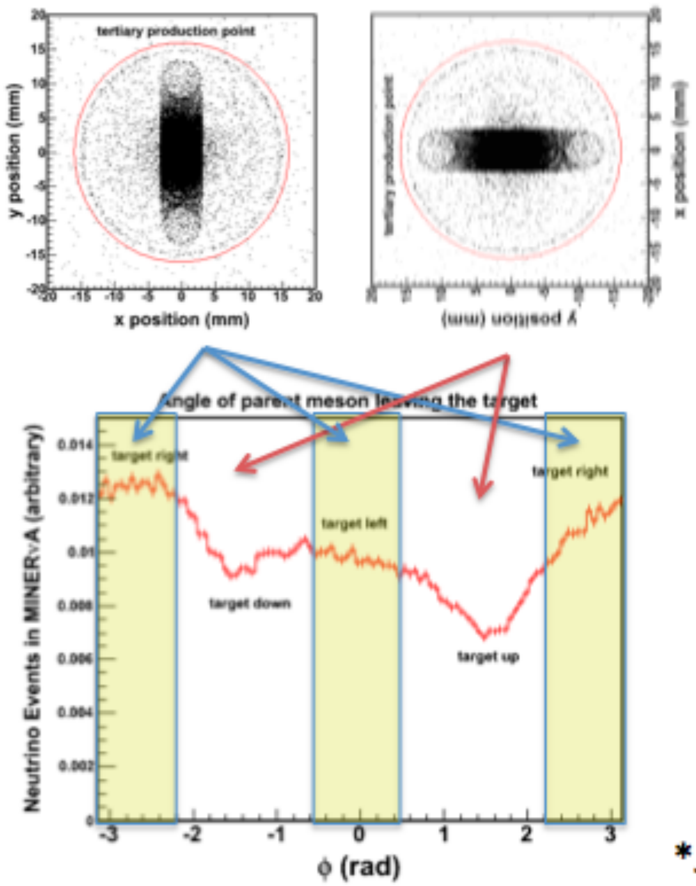


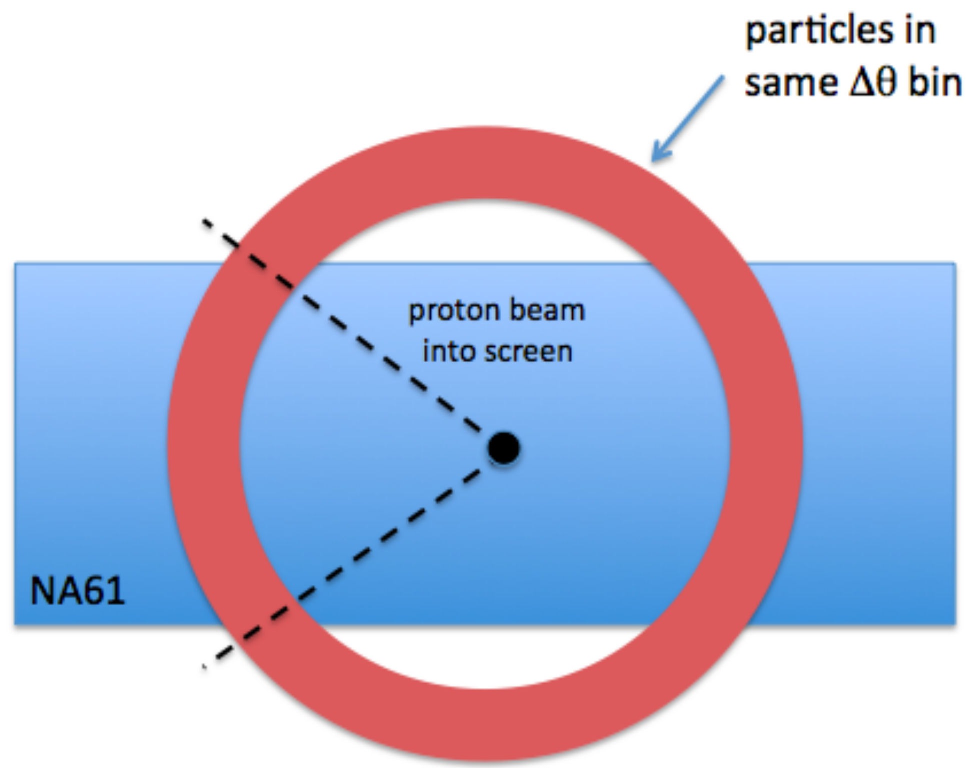
Reweighted flux 20% below
Geant4 flux prediction in the peak!

Phi Dependence of NuMI Beam

Will require taking data in target configurations to map out impact of secondary interactions in the "thin" and "thick" directions

WHY is that?





*Just a cartoon. Width of boxes is not quantified. 21