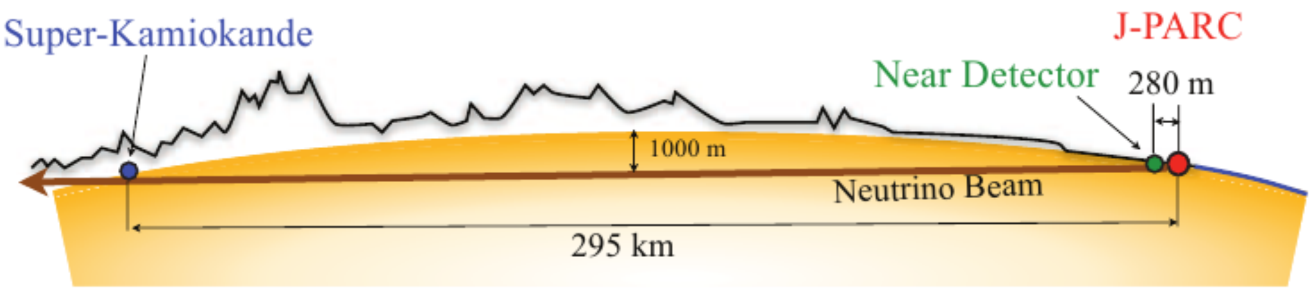
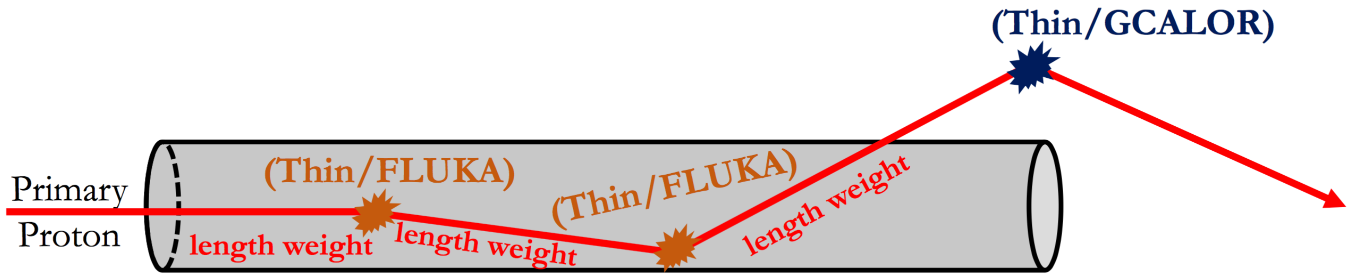
The EMPHATIC Experiment

KHALID GAMEIL

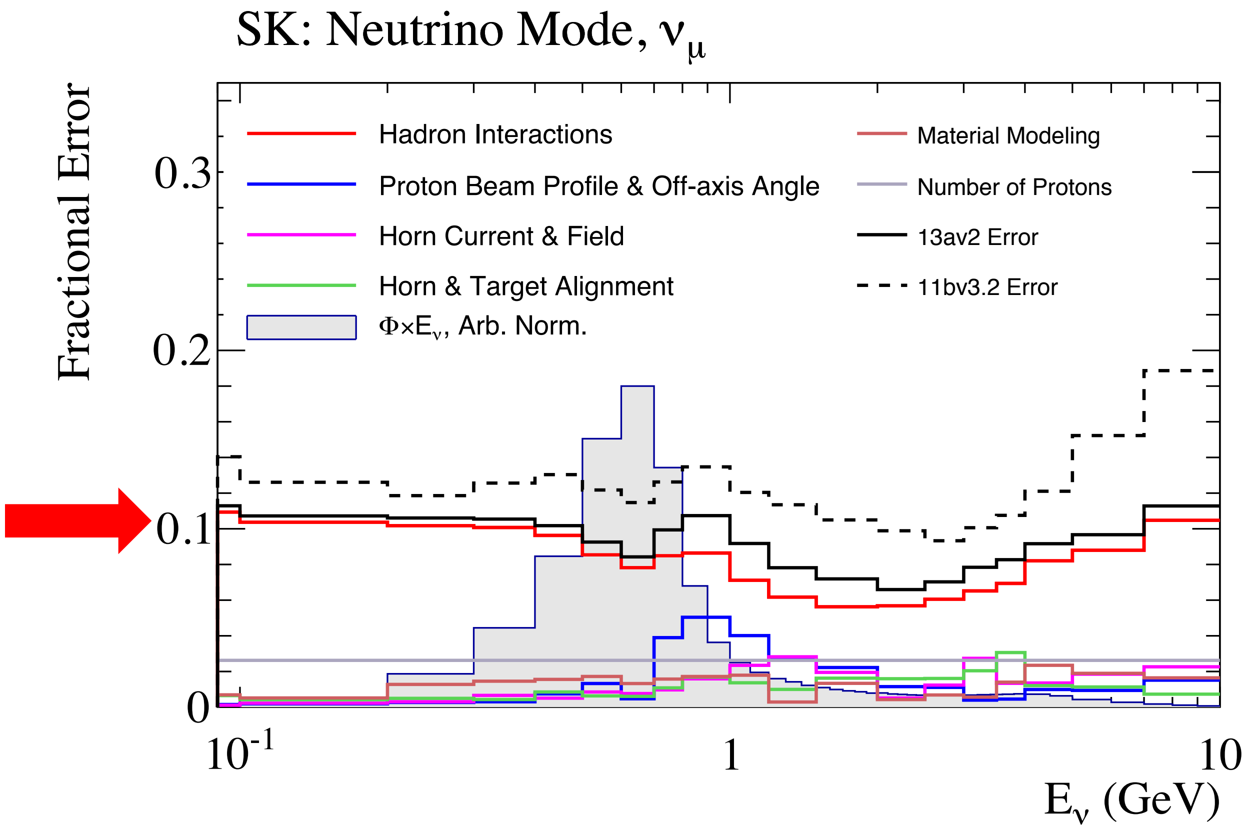
Neutrino Flux Predictions

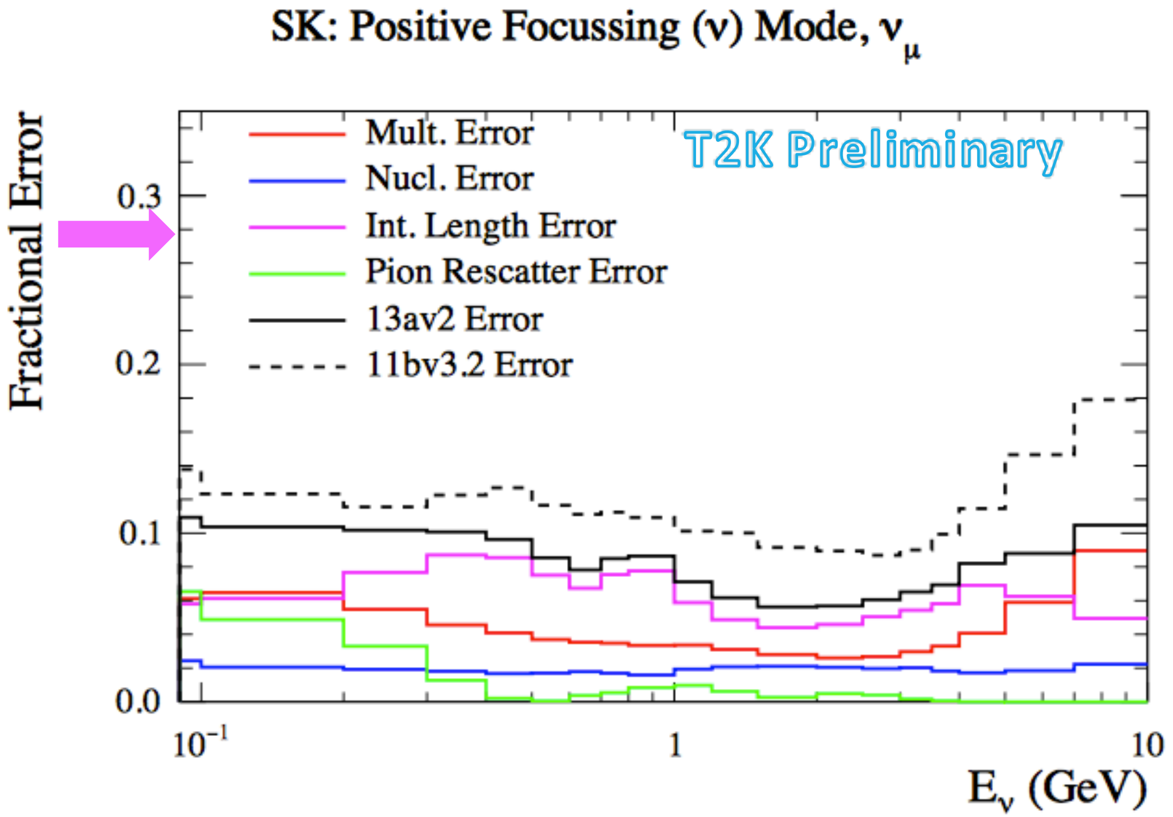


- All neutrino long baseline experiments require a neutrino flux predictions
- It is one of the main systematics of the experiment
- T2K Procedure:
  - Model in-target interactions from T2K beam profile (FLUKA)
  - Modelling out of target interactions in horns and decay volume (GCALOR-GEANT3)
  - Flux is reweighted by external hadron production data and NA61/SHINE



Neutrino Flux Predictions Uncertainties



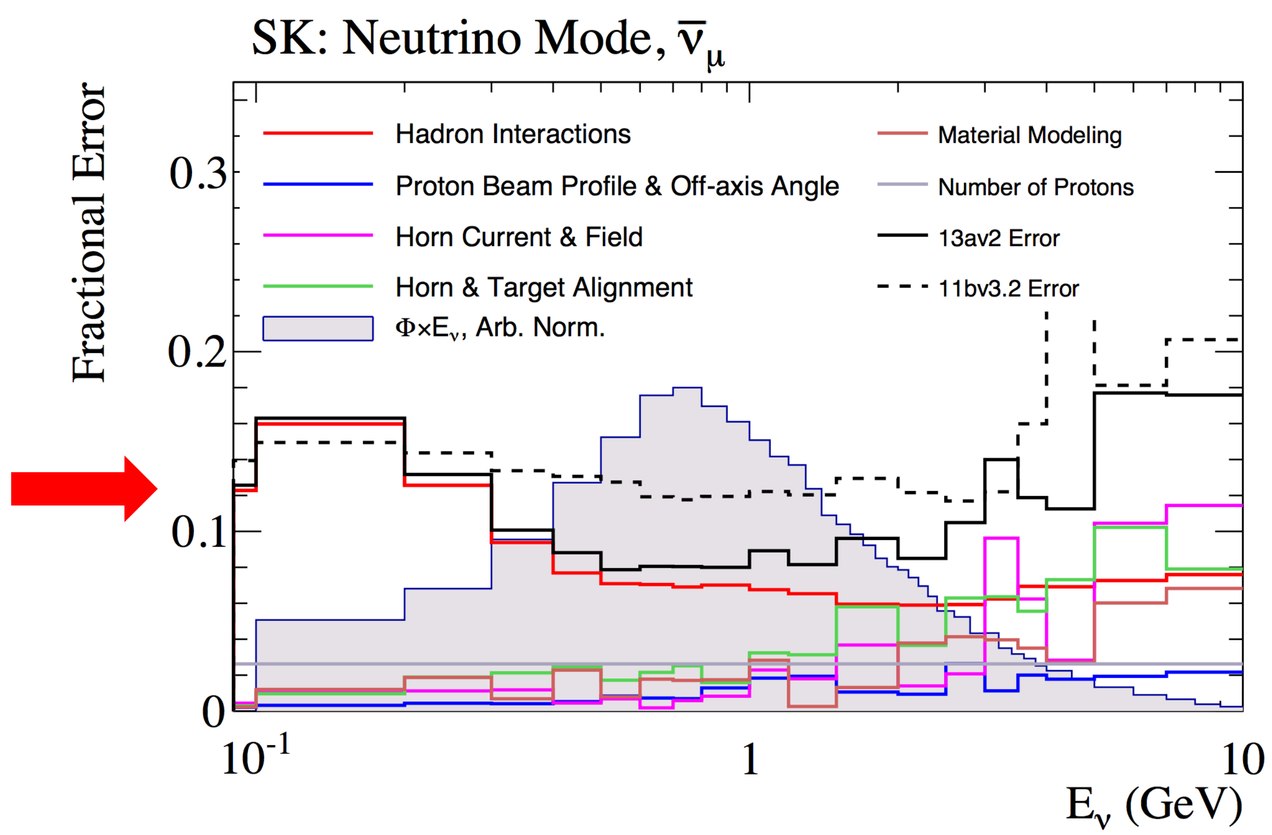


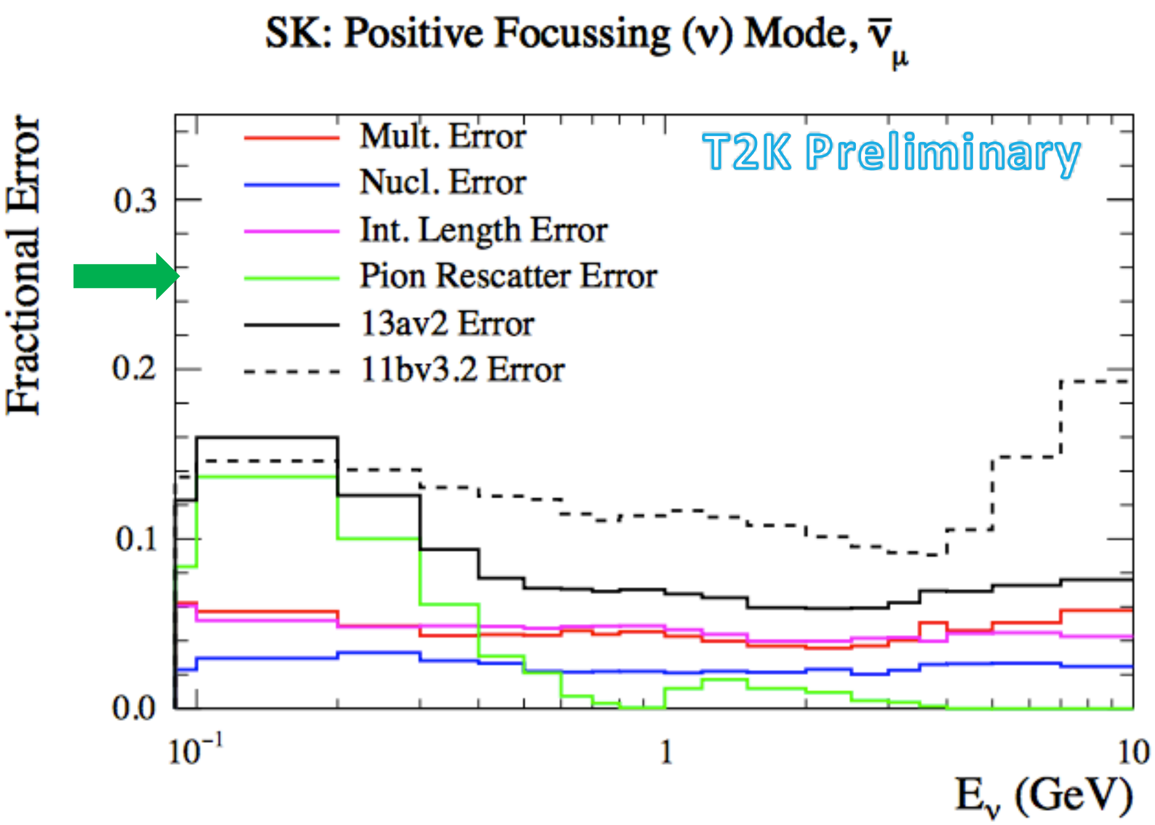
The hadronic interaction contribution is the dominant uncertainty

The dominant uncertainties:

- Interaction Length (production cross section uncertainty)
- Pion Rescatter (out-of-target secondary interaction) for the negative focusing mode

Neutrino Flux Predictions Uncertainties





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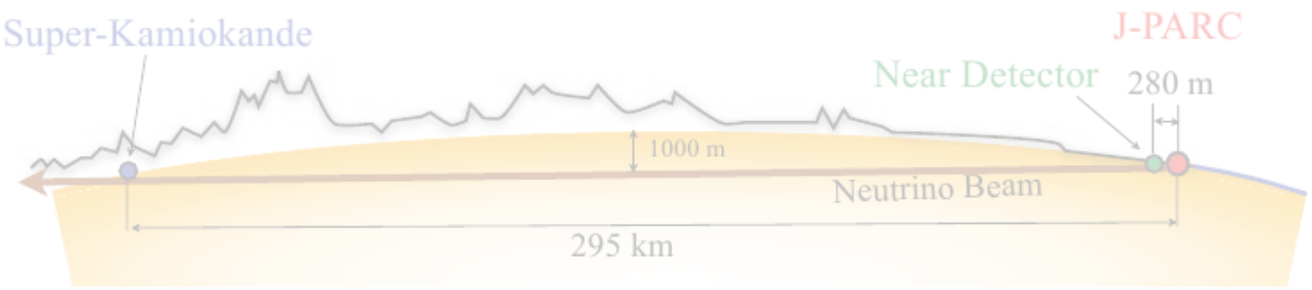

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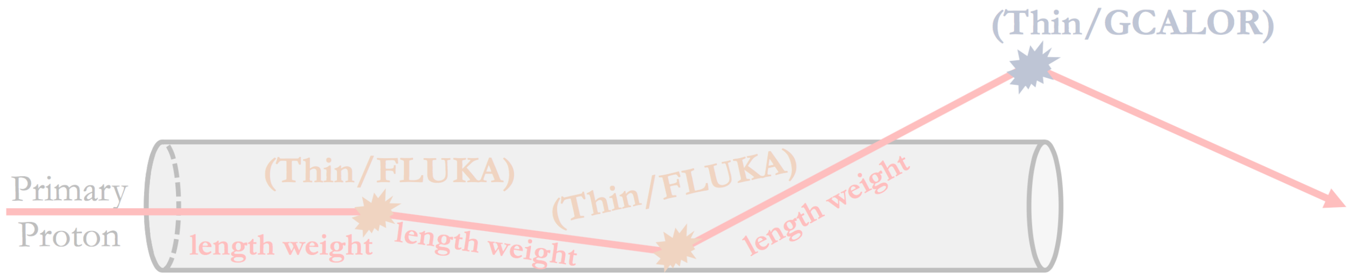
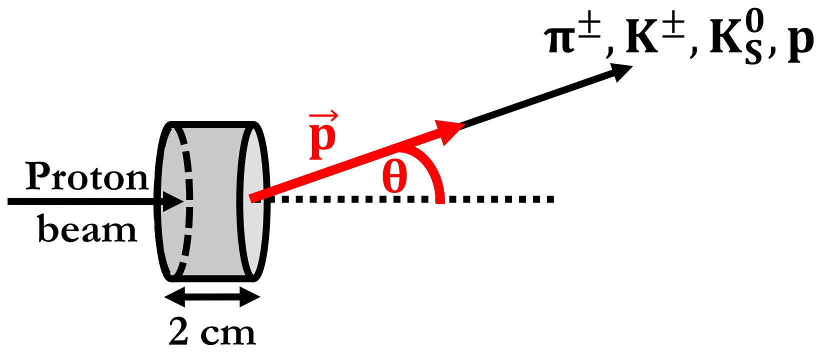


Flux Reweighting

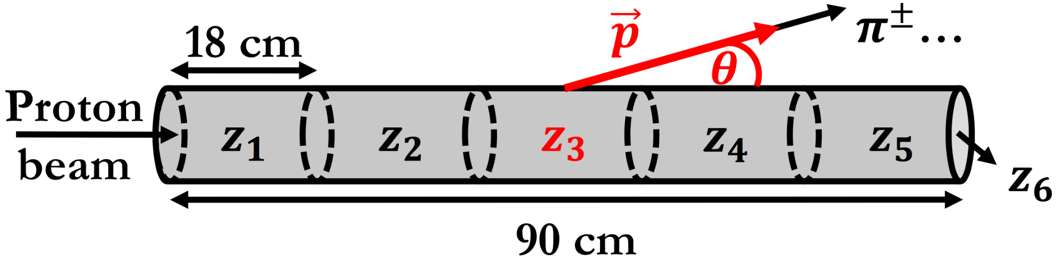
- Flux is reweighted with NA61/SHINE data by the:
  - Interaction Length: the probability that a secondary particle is produced in the target
    $$w = \frac{\sigma'_{Prod}}{\sigma_{Prod}} e^{-x\rho(\sigma'_{Prod} - \sigma_{Prod})}$$
  - Hadronic multiplicities: the number of particles produced in each interactions
- This can be done by a thin target (2cm) or a T2K replica target (90cm)
- The replica target is favorable because it can directly constrain the produced pion multiplicities

Thin Target Reweight



- Thin target $\sigma_{prod} = 230.7 \pm^{7.0}_{4.6}$ mb

Replica Target Reweight

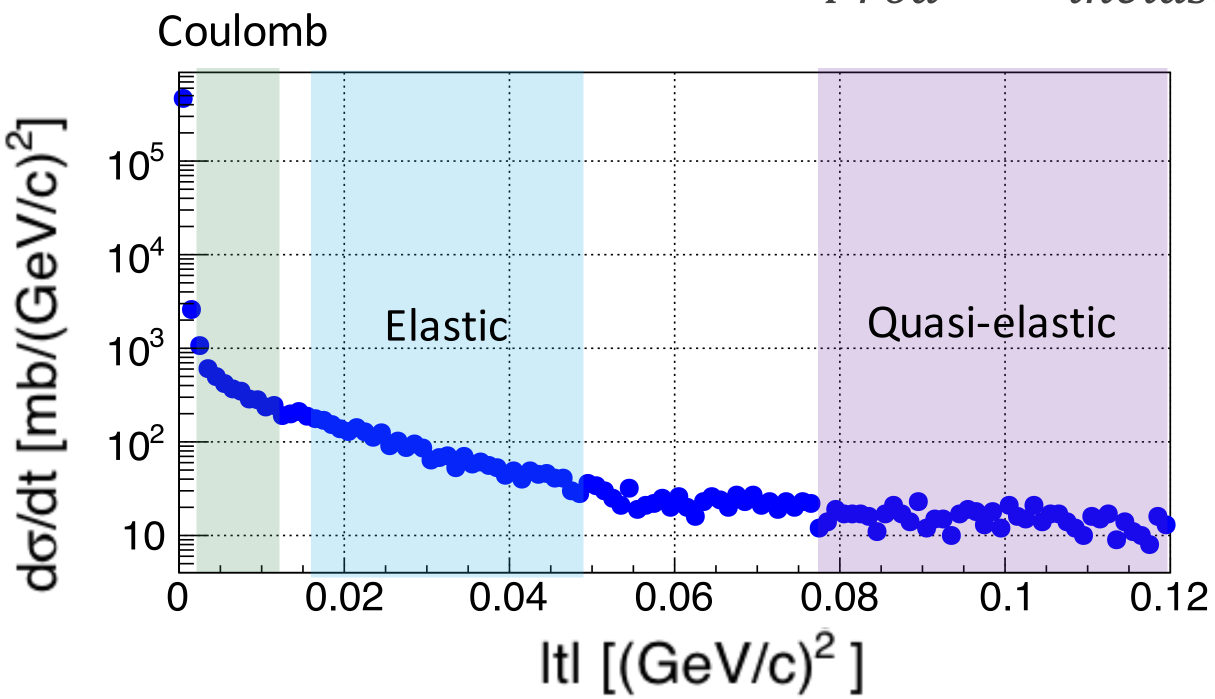


- Replica target $\sigma_{prod} \approx 200$mb (taken by a MC fit)

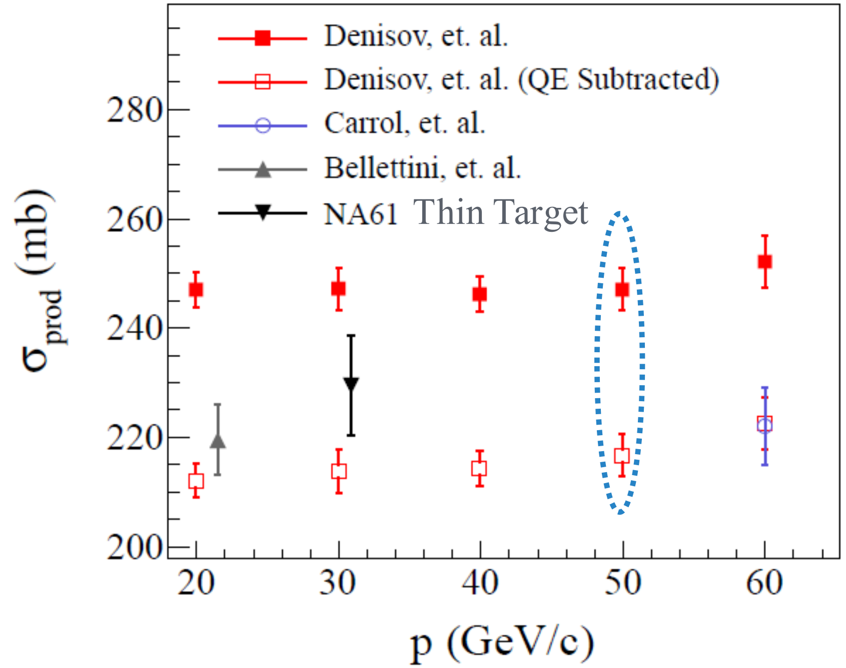
Production Cross Section

- The production cross section is used in reweighting the simulated neutrino flux
- Uncertainties in the existing data gives us large predicted flux uncertainties
- The production cross section is defined as:

$$\sigma_{Prod} = \sigma_{inelastic} - \sigma_{quasielastic}$$

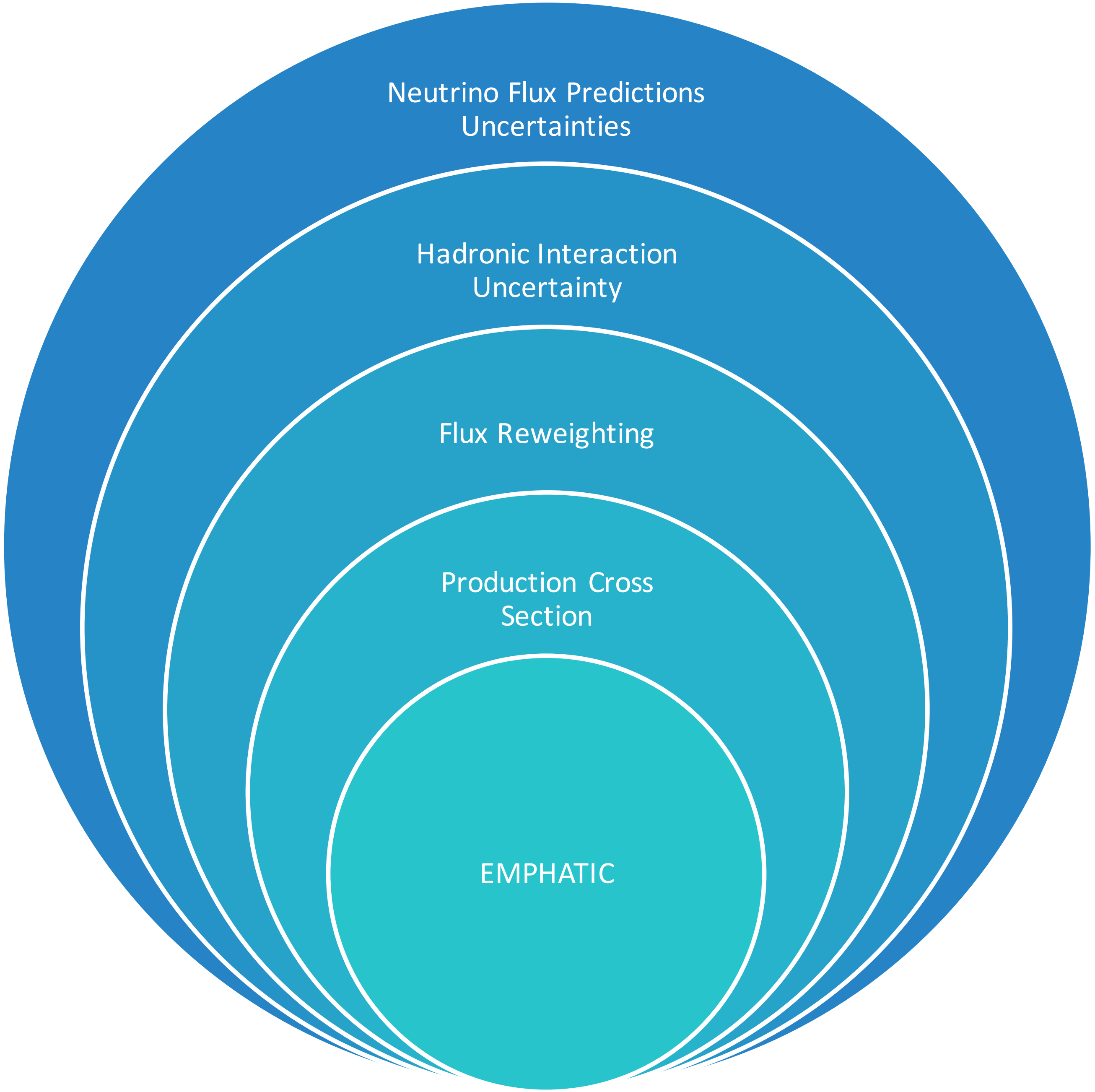


- The different regions are not well defined



- Previous measurements of σ_{Prod} disagree therefore the value $\sigma_{quasielastic}$ as an uncertainty estimate

Quick Recap


Neutrino Flux Predictions Uncertainties
Hadronic Interaction Uncertainty
Flux Reweighting
Production Cross Section
EMPHATIC

Emulsion-based **M**easurement of the **P**roduction of **H**adrons **A**t a **T**est beam **I**n **C**hicagoland

What?

- The EMPHATIC group aims to measure the production cross section and the hadronic multiplicities of multiple particles on targets

Why?

- Reduce the contribution of the hadronic interaction uncertainty
- Disagreement between previous measurements of the
  - Badly defined cross sections!
- Shed light on the NA61/SHINE thin and replica target tuning inconsistencies
- Increase coverage as compared to NA61/SHINE
- Low momentum measurements for atmospheric neutrinos
- High accuracy position measurements -> Emulsion!
- Reduce uncertainties of out-of-target interactions

Where and When?

- Fermilab Test Beam Facility January 2018!

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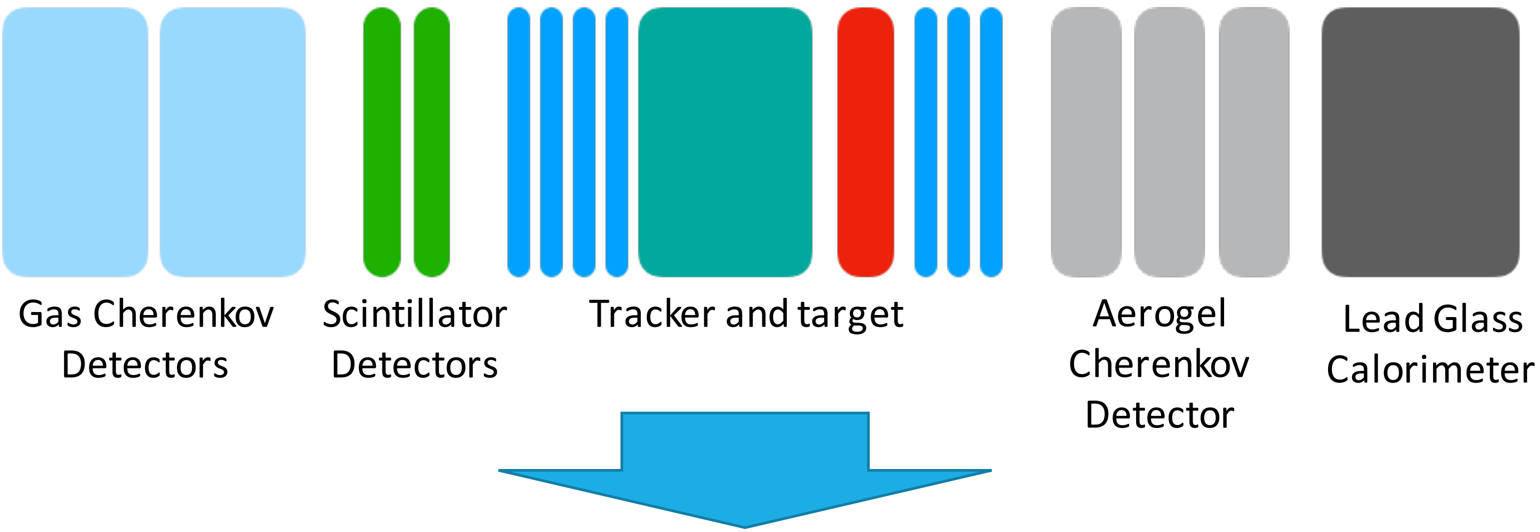
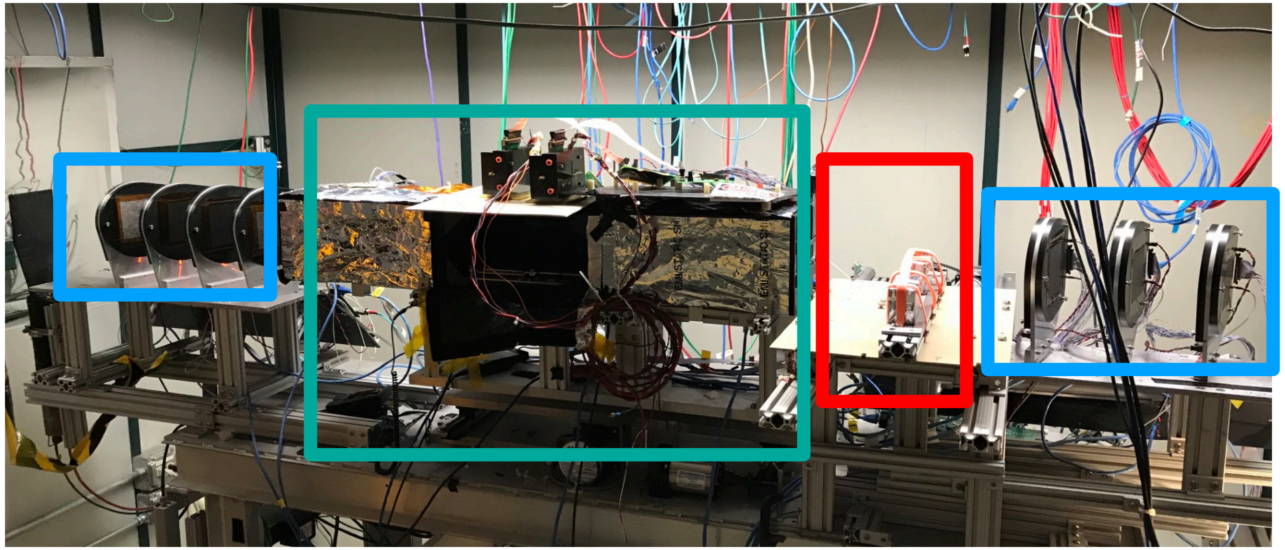
Set up



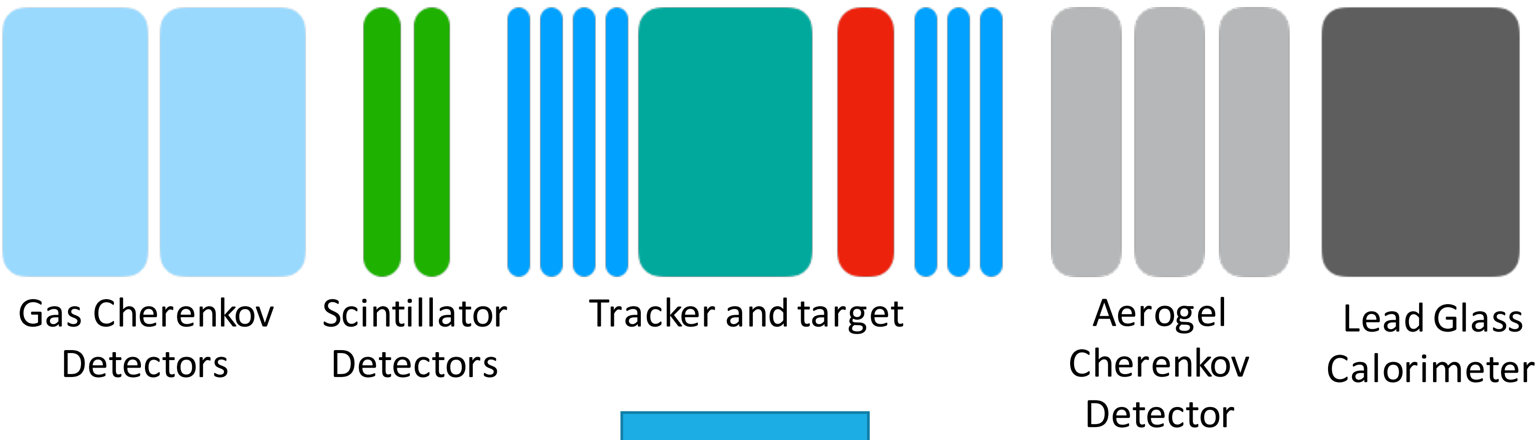


- Silicon Strip detector
- Pixel Detector
- Emulsion and moving table for targets

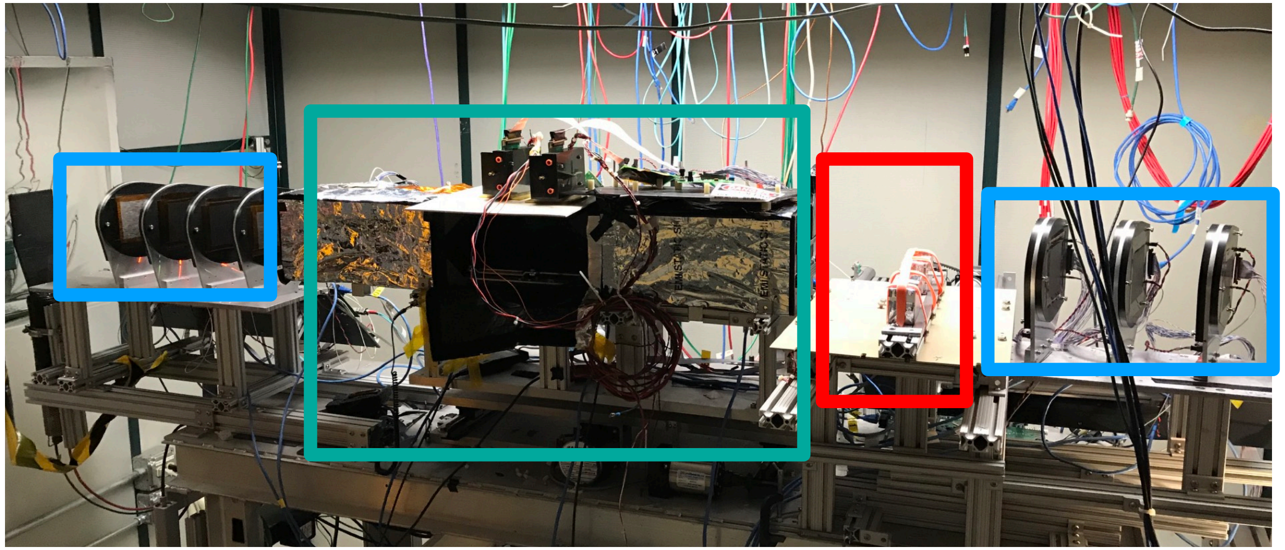
Measurements:
10-120GeV/c beam
C, Empty, Al, and Fe

Analysis:
20 and 30 GeV/c
Proton + C/Empty

Set up



Silicon Strip detector
Pixel Detector
Emulsion and moving table for targets



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Analysis Summary

Only the silicon strip data is used in this analysis:

- The emulsion is still being analyzed
- The pixel detector was inefficient

Directly from the fitted tracks you can calculate $\theta = Scattering\ Angle$

The scattering angle can be used to determine the time channel Mandelstam variable:

$$t = -Q^2 \approx p^2\theta^2$$

Two Analyses Presented in this talk:

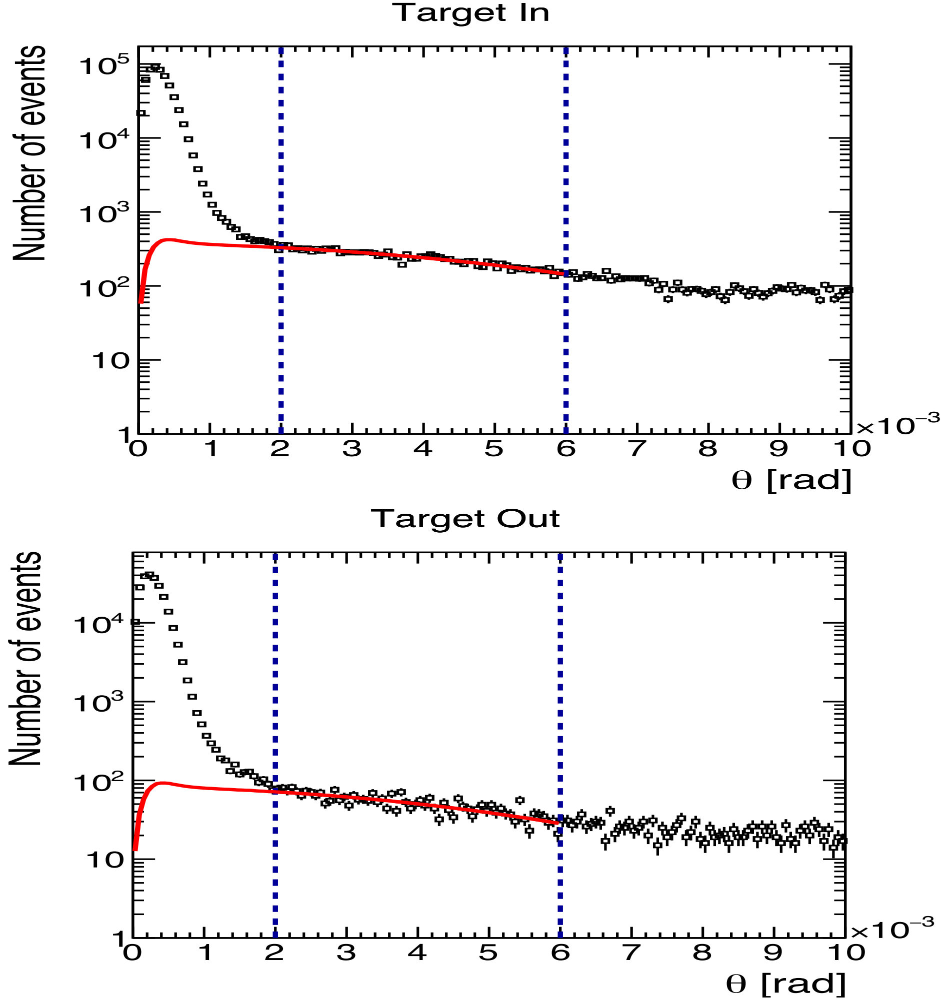
- Total cross section (σ_{Tot}) analysis:

$$P_t = Surival\ probability\ through\ the\ target = e^{-n\sigma_{tot}d}$$

- Elastic and Quasi-elastic cross section analysis: model fit of t distribution

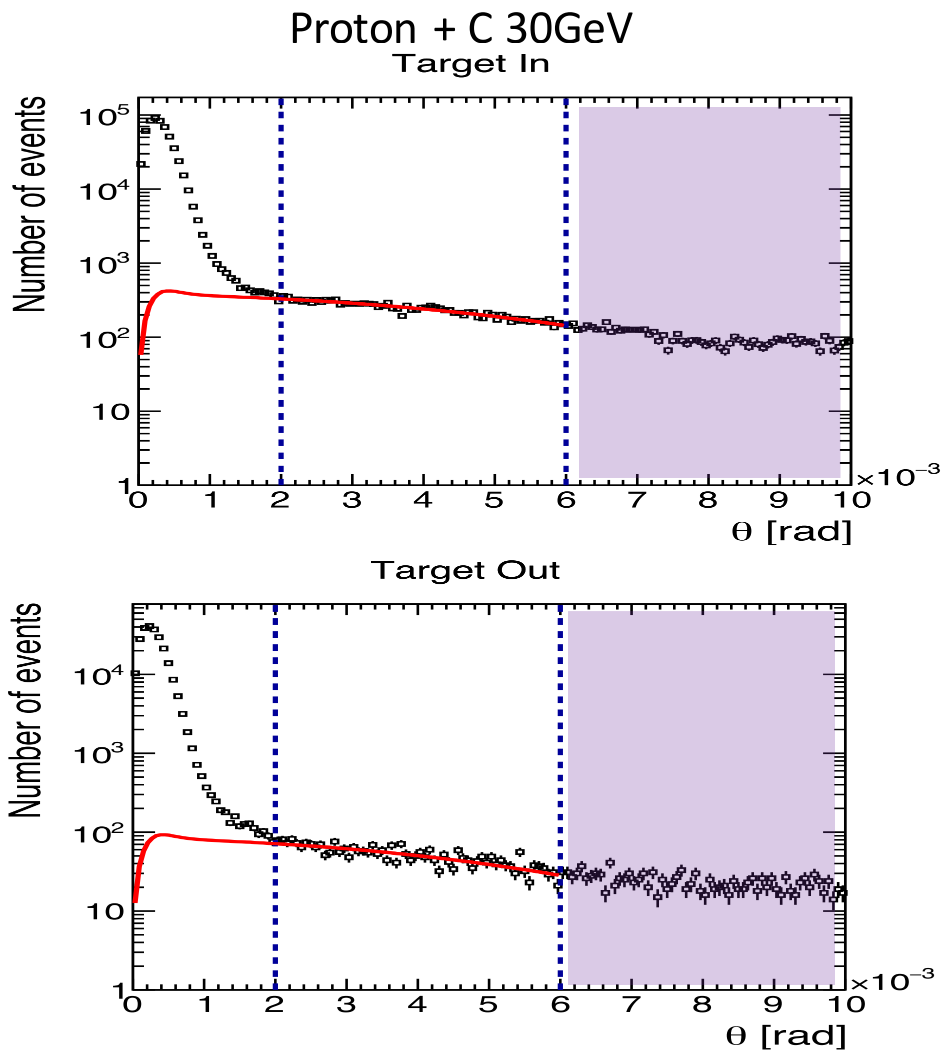
Total Cross section Analysis

Proton + C 30GeV



- Number of surviving particles (N_s) are determined by the distribution of the scattering angle

Total Cross section Analysis



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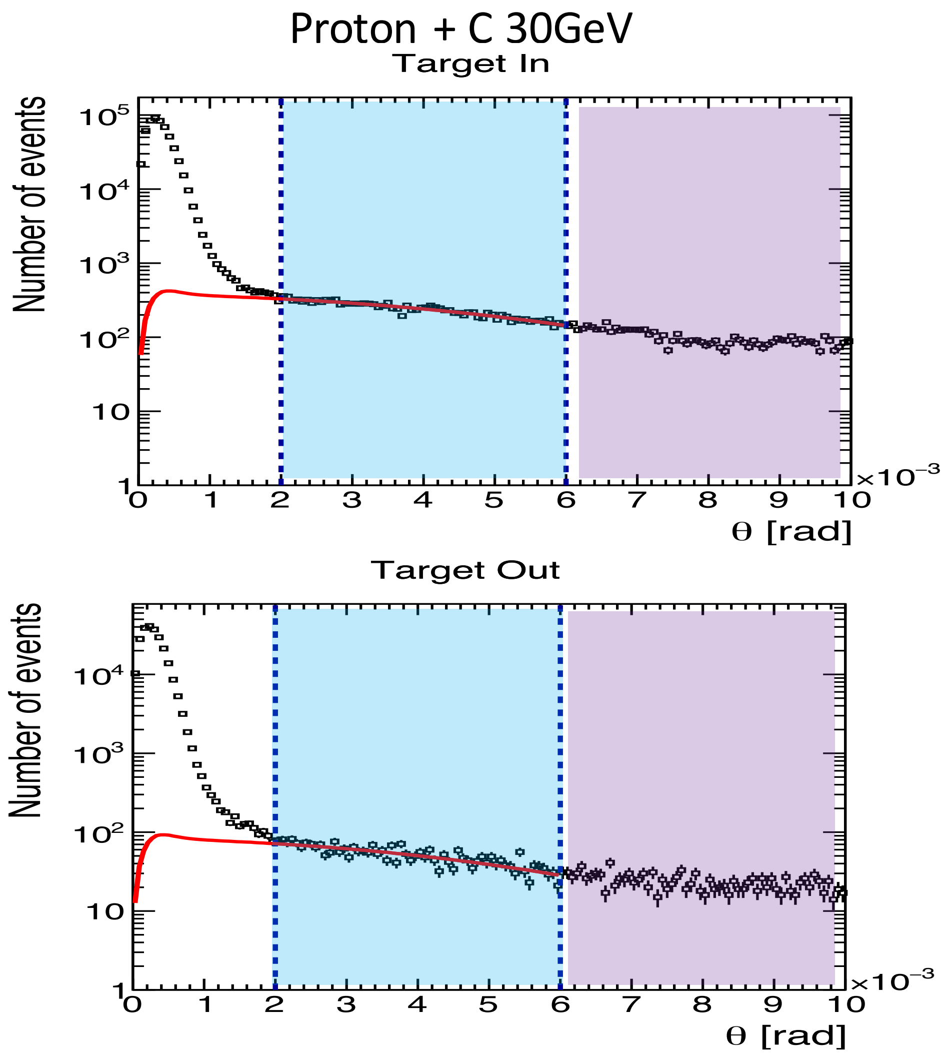
- The quasi-elastic component is not fit

Total Cross section Analysis



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- The elastic component is fit and extrapolated to the coulomb region

Total Cross section Analysis

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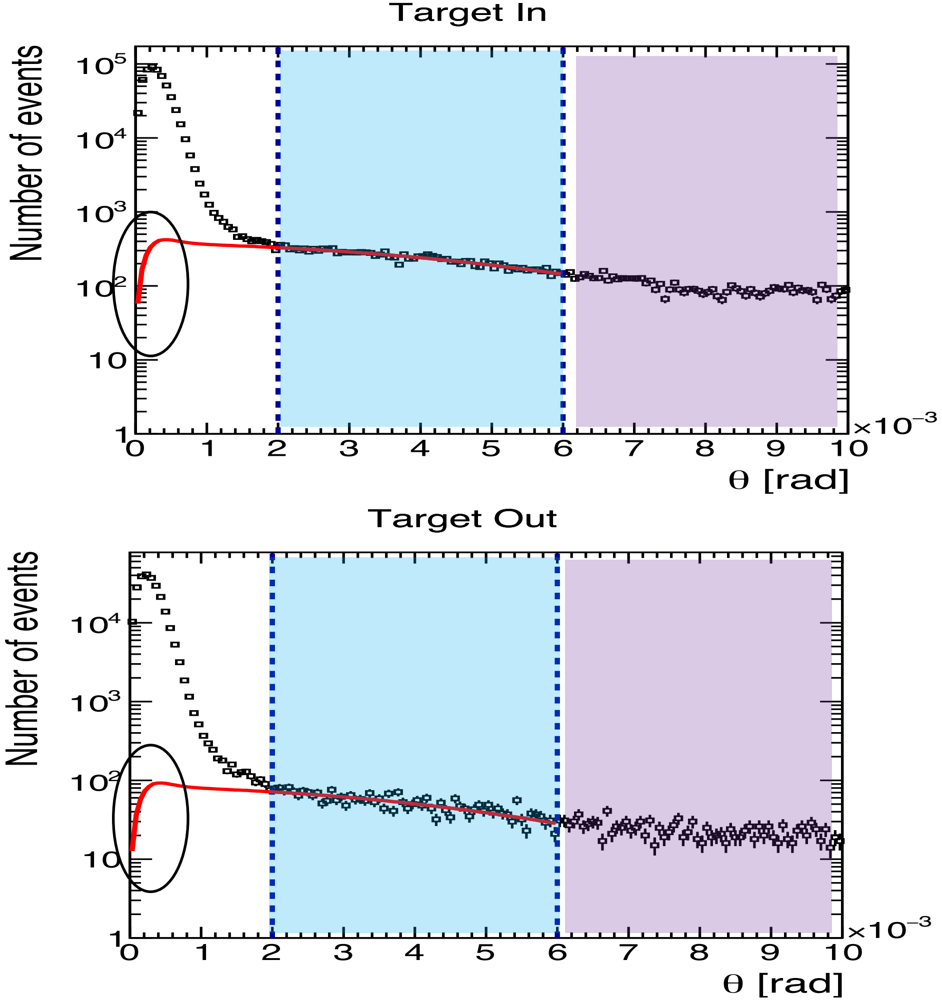

- Number of surviving particles (N_s) are determined by the distribution of the scattering angle
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- The elastic component is fit and extrapolated to the coulomb region
- Multiple scattering and detector resolution smearing is applied to the elastic fit

Total Cross Section Analysis

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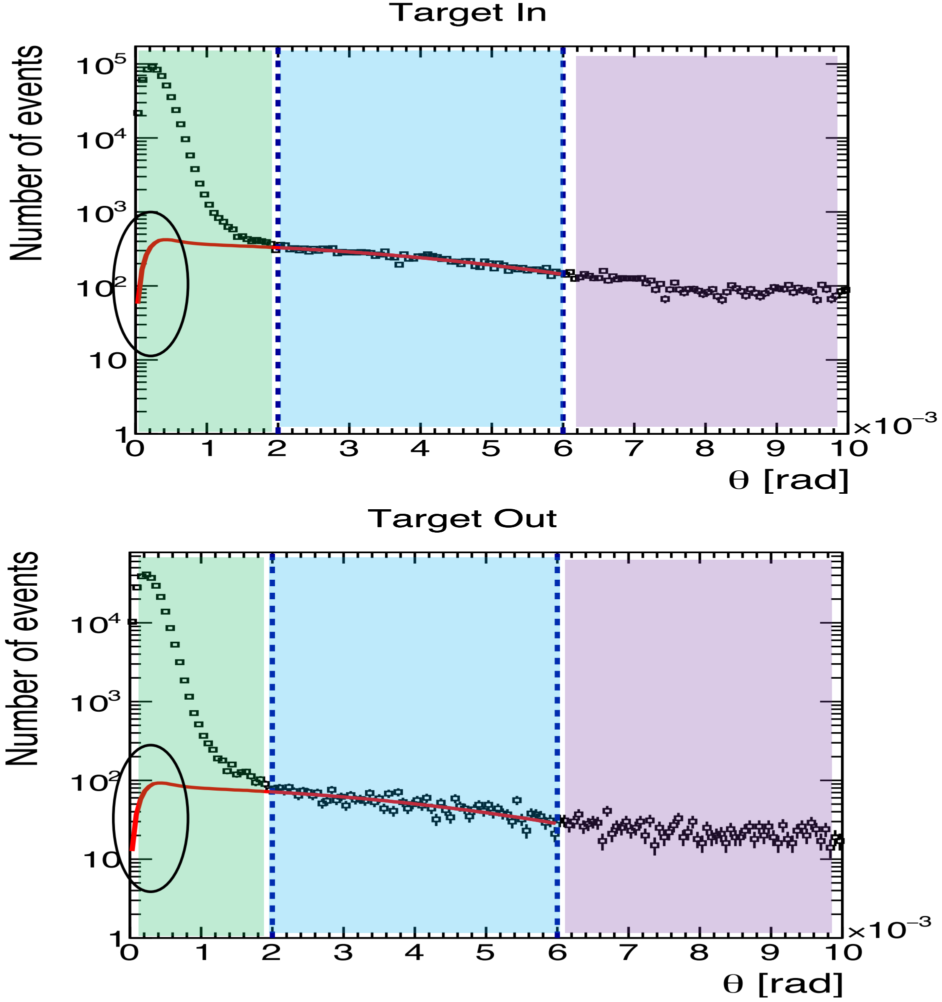
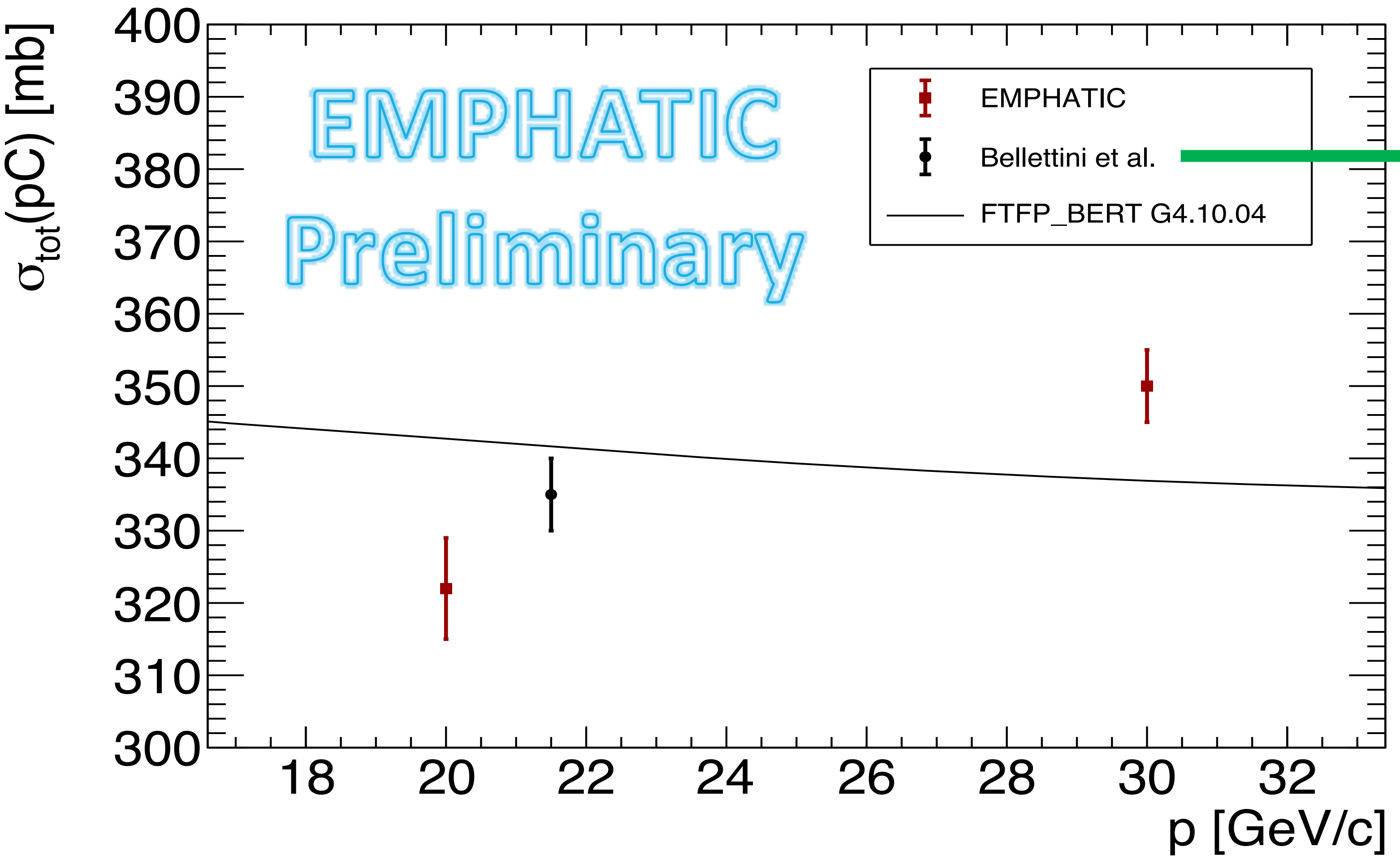


- Number of surviving particles (N_s) are determined by the distribution of the scattering angle
- The quasi-elastic component is not fit
- The elastic component is fit and extrapolated to the coulomb region
- Multiple scattering and detector resolution smearing is applied to the elastic fit
- N_s = # of Events in Coulomb Region – Elastic Fit

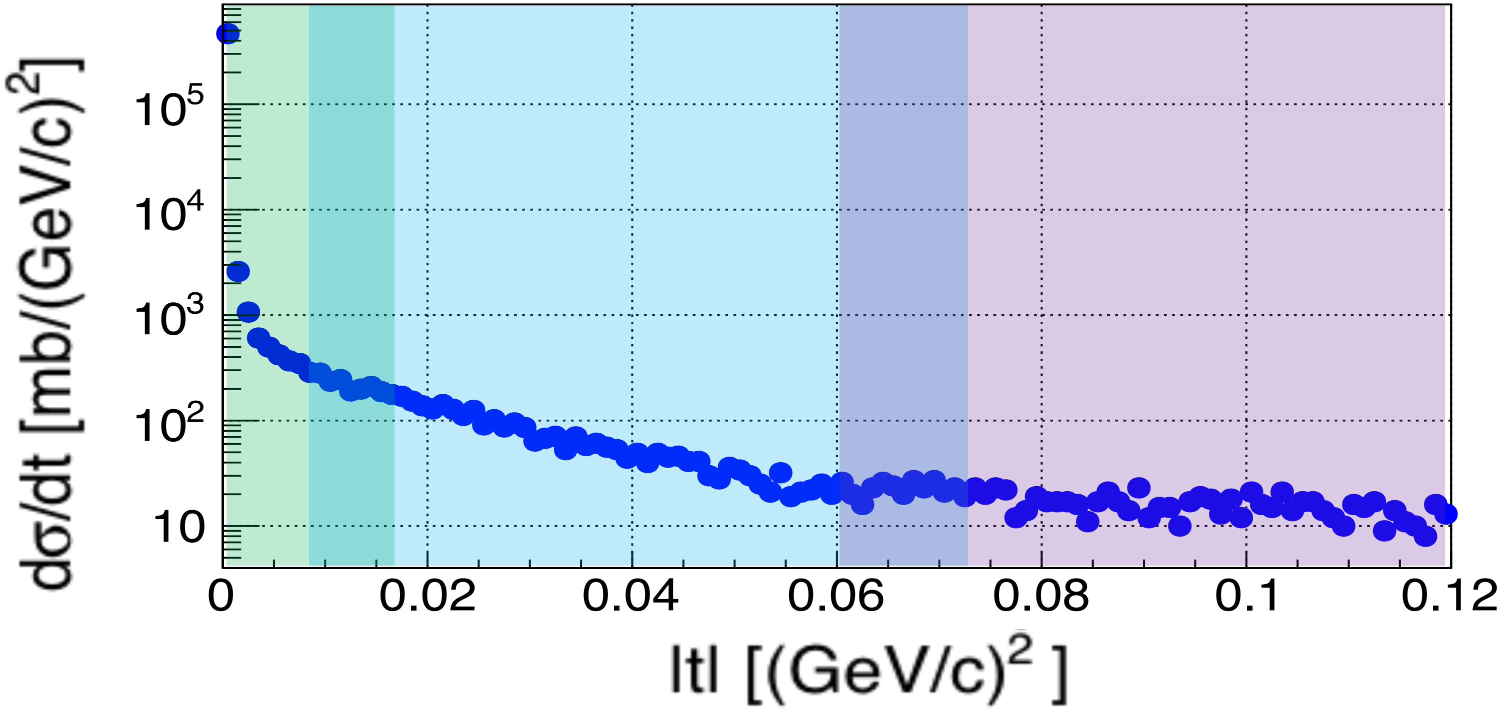
Total Cross Section Results



https://doi.org/10.1016/0029-5582(66)90267-7

Model Fit of t distribution

- Regions to fit:
  - Coulomb Interaction
  - Elastic Interaction
  - Quasi-elastic Interaction
- The overlap regions contain:
  - Cross terms introduce the Coulomb phase
  - Diffraction between elastic and quasi-elastic regions



Preliminary Model fit

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left| -8\frac{\pi\alpha Z\hbar c}{t} e^{-\frac{a^2 t}{4}} e^{-i\phi} + \frac{(\rho + i)\sigma_{tot}}{\hbar c} e^{-\frac{Bt}{2}} + \frac{N(A)(\rho(pN) + i)}{\hbar c}\sigma_{tot}(pN) e^{-\frac{B(pN)}{2}t} \right|^2$$

$$\phi = \alpha Z_1 Z_2 \left[\ln\left(\frac{A^2}{b^2}\right) + Ei(z) - Ei(w) + e^{2\omega}\left(2E_1(2\omega) - E_1(\omega)\right) \right]$$

Fit Results

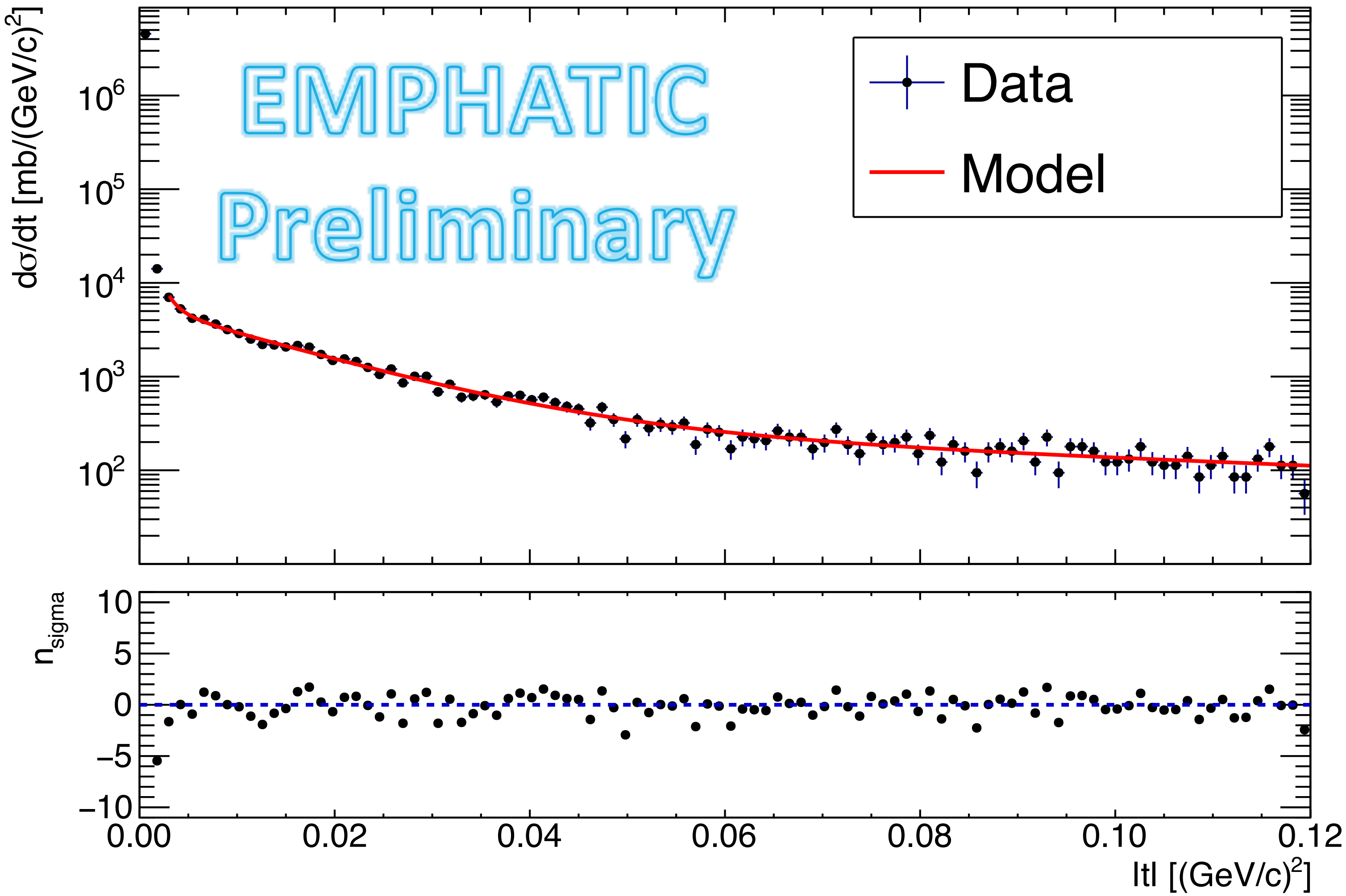
EMPHATIC Fit Results:

- $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$
  - 261.3 ± 1.3 mb
- $\sigma_{prod} = \sigma_{tot} - \sigma_{el} - \sigma_{qe}$
  - 226.1 ± 3.7mb

NA61/SHINE Results*:

- $\sigma_{inel} = 258.4 \pm^{5.9}_{4.2}$ mb
- $\sigma_{prod} = 230.7 \pm^{7.0}_{4.6}$ mb

EMPHATIC preliminary results agree with NA61/SHINE

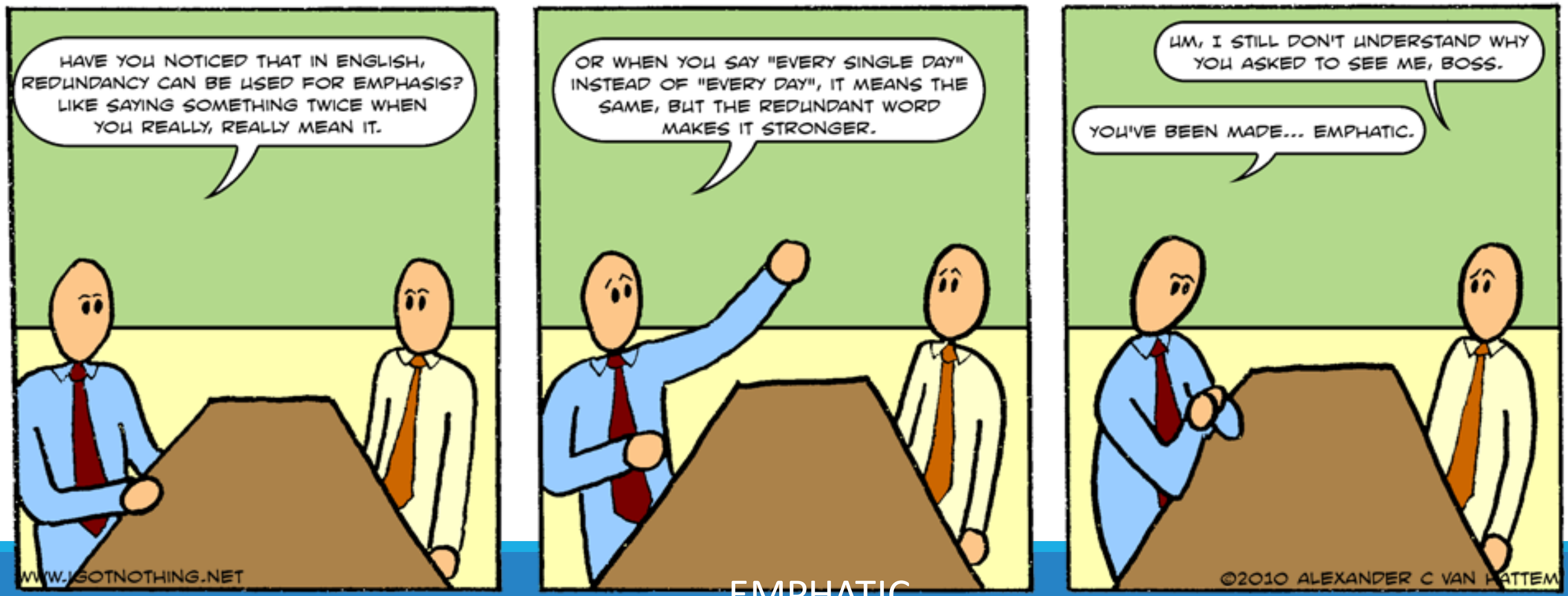


*https://arxiv.org/abs/1510.02703

Summary

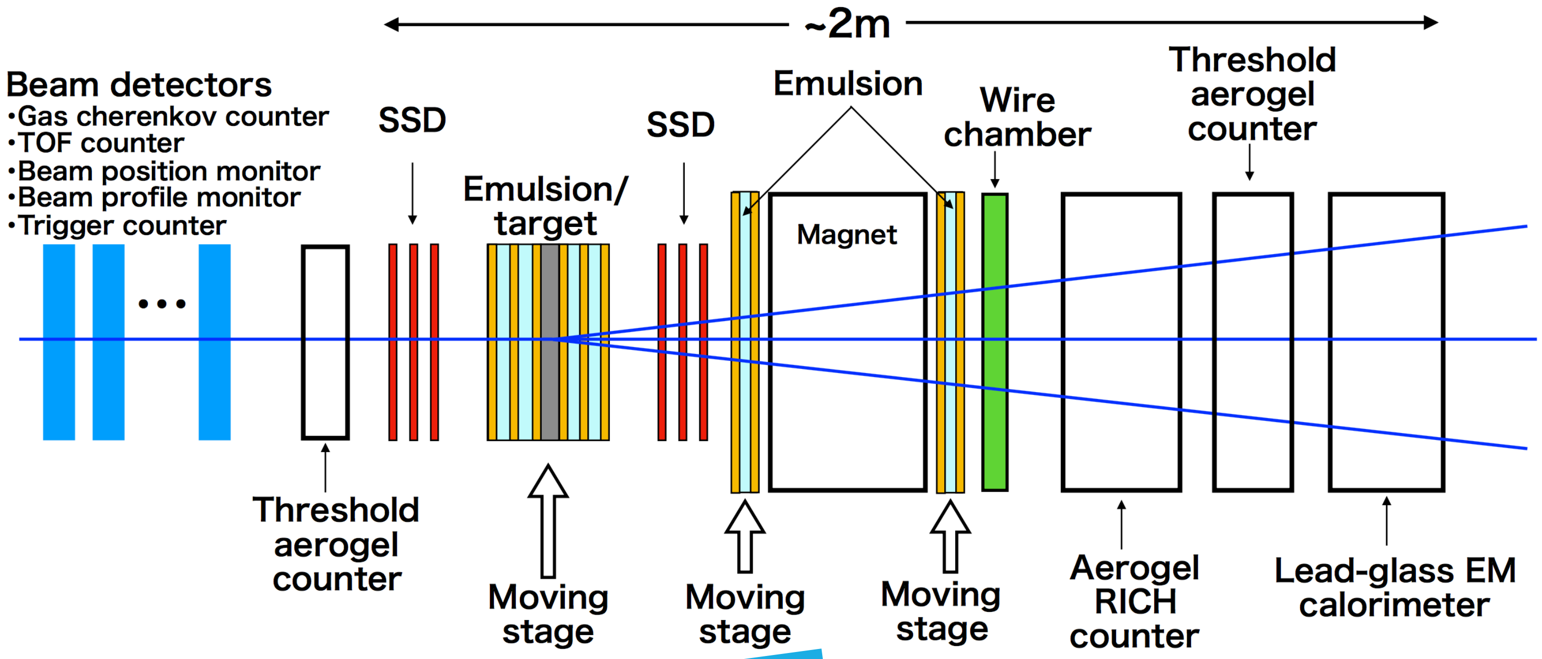
- T2K requires a reduction in its neutrino flux prediction uncertainty
- To do this a few things need to be accounted for:
  - Production cross section uncertainty
  - Untuned secondary interaction
  - NA61/SHINE thin and replica target discrepancy

- The EMPHATIC group has proven it has the potential to help with these discrepancies:
  - Silicon strip measurements of p+C presented and agree with NA61/SHINE measurement
  - Model dependence still a concern
  - A lot of potential in these measurements!

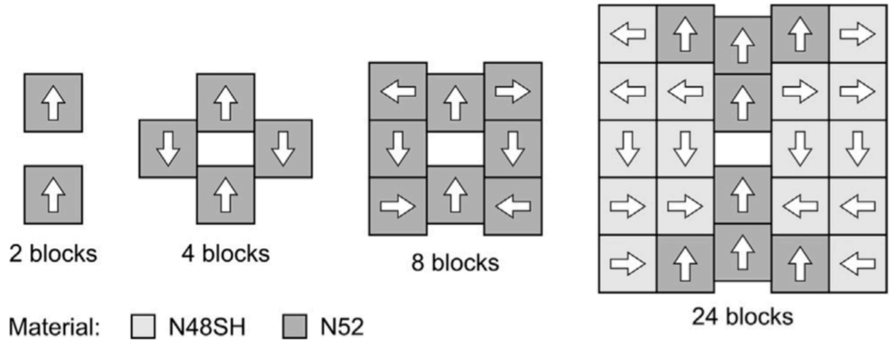


BACKUP

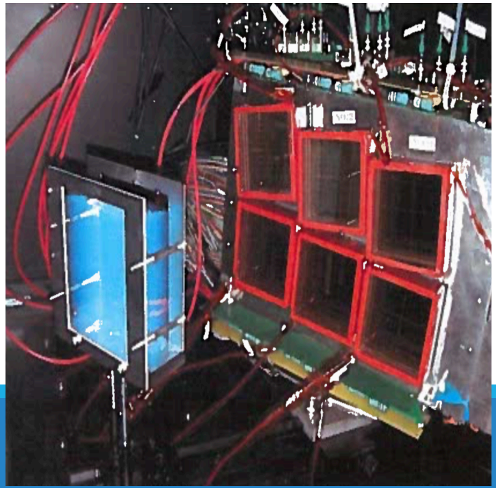
Future Work



Spectrometer made of
Halbach Array of Permanent Magnets



RICH Counter



Model Fit of 4 –momentum Transfer

Preliminary Model fit

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left| -8\frac{\pi\alpha Z\hbar c}{t} e^{-\frac{a^2 t}{4}} e^{-i\phi} + \frac{(\rho+i)\sigma_{tot}}{\hbar c} e^{-\frac{Bt}{2}} + \frac{N(A)(\rho(pN)+i)}{\hbar c}\sigma_{tot}(pN) e^{-\frac{B(pN)}{2}t} \right|^2$$

Coulomb Phase; Total Cross-section; Total Proton-Nucleon Cross-section; Coulomb Form Factor; Real part of the amplitude; Elastic Nuclear Slope; Nuclear Transparency X Atomic Mass; Inelastic Scatter Slope

- Regions to fit:
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  - Quasi-elastic Interaction
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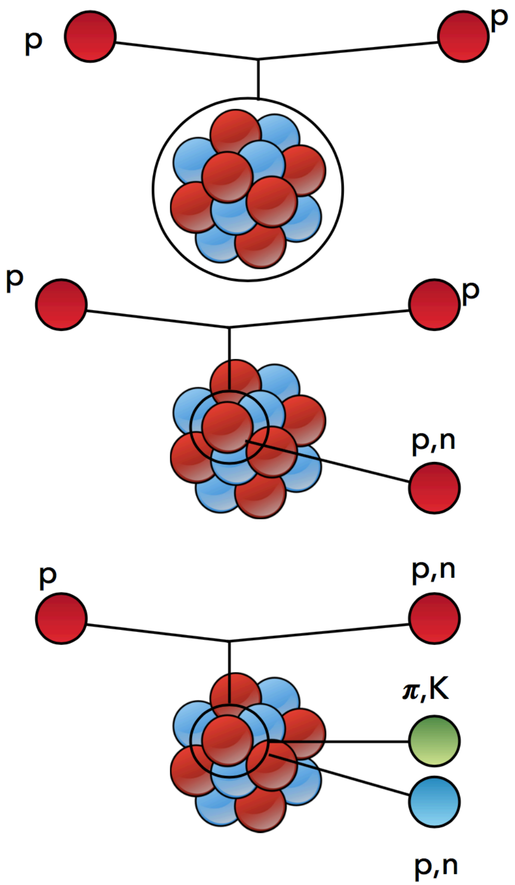
Scattering



Coherent elastic scattering on the nucleus

~20% of the hadronic cross section (at 30 GeV)

Small momentum transfer

Quasi-elastic scattering on bound nucleons

Kinematic properties similar to proton-nucleon elastic scattering

~10% of the hadronic cross section

Scattering with particle production (small contribution from coherent scattering on nucleus)

~70% of the hadronic cross section

Important for neutrino flux estimation

Measurements performed in Fermilab Test Beam Facility (Jan 2018)

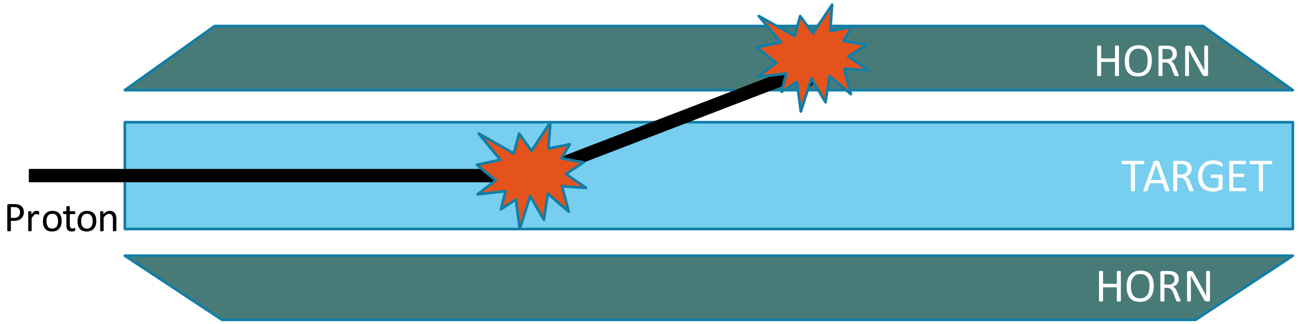
Events Measured

	Graphite	Aluminum	Iron	Empty
120 GeV	1.63M	0	0	1.21M
30 GeV/c	3.42M	976k	1.01M	2.56M
-30 GeV/c	313k	308k	128k	312k
20 GeV/c	1.76M	1.76M	1.72M	1.61M
10 GeV/c	1.18M	1.11M	967k	1.17M
2 GeV	105k	105k	183k	108k

Secondary Interactions

- Secondary interactions are tuned by external data (HARP) which are dominated by particle re-interactions in the TPC
- Also HARP data is limited by the coverage, does not go below $\theta < 0.07$
- Future experiments should focus on reducing material around the target

Error Category	$\delta^{\pi}_{\text{diff}}$ (%)	$\delta^{\pi}_{\text{int}}$ (%)
Track yield corrections:		
Reconstruction efficiency	1.1	0.5
Pion, proton absorption	3.7	3.2
Tertiary subtraction	8.6	3.7
Empty target subtraction	1.2	1.2
Sub-total	**9.5**	**5.1**



Secondary Interaction outside the target