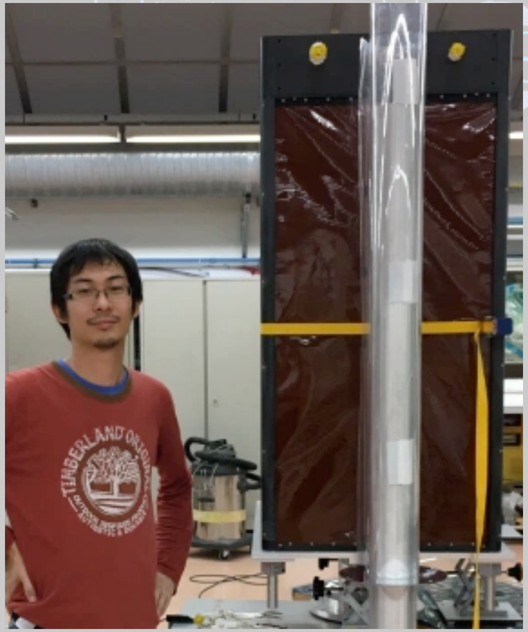
Cross Section Measurements with Hadron Beams on Thin Targets



Yoshikazu Nagai

University of Colorado Boulder

Oct 27, 2020, NA61 Autumn School @ Zoom

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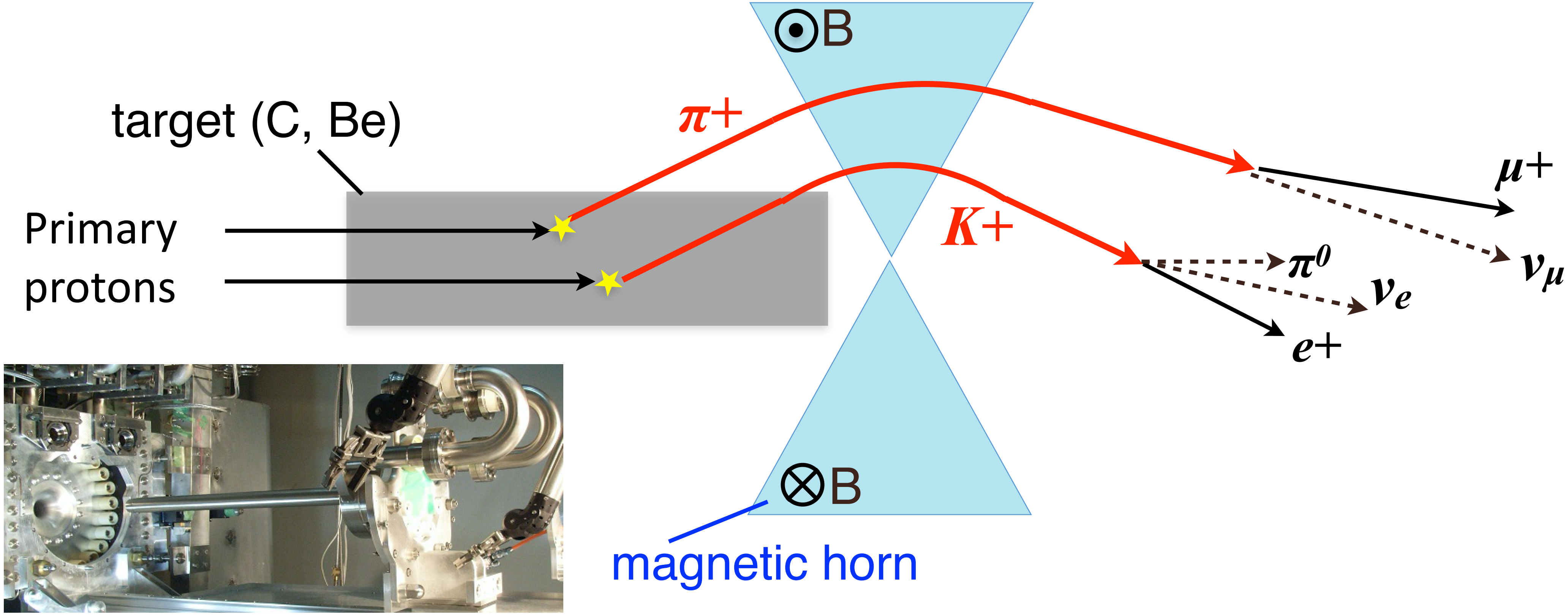
Introduction

Reminder: How to Make a Neutrino Beam

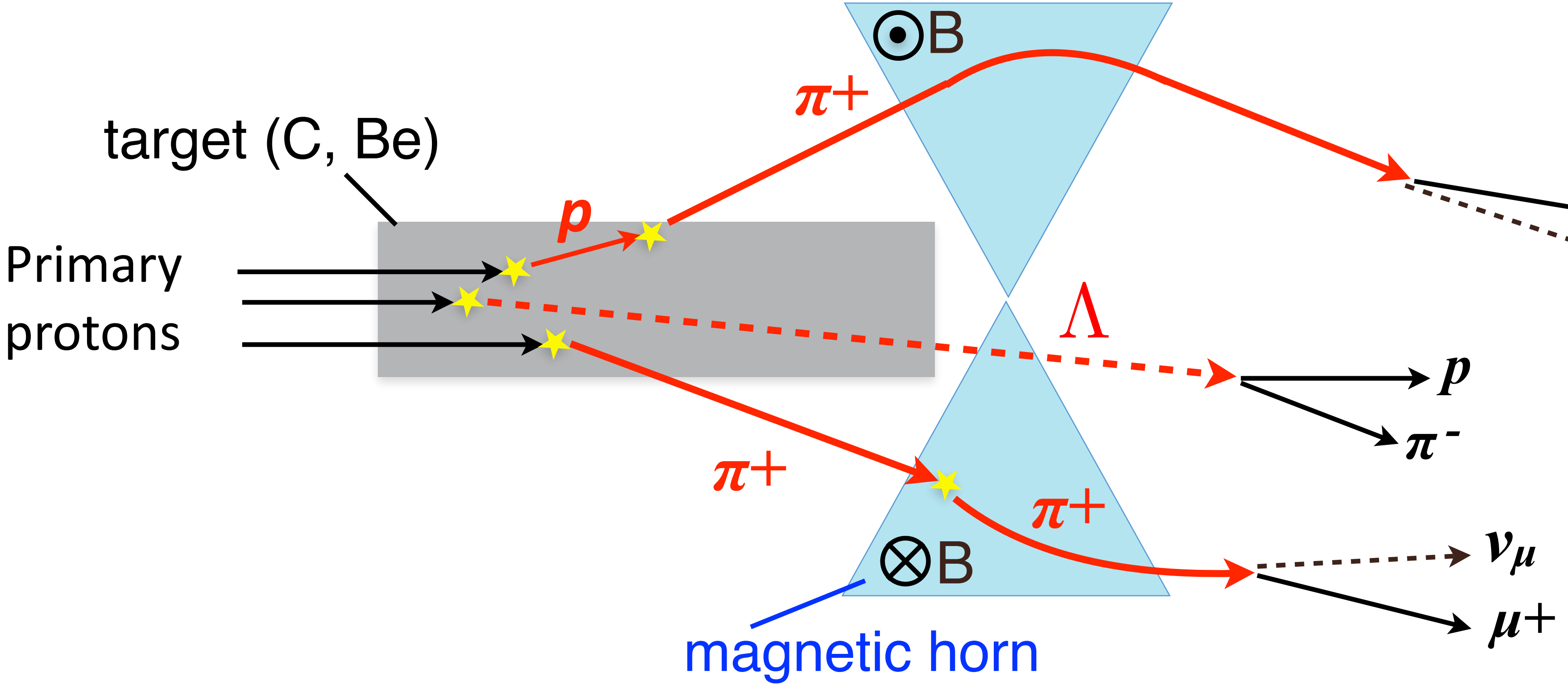


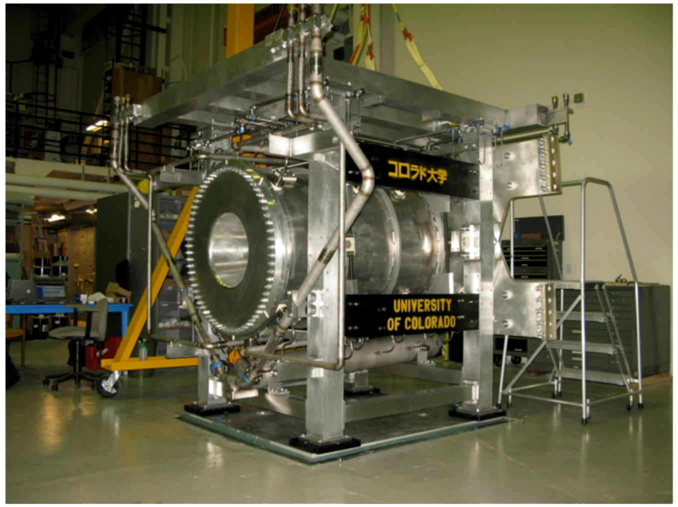
T2K target

Hadron productions of $\pi^{\pm}$ and $K^{\pm}$ through primary interactions in the target (p + C, p + Be)

—> Primary contribution to the neutrino flux

Reminder: How to Make a Neutrino Beam





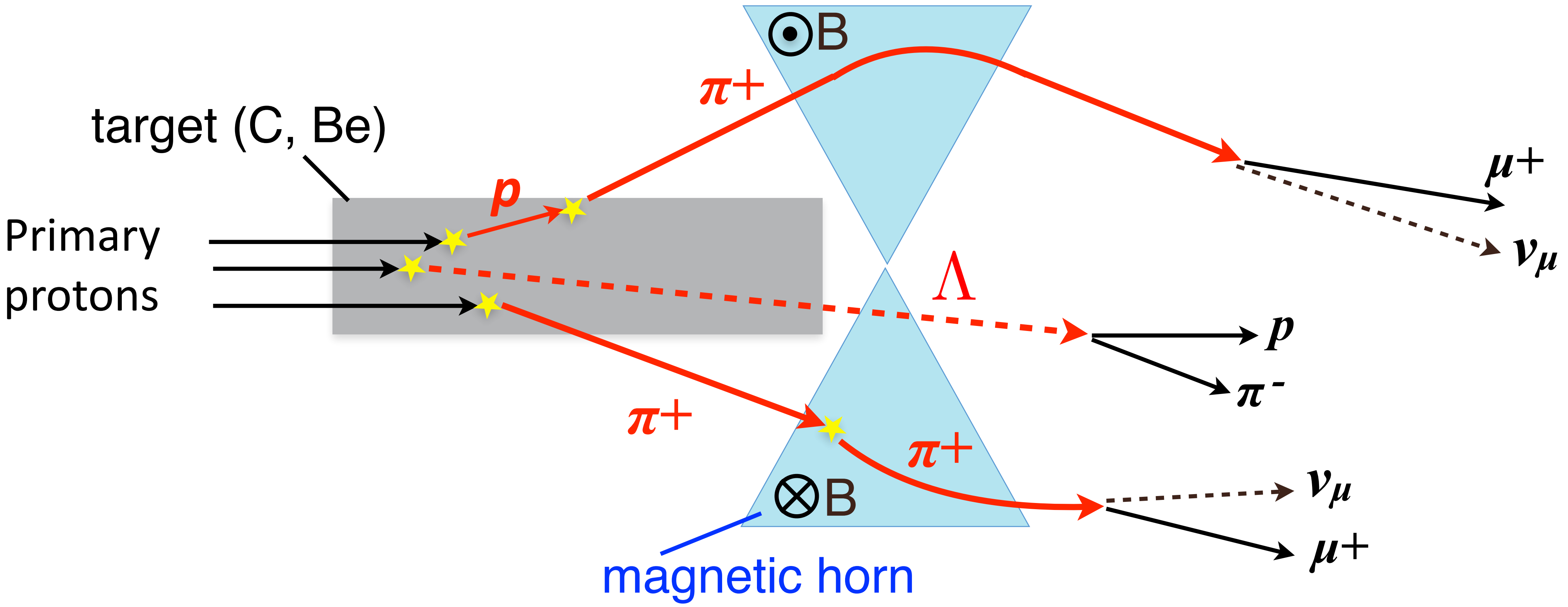
T2K magnetic horn

Hadron production process can be more complex:

- Secondary interactions in the target (hadrons + C/Be)
- Secondary interactions with horn or beamline materials (hadrons + X)
- Neutral hadron decay (p + C / Be —> V^0 + X)

—>Non-negligible contribution to the neutrino flux

Reminder: How to Make a Neutrino Beam



We want to precisely understand these hadron production and interactions

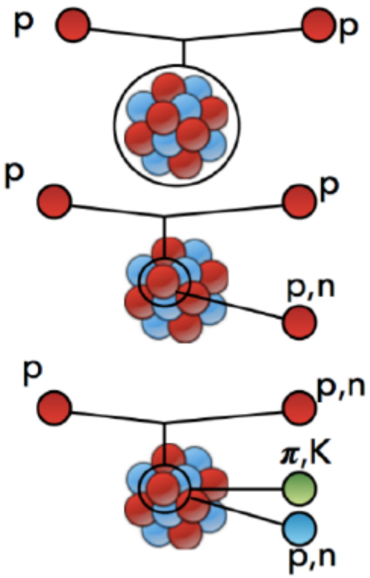
= Hadron production "cross section"

—> Essential input for ν flux prediction

(good flux knowledge is crucial for accelerator-based ν experiment)

Cross Section? What do we measure?

1. Total production and inelastic cross sections



Coherent elastic process:
interaction on the nucleus
σ_{el}

Quasi-elastic process:
interaction on bound nucleons
σ_{qe}

Production process:
interaction with new hadron production
σ_{prod}

σ_{qe}, σ_{prod} → σ_{inel}

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

$$\sigma_{\mathrm{inelastic}} = \sigma_{\mathrm{quasi-elastic}} + \sigma_{\mathrm{production}}$$

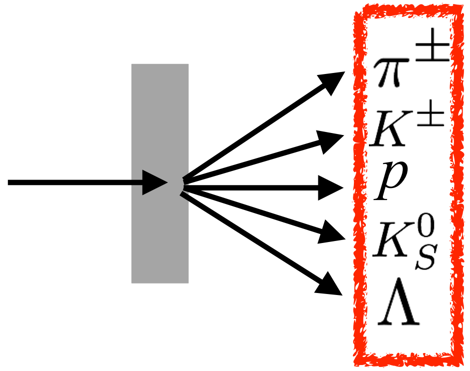
Use this definition through the talk

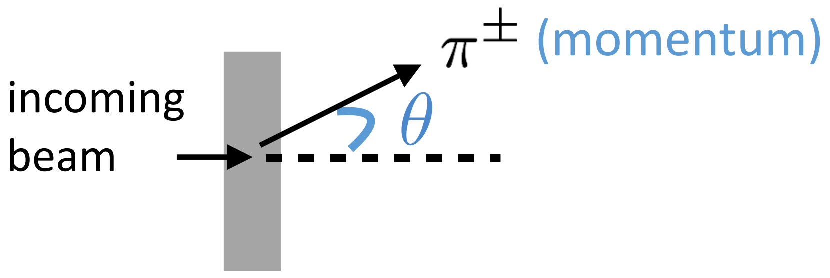
- Not all experiments use the same definition for the production cross section (See backup slides for more detail)

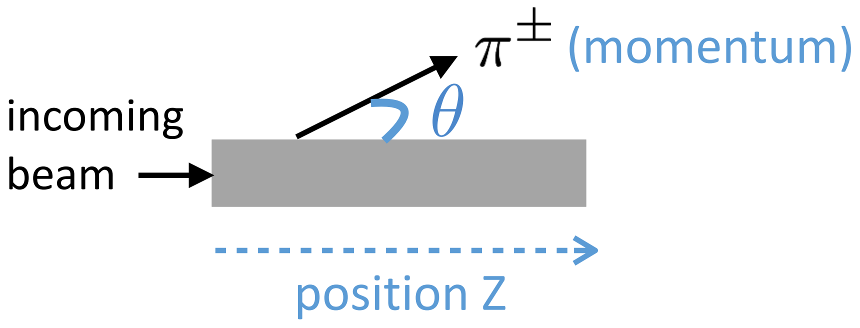
Cross Section? What do we measure?

2. Differential hadron yields (or differential cross section)

= Hadron production cross section per hadron species and phase-space







$$\frac{d^2n}{dpd\theta} = N(p,\theta), \quad \frac{d^2\sigma}{dpd\theta}$$

$$\frac{d^3n}{dpd\theta dz} = N(p,\theta,z)$$

- Experimentally, we measure differential yields ($\frac{d^2n}{dpd\theta}$), then relate it to differential cross section ($\frac{d^2\sigma}{dpd\theta}$) using measured total production cross section

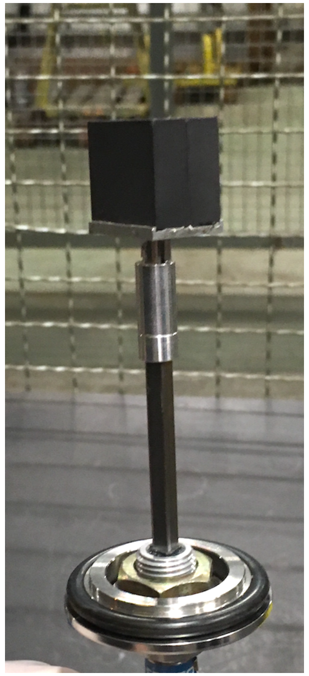
$$\frac{d^2\sigma}{dpd\theta} = \sigma_{\mathrm{prod}} \frac{d^2n}{dpd\theta}$$

Reminder: Strategy of Measurements in NA61/SHINE

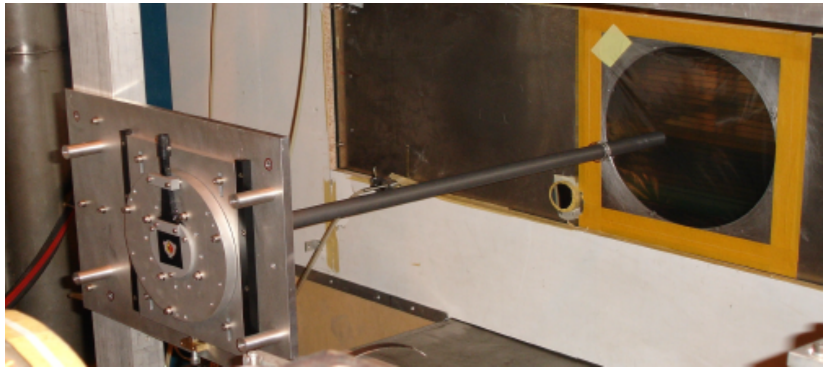
- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Total cross sections (inelastic and production cross sections) (I'll mainly talk about this!)
  - Measurement of differential yields (will hear in Brant's talk)
- Replica (thick) target: same geometry and material as real neutrino beamline
  - Measurement of differential production yields
  - Measurement of beam survival probability

(will hear in Simona's talk)

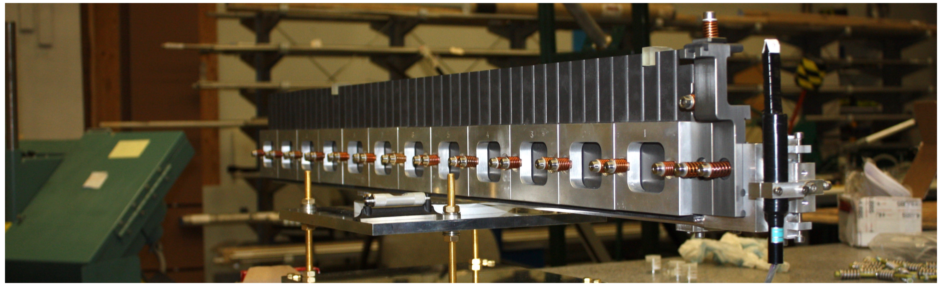
Thin graphite target (1.5 cm, 3.1% of λ)



T2K replica graphite target (90 cm, 1.9 λ)



NuMI replica graphite target (120 cm, 2.5 λ)

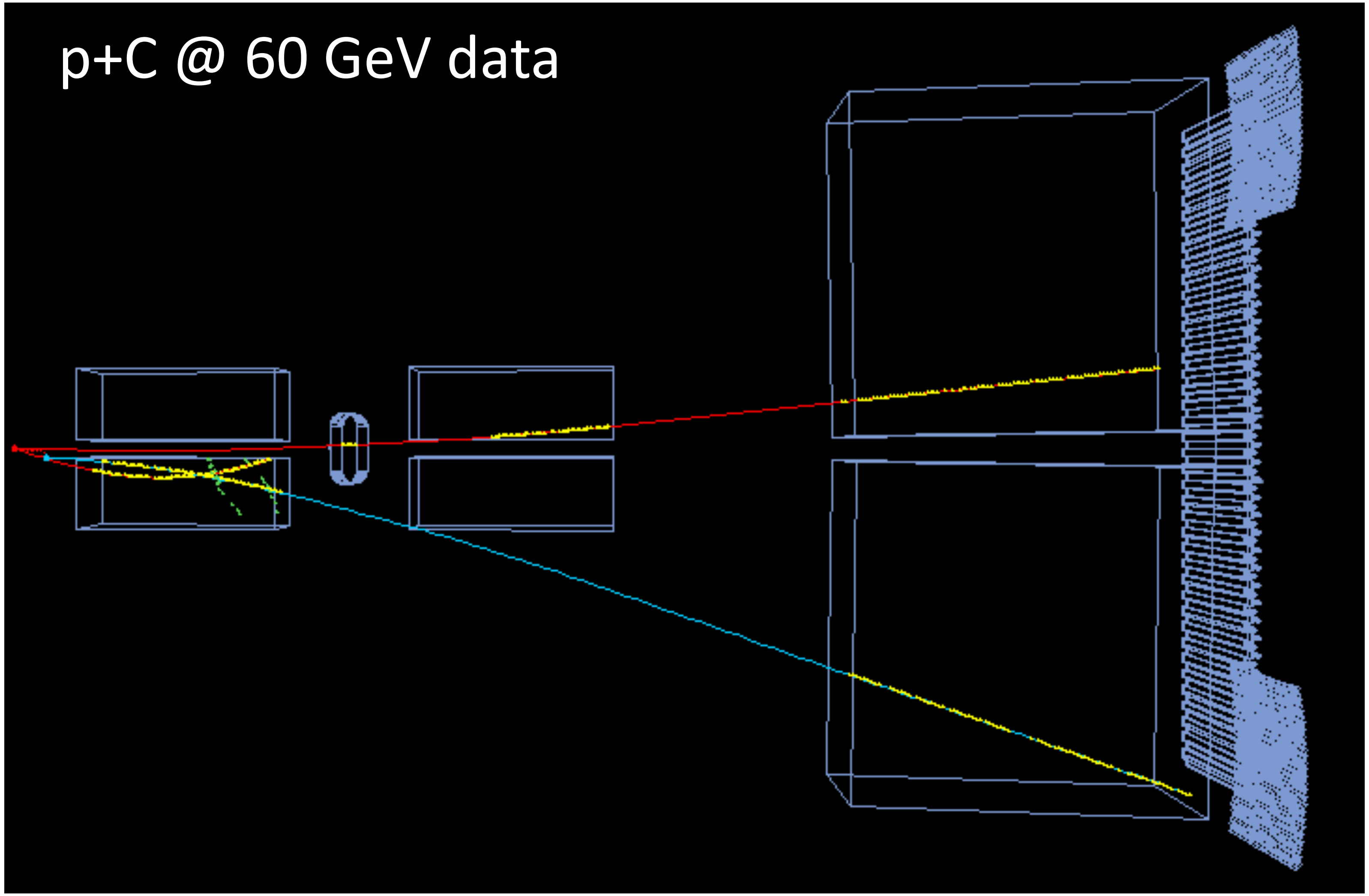


Total Cross Section Measurement

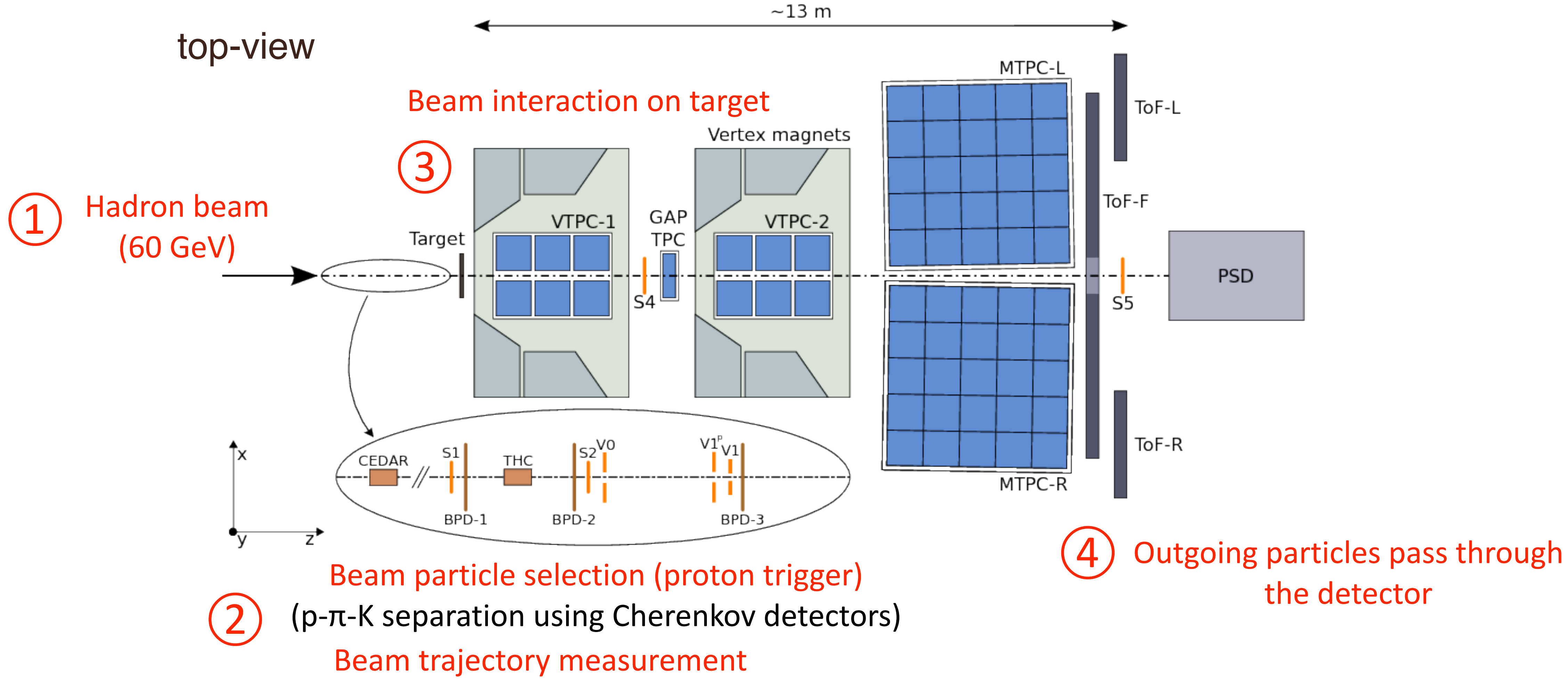
I use p+C@60 GeV data analysis as an example for the following discussion

- Result is published already: Phys. Rev. D100, 112001 (2019) (open access)

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.100.112001



Experimental Setup for p+C@60 GeV

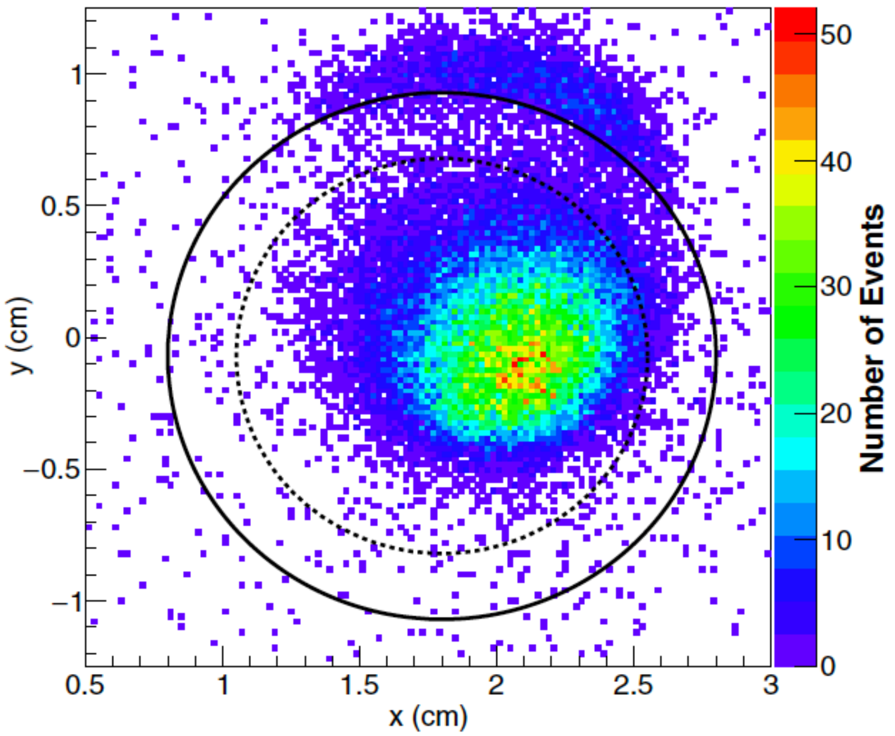


beam trigger: $T_{\text{beam}} = S1 \wedge S2 \wedge \overline{V0} \wedge \overline{V1} \wedge CEDAR$

interaction trigger: $T_{\text{int}} = T_{\text{beam}} \wedge \overline{S4}$

Event Selection

- Minimal selection
  - WFA (wave form analyzer) cut = timing window cut
    —> reject if another beam particle pass the beamline close in time (+/- 2μs)
  - good BPD cut = beam trajectory reconstruction quality cut
  - Radial cut = Kill beam halos which miss trigger counter S4 (mimicking T_{int})



Beam trajectory at the S4 trigger counter position

interaction trigger: $T_{int} = T_{beam} \wedge \overline{S4}$

Total Cross Section Measurement

- The probability of a beam particle interaction inside a thin target is proportional to thickness L, and number density of the target nuclei n
- The interaction probability can be defined in terms of the interaction cross section

$$P_{\text{int}} = \frac{\text{Number of events}}{\text{Number of beam particles}} = n \cdot L \cdot \sigma \quad ①$$

- The counts of beam and interaction triggers (T_{beam}, T_{int}) can be used to estimate the trigger probability in experiment

$$P_{\text{int}}^{\text{trig}} = \frac{N(T_{\text{beam}} \wedge T_{\text{int}})}{N(T_{\text{beam}})} \quad ②$$

(*N* stands for number of events passing each trigger requirement)

- From ① and ②, "trigger" cross section can be written as

$$\sigma_{\text{trig}} = -\frac{m_A}{\rho L N_A} \ln(1 - P_{\text{int}}) \quad ③$$

(N_A: Avogadro's number,
ρ: material density,
m_A: atomic mass)

For detailed calculation, check
Phys. Rev. D98, 052001 (2018)

Total Cross Section Measurement

- Next step is to relate $\sigma_{\rm prod}$ and $\sigma_{\rm inel}$ to measured $\sigma_{\rm trig}$
  —> $\sigma_{\rm trig}$ includes contributions from elastic, quasi-elastic, and production (or inelastic) with some fraction

$$\sigma_{\rm trig} = \sigma_{\rm el} \cdot f_{\rm el} + \sigma_{\rm qe} \cdot f_{\rm qe} + \sigma_{\rm prod} \cdot f_{\rm prod}$$

These are what we want to measure

$$\sigma_{\rm trig} = \sigma_{\rm el} \cdot f_{\rm el} + \sigma_{\rm inel} \cdot f_{\rm inel}$$

Reminder: cross section definition

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

$$\sigma_{\rm inelastic} = \sigma_{\rm quasi-elastic} + \sigma_{\rm production}$$

- We need to know —> We estimate them using Monte Carlo simulation (MC)

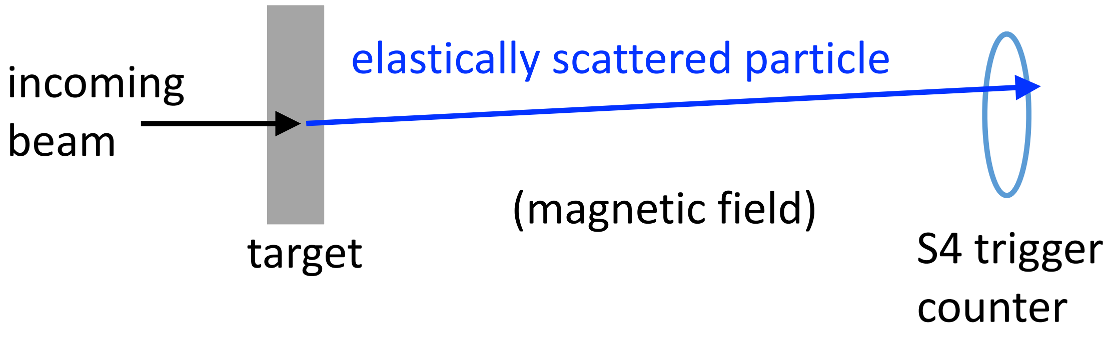
$f_{\rm el,\, qe,\, prod,\, inel}$: fraction of events missing S4 trigger counter

$\sigma_{\rm el,\, qe}$: elastic and quasi-elastic cross sections

(S4 trigger MC correction factors)

S4 trigger MC correction factors

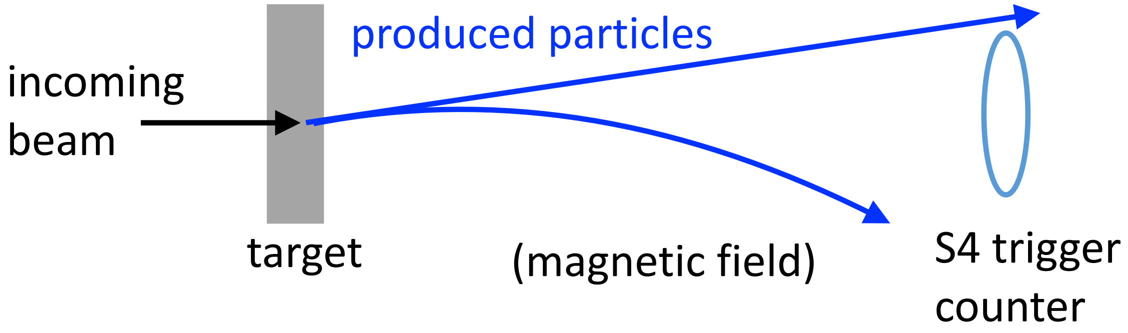
- Elastic scattering events —> likely forward direction, small chance to be triggered



<u>Reminder: interaction trigger</u>

interaction trigger: $T_{int} = T_{beam} \wedge \overline{S4}$

- Production events —> likely large angle production and lower momentum, high chance to be triggered



Estimated MC correction factors for p+C@60 GeV analysis

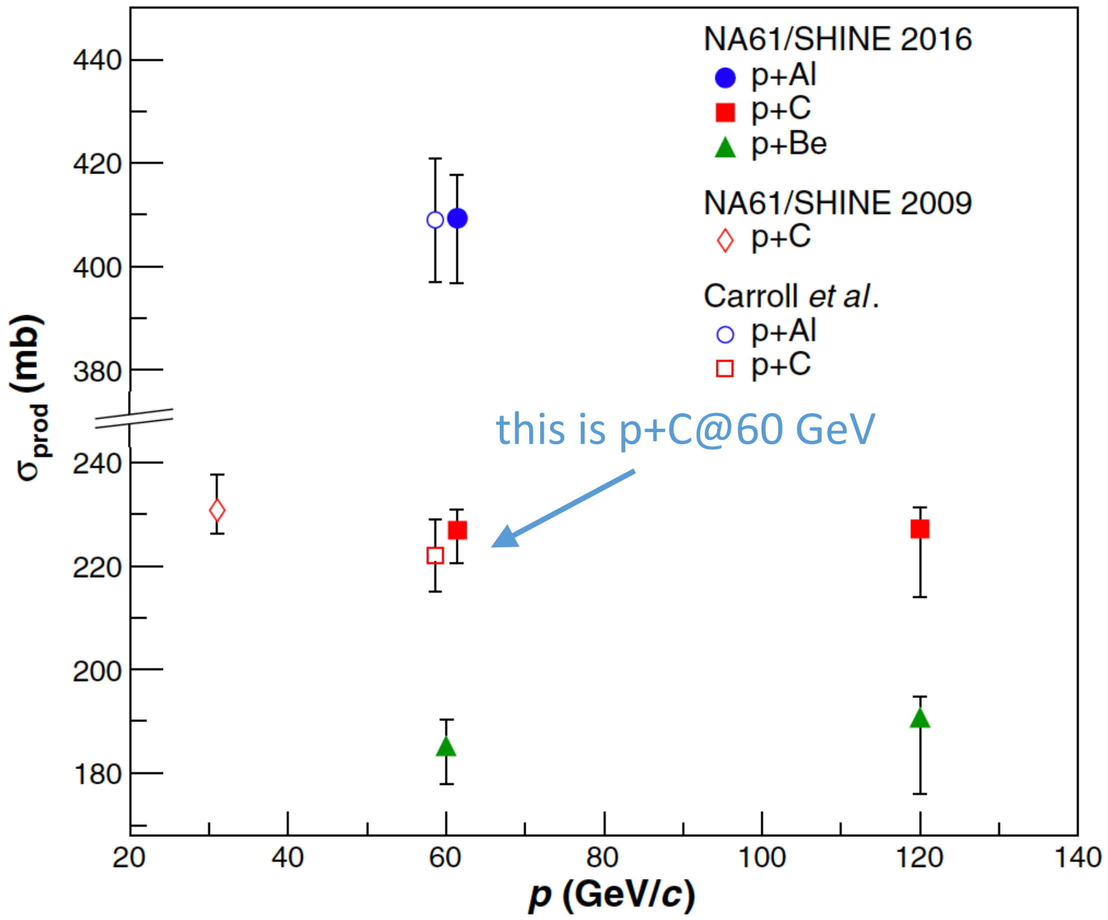
		MC correction factors (nominal)					
Interaction	p (GeV/c)	σ_{el} (mb)	f_{el}	σ_{qe} (mb)	f_{qe}	f_{prod}	f_{inel}
p + C	60	66.6	0.308	25.4	0.788	0.973	0.954

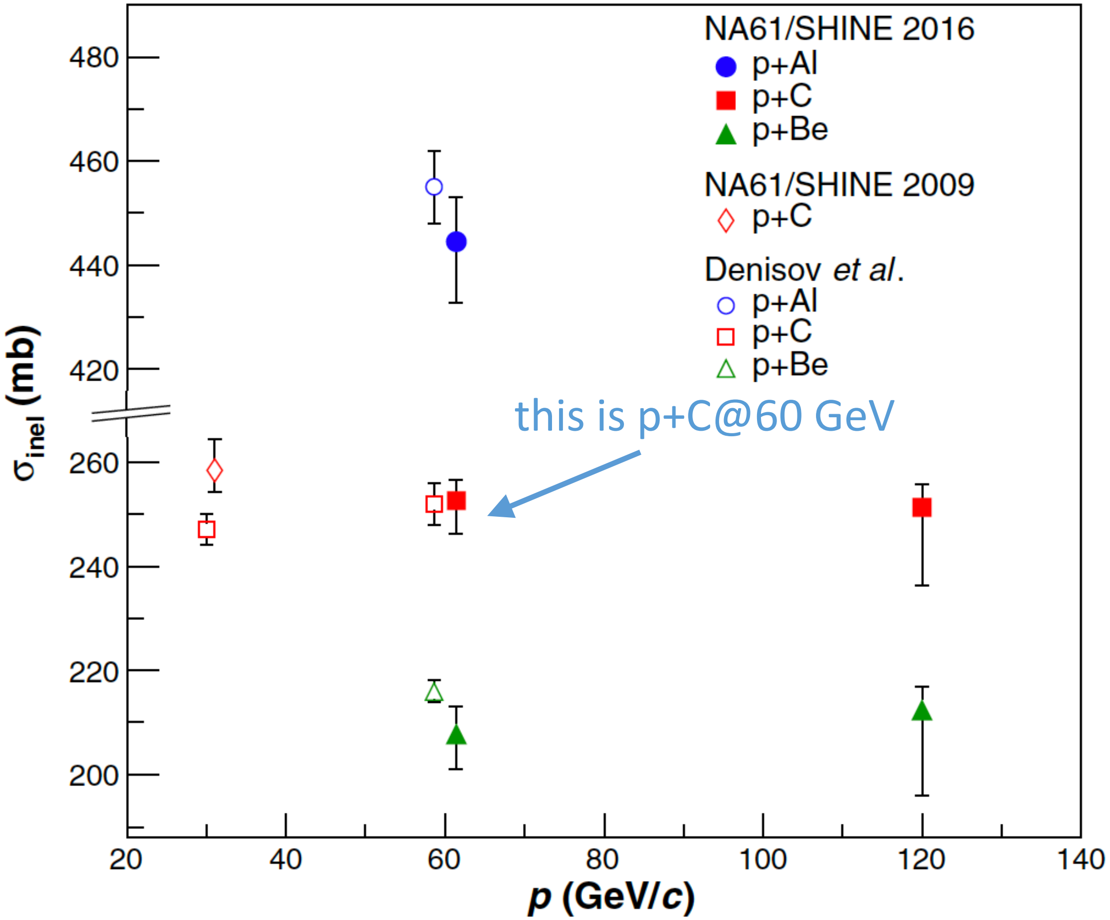
For p+C@60 GeV analysis, we used Geant4 physics models to estimate MC correction factors (FTFP_BERT, QGSP_BERT, QBBC, FTF_BIC)

Results

$$\sigma_{\text{prod}} = \frac{1}{f_{\text{prod}}}\left(\sigma_{\text{trig}} - \sigma_{\text{qe}} \cdot f_{\text{qe}} - \sigma_{\text{el}} \cdot f_{\text{el}}\right)$$

$$\sigma_{\text{inel}} = \frac{1}{f_{\text{inel}}}\left(\sigma_{\text{trig}} - \sigma_{\text{el}} \cdot f_{\text{el}}\right)$$





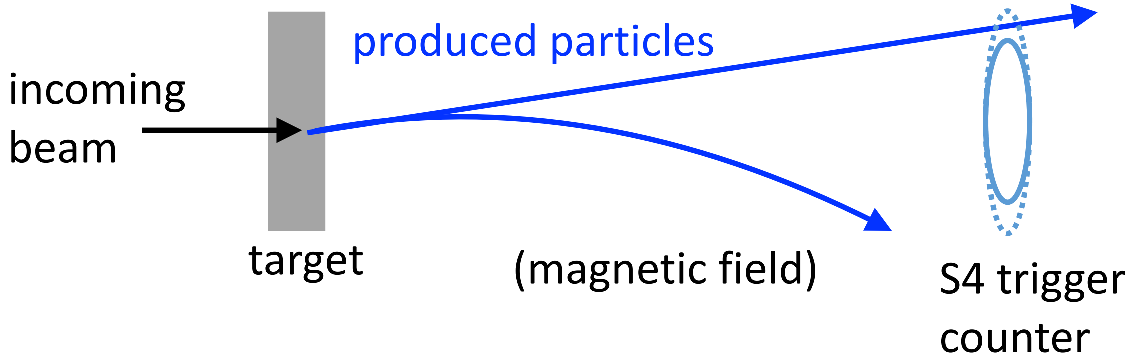
Phys. Rev. D100, 112001 (2019)

Systematic Uncertainty

- Target density: it changes the cross section value

$$\sigma_{\text{trig}} = -\frac{m_A}{\rho L N_{\text{A}}} \ln(1 - P_{\text{int}})$$

- S4 size and position: it change value of S4 MC correction factors



- Physics model uncertainties: we rely on model predictions for MC correction, but different physics model can have different predictions

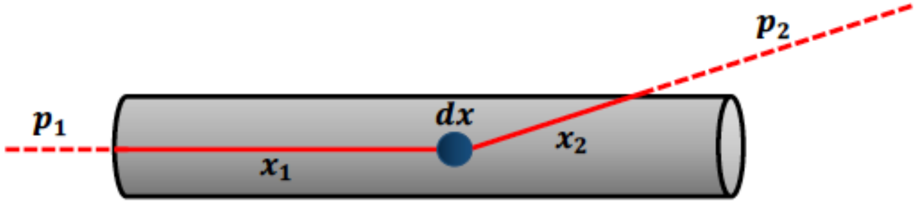
		Production cross section (mb)					
Interaction	p (GeV/c)	σ_{prod}	Δ_{stat}	Δ_{syst}	Δ_{model}	Δ_{total}	$\frac{\sigma_{\text{prod}}}{\sigma_{\text{G4}}}$
p + C	60	226.9	± 3.1	$\pm^{2.6}_{2.9}$	$\pm^{0.2}_{4.8}$	$\pm^{4.1}_{6.4}$	1.05

		Inelastic cross section (mb)					
Interaction	p (GeV/c)	σ_{inel}	Δ_{stat}	Δ_{syst}	Δ_{model}	Δ_{total}	$\frac{\sigma_{\text{inel}}}{\sigma_{\text{G4}}}$
p + C	60	252.6	± 3.2	$\pm^{2.5}_{2.9}$	$\pm^{0.0}_{4.8}$	$\pm^{4.1}_{6.5}$	1.05

How to Use NA61 data (briefly)

Application of Thin Target Measurements

in real neutrino target



—> Thin target results are used to correct hadron interaction length (probability of interaction)

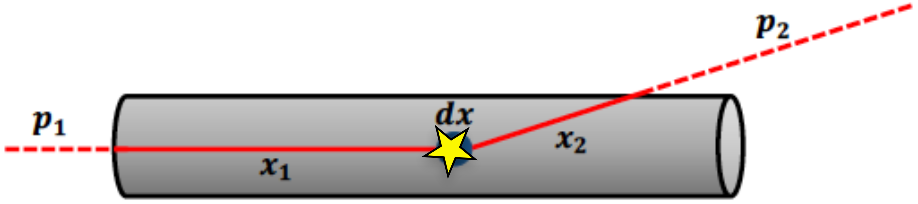
$$W(p_1, p_2, x_1, x_2) = \frac{[P_{\text{interaction}} \cdot P_{\text{escape}}]_{\text{data}}}{[P_{\text{interaction}} \cdot P_{\text{escape}}]_{\text{MC}}}$$

$$= \frac{\sigma_{\text{data}}(p_1)}{\sigma_{\text{MC}}(p_1)} \cdot e^{-x_1[\sigma_{\text{data}}(p_1) - \sigma_{\text{MC}}(p_1)]\rho} \cdot e^{-x_2[\sigma_{\text{data}}(p_2) - \sigma_{\text{MC}}(p_2)]\rho}$$

(Application of total production cross section measurements)

Application of Thin Target Measurements

in real neutrino target



More detail on differential production yield results: Brant's next talk.
(not covered by my talk)

We measure differential production yields ($\frac{d^2n}{dpd\theta} = N(p,\theta)$)

(yield of particles per interaction, momentum, radian)

—> Results are used to calculate weights for each interactions (☆) to correct neutrino flux predictions

$$W(p,\theta) = \frac{N(p,\theta)_{\text{Data}}}{N(p,\theta)_{\text{MC}}}$$

(Application of differential production yields)

Thank you for your attention!

NA61/SHINE Collaboration

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
  - University of Warsaw, Warsaw
  - WUT, Warsaw
  - Jagiellonian University, Kraków
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscov
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

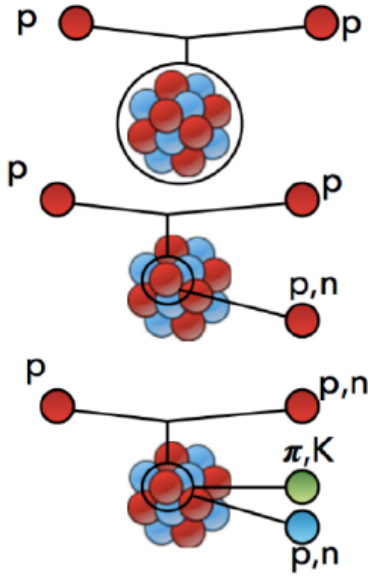
∼150 physicists from ∼30 institutes

http://shine.web.cern.ch

Backup

Note: Notation of Production Cross Section

- Not all experiments use the same definition for the production cross section



Coherent elastic process:
interaction on the nucleus —> σ_{el}

Quasi-elastic process:
interaction on bound nucleons —> σ_{qe}

Production process:
interaction with new hadron production
—> σ_{prod}

—> σ_{inel}

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$$
$$\sigma_{\mathrm{prod}} = \sigma_{\mathrm{inel}} - \sigma_{\mathrm{qe}}$$

<u>Use this definition through the talk</u>
(T2K uses this definition)

- NuMI flux tuning definition: $\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$ —> σ_{prod} in our definition
  $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$ —> σ_{inel} in our definition

- Earlier experiments: mixed up inelastic and production cross sections

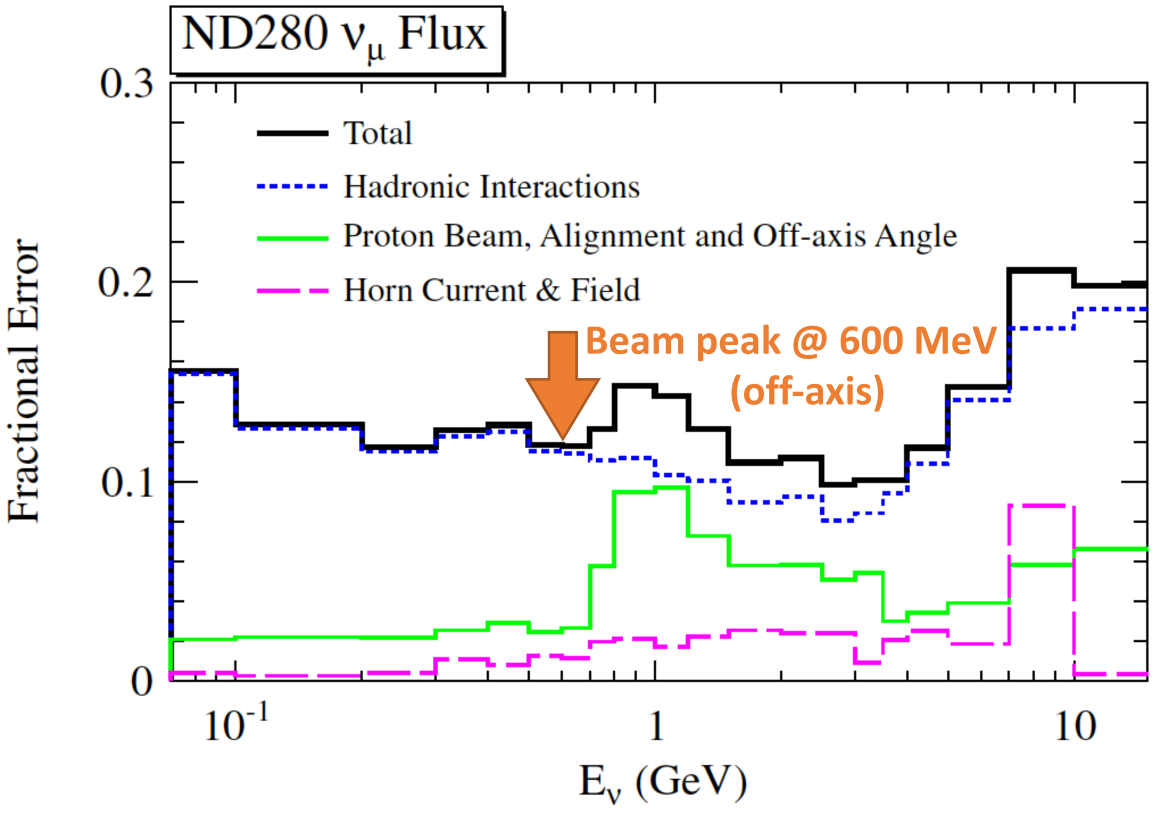
  e.g. Denisov, et. al (1973): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$ —> σ_{inel} in our definition

  e.g. Carroll, et. al (1979): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$ —> σ_{prod} in our definition

Why Hadron Production Measurements?

Hadron Production is the leading uncertainty source of flux predictions

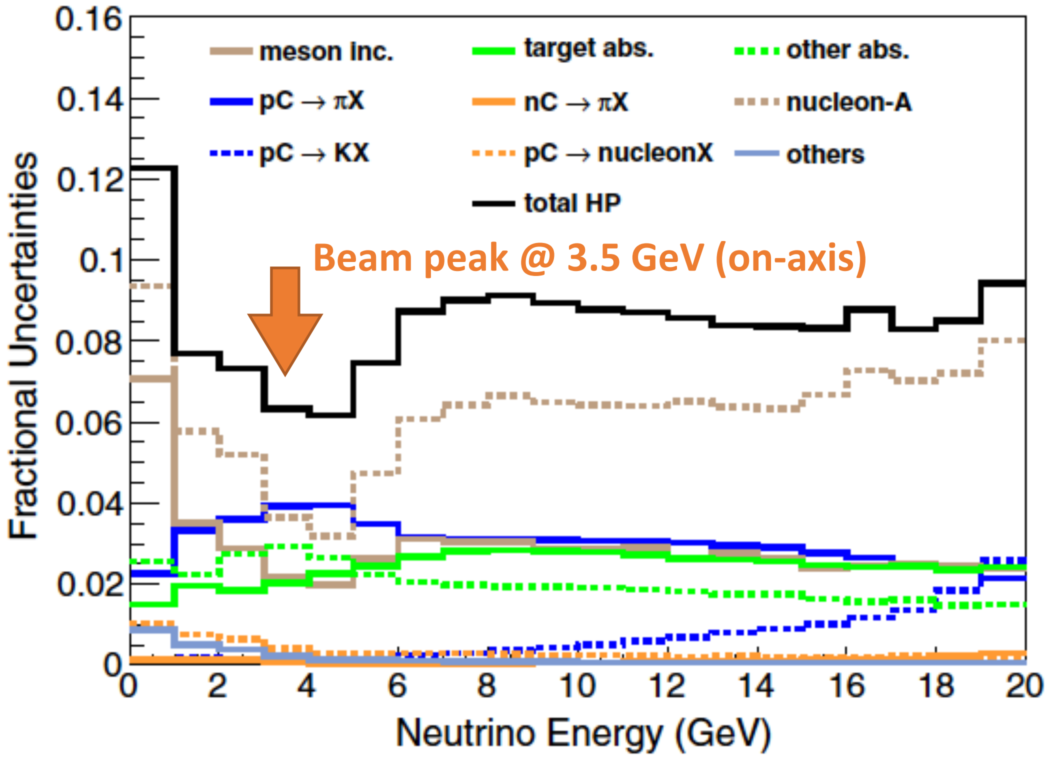
J-PARC beamline (T2K flux)



T2K: Phys. Rev. D87, 012001 (2013)

NuMI beamline (MINERvA flux)

(low energy configuration)



MINERvA: Phys. Rev. D94, 092005 (2016)

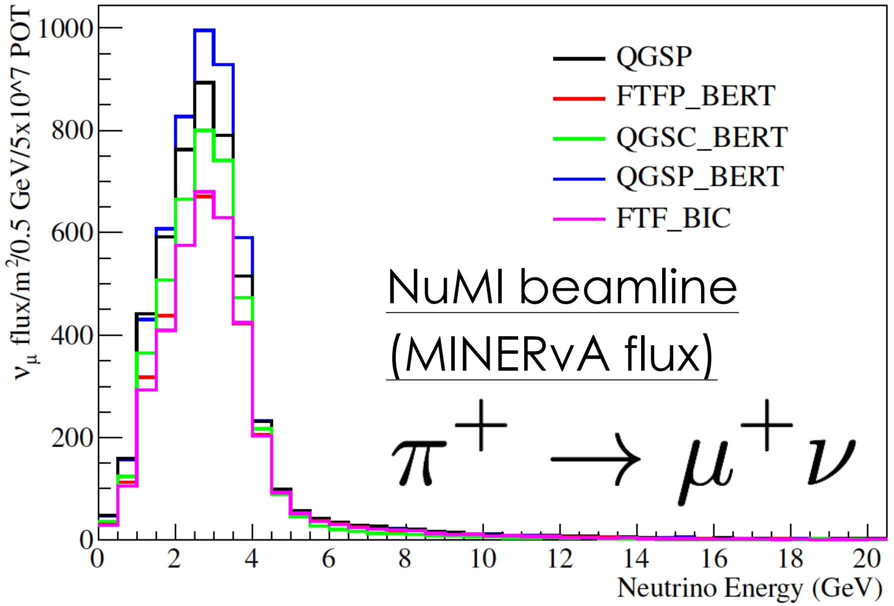
(only hadron production-relating errors)

Why Hadron Production Measurements?

- We rely on hadronic interaction models for the neutrino flux predictions
  - FLUKA (J-PARC/T2K), Geant4 FTFP_BERT (NuMI experiments)

However, hadron production prediction is difficult…

e.g. Five interaction models in Geant 4
—> variations neutrino flux prediction
~40% at the focusing peak



Leonidas Aliaga (Ph.D Thesis, 2016)

Need to constrain neutrino flux uncertainty coming from hadron production

⇨ Hadron production measurements with NA61/SHINE

The NA61/SHINE Experiment

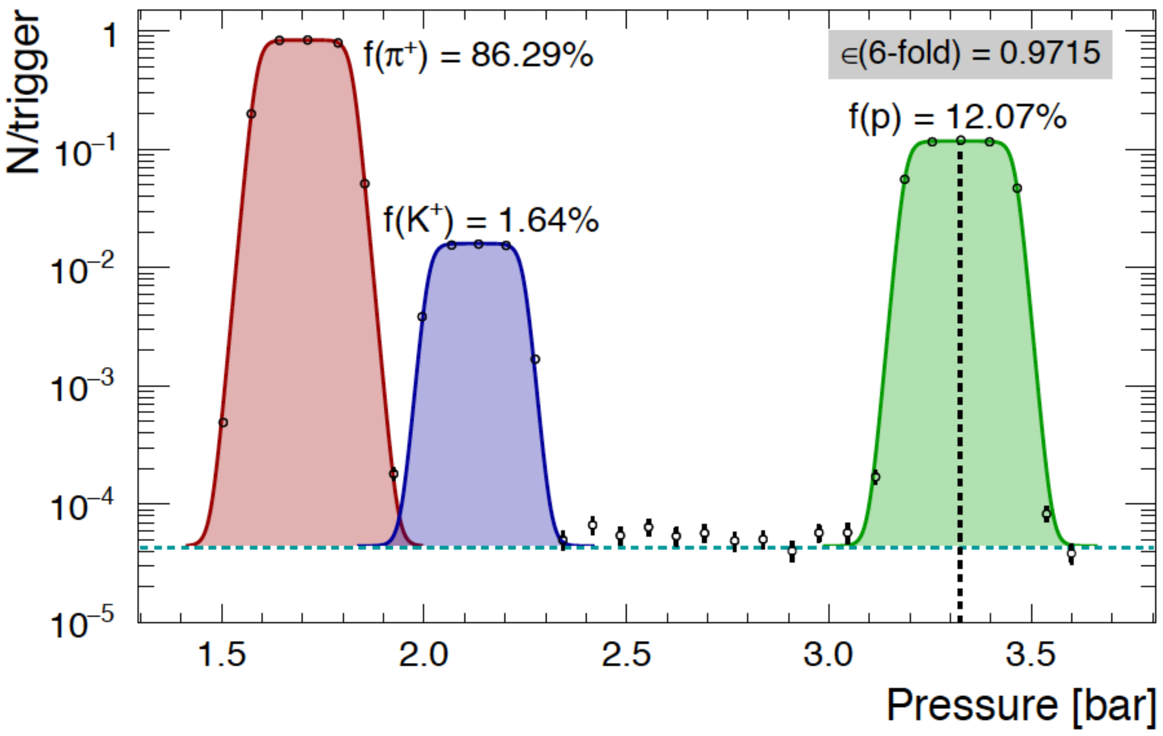
"The SPS Heavy Ion and Neutrino Experiment"

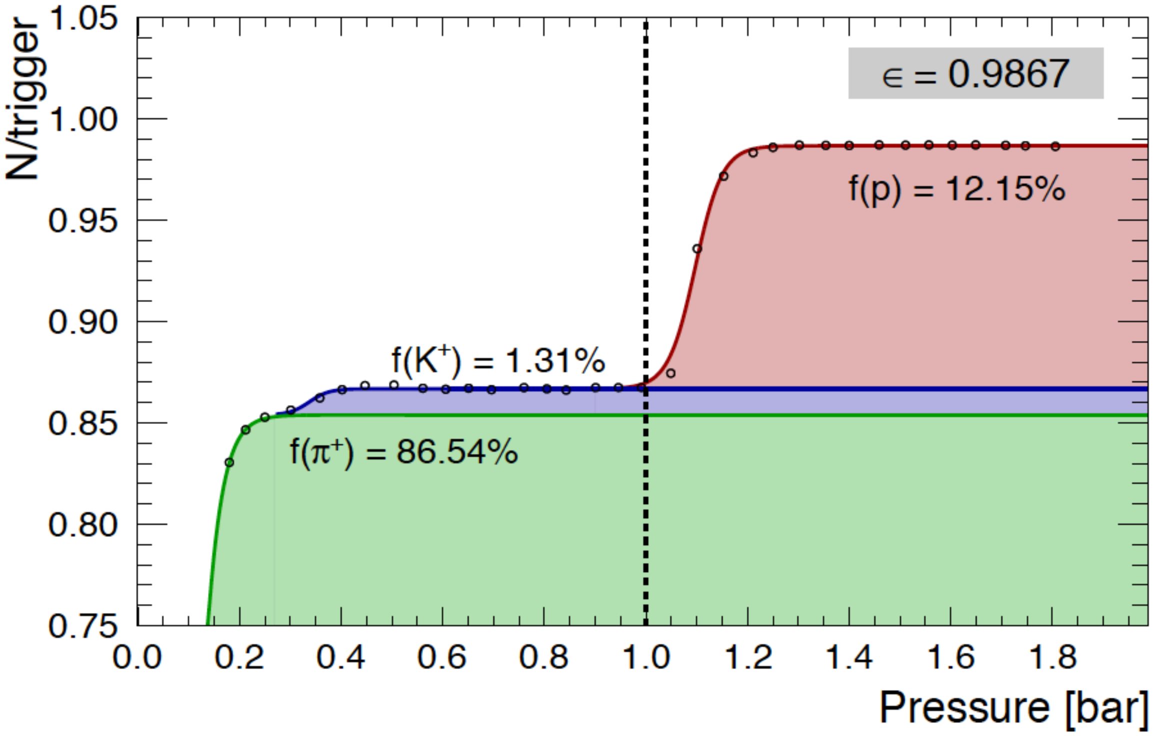
Over 150 physicists from 30 institutions and 15 countries

The NA61/SHINE Experiment

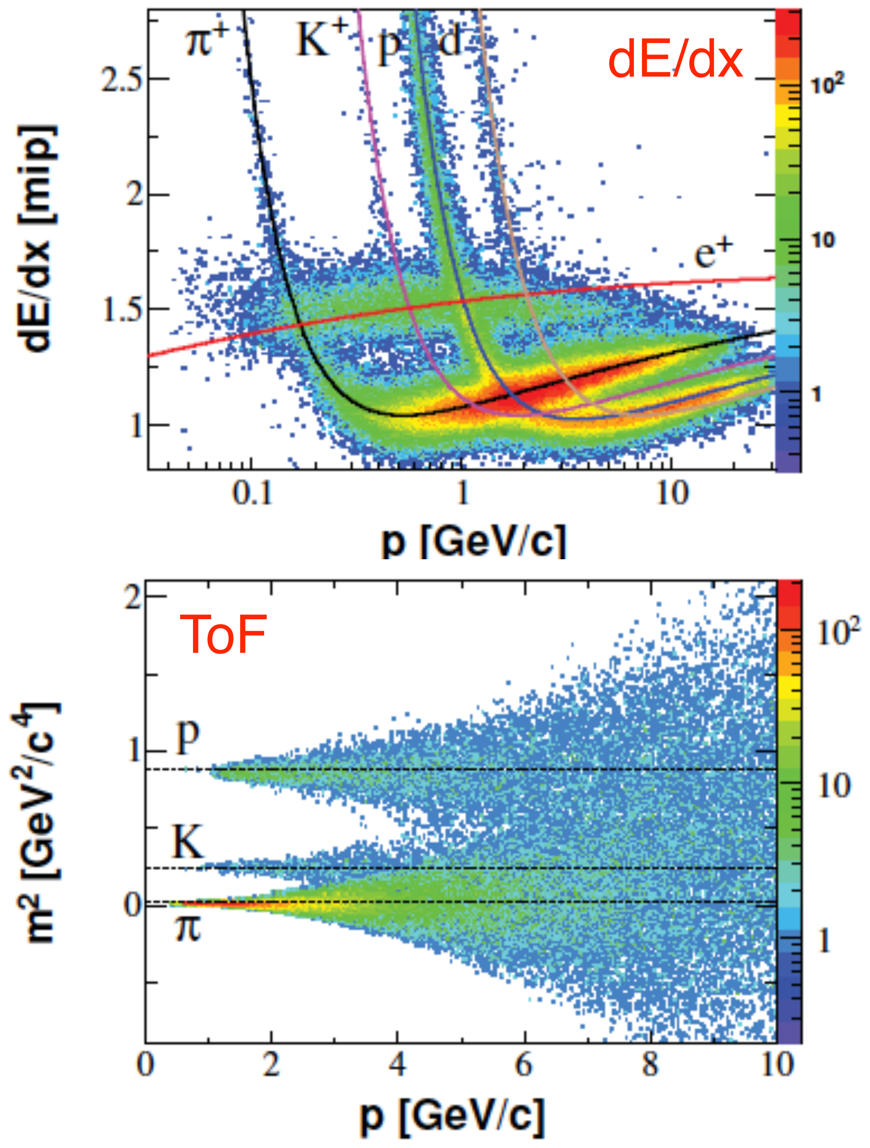
- Hadron beams
  - primary protons at 400 GeV/c
  - secondary hadrons (p, π, K) at 13 - 350 GeV/c
- Ion beams
  - primary (Ar, Xe, Pb) at 13-150 AGeV/c
  - secondary Be at 13 - 150 AGeV/c (from Pb fragmentation)
- Broad physics program
  - Neutrino
    - Hadron production measurements to improve neutrino beam flux predictions
  - Strong interaction / Heavy ion
    - Search for the critical point
    - Study the onset of QCD deconfinement
    - Study open-charm production mechanism
  - Cosmic ray
    - Hadron production measurements to improve air-shower model predictions
    - Study (anti-)deuteron production mechanism for the AMS and GAPS experiments
    - Nuclear fragmentation cross sections to understand cosmic-ray flux

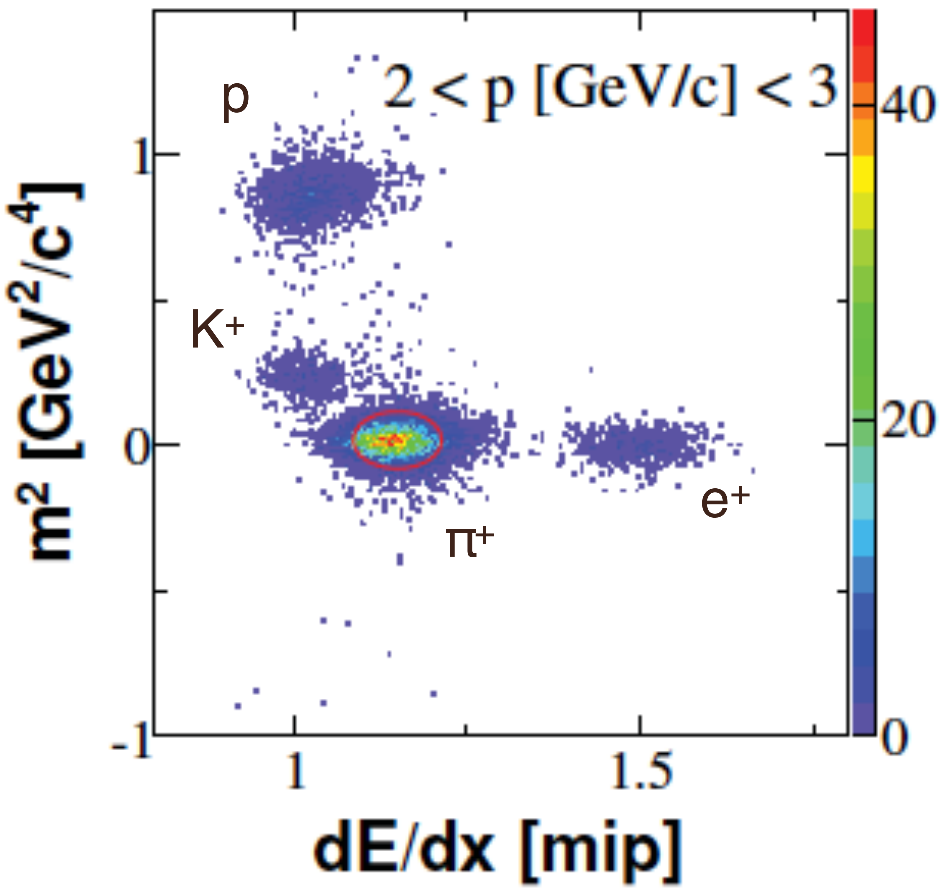
Beam Particle Selection





Particle Identification Performance





Good particle identification including Bethe-Bloch overlap region

NA61/SHINE Detector Performance

typical momentum resolution

$$\frac{\sigma(p)}{p^2} \approx 10^{-4}\ (\mathrm{GeV}/c)^{-1}$$

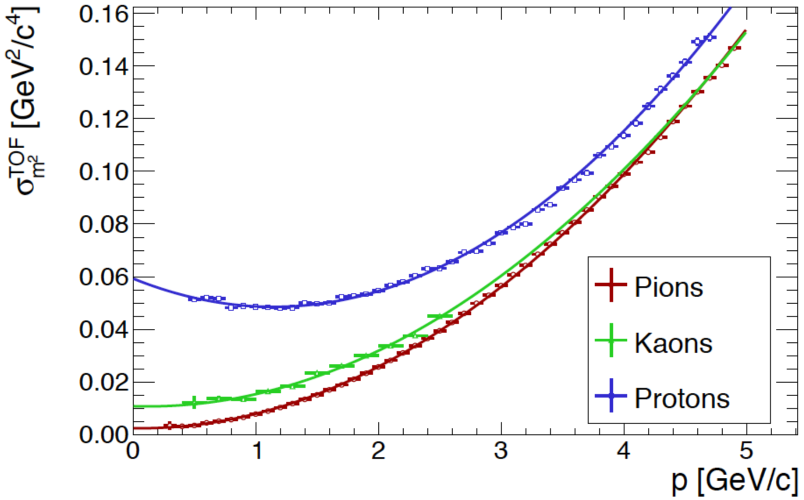
typical dE/dx resolution

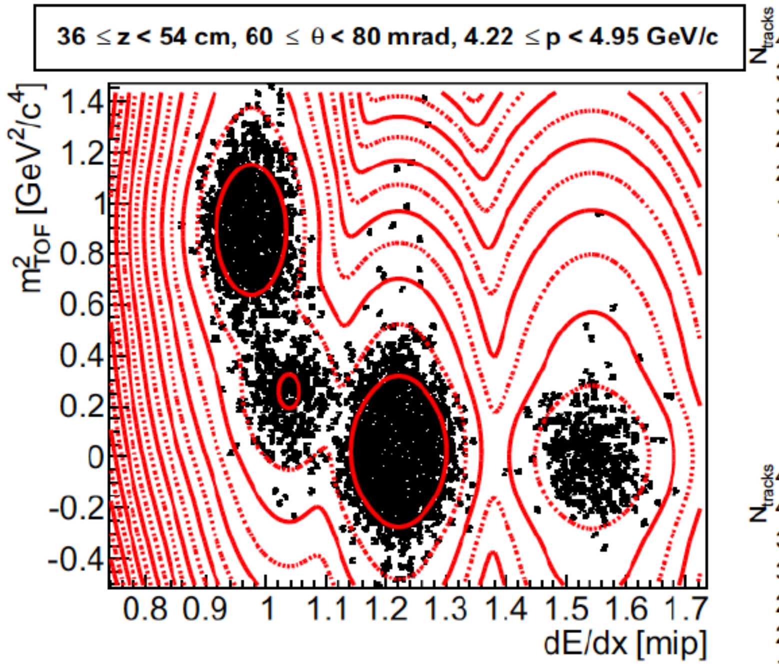
$$\frac{\sigma(dE/dx)}{dE/dx} \approx 0.04$$

ToF resolution

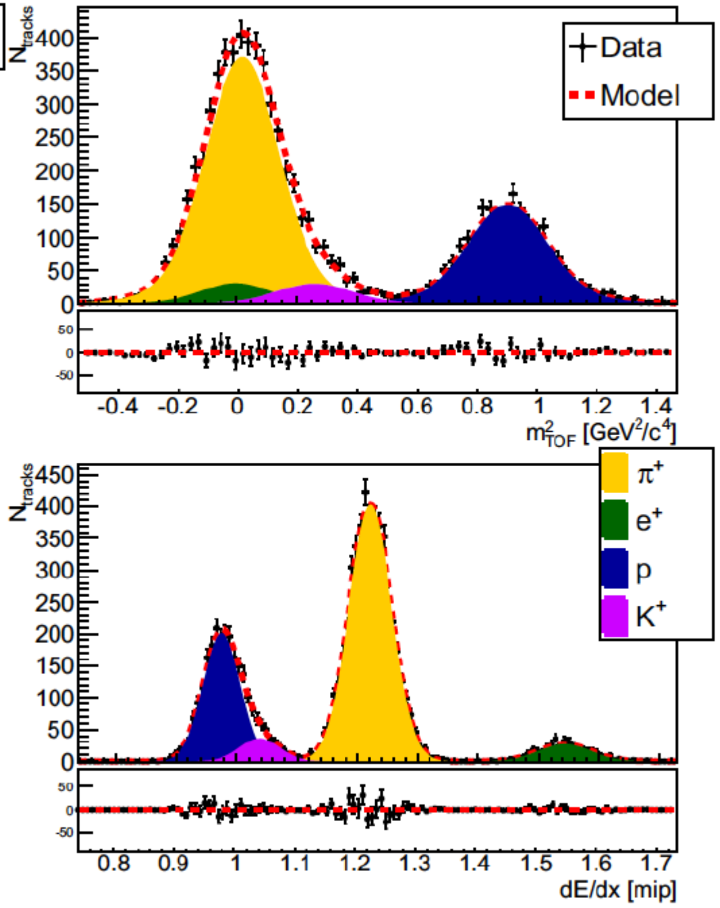
$$\sigma(\text{ToF-L/R}) < 90\ \text{ps}$$

$$\sigma(\text{ToF-F}) \approx 120\ \text{ps}$$





A_p = (2056±46)
A_{K^+} = (399±21)
A_{π^+} = (4732±69)
A_{e^+} = (390±20)



Series of Data Taking for Neutrino Program

- Measurements for T2K (2007-2010): with proton beam at 30 GeV
  - Thin graphite target measurements to study primary interactions
  - T2K replica graphite target measurements

  —> Almost complete data analysis

  —> Further data taking after 2021 is under discussion

- Measurements for Fermilab (2015-2018): with various beam types and energies
  - Thin target (C, Be, Al) measurements to study primary and secondary interactions
  - NOvA replica graphite target measurements

  —> Complete first data taking between 2015 and 2018

  —> Analysis ongoing

  —> Further data taking after 2021 is under discussion