University of Regina

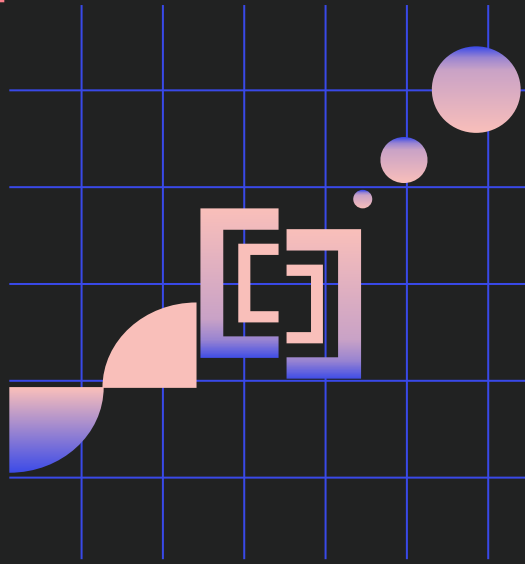
WNPPC 2023

EMPHATIC HYPER HK

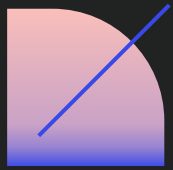
MEASUREMENT OF KAON-CARBON FORWARD SCATTERING WITH EMPHATIC SPECTROMETER

BRUNO FERRAZZI, M.S.

on behalf of the EMPHATIC collaboration

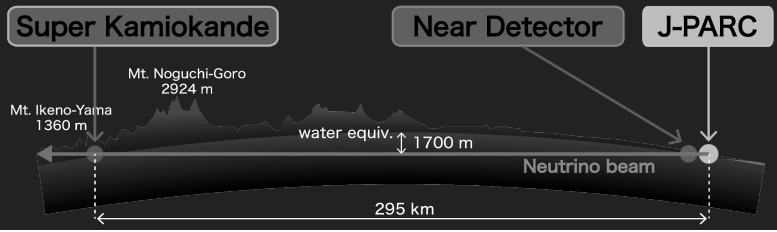


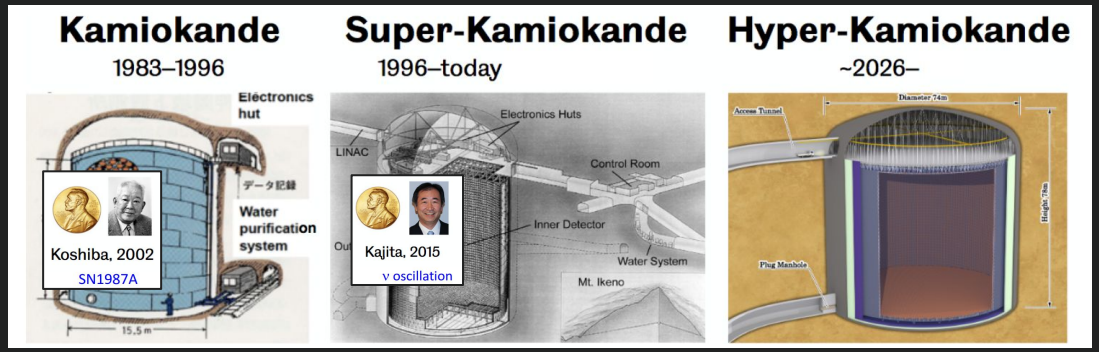
CONTENTS OF THIS TALK

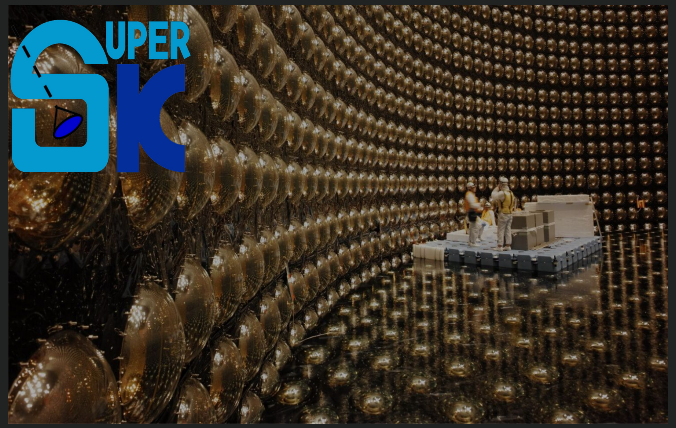


I will present part of my Ph.D. initial work at U of R as a member of the HYPER-K and EMPHATIC collaborations

T2K AND HYPER-K



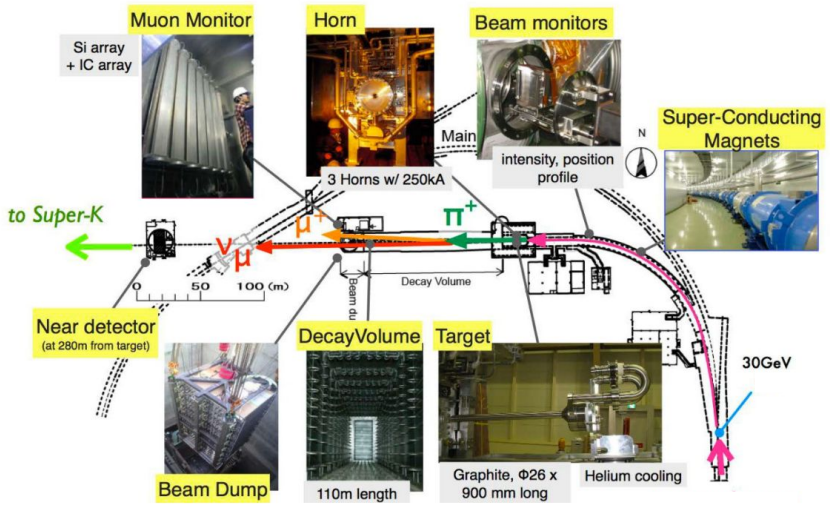


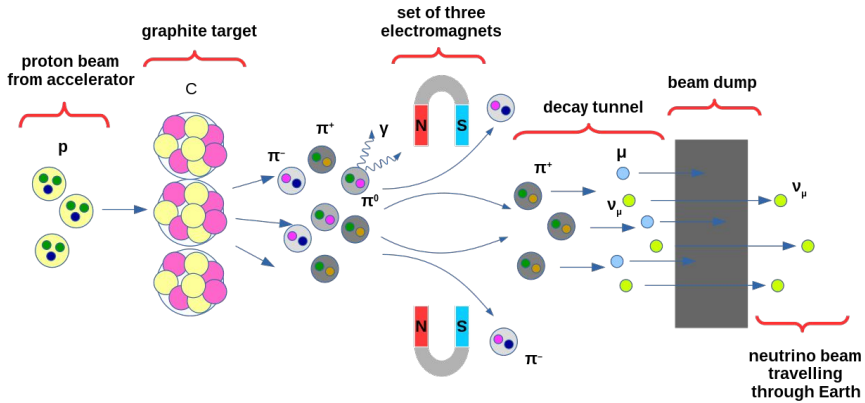


Broad physics research:

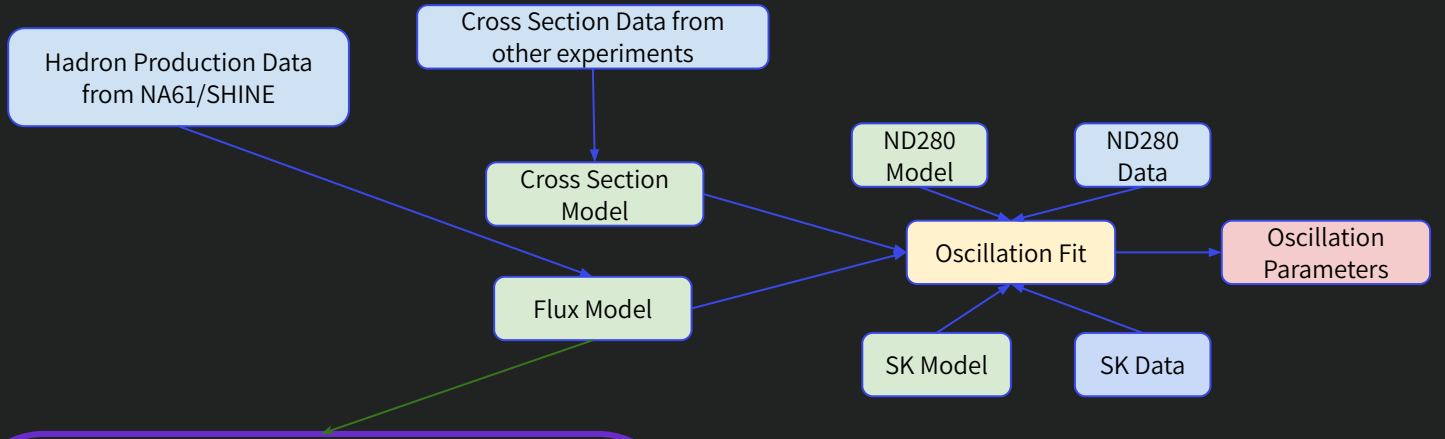
- **Beam, earth's core, atmospheric, solar and supernova neutrinos studies**
- **Proton decay, CP violation and BSM physics**

T2K AND HYPER-K BEAM DELIVERY PATH

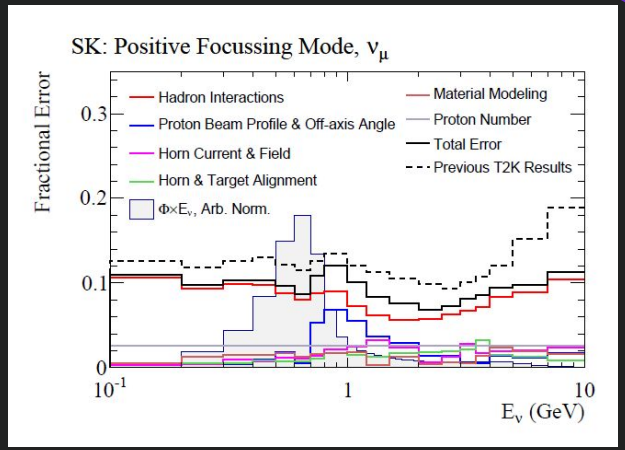




T2K ANALYSIS



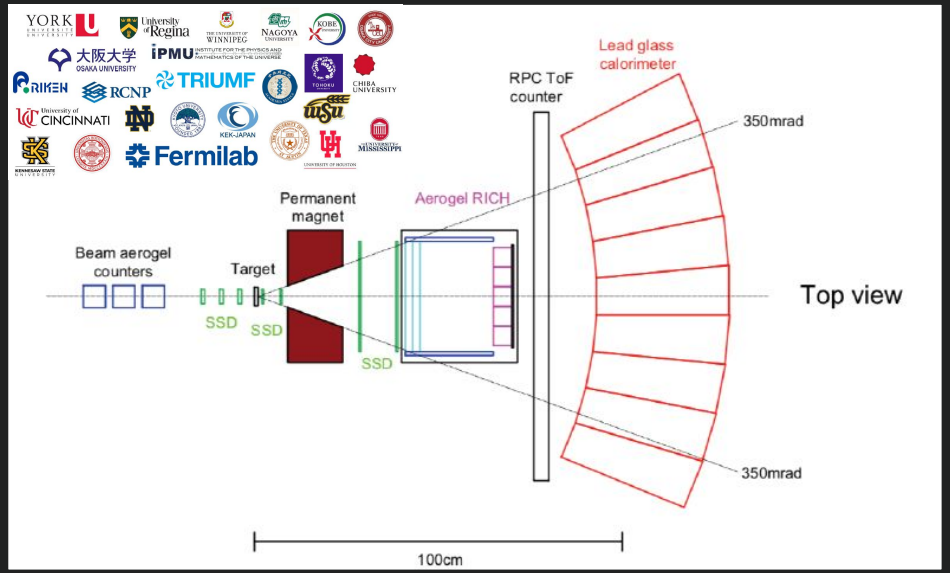
Hadron Production Data from EMPHATIC

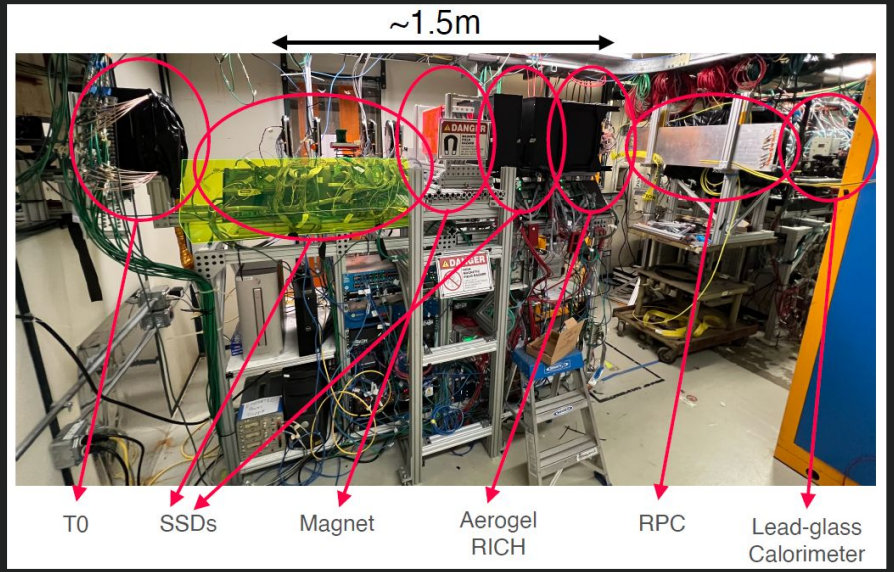


	Statistics [%]	**Flux [%]**	Cross-section model [%]	Detector [%]
σ(ν)	0.87	**9.14**	1.16	2.63
σ(anti-ν)	3.22	**9.37**	2.13	1.82
σ(anti-ν)/σ(ν)	3.22	**3.58**	1.56	1.11

Phys.Rev. D96 (2017) no.5, 052001

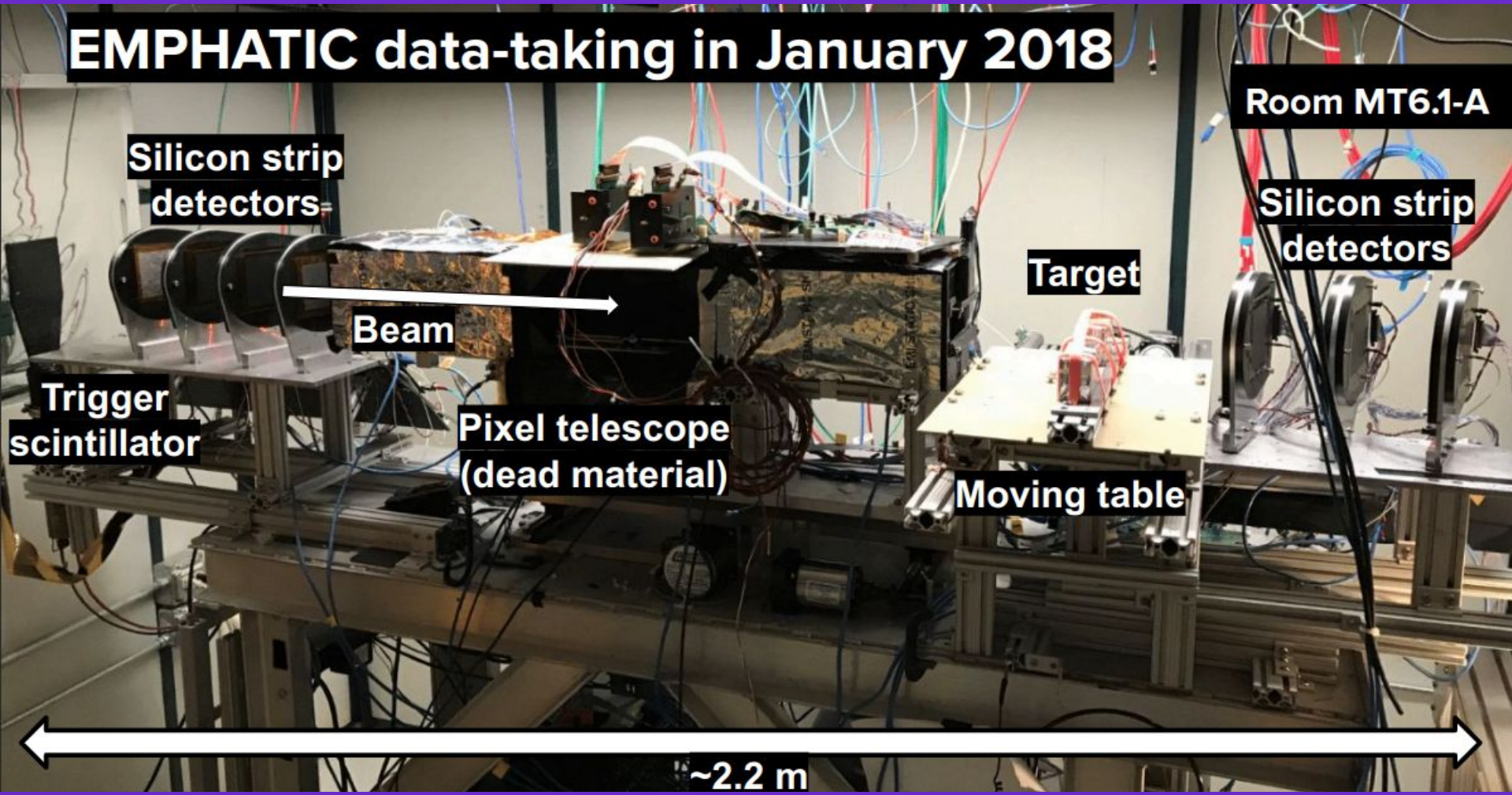
EXPERIMENT TO MEASURE THE PRODUCTION OF HADRONS AT A TEST BEAM IN CHICAGOLAND





The EMPHATIC collaboration has been operating a compact experiment at FERMILAB
Measurement of hadron production cross sections that are particularly relevant to neutrino flux predictions and not possible in other experiments.

EMPHATIC

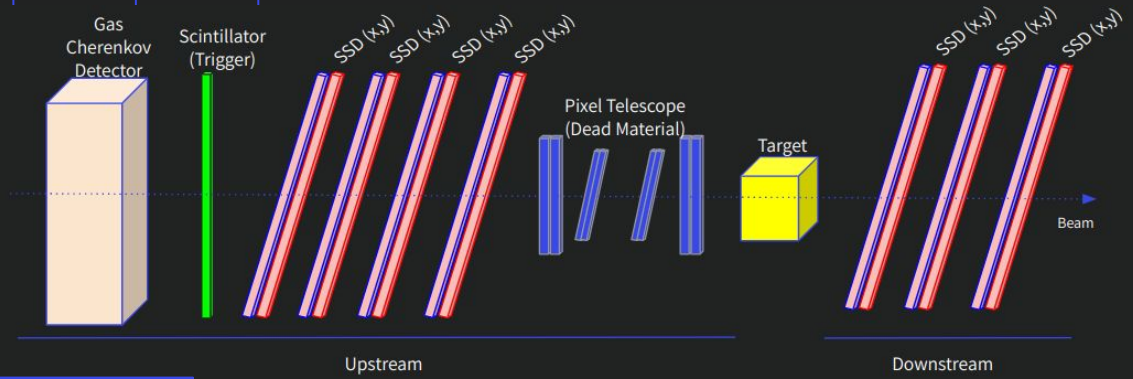

EMPHATIC data-taking in January 2018
Room MT6.1-A
Silicon strip detectors
Silicon strip detectors
Target
Beam
Trigger scintillator
Pixel telescope (dead material)
Moving table
~2.2 m

STEPS OF MY ANALYSIS: KAON FORWARD SCATTERING

BEAM STUDIES
Beam Characterization

ALIGNMENT AND CALIBRATION
Coordinate system

UPSTREAM SELECTION
Interactions before the target

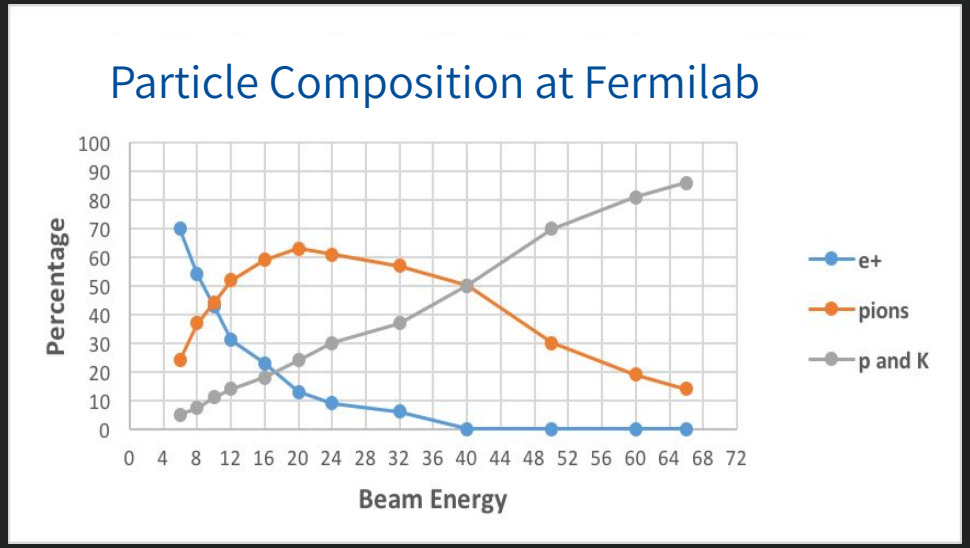


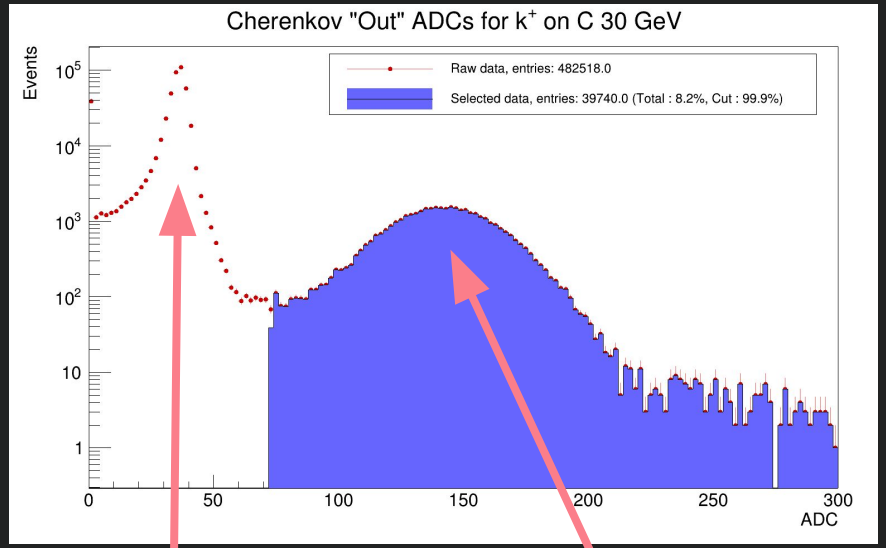
DOWNSTREAM SELECTION
Forward scattering

SYSTEMATICS
Monte Carlo models

MODEL FITTING
Optical theorem

BEAM CONTENT

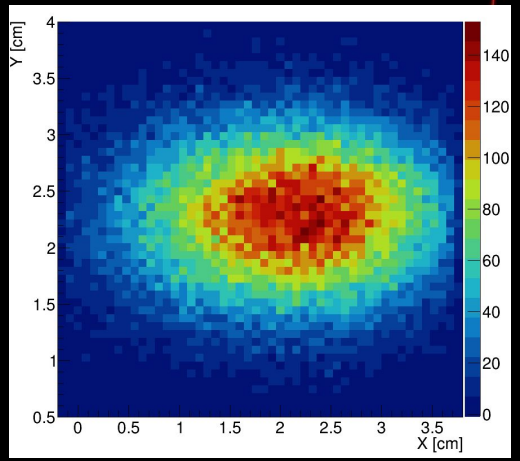




Protons

Kaons

MONTE CARLO GEOMETRY

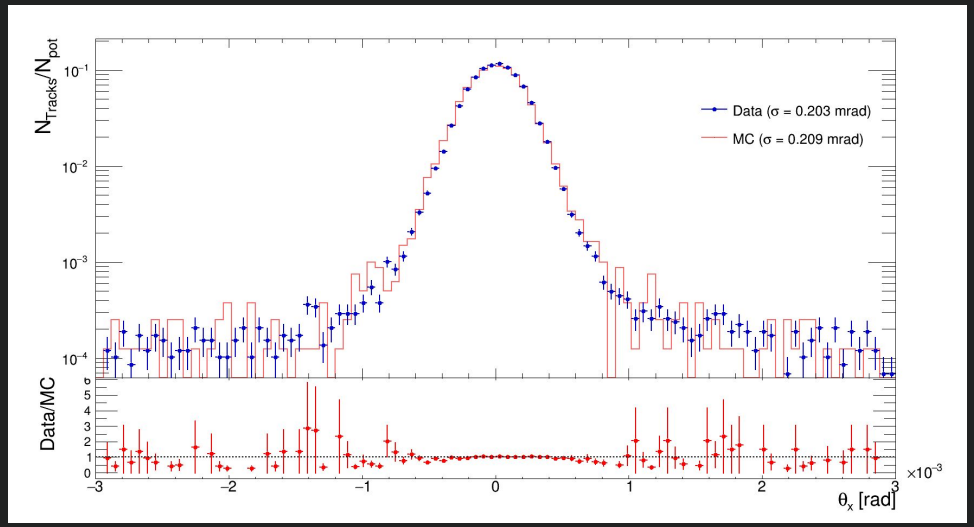


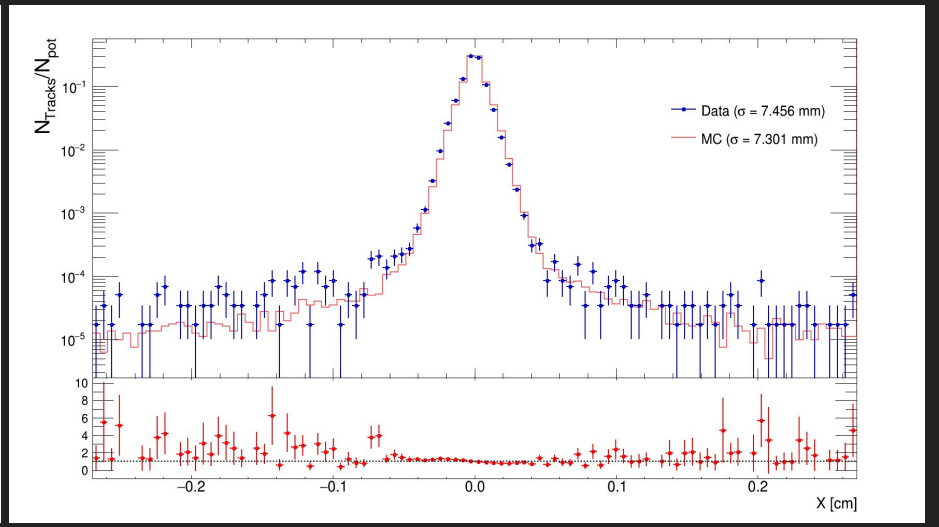
INPUT BEAM PROFILE FROM RECONSTRUCT DATA.

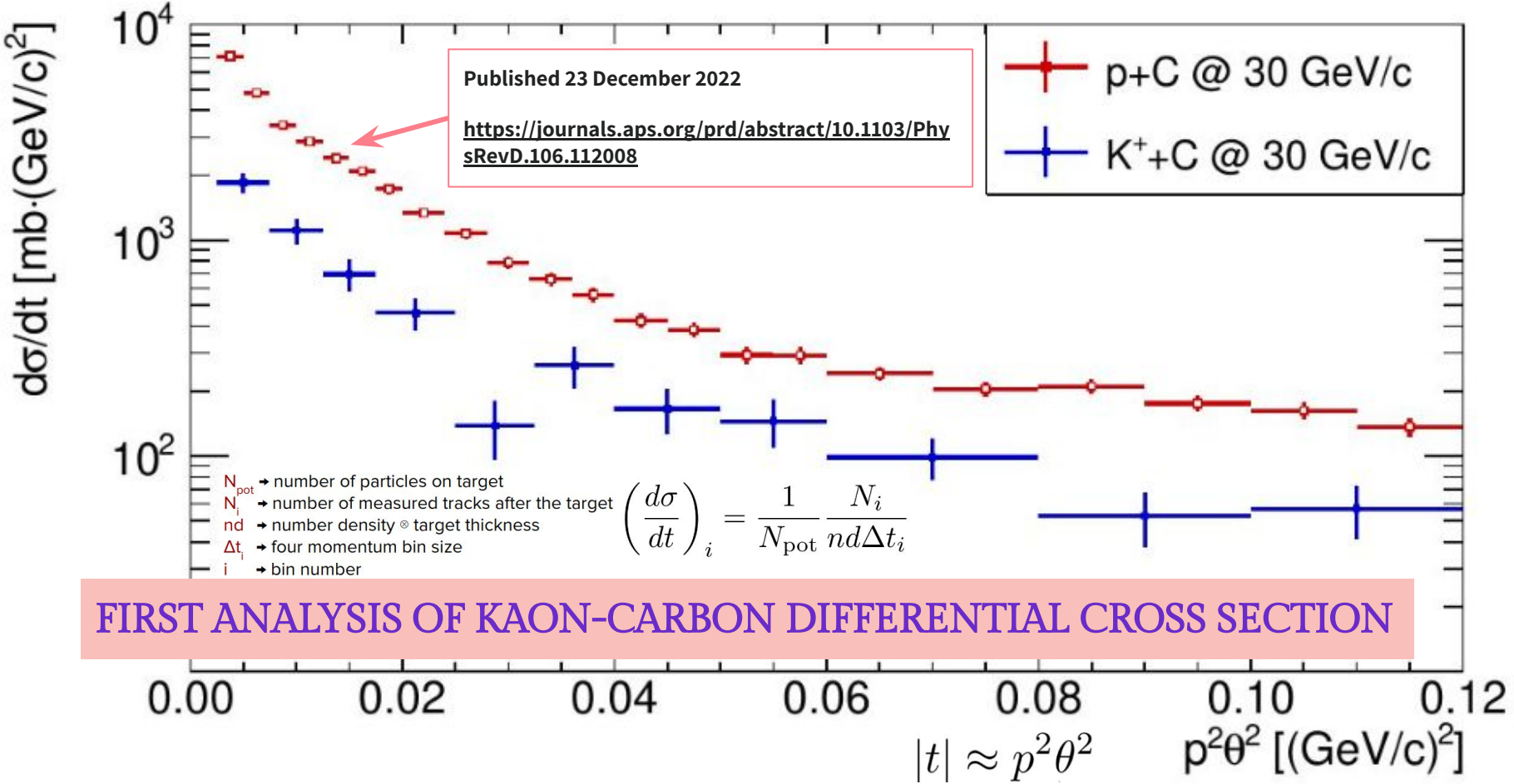
e-
e+
p+
pi+ / pi-
k+ / k-
n
mu+ / mu -
gamma

MONTE CARLO AND DATA

TRACK RECONSTRUCTION CONCORDANCE






dσ/dt [mb·(GeV/c)²]
10⁴
10³
10²
Published 23 December 2022
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.106.112008
p+C @ 30 GeV/c
K⁺+C @ 30 GeV/c
N_pot → number of particles on target
N_i → number of measured tracks after the target
nd → number density ⊗ target thickness
Δt_i → four momentum bin size
i → bin number
$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{N_{\mathrm{pot}}} \frac{N_i}{nd\Delta t_i}$
FIRST ANALYSIS OF KAON-CARBON DIFFERENTIAL CROSS SECTION
0.00
0.02
0.04
0.06
0.08
0.10
0.12
$|t| \approx p^2\theta^2$
p²θ² [(GeV/c)²]

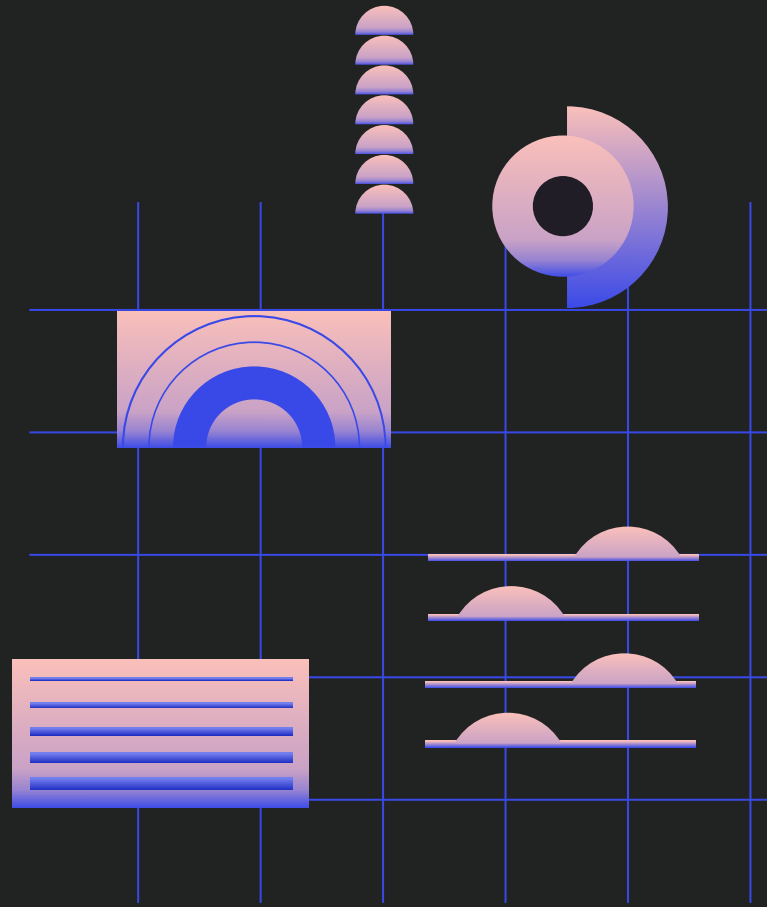
WORK IN PROGRESS

Kaon forward scattering

- The beam impurity needs to be better understood
- The systematics analysis and model fitting are in the initial states
- Optimization of the data cuts is needed

New data and ARICH work

- Data has been produced since 2018
- Canada team is responsible for ARICH operation
- Next experiment cycle beings in Mar-April 2023



ARICH: Aerogel Imaging Cherenkov Detector

THANK YOU!

Do you have any questions?

bferrazzi@uregina.ca

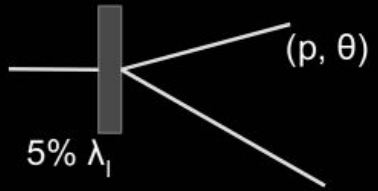
BACKUP

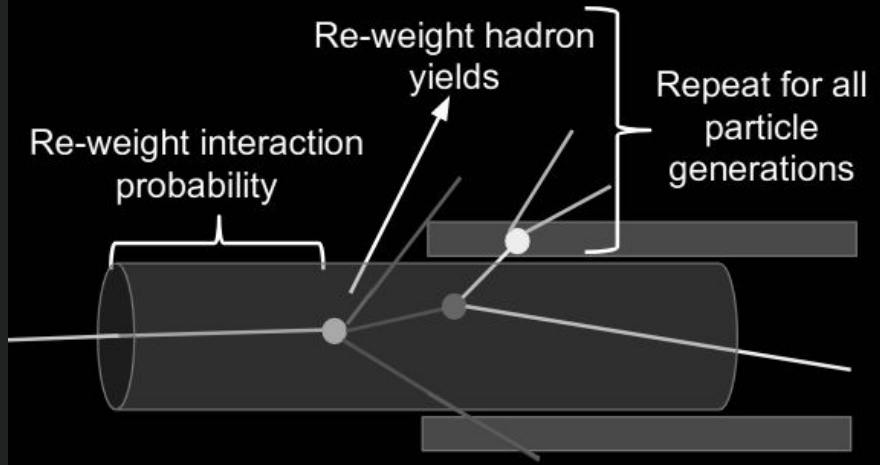
Neutrino beams in accelerator neutrino experiments

- Produced neutrino flux is difficult to measure
  - Near detectors measure flux⊗cross-section
  - ν-e scattering → low statistics
  - Direct measurement of produced hadrons is very challenging (high radiation area, complex geometry)
- Monte Carlo models are used to estimate the neutrino flux
  - ~30% differences between models → large systematic uncertainty
- **Hadron production data is used to scale the models→ re-weighting procedure**

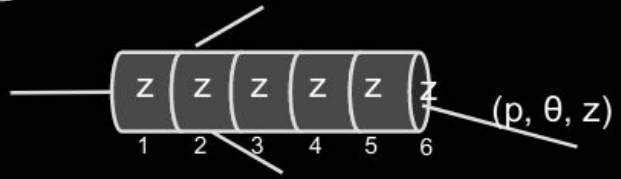
Hadron production measurements

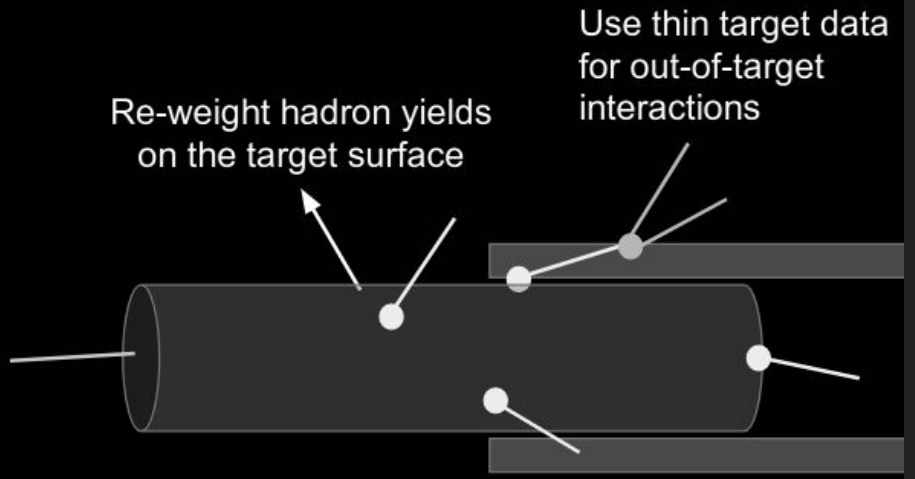
1 Thin target measurements





2 Replica target measurements



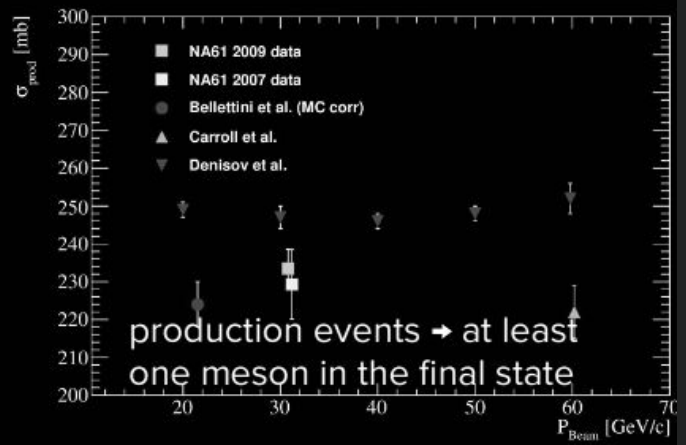


Both approaches are necessary to completely constrain neutrino flux!

Hadron production measurements

- Measurements of cross-sections and hadron yields
  - HARP, MIPP, NA49, NA56/SPY, ...
  - **Systematics and correlations are not understood**
  - Limited phase space coverage
  - Significant differences between measurements

- **Most of the hadron production data in the last decade was taken by NA61/SHINE at CERN SPS**
  - Beam momenta cannot go below 15 GeV/c
  - π/K and p/K separation is very limited between 5-8 GeV/c
  - TPC detectors are hard to calibrate → long time between data-taking and released results



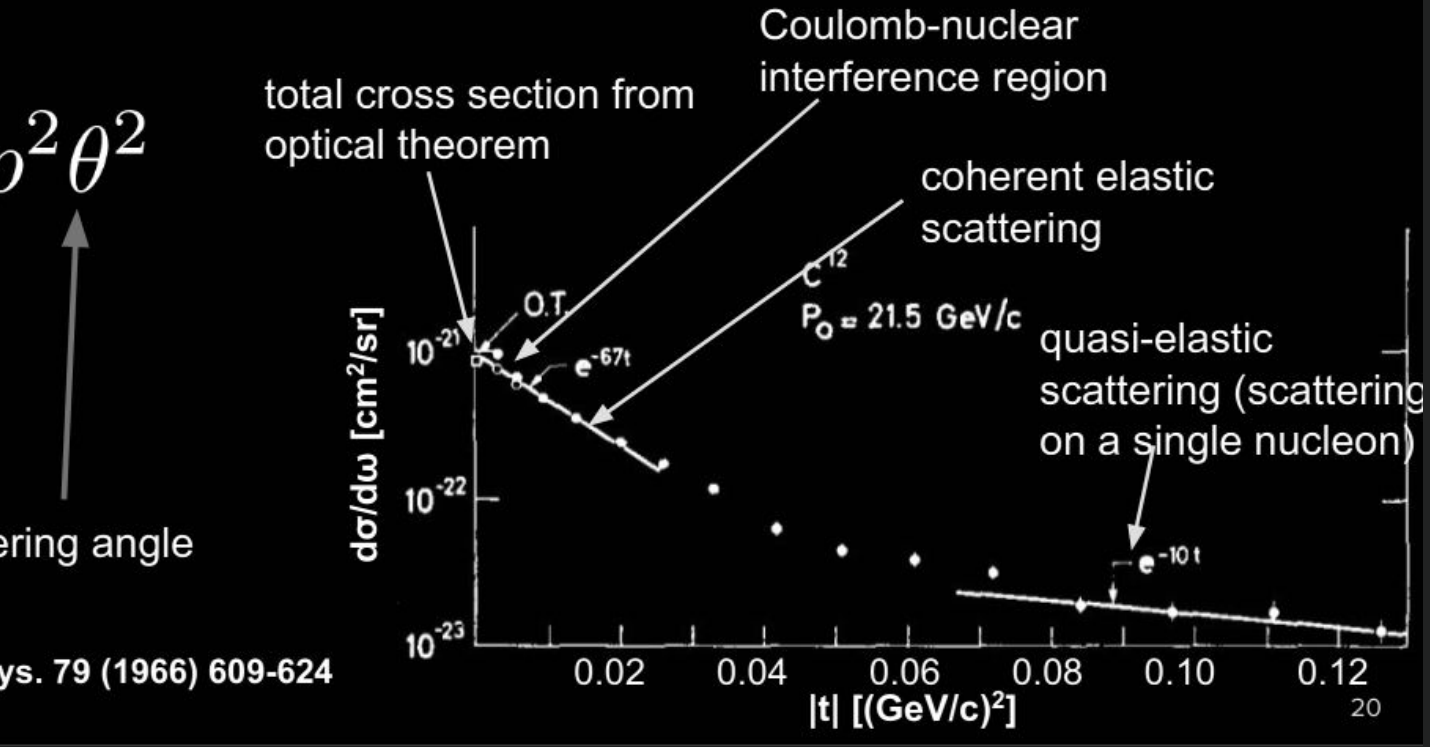
[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Phys.Rev. C89 (2014) no.2, 025205
[4] Eur. Phys. J. C (2016) 76: 84
[5] N. Abgrall et al., Nucl. Instrum. Meth., A701:99, 2013.
[6] N. Abgrall et al., Eur.Phys.J. C79 (2019) no.2, 100
[7] N. Abgrall et al. Eur. Phys. J., C76(11):617, 2016.
[8] Phys.Rev. D98 (2018) no.5, 052001

- **Hadron production remains the dominant neutrino flux uncertainty (5-10%)**

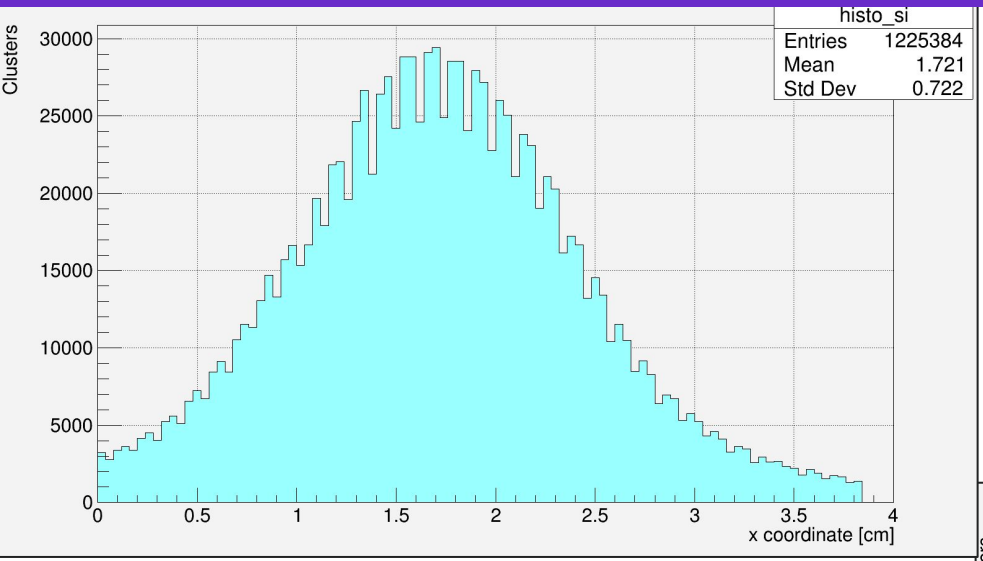
$$|t| \approx p^2\theta^2$$

Beam momentum

Scattering angle

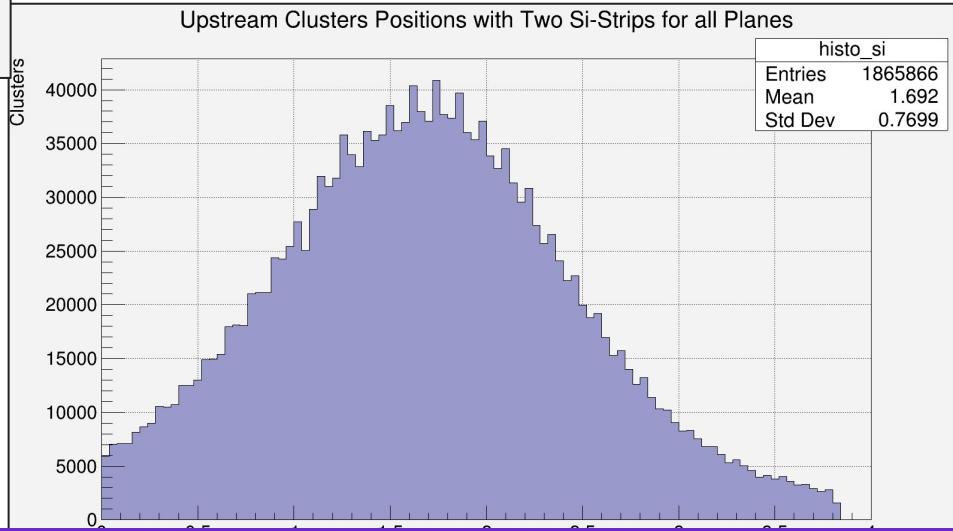


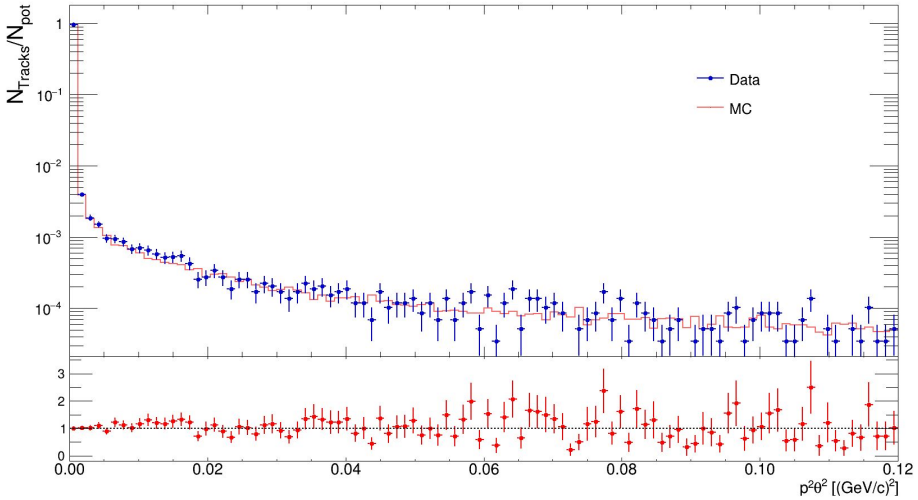
Bellettini et al., Nucl.Phys. 79 (1966) 609-624

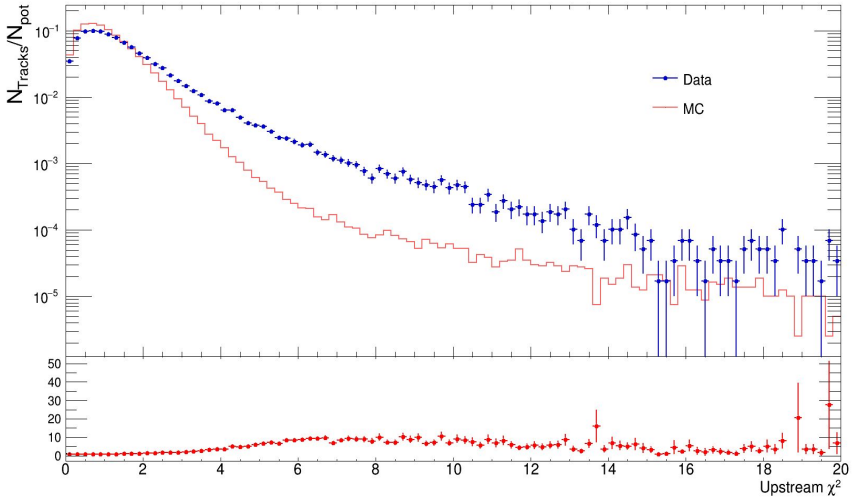


$$x = (i - 0.5) \cdot w$$

$$x = \frac{1}{q_1 + q_2}\left(q_1(i - 0.5) + q_2(i + 0.5)\right) \cdot w$$




N_{Tracks}/N_{pot}
Data
MC
$p^2\theta^2$ [(GeV/c)^2]


N_{Tracks}/N_{pot}
Data
MC
Upstream χ^2

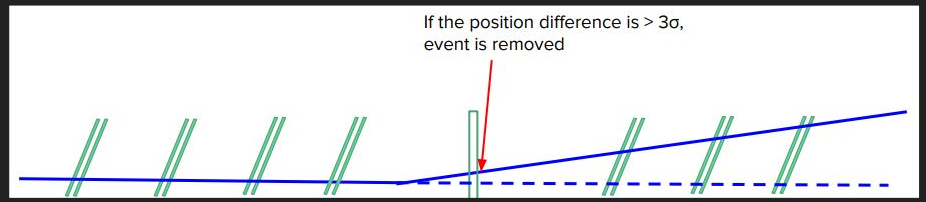
Study of alignment and calibration

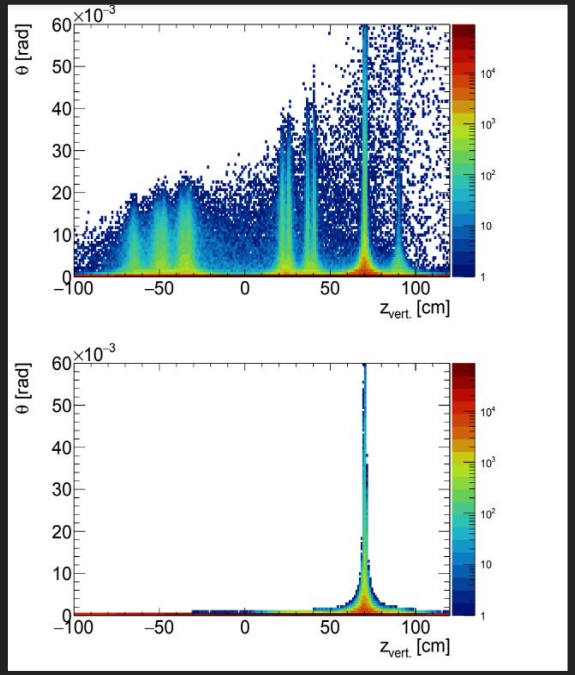
The data alignment is done by selecting events with single cluster in SSD for all planes using empty target. The algorithm goes through a larger portion of the events changing the parameters in order to minimize the chi-squared. The output are values of the position and rotation for SSD planes.


```
        "RunNumber" : 274,
        "Plane" :{
            "Id" : 1,
            "Position" : [0.1553, 0.0000, -99.3000],
            "Rotation" : [0.0000, -15.0000, 0.0000],
        },
        "Plane" :{
            "Id" : 2,
            "Position" : [0.0000, 0.0000, -98.7204],
            "Rotation" : [0.0000, -15.0000, 90.0000],
```

Study of downstream selection and out of target interactions

Goal: Remove background and improve the angular resolution
Single upstream track (1)
Maximum number of clusters (8)
Chi-squared (<6) [broken tracks]
Difference in upstream and downstream x(y) track position at target z position

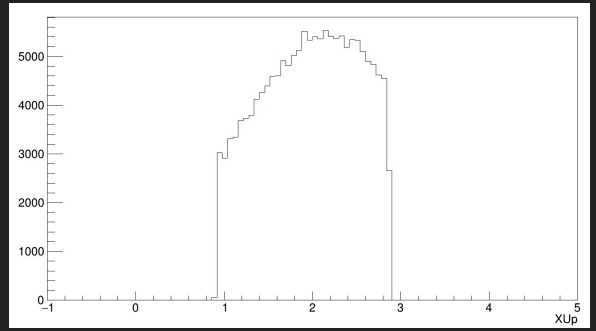




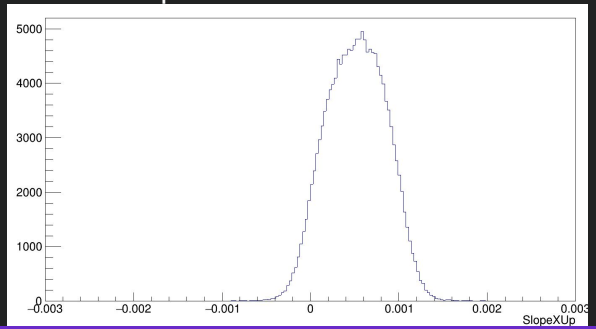
Study of upstream selection, beam profile and upstream interactions

Goal: Remove interactions happening before the target improving the POT number
Cherenkov cut (Pedestal)
Single upstream track (1)
Maximum number of clusters (8)
Chi-squared (<6) [broken tracks]
Beam Divergence (tails)
Beam Profile (tails)

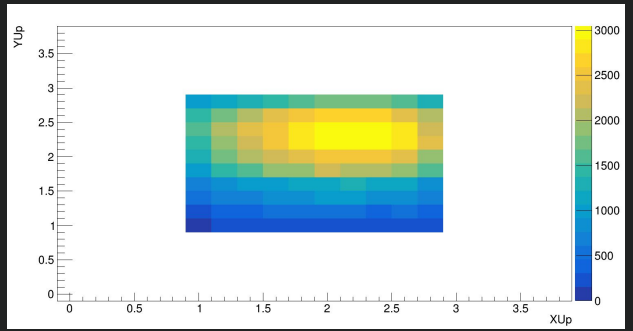
Upstream Beam Slope



Upstream Beam Position



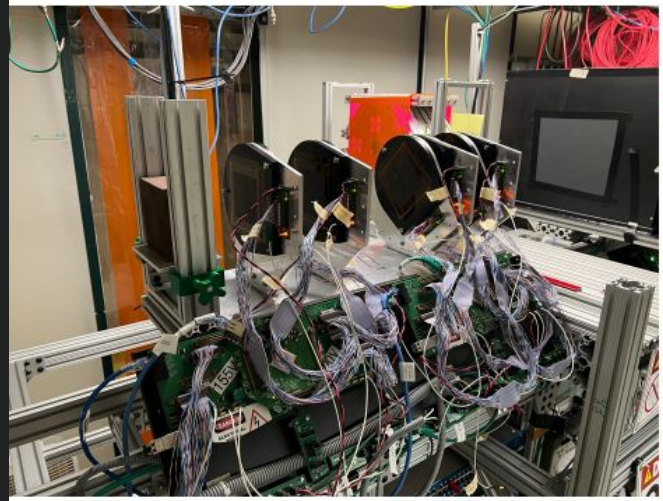
Upstream Beam Profile

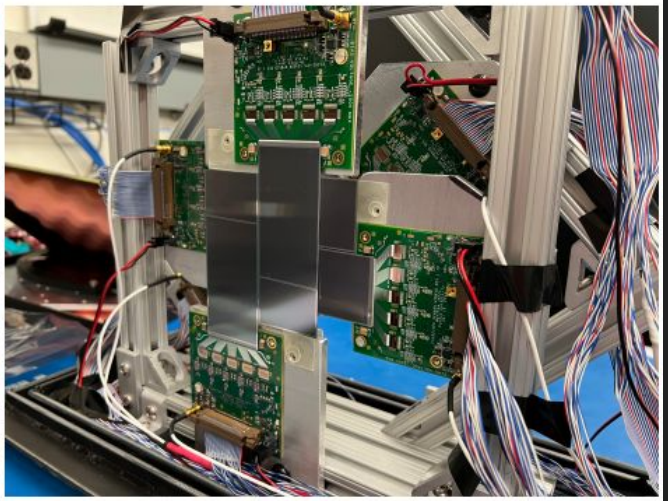


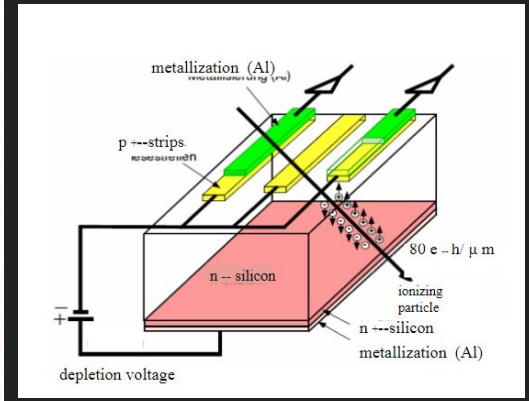
EMPHATIC: Run Plan

Phase	Date	Subsystems	Momenta (GeV/c)	Targets	Goals	Status
0	2018	Beam Gas Ckov + FTBF SiStrip Detectors + Emulsion Bricks	20, 31, 60, 120	C, Al, Fe	Proof-of-concept Forward-scattering measurement w/ 20 mrad acceptance	Complete - Paper submitted to PRD
1	2022-23	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + Small-acceptance magnet + Prototype ARICH + ToF + Small-acceptance Calorimeter	4, 8, 12, 20, 31, 60, 120	C, CH2, Al, Fe, Be, Ti, Ca, H20	Improved elastic and quasi-elastic scattering measurements, 100 mrad-acceptance hadron production measurements	In-progress
2	2023-24	Phase 1 on Motion Table	4, 8, 12, 20, 31, 60, 120	Spare NuMI Target and [unpowered horn] + various thin-targets	Charged-particle spectrum downstream of horn + thin-target measurements at larger angle	Proposed - Under Discussion
3	2024-25	Upgrade spectrometer to 350 mrad acceptance + Hybrid RICH	4, 8, 12, 20, 31, 60, 120	Same as Phase 2	Full-acceptance hadron production with PID up to 15 GeV/c	Concept
4	2025-26	Upgraded spectrometer + Hybrid RICH + Powered Horn	120	Spare NuMI Horn and Target	Charged-particle spectrum downstream of horns	Concept

EMPHATIC: Si Strip Detectors (SSDs)







- Upstream tracking to be done by existing SSDs at the FTBF.
  - 60 μm pitch, ~10 μm resolution