Measurements of p+C differential cross-section at 20, 30, and 120 GeV/c in EMPHATIC

Matej Pavin,
on behalf of the EMPHATIC collaboration

CAP Congress
June 6, 2019

What is EMPHATIC?

- **E**xperiment to **M**easure the **P**roduction of **H**adrons **At** a **T**estbeam **I**n **C**hicagoland
- ~20 people
- Hadron production measurements for neutrino experiments (T2K, NOVA, HyperK, DUNE)
- Fermilab Test Beam Facility (FTBF)

Motivation

- Next generation of accelerator long-baseline neutrino experiments (HyperK, DUNE) will be limited by systematics
- HK-Canada group is trying to reduce all of the major systematics which will affect HyperK
- One of the major systematics is neutrino flux uncertainty
  - Dominant uncertainty in single detector measurements (neutrino-nucleus cross-section, sterile neutrino searches, ...)

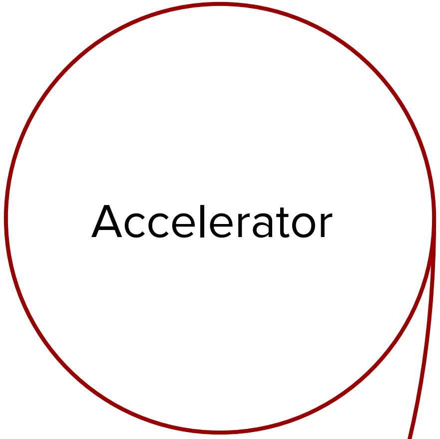
Measurement of (anti)ν_μ charged current inclusive cross-sections in T2K ND

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

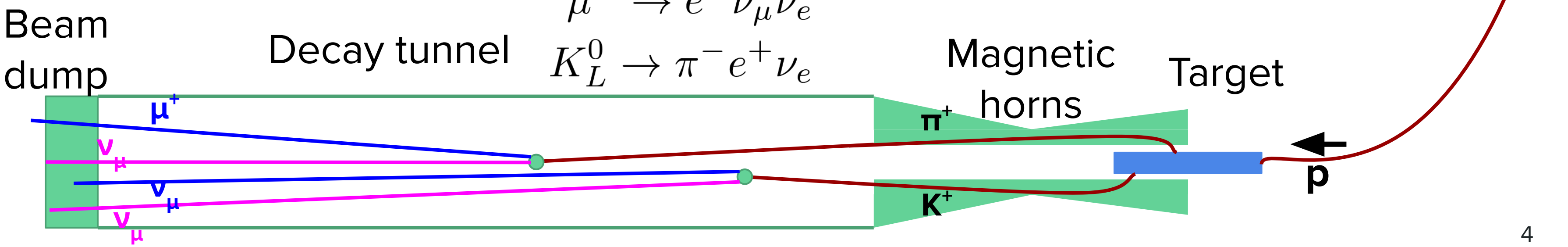
Phys.Rev. D96 (2017) no.5, 052001

Neutrino beams in accelerator neutrino experiments

- T2K, NOvA, MINERvA, **HK, DUNE**
- Proton beam is directed toward a thick target
- Produced hadrons are (de)focused by a set of magnetic horns
- Neutrinos are produced from pion, kaon and muon decays
- Other particles are stopped in the beam dump



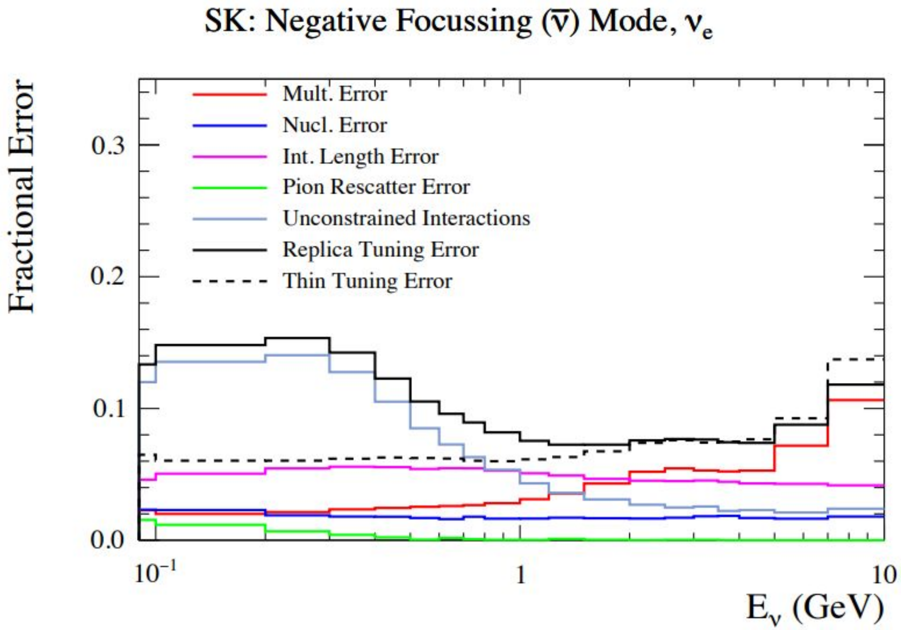
$$\pi^+ \to \mu^+ \nu_\mu$$
$$K^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$
$$K_L^0 \to \pi^- e^+ \nu_e$$



Neutrino flux uncertainty in T2K and HyperK

- MC models are used to simulate neutrino flux
- Hadron production measurements are used to constrain the models
- Particle production in p + C interaction at 30 GeV/c was measured by NA61/SHINE ➔ current ν_μ flux uncertainty in T2K is around 5% at peak energies

- Hadron interactions outside of the target contribute significantly to (anti-)ν_e fluxes
  - $\pi^\pm$ + Al ➔ $\pi^\pm$ + X and $K^\pm$ + Al ➔ $K^\pm$ + X
  - p < 15 GeV/c
  - **No measurements which cover interactions of interest**
  - **ν_e flux uncertainty can impact E61/IWCD/NuPrism measurements (see talk by John Walker)**



EMPHATIC physics goals

- Measurement of untuned interactions in the T2K neutrino beam simulation
- Hadron production measurements for atmospheric neutrinos
- Measurements for Booster neutrino programme
- Low momentum meson interactions in NuMI

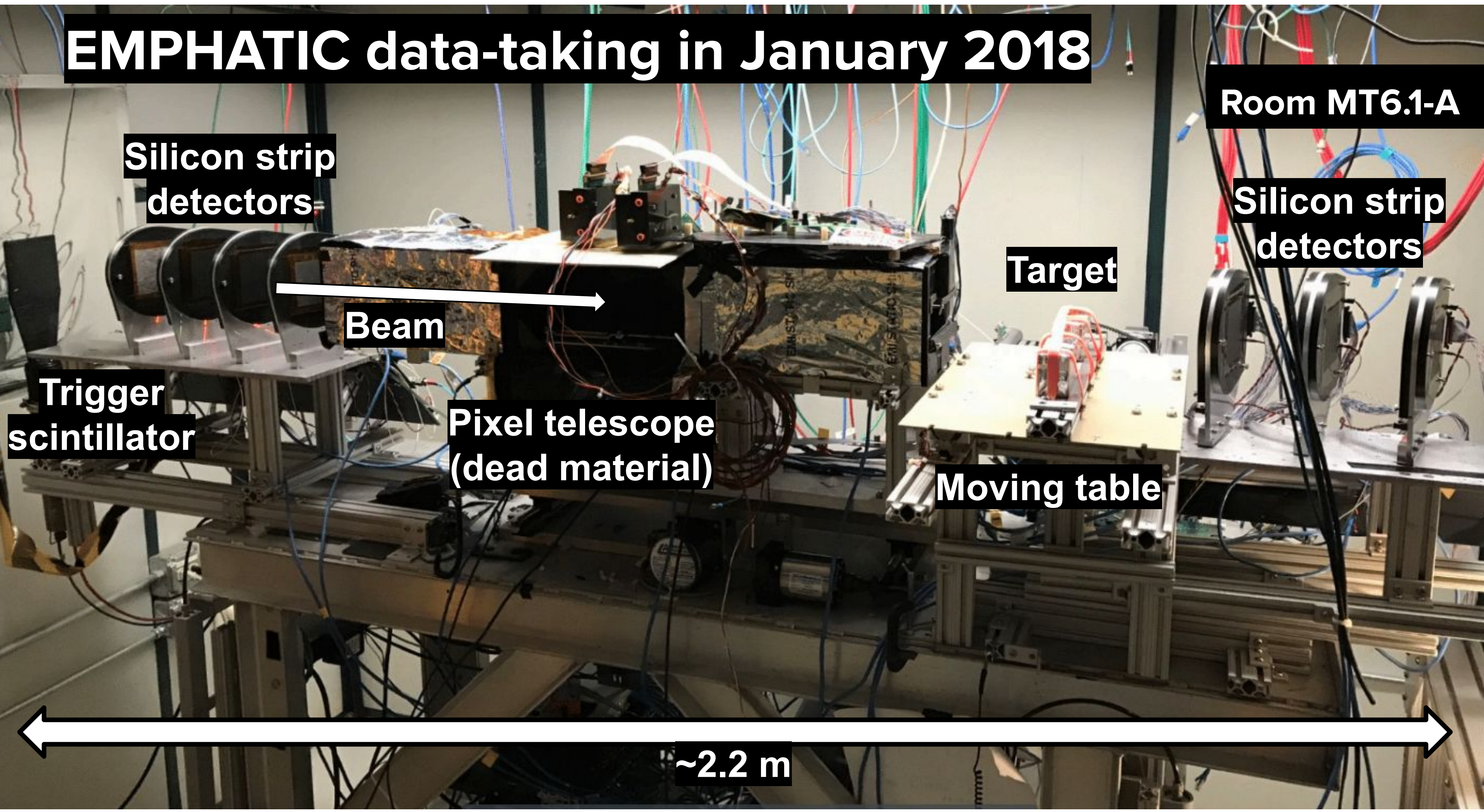
p_b < 15 GeV/c

- Cross-check of the NA61/SHINE measurements
- Resolve inconsistencies between the data
- High momentum measurements for NuMI beam simulation

Beam test in January 2018 (Fermilab Test Beam Facility)

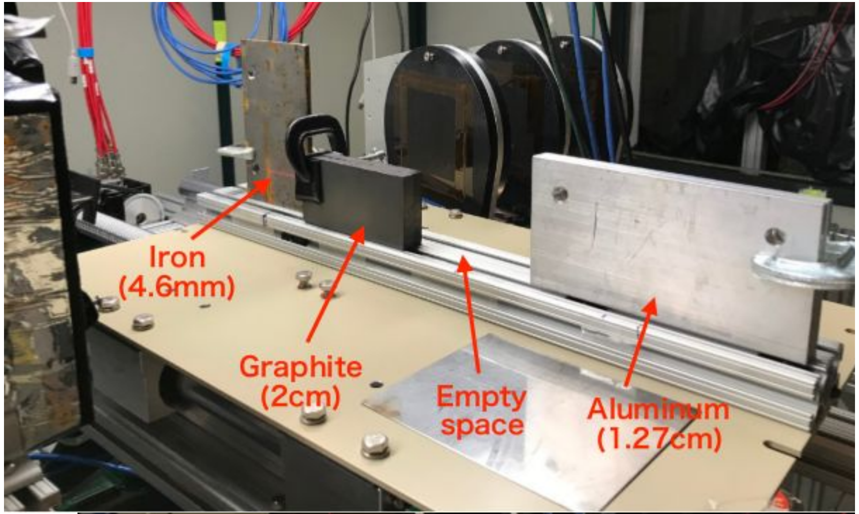
- Test of the FTBF capabilities (silicon strip tracking, gas Cherenkov detectors)
- Test of the aerogel threshold Cherenkov detectors
- Test of the particle tracking with emulsions
- Measurement of the forward proton scattering (coherent elastic and quasi-elastic)

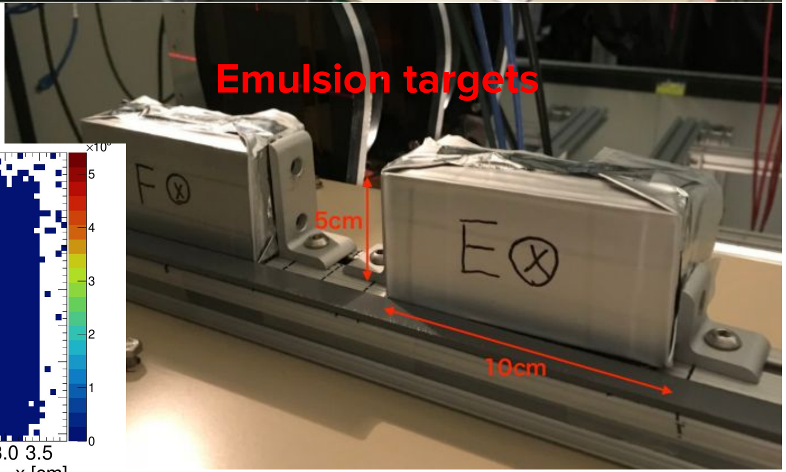
EMPHATIC data-taking in January 2018



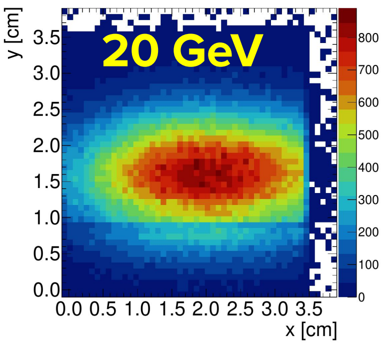
Targets and beam

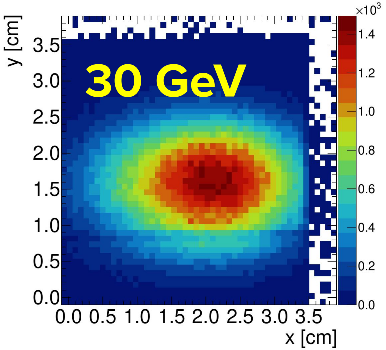
- Graphite, aluminum, steel and empty targets
- Emulsion targets with graphite
- The same graphite is used in T2K
- Beam momentum: 2, 10, 20, 30, 120 GeV/c

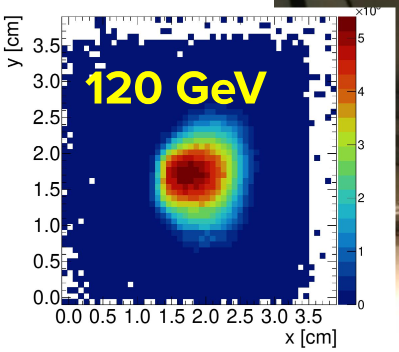




Beam profiles







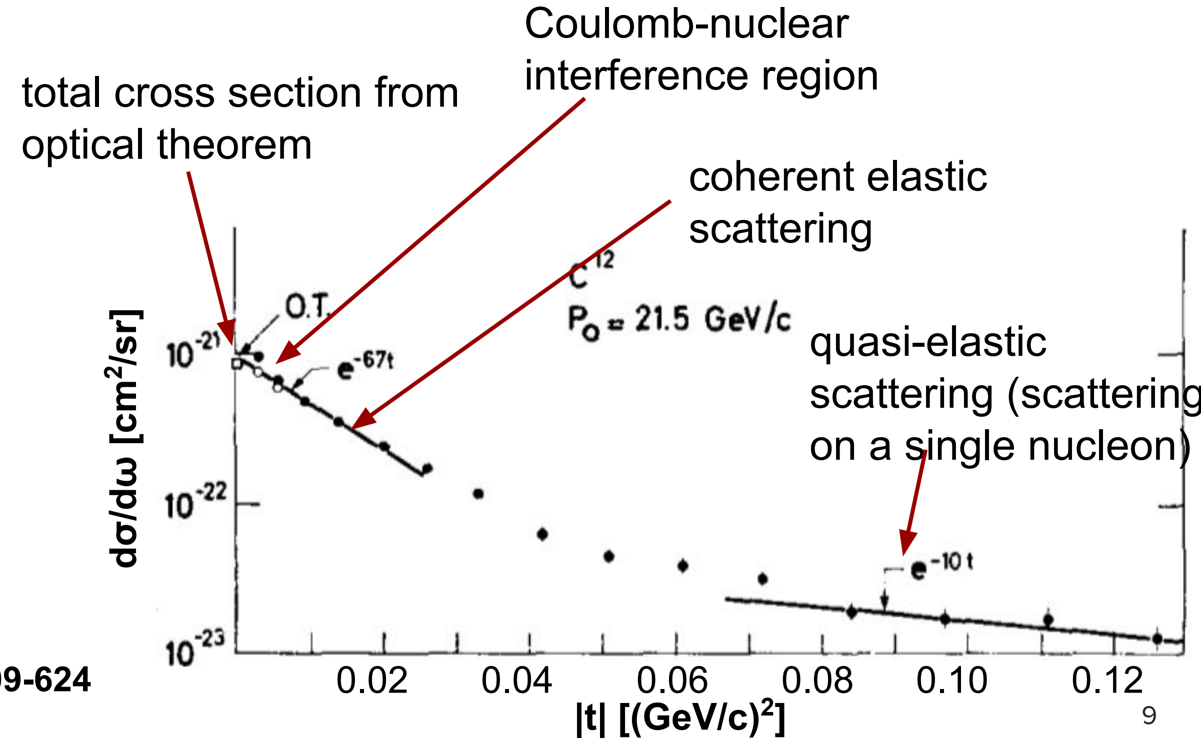
What can we do with the data?

- **p + C @ 20, 30, 120 GeV/c data**
- **Measurement of forward scattering**

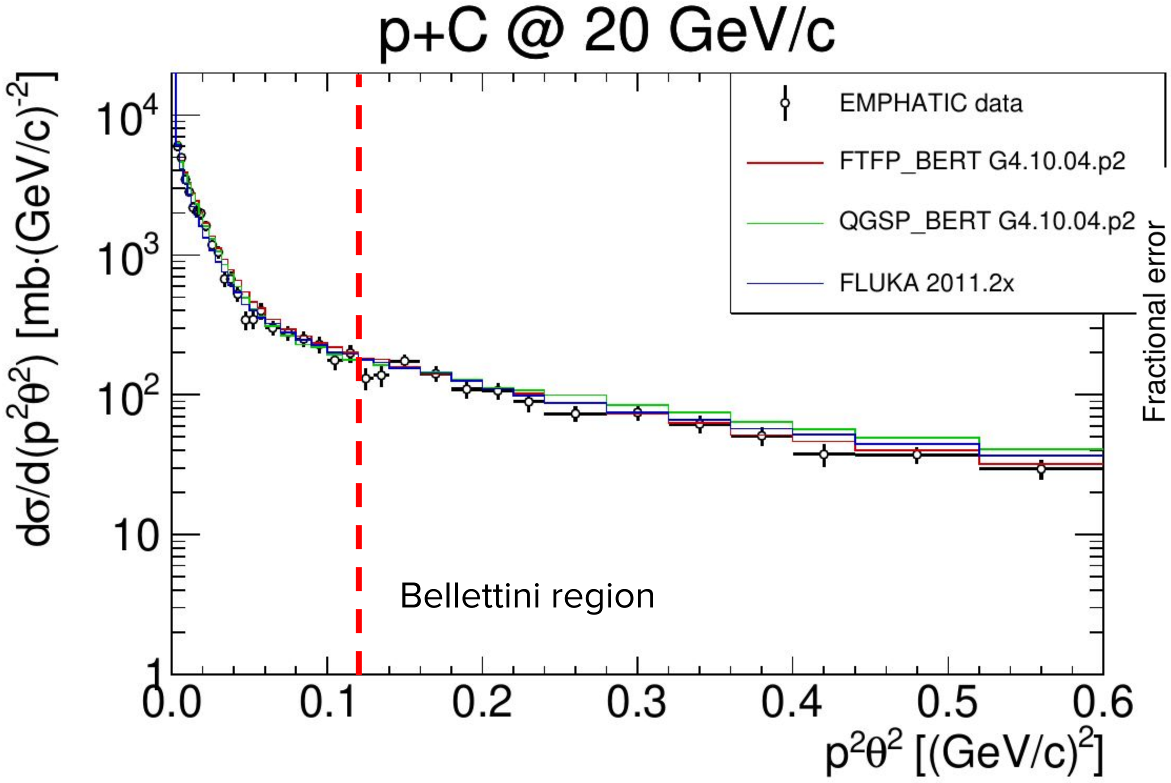
$$|t| \approx p^2\theta^2$$

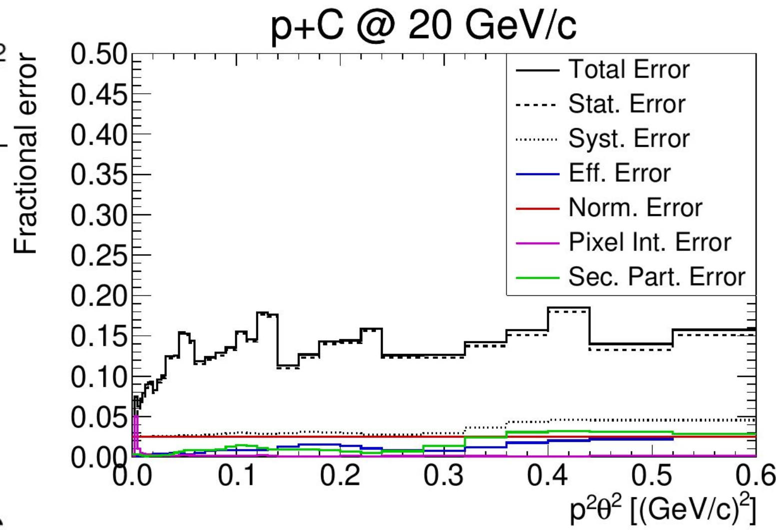
Beam momentum

Scattering angle



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

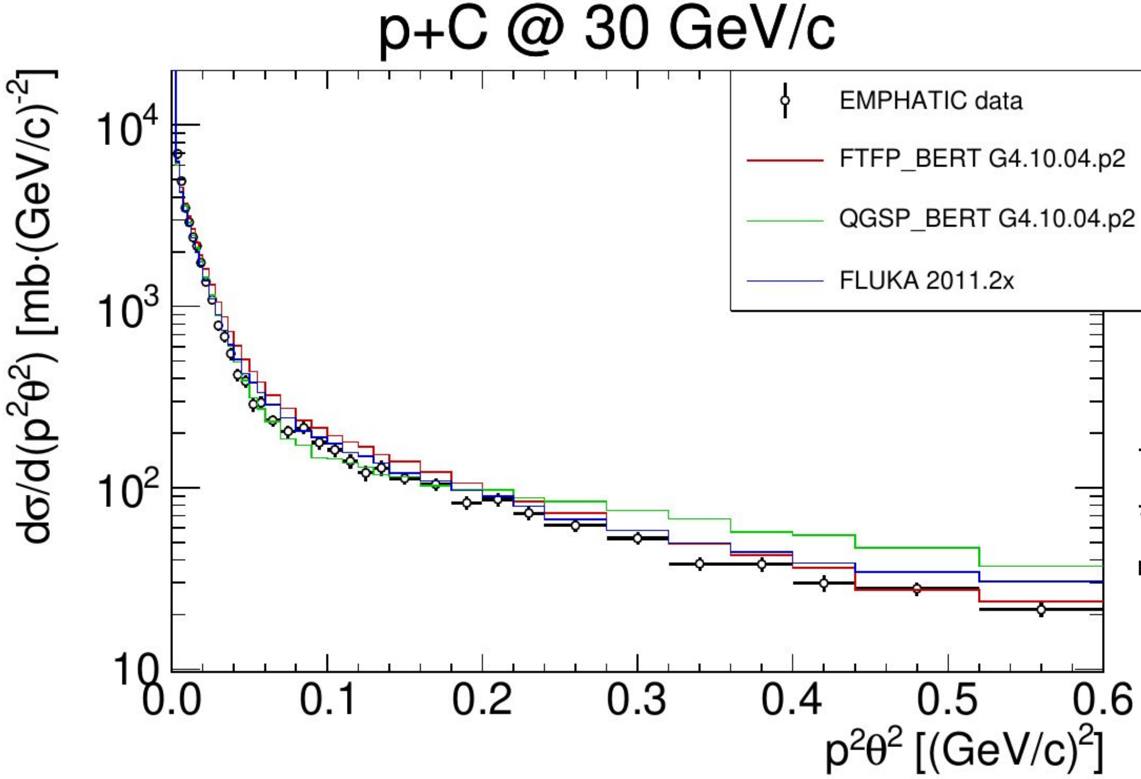


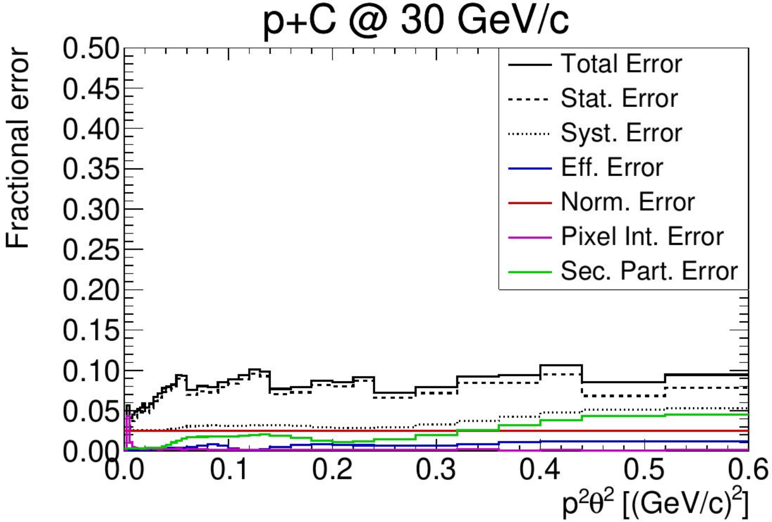


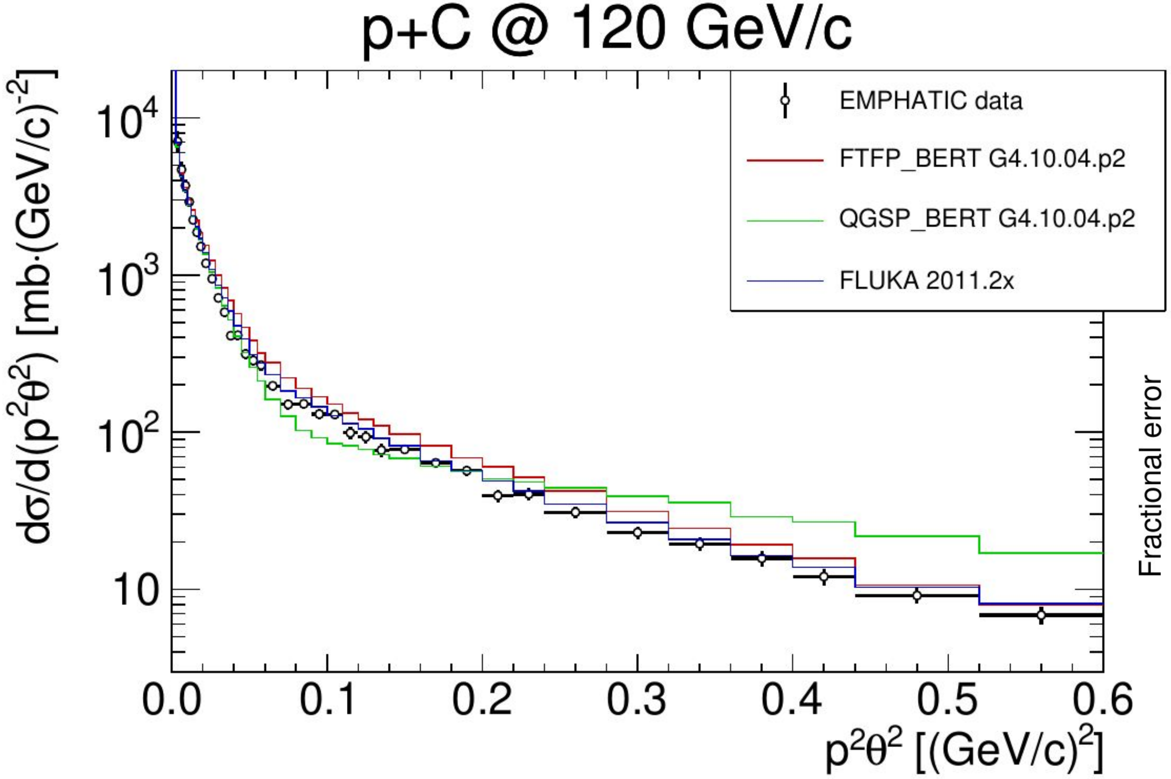
Outgoing track is a leading proton

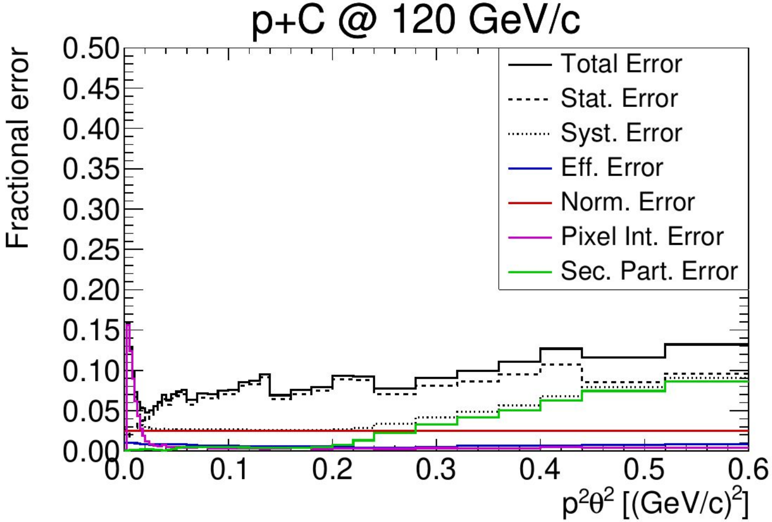
N_{pot} ➔ number of particles on target
N_i ➔ corrected number of measured tracks after the target
nd ➔ number density ⊗ target thickness
Δt_i ➔ four momentum bin size
i ➔ bin number

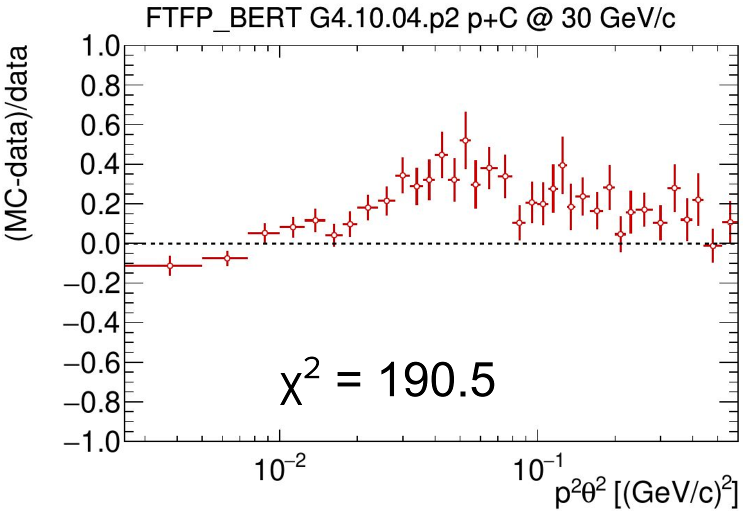
$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{N_{\text{pot}}} \frac{N_i}{nd\Delta t_i}$$

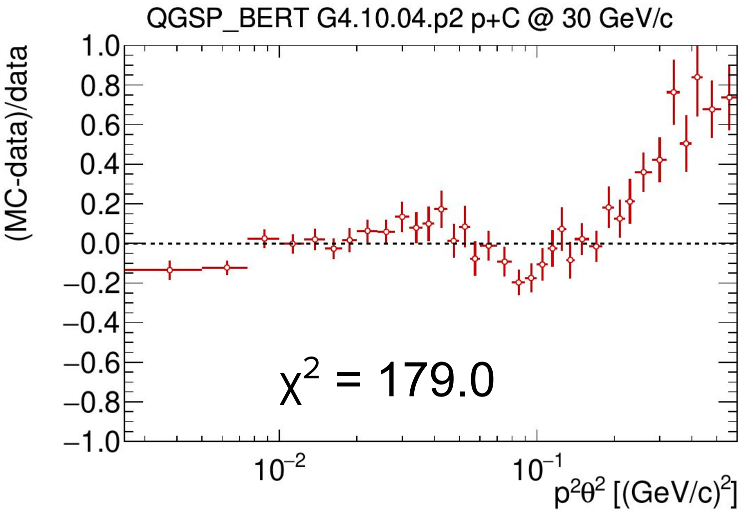

p+C @ 30 GeV/c
EMPHATIC data
FTFP_BERT G4.10.04.p2
QGSP_BERT G4.10.04.p2
FLUKA 2011.2x
dσ/d(p²θ²) [mb·(GeV/c)⁻²]
p²θ² [(GeV/c)²]

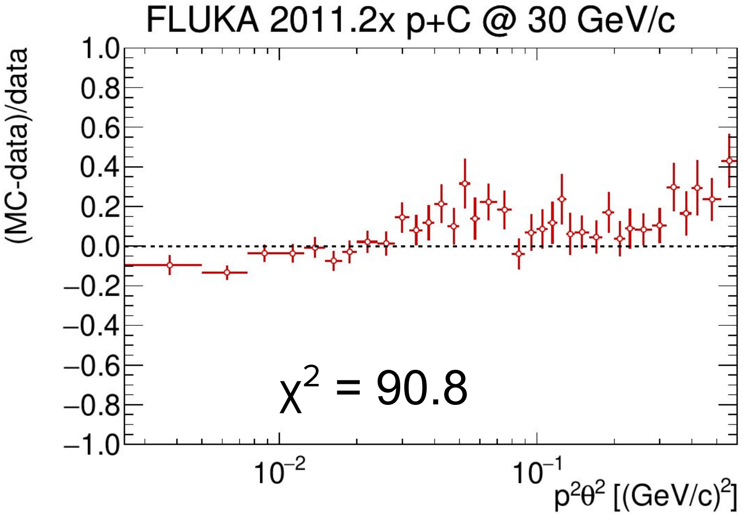

p+C @ 30 GeV/c
Total Error
Stat. Error
Syst. Error
Eff. Error
Norm. Error
Pixel Int. Error
Sec. Part. Error
Fractional error
p²θ² [(GeV/c)²]


p+C @ 120 GeV/c
EMPHATIC data
FTFP_BERT G4.10.04.p2
QGSP_BERT G4.10.04.p2
FLUKA 2011.2x
dσ/d(p²θ²) [mb·(GeV/c)⁻²]
p²θ² [(GeV/c)²]

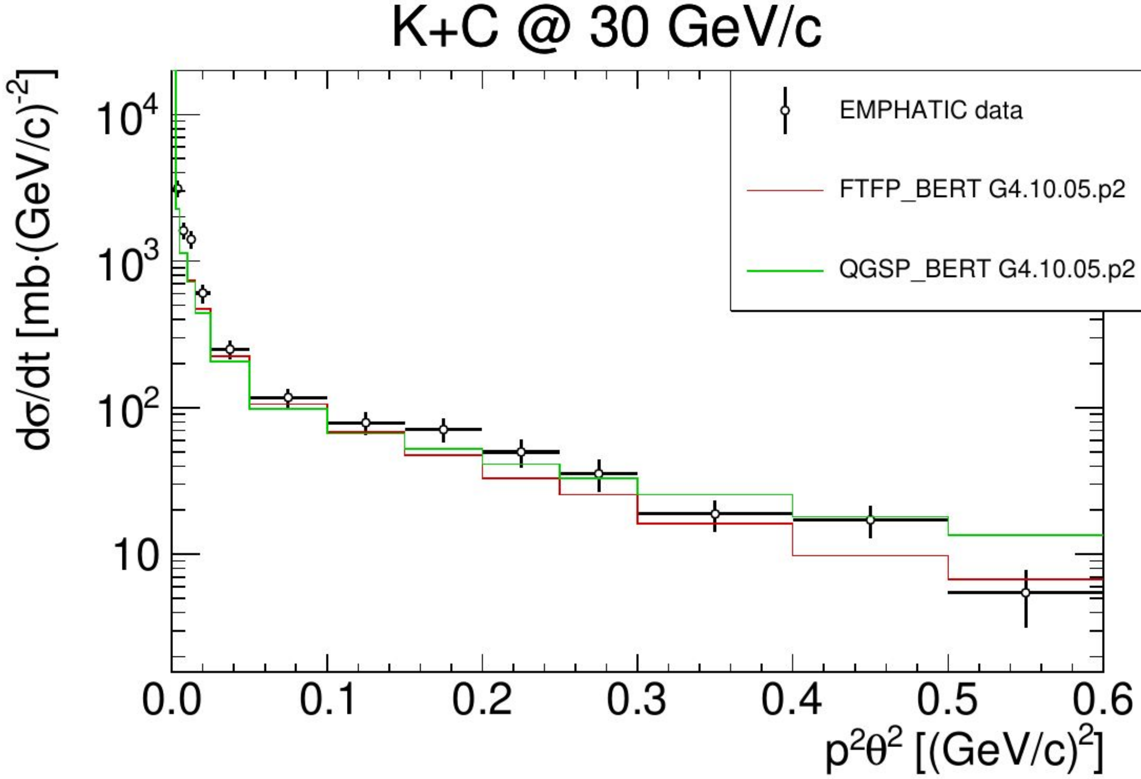

p+C @ 120 GeV/c
Total Error
Stat. Error
Syst. Error
Eff. Error
Norm. Error
Pixel Int. Error
Sec. Part. Error
Fractional error
p²θ² [(GeV/c)²]


FTFP_BERT G4.10.04.p2 p+C @ 30 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 190.5

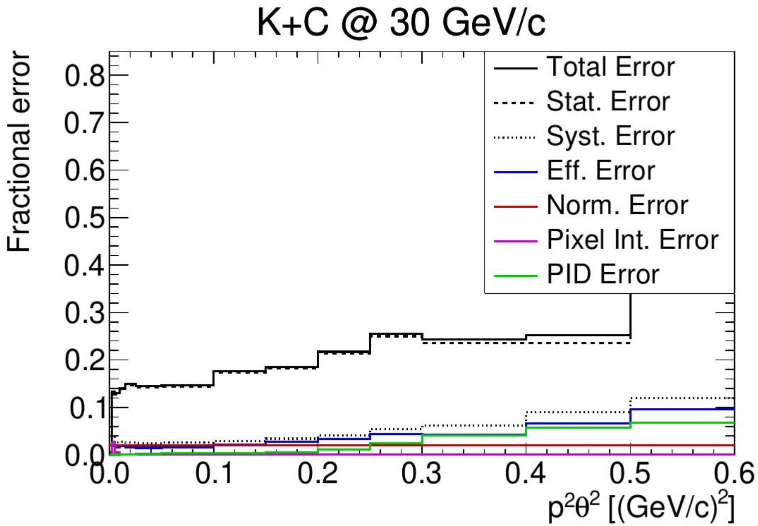

QGSP_BERT G4.10.04.p2 p+C @ 30 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 179.0


FLUKA 2011.2x p+C @ 30 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 90.8

dof = 37

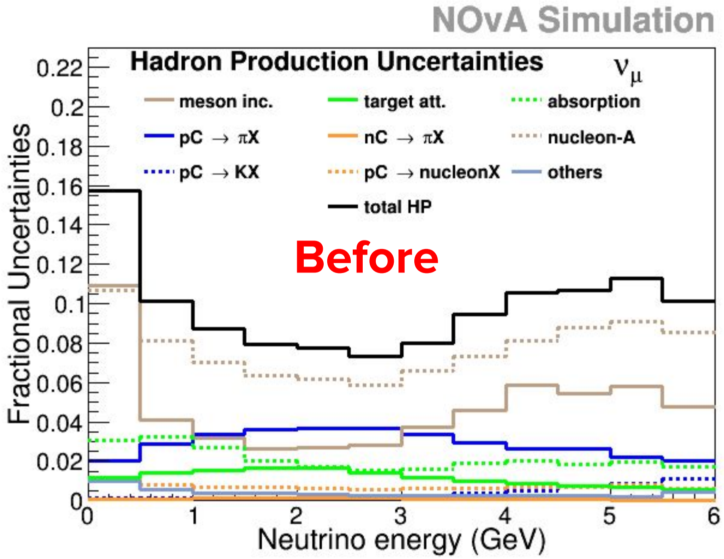


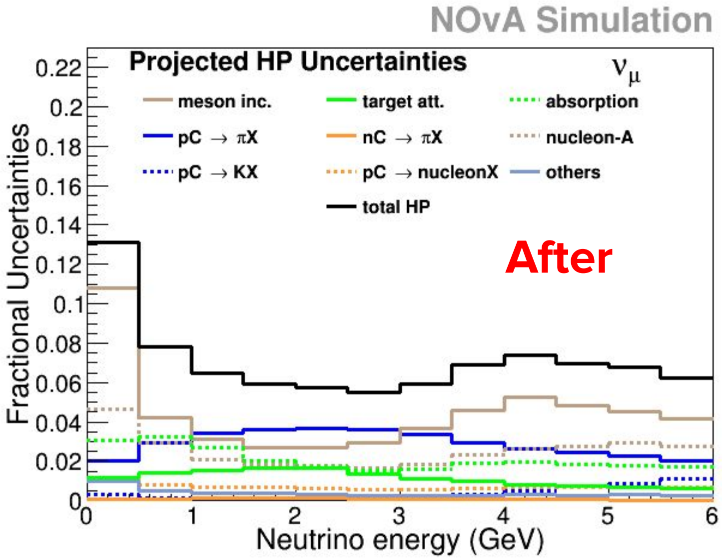
The first measurement of this type



Impact of the current results

- Quasi-elastic cross-section measurements can significantly impact the flux uncertainty in NOvA
- Assuming 10% uncertainty on proton-nucleus quasi-elastic interactions



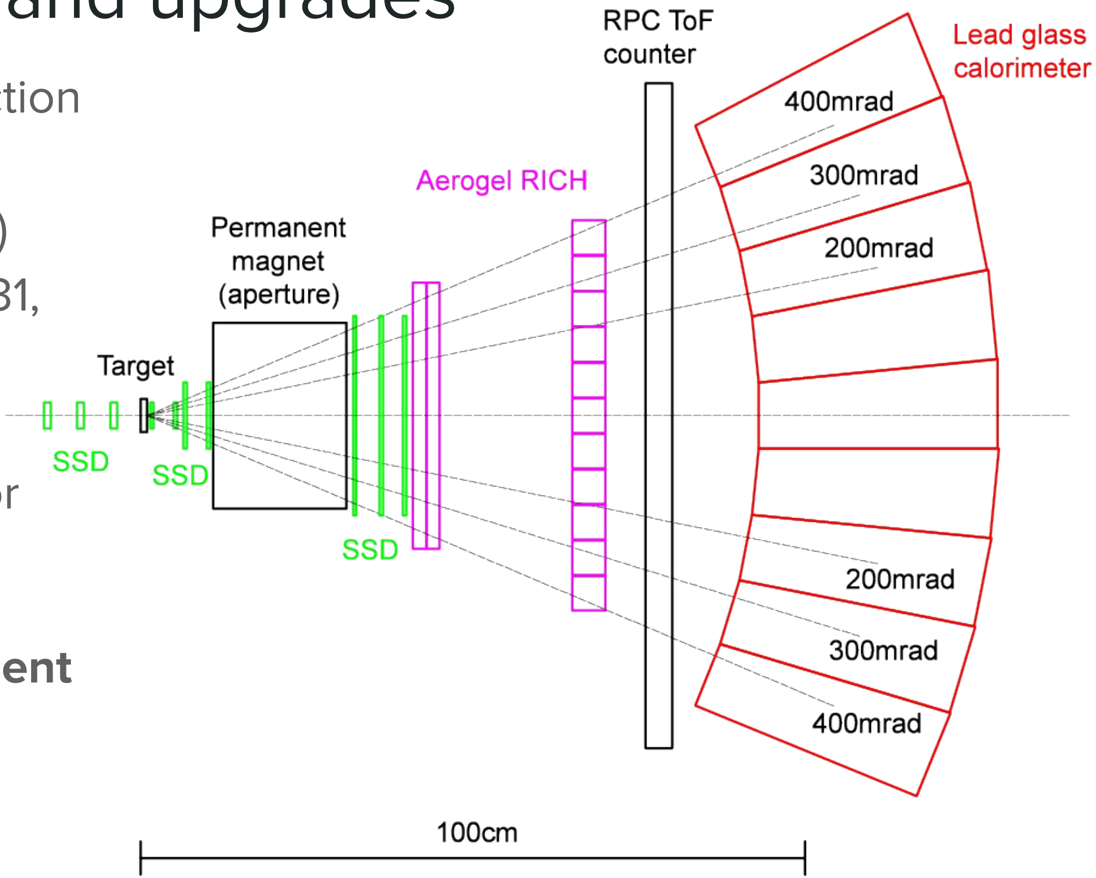


L. Aliaga, L. Cremonesi

Future measurements and upgrades

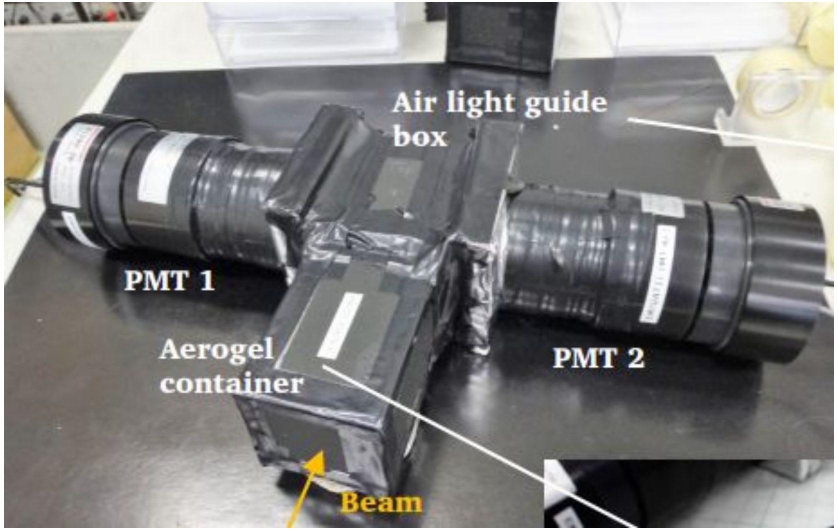
- Measurements of particle production and interaction probability (total cross-section, elastic, inelastic, ...)
- p, π, K + C, Al, Fe, @ 4, 8, 12, 20, 31, 60, 120 GeV/c
- 5, 10 and 20% λ_I C targets
- Additional targets B, BN, B_2O_3 for atmospheric neutrinos

- **We need momentum measurement and PID**



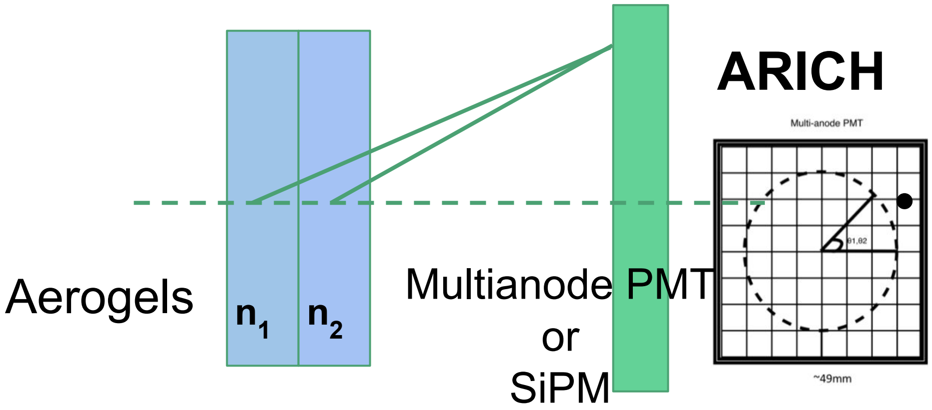
Threshold aerogel detector

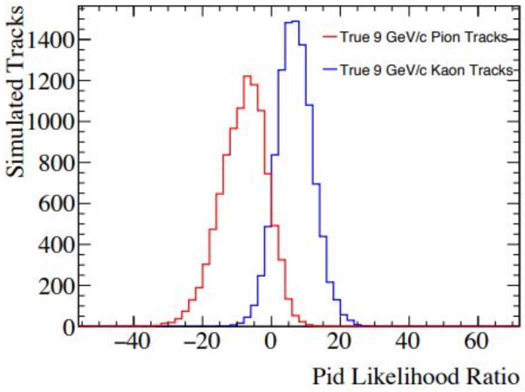
- Beam PID at lower momenta not possible with gas Cherenkov detectors
- Aerogel threshold Cherenkov
- Beam test
  - n = 1.004 ⇒ $N_{p.e.}$ = 5.7 (detection efficiency > 99%)
  - n = 1.012 ⇒ $N_{p.e.}$ = 16.8
  - n = 1.045 ⇒ $N_{p.e.}$ = 41.0

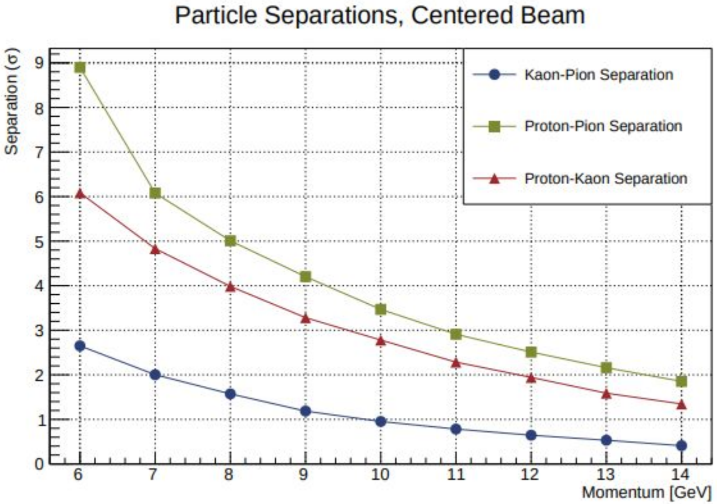


n	π threshold [GeV/c]	K threshold [GeV/c]	p threshold [GeV/c]
1.004	1.6	5.5	10.5
1.012	0.9	3.2	6.0

Aerogel RICH



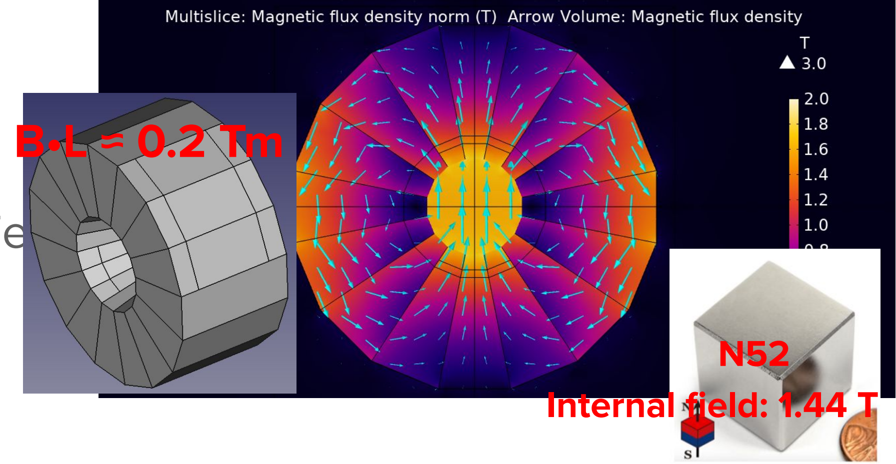


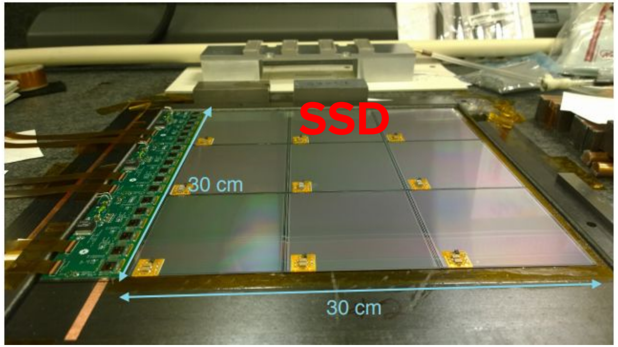


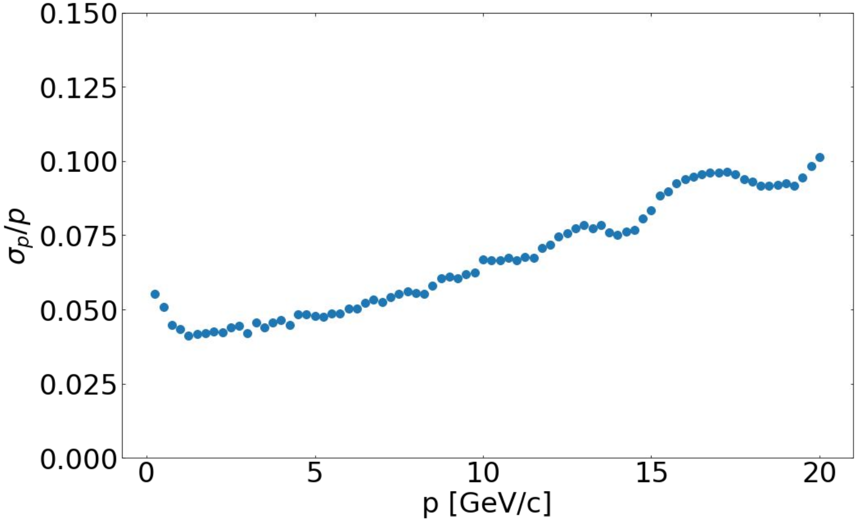
- Based on Belle II RICH detector
- Advances in aerogel production (Chiba U.)
- Beam test at TRIUMF in August
- 2σ π/K separation < 7 GeV/c
- 1σ π/K separation < 10 GeV/c

Particle tracking

- Large silicon strip detectors for tracking
- Compact NdFeB Halbach array → small NdFe segments are stacked to mimic the field inside a strong dipole magnet
- Current magnet design: ∅ 30 cm ⊗ 15 cm (~100 kg), 350 mrad coverage
- Whole tracking region is only 40 cm long
- Momentum resolution 4% - 10% for p < 20 GeV/c







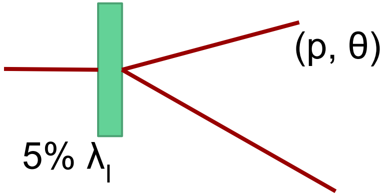
Conclusions

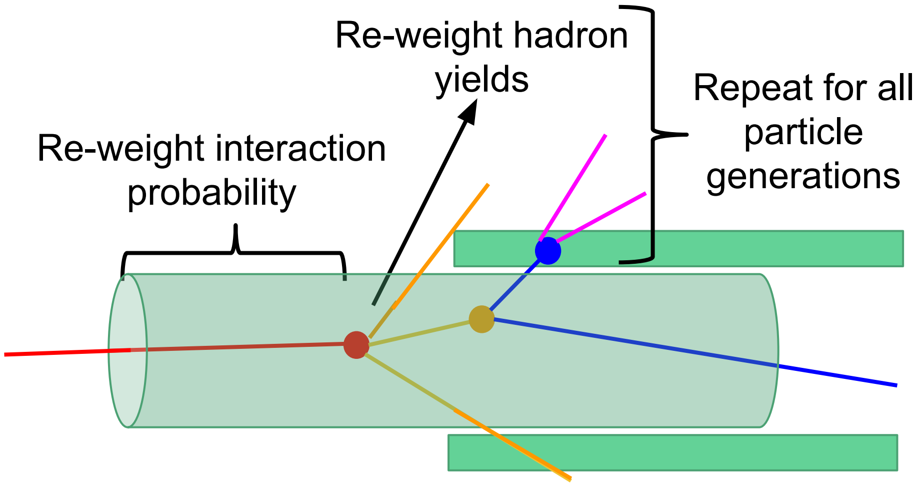
- Neutrino flux is the dominant uncertainty in single detector neutrino measurement
- Significant fraction of hadron interactions below 15 GeV/c are unconstrained ➜ we rely on models ➜ large systematic uncertainties ($>$ 10%)
- EMPHATIC is a table-top hadron production experiment at FTBF
- Main physics goal is to measure hadron interaction below 15 GeV/c
- Preliminary beam test was done in 2018
  - Test of the FTBF capabilities
- We were able to measure forward p+C scattering
- The results can already have significant impact on the NOVA systematics
- Future runs and upgrades are planned

BACKUP

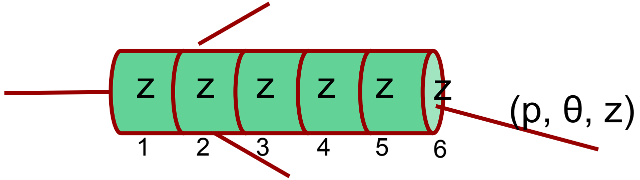
Hadron production measurements

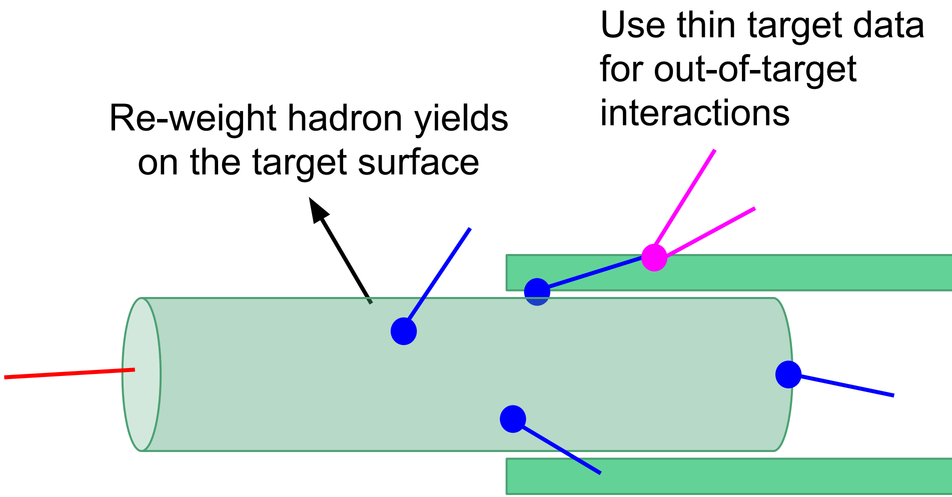
1 Thin target measurements





2 Replica target measurements

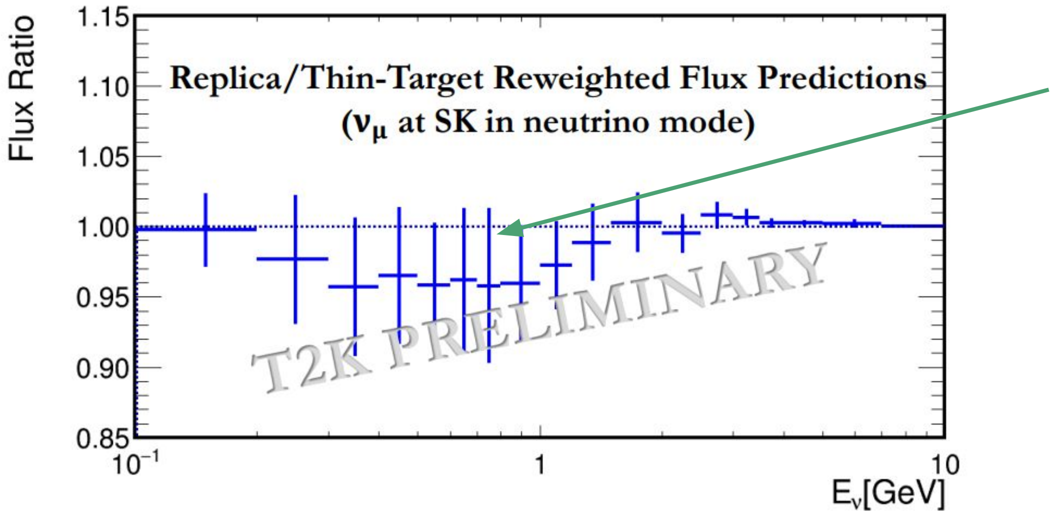




Both approaches are necessary to completely constrain neutrino flux!

Thin vs. replica target tuning

- T2K neutrino flux simulation with the NA61/SHINE replica target tuning predicts 5% lower flux
- Differences between thin vs. replica tuning were also observed when MIPP data was used at Fermilab
- Problems with interaction probability?

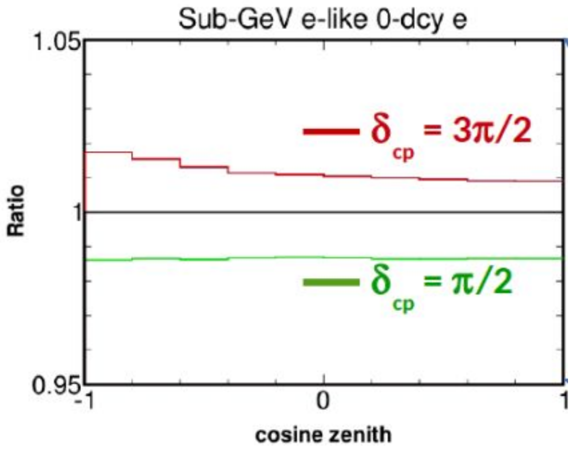


Uncertainty is dominated by differences between production cross-section measurements.

T. Vladisavljevic, arXiv:1804.00272

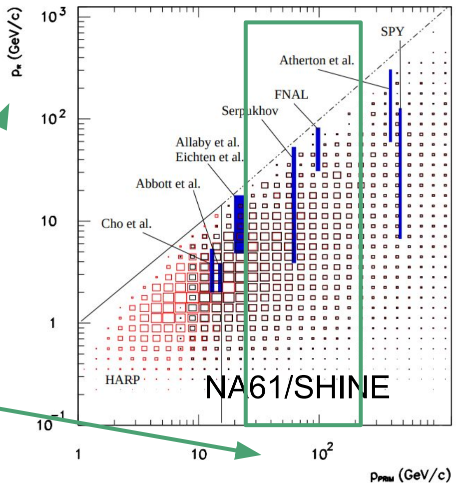
CP violation in atmospheric neutrino oscillations

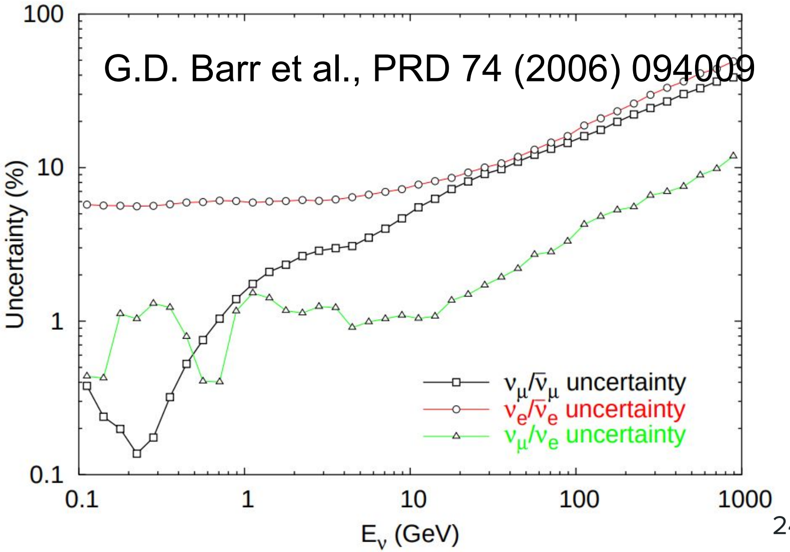
- Small effect (~2%) in sub-GeV neutrino sample
- The uncertainty is dominated by hadron production below 15 GeV (π^+/π^- ratio)
- Only HARP data covers the important region



Momentum of secondary pions

Momentum of primary cosmic ray

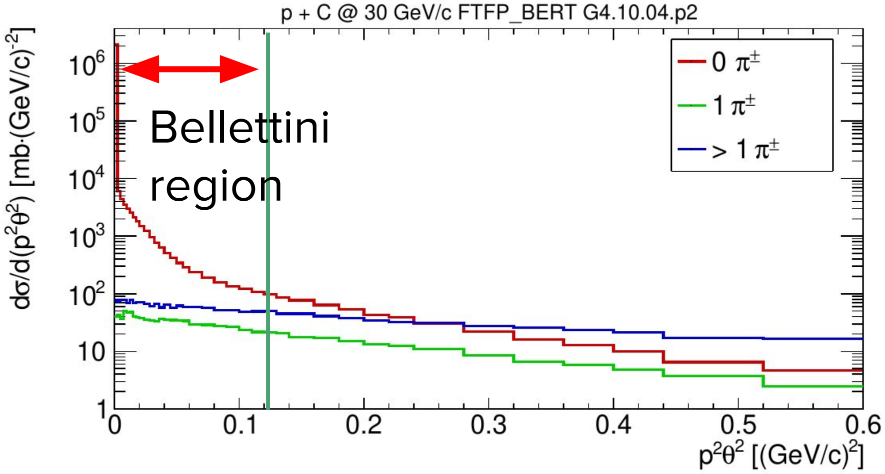




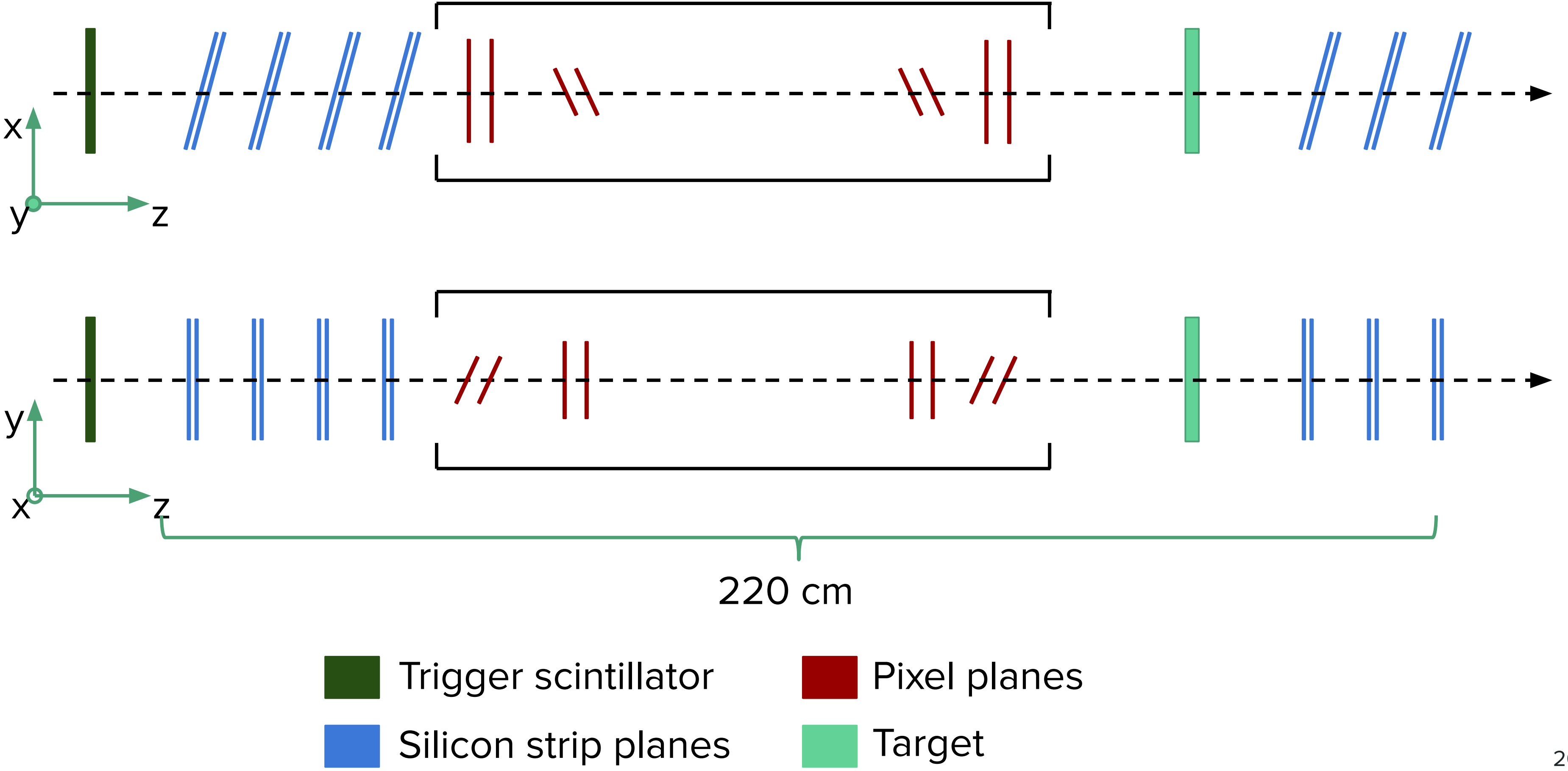
G.D. Barr et al., PRD 74 (2006) 094009

Differential cross-section measurement

- No PID or momentum measurement ➔ contamination from secondary particles and production events
- p + C ➔ p + X,   K + C ➔ K + X
- p or K are leading hadrons (highest momentum particle)
  - This definition minimizes MC corrections

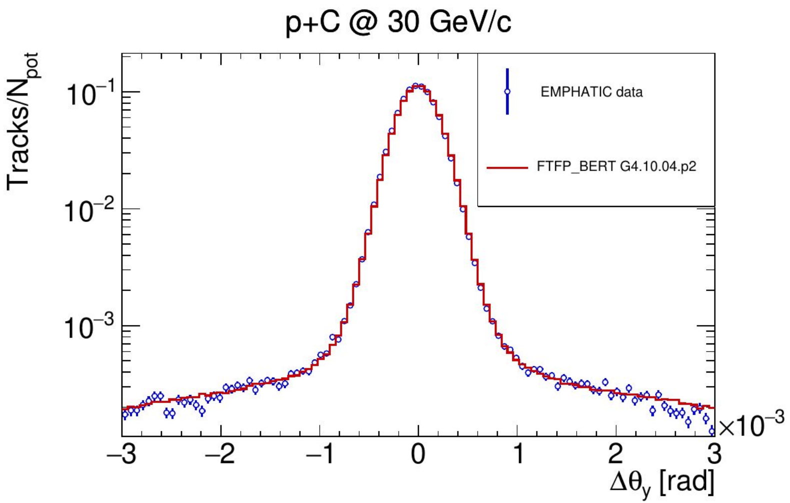


Particle tracking



Monte Carlo simulation

- Geant4.10.03.p02 simulation of the EMPHATIC setup
  - FTFP_BERT
  - QGSP_BERT
- FLUKA 2011.2x
- Beam profile and divergence distributions from the data are used to generate beam particles
- Simulation includes silicon strip planes, pixel planes, trigger scintillator, and the target
- Good agreement between angular resolution in the data and Monte Carlo (<4%)

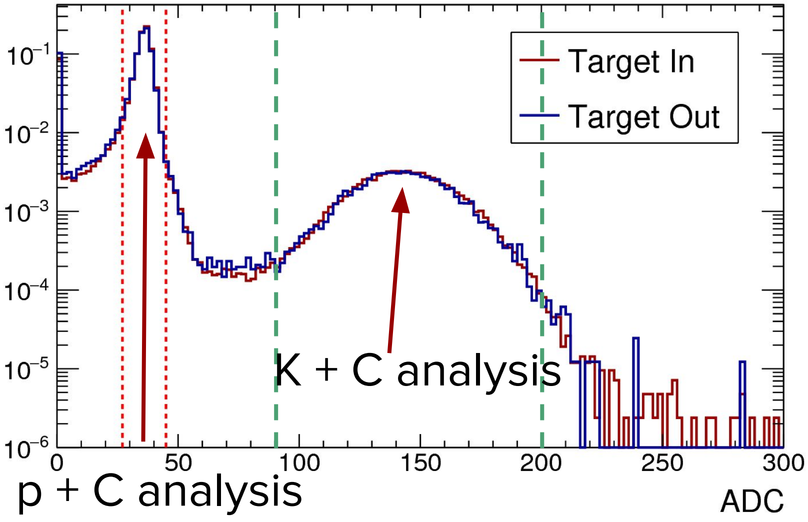


σ (data) = 0.207 mrad
σ (MC) = 0.209 mrad

Upstream selection

- Gas Cherenkov selection
- Single upstream track
- Maximum number of clusters
- Upstream track $\chi^2 < 6$
- Beam divergence cut (remove SSD interactions)
- Beam profile cut

Remove upstream interactions



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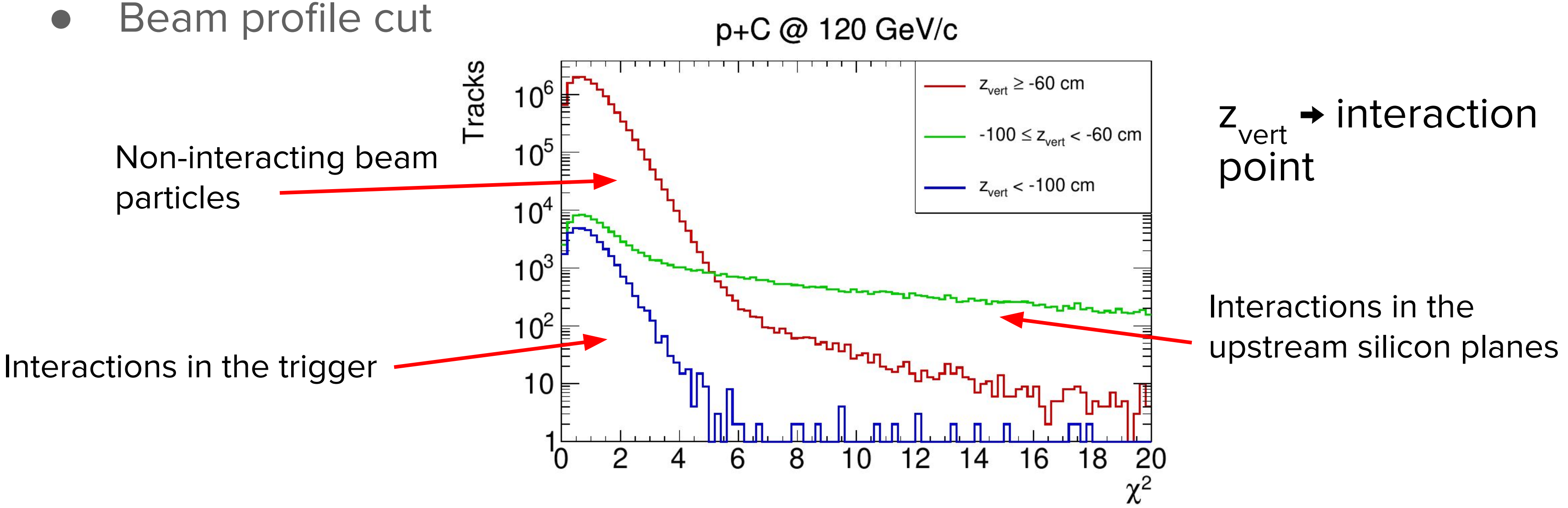

z_{vert} ➔ interaction point

Upstream selection

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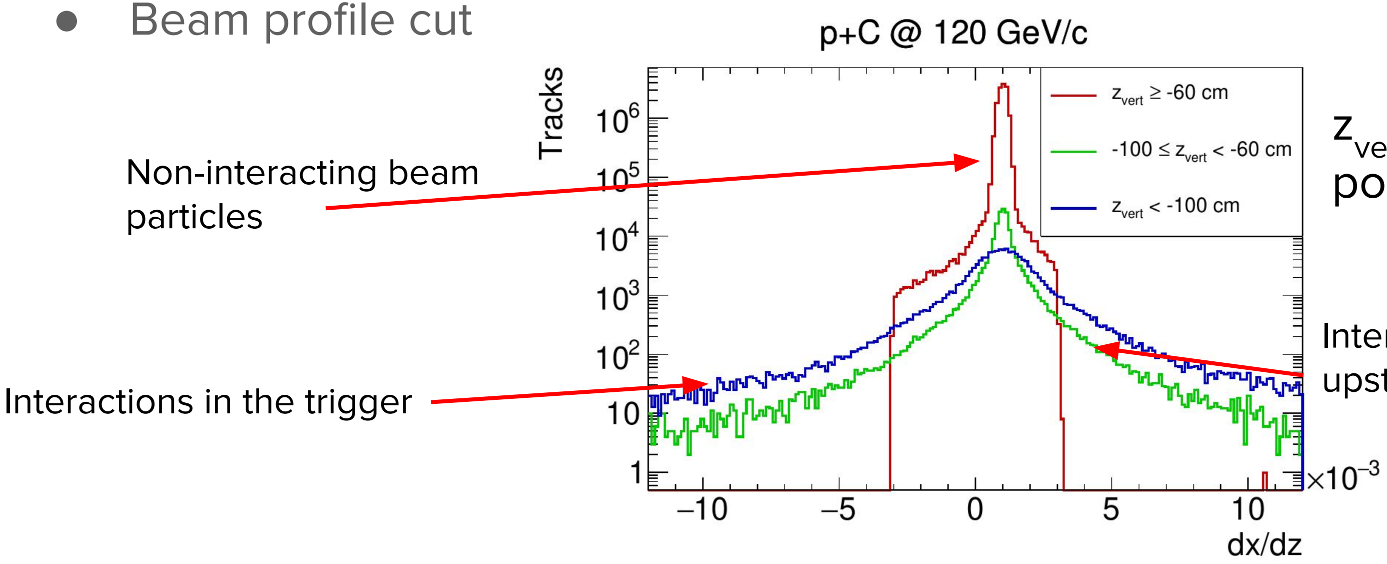
- Beam profile cut

Remove upstream interactions

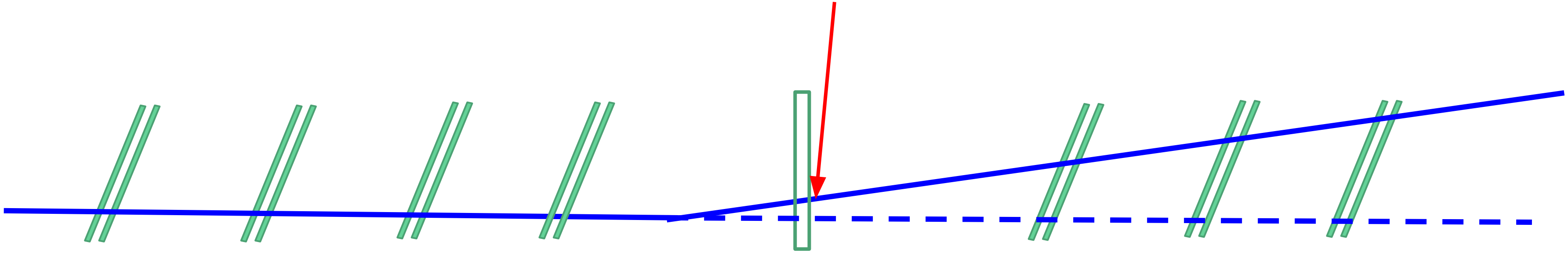


z_{vert} ➜ interaction point

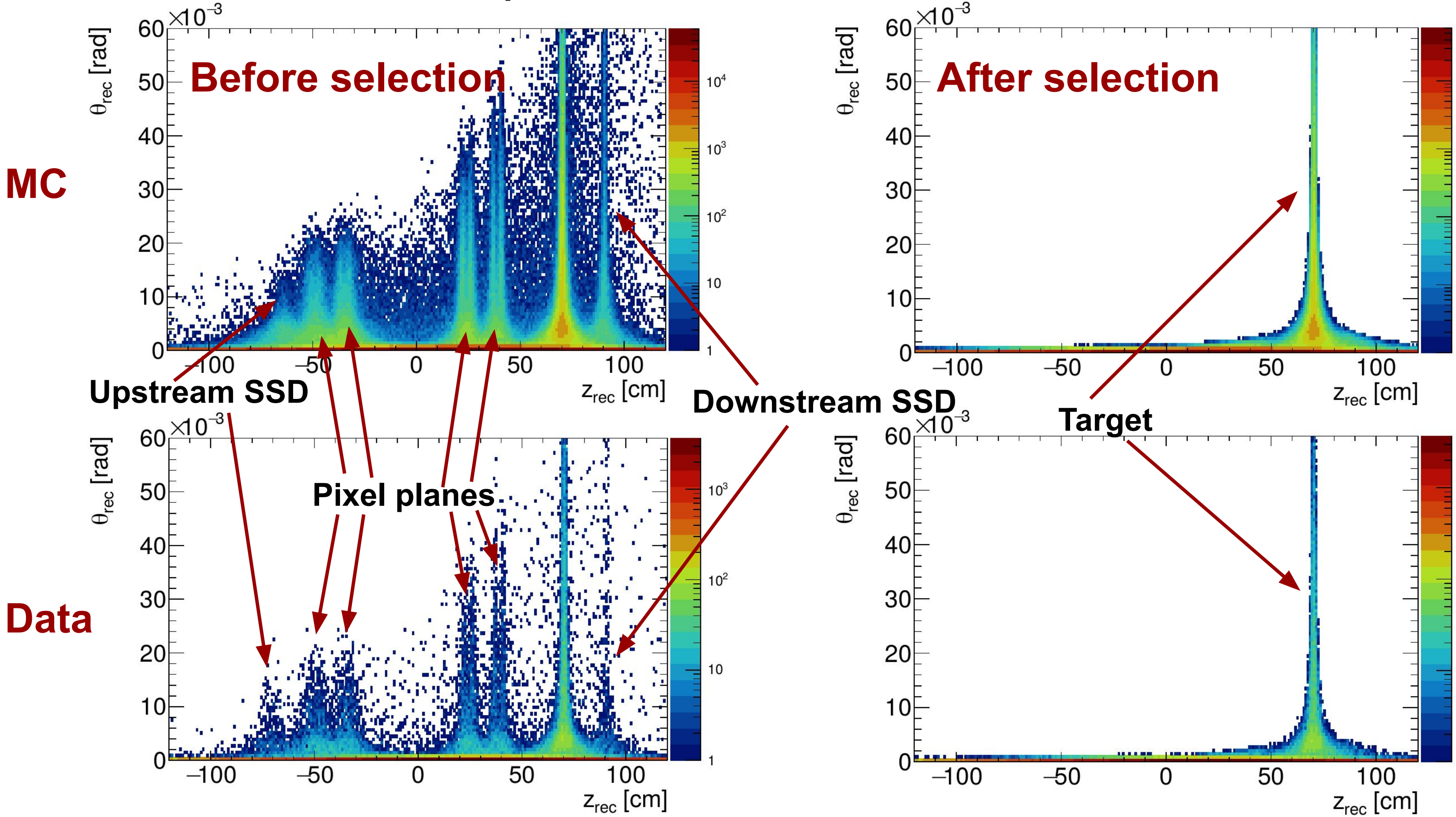
Downstream selection

- Single downstream track
- Maximum number of clusters (6)
- Downstream track $\chi^2 < 4$
- δx and δy cuts ➔ difference in upstream and downstream x(y) track position at target z position

If the position difference is > 3σ,
event is removed

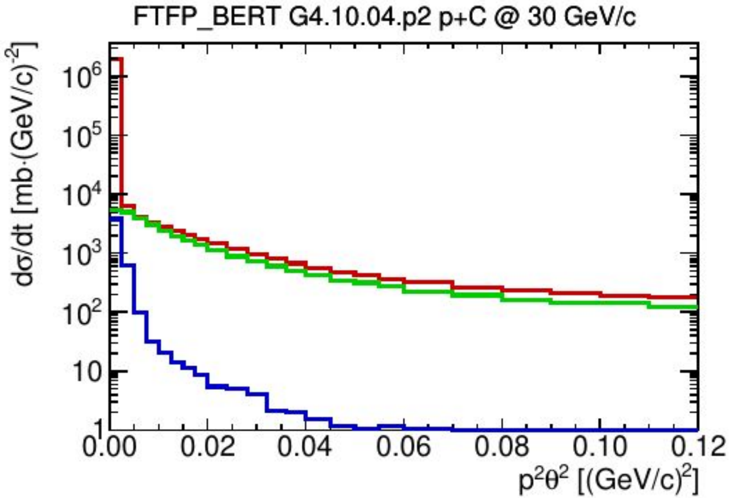


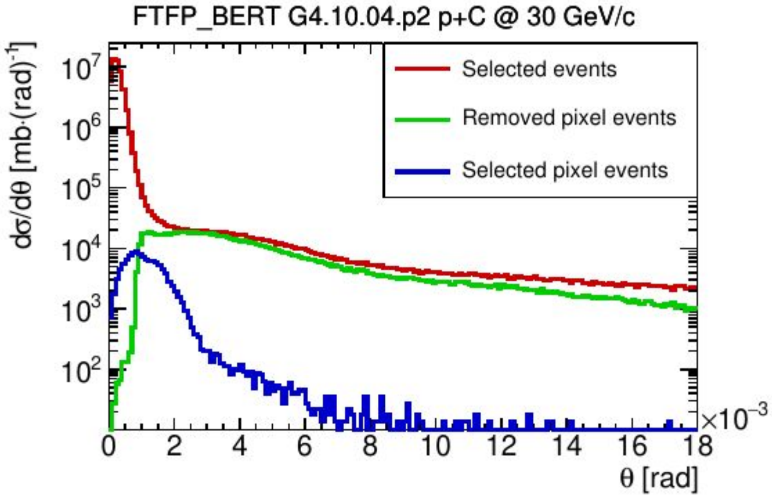
Interactions in the pixel detector



Pixel interactions

- Selected pixel interactions ➔ shape correction only in forward bins
- Lost particles on target ➔ normalization correction



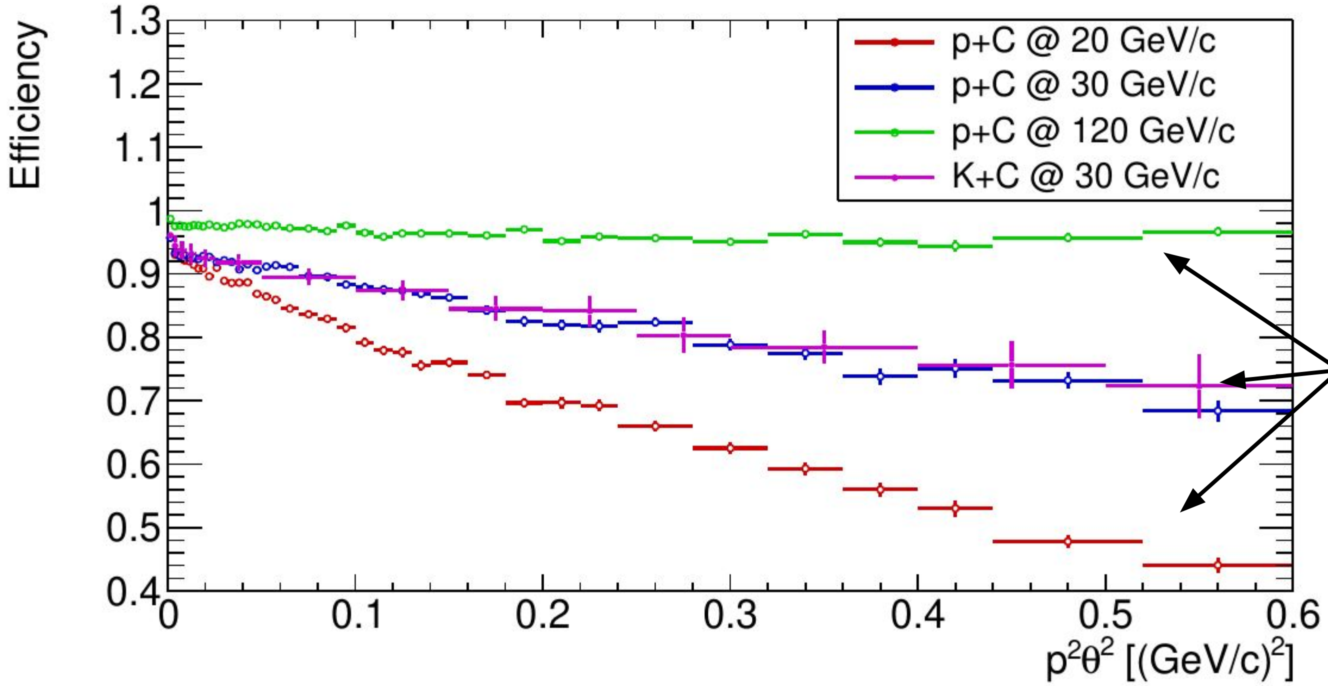


	p+C @ 20 GeV/c	p+C @ 30 GeV/c	p+C @ 120 GeV/c	K+C @ 30 GeV/c
POT correction [%]	**5.2**	**4.5**	**4.3**	**2.9**

Efficiency

$$\epsilon_i = \frac{N_i^{\text{MC true, down. sel.}}}{N_i^{\text{MC true}}}$$

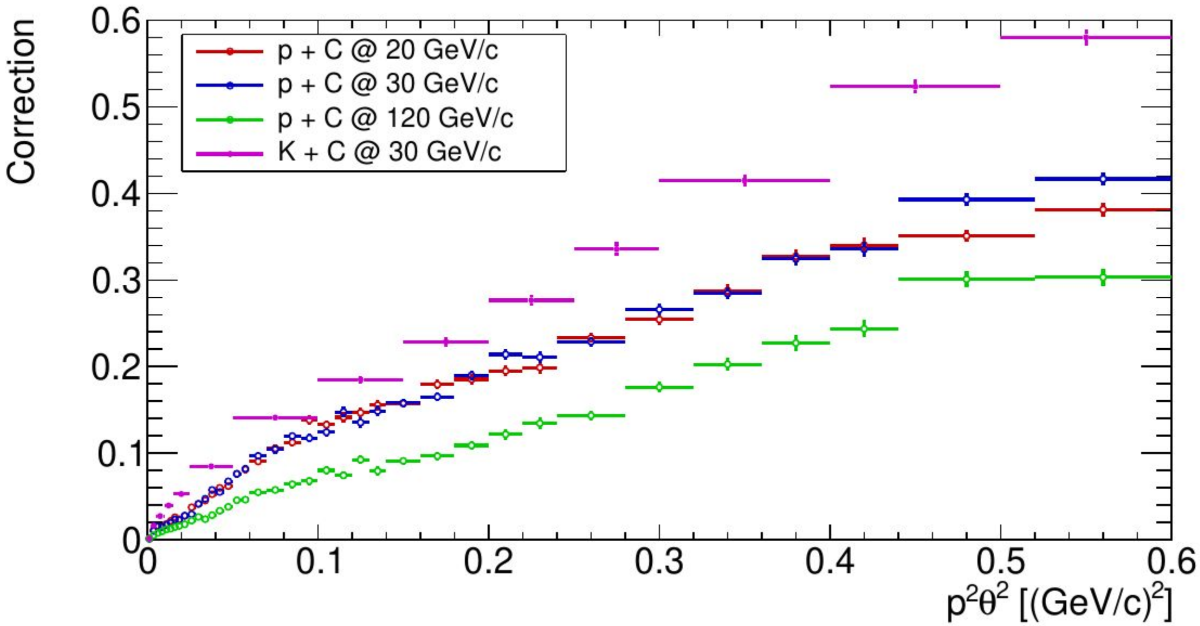
Includes: reconstruction + **acceptance** + selection



Differences between datasets are due to the beam size and acceptance effects.

Secondary particles

- Secondary hadrons produced in the target and reconstructed in downstream layers
  - pions, kaons, and non-leading protons in p+C
  - pions, protons, and non-leading kaons in K+C

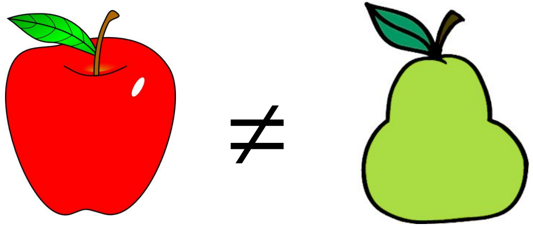


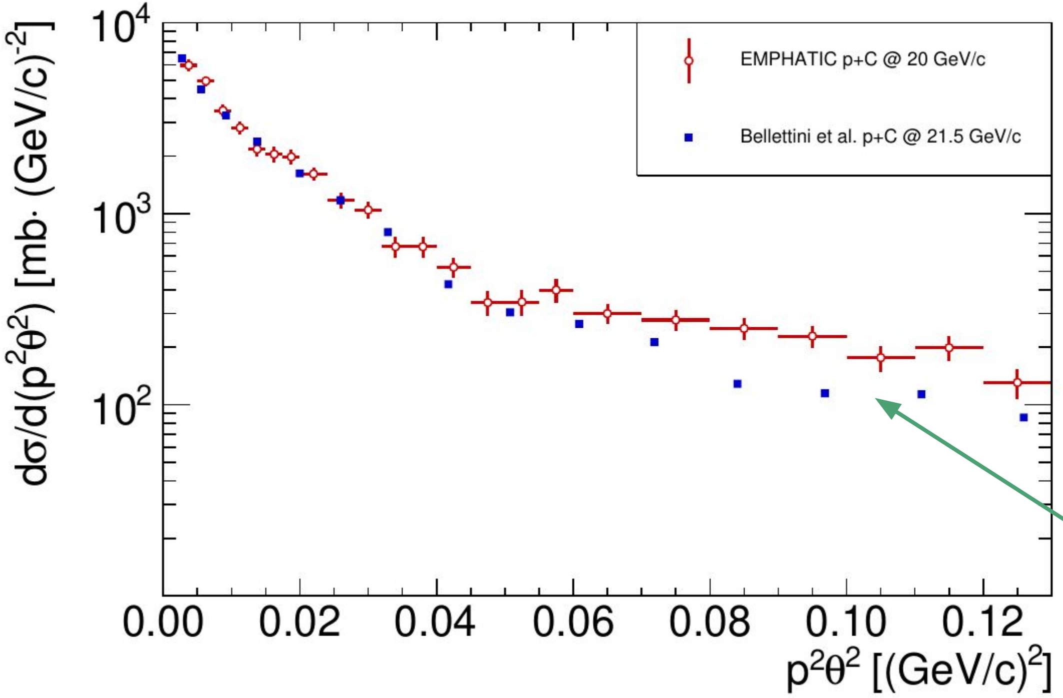
Systematic uncertainties

Strategy:

- Use data to estimate systematics
- If not possible use MC ➜ largest difference between models

1. Beam contamination (kaons in proton beam) ➜ **negligible << 1% contamination**
2. Upstream interactions in the trigger scintillator or SSDs ➜ **negligible < 0.5%**
3. Pixel interactions (shape) ➜ only forward bins **negligible above $t=0.01$ GeV^2**
4. Secondary particles (not leading protons or kaons) **<6%**
5. Efficiency uncertainty (model dependance) **<3%**
6. Normalization (target thickness and density + pixel POT correction)
    a. Dominated by density uncertainty **(2%)** + pixel normalization uncertainty **(0.5%)**





Bellettini et al.

- Angular coverage 1.5 - 20 mrad
- Momentum measurement ➔ contamination of inelastic events 1%
- Uncertainties are not known

EMPHATIC and Bellettini do not measure the same thing!

- EMPHATIC includes resonance production

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