EMPHATIC Results

Matej Pavin,
on behalf of the EMPHATIC collaboration

JETP Seminar, Fermilab
May 10, 2019

EMPHATIC

- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam **I**n **C**hicagoland
- 15-20 people
- Hadron production measurements for neutrino experiments

WICHITA STATE UNIVERSITY

TRIUMF

名古屋大学
NAGOYA UNIVERSITY

KOBE UNIVERSITY

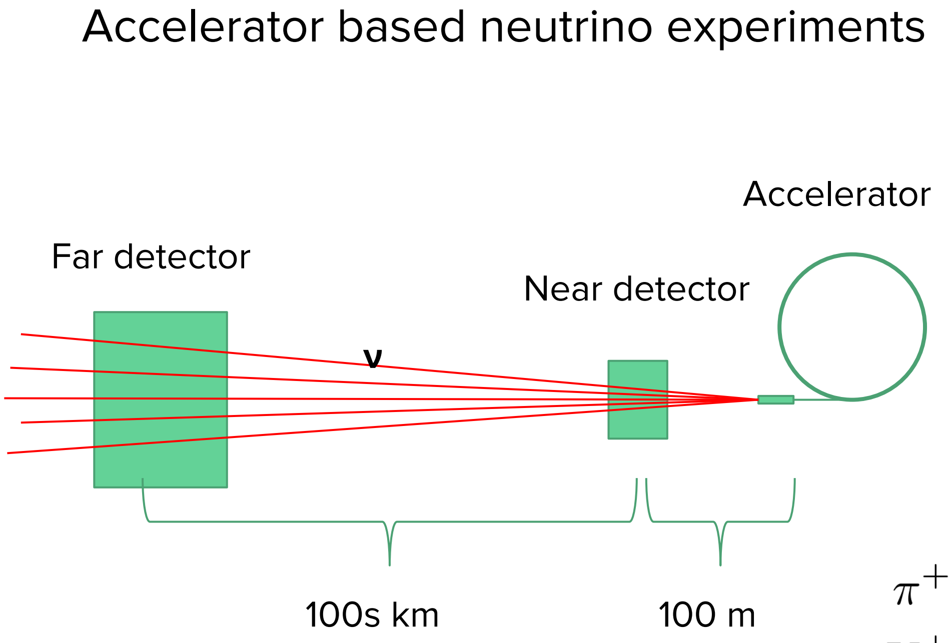
CHIBA UNIVERSITY

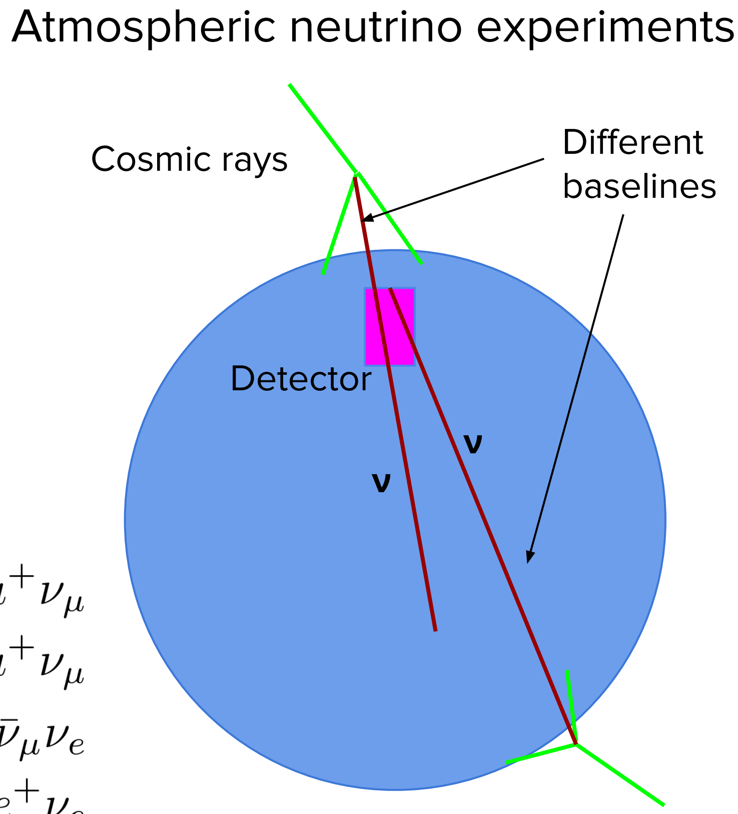
Fermilab

KAVLI IPMU

KEK

Accelerator and atmospheric neutrino experiments



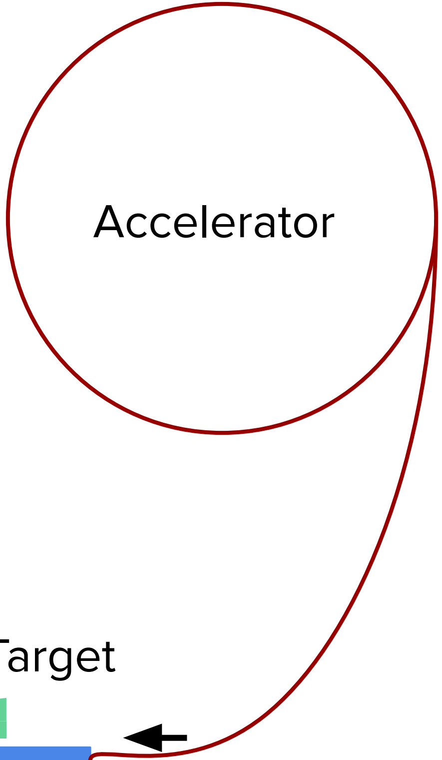


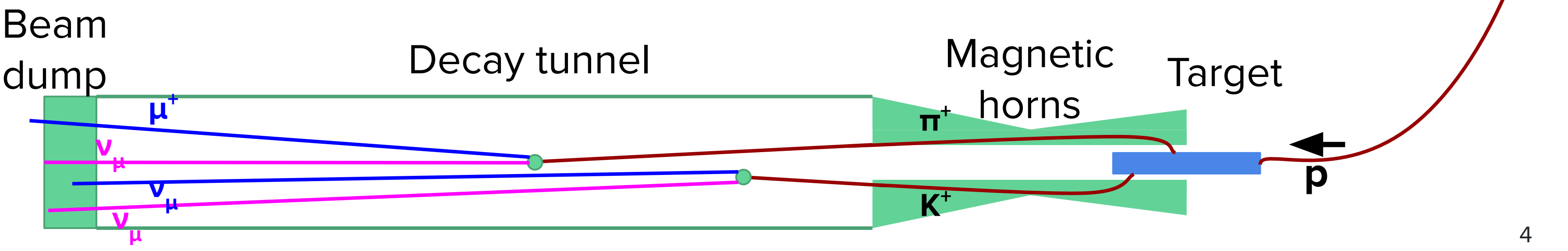
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$K^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$
$$K_L^0 \rightarrow \pi^- e^+ \nu_e$$

In both types of neutrino experiments, neutrino flux is produced from hadronic interactions.

Neutrino beams in accelerator neutrino experiments

- T2K, NOνA, MINERνA, **HK, DUNE**
- Proton beam is directed toward a long target
  - Thickness: ~2 interaction lengths
- Produced hadrons are focused or defocused by a set of magnetic horns
- Neutrinos are produced from pion, kaon and muon decays
- Other particles are stopped in the beam dump



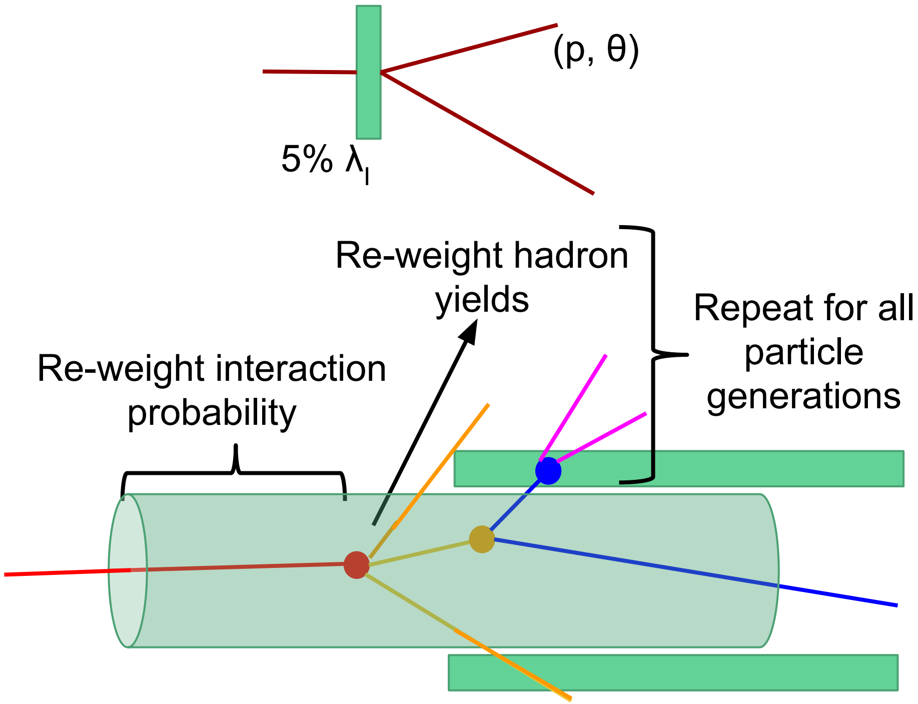


Neutrino beams in accelerator neutrino experiments

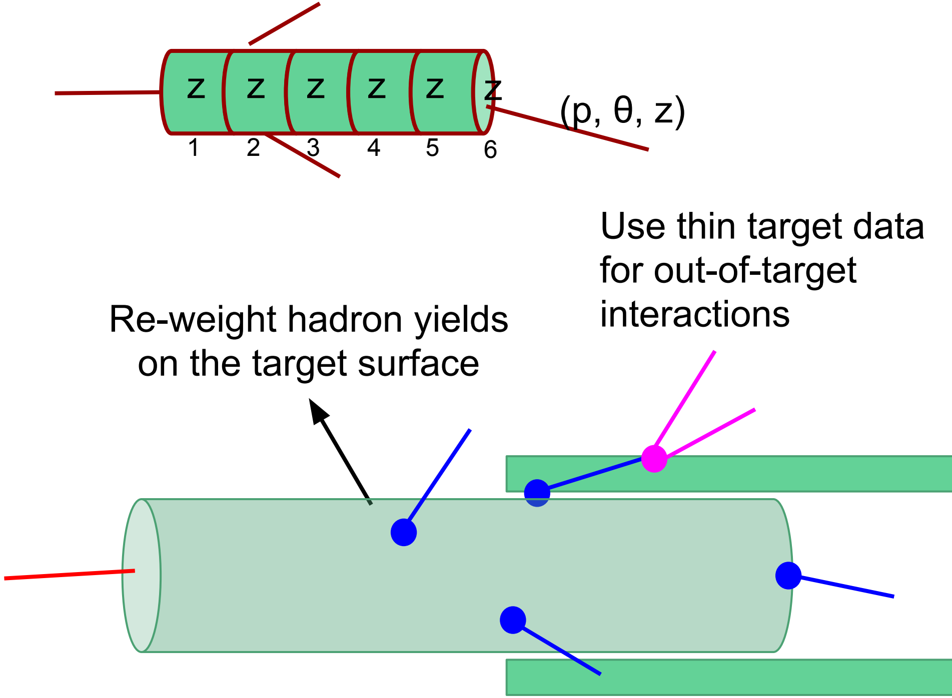
- Produced neutrino flux is difficult to measure
    - Near detectors measure flux⊗cross-section
    - ν-e scattering ➔ low statistics
    - Direct measurement of produced hadrons is very challenging (high radiation area, complex geometry)
- Monte Carlo models are used to estimate the neutrino flux
    - ~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

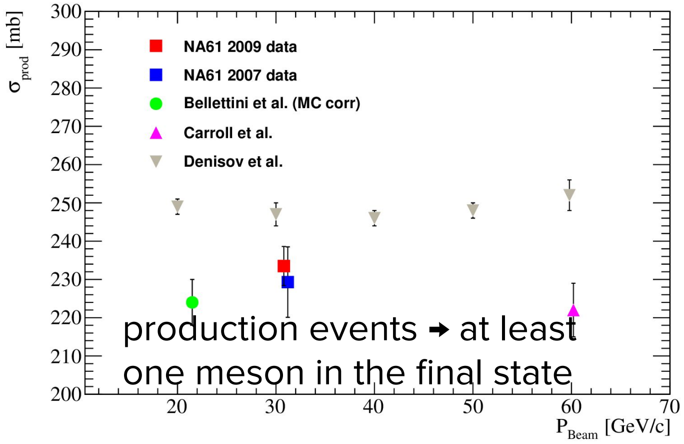


Both approaches are necessary to completely constrain neutrino flux!

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%)**

Is flux uncertainty important?

- Next gen. experiments: DUNE and Hyper Kamiokande
  - limited by systematics
- **Accelerator based neutrino oscillation measurements use far/near ratio → flux systematics mostly cancel out**
- Both experiments will have broad near detector programme
  - Neutrino-nucleus cross-sections
  - Sterile neutrino/ non-standard interactions
  - …
- **Single detector measurements → limited by neutrino flux systematics**
- **CP violation measurement with atmospheric neutrinos is limited by the flux**

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

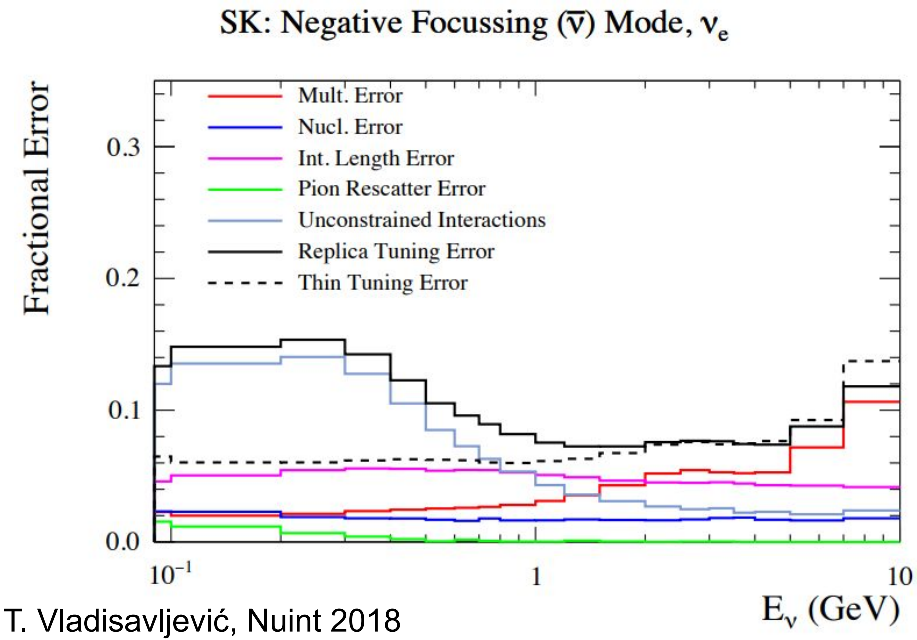
- Measurements with T2K off-axis near detector
- Limited by flux systematics

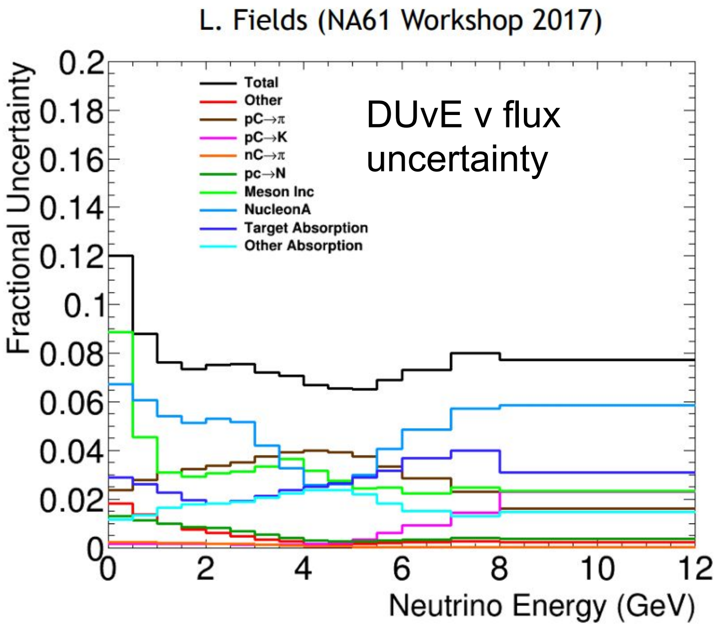
	Statistics [%]	**Flux [%]**	Cross-section model [%]	Detector [%]
σ(ν)	0.87	**9.14**	1.16	2.63
σ(anti-ν)	3.22	**9.37**	2.13	1.82
σ(anti-ν)/σ(ν)	3.22	**3.58**	1.56	1.11

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

Flux uncertainty at T2K(T2HK) and DUNE

- T2K flux uncertainty at low energies is limited by the untuned interactions outside of the target ($\pi^{\pm} + Al \rightarrow \pi^{\pm} + X$, $K^{\pm} + Al \rightarrow K^{\pm} + X$)
  - Untuned ➔ not covered by hadron production measurements
- Nearly 50% of wrong-sign neutrinos come from interactions outside of the target



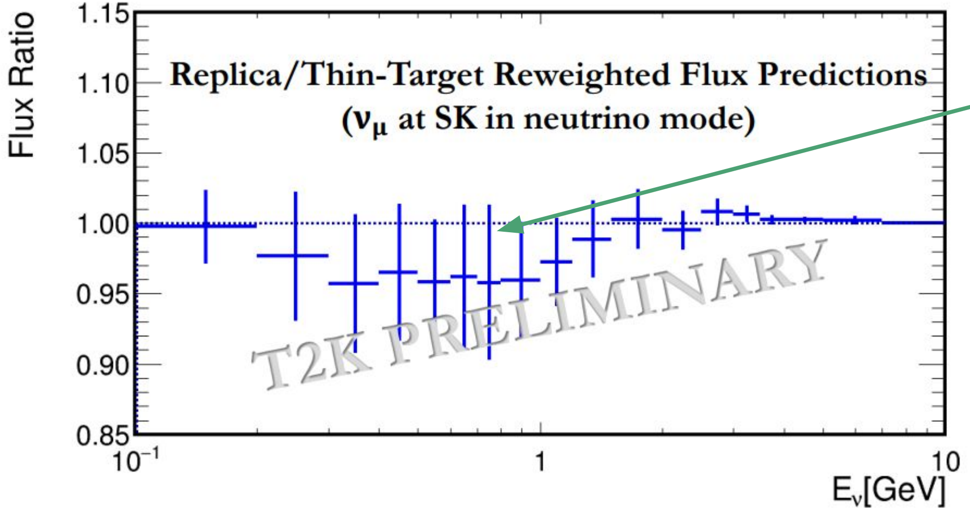


T. Vladisavljević, Nuint 2018

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?

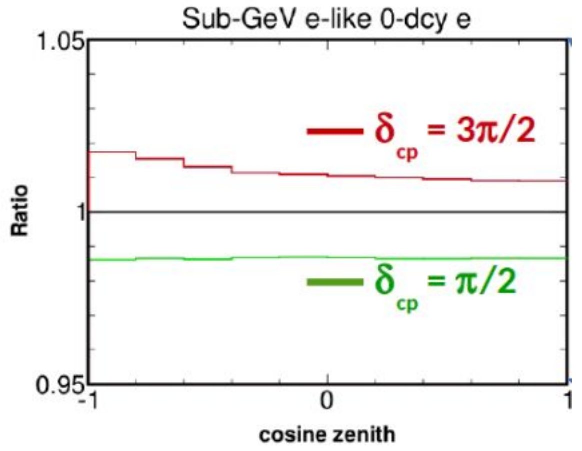
Uncertainty is dominated by differences between production cross-section measurements.



T. Vladisavljevic, arXiv:1804.00272

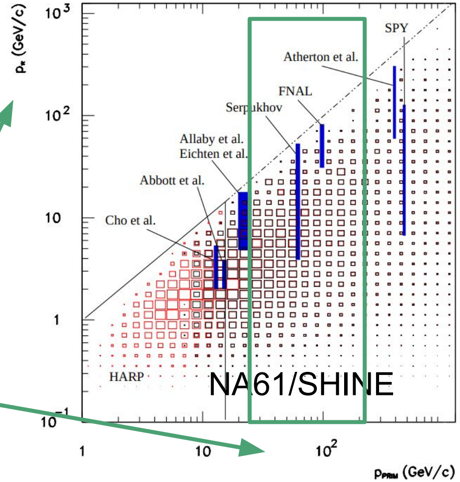
CP violation in atmospheric neutrino oscillations

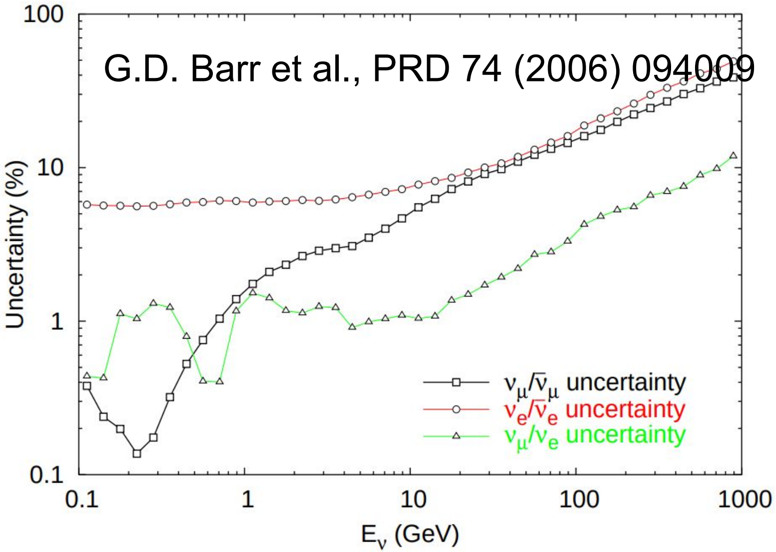
- Small effect (~2%) in sub-GeV neutrino sample
- The uncertainty is dominated by hadron production below 15 GeV (π^+/π^- ratio)
- Only HARP data covers the important region



Momentum of secondary pions

Momentum of primary cosmic ray





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 thin vs. replica target tuning issues
- High momentum measurements for NuMI beam simulation

- **Preliminary beam test was done in January 2018**

EMPHATIC data-taking in January 2018

- Fermilab Test Beam Facility (FTBF)
- 2 weeks
- 16 people, 7 institutions
- Goals:
  - Confirm that FTBF is suitable for hadron production measurements (beam quality)
  - Measure the angular resolution of silicon strip detectors
  - Test of the emulsion data-taking
  - Beam test of threshold aerogel Cherenkov detectors
  - Measurements of total, elastic and quasi-elastic cross-sections (best case scenario)

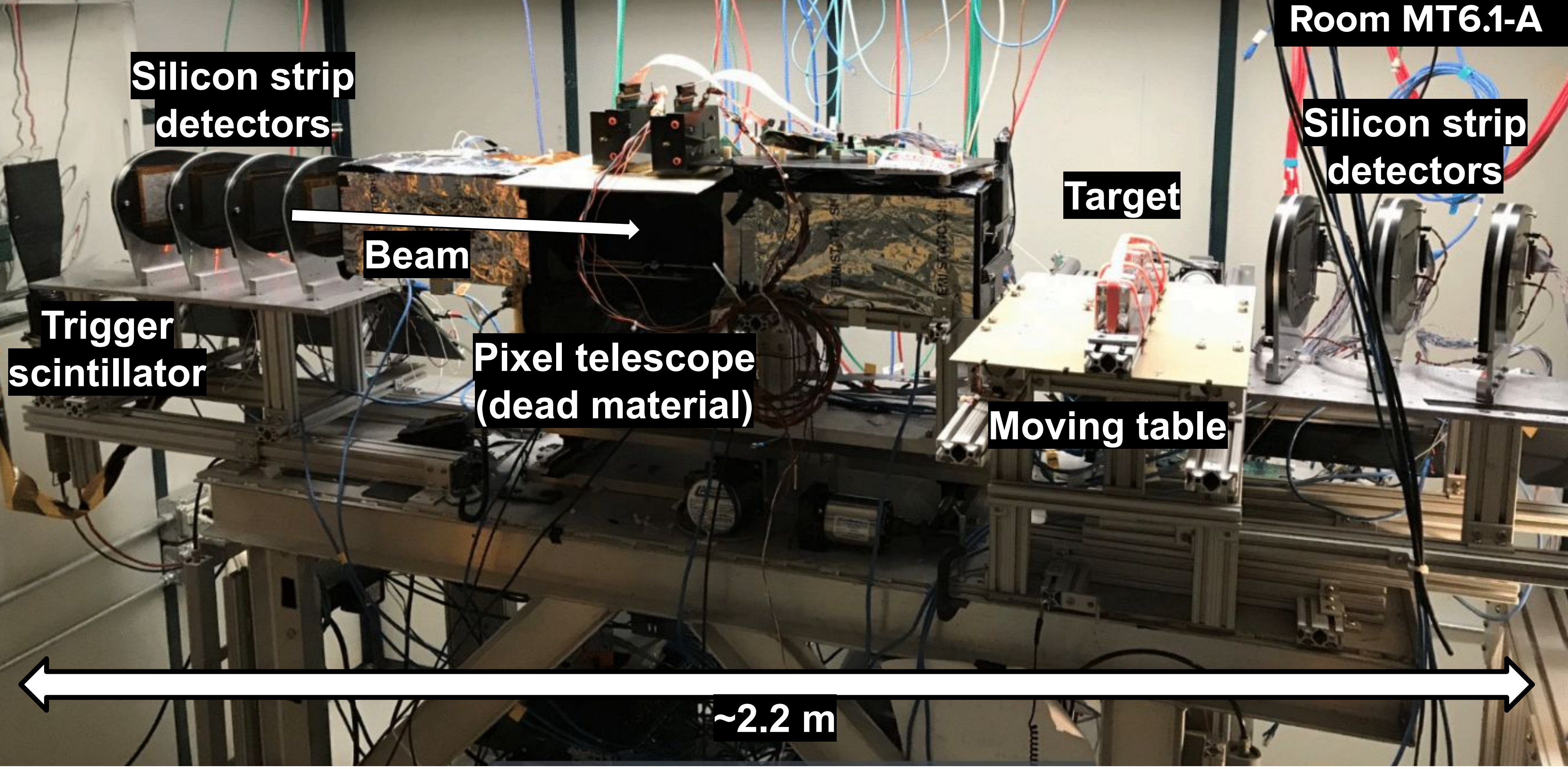
Fermilab Test Beam Facility (FTBF)

- Primary and secondary beams 0.2 - 120 GeV/c
  - Momentum resolution: 2%
- Silicon strip and pixel detectors
- Gas Cherenkov detectors for beam PID
- Lead glass calorimeter

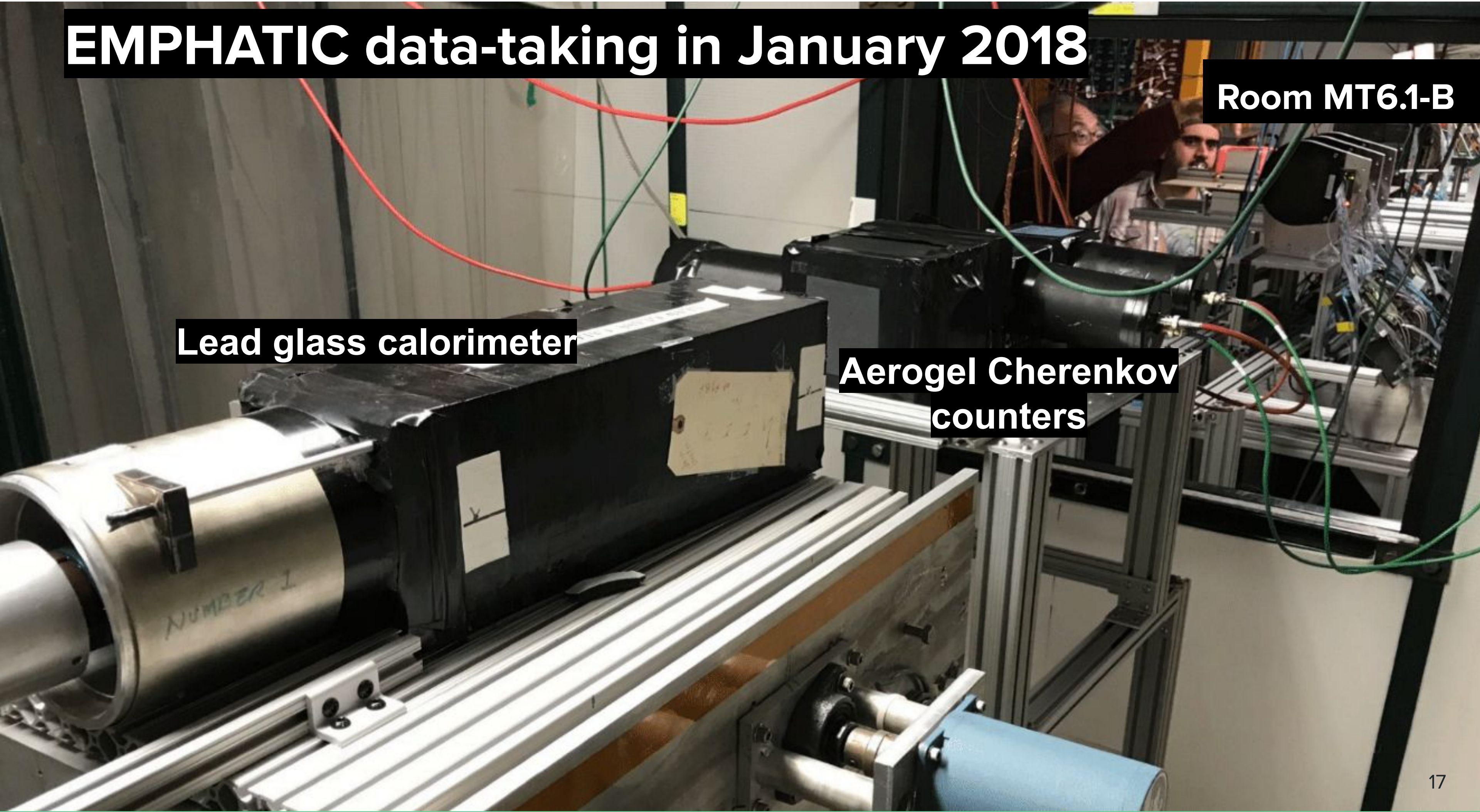
	e	μ	π	K	p
p_{min} [GeV/c]	0.01	1.8	2.4	8	15

- Working in FTBF is an amazing experience
- Experiment setup time 1-2 days
- Many thanks to
  - Mandy Rominski and Todd Nebel for help with the organization and the setup of the detectors
  - Lorenzo Uplegger and Ryan Rivera who stayed until 3 am to help with the silicon strip and pixel DAQ

EMPHATIC data-taking in January 2018

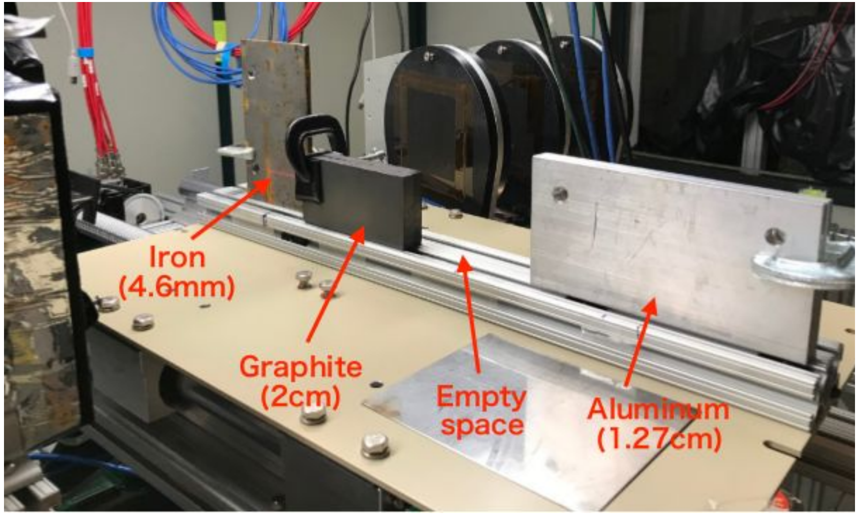


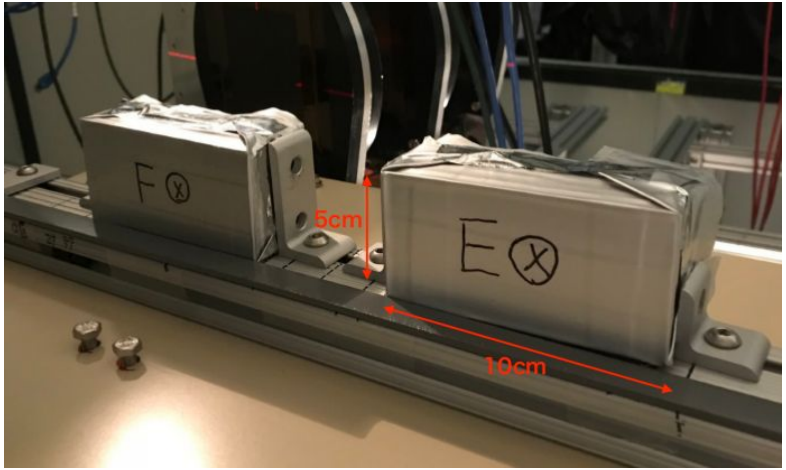
EMPHATIC data-taking in January 2018



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 composition:
  - **p < 10 GeV/c → fraction of $e^{\pm}$ > 50%**
  - **p = 30 GeV/c → fraction of p ~45%, K ~3%, π ~ 50%, e^{+} ~2%**

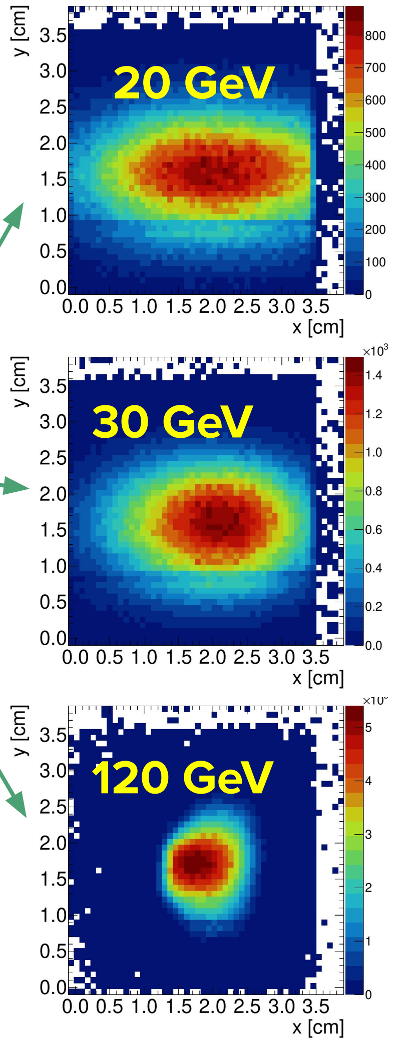




Analysis of proton (kaon) - carbon data

p [GeV/c]	Target	Triggers [10^6]	Veto
20	carbon	0.463	π, μ, e
20	empty	0.410	π, μ, e
30	carbon	1.031	π, μ, e
30	empty	0.197	π, μ, e
120	carbon	1.013	-
120	empty	1.068	-

Beam profiles



One of the gas Cherenkov detectors was used as a veto for π/μ/e

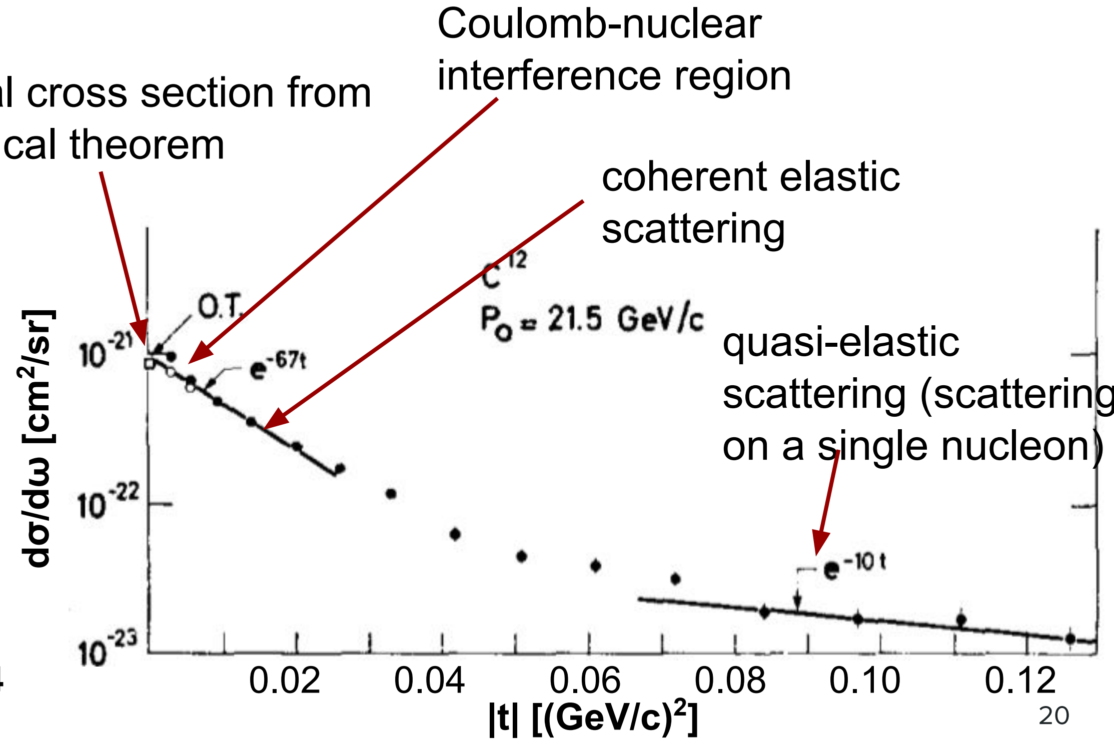
What can we do with the data?

- **p + C @ 20, 30, 120 GeV/c data**
- **Measurement of total, elastic and quasi-elastic cross section**

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

Beam momentum

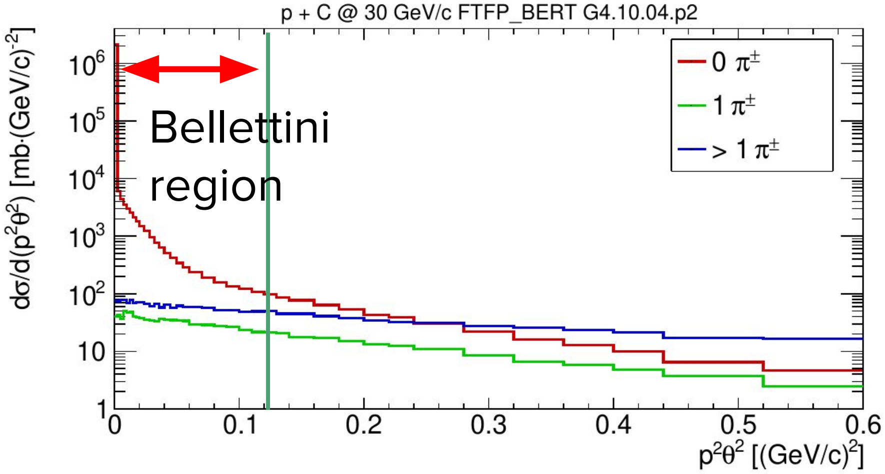
Scattering angle



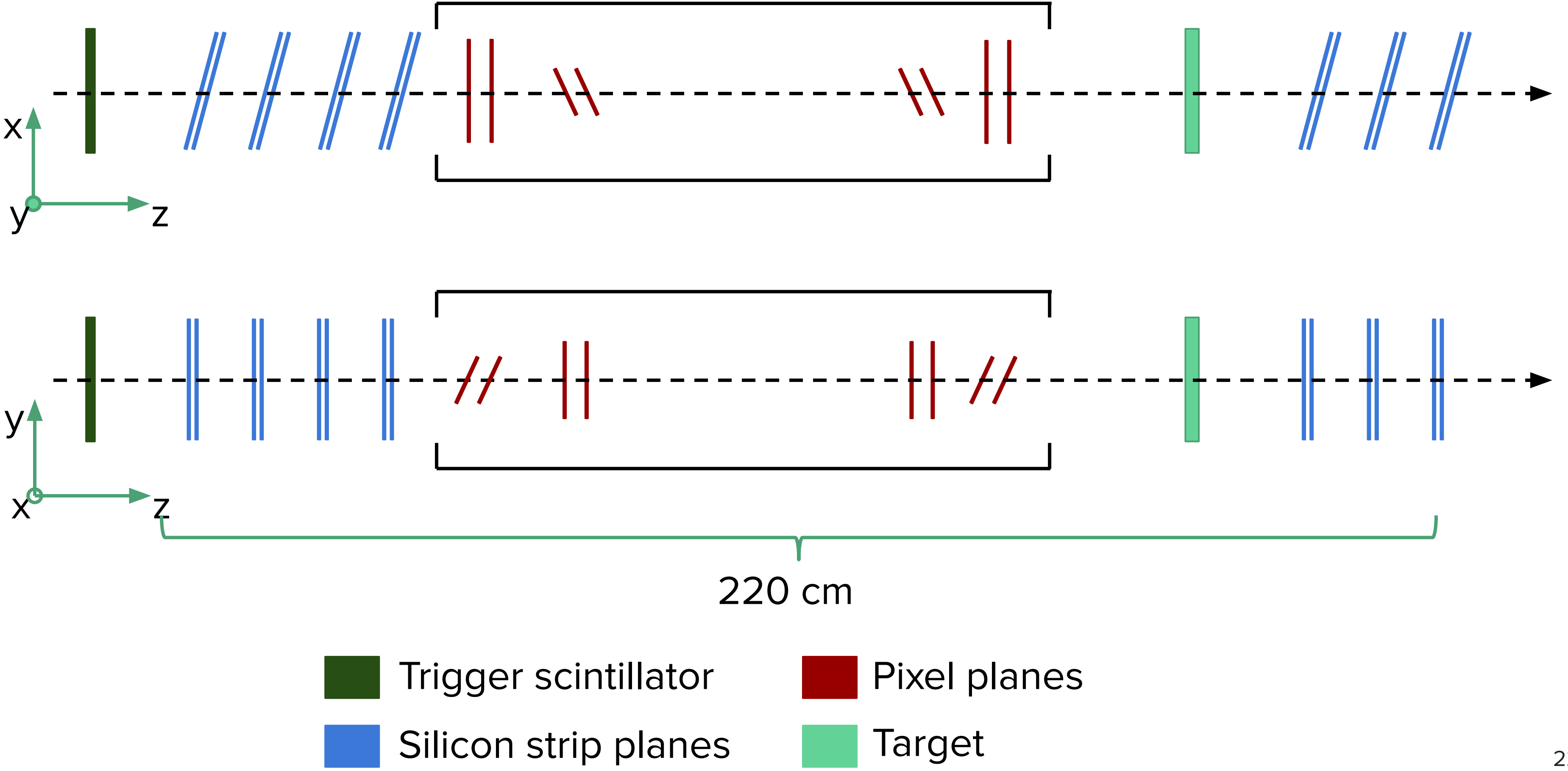
Bellettini et al., Nucl.Phys. 79 (1966) 609-624

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

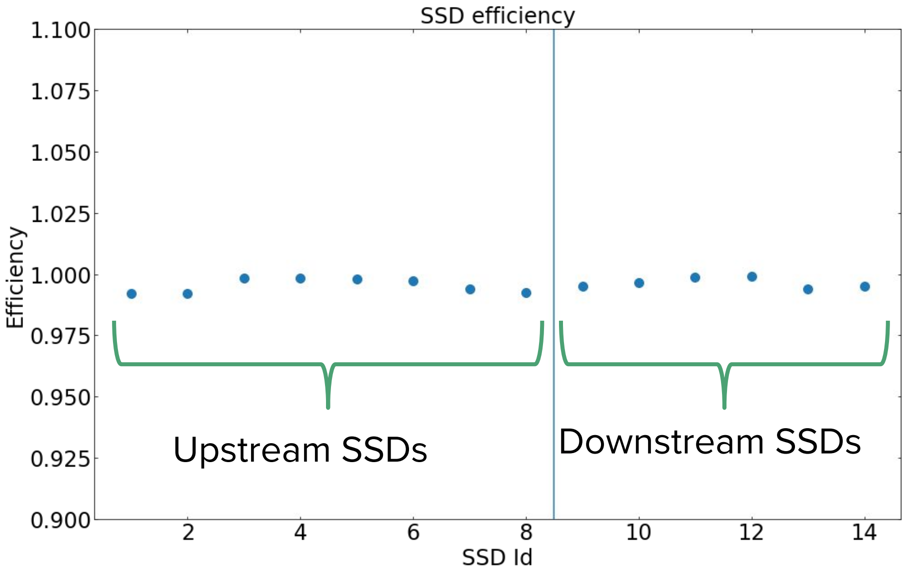


Particle tracking

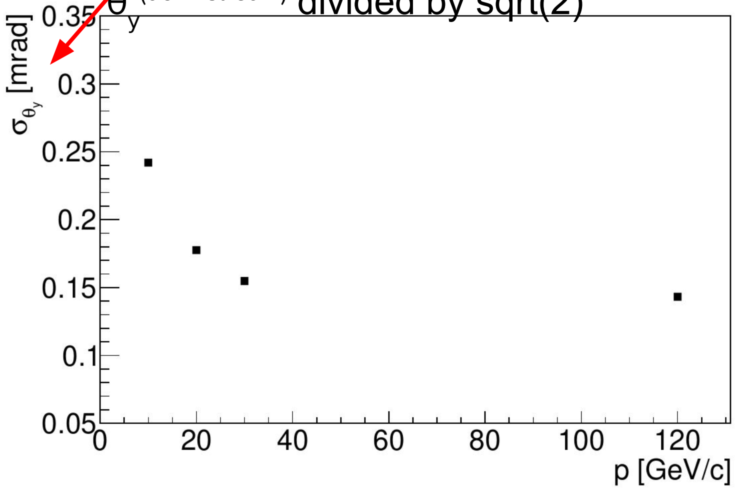


SSD efficiency and angular resolution

- Pitch 60 μm, 3.8 ⊗ 3.8 cm^2
- Efficiency and angular resolution are estimated from the empty target data
- Angular resolution above 20 GeV/c is limited by position resolution, multiple scattering becomes significant below 20 GeV/c

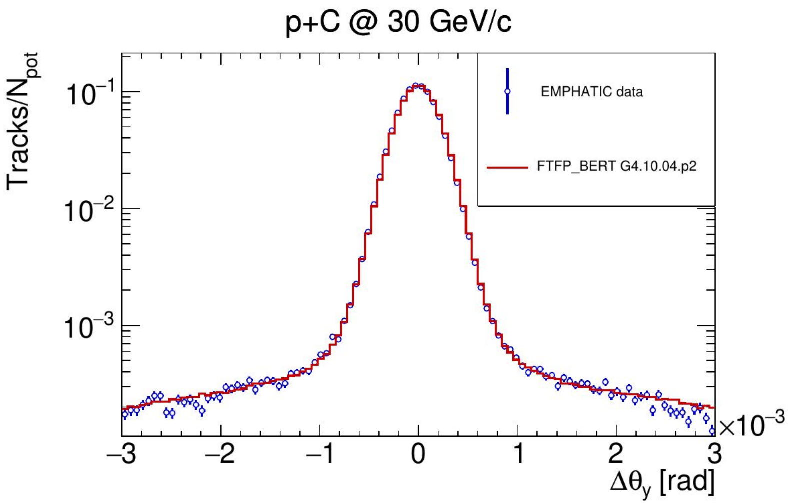


Standard deviation of $\theta_y^{(upstream)} - \theta_y^{(downstream)}$ divided by sqrt(2)



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%)



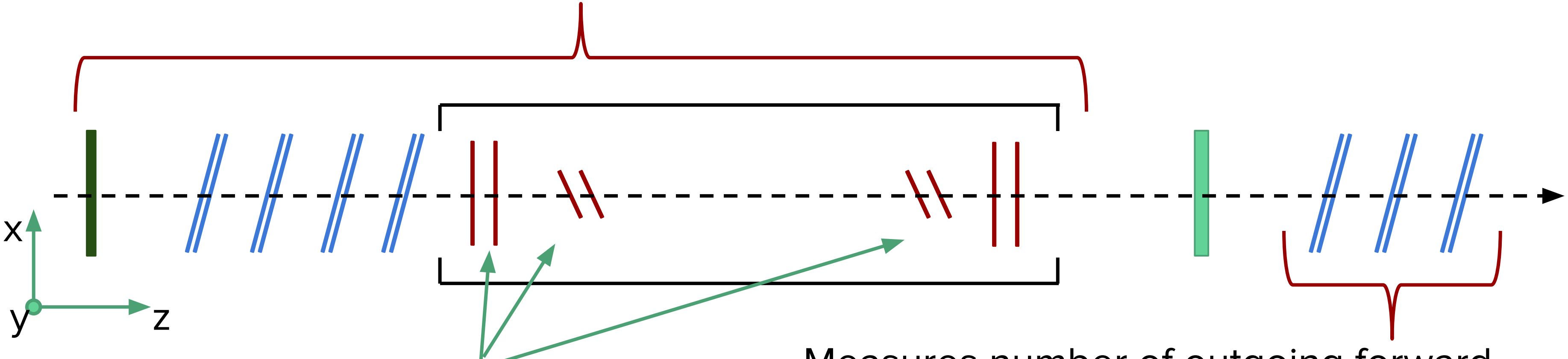
σ (data) = 0.207 mrad
σ (MC) = 0.209 mrad

Differential cross-section measurement

- 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

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

Measures number of particles on the target



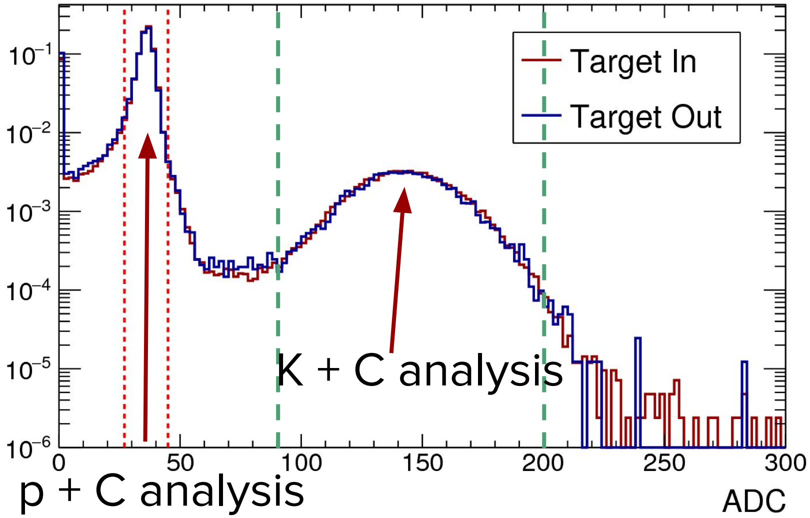
Dead material

Measures number of outgoing forward particles

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

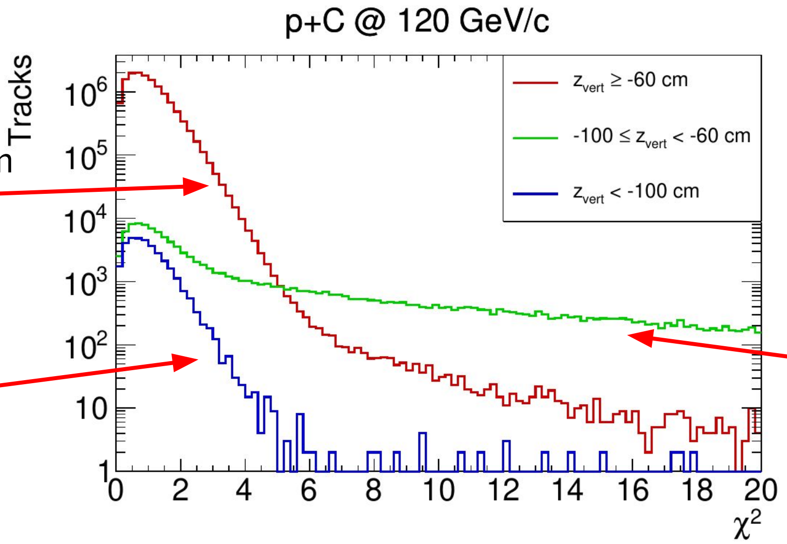
Remove upstream interactions



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



Non-interacting beam particles

Interactions in the trigger

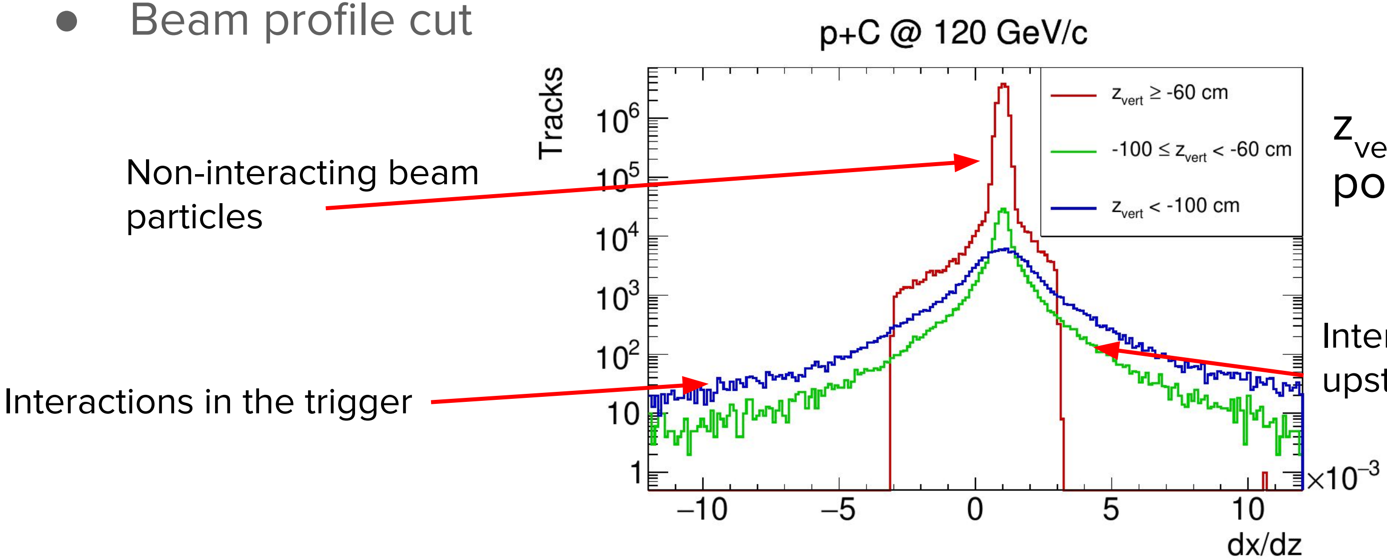
z_{vert} ➔ interaction point

Interactions in the upstream silicon planes

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

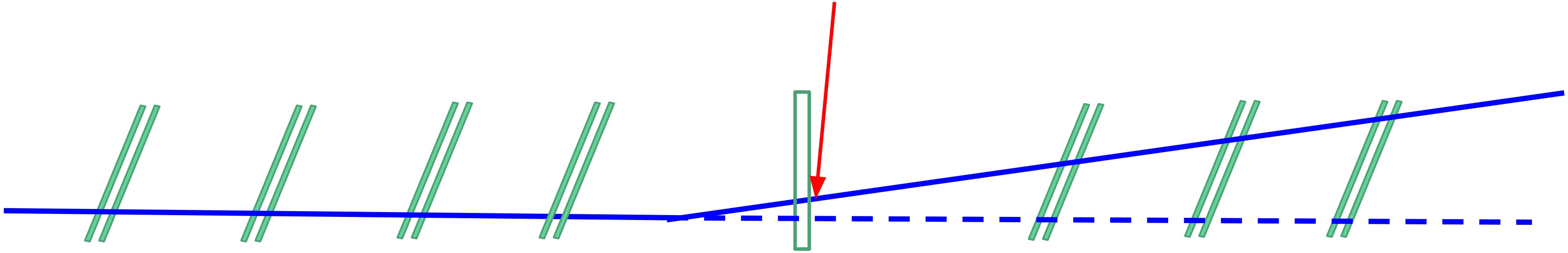


z_{vert} ➜ interaction point

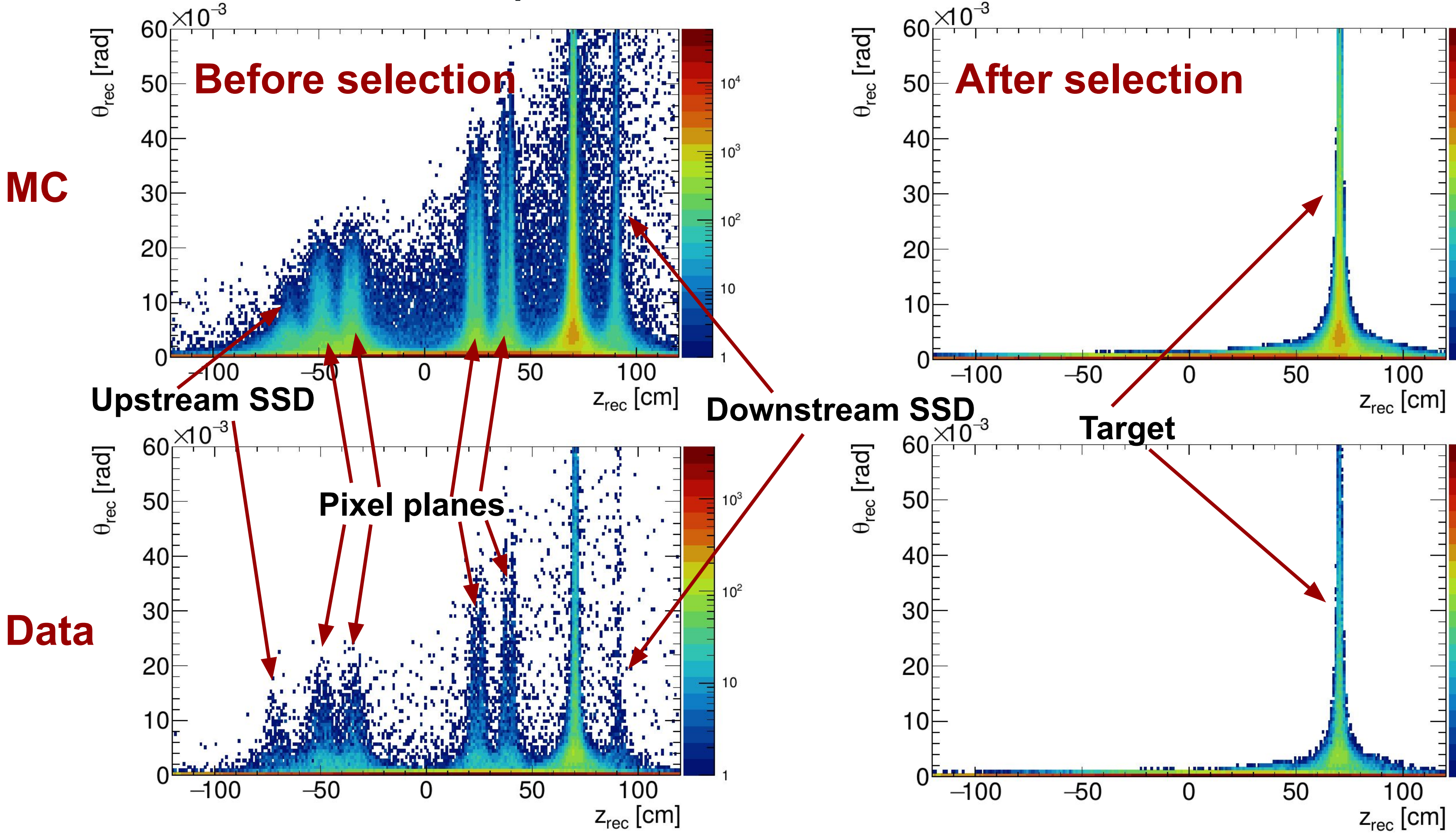
Downstream selection

- 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



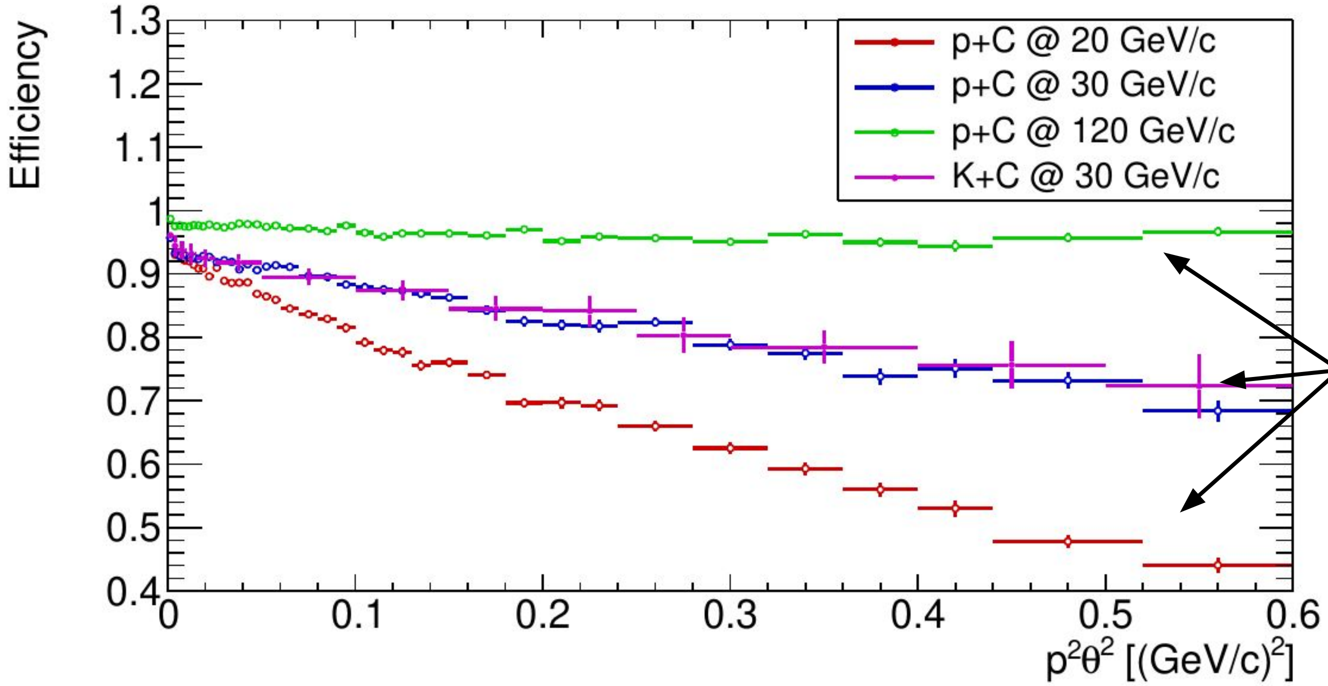
Interactions in the pixel detector



Efficiency

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

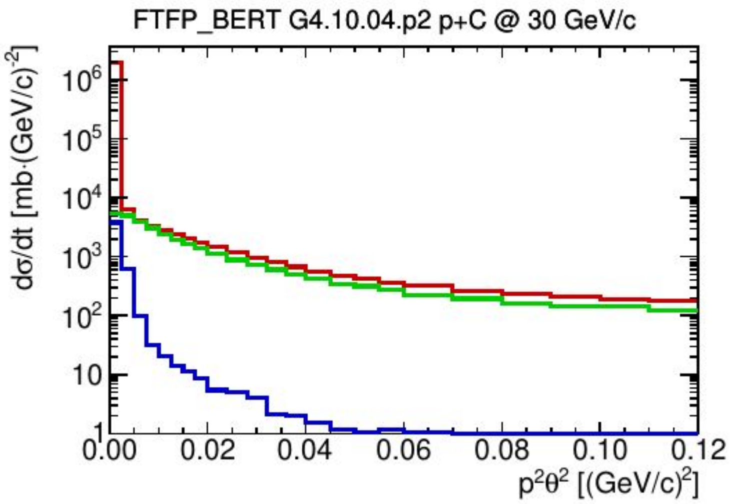
Includes: reconstruction + **acceptance** + selection

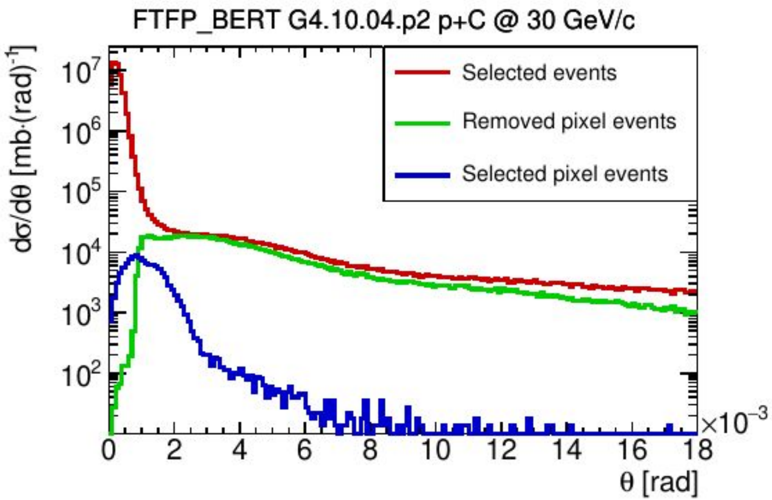


Differences between datasets are due to the beam size and acceptance effects.

Pixel interactions

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

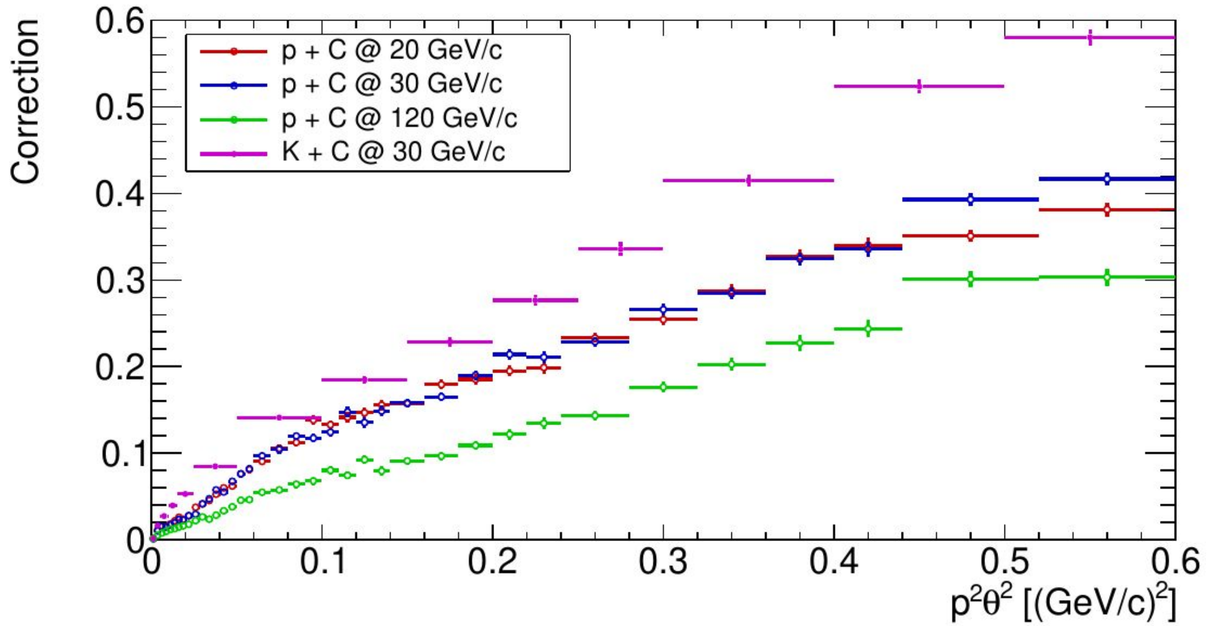




	p+C @ 20 GeV/c	p+C @ 30 GeV/c	p+C @ 120 GeV/c	K+C @ 30 GeV/c
POT correction [%]	**5.2**	**4.5**	**4.3**	**2.9**

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

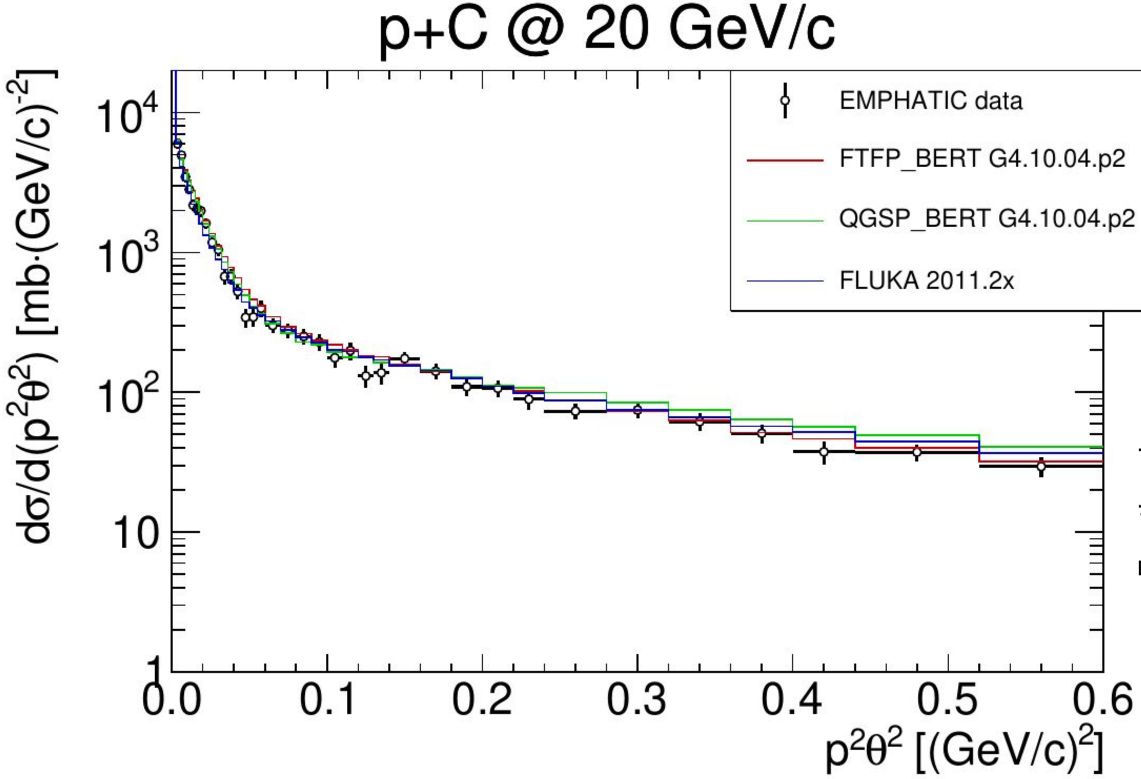


Systematic uncertainties

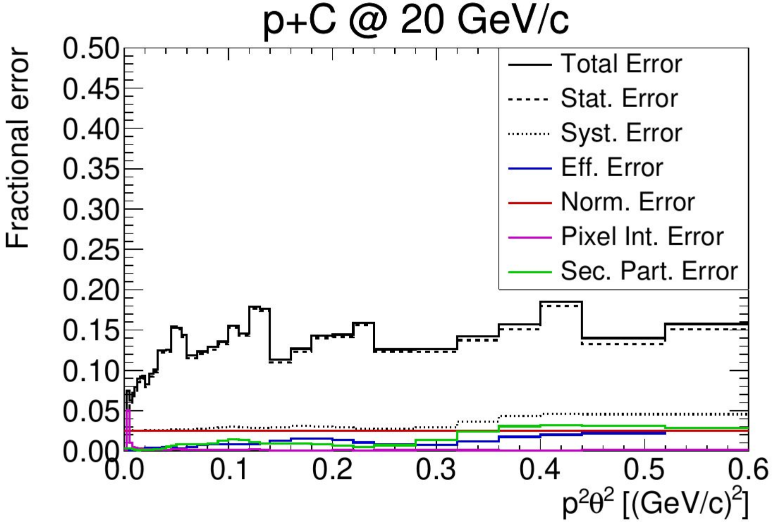
Strategy:

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

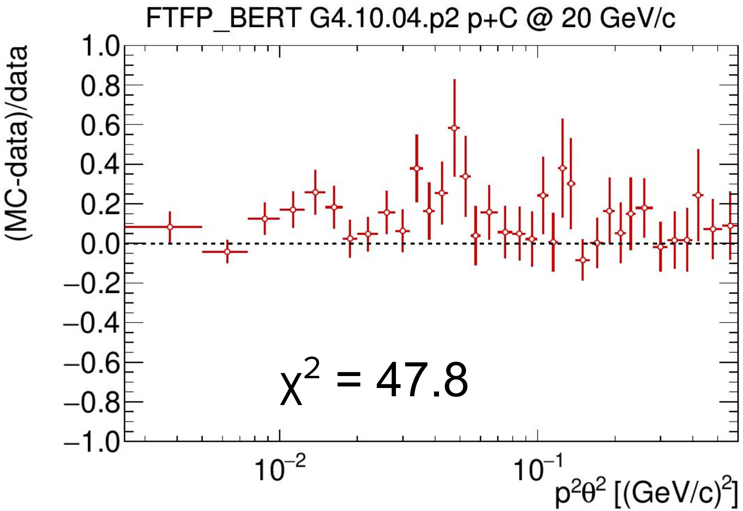
1. Beam contamination (kaons in proton beam) ➜ **negligible << 1% contamination**
2. Upstream interactions in the trigger scintillator or SSDs ➜ **negligible < 0.5%**
3. Pixel interactions (shape) ➜ only forward bins **negligible above t=0.01 GeV^2**
4. Secondary particles (not leading protons or kaons) **<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%)**



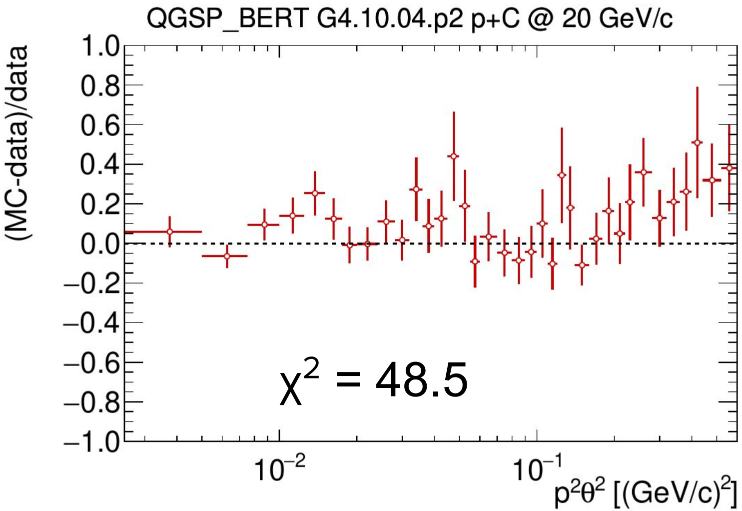
p+C @ 20 GeV/c
EMPHATIC data
FTFP_BERT G4.10.04.p2
QGSP_BERT G4.10.04.p2
FLUKA 2011.2x
dσ/d(p²θ²) [mb·(GeV/c)⁻²]
p²θ² [(GeV/c)²]



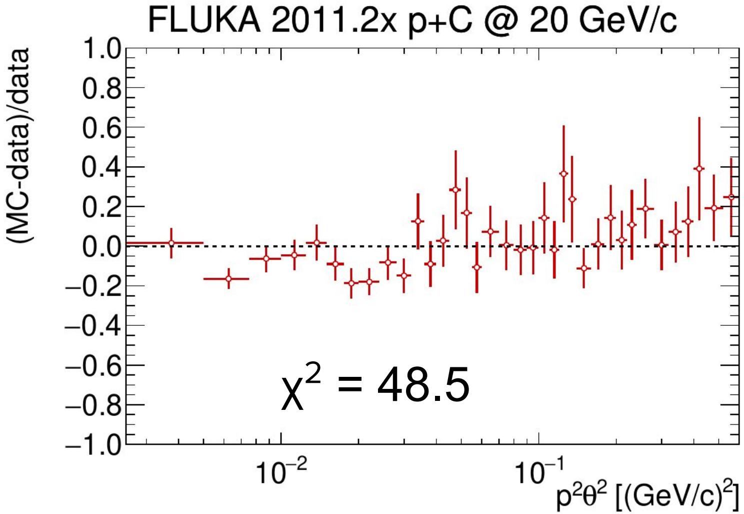
p+C @ 20 GeV/c
Total Error
Stat. Error
Syst. Error
Eff. Error
Norm. Error
Pixel Int. Error
Sec. Part. Error
Fractional error
p²θ² [(GeV/c)²]



FTFP_BERT G4.10.04.p2 p+C @ 20 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 47.8

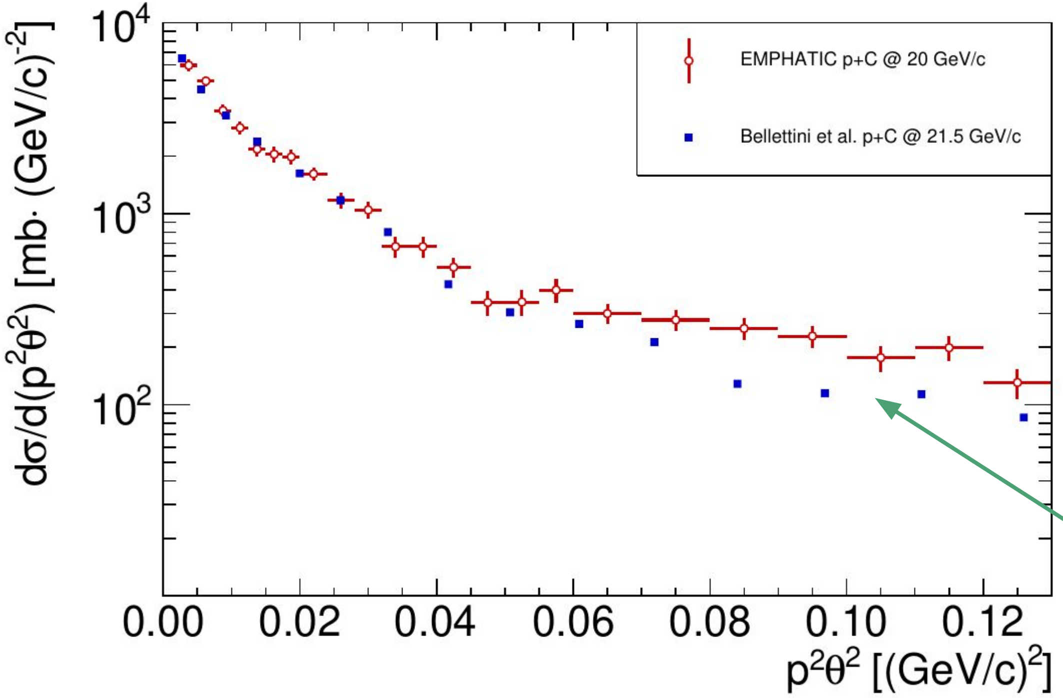


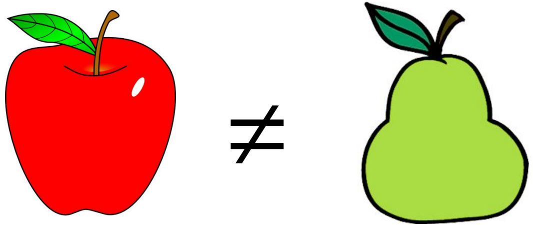
QGSP_BERT G4.10.04.p2 p+C @ 20 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 48.5



FLUKA 2011.2x p+C @ 20 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 48.5

dof = 37





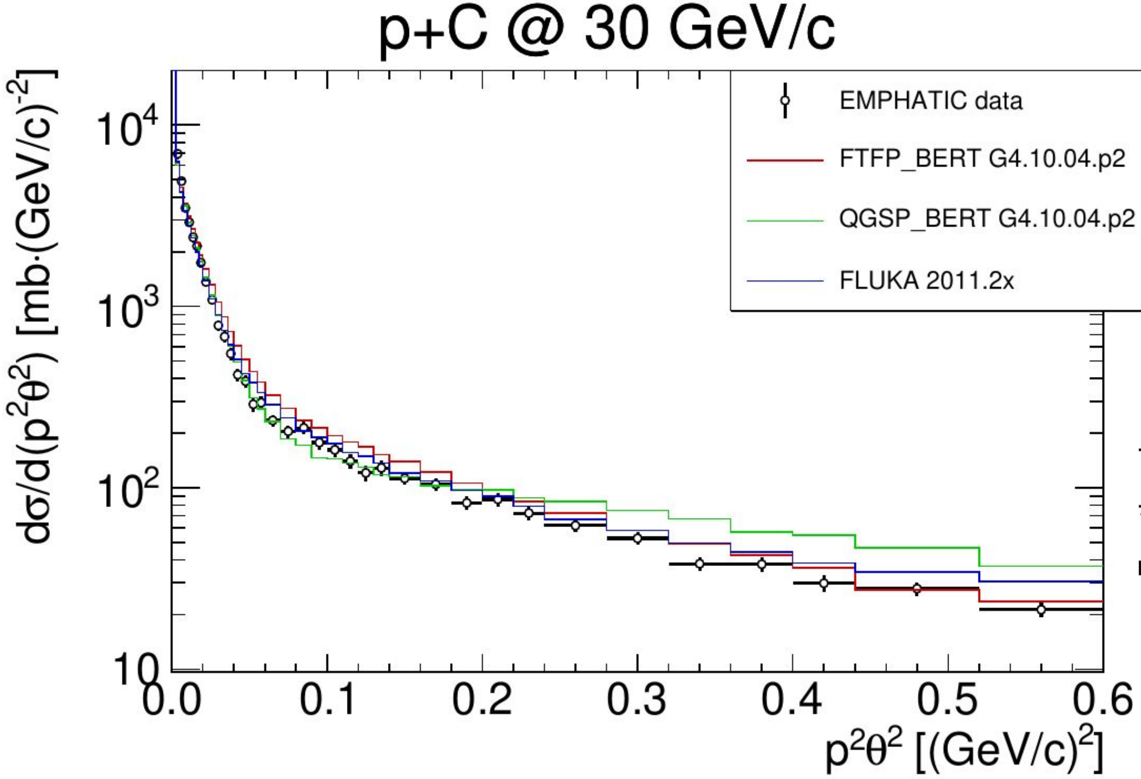
Bellettini et al.

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

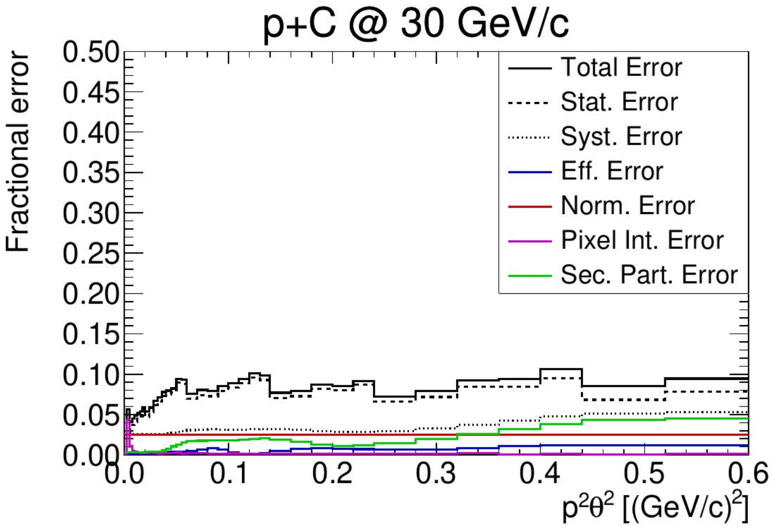
EMPHATIC and Bellettini do not measure the same thing!

- EMPHATIC includes resonance production

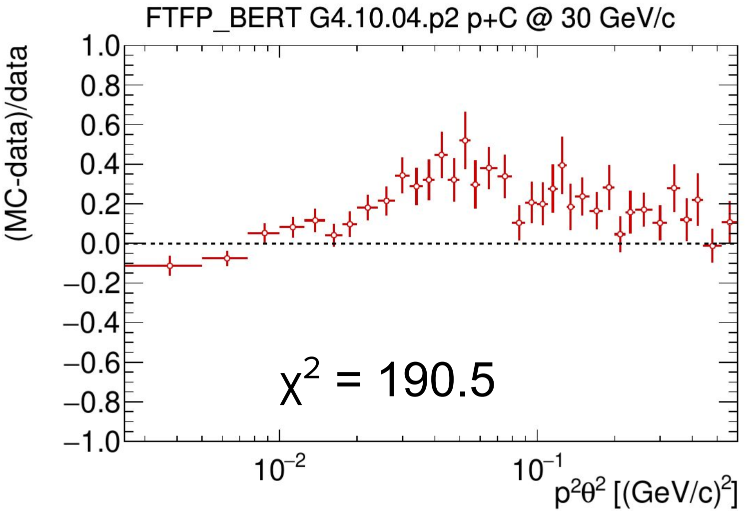
Bellettini et al., Nucl.Phys. 79 (1966) 609-624

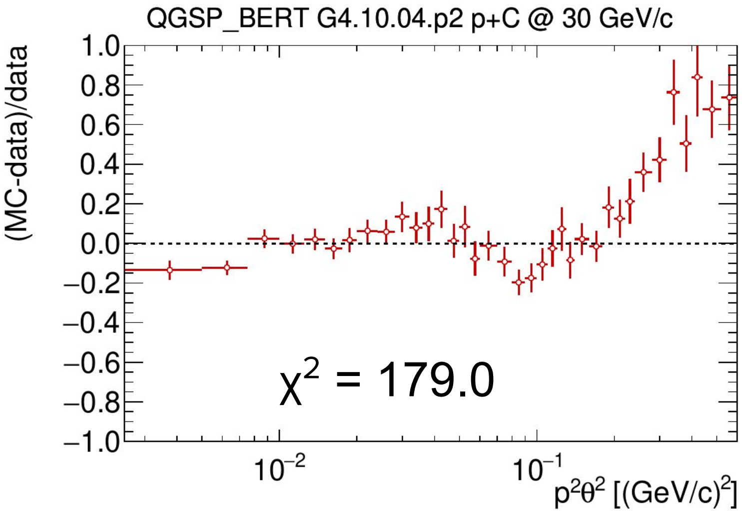


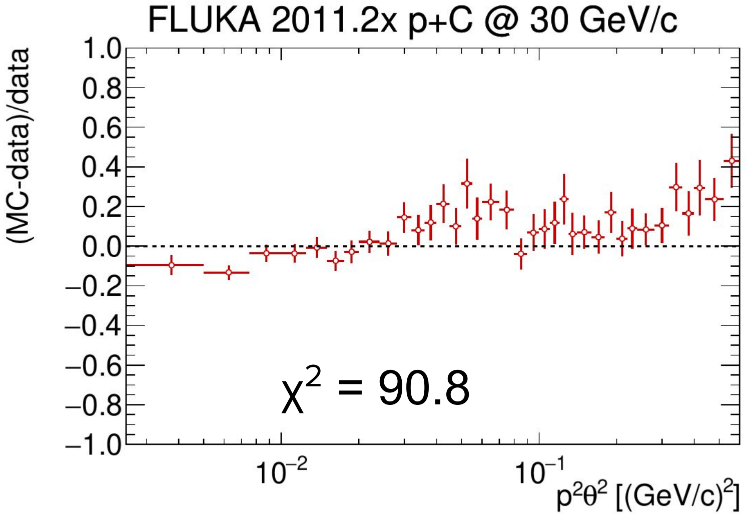
p+C @ 30 GeV/c
EMPHATIC data
FTFP_BERT G4.10.04.p2
QGSP_BERT G4.10.04.p2
FLUKA 2011.2x
dσ/d(p²θ²) [mb·(GeV/c)⁻²]
p²θ² [(GeV/c)²]



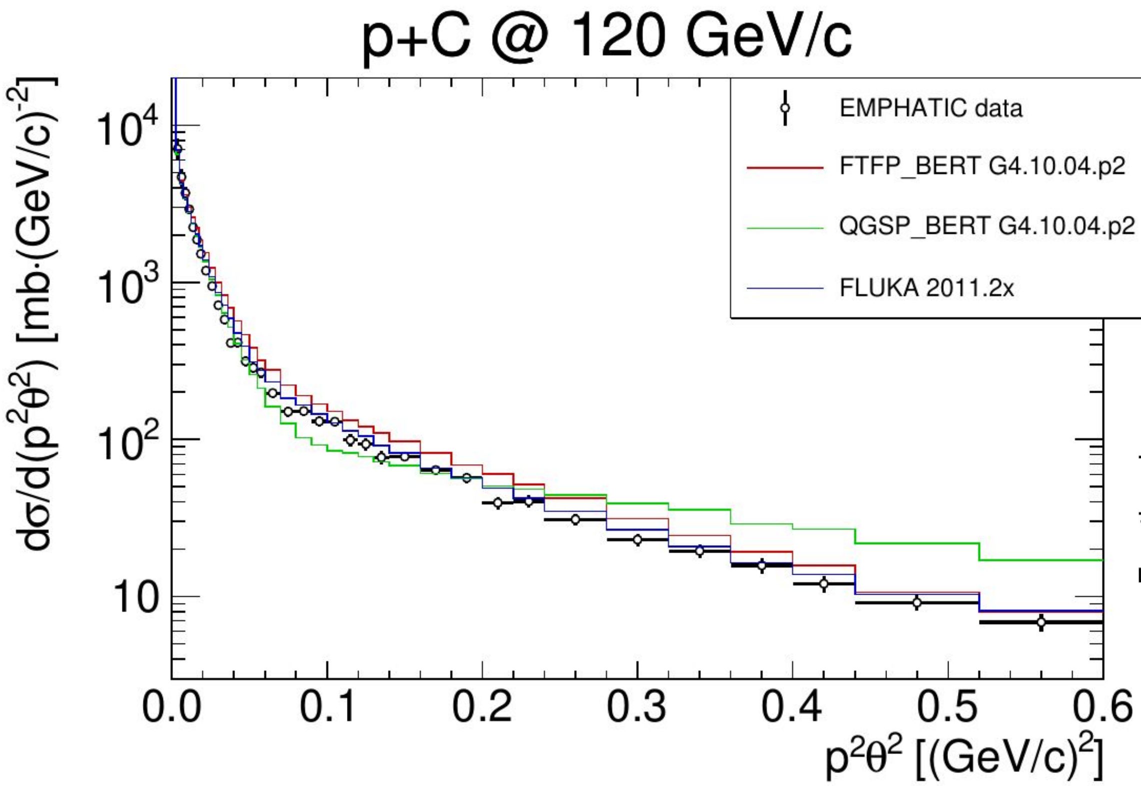
p+C @ 30 GeV/c
Total Error
Stat. Error
Syst. Error
Eff. Error
Norm. Error
Pixel Int. Error
Sec. Part. Error
Fractional error
p²θ² [(GeV/c)²]

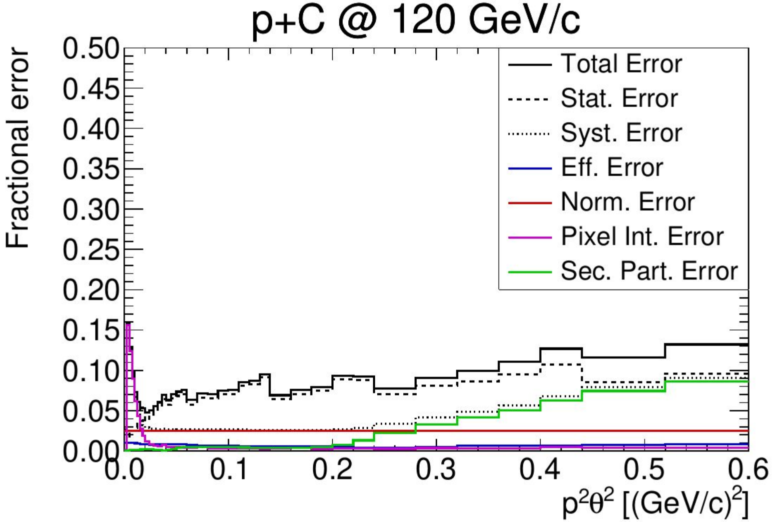

FTFP_BERT G4.10.04.p2 p+C @ 30 GeV/c
(MC-data)/data
$p^2\theta^2$ [(GeV/c)^2]
χ^2 = 190.5

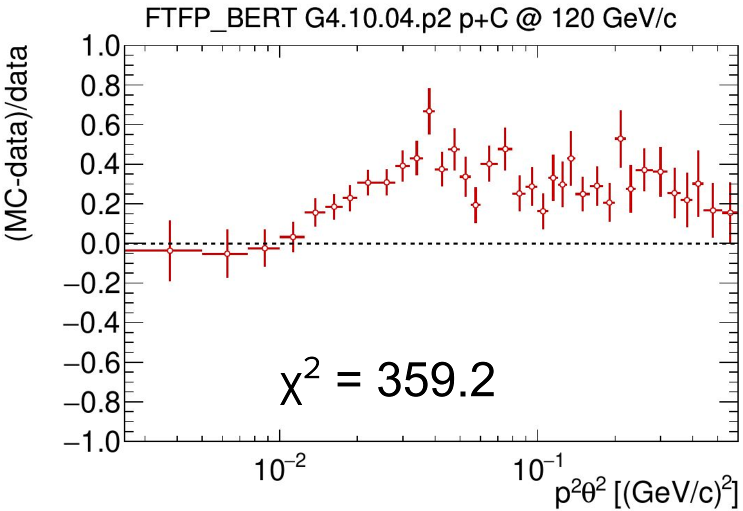

QGSP_BERT G4.10.04.p2 p+C @ 30 GeV/c
(MC-data)/data
$p^2\theta^2$ [(GeV/c)^2]
χ^2 = 179.0

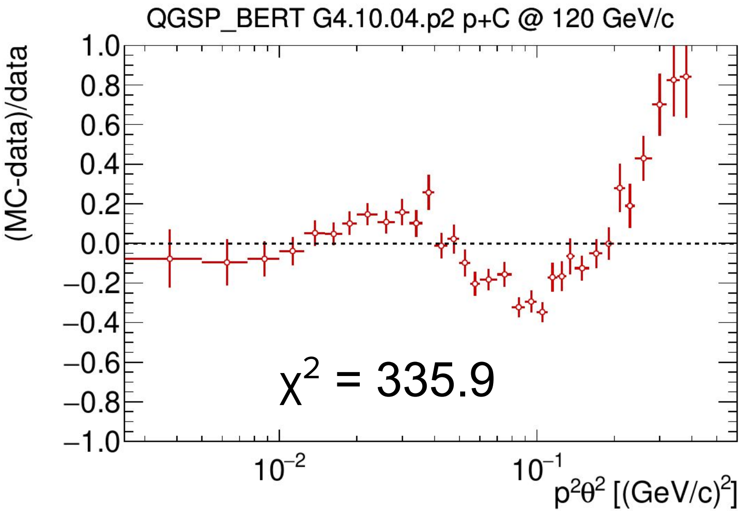

FLUKA 2011.2x p+C @ 30 GeV/c
(MC-data)/data
$p^2\theta^2$ [(GeV/c)^2]
χ^2 = 90.8

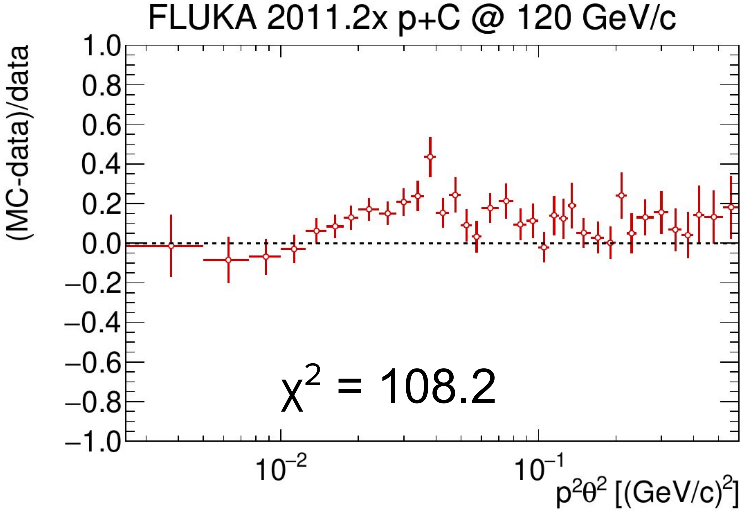
dof = 37


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]

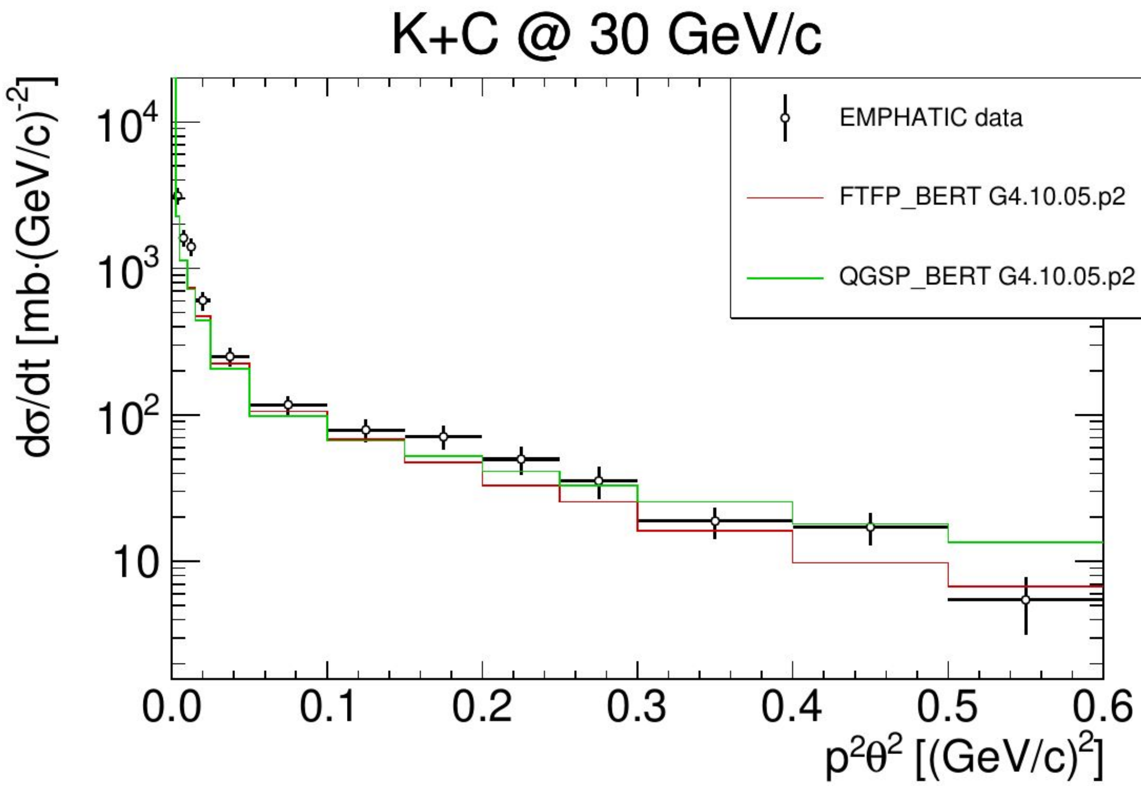

p+C @ 120 GeV/c
Total Error
Stat. Error
Syst. Error
Eff. Error
Norm. Error
Pixel Int. Error
Sec. Part. Error
Fractional error
p²θ² [(GeV/c)²]

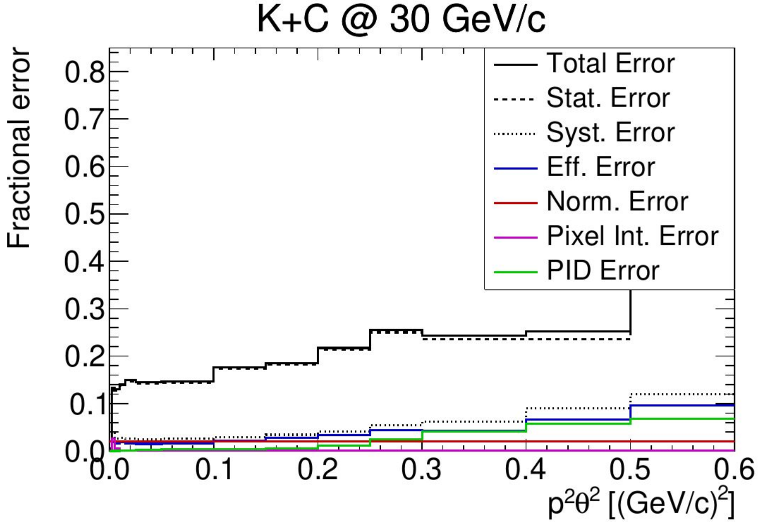

FTFP_BERT G4.10.04.p2 p+C @ 120 GeV/c
(MC-data)/data
χ^2 = 359.2
$p^2\theta^2$ [(GeV/c)^2]


QGSP_BERT G4.10.04.p2 p+C @ 120 GeV/c
(MC-data)/data
χ^2 = 335.9
$p^2\theta^2$ [(GeV/c)^2]

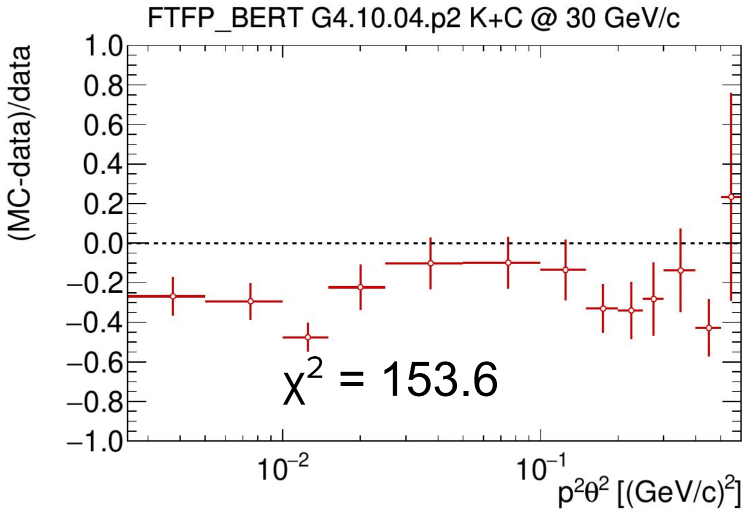

FLUKA 2011.2x p+C @ 120 GeV/c
(MC-data)/data
χ^2 = 108.2
$p^2\theta^2$ [(GeV/c)^2]

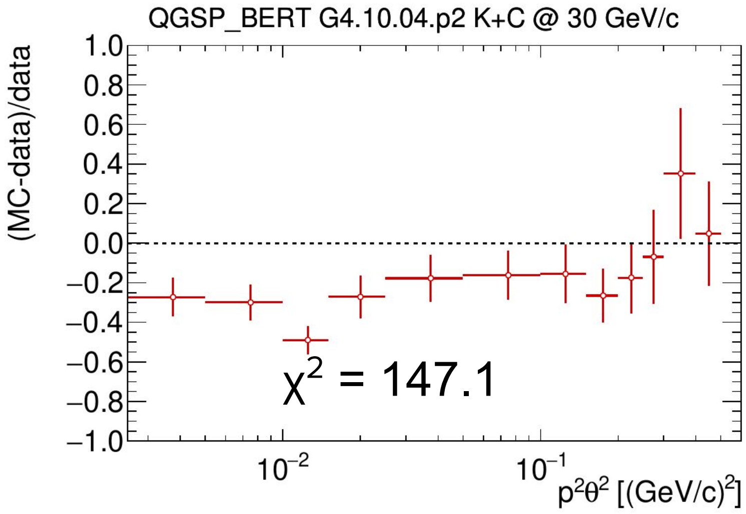
dof = 37





The first measurement of this type

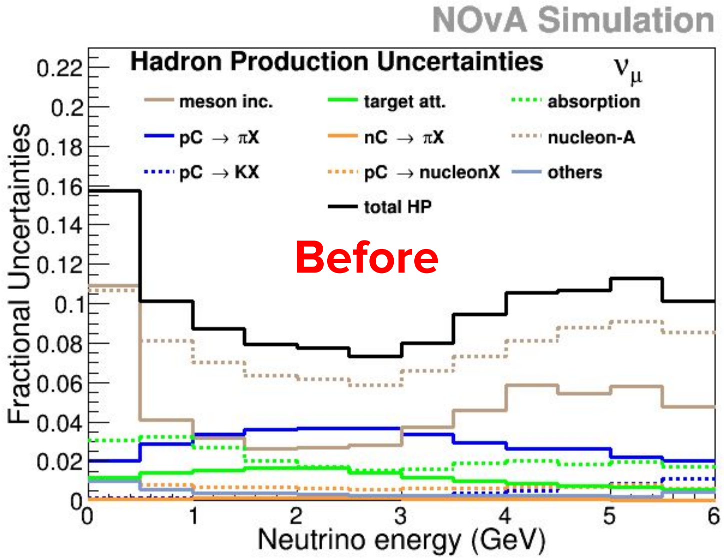

FTFP_BERT G4.10.04.p2 K+C @ 30 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 153.6

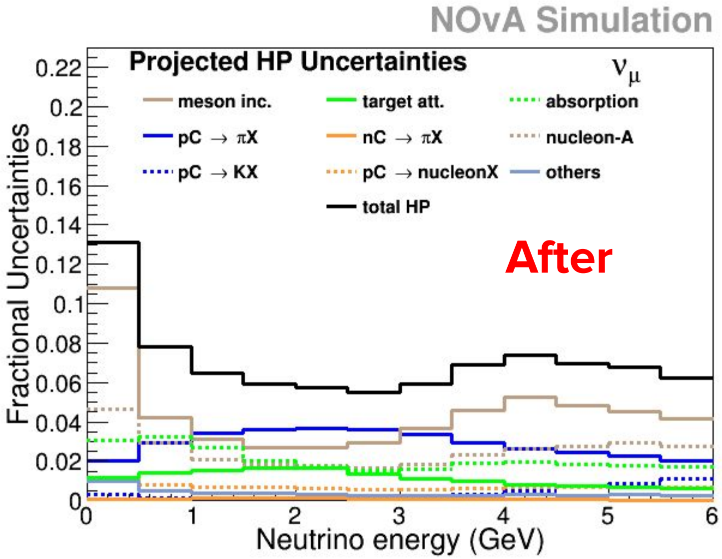

QGSP_BERT G4.10.04.p2 K+C @ 30 GeV/c
(MC-data)/data
p²θ² [(GeV/c)²]
χ² = 147.1

dof = 14

Impact of the current results (I)

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



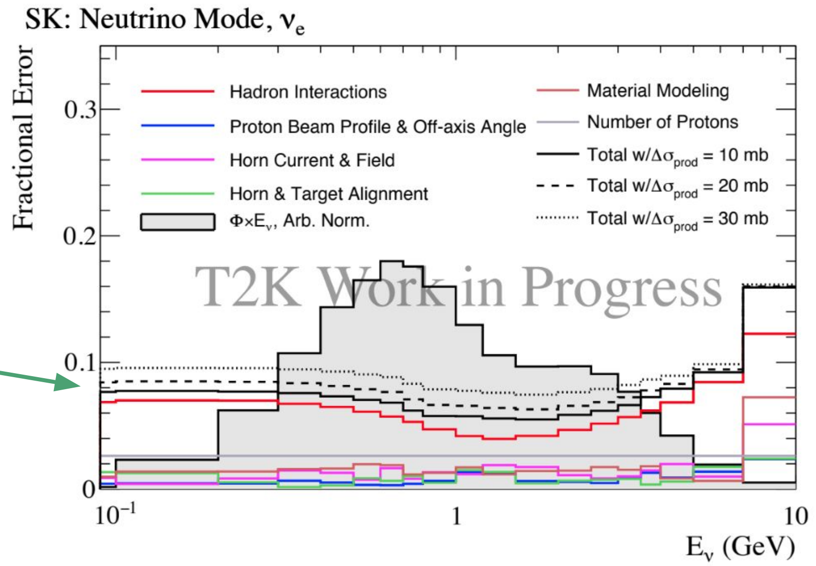


L. Aliaga, L. Cremonesi

Impact of the current results

- Emphatic results can reduce thin target reweighting uncertainty in T2K
- Thin vs. replica differences (under investigation)

Different lines show uncertainty after reducing production cross-section uncertainty to 30, 20 and 10 mb

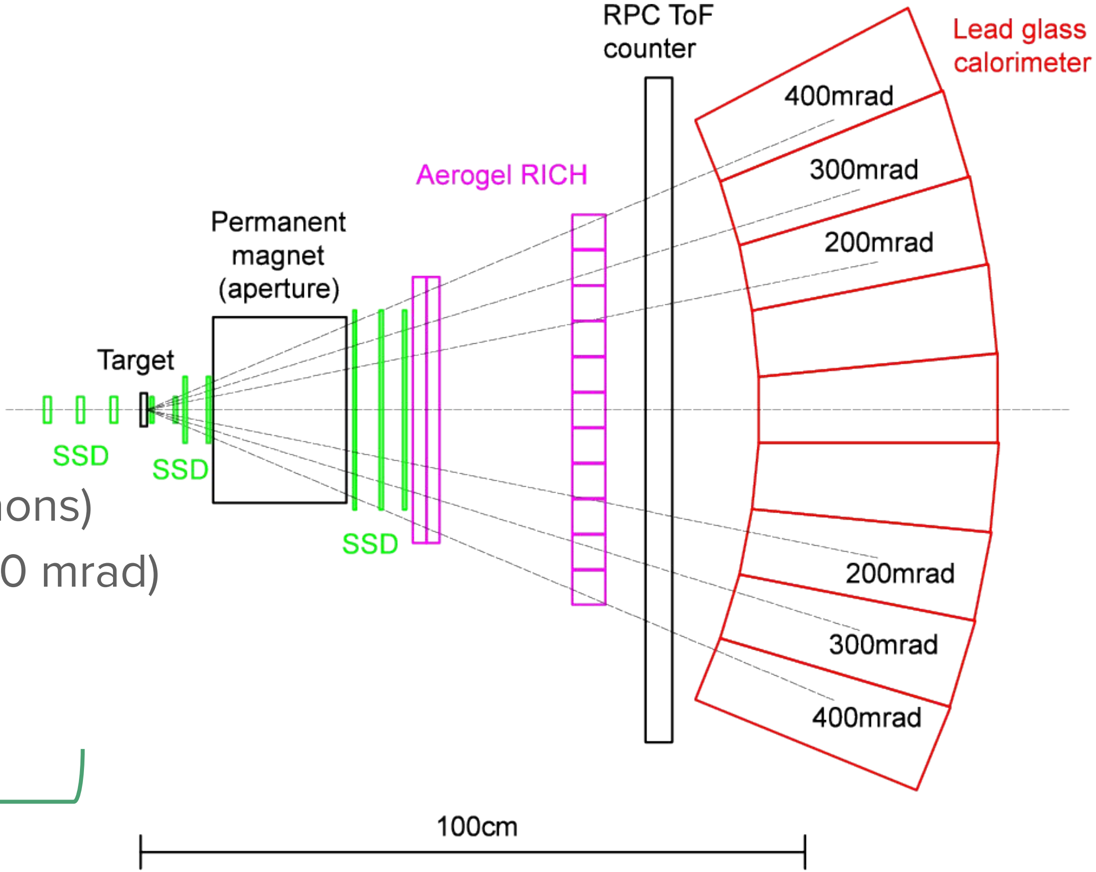


We need measurements of particle production!

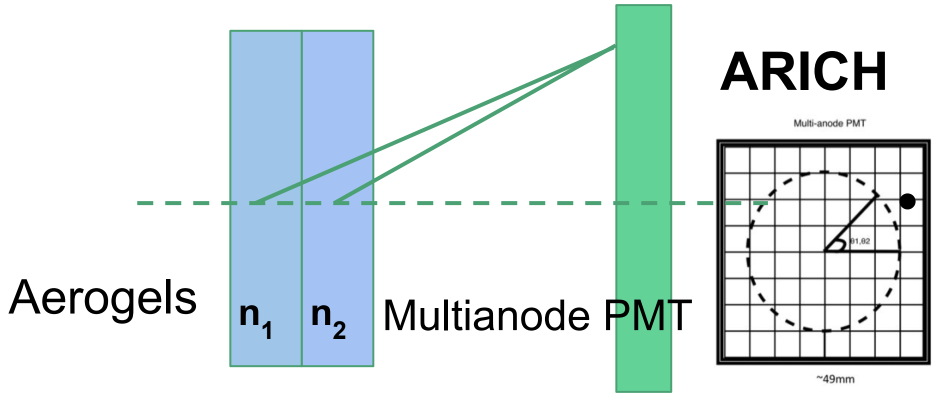
Future upgrades

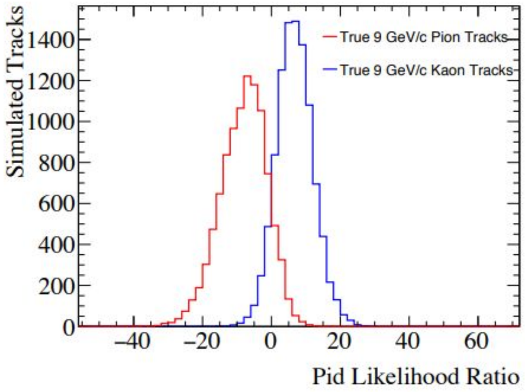
- Beam PID < 15 GeV/c
- Momentum resolution <10%
- Good particle ID (emphasis on kaons)
- Large phase space coverage (400 mrad)
- Low material budget
- Fast calibration and analysis

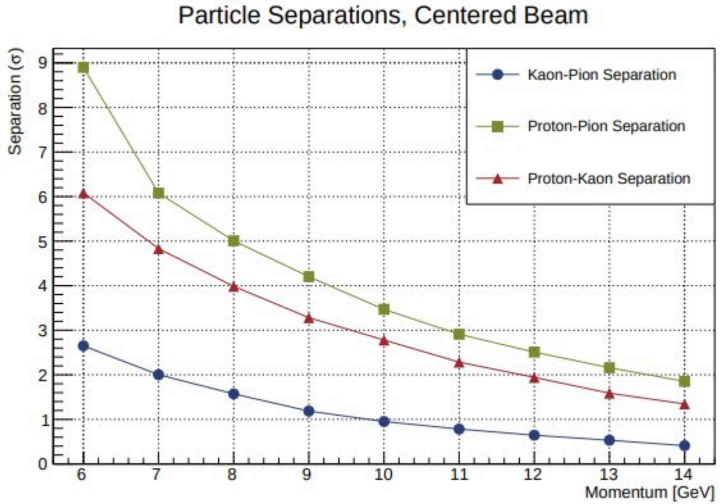
Measurement of particle production



Aerogel RICH



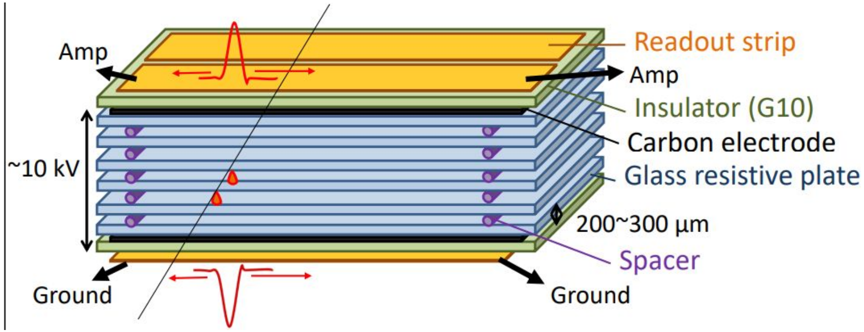


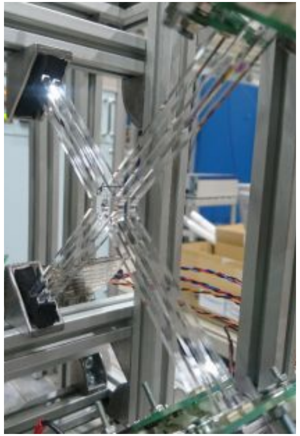


- Based on Belle II RICH detector
- Advances in aerogel production (Chiba U.)
  - new lower index aerogel of n=1.02-1.03 (instead of 1.04-1.05 for Belle II) with good transmittance is developed
- Beam test at TRIUMF in August
- 2σ π/K separation < 7 GeV/c
- 1σ π/K separation < 10 GeV/c

Multigap Resistive Plate Chambers (MRPCs)

- Cooperation with E50 collaboration from Japan
  - Testing of RPCs in EMPHATIC
- TOF measurement ➔ complementary to ARICH (particles below Cherenkov threshold)
- Timing resolution ~70 ps
- PID up to 1.5 GeV/c
- Acrylic Cherenkov start counter
  - 40 ps resolution (intrinsic + TDC)

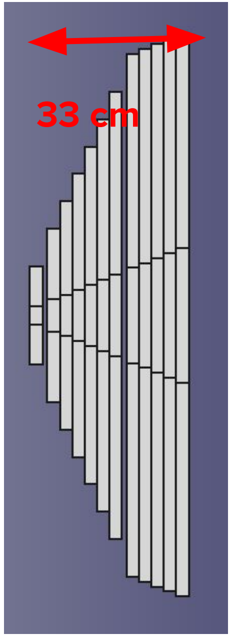


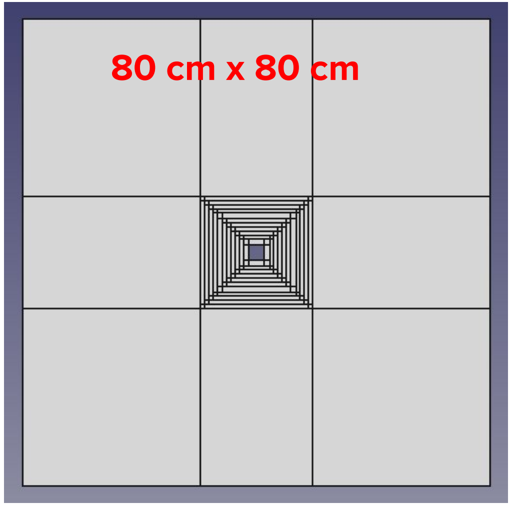


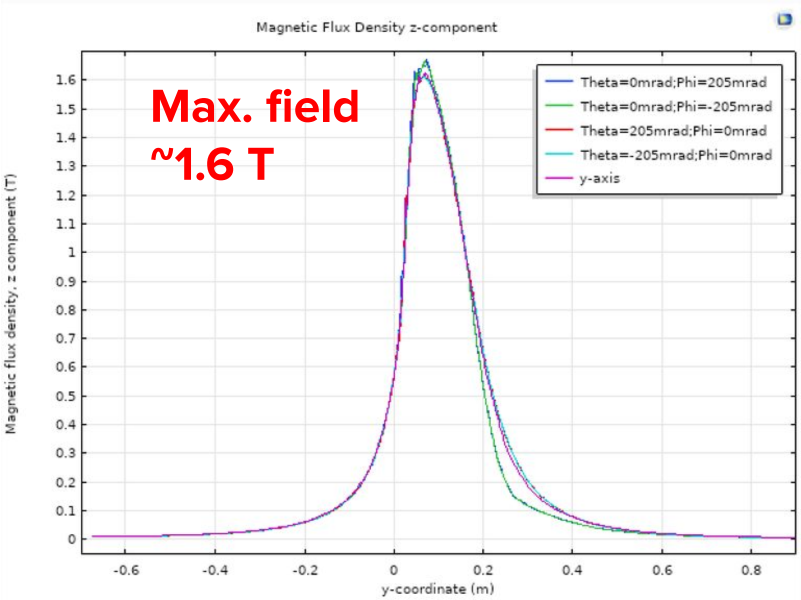
Magnet (Halbach array)

- Halbach array ➔ a special arrangement of the permanent magnets
  - Increases the field in the magnet bore
- Large acceptance ➔ 400 mrad

Journal of Magnetic Resonance Vol. 277 (2017) 143

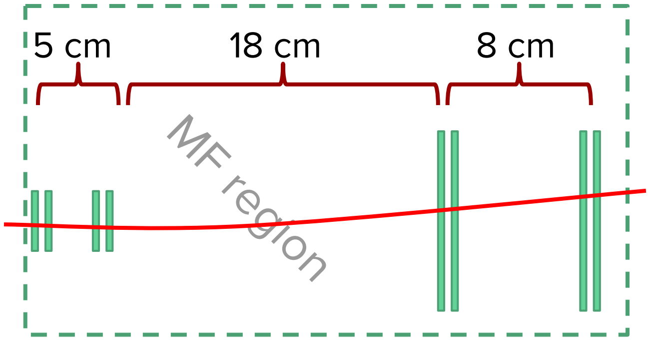


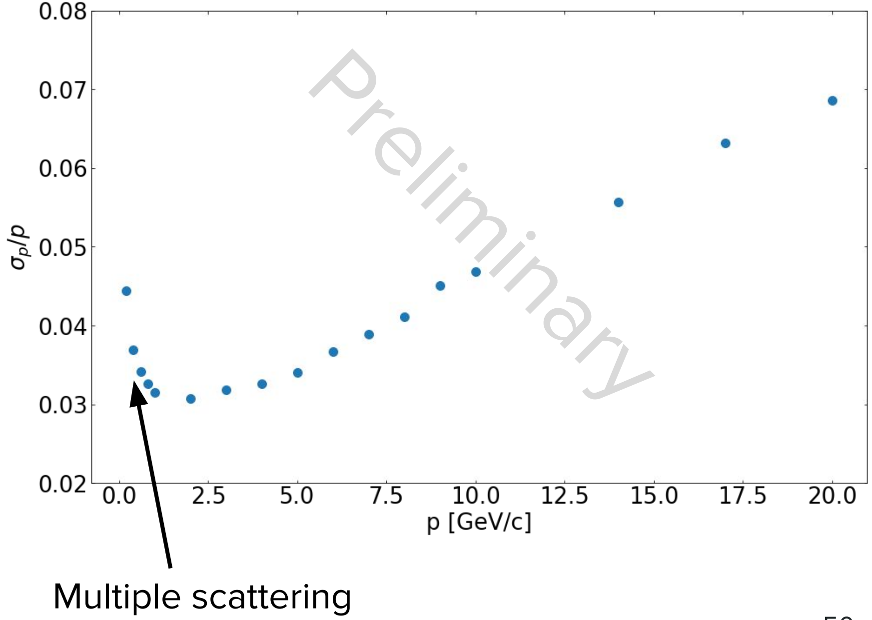


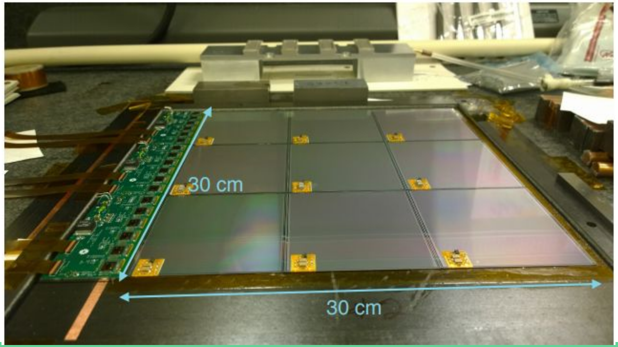


Silicon strip detectors (SSDs)

- Very precise tracking is crucial for momentum measurement in a small detector
- CMS technology
- Smaller SSDs upstream from the target and in front of the magnet
  - Pitch: 60 µm
  - 3.8 ⊗ 3.8 cm^2
- Large SSDs after the magnet
  - Pitch: 122 µm
  - 30 ⊗ 30 cm^2

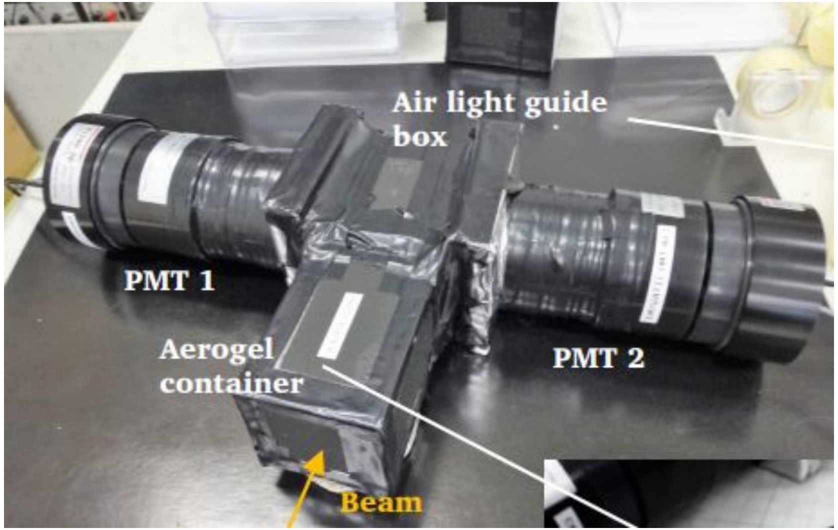






Threshold aerogel detector

- 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



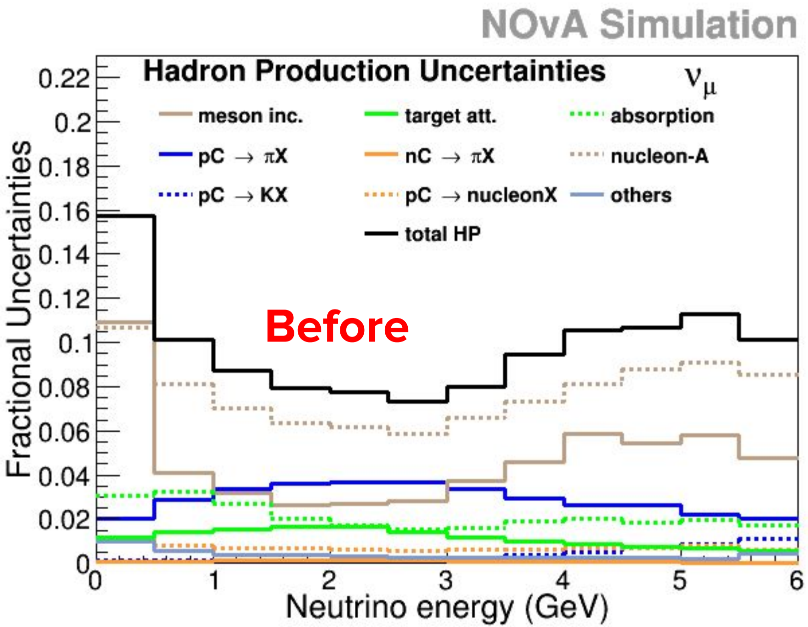
n	π threshold [GeV/c]	K threshold [GeV/c]	p threshold [GeV/c]
1.004	1.6	5.5	10.5
1.012	0.9	3.2	6.0

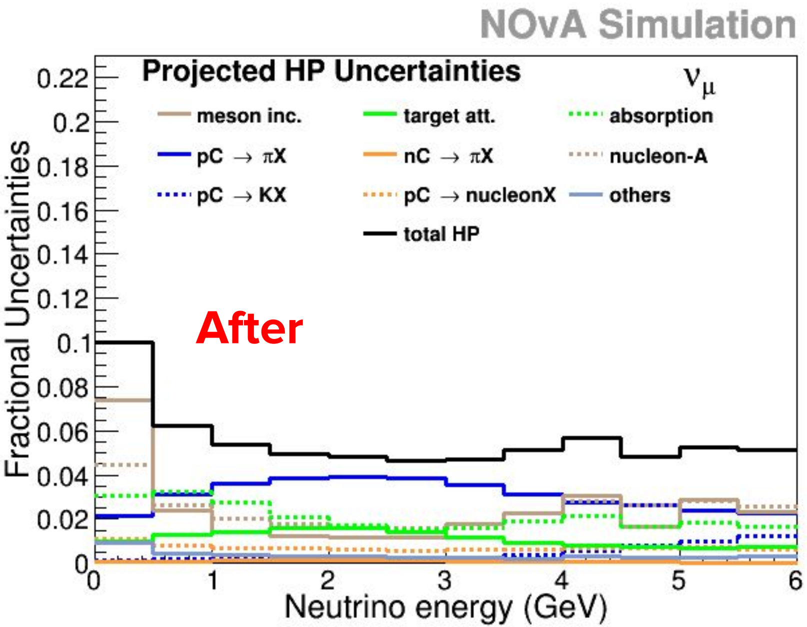
Future EMPHATIC measurements

- 2 phases
- Phase 1 (FY 2020):
  - p, π, K + C, Al, Fe, @ 4, 8, 12, 20, 31 GeV/c
  - 5, 10 and 20% λ_I C targets
  - First measurement of hadron yields (100k interactions for 5% λ_I target → data-taking 3 hours)
  - Beam aerogel Cherenkov
  - Magnet + TOF + Aerogel RICH
  - Calorimeter (lead glass)
- Phase 2 (2020/21):
  - p, π, K + C, Al, Fe @ 4, 8, 12, 20, 31, 60, 120 GeV/c
  - Additional targets B, BN, B_2O_3 for atmospheric neutrinos
  - DAQ upgrades
  - RICH upgrade up to 15 GeV/c

Future impact of EMPHATIC

- Assuming 10% uncertainty on future meason interaction measurements and quasi-elastic measurements





Conclusions (I)

- Neutrino flux uncertainty is the limiting factor for single detector measurements (ν-A cross section, sterile neutrino searches, CP violation measurements in atmospheric neutrinos)
- Additional data below 15 GeV/c is needed to further constrain neutrino flux
  - NA61/SHINE beam cannot go below 13 GeV/c
- EMPHATIC ➡ a table top experiment designed to take additional hadron production data
- Fermilab Test Beam Facility (FTBF)
  - Great asset for Fermilab
  - Fast setup of the experiment

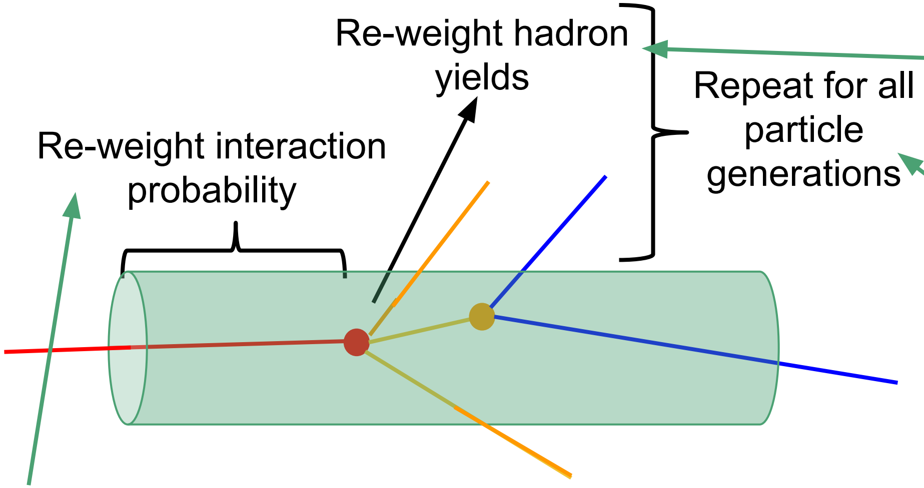
Conclusions (II)

- EMPHATIC test beam in 2018
  - Proof of concept (beam quality, SSD resolution)
- Measurements of forward scattering
  - $p + C \rightarrow p + X$ @ 20, 30, 120 GeV/c
  - $K + C \rightarrow K + X$ @ 30 GeV/c (measured for the first time)
  - Limited by statistics
  - None of the explored models accurately predict our results
  - The impact of the results is under investigation
- EMPHATIC upgrades
  - ARICH, RPCs → 2σ π/K separation < 7 GeV/c
  - Permanent magnet + SSD → momentum resolution < 10%
  - Beam PID with threshold aerogel detectors
- Future runs
  - Measurements of particle production and interaction probability

BACKUP

T2K neutrino flux re-weighting

$$W = \frac{\left[\frac{dn}{dp}(\theta, p_{in}, A)\right]_{data}}{\left[\frac{dn}{dp}(\theta, p_{in}, A)\right]_{MC}}$$



$$W = \frac{P(x; \sigma'_{\mathrm{prod}})}{P(x; \sigma_{\mathrm{prod}})} \cdot \exp(-x(\sigma'_{\mathrm{prod}} - \sigma_{\mathrm{prod}})\rho)$$

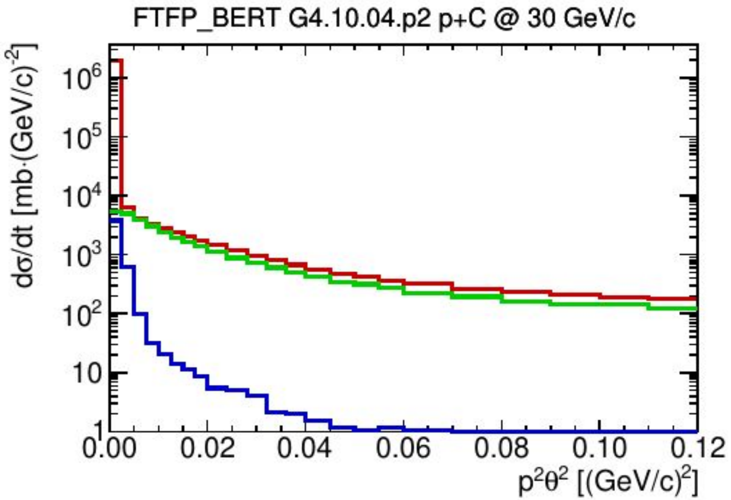
- Feynman scaling to different beam momentum
- A-dependence scaling [1,2,3]
- BMPT fit for extending to full phase space [1]

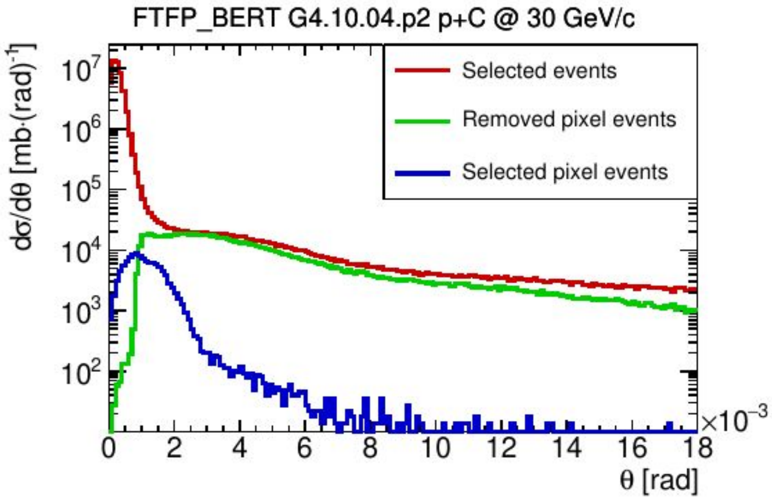
[1] Eur. Phys. J., C20:13–27, 2001.
[2] Phys. Rev., D27:2580, 1983.
[3] Phys. Rev., D18:3115–3144, 1978.

Pixel interactions

1. Missed interactions (normalization correction)
    a. Not in acceptance of the detector or missed by reconstruction
    b. Estimated from empty target data
2. Removed interactions (normalization correction)
    a. Events removed by the downstream selection
    b. Estimated from the number of removed events by $\delta x(y)$ cuts and corrected for purity
3. Selected interactions (normalization and shape correction)
    a. Selected pixel interaction
    b. MC based correction

Pixel interactions





POT correction	p+C @ 20 GeV/c	p+C @ 30 GeV/c	p+C @ 120 GeV/c	K+C @ 30 GeV/c
Missed int. [%]	3.3	2.5	1.9	1.7
Removed int. [%]	1.7	1.8	1.8	1.1
Selected int. [%]	0.2	0.2	0.6	0.1
Total [%]	**5.2**	**4.5**	**4.3**	**2.9**

Downstream selection

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

$$\left|x_{\mathrm{up}} - x_{\mathrm{down}}\right| < n\sigma_x + \tan\left(n\sigma_{\theta_x}\right) \cdot \left|z_{\mathrm{vert}} - z_{\mathrm{targ}}\right|$$