Measurements of hadron yields from the T2K replica target in the NA61/SHINE experiment for neutrino flux prediction in T2K

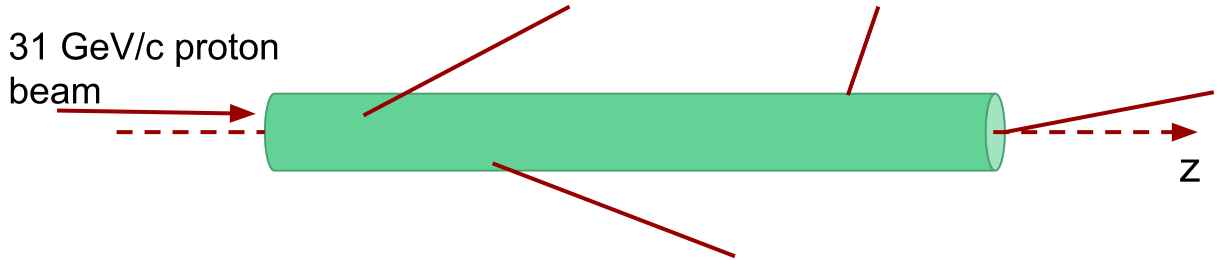
Matej Pavin

27. 09. 2017.

Motivation

- Standard model ➔ very successful but not complete theory of nature
- Neutrinos do not behave as expected from the Standard model
- Precise measurements of the neutrino behaviour ➔ good control of the neutrino source is necessary

- Thesis topic: measurements of the hadron yields coming from a 90 cm long T2K replica target ➔ Improvement of the T2K neutrino flux coming from hadron decays



Hadron yields ($\pi^{\pm}$, $K^{\pm}$ and p) as a function of momentum (**p**), polar angle (**θ**) and longitudinal position (**z**)

Neutrinos

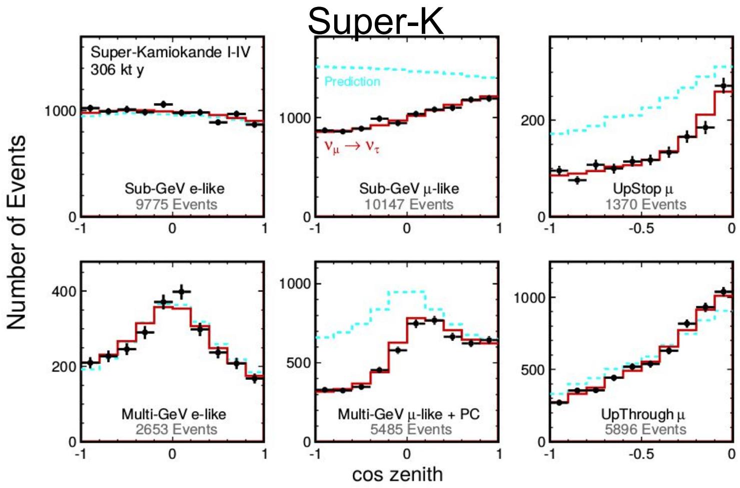
- Weakly interacting particles
- Proposed by Pauli to solve beta decay puzzle
- 3 flavors states: ν_e, ν_μ, ν_τ
- In Standard model only left neutrino chiral states are necessary ➔ no Dirac mass term
- Sources ➔ wide energy range (eV ➔ TeV)

- Natural
  - Solar (nuclear reactions in the Solar core)
  - Atmospheric (cosmic ray showers ➔ pion decays)
  - Earth (radioactive decays in the Earth's interior)
  - Cosmic (supernovae, ...)
- Artificial
  - Reactor
  - Accelerator neutrinos

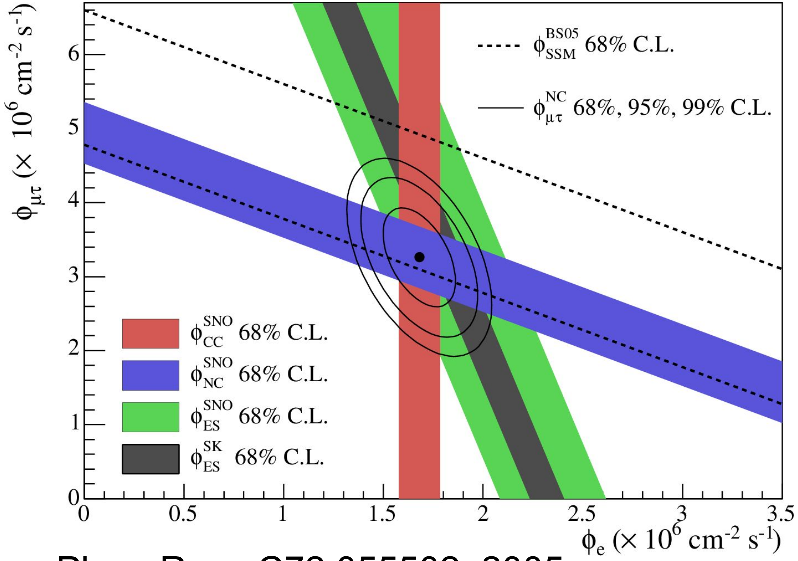
Neutrinos oscillations

2015. T. Kajita and A.B. McDonald

- Solar neutrino puzzle and atmospheric neutrino problem (solved by SK and SNO)
- Flavor states are not mass eigenstates → neutrinos have non-zero mass → oscillations (proposed by B. Pontecorvo)



Phys. Rev., D71:112005, 2005



Phys. Rev., C72:055502, 2005.

Neutrino oscillations

$m_2^2 - m_1^2$

Needs to be tuned in each experiment → maximize oscillation probability

mixing angle

- For 2 neutrinos

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \cdot \Delta m_{21}^2 [eV^2] \frac{L[km]}{E[GeV]}\right)$$

- For 3 neutrinos ➔ Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

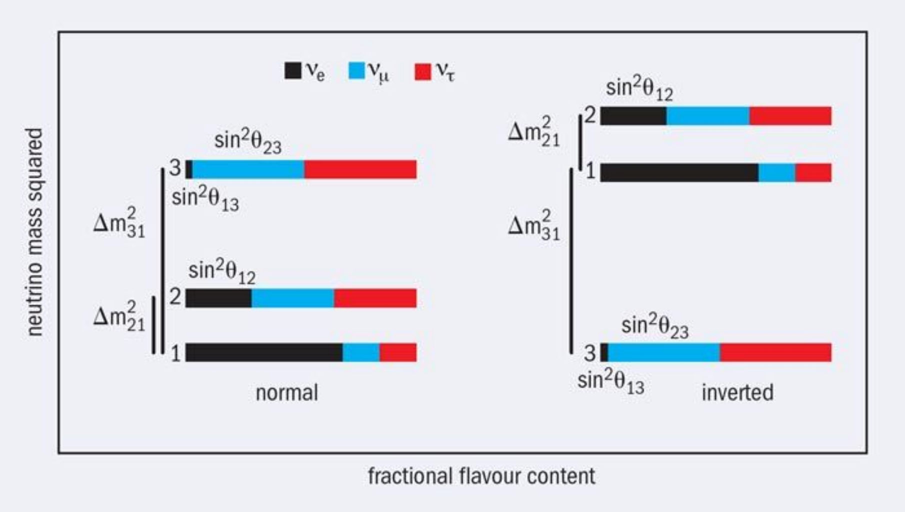
"Solar neutrinos" "Atmospheric neutrinos"

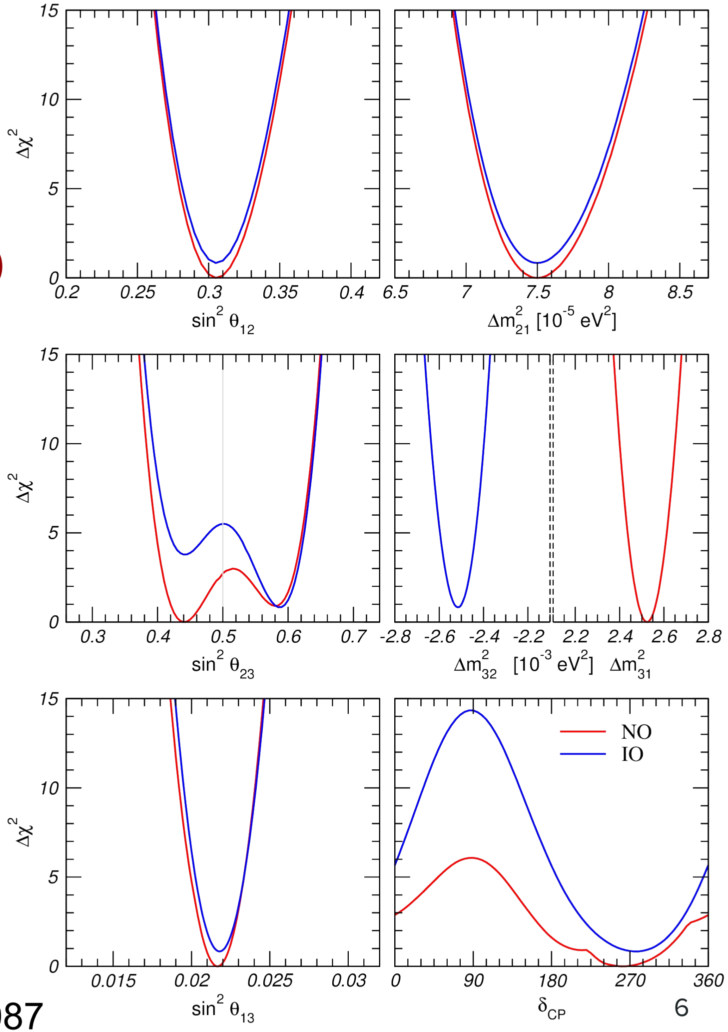
- 3 non zero mixing angles ➔ possible CP violation in the lepton sector

!CP → Neutrinos behave differently than anti-neutrinos! For example: $P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$

Neutrino oscillation parameters

- Open questions
  - CP violation in the lepton sector (FIRST INDICATION)
  - Neutrino mass hierarchy
  - θ_{23} octant





JHEP 01 (2017) 087

T2K (Tokai to Kamioka)

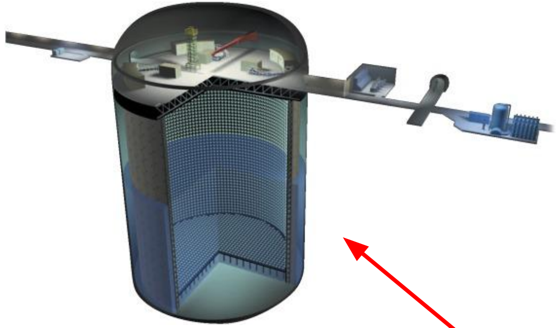
- accelerator long-baseline neutrino experiment

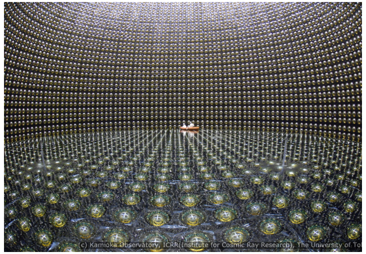
Science goals:

- world-leading measurements of ν_μ disappearance
- discovery of $\nu_\mu \rightarrow \nu_e$ (θ_{13}>0)
- search for the CP violation in the lepton sector
- neutrino-nucleus cross section measurements

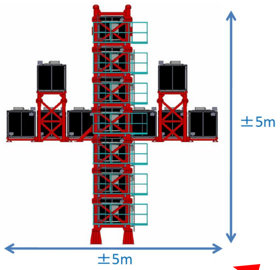
Neutrino flux uncertainty limits the precision of measurements

Super-Kamiokande (off-axis)

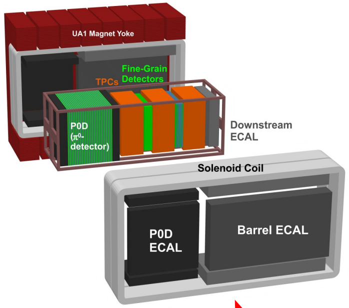




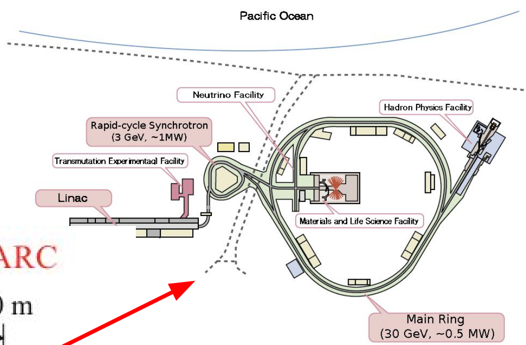
INGRID (on-axis)

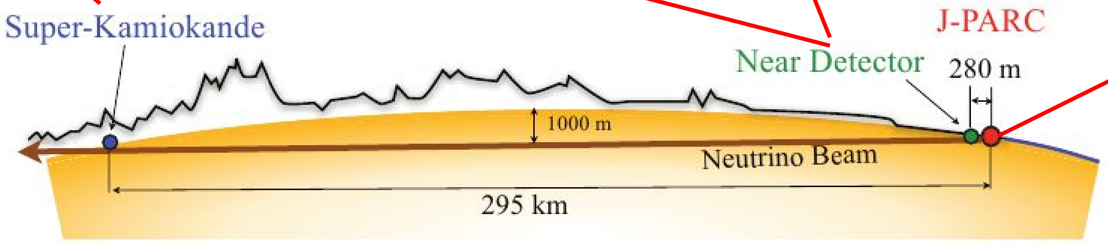


ND280 (off-axis)

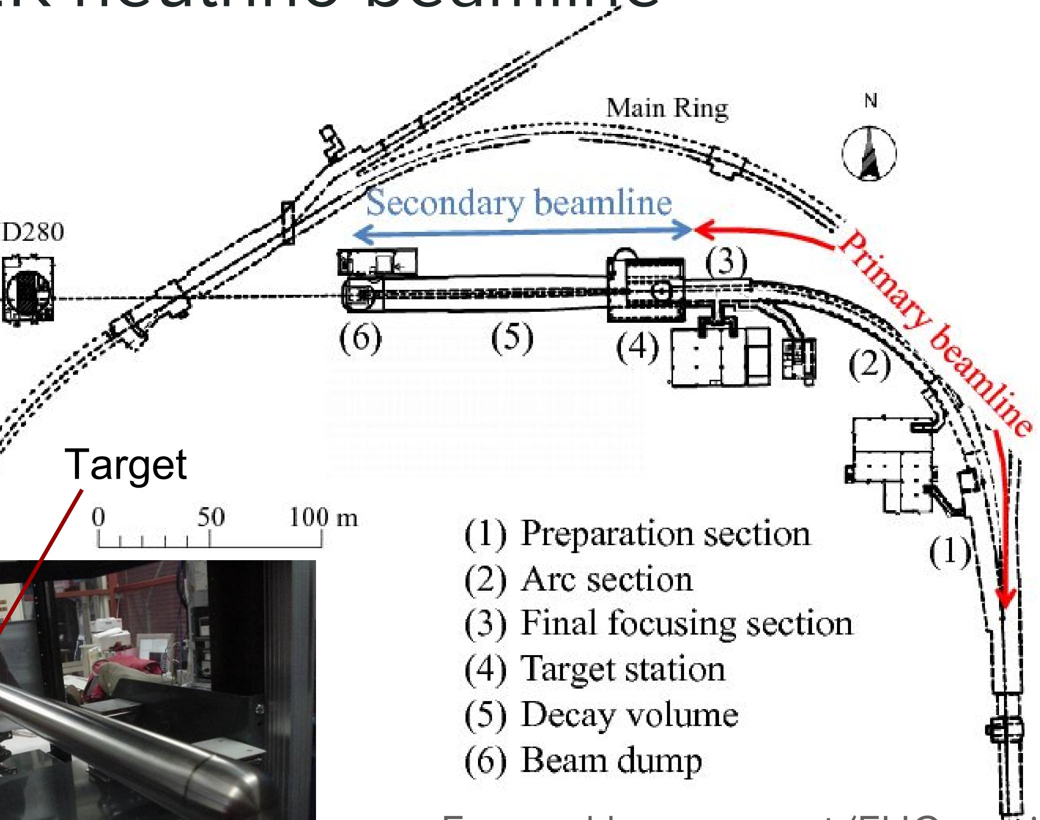


J-PARC



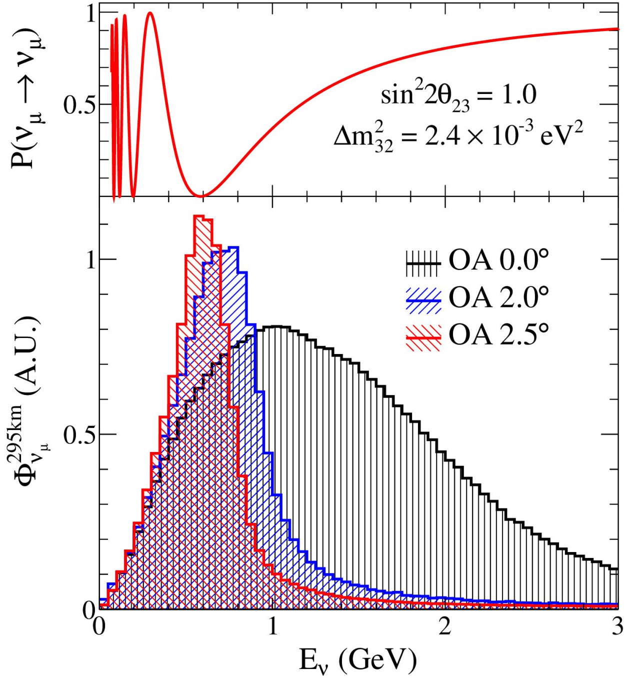


T2K neutrino beamline



Target

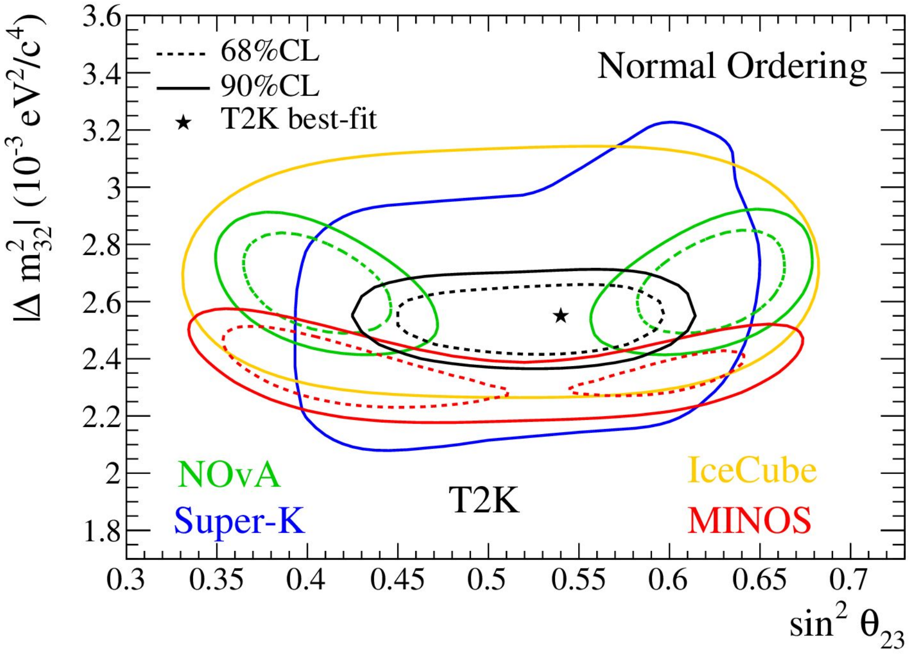
Off-axis method



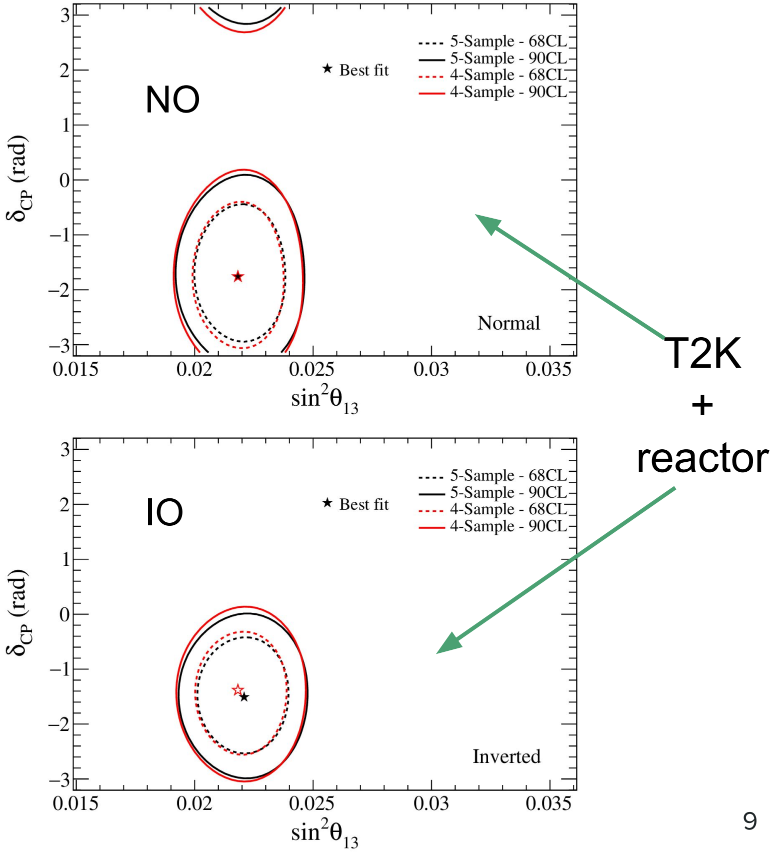
- Forward horn current (FHC, positive focusing) ➔ muon neutrino beam
- Reverse horn current (RHC, negative focusing) ➔ muon antineutrino beam

T2K results (first indication of CP violation)

- 22.54×10^{20} POT (protons on target) = 14.93×10^{20} (FHC) + 7.62×10^{20} (RHC)
- Beam power: 470 kW

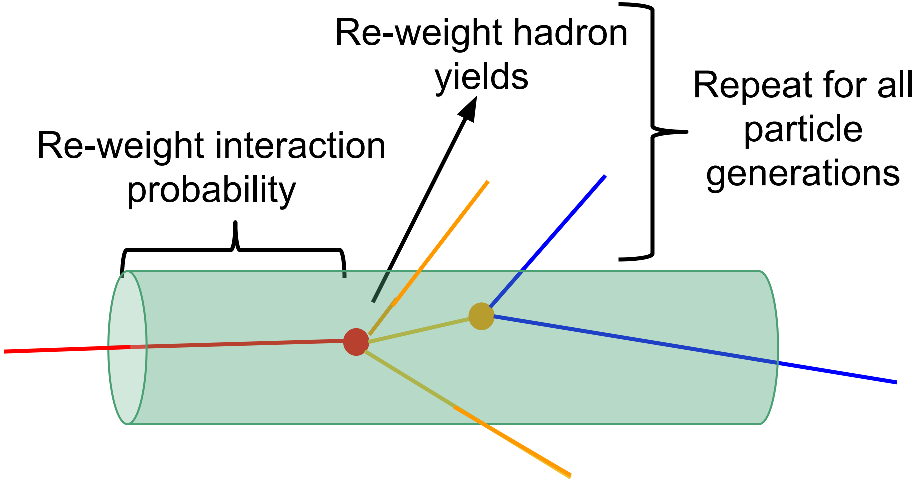


arXiv:1707.01048 [hep-ex]



J-PARC neutrino beam simulation

- FLUKA 2011 (target, baffle) + GEANT3 GCALOR (horns, decay volume, beam tunnel)
  - proton beam is sampled from the measured distributions
  - Hadrons are propagated to the target surface by FLUKA
  - Hadrons are propagated to the beam dump and muon monitor by GEANT3 and forced to decay in the direction of the ND280
  - Neutrino histories are saved
- Multiplicative weights are applied to each neutrino based on its history



Flux re-weighting

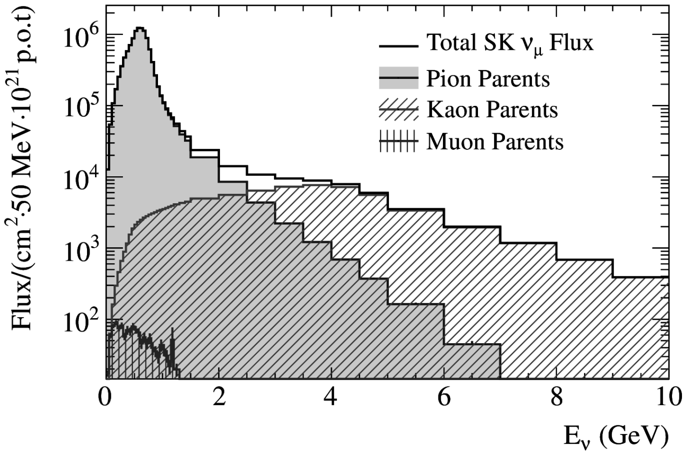
$$W = \prod_{i}^{n} w_i$$

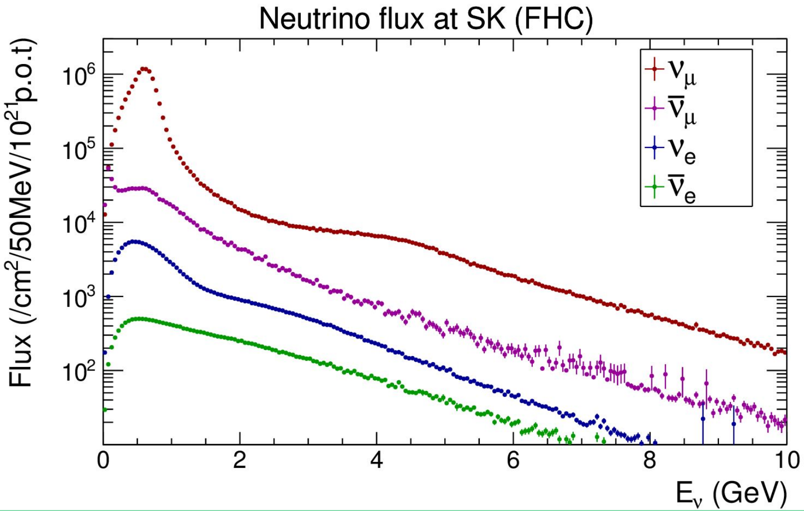
All weights

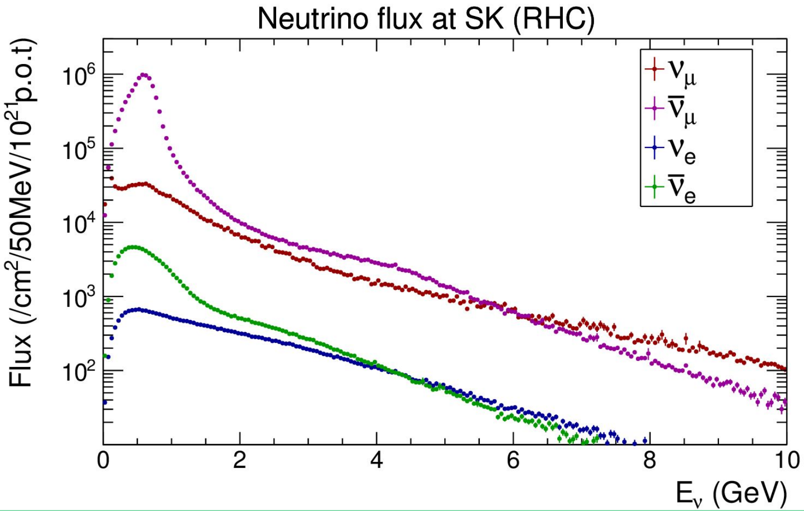
Hadron production data often needs to be scaled (different energies, materials, …)

T2K neutrino flux

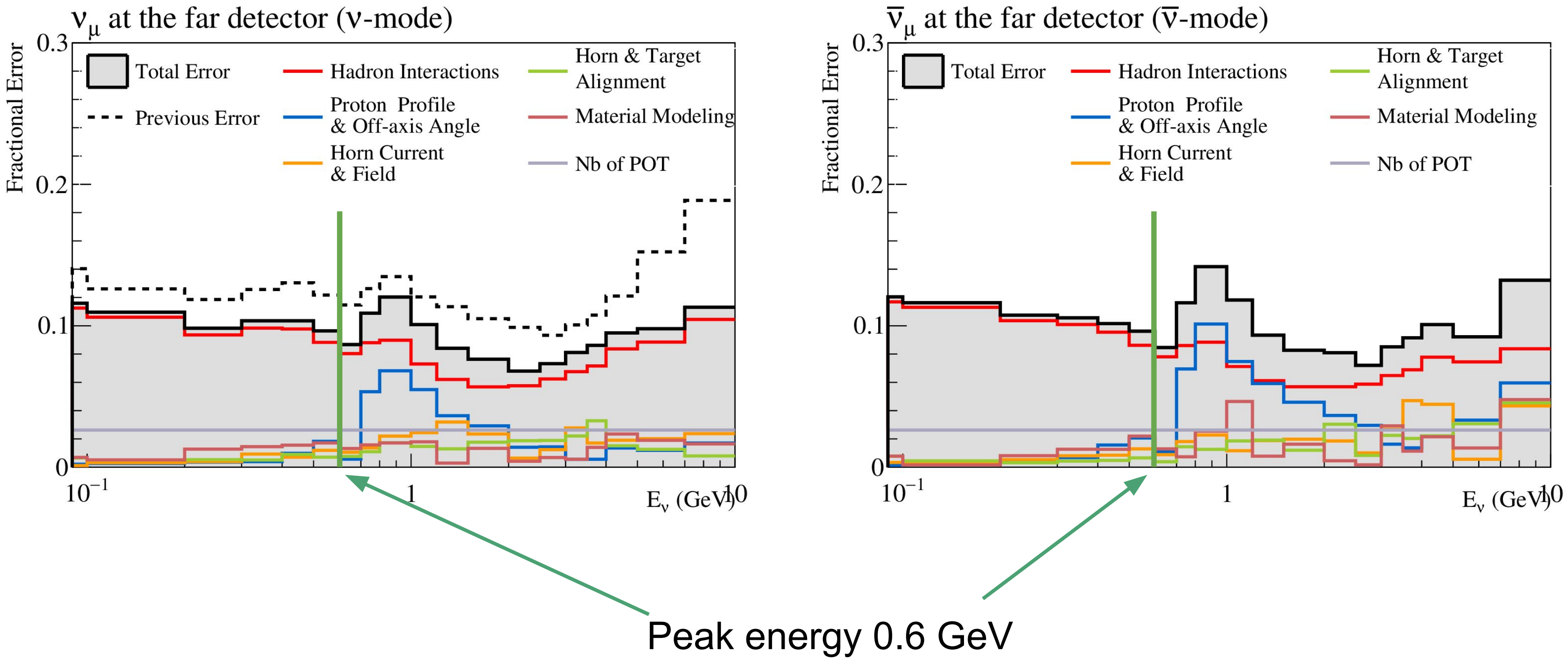
- Pions (95%)
- Kaons (5%)



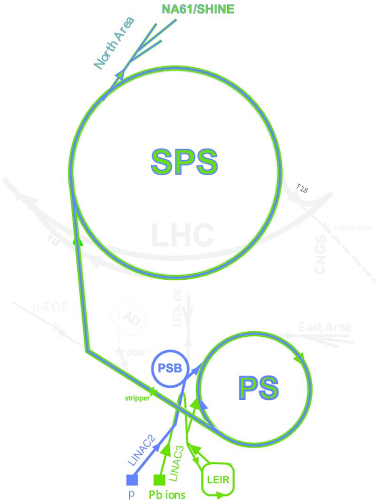


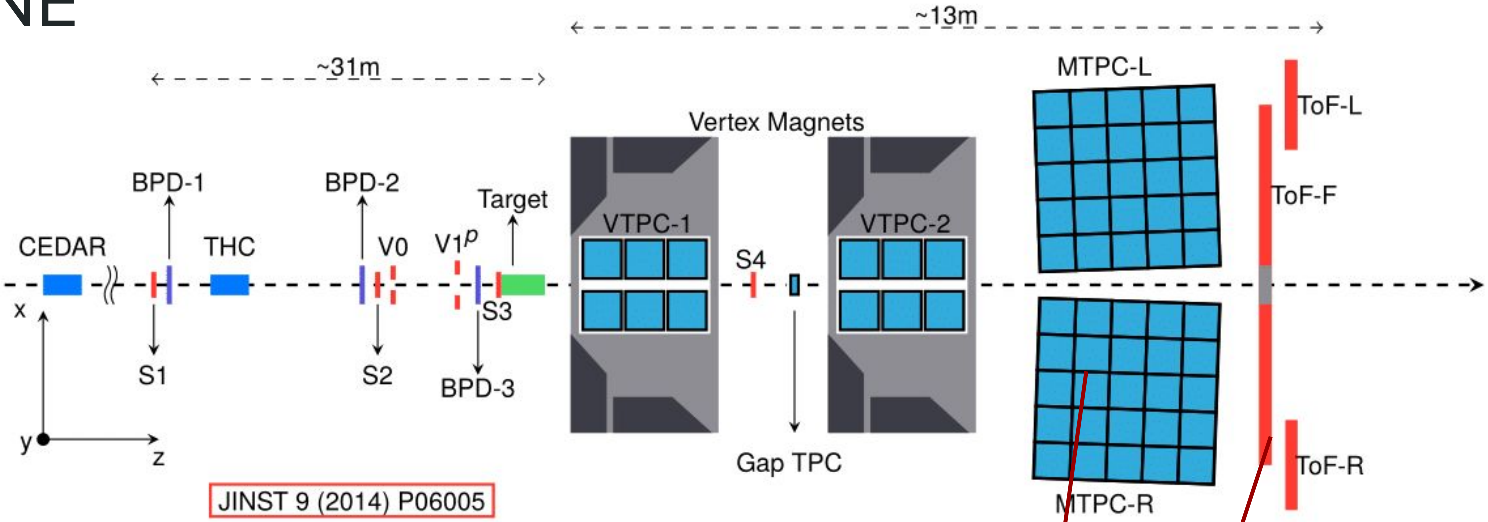


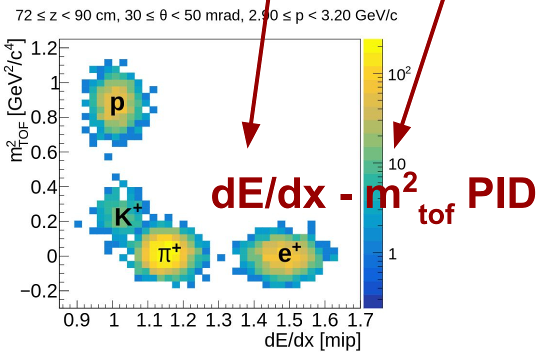
T2K neutrino flux uncertainties



North Area 61 / SPS Heavy Ion and Neutrino Experiment
NA61 / SHINE





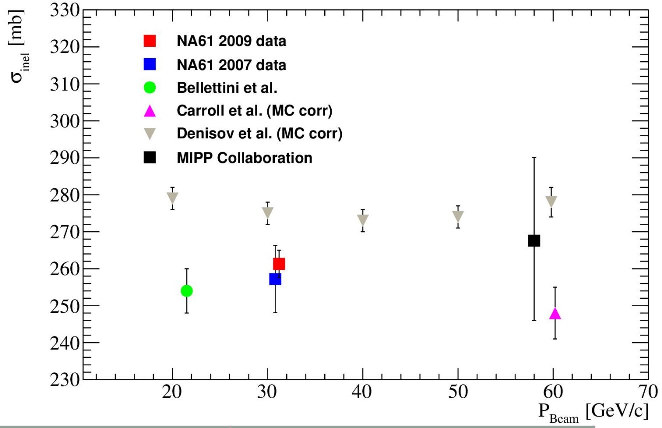


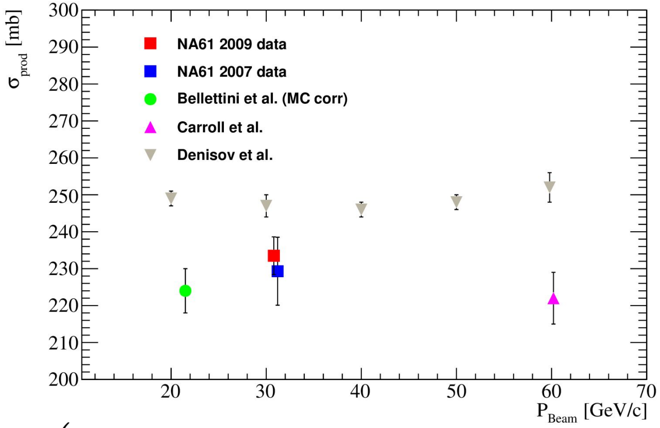
- Precise hadron production measurements for neutrino flux re-weighting in T2K and Fermilab neutrino experiments

- Setup used in 2010 (now is improved) → FTPCs

Thin target measurements for T2K

- 2 cm thick graphite target and 30.92 GeV/c proton beam
- Inelastic and production cross section + double differential hadron (**$\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ**) yields





Year	[10^6] events	Results
2007	0.7	$\pi^{\pm}$, K^{+}, K^0_s, Λ [1,2]
2009	5.4	$\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ [3]

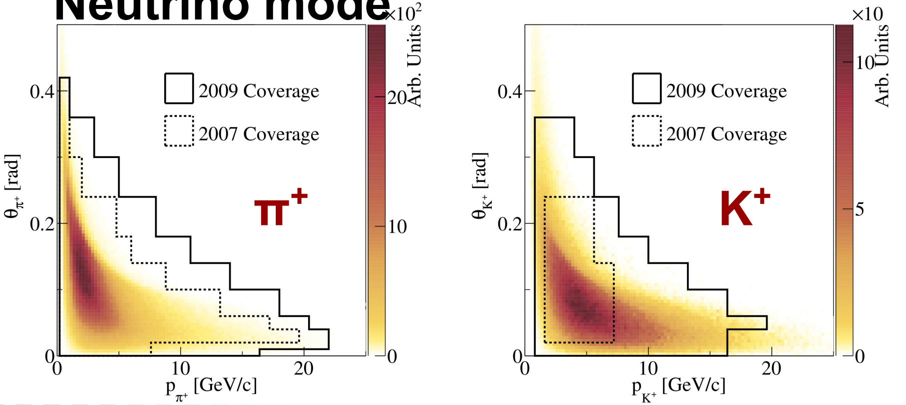
$$\sigma_{inel} = \left(258.4 \pm 2.8\,(\text{stat}) \pm 1.2\,(\text{det})^{+5.0}_{-2.9}\,(\text{mod})\right)\ \text{mb}$$

$$\sigma_{prod} = \left(230.7 \pm 2.7\,(\text{stat}) \pm 1.2\,(\text{det})^{+6.3}_{-3.4}\,(\text{mod})\right)\ \text{mb}$$

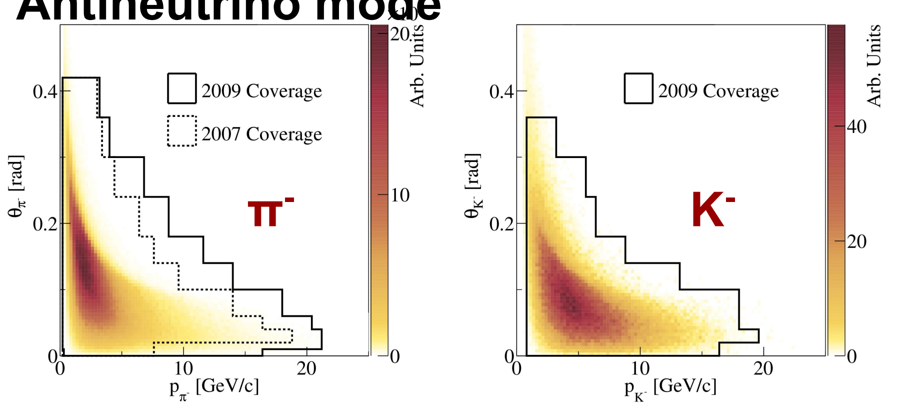
[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Eur. Phys. J. C (2016) 76: 84

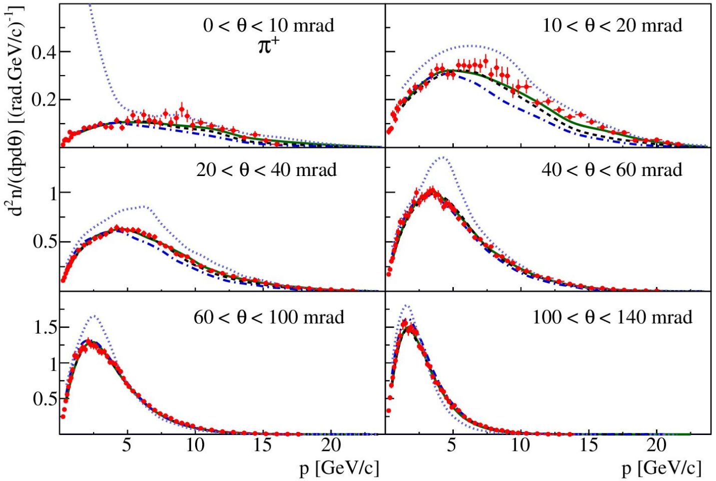
Thin target measurements for T2K

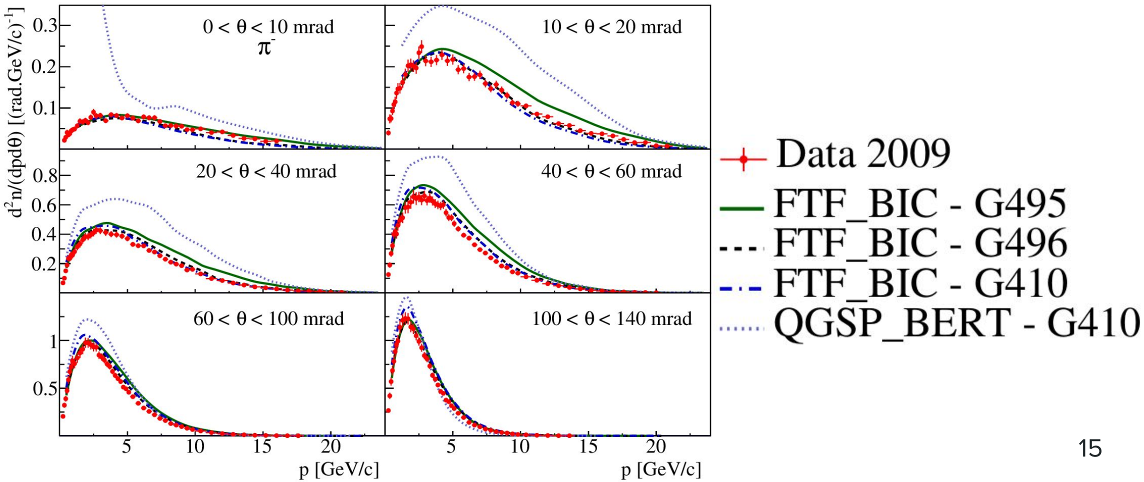
Neutrino mode



Antineutrino mode



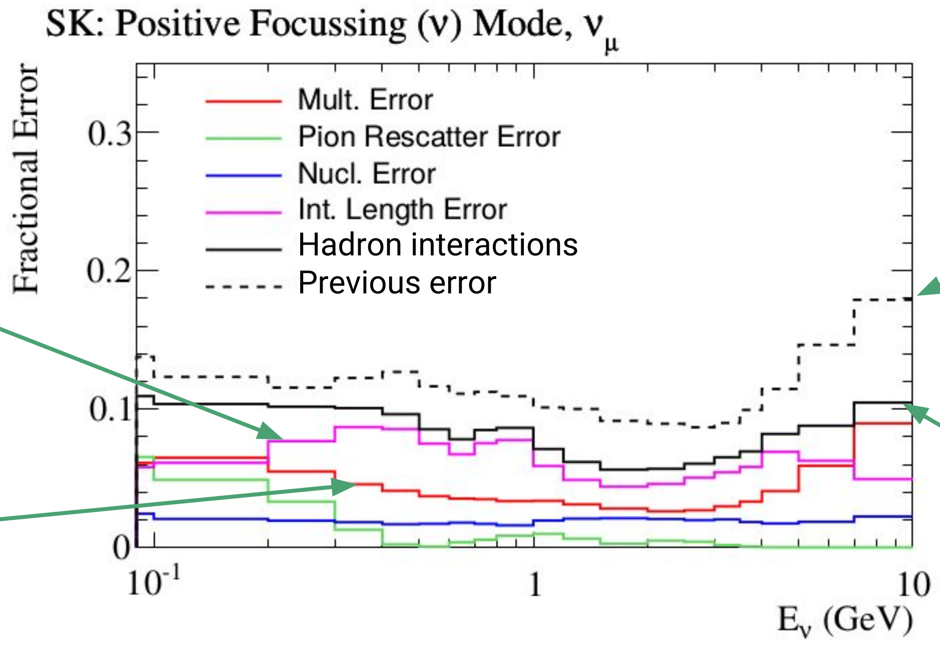




Hadron production uncertainties

Interaction probability re-weighting (σ_{prod})

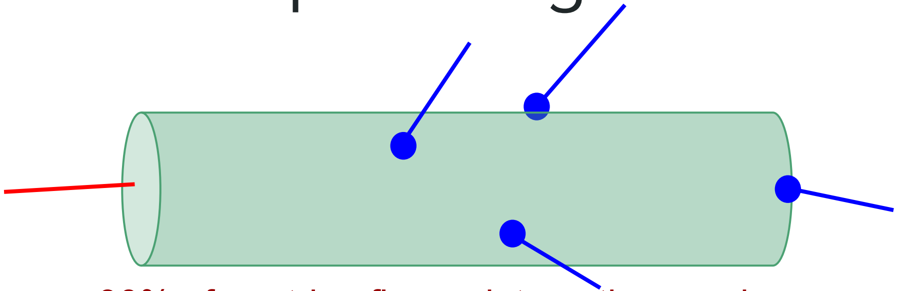
Pion and kaon multiplicity errors



Based on the 2007 thin target data

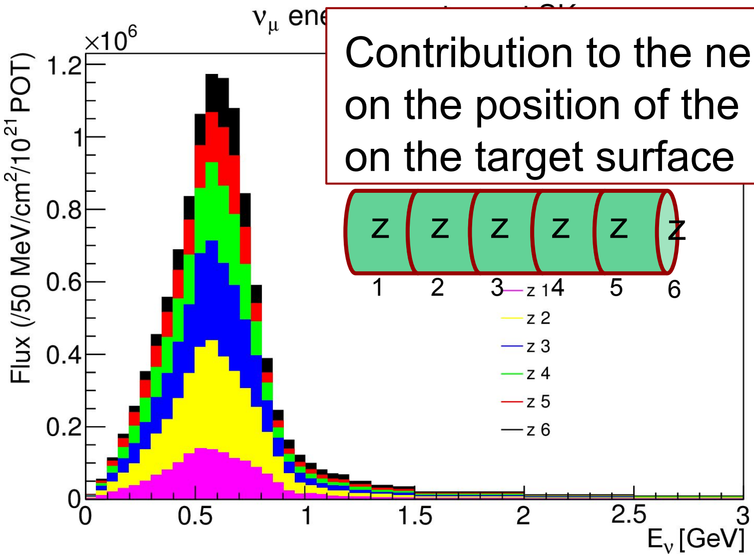
Based on the 2009 thin target data

T2K replica target measurements



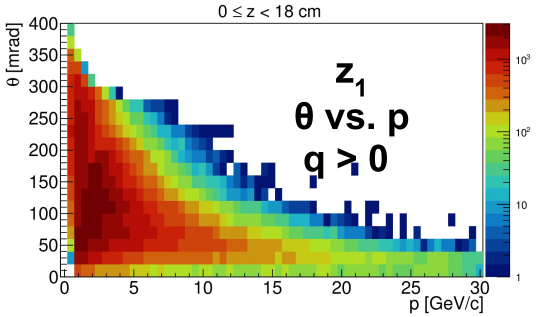
~ 90% of neutrino flux → interactions and re-interactions in the target

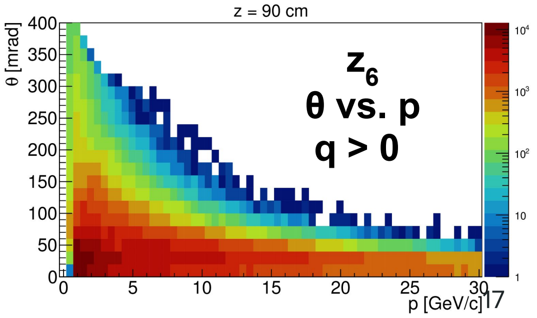
- Re-weight hadron yields on the target surface
  - knowledge of the production cross section not necessary
  - accounts for all interactions and re-interactions inside the target



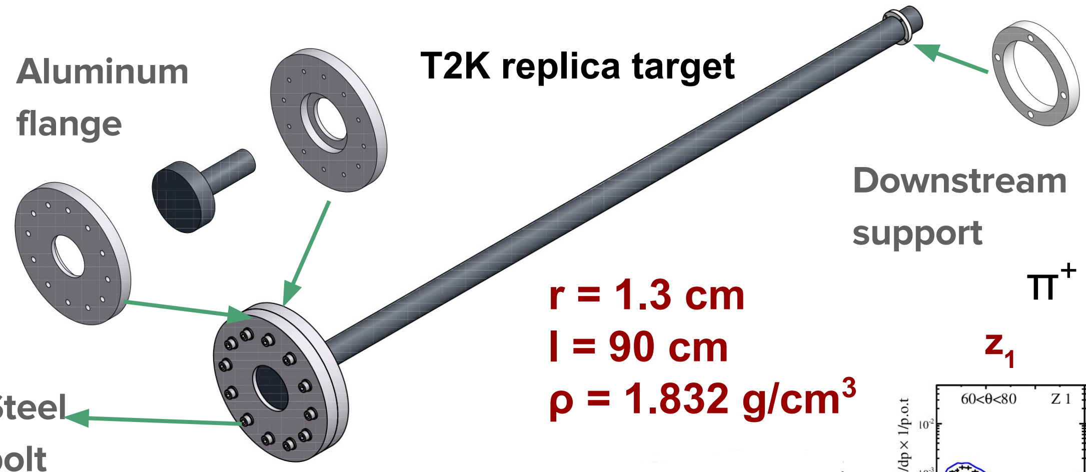
Contribution to the neutrino flux depends on the position of the hadron exit point on the target surface

Measurements are needed in: momentum (**p**), polar angle (**θ**) and longitudinal position (**z**)





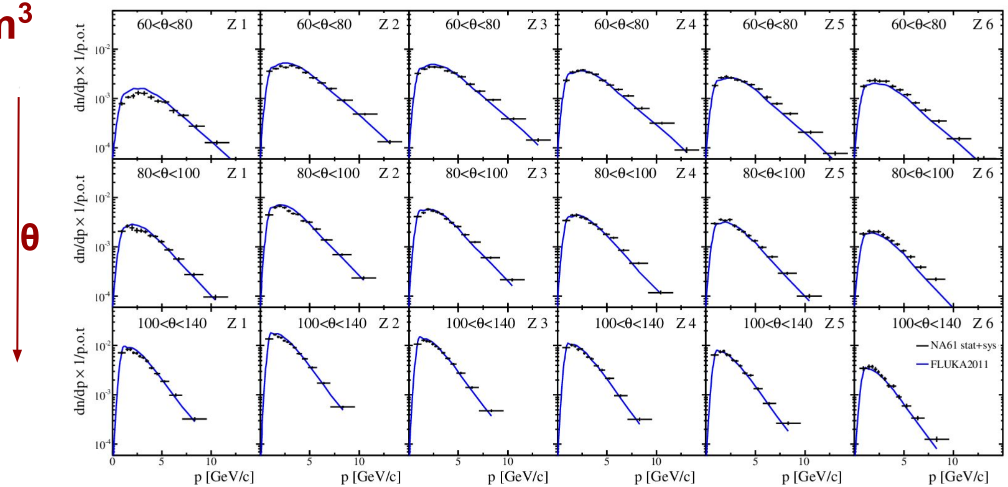
p + T2K RT measurements in NA61/SHINE



- 30.92 GeV/c proton beam

r = 1.3 cm
l = 90 cm
ρ = 1.832 g/cm^3

π^+ yields on the target surface (2009)



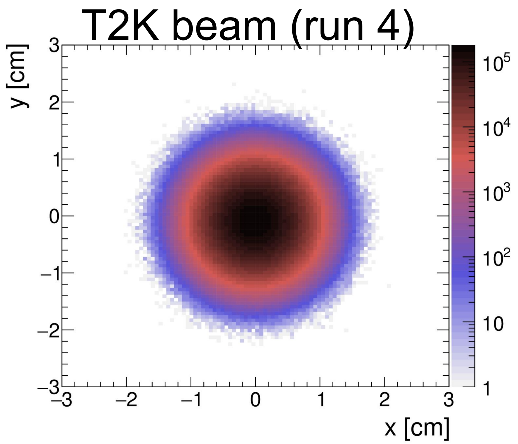
Year	[10^6] events	Results
2007	0.2	proof of concept [1]
2009	4	$\pi^\pm$ yields [2]
2010	**10**	**$\pi^\pm$, $K^\pm$, p yields**

PhD thesis ($K^\pm$, p measured for the first time)

[1] N. Abgrall et al., Nucl. Instrum. Meth., A701:99, 2013.
[2] N. Abgrall et al. Eur. Phys. J., C76(11):617, 2016.

Analysis of 2010 replica target data

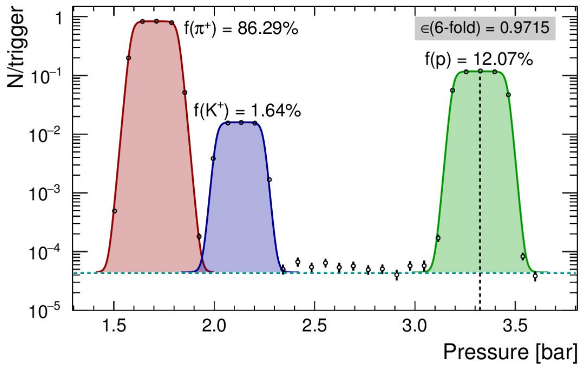
- Data: 10.2×10^6 triggers
  - **9.0×10^6 collected with standard magnetic field**
  - 1.2×10^6 collected with full magnetic field (used for calibration purposes and further analysis)
- MC: FLUKA 2011.2c.5 (generator) + GEANT3 - GCALOR (simulation of the detector)
  - 38.0×10^6 events
- Strategy:
  - Event and track selection
  - Backward extrapolation to the target surface
  - Particle identification (dE/dx + m^2_{tof})
  - Correction factors
  - Systematics
  - **Check for the beam profile dependence**



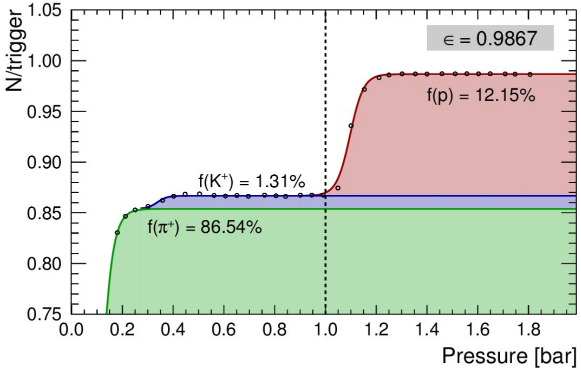
Beam and triggers (2010)

- Secondary beam at 31 GeV/c (12% of protons)
- CEDAR + THC ➔ > 99.9% beam purity

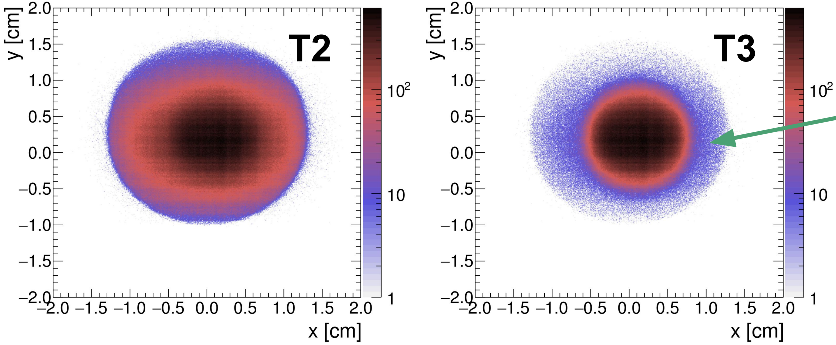
CEDAR



THC



- Wide (T2) and narrow (T3) beam profile



additional counter with hole included in trigger

Event selection

Beam PID

$$T1 = S_1 \cdot S_2 \cdot \overline{V_0} \cdot \overline{V'_1} \cdot CEDAR \cdot \overline{THC}$$

$$T2 = S_1 \cdot S_2 \cdot S_3 \cdot \overline{V'_1} \cdot CEDAR \cdot \overline{THC}$$

$$T3 = S_1 \cdot S_2 \cdot S_3 \cdot \overline{V_0} \cdot \overline{V'_1} \cdot CEDAR \cdot \overline{THC}$$

Glued to the target surface (r = 1.3 cm)

Counter with hole (r = 0.5 cm)

T2 trigger: T2 beam profile, wider than T3 and T2K beam profiles but higher statistics

BPD cut: there are 3 good BPD clusters in x and y (removes multihits, edge clusters, etc …)

Radius cut: removes beam particles close to the edge of the target

Total	T2 trigger		T3 trigger		BPD cut		Radius cut	
$[10^6]$	$[10^6]$	[%]	$[10^6]$	[%]	$[10^6]$	[%]	$[10^6]$	[%]
8.970	**8.239**	**91.85**	**-**	**-**	**6.762**	**75.39**	**6.726**	**74.98**
	-	**-**	**4.982**	**55.53**	**4.110**	**45.81**	**4.106**	**45.77**

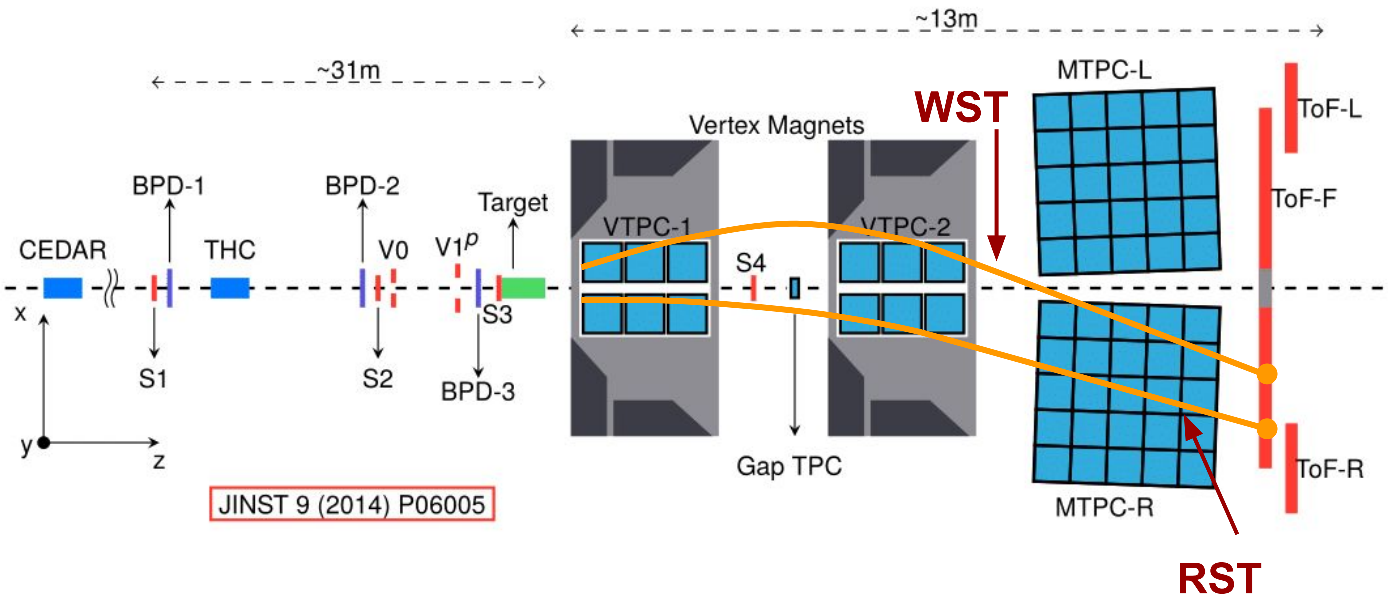
TPC tracks

Right side tracks (RST)

- $q \cdot px > 0$

Wrong side tracks (WST)

- $q \cdot px < 0$

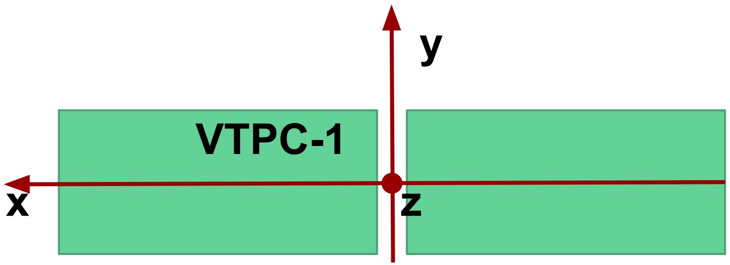


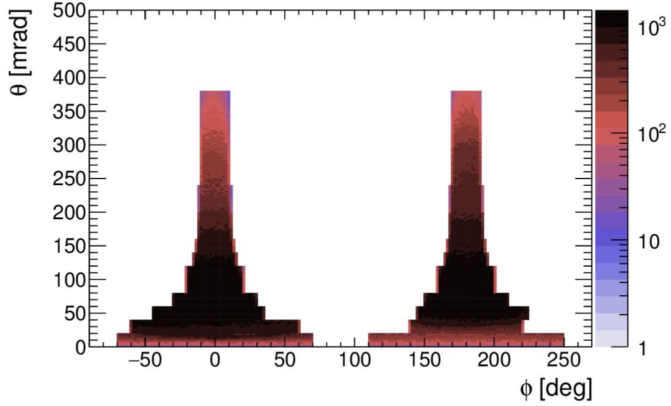
TPC track topologies

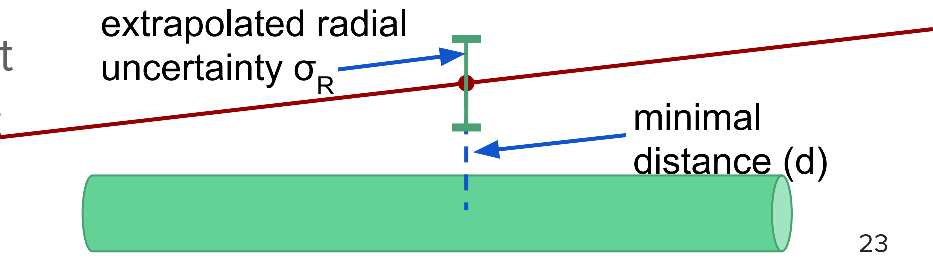
- different momentum and position resolution
- different extrapolation length
- the worst topology: GTPC + MTPC (σ_p/p: 2.5% - 7%), $l_{ext} \cong 4$ m
- the best topology: VTPC1 + VTPC2 + (GTPC) + MTPC ($\sigma_p/p < 1\%$)

Track selection

- **p fit** → track has fitted momentum larger than 0.2 GeV/c
- **dE/dx - tof** → good measurement of energy loss and time of flight
- **Clusters**
  - GTPC + MTPC = 5 + 30
  - VTPC1(2) + MTPC = 30 + 0
  - VTPC1+2 + MTPC = 20 + 0
- **ϕ angle** → azimuthal acceptance of the detector
- **d_{targ}/σ_R** → track distance from the target surface is less than $3\sigma_R$ from the target surface







Software and calibrations

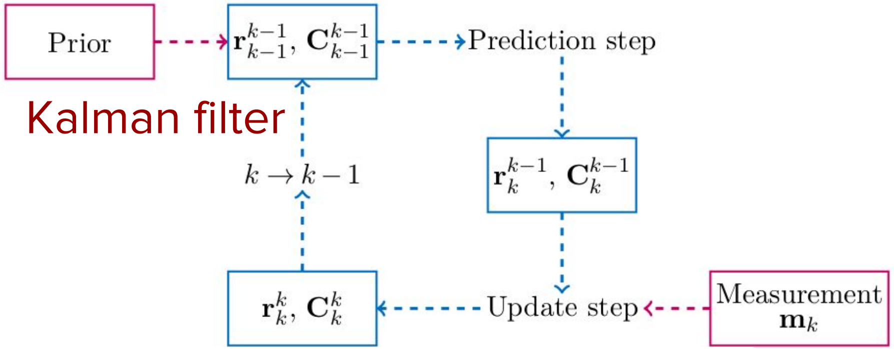
Analysis tools

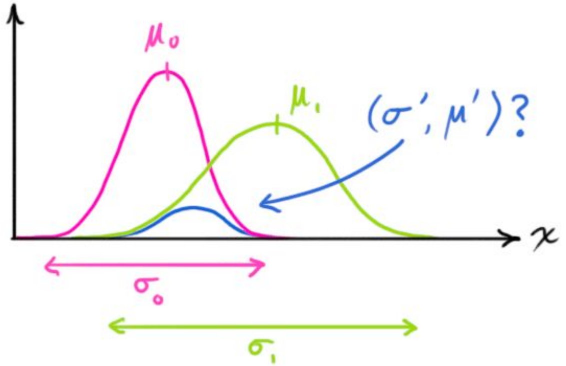
- Several modules in the SHINE framework ➔ selection, extrapolation, fitting, MC corrections

Track extrapolation in MF

- Extrapolation of tracks with full covariance matrix propagation
    - Developed for high level trigger in CBM [1]
    - Multiple Coulomb scattering ➔ updated covariance matrix [2]
    - Kalman filter [3]

$$\sigma(\theta_s) = \frac{13.6}{\beta c p} z \sqrt{\frac{X}{X_0}} \left[1 + 0.038 \cdot \log\left(\frac{X}{X_0}\right)\right]$$





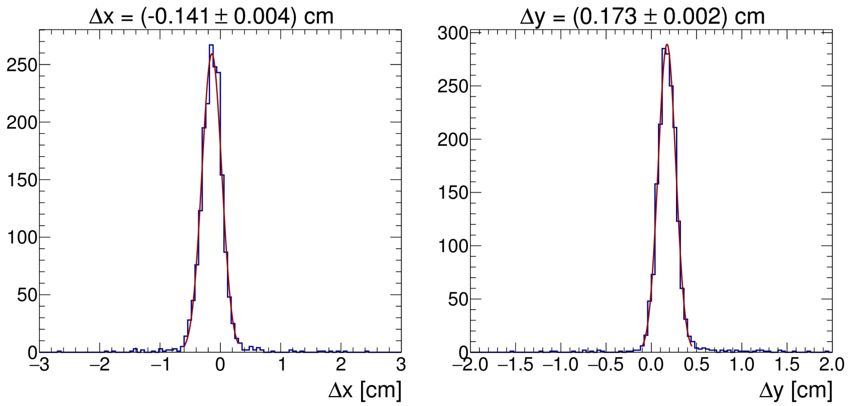
[1] Nucl. Instrum. Meth., A559:148–152, 2006.
[2] Nucl. Instrum. Meth., A329:493–500, 1993
[3] Nucl. Instrum. Meth., A262:444–450, 1987

Software and calibrations

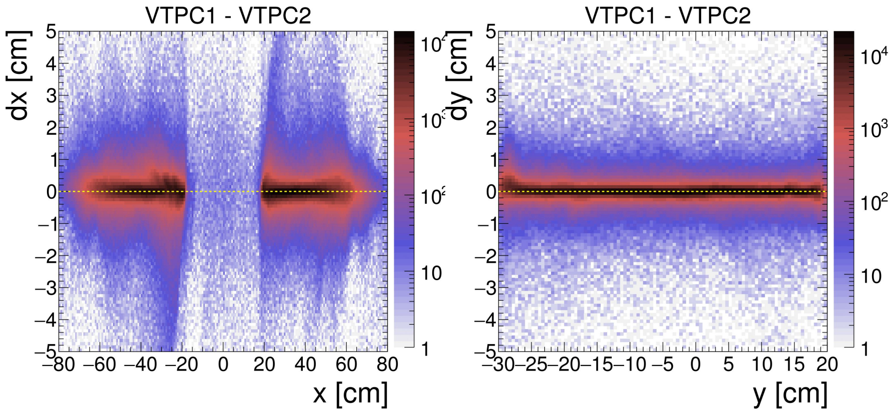
Calibration task done:

- TOF-F calibration, TPC alignment, residual corrections in TPC, beam-TPC alignment, target position

Beam - TPC alignment



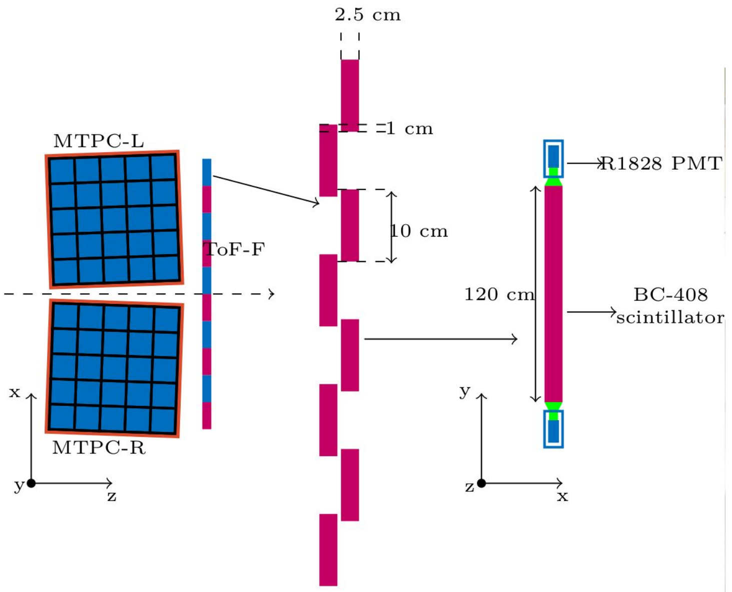
TPC alignment

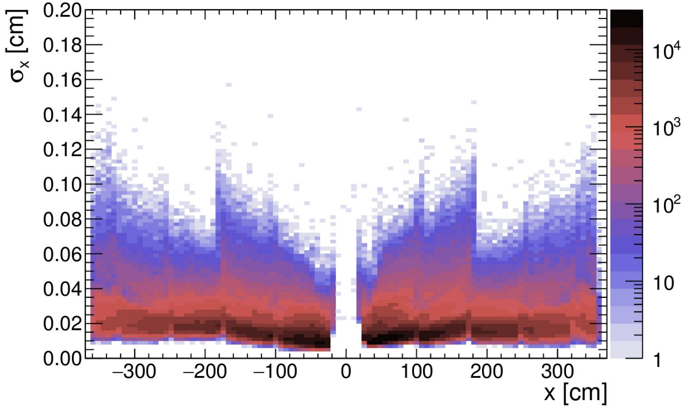


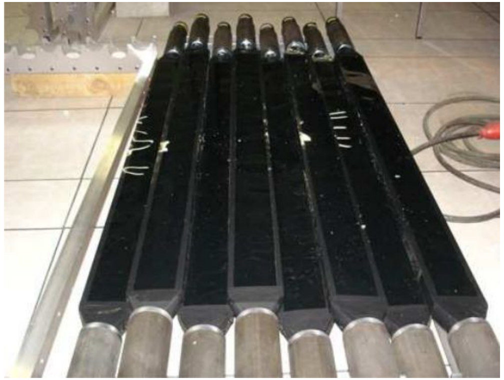
TOF-F calibration

$$tof = \frac{1}{2}\left(tof^{top} + tof^{bottom}\right)$$

- 80 scintillator bars (2 PMTs per bar)
- Correction of measured tof for delays (cables), beam time, start signal jitter
- Extrapolation tools used for the calibration



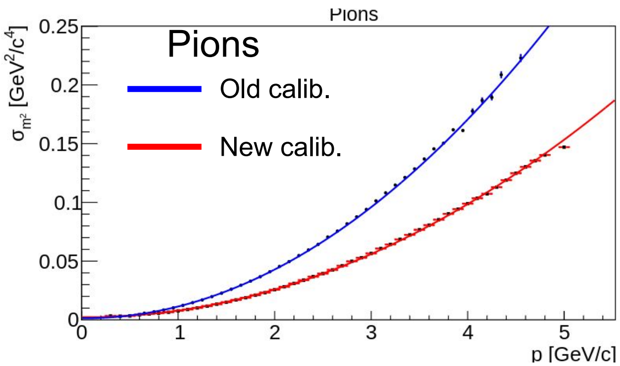


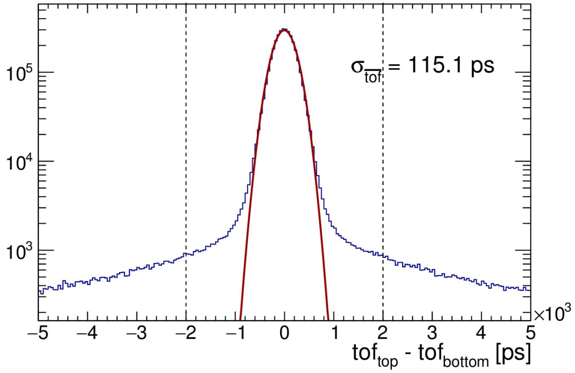


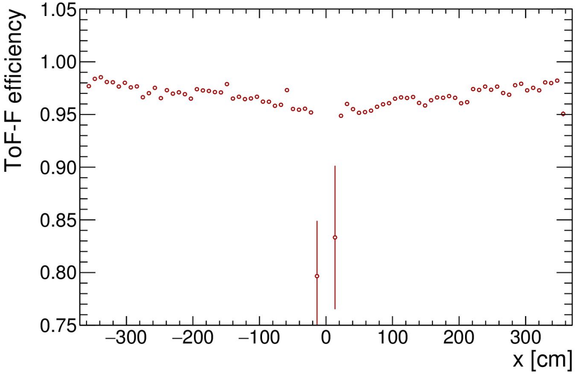
TOF-F performance

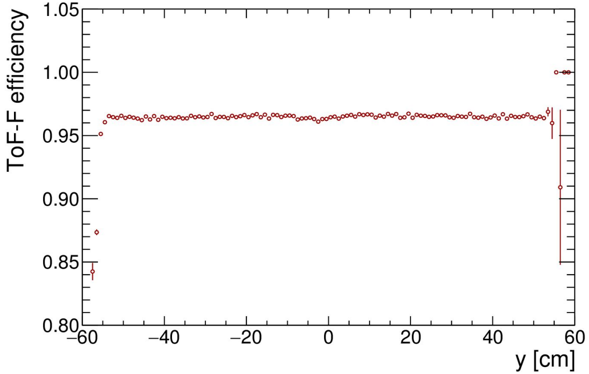
- Large contribution from the start signal jitter
- Intrinsic TOF-F resolution ➔ 115 ps
- 4 scintillators with one PMT working ➔ sqrt(2)·115 ps
- Efficiency 95% - 98% (track density and quality cut)

TOF calibration



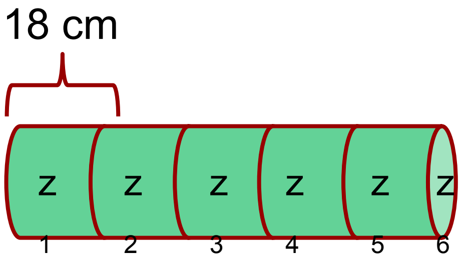


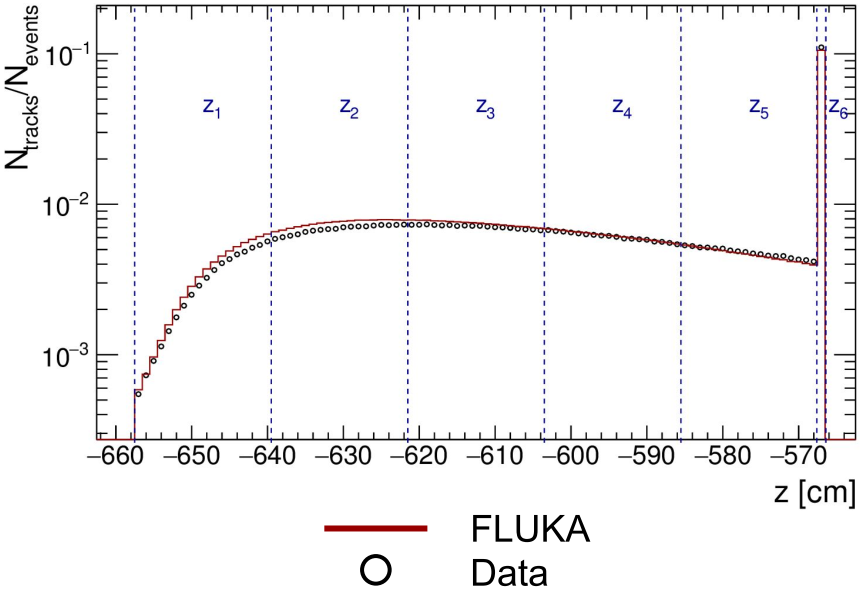




Phase space

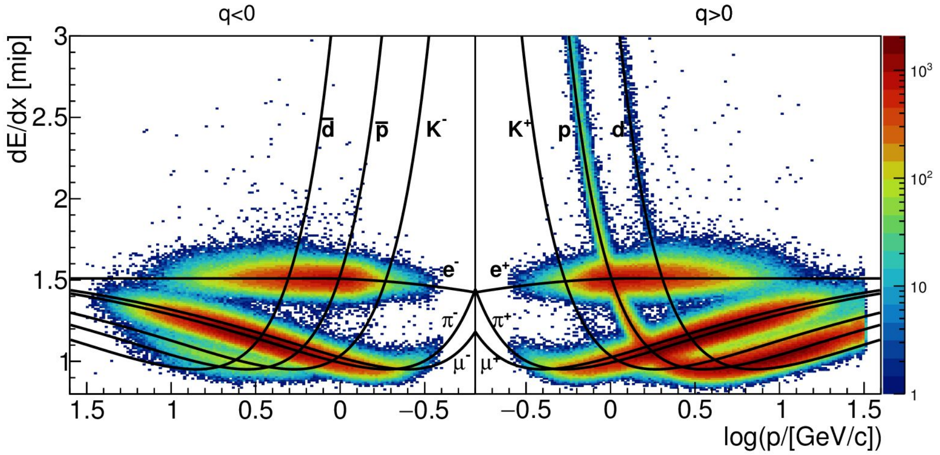
- 5+1 longitudinal bins (z)
- Polar angle (**θ**) and momentum bins (**p**)
  - Number of (θ, p) bins for each z bin may be different
  - **880 for pions**
  - **576 for protons**
  - **141 for kaons**

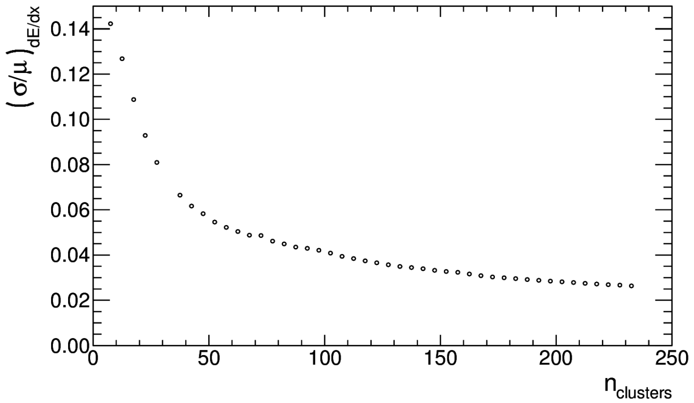




Particle identification

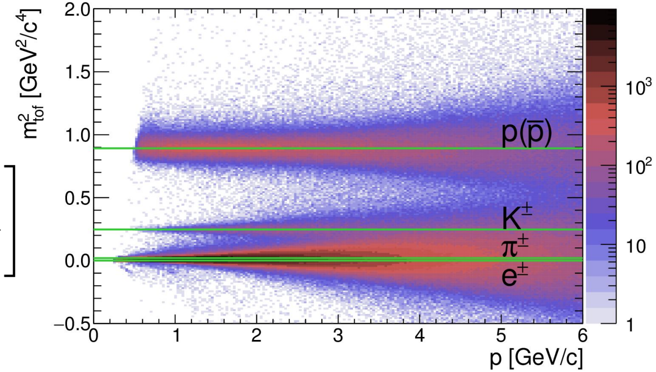
- Energy loss → crossing of the energy loss distributions for low momenta

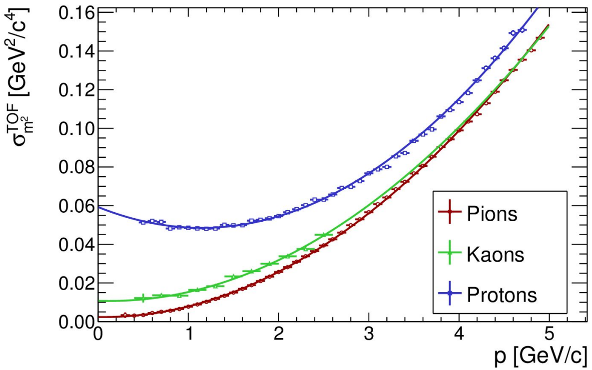




- time of flight → not sensitive above 8 GeV/c

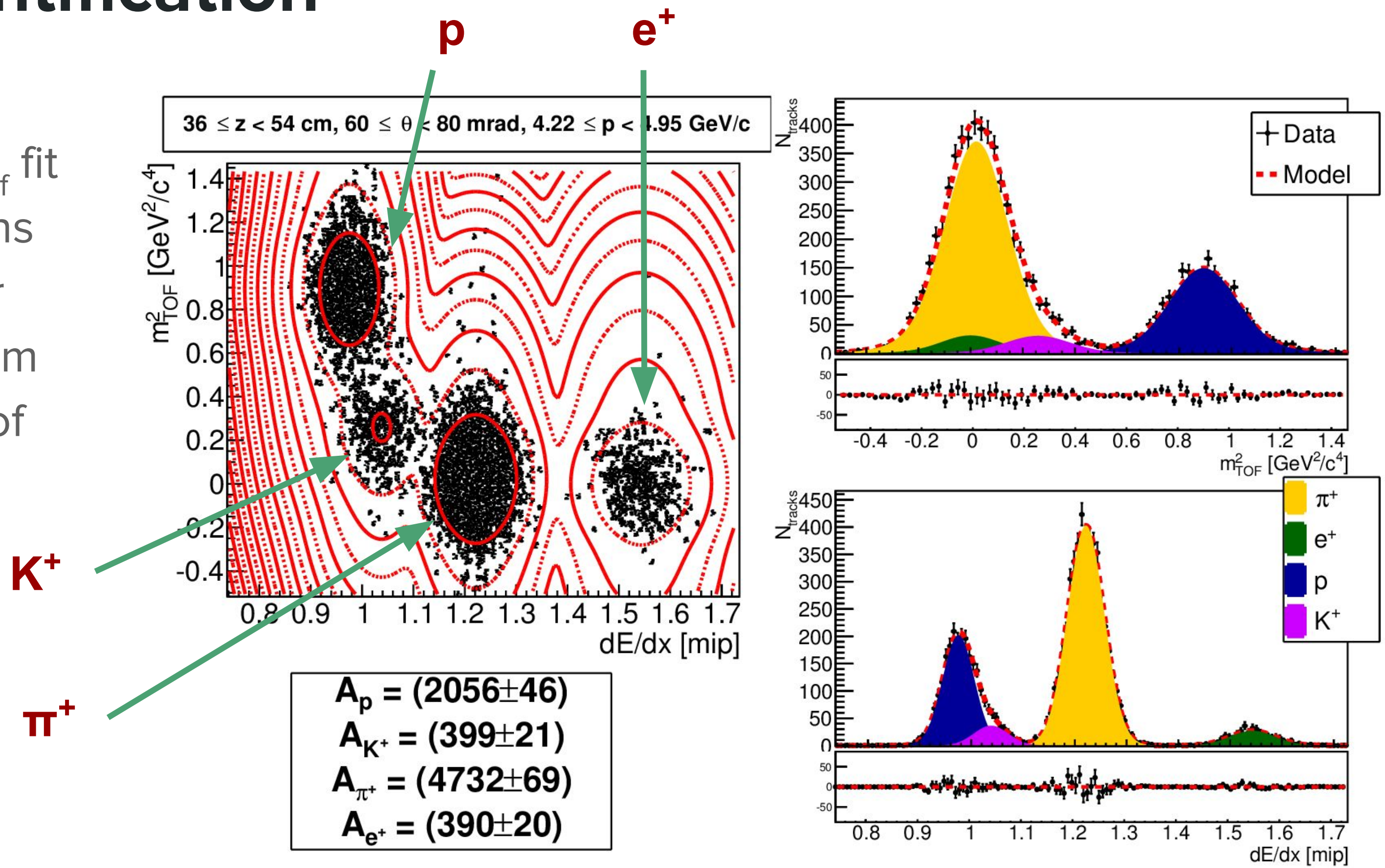
$$m^2_{tof} = \left(\frac{p}{c}\right)^2 \left[\left(\frac{c \cdot tof}{l}\right)^2 - 1\right]$$





Particle identification

- Joint dE/dx-m^2_{tof} fit
- 4 × 2D Gaussians
- Initial parameter values taken from the dE/dx and tof calibrations



Corrections

MC correction factor

$$C_{ijk}^{-1} = \left(\frac{n}{N}\right)_{ijk} = \epsilon_{fdown} \cdot \epsilon_{mig} \cdot \epsilon_{rec} \cdot \epsilon_{hloss} \cdot \epsilon_{acc}$$

Number of rec. and sel. MC tracks

Feed down - contribution from week decays, outside of the target
$K^0_s \to \pi^+ + \pi^-$
$\Lambda \to p + \pi^-$

Hadron loss due to decays, re-interactions, etc...

Bin number

Number of generated tracks coming from target surface

Bin migration

Reconstruction efficiency

Geometrical acceptance

TOF correction factor

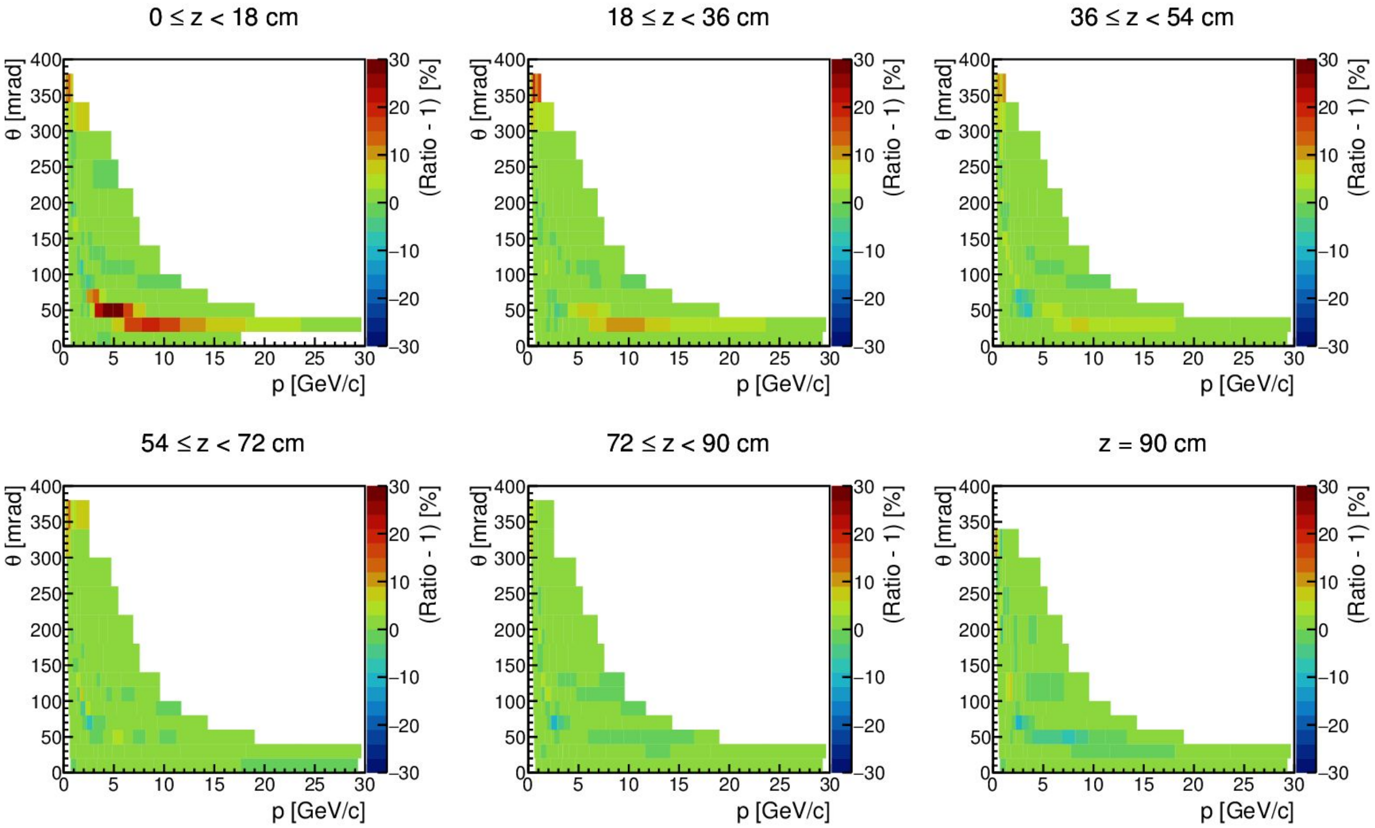
- TOF signals are not simulated in MC
- Efficiency based on the data → percentage of tracks hitting the downstream end of MTPCs with reconstructed TOF hits
- Depends on TOF slat (**95% - 98%**, lower for slats closer to the beamline)

Systematics

- Systematic uncertainties are estimated for each contribution to the total correction factor
  - Exception ➔ geometrical acceptance

1. Repeat analysis with changed cut(s) or parameter(s)
2. Calculate ratio: **yields(changed) / yields(standard)**
3. **Systematics ➔ |ratio - 1|**

Hadron loss systematics (π^+)



Uncertainties

Max. range

Majority of bins

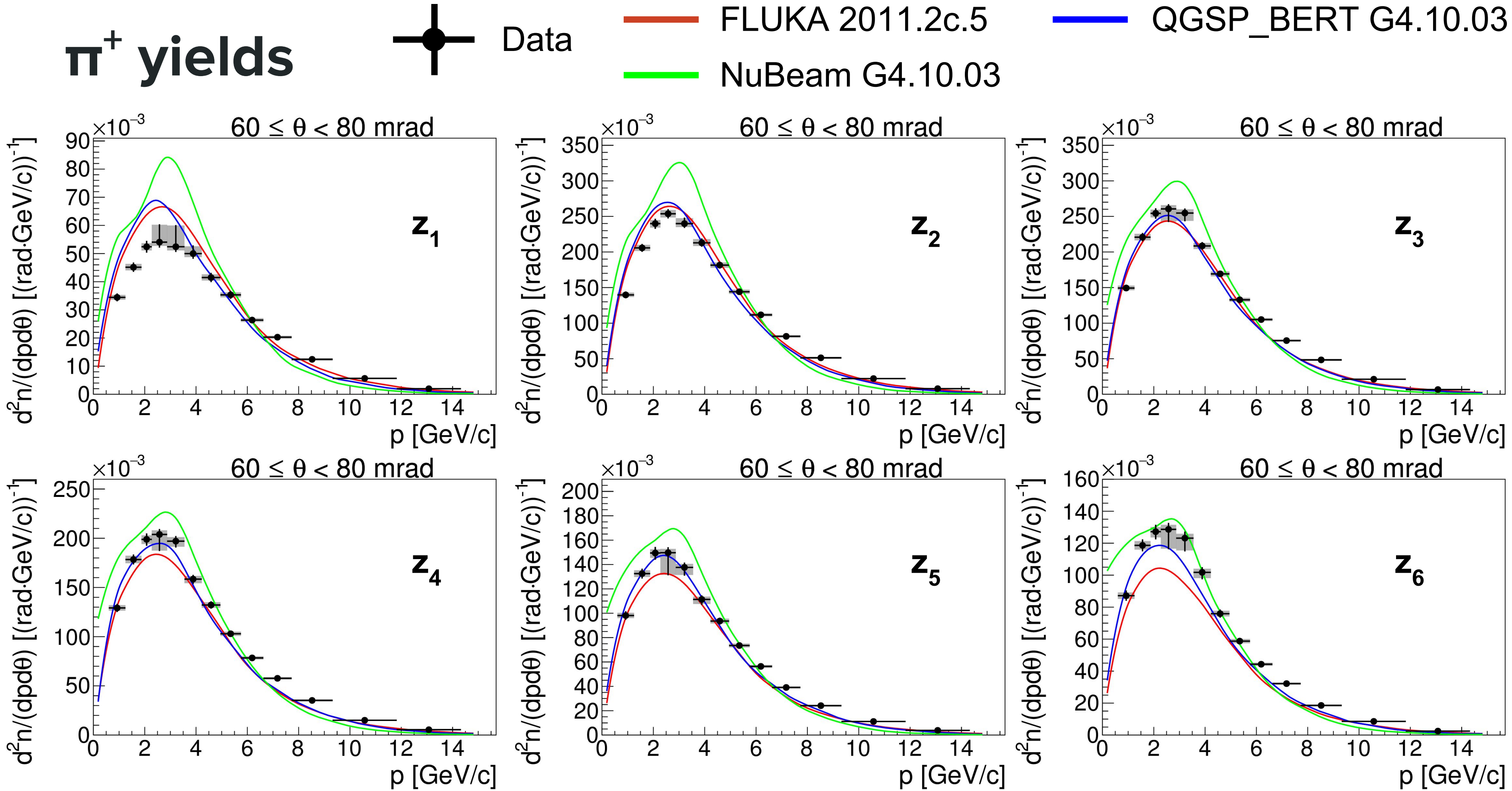
Uncertainty	π^+	π^-	K^+	K^-	p
Statistical	1% - 25% (< 4%)	1.5% - 25% (< 4%)	3% - 25% (5% - 10%)	5% - 25% (7% - 12%)	1%-25% (< 5%)
Bin migration	< 8% (< 1%)	< 10% (< 1%)	< 3% (< 1%)	< 3% (< 1%)	< 8% (< 1%)
TOF efficiency	< 1.5% (< 0.8%)	< 3% (< 0.8%)	< 0.8%	< 0.8%	< 1.5% (< 0.8%)
Hadron loss	< 35% (< 1%)	< 35% (< 1%)	< 10% (< 1%)	< 10% (< 1%)	< 25% (< 1%)
Feed-down	< 1.5%	< 2.5%	-	-	< 3.5%
PID	< 2% (0%)	< 2% (0%)	< 30% (< 8%)	< 14% (< 8%)	< 2% (0%)
Reconstruction	2%	2%	2%	2%	2%
Total	**< 5%**	**< 6%**	**< 11%**	**< 15%**	**< 6 %**
Total (2009)	**~7%**	**~9%**			

Double differential yields

$$\left(\frac{d^2 n_\alpha}{dp\, d\theta}\right)_{ijk} = \frac{1}{N_{pot}} \frac{n^{\alpha}_{ijk}}{\Delta p_{ijk} \cdot \Delta\theta_{ij}} C^{MC}_{ijk} C^{tof}_{ijk}$$

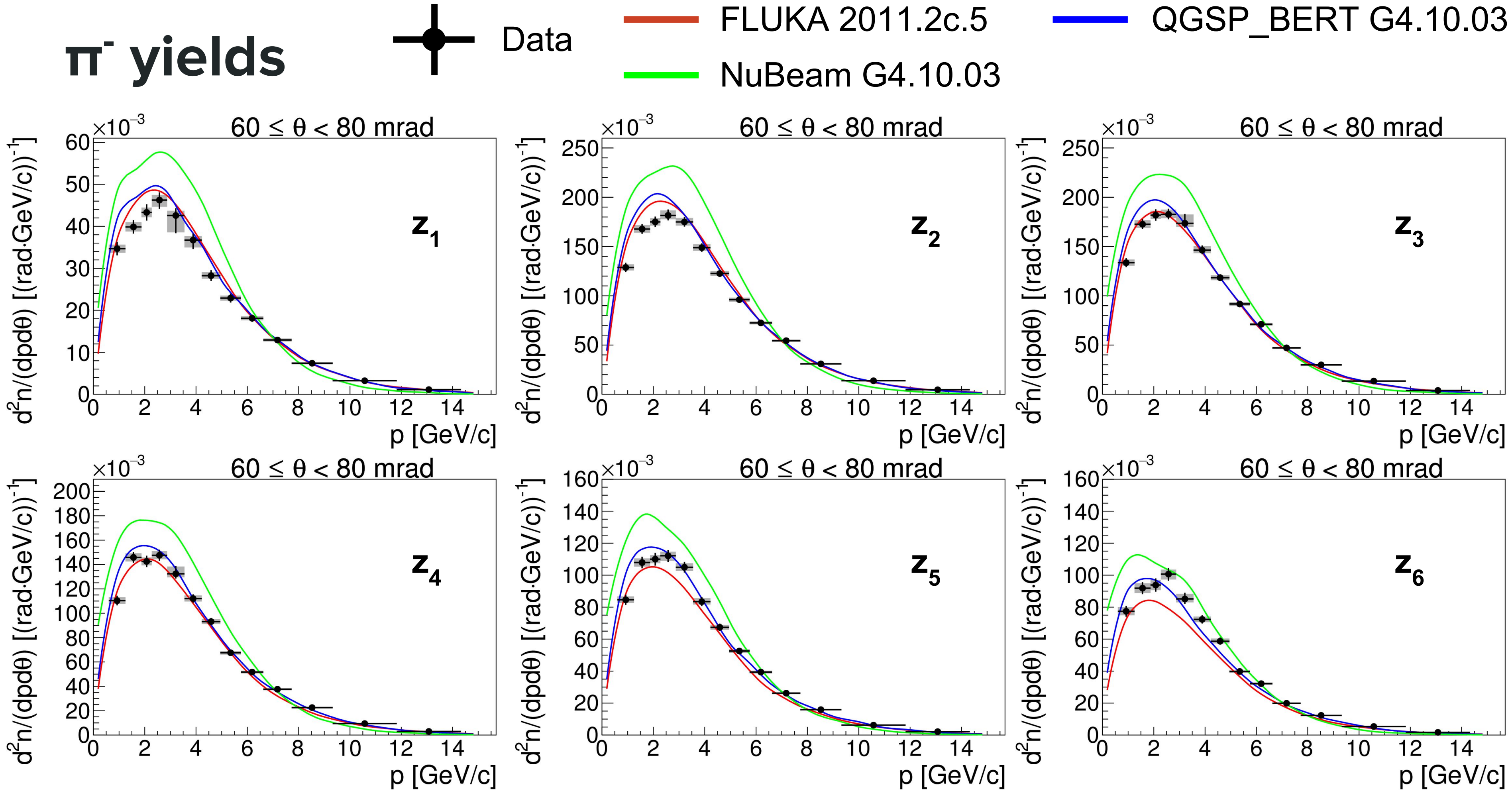
- α → particle species: $\pi^{\pm}$, $K^{\pm}$, p
- i → z bin number
- j → θ bin number
- k → p bin number
- N_{pot} → number of protons on target (number of selected events)
- n^{α}_{ijk} → number of extracted particles from PID fit in a given phase space bin
- Δp_{ijk} → momentum bin size
- $\Delta\theta_{ij}$ → polar angle bin size
- C^{MC}_{ijk} → Monte Carlo correction factor
- C^{tof}_{ijk} → time of flight correction factor

π^+ yields



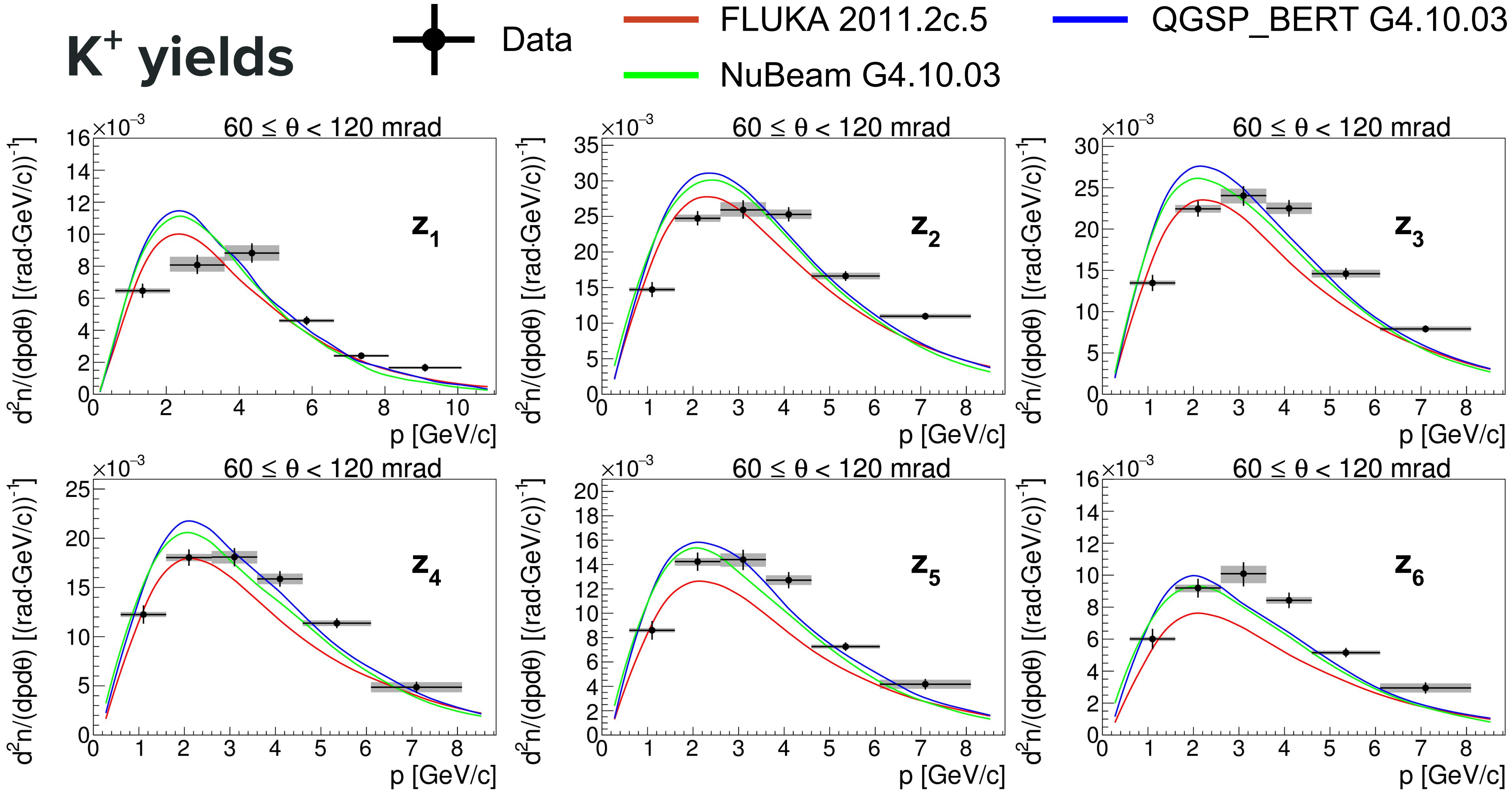
Full comparisons: https://edms.cern.ch/document/1828979/1

π^- yields



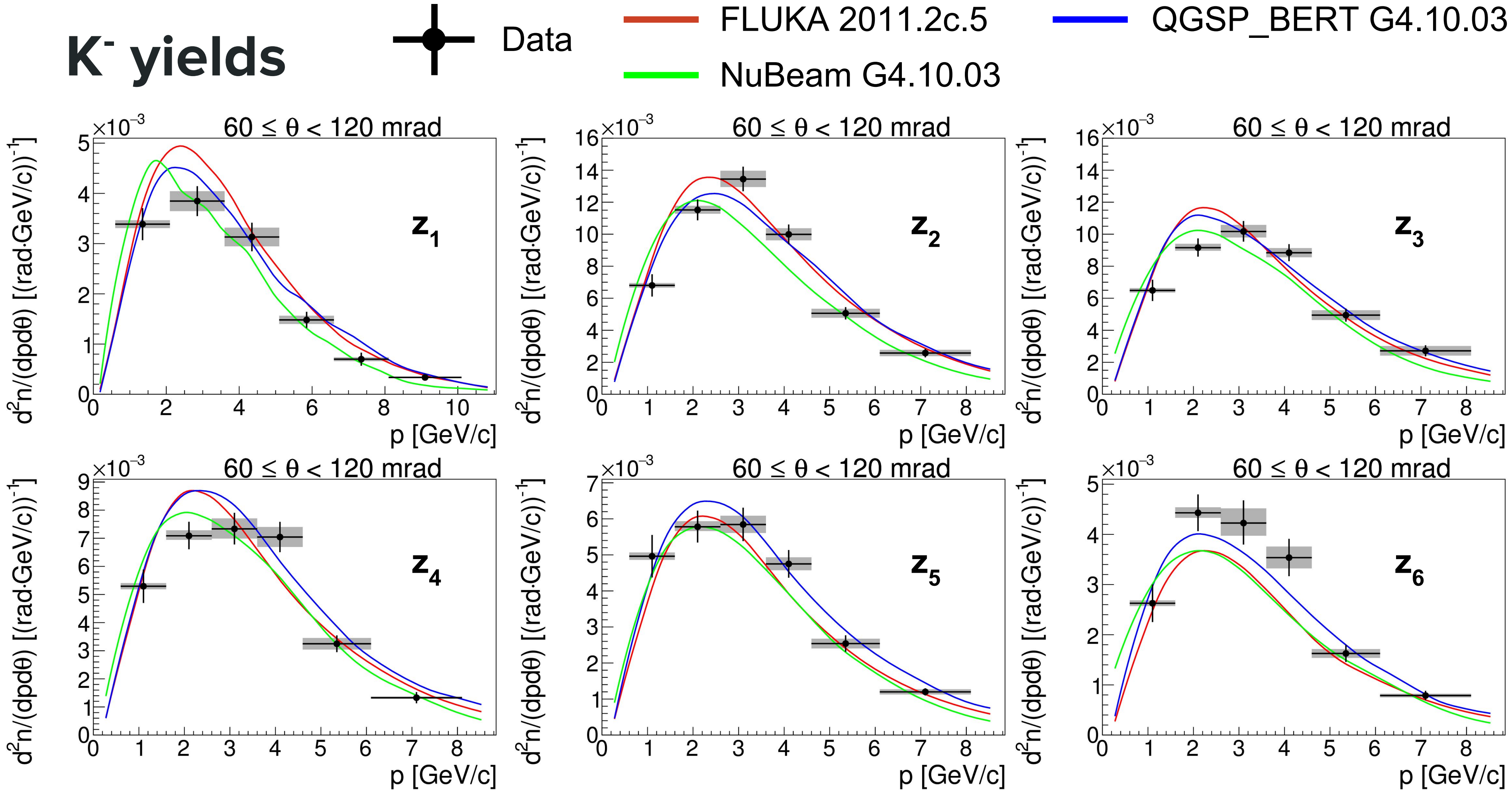
Full comparisons: https://edms.cern.ch/document/1828979/1

K^+ yields



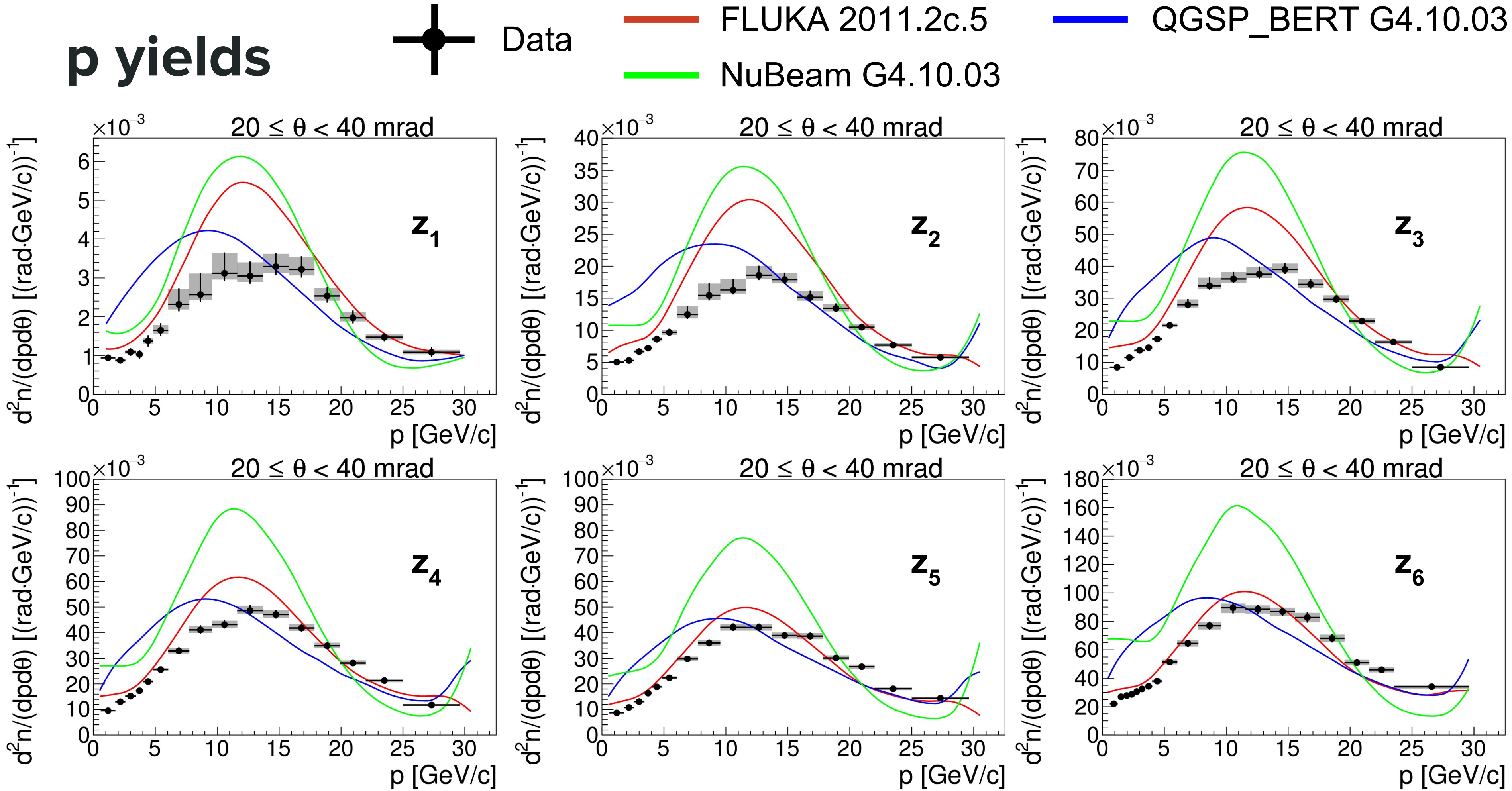
Full comparisons: https://edms.cern.ch/document/1828979/1

K^- yields



Full comparisons: https://edms.cern.ch/document/1828979/1

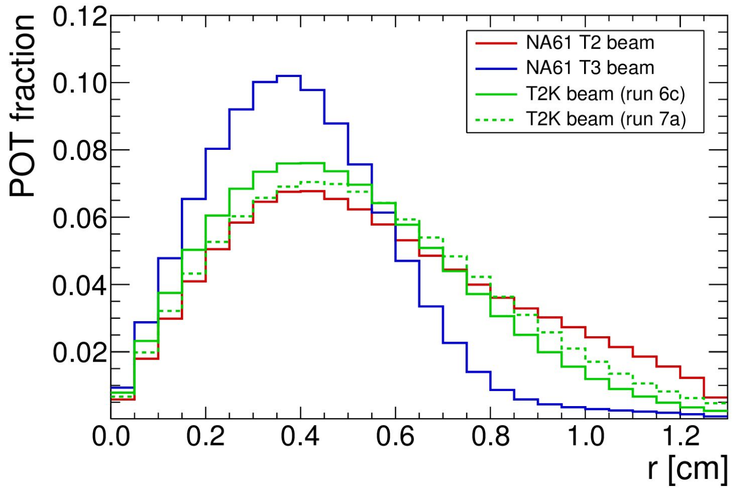
p yields



Full comparisons: https://edms.cern.ch/document/1828979/1

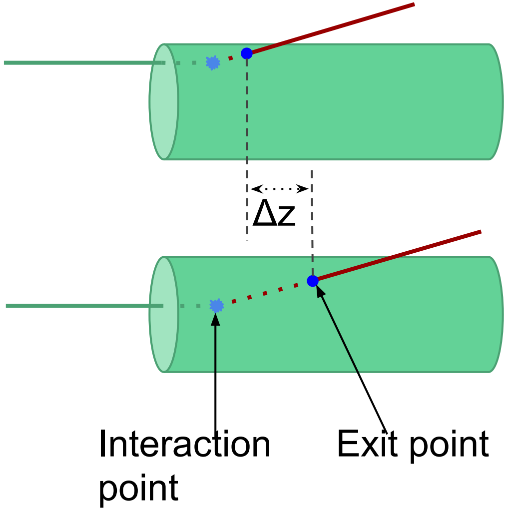
Beam profile re-weighting

- hadron yields on the target surface depend on the beam profile
- narrower beam profile ➔ suppression of hadron yields for low θ and upstream z bins
- Only important parameter is radial position on the upstream target face
- T2K beam profile ≠ NA61 beam profile

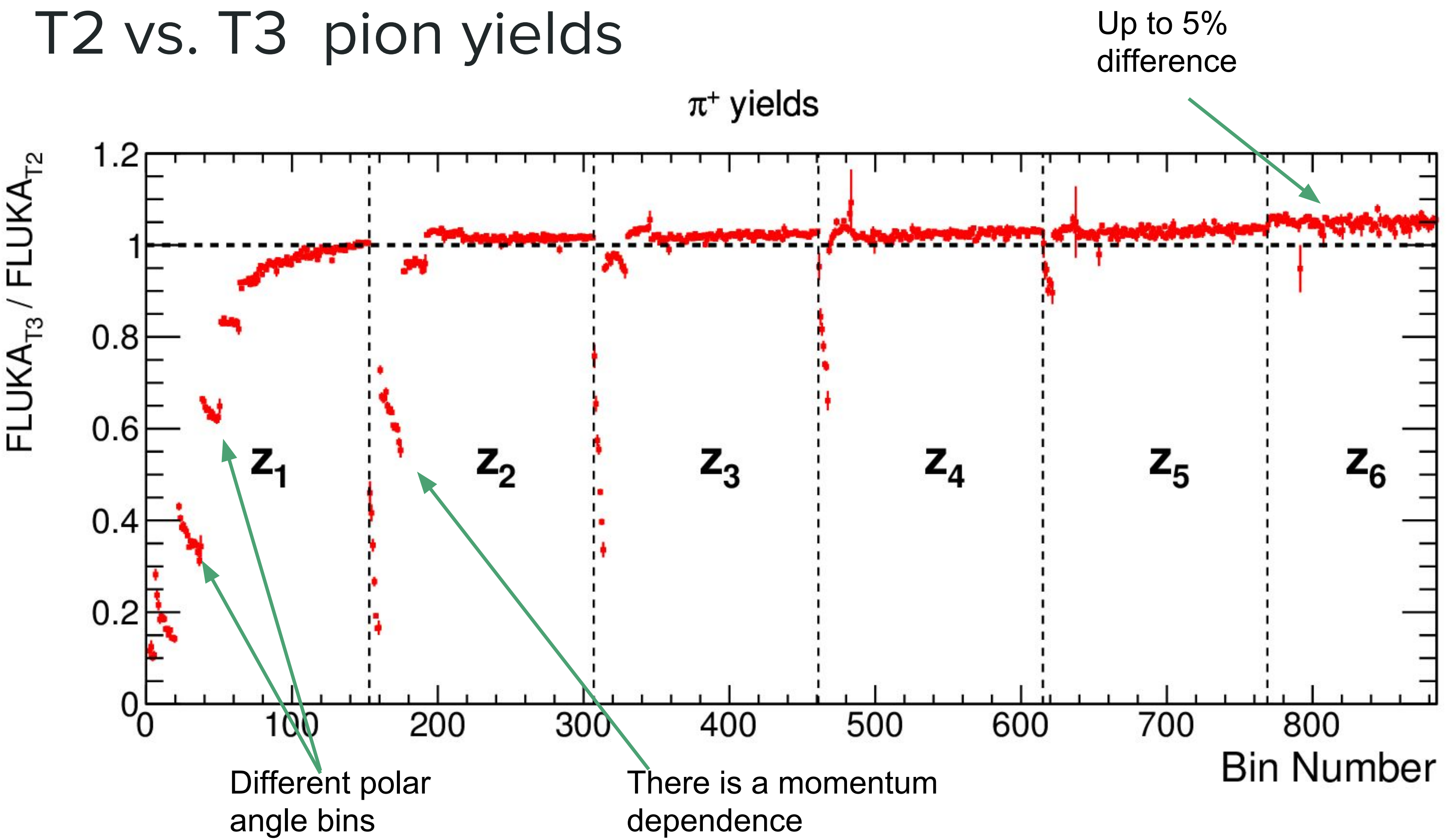


r_b = 0.65 cm, θ = 20 mrad → Δz = 32.5 cm
θ = 250 mrad → Δz = 2.5 cm

r_b = 1.00 cm, θ = 20 mrad → Δz = 15.0 cm
θ = 250 mrad → Δz = 1.2 cm



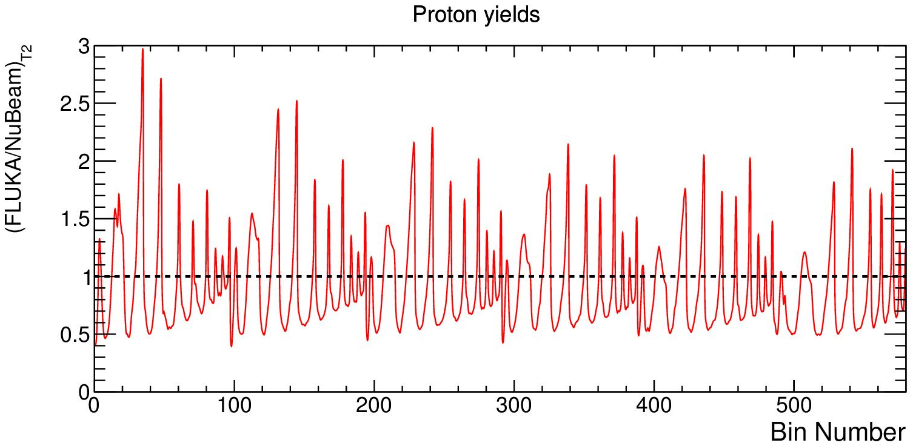
T2 vs. T3 pion yields

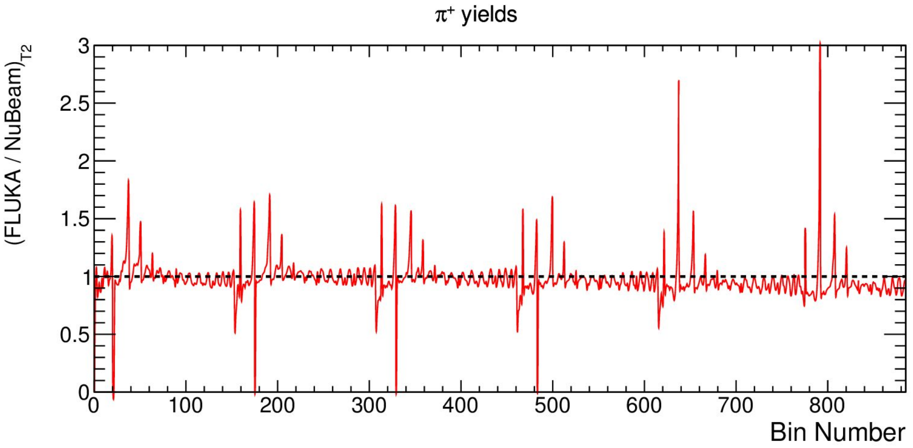


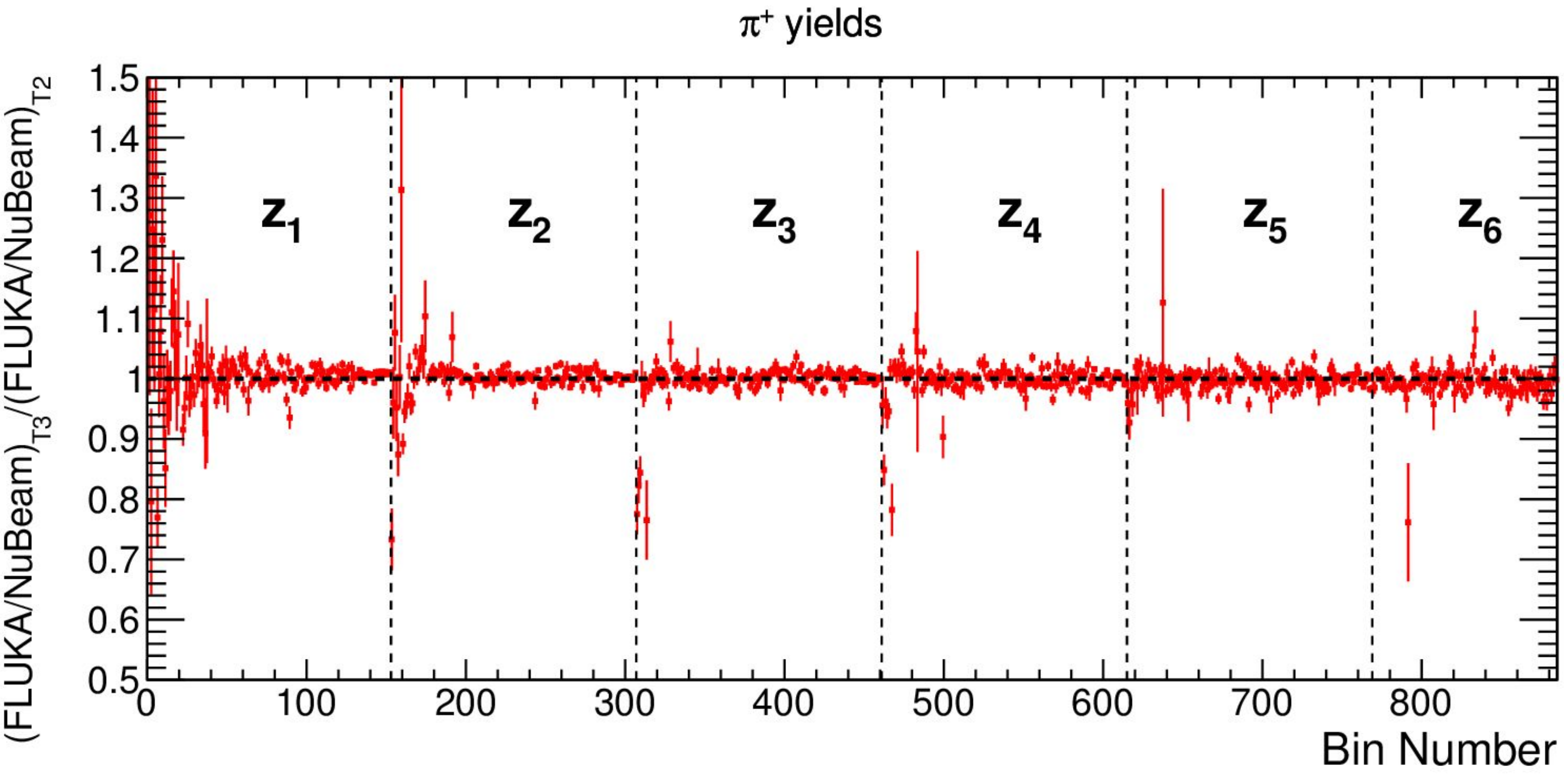
T2K Flux re-weighting with replica target yields

$$W_{ijk} = \left(\frac{1}{N_{pot}} \frac{n_{ijk}}{\Delta\theta\Delta p} \right)_{data} \Big/ \left(\frac{1}{N_{pot}} \frac{n_{ijk}}{\Delta\theta\Delta p} \right)_{MC}$$

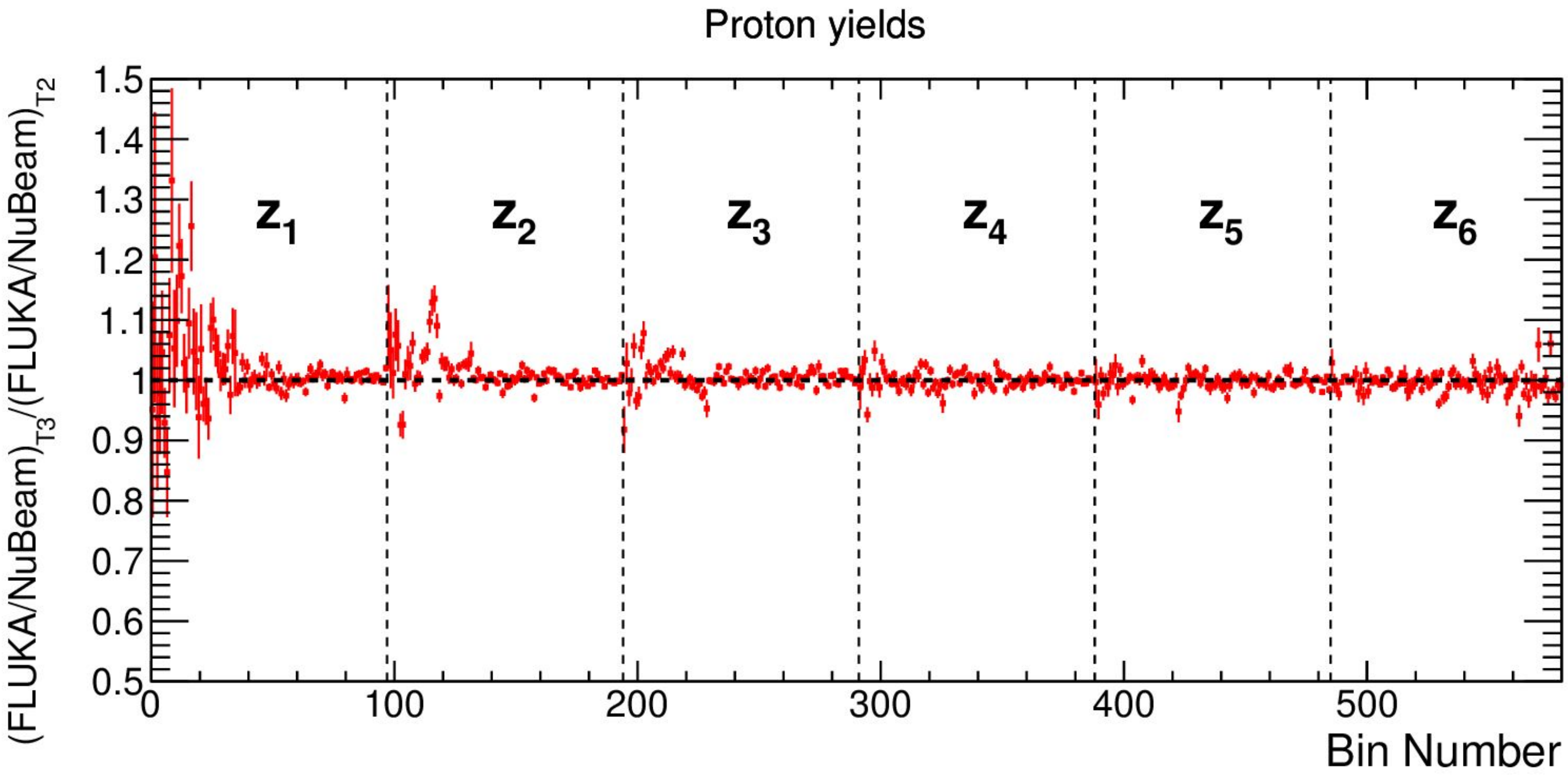
- Weights are applied to pions, kaons and protons on the target surface
- Are weights invariant (or close to being invariant) under the beam profile change?







π^+ yields
(FLUKA/NuBeam)$_{T3}$/(FLUKA/NuBeam)$_{T2}$
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0
100
200
300
400
500
600
700
800
Bin Number
z_1
z_2
z_3
z_4
z_5
z_6



- T2 beam width > T2K beam width > T3 beam width ➔ when using this data in T2K any bias would be smaller

T2K Flux re-weighting with the replica target yields

1. Simulate hadron yields with the NA61 T2 beam profile
2. Calculate weights based on the simulation with T2 beam profile
3. Apply weights to the hadron yields simulated with the T2K beam profile

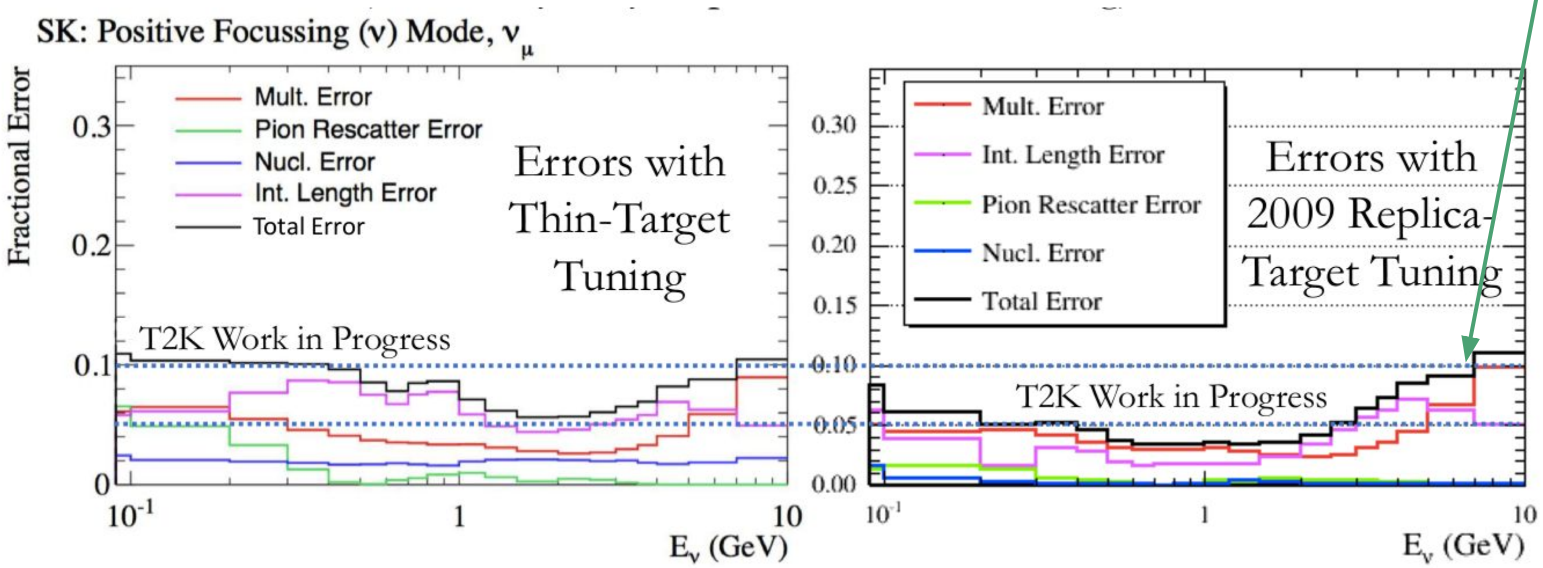
- Beam width T3 < width T2K < width T2

T2K neutrino flux re-weighting with RT measurements

- Pion yields measured with 2009 data

Kaons not measured in 2009

Hadron production uncertainty

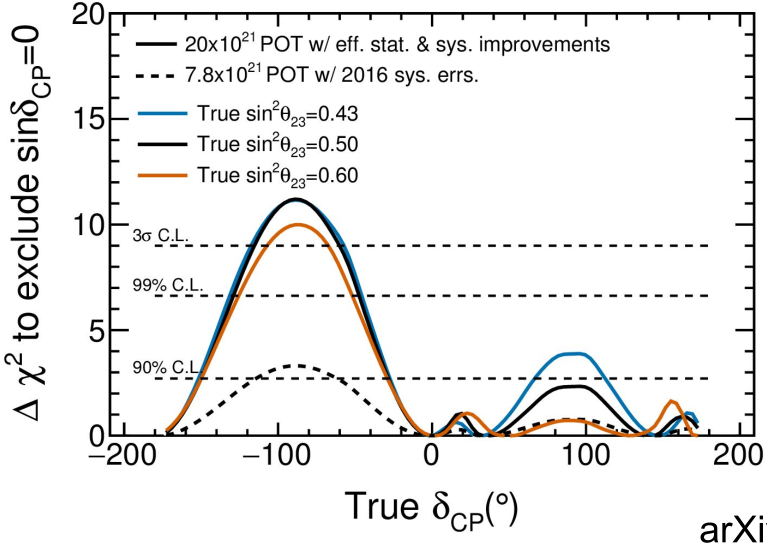


T2K II sensitivity to CP violation

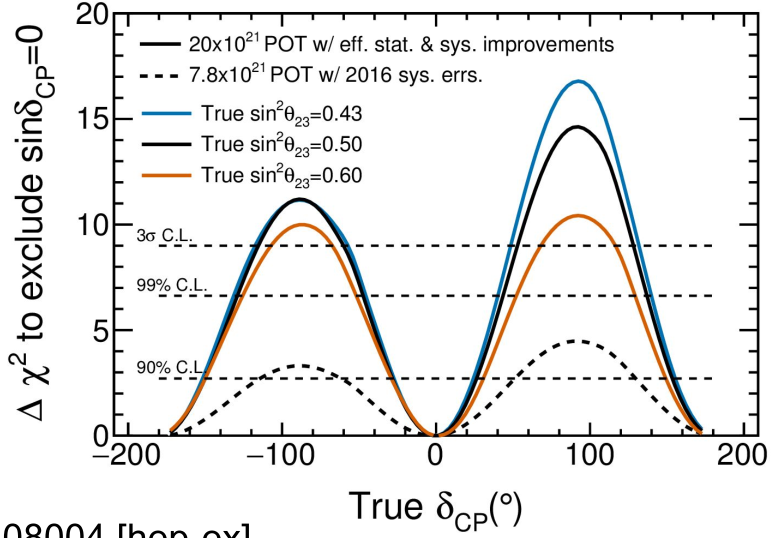
- 20×10^{21} POT
- Only possible if systematics are reduced
  - Largest contributions: SK detector, cross section & flux

Source	ν_e CCQE-like	ν_μ	ν_e CCπ^+-like
SK detectors	2.4%	3.9%	9.3%
Flux and cross sections	4.2%	2.9%	5.0%
FSI+SI+PN	2.5%	1.5%	10.5%
Total	5.5%	5.1%	14.8%

MH not known



MH known



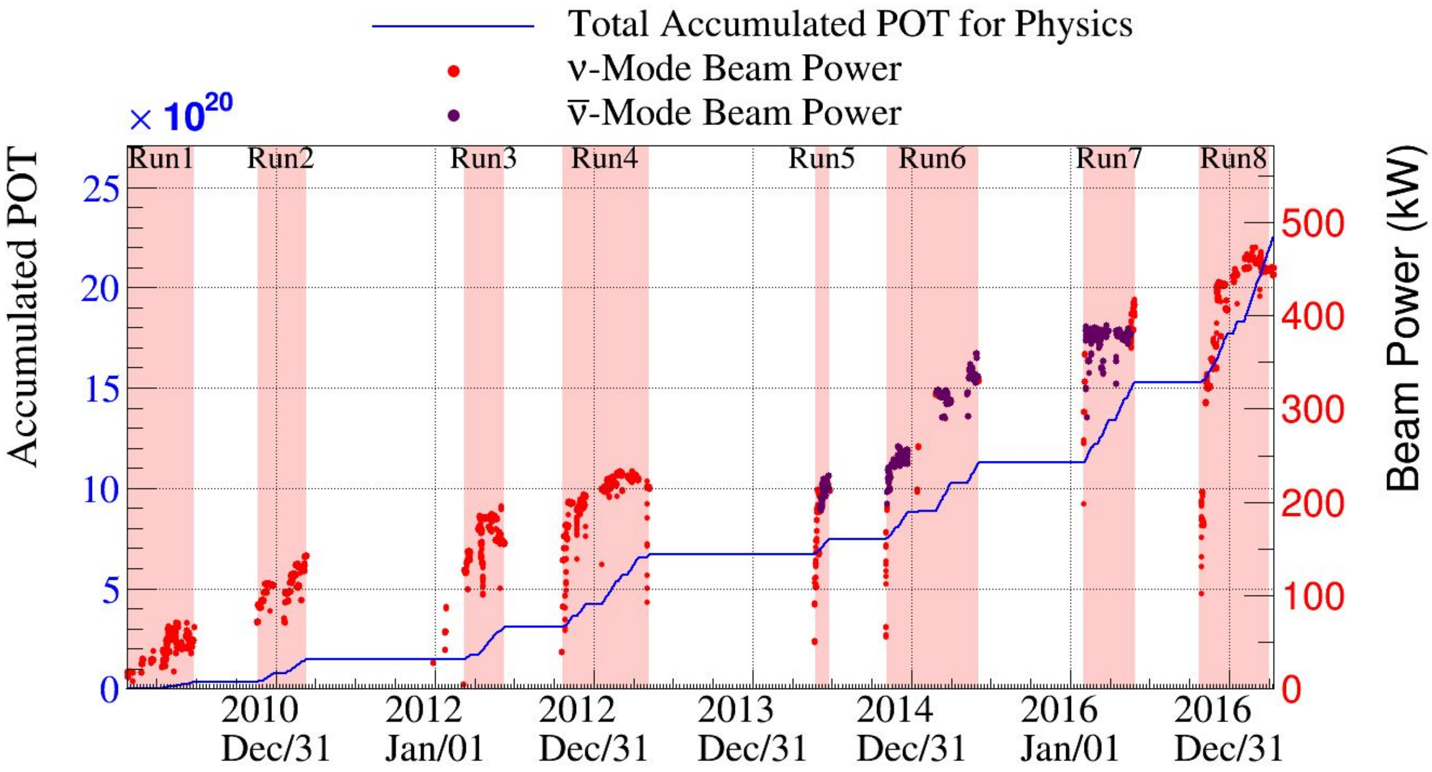
arXiv:1607.08004 [hep-ex]

Conclusions

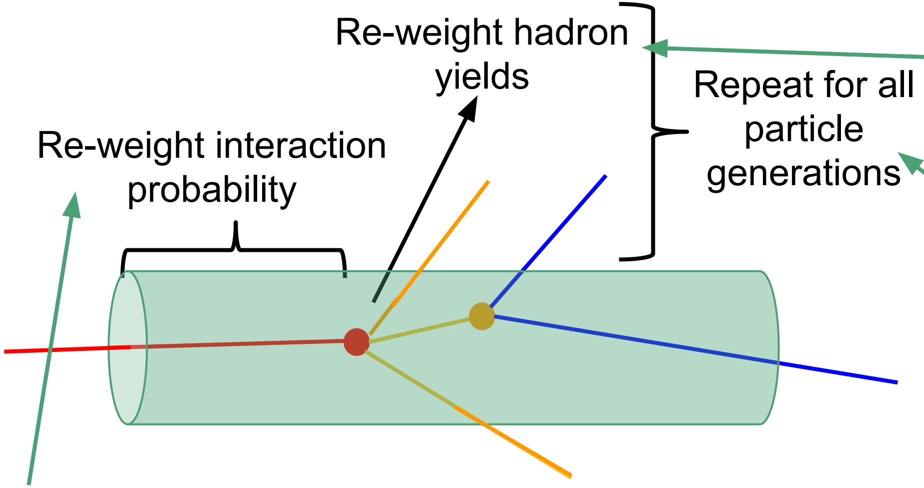
- $\pi^{\pm}$, $K^{\pm}$ and p double differential yields coming from the surface of the T2K replica target
  - $\pi^{\pm}$ statistical uncertainty 1.5 - 2x smaller than in 2009
  - $K^{\pm}$ and p yields measured for the first time
  - Comparison with MC models
- T2K re-weighting factors are invariant under the beam profile change
- Paper in progress
- T2K flux uncertainty is expected to go down below 5% ➔ necessary for future measurements of δ_{CP}
- NA61/SHINE ➔ only experiment on the market capable of providing hadron production measurements for neutrino experiments (new measurements ongoing for the Fermilab neutrino beams)

BACKUP

T2K data-taking periods



T2K neutrino flux re-weighting



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

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

- 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.

Track selection

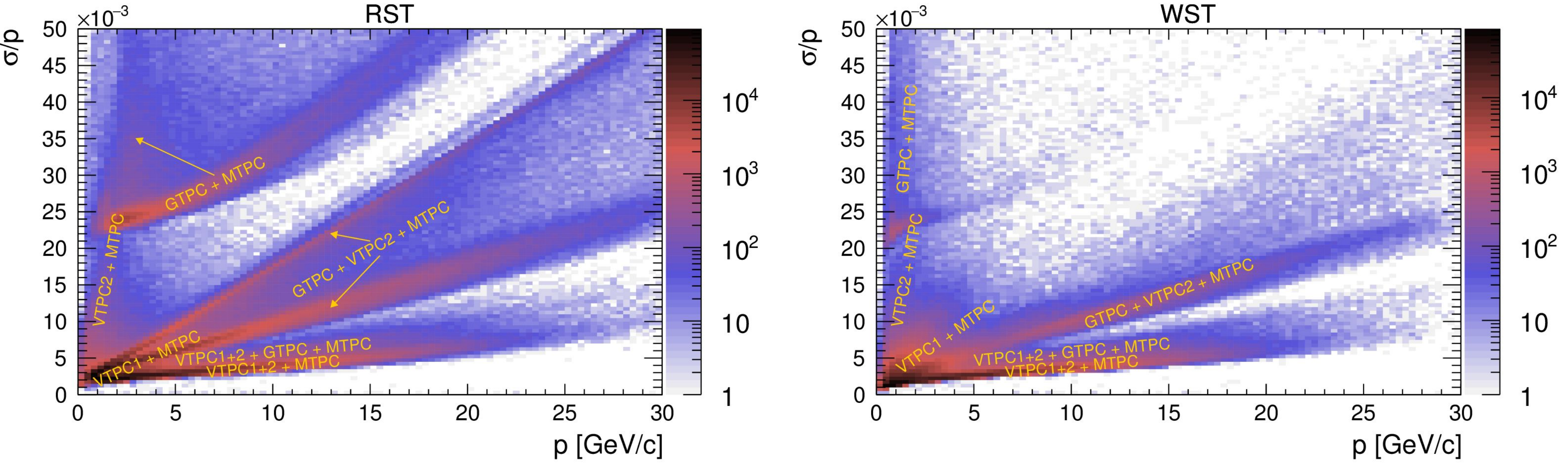
- EM processes below < 0.1 GeV cut out in MC
- TOF-F not simulated ➔
  - in the data, pions below 0.2 GeV/c do not hit TOF-F inside the time acquisition window
  - it is same for the protons below 0.5 GeV/c and kaons below 0.3 GeV/c
  - TOF-F inefficiency

After all effects are taken into account

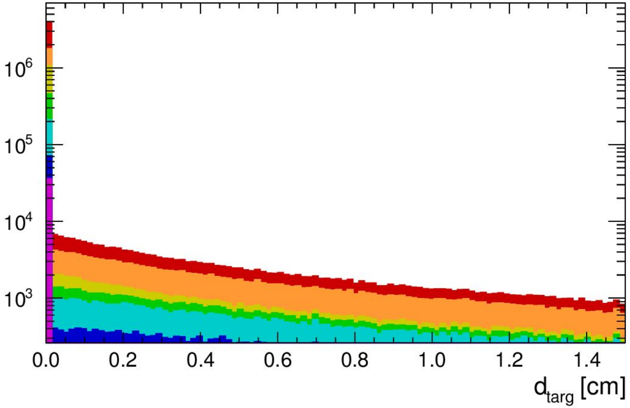
$$\left(\frac{N_{tr}^{sel}}{N_{pot}}\right)_{MC} \Big/ \left(\frac{N_{tr}^{sel}}{N_{pot}}\right)_{data} = 1.02$$

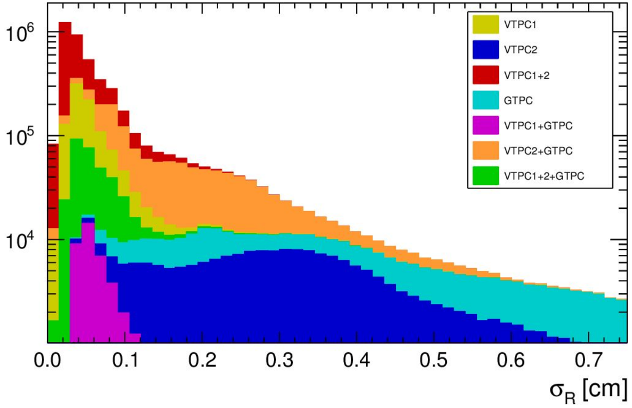
	Total	p fit		dE/dx - tof		Clusters		ϕ angle		d_{targ}/σ_R	
	$[10^6]$	$[10^6]$	[%]	$[10^6]$	[%]	$[10^6]$	[%]	$[10^6]$	[%]	$[10^6]$	[%]
Data	83.081	38.188	100	6.353	16.64	6.166	16.15	4.677	12.25	**4.118**	**10.78**
MC	253.751	166.237	100	36.876	22.18	36.200	21.77	26.484	15.93	**25.187**	**15.15**

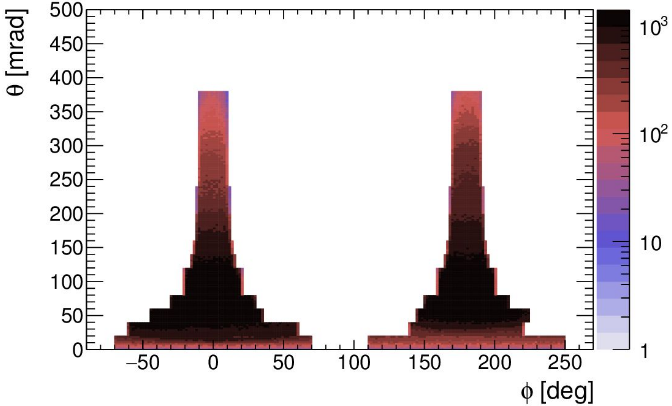
Momentum resolution

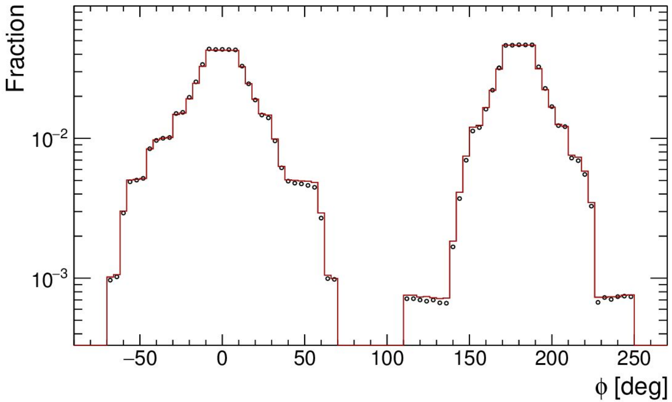


Track selection (II)

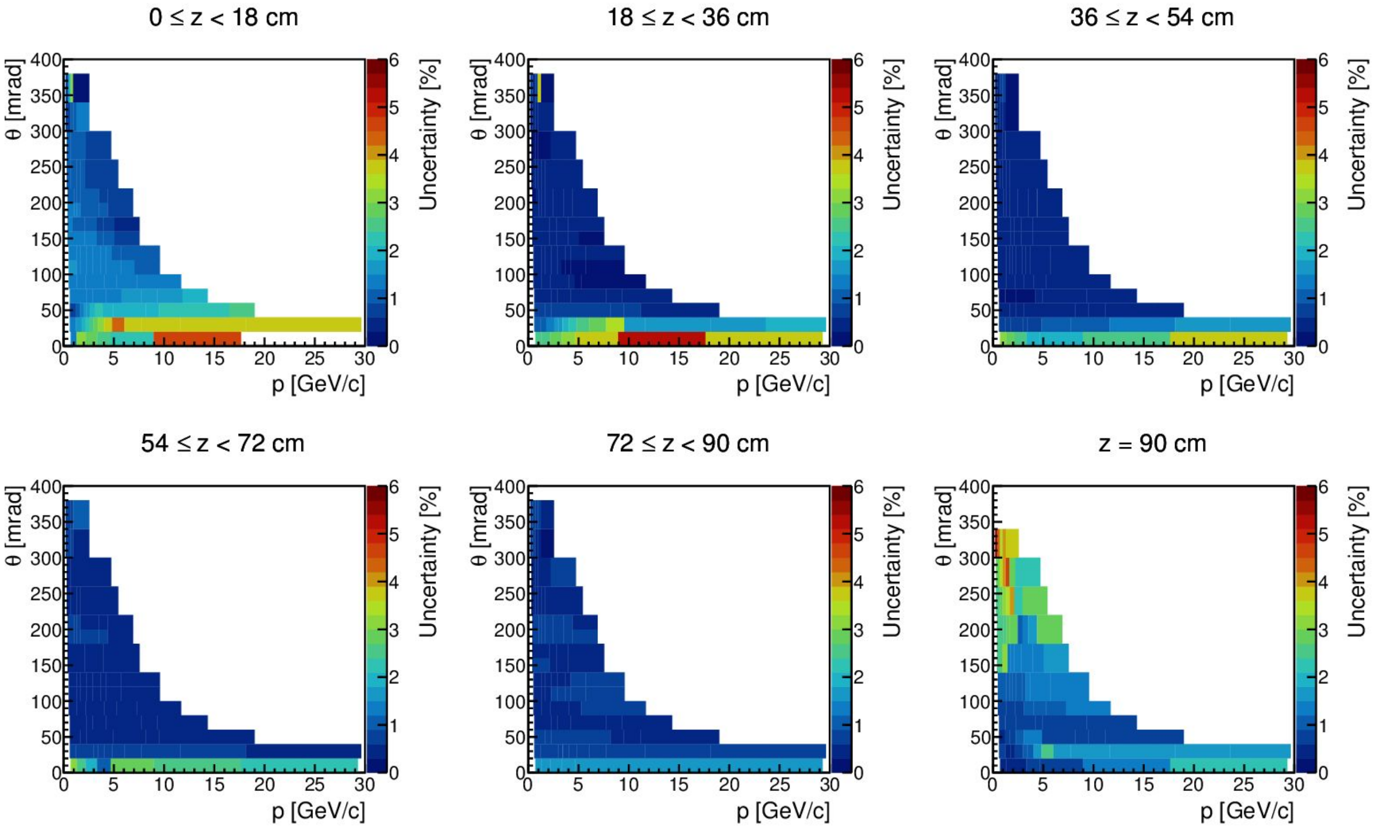




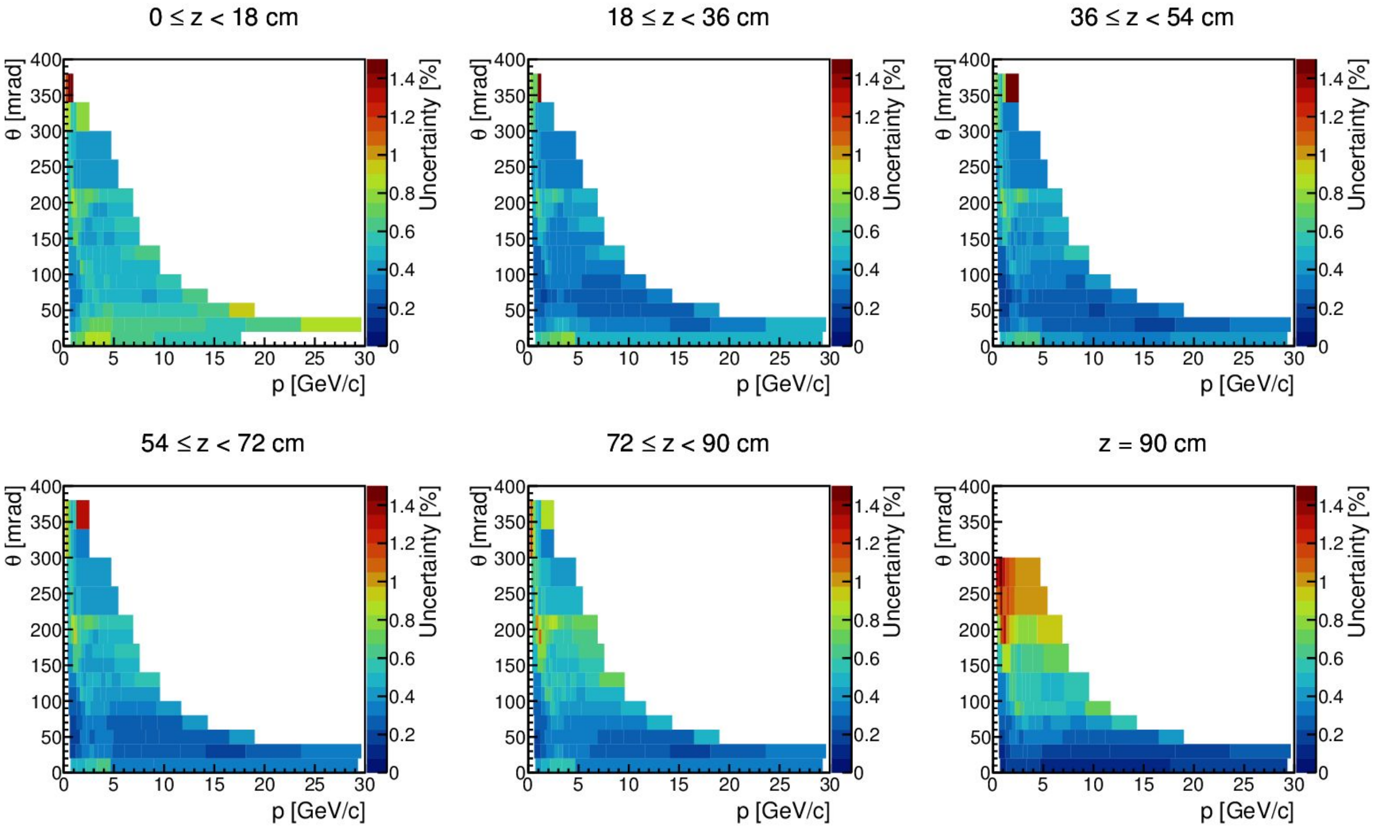




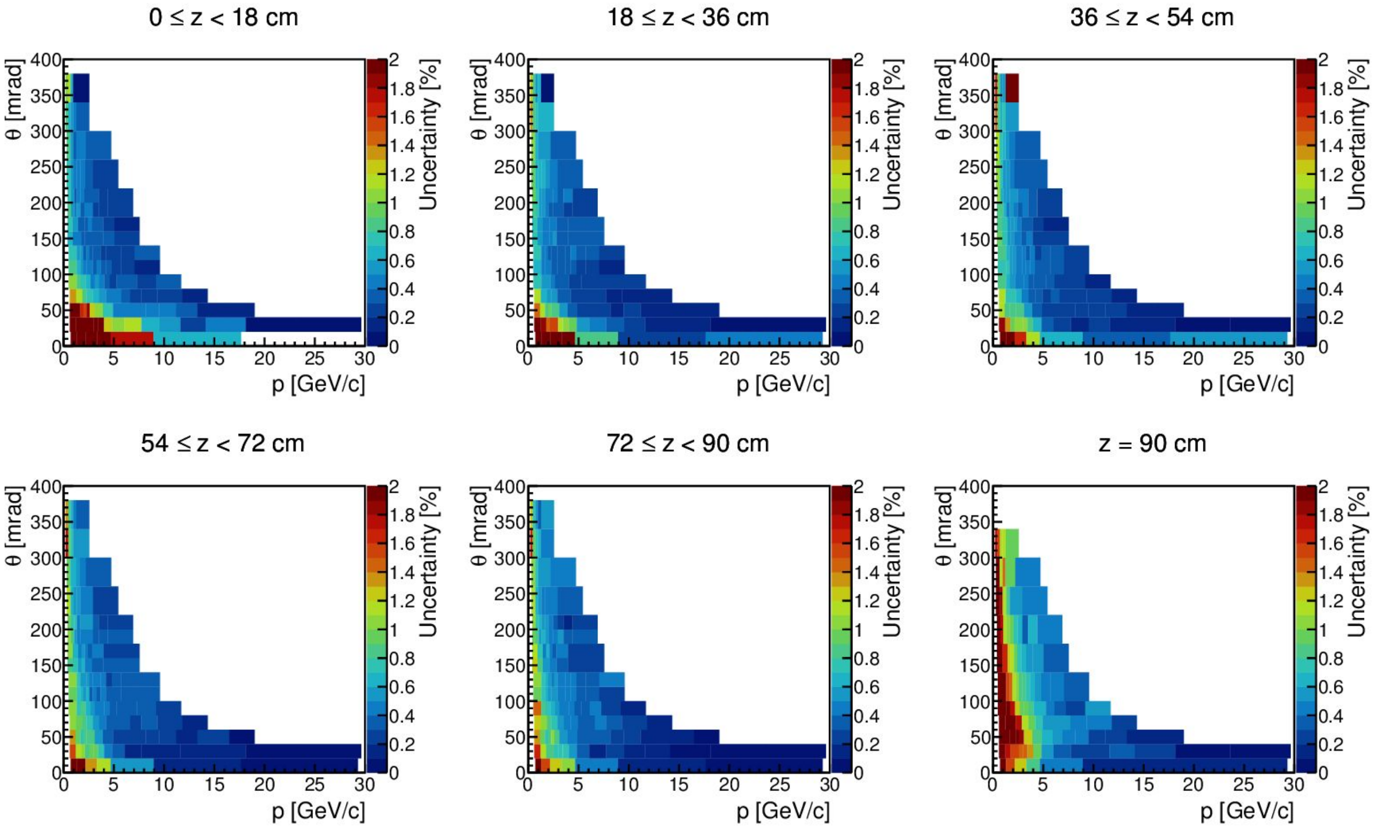
Backward track extrapolation systematics (π^+)



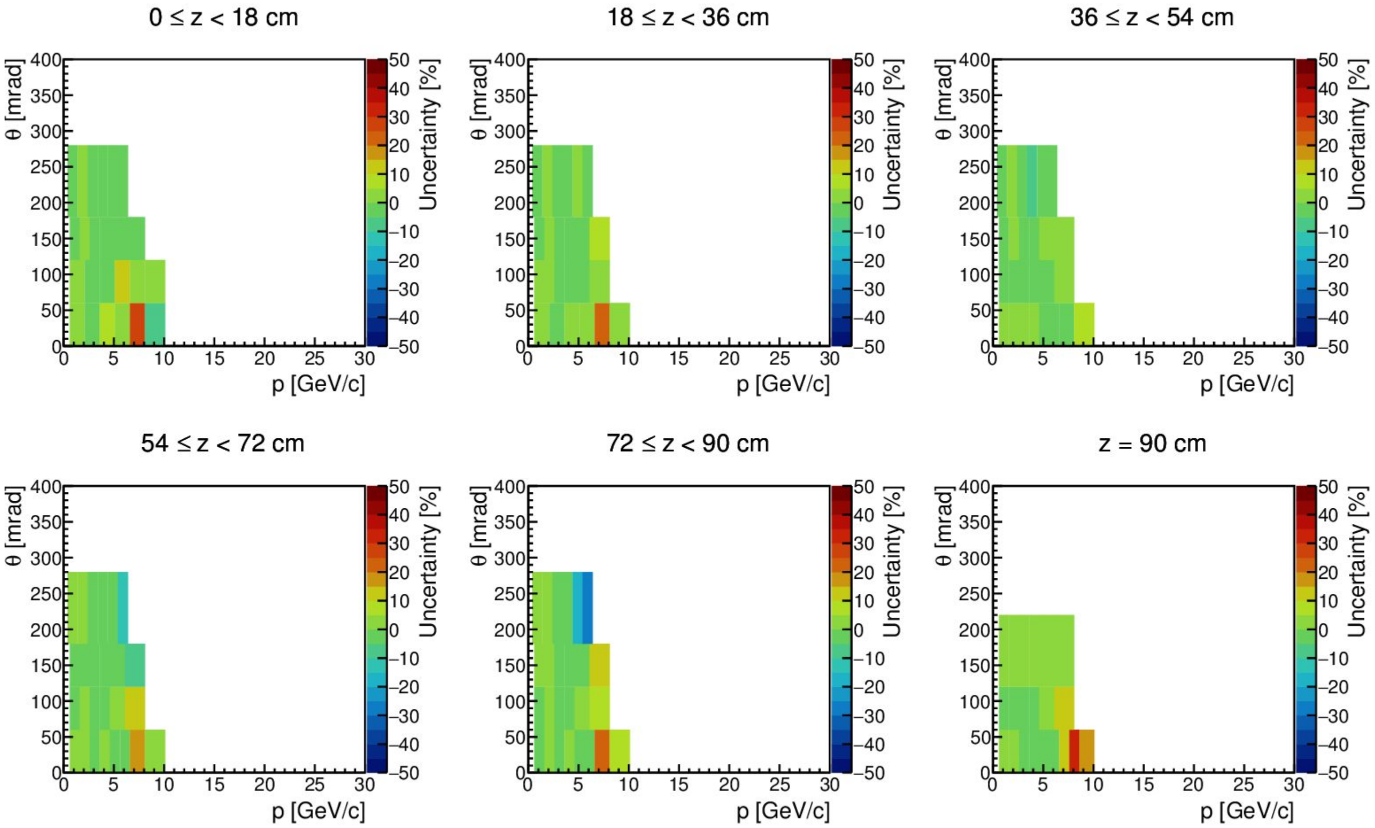
TOF-F efficiency systematics (π^+)



Feed-down systematics (π^-)

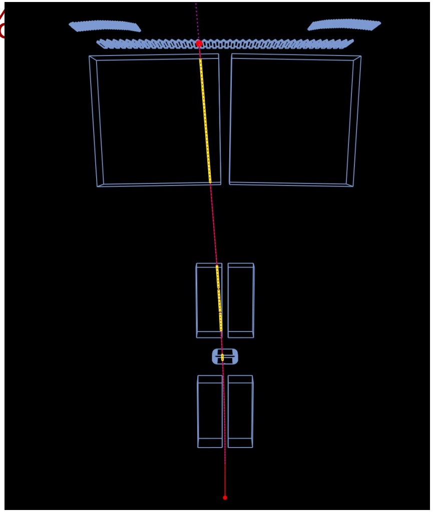


PID systematics (K^+)



Measurement of beam survival probability

- 10% of events taken with max. mag. field configuration (1.5 T)
- Beam particles bent to TPCs
- proton peak: $\sigma_p/p = 0.7$ %



$$P_{surv} = \frac{N_{tpc}}{N_{beam}} \cdot C_{MC} \cdot C_{tof} = e^{-Ln\sigma_{prod}}$$

- P_{surv} ➔ survival probability
- N_{tpc} ➔ number of high momentum tracks measured in TPCs with time of flight hit
- N_{beam} ➔ number of selected events
- C_{MC} ➔ Monte Carlo correction factor
- C_{tof} ➔ tof efficiency correction factor
- L ➔ length of the proton trajectory through the target
- n ➔ number of carbon atoms per unit volume
- **σ_{prod} ➔ production cross section ➔ at least one new hadron (pion) produced**

Measurement of survival probability

WORK IN PROGRESS!
JUST FOR ILLUSTRATION!

- Proton peak at 30.52 GeV/c ➔ selected tracks are 2σ around peak
- tof hits ➔ remove off-time beam particles
- **Results WITHOUT MC corrections (sel. and rec. efficiency, ...) :**

P_{surv}(data, rec) = 0.1353 ± 0.0005 (stat)

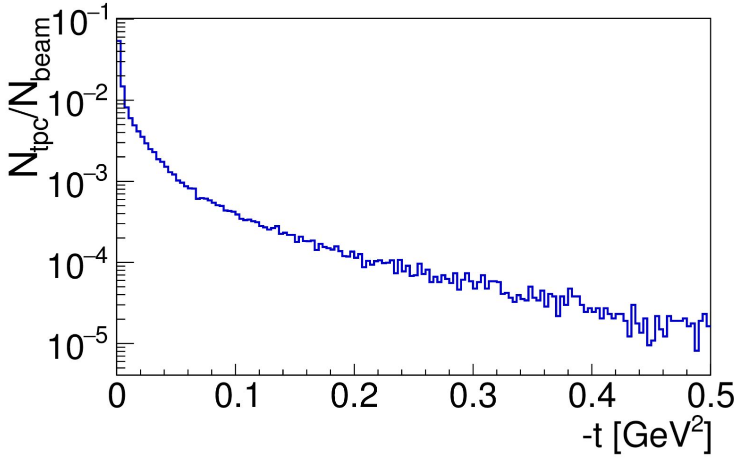
P_{surv}(FLUKA, rec) = 0.1196 ± 0.0002 (stat)

$$\sigma^{MC}_{prod} - \sigma^{data}_{prod} = -\frac{1}{nL} \ln\left(\frac{P^{MC}_{surv}}{P^{data}_{surv}}\right)$$

→ ~ 15 mb higher σ_{prod} in FLUKA 2011.2c.5

Possible systematics:

- time of flight
- target density
- target length
- momentum resolution in MC
- **Elastic, quasi-el. or production events?**



Hadron production experiments

HARP

- CERN PS
- 1.5 - 15 GeV/c, different targets
- Phys.Rev., C80:035208, 2009.

MIPP

- CERN PS
- 5 - 120 GeV/c, different beams and targets
- arXiv:1311.2258

NA56/SPY

- 450 GeV/c proton beam and different Be targets

Unfolding vs Standard correction (2009)