Measurements of hadron yields from T2K replica target

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for the NA61/SHINE collaboration

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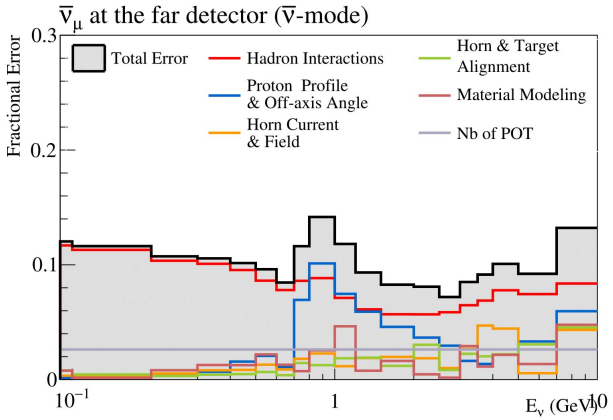
Outline

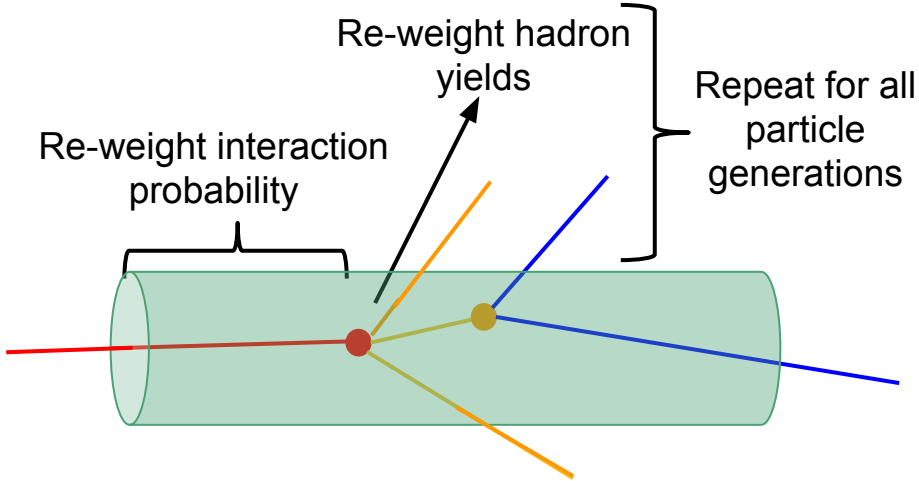
- p + T2K RT @ 31 GeV/c (taken in 2010)
- Measurements of hadron yields from surface of the T2K replica target
- Motivation
- Setup and target
- Analysis
- Systematics
- π^+, π^- yields
- K^+, K^-, p yields ➔ measured for the first time
- Comparison with measurements performed using 2009 data
- Beam survival probability

Hadron production measurements

- Hadron production in T2K beam simulation→ FLUKA2011 and GCALOR models → large uncertainties

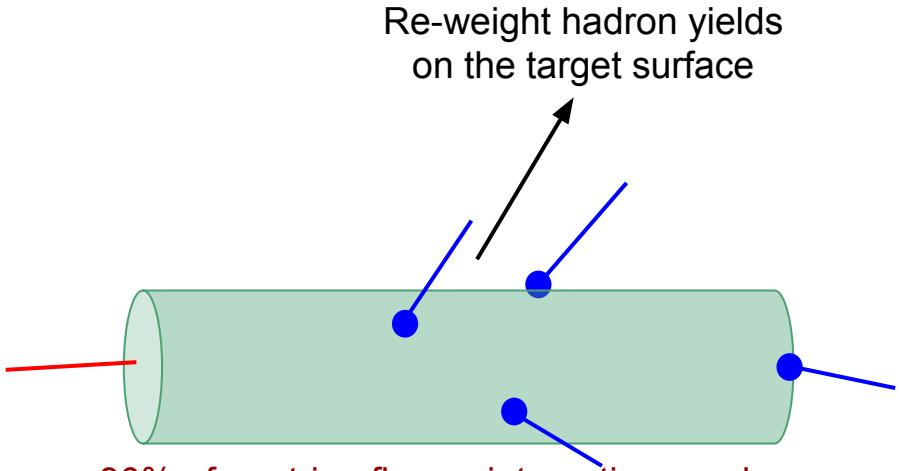


1 Thin target measurements



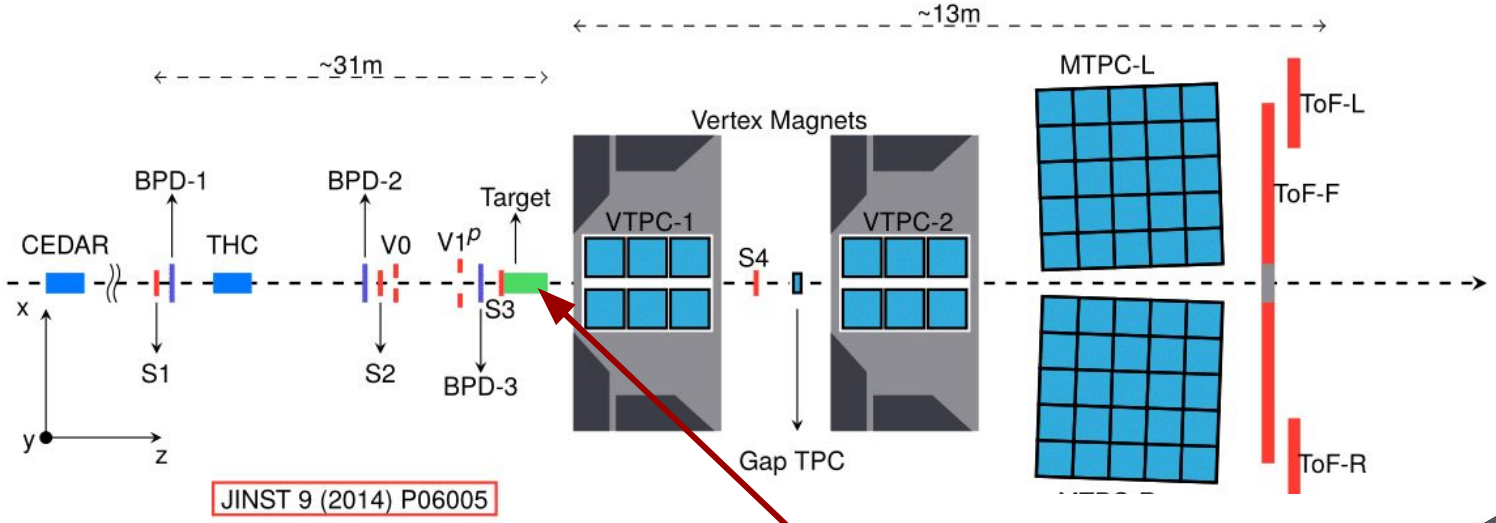
Sparse measurements → scaling to different beam particles and different energies

2 Replica target measurements



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

p + T2K RT measurements in NA61/SHINE

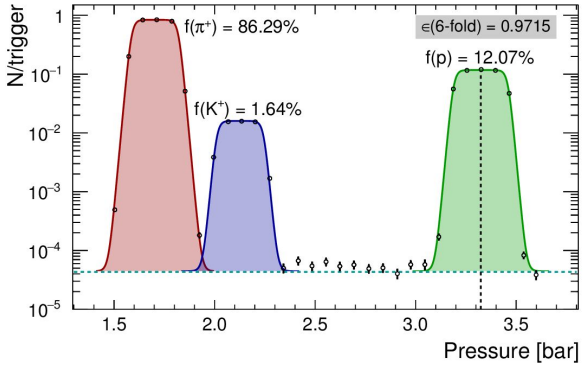


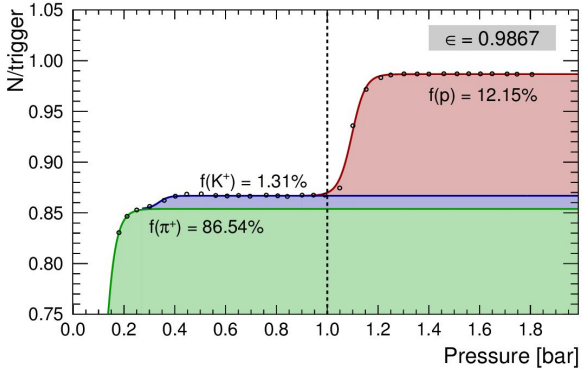
Year	[10^6] events	Results
2007	0.2	proof of concept [1]
2009	4	$\pi^{\pm}$ yields [2]
2010	**10**	**$\pi^{\pm}$, $K^{\pm}$, p yields**

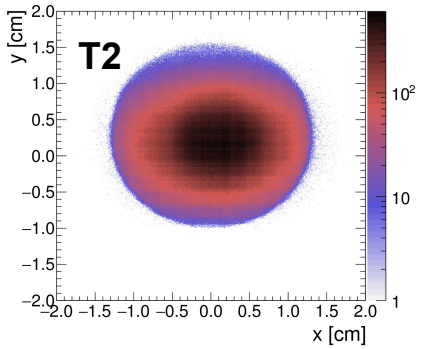
[1] N. Abgrall et al., Nucl. Instrum. Meth., A701:99, 2013.
[2] N. Abgrall et al. Eur. Phys. J., C76(11):617, 2016.

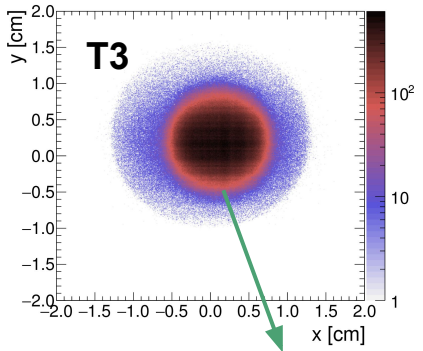
Beam and triggers (2010)

- Secondary beam at 31 GeV/c (12% of protons)
- CEDAR + THC ➔ > 99.9% beam purity
- Wide (T2) and narrow (T3) beam profile

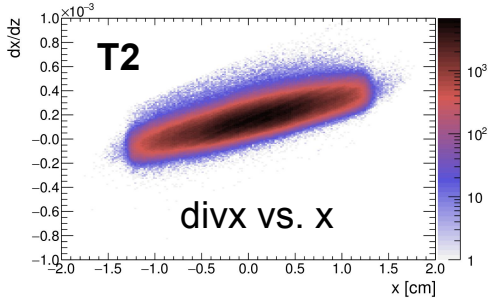


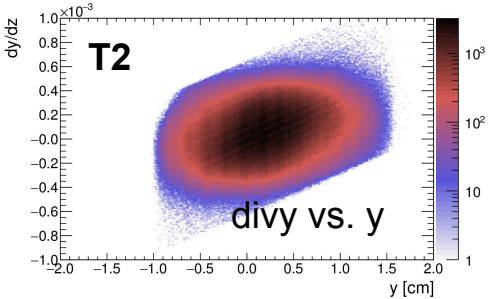






additional counter with hole included in trigger





Analysis procedure

1. **Event selection**
   - Good measurement of beam position
   - Insure that beam particle enters the target
   - 75% of events are selected

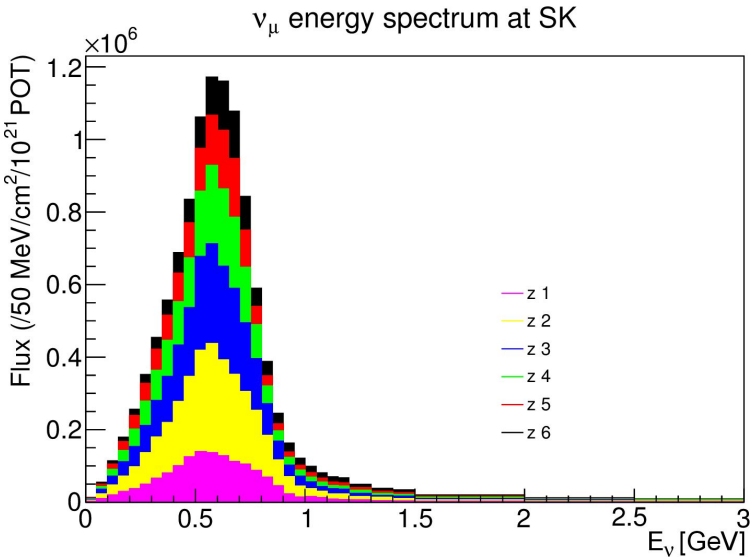
2. **Track selection**
   - PID requirements
   - Quality cuts
   - Extrapolation towards the target surface with covariance matrix propagation (for some topologies, couple of meters)

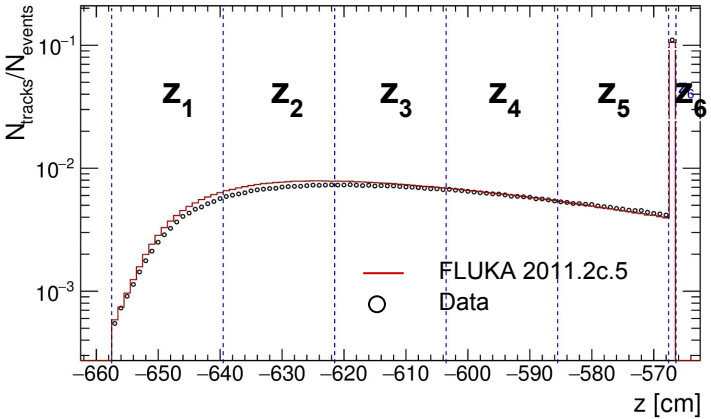
3. **PID**
   - dE/dx - tof

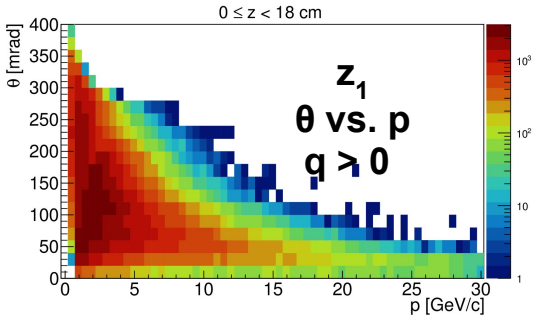
4. **Correction factors**

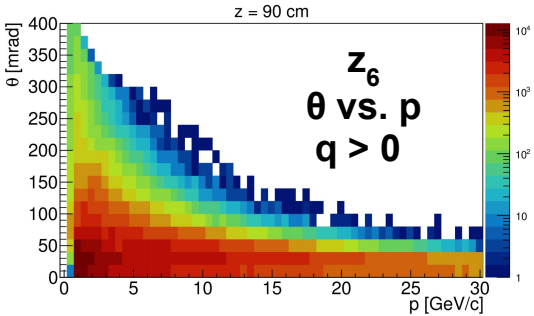
Phase space

- neutrino flux depends on the longitudinal position on the target surface
- 5 longitudinal (z) bins + downstream target face
- polar angle (θ) and momentum (p) bins
  - different for different particle species



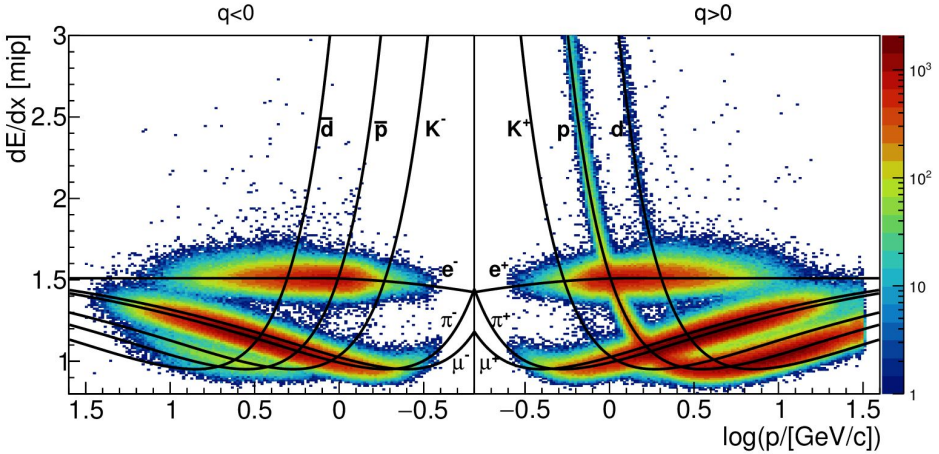


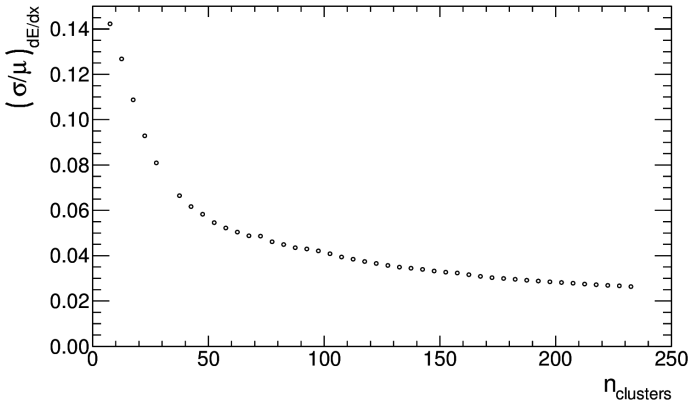




Particle identification

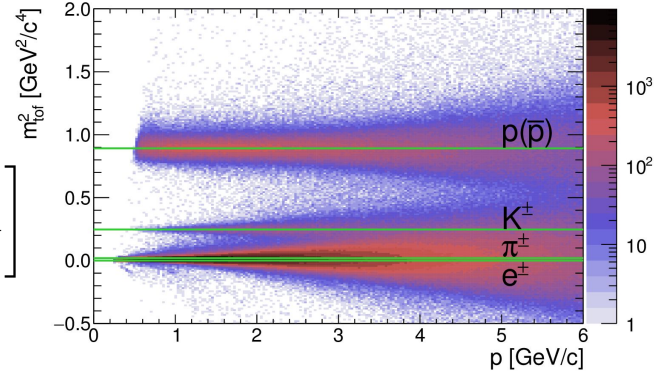
- Energy loss→ crossing of the energy loss distributions for low momenta

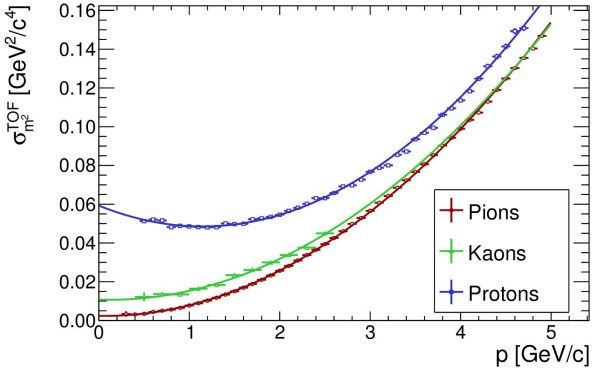




- time of flight→ not sensitive above 8 GeV/c

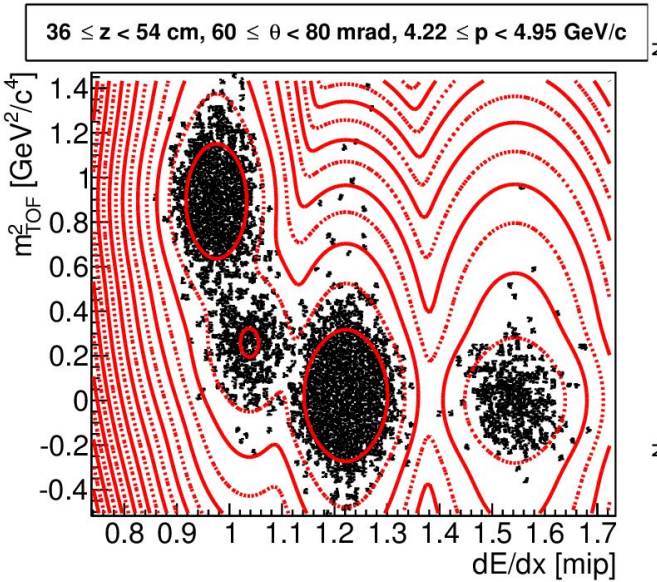
$$m^2_{tof} = \left(\frac{p}{c}\right)^2 \left[\left(\frac{c \cdot tof}{l}\right)^2 - 1\right]$$



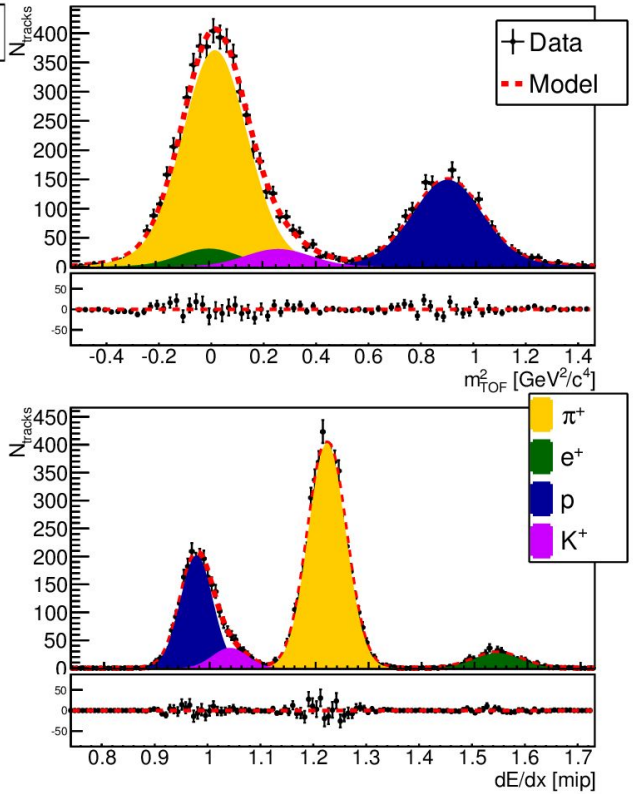


Particle identification

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

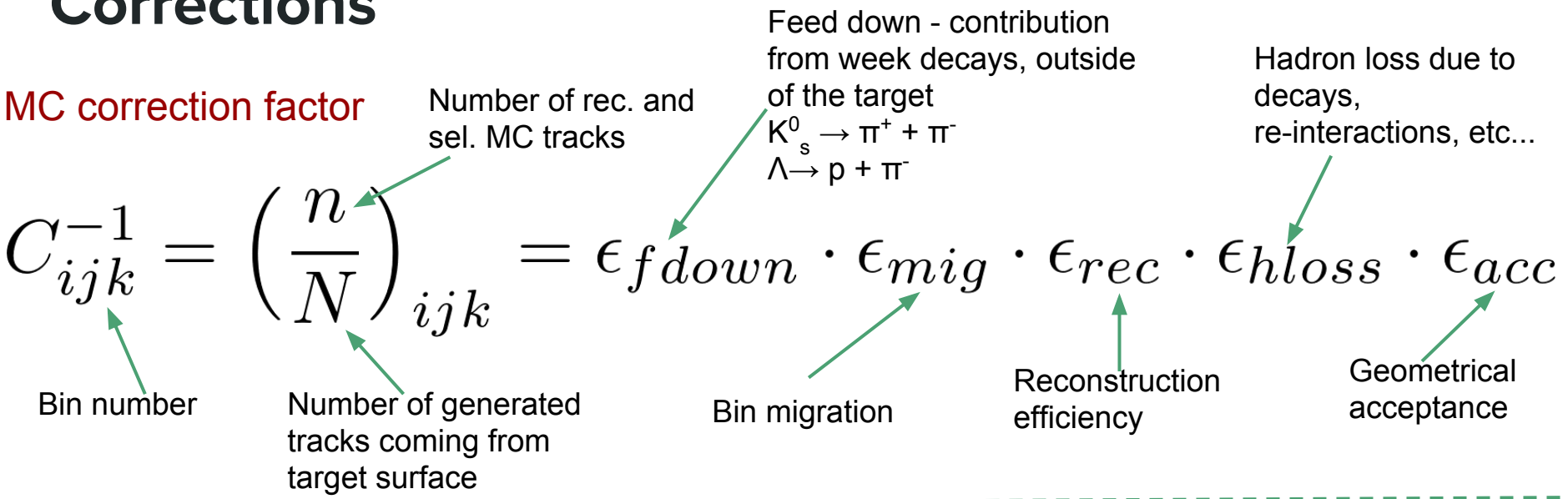


$A_p = (2056 \pm 46)$
$A_{K^+} = (399 \pm 21)$
$A_{\pi^+} = (4732 \pm 69)$
$A_{e^+} = (390 \pm 20)$



Corrections

MC correction factor



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)

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

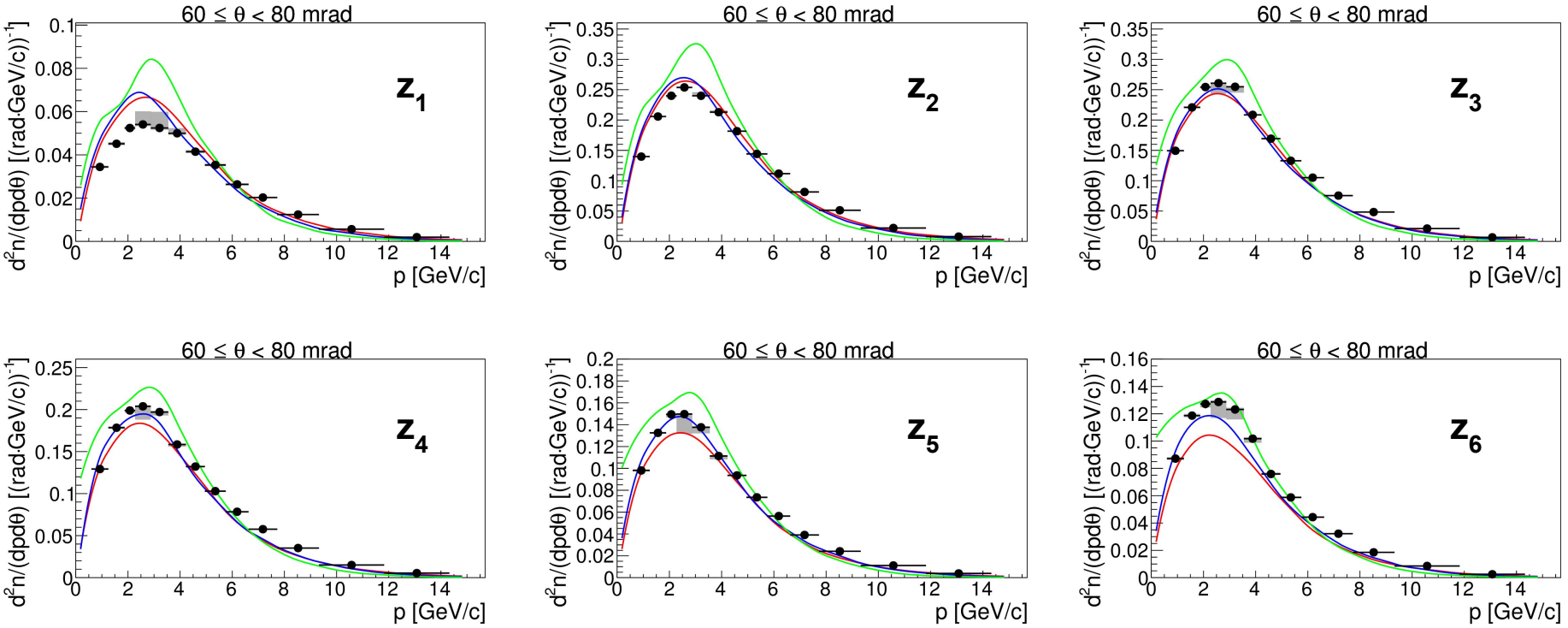
Uncertainties

Max. range

Majority of bins

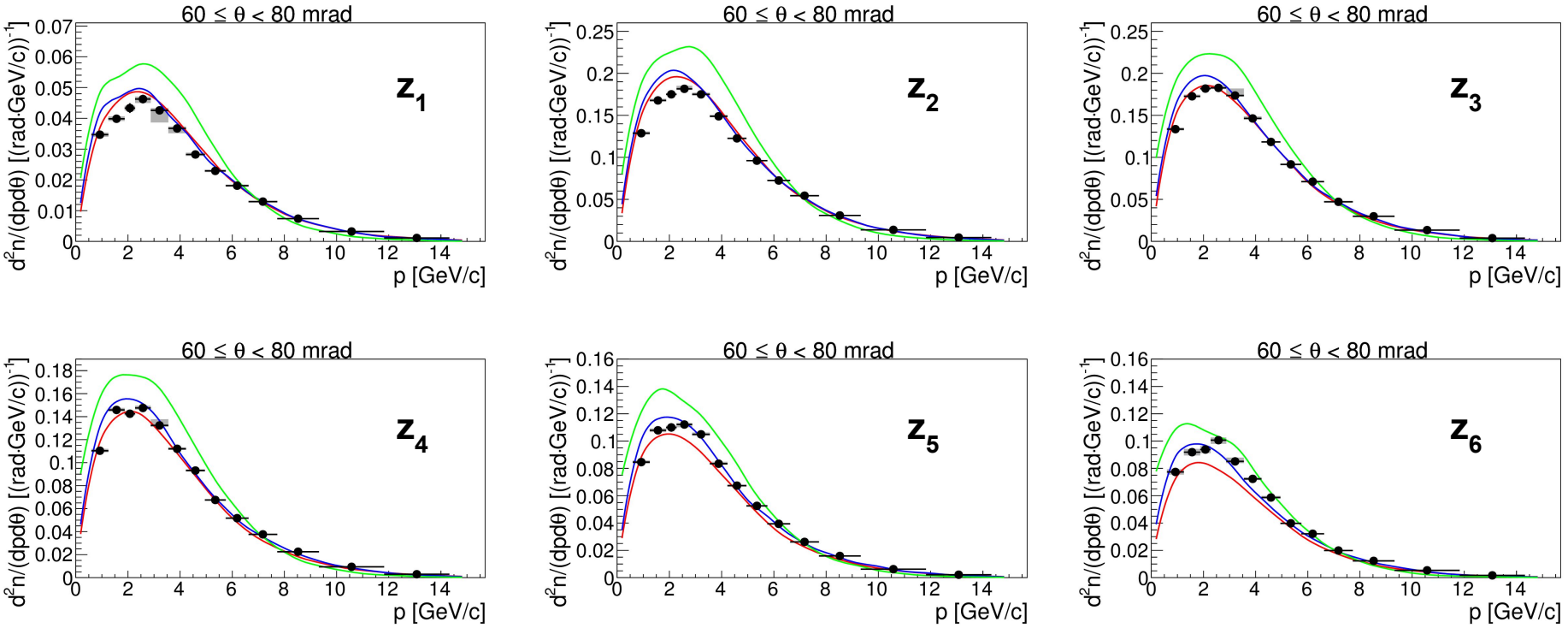
Uncertainty	π^+	π^-	K^+	K^-	p
Statistical	1% - 25% (< 4%)	1.5% - 25% (< 4%)	3% - 25% (5% - 10%)	5% - 25% (7% - 12%)	1%-25% (< 5%)
Bin migration	< 8% (< 1%)	< 10% (< 1%)	< 3% (< 1%)	< 3% (< 1%)	< 8% (< 1%)
TOF efficiency	< 1.5% (< 0.8%)	< 3% (< 0.8%)	< 0.8%	< 0.8%	< 1.5% (< 0.8%)
Hadron loss	< 25% (< 1%)	< 25% (< 1%)	< 10% (< 1%)	< 10% (< 1%)	< 25% (< 1%)
Feed-down	< 1.5%	< 2.5%	-	-	< 3.5%
PID	< 2% (0%)	< 2% (0%)	< 12%	< 12%	< 2% (0%)
Reconstruction	2%	2%	2%	2%	2%

π^+ yields



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

π^- yields



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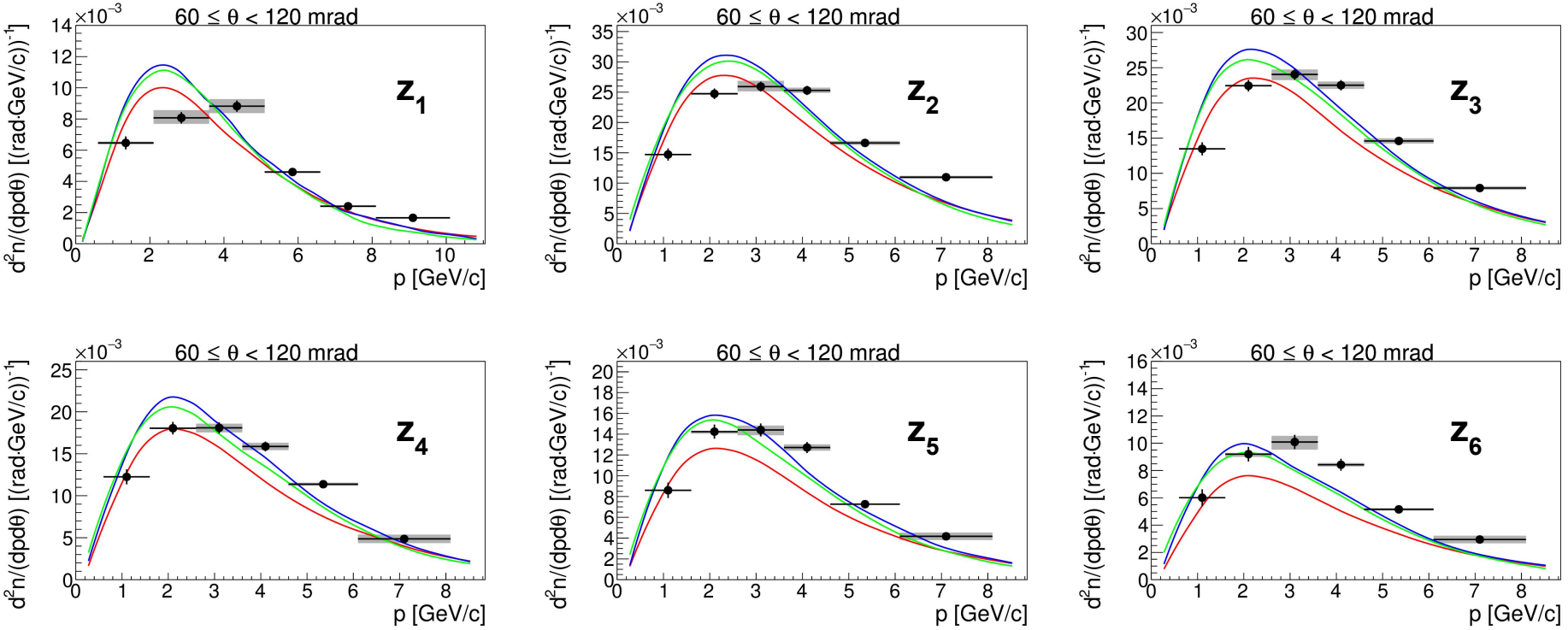
K^+ yields



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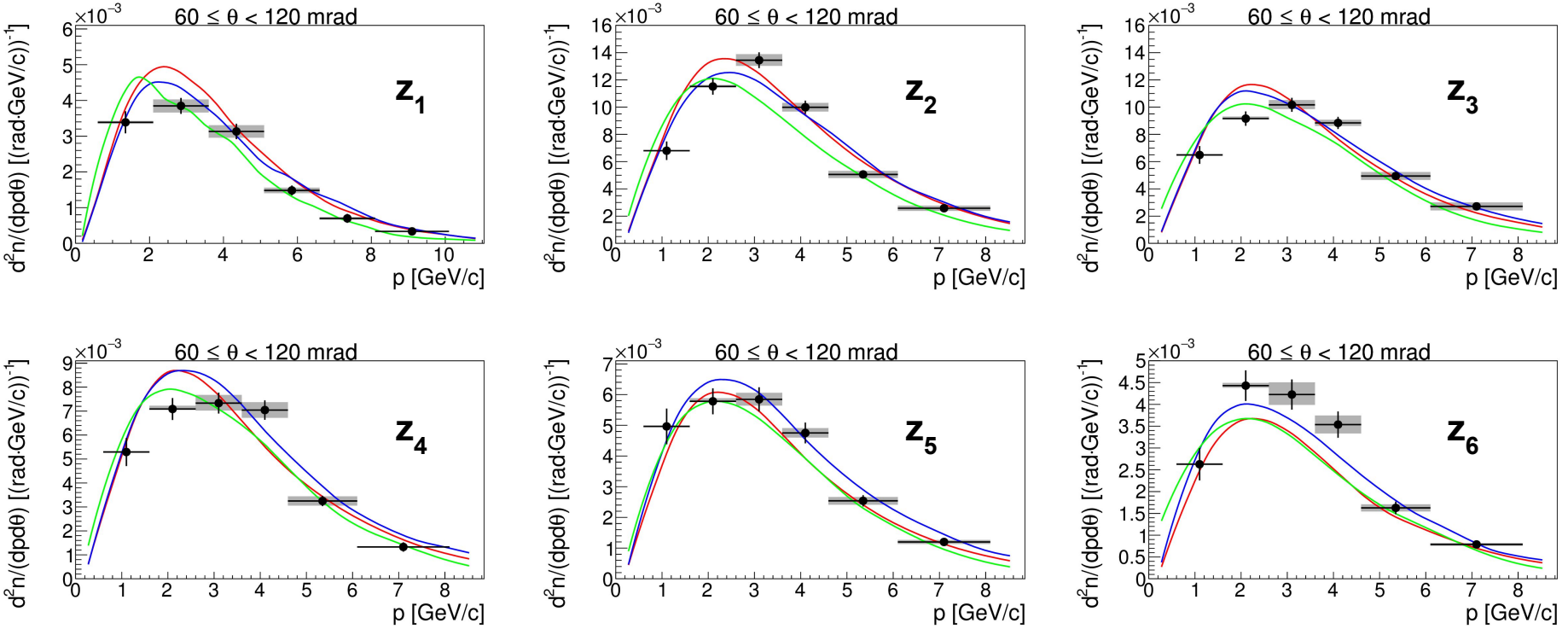
K^- yields



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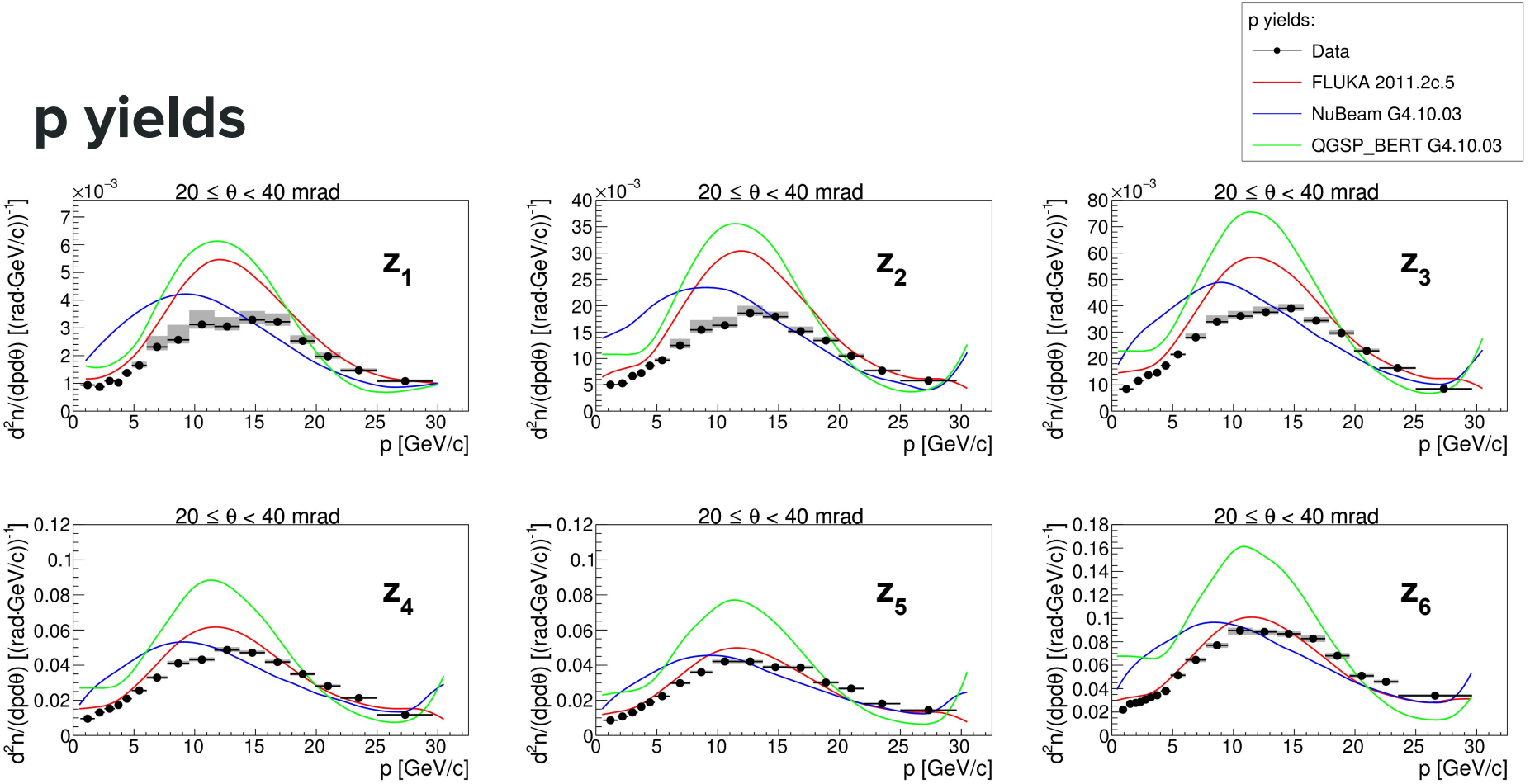
p yields



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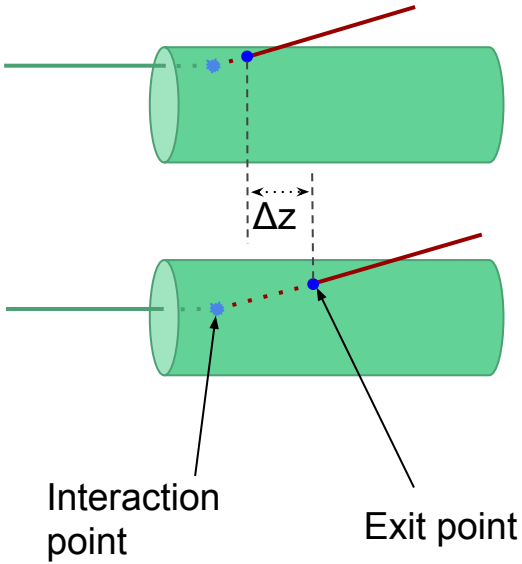
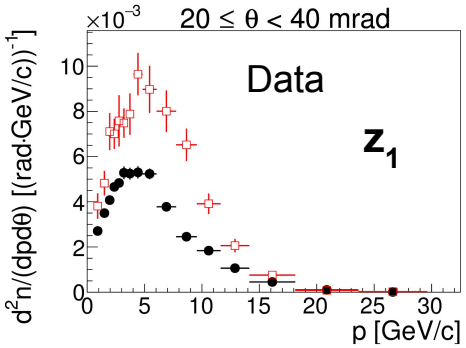
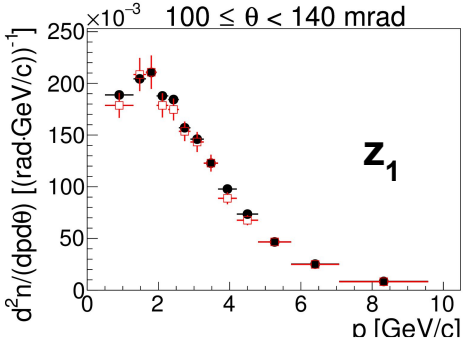
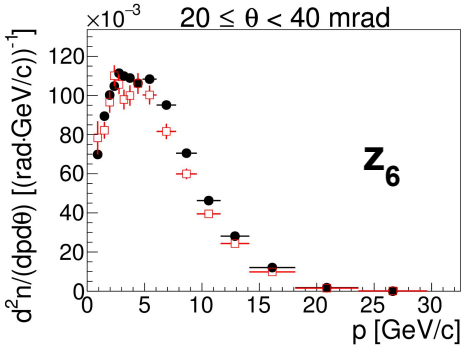
2009 vs. 2010 data

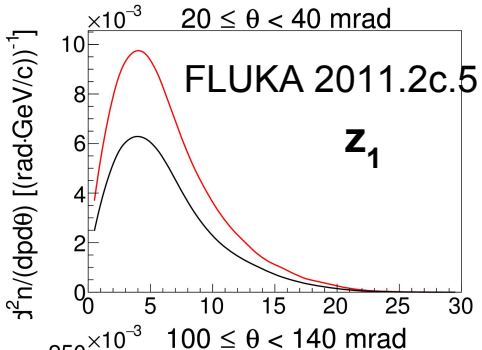
- hadron yields depend on the beam size, width and position
- 2009 beam profile ≠ 2010 beam profile (wider in 2009)

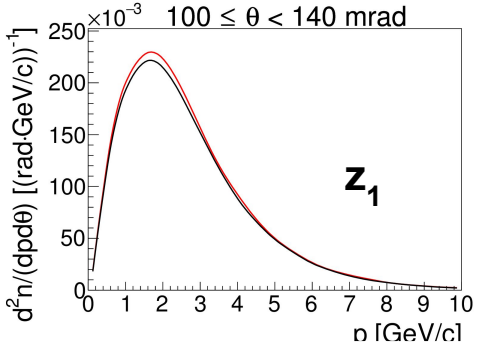


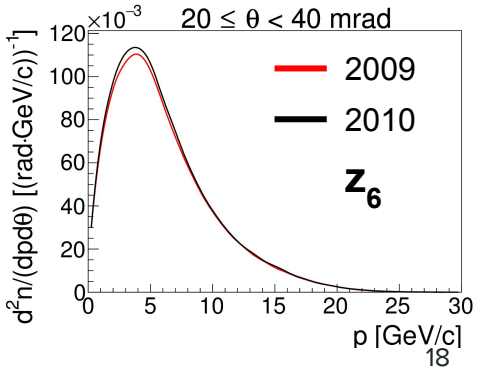






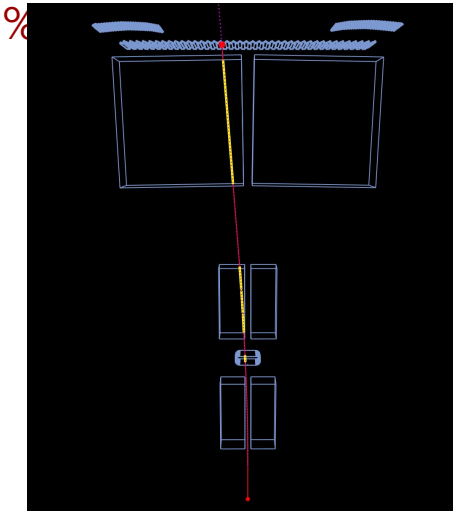






Measurement of beam survival probability

- 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)

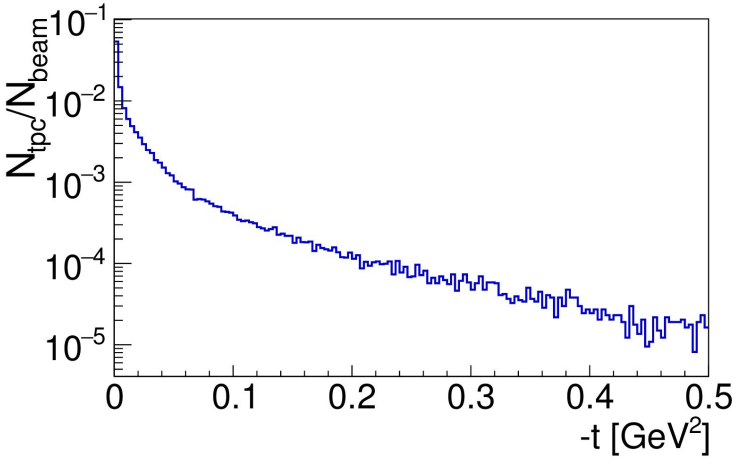
P_{surv}(FLUKA, rec) = 0.1196 ± 0.0002 (stat)

$$\sigma_{prod}^{MC} - \sigma_{prod}^{data} = -\frac{1}{nL} \ln\left(\frac{P_{surv}^{MC}}{P_{surv}^{data}}\right)$$

→ ~ 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?**



Conclusion

- Hadron yields coming from the surface of the T2K replica target
  - Data taken in 2010 (Analysis successfully finalized)
  - π^+, π^- ➔ reduced uncertainty when compared to measurements performed using 2009 data
  - K^+, K^-, p yields ➔ measured for the first time
  - FLUKA 2011.2c.5 gives the best overall prediction of the results
  - Comparison of π yields with measurements performed using 2009 data shows expected differences due to different beam profiles
  - **Paper in preparation**
- The measurements are expected to further reduce neutrino flux uncertainty in T2K below 5%
- Possible measurement of survival probability
- NA61/SHINE spectrometer is currently a unique opportunity to perform high-quality hadron production measurements for ongoing and future neutrino experiments