SHINE Autumn School @ CERN: Physics and Facility
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Cross section and spectra measurements with hadron beams on long targets

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for the NA61/SHINE collaboration

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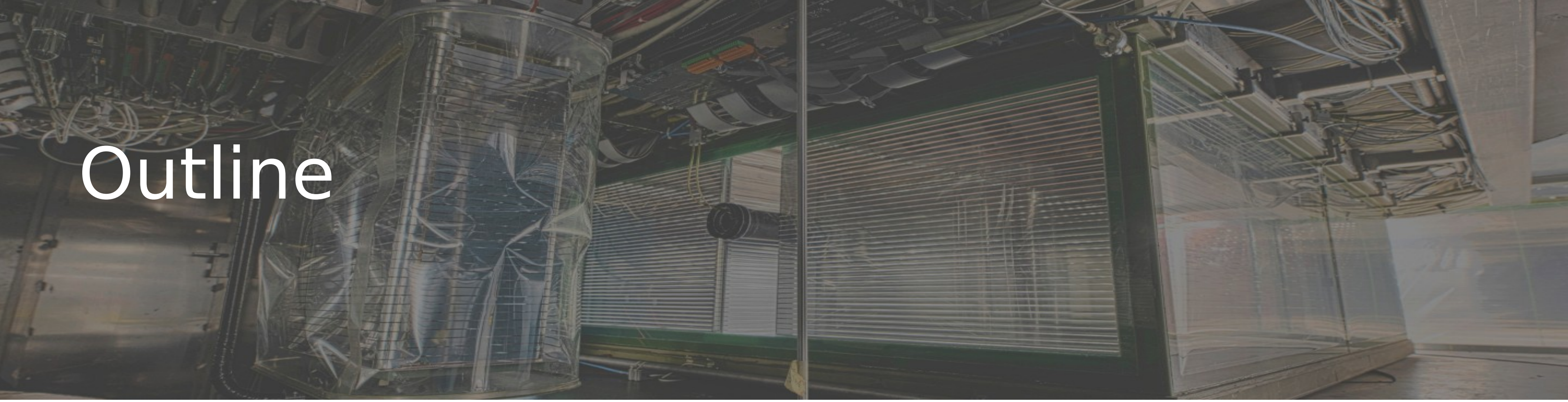
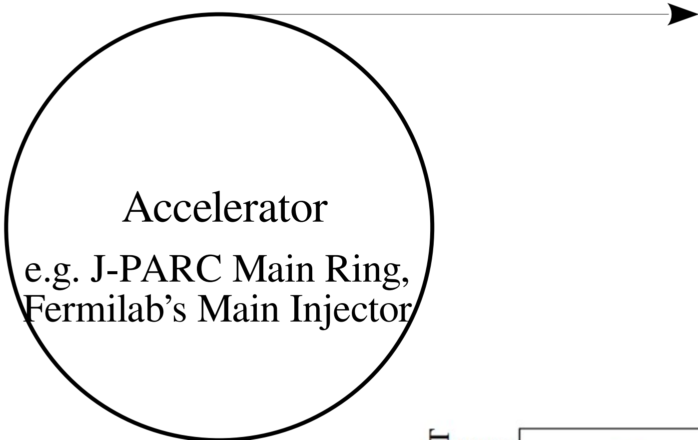


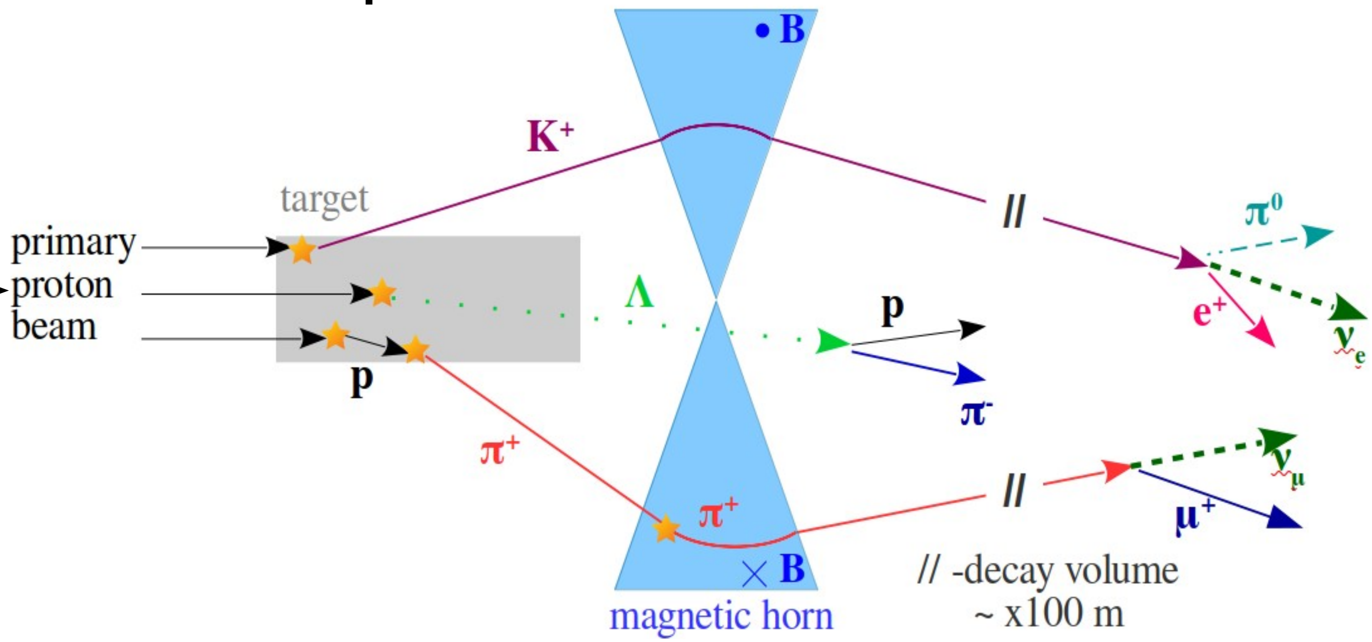
Outline

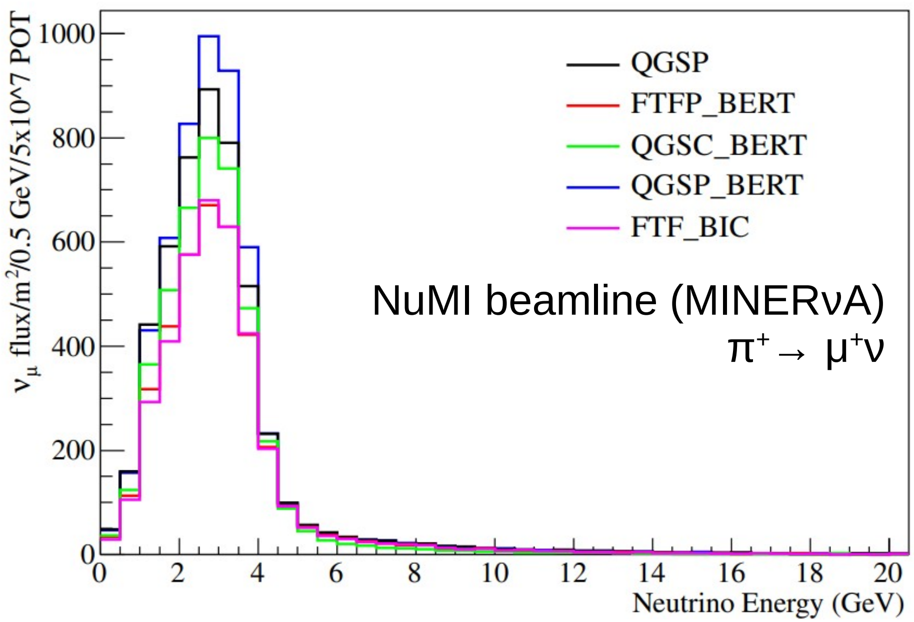
- Why perform long target measurements?
- What type of measurements?
  - Production cross section – method & results
  - Double differential particle yields – analysis techniques & results
- Summary

Why long target hadron production measurements?

<u>The making of a laboratory neutrino beam:</u>





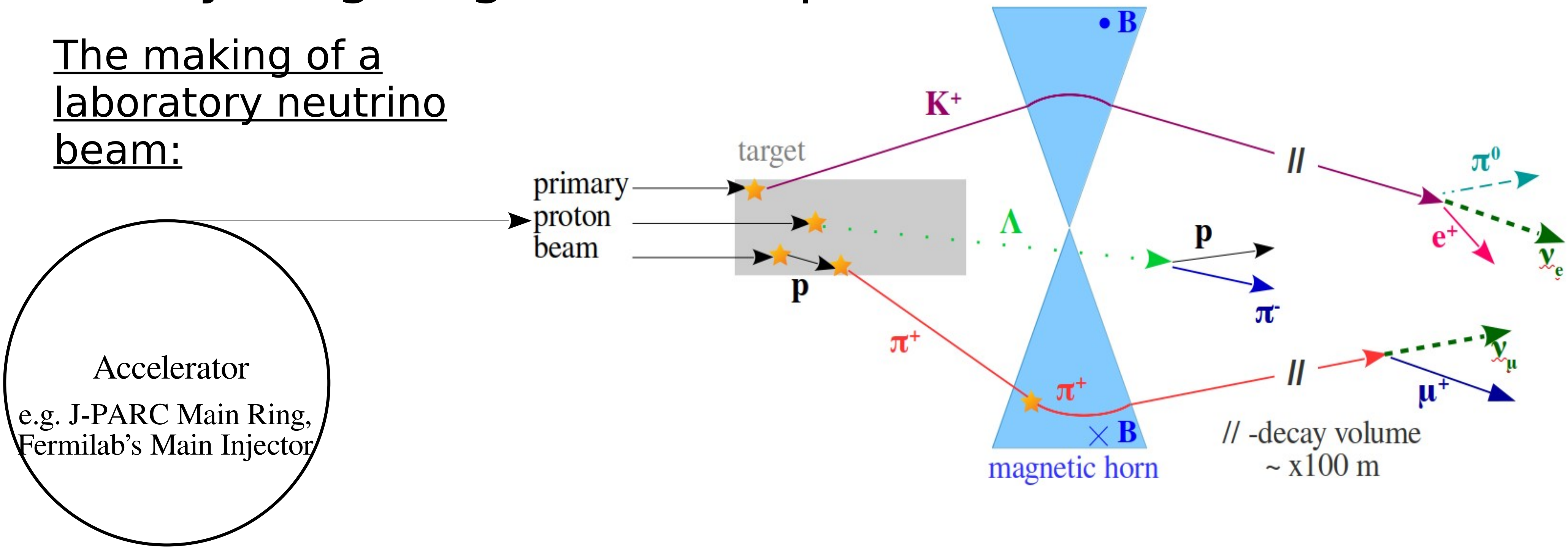


Leonidas Aliaga (Ph.D Thesis, 2016)

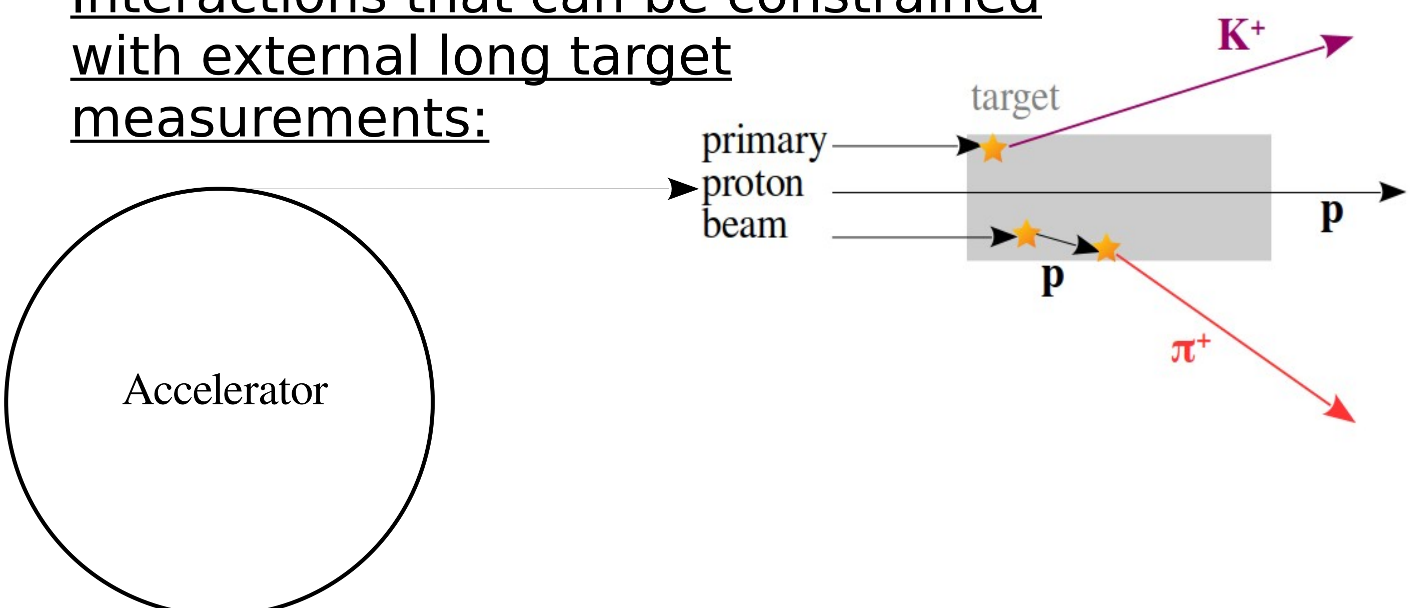
- Monte Carlo hadronic interaction models give different predictions of the neutrino flux

Why long target hadron production measurements?

<u>The making of a laboratory neutrino beam:</u>



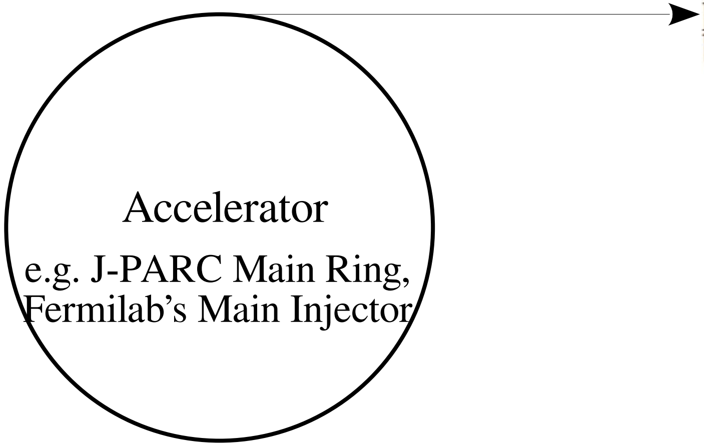
<u>Interactions that can be constrained with external long target measurements:</u>

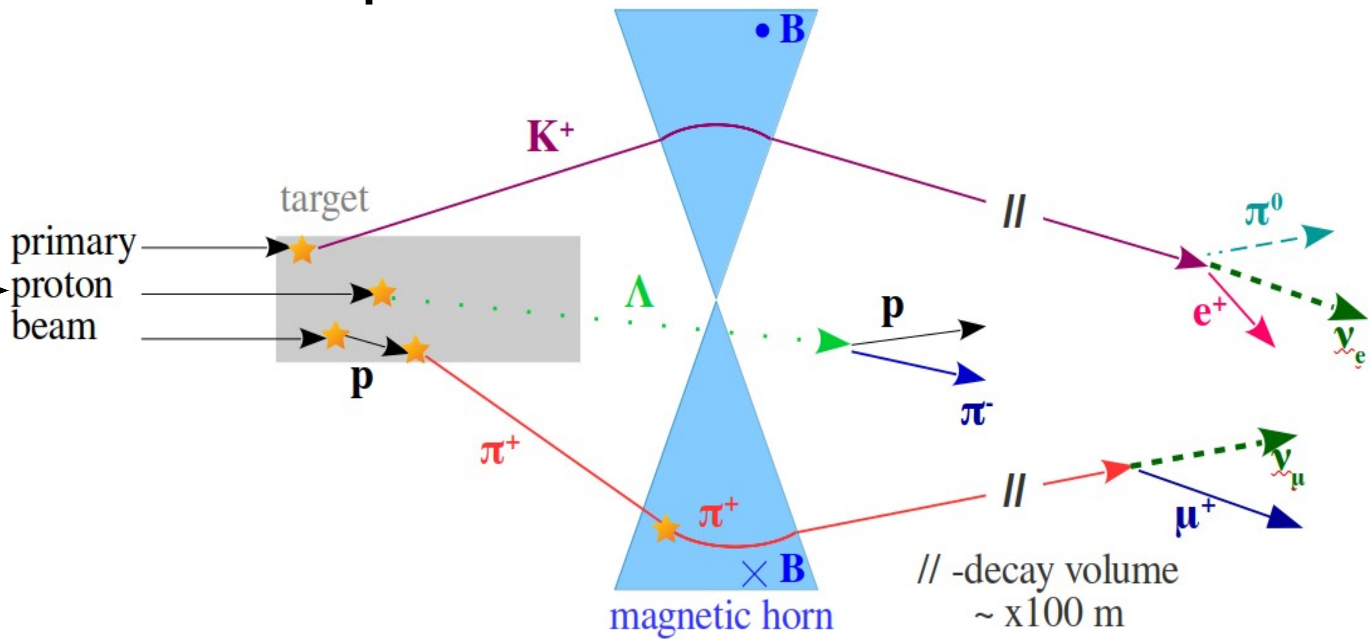


- Study primary and secondary interactions inside the target at once
- Count the number of penetrating beam protons
- Count the number of produced particles respecting particle type

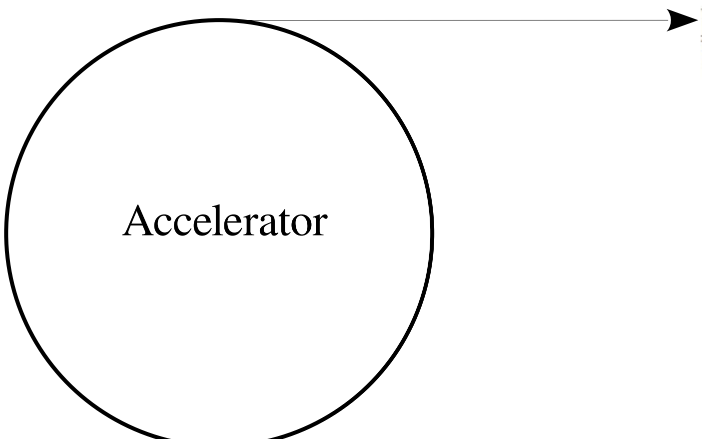
Why long target hadron production measurements?

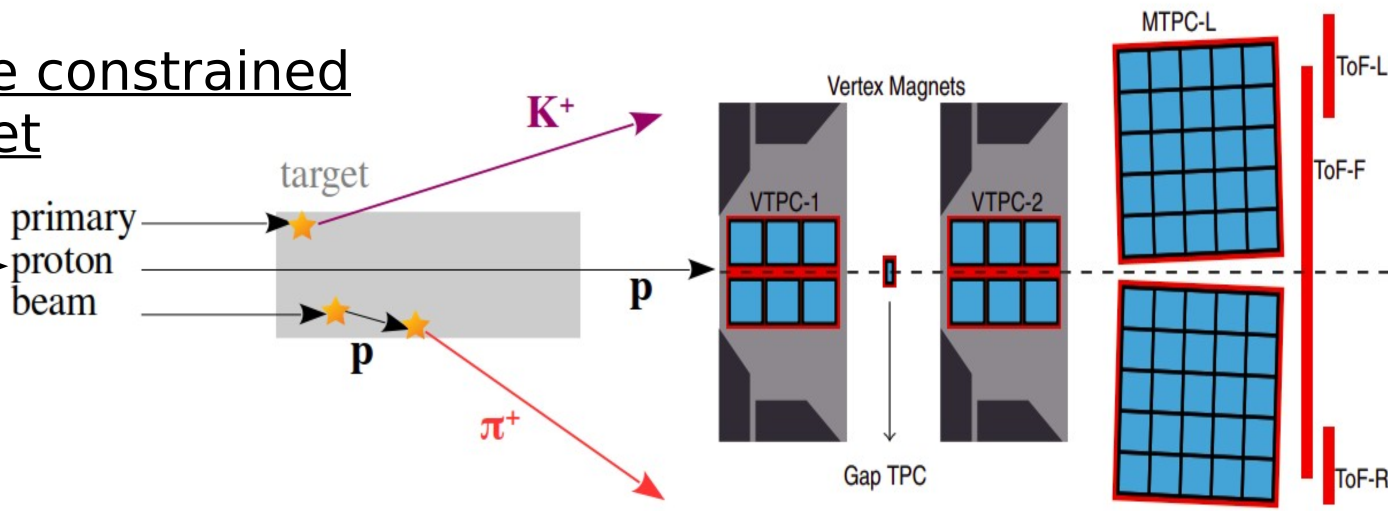
The making of a laboratory neutrino beam:





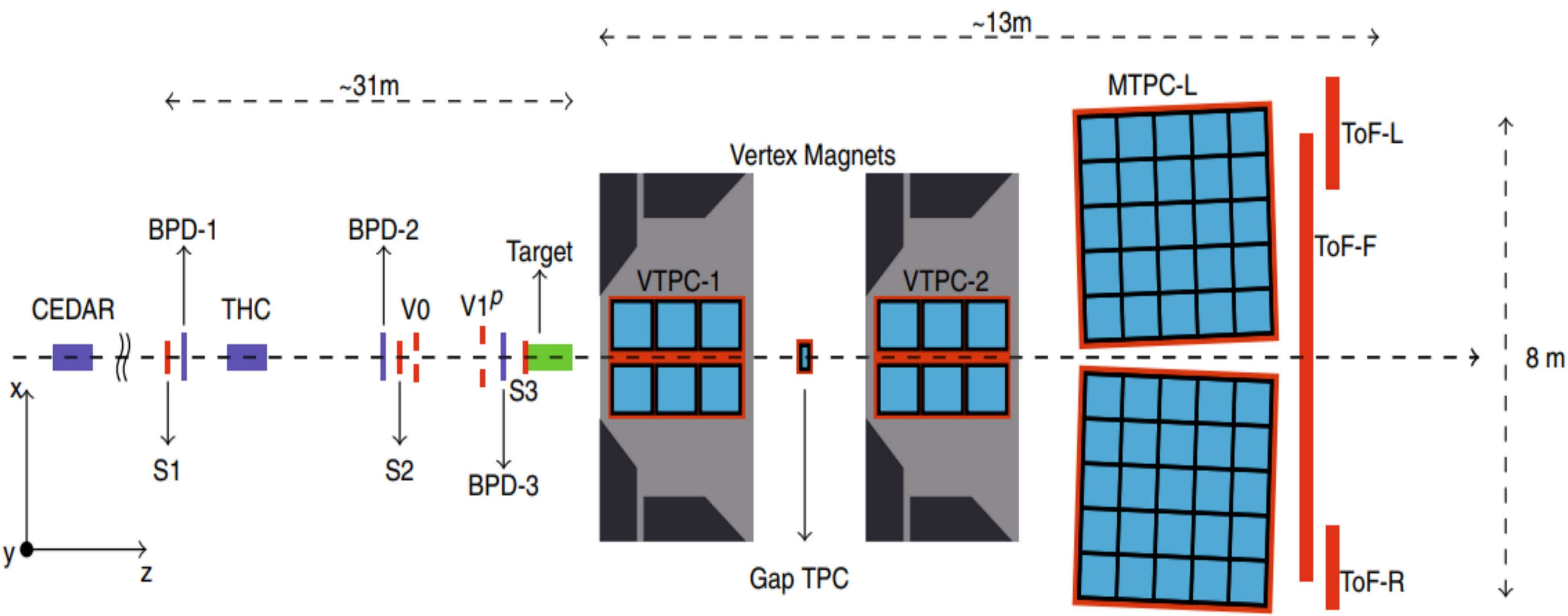
Interactions that can be constrained with external long target measurements:





NA61/SHINE

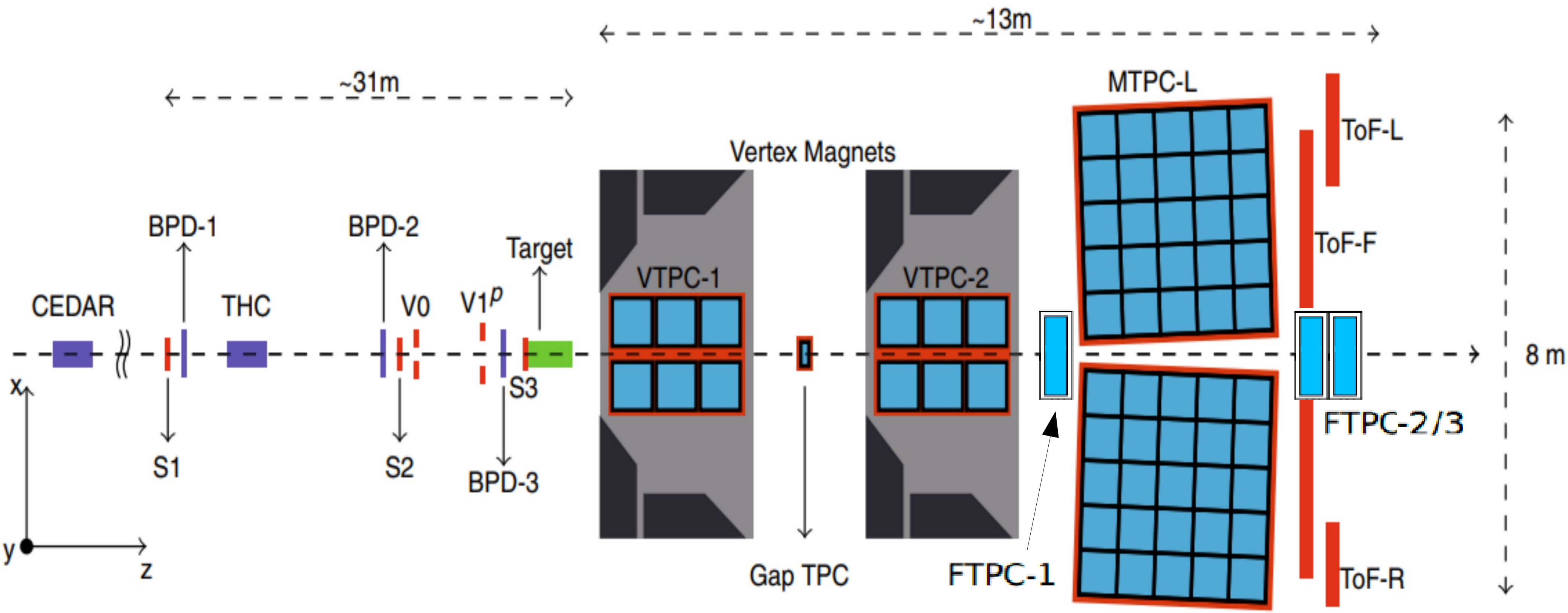
NA61/SPS Heavy Ion and Neutrino Experiment



NA61/SHINE setup in 2010

- fixed-target experiment at CERN’s SPS
- operating with ion and hadron beams in range 13 - 400 GeV/c
- momentum, charge and dE/dx measurements provided by TPC tracking system
- particle ID with TPC and TOF detectors

NA61/**S**PS **H**eavy **I**on and **N**eutrino **E**xperiment



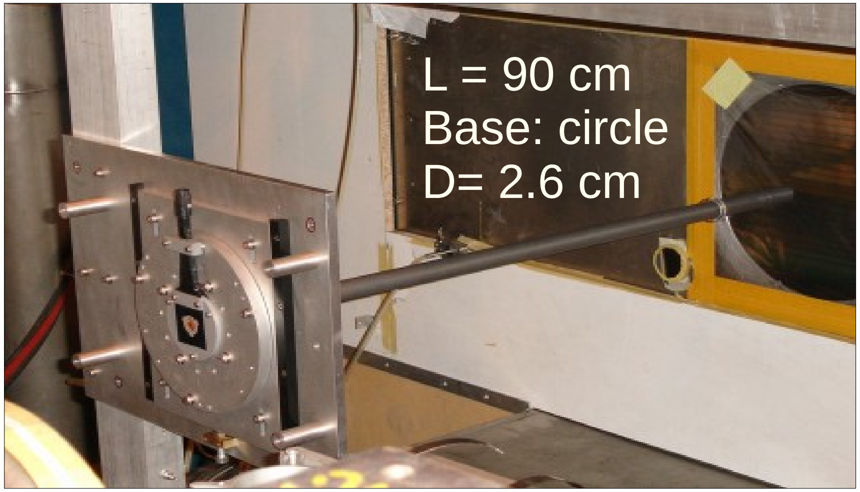
Forward TPCs installed in 2017

- fixed-target experiment at CERN's SPS
- operating with ion and hadron beams in range 13 - 400 GeV/c
- momentum, charge and dE/dx measurements provided by TPC tracking system
- particle ID with TPC and TOF detectors

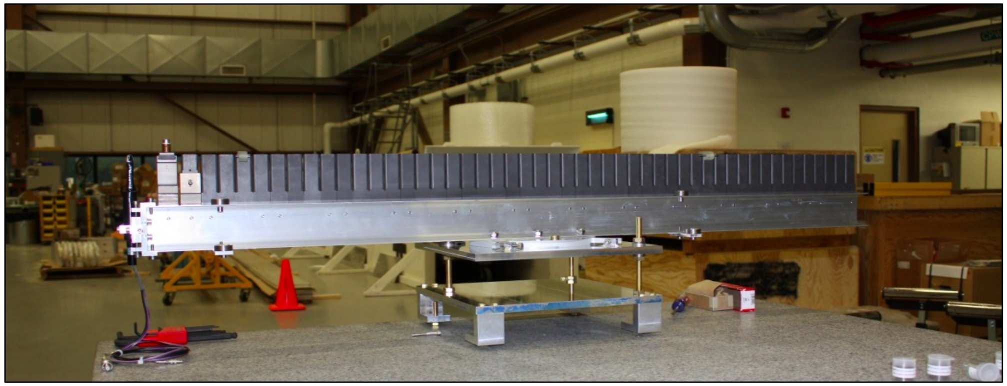
Thick(replica) targets

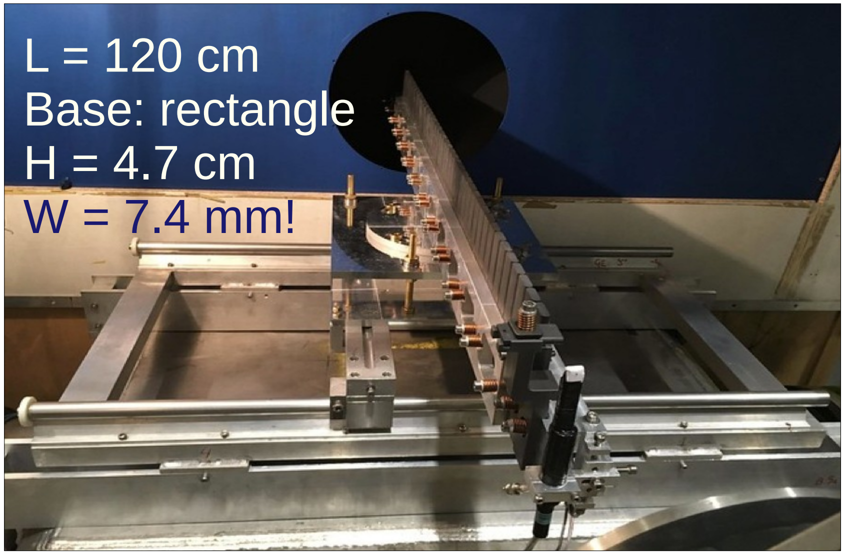
T2K replica target -
90-cm-long graphite rod; 1.9λ

- **Replica target** – a copy of the target used to initiate neutrino beams at long-baseline neutrino experiments



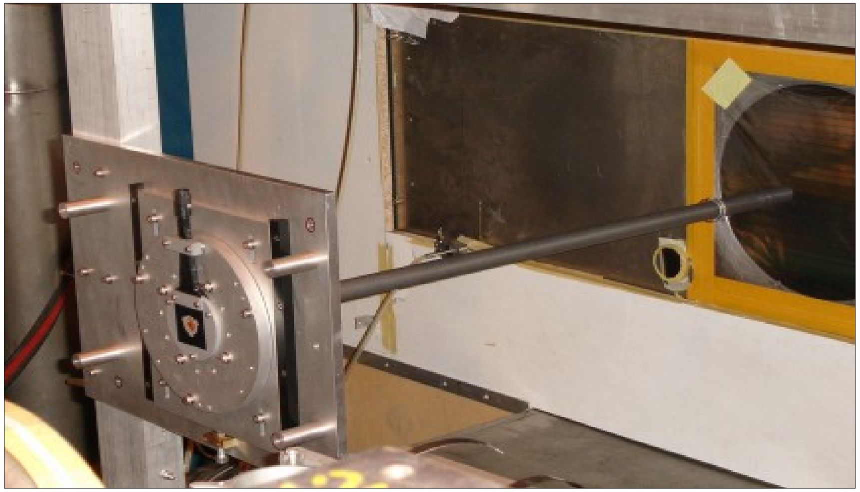
NuMI replica target -
120 cm of graphite fins; 2.5λ



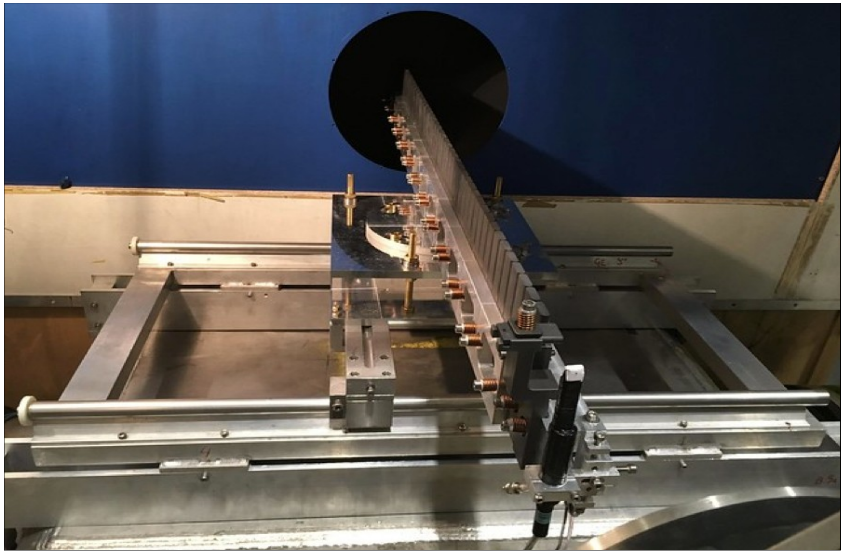


Thick(replica) targets measurements

T2K replica target:
p+C@31GeV/c → analyzed



NuMI replica target:
p+C@120GeV/c → calibration



with FTPCs installed in 2017

Thick target measurements

- **Proton** beams on **replica** targets
- Study both **primary** and **secondary** interactions inside the target at once

Results include :

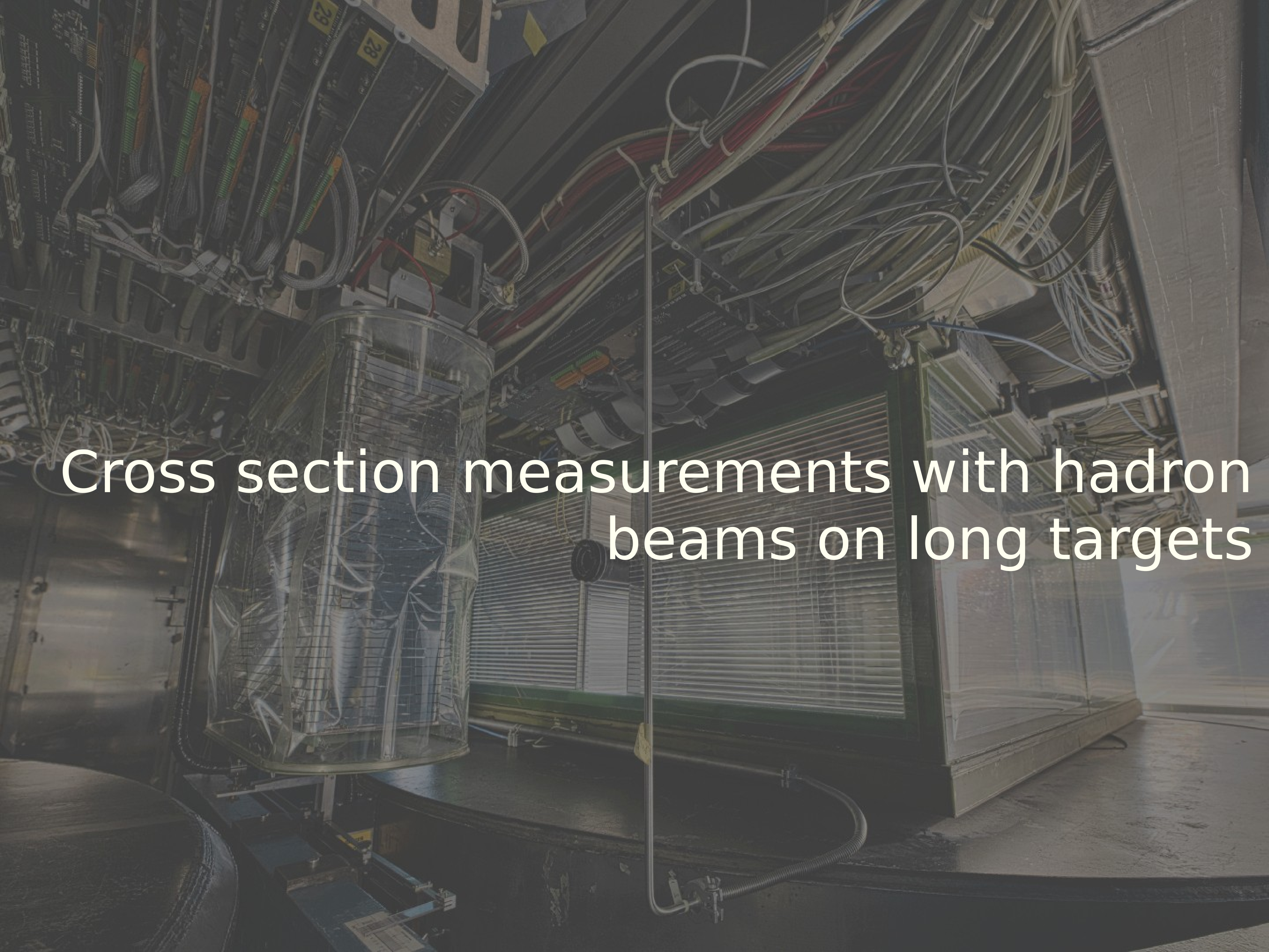
- Differential **hadron yields** on target surface
- Beam survival probability and related **production cross section** →

$$P_{survival} = e^{(-L n \sigma_{prod})}$$

L target length; n number density of nuclei

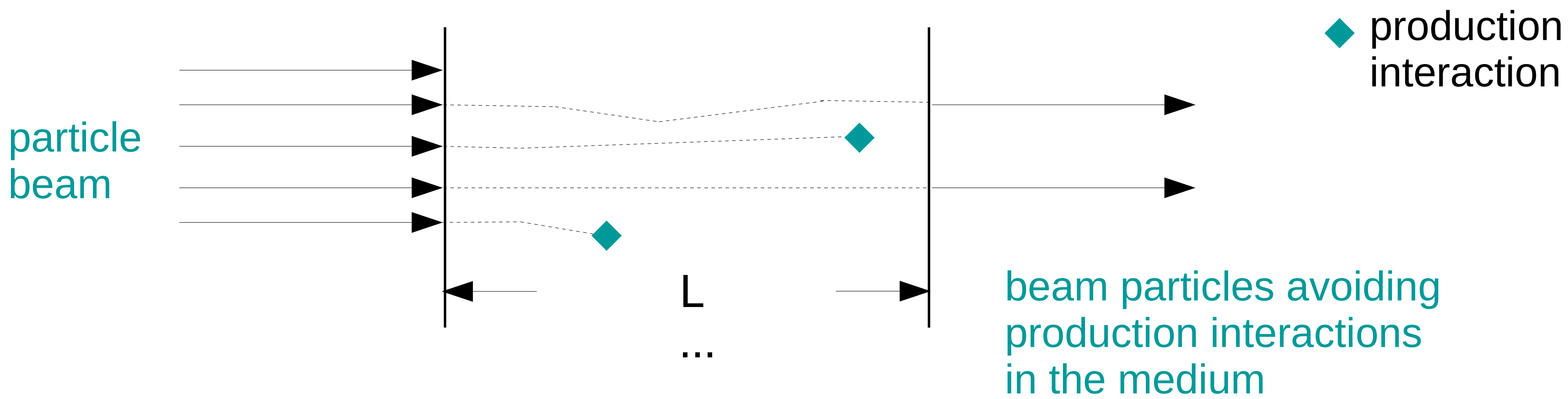
Production process:
Interaction with new hadron production (σ_{prod})

Cross section measurements with hadron beams on long targets



Method for production cross section estimation

A particle flux attenuates exponentially when going through a material of a given length:



Define beam survival probability:

$$P_{survival} = \frac{N_{EL+QE\,scatt.\,beam\,particles}}{N_{beam\,particles}}$$

Then $P_{survival}$ is related to the production cross section σ_{prod} via

$$P_{survival} = e^{-Ln\sigma_{prod}}$$

L – thickness of medium, n – the number density of nuclei in the medium

Strategy:

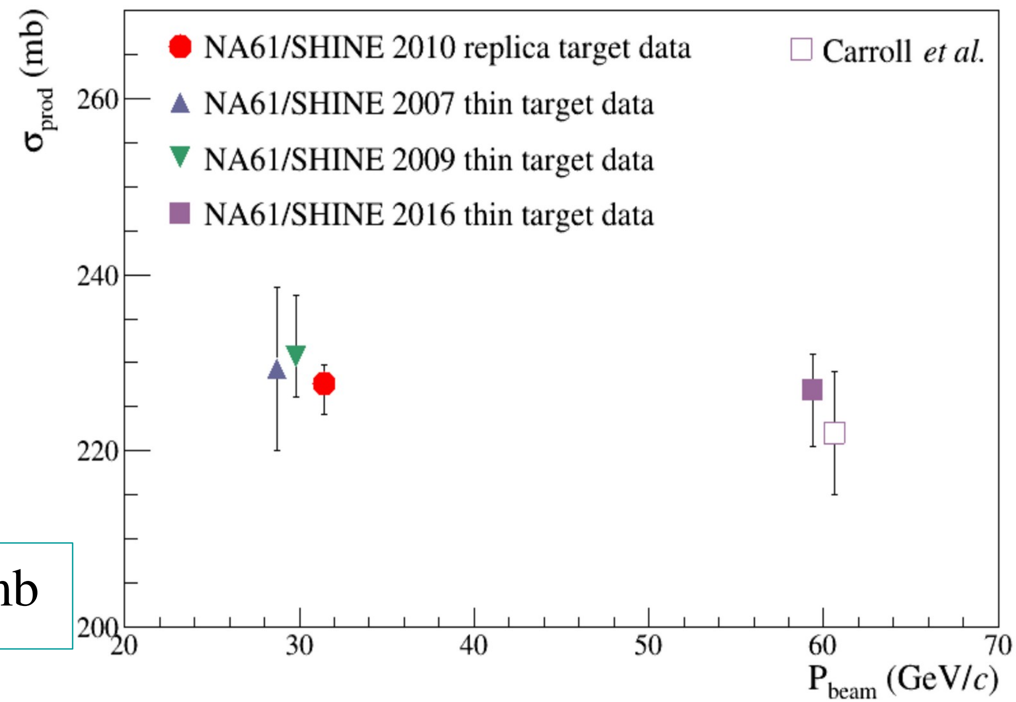
Estimate **beam survival probability** → calculate **production cross section**

→ Select EL+QE interactions in the medium

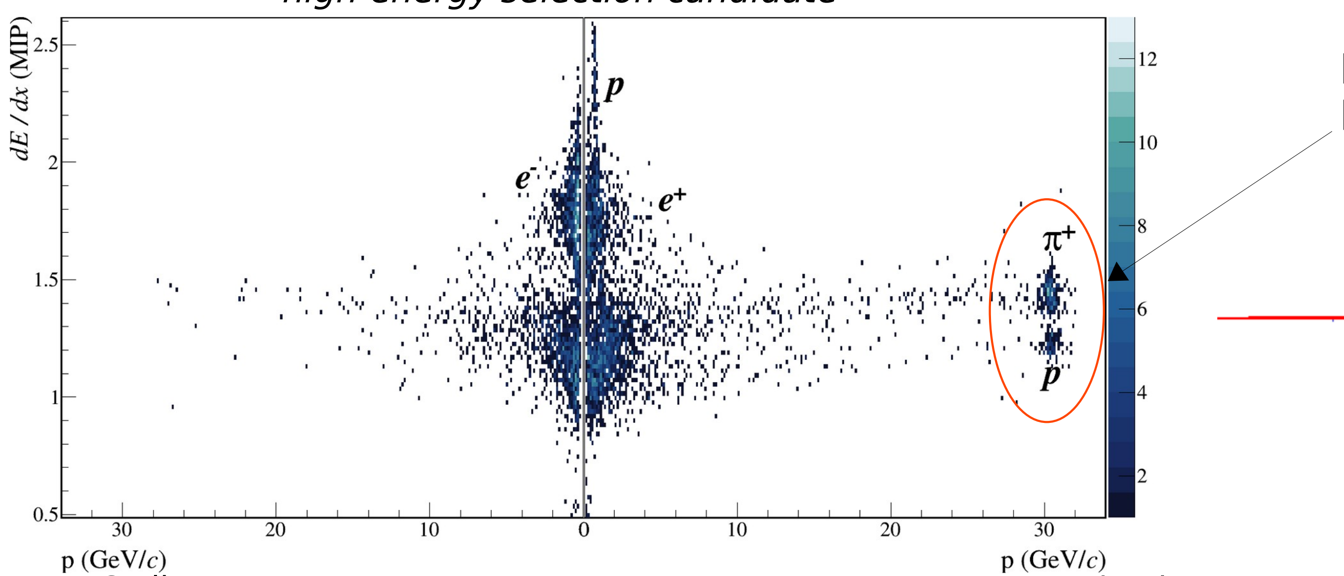
Production cross-section measurement

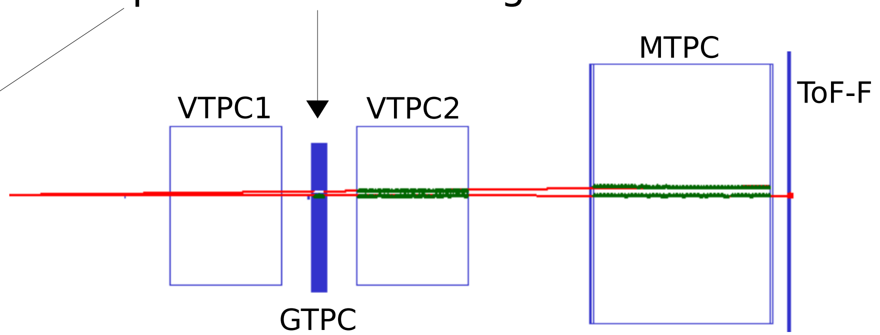
- Cut-based analysis arXiv/2010.11819
- Direct measurement of production cross-section in p+C@31GeV/c
- Complementary to thin-target measurements
- Minimizes model dependence (<0.4%)
- Leading syst. sources are pile-up events, target density and track reconstruction

$$\sigma_{prod} = 227.6 \pm 0.8\ (\mathrm{stat})\ {}^{+1.9}_{-3.2}\ (\mathrm{sys})\ - 0.8\ (\mathrm{mod})\ \mathrm{mb}$$



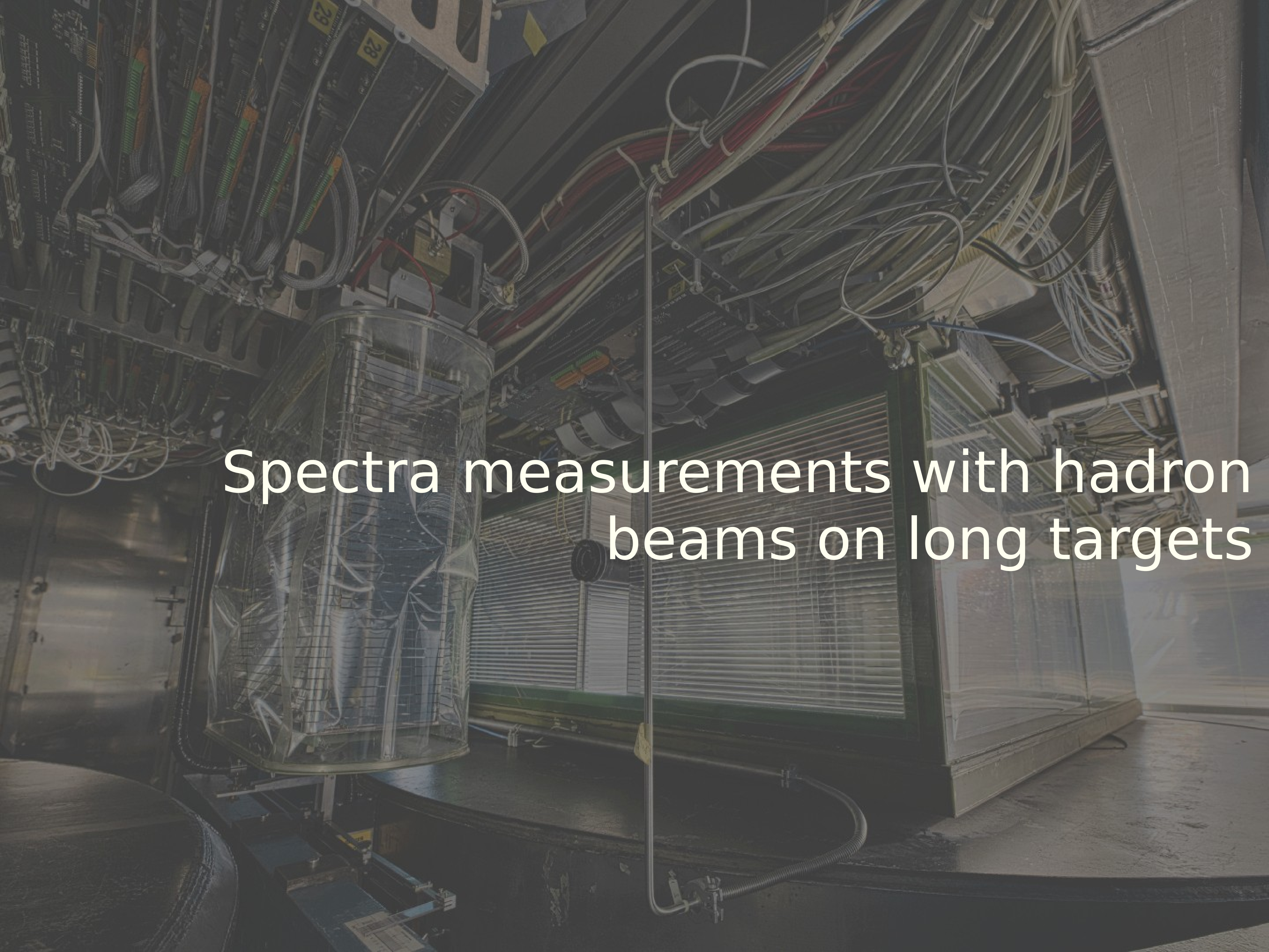
dE/dx vs p distribution for tracks produced alongside the high-energy selection candidate





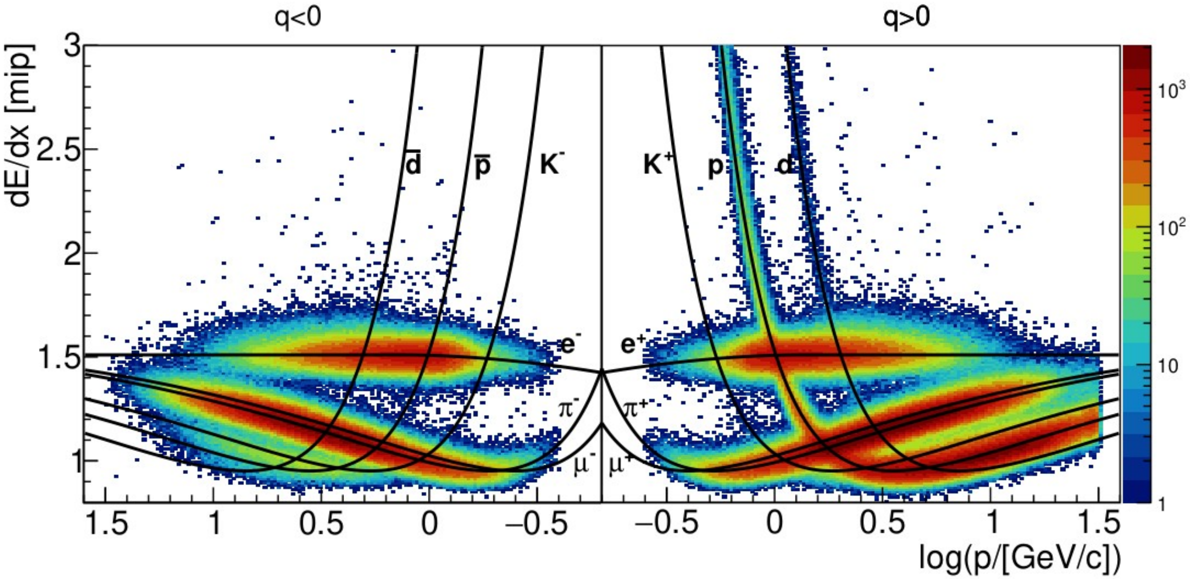
NA61/SHINE event display
y-z plane

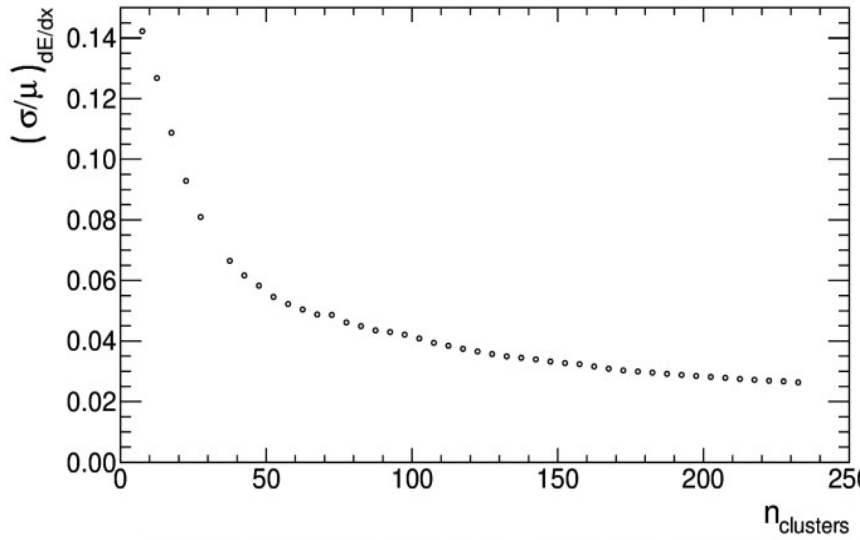
Spectra measurements with hadron beams on long targets



Particle identification

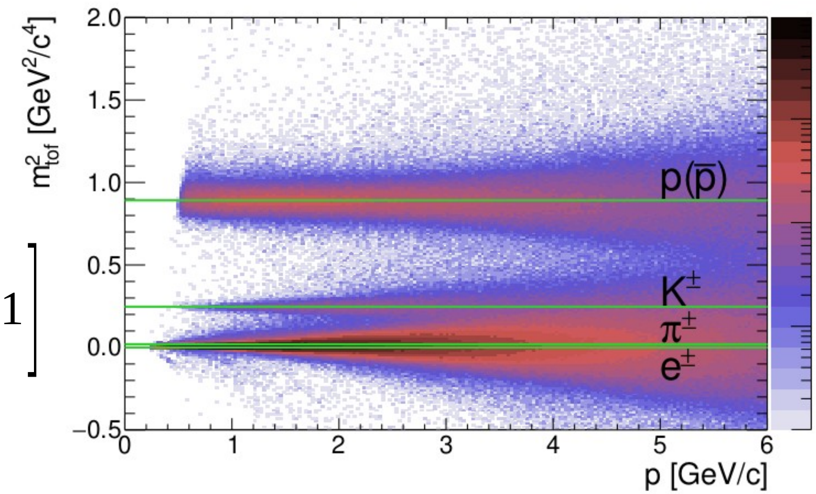
- Energy loss (dE/dx) → low momenta cross-over regions

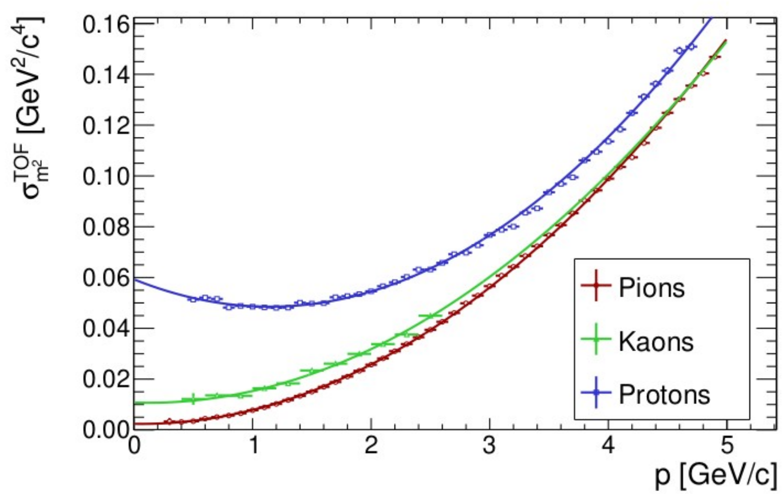




- Time of flight → sensitive up to 8 GeV/c

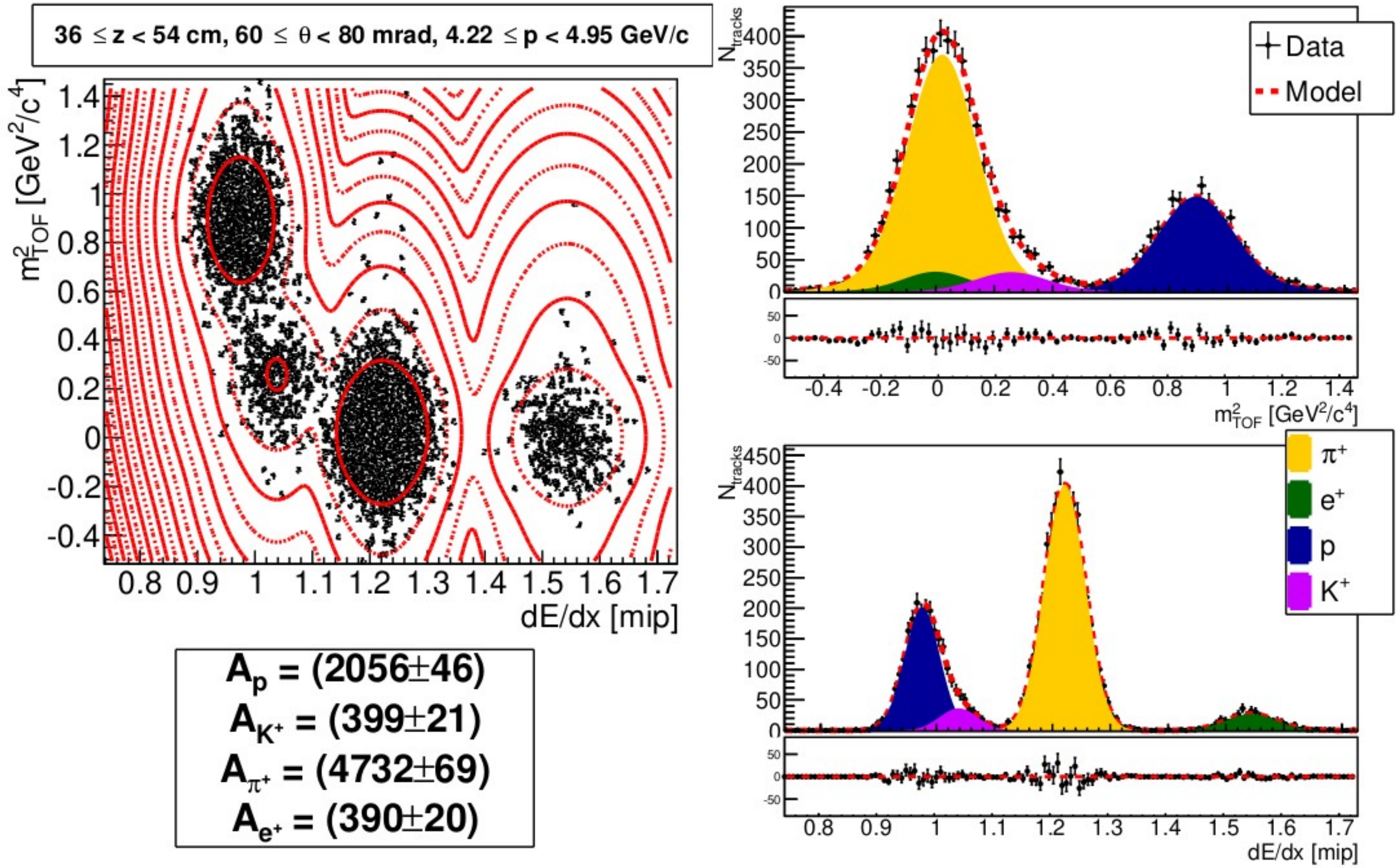
$$m_{tof}^2 = \left(\frac{p}{c}\right)^2 \left[\left(\frac{c\,.\,tof}{l}\right)^2 - 1\right]$$





Particle identification

- Joint m^2_{tof}-dE/dx fit → cover PID in all bins

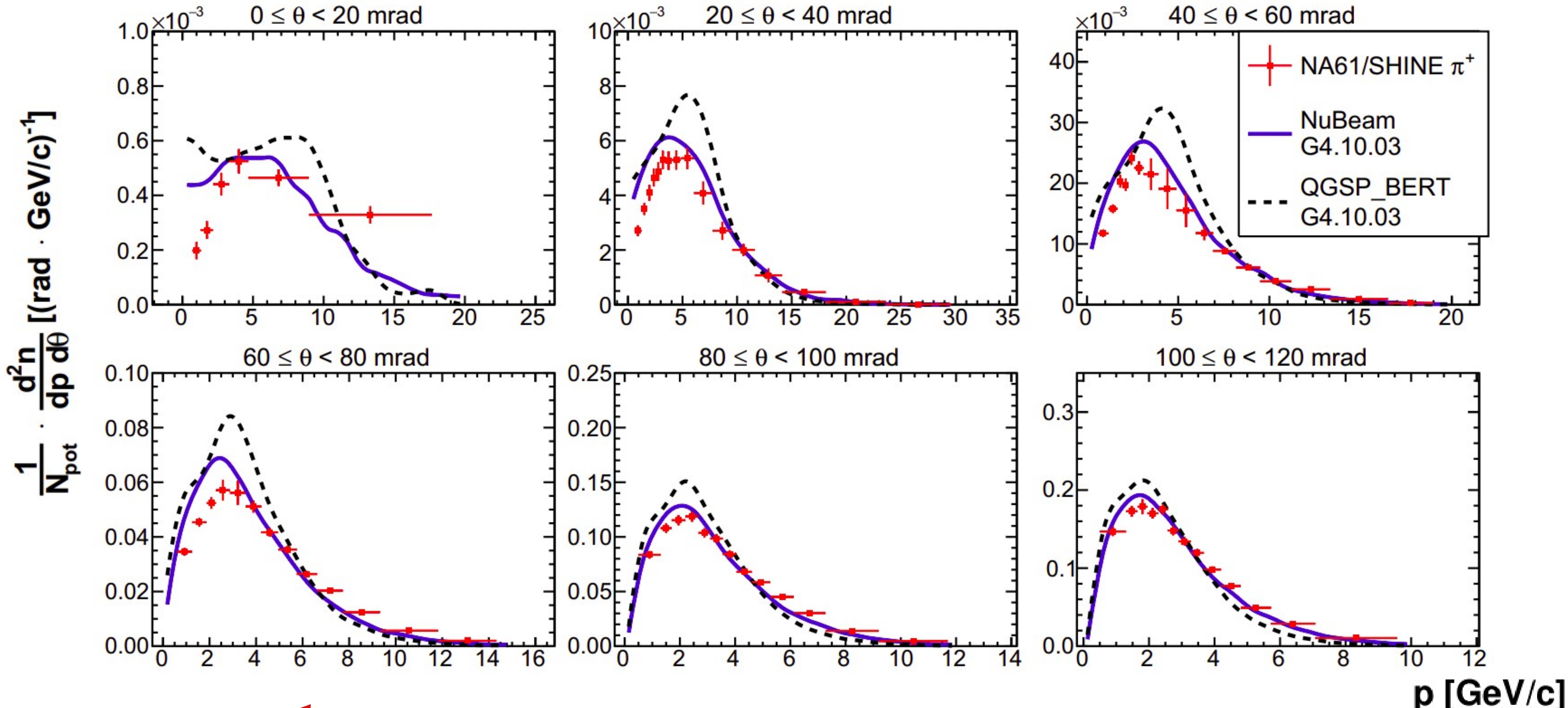


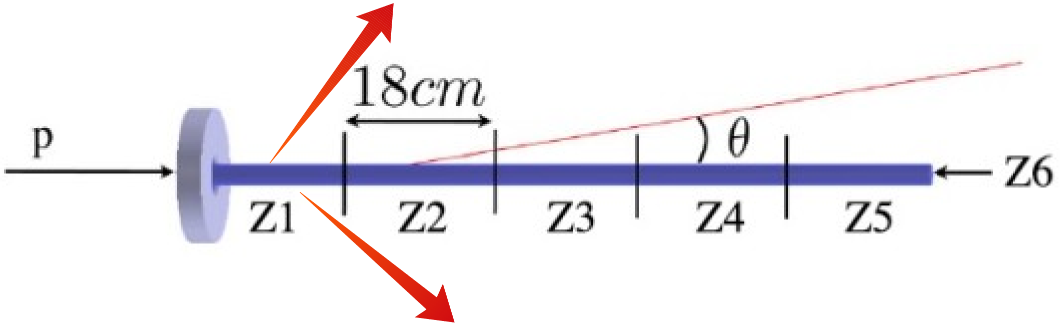
- 4 x 2D Gaussians, one for each particle species ($e^\pm$, $\pi^\pm$, $K^\pm$, $p(\bar{p})$)
- 20 parameters in the fit: 8 mean values, 8 standard deviations, and 4 particle multiplicities

Double differential particle yields

T2K replica target measurement

π⁺ production in *p + C @ 31 GeV/c* and 0 ≤ z ≤ 18 cm





- $\pi^{\pm}$, $K^{\pm}$, p double differential yields from the surface of the T2K replica target in *p+C* @31GeV/c

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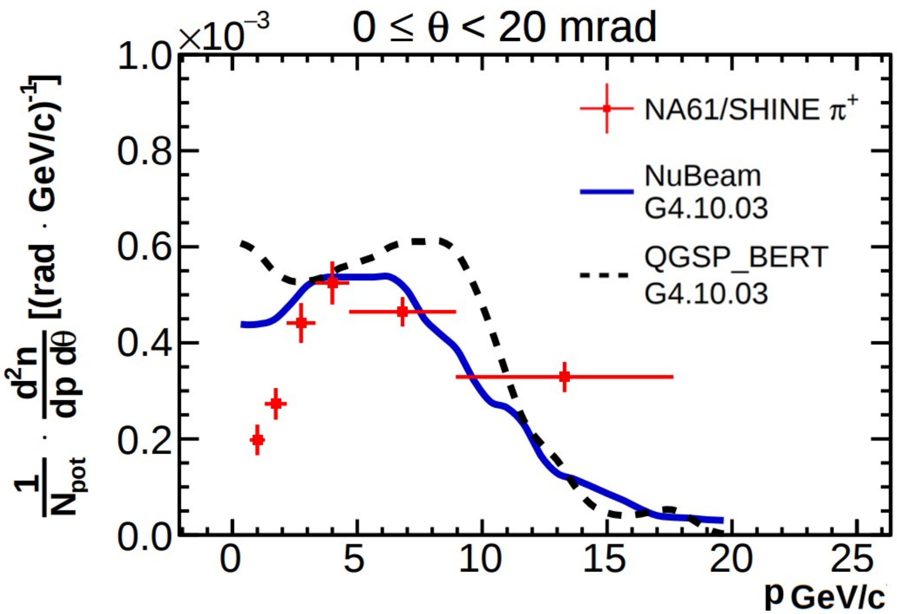
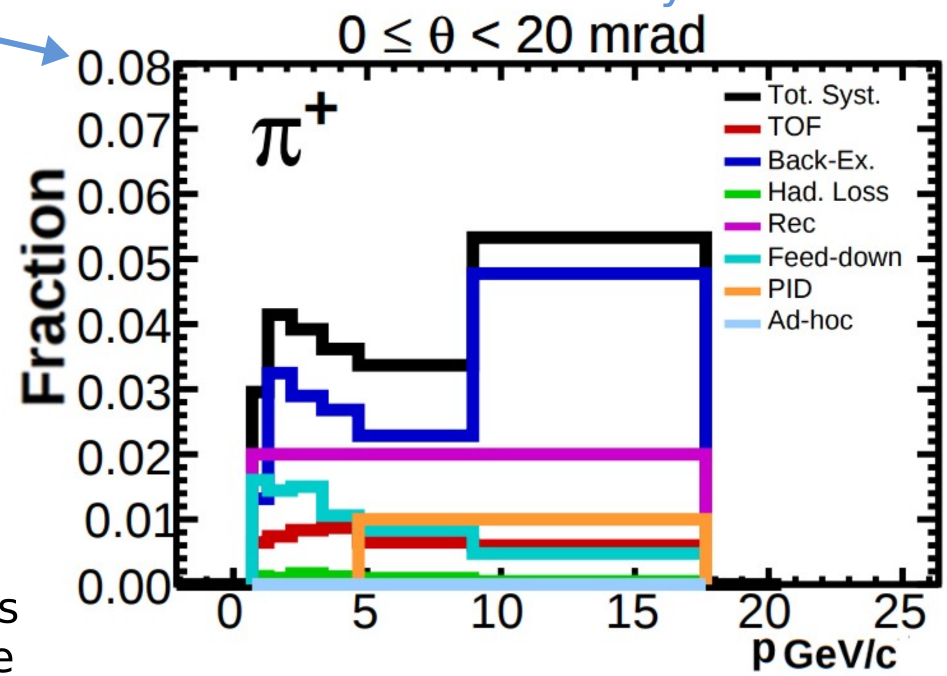
Double differential particle yields - systematics

T2K replica target measurement

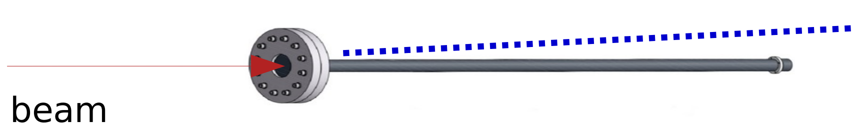
***π⁺* production in** *p + C @ 31 GeV/c* and 0 ≤ z ≤ 18 cm

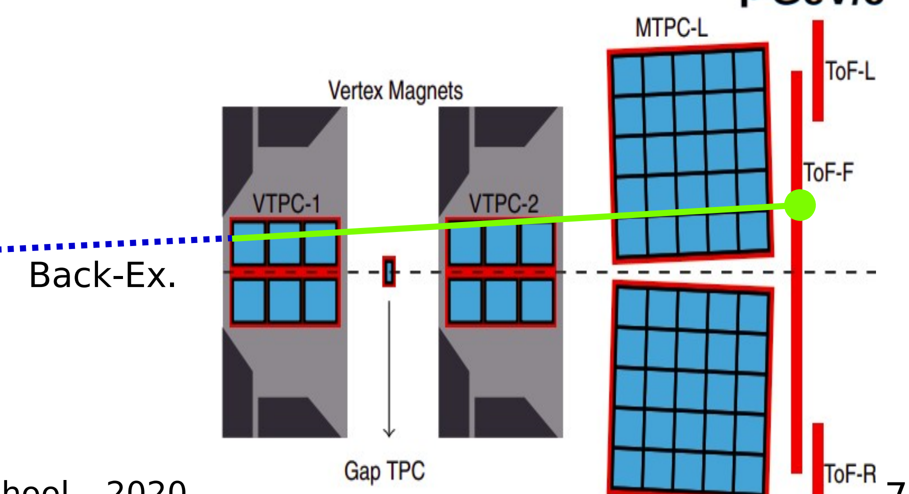


corresponding systematic uncertainty



- In most (p,θ z) bins the dominant syst. source is Backward track extrapolation (Back-Ex.) i.e. the track position uncertainty on the target surface
- Future detector upgrade: having an additional tracker surrounding the target





Re-weighting of the neutrino flux predictions with replica target data

Interaction probability re-weighting:

- Meant is production interaction probability re-weighting
- The weight is the ratio of the probabilities

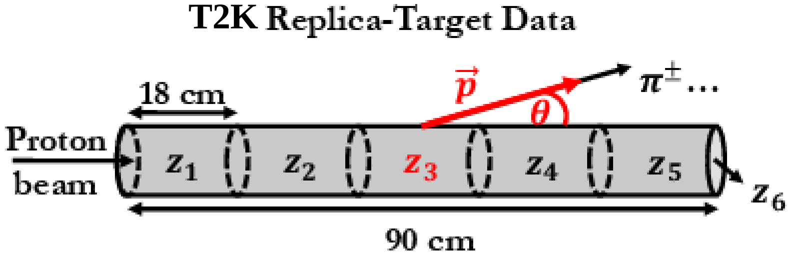
$$W = \frac{P\left(x; \sigma_{\text{prod}}^{NA61\,data}\right)}{P\left(x; \sigma_{\text{prod}}^{MC}\right)}$$

that a particle travels a distance x through a material of nuclear density ρ and interacts to produce new hadrons

$$W = \frac{\sigma_{\text{prod}}^{NA61\,data}}{\sigma_{\text{prod}}^{MC}} e^{-x\left(\sigma_{\text{prod}}^{NA61\,data} - \sigma_{\text{prod}}^{MC}\right)\rho}$$

attenuation of the particle flux over the distance traveled

Hadron differential production re-weighting:



- The weight is calculated as a ratio between the data and Monte Carlo

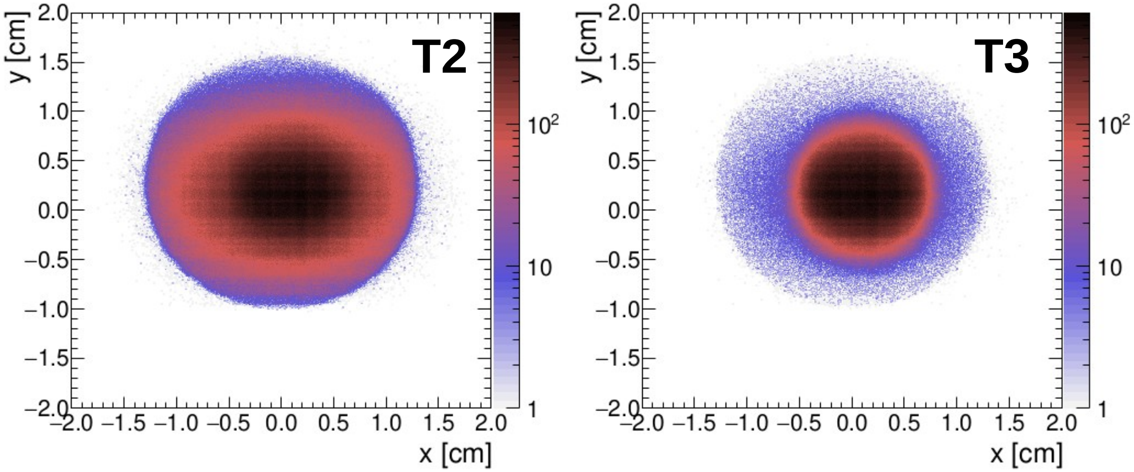
$$W_{ijk} = \left(\frac{1}{N_{pot}} \frac{n_{ijk}^{\alpha}}{\Delta\theta\Delta p}\right)_{NA61\,data} / \left(\frac{1}{N_{pot}} \frac{n_{ijk}^{\alpha}}{\Delta\theta\Delta p}\right)_{MC}$$

where n_{ijk} is the number of produced particles of given type α in z bin number *i*, polar angle *θ* bin *j* , and momentum *p* bin *k*. N_{pot} is the number of protons on target.

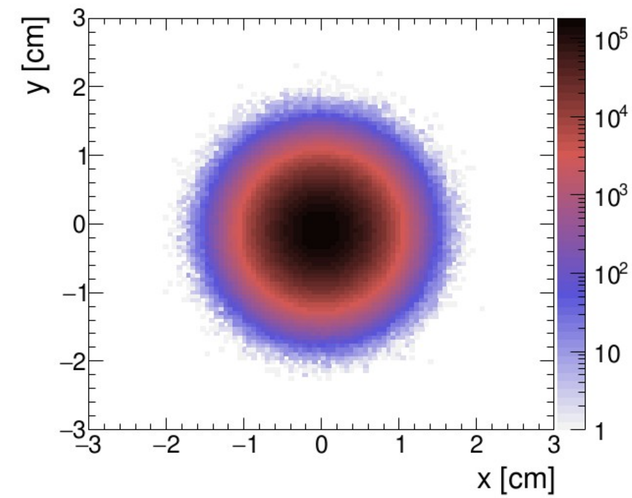
Beam profile at upstream target face

- NA61/SHINE beam profile is not the same as the T2K beam profile
- Hadron yields on the target surface depend on the beam profile → geometrical effect

NA61/SHINE

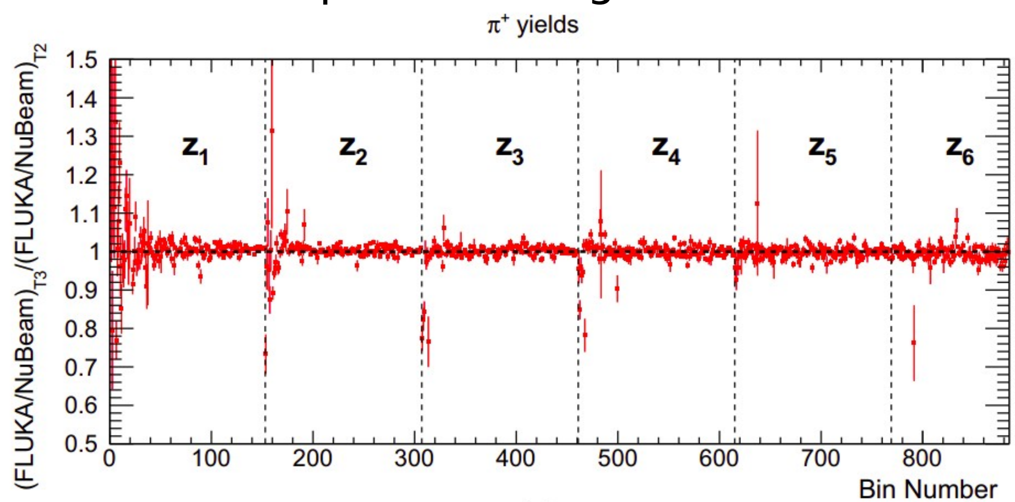


J-PARC; T2K Run4



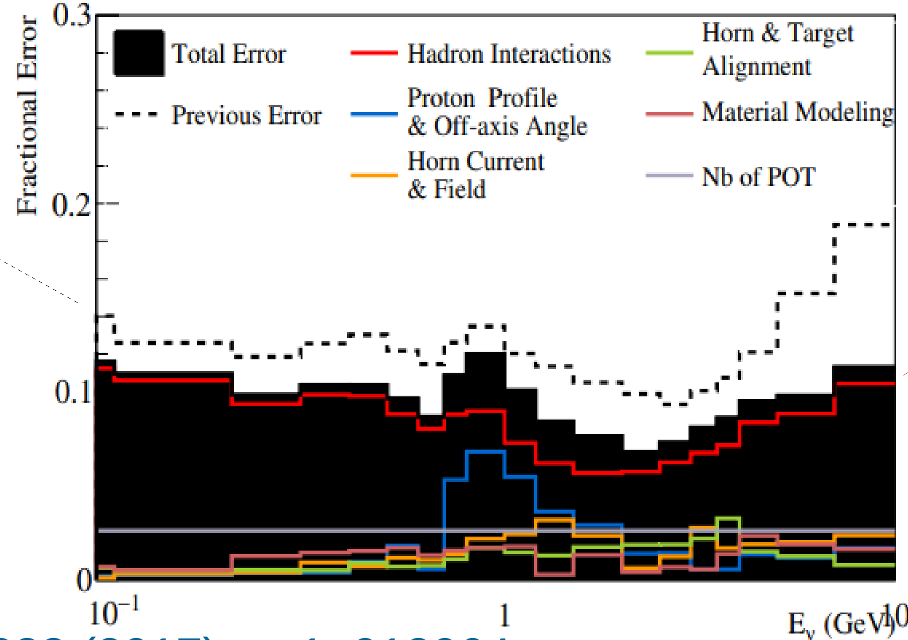
- Are re-weighting factors invariant under the beam profile change?

- Deviations from unity are present for upstream z bins
- For other bins differences are <2%



Impact on the T2K neutrino flux prediction

with 2007 NA61/SHINE
thin target data



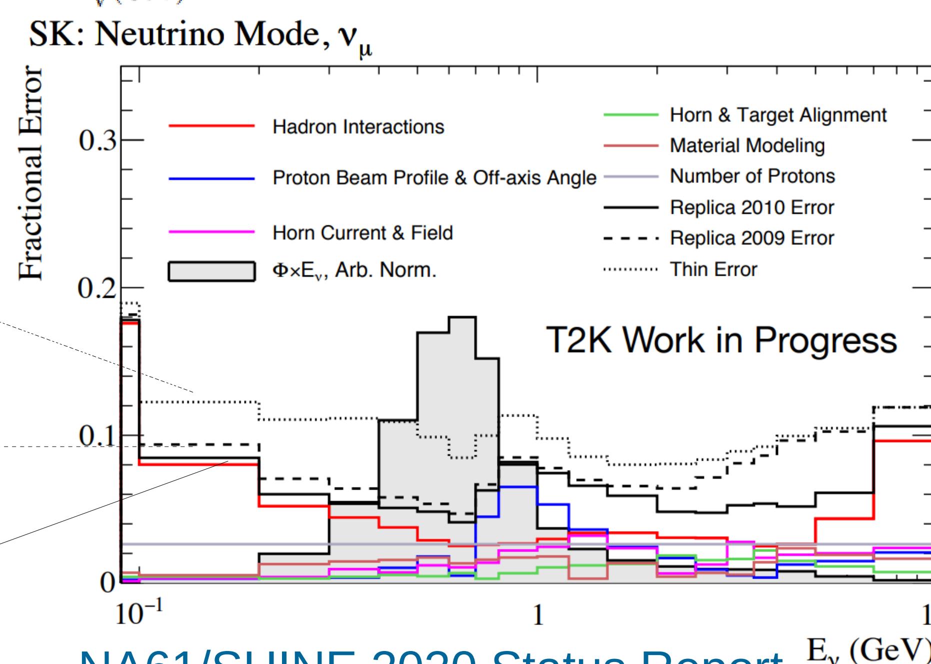
with 2009 NA61/SHINE
thin target data

J.Phys.Conf.Ser. 888 (2017) no.1, 012064

with 2009 NA61/SHINE
thin target data

with 2009 NA61/SHINE
T2K **replica target data**
- $\pi^{\pm}$ diff. yields meas.

with 2010 NA61/SHINE
T2K **replica target data**:
- $\pi^{\pm}$, $K^{\pm}$, p diff. yields meas.



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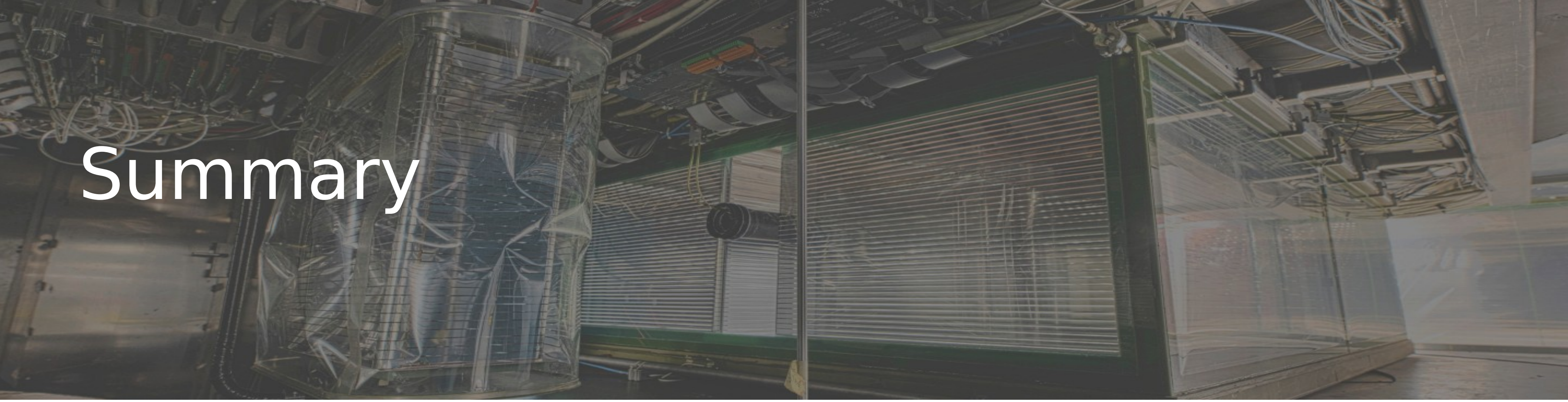

Summary

- External hadron production measurements with long targets are necessary to constrain primary and secondary interactions in the target, which give rise to neutrino-yielding hadrons and initiate the neutrino beams at long-baseline neutrino experiments

- NA61/SHINE performed thick target measurements with the T2K and the NuMI replica targets
  - Reduction in the T2K neutrino flux prediction to ~ 5% at peak beam energy is achieved using the NA61/SHINE thin and replica target data (excluding the recently obtained replica target prod. Xsec)

- Replica target production cross-section measurement is complementary to the thin target ones

- Thick target measurements are used to re-weight both
  - Interaction rate → via production cross section
  - Particle production → via particle yields on target surface

Acknowledgements

https://shine.web.cern.ch

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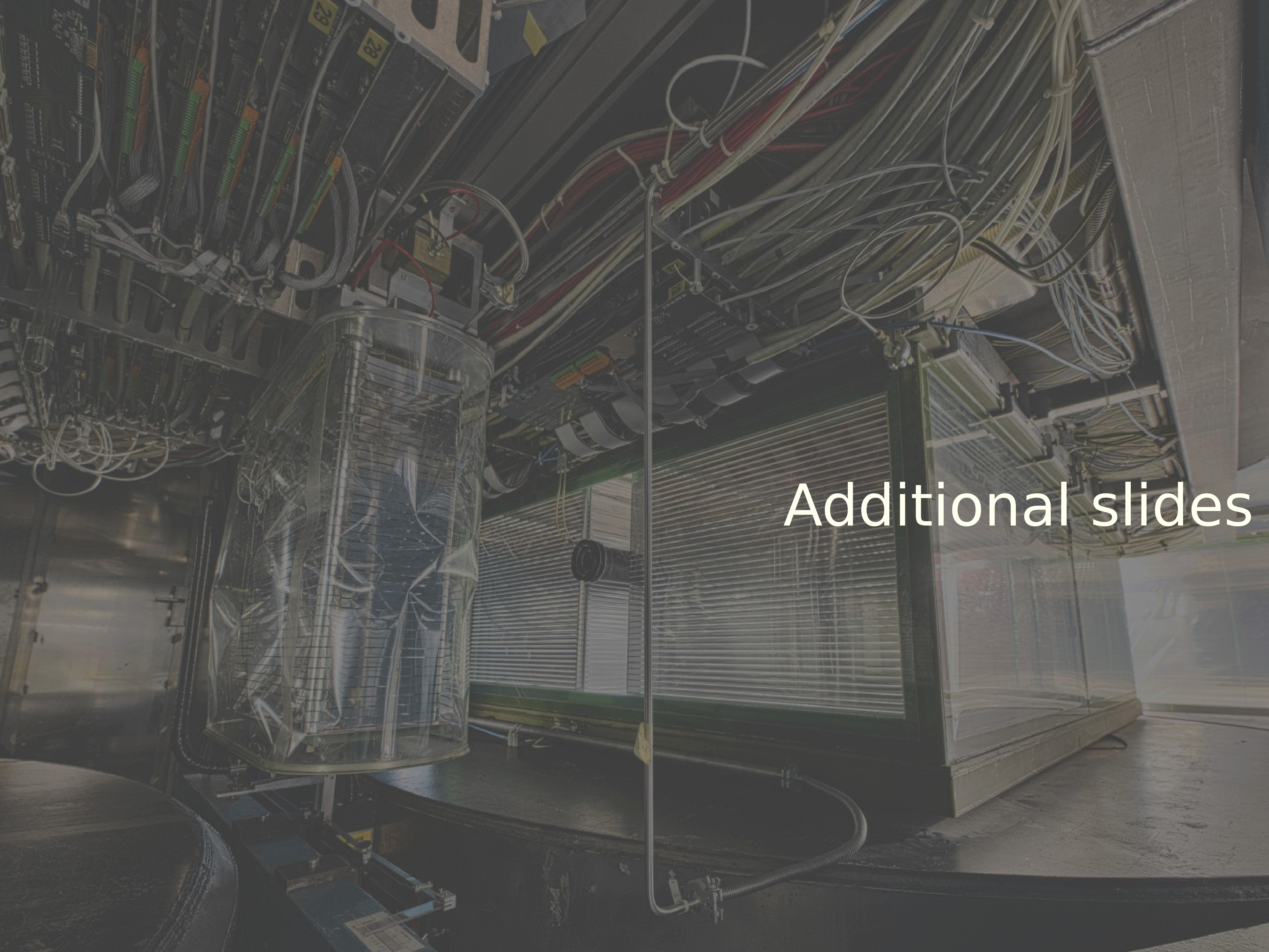
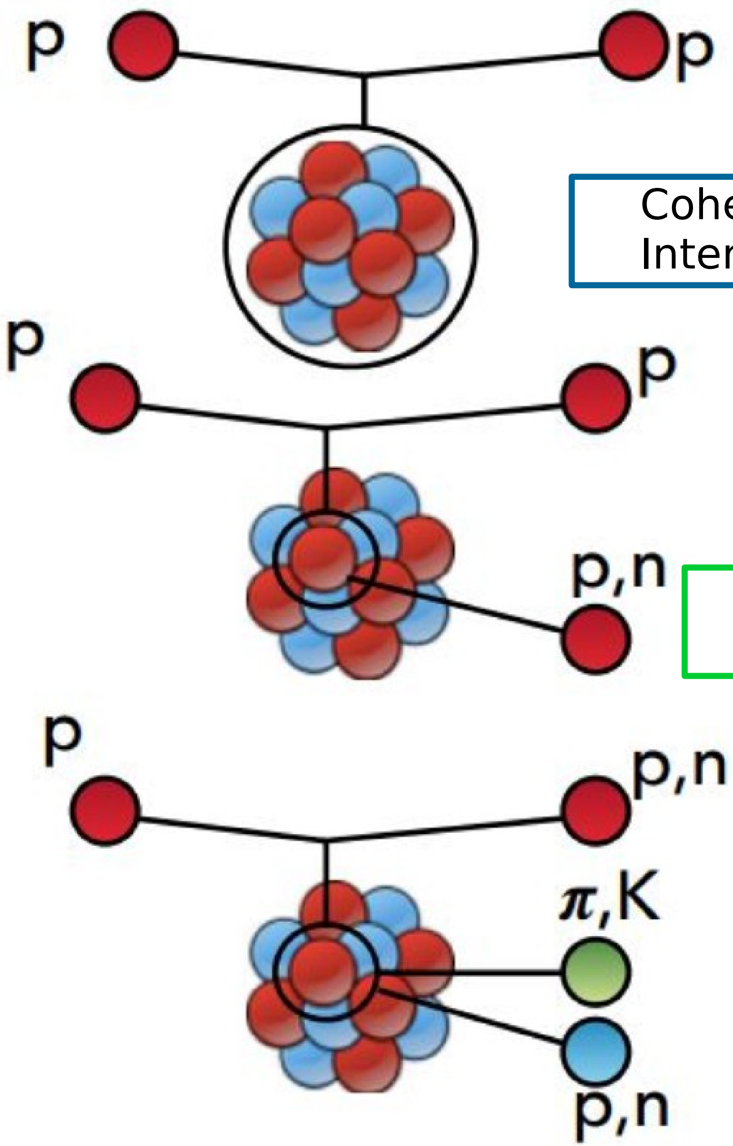
Additional slides



Employed classification of nuclear interactions



$$\sigma_{inel} = \sigma_{total} - \sigma_{el}$$

$$\sigma_{prod} = \sigma_{inel} - \sigma_{qe}$$

NA61/SHINE and T2K use this definition
NuMI definition is slightly different:

$\sigma_{prod} \rightarrow \sigma_{inel}$

$\sigma_{inel} \rightarrow \sigma_{absorption}$

Coherent elastic scattering:
Interaction on the nucleus (σ_{el})

Quasi-elastic scattering:
Interaction on nucleons (σ_{qe})

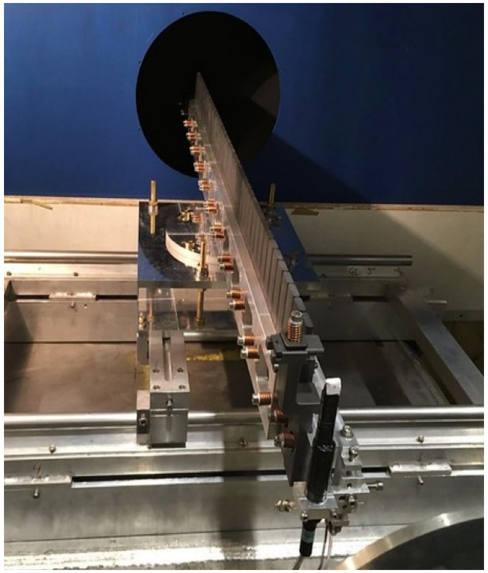
Inelastic process:
(σ_{inel})

Production process:
Interaction with new hadron production (σ_{prod})

Hadron production measurements in p interactions

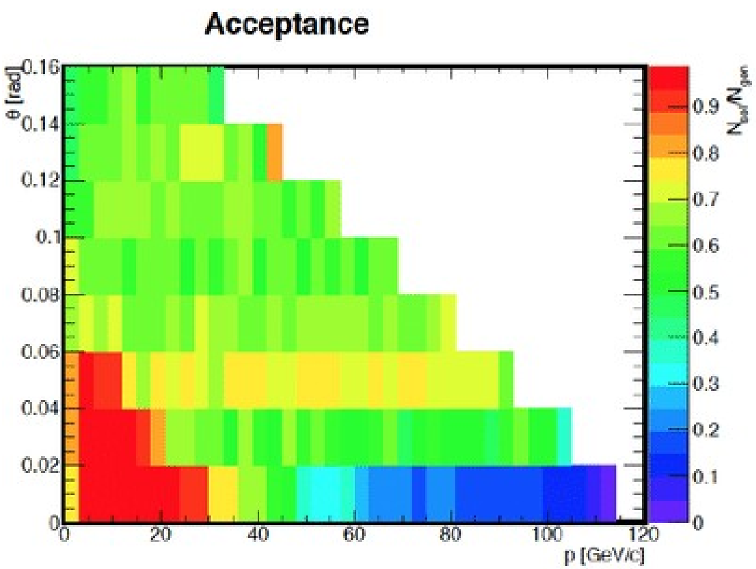
NuMI replica target measurement

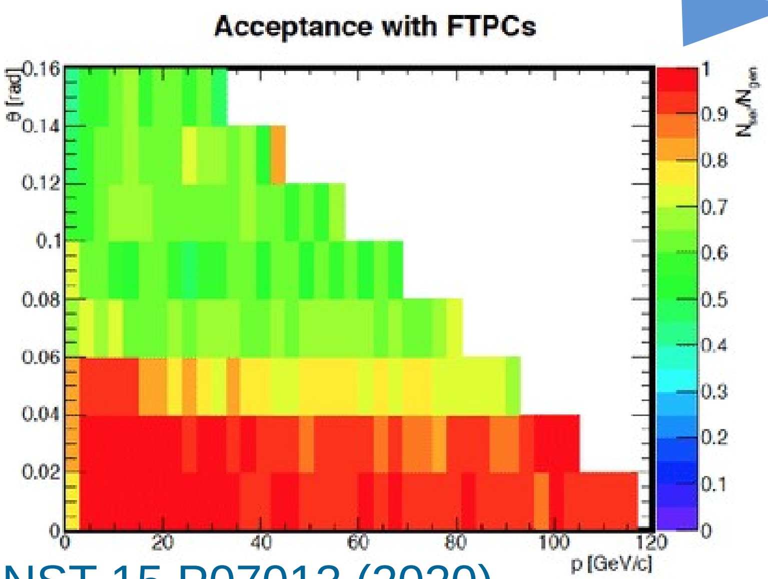
p + C @ 120 GeV/c



Main objective:
NuMI beamline
NOνA experiment

- Three Forward TPCs (FTPCs) installed in 2017
  - Improve forward acceptance
  - Allow separation of protons and pions @100GeV/c
- 5 weeks of data taking in 2018
- 15M recorded events
- Data Analysis Status: Calibration





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