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

Large-acceptance spectrometer



JINST 9 (2014) P06005
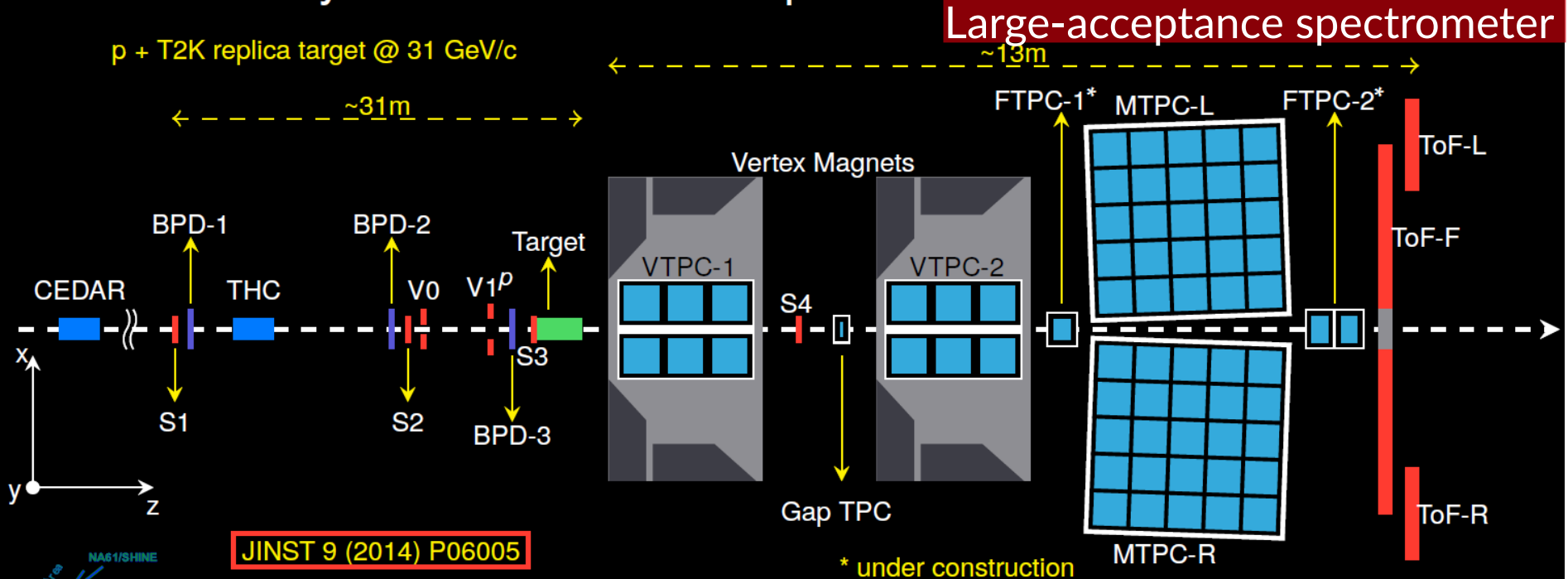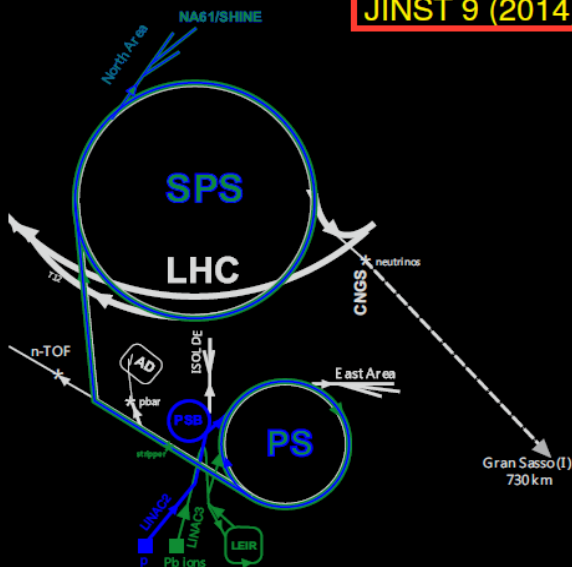
► Search for the critical point of strongly interacting matter (p+p, p+A, A+A)

► Precise hadron production measurements for neutrino flux predictions in T2K and Fermilab neutrino experiments

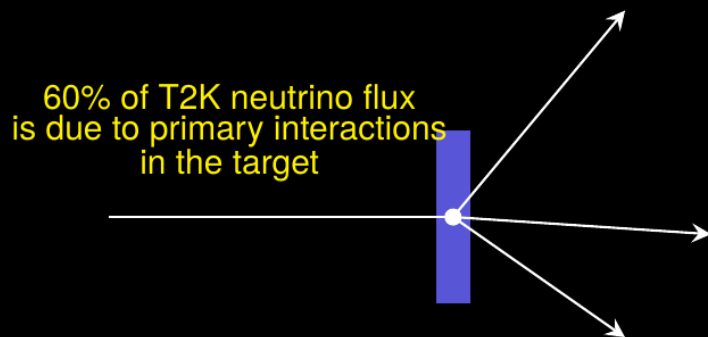► More reliable simulations of cosmic-ray air showers

Boris A. Popov

Thin carbon target

▶ $2.5 \times 2.5$ cm$^2$ , L = 2 cm = 0.04 $\lambda_{int}$

▶ Measurements of production cross section and spectra of $\pi^\pm$, K$^\pm$, K$_s^0$, p, $\Lambda$   L.Zambelli's PhD

60% of T2K neutrino flux is due to primary interactions in the target

T2K replica target

▶ L = 90 cm = 1.9 $\lambda_{int}$, r = 1.3 cm

▶ Measurement of charged pion spectra exiting the target

90% of T2K neutrino flux is due to primary interactions and re-interactions in the target
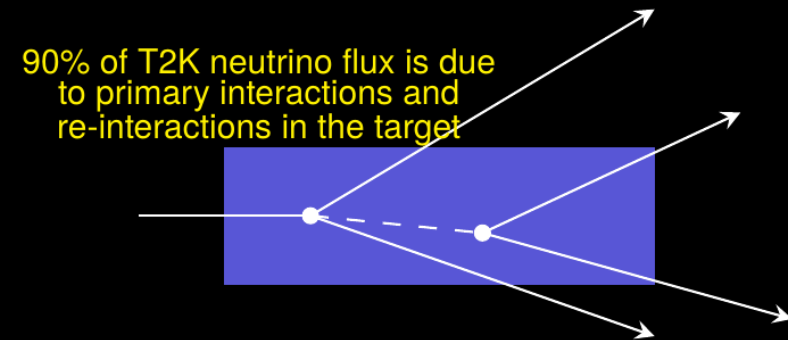


| Beam | Target | Year | Triggers [$10^6$] | Status | Comment |
| --- | --- | --- | --- | --- | --- |
| | thin | 2007 | 0.7 | published ($\pi^\pm$, $K^+$, $K_0^s$, $\Lambda$)[1,2] | has been used for T2K |
| protons | replica | 2007 | 0.2 | published ($\pi^\pm$)[3,4] | proof of principle |
| at | thin | 2009 | 5.4 | published ($\pi^\pm$, $K^\pm$, $p$, $K_0^s$, $\Lambda$)[5,6] | being used in T2K |
| 31 GeV/c | replica | 2009 | 2.8 | published ($\pi^\pm$)[7,8] | being used in T2K |
| | replica | 2010 | 10.2 | analysis finalized (M.Pavin's PhD) | prepared for use in T2K |

[1] Phys. Rev. C84, 034604 (2011).

[2] Phys. Rev. C85, 035210 (2012).

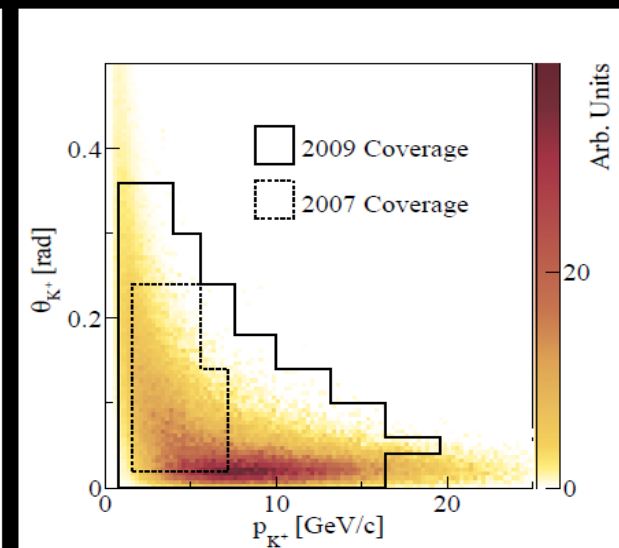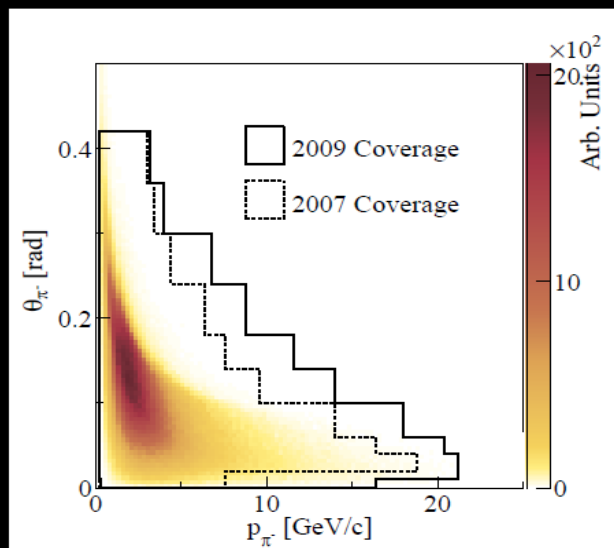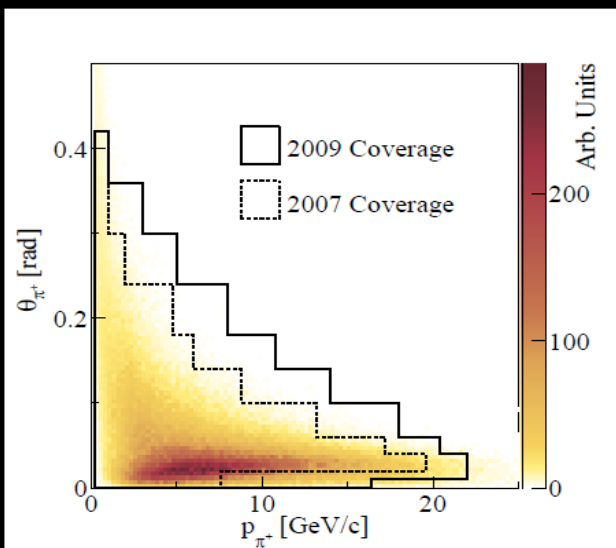[3] Nucl. Instrum. Meth. A701, 99 (2013).

[4] CERN-THESIS-2011-165

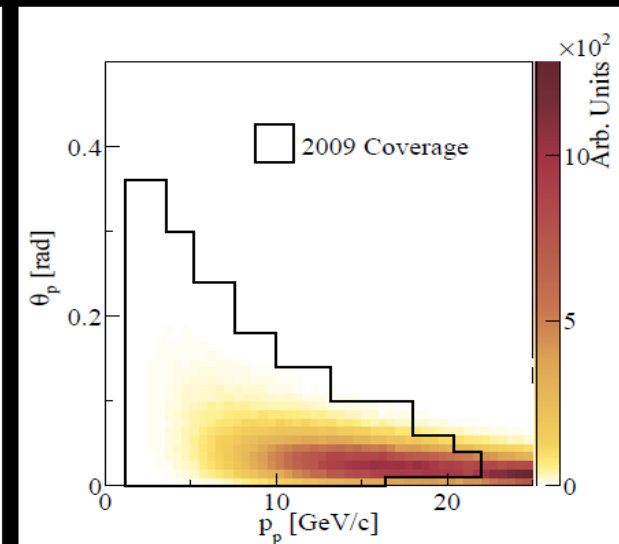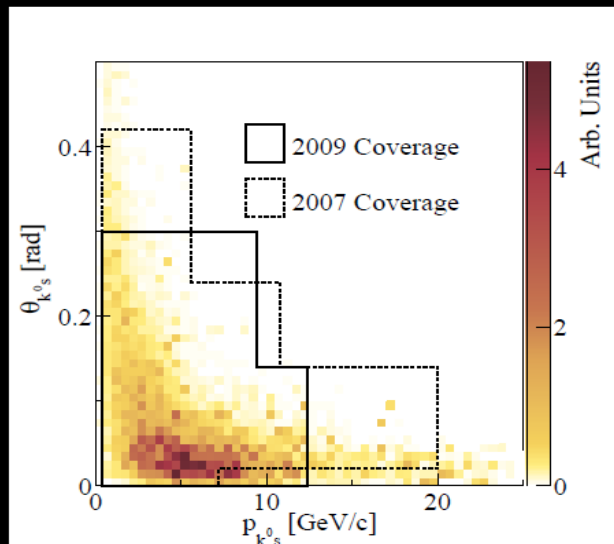[5] CERN-THESIS-2013-290

[6] Eur. Phys. J. C76, no.2, 84 (2016)

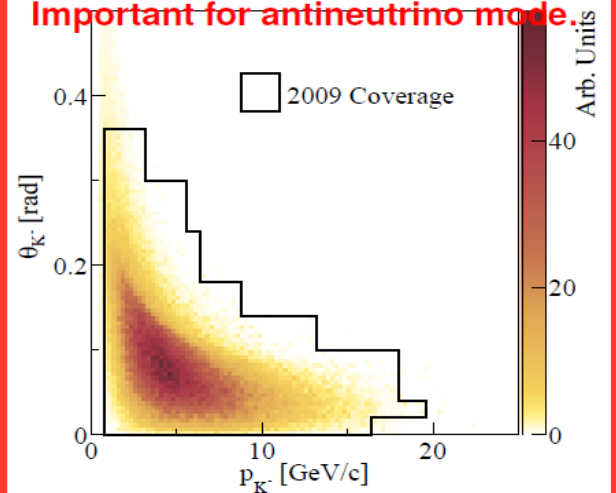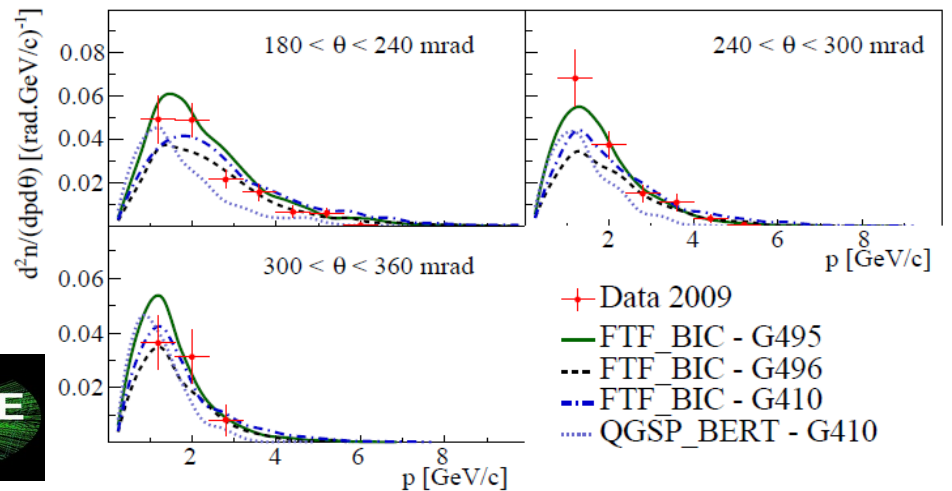[7] CERN-THESIS-2015-103

[8] Eur. Phys. J. C76, no.11, 617 (2016)

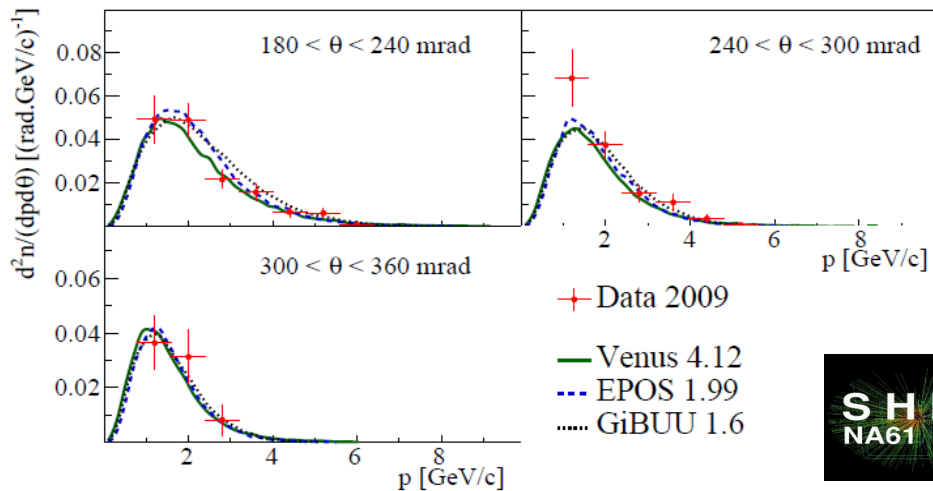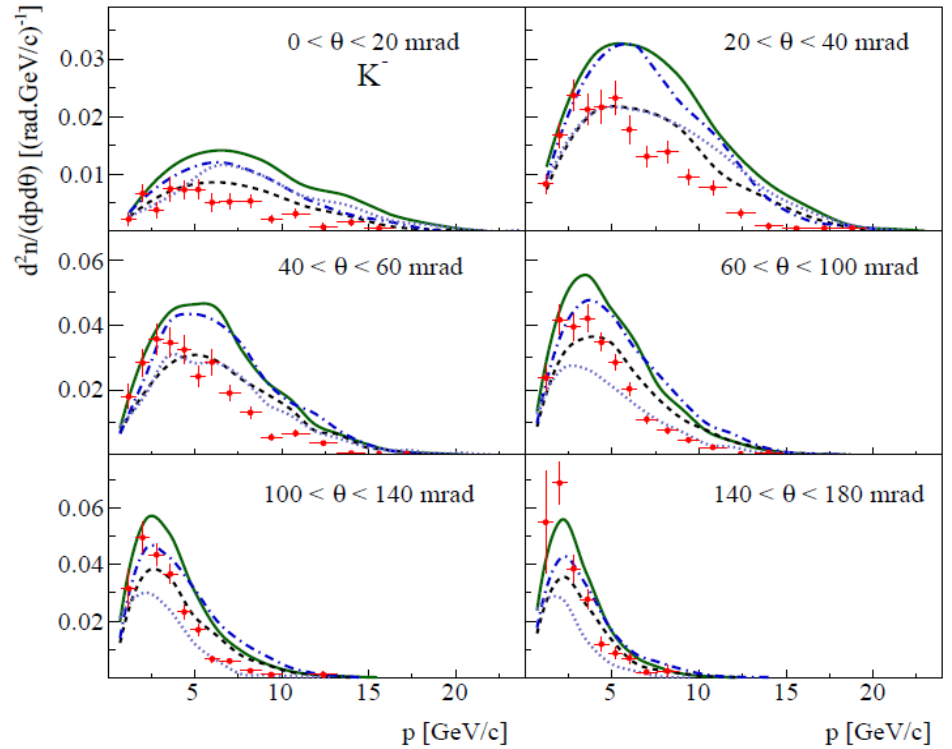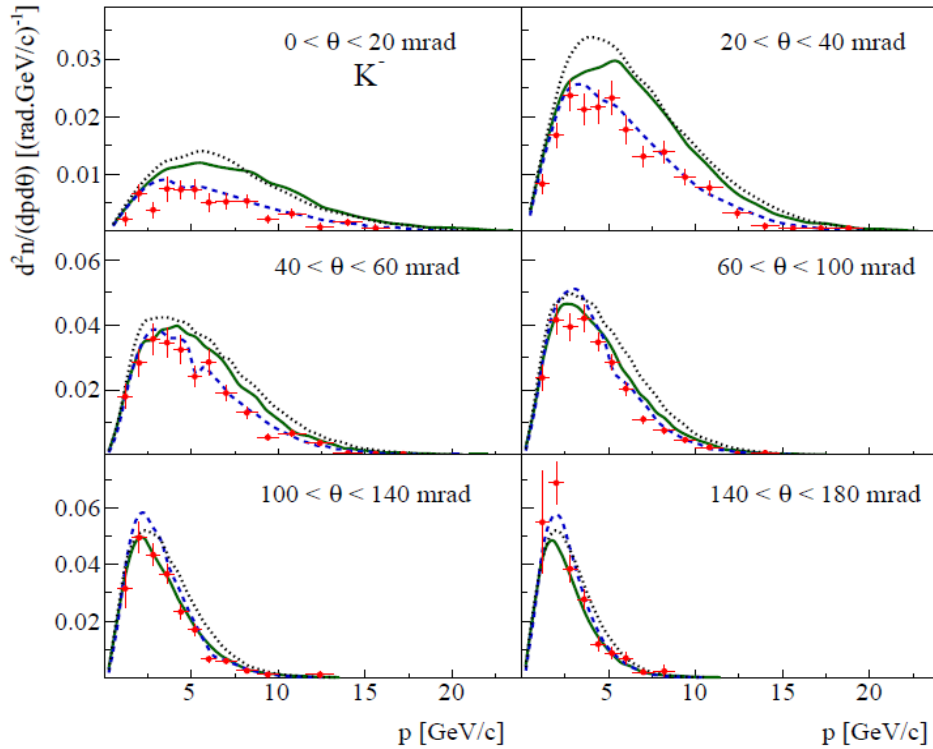(g) $\pi^+$

(h) $\pi^-$

(i) $K^+$

First measurements of $K^-$ spectra.
Important for antineutrino mode.

(j) $K^-$

(k) $K_S^0$

(l) proton

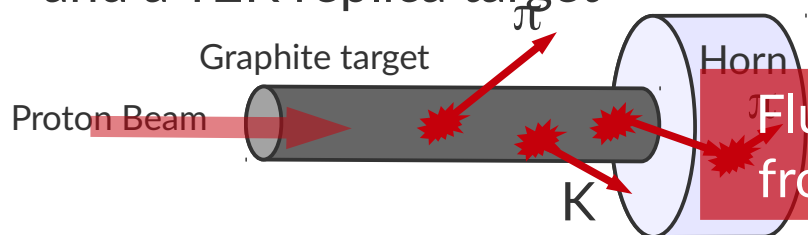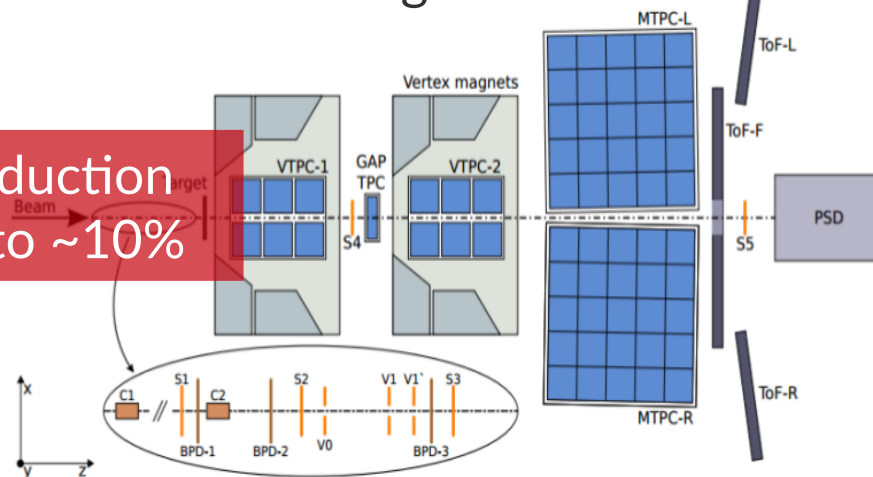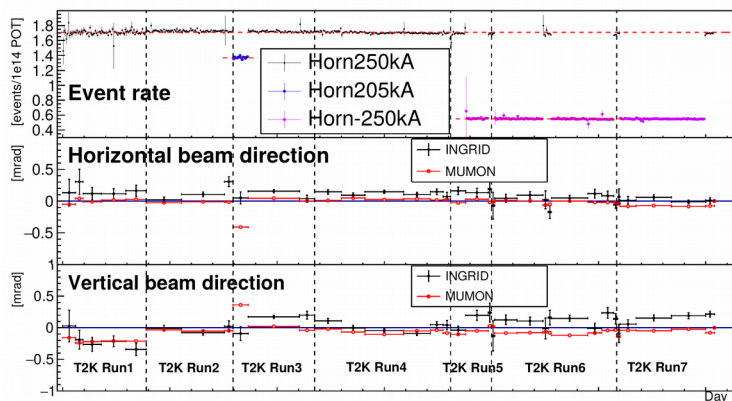# Comparison of K- spectra with models

# The neutrino beam: flux predictions

- Fluxes are predicted from a data-driven simulation → NA61/SHINE experiment measures hadron production cross-sections using a thin carbon and a T2K replica target

Proton Beam
Graphite target
π
Horn
K

**Flux error reduction from ~25% to ~10%**

MTPC-L
ToF-L
Vertex magnets
ToF-F
VTPC-1
GAP TPC
VTPC-2
Beam
Target
S4
S5
PSD
MTPC-R
ToF-R

x
y
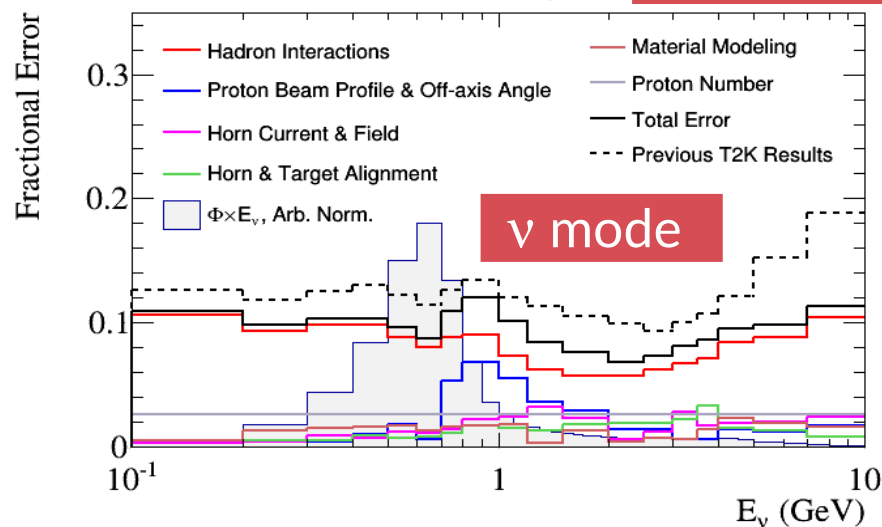z
C1
S1
C2
S2
V1 V1' S3
V0
BPD-1
BPD-2
BPD-3

- Beam alignment monitoring provides input to estimations of beam systematics

- INGRID detector provides high-statistics monitoring of the beam intensity, direction, profile and stability



Event rate
[events/1e14 POT]
Horn250kA
Horn205kA
Horn-250kA
Horizontal beam direction
[mrad]
INGRID
MUMON
Vertical beam direction
[mrad]
INGRID
MUMON
T2K Run1  T2K Run2  T2K Run3  T2K Run4  T2K Run5  T2K Run6  T2K Run7
Day

**Flux errors**

SK: Positive Focussing Mode, $\nu_\mu$



Fractional Error

0.3

— Hadron Interactions
— Proton Beam Profile & Off-axis Angle
— Horn Current & Field
— Horn & Target Alignment
▨ $\Phi \times E_\nu$, Arb. Norm.
— Material Modeling
— Proton Number
— Total Error
--- Previous T2K Results

0.2

**$\nu$ mode**

0.1

0

$10^{-1}$         1         10

$E_\nu$ (GeV)

**Flux errors are further constrained with the ND280 analysis of $\nu_\mu$ and $\bar{\nu}_\mu$ CC events**

# p+RT @ 31 GeV/c analysis

- $tof - dE/dx$ and $h^-$ analysis

- Vertex position is not required → TPC tracks are extrapolated towards the target surface

- Phase space: momentum $p$, polar angle $\theta$ and position along the target surface $z$

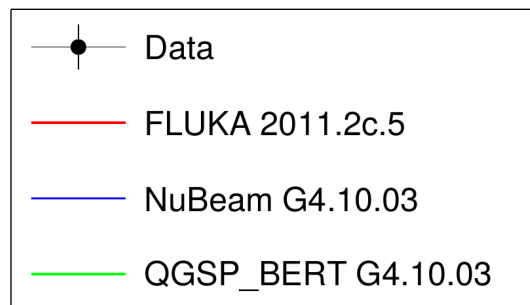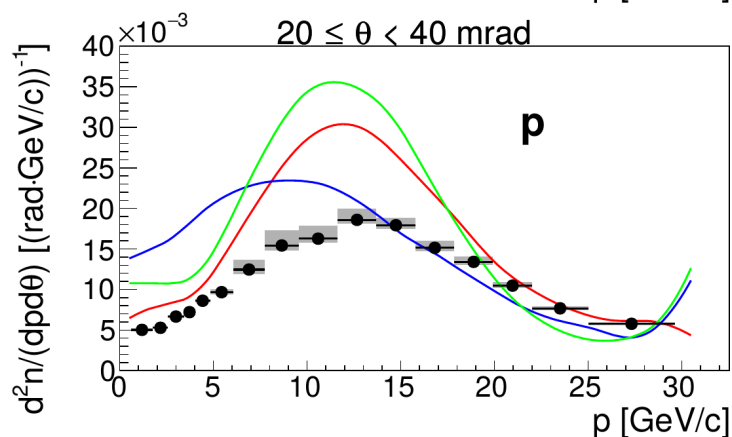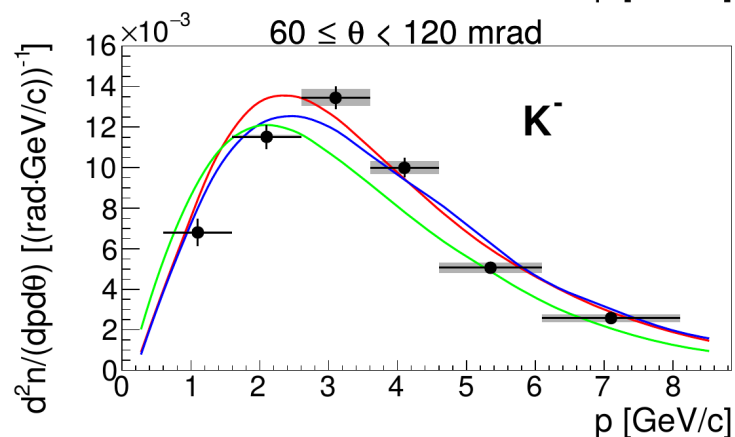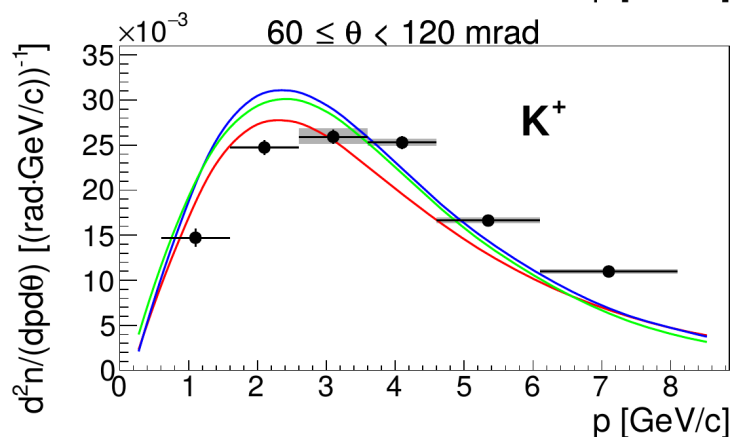- Shape of the spectra depends on the track position → 5 longitudinal bins + downstream target face
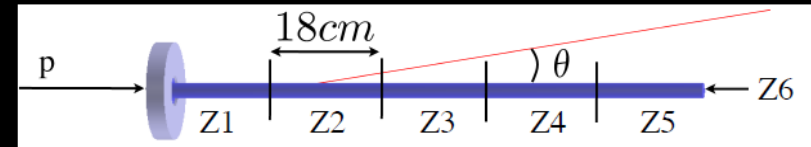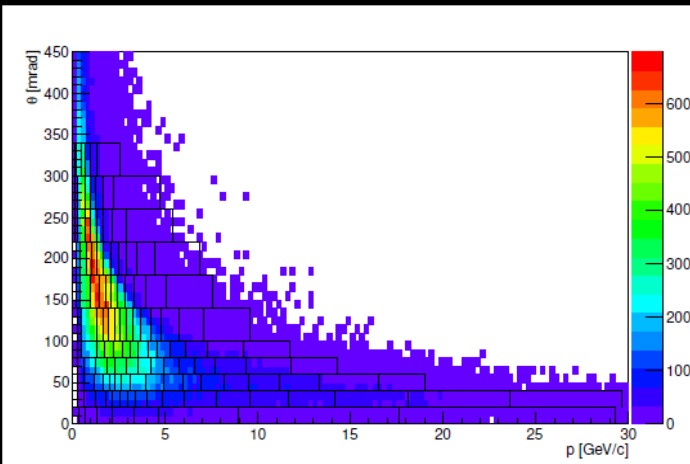


- z bin contribution to the $\nu_\mu$ flux at SK
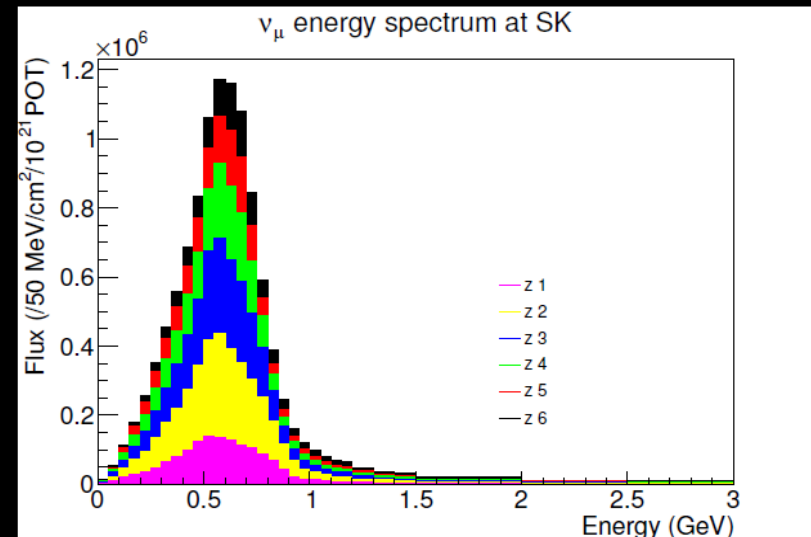


Systematic uncertainties

- Backward track extrapolation (up to 10% for small $\theta$)

- Other contributions: less than 5%

# NA61/SHINE: T2K replica-target results
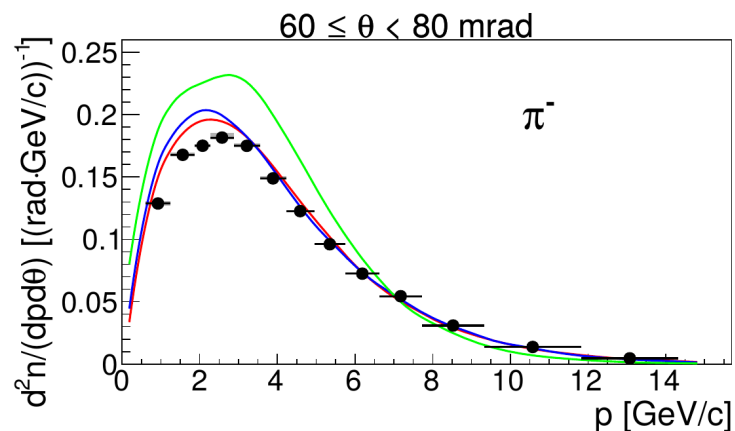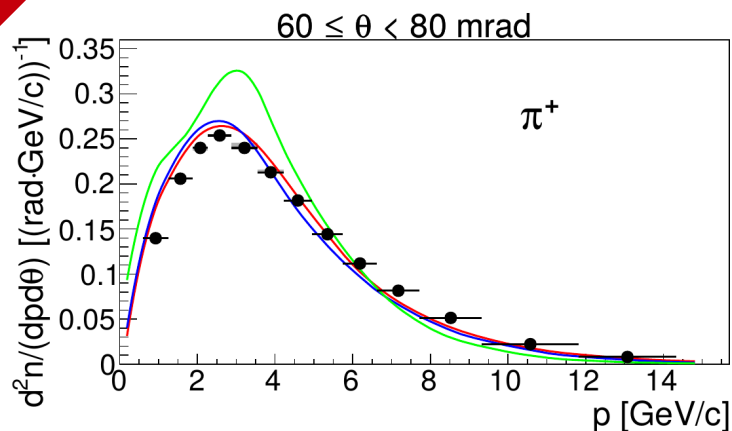


Measured hadron yields from second longitudinal (18-cm long) target bin in a selected polar angle interval.

Comparison with model predictions.

These new data are being prepared for publication.

They will be used for further reduction of uncertainties on (anti-)neutrino flux in T2K, see later.

M.Pavin's PhD

# NA61/SHINE beyond 2020



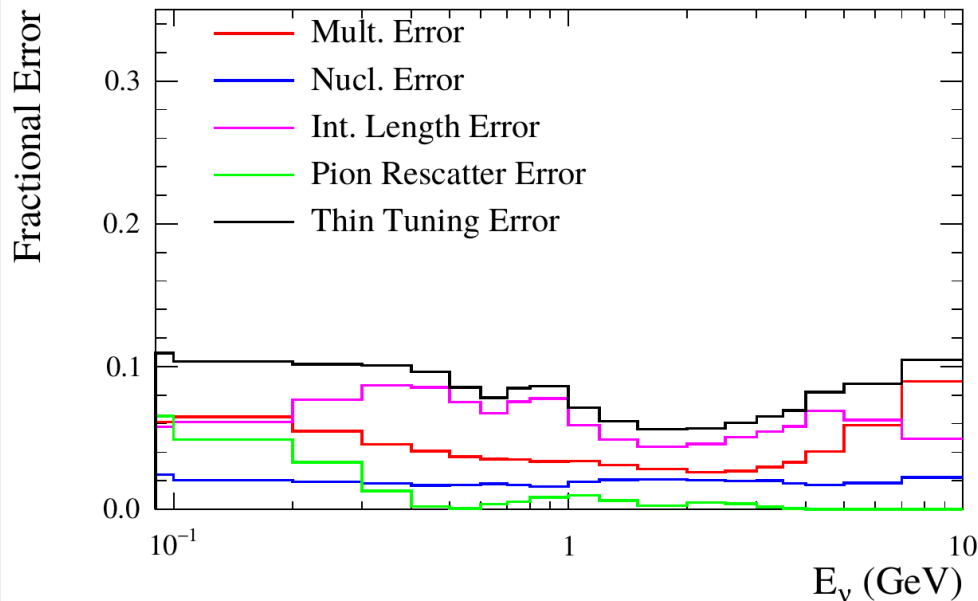The usage of replica-target NA61/SHINE would allow for further improvement in T2K (anti-)neutrino flux uncertainty (down to ~5%). Even better knowledge is desired for T2K-II and Hyper-K. New measurements are planned for DUNE and Hyper-K after the CERN LS2 (see, CERN-SPSC-2018-008):

- improved measurements with T2K replica target, considering alternative target material – Super-Sialon ($Si_3N_4Al_2O_3$);

- with additional tracking detectors surrounding the long target;
- hadron production with low momentum beam (<12 GeV/c).

NA61++

# NA61/SHINE beyond 2020

Documents submitted to the SPSC:

https://cds.cern.ch/record/2309890

https://cds.cern.ch/record/2621751

Positive feedback received recently from the SPSC:

*' The SPSC recognises the broad interest of the NA61 physics programme after Long Shutdown LS2 as outlined in the addenda CERN-SPSC-P-330-ADD-10/11.*
*The Committee recommends approval of beam times in 2021 for detector commissioning with hadron beams, for the measurement of hadron production with the T2K target with proton beams, and for the measurement of open charm production with Lead ion beams.'*

Additional manpower would be required to execute all these measurements.

**Truly European contribution to the future world-wide neutrino programme.**

NA61++

**Summary and conclusions**

LPNHE group made significant contributions to **NA61/SHINE**
The analysis of data samples collected for T2K
(with a thin carbon target and a replica of the T2K target)
allowed to reach <10% uncertainty on (anti-)neutrino fluxes

Many important hadron production results already published!
The recently finalised analysis of the ultimate 2010 Replica
Target data (Matej Pavin's PhD) could allow to further reduce
the T2K flux uncertaities down to ~5%. Paper in preparation.

Given the success of the 'NA61/SHINE for T2K' program,
similar measurements are now being performed for **Fermilab
neutrino beams**.

Program of **future measurements beyond 2020** is formulated.
*Should be included into ESPP update!*

# 11 Backup