The NA61/SHINE experiment

Review of hadron production measurements

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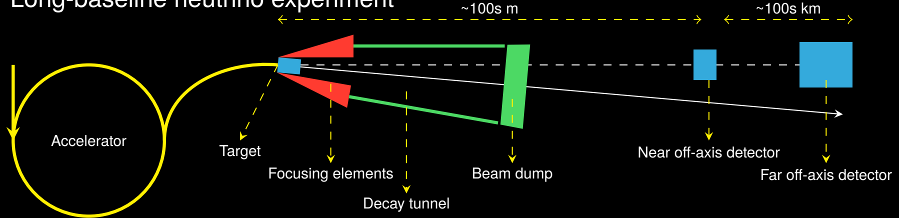
Outline

1. Hadron production measurements $\longrightarrow$ requirements
2. The NA61/SHINE experiment
   - Beam
   - PID
   - Phase space coverage
3. Hadron production measurements for the T2K experiment
4. Future of NA61/SHINE hadron production measurements

Motivation

Long-baseline neutrino experiment



- Interactions and re-interactions in the target and the beam elements $\rightarrow$ hadrons ($\pi^{\pm}$, $K^{\pm}$, K_s^0, K_L^0, Λ, ...) $\rightarrow$ neutrinos
- Neutrino flux is simulated with the MC models $\rightarrow$ huge uncertainties of the hadron production models $\rightarrow$ huge uncertainties of the neutrino oscillation parameters

Hadron production measurements are needed for reducing flux uncertainties!!!

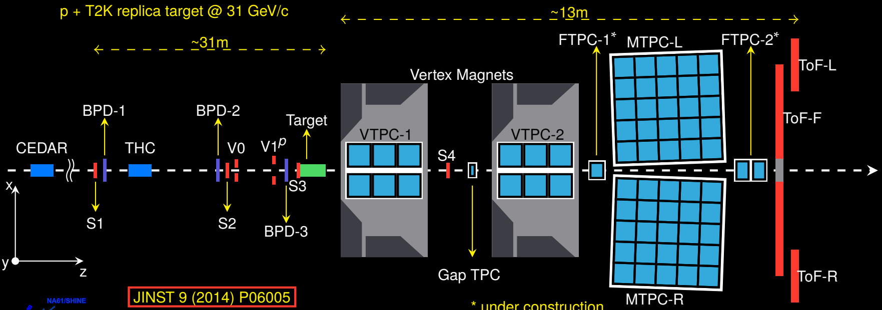
Requirements for the hadron production experiment

1. Same beam composition and same (or similar) beam momentum
2. Precise momentum reconstruction and good PID capabilities (extract differential yields of $\pi^{\pm}$, $K^{\pm}$, p and possibly Λ, K_s^0)
3. Large phase space coverage (in order to maximize coverage of neutrino parents)

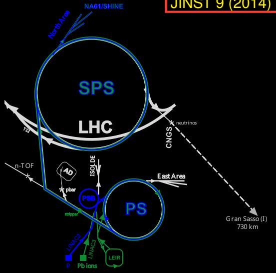
- Why is the NA61/SHINE experiment the best candidate on the market for hadron production measurements?

NA61/SHINE Experiment

- SPS Heavy Ion and Neutrino Experiment



JINST 9 (2014) P06005

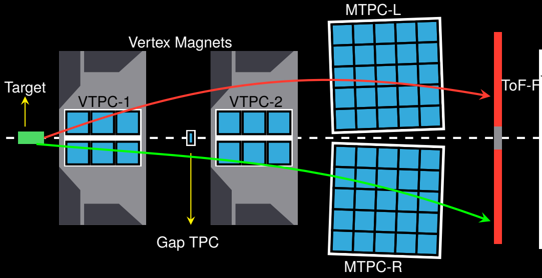


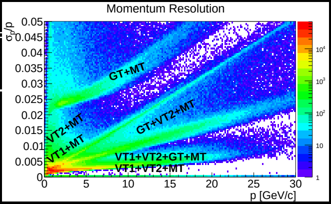
- Search for the critical point of strongly interacting matter (p+p, p+A, A+A)
- Precise hadron production measurements for the neutrino flux re-weighting in the T2K and Fermilab neutrino experiments
- More reliable simulations of the cosmic-ray air showers

Beam

- NA61/SHINE profits from the SPS H2 beam-line (hadron and ion beam)
- Hadron beam
  - 400 GeV protons hit primary target
  - Mix of the $e^{\pm}$, secondary hadrons and tertiary hadrons (re-interaction with collimators) - momentum spread $<$ 1%
  - Identification is done by CEDAR: Cherenkov Differential Counter with Achromatic Ring Focus
  - Another detector (treshold Cherenkov) used in anti-coincidence
  - 95% efficiency, misidentification <0.8%
  - $\pi^{\pm}$, $K^{\pm}$, p beam

TPC tracking system and momentum resolution

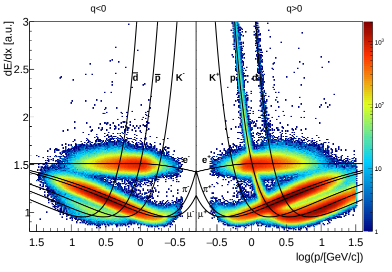




*Momentum resolution for T2K measurements

- VTPCs: 2×2.5 m^2
- MTPCs: 3.9×3.9 m^2 - inherited from the NA49 experiment
- GTPC - light and small forward TPC
- Gases: Ar : CO_2 = 95% : 5% in MTPCs and 90% : 10% in VTPCs
- 2 different topologies: RST ($p_x \cdot q > 0$) and WST ($p_x \cdot q < 0$)
- 2 superconducting magnets: maximum bending power is 9 Tm

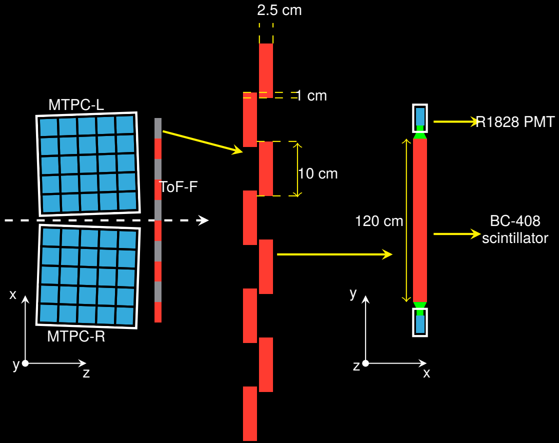
PID (dE/dx)



Nucl.Instrum.Meth. A430 (1999) 210-244

- $\sigma_{dE/dx} = 4\%$

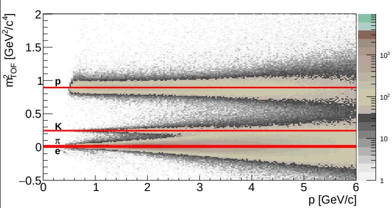
TOF-F detector

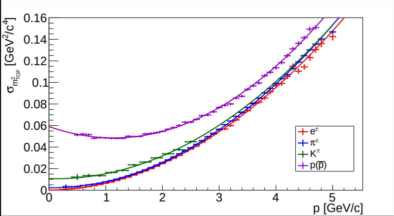


- 10 modules = 80 scintillators (120 × 10 × 2.5 cm) = 160 PMTs
- Intrinsic resolution ~110 ps
- Acquisition window 100 ns - beam intensity is low enough for TOF to discard off-time tracks

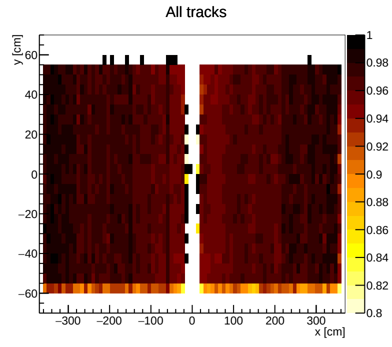
PID (TOF)

- $m^2_{TOF}c^4 = p^2c^2\left(\frac{c^2 tof^2}{l^2} - 1\right)$
- $l \approx 14.5$ m



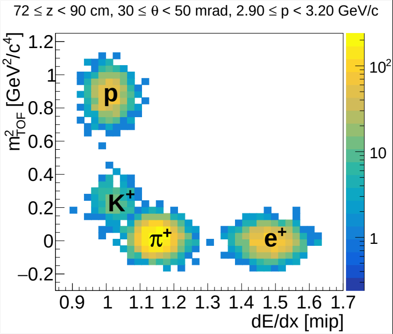


- TOF efficiency - depends on track density
- Discarded hit → if 2 or more tracks hit same slab
- for p + C interactions at 31 GeV/c efficiency is 97-98%



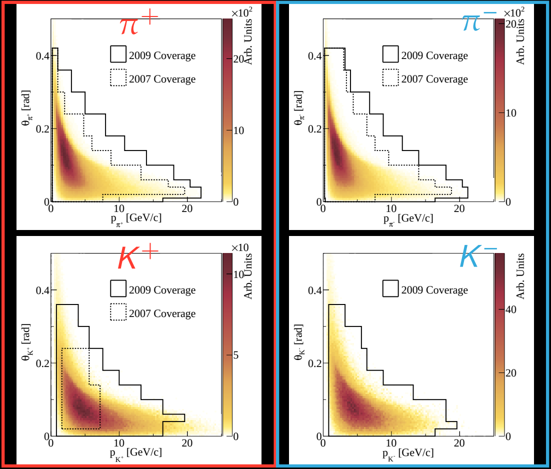
Combined $m^2_{TOF} - dE/dx$ PID

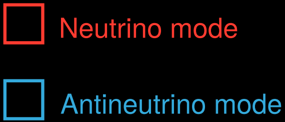
- Maximum coverage of the phase space
  - *dE/dx* and *tof* measurements are complementary
- K^+ PID is most difficult one



Phase space coverage

- Limited mostly by TOF wall size
- T2K phase space coverage

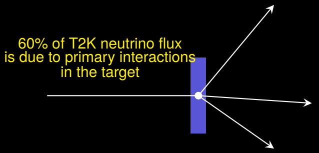




Hadron Production Measurements for the T2K Experiment

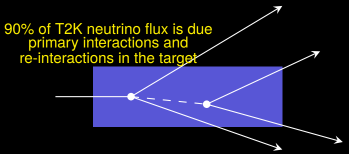
Thin carbon target

- 2.5×2.5 cm^2 , L = 2 cm = 0.04 λ_{int}
- Measurement of the production cross section and the spectra of $\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ



T2K replica target

- L = 90 cm = 1.9 λ_{int}, r = 1.3 cm
- Measurement of the charged pion spectra exiting the target



Beam	Target	Year	Triggers [10^6]	Status	Comment
	thin	2007	0.7	published ($\pi^{\pm}, K^{+}, K^s_0, \Lambda$)[1,2]	has been used for T2K
protons	replica	2007	0.2	published ($\pi^{\pm}$)[3]	proof of principle
at	thin	2009	5.4	recently published ($\pi^{\pm}, K^{\pm}, p, K^s_0, \Lambda$)[4]	being used in T2K
31 GeV/c	replica	2009	2.8	submitted to EPJ C ($\pi^{\pm}$)[5]	-
	replica	2010	10.2	analysis in progress	-

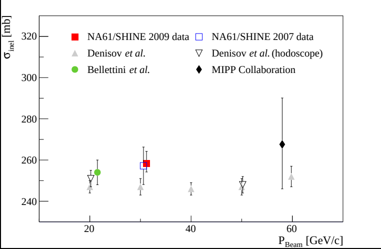
[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Nucl. Instrum. Meth. A701, 99 (2013).
[4] Eur. Phys. J. C (2016) 76: 84
[5] arXiv:1603.06774 [hep-ex]

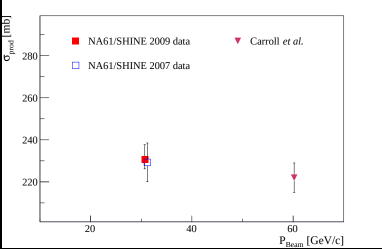
Inelastic and Production Cross Section (p + C @ 31 GeV/c)

- Trigger inefficiencies → corrected with MC
- Production cross section $\sigma_{prod} = \sigma_{inel} - \sigma_{qel}$ → production of a new particle
- σ_{qel} - quasi-elastic cross section

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

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

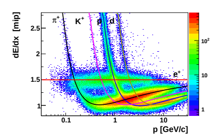


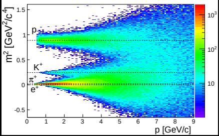


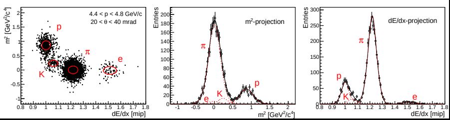
Analysis of the p + C Interactions at 31 GeV/c (2009)

Charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p)

- Complementary analyses in different momentum ranges
  - dE/dx
  - dE/dx-tof
  - h^{-} (no PID, just for π^{-})

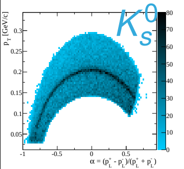


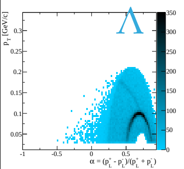


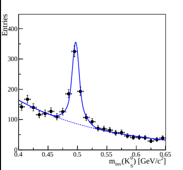


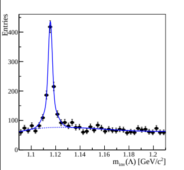
Neutral hadrons (K_s^0, Λ)

- V0 analysis - 2 body decays of the neutral hadrons
- Sample of K_s^0 or Λ is selected by cuts
- Invariant mass fits







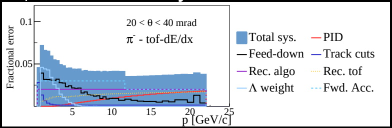


Analysis of the p + C Interactions at 31 GeV/c (2009)

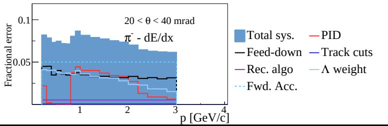
Systematic uncertainties

- PID ($dE/dx - tof$, dE/dx, 2% for $\pi^{\pm}$ and up to 20% for $K^{\pm}$)
- Feed-down and Λ weighting (data based feed-down correction for π^{-}), 30% of correction factor
- Track cuts (1%)
- Reconstruction efficiency (2%)
- Forward acceptance (4%)
- Analysis specific errors (TOF efficiency, hadron loss, K^{-} and $\overline{p}$ contamination, etc.), 1-5%

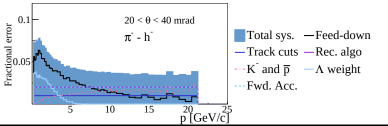
$dE/dx - tof$ analysis



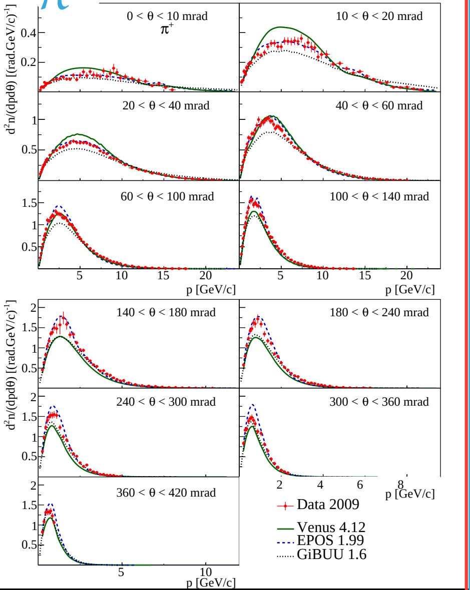
dE/dx analysis

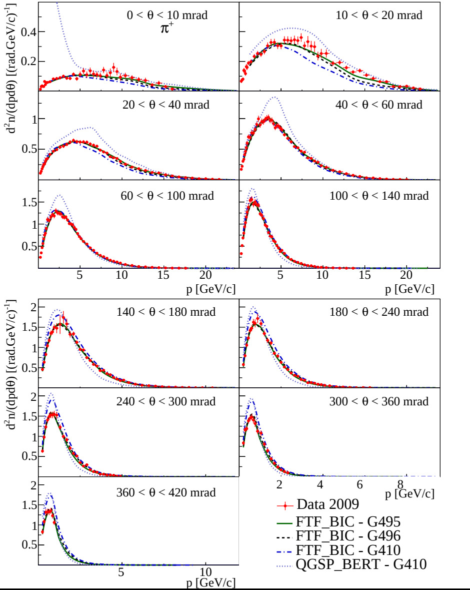


h^{-} analysis



π^+


0 < θ < 10 mrad
π+
10 < θ < 20 mrad
20 < θ < 40 mrad
40 < θ < 60 mrad
60 < θ < 100 mrad
100 < θ < 140 mrad
140 < θ < 180 mrad
180 < θ < 240 mrad
240 < θ < 300 mrad
300 < θ < 360 mrad
360 < θ < 420 mrad
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
Data 2009
Venus 4.12
EPOS 1.99
GiBUU 1.6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π+
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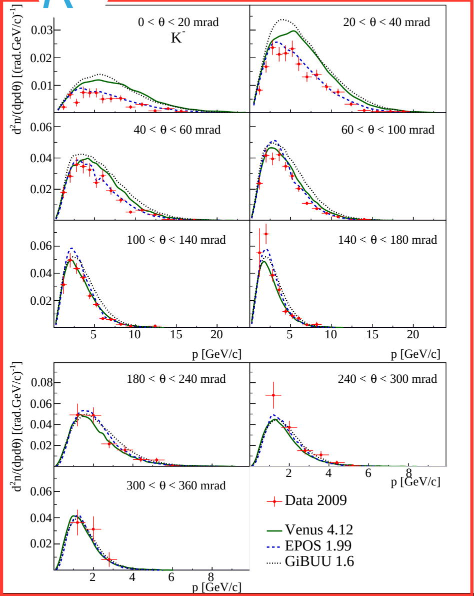
180 < θ < 240 mrad
240 < θ < 300 mrad
300 < θ < 360 mrad
360 < θ < 420 mrad
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
Data 2009
FTF_BIC - G495
FTF_BIC - G496
FTF_BIC - G410
QGSP_BERT - G410

K^-


0 < θ < 20 mrad
K⁻
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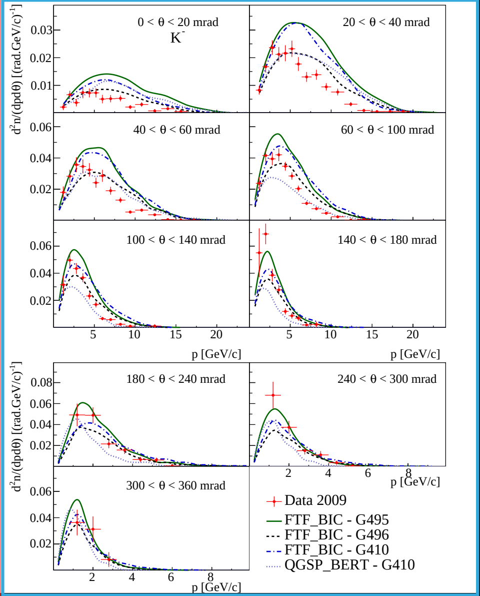
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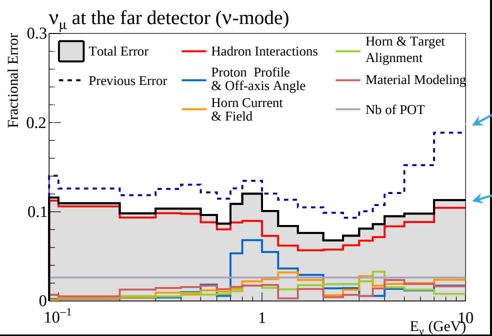
300 < θ < 360 mrad
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
Data 2009
FTF_BIC - G495
FTF_BIC - G496
FTF_BIC - G410
QGSP_BERT - G410

T2K Flux Uncertainty

- Flux uncertainty > 20%
- Flux uncertainty after re-weighting with the p + C at 31 GeV/c results is around 10%
- T2K goal is to reach uncertainty below 5% → replica target results are needed



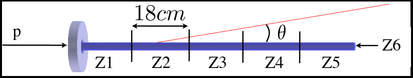
With NA61/SHINE measurements from 2007

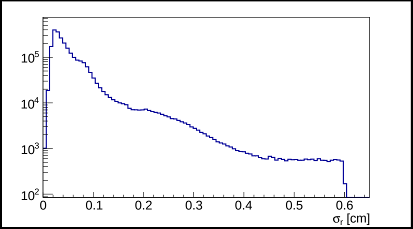
With NA61/SHINE measurements from 2009

1. Phys. Rev. D 87, 012001 (2013)
2. Flux Tuning and Uncertainty Updates for the 13a Flux (http://www.t2k.org/docs/technotes/217)

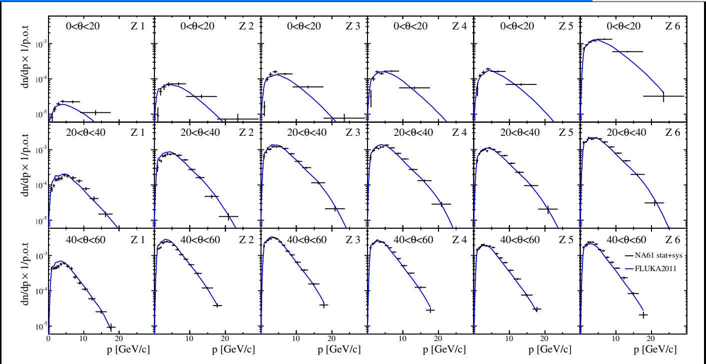
Analysis of the p + T2K Replica Target Data (2009)

- Input: beam → output: particle yield at target surface
- Shape of the neutrino spectra depends on the track position (z) on the target surface → additional binning in z
- Track extrapolation towards target surface
- Systematics: up to 15% (track extrapolation)
- Limited statistics → only $\pi^{\pm}$ spectra obtained





π^+



0<θ<20 Z 1
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0<θ<20 Z 3
0<θ<20 Z 4
0<θ<20 Z 5
0<θ<20 Z 6
20<θ<40 Z 1
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20<θ<40 Z 6
40<θ<60 Z 1
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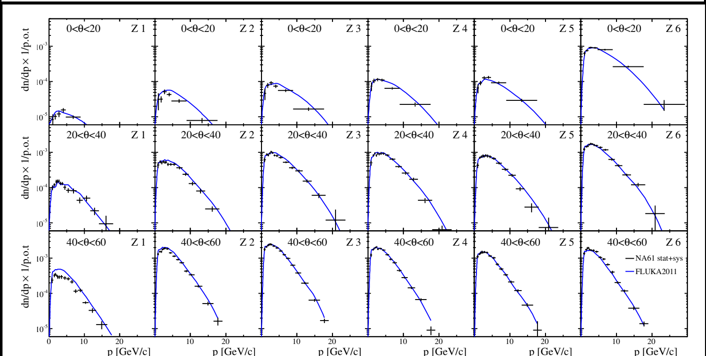
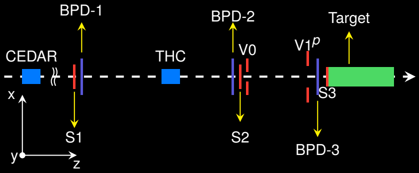
40<θ<60 Z 3
40<θ<60 Z 4
40<θ<60 Z 5
40<θ<60 Z 6
dn/dp× 1/p.o.t
p [GeV/c]
NA61 stat+sys
FLUKA2011

π^-



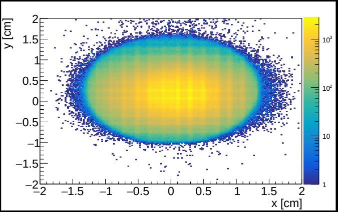
0<θ<20 Z 1
0<θ<20 Z 2
0<θ<20 Z 3
0<θ<20 Z 4
0<θ<20 Z 5
0<θ<20 Z 6
20<θ<40 Z 1
20<θ<40 Z 2
20<θ<40 Z 3
20<θ<40 Z 4
20<θ<40 Z 5
20<θ<40 Z 6
40<θ<60 Z 1
40<θ<60 Z 2
40<θ<60 Z 3
40<θ<60 Z 4
40<θ<60 Z 5
40<θ<60 Z 6
dn/dp× 1/p.o.t
p [GeV/c]
NA61 stat+sys
FLUKA2011

p + T2K RT Dataset (2010)

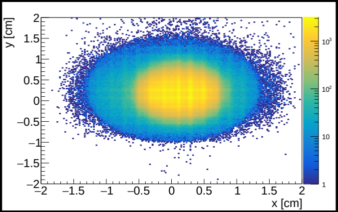


- High statistics dataset (extraction of $\pi^{\pm}$, $K^{\pm}$ and p yields is possible
- T2 trigger - standard trigger
- T3 trigger - more narrow beam profile

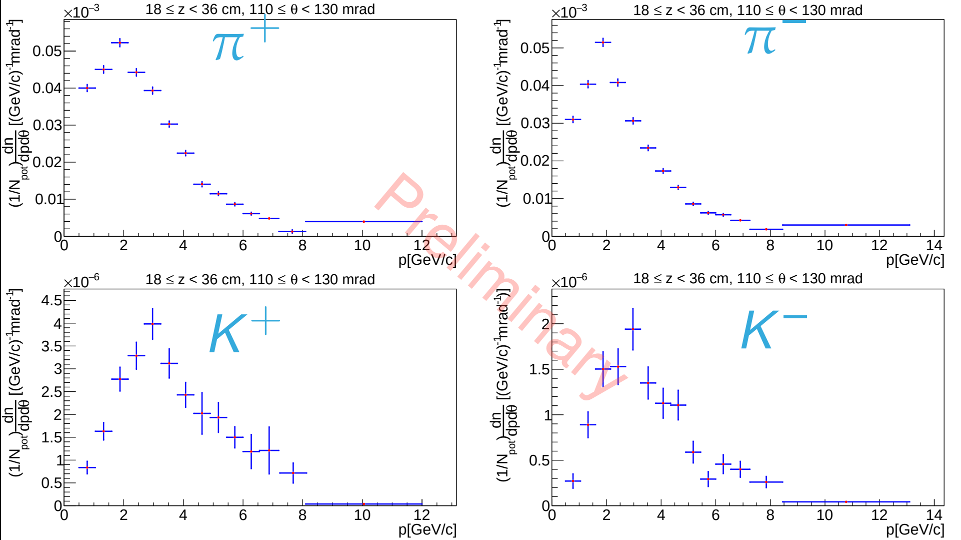
- T2 beam profile



- T3 beam profile



Uncorrected spectra of the charged hadrons



Thin vs. replica target measurements

- Replica target measurements
  - Primary interactions + re-interactions
  - Depends on beam profile
  - Does not require normalization
  - Extrapolation uncertainty

- Thin target measurements
  - Only primary interactions
  - Does not depend on the beam profile
  - Requires normalization (σ_{prod})
  - No extrapolation uncertainty

- It is possible to measure re-interactions in the long (replica) target with thin target measurements (eg. by using $\pi^{\pm}$ beam)

Future NA61/SHINE Neutrino Program

- Measurements for the Fermilab neutrino beams

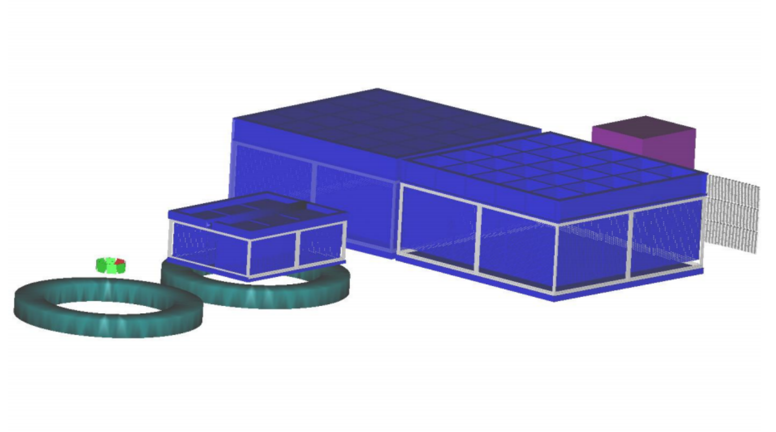
Beam Prim.	Beam Sec.	Target	Momentum (AGeV/c) prim. (sec.) beam	Year	Days	Physics
p	h^+	A	400(40-400)	2016	4x7 days	tests
p	p	p	400 (400)	2016	28 days	SI
p	**h^+**	**A**	400 (30–120)	2016	42 days	ν
Pb		Pb	13, 19, 30, 40	2016	40 days	SI
Pb		Pb	150	2016	5 days	tests
p	p	p/Pb	400 (13, 19, 30, 40, 75)	2017	35 days	SI
p	**h^+**	**A**	400 (30–120)	2017	42 days	ν
Xe		La	13, 19, 30, 40, 75, 150	2017	60 days	SI
p	p	p/Pb	400 (13, 19, 30, 40, 75)	2018	35 days	SI
p	**h^+**	**A**	400 (30–120)	2018	42 days	ν
Pb		Pb	75, 150	2018	40 days	SI

- Targets: C, Al, thin, replica
- Beams: p, π^+
- Beam momentum 30-120 GeV/c
- New hardware: 2 additional forward TPCs + vertex detector

Report from the NA61/SHINE experiment, http://cds.cern.ch/record/2059310

NA61/SHINE beyond 2020 (preliminary ideas)

- Removal of VTPC-1 - target will be inside magnetic field surrounded by vertex detector
- Upgrade of the TPC electronics (ALICE electronics)



Conclusions - NA61/SHINE pros

- Various hadron ($\pi^{\pm}$, $K^{\pm}$, p, 9 – 400 GeV/c)and ion beams
- Various targets (thin, long, ...)
- PID: $m^2_{TOF} - dE/dx$ - allows identification in wide range of momentum (for T2K 0.1 – 30 GeV/c)
- V0 (K^0_s, Λ) measurement - $\pi^{\pm}$ feed down correction - reduces model dependence of results
- Large acceptance (covers most of the T2K phase space) - tunable by changing target position and magnetic field

Conclusions - NA61/SHINE cons

- Cannot measure elastic cross-section - σ_{prod} is model dependent
- Poor forward coverage (only 6 clusters in GTPC) - it will significantly improve (FTPC-1, FTPC-2)
- K^+ - high systematic uncertainty due to PID
- Long (replica) target is outside tracking system - uncertainty due to track extrapolation can be up to 15%
- Wide beam profile (for lower momentum)