Hadron Production Measurements for Accelerator-Based Neutrino Experiments with NA61/SHINE

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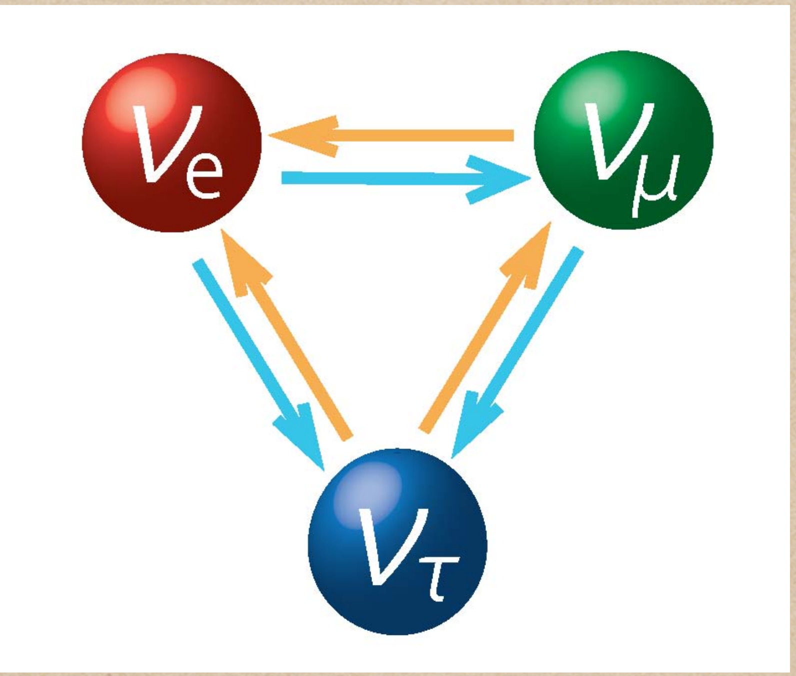
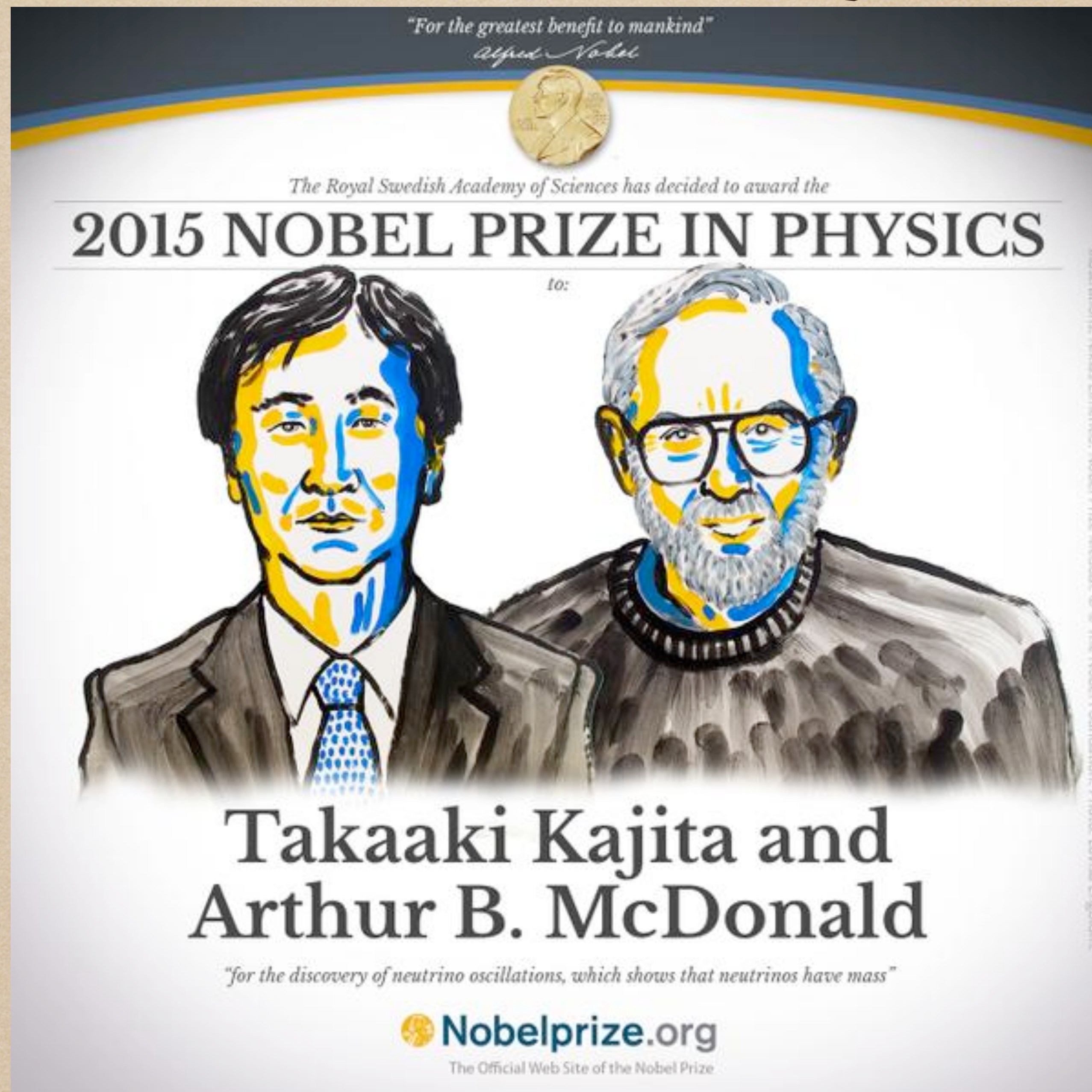
12th October 2015, CPPM seminar

Contents

Introduction



The Nobel Prize in Physics 2015



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Congratulations!!

Neutrino Mixing

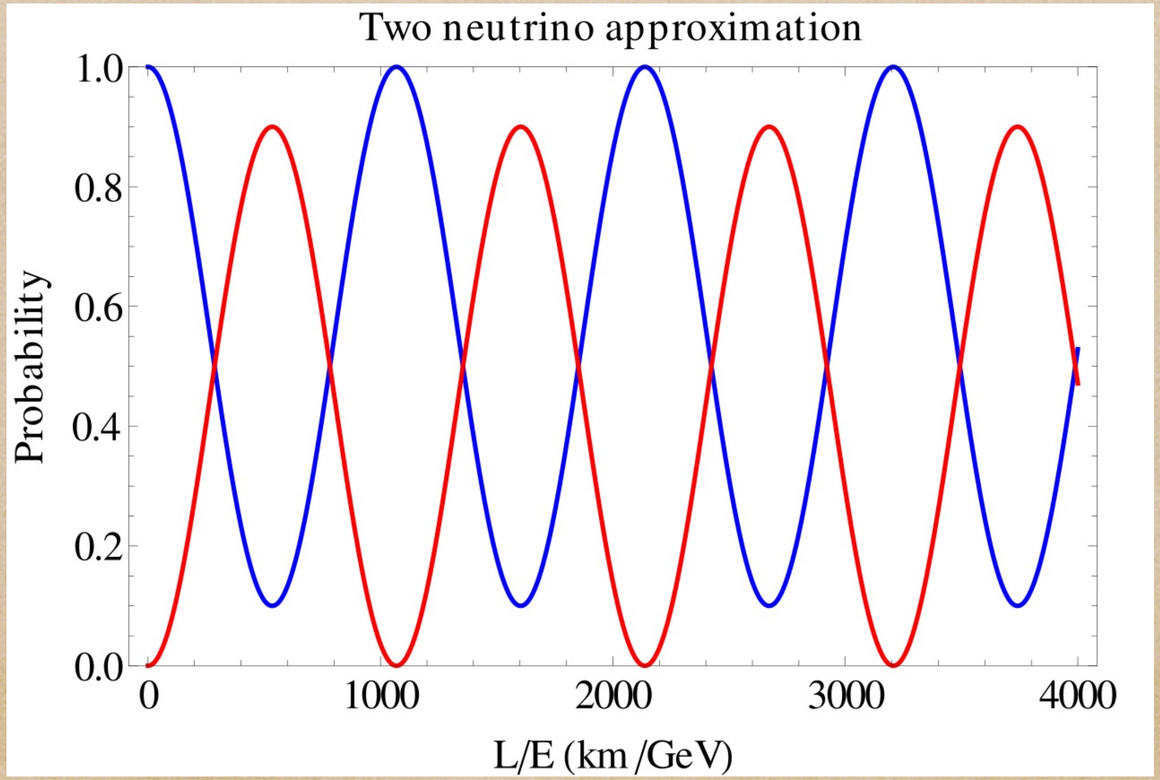
- Neutrinos are massive

—> Flavor state of neutrino is a mixture of the mass states

$$P_{\alpha\to\beta} = \sin^2\theta sin^2\left[1.27\frac{\Delta m^2 L}{E}\right]$$

The probability to observe ***β*** at distance ***L***(km)

E: Energy of neutrino in GeV   **Δ**m^2: $m_1^2 - m_2^2$



Neutrino Mixing

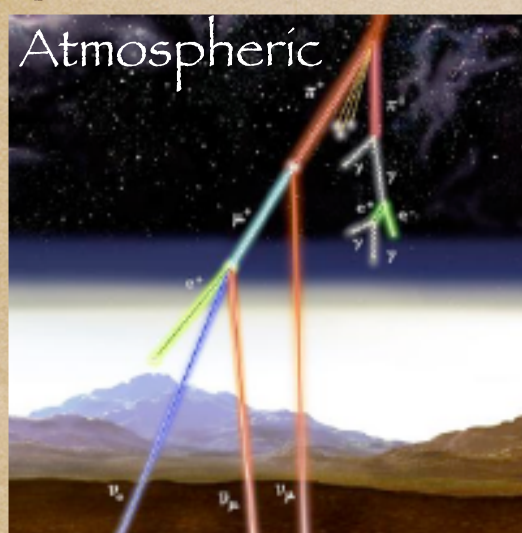
- 3 flavor: PMNS matrix expresses how flavor and mass eigenstate are related

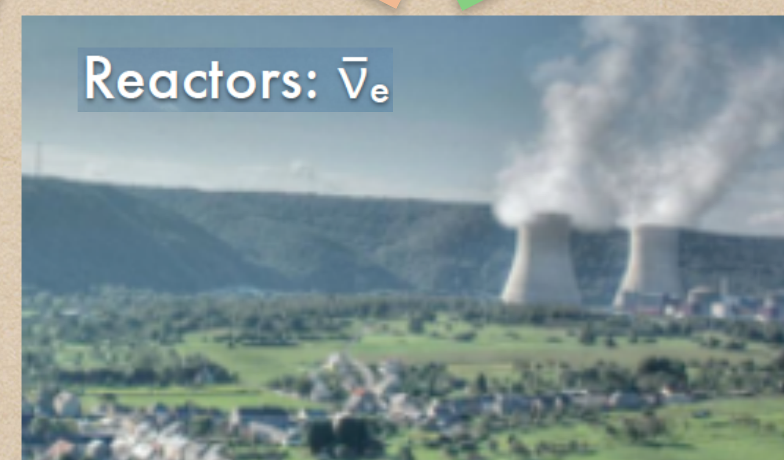
c_{ij}=cosθ_{ij}, s_{ij}=sinθ_{ij}

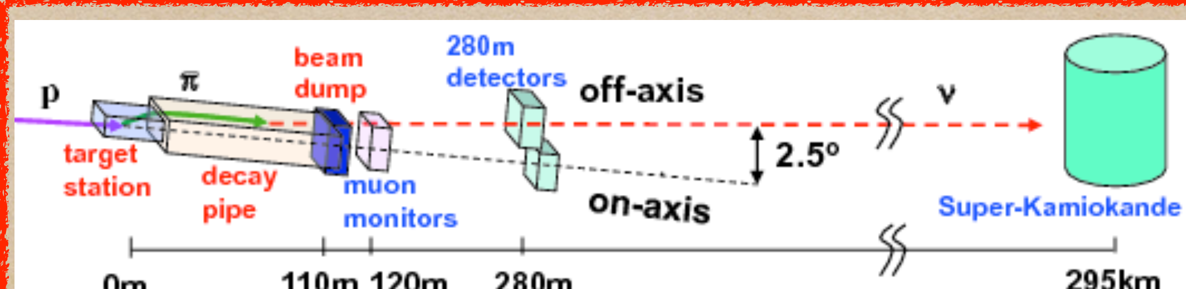
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

Flavor eigenstate

Mass eigenstate







Accelerator-based neutrino

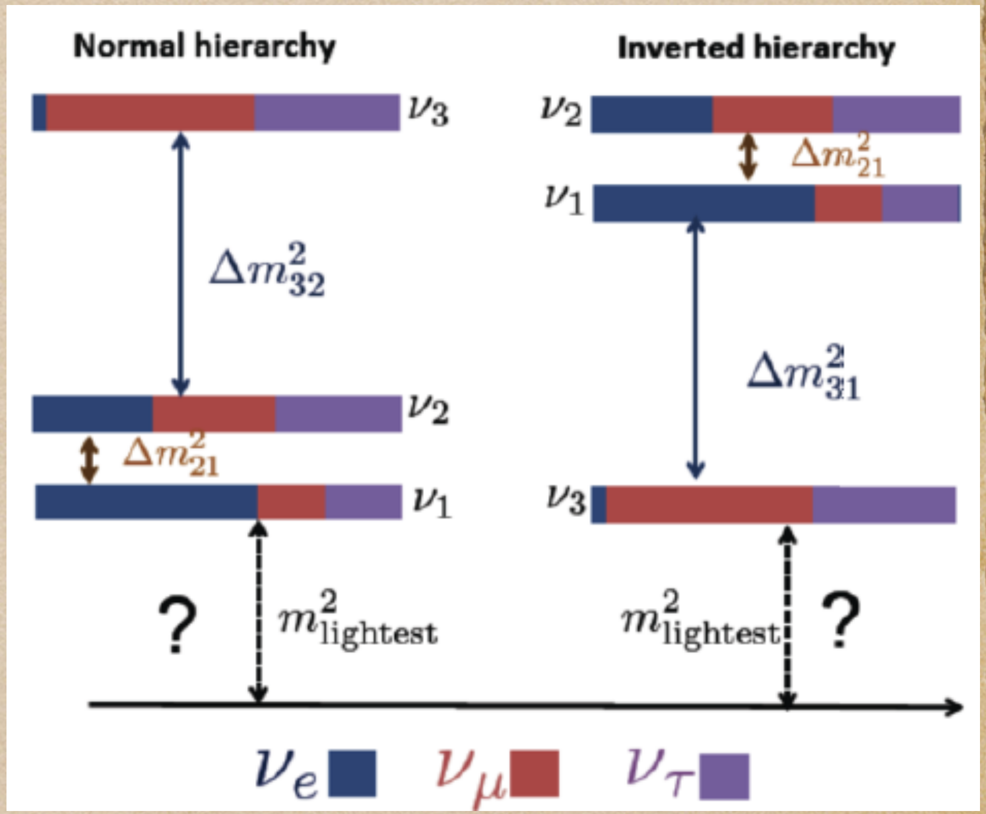
- Measurements of mixing parameters are performed via various sources

Status of Neutrino Oscillation Measurements

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

- What we know:
  - 3 mixing parameters
    - $\theta_{23} = 45.8 \pm 3.2^\circ$
    - $\theta_{13} = 8.88 \pm 0.39^\circ$
    - $\theta_{12} = 33.4 \pm 0.85^\circ$
  - Two mass differences
    - $\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\ \mathrm{eV}^2$
    - $|\Delta m^2_{32}| = 2.44 \pm 0.06 \times 10^{-3}\ \mathrm{eV}^2$

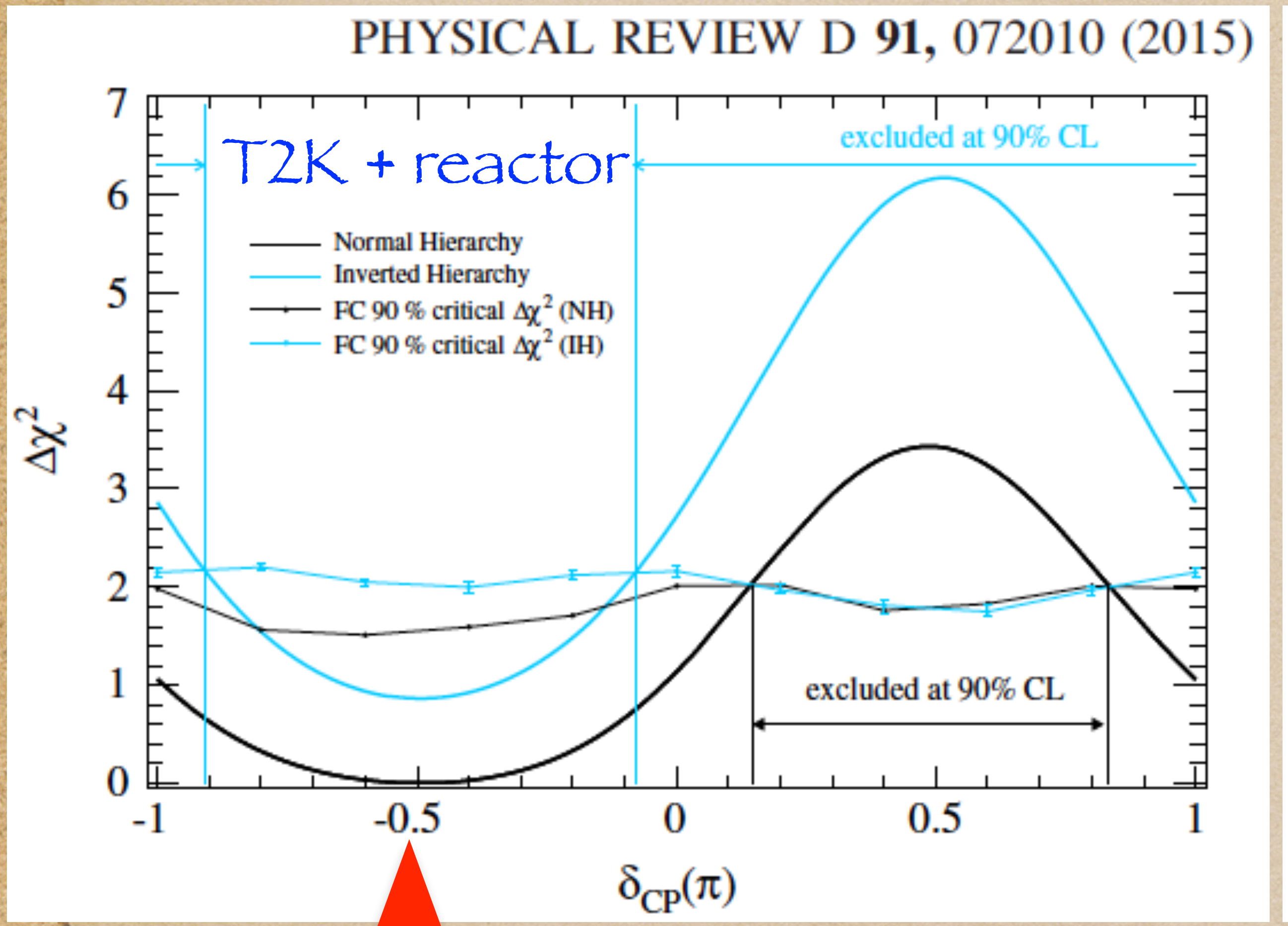
All mixing angles are known with < 10% uncertainty

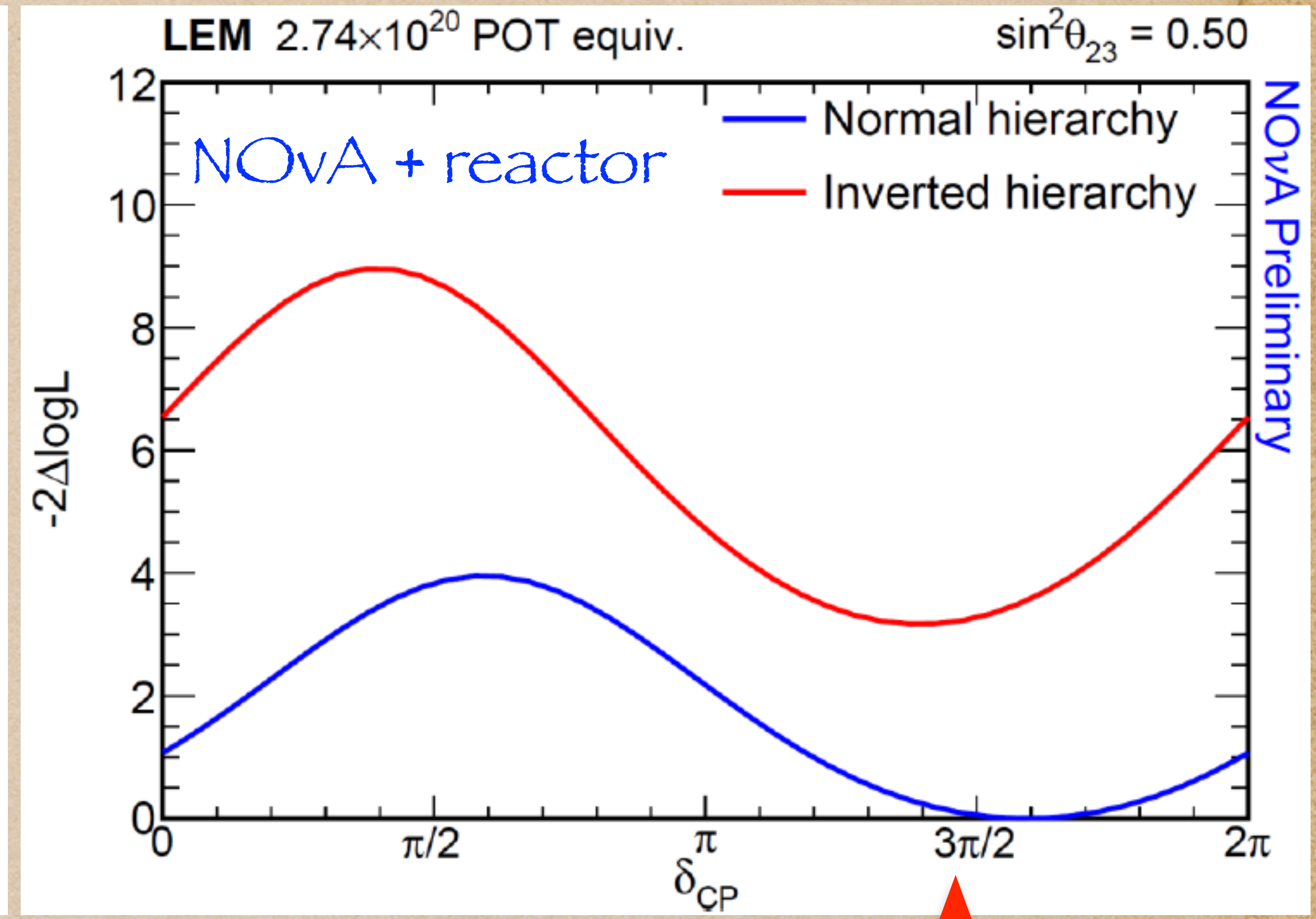


- What we do not know:
  - Which Mass hierarchy ?
  - Is CP phase non-zero ?
  - $\theta_{23} < 45^\circ$, $\theta_{23} > 45^\circ$, or $\theta_{23} == 45^\circ$?

Questions for neutrino oscillation experiments

Recent Results from accelerator-based experiments





Preferred

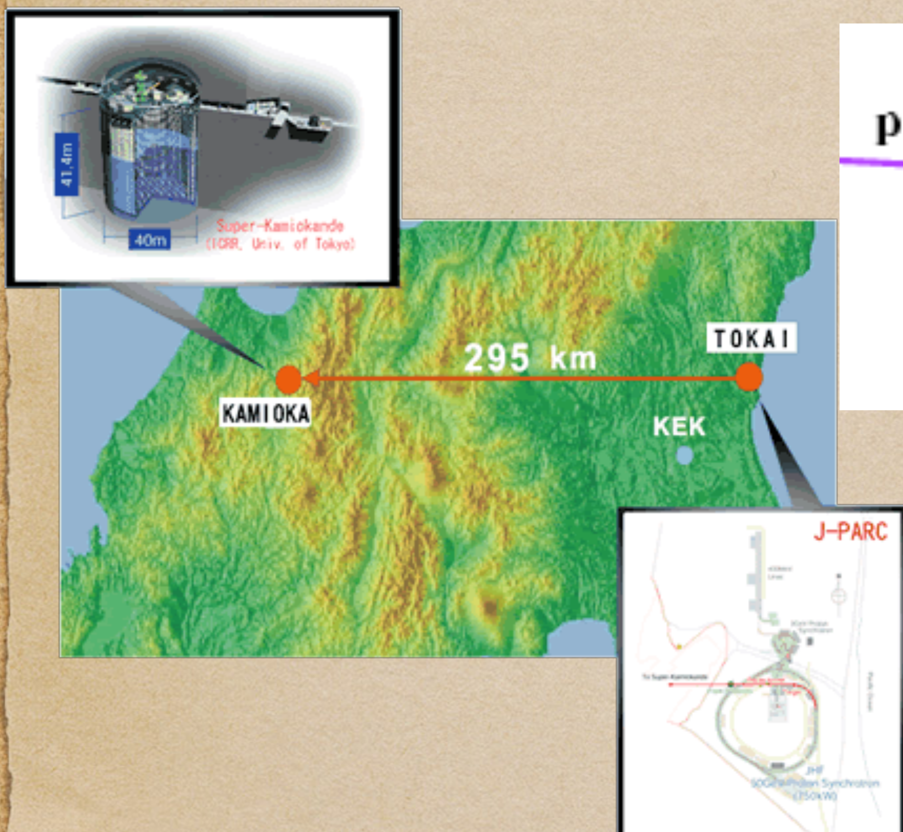
Preferred

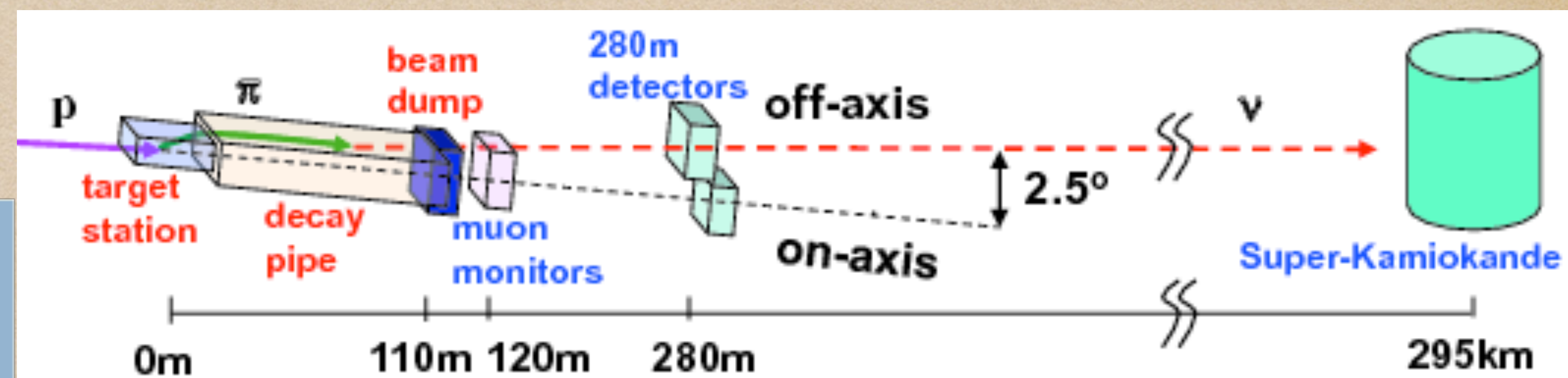
Some hints on δ_{CP} and mass hierarchy

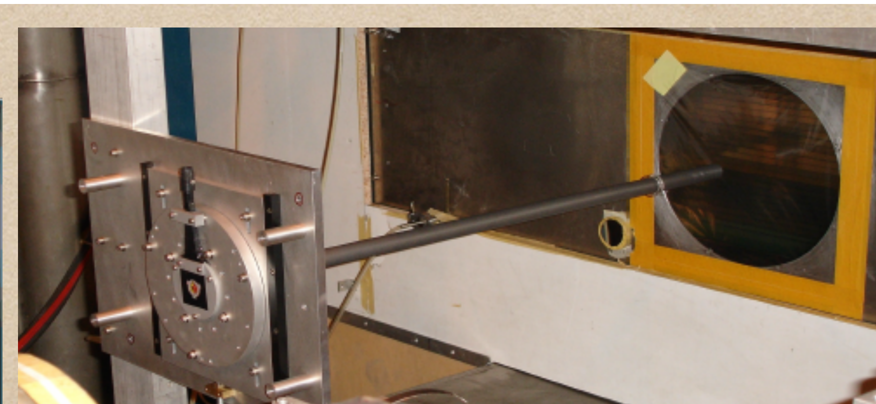
—> However, not enough sensitive

T2K experiment

- A long baseline accelerator based neutrino experiment in Japan

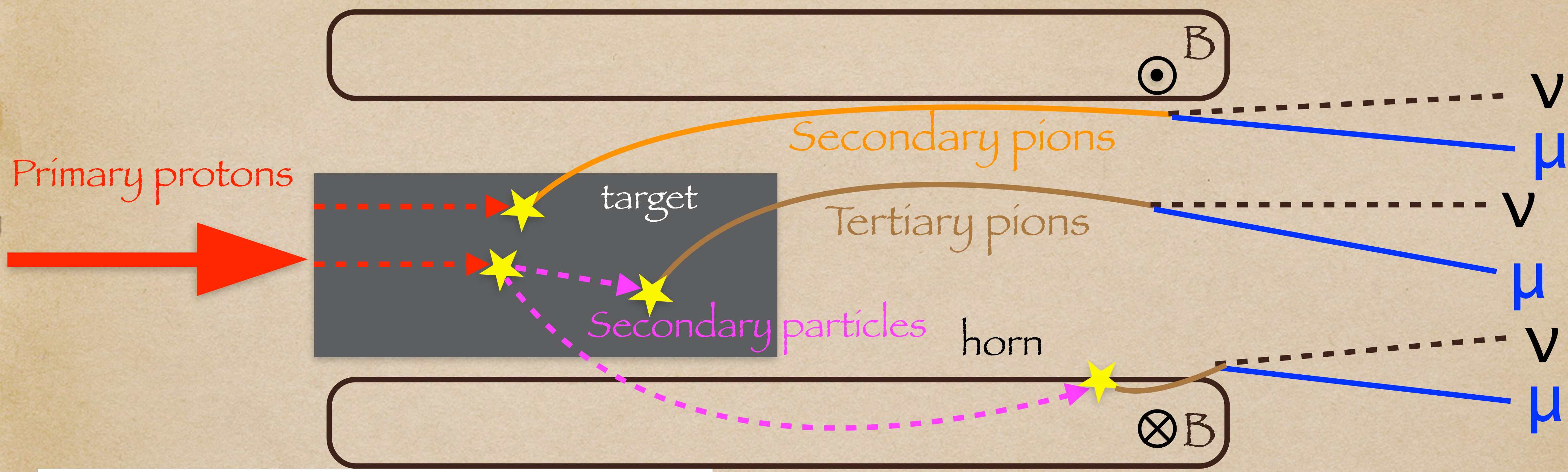


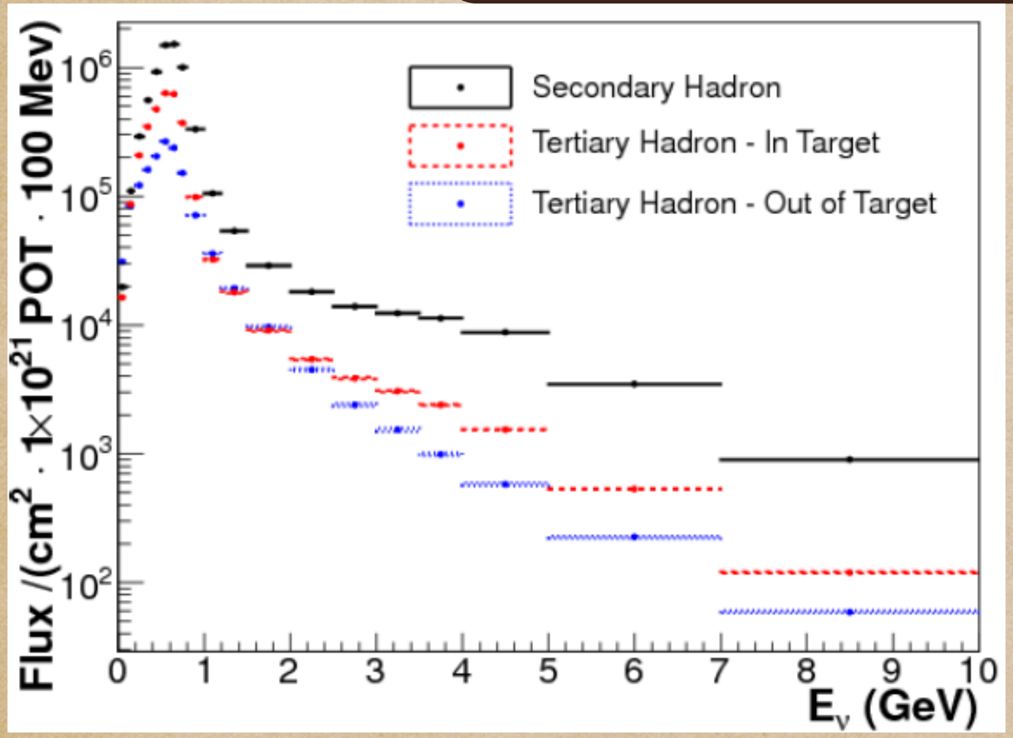




- 30 GeV proton beam (kinetic energy)
- graphite bar target: 90cm (1.9 λ)
- 295 km off-axis baseline
- Far-detector: Super-Kamiokande

Neutrino Beam





e.g. T2K neutrino beam

- 60% of ν's from primary interactions
- 30% of ν's from re-interactions in target
- 10% of ν's from support, horn, etc..

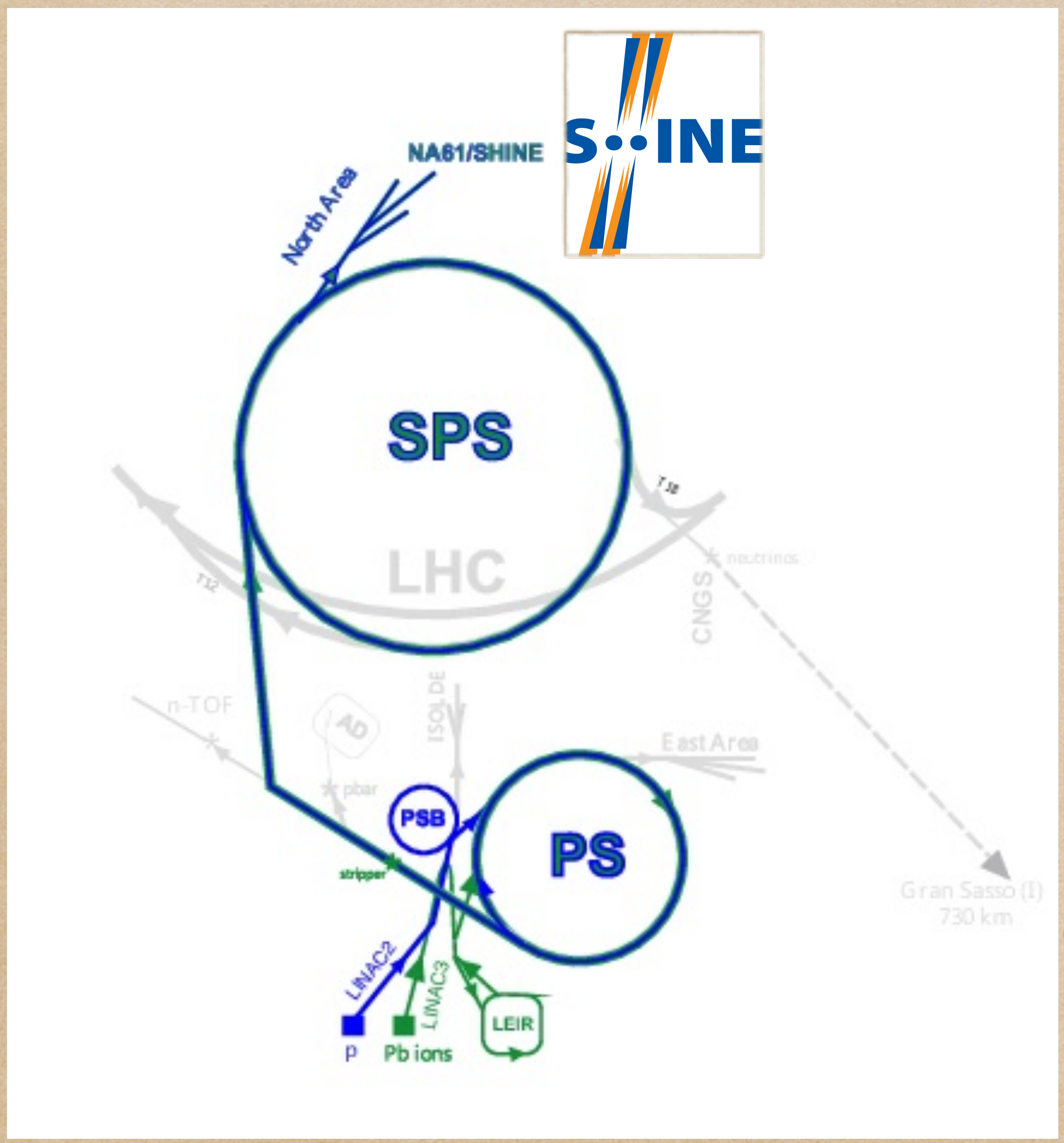
NA61/SHINE: NIM A701 (2013) 99

Key ingredient for experiment: Good neutrino flux prediction

—> Important to understand both of primary productions & secondary interactions

NA61/SHINE experiment

"The SPS Heavy Ion and Neutrino Experiment" @ CERN



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Ruder Boskovic Institute, Croatia
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Karlsruhe Institute of Technology, Germany
Fachhochschule Frankfurt, Germany
Institut für Kernphysik, Goethe-Universität, Germany
Nuclear and Particle Physics Division, University of Athens, Greece
Wigner RCP, Hungary
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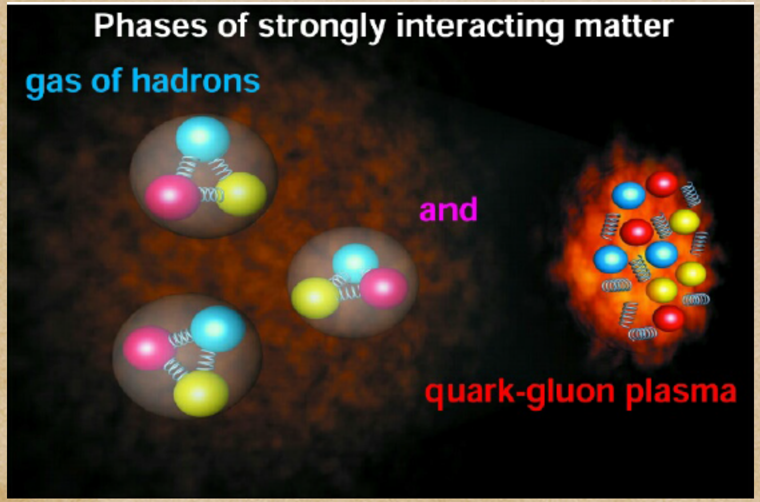
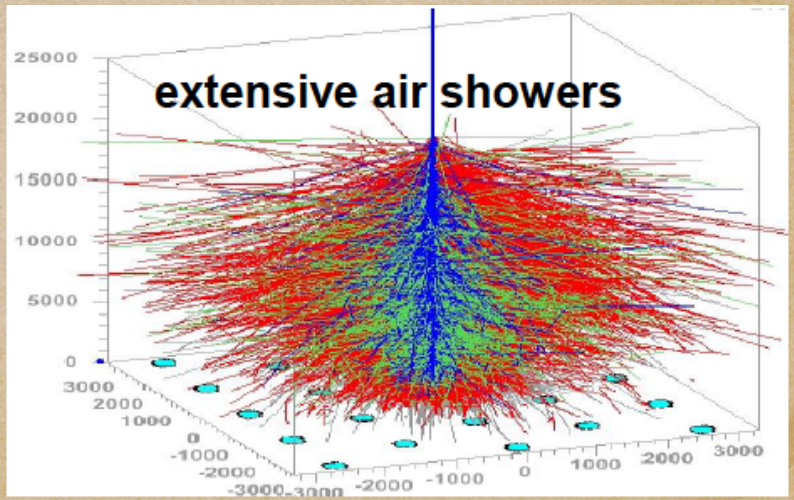
University of Geneva, Switzerland
University of Colorado Boulder, USA
Los Alamos National Laboratory, USA
Department of Physics and Astronomy, University of Pittsburgh, USA
Fermilab, Neutrino Division, USA

The NA61/SHINE experiment

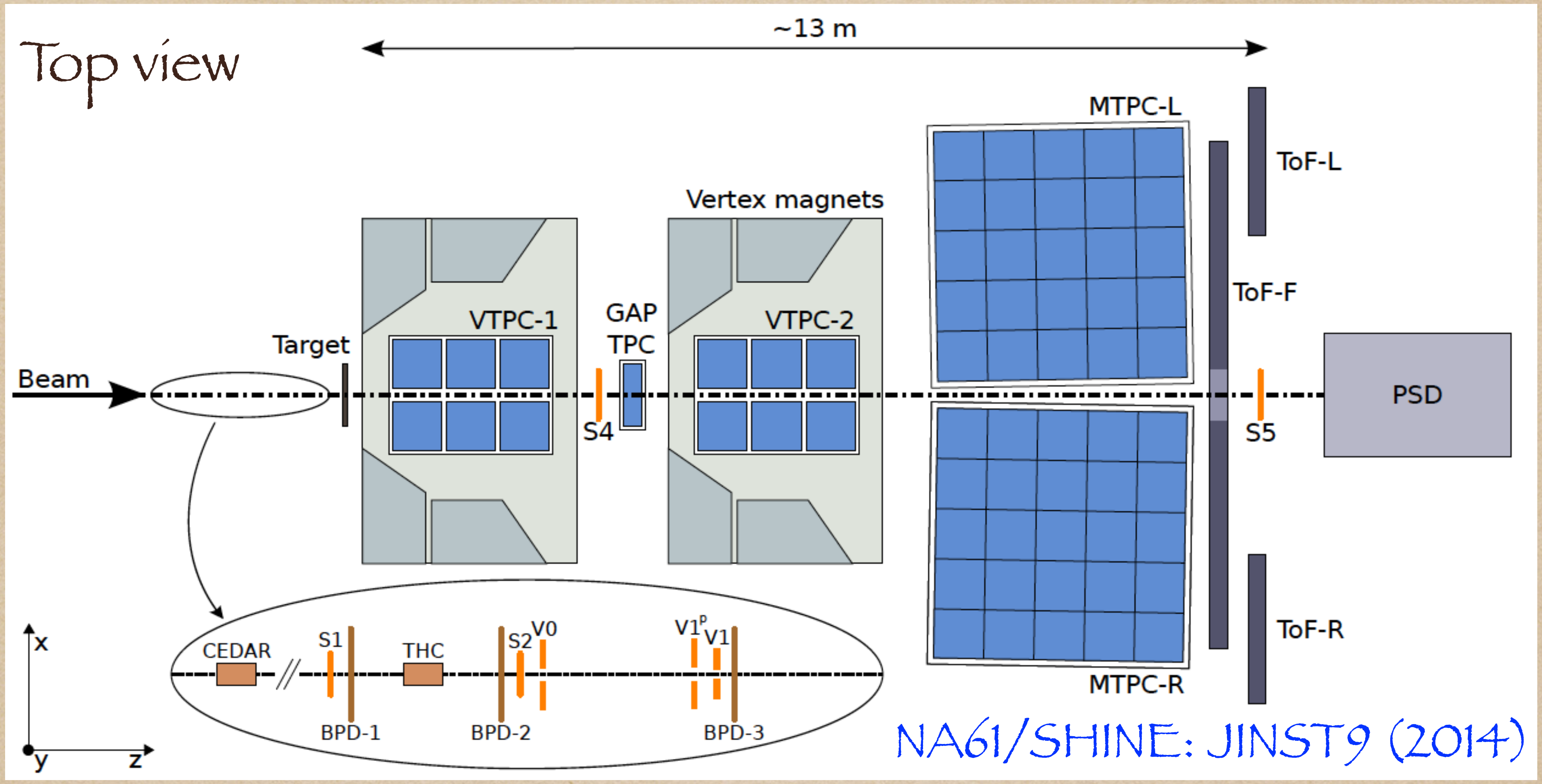
- Unique multipurpose facility at SPS H2 beamline
  - Heavy ion: Search for the critical point in strong interactions
  - Neutrino: Hadron production measurements on the target to improve neutrino beam flux prediction for T2K and US neutrino programs
  - Cosmic ray: Hadron production measurements to improve air shower model
- Hadron productions in:
  - h + p (20 - 350 GeV/c) [h = p, $\pi^{\pm}$, $K^{\pm}$]
  - h + A (20 - 350 GeV/c) [A = Be, C, Al, Sc, Pb,…]
  - A + A (13A - 150A GeV/c)

Ideal energy range for neutrino physics





The NA61 Detector

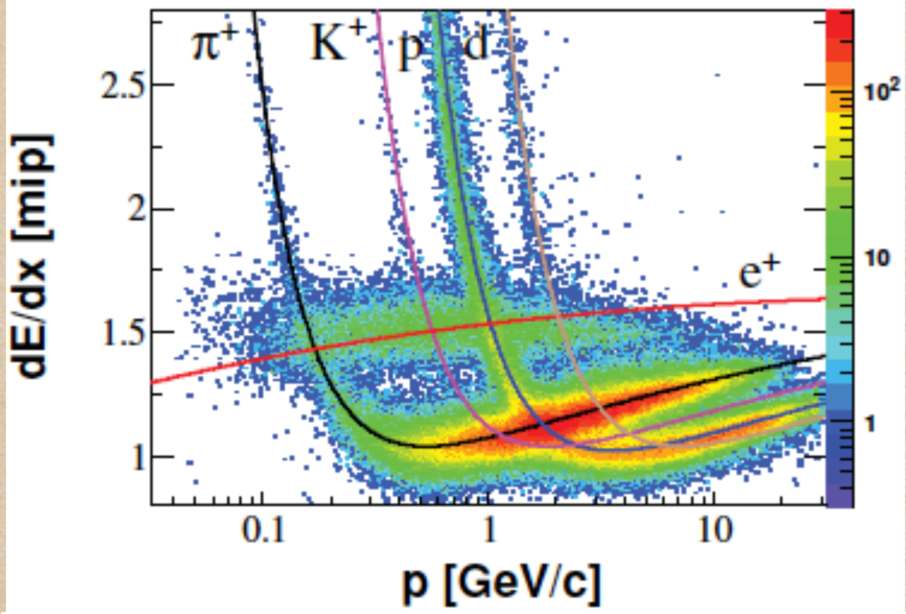


NA61/SHINE: JINST9 (2014) P06005

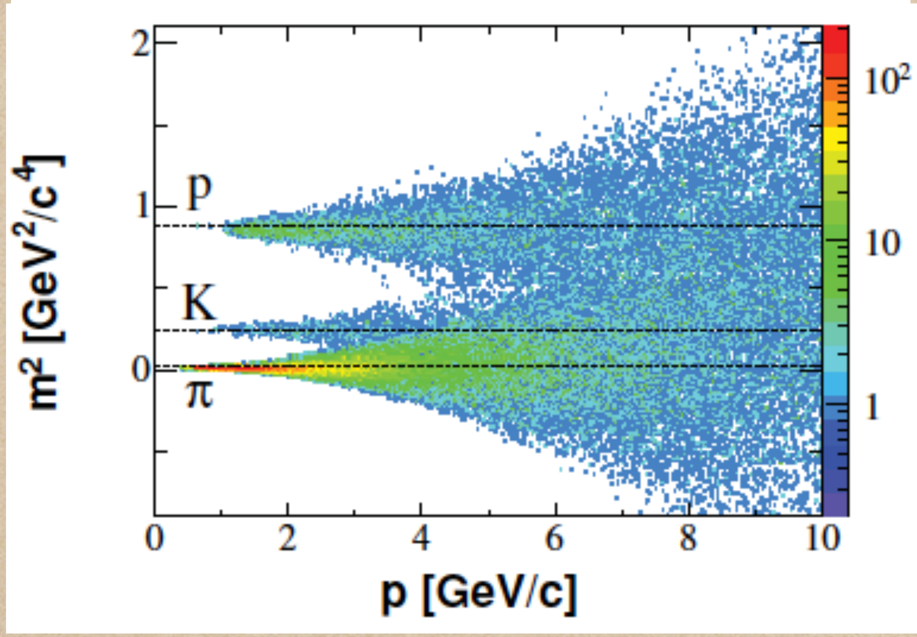
- Large acceptance spectrometer for charged particles
  - TPCs as main tracking detector
  - 2 dipole magnets with up to 9 Tm over VTPC-1 and VTPC-2
  - Particle identification with TPC and Time-of-Flight

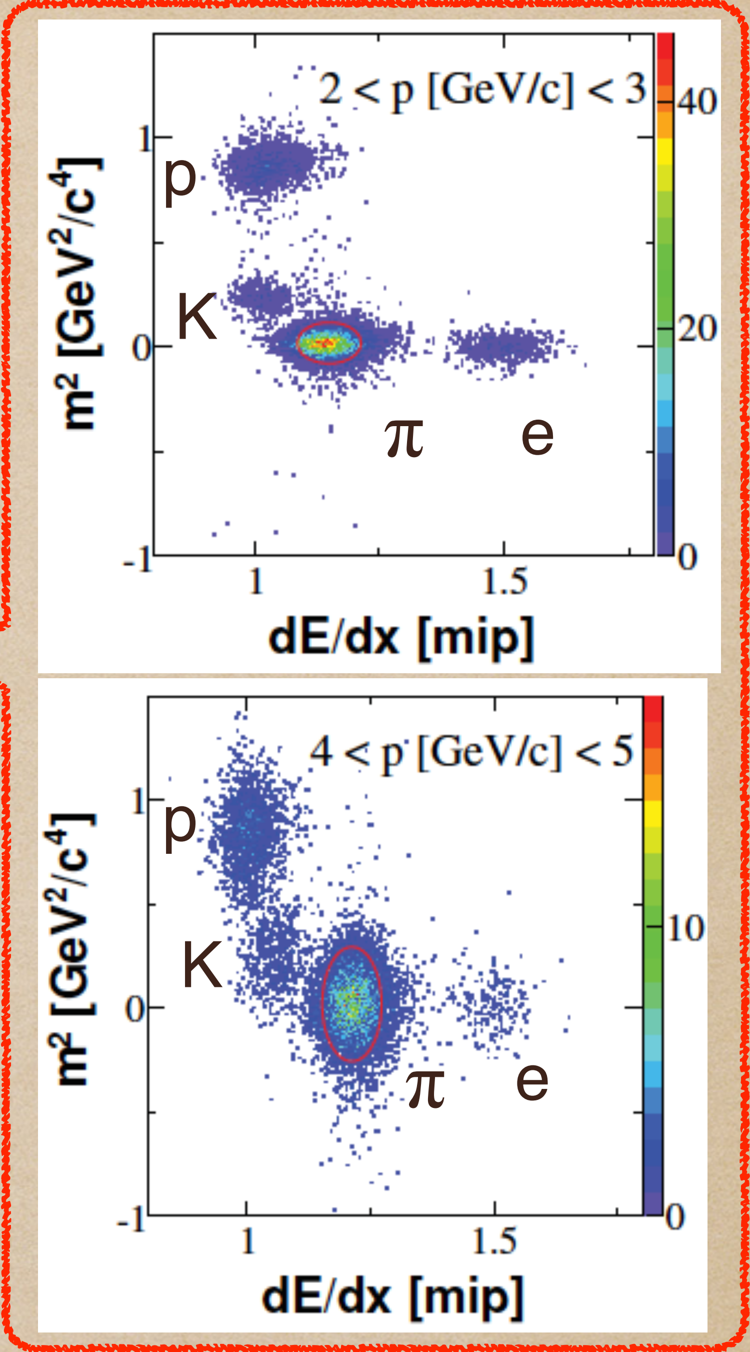
Particle Identification in NA61

dE/dx in TPC



Time-of-flight



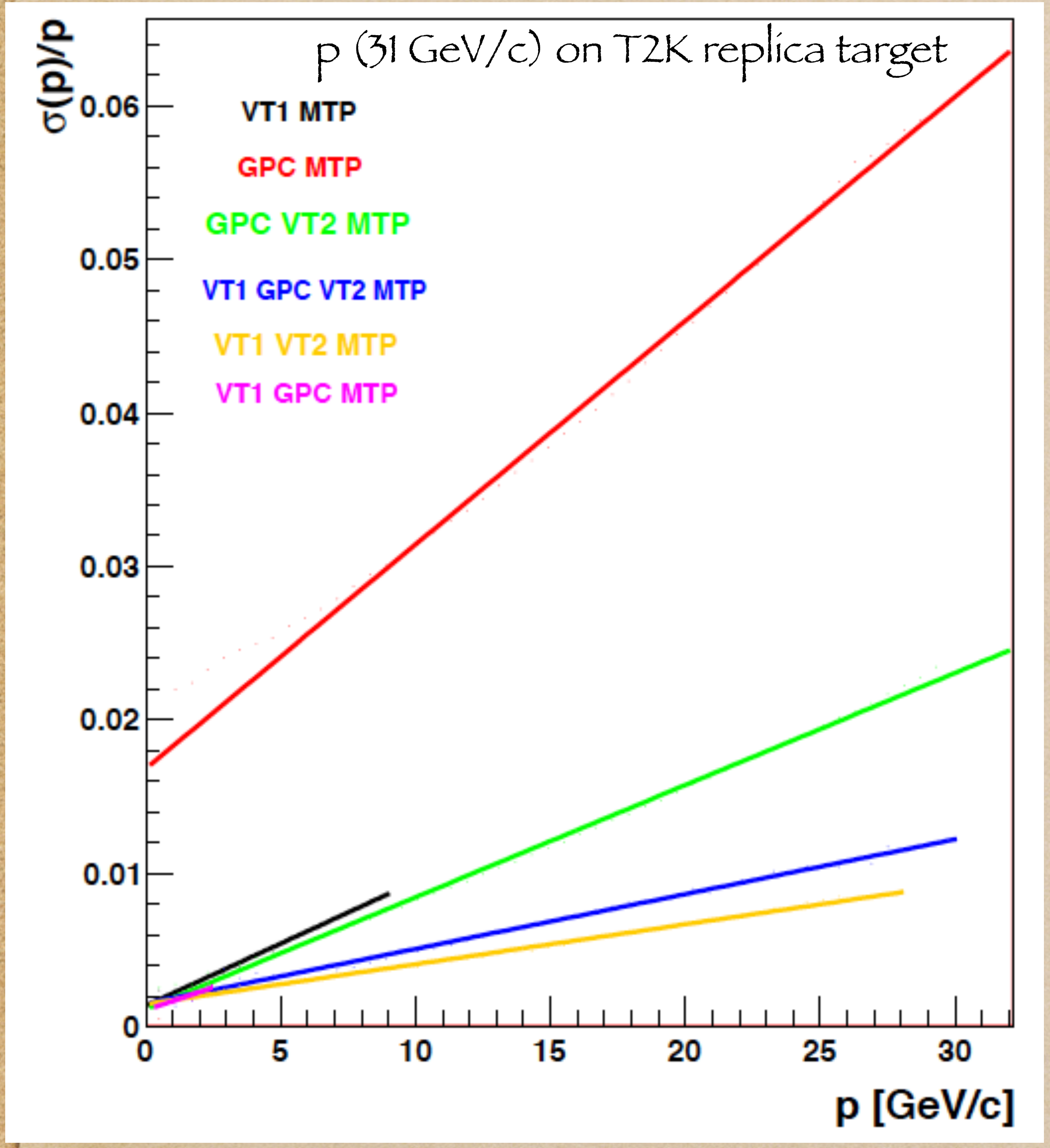


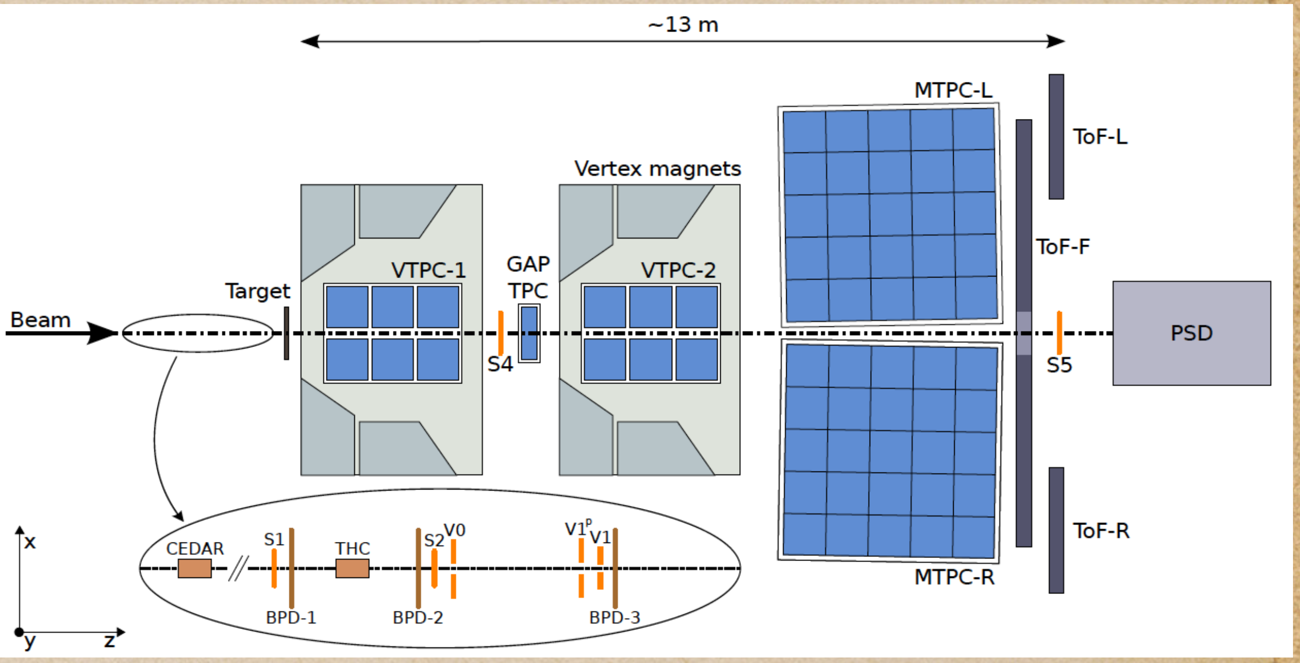
NA61/SHINE: PRC 84, 034604 (2011)

- dE/dx can provide a good particle ID for region of interests, except Bethe-Bloch overlap region
- Time-of-Flight provides a good discrimination for p < 6 GeV/c

resolution: σ(dE/dX) / (dE/dX) ≈ 0.04, σ(ToF-L/R) < 90 ps, σ(ToF-F) ≈ 115 ps

Momentum Resolution in NA61





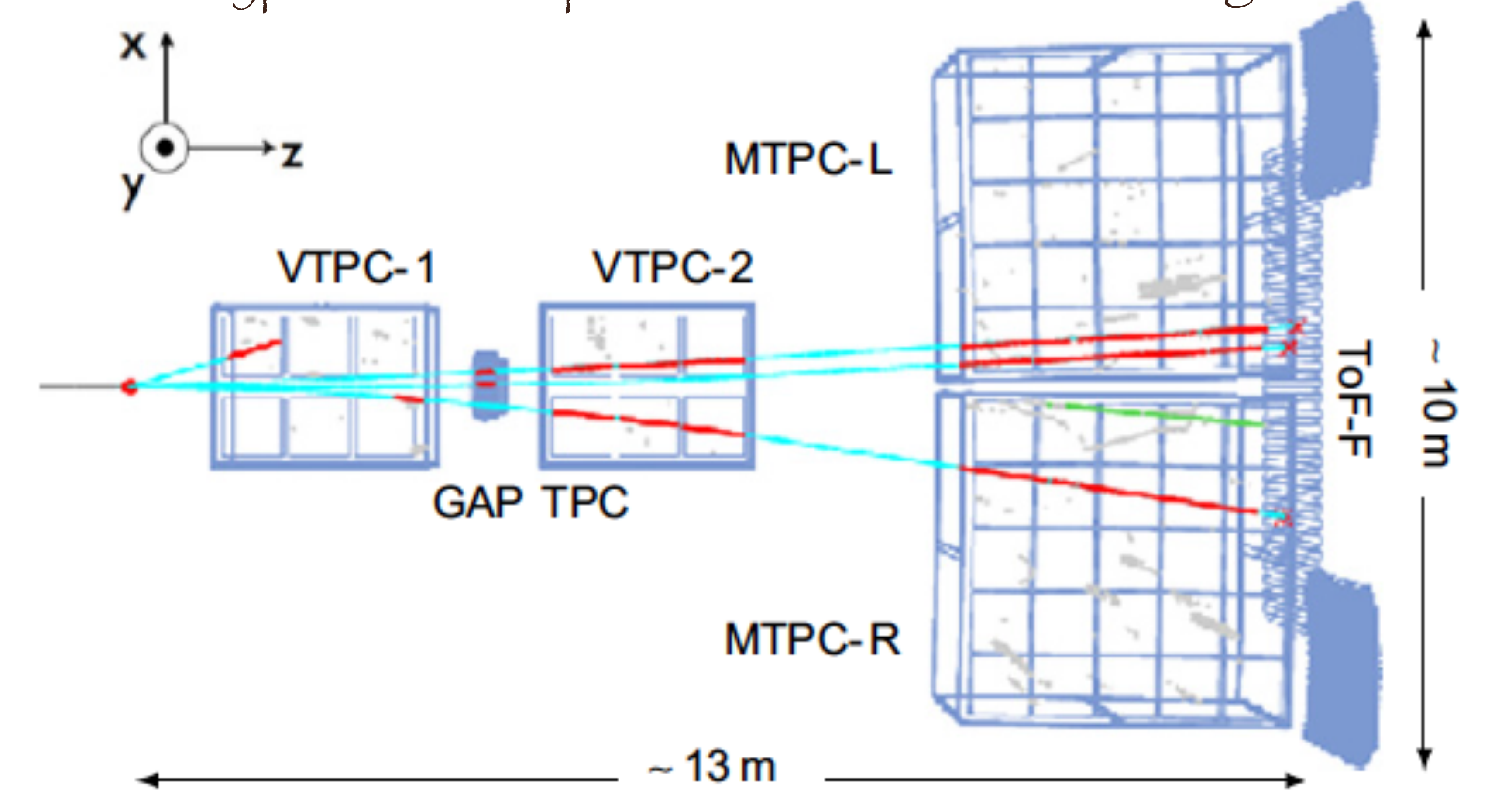
- Momentum resolution depends on track kinematics

Best: tracks passing through VTPC-1 —> VTPC-2 —> MTPC

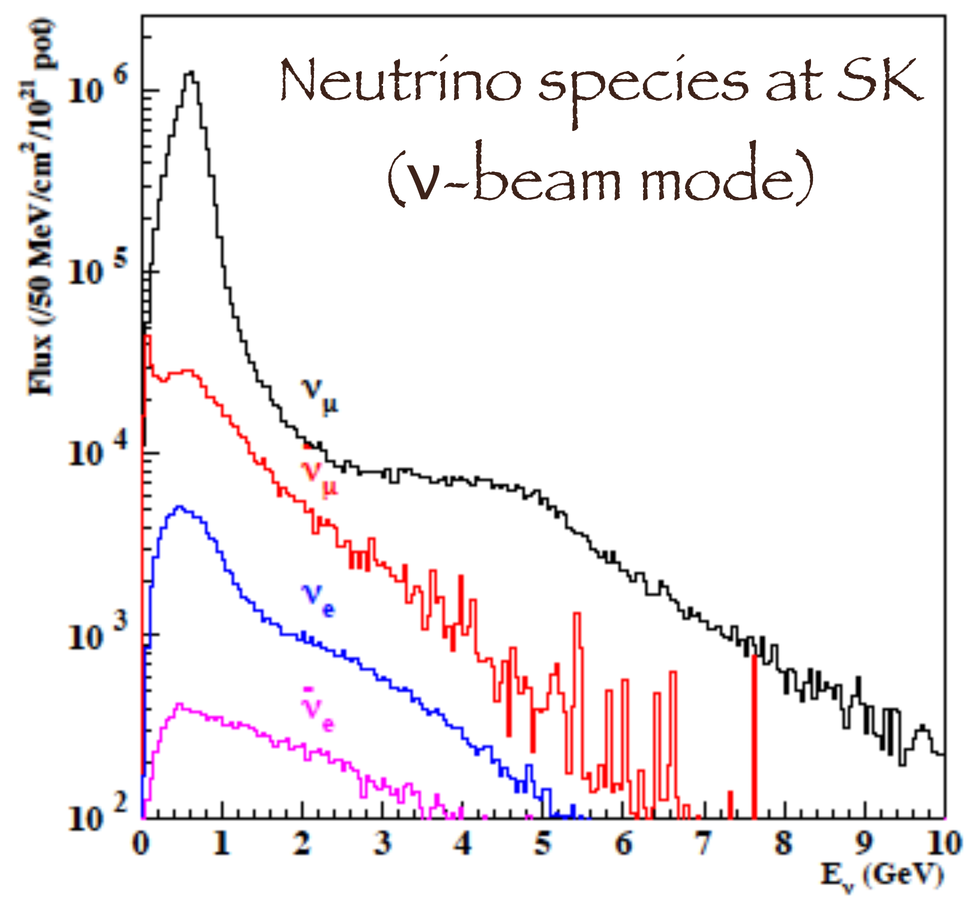
Worst: tracks passing through GAP-TPC —> MTPC (forward tracks)

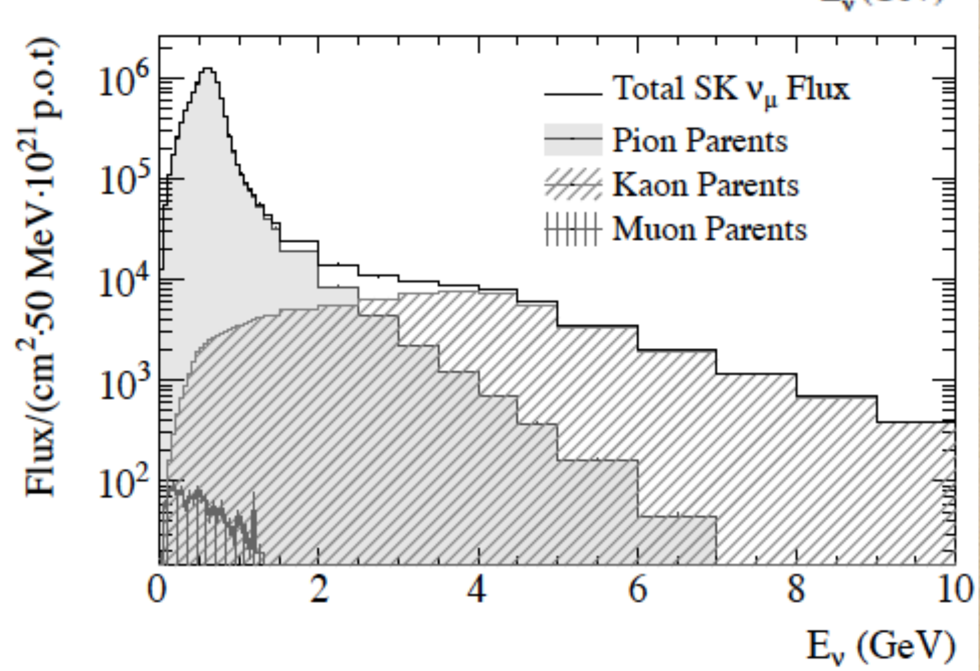
Hadron production measurements for T2K

typical event for proton (31 GeV/c) on carbon target



T2K Neutrino Beam





- Neutrinos mostly come from pion parents at the peak energy (~700 MeV)
- Kaon parents contribute for higher energy neutrinos

Particle	Decay Products	Branching Fraction (%)
π^+	$\rightarrow \mu^+\nu_\mu$	99.9877
	$\rightarrow e^+\nu_e$	1.23×10^{-4}
K^+	$\rightarrow \mu^+\nu_\mu$	63.55
	$\rightarrow \pi^0\mu^+\nu_\mu$	3.353
	$\rightarrow \pi^0 e^+\nu_e$	5.07
K^0_L	$\rightarrow \pi^-\mu^+\nu_\mu$	27.04
	$\rightarrow \pi^- e^+\nu_e$	40.55
μ^+	$\rightarrow e^+\bar{\nu}_\mu\nu_e$	100

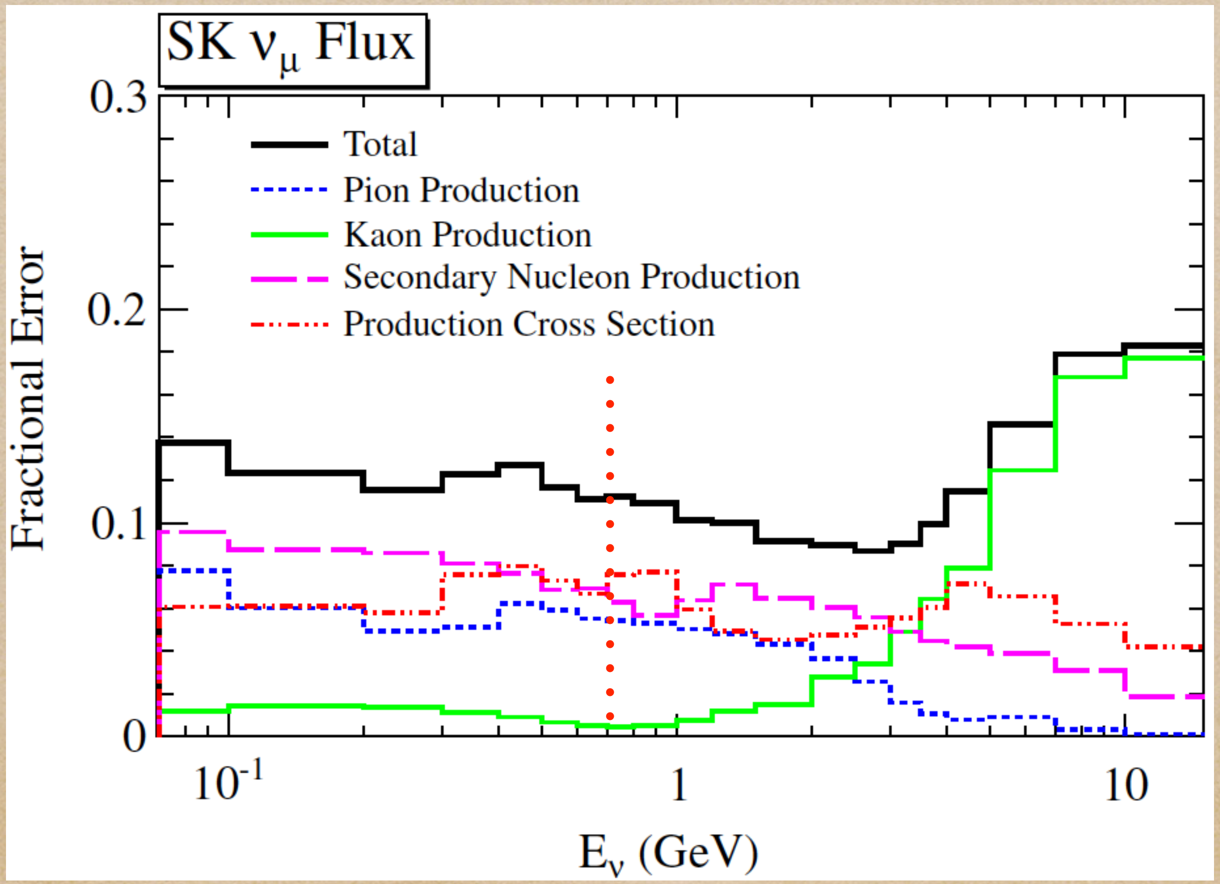
—> Understand pions/kaons production on target

Neutrino Flux Prediction

- Rely on hadron production models (π, K, etc... —> ν + X)
  - However, no perfect model exists (FLUKA, GEANT4, etc)

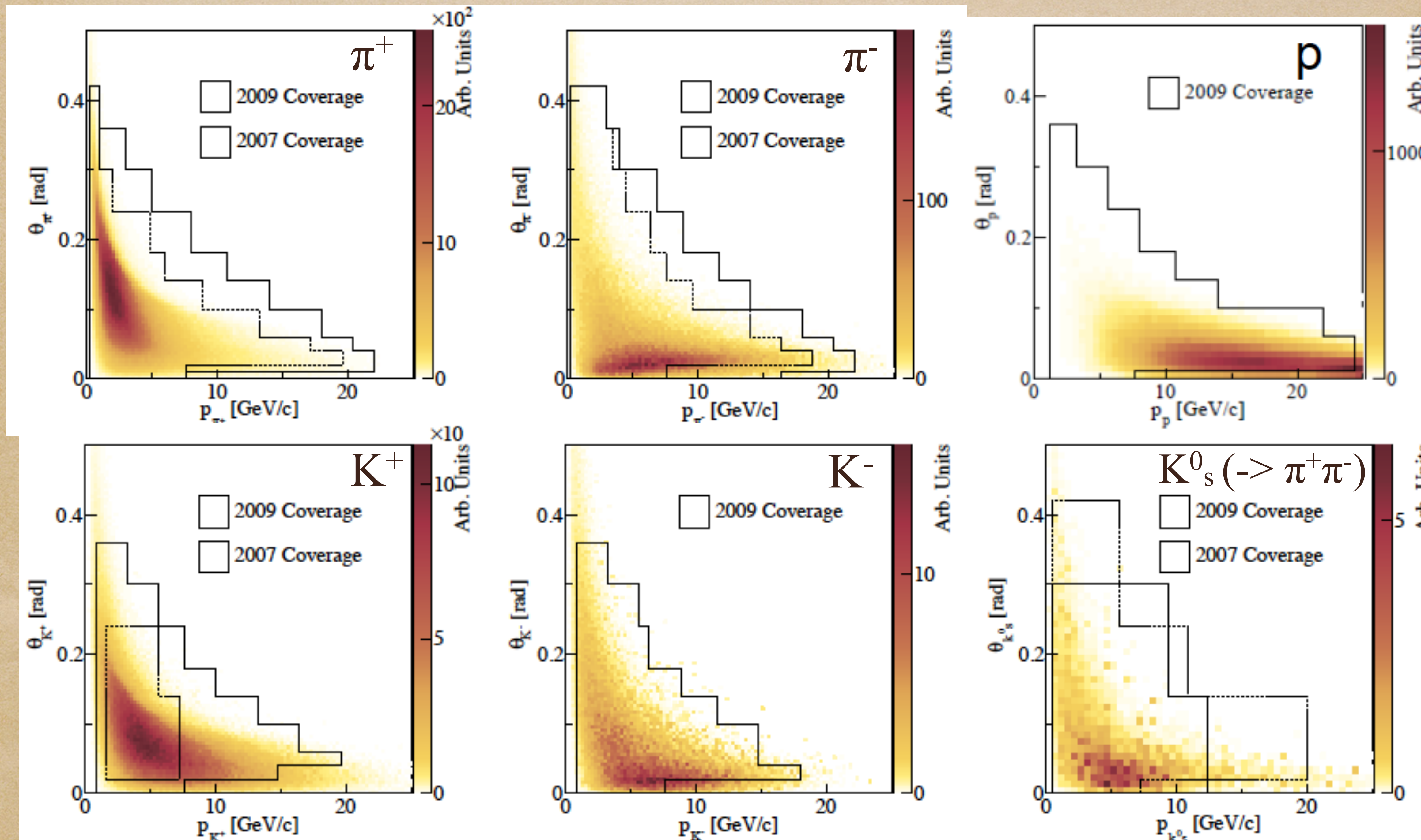
—> any model needs to be tuned with dedicated hadron production measurement

- The leading systematic uncertainty source for the flux prediction
  - Precise hadron production measurement needed to achieve physics goals
  - Both primary hadrons (p+C —> π/K + X) and secondary interactions (p+C —> p + X —> π/K + X) are important



T2K: PRD 87, 012001 (2013)

T2K Phase space of hadrons vs NA61 acceptance



Large fraction of phase space contributing to the neutrino flux are within NA61 acceptance

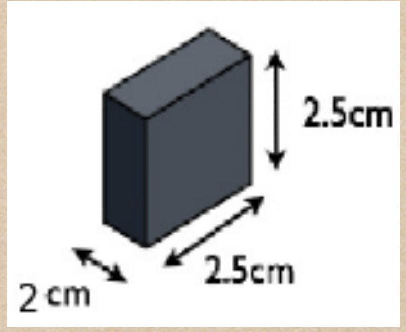
Datasets and target

- 2 type of datasets are taken to constrain T2K flux predictions
  - Thin carbon target (2cm, 0.04λ) p+C 31 GeV/c

—> hadrons from primary interactions

—> at least 60% of ν's can be constrained

—> measure spectra for $\pi^{\pm}$, $K^{\pm}$, K^0_s, Λ, proton

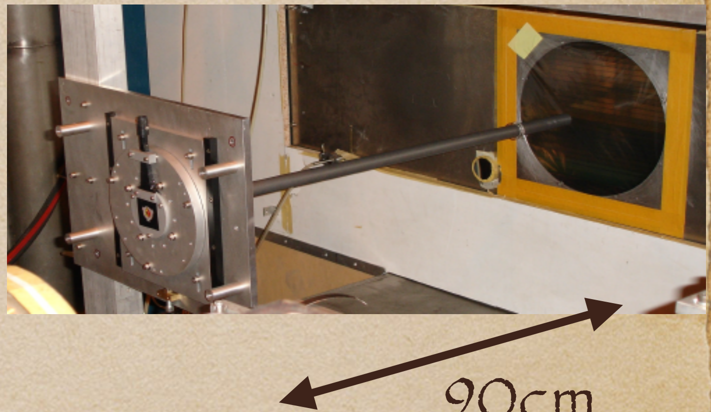


  - T2K replica target (90cm, 1.9λ) p+T2K replica 31 GeV/c

—> hadrons exiting from target (primary+secondary interaction)

—> up to 90% of ν's can be constrained

—> measure spectra for $\pi^{\pm}$



90cm

beam+target	year	p (GeV/c)	N_{event}	comments
p+C	2007	31	0.7×10^6	published, pilot run
p+T2K replica	2007	31	0.2×10^6	published, pilot run
p+C	2009	31	5.4×10^6	new preliminary results
p+T2K replica	2009	31	2.8×10^6	new preliminary results
p+T2K replica	2010	31	7.2×10^6	analysis ongoing

New results!

p+C 31GeV: Analysis Method

3 complementary analyses performed

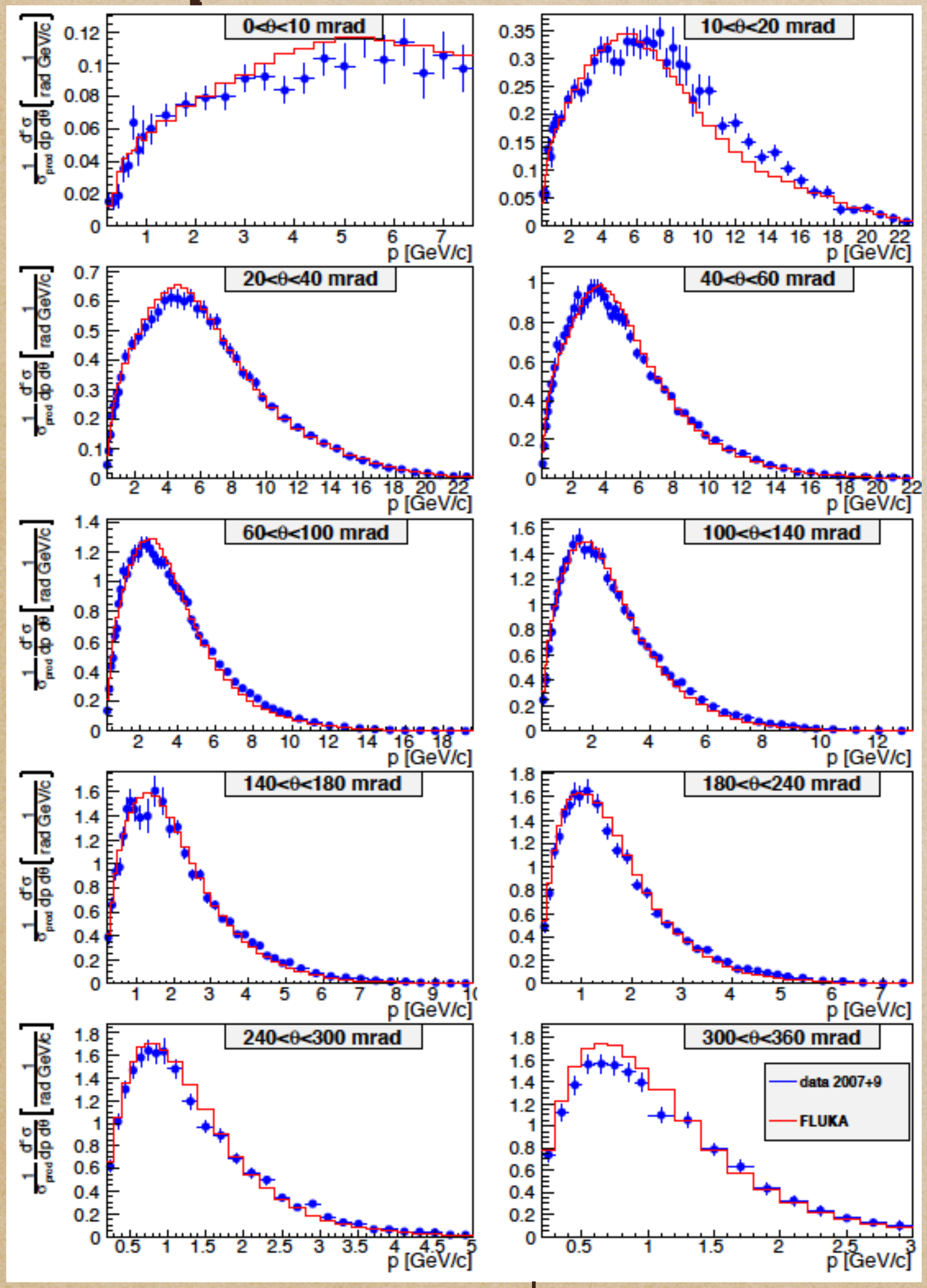
- $p > 0.8$ GeV/c (dE/dX + ToF) —> Primary result
    - particle ID based on dE/dX and ToF

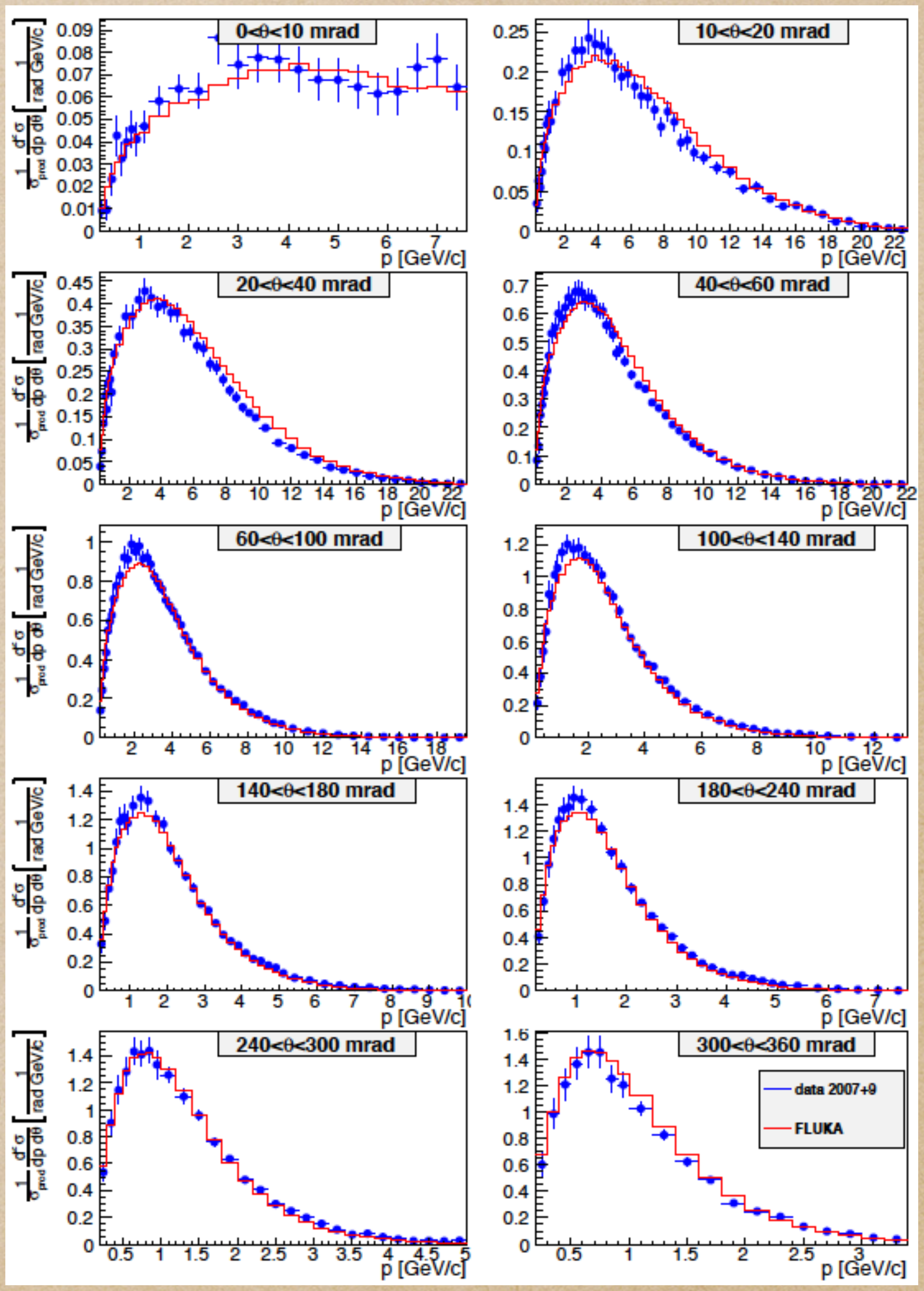
      —> Analysis relies on TPCs and ToF detectors
- $p < 1$ GeV/c (dE/dX)
    - particle ID based on dE/dX only

      —> Analysis relies on TPCs
- Negative hadrons (h^-)
    - no particle ID, most of negative hadrons are π^- (> 90%) at 31 GeV/c beam
    - few K^- contamination (< 5%)

      —> Analysis only relies on TPC tracking

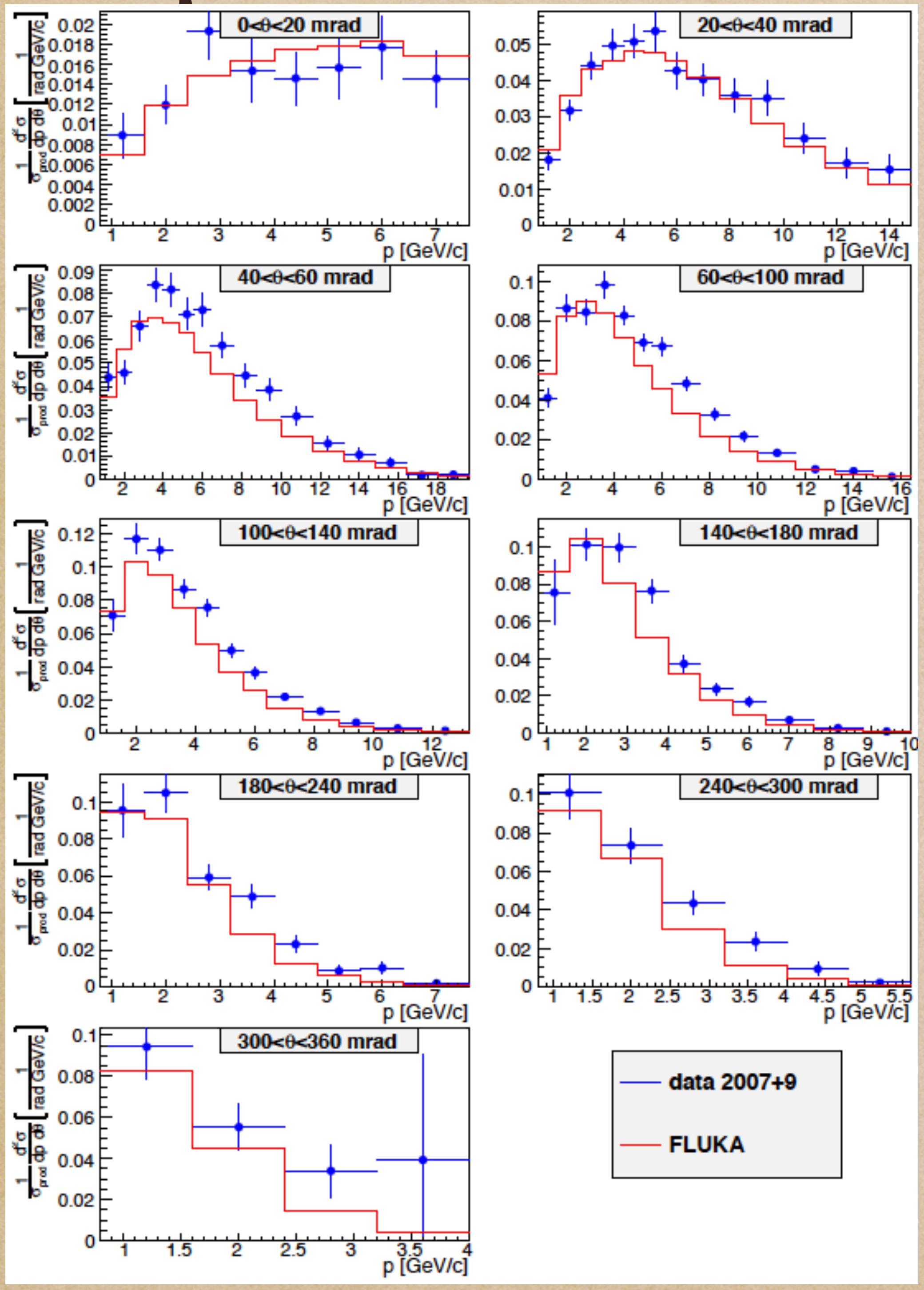
p+C —> $\pi^{\pm}$ + X at 31 GeV/c

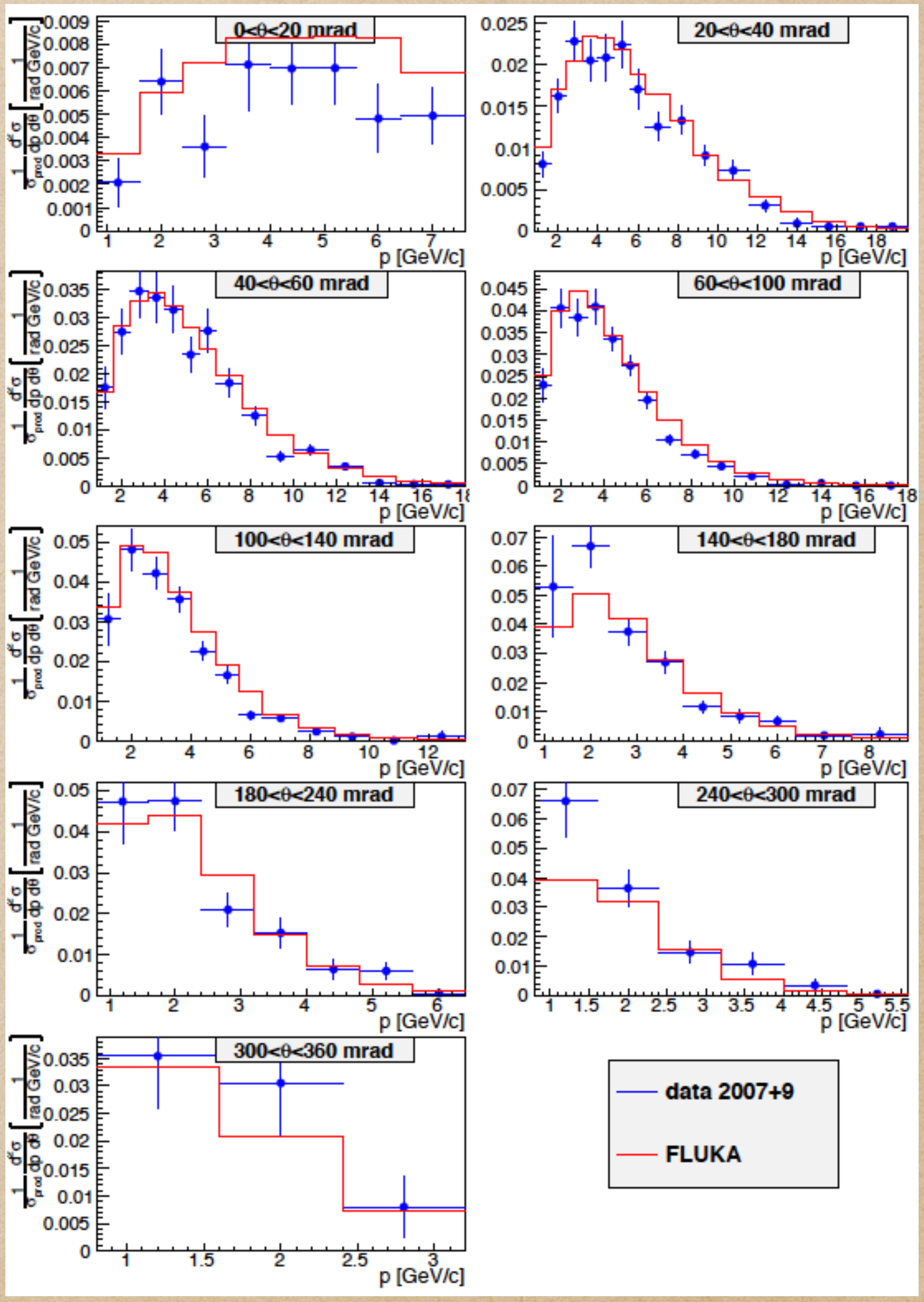




π^{+} CERN-PH-EP-2015-278 π^{-} (dE/dX + ToF)

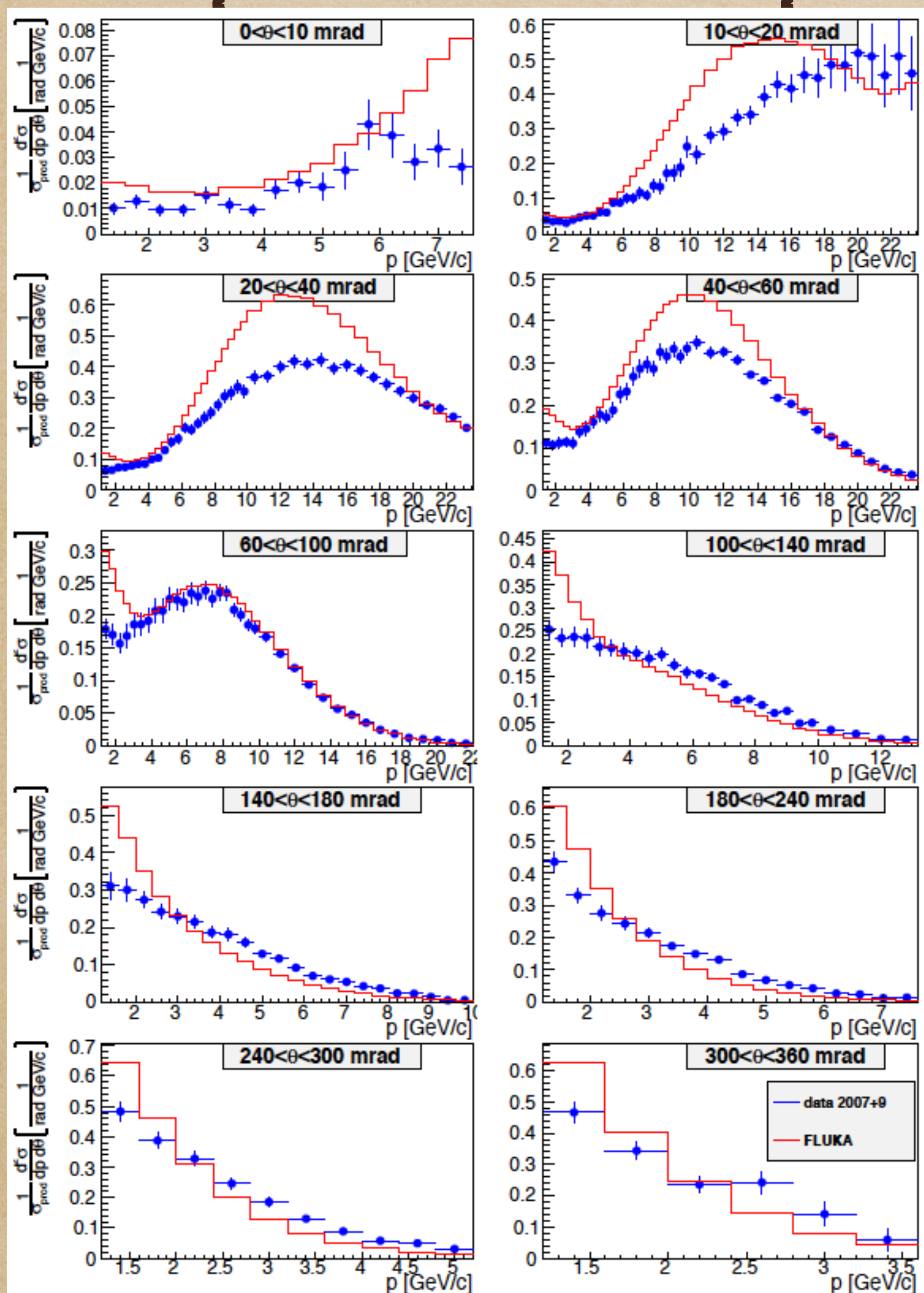
p+C —> $K^{\pm}$ + X at 31 GeV/c





K^+ CERN-PH-EP-2015-278 K^- (dE/dX + ToF)

p+C —> p + X at 31 GeV/c



proton modeling in FLUKA is poor

p

CERN-PH-EP-2015-278

(dE/dx + ToF)

arXiv.org > hep-ex > arXiv:1510.02703

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High Energy Physics - Experiment

Measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton-carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS

N. Abgrall, A. Aduszkiewicz, Y. Ali, E. Andronov, T. Antićić, N. Antoniou, B. Baatar, F. Bay, A. Blondel, J. Blümer, M. Bogomilov, A. Bravar, J. Brzychczyk, S.A. Bunyatov, O. Busygina, P. Christakoglou, T. Czopowicz, N. Davis, S. Debieux, H. Dembinski, M. Deveaux, F. Diakonos, S. Di Luise, W. Dominik, T. Drozhzhova, J. Dumarchez, K. Dynowski, R. Engel, A. Ereditato, G.A. Feofilov, Z. Fodor, M. Gaździcki, M. Golubeva, K. Grebieszkow, A. Grzeszczuk, F. Guber, A. Haesler, T. Hasegawa, A. Herve, M. Hierholzer, S. Igolkin, A. Ivashkin, D. Joković, S. Johnson, K. Kadija, A. Kapoyannis, E. Kaptur, D. Kiełczewska, J. Kisiel, T. Kobayashi, V.I. Kolesnikov, D. Kolev, V.P. Kondratiev, A. Korzenev, K. Kowalik, S. Kowalski, M. Koziel, A. Krasnoperov, M. Kuich, A. Kurepin, et al. (78 additional authors not shown)

(Submitted on 9 Oct 2015)

Measurements of hadron production in p+C interactions at 31 GeV/c are performed using the NA61/ SHINE spectrometer at the CERN SPS. The analysis is based on the full set of data collected in 2009 using a graphite target with a thickness of 4% of a nuclear interaction length. Inelastic and production cross sections as well as spectra of $\pi^{\pm}$, $K^{\pm}$, p, K^0_S and Λ are measured with high precision. These measurements are essential for improved calculations of the initial neutrino fluxes in the T2K long-baseline neutrino oscillation experiment in Japan. A comparison of the NA61/SHINE measurements with predictions of several hadroproduction models is presented.

Comments:	submitted to EPJ C
Subjects:	**High Energy Physics - Experiment (hep-ex)**; Nuclear Experiment (nucl-ex)
Report number:	CERN-PH-EP-2015-278
Cite as:	arXiv:1510.02703 **[hep-ex]**
	(or **arXiv:1510.02703v1** **[hep-ex]** for this version)

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References & Citations

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Bookmark (what is this?)

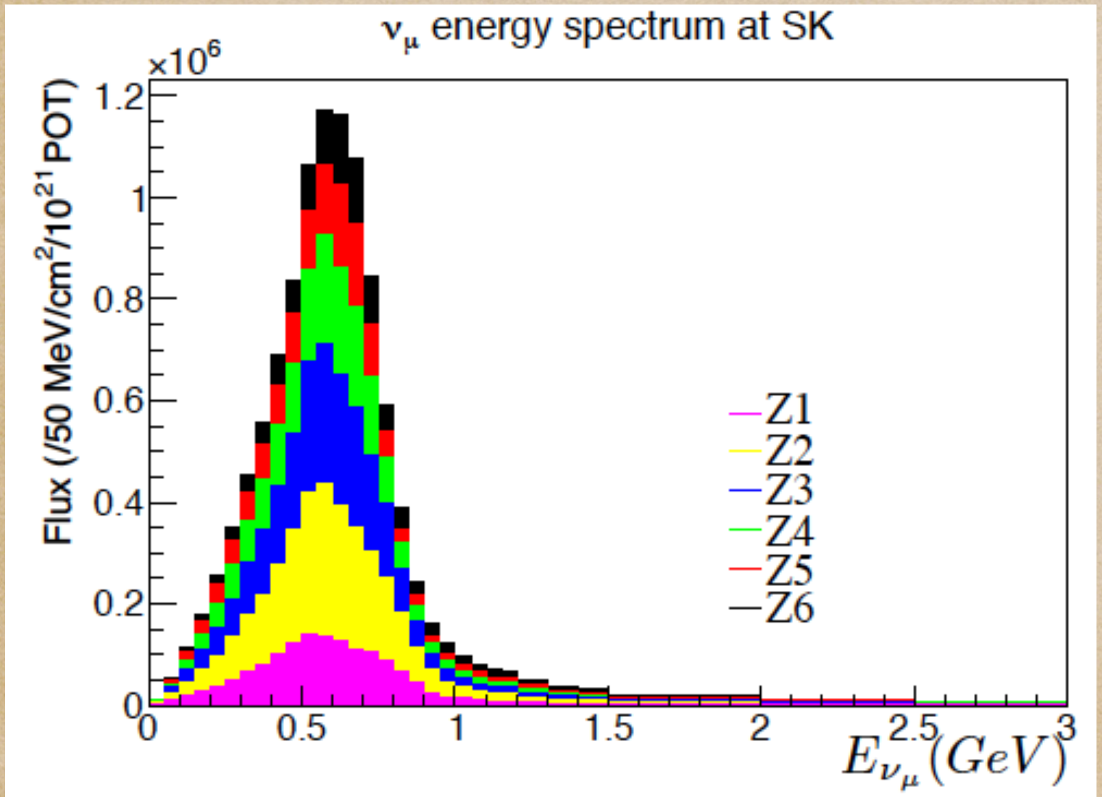
Thin target measurements:

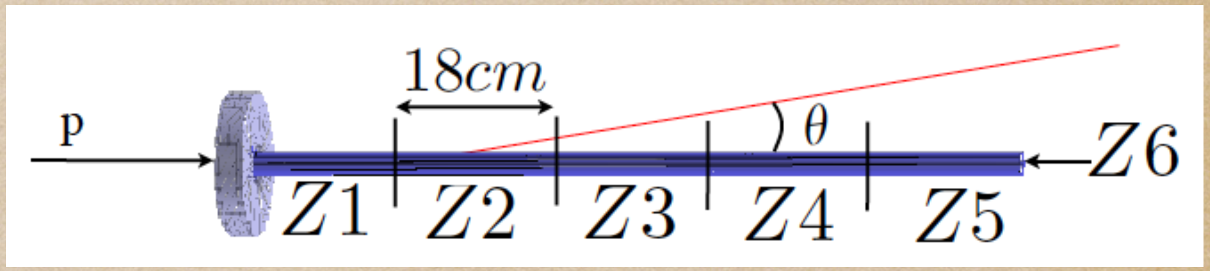
Just appeared on arXiv !!

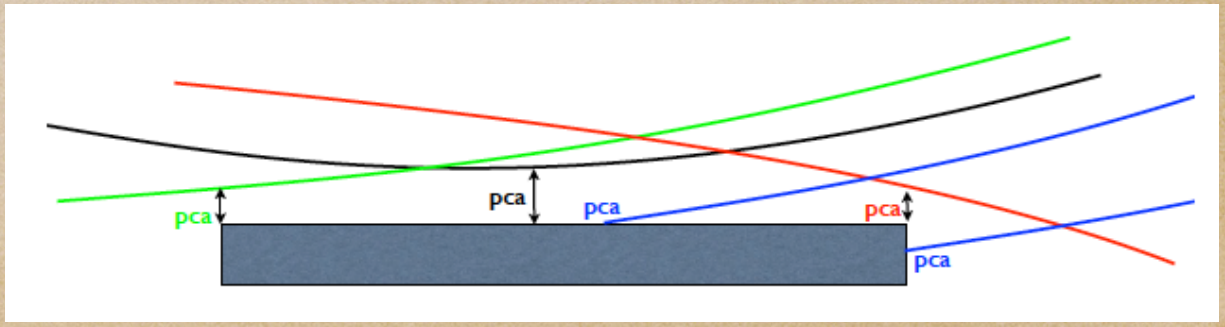
p+T2K replica: Analysis Method

2 complementary analysis performed

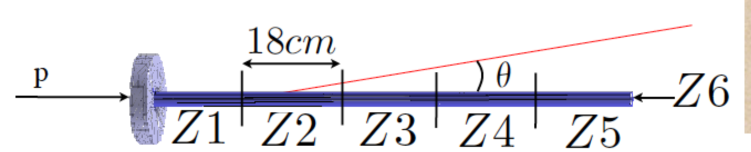
- dE/dX + ToF, h^-
- 5 bins of 18cm target surface and 1 bin of downstream face
  —> Neutrino energy spectrum has position dependence on target
- Determine exiting surface position by backward extrapolation
  —> Not like the thin target, difficult to reconstruct vertex position

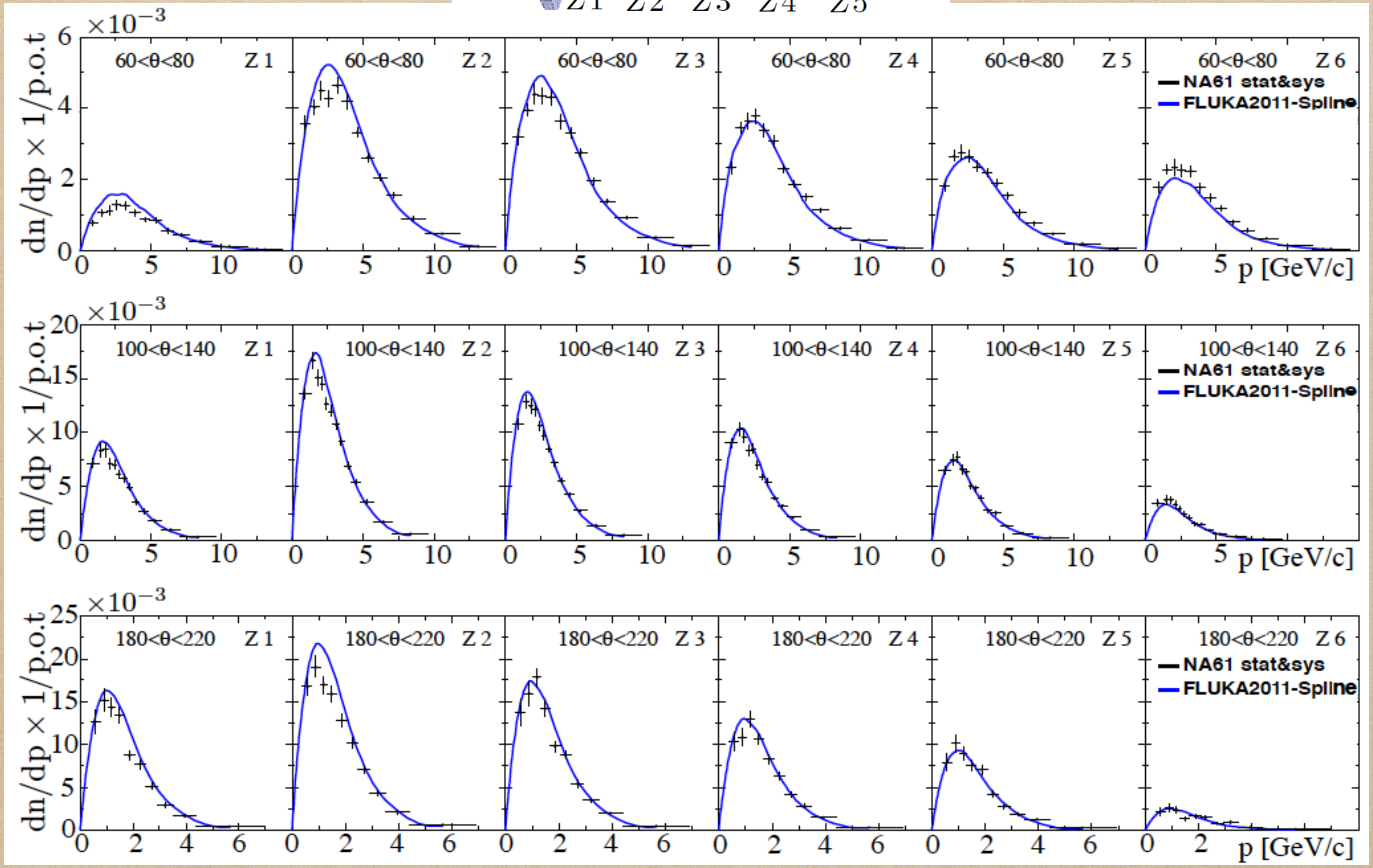






π^+ spectra on target surface



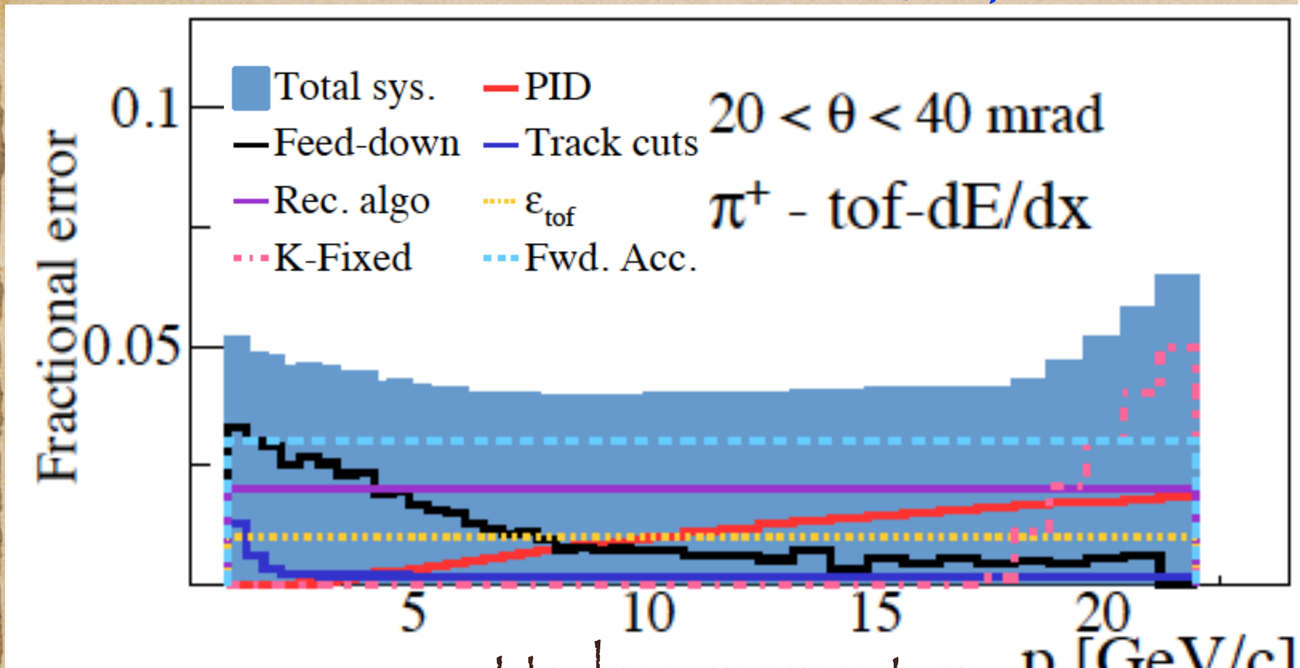


NA61 preliminary

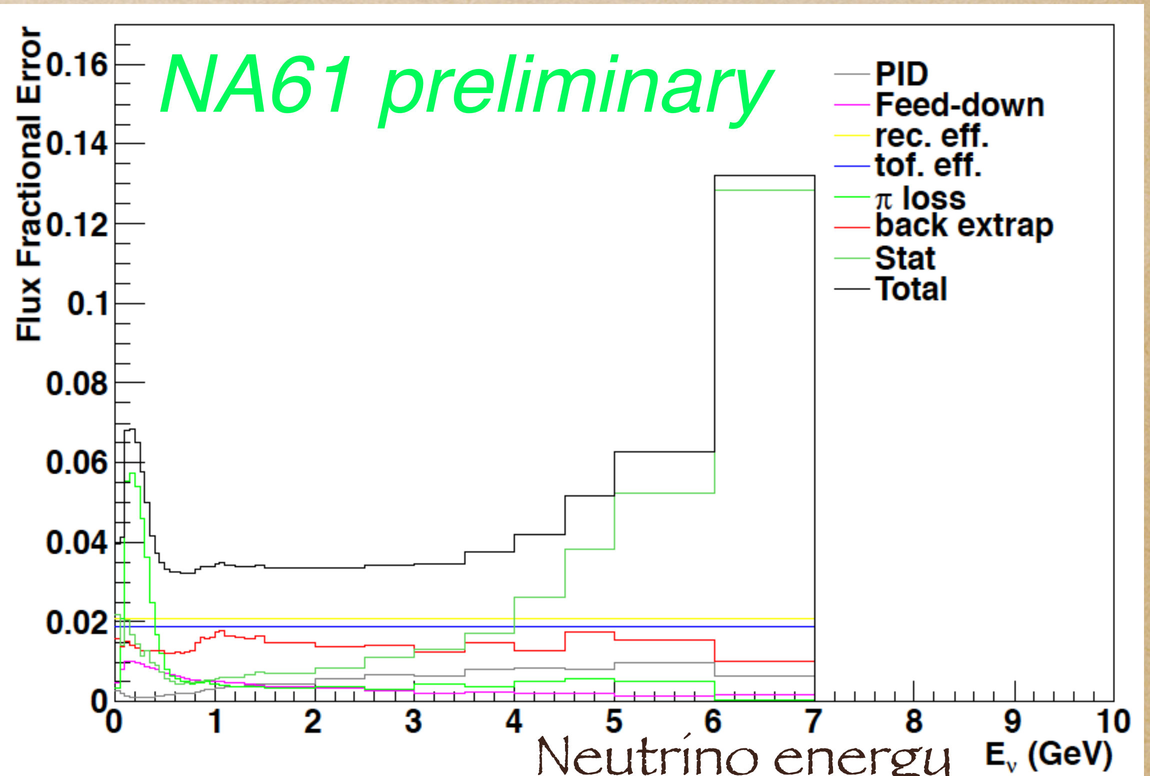
(Ph.D thesis: A. Häsler, univ. of Geneva)

Systematic uncertainties on T2K measurements

CERN-PH-EP-2015-278



Hadron momentum



Neutrino energy

Thin target uncertainty

Compared to published 2007 data

- Stat. uncertainty improved by factor 3
- Syst. uncertainty reduced by factor 2

T2K replica target uncertainty

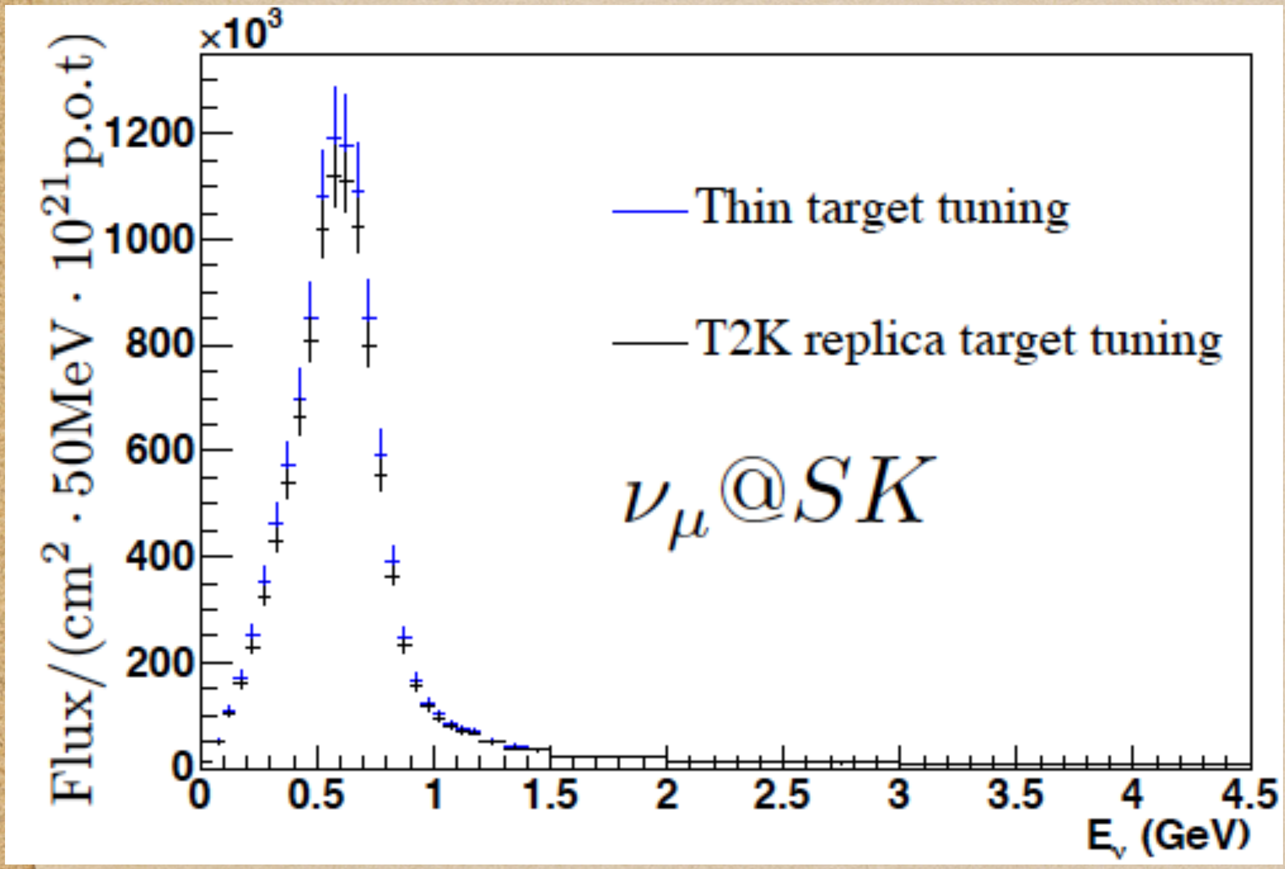
Compared to published 2007 data

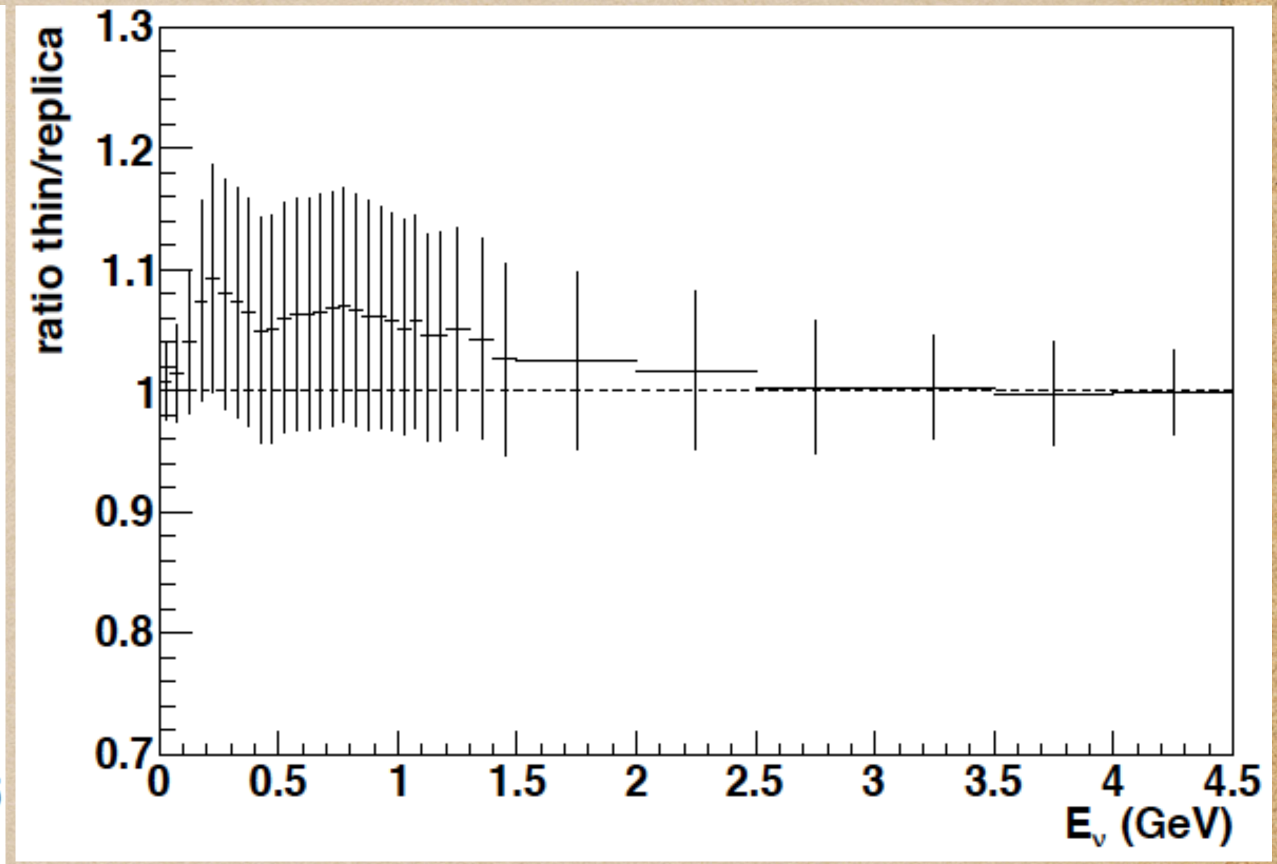
- Stat. uncertainty improved by factor 4
- Syst. uncertainty reduced by factor 2

Phys. Rev. C 84, 034604 (2011): $\pi^{\pm}$
Phys. Rev. C 85, 035210 (2012): $K^{\pm}$
Phys. Rev. C 89, 025205 (2012): K_s^0 & hyperon

Nucl. Inst. and Meth. A 701 (2013) 99: $\pi^{\pm}$

thin target vs replica target result

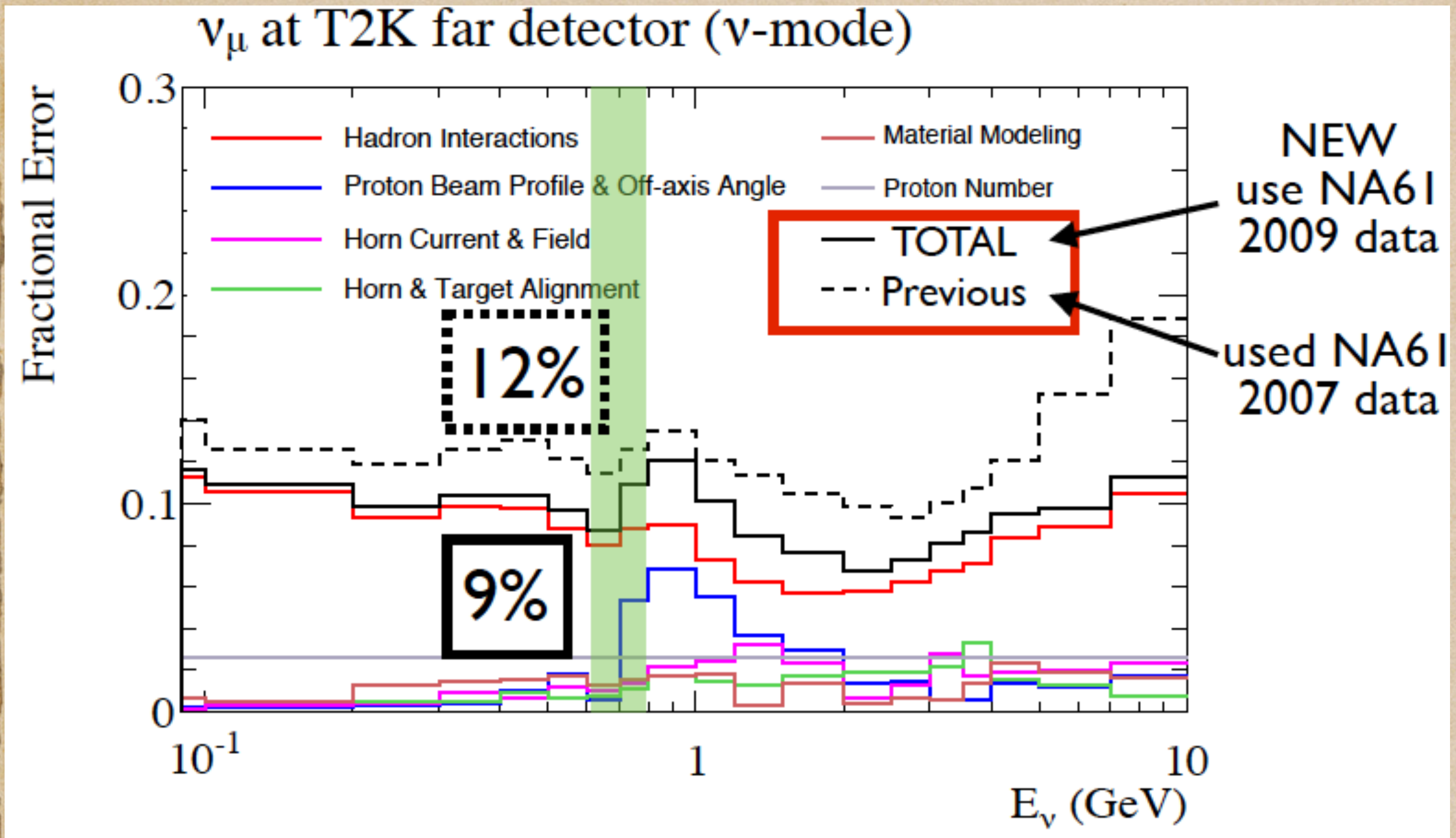




(Ph.D thesis: A. Häsler, univ. of Geneva)

good agreement within uncertainty

T2K flux uncertainty with new measurements



Including NA61 thin target measurements only

(EPS2015, L. Zambelli)

- T2K ν-flux uncertainty improves ~25% compared to former result

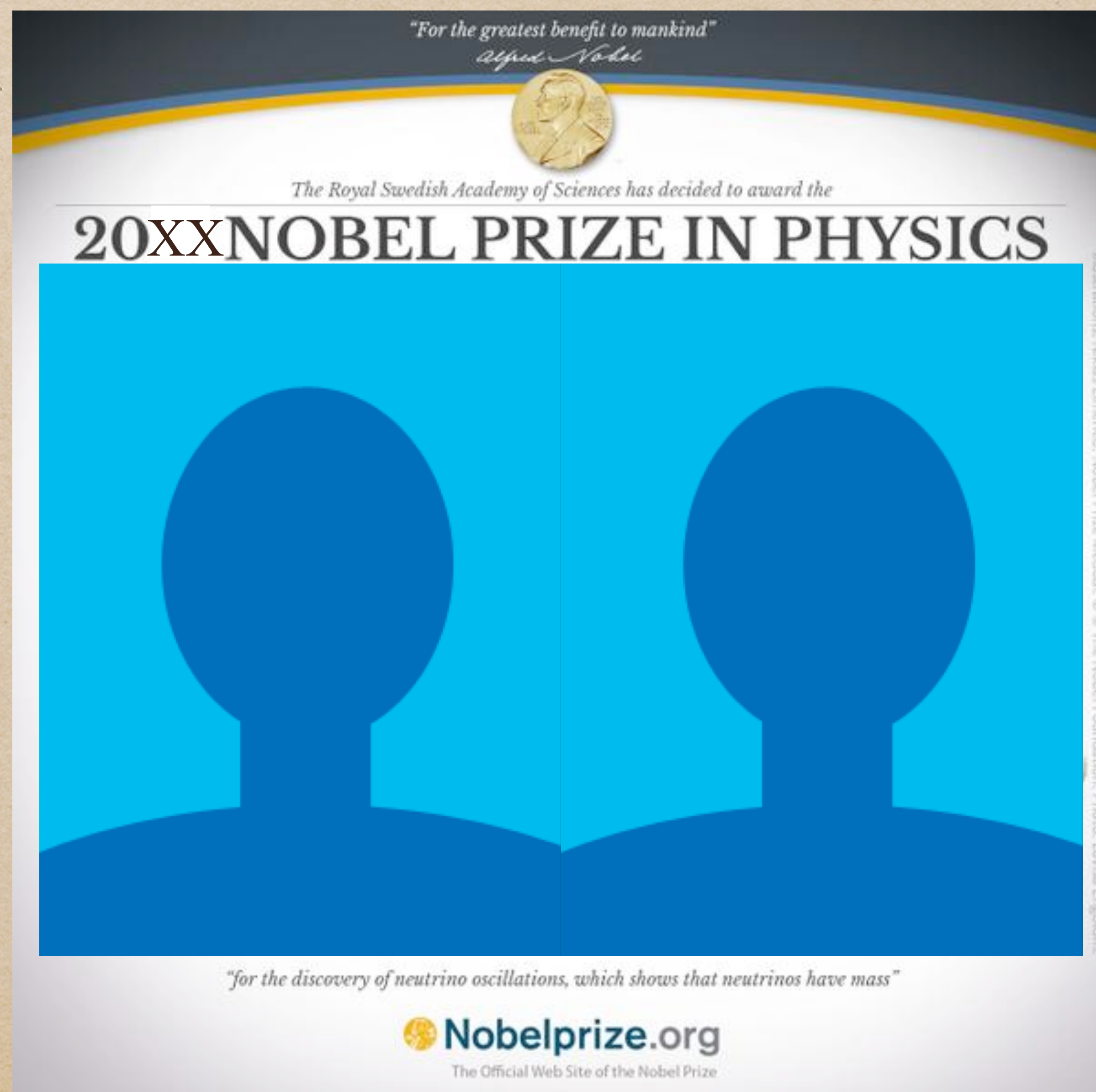
—> Uncertainty coming from secondary hadron interactions is now dominant

—> Further improvements expected with T2K replica target measurement

(2009 T2K replica analysis is ready for T2K simulation)

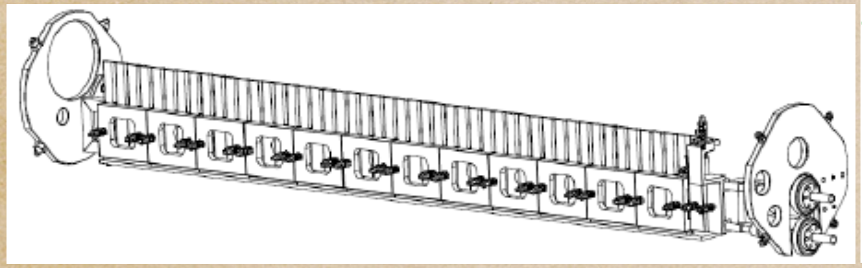
—> T2K replica analysis with 2010 data is ongoing (x4 statistics)

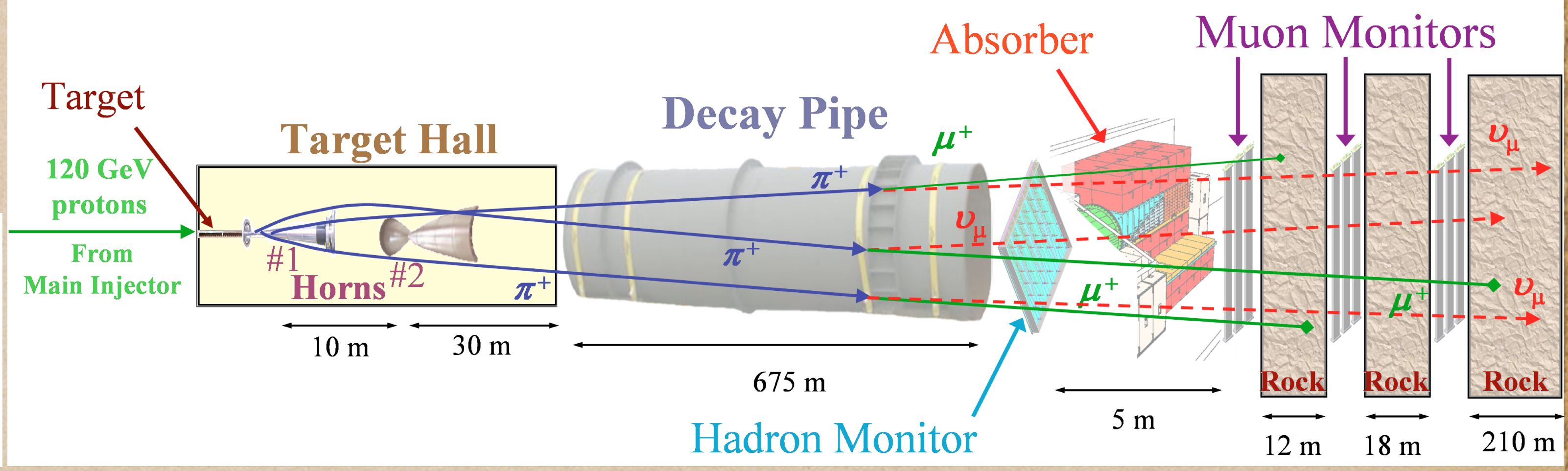
Future Prospects



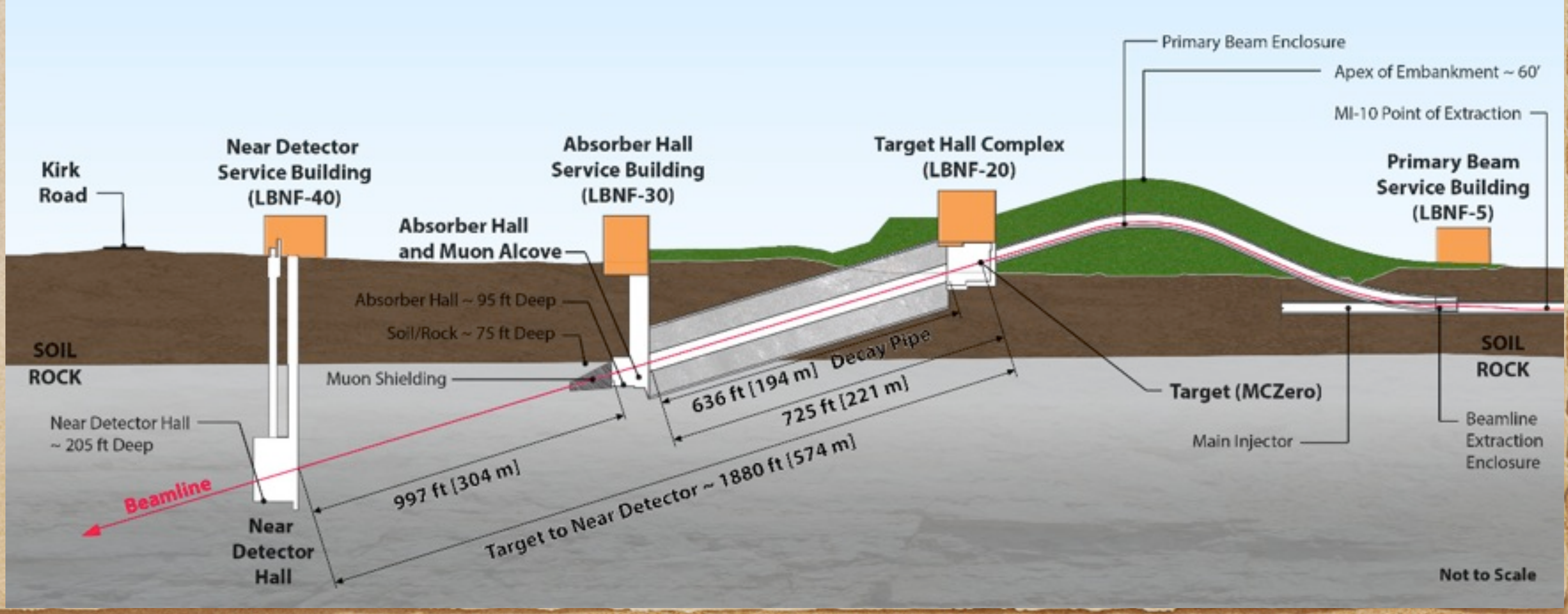
US neutrino programs: Now and Future

- NuMI: Neutrinos at the Main Injector
  - 120 GeV/c protons on target
  - target: graphite fins (2.0 λ)
  - max power of 700 kW



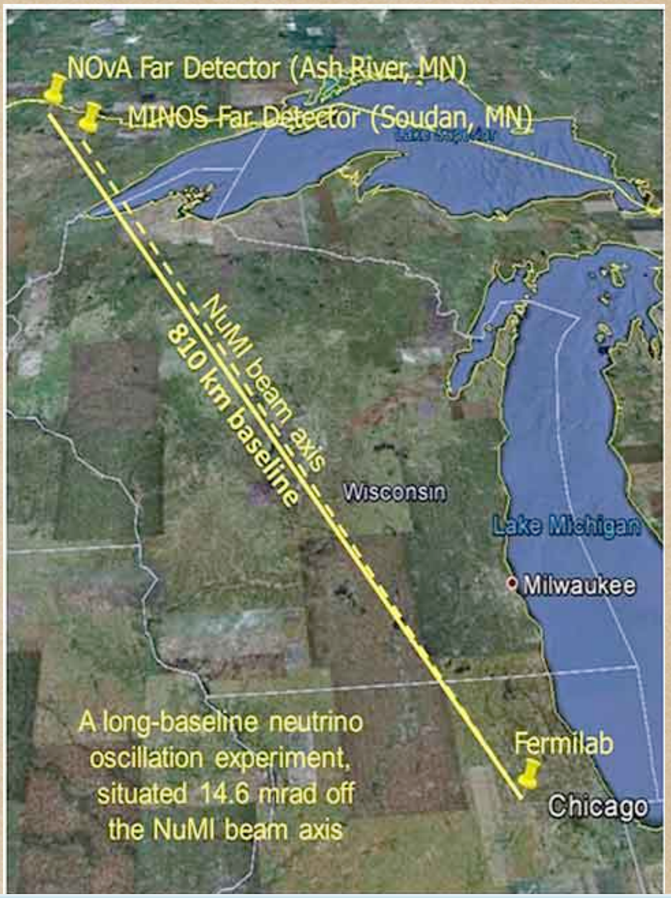


- LBNF: Long Baseline Neutrino Facility
  - 60-120 GeV/c protons on target
  - target: graphite (primary), Be (alternative)
  - max power of 2.4 MW



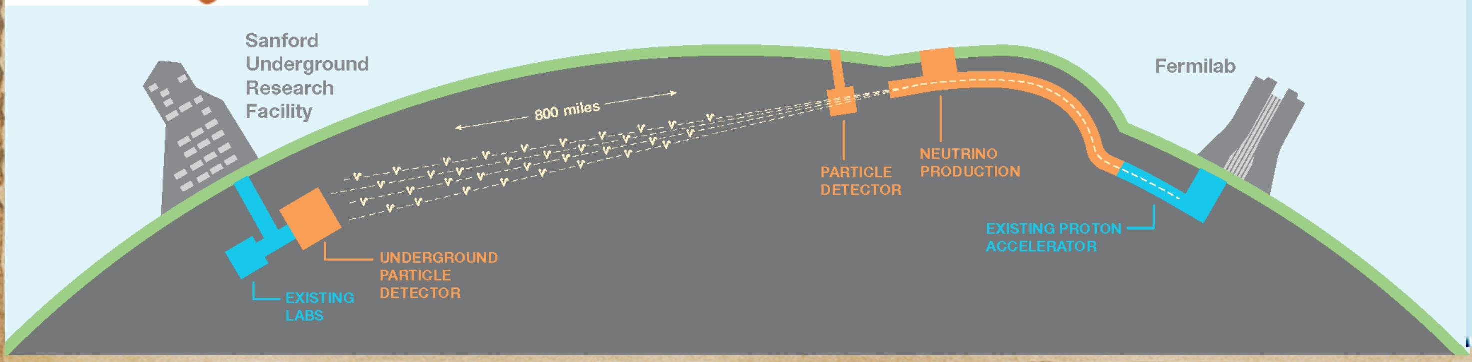
US neutrino programs: Now and Future

- NuMI: Neutrinos at the Main Injector
  - 730 km on-axis baseline: MINOS(+), MINERvA
  - 810 km off-axis baseline: NOvA

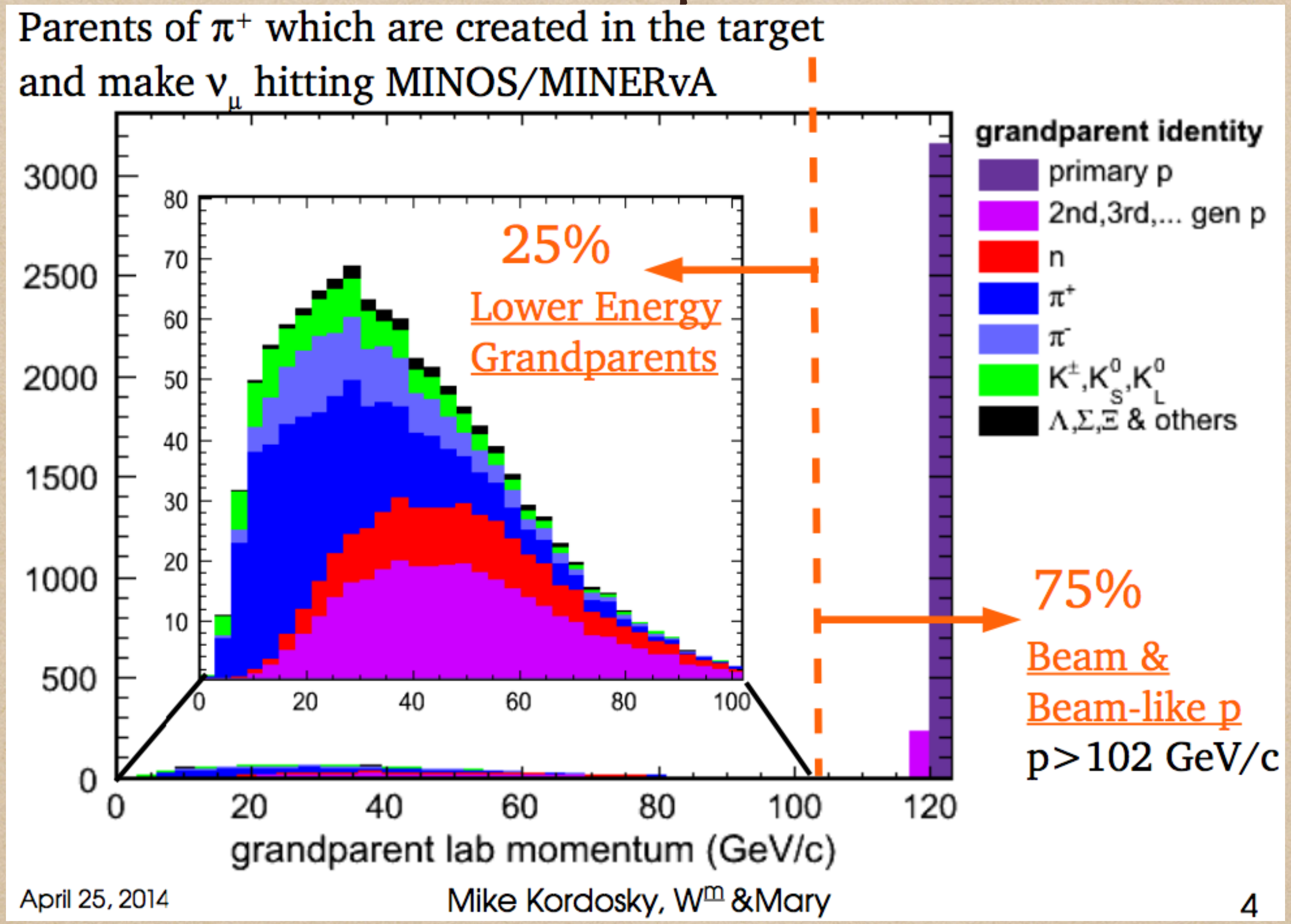


- LBNF: Long Baseline Neutrino Facility
  - 1300 km off-axis baseline
  - Far-detector: DUNE in South Dakota
  - 10 kton liquid argon module x 4 = 40 kton

Deep Underground Neutrino Experiment



Neutrino's grandparent
— 120 GeV/c proton beam —



(M. Kordosky, William&Mary)

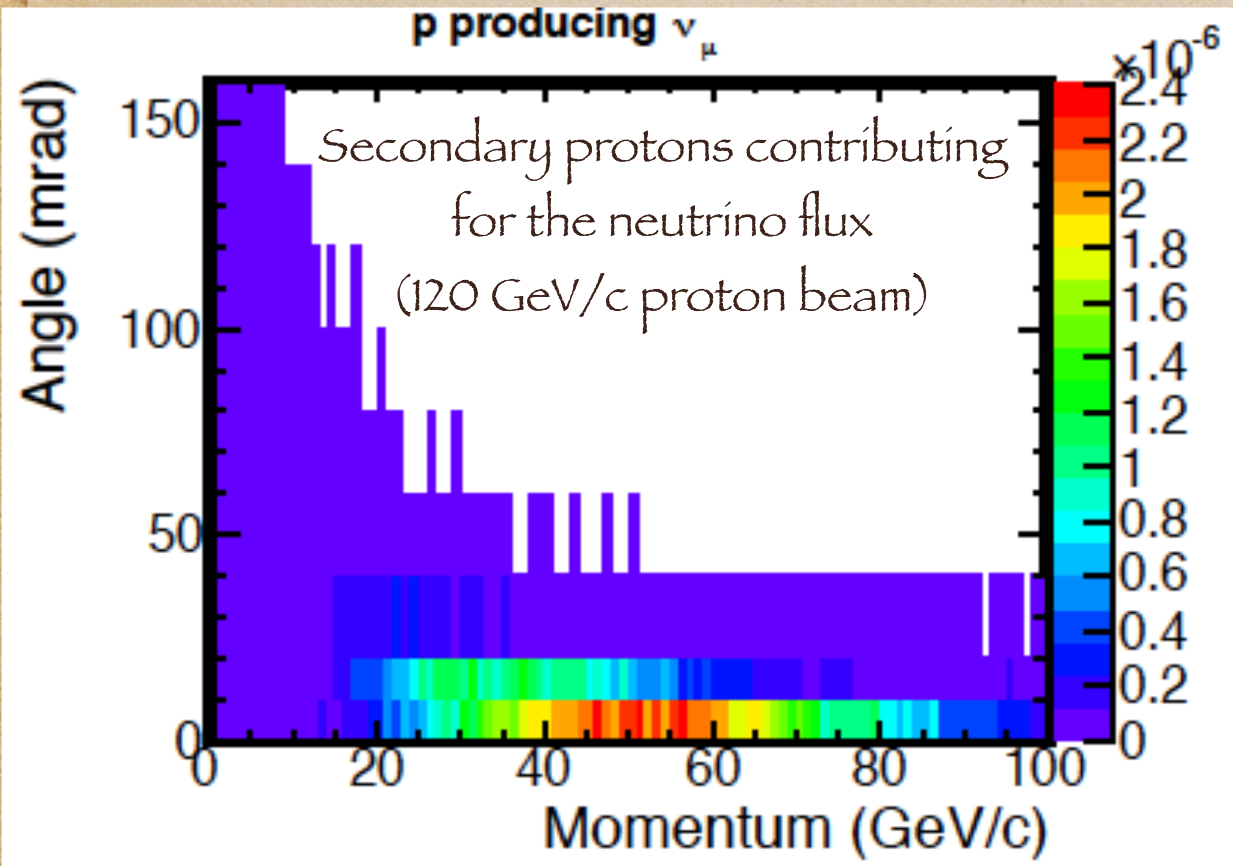
- *75% of neutrino is produced via primary(-like) protons*
- 25% of neutrino has lower energy protons/neutrons/pions grandparents

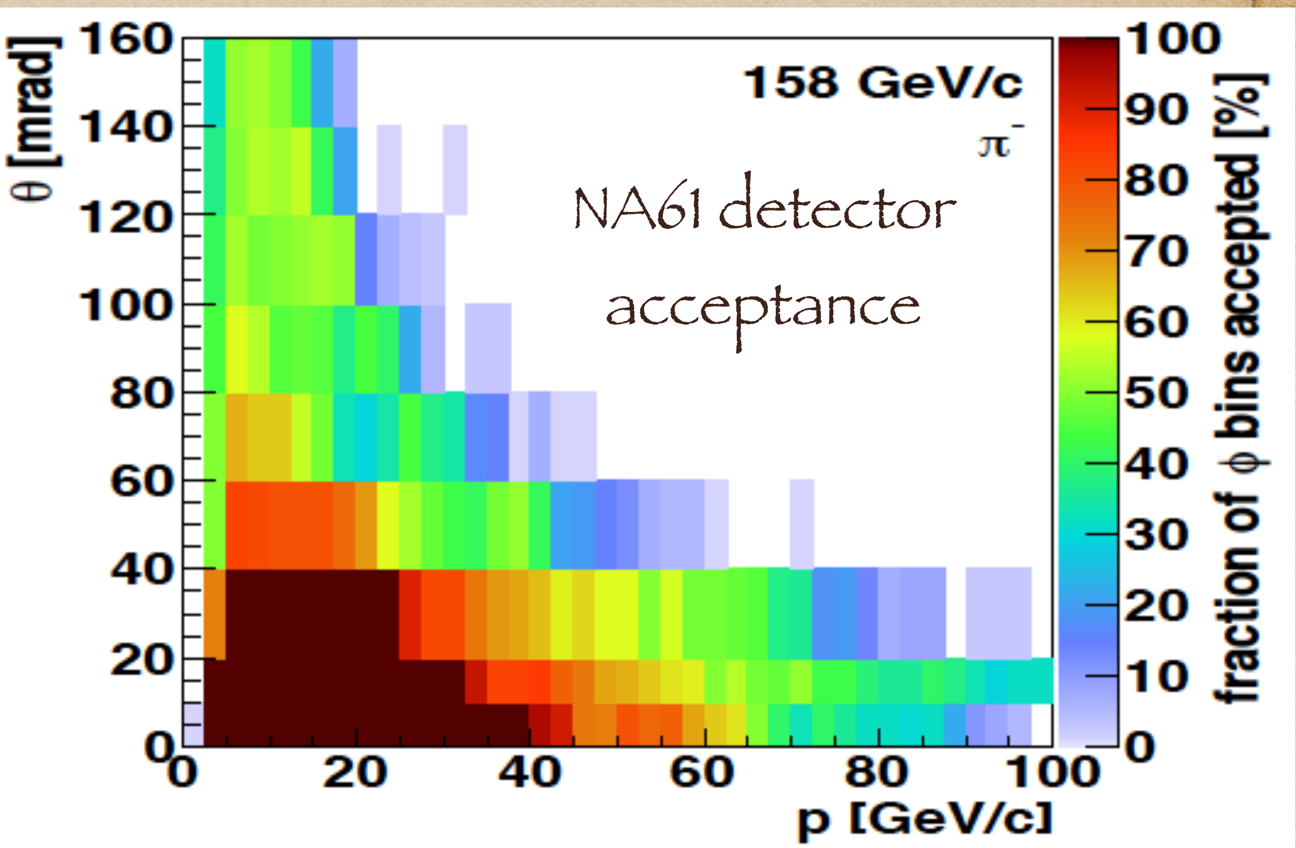
—> Worth to take not only proton data but also π^+ on C/Al/Be target data

(Analysis is ongoing for 31 GeV/c π^+ beam on C target using 2009 data for T2K!)

Phase space and NA61 acceptance

— 120 GeV/c proton beam —



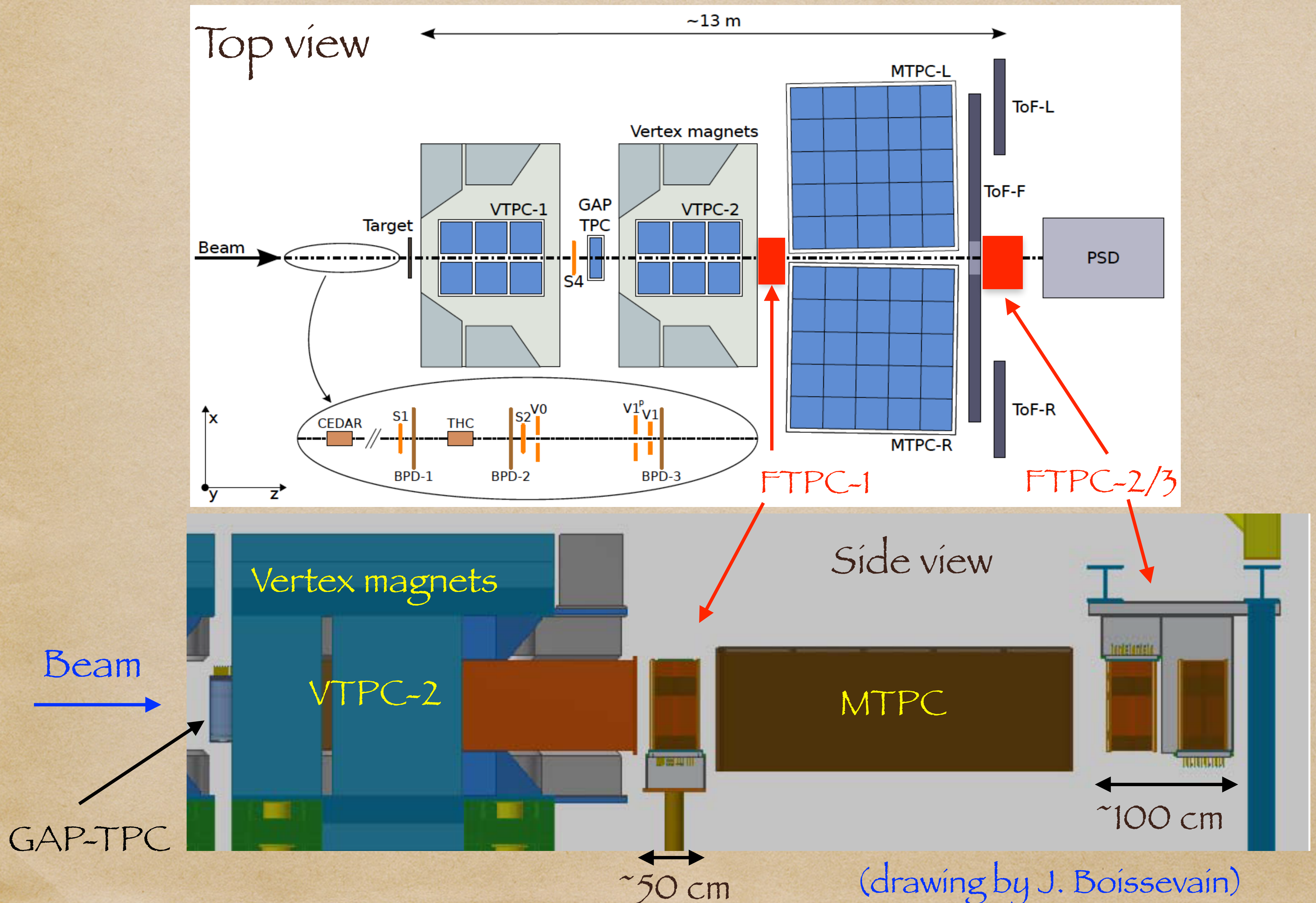


- Secondary protons contributing for the neutrino flux are in the forward direction

  —> NA61 acceptance is poorer because of the gap between MTPCs

NA61 TPC Upgrade

- New forward TPCs (FTPC) to gain forward proton acceptance

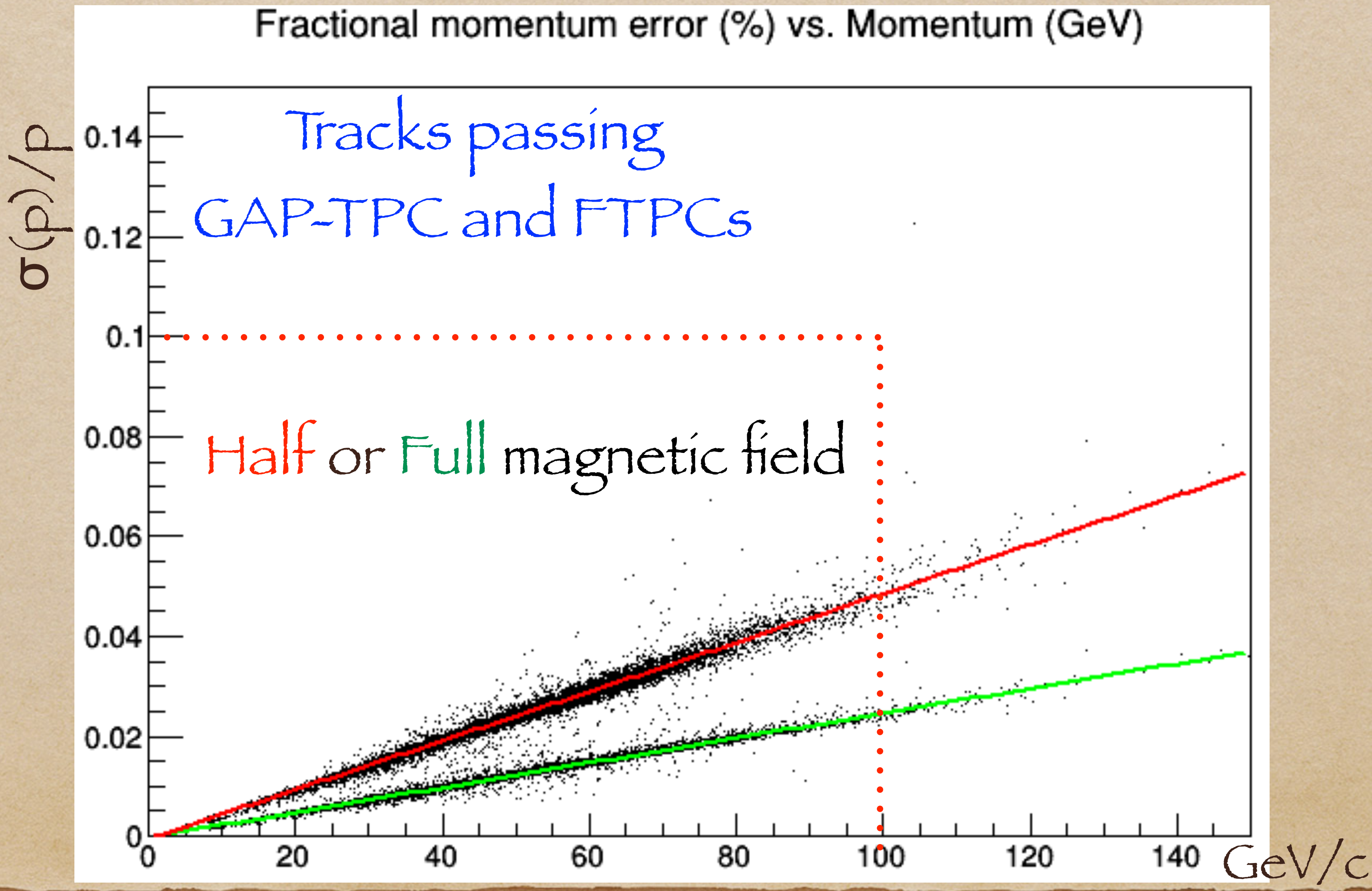


(drawing by J. Boissevain)

FTPCs

- Detector requirements
  - Good acceptance for forward particles —> Locate on the beam-axis
  - Good momentum resolution targeting $\sigma(p)/p < 10\%$ at 100 GeV/c

—> FTPCs track position resolution (600-900 μm) satisfy this requirement



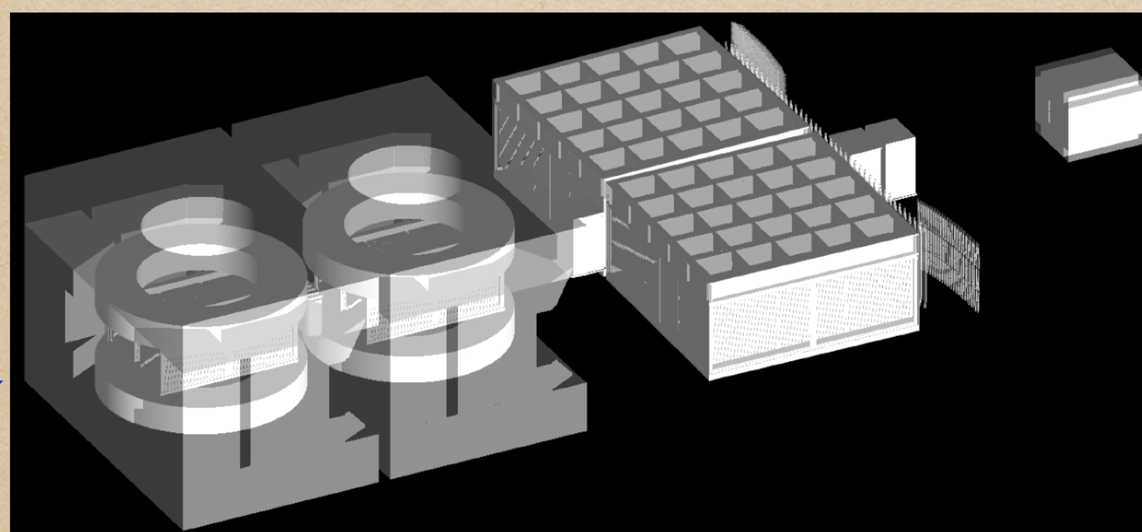
FTPCs

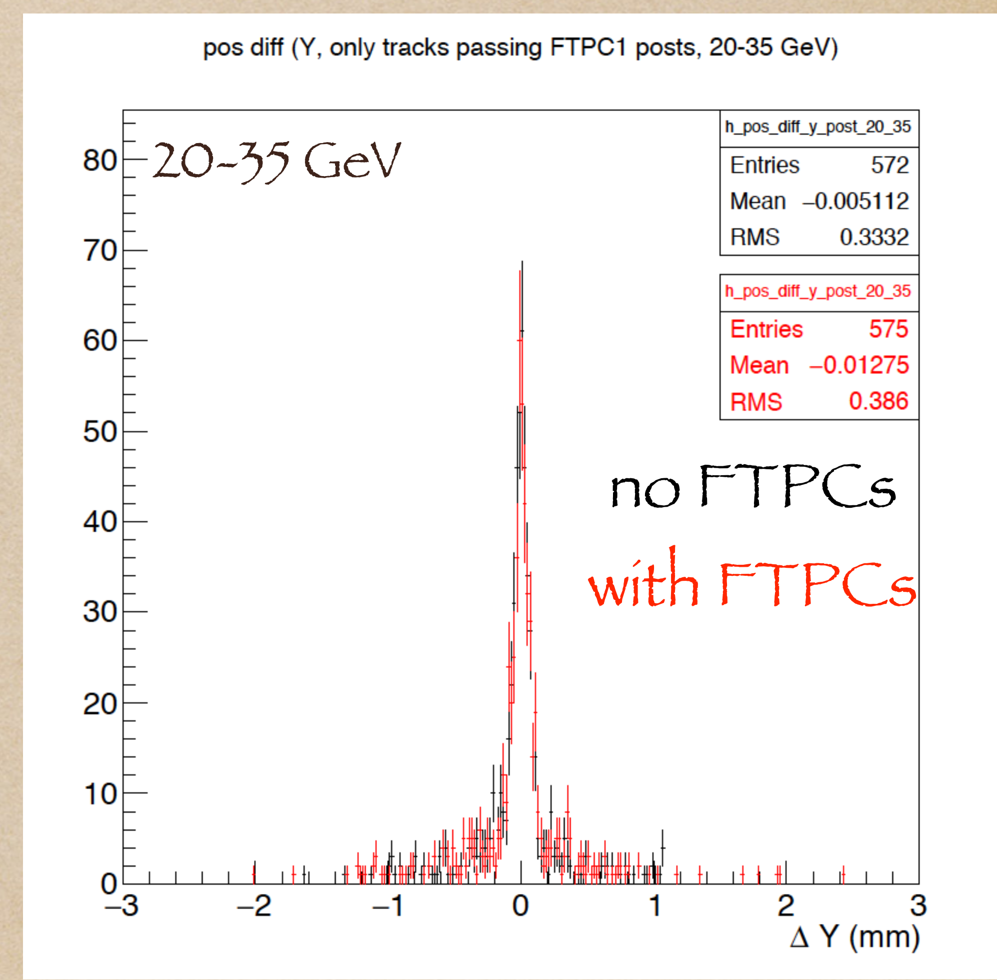
- Detector requirements
  - Minimal multiple scattering because of material shadowing

—> Estimate with Geant4 simulation   Δy = (Truth - estimated position)

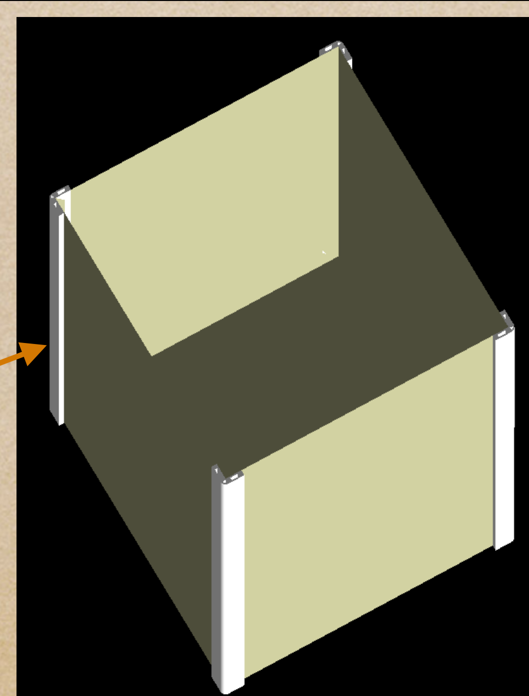
at MTPC

Beam





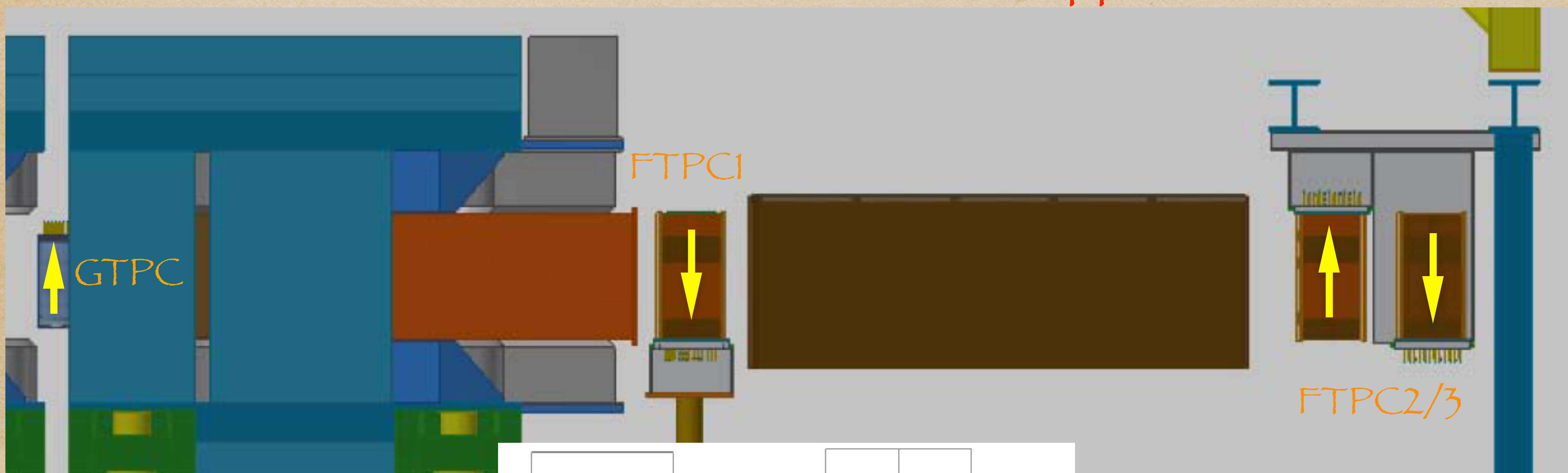
track passing
through the corner materials



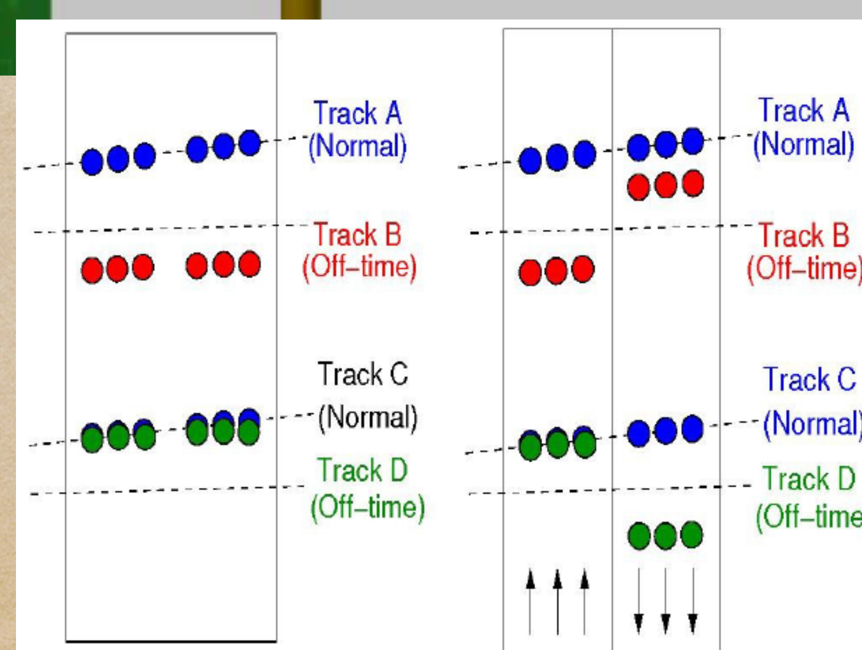
~50um effect
—> small enough

FTPCs

- Detector requirements
  - Rejection power for pile-up tracks
    —> each combination of forward TPCs has opposite drift direction



(From Jan Boissevain)



(from Dezso Varga, Budapest)

NA61 schedule for neutrino program

- Experimental settings
  - Beam energy: 60 - 120 GeV/c for protons/pions
  - Target: graphite, Aluminum, Beryllium
- 2015
  - 120 GeV and 60 GeV proton/pion beam on C/Al/Be target —> Postponed
- 2016
  - Beam commissioning of FTPCs completes by mid-July
  - 120 GeV and 60 GeV proton/pion beam on C/Al/Be target from October
  - NuMI target replica may be used (under discussion)
- 2017-2018
  - Continue data taking (details are under discussion)
- 2019-2020 LS2 (no beam)

NA61 neutrino program beyond 2020

- LBNF/DUNE
  - Beam energy and target design will likely be determined

    —> Hadron production measurements with DUNE replica or prototype target?
- T2HK (Successor of the T2K experiment)
  - New far detector with upgraded high-intensity neutrino beam from J-PARC
  - New target design is likely necessary

    —> Dedicated hadron production measurements for T2HK target?

Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

Systematic error Errors used in the sensitivity studies

~ Realistic estimation of the errors based on the experiences ~

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	2.9	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	4.9
Far Det. +FSI	0.7	1.0	1.7	1.1	3.5	5.6
Total	3.3	3.3	6.2	4.5	6.8	8.1

(Neutrino 2014, Y. Hayato)

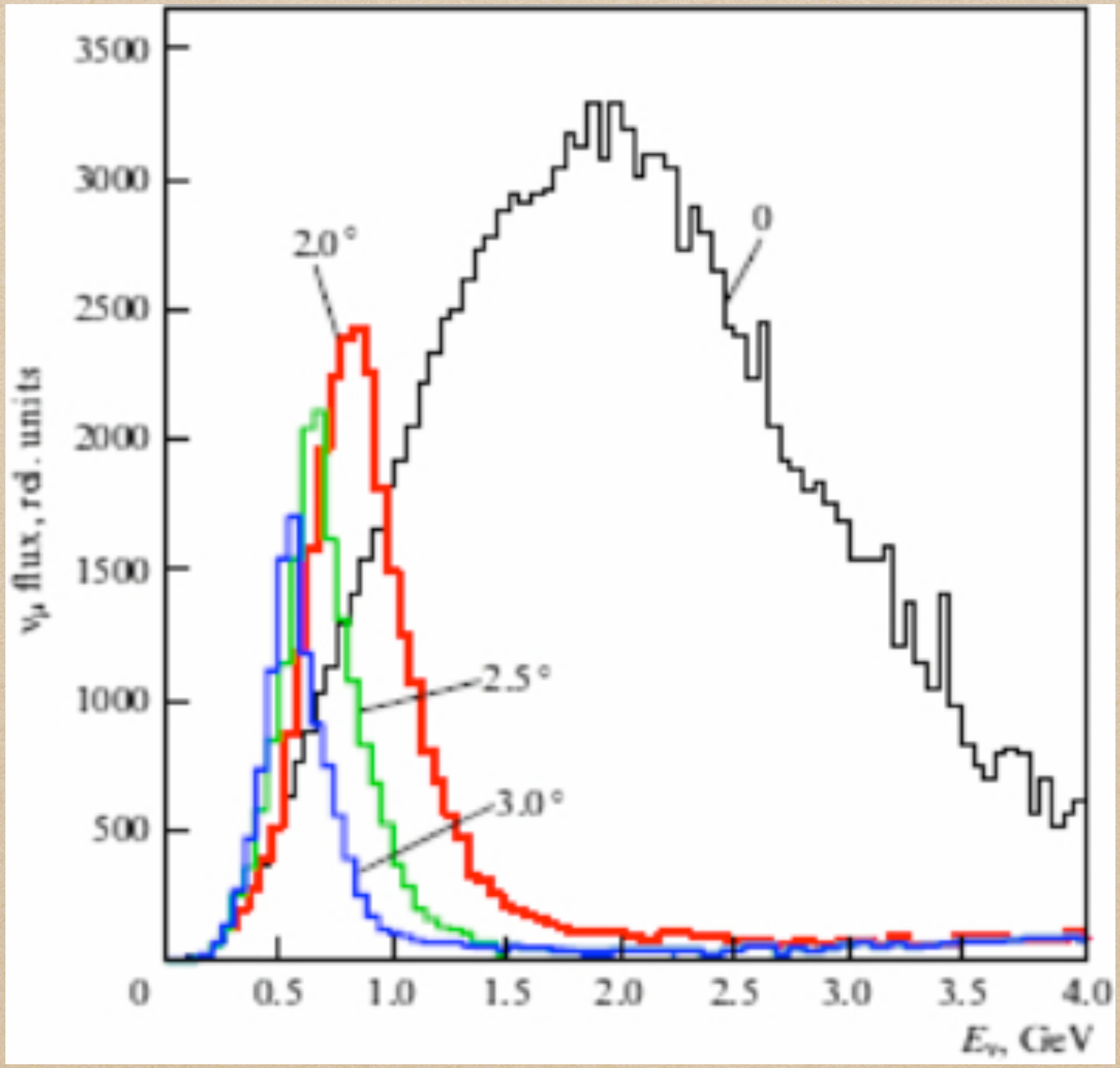
Summary

- T2K neutrino flux uncertainty is successfully constrained
  - Have taken thin and replica target data
  - Replica target analysis with full statistics is ongoing
- Hadron production measurements for US neutrino program will follow
  - New forward TPCs will be installed in 2016
  - 2016-2018: taking data for p/π 60 - 120 GeV/c beam on thin C/Al/Be target
- Discussions for post-LS2 measurements have just started
  - Measurements with replica target of LBNF and T2HK are possibility

Stay tuned !!

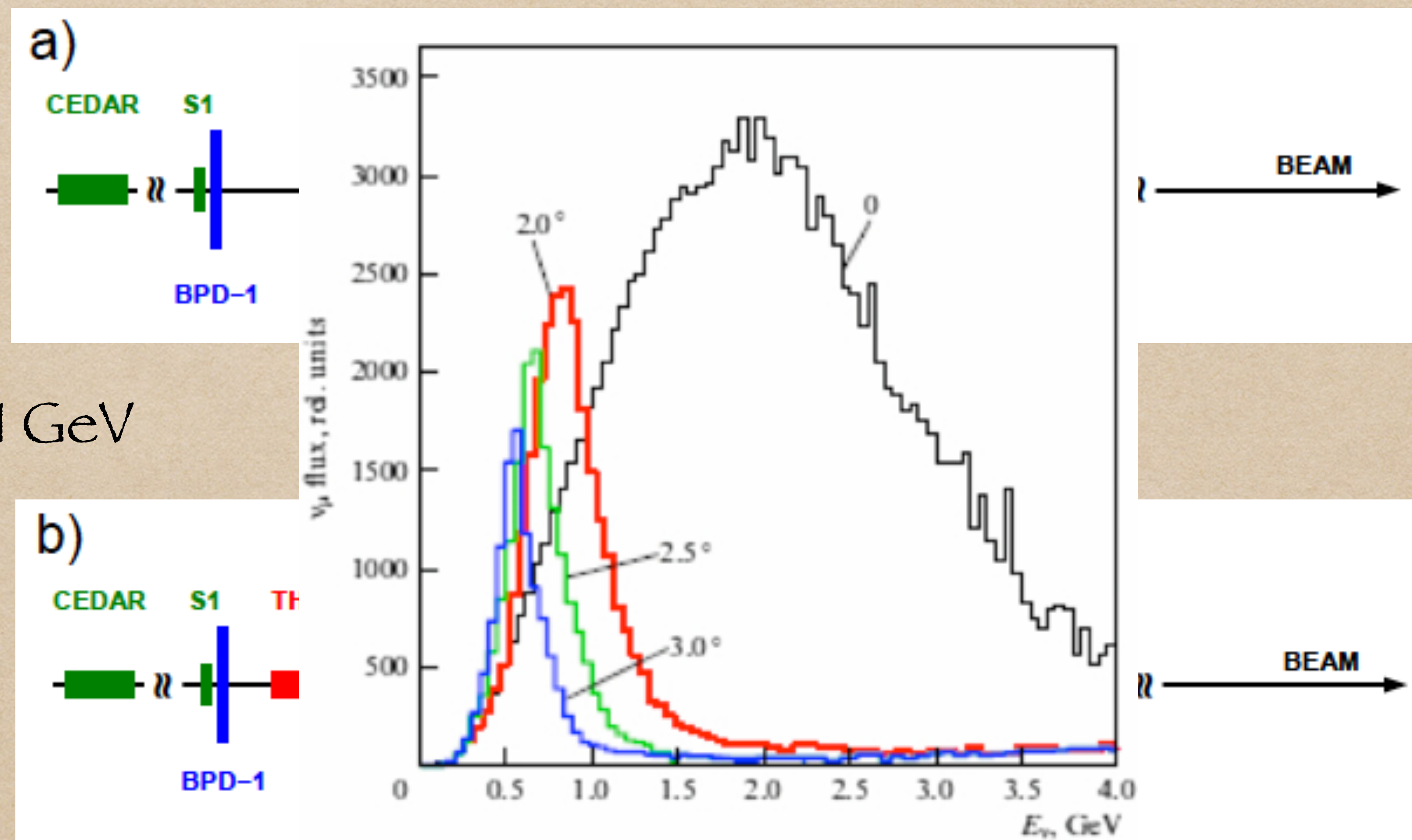
backup

Off-axis beam (T2K)



Trigger

- p+C 31 GeV
- p+T2K 31 GeV



T1	T2	T3	T4
$S1S2\overline{V1'}\ CED\ \overline{C}$	$S1S2S3\overline{V1'}\ CED\ \overline{C}$	$S1S2S3\overline{V0}\ \overline{V1'}\ CED\ \overline{C}$	$S1S2S3\overline{V1'}$

Cedar Scan

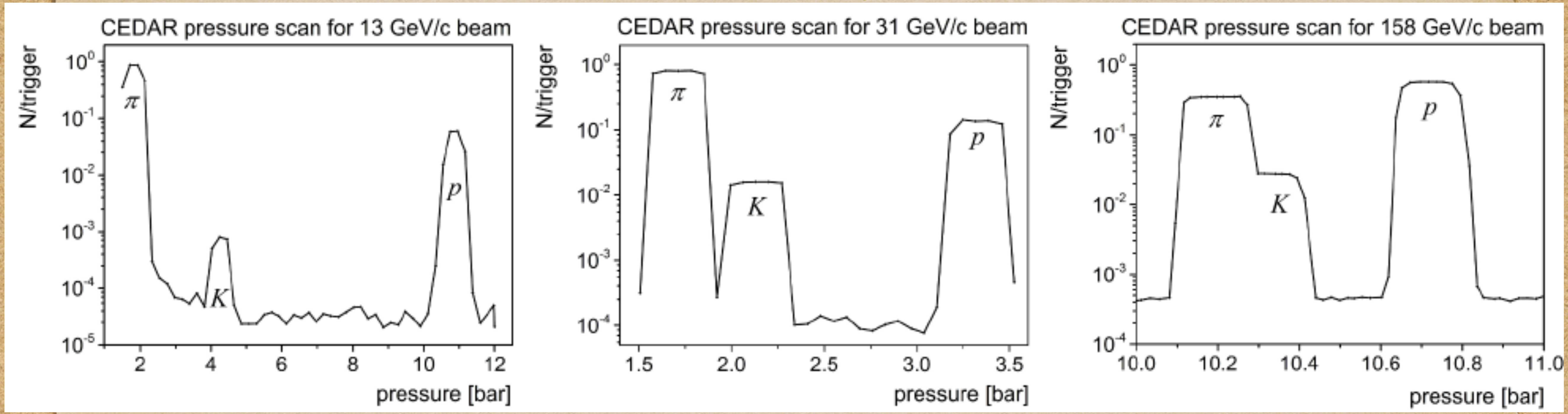
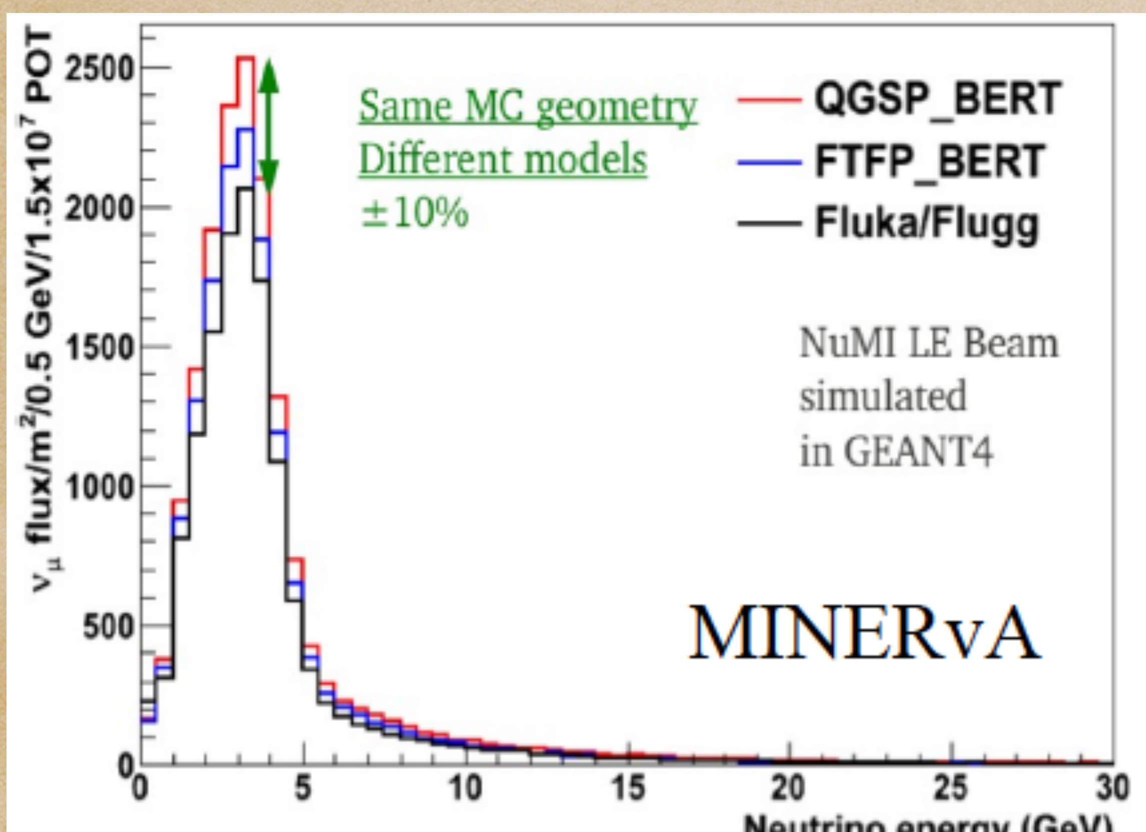


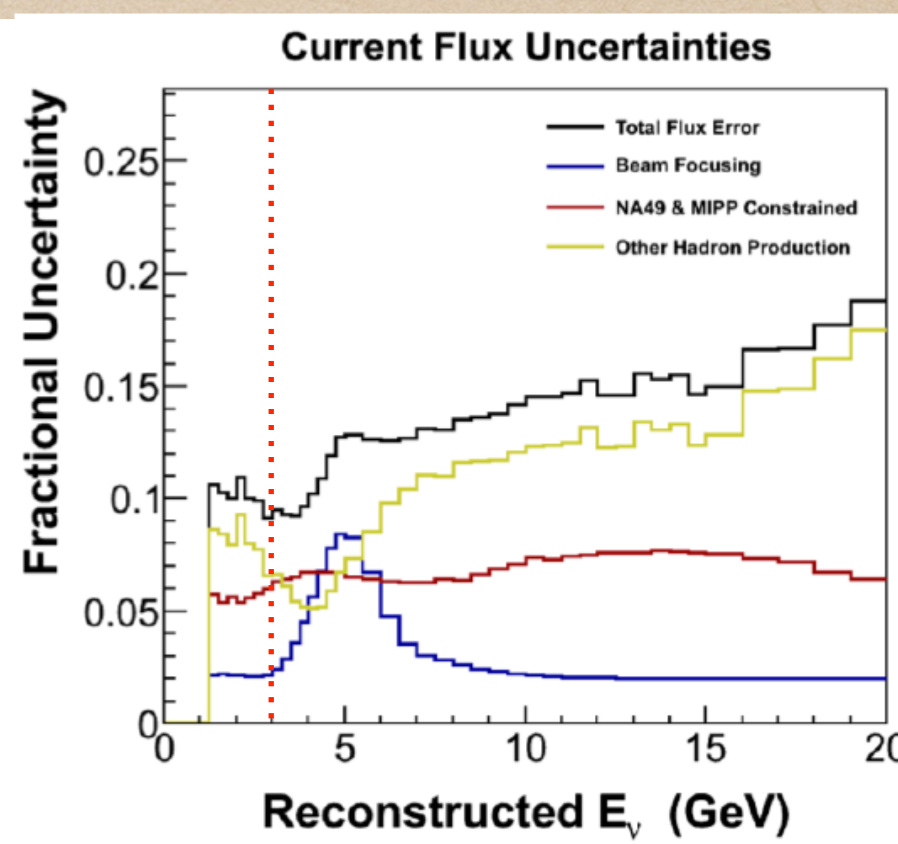
Figure 4. Counts of hadrons per incident beam particle from the CEDAR counter as a function of the gas pressure within the pressure range which covers maxima of pions, kaons and protons at 13 (*left*), 31 (*middle*) and 158 GeV/*c* (*right*).

2014 JINST 9 P06005

Neutrino Flux Prediction for NuMI

- Rely on hadron production models (π, K, etc… —> ν + X)
  - No perfect model exists (e.g. FLUKA, GEANT4)
- The leading systematic uncertainty sources for the flux prediction

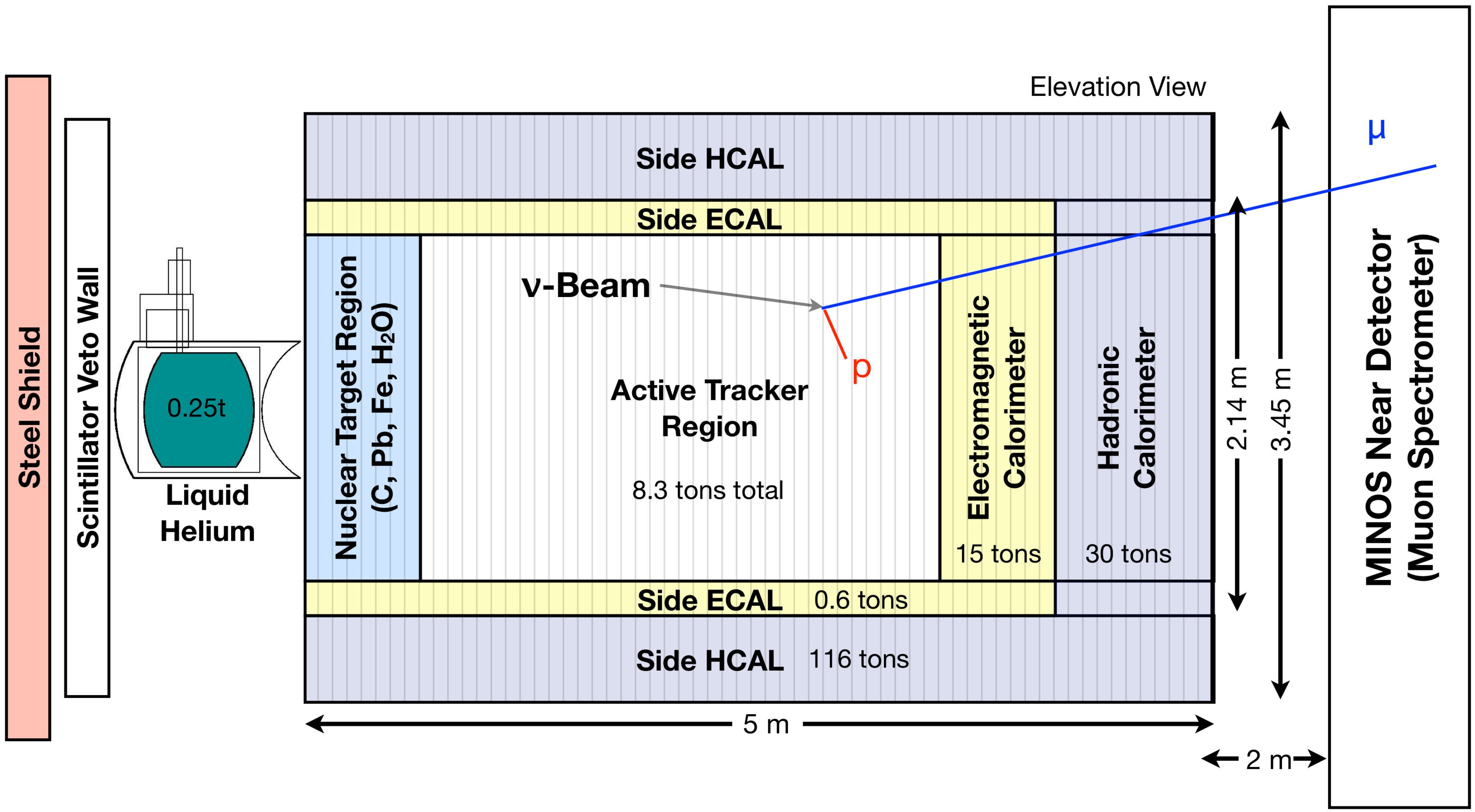




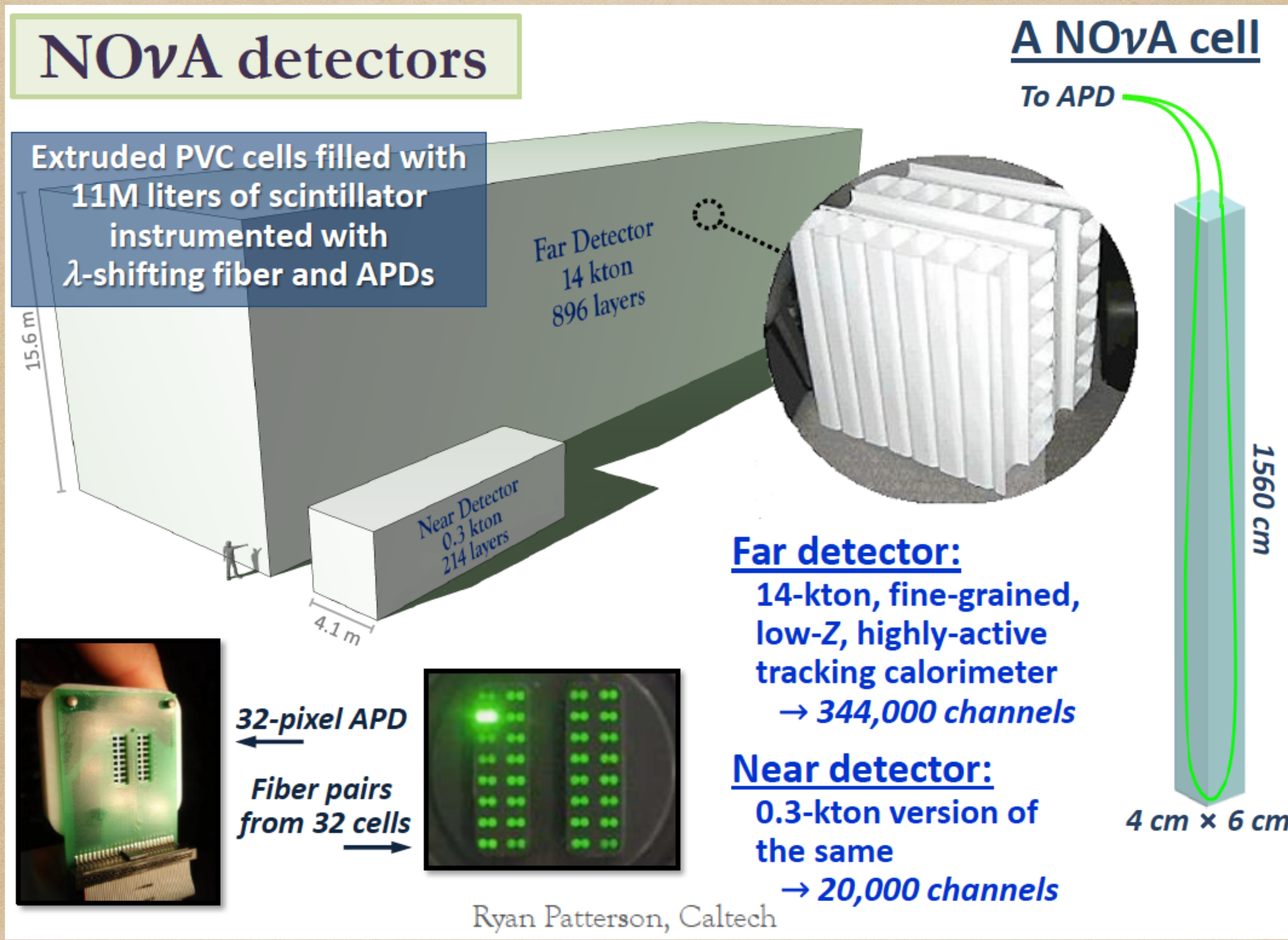
(NuINT 2014, D. Harris)

—> Precise hadron production measurements required

MINERvA detector

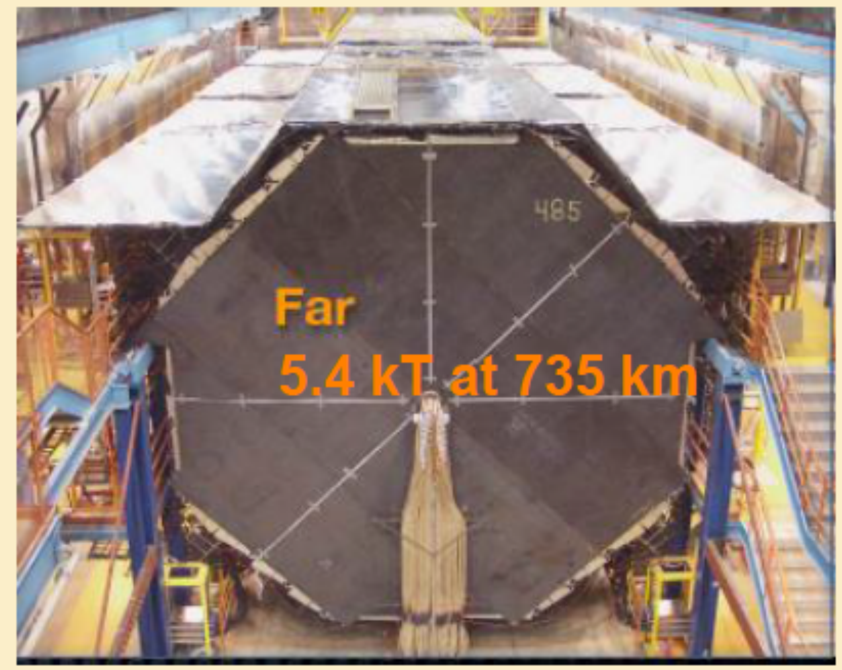


NOvA


NOνA detectors
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs
15.6 m
Far Detector
14 kton
896 layers
Near Detector
0.3 kton
214 layers
4.1 m
A NOνA cell
To APD
1560 cm
4 cm × 6 cm
Far detector:
14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ 344,000 channels
Near detector:
0.3-kton version of the same
→ 20,000 channels
32-pixel APD
Fiber pairs from 32 cells
Ryan Patterson, Caltech

MINOS (+)

MINOS DETECTORS



Steel/Scintillator Tracking Calorimeters

- As similar as possible functionally
- Alternating layers of steel (2.5 cm thick) and scintillator
- Alternating scintillator planes at 90 degrees
- Light collection by wavelength shifting fibers
- **Magnetized**, average B field 1.3 T
  - Able to distinguish between μ_- and μ_+

ND Measurements are Used to Predict Spectrum in FD