Hadron Production Measurements for Neutrino Experiments

This presentation is largely based on this workshop and its conclusions

Hadroproduction experiments provide an inportant input for the creation of a good neutrino flux model for neutrino oscillation experiments

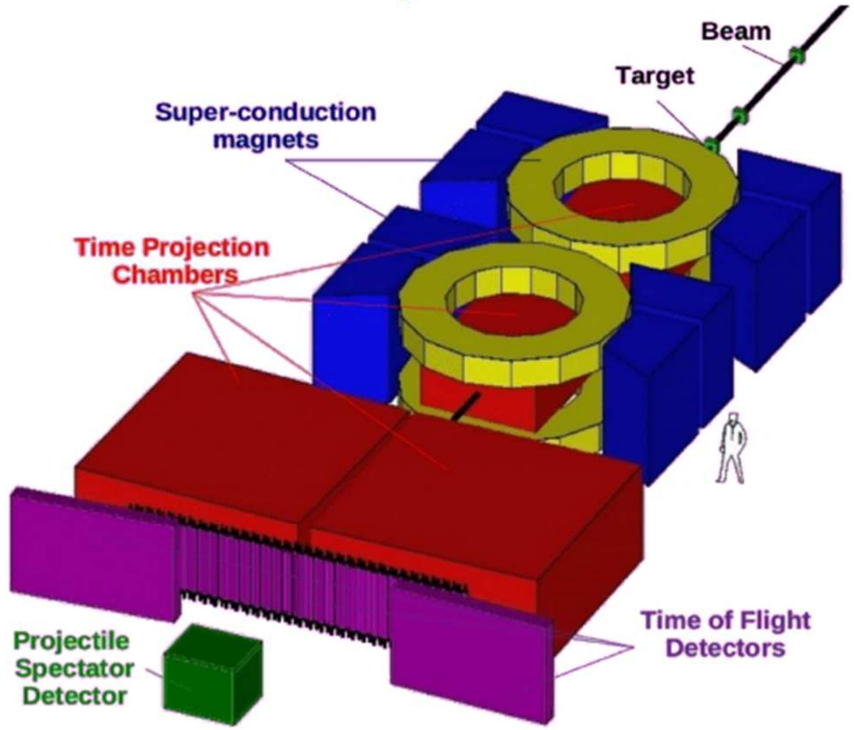
The typical neutrino oscillation experiment comprises

-- target, in which pi/K/hyperons are produced → neutrinos
-- focusing system in which particles are bent and do interact
-- decay tunnel
-- beam monitoring instrumentation
    -- muon monitors,
    -- neutrino monitors such as INGRID in T2K
-- near detector to measure cross-sections and topologies
«flavour and energy of neutrino interactions before the oscillations»
-- far detector
«flavour and energy of neutrino interactions after the oscillations»

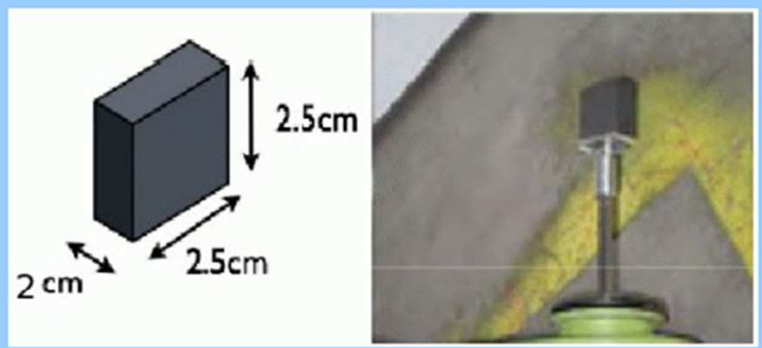
Deliverables
-- flux and errors on flux for the various neutrino flavours
    -- also their ratios (ν_e/ν_μ) and errors
-- near/far detector flux ratio (in absence of oscillations)

SPS Heavy Ion and Neutrino Experiment

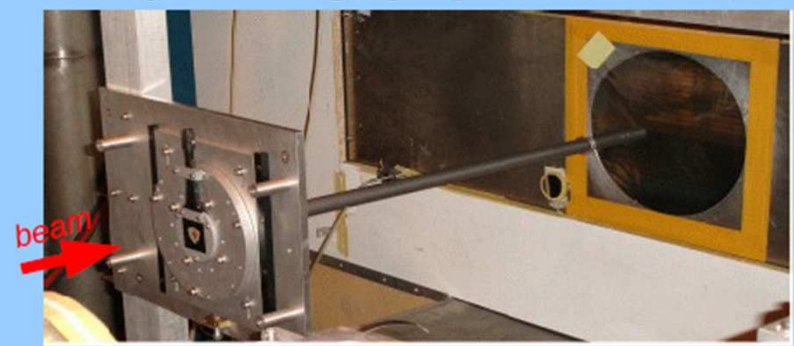
- **NA61/SHINE** has been approved in 2007
- Successor of NA49, situated at H2 beamline of CERN SPS
- Secondary beam particles produced from 400 GeV SPS's protons: momentum range 13-350 GeV/*c*
- Particle identification by ToF and dE/dx in TPC
- Two target configurations:
  - Thin: for the cross section measurements
  - T2K replica: model independent way for hadron multiplicities



thin target: graphite, $0.04 \cdot \lambda_I$



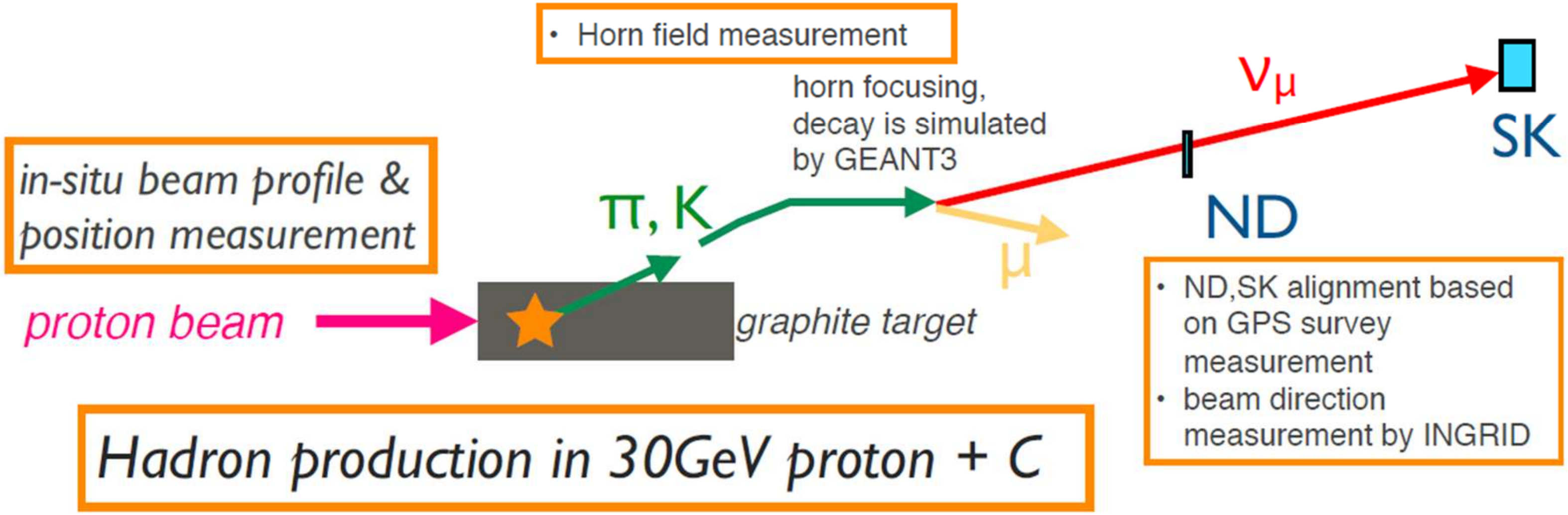
T2K replica targ: graphite, 90 cm, $1.9 \cdot \lambda_I$



-- Thin Target --

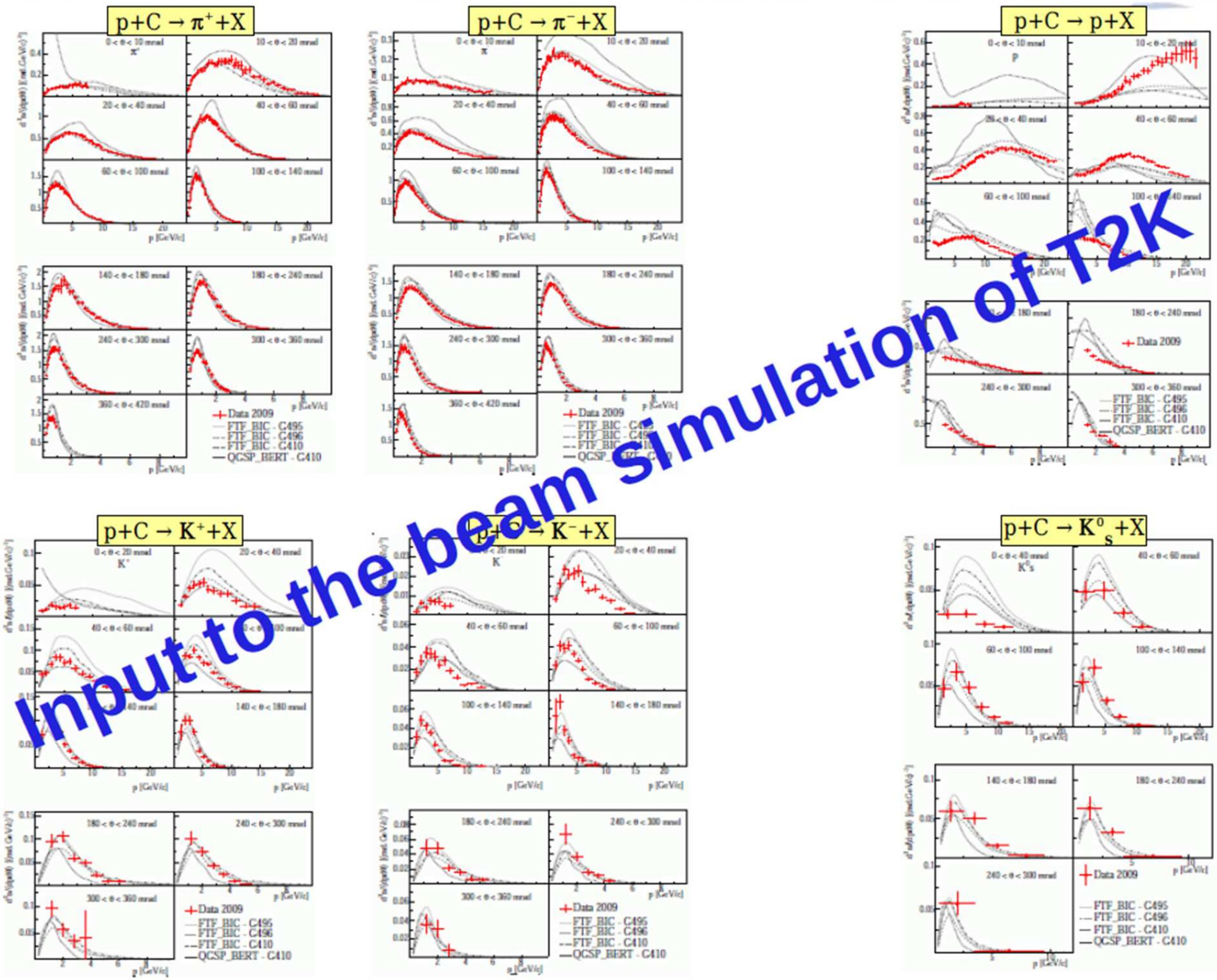
Neutrino flux prediction

T2K Neutrino beam simulation based on "measurement"



- ***Use CERN NA61/SHINE pion & kaon measurement (large acceptance: >95% coverage of ν parent pions)***
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

Sakashita



Models are not good at reproducing the proton rates at all

The cross-section issue

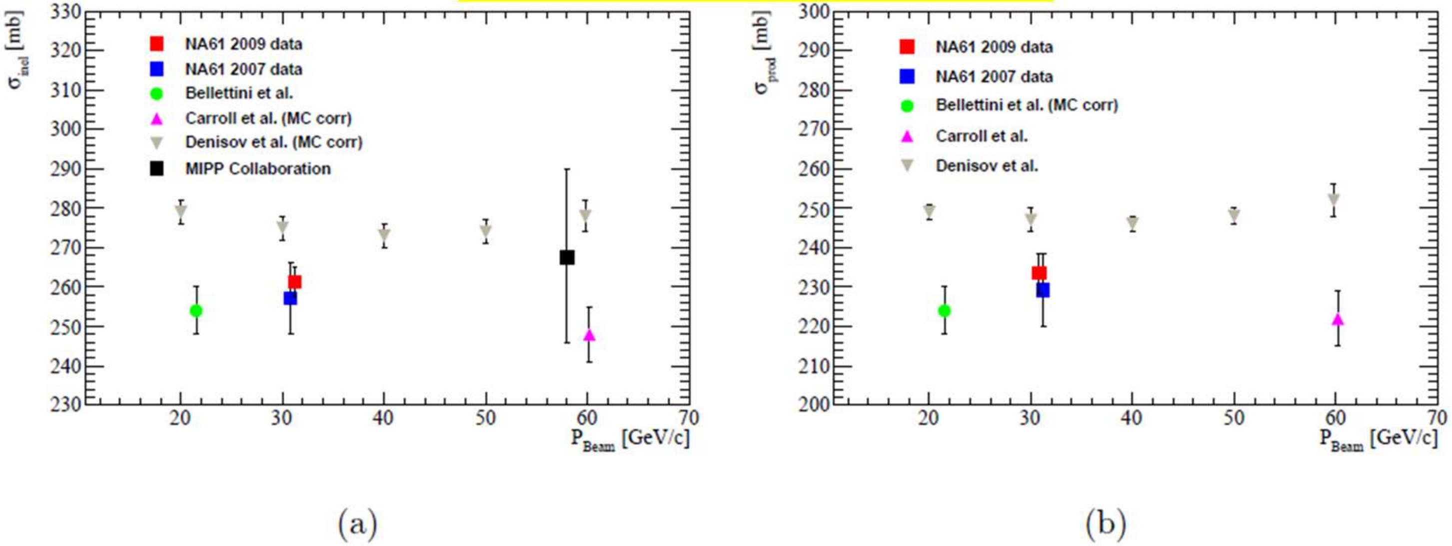


Figure 3.1: Measurements of the inelastic cross-section (a) and production cross-section (b). The results are compared with other measurements, in particular with the NA61/SHINE measurement from 2007.

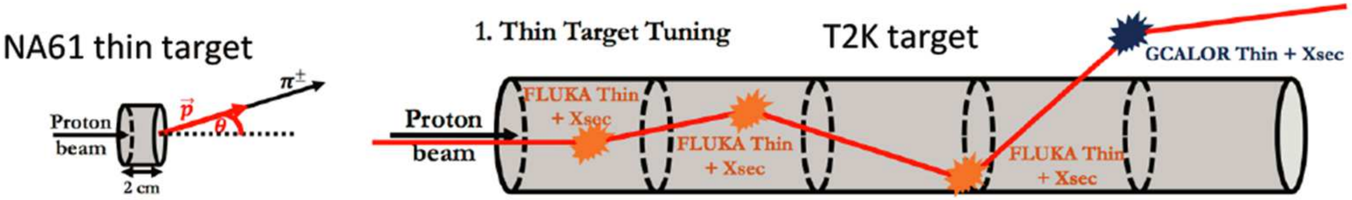
Several definitions of cross-sections ‘elastic’, ‘inelastic’, ‘production’ lead to inconsistent results (up to 20mb out of 230) in the littérature.

This is important for the thin target data: because the total acceptance of the final state particles is small we cant count the interactions, only produced particles. + we veto elastic interactions with downstream scint.

Furthermore (unlike partial decay widths) cross-sections are not additive in a finite interaction volume, but the interaction length determines the distribution of particles produced along the target.

In the flux prediction, hadron production tuning is performed in the two step

(1) interaction rate tuning



- interaction rate is tuned using the experimental $\sigma_{\text{prod.}}$ (= $\sigma_{\text{inel.}}$ - $\sigma_{\text{qe.}}$)
- 30GeV p+C interaction rate tuning is based on the NA61 data

NA61 $\sigma_{\text{prod}} = 230.7 \pm 2.8(\text{stat}) \pm 1.2(\text{det}) ^{+6.3}_{-3.5}(\text{mod})\text{ mb}$

FLUKA σ_{prod} = 240.3 mb

- uncertainty size is determined by the size of σ_{qe} (=33.3mb@30GeV)

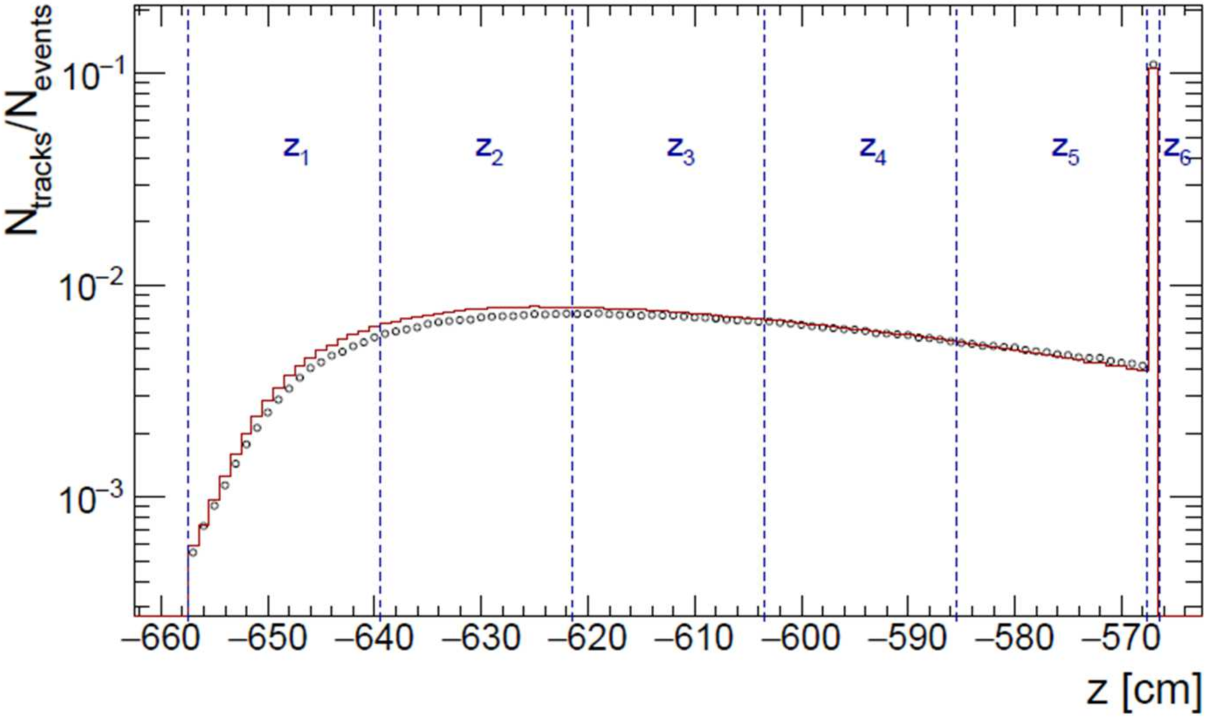
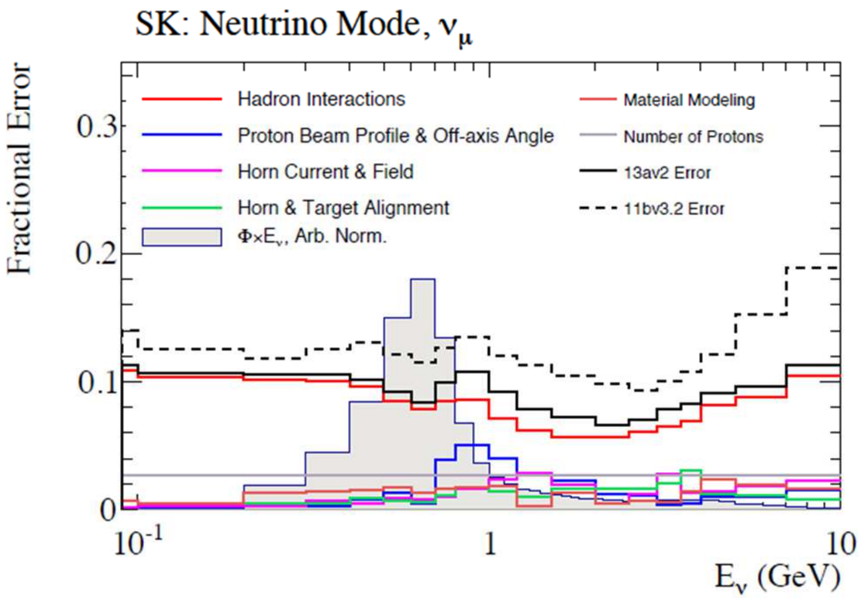
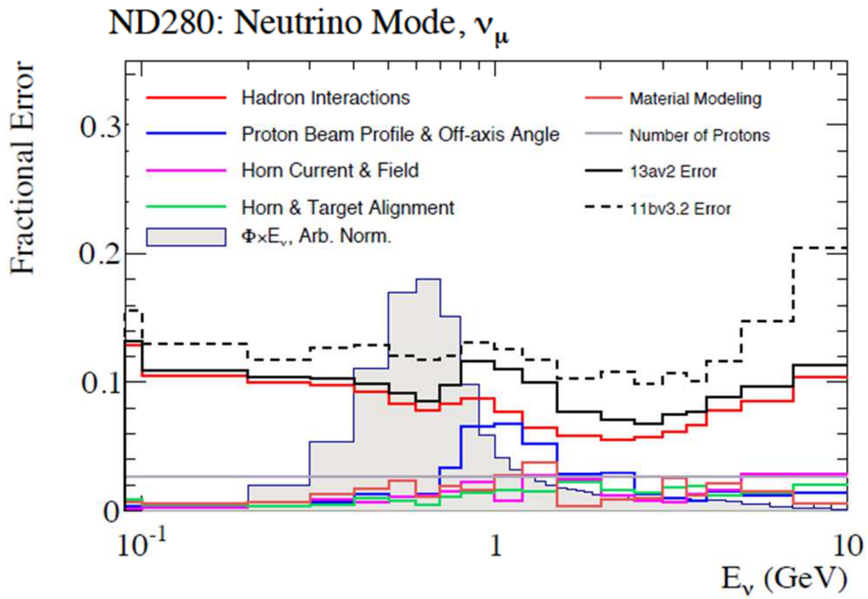


Figure 5.10: Extrapolated z distribution for the data (black points) and for the Monte Carlo simulation (red line). Longitudinal bin borders are overlaid on the top of the distribution.

-- **Thin Target** --

T2K flux uncertainty

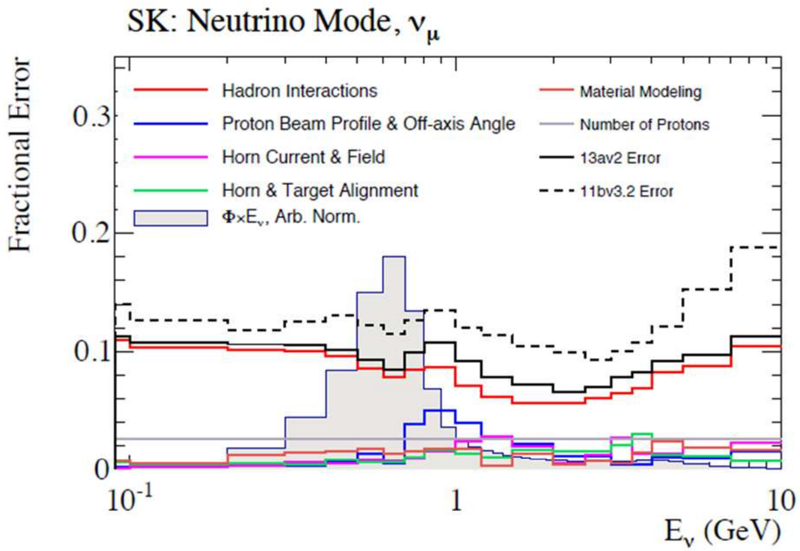




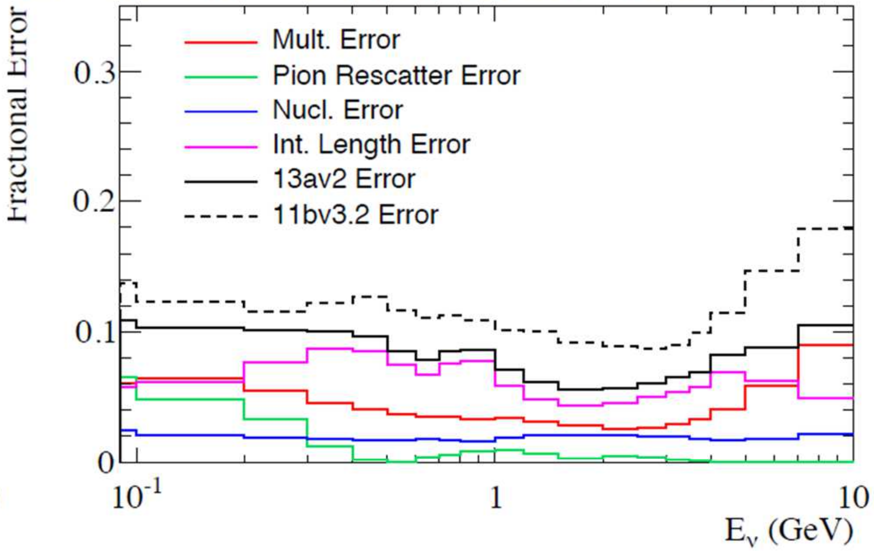
- total uncertainty is ~10% at peak (it is comparable between ν and anti-ν mode)

-- Thin Target --

T2K flux uncertainty (cont.)



Breakdown of "Hadron interactions"

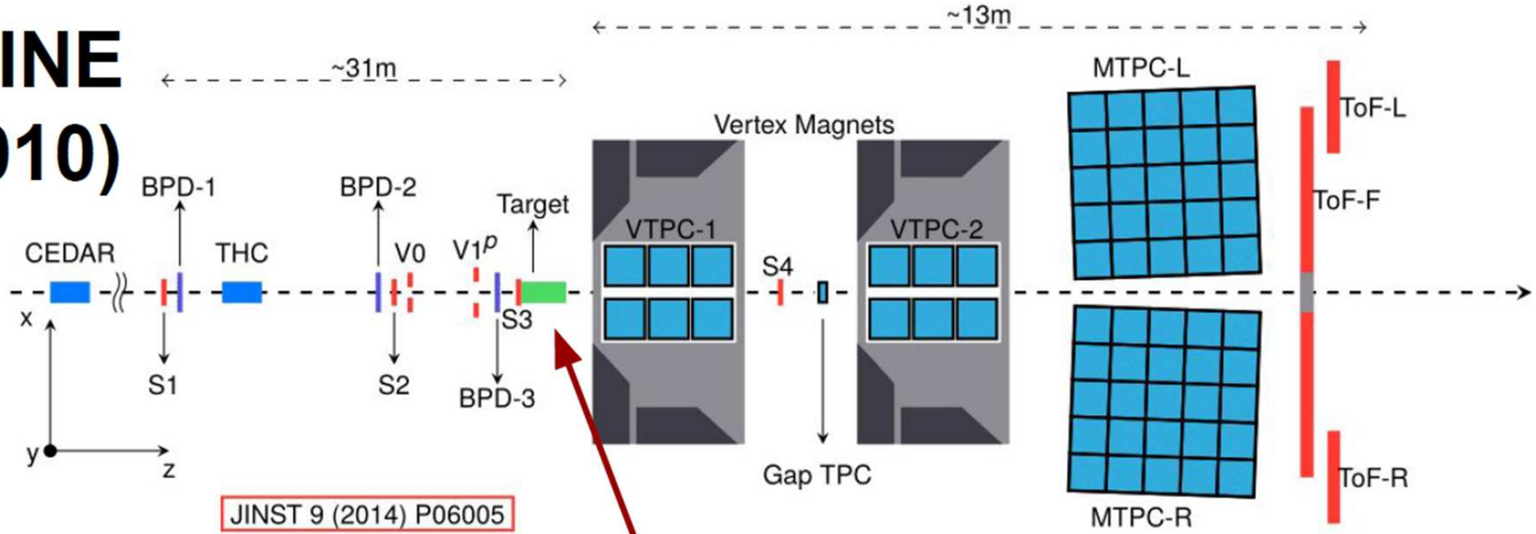


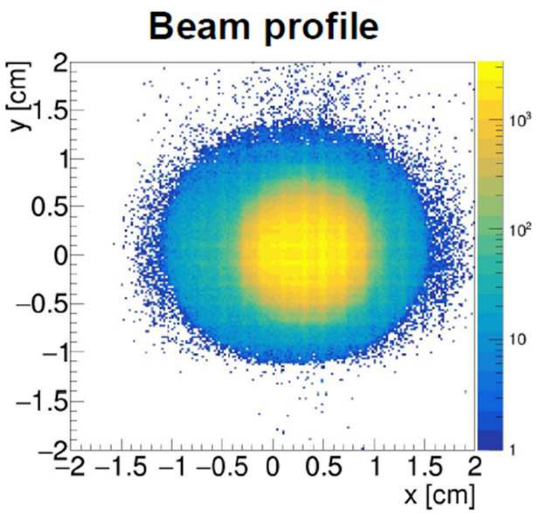
The interaction length error is the largest source of error.

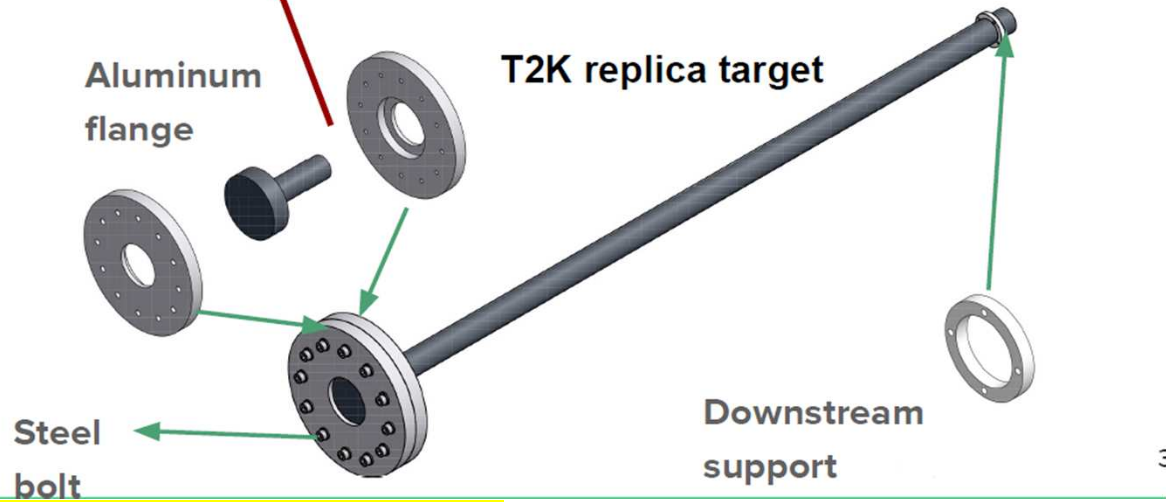
The rest is due to re-interactions inside the target and in the material in the beam line.

A significant remaining error is due to the knowledge of the off-axis angle and proton beam profile uncertainty (falling edge of pion Jacobian peak)

NA61/SHINE setup (2010)







5 times more data in 2010

– four different simultaneous triggers

-- high field data

-- doing the kaons too.

2009 RT paper.

N. Abgrall et al. Eur. Phys. J., C76(11):617, 2016.

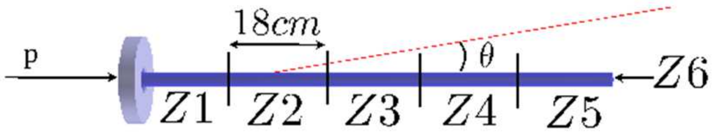


Figure 4.12: Sketch of the longitudinal binning of the target.

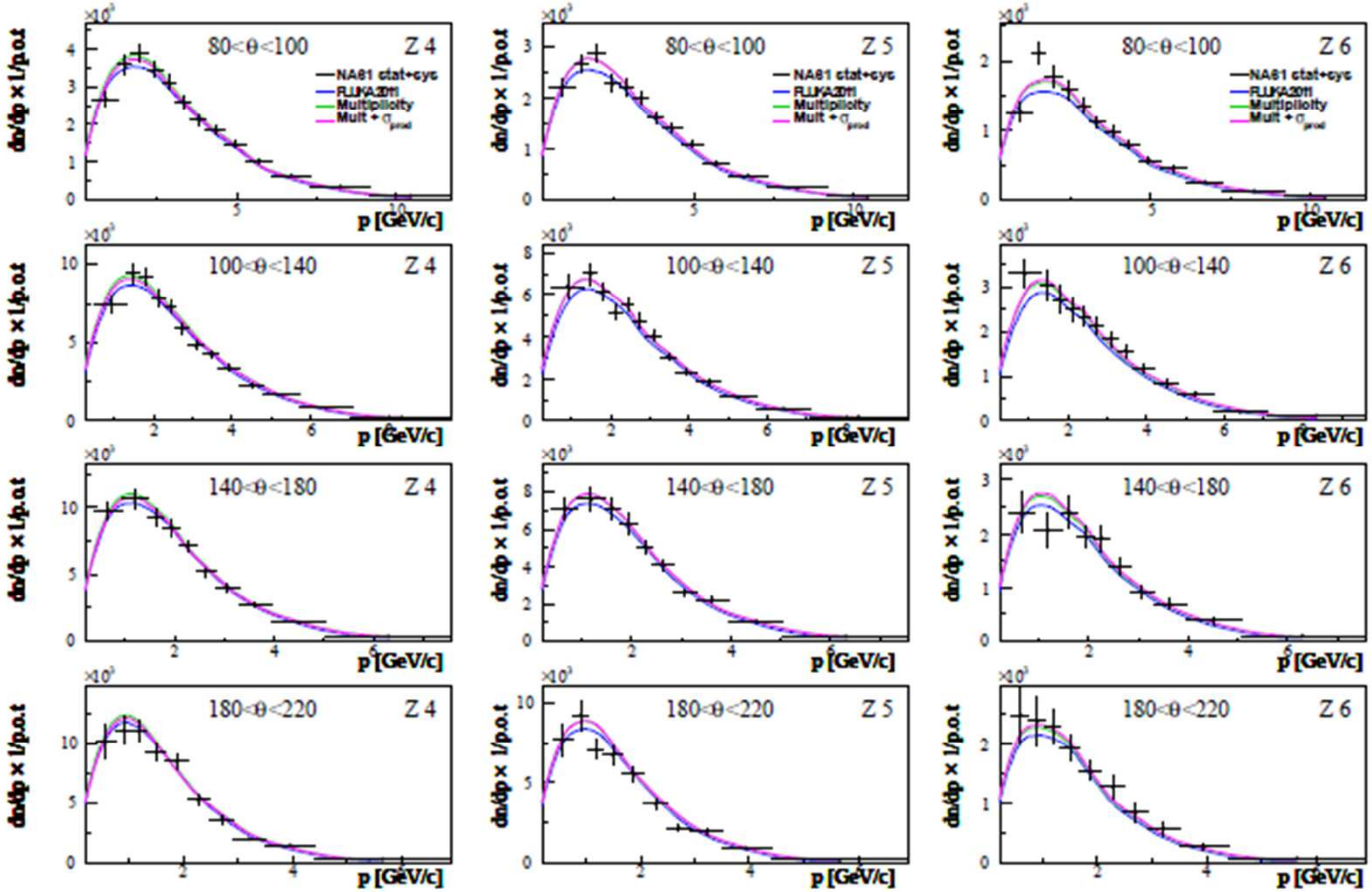


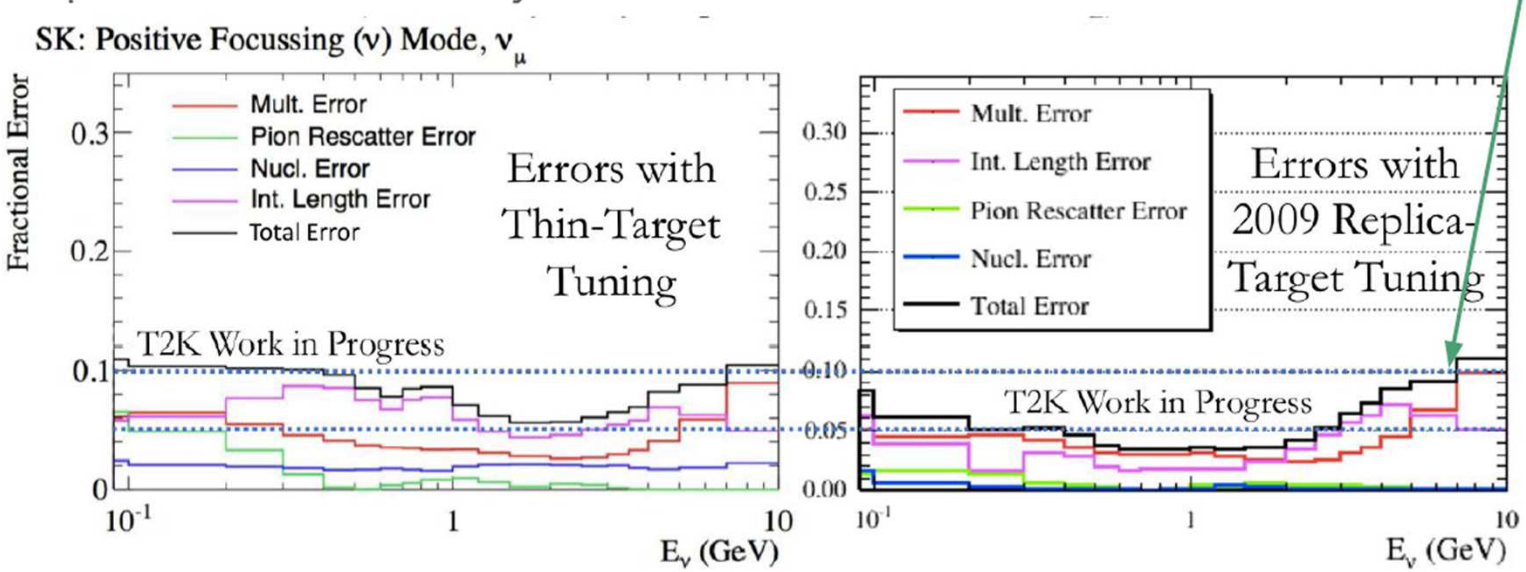
Figure 4.48: T2K replica target results for negatively charged pions with nominal FLUKA predictions (blue), FLUKA re-weighted for the multiplicities (green) and FLUKA re-weighted for multiplicities and production cross-section σ_{prod} for the three downstream longitudinal bins and in the polar angles between 80 and 220 mrad plotted as a function of momentum

T2K neutrino flux re-weighting with RT measurements

- Pion yields measured with 2009 data

Kaons not measured in 2009

Hadron production uncertainty



High energy error will be reduced from 2010 LT data

Consistency check:
-- compare flux predicted with thin target and replica target

thin/replica with nominal σ_{int} **thin/replica with σ_{int} reduced by 20mb**

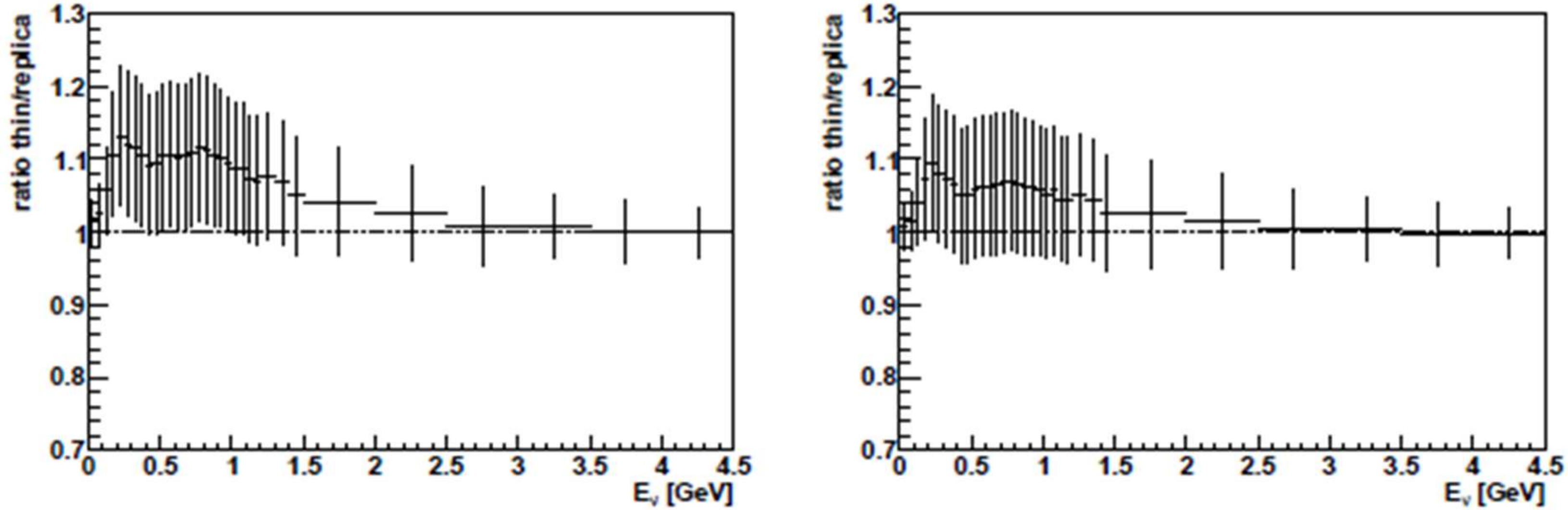


Fig. 28: Ratio of the ν_μ flux at SK re-weighted with the thin target procedure to the p+(T2K RT)@31 GeV/c flux. For the latter pion spectra presented in this paper have been used in the re-weighting. The dominant part of the ν_μ spectra at high E_ν comes from kaons and thus is not affected by the re-weighting of the pion spectra. The left plot shows the ratio calculated using the FLUKA production cross section, whereas the FLUKA cross section reduced by 20 mb was used to obtain the ratio presented in the right plot. Vertical error bars show the full uncertainties on the ratio which are dominated by systematical uncertainties.

cross-section error has an effect, but errors at the early part of the target are also important.

There is something one can measure very precisely which is related to interaction length!

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)

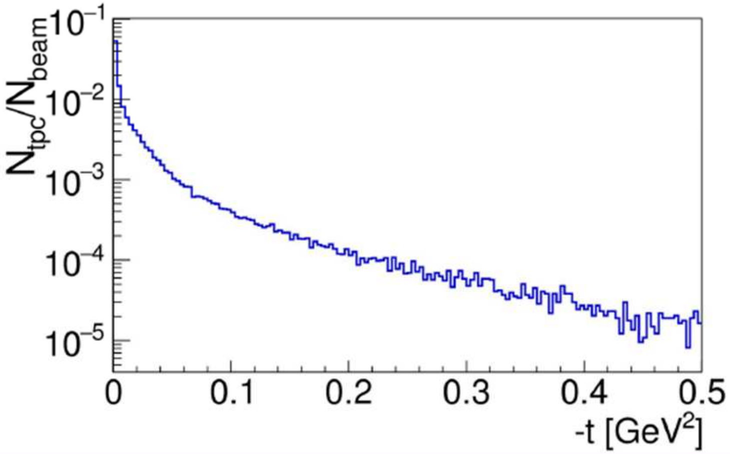
P_{surv}(FLUKA, rec) = 0.1196 ± 0.0002 (stat)

$$\sigma^{MC}_{prod} - \sigma^{data}_{prod} = -\frac{1}{nL}\ln\left(\frac{P^{MC}_{surv}}{P^{data}_{surv}}\right)$$

→ ~ 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?**



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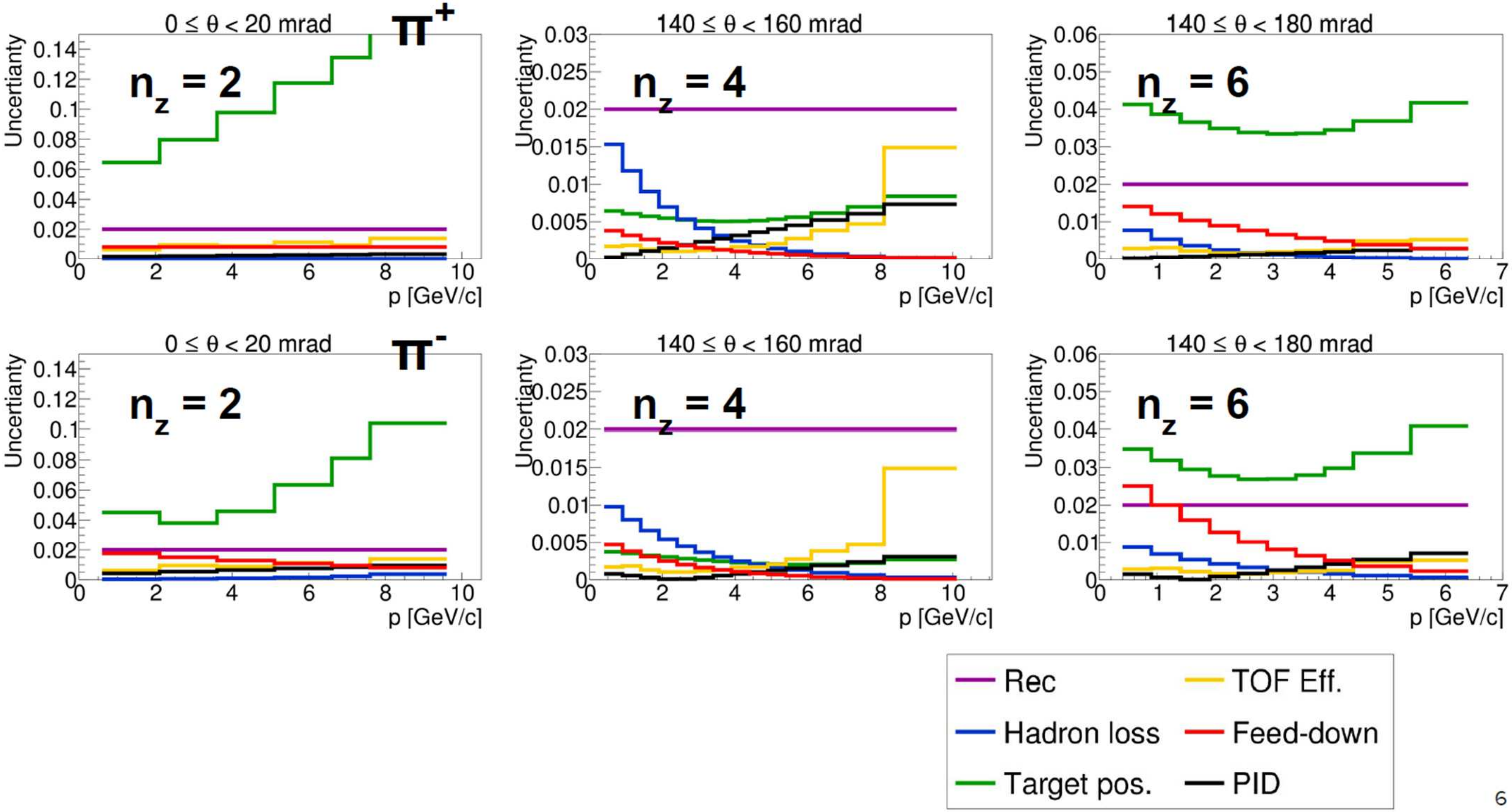
Popov

Systematic uncertainties

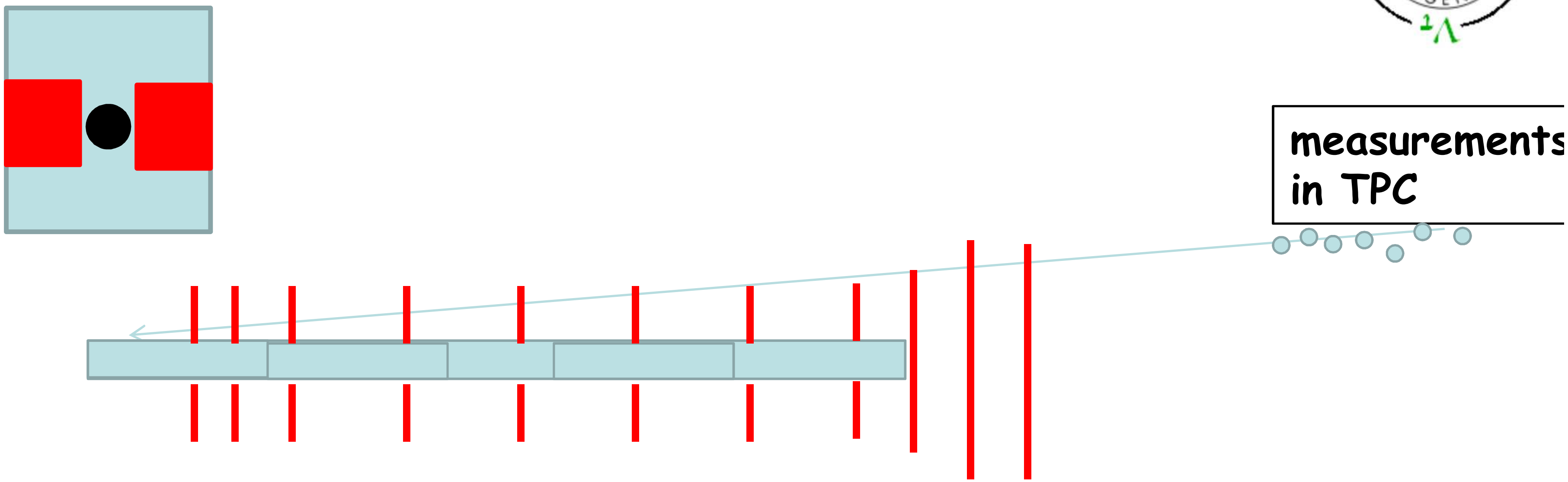
1. TOF efficiency
2. Hadron loss
   - Hadron loss should be only due to decays or re-interactions before FTOF
   - By selecting tracks with longer(shorter) segments in MTPC yields are expected to stay the same
   - Change in the cuts: no cut on points in MTPC or 50 points
3. Target position (extrapolation efficiency and bin migration)
   - How change of the target position changes the spectra
4. Feed-down
   - Contribution to the pions coming from the V0 decays and re-interactions in the detector (strongly model dependent) → taken as 30% of the correction
5. Reconstruction (assigned **2%**)
   - Track merging and fitting algorithms
6. PID
   - 1 Gaussian → 2 Gaussians

Dominant (and curable)
-- backward extrapolation
-- reconstruction efficiency
-- PID, TOF efficiency etc…



π+
π-
0 ≤ θ < 20 mrad
140 ≤ θ < 160 mrad
140 ≤ θ < 180 mrad
n_z = 2
n_z = 4
n_z = 6
Uncertainty
p [GeV/c]
Rec
TOF Eff.
Hadron loss
Feed-down
Target pos.
PID
6

surround the target with a precise tacking device (assume pixel)



-- number of sensors should be optimized by simulation
-- transverse size do not need to exceed 5cm
-- Typical track should have 3-4 points.

-- Essential to have tracker downstream of target with no hole !
to ensure good extrapolation of low angle tracks.

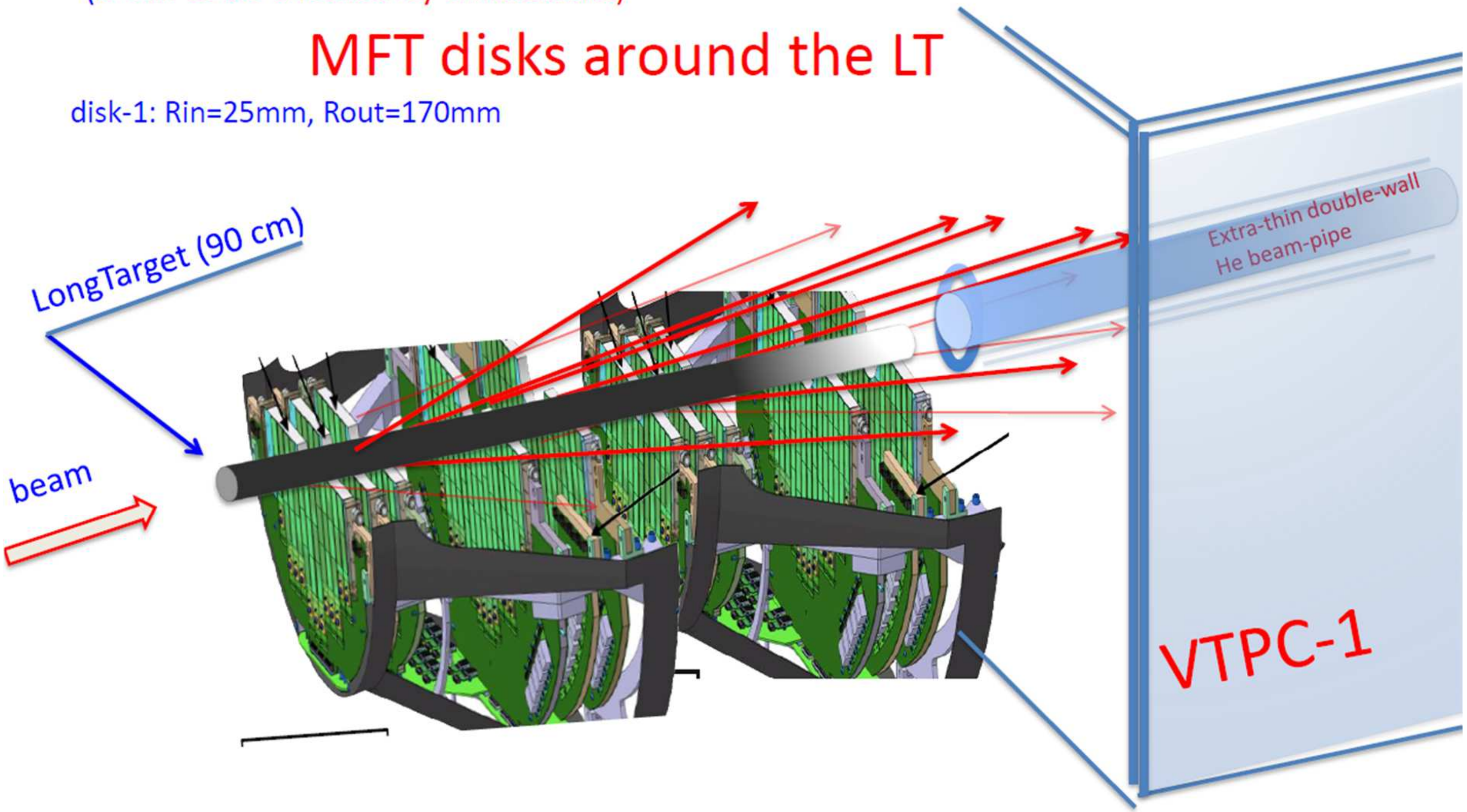
Vertexing for T2K LongTarget (LT) replica ?

Conceptual Option-1

(is still to be checked by simulations)

MFT disks around the LT

disk-1: Rin=25mm, Rout=170mm



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yes, but need detectors on x-z plane + downstream of target.

Fractional error on N_{FD} (T2K 2016 OA paper)

Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

NB T2K does not measure any cross-section with 3% error! this is the error on the number of predicted events in SK given the number of events observed in ND280!

e.g. N/F flux ratio is known to <2%.

Measurement of the ratio of electron to muon cross-sections

This is an important systematic uncertainty in the determination of oscillation parameters from the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels

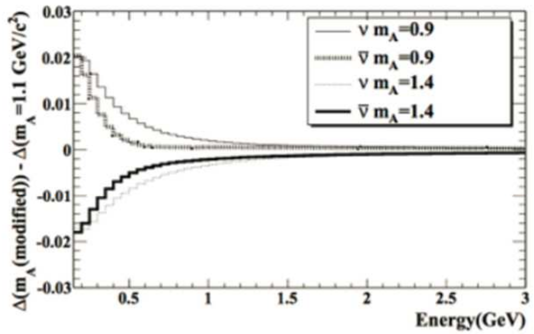
Current T2K systematic errors

Systematic Error Type	1Re Neutrino Mode	1Re Antineutrino Mode
Far Detector Model	2.39%	3.09%
Final State/Secondary Interactions	2.50%	2.46%
Extrapolation from Near Detector	2.88%	3.22%
ν_e(bar)/ν_μ(bar)	2.65%	1.50%
NC1γ	1.44%	2.95%
Other	0.16%	0.33%
Total	5.42%	6.09%

Mark Hartz

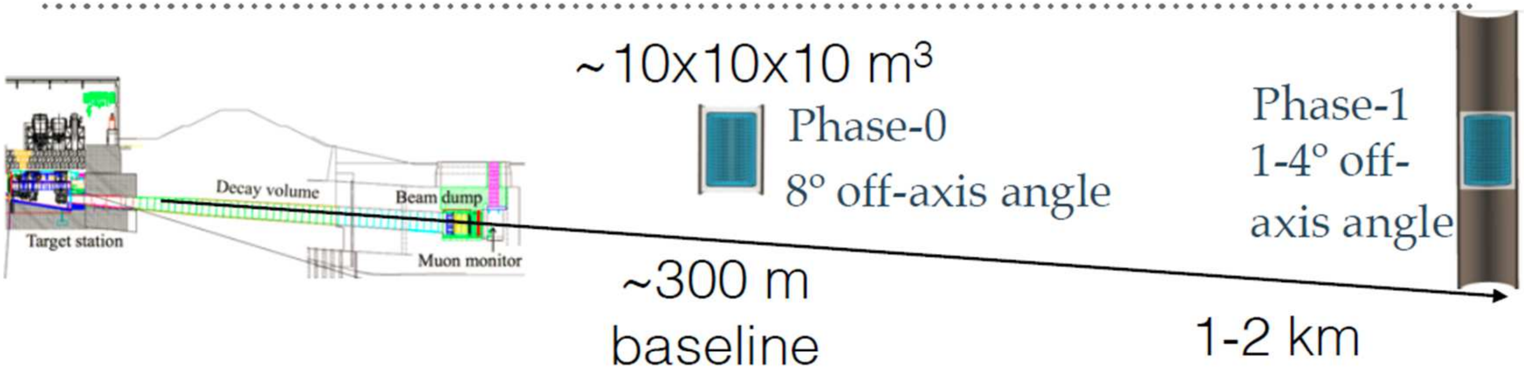
- *Uncertainties can arise from:*
  - *Form factor uncertainties in cross section terms that depend on lepton mass*
  - *Phase nuclear effects combined with phase space differences due to mass*
  - *Radiative corrections (should be calculable)*

Phys.Rev. D86 (2012) 053003



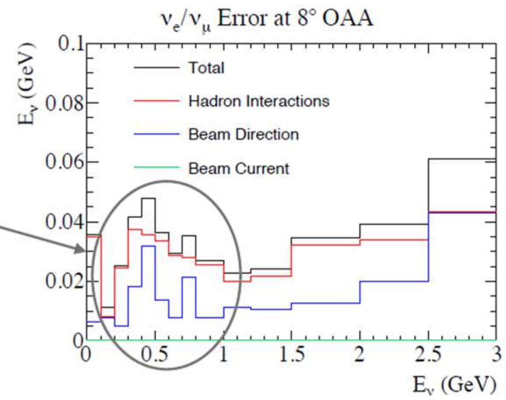
Uncertainty on relative cross section due to axial form factor uncertainty.

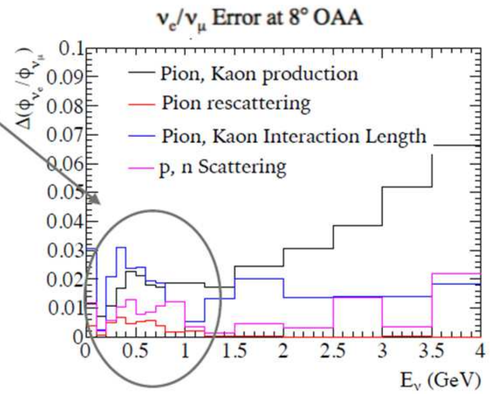
THE E61 EXPERIMENT



FLUX RATIO UNCERTAINTY

- *Hadron interaction uncertainties are dominant in the 0.2-1.0 GeV range for the flux ratio*
- *Largest error sources:*
  - *Pion and kaon interaction lengths*
  - *Pion and kaon production*





In addition to the replica target measurements these measurements also benefit from further cross-section measurements for pions and kaons in the few GeV to 15 geV regime

Additional NA61 Data to Improve Errors ?

- Out-of-target interactions (on Al, Fe, Ti) contribute to a significant fraction of the wrong sign flux
  - Can be substantial contribution to $\bar{\nu}$-mode beam flux (compared to ν-mode) since :
    - In ν-mode, $\sim$0.12 interactions/ν take place outside of the target
    - In $\bar{\nu}$-mode $\rightarrow$ $\sim$0.43$\sim$0.5 interactions/ν
- NA61 data are used to tune the predicted production of mesons in secondary or tertiary interactions
  1. For incident neutrons, assume an isoscalar nuclear target and apply an isospin rotation to the NA61 data
  2. Since the incident secondary or tertiary proton or neutron has energy less than 30 GeV, scaling is applied so that the NA61 tuning can be applied to the interaction
  3. For out-of-target interactions, NA61 data are scaled to Al, Fe, Ti targets using parameterized fits to multiplicity data on multiple nuclear targets
     - Use parameterized fits to Allaby, BNL-E802, HARP data + cross check to Eichten
- May be useful to take dedicated NA61 data on different targets (Al, Fe, Ti, H_2O ?), at lower beam energies (down to $\sim$10GeV)

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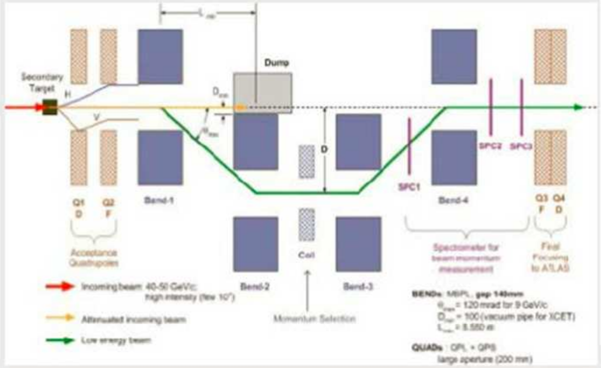
H2-VLE (2003)

H2-VLE (2017)

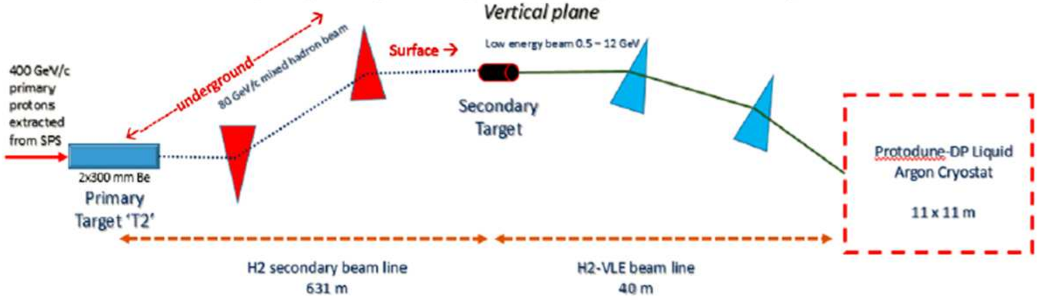
- **Four-bends layout**
  - Available magnets: **MBPL 120mrad for 1-9 GeV beams**



  - design used for the ATLAS(H8) &CMS(H2) calorimeters in the past
  - suffers from large background from the direct secondary beam

Courtesy: I. Efthymiopoulos

Layout of existing secondary H2 and tertiary H2-VLE beam lines of EHN1
Vertical plane



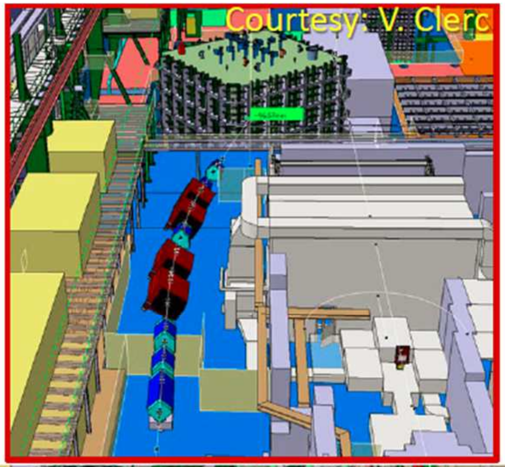
→ Using large angles and off-axis placement of the detector wrt the secondary beam reduces the muon background

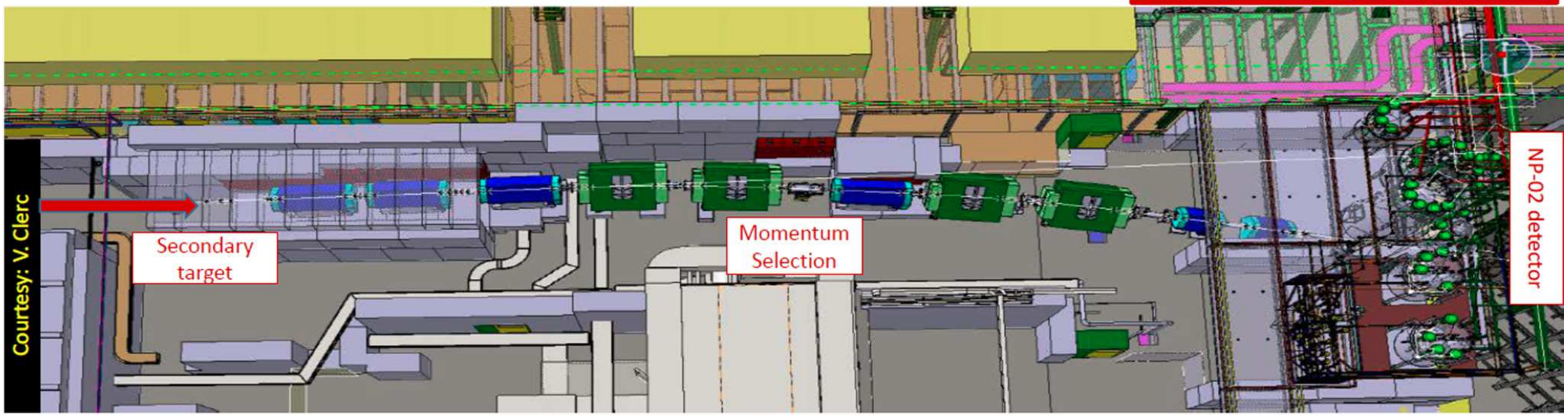
27/7/2017 N. Charitonidis - Very Low Energy Beams in EHN1 9

So far beam for NA61 is limited to energies > 13 GeV.
Esp. for mesons, it is possible to study a beamline that goes down to 1-2 GeV, similar to that prepared for the Larg protoDUNE's

Beam Layout - H2-VLE

- Tilted dipoles & quadrupoles
  - 34.9 degrees with respect to x-plane
  - Total bend angle : 234.8 mrad in the bending plane
- Momentum selection collimator available
  - Full acceptance δp/p: 5%

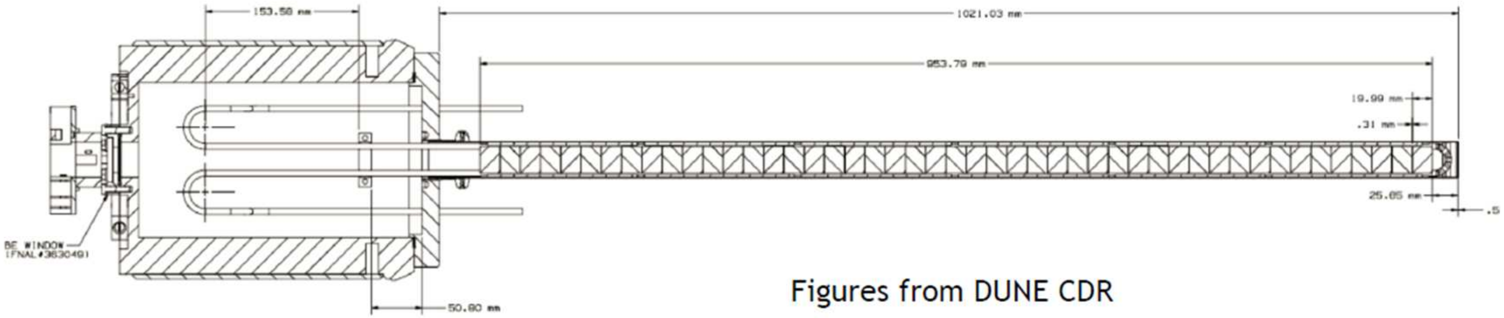




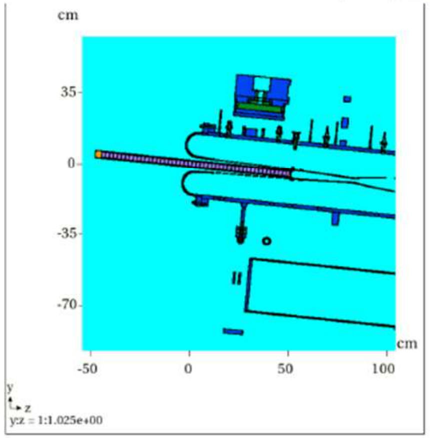
Targets for DUNE

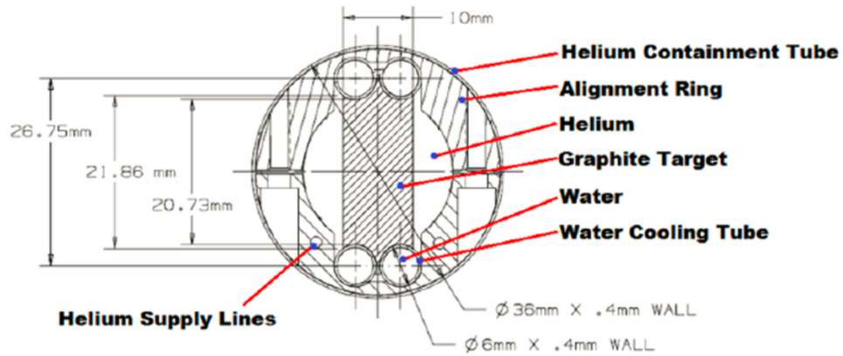
Target Options

- Reference Target



Figures from DUNE CDR

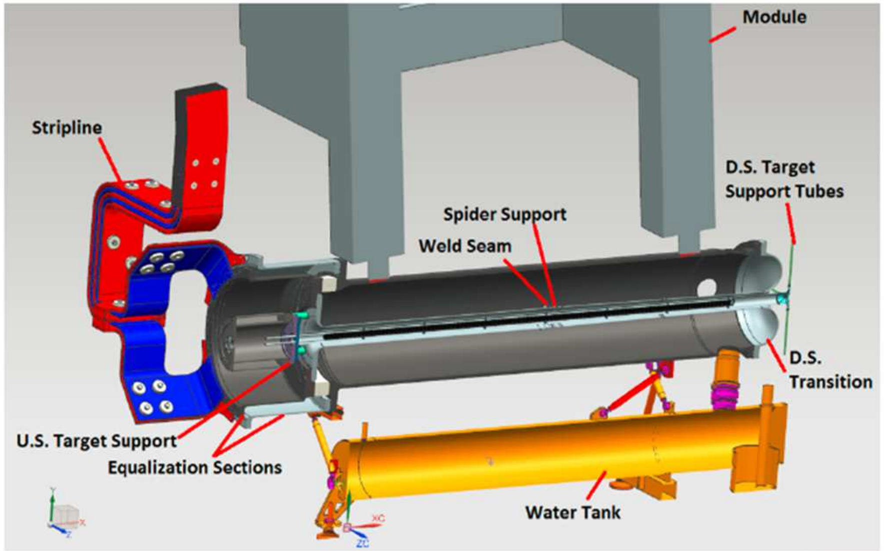


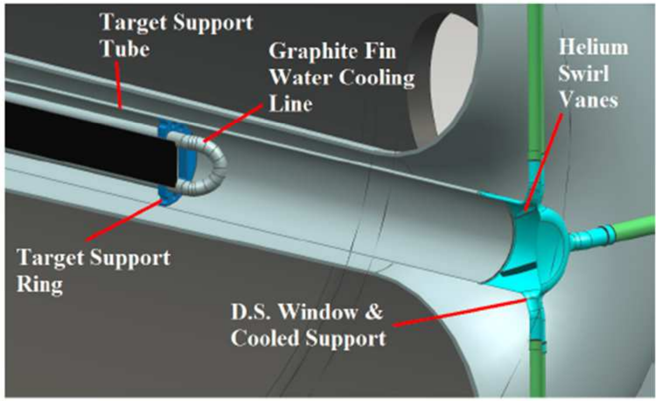


24 07.28.17 Laura Fields I LBNF Hadron Production

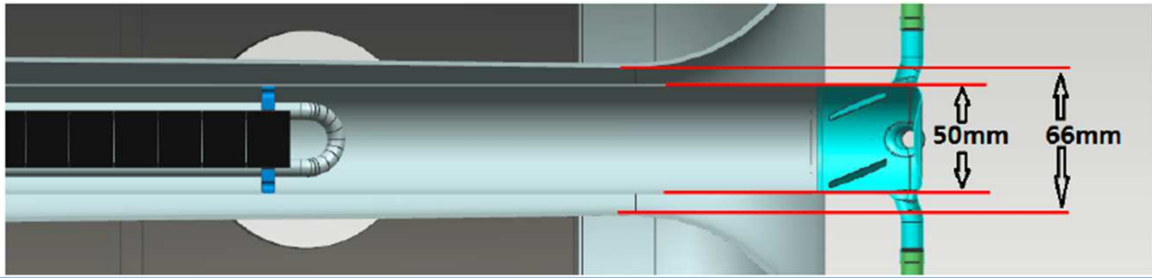
Target Options

- Optimized Fin Target



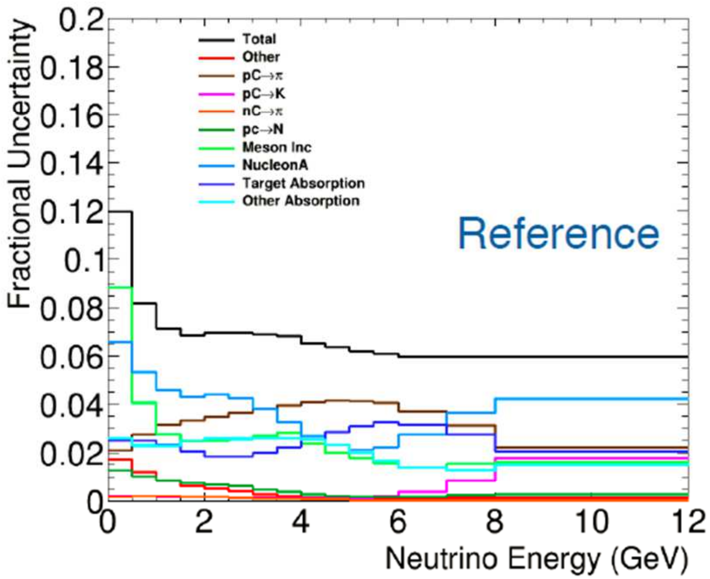


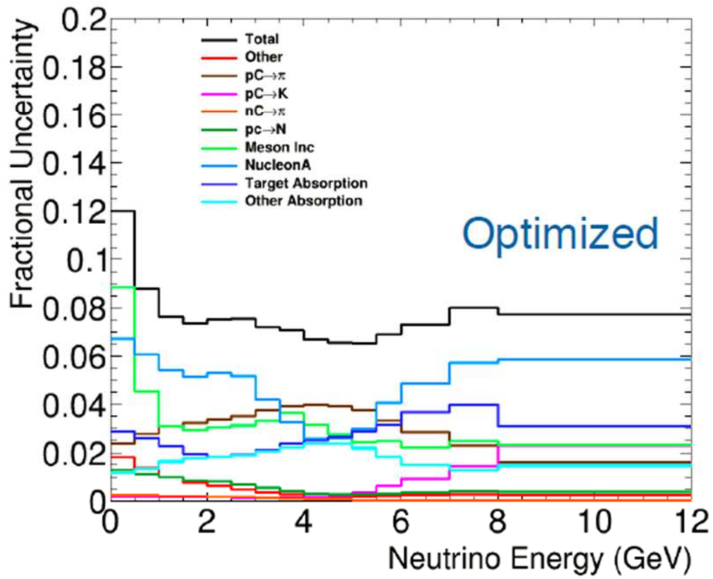
Figures courtesy Cory Crowley



Hadron Production Uncertainties

- Comparison of reference and optimized beam

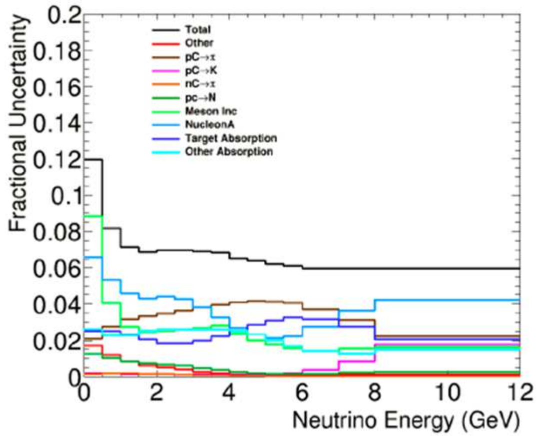




Very similar in focusing peak; Optimized has slightly larger uncertainties at high energy, primarily due to having more interactions not covered by data

Hadron Production Needs

- When we look at which interactions are not covered by data, largest component is **proton on carbon data outside of the region covered by NA49** (esp. quasi-elastics)
- More data here would have biggest direct impact on uncertainties
  - Also: **improving precision in range covered by NA49**



- Other needs
  - **pion/kaon reinteractions** on Carbon
  - **Total inelastic cross section** for p, pi, and k in carbon, aluminum and iron (see absorption uncertainties to left)
  - **pi/k production from protons on e.g. aluminum, titanium, iron** (See NucleonA uncertainty)

Hadron Production Needs

- **Replica target data** would also obviously be fantastic
- If the optimized design is chosen, replica target would be **~ 2 m long**
- **Timescale** is another challenge
  - DUNE expects to receive beam in **2026**
  - Do not expect to have full replica targets significantly before that
  - **Prototypes** will be available of course, but likely will not be exactly the same as actual LBNF targets
- **Thin target data** would likely to have the longest-lasting impact on DUNE prior to production targets being available
  - It is also likely possible to use thick target data to constrain fluxes on **similar (but not identical) targets** but techniques to do this would need to be developed

New replica target measurements?

-- requires DUNE/HyperK request based on experimental justification
-- marked improvement of present detector setup
-- knowledge of replica target design is necessary.
➔ probably not ready in 2020 but for later development

- LT MEASURMENTS FOR AN NEUTRINO EXPERIMENT:
- MUST BE AN EXPLICIT, WELL JUSTIFIED, REQUEST FROM THE EXPERIMENT IN QUESTION,
- NEW COLLABORATORS SHOULD JOIN NA61/SHINE

Further π/K/Λ cross-section measurements?

-- there is a synergy with Cosmic ray community to take more data for production of particles and antiparticles
-- more precision on total cross-section necessary
-- this can be programmed now and will have long lasting impact.
➔ probably the next thing to do

Conclusions and advertisement

The importance of hadron production measurements was strongly emphasized by all neutrino physics speakers. Many accelerator and atmospheric neutrino experiments expressed interest in thin-target measurements. These range from very low beam momenta to 120 GeV/c.

NA61's measurements for T2K have been critical for T2K to reduce flux systematic errors by a factor of two, and further improvement is expected as the long target results are added into T2K's flux model.

by another factor ~2

An idea to construct a tertiary hadron beam-line for beams at very low momenta (< 10 GeV/c) was presented by Nikolaos Charitonidis. Proponents of the measurements at very low momenta are encouraged to work together with Nikos on this proposal.
Replica targets for DUNE and HyperK will be ready only after 2025. Thus, the measurements with exact replica targets are not requested, though measurements with prototypes may be useful. The replica target runs would be very valuable even if they take place after LS3.

present

Whether new measurements with the T2K replica target are needed will be concluded after introducing the NA61 LT 2010 results in the T2K beam simulation.

Some new detector ideas were suggested at the workshop, including the idea of a very long target in a more downstream position. The target could be surrounded by a set of tracking detectors to pinpoint low-angle tracks from the upstream end of the target. The value of empty target and high field exposure were also emphasized.

Options other than NA61 are being considered by some collaborations. However, these would require major new detector construction and personnel commitments.