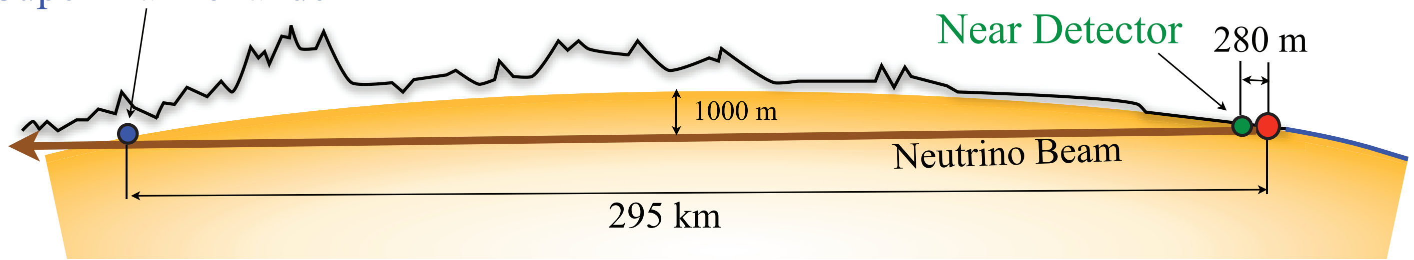
T2K flux uncertainties

Sebastien Murphy

on behalf of the NA61/SHINE and T2K collaboration

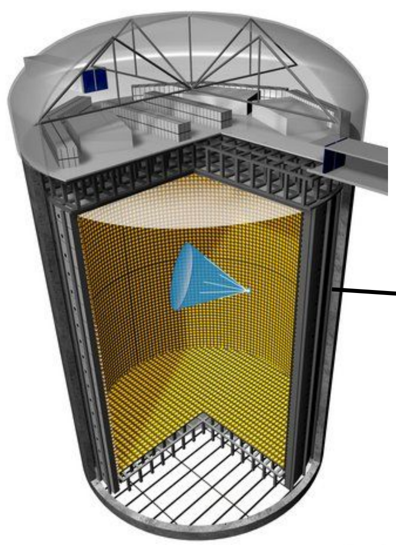
The T2K experiment

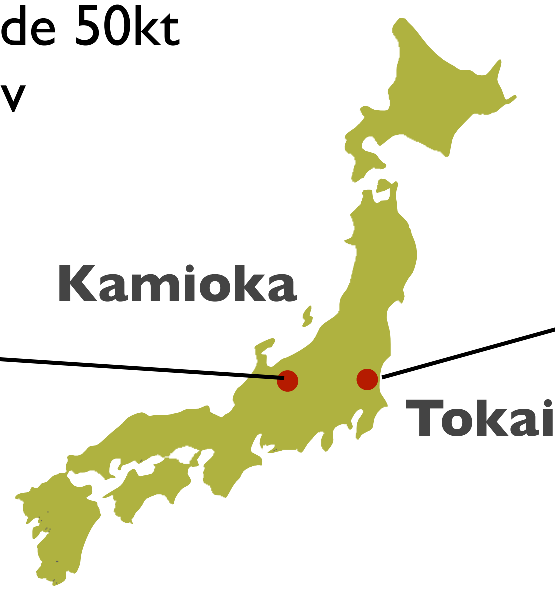
Tokai to Kamioka

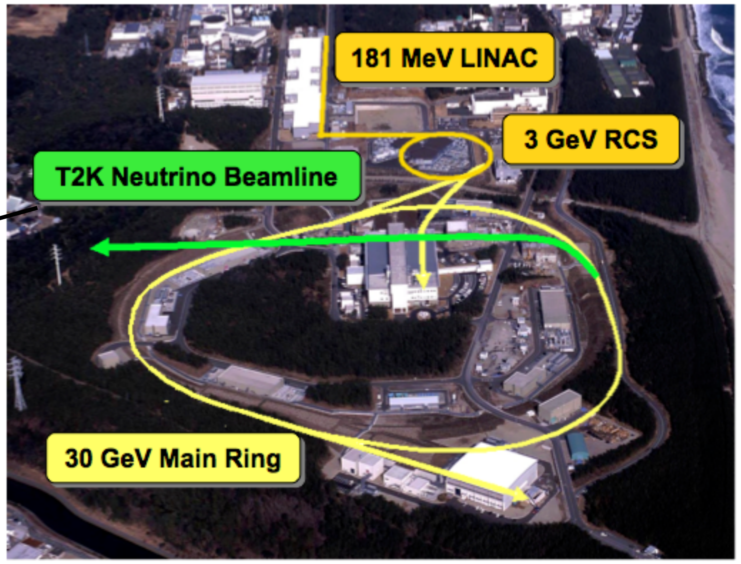


30 GeV proton beam
design power 0.75 MW

Super Kamiokande 50kt water Cherenkov detector







pure muon neutrino beam of <E_ν>≈600 MeV for a baseline 295 km => L/E≈0.5 km/MeV

T2K measurements

ν_μ disappearance

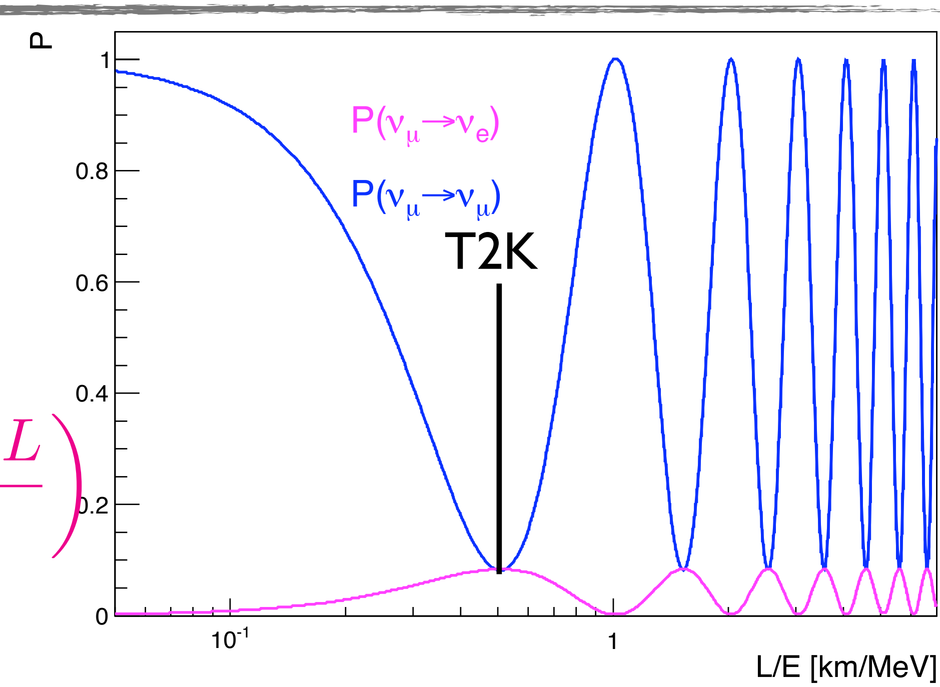
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta M^2 L}{4E}\right)$$

=Precise measurement of $\{\Delta M^2, \theta_{23}\}$

ν_e appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx 1 - \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta M^2 L}{4E}\right)$$

=measurement of θ_{13}



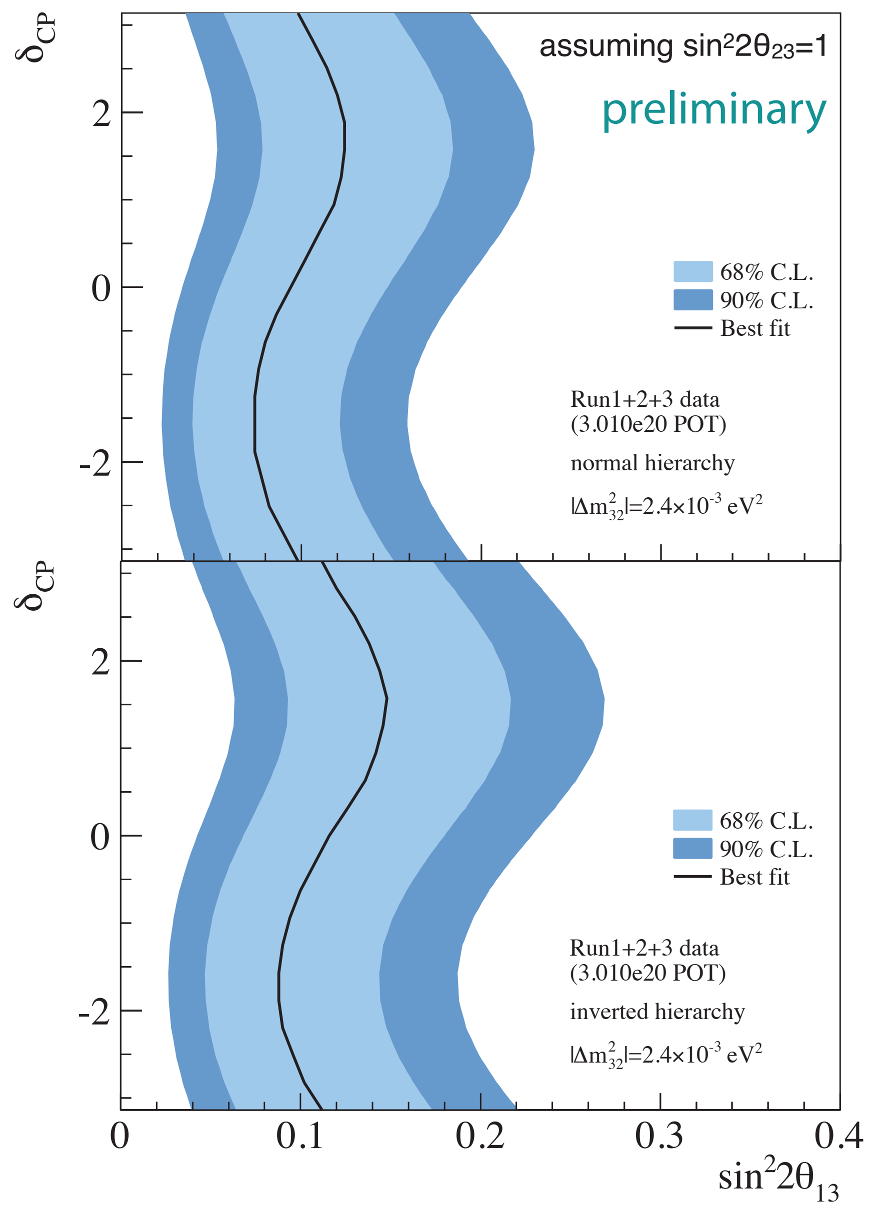
T2K results

Update on ν_e appearance search (ICHEP 2012):

11 ν_e events in the far detector. 3.22±0.43 (syst.) expected if $\theta_{13}=0$,

$\theta_{13}\neq0$ at 3.2 σ. First signal of neutrino appearance!

ν_e disappearance



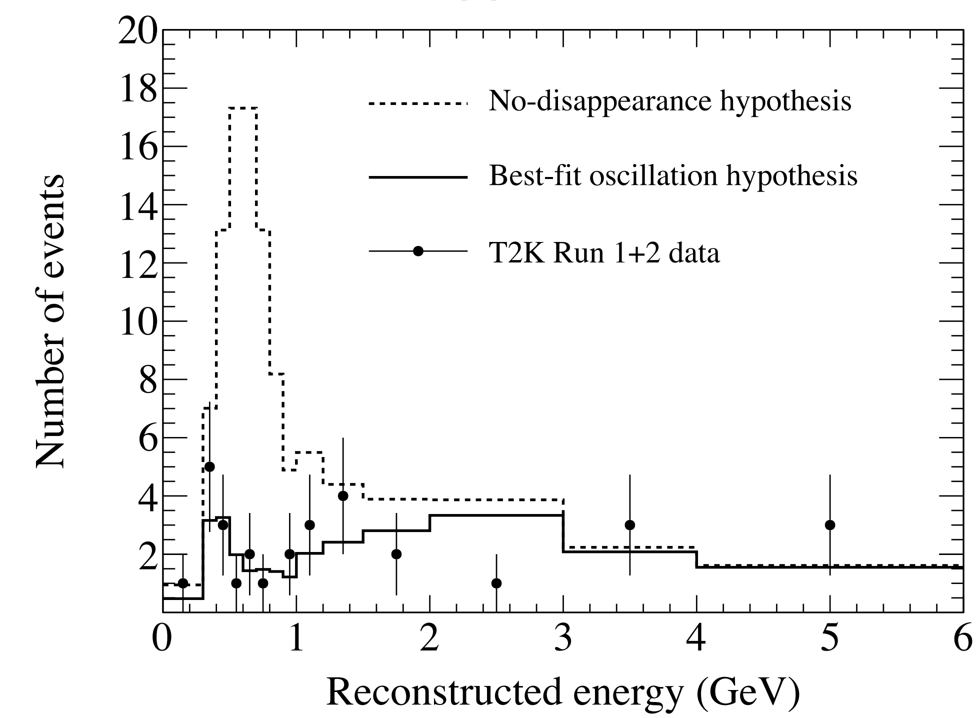
Best fit **$\sin^2 2\theta_{13}=0.094^{+0.053}_{-0.040}$**

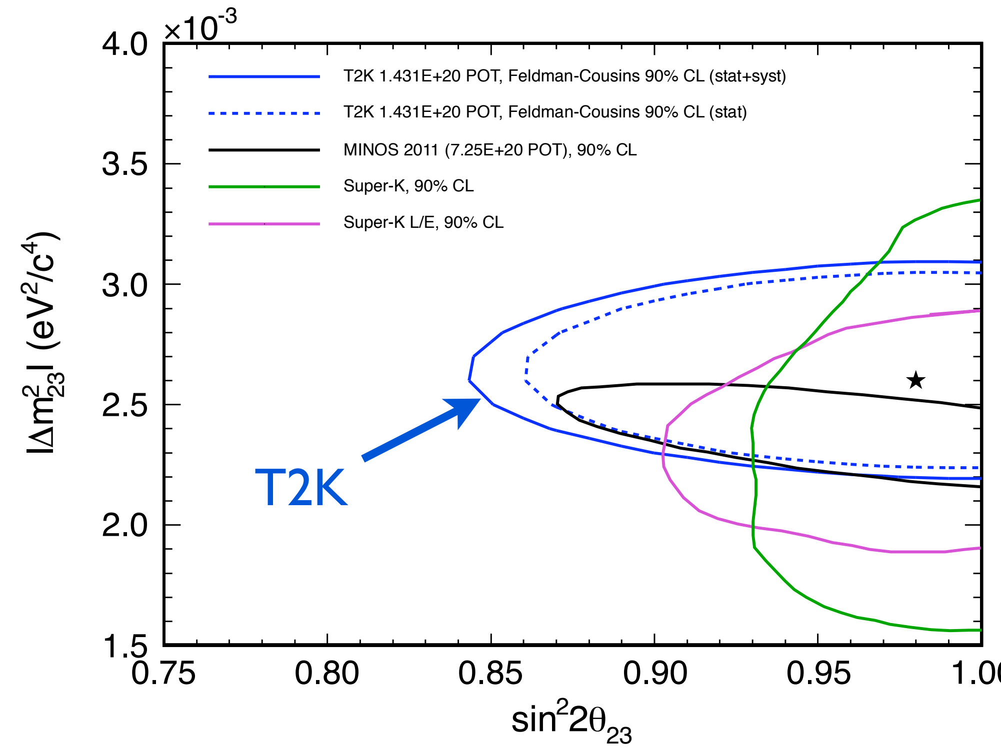
(for δcp=0, normal hierarchy)

previous results :

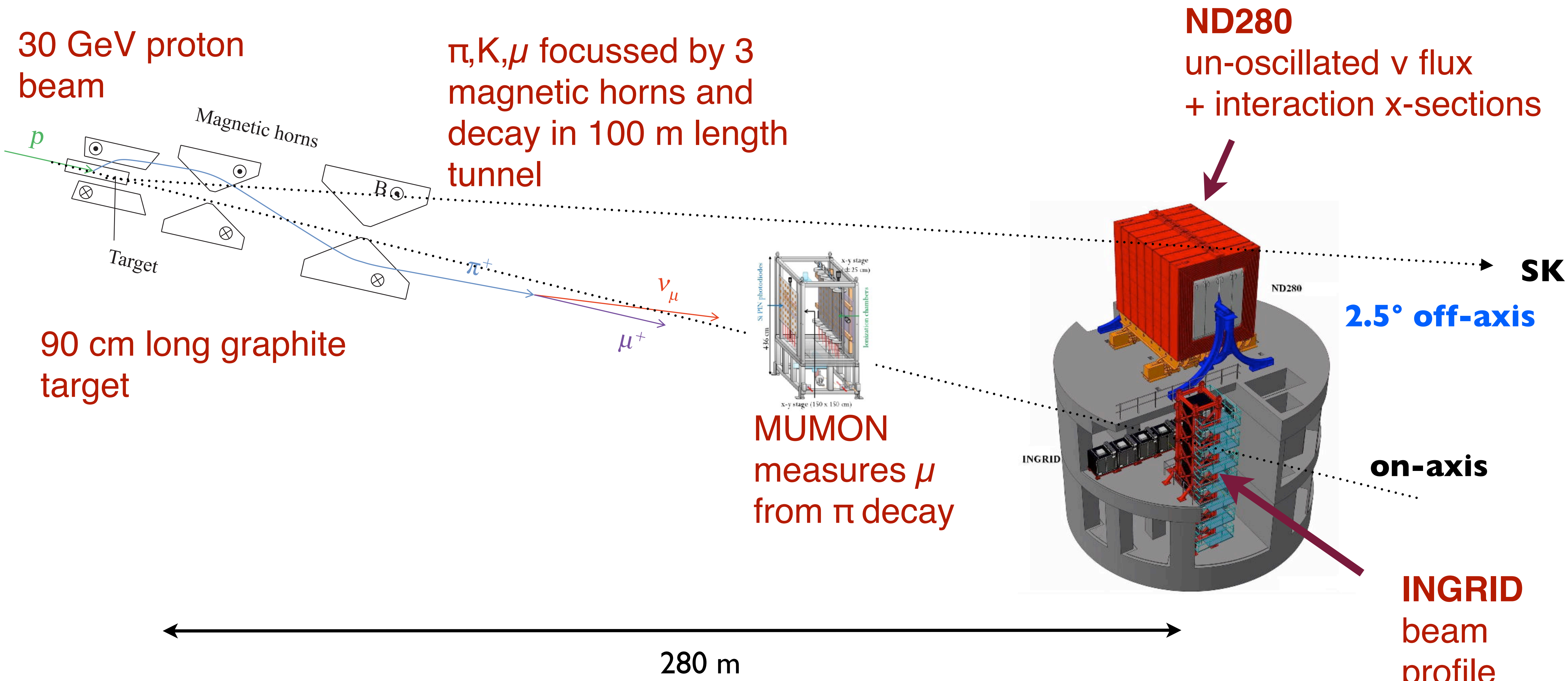
Phys. Rev. Lett. 107 no. 4, (Jul, 2011) 041801: $\sin^2 2\theta_{13}=0.11^{+0.10}_{-0.06}$

ν_μ appearance



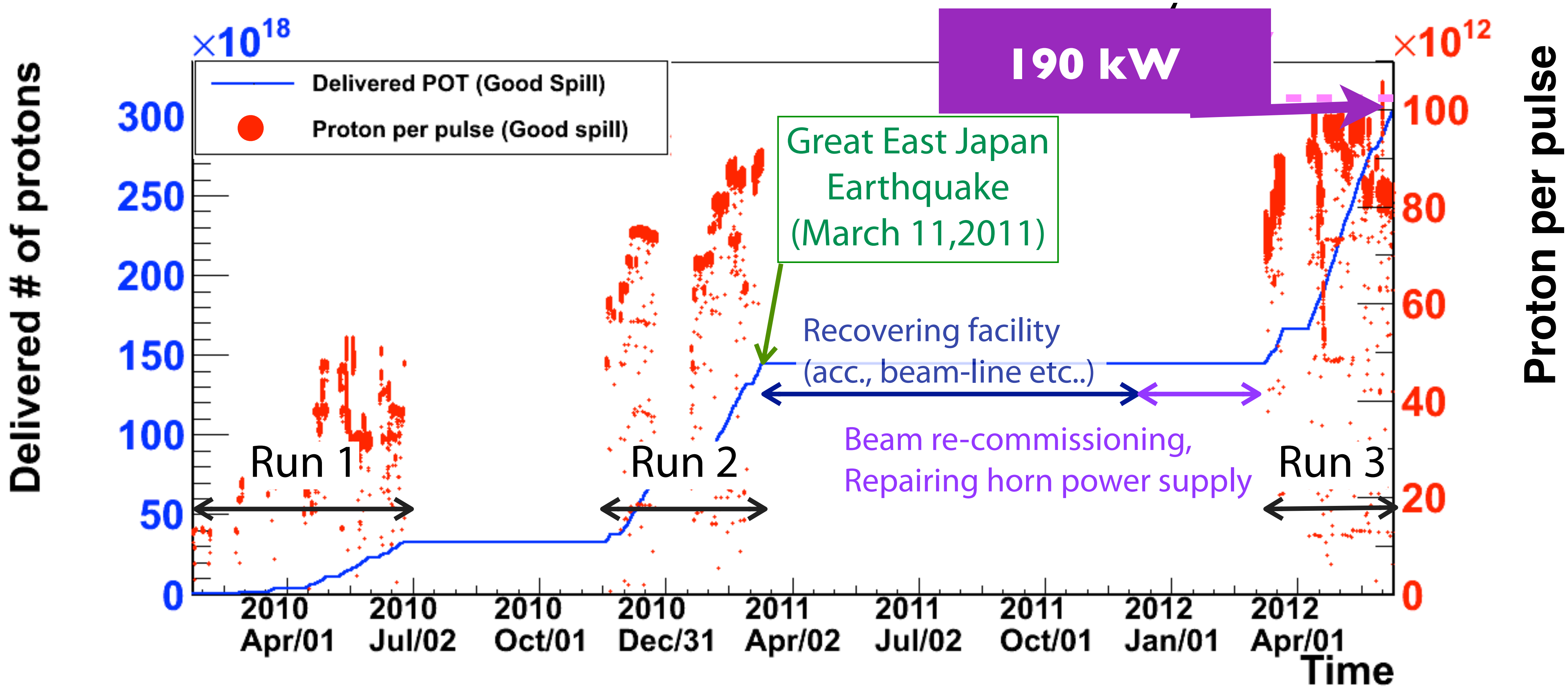


Creation of a high power neutrino beam



- 30 GeV ~1x10^{14} protons extracted every 2.5~3 sec directed to the carbon target
- secondary π^+ (and K^+) focussed by three electromagnetic horns (250 kA/200 kA)
- MUMON+INGRID: measure beam stability (< 1mrad ~2% E_ν shift@SK)
- ND280: measures flux and flavour content before oscillation + ν cross sections
- SK: measures oscillated spectrum

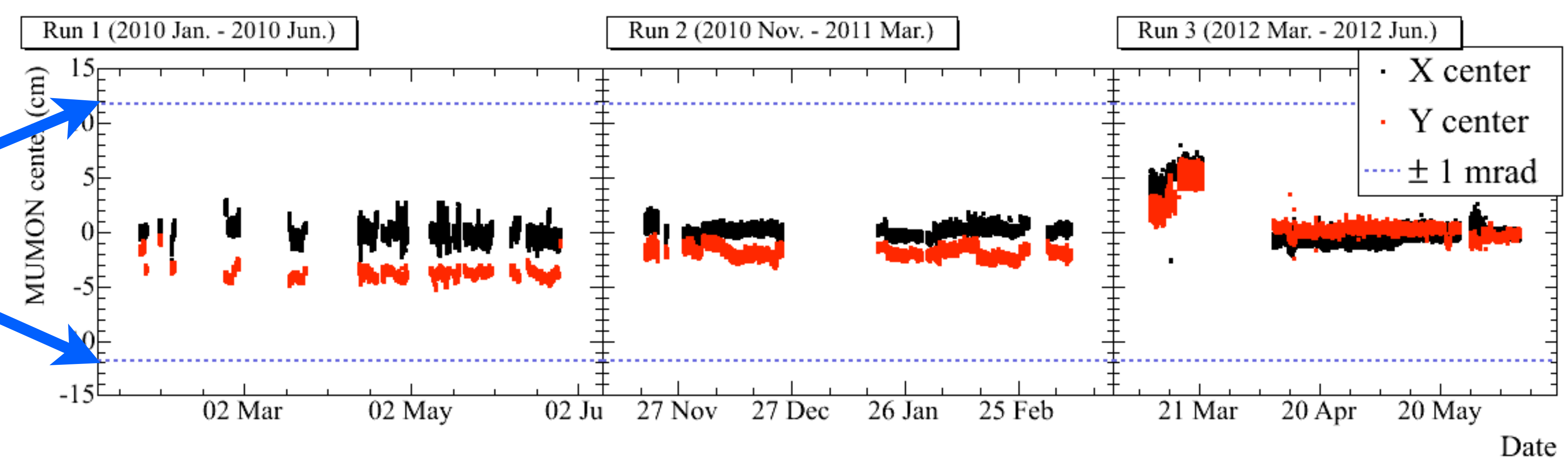
Collected data



3.01 10^{20} POT collected so far (as of ICHEP 2012)

Stability of the beam direction from the muon monitor:

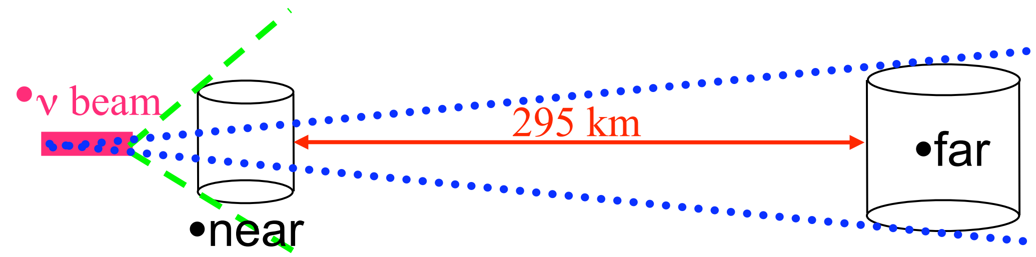
correspondence between angle and shift of peak energy (1mrad 2%)



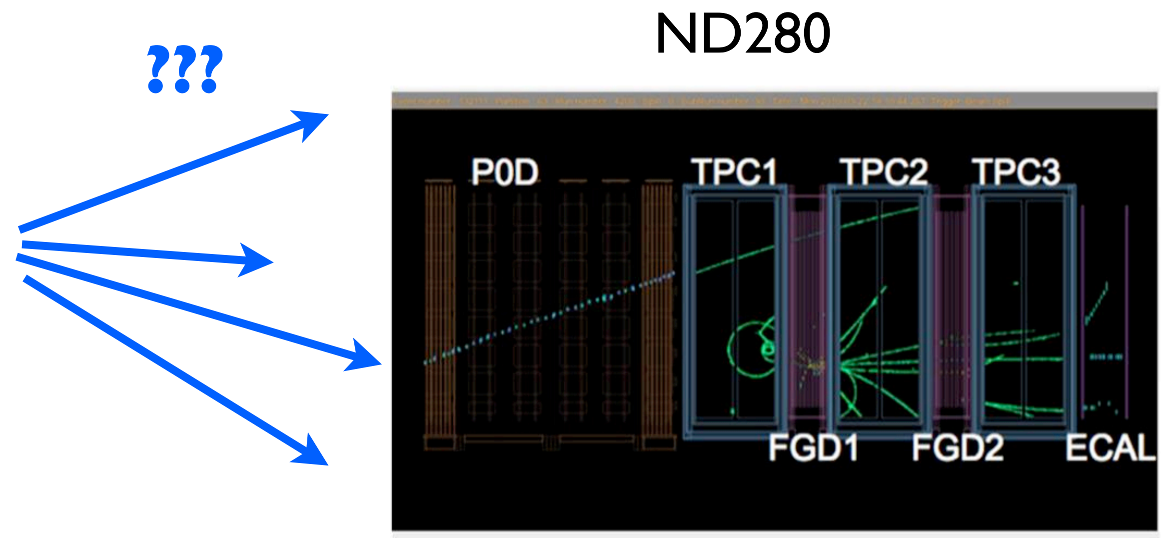
Why is the prediction of the neutrino flux important?

To predict the number of events at T2K:

- The measured flux in the ND has a different shape than that of SK (non point like source)
- The intrinsic ν_e contamination of the ν_μ beam is an irreducible background for the appearance signal.



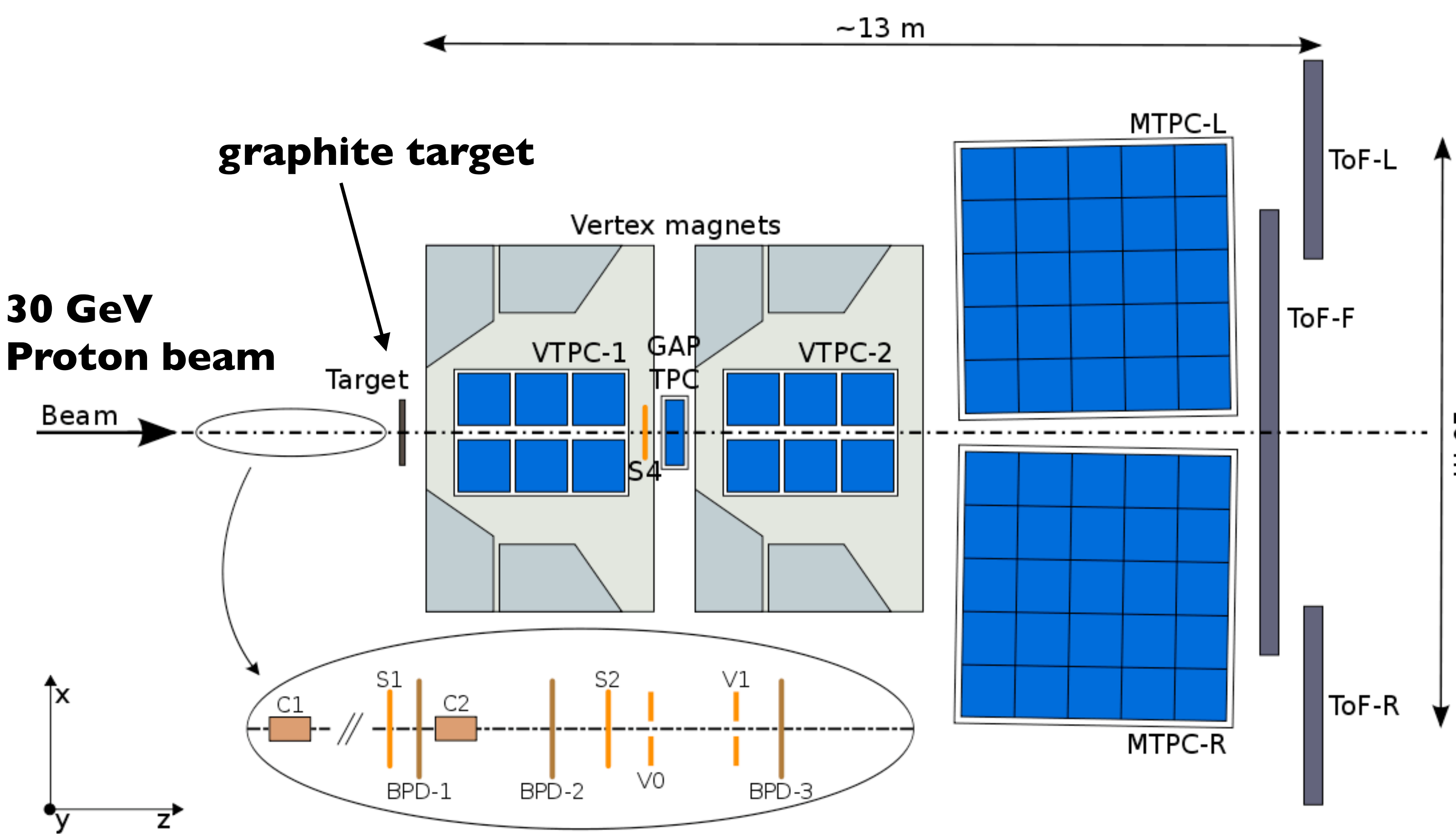
To evaluate the flux at the ND for cross section measurements (which are needed for the oscillation analysis).

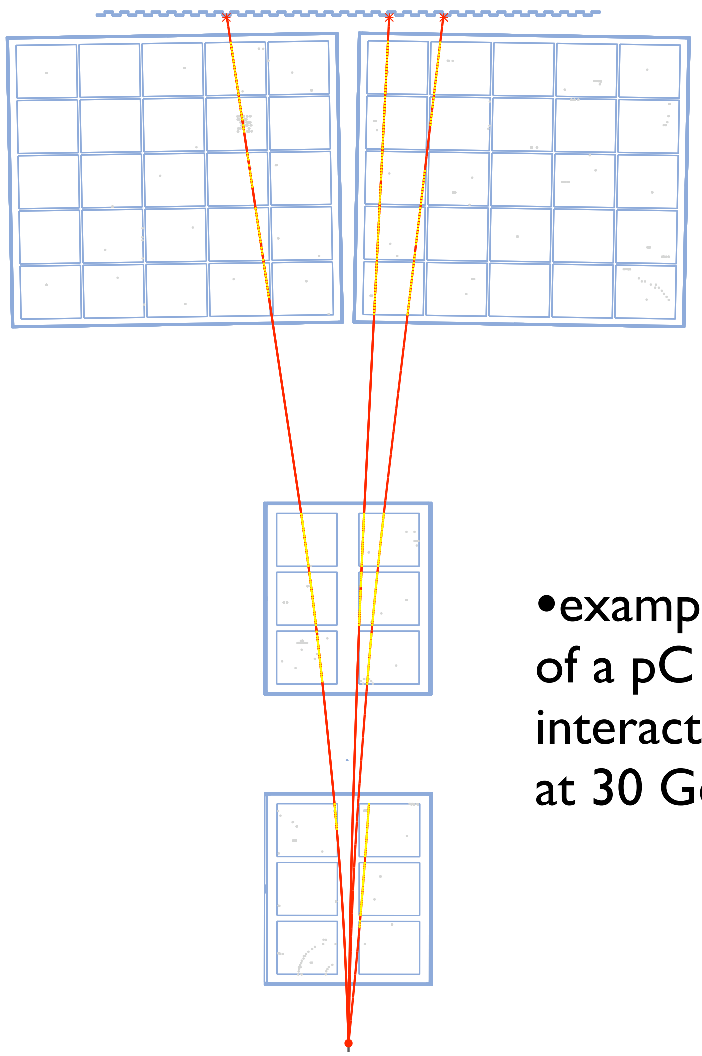


In any case, the estimation of the flux depends on the production of the hadrons at the target.
=> Need hadron production data at p+C 30 GeV to constrain the flux.

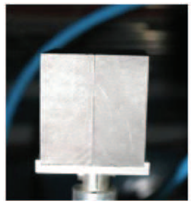
The NA61/SHINE detector at CERN SPS

30 GeV proton-carbon (pC) interactions





•example of a pC interaction at 30 GeV



- **3 BPDs** (Beam position detectors)
- **5 TPCs** $\sigma(p)/p^2 \sim 10^{-4}$
- **3 Time of flight**: TOF,L,R resolution ~70 ps
  FTOF resolution ~110ps <=Added in 2007 for T2K measurements and extended in 2009
- **2 Targets:** Thin target: 0.04 λ_I
  T2K replica target: 1.9 λ_I

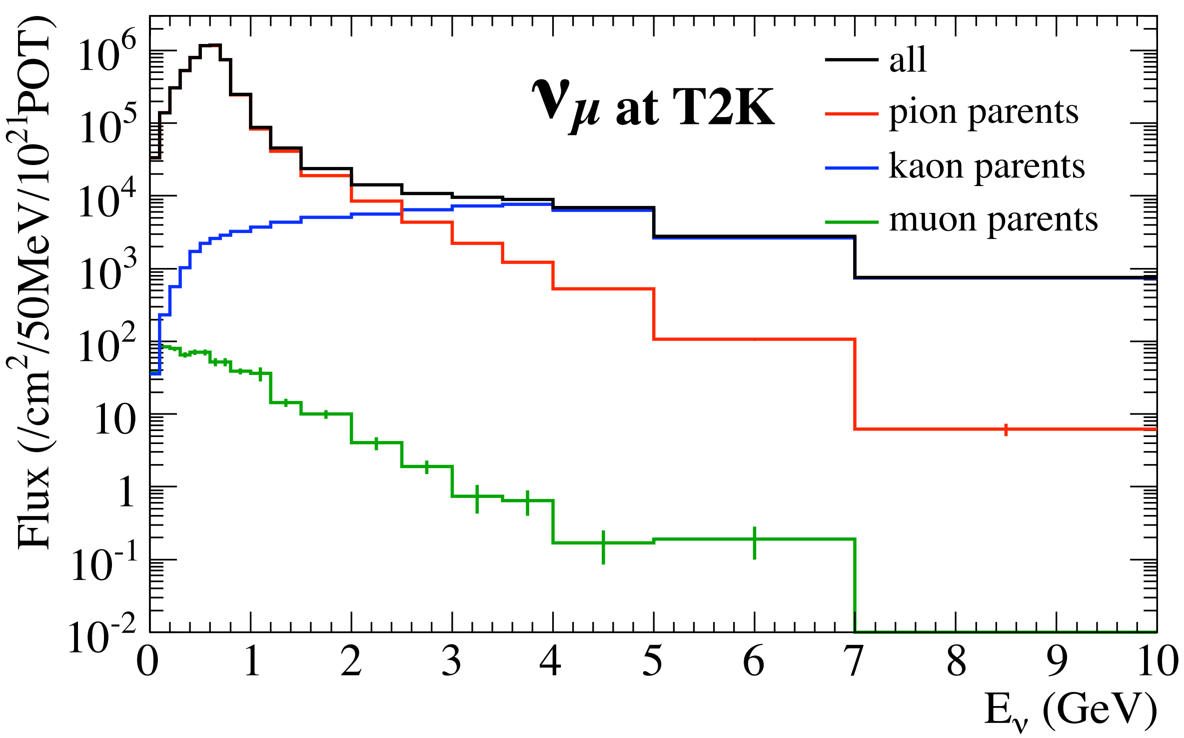
Both targets are required to understand pC interactions and model reliably of the neutrino flux.

What cross-sections should NA61/SHINE measure?

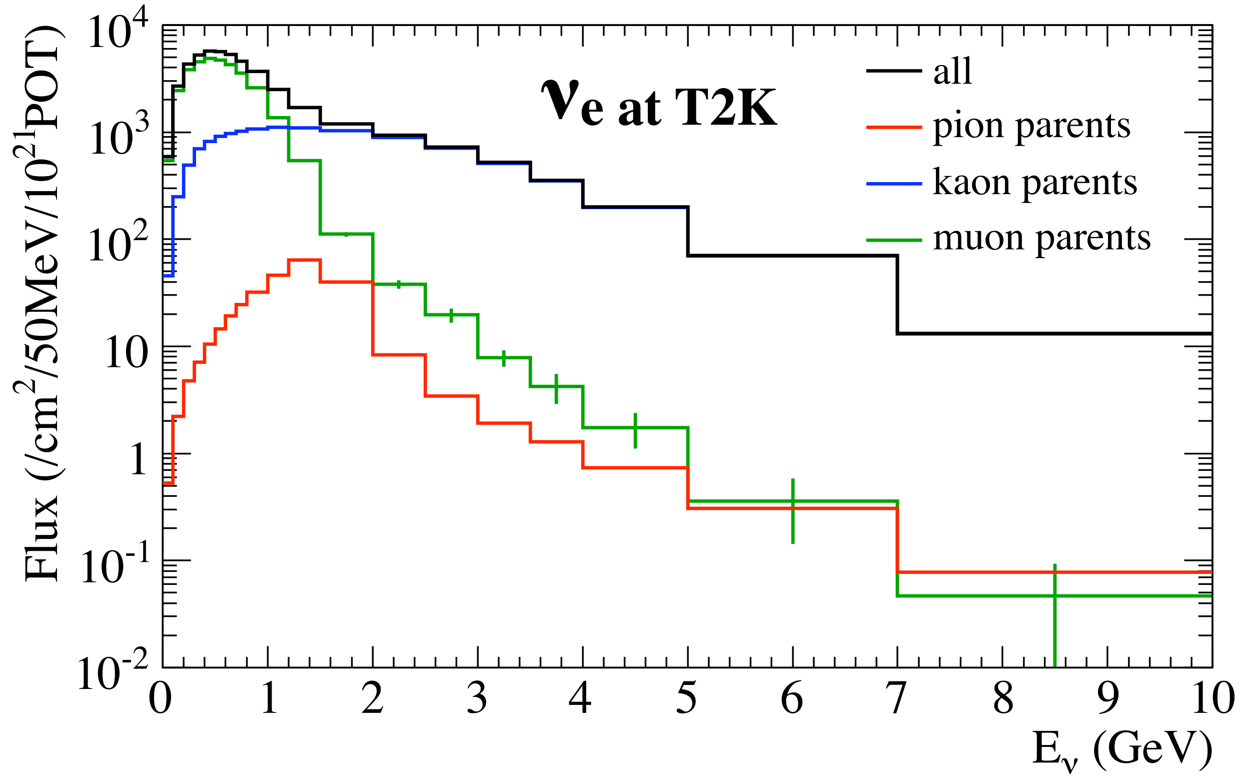
Which cross sections measurements are needed?

What is the composition of the ν_μ and ν_e flux in terms of hadrons exiting the target?

far detector



far detector

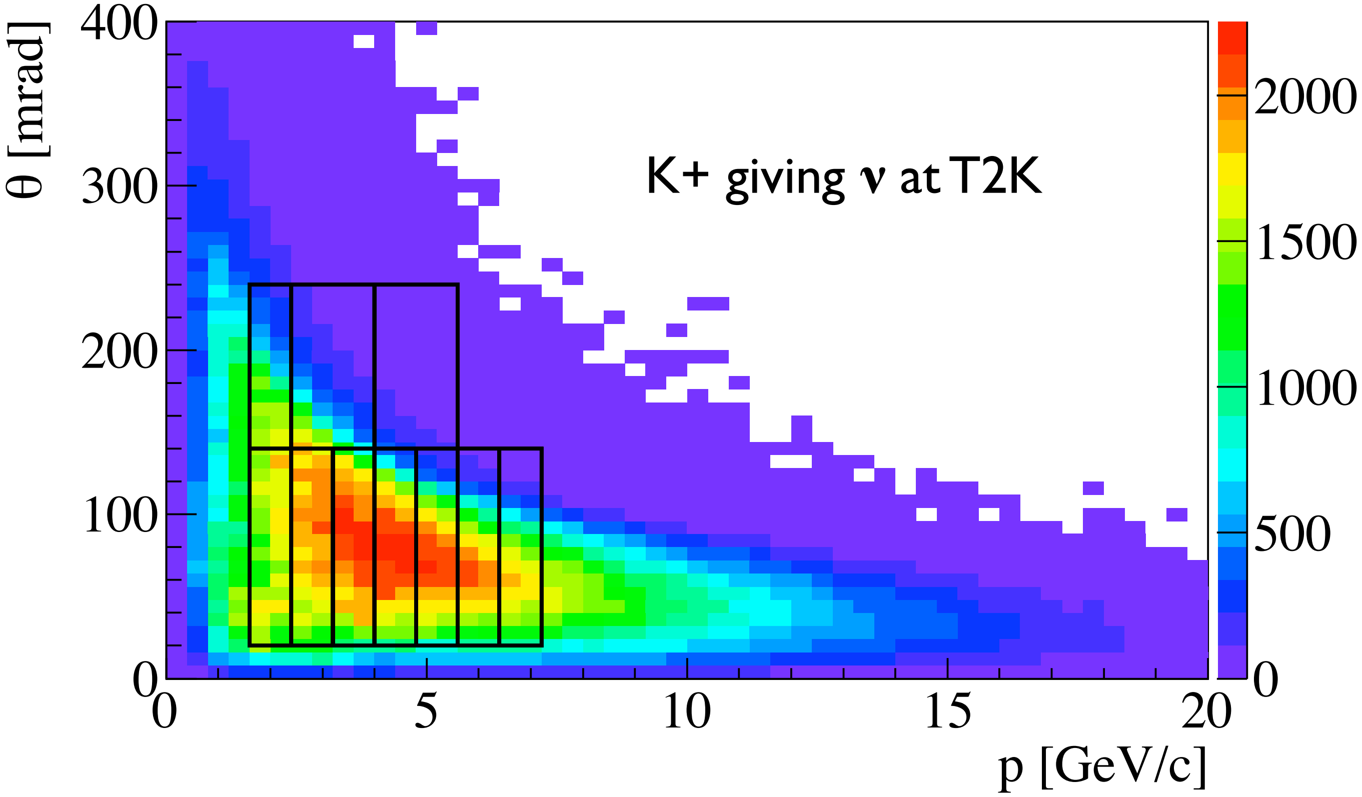


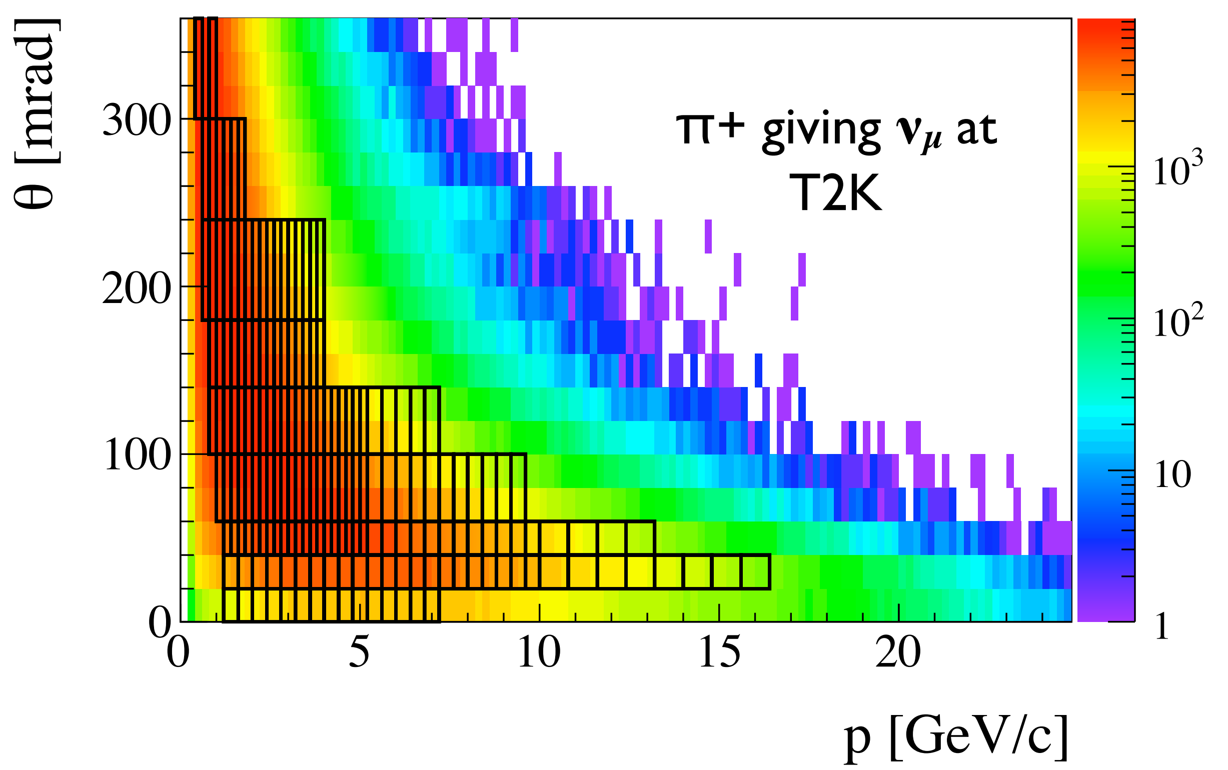
ν_μ predominantly from π^+ decay at peak energy, higher energy tail from kaon decay

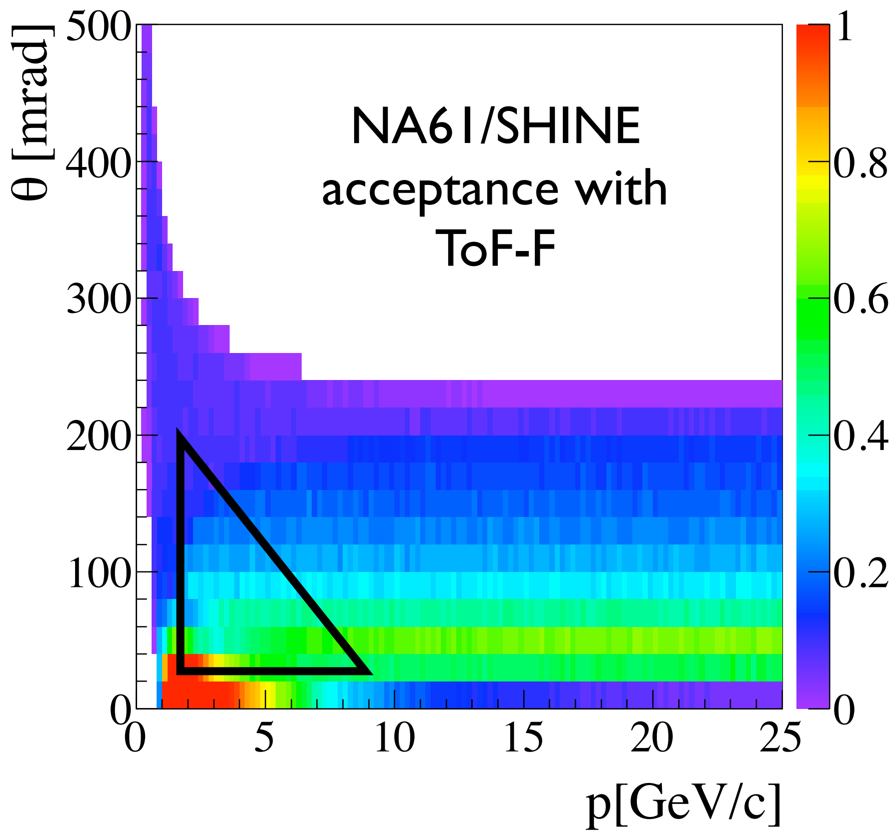
ν_e predominantly from μ^+ and K^+ decay at peak energy, higher energy tail from kaon decay

NA61/SHINE has the required acceptance

NA61/SHINE fully covers the T2K phase-space







NA61/SHINE data taking for T2K

2007 pilot run:
thin target ~ 660 k triggers
replica target ~ 230 k triggers

USED for T2K flux prediction

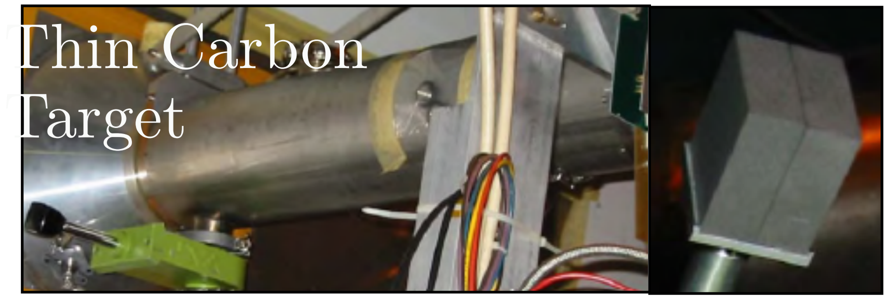
2009 run:
thin target ~ 6 M triggers
replica target ~ 2 M triggers

Currently being analysed

2010 run:
replica target ~ 10 M triggers

Calibration phase

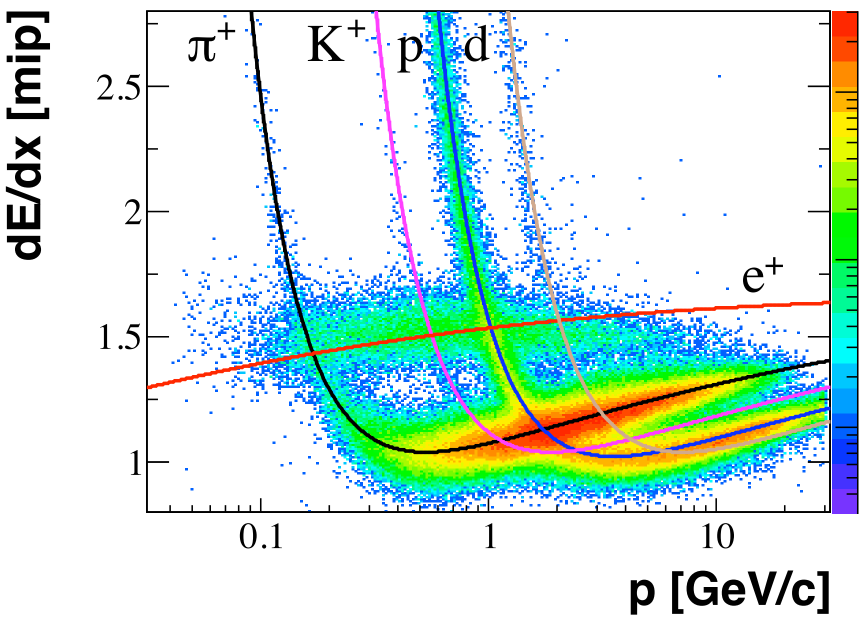
2 different graphite (carbon) targets

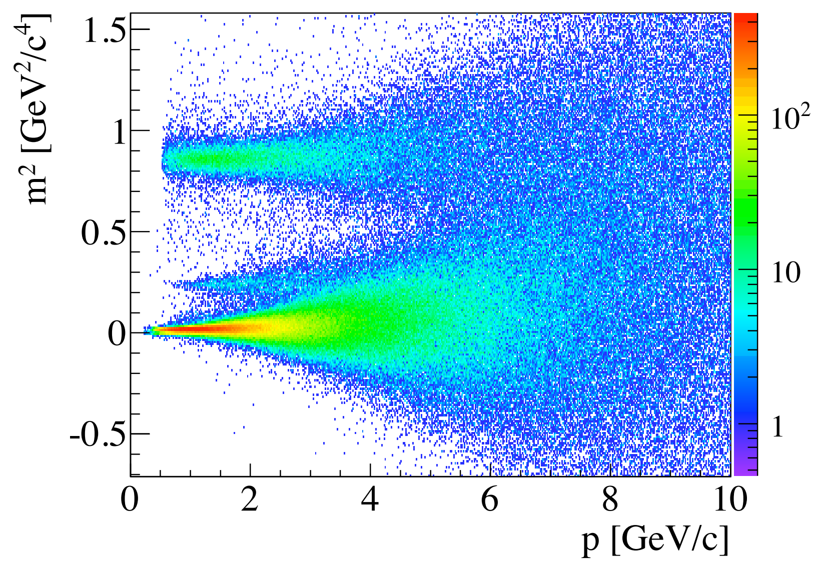


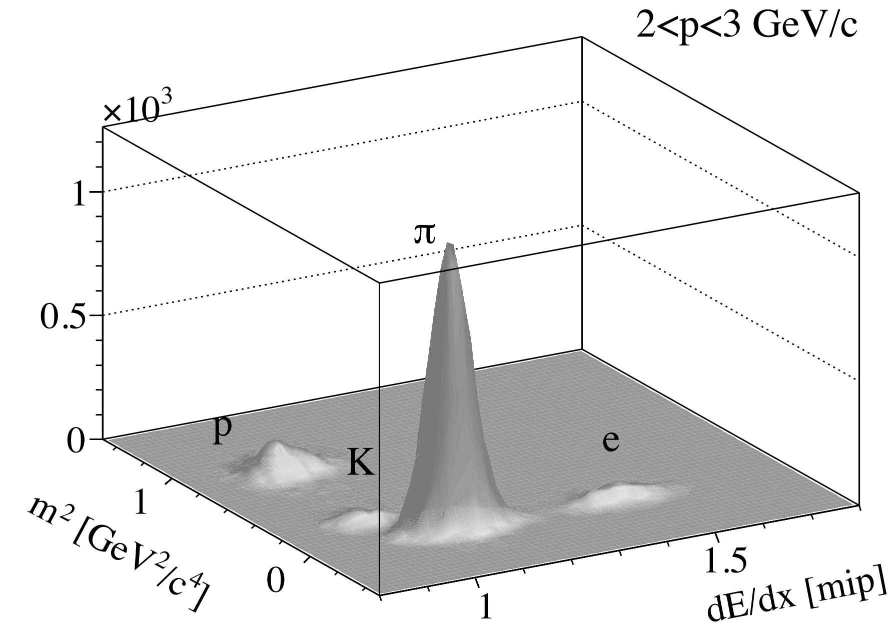
- Both targets are required to understand pC interactions and model reliably of the neutrino flux.
- Many different analysis were performed on the 2007 thin target data (very important for x-check)
- from the 2007 data we extracted: charged pions, K^+, protons and K^0_s
- published 2 PRC papers

Particle identification in NA61/SHINE

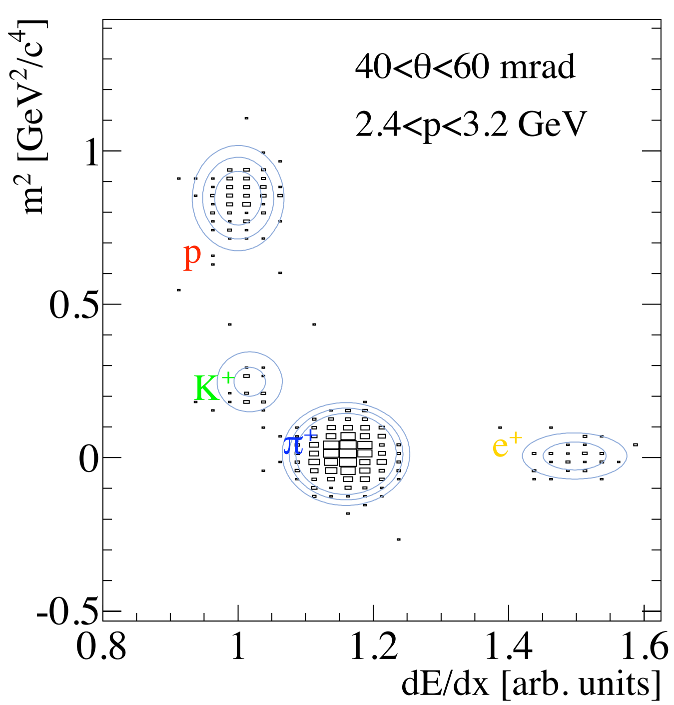
Combine *dE/dx* from TPCs at high momentum with m^2 from ToF-F at low momentum

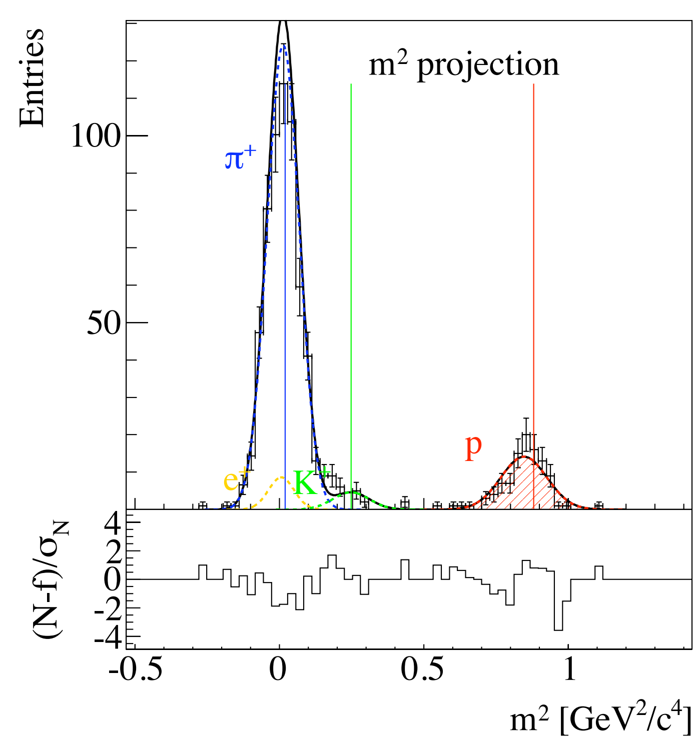


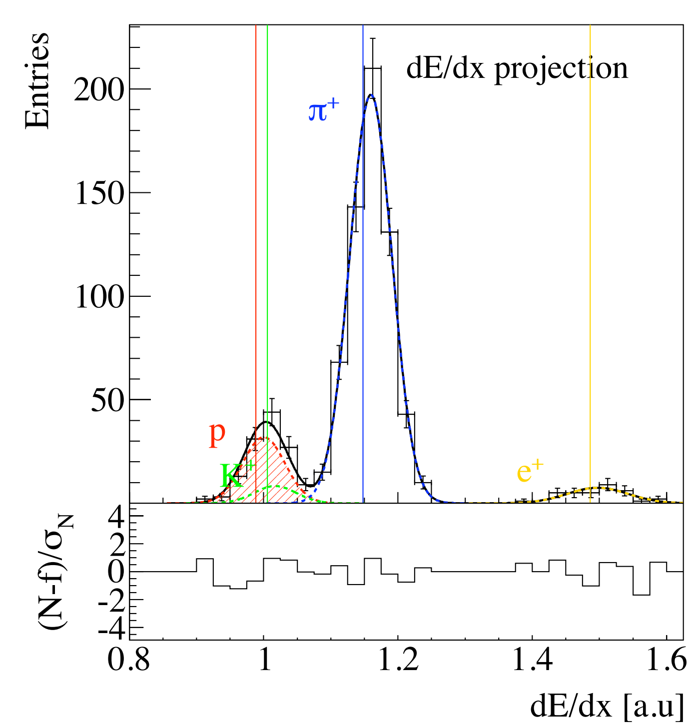




to obtain **high purity** particle identification over the entire phase-space: **Combined *tof-dE/dx* PID**

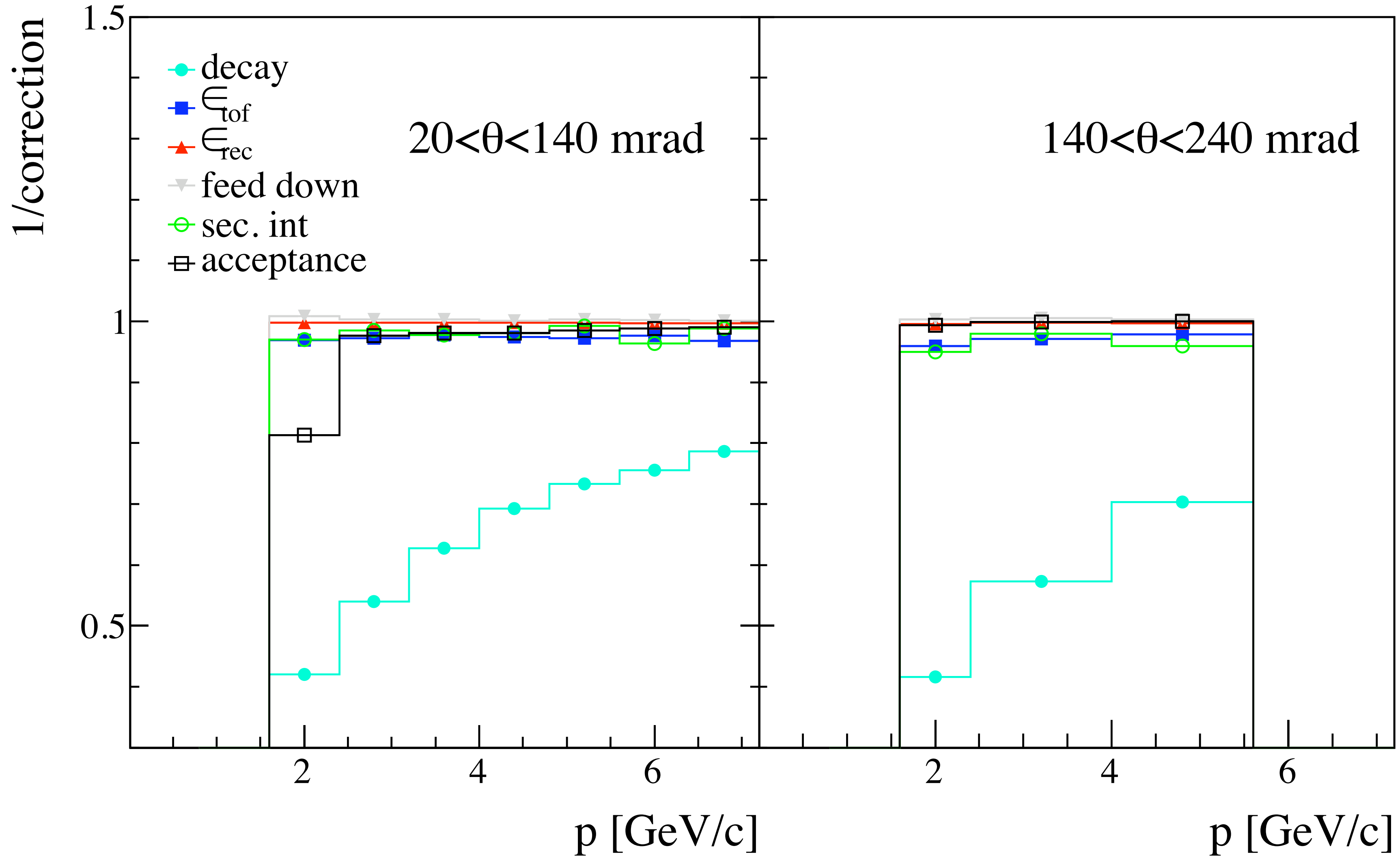






NA61/SHINE has high efficiencies

Breakdown of the MC corrections for the K^+ spectra



Thanks to azimuthal cuts and selection of long tracks:

- -acceptance,
- -reconstruction efficiency,
- -ToF efficiency,

=>all close to 100%

Effectively the only correction for K^+ is decay in flight

- •ToF efficiency: probability for a track to generate a valid m^2 measurement in the ToF-F.
- •Reconstruction efficiency: efficiency of the reconstruction algorithm.
- •feed down: K^+ from weak decays fitted to primary vertex.
- •Secondary interactions: interactions of K+ in the target or detector material

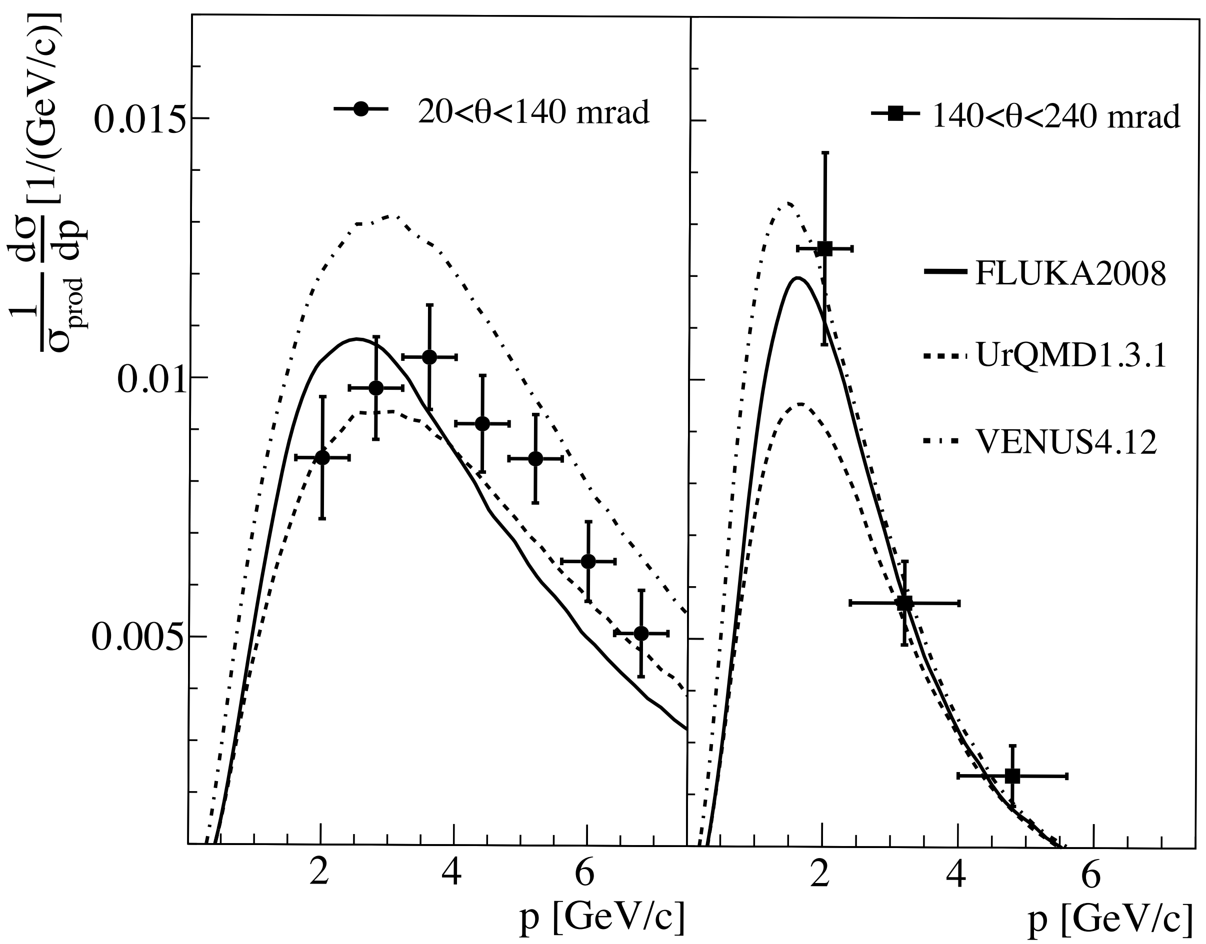
<= are model dependent

- •Acceptance: correction for the geometry of the detector

NA61/SHINE results - K^+

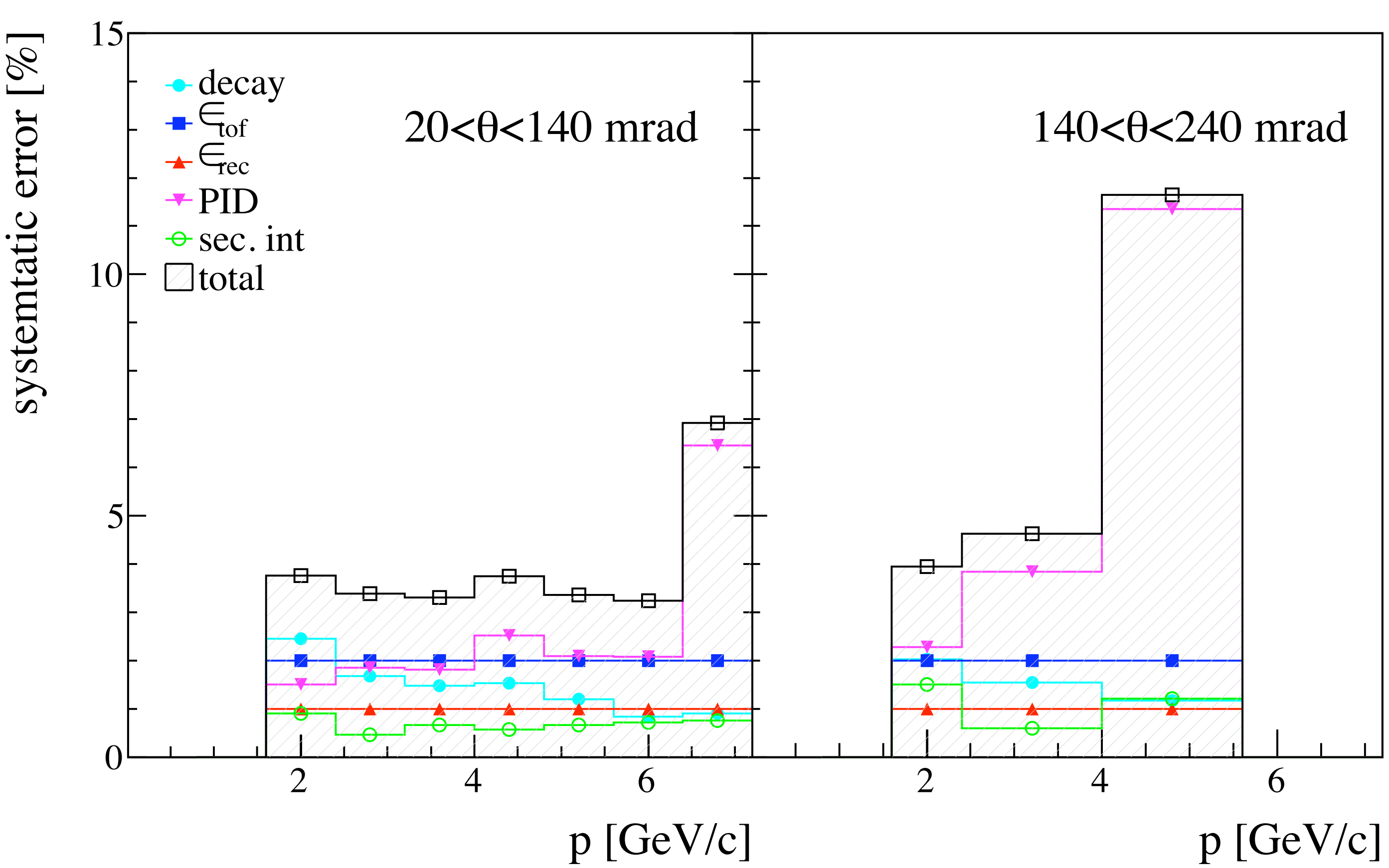
N. Abgrall *et al.* Measurement of production properties of positively charged kaons in proton-carbon interactions at 31 GeV/c *Phys. Rev.* ***C 85*** *(Mar, 2012) 035210.*

normalised to mean multiplicity in all p+C production interactions.



Comparison with models (UrQMD, FLUKA and VENUS4.12, which is the model used in our MC)

systematic uncertainties



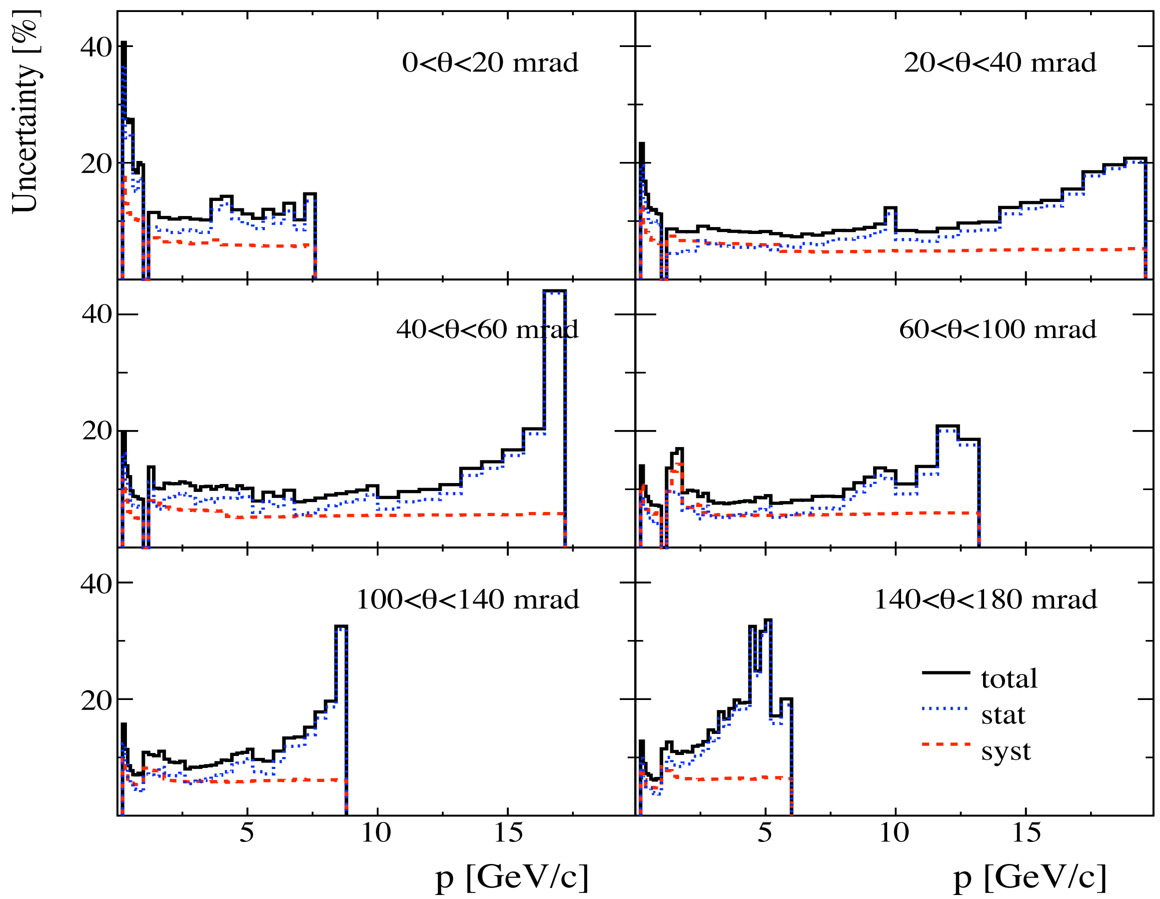
Typically 15% stat. 5% sys.

NA61/SHINE results - $\pi^{\pm}$

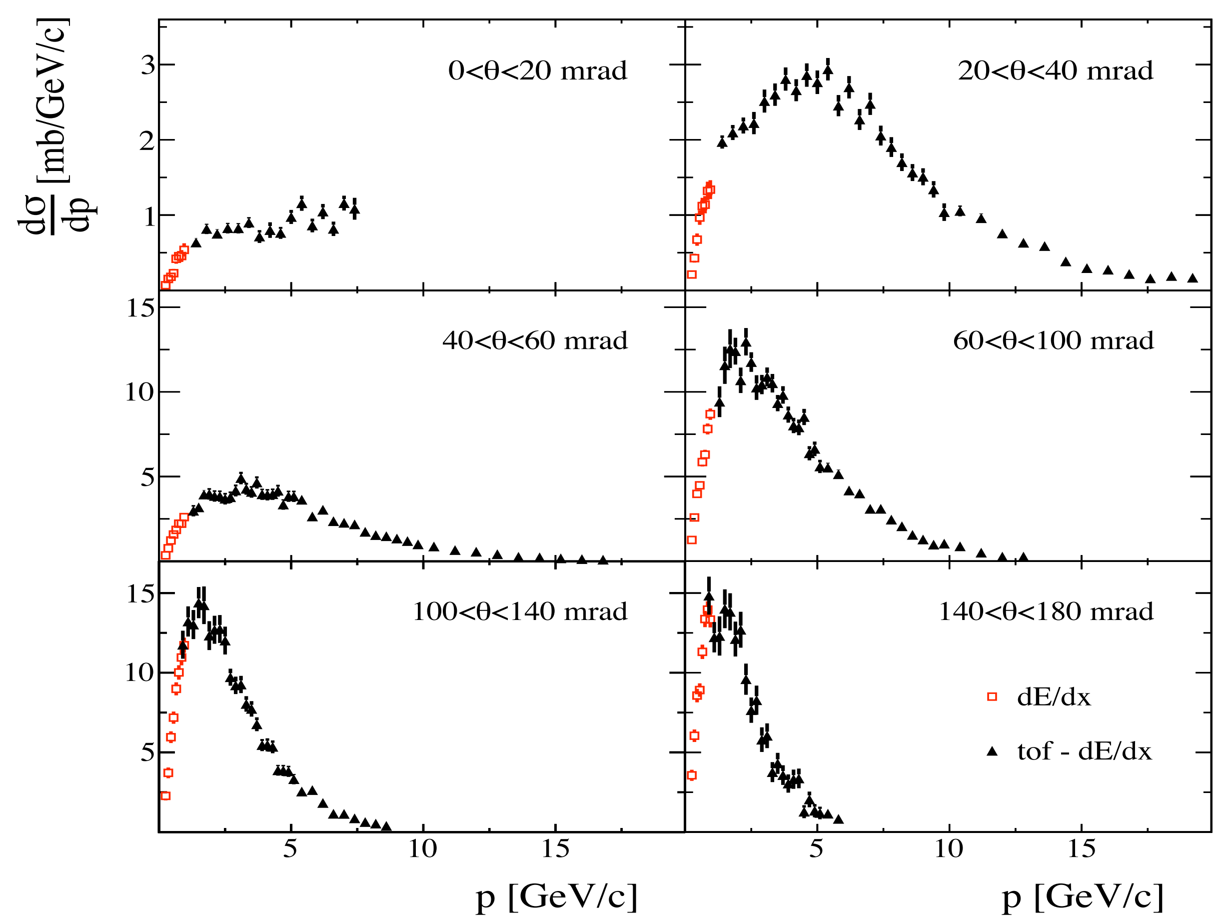
N. Abgrall et al., "Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c," *Phys. Rev. C84 (2011) 034604*

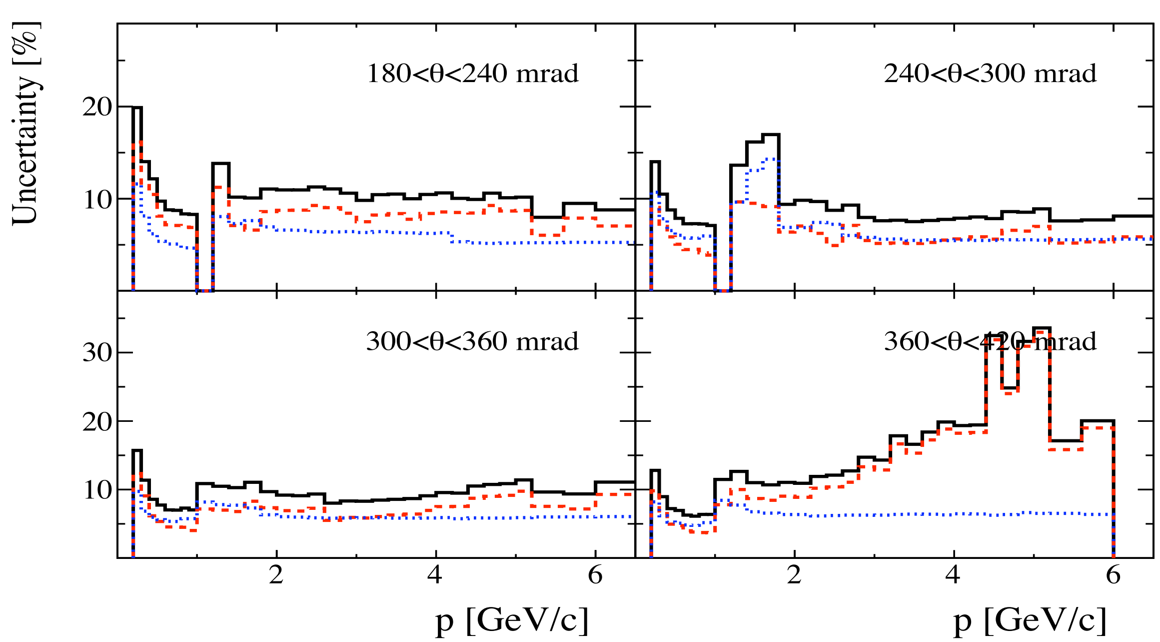
Typically 10% stat. 7% sys. (main source of sys. is PID)

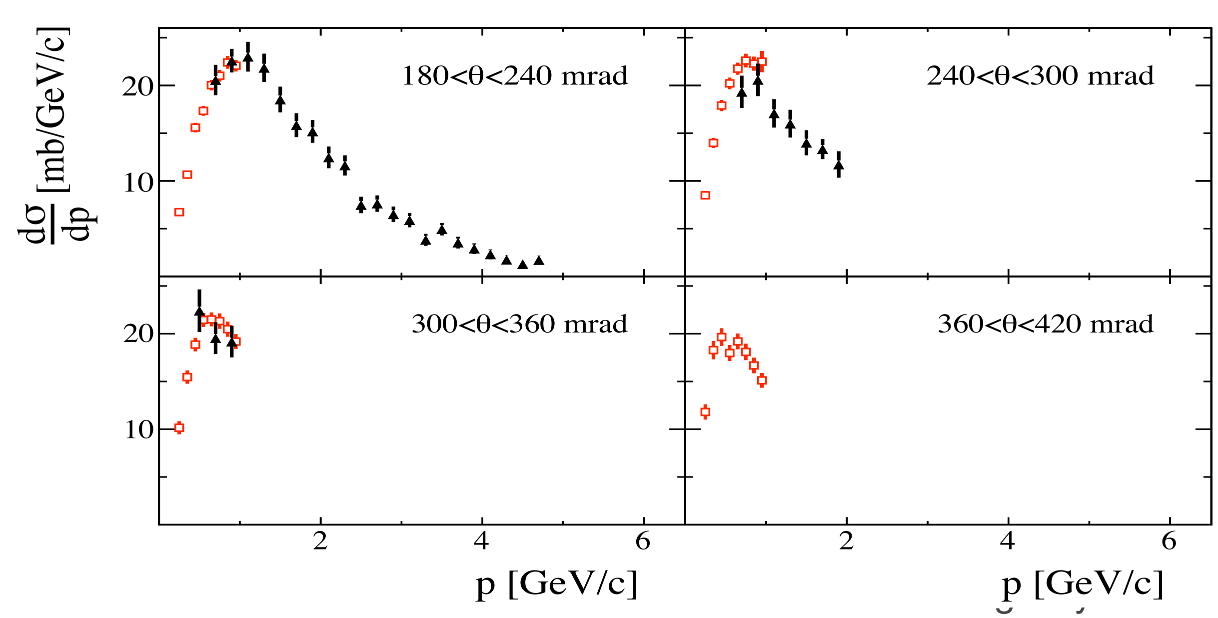
relative errors



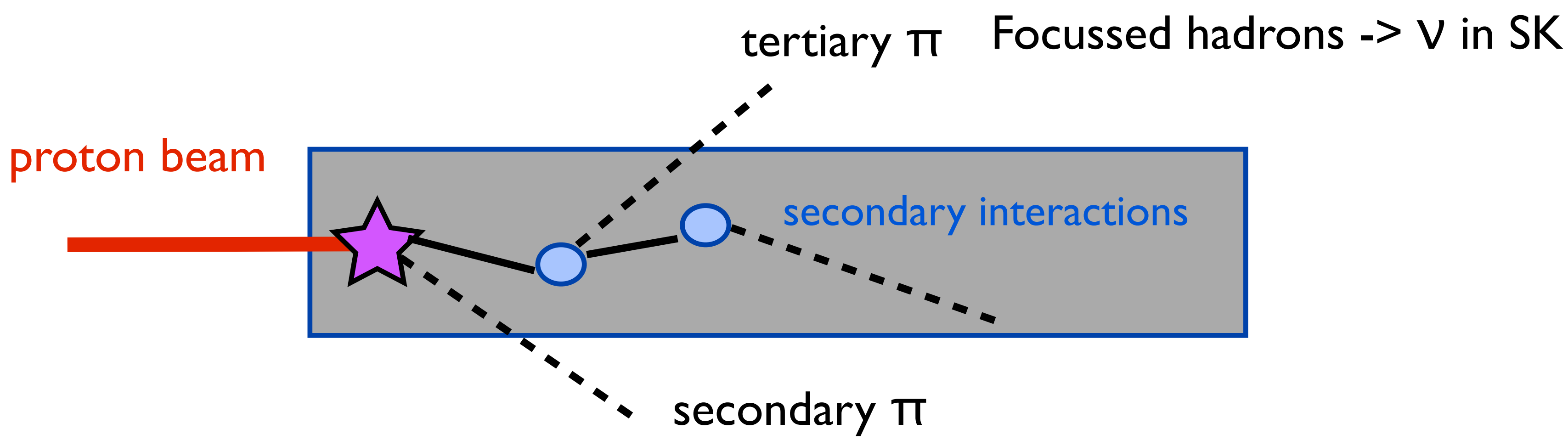
π+





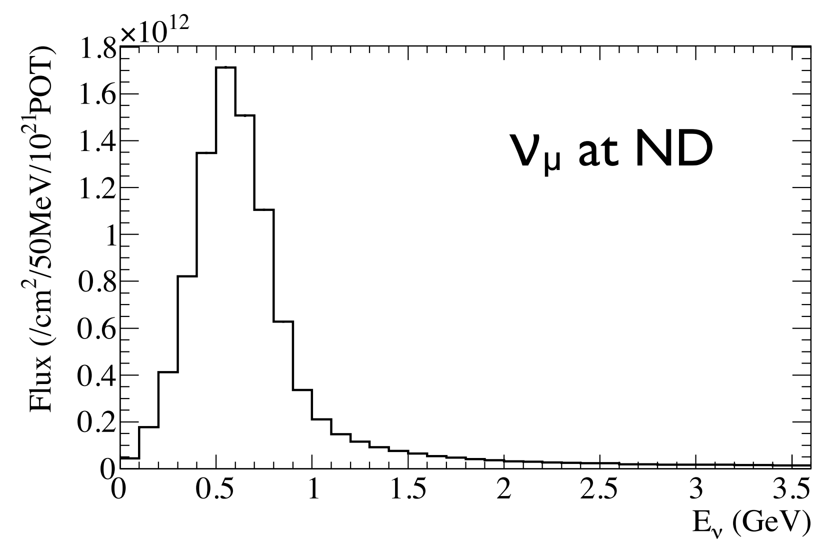


The T2K beam Monte Carlo



With the NA61/SHINE thin target data we only have direct information on the primary interaction.

primary proton interaction in carbon (Fluka 2008 3d) → tracking through horns, magnetic field and decay pipe (GEANT3) → Adjust flux using NA61/ SHINE data →



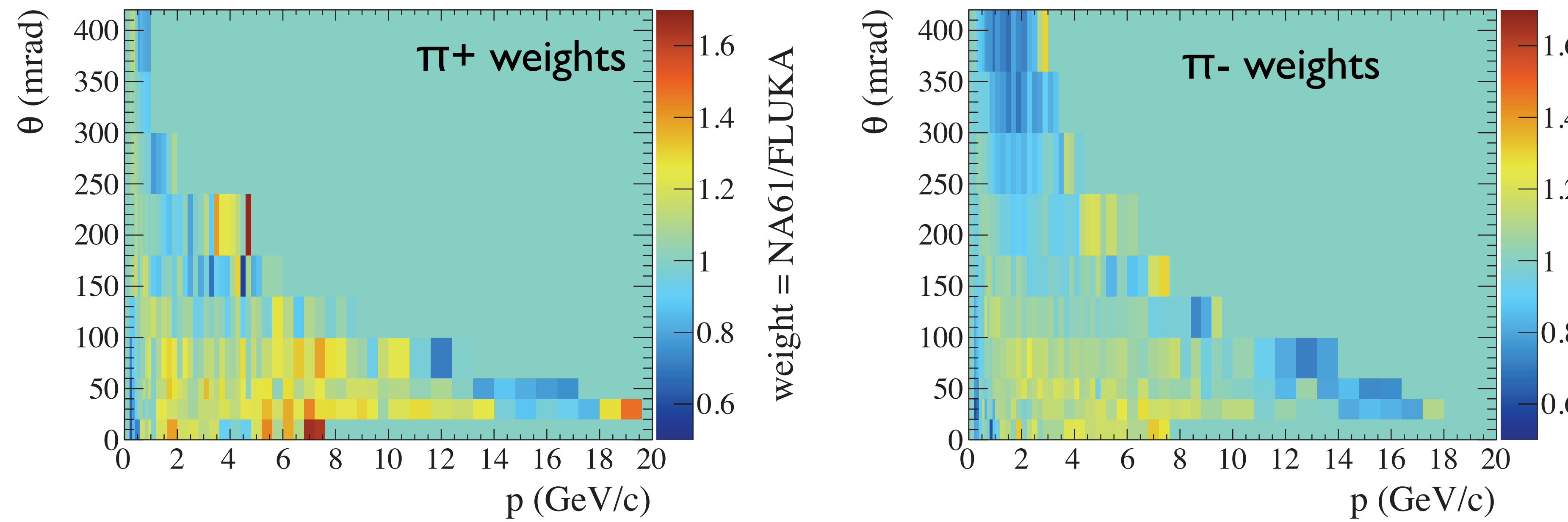
Obtain data driven flux prediction

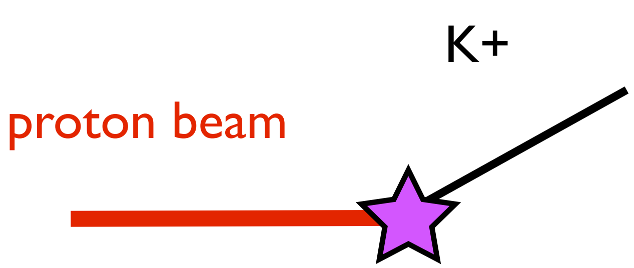
Constraining the T2K flux - primary interactions

weight the Fluka pion and kaon production with NA61/SHINE.

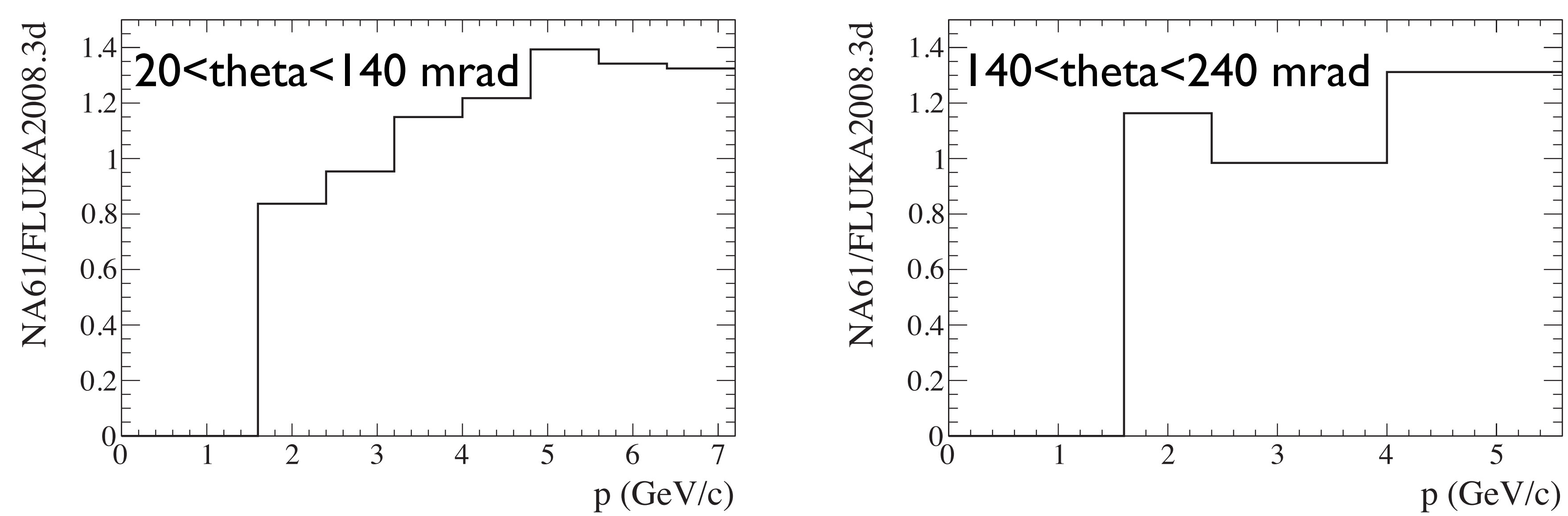
weight=measured/simulated multiplicities $\quad w(p,\theta) = \frac{d^{\theta}n_{\mathrm{NA61}}}{dpd\theta} \Big/ \frac{d^{\theta}n_{\mathrm{MC}}}{dpd\theta}$

Pion weights





K+ weights



Extend kaon coverage

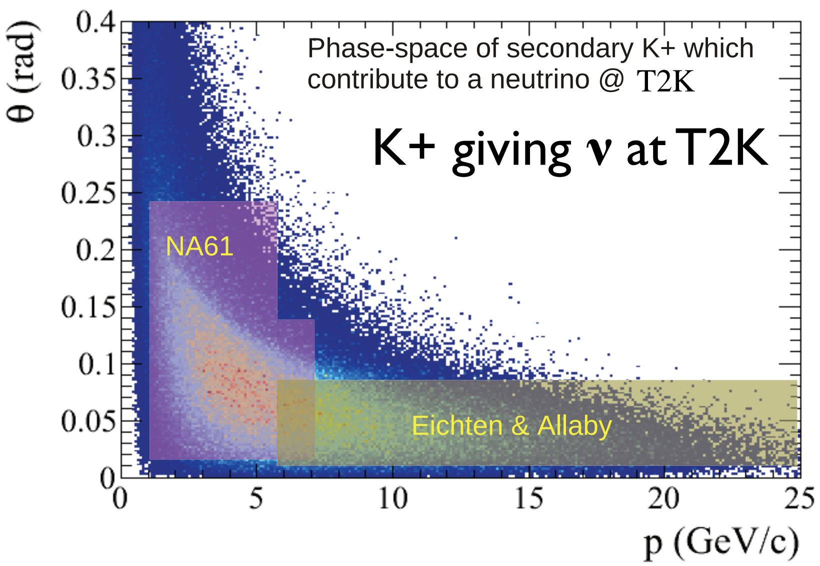
NA61 (for the moment) has a limited kaon coverage both in terms of kaon charge and phase-space.

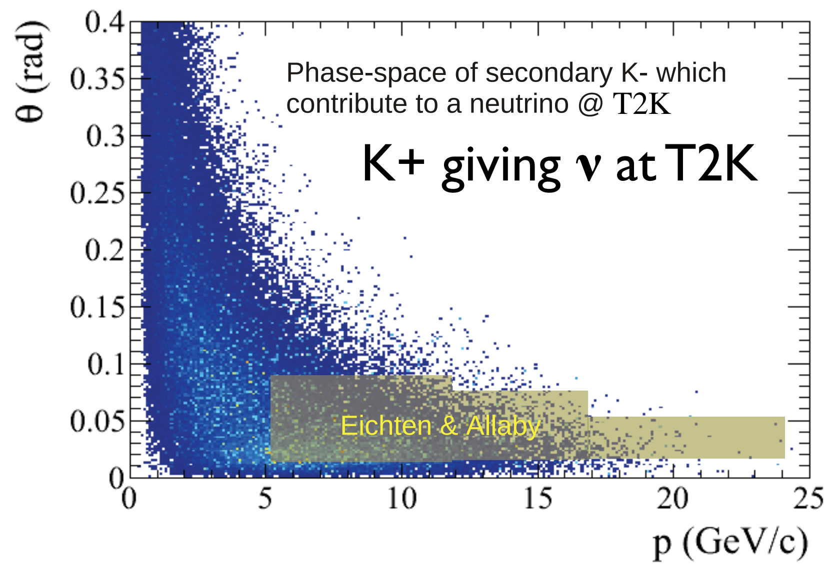
Use other external data to constrain
Eichten *et al.*: p+Be 24 GeV/c.
Allaby *et al:* p+Be 19.2 GeV/c.

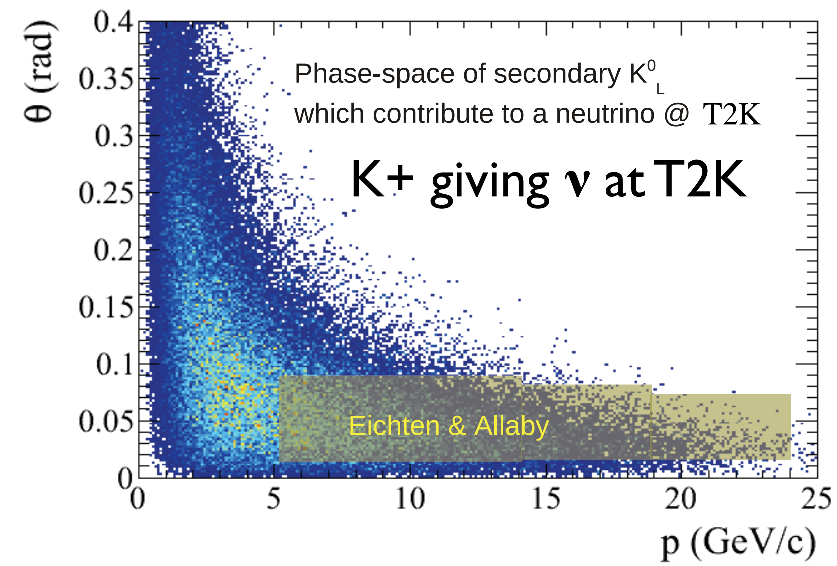
estimate neutral kaon production

$$K_l^0 = \frac{1}{4}(K^+ + 3K^-)$$

(M. Bonesini et al. Eur. Phys. 1084 J. C , 20, 2001)





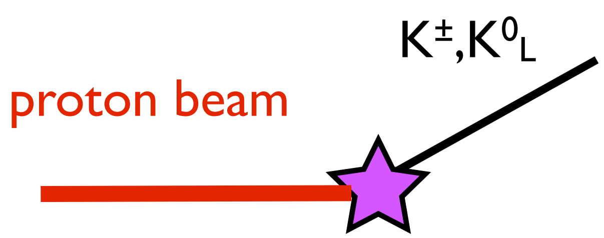


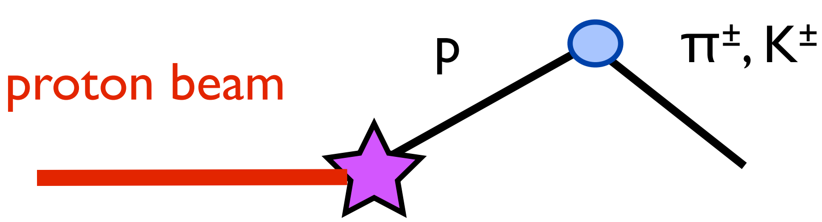
Using Eichten and Allaby data

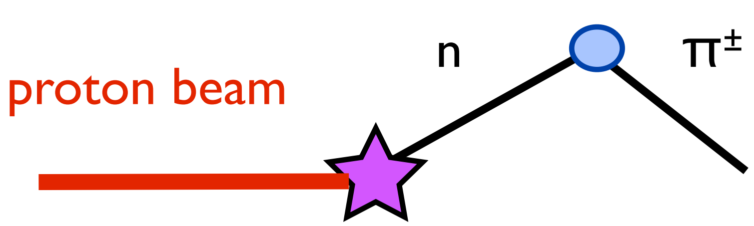
- Extend phase space + complete data driven kaon production
- Requires scaling to different beam momentum and different target materials

=> will increase NA61 kaon coverage in the near future

Systematic errors on particle production





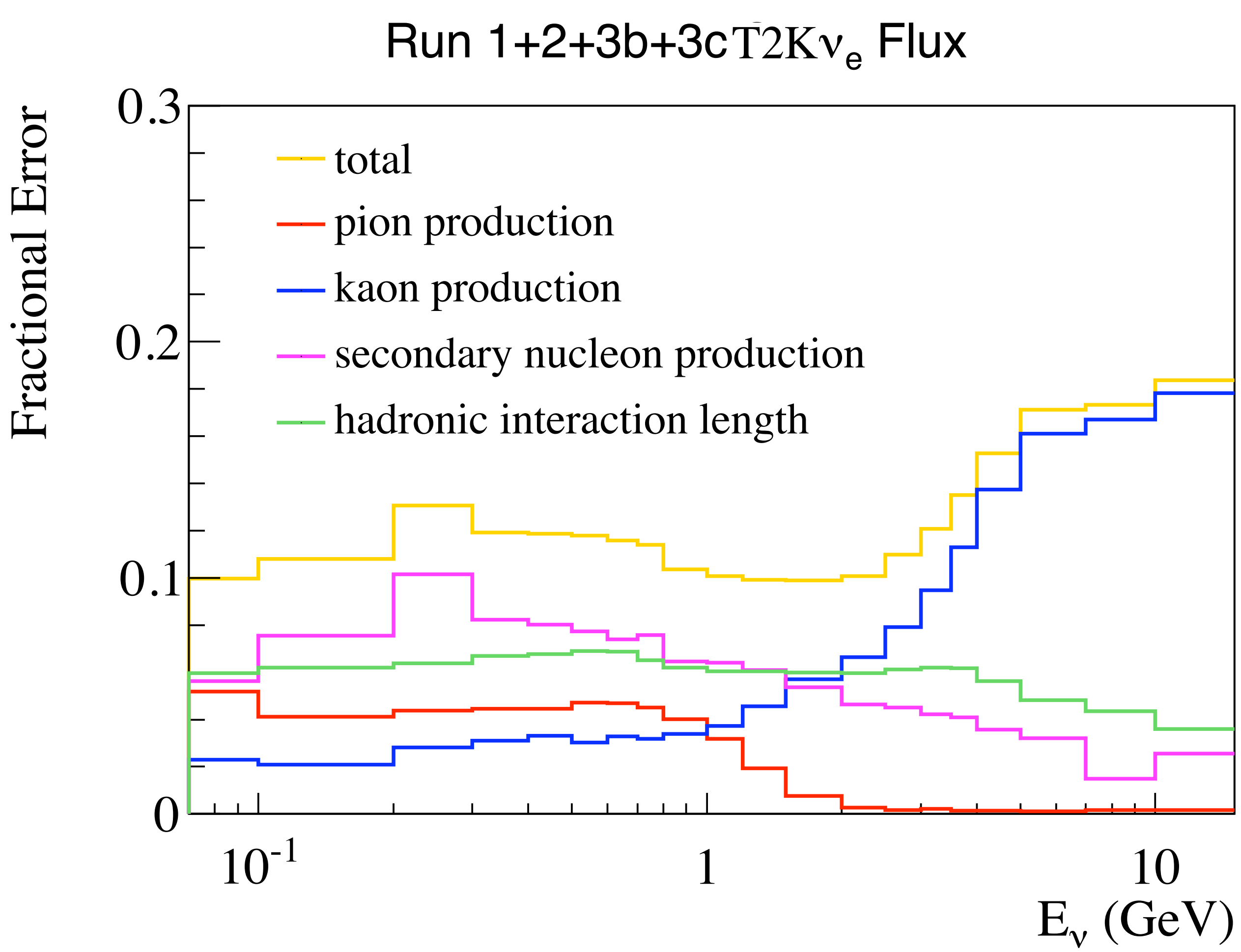


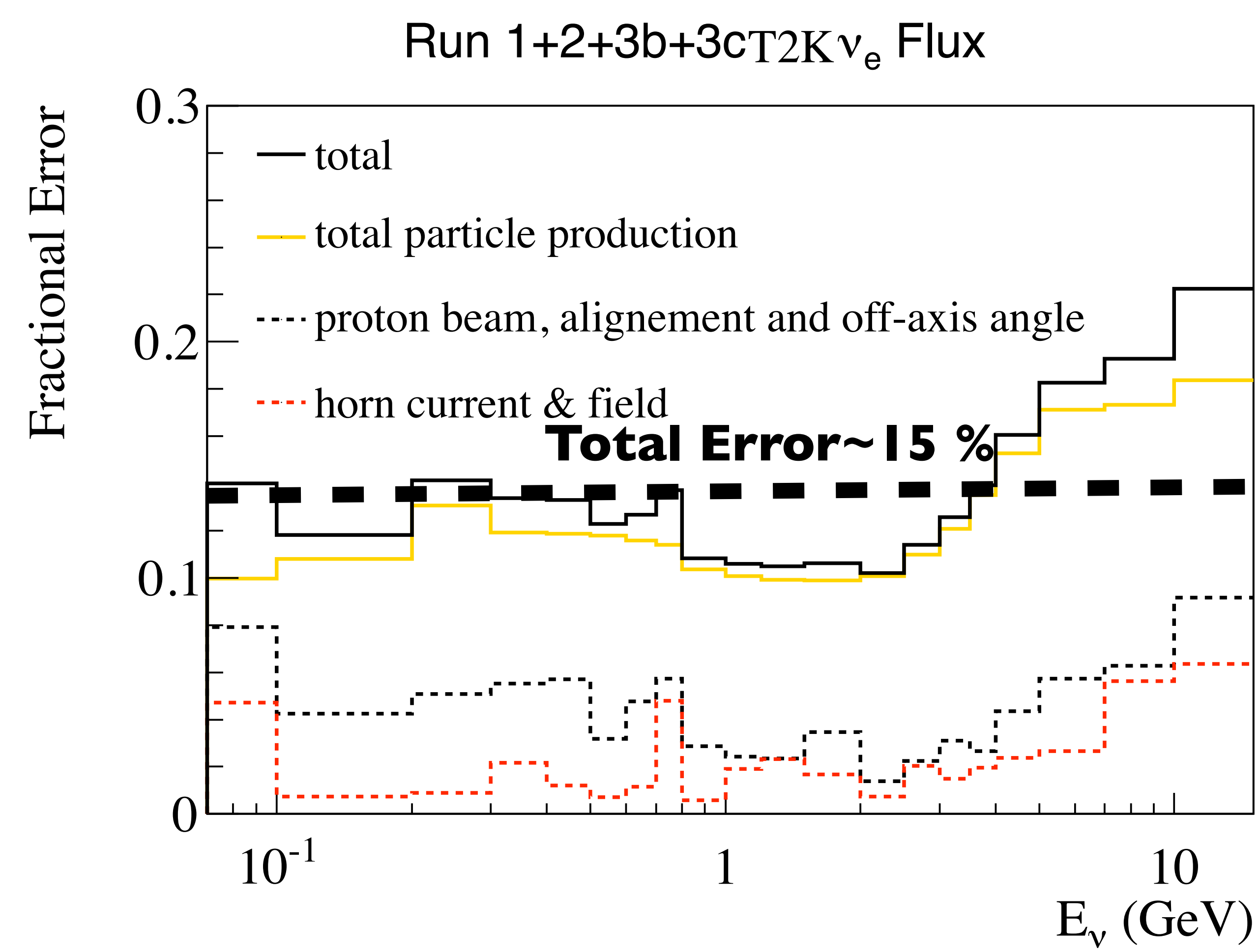
Process	ν_μ contribution	ν_e contribution	
1	70%	40%	Systematic error of NA61/SHINE
2	8%	39%	Systematic error of NA61/SHINE (for K+) Systematic error of Eichten & Allaby + error on momentum/material scaling
3	16%	13%	Discrepancy between Eichten & Allaby data and Fluka + error on momentum/material scaling
4	5%	5%	NA61 pion error based on isospin invariance + error on momentum/material scaling

Other sources of systematic uncertainties

Systematic uncertainty	Evaluated from
Horn and target alignment	Geometrical Survey
Neutrino beam direction (off-axis angle)	INGRID measurements
proton beam	proton beam monitors (position, angle, divergence, width)
Horn currents	uncertainty from horn current measurements

Flux error envelopes





The total error is of the order of 15 % in the oscillation region (<1 GeV)

It is dominated by uncertainties in particle production

Uncertainty on secondary nucleon production dominates (not tuned yet so this error will go down in the future)

Flux uncertainties on the number of ν_e events

$\sin^2(2\theta_{13})=0.1$ $\Delta m^2_{32}=2.4\times10^{-3}\ \mathrm{eV}^2$ $\sin^2(2\theta_{23})=1.0$

	% Errors on Sample Predictions		
	N_{ND}	N_{SK}	N_{SK}/N_{ND}
Pion Production	3.41	4.97	1.88
Kaon Production	3.48	1.17	2.99
Secondary Nucleon Production	5.46	6.61	1.34
Hadronic Interaction Length	5.78	6.56	1.90
Proton Beam, Alignment & Off-axis Angle	3.45	2.08	1.75
Horn Current and Magnetic Field	1.40	1.16	1.39
Total	10.04	10.94	4.78
For comparison: -Total error July 2011 result	15.4	14.9	8.5

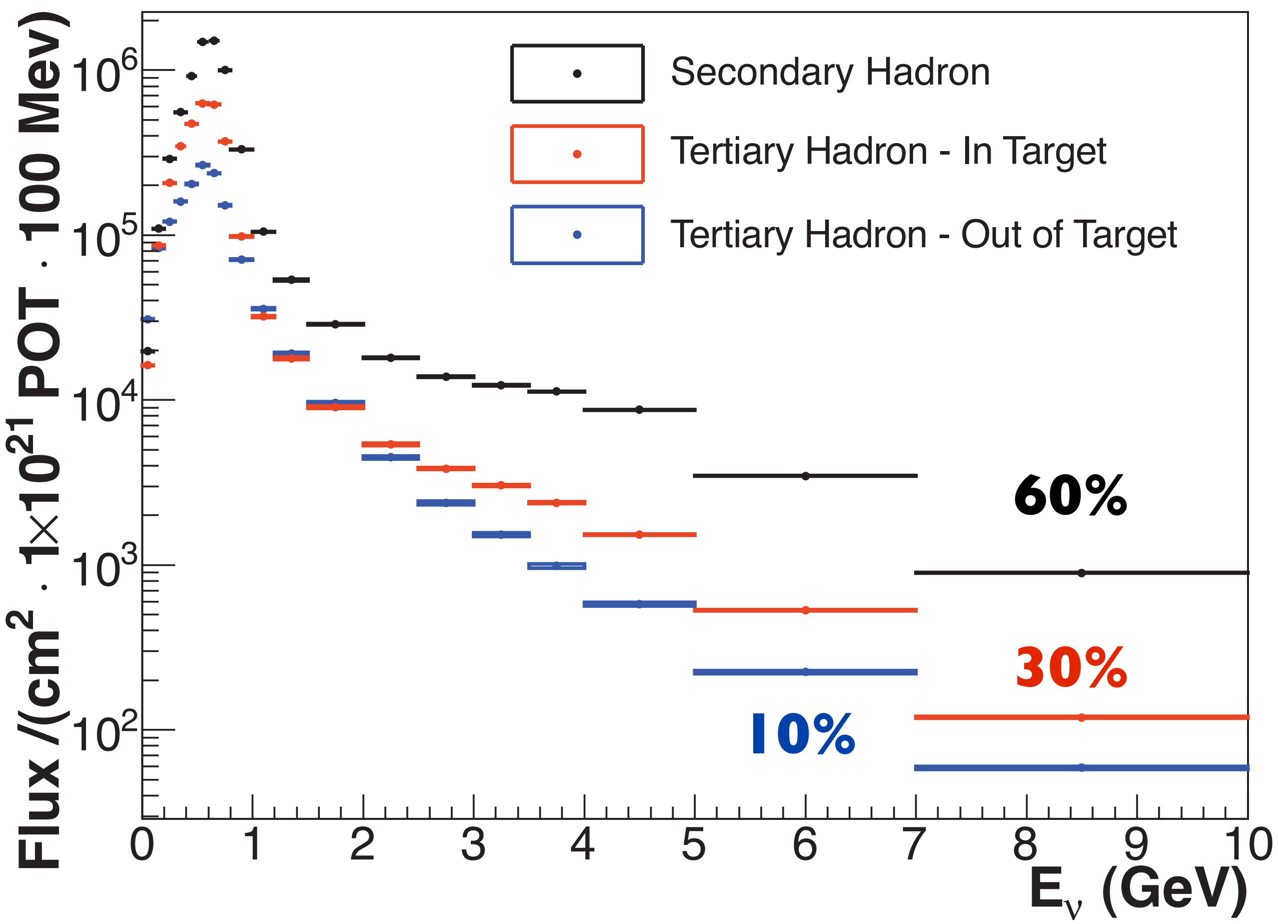
Clear improvement on flux uncertainties since 2011 results!

2011 results were without NA61 kaon data

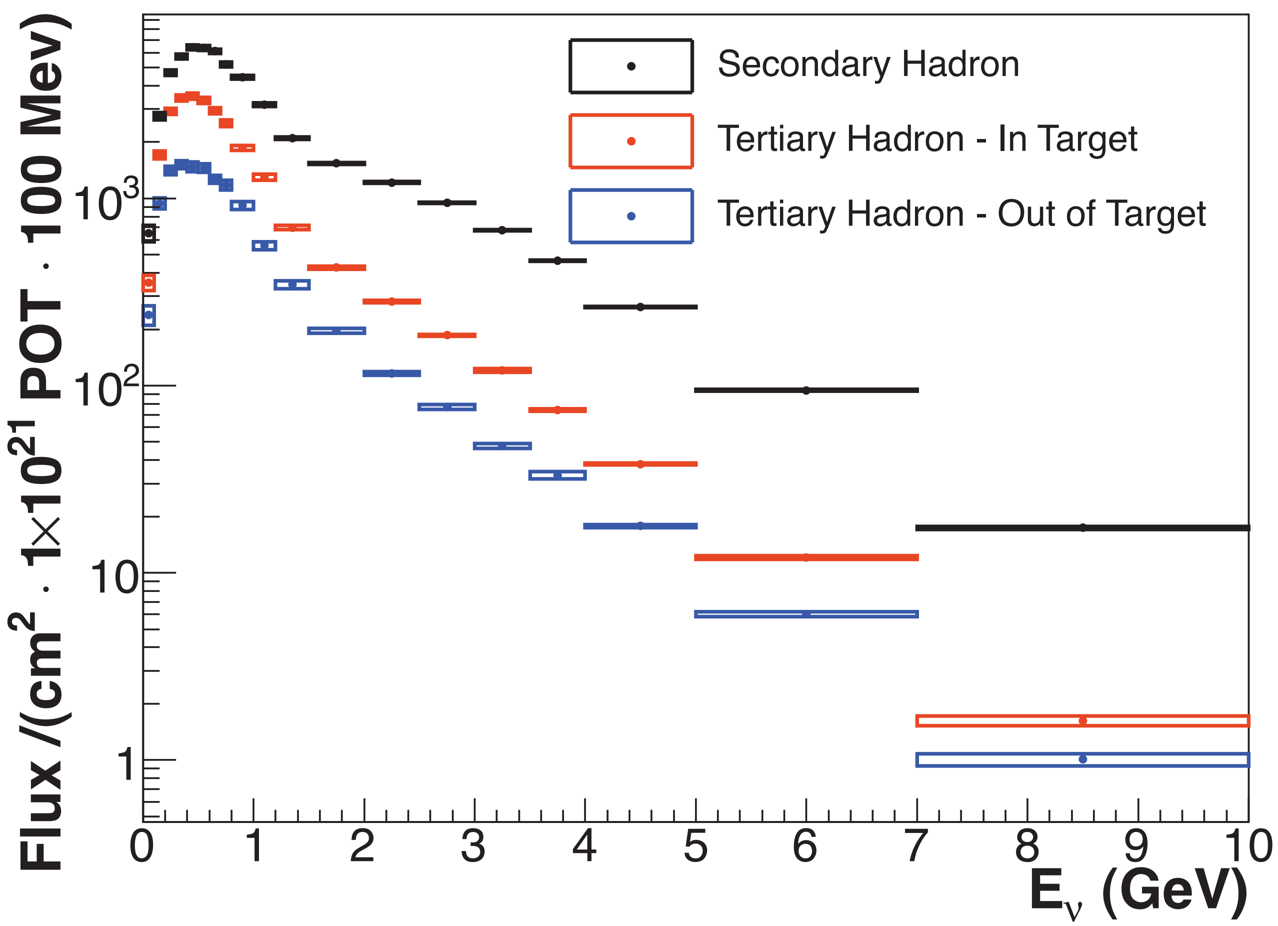
Future improvements with replica target data

Approx. **60%** of the flux comes from the **primary interaction**, **30%** from **secondary interactions** and **10%** from interactions **out of target** (mainly focussing horns)

ν_μ at T2K



ν_e at T2K



Need to constrain the secondary interactions with replica target!

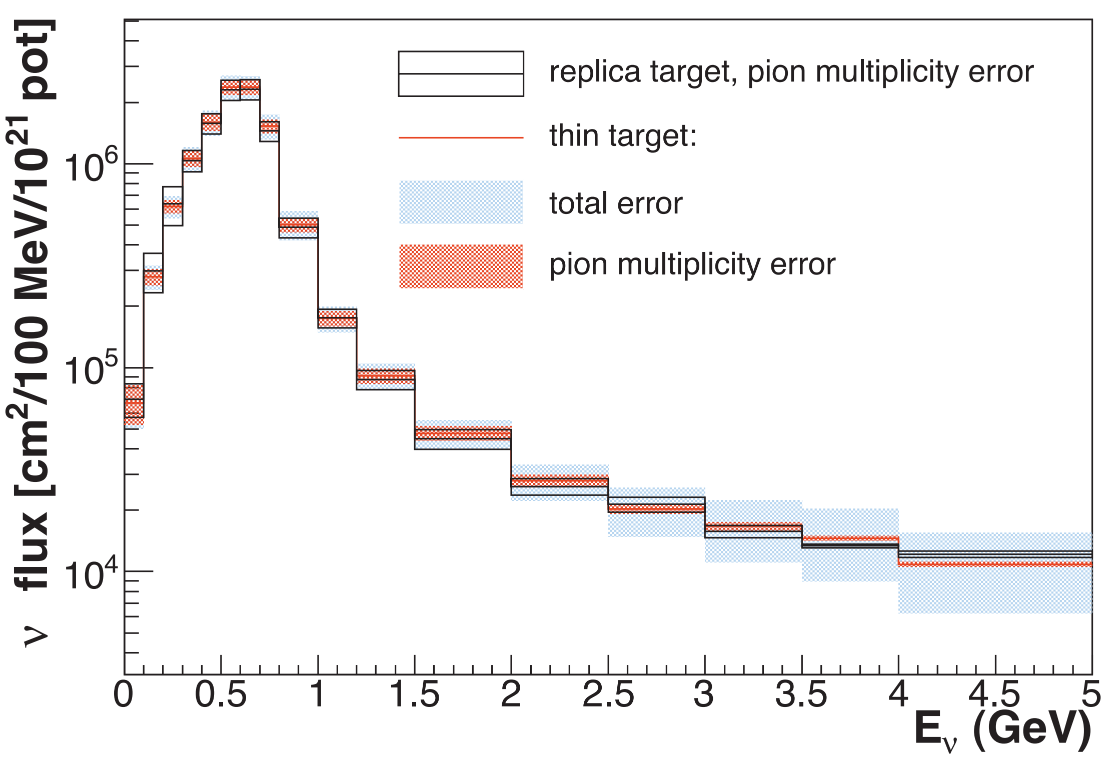
Future improvements with replica target data

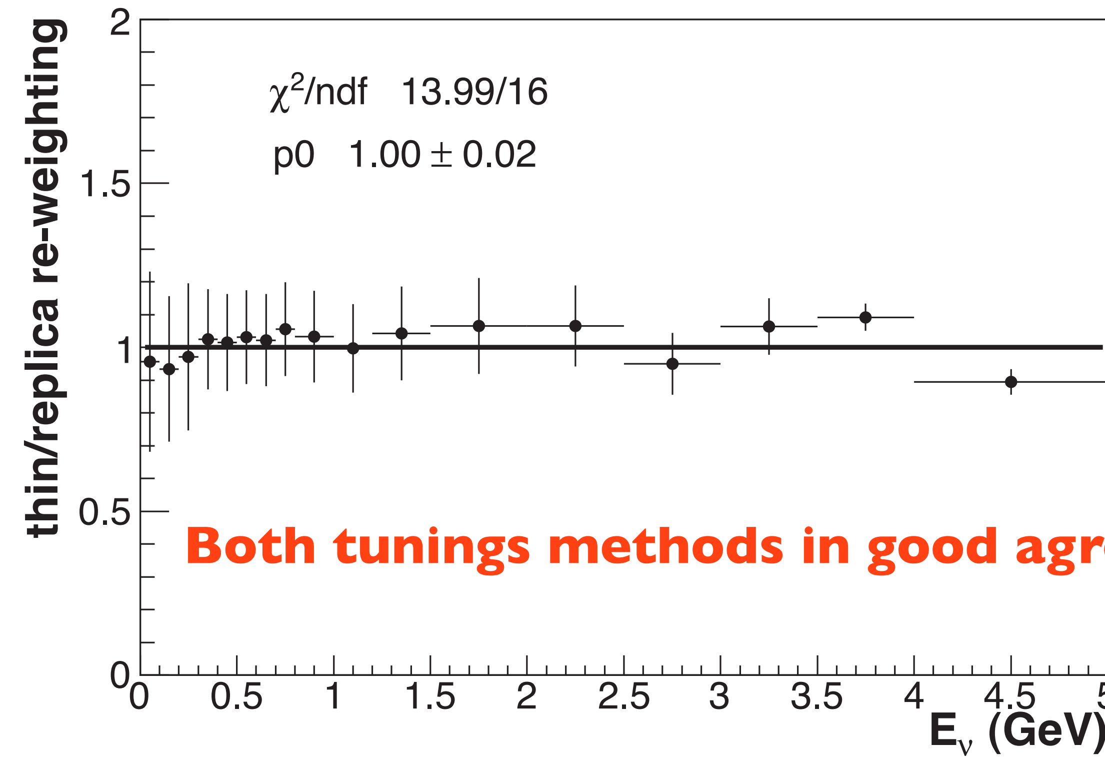
arXiv:1207.2114v1 [hep-ex] (submitted to Nucl. Inst. Meth. B)

Strategy:
-compare raw yields out of target skin directly with Monte Carlo and produce re-weighting factors of the T2K event generator within the NA61/SHINE analysis framework.

First time such a measurement is pushed to the end for a neutrino flux prediction

comparison of ν_μ flux prediction with thin and replica target:





Both tunings methods in good agreement!

- Data from replica target is however currently limited by low statistics of 2007 data (~15%).
- 2009/2010 data sets: significantly reduce stat. + syst. unc. expected <= 5%

Conclusion

- Estimation of the neutrino flux is a crucial part of the T2K oscillation analysis.

- NA61/SHINE has successfully completed data taking for T2K.

- 2007 low statistics thin target results have already had a significant impact on the improvement of the flux related errors.

- The error on the prediction of the T2K flux is now dominated by NA61/SHINE systematic uncertainties and errors due to poor knowledge of secondary interactions in the target.

  =>Results from 2009 thin target and long target expected soon (see poster A. Haesler)

Conclusion II

while we wait for a Nu Factory.. Flux uncertainties matter

No MC model or data-parametrizations can provide accurate flux estimations and reasonable descriptions of the associated errors

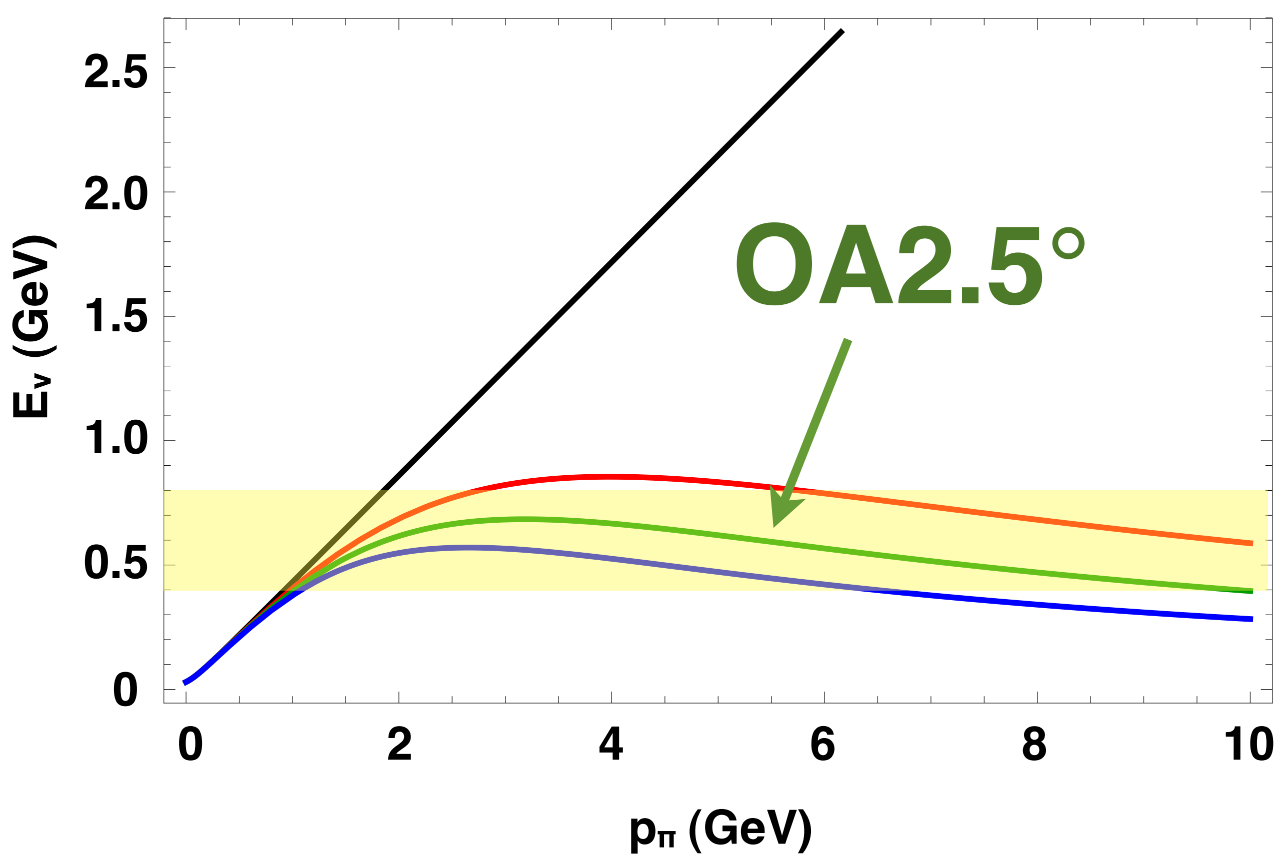
Have to get direct measurements

- ***Thanks to the NA61/SHINE data the T2K neutrino flux prediction is now , for a large part, based on data.*** However we still rely on parametrizations and scalings to constrain secondary interactions and extend the phase-space coverage.

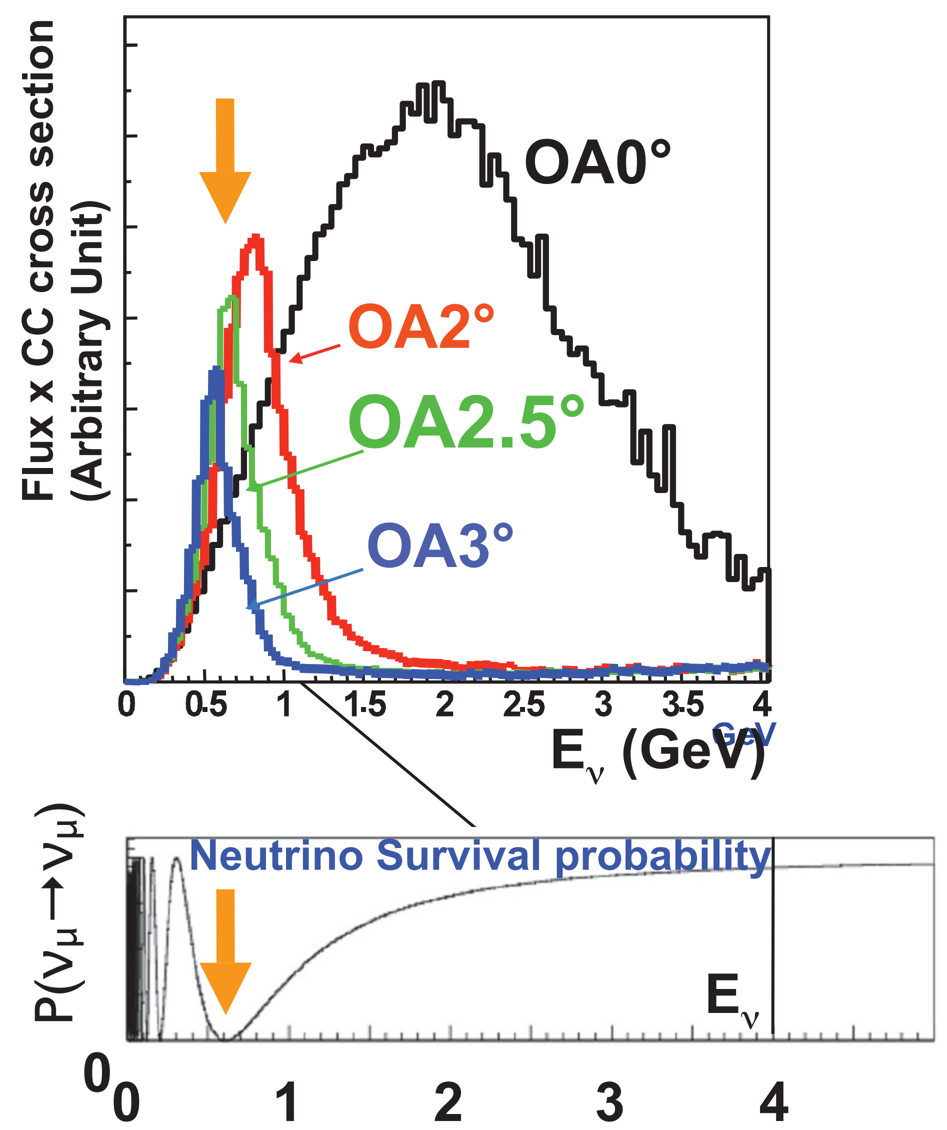
The goal in the near future is to have the neutrino flux - almost- completely data driven.

Backup

Why go off-axis?



Off-axis ν beam, peak energy at oscillation maximum ~650 MeV

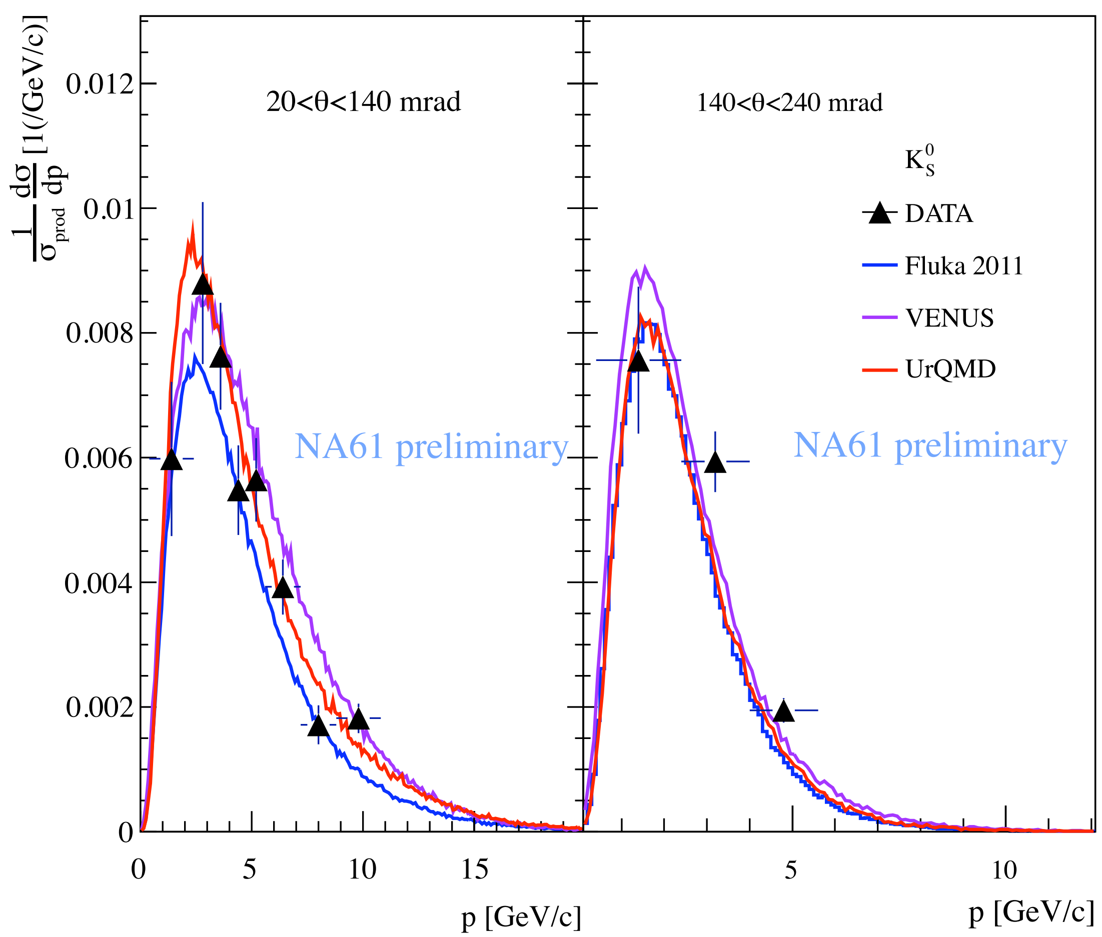


- Narrow beam peaked at the maximum oscillation probability
- Minimises background by reducing high-energy tail

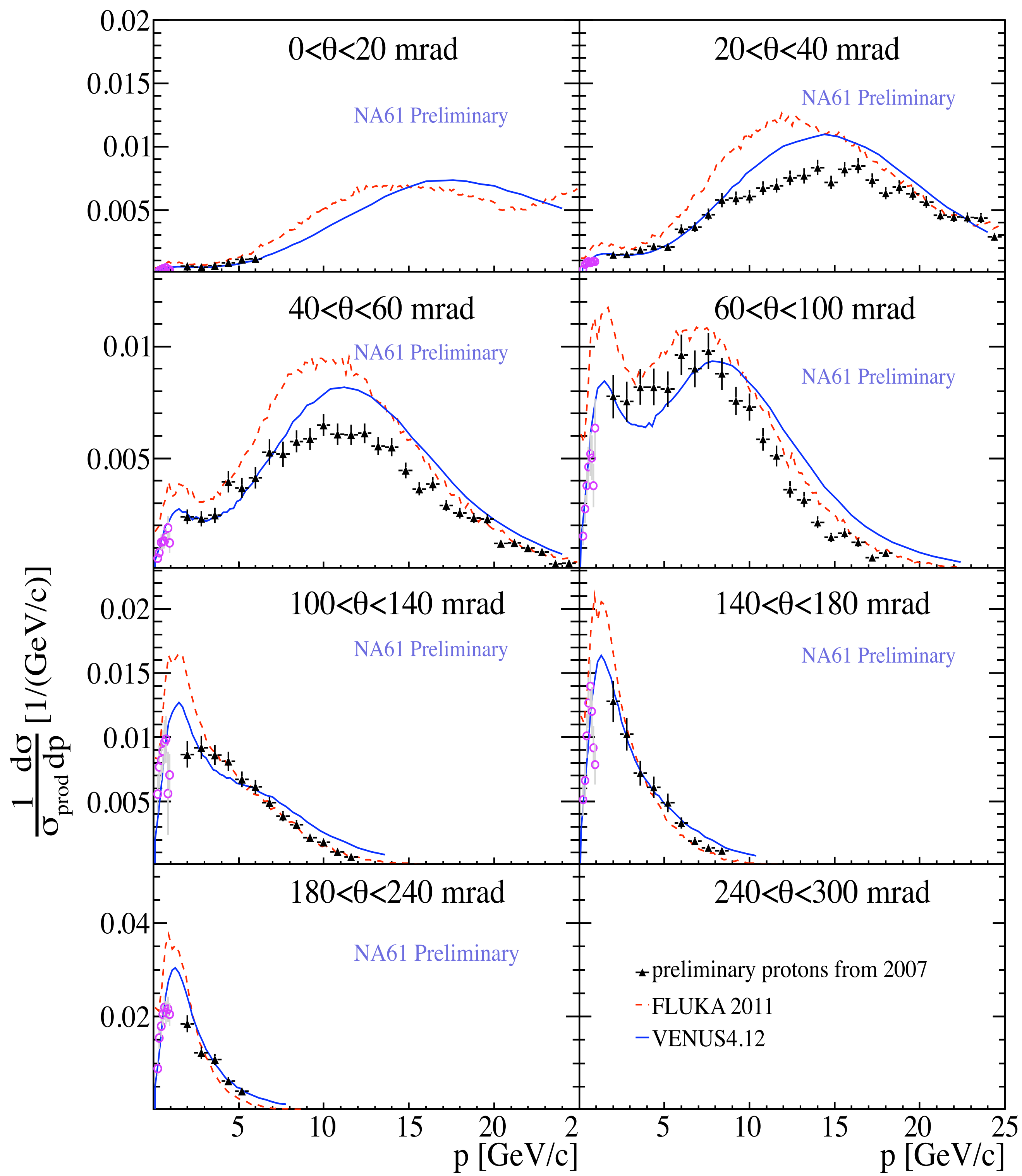
Future improvements

New NA61 thin target preliminary results

K^0_s cross-sections

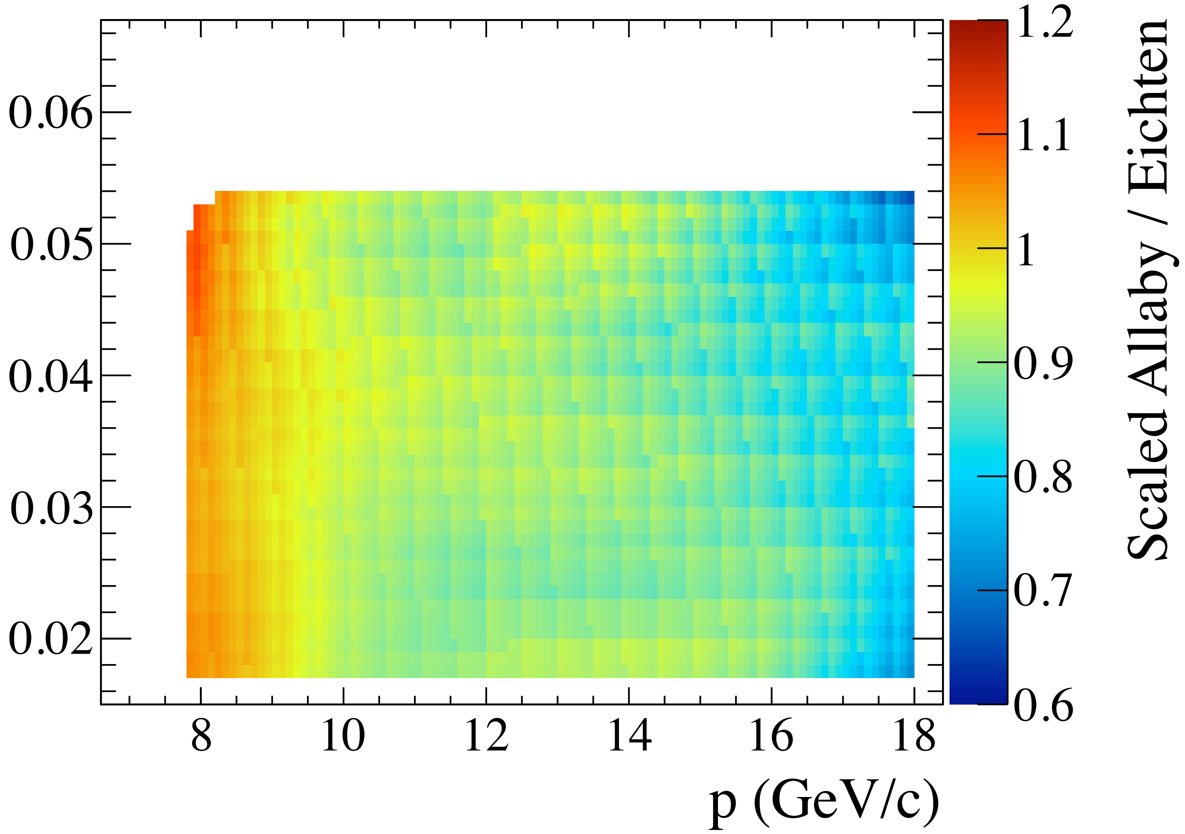


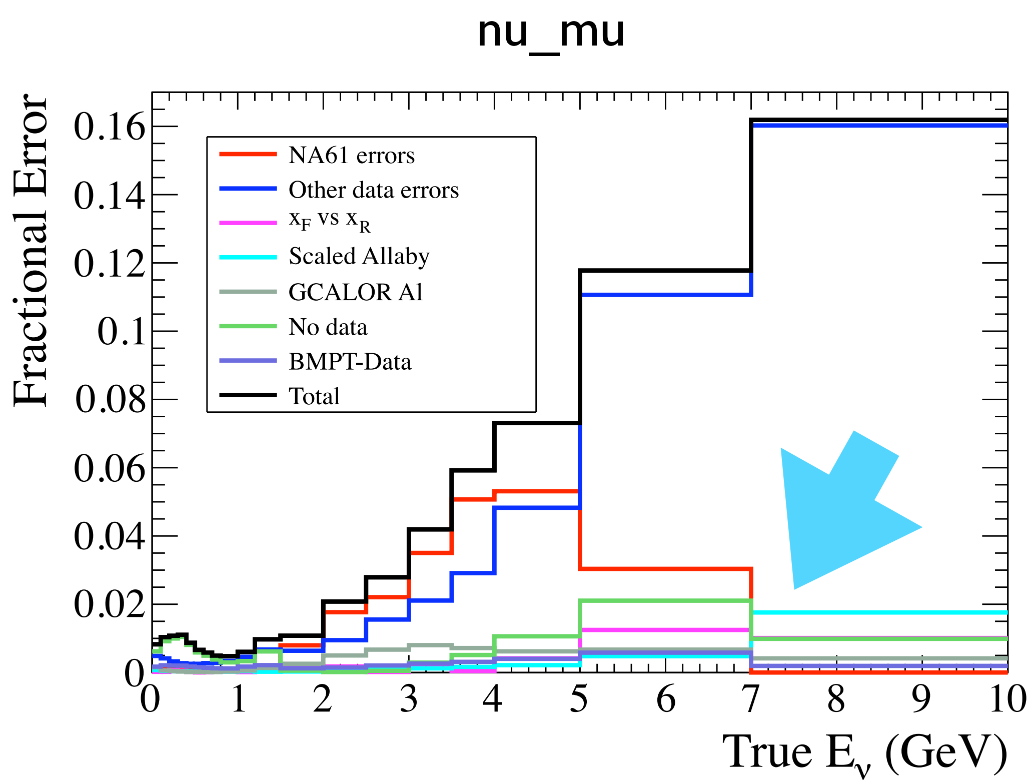
proton cross-sections

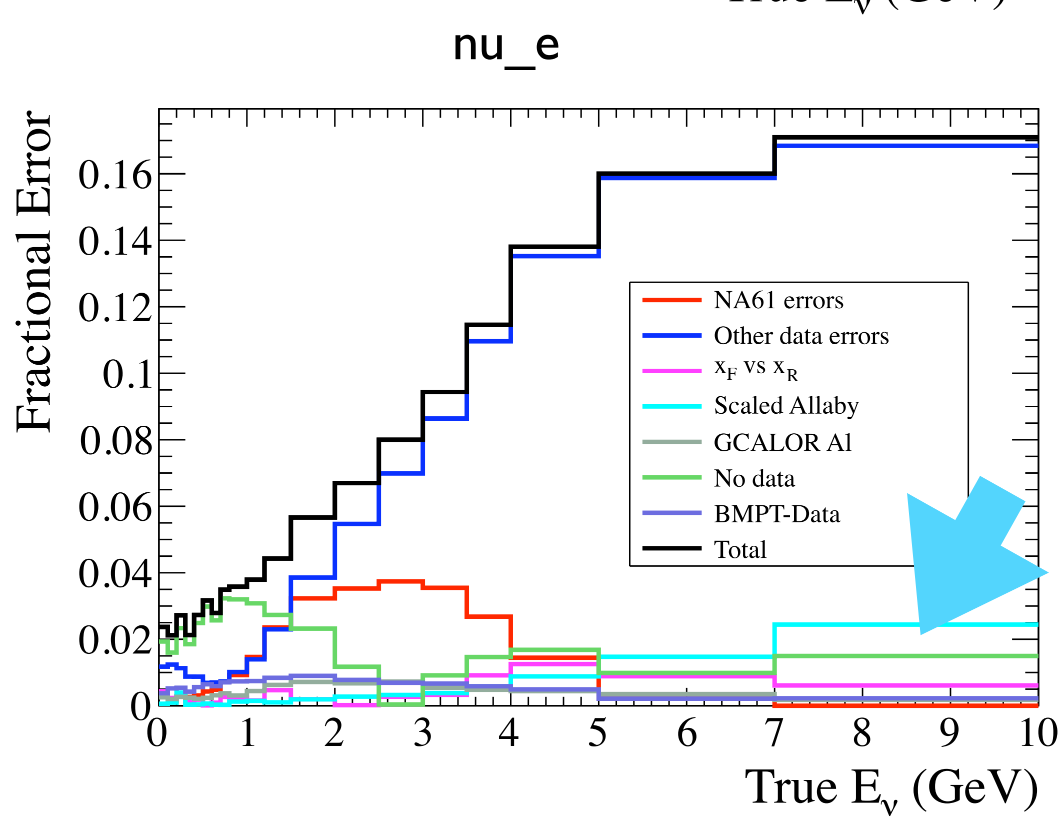


Error on K^+ momentum scaling

Scale Allaby (19.2 GeV) to Eichten (24 GeV).
=>compare scaled Allaby to Eichten







Modify Eichten weights by those ratios and see effects on flux =>