ND physics – CDR assessment study

DUNE PWG convener's meeting
Jan. 17, 2017
S. Manly, M. Kordosky

CDR claims for reference near detector (FGT option)

Missing your favorite claim/number? Let's add it.

Flux

- Abs nu flux < 3% (0.5<Enu<10 GeV) nu-e- scattering
- Abs nu flux < 3% (15<Enu<50 GeV) inverse muon decay
- Abs nu flux < 5% (5<Enu<20 GeV) Coherent pion & rho production
- Abs numubar flux <?% using QE scat on hydrogen by using hydrocarbon – carbon QE signal
- Abs shape of numu and numubar fluxes to 1-2% (1<Enu<50 GeV) Low-nu method
- Measure numu-, numubar-, nue-, nuebar-CC fluxes precisely allows decomposition of hadron contents in neutrino beam and gives FD/ND(Enu) flux ratio to few %
  - In particular, nue/numu < 1% and nuebar/numubar < 1%
- Near/Far flux uncertainty <2%

Detector

- Muon energy scale uncertainty < 0.2%
- Momentum resolution (e, pi, p) < 5%
- Charged particle angular resolution < 2 mrad

Physics

- NC pizero/nue-CC rejection < 0.1%
- NC photon/nue-CC rejection < 0.2%
- numu-CC/nue-CC rejection < 0.01%
- ND tuning give FD hadronization error < 2.5% (means neutrino model interaction systematic?)

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Claims not all independent

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MINERvA experience
Needs study (Either not studied carefully for CDR or based on NOMAD experience, nice to see it done with careful DUNE energy study)
MINOS, NOvA and T2K experience
Analytical and ND task force figures of merit

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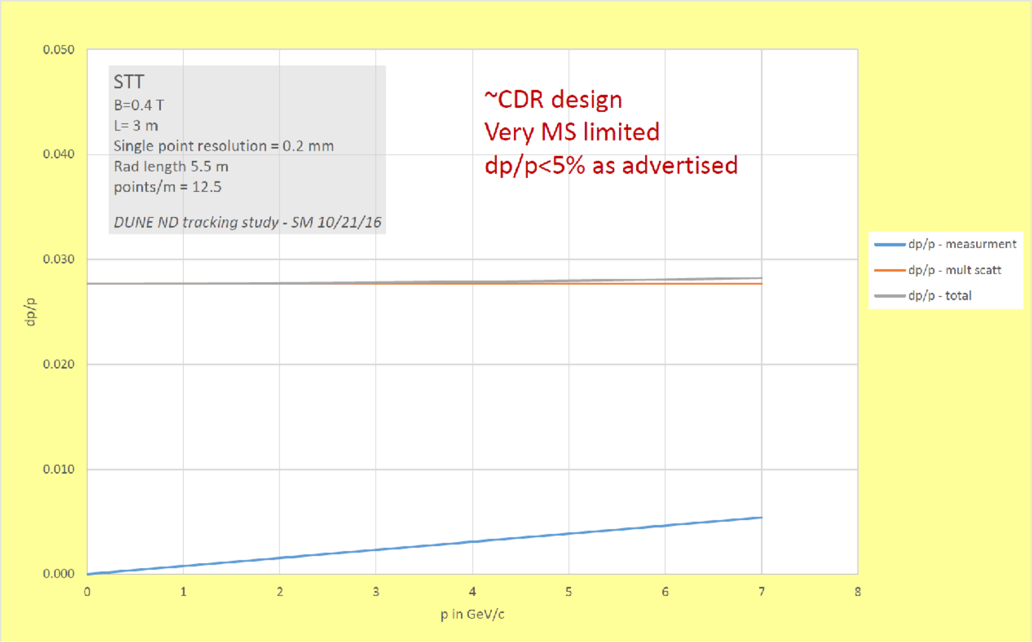
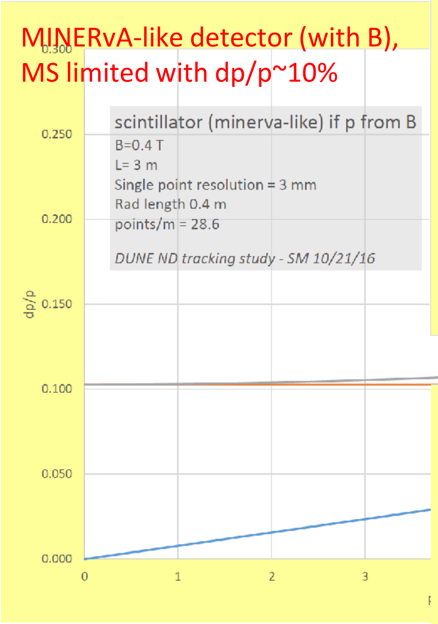
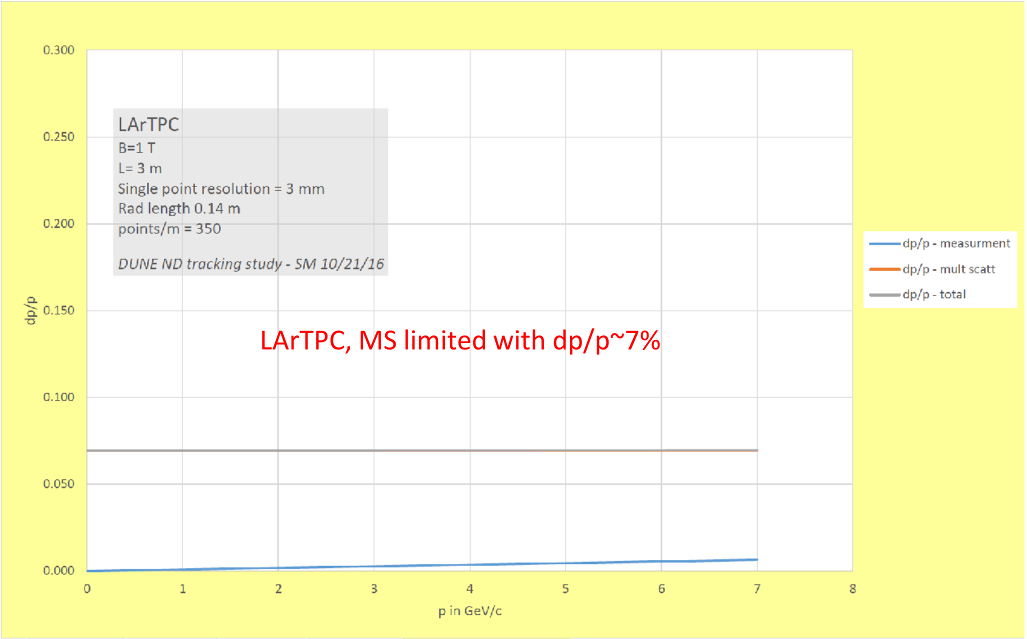
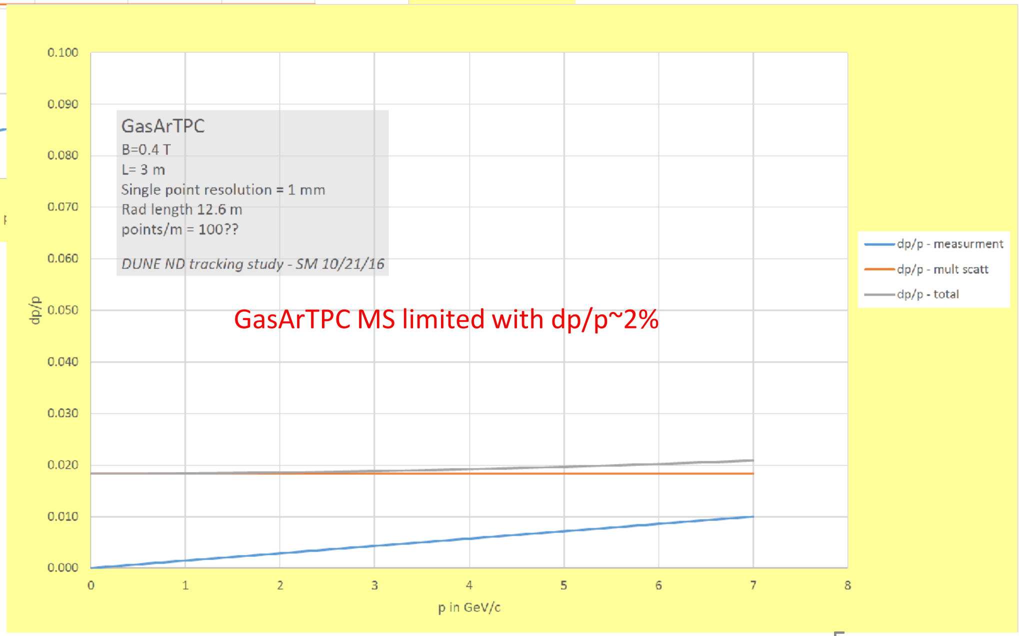
Momentum resolution <5% for mu, e, pi, protons

$$\left(\frac{\delta p}{p}\right)^2 = \left(\frac{\sigma_s p}{0.3BL^2}\sqrt{\frac{720}{N+4}}\right)^2 + \left(0.045\frac{1}{B\sqrt{LX_o}}\right)^2$$









Analytical tracking performance study bears out CDR claim for charged particle tracking. MS limited. LArTPC slightly worse than 5%. GasArTPC better than FGT.

Electrons in B field can be tricky with generic tracking due to bremsstrahlung. Needs study.

Angular resolution < 2 mrad

$$\vartheta_{rms}\Big|_{multscatt} = \frac{0.015}{p}\sqrt{\frac{t}{X_o}}$$

Option	~thickness	Xo	θrms @ 1 GeV/c
Minerva-like	7 cm (3 hits)	40 cm	6.3 mrad
LArTPC	1 cm?	14 cm	4 mrad
STT	16 cm (4x and 4y hits) 8 cm (~2x and ~2y hit)	5.5 m	2.5 mrad 1.3 mrad
GasArTPC	1 cm?	12.6 m	0.4 mrad

Detector options differ, physics case important, would love to see studies sooner rather than later

STT design satisfies criterion

Argument that missing Pt can be used to remove NCpizero backgrounds from NueCC sample (rejection to 0.1% level) AND to use Pt in measuring nuclear effects in-situ relies on good resolution.

NEEDS STUDY: Can this really be done if resolution is 2 mrad? Can it work at 4 mrad?

Note that the missing Pt algorithms are marginal for MINERvA. Under study, but seems hard.

Expect to see a small fraction of electron tracks with very poor resolution due to early brem. Have to get these calorimetrically or with a cone algorithm.

CDR claims for reference near detector (FGT option)

MINERvA experience, Aggressive but not crazy, needs study to see how error in number of reconstructed events translates into flux spectrum error

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MINERvA experience, 3-4% doable, 1-2% perhaps aggressive, would like to see work understanding high energy normalization, esp. for anti-neutrinos

Detector

- Muon energy scale uncertainty < 0.2%
- Momentum resolution (e, pi, p) < 5%
- Charged particle angular resolution < 2 mrad

Okay with FGT, depends on ND built

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Studied by USC group, would like to see study with full simulation, stats and control of two-track background

Interesting, not studied carefully yet

Okay if beam monitoring sufficient (L.Fields talk last collab. Meeting)

ty < 0.2%

MINERvA experience: nue/numu < 1% is aggressive
Flux model uncertainties depend on tertiary production, post-horn measurements important. Will require significantly better detector and interaction systematics than achieved by MINERvA (both errors larger than the flux error for MINERvA).
Need the NC pizero/nue-CC rejection which seems aggressive and extrapolated from NOMAD, need DUNE energy studies,

Physics

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- ➢ Near/Far flux uncertainty <2%

Would like to see study with full simulation, including reconstruction and backgrounds

Detector

- ➢ Muon ener
- ➢ Momentur
- ➢ Charged pa

TABLE XX: Relative uncertainty (1σ) on the predicted rate of ν_μ CC and ν_e CC candidate events.

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	[illegible]	[illegible]
FSI+SI(+PN)	[illegible]	[illegible]
Total		
(w/o ND280 constraint)	[illegible]	[illegible]
(w ND280 constraint)	7.7%	6.8%

?

ND will be insensitive to some processes seen in FD, will come in with larger error

From a recent T2K oscillation paper – PRD 92, 112003 2015, p. 77

Physics

- ➢ NC pizero/nue-CC rejection < 0.1%
- ➢ NC photon/nue-CC rejection < 0.2%
- ➢ numu-CC/nue-CC rejection < 0.01%
- ➢ ND tuning give FD hadronization error < 2.5% (means neutrino xsec systematic?)

ND technology choice

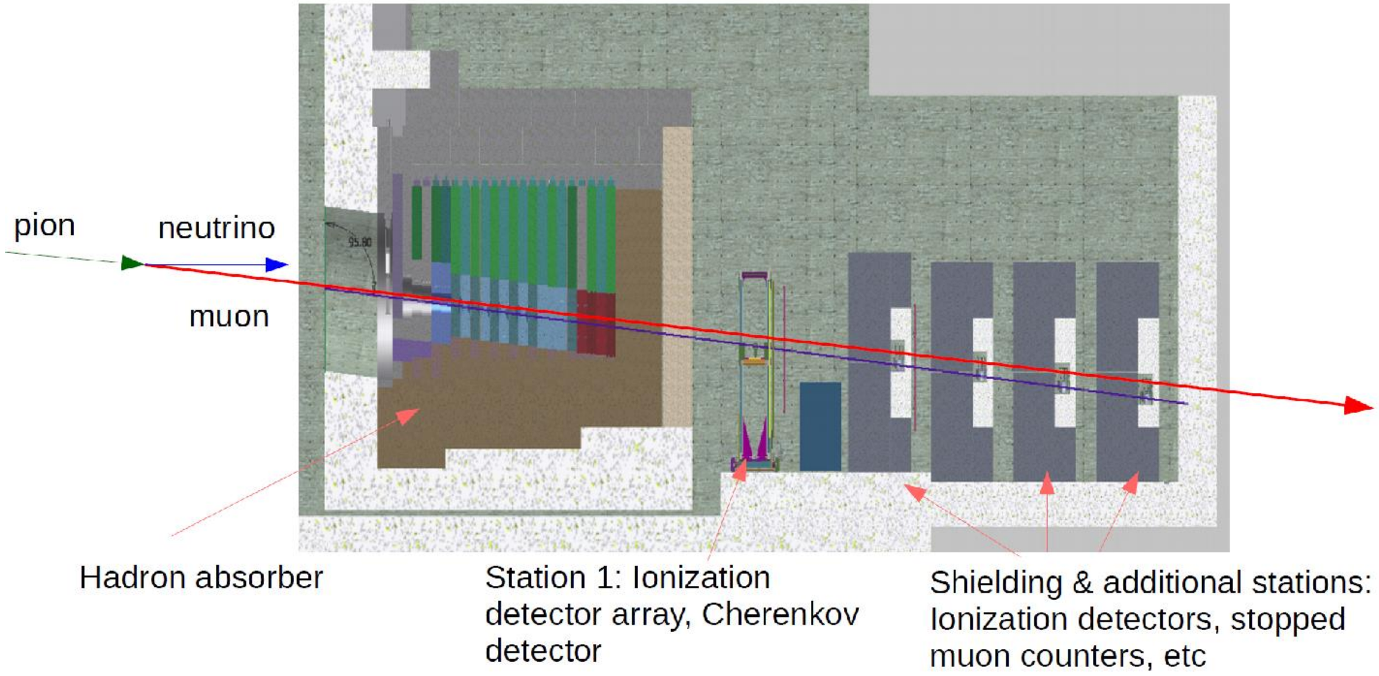
Option	Xo	ϴrms @ 1 GeV/c	dp/p in % (all MS dominated)
Minerva-like	40 cm	6.3 mrad (might improve with smaller scint)	10
LArTPC	14 cm	4 mrad	7
STT	5.5 m	1.3-2.5 mrad	3
GasArTPC	12.6 m	0.4 mrad	2

Game-changing arguments made in CDR (relative to MINERvA, MINOS, NOvA, T2K) that one can use pt balance to separate NC events from CC (and NC pizero from nue-CC, in particular) as well as to take out nuclear effects. MINERvA and T2K are exploring this (see Dolan, Lu, Pickering, Vladisavljevic, Weber, arXiv:1610.05077). Some success on statistical basis but

Does this work at DUNE energies with ND full simulations?
If so, is it critical to have low density tracker like the STT?

ND and ND facility beam monitoring

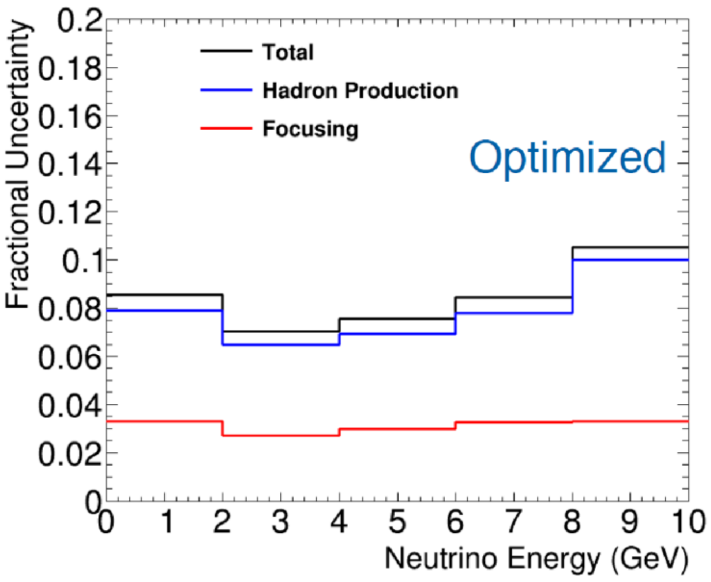
Assumed to some extent in CDR, needs attention

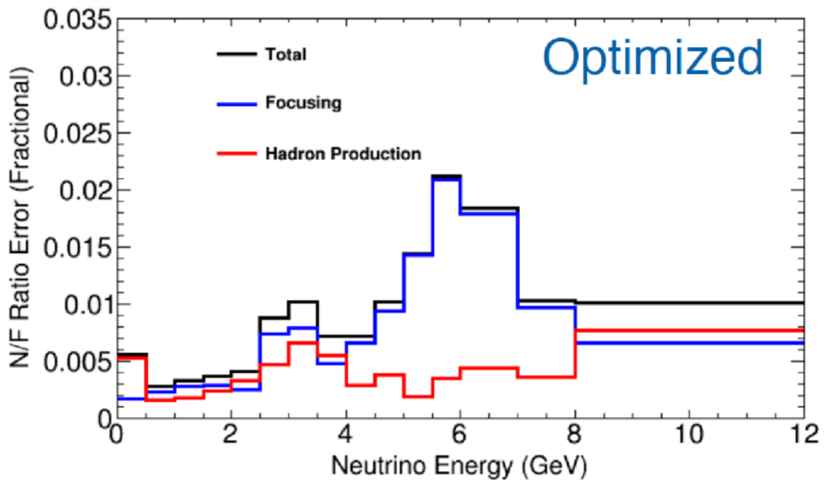


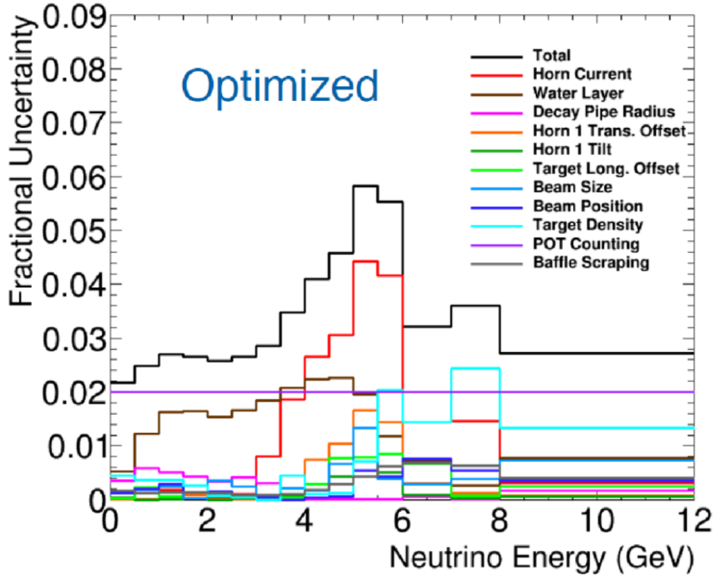
- ➢ LBNF has a number of different fast beam monitors
- ➢ ND hall detectors can provide additional time-dependent post-hadron and post-focusing monitoring of beam
- ➢ Detectors in ND hall are slow monitors of beam but sensitive to all sources of beam errors (water in target and horn tilts, for example)

Focusing uncertainties dominate in the flux N/F ratio

For electron neutrinos



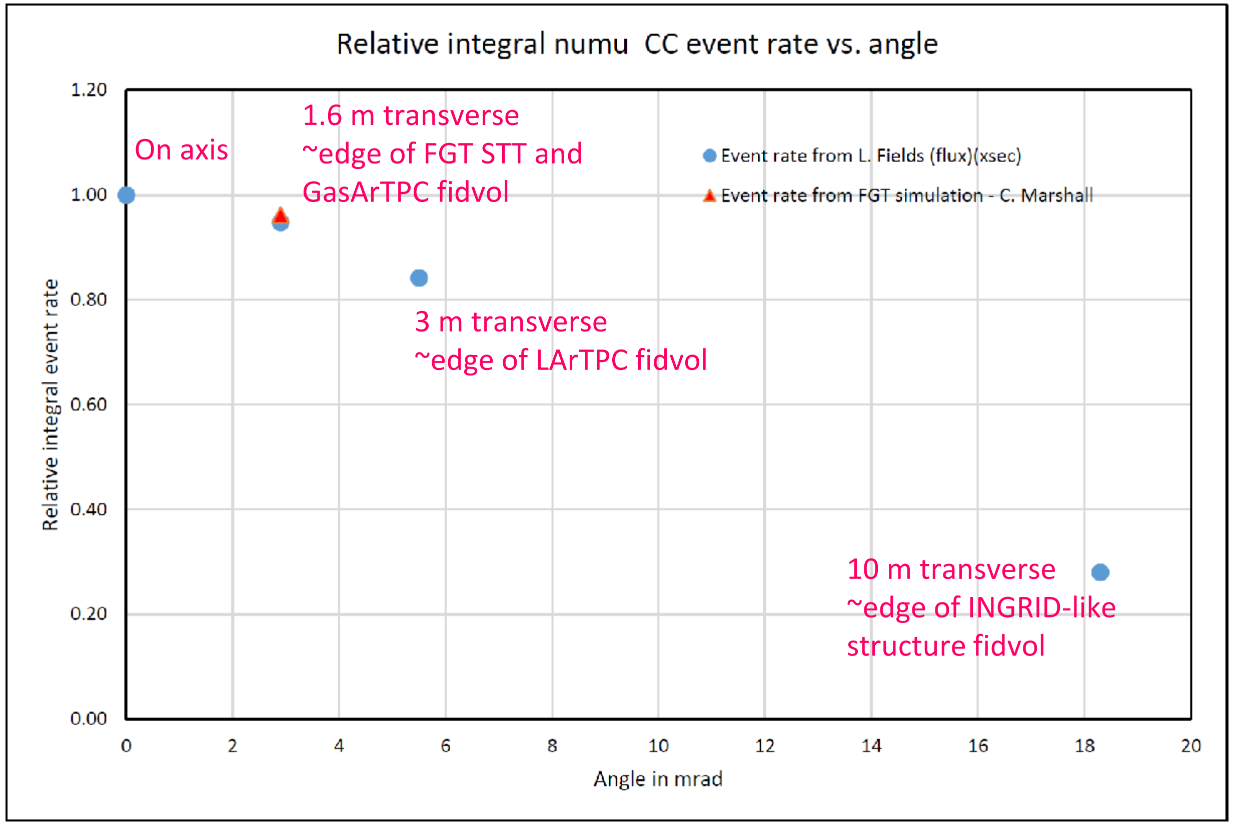




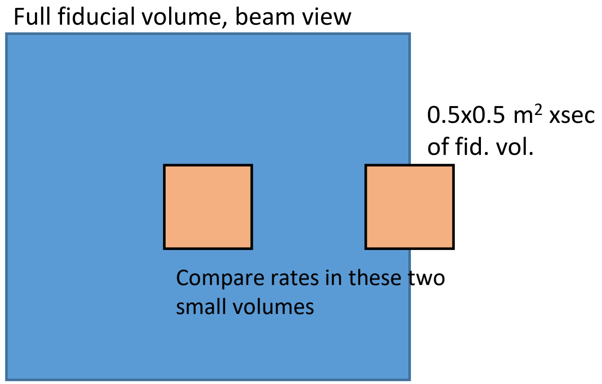
Shown in talk on a priori flux uncertainties by L. Fields in Sept. 2016 DUNE collaboration meeting

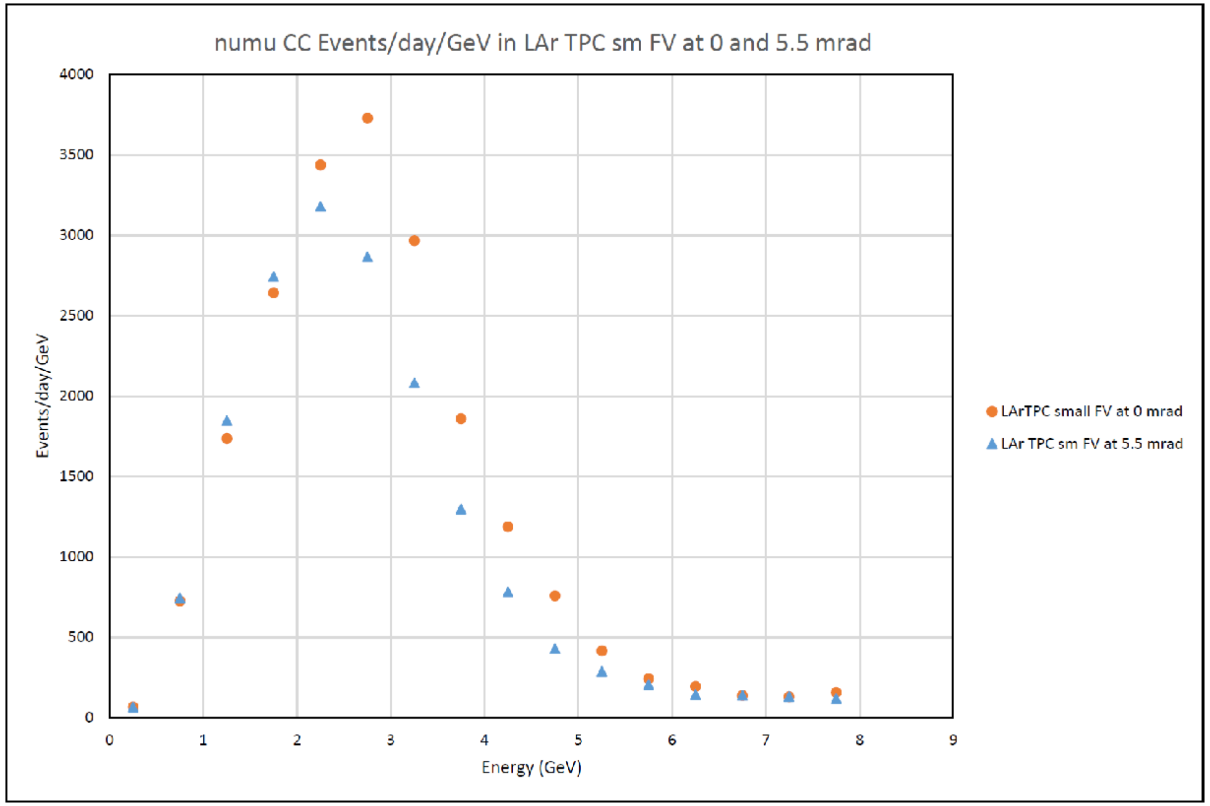
CDR says uncertainty in the beam flux after N/F extrapolation is 2%

ND sensitive to rate, energy spectrum and angle of beam



Shown in talk on ND beam monitoring by SM in 1/12/17 DUNE beam interface/optimization/simulation meeting





ND and ND facility beam monitoring - questions

- What are beam requirements to hold N/F flux ratio uncertainty to <2%?
- How big beam spectrum and/or angle error can we tolerate?
- What is the time frame needed for the feedback (stats plus processing, can use non-Ar events, rock muons)?
- Can ND alone meet requirements?
- To what extent would partial INGRID-like structure provide information on beam profile that could prove critical in constraining/reducing the N/F flux uncertainty?
- If INGRID-like structure proves valuable, cost? Can it be done using shaft instrumentation?

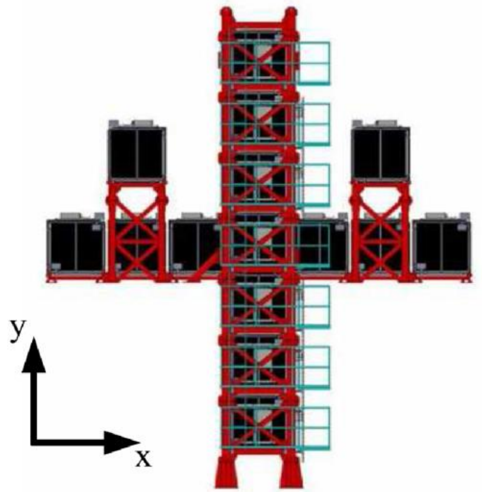


Figure 11: INGRID on-axis detector

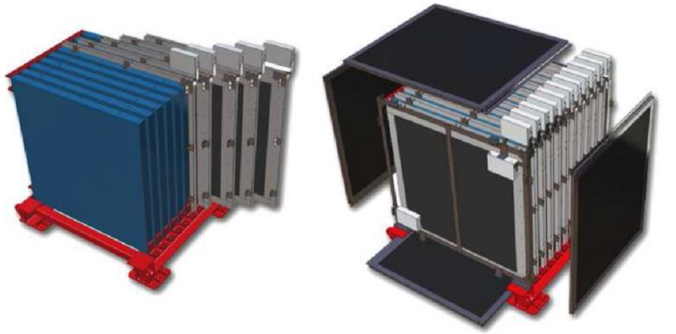


Figure 12: An INGRID module. The left image shows the tracking planes (blue) and iron plates. The right image shows veto planes (black).

T2K's INGRID detector
~14 7.1 ton iron-scintillator modules, measures beam angle to 0.4 mrad and useful daily beam intensity measures

Backup slides

DUNE ND assessment

From Ryan Patterson:

Which assumptions (from CDR or latest state-of-the-art) absolutely **must be replaced** with something "better"? Which ones **could be defended** as they stand, in a pinch?

SM-Which ones are unrealistic and need to be modified? What are implications of that?

Intent is to be aggressive but not crazy. Many CDR numbers from studies and intuition informed by NOMAD experience. Backed up by MINERvA/T2K experience? Can it work at the lower energy of DUNE?

Timing perfect for ND

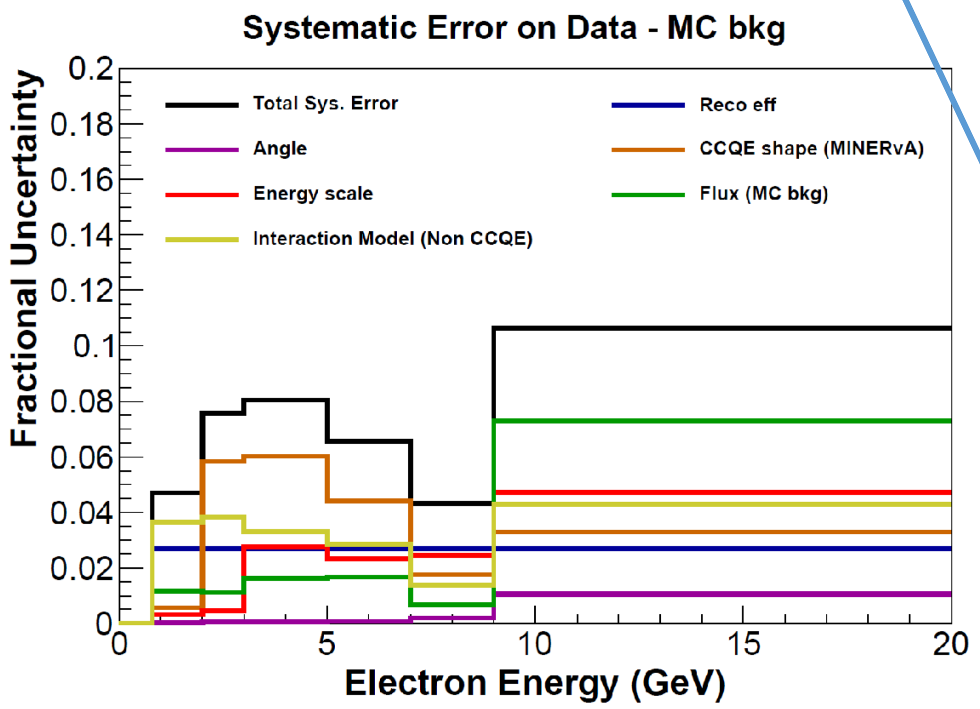
- helps us think through the essential figures of merit and ponder what is the required performance

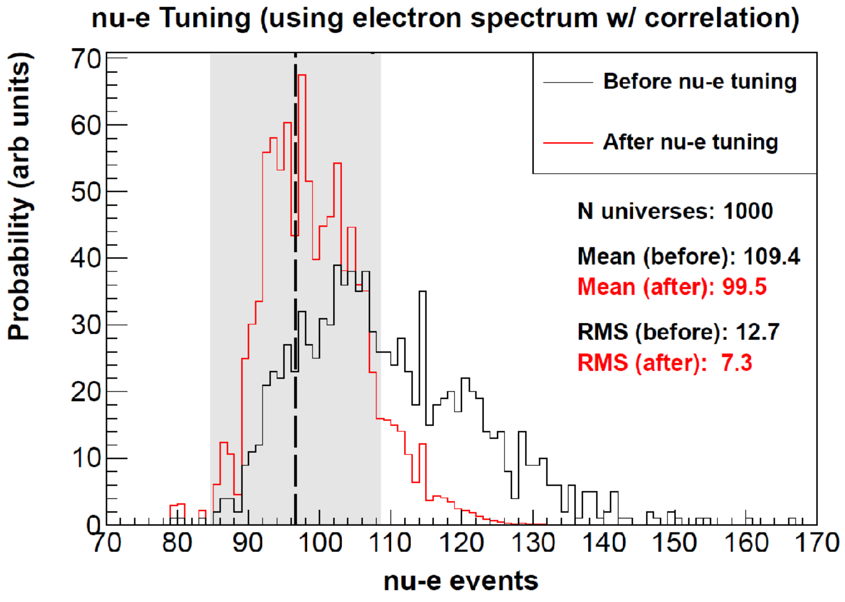
Timing stinks for ND

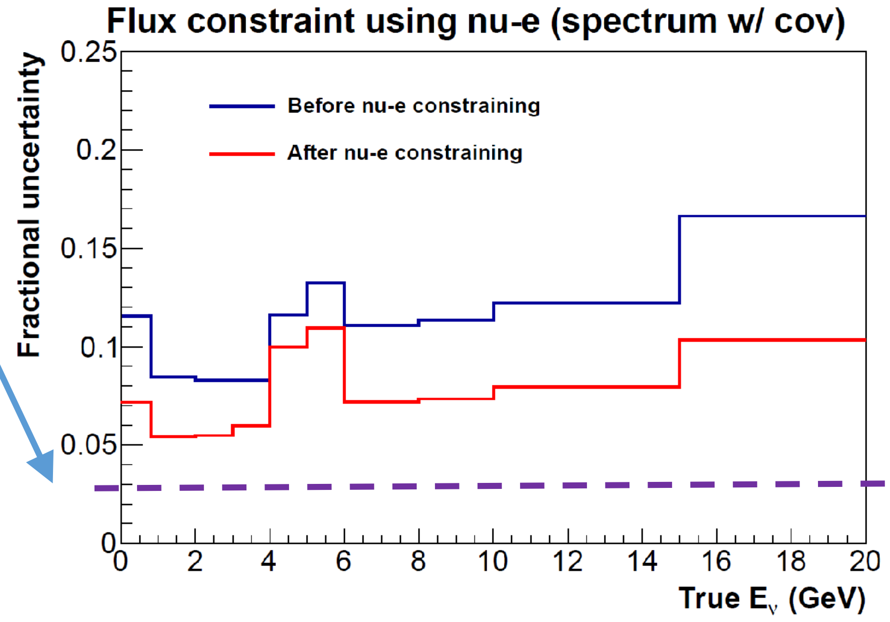
- Not sure what we hope to build

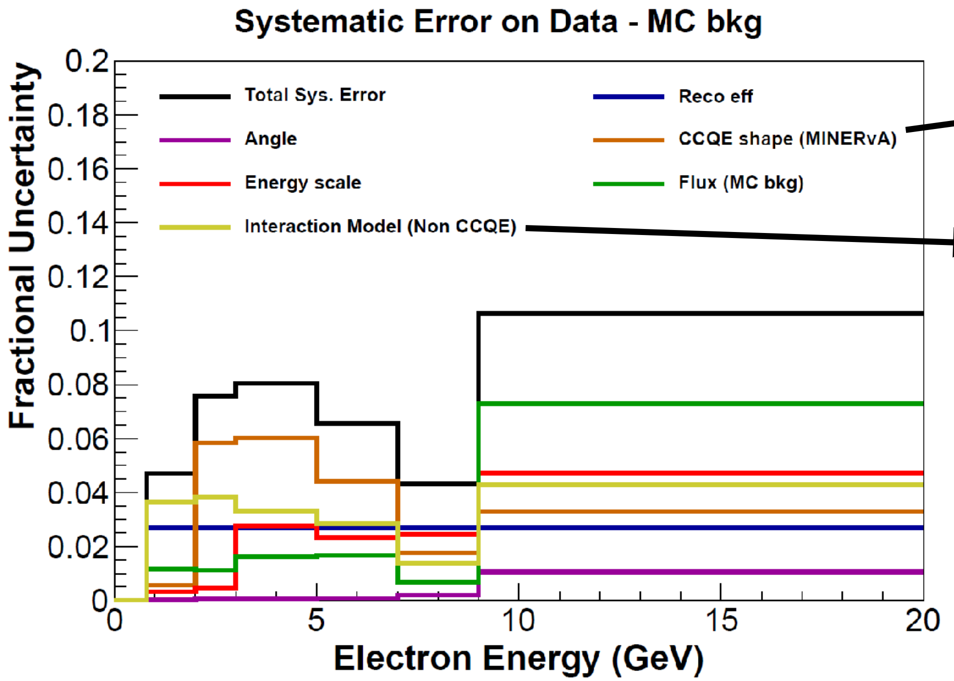
CDR (physics 6-93) states absolute neutrino flux known to <3% in 0.5-10 GeV neutrino energy range

Neutrino-electron scattering state-of-art
MINERvA PRD









Not relevant for DUNE

Some improvement
for DUNE perhaps

- DUNE – higher stats (can use non-Ar part of FGT)
- Premium on EM energy recon and electron angular resolution (for background rejection)
- EM energy scale error important (want test beam probably)
- Full analysis should be done to see how a 3% error in number of events as function of electron energy translates into error in absolute flux as function of neutrino energy

- Aggressive but perhaps not crazy

Low ν method

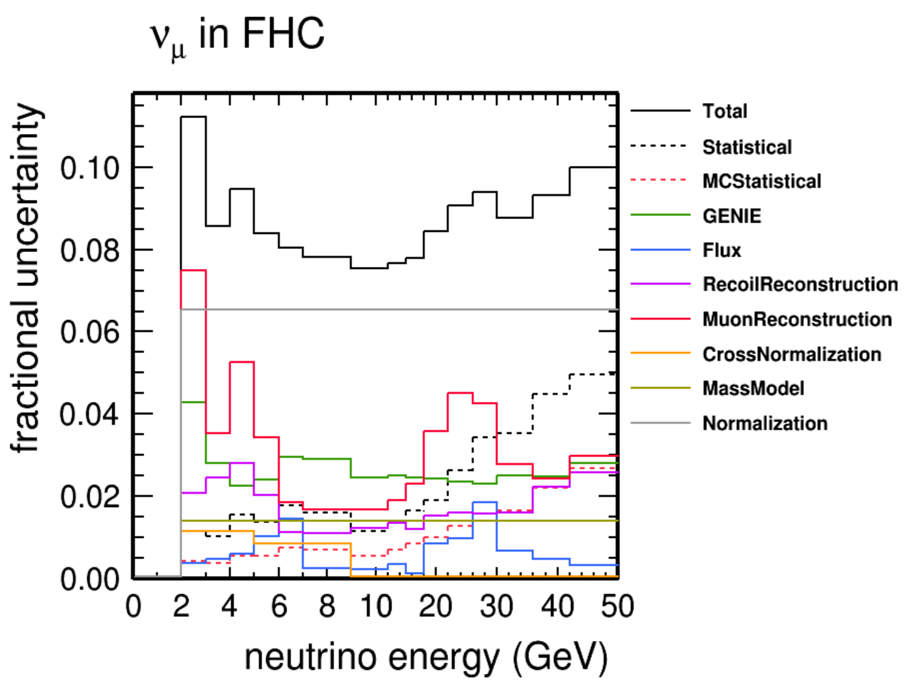
Claim gives absolute shape of numu and numubar flux to 1-2% precision for 1<Ev<50 GeV.
Gives FD/ND(Ev) to 1-2% precision.

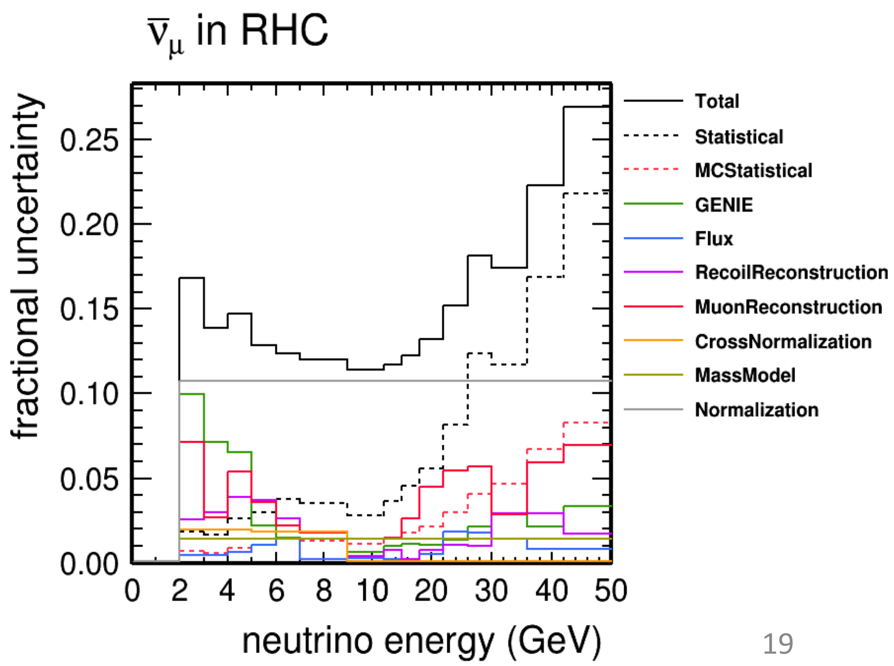
MINERvA reports flux shape from Low nu with lower limit Ev=2 GeV due to worries about sensitivities to mis-modeling for ν<300 MeV.

MINERvA normalizes to NOMAD data in the 9-12 GeV region with a 3.6% uncertainty. Statistical error in the normalization bin (9-12 GeV) blows up the normalization error. FD/ND should be much smaller.

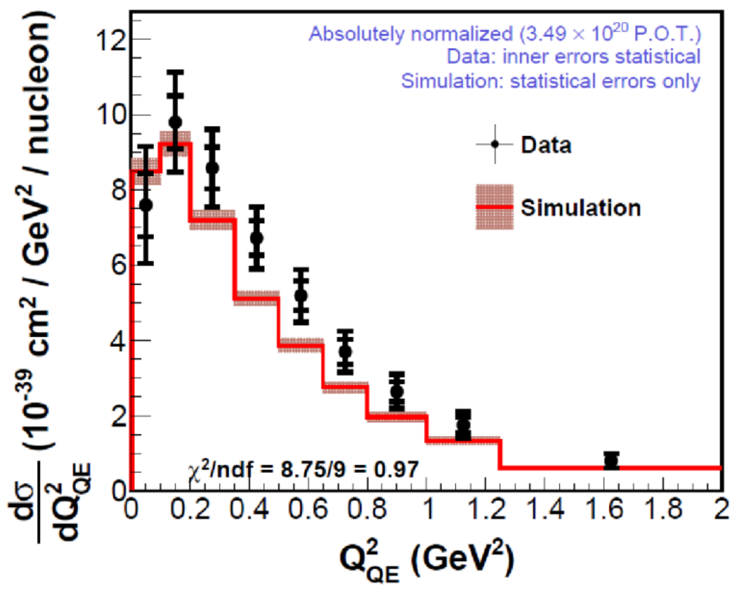
For antineutrinos lack of good normalization data has MINERvA normalizing to GENIE tuned to world average neutrino xsec

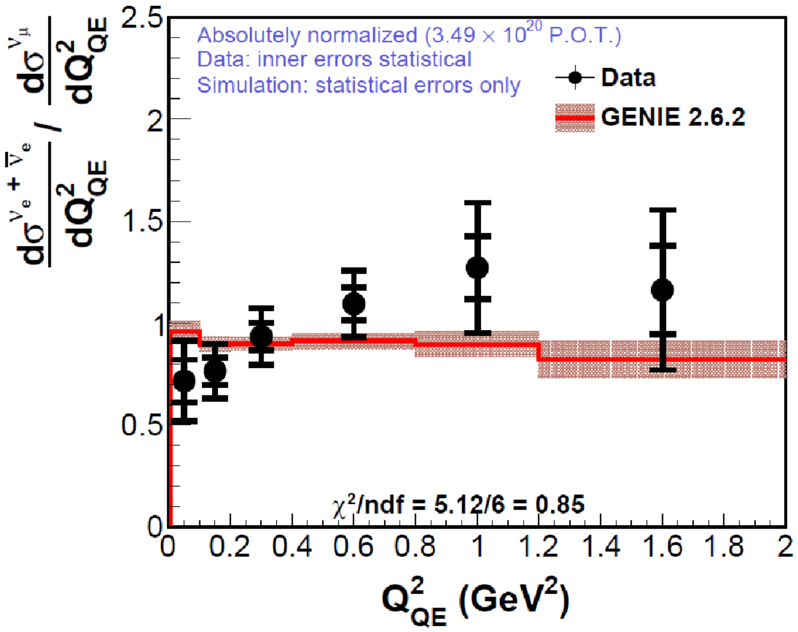
Needs study. (1-2% seems optimistic. 3-4% likely doable)
DUNE ND might have better stat error. But not clear to me there is a better normalization at higher energy to use. Not sure how plays out in the ratio.

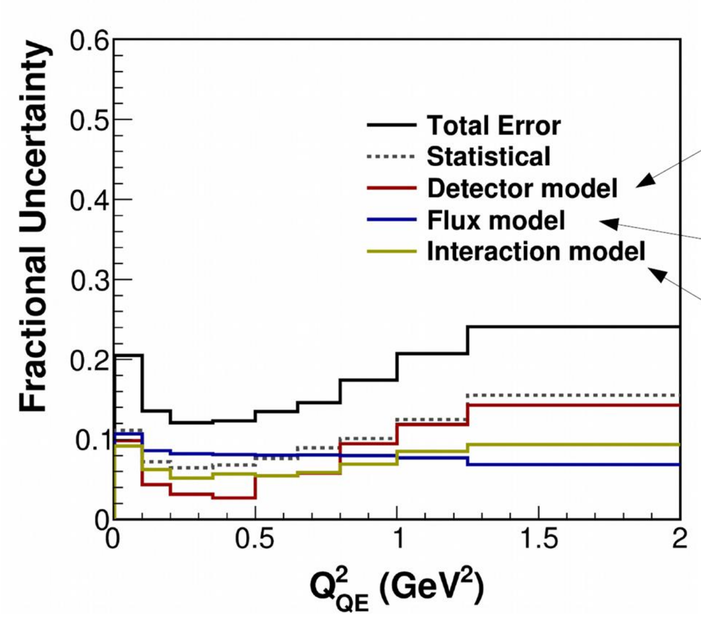




nue/numu <1%?



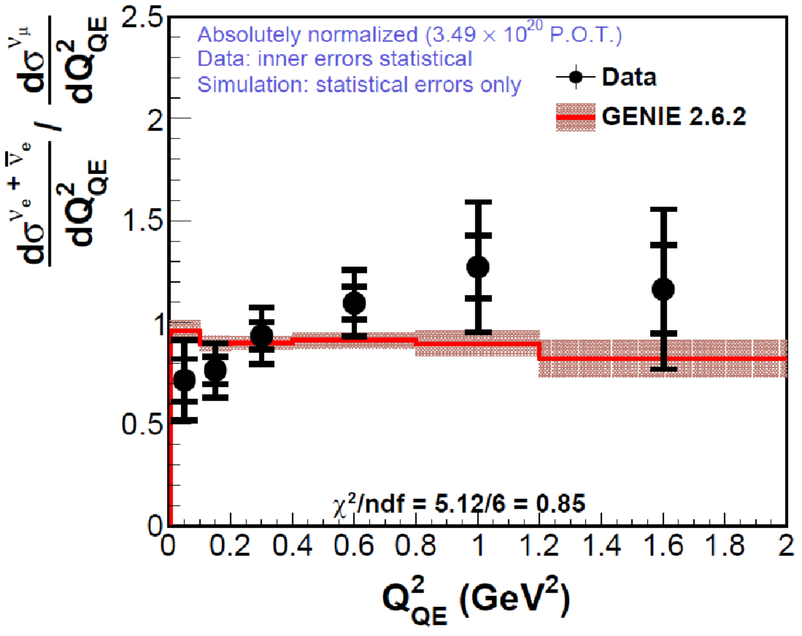


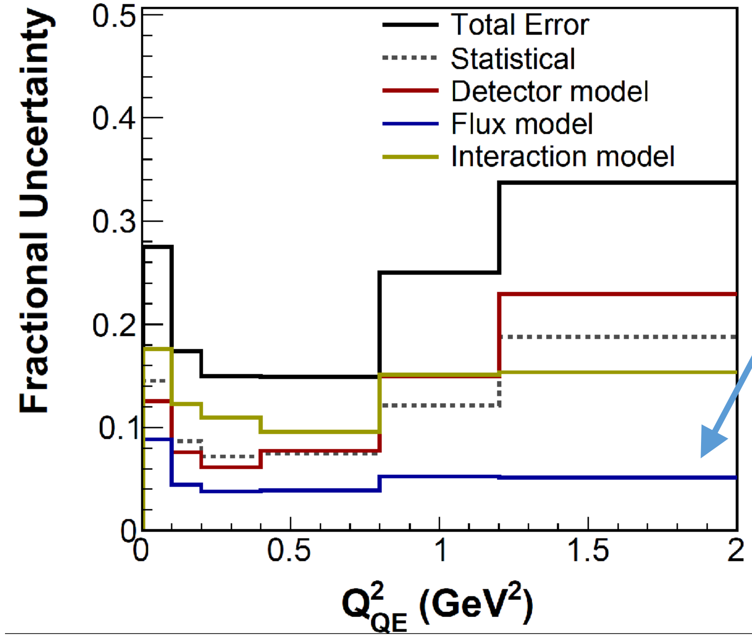


Includes energy scale estimated using the π^0 mass peak in a separate measurement; resolutions; other detector effects

Constrained as noted previously

Mostly enters in background subtraction (from GENIE 2.6.2)

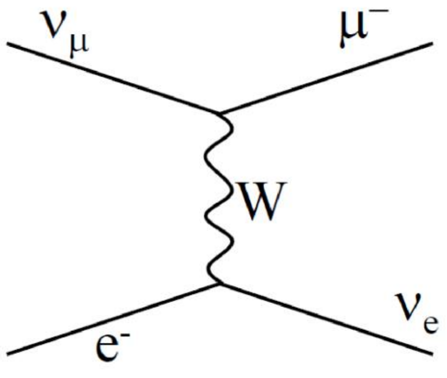




Flux model error is dominated by kaon production and tertiary production (re-interactions upstream of neutrino production, say in the horns)

1% is an aggressive goal. If LBNF post-horn hadron measurements happen, seems hopeful. Also the nue, nuebar separation with DUNE and maybe the NC pizero and nue-, nuebar-CC separation will help.

Inverse muon decay (numu CC scatter off atomic electrons)



Claim gives absolute numu flux to 3% precision for 15<Ev<50 GeV

Threshold at 11 GeV
Main background numu CC events (constrained with two-track numu CC sample)

Concerns:
Stats (tail of flux, small xsec~QE/500)
Upper limit of reliable muon momentum measurement
Background vulnerability/constraint
USC group examined, more careful study needed

- ➢ What is overlooked? (to add to the list of important CDR numbers, studies supporting earlier numbers)

- ➢ What are numbers that need study which are most essential to detector selection
  - use of pt to separate NC pizero from nue-CC and to take out nuclear effects in-situ