

Flux measurement from $\nu+e$

Chris Marshall, LBNL
Callum Wilkinson, Bern
Kevin McFarland, Rochester
Steve Dennis, Liverpool
ND workshop
7 November, 2017

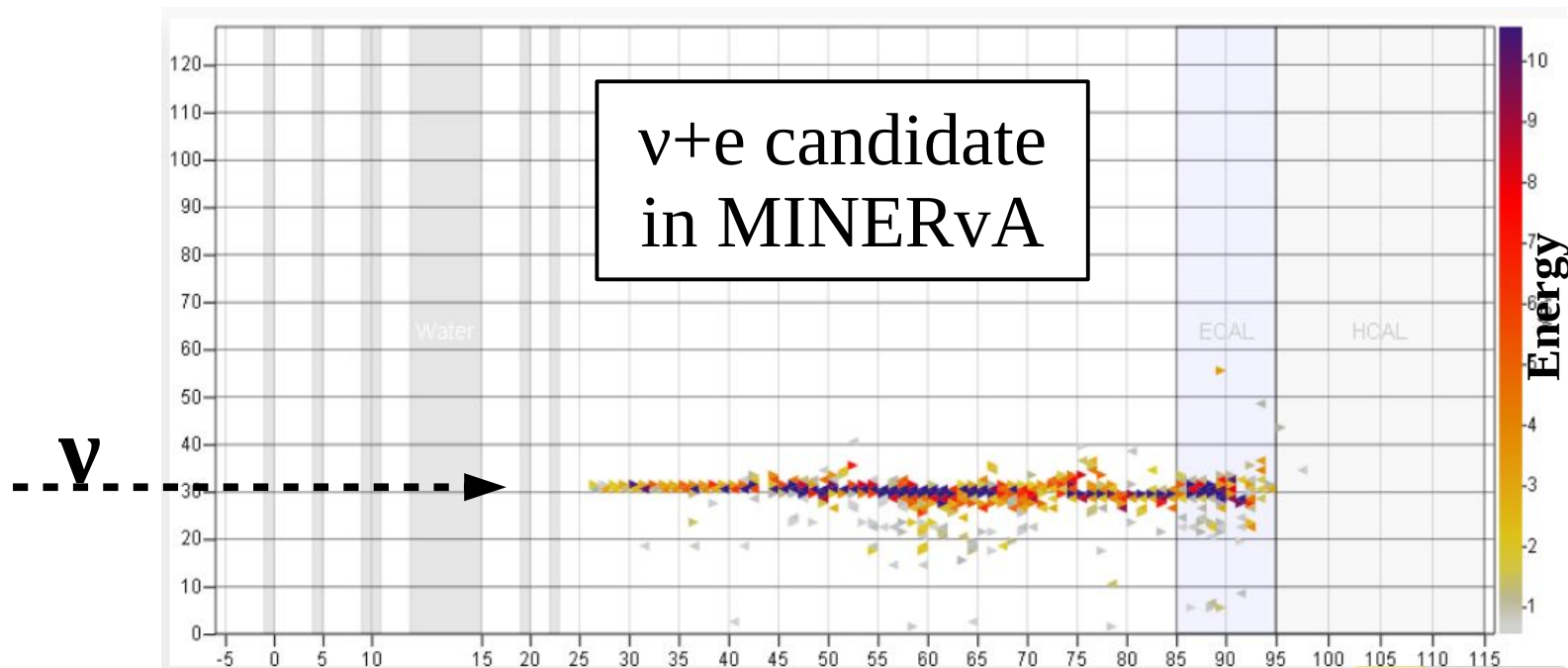


Neutrino-electron scattering

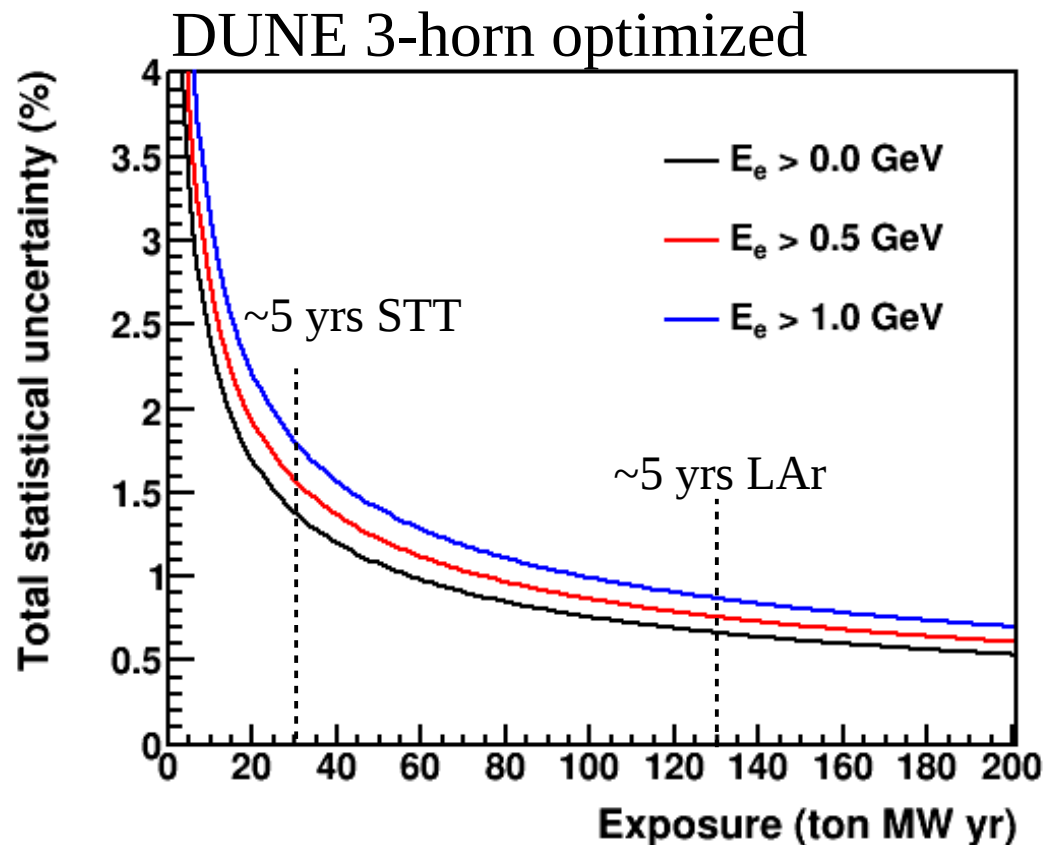
- Pure EW process with known cross section:

$$\frac{d\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-)}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} \left[\left(\frac{1}{2} - \sin^2 \theta_w \right)^2 + \sin^4 \theta_w (1-y)^2 \right]$$

- Signal is single electron, with kinematic constraint $E_e \theta^2 < 2m_e$ – very forward electron



Flux measurement for DUNE

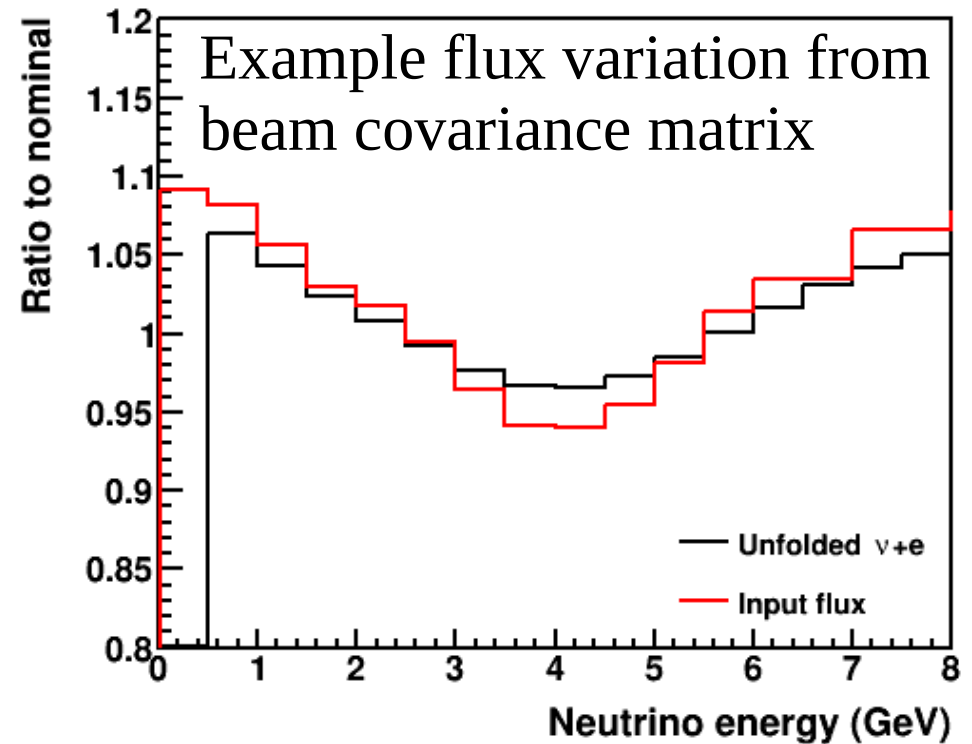
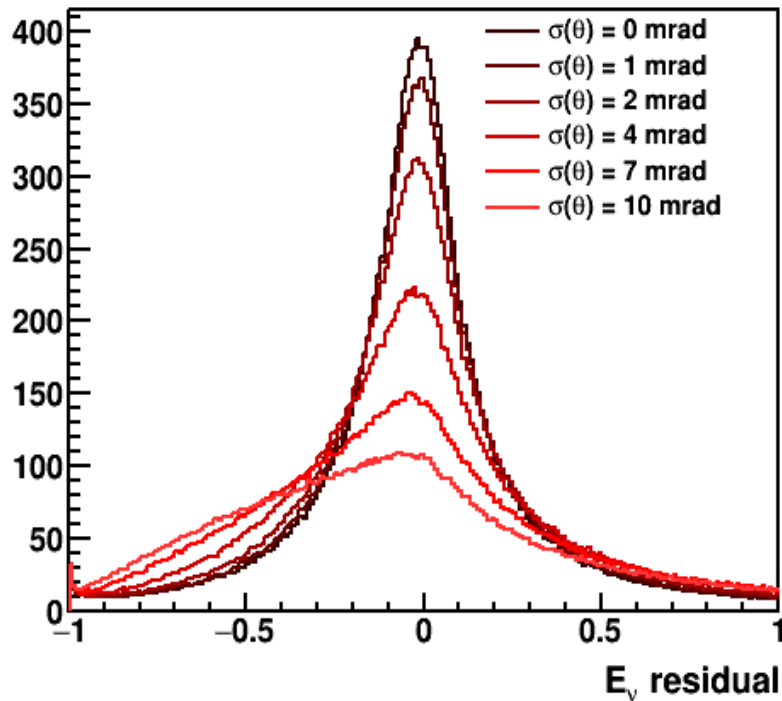


$$E_\nu = \frac{E_e}{1 - \frac{E_e(1 - \cos \theta)}{m}} \approx \frac{E_e}{1 - \frac{E_e \theta^2}{2m}}$$

- DUNE ND will get ~1% statistical precision on rate-only measurement
- Shape can be measured by using energy and angle of outgoing electron
- Sensitive especially to θ_e

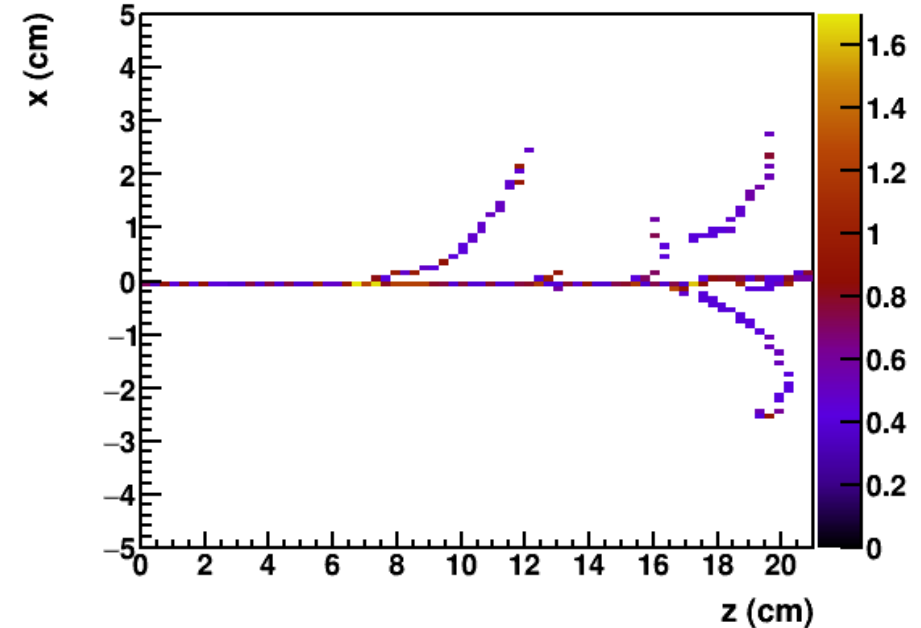
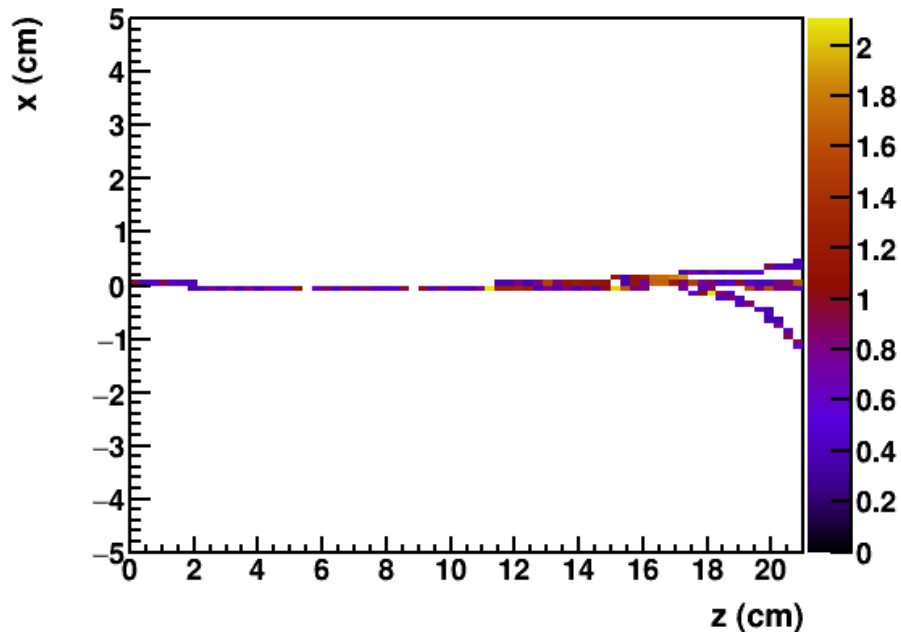
Previous work

$\sigma(E) = 5\%$



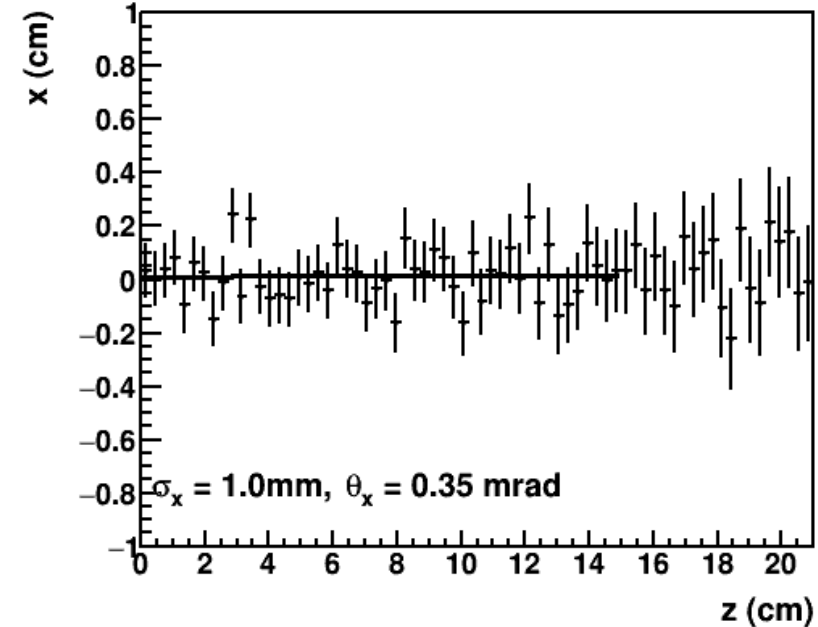
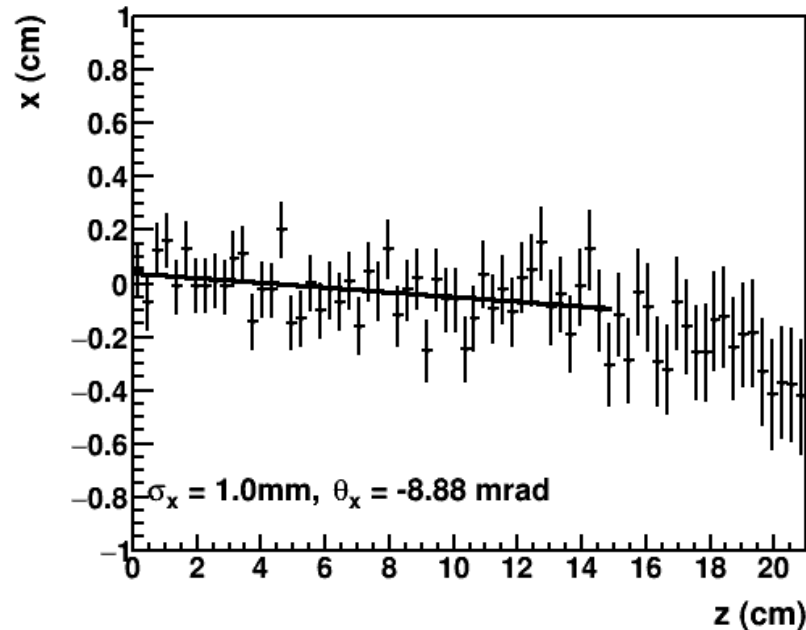
- Previously, showed analysis with very simple (flat) resolution assumptions
- Extracting flux looked promising, even with ~ 5 mrad angular resolution (right plot)

Improved LAr angular resolution from Geant4 simulation



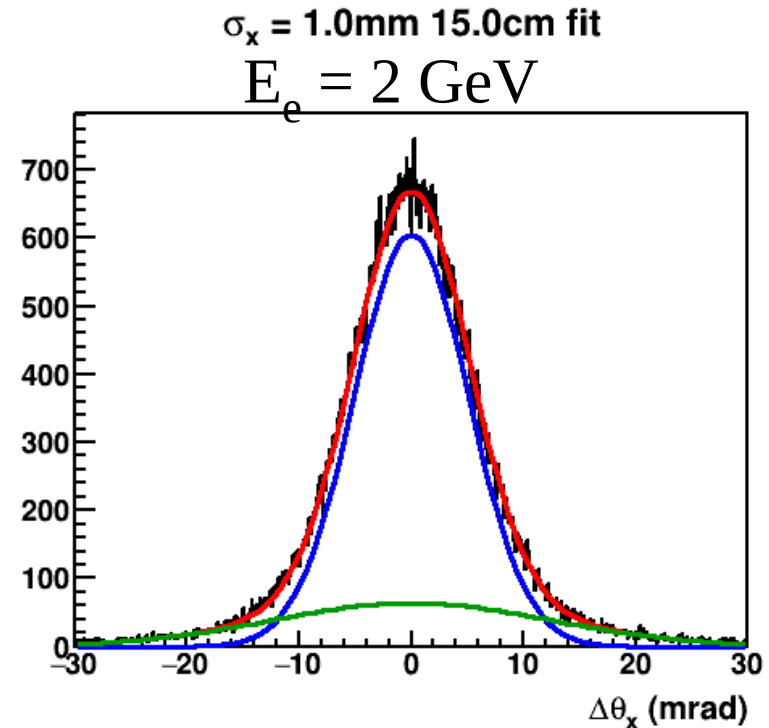
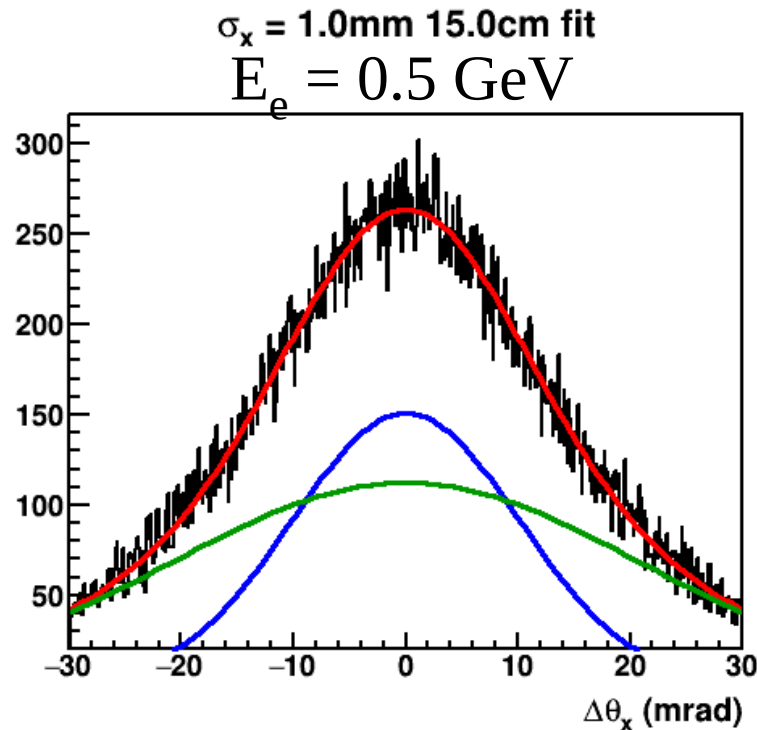
- Simulate forward electrons in LAr, with measurement every 3mm
- At each 3mm plane, track position is whichever is closer to 0 of:
 - The true electron trajectory
 - The charge-weighted centroid of the shower

Straight-line fit to tracks



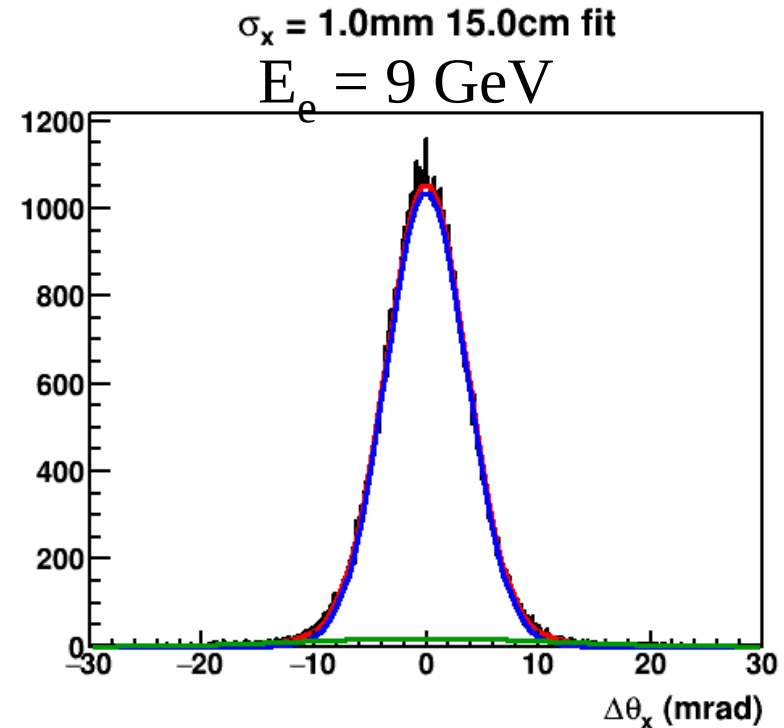
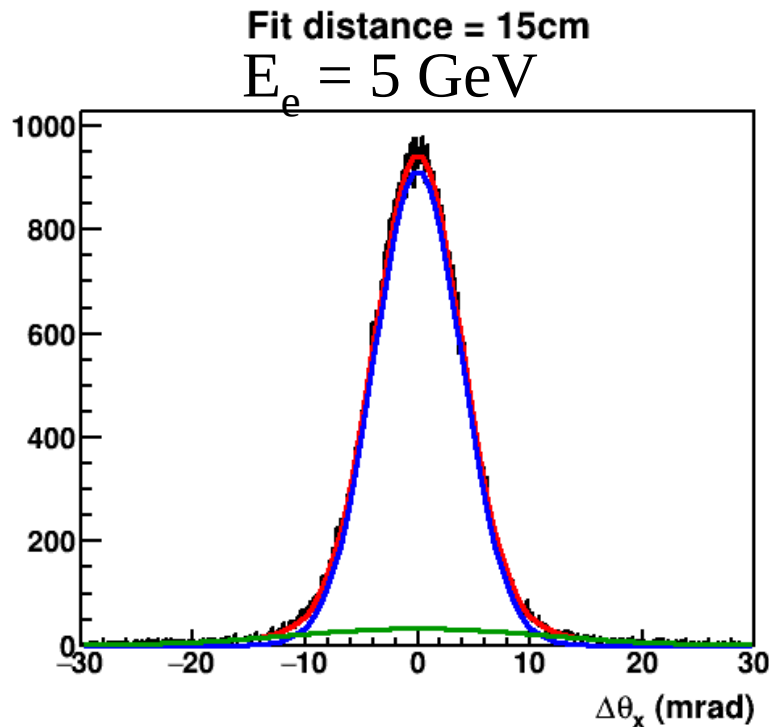
- Smear the measurement at each 3mm point by a Gaussian with some σ_x , shown here 1mm
- Uncertainty at each point is σ_x + expected multiple scattering, in quadrature
- Fit each event to a straight line to determine θ_x

Fit resulting $\Delta\theta_x$ distributions to double gaussians



- Wide Gaussian takes into account non-Gaussian multiple scattering tail
- Width of central peaks follow expected $1/E_e$ form

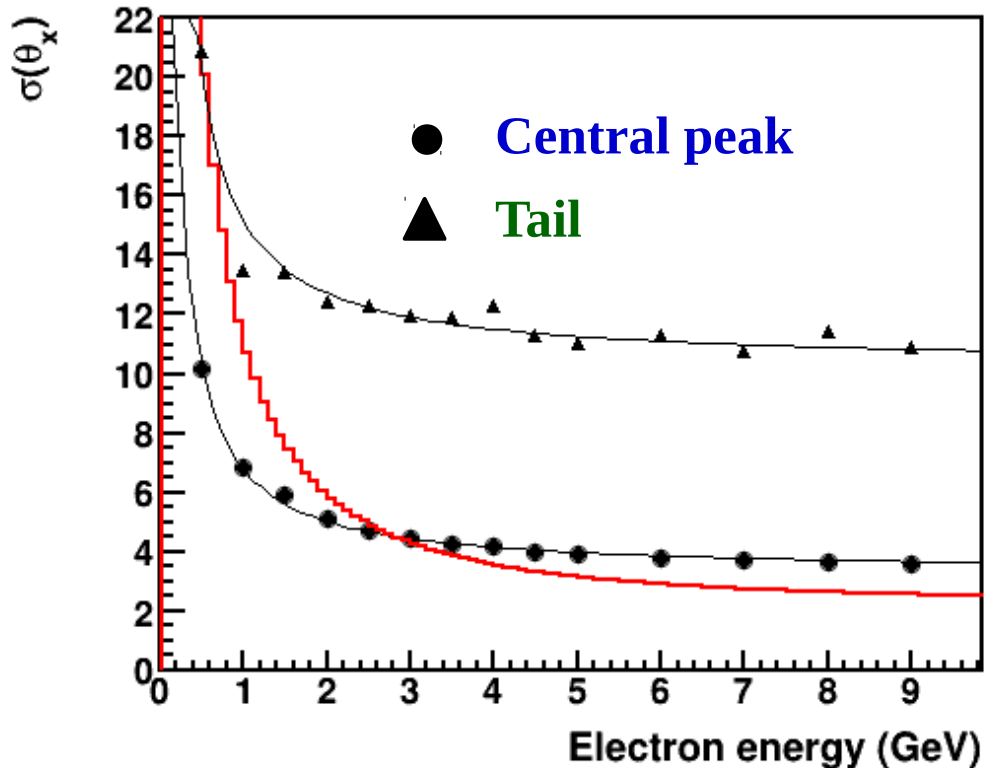
Fit resulting $\Delta\theta_x$ distributions to double gaussians



- Width of multiple scattering decreases as $1/p$
- Normalization of Moliere component also falls with electron energy

Double gaussian sigmas

15cm fit



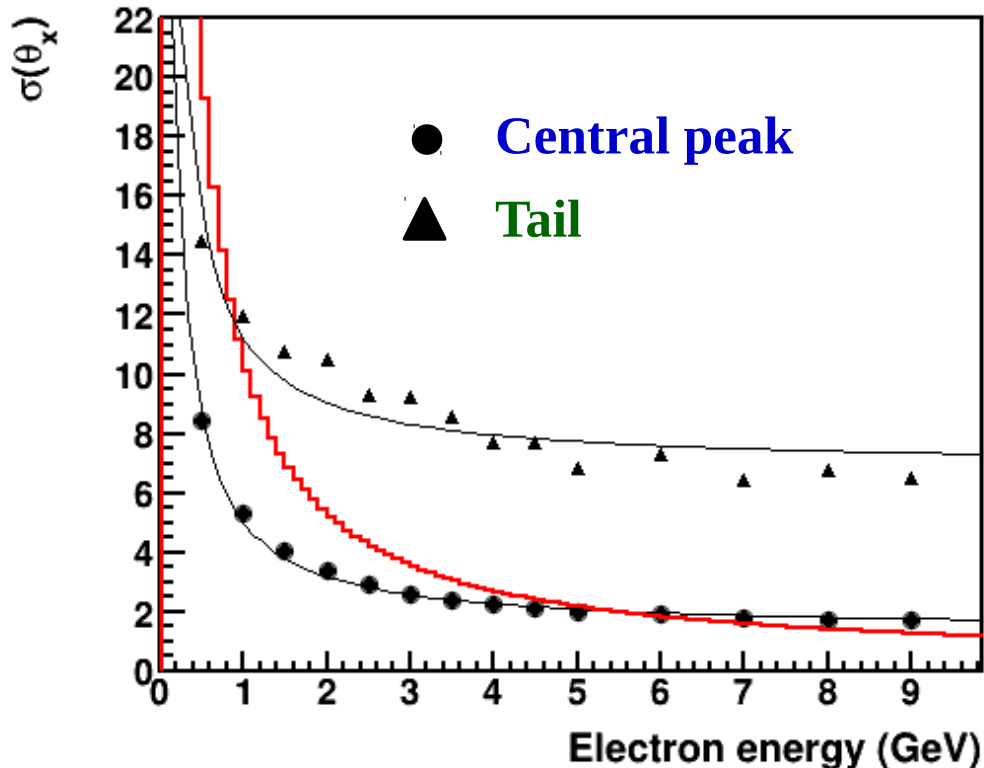
- y axis is fitted σ for angle in XZ plane only, in mrad
- Red line is what is expected from equation, assuming same measurement uncertainty on every point, and neglecting tails

$$\sigma_{samp} = \sqrt{\frac{\sigma_x^2}{(N+1)L^2} \frac{12N}{N+2}}$$

$$\sigma_{MS} = \frac{0.015 \text{ GeV}}{p} \sqrt{\frac{L}{X_0}}$$

If $\sigma_x = 200\mu\text{m}$

9cm fit



- If you reduce the uncertainty on each track point measurement to $200\mu\text{m}$
- For example, by using triangular pads with charge sharing
- No change to multiple scattering

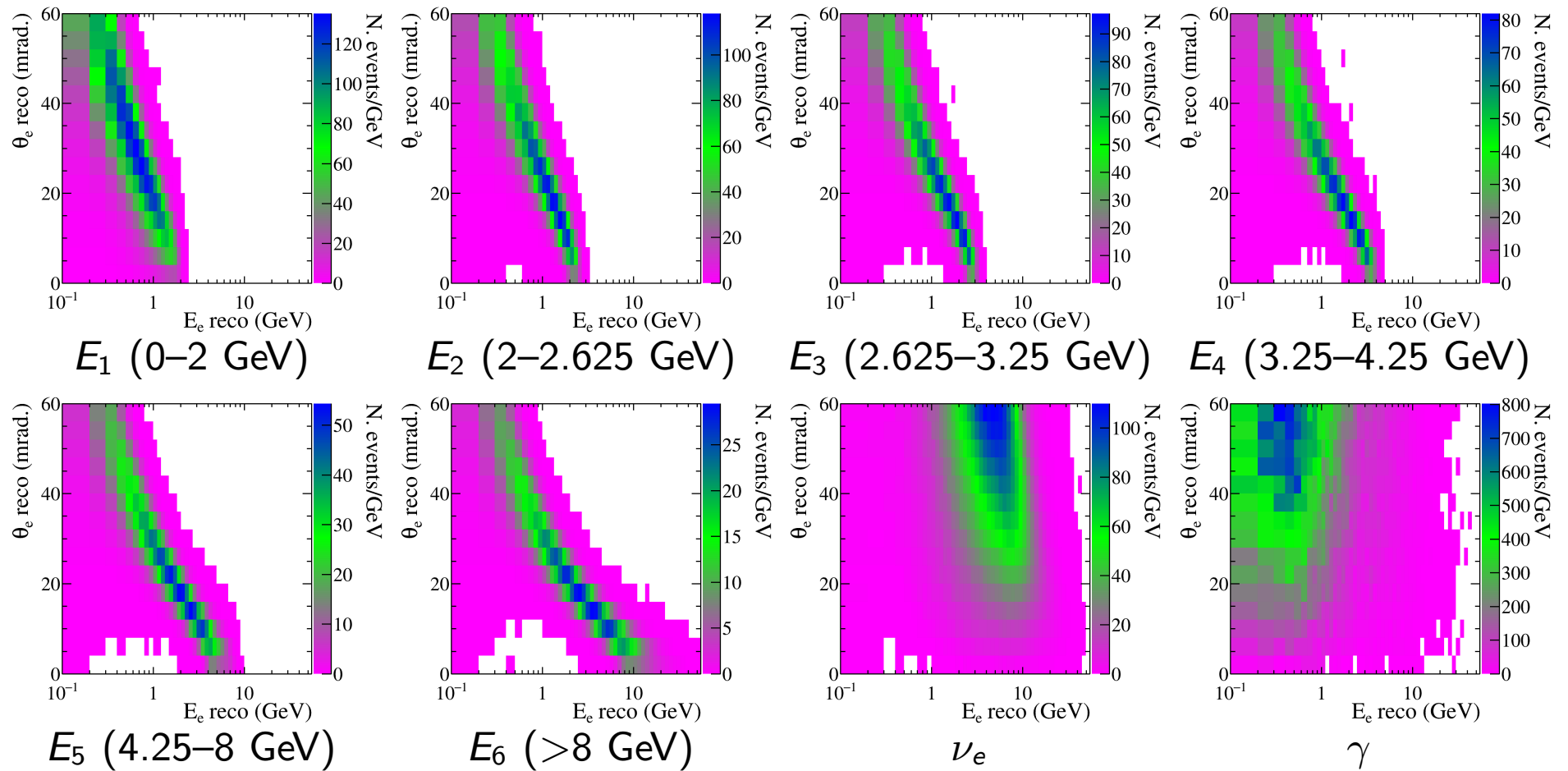
Backgrounds

- Two backgrounds are considered, using GENIE
 - ν_e CC scattering
 - Photon backgrounds, mostly from NC π^0
- ν_e selection:
 - One electron
 - Other charged particle kinetic energy < 20 MeV
 - No additional π^0 or γ
- Photon selection:
 - Second photon energy < 50 MeV
 - Suppressed by 0.1 to account for e/γ separation from dE/dx

Fitting ν - e^- data

- ▶ Aim: test how well we can constrain the flux normalization and shape from E_e, θ_e distributions
 - ▶ Include beam divergence
 - ▶ Include realistic detector smearing from previous studies
 - ▶ Include beam related backgrounds ν_e and γ
- ▶ Use 2D template fit, where each E_ν template is required to have ≥ 500 events (Gaussian)
- ▶ Use event rates based on various potential ND designs:
 - ▶ HPG: 850 events, **not used – rate too low for a binned fit**
 - ▶ STT (5 tons, 5 years): 4250 events, 6 E_ν bins
 - ▶ Nominal IAr (15 tons, 5 years), 3mm pixels: 12750 events, 16 E_ν bins
 - ▶ Enhanced IAr, 5mm triangular pixels, charge sharing: *as above*
 - ▶ Scintillator (CH): 4250 (rough comparison with STT)

Example templates (STT)



- Each E_ν bin adds an E_e, θ_e template to the fit
- ν_e and γ backgrounds also add templates to the fit
- **Note that all flavours contribute to each template!**

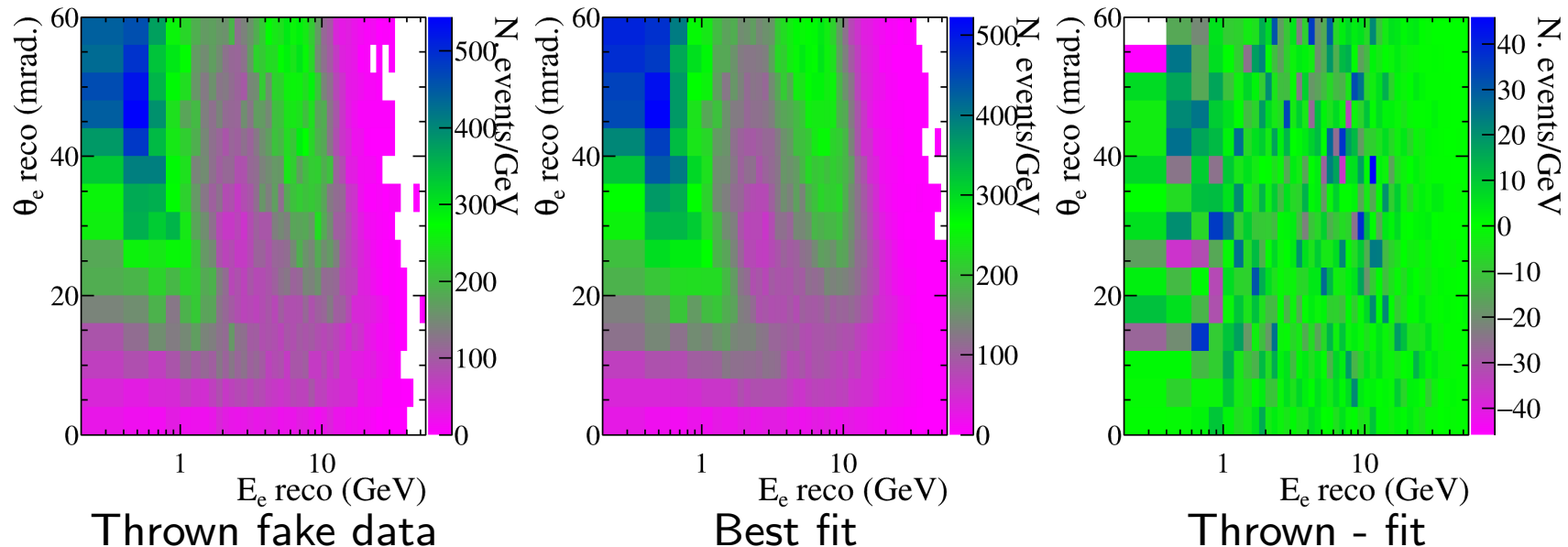
The fitter

- Minimize the Poisson-Likelihood:

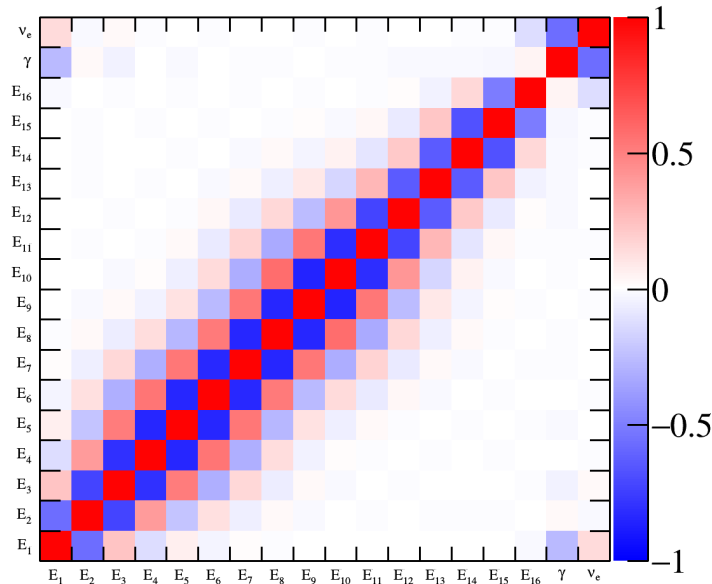
$$\chi^2 = 2 \sum_{i=1}^N \left[\mu_i(\vec{\mathbf{x}}) - n_i + n_i \ln \frac{n_i}{\mu_i(\vec{\mathbf{x}})} \right],$$

where n_i is the number of data events in the i th E_e, θ_e bin and $\mu_i(\vec{\mathbf{x}})$ is the MC prediction, a function of template normalizations, $\vec{\mathbf{x}}$.

- Exclude bins below a threshold, $E_e \geq 0.5$ GeV used here



Example fit result (nominal IAr)



- ▶ Deliberately fine template binning to reduce bias and maximize power of constraint
- ▶ Very strong bin-to-bin anticorrelations in the output covariance matrix \rightarrow that's fine, ≥ 500 events/template ensures everything is nice and Gaussian
- ▶ Good discrimination between signal and background templates

Flux constraining power (1)

- ▶ Difficult to express constraint without reference to some model:
 - ▶ Different flavours have a different ν - e^- cross section
 - ▶ Fit output will always correlate bins
- ▶ Interested in whether we can do better than flux predictions from beamline simulations with known hadron production uncertainties etc
- ▶ Consider how well a ν - e^- constraint could restrict the flux covariance matrix from the beam group (latest 3-horn optimized design)

Flux constraining power (2)

- ▶ MINERvA¹ calculate a probability that their ν - e^- data \vec{N} is predicted by model \vec{M} for κ bins:

$$P(\vec{N}|\vec{M}) = \frac{1}{(2\pi)^{\kappa/2}} \frac{1}{|\Sigma_N|^{1/2}} \exp \left[\frac{1}{2} (\vec{N} - \vec{M})^T \Sigma_N^{-1} (\vec{N} - \vec{M}) \right]$$

where Σ_N is the data covariance, and $|\Sigma_N|$ is its determinant.

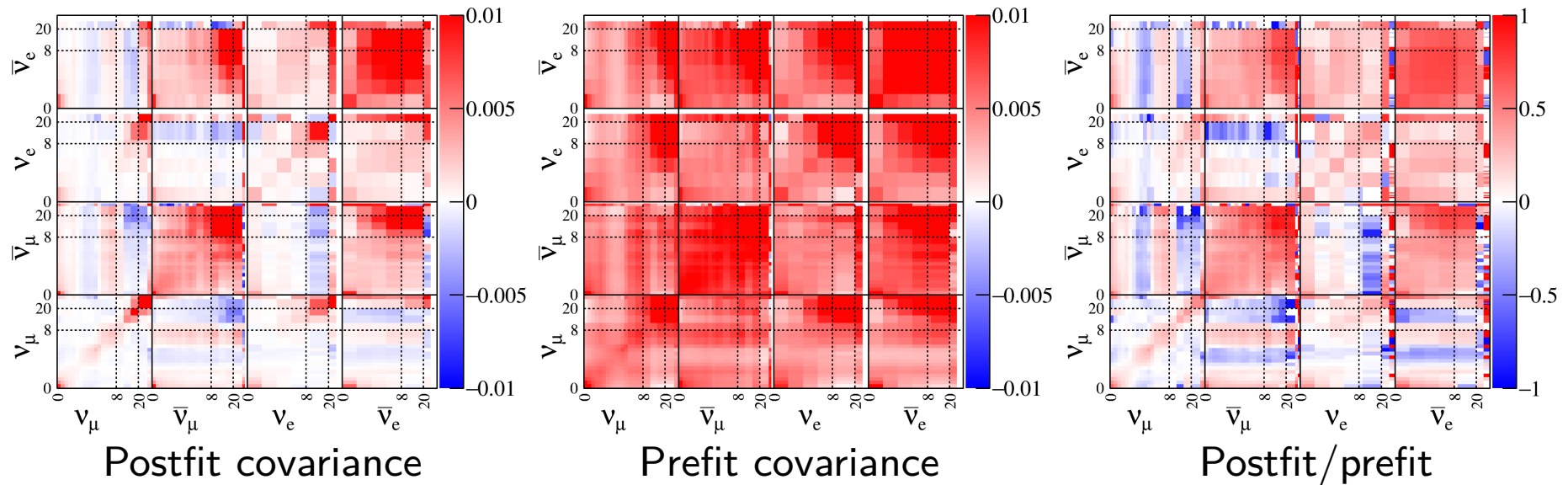
- ▶ Use the same approach: \vec{N} is the postfit E_ν template norms.; \vec{M} is the model in template binning
- ▶ Calculate postfit covariance matrix Ξ_{ij} for k throws of the original flux matrix:

$$\Xi_{ij} = \frac{1}{N_k} \sum_k \left[P(\vec{N}|\vec{M})_k (M_{ik} - \bar{M}_i) (M_{jk} - \bar{M}_j) \right]$$

where the weighted average in the i th bin is $\bar{M}_i = 1/N_k \left[\sum_k P(\vec{N}|\vec{M})_k M_{ik} \right]$

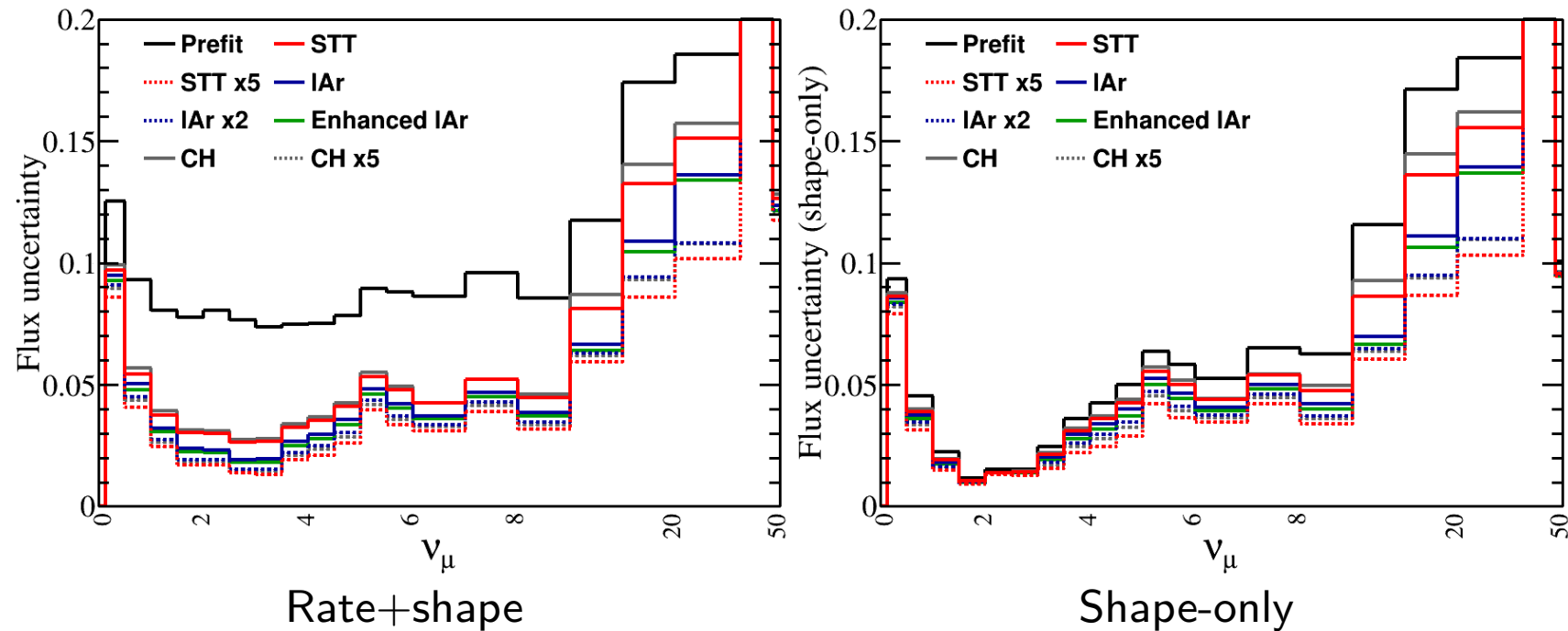
¹J. Park, *et al.*, *Phys. Rev.* **D93**, 112007 (2016)

Flux constraint example: nominal IAr



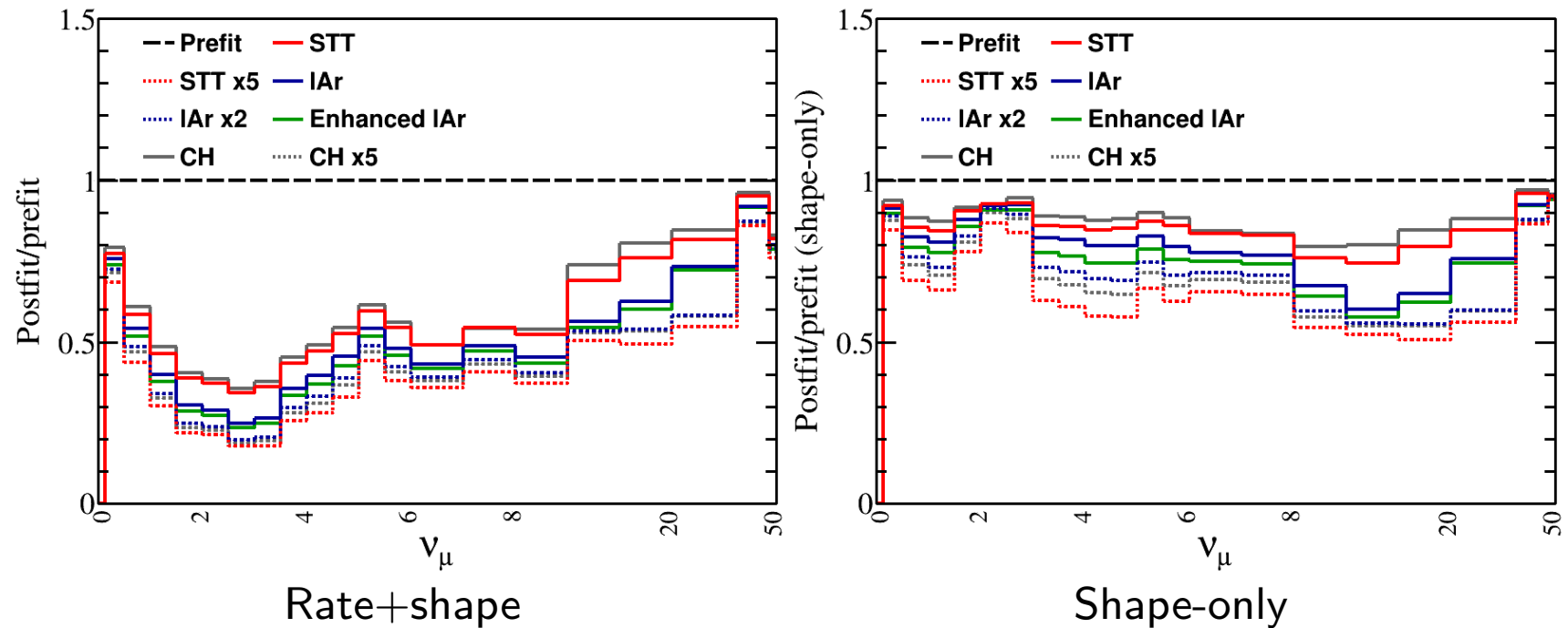
- ▶ Difficult to interpret covariances, so I will compare the diagonals for different configurations
- ▶ Also interesting to look at shape-only matrices to look at what improvements you get over a rate-only measurement

Different ND configurations



- ▶ Significant reduction in diagonals of rate+shape matrix, less obvious for shape-only matrix
- ▶ Greater stats for the IAr scenarios give a better shape constraint than nominal STT. But STT x5 much better
- ▶ Appears that most of the power comes from increasing detector mass

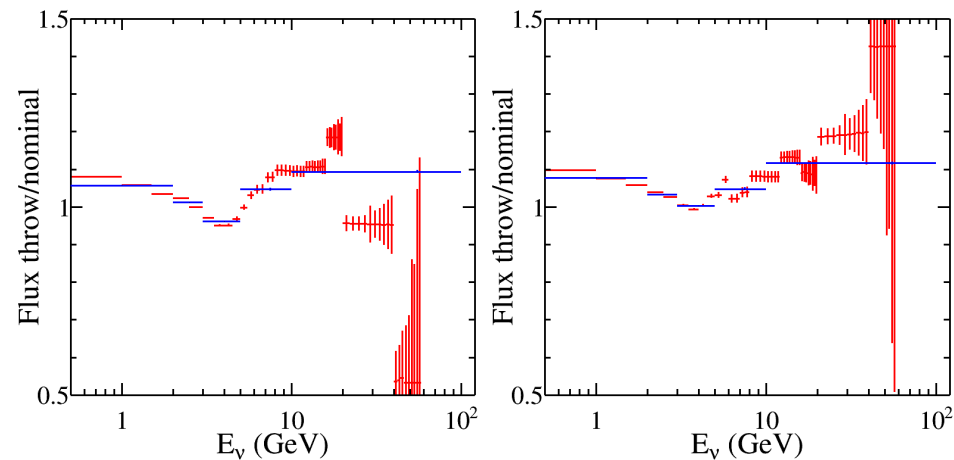
Different ND configurations



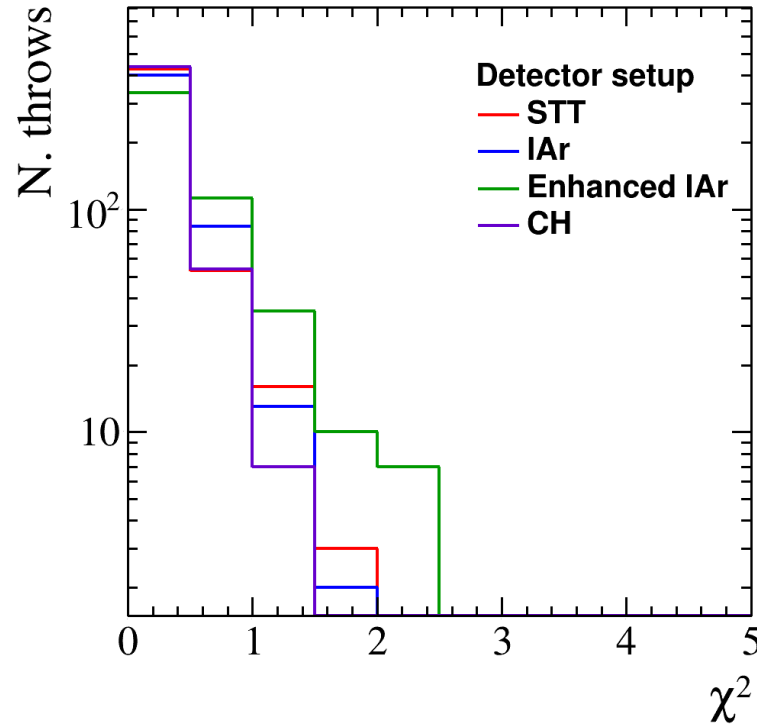
- ▶ Significant reduction in diagonals of rate+shape matrix, less obvious for shape-only matrix
- ▶ Greater stats for the IAr scenarios give a better shape constraint than nominal STT. But STT x5 much better
- ▶ Appears that most of the power comes from increasing detector mass

Bias tests

- ▶ Want the fit result to be independent of the input flux.
- ▶ Test by fitting MC formed from nominal flux prediction to throws of the flux covariance matrix.
- ▶ Expect some bias towards the input flux because:
 1. Only fit a single number in each E_ν bin, integrated over flavours \rightarrow implicitly assumes the proportion of flavours from the nominal throw.
 2. The flux uncertainties modify the flux on a smaller scale than the fit can be binned in



Flux bias tests

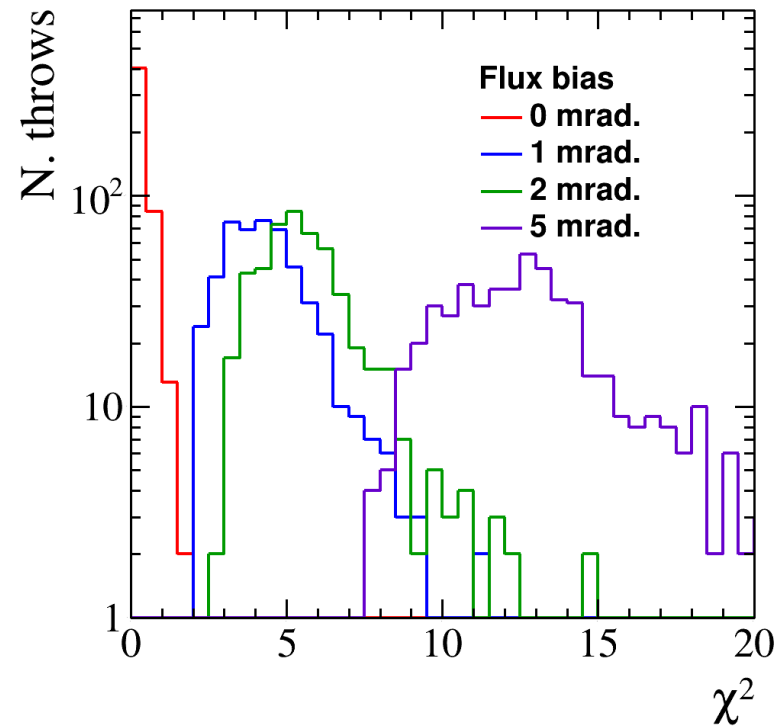


- For each flux throw:
 - Reweight the fake data according to the new flux
 - **Do not make a statistical throw**
 - Fit the templates (built with the nominal flux)
 - Calculate the Hessian at the best fit point

- Bias:

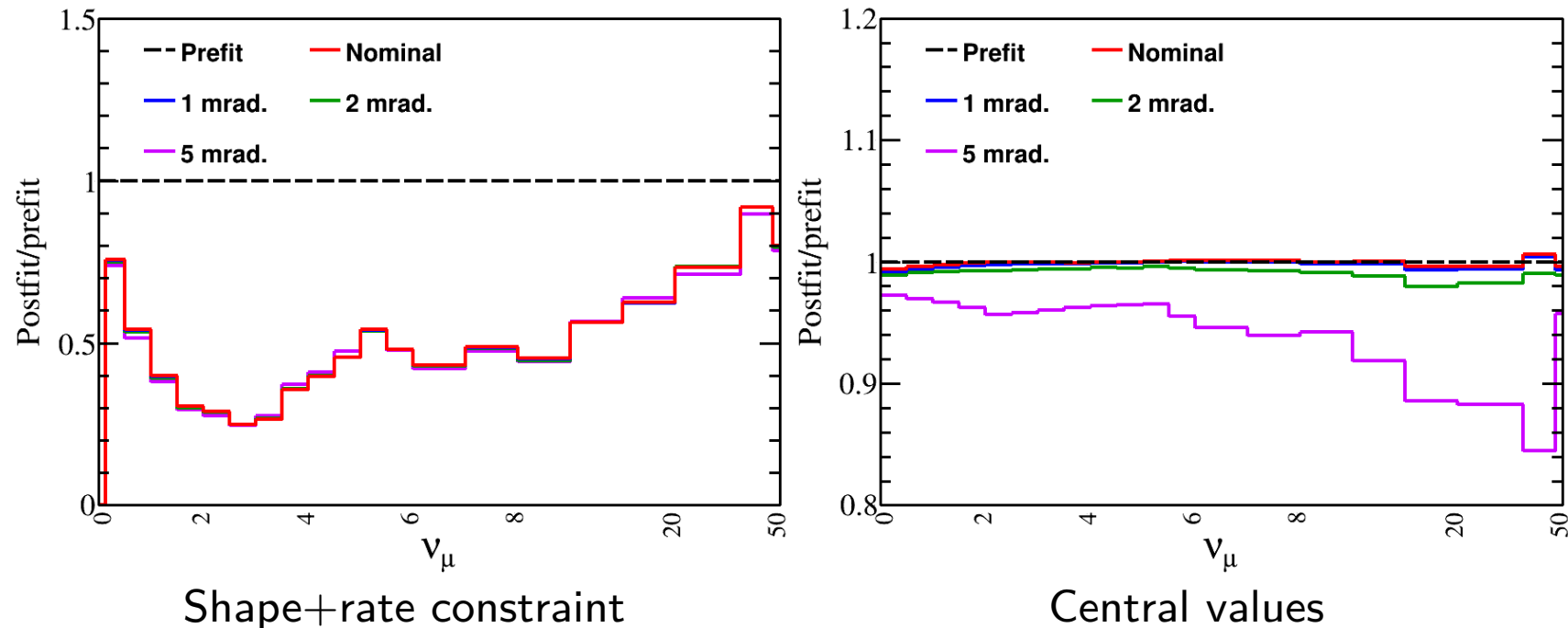
$$\chi^2 = \sum_{i=0}^N \sum_{j=0}^N \left(\nu_i^{TRUE} - \nu_i^{FIT} \right) M_{ij}^{-1} \left(\nu_j^{TRUE} - \nu_j^{FIT} \right)$$

Flux bias test: nominal IAr



- ▶ Interested in what happens if we offset the beam direction, but assume we don't know about it. Mimics a beam pointing error
- ▶ Offset beam by 1, 2, 5 mrad., and fit assuming the nominal is true
- ▶ Reasonably large biases (16 bins in χ^2). But probably tolerable for biases $\leq 1\text{mrad.}$

Flux biases

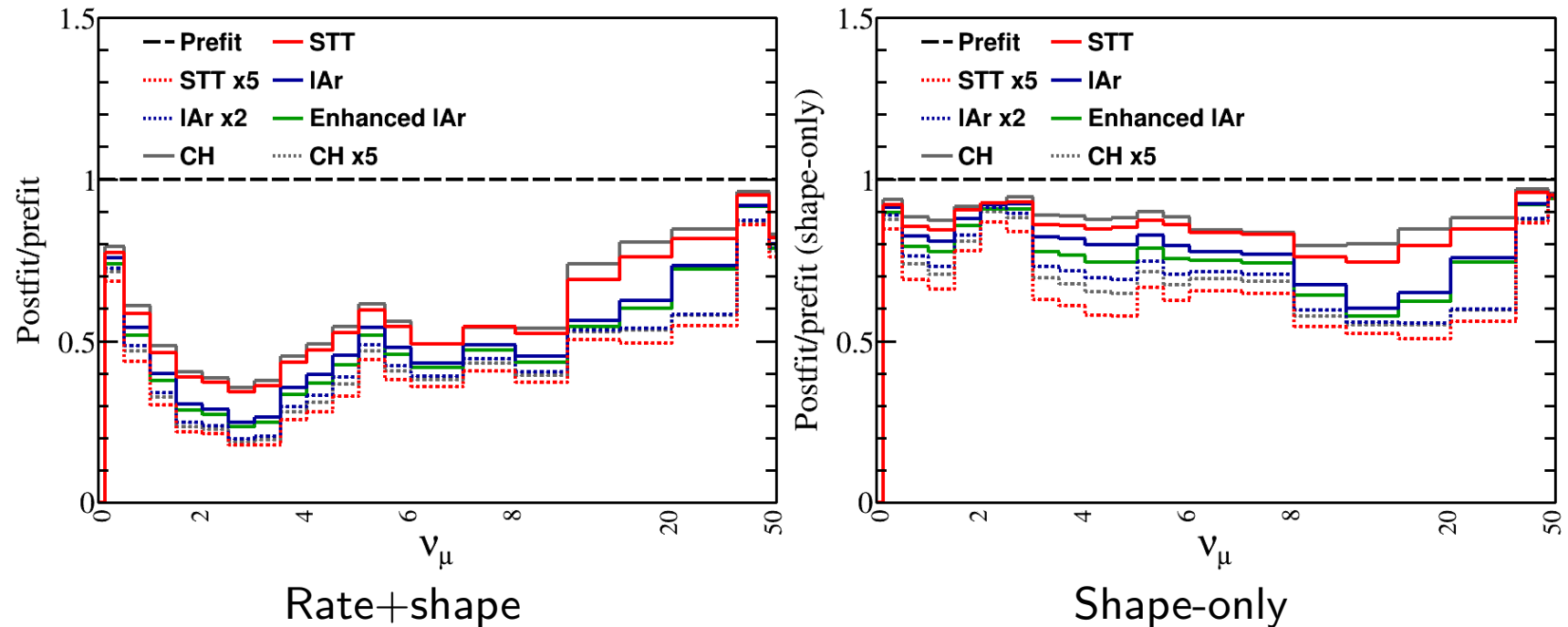


- ▶ No significant change to the output covariance matrix
- ▶ Clear shape dependence to the bias. Not surprising, but effect grows rapidly with the beam bias.

Future and to do

- ▶ Various bias tests to be done with background model changes
- ▶ Look at the effect of mis-modeling the E_e resolution. E.g. bias tests with a low-side tail
- ▶ Radiative corrections are missing from the GENIE ν - e^- model, find a way to approximate their effect
- ▶ Investigate RHC flux. Potentially will not work due to larger ν -contamination in $\bar{\nu}$ beam \rightarrow larger flux biases

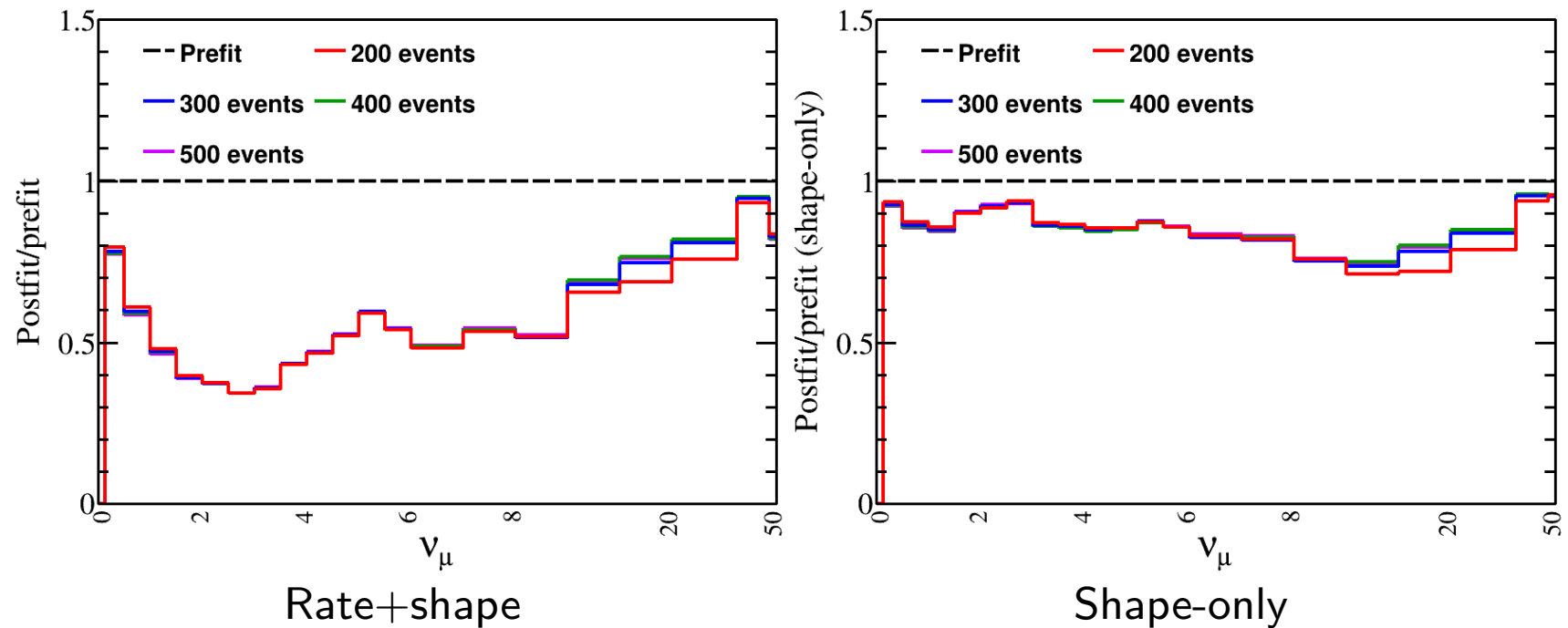
Conclusions



- ▶ Technique seems robust, ν - e^- scattering has potential to constrain the flux well
- ▶ Poor shape constraint for any detector smearing considered here
- ▶ Adding mass to ND will increase the power of the ν - e^- constraint

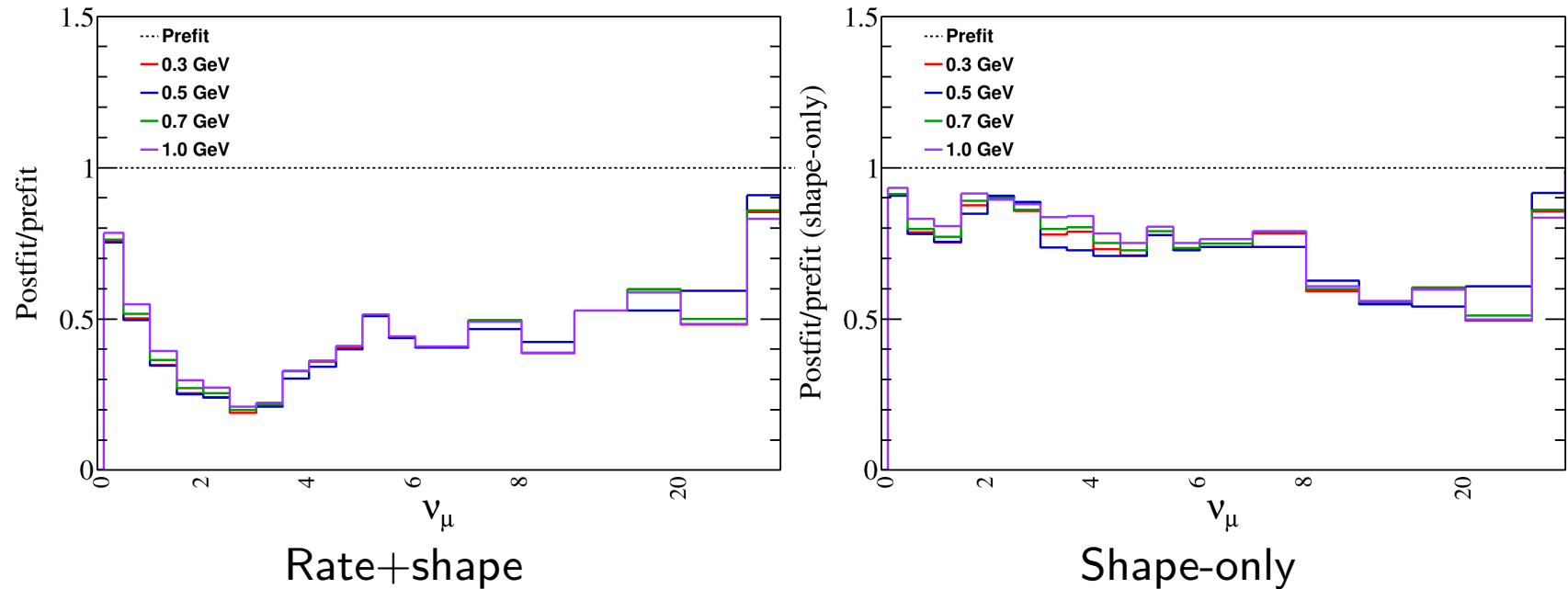
Backup

Changing minimum events (STT)



- ▶ Require ≥ 500 events/template ensures Gaussian statistics, necessary to parameterize with covariance matrix
- ▶ But 500 is a conservative guess, important to check that this choice does not bias conclusions of study
- ▶ Changing the minimum number of events makes a difference at high energies, but does not qualitatively change the results

Changing E_e threshold (nominal IAr)



- ▶ None of the detector setups are particularly sensitive to changes in the E_e threshold
- ▶ Unsurprising as lowest E_ν template always has a range of around 0–1.5 GeV

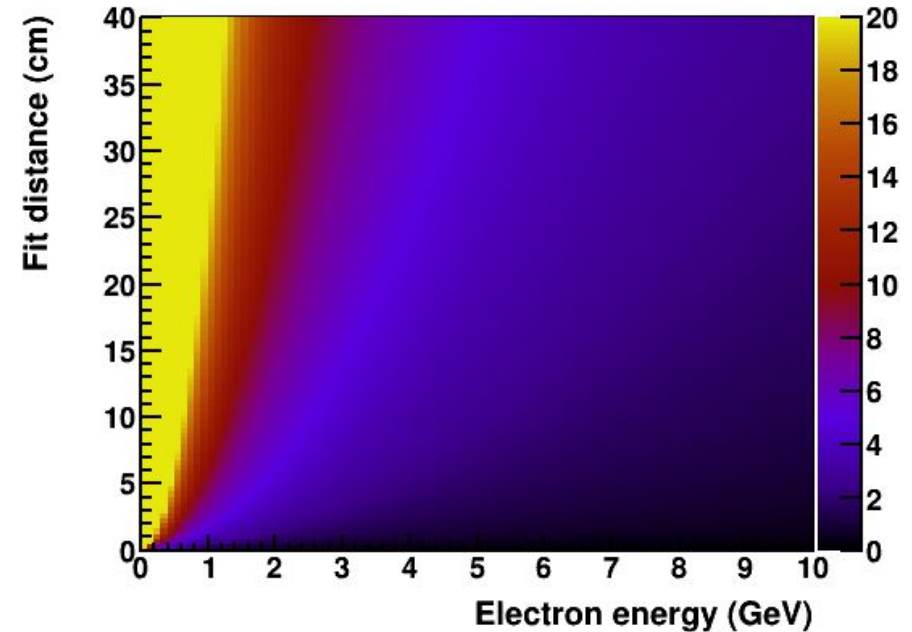
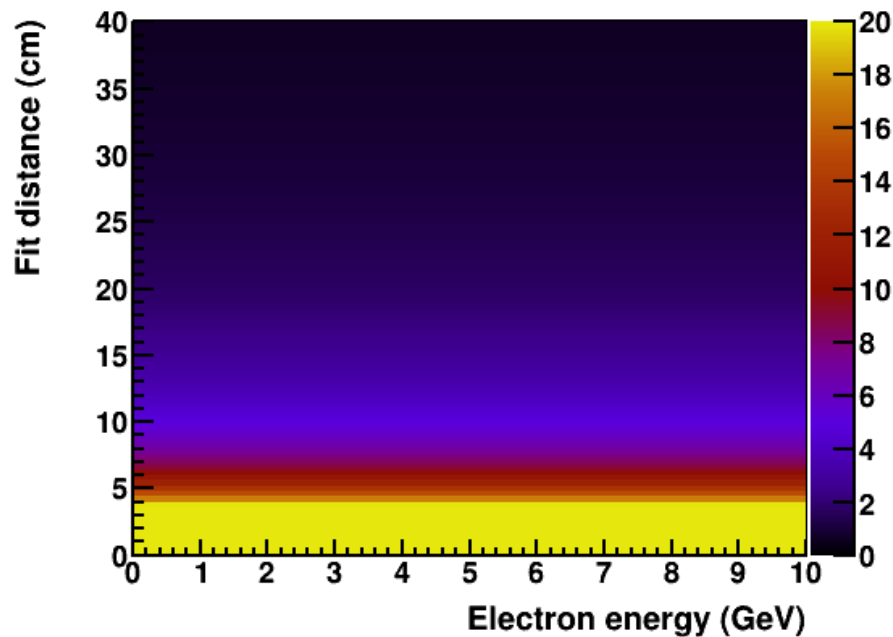
Sampling and MS terms

- Sampling: assume same uncertainty on each point σ_x , and that successive points are not correlated

$$\sigma_{\text{samp}} = \sqrt{\frac{\sigma_x^2}{(N+1)L^2} \frac{12N}{N+2}}$$

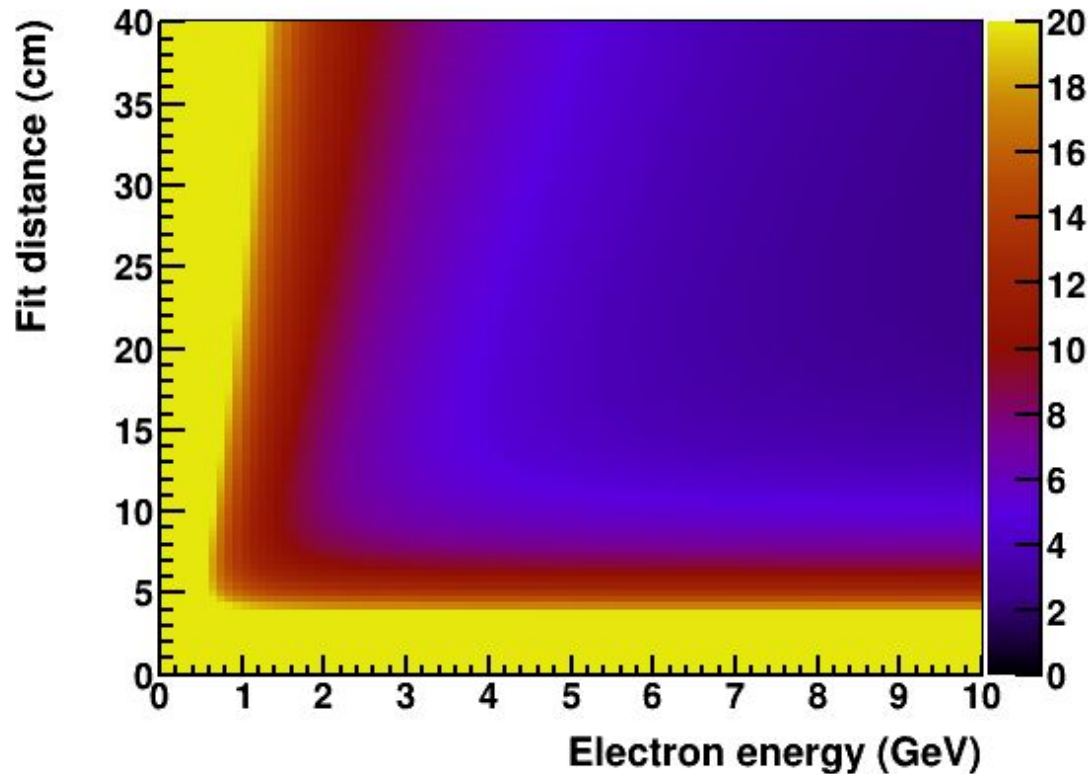
$$\sigma_{MS} = \frac{0.015 \text{ GeV}}{p} \sqrt{\frac{L}{X_0}}$$

Angular resolutions, in mrad, from equations, vs. fit distance



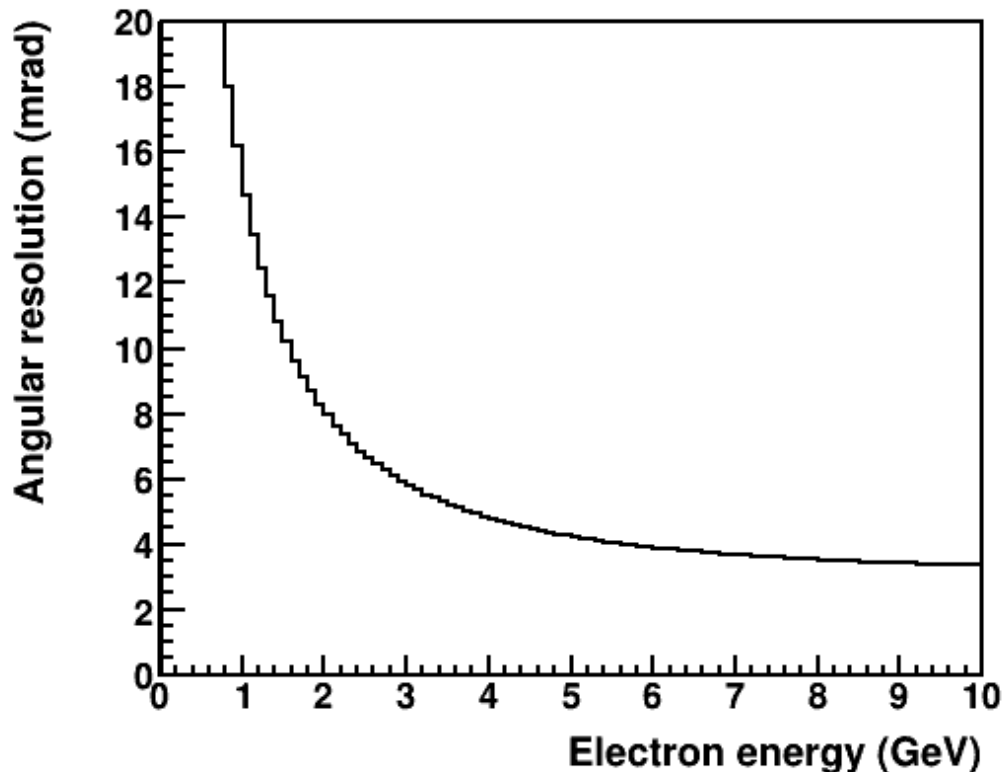
- Sampling (left) is flat vs. energy
- Multiple scattering (right) is $1/p$

Added in quadrature – total uncertainty from sampling + MS



- Optimal fit distance is around 1 radiation length
- Measurement term is ~ 3 mrad
- But multiple scattering with $L = 14$ cm is large below a few GeV

For 14cm fit

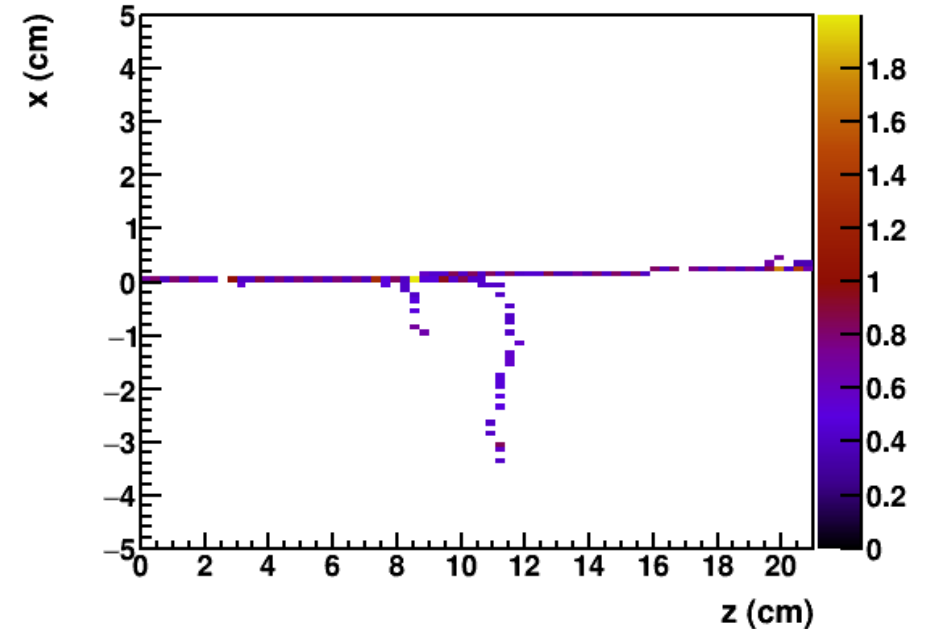
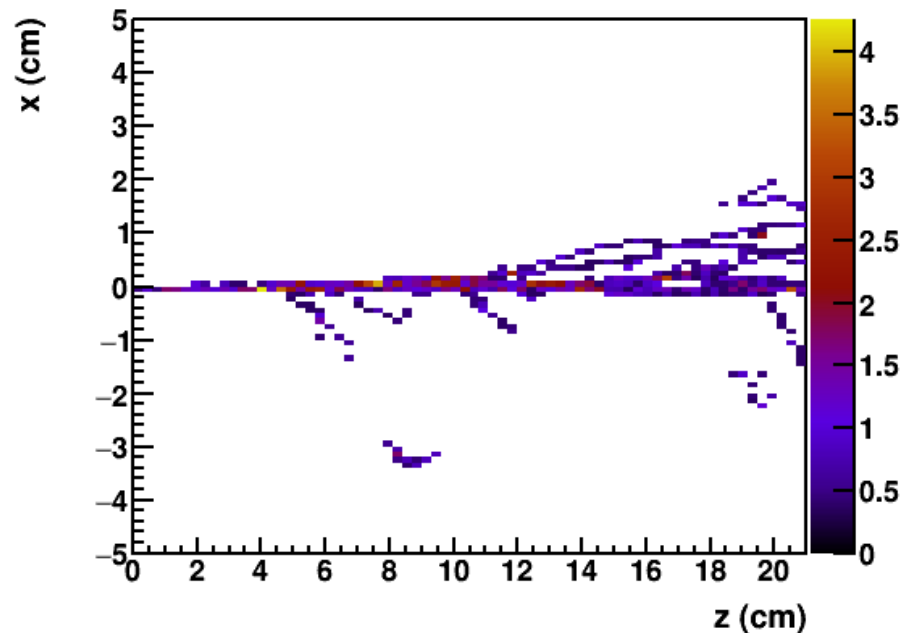


- Still assumes Gaussian
- Assumes $\sigma_x = 3\text{mm}/\sqrt{12}$
- And assumes each sampling point is uncorrelated with the others, which is not really true for pixels

...But we can do better

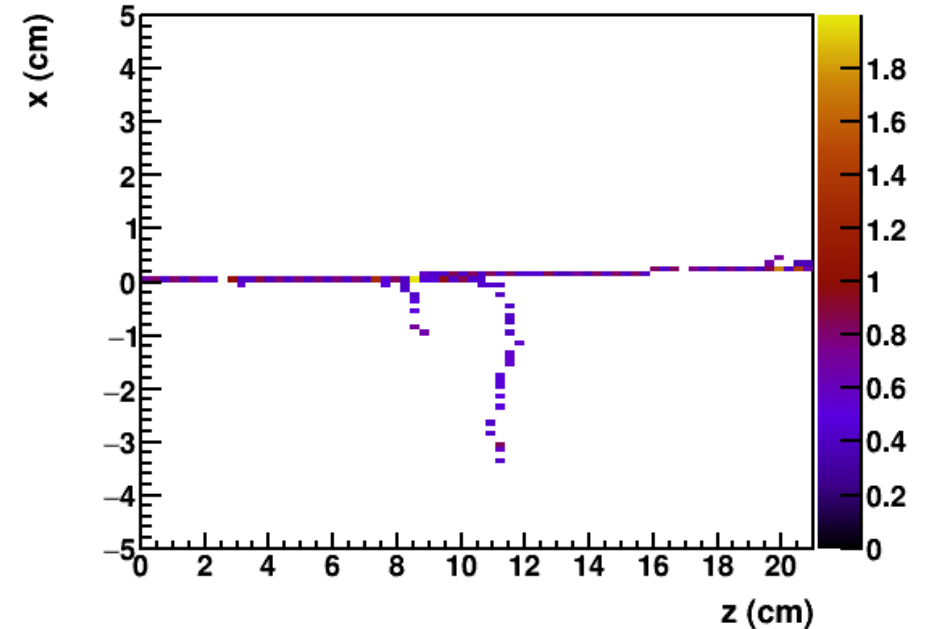
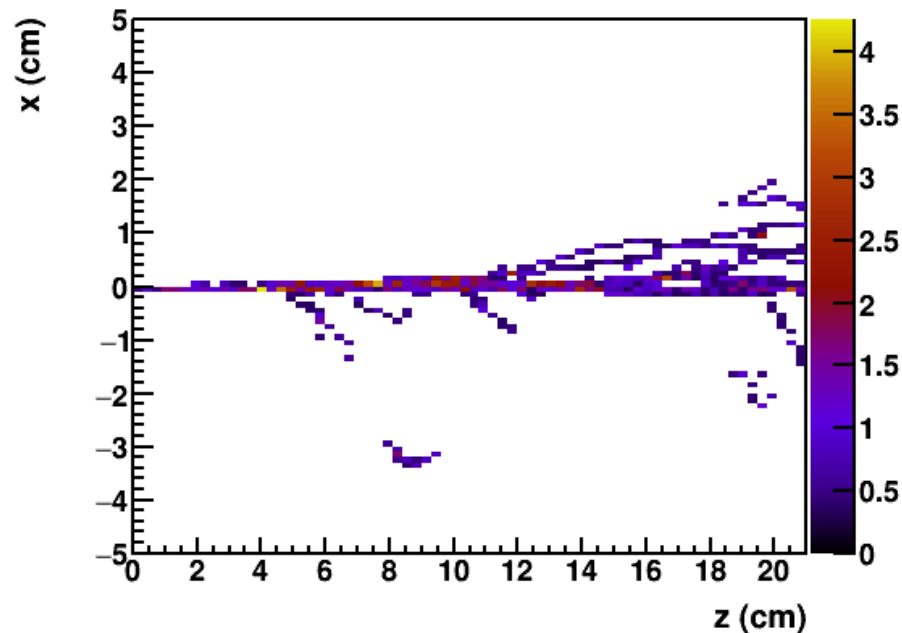
- Sampling uncertainty equation assumes equal error at each point, but in reality we have smaller uncertainties initially (due to multiple scattering)
- And multiple scattering isn't the only effect, there are also hard brems
- Want to fit for both simultaneously with full geant simulation of electrons in LAr

Example events of why it's hard



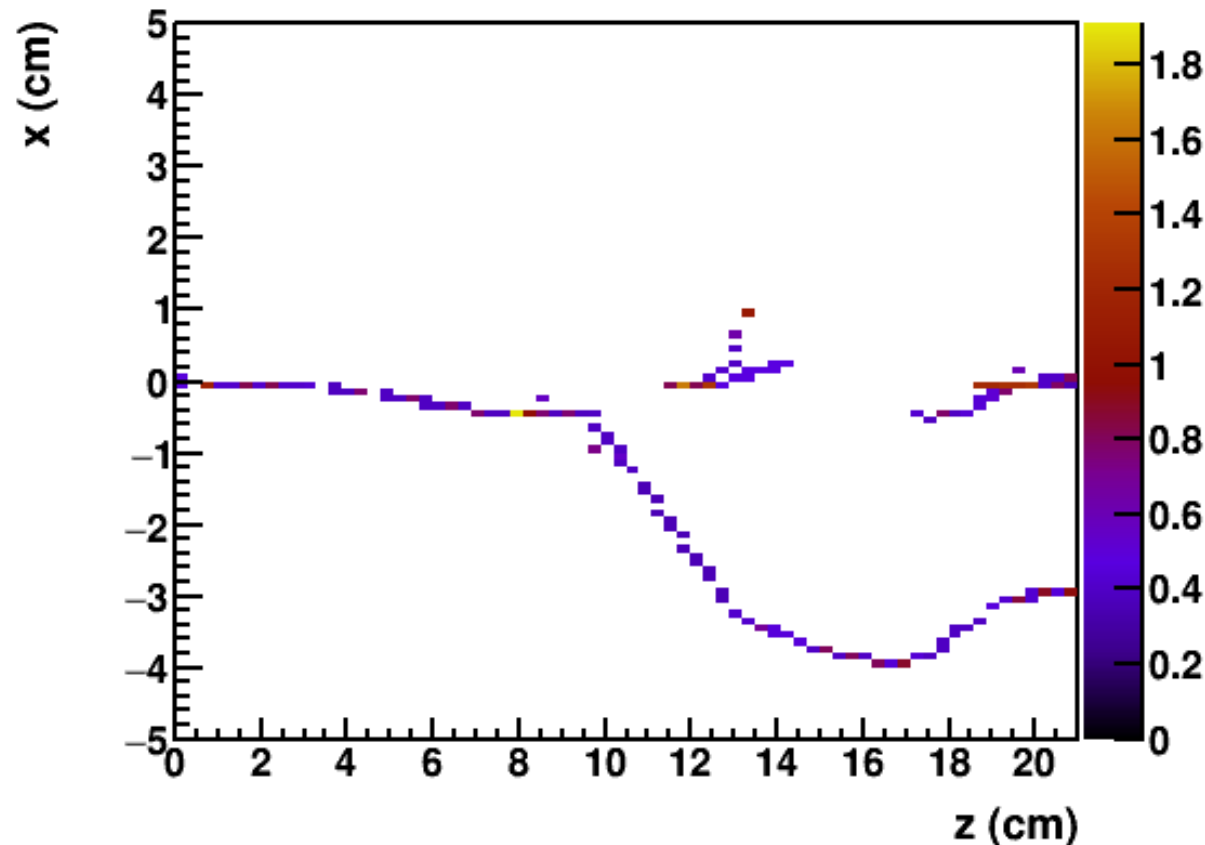
- Technique #1: Follow the true electron trajectory
 - At each point, smear the transverse position by σ_x
 - Uncertainty is σ_x plus the average multiple scattering deflection, in quadrature
 - Fit to a straight line

Example events of why it's hard



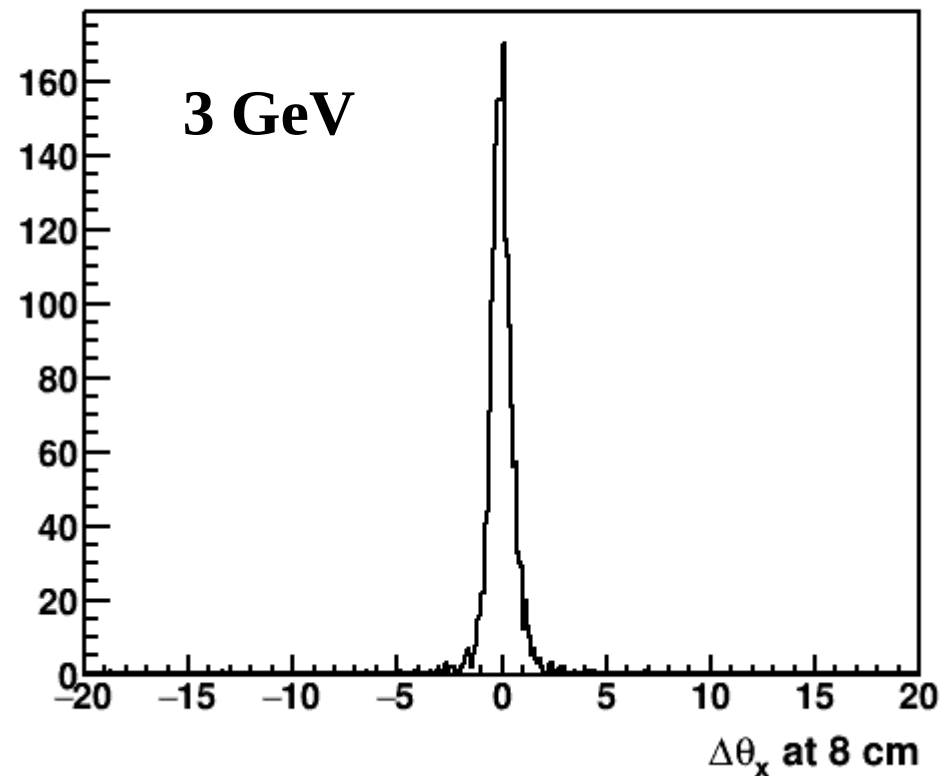
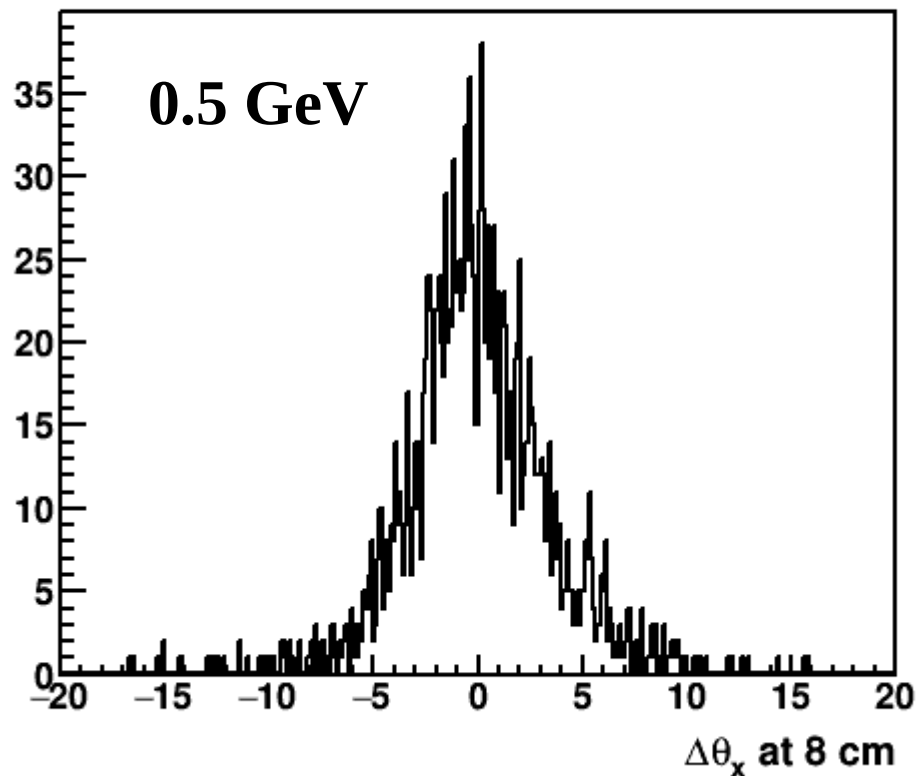
- Technique #2: Charge centroid
 - In each plane, take the charge-weighted average position of all hits
 - Uncertainty is σ_x plus the average multiple scattering deflection, in quadrature
 - Fit to a straight line

There is a tail



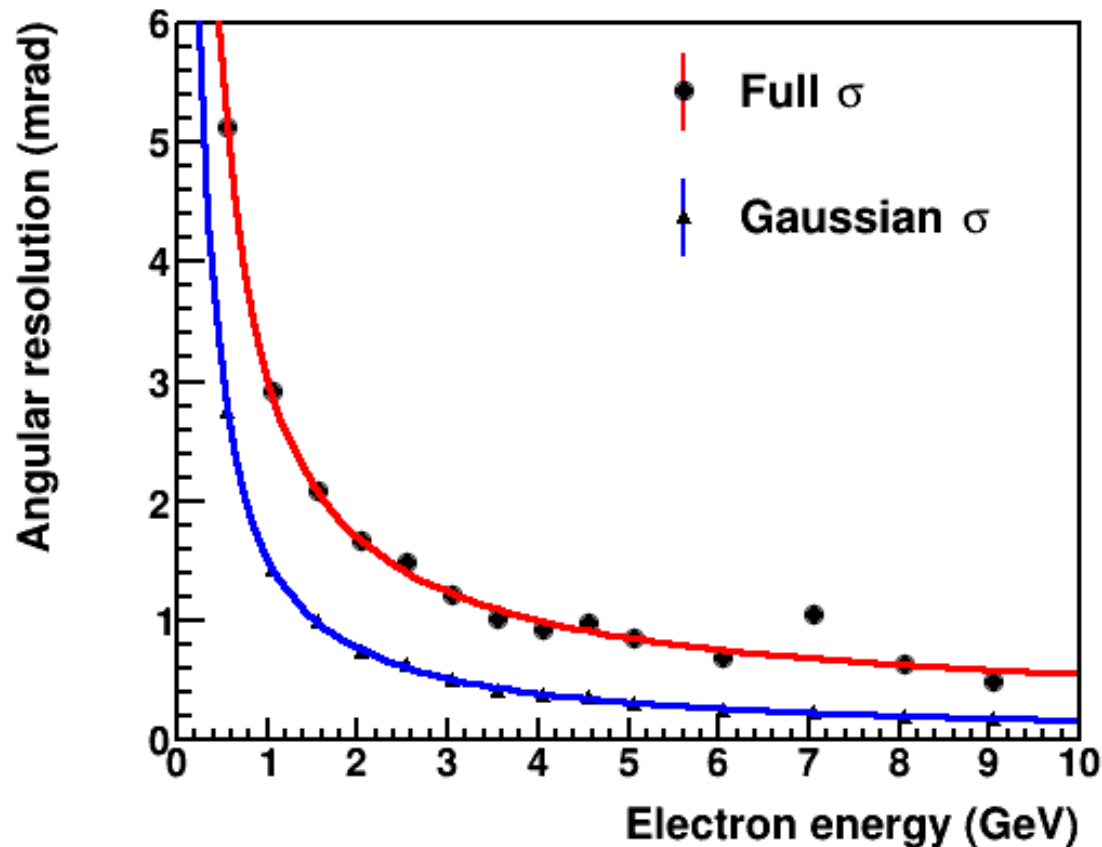
- There are events with very hard scatters, where the angular measurement is terrible
- Gives long tails in the distributions

STT resolutions



- Scattering from Geant4 simulations in $0.1\text{g}/\text{cm}^2$ argon gas
- Assume an angle measurement can be made in 8cm, which is 2 STT modules

Angular resolution vs. energy



- Blue is if you fit the Gaussian peak only to the distributions on the previous slide
- Red is used in the analysis – takes into account the non-Gaussian tails
- Double Gaussian (used for LAr analysis) would be better