Trying to put a better spec on sign selection for TMS/SSRI

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Goal: what sign-selection is required for LBL physics?

- It is easy to determine the required sign mis-ID rate in order to produce a wrong-sign sample of some purity
- But what would such a sample actually do for the short-term long-baseline physics goals? What is the minimum right-sign purity required for the first 3 years physics?
- What is the uncertainty on the wrong sign fraction from the beam model? Can we constrain it further with SSRI?

FD measures ν+ν̄ appearance

FHC ("ν-mode") 3.5 Staged Years

	normal ordering		
	δ_{CP}=0	δ_{CP}=-π/2	Variation
$\nu_\mu \rightarrow \nu_e$	1155	1395	**0.21**
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	19	14	
Beam $\nu_e + \bar{\nu}_e$	228	228	
Other bkg	135	134	
Total	**1537**	**1771**	**0.15**

RHC ("$\bar{\nu}$-mode") 3.5 Staged Years

	normal ordering		
	δ_{CP}=0	δ_{CP}=-π/2	Variation
$\nu_\mu \rightarrow \nu_e$	81	95	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	236	164	**0.44**
Beam $\nu_e + \bar{\nu}_e$	145	145	
Other bkg	68	68	
Total	**530**	**475**	**0.12**

- For a particular δ, impact on expected signal has opposite sign for wrong sign component
- Tiny effect in FHC, but large effect in RHC
- Wrong-sign neutrino fraction is not measured at FD, must be measured at ND or taken from beam prediction

Impact of changing wrong sign fraction on "variation"

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- FD will measure sum of $\nu_e + \bar{\nu}_e$, and use ND constraint (or MC) to determine the relative amount of each, which impacts the expected "variation" vs. δ
- If you get this wrong, you will measure sinδ wrong
- What happens to "variation" and thus measured δ, if you change the assumed wrong sign fraction (assume you still get other backgrounds right)?

Impact of changing wrong sign fraction on "variation"

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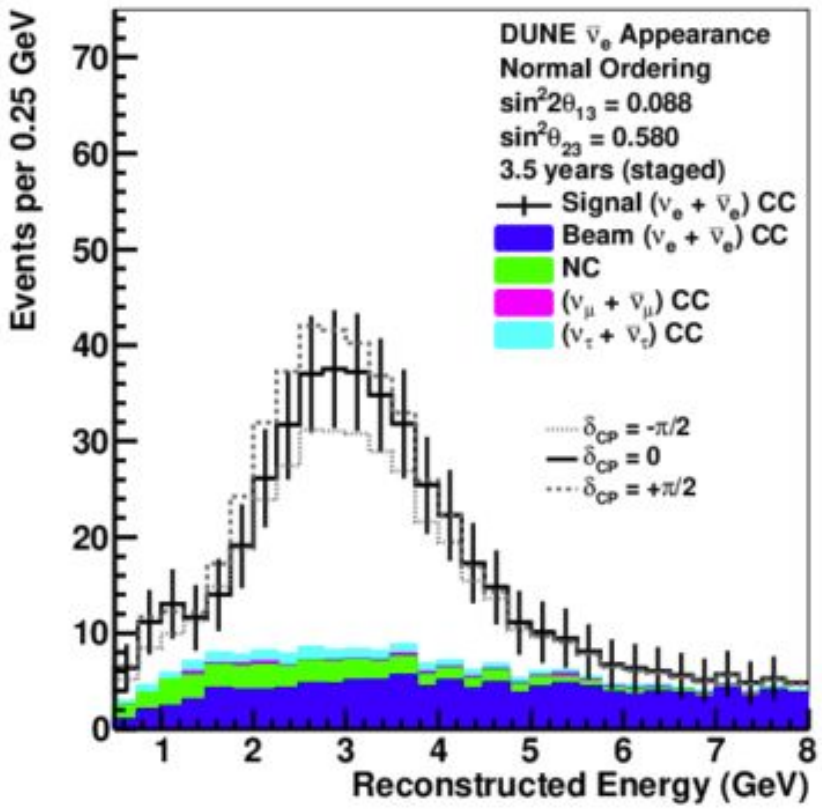
- Changing the assumed wrong-sign fraction by 1 percentage point changes "variation" by 0.004 (FHC) and 0.003 (RHC), each about 2.5% of themselves
- For a 3σ CPV measurement, that 0.15 must be measured at 3σ, so 1σ ~ 0.05, and the bias from the 1pp change in wrong sign fraction is ~7% of that, in quadrature this would have the effect of 3σ → 2.99σ

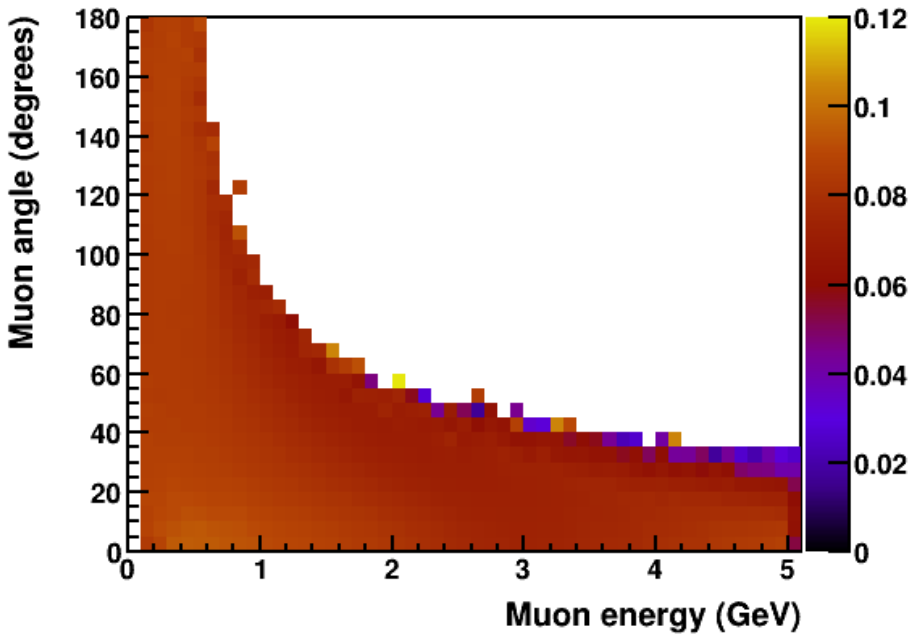
ND must measure wrong sign as a function of neutrino energy



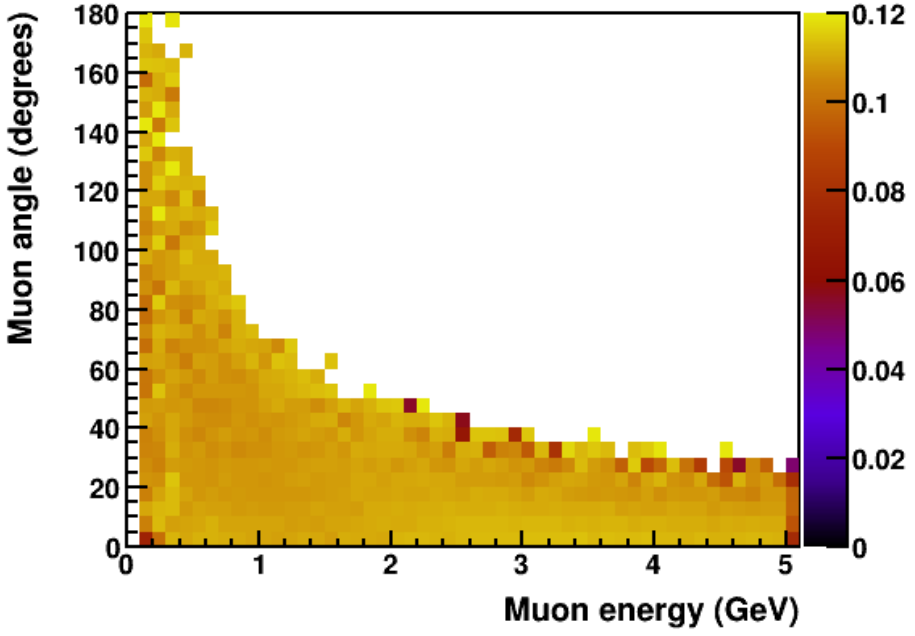
- Drawing the dashed curves on this plot for different values of δ requires knowing the fraction of wrong sign as a function of neutrino energy

FHC flux fractional uncertainty

Right sign (neutrino)



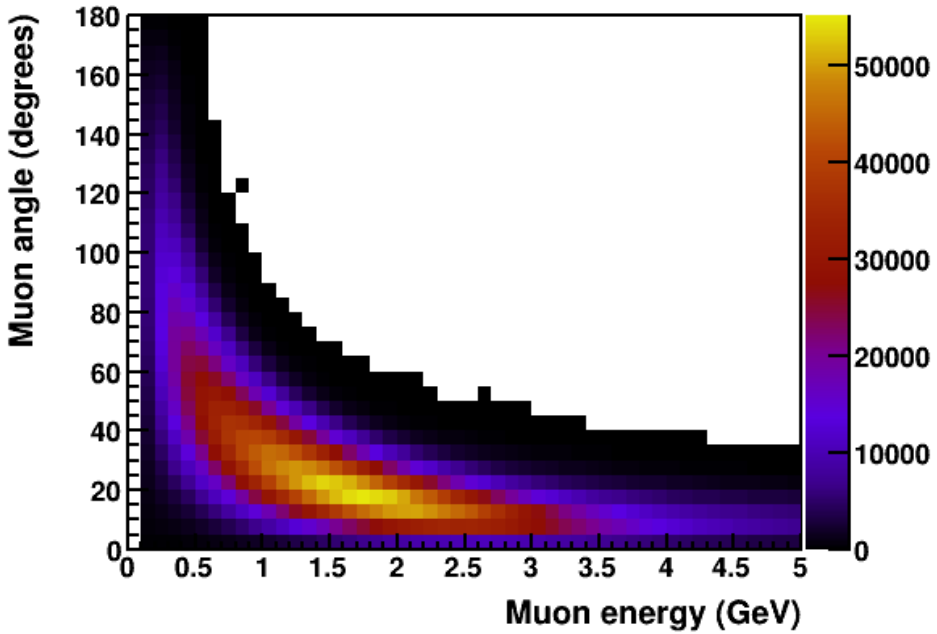
Wrong sign (antineutrino)



- Flux uncertainty is ~8% on the right-sign component and ~11% on the wrong-sign, basically flat vs. neutrino energy in the peak and hence little shape here

FHC event rate

Right sign (neutrino)



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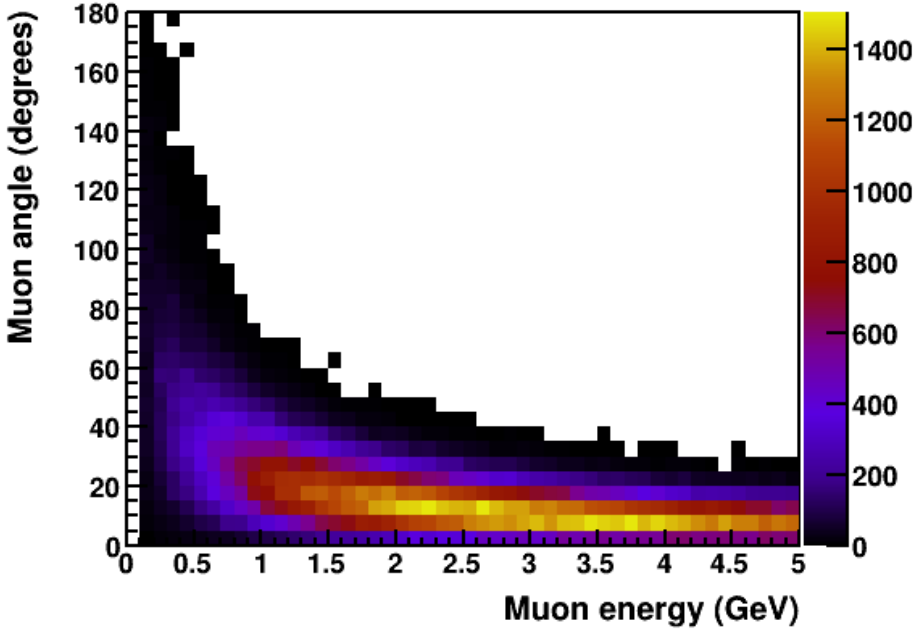
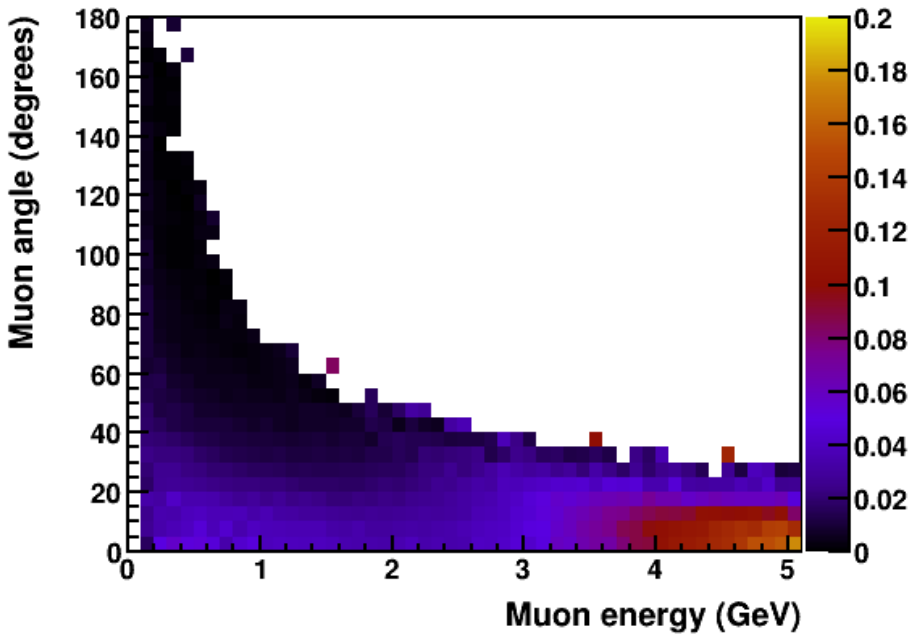


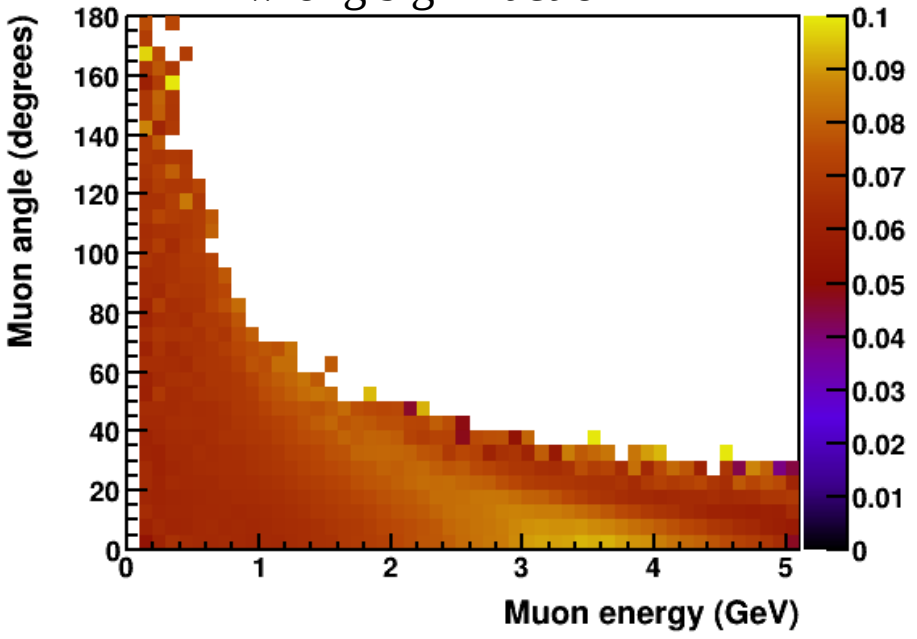
- Arbitrary units
- Peaked from 1-2 GeV and 10-20°
- Wrong-sign antineutrinos are higher-energy and more forward

Wrong sign fraction

Wrong sign fraction



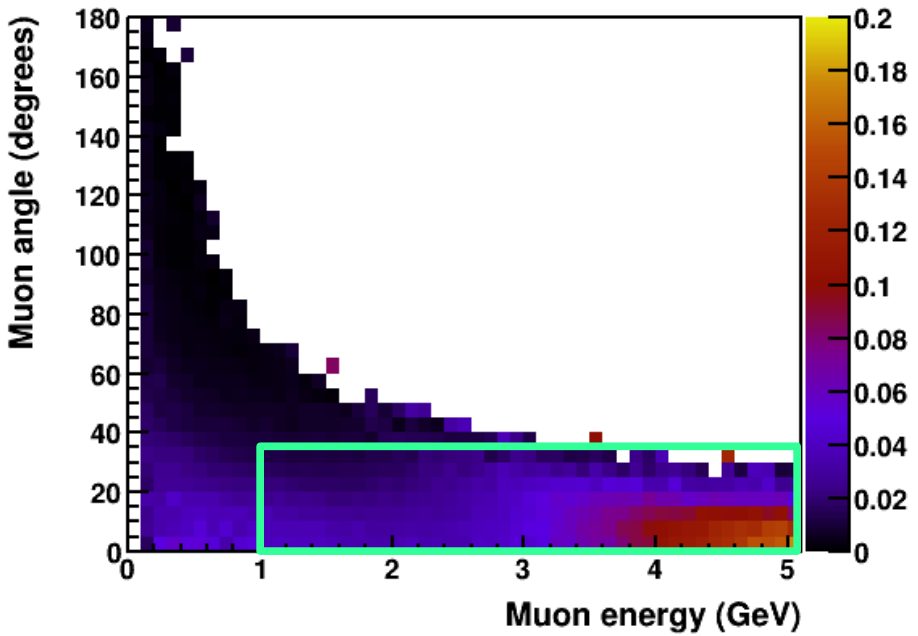
(Fractional) uncertainty on wrong sign fraction



- Wrong-sign fraction is ~3% in the flux peak, but high in the tail and especially for more forward muons
- Uncertainty on wrong-sign fraction from beam model is ~7%, i.e. wrong sign fraction is (3.0 ± 0.2)%

Wrong sign fraction

Wrong sign fraction



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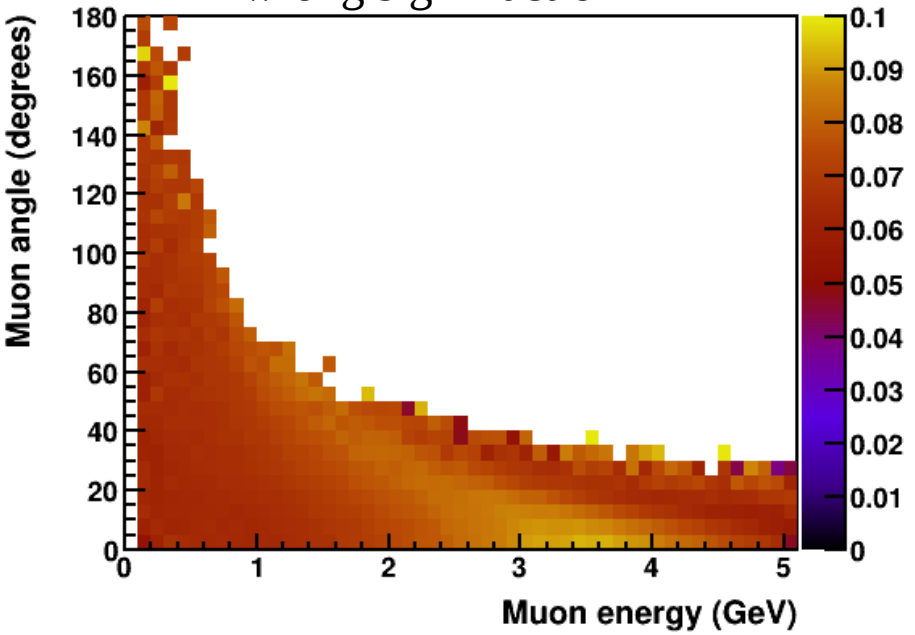
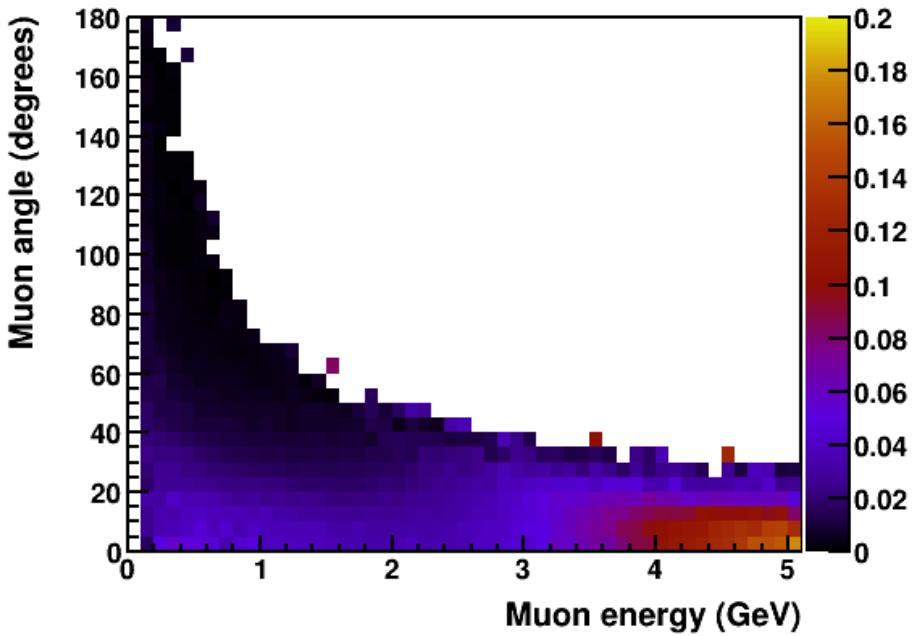


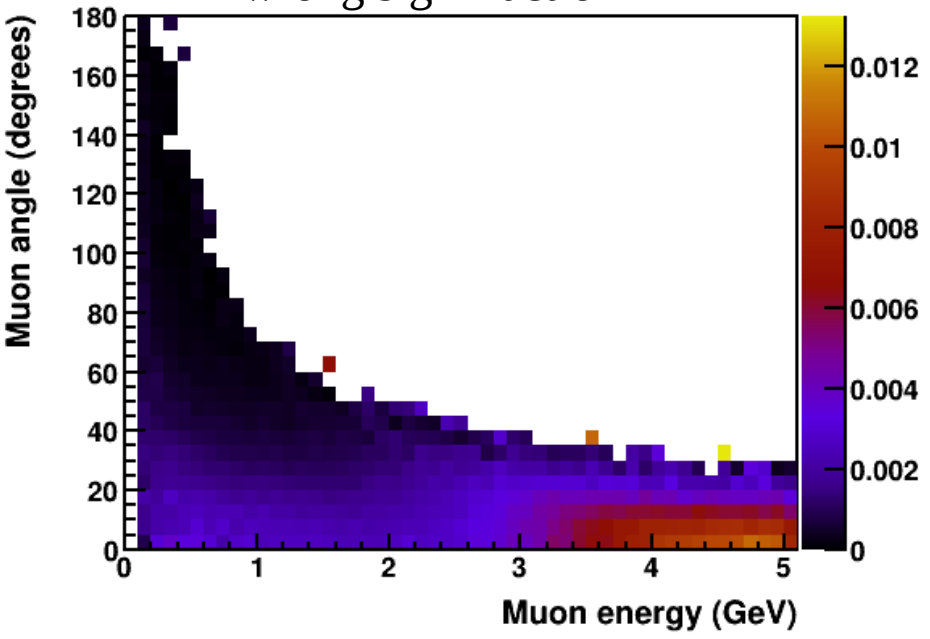
- SSRI covers forward region above ~1 GeV muon energy and up to 5 GeV
- Low-energy, high-angle region where muons are all contained has very tiny wrong-sign fraction in FHC

Wrong sign fraction

Wrong sign fraction



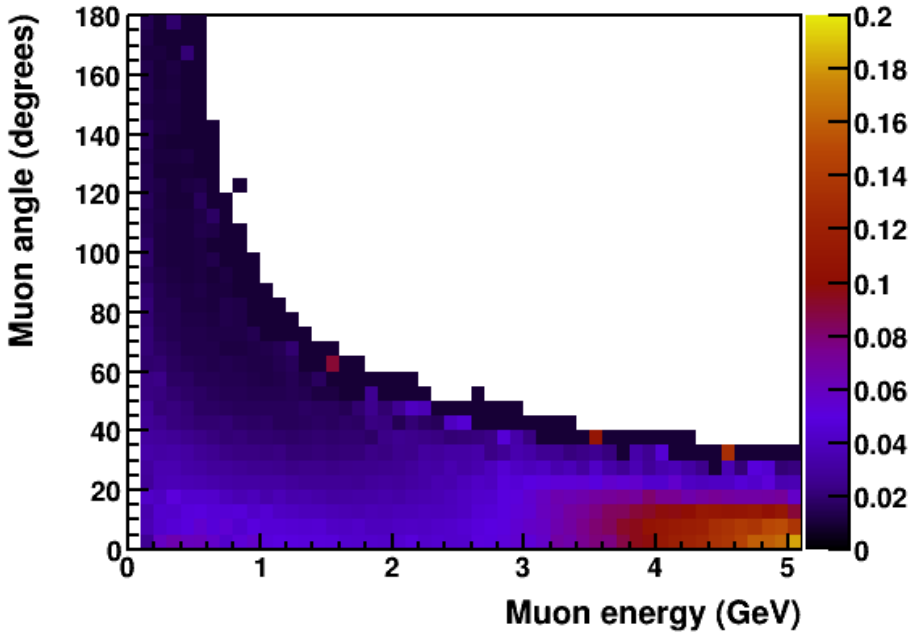
(Absolute) uncertainty on wrong sign fraction



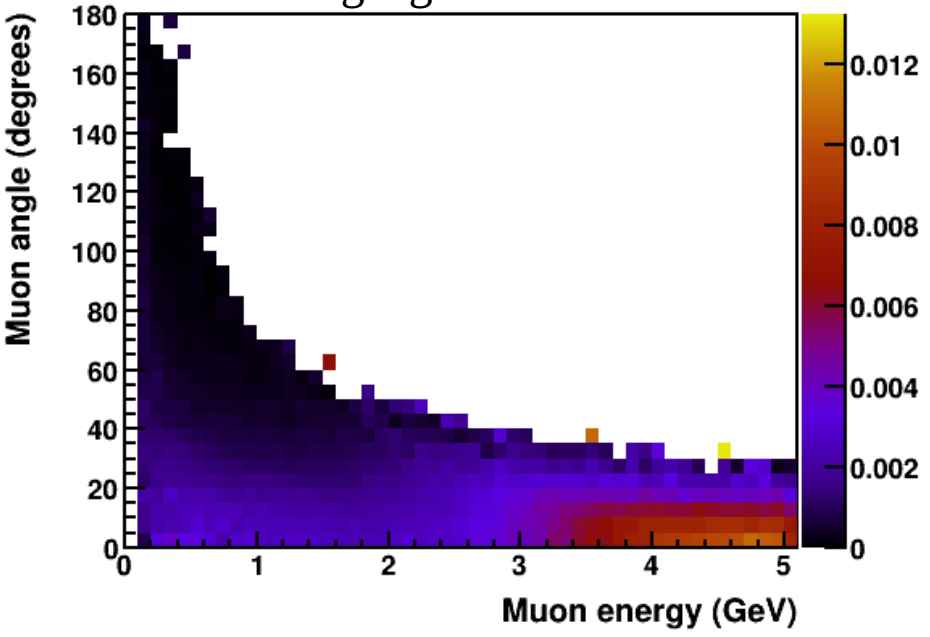
- There is very little shape in the fractional uncertainty on the wrong sign fraction
- In the peak region, the uncertainty is 0.002, i.e. the wrong sign fraction is (3.0 ± 0.2)%

Measured wrong sign fraction

Reco wrong sign fraction
with 1% misID rate



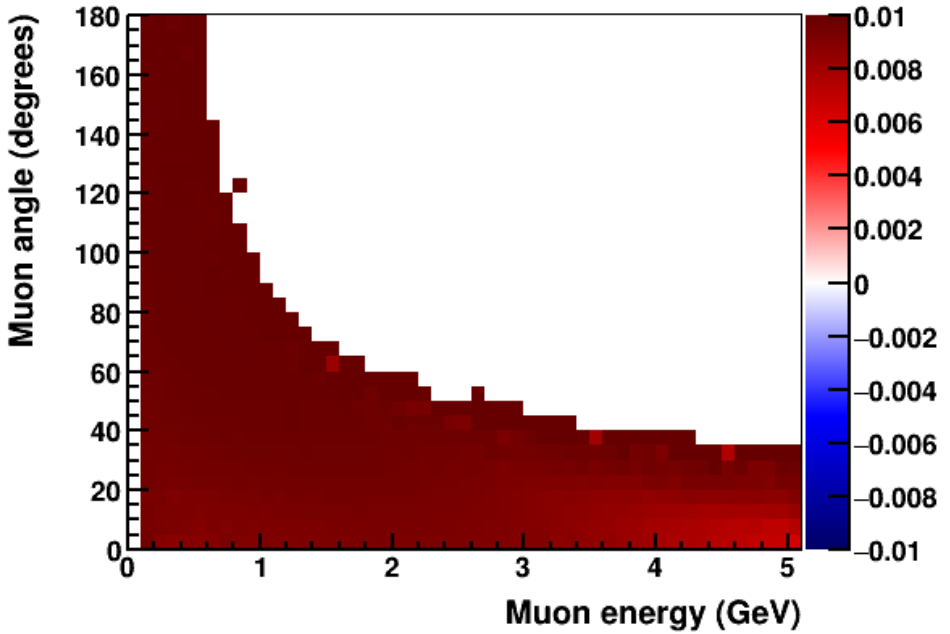
(Absolute) uncertainty on
wrong sign fraction



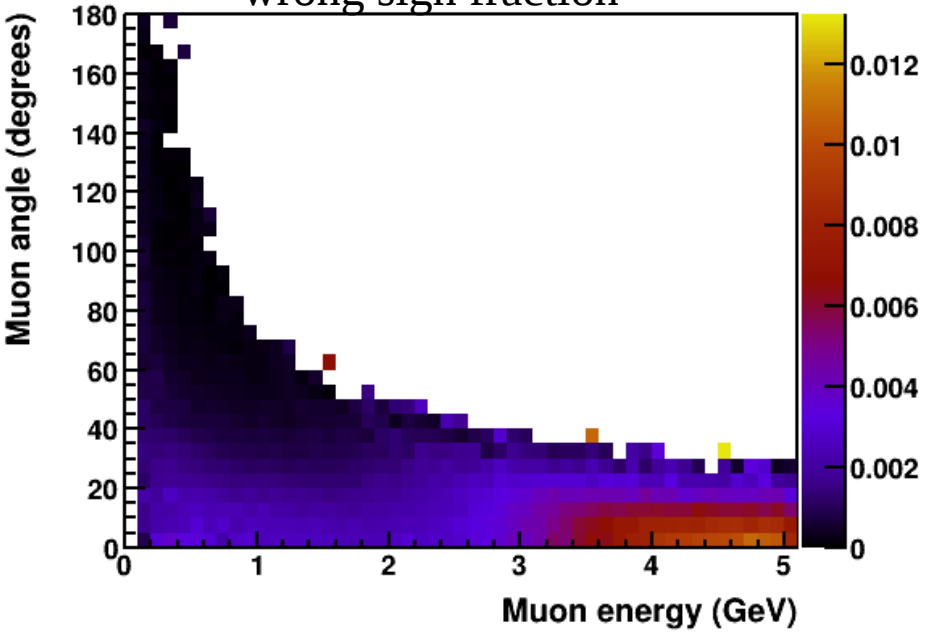
- Measured wrong sign fraction is basically ~1% higher because 1% of true μ^- are reconstructed as μ^+

Effect of 1% misID compared to beam uncertainty

Reco – True μ^+ fraction



(Absolute) uncertainty on wrong sign fraction



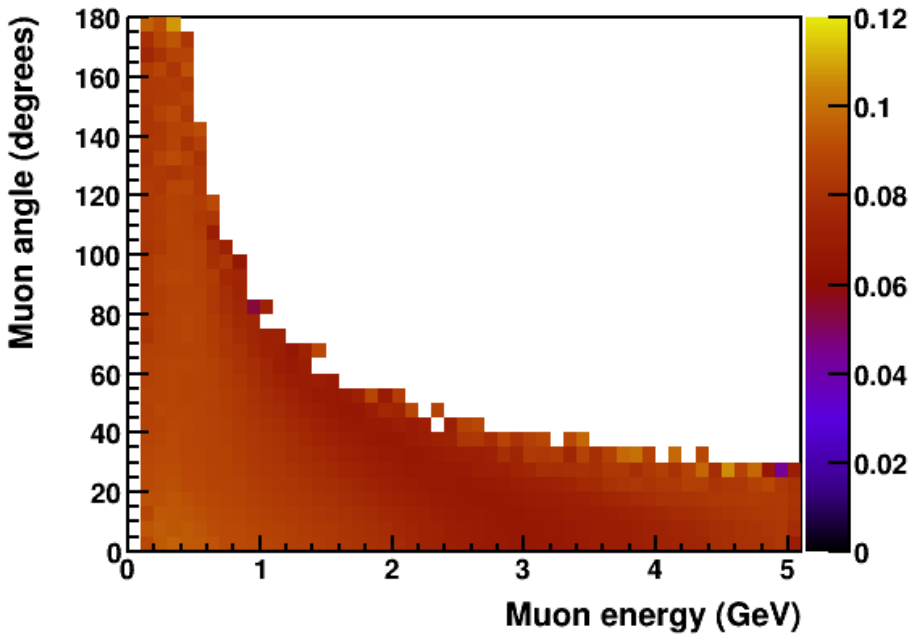
- Measured μ^+ fraction will provide a better constraint than the beam model if mis-ID rate is <0.2%
- Or if you know the 1% mis-ID rate to 20% as a function of muon momentum so that you can correct for the measured

Conclusion: FHC

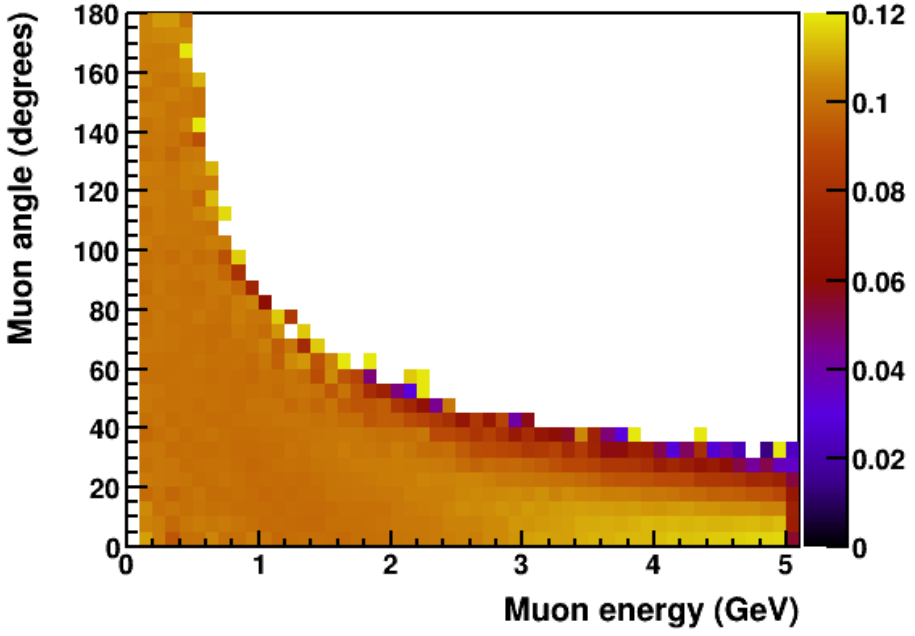
- Providing a more stringent constraint on the wrong-sign fraction that the uncertainty from the beam model requires the uncertainty on the mis-ID rate to be less than 0.2 percentage points
- The impact of this uncertainty on short-term oscillation physics goals, namely MH and 3σ CPV for $\delta = -\pi/2$, is minimal
- Cross-checking the beam model would be valuable, but a constraint at the 1pp level is probably not useful

RHC flux fractional uncertainty

Right sign (antineutrino)



Wrong sign (neutrino)



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RHC event rate

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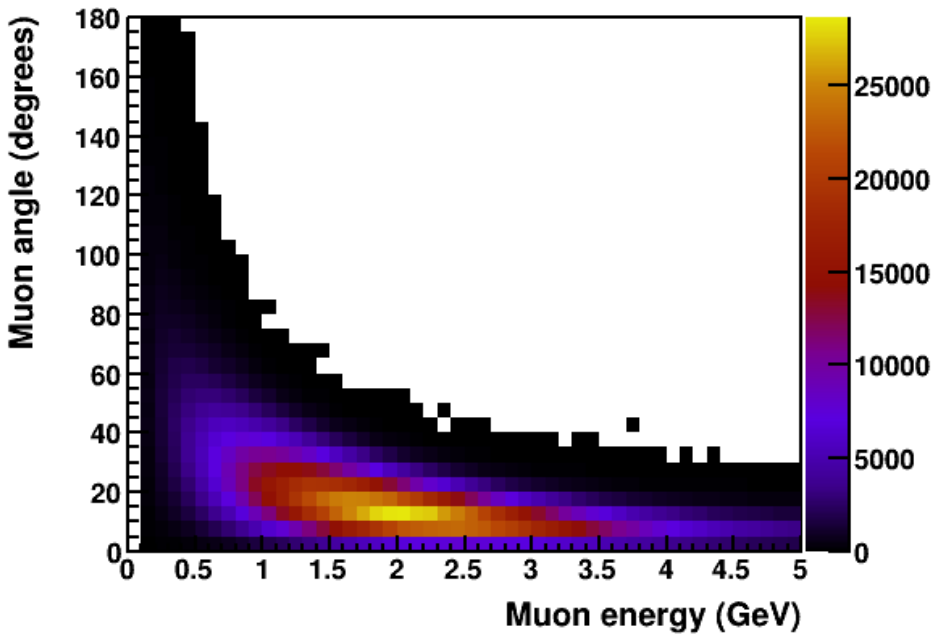

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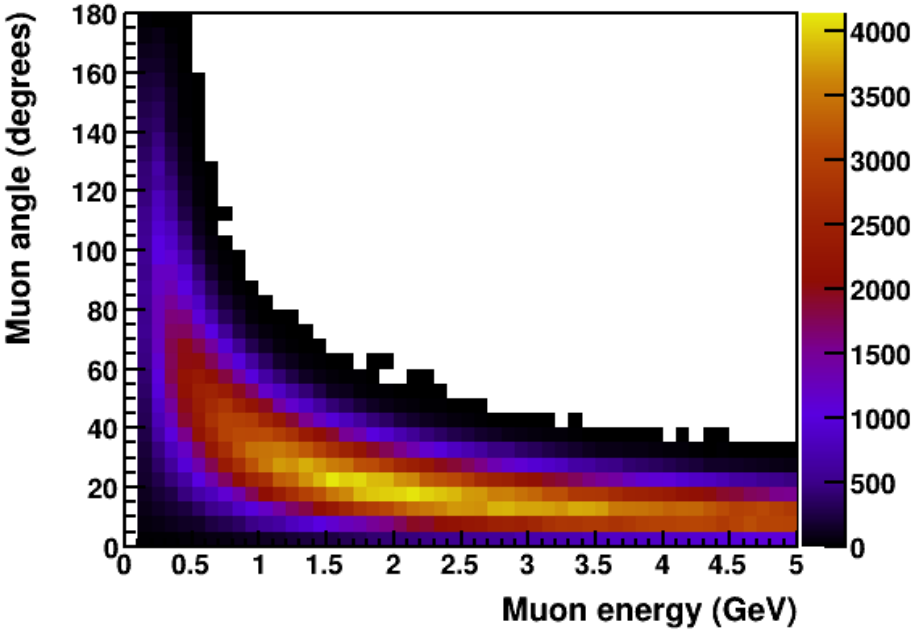
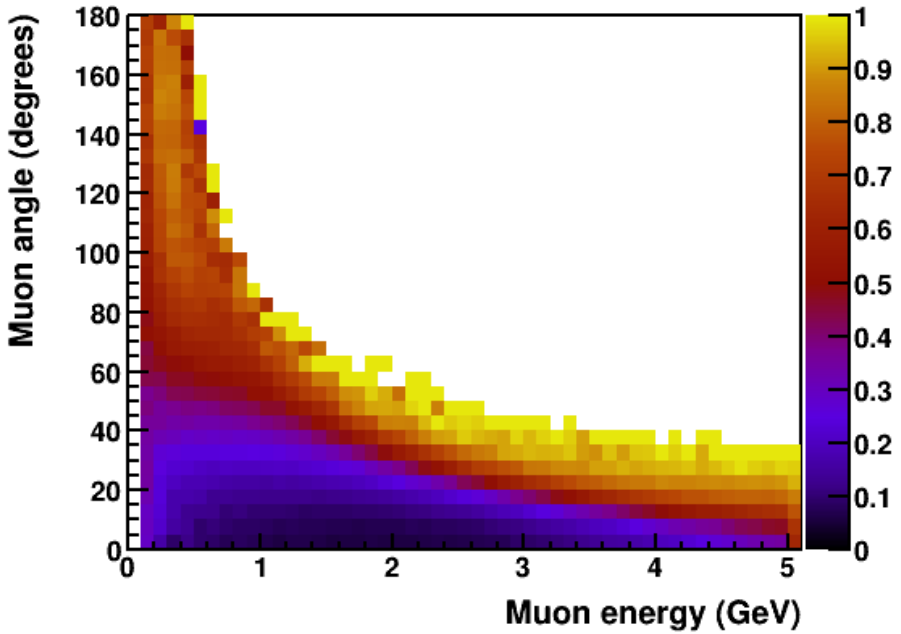


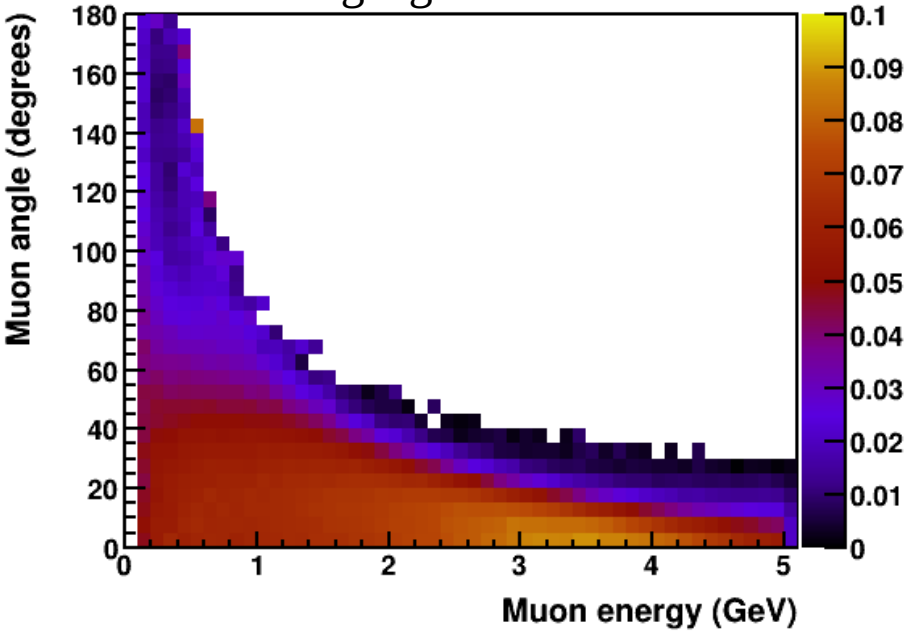
- Compared to FHC, the right-sign events peak at somewhat higher muon energy ~2 GeV, and is more forward, due to the antineutrino cross section
- Wrong-sign neutrinos are less forward

RHC wrong sign fraction

Wrong sign fraction



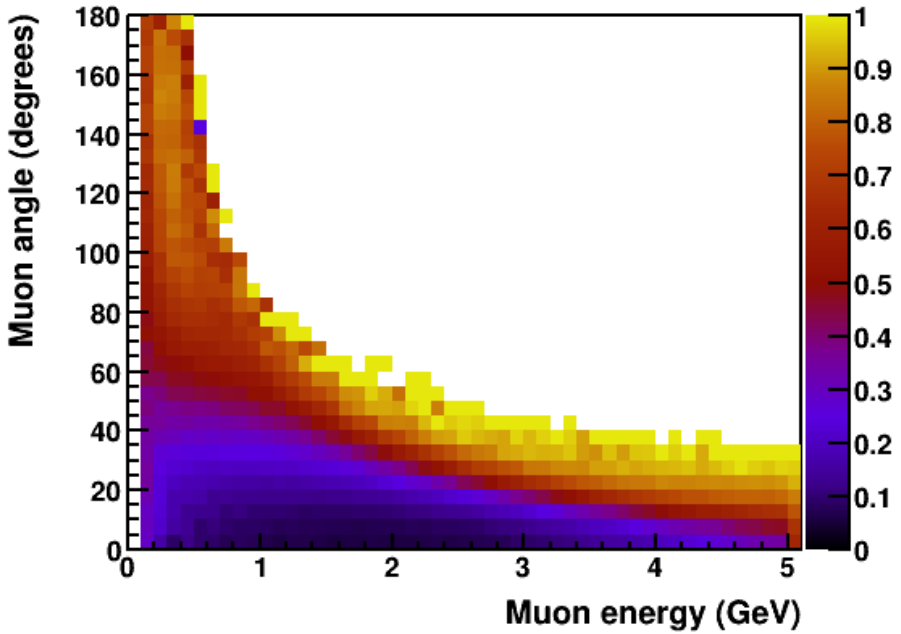
Fractional uncertainty on wrong sign fraction



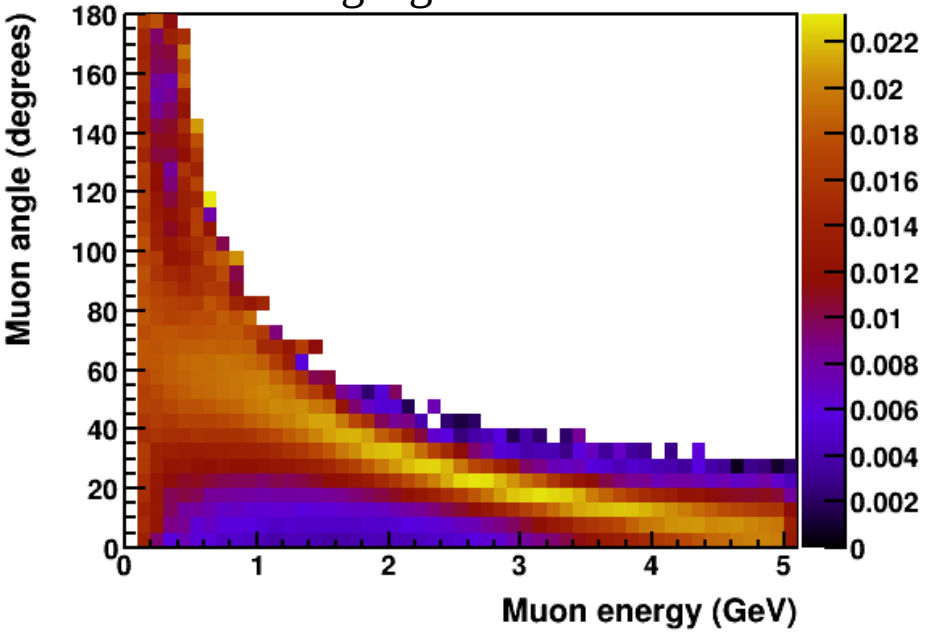
- Wrong-sign dominated at high-y, where cross section differences give mostly neutrino events
- Forward TMS region is >90% antineutrino except at very high muon energy, where flux purity falls to ~50% in the tail

RHC wrong sign fraction

Wrong sign fraction



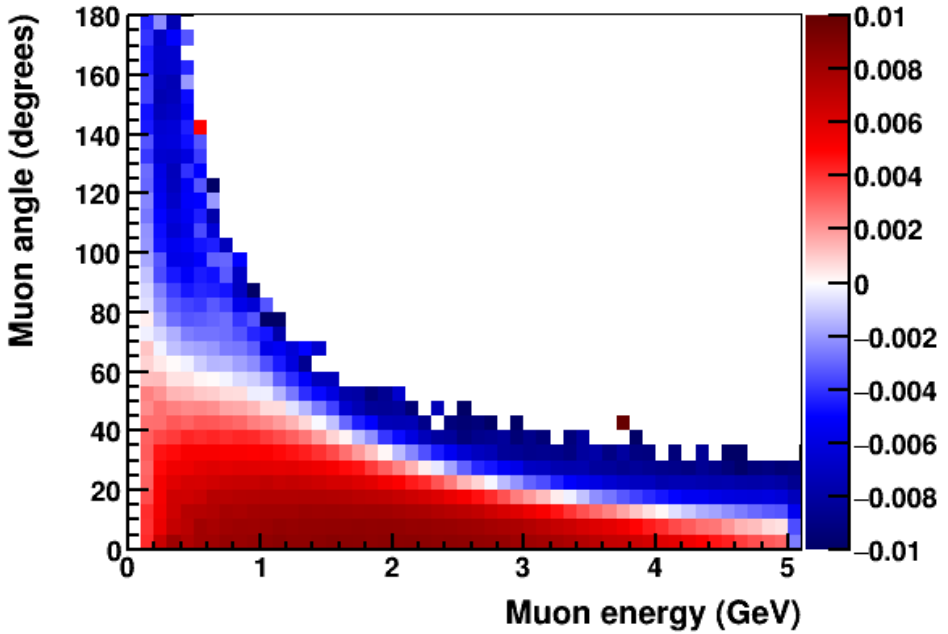
Absolute uncertainty on wrong sign fraction



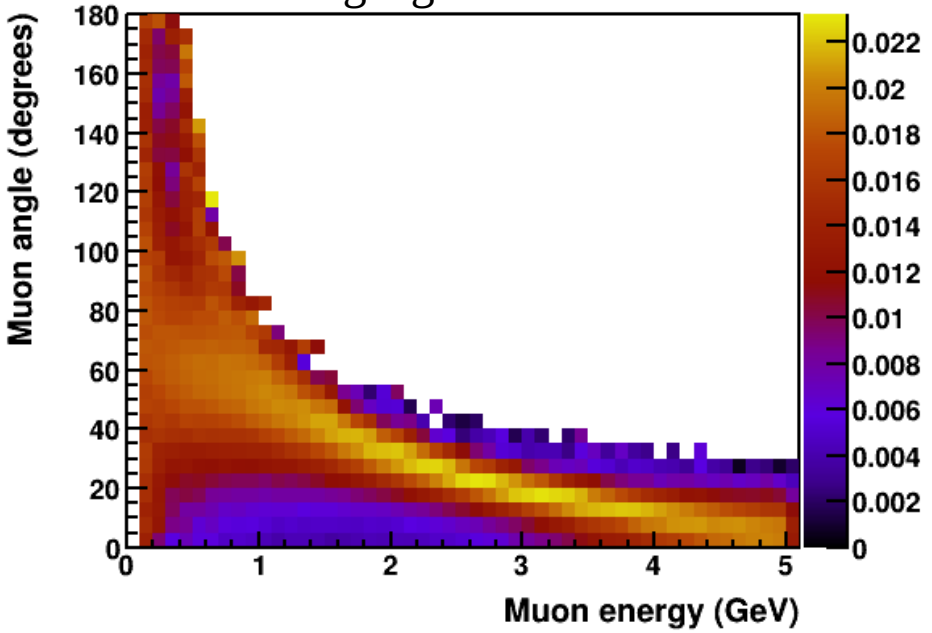
- Uncertainty shown now is absolute on the fraction, i.e. from zero to 2 percentage points
- ~0.5pp in the peak TMS region, but above 3 GeV it is ~2pp

RHC wrong sign fraction

Reco – True wrong sign fraction for 1% misID



Absolute uncertainty on wrong sign fraction



- Effect of 1% misID is larger than the beam uncertainty in the peak (2 GeV, forward), but in the tail from 3-5 GeV the measurement would constrain the uncertainty ~50% beyond the beam model

Conclusion: RHC

- RHC wrong sign fraction is higher at wide angles due to cross section differences, and also at high energy due to lower intrinsic flux purity
- This could be constrained beyond the beamline uncertainty with a mis-ID rate < 2%, or with some calibration so that the mis-ID rate can be corrected, but this would need to be vs. muon kinematics as the underlying wrong-sign fraction (and hence the impact of mis-ID) varies significantly
- It's not clear that this measurement is required – the impact on LBL physics of taking the full beam model uncertainty is minimal if we restrict ourselves to ~3-year analyses

SAND constraint

- In the scenario where SAND is magnetized on day 1, the wrong-sign ratio can be constrained there much better than in SSRI anyway; this would vary off-axis but it's unlikely that SSRI would provide a better constraint than SAND + focusing simulation

Overall conclusions

- If we trust the beam model prediction of the wrong sign ratio and its uncertainty, then SSRI is not going to constrain the wrong sign flux meaningfully in FHC, and could provide a constraint that is ~50% better than the beam model in RHC
- The impact of eating the full beam model uncertainty on the early-stage analysis (CPV at 3σ for maximal δ) is tiny