ND Key Requirements

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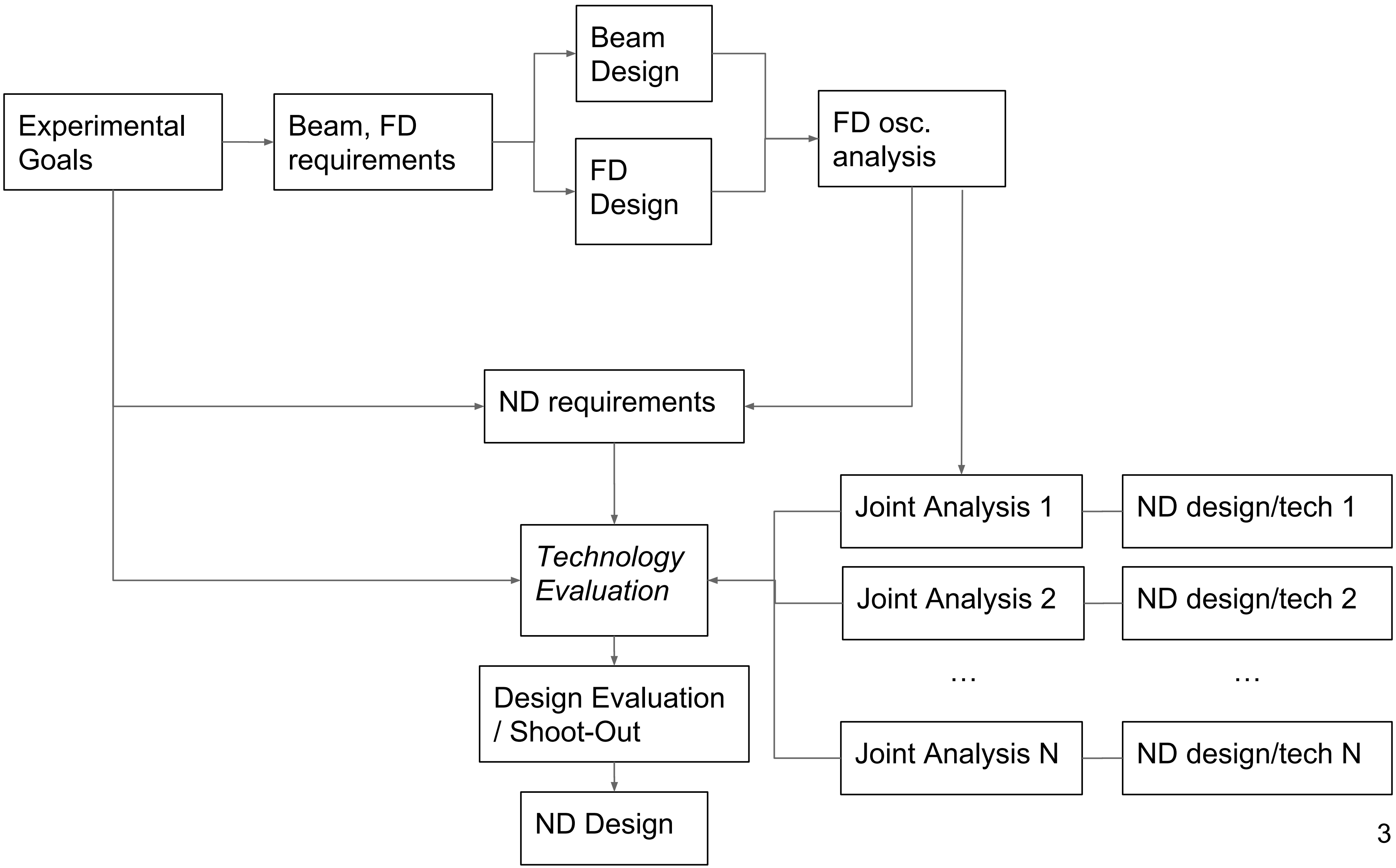
Abstract

- How I think of this process
- What is a requirement?
- Some starting requirements

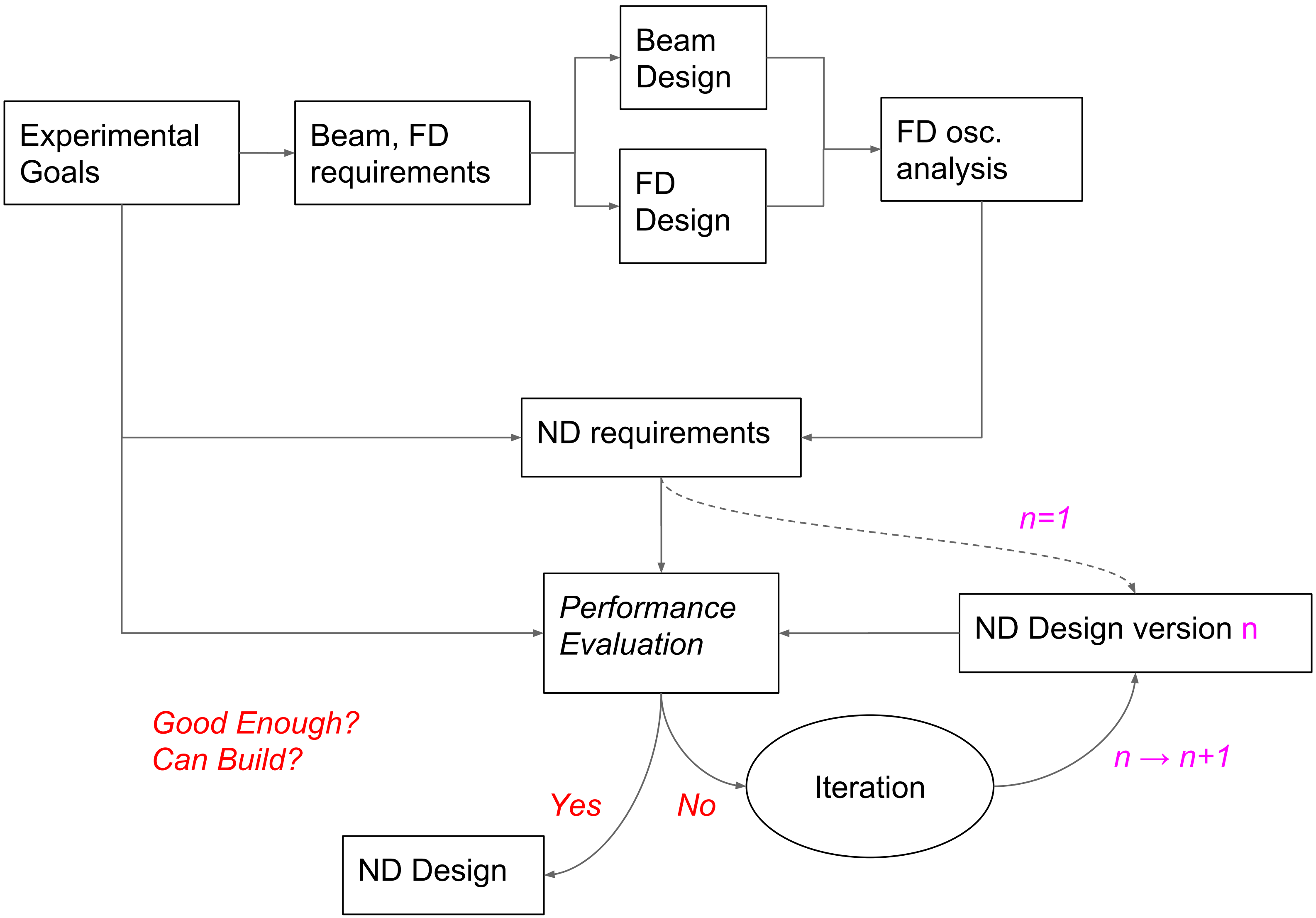
Deciding on an ND design: Method A



Comments on method A

- Similar to the NDTF process
- But, NDTF process was focused on developing the tools to do the joint analysis
  - Simulation of technologies
  - Reconstruction (cheated or not)
  - Joint FD & ND analysis
- My take:
  - The various ND technologies all look reasonably capable
  - But have different strengths and weaknesses
  - Rather than a shoot-out, we need a synthesis, evaluation and iteration

Deciding on an ND design: Method B



Comments on method B

- "You have to start somewhere"
  - Based on the NDTF and our own judgement we can come up with an n=1 design
  - Implement it, study it, and improve
- Evaluation procedure is grounded in physics
  - But could include practicalities
- In reality the evaluation procedure and iteration from n→ n+1 seems unlikely to be a rigid process
  - Potential refactorization of the requirements as we learn more about ND performance
  - Evaluation procedure itself might vary.
    - Evaluating one or a few or different performance metrics each iteration
    - Increasing realism/detail/complexity over time?

Key requirements - an outline

- **Requirement:** What is it?
- **Purpose:** What role does it serve?
- **Precision:** How well must we do it?
- **Detector Requirements & Methodology:** What sort of detector is required? How is the measurement made? What are the significant issues (rates, reconstruction, background,etc) that the measurement encounters?

Requirement: What is it?

- Physics requirement: generally a measurement or collection of related measurements or capabilities.
  - Ability to measure process X as a function of some variable(s)
  - Inclusive or exclusive event rates.
  - Inclusive or exclusive cross-sections.
  - Fluxes.
  - ...
- Also, perhaps, operational concerns?
  - Uptime? Location? Movability?

Requirement: What level?

- A facile requirement: “The ND must enable the FD to establish CP violation at N-sigma.”
  - Of course, but unspecific & unproductive.
  - Needs factorization
- A myopic requirement: “The ND must measure <some exclusive channel> with X precision.”
  - Maybe, but it will be hard to fill in the the full phase space of ND requirements at this granularity.
  - Even if we could, it’s hard to evaluate all of them and iterate.
- Need something in between
  - general requirements on the ND performance using our best judgement

Purpose: What role does it serve?

- Why do we need to make the measurement?
- How does it fit into the oscillation analysis?
- Implies a procedure to digest & include ND measurements in the analysis
  - Fitting models to ND data
  - Direct extrapolation procedures ND $\rightarrow$ FD

An aside: Model Fits vs Direct Extrapolation

- **Model fits:**
  - Like T2K. Good when ND and FD detectors are sufficiently different. Also pursued by MINOS early on.
  - Model of fluxes and cross-sections tuned with ND data
  - Tuned model then predicts event rates at FD as a function of oscillation probabilities.
  - Errors propagated via covariance matrix among energy bins, or nuisance parameters, or parameter shifts in FD ("star plot").
  - Drawbacks: Too complex? What if your collection of models cannot fit the data? Do all features of the data need to be fit with a model to do the oscillation analysis?

An aside: Model Fits vs Direct Extrapolation

- **Direct extrapolation:**
  - Like MINOS and NOvA. Good when ND and FD detectors are sufficiently similar.
  - Event samples (one or a few) are propagated to the FD "directly"
    - Ex: unfold sample → multiply by FD/ND ratio or matrix → oscillate → smear → include in fit
  - Can help cancel common uncertainties directly, even ones without a model → Ex: initial state nuclear effects, detector effects
  - Drawbacks: Too simple? Overly model dependent? The FD and (similar ND) don't have the resolution/capability to recognize systematic effects?

An aside: Model Fits vs Direct Extrapolation

- **A hybrid model?**
  - ND has a “hi-res” subsystem that is capable of measuring neutrino interactions with higher detail than FD.
    - Large acceptance, good identification of the final state. Gas TPC, FGT, possibly scintillator.
    - Enables model tuning, understanding processes that the FD cannot recognize.
    - Good kinematic acceptance.

An aside: Model Fits vs Direct Extrapolation

- **A hybrid model?**
  - And a subsystem that is as similar as feasible to the FD.
    - An LAr TPC of some form. Tens of tons. (think 35t proto).
    - Is it possible to have a calorimeter section inside? Optical readout of scintillator light from sampling sections on the walls?
    - Enables a (perhaps imperfect) direct extrapolation.
    - Possible cancellation of nuclear / detector effects.
    - Direct extrapolation aided by hi-res model tuning → but, perfection probably not required.

Precision: How well must we do it?

- Driven by the needs of the oscillation analysis.
- Implies a process to evaluate the effect of the precision of this measurement on the oscillation analysis. Examples:
    - Translating systematic effects from other experiments.
    - Redoing a mock oscillation analysis with and without the measurement.
    - Redoing a mock analysis with varying precision.

Detector Requirements & Methodology:
How do we do it?

- How will the measurement be made?
- What statistics and backgrounds?
- Effect of systematics on the measurement?
- Two ways of looking at this:
    - Given the need to do the measurement, what detector system is needed?
    - Given a particular detector system, can it do the measurement?

Some starting requirements

Originated in Alfons's talk at May 19 collaboration meeting

Note: numu also implies numu-bar

1. Rate of numu-CC vs energy
2. Shape of the numu flux vs energy
3. Absolute normalization of the numu flux
4. Rate of beam nue vs energy
5. Constrain numu-CC and NC background to nue-CC
6. Constrain the cross-section ratio: nue-CC / numu-CC

Rate of numu-CC vs energy

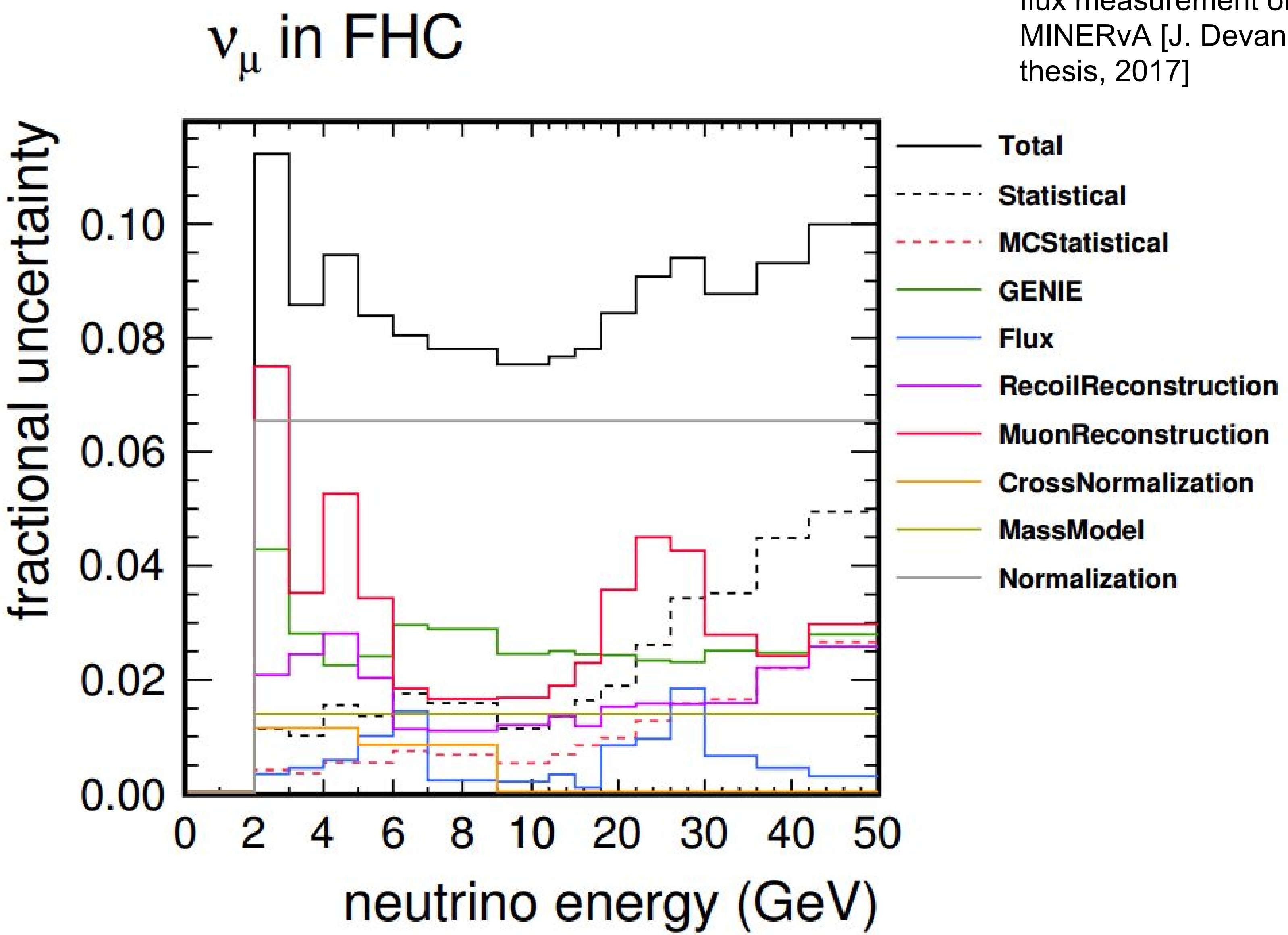
- **Purpose:** We must measure this foundational sample which "disappears" and oscillates to nue.
- **Precision:** Unclear; *a priori* F/N uncertainty from flux model is < 2%. Would like ND smaller → 1%?
- **Detector Requirements & Methodology:**
  - Should be on Ar to constrain nuclear effects.
  - LAr could, depending on size, help with constraining measurement of Ehad in the FD.
  - Should have a kinematic acceptance equal or better than the FD. Could be difficult to achieve with a smaller ND. Likely motivates both an LAr and hi-res detector.

Shape of the numu flux vs energy

- **Purpose:** Disentangle flux and cross-section. Provide a constraint on the a priori flux model prediction of F/N.
- **Precision:** Unclear; 3% for following discussion
- **Detector Requirements & Methodology:**
  - Low-nu method. Forward muon and low nu=Ehad.
  - High statistics and good resolution at low Ehad helpful in enabling a single nu cut
  - Could probably be done in a LAr TPC, given previous experience. Unclear if hi-res measurement (with lower statistics) needed.

Thoughts on low-nu precision

Uncertainty on the low-nu flux measurement of MINERvA [J. Devan thesis, 2017]



Thoughts on low-nu precision

Uncertainty on the low-nu flux measurement of MINERvA [J. Devan thesis, 2017]

- Say we have a 3% target on the flux shape below 5 GeV.
- Ignore normalization. Biggest uncertainties are due to muon energy scale : Ehad energy scale : GENIE.
- I read those as 5.0% : 2.5% : 3.0%
- We need to get each to 1.7% since 3.0%=sqrt(3*1.7%)
- Muon energy scale uncertainty itself is 2-3%
  - 5%/1.7% ~ 3 so the muon energy scale uncertainty would need to drop to **⅔ - 1%**. This is a tough sounding requirement.

Thoughts on low-nu precision

Uncertainty on the low-nu flux measurement of MINERvA [J. Devan thesis, 2017]

- Uncertainty on the flux due to hadron response is 2.5%
  - Want to get this to 1.7% → 2.5%/1.7% = 1.5
- Hadron energy uncertainties
  - 10% (15%) for numu (numubar) at low energy (few 100 MeV)
  - 6% at high energy (10 GeV)
  - This is a combination of the uncertainty on protons:neutrons:pi+/-:EM of 10%:15%:6%:3%
  - At lower energies and lower nu cuts (our region of interest) most of the energy is carried by nucleons. 10%/1.5 = 6.7%, so you would like to get the uncertainty on the proton energy scale to be less than ~7%

Thoughts on low-nu precision

Uncertainty on the low-nu flux measurement of MINERvA [J. Devan thesis, 2017]

- The GENIE uncertainty is complicated, but most of the uncertainty in the few GeV region comes from the RPA and MEC models.
- We would need to get that down by a factor of 3/1.7=1.8 (i.e, shrink it to 1/1.8 = 57% of its current value).
    - Assessing this is pretty hard for me! It seems doable though as there has been a lot of recent progress. Plus the DUNE ND will likely be more capable of measuring these effects than e.g., MINERvA.

Absolute normalization of the numu flux

- **Purpose:** Provide reference to normalize the flux shape. Constrain the *a priori* flux simulation.
- **Precision:** Assume 3% for discussion, a number that appears in the CDR v2, ch6.
- **Detector Requirements & Methodology:**
  - nu e → nu e scattering
  - Statistical uncertainty of 3% requires 1000 events. Better to have 10x this number.
  - MINERvA systematics =5.1% from a variety of sources

Source	Fractional Uncertainty
Flux (simulated background)	0.2%
GENIE (not including CCQE)	2.3%
CCQE shape	3.1%
Beam angle	0.2%
Electromagnetic energy scale	1.8%
Reconstruction Efficiency	2.7%
Total Systematic Uncertainty	5.1%
Statistical Uncertainty	12.2%

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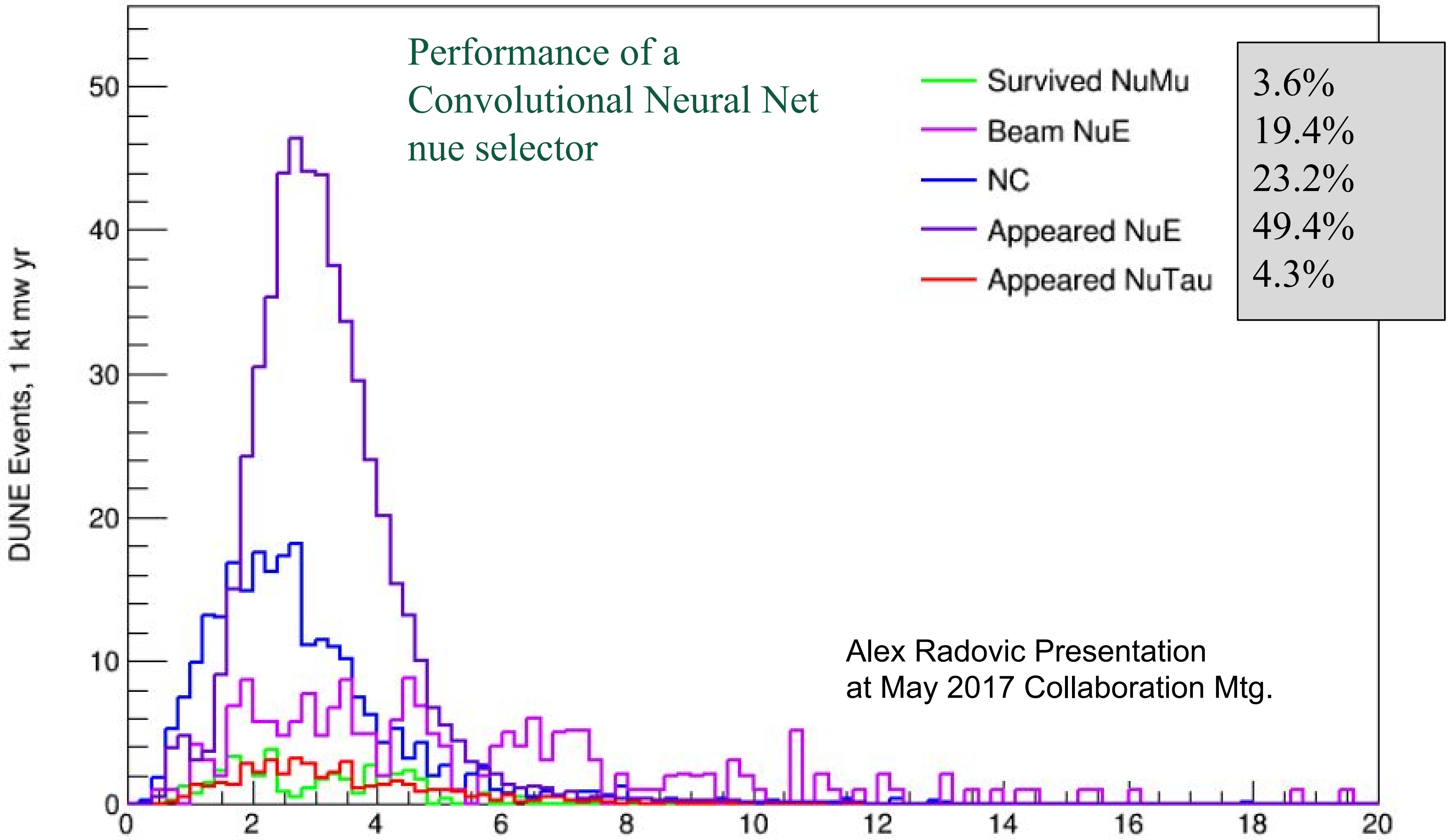
Rate of beam nue-CC vs energy

- **Purpose:** This is a major irreducible background to the nue appearance measurement
- **Precision:** CDR v2, ch3 says 5%
- **Detector Requirements & Methodology:**
  - Should be on Ar to constrain nuclear effects.
  - A reasonably sized LAr ND will have similar containment as the FD, especially for the lepton.
  - Statistics are not a problem for a reasonable LAr ND
  - Seems possible to get some detector systematics cancellation.
  - How do you know if you are measuring beam nue rather than backgrounds? → having this measurement in the hi-res detector is useful.
  - Numu flux constrains nue → needs a study

Constrain numu-CC and NC backgrounds to nue

- **Purpose:** These are major backgrounds to nue appearance. They include events with neutral pions and photons.
- **Precision:** CDR v2, ch3 says 5%
- **Detector Requirements & Methodology:**
  - Should be on Ar to constrain nuclear effects.
  - A reasonably sized LAr ND will have similar containment as the FD, especially the photons.
  - Statistics are not a problem for a reasonable LAr ND
  - Seems possible to get some detector systematics cancellation.
  - Seems essential to have a hi-res detector which can distinguish these channels better, and with different systematics, than an LAr detector

numu-CC and NC backgrounds to nue



Discussion?