On the proposed LBNF Spectrometer: Justifications & Concept.

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Context: The LBNF neutrino beam,

and the LBNF Spectrometer

We proposed a direct measurement of the neutrino's progenitor flux (pions, kaons, muons) in a replica of the real LBNF chase in order to constraint the uncertainties in precision studies of neutrino oscillation.

- This measurement could be done at a Fermilab Fixed target beamline, using spare “hot spare” parts for the target/focusing components and existing technologies for the spectrometer.

Disclaimer/Intro

This disclaimer informs readers that the views, thoughts, and opinions expressed in the text belong solely to the author, and not necessarily to the current Nova/NuMI/Minos proponents, not DUNE/LBNF.

However, we (Laura F., Alberto M., …) had strong support from the LBNF/DUNE in pursuing the work in (I) strengthening the physics case and, (ii) articulate the concept for it.

- I'd like to thank the convener of this forum for having the opportunity to do so.
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- I also acknowledge the input from Laura Fields, my co-conspirator. I borrowed heavily on the very complete talk she presented to the NA61-2020 workshop, CERN, July 28 2017.

What the LBNF spectrometer (LBNFS) is not:

A replacement for the DUNE/LBNF Near Detector. While LBNFS is a good tool to determine the neutrino flux at ND and FD, it tells us nothing about neutrino cross-sections, by fiat.

- **A complicate add-on to the real LBNF chase.** An implementation in-situ of a complete spectrometer (tracking, momentum determination and particle id) has been found to be very costly (requires yet an other extension (longitudinal & transverse!) of the chase, and new chase modules to extract and insert the spectrometer. ==> go “ex-situ”

- **A side-show to an existing Fixed target experiment.** ~ one percent precision in the systematic uncertainty in a any single particle flux measurement is difficult. Not a good idea to start with constraint. Let us propose a dedicated design.

What LBNFS brings to DUNE ?

A global cross-check on the determination of the ν oscillation parameters, and related physics. Can we really assert with 100 % confidence that the ND, and our g4lbnf code, will be good enough to reach our stated goals ?

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- *What do I mean "related physics? "*. Mostly, NSI...That is cross-check of the consistency of our integrated analysis of the PMNS matrix. But I acknowledge the nostalgia for 1969 cultur(s) (medium energy particle physics with neutrino)

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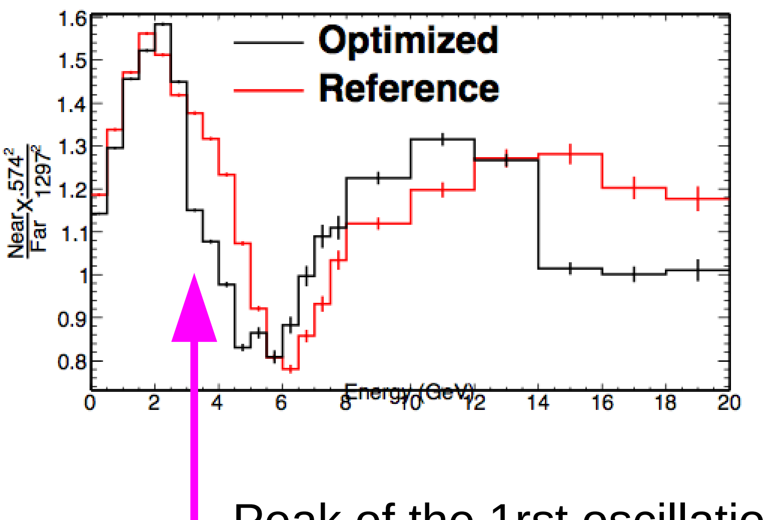
Why do I mention the dread-full MC ?

ND alone is not good enough..

- The ND/FD ratio does depend on the neutrino energy.
- In a non-trivial way: focusing effect and phase space density of the neutrino's progenitor matters
- Different for signal and background.

Range : 0.8 to 1.6



Peak of the 1rst oscillation

Credit: Amit Bashyal

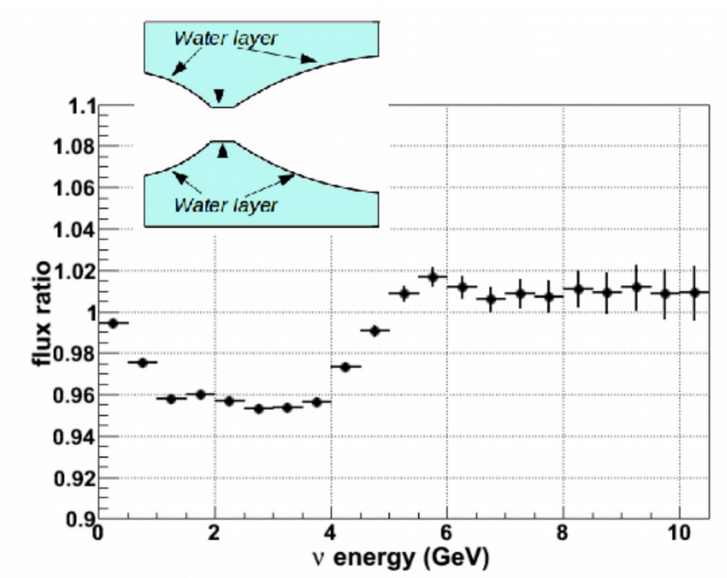
(Dune Docdb 4178)

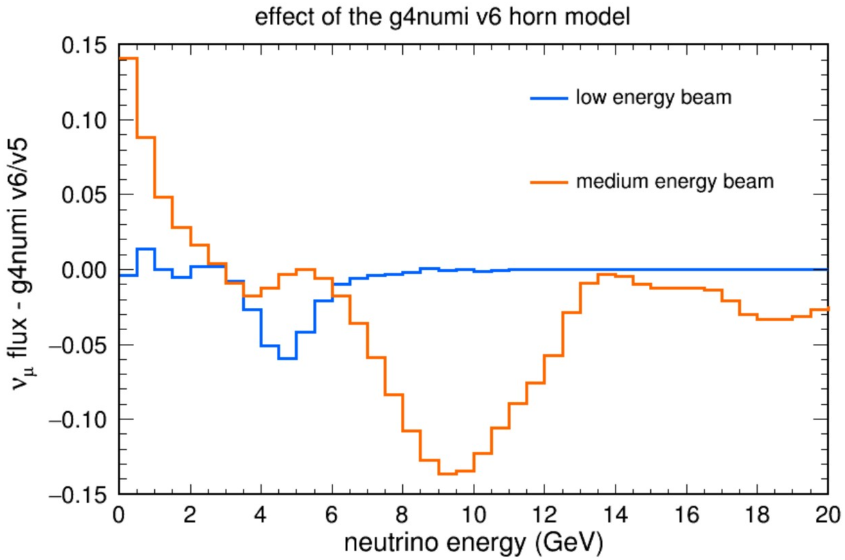
G4LBNF Uncertainties.

- “Focusing Uncertainties”. How well can we model the components of the Chase.
- How well can we model the hadronic interaction in such a complex environment?

Learned lessons from G4NuMI

Two **recent issues from NuMI beam simulation**: omission of cooling water layer from simulation, and simplified horn shape model





MINERvA plots from L. Aliaga, Fermilab JTEP, Dec 2015

… expected uncertainty for LBNF only ~3% … But!...

… More recent work on G4LBNF/G4NuMI

Prompted by studies of a comparison of the observed neutrino interaction rate in MINOS and Minerva detector, NuMI “Low Energy” vs “High Energy” configuration..

At a given energy, using the same detectors, these interaction rates don't quite agree within expected systematic uncertainties … (stay tuned).. (No, I do not have yet a reference..)

==> New round of G4NuMI studied, with code borrowed from G4LBNF. Example, a preliminary study of the magnetic field distortion due to the finite length of the downstream current equalizer section, and, the ….

… What if the measurements of $\sin^2\theta_{23}$ does become significant?

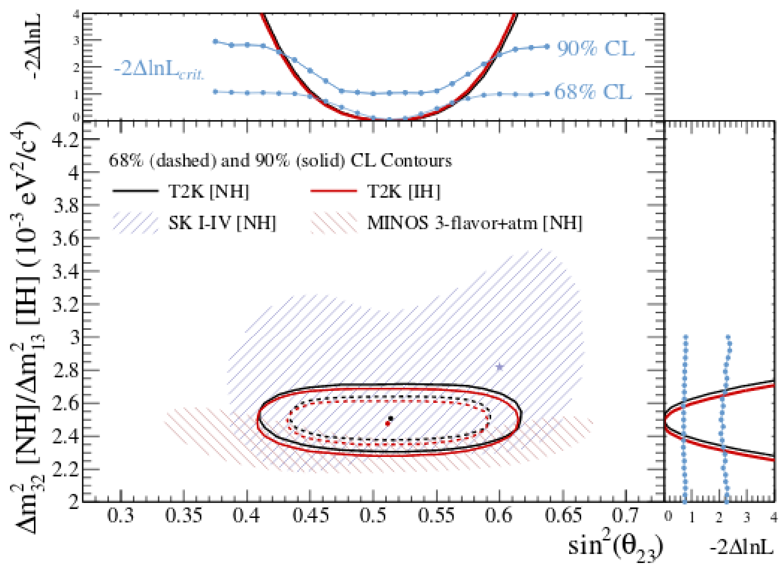
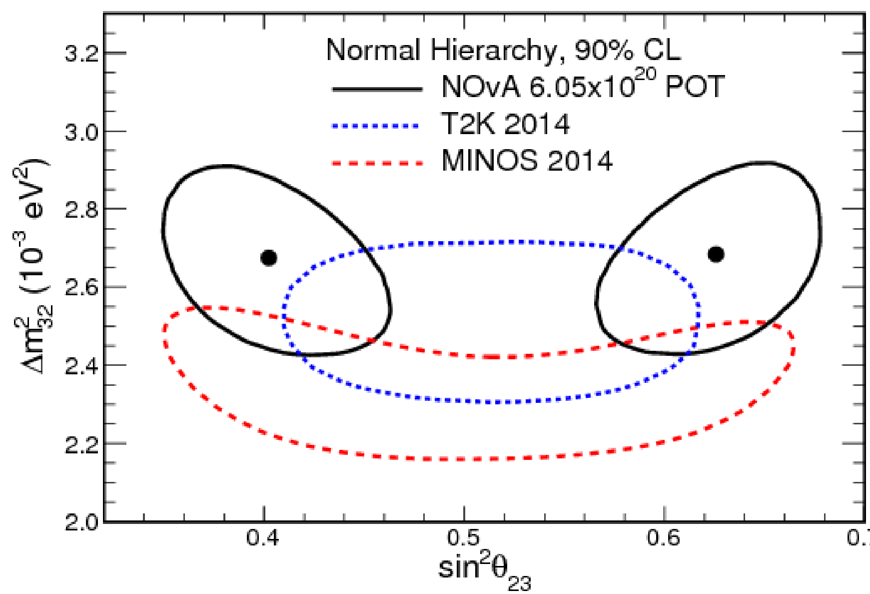


FIG. 3. The 68% and 90% C.L. confidence regions for $\sin^2(\theta_{23})$ and Δm^2_{32} (NH) or Δm^2_{13} (IH). The SK [49] and MINOS [7] 90% C.L. regions for NH are shown for comparison. T2K's 1D profile likelihoods for each oscillation parameter separately are also shown at the top and right overlaid with light blue lines and points representing the 1D $-2\Delta\ln\mathcal{L}_{\mathrm{critical}}$ values for NH at 68% and 90% C.L.



For now, probably at tempest in a teapot,
But the statistical uncertainties will improve.

G4LBNF Uncertainties.

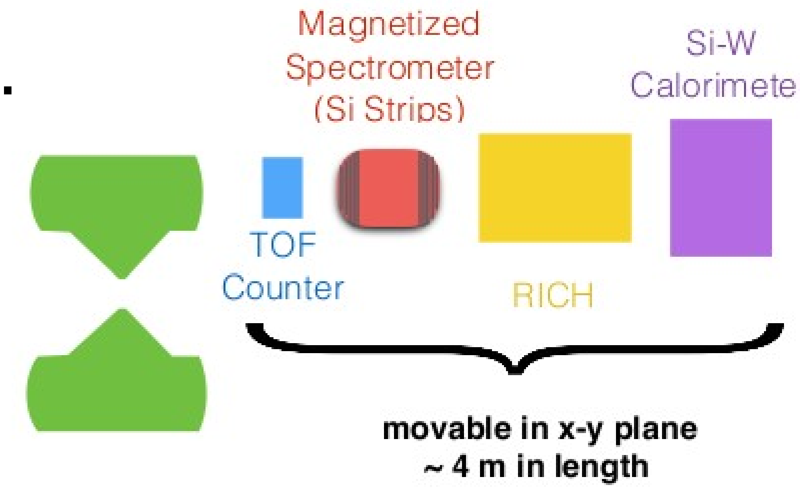
- “Focusing Uncertainties”. How well can we model the components of the Chase.
- How well can we model the hadronic interaction in such a complex environment?
- Focusing/Hadronic: don't always “factorises”: one hadronic uncertainty may be more important given known unknowns in the Geant4-based geometry.

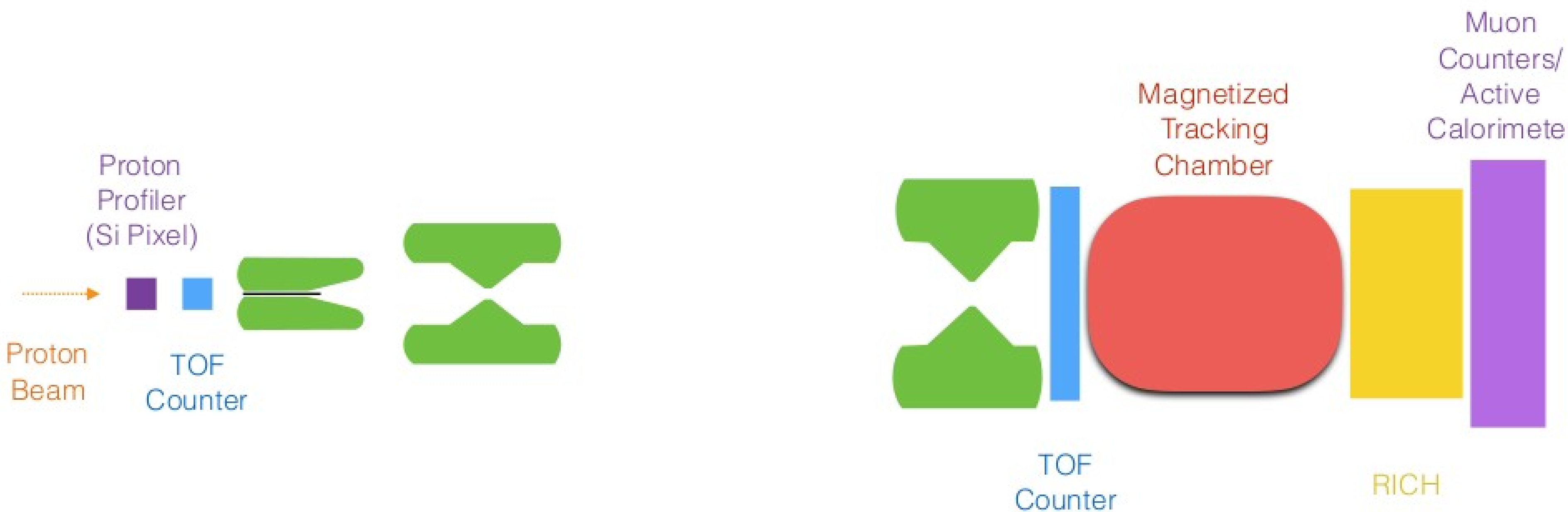
A direct measurement of the ν progenitors

- We know how to decay hadrons and muons... And...
- Hadronic interaction in the decay pipe volume (Helium) and walls are a 2^{nd} order correction. (i.e., much smaller than similar uncertainties in the target and inner conductor's horns)
- So, the LBNF Spectrometer is not a replacement for the G4LBNF package (or FLUKA-LBNF), it is an opportunity to X-check in details the flux predictions, and constraint it to ~ 1 to 2%. (a difficult, but realistic goal).

The LBNF Spectrometer Concept, “Ex-situ”

Different architectures possible...





Credits: Laura Fields

Evolution of the conceptual design.

- A movable, small aperture (3” x 6”, fiducial, easy Si tracking with limited material in this aperture), single arm spectrometer reduce capital cost, but could increase running time..more on this later.
- However, a small aperture magnet drives the background into the downstream tracking planes, and the RICH to unacceptably high level.. (full G4 simulation).
- ==> Use an existing large aperture magnet, but a small aperture tracking system (an Particle ID). This is the basis for the current architecture...

Rate: A drawback of the small aperture LBNF-Spectromer.

- We will need to make many measurements of the hadron flux: Misalignment studies, targets (plural), study systematic uncertainties in the LBNF-Spectrometer itself..
- In little time: Using spare equipment!
- Goal : one complete scan of the ~ 1.6 sq. meter (~ 100 to 200 spectrometer position) of the HornC downstream aperture, **in a week, real time**
- High Rate Detectors: 40 MHz is a reasonable goal and is achievable
- With very good pattern recognition capabilities, as we are behind 4 interaction length, and some non-negligible number of radiation lengths ==> Plenty of ~ tens of MeV to a few GeV photons. ==> High granulatiry (Si Pixel device, of for RICH, < 1 cm optical sensors.)

LBNF duty cycle:brief introduction

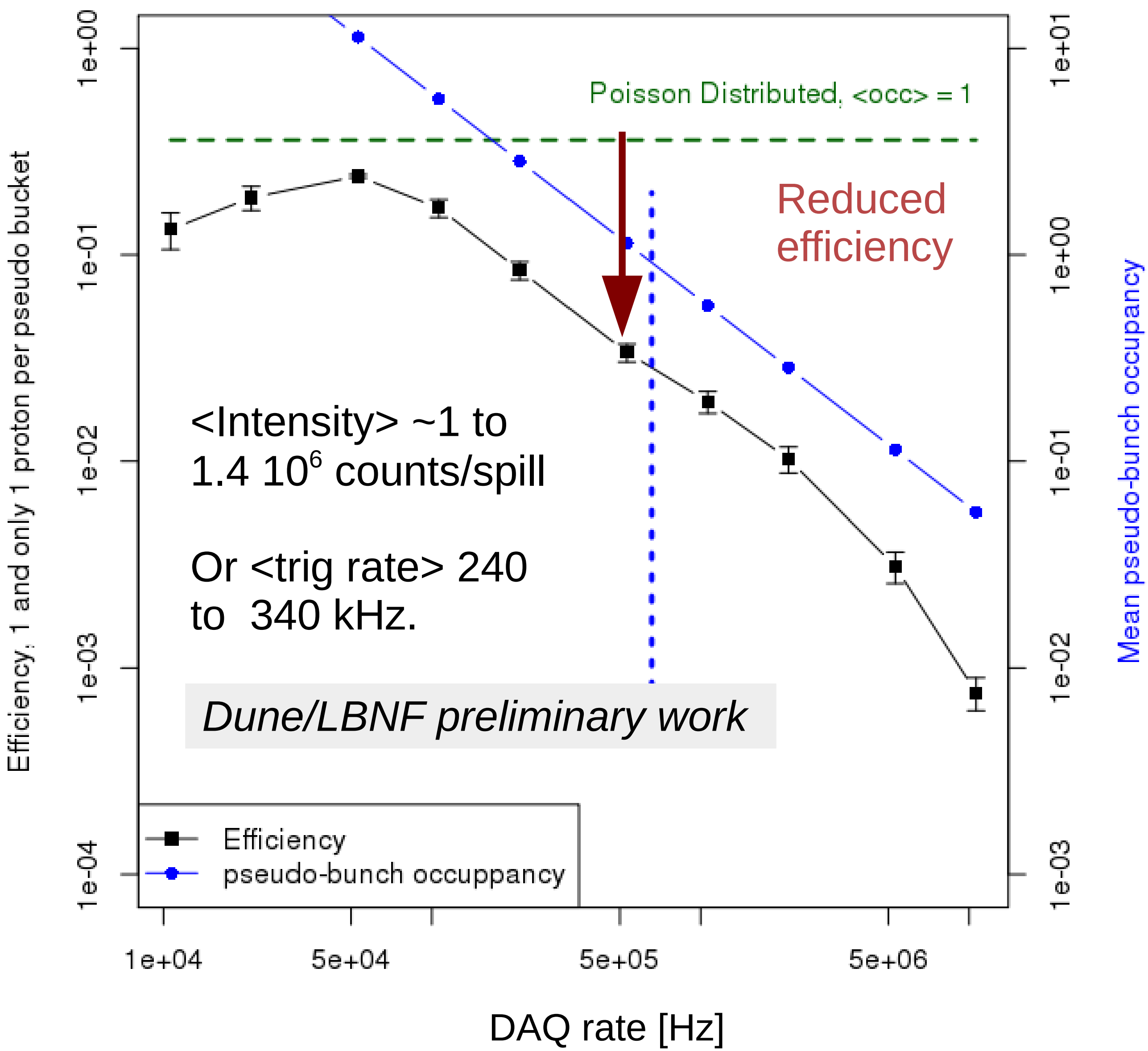
A direct measurement of the neutrino's progenitors, with the target, and the focusing system turned “on” implies a stringent upper limit on the duty cycle of the spectrometer: About $6x5.e^{-5}/60$, or ~ $5e^{-6}$. The first term is the number of pulses per 4.1 second M.I. spill the LBNF power horn power supply can deliver, the 2^{nd} term is the horn pulse duration, at “reasonable” flat top, when we have the near nominal focusing field, and the last term is M.I. fixed target inter-spill duration, 60 secs.

If a statistical precision of ~ 1% for a small aperture which covers only ~1% of the total aperture (1.6 m^2), we need 1 e6 pions. Running at 20 MHz, it will take less than a day to take the data, assuming that (I) one proton per 50 ns long “time unit” (ii) assuming a “perfectly smooth spill”, one proton per time bin ==> only a loss of ~ 36%, based on Poisson statistics.

Is this a correct assumption? As measurement in the Meson test Beam Facility, Fermilab, we could be off by a factor ten.. Remmember, we plan to so such measurement many times..

Summary plot, Spectrometer Efficiency vs DAQ rate capability

Requiring one, one only, incident proton/"pseudo bunch"



Based on NimPLUs profile

The "Rate" is the inverse of the (arbitrarily) chosen "time unit" or "pseudo bunch" duration.

Since the FTBF is limited to ~ 1 10^6 particle per spill, our relevant range of rate is ~20 time lower than what could be done for LBNF Spectrometer.

Yet, the optimum efficiency for "one and only one proton per pseudo bunch" is at lower rate, by a factor 10, or, conversely, at the rate at which the mean occupancy is one, our effective efficiency is 10 ~ times lower then the one dictated by Poisson law.

However,...

The range of frequencies at which these deviations from Poisson law occur is kHz to fraction of 1 MHz,

Likely to be due to ripples in the magnetic elements the implement the resonant extraction system, in the M.I. Not the fluctuation of particle density, bunch to bunch, of Booster batch to Booster batch.

This could be improved upon..We hope.. Clearly more work needed.

Recent Design work.

The Silicon strip tracking system is fairly straightforward, thanks to LHC, and more recently HL LHC R&D effort.

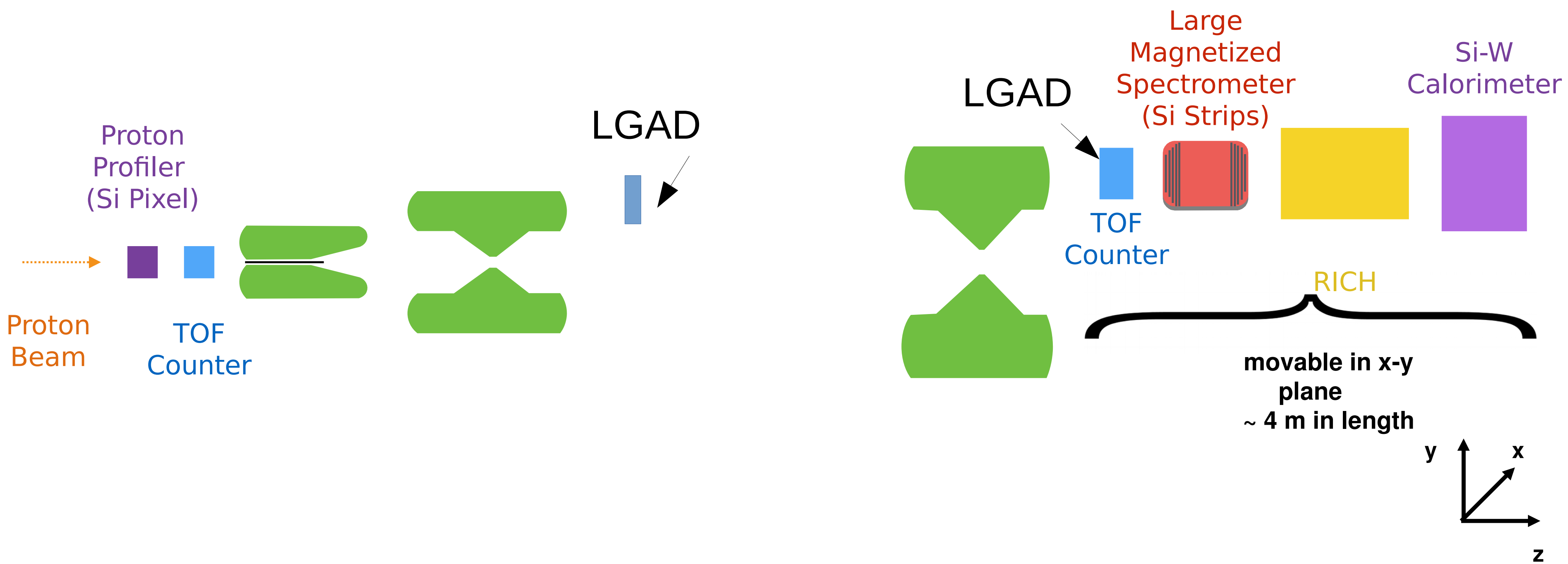
The Particle Identification will consist of three subsystem:

(I) Time of flight based on Silicon Low Gain Avalanche Detectors

(II) RICH detector, downstream of tracking system

(iii) muon wall.

The Spectrometer Concept, revisited



Running at ~ one PoT per M.I. r.f. frequency.
(~10 orders of magnitude smaller than nominal intensity)

The Spectrometer Concept, revisited ..

One more addition: An ionization counter, or "loss monitor" installed in the real chase, downstream of HORN C

And in the back of the LBNF-Spectrometer, in the simulated Chase.

Off -axis, with small direct solid angle to the target, a well calibrated "loss monitor".. Tricky!..

Running at ~ one PoT per M.I. r.f. frequency.

(~10 orders of magnitude smaller than nominal intensity)

A Staged Approach

- While informal discussions with Fermilab PPD on the putative siting of LBNFS (M-West being the most likely candidate)..
- The U.S-Japan collaboration on Hadroproduction for neutrino physics is schedule to take beam at M-Test, in January 2018, with an emulsion target, a small aperture magnet and silicon strip detectors
- Not a bad start.. The LBNFS program could, and should start with testing devices in M-Test, in collaboration with other efforts, and start design the dedicated siting today, at M-West, for instance.

Conclusion

- A dedicated spectrometer to measure the hadron flux downstream of the LBNF focusing system has been sketched.
- It's architecture is rather different than previously multiple final state spectrometer. (single arm, small aperture, high rate)
- A staged approach makes sense.
- While originally proposed in the context of DUNE/LBNF, our existing neutrino oscillation program (T2K & Fermilab) is likely to require renewed effort to constrain the hadron flux downstream of the horn. The LBNFS concept is relevant sooner than later.