Fermilab
50 Years of Discovery

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Neutrino beams beyond LBNF

With a focus on accelerator-based beams

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Neutrino beams

- It has been more than 50 years since Simon van der Meer invented the magnetic horn in order to improve the performance of neutrino beam production at accelerators
- We have been doing it more or less the same way ever since, save some notable exceptions:
  - Quad-focused beams
  - Sign-selected (dipole), narrow band
  - Tagged neutrino beams from K decay (proposed, but not built at Fermilab. New R&D, however).
- Over the past 20 years there has been an enormous effort to try to develop alternative designs for accelerator-based neutrino beams
  - Centered around the Neutrino Factory Studies

Overview

- For close to 45 years physicists have been talking about doing ν experiments with νs from μ decay

Well-understood neutrino source:

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

μ Decay Ring:

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

- Flavor content fully known
- "*Near Absolute*" Flux Determination is possible in a storage ring
  - Beam current, polarization, beam divergence monitor, μ_p spectrometer
- Overall, there is tremendous control of systematic uncertainties with a well designed system

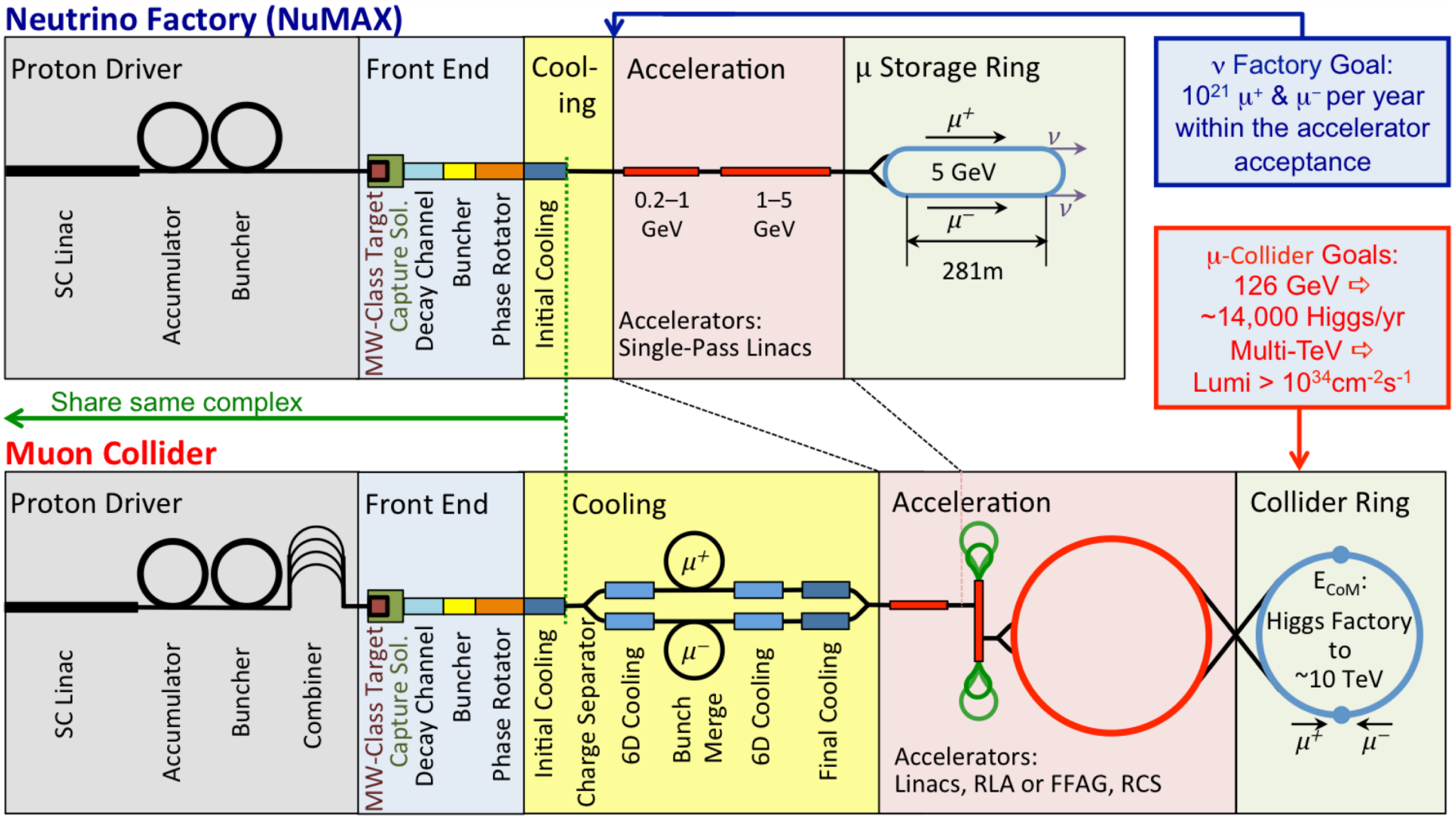
Neutrino Factory Studies

- Study 1 (US-Fermilab) [2000]
- Study 2 (US-BNL) [2001]
- NuFact-J study [2001]
- CERN NF study [2002]
- Study 2a (APS Multidivisional Neutrino Study) [2004]
- ISS (first international study; ISS group) [2006]
- International Design Study for a Neutrino Factory [2011]
- + nuSTORM & nuPIL

Yes, we generated a lot of paper & almost 1 neutrino

Then came P5: And the R&D ramped down quickly

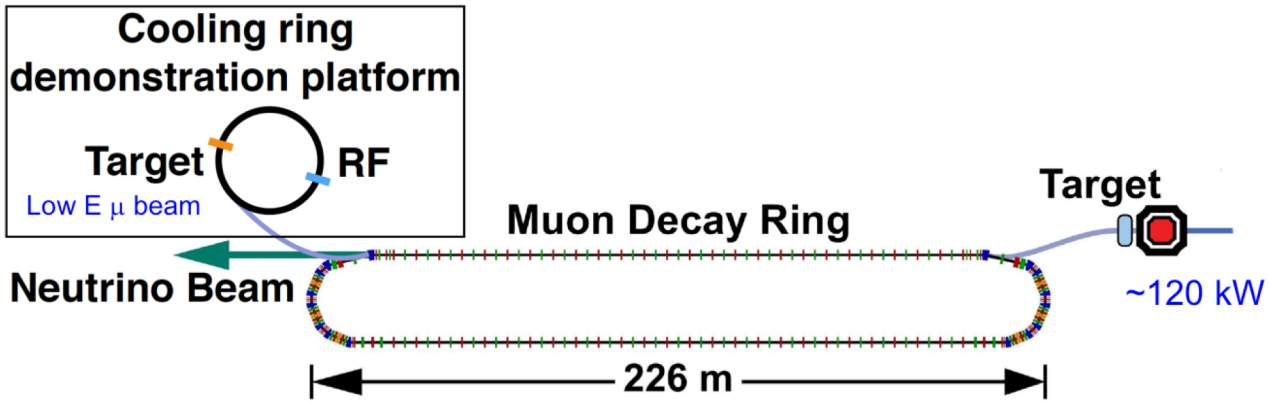
Muon Accelerator Program (MAP): Where we wound up



Staging, start small: nuSTORM (short baseline)

Neutrino Factory Light: conventional target + horn, pion capture & then injection into a ring

Annual Reviews of Nuclear and Particle Science, Volume 65, Adey *et al.*



5 ± 0.5 GeV/c pion injection
3.8 ± 0.4 GeV/c circulating muon beam

From μ decay

$$\mu^+ \rightarrow e^+ \overline{\nu}_\mu \ \nu_e$$

$$\mu^- \rightarrow e^- \nu_\mu \ \overline{\nu}_e$$

From π decay

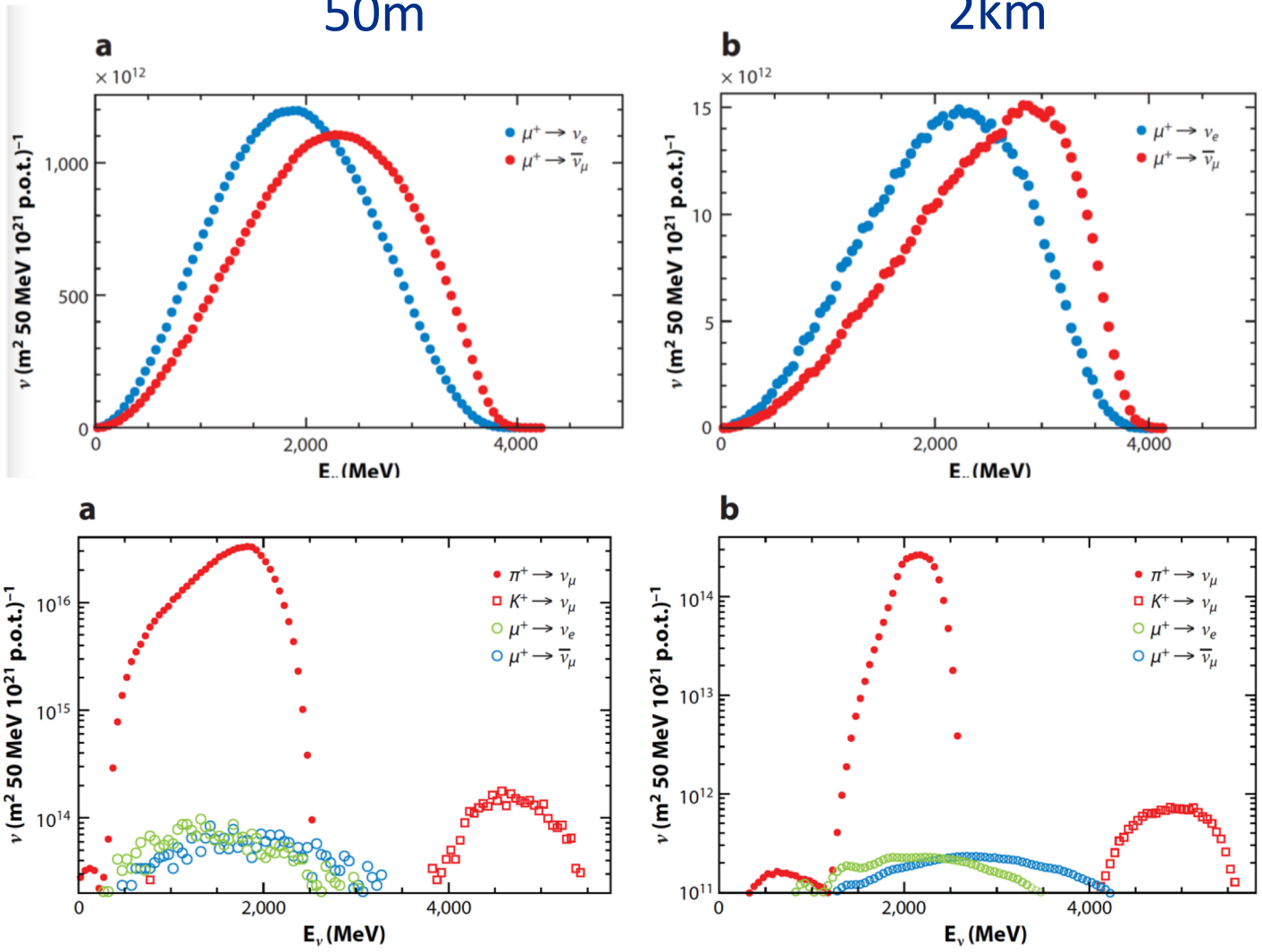
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

nuSTORM: Flux

50m

2km



μ

π

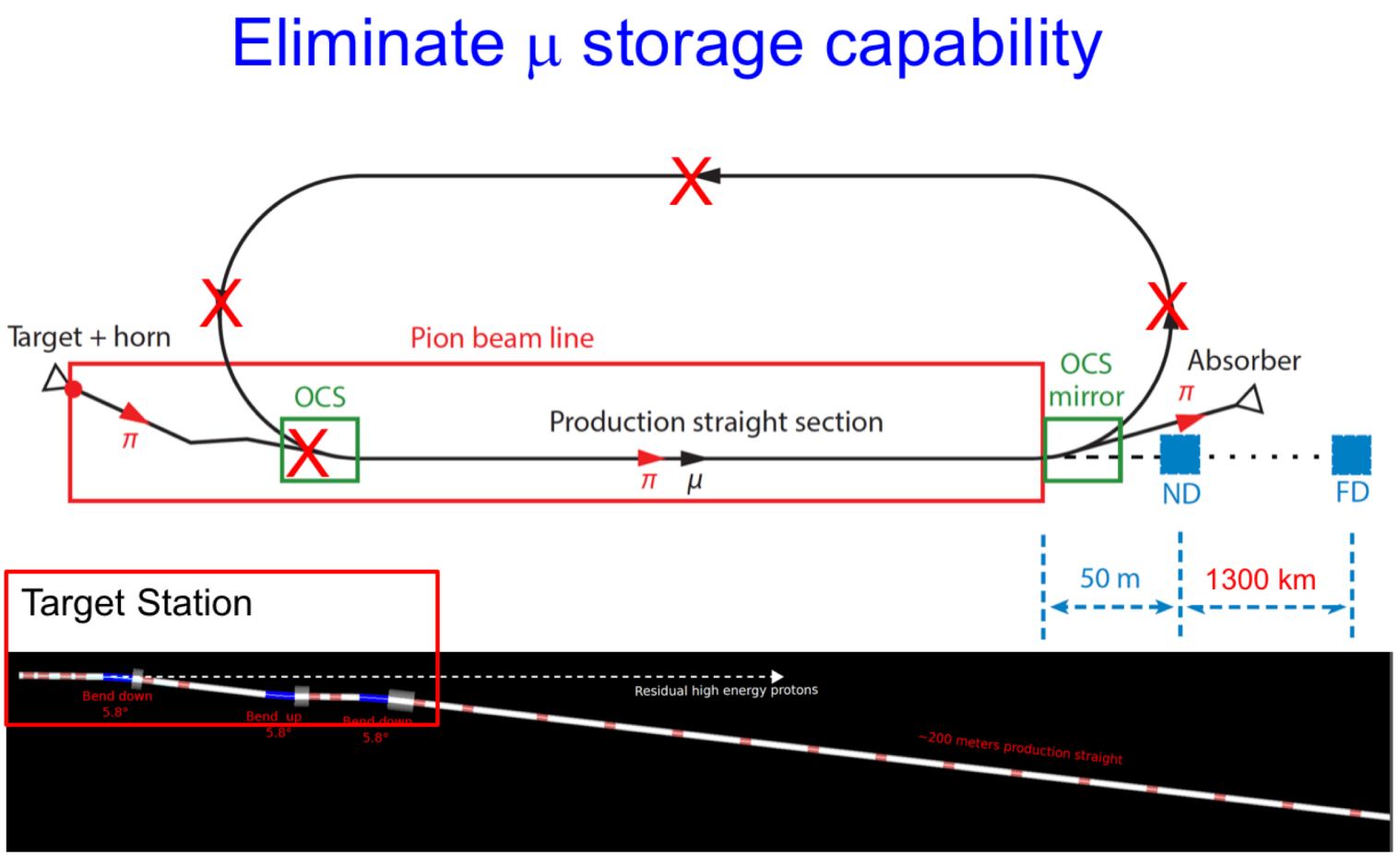
nuSTORM: Rates @ near site

For 100T target mass and 10^{21} POT

μ^+ stored channel	k events	μ^- stored channel	k events
ν_e CC	5,188	$\bar{\nu}_e$ CC	2,519
$\bar{\nu}_\mu$ CC	3,030	ν_μ CC	6,060
ν_e NC	1,817	$\bar{\nu}_e$ NC	1,002
$\bar{\nu}_\mu$ NC	1,174	ν_μ NC	2,074
π^+ injected channel	k events	π^- injected channel	k events
ν_μ CC	41,053	$\bar{\nu}_\mu$ CC	19,939
ν_μ NC	14,384	$\bar{\nu}_\mu$ CC	6,986

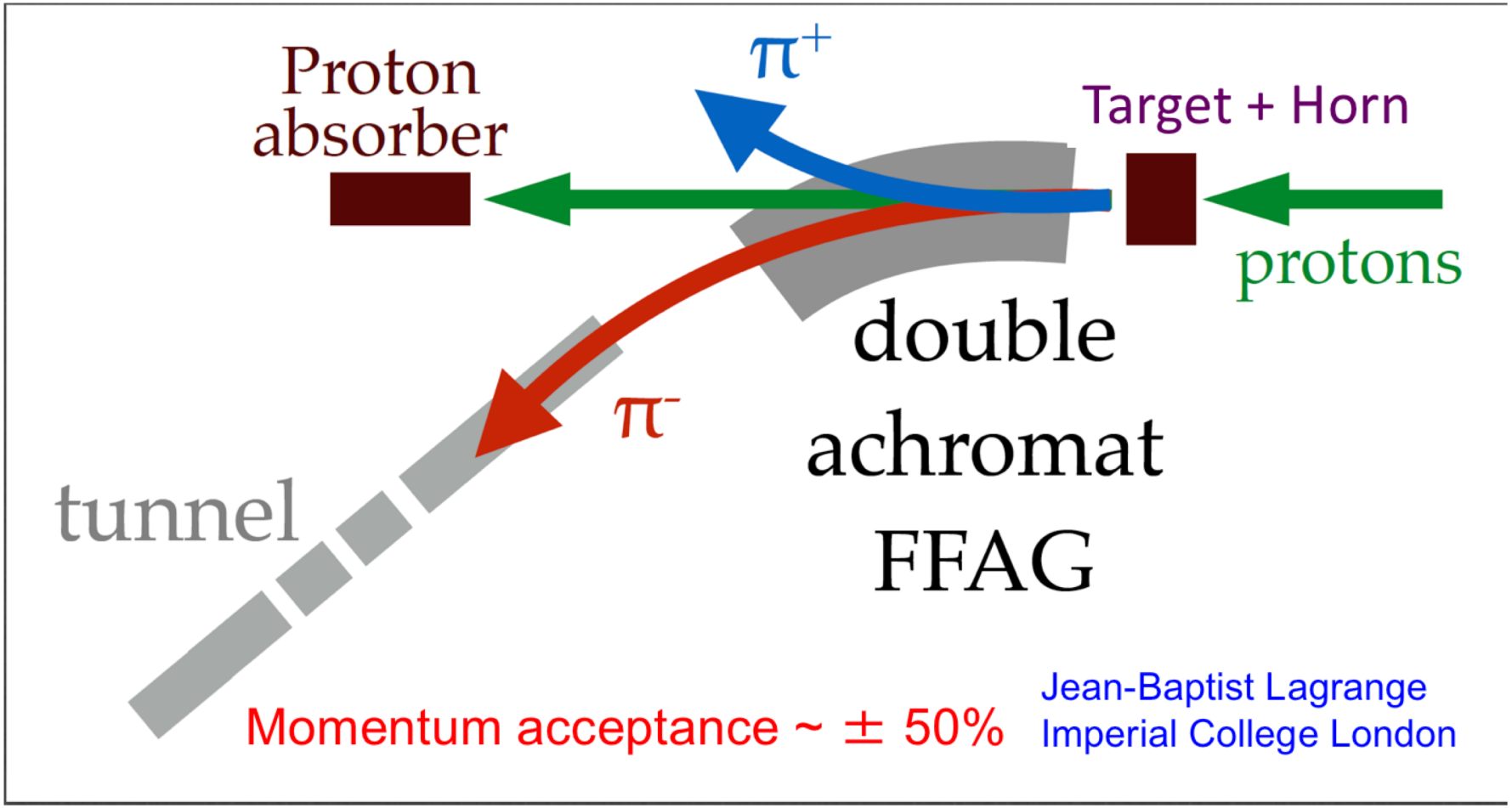
Forget the muons: Neo-conventional neutrino beam

- **nuPIL**: neutrinos from a pion injection line



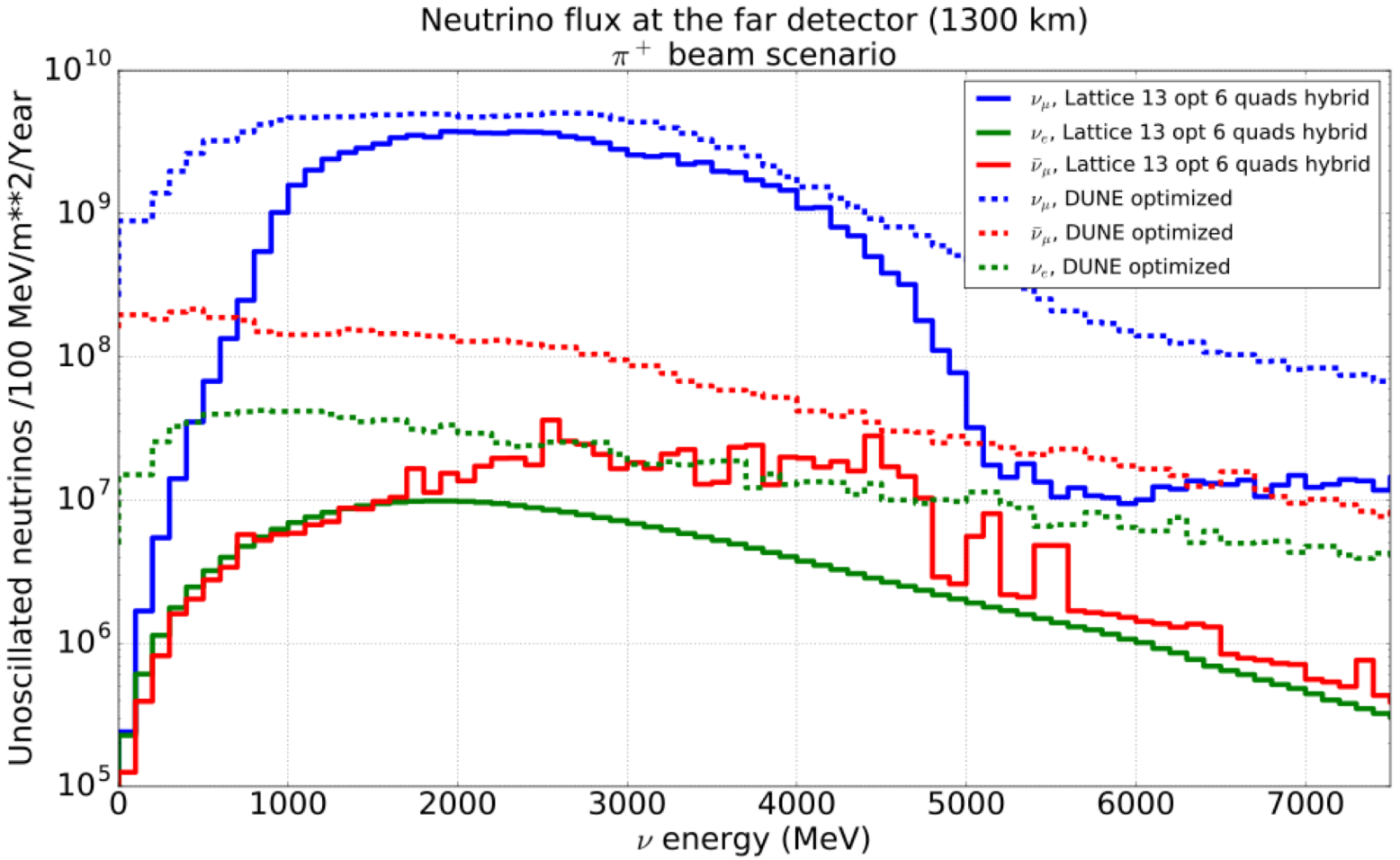
nuPIL

ν from a pion injection line



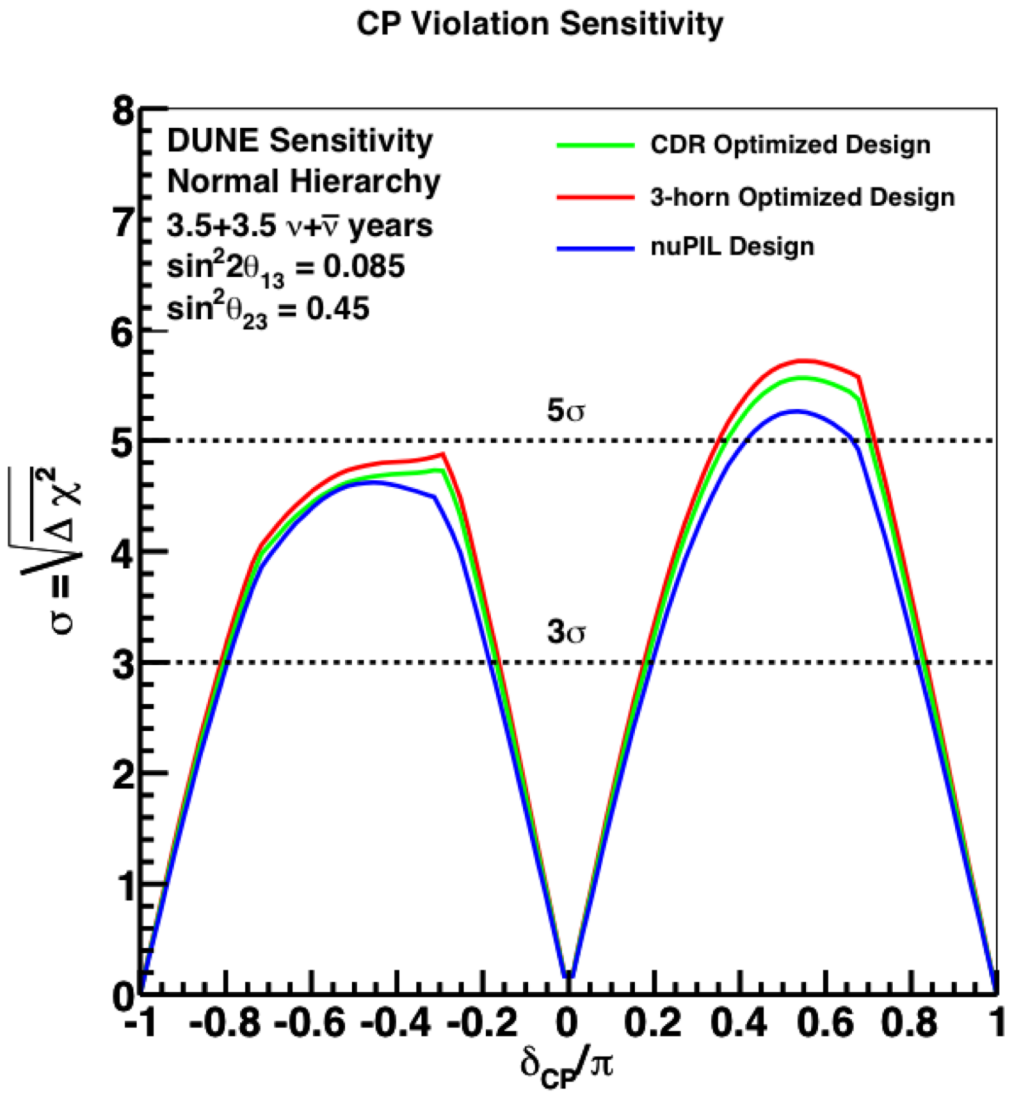
nuPIL

nuPIL Lattice13-Hybrid vs. LBNF/DUNE 3-Horn Opt



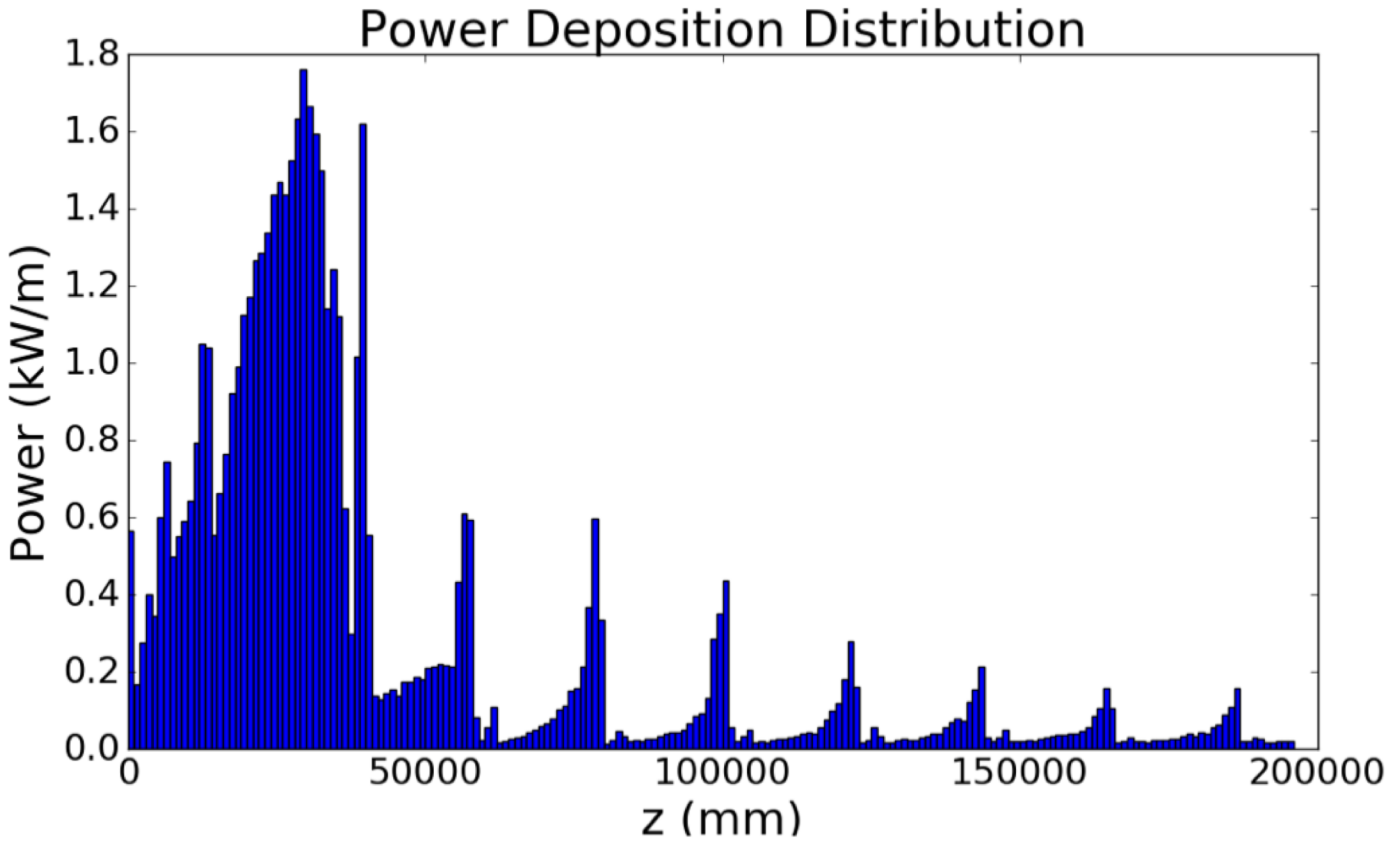
nuPIL(Σ_ν)/3-HornOpt (Σ_ν) =0.54

nuPIL

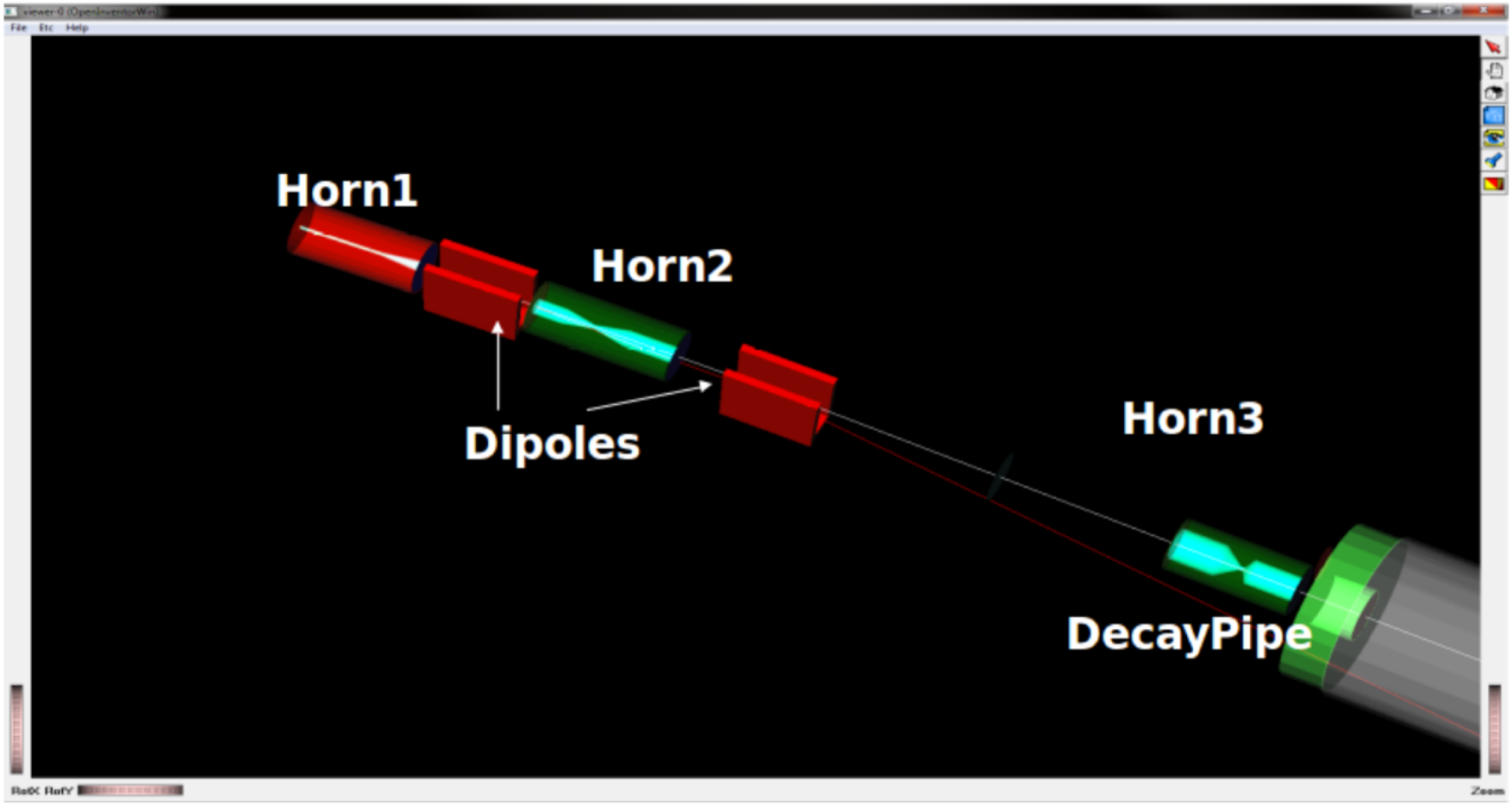

CP Violation Sensitivity
DUNE Sensitivity
Normal Hierarchy
3.5+3.5 ν+ν̄ years
sin²2θ13 = 0.085
sin²θ23 = 0.45
CDR Optimized Design
3-horn Optimized Design
nuPIL Design
5σ
3σ
σ = √Δχ²
δCP/π
0
1
2
3
4
5
6
7
8
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Problem with nuPIL

Never achieved good match between bend and straight
Lost ~½ the π beam power (~40kW) in matching section



nuPIL Lite (Milorad Popovic): No straight, simple bend



New twist (M. Bishai): use periodically as calibration beam for DUNE near detectors

Some ongoing R&D

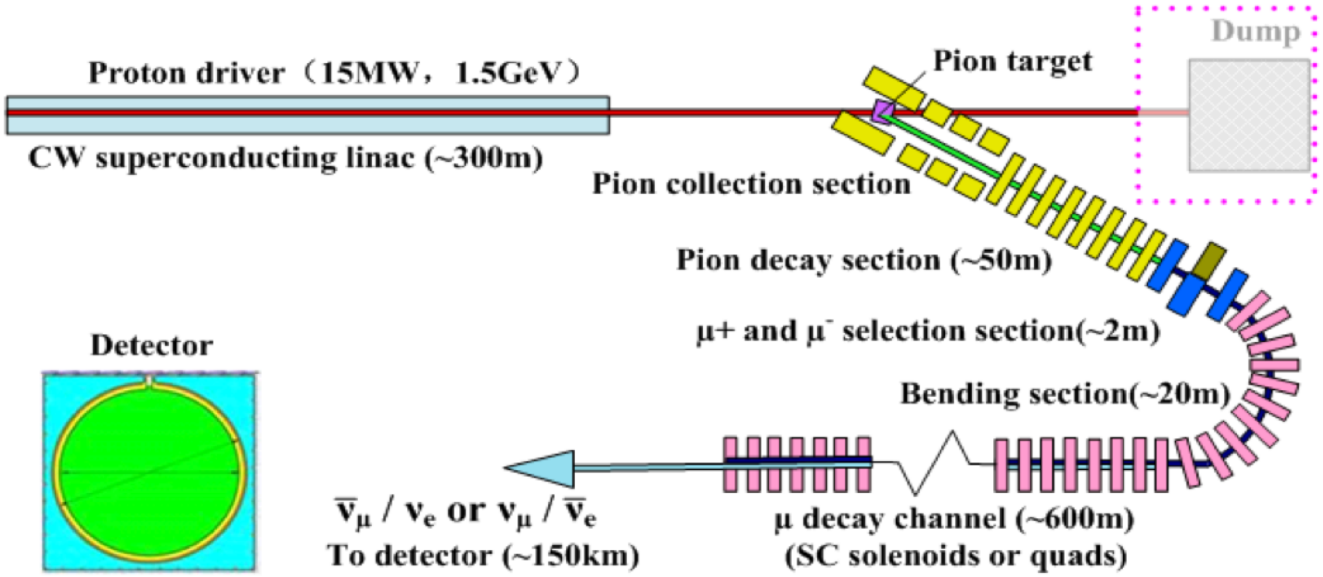
Outside US, R&D continues: MOMENT (China)

- Features:
  - Using a CW proton linac as the proton driver: 15 MW
  - China-ADS linac development
  - Fluidized target in high-field SC solenoid
  - Muon transport and decay channel (Pure μ+ or μ- decay, managed beam)
  - Also possible with π-decayed beam and Decay-at-Rest neutrinos

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{-} \rightarrow e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$

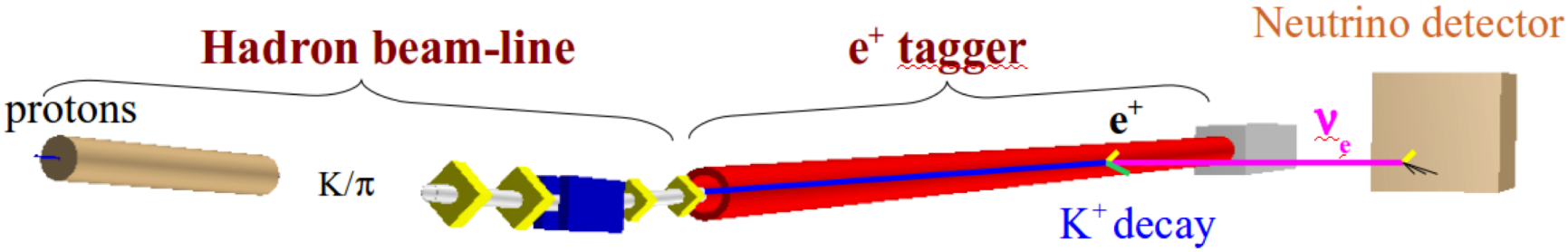
$$\mu^{+} \rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$



Post 2026

Tagged ν beams: ENUBET (INFN/CERN)

- Enhanced NeUtrino BEams from kaon Tagging
- Build a detector capable of performing positron identification in K_{e3} decays while operating in the harsh environment of a conventional neutrino beam decay tunnel.
- Project has been approved by the European Research Council (Host Institution INFN) for a five year duration (2021) and a 2.0M Euro budget



In US: π decay-at-rest sources

- DAEδALUS: δCP via π,μ decay
  - 800 MeV protons
  - Paired with HyperK
- IsoDAR: Sterile Neutrino search via ^{8}Li beta decay
  - 60 MeV protons
  - Paired with KamLAND
- No neutrino “beam” per se
  - 4π distribution
  - Low energy implies short baseline
  - $P_{osc} \sim A \sin^2(1.27\ \Delta m^2\ L/E)$
- What can these sources add in the beyond 2026 time frame?

Moving forward?

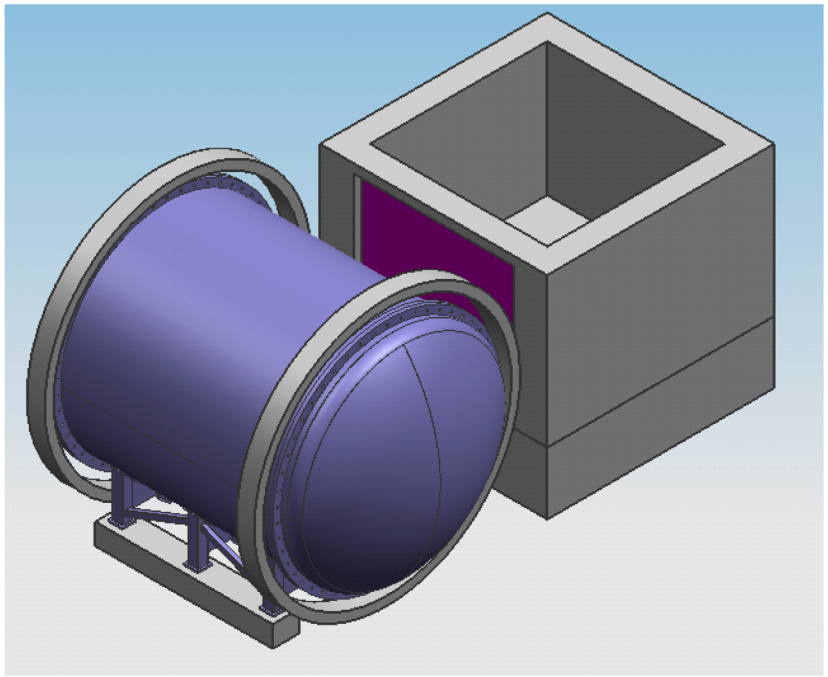
- Many good ideas, but will any of them be needed in 2026+?
- nuPIL
  - Too late really
- nuSTORM
  - x-sections? Will be done already?
  - Steriles? Will be dead already?
  - R&D platform (argument was for muon collider)? Is Dead?
- Neutrino Factory (including π decay-at-rest sources)
  - What known unknowns within the SνM will still be unknown?
    - MOMENT nor the π DAR beams are not likely to be able to add much in post 2026
  - Stepping stone to MC? Again, Dead already?
    - ???
- **Am I too pessimistic?**

Well, Yes and No

- Although is has been difficult to make much progress on reducing beam uncertainties for the LBNF beam, progress has been made in other areas.
- Near Detectors

DUNE near detector suite

- The DUNE ND WG has now developed a very powerful detector system.
  - Not your father's neutrino detector
- My choice: Pixelated LAr + HPgTPC (magnetized) + 3DST



- Fiducial target masses
  - LAr: 25t (64M ν_μ CC evts/yr)
    - ~5k ν-electron elastic/yr.
  - HPgTPC: 1t (1.6M ν_μ CC evts/yr)
  - 3DST: 5t (8M ν_μ CC evts/yr)
- Also implement DUNE-Prism
- So, many of the things we thought we needed nuSTORM and/or the NF for we can do with LBNF-DUNE by utilizing this powerful multi-purpose detector system.
  - Hard, but doable.
  - When it comes to Known unknowns

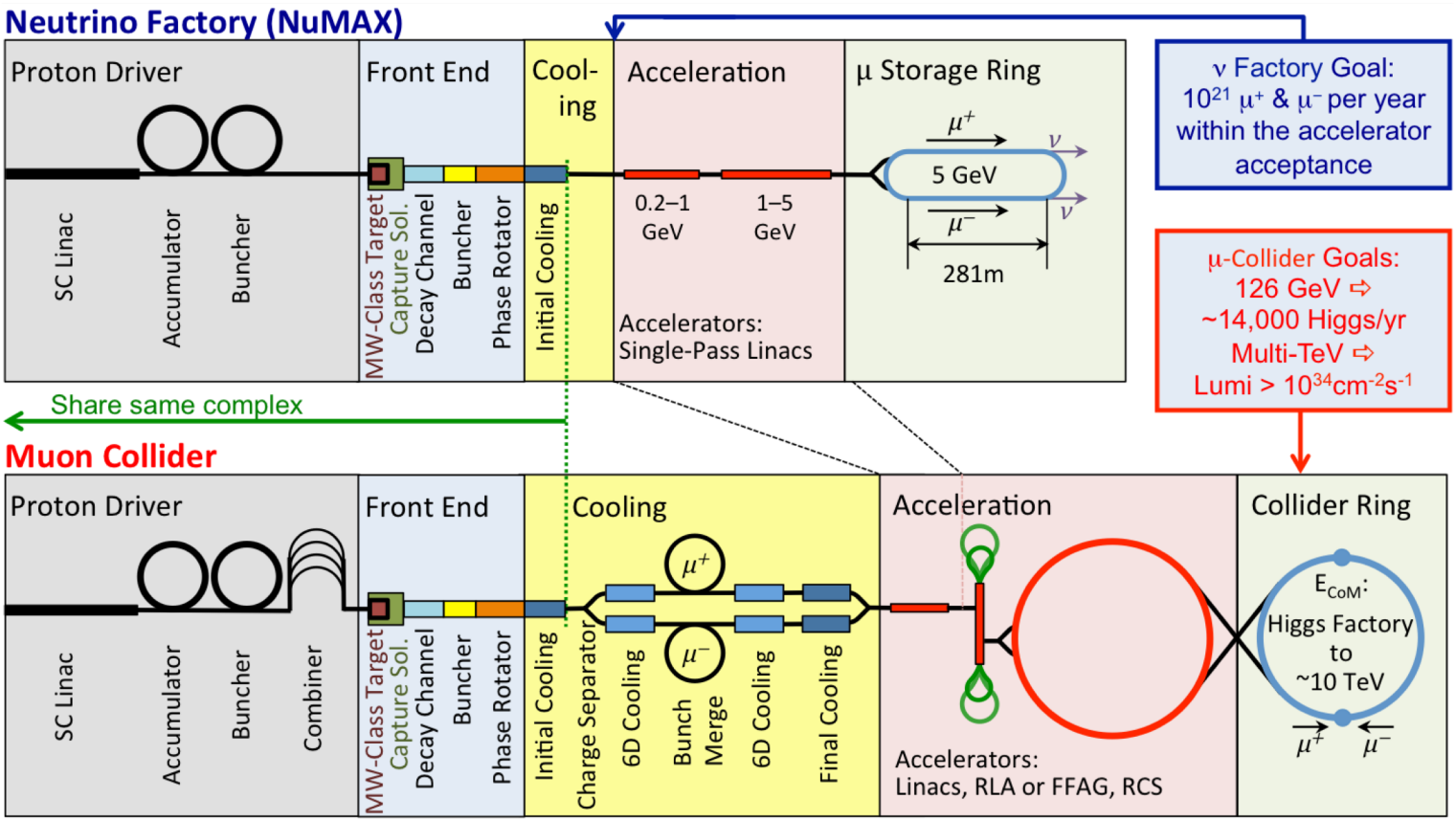
Game Changers

- SBN and/or very-short baseline reactor experiments discovery something beyond the SνM.
  - Better yet, they both do, but don't agree
- ➢ Then only nuSTORM or a facility like it will be able to sort it out.
  - ➢ π DAR can also contribute

- We find something that requires an intense neutrino beam with much higher energy.
- ➢ Then we need a Neutrino Factory

  - WHY IS THE BEAM FROM A NF DIFFERENT FROM ALL OTHER NEUTRINO BEAMS?

Because E_ν is completely uncorrelated with E_p



NSIs? – 50 GeV Neutrino Factory had tremendous reach

But

Its Baaacckkkk.

Can Muons - Which Live For Just Microseconds - Save Experimental Particle Physics?

Starts With A Bang

The Universe is out there, waiting for you to discover it FULL BIO

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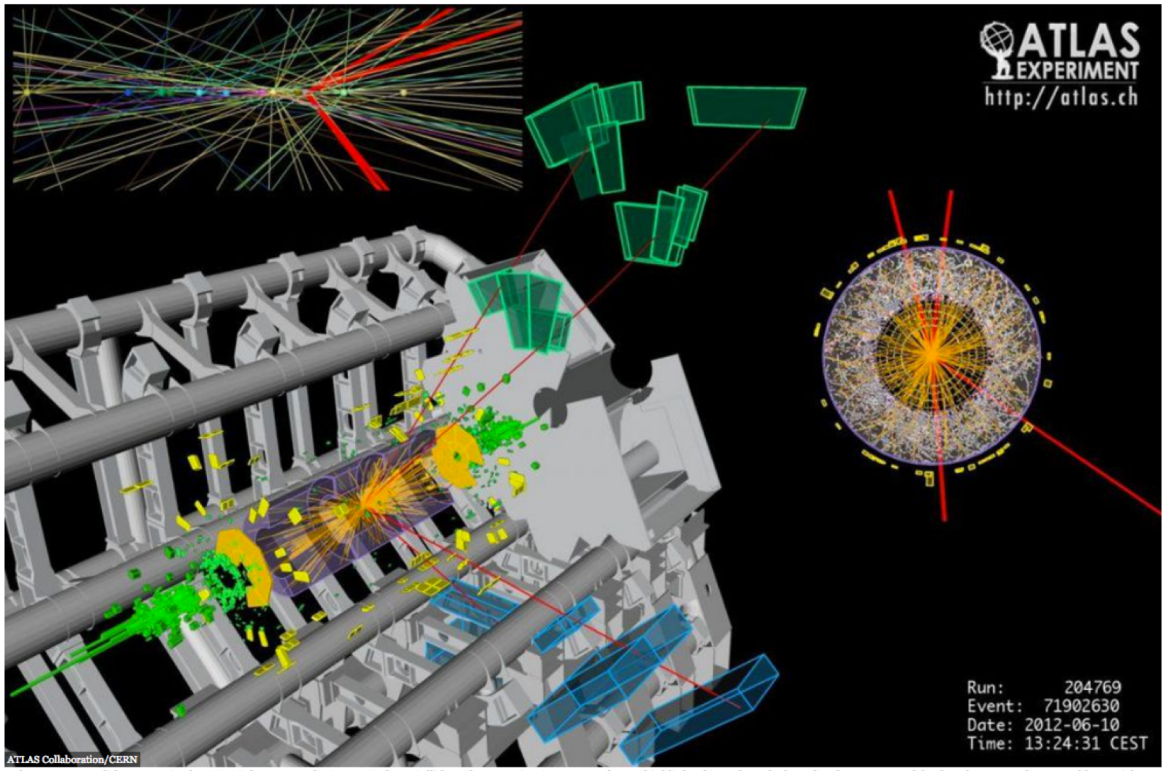
Ethan Siegel, Contributor

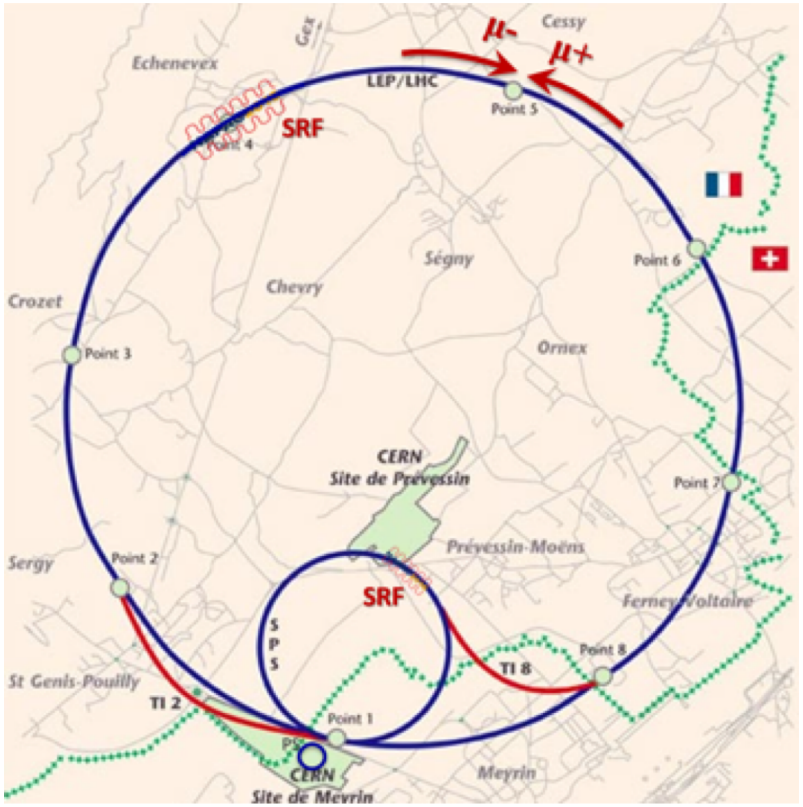


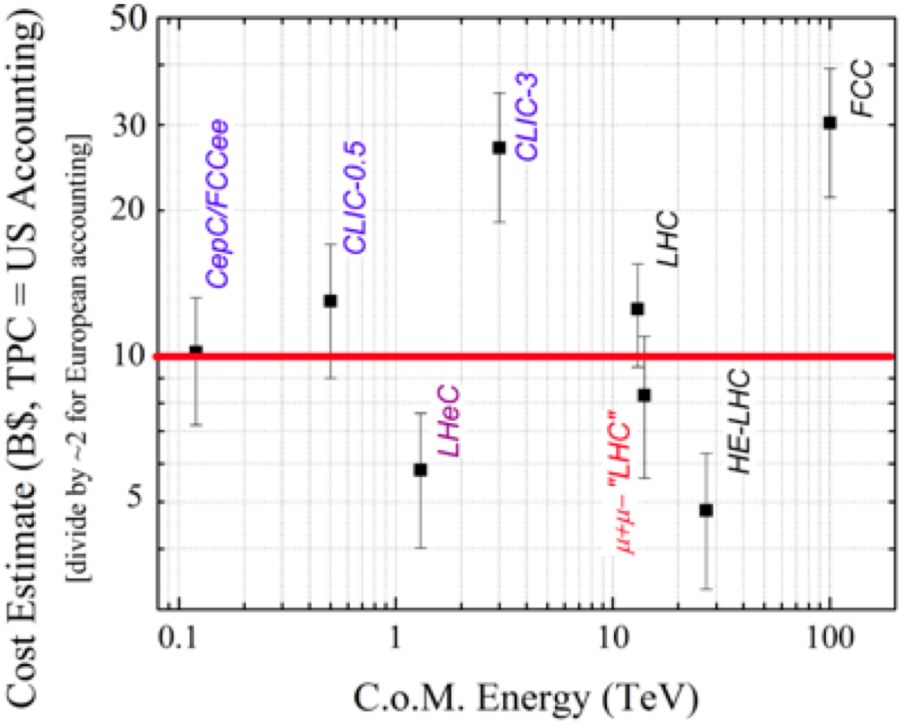
A four-muon candidate event in the ATLAS detector at the Large Hadron Collider. The muon/anti-muon tracks are highlighted in red, as the long-lived muons travel farther than any other unstable particle.

From Forbes
4/7/2017

$\mu^+ \mu^-$ Collider in the LHC tunnel (Neuffer & Shiltsev)

To be presented at IPAC18 in May





$$\theta_\upsilon = \frac{m_\mu}{E_\mu(TeV)} = \frac{10^{-4}}{7} = 14\mu R$$

Conclusions

- There has been an enormous amount of work done in the last 20 years on new accelerator based neutrino sources.
  - Many of the technical challenges of these new facilities have been overcome and feasibility has been demonstrated for most, if not all, subsystems.
- Their need beyond the 2026 time frame will be physics driven and (in my opinion) very limited unless there is physics beyond the SνM.
- So it comes down to determining what is the correct resource allocation now in order to be prepared for 2026+
- A renewed interest in Muon Colliders may change the outlook regarding R&D on muon sources
- Some R&D continues
  - US
    - π decay-at-rest sources
  - CERN
    - nuSTORM in the *Physics Beyond Colliders* initiative
    - ENUBET
  - China
    - MOMENT

THANK YOU