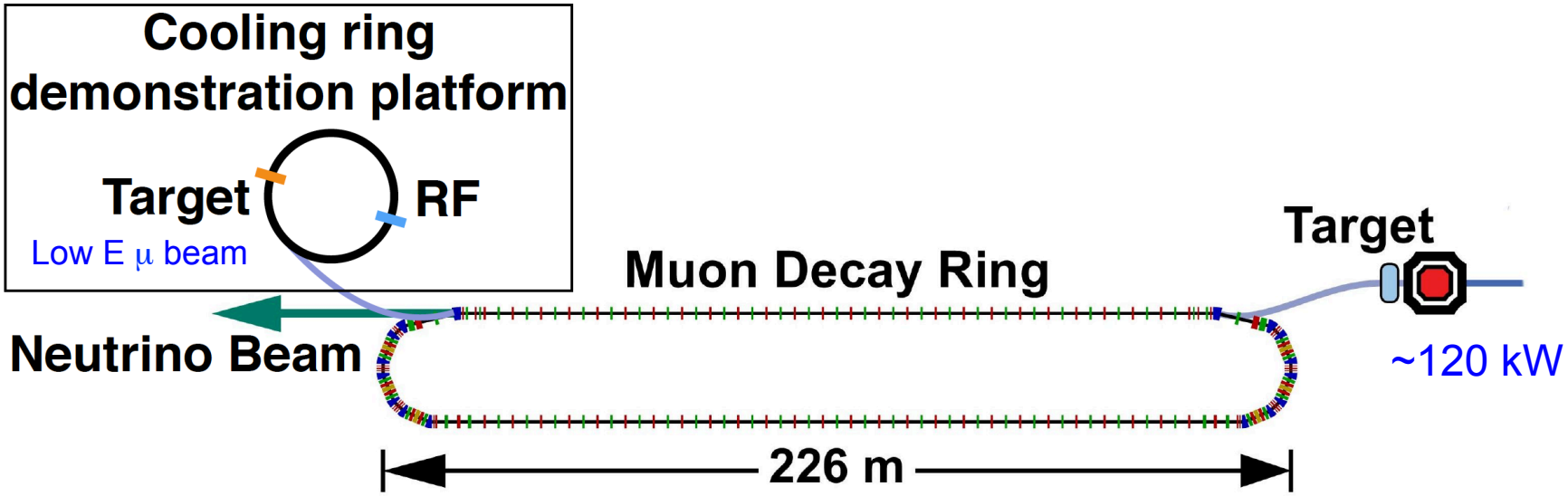
Status of nuSTORM

& non-conventional ν_μ beams

What is nuSTORM?

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

nuSTORM

- nuSTORM produces ν beams from μ decay as in the conventional NF

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

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

- But, it also produces a ν beam from π decay:

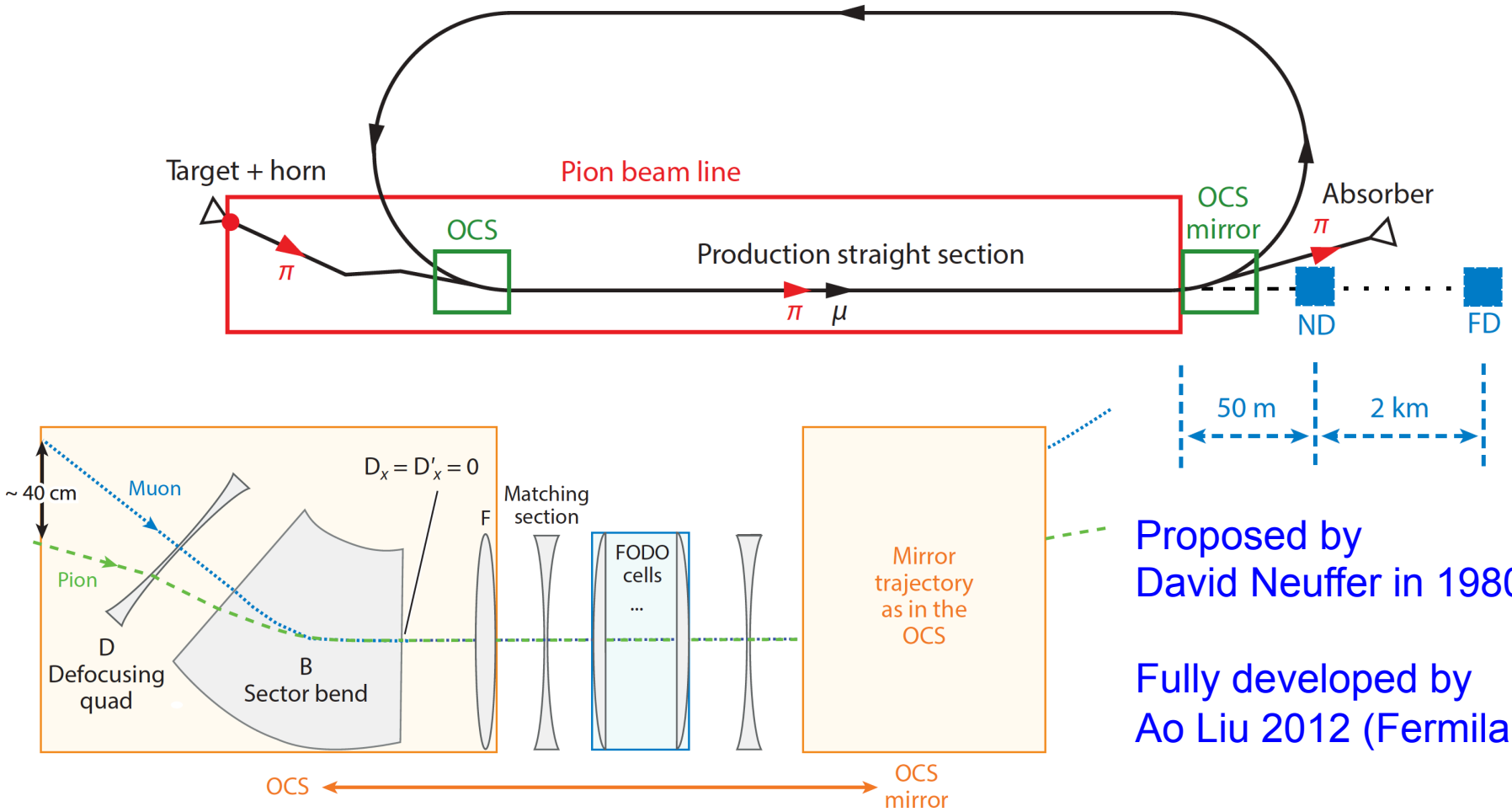
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

- It is a Hybrid-NF

Operation

At Fermilab: Extraction of 1 Booster-batch (1.6 μs) fills ring

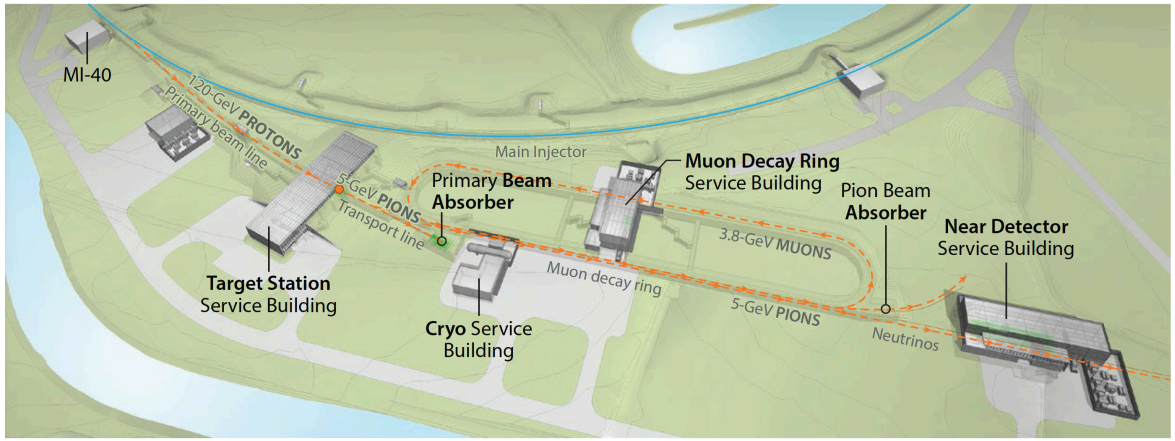


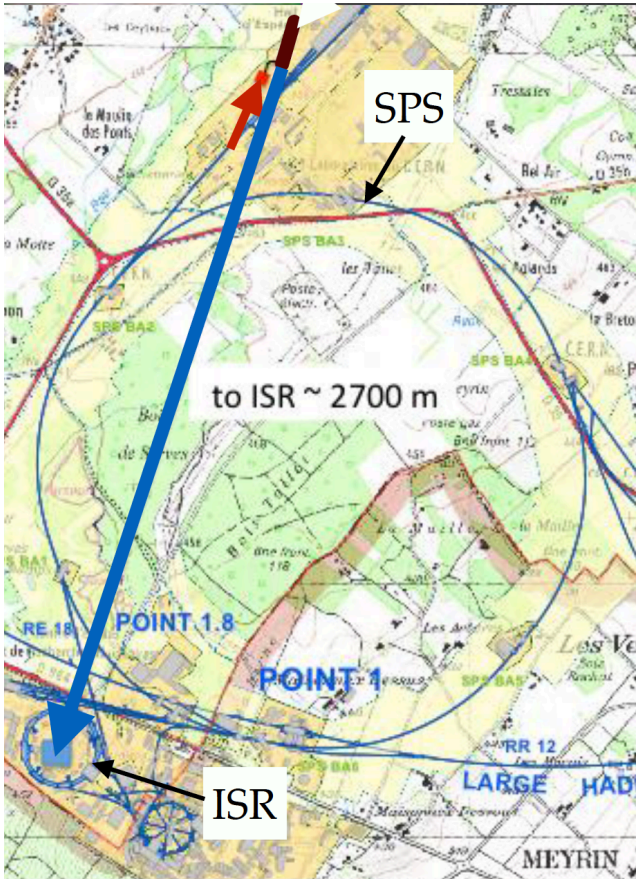
Proposed by David Neuffer in 1980

Fully developed by Ao Liu 2012 (Fermilab)

Status

- CDR developed for siting at Fermilab
- EOI for developing a siting option at CERN presented to CERN SPC





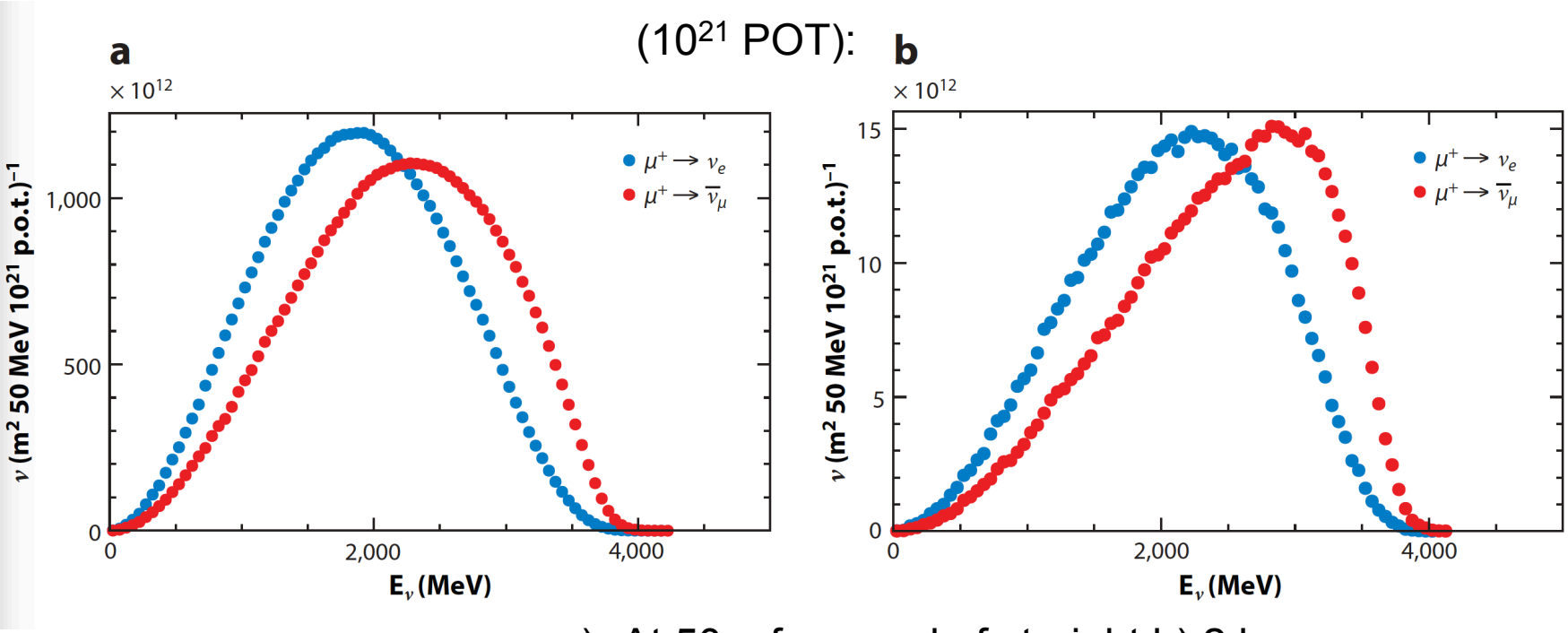
- Fermilab: 120 GeV protons from MI
- CERN: 100 GeV protons from SPS
  - ~2/3 flux in CERN siting

ν Beams from μ decay

- nuSTORM IS the ν beams it produces

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

(10^21 POT):



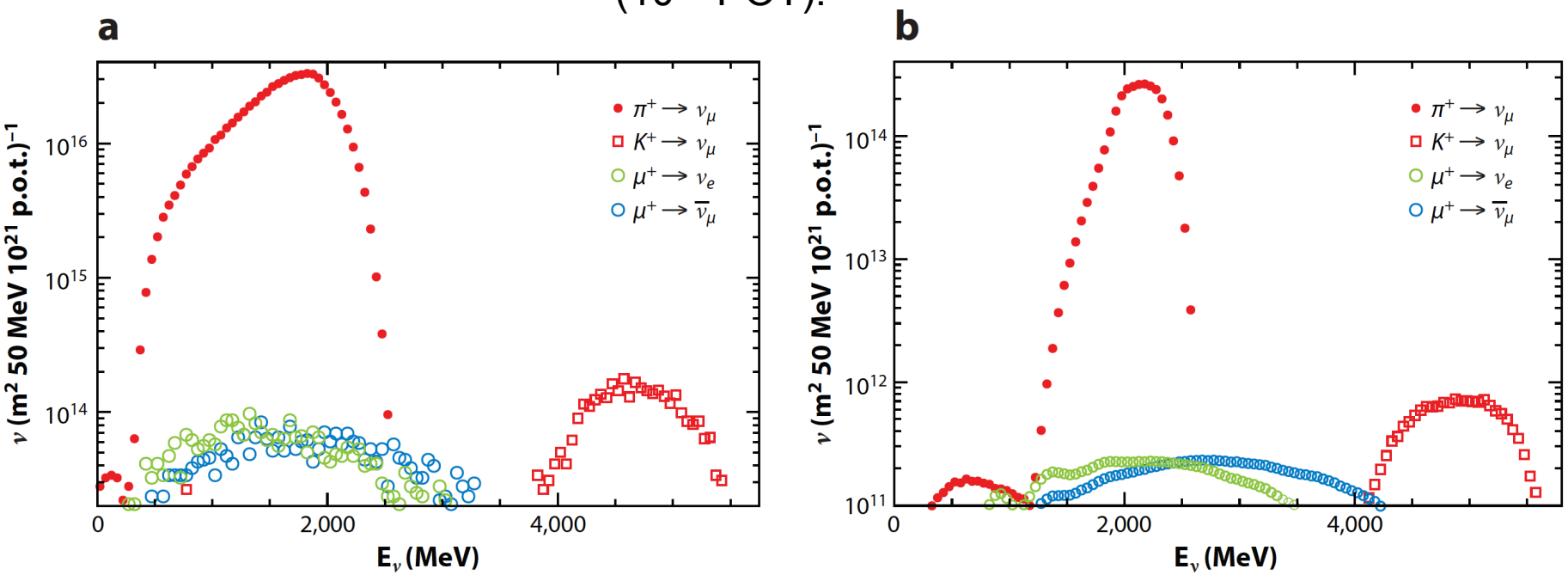
a) At 50m from end of straight b) 2 km

Flux know at the ~.5% (absolute & bin-bin) via beam line instrumentation

ν Beams from π decay

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

(10^{21} POT):



Note: Zero ν-bar from π^- decay (& vice versa)
High-energy flavor-pure ν_μ beam

Rates @ 50 m

Table 4 Event rates at 50 m from the end of the decay straight section per 100 T fo 10^{21} POT[a]

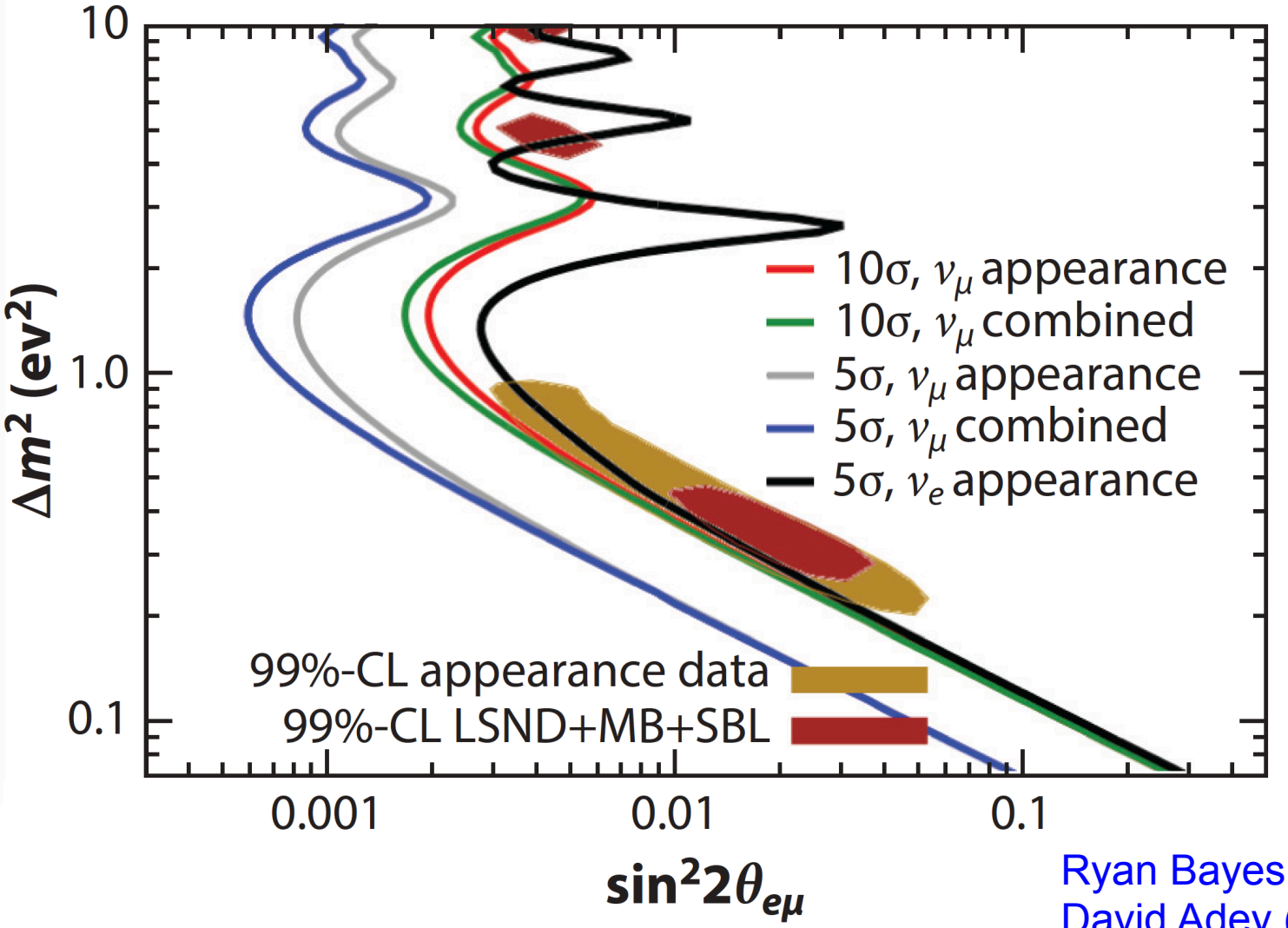
μ^+ stored channel	k events	μ^- stored channel	k events
ν_e CC	5,188	$\bar{\nu}_e$ CC	2,519
$\bar{\nu}_\mu$ CC	3,030	ν_μ CC	6,060
ν_e NC	1,817	$\bar{\nu}_e$ NC	1,002
$\bar{\nu}_\mu$ NC	1,174	ν_μ NC	2,074
π^+ injected channel	**k events**	**π^- injected channel**	**k events**
ν_μ CC	41,053	$\bar{\nu}_\mu$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

Rates @ 2km

Table 5 Event rates due to CC interactions at 2 km per 1.3 kt for 10^{21} POT [a]

μ^+ stored		
Channel	No oscillation	Oscillation 3+1
$\nu_e \rightarrow \nu_\mu$	0	288 Golden
$\nu_e \rightarrow \nu_e$	188,292	176,174
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	99,893	94,776
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0	133
π^+ stored		
Channel	No oscillation	Oscillation
$\nu_\mu \rightarrow \nu_\mu$	915,337	854,052
$\nu_\mu \rightarrow \nu_e$	0	1,587

Steriles search



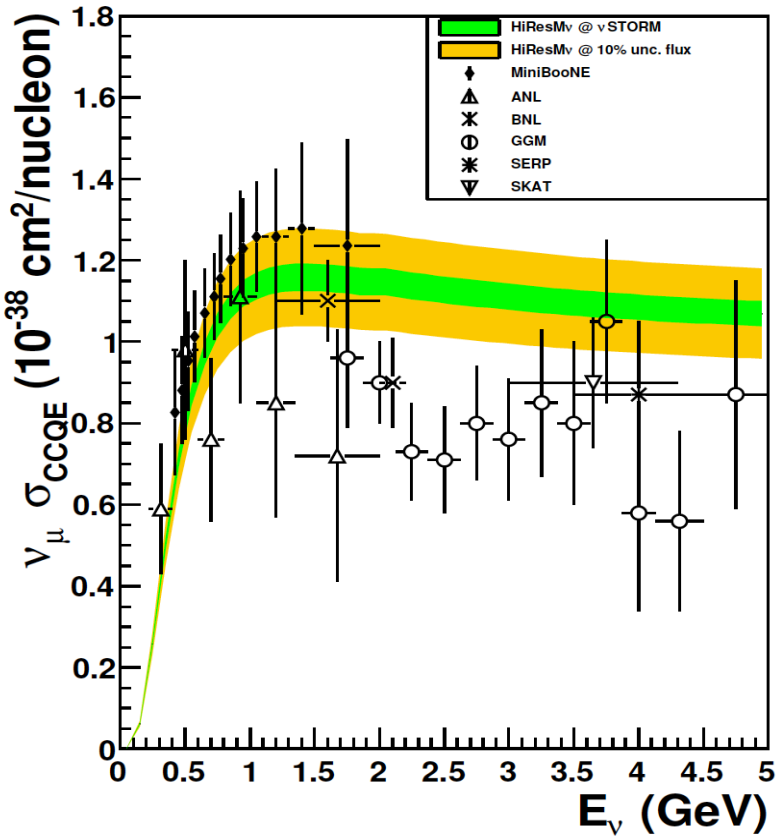
Ryan Bayes (Glasgow)
David Adey (Fermilab)

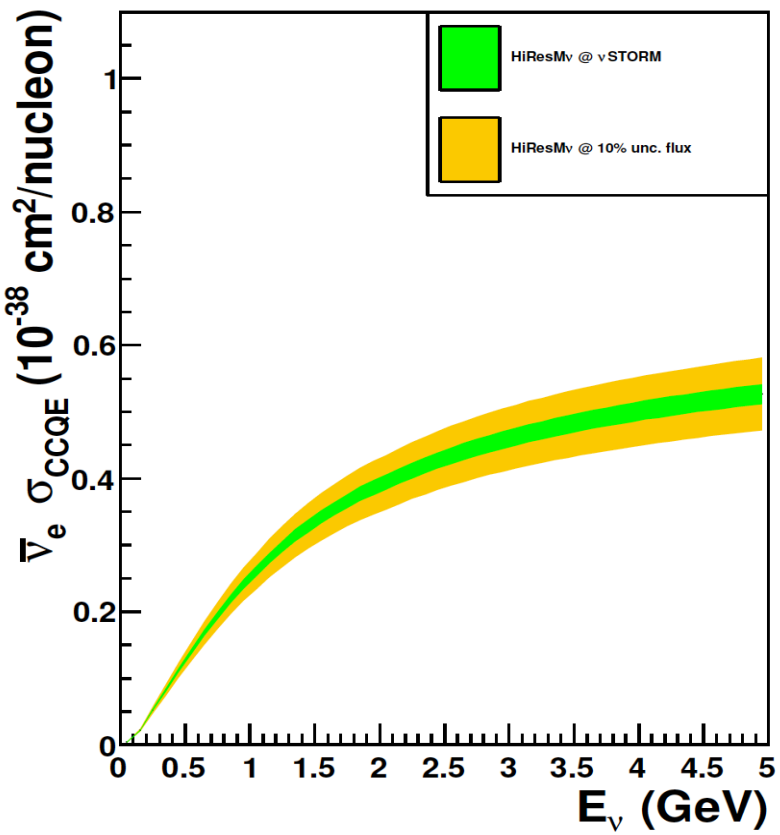
Neutrino interaction physics

- Very rich physics programme (just some examples):
  - Electron neutrino and anti-electron neutrino cross-section measurements
  - π^0 production in neutrino interactions
  - Charged π and K production
  - Neutrino-electron scattering
  - Neutrino-nucleon scattering: charged current and neutral current (NC/CC ratio and $\sin^2\theta_W$)
  - Nuclear effects in neutrino interactions
  - Semi-exclusive and exclusive processes: measurement of $K_s, \Lambda, \overline{\Lambda}$ production
  - New physics and exclusive processes: test of universality, heavy neutrinos, eV-scale pseudo-scalar penetrating particles ….

Neutrino interactions at nuSTORM

– Data for ν_μ and $\bar{\nu}_e$ cross-sections





ν interaction physics

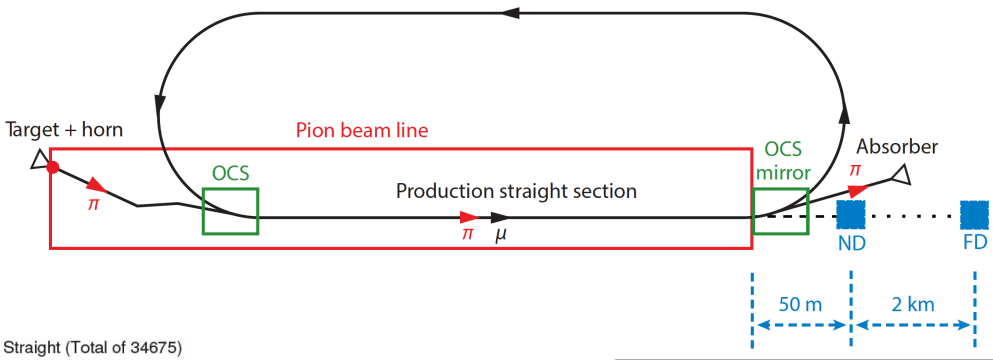
- 10's of millions of evts for 100T detector

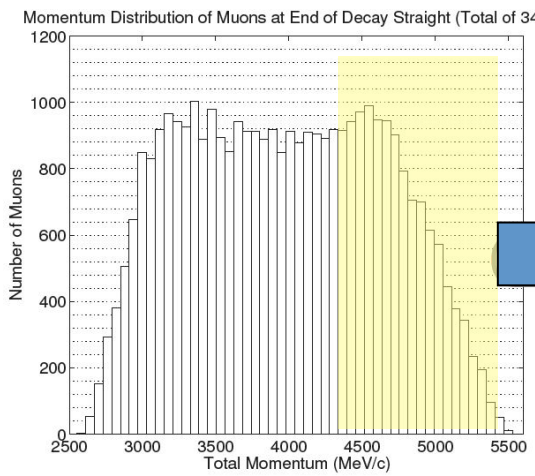
Interaction channels

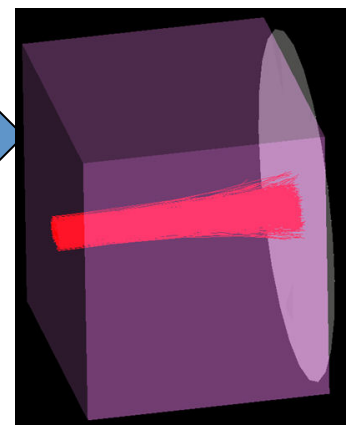
data exist

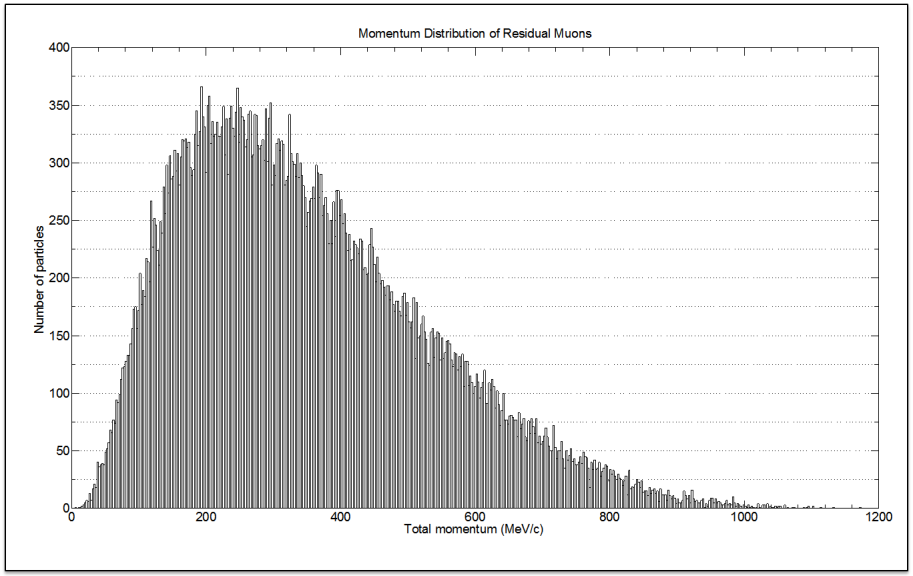
ID	Stored μ^+	Stored μ^-
1	$\bar{\nu}_\mu p \to \mu^+ n$	$\nu_\mu n \to \mu^- p$
2	$\nu_e n \to e^- p$	$\bar{\nu}_e p \to e^+ n$
3	$\bar{\nu}_\mu n \to \mu^+ \pi^- n$	$\nu_\mu n \to \mu^- \pi^+ n$
4	$\bar{\nu}_\mu p \to \mu^+ \pi^0 p$	$\nu_\mu n \to \mu^- \pi^0 p$
5	$\bar{\nu}_\mu p \to \mu^+ \pi^- p$	$\nu_\mu p \to \mu^- \pi^+ p$
6	$\nu_e n \to e^- \pi^+ n$	$\bar{\nu}_e n \to e^+ \pi^- n$
7	$\nu_e p \to e^- \pi^0 p$	$\bar{\nu}_e p \to e^+ \pi^0 n$
8	$\nu_e p \to e^- \pi^+ p$	$\bar{\nu}_e p \to e^+ \pi^- p$
9	$\bar{\nu}_\mu, \nu_e \to X$	$\nu_\mu, \bar{\nu}_e \to X$

Note on muon beam for advanced cooling demo
Low Energy μ beam









At end of straight we have a lot of πιs, but also a lot of υs with 4.5 < P(GeV/c) < 5.5

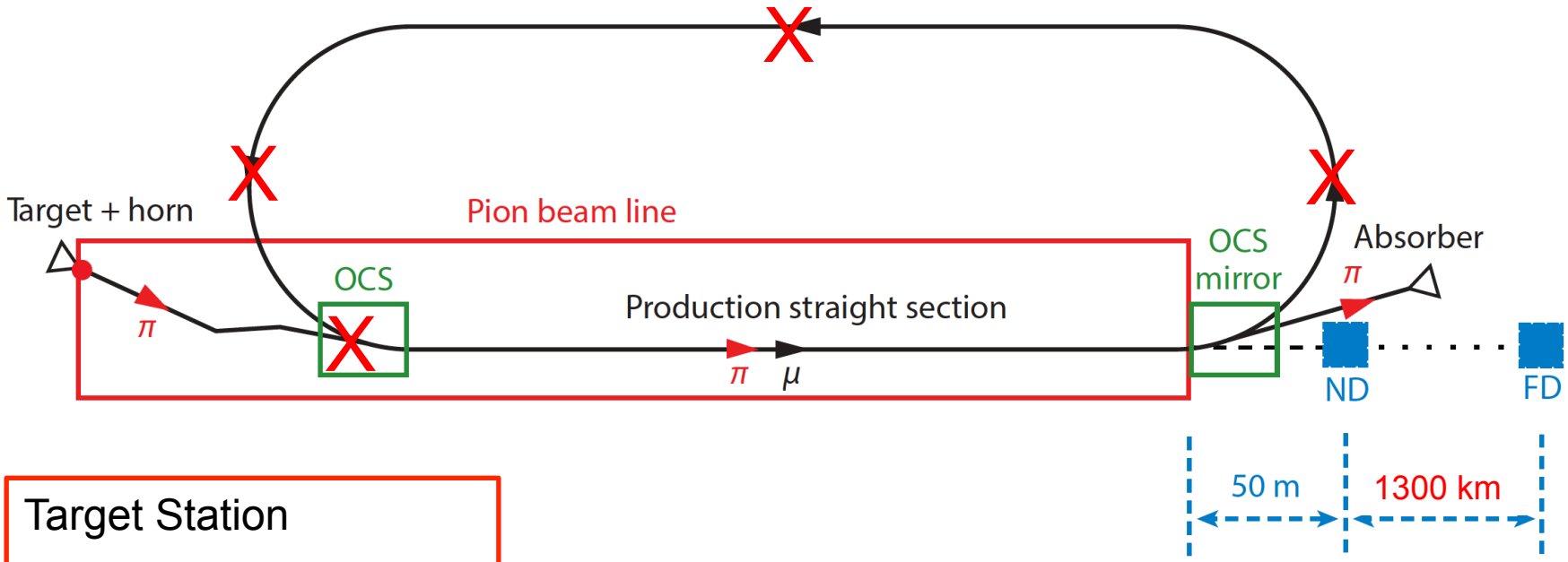
After 3.48m Fe, we have ≈ 10^{10} μ/pulse in 100 < P(MeV/c) < 300

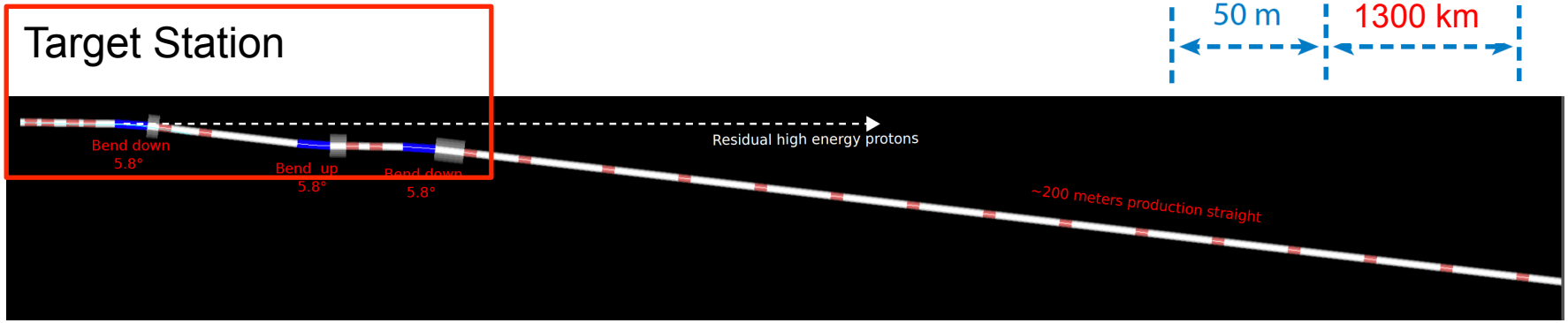
Extending the technique to Long Baseline?

- The flux from μ decay in nuSTORM is too small to be useful for a LBL experiment
- However, could the pion injection line produce a useful beam?

Pion Injection Line (PIL)

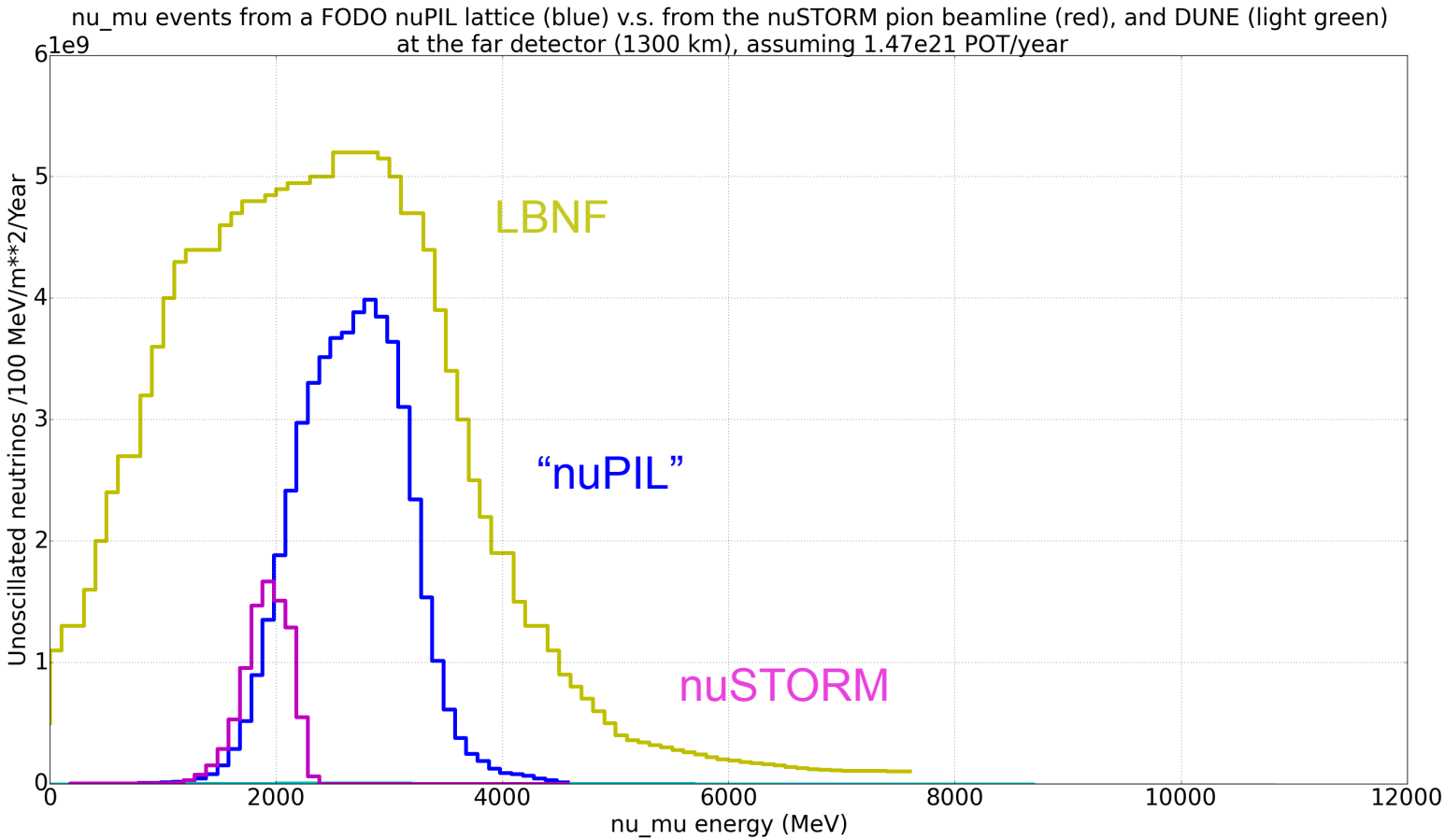
Eliminate μ storage capability & optimize production straight only for πs





nuSTORM pion injection line vs. dedicated pion injection line

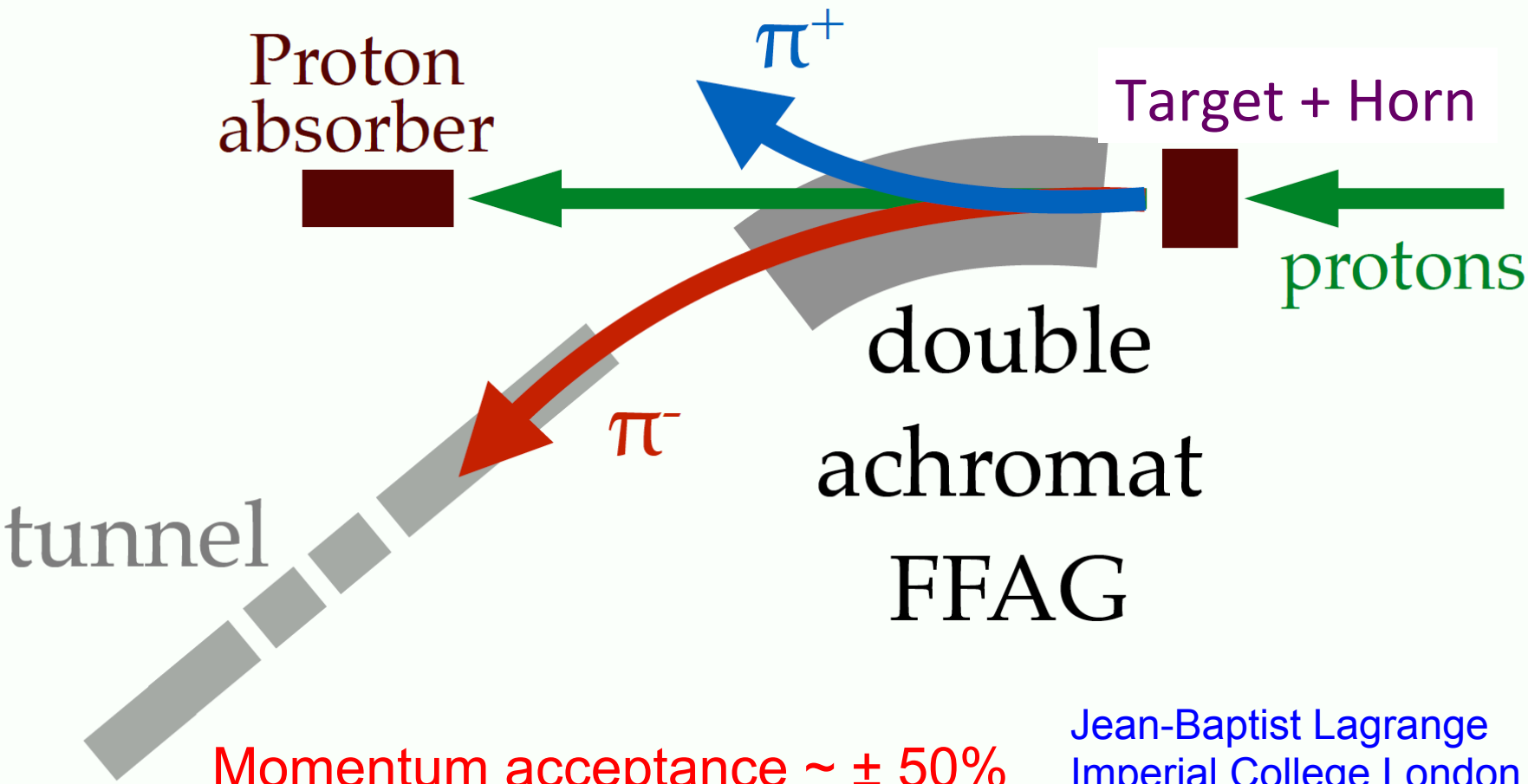
Ao's new FODO PIL



FODO extension of nuSTORM π beamline: P_0=7 GeV/c with larger acceptance

Not there yet, but….

ν from a pion injection line



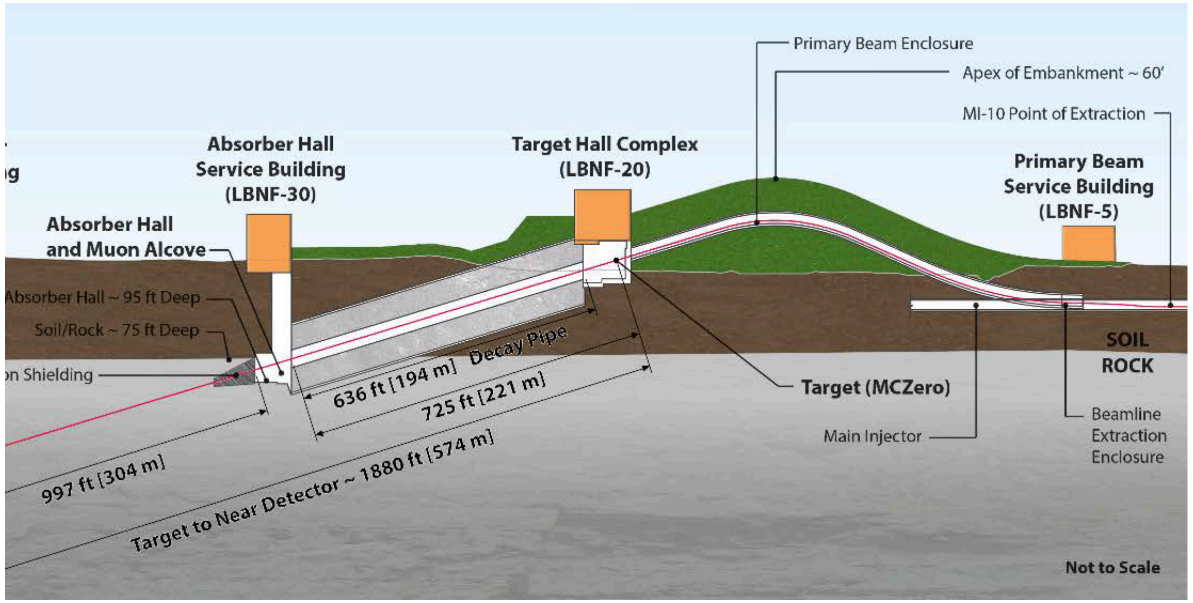
Momentum acceptance ~ ± 50%

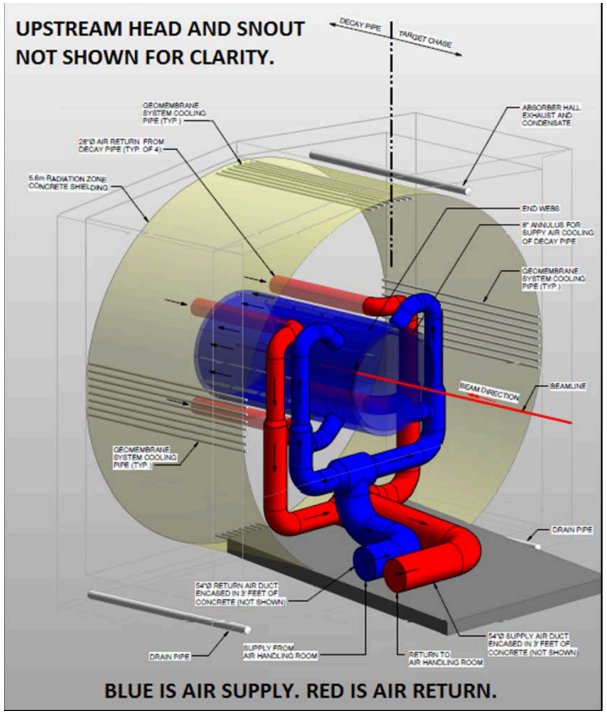
Jean-Baptist Lagrange
Imperial College London

Why is this interesting?

- No ν_μ in ν_μ-bar and no ν_μ-bar in ν_μ
- No high-energy tail
- Reduced background from K and μ decay
- Beam systematics of concern for conventional horn-focused ν beam line
  - Secondary particle production
    - Particle types, flux and energy distribution
  - Proton beam targeting stability
  - Target degradation/change
  - Horn stability
  - +++?
  - All of these become unimportant since the pion flux is measured by the beam line instrumentation (flux, momentum distribution, emittance)
    - R&D issue here – never been done

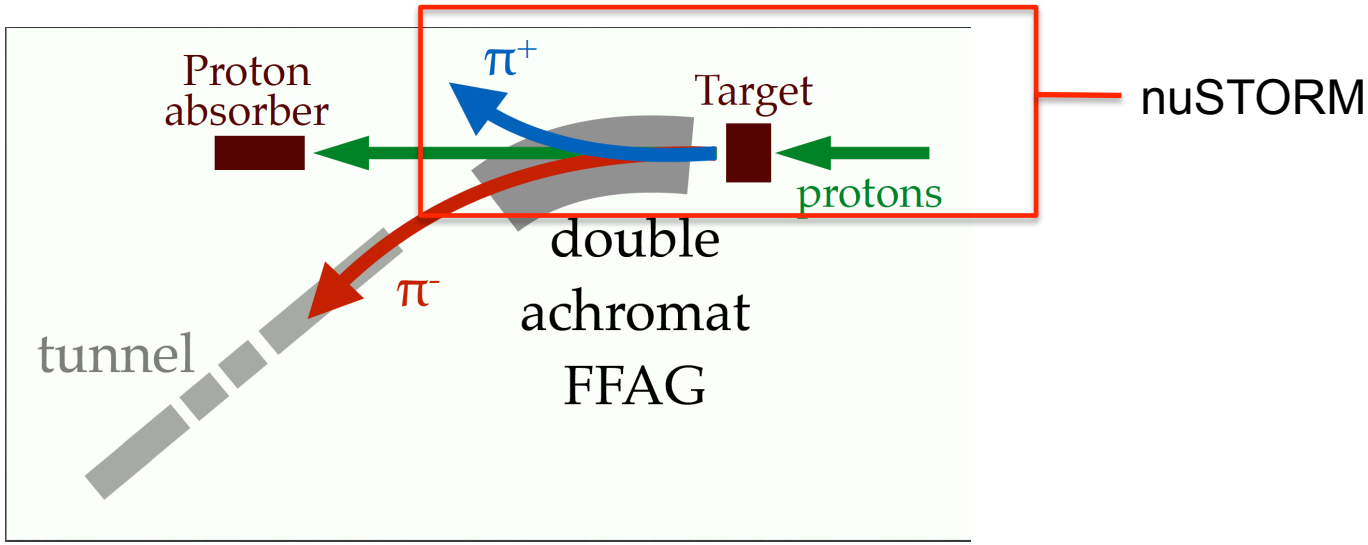
Practical considerations
Case in point: LBNF





- Primary proton beam line, target station and proton dump all at grade
  - No hill
- Decay straight is no longer a “decay pipe”, but a beam line
  - Radiation safety considerations VERY different
  - High-power beam does not go underground
  - ~6-7 m concrete annulus is not required
    - Will have to be vetted by Rad Safety
  - Has significant cost impact

But wait…
There's more

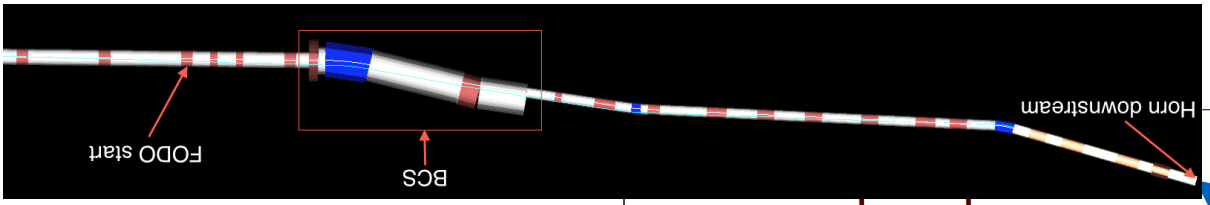


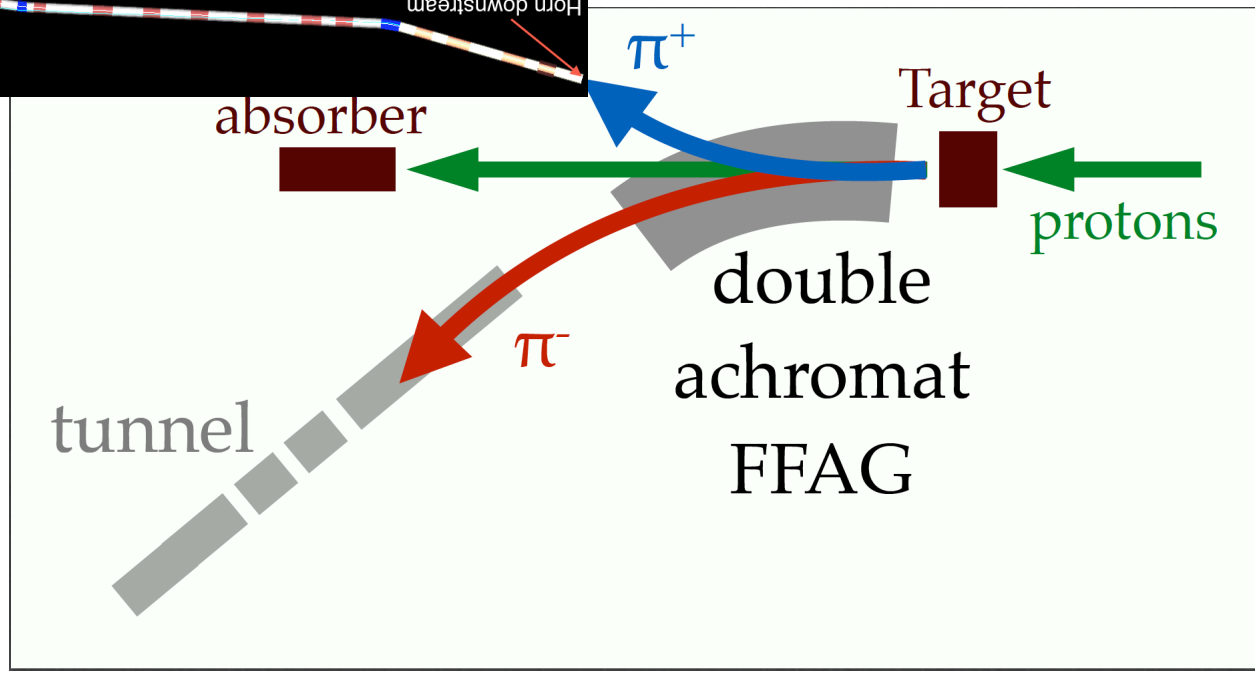
- IF DBA FFAG "C" type magnets
  - Extract π^+ , collect and send to nuSTORM
    - Partial momentum acceptance
- So, LBNF ➔ nuPIL ⊕ nuSTORM
  - Neutrino running @ LBL concurrent with anti-neutrino at nuSTORM

Powerpoint engineering

But, you get the point

Get your μs back: νe & νe-bar + low-energy μ beam





Conclusion

- nuSTORM continues to offer exceptional physics reach for neutrino interaction physics and for the search (& possible eventual study of) sterile neutrinos
- The nuPIL concept potentially offers the option to simultaneously support a LBL program and a SBL program with neutrino beams of unprecedented precision.

END

Thank You