Muon Colliders and Neutrino Factories

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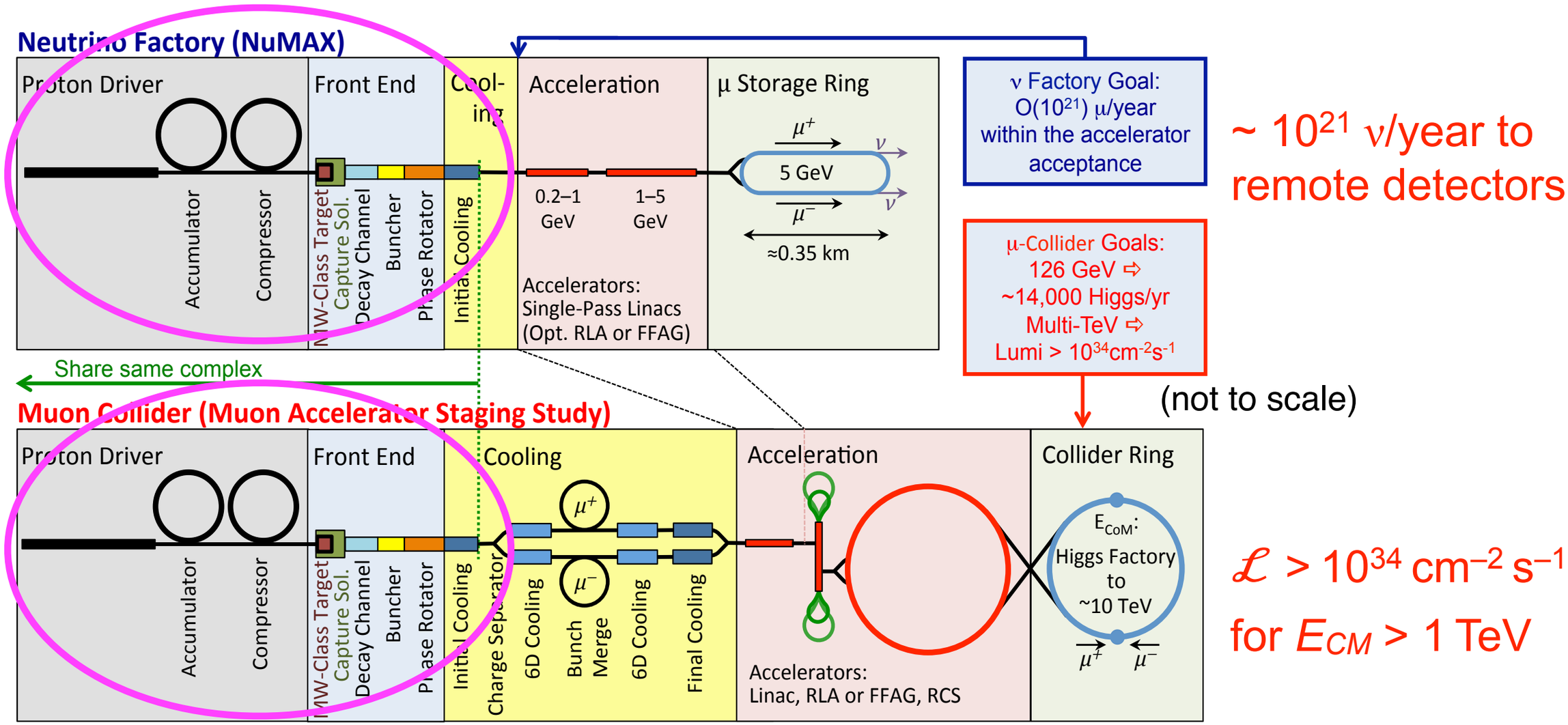
Outline

- Neutrino Factories and Muon Colliders
- Muon cooling
- Muon Ionization Cooling Experiment (MICE)
- Conclusions

νF and μC



~ 10^{21} ν/year to remote detectors

(not to scale)

$\mathcal{L} > 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_{CM} > 1$ TeV

- Strong similarities! (Upstream ends nearly identical)
  - stored-muon facilities that start with ~MW *p* beam on high-power tgt → π → μ, then cool, accelerate, & store the μ

Key ν-mixing physics questions:

1. What is the neutrino mass hierarchy?
2. Why is pattern of neutrino mixing so different from that of quarks?
3. How close to zero is the PMNS phase δ?
4. Is 3-generation mixing the whole story?

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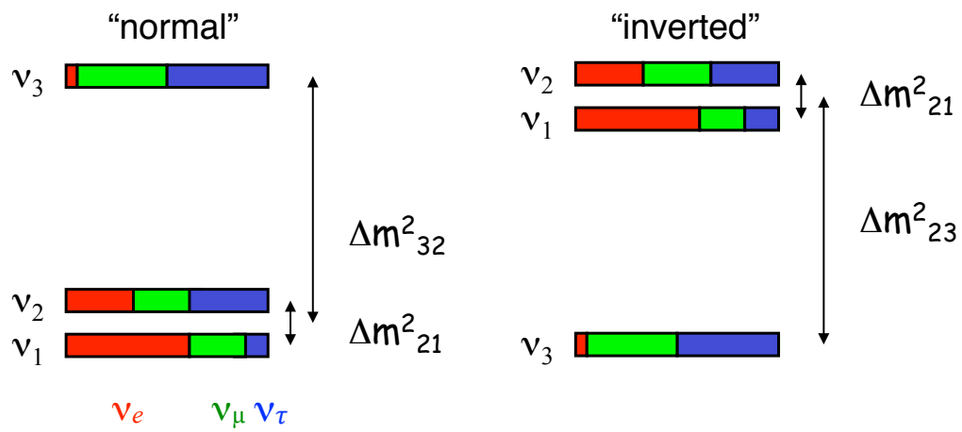

Relevant to cosmology, since neutrinos are 2nd-most-abundant particle in universe!

Emerging expert consensus: next-generation experiments will determine hierarchy

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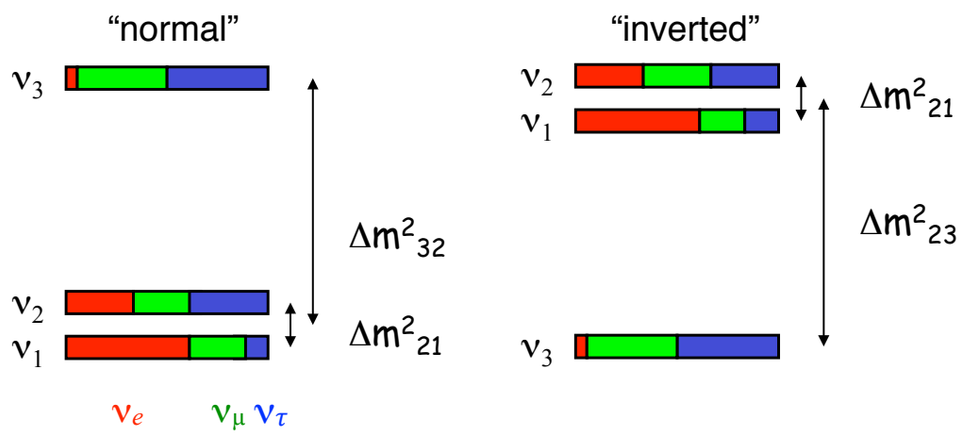

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CKM matrix:

$\theta_{12} \cong 12.8°$
$\theta_{23} \cong 2.2°$
$\theta_{13} \cong 0.4°$

} **hierarchical & nearly diagonal**

PMNS matrix:

$\theta_{12} = 30°$ (solar)
$\theta_{23} = 45°$ (atmospheric)
$\theta_{13} = 9°$ (Daya Bay + Reno + Double Chooz...)

$$\begin{pmatrix} \sim\frac{\sqrt{2}}{2} & \sim-\frac{\sqrt{2}}{2} & \sin\theta_{13}e^{i\delta} \\ \sim\frac{1}{2} & \sim\frac{1}{2} & \sim-\frac{\sqrt{2}}{2} \\ \sim\frac{1}{2} & \sim\frac{1}{2} & \sim\frac{\sqrt{2}}{2} \end{pmatrix}$$

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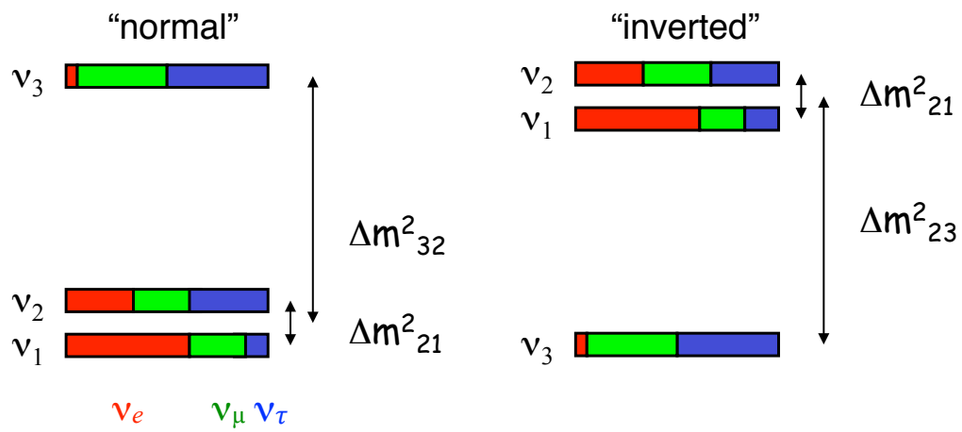

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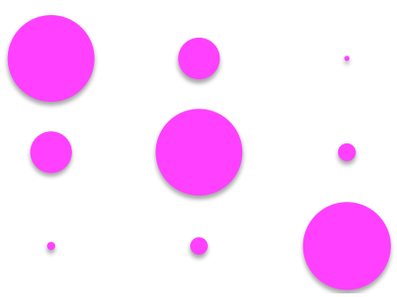

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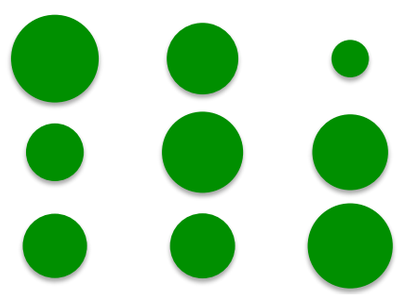

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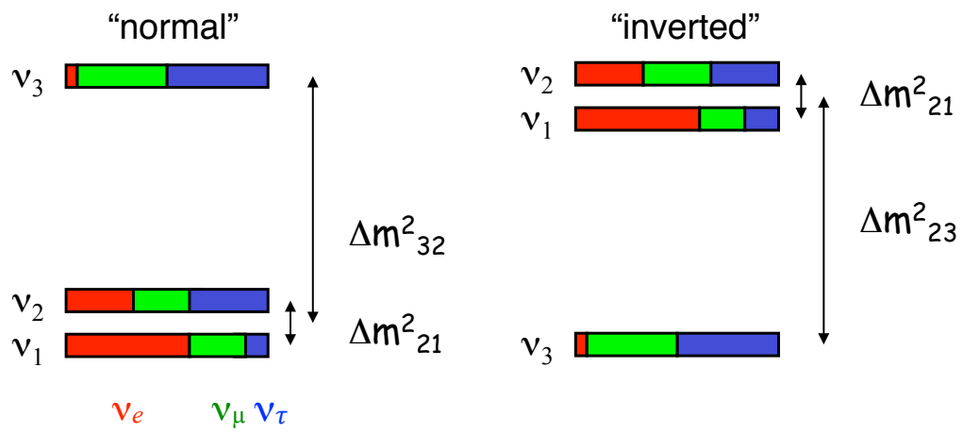

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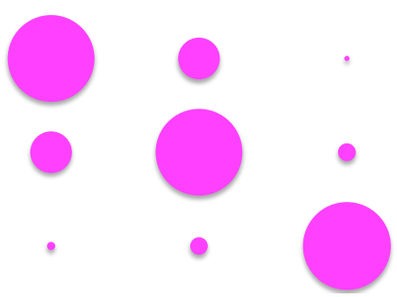

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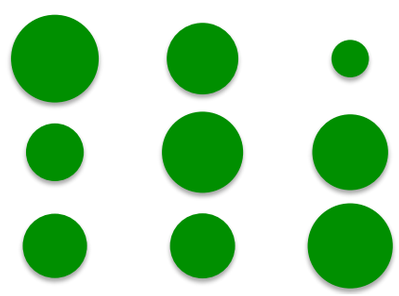

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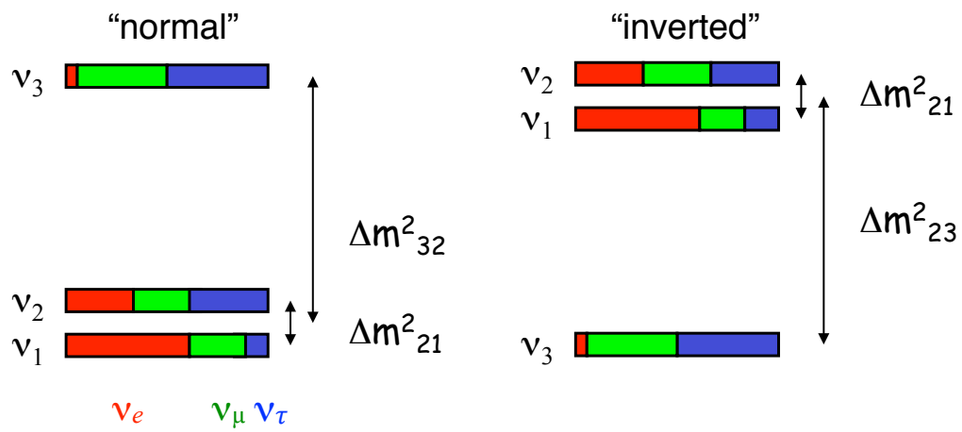

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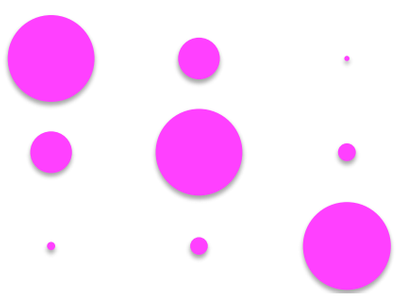

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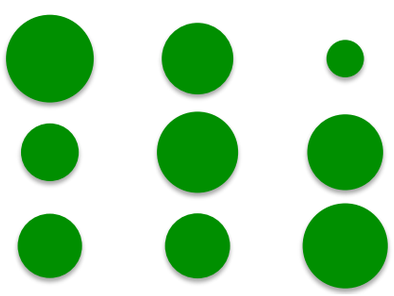

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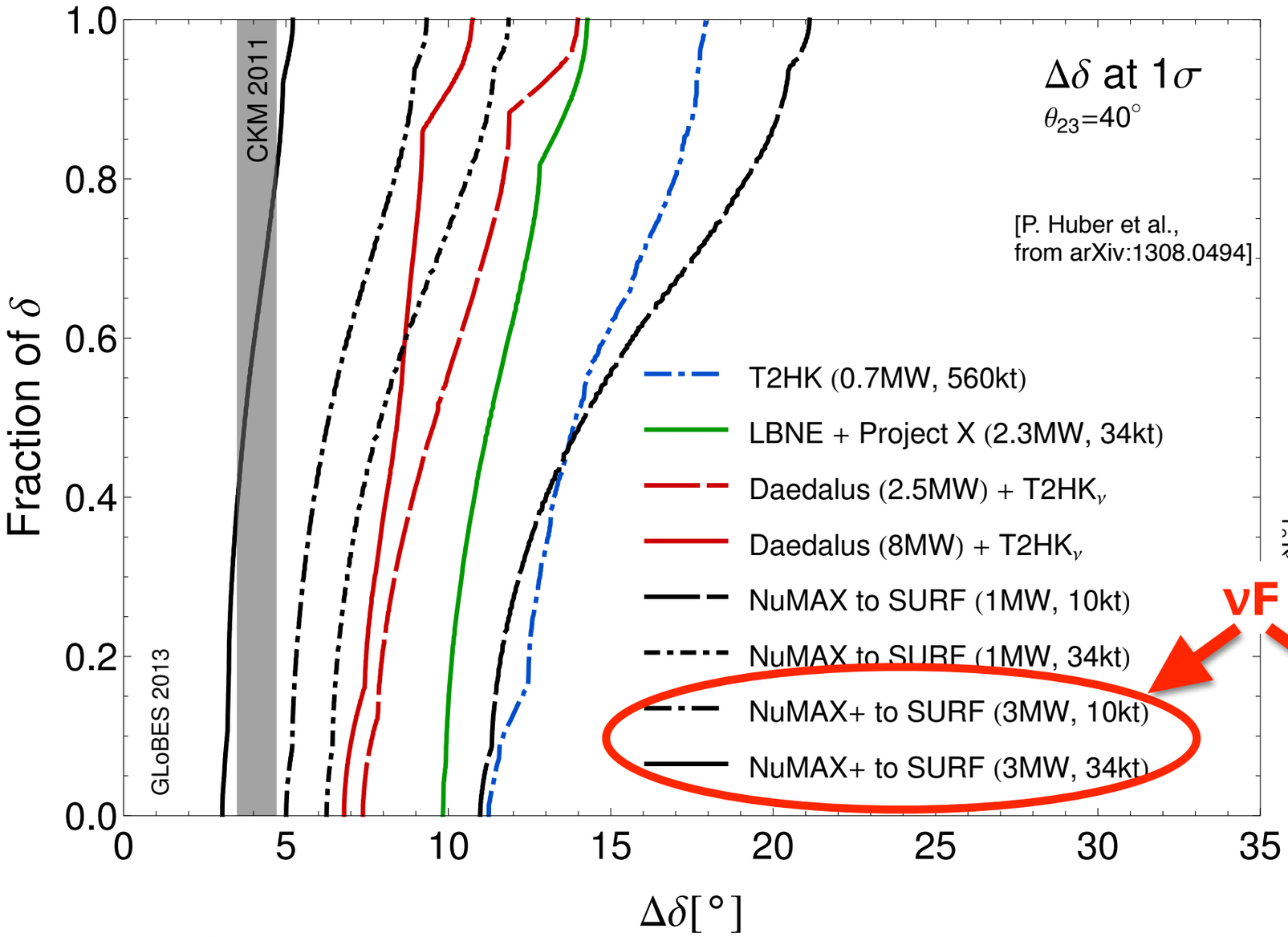
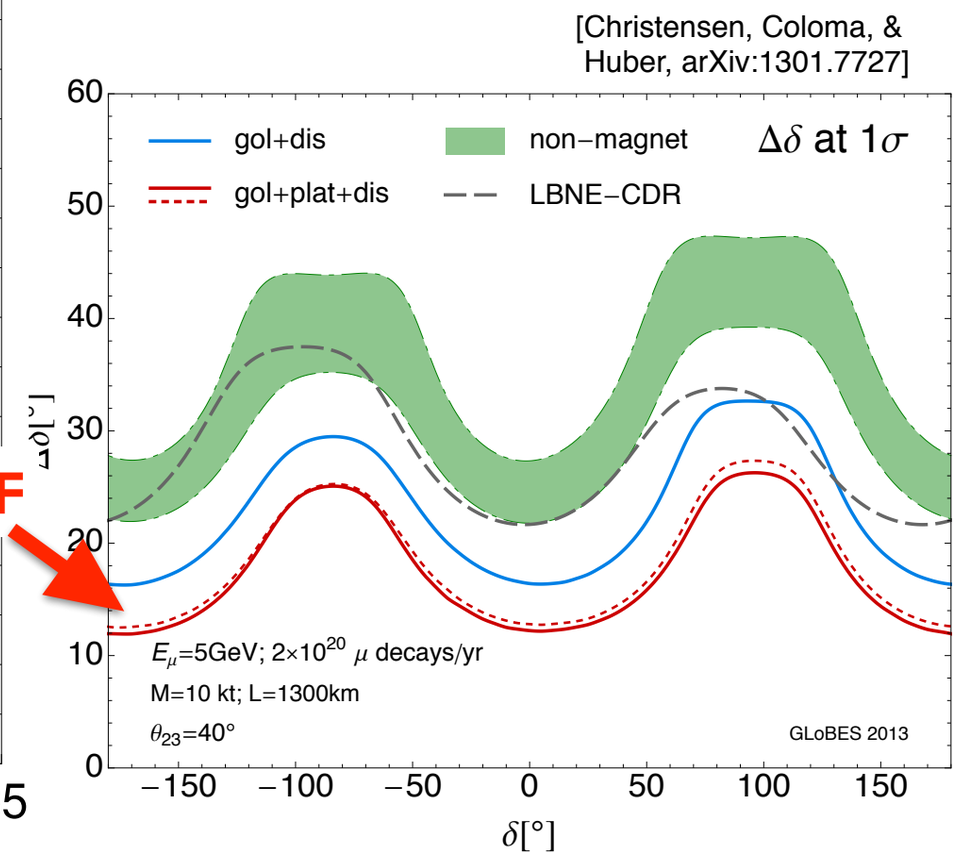
∃ sterile neutrinos? additional dynamical effects: ν decay or decoherence…?

⟹ Need precision measurements→μ storage rings can provide

Neutrino Factory Physics Reach

- CPV sensitivity comparison:





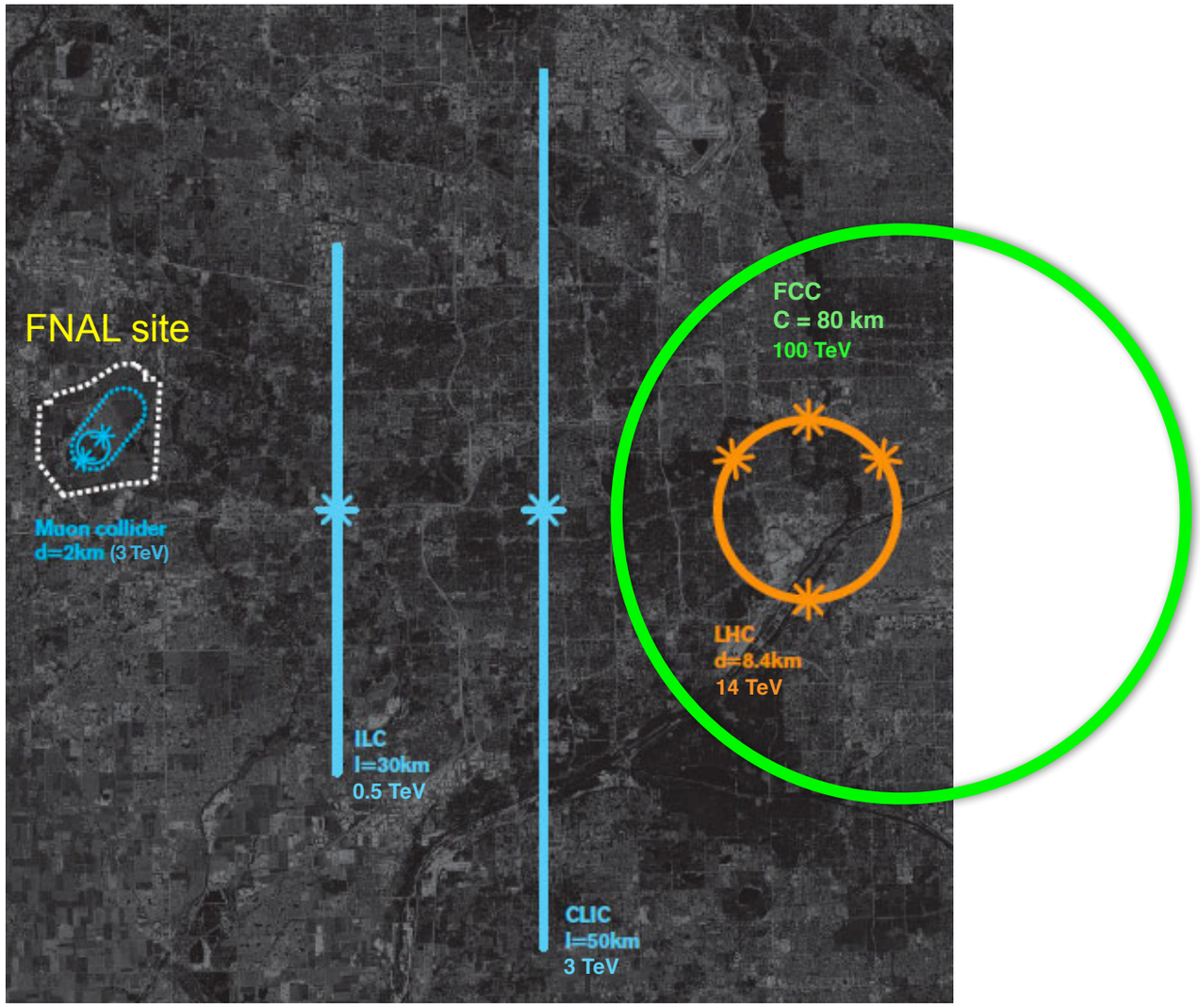
➡ νF has greatest reach…and will ultimately be required!

- only technique with sensitivity comparable to quark sector

What about Muon Colliders?

- An option for *high-energy* lepton colliders
  - unlike e^+e^-, $\sqrt{s}$ not limited by radiative effects

➡ a μC can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV:



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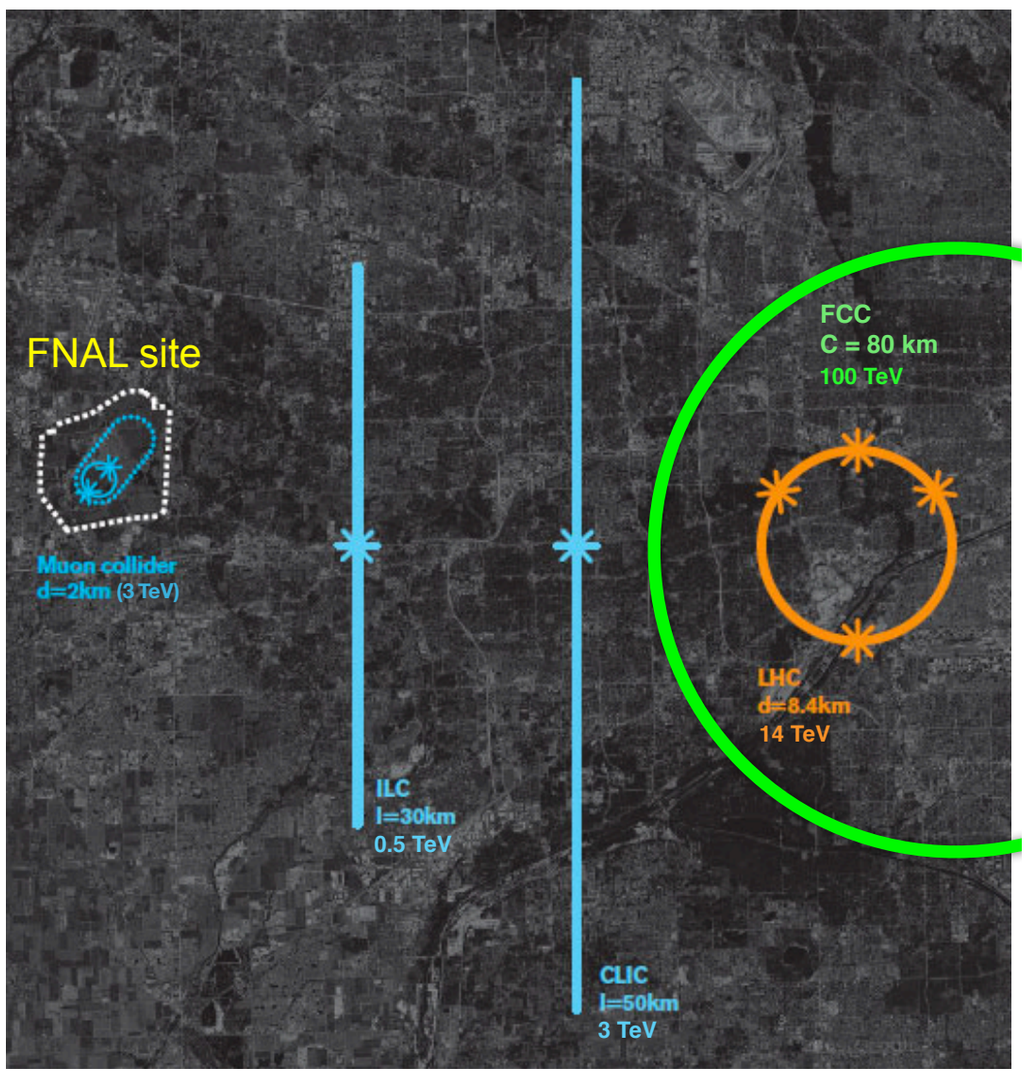

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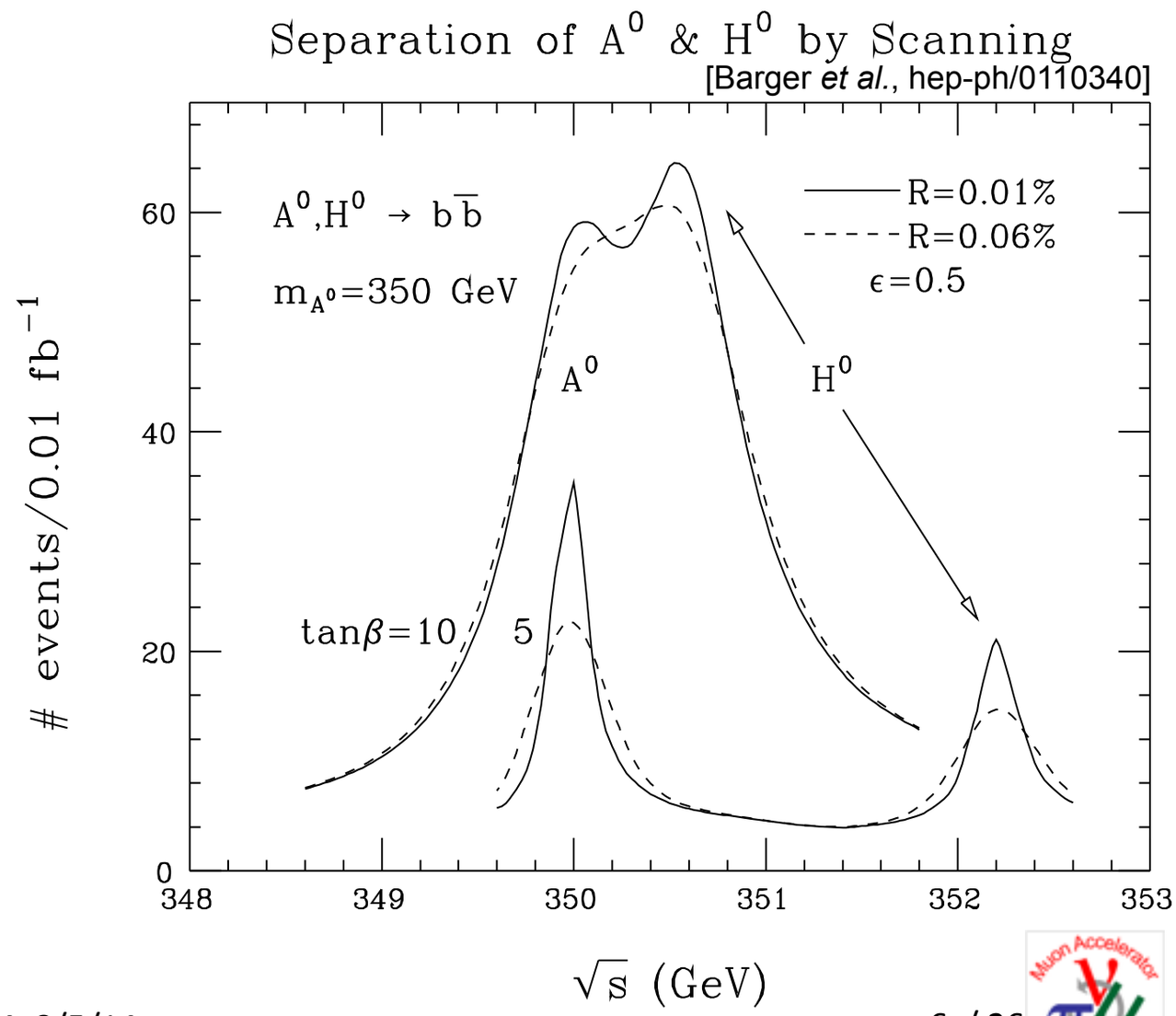
- Also,
  - s-channel coupling of Higgs to lepton pairs $\propto m_{\text{lepton}}^2$

➡ μC resolution can separate near-degenerate scaler and pseudo-scalar Higgs states of high-tan β SUSY



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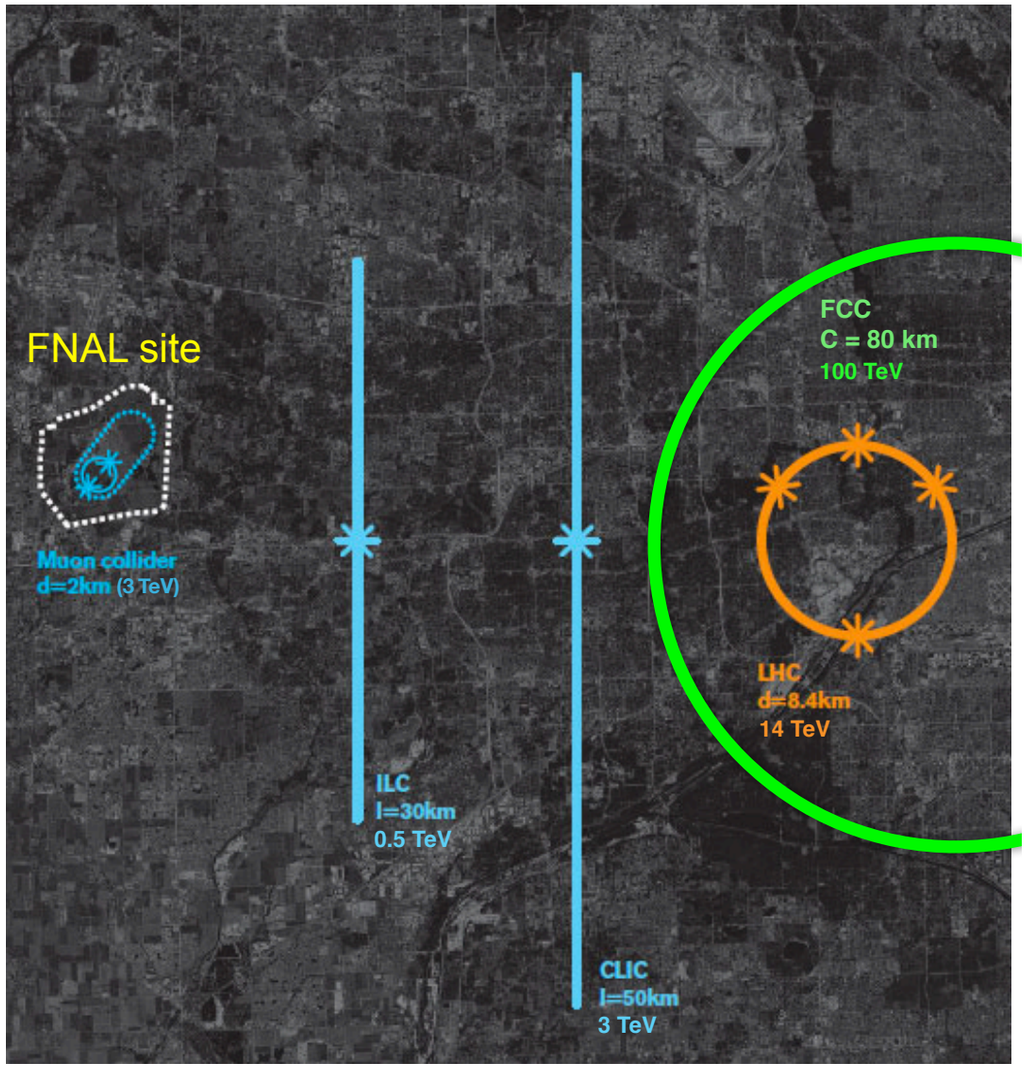

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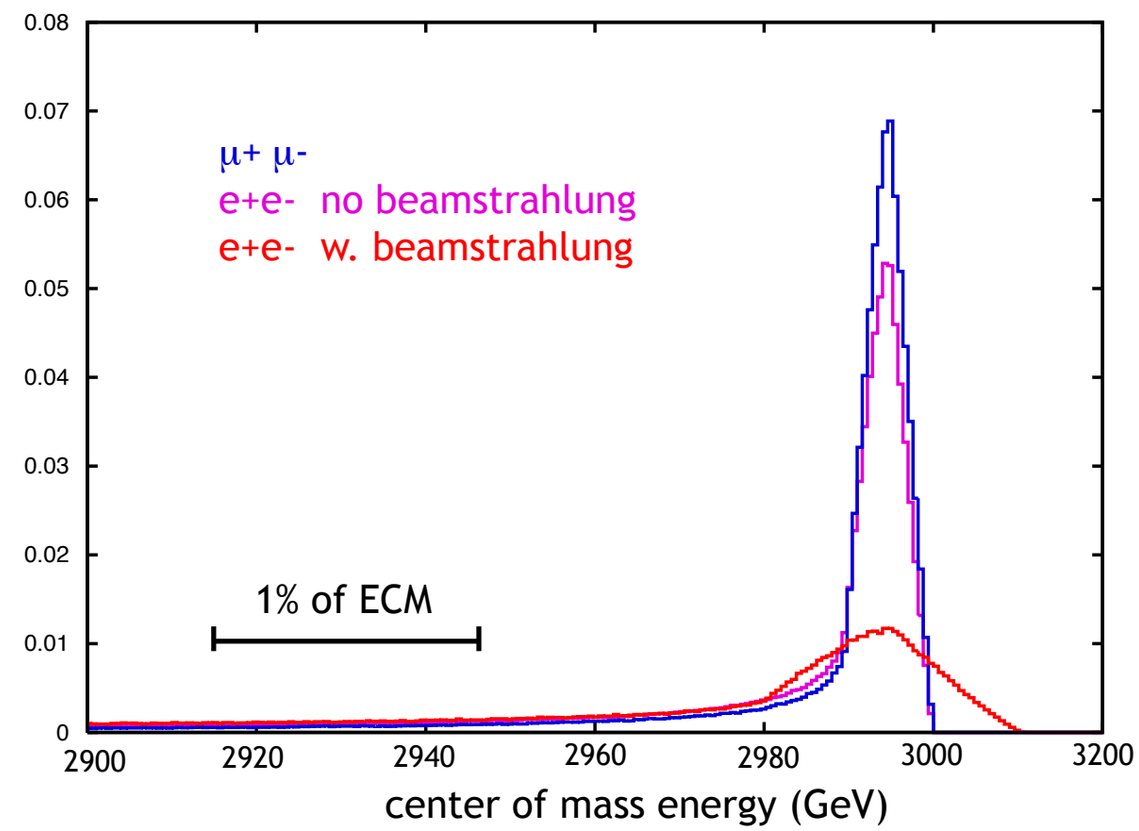


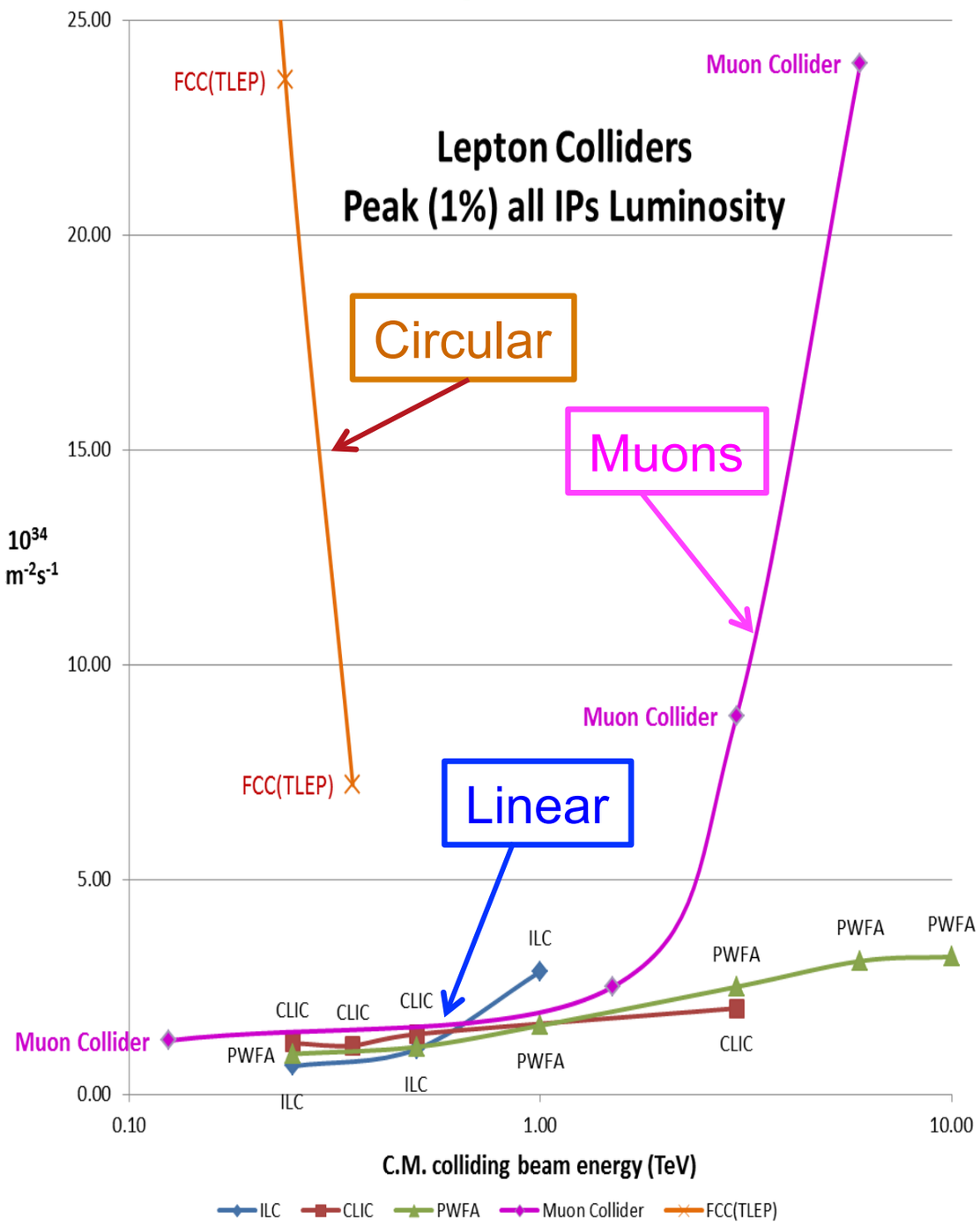
➡ while *any* H.E. e^+e^- collider has long tail to low energy

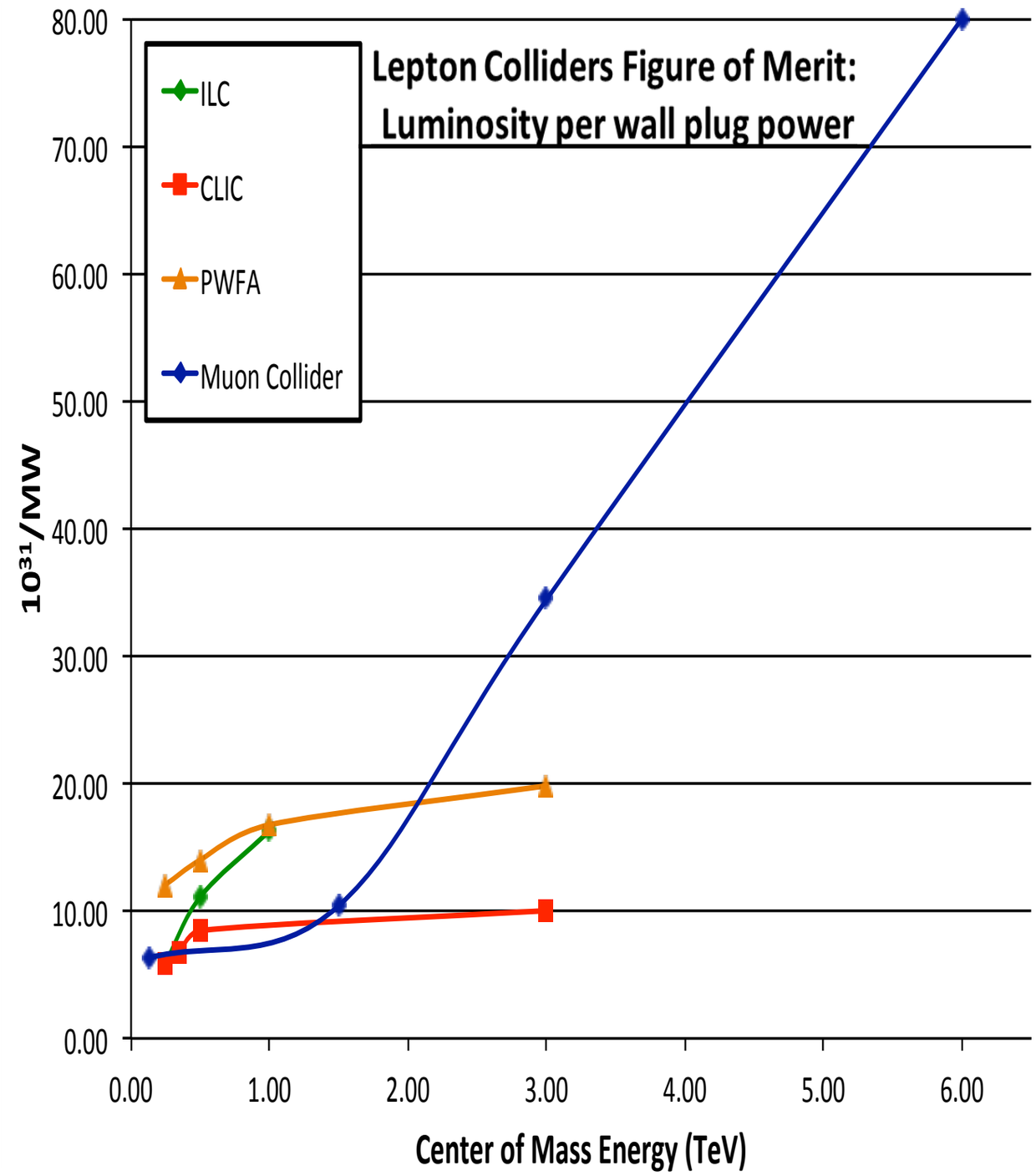
➡ as well as much higher operating costs for $E > 2$ TeV

Lepton Collider Comparisons

[from J.-P. Delahaye]

- Negligible radiative effects, and multiple interaction regions, make muons the lepton of choice for multi-TeV colliders





Technical Challenges*

1. High-power (multi-MW) *p* beam and target

   (e.g., SNS, ESS,…)

   - > 4 MW Hg jet feasible [MERIT@CERN, 2007]

2. Muon beam cooling in all 6 phase-space dimensions

   - μ unstable, τ_μ = 2.2 μs ⇒ must cool quickly! [MICE]
   - requires high-gradient RF cavities in *B* > 1 T fields [FNAL MTA]

3. *Rapid* acceleration

   - Linac–RLAs–(FFAGs)–RCS
     [EMMA@DL, 2011; proposed JEMMRLA@JLab]

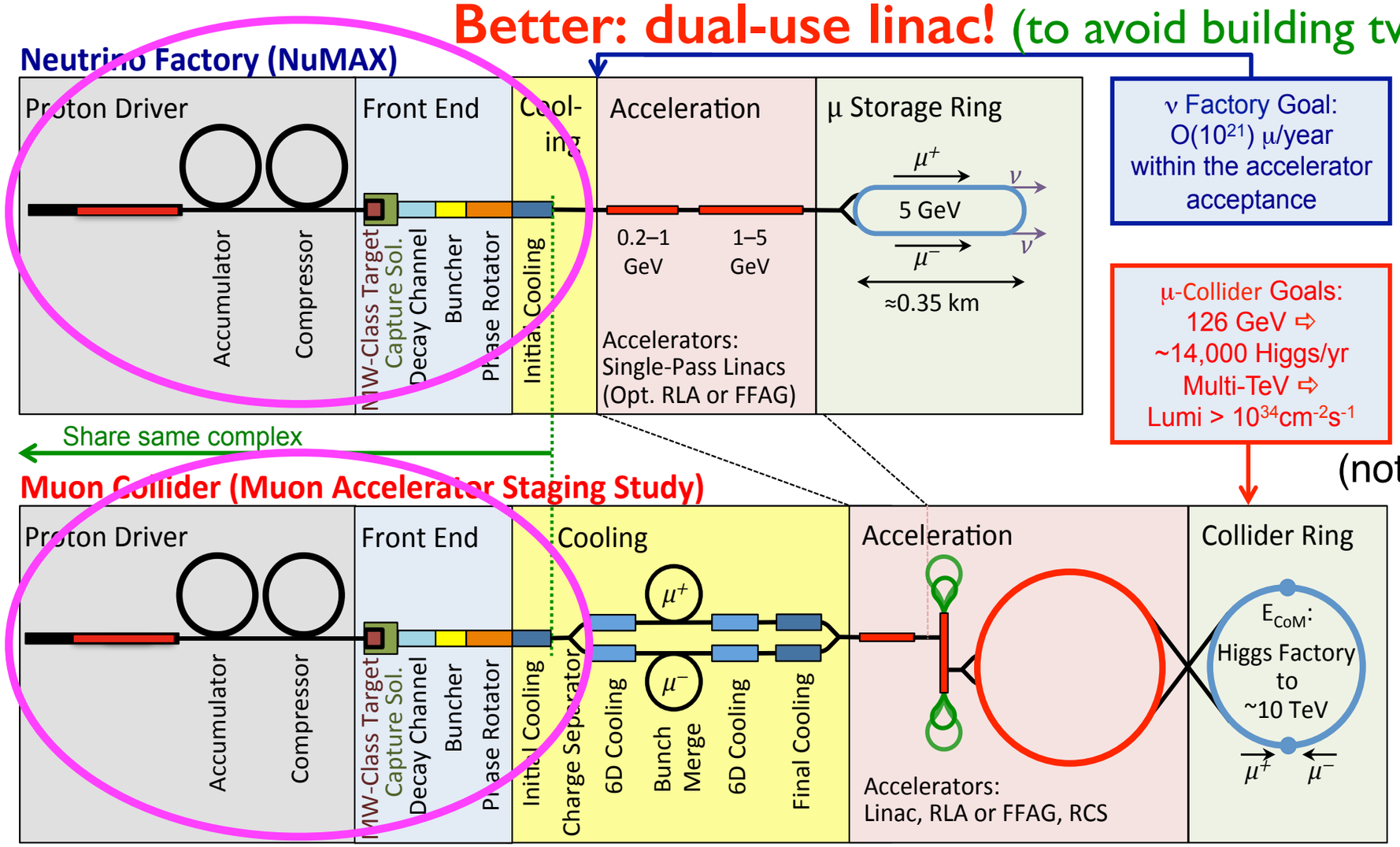
4. High storage-ring bending field (to maximize # cycles before decay) and small $\beta_\perp$, for high $\mathcal{L}$

   - Solution devised @ FNAL: *B* ~ 10 T, β ~ 1 cm

*[& demonstration experiments]

νF and μC

Better: dual-use linac! (to avoid building two expensive SC linacs)



ν Factory Goal: $O(10^{21})$ μ/year within the accelerator acceptance

μ-Collider Goals: 126 GeV ⇨ ~14,000 Higgs/yr Multi-TeV ⇨ Lumi > 10^{34} cm^{-2}s^{-1}

(not to scale)

~ 10^{21} ν/year to remote detectors

$\mathcal{L} > 10^{34}$ cm^{-2} s^{-1} for $E_{CM} > 1$ TeV

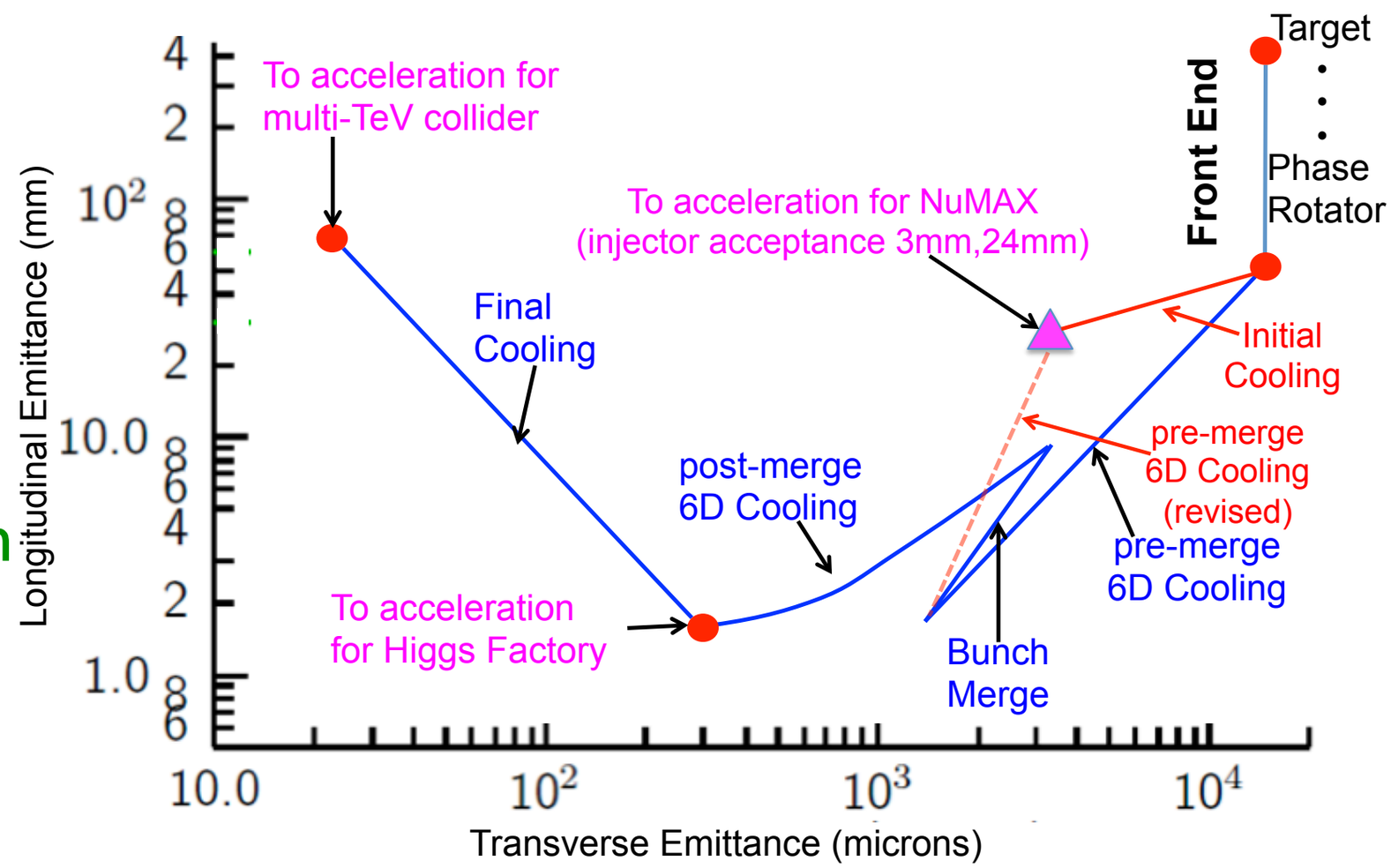
- Strong similarities! (Upstream ends nearly identical)
  - stored-muon facilities that start with ~MW *p* beam on high-power tgt → π → μ, then cool, accelerate, & store the μ
  - note two similar few-GeV linacs: one in Proton Driver, one after cooling

Muon Cooling

- Beam cooling best understood in terms of beam's normalized emittance $\epsilon_n = \gamma\beta\epsilon = \epsilon p/m$
- Physics of multi-TeV lepton collisions calls for $\mathcal{L} > 10^{34}$ cm^{-2} s^{-1}

  $\Rightarrow$ must cool both $\epsilon_\perp$ & $\epsilon_{||}$

  - need factor 10^6 in total 6D emittance reduction



- Higgs physics requires $\mathcal{L} \sim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
- Neutrino factory with dual-use linac requires more modest, x 50 6D cooling factor

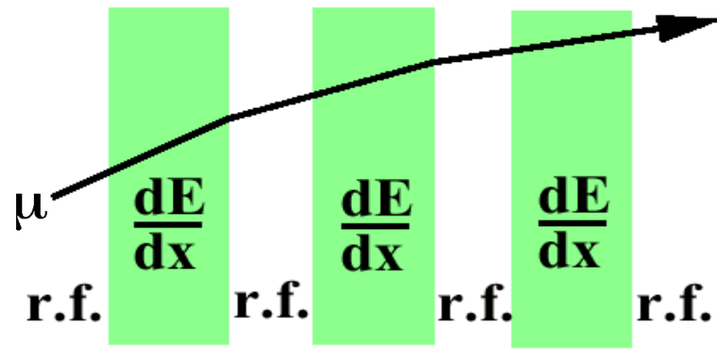
How to cool muons?

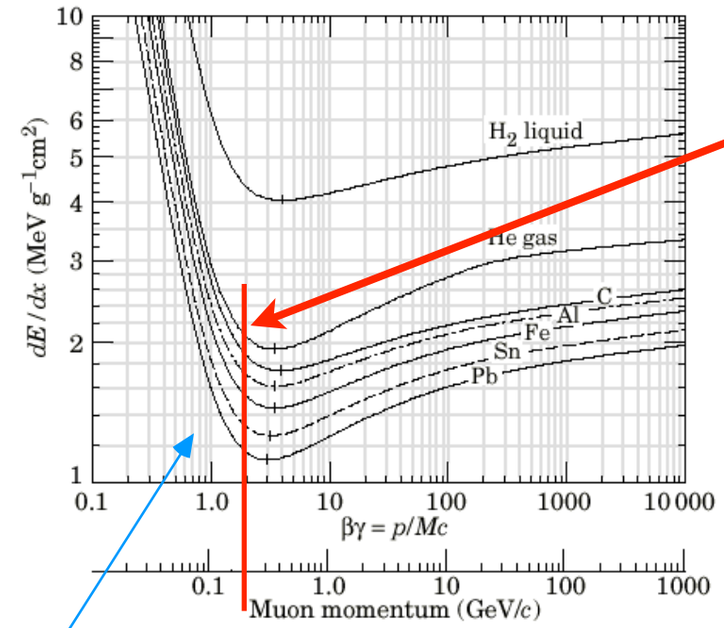
- Problem: Average lifetime at rest = 2.2 μs
- But established cooling methods (stochastic, electron) take seconds to hours!

- What cooling method can work in << 2.2 μs?
  - There is only one:
    - electron cooling with an *extremely dense* electron "gas" – denser than any beam…

Ionization Cooling!

- Muons cool via *dE/dx* in low-*Z* medium:





- optimal working point is ≈ ionization minimum

– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- 2 competing effects ⇒ equilibrium emittance: $\varepsilon_0 \propto \beta_\perp / \langle dE/ds \rangle X_0$

– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

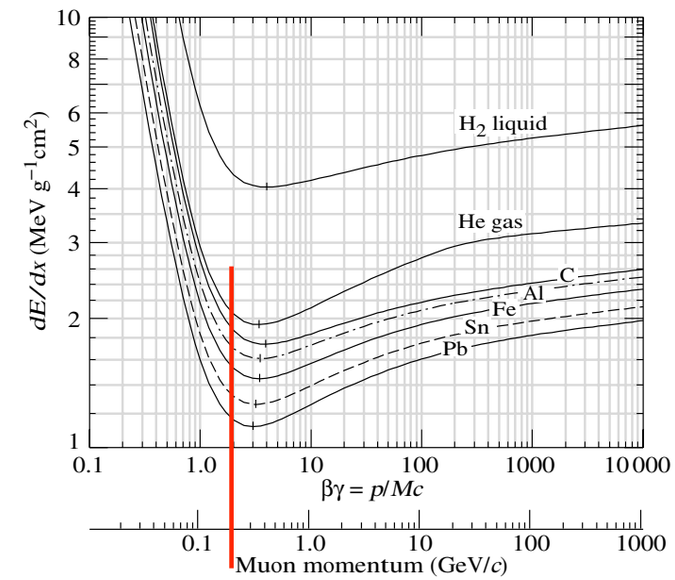
(emittance change per unit length)

- Only* practical way to cool within μ lifetime
- Expt'l demo in progress…[MICE]

*Optical stochastic cooling?

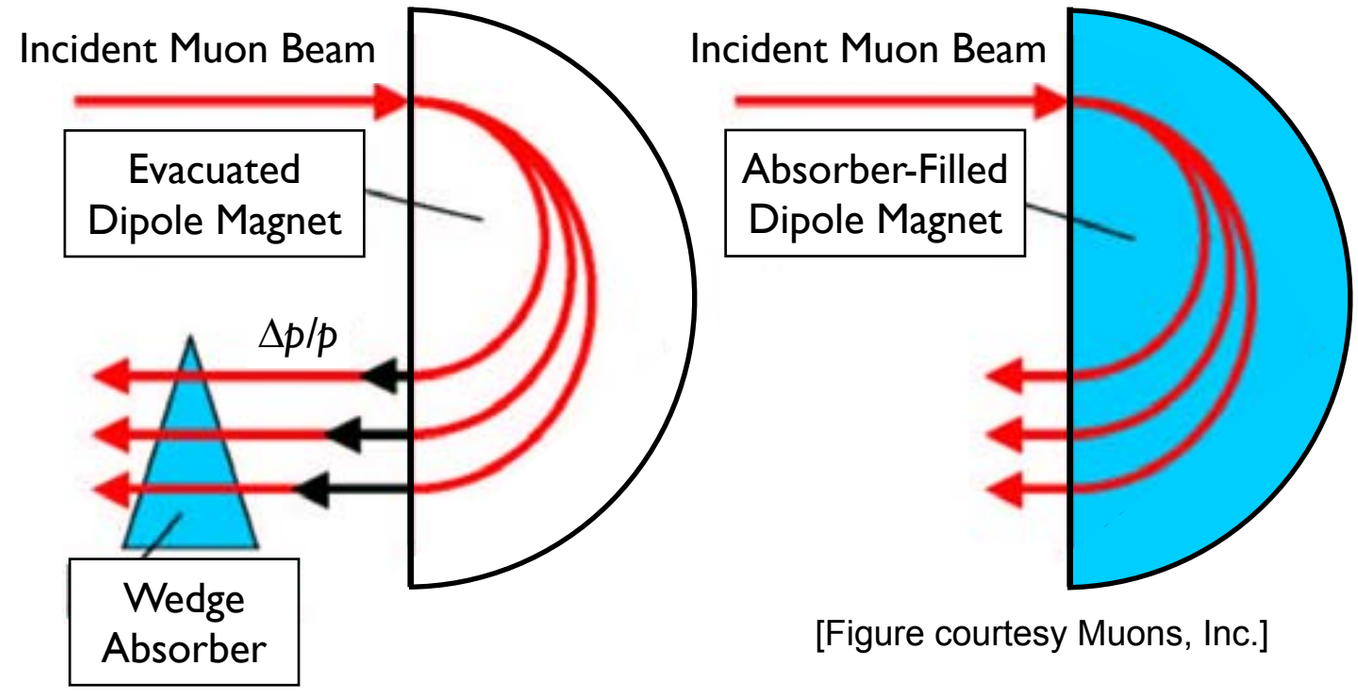
How to cool in 6D?

- Work above ionization minimum to get negative feedback in p_z?
- No – ineffective due to straggling



⇒cool longitudinally via *emittance exchange*:

- use dispersion to create appropriate correlation between momentum and position / path length



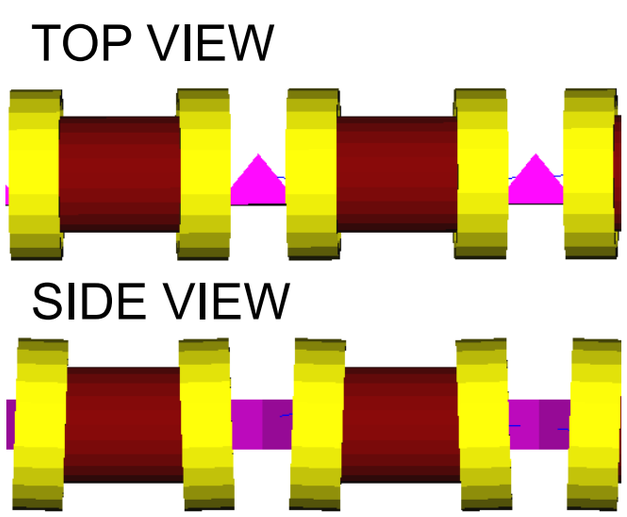
[Figure courtesy Muons, Inc.]

- Cool $\epsilon_\perp$, exchange $\epsilon_\perp$ & $\epsilon_{||}$ → 6D cooling

How to cool in 6D?

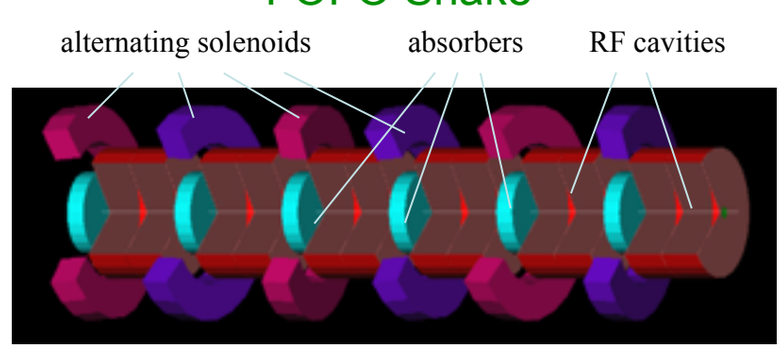
- Tricky beam dynamics: must handle dispersion, angular momentum, nonlinearity, chromaticity, & non-isochronous beam transport
- 3 types of solutions viable in simulation:

Rectilinear FOFO



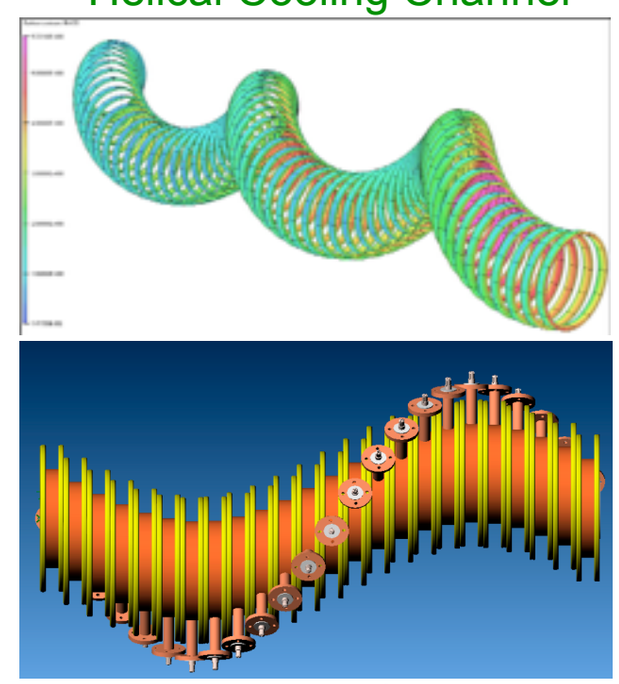
BNL & FNAL

FOFO Snake



Y. Alexahin, FNAL

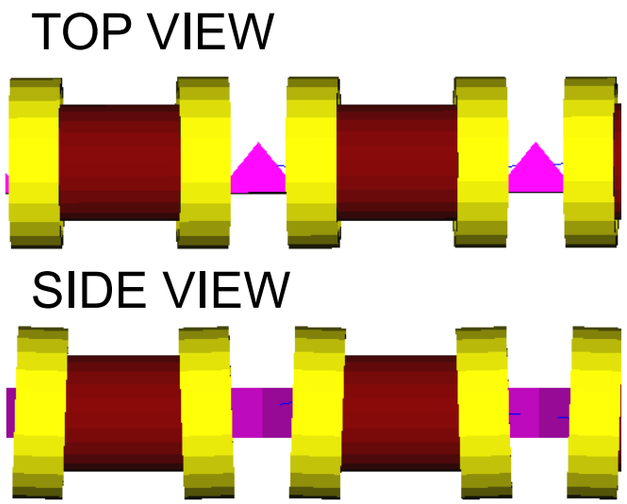
Helical Cooling Channel



Muons, Inc. & FNAL

How to cool in 6D?

Rectilinear FOFO



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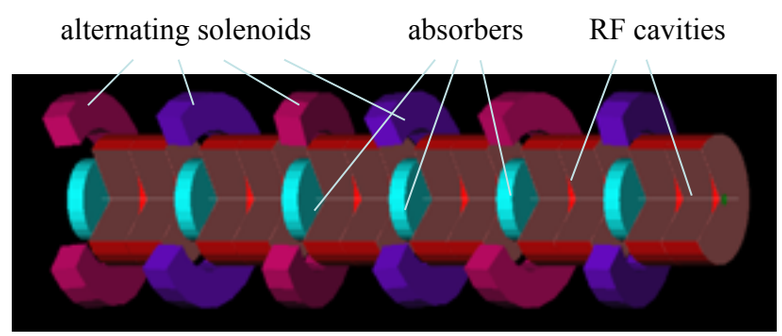

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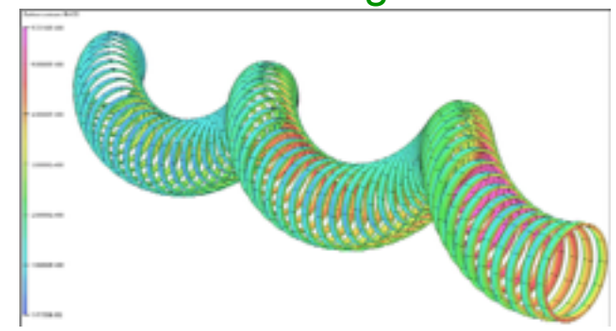
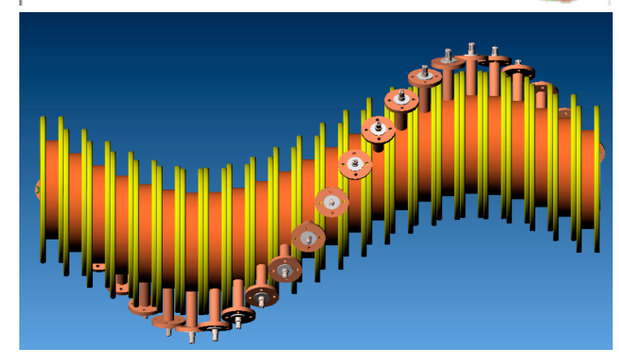


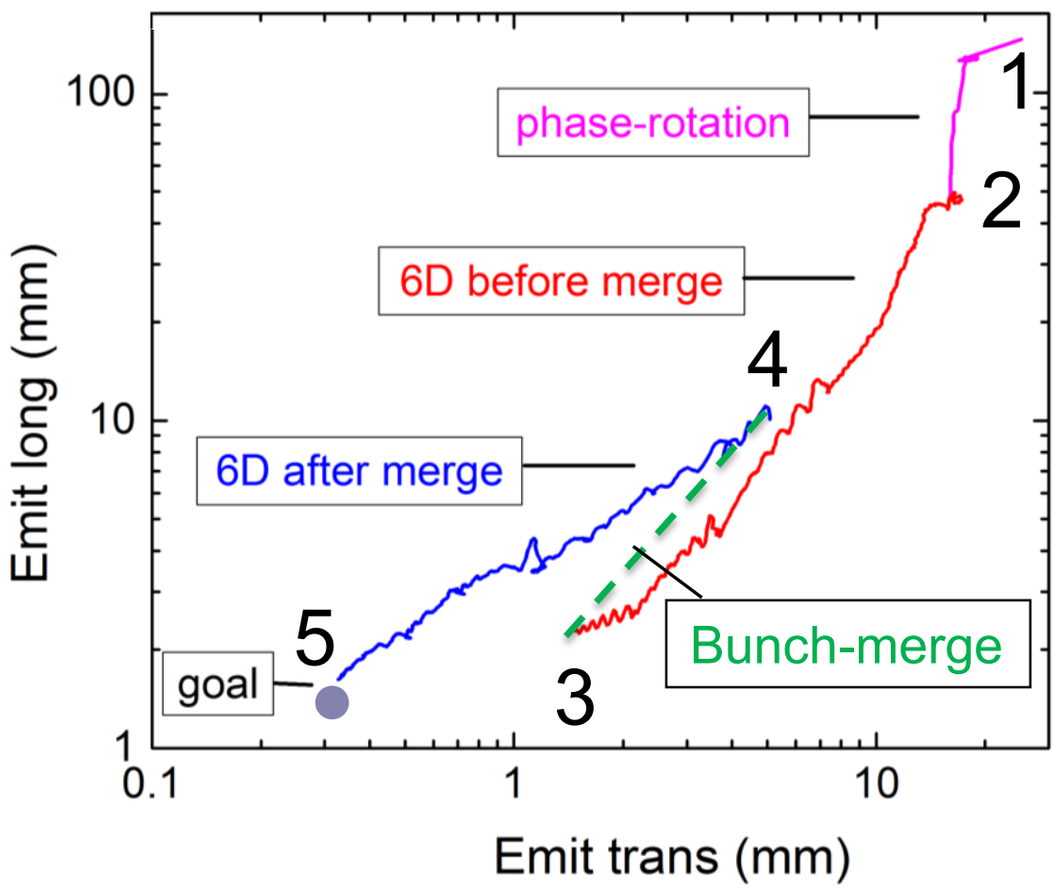


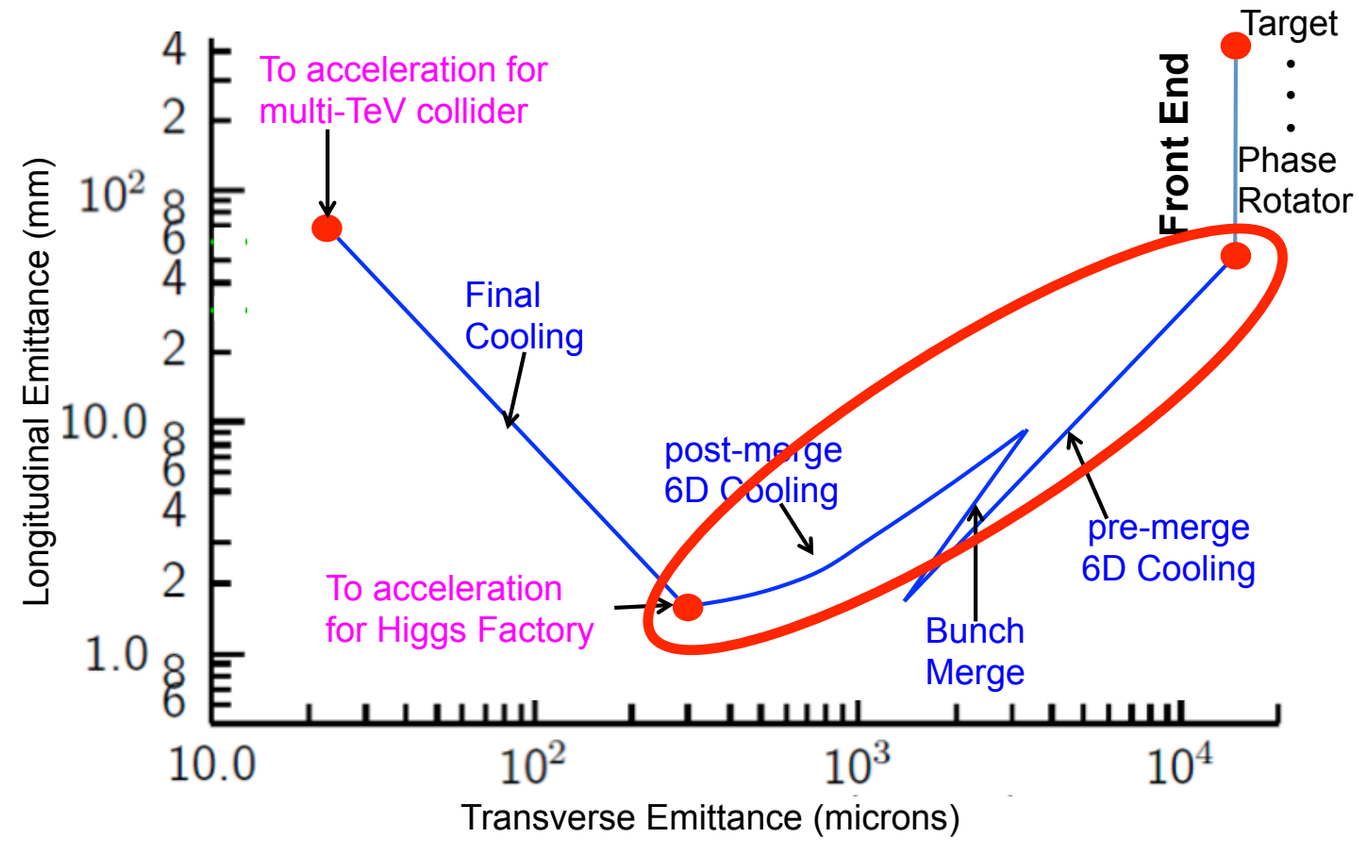
Muons, Inc. & FNAL

- FOFO Snake can cool both signs at once but may be limited in $\beta_{\perp,min}$ ⇒ may be best for initial 6D cooling
- HCC may be most compact
- Performance limits of each not yet clear, nor which is most cost-effective

How to cool in 6D?

- Rectilinear FOFO end-to-end simulation:



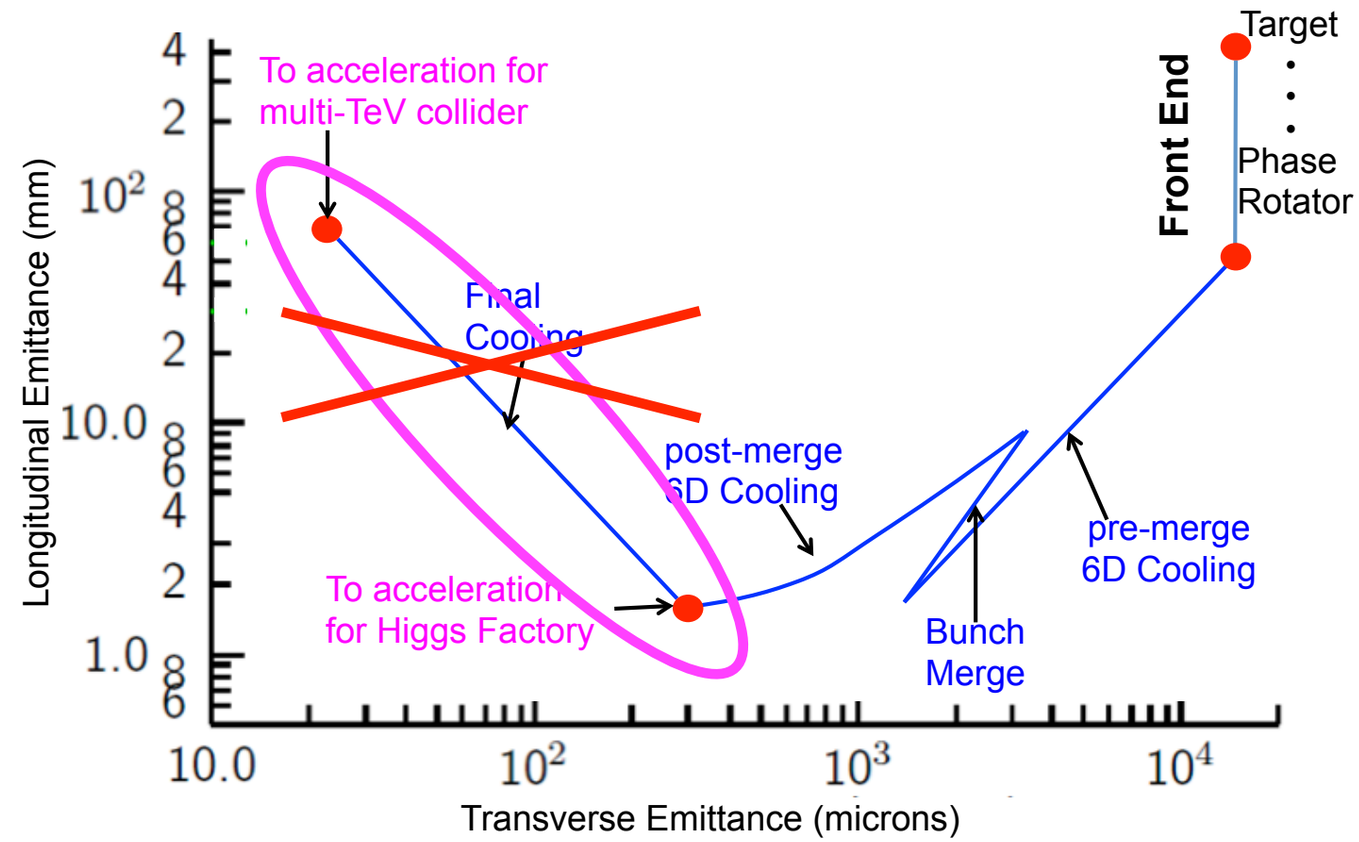


- Achieves ~ desired ϵ_{6D}
  - good match to Higgs Factory
  - but high $\mathcal{L}$ required in multi-TeV regime calls for $\epsilon_\perp \leq 25$ μm→"final cooling"

Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires *exquisite* energy precision:
  - use $\mu^+\mu^- \rightarrow h$ s-channel resonance: $\Gamma_h^{SM} = 4$ MeV
    $\rightarrow$ want $dE/E \approx 0.003\%$

    $\Rightarrow$ omit final cooling



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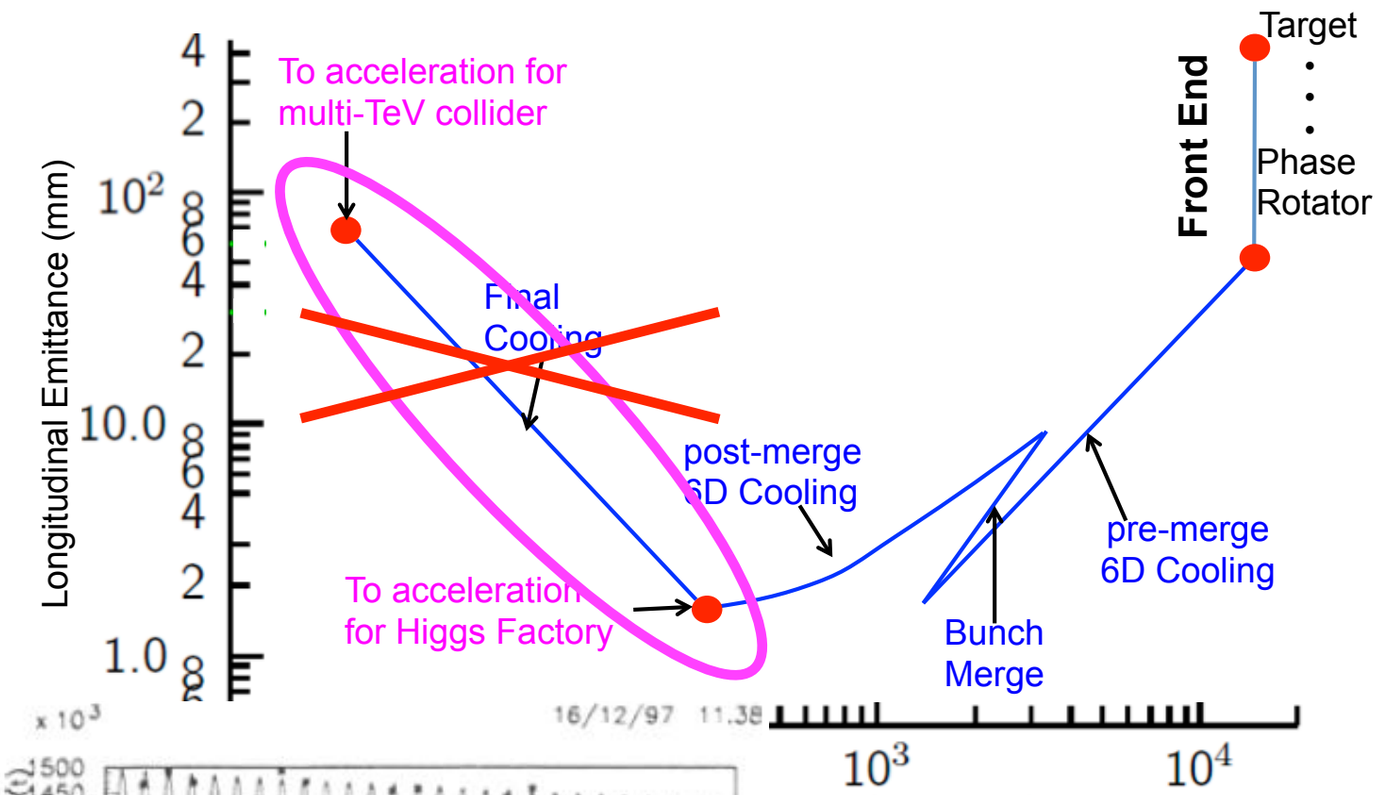
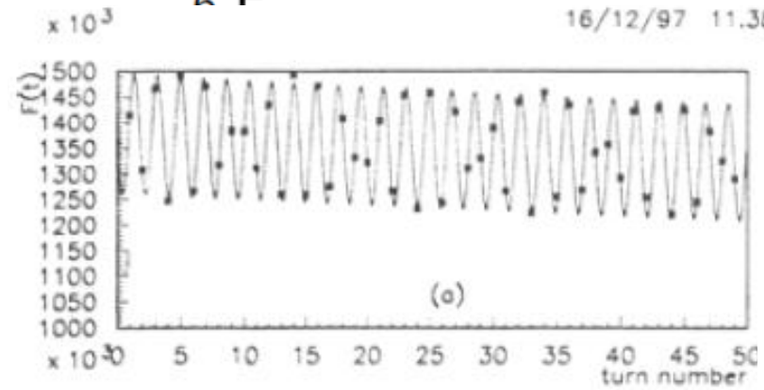
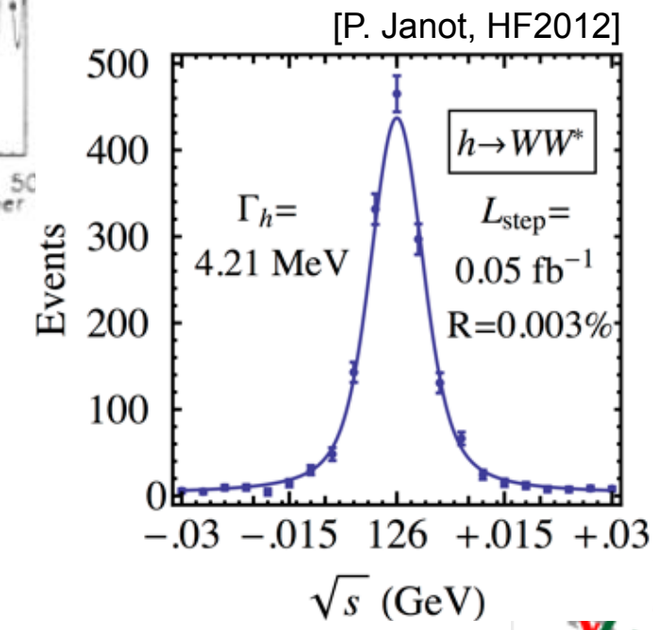
    $\to$ want $dE/E \approx 0.003\%$
    $\Rightarrow$ omit final cooling
  - 10^{-6} energy calib. via $(g-2)_\mu$ spin precession!
  - measure Γ_h, lineshape (& m_h) via $\mu^+\mu^-$ resonance scan
    - the only way to do so!
    - and a key test of the SM





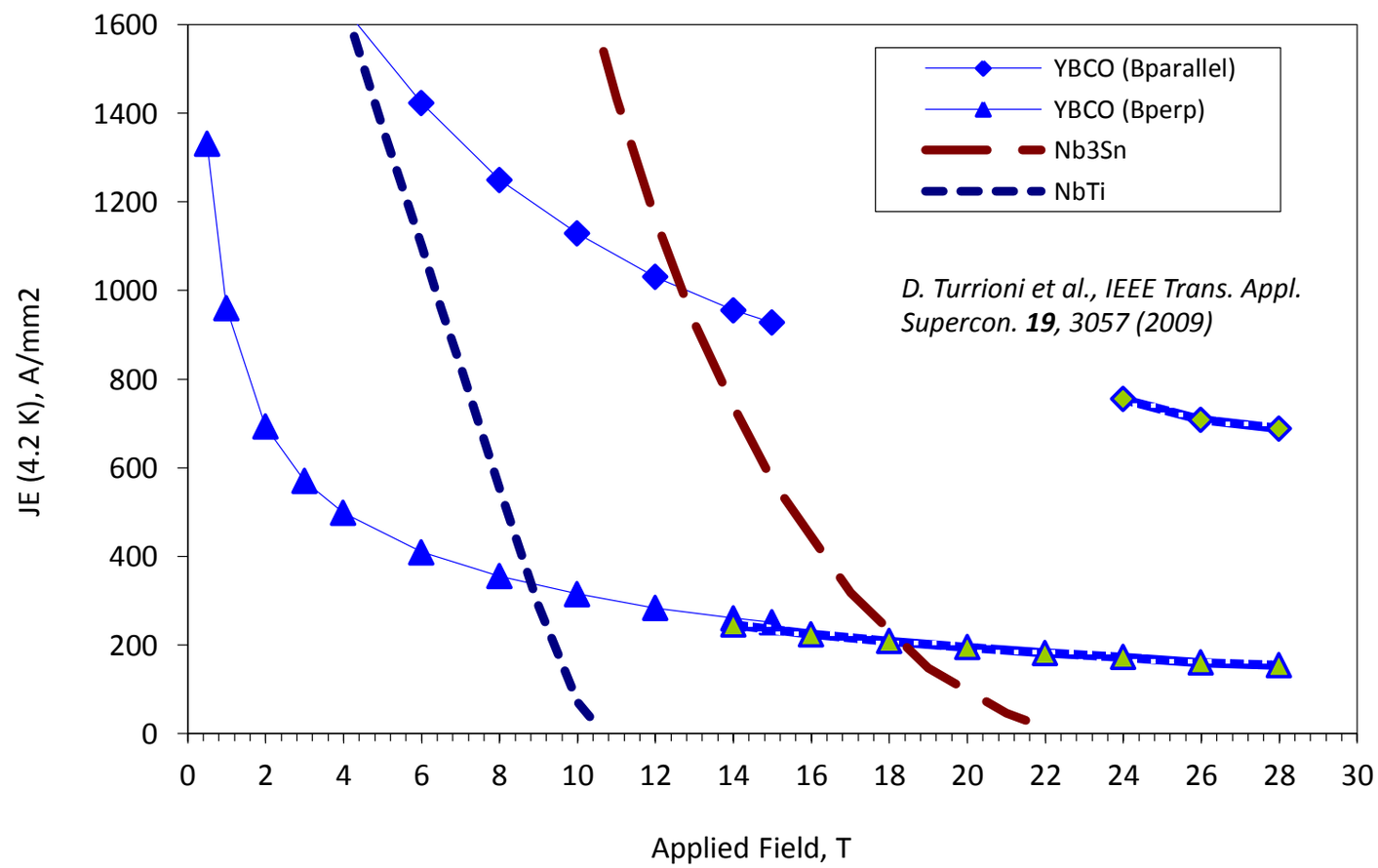
[P. Janot, HF2012]



Beyond 6D Cooling

- To reach ≤ 25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with *B* ~ 30 T at low momentum
  - gives lower β & higher *dE/dx*:

$$\beta_\perp \sim \frac{p}{B}$$



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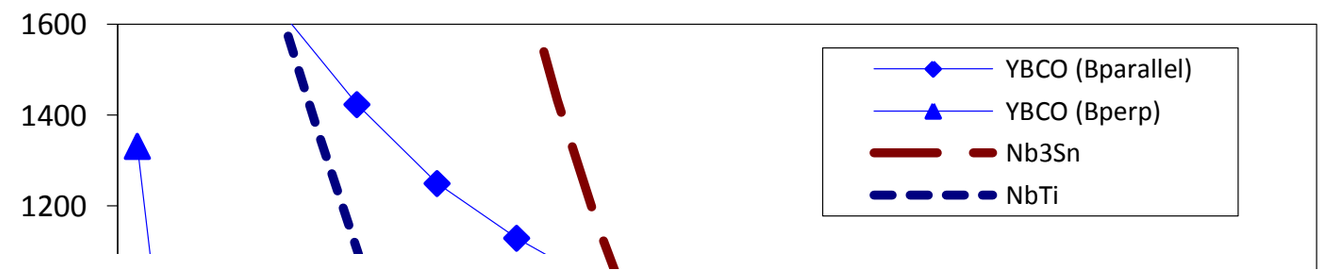
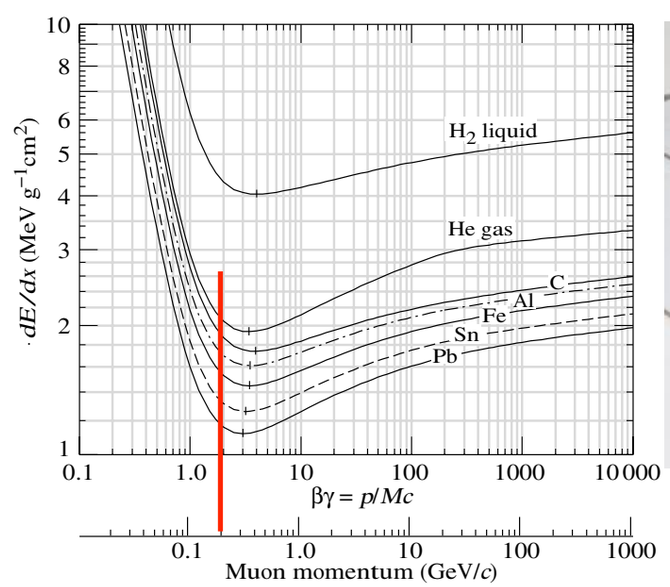
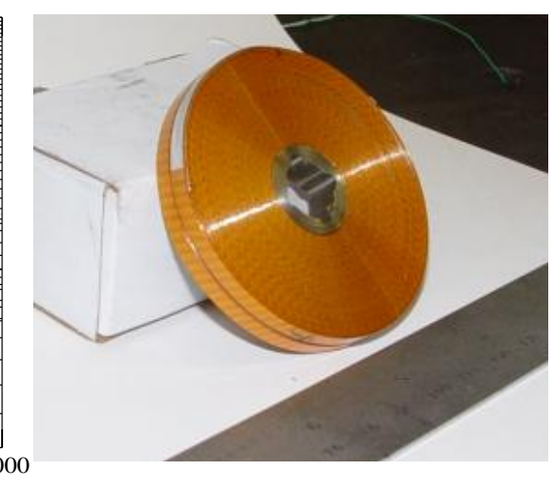






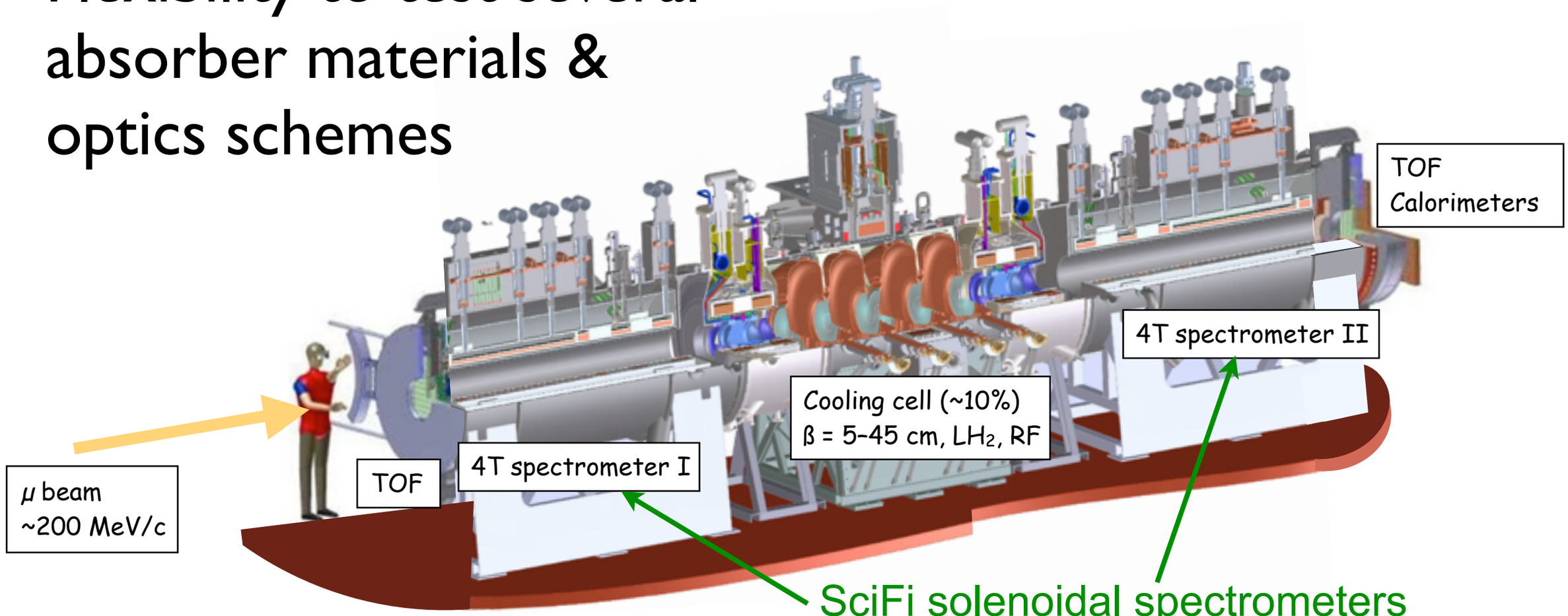
High-field YBCO solenoid (BNL/Particle Beam Lasers, Inc.)

Achieved world-record field in an all-HTS magnet: 15 T on axis

- Lower-*B* options under study as well (Derbenev "PIC/REmEx," lithium lenses)

MICE

- International Muon Ionization Cooling Experiment at UK's Rutherford Appleton Laboratory (RAL)
- Flexibility to test several absorber materials & optics schemes



SciFi solenoidal spectrometers measure emittance to 1‰ (muon by muon)

- Status: under construction

Principles of MICE

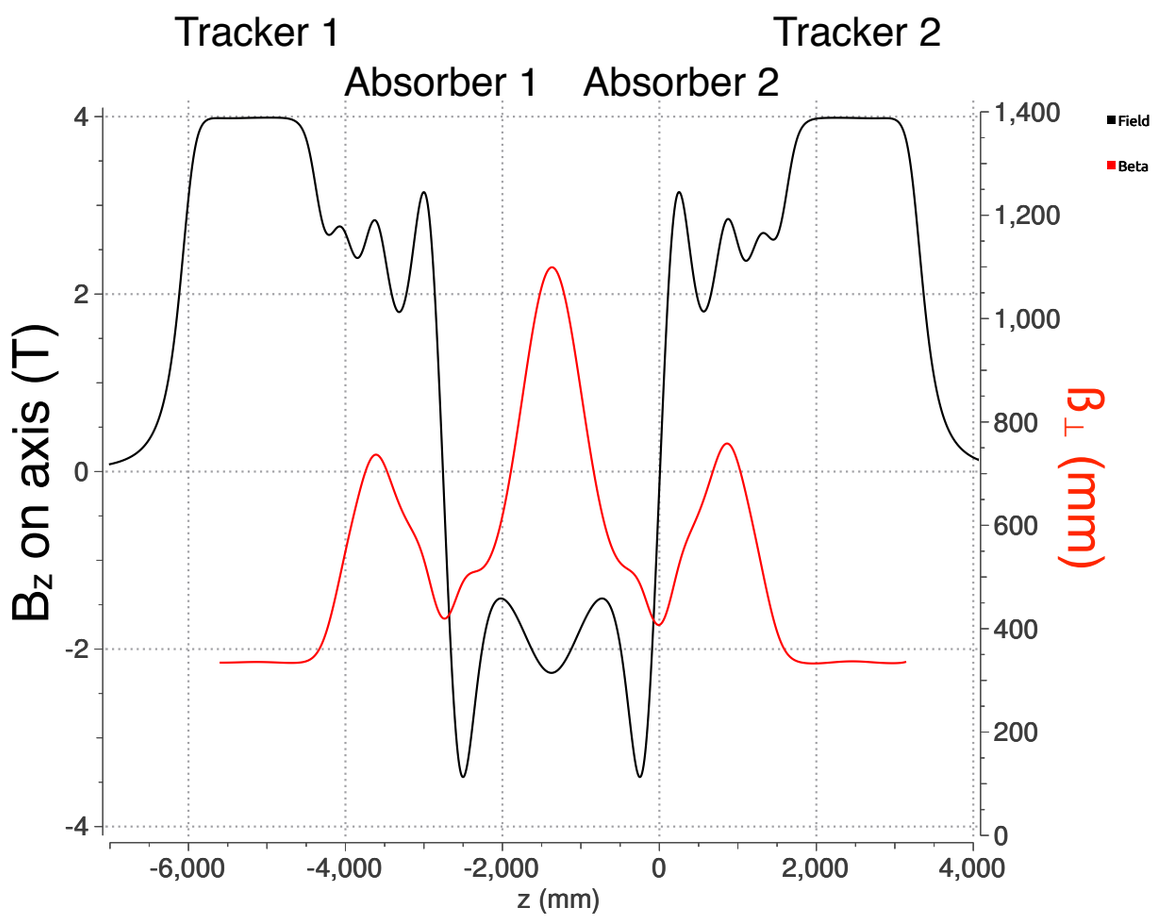
- Build minimum cooling channel that suffices
  - sufficient length to give ≈10% cooling effect
- Measure emittance with 0.1% precision
  - allows even small cooling effects near equilibrium emittance to be well measured

  ⇒ need to measure muon beam one muon at a time
- Vary all parameters to explore full performance range, validate simulation tools

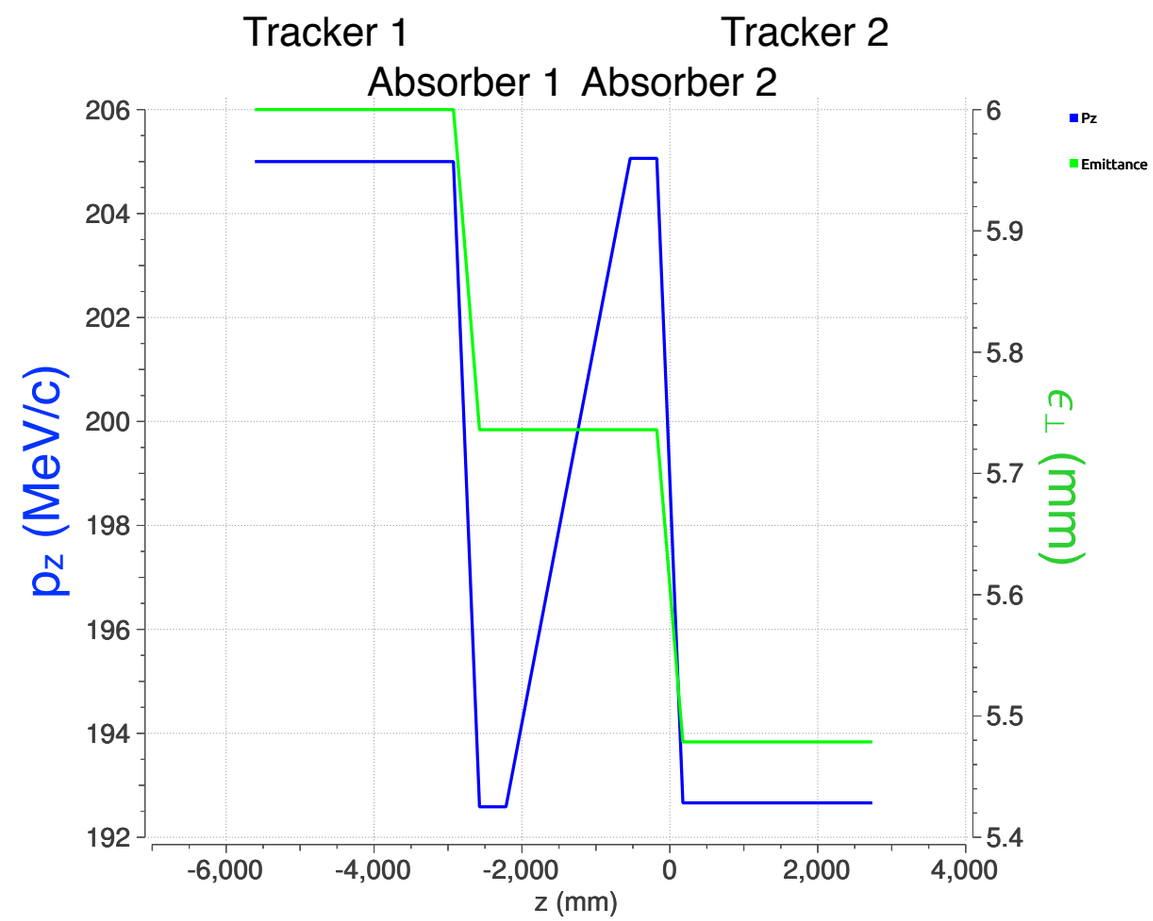
Principles of MICE

(Step V Configuration, nominal beam & optics)

- Optics vs. z:

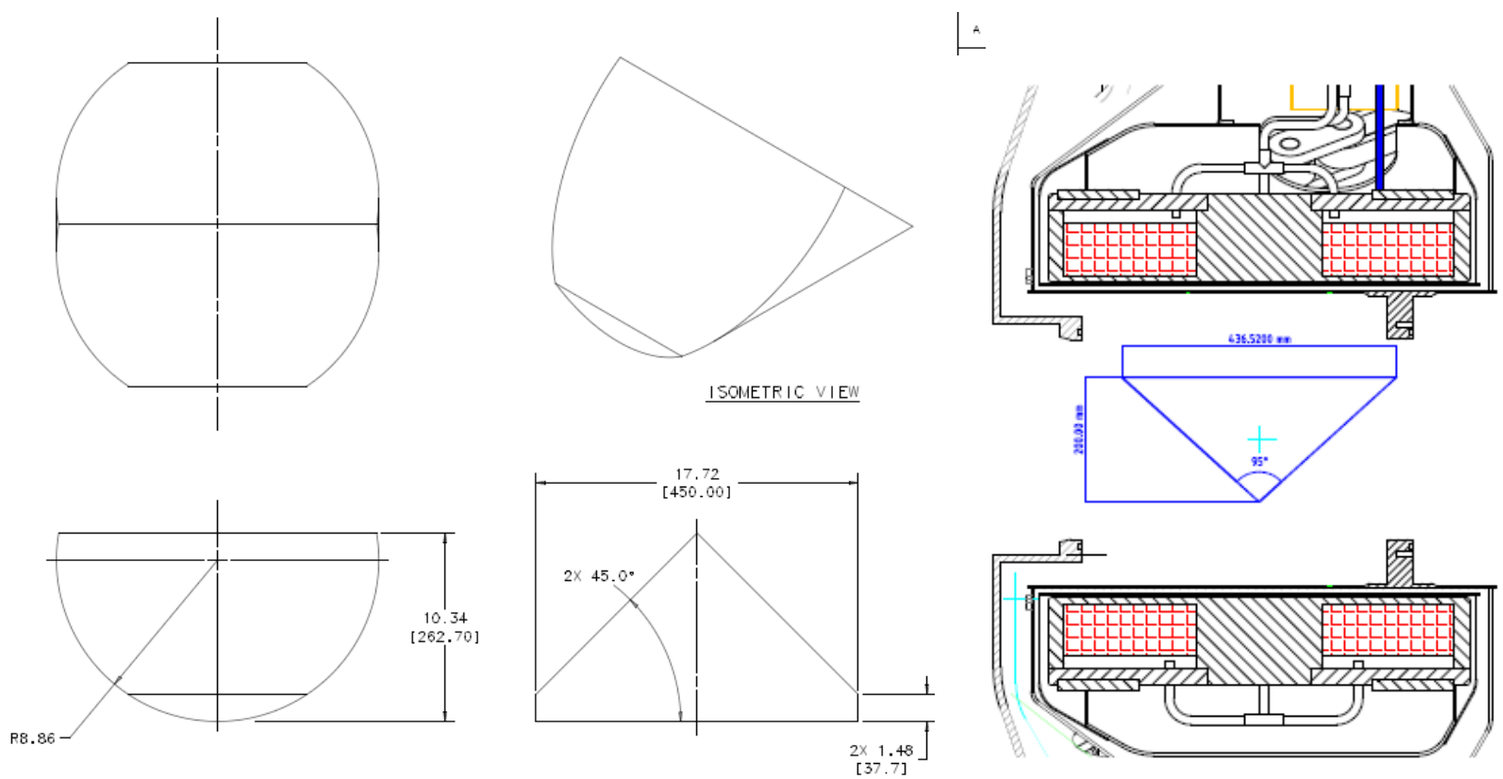


- Beam behavior vs. z:



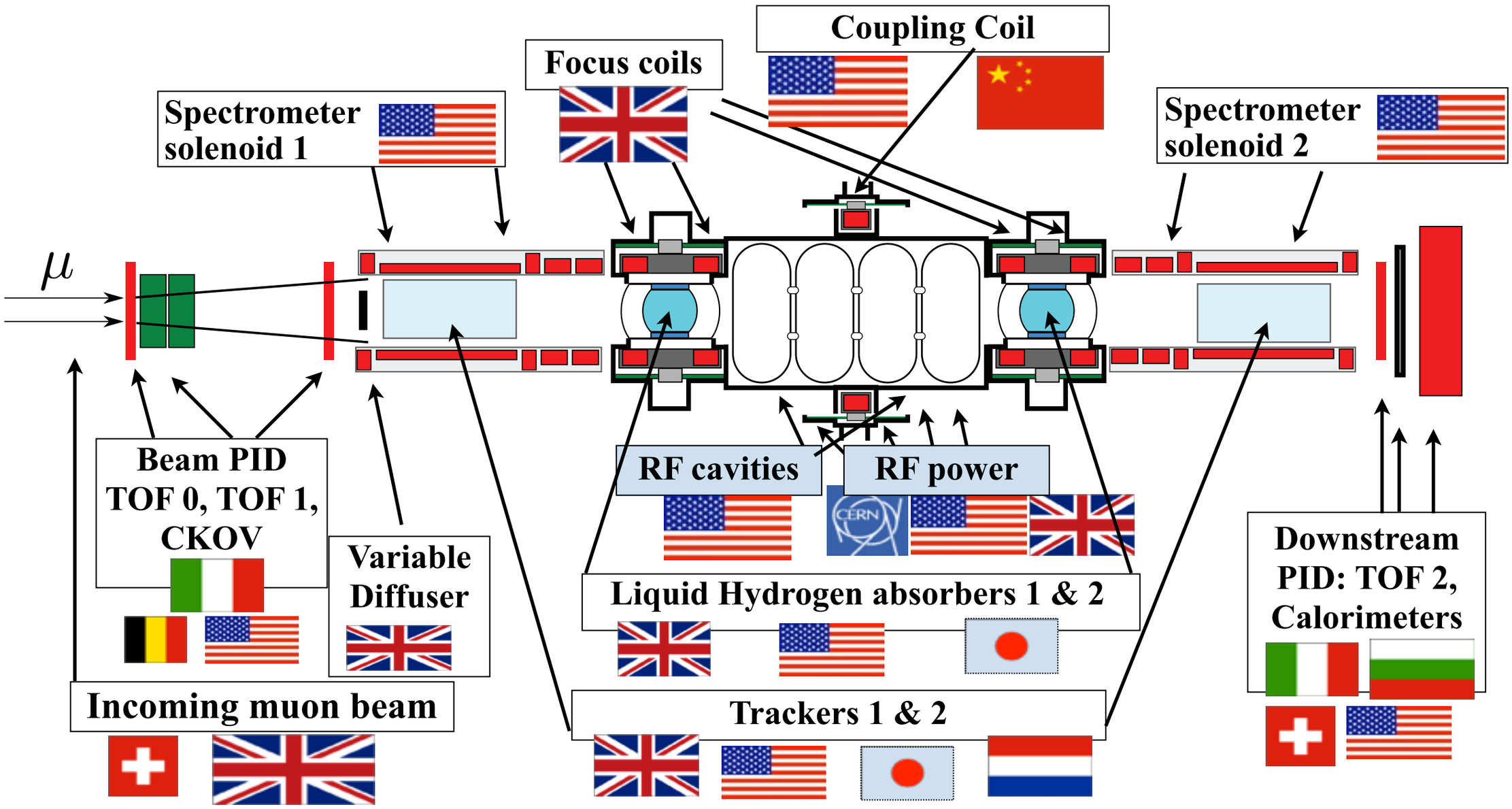
1st Test of Emittance Exchange

- Some aspects of 6D cooling / emittance exchange can also be tested, by inserting wedge absorbers in MICE
  - wedge design:



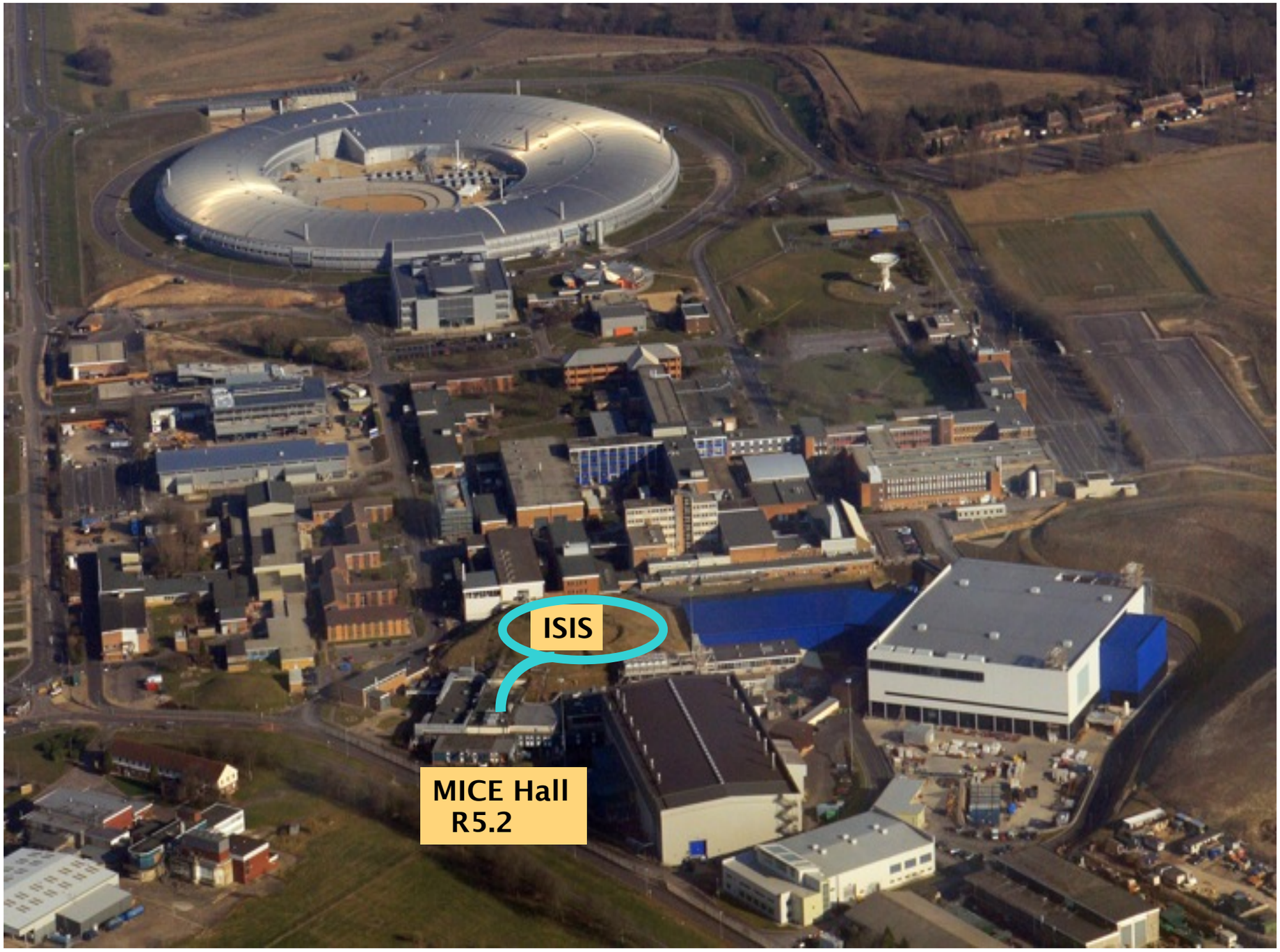
MICE

- International collaboration:



MICE

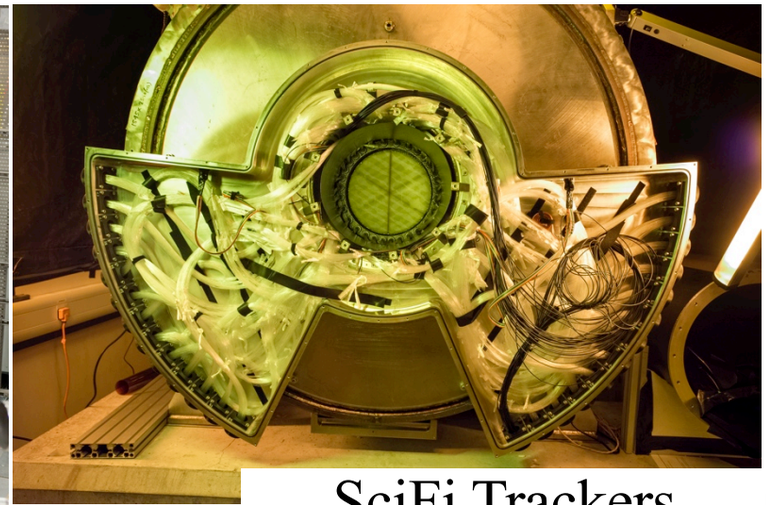
- Quick tour:



MICE

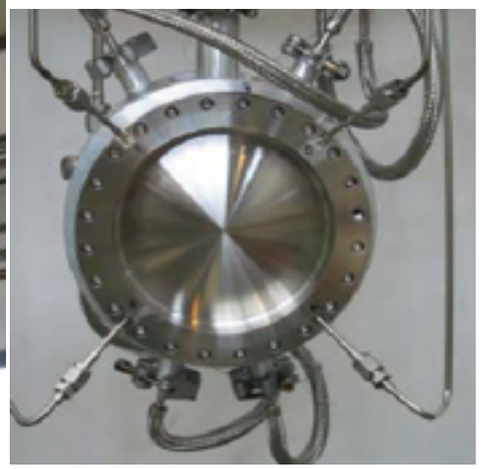
- Quick tour:

Spectrometer Solenoids

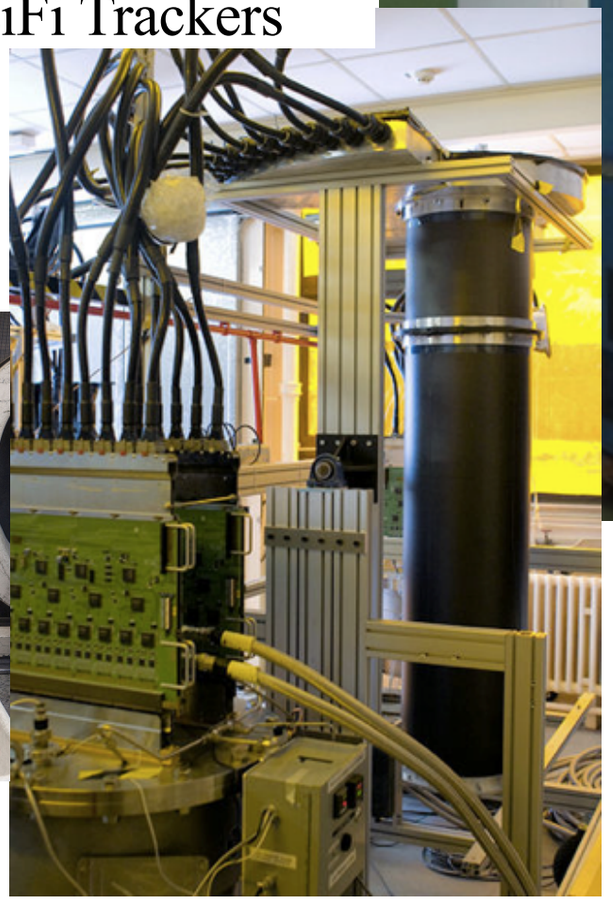


RF Power Supplies

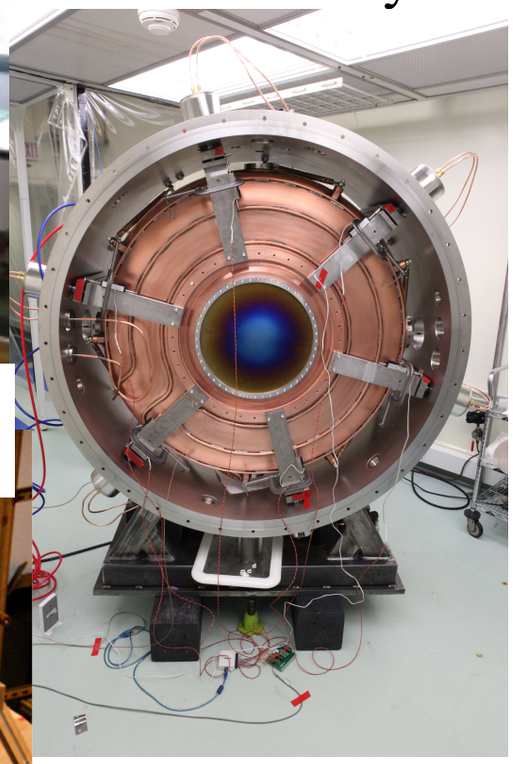
LH_2 Absorber



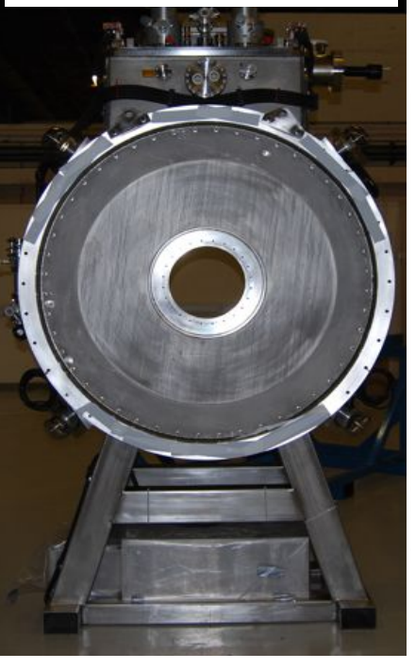
SciFi Trackers



1st RF Cavity

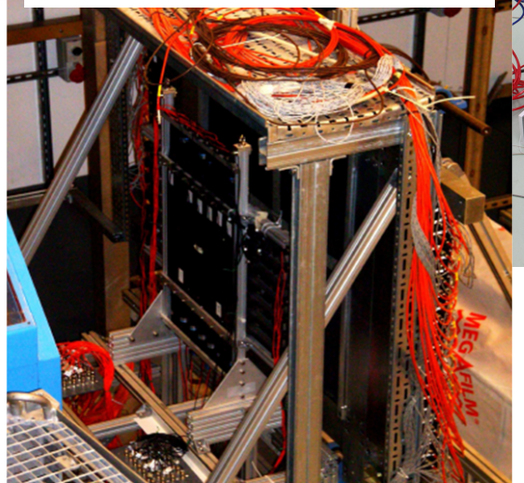


Focus Coils



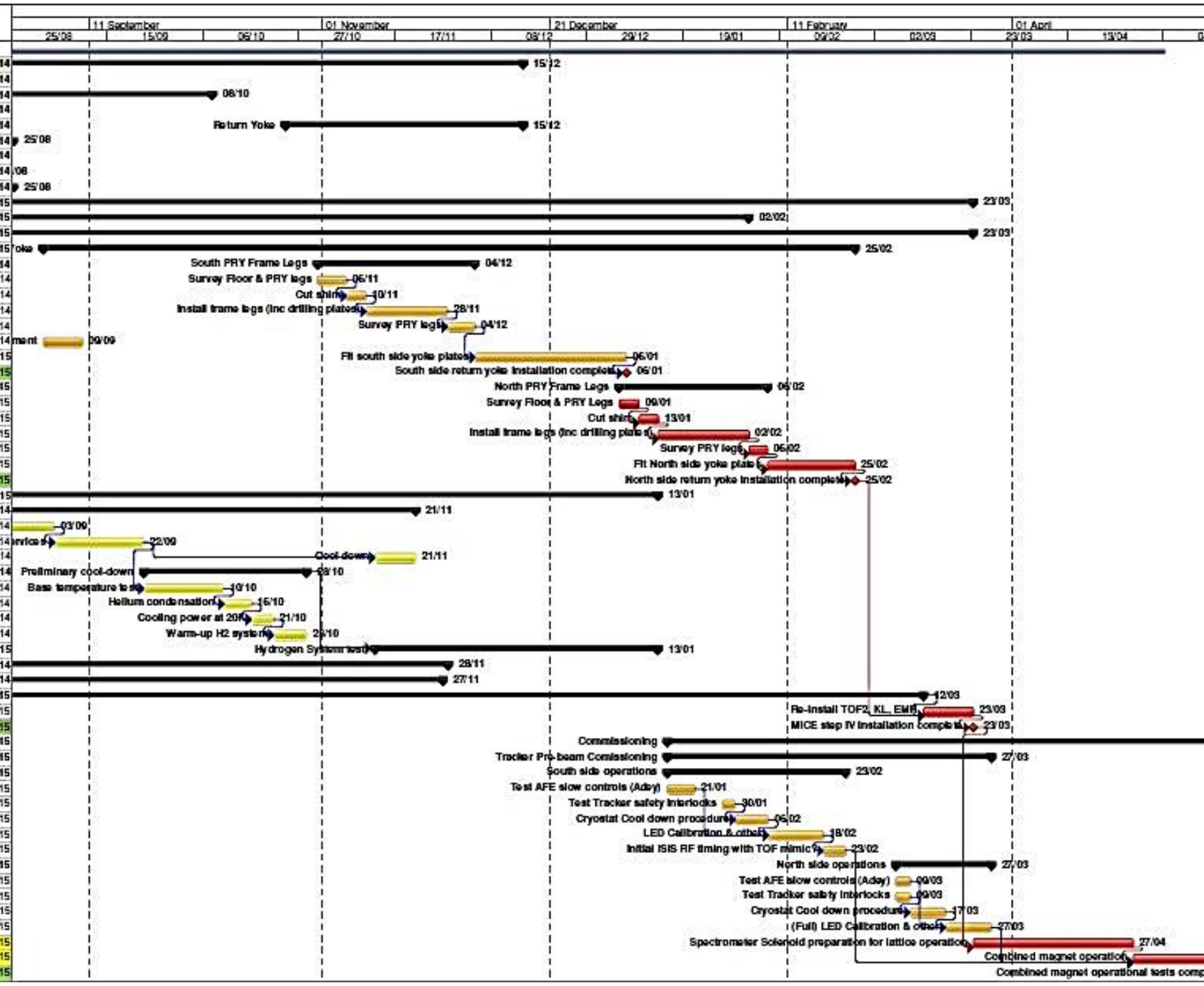
LiH Absorber

Time-of-Flight Counters



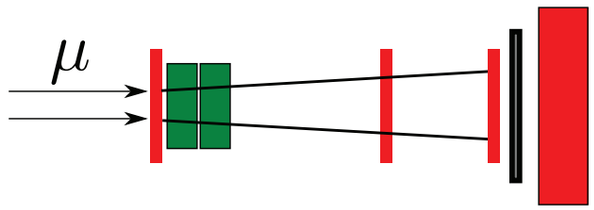
MICE Construction Schedule

WBS	Task Name	Baseline Finish	Start	Finish
2	ISIS Run Cycle		Mon 01/09/08	
3	Shipping	Mon 15/12/14	Mon 05/10/09	Mon 15/12/14
3.2	Spectrometer Solenoids (Tracker)	Mon 16/06/14	Wed 01/05/13	Mon 30/06/14
3.4	Liquid Hydrogen System	Wed 08/10/14	Fri 22/10/10	Wed 08/10/14
3.8	Diffuser	Thu 01/05/14	Thu 01/05/14	Thu 31/07/14
3.9	Return Yoke	Mon 15/12/14	Fri 24/10/14	Mon 15/12/14
4	Pre Installation Work	Mon 04/08/14	Wed 01/06/11	Mon 25/08/14
4.4	AFC#1 Field tests R9	Fri 25/07/14	Wed 31/10/12	Thu 14/08/14
4.5	Spectrometer Solenoid - Upstream	Wed 14/05/14	Thu 10/10/13	Wed 20/08/14
4.8	Tracker Installation - Downstream	Mon 04/08/14	Wed 04/06/14	Mon 25/08/14
5	Installation	Mon 02/03/15	Thu 01/04/10	Mon 23/03/15
5.1	Infrastructure	Thu 13/11/14	Thu 01/04/10	Mon 02/02/15
5.4	MICE Step IV Installation	Mon 02/03/15	Mon 17/01/11	Mon 23/03/15
5.4.5	Return Yoke	Wed 11/02/15	Mon 01/09/14	Wed 25/02/15
5.4.5.1	South PRY Frame Legs	Tue 25/11/14	Fri 31/10/14	Thu 04/12/14
5.4.5.1.1	Survey Floor & PRY legs	Tue 04/11/14	Fri 31/10/14	Thu 06/11/14
5.4.5.1.2	Cut shim	Thu 06/11/14	Thu 06/11/14	Mon 10/11/14
5.4.5.1.3	Install frame legs (inc drilling plates)	Thu 20/11/14	Mon 10/11/14	Fri 28/11/14
5.4.5.1.4	Survey PRY legs	Tue 25/11/14	Fri 28/11/14	Thu 04/12/14
5.4.5.2	Fit Yoke mount services management	Fri 05/09/14	Mon 01/09/14	Tue 09/09/14
5.4.5.3	Fit south side yoke plates	Tue 09/12/14	Thu 04/12/14	Tue 06/01/15
5.4.5.4	South side return yoke installation complete	Tue 09/12/14	Tue 06/01/15	Tue 06/01/15
5.4.5.5	North PRY Frame Legs	Wed 28/01/15	Mon 05/01/15	Fri 06/02/15
5.4.5.5.1	Survey Floor & PRY Legs	Wed 07/01/15	Mon 05/01/15	Fri 09/01/15
5.4.5.5.2	Cut shim	Fri 09/01/15	Fri 09/01/15	Tue 13/01/15
5.4.5.5.3	Install frame legs (inc drilling plates)	Fri 23/01/15	Tue 13/01/15	Mon 02/02/15
5.4.5.5.4	Survey PRY legs	Wed 28/01/15	Mon 02/02/15	Fri 06/02/15
5.4.5.6	Fit North side yoke plates	Wed 11/03/15	Fri 06/02/15	Wed 25/02/15
5.4.5.7	North side return yoke installation complete	Wed 11/03/15	Wed 25/02/15	Wed 25/02/15
5.4.6	AFC - Focus coil for step IV	Thu 27/11/14	Fri 15/08/14	Tue 13/01/15
5.4.6.1	AFC#1 Installation	Thu 30/10/14	Fri 15/08/14	Fri 21/11/14
5.4.6.1.1	Installation, survey & alignment of AFC#1	Fri 08/08/14	Fri 15/08/14	Wed 03/09/14
5.4.6.1.2	Connection of services	Fri 22/08/14	Wed 03/09/14	Mon 22/09/14
5.4.6.1.3	Cool down	Thu 30/10/14	Wed 12/11/14	Fri 21/11/14
5.4.6.2	Preliminary cool-down	Thu 18/09/14	Tue 23/09/14	Tue 28/10/14
5.4.6.2.1	Base temperature test	Fri 05/09/14	Tue 23/09/14	Fri 10/10/14
5.4.6.2.2	Helium condensation	Wed 10/09/14	Fri 10/10/14	Thu 16/10/14
5.4.6.2.3	Cooling power at 20K	Fri 12/09/14	Thu 16/10/14	Tue 21/10/14
5.4.6.2.4	Warm-up H2 system	Thu 18/09/14	Tue 21/10/14	Tue 28/10/14
5.4.6.3	Hydrogen System test	Thu 27/11/14	Wed 12/11/14	Tue 13/01/15
5.4.7	Upstream Spectrometer Solenoid & Tracker Assy	Wed 05/11/14	Tue 15/04/14	Fri 28/11/14
5.4.8	Downstream Spectrometer Solenoid & Tracker Assy	Tue 04/11/14	Wed 23/07/14	Thu 27/11/14
5.4.9	Tracker Hall Integration	Mon 23/02/15	Mon 05/05/14	Thu 12/03/15
5.4.10	Re-install TOF2, KL, EMR	Mon 02/03/15	Thu 12/03/15	Mon 23/03/15
5.4.11	MICE step IV installation complete	Mon 02/03/15	Mon 23/03/15	Mon 23/03/15
6	Commissioning	Thu 23/04/15	Thu 15/01/15	Mon 01/06/15
6.1	Tracker Pre-beam Comissioning	Thu 05/03/15	Thu 15/01/15	Fri 27/03/15
6.1.1	South side operations	Tue 27/01/15	Thu 15/01/15	Mon 23/02/15
6.1.1.1	Test AFE slow controls (Aday)	Fri 19/12/14	Thu 15/01/15	Wed 21/01/15
6.1.1.2	Test Tracker safety interlocks	Fri 09/01/15	Tue 27/01/15	Fri 30/01/15
6.1.1.3	Cryostat Cool down procedure	Thu 15/01/15	Fri 30/01/15	Fri 06/02/15
6.1.1.4	LED Calibration & other	Fri 23/01/15	Fri 06/02/15	Wed 18/02/15
6.1.1.5	Initial ISIS RF timing with TOF mimic?	Tue 27/01/15	Wed 18/02/15	Mon 23/02/15
6.1.2	North side operations	Thu 05/03/15	Fri 06/03/15	Fri 27/03/15
6.1.2.1	Test AFE slow controls (Aday)	Thu 19/02/15	Fri 06/03/15	Mon 09/03/15
6.1.2.2	Test Tracker safety interlocks	Thu 19/02/15	Fri 06/03/15	Mon 09/03/15
6.1.2.3	Cryostat Cool down procedure	Wed 25/02/15	Mon 09/03/15	Tue 17/03/15
6.1.2.4	(Full) LED Calibration & other	Thu 05/03/15	Tue 17/03/15	Fri 27/03/15
6.2	Spectrometer Solenoid preparation for lattice operation	Fri 27/03/15	Mon 23/03/15	Mon 27/04/15
6.3	Combined magnet operation	Thu 23/04/15	Mon 27/04/15	Mon 01/06/15
6.4	Combined magnet operational tests complete - milestone	Thu 23/04/15	Mon 01/06/15	Mon 01/06/15



- Being carefully managed – so far, so good!

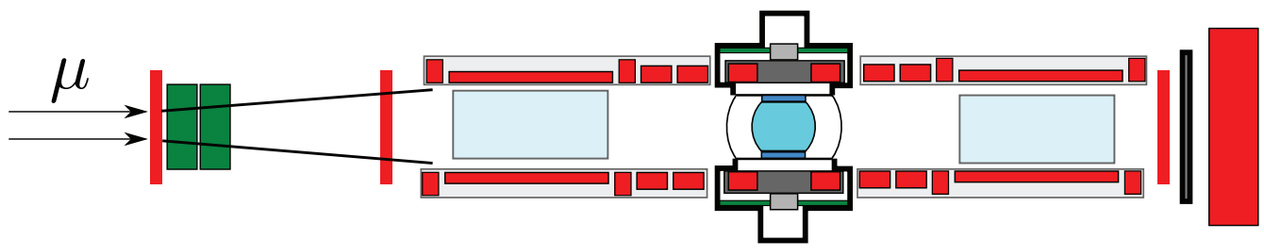
MICE Running Schedule



STEP I

Complete

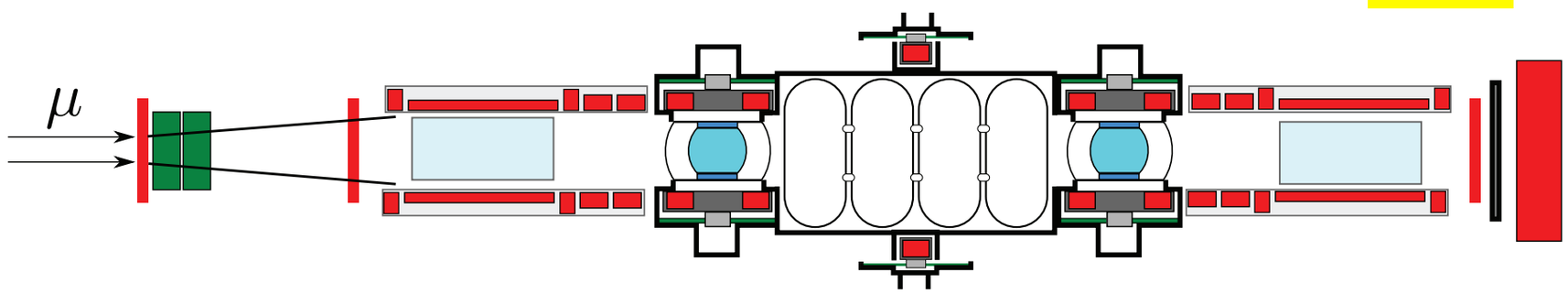
Absorber materials study; 1st observation of $\epsilon_{\perp,n}$ reduction



STEP IV

2015

1st demonstration of *sustainable* μ cooling; thorough Monte Carlo validation

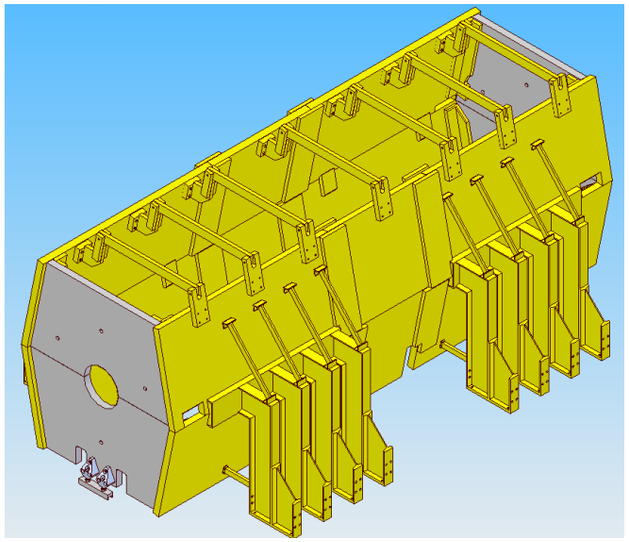


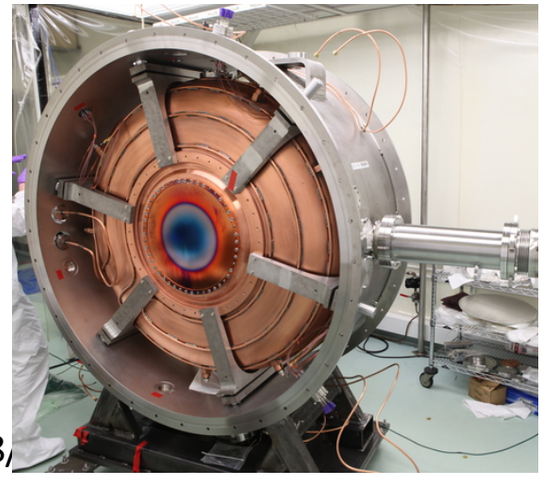
STEP V

2017-18

Current MICE Status

- Beamline and all detectors installed and operational
- All solenoids needed for Step IV delivered & field-mapped
- Step IV Partial Return Yoke iron on order
- Coupling Coil cold mass (needed for Step V) trained @ FNAL & cryostat completed (LBNL); magnet assembly in progress
- All RF cavities (Step V) built, 1st under test @ MTA





Conclusions

- Higgs and θ_{13} discoveries "set the stage" for stored-μ facilities
- 10^{21} ν/year Neutrino Factory feasible

S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, arXiv:1112.2853 [hep-ex]

→ world's best measurements of neutrino oscillation parameters

& best opportunity to find new, "beyond oscillation" physics

- High-$\mathcal{L}$ Muon Collider looks feasible
  - possibly buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way to multi-TeV!
- Muon Collider technology selection & feasibility assessment were main goals of MAP 6-year R&D program
  - reassessing after P5 recommendations; hope to progress some technical feasibility issues under DOE "general accelerator R&D" (GARD) auspices

▶ If desired, 1st Neutrino Factory construction might start in 2020s

▶ & 1st Muon Collider by late 2020s, should physics so require