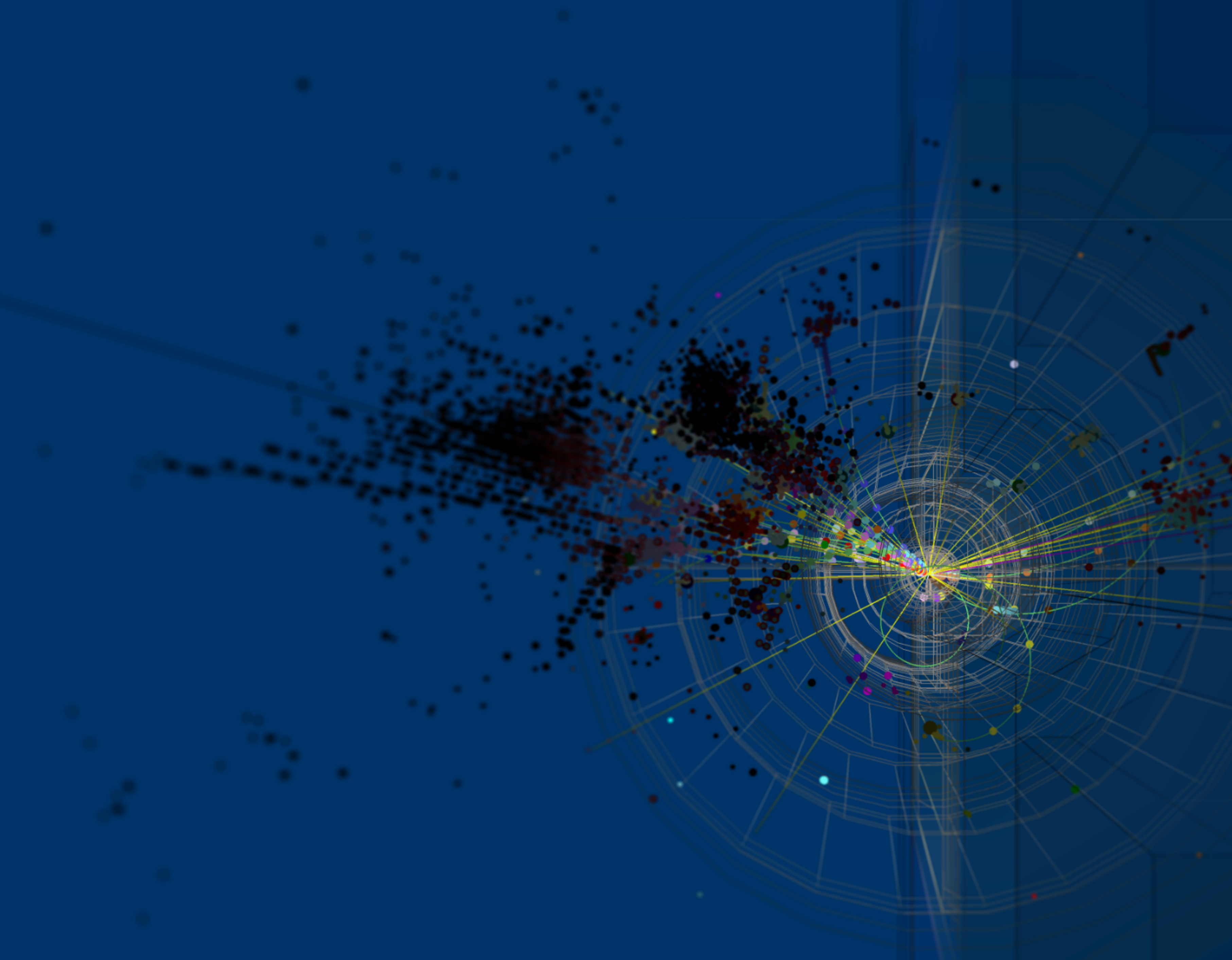


Future Fermilab Colliders

For the energy frontier

Lawrence Lee
(Larry)

The University of Tennessee Knoxville

UTK CMS

Future Fermilab Colliders

For the energy frontier

“Extreme length scales” means the shortest interaction scales.

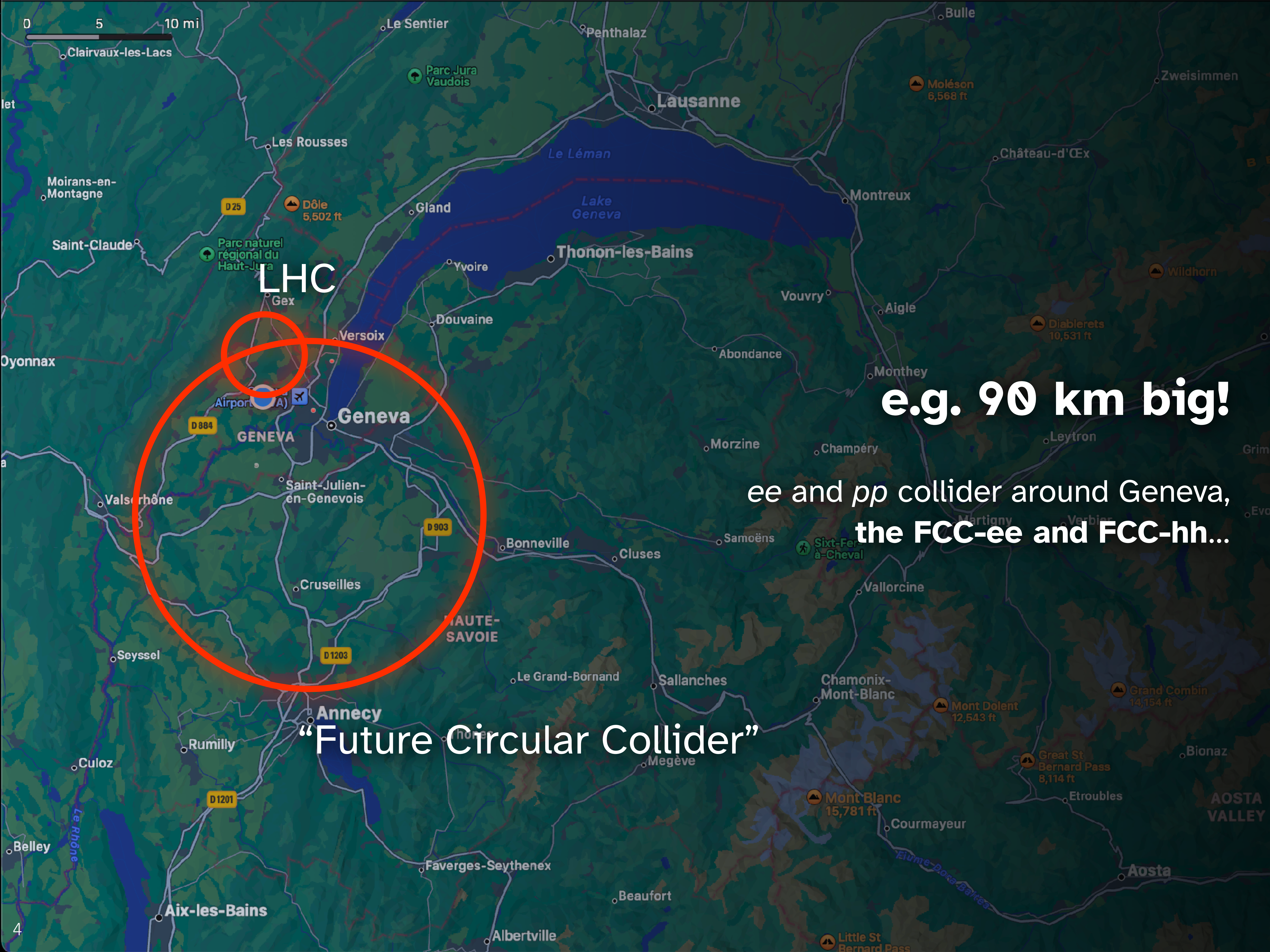
Historically implies “largest experiments”!

Discovery and insight at extreme energy scales and extreme length scales

LHC is enormous

Lots of directions a talk on future colliders can go.

Temptation is often to “go big”



e.g. 90 km big!

ee and *pp* collider around Geneva,
the FCC-ee and FCC-hh…

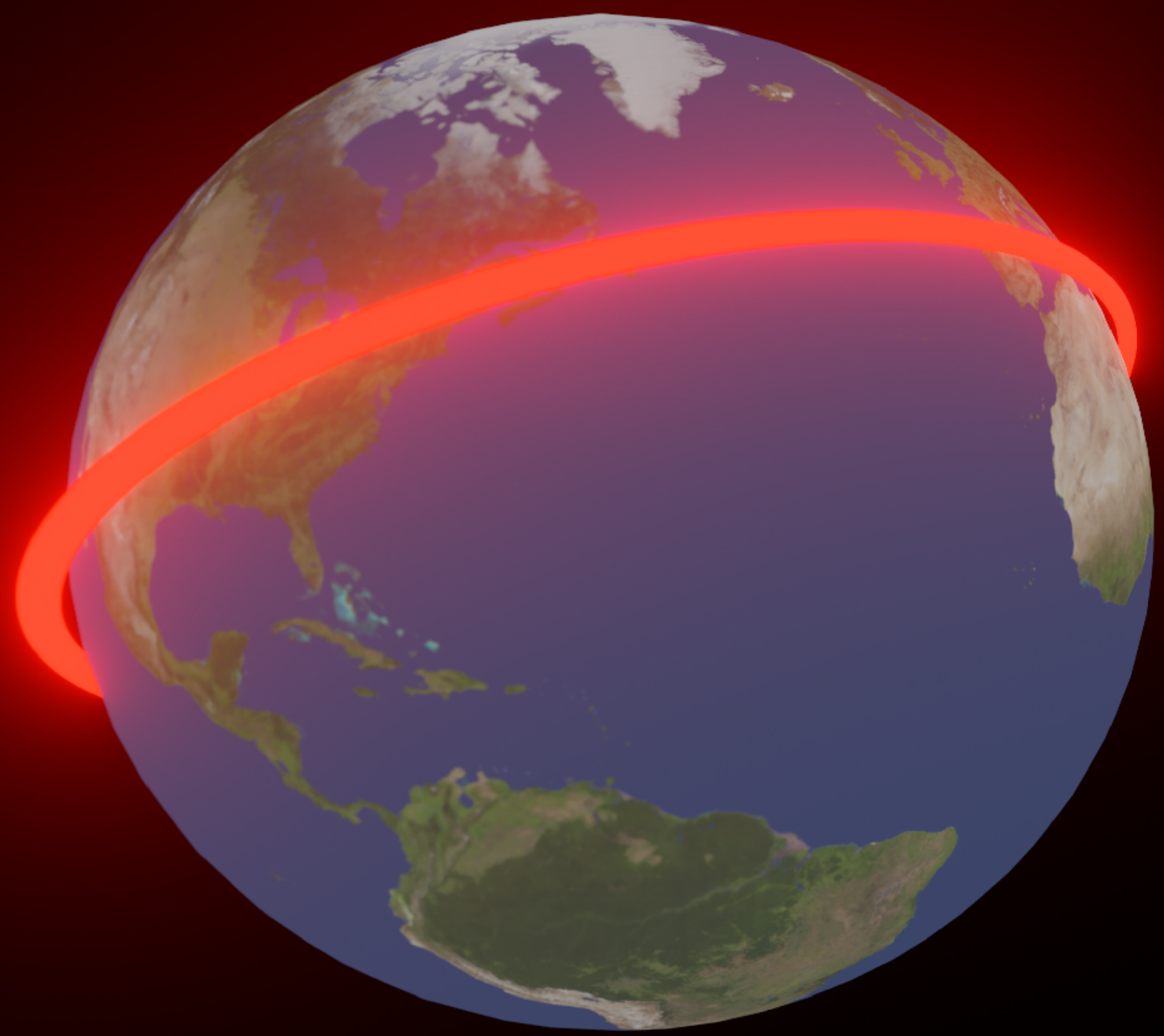
The **US and FNAL are crucial partners with CERN** in the exploration of the FCC

FCC studies ongoing; Feasibility report to be delivered in 2025

- → Input for European Strategy Update 2026
- → Seeking CERN Council Approval in ~2028
- → Break ground in 2030s
- → *ee* Higgs Factory few years after HL-LHC ends

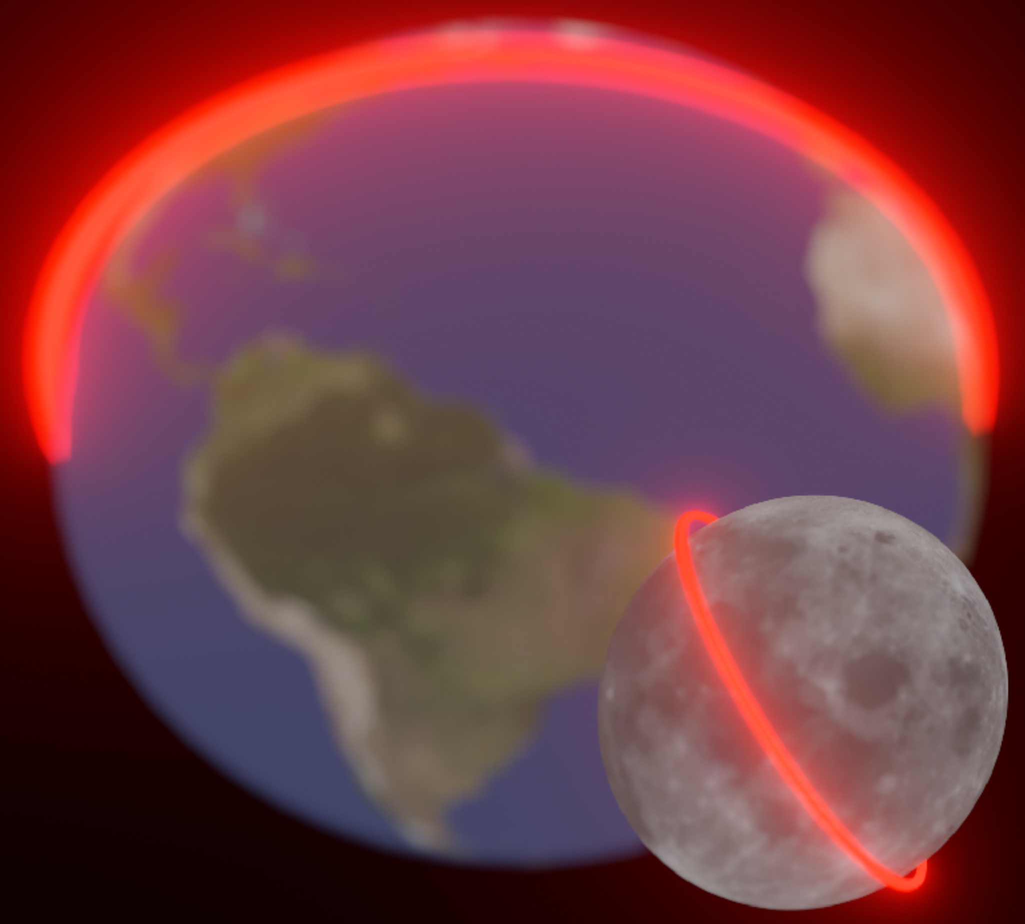
US *has* and *will* play a major role in any FCC activities

Long term:
Temptation to push even bigger…



Fermi’s Globatron (1954)

Long history of proposals that are even more “romantic” than a 90 km tunnel.



Fermi’s Globatron (1954)

Collider on the moon (2021)
[2106.02048]

Literal Pipe-Dreams...

But this is often our natural instinct when we start to dream!

~~Go Big!~~

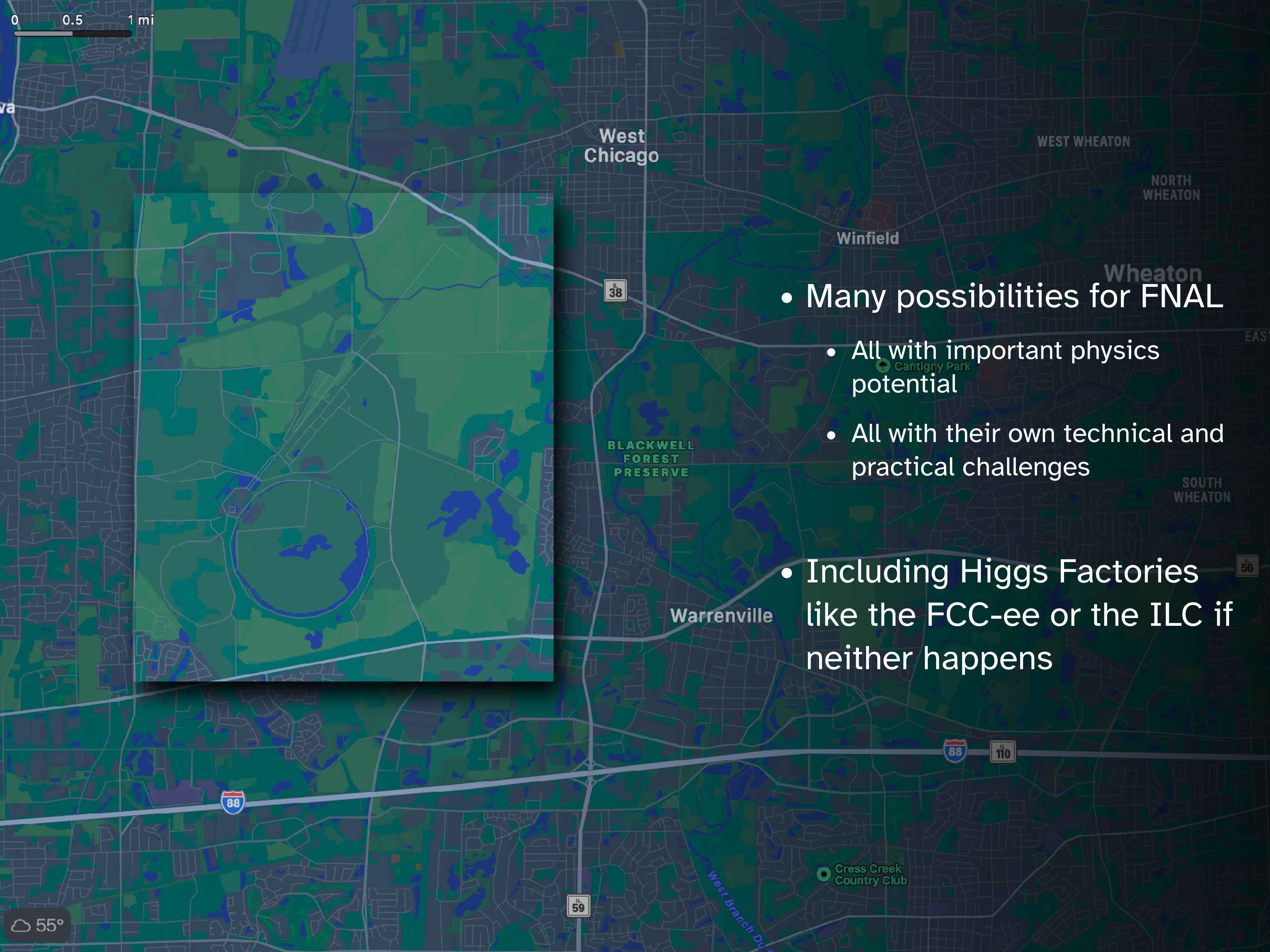
“Go Home”

This meeting:
“New Ideas for Future Projects”

Celebration of the potential for FNAL

How can the FNAL community lead the future of the energy frontier, on US soil

Fermilab

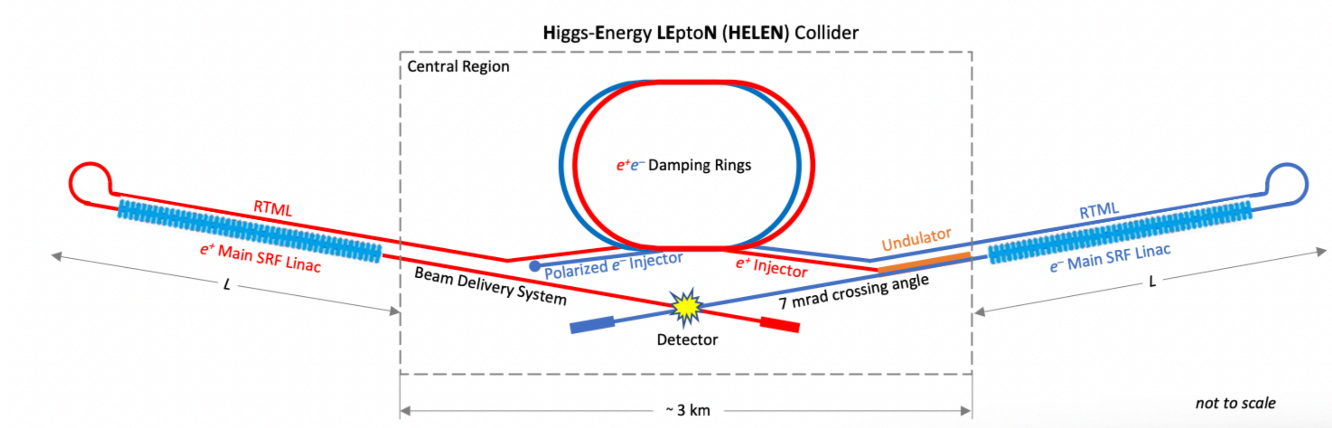


- Many possibilities for FNAL
  - All with important physics potential
  - All with their own technical and practical challenges
- Including Higgs Factories like the FCC-ee or the ILC if neither happens

HELEN (Higgs Energy LEptoN) Collider

[2203.08088],
[2203.08211]

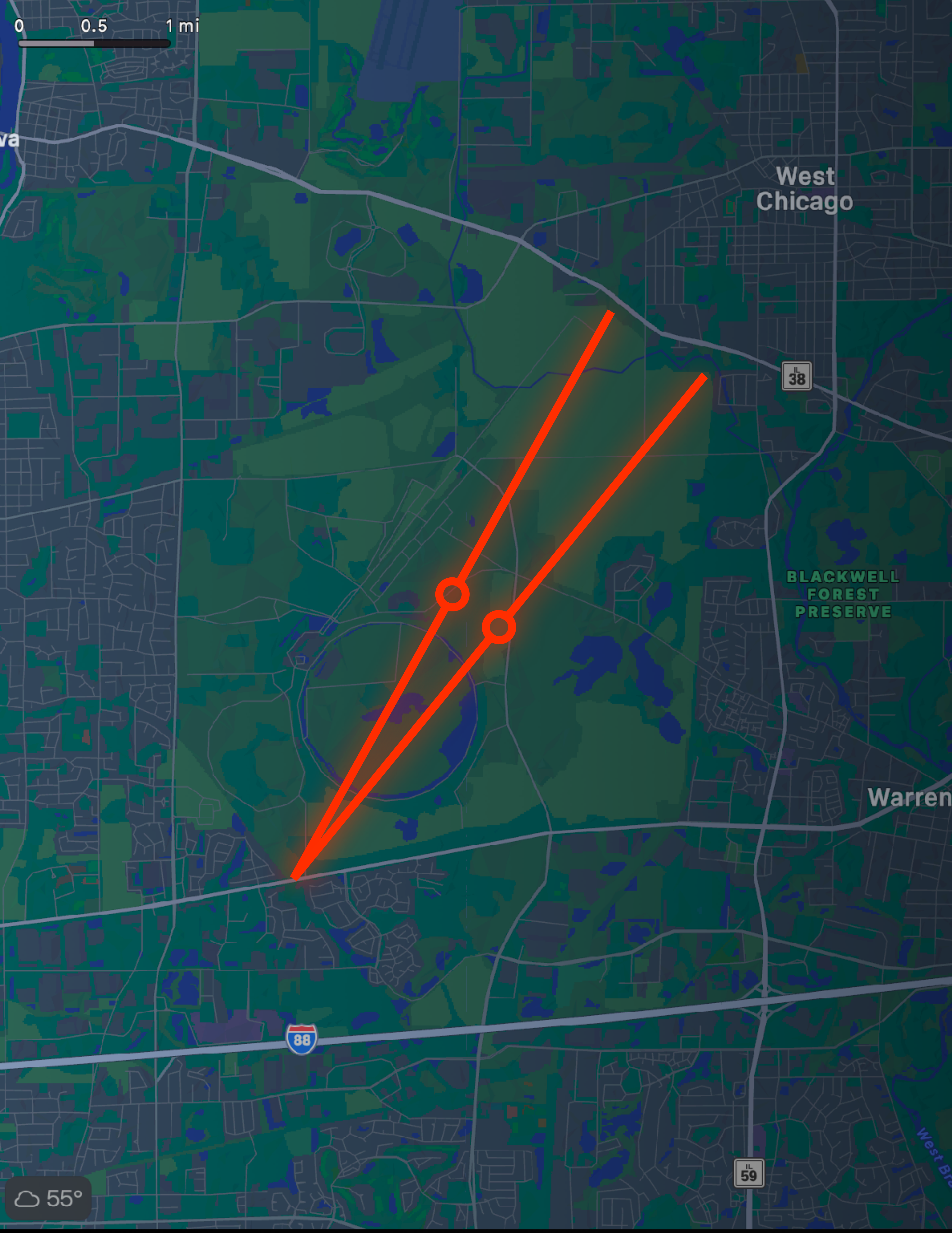
- Latest and greatest in Superconducting RF (SRF)
  - >2x the accelerator gradients w.r.t. ILC, ~50-90 MV/m
  - ILC-like machine but much more compact — less than half the size!



Both options can fit a Higgs factory on FNAL site!

C³ (Cool Copper Collider)

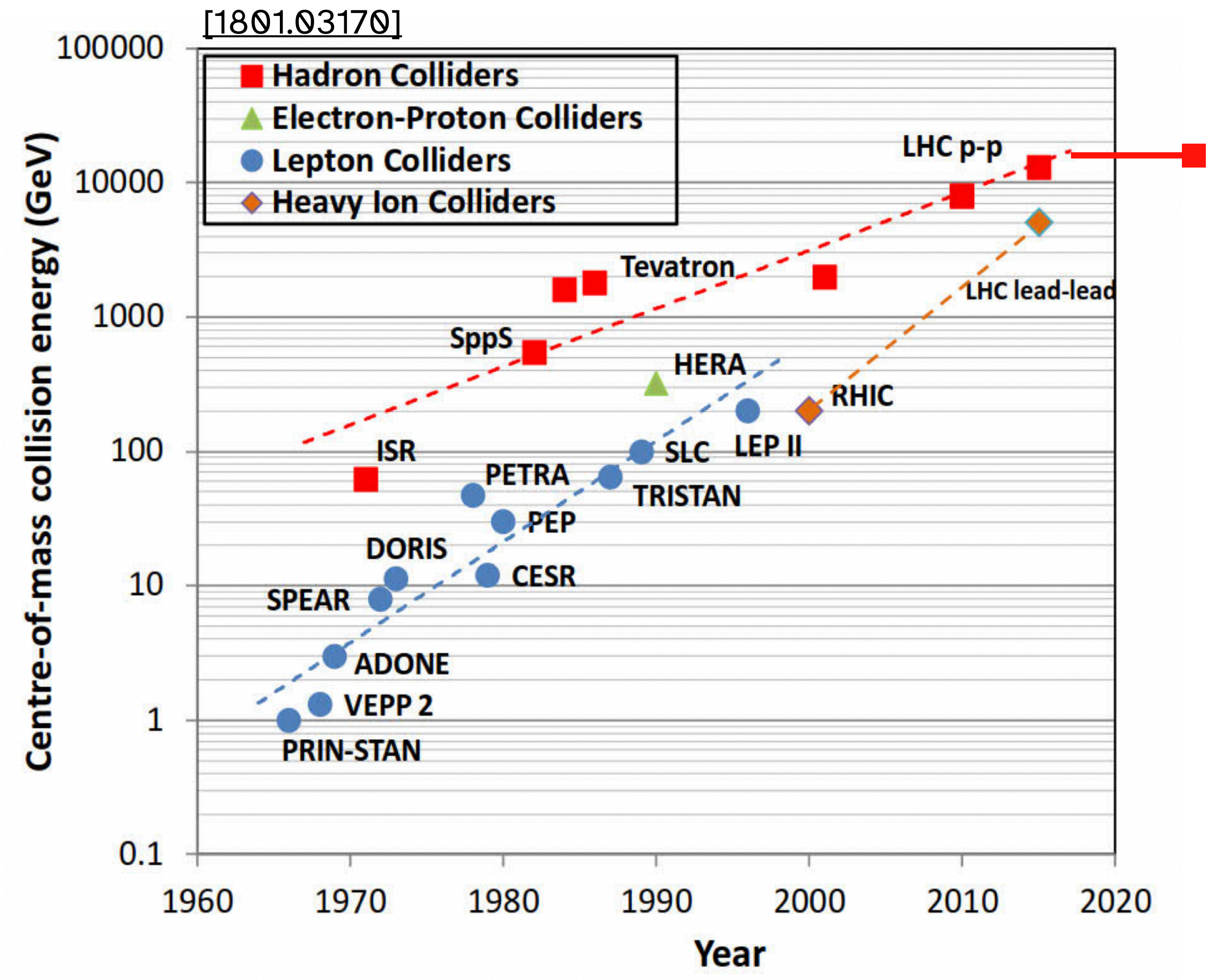
- Or ditch the SRF entirely! C³ uses normal conducting cavities, specifically optimized for efficiency
- Unlike SRF, LN_2 temps suffice! Potentially cheaper, much easier.
- Already demonstrated peak 150 MV/m on small scale and expect a robust 120 MV/m operation



Possible on-campus 7km layouts For C^3, HELEN, or other Higgs Factories

But if FCC-ee happens, the center of Higgs factory physics will be at CERN

What can we pursue concurrently for Fermilab?



- LHC collides protons at 13-14 TeV
  - **Since *p* is composite, probes interactions scales of ~1 TeV**
- Want to continue tradition of pushing to larger energy scales
  - **Next big step will be to 10 TeV interaction scale**

- This exploration will require an investment in accelerator technology research to
  - Contribute to the international effort to build a Higgs factory at CERN
  - Revitalize accelerator and detector R&D towards a next-generation multi-TeV energy frontier machine
- *Fermilab is poised to host a next generation multi-TeV energy frontier collider, as a global endeavor, following the completion of the full DUNE program*

Exactly the vision of the lab for post-DUNE priorities

B Fleming at P5 Town Hall

Getting to the 10 TeV Scale

- **Why** invest resources, person-power, and our personal energy pushing the energy frontier forward?
- **What** tools might we use to do so here in Batavia?
- **How** do we realize this and what are the realistic steps towards making it happen?

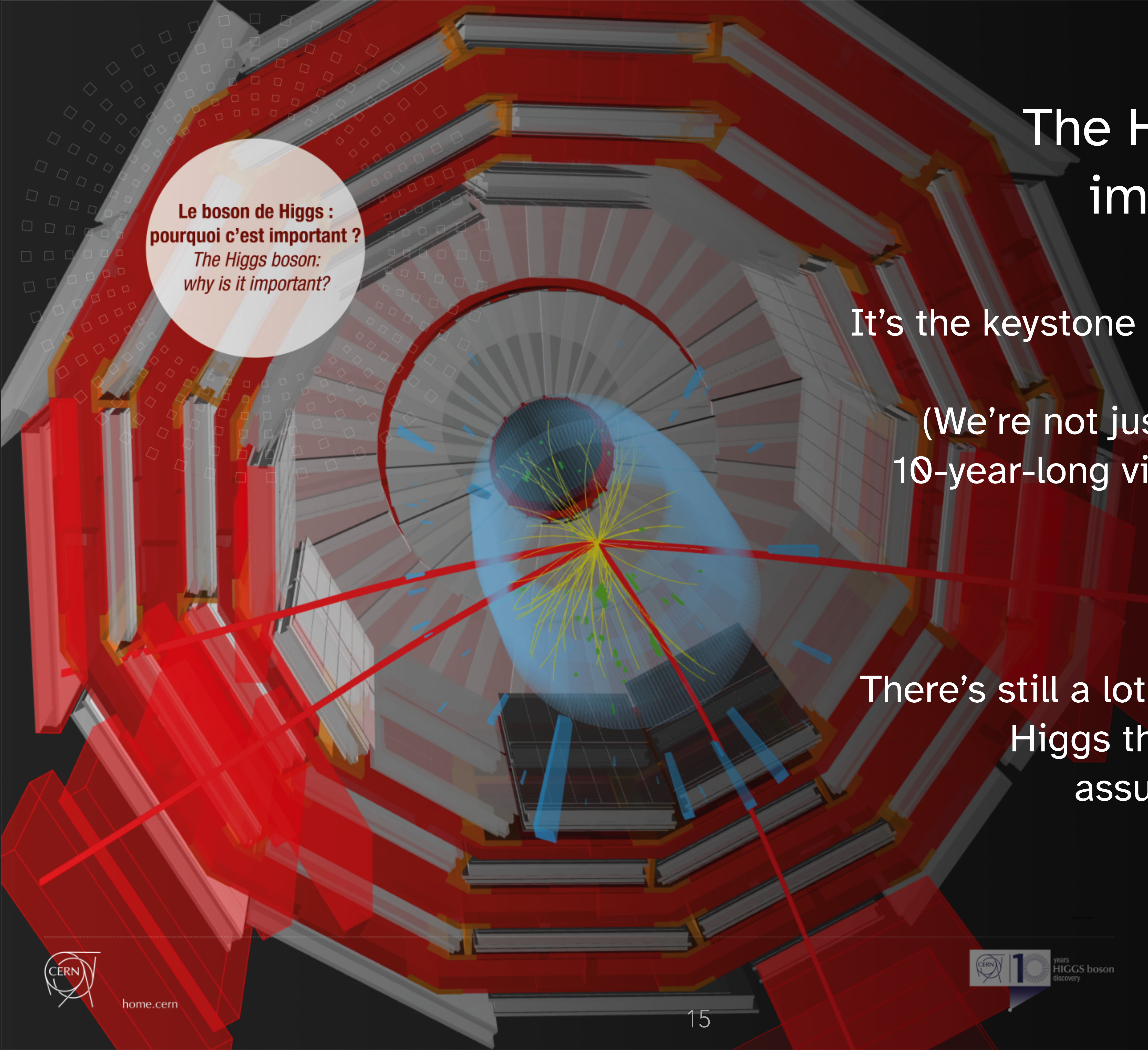
Why?

The Higgs is important

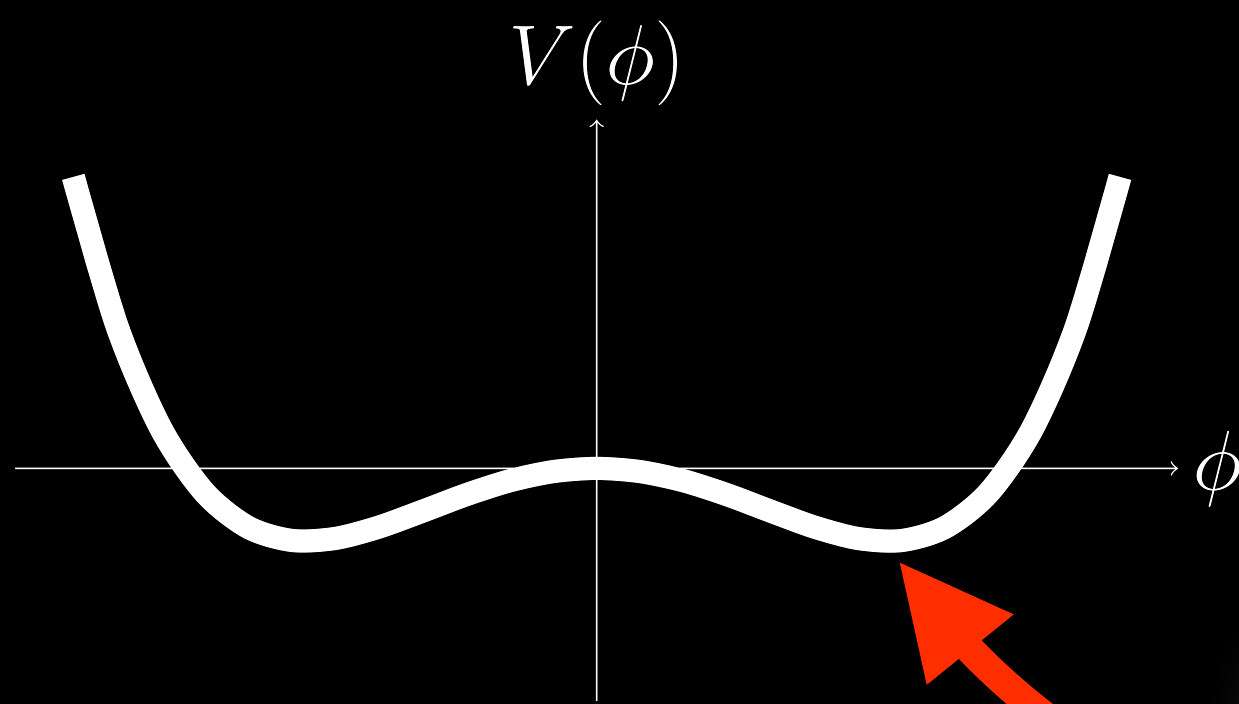
It's the keystone of the SM.

(We're not just taking a 10-year-long victory lap!)

There's still a lot about the Higgs that remain assumptions…

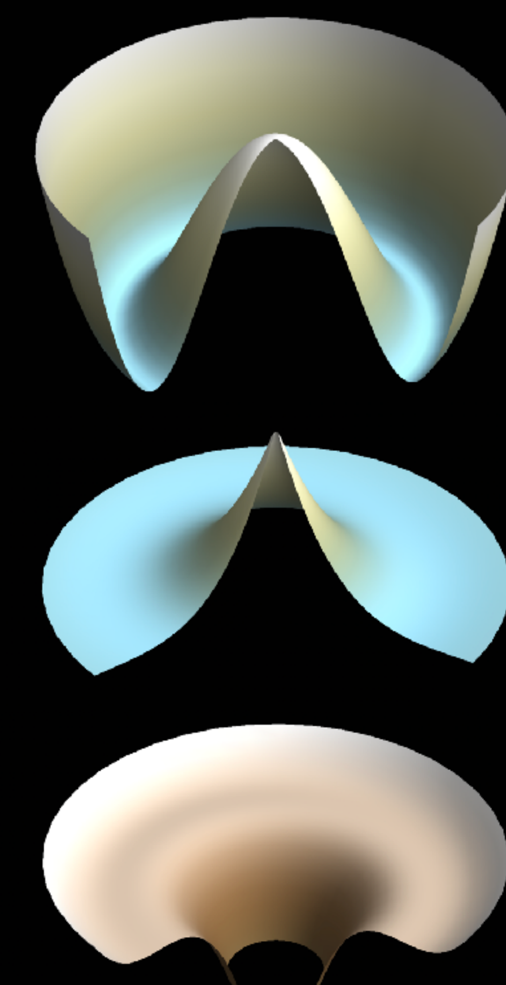


Remember: The Higgs Boson is the massive radial degree of freedom about the minimum of the Higgs potential

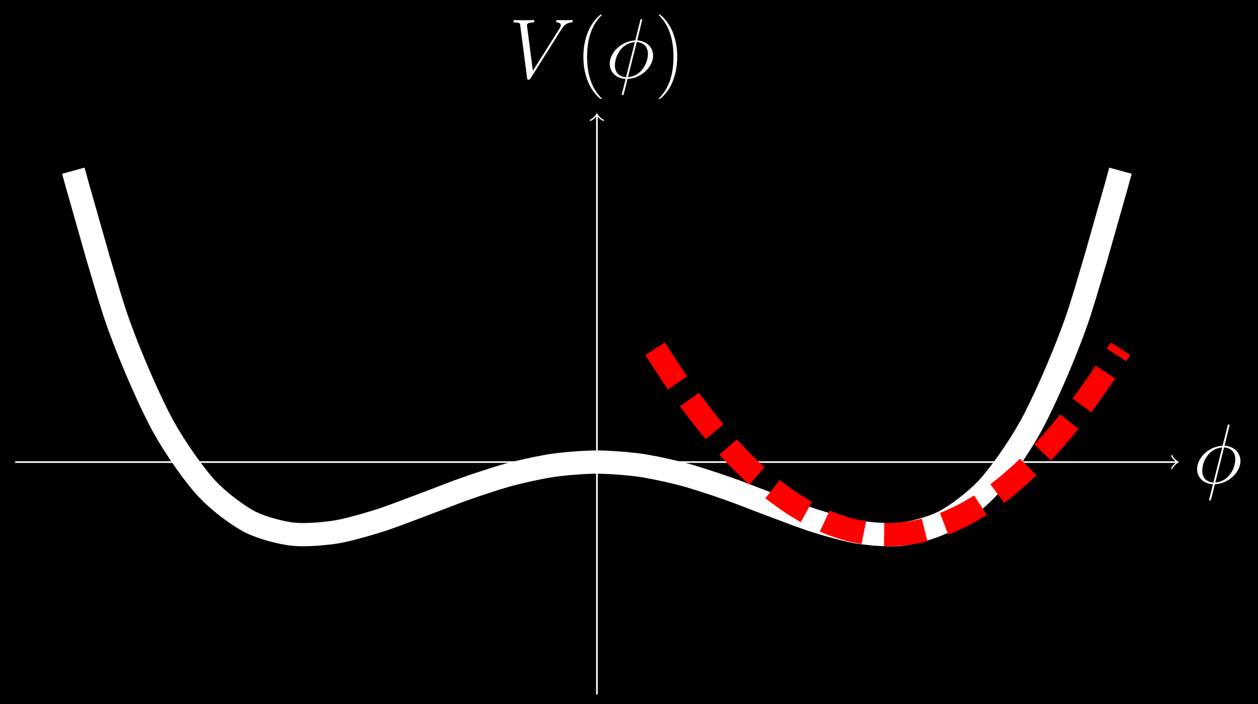


Higgs discovery **only confirms there's a minimum** of the Higgs potential

Current knowledge consistent with a wide range of Higgs potential shapes



N Craig & R Petrossian-Byrne

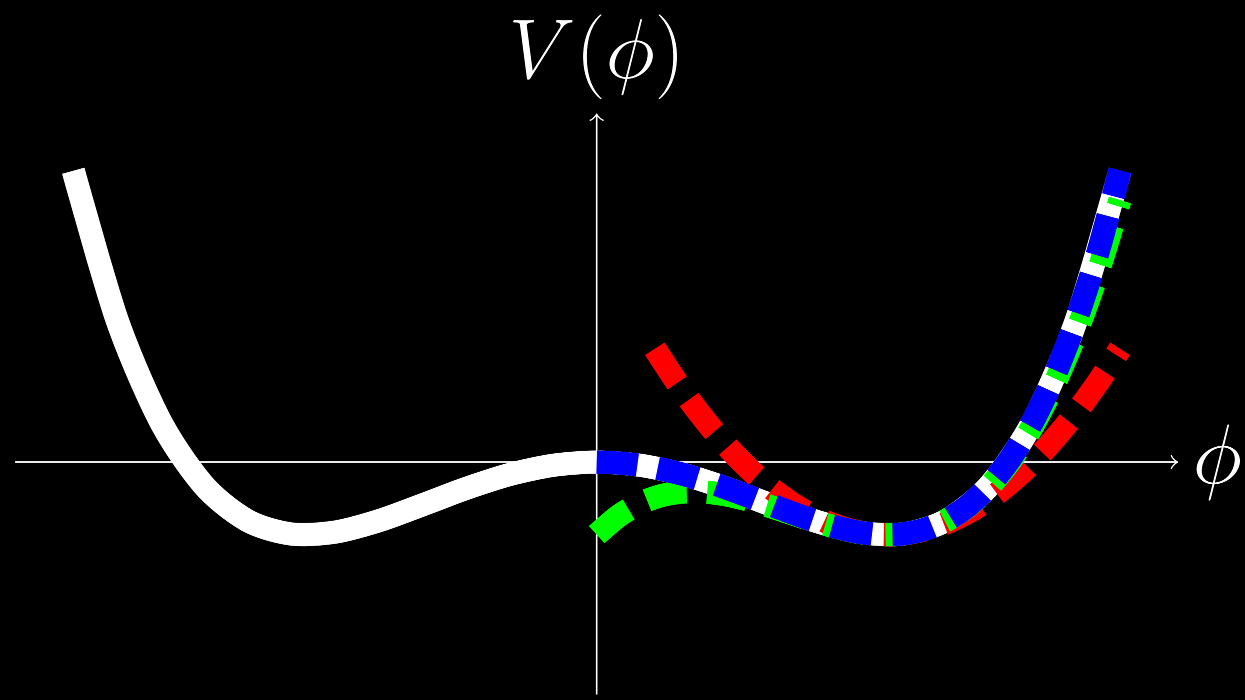


We've only confirmed the Harmonic Oscillator term of Taylor expansion around minimum

To measure full shape of the Higgs potential,

must measure higher order terms
we need multi-Higgs production

$$O(H^2) + O(H^3) + O(H^4)$$



To understand the shape of the Higgs potential, **we need multi-Higgs production**

BSM Contributions?

$$O(H^2) + O(H^3) + O(H^4) + O(H^5) + \ldots$$

Higgs self coupling
→ HH production

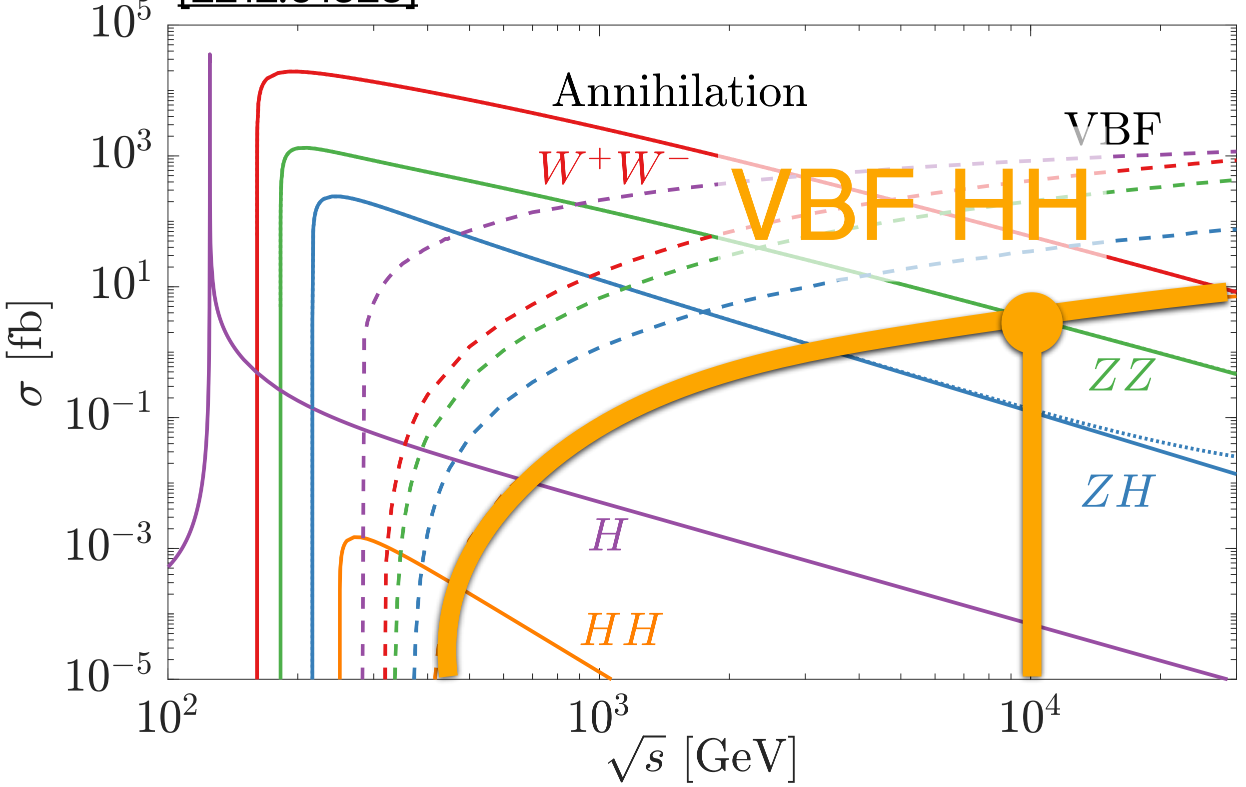
(HL-LHC can make first measurement, but need more precision)

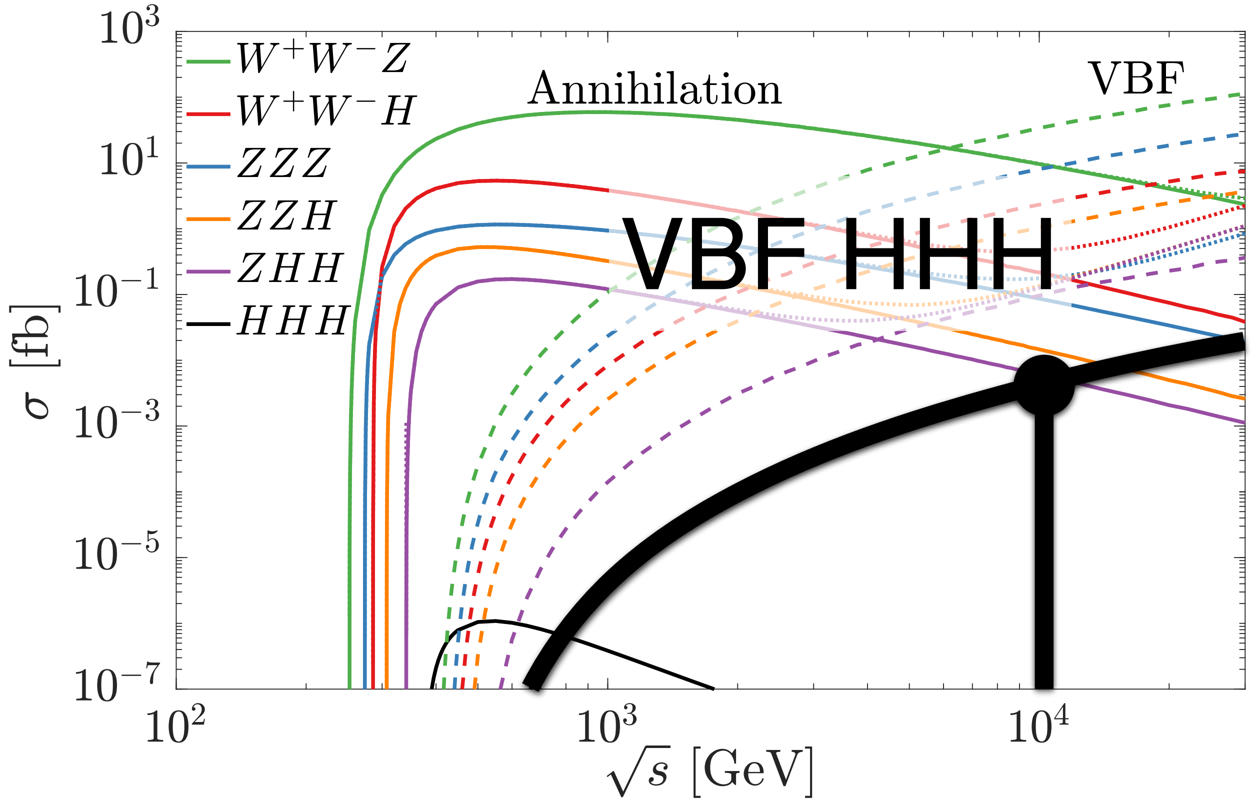
Quartic coupling
→ HHH production

To map out Higgs potential, need to measure multi-Higgs processes.

To produce enough events, need high-luminosity 10-TeV scale colliders

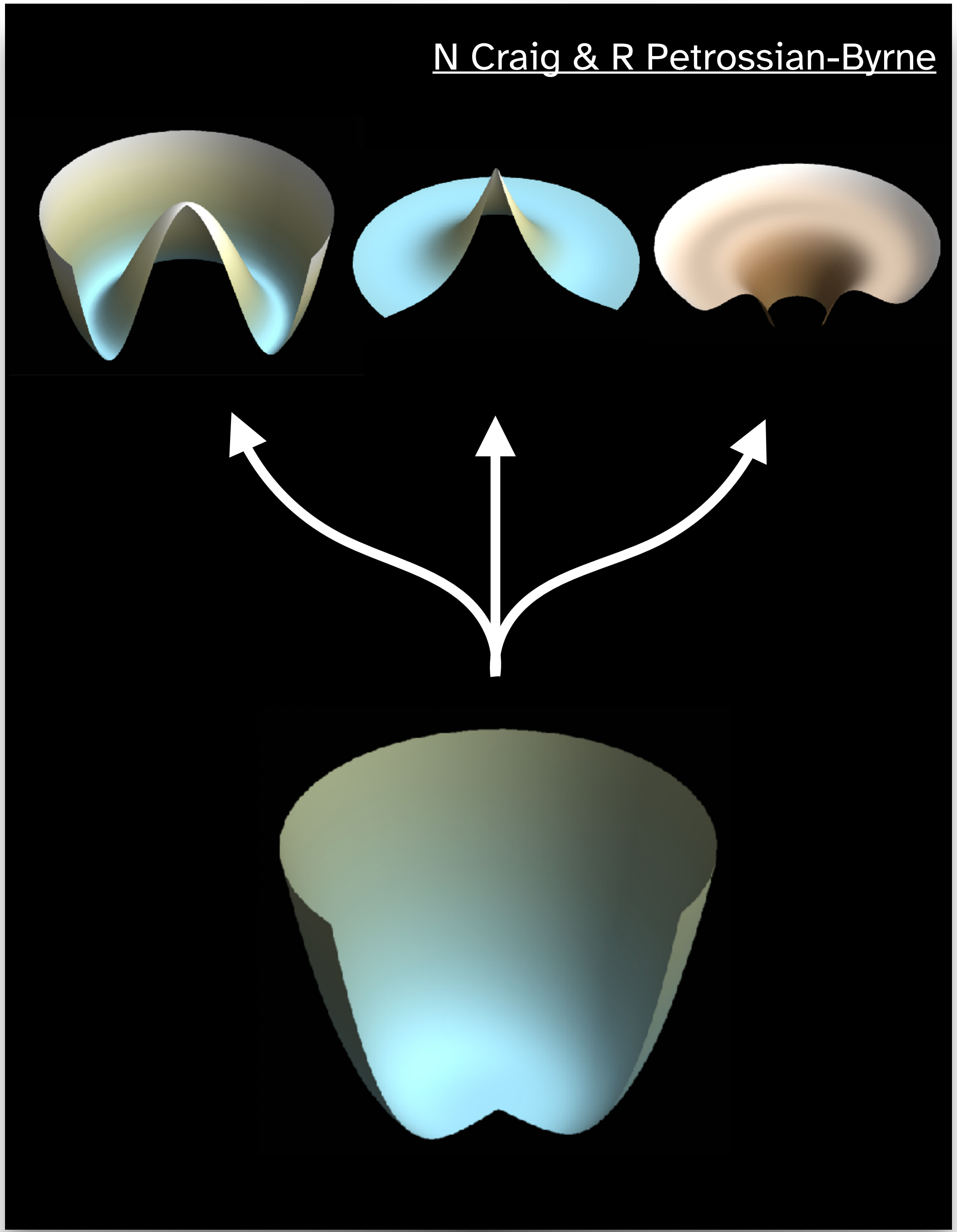
[2212.01323]





"Why" you should care!

- **SM predicts wine bottle potential; we usually just assume it's right**
  - But we only know there's a minimum...
  - What if it's only a local minimum? Is the universe waiting to tunnel to a global minimum?
- **Currently only know *that* EWSB happens! Not how or why!**
  - Probe the potential well above EW-scale → See EW symmetry restoration
- **This is about the birth and eventual fate of the universe**
  - **And *requires* the 10 TeV scale**

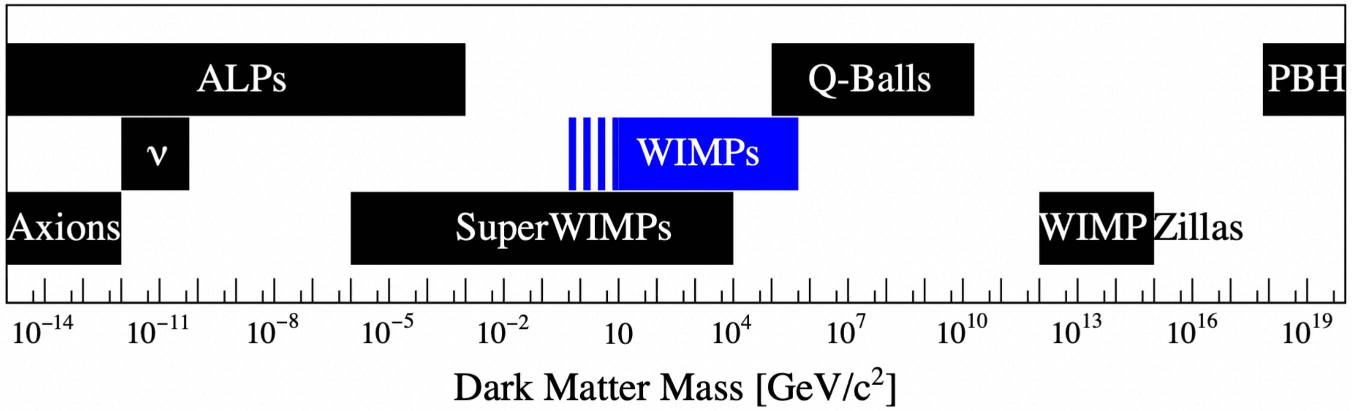


WIMP Dark Matter: Still Miraculous

(If DM couples to SM Weak Force and has TeV-scale mass, Early-universe production gets correct relic density!)

[1903.03026]

- **Turns out: Simplest relic WIMP models are still far from excluded**
- The loss in excitement over WIMPs does not come from the loss of their viability!

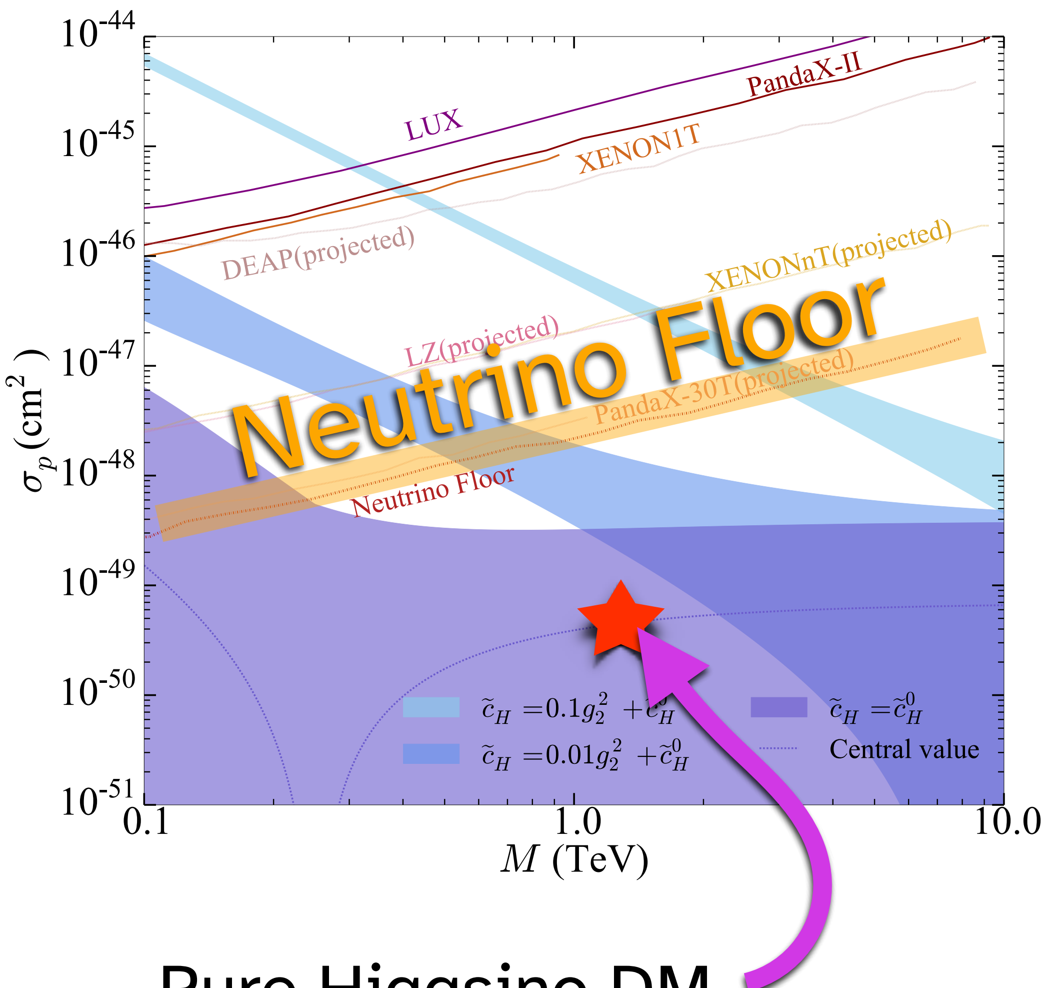


e.g. Thermally-produced Higgsino-like DM should have ~1 TeV masses.
We've ***never*** had sensitivity this!

This is one of the simplest, most motivated DM models possible!

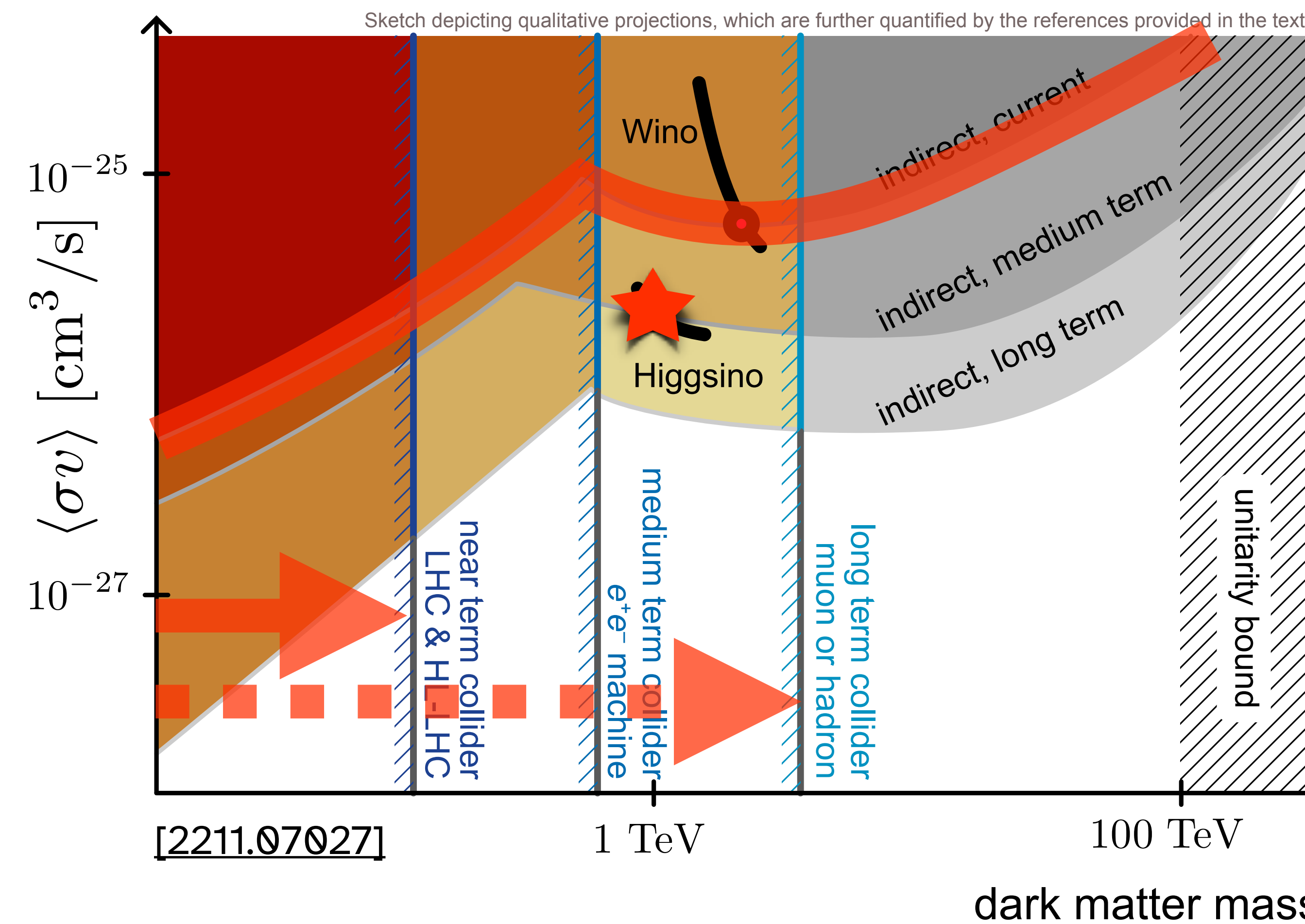
The *simplest* WIMP Dark Matter models have yet to be probed!

[1912.07795]



Pure Higgsino DM **Direct Detection** is under neutrino floor!

Pure Higgsino DM **Indirect Detection** not yet sensitive



A multi-TeV-scale collider would produce Higgsino thermal relics for the first time

Why?

1) What does the Higgs potential look like + why
2) Are the simplest WIMP DM models are true?
3) Naturalness

Only the multi-TeV scale will tell us this!

3) The humility to know that there must be something more to discover.

Motivations for going as high as possible?

What?

What tools can we build in Batavia?

To unlock the **10 TeV scale**, need a *circular* collider

16 km ring can fit on FNAL campus

∃ concepts for potential circular **ee (240 GeV), pp (27 TeV), and μμ (10 TeV)**

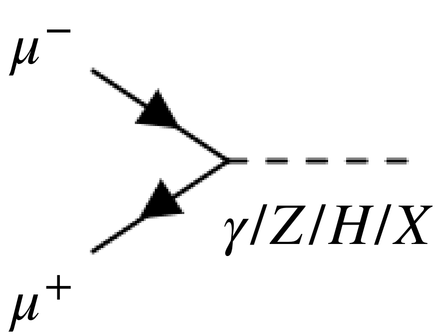
I'm going to focus on μμ

Muon Collider

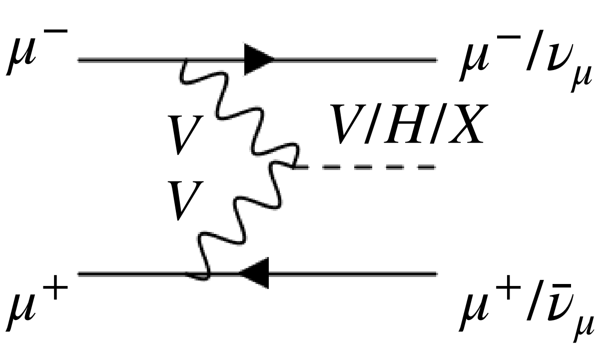
- μ's are fundamental → 10 TeV $\mu\mu$ collider is comparable w/ 100 TeV *pp* collider
- Since $m_\mu >> m_e$, very low synchrotron radiation. Get to much higher energies than *ee* machines
  - Hopes to achieve 10 TeV scale and beyond!
- μμ annihilation at high energies, but also VBF
  - *pp*-like discovery spread from effective "Vector Boson Distribution Function"
  - ("VDF"s à la PDFs)
  - Precision+Discovery machine. A new paradigm.

collider	*hh*
HL-LHC [78]	50%
ILC_{250}/C^3-250 [51, 52]	–
ILC_{500}/C^3-550 [51, 52]	20%
$CLIC_{380}$ [54]	–
$CLIC_{1500}$ [54]	36%
$CLIC_{3000}$ [54]	9%
FCC-ee [55]	–
FCC-ee (4 IPs) [55]	–
FCC-hh [79]	3.4-7.8%
μ(3 TeV) [64]	15-30%
μ(10 TeV) [64]	4%

[2209.07510]



μμ Annihilation



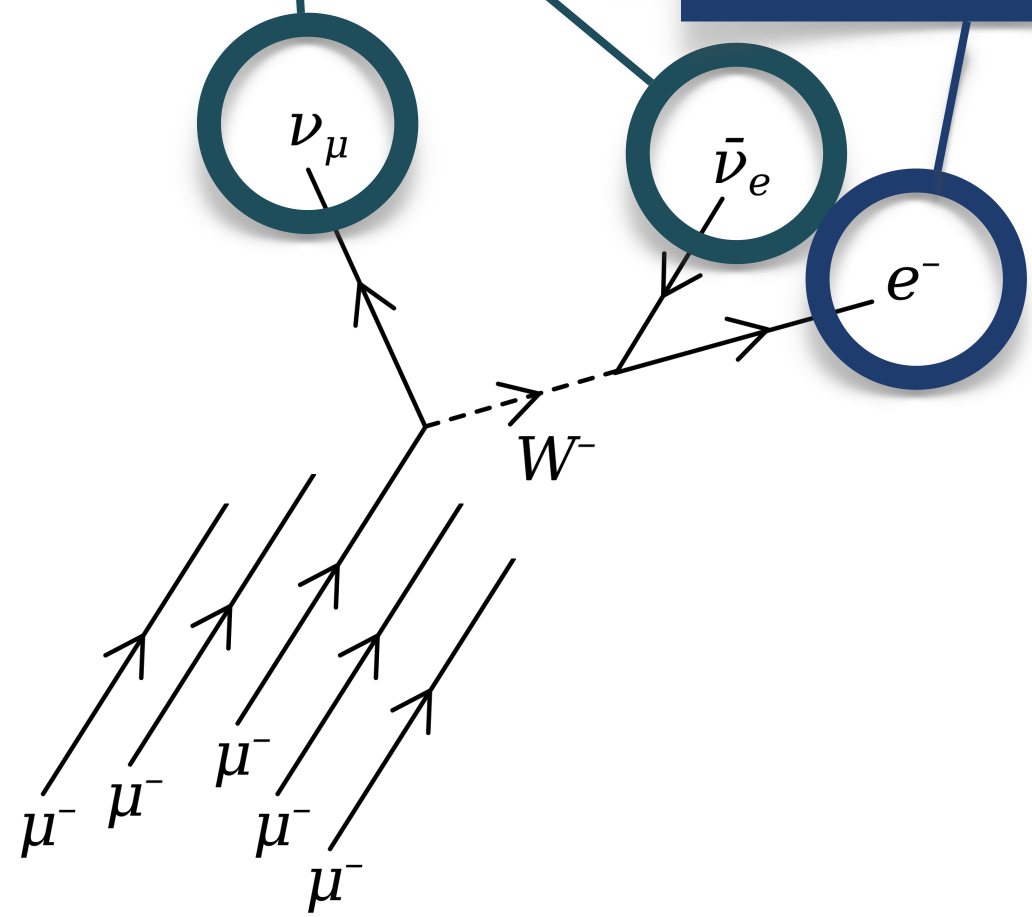
Vector Boson Fusion

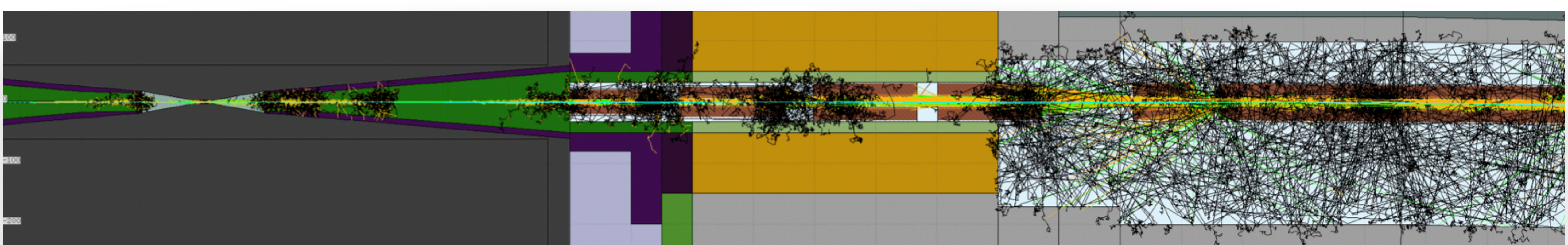
Muon Beams

- Engineering challenge to produce focused, intense beams for high luminosity
  - Phase space volume reduction ("cooling")
- But unlike protons or electrons, μ's decay!
  - Accelerator, experimental challenges
- τ_μ ~ 2 μs isn't very long
  - **Dilate Time:** Boost to high speeds, γ>10k to **delay decay in lab frame!**
  - Buys just enough time to **produce, cool, accelerate, and collide beams!**

Careful handling of neutrinos to keep radiation levels below limits. Many technologies to tackle this.

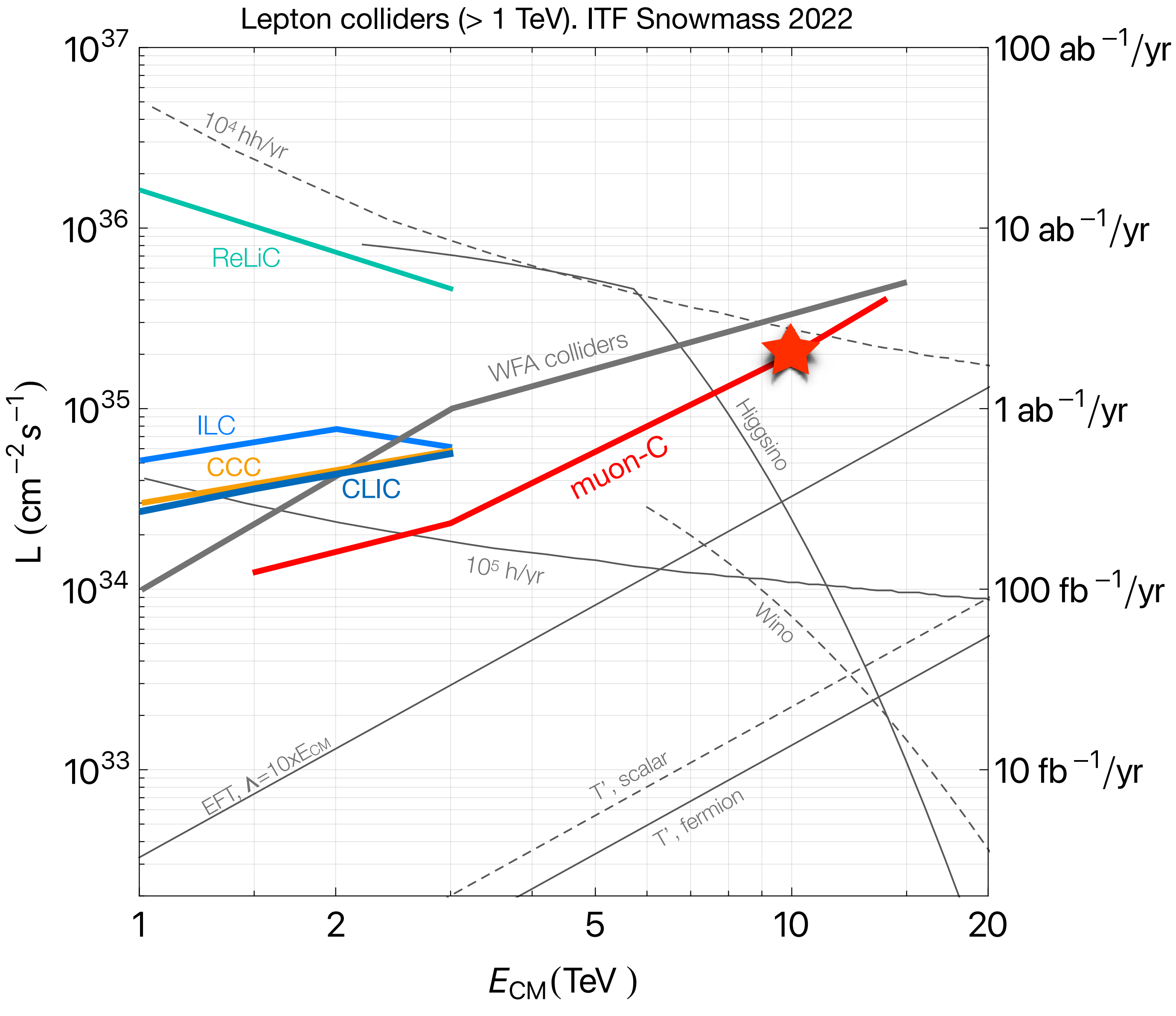
Resulting e's create beam-induced detector background

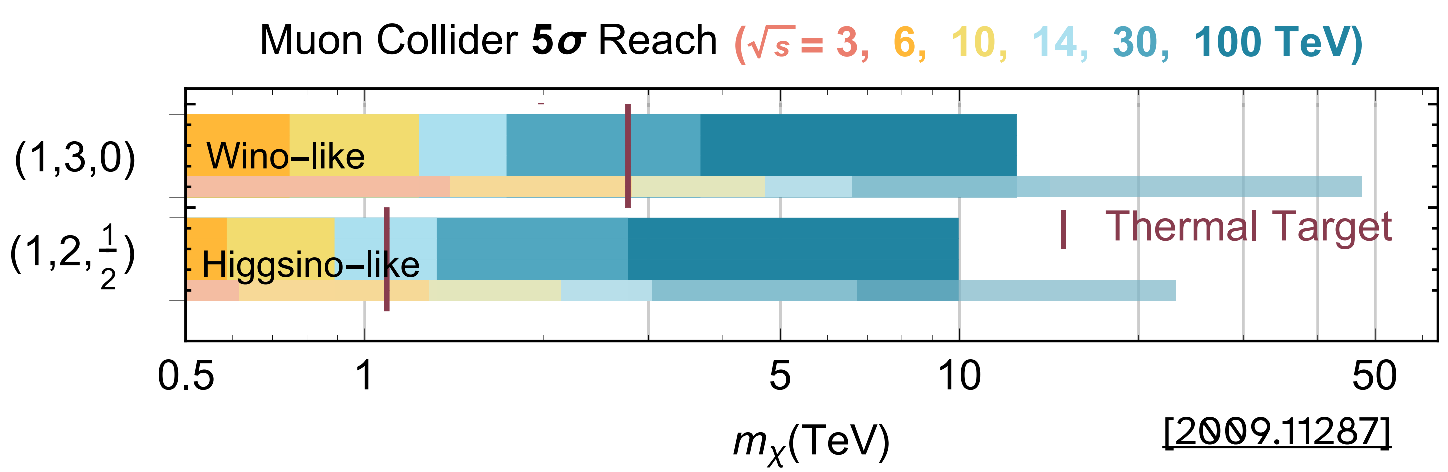




Muon Collider Physics

- **Would be a huge paradigm shift for the field**
- Once we meet these challenges with significant R&D, great physics potential
- A 10 TeV muon collider could have **large lumi** (2 ab^{-1}/year)
    - >10^6 Higgs events per year
    - ~10^4 Di-Higgs events per year
    - ~10^1 Tri-Higgs events per year
- **5σ sensitivity to *simple* thermal relic WIMP DM targets**
- **BSM exploration** far beyond the HL-LHC





[2009.11287]

Muon Collider @ Fermilab

∃ serious FNAL site-filler muon collider concept that reuses Tevatron ring

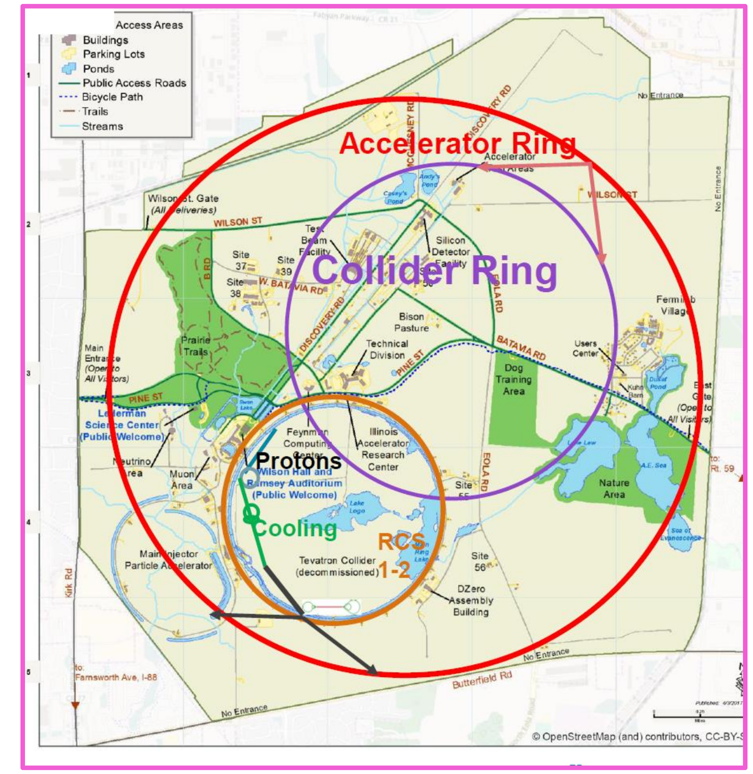
Requires a high power proton driver on target

→ Builds on **Accelerator Complex Evolution (ACE)**

ACE can provide a path to the muon collider proton driver

ACE Workshop, 2 weeks ago

- A concept design for a Fermilab **6-10 TeV MuC** is in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (3 stages)
  - Linac + RLA → **65 GeV**
  - RCS #1, #2 → **1 TeV (Tevatron size)**
  - RCS #3 → **3-5 TeV (site filler)**
- 6-10 TeV collider
  - Collider radius: 1.65 km



- In the next **5 years**, have a baseline design including the neutrino flux mitigation system

13 IMCC Annual Meeting Fermilab

Diktys Stratakis at IMCC Meeting Last Week

Significant synergies w/ existing accelerator and neutrino programs at FNAL

→ **Fermilab is ideal lab for leading R&D, demonstrators, and hosting**

- ∃ great options for linear ee Higgs factories
- A muon collider is the only option for probing the 10 TeV scale at FNAL

How?

How do we make any of this happen?

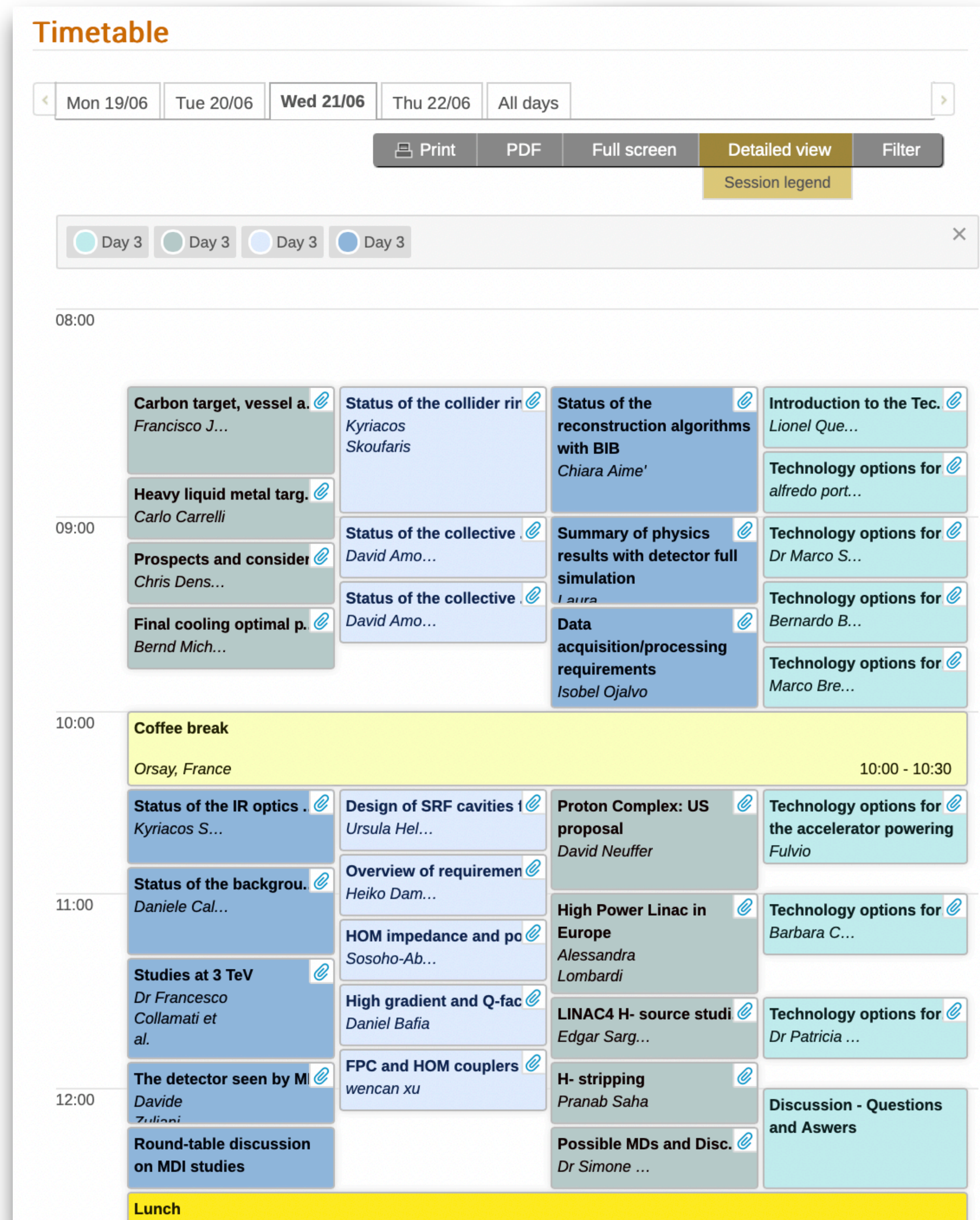
Need extensive R&D and demonstrators for **accelerators, detectors, electronics, computing, physics**

Proposed national accelerator R&D program: [2207.06213]

So much of this is **new and challenging**

Muon Collider R&D

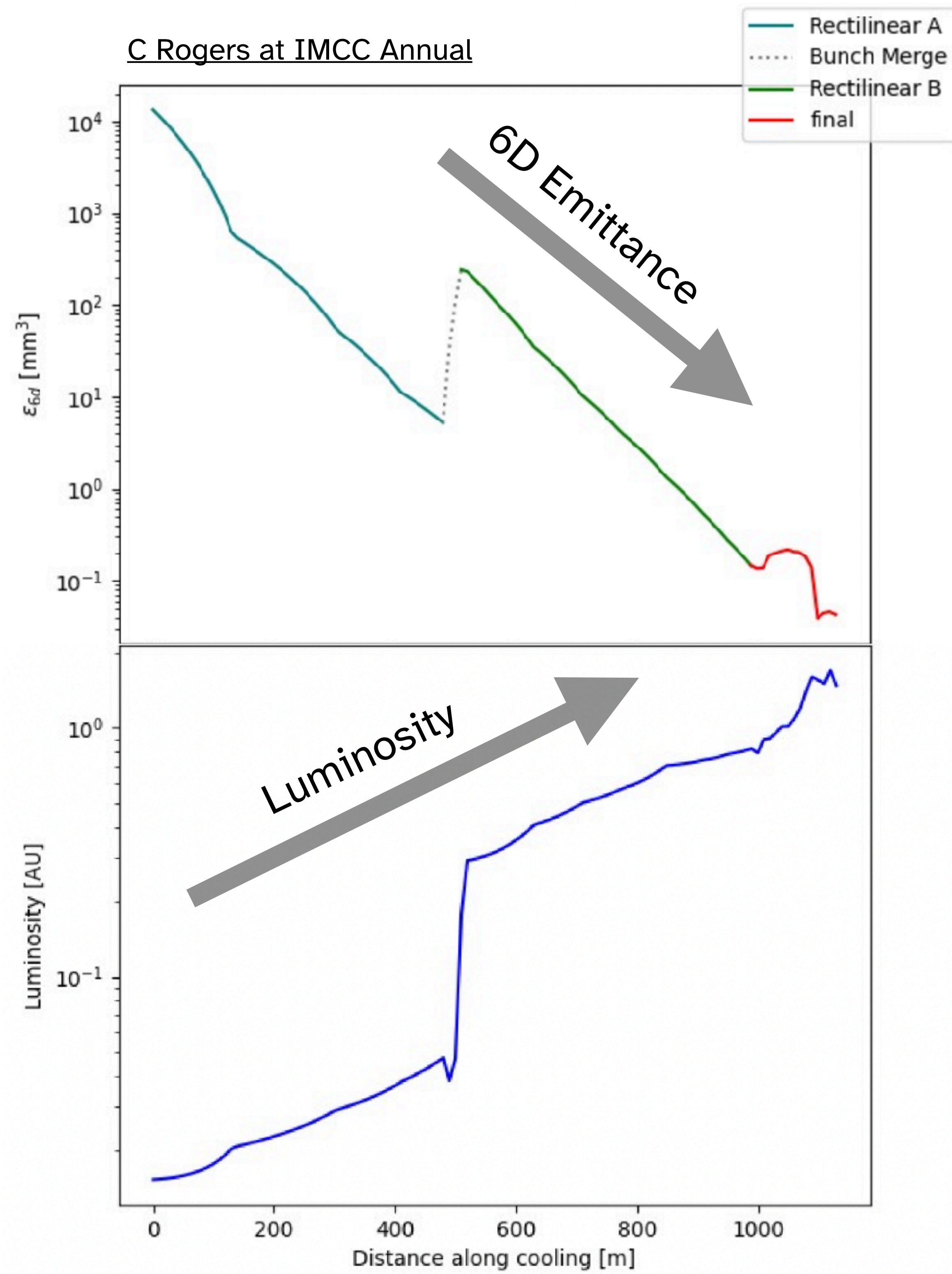
- **Rapidly moving field.** Enormous advances to muon collider feasibility studies.
  - Incredible progress *month after month*
- CERN hosts **International Muon Collider Collaboration (IMCC)**
  - Second annual meeting last week, IJCLab, Orsay
  - Huge number of talks!
- **“MuCol” project funded by EU**
  - Design study for collider complex at 10 TeV, includes 2 US associate institutions
- **US Muon Collider Coordination Group** formed to coordinate funding request to P5
- Last half-year: 4+ major meetings dedicated to muon colliders

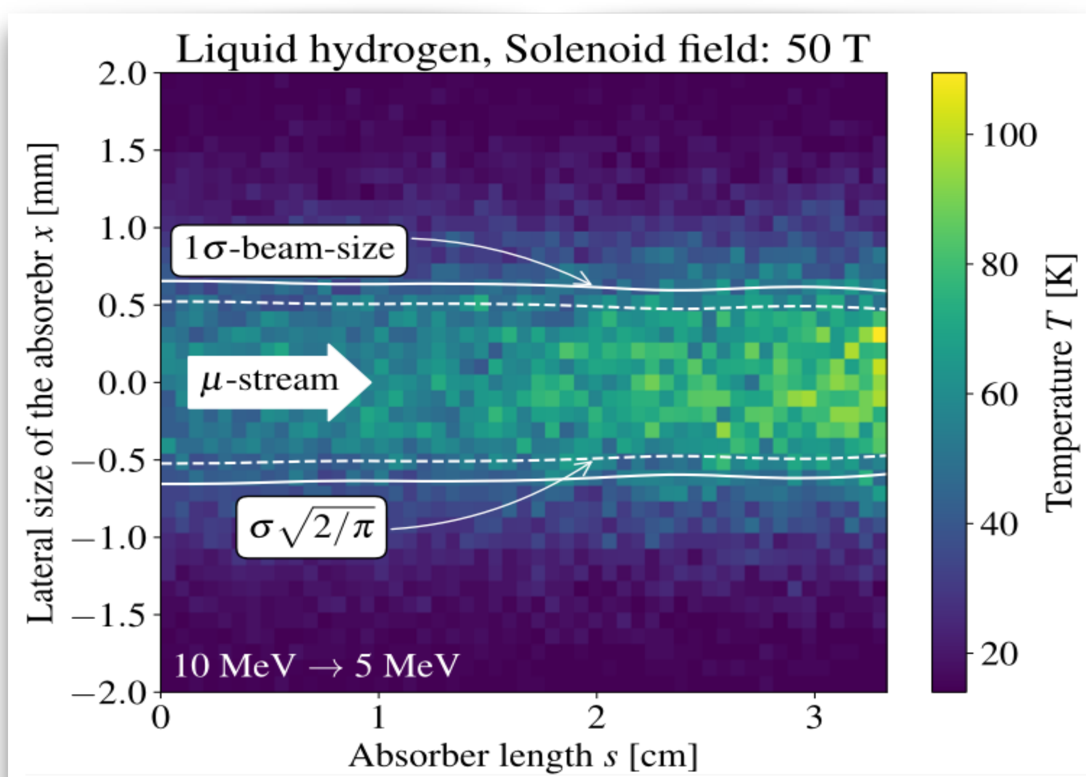


Muon Collider R&D

- Lots of new studies presented **last week**
- **Detailed technical studies on all fronts**
  - Proton complex
  - Muon production & Cooling
  - Accelerator & Collider
  - RF & Magnet Systems
  - Physics & Detectors
- **Many engineering studies have been conducted and reported**
- **Incredibly exciting time!**

C Rogers at IMCC Annual



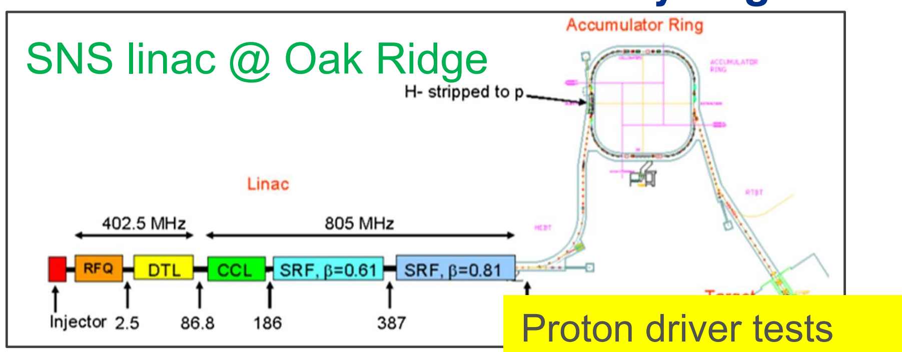


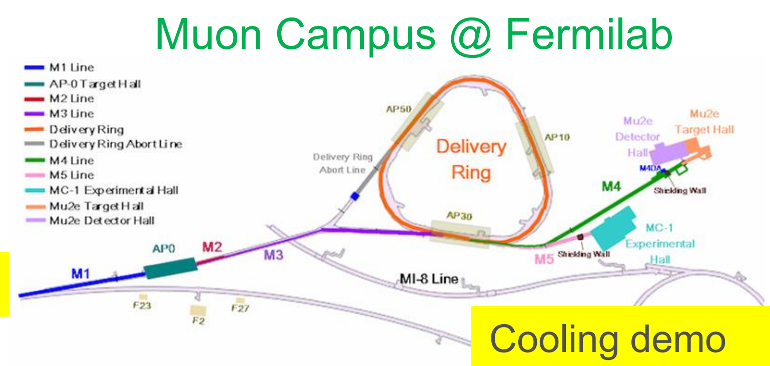
D Schulte at IMCC Annual

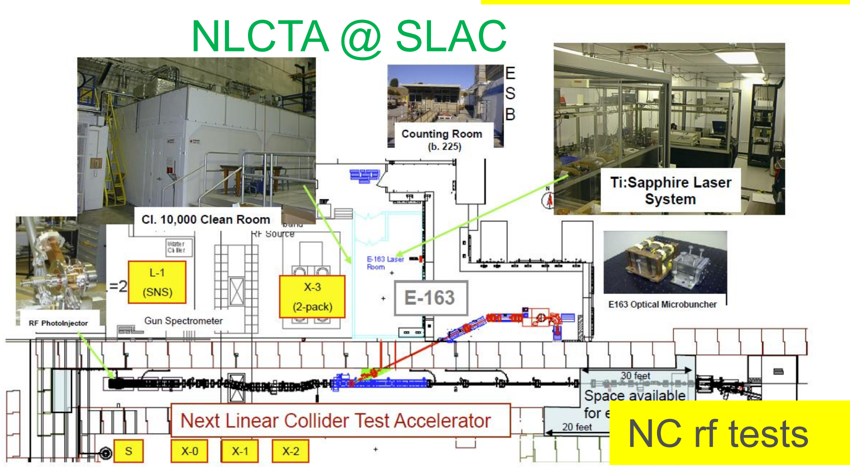
Muon Collider R&D in US

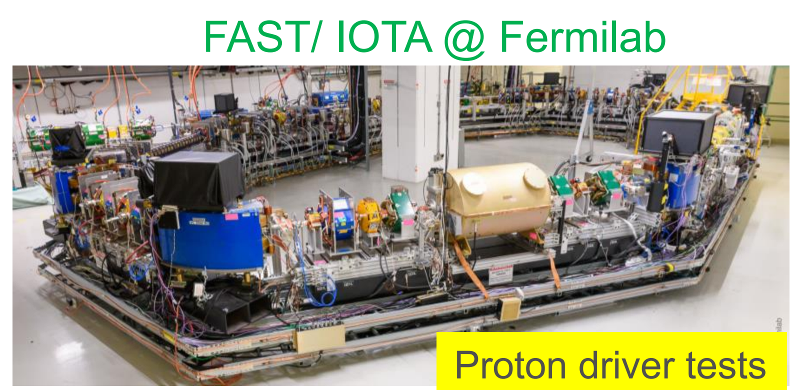
Further possibilities within the US

- Several **existing US based facilities** can aid the MuC R&D program: **they expressed interest** and are currently explored
  - **More discussions at the Synergies workshop on Friday**









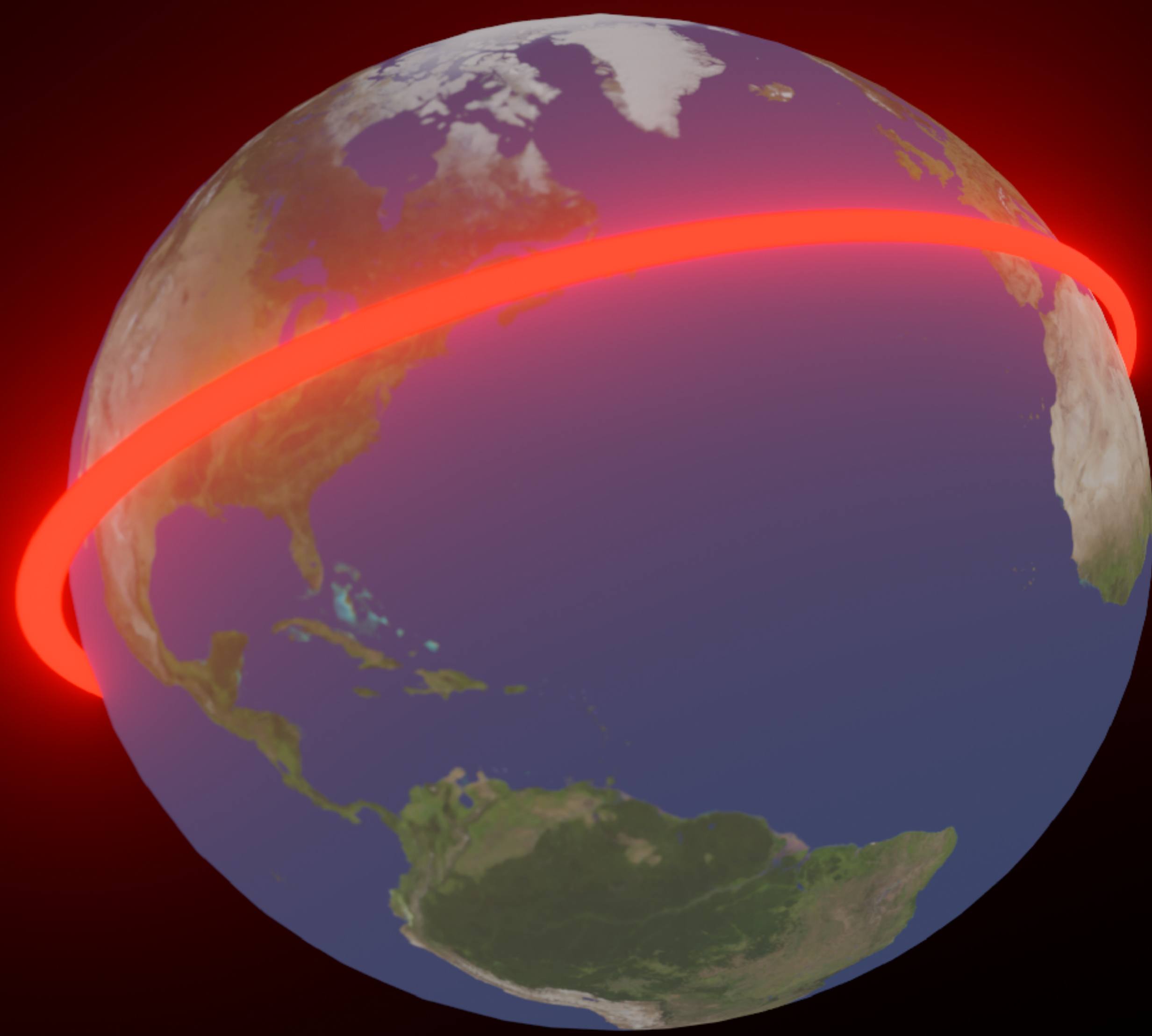
Fermilab

Tests and demonstrators needed for a muon collider

Identified interest and opportunities at many US national labs and universities

US is uniquely suited to lead program and overcome engineering challenges

Diktys Stratakis at IMCC Meeting Last Week

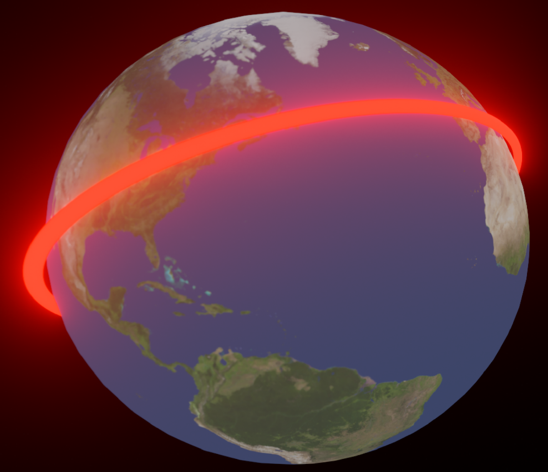


Fermi's Globatron (1954)

40 Years in the future (1994)
40,000 km
~3 TeV CoM proton collisions

This is **BIG** science like we've never known.

A few lessons to learn from this…



Fermi's Globatron (1954)

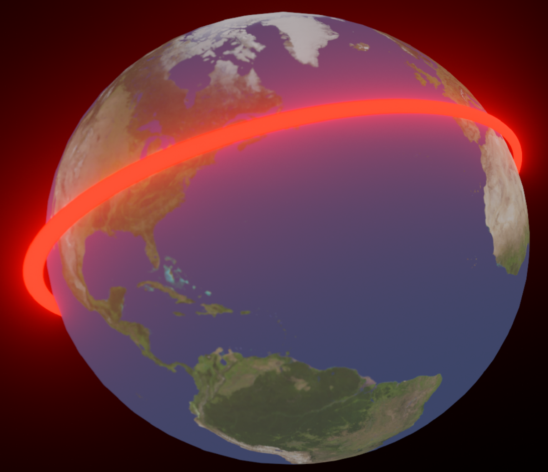
40 Years in the future (1994)
40,000 km
~3 TeV CoM proton collisions

Globatron Lesson #1:

- Not great at projecting 40 years in the future!
  - We ***did*** reach TeV hadron collisions in the 90s (at his namesake lab) w/ the Tevatron
  - **But we didn't need 40,000 km to do it!**

Be **smart, open-minded, and take advantage of opportunities** to achieve physics goals

Realize seemingly impossible physics w/ technology, engineering, ingenuity



Fermi’s Globatron (1954)

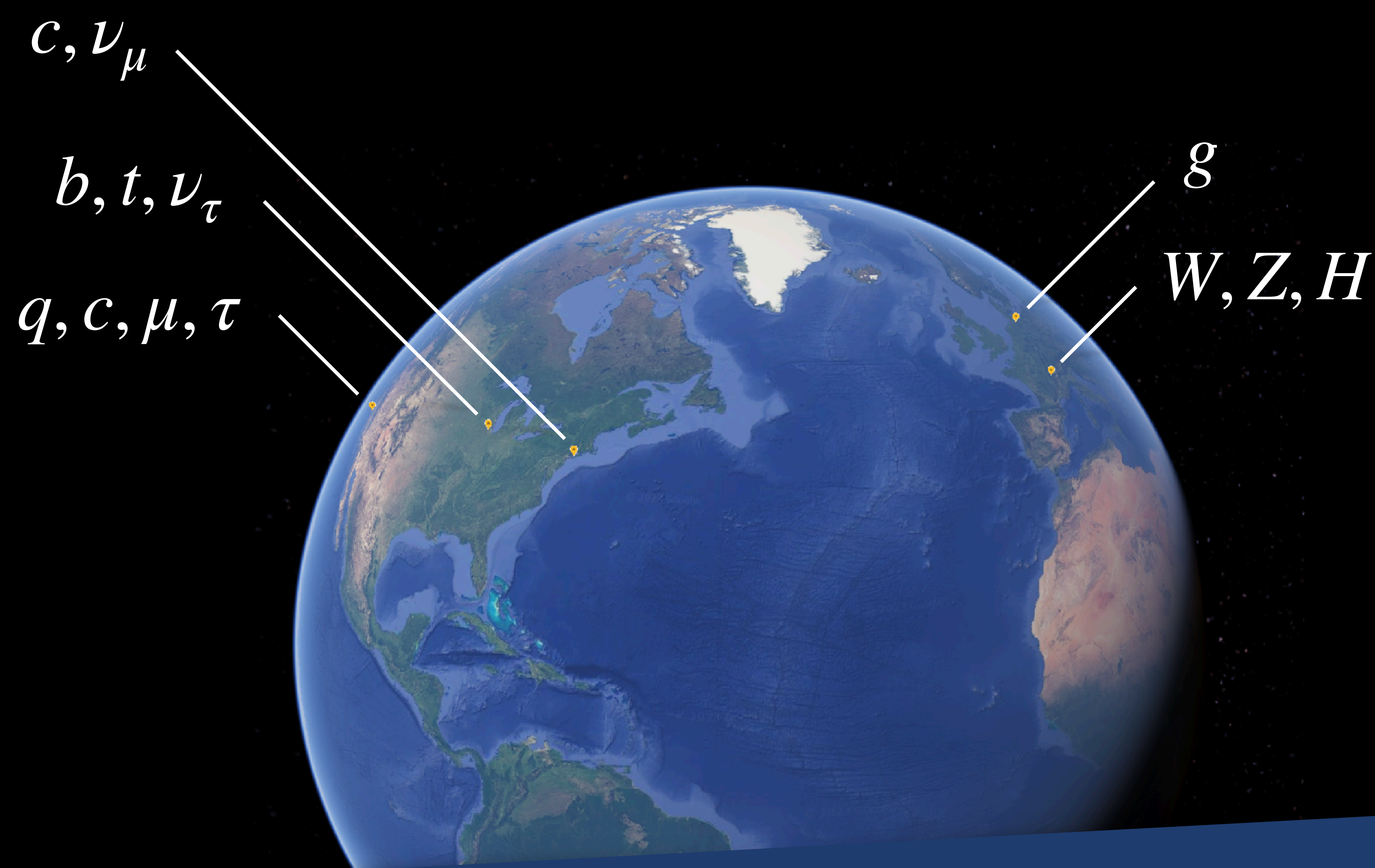
40 Years in the future (1994)
40,000 km
~3 TeV CoM proton collisions

Globatron Lesson #2:

Globatron Dream → Tevatron Reality

Fermilab has tradition of being a leader and hosting these revolutions

Has expertise, technologies, campus, and enthusiastic user community
to lead the future of the Energy Frontier



Reminder: Fermions seem to like to be discovered in the US, Bosons in Europe

Higgsino DM is waiting for us to make the next move!

Google Earth

Thanks for your attention!

LL is supported by the Department of Energy, Office of Science, under Grant No. DE-SC0023321 and the National Science Foundation, under Award No. 2235028.

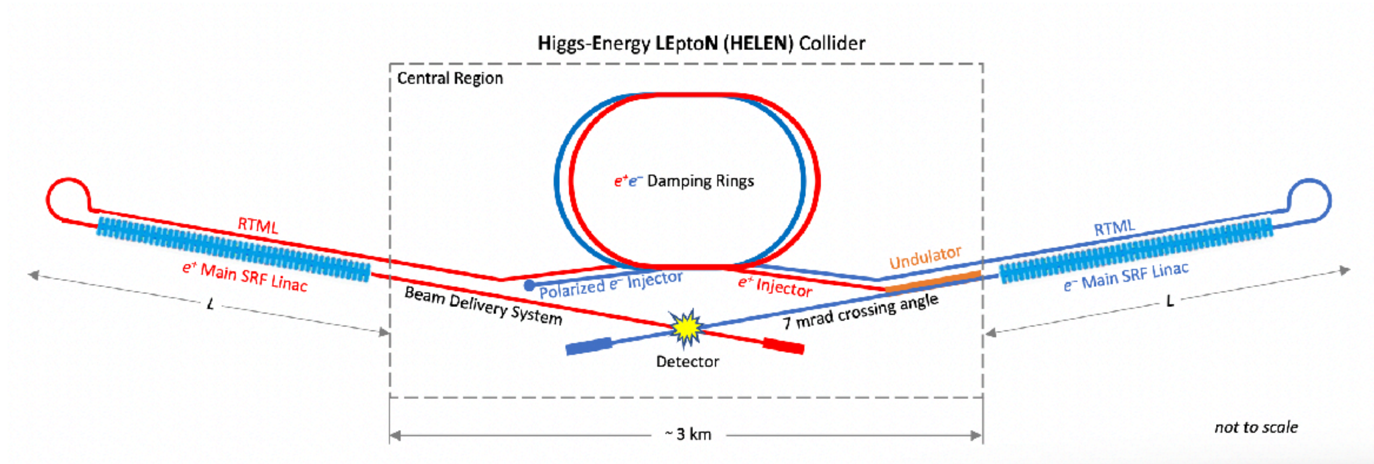
BACKUP

Midjourney: “Two bison from Fermilab in a field aggressively butting heads with a bright light and lots of curved lines emerging from a single point between them with a huge explosion volumetric lighting”

[2203.08088], [2203.08211]

HELEN (Higgs Energy LEptoN) Collider

- ILC parameters baselined in 2013. 10y of superconducting RF (SRF) developments since!
- New design w/ advanced SRF → HELEN
  - With intensive R&D, >2x the accelerator gradients w.r.t. ILC, ~50-90 MV/m
  - ILC-like machine but much more compact — less than half the size!



Both options can fit a Higgs factory on FNAL site!

C^3 (Cool Copper Collider)

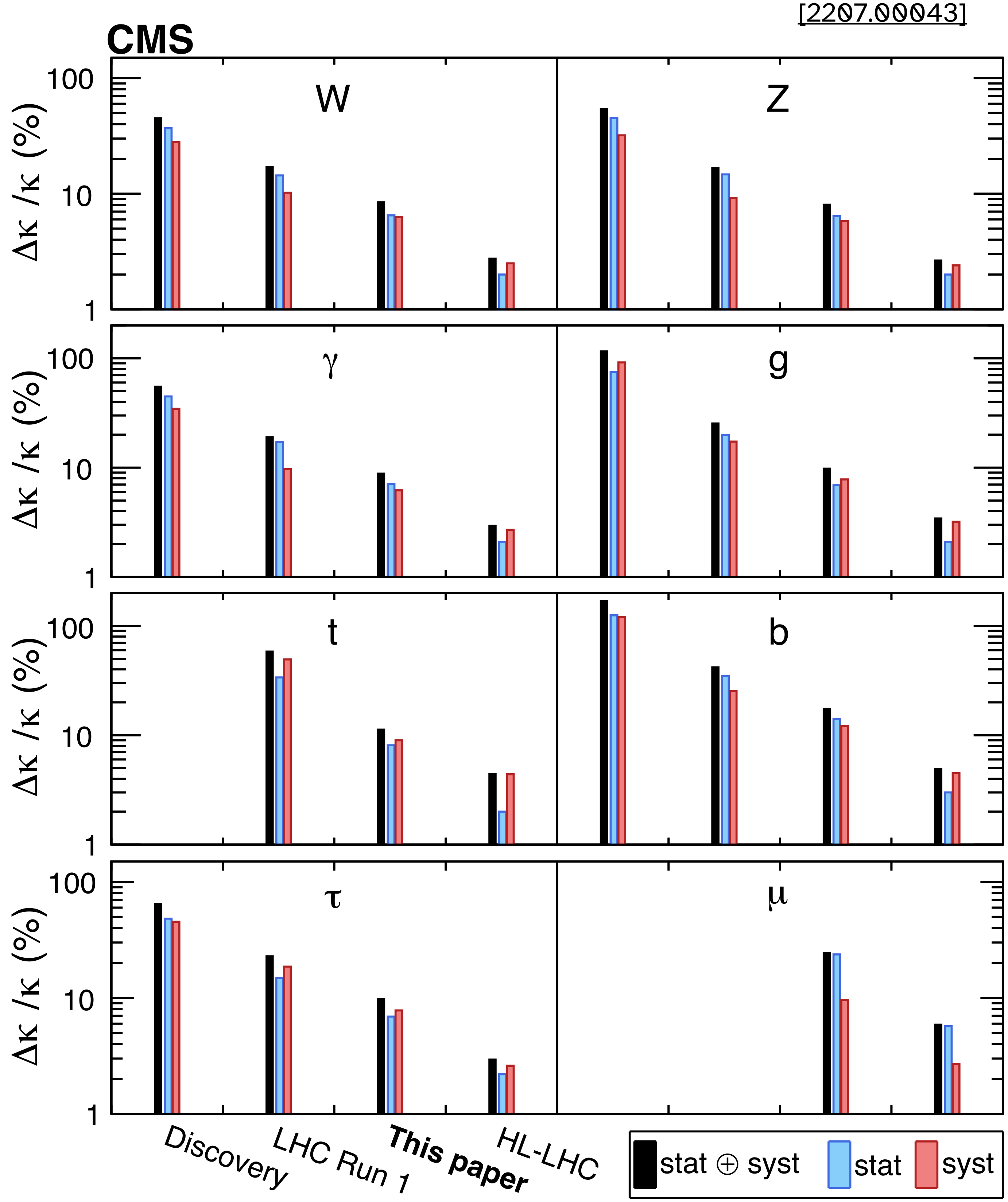
- Or ditch the SRF entirely! C^3 uses normal conducting cavities, specifically optimized for efficiency
- Unlike SRF, LN_2 temps suffice! Much cheaper, much easier.
- Already demonstrated peak 150 MV/m on small scale and expect a robust 120 MV/m operation
- With more space, can extend to 550 GeV HH factory, or even to 3 TeV machine

Extend beyond the perimeter of FNAL site by using Commonwealth Edison power company’s easement, increase length (i.e. energy) up to 12 km

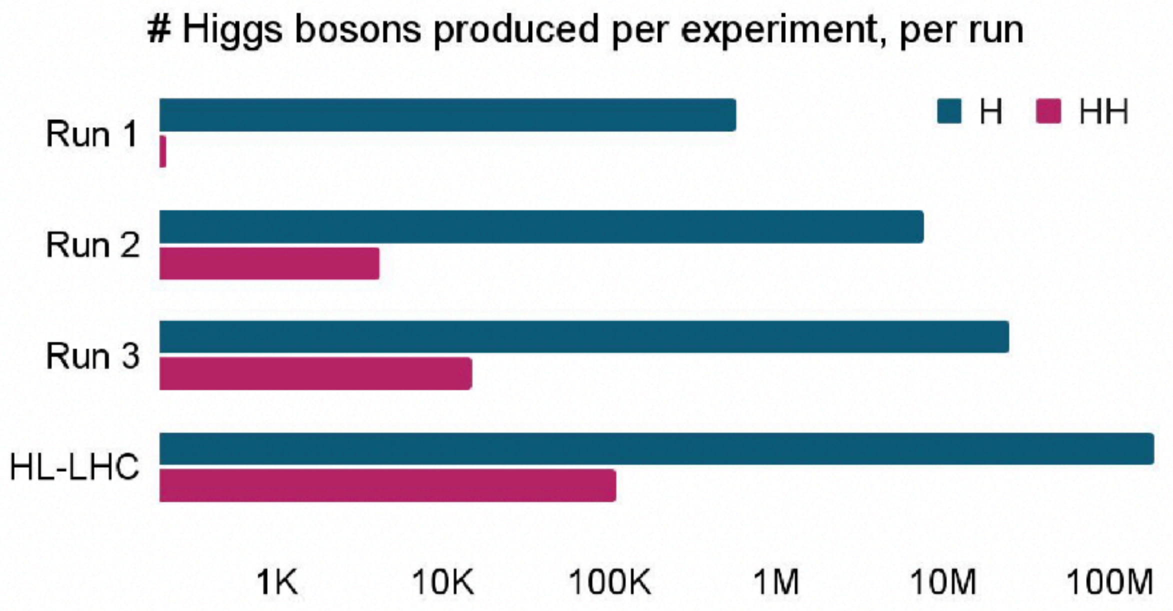
Google Street View

- Many Higgs parameters have been measured @ LHC
    - HL-LHC will significantly increase precision
- But will only have rough sketch that looks roughly like the SM as far as we can tell
- **Need to measure Higgs properties at high precision**
    - Aim for 1% or per-mille uncertainties
    - **Need a large dataset of Higgses!**

[2207.00043]

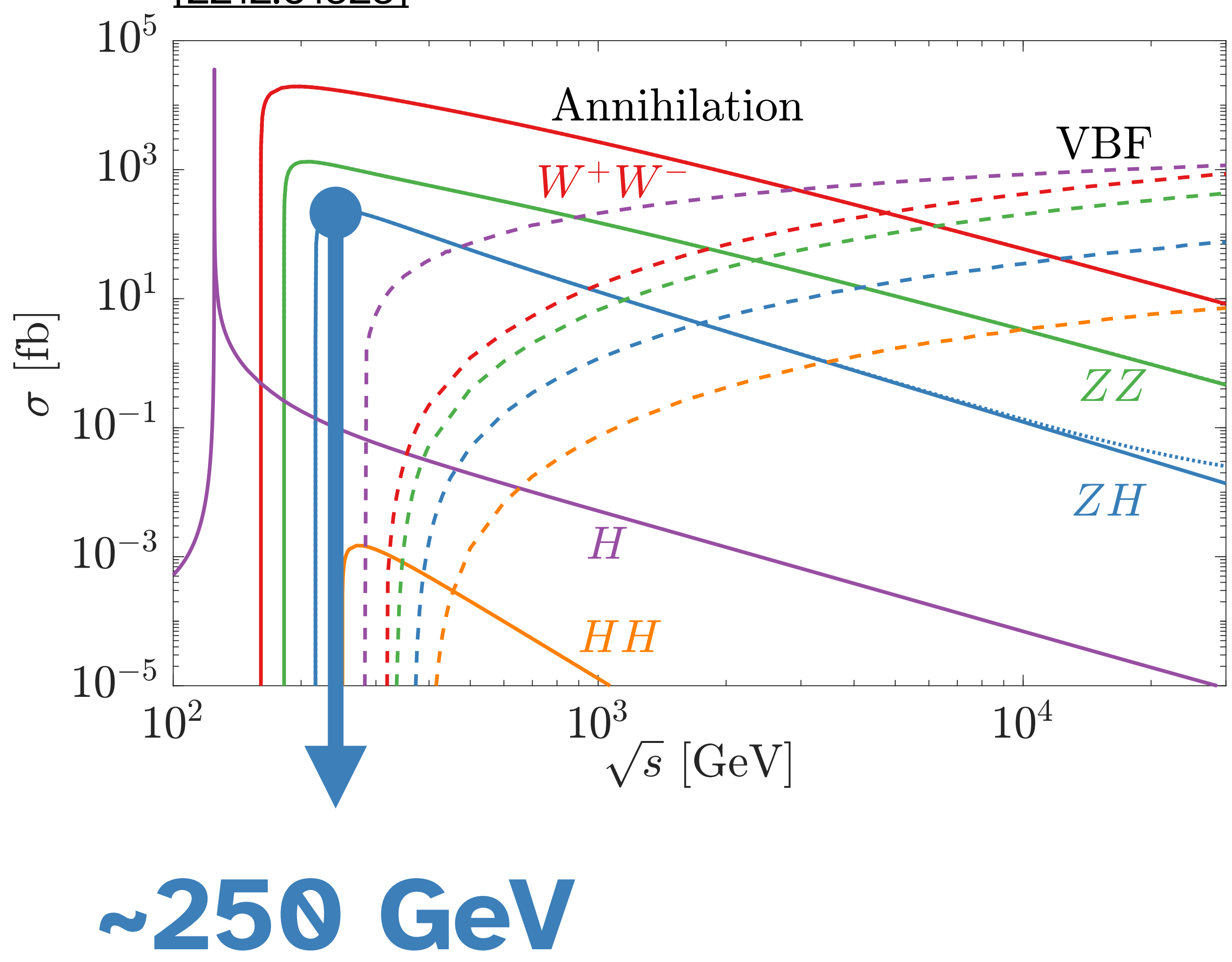


E Brost



- LHC produces a lot of Higgses
  - But LHC (pp) is messy
- To better measure the Higgs → Make a lot of them in a clean environment
  - **Need Higgs factory**
- **ee collider with E_{CM}~250 GeV to produce a lot of clean ZH events**

[2212.01323]



Personal Perspective:

- SM Higgs **unnaturalness** is a problem
- What's broken about our theory such that m_H is many orders smaller than its quantum corrections?
- **Some explanation is waiting to be found!**

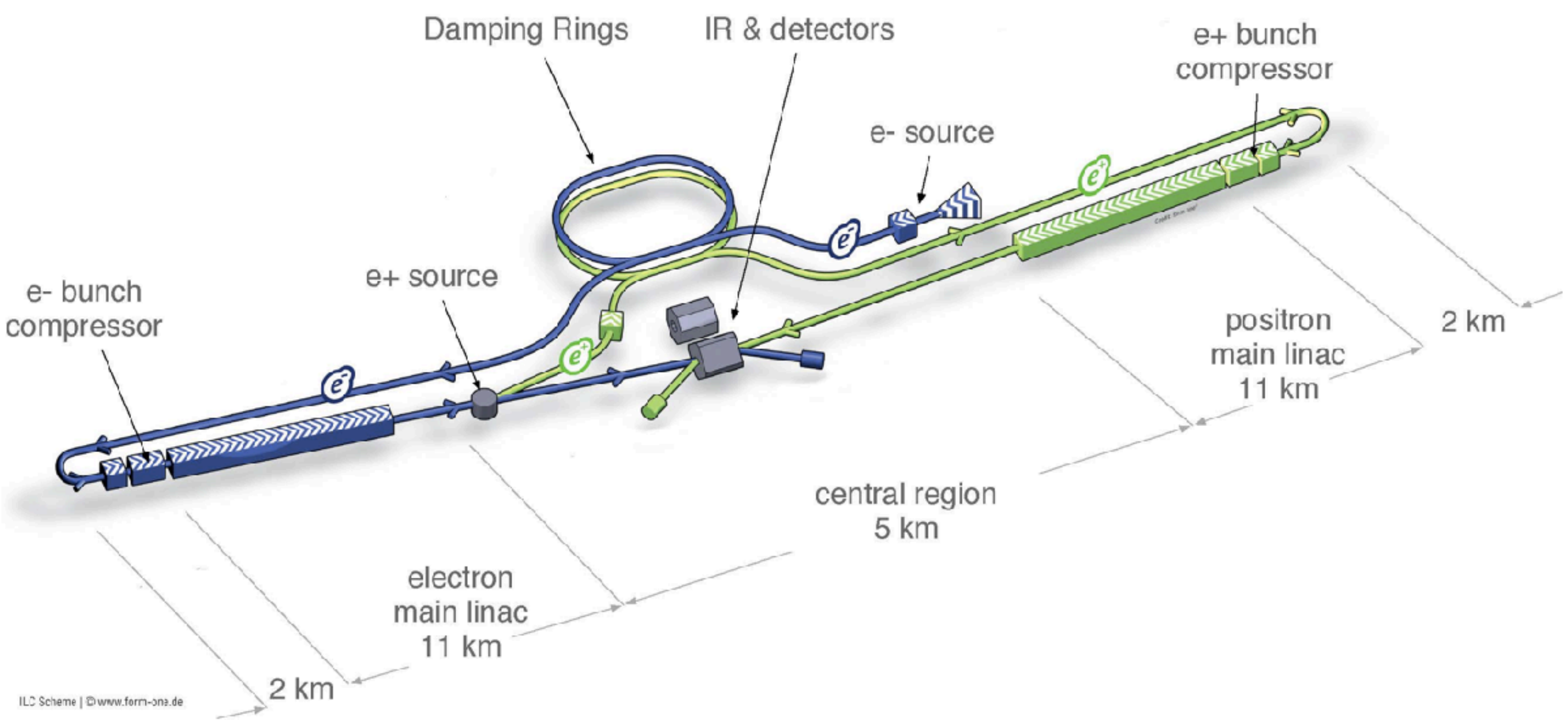
But that's not everybody's cup of tea… Instead…

- (60 year old) SM describes 0-1 TeV interactions amazingly;
  Was deduced from experiments at 0-1 TeV
  - **Tiny a blip on the scale of the universe**
- Silly to think we understand everything from the LHC-scale to m_{Pl}
- Every energy step we take → more to learn about the universe

Purest goal of the Energy Frontier. **Explore the unknown** at the highest energies, at the smallest scales, possible.

International Linear Collider (ILC)

- For decade, ILC has been the de facto next step
  - 20 km ee Higgs factory (ILC250)
  - Most quickly realizable Higgs factory option!
  - Higgs factory ~today! Mature tech, ready to build. Stalled. 😞
- If Japanese partners don't realize the ILC:
  - Bring the shovel-ready ILC250 to the US and potentially Fermilab?
  - Doesn't fit on FNAL campus, but multiple locations identified in region



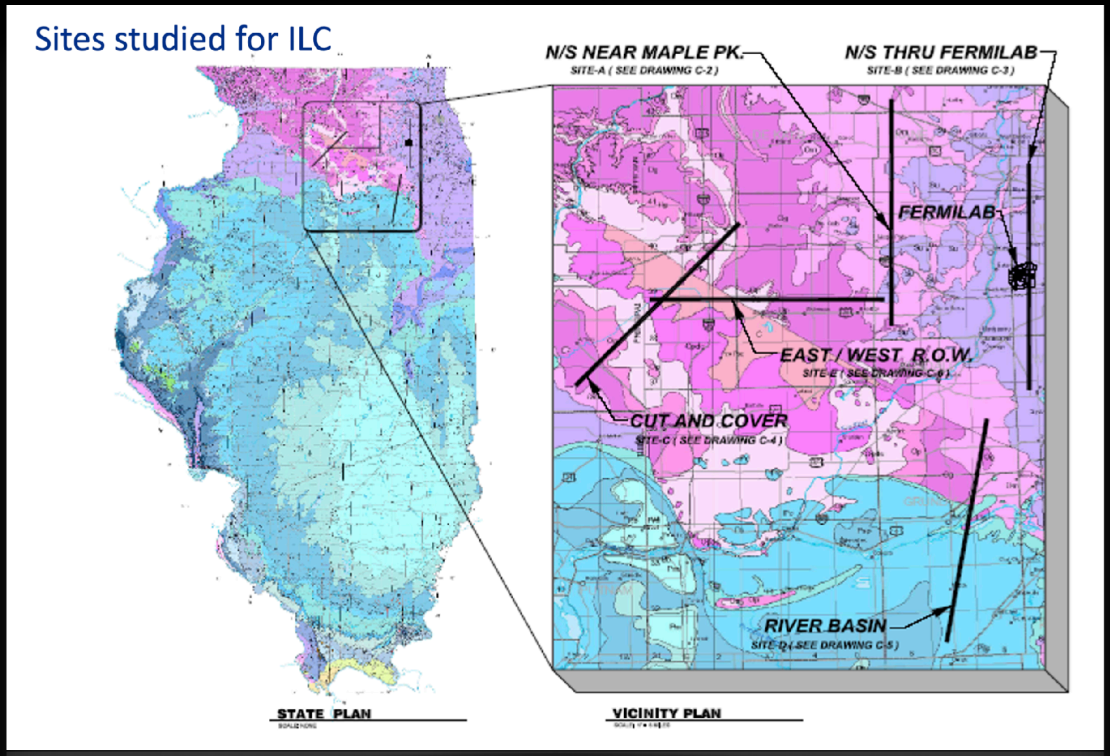
[2208.06030]

Collider Name - c.m.e. (TeV)	ITF Judgement Combined "Time to the First Physics"
ILC-0.25	< 12 yrs
ILC (6x lumi)	13-18 yrs
CLIC-0.38	13-18 yrs
FCCee-0.36	13-18 yrs
CEPC-0.24	13-18 yrs
CCC-0.25	13-18 yrs
FNALee-0.24	13-18 yrs
CERC-0.6	19-24 yrs
HELEN-0.25	19-24 yrs
ReLiC-0.25	> 25 yrs
ERLC-0.25	> 25 yrs
MC-0.125	19-24 yrs
XCC-0.125	19-24 yrs
SWLC-0.25	19-24 yrs

- All plans have pointed to ILC in Japan
  - Despite ***amazing*** public outreach, stalled for a decade+
- If Japanese partners don't realize the ILC:
  - Bring the shovel-ready ILC250 to the US and potentially Fermilab?

Highly Recommended Outreach Video from 2013

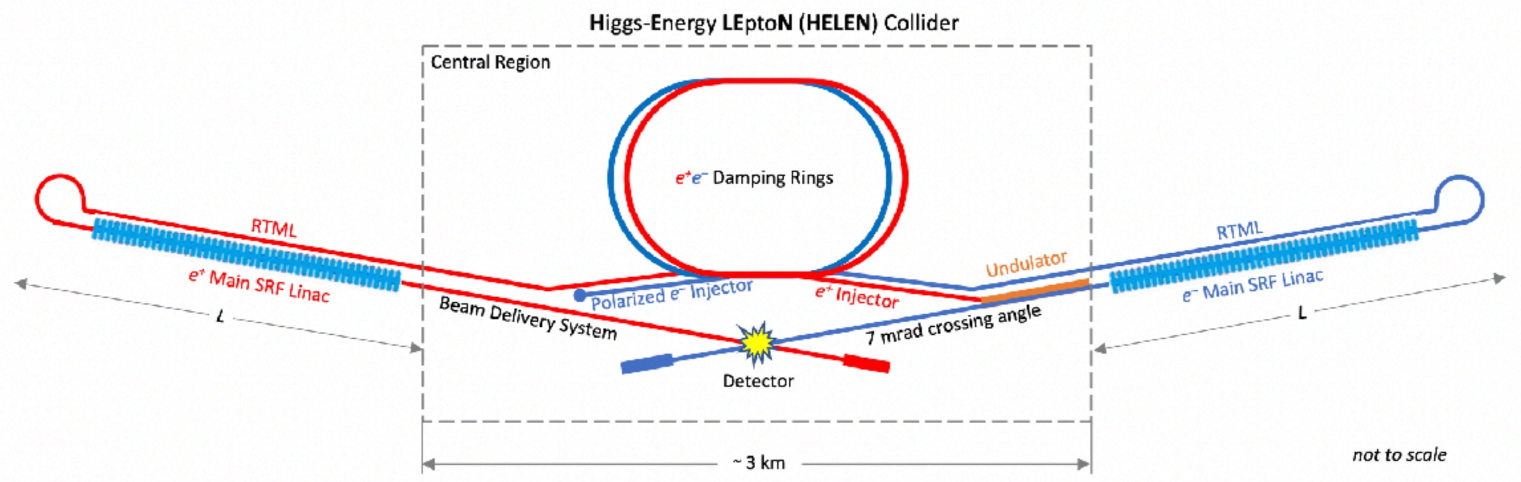
[2203.08088]



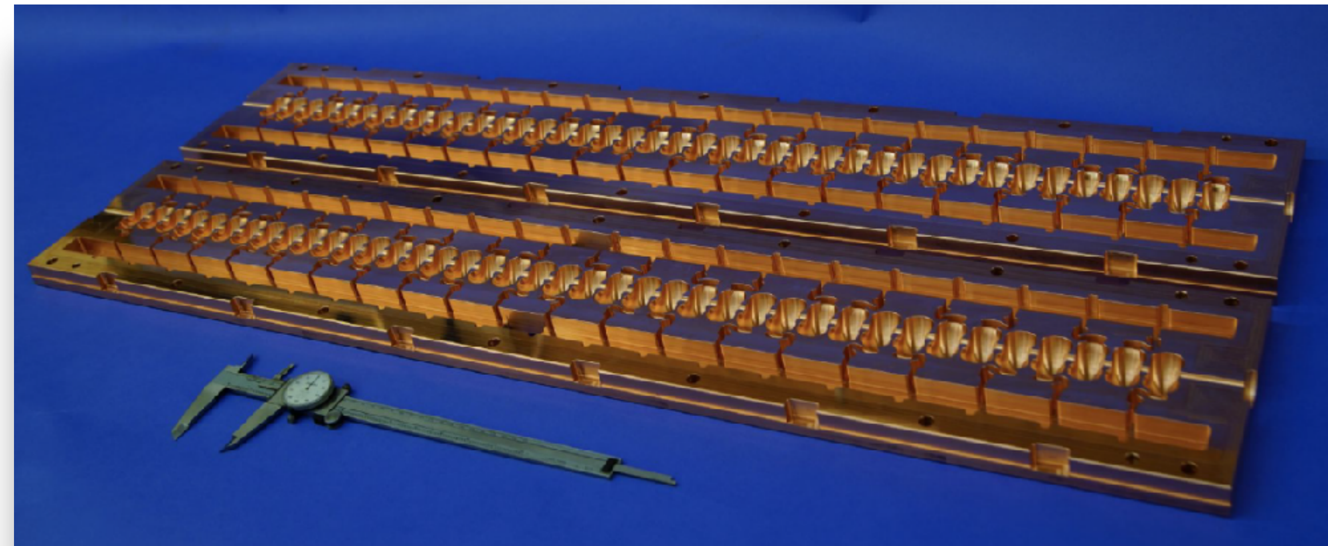
ILC doesn't fit on FNAL campus, but multiple locations identified in region

HELEN (Higgs Energy LEptoN) Collider

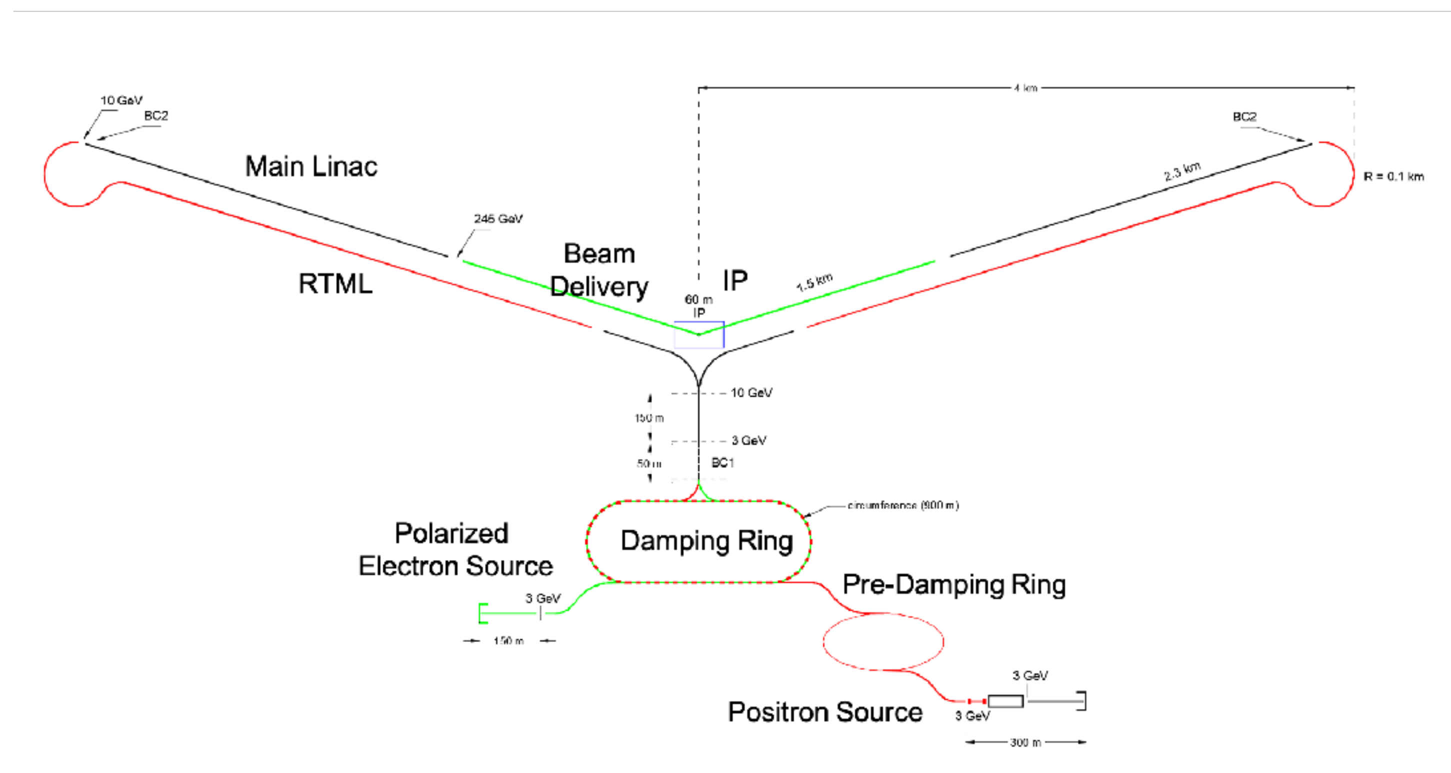
- ILC parameters baselined in 2013
- A decade of superconducting RF (SRF) developments since!
- New design w/ advanced SRF, HELEN
  - With intensive R&D, >2x the accelerator gradients w.r.t. ILC
    - Baseline: ~70 MV/m
    - w/ further advances: ~90 MV/m
  - ILC-like machine but much more compact — less than half the size!
- **Allows Higgs factory to potentially fit inside FNAL site!**



C^3 (Cool Copper Collider)

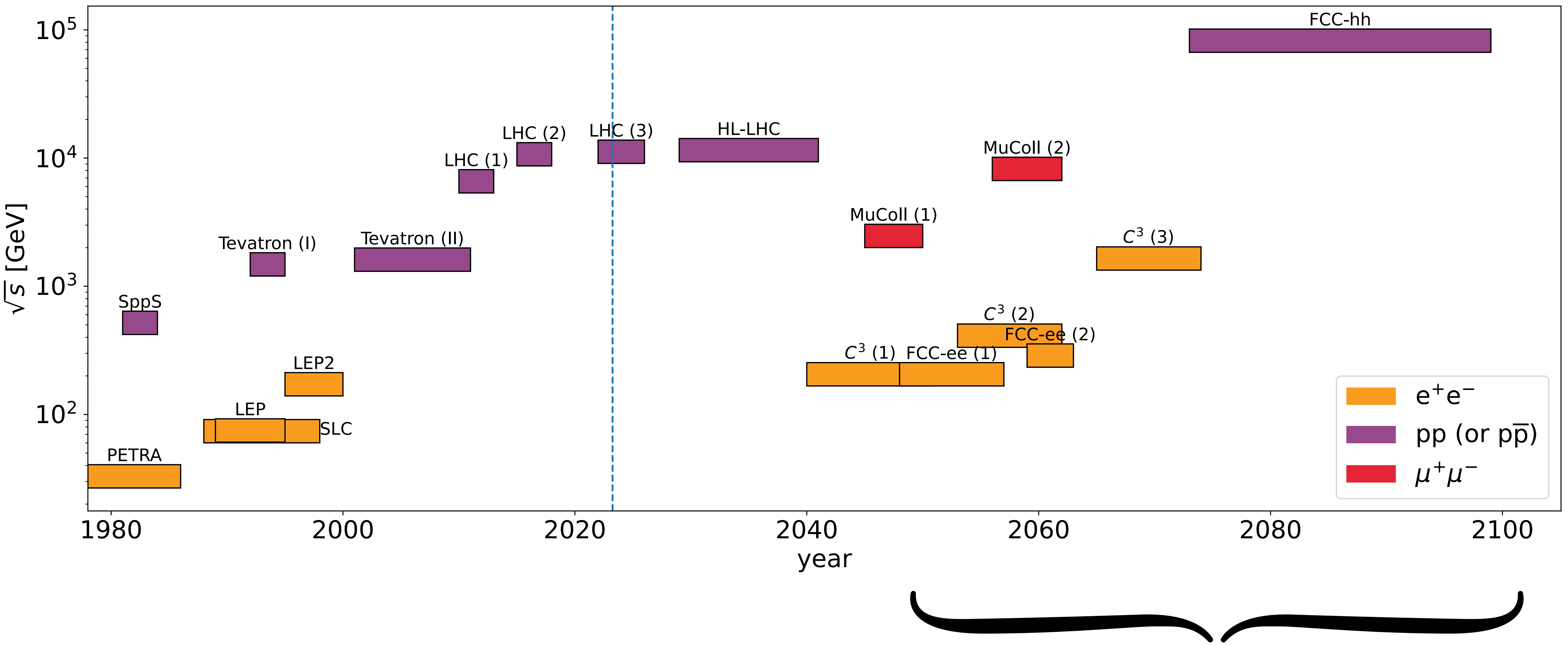


- Or ditch the SRF entirely!
- C^3 uses normal conducting cavities, specifically optimized for efficiency
    - At E_{CM}=250 GeV, expected total power required ~150 MW.
    - Unlike SRF, LN_2 temps suffice! Much cheaper, much easier.
- Already demonstrated peak 150 MV/m on small scale and expect a robust 120 MV/m operation
- **Higgs factory could fit on FNAL campus**
    - With more space, can extend to 550 GeV HH factory, or even to 3 TeV machine



[2110.15800]

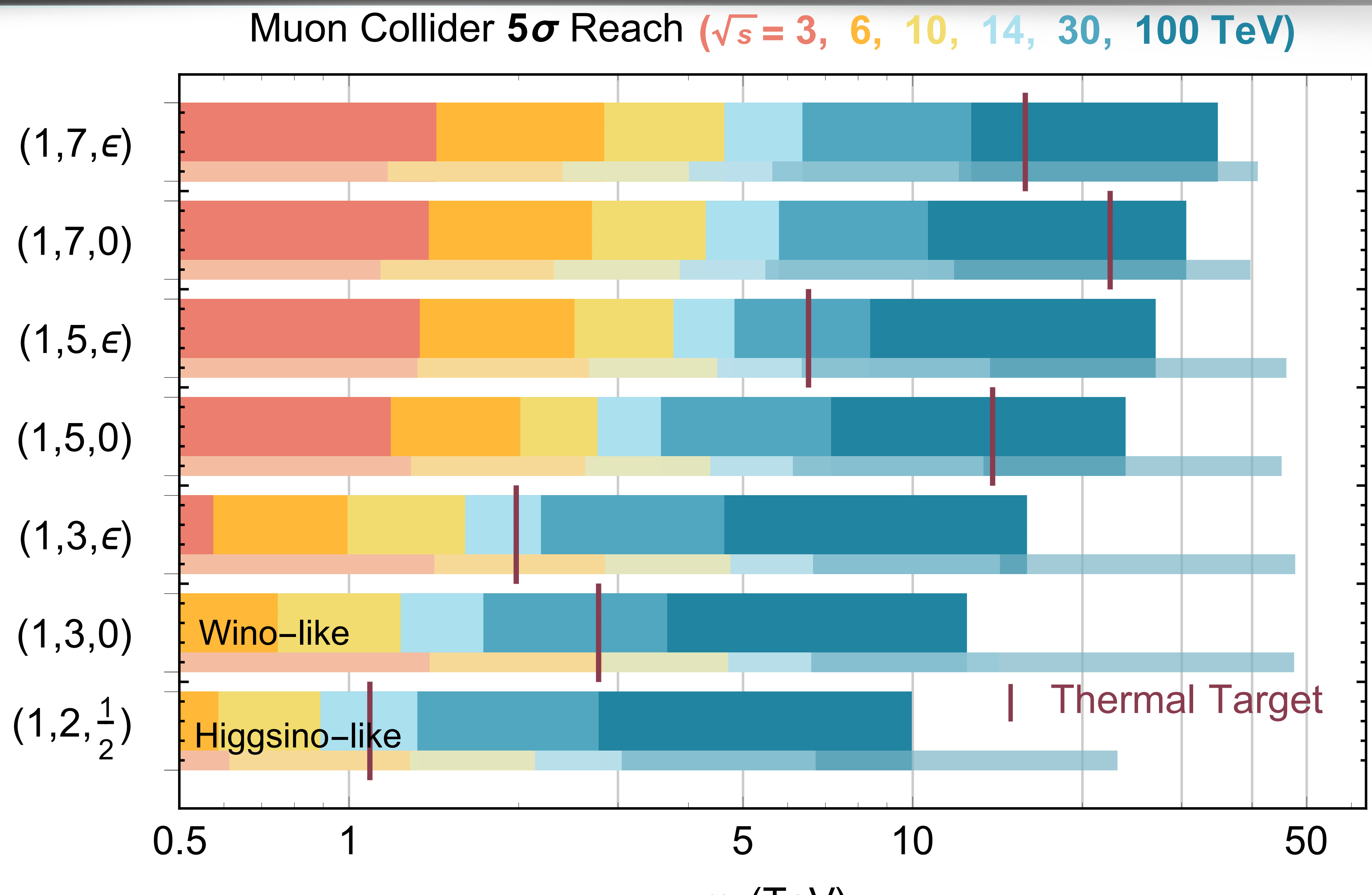
K Pedro

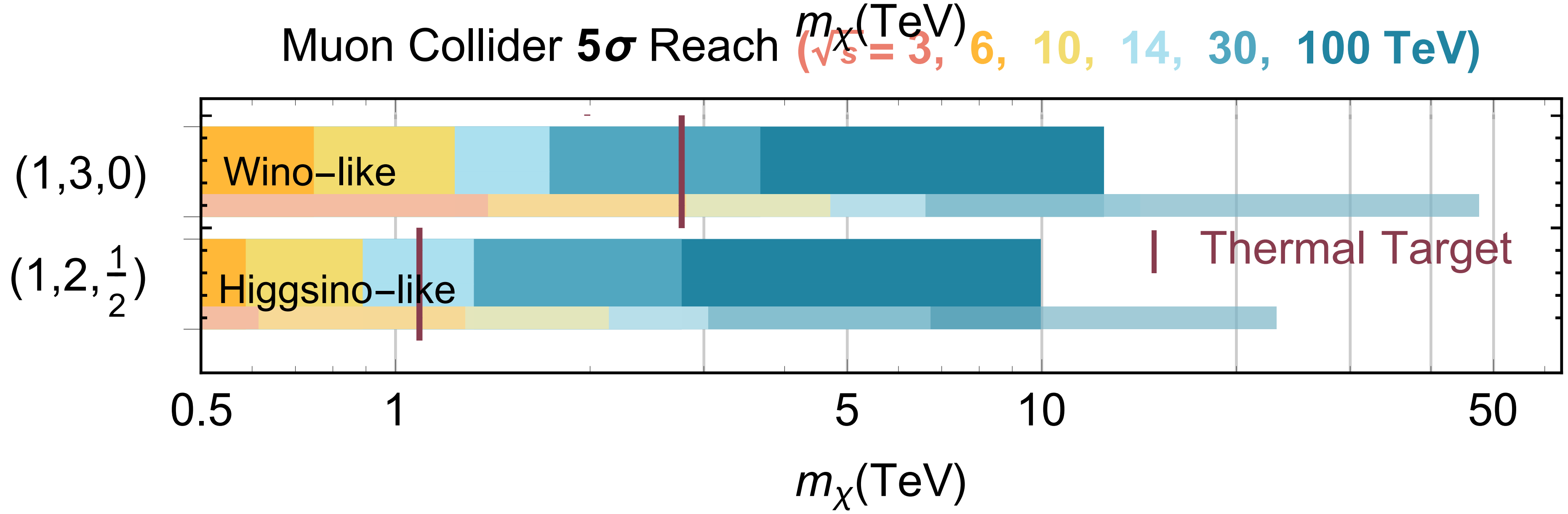


Physics of the second half of the century

We often talk about "early career issues". And many people think that has to do with jobs. Unfortunately many people think that only means DEI efforts. But looking at these timelines, **everything to do with planning for the coming decades uniquely affects early career researchers.**

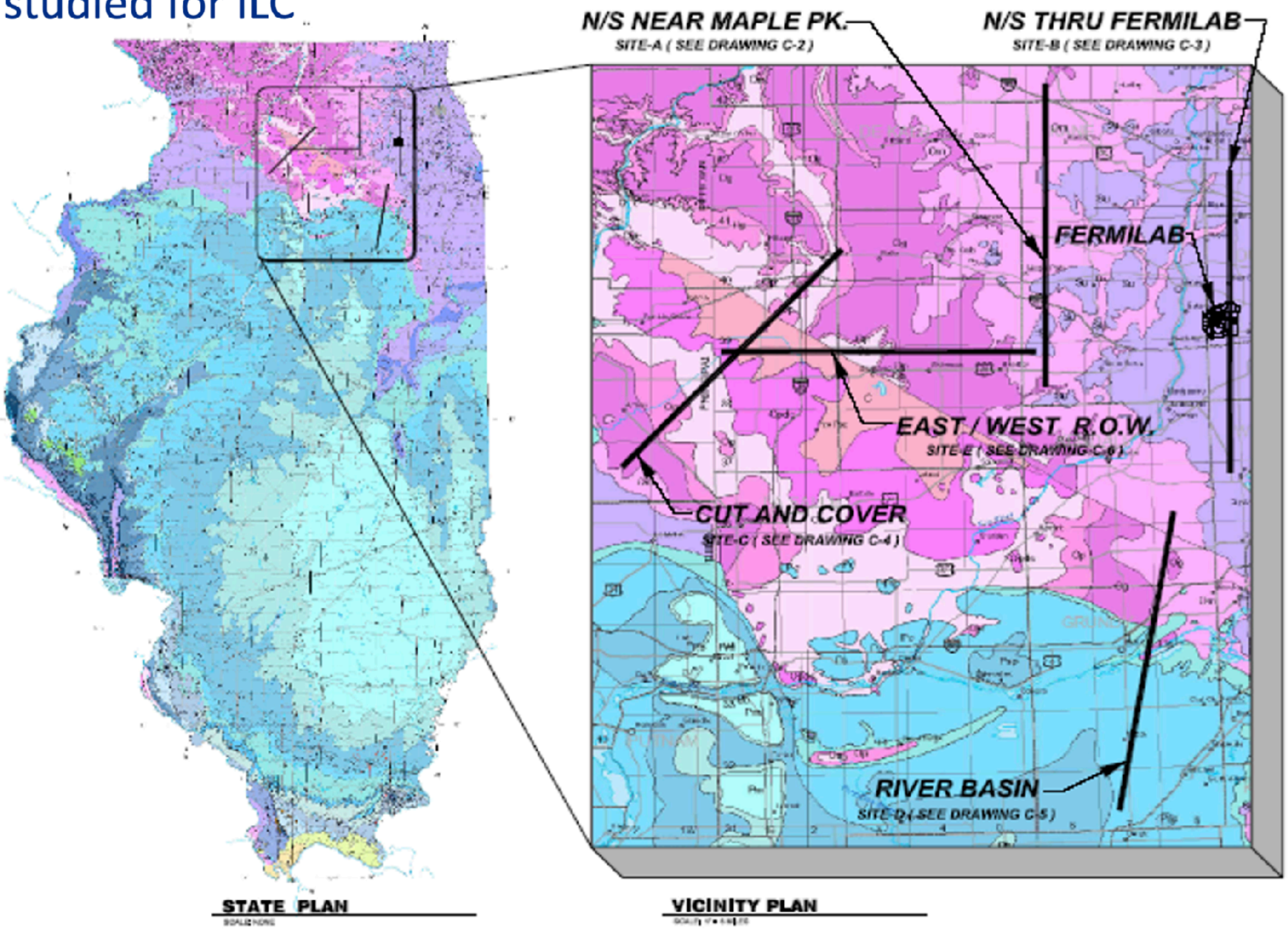
- Dark Matter



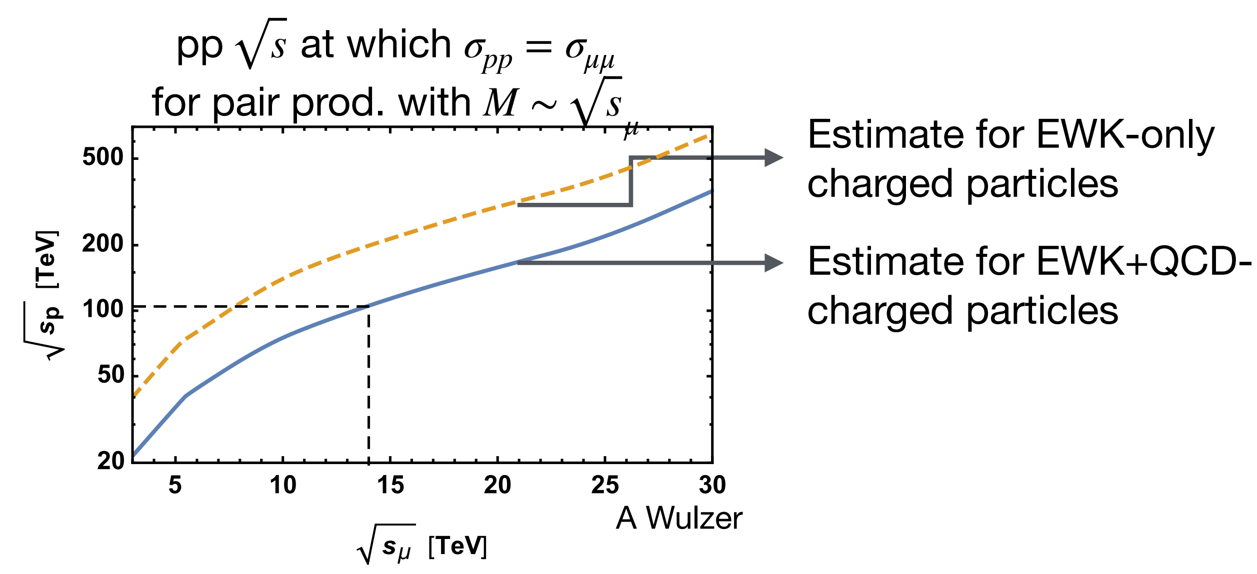


[2009.11287]

Sites studied for ILC



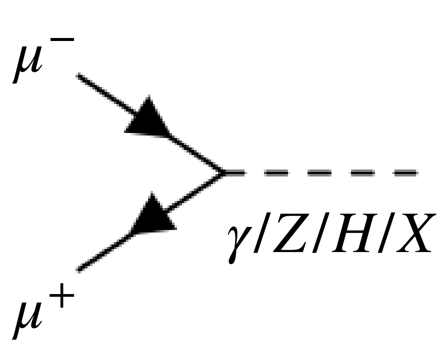
Muon Collider



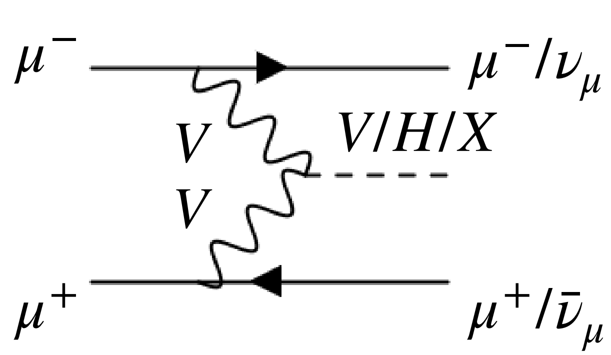
- μ's are fundamental → 10 TeV $\mu\mu$ collider is comparable w/ 100 TeV *pp* collider
  - Since $m_\mu >> m_e$, very low synchrotron radiation. Get to much higher energies than *ee* machines
  - Hopes to achieve 10 TeV scale and beyond!
- μμ annihilation at high energies, but also VBF
  - *pp*-like discovery spread from effective "Vector Boson Distribution Function"
  - ("VDF"s à la PDFs)
  - Precision+Discovery machine. A new paradigm.

collider	hh
HL-LHC [40]	50%
ILC_{250}/C^3-250 [31, 33]	–
ILC_{500}/C^3-550 [31, 33]	20%
ILC_{1000}/C^3-1000 [31, 33]	10%
$CLIC_{380}$ [35]	–
$CLIC_{1500}$ [35]	36%
$CLIC_{3000}$ [35]	9%
FCC-ee [36]	–
FCC-ee (4 IPs) [36]	–
FCC-hh [41]	3.4-7.8%
μ(3 TeV) [39]	15-30%
μ(10 TeV) [39]	4%

[2209.07510]



μμ Annihilation

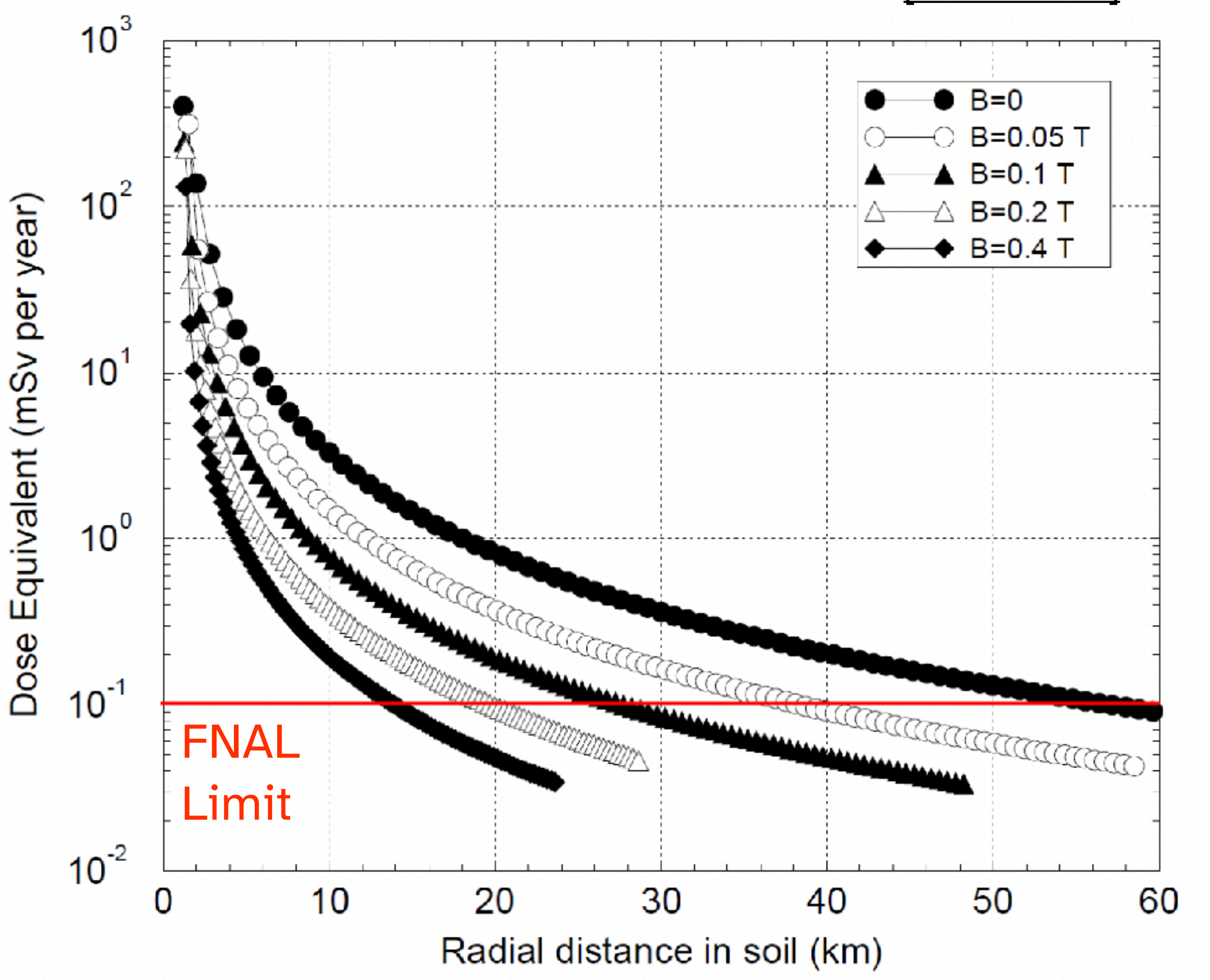


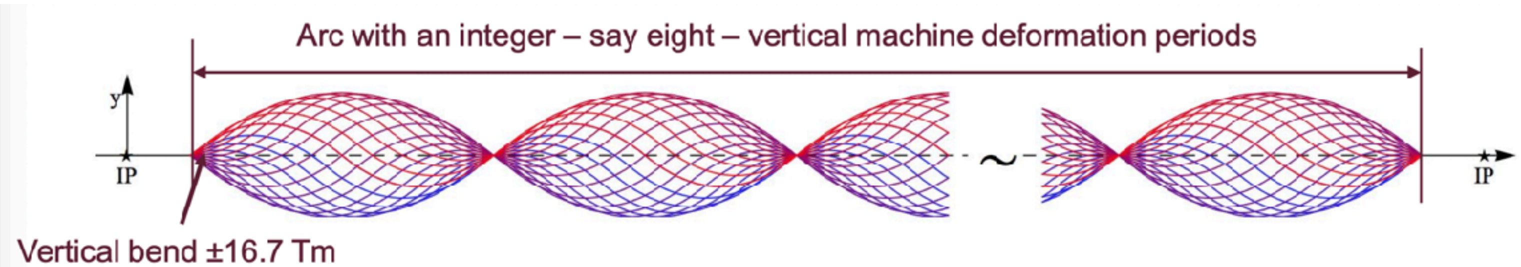
Vector Boson Fusion

Neutrino Flux from Muon Colliders

- Unlike normal case, shielding only increases the radiation dose
  - Neutrino ***interactions*** induce charged particle production → Dose
- Lots of clever concepts for neutrino flux mitigation
  - Isolate collider campus
  - Minimize straight sections
  - Use straights to send neutrino beam to rad-controlled area to exit earth
    - Put a neutrino experiment there!
  - Wiggle beam to spread neutrino flux
  - Place collider above ground?

[2209.01318]

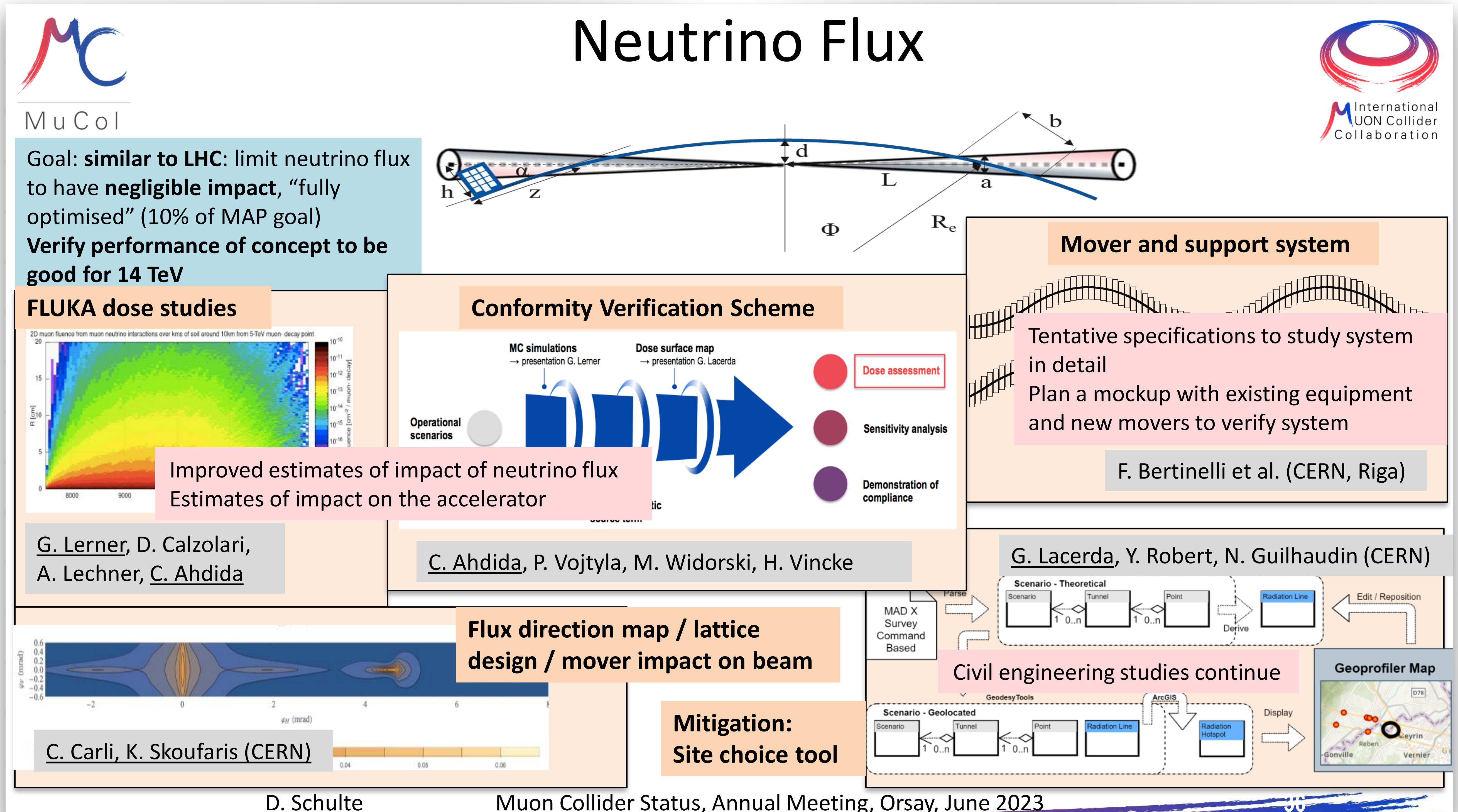




C. Carli at IMCC Annual Meeting

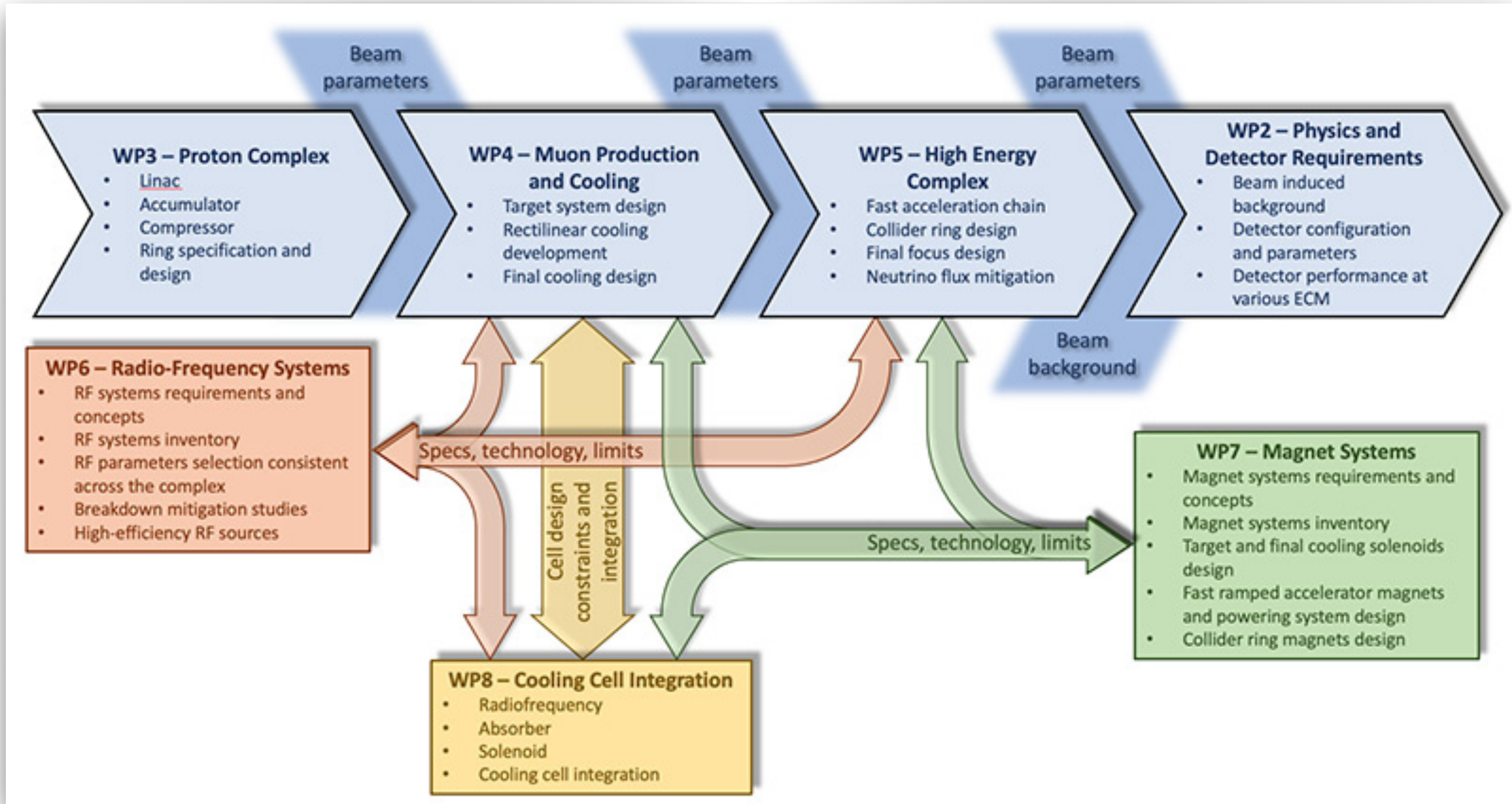
Neutrino Flux from Muon Colliders

D Schulte at IMCC Annual

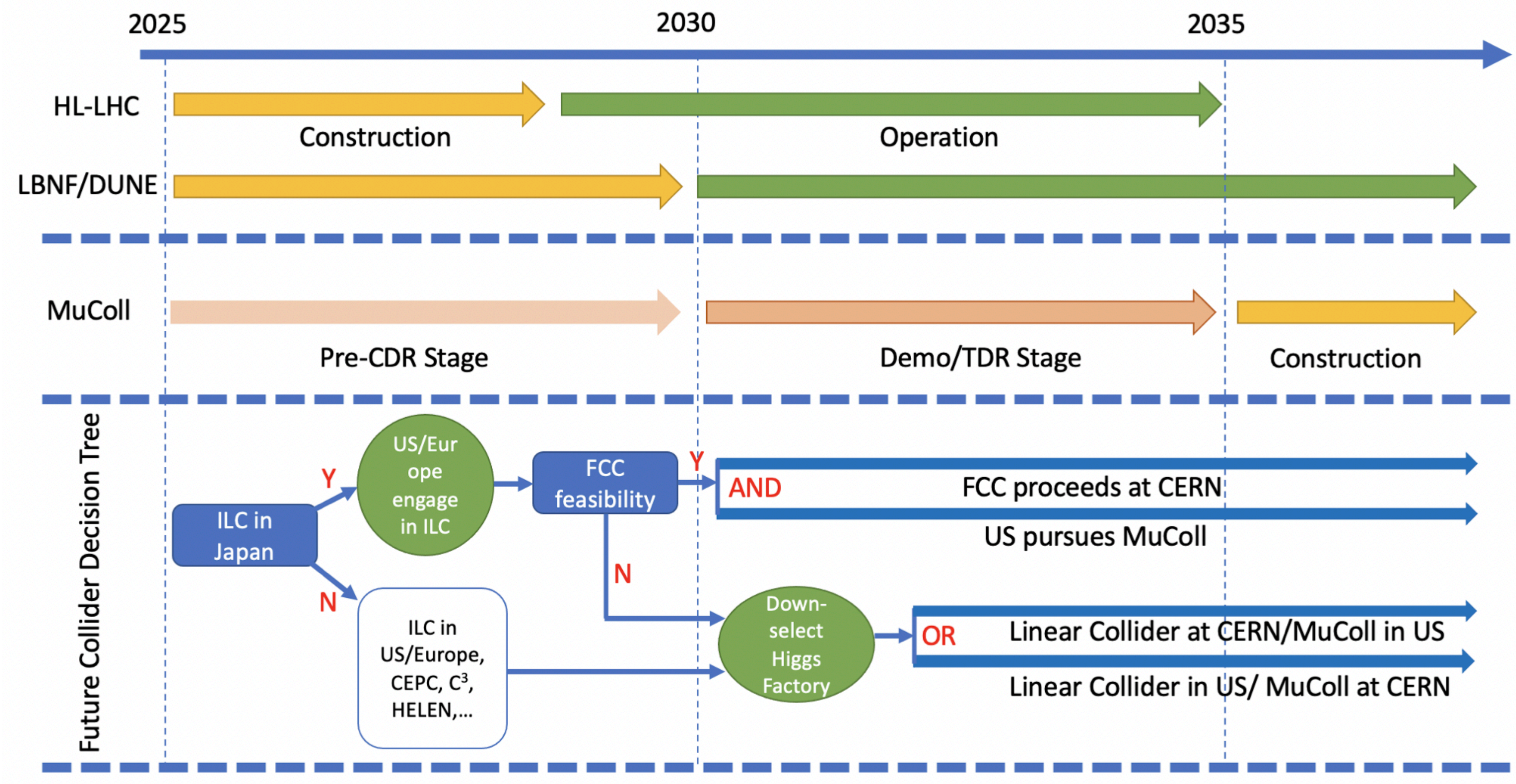


Neutrino Flux from Muon Colliders

D Schulte at IMCC Annual



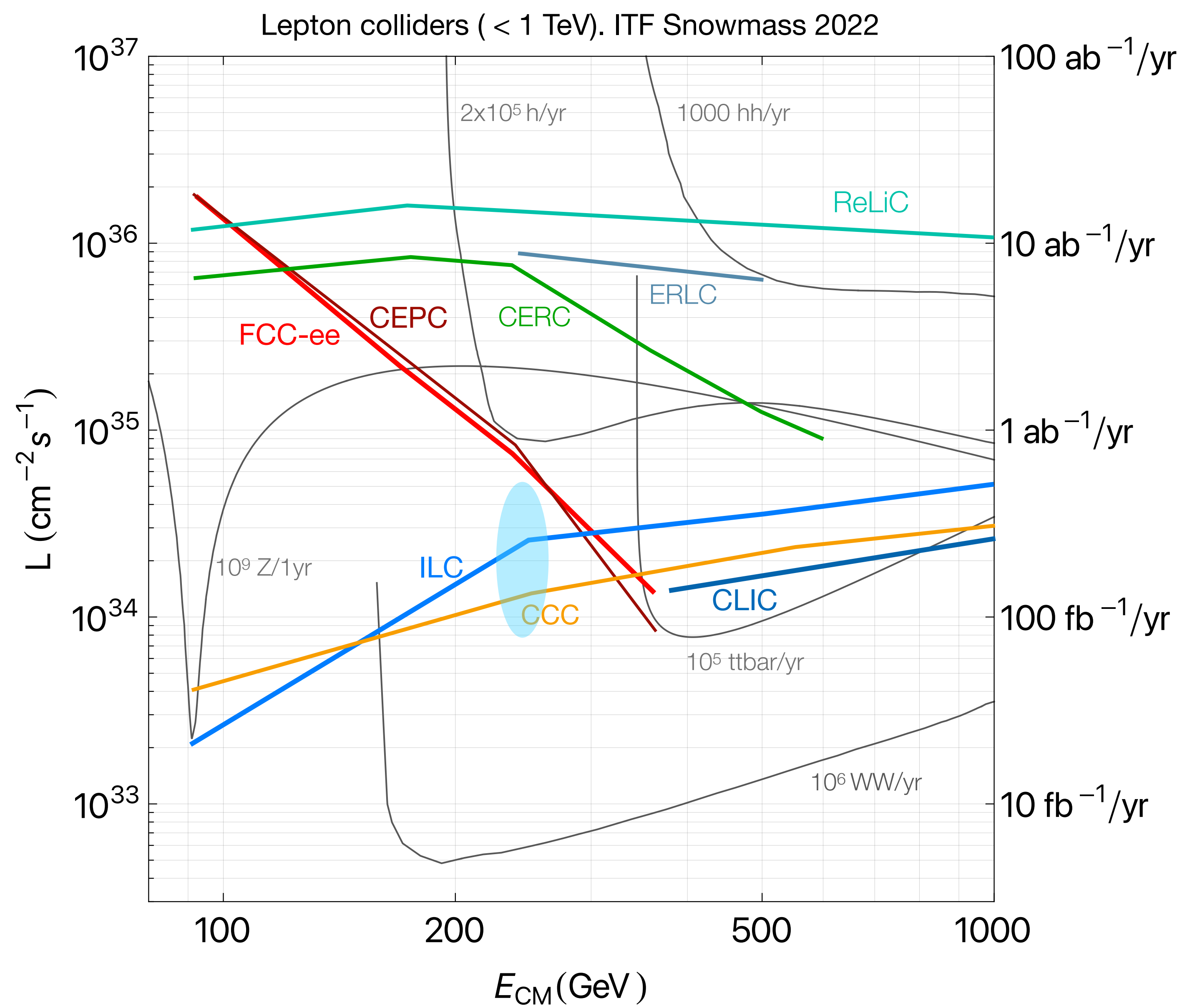
Potential Muon Collider Timelines



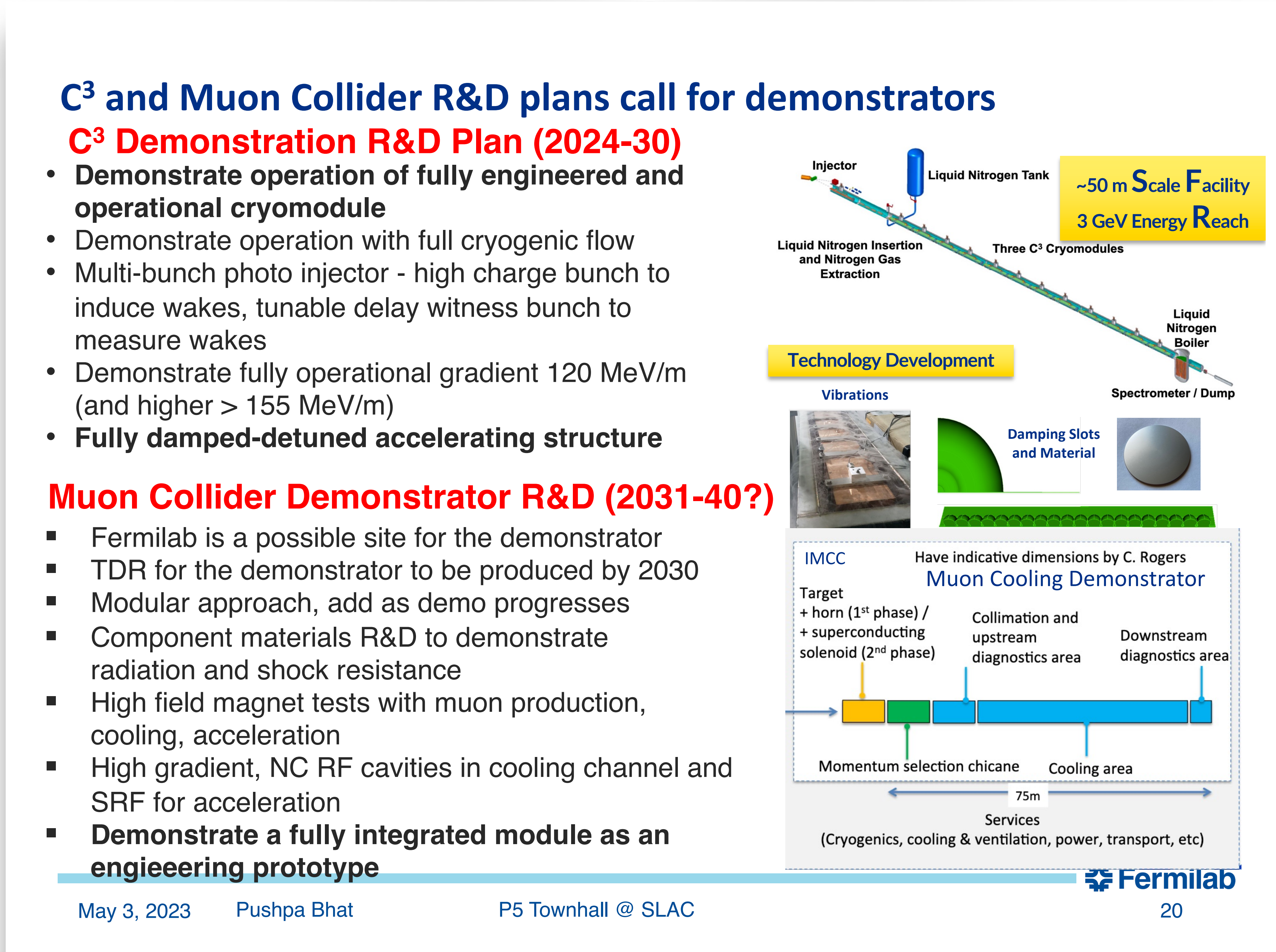
[2209.01318]

- These linear ee Higgs factories able to produce >10⁴ clean H events per year
- Existing FAST R&D facility at Fermilab can serve as a demonstrator for any of these linear machines

[2208.06030]



Clear demonstrations of necessary technologies and scale-ups



C^3 and Muon Collider R&D plans call for demonstrators

C^3 Demonstration R&D Plan (2024-30)

- **Demonstrate operation of fully engineered and operational cryomodule**
- Demonstrate operation with full cryogenic flow
- Multi-bunch photo injector - high charge bunch to induce wakes, tunable delay witness bunch to measure wakes
- Demonstrate fully operational gradient 120 MeV/m (and higher > 155 MeV/m)
- **Fully damped-detuned accelerating structure**

Muon Collider Demonstrator R&D (2031-40?)

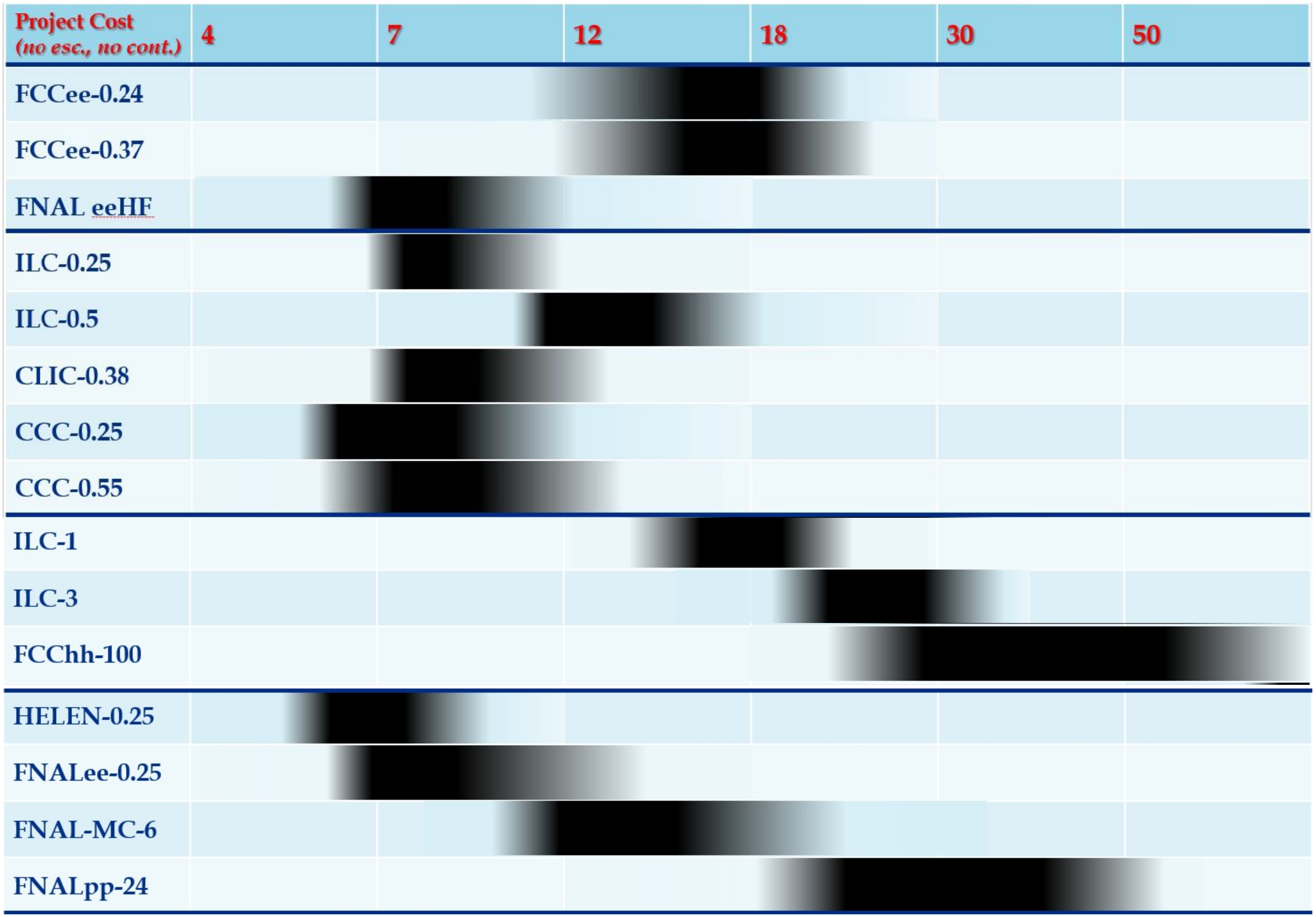
- Fermilab is a possible site for the demonstrator
- TDR for the demonstrator to be produced by 2030
- Modular approach, add as demo progresses
- Component materials R&D to demonstrate radiation and shock resistance
- High field magnet tests with muon production, cooling, acceleration
- High gradient, NC RF cavities in cooling channel and SRF for acceleration
- **Demonstrate a fully integrated module as an engieeering prototype**

May 3, 2023 Pushpa Bhat P5 Townhall @ SLAC 20

Pushpa Bhat at P5 Townhall

Roadmap of technical milestones. A challenging "check-list".

[2208.06030]



B$

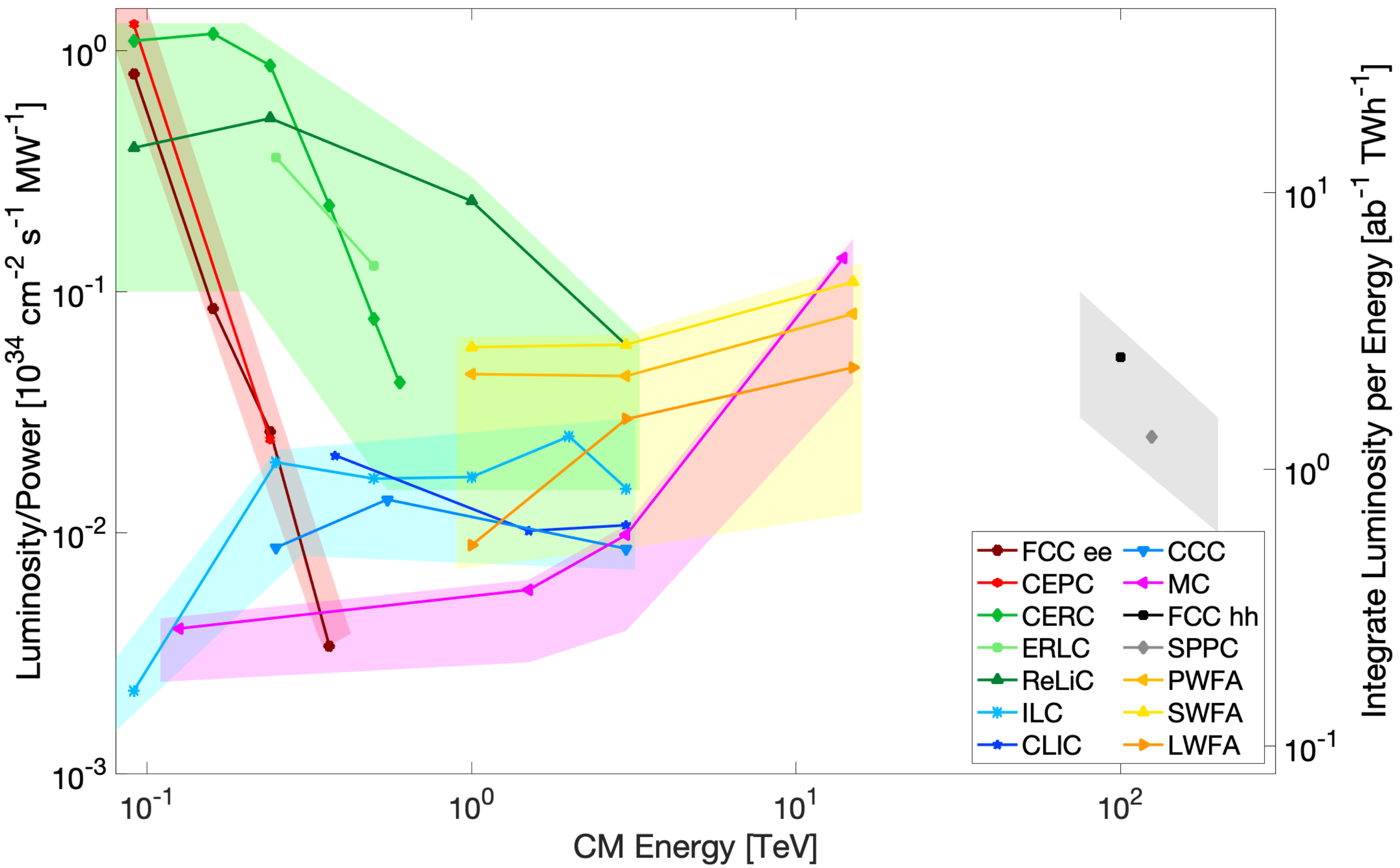
A wide range of project proposals come with a wide range of price tags, all with large error bars

@FNAL.gov

Collider Name - c.m.e. (TeV)	Subm'd R&D Durat'n to CDR (yrs)	Subm'd Design to TDR Durat'n (yrs)	Subm'd Project Constrn. Time (yrs)	ITF Judgement Duration Preproject R&D to CDR	ITF Judgement Design & Industr'n Duration to TDR	ITF Judgement Project Constrn. Duration post CD4	ITF Judgement Combined "Time to the First Physics"
ILC-0.25	0	4	9	0-2 yrs	3-5 yrs	7-10 yrs	< 12 yrs
ILC (6x lumi)	10	5	10	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CLIC-0.38	0	6	6	0-2 yrs	3-5 yrs	7-10 yrs	13-18 yrs
FCCee-0.36	0	6	8	0-2 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CEPC-0.24	6	6	8	0-2 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CCC-0.25	2-3	4-5	6-7	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
FNALee-0.24	tbd	tbd	tbd	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CERC-0.6	3	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
HELEN-0.25	tbd	tbd	tbd	5-10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
ReLiC-0.25	3	5	10	5-10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
ERLC-0.25	8	5	10	5-10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
MC-0.125	11	4	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
XCC-0.125	2-3	3-4	3-5	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
SWLC-0.25	8	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs

Collider Name - c.m.e. (TeV)	Subm'd R&D Durat'n to CDR (yrs)	Subm'd Design to TDR Durat'n (yrs)	Subm'd Project Constrn. Time (yrs)	ITF Judgement Duration Preproject R&D to CDR	ITF Judgement Design & Industr'n Duration to TDR	ITF Judgement Project Constrn. Duration post CD4	ITF Judgement Combined "Time to the First Physics"
ILC-1	10	5	5-10	5-10 yrs	3-5 yrs	10-15 yrs	13-18 yrs
ILC-2	10	5	5-10	> 10 yrs	3-5 yrs	10-15 yrs	19-24 yrs
ILC-3	20	5	10	> 10 yrs	3-5 yrs	10-15 yrs	19-24 yrs
CLIC-3	0	6	6	3-5 yrs	3-5 yrs	10-15 yrs	19-24 yrs
CCC-2	2-3	4-5	6-7	3-5 yrs	3-5 yrs	10-15 yrs	19-24 yrs
ReLiC-2	3	5	10	5-10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
MC-1.5	11	4	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
MC-3	11	4	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
MC-10	11	4	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
MC-14	11	4	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
PWFA-LC-1	15	tbd	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
PWFA-LC-15	15	tbd	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
LWFA-LC-3	15	tbd	tbd	> 10 yrs	> 10 yrs	10-15 yrs	> 25 yrs
LWFA-LC-15	15	tbd	tbd	> 10 yrs	> 10 yrs	> 16 yrs	> 25 yrs
SWFA-LC-1	tbd	tbd	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
SWFA-LC-15	tbd	tbd	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
FCChh-100	2	20	15	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
SPPC-75	15	6	8	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
Coll.-Sea-500	10	6	6	> 10 yrs	5-10 yrs	> 16 yrs	> 25 yrs
CEPC-SPPC	tbd	tbd	tbd	3-5 yrs	3-5 yrs	< 6 yrs	> 25 yrs
LHeC	0	5	5	0-2 yrs	3-5 yrs	< 6 yrs	13-18 yrs
FCC-eh	0	5	5	0-2 yrs	3-5 yrs	< 6 yrs	> 25 yrs

[2208.06030]



A Muon Collider's power efficiency increases with beam energy

Power considerations are crucial.
But environmental impact of e.g. tunnel digging is large and can't be forgotten

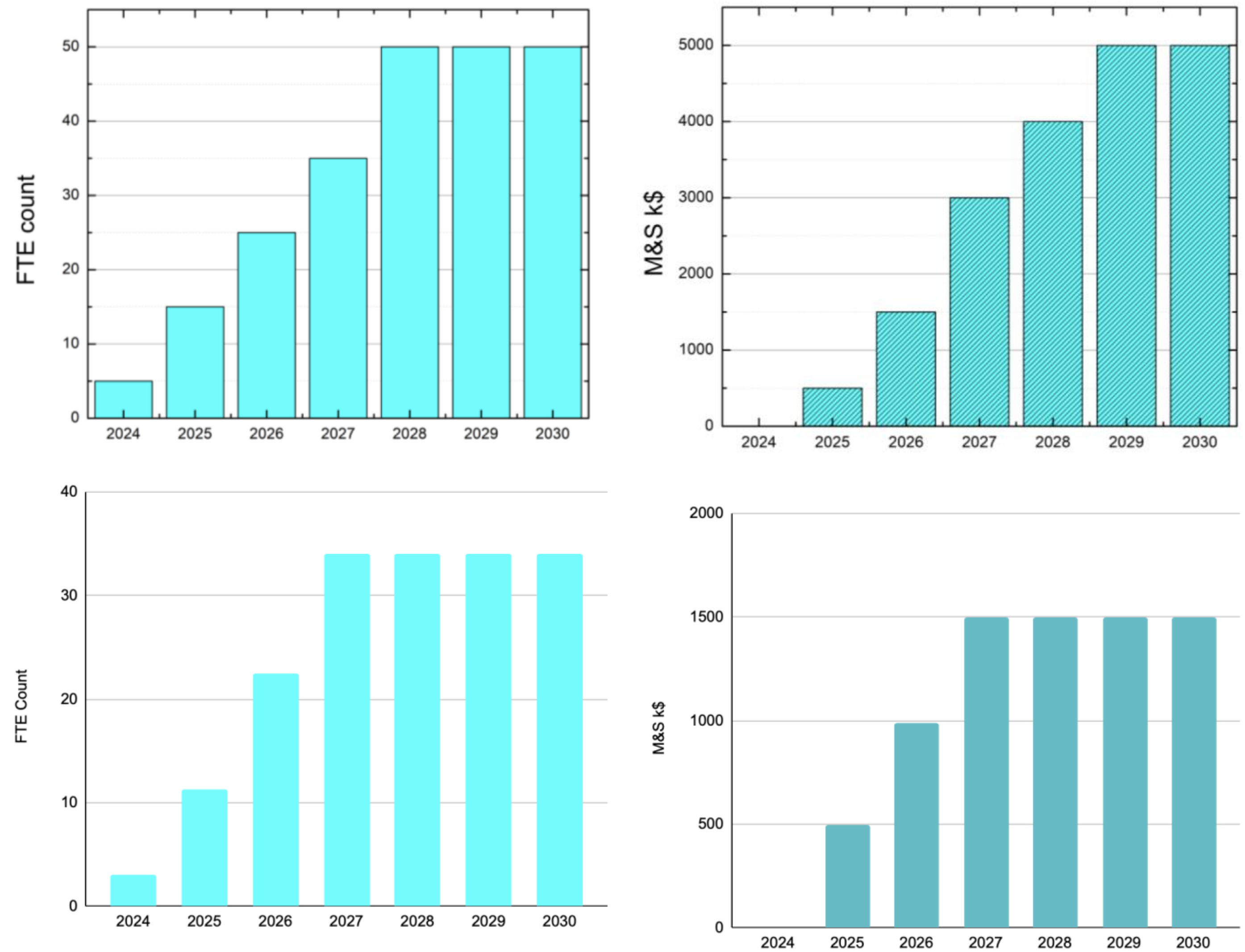
Muon Collider

Our ASK for P5

- The Detector and Accelerator ASK at the P5 townhalls was:
  - Recommend establishing a Muon Collider R&D program with the aim for delivering a RDR report for the final facility & TDR report for the demo facility by 2030 AND with an overall goal of having a TDR for the final facility by 2040
  - Recommend that DOE and NSF recognize Muon Collider work within the AF and EF base program proposals
  - Support the formation of a US Muon Collider effort to coordinate US impact while engaging in the international effort
  - Support the National Collider Initiative R&D program
  - Enable US to compete for hosting a Muon Collider

Diktys Stratakis at IMCC Meeting Last Week

Muon Collider budget profile (2024-2030)



Accelerator

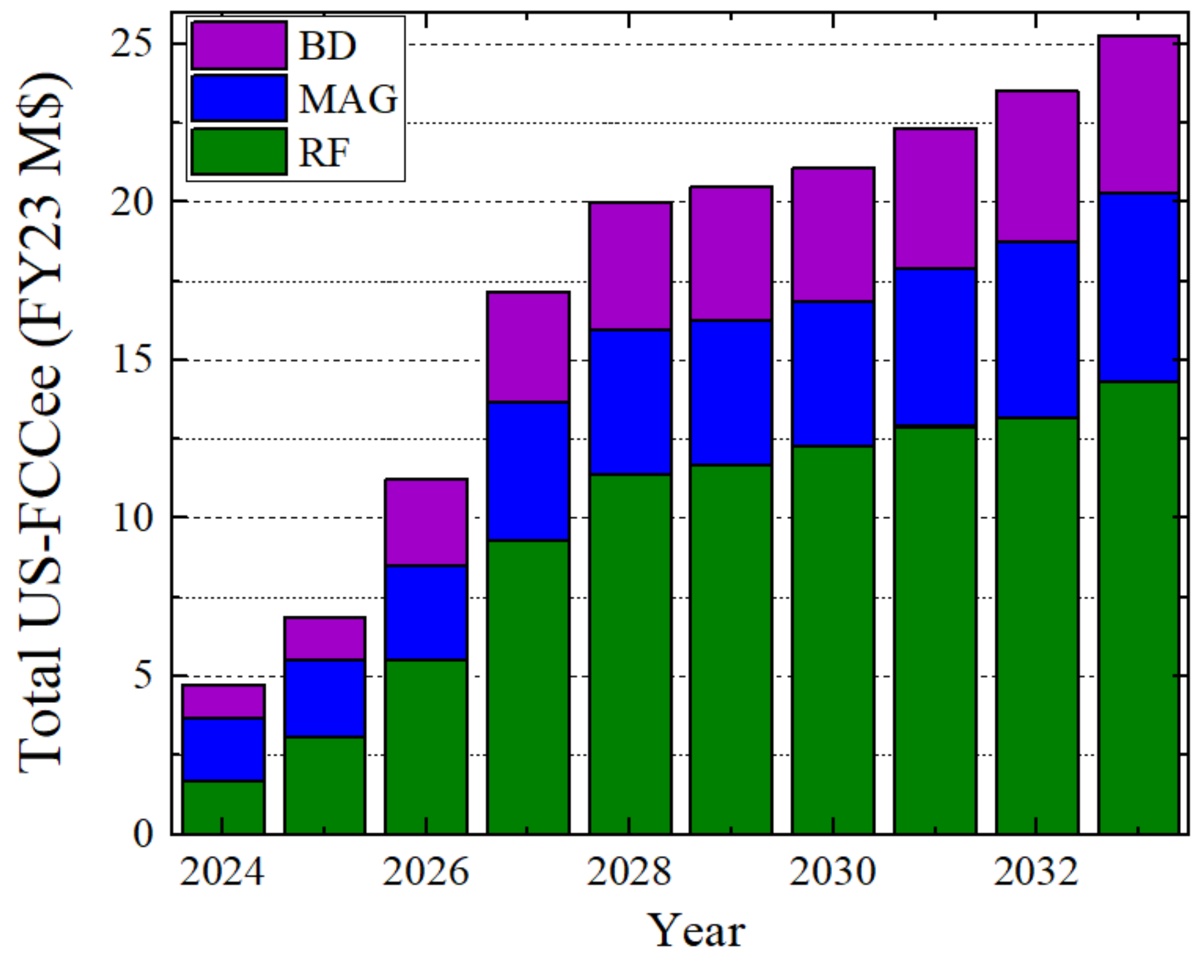
Detector

- **GOAL:** By 2030, achieve enough technical maturity for the construction of the demo facility in 2030s and potential construction of the collider facility in the 2040s.

Diktys Stratakis at IMCC Meeting Last Week

FCC-ee

Possible US-FCC-ee pre-CD2 Contributions



Total 2024-33: 184M$
Incl. Labor: 333 FTEs

Area	Total M$	Incl. FTEs
RF systems	95	127
Magnets/MDI	53	116
Design/Dynamics	36	90

NB: cost of the post CD-2 (2033) fabrication phase is much higher and depends on the scope/elements (TBD)

8 Vladimir Shiltsev | US FCC Accel.

Vladimir Shiltsev at P5 Townhall

C^3

C^3 Demo Cost

Bottoms Up Cost Estimate with Technically Limited Timeline

F. Wang, C^3 Demo PD Team

- Location for basis of estimate is SLAC NLCTA Bunker
  - *Multiple options for Stage 2 + 3 location*
  - **Stage 1 + 2 completed external review**
  - *Stage 3 based on current boundary conditions*
- ~30% of labor by postdoctoral researchers, training for 20 FTE (10 x 2-year postdocs)
- 3.5% escalation and quotes for equipment over $50k
- **Multi-Lab, university and industry consortium ideal**

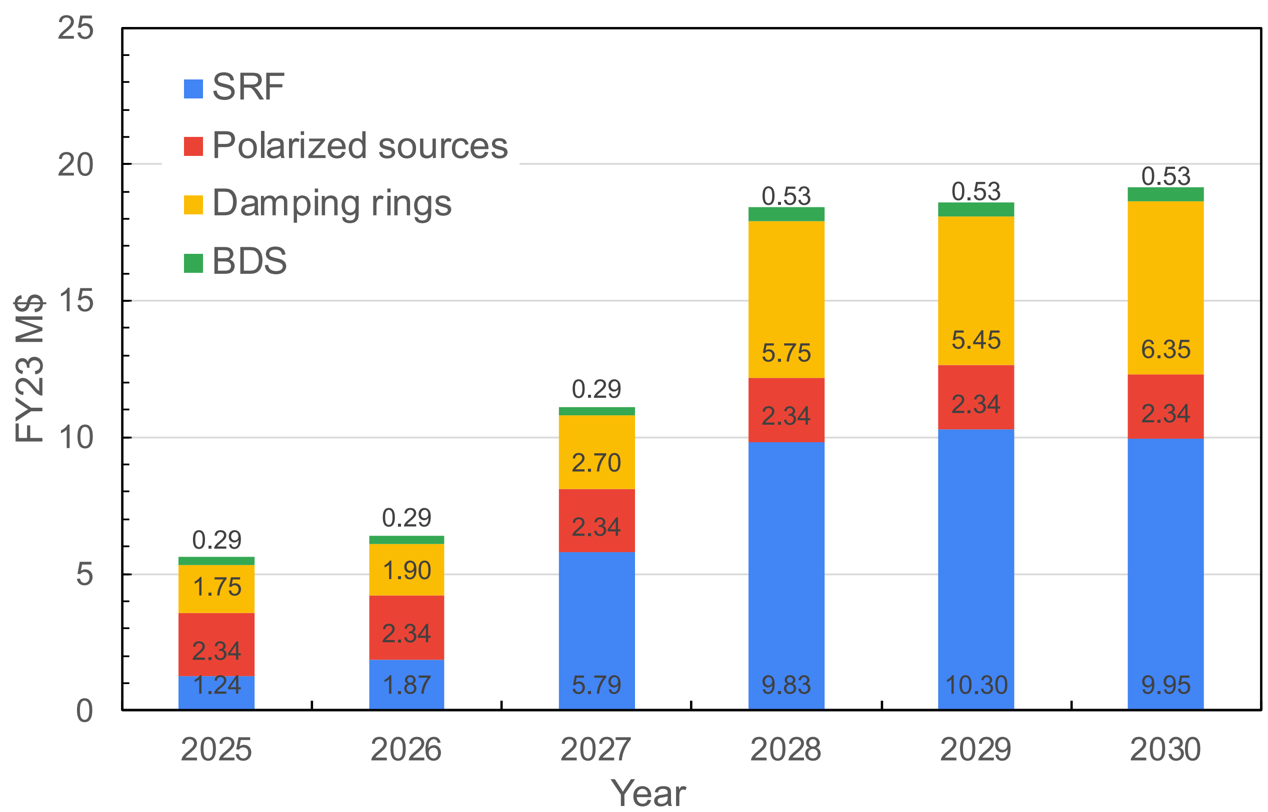
	Stage 1	Stage 2	Stage 3	Total
M&S ($M)	**$3.5**	**$22.6**	**$30**	**$56**
Labor (FTE)	**15**	**31**	**23**	**68**
TPC ($M)	**$8.5**	**$34.9**	**$42**	**$85**
TPC ($M) + Contingency (40%)	**$11.9**	**$48.8**	**$58**	**$120**

	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Stage	1					
			2			
				3		
M&S ($M)	**$3.2**	**$9.8**	**$13.0**	**$15**	**$15**	**$56**
Labor ($M)	**$3.7**	**$3.7**	**$8.5**	**$8**	**$6**	**$29**
TPC ($M)	**$6.9**	**$13.5**	**$21.4**	**$22**	**$21**	**$85**
TPC ($M) + Contingency (40%)	**$9.7**	**$19.0**	**$30.0**	**$31**	**$29**	**$120**

Emilio Nanni, Caterina Vernieri at P5 Townhall

ILC

Possible U.S. budget through ITN and Preparatory Phases



- Total ~ 80M$ for ITN and Preparatory phases
- Including FTEs increasing from 13.7 in 2025 to 50.6 in 2030

5/3/2023 S. Belomestnykh | U.S. contributions to ILC 37

Tatsuya Nakada at P5 Townhall