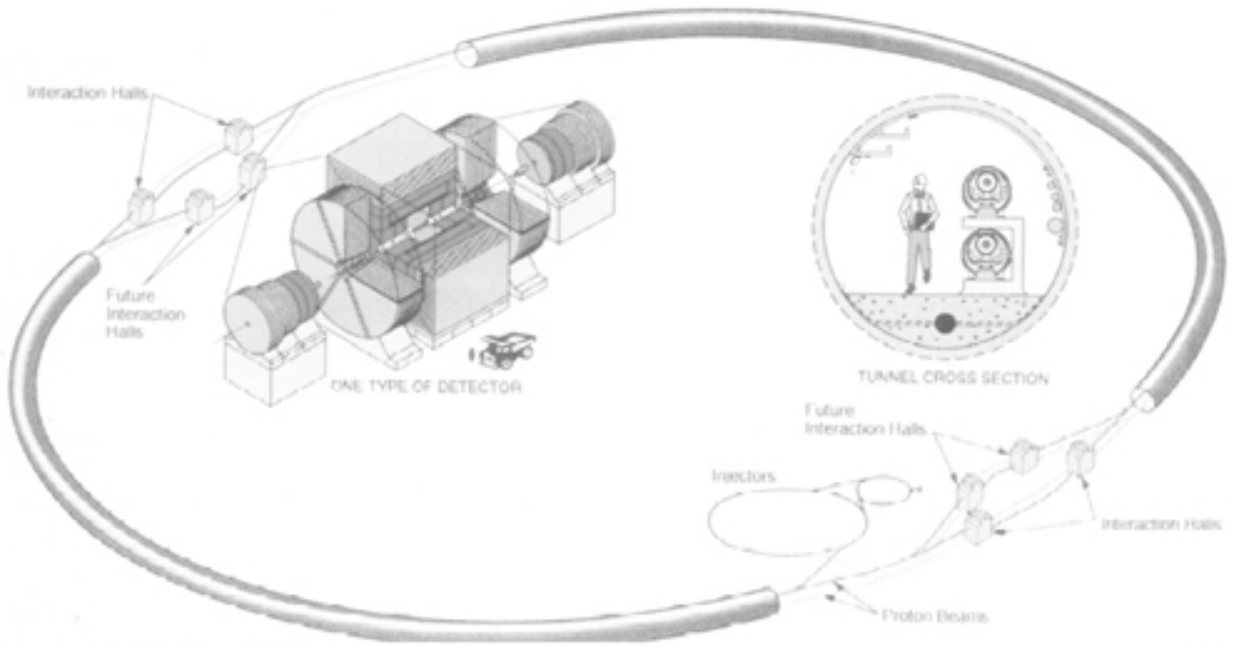
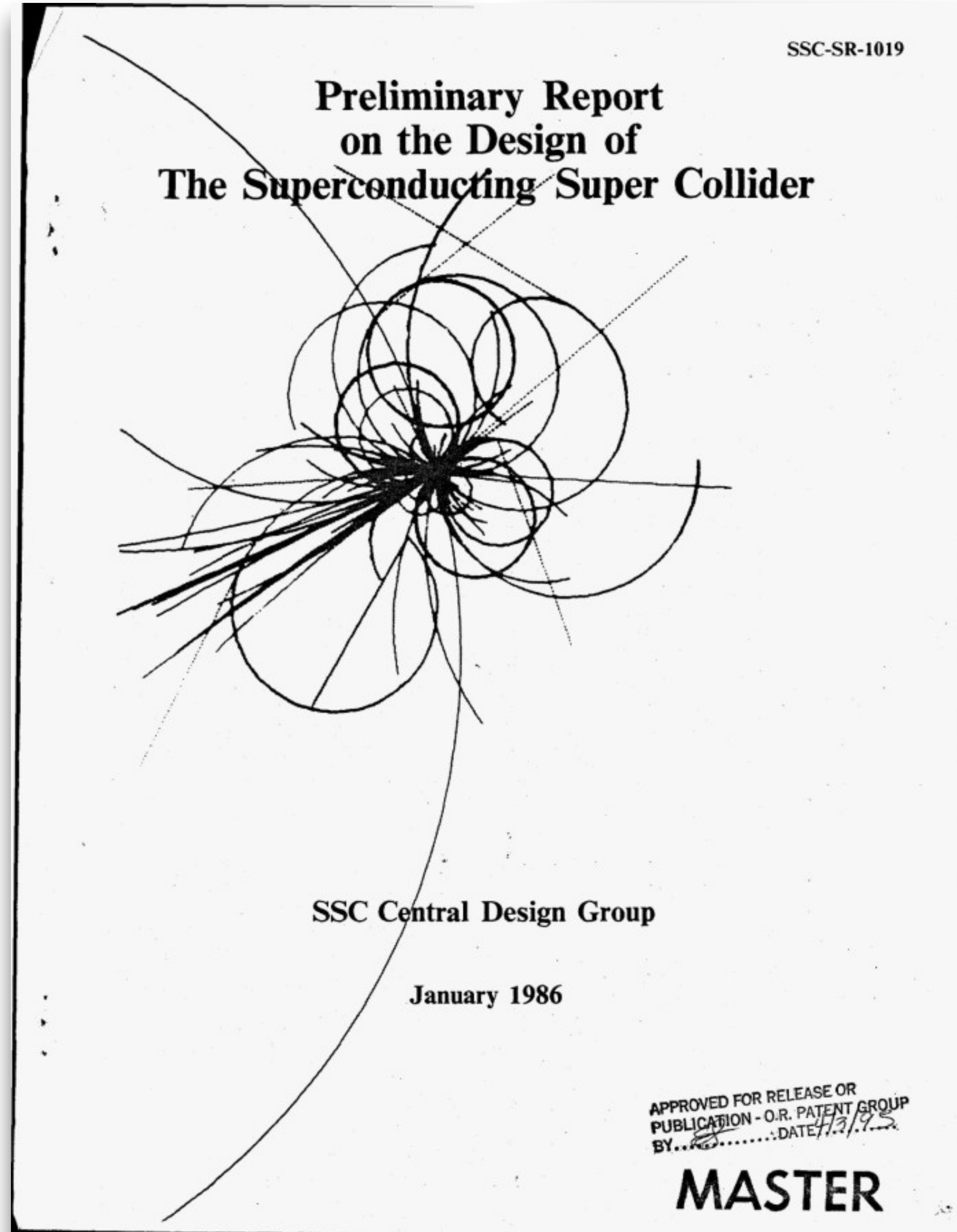
How to Build a Muon Collider

Lawrence Lee





SSC-SR-1019

Preliminary Report on the Design of The Superconducting Super Collider

SSC Central Design Group

January 1986

APPROVED FOR RELEASE OR PUBLICATION - O.R. PATENT GROUP
BY........DATE

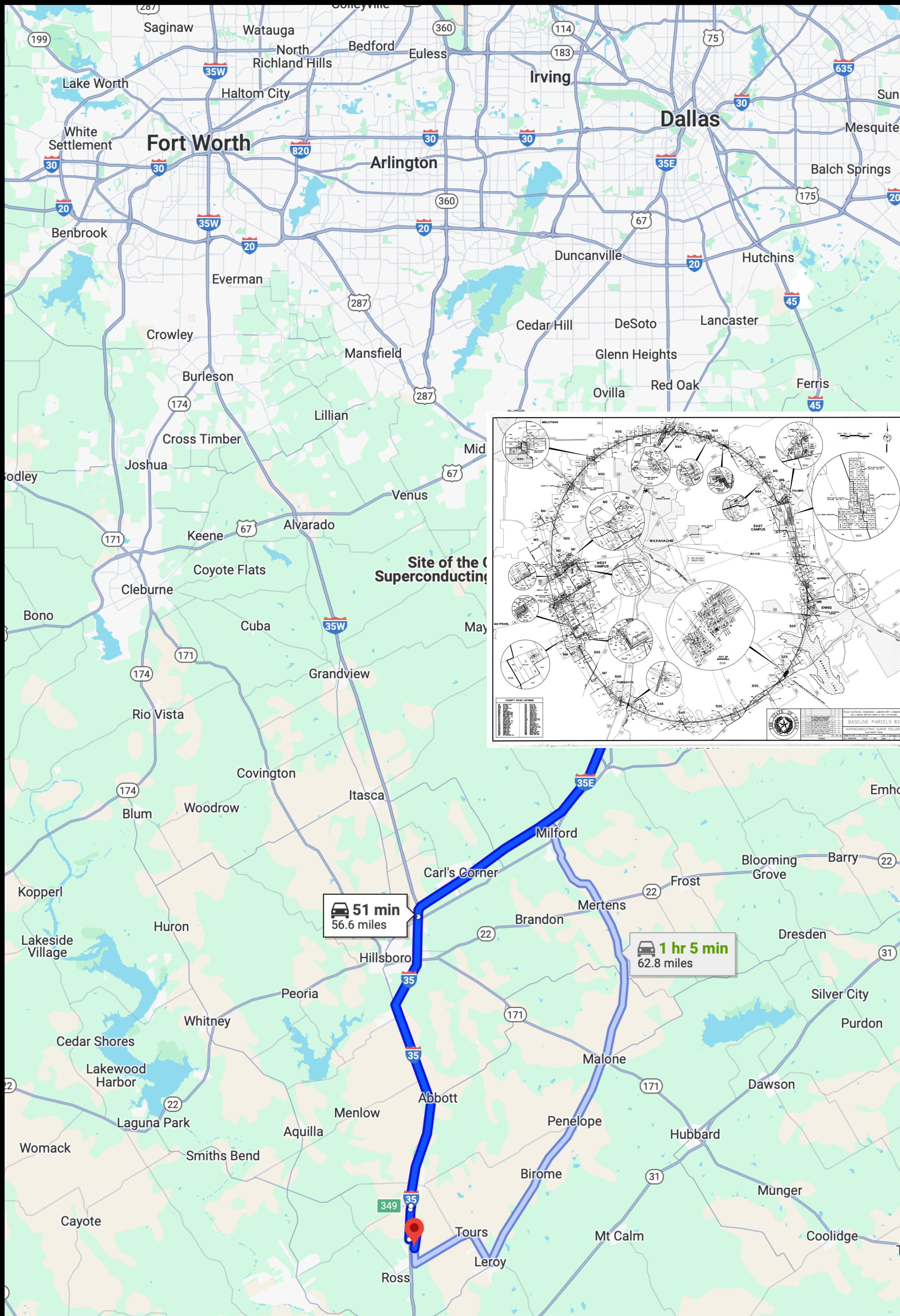
MASTER

CRASH
at
CRUSH
(1896)

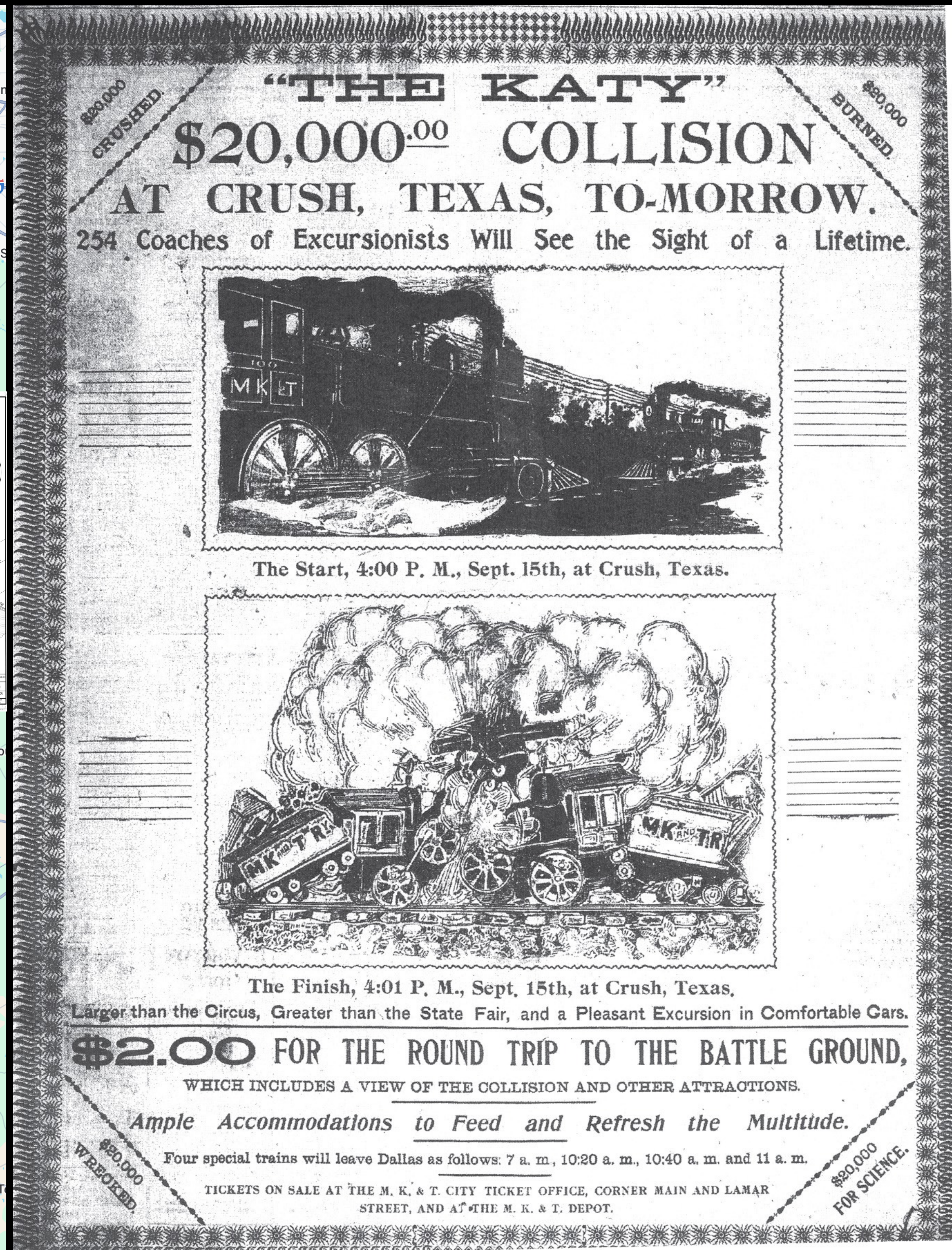
The Trains Just as They Struck.

Views of the Head End Collision at Crush, Texas, September 15, 1896.

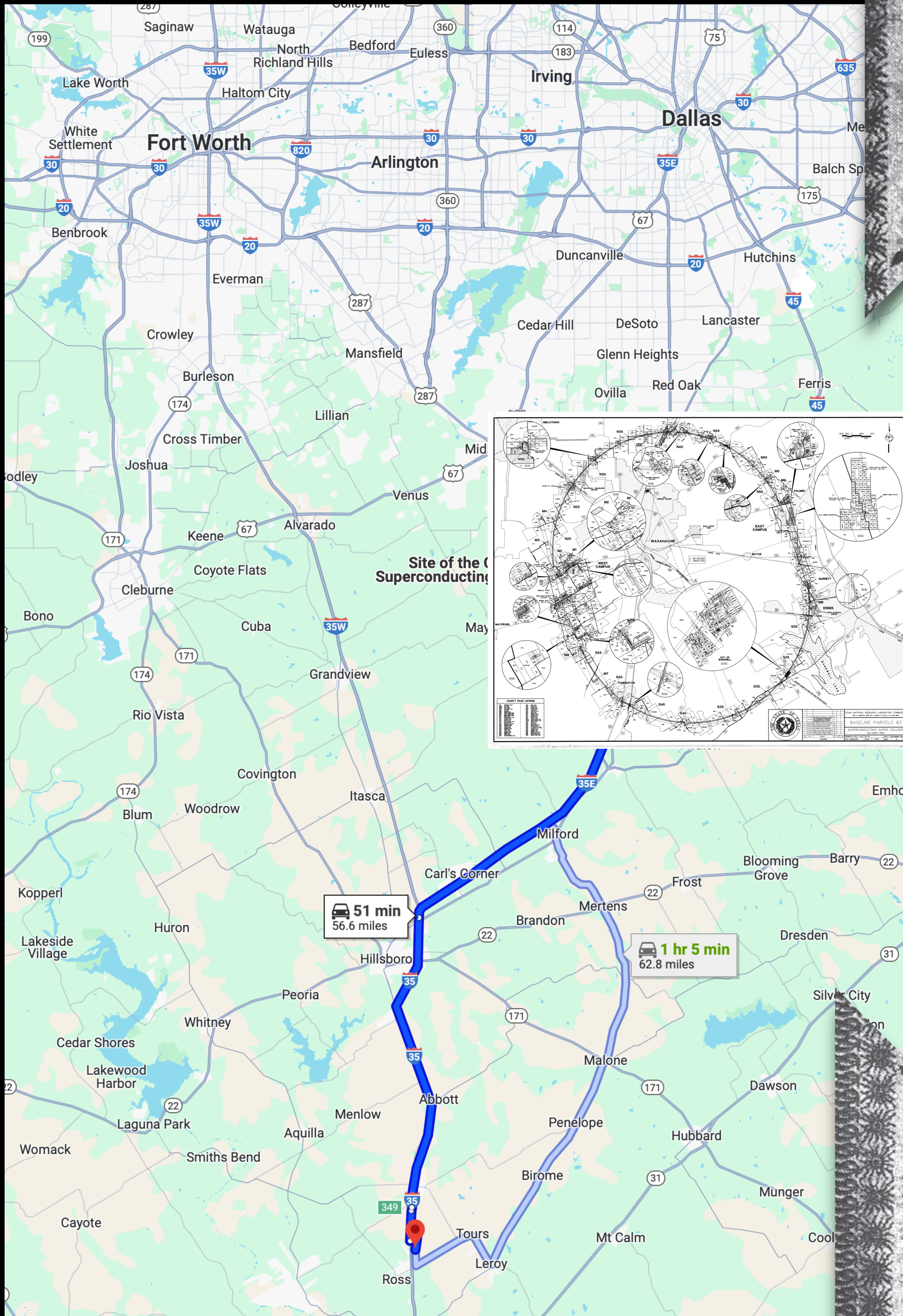
Photographed by Deane, OF DALLAS, FORT WORTH, Waco and Houston



Fort Worth
Dallas
Arlington
Irving
Site of the
Superconducting
51 min
56.6 miles
1 hr 5 min
62.8 miles
Hillsboro
Milford
Abbott
Ross



$20,000 CRUSHED.
$20,000 BURNED.
"THE KATY"
$20,000.00 COLLISION
AT CRUSH, TEXAS, TO-MORROW.
254 Coaches of Excursionists Will See the Sight of a Lifetime.
The Start, 4:00 P. M., Sept. 15th, at Crush, Texas.
The Finish, 4:01 P. M., Sept. 15th, at Crush, Texas.
Larger than the Circus, Greater than the State Fair, and a Pleasant Excursion in Comfortable Cars.
$2.00 FOR THE ROUND TRIP TO THE BATTLE GROUND,
WHICH INCLUDES A VIEW OF THE COLLISION AND OTHER ATTRACTIONS.
Ample Accommodations to Feed and Refresh the Multitude.
Four special trains will leave Dallas as follows: 7 a. m., 10:20 a. m., 10:40 a. m. and 11 a. m.
TICKETS ON SALE AT THE M. K. & T. CITY TICKET OFFICE, CORNER MAIN AND LAMAR STREET, AND AT THE M. K. & T. DEPOT.
$20,000 WRECKED.
$20,000 FOR SCIENCE.

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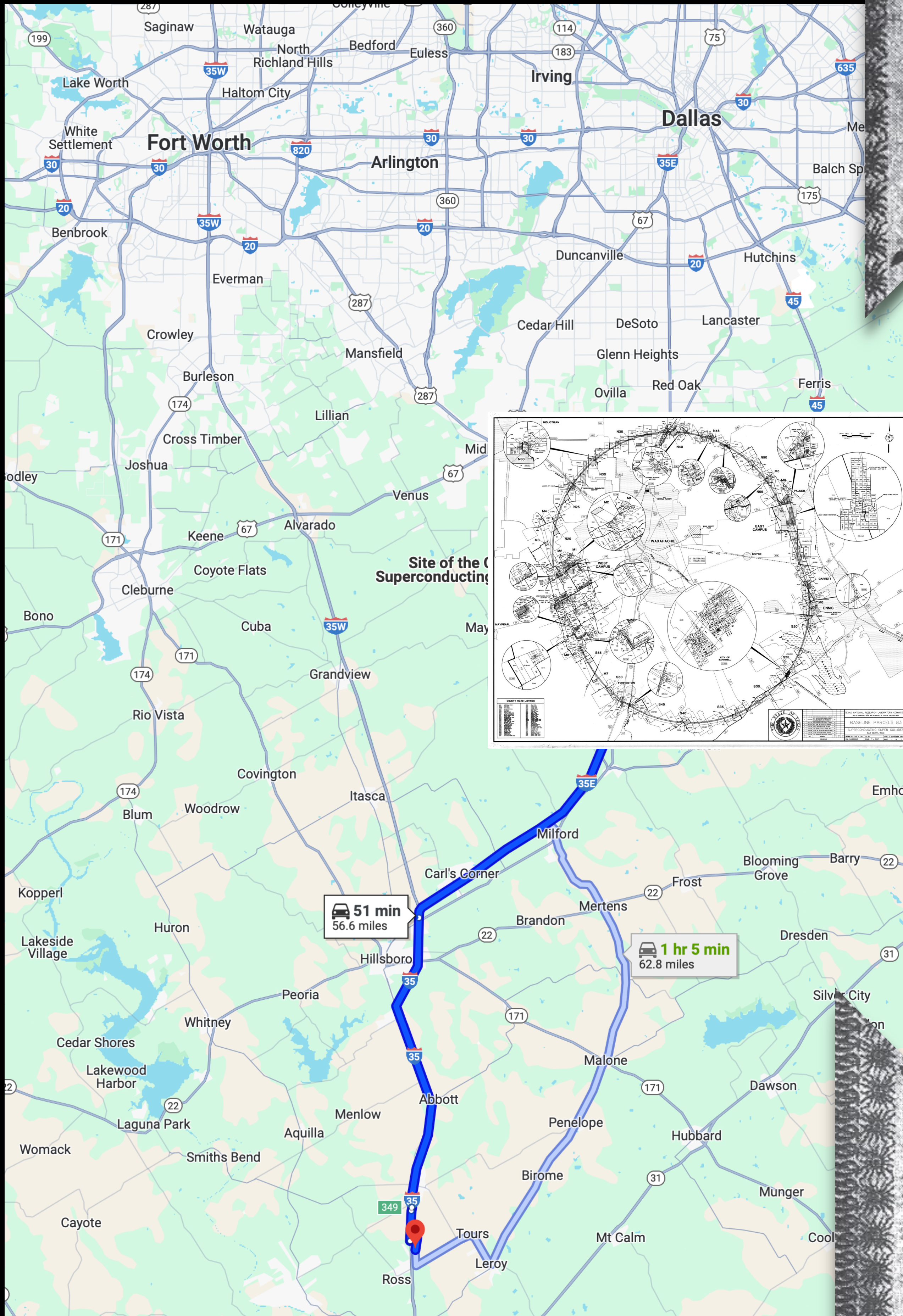

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$20,000 WRECKED.

$20,000 FOR SCIENCE.


THE KATY IS STRICTLY IN IT. SO WILL THE
2x 35 ton locomotives
45 mph
6 MJ, O(1e13) TeV

Hugely popular

40k attendees

(2 deaths, many injuries)

- “Head On Joe” Connolly

"I believed that somewhere in the makeup of every normal person, there lurks the suppressed desire…

- "Head On Joe" Connolly

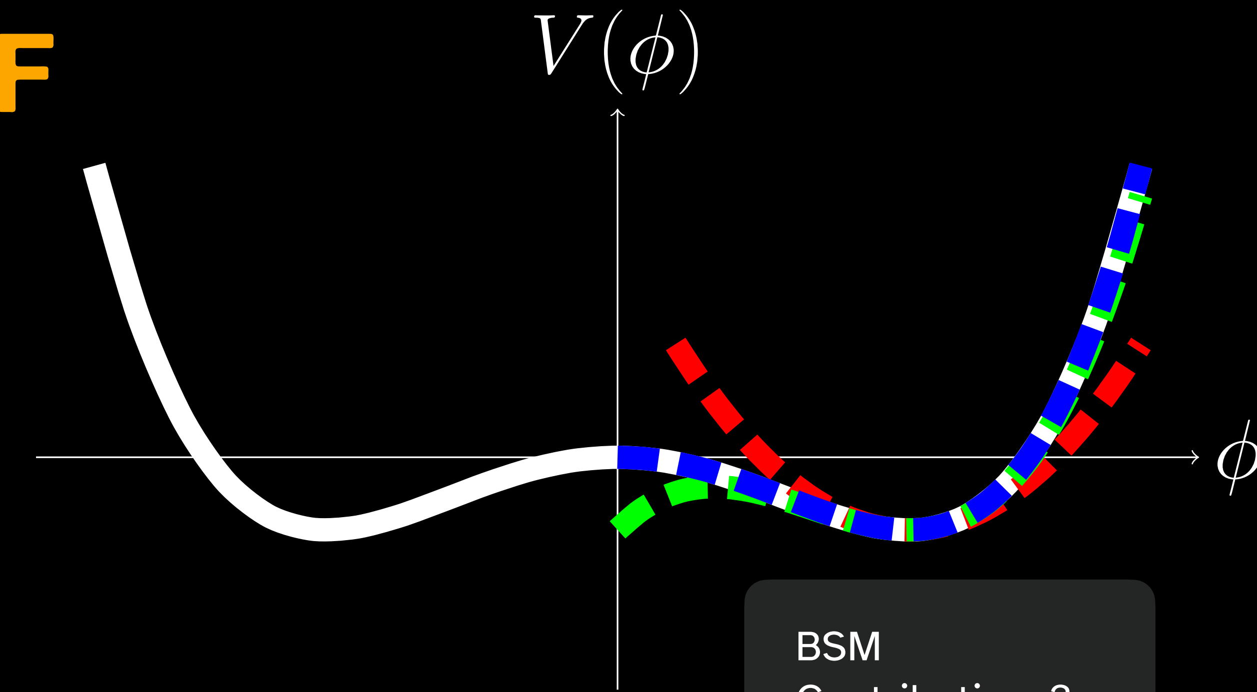
"I believed that somewhere in the makeup of every normal person, there lurks the suppressed desire…

to smash things up."

- "Head On Joe" Connolly

SMASHING STUFF AT 10 TEV

- Other talks: Go to new heights with **concrete physics targets**
  - EWK Restoration Limit (v/E)
  - True shape of the Higgs Potential
  - Discovery reach WIMP DM Thermal Targets
  - (Naturalness 🤫)
  - …



BSM Contributions?

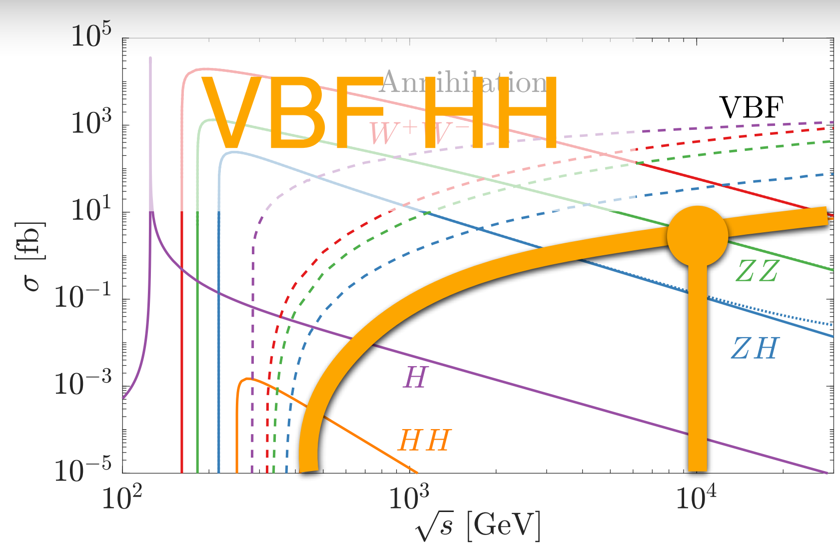
$$O(H^2) + O(H^3) + O(H^4) + O(H^5) + \dots$$

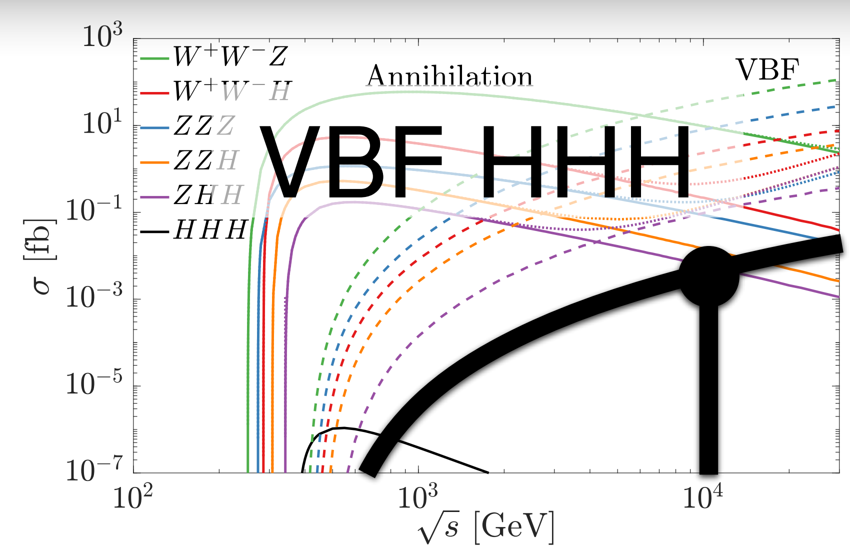
Higgs self coupling → HH production

Quartic coupling → HHH production

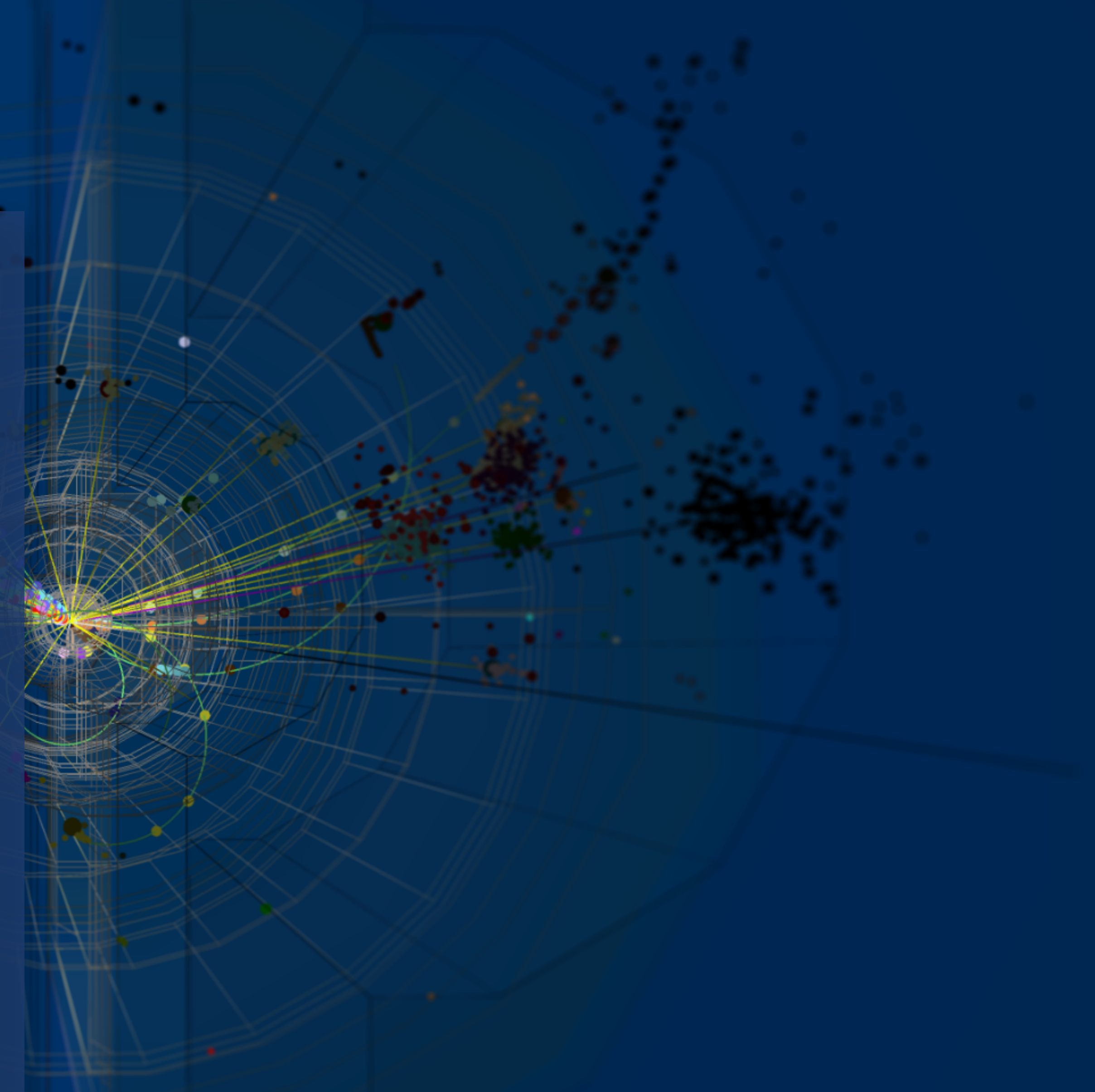
Need multi-TeV scale to probe these processes

[2212.01323]





Smashing Muons at 10 TeV



A μμ collider is a perfect way to do it!

Get to super high energy because:

200x more massive than electron

➡ Not limited by synchrotron radiation like e^+e^- machines

μ's are not composite

➡ More of the beam energy goes into the hard scatter than for hadrons

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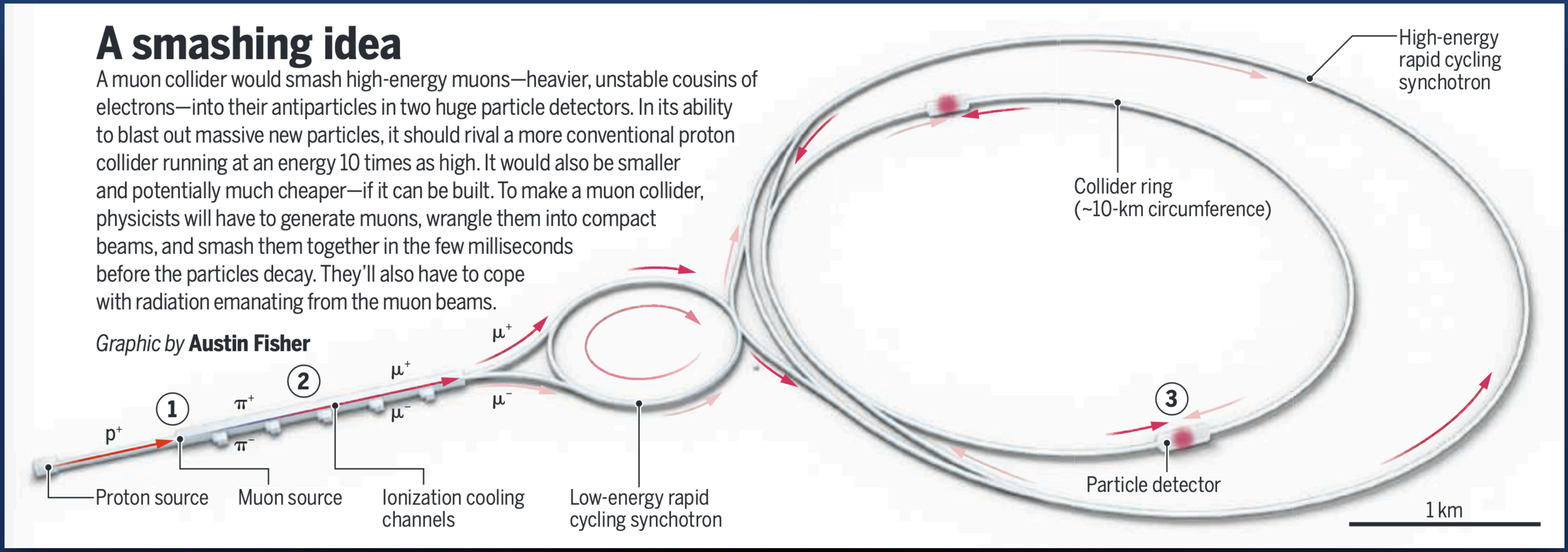
Accelerator colleagues tell us it might be possible!

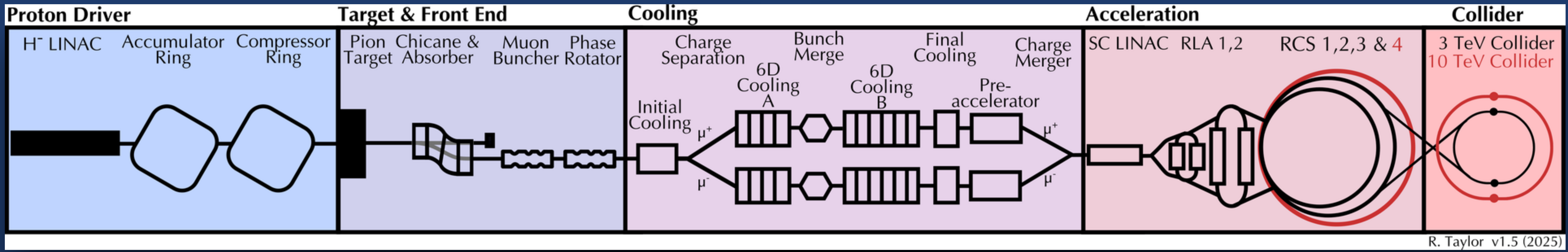
(With a lot of work…)

Success requires HEP to value and support accelerator research and training.

Maybe even dip out of "our lane" and help out where we can!

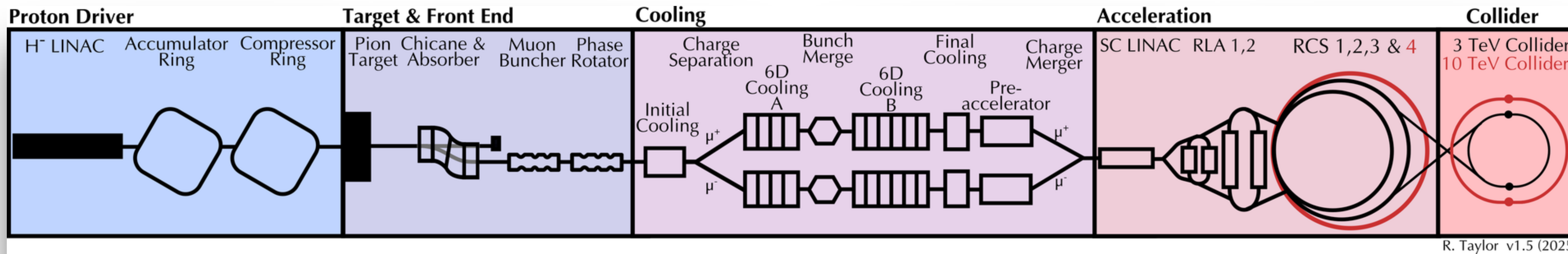


Science, Vol 383 Issue 6690



A baseline conceptual design exists

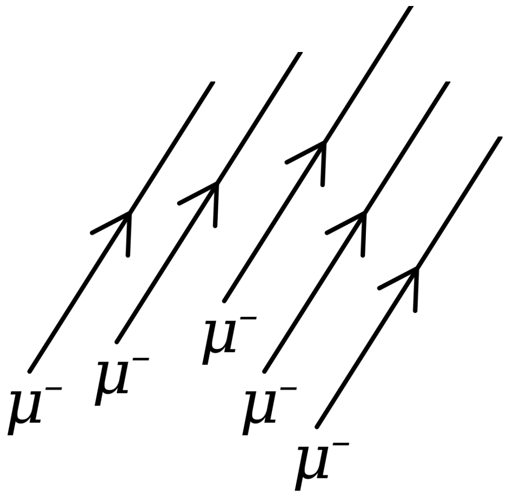
Largely from US Muon Accelerator Program (MAP) and updates from IMCC



Overly simplified:

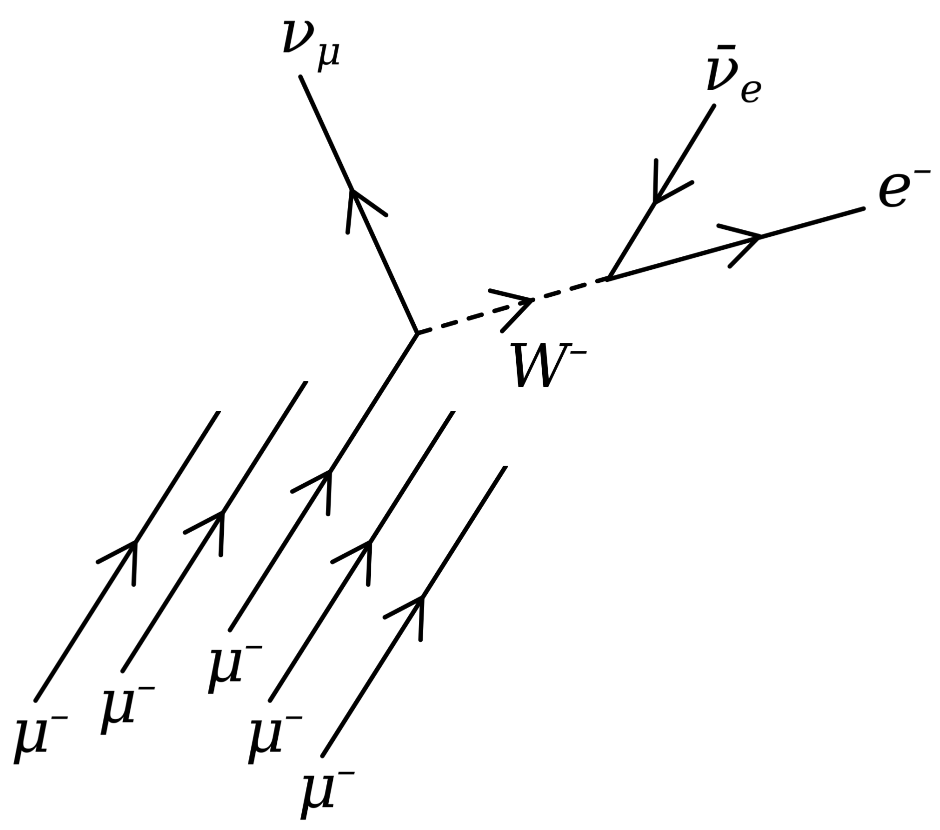
- O(1) **MW** beam of **protons** on **target**
- Intense pion production → **Capture** diffuse muon decay products
- "**Cool**" the muon beam. Reduce phase-space volume of beam
- **Accelerate, Collide, Measure**

Muon Beams



Muon Beams Decay

$\tau_\mu \approx 2\ \mu s$



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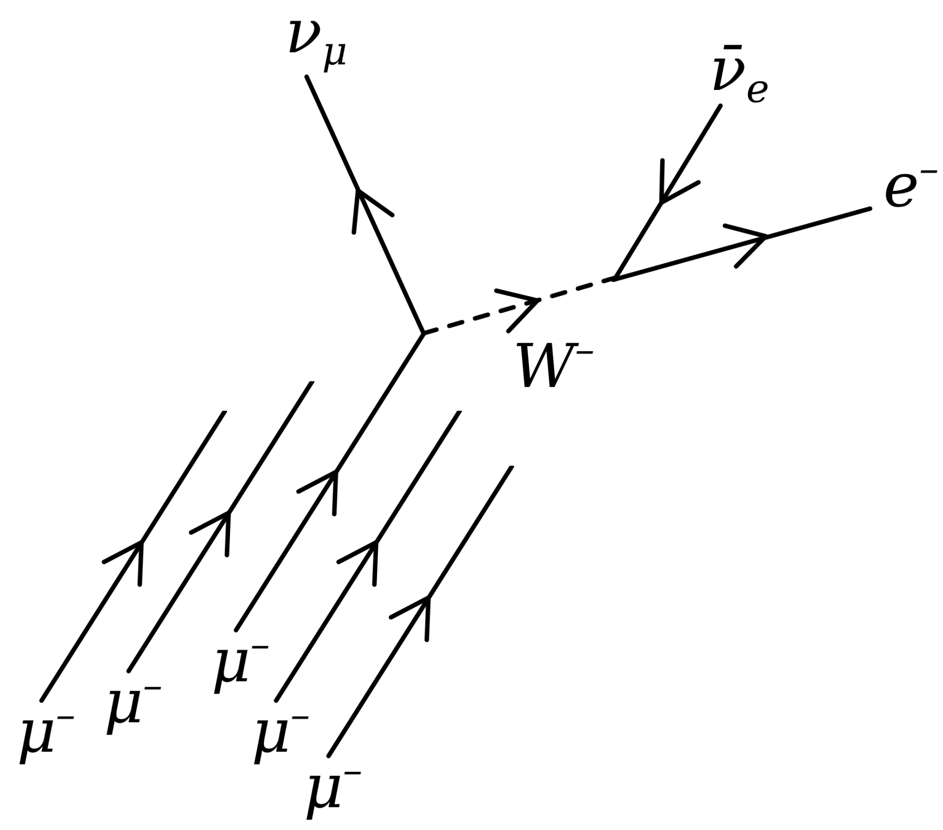
$\tau_\mu \approx 2\ \mu s$

Boost the hell out of them.
At 5 TeV, $\gamma = 50000$,
$\tau_{lab} \approx 100\ ms$



Muon Beams Decay

$\tau_\mu \approx$ ~~2~~ μs

Boost the hell out of them.

At 5 TeV, $\gamma = 50000$,

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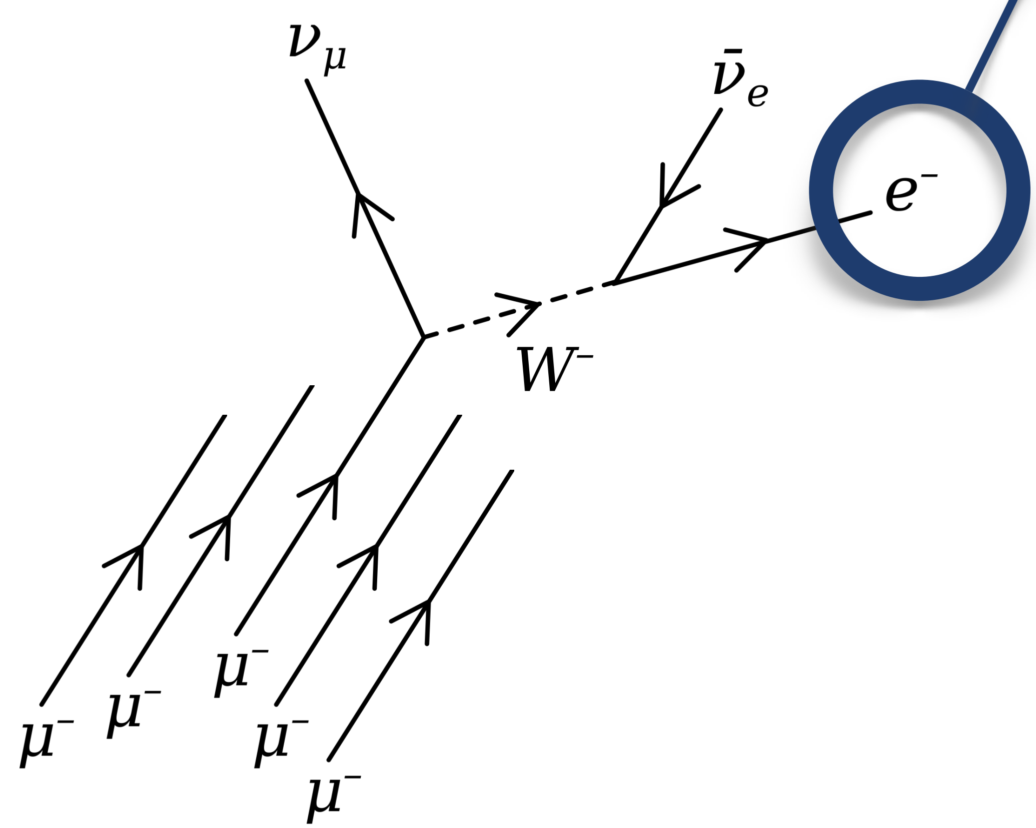
Resulting e's create beam-induced background



5 TeV muons → TeV scale electrons hit detector and deposit energy to accelerator complex

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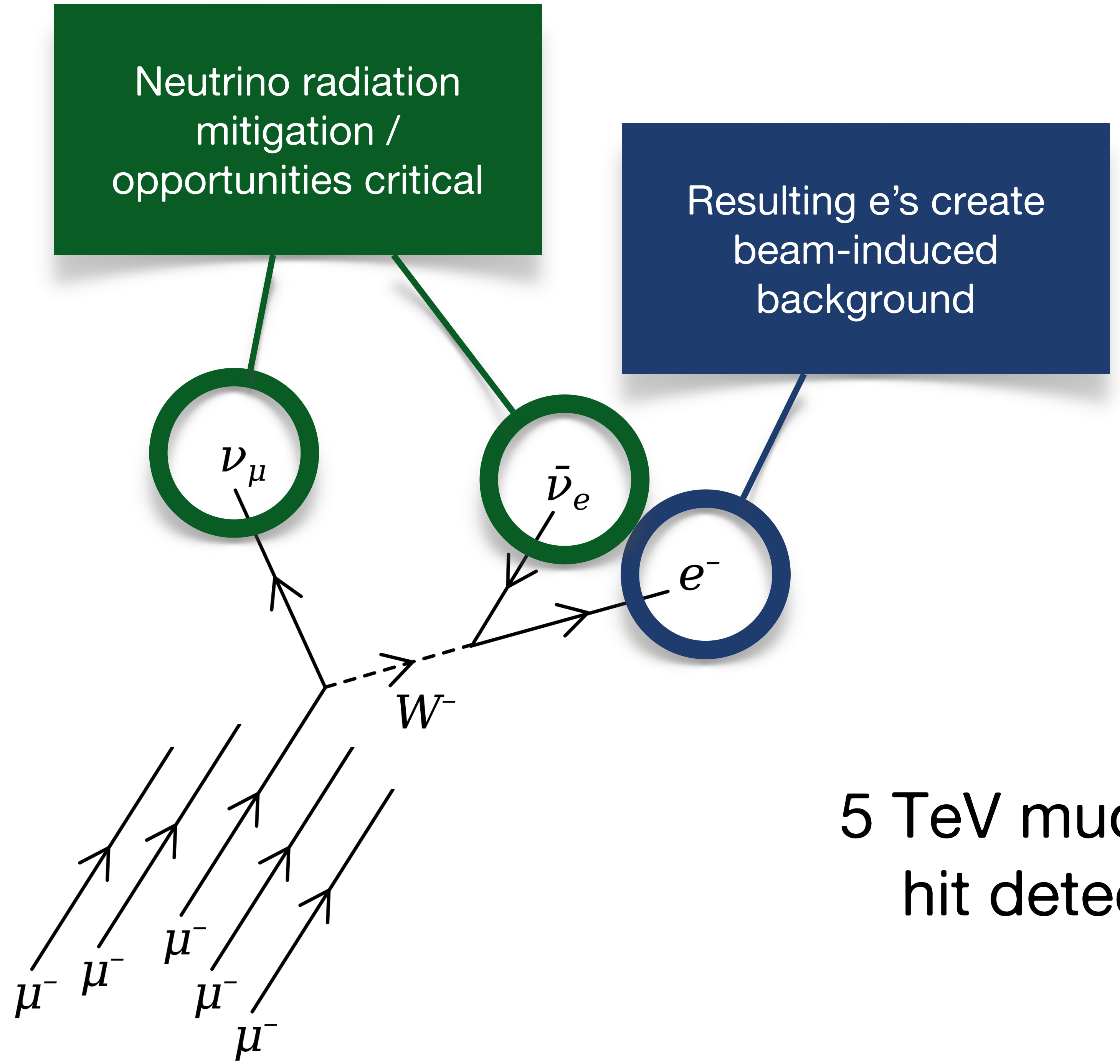

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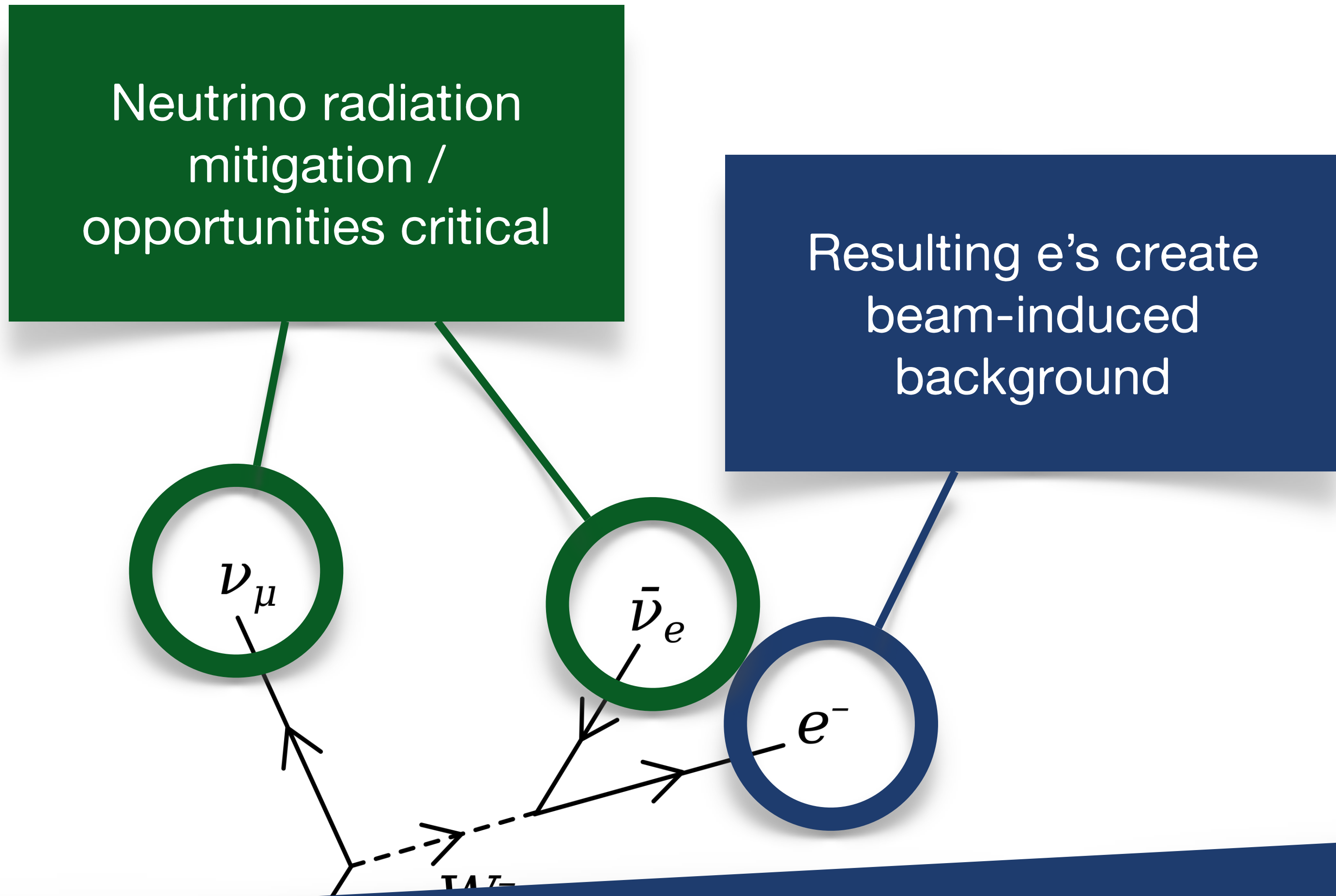
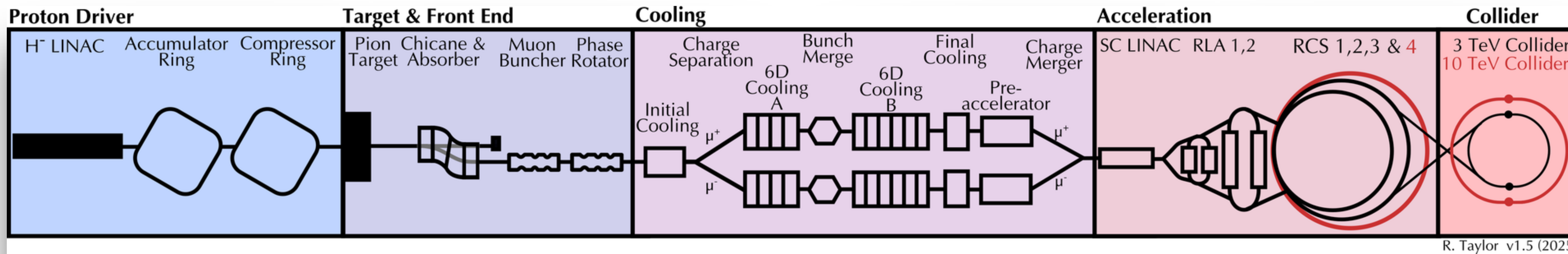


Everything has to be:

Done very quickly
Shielded and radiation hard

Almost all μC challenges are due to this short lifetime



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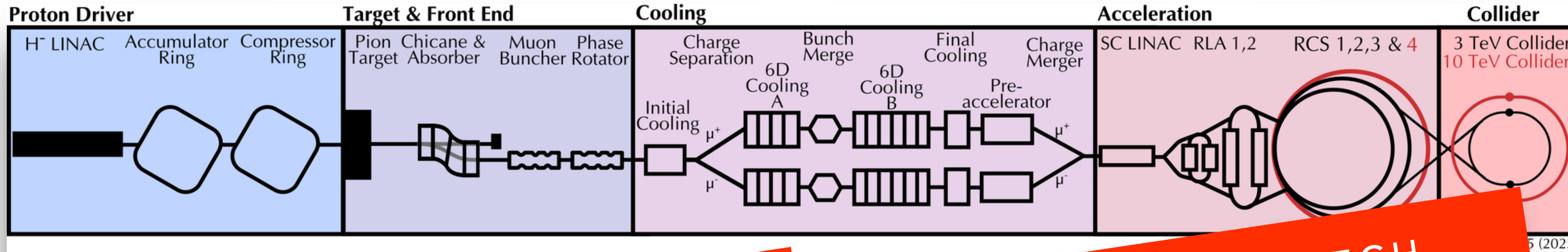
- Intense pion production → **Capture** diffuse muon decay products !!!
- “**Cool**” the muon beam. Reduce phase-space volume of beam !!!!!!
- **Accelerate, Collide, Measure** !!! !!! !!!



Overly simp

EXTREME SPACE CHARGE

NEW TARGET TECH NEEDED

- O(1) **MW** beam of **protons** on **target**

20T IN HIGH RADIATION ENV

!!!

- Intense pion produ → **Capture** diffu y

WTF 10-6 VOLUME REDUCTION

40T MAGNET?

!!!!!!

- "**Cool**" the muon ce phase ume of beam

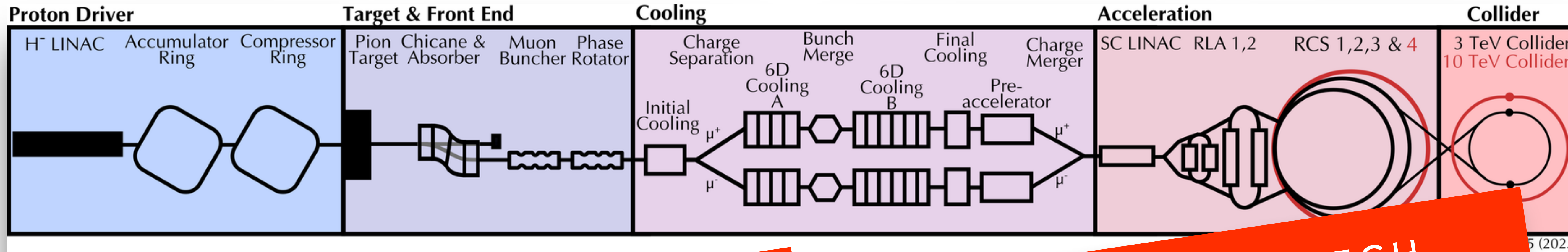
FAST RAMPING MAGNETS (~10 T/ms)

20T MAGNETS GALORE

LARGE EXP BACKGROUNDS

!! !!!

- **Accelerate, Collide, Measure**



Overly simp

EXTREME SPACE CHARGE

NEW TARGET TECH NEEDED

5-year goal:

Conceptual Design → **“Reference Design”**

w/ full simulations, end-to-end technical requirements

- **“Cool”** the muon ... ce phase ... ume of beam

!!! !!! !!!

FAST RAMPING MAGNETS (~10 T/ms)

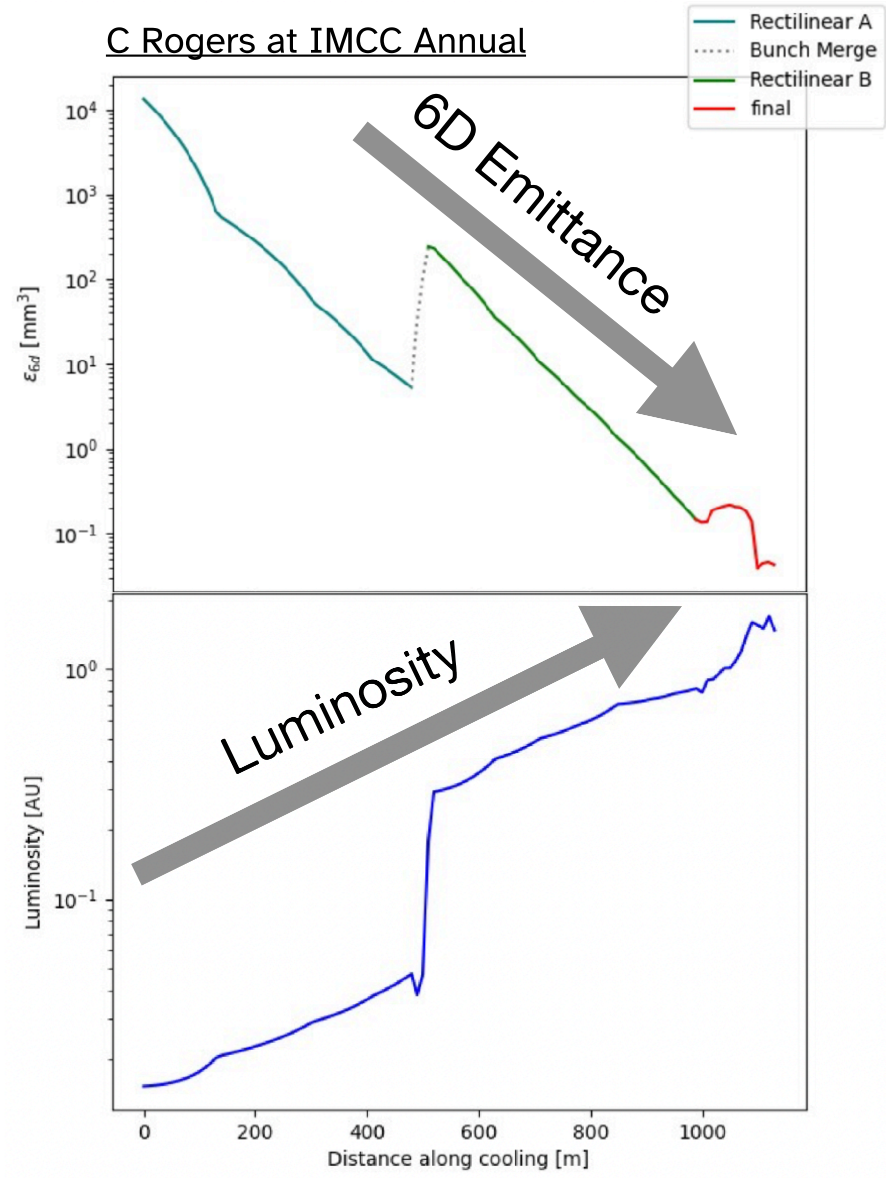
20T MAGNETS GALORE

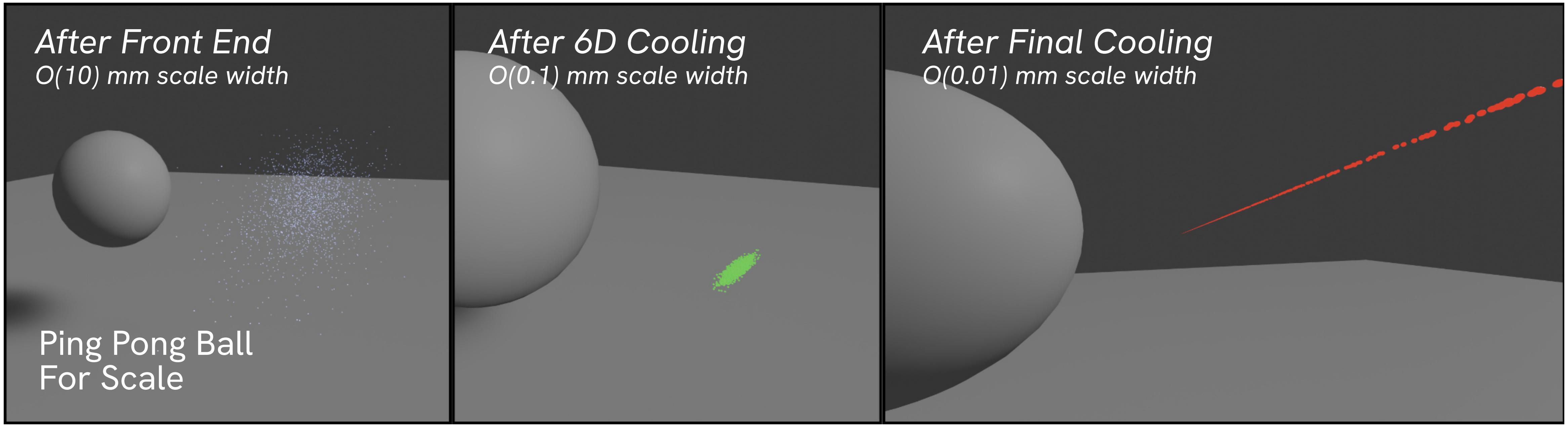
LARGE EXP BACKGROUNDS

- **Accelerate, Collide, Measure**

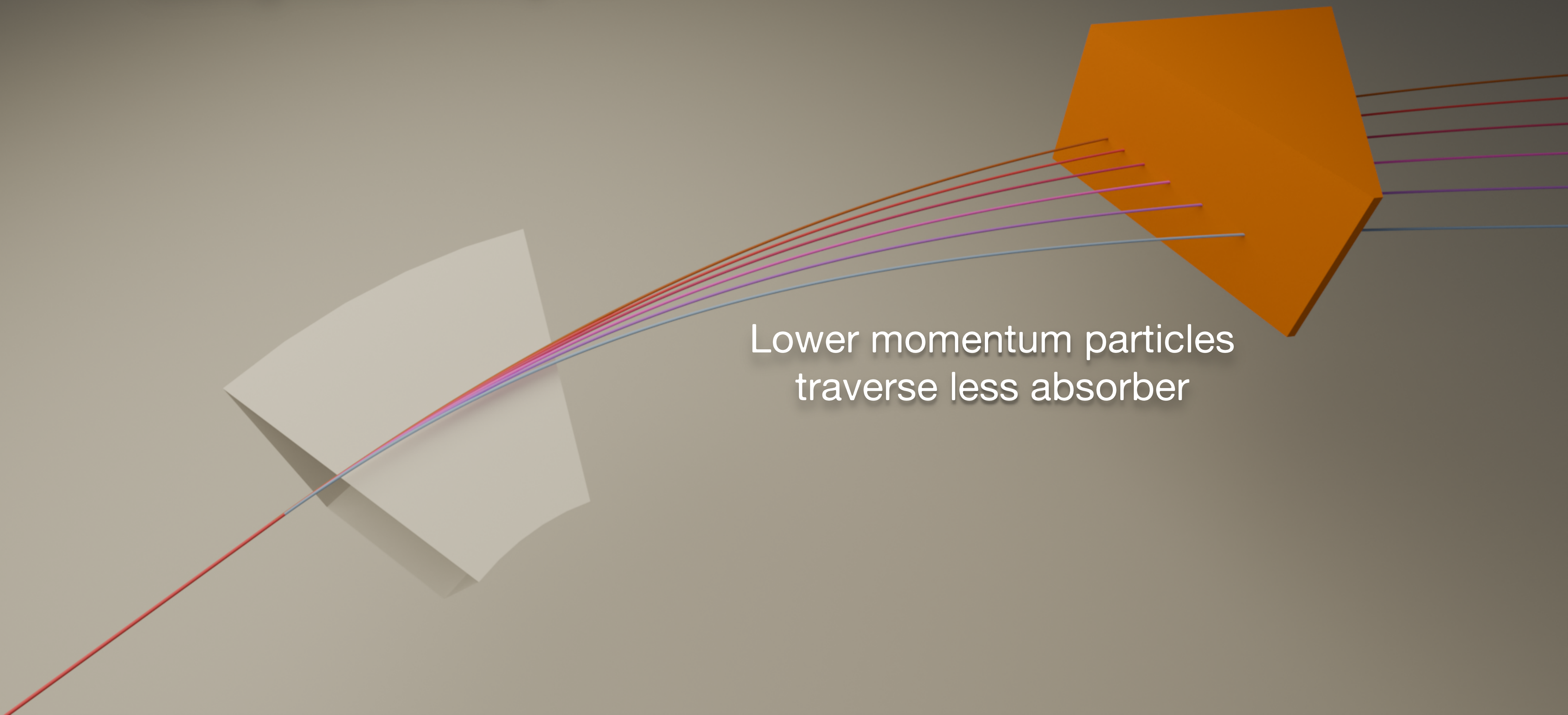
Muon Cooling

- Muons produced this way have **huge phase-space volume**
  - Large 6D emittance
- But colliders need **low emittance** beams to achieve useful lumi
- Reducing phase-space volumes requires **nonconservative process** (Liouville's theorem)
  - Remove energy from system → **“Cooling”**

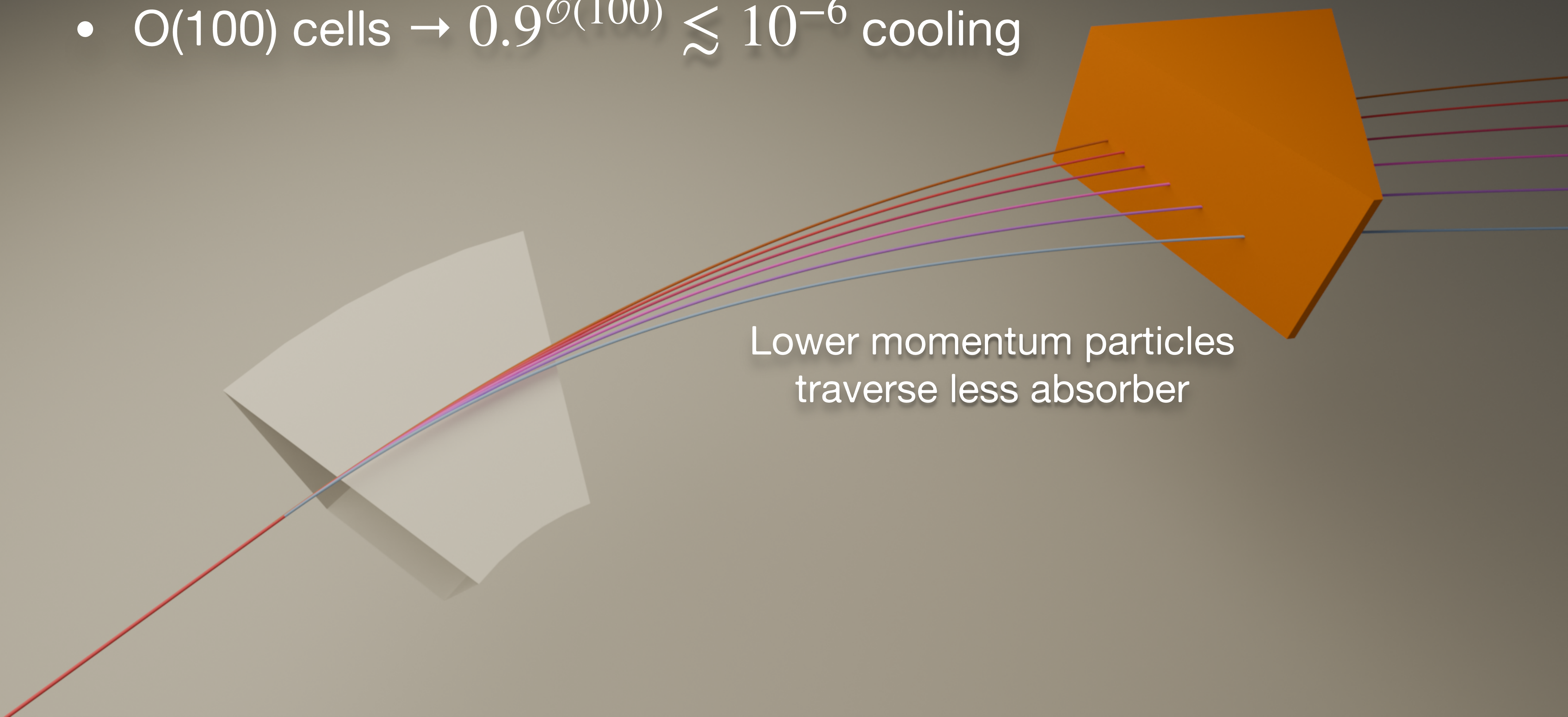




- **Ionization Cooling Example**
  - Introduce **dispersion** with dipole → Correlate momentum with position
  - Higher momentum particles through more absorber, **losing more integrated dE/dx**



- After absorber, beam more **mono-energetic**
  - ~10% emittance reduction per cell
- **RF cavities** restore the energy
- Rinse and **repeat**
  - O(100) cells → $0.9^{\mathcal{O}(100)} \lesssim 10^{-6}$ cooling



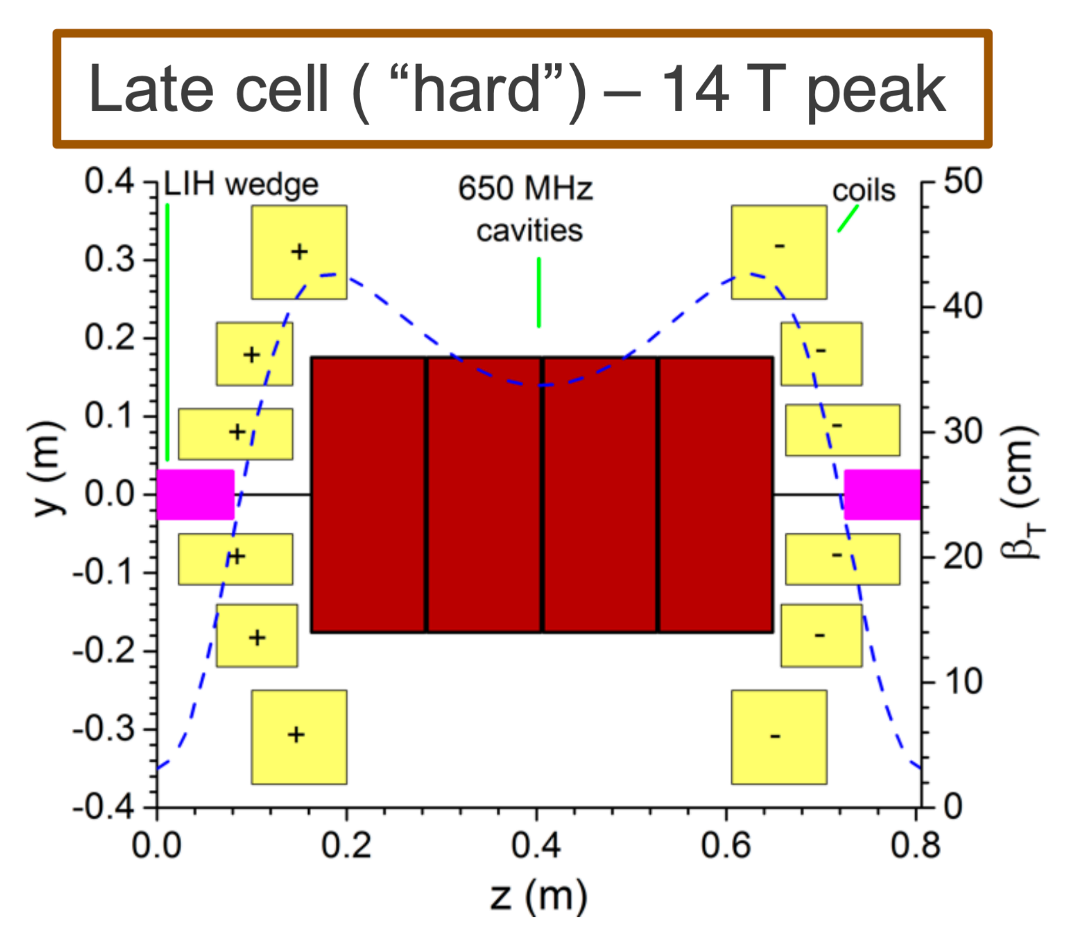
Rinse & Repeat model isn't so simple

Late stage cooling cells much more challenging to build
(14T, ≥30T, RF)

Don't need a "proof of concept" to believe in dE/dx

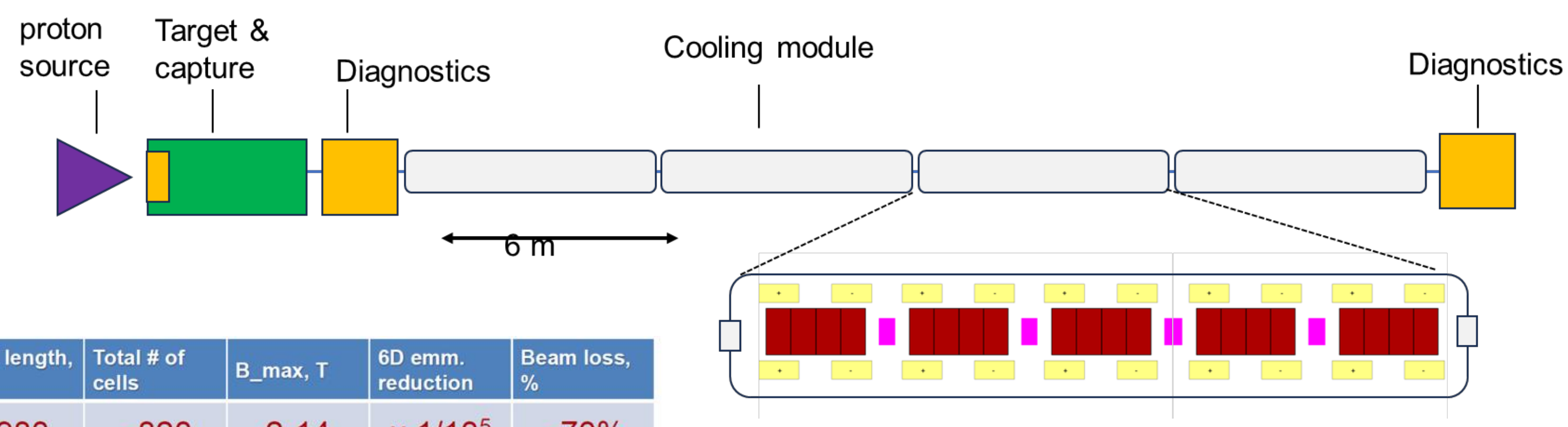
Need a **"proof of engineering"** demonstration

Need to demonstrate that channel can be physically constructed!



Last week's DPF/DPB Forum

Cooling Demonstrator Facility

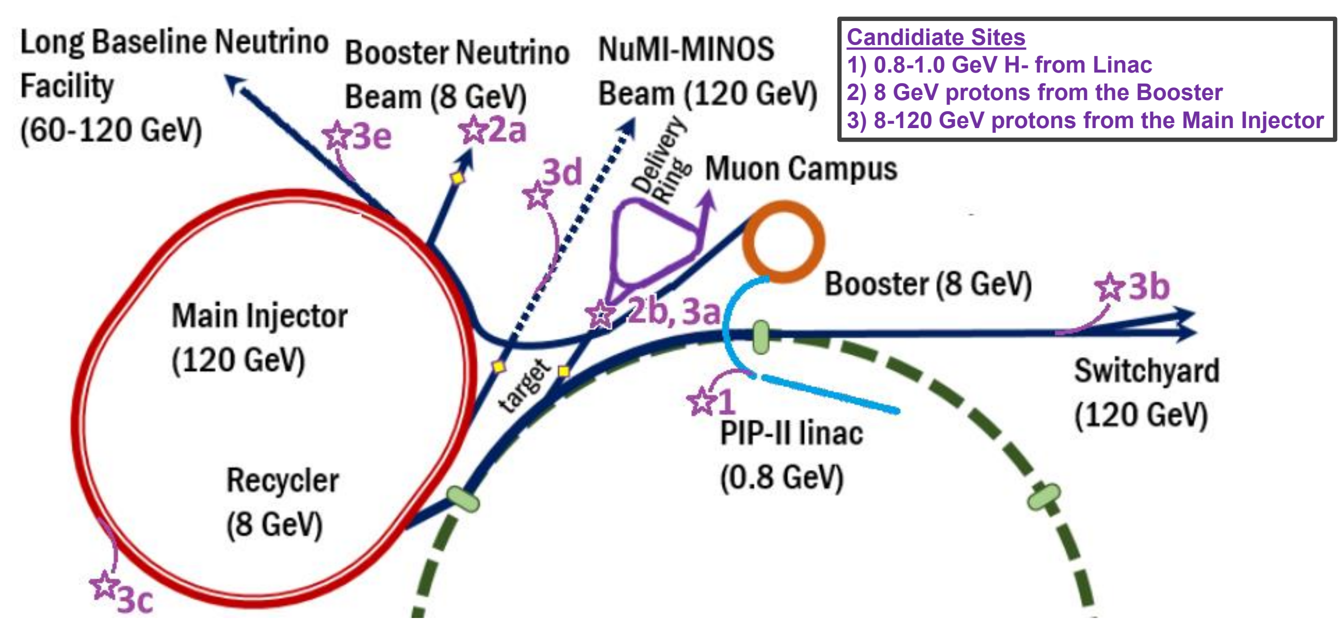


	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x $1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%

- The design will depend on the choice of the beam parameters
- Fermilab Accelerator could offer different potential beams for the Demonstrator
- Need to have advanced demonstrator design in 3-5 years for the P5 “collider panel”

Fermilab

Demonstrator Candidate Sites



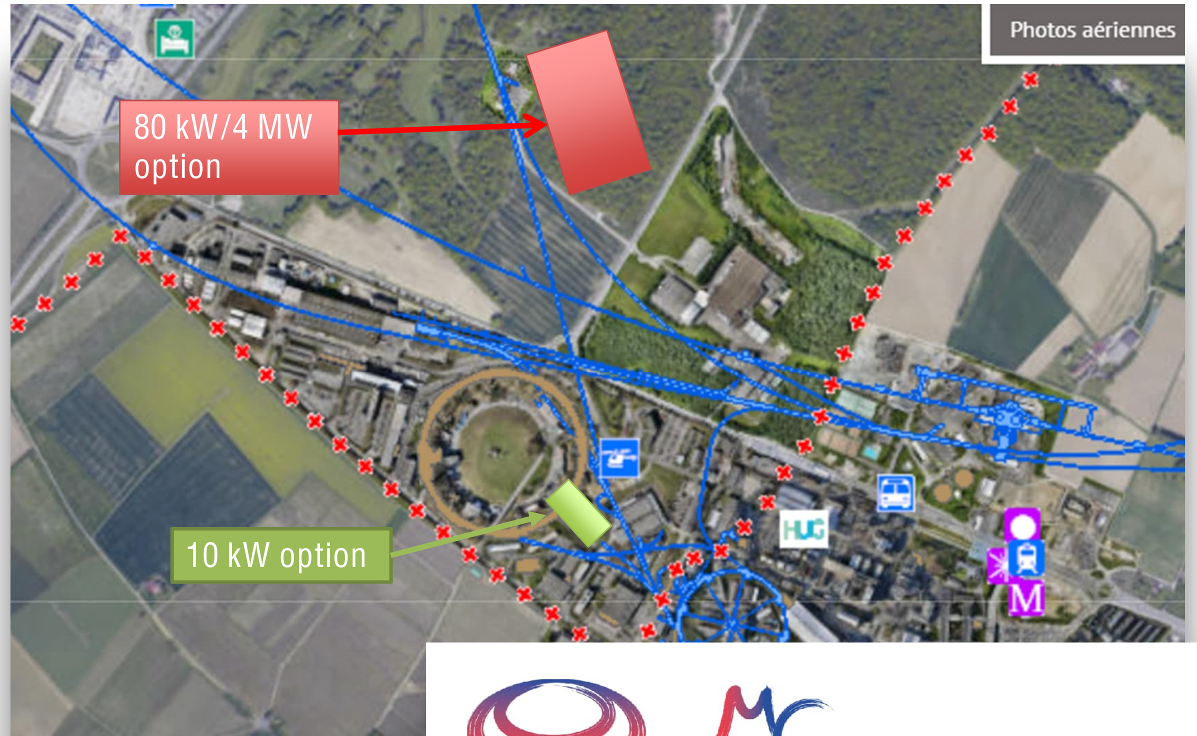
Fermilab

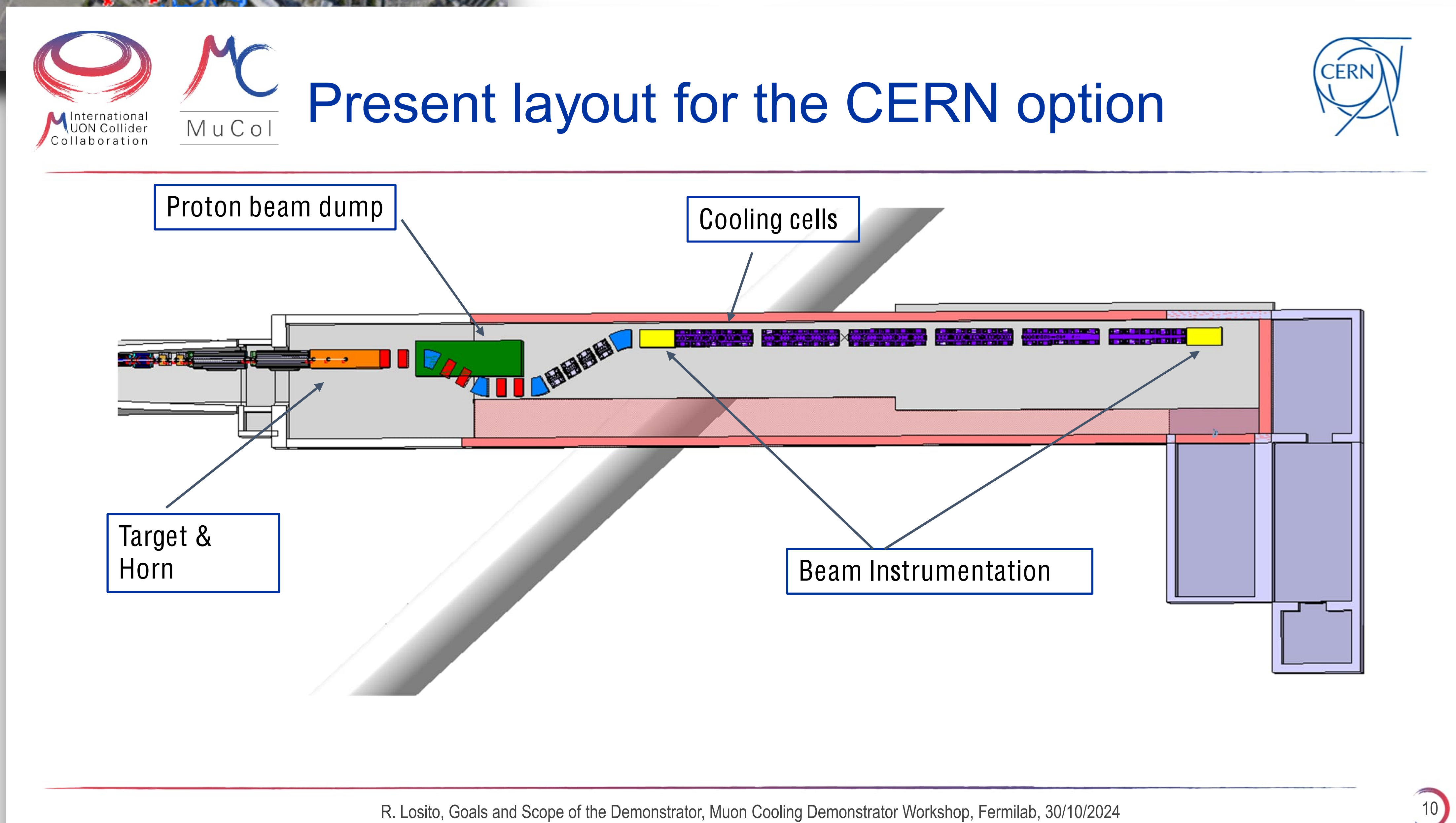
12 J. Eldred I Muon Cooling Demonstrator Siting at Fermilab 11/1/2024

Cooling demonstration at Fermilab?

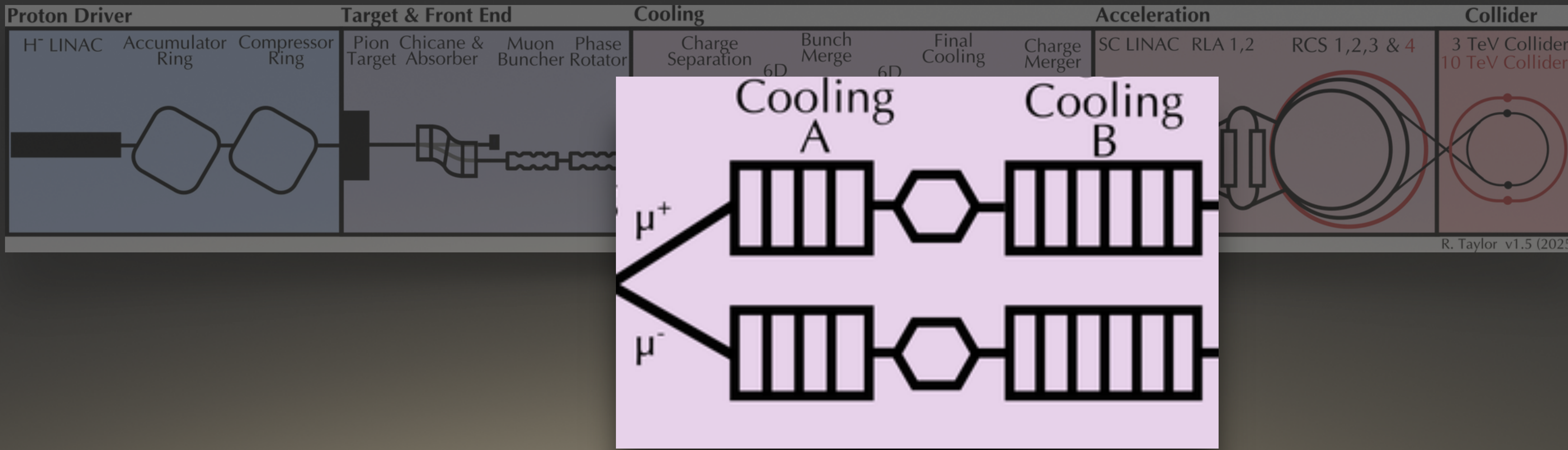
Strong synergies with proposed Accelerator Complex Evolution (ACE)

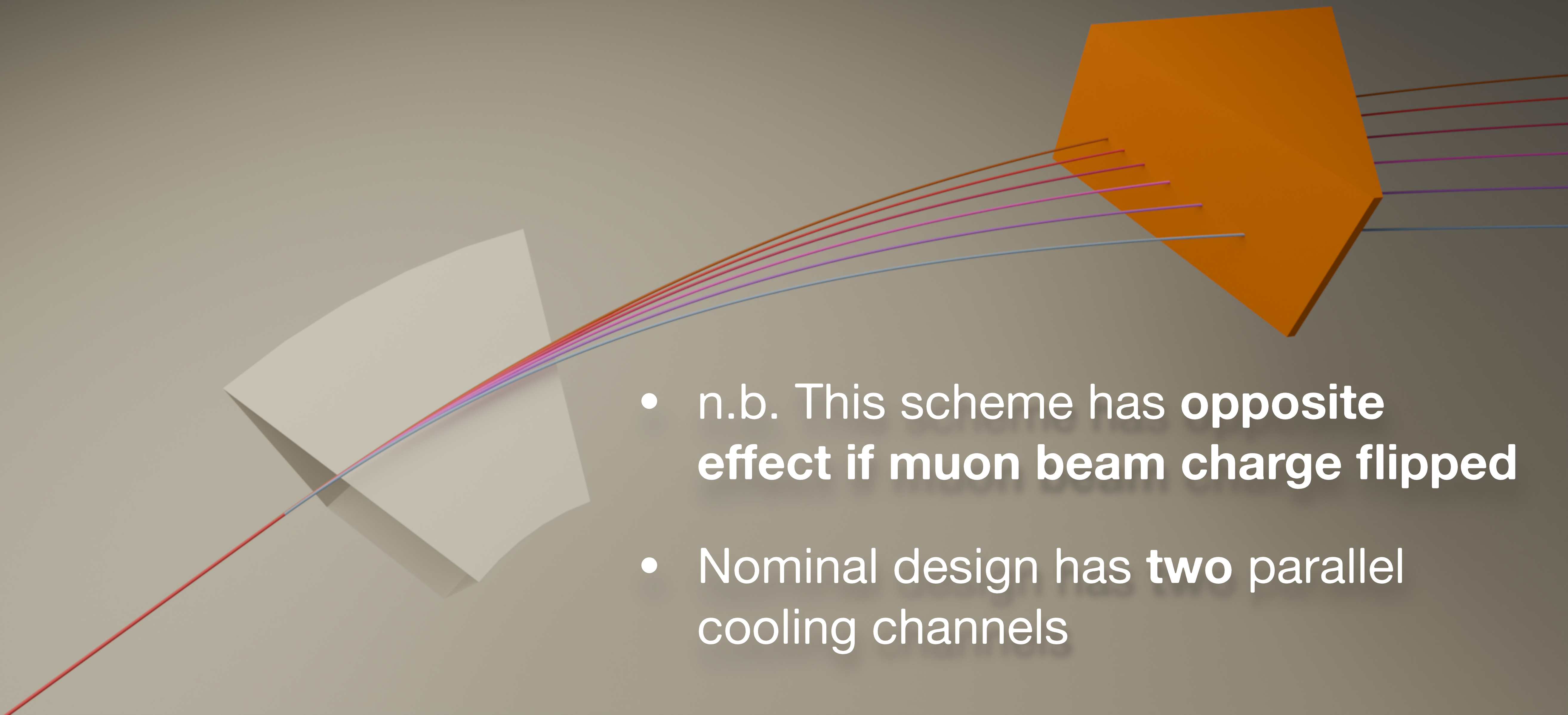
Cooling demonstration at CERN?



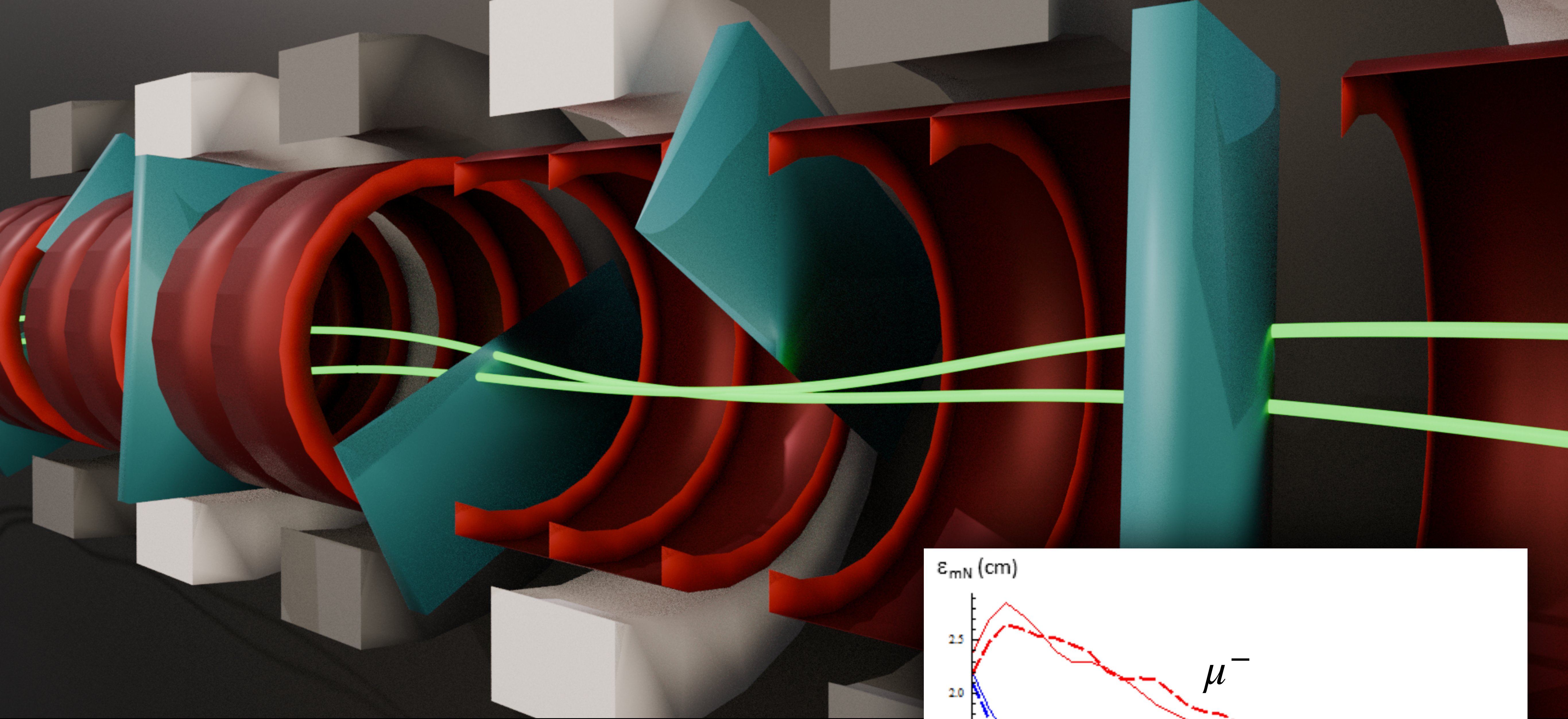


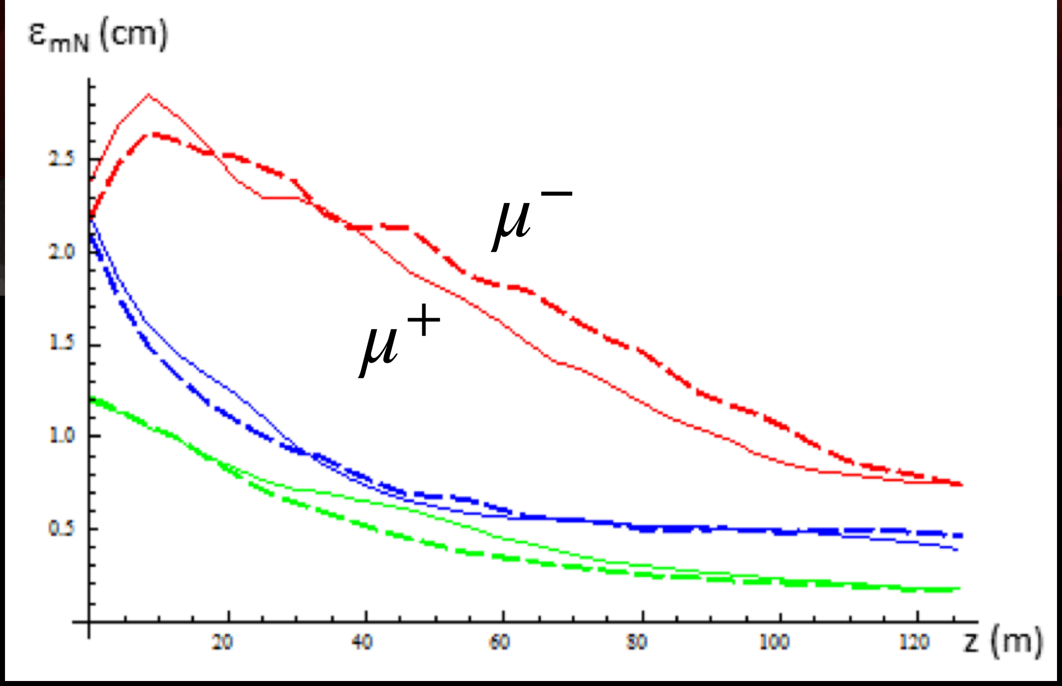
Link





- n.b. This scheme has **opposite effect if muon beam charge flipped**
- Nominal design has **two** parallel cooling channels



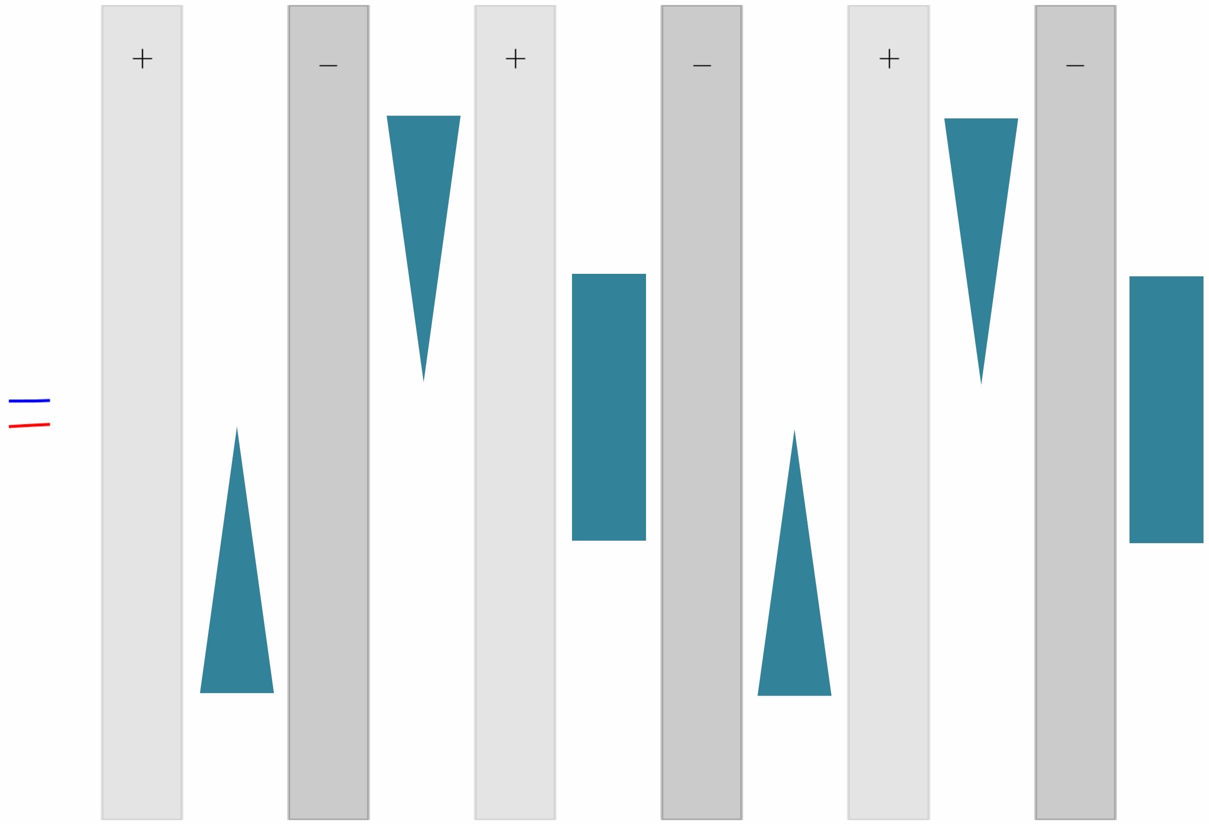


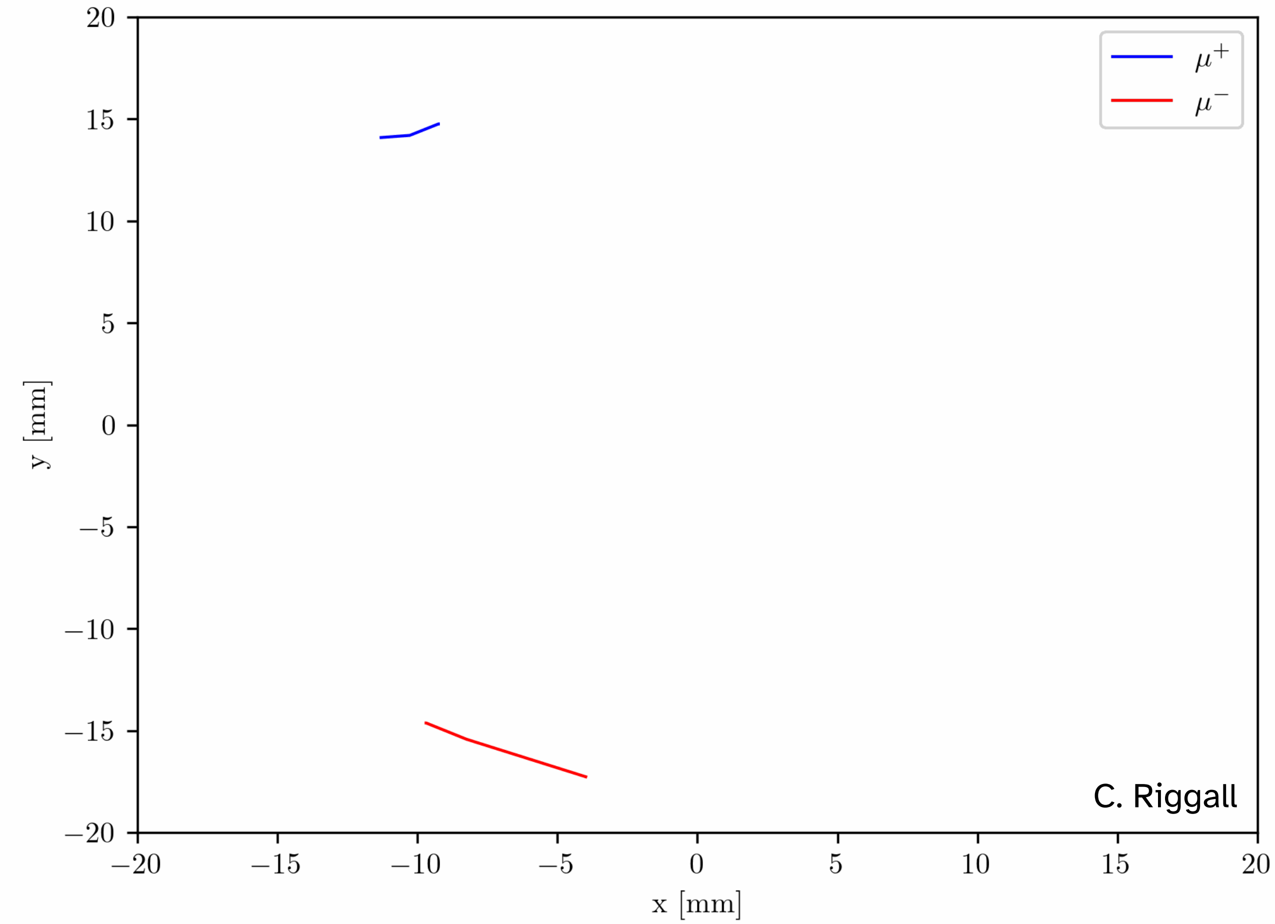
Recently revived Helical cooling design “Helical FOFO Snake”

Yuri Alexahin (FNAL)
Continued by Caroline Riggall, Rithika Ganesan, LL, Tova Holmes (UTK) w/ support from BNL, FNAL, ORNL

THE UNIVERSITY OF TENNESSEE KNOXVILLE
Fermilab
OAK RIDGE National Laboratory
Brookhaven National Laboratory

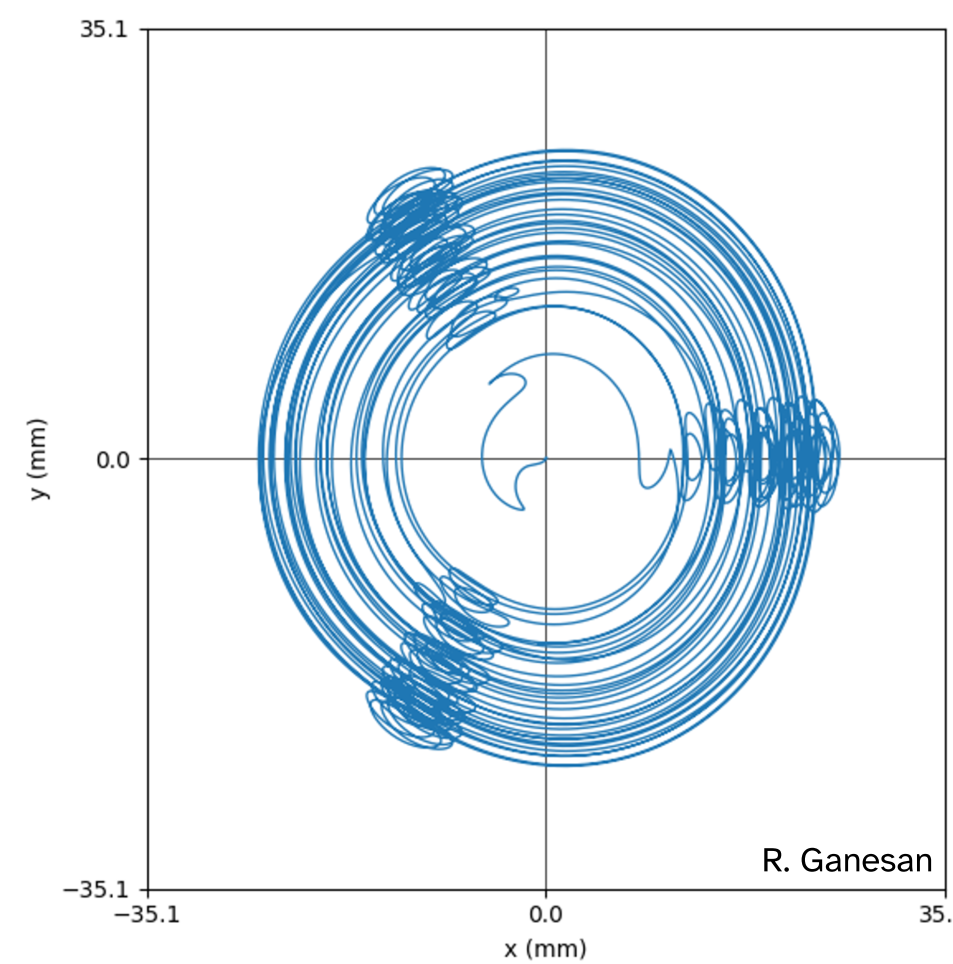
Beam spun into rotating double helix
Cools both μ^+ and μ^- in single channel
Significant cost savings for 6D cooling



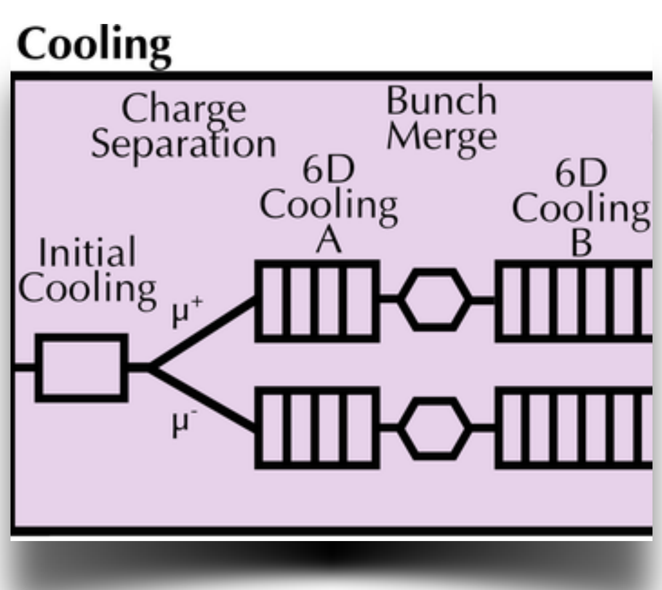


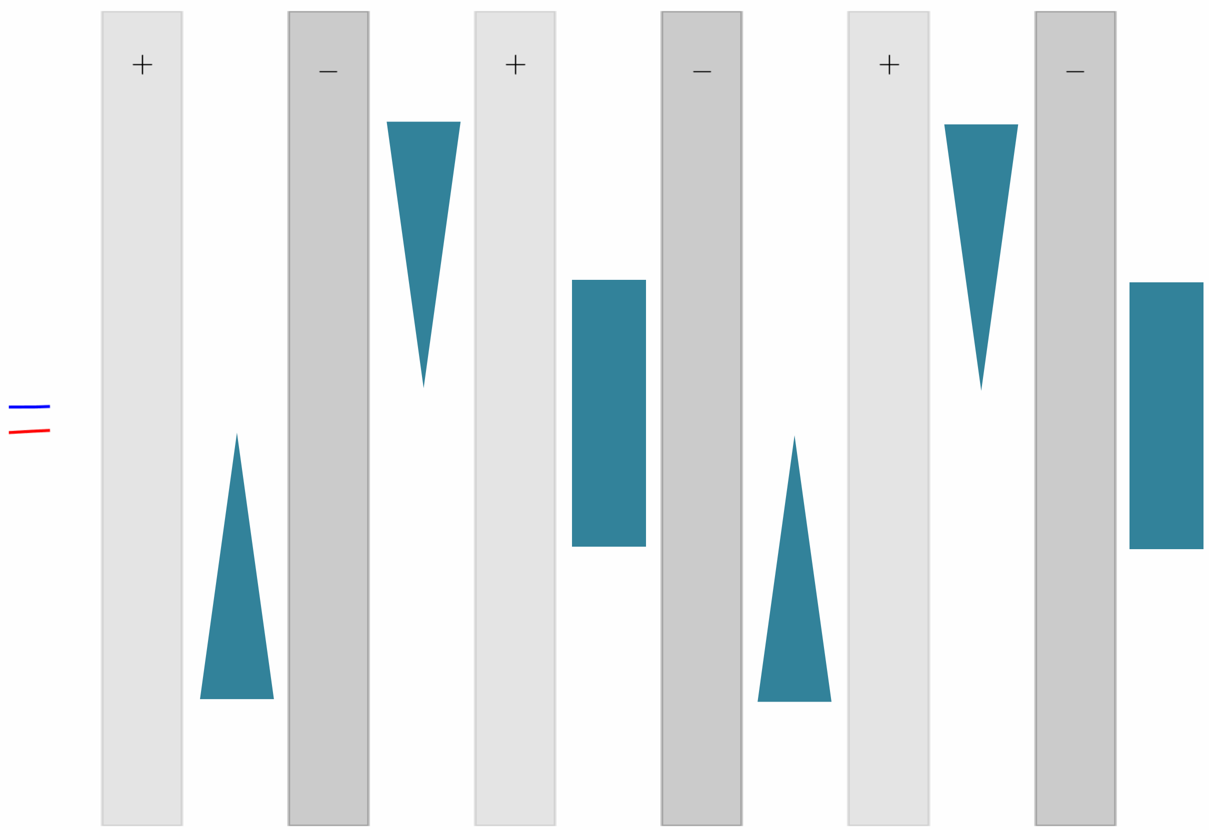
$\mu^+\mu^-$ share helical trajectory
from discrete translational symmetry

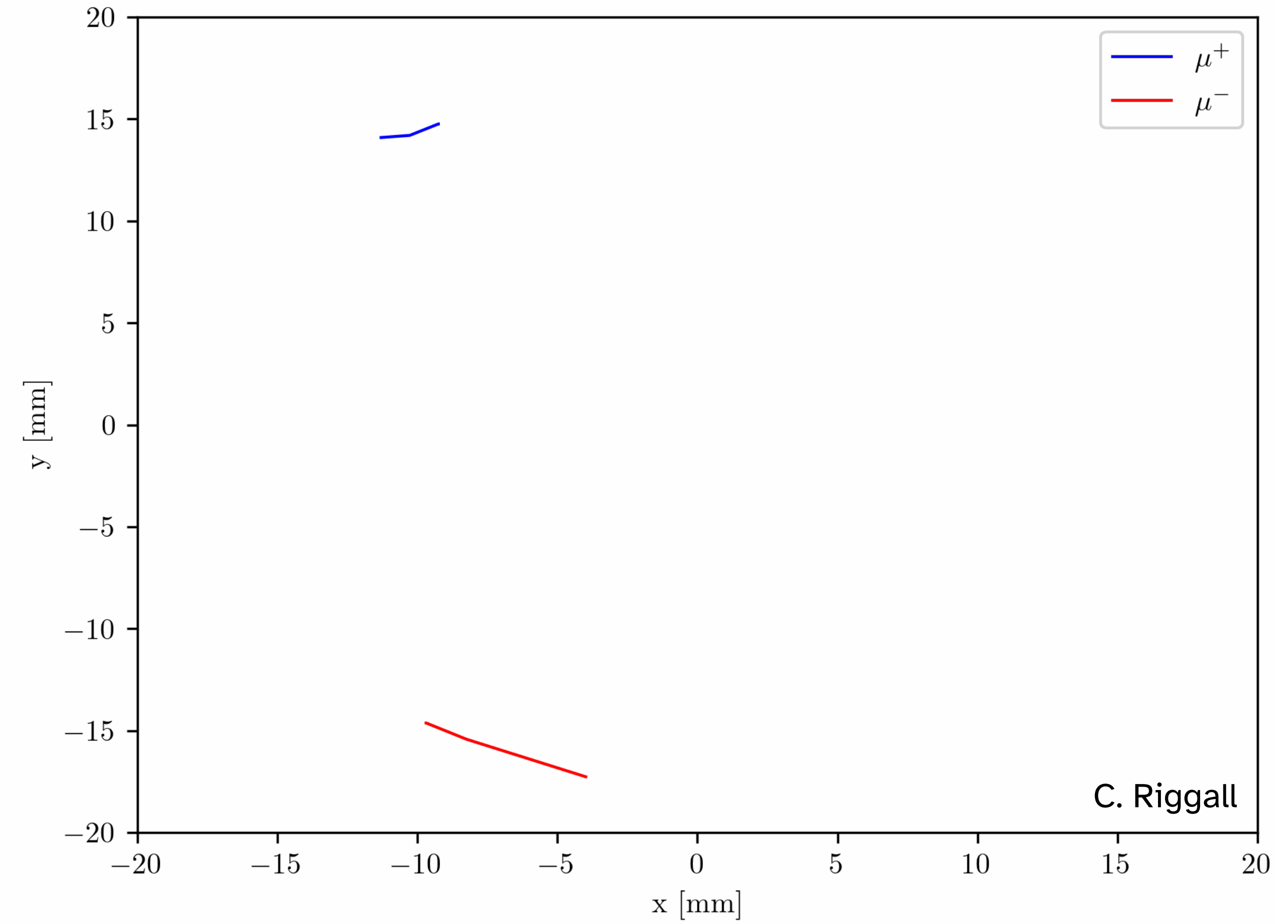
Charge flip → Phase shift in Larmor motion



Interesting candidate for initial cooling stage







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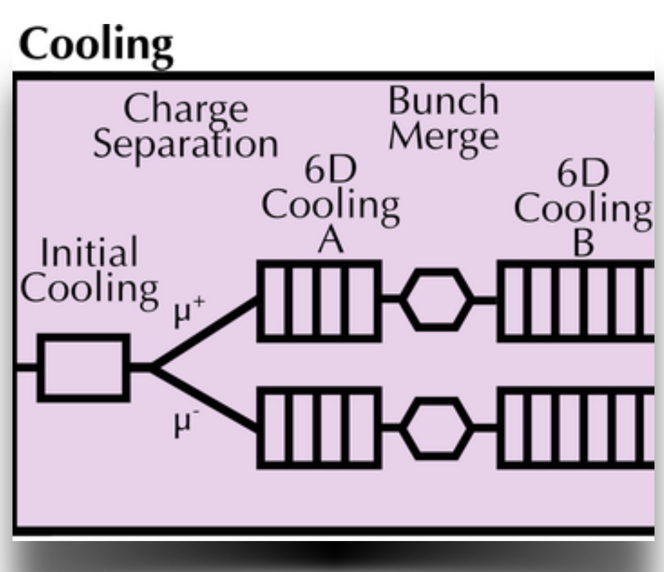
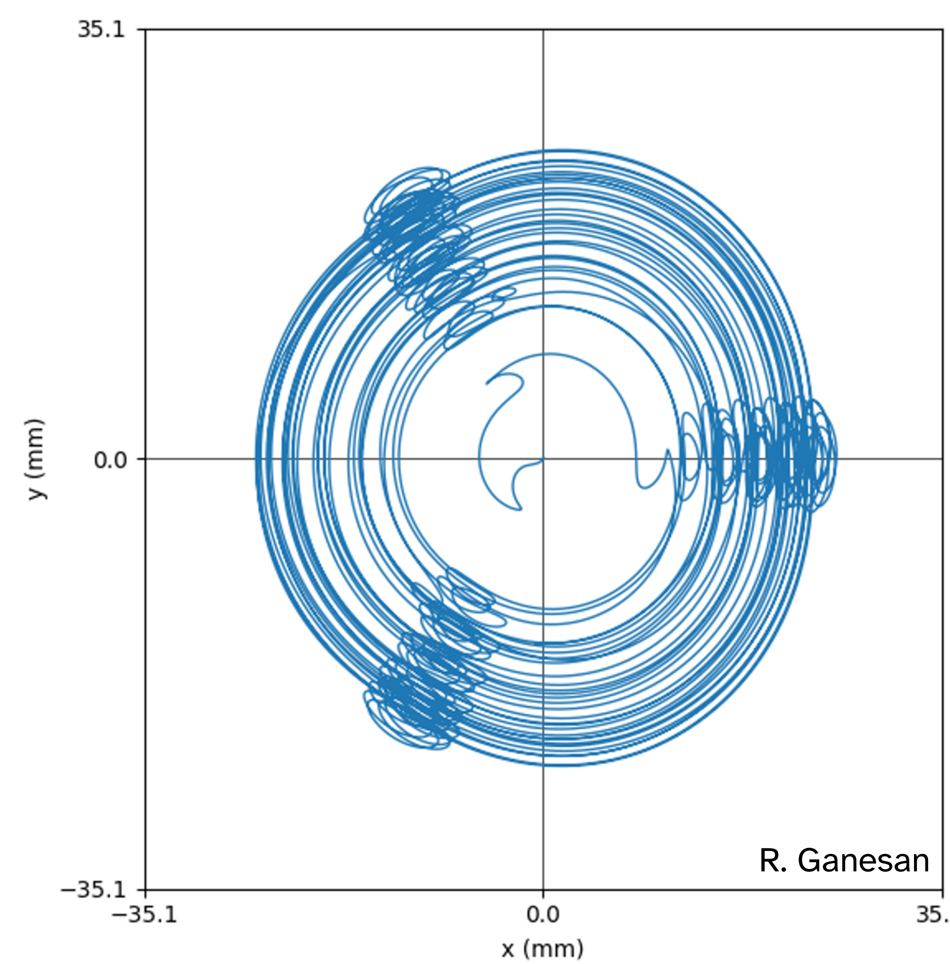
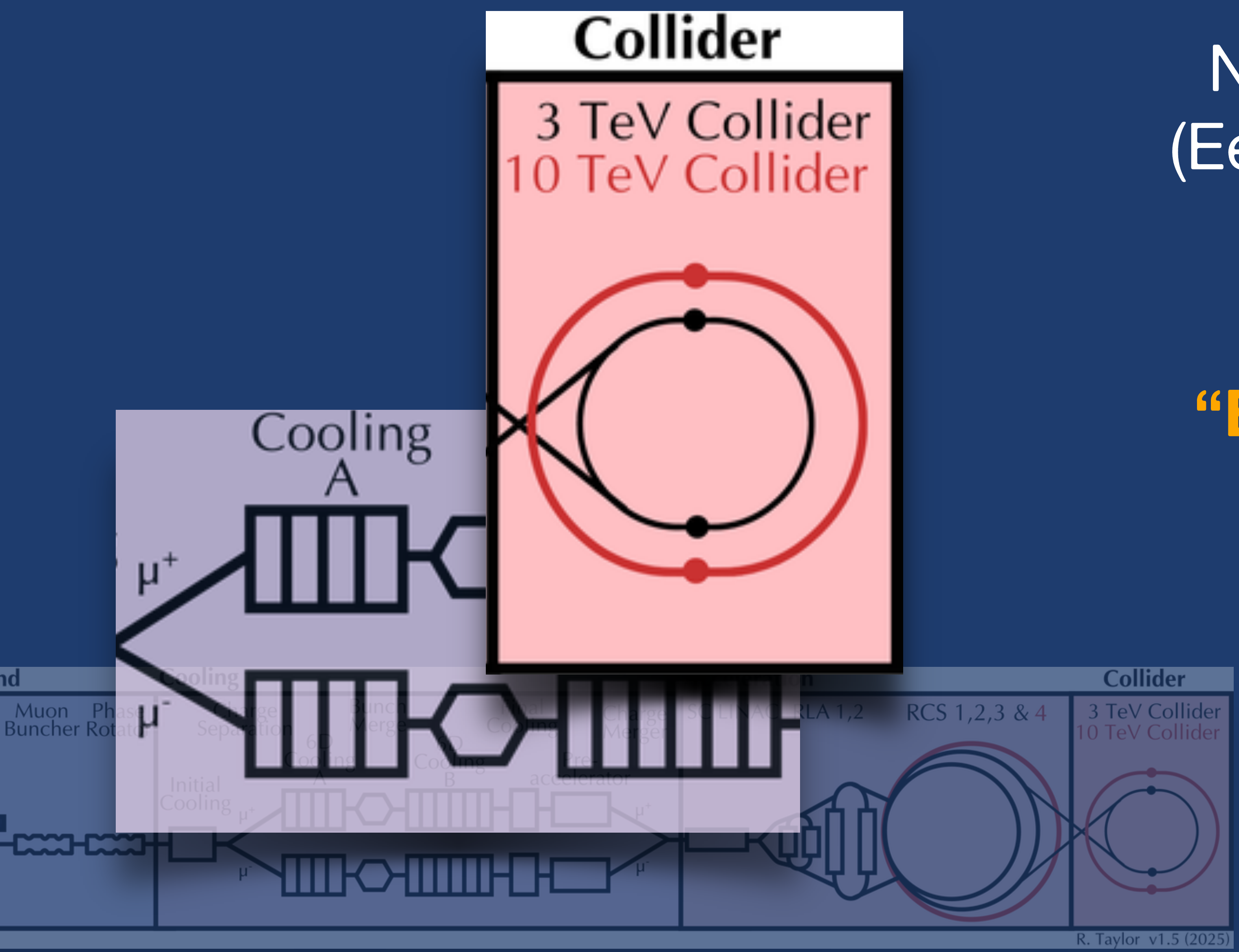




Skipping a bunch of steps and details…

Focus on studying the collisions



Near the collision, lots of energy (EeV!) thrown into detector region from decaying muons

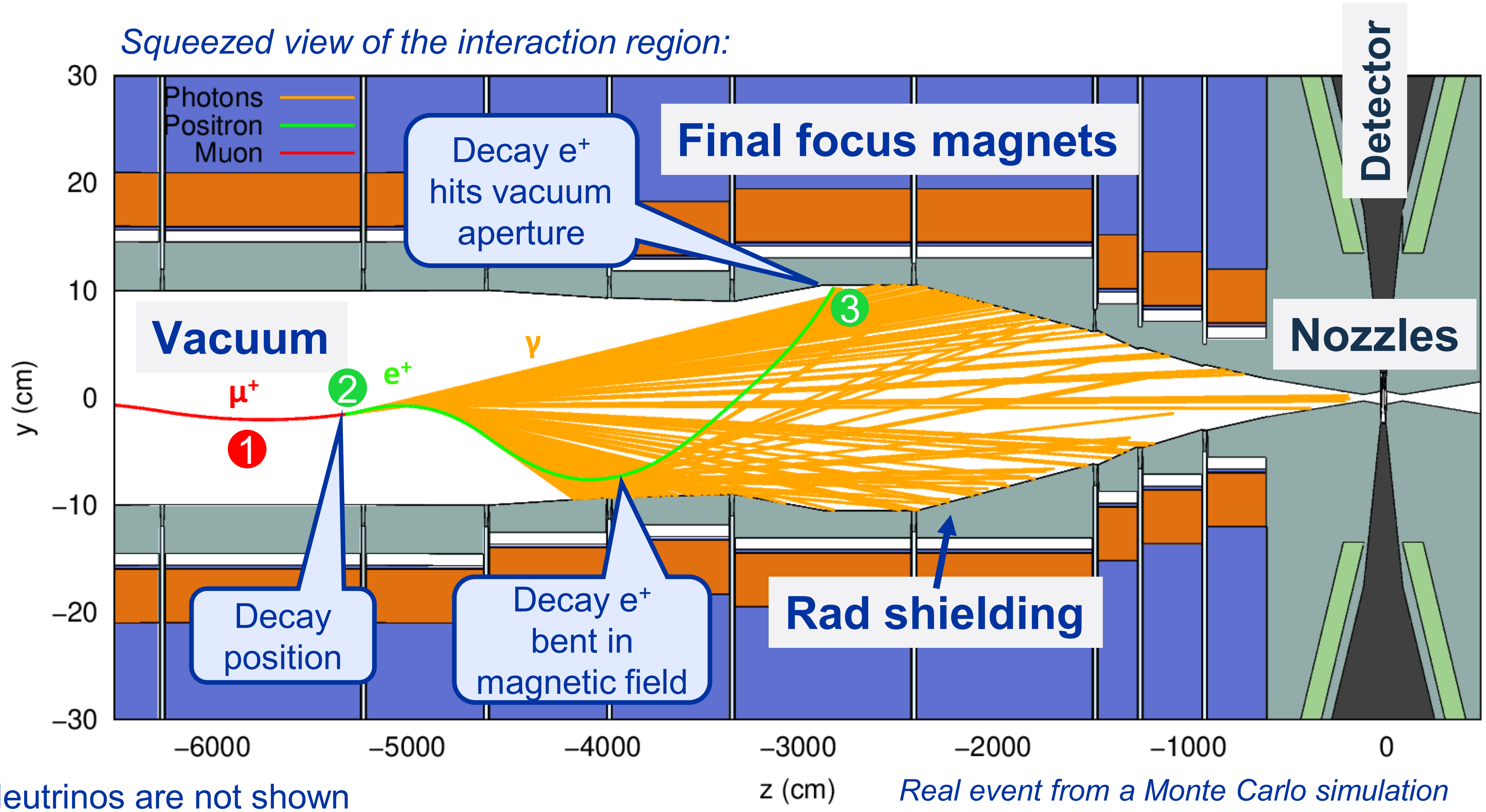
“Beam-Induced Backgrounds” (BIB)

Enormous background in detectors

Example of a muon decay in the machine

The lower-energy decay e^-/e^+ are overbent by the strong magnetic fields and emit synchrotron radiation (SR)

Squeezed view of the interaction region:



Neutrinos are not shown

Real event from a Monte Carlo simulation

Here:

1. μ^+ (5 TeV)
2. e^+ (1.20 TeV)
3. e^+ (0.45 TeV)

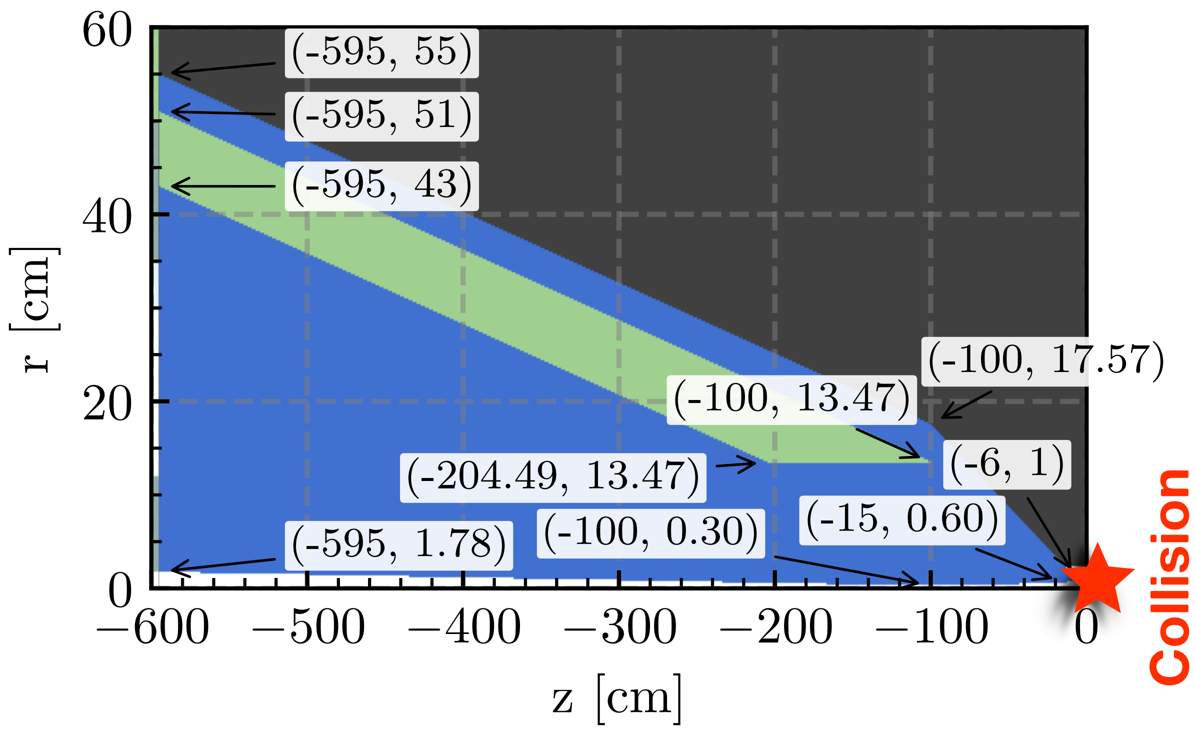
0.75 TeV emitted as SR photons

Because of the smaller mass, the decay e^+/e^- emit much more SR power than the muons of the beam

Anton Lechner, first week

Will happen O(10M) times per bunch crossing!

First Order BIB Mitigation



1. **Work closely w/ accelerator design to minimize**
    - Collaboration with accelerator community on Machine-Detector Interface (MDI) is crucial
2. **Shield ourselves**
    - Reduces BIB in detector by **many orders of magnitude**
    - Interactions with shielding → Bleed secondary energy into the detector
        - Turns highly localized incident energy into diffuse energy in detector

Shielding changes **character** of BIB s.t. it can be rejected through **measurement**

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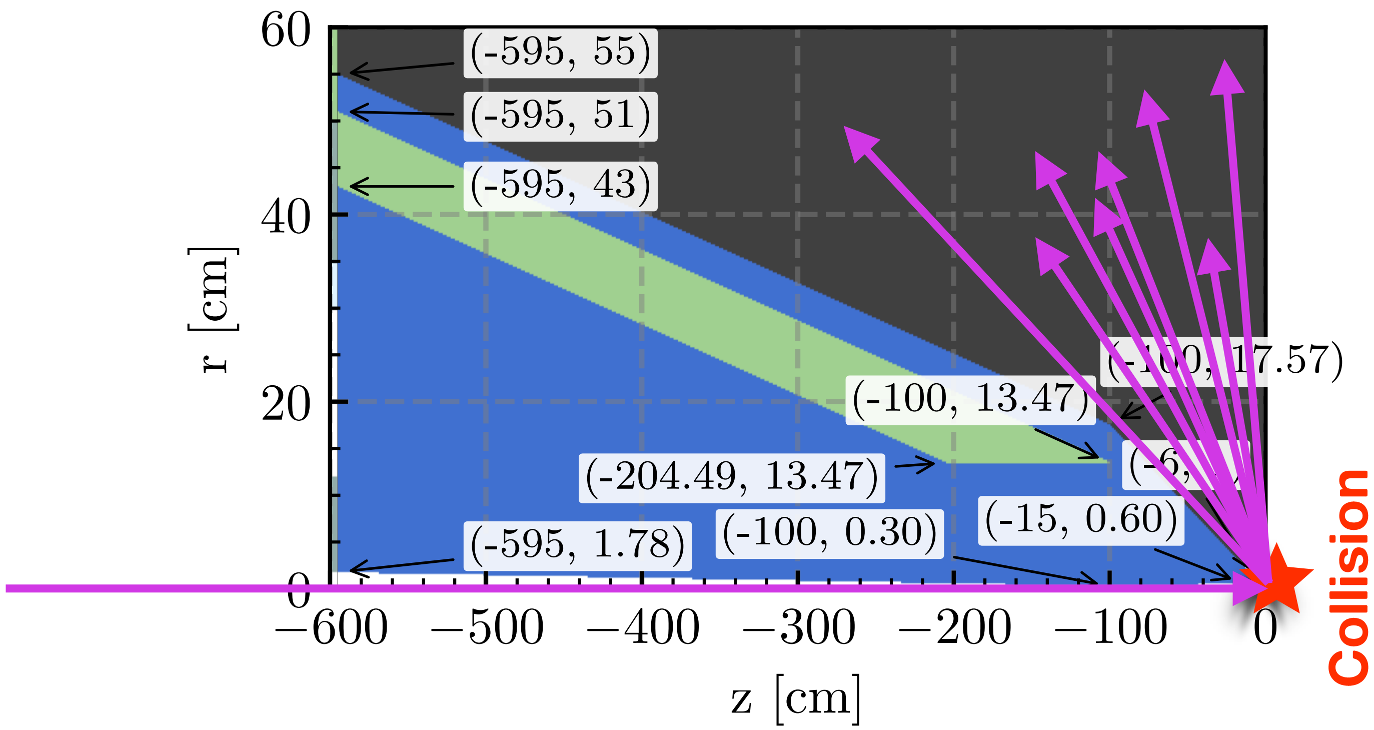

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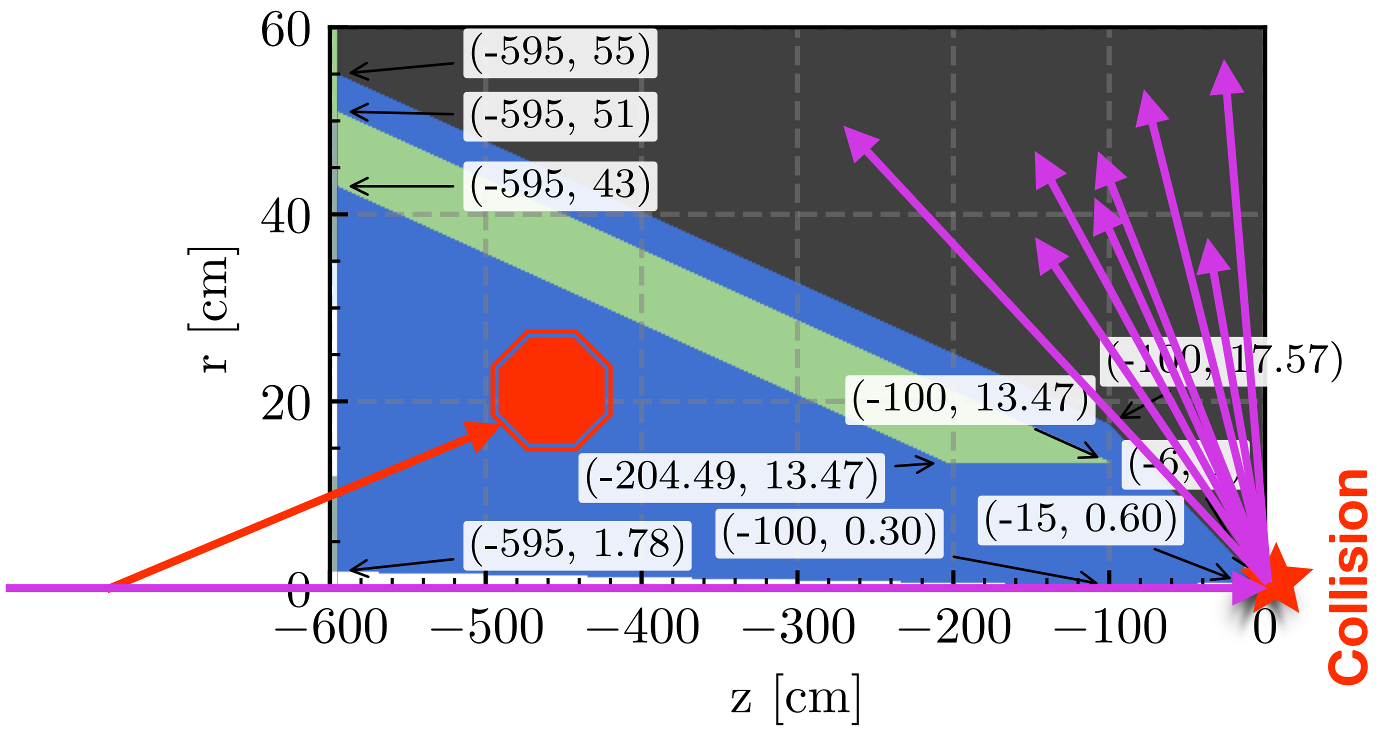

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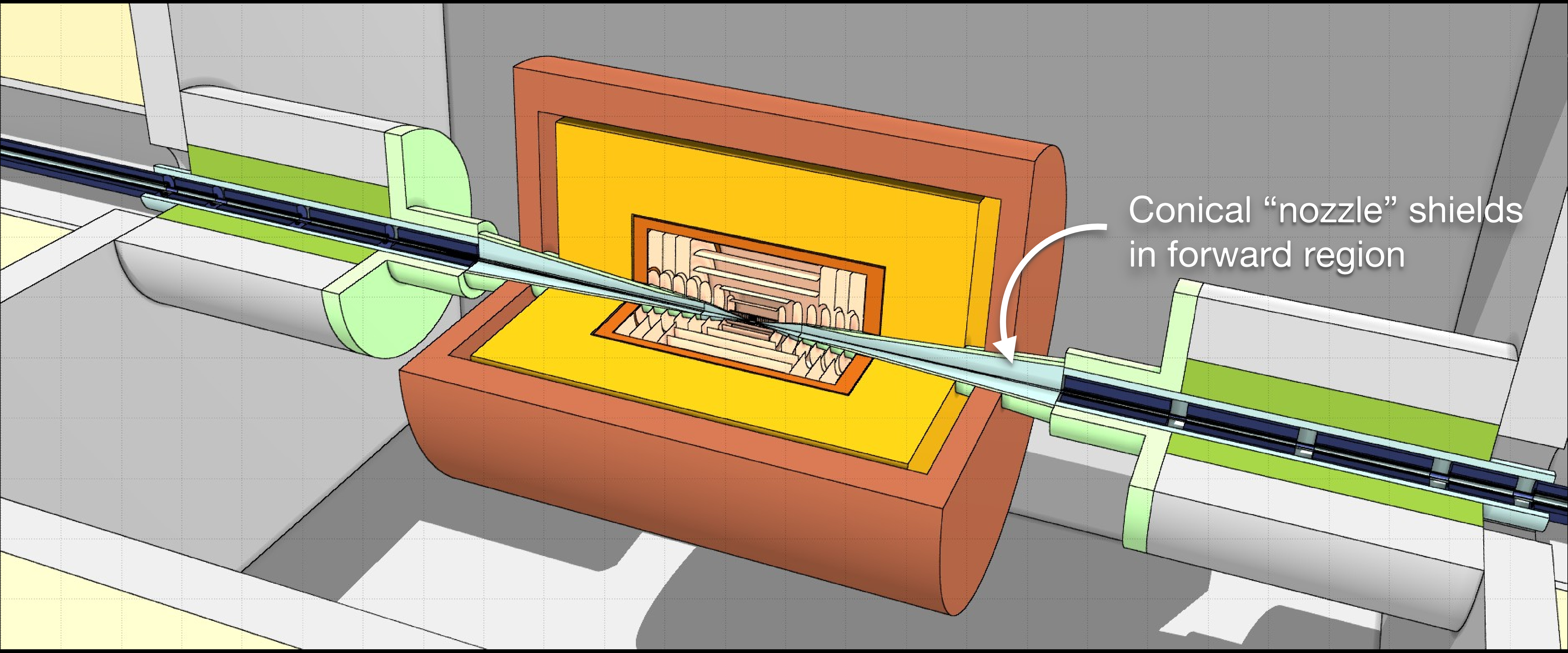
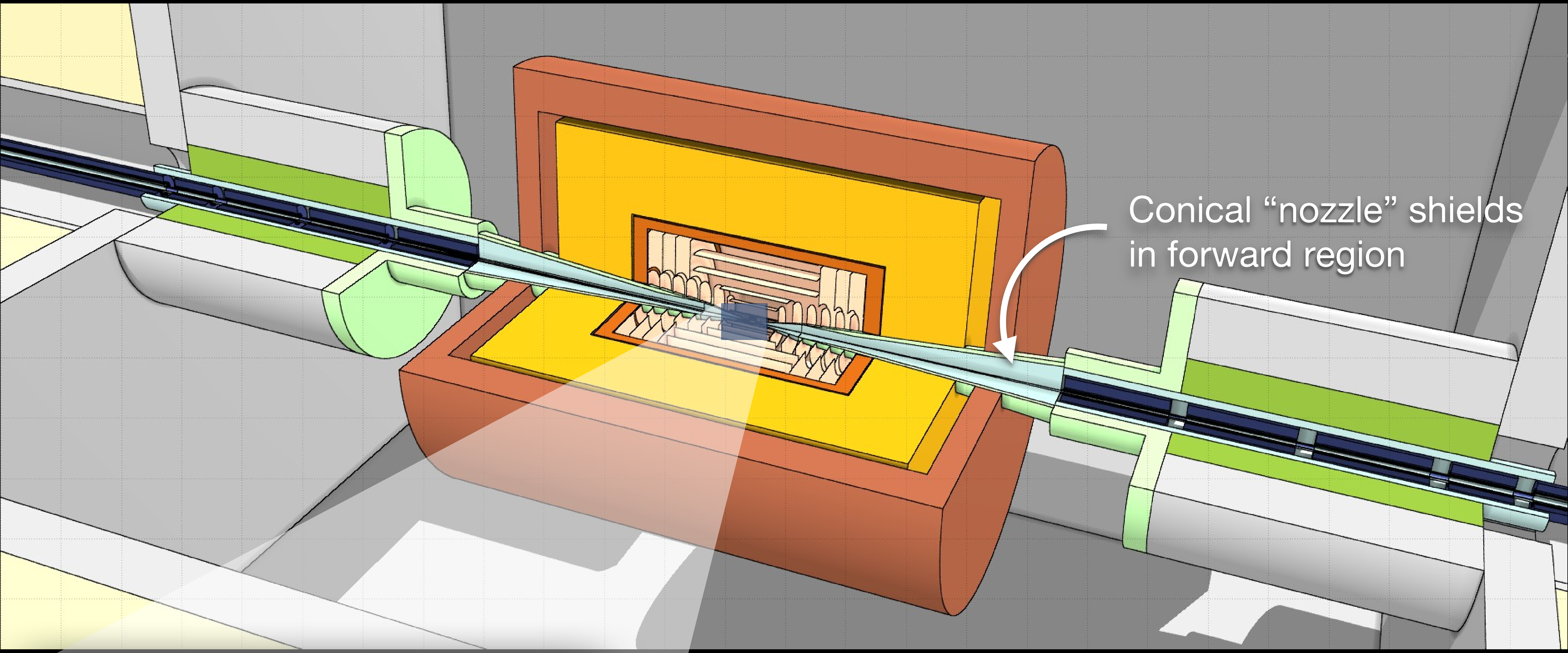
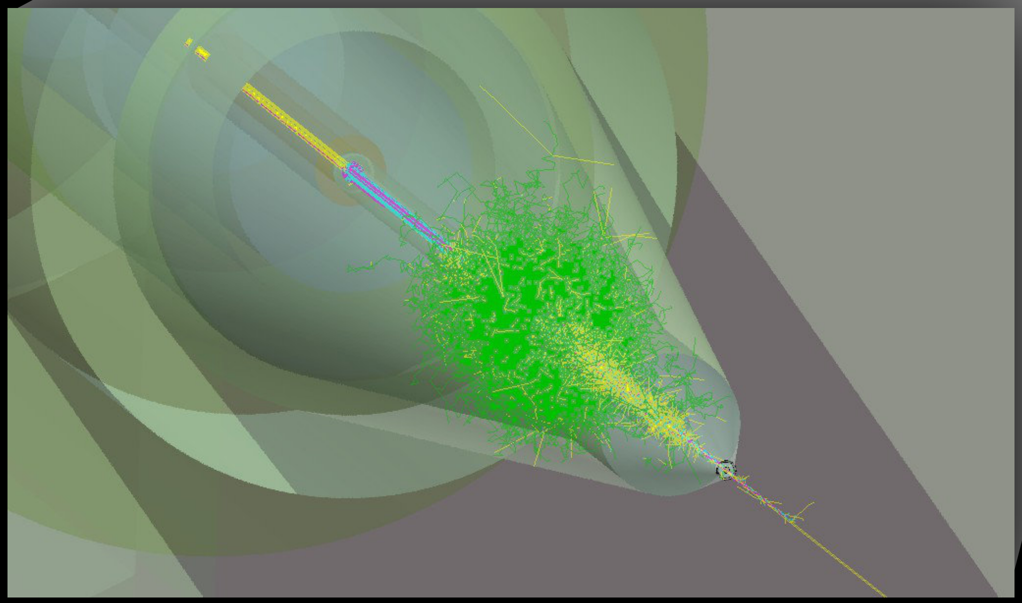


Images from Slides by D. Calzolari





Particle production from single muon decay 25m away. Nicely absorbed by nozzle.

Now imagine ~10M of these decays…

Images from Slides by D. Calzolari


How to Build a
Muon Collider
Lawrence Lee
The University of
Tennessee
Knoxville

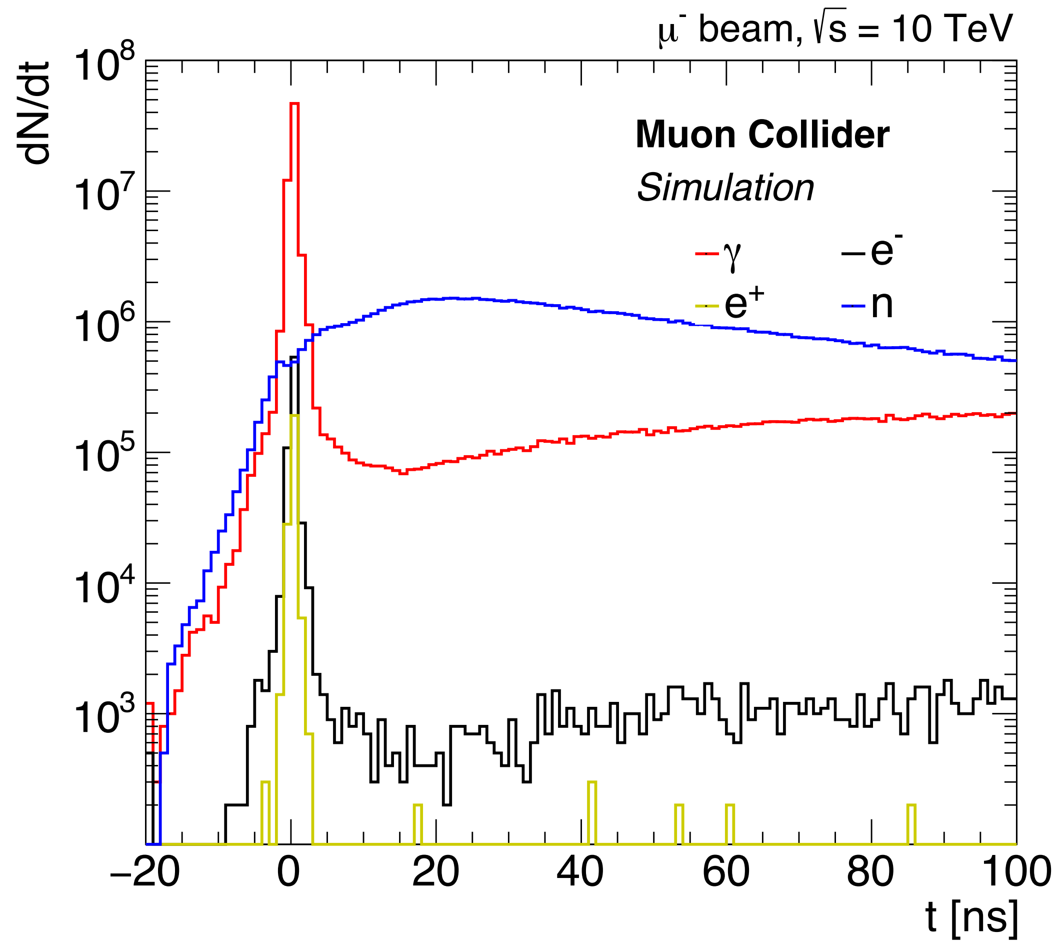

BUILD A
THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

Central Challenges

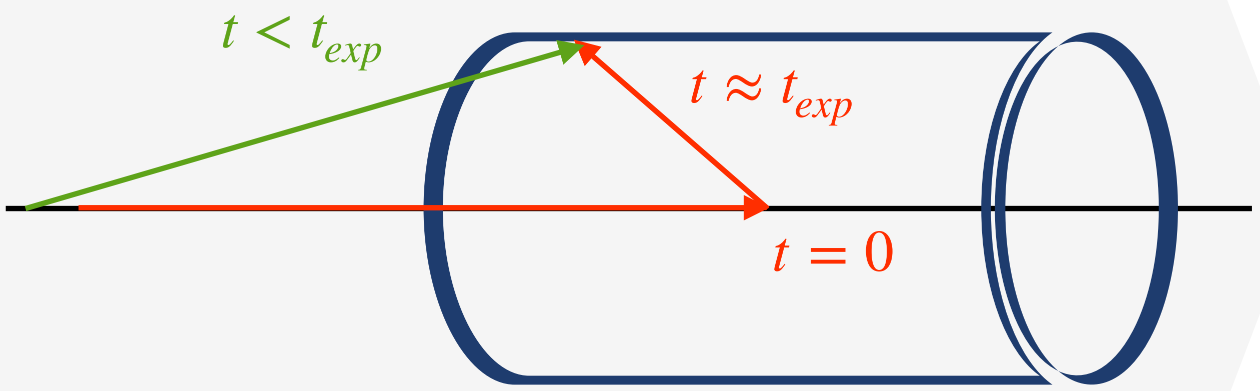
1. **Build a detector robust against residual BIB**

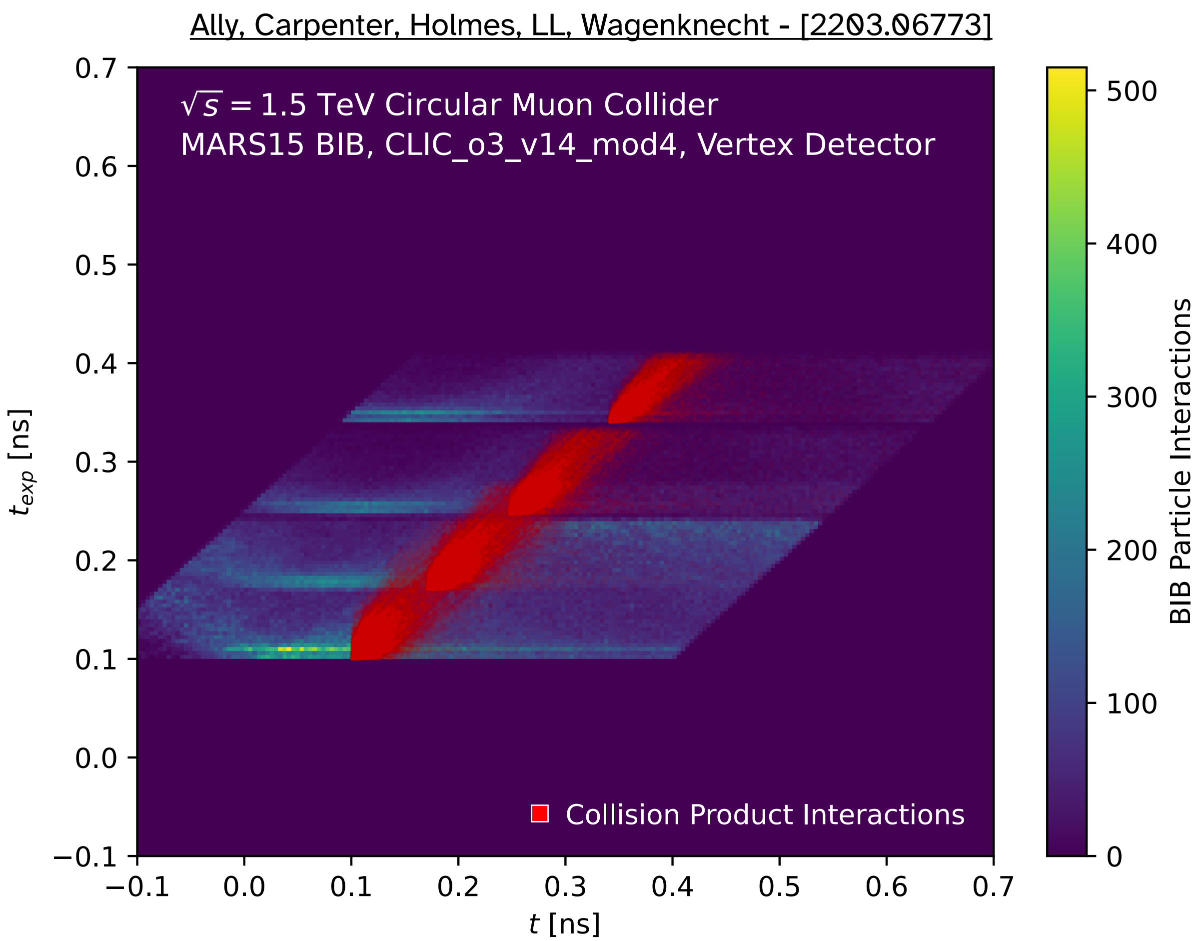
In detector region, dominated by MeV-scale neutrals

Luckily not particularly in time, and not projective from collision point



- **BIB signals prompt** *and* **late**
- Shorter path length → in-time BIB arrives **earlier** than collision particles
- **O(10-100) ps timing measurements necessary** to get physics out of a muon collider





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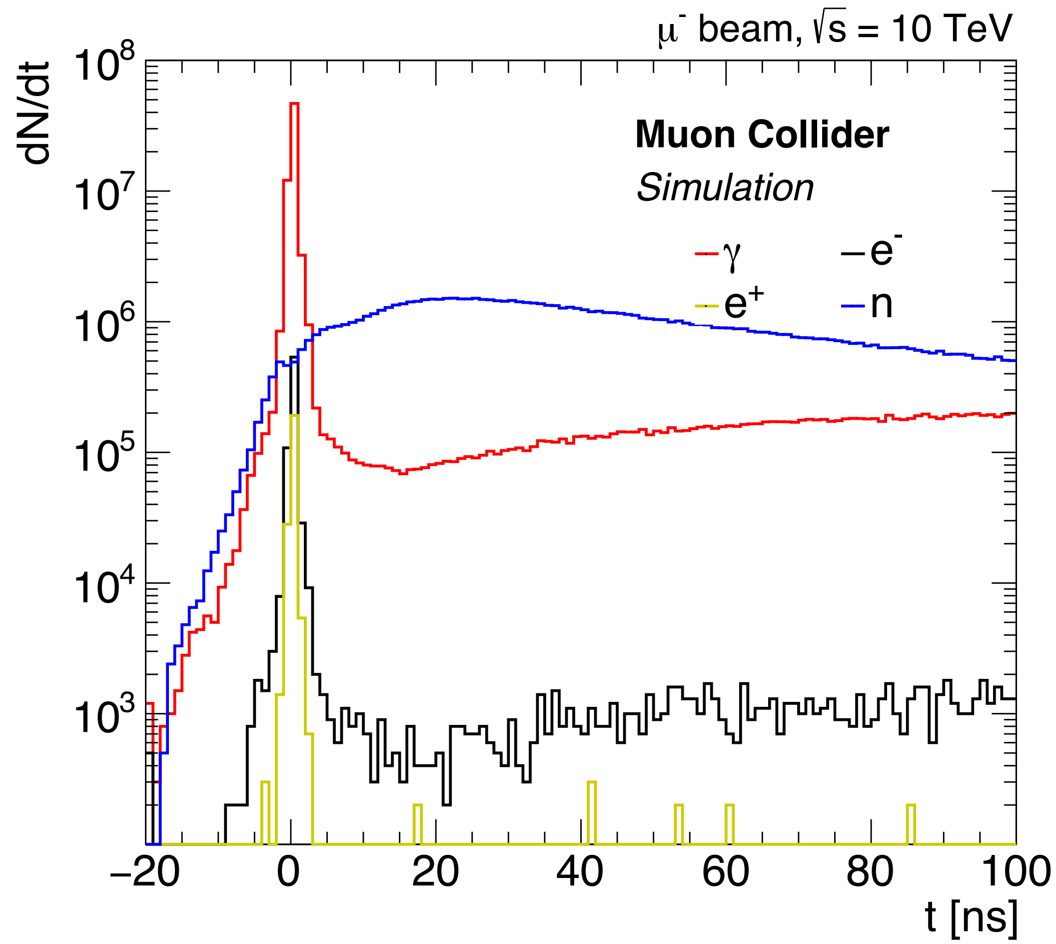
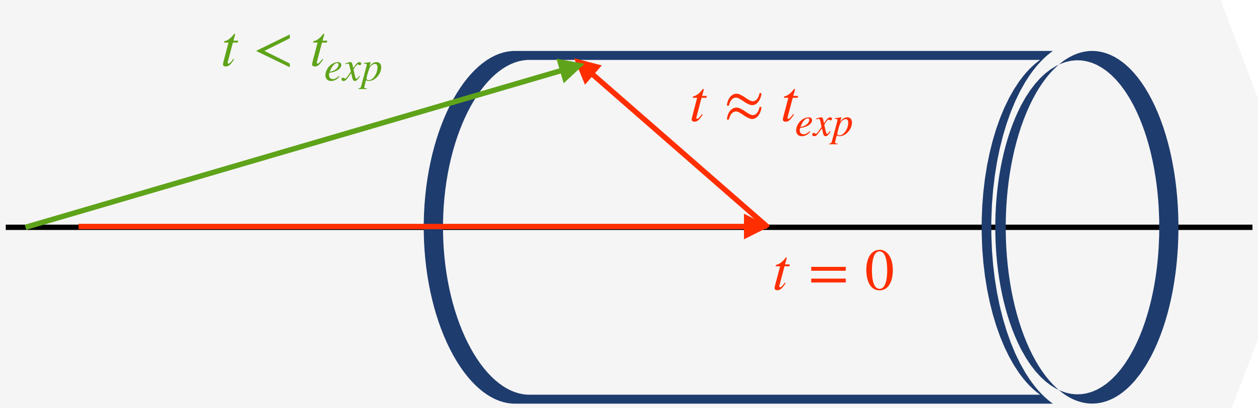
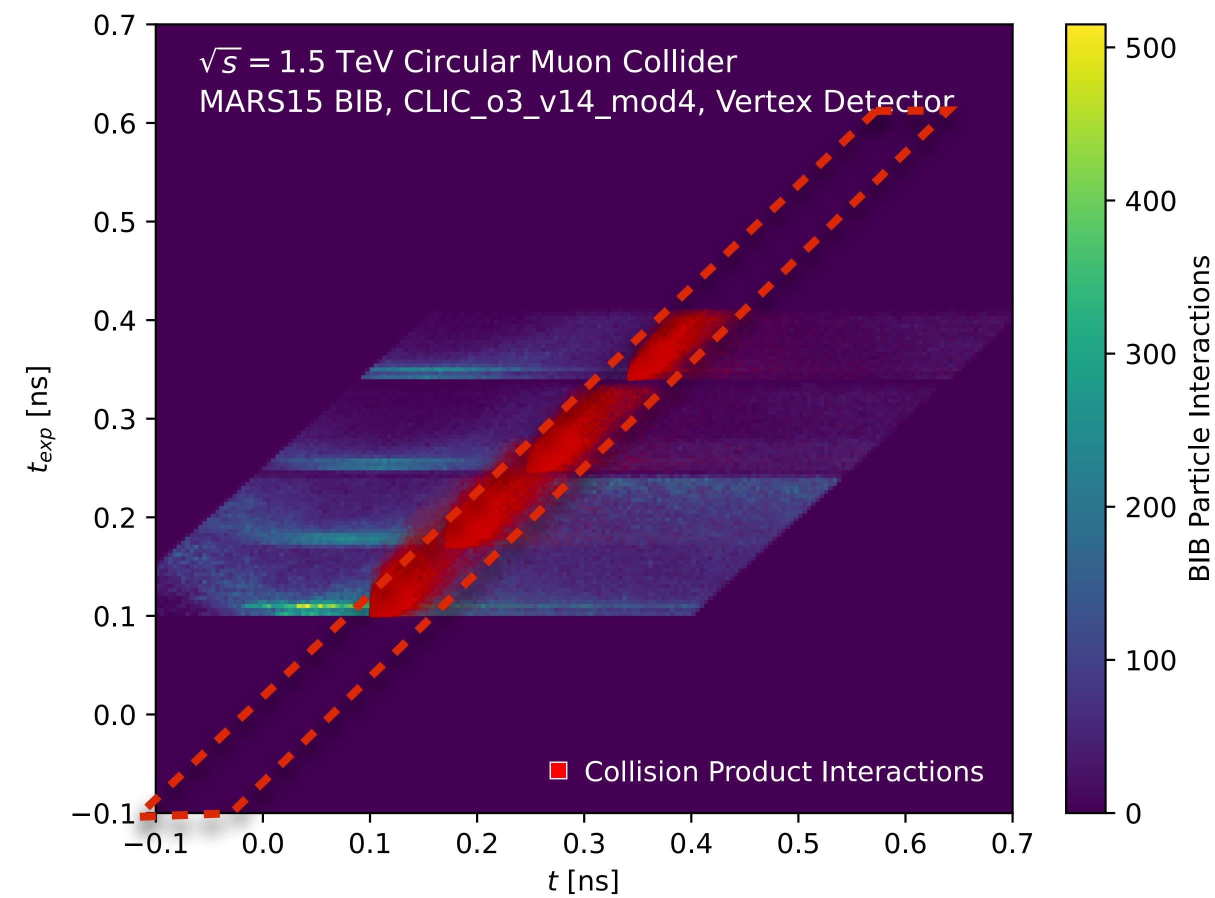




Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]



Central Challenges

1. **Build a detector robust against residual BIB**

2. **At 10 TeV, annihilation processes will always give multi-TeV objects!**

   Very high momentum will be common and not just in the tails of steeply falling distributions

   And last week Patrick Meade told us he wants hadronic W/Z/H discrimination at 5 TeV!

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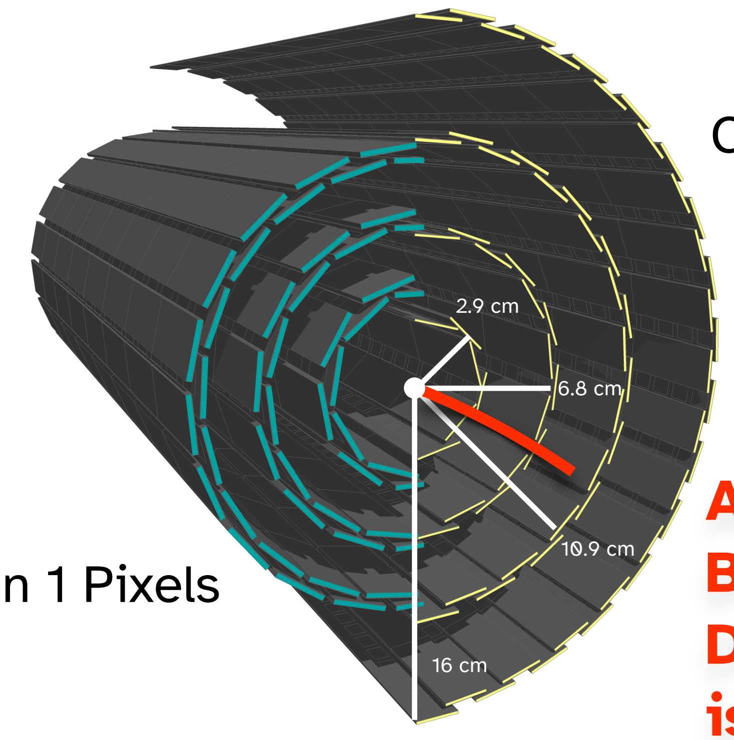
   Very high momentum will be common and not just in the tails of steeply falling distributions

   And last week Patrick Meade told us he wants hadronic W/Z/H discrimination at 5 TeV!

Incredibly small opening angles!

$$\Delta R \sim \frac{2m}{p_T} \sim 0.04$$

- **Making TeV objects the norm**
- **Objects live longer in lab frame**
- Need more interaction lengths to stop calo showers
- Interaction cross sections look different!
    - Fraction of muons that shower in calo



Decays happening well into tracker!
A lot more precision silicon tracking required.

Today's "exotic" signatures will become Bread and Butter

- **Making TeV objects the norm**
- Objects live longer in lab frame
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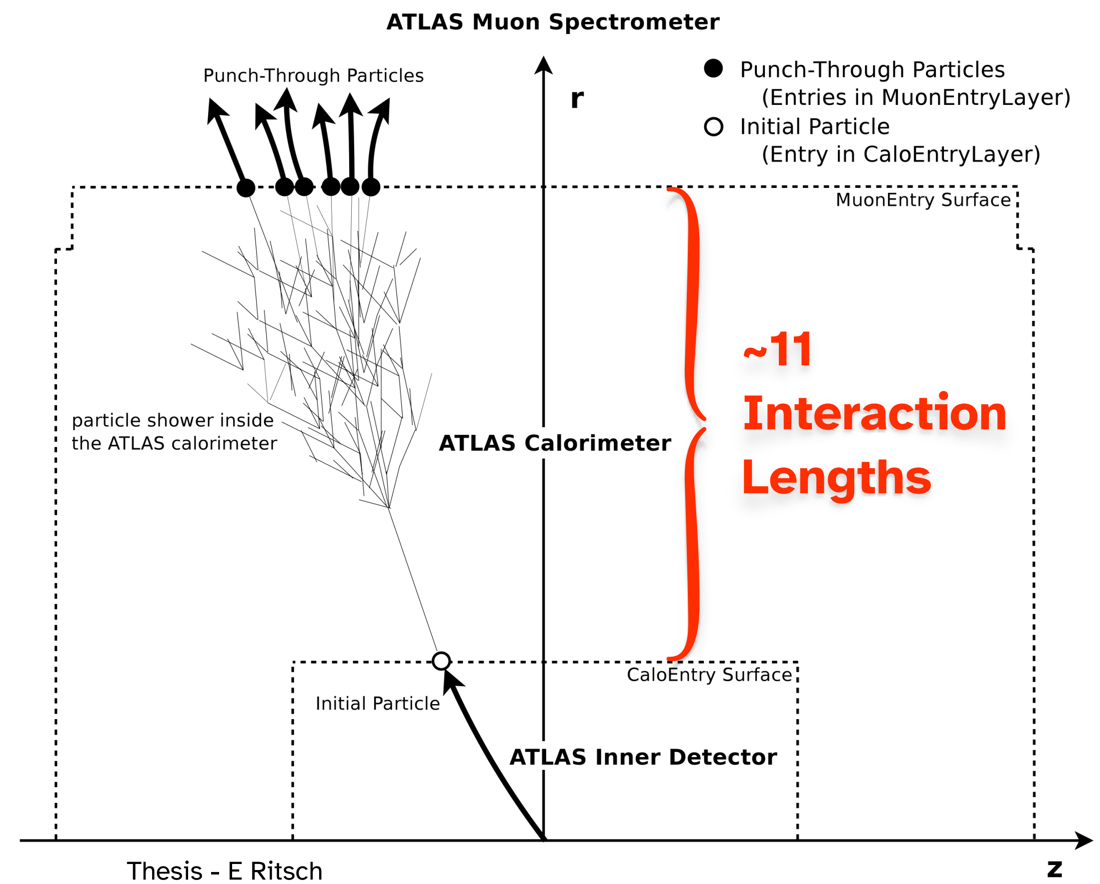
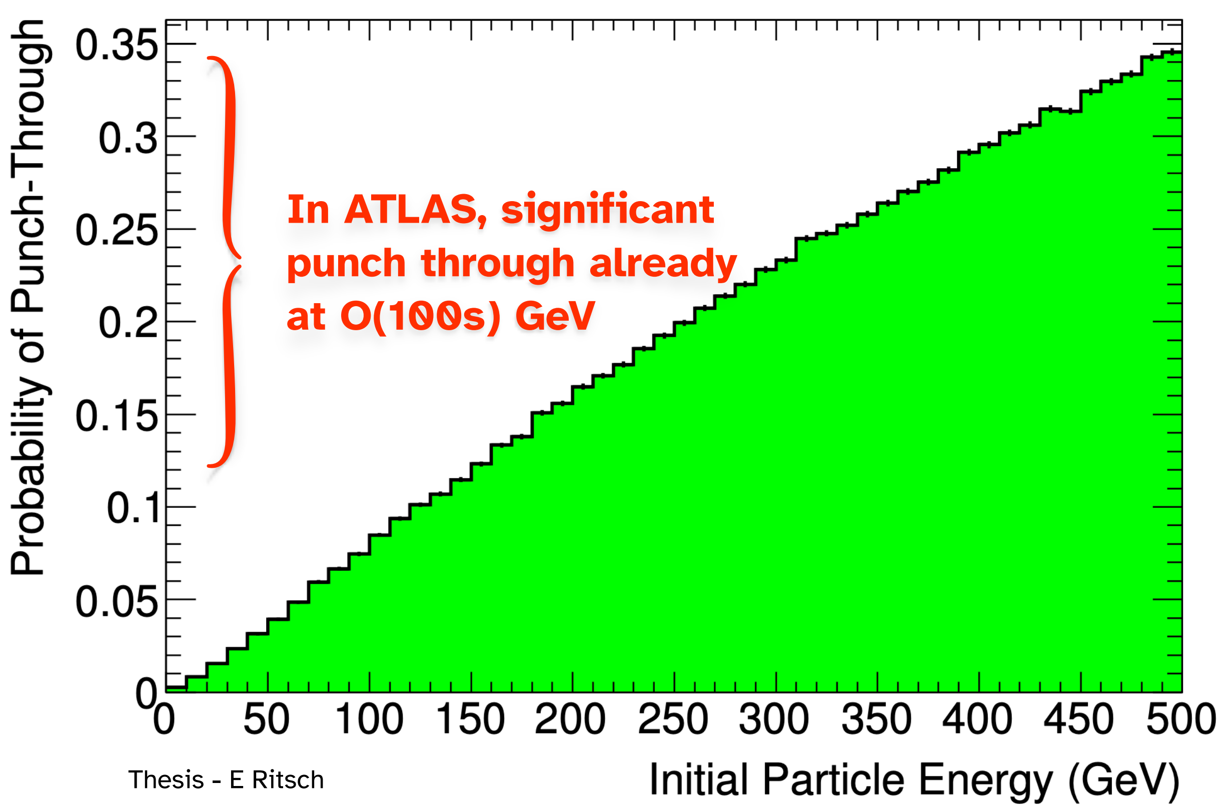




Central Challenges

1. Build a detector robust against residual BIB

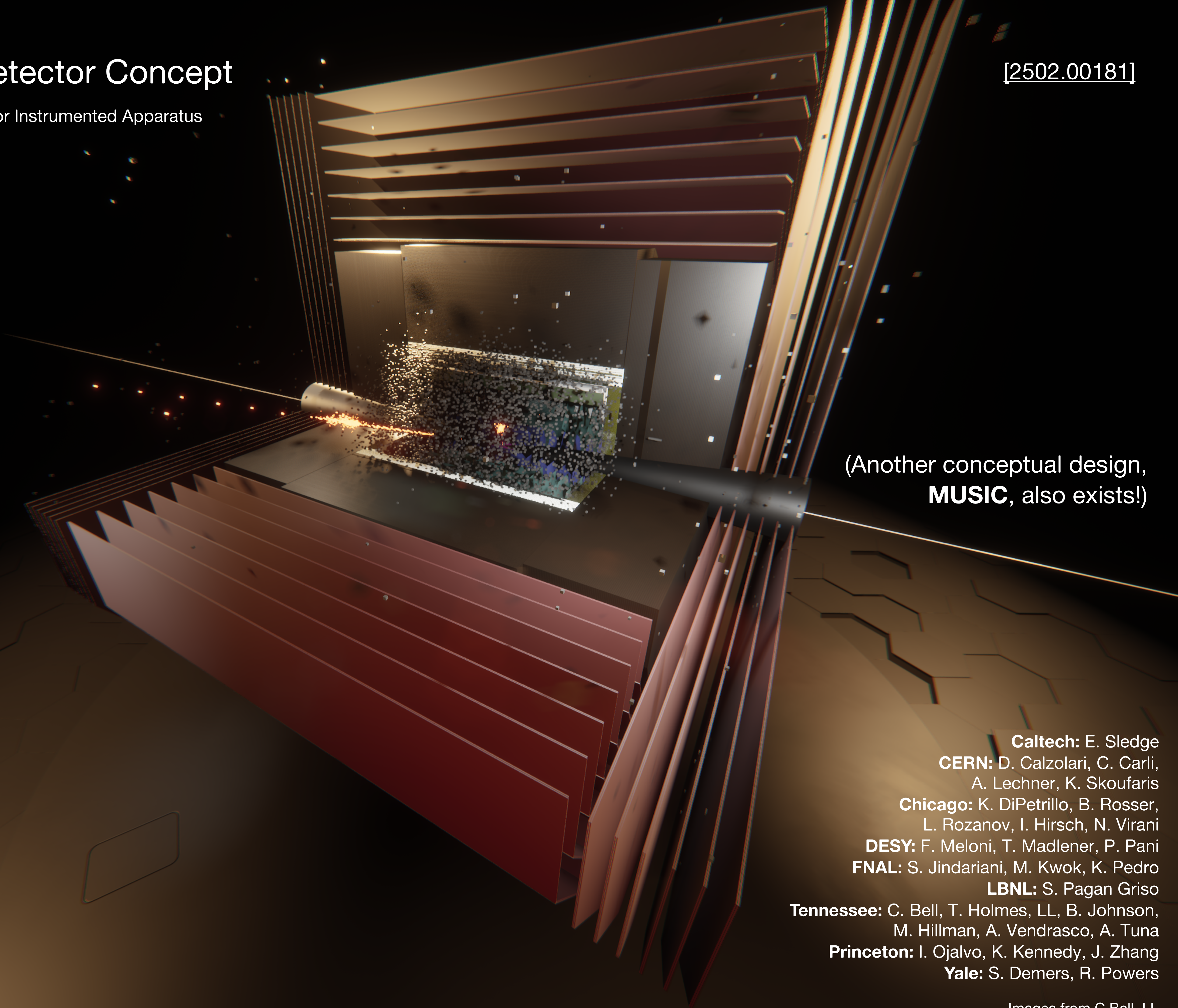
2. At 10 TeV, annihilation processes will always give multi-TeV objects!

Challenging environment for particle physics.
Let's try to build an experiment…

MAIA Detector Concept

Muon Accelerator Instrumented Apparatus

[2502.00181]



(Another conceptual design, **MUSIC**, also exists!)

Caltech: E. Sledge
CERN: D. Calzolari, C. Carli, A. Lechner, K. Skoufaris
Chicago: K. DiPetrillo, B. Rosser, L. Rozanov, I. Hirsch, N. Virani
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Images from C Bell, LL

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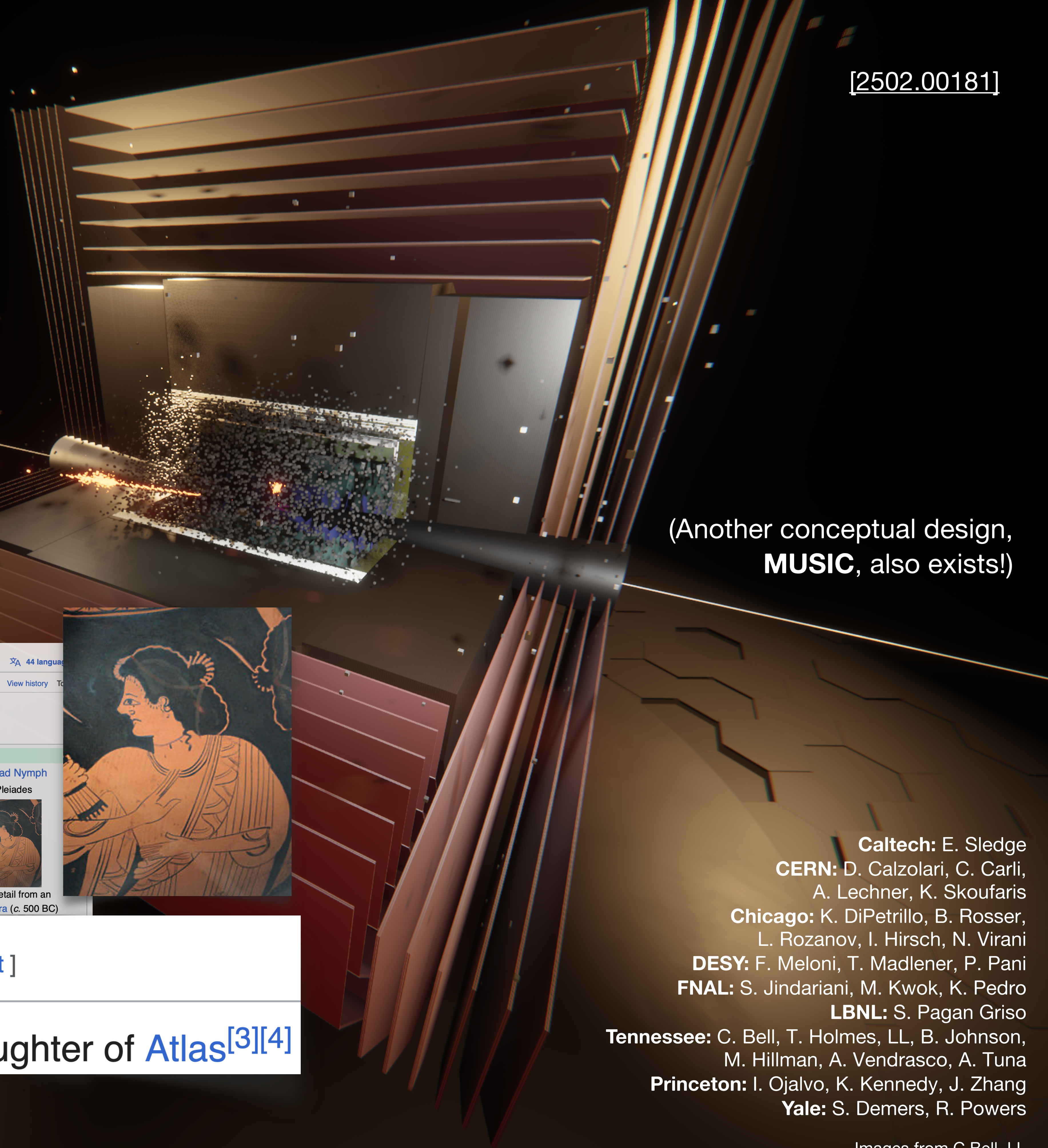

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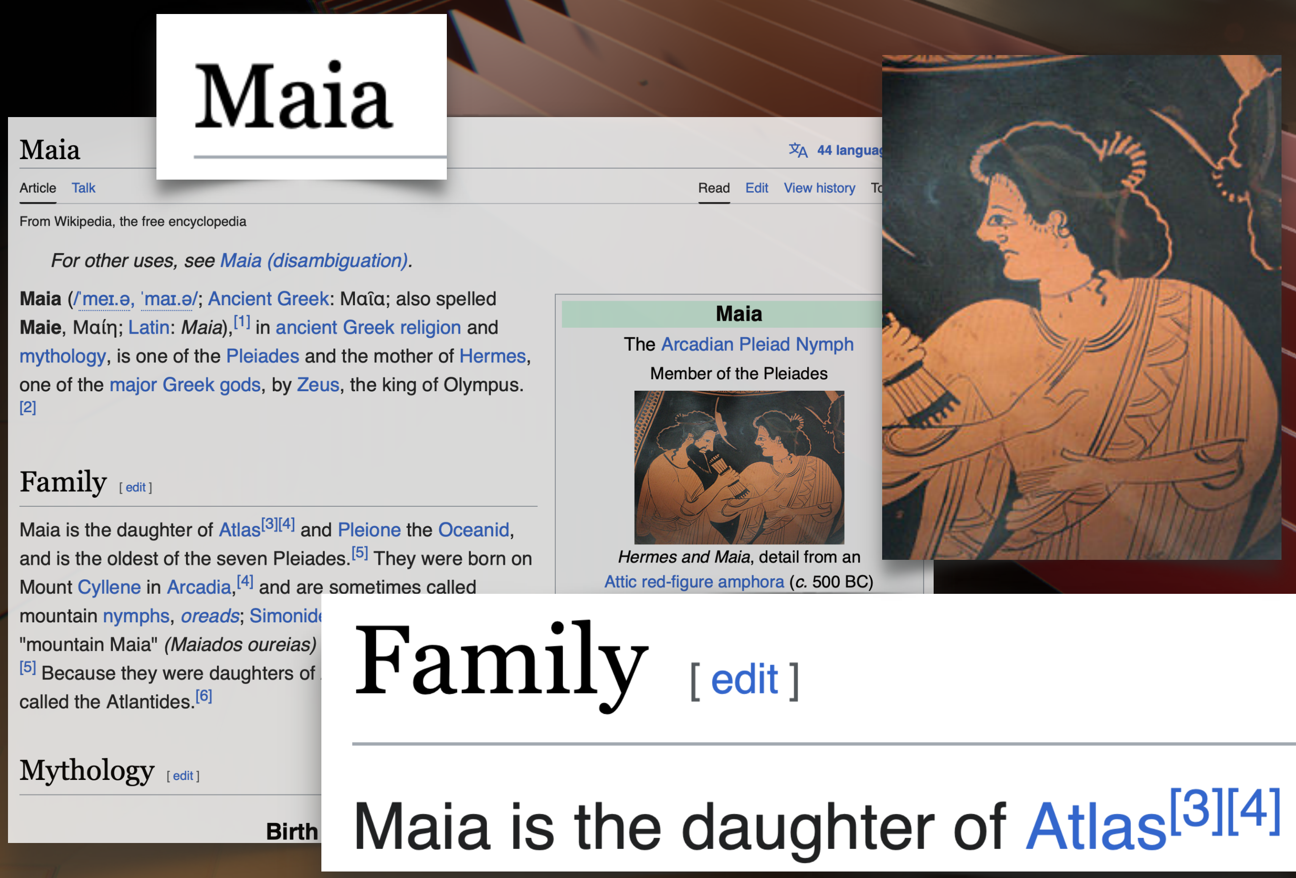

Maia

Maia

Article Talk

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44 languag

From Wikipedia, the free encyclopedia

For other uses, see Maia (disambiguation).

Maia (/ˈmeɪ.ə, ˈmaɪ.ə/; Ancient Greek: Μαῖα; also spelled **Maie**, Μαίη; Latin: *Maia*),[1] in ancient Greek religion and mythology, is one of the Pleiades and the mother of Hermes, one of the major Greek gods, by Zeus, the king of Olympus.[2]

Maia

The Arcadian Pleiad Nymph

Member of the Pleiades

Hermes and Maia, detail from an Attic red-figure amphora (*c.* 500 BC)

Family [edit]

Maia is the daughter of Atlas[3][4] and Pleione the Oceanid, and is the oldest of the seven Pleiades.[5] They were born on Mount Cyllene in Arcadia,[4] and are sometimes called mountain nymphs, *oreads*; Simonide "mountain Maia" *(Maiados oureias)*[5] Because they were daughters of called the Atlantides.[6]

Mythology [edit]

Birth

Family [edit]

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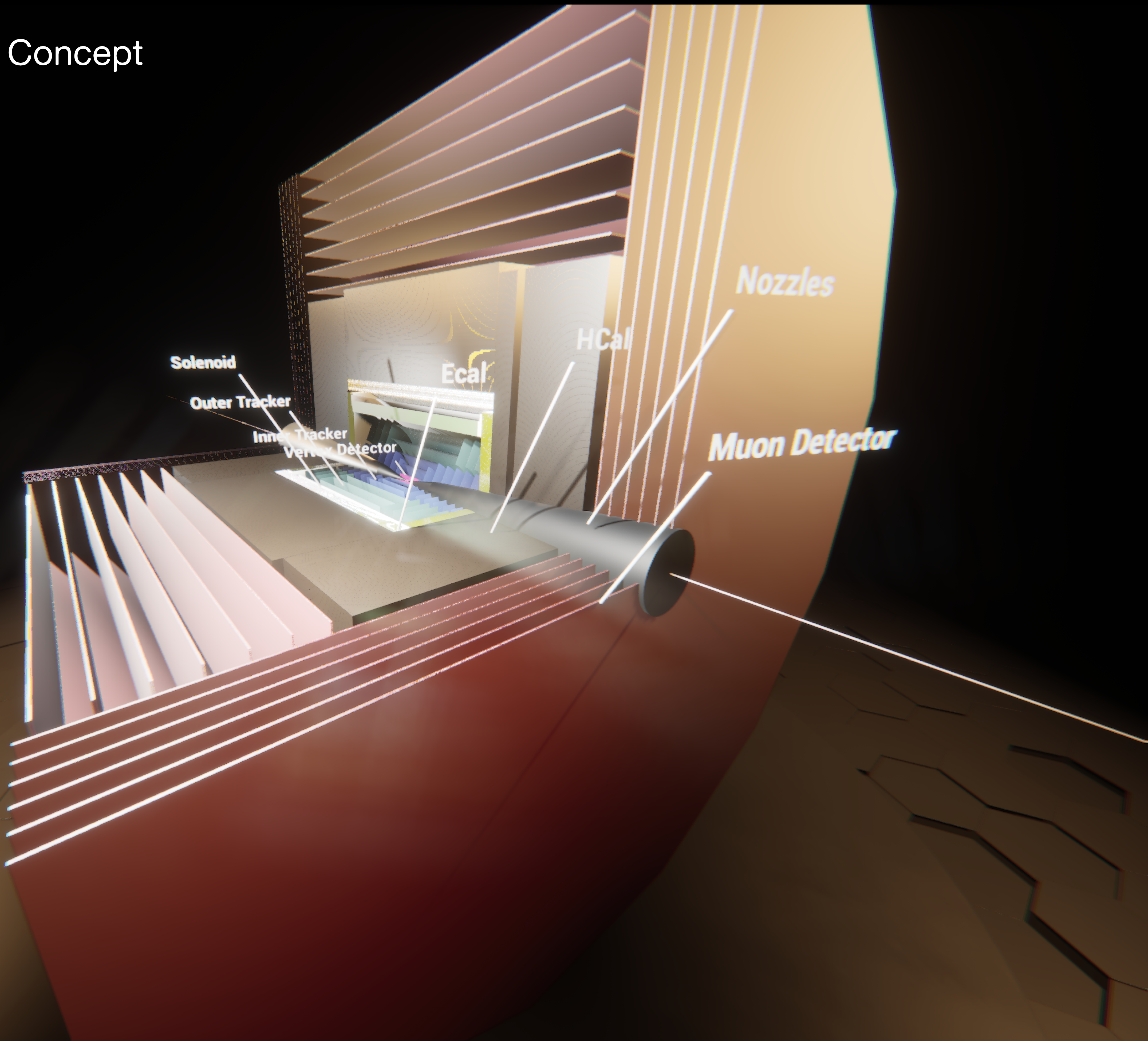

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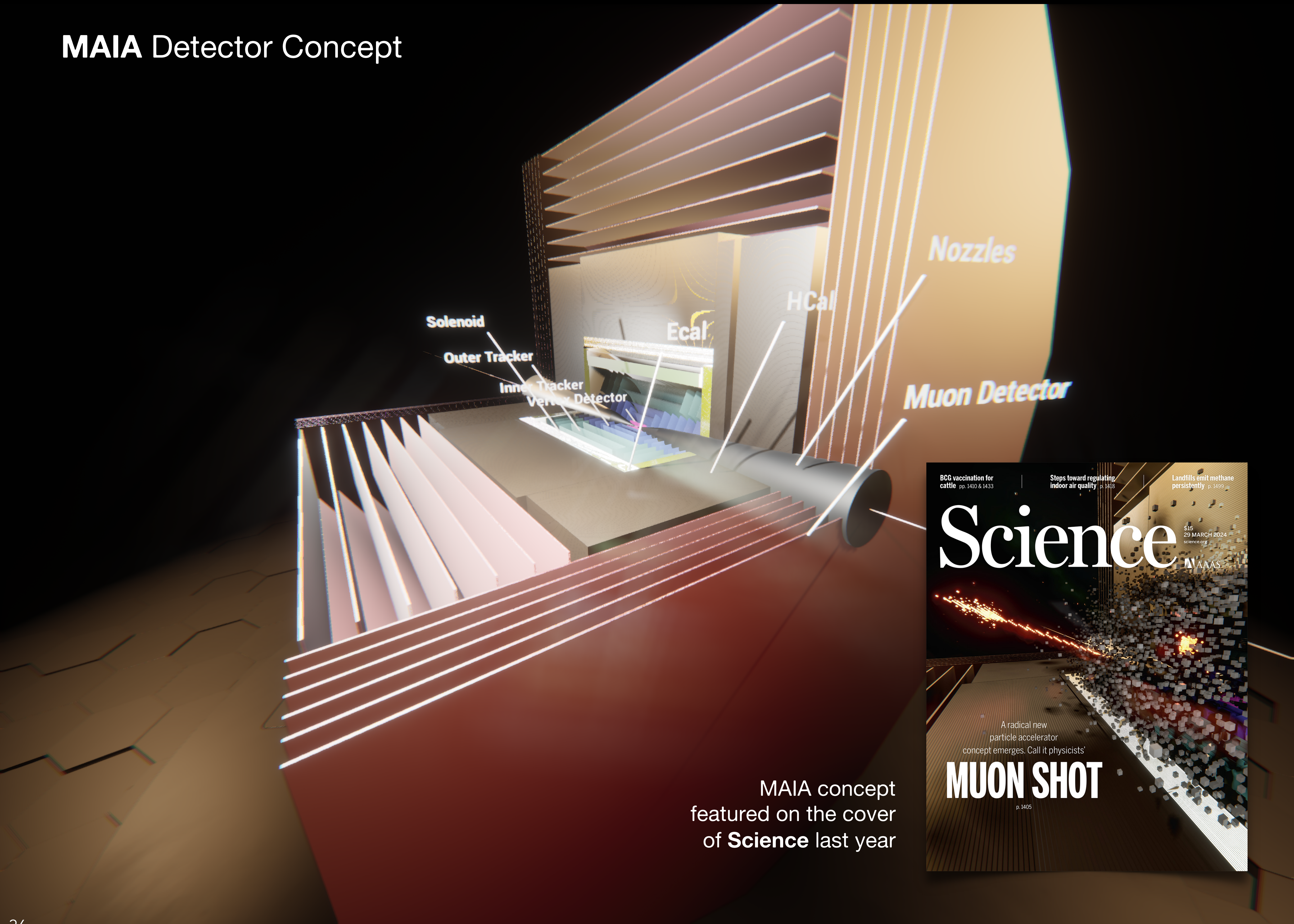


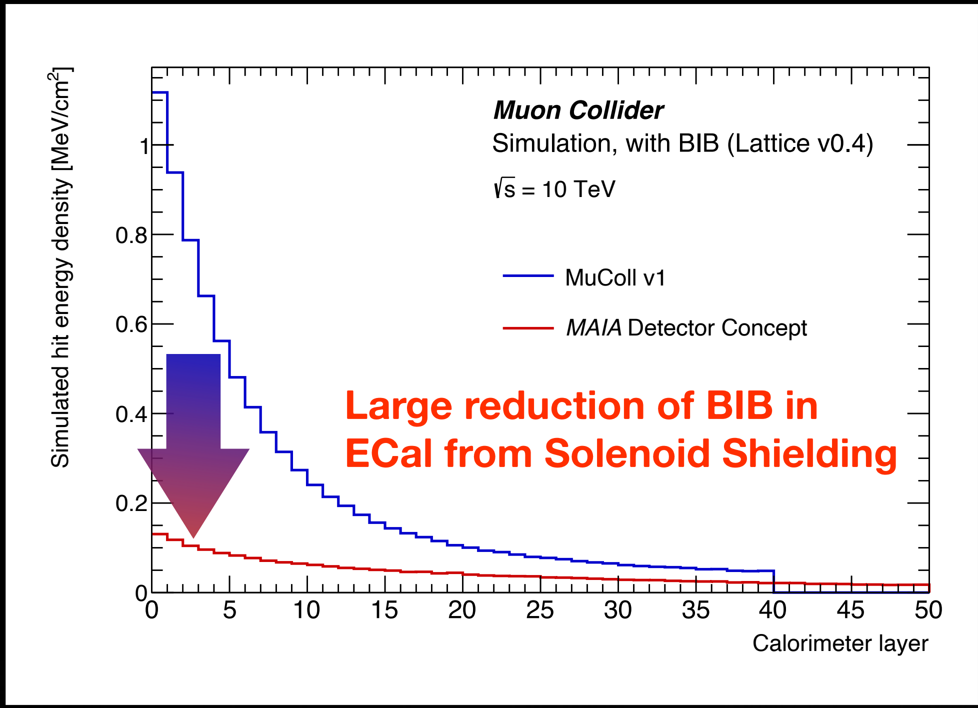
MAIA concept featured on the cover of **Science** last year

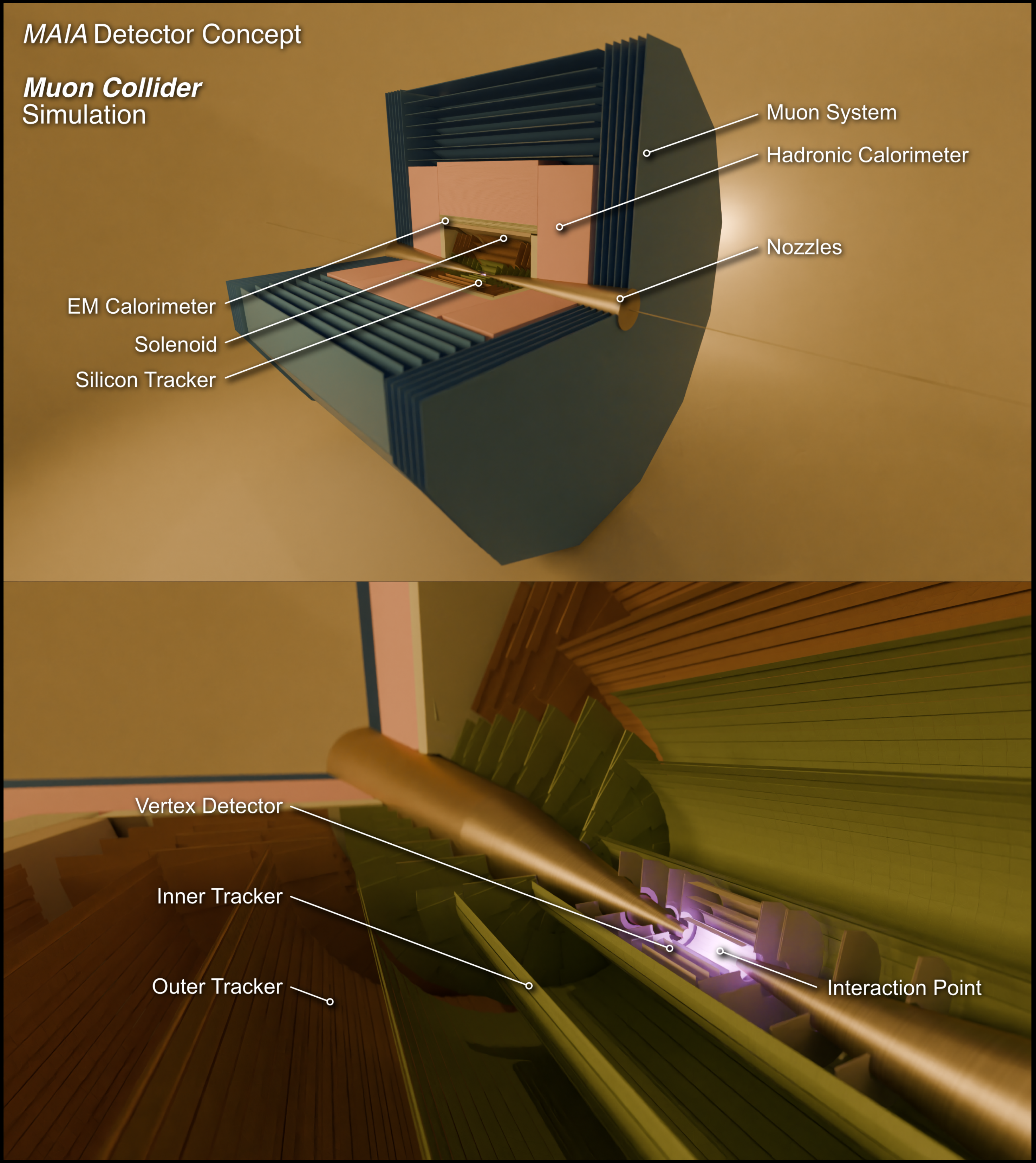
Images from C Bell, LL

MAIA Detector Concept: Overall Design

[2502.00181]

- Scale up detector!
  - But **making the magnet bigger has unique challenges…**
- Like ATLAS: **Solenoid before calorimeters**
  - 1.7m radius; 5T, 1T return
  - Allows for bigger calorimeters and higher field
  - Before ECal: Reduces e/ɣ precision but…
    - Easier magnet to build/operate
    - **And shields the calos from BIB!**

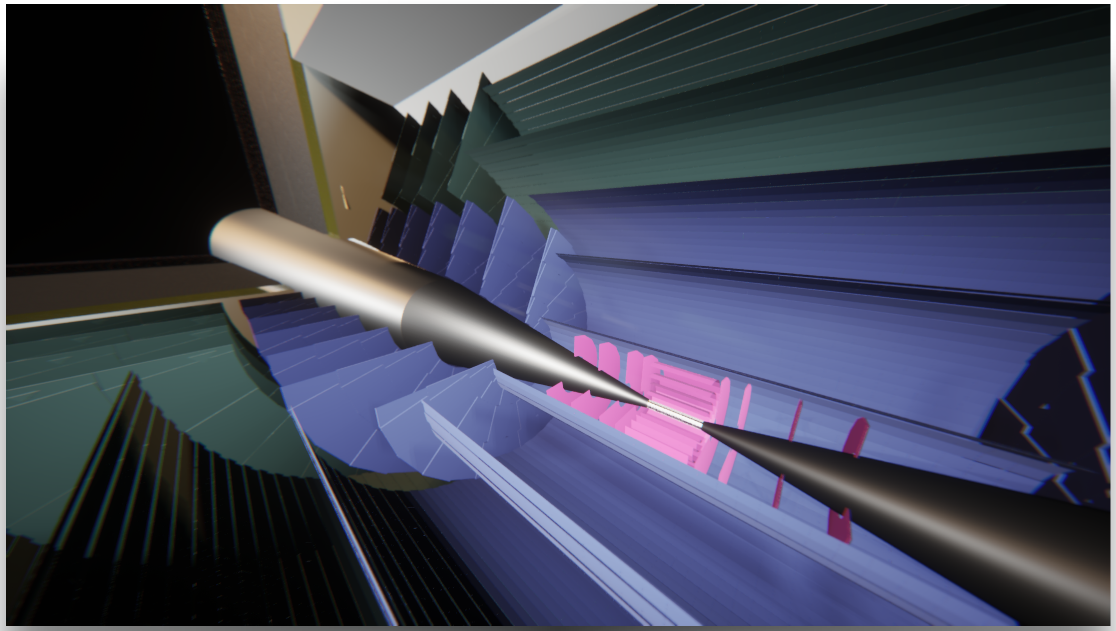


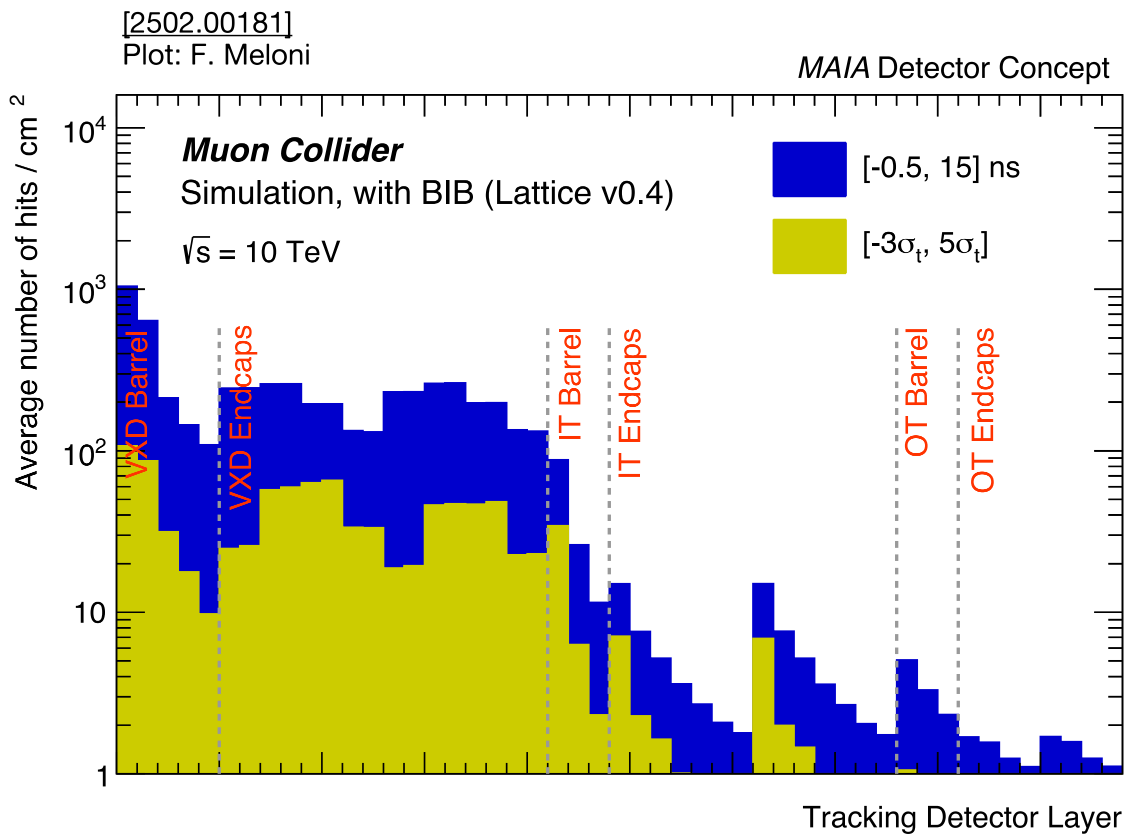


MAIA Detector Concept: Tracker

- ~10 measurements on track in barrel
  - Vertex detector of pixel sensors w/ one doublet layer.
  - Macro-pixel, strips in Inner, Outer Tracker
- **Prioritize timing resolution** to reject BIB at readout and/or offline
- Timing requirements reduce occupancy by 10x in most affected layers

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macropixels	microstrips
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps





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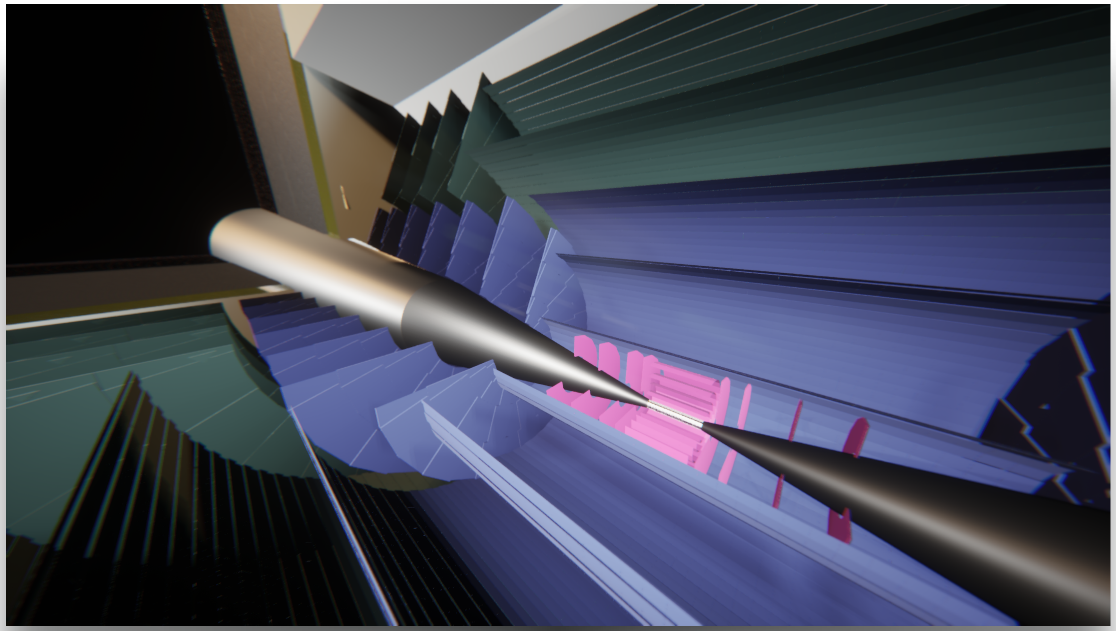

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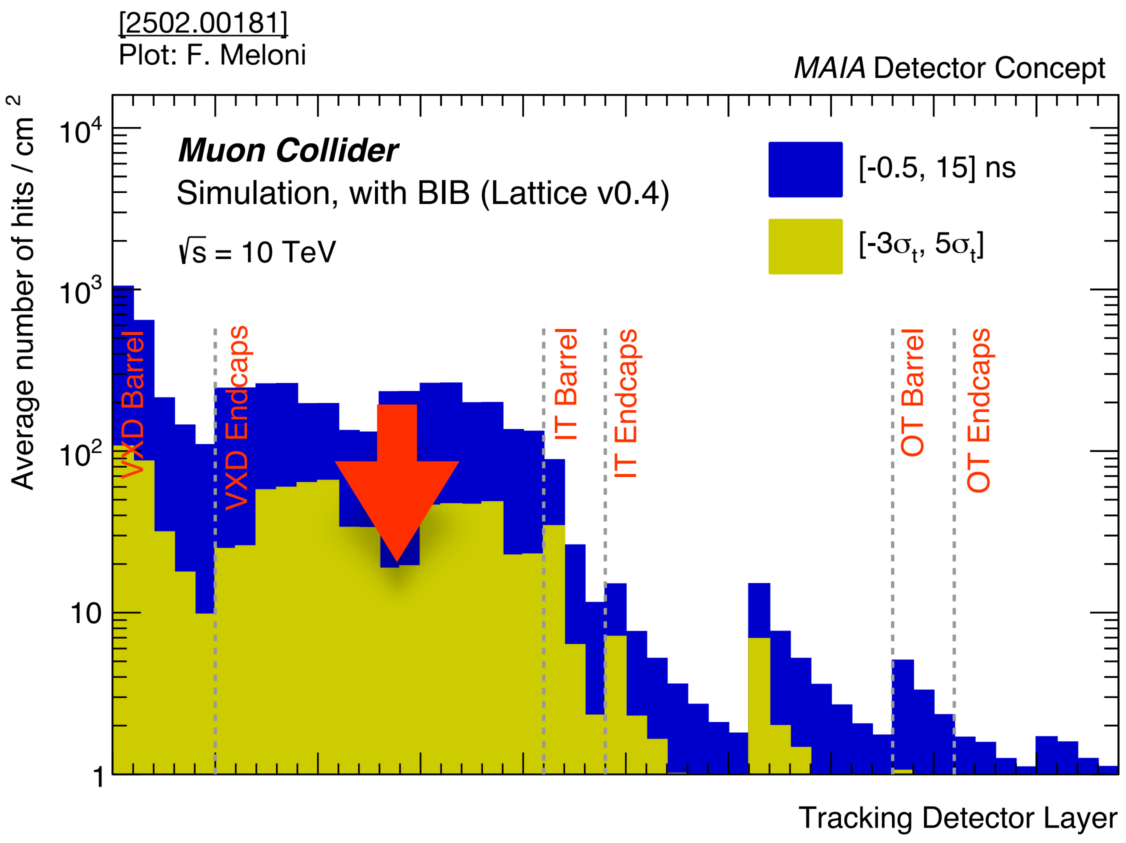
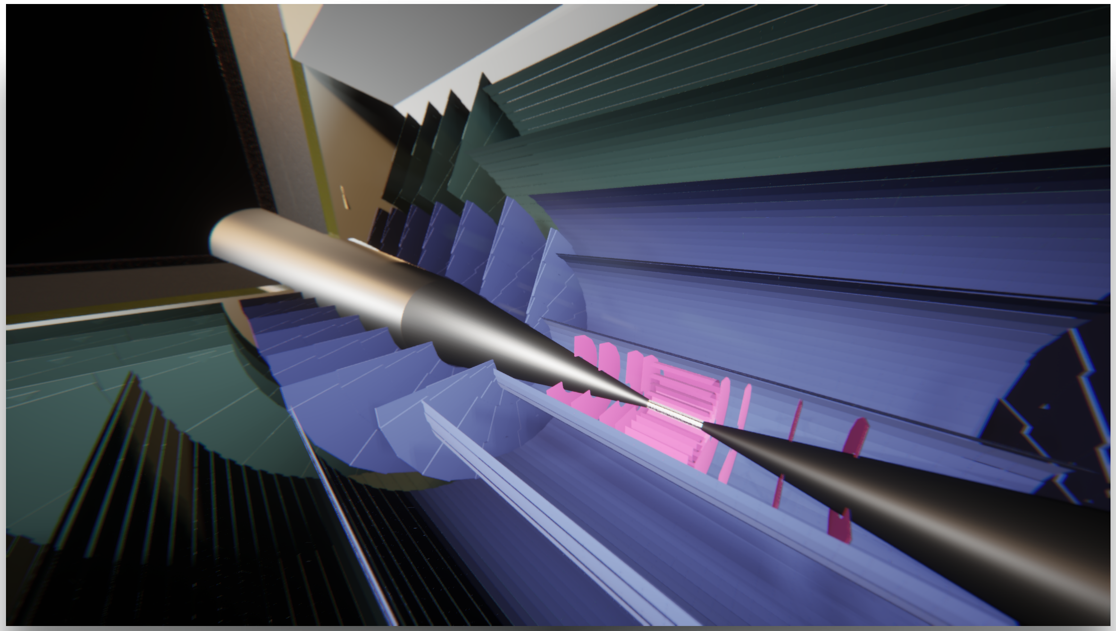
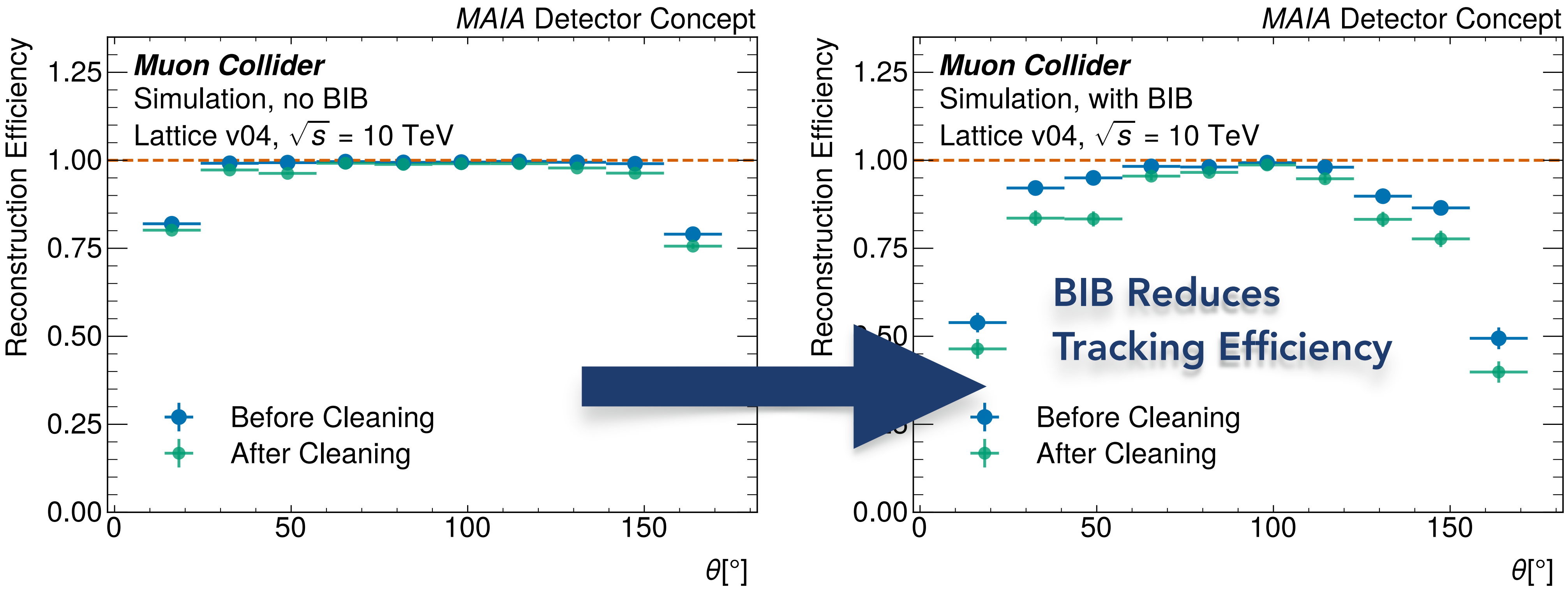


MAIA Detector Concept: Tracking

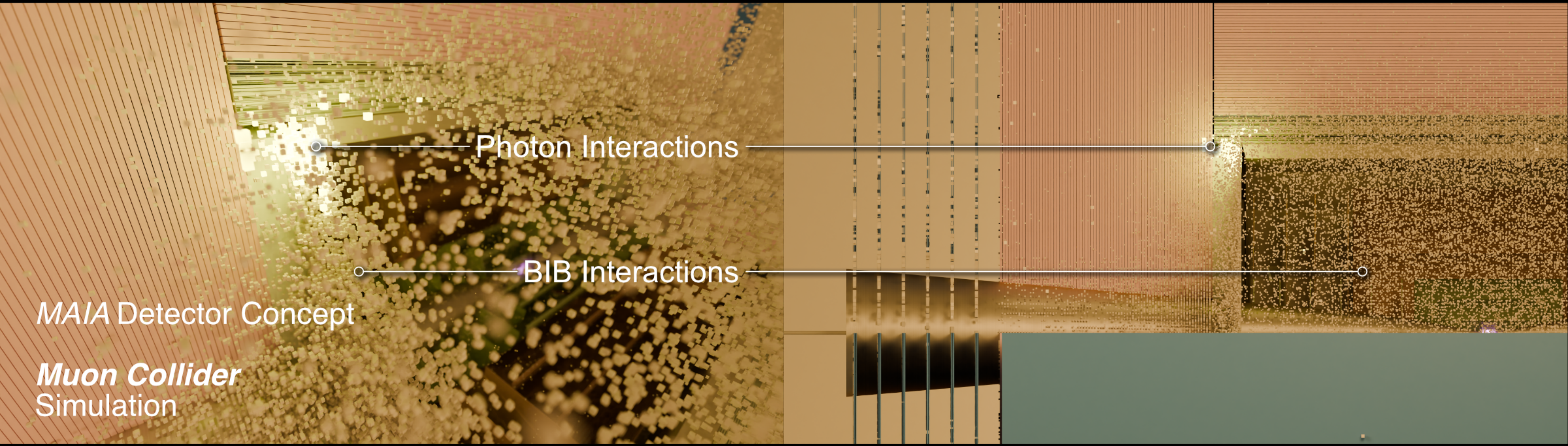
- **Using ACTS**, experiment-independent tracking toolkit
- Tracking performance reasonable despite large BIB occupancy
  - High reco efficiency
  - 1 TeV tracks w/ **p_T resolution as low as 2%!**
- Full workflow now enables further optimization of detector layout





[2502.00181]
Plots: L. Rozanov, K DiPetrillo, et al

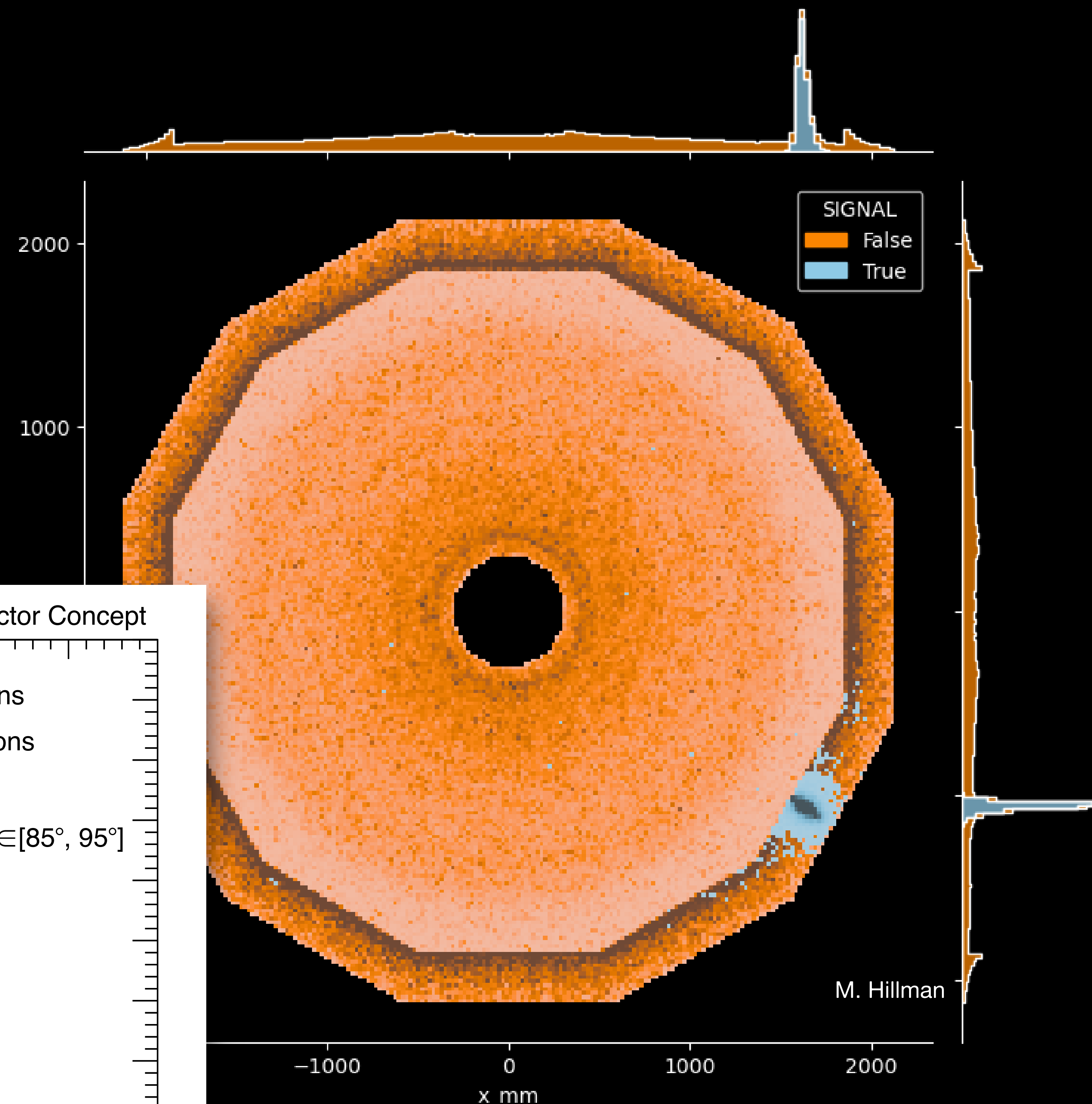
MAIA Detector Concept: EM Calorimeter

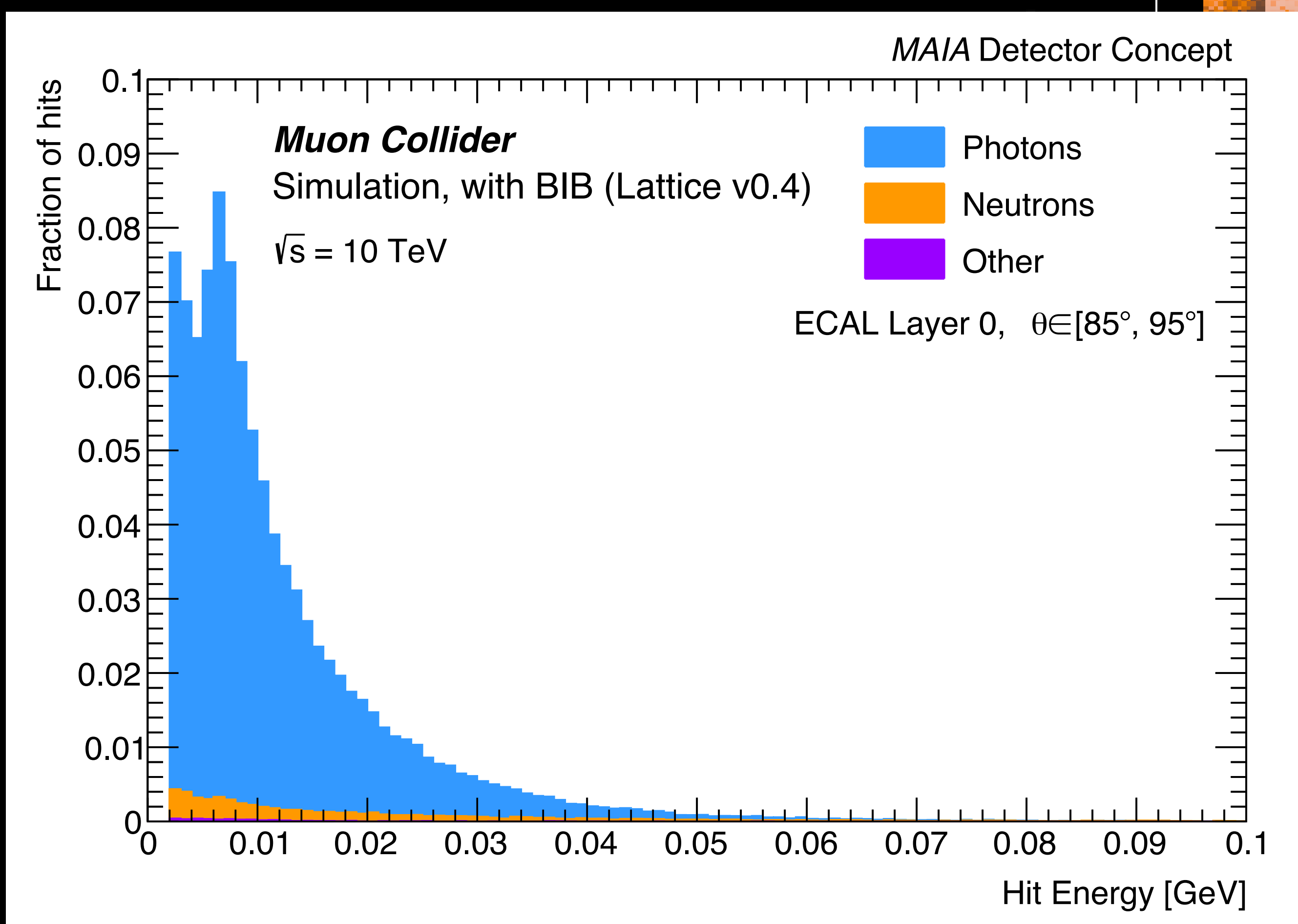


[2502.00181]

MAIA Detector Concept: EM Calorimeter

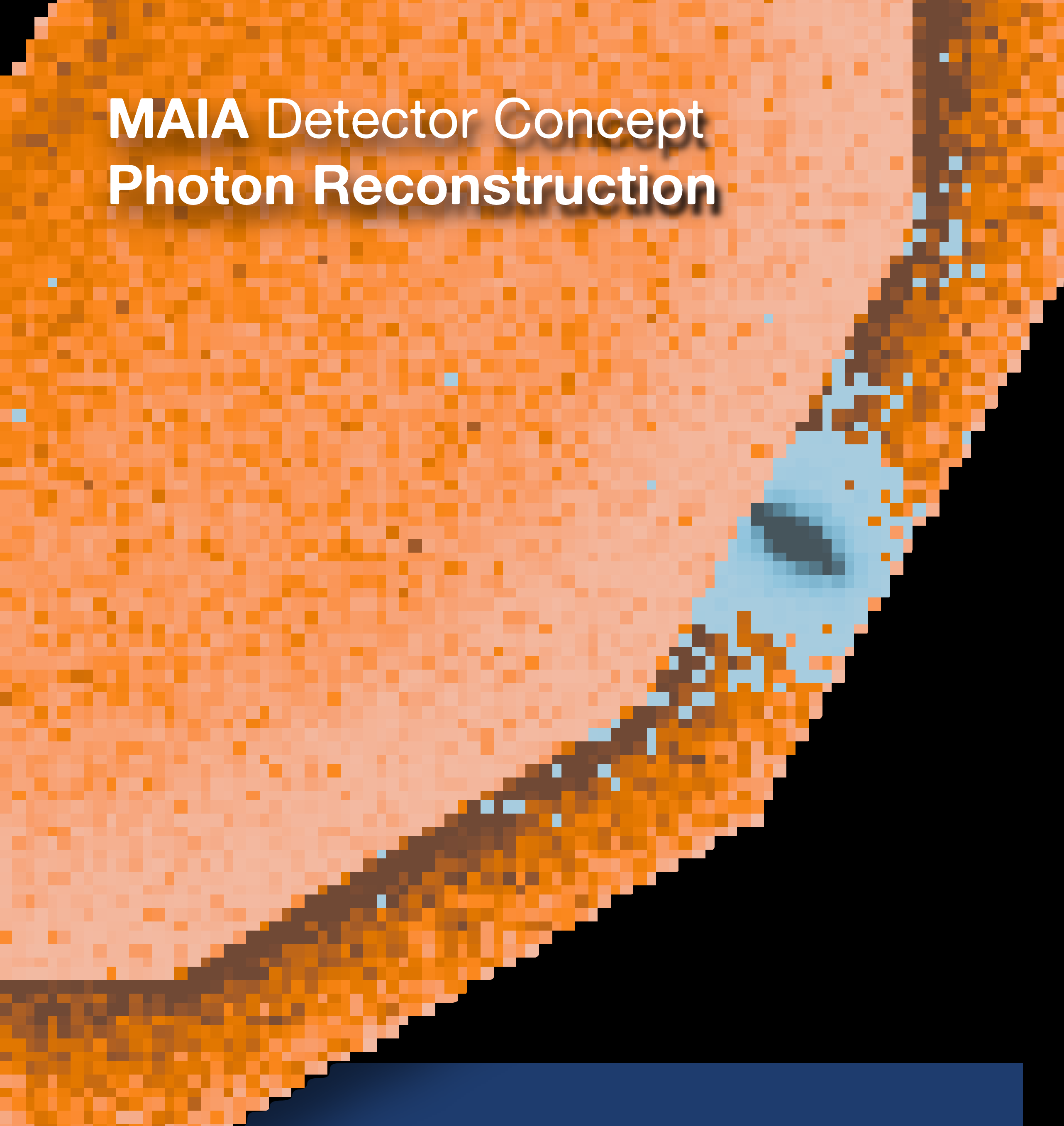
- Using W+Si design
- Very sensitive to large photon BIB contribution **in first few layers**
- Longitudinal segmentation is key to rejecting BIB



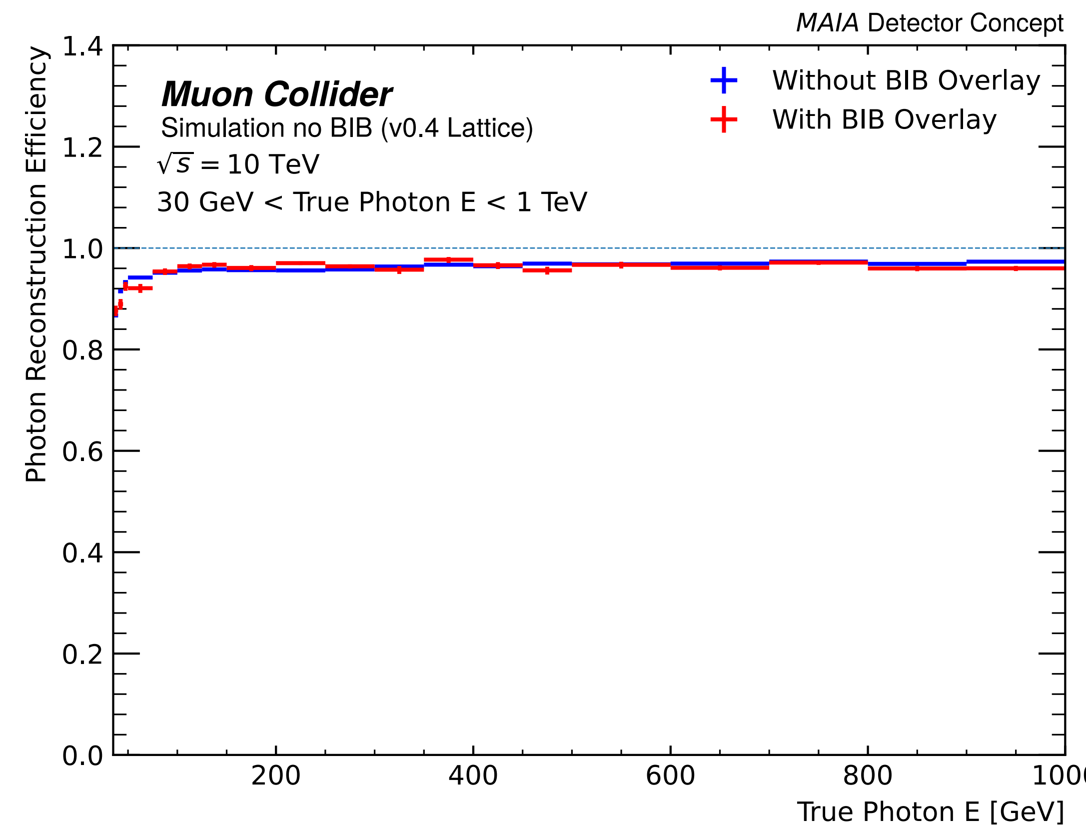


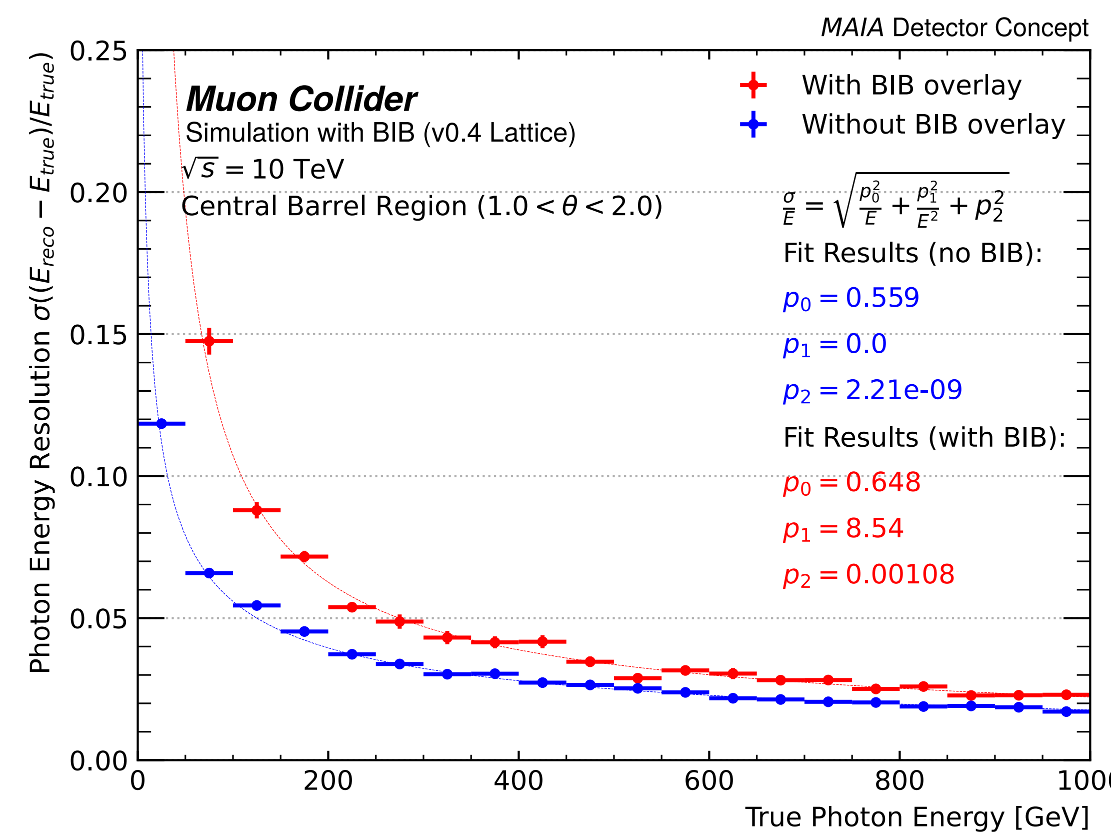
[2502.00181]

MAIA Detector Concept
Photon Reconstruction



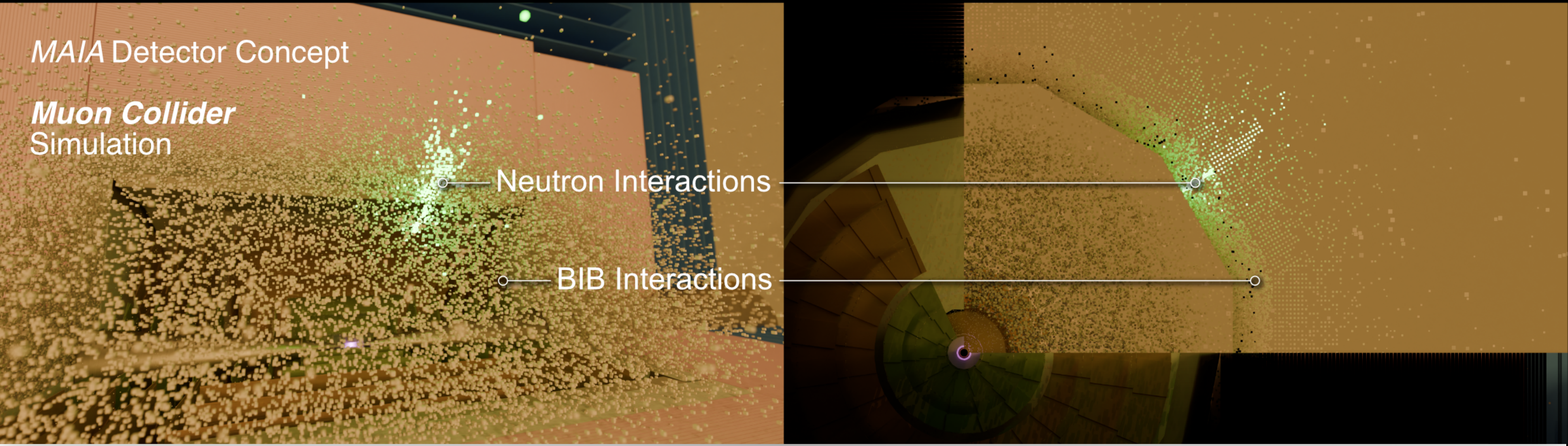
- Even w/ BIB, still have photon reco efficiency >95%
- And with calibration, minimal hit to photon energy resolution

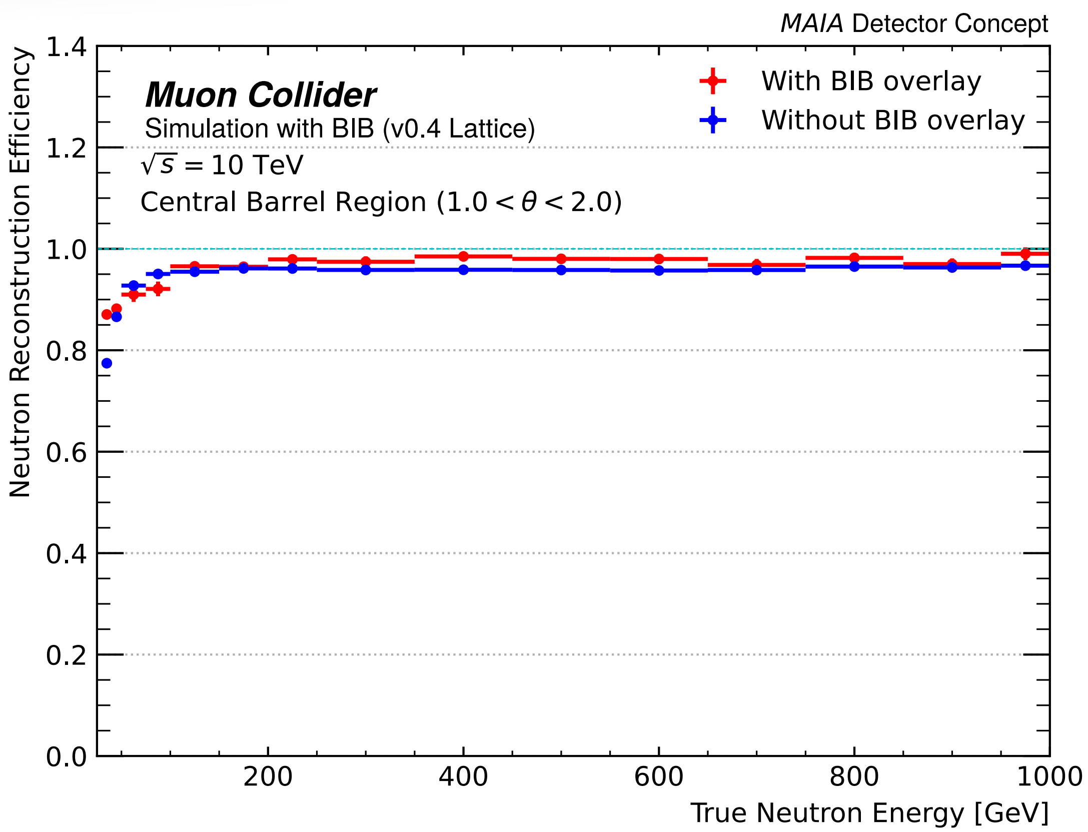


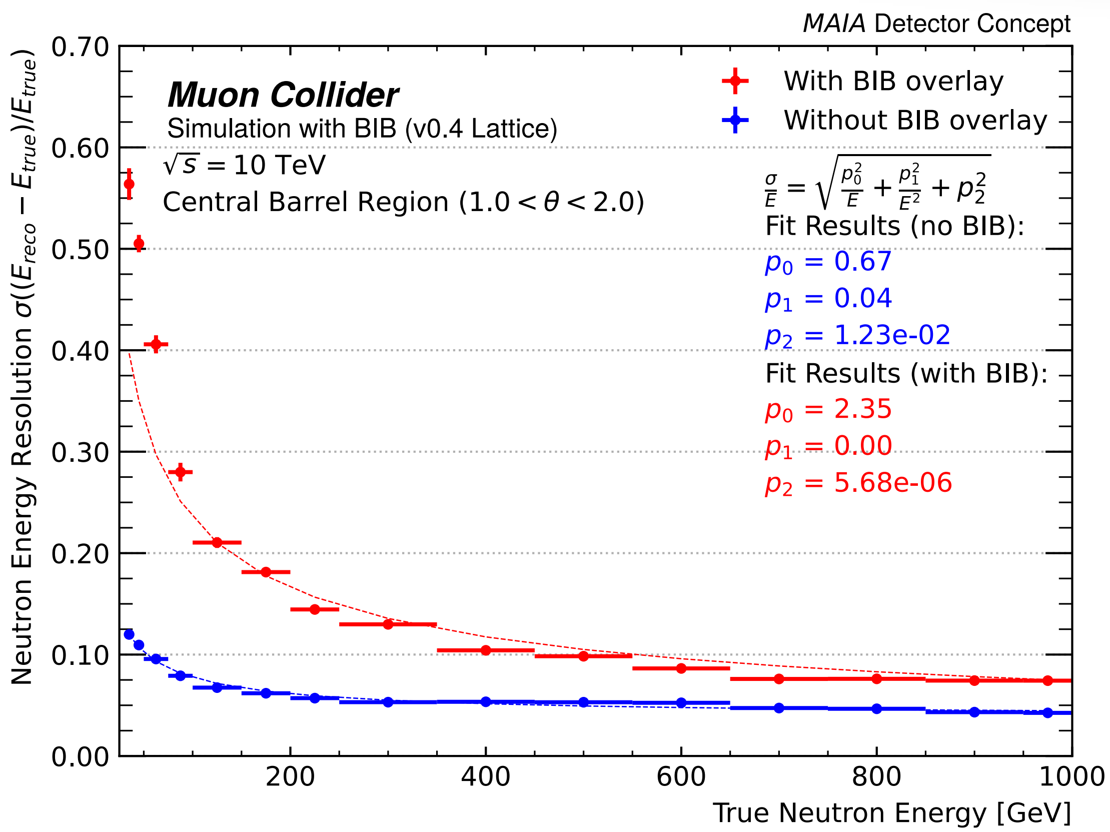


[2502.00181]
Plots: R. Powers, T. Holmes, et al

MAIA Detector Concept: Hadronic Calorimeter







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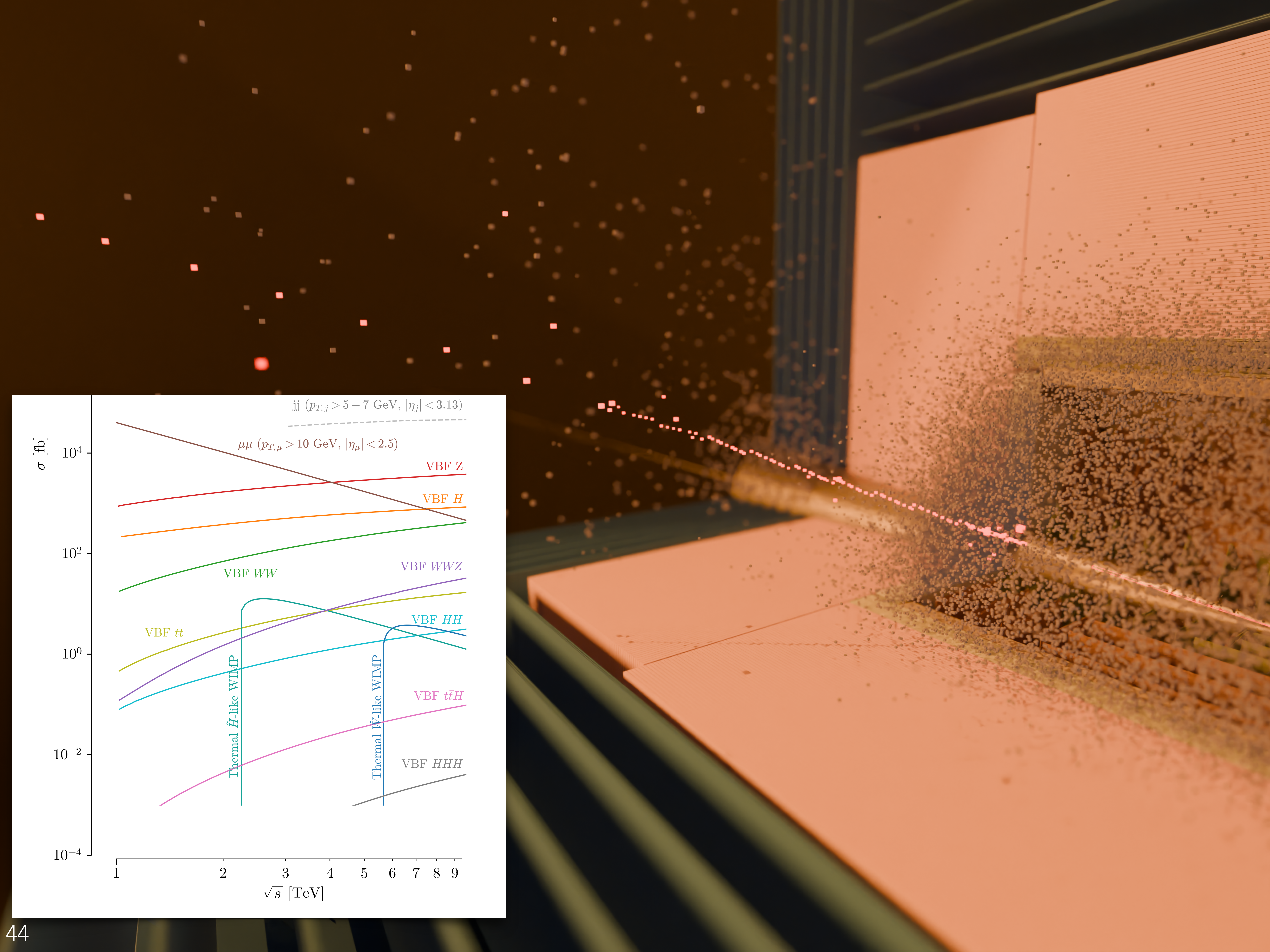
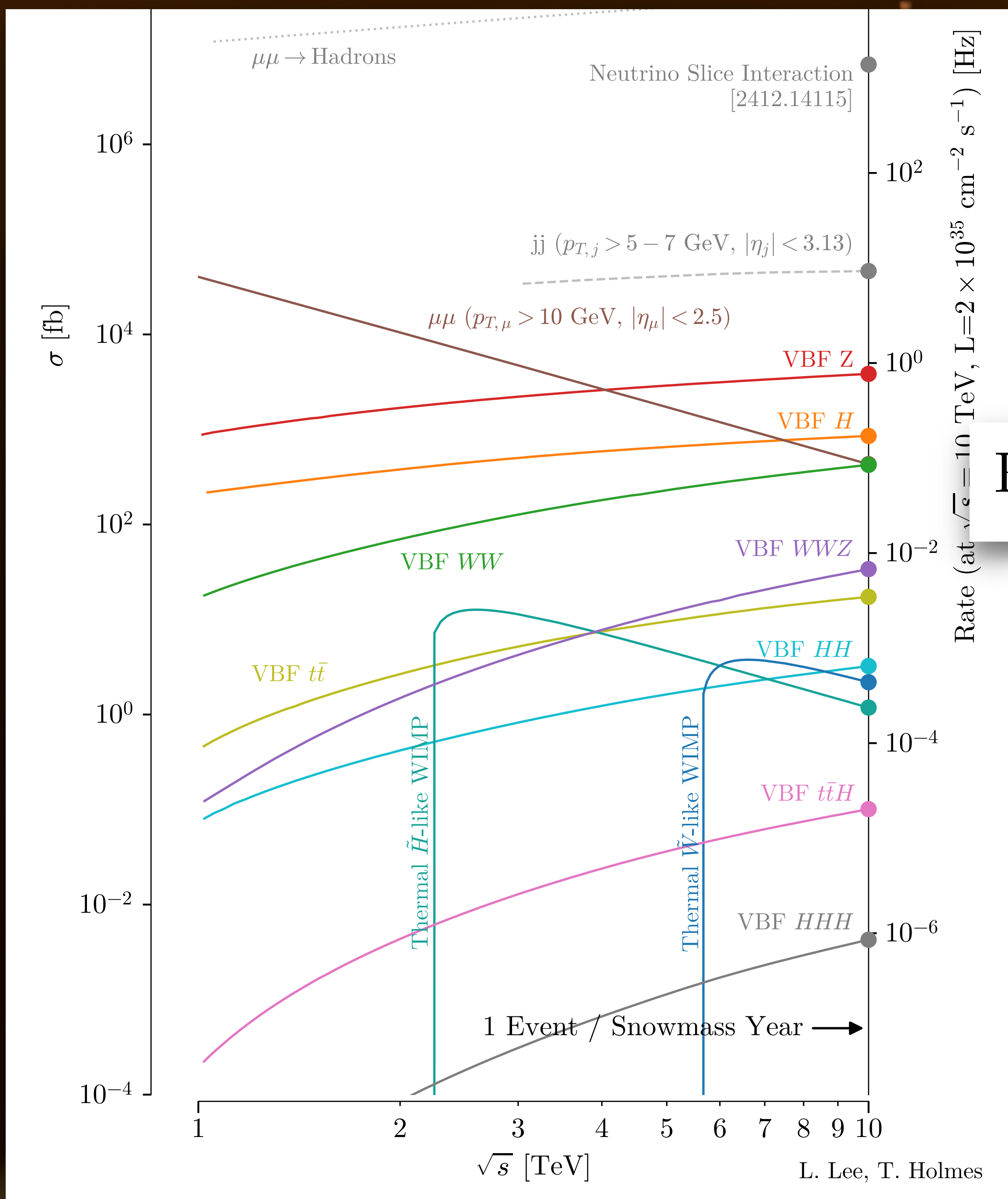
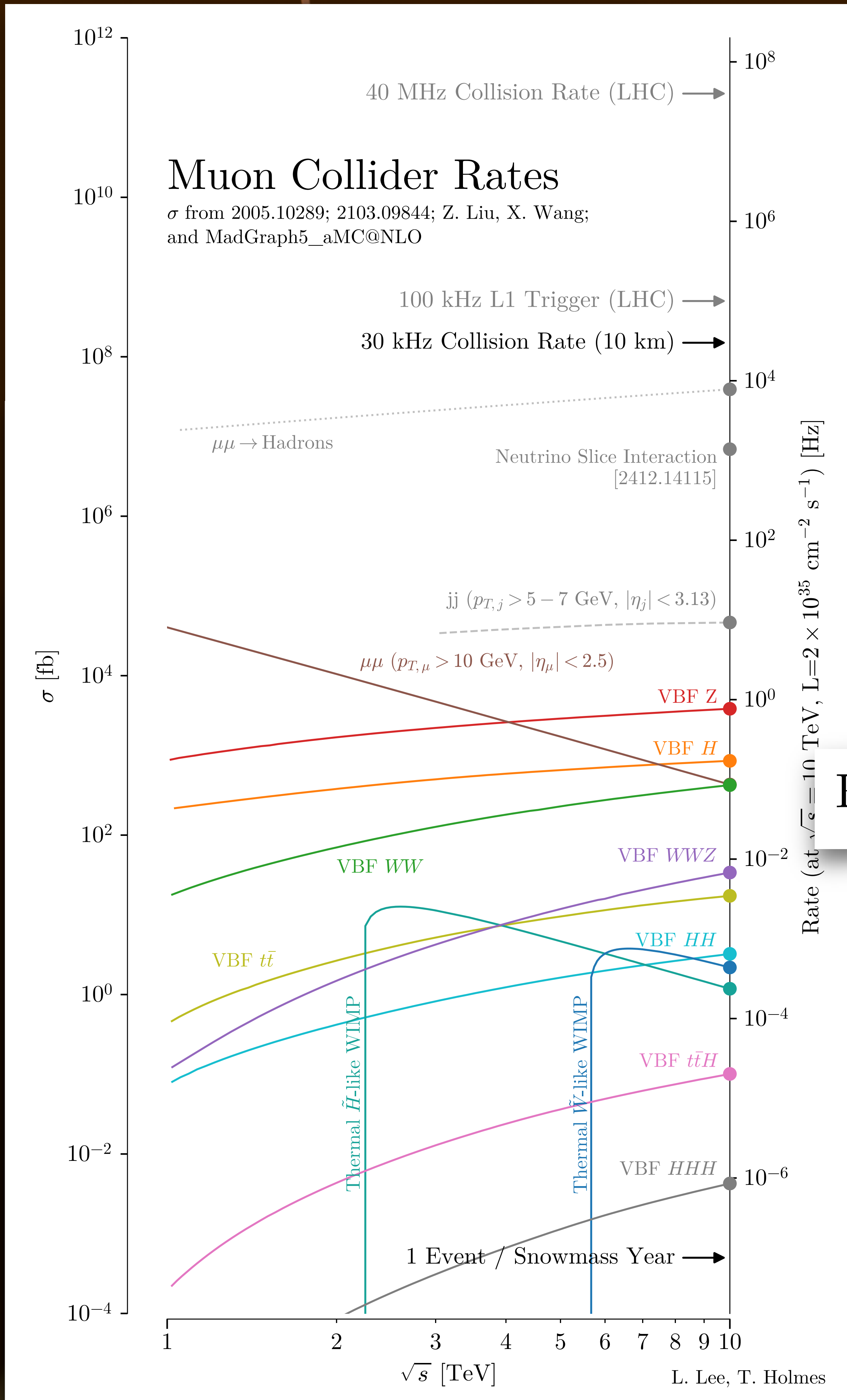
Plots: E. Sledge, et al



jj ($p_{T,j} > 5-7$ GeV, $|\eta_j| < 3.13$)
$\mu\mu$ ($p_{T,\mu} > 10$ GeV, $|\eta_\mu| < 2.5$)
VBF Z
VBF H
VBF WW
VBF WWZ
VBF $t\bar{t}$
VBF HH
Thermal $\tilde{H}$-like WIMP
Thermal $\tilde{W}$-like WIMP
VBF $t\bar{t}H$
VBF HHH
σ [fb]
10^4
10^2
10^0
10^{-2}
10^{-4}
1
2
3
4
5
6
7
8
9
$\sqrt{s}$ [TeV]



Rate (at $\sqrt{s} = 10$ TeV, L=2×10^{35} cm^{-2} s^{-1}) [Hz]



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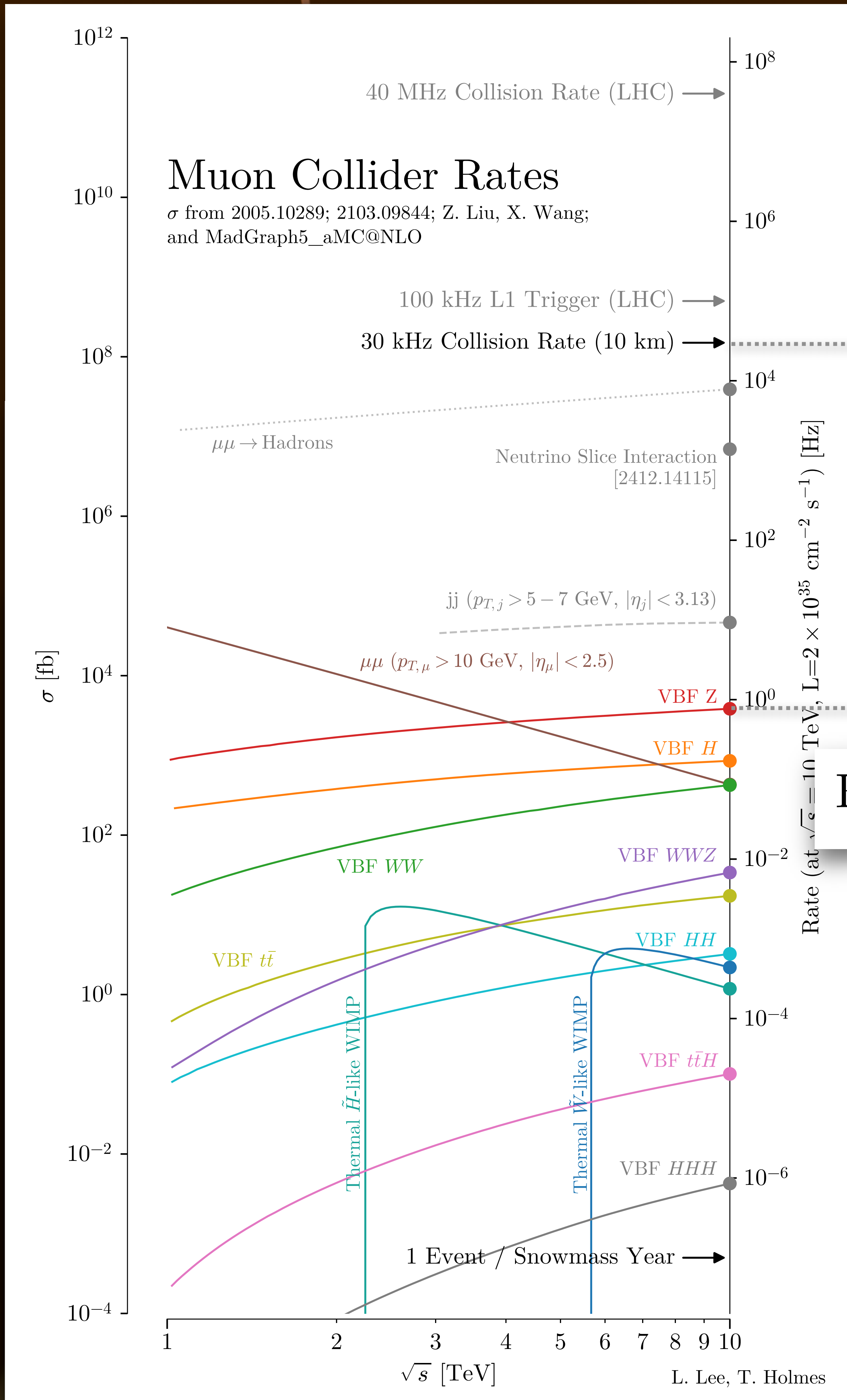
- Muon Smasher's Guide's σ_{tot} (VBF Z/W) is < 10^{-4} × collision rate!
- We've been thinking about this wrong…
- Huge implications for detector design in trigger and DAQ



Swamped by uninteresting stuff

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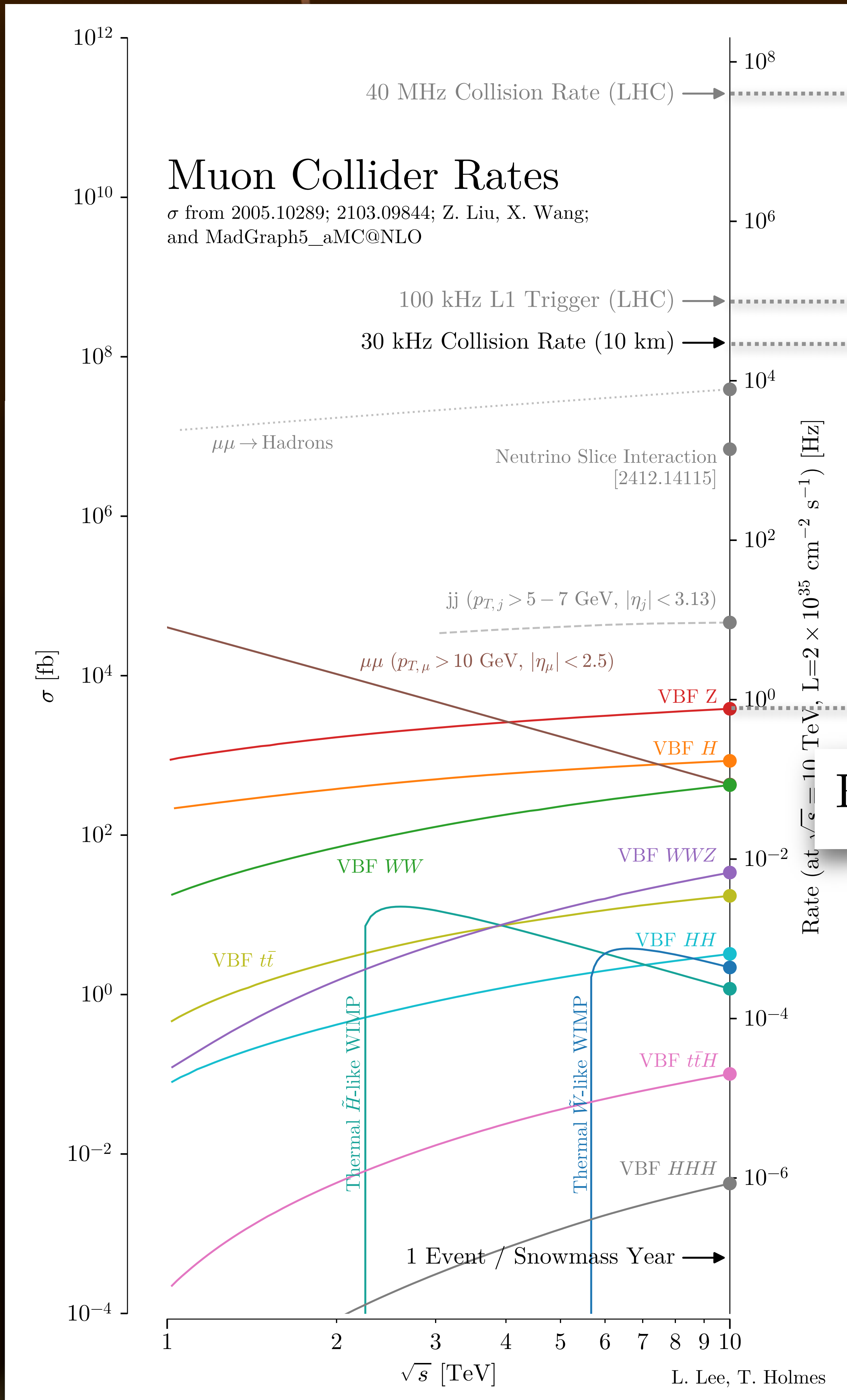

Larger fraction than LHC throws away at L1!

Swamped by uninteresting stuff

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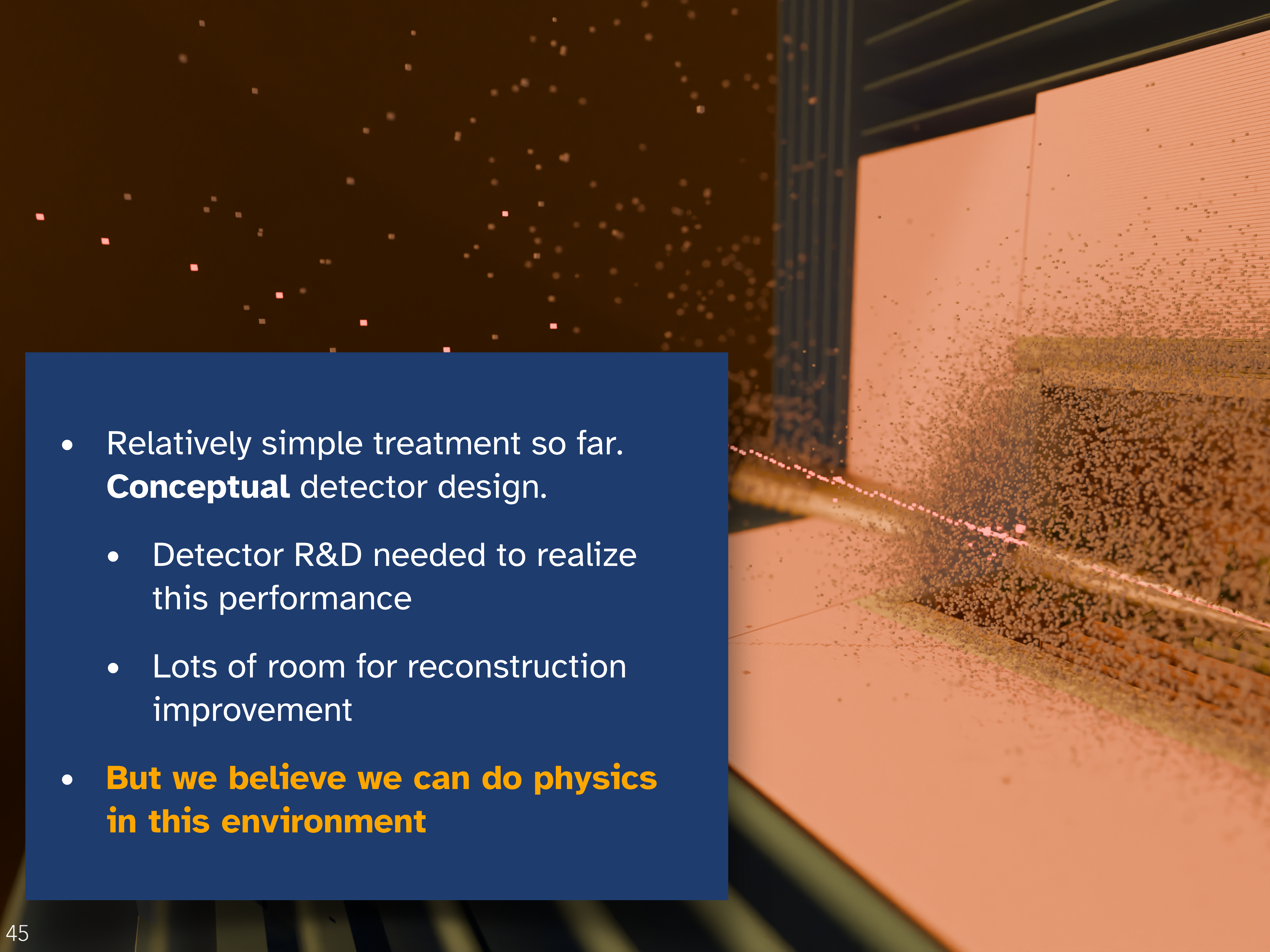

- Relatively simple treatment so far. **Conceptual** detector design.
  - Detector R&D needed to realize this performance
  - Lots of room for reconstruction improvement
- **But we believe we can do physics in this environment**

- There isn't a no-go theorem we've found yet (and we've looked)
  - **But there are many significant challenges that require hard work and ingenuity to solve**
- Such a collider is decades away
  - **But the work starts now**

Humanity just wants to know what happens if we smash stuff harder
because we don't yet know.

The only way to continue this program of discovery far into the future is with
muon colliders

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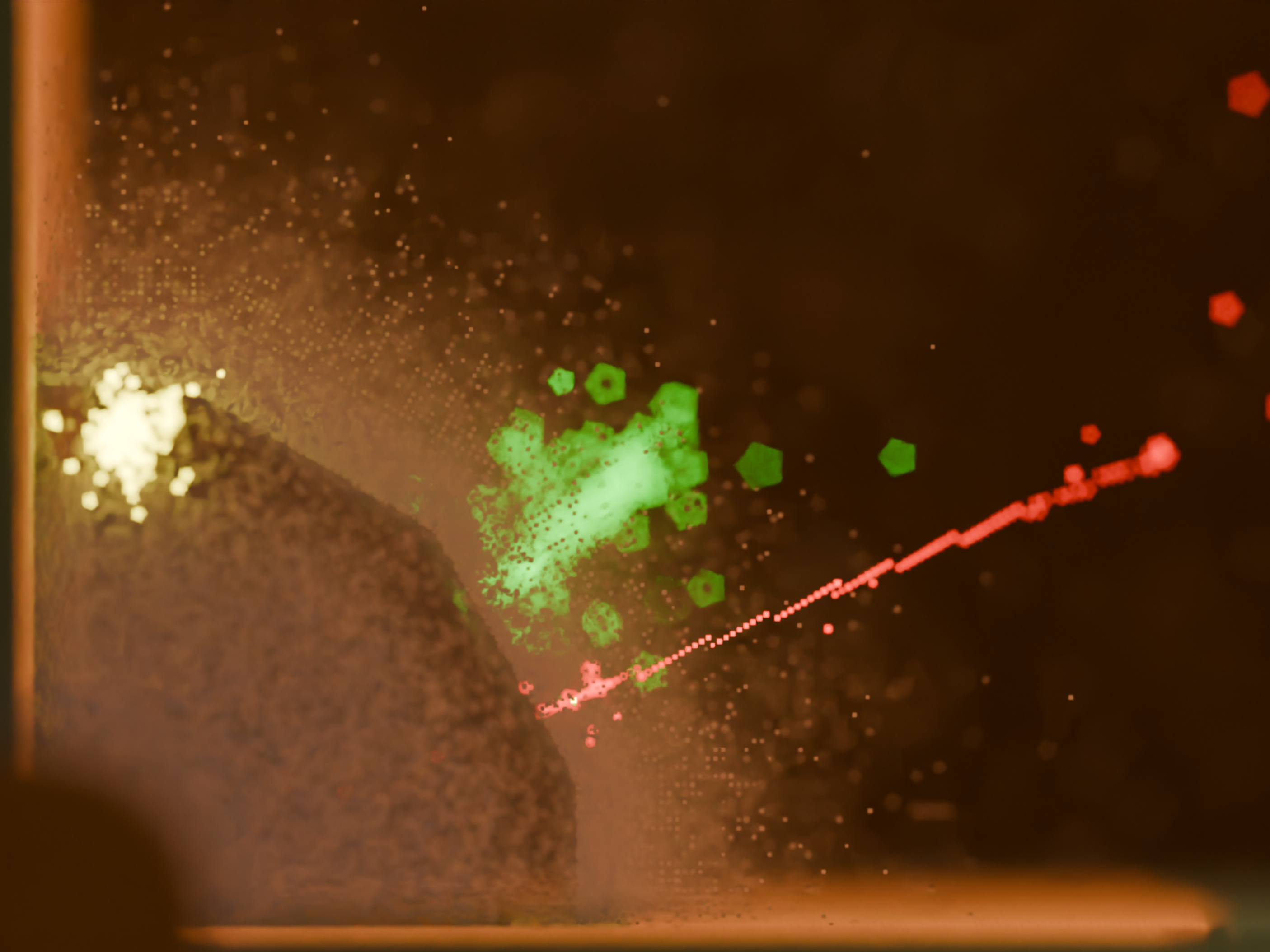

Thanks for your attention!

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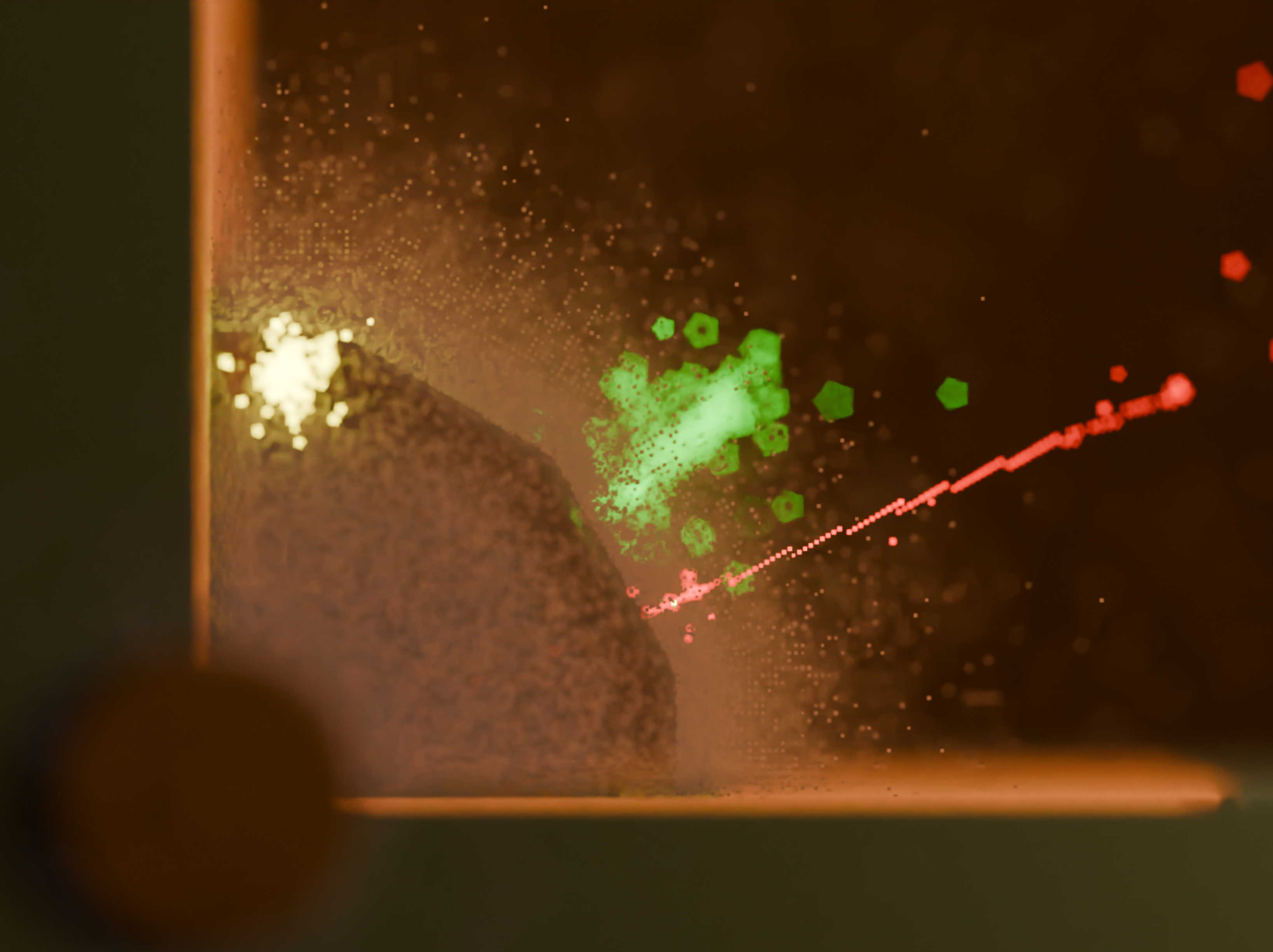
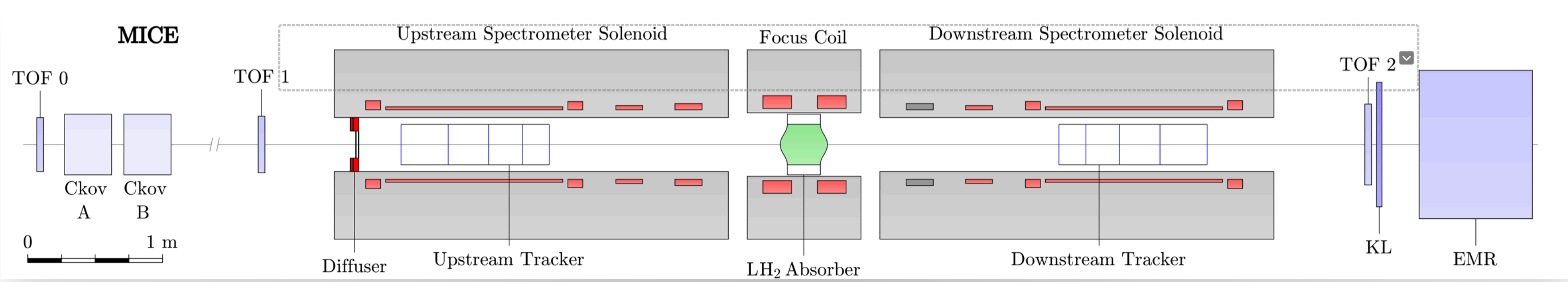


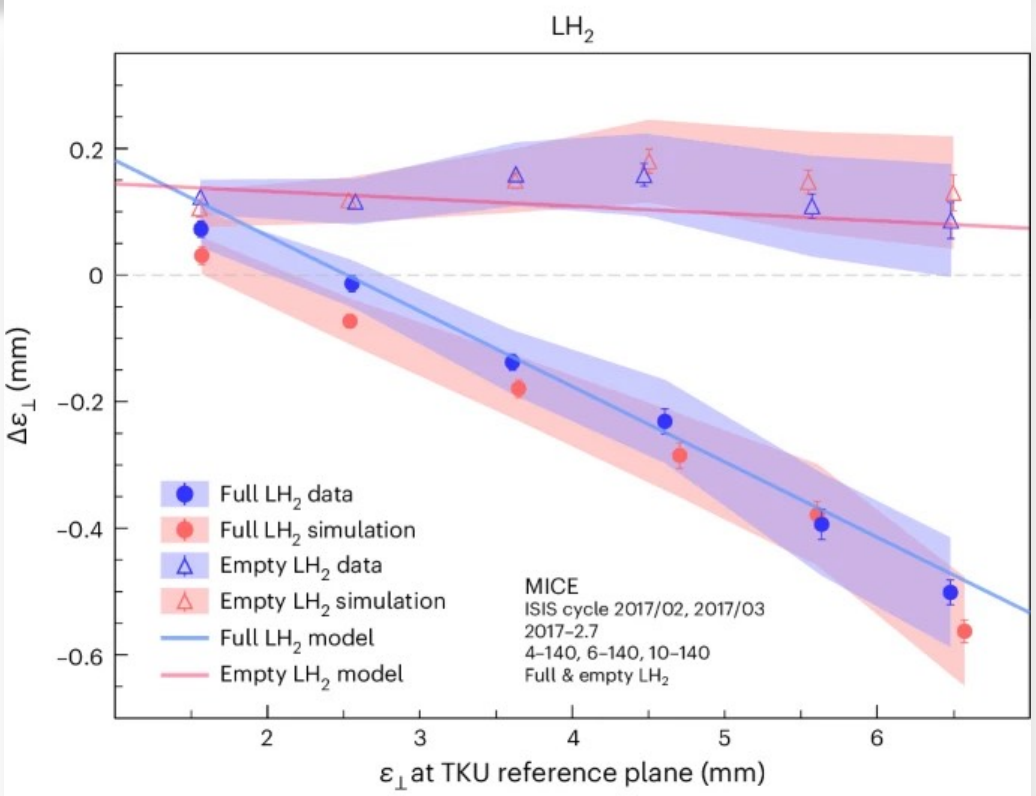
Backup

Ionization Cooling Demonstrations

[2310.05669]



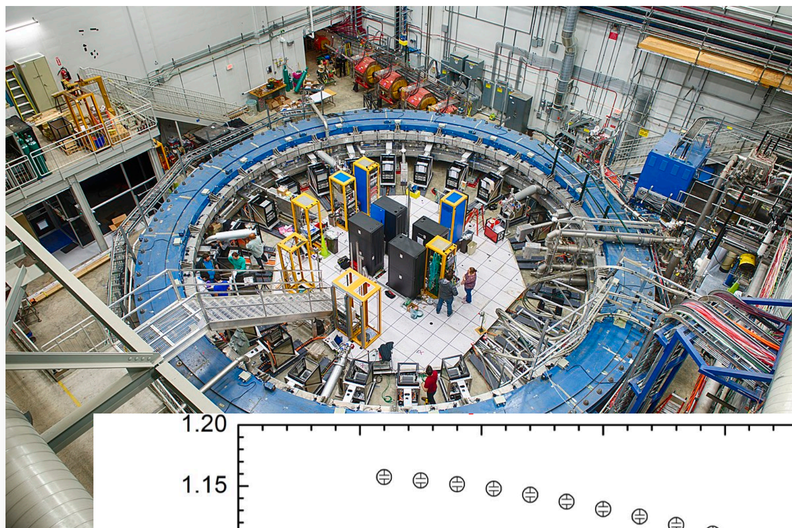
MICE demonstrated 4D cooling in 2020

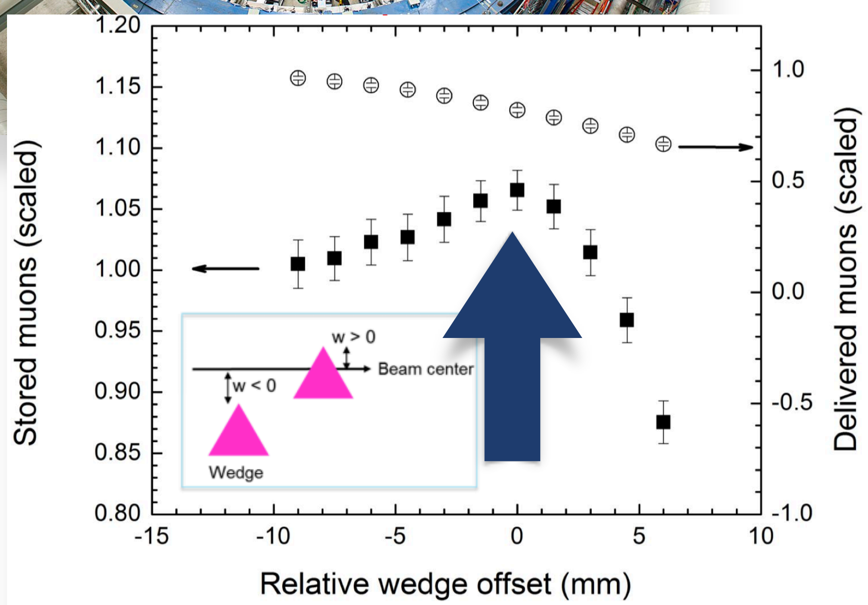


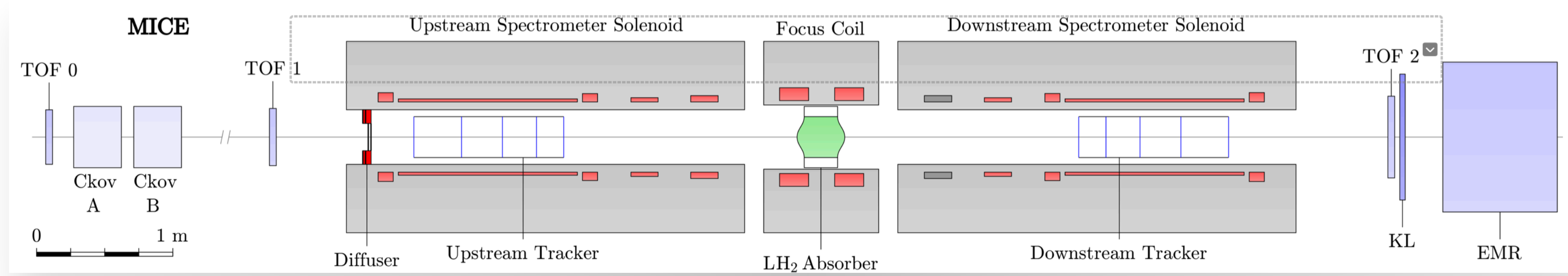
Ionization Cooling Demonstrations

[2310.05669]

[D Stratakis]







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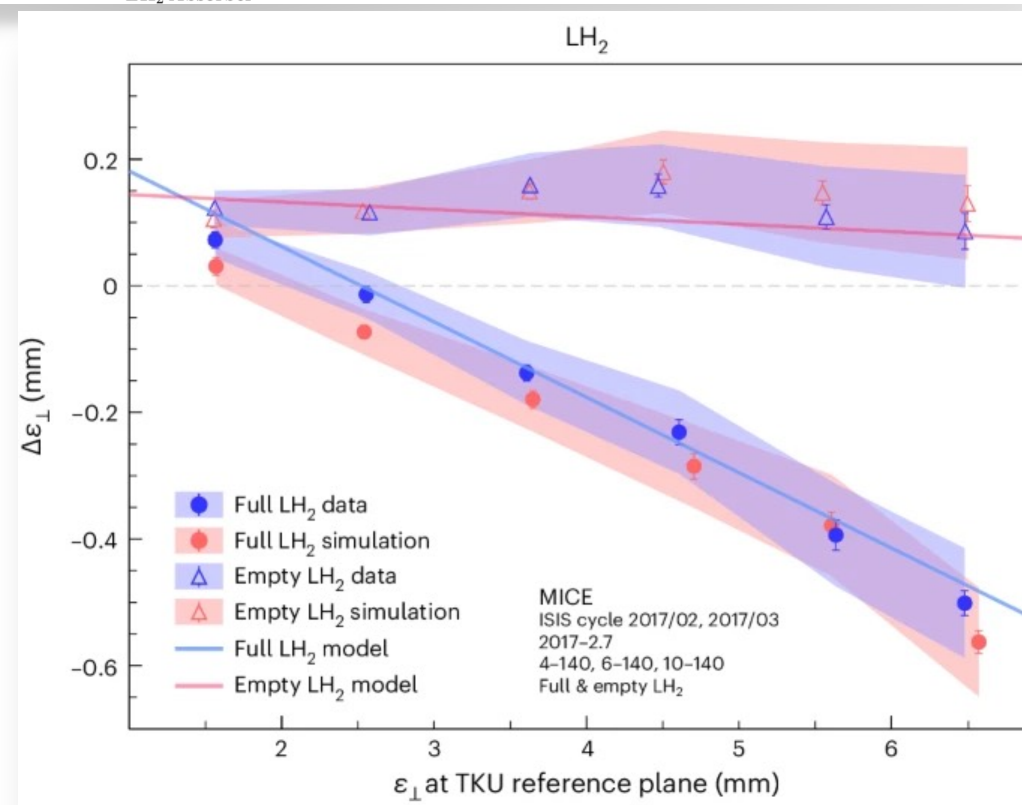
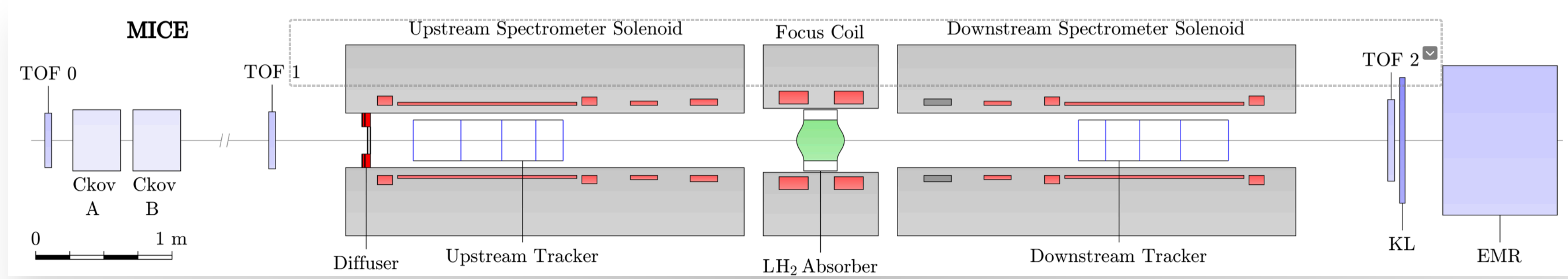


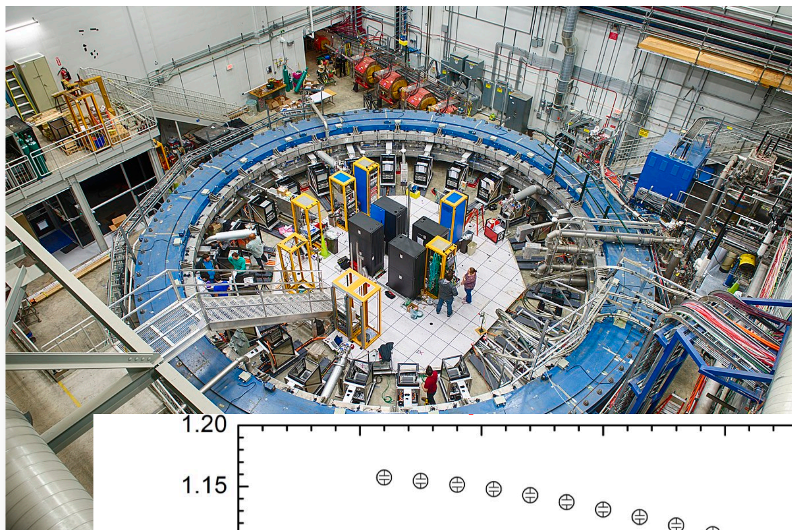
FNAL Muon g-2 demonstrated wedge cooling to increase beam quality

Ionization Cooling Demonstrations

[2310.05669]



[D Stratakis]



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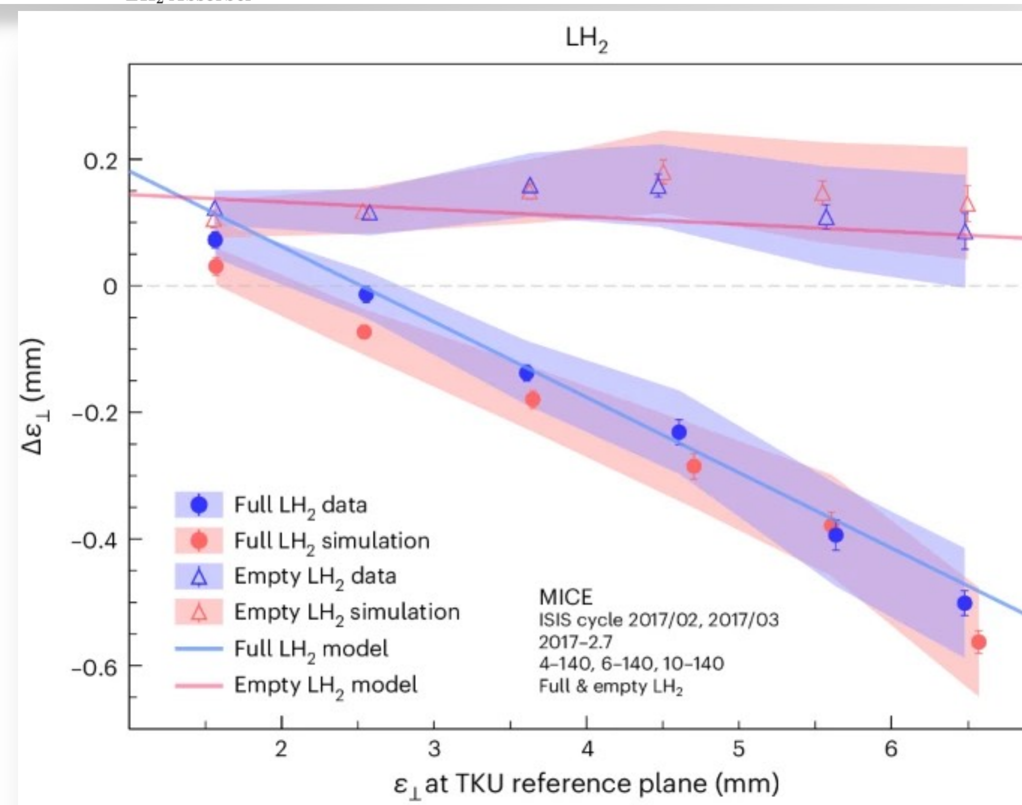
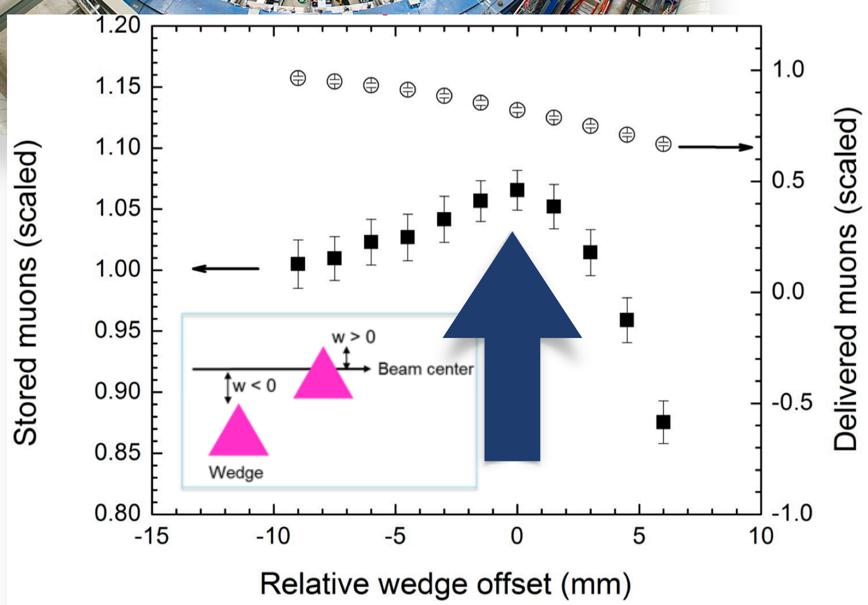
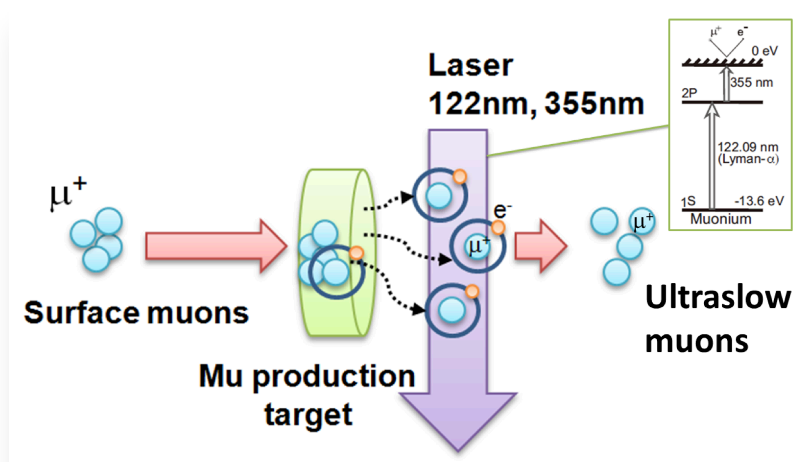




FNAL Muon g-2 demonstrated wedge cooling to increase beam quality

J-PARC created muonium (μ^+e^-)-based **ultra cold muon source** for Muon g-2

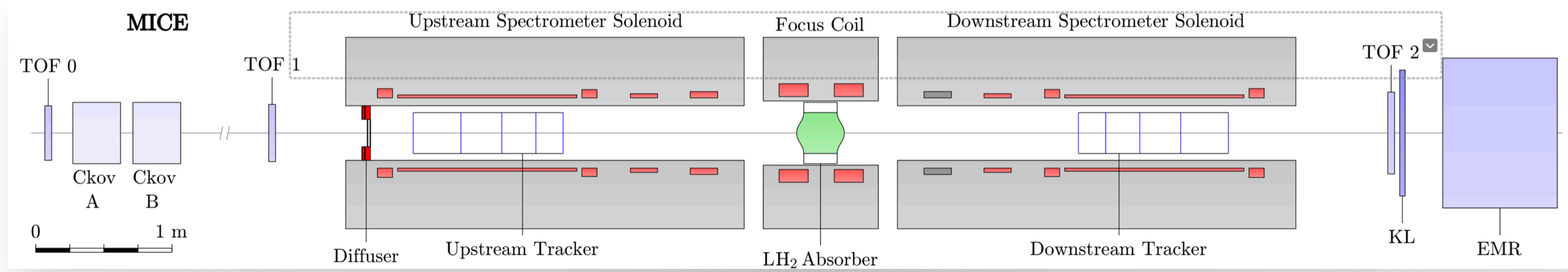
(*Not ionization cooling)



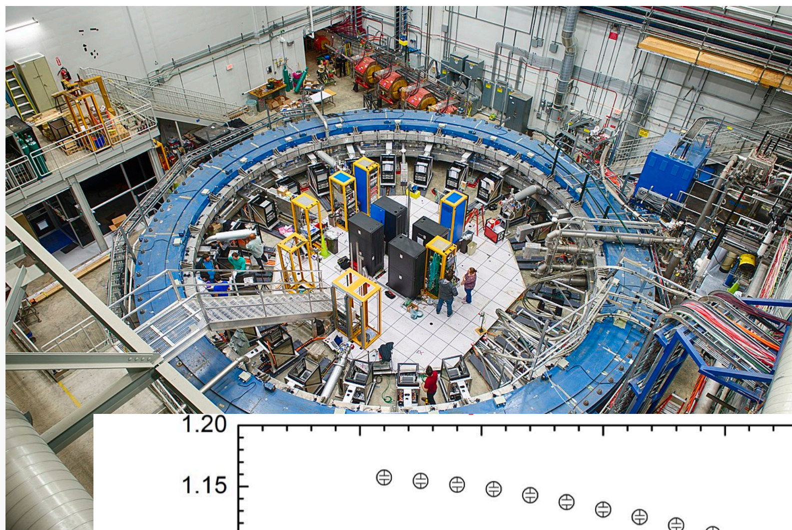
[Kondo, et al]

Ionization Cooling Demonstrations

[2310.05669]



[D Stratakis]



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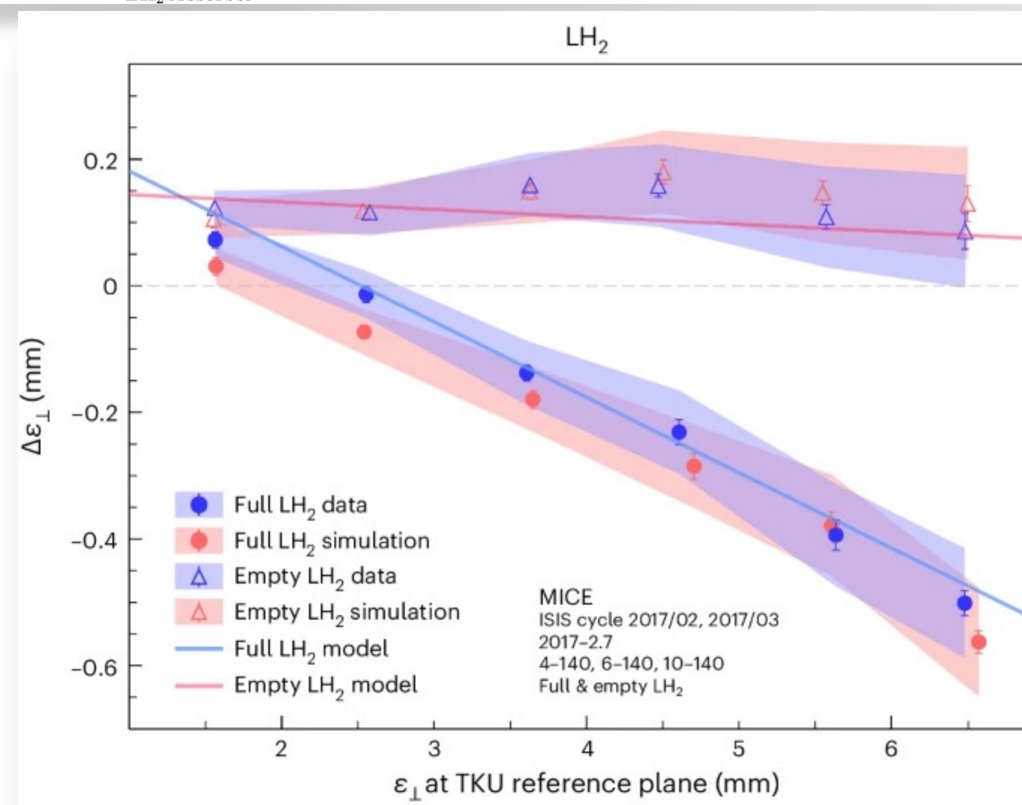

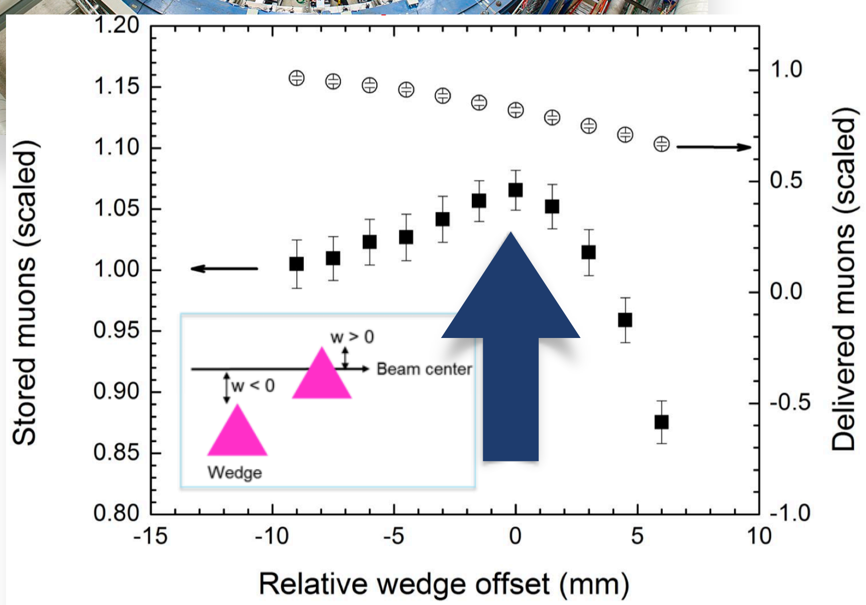

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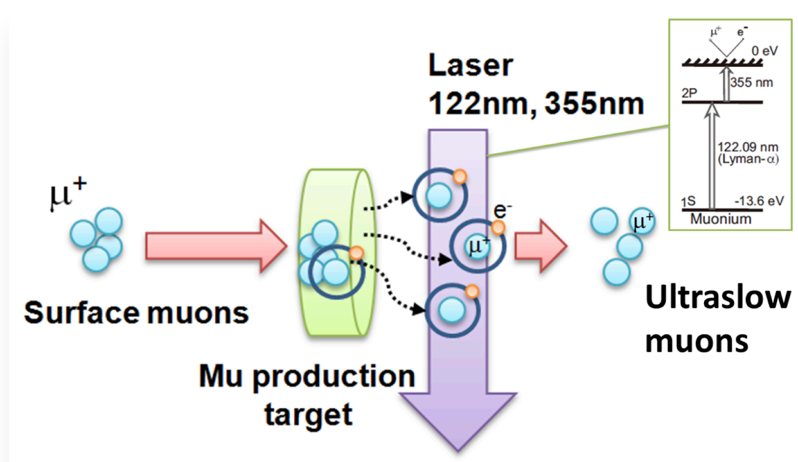
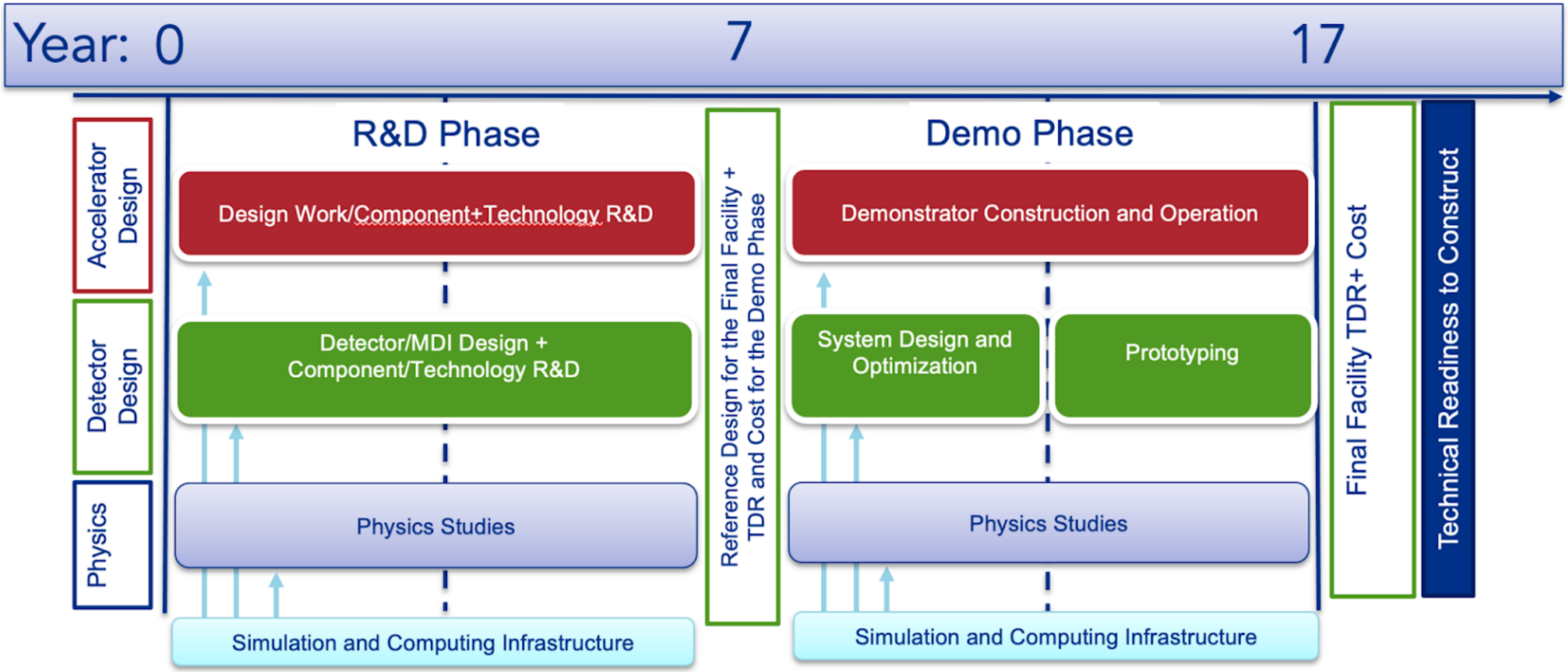


[Kondo, et al]

∃ ways to create cool muon beams!

Physics of ionization energy loss is not in dispute.



Today's Muon Collider Community has very healthy engagement and cross-talk between

HEP **Accelerator**, **Experiment**, and **Theory** communities

Given the resources(*), could start construction in as little as 20 years

- Demo phase “success” still to be defined
- Will probably be costly (≳100M)
  - **Need synergies to get the most out of this R&D program!**
    - Cool muon beam at ~200 MeV (or more?) on fixed target
    - Intense neutrino beams (1e8/s, 1e15/y)
    - ns-scale bunches of protons
    - …?

We have a lot of work and long road ahead to **realize this vision and do the seemingly impossible**

Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
Solenoid	Barrel	150.0 – 185.7	230.7	Al
ECAL	Barrel	185.7 – 212.5	230.7	W + Si
	Endcap	31.0 – 212.5	230.7 – 257.5	W + Si
HCAL	Barrel	212.5 – 411.3	257.5	Fe + PS
	Endcap	30.7 – 411.3	257.5 – 456.2	Fe + PS
Muon Detector	Barrel	415.0 – 715.0	456.5	Air + RPC
	Endcap	44.6 – 715.0	456.5 – 602.5	Air + RPC

Table 1: Boundaries and materials of individual subdetectors.

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	micro-strips
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

	Electromagnetic Calorimeter	Hadron Calorimeter
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	5.1 mm × 5.1 mm	30.0 mm × 30.0 mm
Sensor Thickness	0.5 mm	3.0 mm
Absorber Thickness	2.2 mm	20.0 mm
Number of layers	50	75

~CMS HGCAL

~ATLAS TileCal

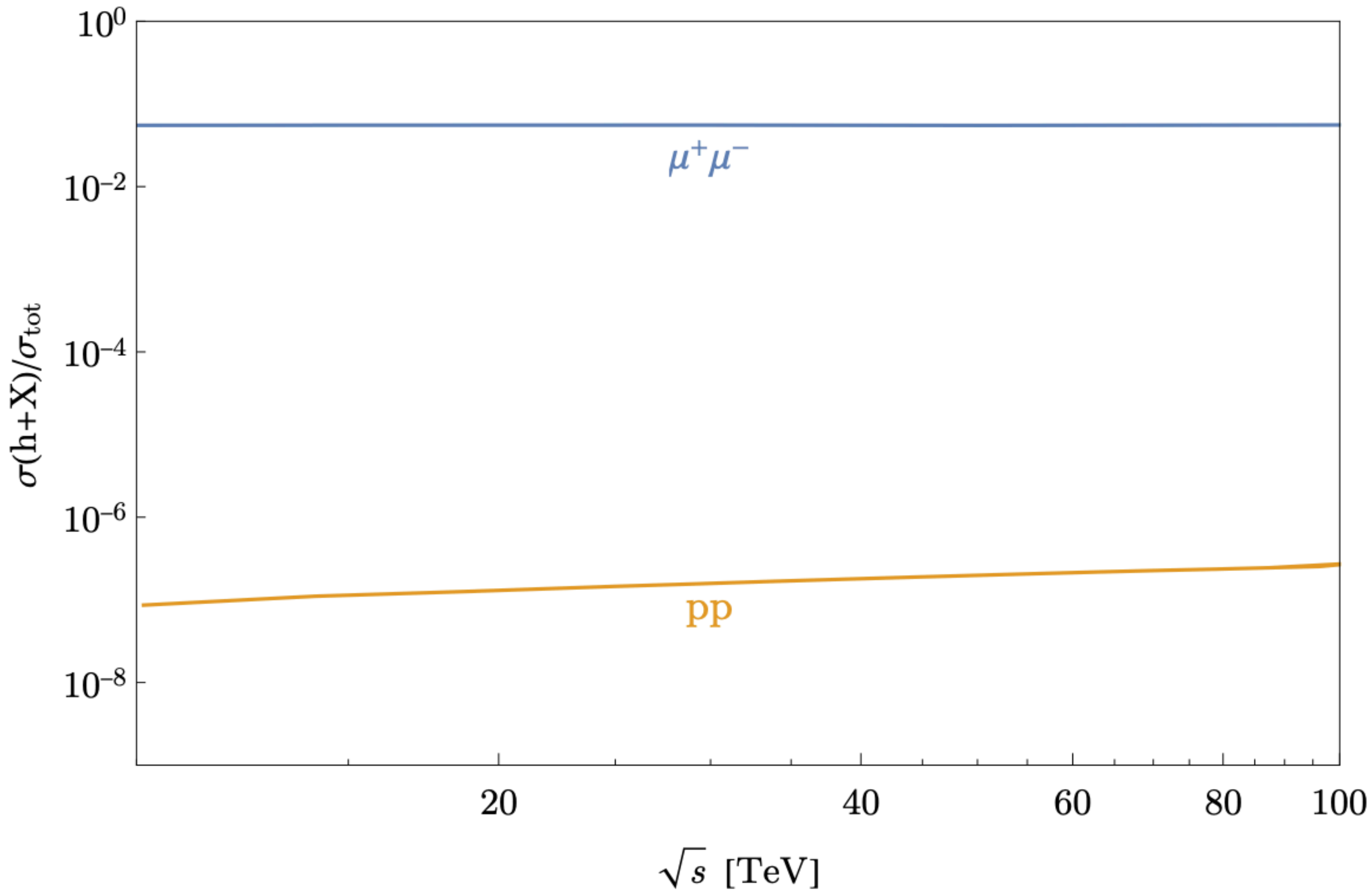


Figure 4: Higgs production cross section $\sigma(h+X)$ as a fraction of a representative "total" cross section σ_{tot} for $\mu^+\mu^-$ and pp colliders. For $\mu^+\mu^-$ colliders, we compute Higgs production using the LO cross section for $\mu^+\mu^- \to h + \nu\bar{\nu}$, while the "total" cross section σ_{tot} is taken to be the rate for single electroweak boson production, which is dominated by VBF production of W, Z, h, γ at these energies. For pp colliders we take the Higgs production cross section to be the N3LO cross section for $gg \to h$ [50] presented in [51], while the "total" cross section σ_{tot} is taken to be the $pp \to b\bar{b}$ cross section computed by MCFM [52].

[2103.14043]

Experimental Future

Some Sociological Comments on High Energy Physics

LEON M. LEDERMAN
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

In order to project into the experimental future, we need some historical perspective. We should be aware of trends (e.g., vectors) so that we can see where a "natural" evolution of HEP will take us and we should be sensitive to problems that, although minor in the 1960s and manageable in the 1970s, have reached near crises states in the 1980s and will become the death knell of the subject in the 1990s. Although I started this review with an idea of seeing how we were doing with our ability to measure in space and time resolution, I became trapped into sociology, so I must then also discuss this as well.

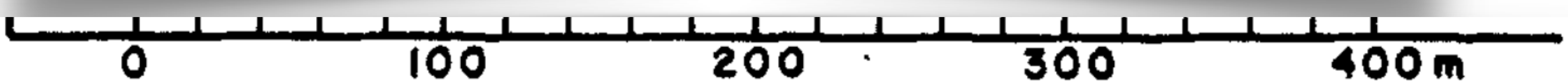


FIGURE 14. A five function interaction region: (1) A 4π calorimeter surrounds the interaction point; (2) Calibration beams are available and useful in physics; (3) Neutral beams have good, ≥ 1 TeV, neutrino flux; (4) Neutral beams may be triggered by the 4π detector; (5) No background for neighbors.

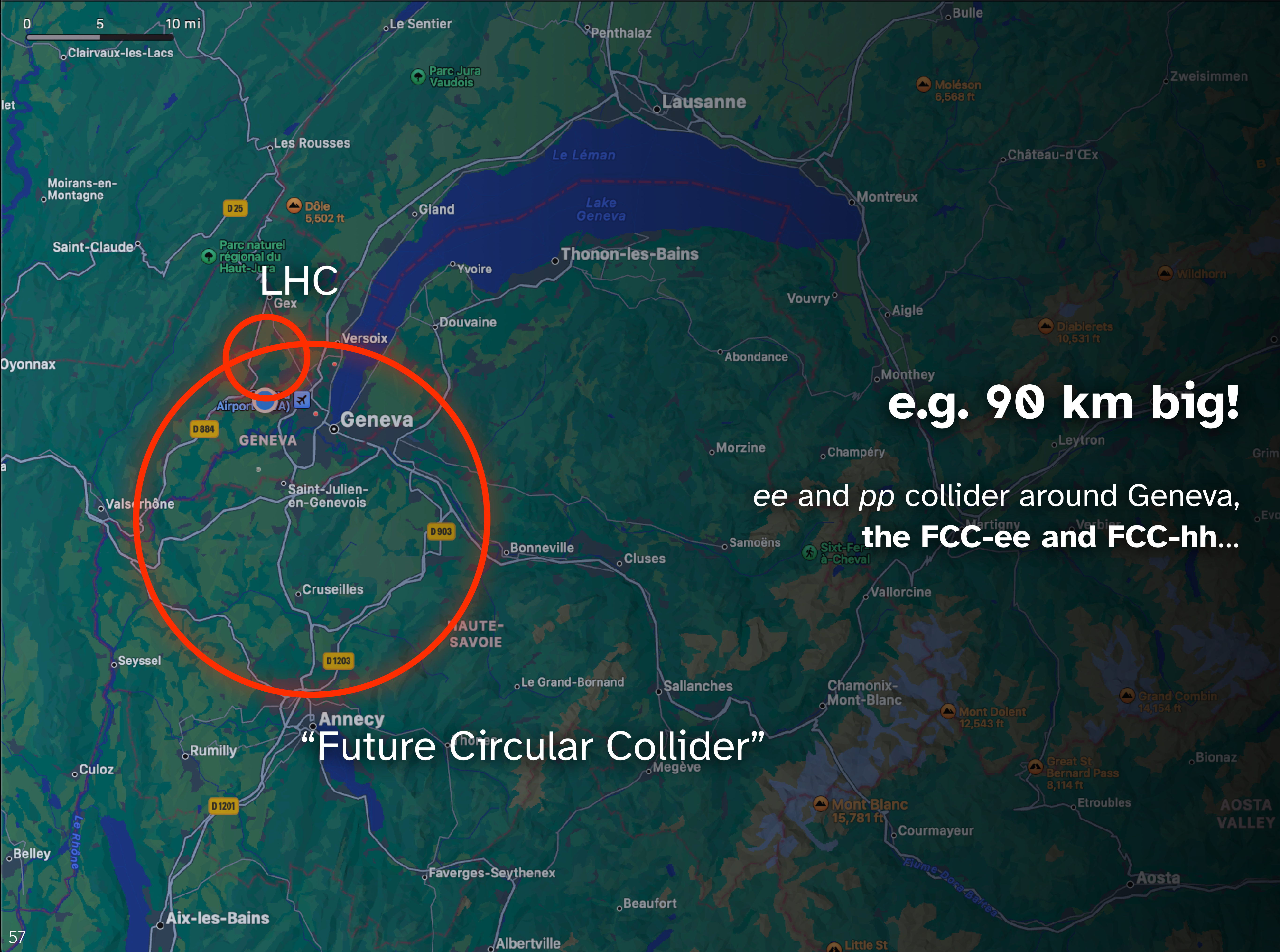
In conclusion, I have put down in this lecture some of the concerns that many of us must be feeling, if only subliminally. My attempts at resolving the problems we face are pathetic. However, the upbeat finale is that the problems are part of the process of a tremendous thrust into the unknown, an adventure that will require all of our imagination and all of our energies.

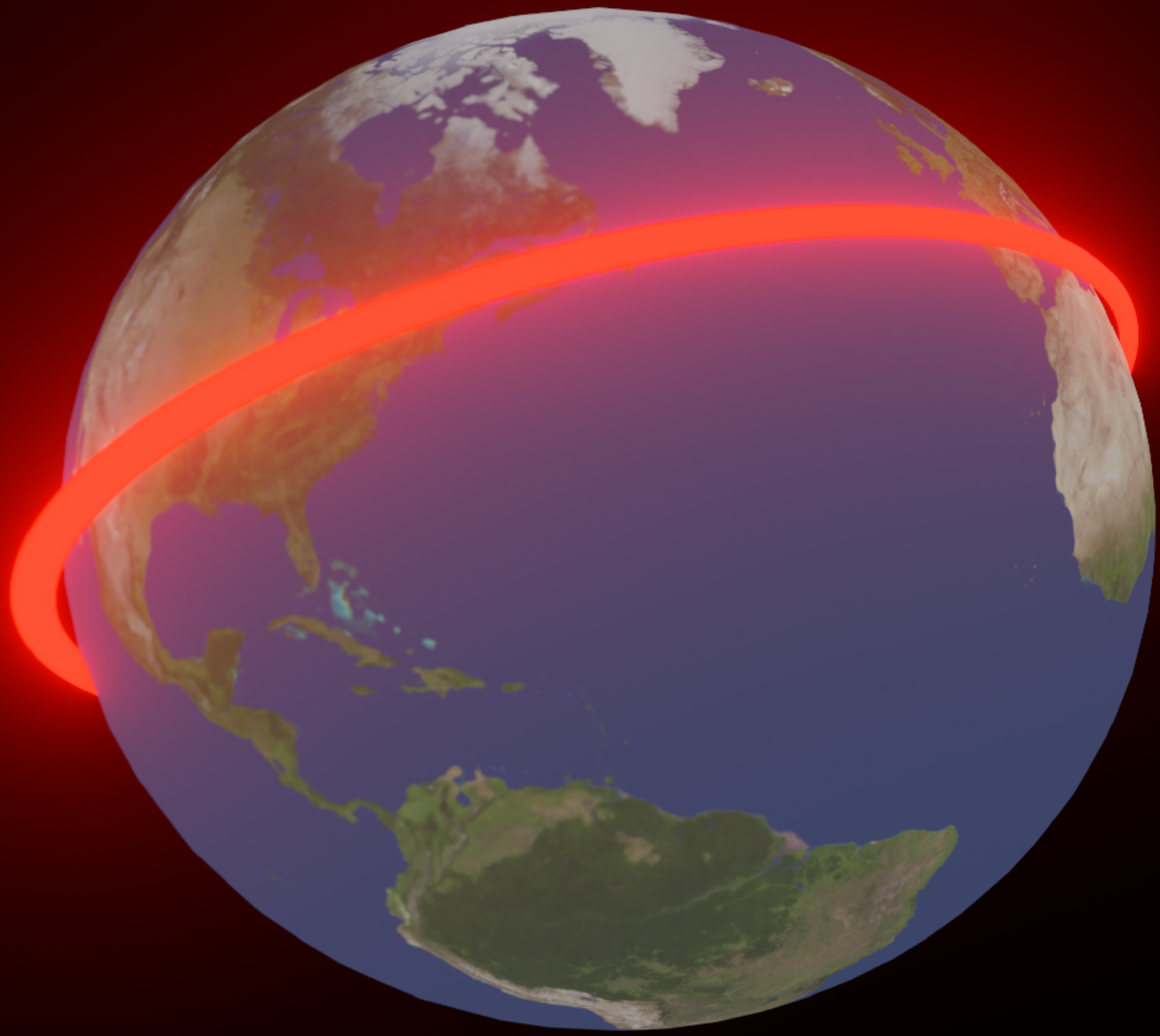
LHC is enormous

LHC is enormous

Lots of directions a talk on future colliders can go.

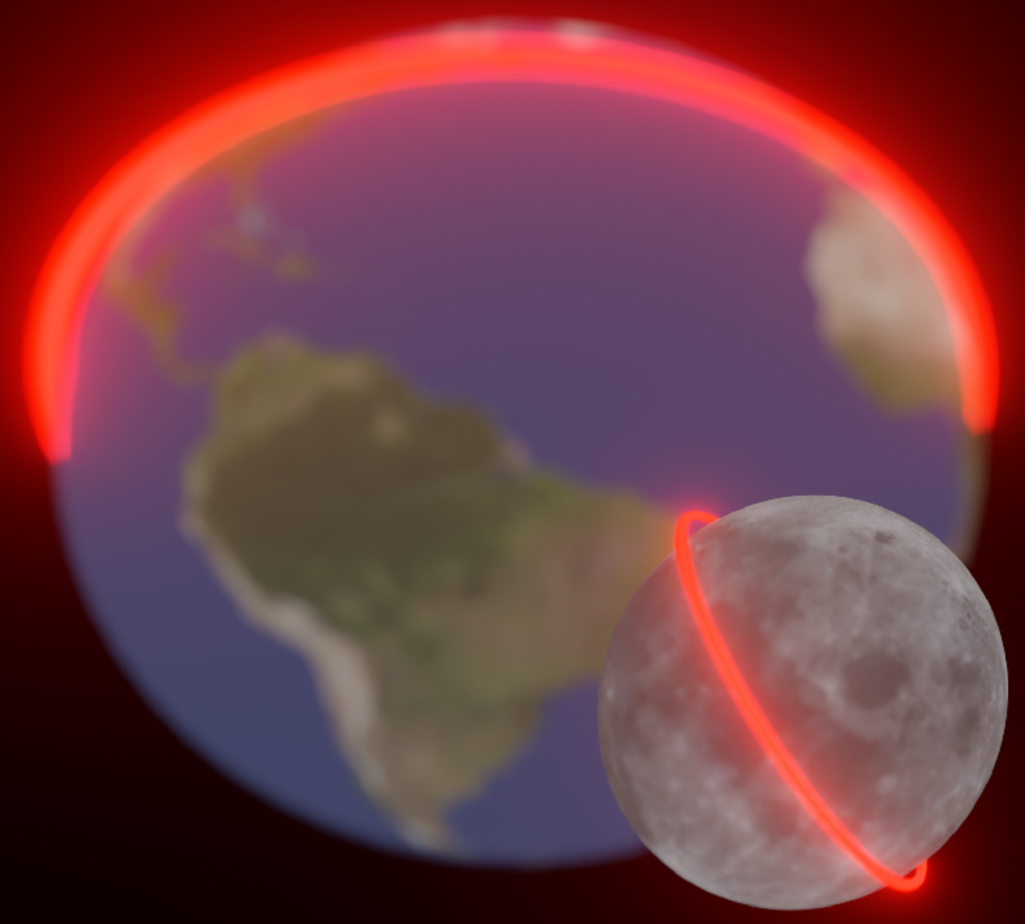
Temptation is often to “go big”


LHC
e.g. 90 km big!
ee and *pp* collider around Geneva,
the FCC-ee and FCC-hh...
“Future Circular Collider”
0 5 10 mi
Clairvaux-les-Lacs
Le Sentier
Penthalaz
Bulle
Parc Jura Vaudois
Lausanne
Moléson 6,568 ft
Zweisimmen
Les Rousses
Le Léman
Château-d'Œx
Moirans-en-Montagne
D 25
Dôle 5,502 ft
Gland
Lake Geneva
Montreux
Saint-Claude
Parc naturel régional du Haut-Jura
Yvoire
Thonon-les-Bains
Wildhorn
Gex
Vouvry
Aigle
Douvaine
Diablerets 10,531 ft
Versoix
Abondance
Oyonnax
Monthey
Geneva
D 884
GENEVA
Morzine
Champéry
Leytron
Saint-Julien-en-Genevois
Valserhône
D 903
Samoëns
Bonneville
Cluses
Sixt-Fer-à-Cheval
Vallorcine
Cruseilles
HAUTE-SAVOIE
Seyssel
D 1203
Le Grand-Bornand
Sallanches
Chamonix-Mont-Blanc
Grand Combin 14,154 ft
Mont Dolent 12,543 ft
Annecy
Rumilly
Culoz
Megève
Great St Bernard Pass 8,114 ft
Bionaz
D 1201
Mont Blanc 15,781 ft
Etroubles
AOSTA VALLEY
Courmayeur
Belley
Le Rhône
Faverges-Seythenex
Aosta
Beaufort
Aix-les-Bains
Albertville
Little St Bernard Pass



Fermi’s Globatron (1954)

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



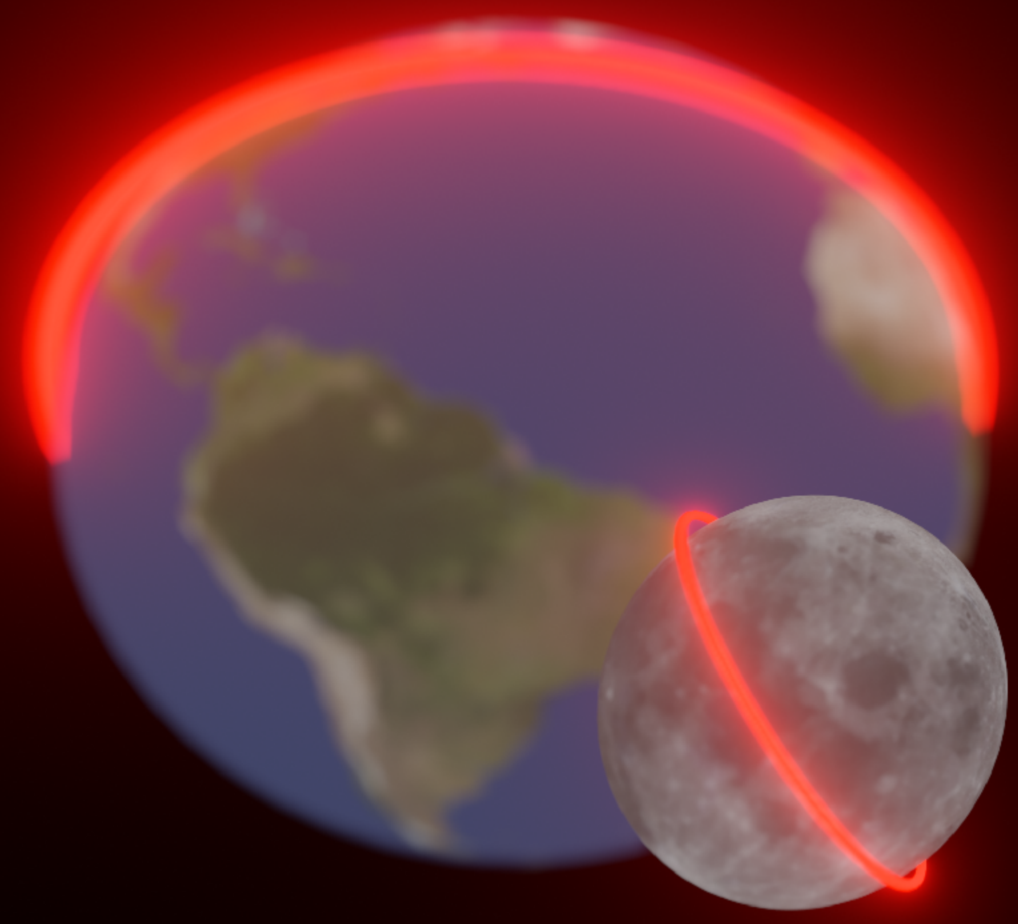
Fermi’s Globatron (1954)

Collider on the moon (2021)
[2106.02048]

Literal Pipe-Dreams...

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

Go Big!

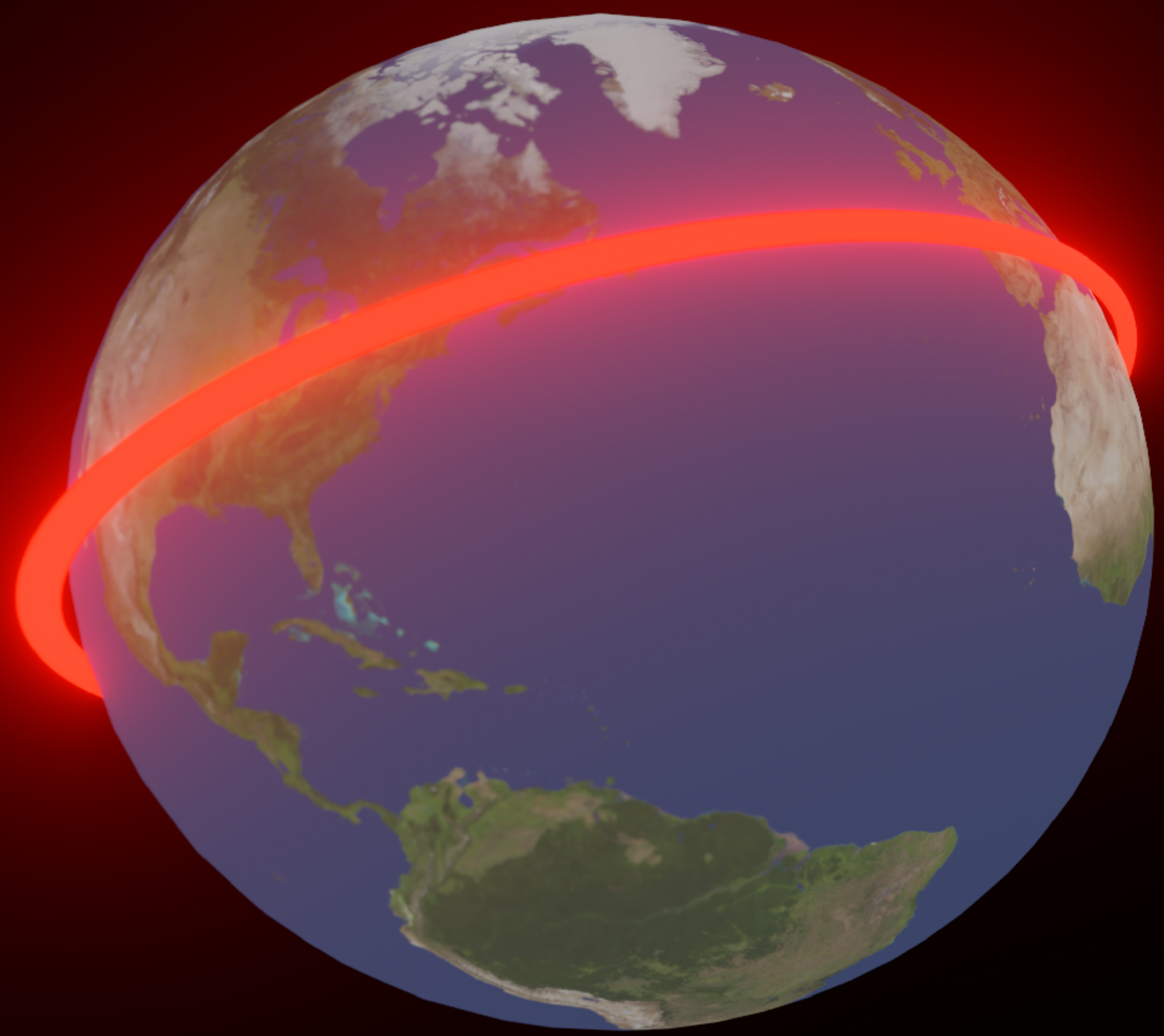


~~Go Big!~~

“Go Home”

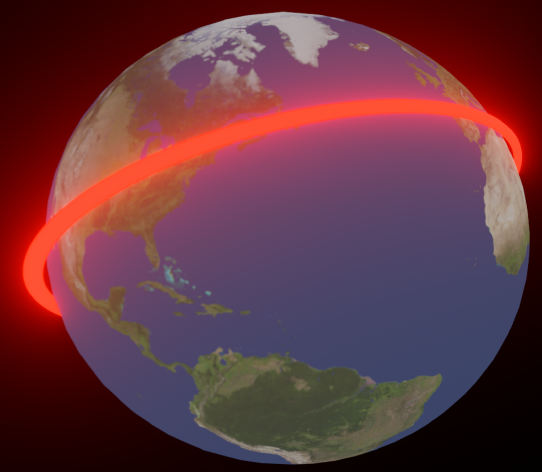
How can the FNAL community lead the future of the energy frontier, on US soil

Fermilab



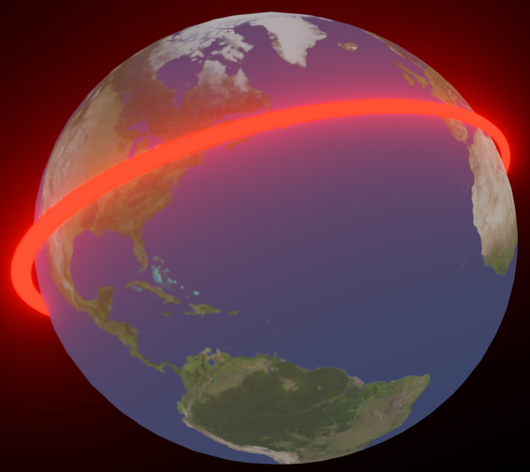
Fermi’s Globatron (1954)

40 Years in the future (1994)
40,000 km



Fermi's Globatron (1954)

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



Fermi's Globatron (1954)

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

Moral:

- 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 new opportunities** to achieve physics goals

Realize seemingly impossible physics
w/ technology, engineering, ingenuity, elbow grease

I was always told:

“Discovery of new particles is for hadron machines”

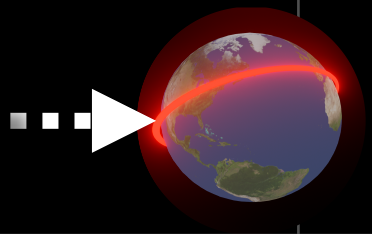
I was always told:

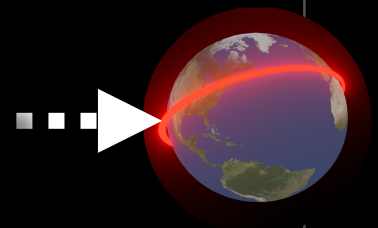
"Discovery of new particles is for hadron machines"

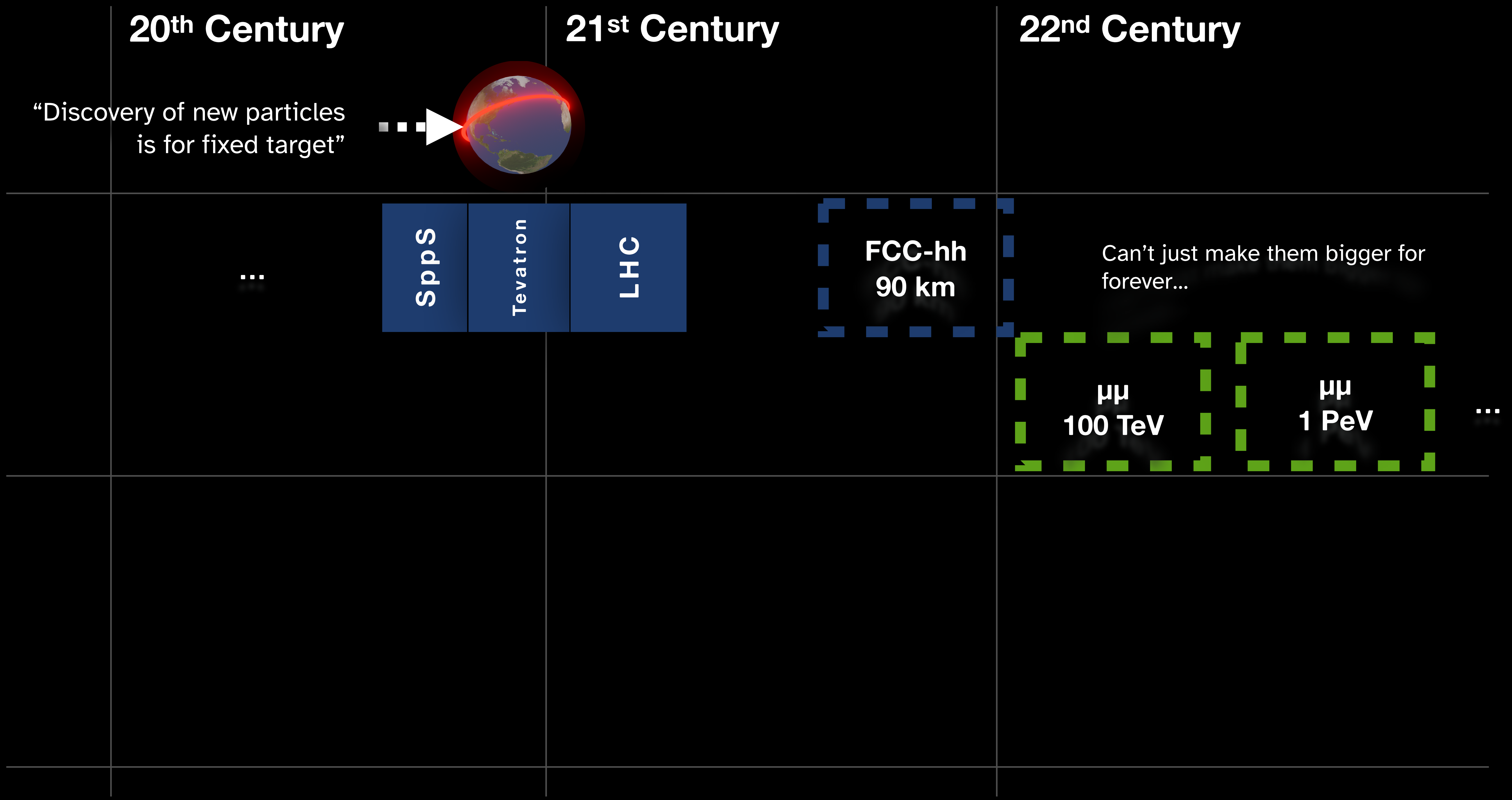
- ✅ Historically true!
- ✅ Could keep going with this!

	20th Century	21st Century	22nd Century

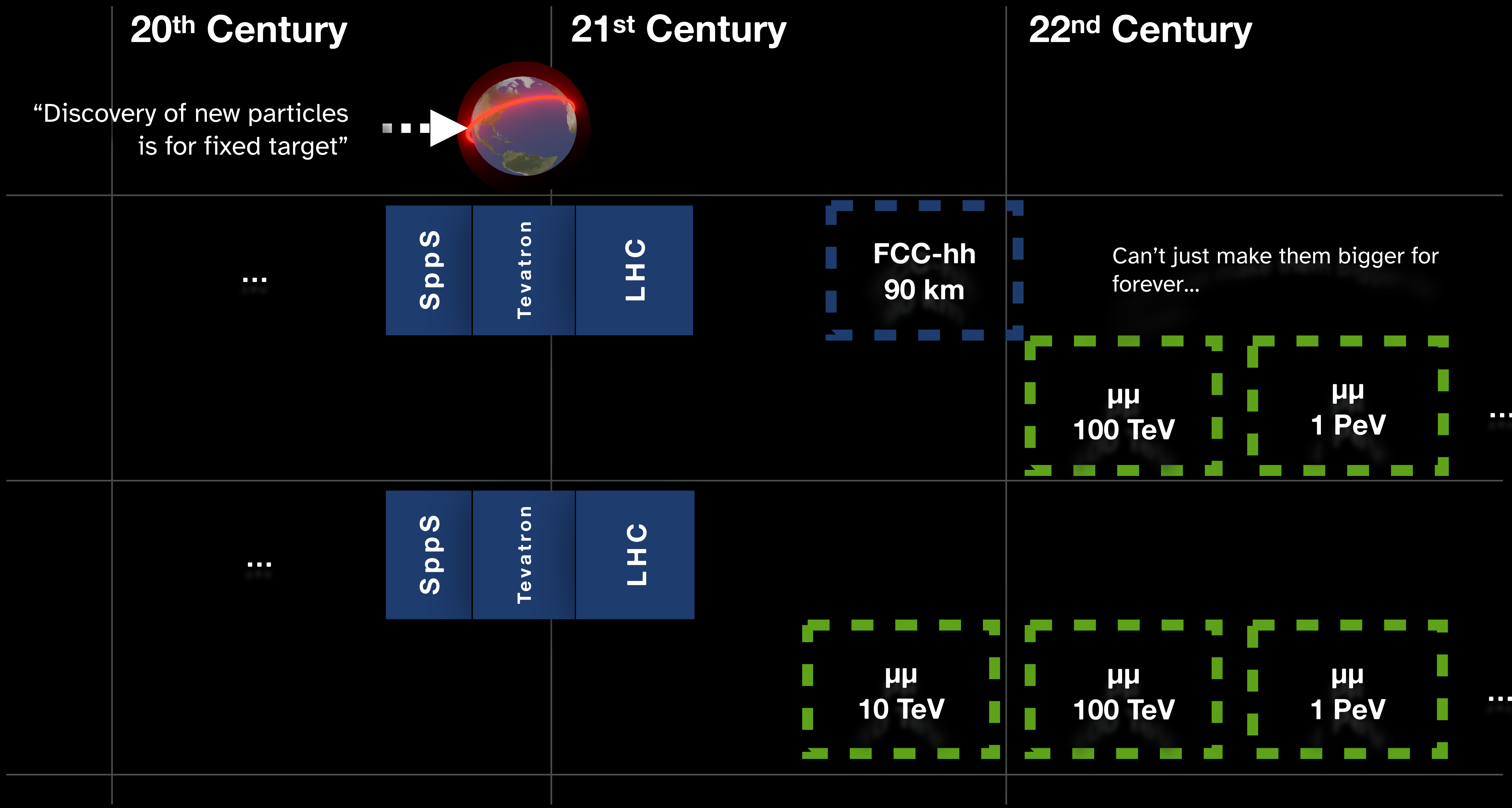
"Discovery of new particles is for fixed target"



	20th Century	21st Century	22nd Century
	“Discovery of new particles is for fixed target” 		
	… SppS Tevatron	LHC FCC-hh 90 km	Can’t just make them bigger for forever…



20th Century
21st Century
22nd Century
“Discovery of new particles is for fixed target”
...
SppS
Tevatron
LHC
FCC-hh
90 km
Can’t just make them bigger for forever...
μμ
100 TeV
μμ
1 PeV
...


20th Century
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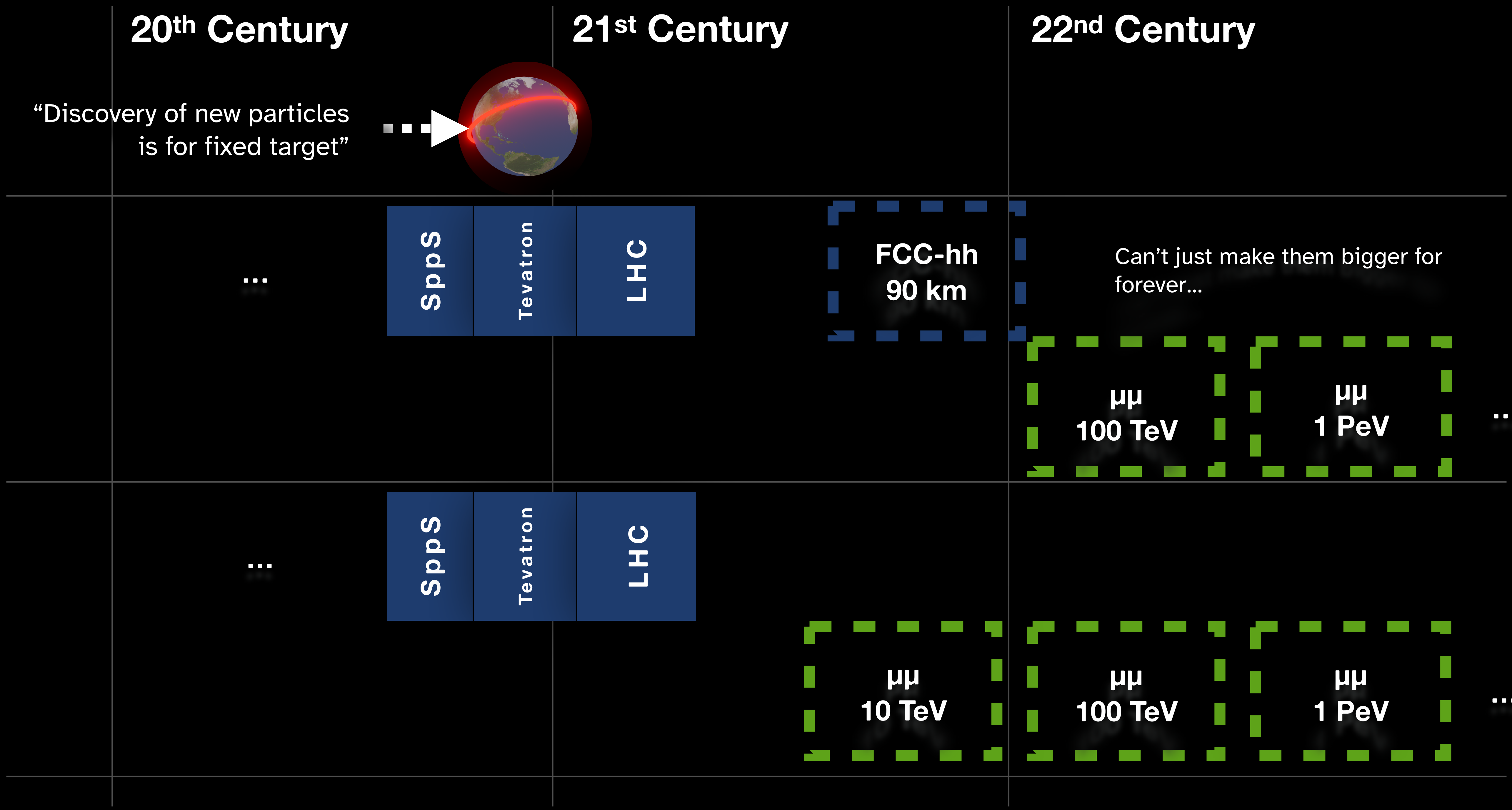
μμ
100 TeV
μμ
1 PeV
...
...
SppS
Tevatron
LHC
μμ
10 TeV
μμ
100 TeV
μμ
1 PeV
...

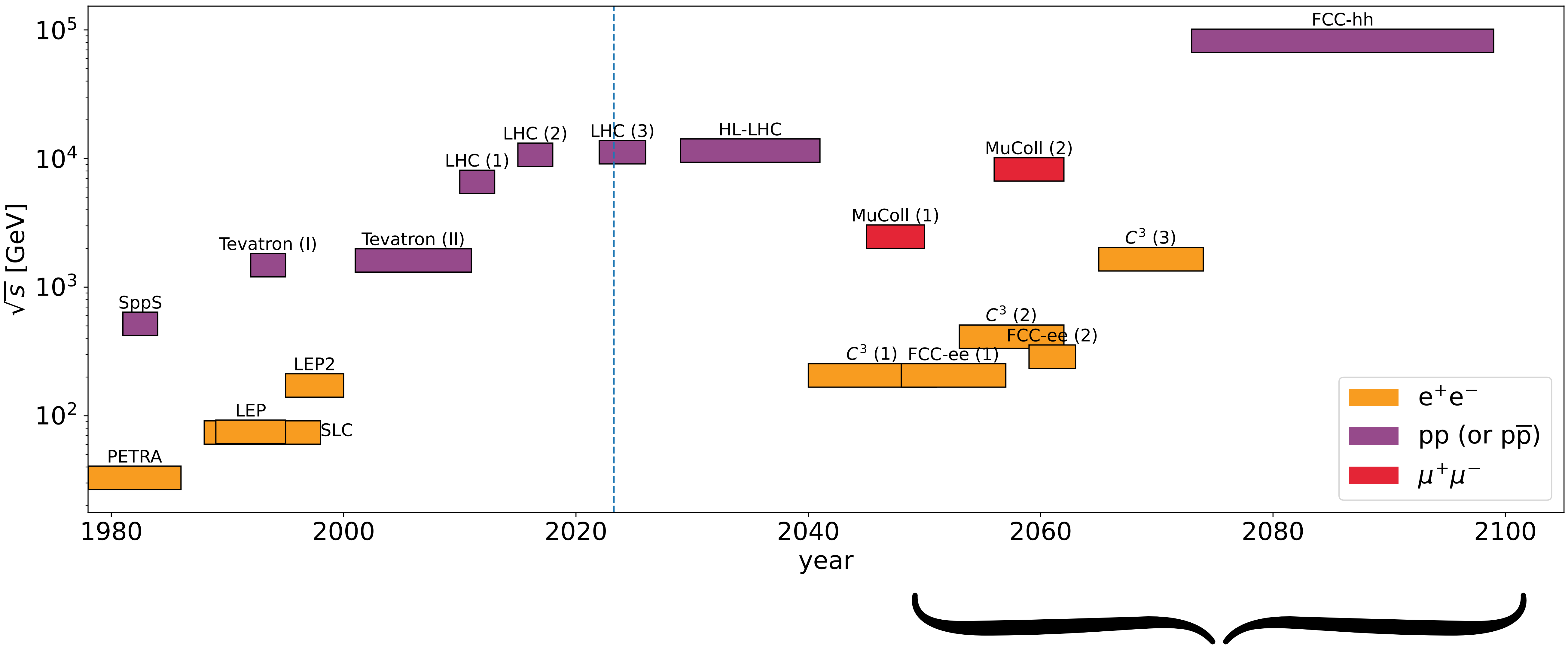


Ask ourselves:

Do we want to work on the last chapter of a 20th c story?

Or do we start a new discovery program that will continue into the 22nd c?

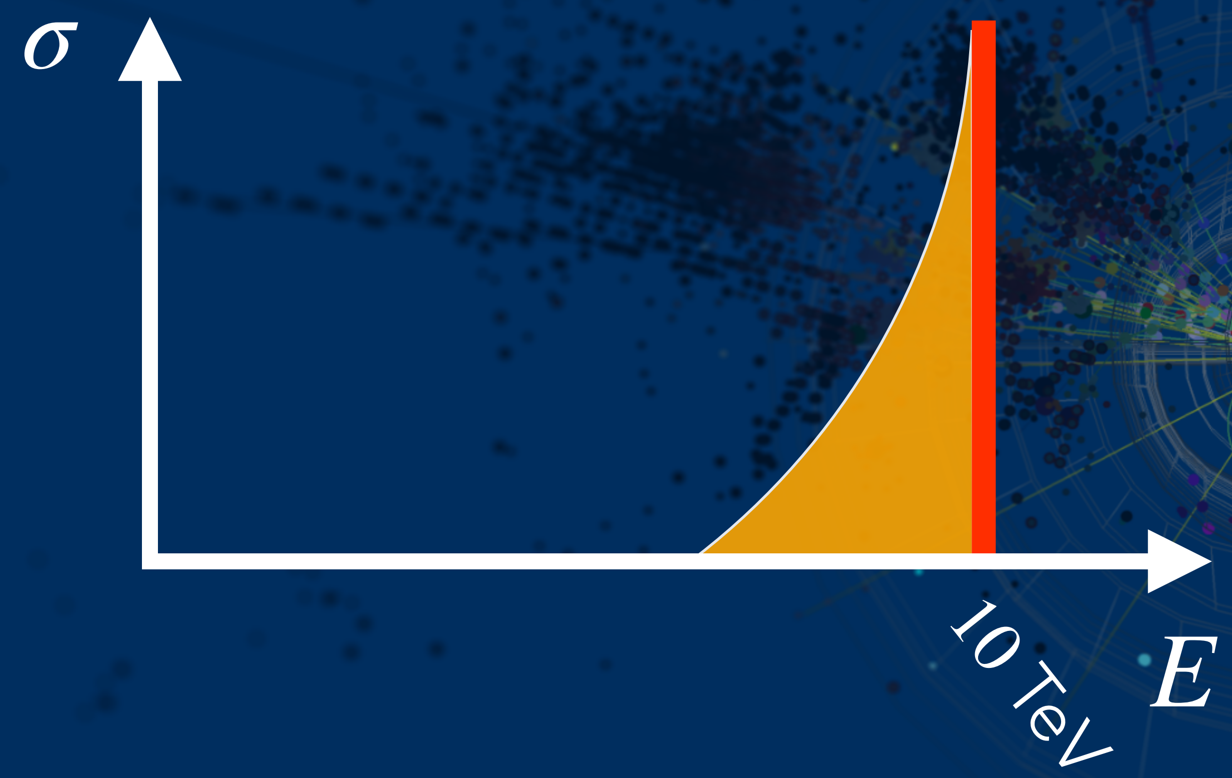
K Pedro



Physics of the second half of the century

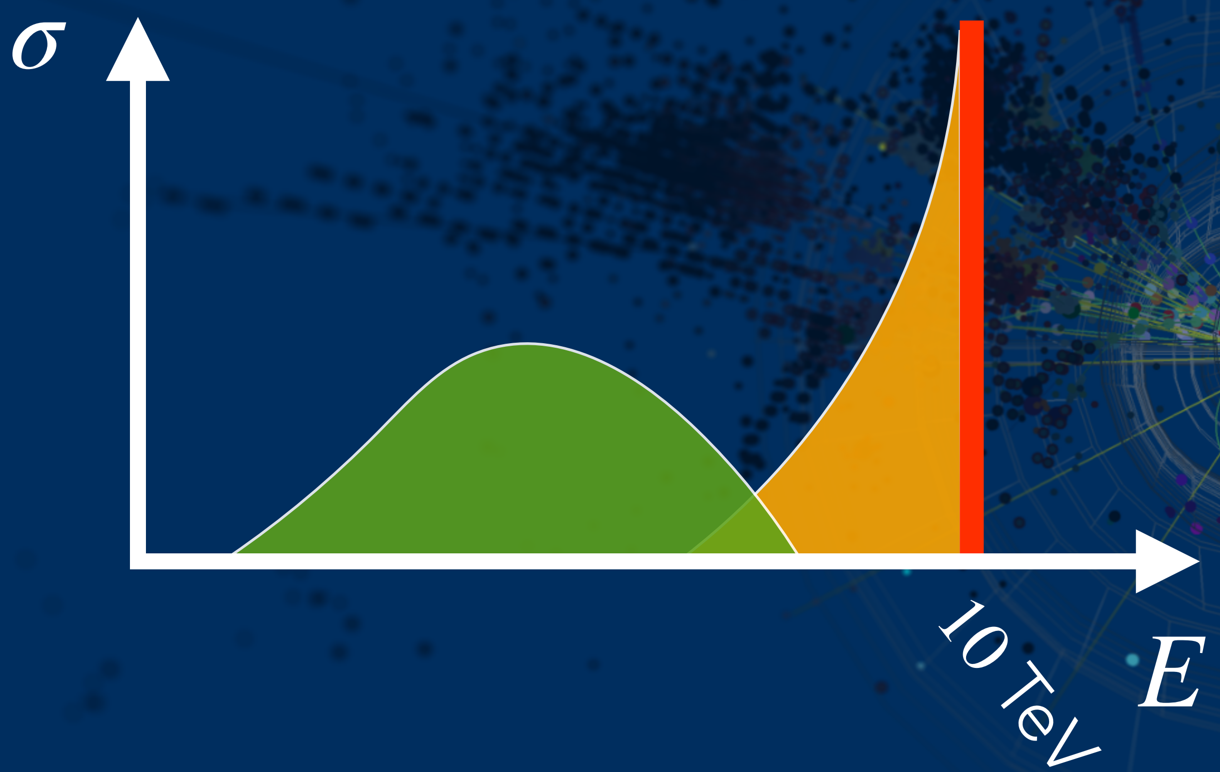
We often talk about "early career issues". And many people think that has to do with jobs. Unfortunately many people think it only means DEI efforts. But looking at these timelines, **everything to do with planning for the coming decades uniquely affects early career researchers.**

Say you have a 10 TeV μμ collider...



Annihilation processes with potential **radiation** effects

Say you have a 10 TeV μμ collider...



Annihilation processes with potential **radiation** effects

Or μ's radiate **vector bosons** which then interact

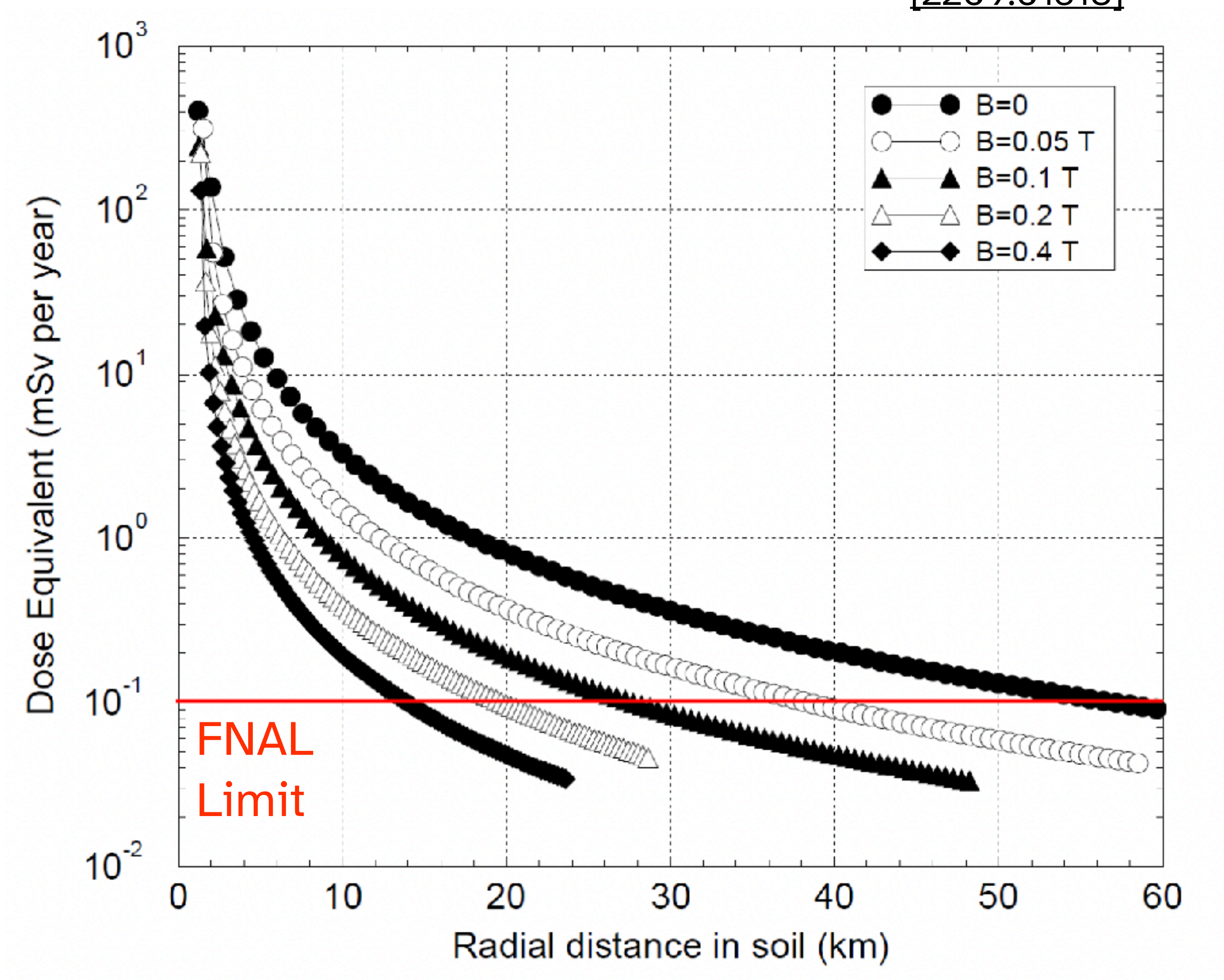
A virtual cloud of bosons interacting.

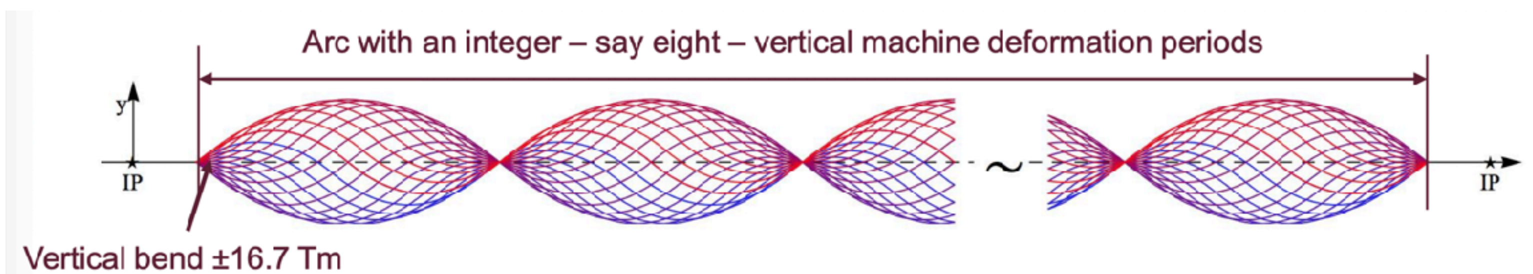
"**VDF**" Vector Boson Distribution Function gives a spread of hard scatter energies

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!
  - Move beam to spread neutrino flux
  - Place collider above ground?

[2209.01318]

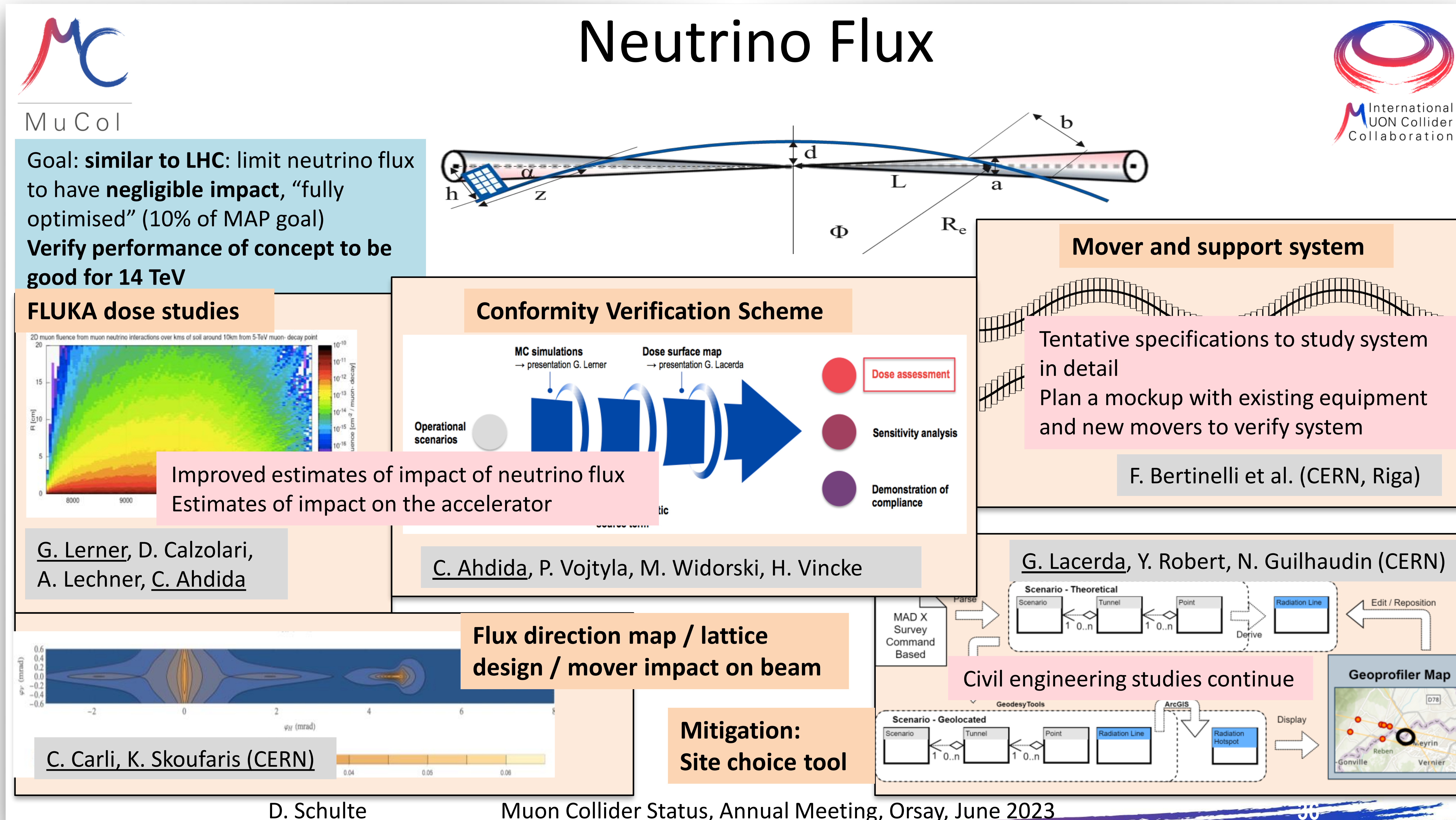


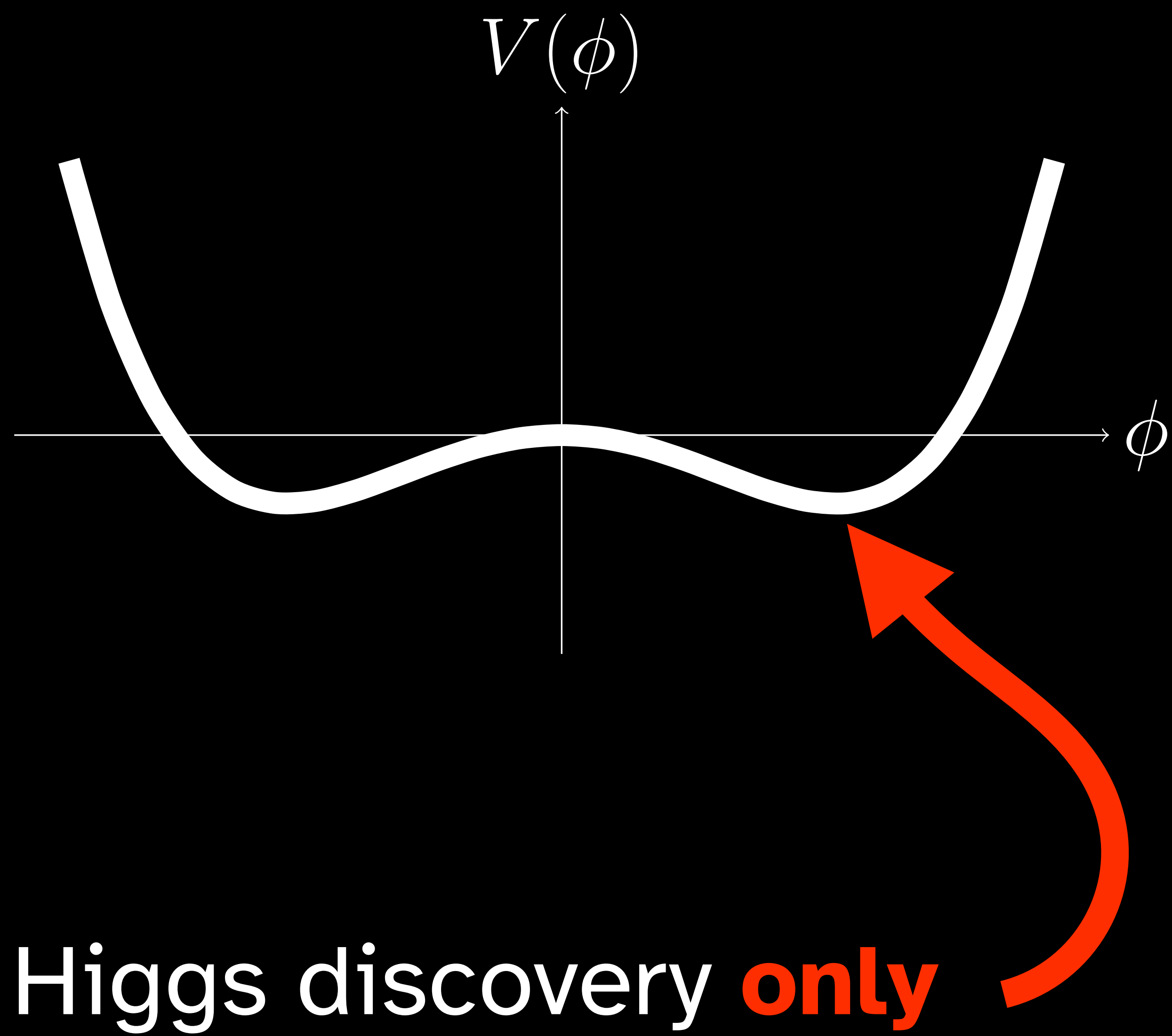


C. Carli at IMCC Annual Meeting

Neutrino Flux from Muon Colliders

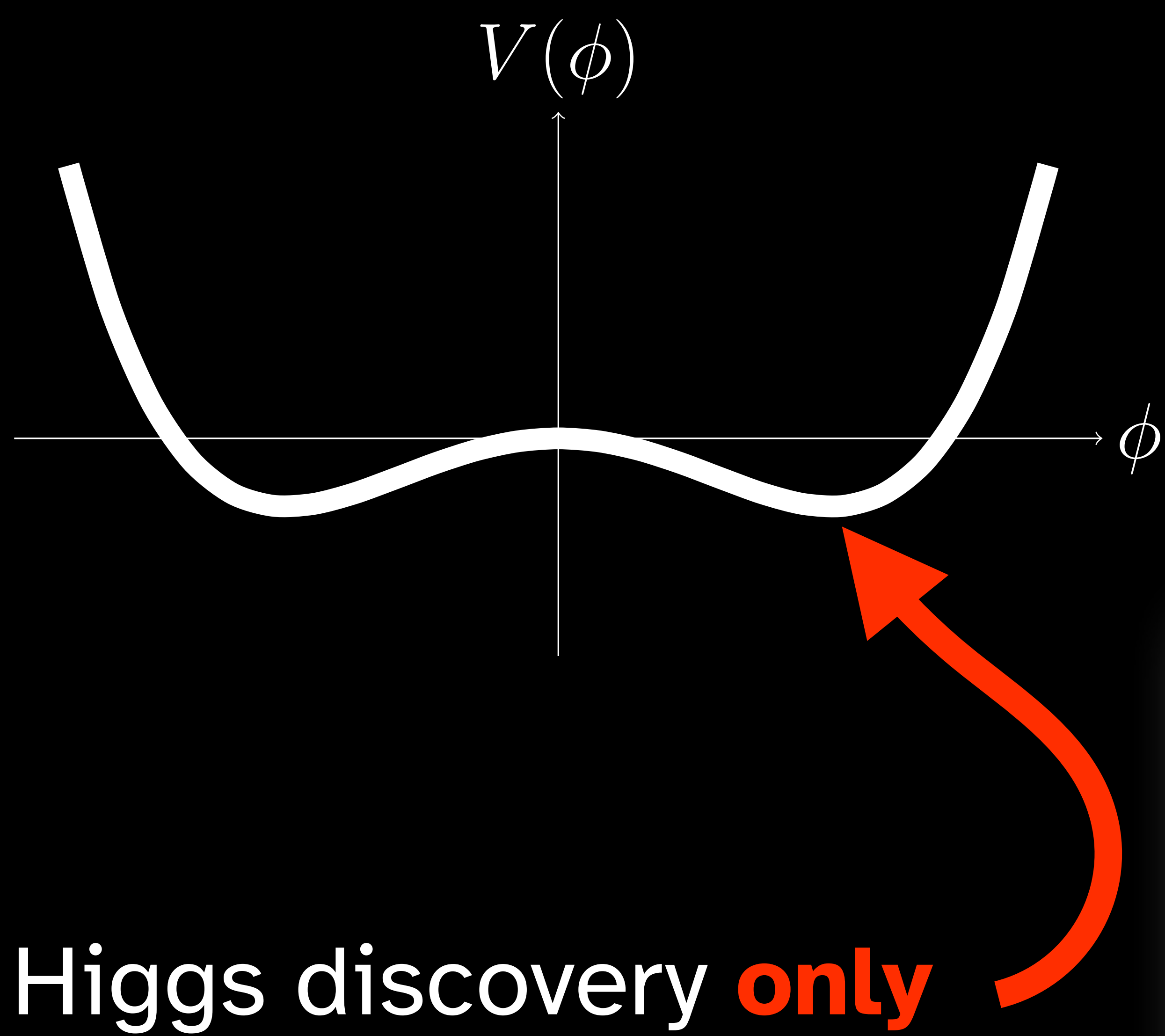
D Schulte at IMCC Annual





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



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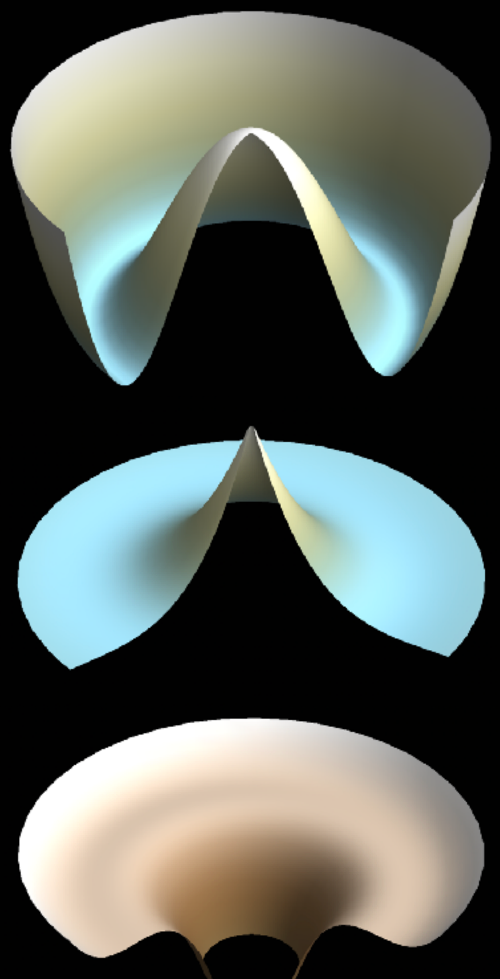
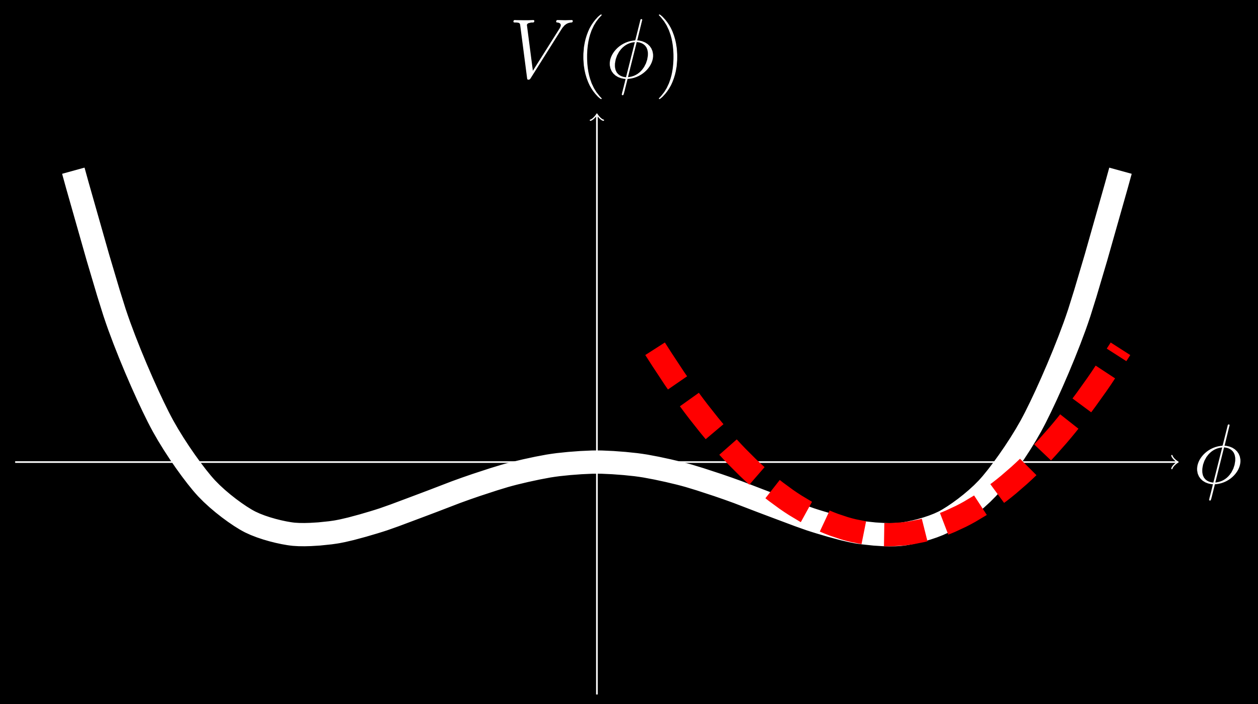


Current knowledge consistent with a wide range of Higgs potential shapes

N Craig & R Petrossian-Byrne

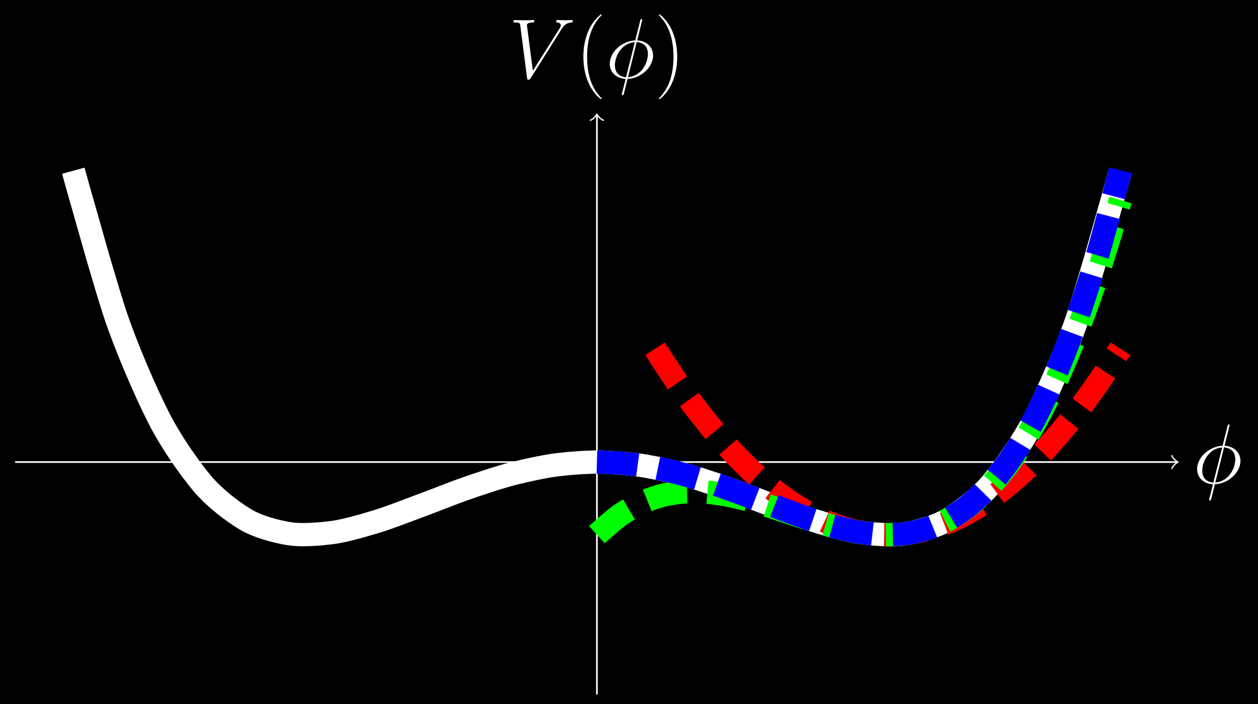


We've only confirmed the Harmonic Oscillator term of Taylor expansion around minimum

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

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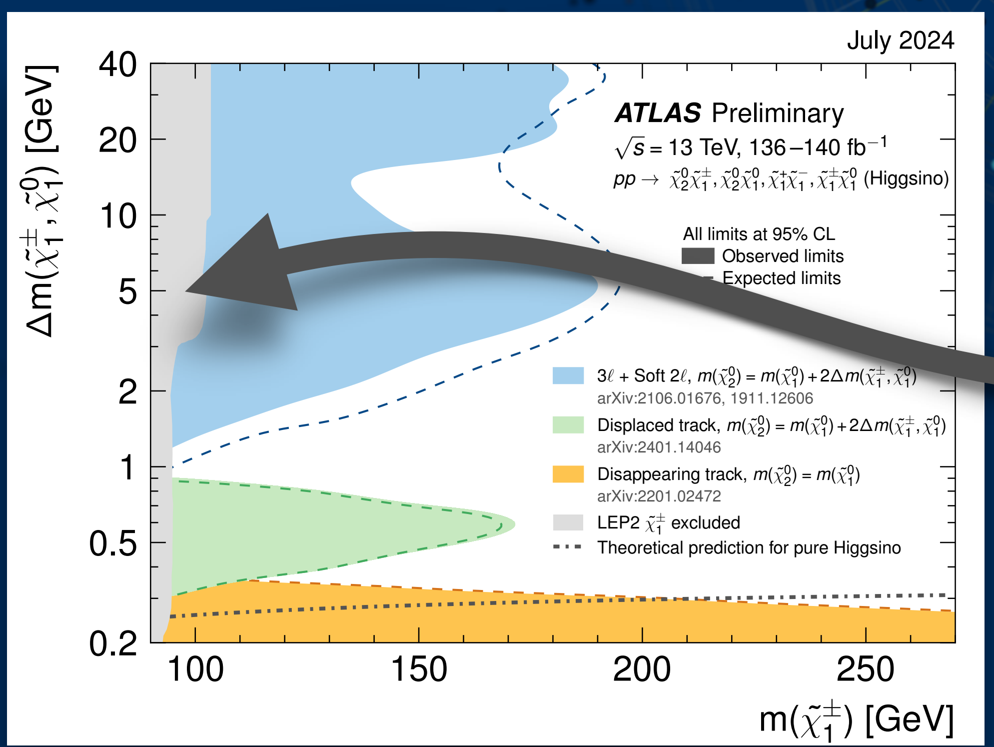
Annihilation processes with potential radiation effects

Or μ's radiate Vector bosons which then interact

A virtual cloud of bosons interacting. "**VDF**" Vector Boson Distribution Function gives a spread of hard scatter energies

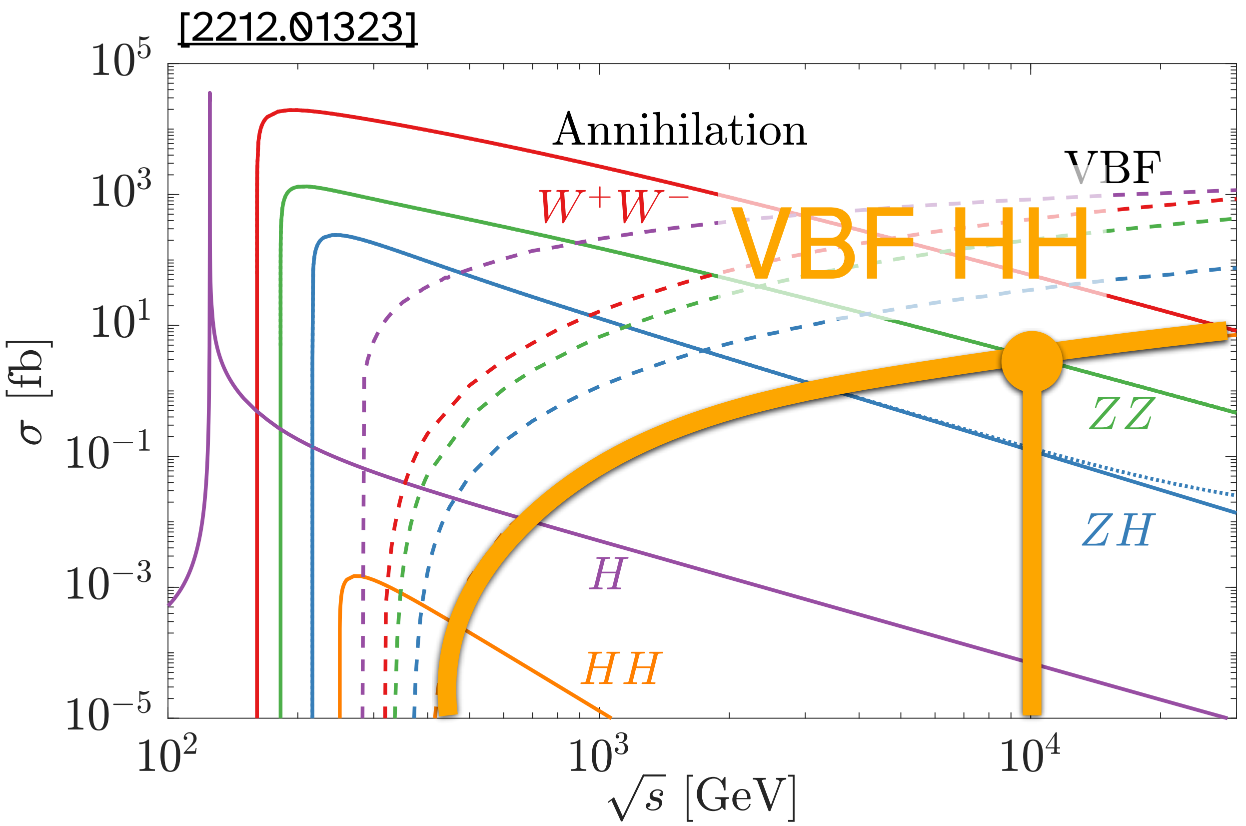


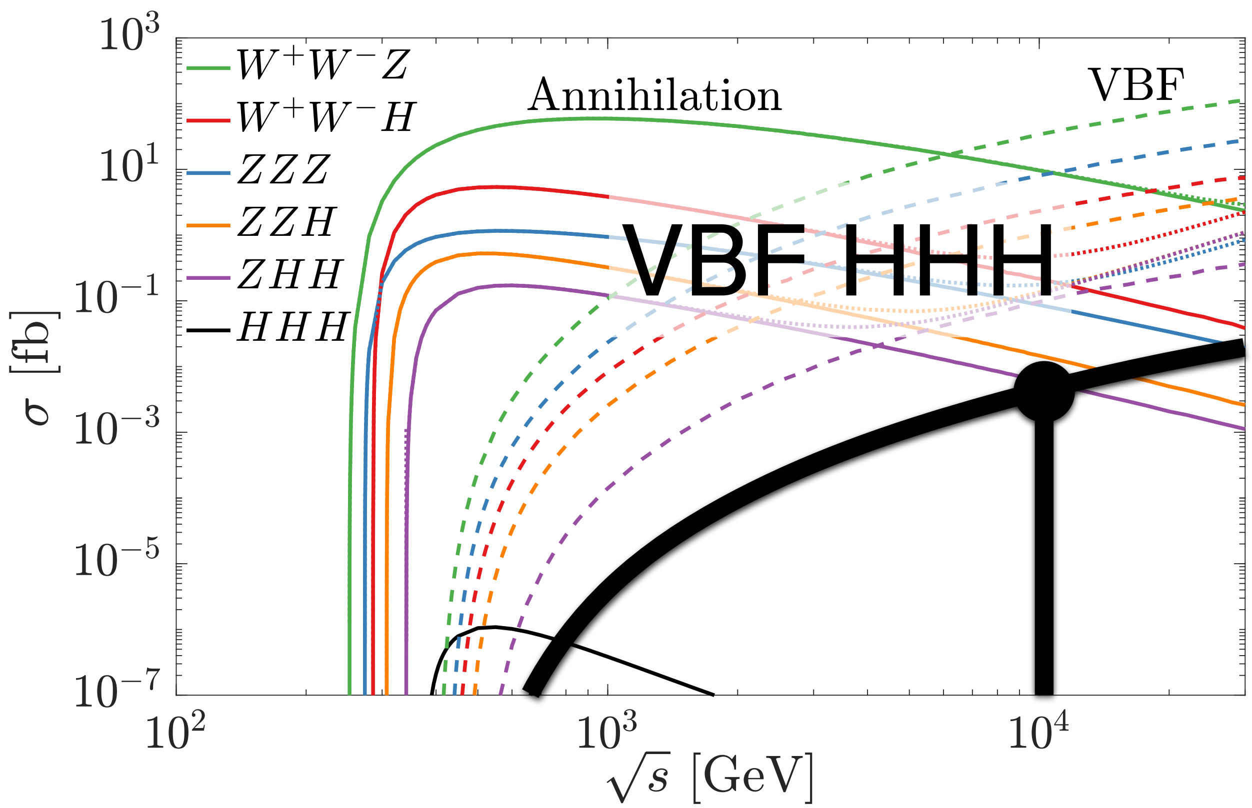
LEP also benefitted from this effect (in ɣɣ)

@10 TeV, you get massive vector boson radiation!

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

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





“Why” you should care!

"Why" you should care!

- **SM predicts wine bottle potential; we usually just assume it's right**
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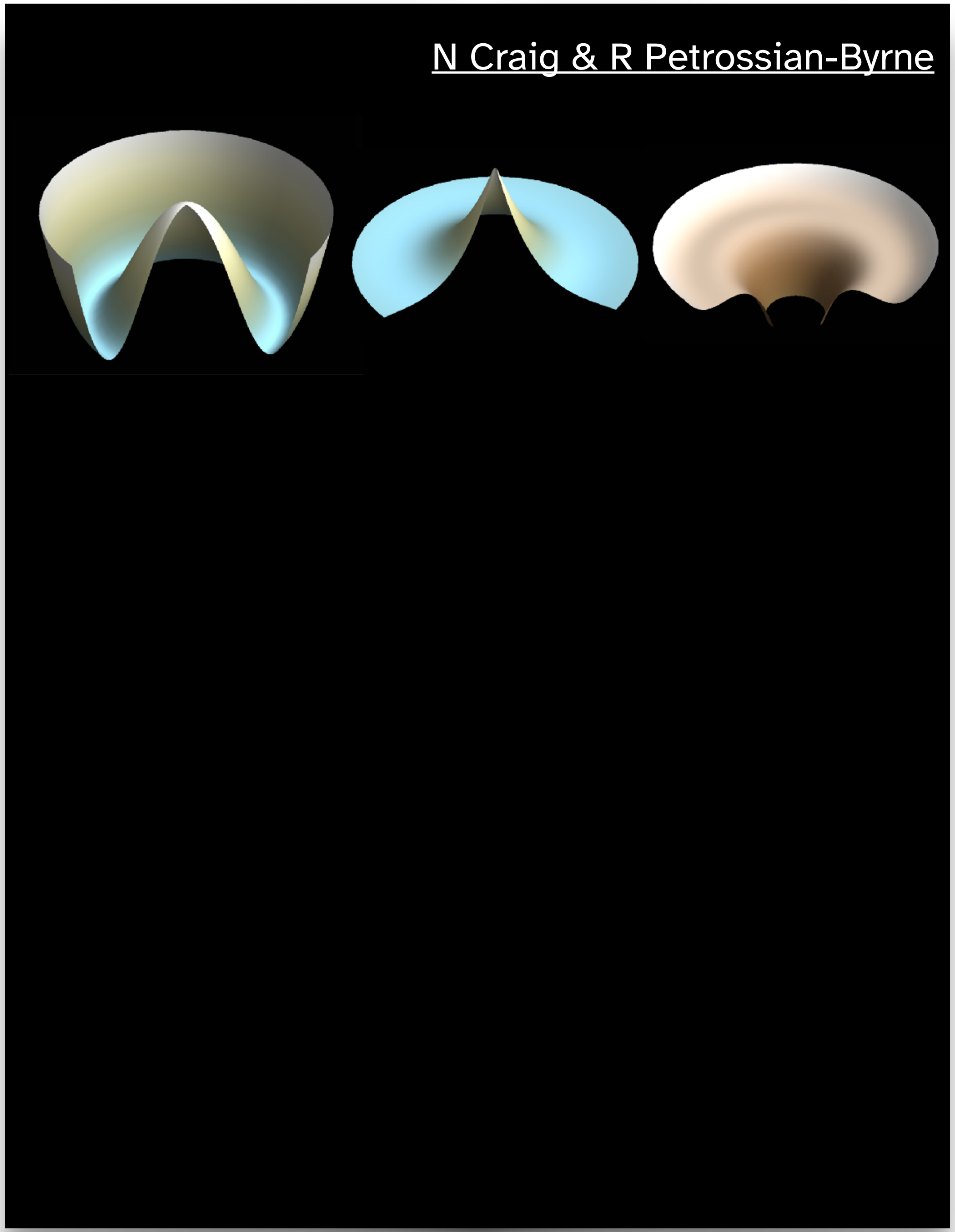
  - What if it's only a local minimum? Is the universe waiting to tunnel to a global minimum?



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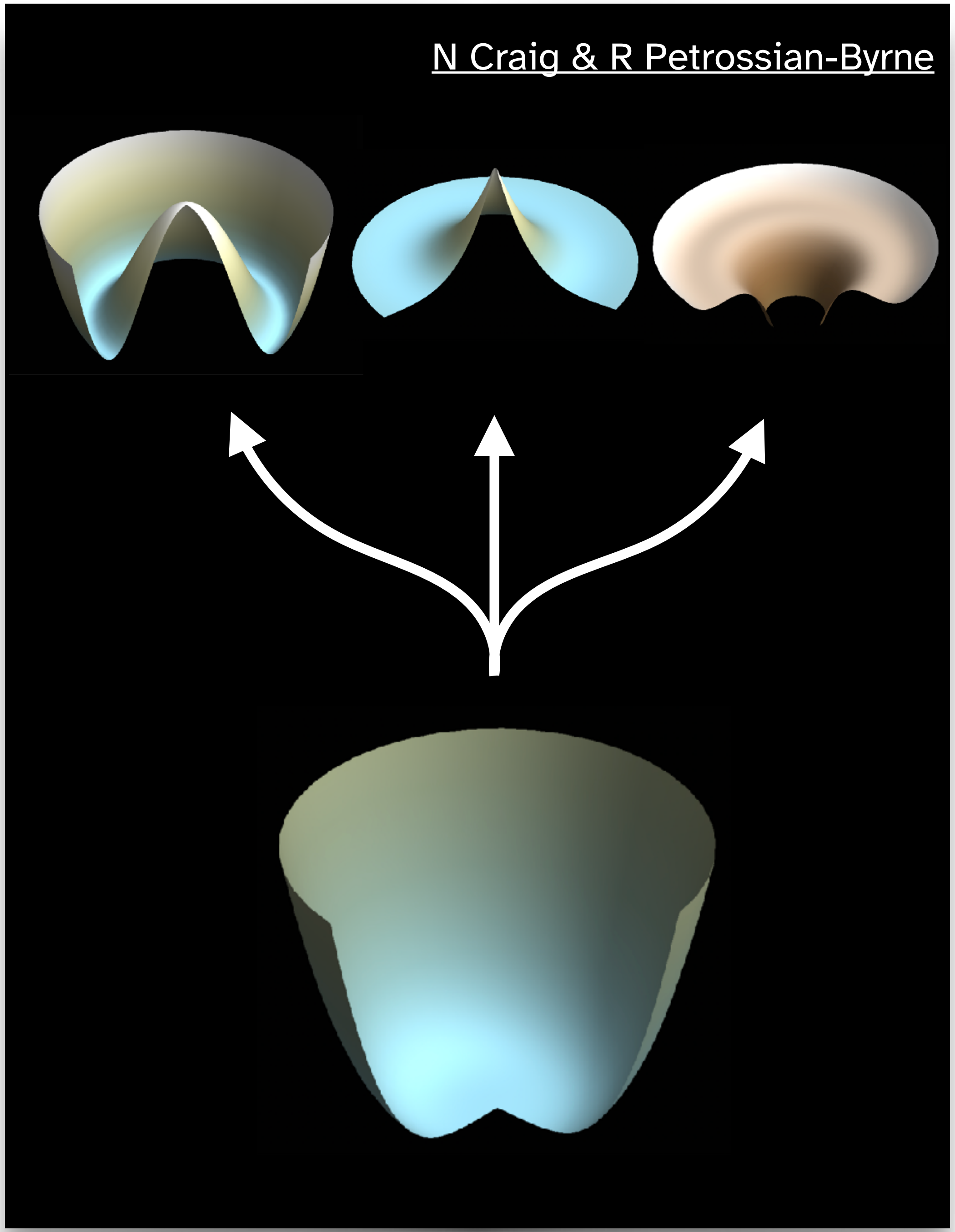
  - Probe the potential well above EW-scale → See EW symmetry restoration



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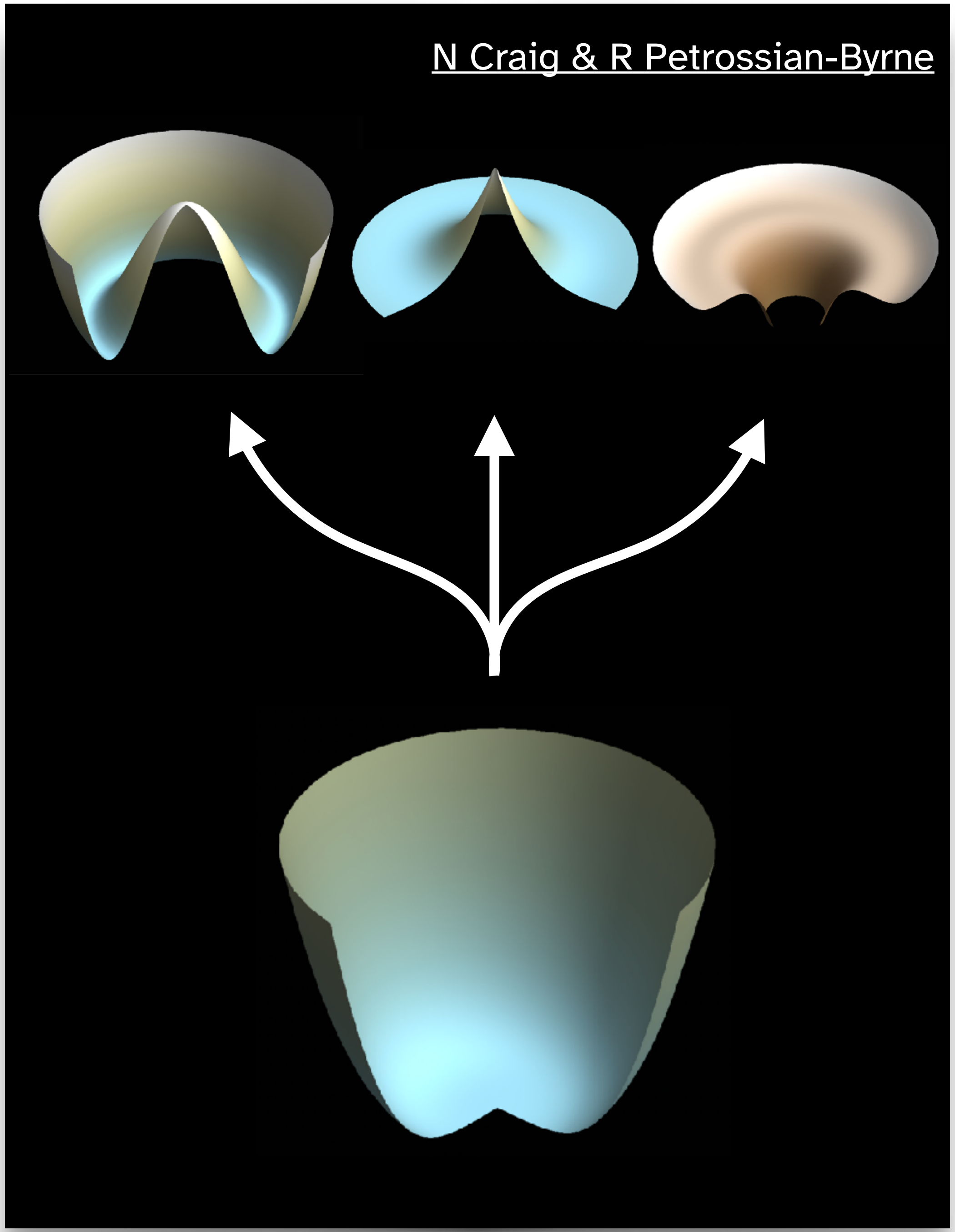
- **Currently only know *that* EWSB happens! Not how or why!**
  - Probe the potential well above EW-scale → See EW symmetry restoration
- **This is about the birth and eventual fate of the universe**
  - **And *requires* the 10 TeV scale**

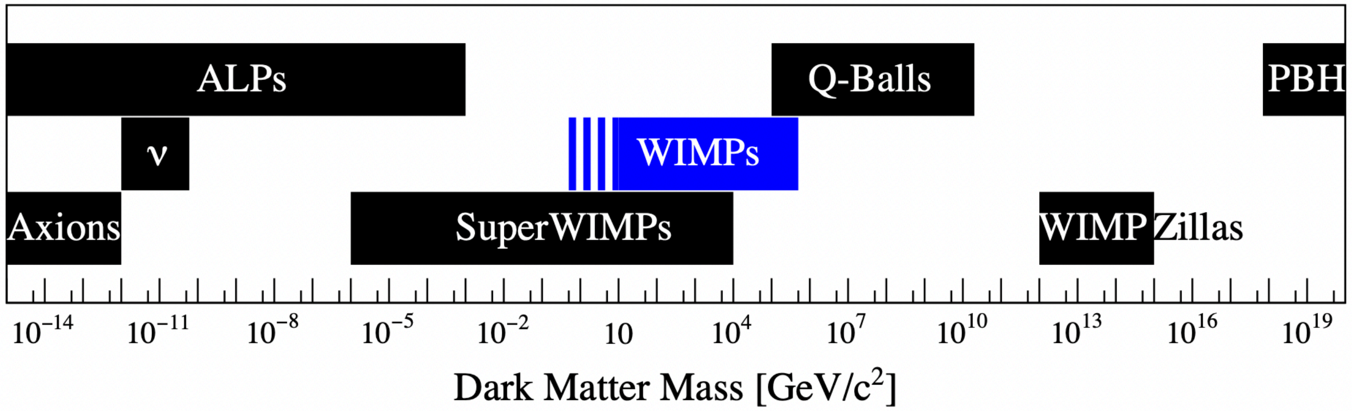


WIMP Dark Matter: Still Miraculous

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!



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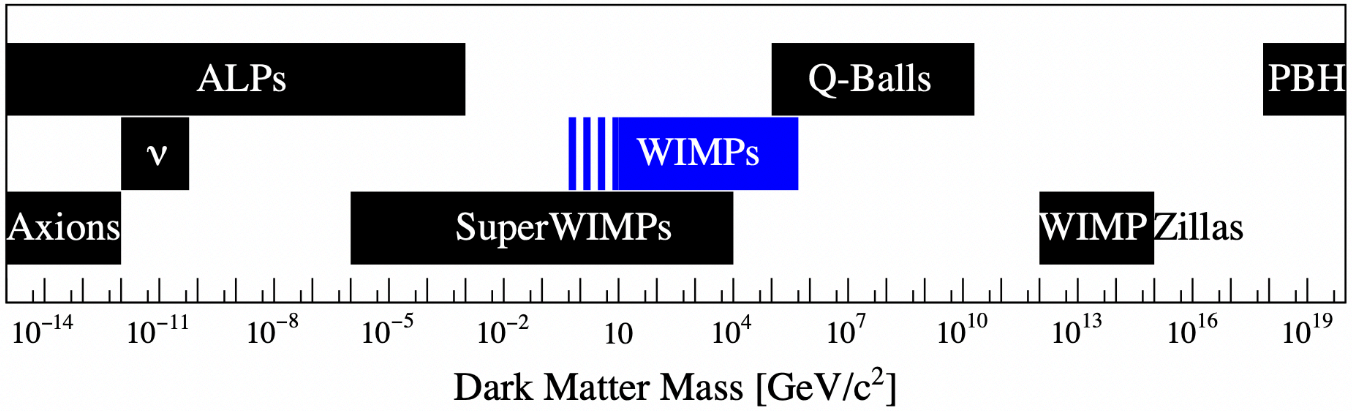
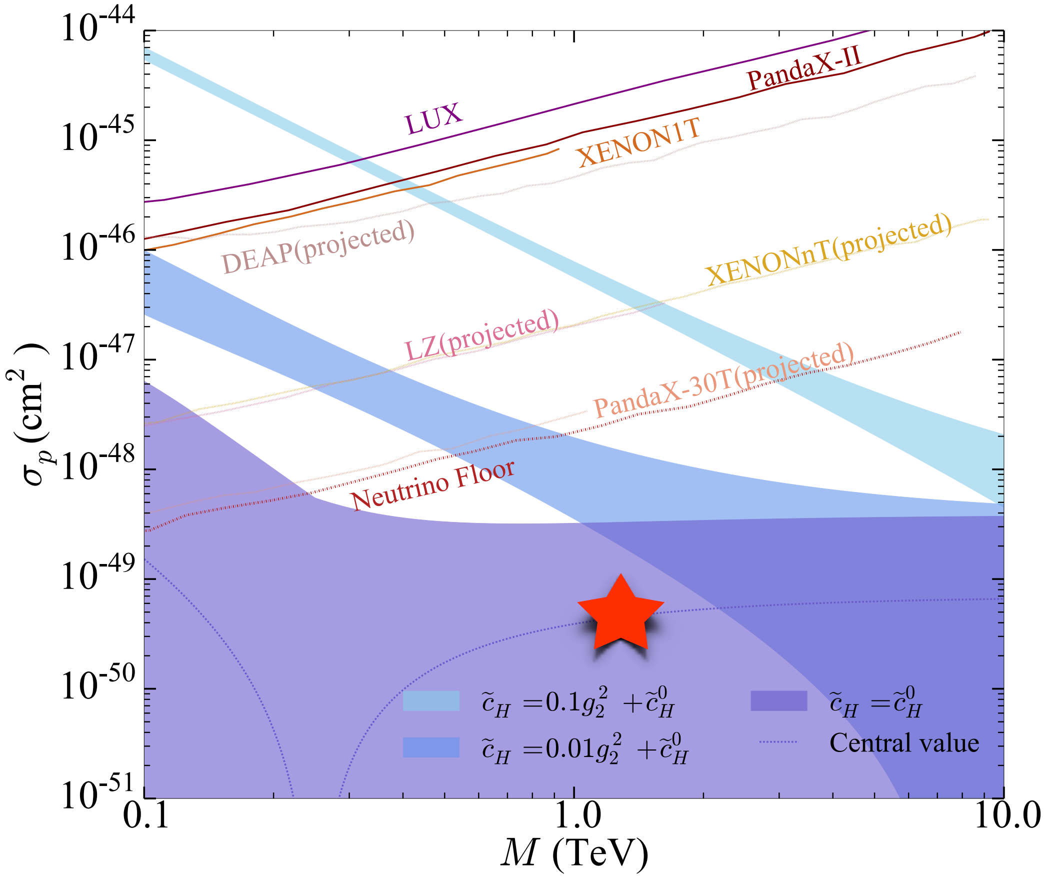


e.g. Thermally-produced Higgsino-like DM should have ~1 TeV masses.
We've ***never*** had sensitivity this!

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

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

[1912.07795]



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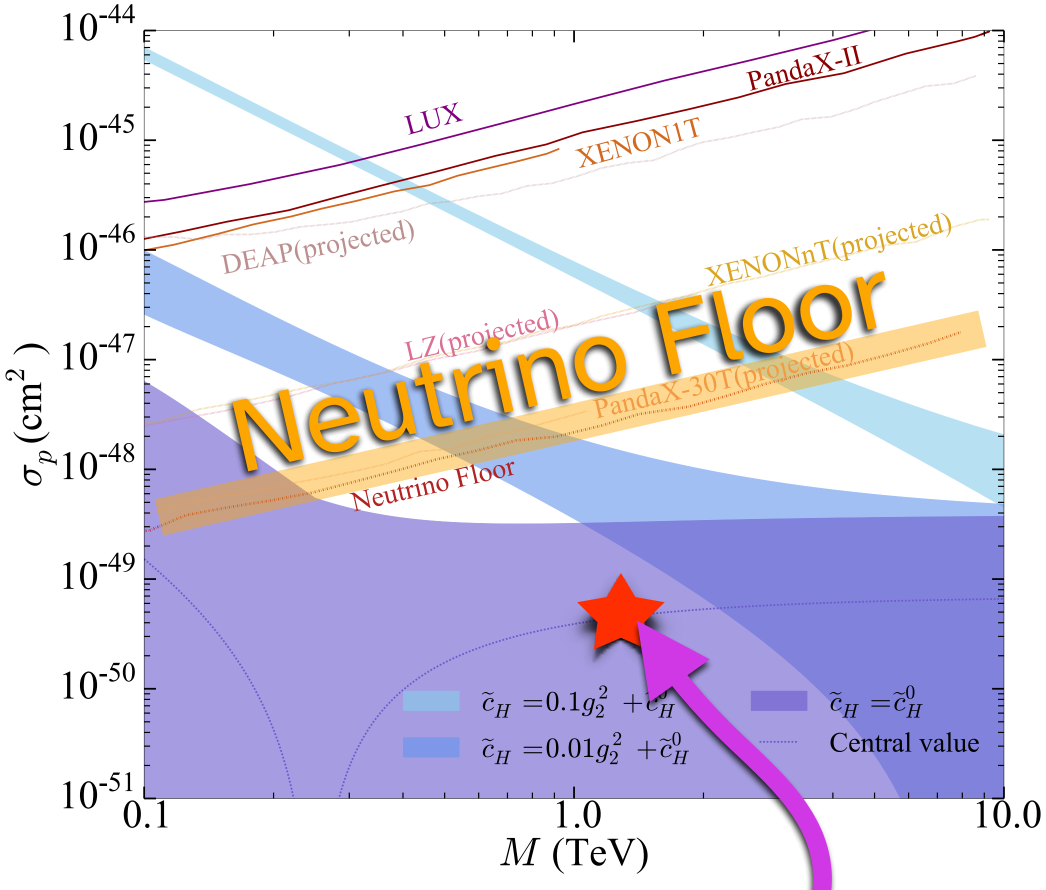

Pure Higgsino DM **Direct Detection** is under neutrino floor!

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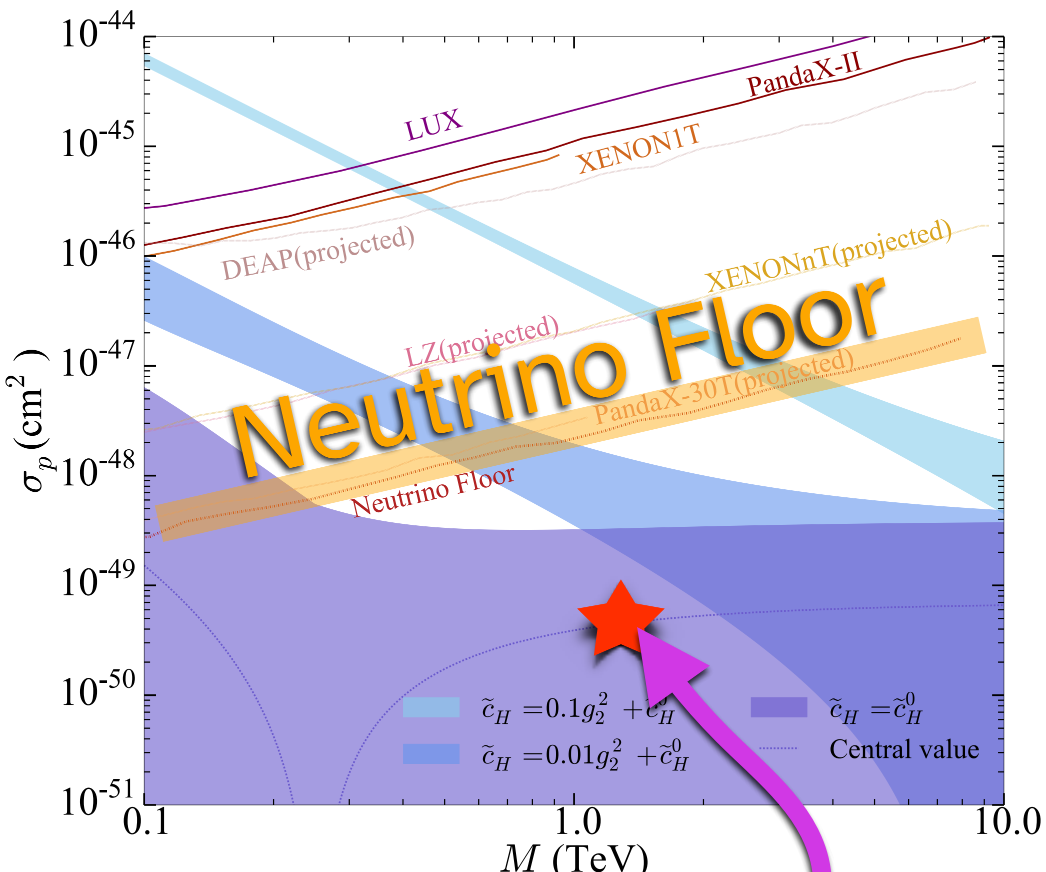

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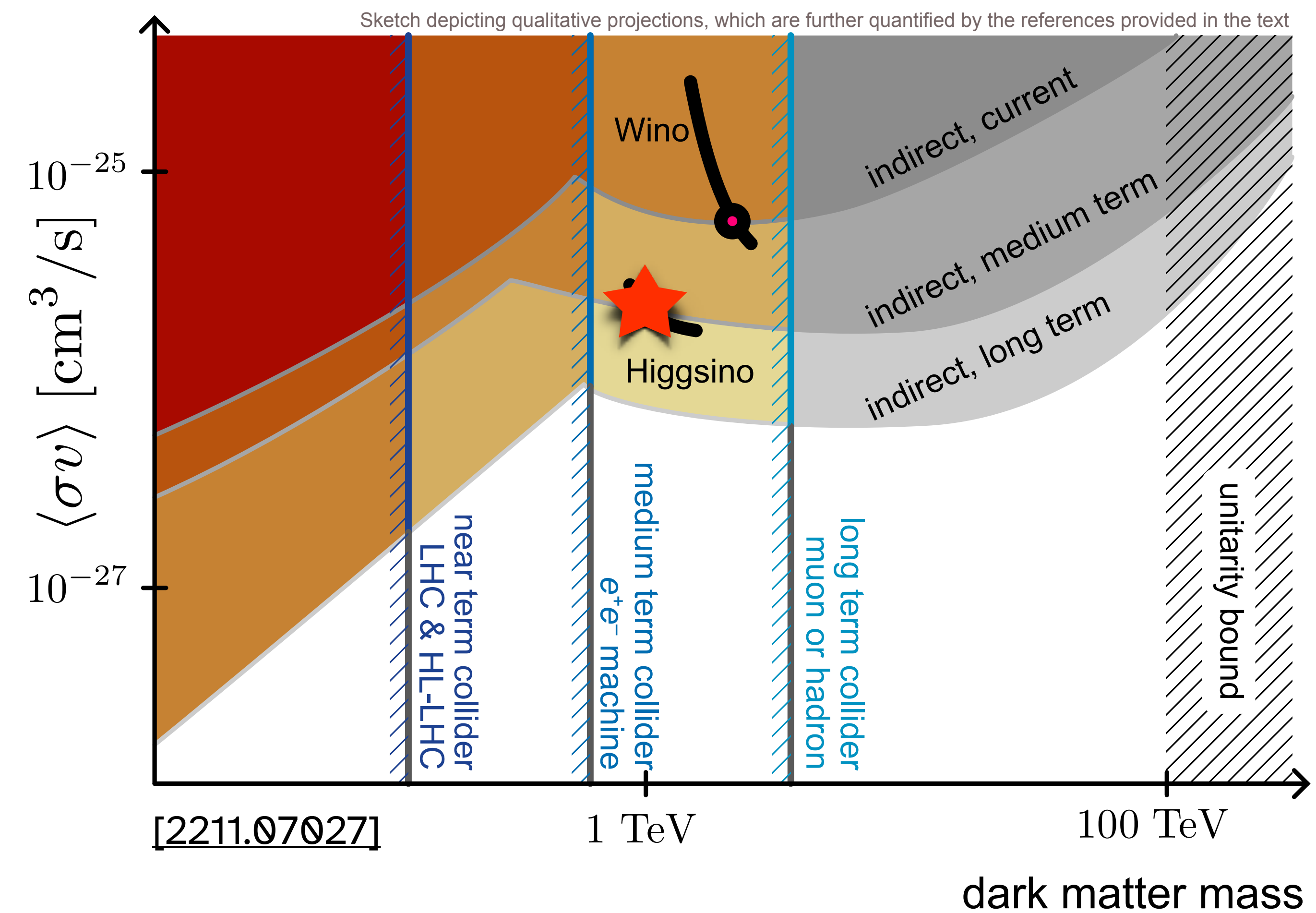
Pure Higgsino DM **Indirect Detection** not yet sensitive



[2211.07027]

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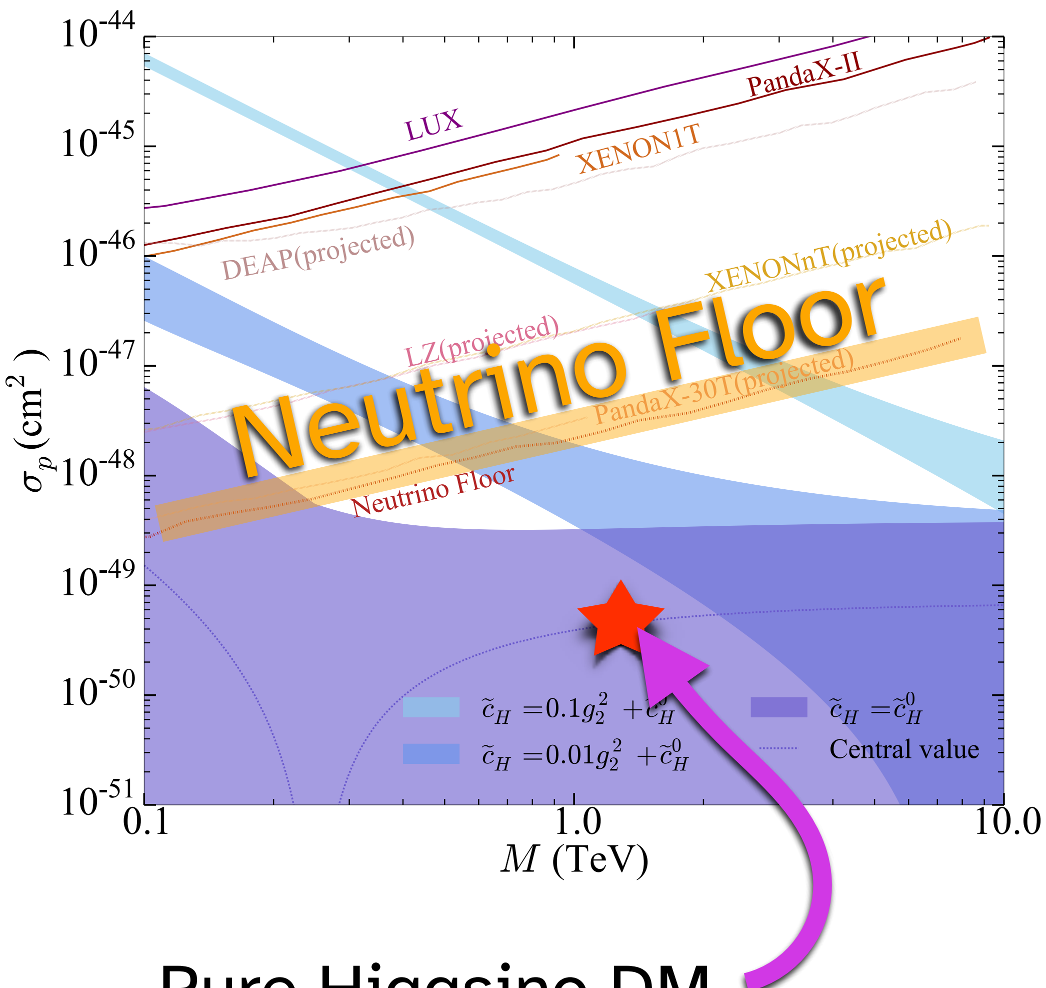

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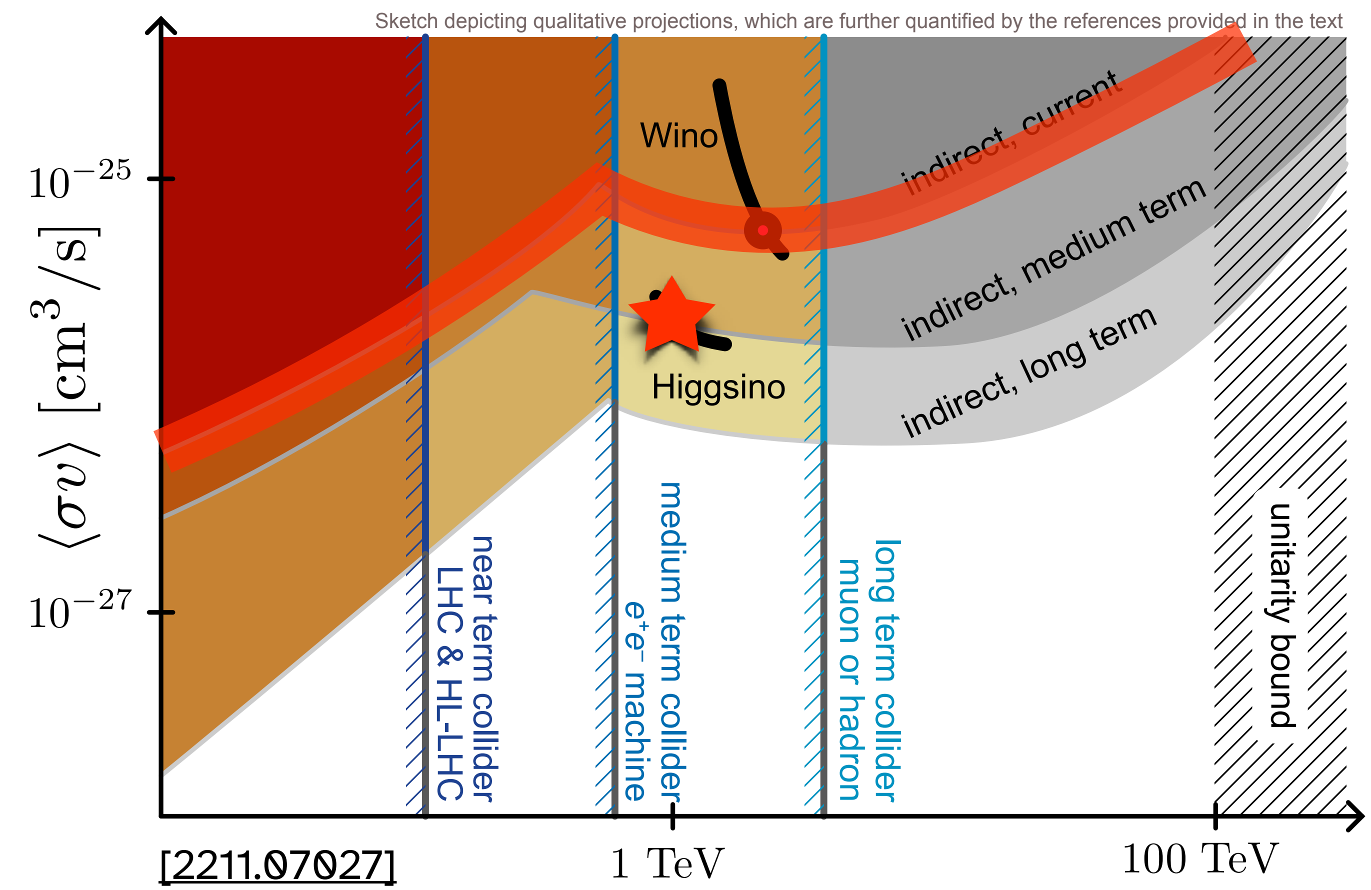

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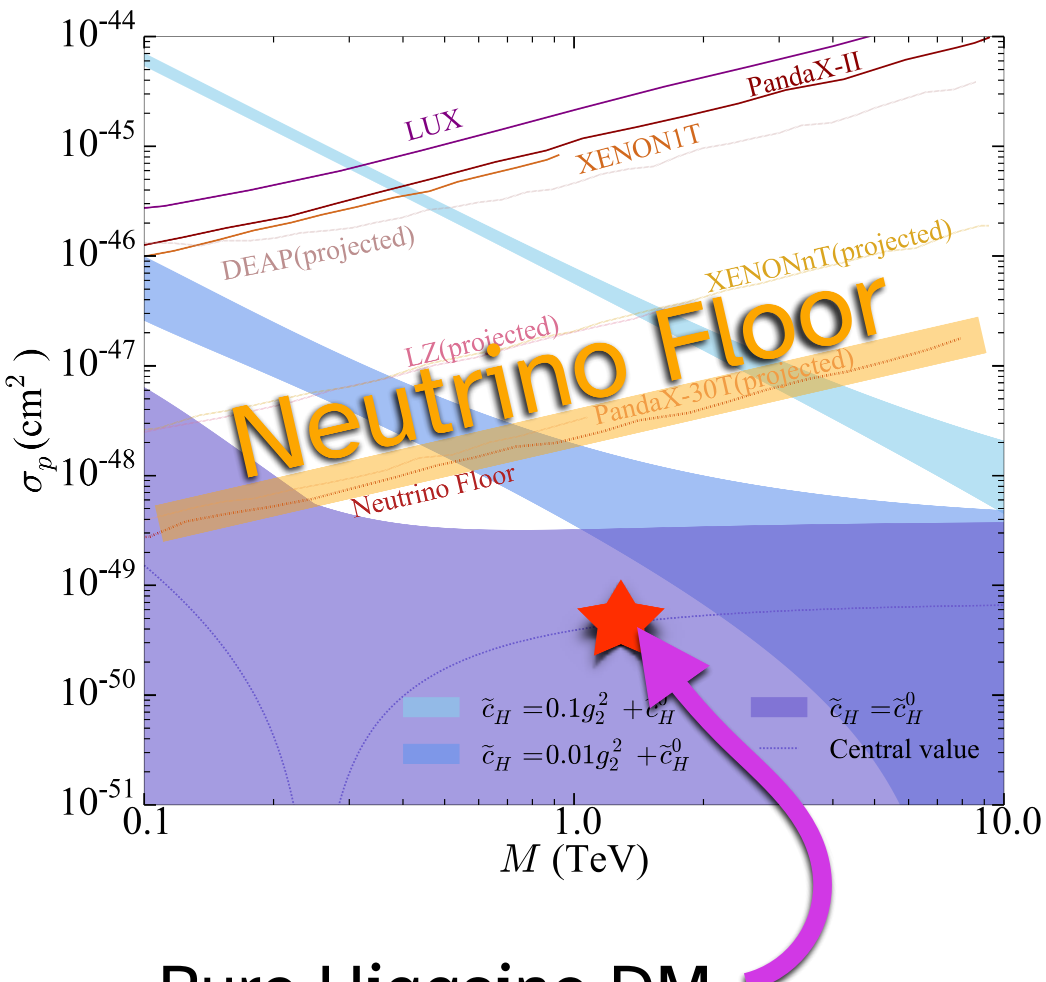

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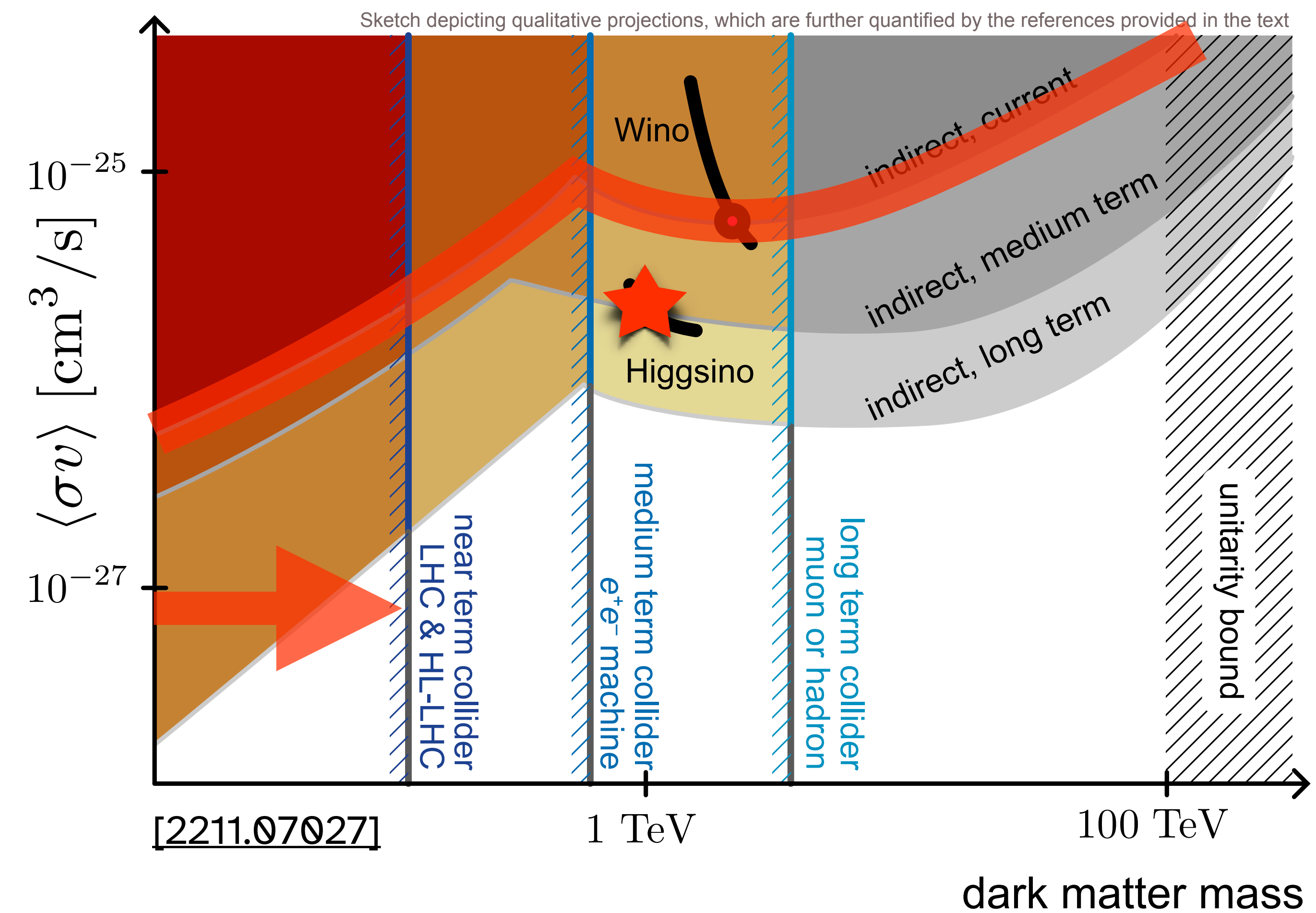

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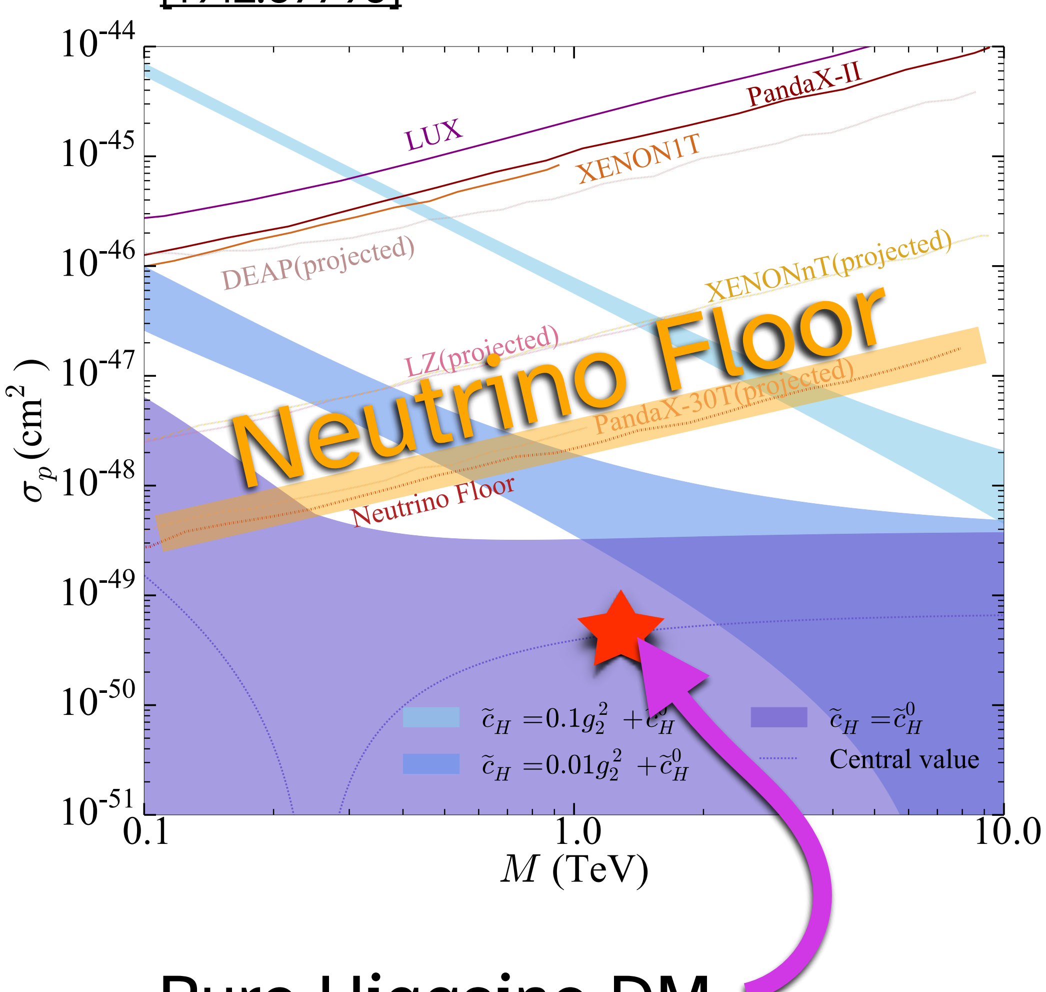

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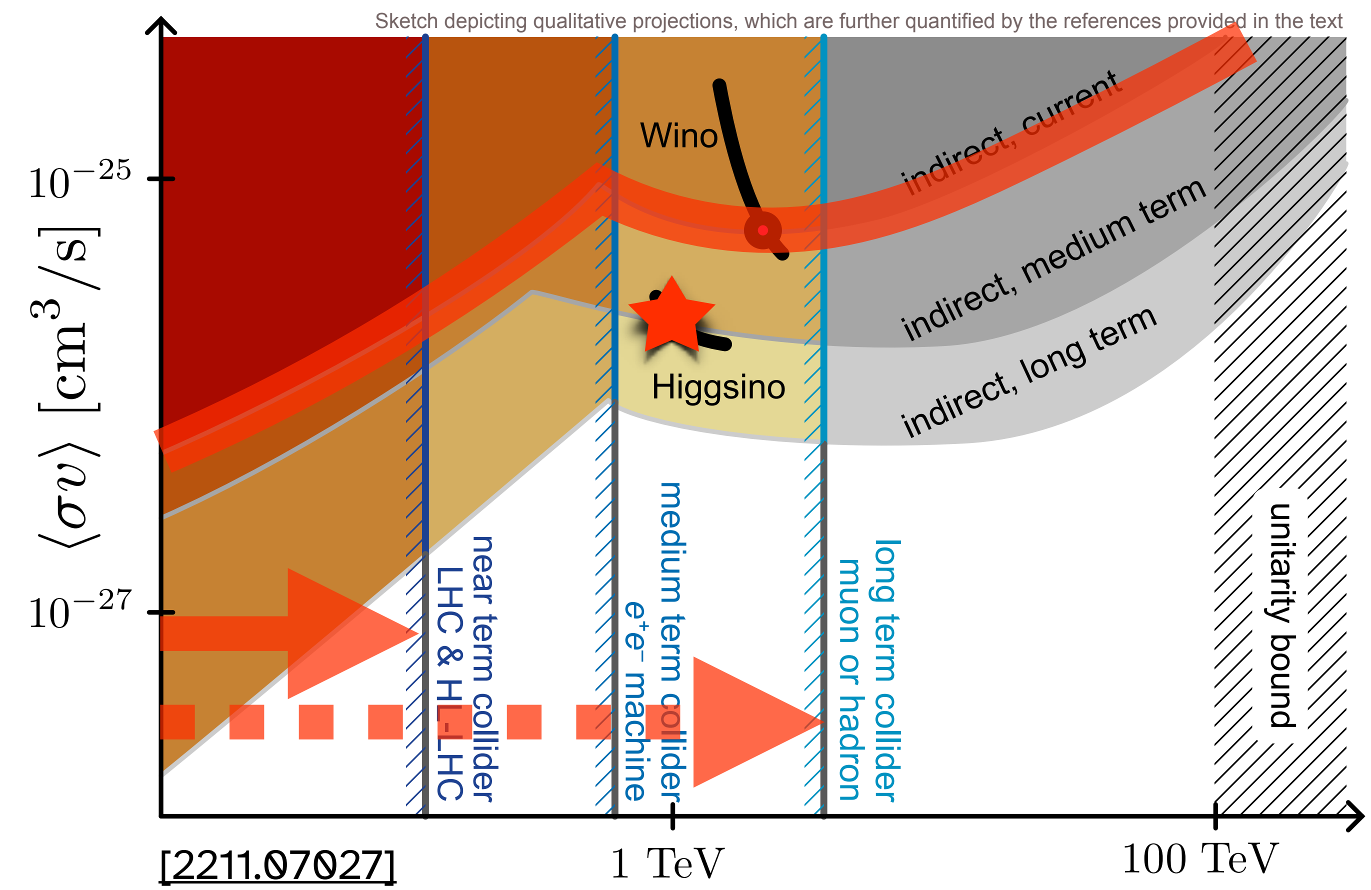

[2211.07027]

A multi-TeV-scale collider could see 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?

}

Only the multi-TeV scale will tell us this!

Motivations for going as high as possible?

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3) Naturalness

}

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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?

pp ee

μμ

Often hear:

“ μμ has **discovery** power of pp & **precision** of ee.[1] ”

[1] Except w/ the BIB it looks nothing like ee. Don’t worry about it…

pp ee

μμ

Often hear:

“ μμ has **discovery** power of pp & **precision** of ee.[1] ”

[1] Except w/ the BIB it looks nothing like ee. Don’t worry about it…

μμ is **very messy** and does **not** give the level of cleanliness of ee.

These are not easy experiments.
Have large instrumental BGs like at pp!

pp ee

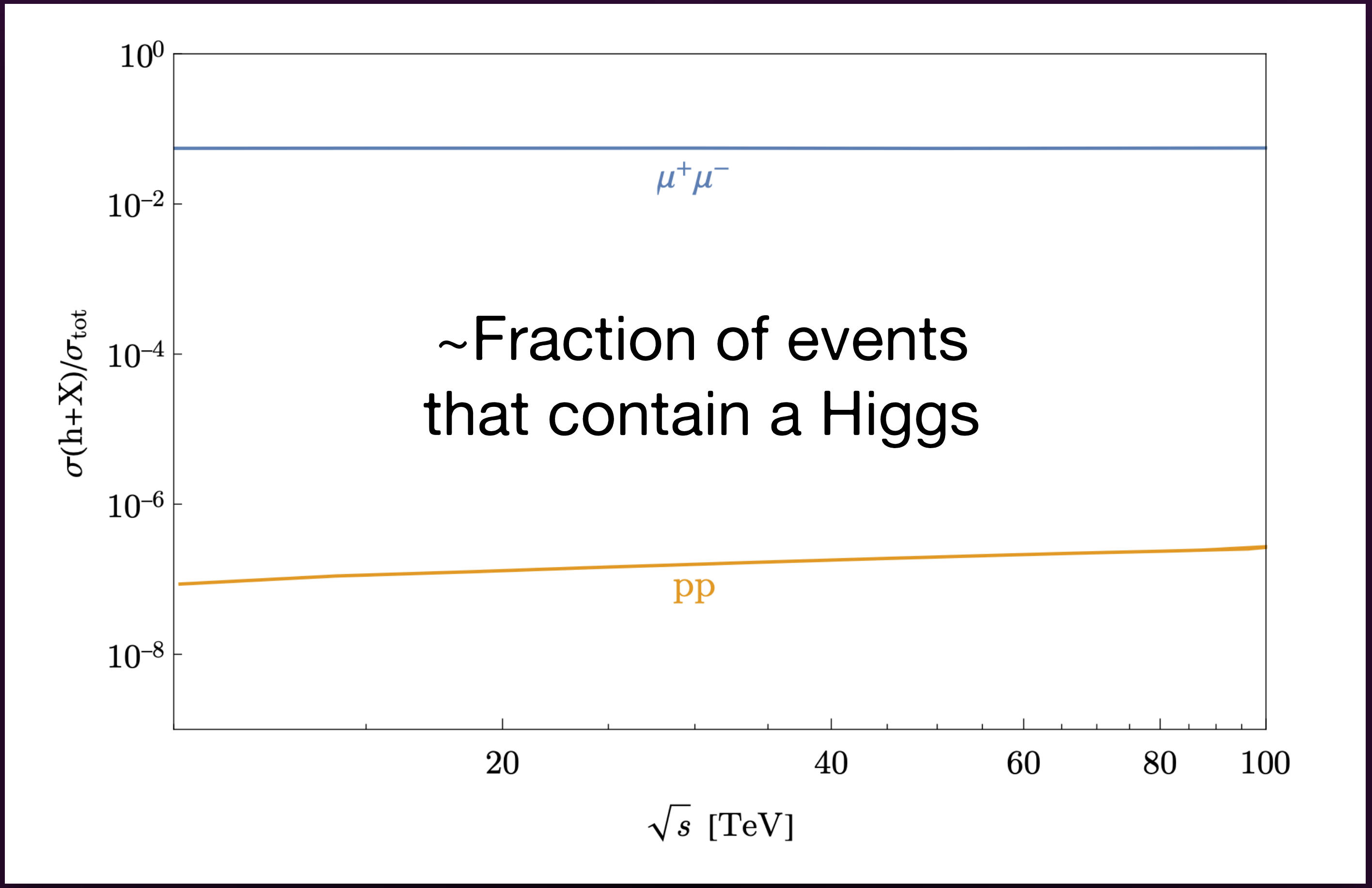
μμ

Muon Smasher's Guide

But… the physics **processes are clean!**

μμ is not swamped in the QCD gunk that hadron colliders have…

We're lucky to be dominated by instrumental BGs!



pp ee

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Muon Smasher's Guide

But… the physics **processes are clean!**

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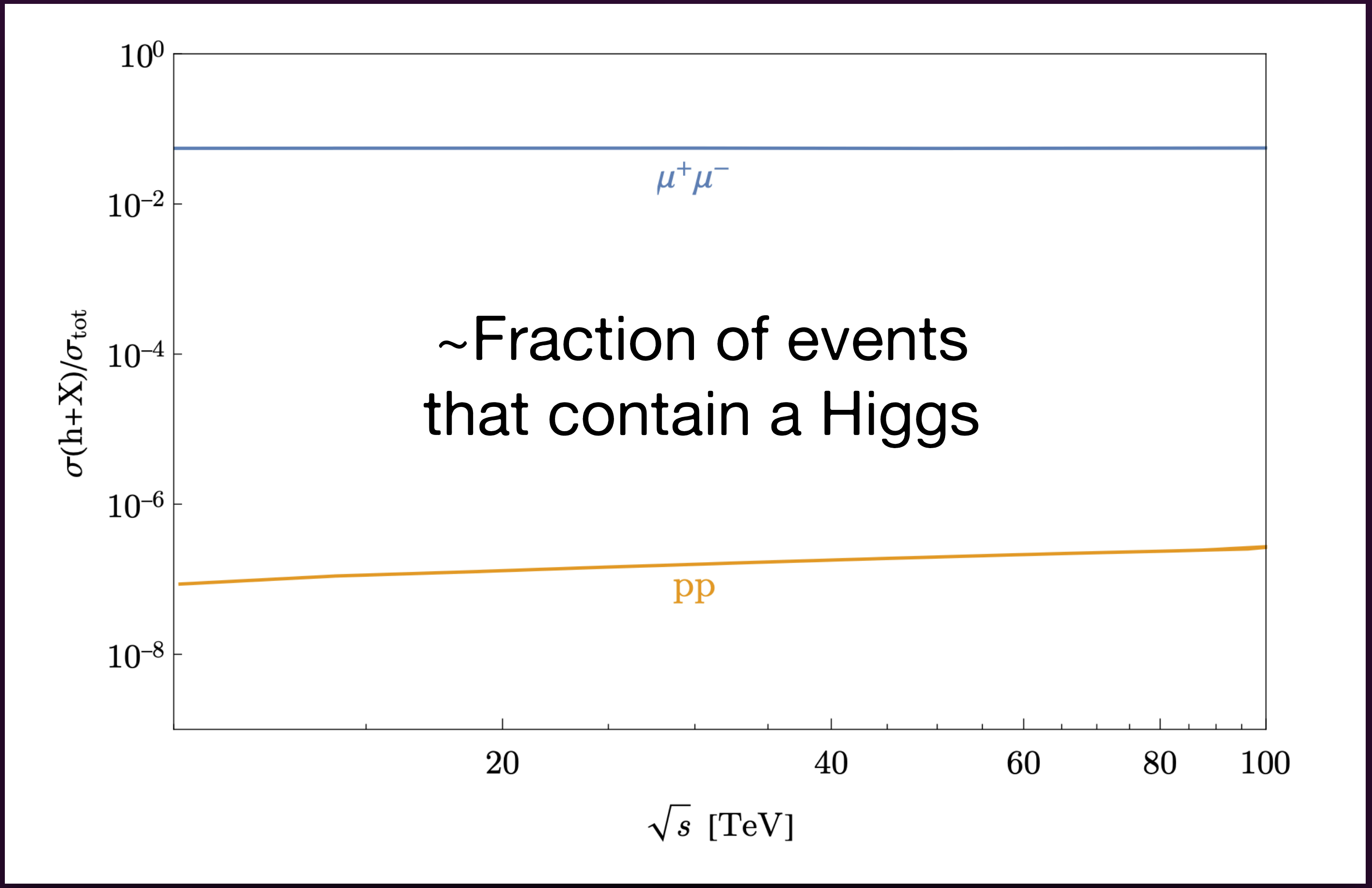
We're lucky to be dominated by instrumental BGs!

Without caveat, it's true that we get **some of the best features of both worlds!**



" μμ has **discovery** power of pp & **precision** of ee.[1] "

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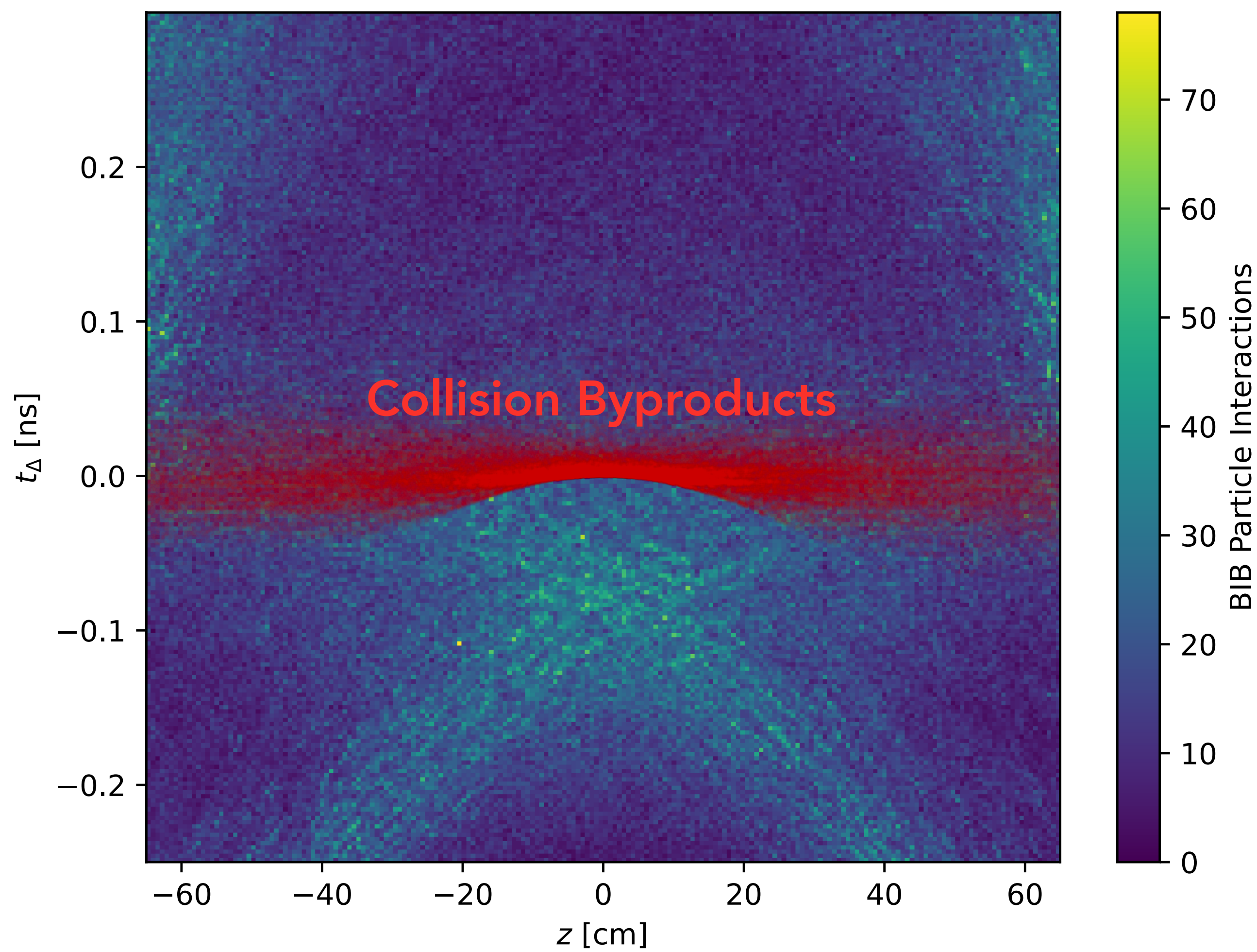
E.G. TRACKER

- **Closest to the beam — most affected by BIB**
- BIB hits plague readout and offline tracking algorithms
- Build trackers with more information to reject BIB hits on-/off-detector
- Instead of a point in 3-space:
  - Every hit should be an event in **space-time** with precision timing
- **Precision timing is central to any muon collider detector design**

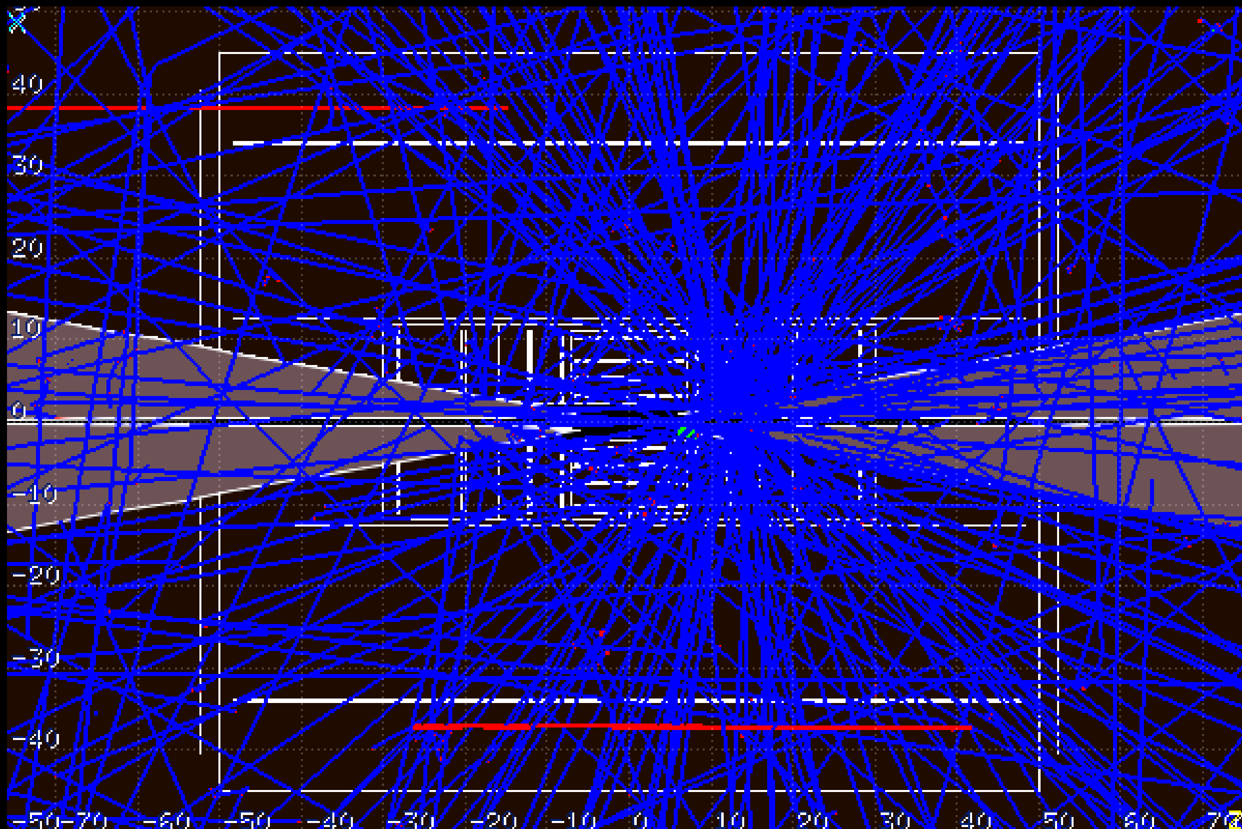
$$t_\Delta = t - t_{exp}(\beta = 1)$$



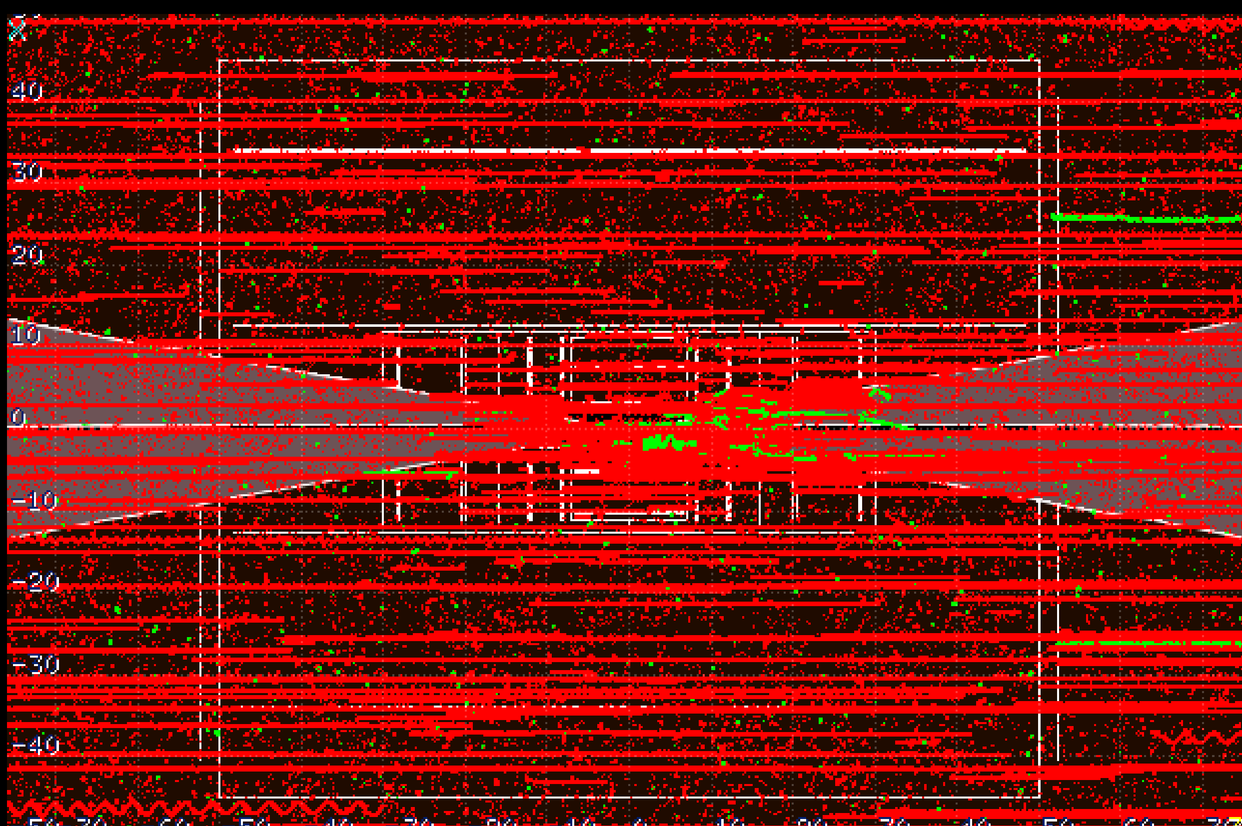
∃ information on ~10 ps scale to differentiate **BIB** from **signal**

Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]

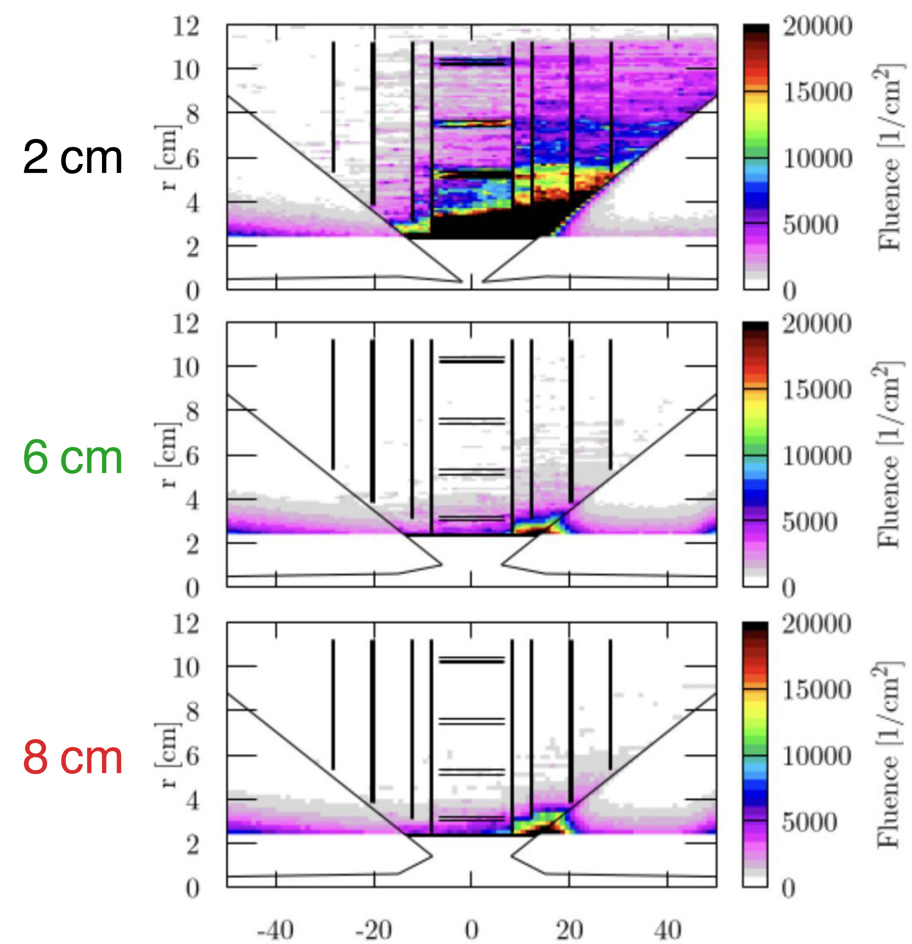
0.003% of BIB, dominated by stray photons



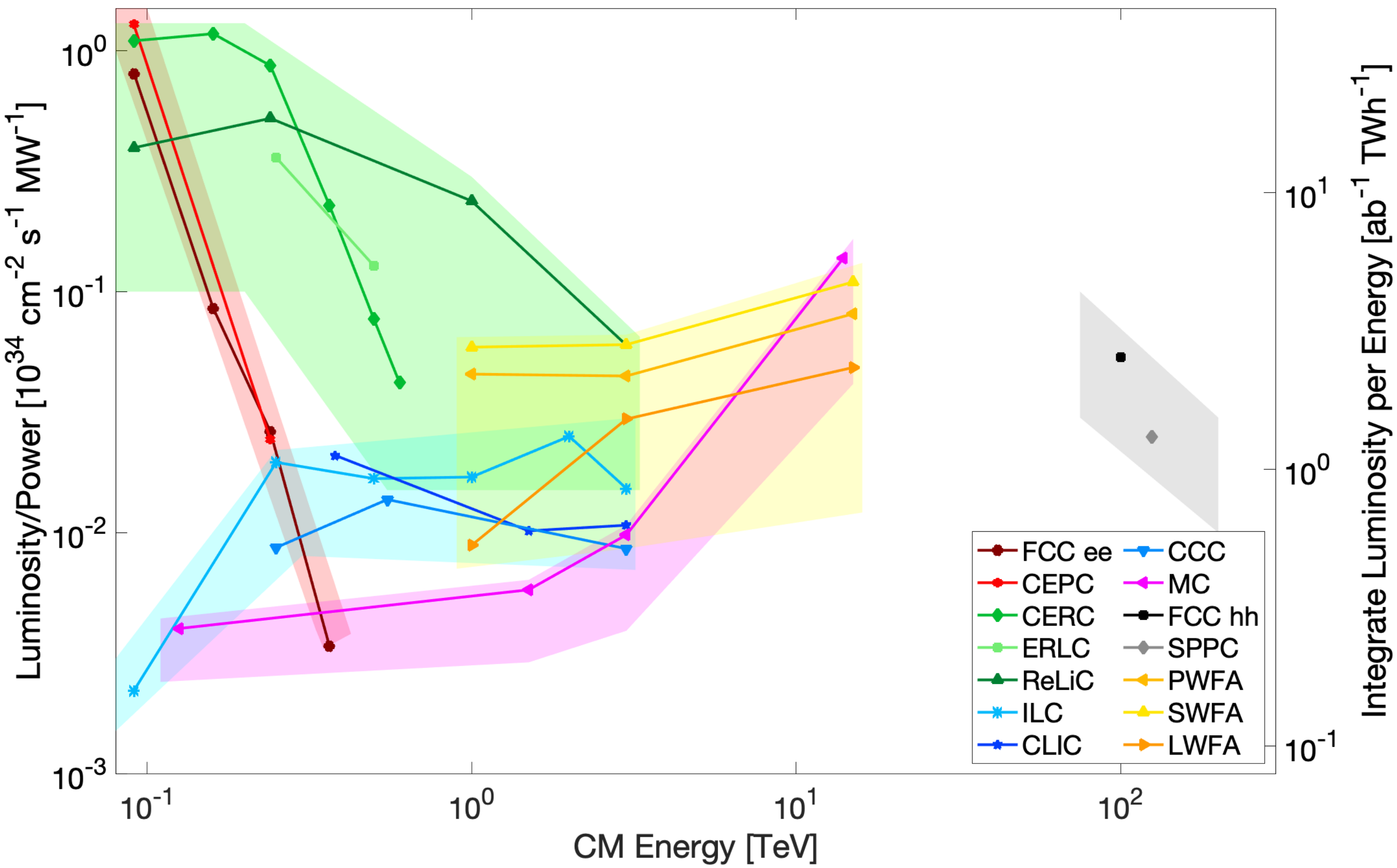
0.03% of BIB, w/ photons removed



D. Calzolari via Slides by T Holmes



[2208.06030]



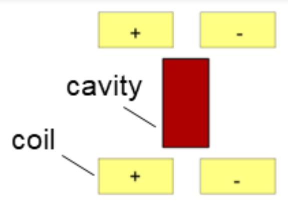
A Muon Collider's power efficiency increases with beam energy

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

Demonstrator staging

- Parameters are aspirational and may need modifications based on available funding and resources

Phase-I

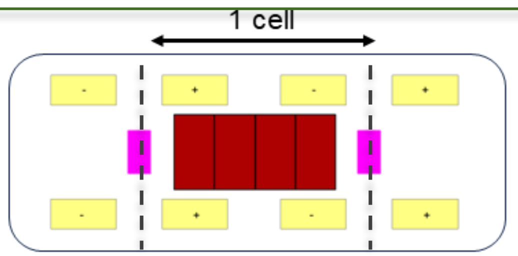


RF studies in B-fields

Material studies & cryogenics

600-800 MHz NC cavity, with coils making 10-14 T on axis

Phase-II

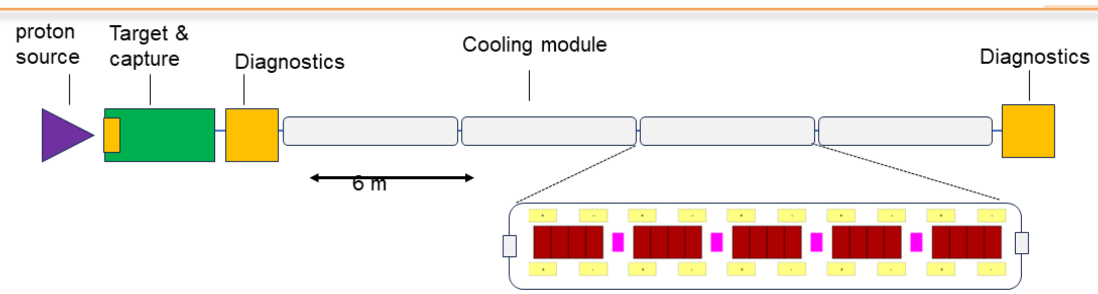


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III



Full demonstrator with beam

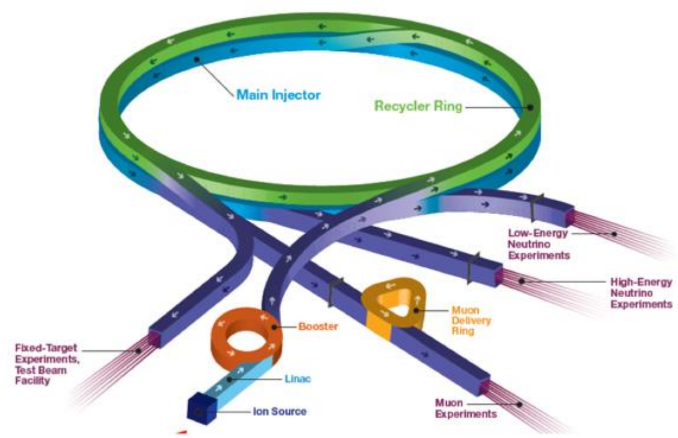
Coils producing 7-10 T axial fields

Potential to achieve 50% 6D cooling

Fermilab

Fermilab acceleration evolution plan

- **Fermilab's ACE program** could become the basis for developing a proton driver and R&D platform for a Muon Collider
- Includes a rigorous target R&D program for 2+ MW beams in the next decade
- Can serve as a basis for a Muon Collider demo facility and a Muon Collider front-end



1.2 MW
- PIP-II Project replaces Linac
- Modernization/upgrades of complex

< 2030 → A path for a MuC demonstrator

ACE

2 MW
- Reliability upgrades
- Main Injector capabilities (cycle time)

ACE-MIRT Upgrades to existing machines

- Target Systems capability improvements

~ 2030 → A path for MuC targetry R&D

2.4 MW
- Booster replacement
- New physics capabilities

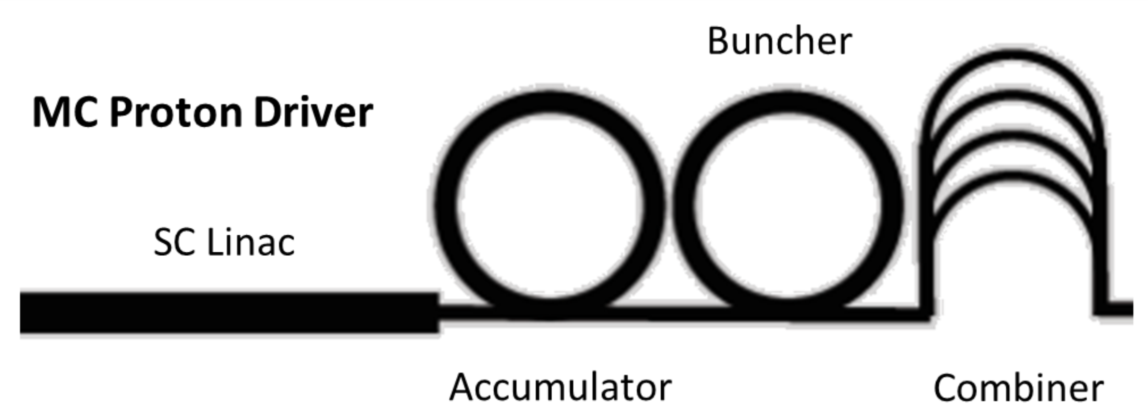
ACE-BR New machine

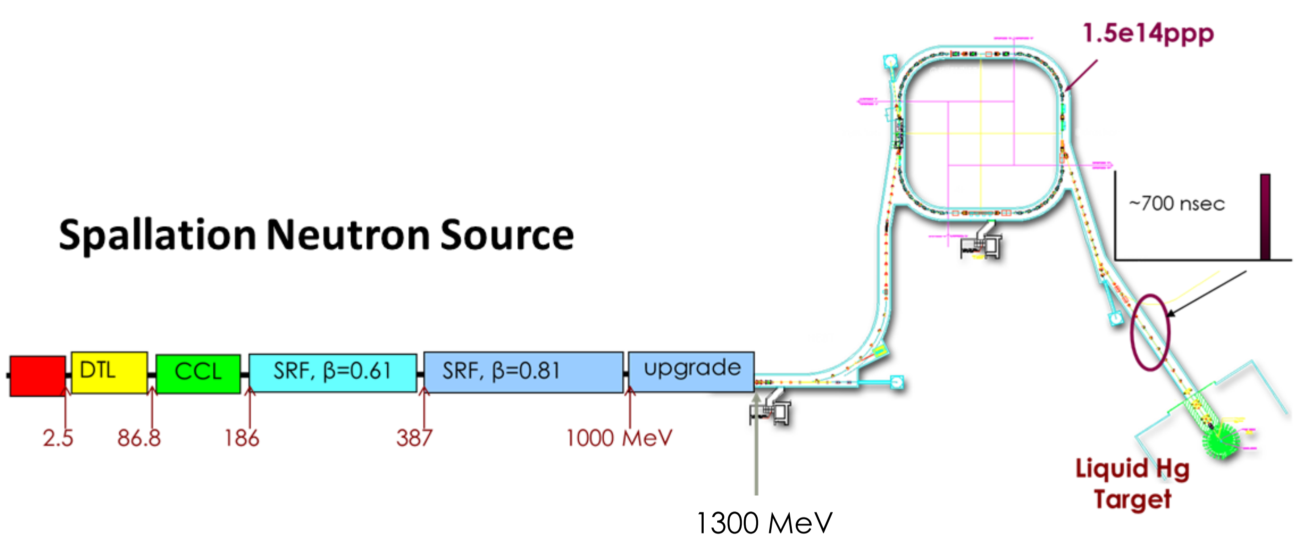
>2030 → A path for a MuC proton driver

SNS versus Muon Proton Driver

- SNS is a close lower-energy analog of muon collider proton driver
- $\beta^{-2}\gamma^{-3}$energy scaling of space-charge effects makes up for some of the lower bunch density
- Perveance
  $K \equiv 2\, r_p N_p / (\sqrt{2\pi}\sigma_z\, \beta^2\gamma^3)$

Parameter	SNS (nominal)	MC Proton Driver (compressed)
P (MW)	2.8	2 – 4
T (GeV)	1.3	5 – 30
N_p (10^{14})	2.2	0.4 – 10
R (Hz)	60	5 – 10
σ_z (m)	95	0.3 – 0.9
K	$2.6 \cdot 10^{-7}$	$1.6 \cdot 10^{-9} – 1.7 \cdot 10^{-5}$





SNS at Oak Ridge

Muon Collider Challenges and Progress

Challenge	Progress	Future work
Multi MW proton sources with short bunches	Multi-MW proton sources have been and are being produced for spallation neutron sources and neutrino sources (SNS, ESS, J-PARC, Fermilab)	Refine design parameters, including proton acceleration to 5-10 GeV. Accumulation and compression of bunches.
Multi MW targets	Neutrino targets have matured to 1+MW. RADIATE studies of novel target materials and designs aim at 2.4MW.	Develop target design for 2 MW and short muon collider bunches. Produce a prototype in 2030s.
Production solenoid	ITER Nb3Sn central solenoid with similar specifications and rad levels produced	Study cryogenically stabilized superconducting cables and validate magnet cooling design. Investigate possibility of HTS cables.
Cooling channel solenoids	Solenoid with 30+T field now exists at NHMFL. Plans to design 40+T solenoids in place.	Extend designs to the specs of the 6D cooling channel, fabrication for the demo experiment
Ionization cooling	MICE transverse cooling results published. Longitudinal cooling via emittance exchange demonstrated at g-2.	Optimize with higher fields and gradients. Demonstrate 6D cooling with re-acceleration and focusing
RF in magnetic field	Operation of up to 50 MV/m cavity in magnetic field demonstrated, results published	Design to the specs of the 6D demo, experiment; fabrication

Muon Collider Challenges and Progress

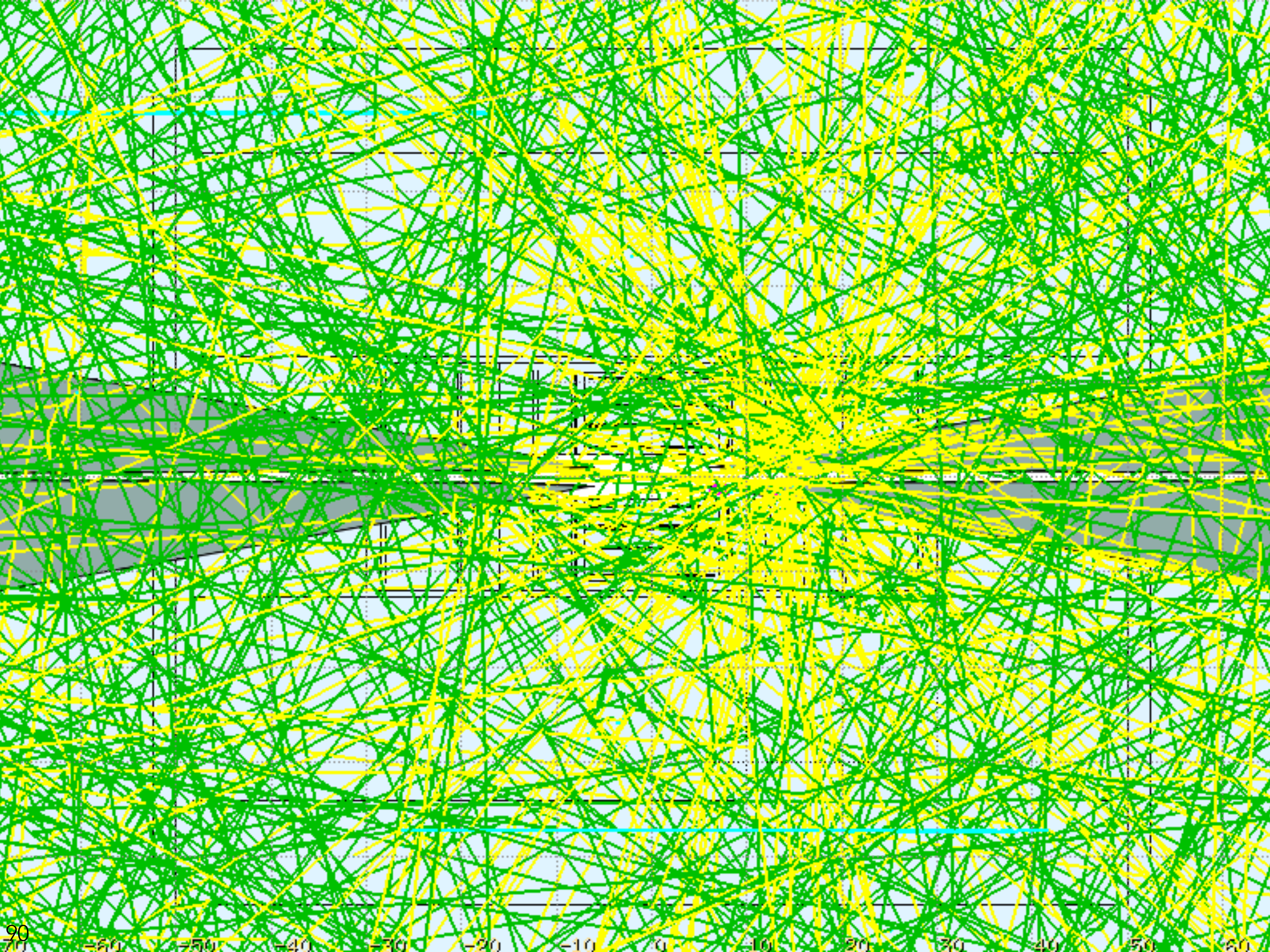
Challenge	Progress	Future work
Fast Ramping Magnets	Demonstrated with 290 T/s up to 0.5T peak field at FNAL. Ramps up to 5000 T/s demonstrated with small magnets.	Design and demonstration work to achieve higher ramp rates (up to 1000 T/s) and peak fields of ~2T with large magnets
Very Rapid Cycling Synchrotron Dynamics	Lattice design in place for a 3 TeV accelerator ring	Develop lattice design for a 5 TeV accelerator ring
Neutrino Flux Effects	Mitigation strategies based on placing the collider ring at 200m and introducing beam wobble has been shown to achieve necessary reduction up to 10-14 TeV	Study mechanical feasibility, stability and robustness of the mover's system and impact on the accelerator and the beams
Detector shielding and rates	Demonstrated to be manageable in simulation with next generation detector technologies	Further develop and optimize 3 and 10 TeV detector concepts and MDI. Perform detector technology R&D and demonstration.
Open aperture storage ring magnets	12-15T Nb3Sn magnets have been demonstrated	Design and develop larger aperture magnets 12-16T dipoles and HTS quads
Low-beta IR collider design and dynamic aperture	Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits	Develop lattice design for a 10 TeV collider

Muon Collider Synergies

Facility/Experiment	Physics Goals	Synergy
nuStorm	Short baseline neutrino program, including searches for sterile neutrino and cross section measurements	100kW proton source, muon production and collection, storage ring operation
Neutrino Factory (e.g. nuMax)	Better CP, mixing angles, mass splitting, non-standard interactions	MW class proton source, muon production and collection, 6D partial cooling and muon acceleration (up to ~5 GeV)
Dark Sector searches	Searches for particles from Dark Sectors produced in fixed target experiments using high intensity proton beam	MW class high-intensity proton beams
Charged Lepton Flavor Violation (e.g. AMF)	Searches for rare lepton flavor violating proceses (mu2e, mu2eg, mu3e, etc)	MW class proton source, muon production and collection, storage ring
Beam dump experiments	Searches for exotic particles (dark photons, Lmu-Ltau, etc) in muon beam dump experiments	100kW – MW proton source, muon production and collection, partial cooling and acceleration
Neutrinos from collider beam muon decays	DIS in neutrino-nucleus interactions, better nuclear PDF, atmospheric neutrinos FASERv like experiment with smaller flux uncertainties	Everything up to multi-TeV energy collider beams
Muon Ion Collider	A broad program addressing many fundamental questions in nuclear and particle physics	Everything up to multi-TeV energy collider beams

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} $cm^{-2}s^{-1}$]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

Snowmass Implementation Task Force Report
2208.06030


90
-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60

0.0003% of BIB shown

Enormous contribution **into detector region** from glowing nozzles

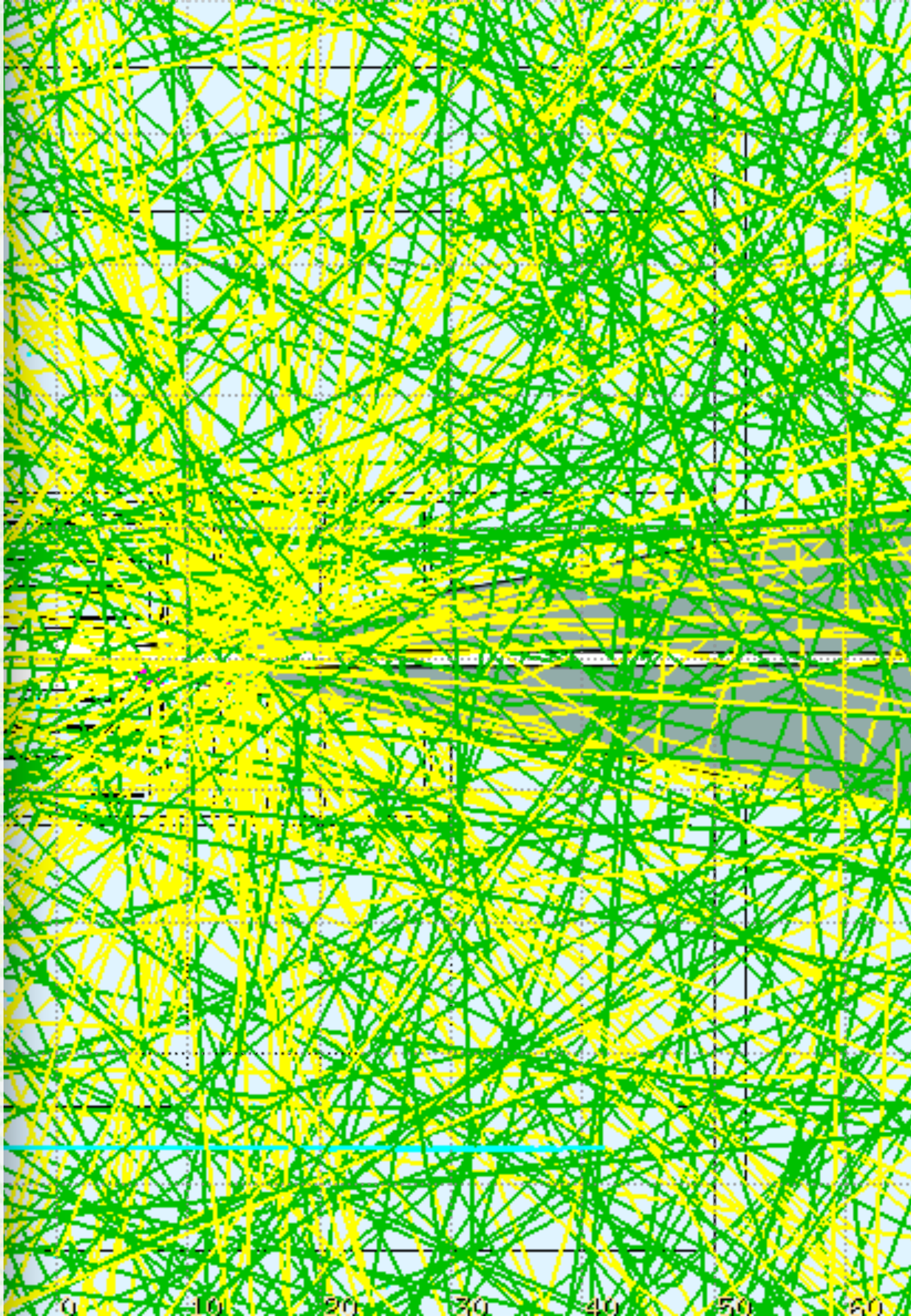
Neutrons

Photons

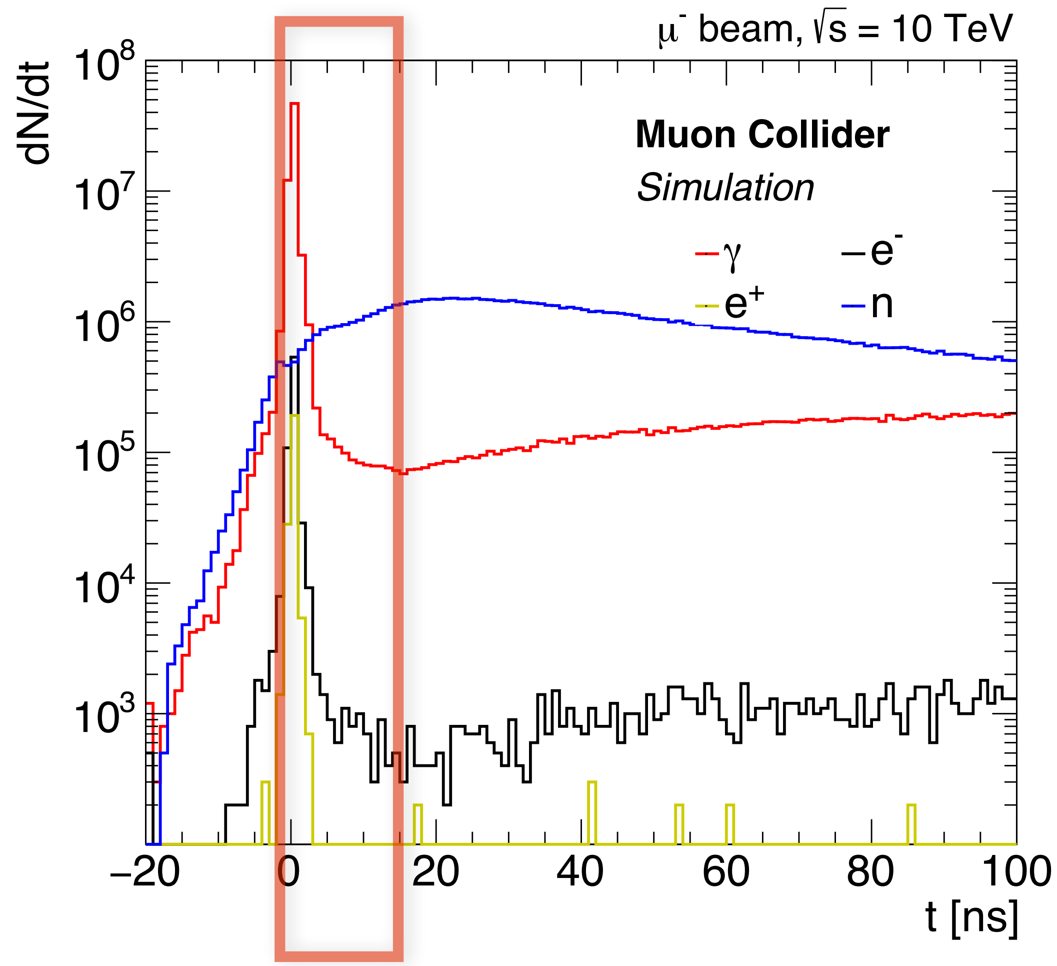
Electrons

Positrons

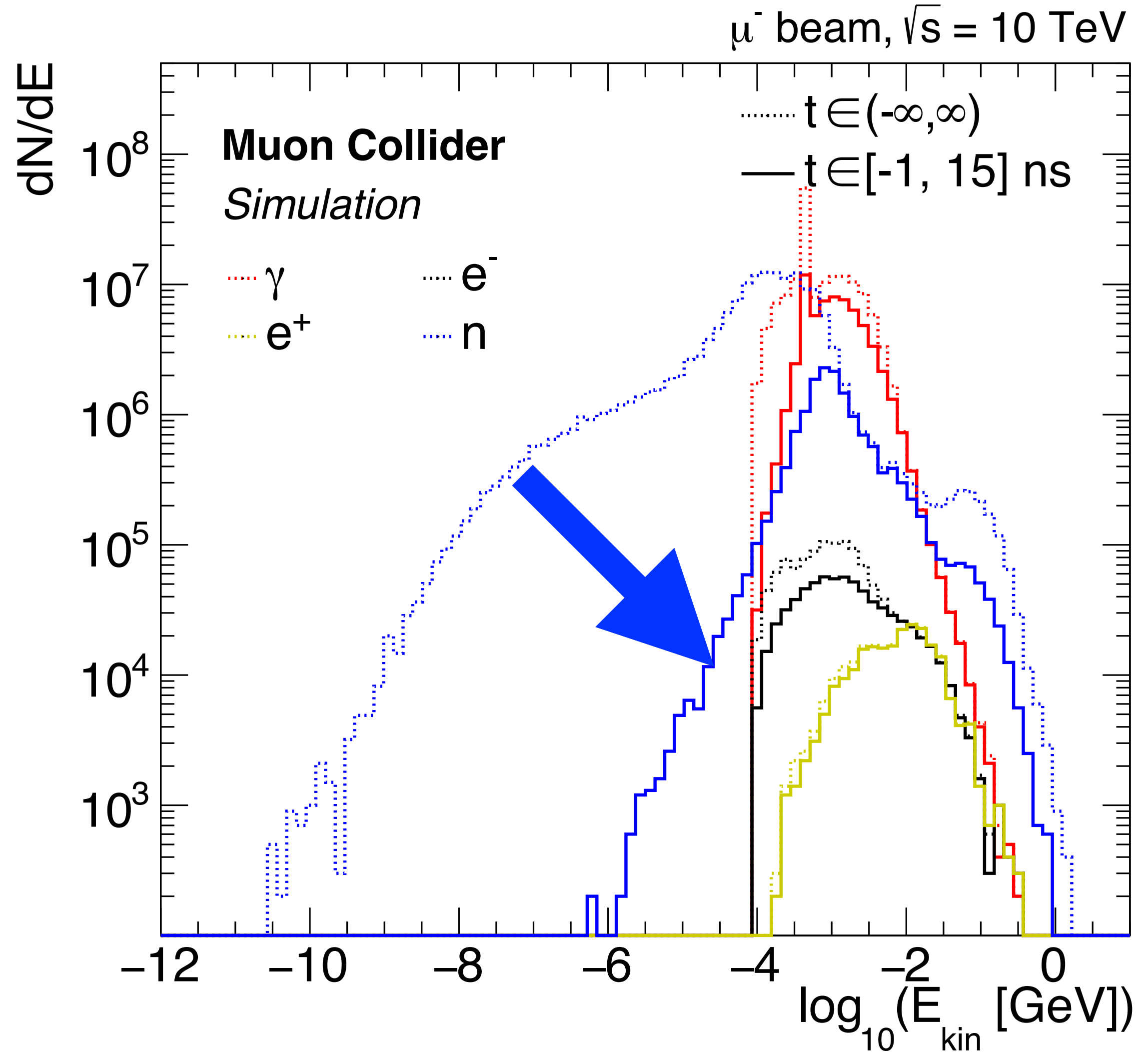
Luckily total ionizing dose/year is **comparable** to **HL-LHC**
And **orders of magnitude less** than **FCC-hh**



D. Calzolari



- Broad timing cuts @ **[-1, 15] ns**
  - Reduce BIB effects by orders of magnitude
  - Especially low energy, diffuse contributions
- **But large contributions remain!**
- **High precision timing** measurements O(10-100) ps necessary to get physics out of a muon collider



Coarse timing info helps a lot, but not enough