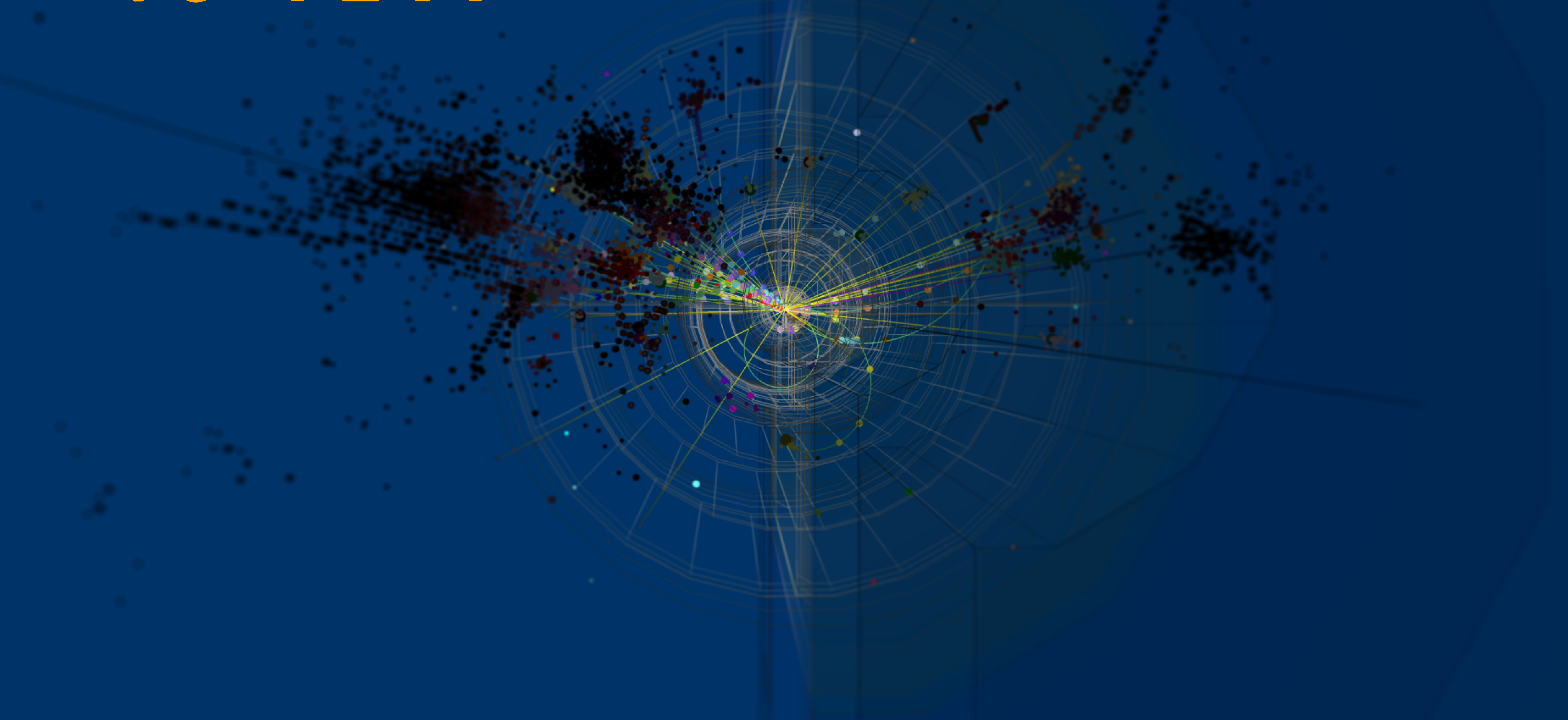
Overview of the Experiment

Lawrence Lee

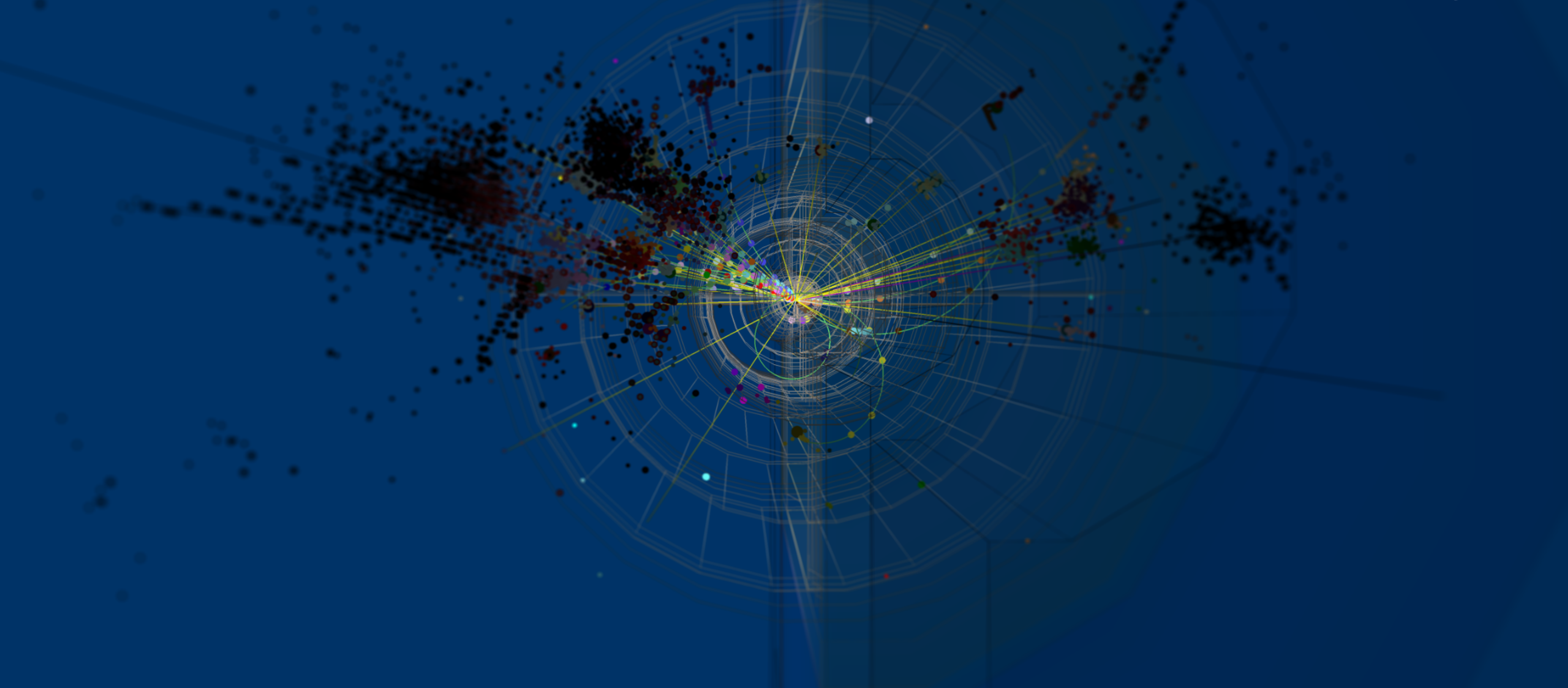
THE UNIVERSITY OF TENNESSEE KNOXVILLE

We want 10 TeV!



We want 10 TeV!

(LHC collides protons at ~13-14 TeV, but the fundamental interactions scales are much lower. ~1 TeV)



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A μμ collider is a perfect way to do it!

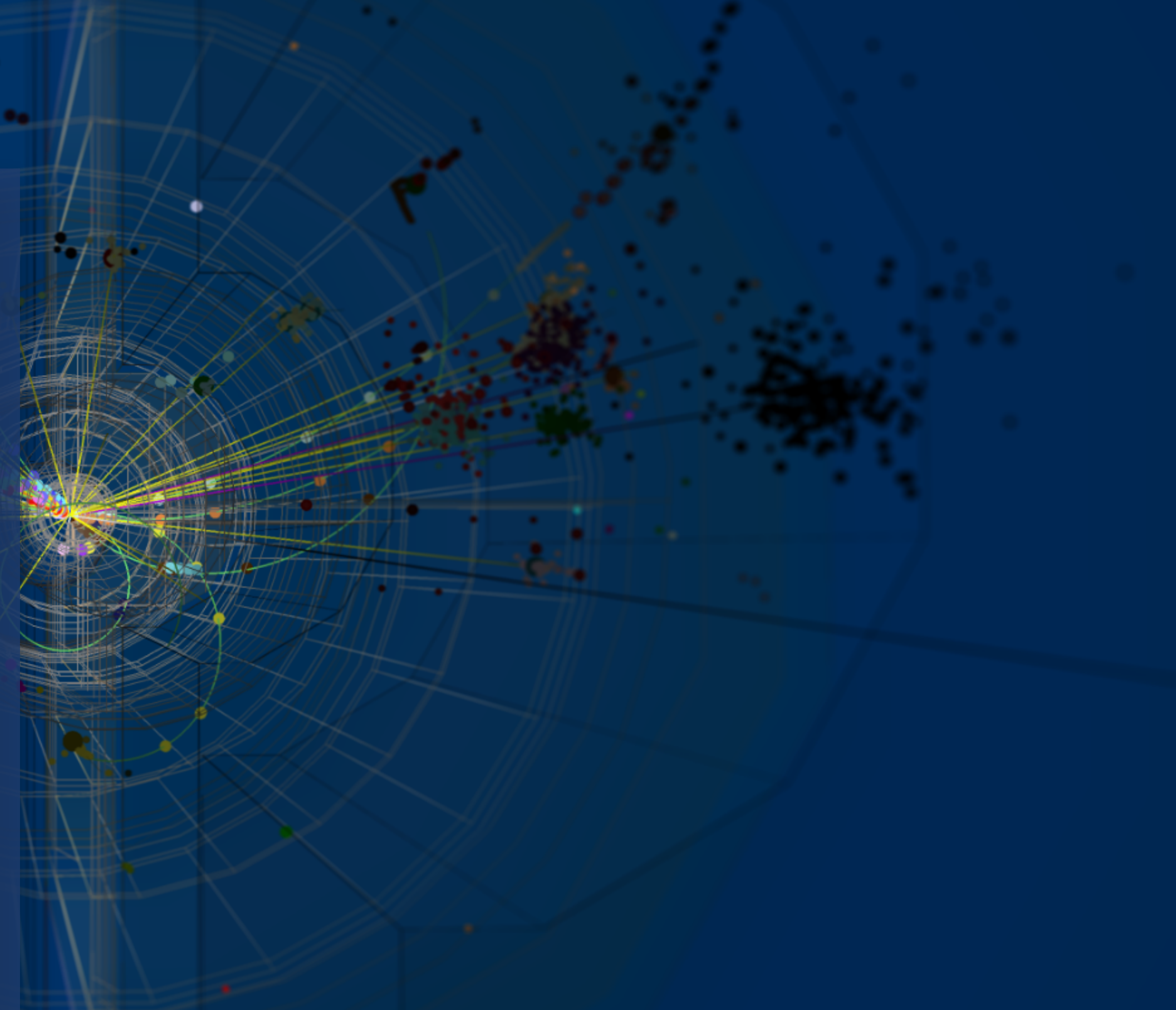
Get to super high energy because:

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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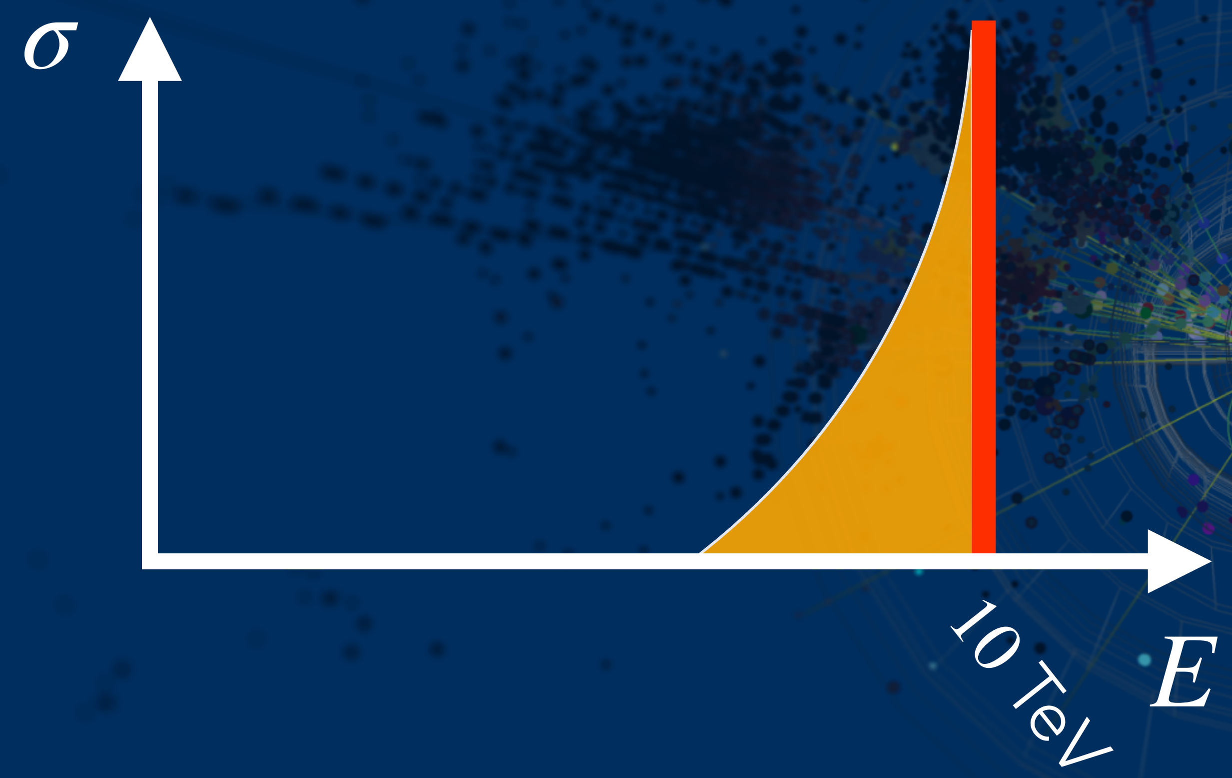
Accelerator colleagues tell us it might be possible!

(With a lot of work…)

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

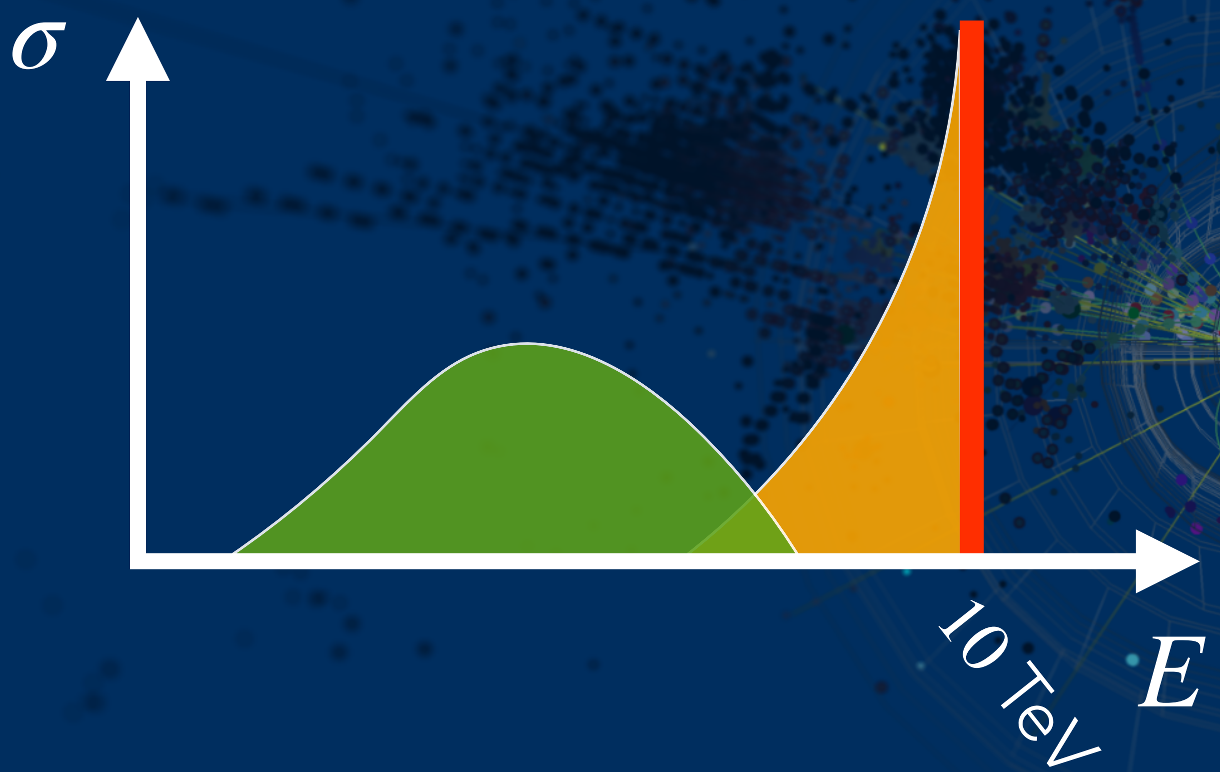
Maybe even dip out of "our lane" and help out where we can!

Say you have a 10 TeV μμ collider…



Annihilation processes with potential **radiation** effects

Say you have a 10 TeV μμ collider…



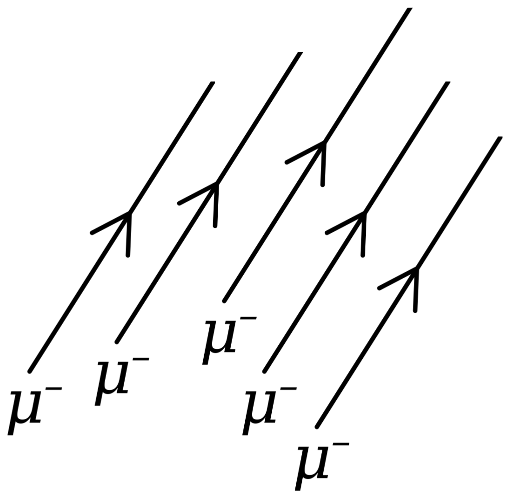
Annihilation processes with potential **radiation** effects

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

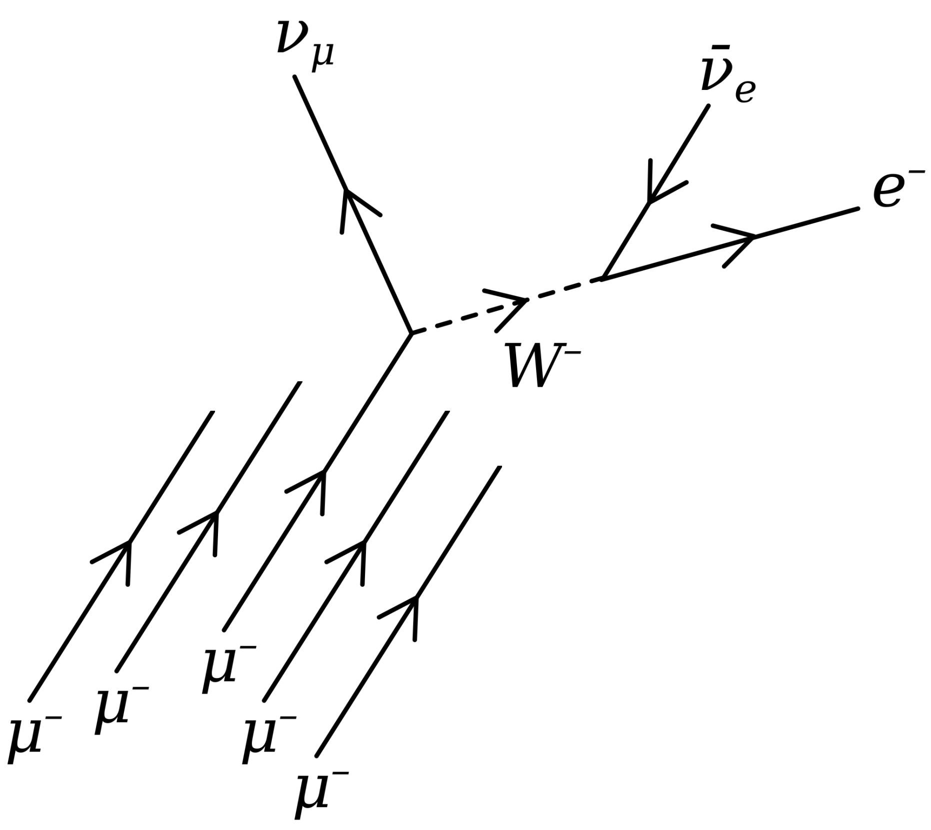
A virtual cloud of bosons interacting.

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

Muon Beams



Muon Beams Decay



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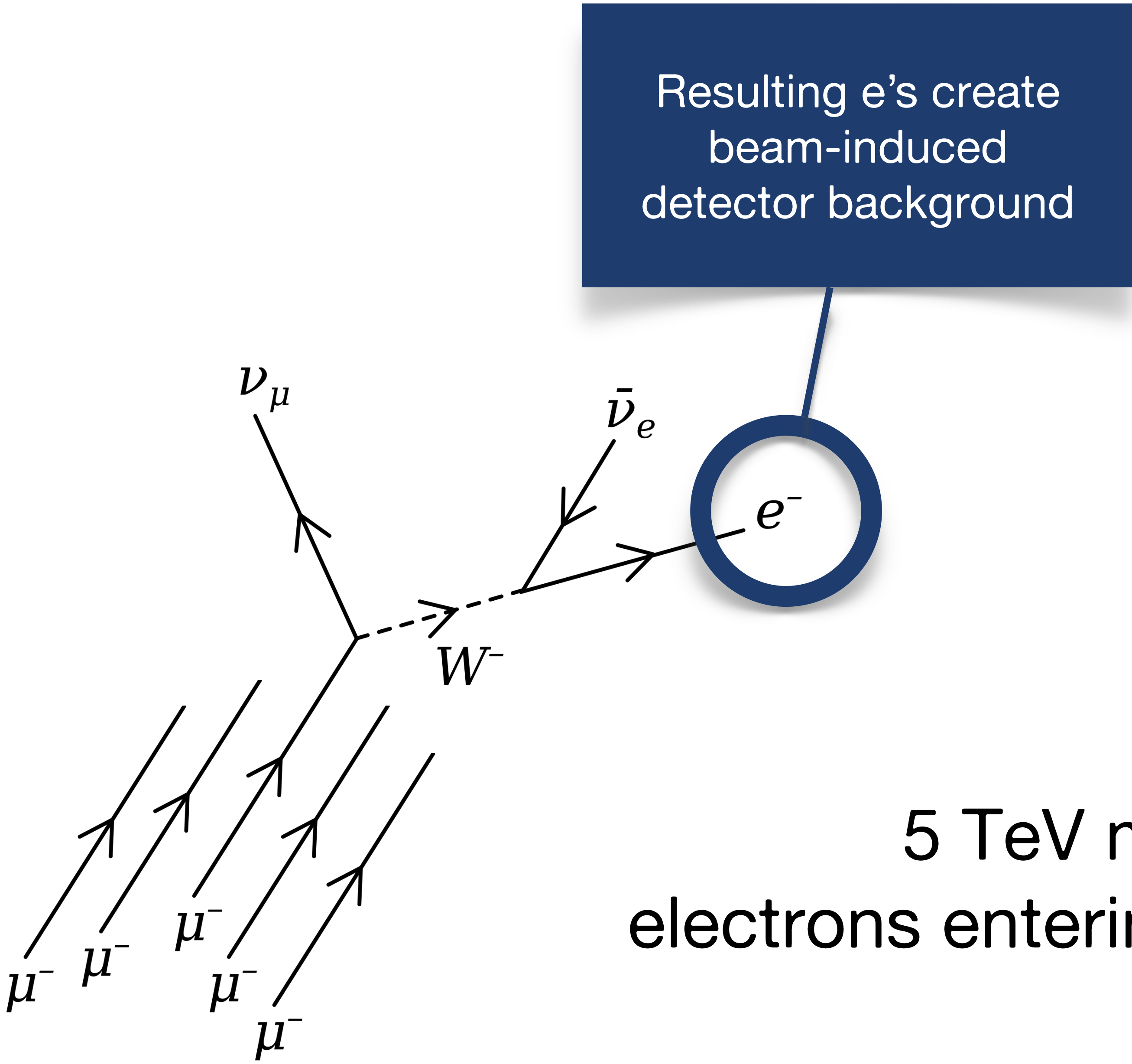
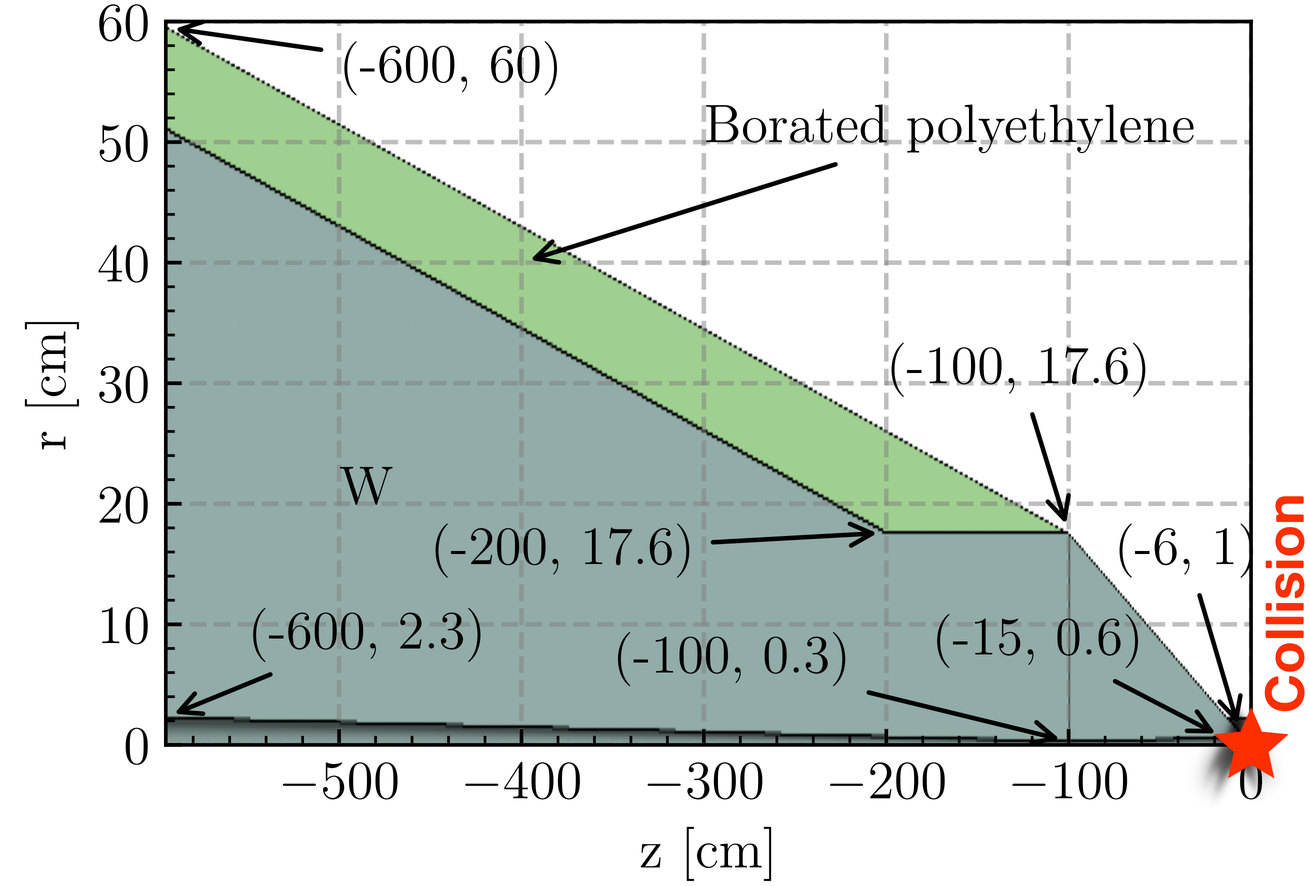


Beam Induced Background (BIB)

5 TeV muons will decay to TeV scale electrons entering into the experimental area!

Which can shower and make a mess

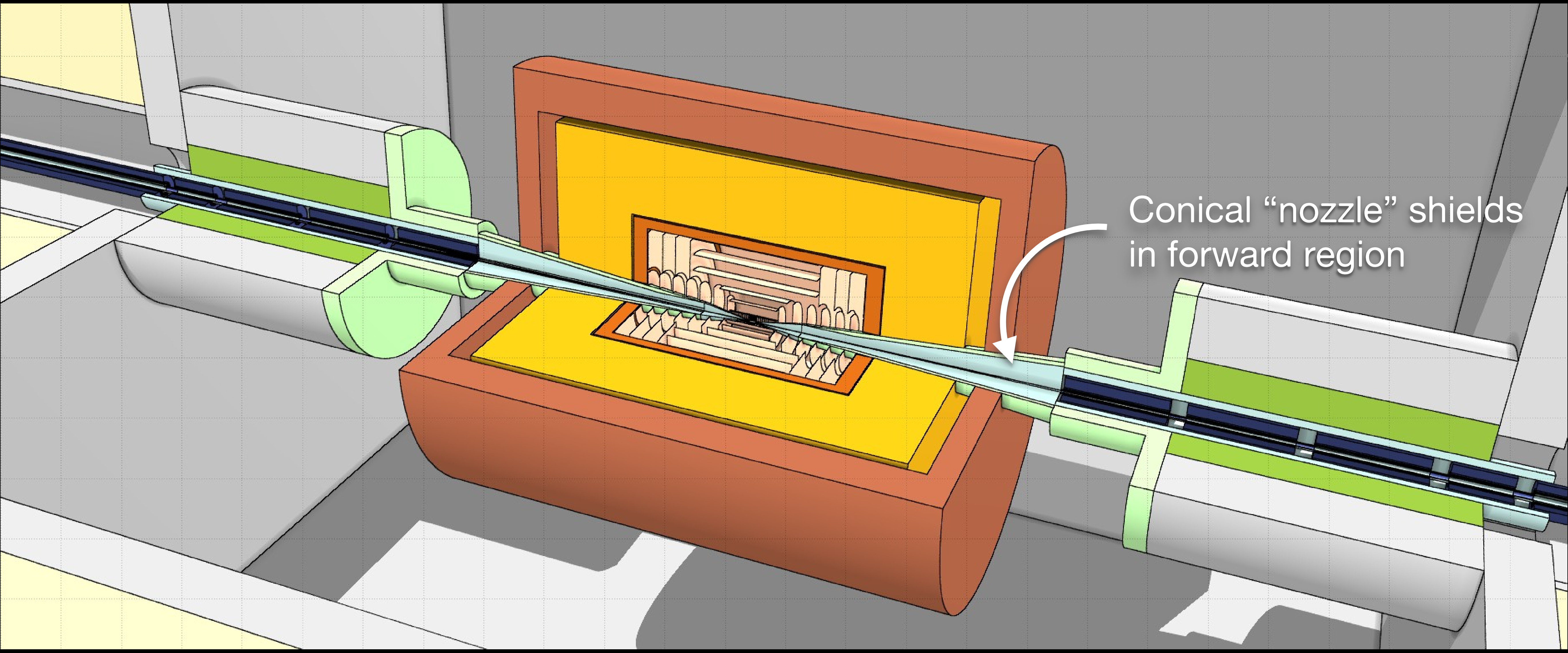
First Order BIB Mitigation



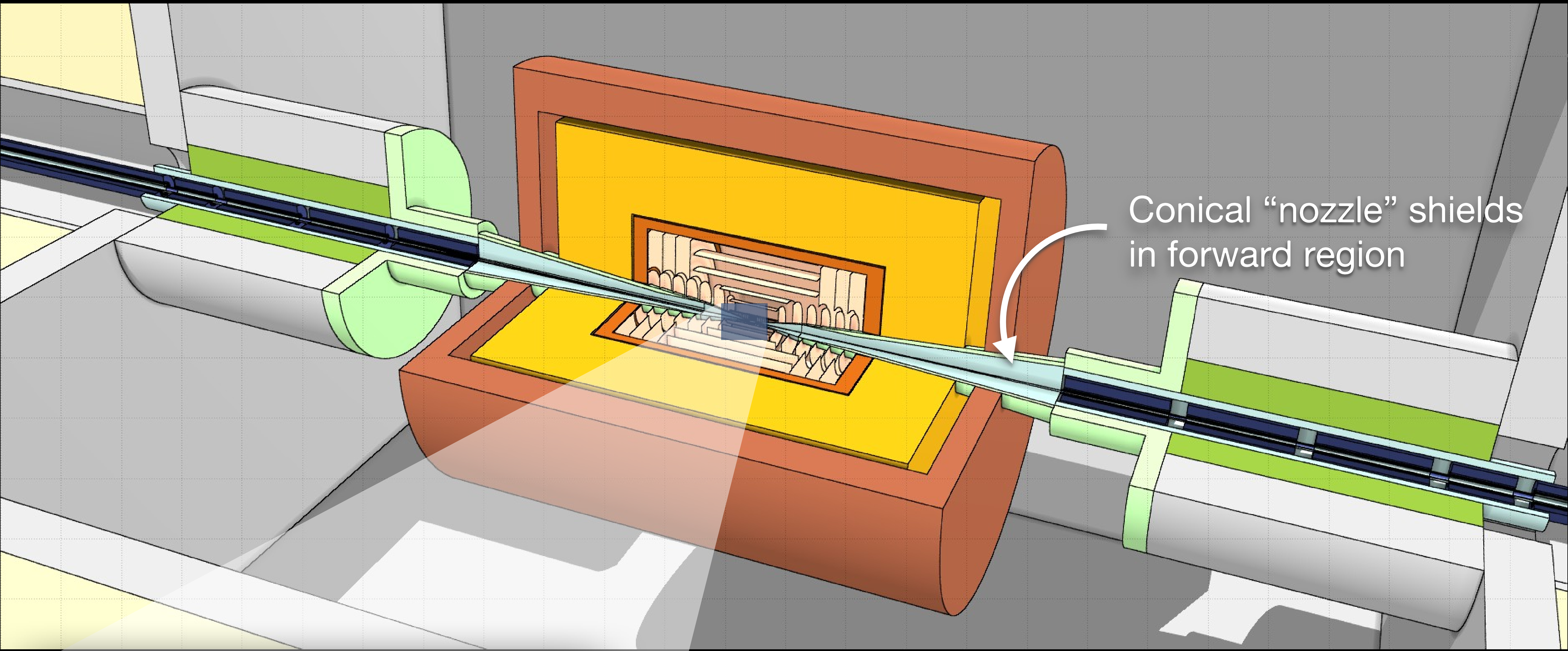
Enormous number of particles in detector region from decaying muons and their byproducts

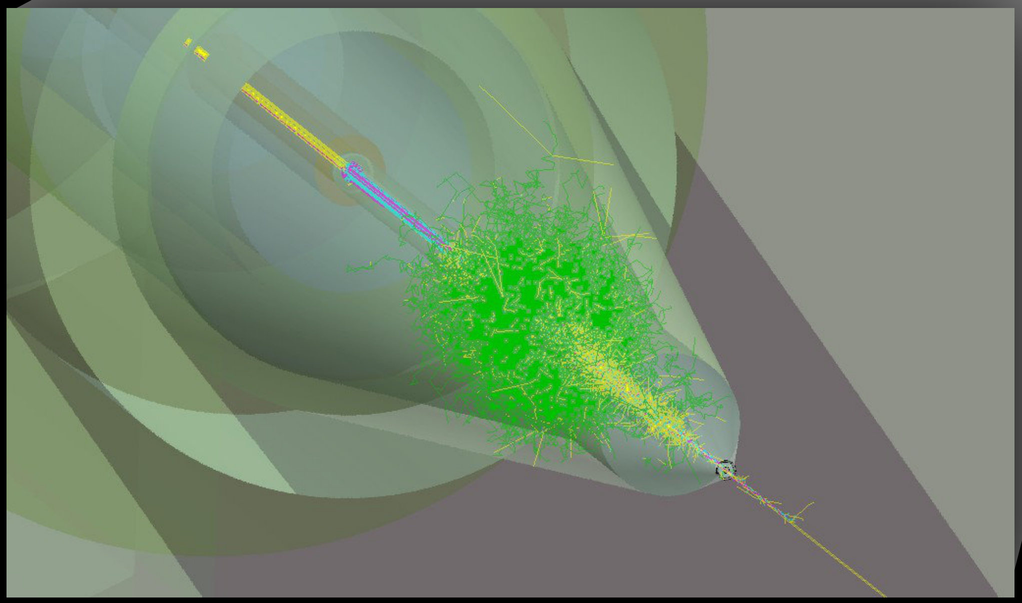
1. **Work closely w/ accelerator design to minimize**
2. **Shield ourselves**
    - Reduces BIB in detector by **many orders of magnitude**
    - Interactions with shielding → Bleed secondary energy into the detector
        - Turns highly localized incident energy into diffuse energy in detector

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



Images from Slides by D. Calzolari

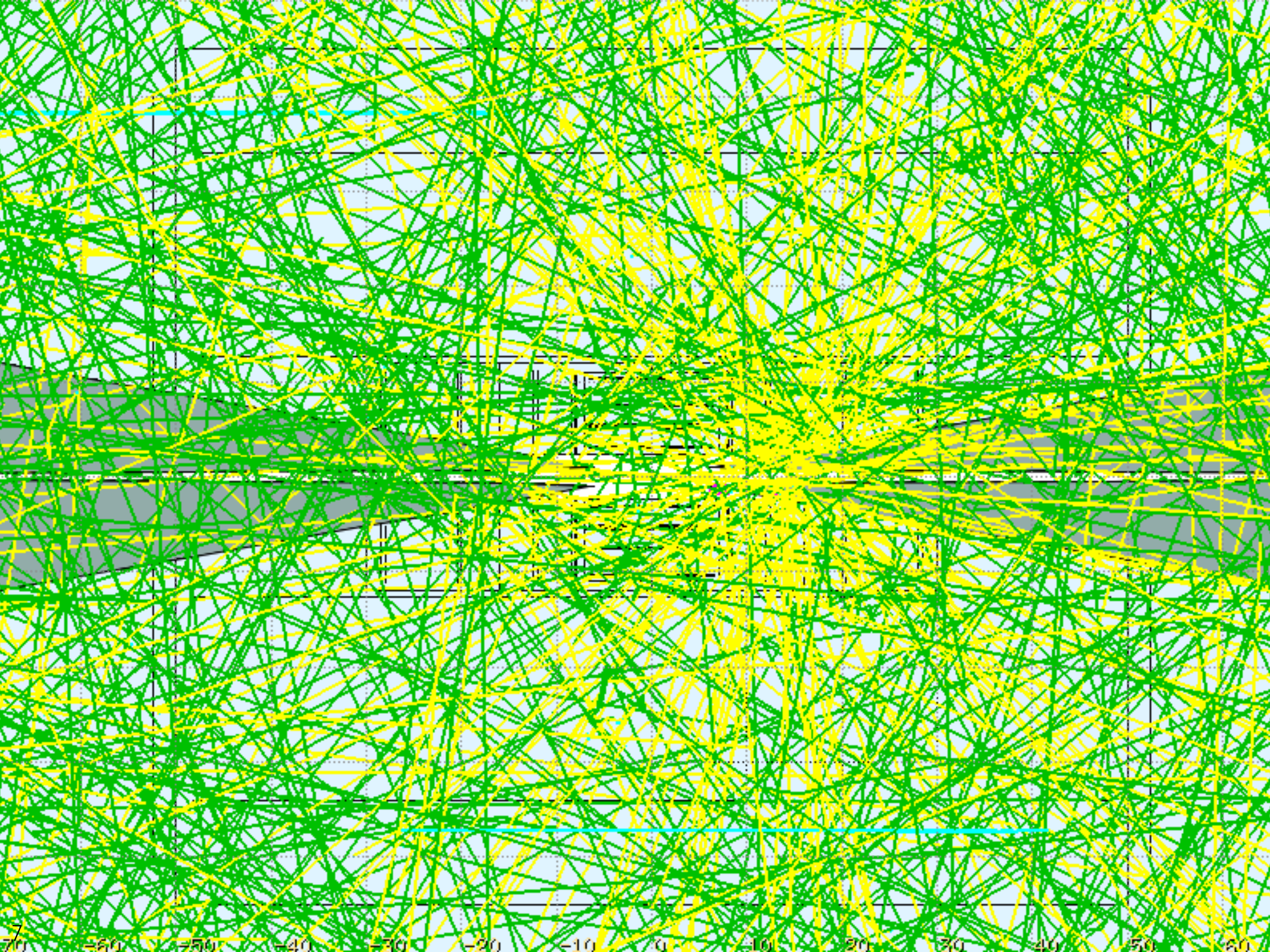




Particle production from single muon decay 25m away.
Nicely absorbed by nozzle.

Now imagine ~10M of these decays…

Images from Slides by D. Calzolari


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

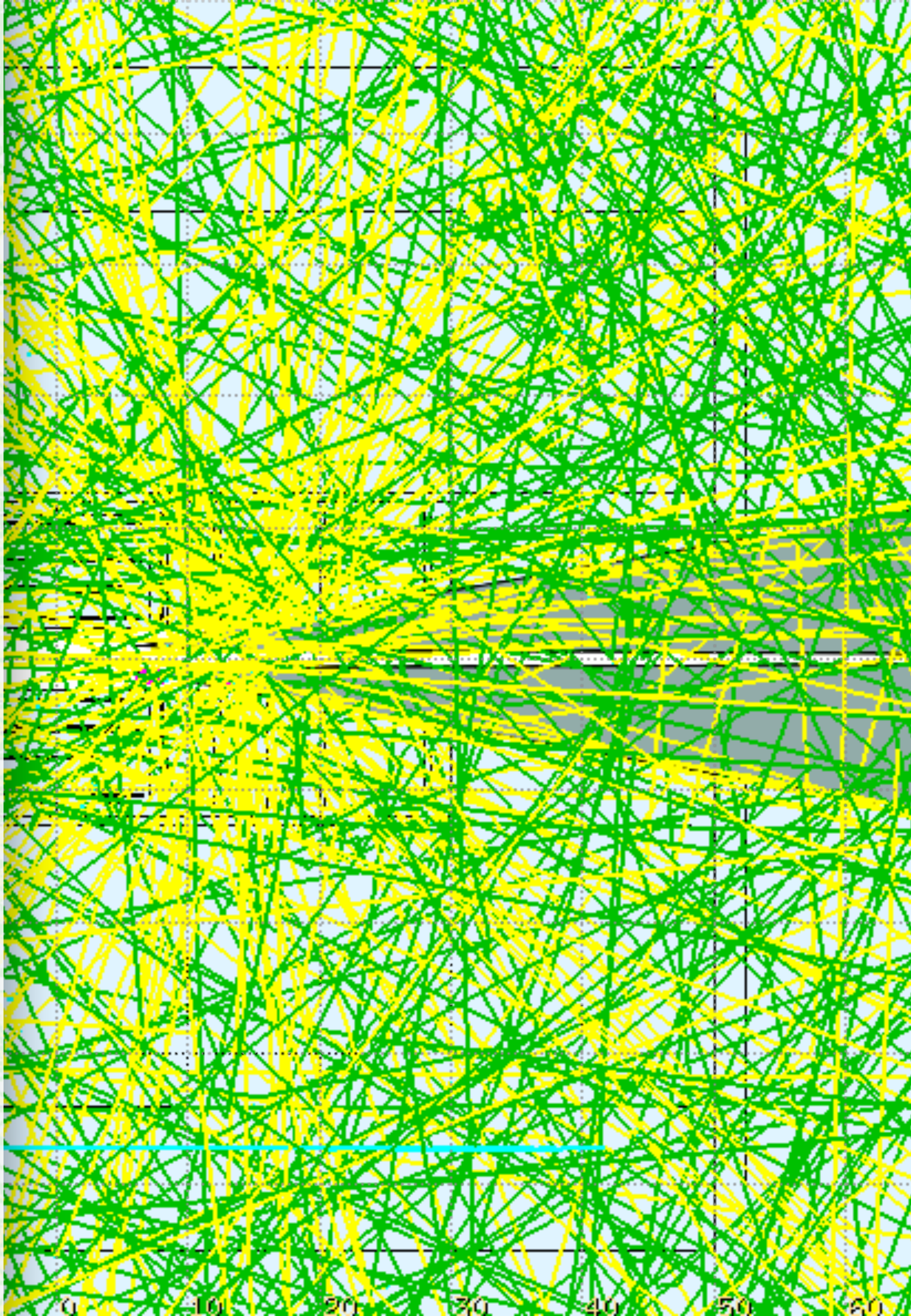
0.0003% of BIB shown

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**

Much more about the **Machine-Detector Interface (MDI)** this afternoon from Kiley Kennedy and Daniele Calzolari



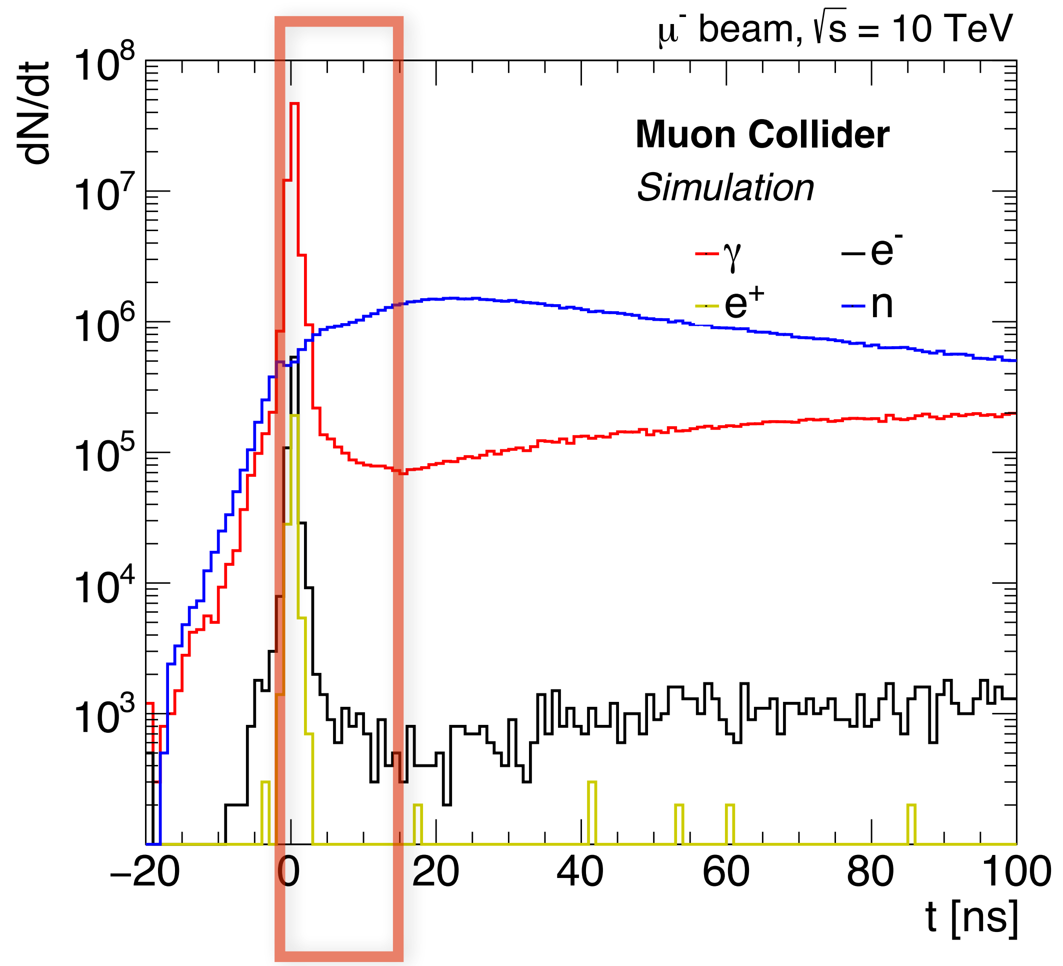
D. Calzolari

Central Challenges

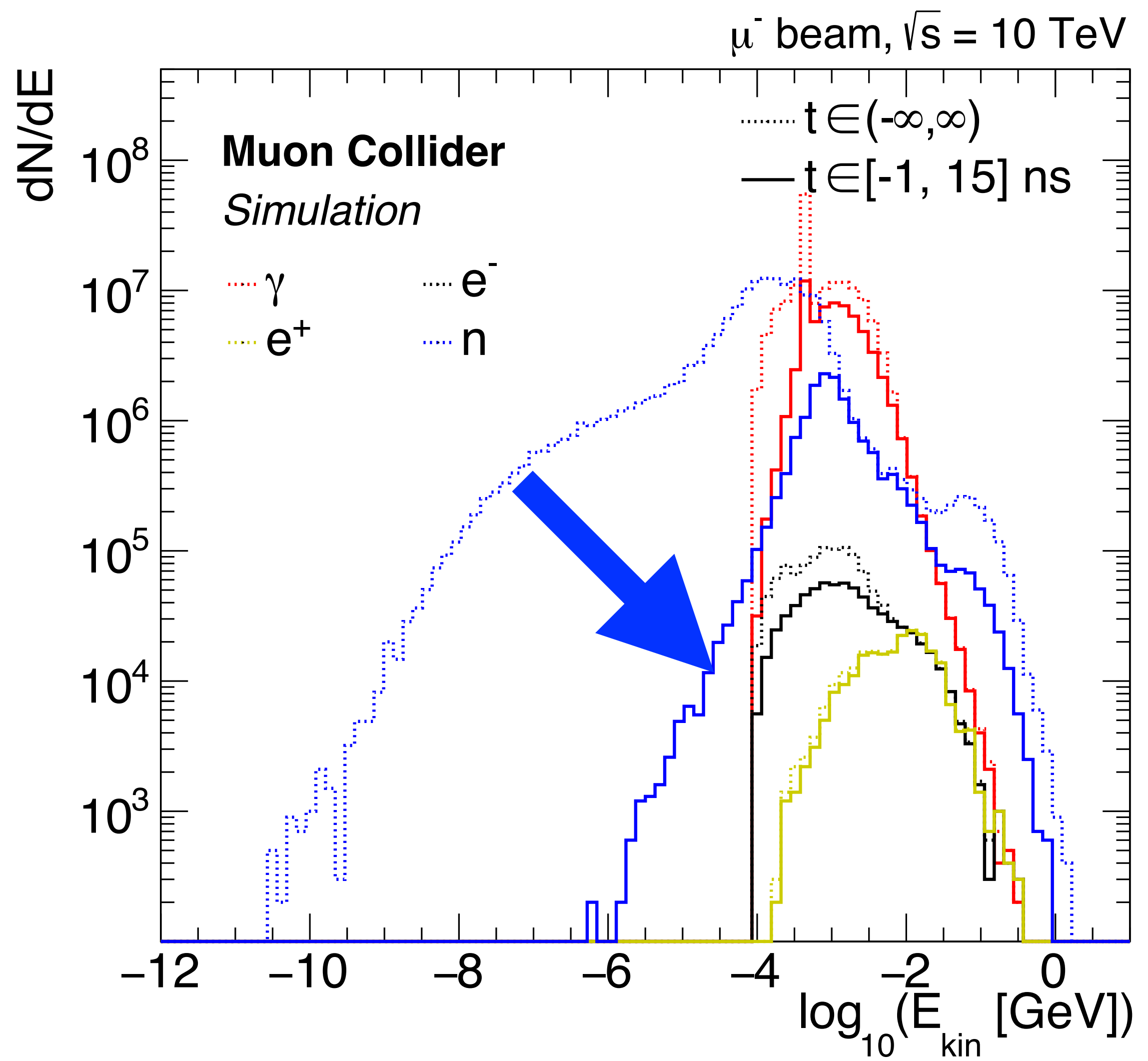
1. Build a detector robust against residual BIB

In detector region, dominated by MeV-scale neutrals

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



- 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

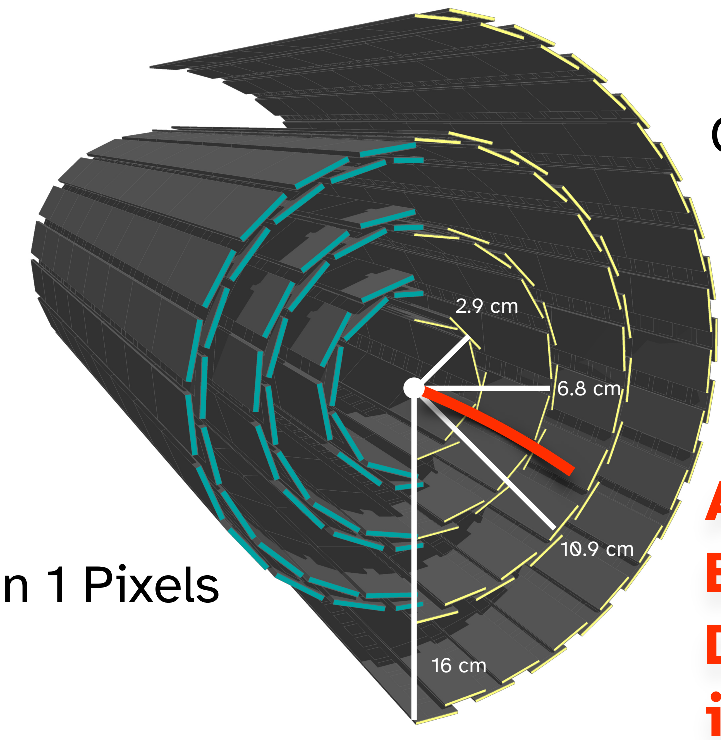
Central Challenges

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

- **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

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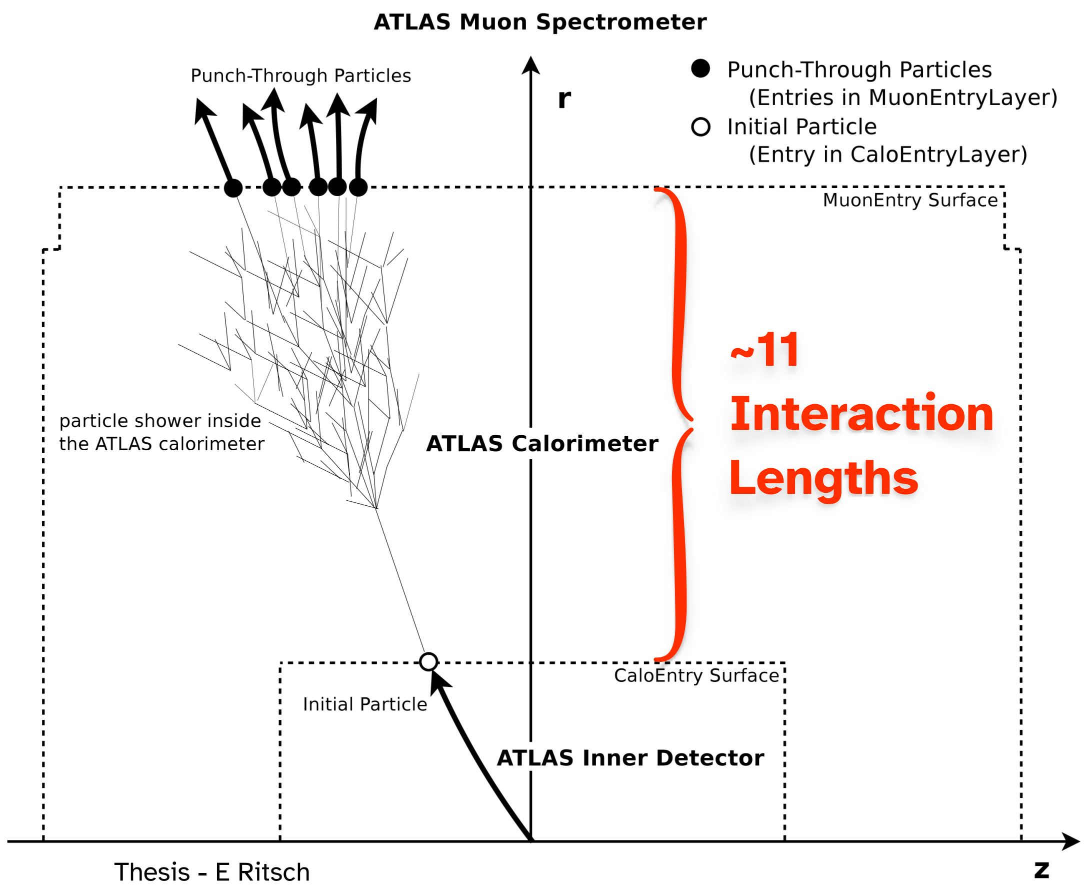
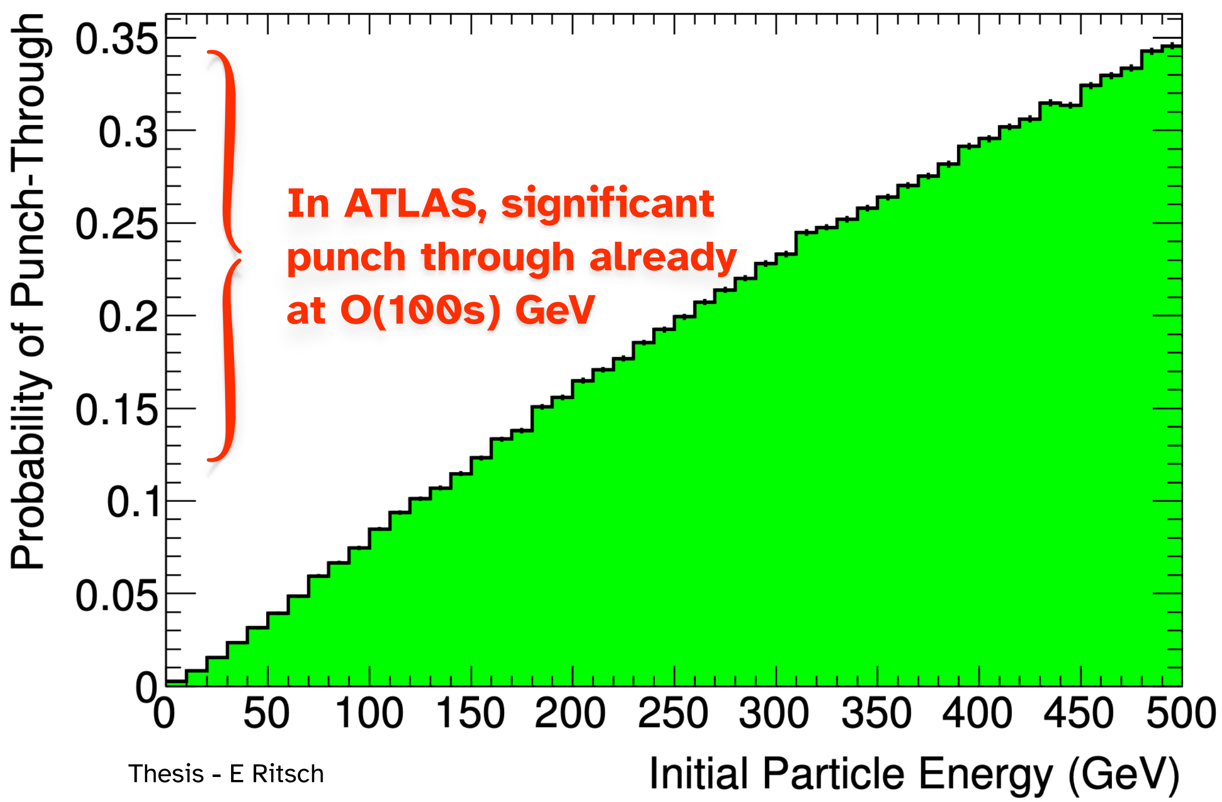




Central Challenges

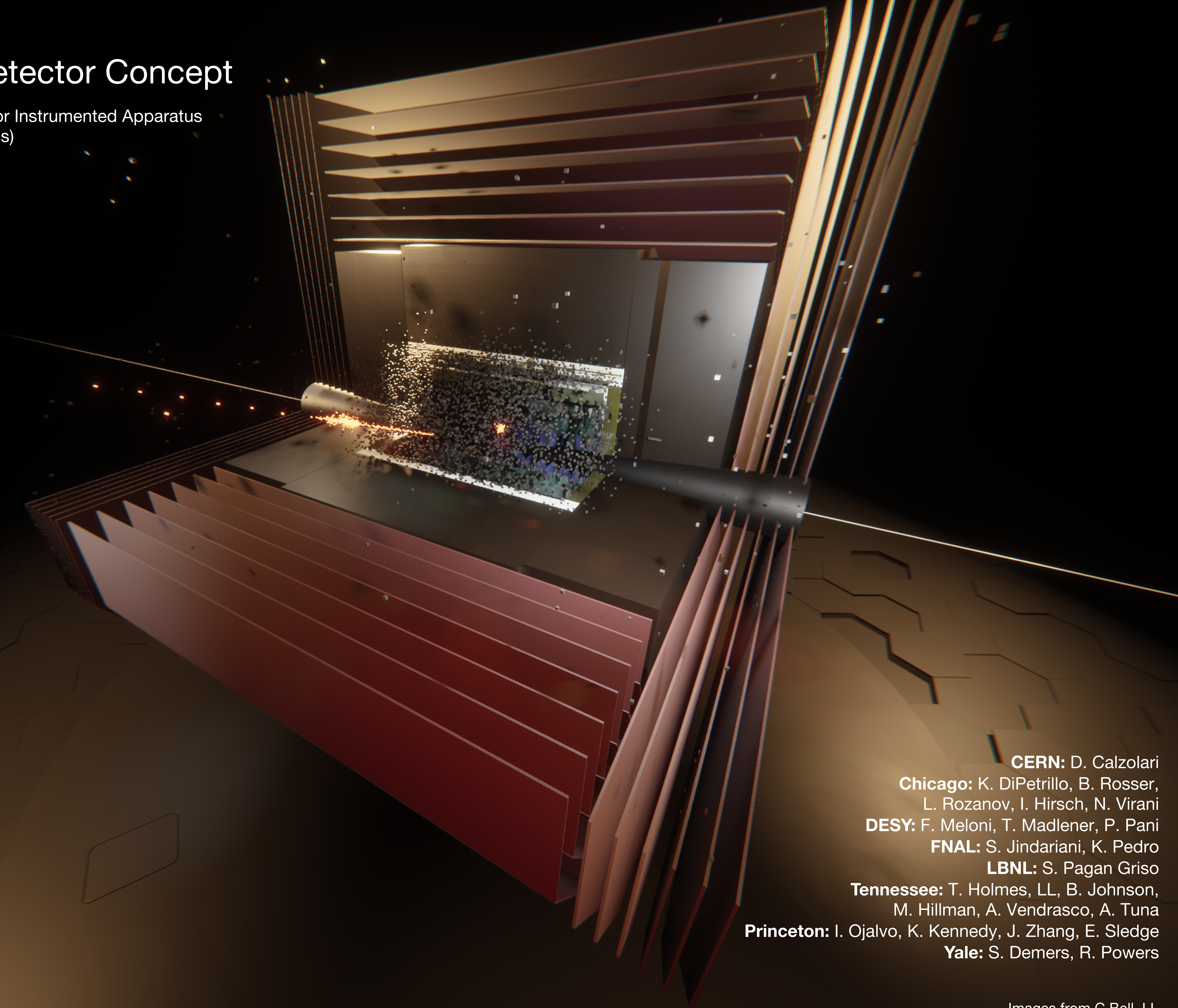
1. Build a detector robust against residual BIB

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
(Work in Progress)



CERN: D. Calzolari
Chicago: K. DiPetrillo, B. Rosser, L. Rozanov, I. Hirsch, N. Virani
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FNAL: S. Jindariani, K. Pedro
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Images from C Bell, LL

MAIA Detector Concept

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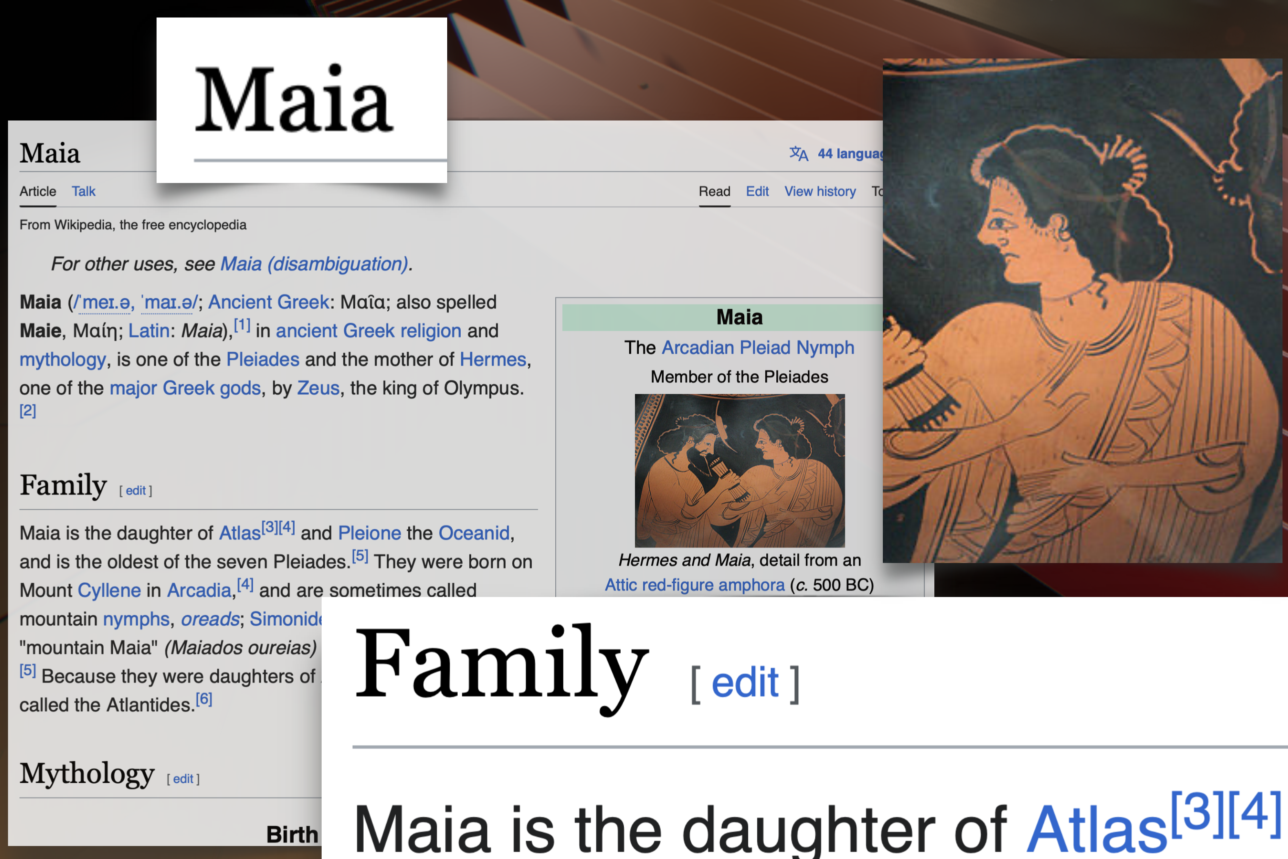
Maia

Maia

Article Talk

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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]

Maia is the daughter of Atlas[3][4]

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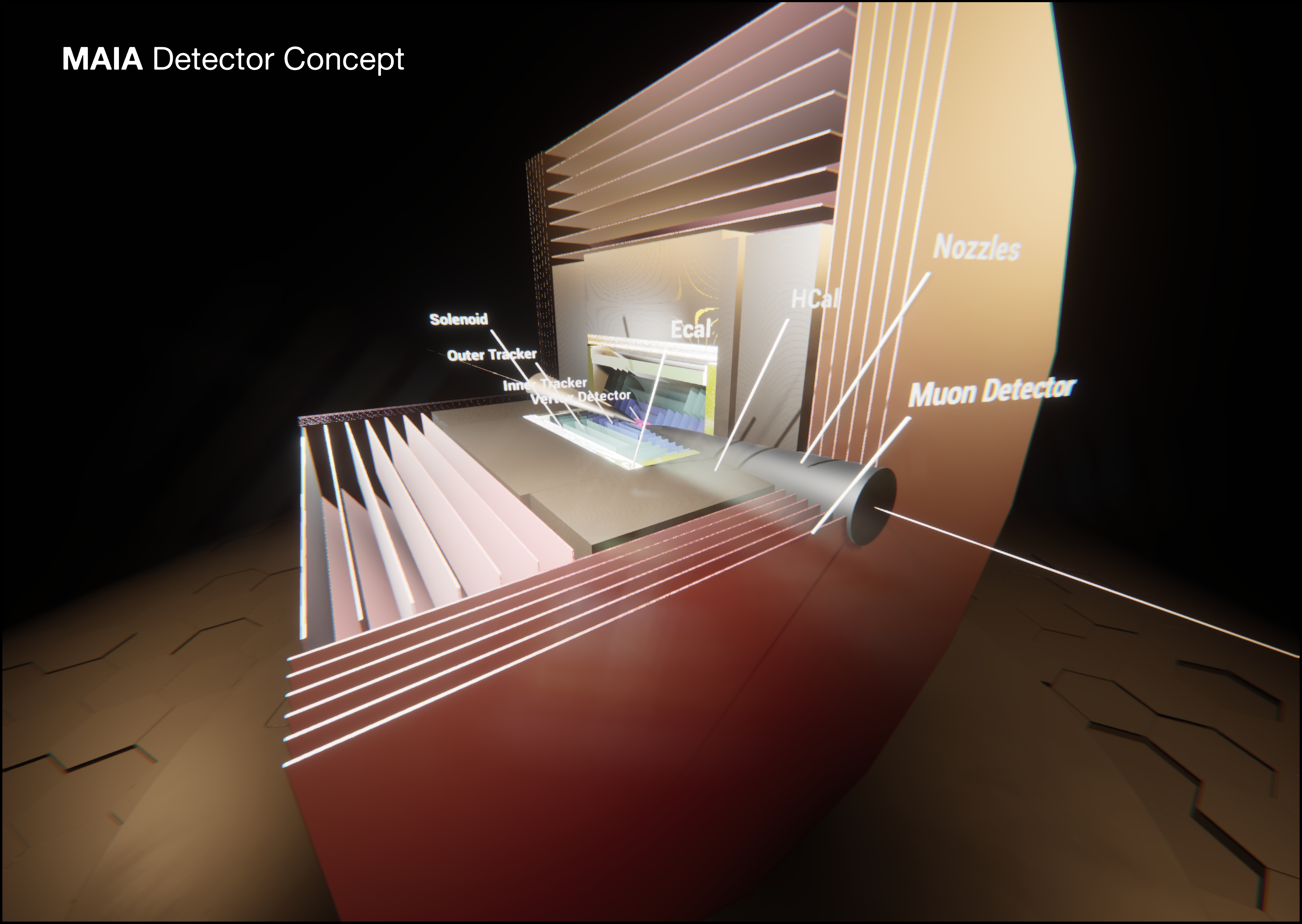

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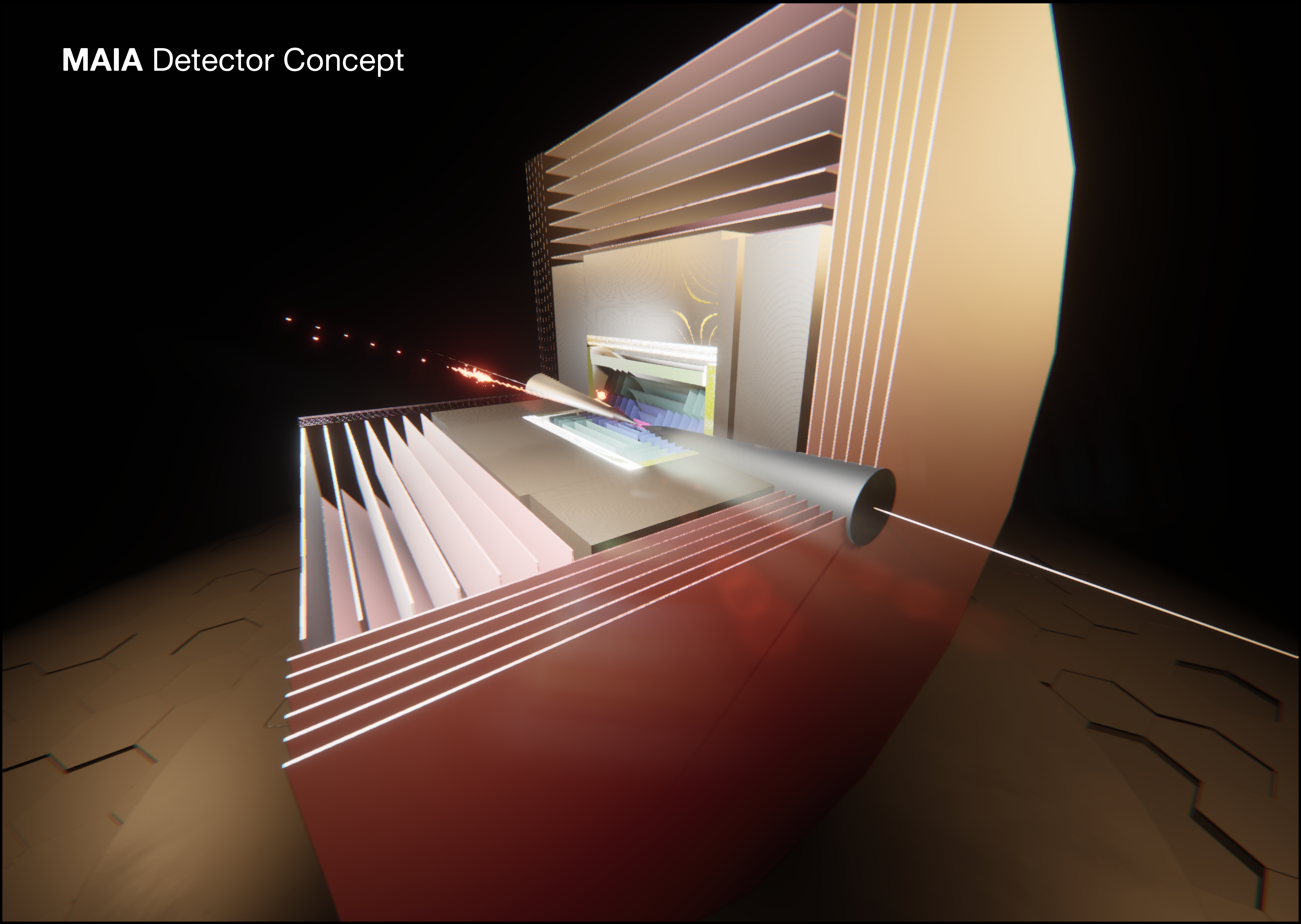

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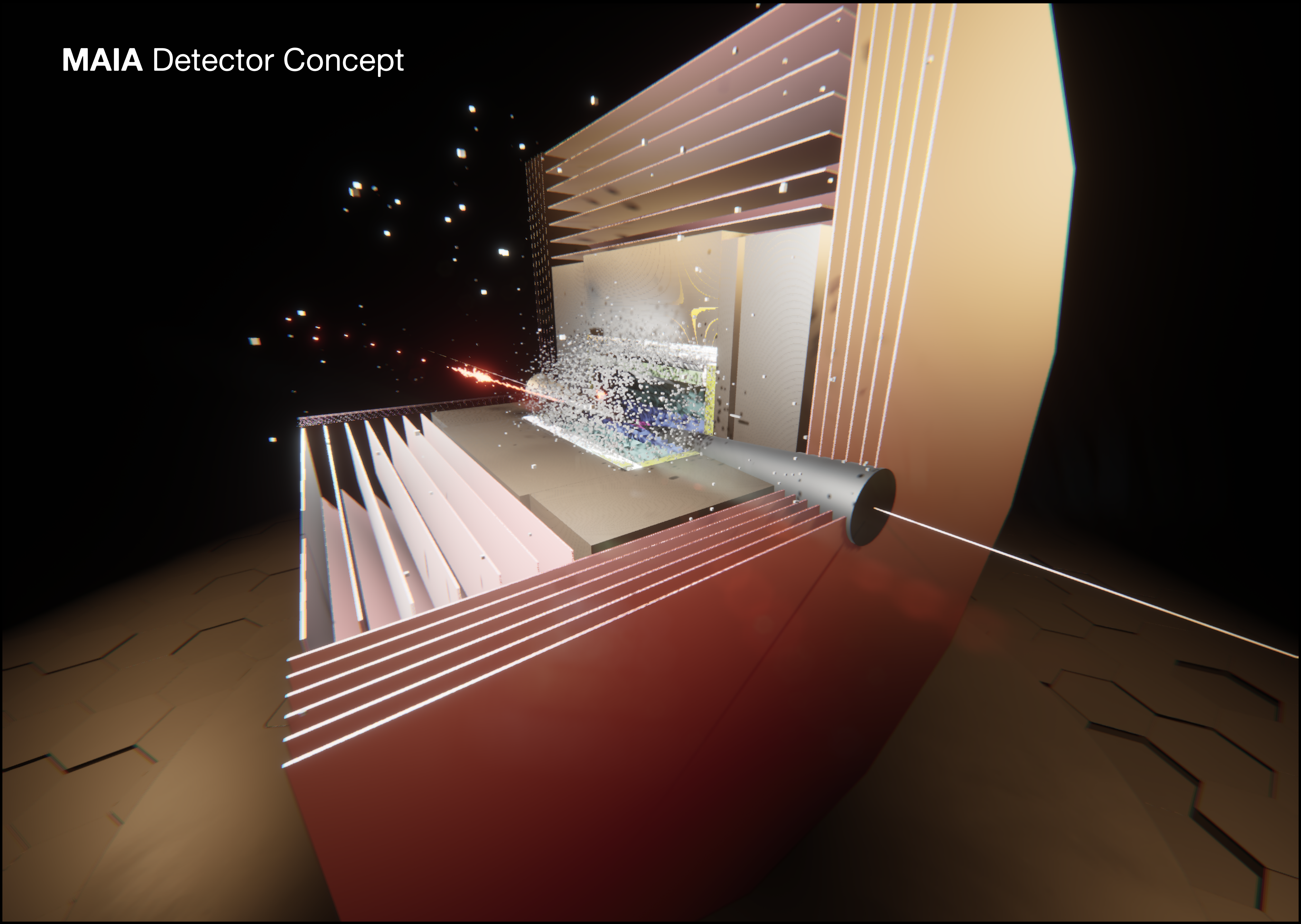

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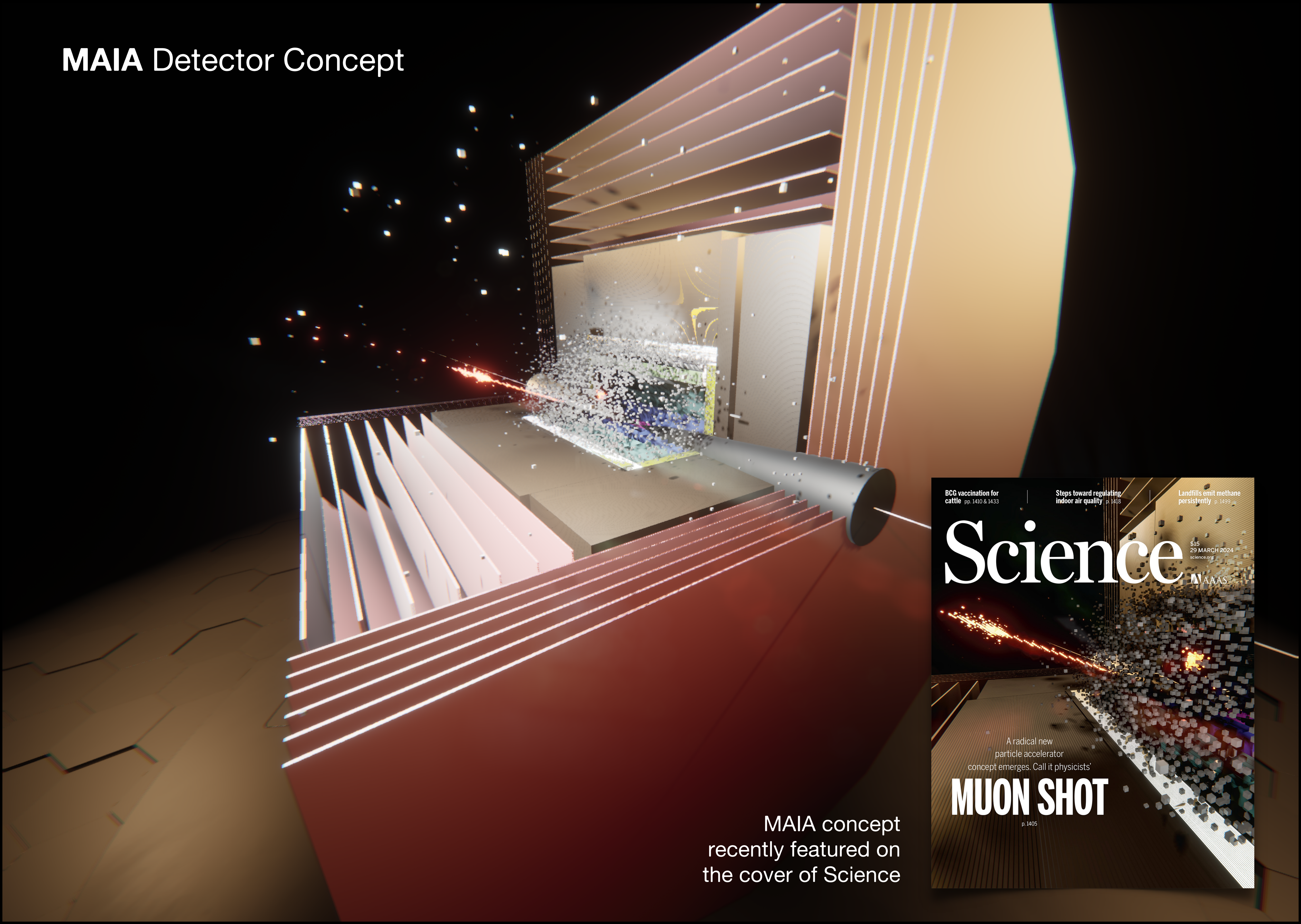
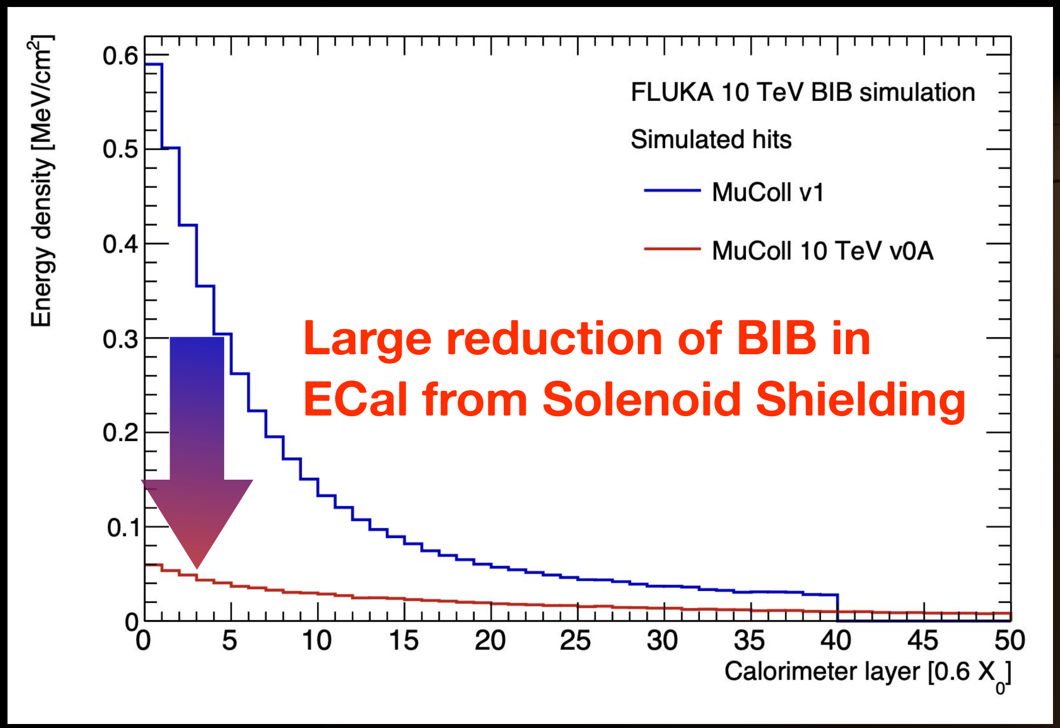


MAIA concept recently featured on the cover of Science

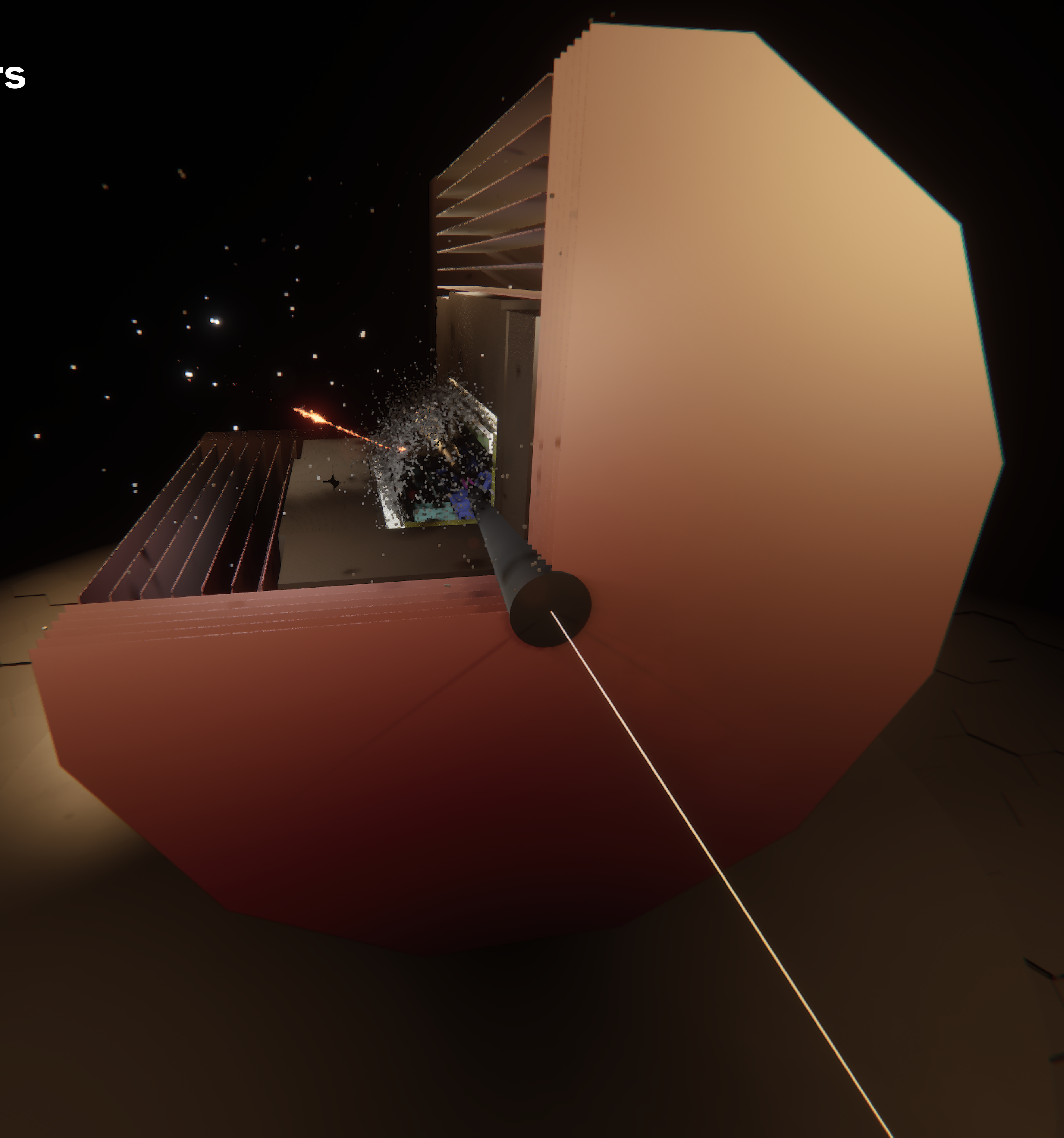
Images from C Bell, LL

MAIA Detector Concept: Overall Design

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



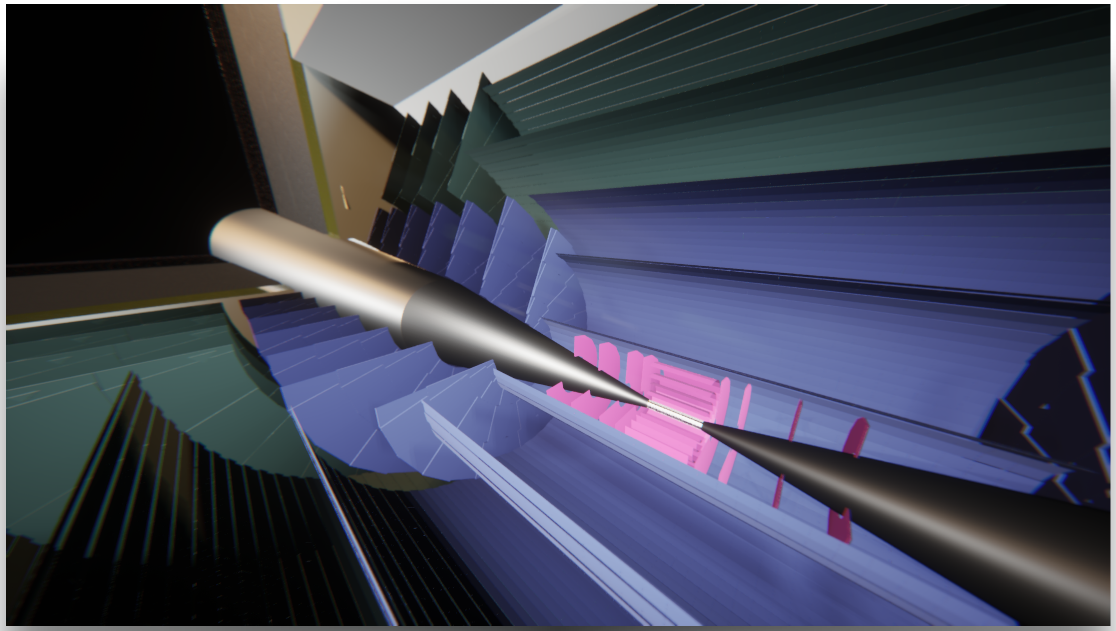
F. Meloni via slides by K. Kennedy



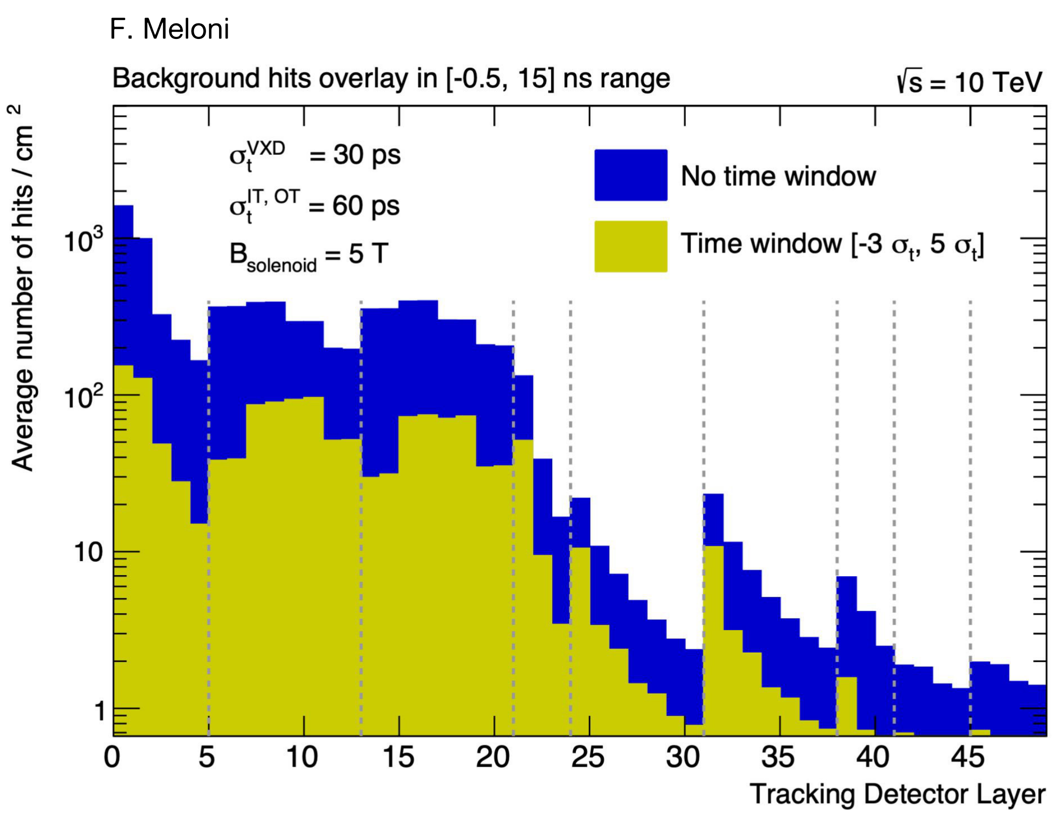
Images from C Bell, LL

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



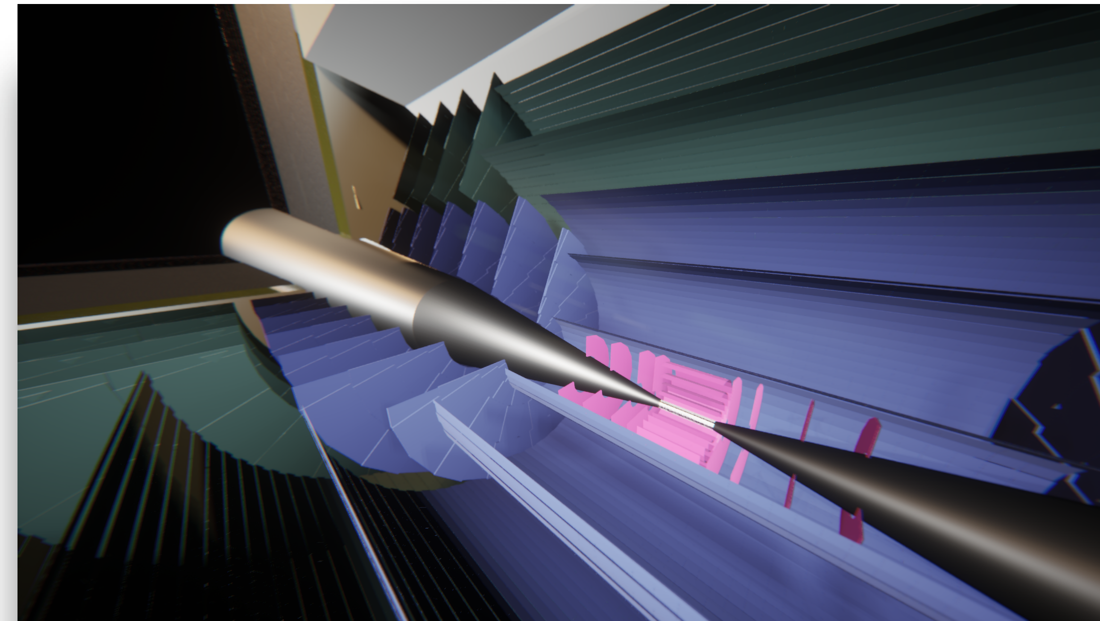
	Vertex Detector	**Inner Tracker**	**Outer Tracker**
Sensor type	pixels	macropixels	microstrips
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps

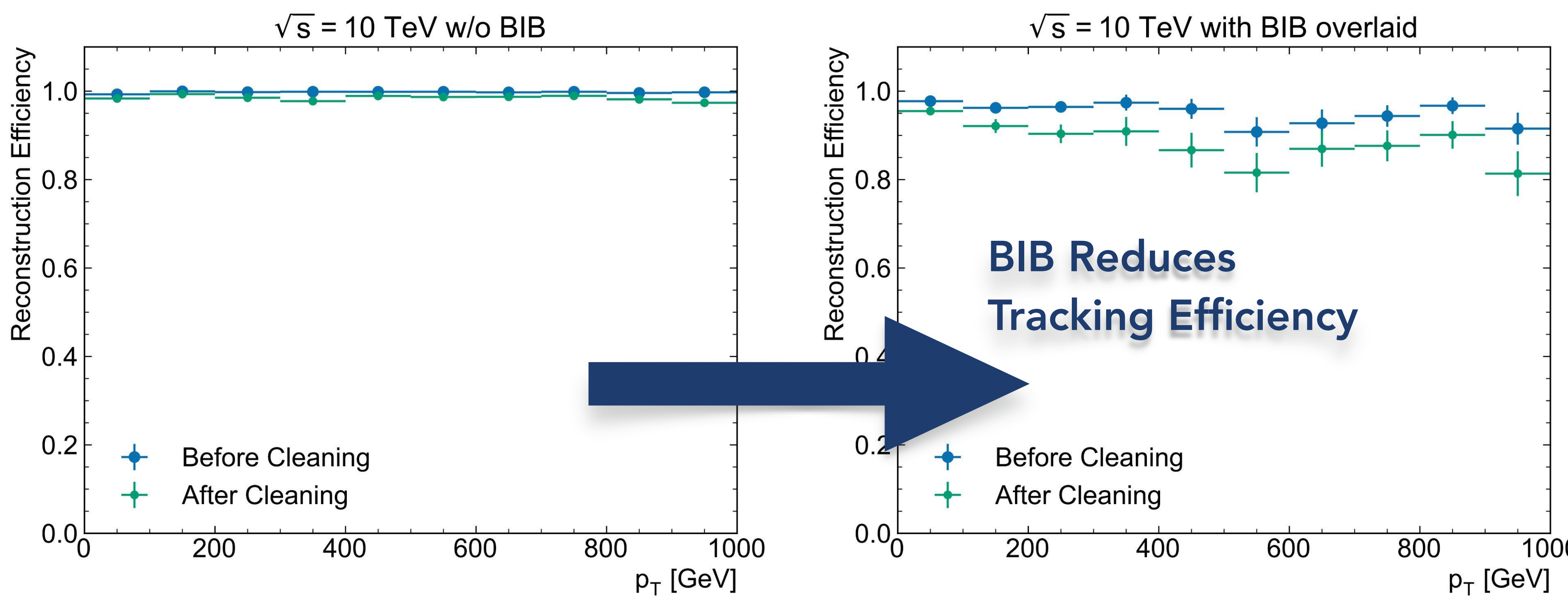


Images from C Bell, LL

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



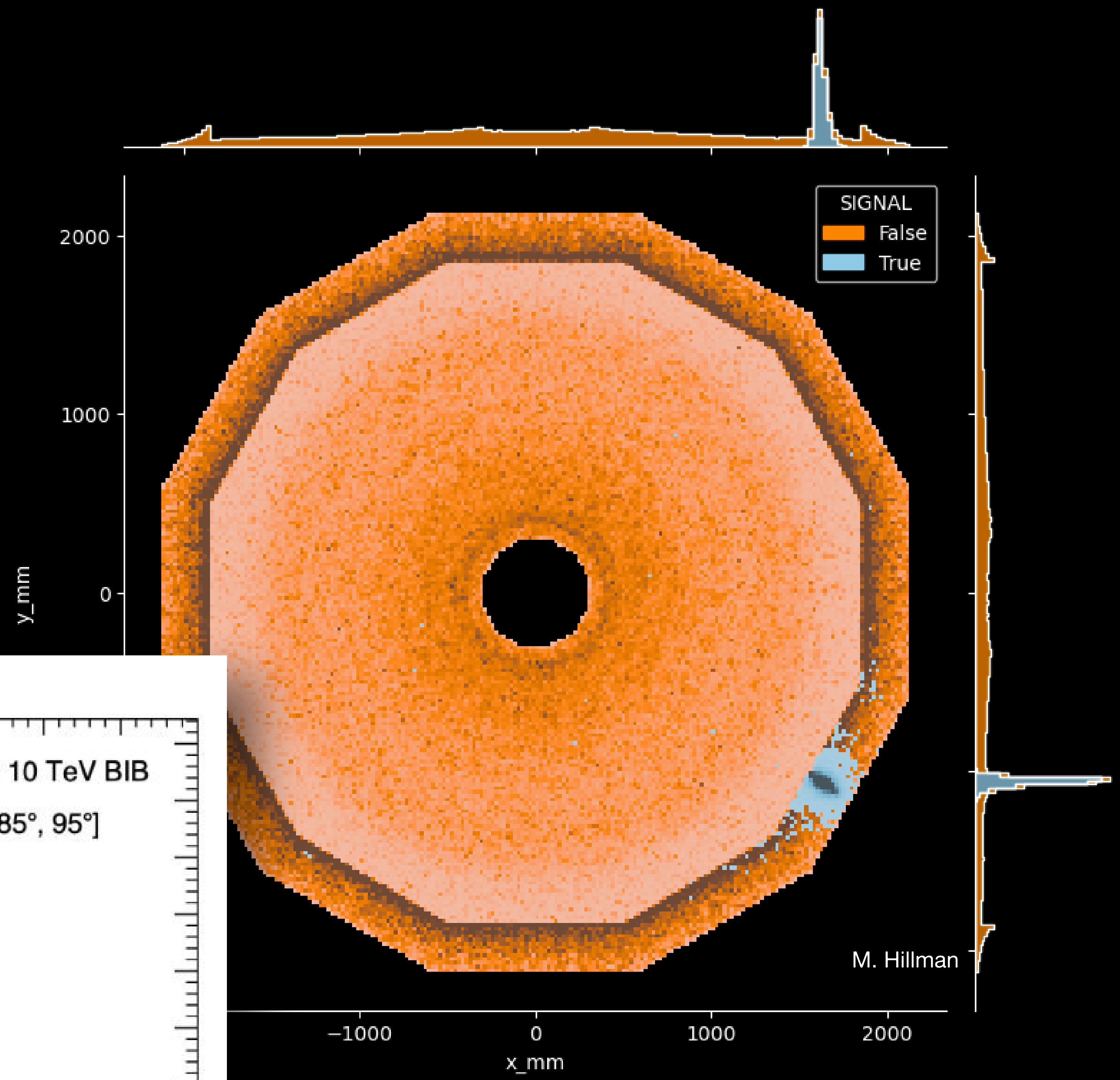


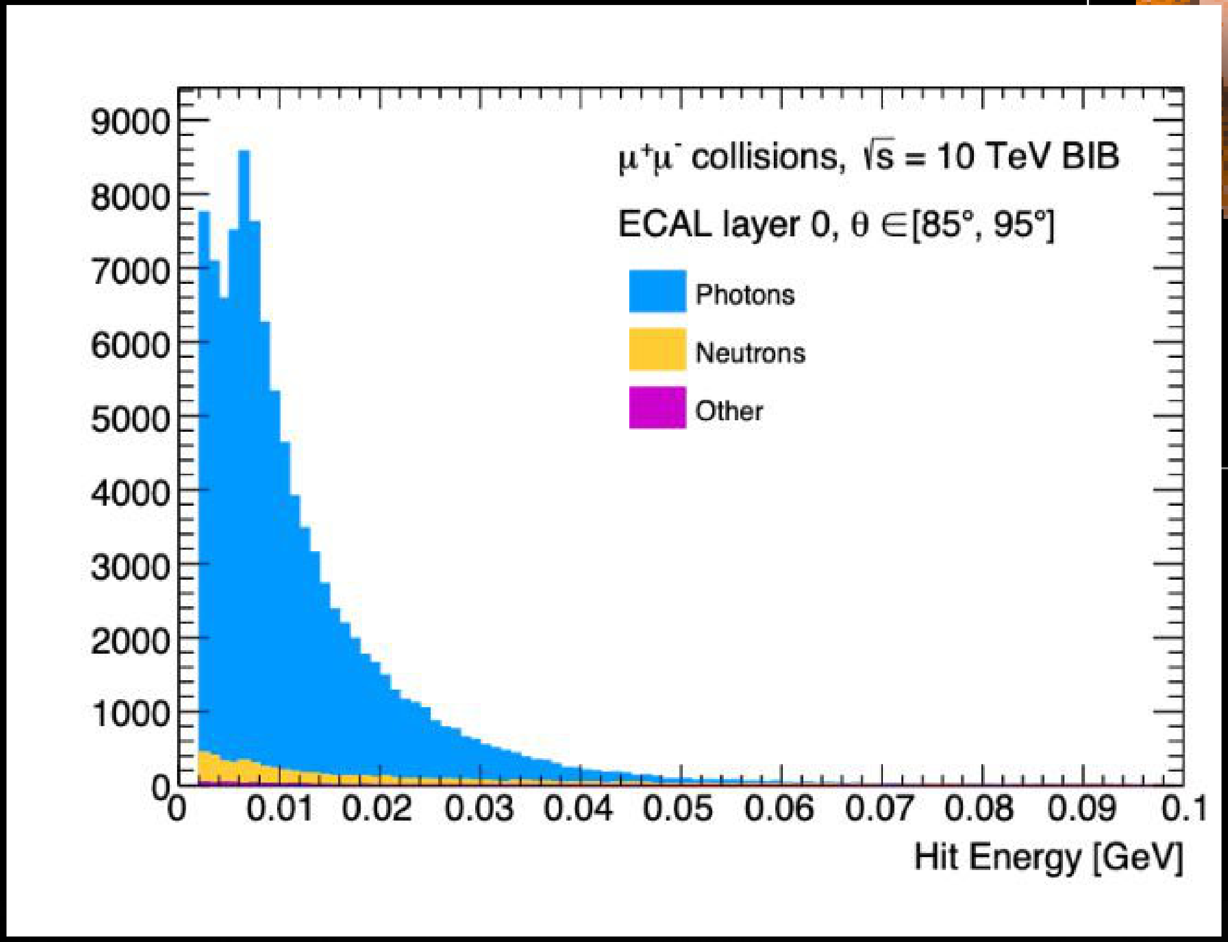
L. Rozanov

Images from C Bell, LL

MAIA Detector Concept: EM Calorimeter

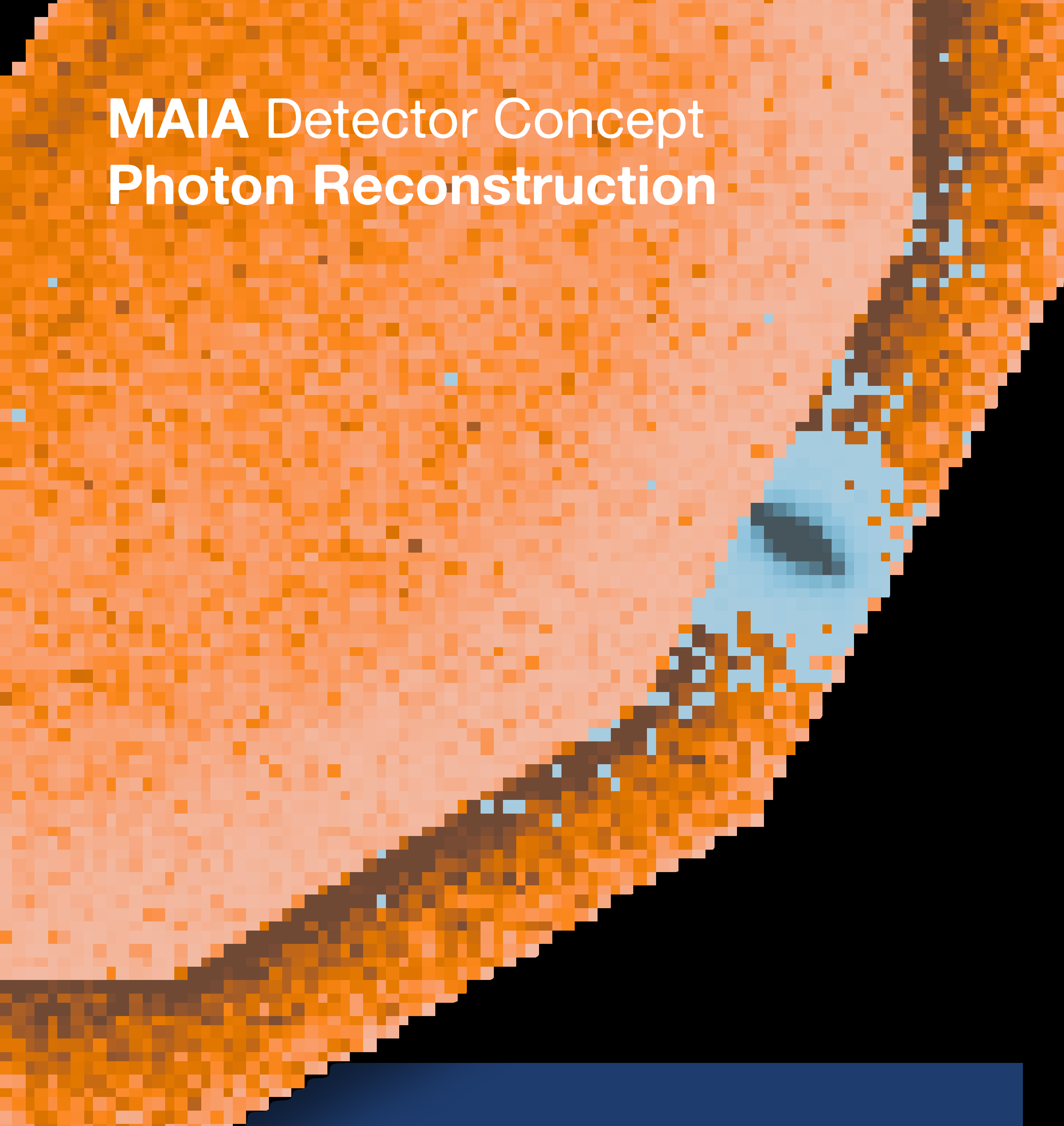
- Using W+Si design
- Very sensitive to large photon BIB contribution **in first few layers**
- Longitudinal segmentation is key to rejecting BIB





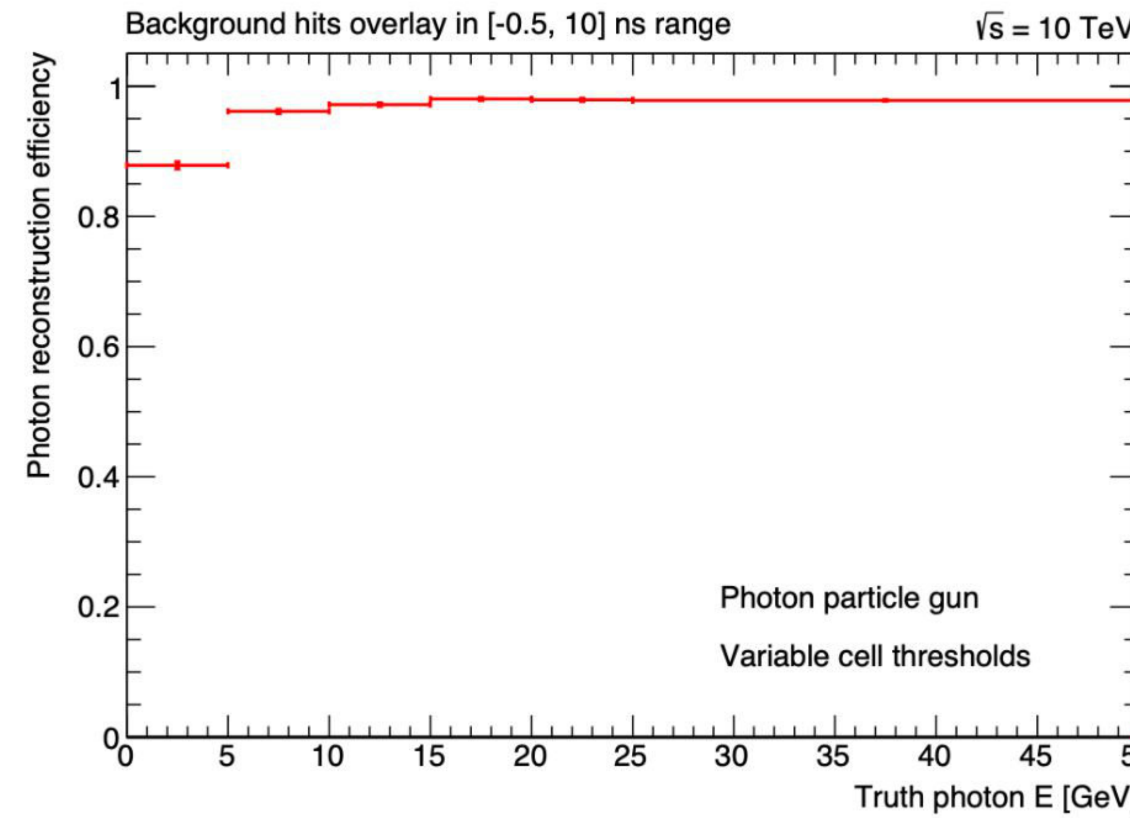
F. Meloni via slides by K. Kennedy

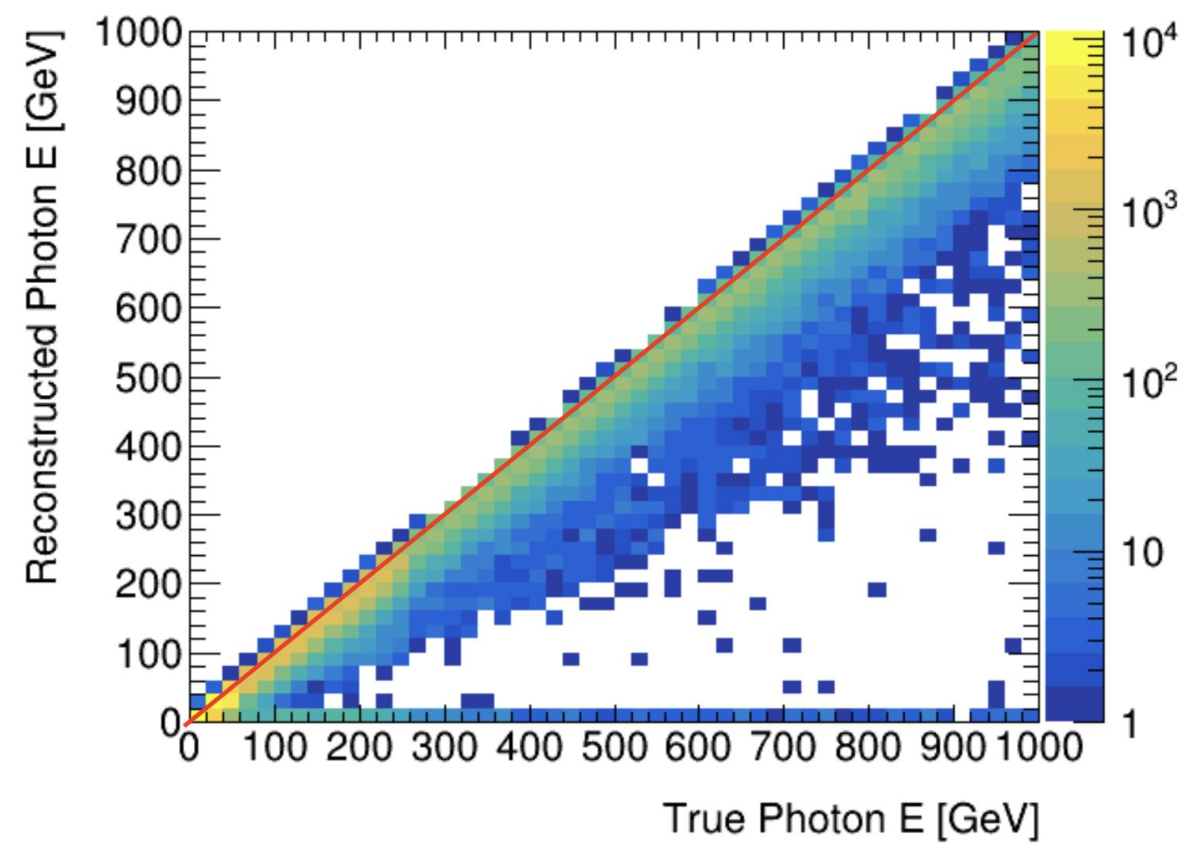
MAIA Detector Concept
Photon Reconstruction



M. Hillman

- Even w/ BIB, still have high photon reco efficiency. ~100% for >15 GeV
- But the solenoid in the way makes for worse resolution, complicated calibration

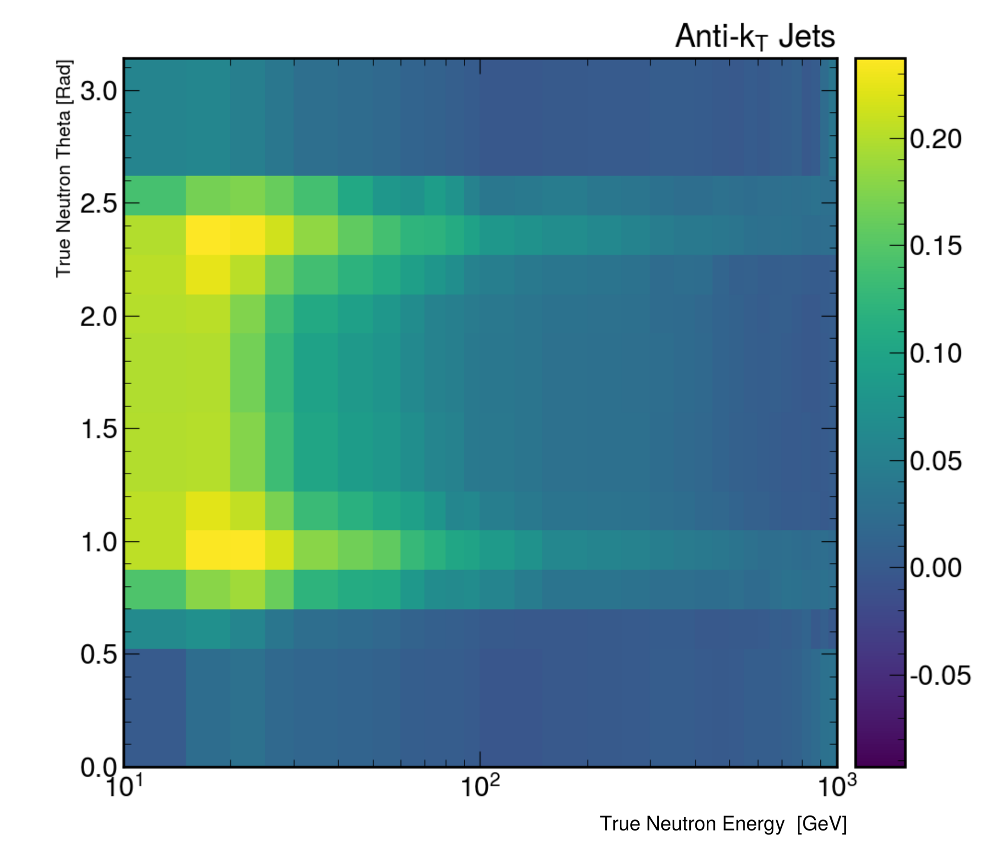


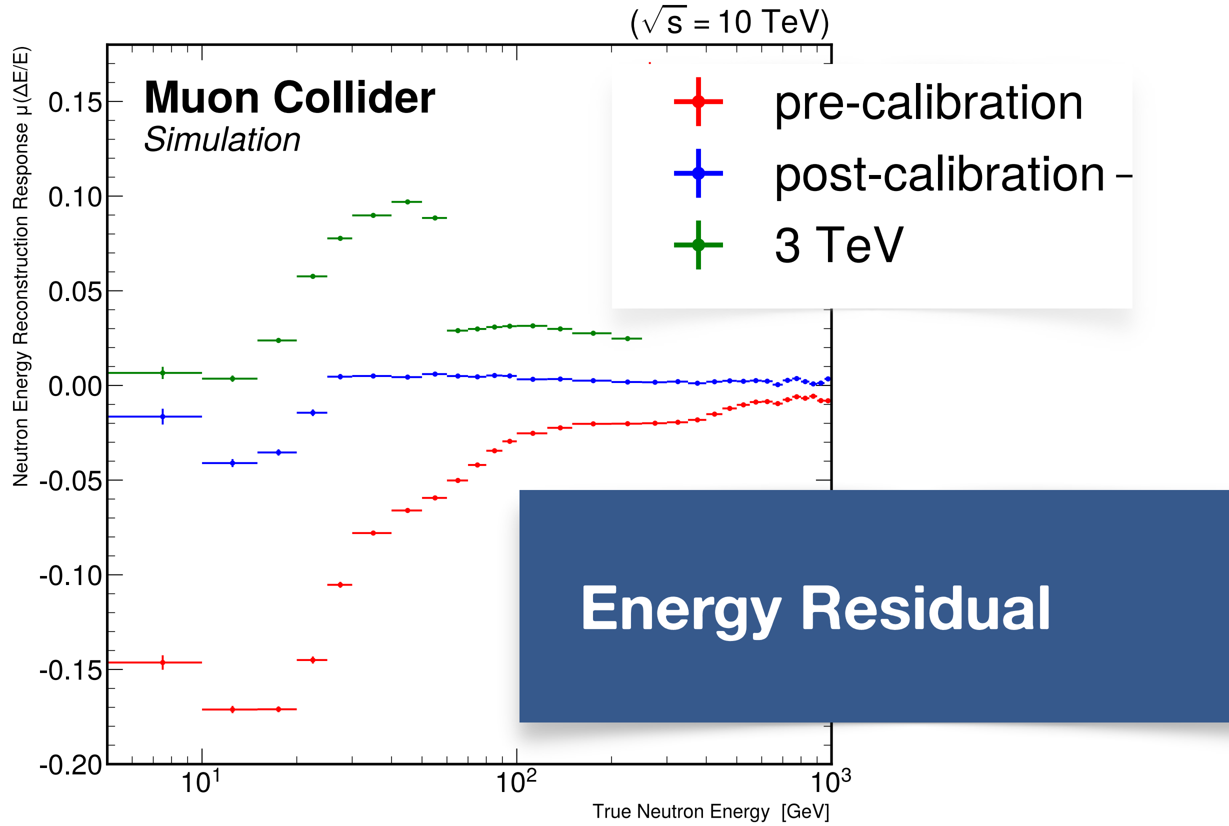


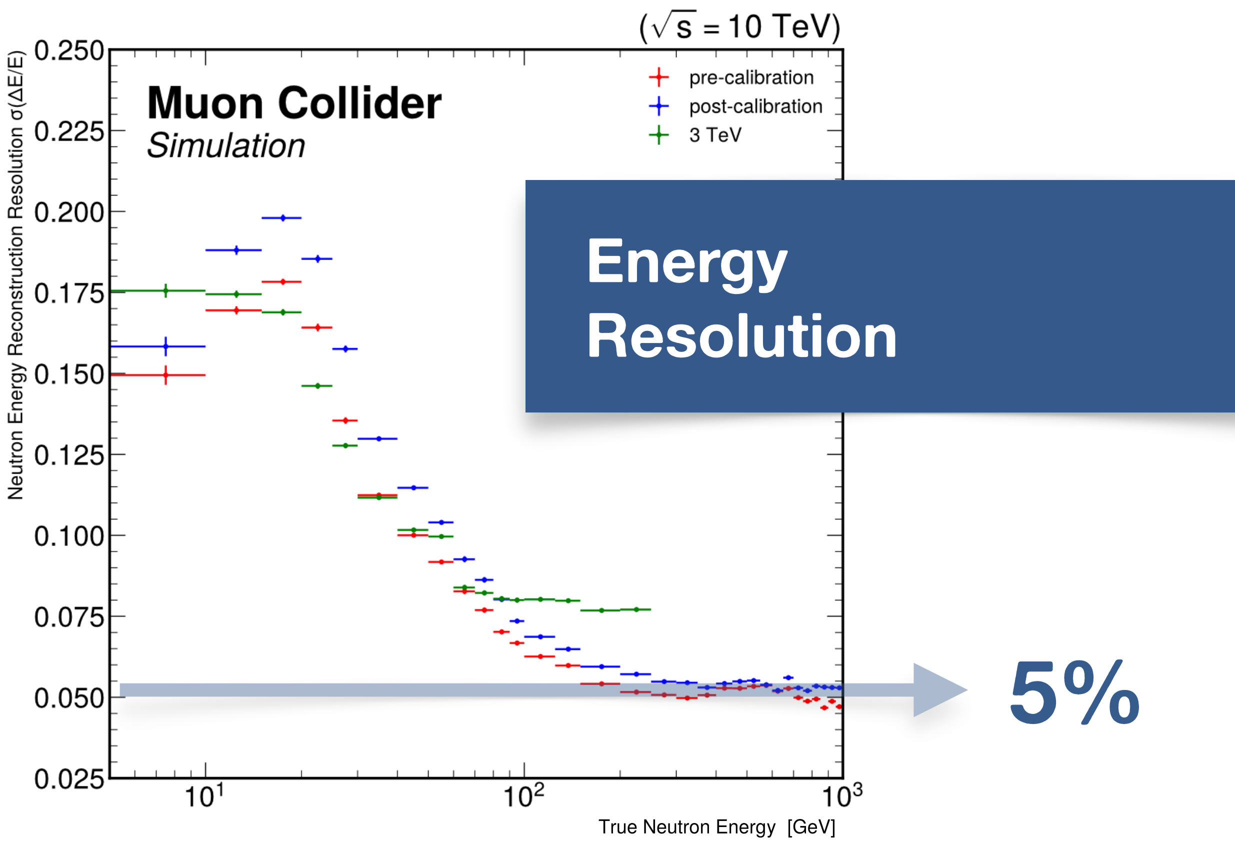
T. Holmes, R. Powers via slides by K. Kennedy

MAIA Detector Concept: Hadronic Calorimeter

- Initial calibrations give **nice performance for single neutron reconstruction** in HCal
- Building up to **full hadronic jet** performance studies



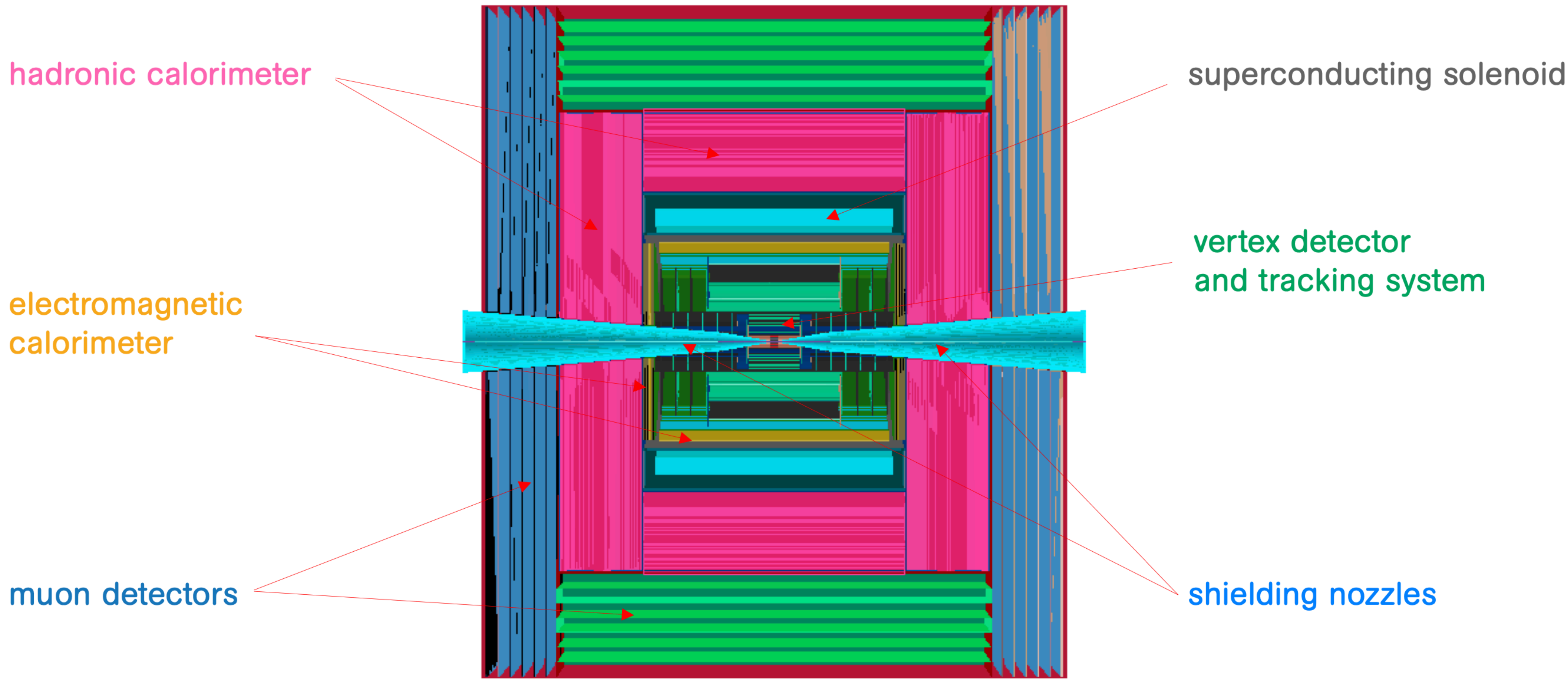




Slides by E. Sledge

MUSIC Detector Concept

Muon Smasher for Interesting Collisions



- **Another detector concept**
- Shared genealogy with MAIA in earlier 3 TeV concept, so many assumptions are shared
- Scale up tracker with new design
- Let the solenoid grow and place it between ECal and HCal

M. Casarsa, C. Giraldin, D. Lucchesi,
L. Palombini, L. Sestini, D. Zuliani
INFN-Trieste, University of Padova, INFN-Padova

Images from slides from M. Casarsa

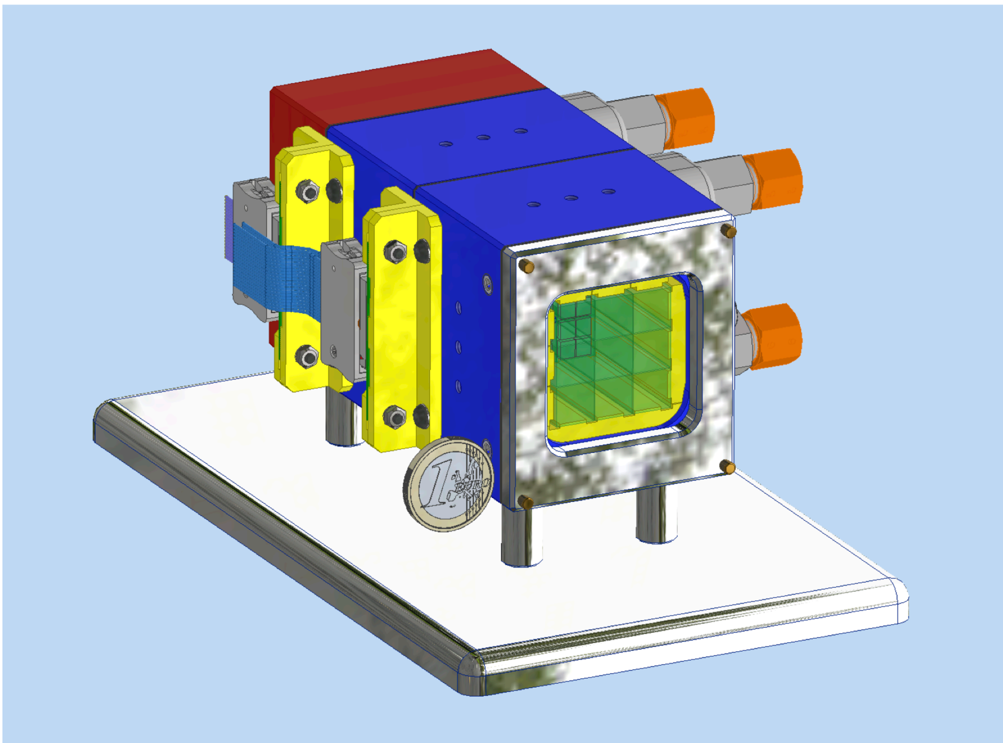
MUSIC Detector Concept: Solenoid

Serious focus on a serious solenoid

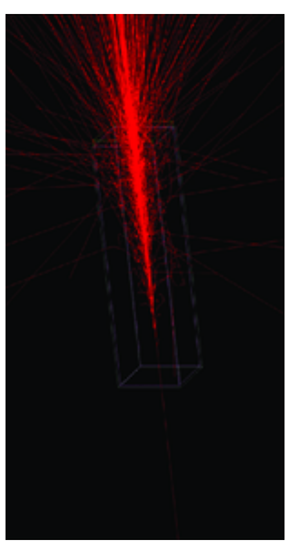
- **Much larger volume.** Large lever arm for high p_T measurements
- 2.4m radius 4-5 T solenoid between ECal and HCal
- Focus on capturing **return field** at 1.9T (a la CMS)
- Solenoid is 3x thicker than MAIA's to handle high current

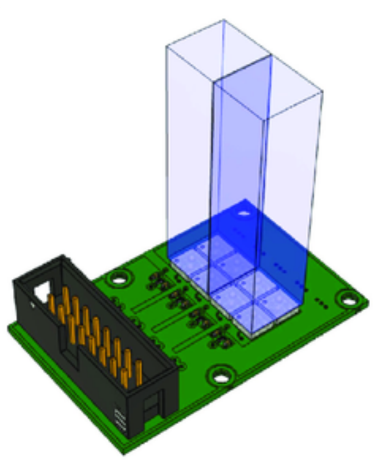
Images from slides from M. Casarsa

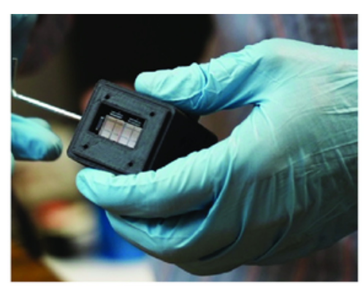
MUSIC Detector Concept: EM Calorimeter



[2206.05838, I. Sarra Talk at IMCC]







- MUSIC ECal centered on CRILIN concept
- **CRILIN: CRYstal calorimeter with Longitudinal InformatioN**
  - EM calo of lead fluoride crystals
  - Lots of **longitudinal information**
  - Critical for separating out BIB in first few layers
  - Time resolution down to 15 ps
- Instead of shielding the ECal and reducing signal resolution, use longitudinal info to actively reject BIB

Experimental studies are maturing quickly

Full sim studies with BIB are becoming the norm

Adding **physics BG effects** like incoherent pair production

Studies for **forward muon tagging** to distinguish ZZ vs WW VBF

Calibration workflows are developing

Modern Software Workflows
Spack package management, CI/CD workflows, and containerization

...

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Still so much work to do!

Lots of opportunities to contribute

Detector **calibration and optimization**

Object calibration and performance w/ conceptual detectors

Move beyond low level studies to **test physics performance w/ full sim**

Realistic **services, support structures**, etc

Lots of **detector R&D** to meet the resolution, radiation, readout, and power requirements of these detectors

Many **computing challenges**!

Weight of computing workflow prevent many optimizations

Software workflows still being defined and opportunities for optimization

Many areas have very few experts
[Go to the tutorials!]

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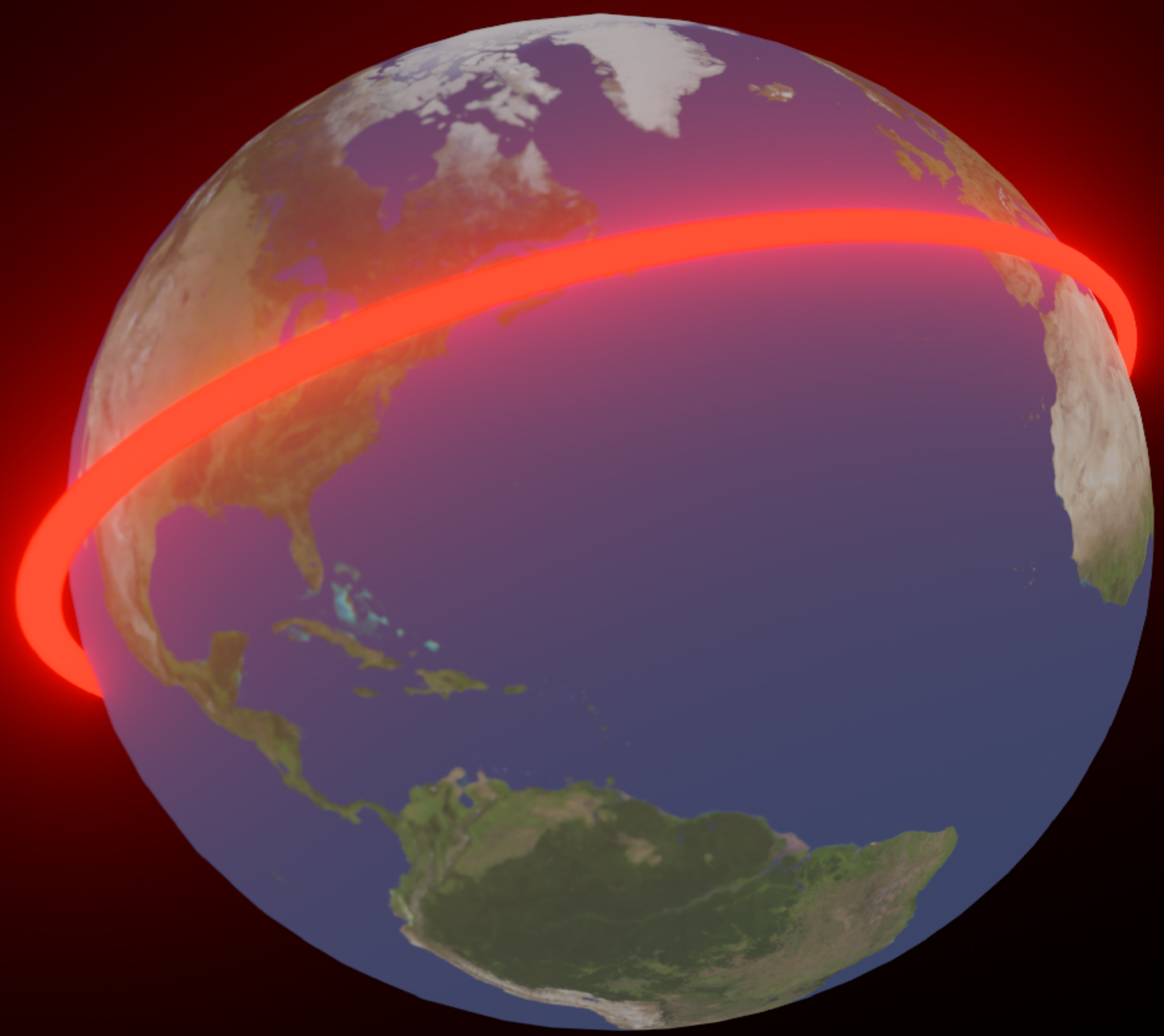
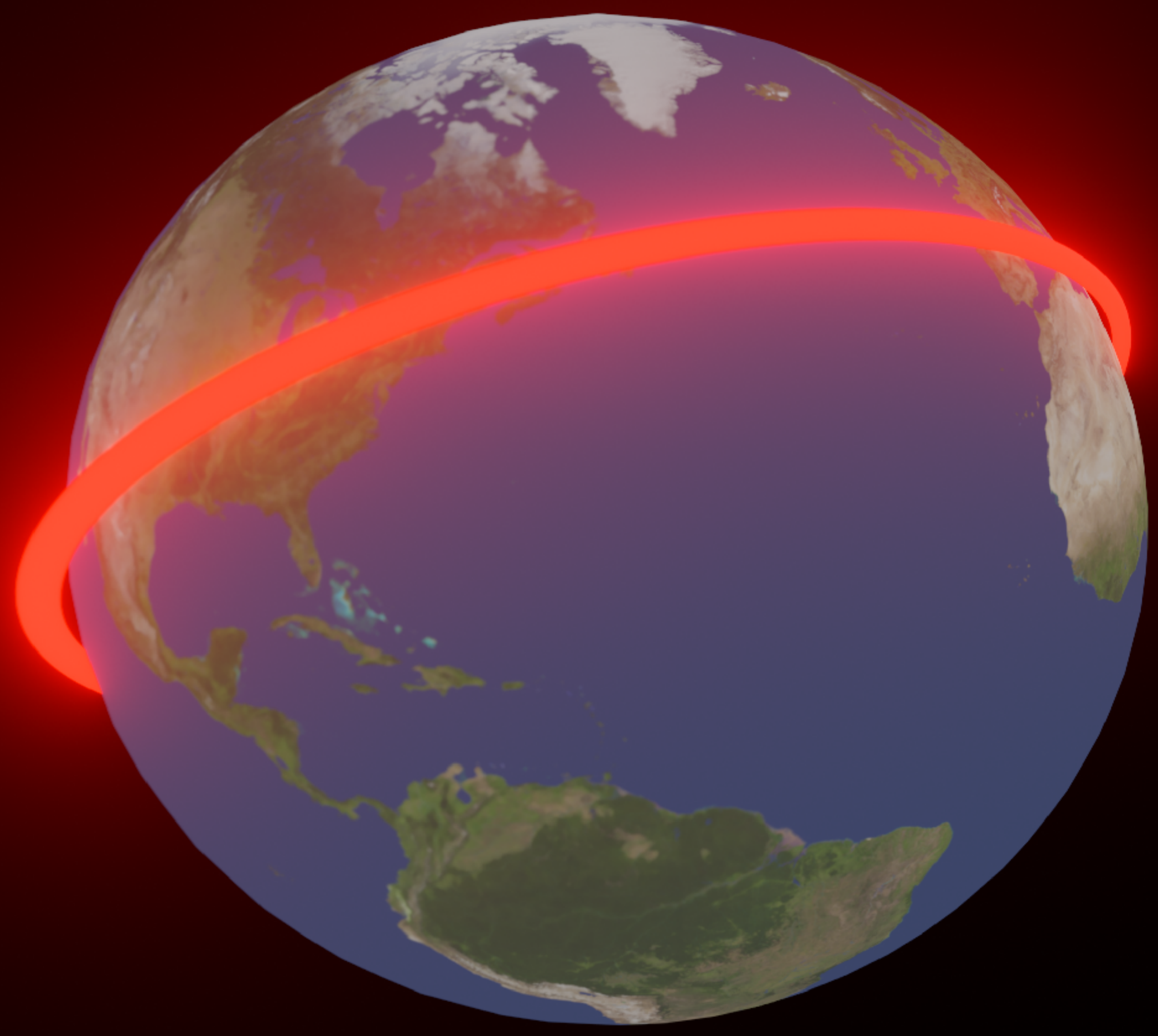


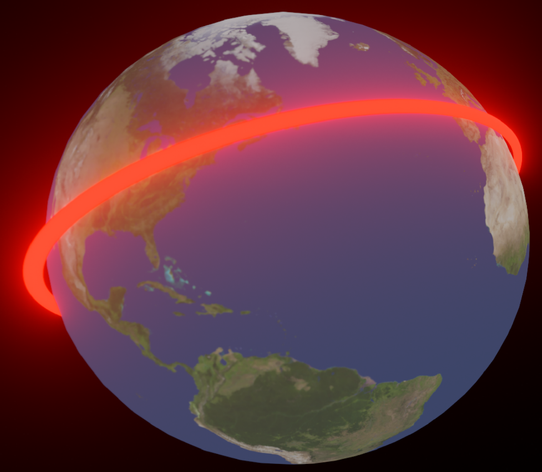
Fermi’s Globatron (1954)

This one’s been brought up a bunch recently…



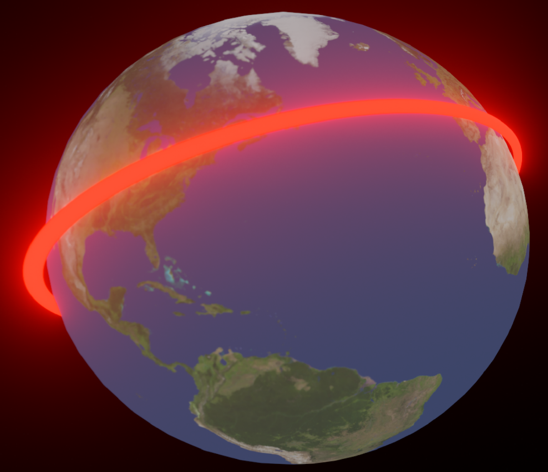
Fermi's Globatron (1954)

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"

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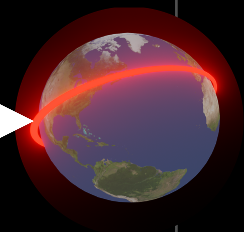
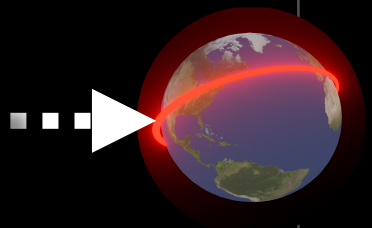
"Discovery of new particles is for hadron machines"

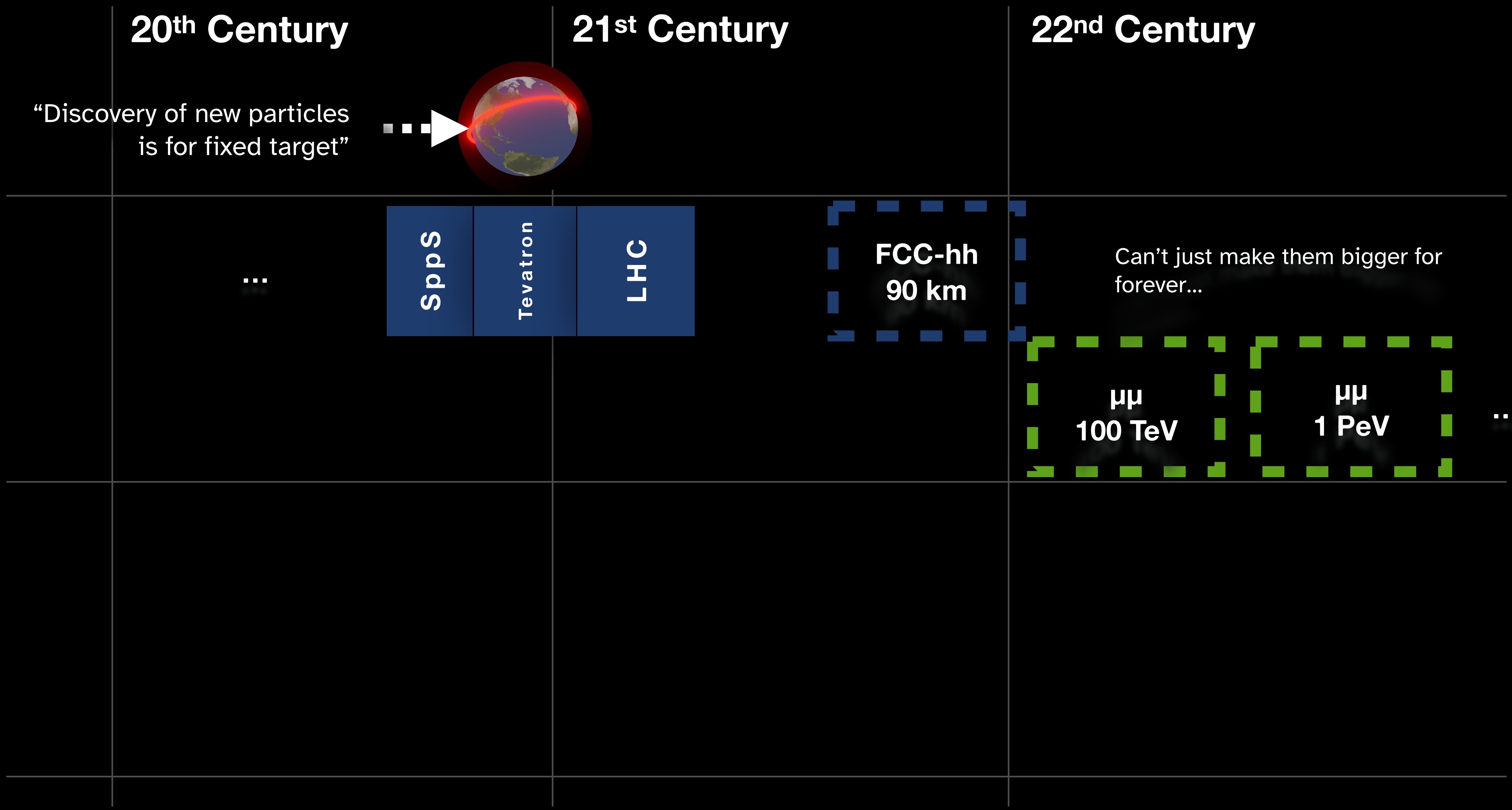
✅ Historically true!
✅ Could keep going with this!

	20^{th} Century	21^{st} Century	22^{nd} Century

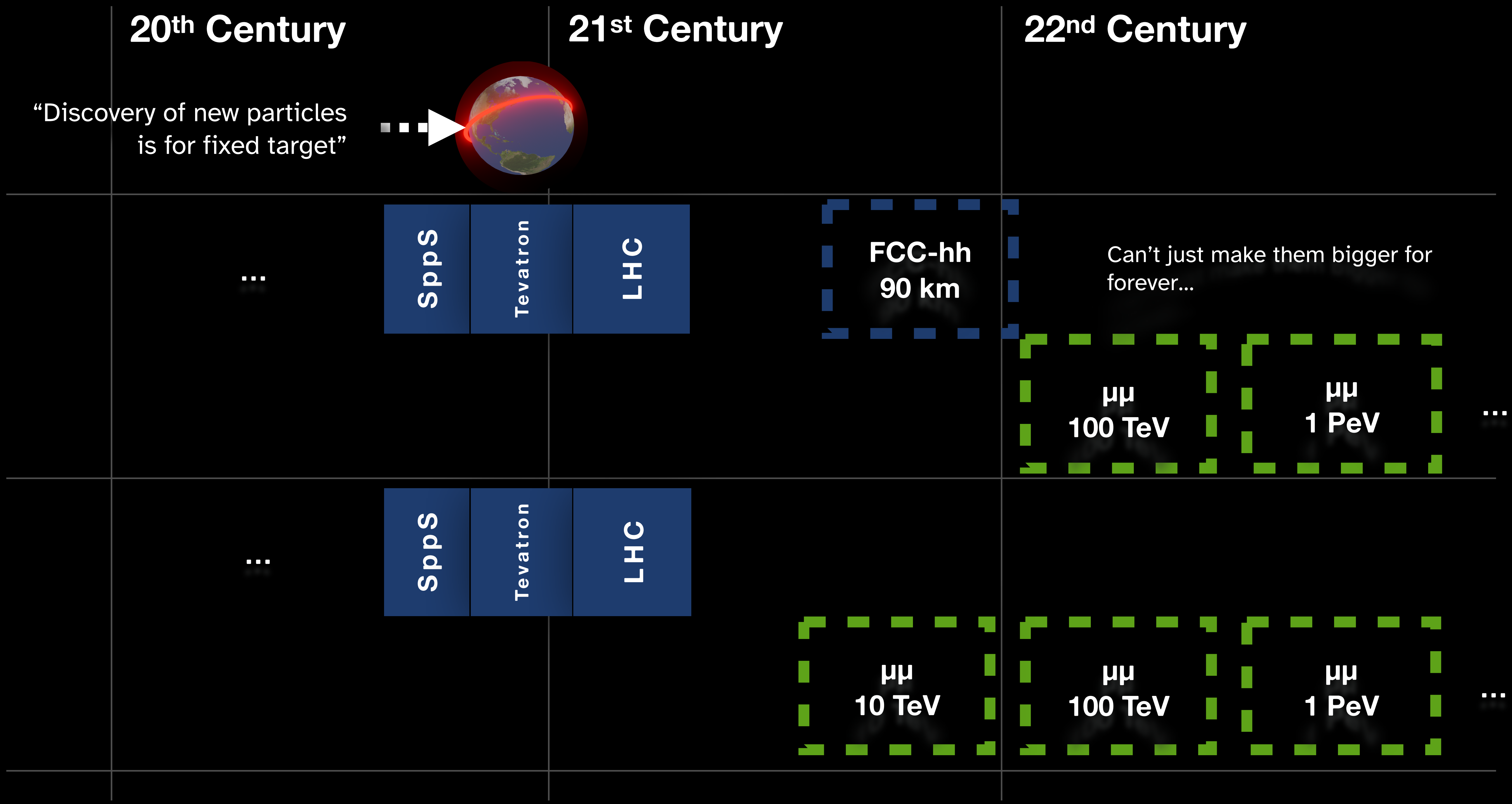
"Discovery of new particles is for fixed target"



	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
...



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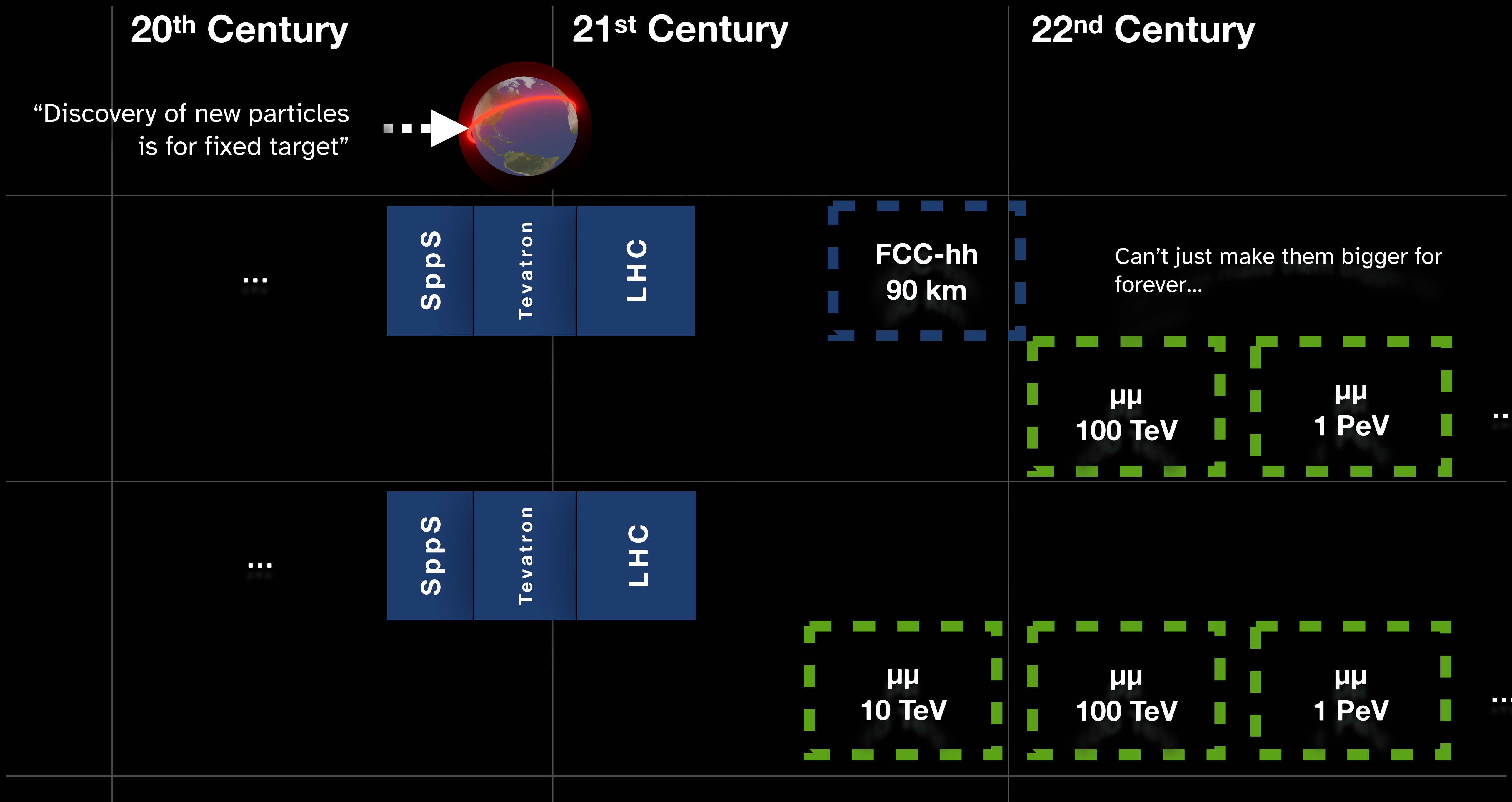
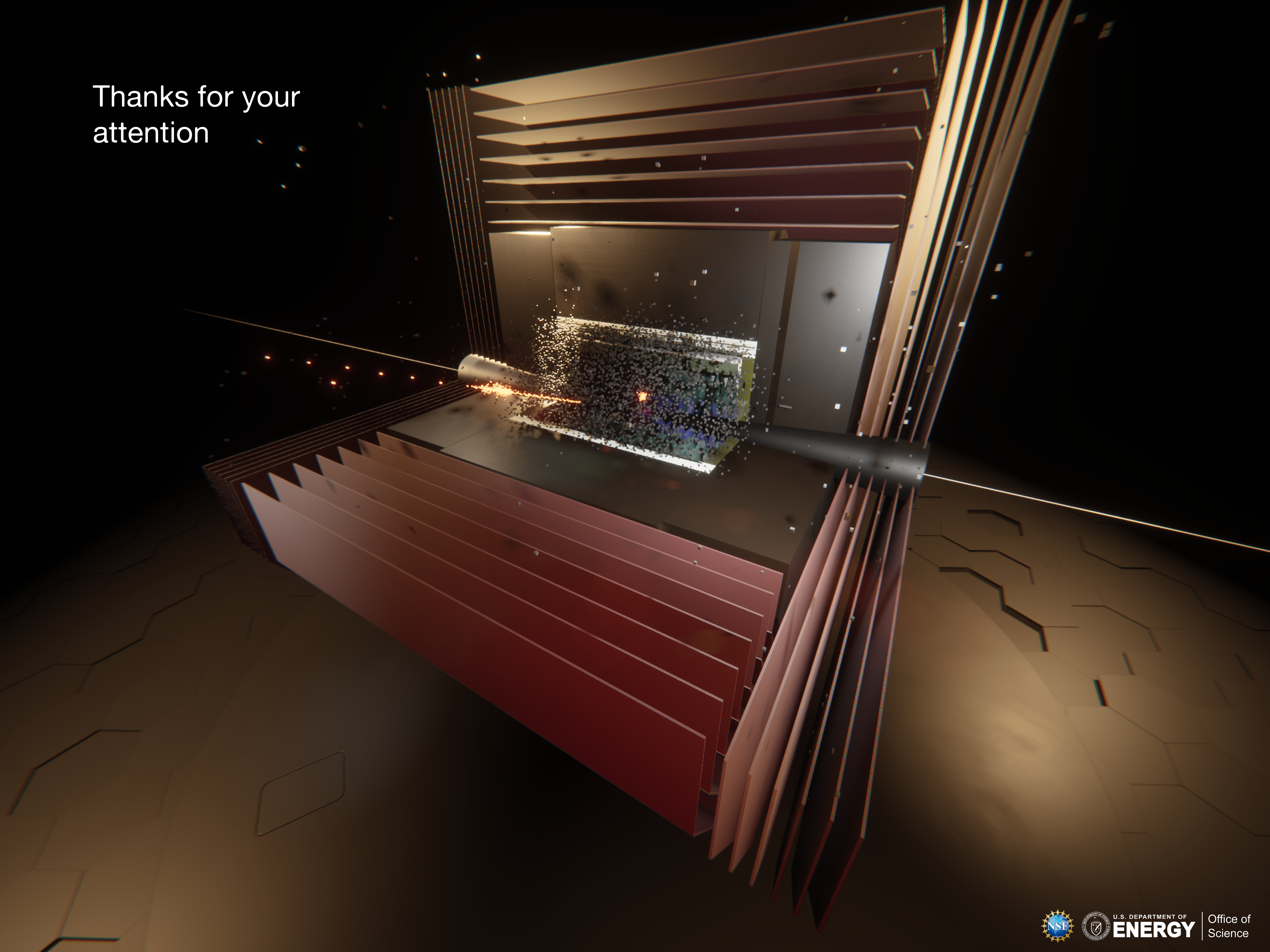


Ask ourselves:

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?

Thanks for your attention



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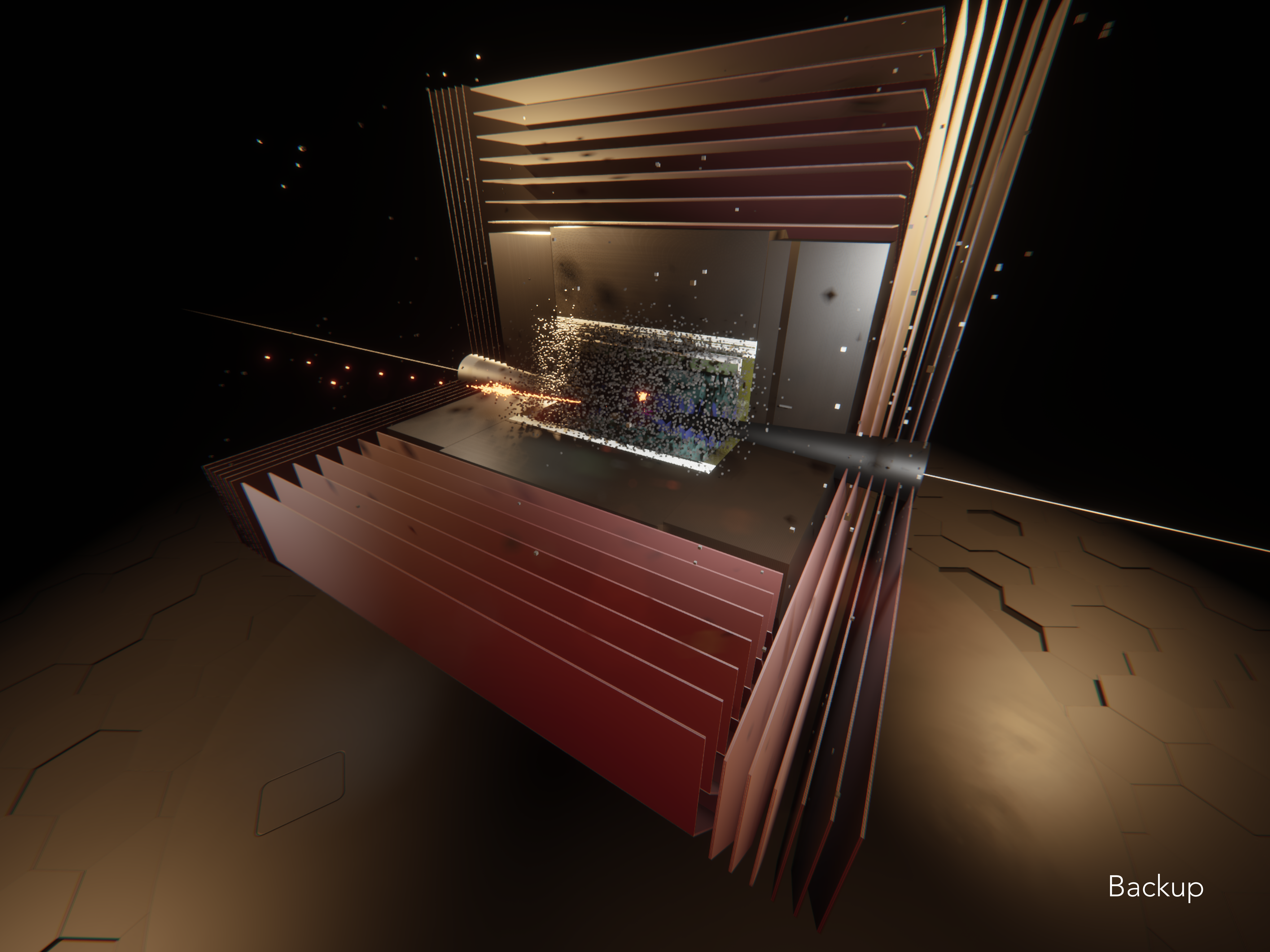

Backup

“About Discovery”
Energy spread, High energy

pp ee

“Clean and Precise”
Clean events, known initial state

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…

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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!

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Energy spread, High energy

pp

ee

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Clean events, known initial state

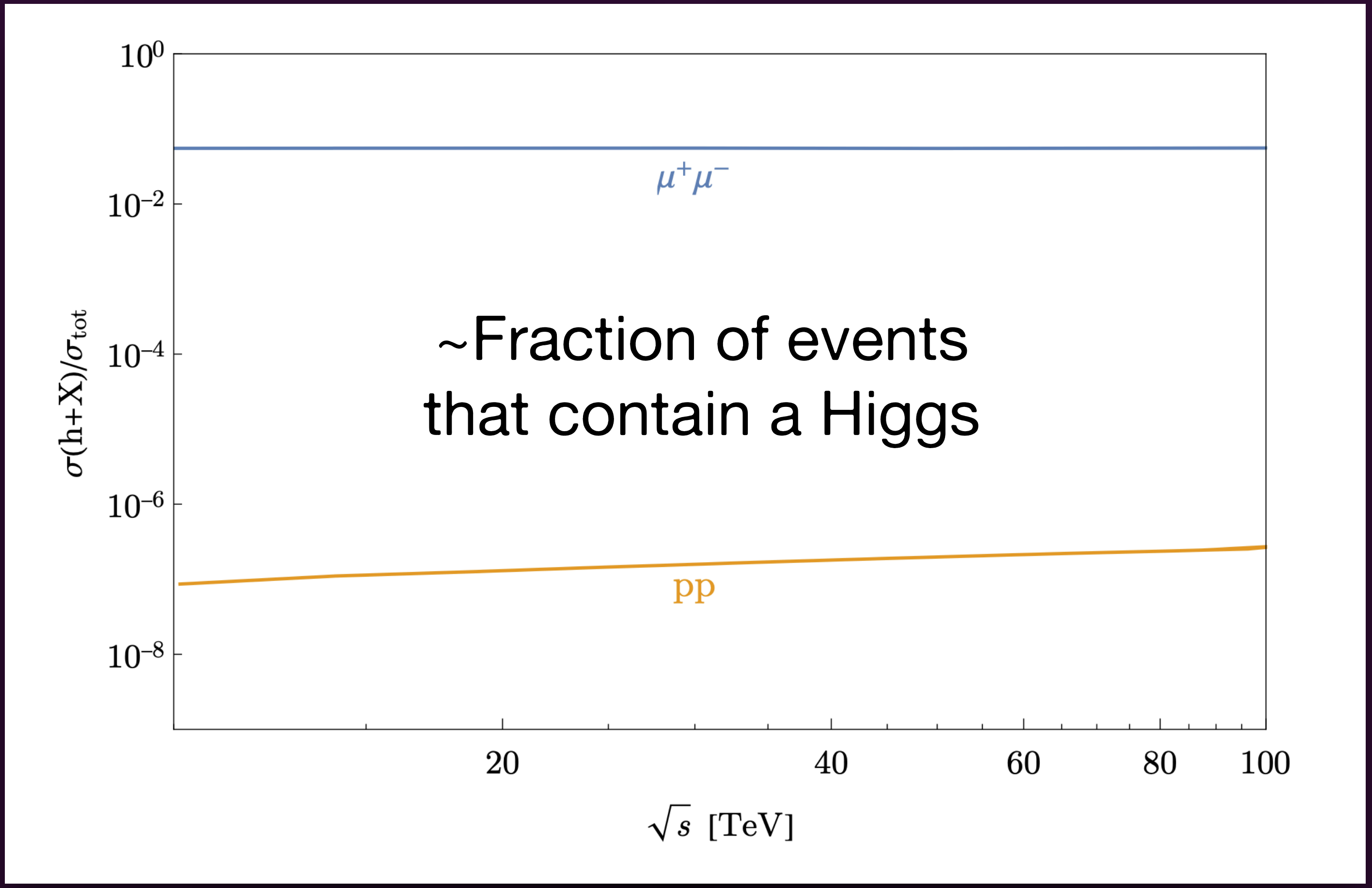
μμ

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!



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Muon Smasher's Guide

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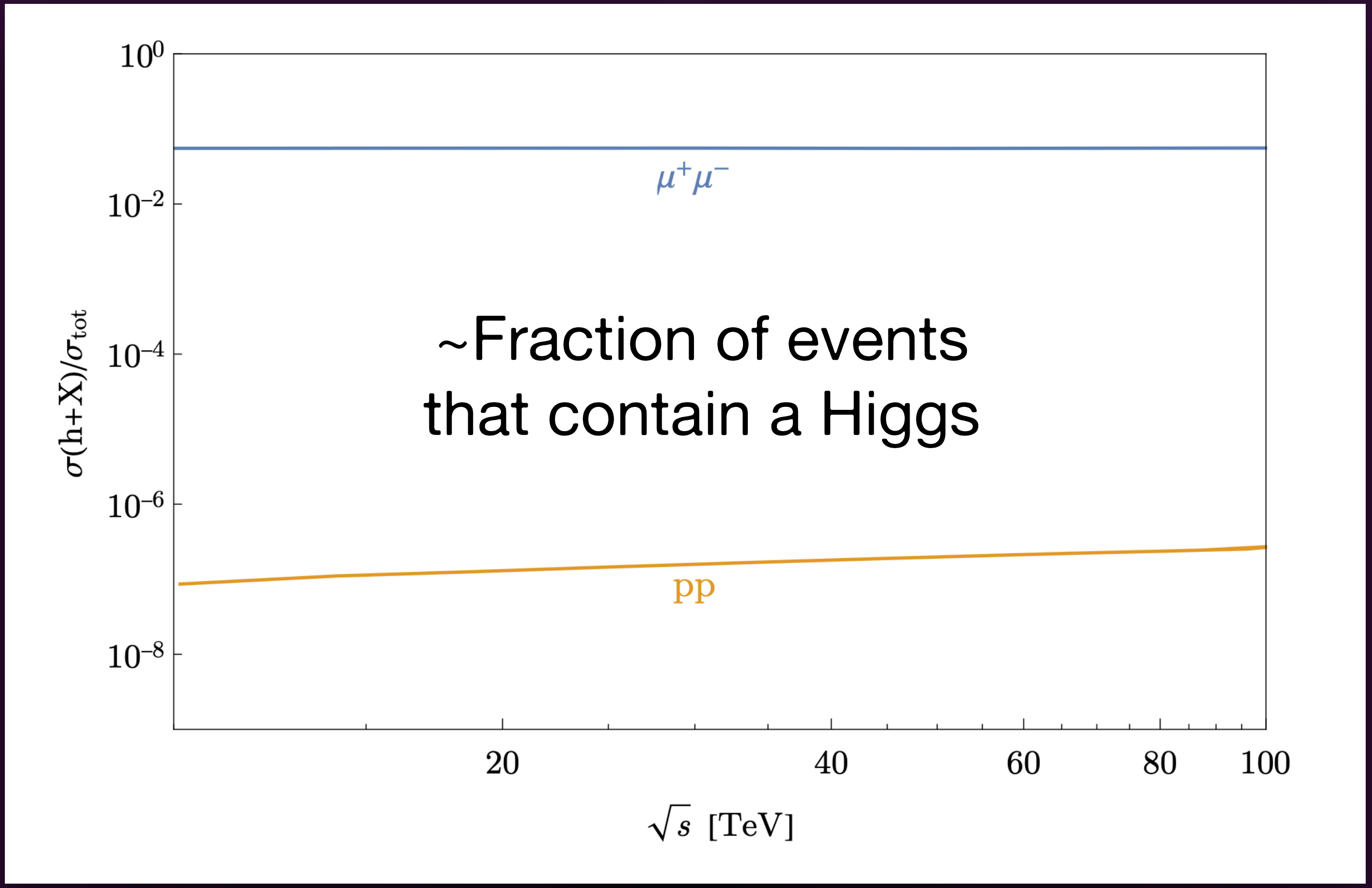
We’re lucky to be dominated by instrumental BGs!

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



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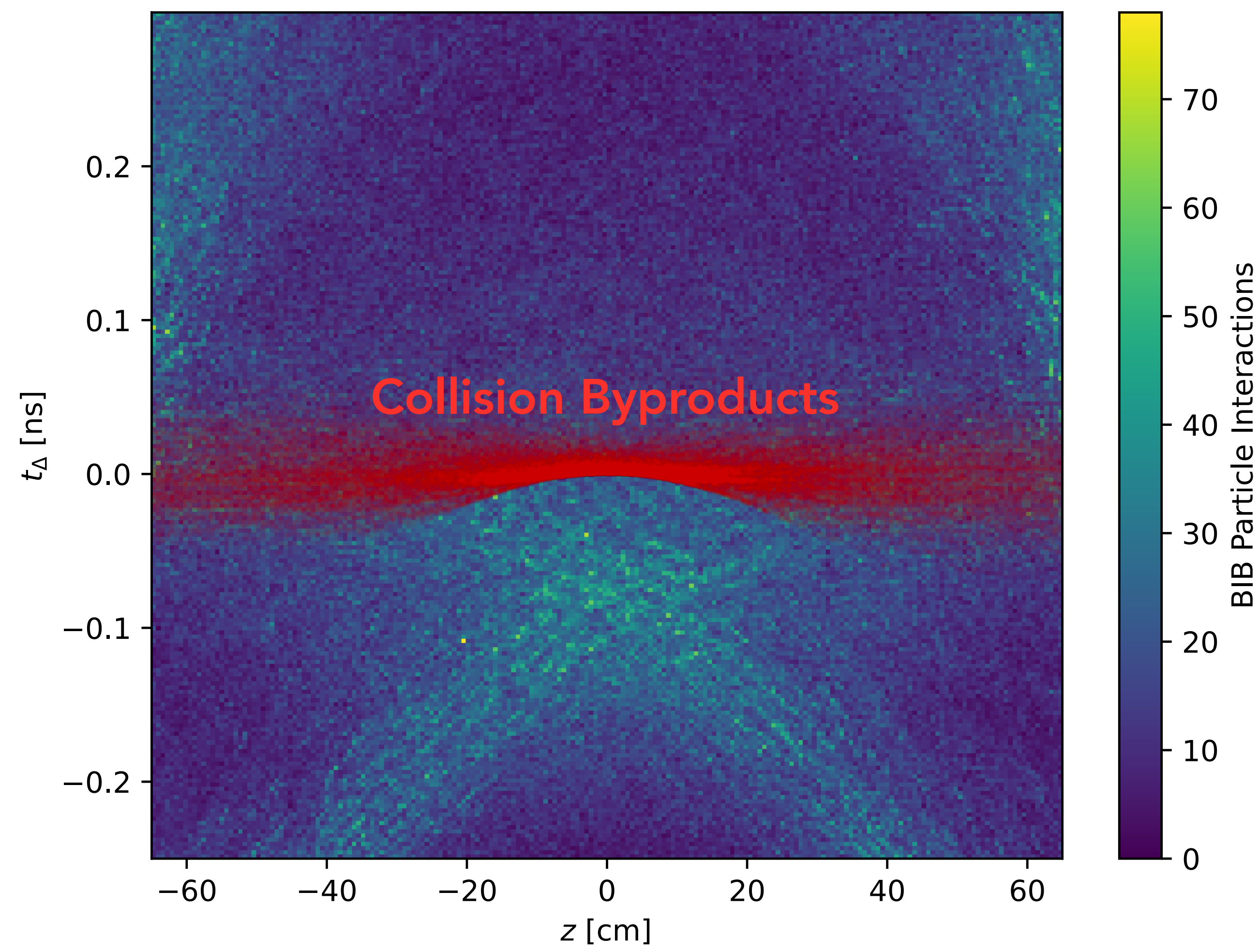
~~[1] Except w/ the BIB it looks nothing like ee. Don’t worry about it…~~

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**

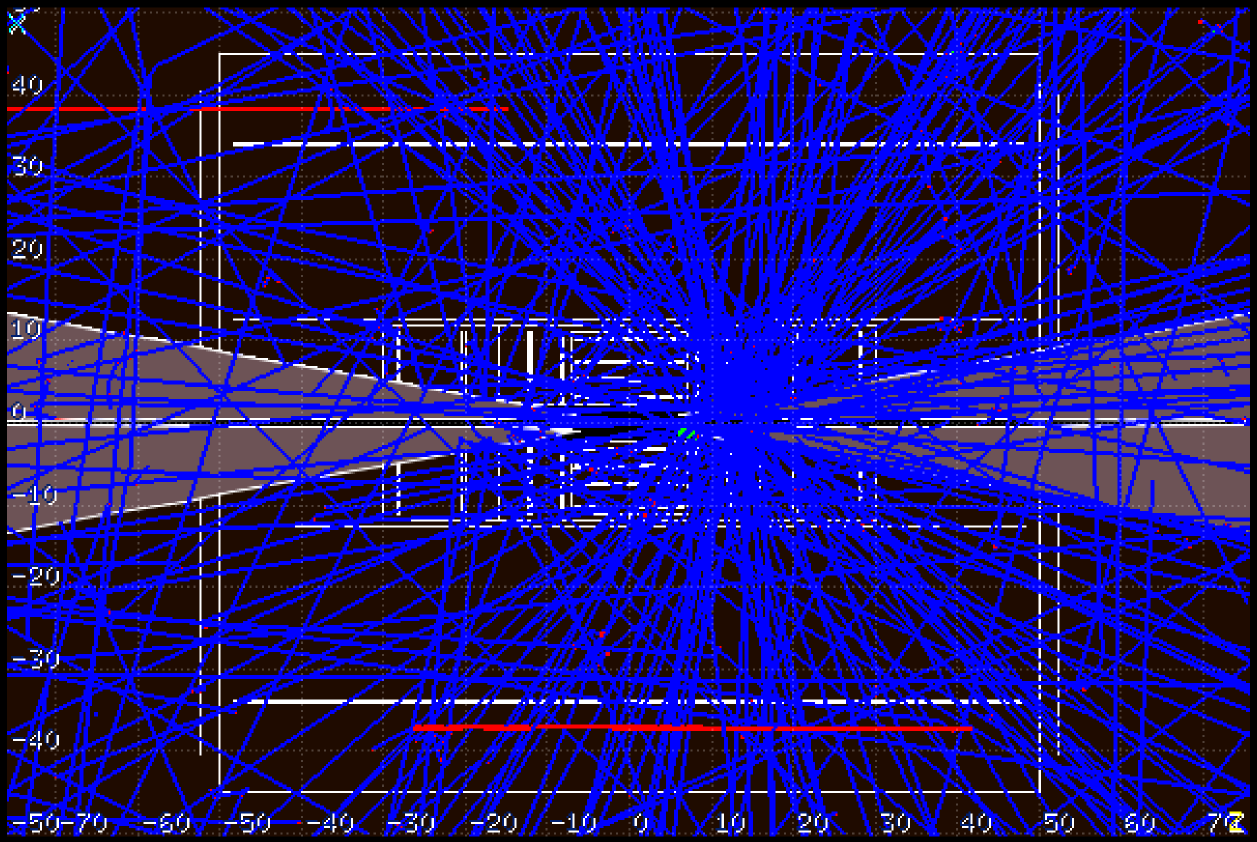
$$t_\Delta = t - t_{exp}(\beta = 1)$$



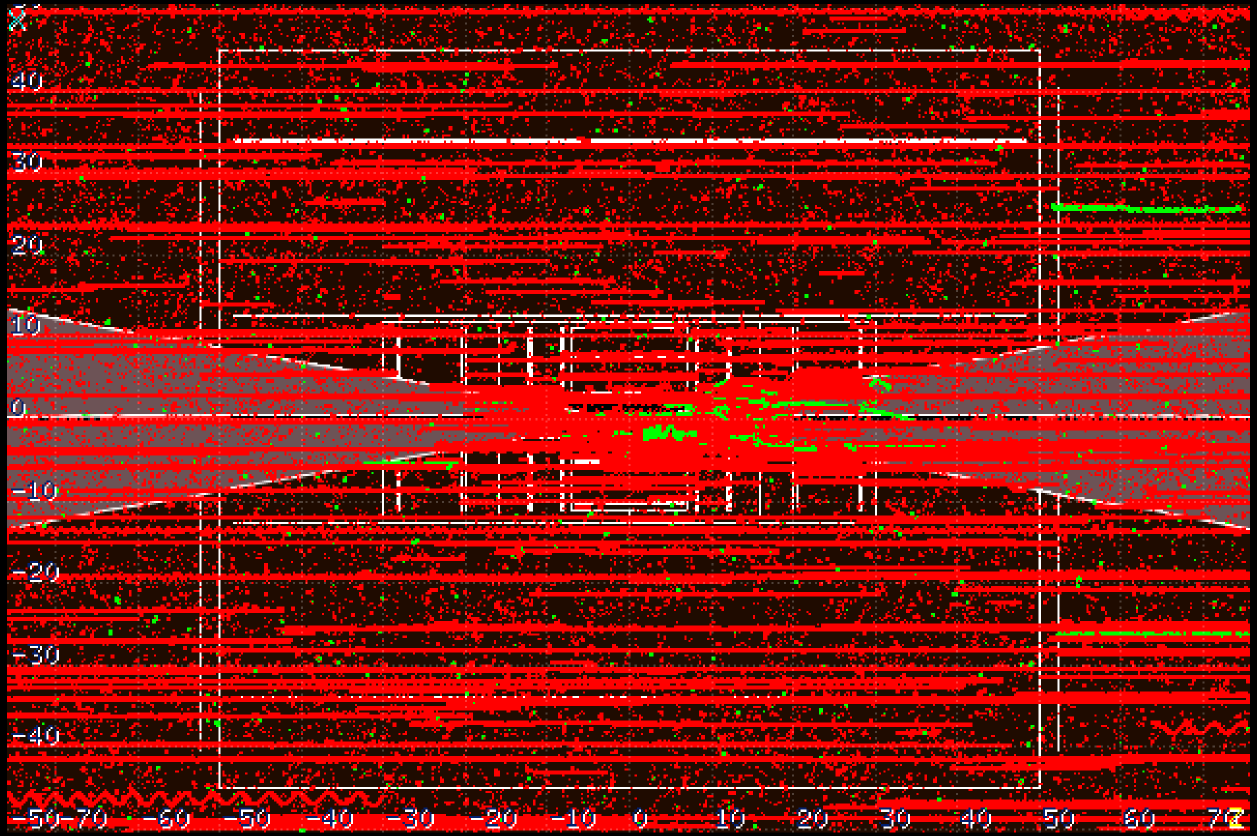
∃ information on ~10 ps scale to differentiate **BIB** from **signal**

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

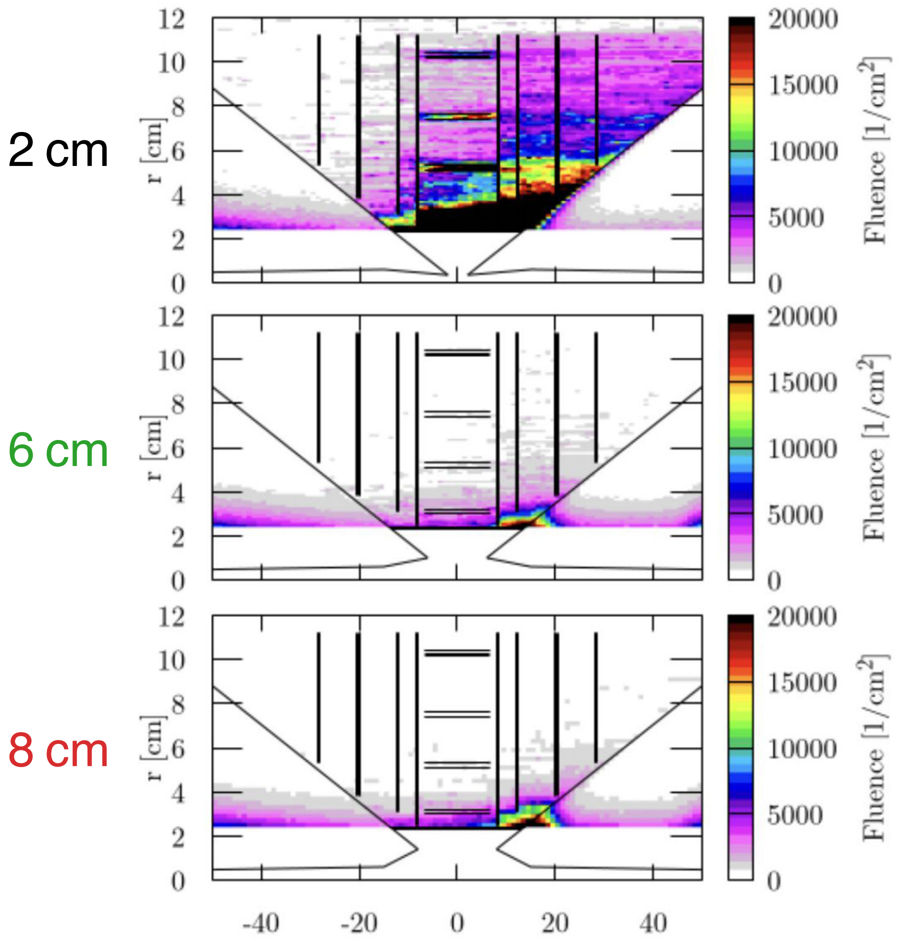
0.003% of BIB, dominated by stray photons



0.03% of BIB, w/ photons removed



D. Calzolari via Slides by T Holmes



Detector concept for $\sqrt{s}$ = 3 TeV

hadronic calorimeter

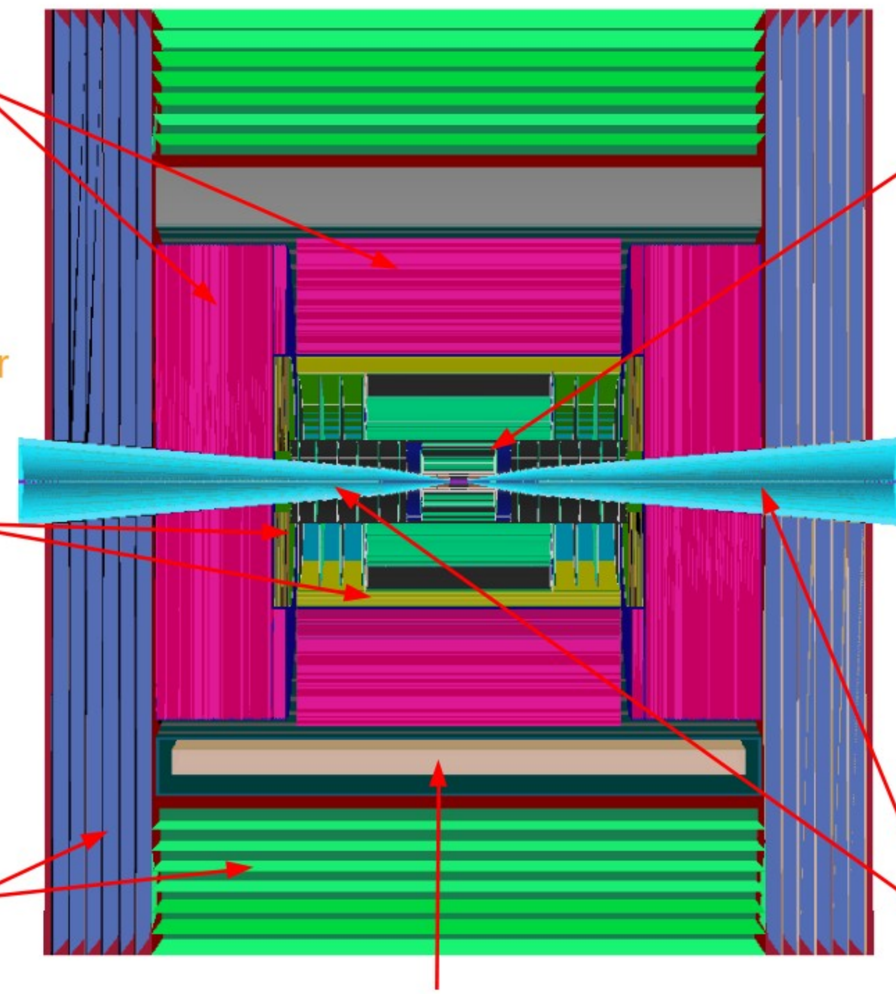
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

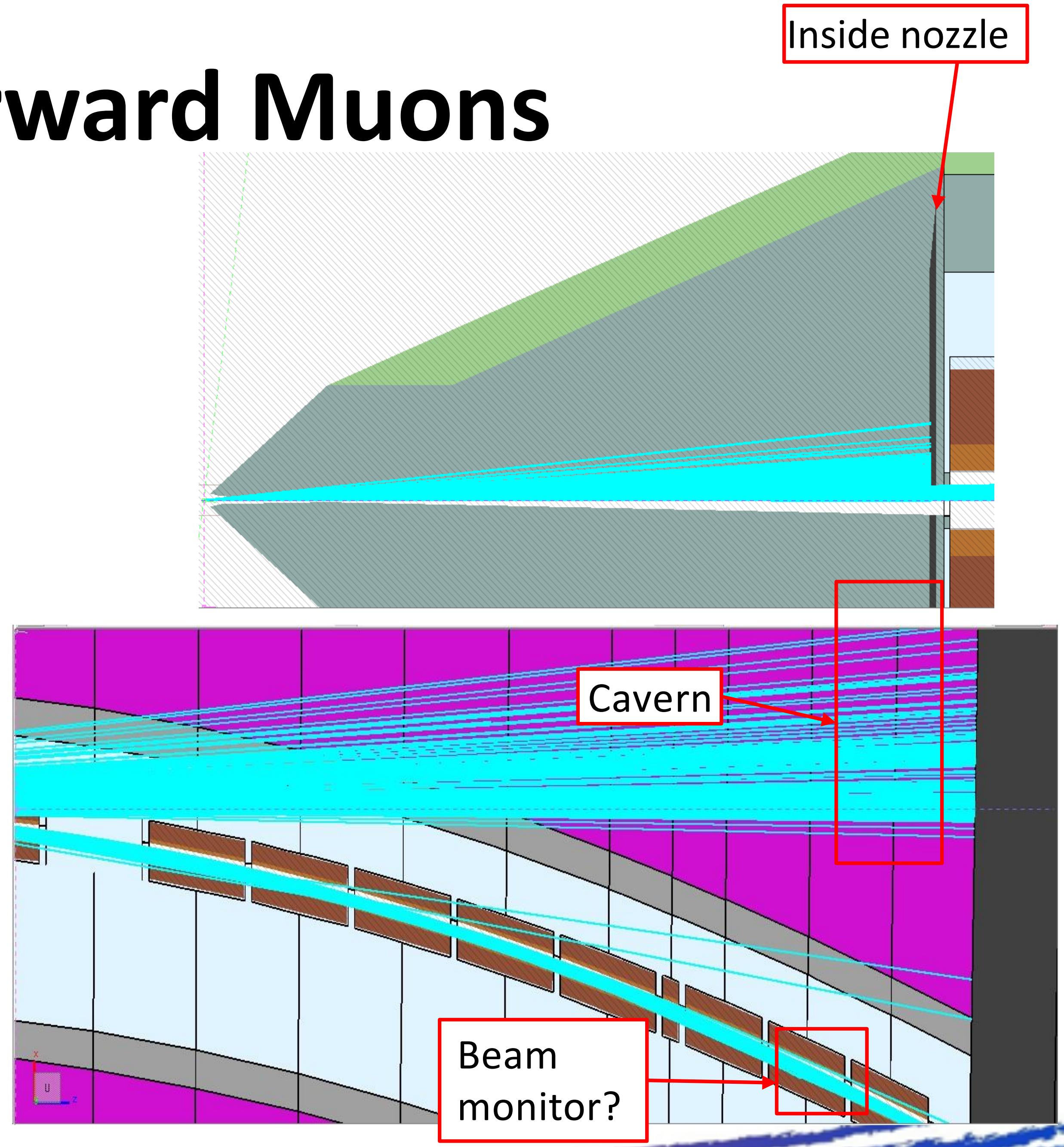
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

Detecting Forward Muons

- Two main candidates:
  - Nozzle: Small detector, high dose for BIB
  - Cavern: Large detector, clean environment
- Detectors can tag only muons not captured in the beam pipe



Slides from L. Castelli

Reading out the detector…

much slower event rate than what we're accustomed to

$$t = 33\ \mu s \times \left(\frac{L}{10\ \mathrm{km}}\right)$$

plenty of time to process a given event

but reading out all BIB hits requires increased cabling, cooling

pushes the challenge from trigger to on-detector processing

	Readout Window	E Threshold	Hit Size	Total Rate
Tracker	1 ns	n/a	32 bits	~30 Tb/s
ECAL	15 ns	0.2 MeV	20 bits	~30 Tb/s
HCAL	15 ns	0.2 MeV	20 bits	~3 Tb/s
Total				60 Tb/s

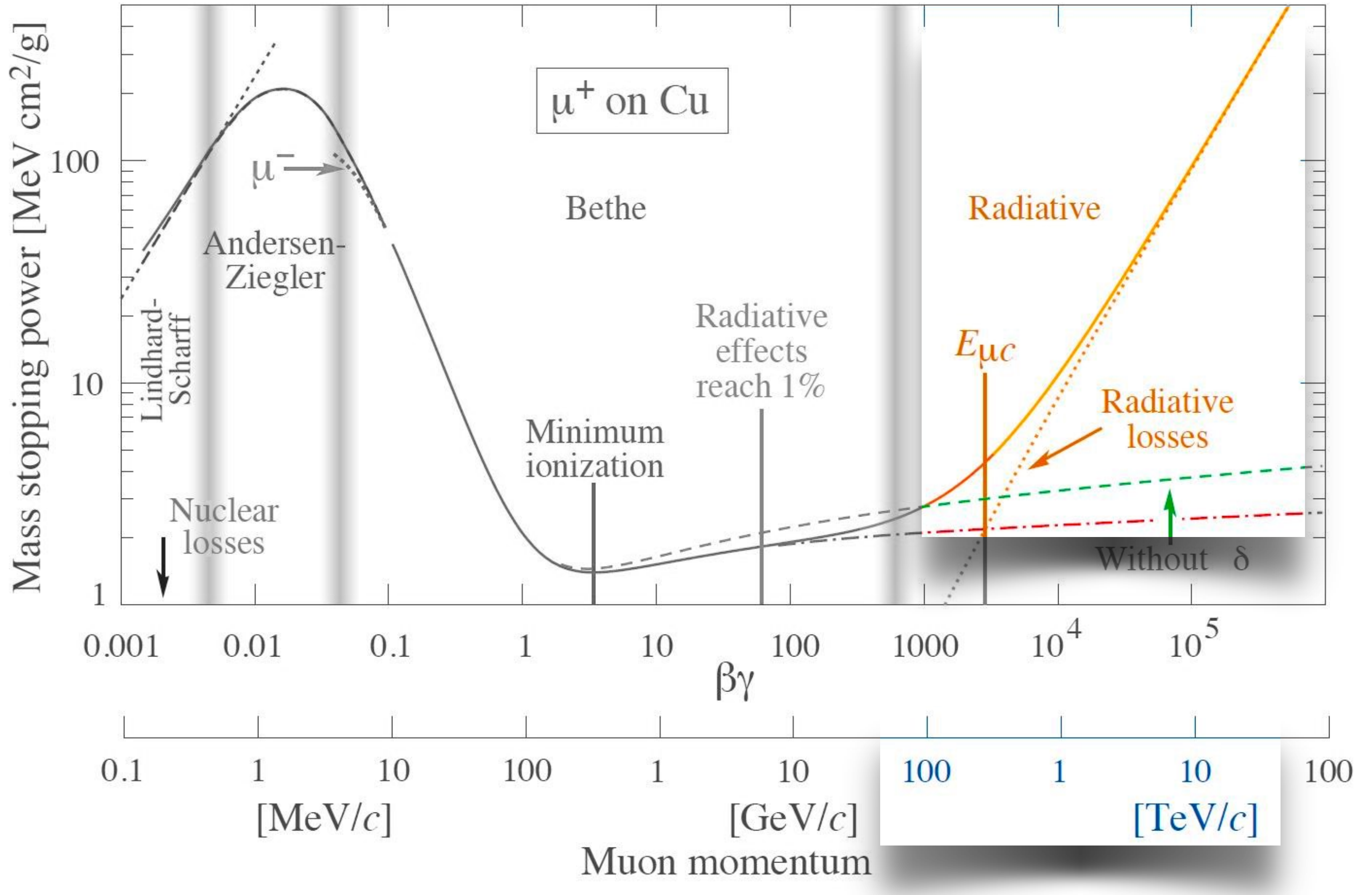
→ same as the CMS HL-LHC max HLT input rate

CMS DAQ and HLT TDR   Technology and R&D for a Muon Collider Detector

Slides from T. Holmes

- **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**

- Above a few 100 GeV, radiative energy loss dominates for muons
- Radiation leads to significant showers in calorimeters
- **These muons are far from MIP-like!**
- To be accounted for in **reconstruction and design of calo and muon detectors**

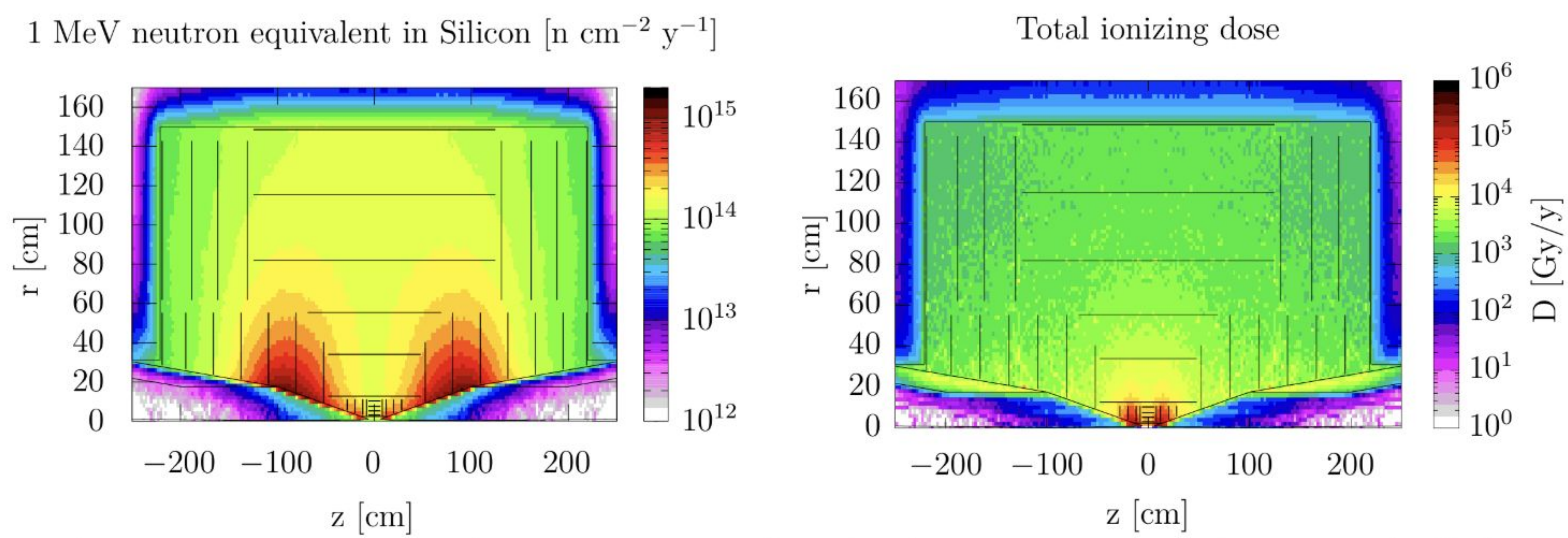


Kieseler, et al, EPJC 82 (2022) 1, 79

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

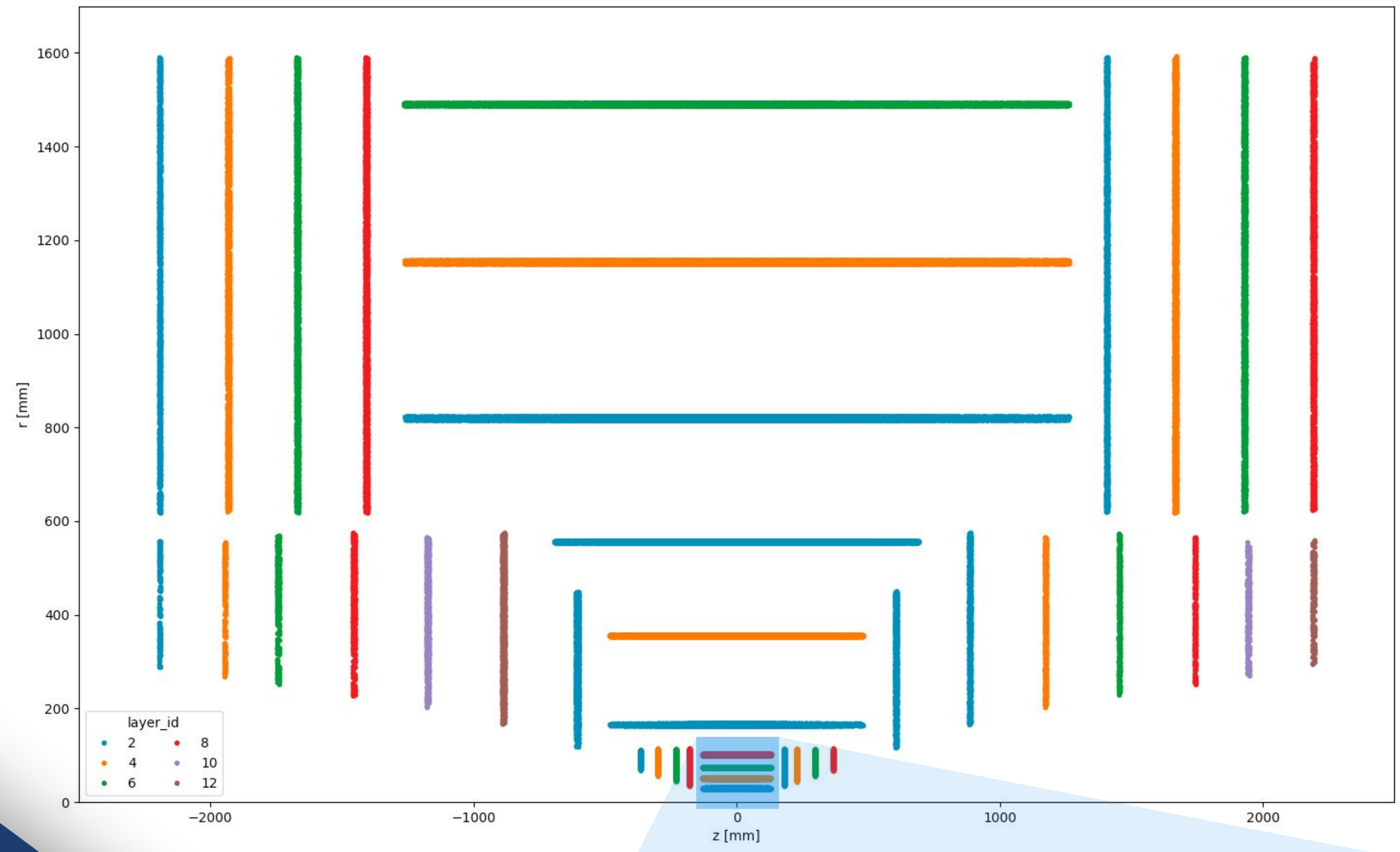
Backup | *Radiation Damage*

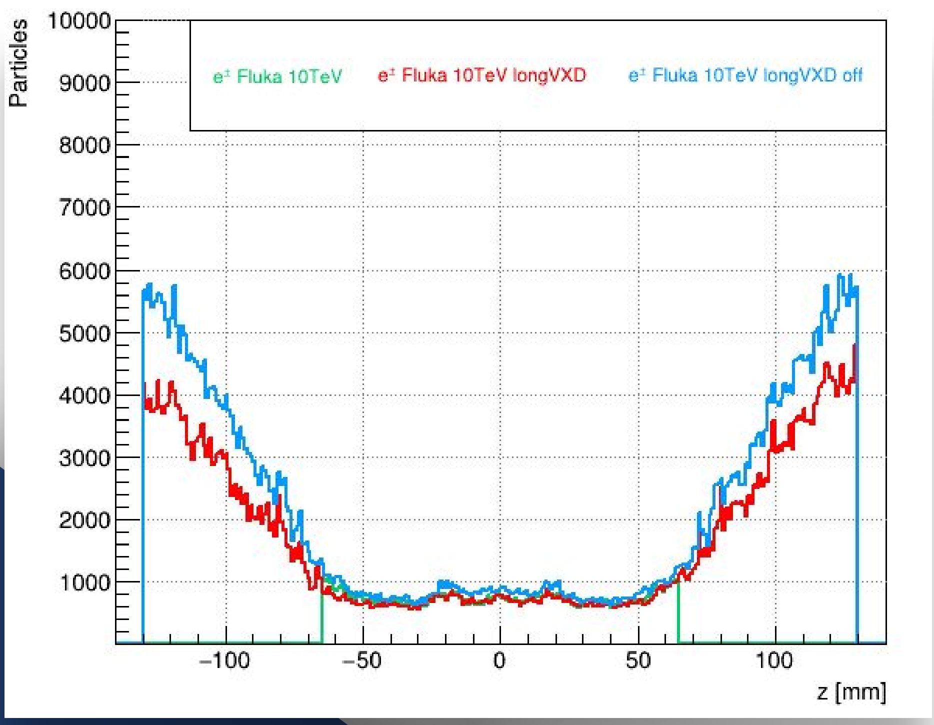
➔ Radiation at 10 TeV comparable to HL-LHC and previous 3 TeV muon collider studies; much lower than FCC-hh (1018 1 MeV-neq/cm2) (2209.01318, 2105.09116)



	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

MUSIC Detector Concept: Tracker

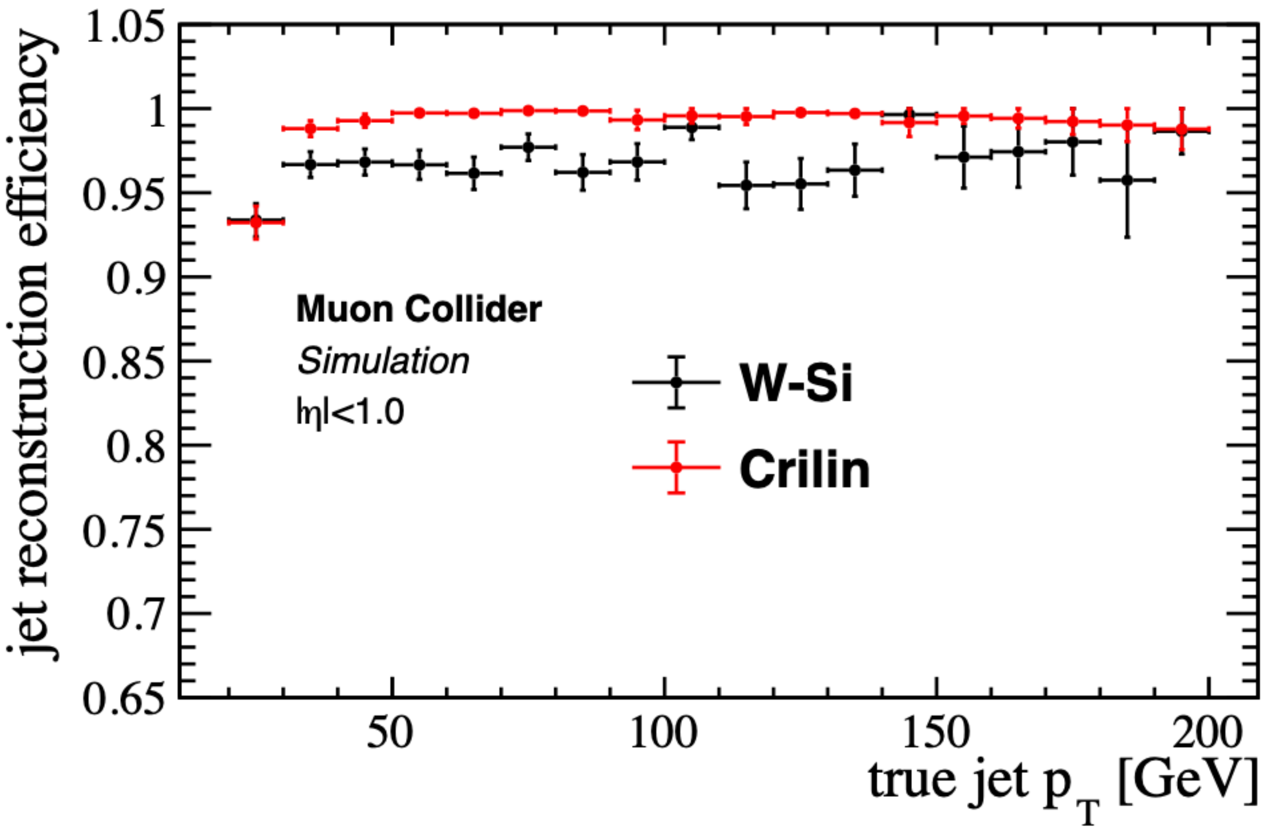


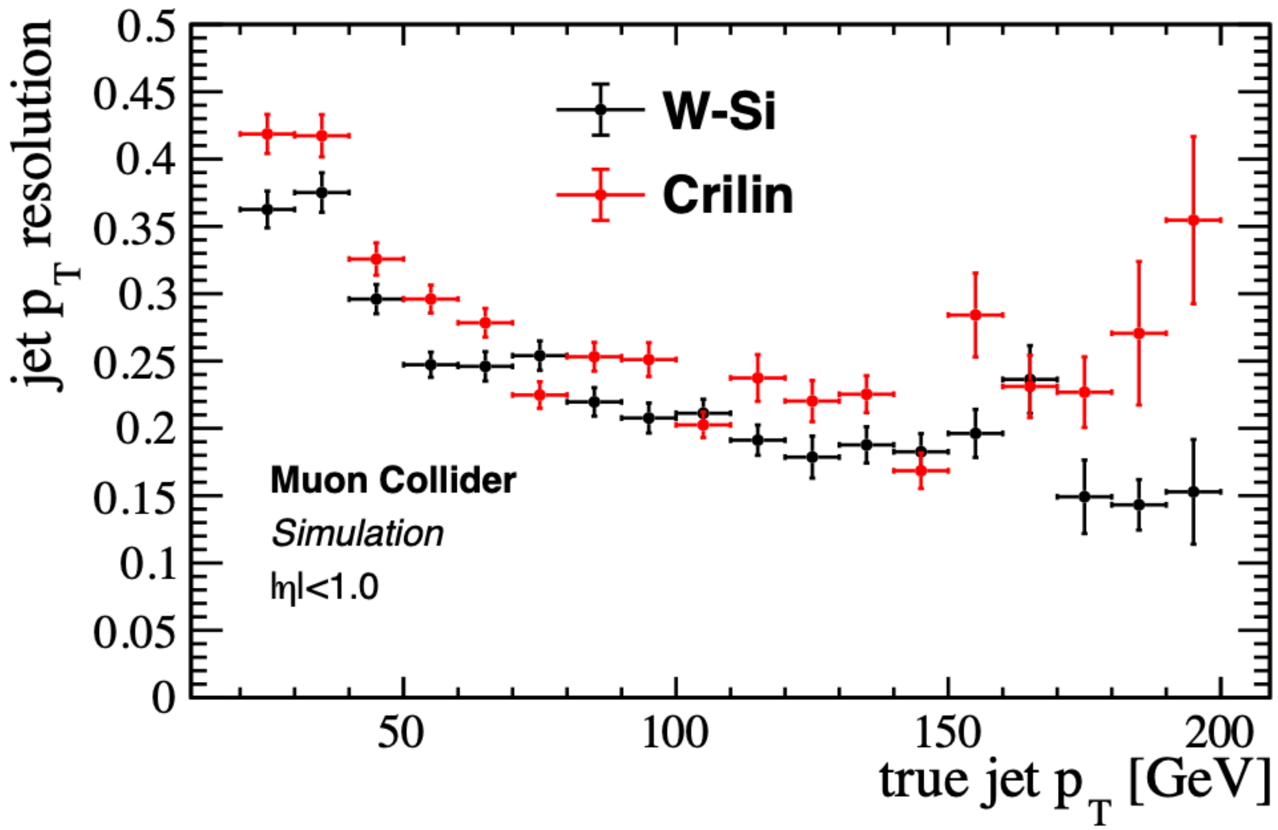


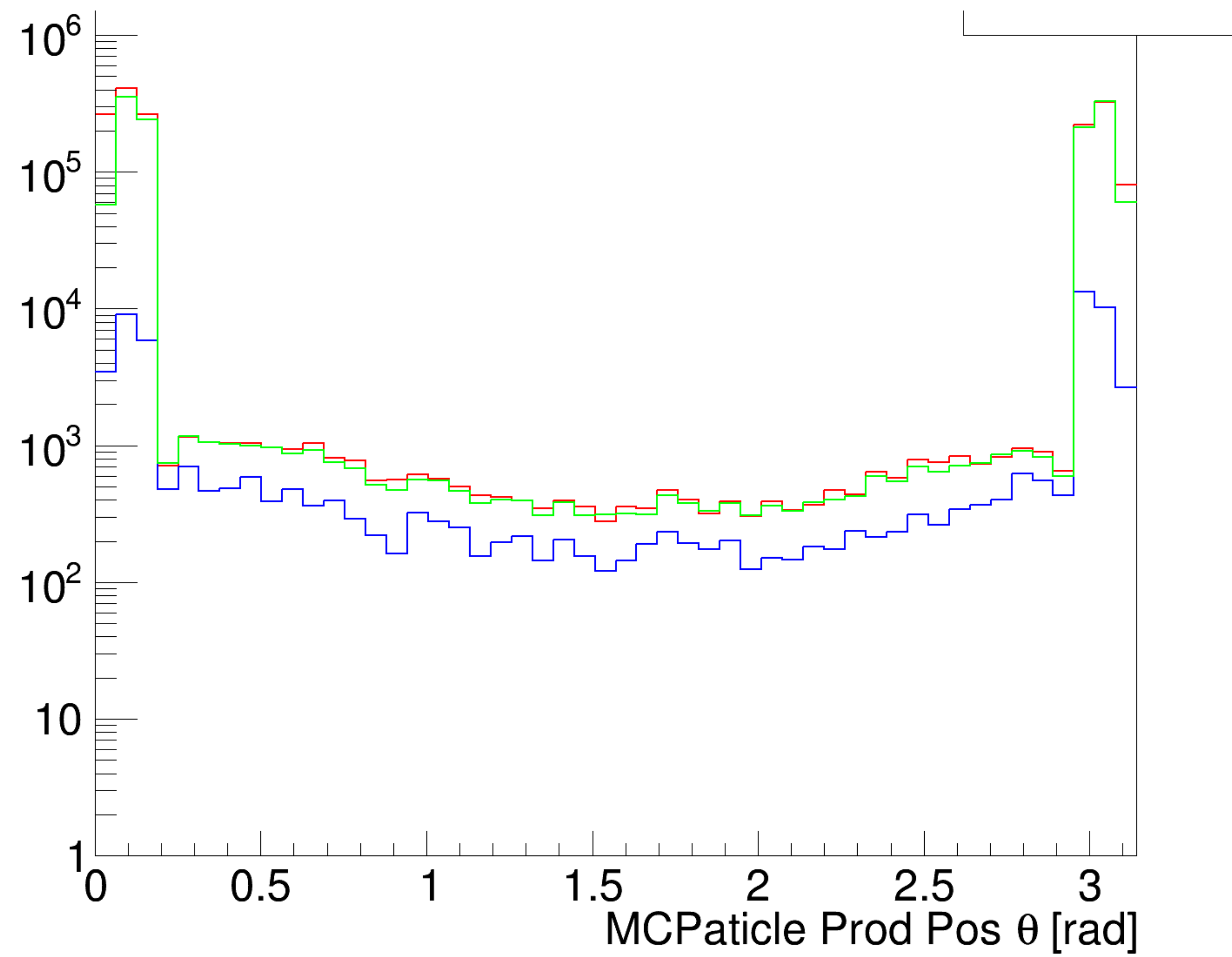
- Reoptimized tracker, all single layers
- Areas of vertex detector closest to nozzles **still full of BIB**
- **ACTS newly implemented in MUSIC** and should provide offline robustness to BIB

Images from slides from D. Zuliani

CRILIN Performance Studies

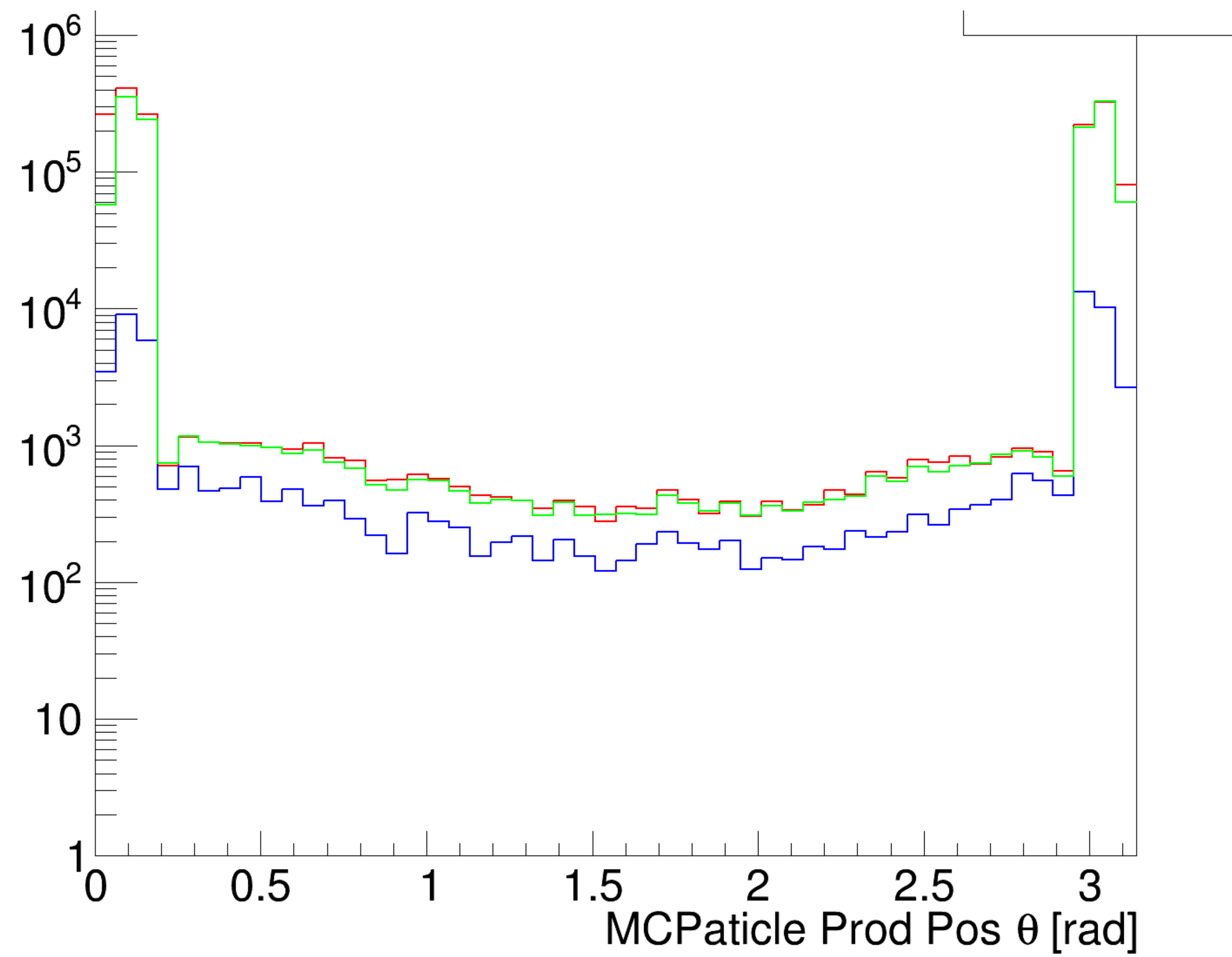


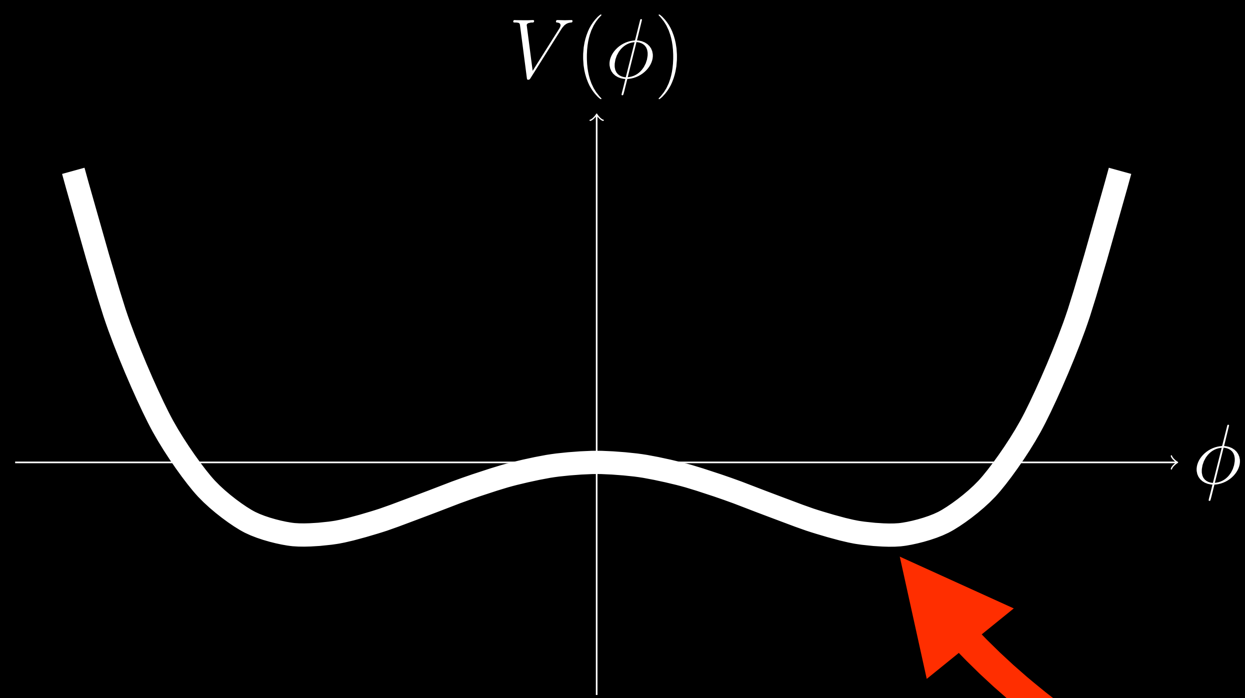




10^6
10^5
10^4
10^3
10^2
10
1
0
0.5
1
1.5
2
2.5
3
MCPaticle Prod Pos θ [rad]

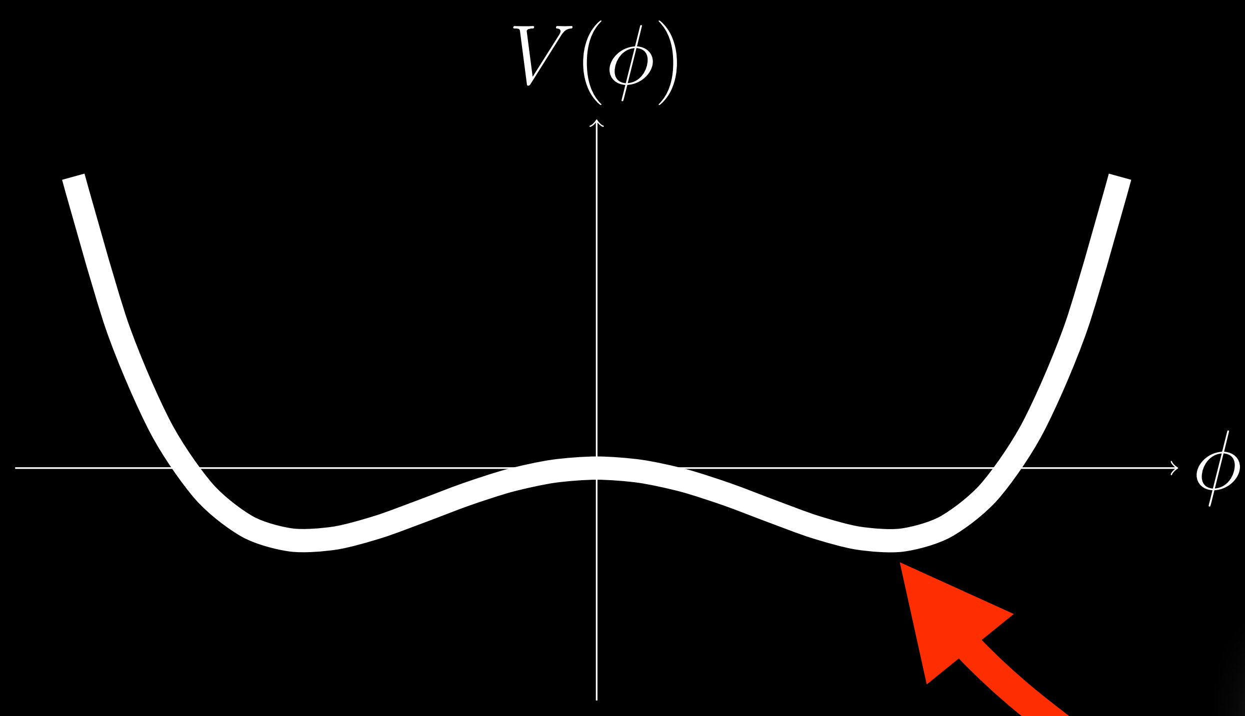
- **Nozzle Computational Problem. See poster!**





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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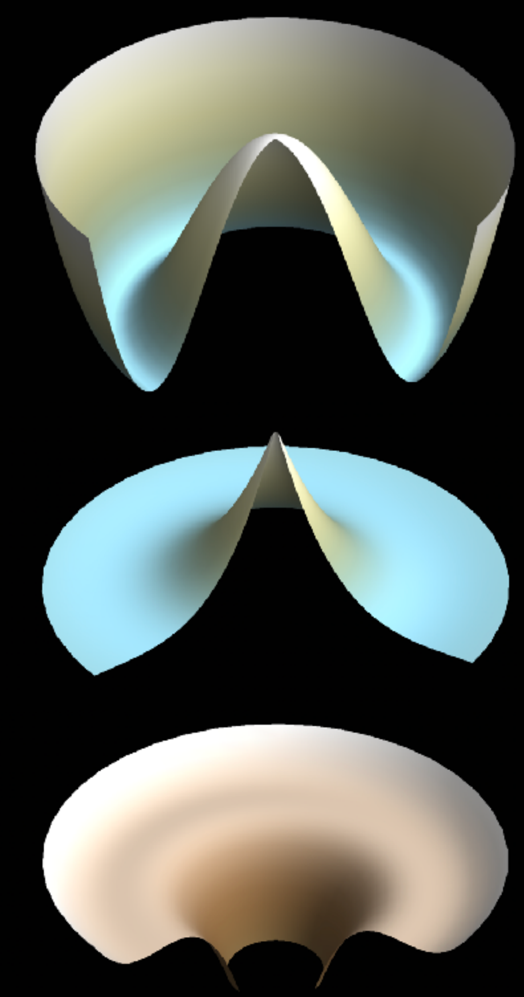
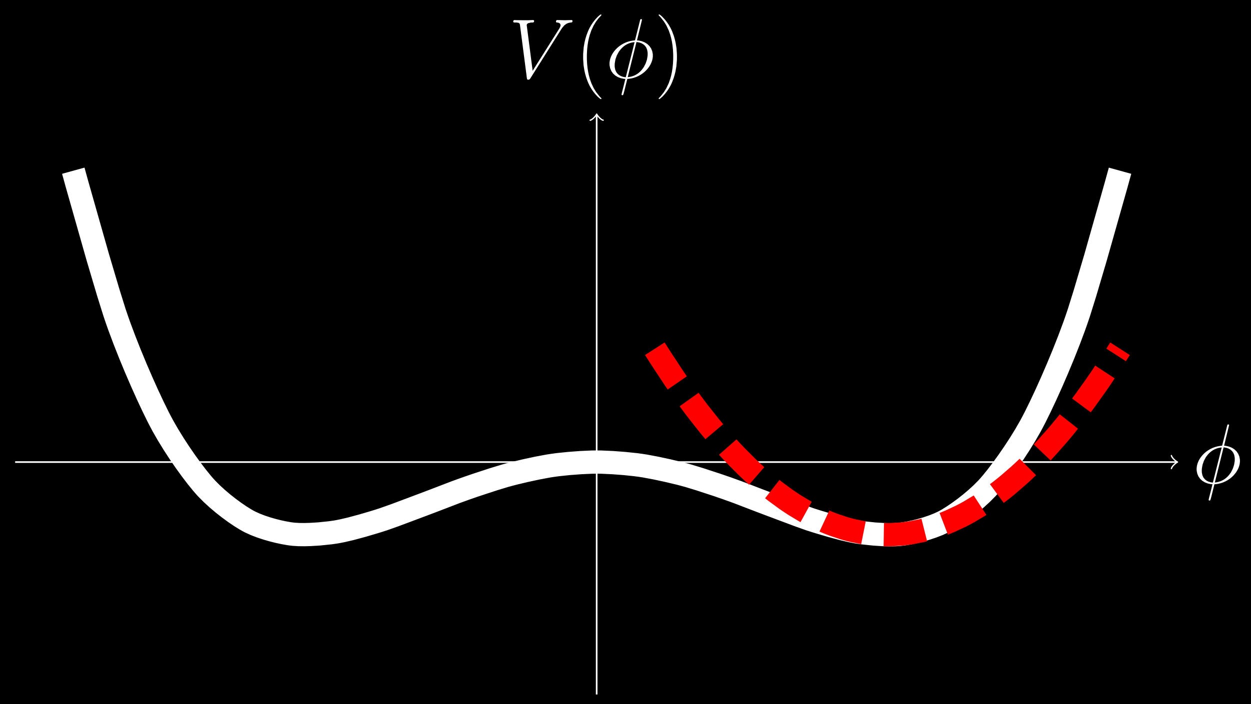


Current knowledge consistent with a wide range of Higgs potential shapes

N Craig & R Petrossian-Byrne

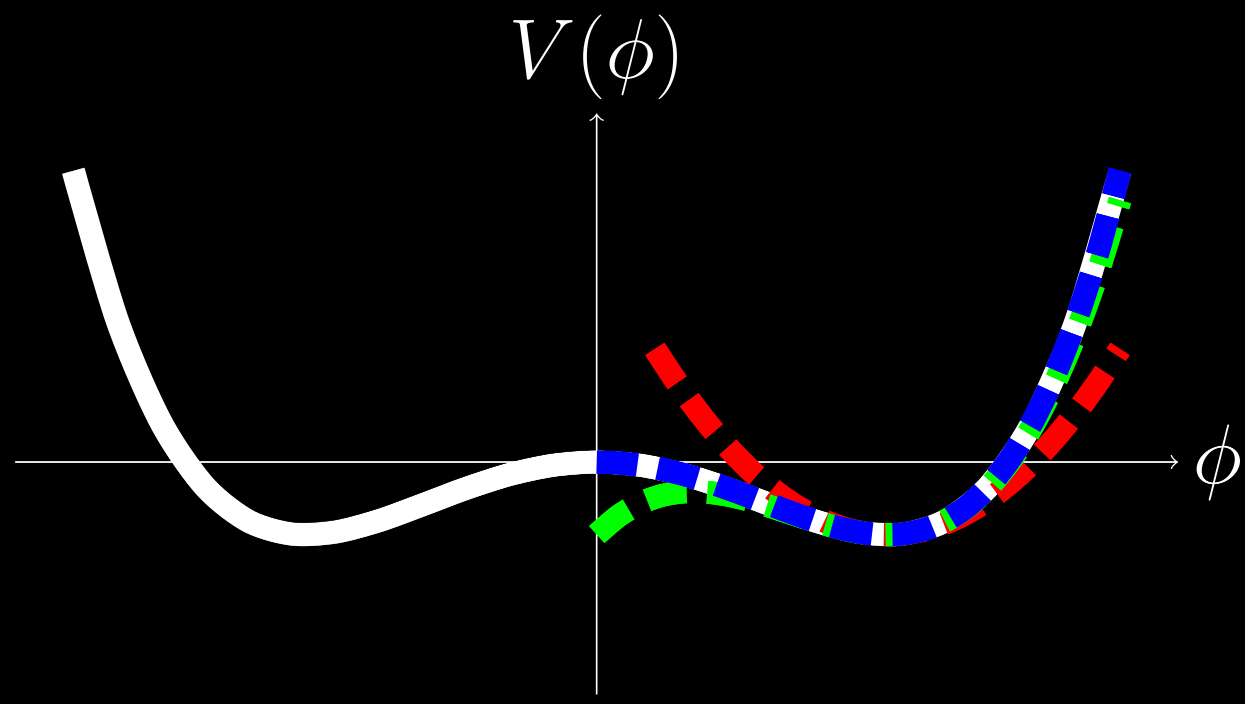


We've only confirmed the Harmonic Oscillator term of Taylor expansion around minimum

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

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

SAY YOU HAVE A 10 TEV μμ COLLIDER…

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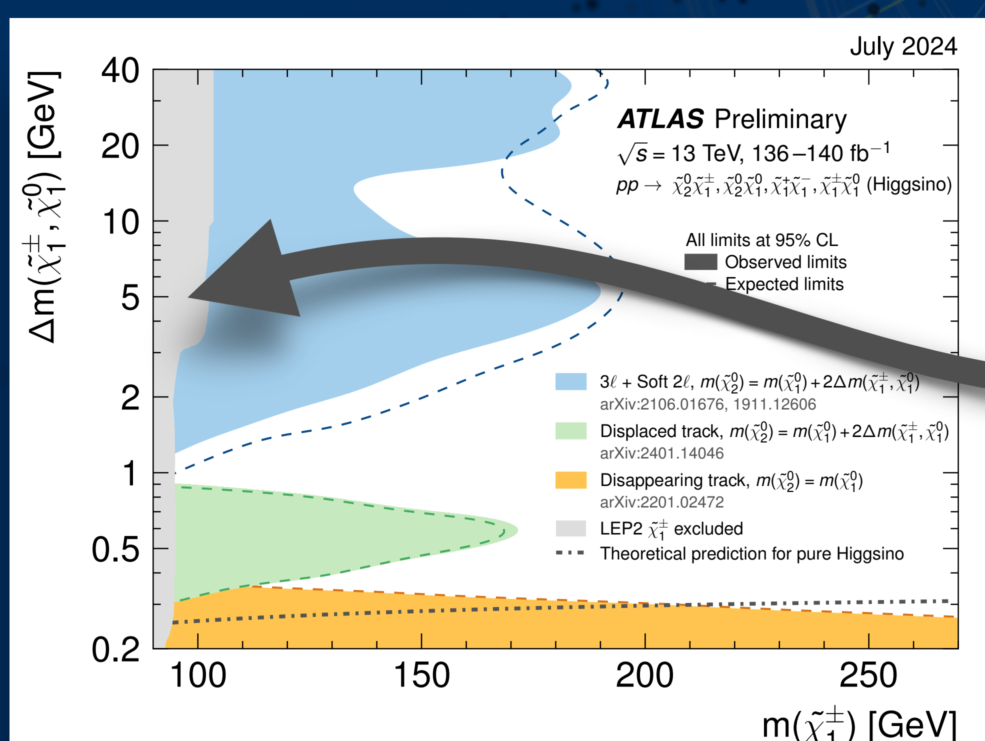


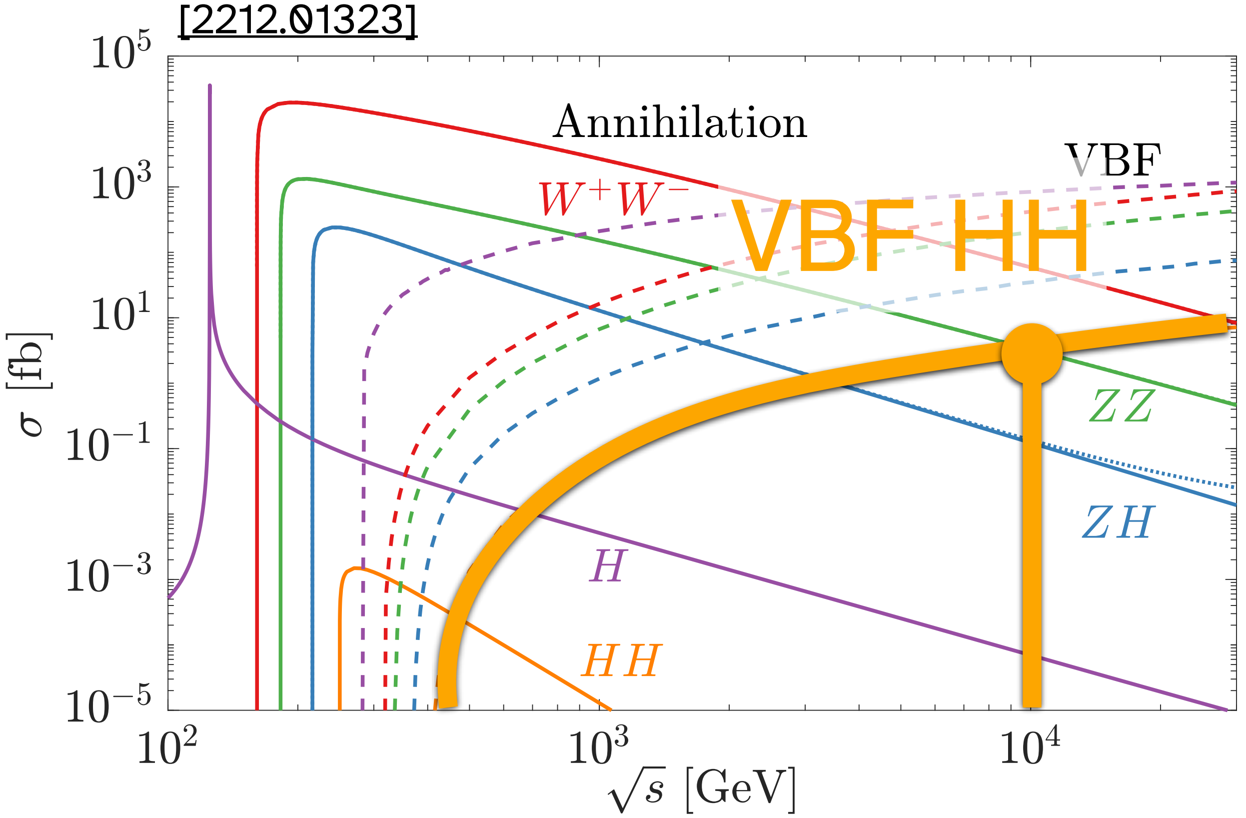
LEP also benefitted from this effect (in γγ)

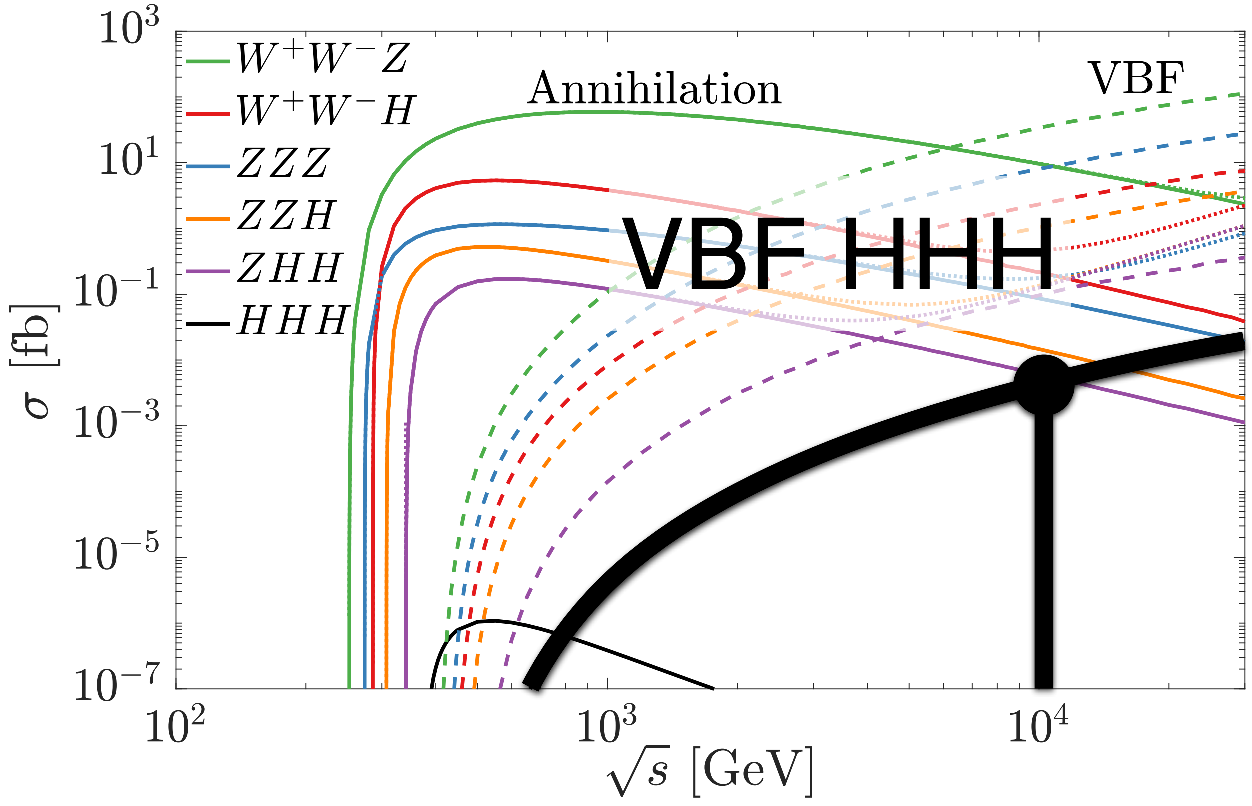
@10 TeV, you get massive vector boson radiation!

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

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

[2212.01323]

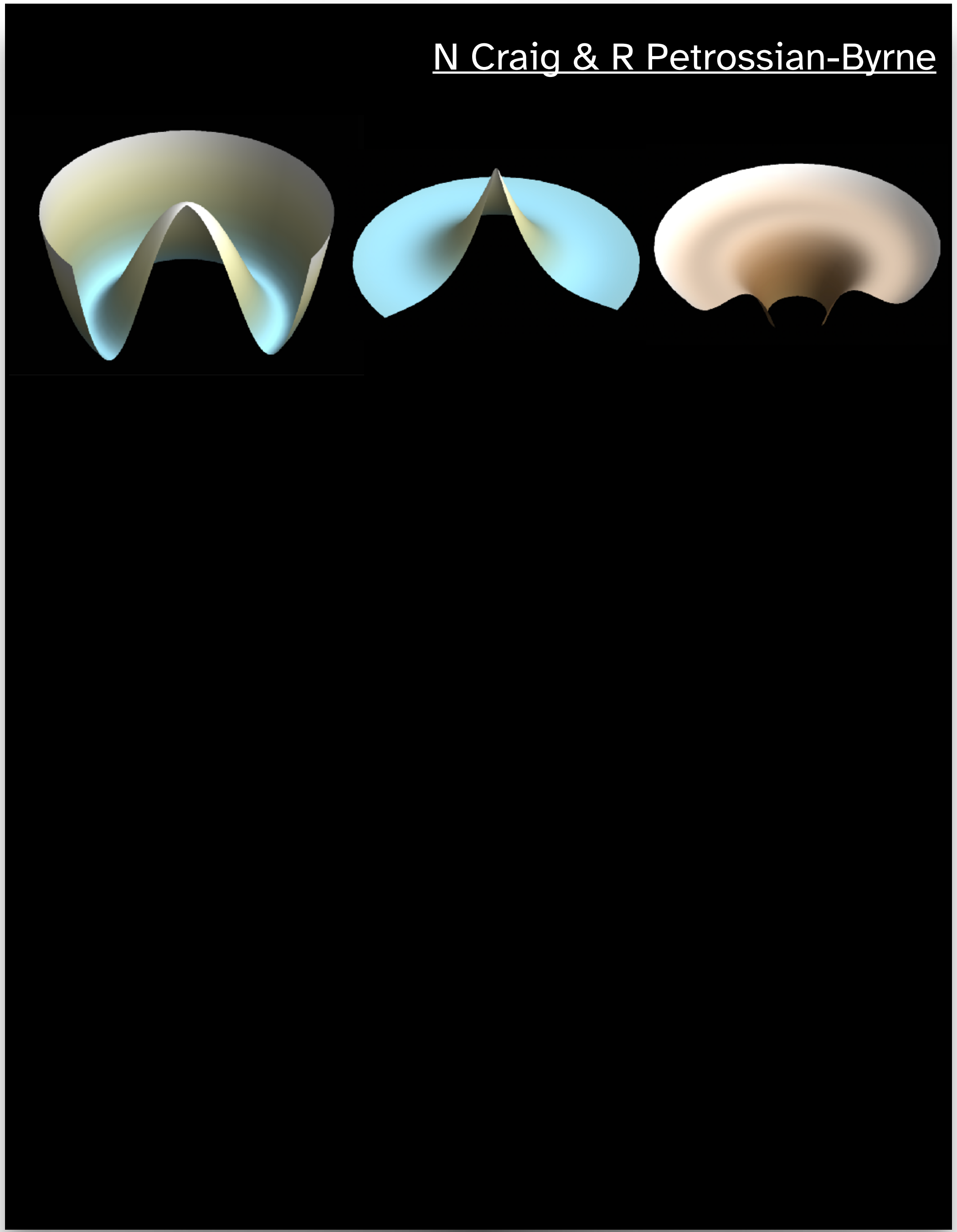




"Why" you should care!

"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?



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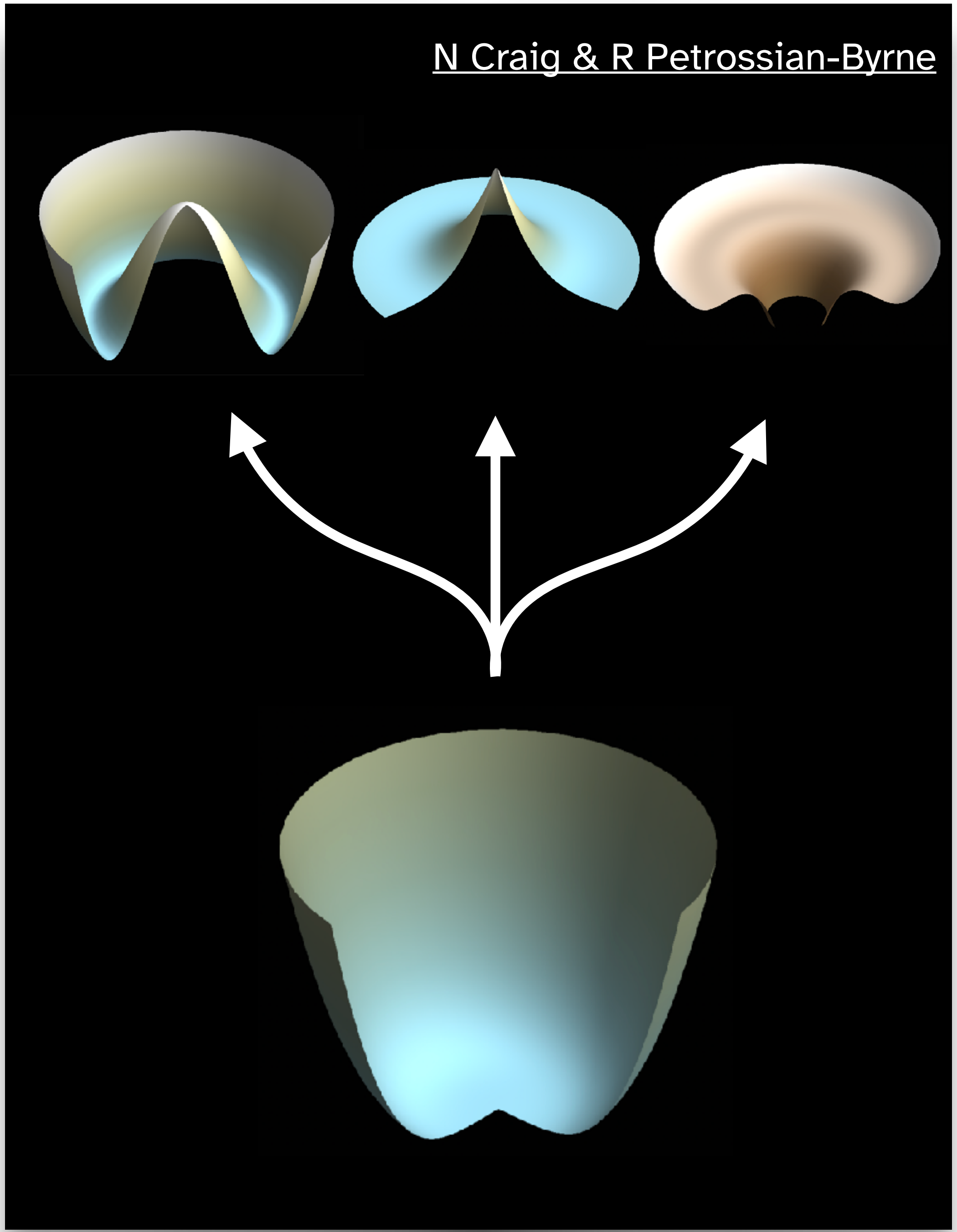
- **Currently only know *that* EWSB happens! Not how or why!**
  - Probe the potential well above EW-scale → See EW symmetry restoration



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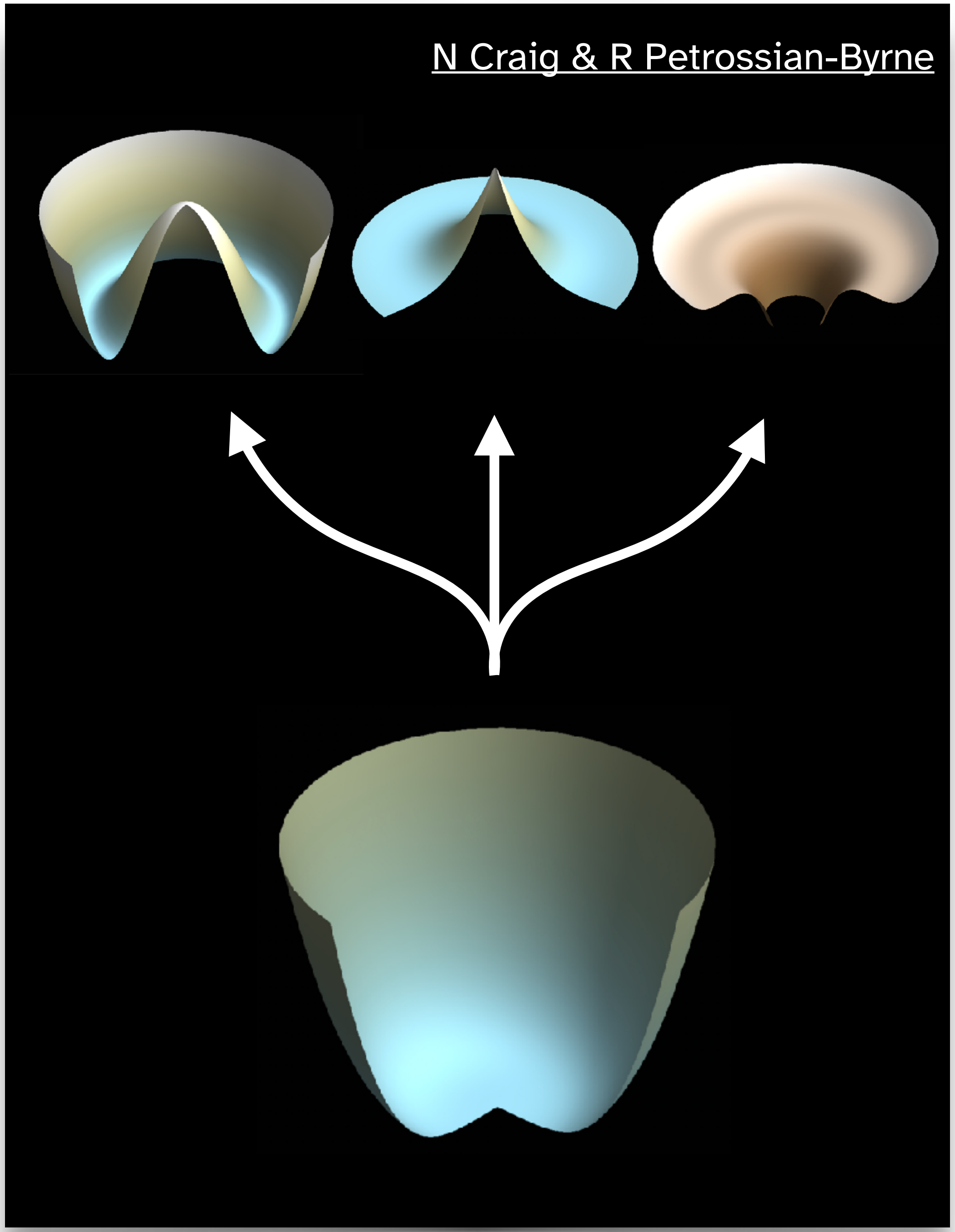
- **Currently only know *that* EWSB happens! Not how or why!**
  - Probe the potential well above EW-scale → See EW symmetry restoration
- **This is about the birth and eventual fate of the universe**
  - **And *requires* the 10 TeV scale**

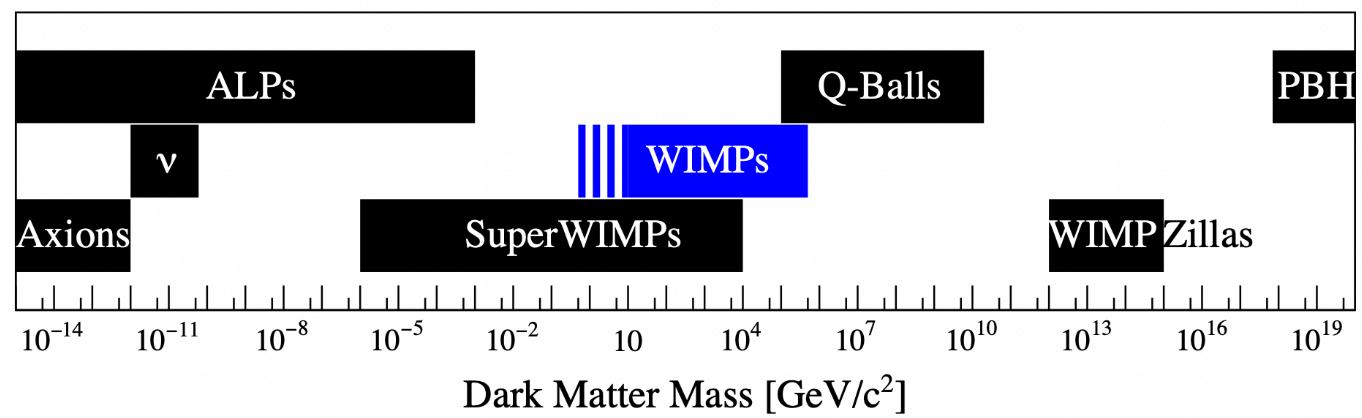


WIMP Dark Matter: Still Miraculous

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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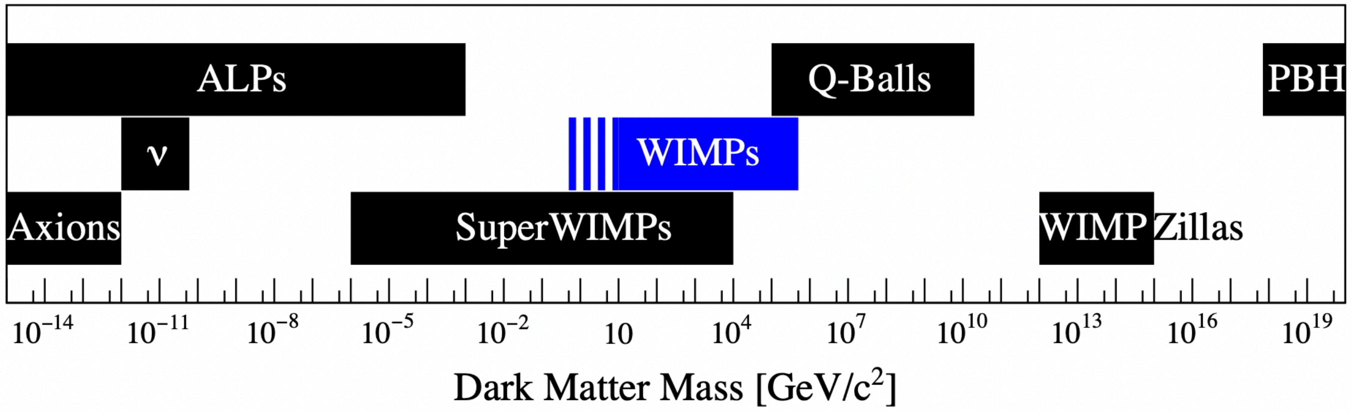
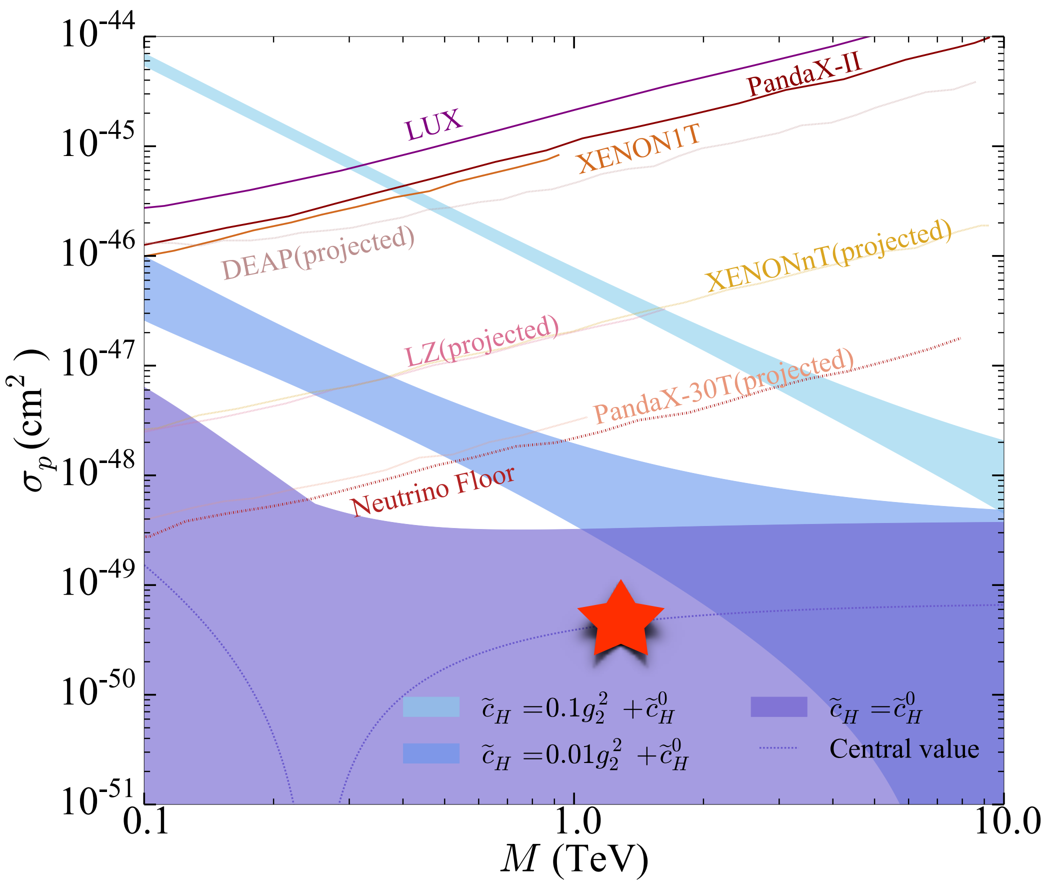


e.g. Thermally-produced Higgsino-like DM should have ~1 TeV masses.
We've ***never*** had sensitivity this!

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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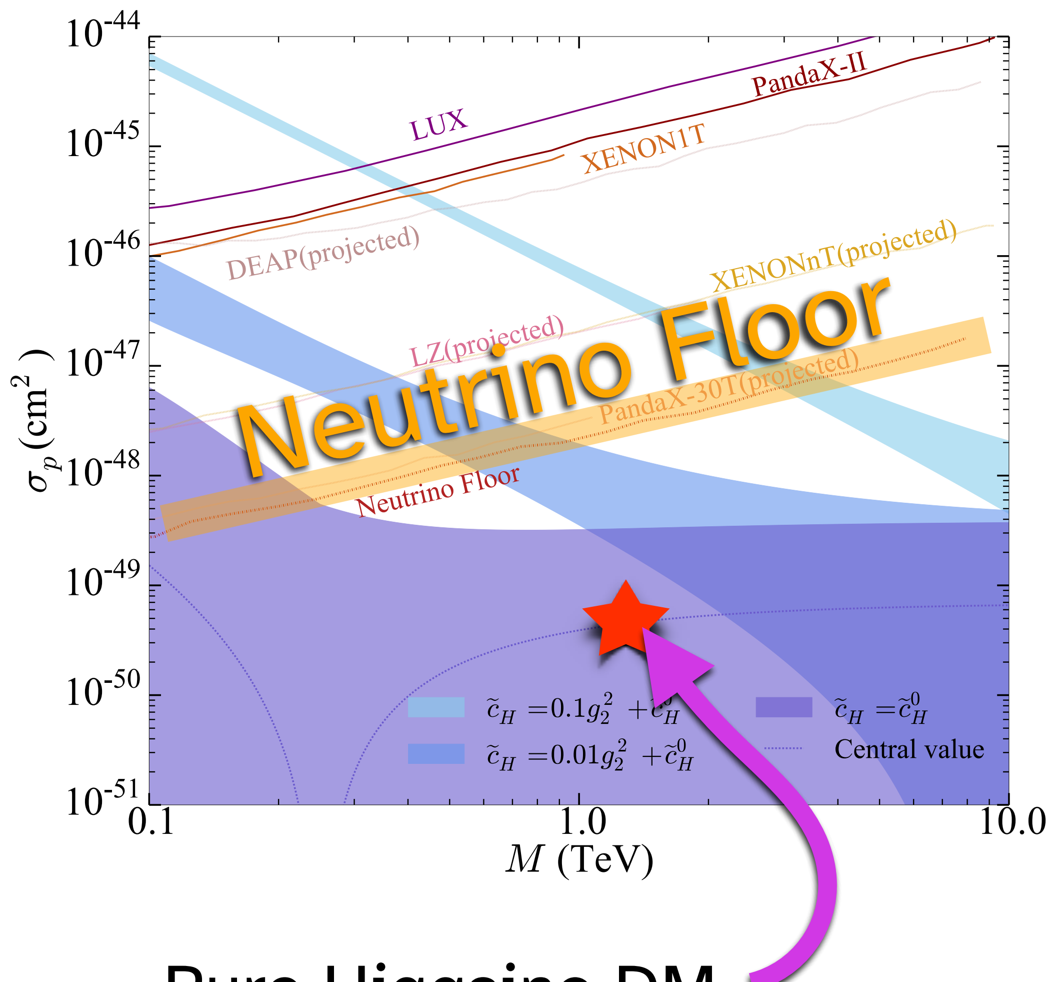
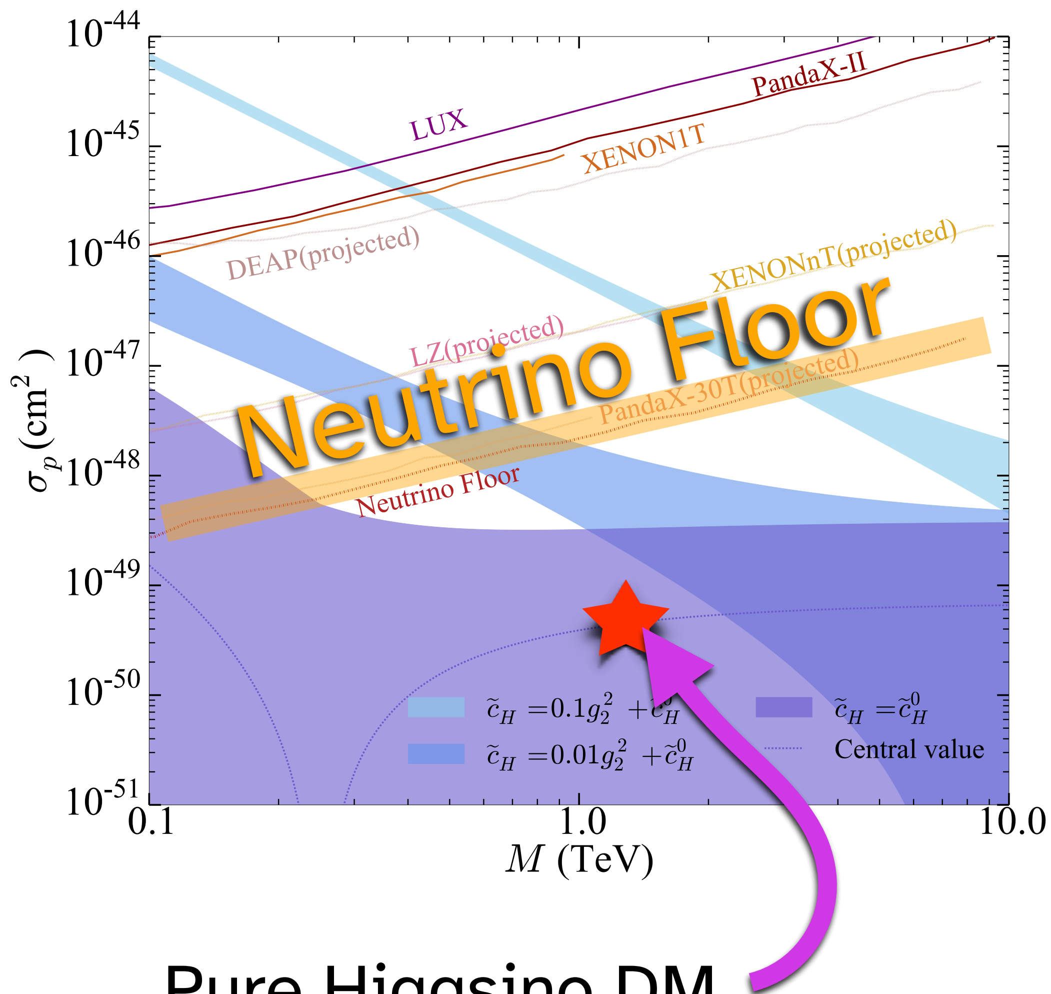
[1912.07795]



Pure Higgsino DM
Direct Detection is under neutrino floor!

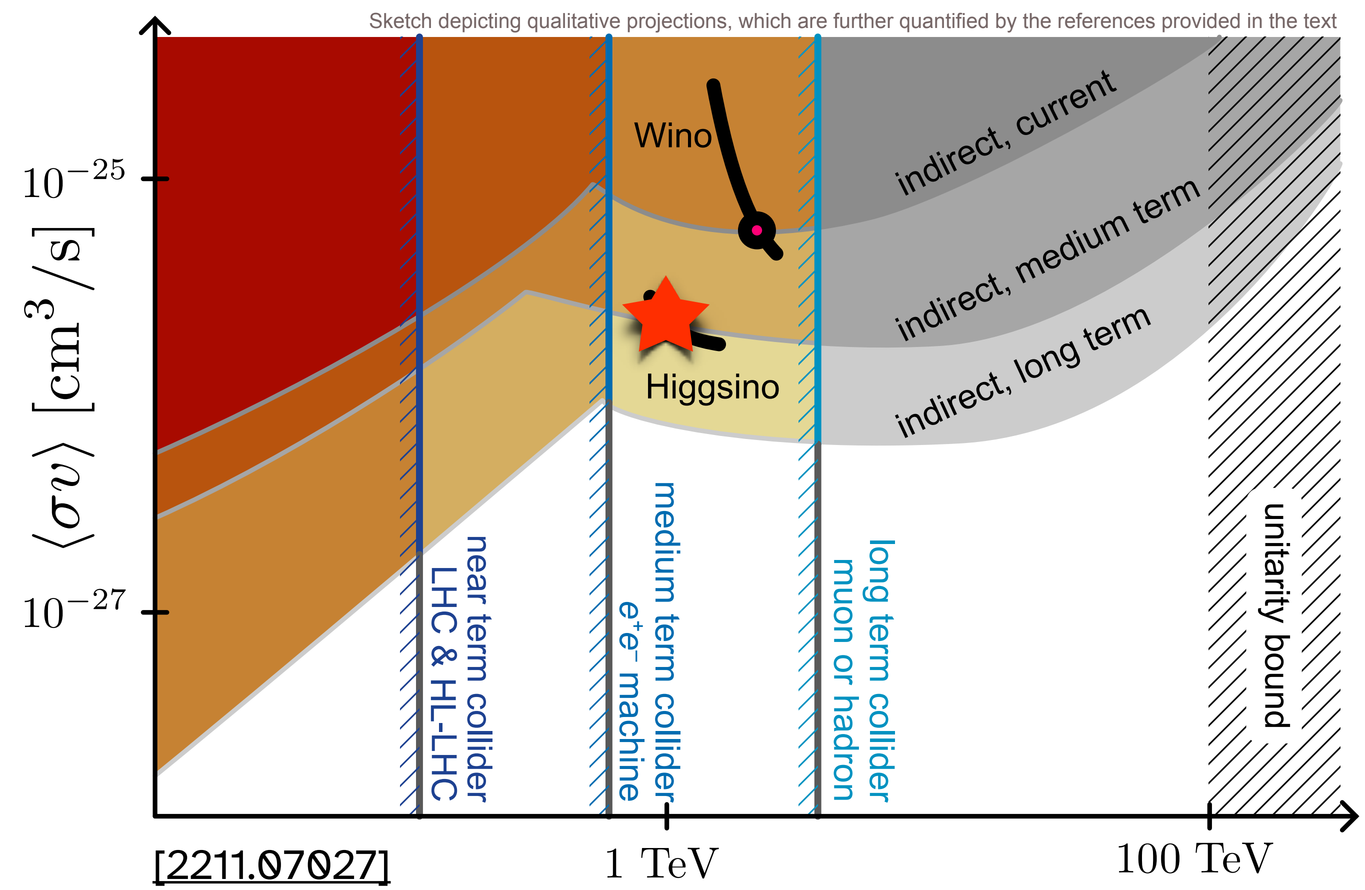
The *simplest* WIMP Dark Matter models have yet to be probed!

[1912.07795]



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

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



[2211.07027]

dark matter mass

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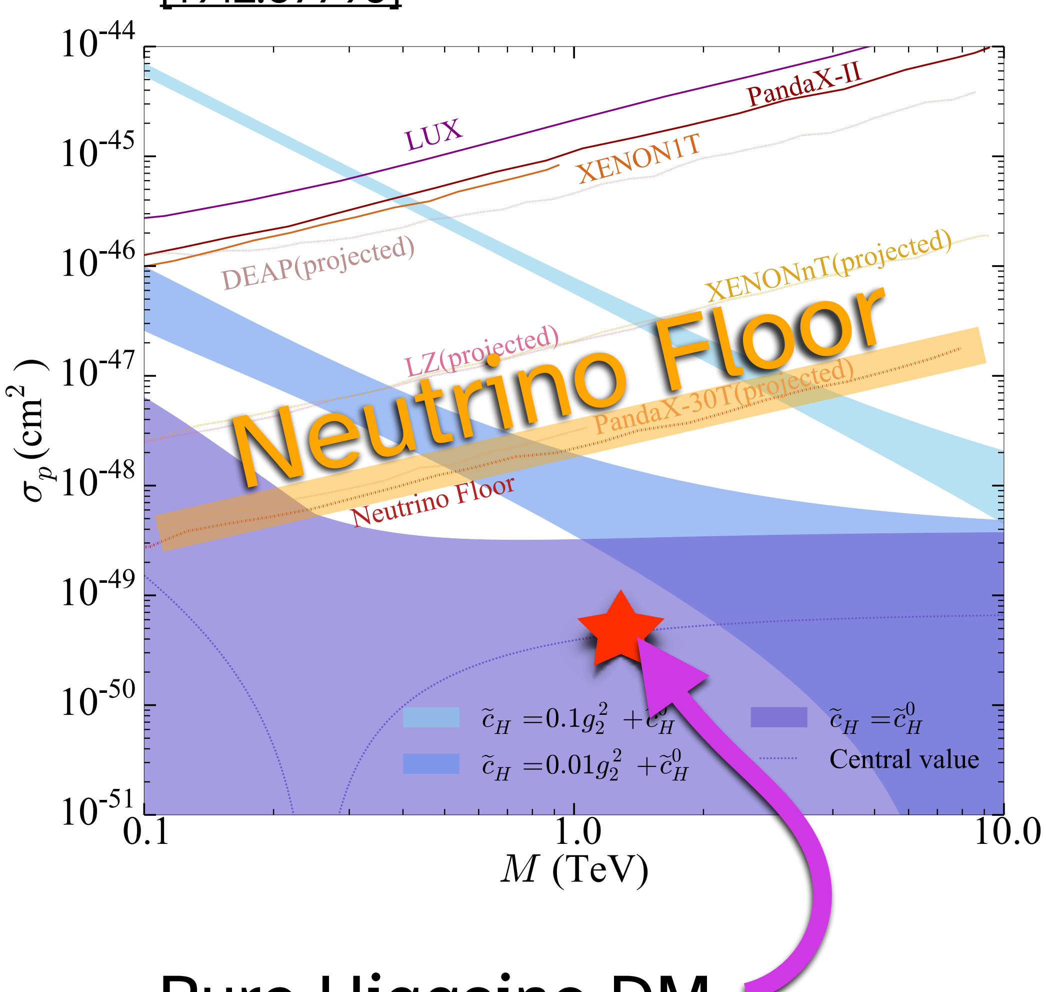
[1912.07795]



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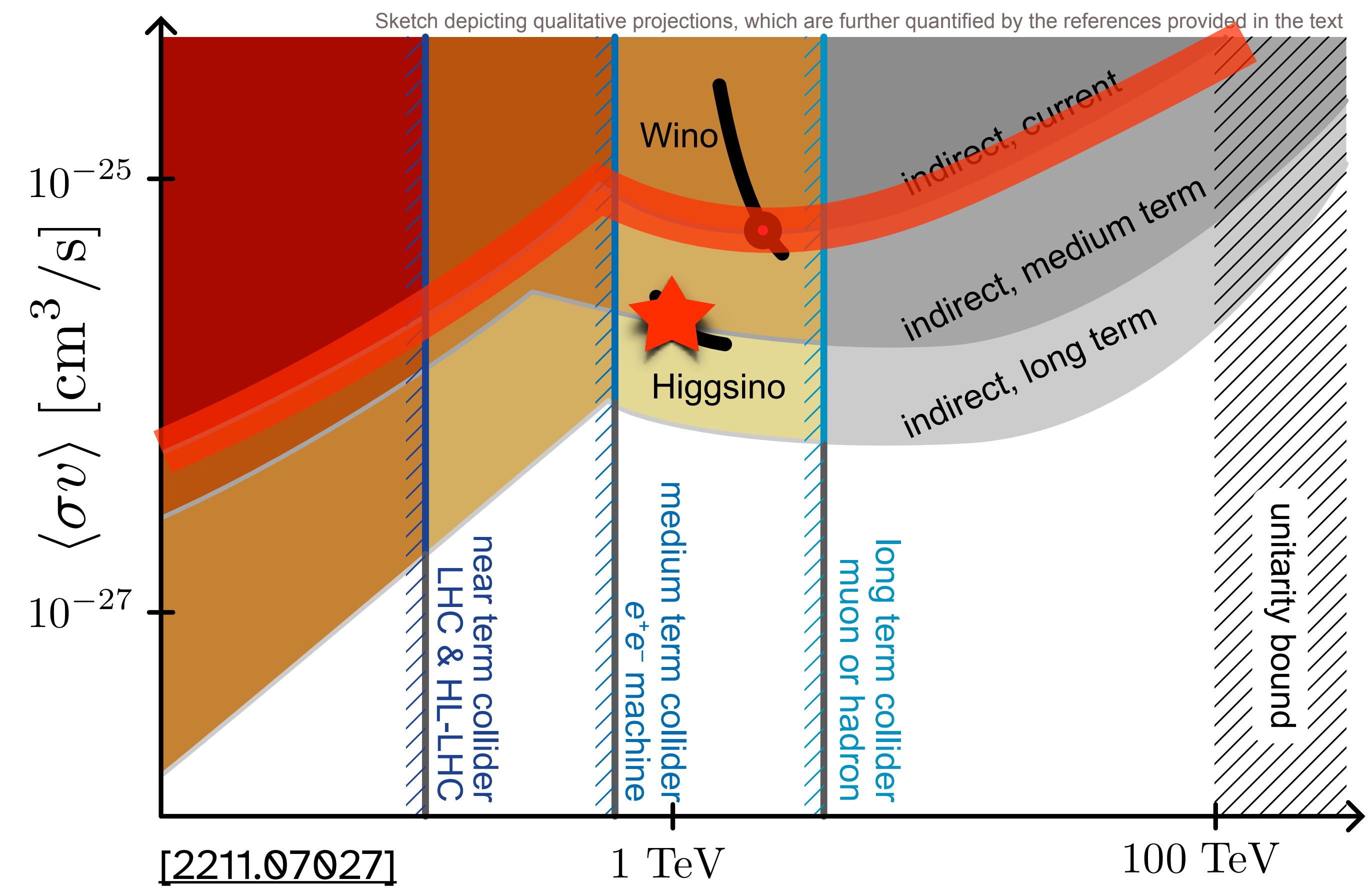

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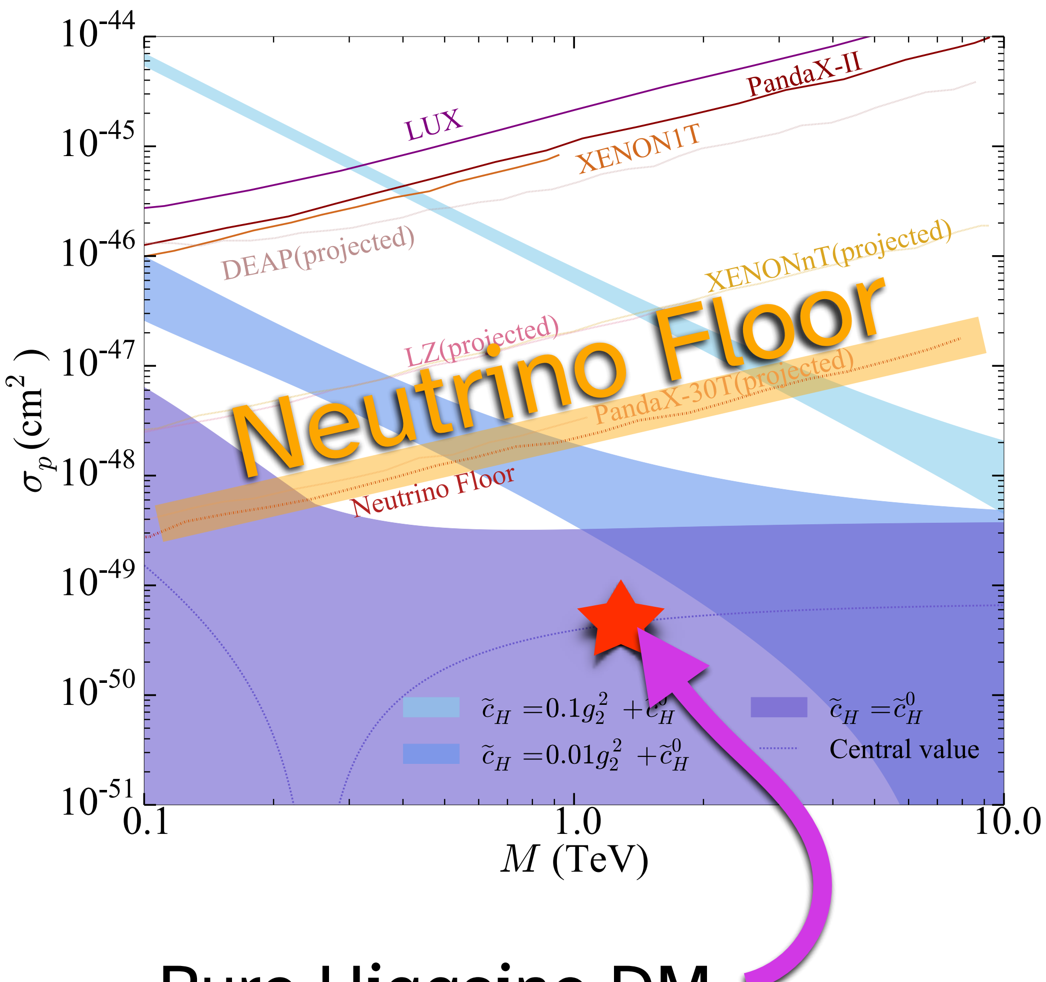

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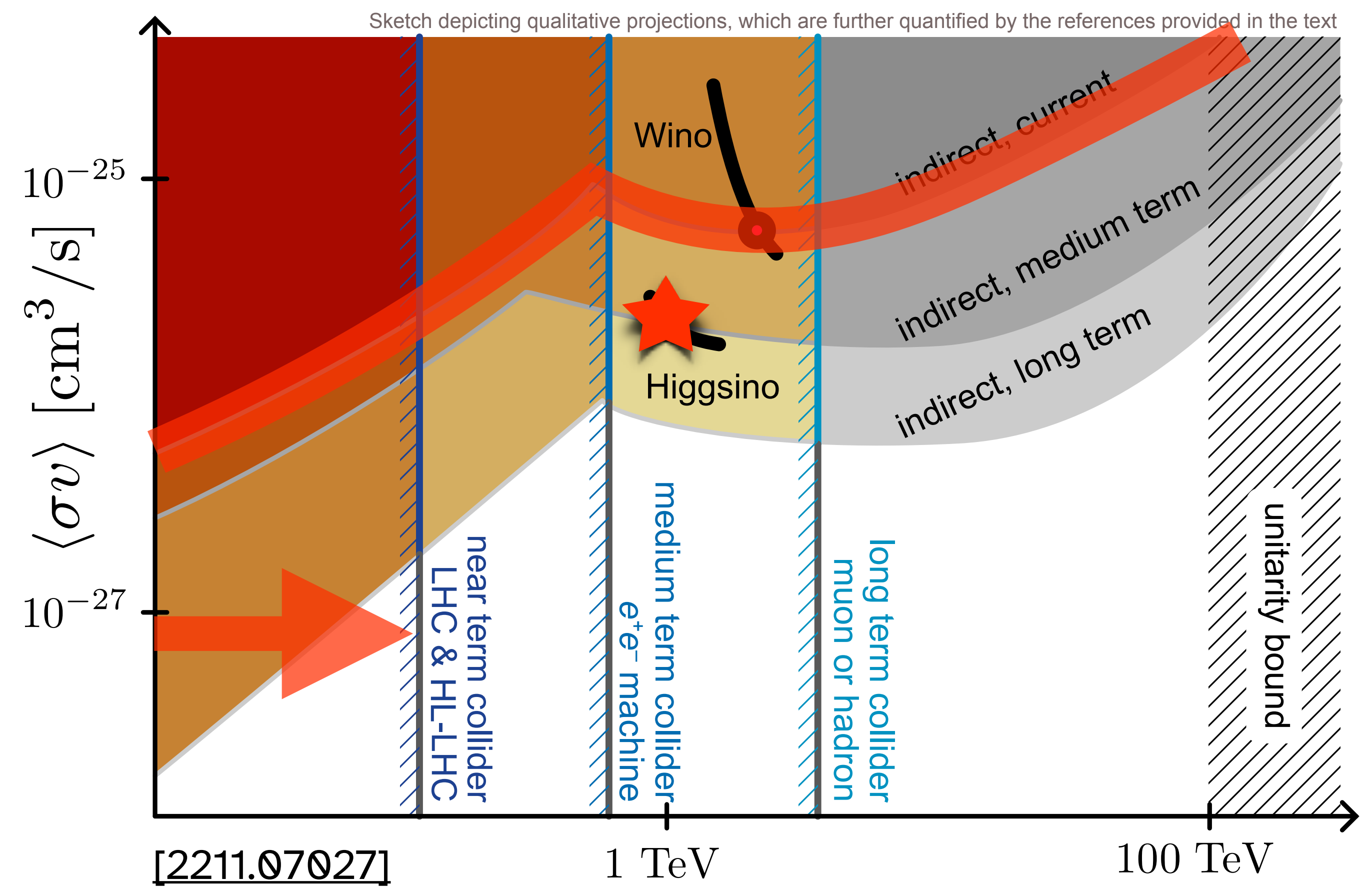

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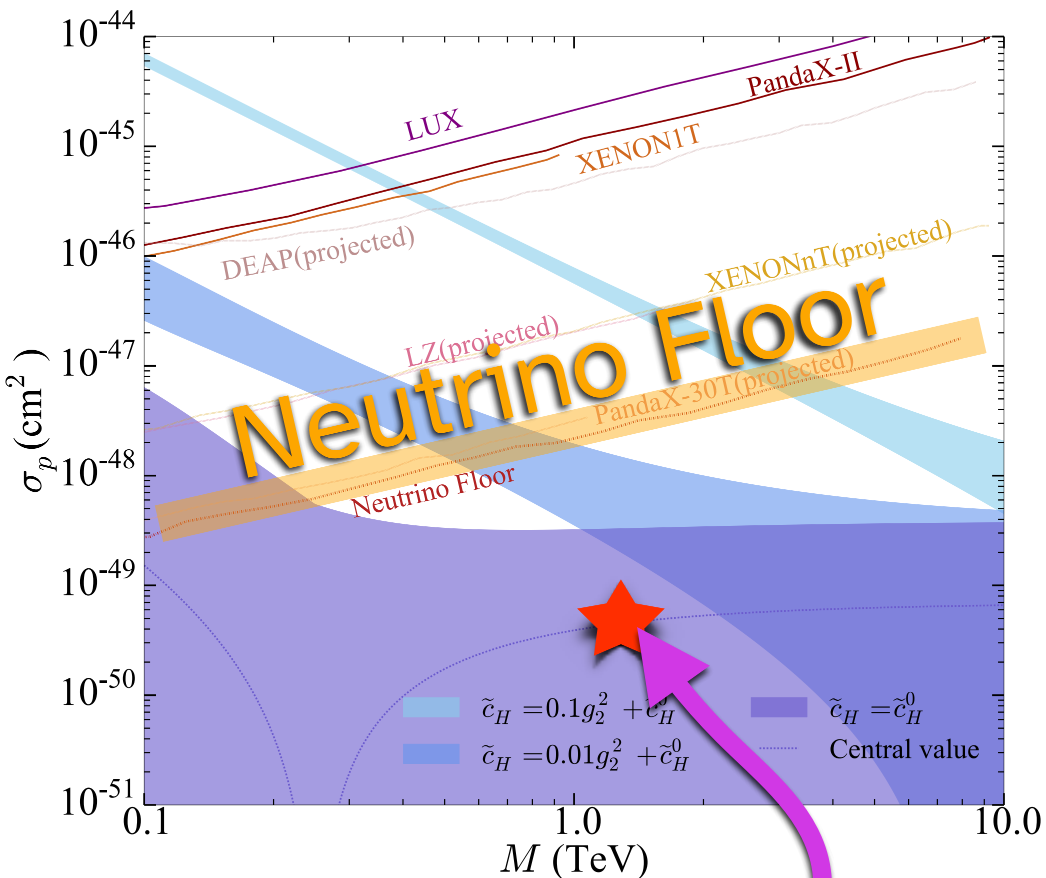

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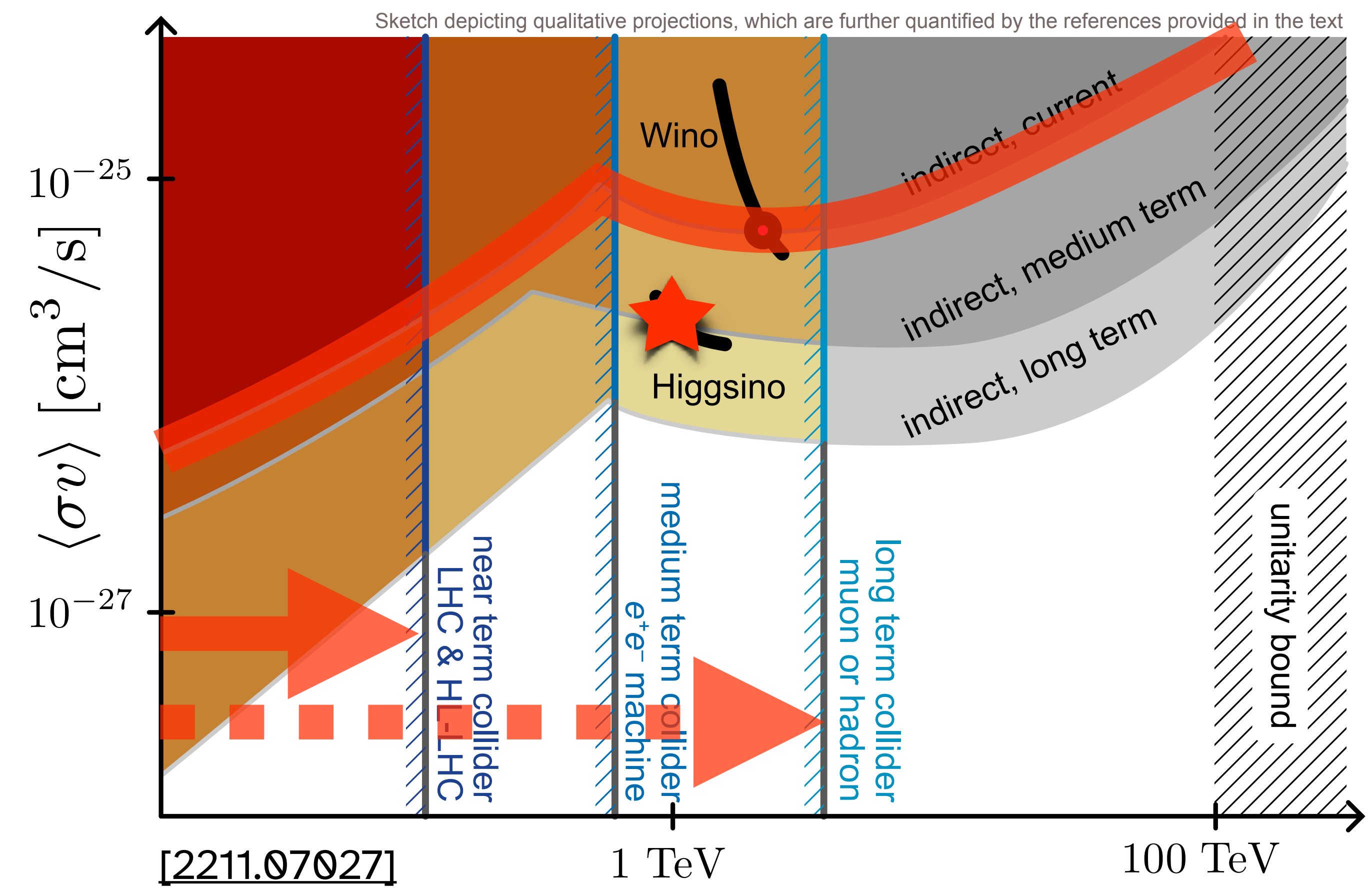

[2211.07027]

dark matter mass

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?

Why?

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

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Motivations for going as high as possible?

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?