Muon Collider

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PURSUE’2024

Fermilab, July 2024

About Me

- Senior Scientist in CMS group
- Joined Fermilab as Wilson Fellow in 2012
- LHC Physics Center Coordinator (2017-2021)
- Future Colliders Group deputy head

- Level-1 Trigger
- Real-time data processing systems
- Machine Learning
- Muon Collider

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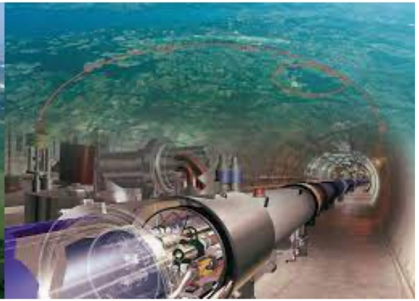
Outline

- Why new Collider?
- Why Muon Collider?
- How do we get there?

100 Years of Discoveries

*1919 proton, 1927 beta decay spectrum, 1932 neutron, 1932 positron, 1936 muon, 1947 kaon, 1947 pion, 1955 antiproton, 1956 electron neutrino, 1962 muon neutrino, 1968 partons, **1974 charm quark**, 1977 b quark, **1977 tau, 1979 gluon, 1983 W and Z bosons, 1995 top quark**, 1998 neutrino oscillations, 2000 tau neutrino, **2000 quark-gluon plasma, 2012 Higgs boson***





- **Colliders as essential probes to decode Nature at its most fundamental level**
  - **Exploring ~ all sectors of the SM and the Unknown @ one experimental complex**

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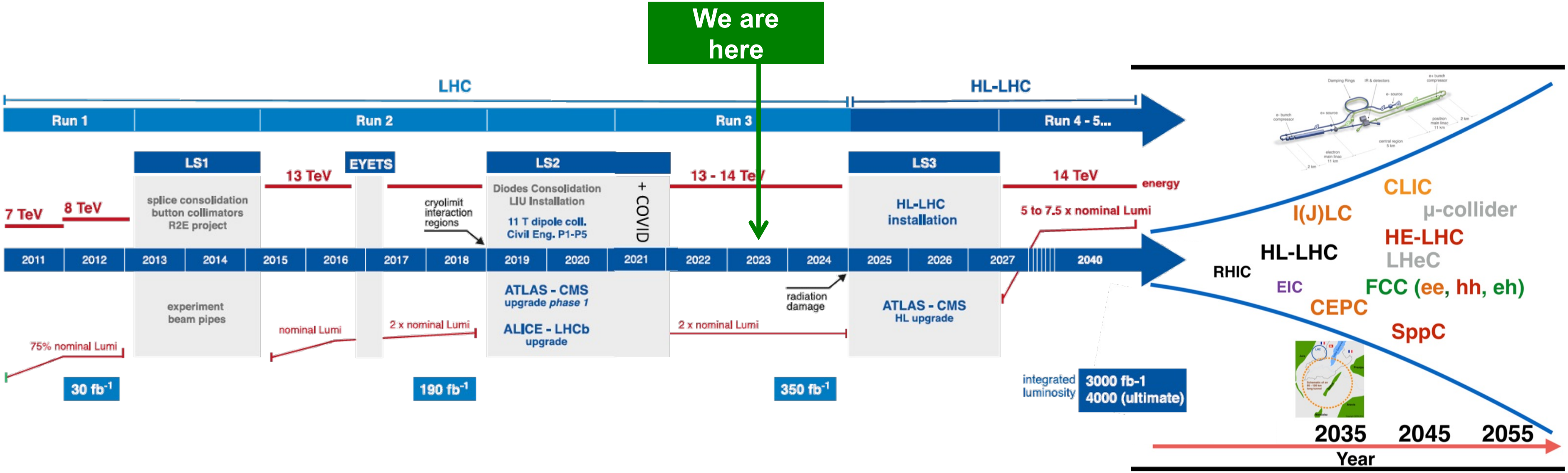
Collider Landscape



LHC + HL-LHC is the largest **pp** dataset for the next few decades

Variety of post-LHC colliders proposed globally

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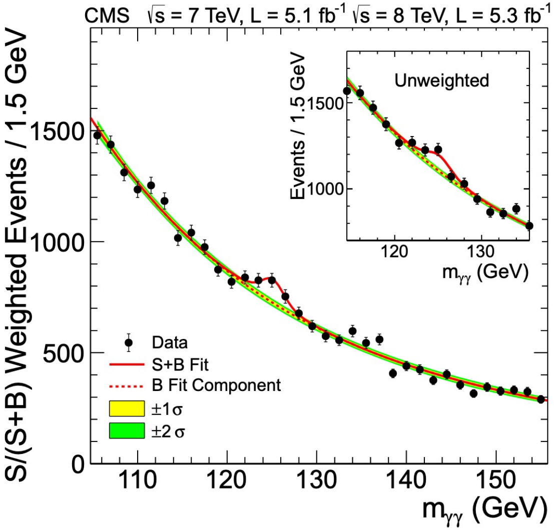
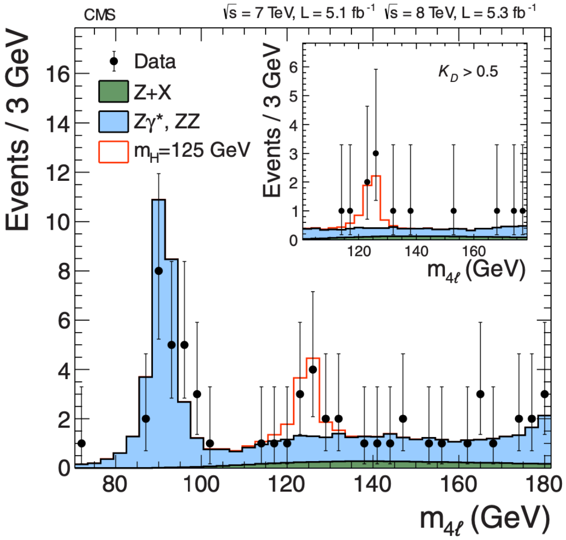
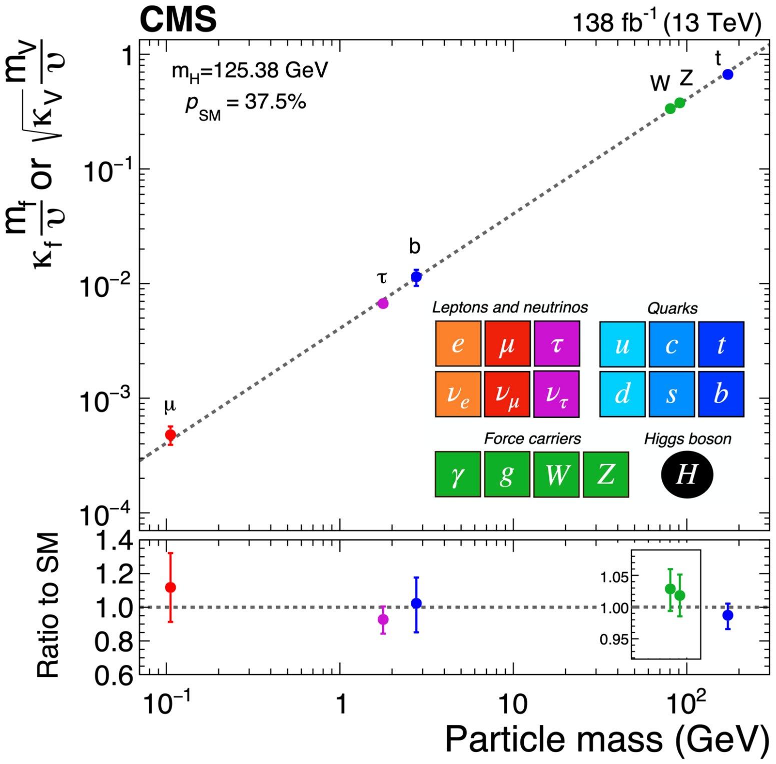
The latest discovery - Higgs Boson in 2012



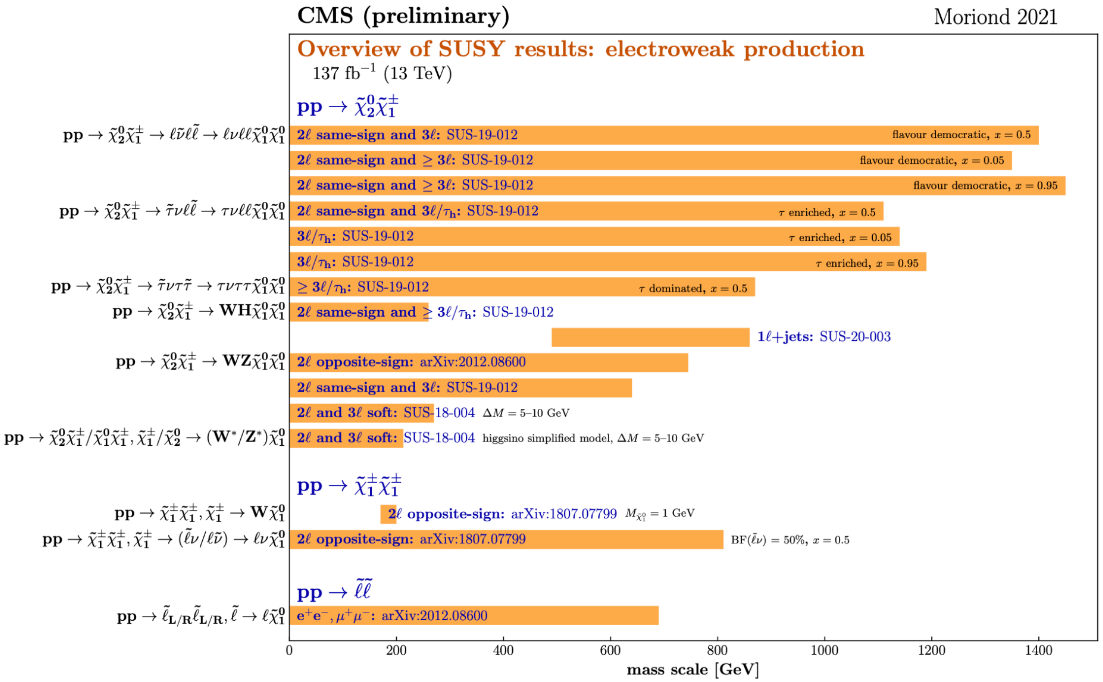


Since then….


CMS
138 fb-1 (13 TeV)
mH=125.38 GeV
pSM = 37.5%
μ
τ
b
W Z
t
Leptons and neutrinos
Quarks
Force carriers
Higgs boson
Ratio to SM
Particle mass (GeV)

Since then….

Exclusions up to ~1 TeV



Discoveries may still come at the LHC (only ~5% of data collected so far), but we should also start planning for what is to come after!

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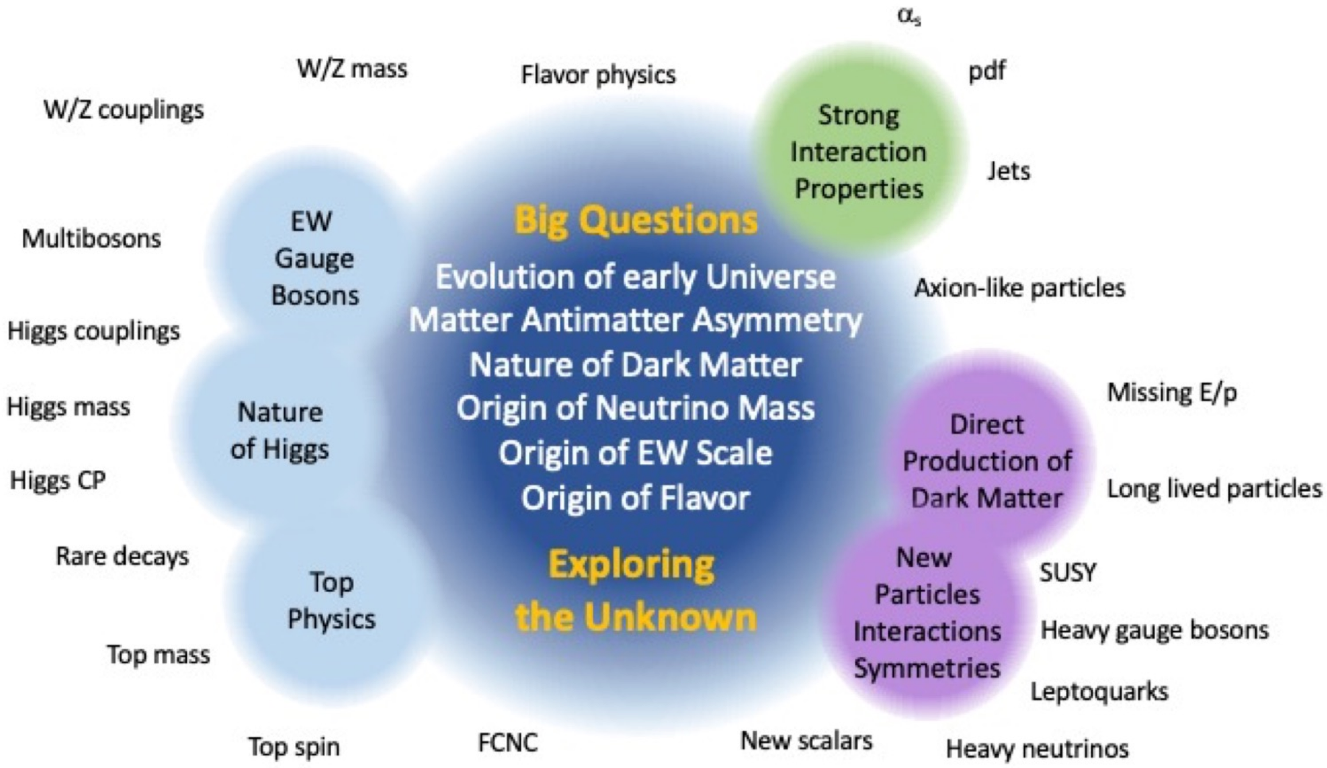
Many Questions Remain



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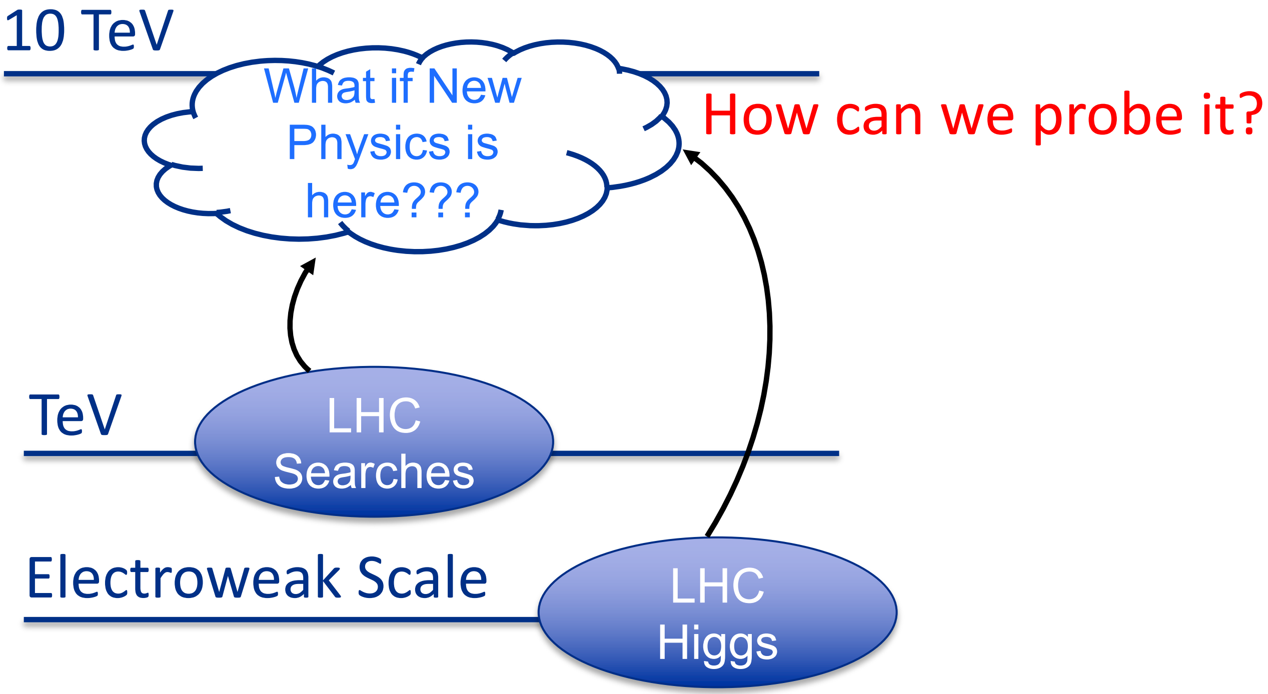
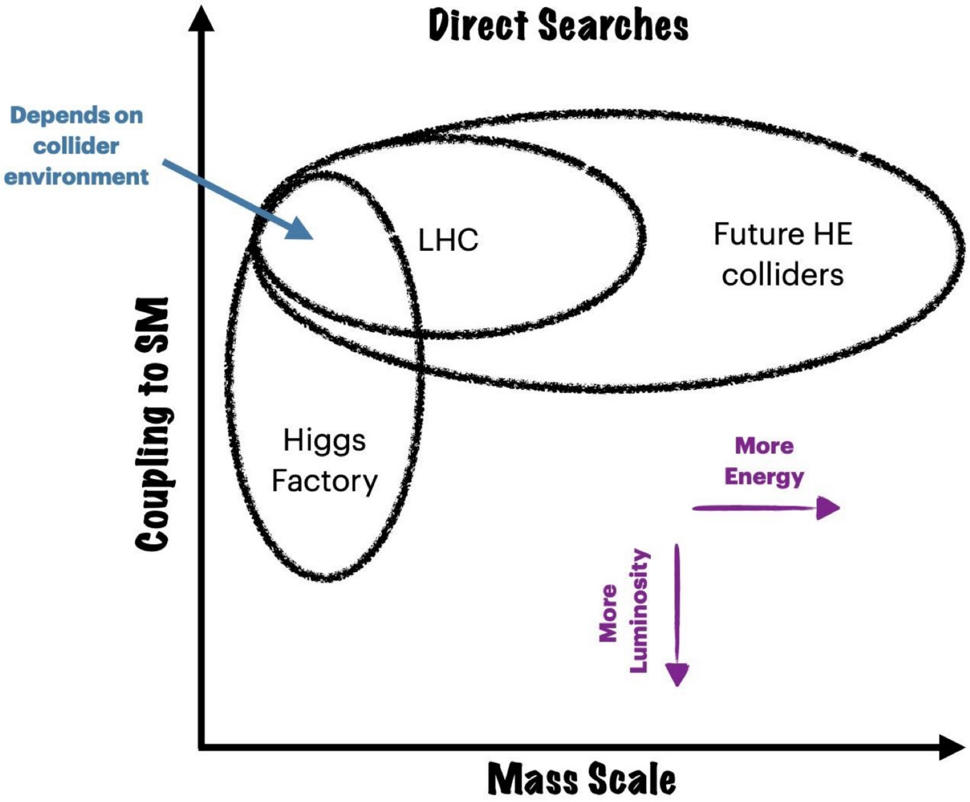
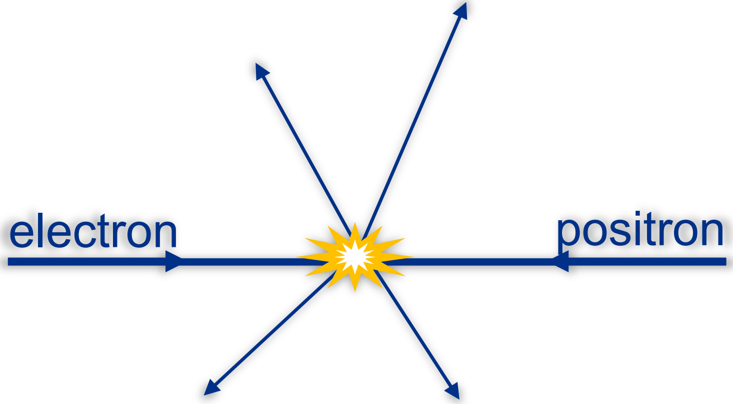
Is there a gap?



Complementarity of direct and indirect probes

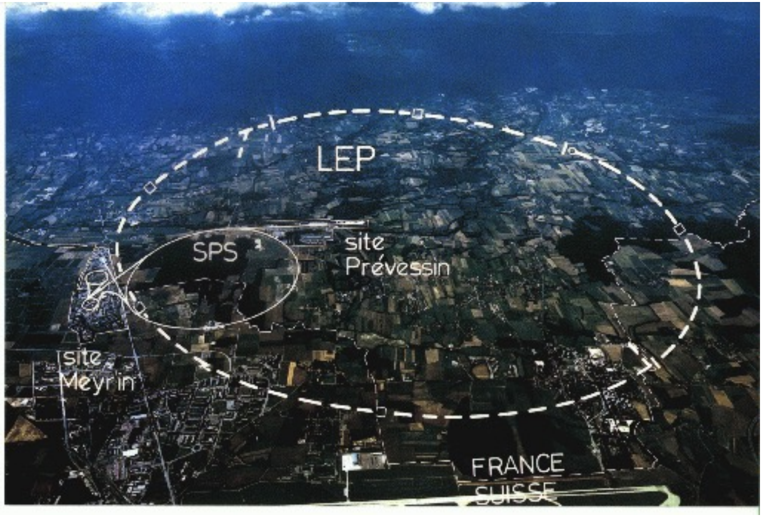


Two types of Colliders



- Clean environment = precision
  - Energy reach very limited

LEP: e+e- up to 209 GeV



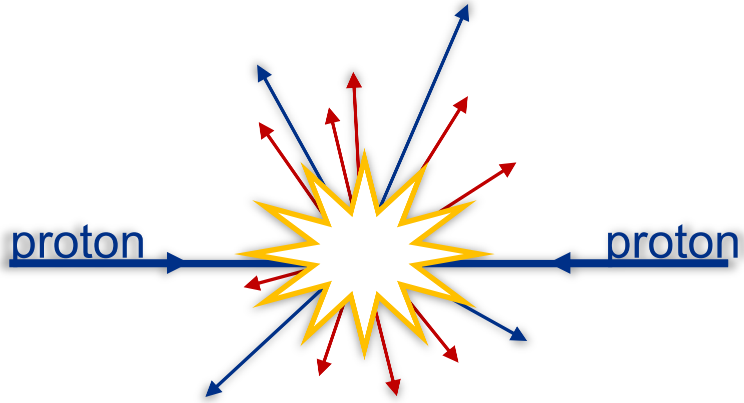
As the trajectory of a charged particle is deflected, it emits "synchrotron radiation"

$$\text{Radiated Power} \propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4$$

Radius of curvature

An electron will radiate about 10^{13} *times more power* than a proton of the same energy!!!!

Two types of Colliders

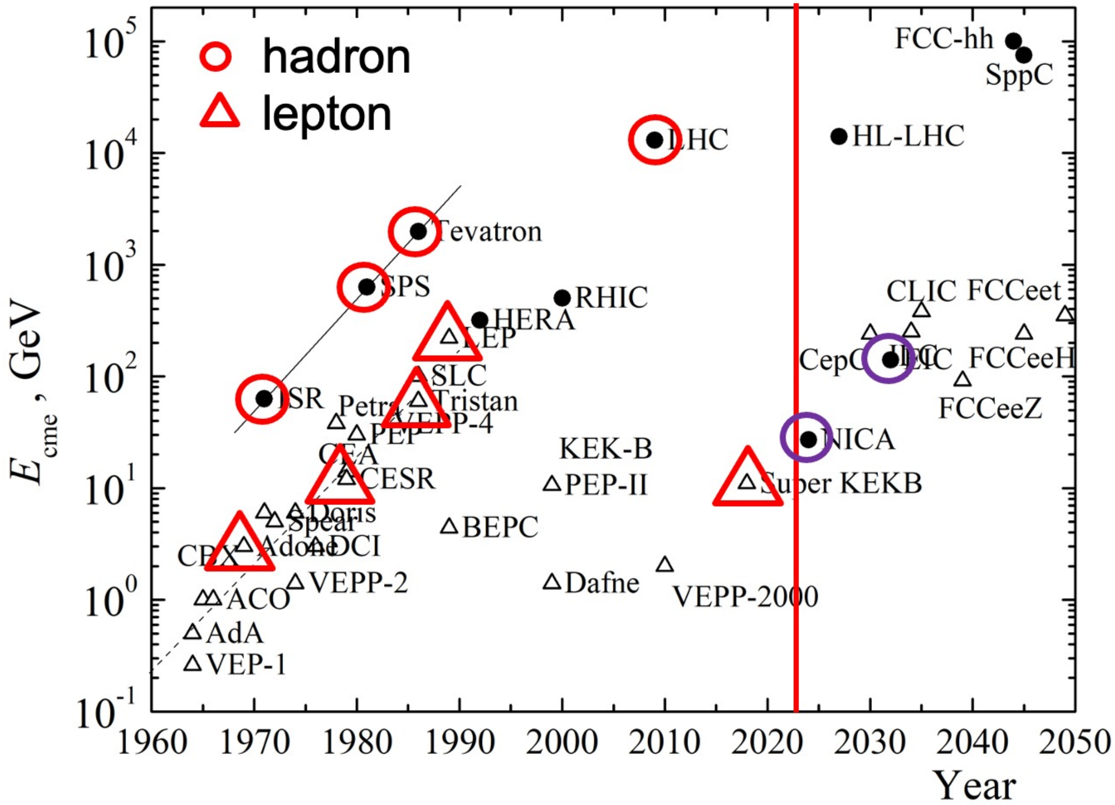


LHC = 13.6 TeV pp collider

- Energy can be high
- Fraction of energy O(1 TeV) carried by the interacting quarks/gluons

Messy environment

Colliders: Livingston Plot



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We need a shift of paradigm!

Collider in the Sea?

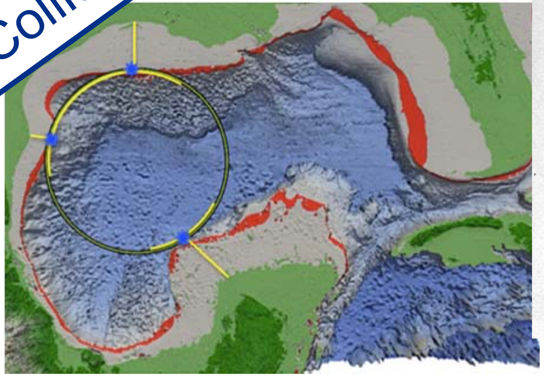
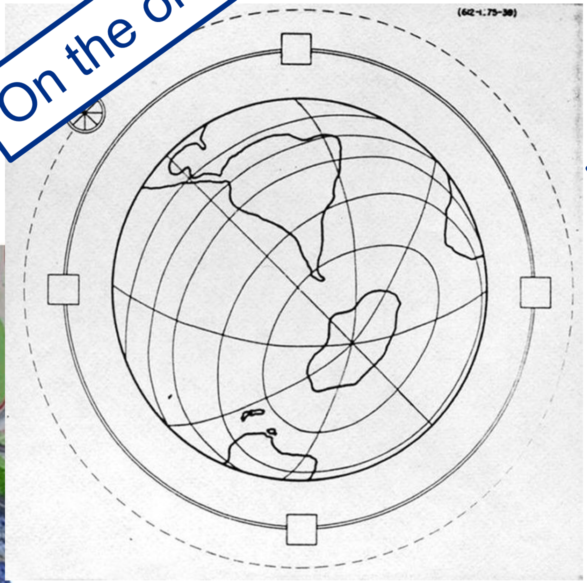


Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron collider. Red =100➔200 m isobaths; gray = 0-100 m isobaths; blue = detectors; green = surface topography.

On the orbit?



On the Moon?

FIG. 1. Three potential Earth-based sites for a circular collider approximately the same size as a collider encircling the Moon of ~11000 km in circumference, represented by images of the Moon overlaid on a map of the surface of the Earth. Each potential Earth-based site for such a large collider project is accompanied by significant geographical, technological, or political challenges. Adapted from Ref. [13] and Ref. [14].

Ever growing Size, Cost, Power

Cost is set by the scale (*energy, length, power*) and technology

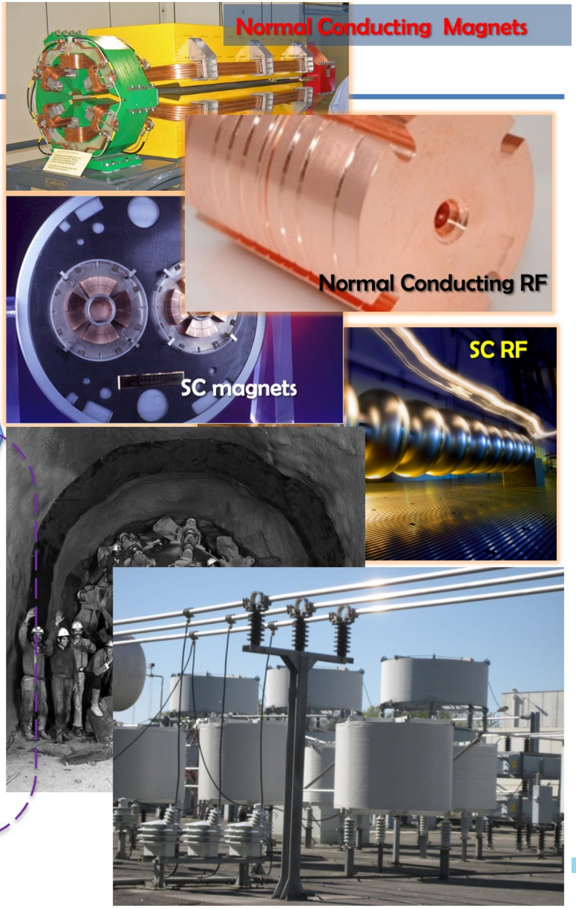
~50±10 %

- *Accelerator technology* (magnets NC and SC, RF and SCRF)
- *Civil construction technology*

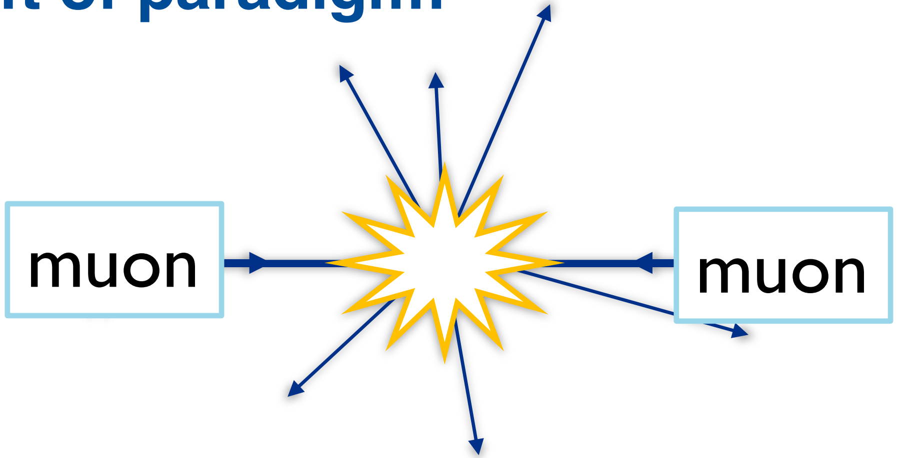
~35±15 %

- *Power delivery, transformation and distribution technology*

~15±10 %



We need a shift of paradigm!



IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

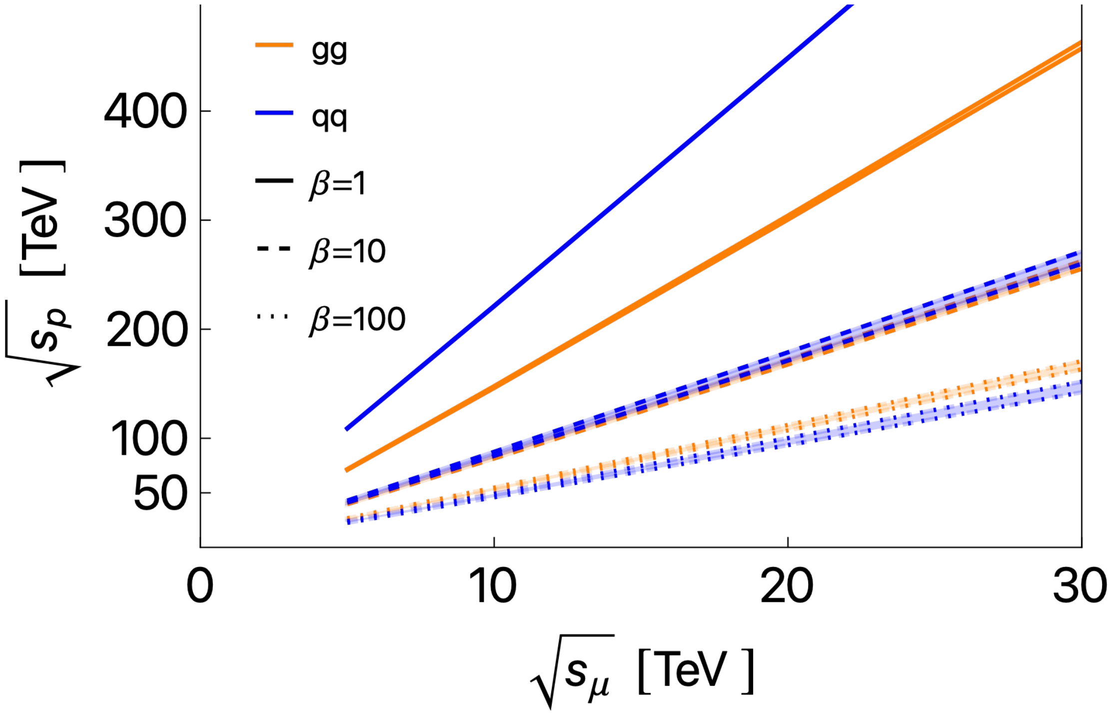
VBA

L. M. Lederman

Columbia University, New York, N.Y. 10027

Collisions of electrons and protons in storage rings and competing high intensity muon beams can be used to study quark dynamics. It is easy to see that 10 TeV muon beams of very high luminosity ($\sim 10^{36}cm^{-2}$ sec^{-1}) can be achieved.

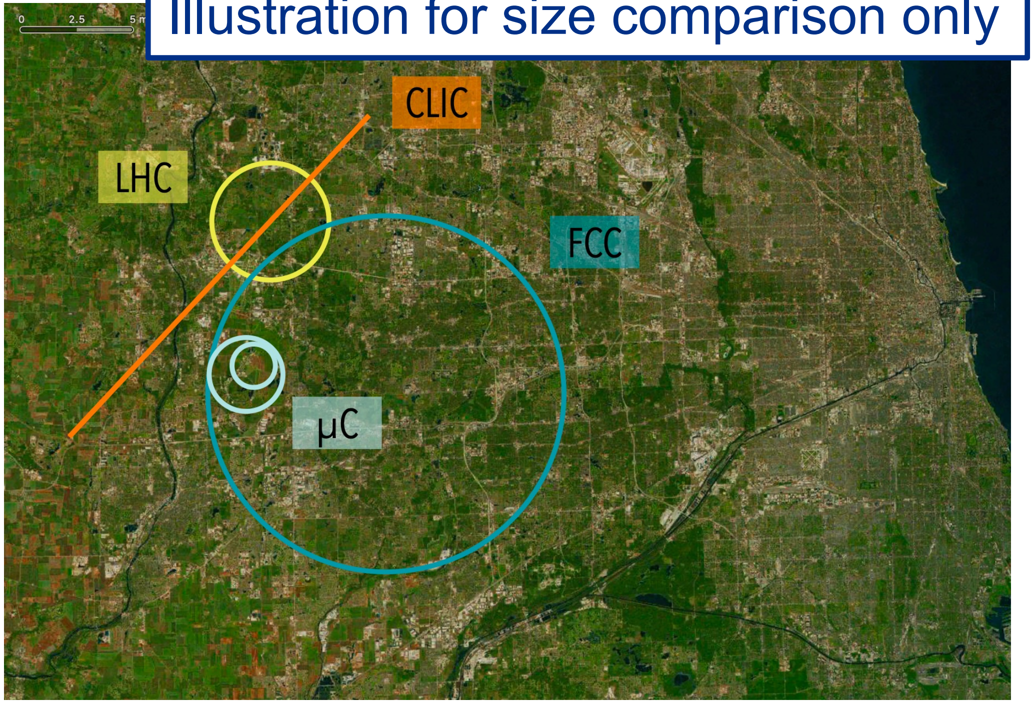
Colliding Muons: energy reach



A 10 TeV muon collider can go beyond 100 TeV pp depending on the process

Why Muons – size

Illustration for size comparison only



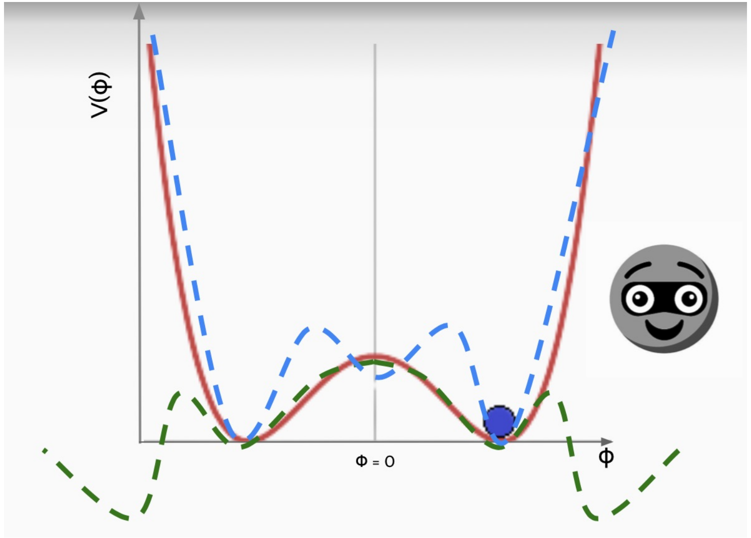
Way smaller footprint than hadron colliders with equivalent physics reach

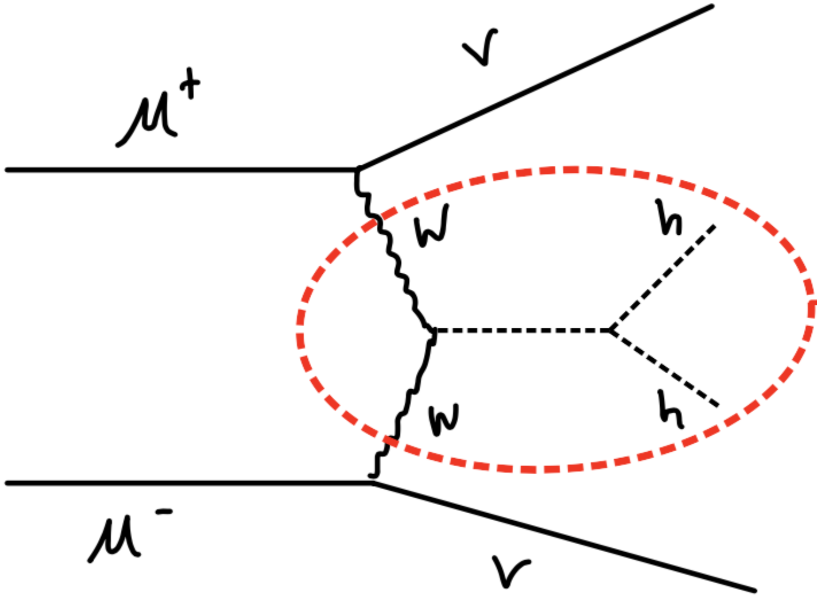
Why Muons – cost and power

More details: Snowmass'21 ITF report

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

Probing New Particles via Higgs





Need sub-% precision to fully characterize the Higgs potential

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The ”past and future of the Universe”

Credit: R. Petrossian-Byrne, N. Craig

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

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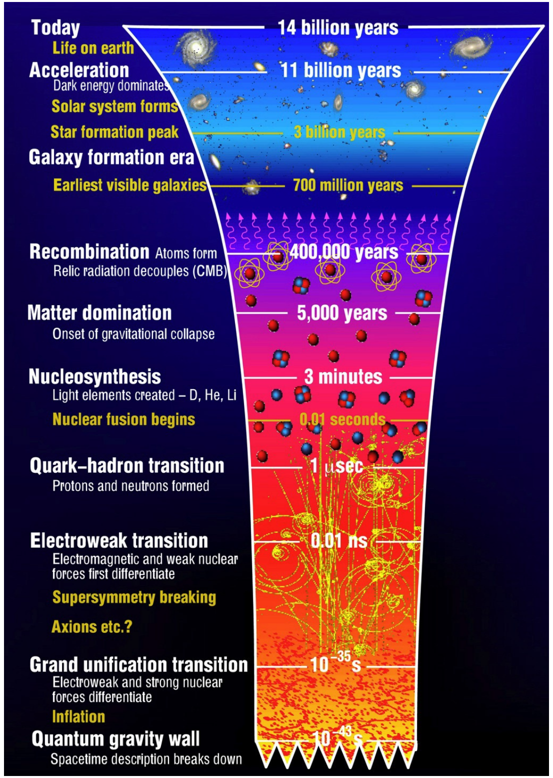
What is Dark Matter?

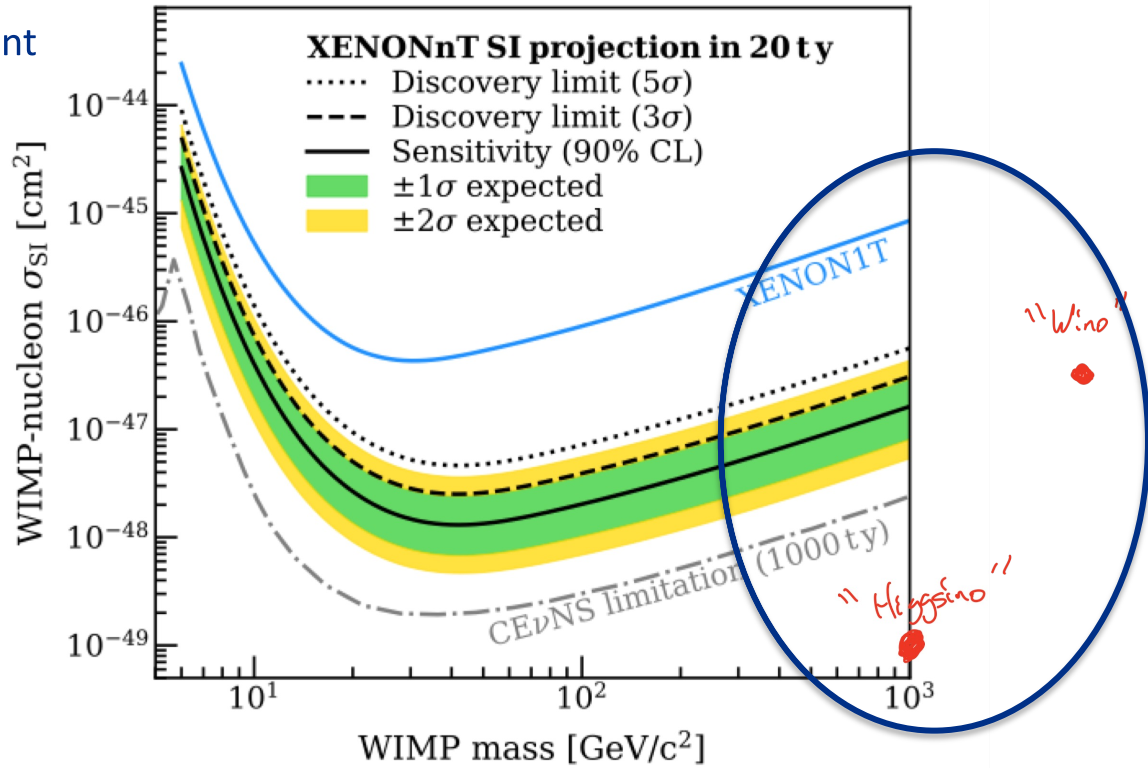


Thermal freeze out story works well for the world around us

Mimic for DM? → WIMP → Probe at Colliders

Long Live the WIMP

XENON1T, a direct DM detection experiment



Colliding Muons - challenges

- Muons are difficult to produce
  - Most effective way is tertiary production from a multi-MW proton beam on a target: protons → pions → muons
  - Beams must be **cooled** to produce luminosity in a collider

- Muons decay (in 2 microseconds at rest!)
  - All beam manipulations must be done **fast**
  - Particles from muon decays deposit significant energy in the accelerator components and physics detectors

The Machine Concept at ~10 TeV

- The goal is to get to **10 TeV center-of-mass energy** with $L \sim 10^{35}$ cm^{-2} s^{-1} (driven by the Higgs physics requirements)

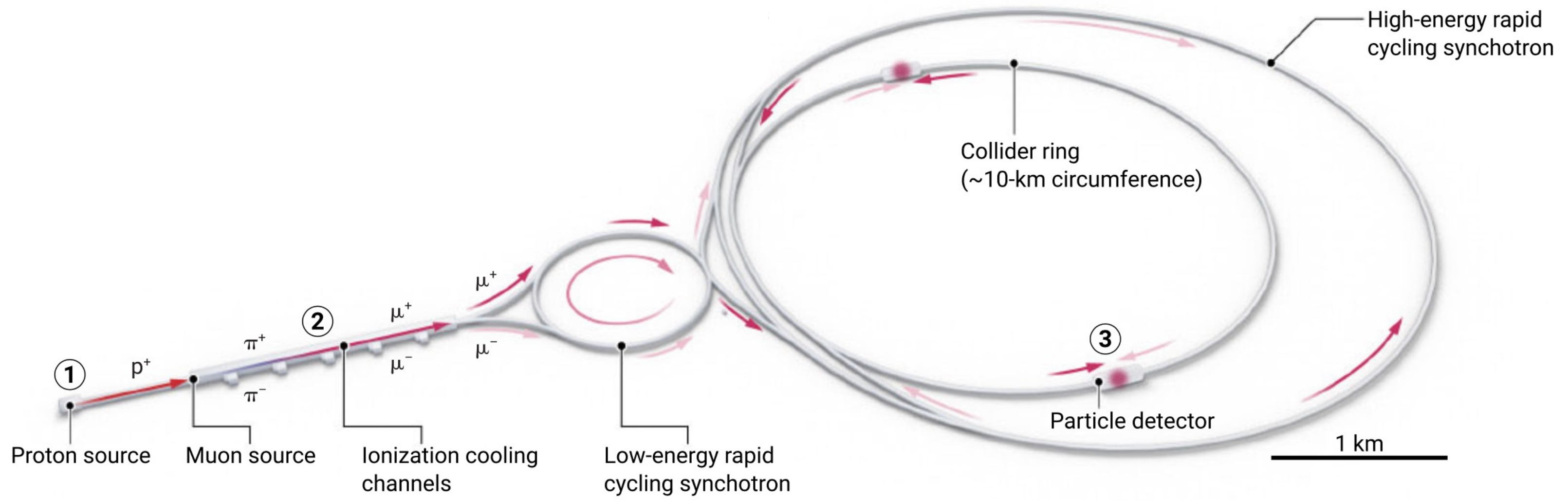


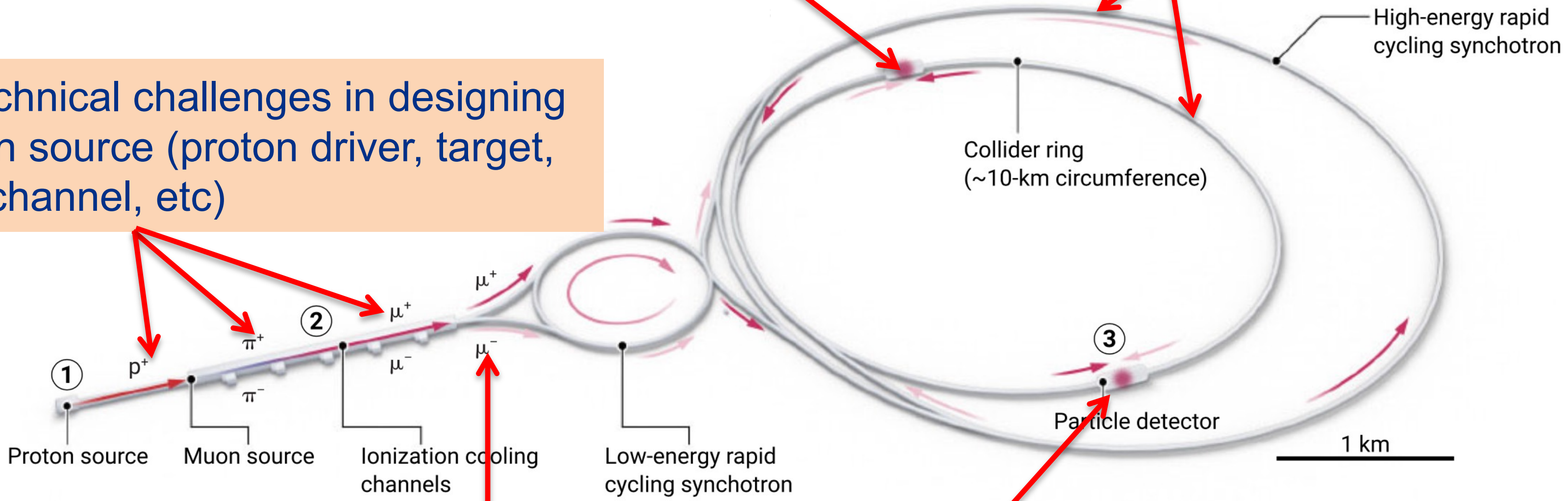
Image courtesy of A. Fisher and the Science magazine

Major Challenges

Dense neutrino flux needs to be mitigated

Challenging magnets in many places

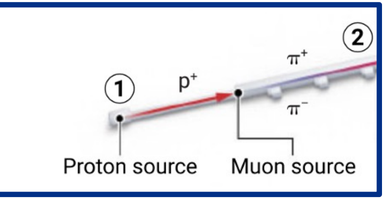
Many technical challenges in designing the muon source (proton driver, target, cooling channel, etc)



High-gradient RF for fast acceleration

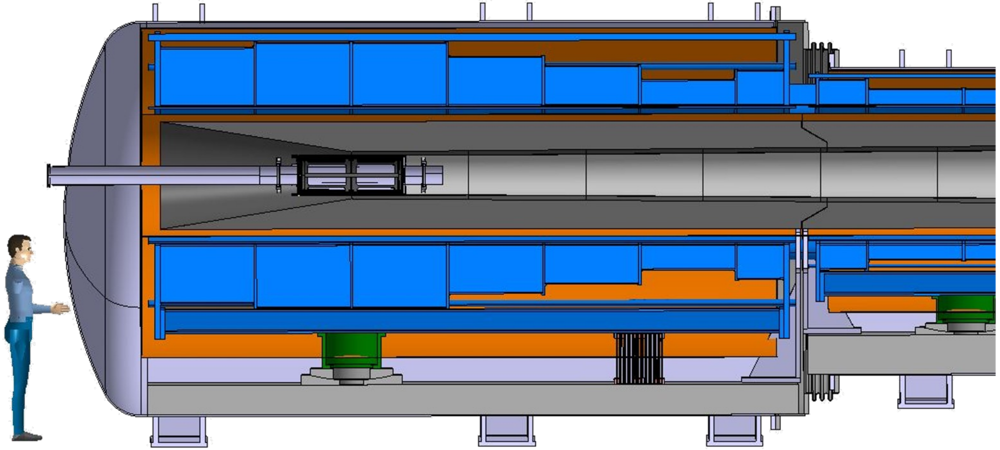
Beam-induced background in the detectors

Target and Capture



in target — decay

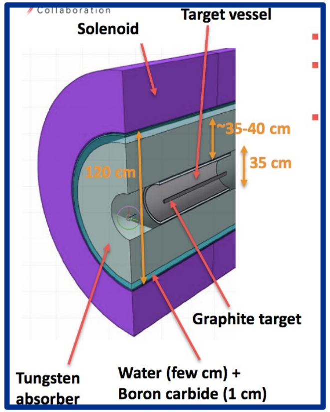
protons → pions → muons



Graphite **Target**

20 T **solenoid**
to guide pions and muons

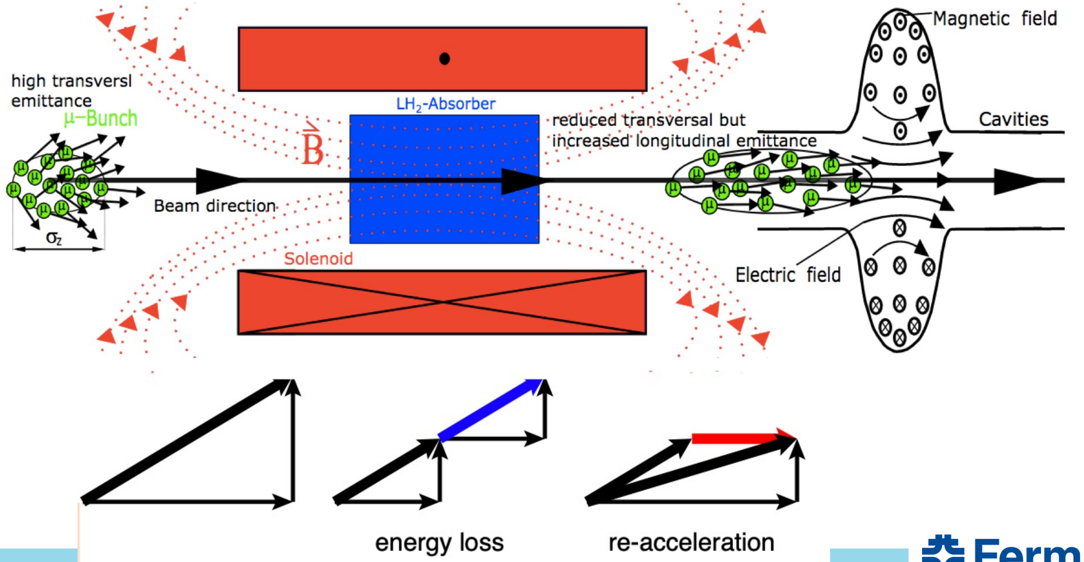
Tungsten shielding
To protect magnet



- Thermal and structural shock on the target due 2-4 MW and short proton bunches
- Study different materials, shapes, size optimization, advanced target concepts
- Focusing magnet is challenging due to field strength, size and radiation load

Ionization Cooling

- The newborn beam has >100% momentum spread
  - It's impossible to accelerate such a broad beam ➔ cooling needed
  - Better be fast → ionization cooling is the only known way



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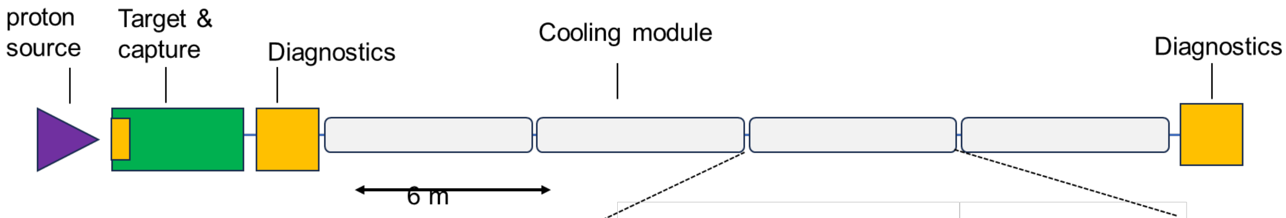
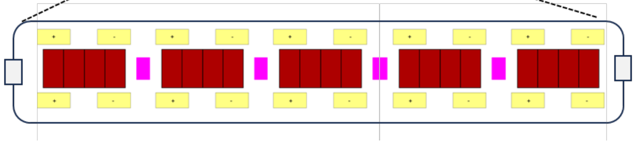
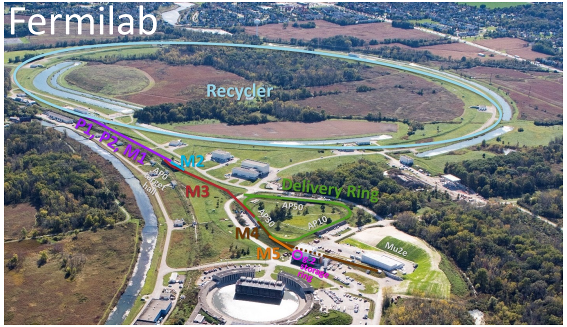
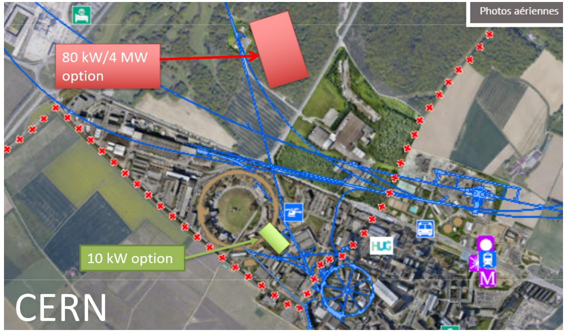
Cooling Demonstrator





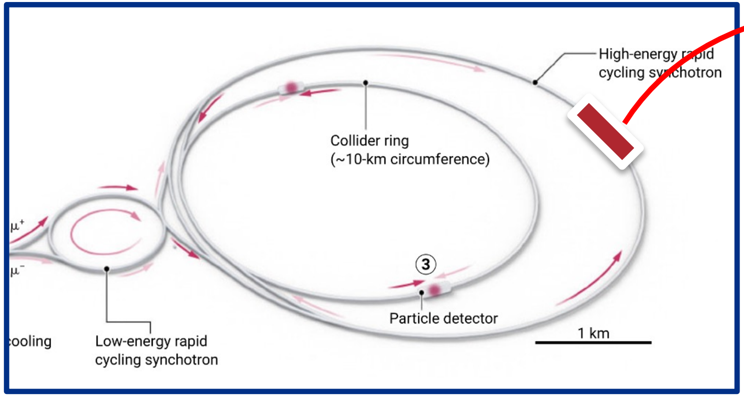
	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x 1/10^5	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%

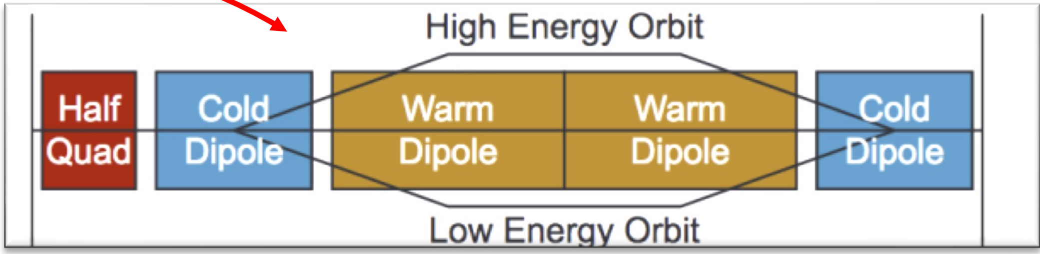




Need to have advanced demonstrator design in 3-5 years for the P5 “collider panel”

Acceleration of Muons





DC field Pulsed from $-B_w$ to $+B_w$

- Rapid Cycling Synchrotron accelerators
- Fast ramping magnets (up to 1000 T/s) accompanied with 16 T DC magnet
- Design of efficient energy sources with good power management (10s of GW) for pulsed magnets is the key

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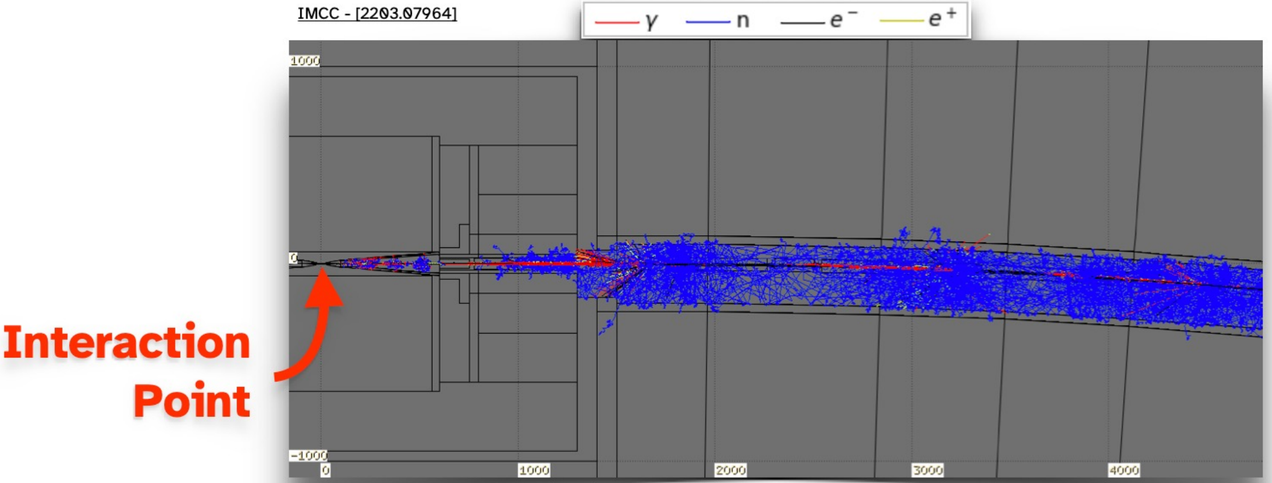
Why Special Detectors?

- Unique feature/challenge of Muon Collider detectors – beam induced background (BIB)
- Most of the energy in the detector is from muon decays that eventually result in a high rate of out-of-time neutrons and photons reaching the detector → need special detectors to suppress it



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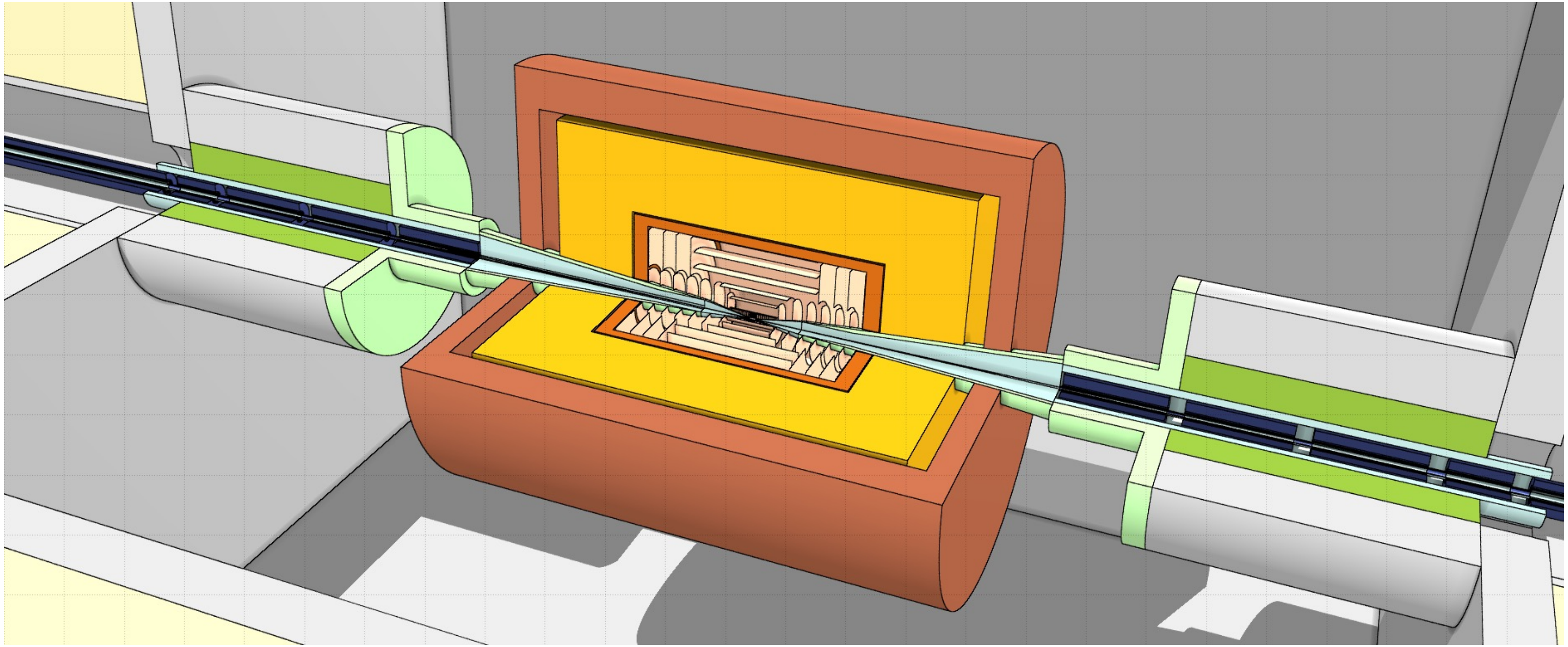
The Detector



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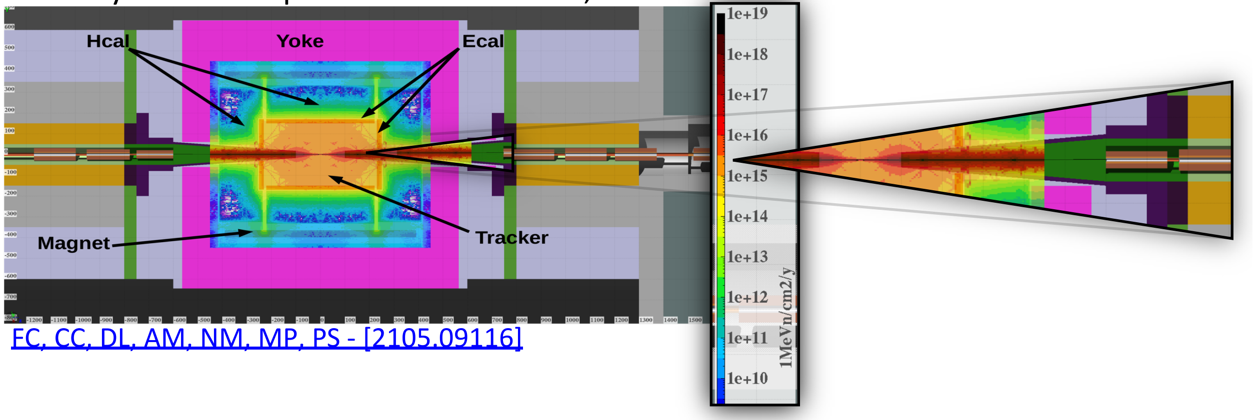
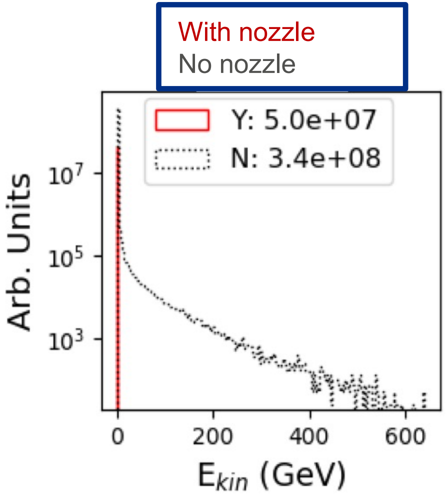
Machine-Detector Interface (MDI)

200-day 1-MeV-neq Fluence - √s=1.5 TeV, MARS15+FLUKA



[FC, CC, DL, AM, NM, MP, PS - [2105.09116]](https://arxiv.org/abs/2105.09116)



Forward region covered by coated tungsten nozzles:

- Reduces BIB in detector by orders of magnitude
- Turns highly localized incident energy into diffuse detector energy

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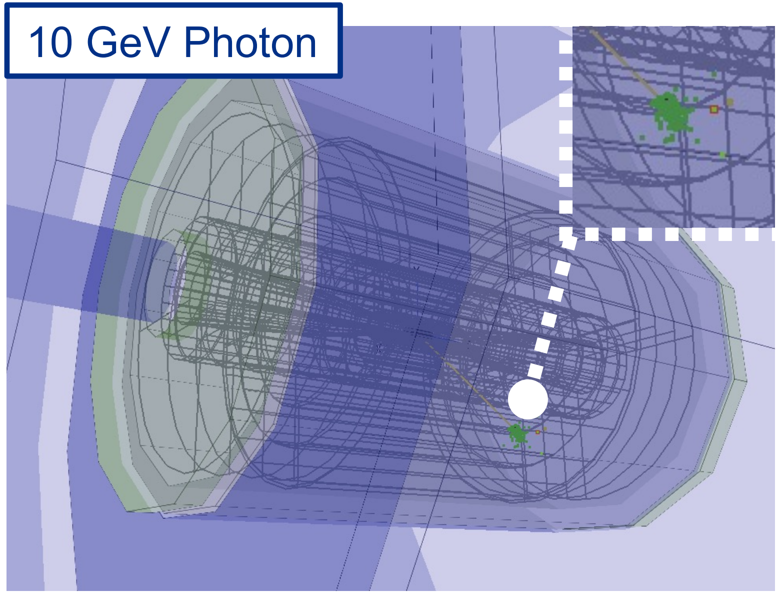
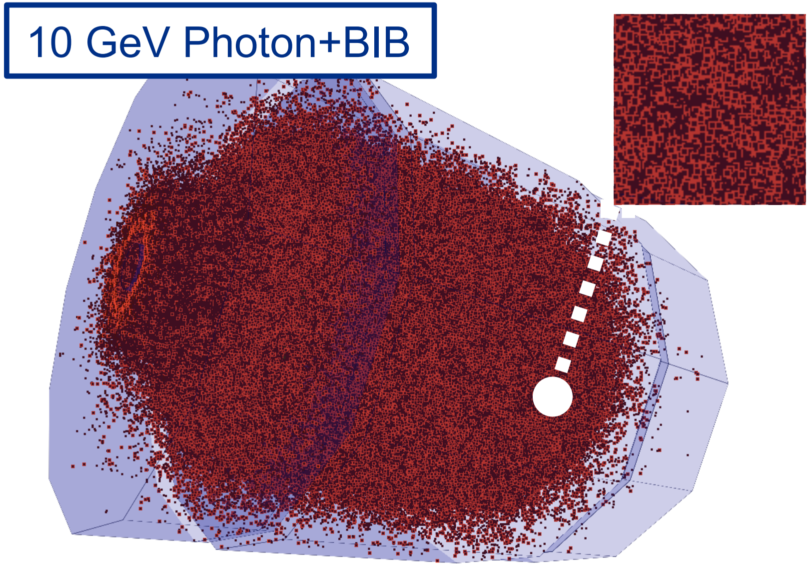
Calorimeter

- BIB dominated by low energy neutrals: photons (96%) and neutrons (4%)
- A low energy noise cloud that needs to be subtracted





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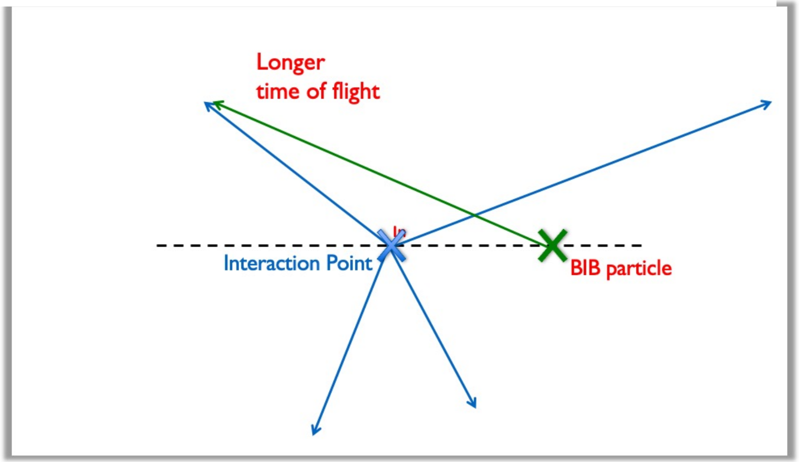
BIB Supression

- The BIB is mostly low energy, out of time and not pointing to the Interaction Point
- Some similarities with LHC pileup - **can build on that experience!**



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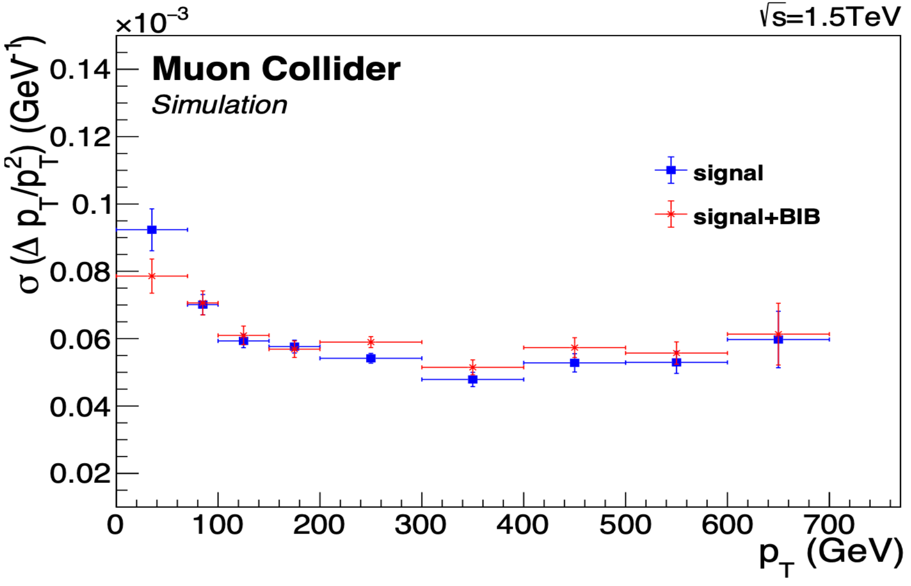
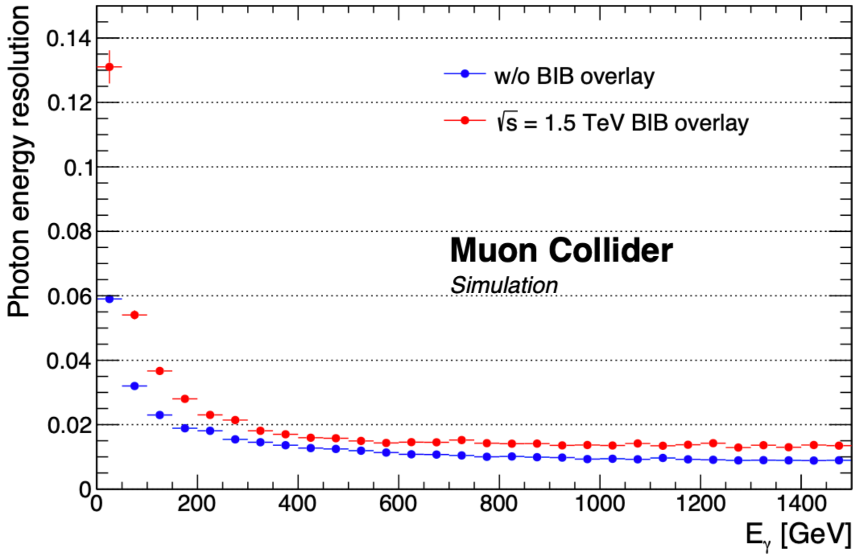
Performance Examples

Track relative momentum resolution
BIB effects are small



Few % Photon Energy Resolution
Improvements possible at low E_T



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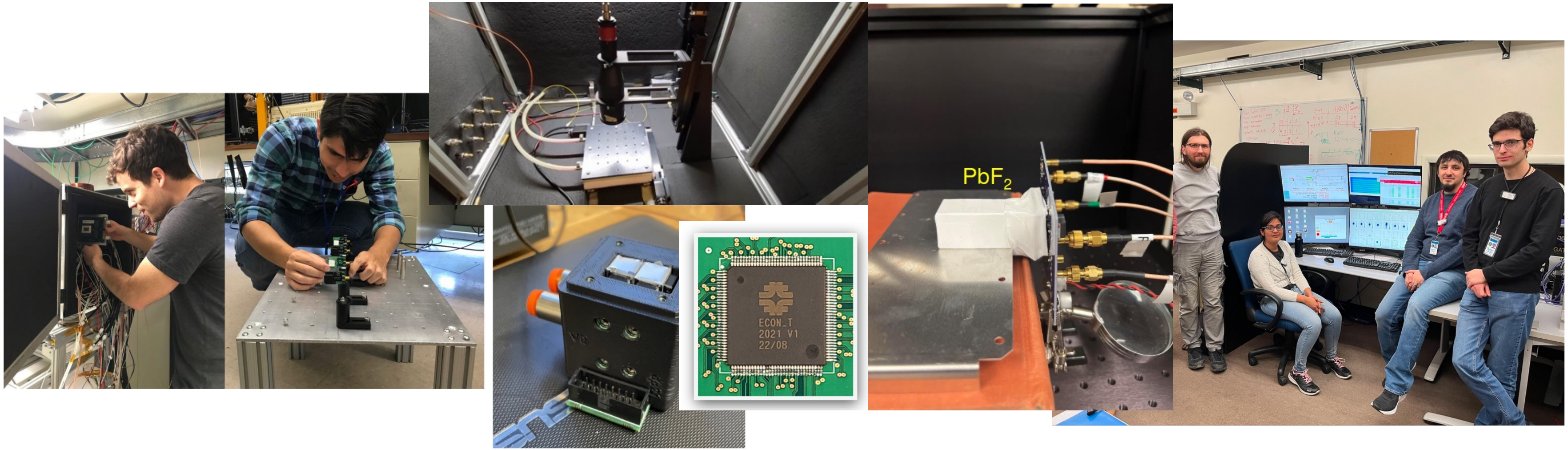
Opportunities

- Strong interest amongst Early Career – build a diverse community of future US particle physics leadership!
- Unique training ground for future generations of accelerator and particle physicists
- Cutting edge technology + highly impactful research = Draw the best talent



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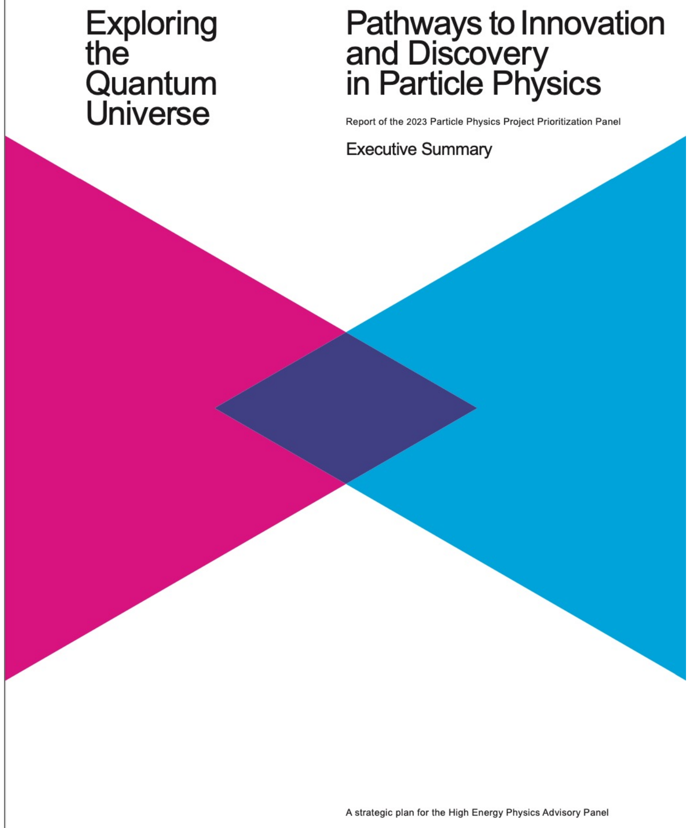
Technology spinoffs

- Magnets – medical imaging, nuclear fusion
- RF - light sources for material properties studies
- Muon beams – large scale object imaging
- muSR – material studies
- Detectors – rad hard sensors, silicon photonics, high speed serial links
- Algorithms

Snowmass process – once every 10 years

A two-year long study process to determine future directions for the field

The 2023 P5 Panel and Report



The Path to 10 TeV (excerpts from the 2023 P5 report)

- The proposed program aligns **with the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

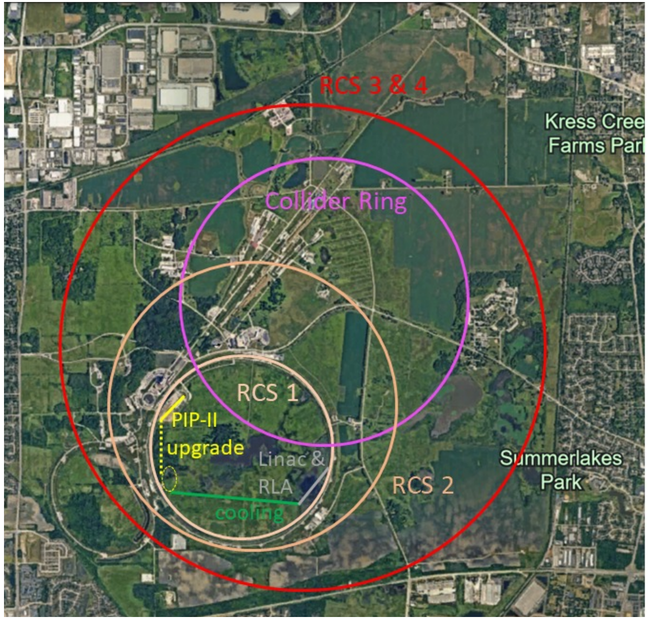
- In particular, **a muon collider** presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a **10 TeV muon collider is almost exactly the size of the Fermilab campus.**

- Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, ...

- At the end of the path is an unparalleled global facility on US soil.

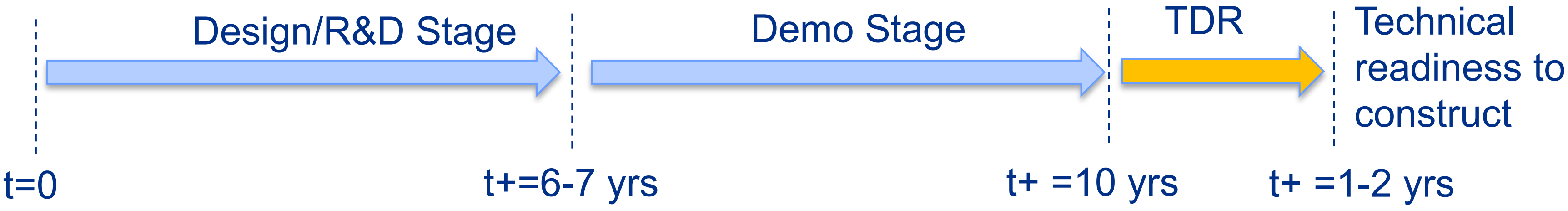
Muon Collider at Fermilab

- Initial concept for 10 TeV machine
- Proton source
  - PIP-II → ACE-BR → Target
- Ionization cooling channel
- Acceleration (4 stages)
  - Linac + RLA → **173 GeV**
  - RCS #1 → **450 GeV (Tevatron size)**
  - RCS #2 → **1.7 TeV (col. ring size)**
  - RCS #3, 4 → **5 TeV (site fillers)**
- Collider ring, 10.5 km long



This design is very preliminary. Need further, more detailed development

“Sketch” Timeline



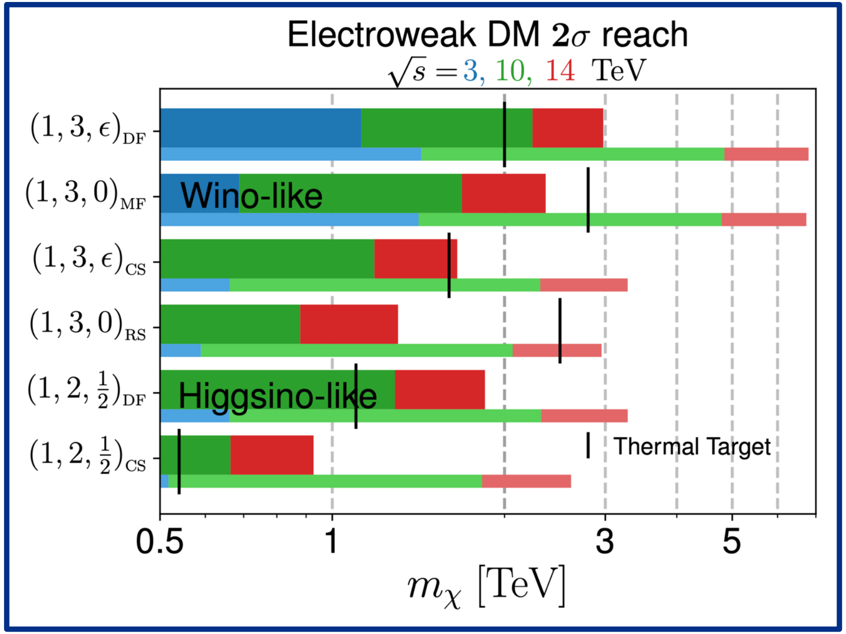
- The actual construction start time is subject to:
  - Successful outcome of **the proposed extensive R&D program**
  - Availability of funding + resources
  - Host laboratory, and international agreements
- Development will take a long time:
  - LHC concept was born in early 1980s, first operation in 2009
  - **Need to start R&D now!**

Summary

- Muon Collider is an exciting future collider option. A machine that can provide both precision and energy reach
- Requires new ideas in accelerator and detector design, reconstruction, simulation and computing
- A great place for junior scientists to contribute. This can be a discovery machine for your generation to build!

Backup

Colliding Muons: Dark Matter



- Conclusive statement about minimal-DM models all the way to the Thermal Targets (*not accessible at current/planned direct DM experiments*)

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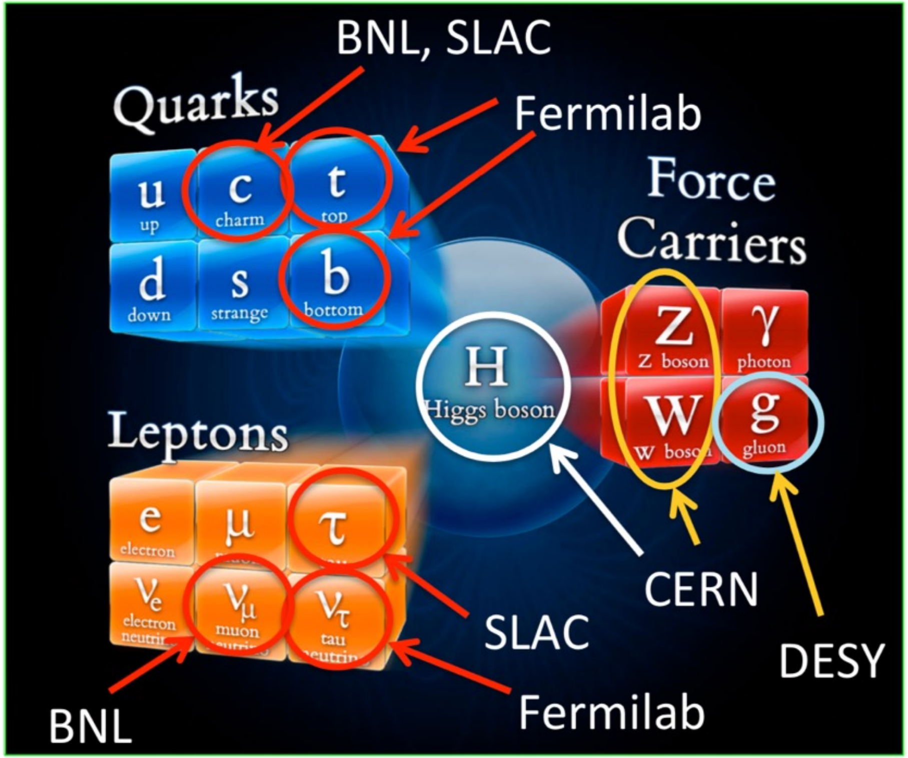
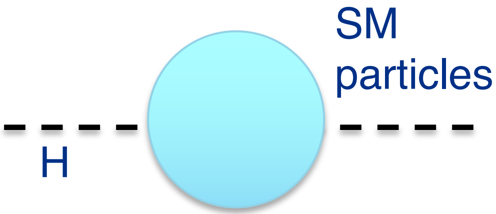
90 years of Accelerators



- Charm quark (1974)
- Tau lepton (1975)
- bottom quark (1977)
- Gluon (1978/79)
- W,Z bosons (1983)
- Top quark (1995)
- Tau neutrino (2000)
- Higgs boson (2012)

Hierarchy Problem



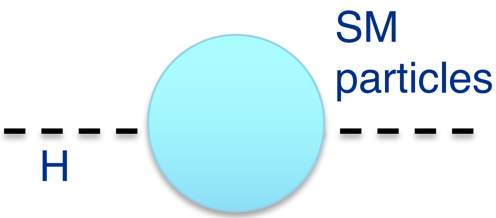
$$m_{obs}^2 = m_{bare}^2 - \frac{\lambda_f^2}{8\pi^2}\Lambda^2$$

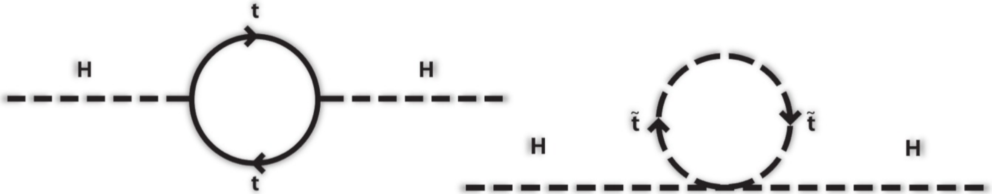
125 GeV

10^{19} GeV?

10^{19} GeV

Hierarchy Problem





$\delta M_H \sim -(125\text{GeV})^2(\Lambda/600\text{GeV})^2$

$\delta M_H \sim +(125\text{GeV})^2(\Lambda/M_{New})^2$

We have seen this already with e+/e-!

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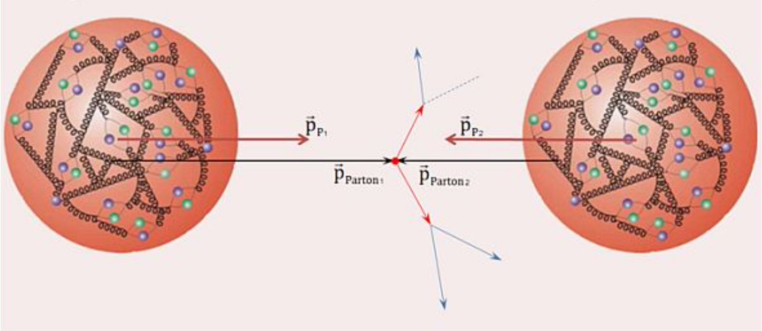
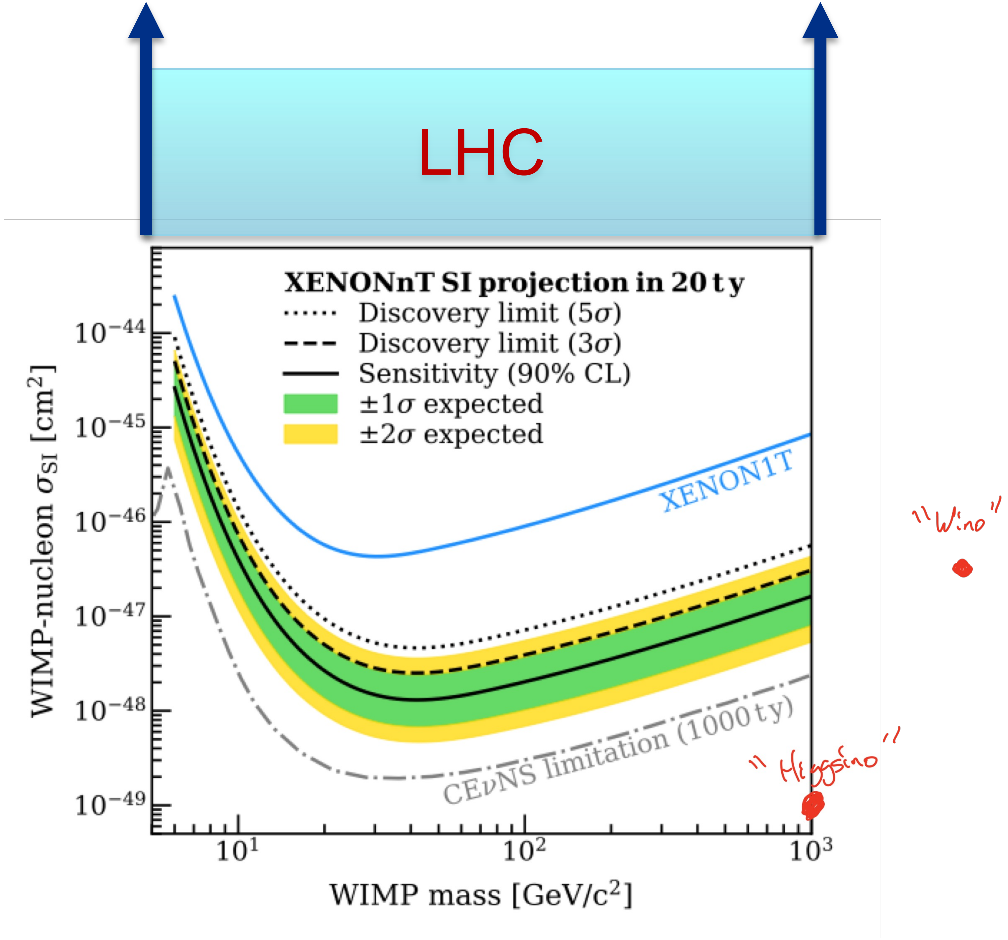
Can LHC Probe EWK DM?





LHC collides composite particles

Only fraction of proton energy goes into collision

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Fermilab at the Energy Frontier

- Fermilab is the US Premier Particle Physics Laboratory with:
  - Long history of leadership at the EF
  - Strong interests and deep expertise in collider physics
  - Home to advanced accelerator and detector technologies
  - Unique infrastructure (Sidet, test-beams, ITA, ASIC, etc)
- Snowmass was an opportunity to:
  - Engage in global planning to advance Energy Frontier
  - Pay special attention to Fermilab's role in future collider facilities
- Develop future of Fermilab beyond PIP-II/LBNF/DUNE
  - The development of the accelerator complex for LBNF/DUNE provides robust infrastructure for planning future world-leading facilities
- We think that it is important for Fermilab to maintain leadership in EF

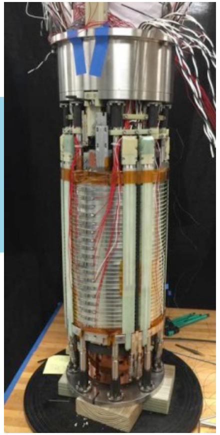
Future Detector Needs

- Detectors at future colliders have more stringent requirements than at HL-LHC and require significant R&D
- Electron Colliders:
  - High granularity and low mass trackers
  - High Granularity Calorimeters
- Hadron Colliders
  - High Granularity Trackers and Calorimeters
  - Rad hard sensors and FE electronics
  - Electronics, trigger systems, high speed links
- Muon Collider
  - High granularity and Fast timing requirements
  - Moderate radiation tolerance
  - Lots of synergies with e+e- and pp
- Fermilab group's Detector R&D (Petra's talk) efforts are well aligned with these needs

Magnet Technology

- **Cooling:** Designs consider B-fields of 30-40 T
- commercial MRI 29 T magnets.
- Record 32 T achieved at NHMFL.
- A funded proposal to design purely SC 40 T magnet in place

Record SC 32 T @ NHMFL

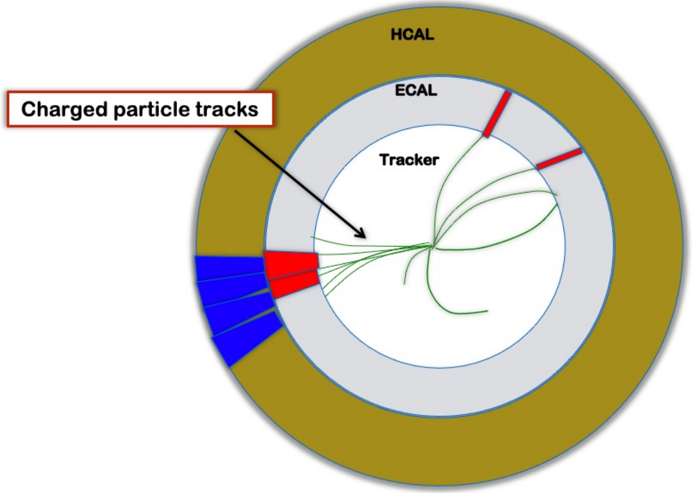


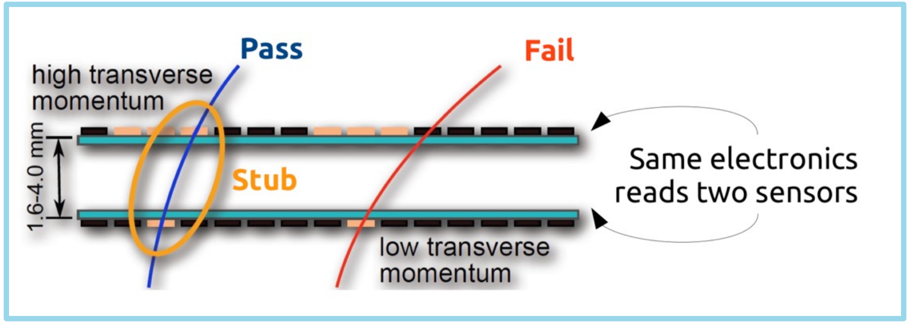
HTS demo at Fermilab

- **Acceleration:** Fast cycling magnets with 1000 T/s
- Demonstrated record ramp rate of 300 T/s with HTS – upgrades for higher fields proposed

- **Collider Ring:** Large 16 T arc dipoles
- Plans in 4-5 years to demonstrate 12-15 T dipoles

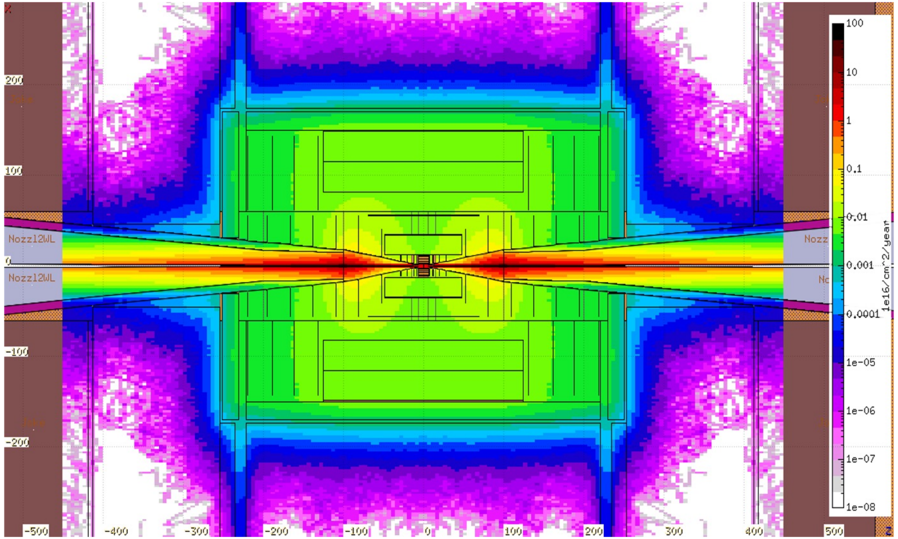
Detector Technologies - pointing



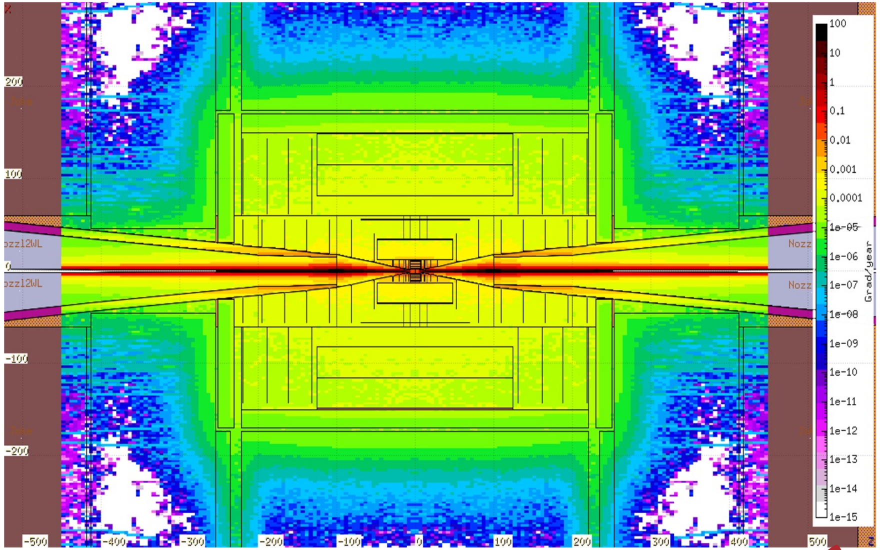


Radiation Levels

1-MeV-neq fluence for one year of operation (200 days)



Total Ionizing Dose for one year of operation (200 days)



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

Much lower than FCC-hh

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Costs

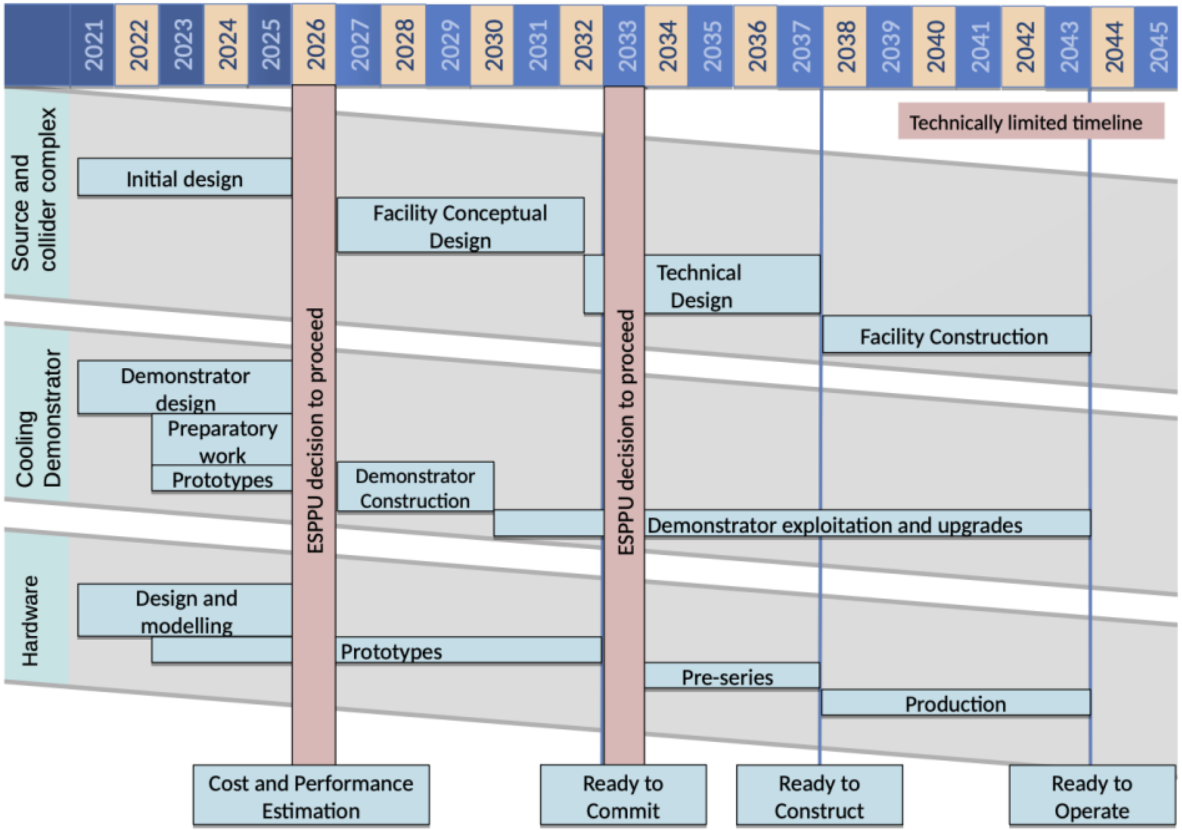
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
High Energy ILC	3 (1-3)	6.1	5-10	19-24	18-30	~400
High Energy CLIC	3 (1.5-3)	5.9	3-5	19-24	18-30	~550
High Energy CCC	3 (1-3)	6.0	3-5	19-24	12-18	~700
High Energy ReLiC	3 (1-3)	47	5-10	>25	30-50	~780
Muon Collider	3 (1.5-14)	2.3	>10	19-24	7-12	~230
LWFA - LC (Laser-driven)	3 (1-15)	10	>10	>25	12-80	~340
PWFA - LC (Beam-driven)	3 (1-15)	10	>10	19-24	12-30	~230
Structure WFA - LC (Beam-driven)	3 (1-15)	10	5-10	>25	12-30	~170

Costs

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	>10	>25	12-18	~300
LWFA - LC - $\gamma\gamma$ (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~210
PWFA - LC - $\gamma\gamma$ (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~120
Structure WFA - LC - $\gamma\gamma$ (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~90
FCC-hh	100	30	>10	>25	30-50	~560
SPPS	125 (75-125)	13	>10	>25	30-80	~400

R&D Timeline

More details: https://arxiv.org/abs/2201.07895



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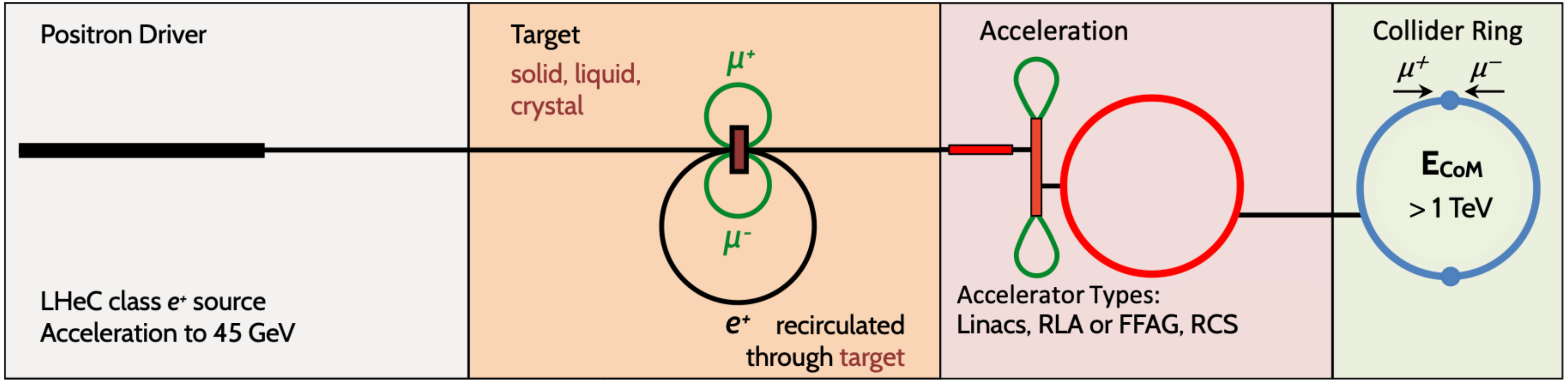
S. Jindariani, PURSUE 2023

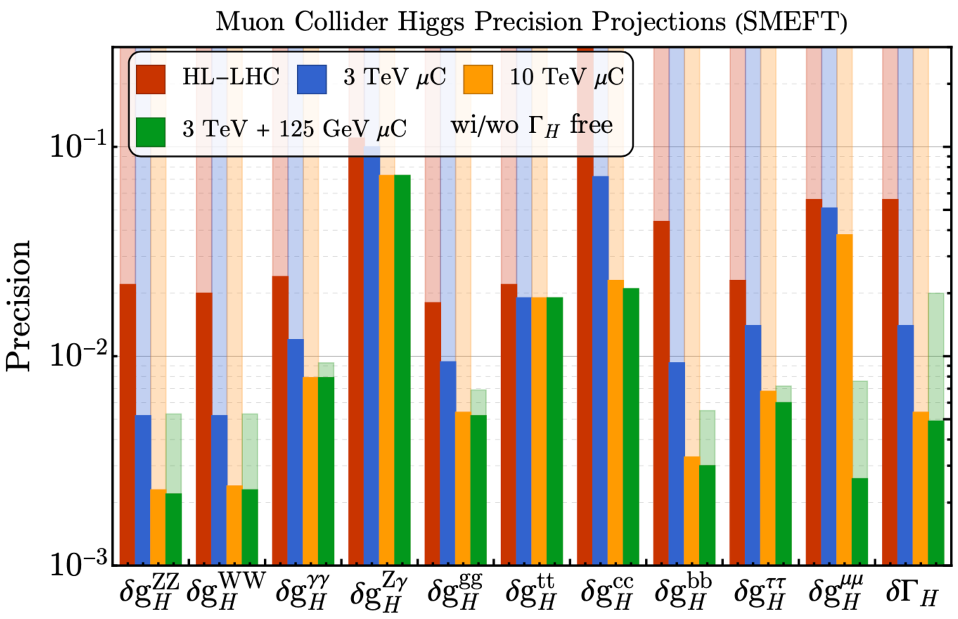
LEMMA Scheme

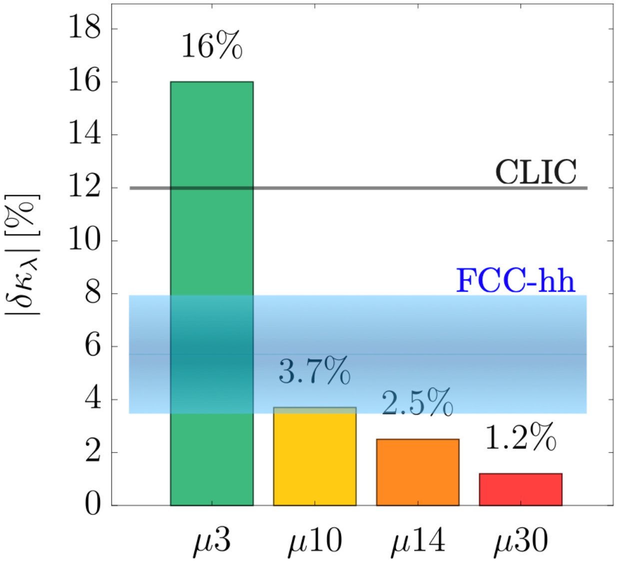


Produce muons at threshold → no cooling needed

Excellent idea but studies show that a very large positron bunch charge is needed to get to desired luminosity → need a game changing invention

Higgs Physics





Order of magnitude in Higgs precision wrt HL-LHC and can directly probe *the scale implied in same machine!*

Self-coupling: at 3 TeV better than LHC. At 10 TeV similar or better than FCC-hh.

λ4 is 50% at 14 TeV

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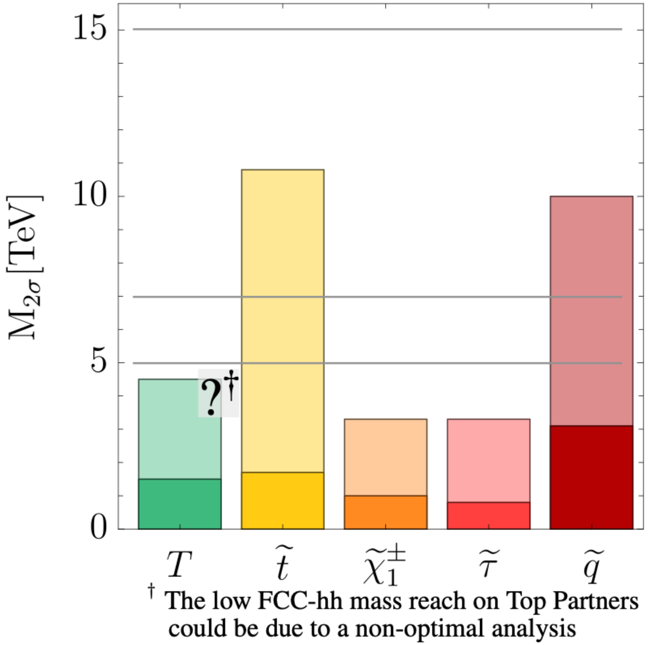
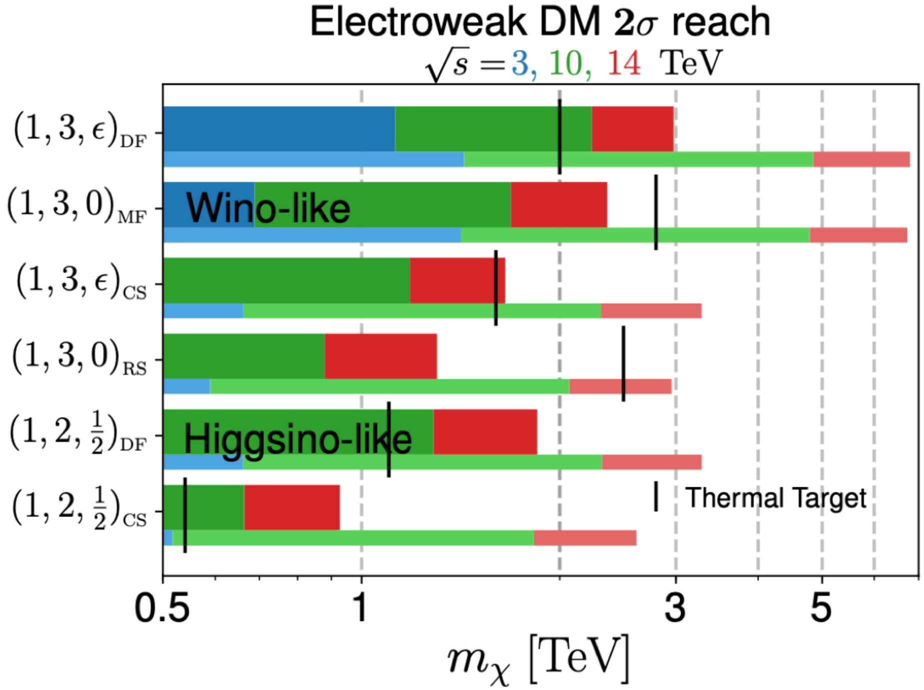
Physics BSM





At 10 TeV rivals FCC-hh.
Unmatched at 30 TeV

Covers *simplest* WIMP candidates hard or impossible with next gen DM direct detection

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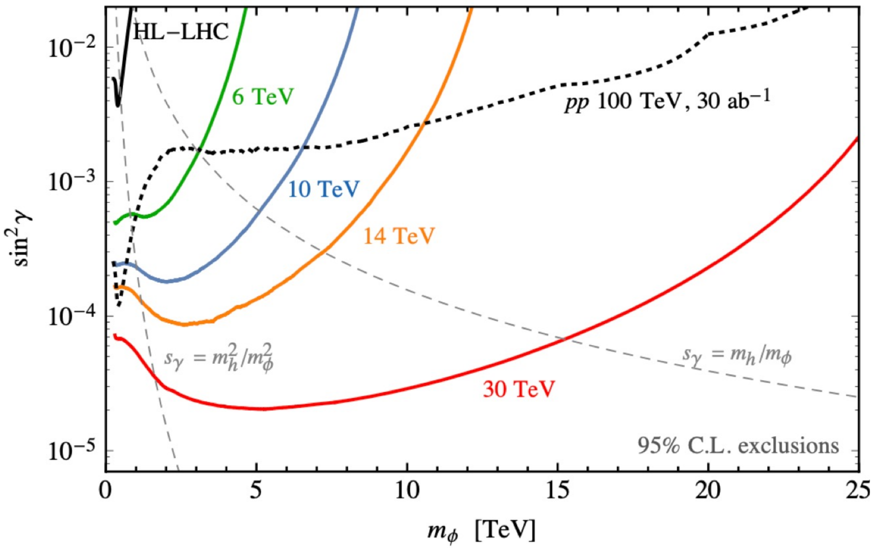
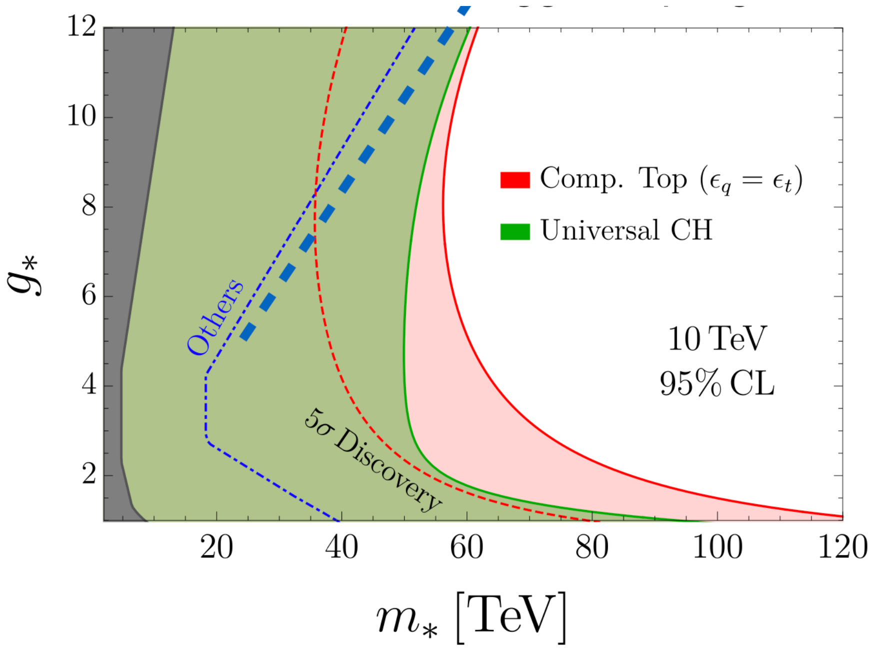
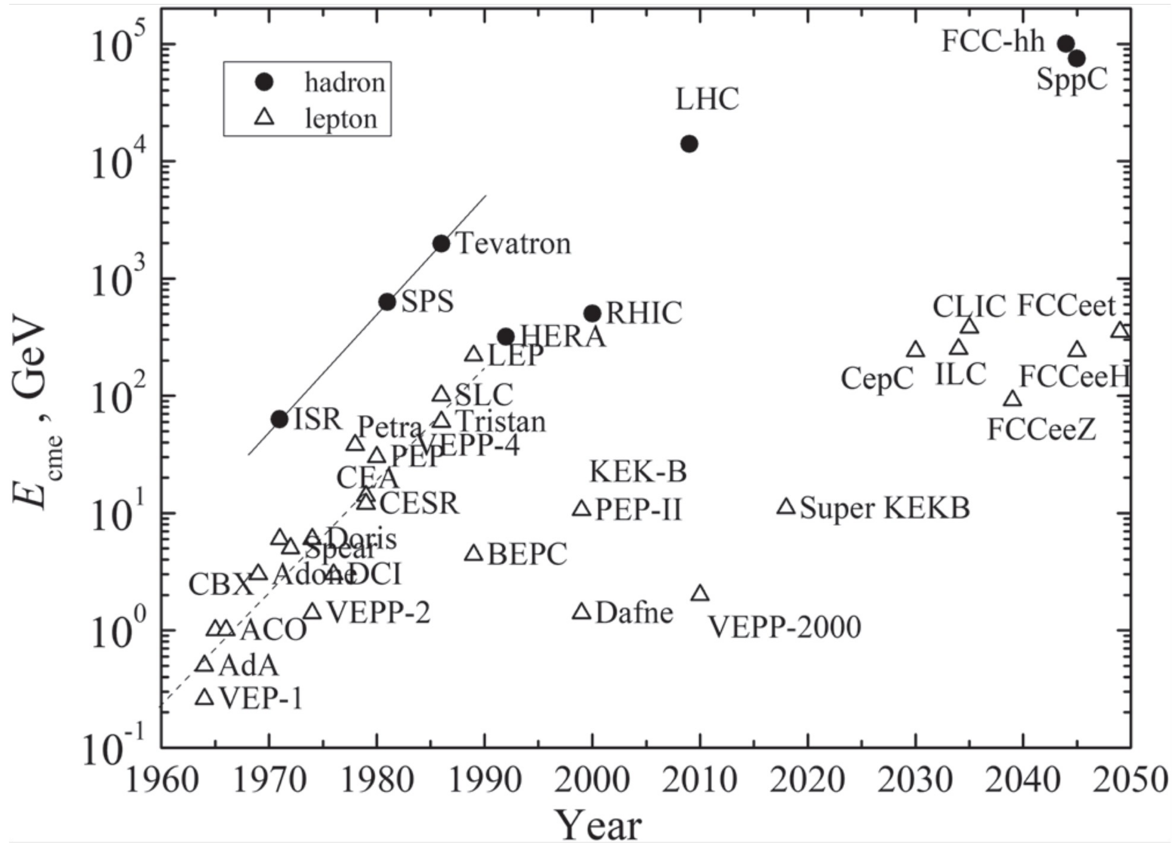
Physics BSM



New singlet extension



Compositeness


hadron
lepton
FCC-hh
SppC
LHC
Tevatron
SPS
HERA
RHIC
LEP
SLC
ISR
Petra
Tristan
VEPP-4
PEP
CEA
CESR
KEK-B
PEP-II
Super KEKB
Doris
Spear
CBX
Adone
DCI
BEPC
VEPP-2
ACO
Dafne
VEPP-2000
AdA
VEP-1
CLIC
FCCeet
CepC
ILC
FCCeeH
FCCeeZ
E_{cme}, GeV
Year