A Muon Collider in the Future of Particle Physics

Simone Pagan Griso (LBNL)

Wine & Cheese Seminar
Fermilab, Dec 16th 2022

BERKELEY LAB
Lawrence Berkeley National Laboratory

Muon Collider Physics and Detector workshop

Fermilab, Dec 14^{th}-16^{th} 2022

Design by
T. Holmes, K. Di Petrillo

<u>Wed 12/14</u>

Tutorial on muon collider detector simulation
Colloquium (V. Shiltsev) on landscape of future particle accelerators

<u>Thu 12/15</u>

Status and Organization of muon collider activities
Accelerator needs
Physics opportunities

<u>Fri 12/16</u>

Simulation framework
Detector needs
Synergies

https://indico.fnal.gov/event/56615/

Outline

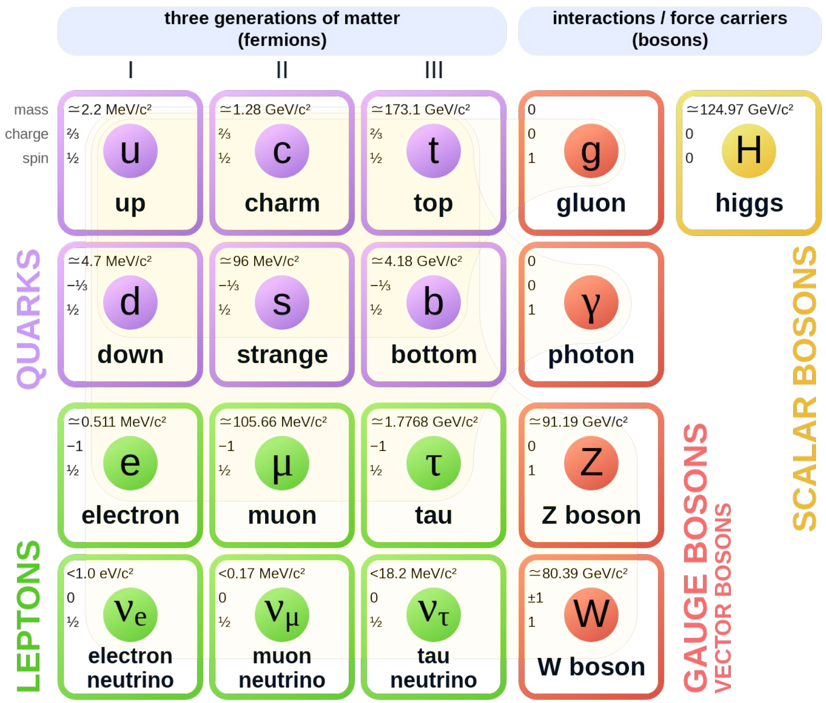
A look into the future: motivation for a muon collider

Experimental challenges and opportunities

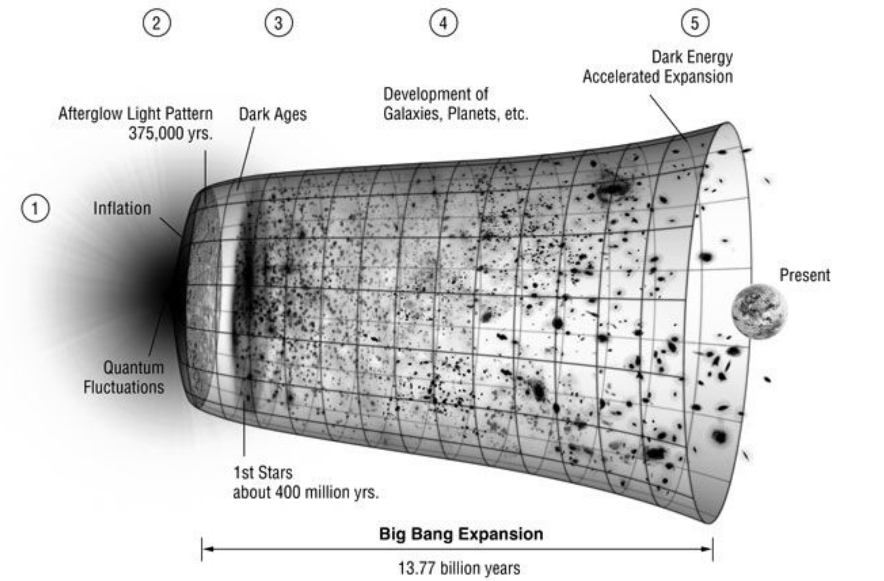
Discovery potential

Prelude

Within the last century we have built an impressive synthesis of the fundamental physics at the (smallest and) largest scales.



Adapter from source: Wikimedia



Adapter from source: NASA/ LAMBDA Archive / WMAP Science Team NASA/WMAP Science Team

We all work to ensure that the next century will be even more exciting!

Snowmass '21

Science study to build a vision for the future of particle physics in the U.S. and its international partners.

Work divided in 10 frontiers and several dedicated cross-frontiers groups
- final reports available

Energy Frontier Report, arXiv:2211.11084
Muon Collider Forum Report, arXiv:2209.01318
Implementation Taskforce Report, arXiv:2208.06030
… and many more (see https://snowmass21.org)

Input to the Particle Physics Project Prioritization Panel (aka P5):
- In charge of formulating a 10-year plan (20-year vision) within funding constraints
- Panel members just appointed
- Expect report by the end of 2023

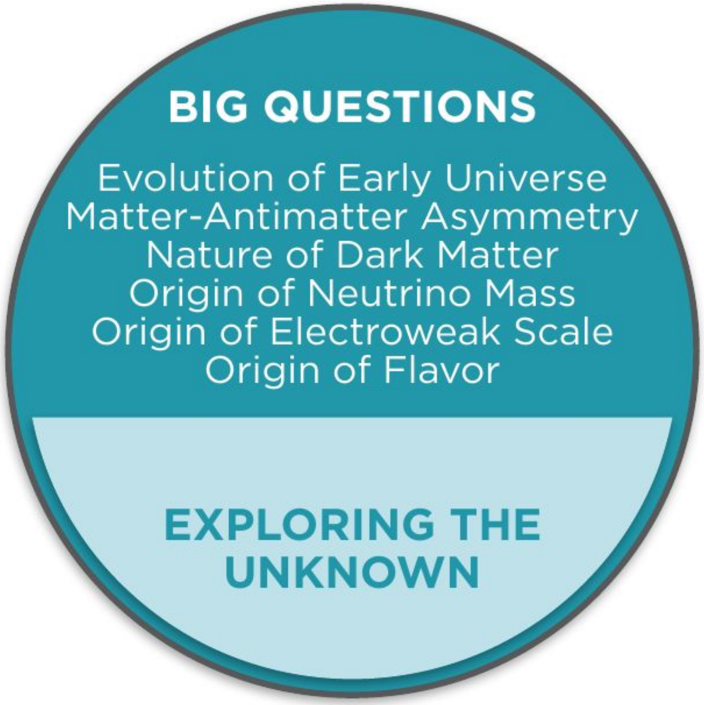
2014 P5 Drivers

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

- Higgs boson as tool for discovery
- Physics of Neutrino mass
- Identify new physics of dark matter
- Dark Energy and Inflation
- Explore the unknown

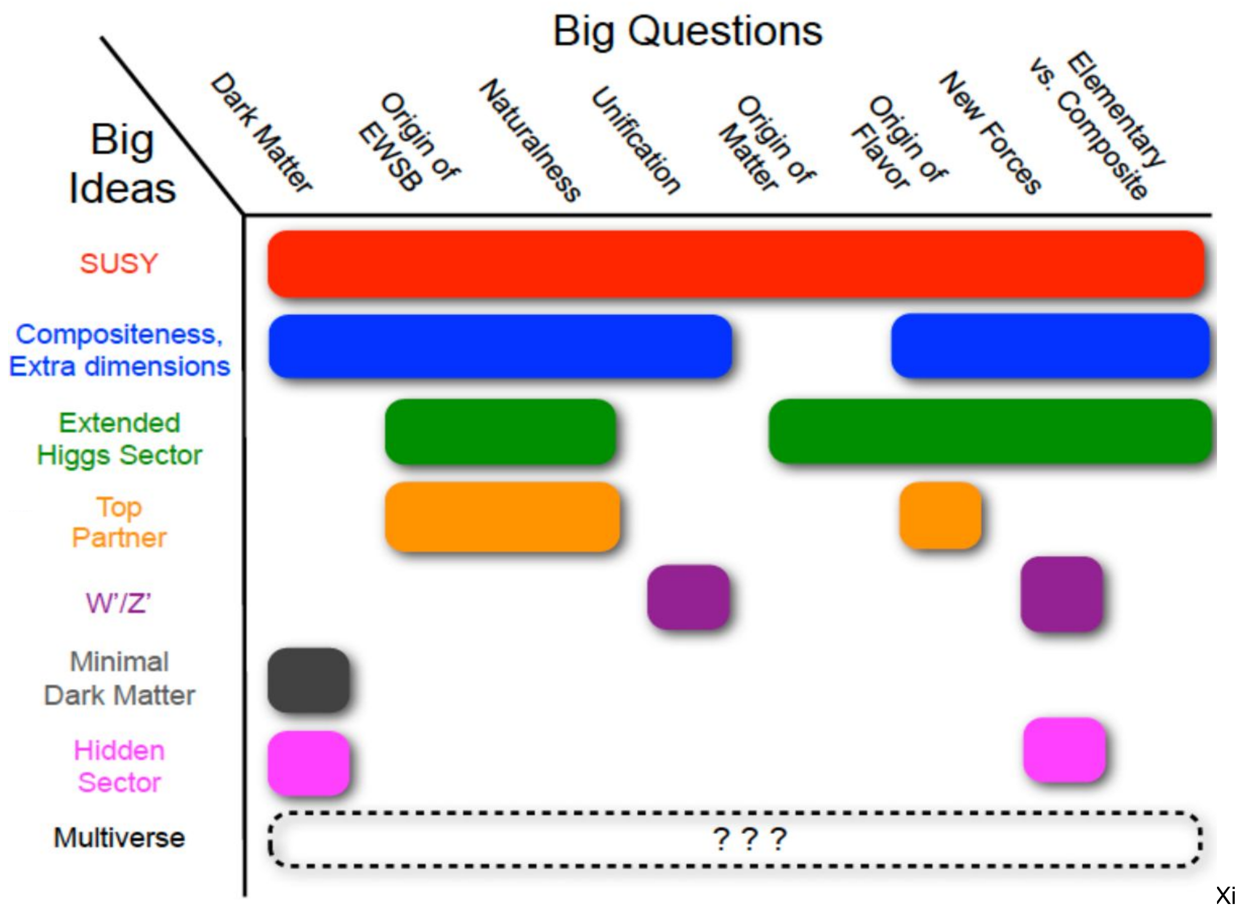
The Energy Frontier



Content: Snowmass EF Report
Alternative design by T. Holmes

The (current) Standard Model is not enough!

Plenty of extensions of the Standard Model have the potential of addressing these questions, including the ones we haven't thought of yet

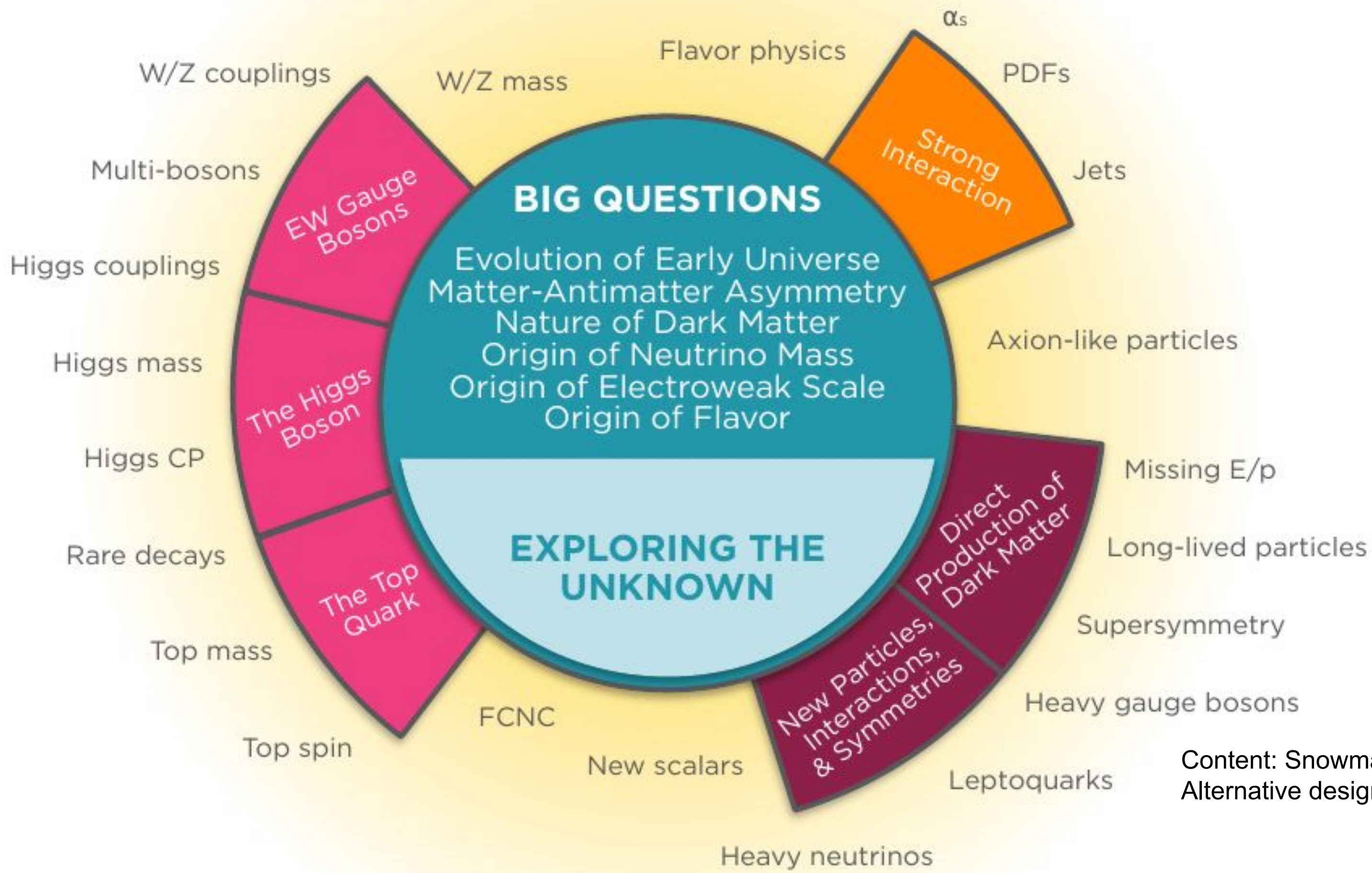


Xiv:1311.0299

Most pointing to higher energy scales where new particles will manifest

Probes and Signatures of new physics at colliders

The **breadth of the experimental program** is of paramount importance



Content: Snowmass EF Report
Alternative design by T. Holmes

Colliders offer the unique ability to probe, with a single experimental setup, all sectors of the SM and its extensions

The Energy Frontier Vision

Three main thrusts emerging from the Energy Frontier report:

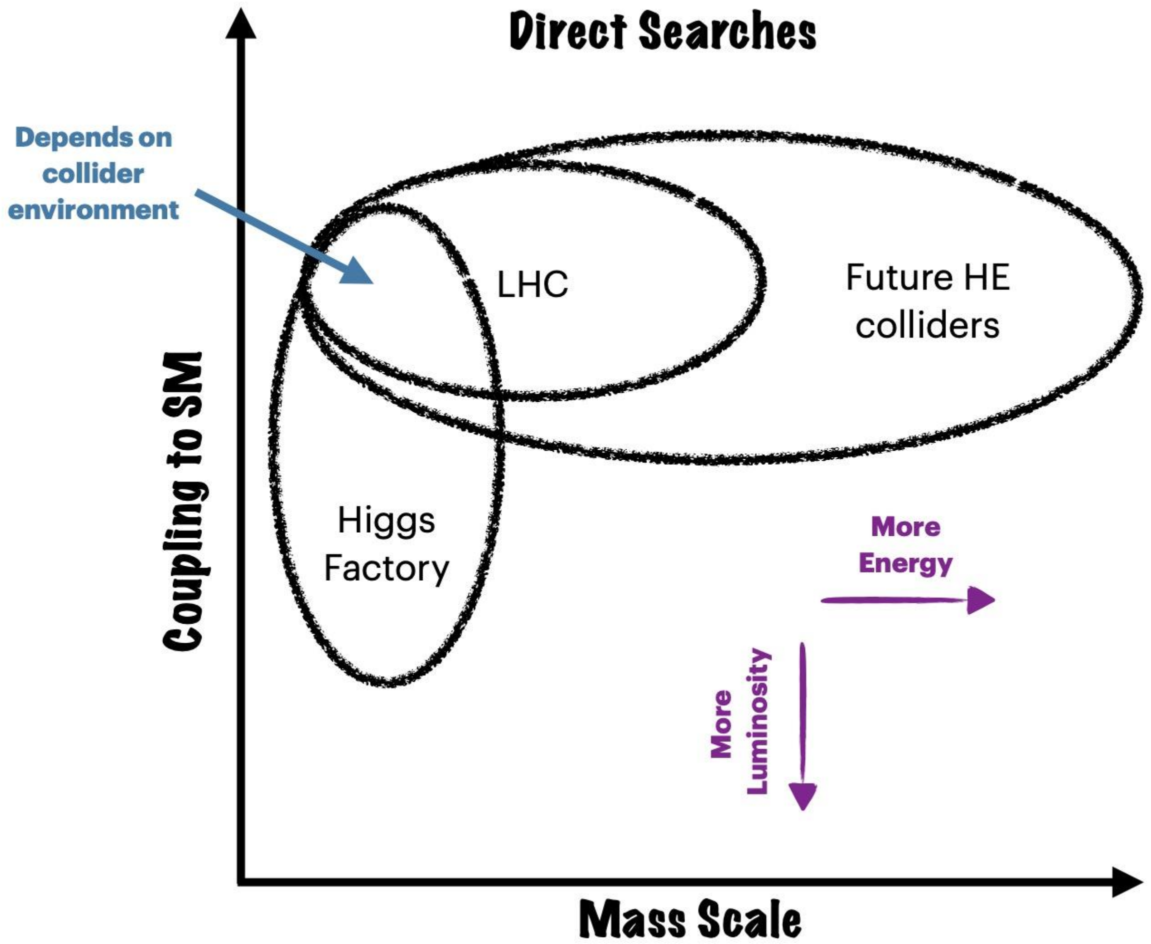
1) “The EF supports continued strong US participation in the success of the LHC, and the HL-LHC”

2) “The EF supports a fast start for construction of an e+ e− Higgs factory (linear or circular),”

3) “and a significant R&D program for multi-TeV colliders (hadron and muon).”

“The US EF community has also expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil while maintaining its international collaborative partnerships and obligations.”

The Energy Frontier Vision

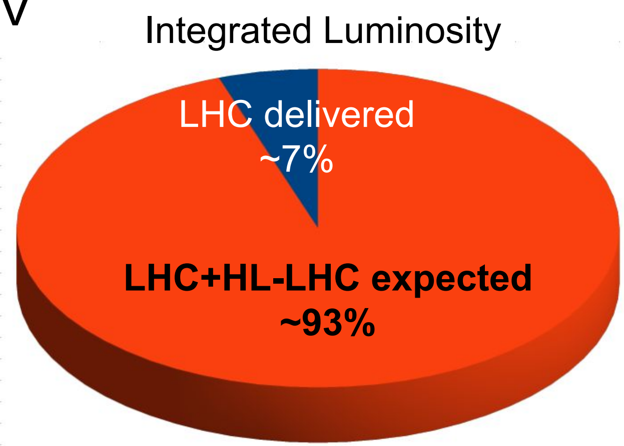


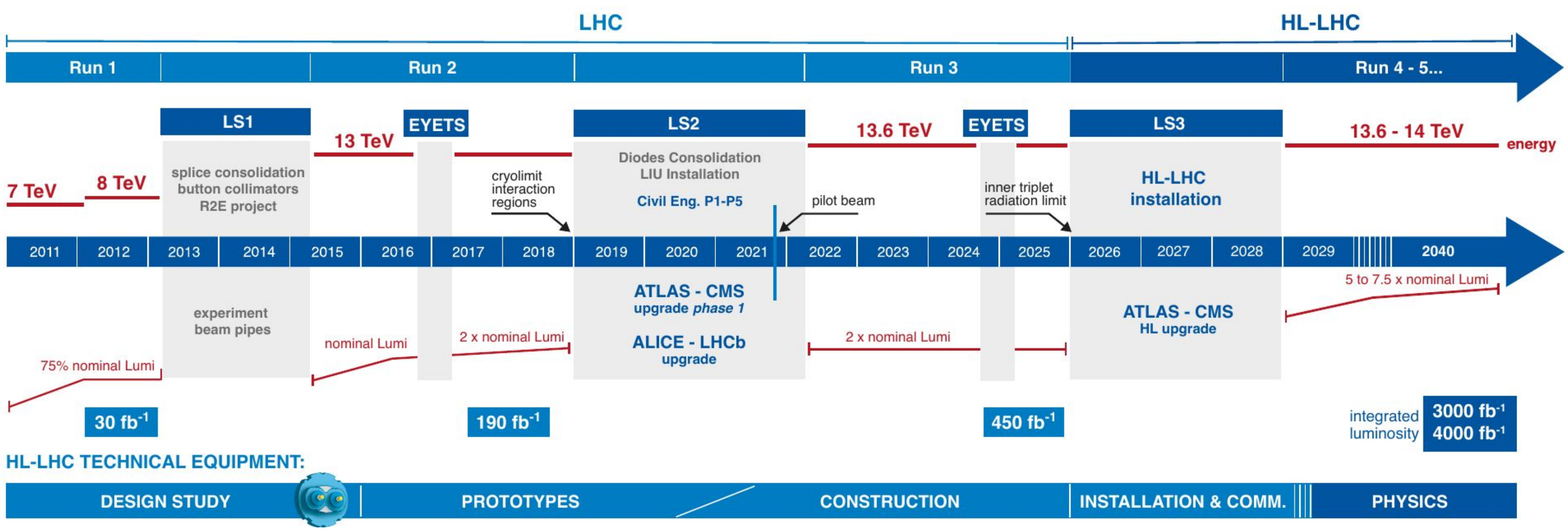
The Large Hadron Collider

Finished first year of Run 3 data-taking @ 13.6 TeV

Only a fraction of the p-p center-of-mass energy is transferred through the hard-scattering interaction => Large integrated luminosity allows access to higher energy scales

End of data-taking expected around early 2040s



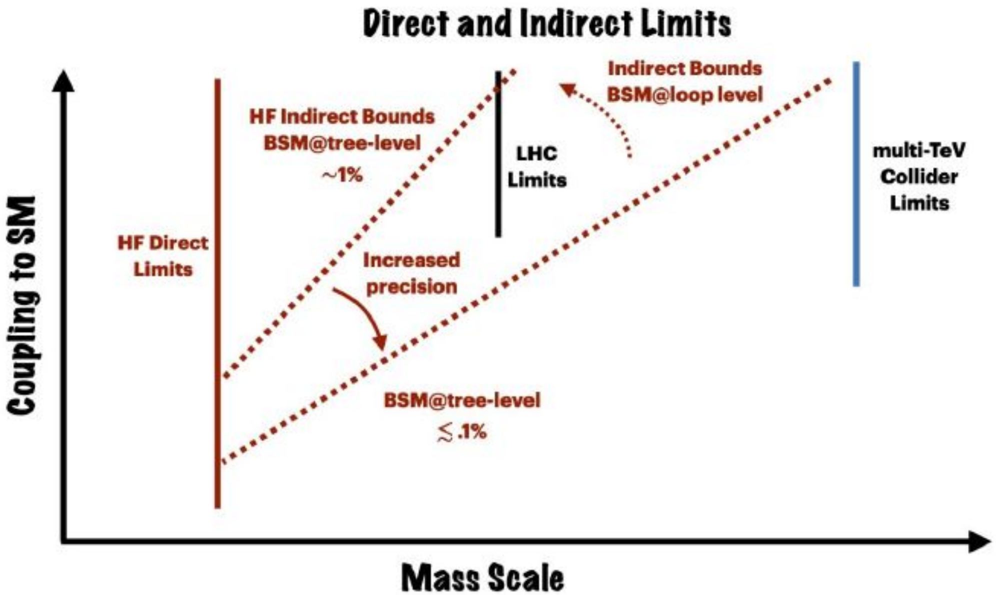


Higgs Factories

Primarily aim to study in great depth the Higgs sector of the Standard Model

Two key areas:

- Direct search of new “light” states
- Precision measurements



$$\delta\eta_{\rm SM} \sim g^2_{\rm BSM}\,\frac{v^2}{M^2}$$

$$\sim 5\% \cdot \left(\frac{1\ \rm TeV}{\Lambda}\right)^2$$

Need to reach precision on Higgs couplings < 1% to prove multi-TeV scales. Any indirect sign of new physics will need a higher energy collider to fully characterize what’s at play.

How to reach higher center-of-mass energy?

pp

e^+e^-

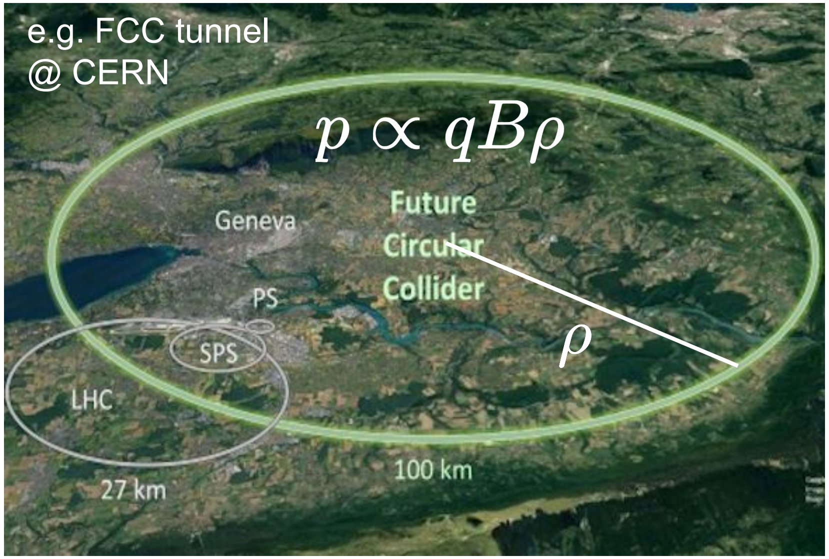
$\mu^+\mu^-$

multi-TeV lepton-hadron colliders also considered, not discussed here

How to reach higher center-of-mass energy?

pp | e^+e^- | $\mu^+\mu^-$

- Large collider ring, stronger magnets
  - re-use FCC-ee/SpeC tunnel
- Large power consumption (~ 2-3 x LHC)
- Need large statistics (luminosity) to sample highest energy scales

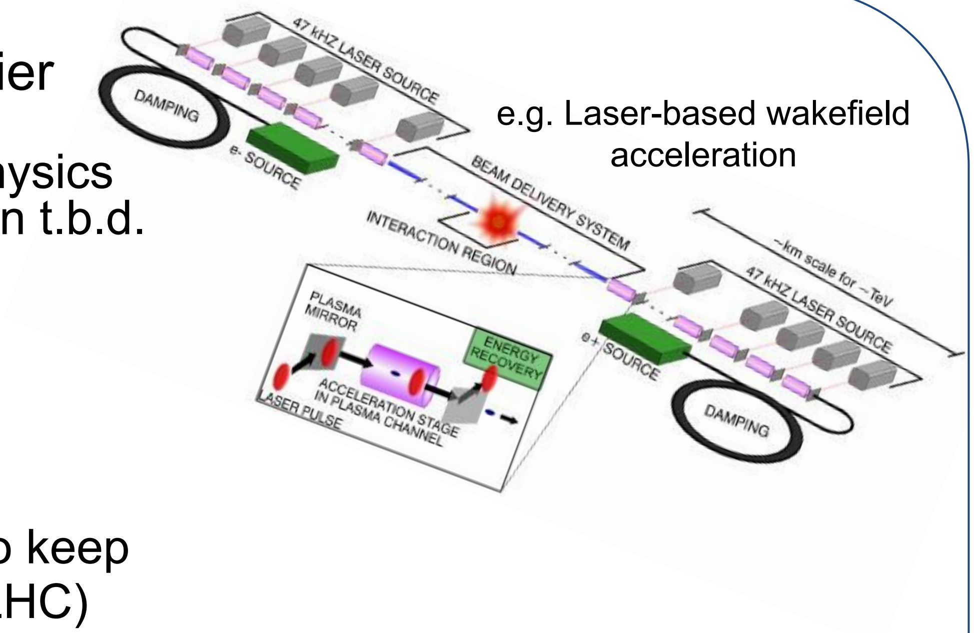


	FCC-hh	SppC
Center-of-mass [TeV]	100	75 (125-150)
Circumference [km]	91	100
Luminosity [/ab/yr] / IP	3	~1

How to reach higher center-of-mass energy?

pp | e^+e^- | $\mu^+\mu^-$

- Low physics backgrounds, easier event reconstruction
  - γγ technically preferred, but physics less compelling, e^+ acceleration t.b.d.
- Large power loss by radiation
  - Synchrotron radiation => linear accelerator
  - Direction of motion => huge power consumption to keep energy monochromatic (~5 x LHC)



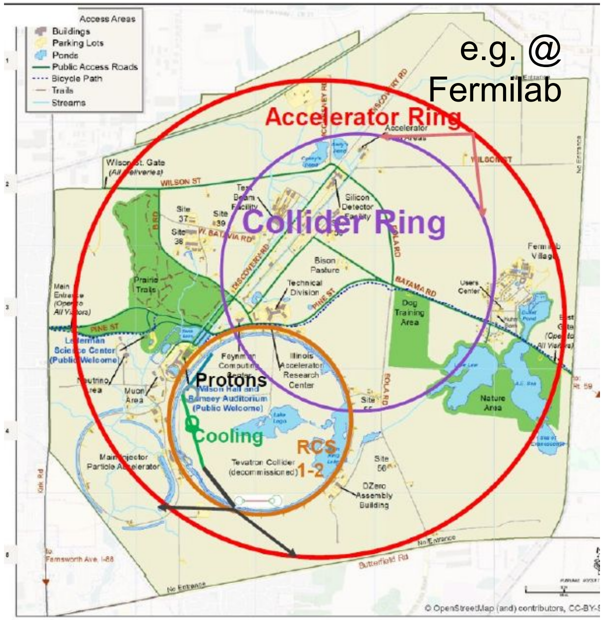
e.g. Laser-based wakefield acceleration

	ILC/CLIC/CCC	Wakefield Accelerators
Center-of-mass [TeV]	3	15
Length [km]	27-59	1.3 - 18
Luminosity [/ab/yr]	0.6	~1.3

How to reach higher center-of-mass energy?

pp | e^+e^- | $\mu^+\mu^-$

- Low physics backgrounds
- Large muon mass implies low P_{loss}
  - Compact ring for very high energies
- Most energy efficient (P ~ 1.5 x LHC)
- Lowest estimated cost
- In principle scalable to even higher E
- Small muon/beam lifetime: $\tau_0^{\mu} \sim 2\ \mu s$



	MuC-3	MuC-10
Center-of-mass [TeV]	3	10 (14)
Circumference [km]	4.5	10
Luminosity [/ab/yr]	0.2	2

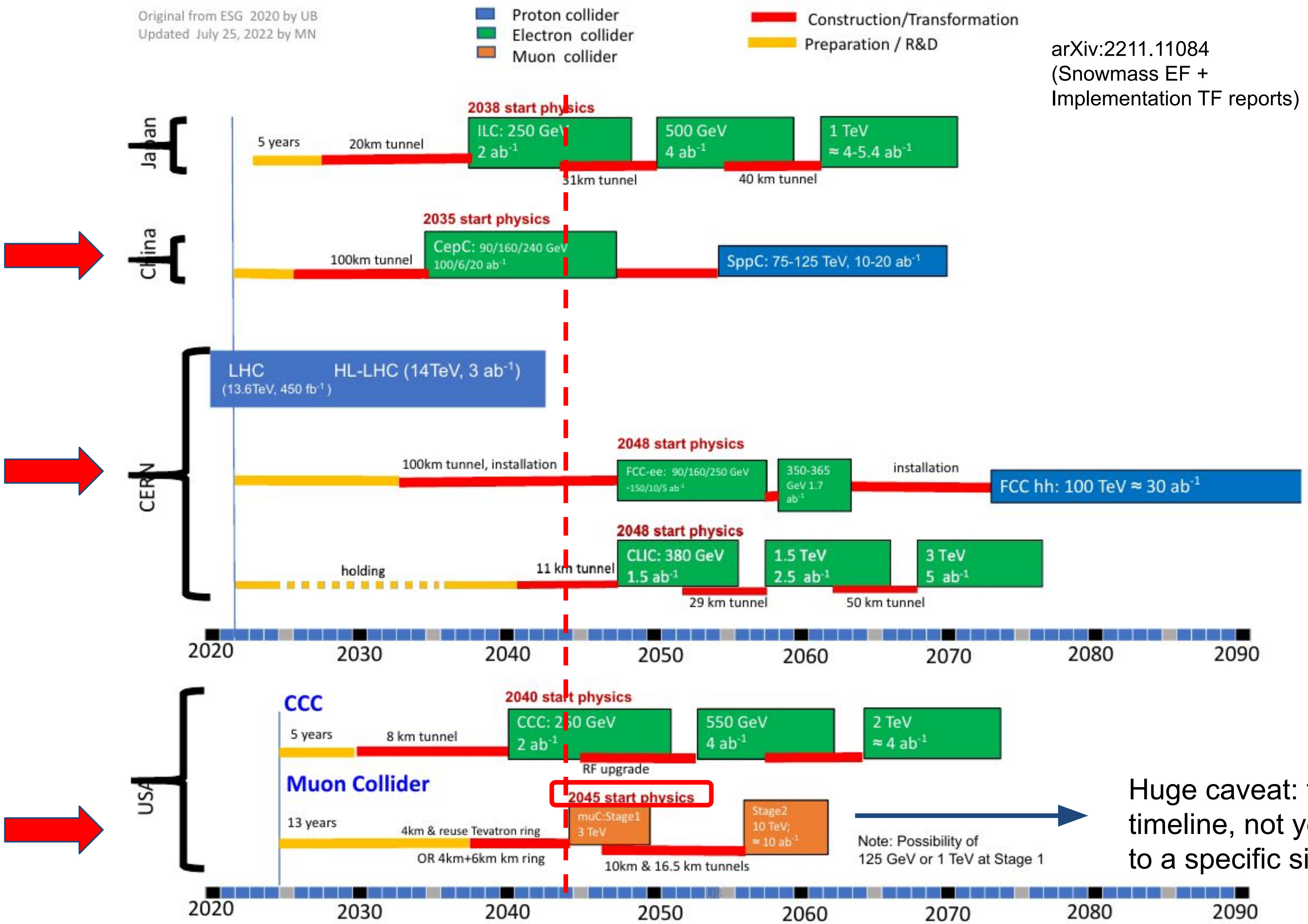
Snowmass Implementation Taskforce

Snowmass collider options evaluated by a panel of experts to ensure homogeneous metrics.

ITF Report – T.Roser, et al, arXiv:2208.06030

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	*O*(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

About Timelines



arXiv:2211.11084 (Snowmass EF + Implementation TF reports)

Huge caveat: technical timeline, not yet attached to a specific site!

The Muon Collider Community

The Muon Collider concept has been studied for decades

- From initial proposals back in the '80s
- To more recent Muon Accelerator Program (MAP) initiated at Fermilab [2011-2014]. Lots of progress still very relevant nowadays.

Nowadays…

Following the most recent European Strategy Report

International
MUON Collider
Collaboration

International Collaboration making great progress in all areas.

Large community interest during Snowmass

- ~40 EF contributed papers on muon colliders out of ~150 (only second to HL-LHC!)
- > 60 early-career authors in muon collider forum report

Great interplay with IMCC, including

- Five comprehensive snowmass whitepaper, on accelerator, detectors, physics reach

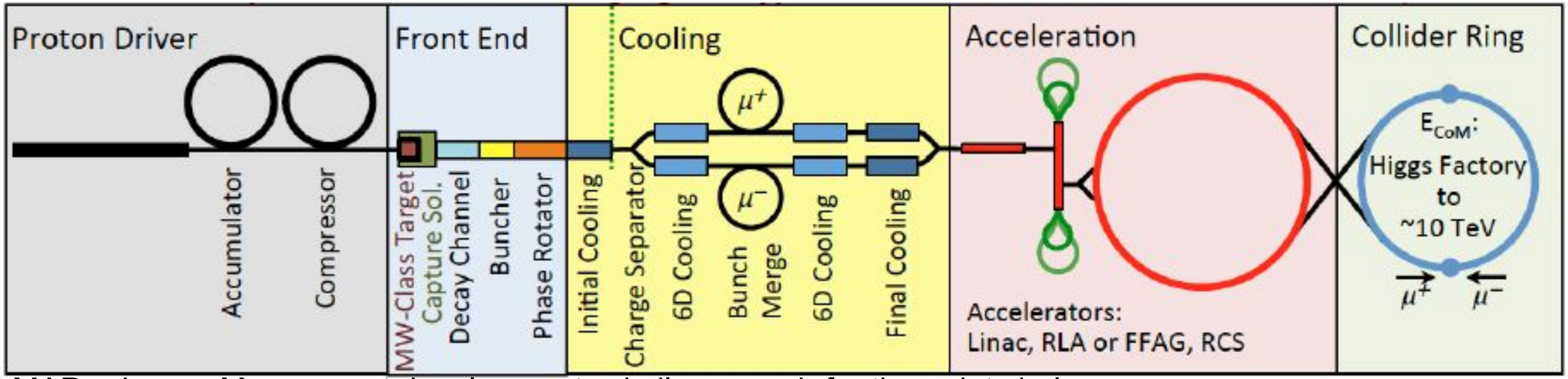
Outline

A look into the future: motivation for a muon collider

Experimental challenges and opportunities

Discovery (and precision measurements) potential

Muon Collider: accelerator design

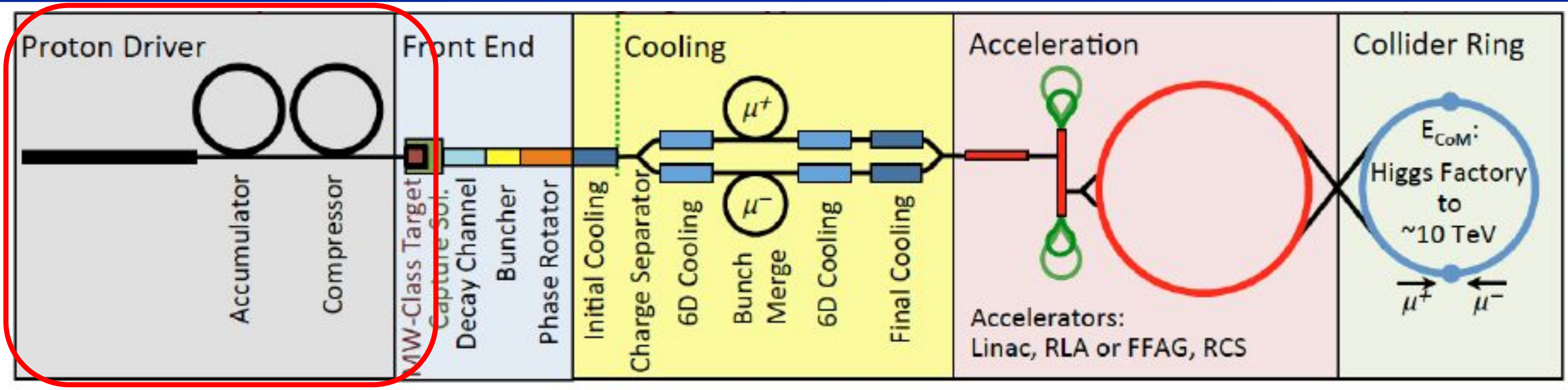


MAP schema. More recent developments similar enough for the points below.
Alternative acceleration concept (positron-based) being also explored

Basic principle:

$$p + X \to \pi^{\pm} + Y \to \mu^{\pm} + Z$$

Muon Collider: accelerator design



Basic principle:

$$p + X \rightarrow \pi^{\pm} + Y \rightarrow \mu^{\pm} + Z$$

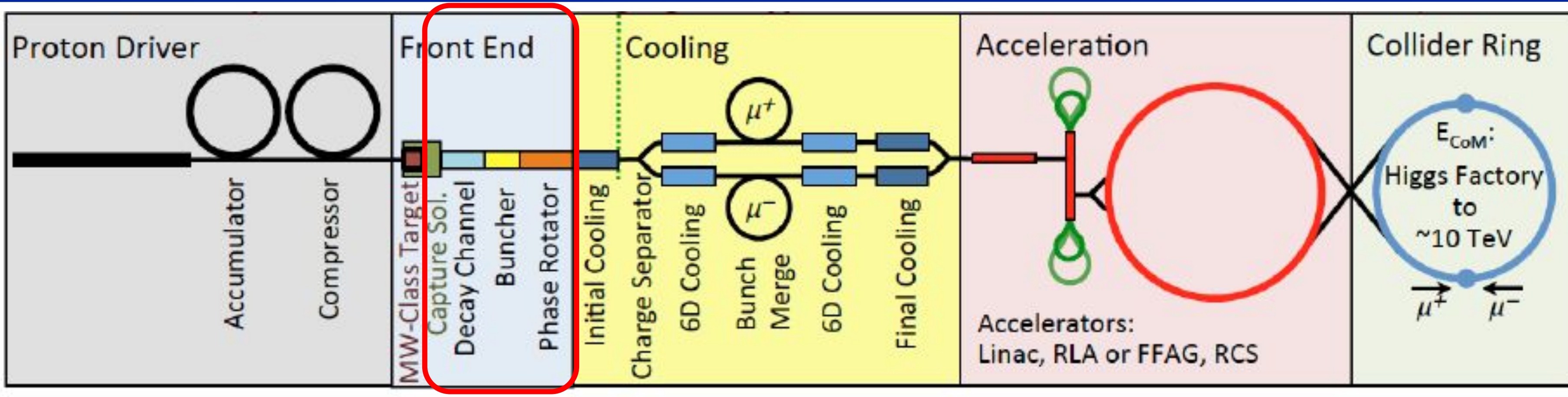
Proton source:

- High-Intensity (multi-MW) producing multi-GeV protons at 5-15 Hz
- Within capabilities of current technology and, if planned, potential synergies with other programs

High-Z target

- Need to sustain the intense beam
- Novel material likely required to meet its *target*

Muon Collider: accelerator design



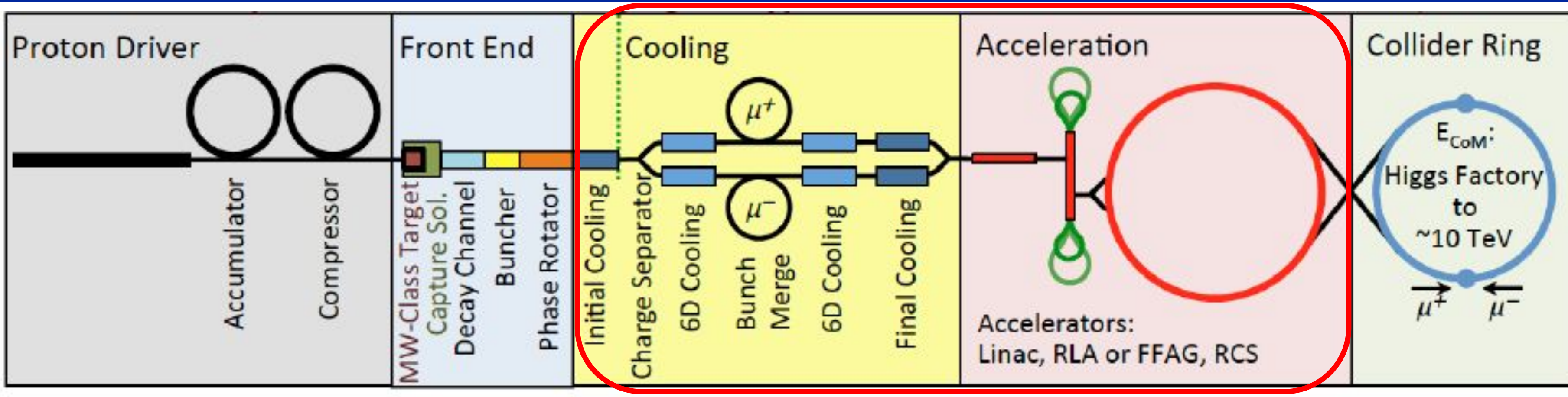
Basic principle:

$$p + X \to \pi^{\pm} + Y \to \mu^{\pm} + Z$$

Pion decays give a muon beam

- Large phase space
- Need to act fast to reduce its energy spread and transverse size before (too many) muons decay

Muon Collider: accelerator design



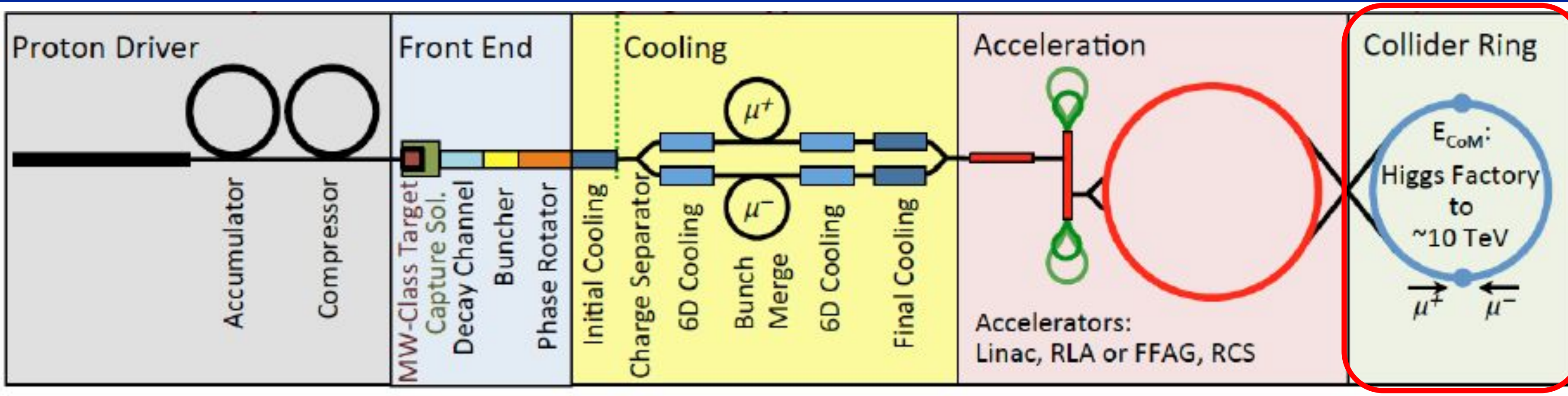
Basic principle:

$$p + X \to \pi^{\pm} + Y \to \mu^{\pm} + Z$$

Rapid focusing and phase-space reduction, before (too many) muons decay

- R&D needed for high magnetic field and high-gradient RF cavities
- Initial demonstration of cooling technique by MICE collaboration
- New demonstrator being designed within the IMCC effort

Muon Collider: accelerator design



Basic principle:

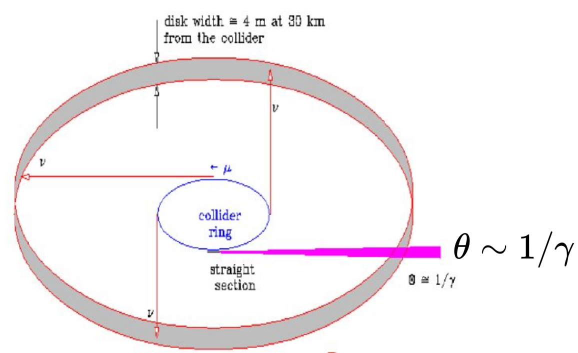
$$p + X \to \pi^{\pm} + Y \to \mu^{\pm} + Z \qquad \mu \to e + \nu_e + \nu_\mu$$

Collider Ring:

- Quite advanced conceptual design for Higgs factory, 1.5, 3, 6 TeV
- Aim to design up to ~ 10 TeV

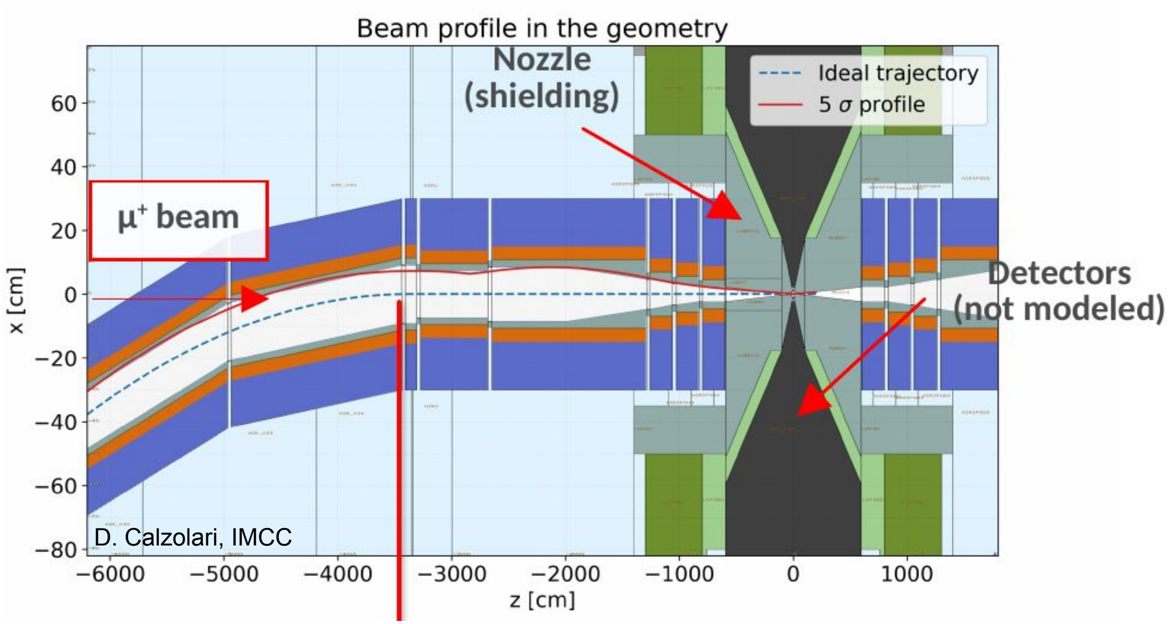
Radiation from collimated neutrinos

- Interacting near exit point
- Mitigation techniques developed and under study



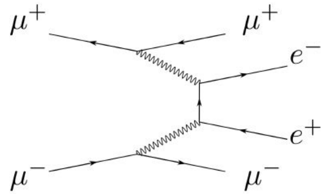
Beam-Induced Background (BIB)

Detailed accelerator design studies are needed to understand the environment around the interaction point

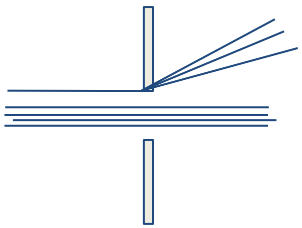


Main sources of BIB:

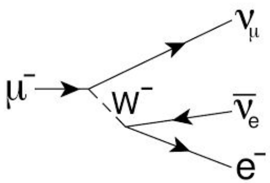
- e+e- pair production



- Beam halo loss on collimators



- Muon beam decays



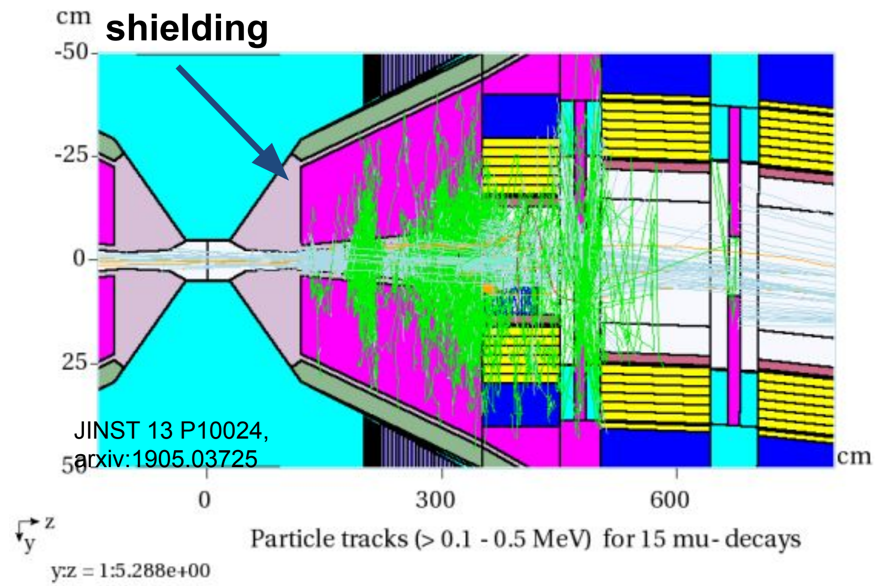
Beam-Induced Background (BIB)

Large particle multiplicity entering the detector after showering on dedicated shielding

Studied at different c.o.m. energies:

- longer lab-frame muon lifetime
- more energetic decay products

The two effects roughly balance



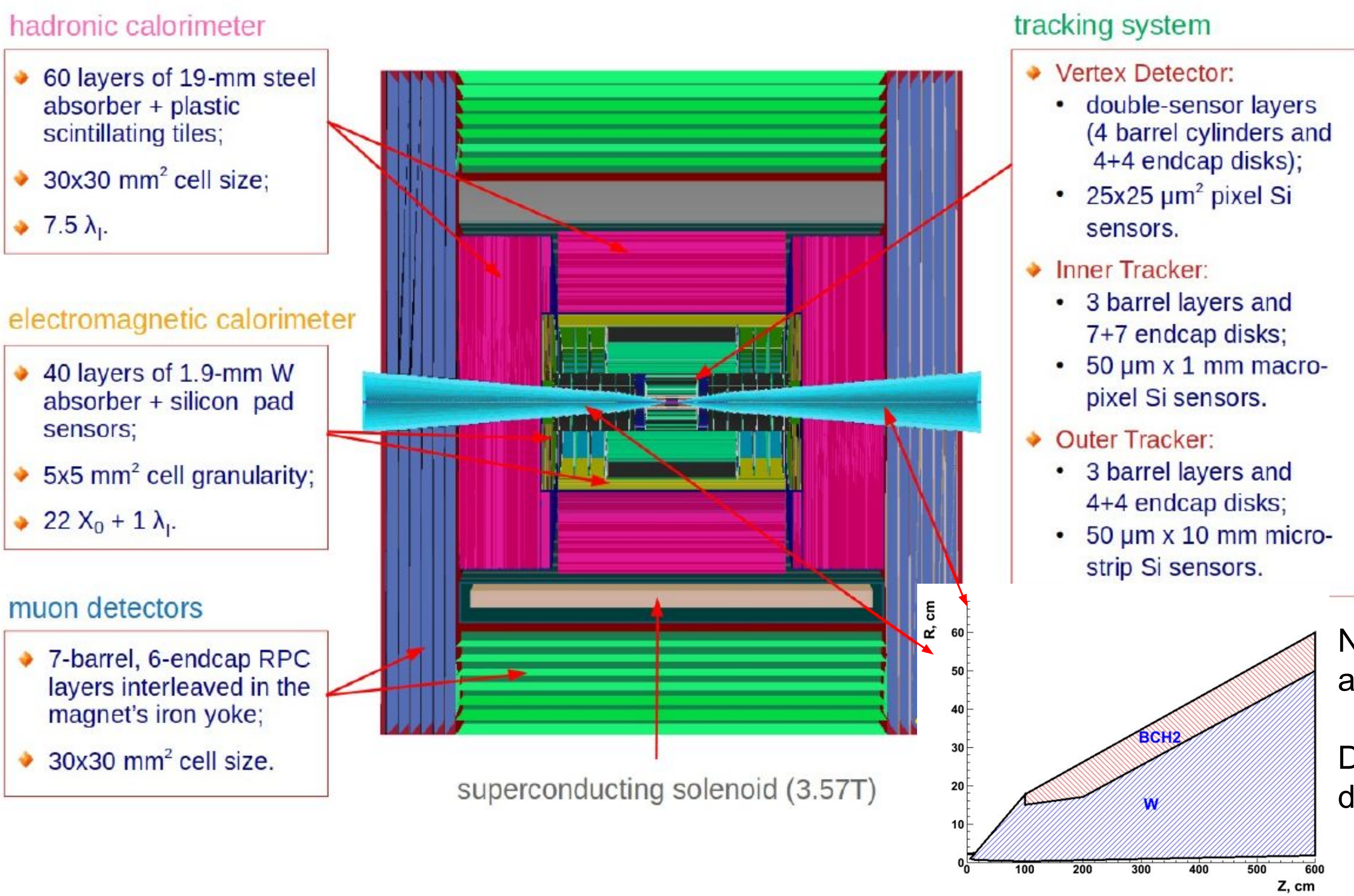
	MARS15	MARS15	FLUKA	FLUKA	FLUKA
beam energy [GeV]	62.5	750	750	1500 (MDI Not Optimized)	5000 (MDI Not Optimized)
μ decay length [m]	3.9×10^5	46.7×10^5	46.7×10^5	93.5×10^5	311.7×10^5
μ decays/m per beam (for 2×10^{12} μ/bunch)	51.3×10^5	4.3×10^5	4.3×10^5	2.1×10^5	0.64×10^5
photons/BX ($E_\gamma > 0.1$ MeV)	170×10^6	86×10^6	51×10^6	70×10^6	116×10^6
neutrons/BX ($E_n > 1$ meV)	65×10^6	76×10^6	110×10^6	91×10^6	89×10^6
$e^\pm$/BX ($E_e > 0.1$ MeV)	1.3×10^6	0.75×10^6	0.86×10^6	1.1×10^6	0.95×10^6
charged hadrons/BX ($E_h > 0.1$ MeV)	0.011×10^6	0.032×10^6	0.017×10^6	0.020×10^6	0.034×10^6
muons/BX ($E_h > 0.1$ MeV)	0.0012×10^6	0.0015×10^6	0.0031×10^6	0.0033×10^6	0.0030×10^6

A First Muon Collider Detector Design

Heavily based on CLIC detector, with modification for BIB suppression

So far optimized for a lower-energy option: √s = 1.5 TeV

- Re-dimension and optimization in progress for √s = 10 TeV



Nozzle design limits acceptance to θ=10°

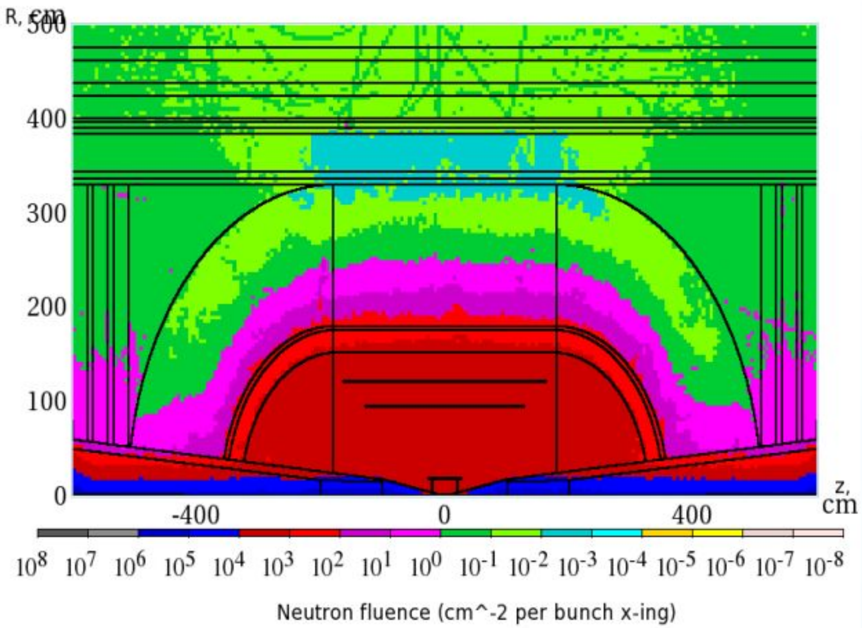
Different √s might allow different designs

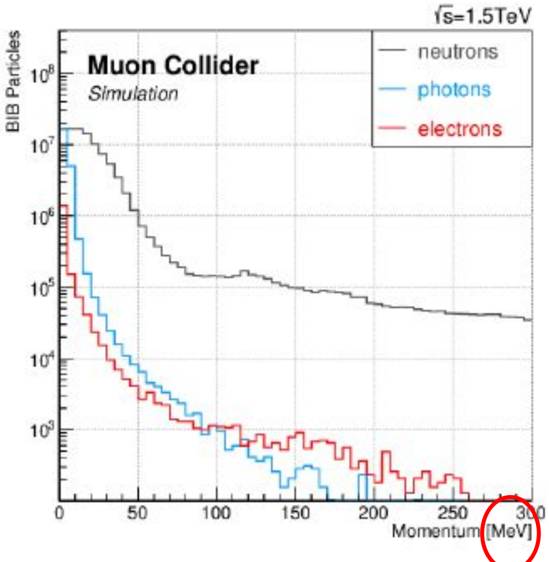
BIB in the detector

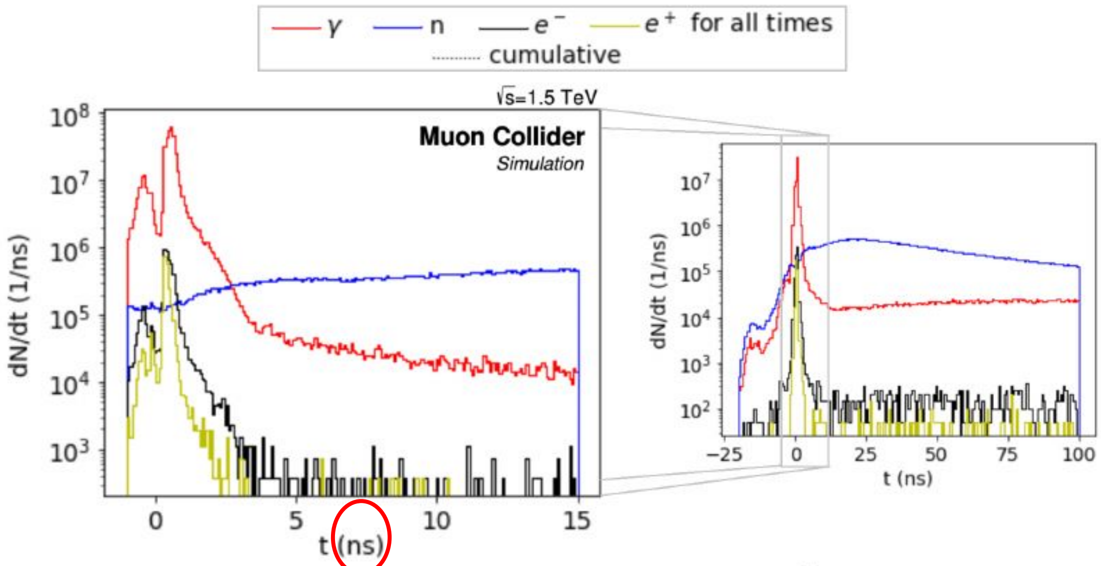
Radiation hardness of detectors not that different from HL-LHC

	Maximum Dose (Mrad)	
	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1
HL-LHC	100	0.1

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

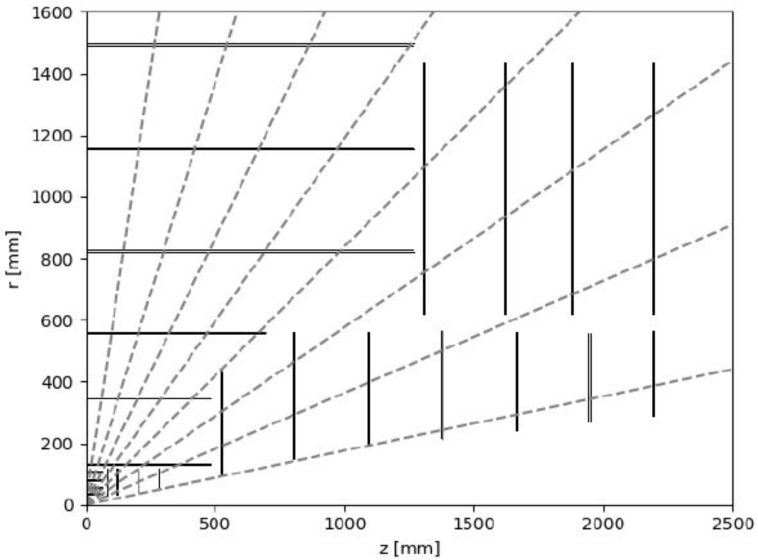


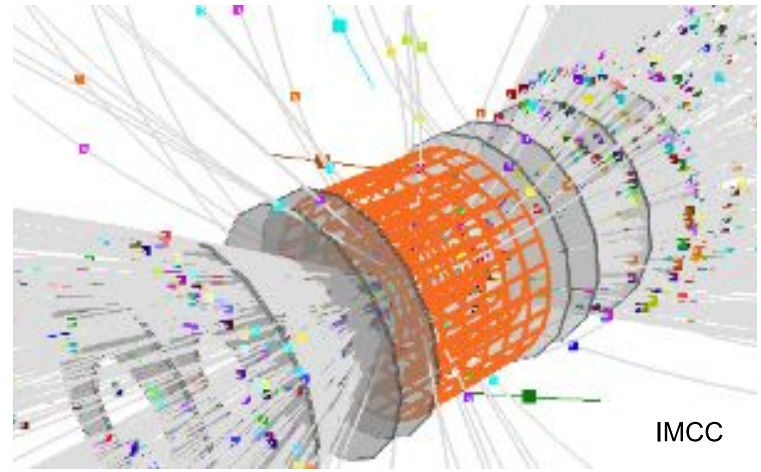




BIB in the Tracking system

Adds complexity in the event readout and reconstruction, e.g. in the inner tracker:





IMCC

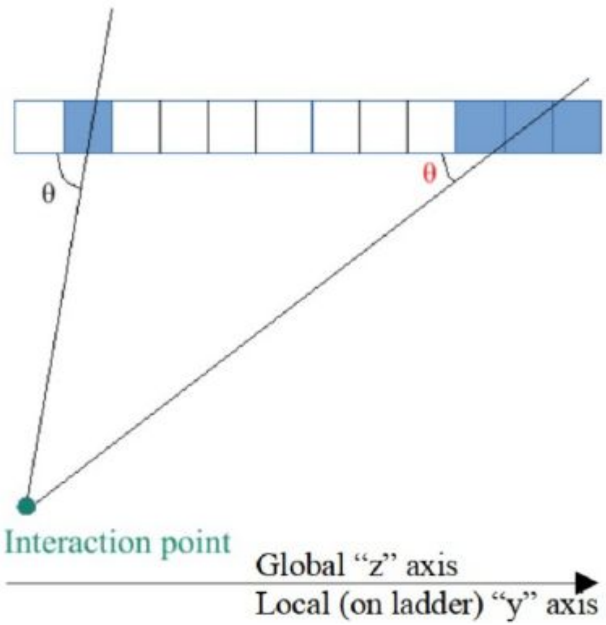
Detector	HL-LHC Hit Density [mm^{-2}]	Muon Coll Hit Density [mm^{-2}]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.22	0.51
Strip Layer 1	0.003	0.03

Hit density for roughly equivalent radius, after timing selections
Using as ref. the ATLAS Inner Tracker for HL-LHC (ref, ref)

Reducing the impact of BIB in the Tracker

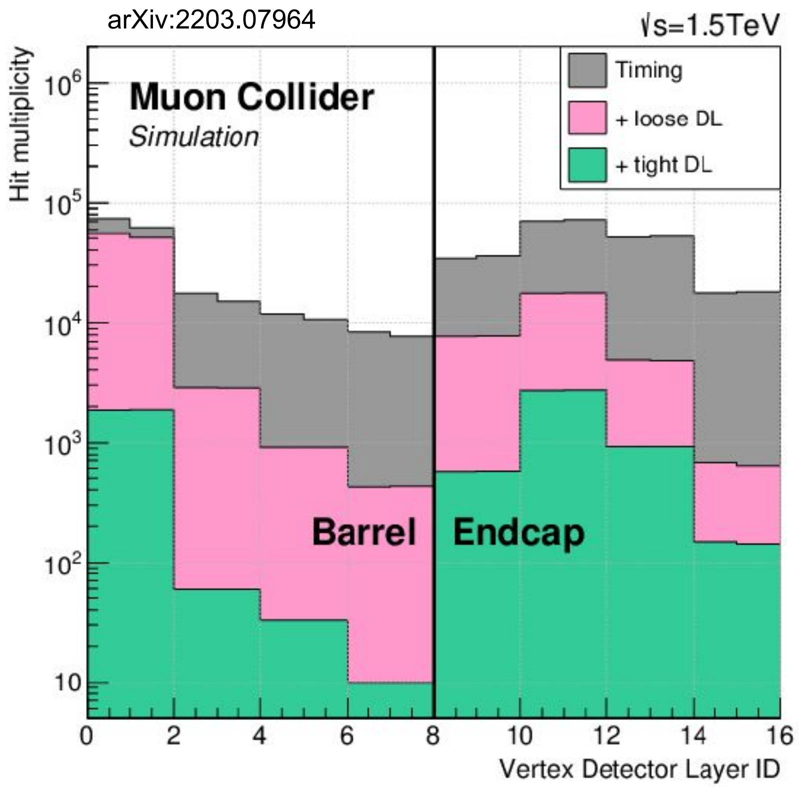
Key handles for discrimination:

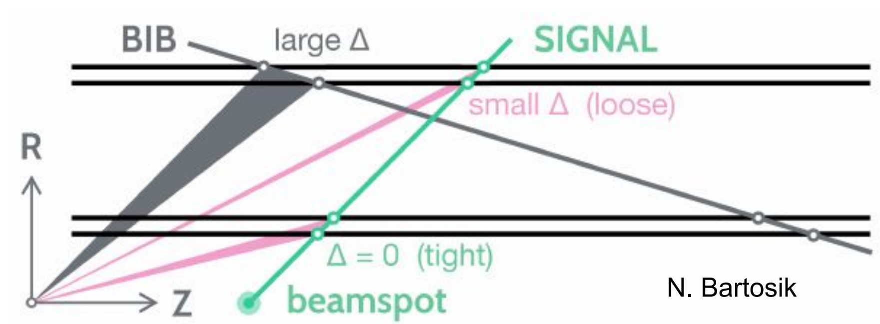
- Timing
- Directional information
  (not from interaction point)
- Energy deposition / pulse-shape
  analysis (esp. against soft photons)



Cut efficiency	Loose	Tight
Single-μ	99.3 %	99.1 %
Single-μ and BIB	37.4 %	30.7 %

arXiv:2203.07964

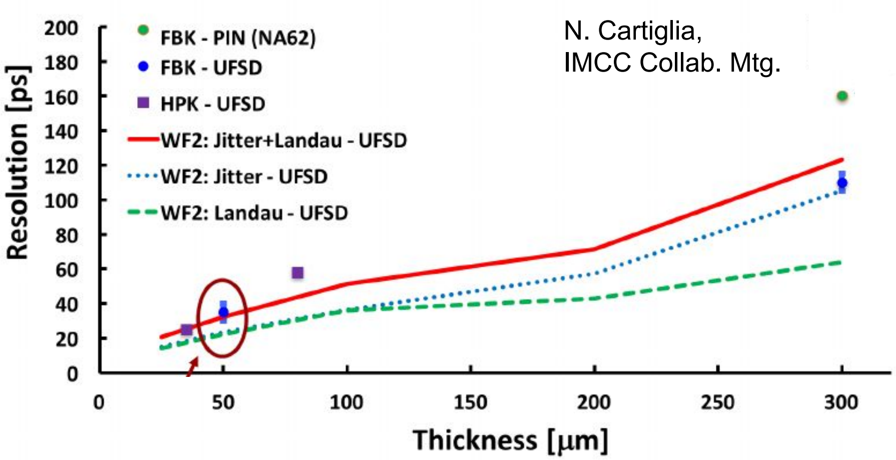




N. Bartosik

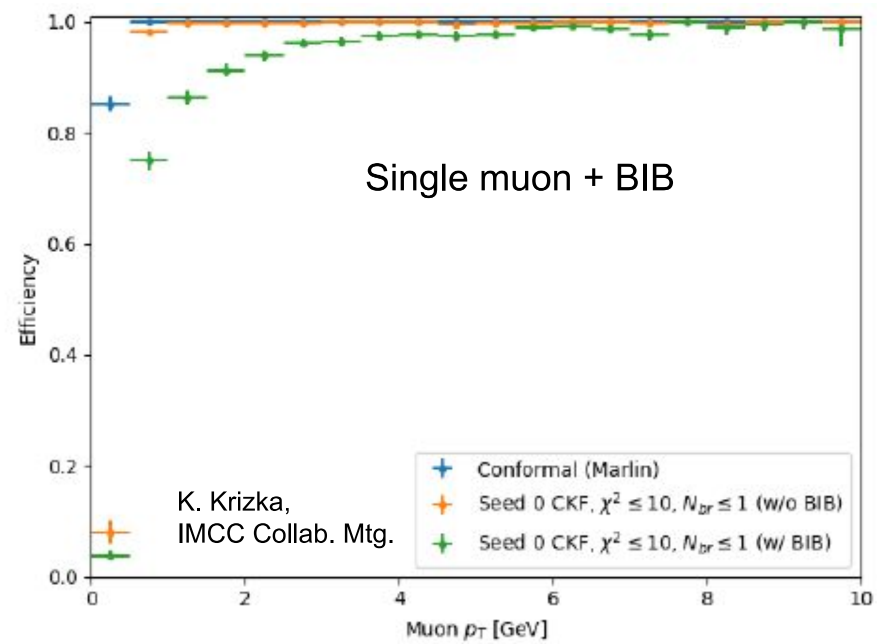
Tracking detectors: hardware & software

Need for precise 4D tracking
- Hybrid pixels, CMOS-based, LGAD-based, …
- synergy with HL-LHC and other projects
- Unlock more on-chip logic with smaller feature size



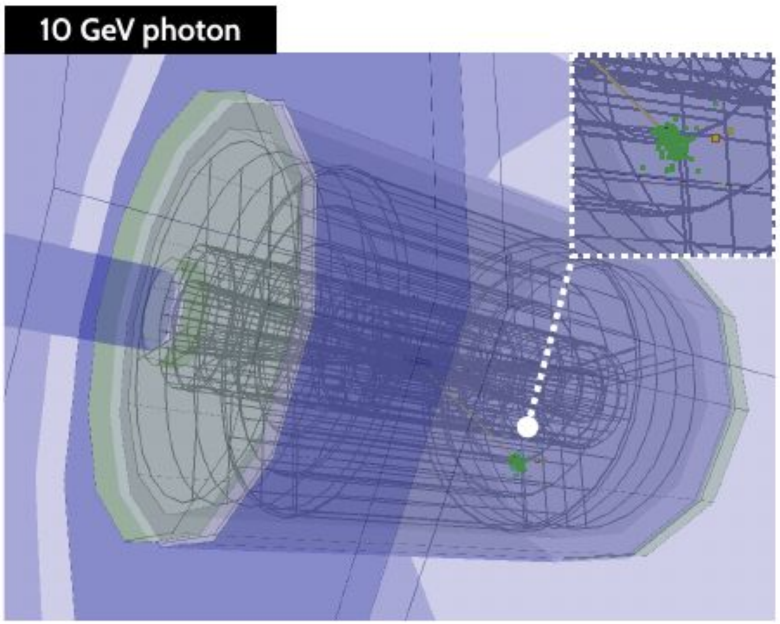
Particle identification detectors also merit more attention

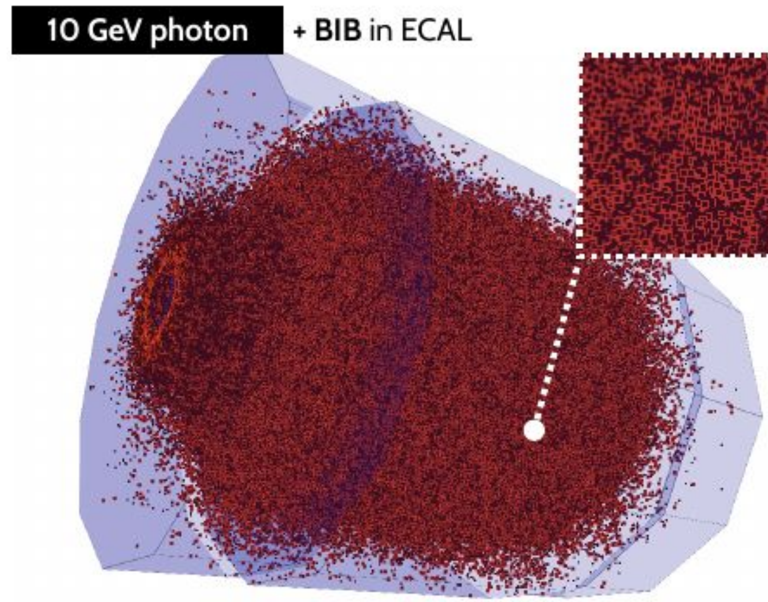
Smart algorithms for event reconstruction
- Moved from ILC-style to LHC-style algorithms
- Modern and well-maintained code libraries (ACTS)
- Allowed full event reconstruction in ~4 min/event (was: days/∞)
- BIB/fake tracks from 100k / event to < 1 / event



Calorimeters

Diffuse Beam-Induced Background energy deposits in both electromagnetic and hadronic calorimeters.





N. Bartosik, IMCC Annual Meeting

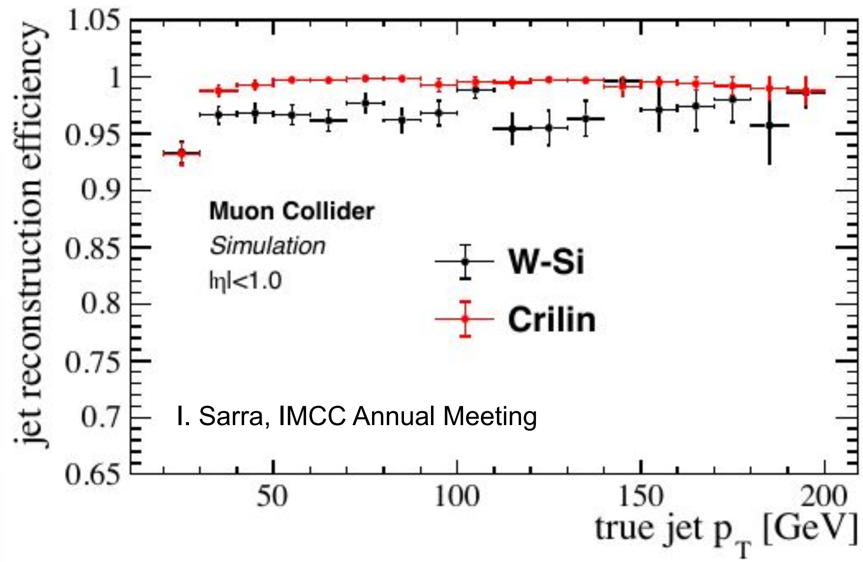
Somewhat similar in nature to what we're learning to deal with for HL-LHC.

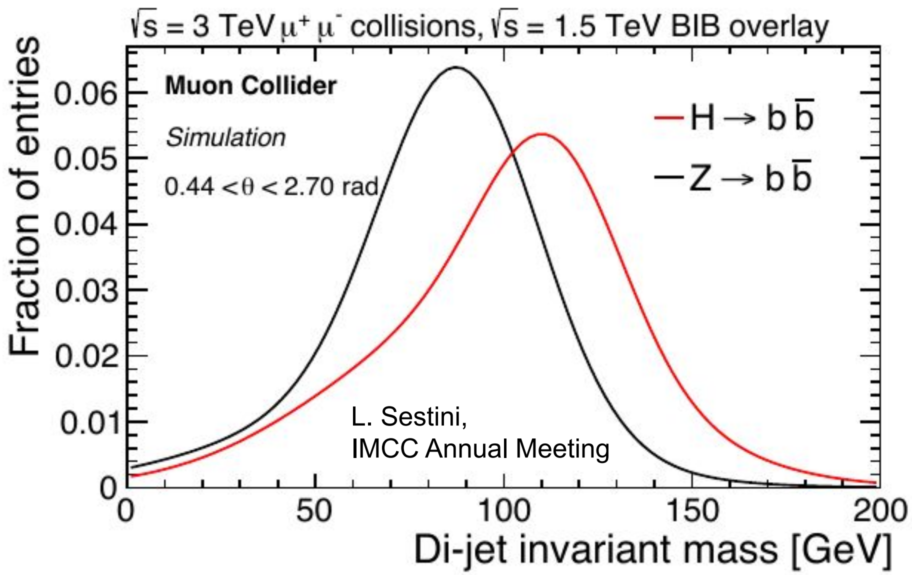
Calorimeters

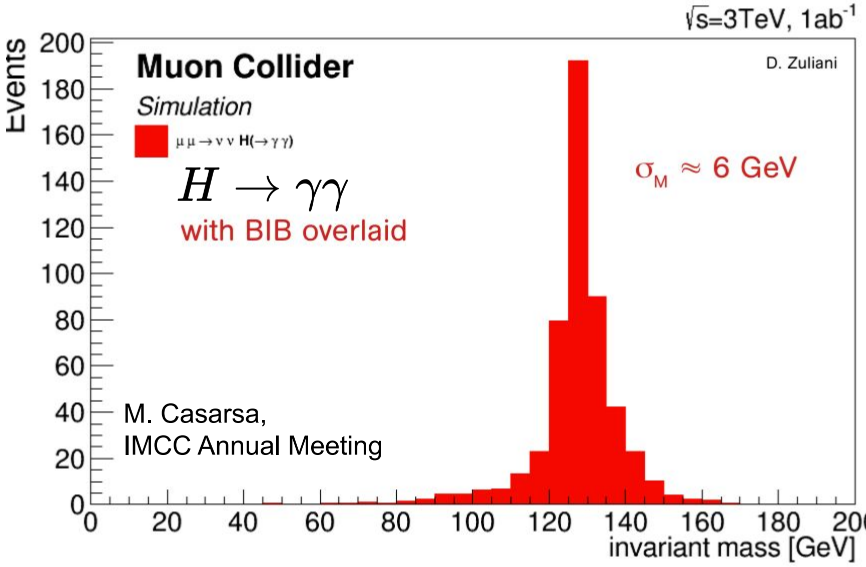
Timing and segmentation crucial for efficient background subtraction.

Alternative designs being explored

- Short readout window
- Good radiation hardness
- Great granularity (1x1x3 cm^3)
- E.g. Crilin (INFN)







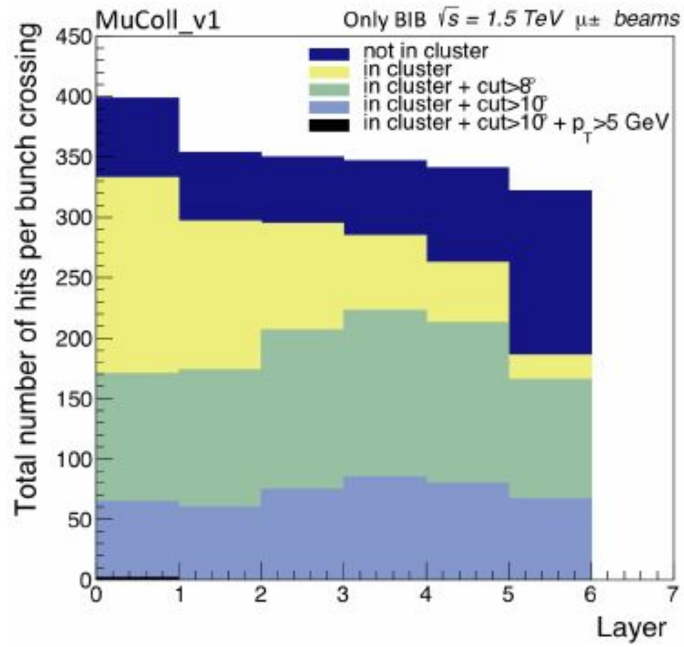
Muon and Other systems

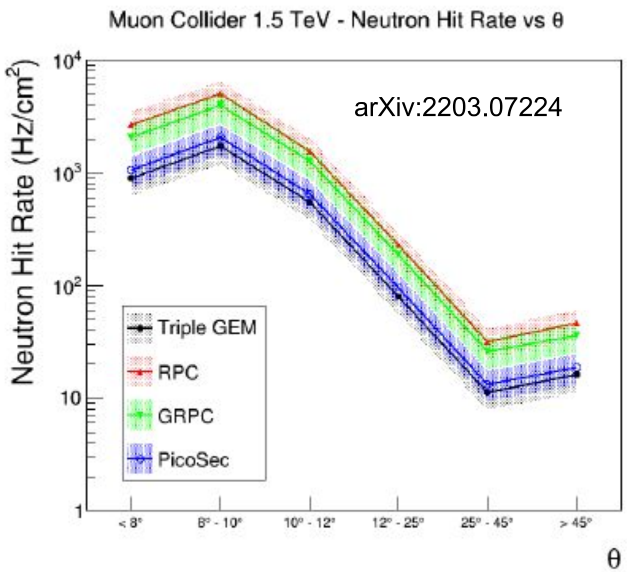
Much reduced BIB flux if readout window kept reasonable small

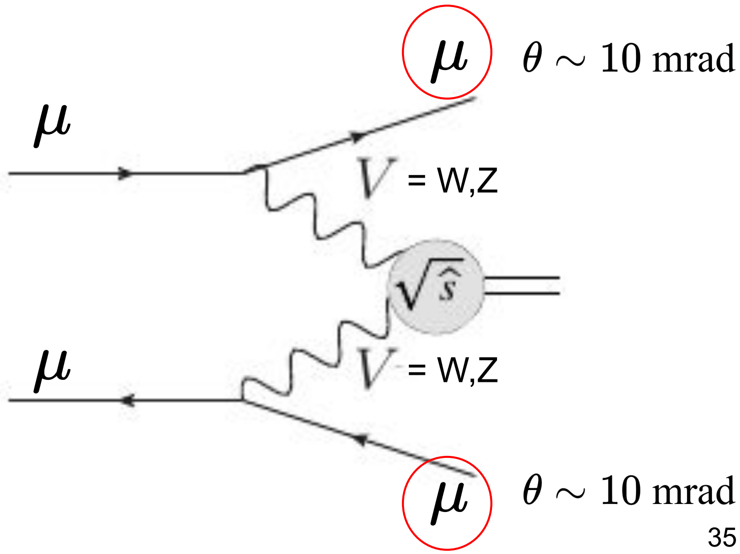
Interesting physics case if we can tag very forward muons

(Almost) triggerless readout seems reachable (~100kHz event rate)

arXiv:2203.07964





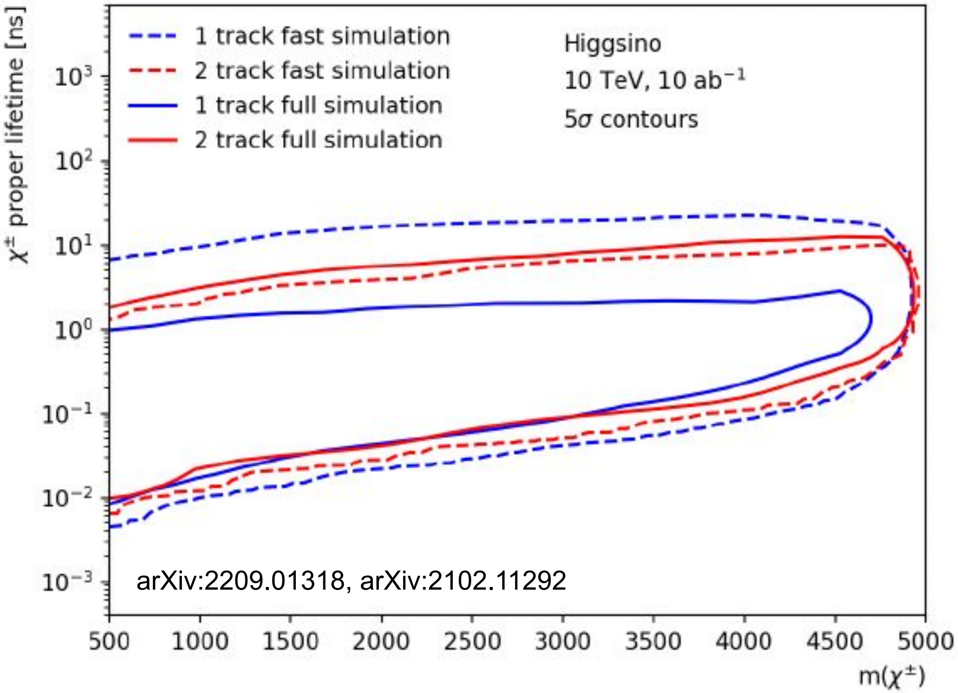


Fast Simulation

A fast parametric simulation allows a much larger set of physics objectives to be explored

- DELPHES implementation available
- Work to provide new cards to “bracket” performance ongoing

Important to validate results using detailed simulations!



Cross-section measurement uncertainty

Full sim		Fast sim	
H->WW	2.9%	H->WW	1.7%
H->ZZ	17%	H->ZZ	11%
H->bb	0.75%	H->bb	0.76%
H->μμ	38%	H->μμ	40%
H->γγ	8.9%	H->γγ	6.1%

L. Giambastiani, IMCC Annual Meeting
See also arXiv:2203.09425

[Very preliminary. Lots of work in progress]

Outline

A look into the future: motivation for a muon collider

Experimental challenges and opportunities

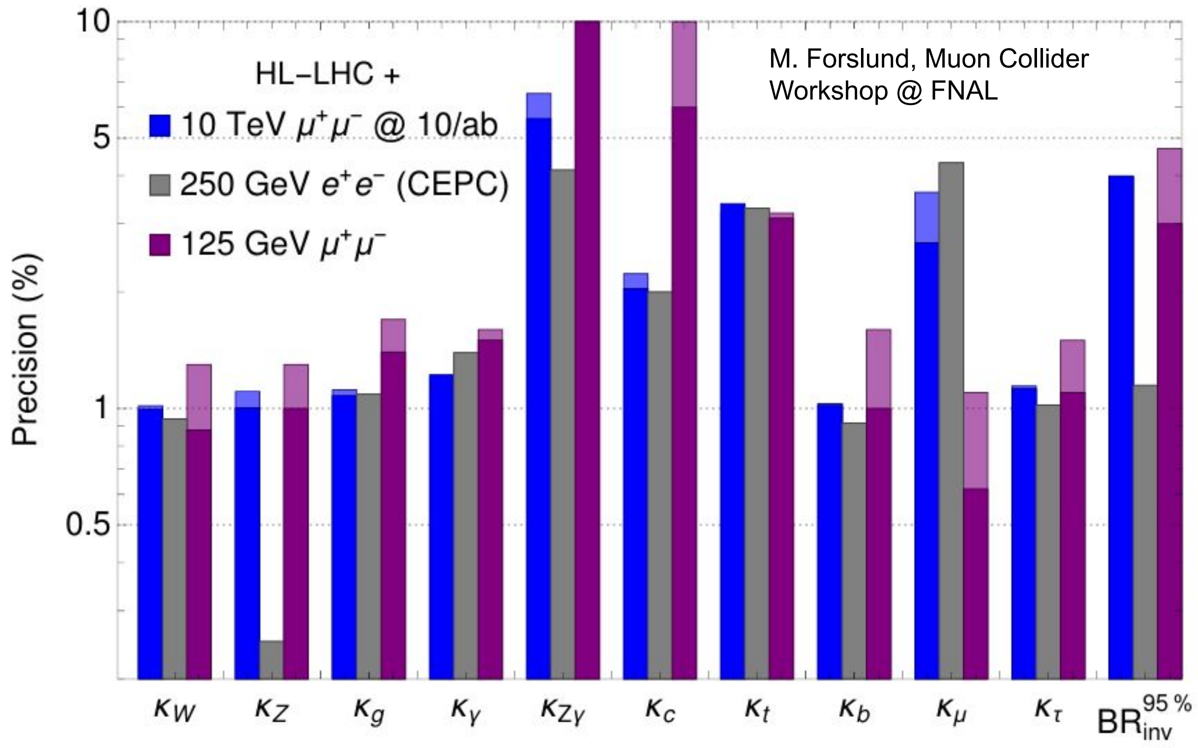
Discovery (and precision measurements) potential

High Energy <-> High Luminosity <-> High Precision

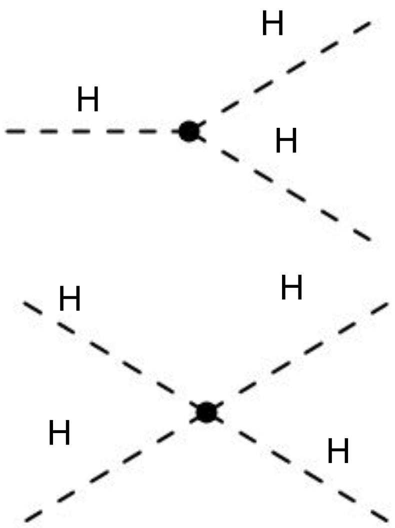
HE machines, with appropriate detector, can be precision measurement devices!

	H factories	l^+l^- @ 3 TeV	l^+l^- @ 10 TeV	pp @ 100 TeV
# Higgs bosons	~10^6	~$5 \cdot 10^6$	10^7	~10^{10}

Obviously an over-simplification, control of systematics and physics background play very important roles!



The nature of the Higgs: the Higgs potential



collider	Indirect-h_{SM}	$h_{SM}h_{SM}$	combined
HL-LHC [27]	100-200%	50%	50%
ILC_{250}/C^3-250 [20, 17]	49%	–	49%
ILC_{500}/C^3-550 [20, 17]	38%	20%	20%
ILC_{100}/C^3-1000 [20, 17]	36%	10%	10%
$CLIC_{380}$ [22]	50%	–	50%
$CLIC_{1500}$ [22]	49%	36%	29%
$CLIC_{3000}$ [22]	49%	9%	9%
FCC-ee [23]	33%	–	33%
FCC-ee (4 IPs) [23]	24%	–	24%
FCC-hh [28]	-	2.9-5.5%	2.9-5.5%
μ(3 TeV) [26]	-	15-30%	15-30%
μ(10 TeV) [26]	-	4%	4%

Extremely rare process:

only multi-TeV colliders can probe it accurately

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

Credit: R. Petrossian-Byrne, N. Craig

What's beyond the Standard Model?

Reasons for looking beyond the Standard Model of Particle Physics

1. Observed phenomena lacking a fundamental explanation

- Dark Matter
- Matter-Antimatter asymmetry in the Universe
- Origin of neutrinos masses
- …

2. Guiding theoretical principles

- Natural energy scale "cut-offs"
- Flavor structure of the SM
- …

3. Unexpected new phenomena

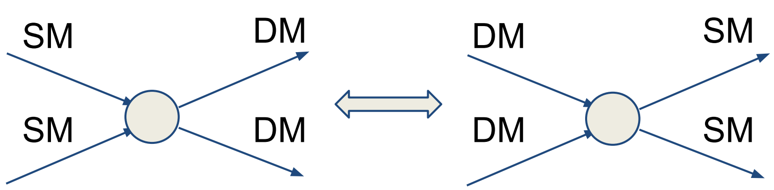
- Historically have opened roads to revolutionary discoveries

Dark Matter at Colliders

Aim to create Dark Matter in laboratory and study its properties in detail

Example: Weakly-Interactive Massive Particle (WIMP) in minimal models

- A representative case is the dark matter particle being the lightest member of an electroweak (EW) multiplet
- Evolution of dark matter density regulated by production/annihilation processes



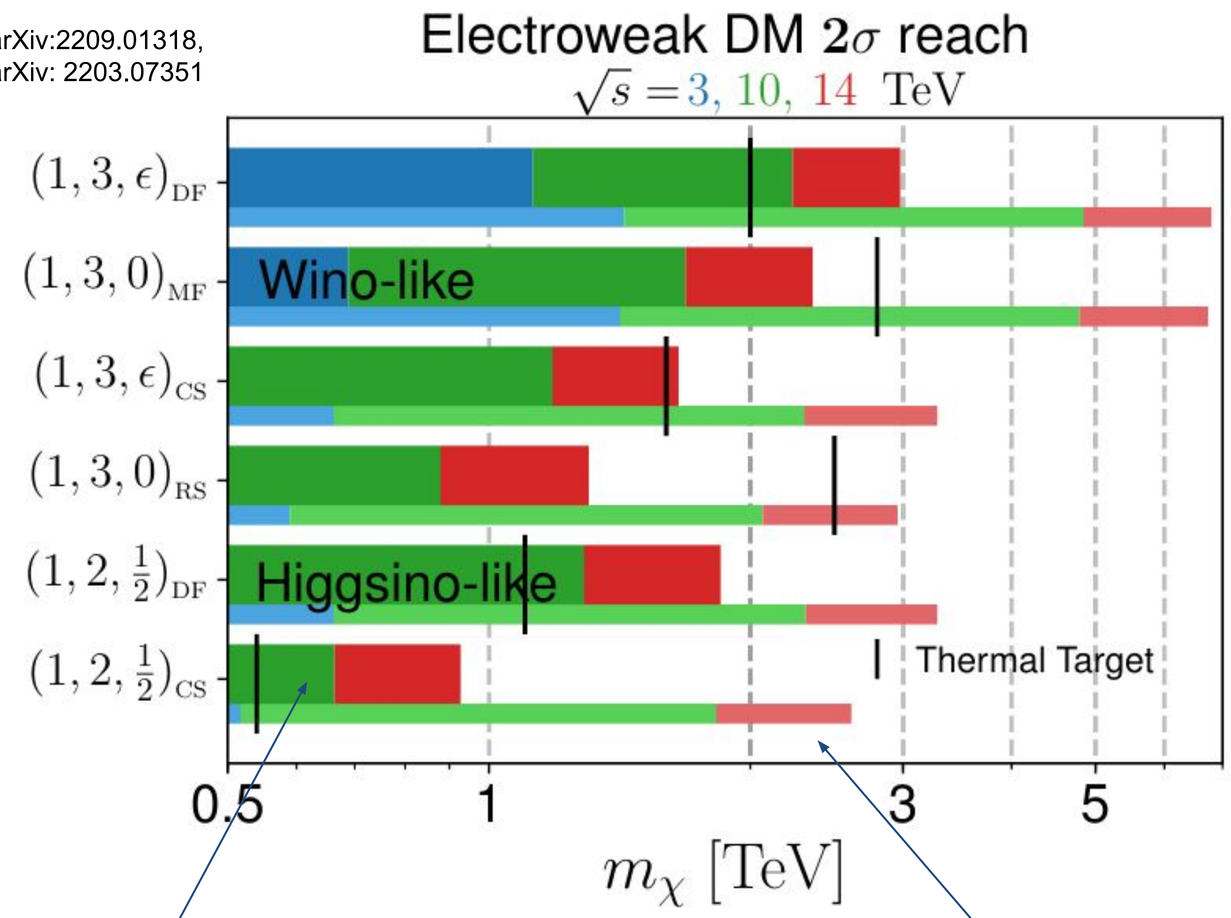
$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ {\rm pb} \cdot c}{\langle \sigma_A v \rangle}$$

Typical EWK cross-section from unrelated quantities

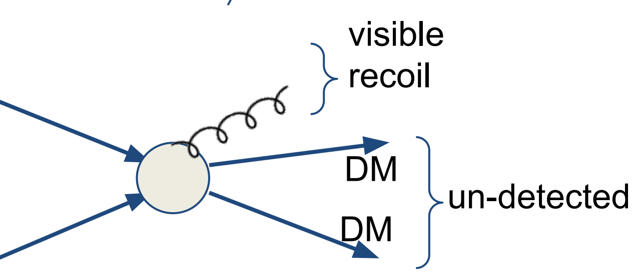
- Fixing its structure allows to compute rates
- Comparing with observed density **can derive a target DM particle mass**

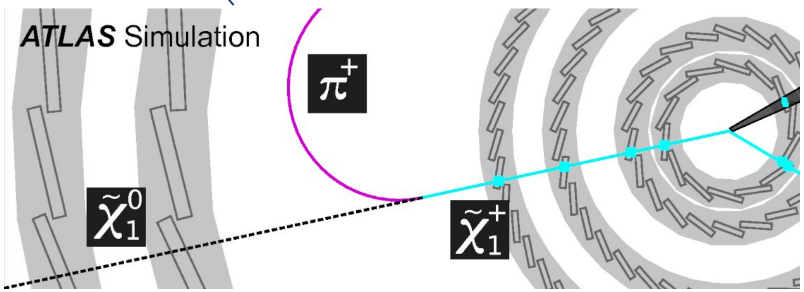
A statement on the WIMP paradigm at colliders

arXiv:2209.01318,
arXiv: 2203.07351

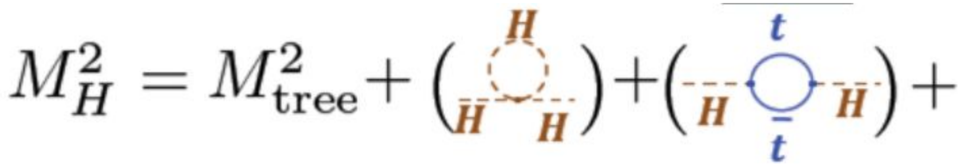


A 10 TeV Muon Collider hits the target in most scenarios



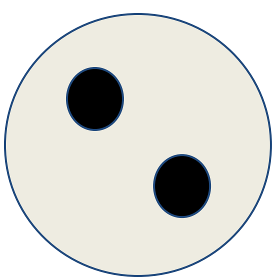


Solutions to the hierarchy problem

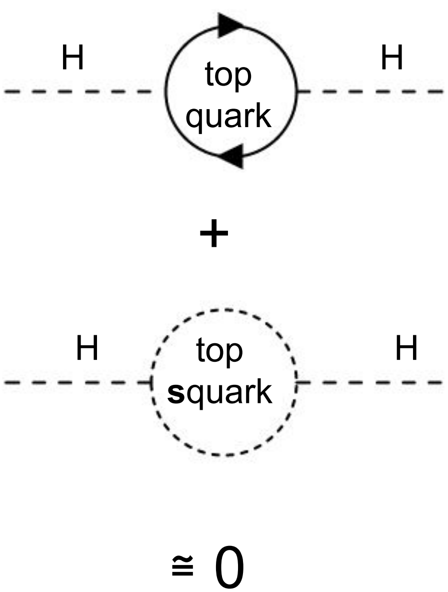


The unique scalar nature of the Higgs boson suggests new physics
Testing the ≲ 10 TeV regime provides very strong tests of this arguments
(other options are also possible)

<u>Compositeness</u>



<u>New "symmetries"</u>

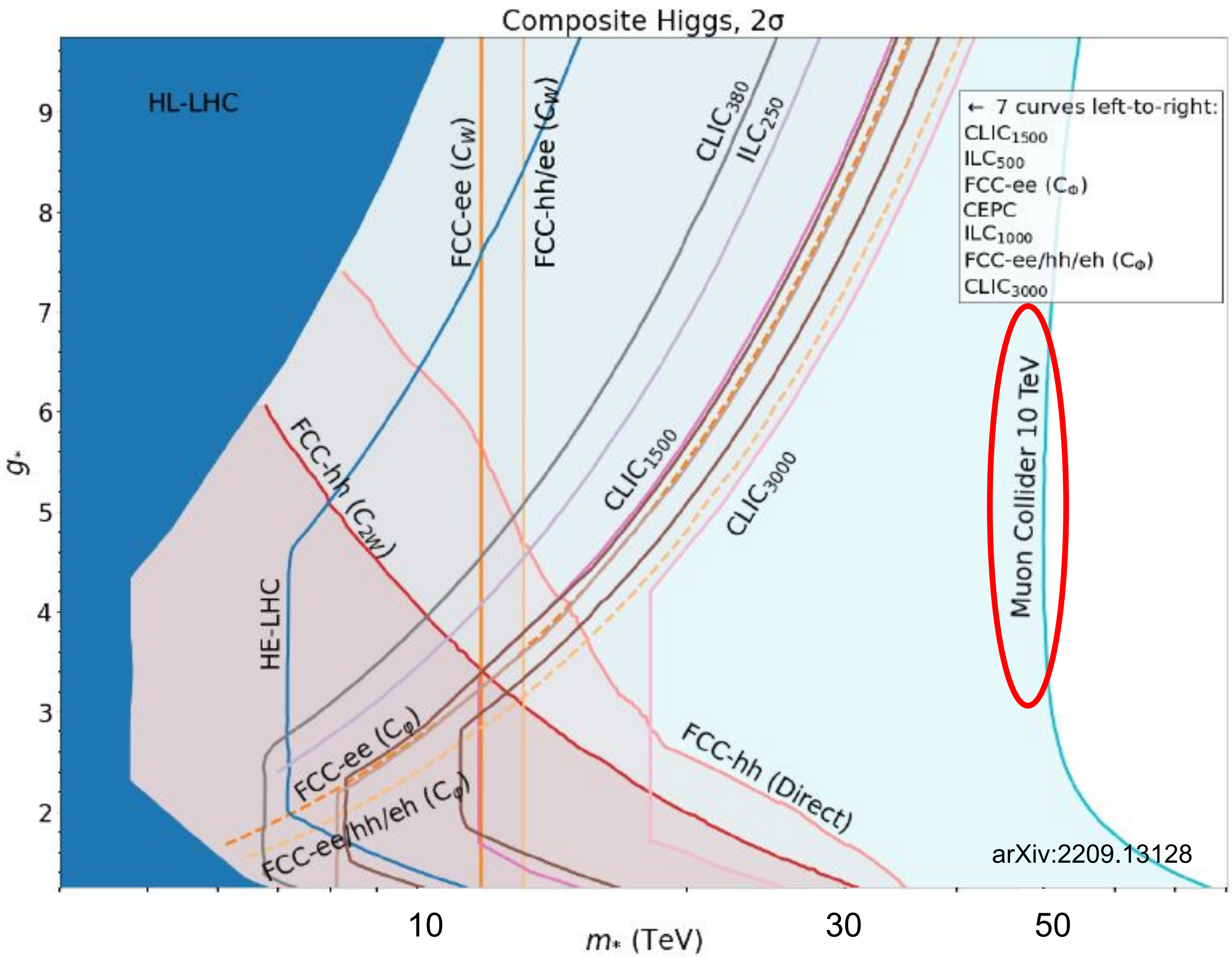


Higgs compositness

New constituents and inevitable a new “strong force” to bind them together

- Visible effects from direct searches as well as precision measurements
- Evaluated through sensitivity of effective Wilson coefficients

Unitarity limit ~4π



Expect a strong coupling

Supersymmetry

Long-sought for very good reasons

- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)

Large model-parameters space and vast phenomenology

Simplified classes of signatures

Full models with additional assumptions

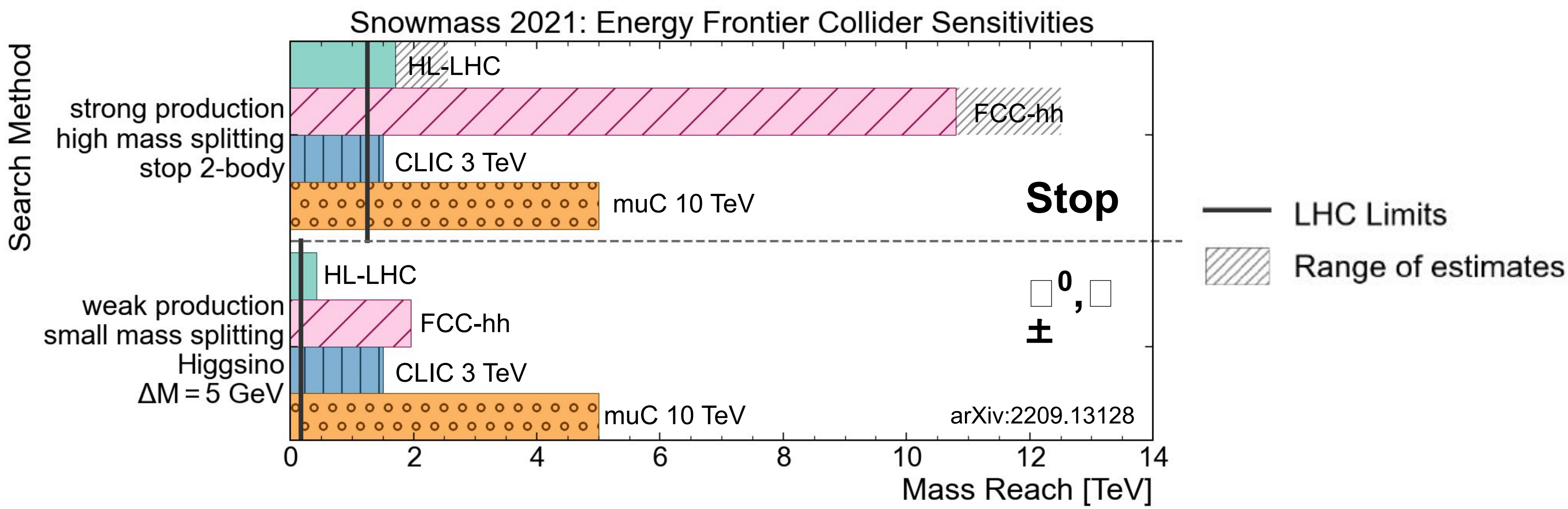
Supersymmetry

Long-sought for very good reasons

- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)

Large model-parameters space and vast phenomenology

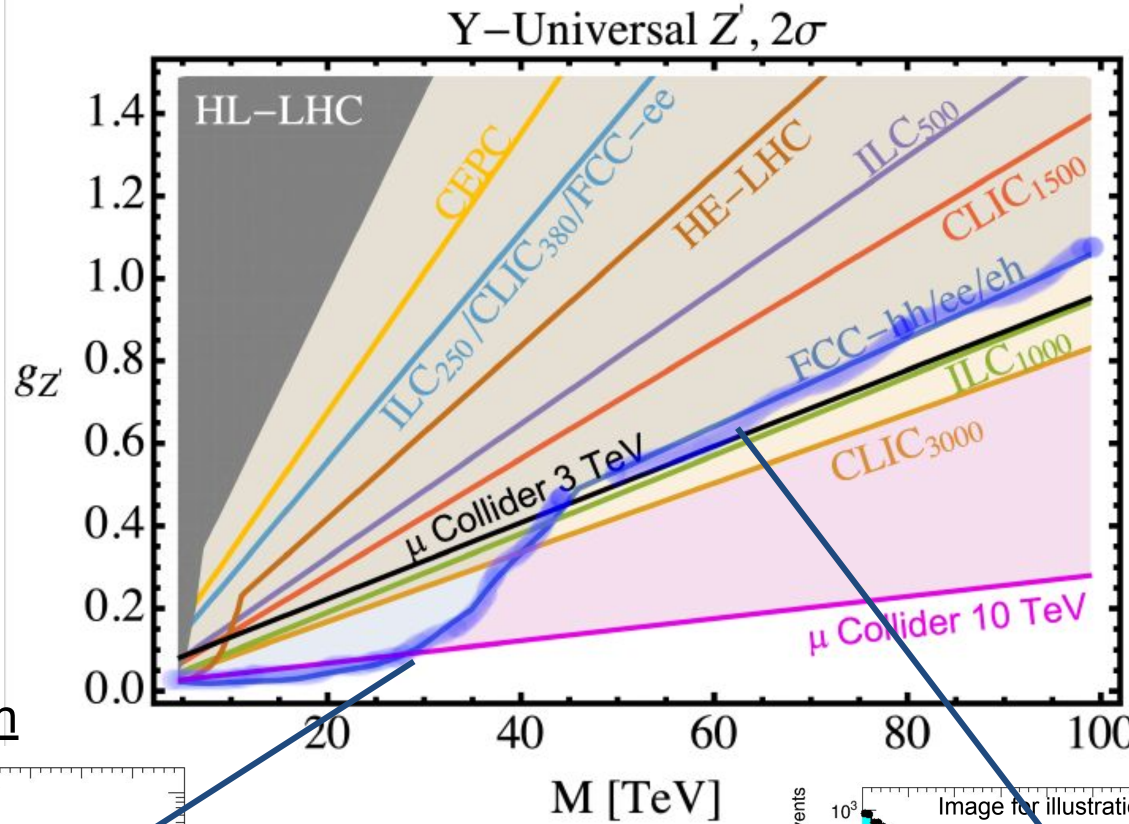
<u>Simplified classes of signatures</u>   <u>Full models with additional assumptions (in backup)</u>



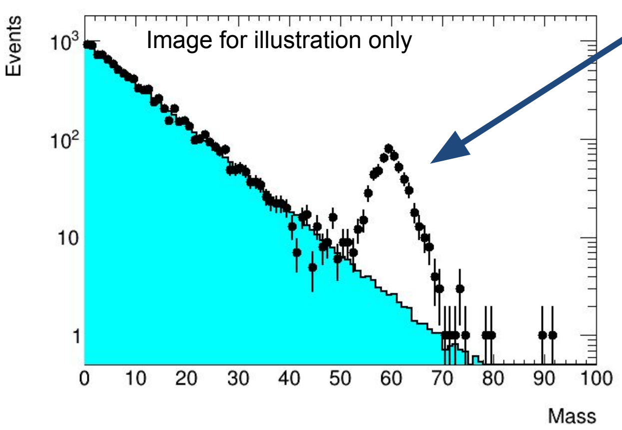
A Muon Collider is sensitive, for a large variety of signatures, to new particle masses ~ √s/2 (only a couple of examples shown above)

Exploring the unknown: new forces

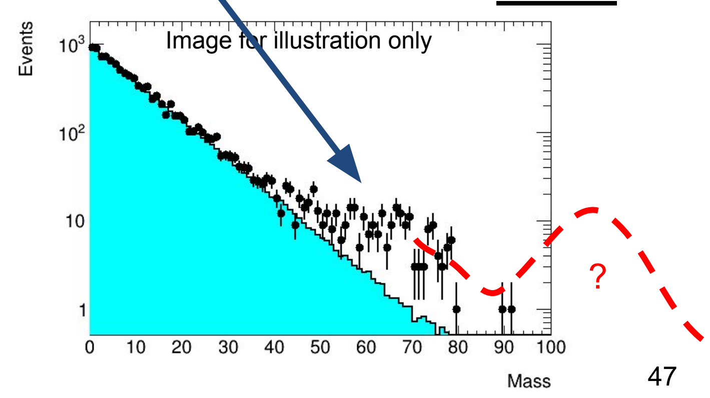
Probe mediator of new forces to the tens of TeV range!



Direct reach



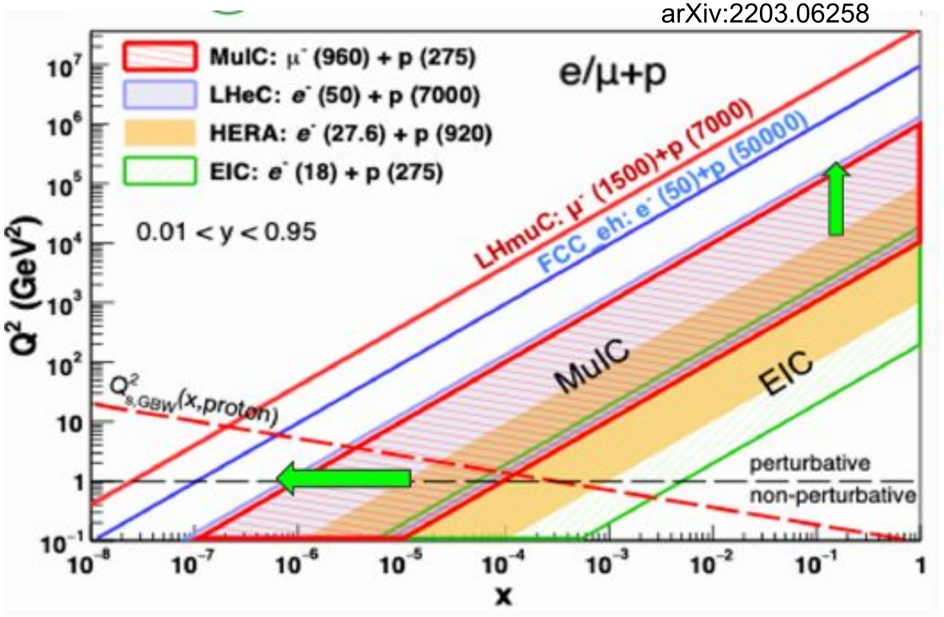
Indirect reach

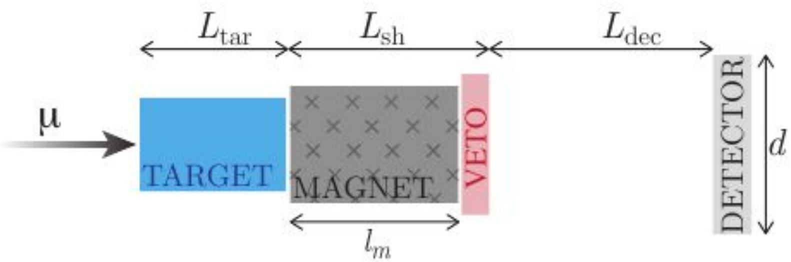


Synergies and Related Ideas

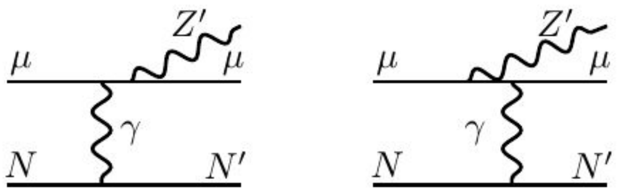
- Muon-Ion collider
  - New energy scales
  - Potential as upgrade to EIC
- Beam-dump experiments
- Low-energy neutrino factory
  - Very well-measured flux
- High-Energy neutrinos
  - BSM-like physics
- New facilities for charged-lepton flavor violation studies
- … and many more ideas!

arXiv:2203.06258





arXiv:2202.12302



Back to the Snowmass Energy Frontier Vision – A Path Forward for the Muon Collider US efforts –

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory detector R&D program,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,
4. Support critical detector R&D towards EF multi-TeV colliders.

For the five year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of an e^+e^- Higgs factory,
3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs Factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

A Path Forward for the Muon Collider US efforts

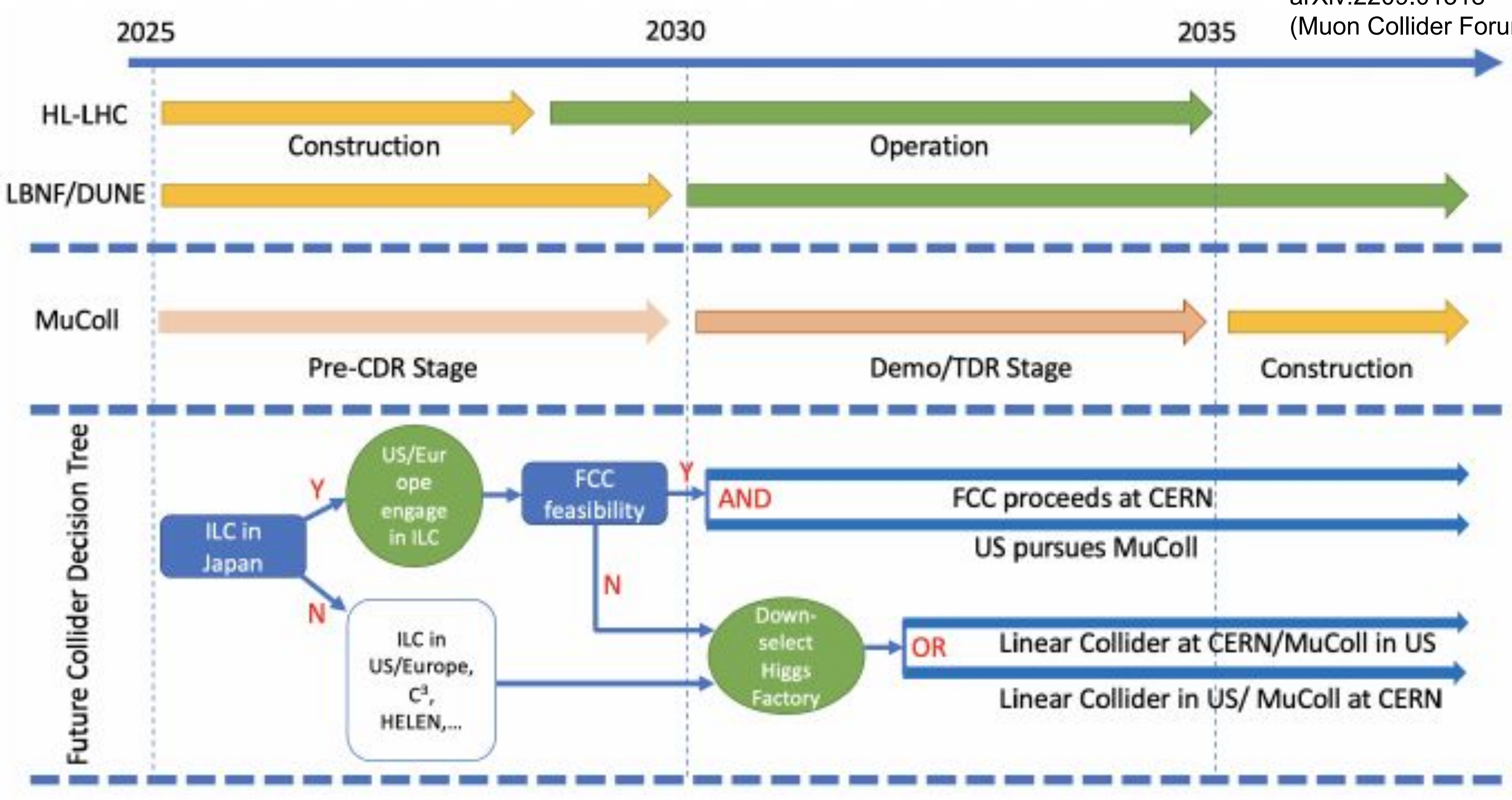
Aim to have US institutions participating in the global IMCC efforts

- Including a national framework to support R&D

Study at the same time options for hosting a muon collider in the US!

- Leverage synergies and existing facilities / expertise
- An ambitious and very exciting possibility!

arXiv:2209.01318
(Muon Collider Forum report)



Conclusions

We have several fundamental questions awaiting answers
- Snowmass summarized ideas we have to tackle them

At the Energy frontier, complex accelerator-based experimental setups require long timescales for development and operations
- At the same time, they offer the largest breadth of physics output
- A key for such long-term projects, in my opinion, is flexibility: to adapt to what we'll find along the way!

From the Snowmass process, a Muon Collider (re-)emerged as a very compelling possibility for the future of the field
- Most energy efficiency, scalable, affordable for multi-TeV regimes
- Great synergy of precision measurements and discovery reach

Large community support, and now that the community has spoken, we eagerly await the work of P5 to support a strong R&D program, making multi-TeV colliders a realistic option for the future of the field.

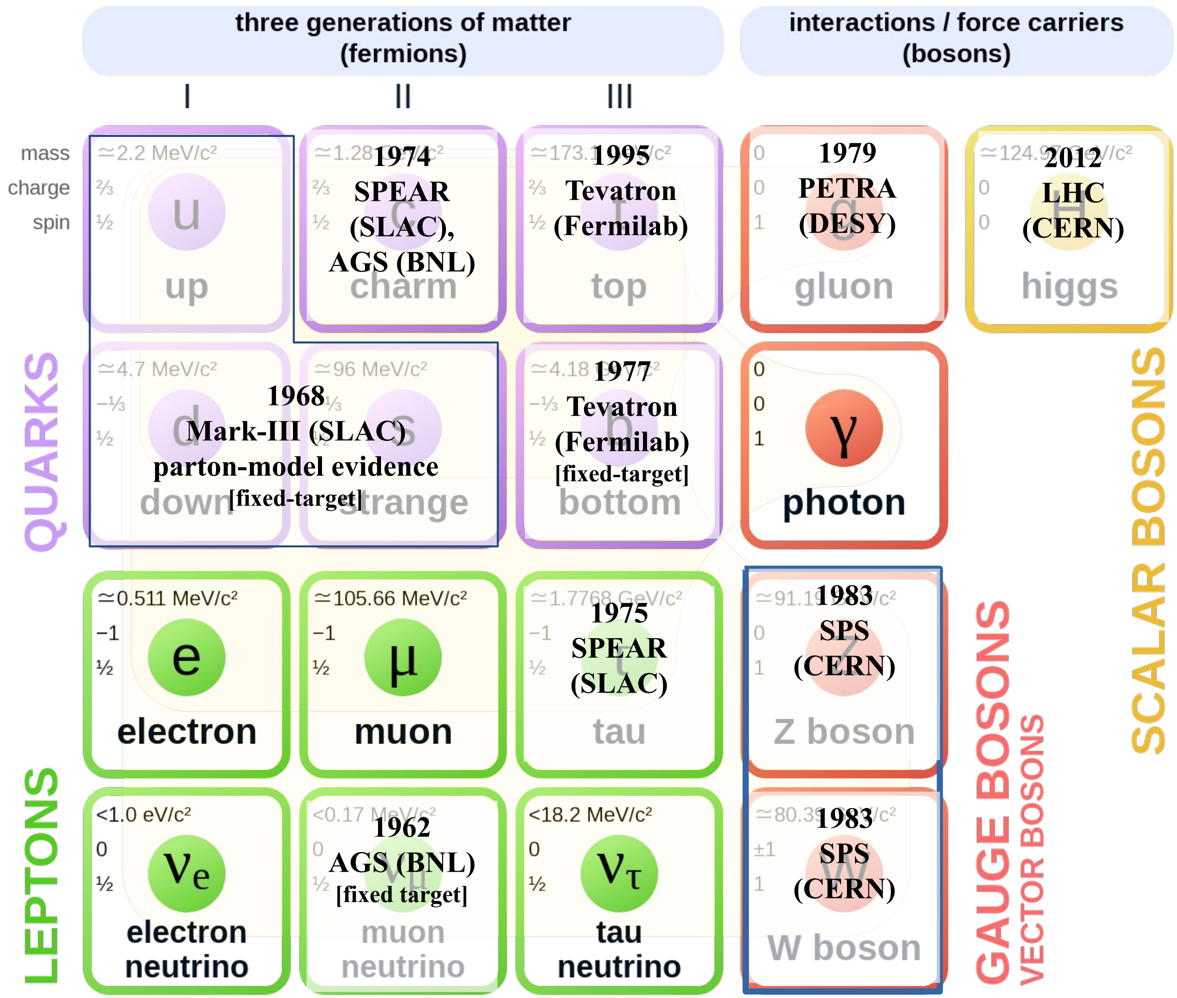
BACKUP

Need to be ready to react!

Anomalies, as e.g. muon g-2

The role of colliders at the Energy Frontier

Colliders at the Energy Frontier have been instrumental in understanding the building blocks of the Standard Model (SM) of Particle Physics



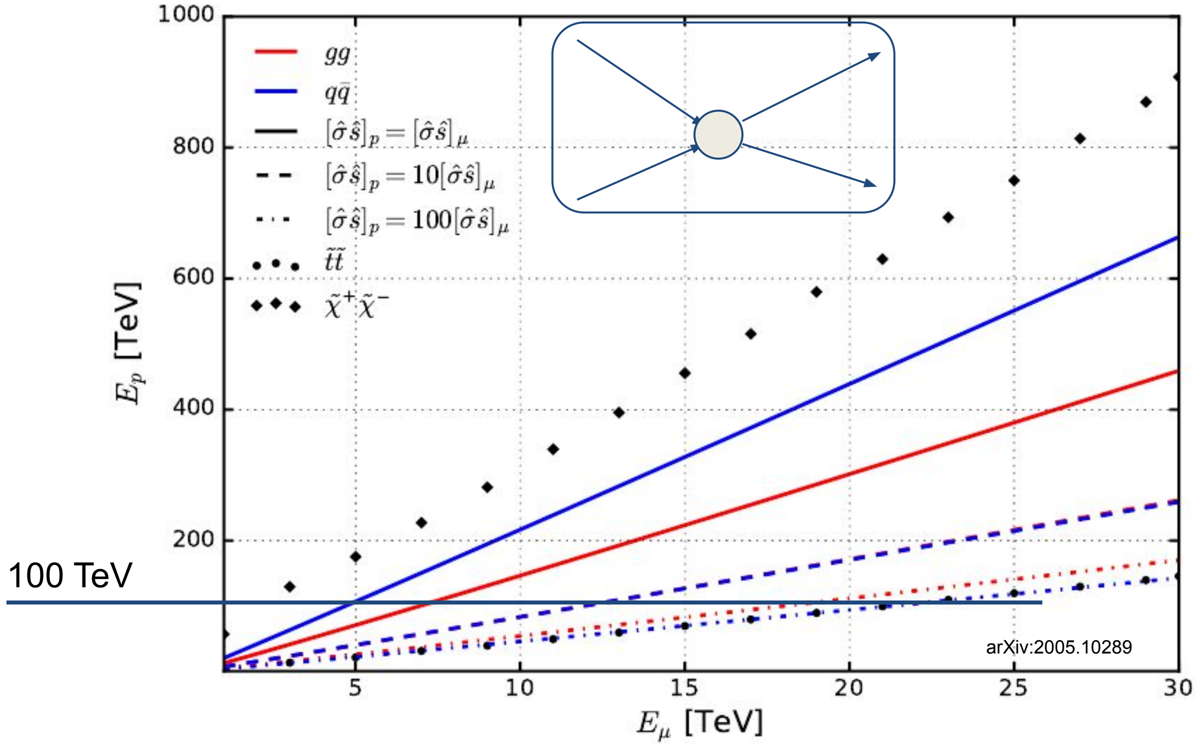
Adapter from source: Wikimedia

Lepton vs Hadron colliders: expected signals

Protons: involve scattering of constituents (partons)
Leptons: at leading-order, full center-of-mass energy available in collisions

A rough guide for comparing different center-of-mass energy can be made looking at classes of processes, with assumptions on "partonic" cross-sections

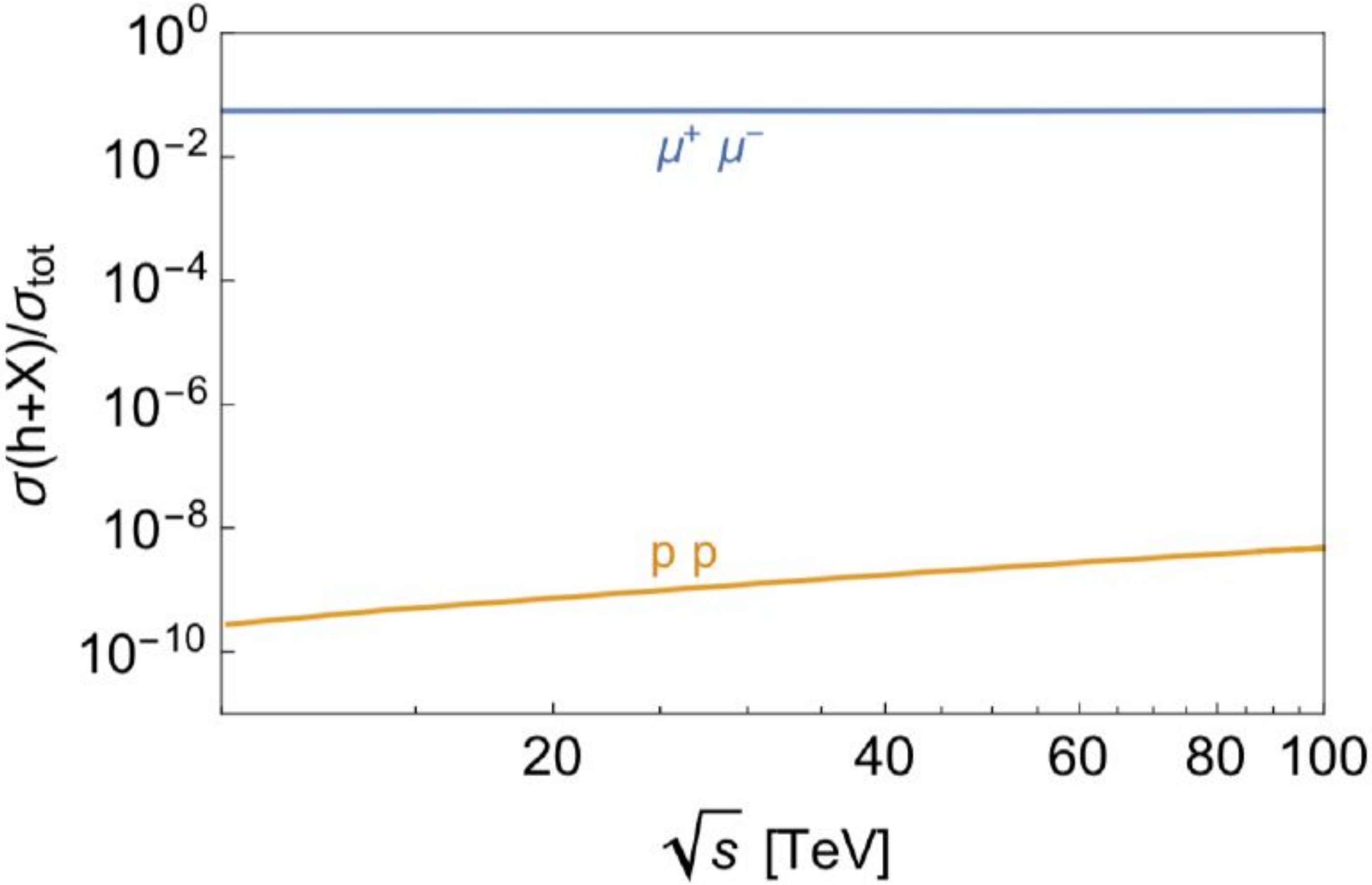
e.g. 2->2 processes



Practically, a lot of details that depend on the specific process, hence the need for a broad set of studies that are detailed in the Energy Frontier report and will only partially be highlighted in this presentation.

Lepton vs Hadron colliders: expected backgrounds

The rate of physics backgrounds play an equally important role

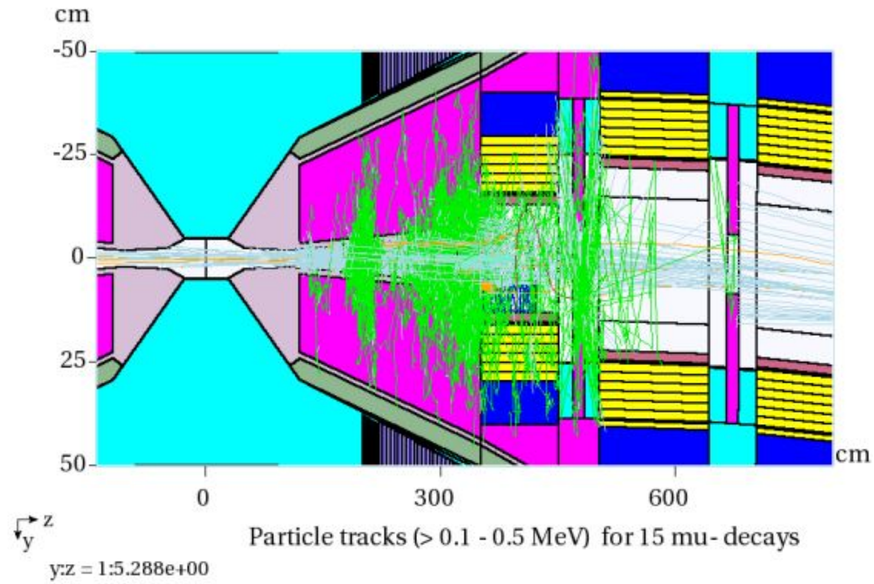


Beam-Induced Background

Detailed accelerator design studies are needed to understand the environment around the interaction point

Main sources of BIB:

- Incoherent e+e- pair production
- Beam halo loss on collimators
- <u>Muon beam decays</u>



Particle tracks (> 0.1 - 0.5 MeV) for 15 mu- decays

Large particle multiplicity entering the detector after showering on dedicated shielding

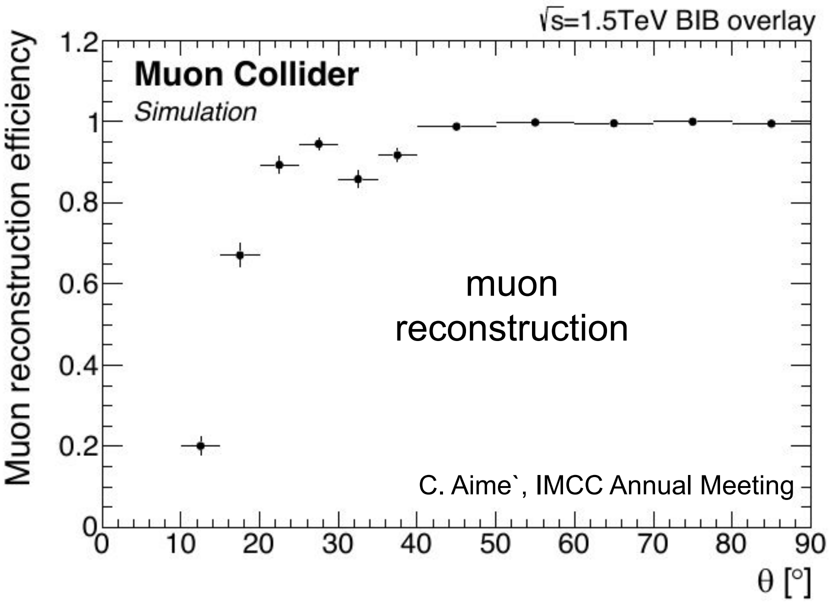
Now studied at different c.o.m. energies:

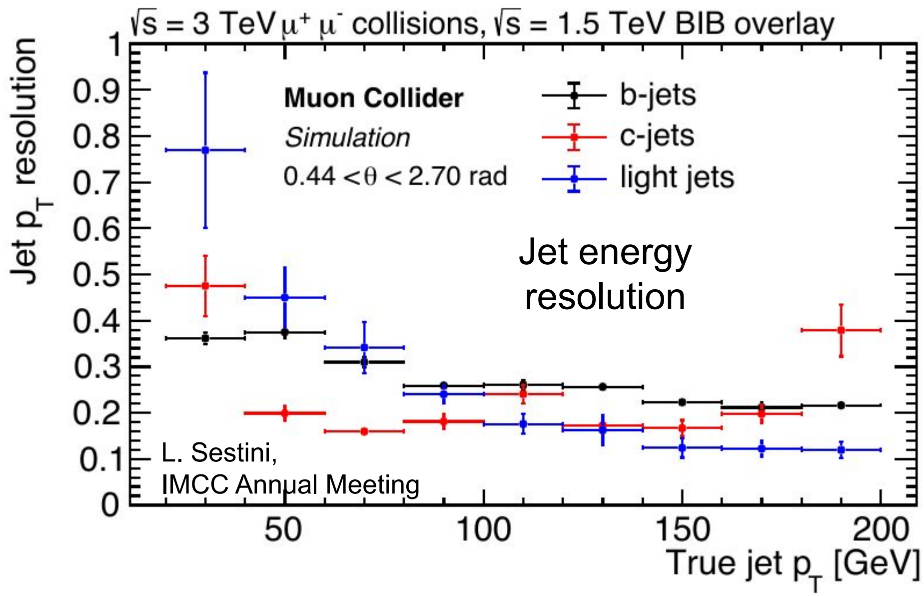
- longer lab-frame muon lifetime
- more energetic decay products

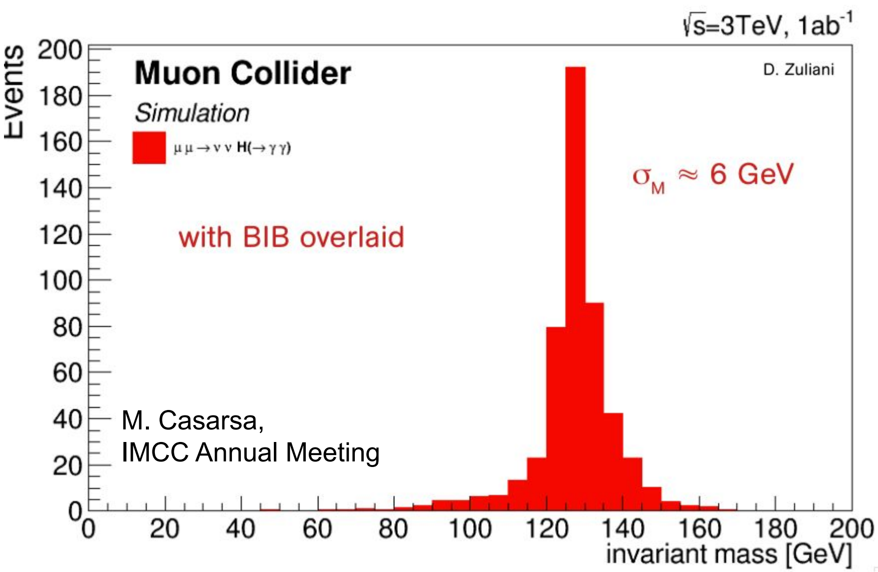
The two effects roughly balance

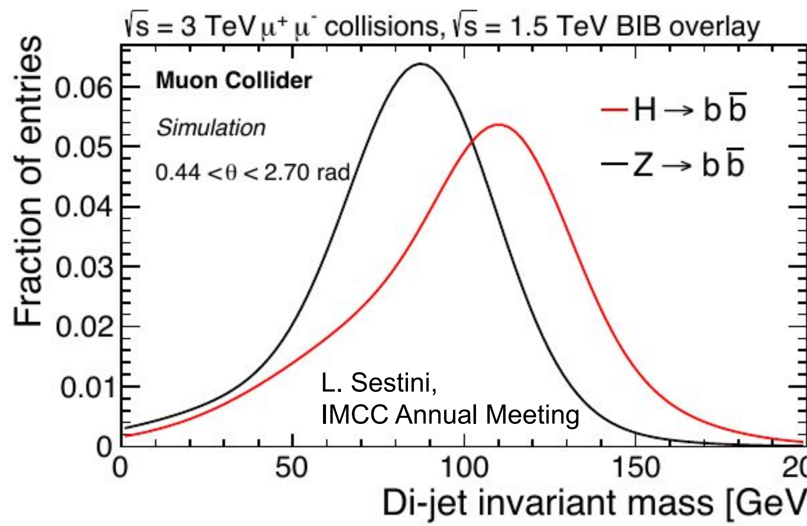
	MARS15	MARS15	FLUKA	FLUKA	FLUKA
beam energy [GeV]	62.5	750	750	1500 MDI Not Optimized	5000 MDI Not Optimized
μ decay length [m]	3.9×10^5	46.7×10^5	46.7×10^5	93.5×10^5	311.7×10^5
μ decays/m per beam (for 2×10^{12} μ/bunch)	51.3×10^5	4.3×10^5	4.3×10^5	2.1×10^5	0.64×10^5
photons/BX (E_γ > 0.1 MeV)	170×10^6	86×10^6	51×10^6	70×10^6	116×10^6
neutrons/BX (E_n > 1 meV)	65×10^6	76×10^6	110×10^6	91×10^6	89×10^6
$e^\pm$/BX (E_e > 0.1 MeV)	1.3×10^6	0.75×10^6	0.86×10^6	1.1×10^6	0.95×10^6
charged hadrons/BX (E_h > 0.1 MeV)	0.011×10^6	0.032×10^6	0.017×10^6	0.020×10^6	0.034×10^6
muons/BX (E_h > 0.1 MeV)	0.0012×10^6	0.0015×10^6	0.0031×10^6	0.0033×10^6	0.0030×10^6

Other object reconstruction performance





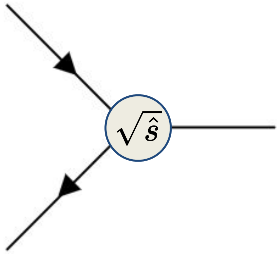




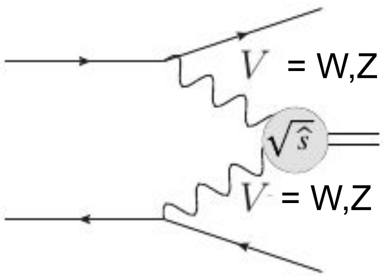
Not a "simple" jump in Energy

Moving to ~10 TeV parton/lepton energy scale has qualitative new features

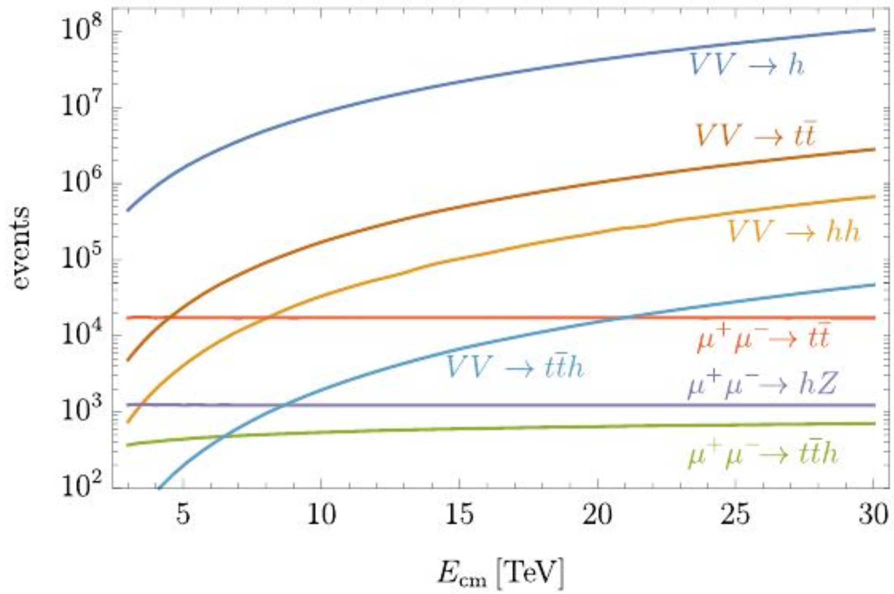
Just one example: **new dominant production mechanisms**



$$\sigma \sim 1/\hat{s}$$



$$\sigma \sim \log \hat{s}$$



About Timelines

Project	Construction		
	Start date (yr)	End date (yr)	Cost B$
Higgs Factories			
CepC	2026	2035	12-18
CCC (higgs Fac)	2030	2040	7-12
ILC (higgs Fac)	2028	2038	7-12
CLIC	2041	2048	7-12
FCC-ee	2033	2048	12-18
Multi-TeV Colliders			
Muon Collider (3 TeV)	2038	2045	7-12
Muon Collider (10 TeV)	2042	2052	12-18
SppC	2043	2055	30-80
HE CCC	2055	2065	12-18
HE CLIC (3 TeV)	2062	2068	18-30
FCC-hh	2063	2074	30-50

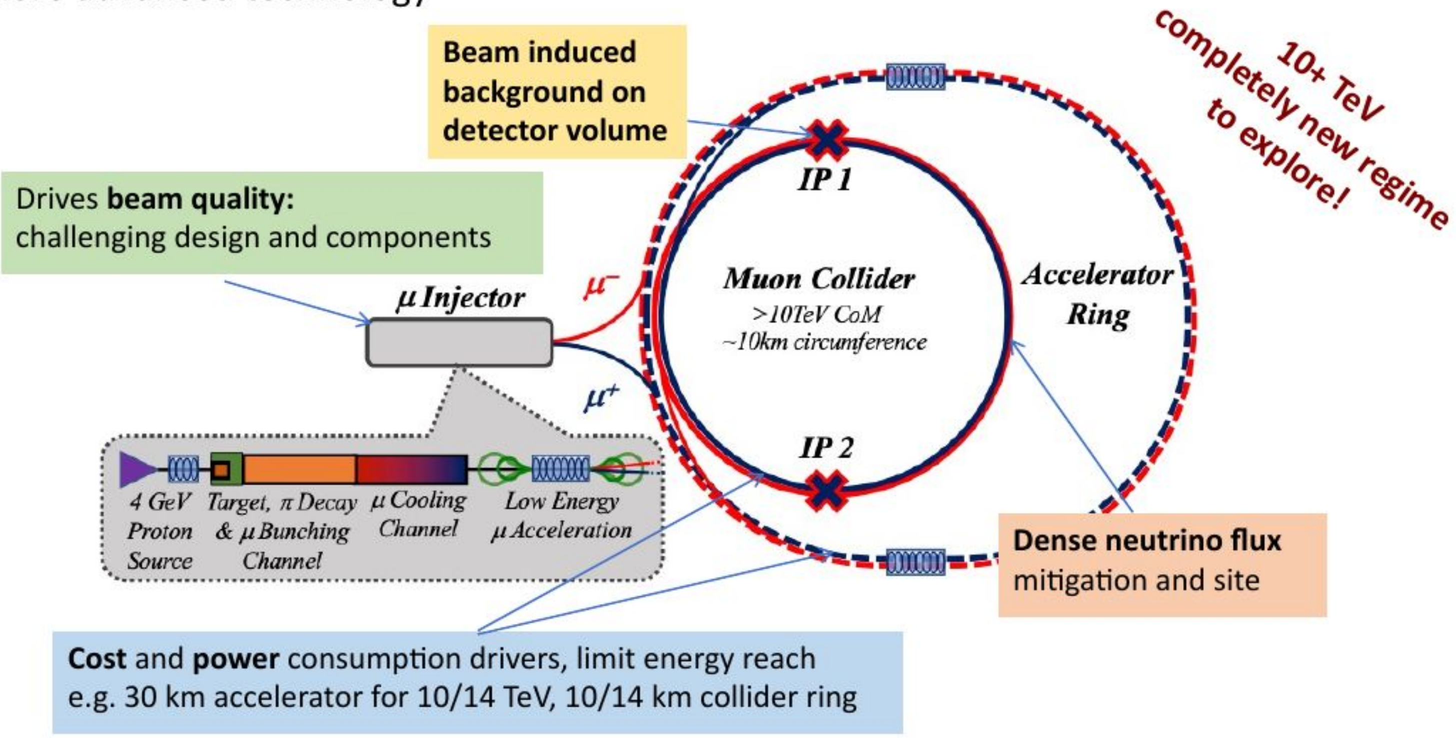
International Design Study facility

- **Focus on two energy ranges:**

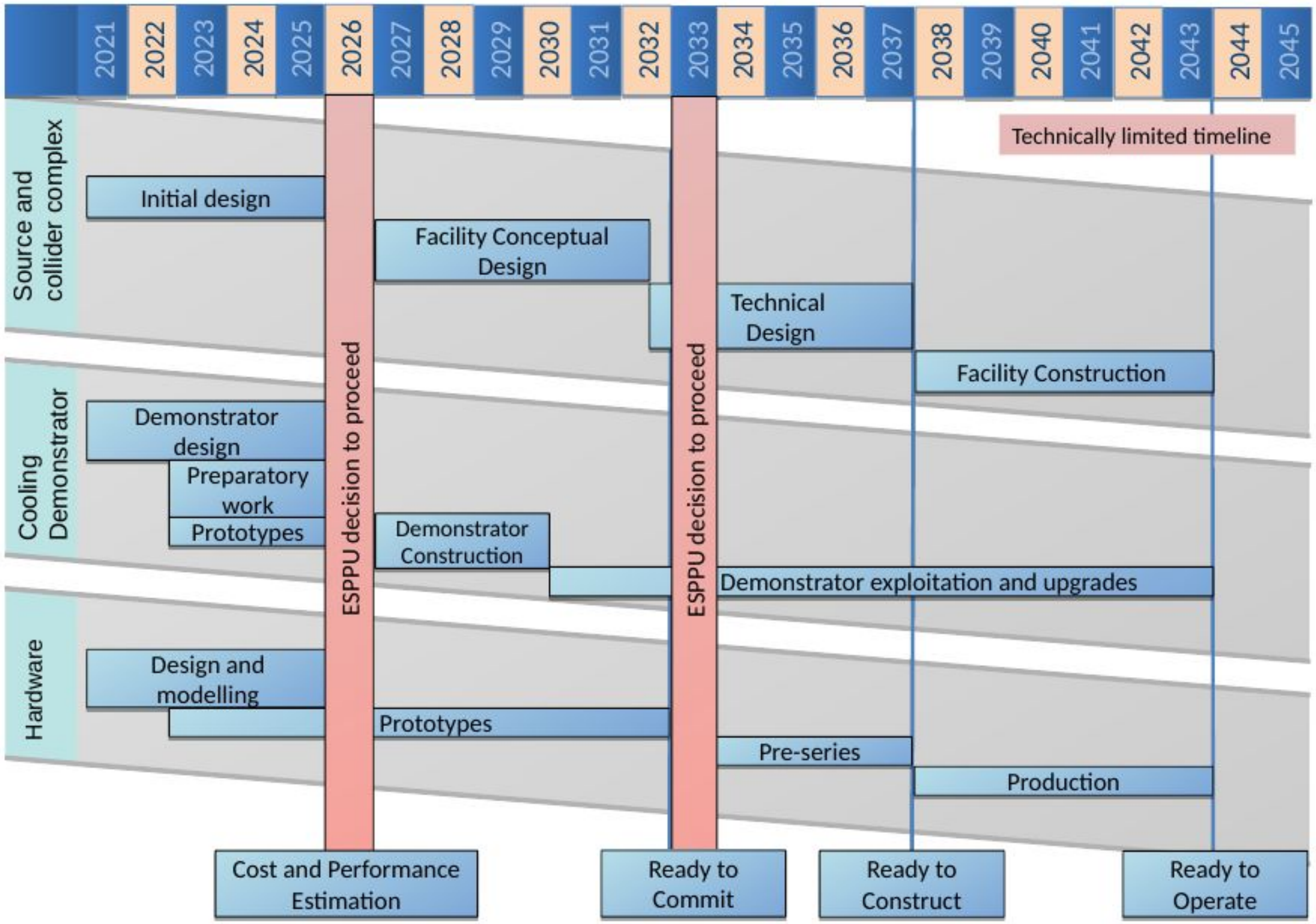
3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology

Proton driver production as baseline



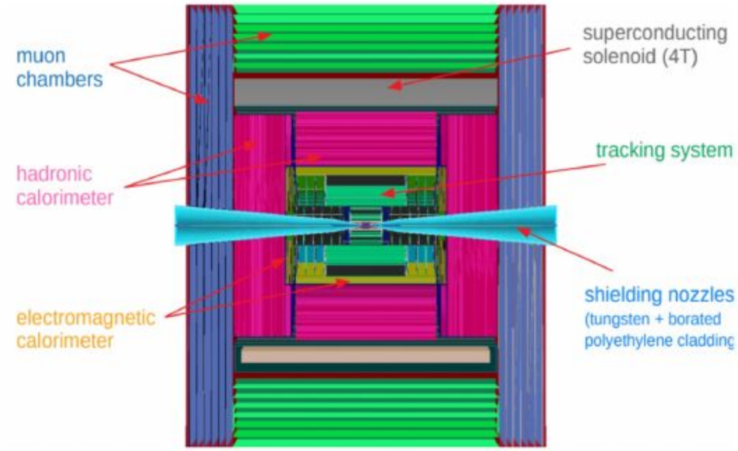
N. Pastrone, Fermilab MC Workshop



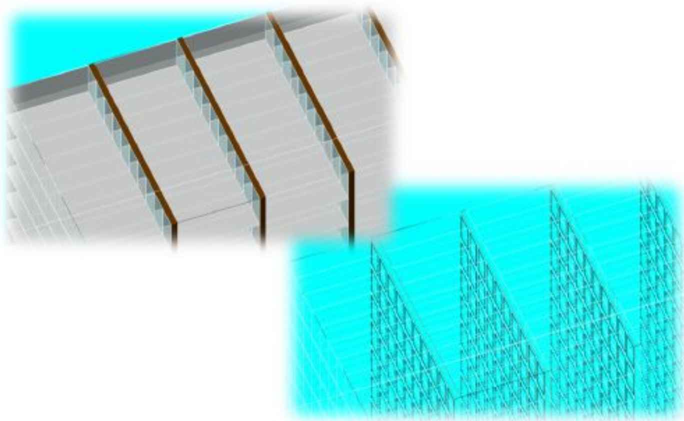
A technically limited timeline for the Muon Collider R&D program

Crilin: an alternative solution

- Actual design of the ECAL: 40 layers of 1.9 mm W absorber + silicon pad sensors (~64M channels for the Barrel)
  - 5x5 mm^2 cell granularity
  - 22 X_0 (1 λ_i)



- Crilin (Crystal calorimeter with longitudinal information) represent a **valid** and **cheaper backup solution**
  - Based **on Lead Fluoride** (PbF_2) crystals readout by **2 series of two UV-extended 10μm pixel SiPMs each.**
  - Crystal dimensions are 10x10x40mm^3 and the surface area of each SiPM is 3x3 mm^2, to closely match the crystal surface.
  - Modular architecture based on stackable submodules



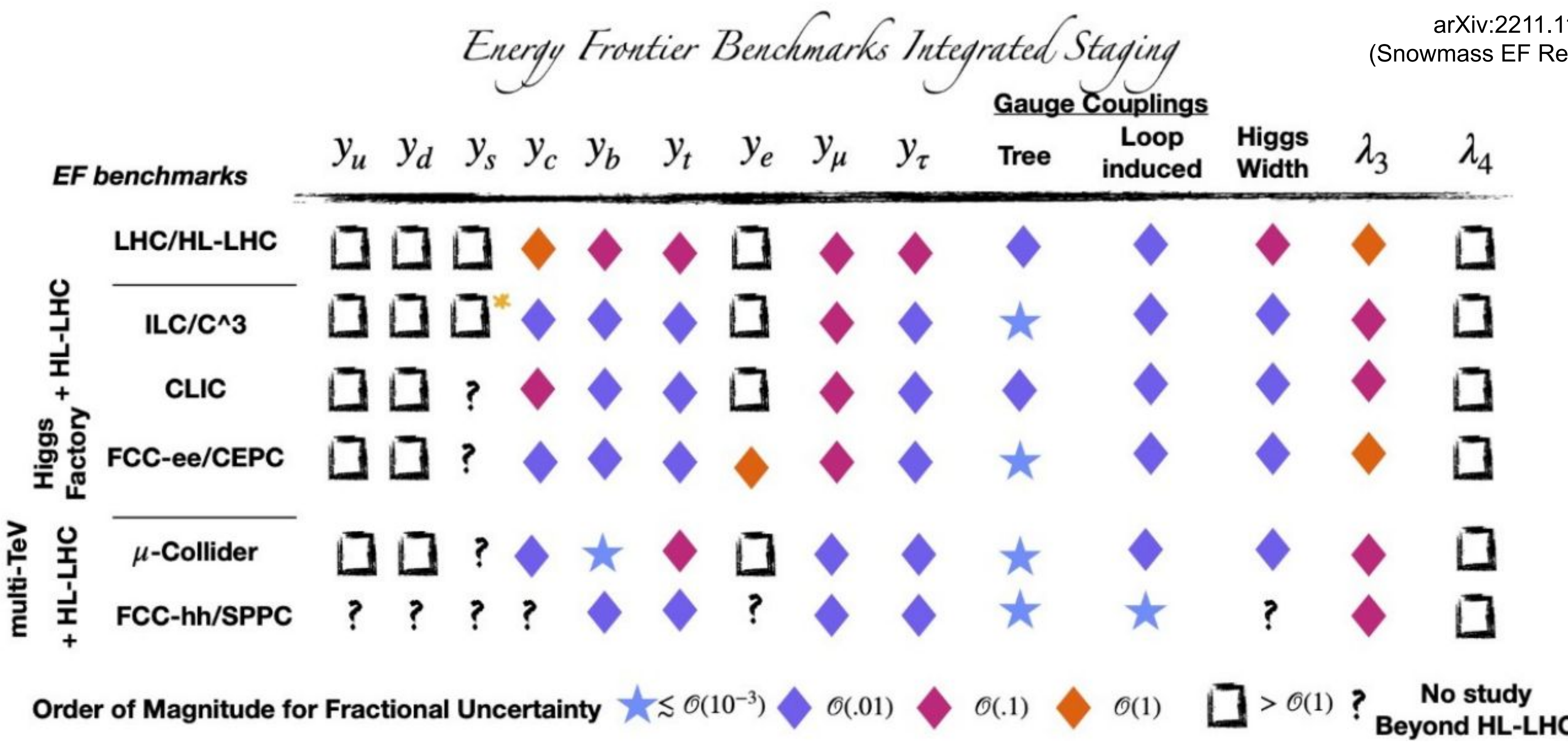
High Energy <-> High Luminosity <-> High Precision

HE machines, with appropriate detector, are also precision measurement devices!

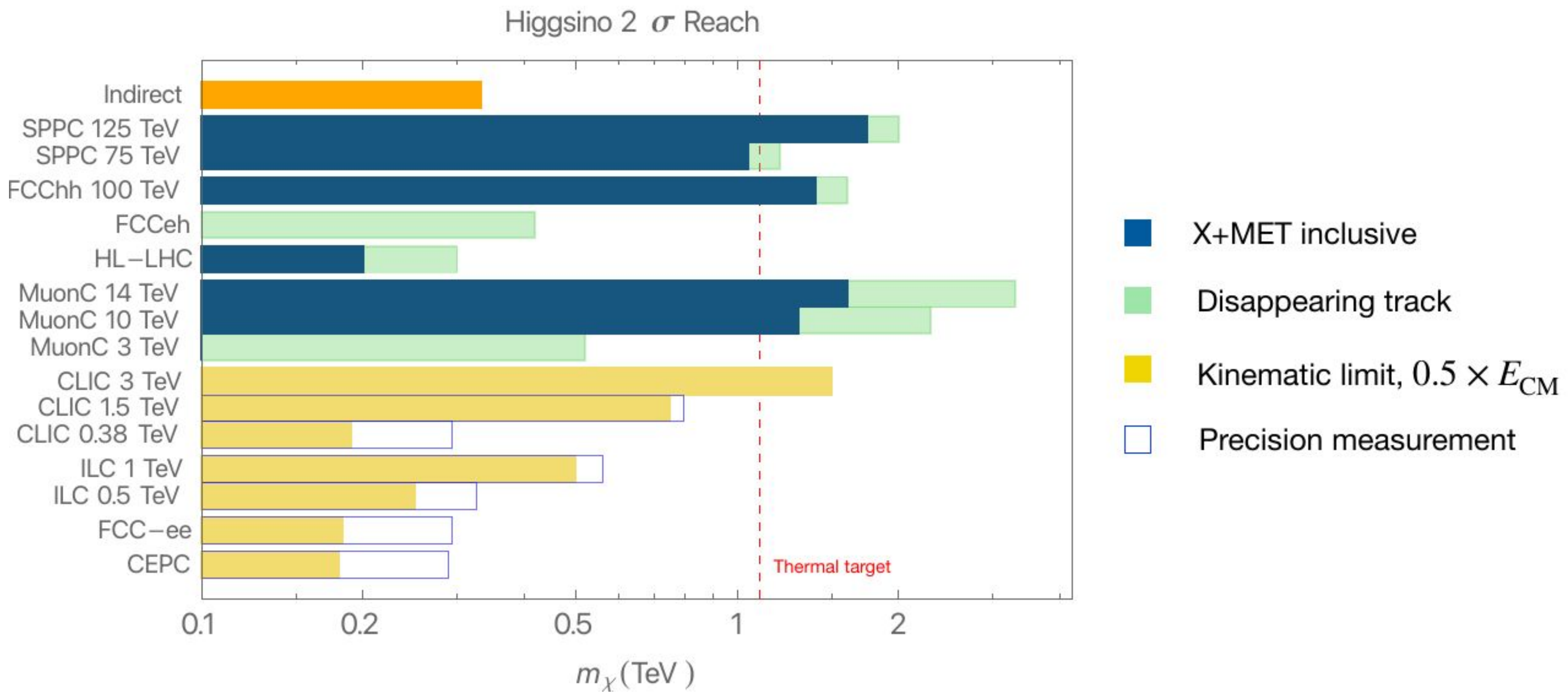
	H factories	l^+l^- @ 3 TeV	l^+l^- @ 10 TeV	pp @ 100 TeV
# Higgs bosons	~10^6	~$5\cdot10^6$	10^7	~10^{10}

Obviously an over-simplification, control of systematics and physics background play very important roles!

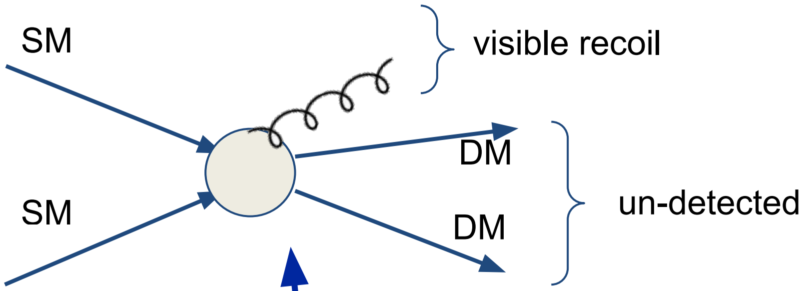
arXiv:2211.11084
(Snowmass EF Report)

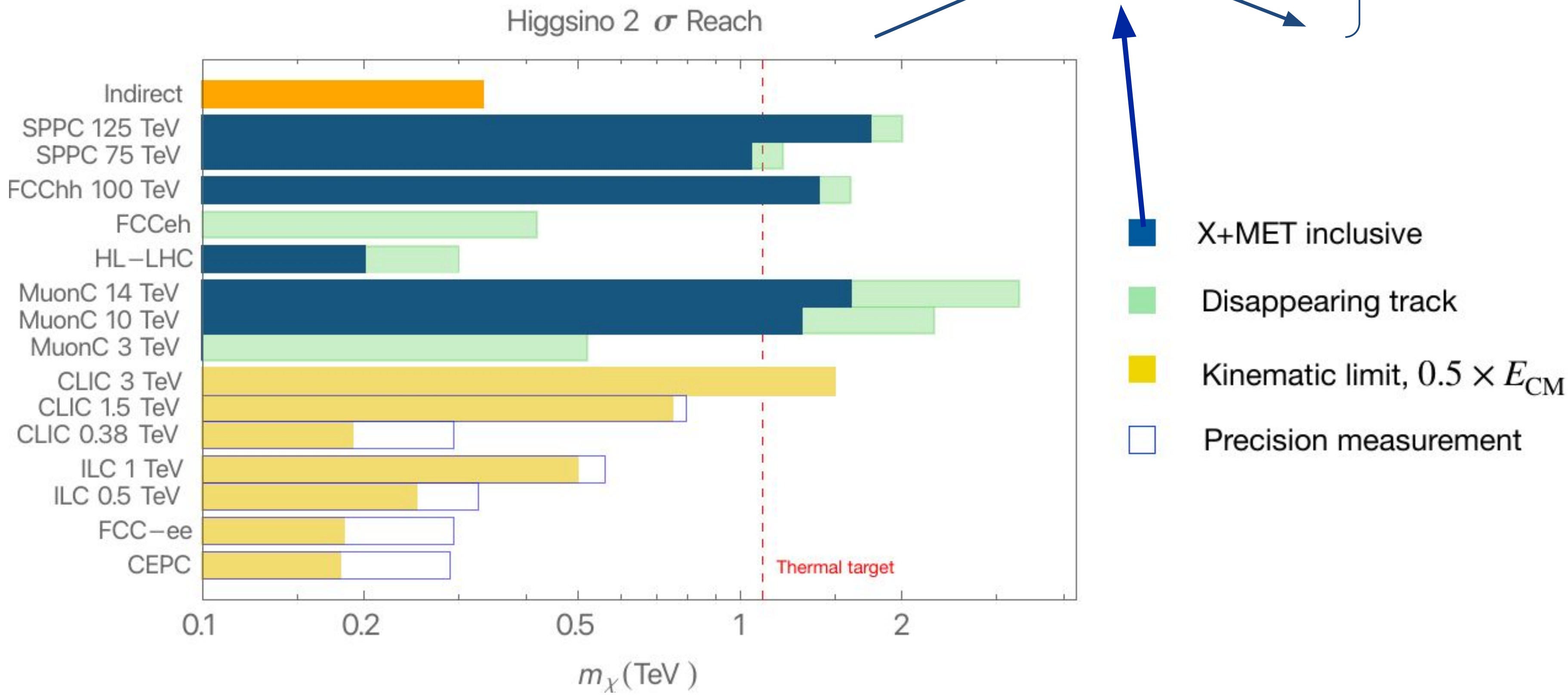


A statement on the WIMP paradigm at colliders



A statement on the WIMP paradigm at colliders





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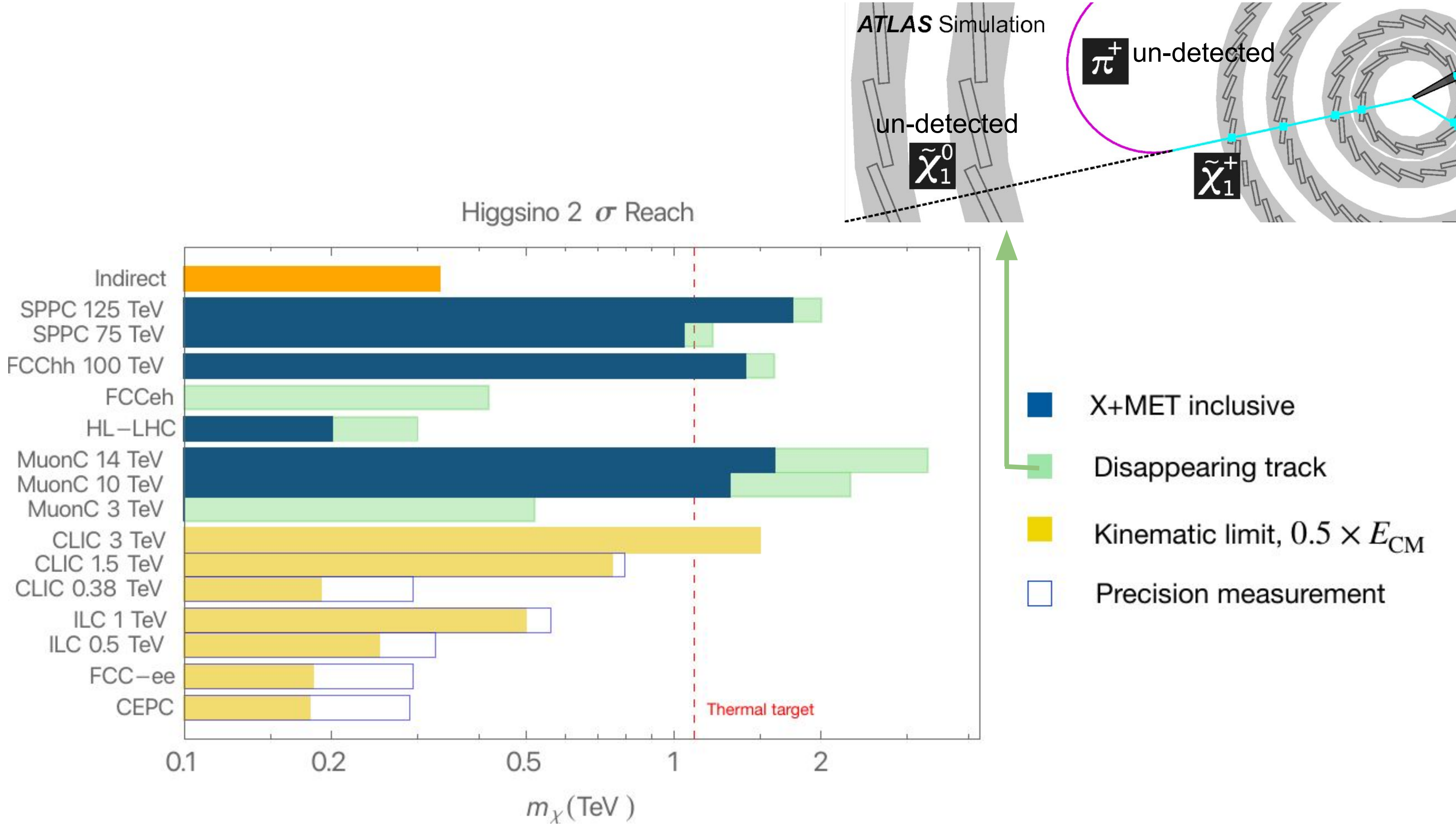

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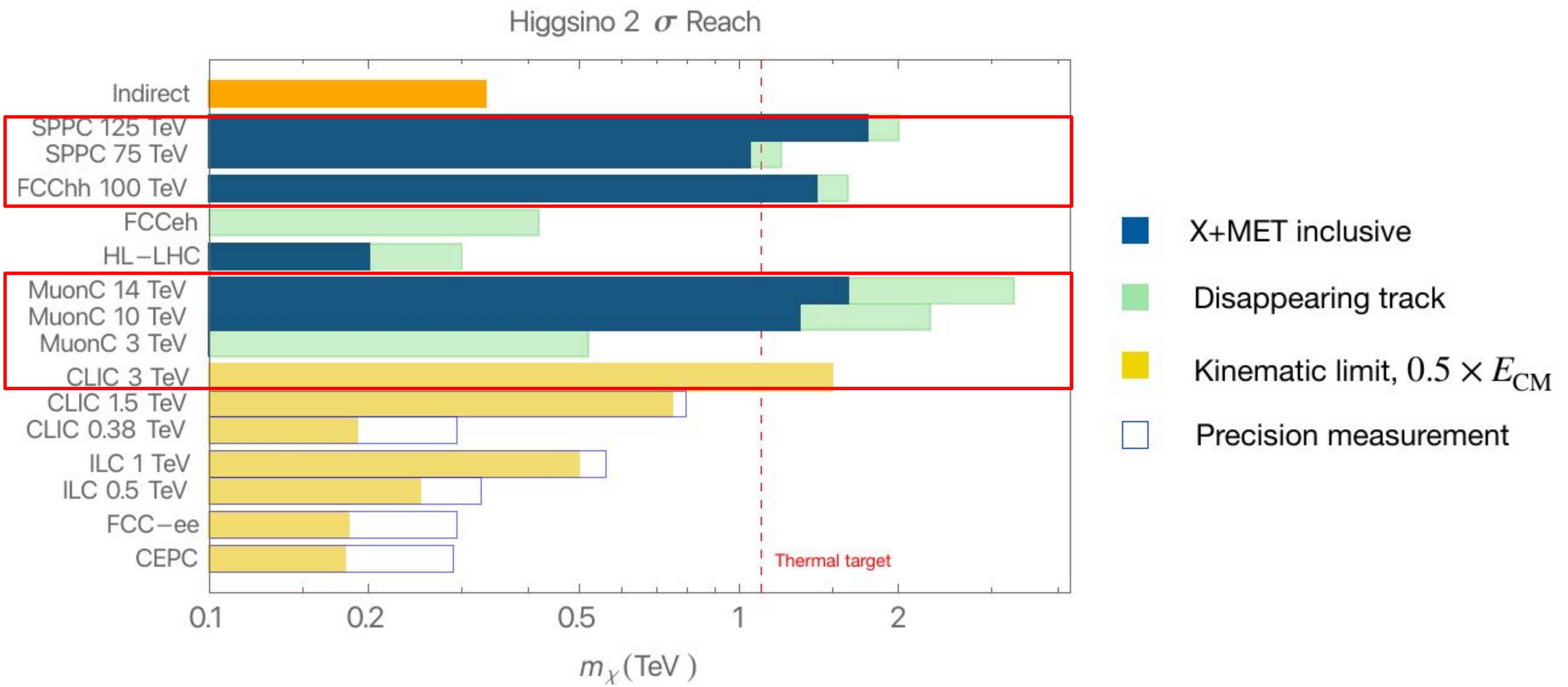

Need multi-TeV colliders to arrive to this natural target