The Muon Collider

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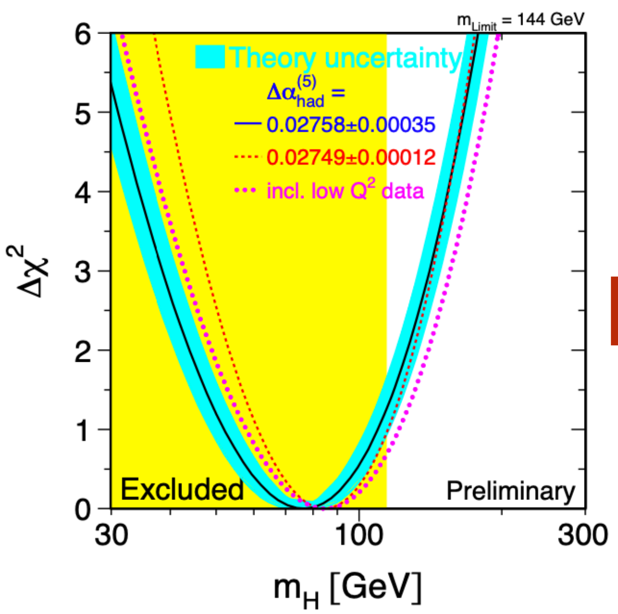
The case for a new discovery machine

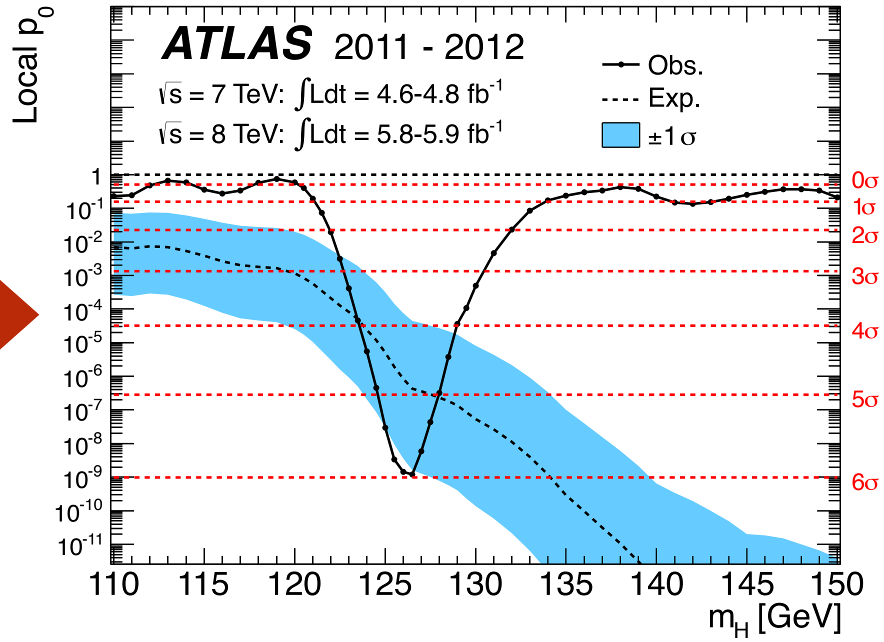
One can gain a wealth of information from precision measurements at low(er) energy…

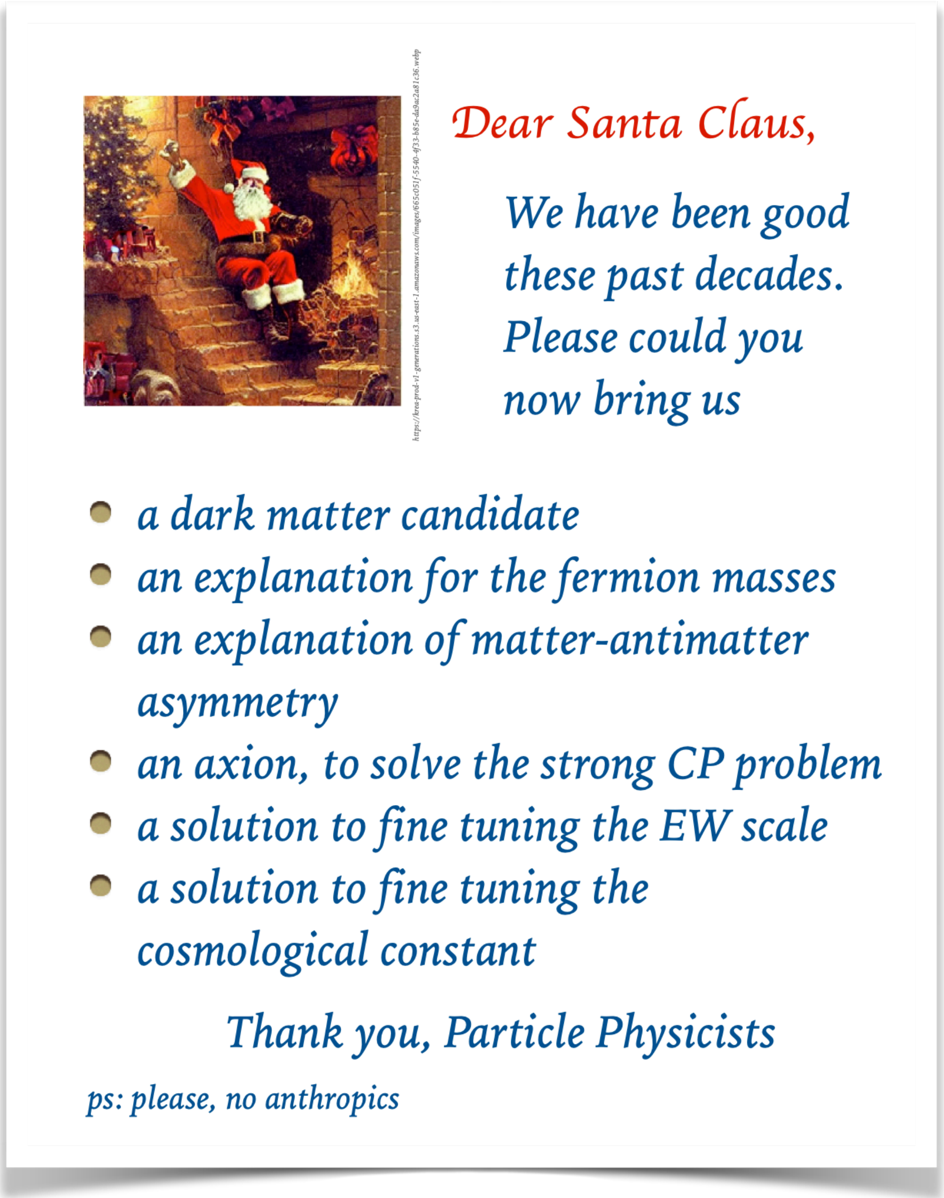
- as I hope the preceding presentation illustrated

But nothing beats a direct discovery!

- an excellent example: the Higgs boson







Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

Thank you, Particle Physicists

ps: please, no anthropics

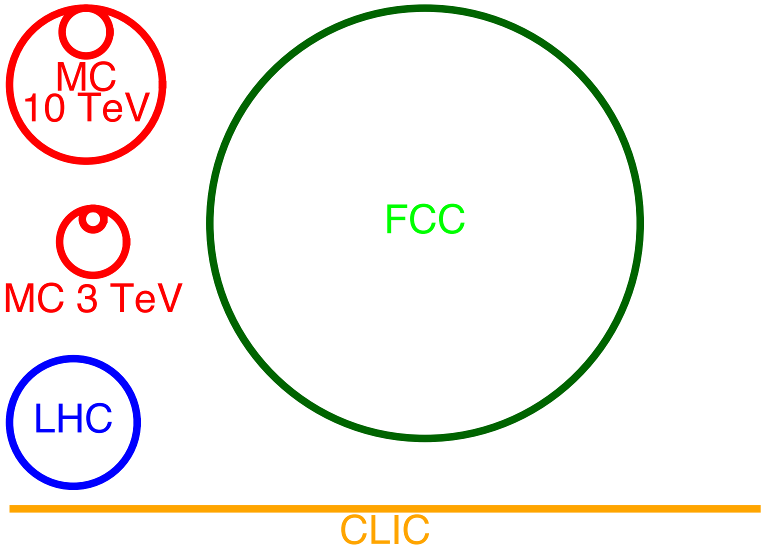
(Gavin Salam, 2023 FCC Week)

However, there are many who are not appealed by the prospect of having to wait for this for over 40 years

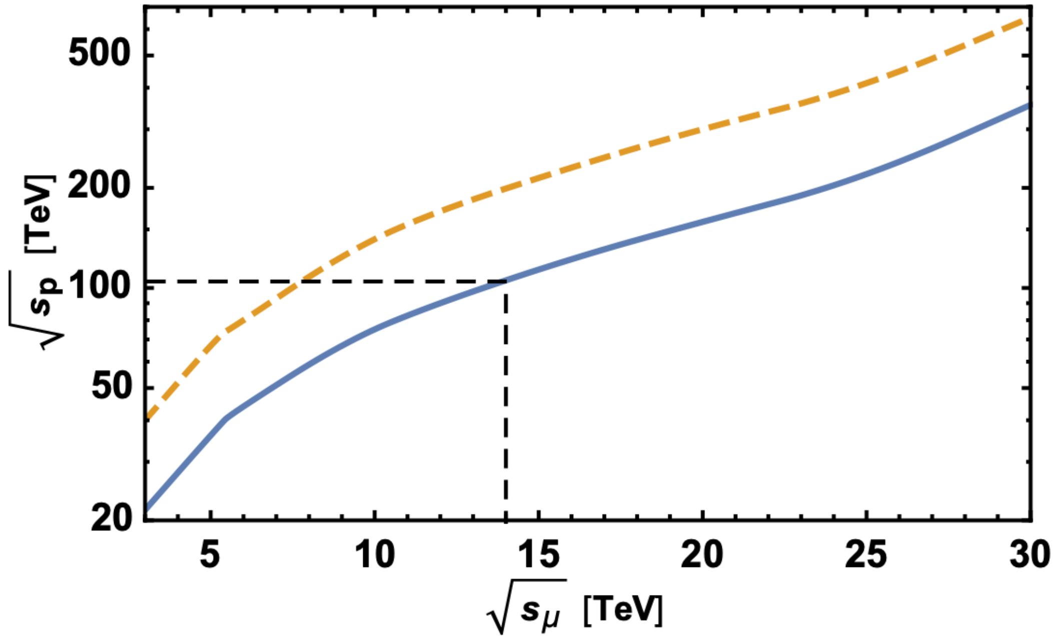
- are there alternatives?

Colliding heavy elementary particles

Using muons has the potential to offer the same energy reach with a much smaller circumference collider



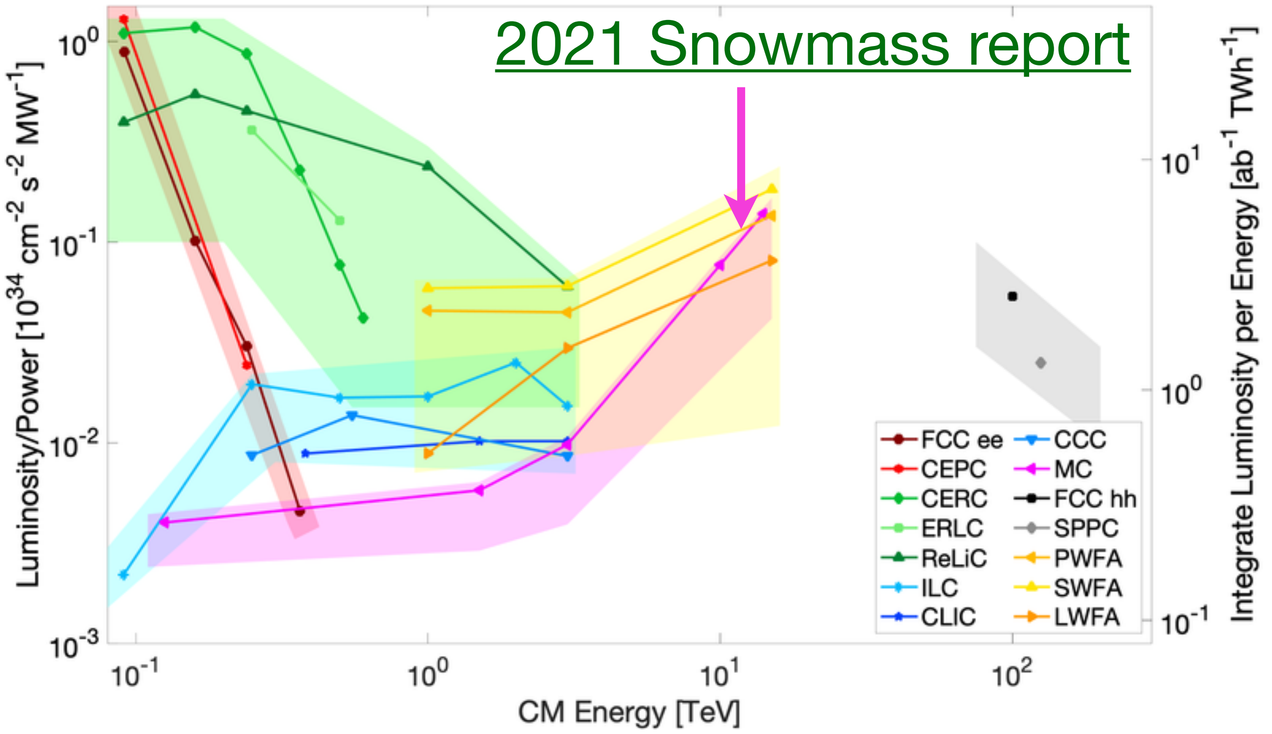
arXiv:1901.06150 (assumes both $q\bar{q}, gg$ contribute for $p-p$)



- $\mu^\pm$ are elementary particles ➠ $\mu^+\mu^-$ collisions offer sensitivity to physics at energy scales up to full CM energy
- $m_\mu \approx 207\, m_e$ ➠ synchrotron radiation ($\sim \gamma^4$) is not a limiting factor

Focus on $\sqrt{s}$ = 10 TeV, but anticipate initial stage (e.g. 3 TeV)

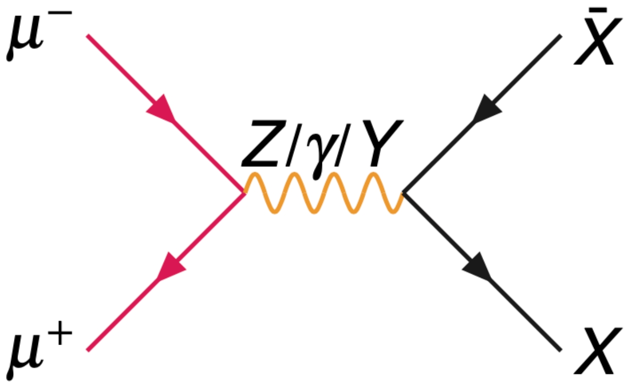
- higher E helps (Liouville's theorem)!



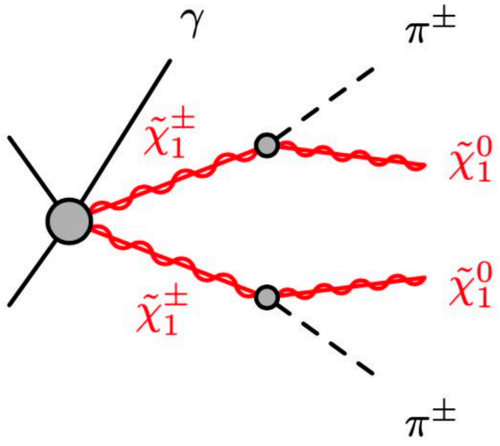
2021 Snowmass report

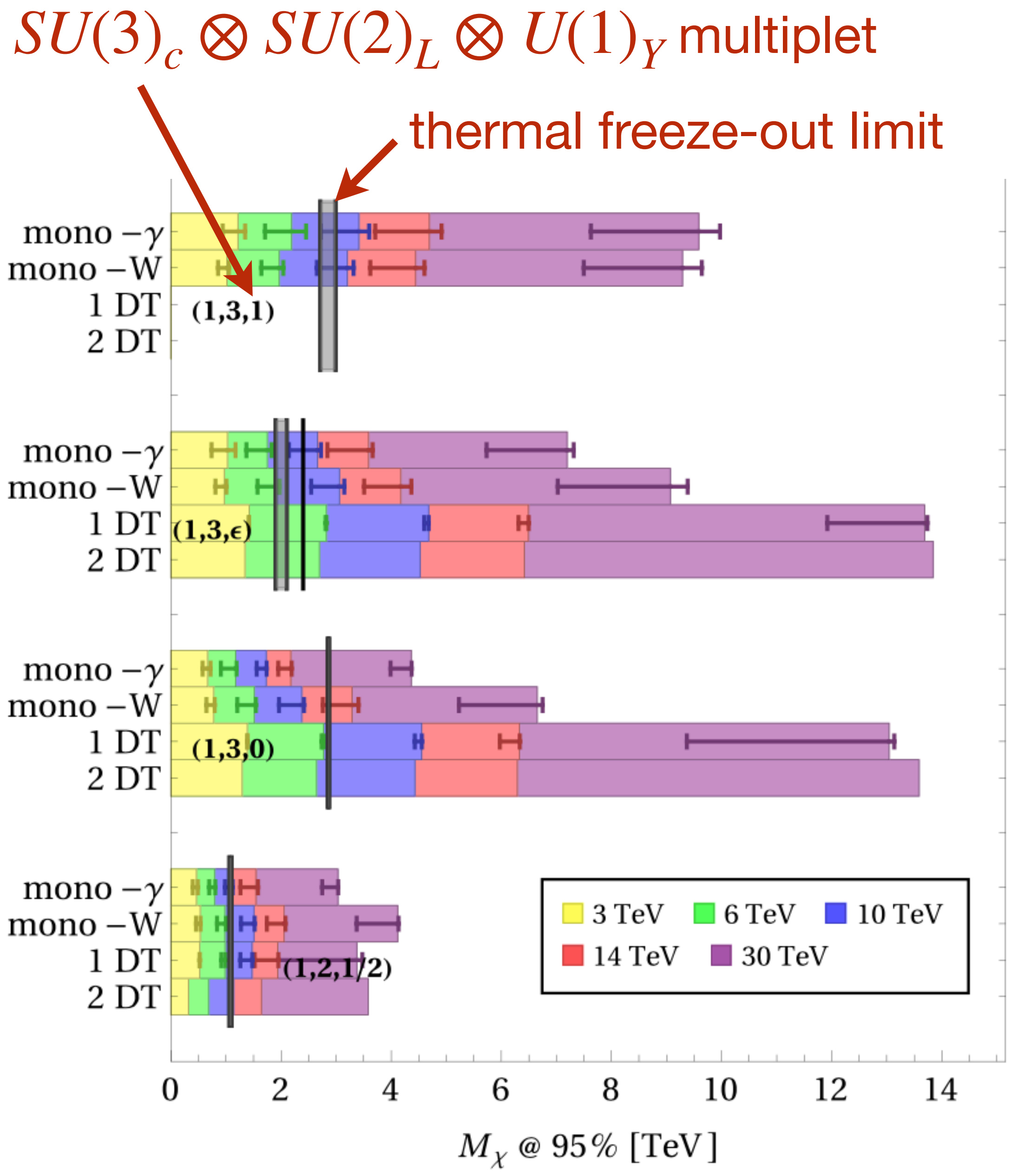
Direct BSM reach

Benefit of having high $E_{\rm CM}$ is most clear in the case of pair production of new particles: access to particles with mass $m_X \lesssim E_{\rm CM}/2$



- "straightforward" if X decay yields multiple visible decay products
- more detailed studies have been carried out to assess sensitivity to e.g. displaced tracks (as relevant in compressed SUSY WIMP DM scenarios)





$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ multiplet

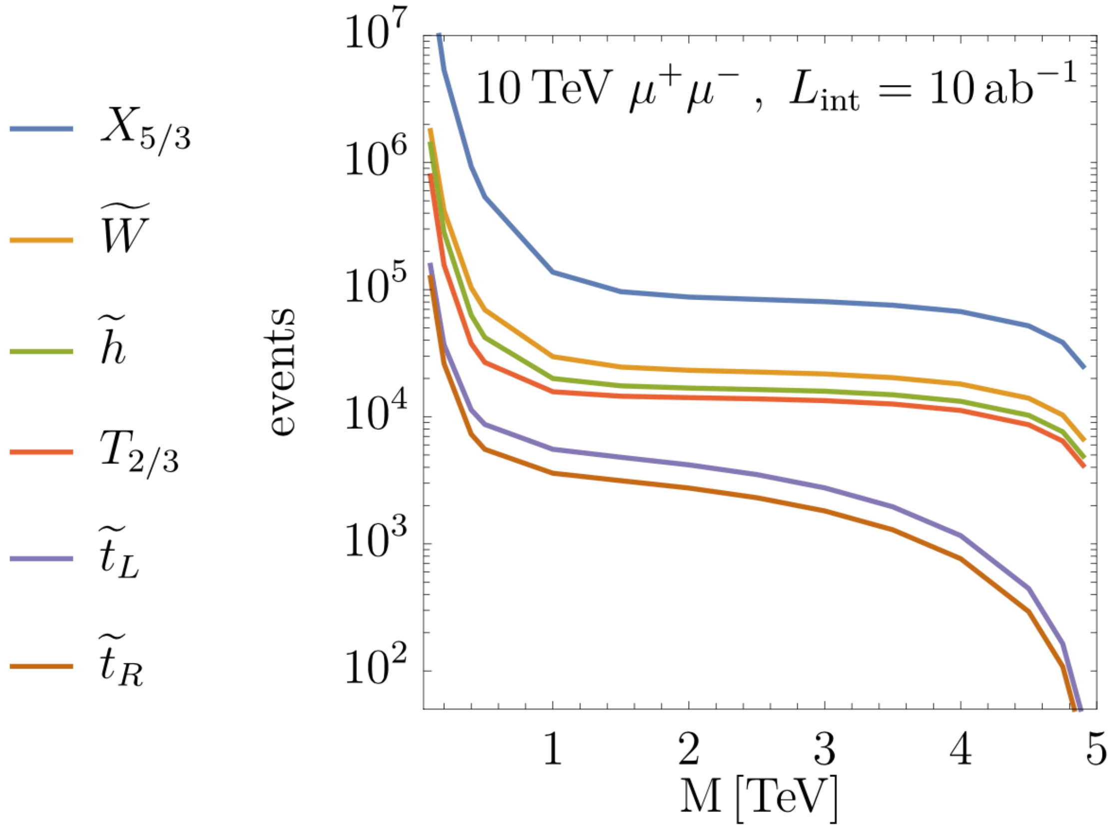
thermal freeze-out limit

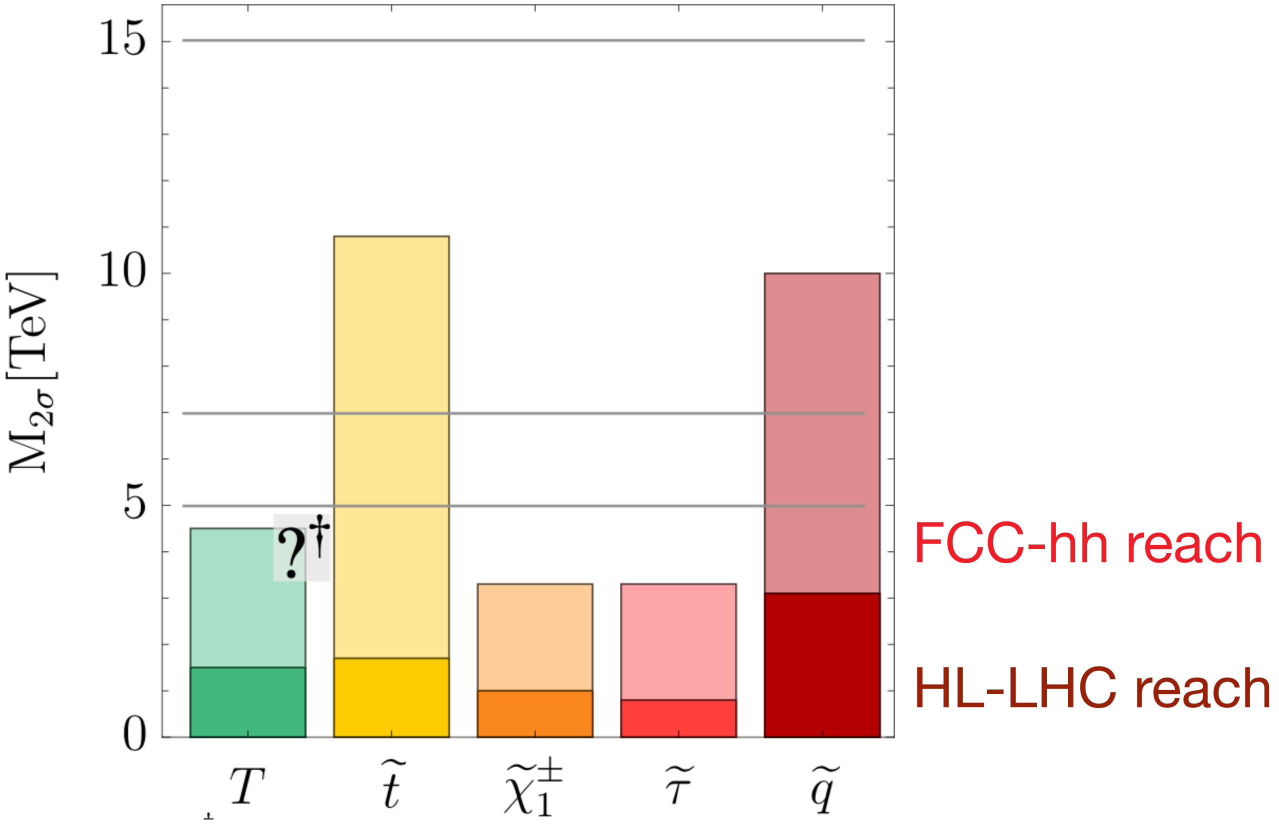
(from EPJC 2023)

Direct BSM reach

Absent clear evidence for specific BSM physics scenarios, study benchmark pair production of BSM particles

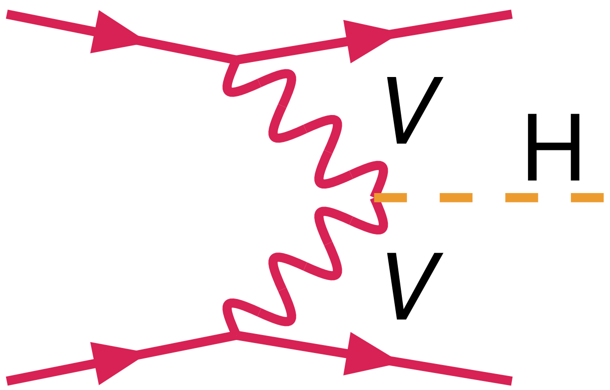
- production through gauge couplings relatively model-independent; mass reach for multiple production processes ($T, \chi_1^{\pm}, \tilde{\tau}$) may exceed that of a 100 TeV FCC-hh
- clearly conclusions change if new particles have strong couplings

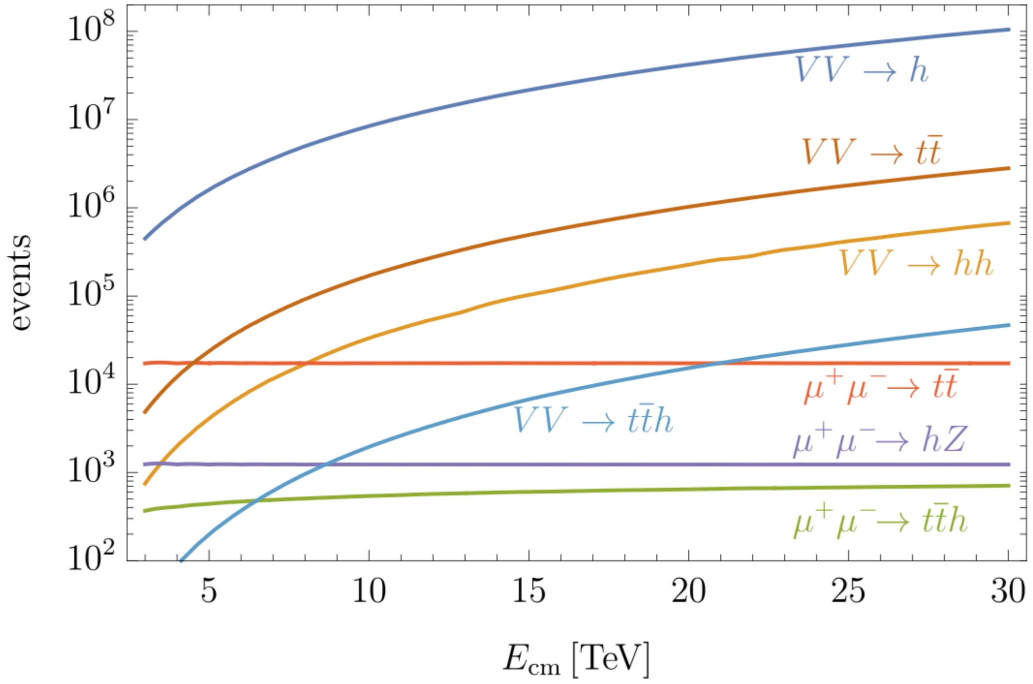




(Single-)Higgs Physics

Despite the muons’ elementary nature, the Higgs production cross section is dominated by much lower energy scales: VBF ($V = W, Z$)

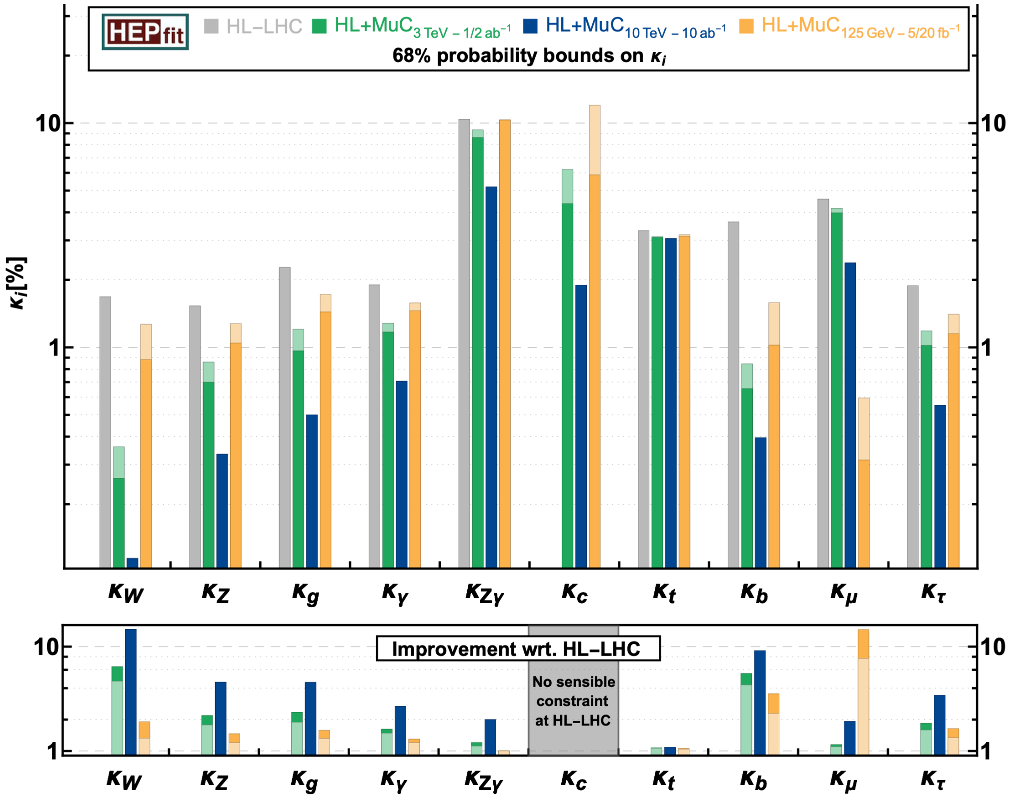




- expect ~ 10^7 single-H events in 10 ab^{-1} of 10 TeV data
- interpretation in terms of coupling constants:

$$\frac{\sigma_{i\to H}\cdot \mathrm{BR}_{H\to f}}{\sigma^{\mathrm{SM}}_{i\to H}\cdot \mathrm{BR}^{\mathrm{SM}}_{H\to f}} = \frac{\kappa_i^2\kappa_f^2}{\kappa_H^2},$$

$$\kappa_H^2 = \sum_f \kappa_f^2 \mathrm{BR}^{\mathrm{SM}}(H\to f)$$



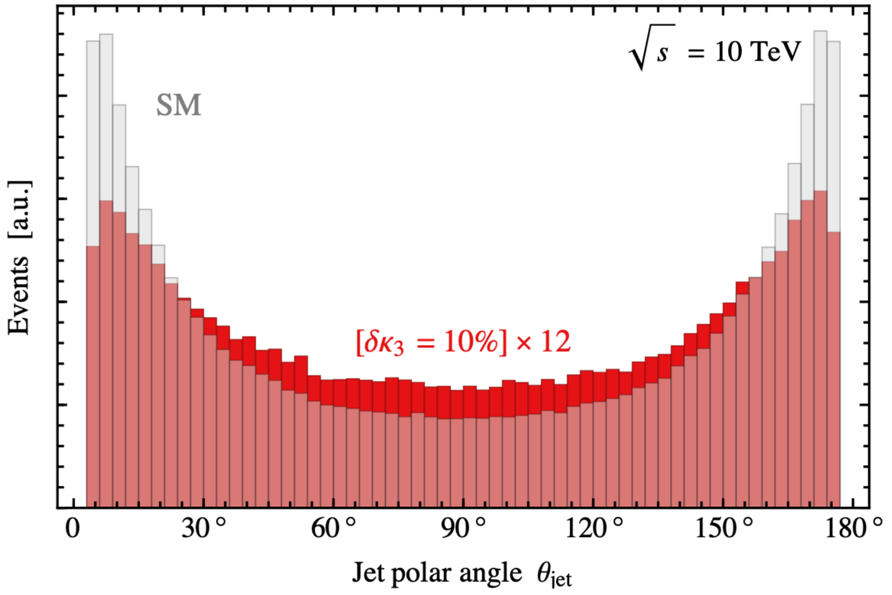
precision comparable to that obtainable with (other) Higgs factories

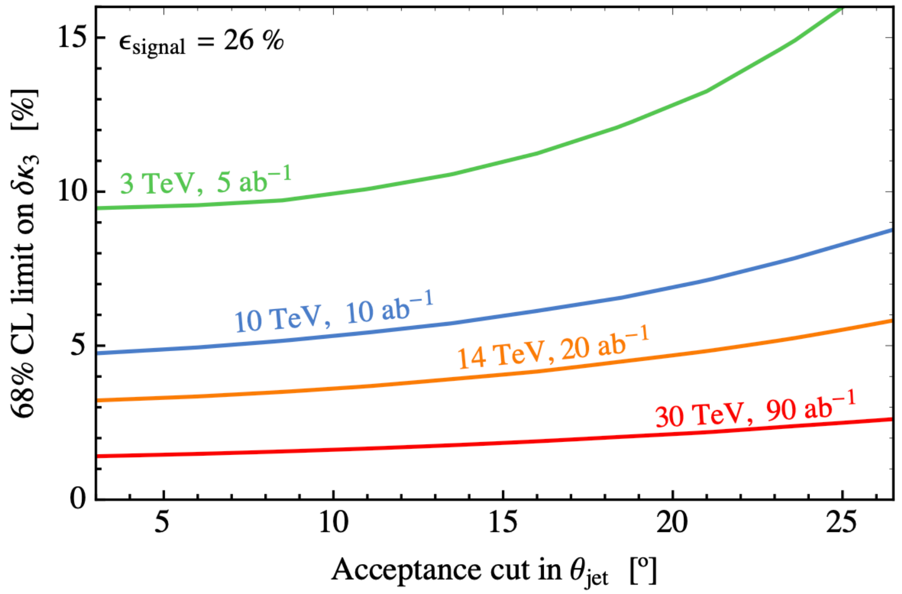
Higgs self-couplings

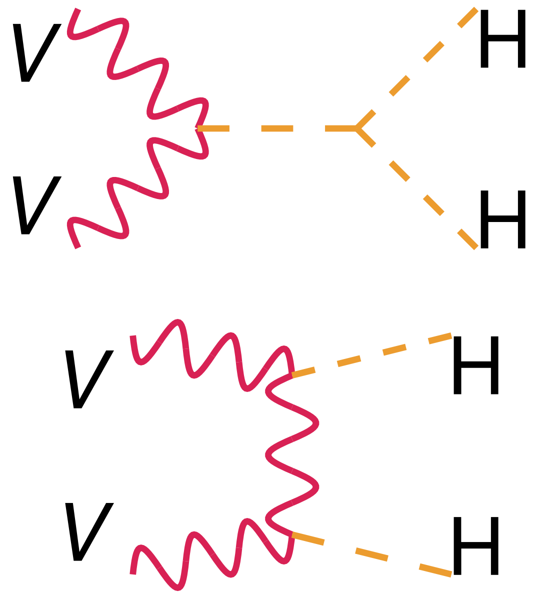
10 ab^{-1} of 10 TeV data ➠ also ~ $3\cdot10^4$ VBF-produced HH events expected according to SM: wealth of data to study the Higgs potential

$$V = \frac{m_H^2}{2}\,H^2 + \frac{m_H^2}{2v}(1+\delta\kappa_3)\,H^3 + \frac{m_H^2}{8v^2}(1+\delta\kappa_4)\,H^4$$

- in tree level EFT formulation: $\delta\kappa_3 = v^2(C_6 - \frac{3}{3}C_H)$ (coefficients of $\mathcal{O}_6$, $\mathcal{O}_H$ operators): $\mathcal{O}_6 = -\frac{m_H^2}{2v^2}(\Phi^\dagger\Phi - v^2/2)^2$, $\mathcal{O}_H = \frac{1}{2}(\partial_\mu(\Phi^\dagger\Phi))^2$







Expect ~ 5% uncertainty on $\delta\kappa_3$, somewhat dependent on angular acceptance

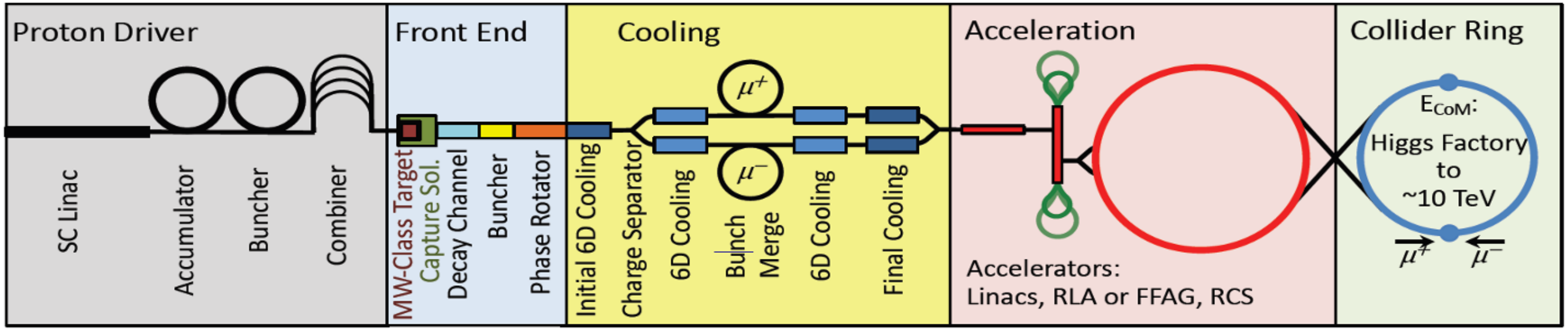
- lift degeneracy between C_6, C_H by considering high-m_{HH} tail specifically ($\mathcal{O}_H$ sensitive to compositeness)

Challenge: $\mu^{\pm}$ production

$\tau_\mu \approx 2.2\,\mu\text{s}$ ➠ need a high muon production rate

Baseline: production from $\pi^{\pm} \to \mu^{\pm}\nu_\mu(\bar{\nu}_\mu)$, with $\pi^{\pm}$ produced in proton-nucleus collisions

- premium on high-power (2—4 MW) target (Hg jet) and efficient capture of $\pi^{\pm}$ ($B \lesssim 20$ T solenoid) to produce ~ 10^{11} μ / s



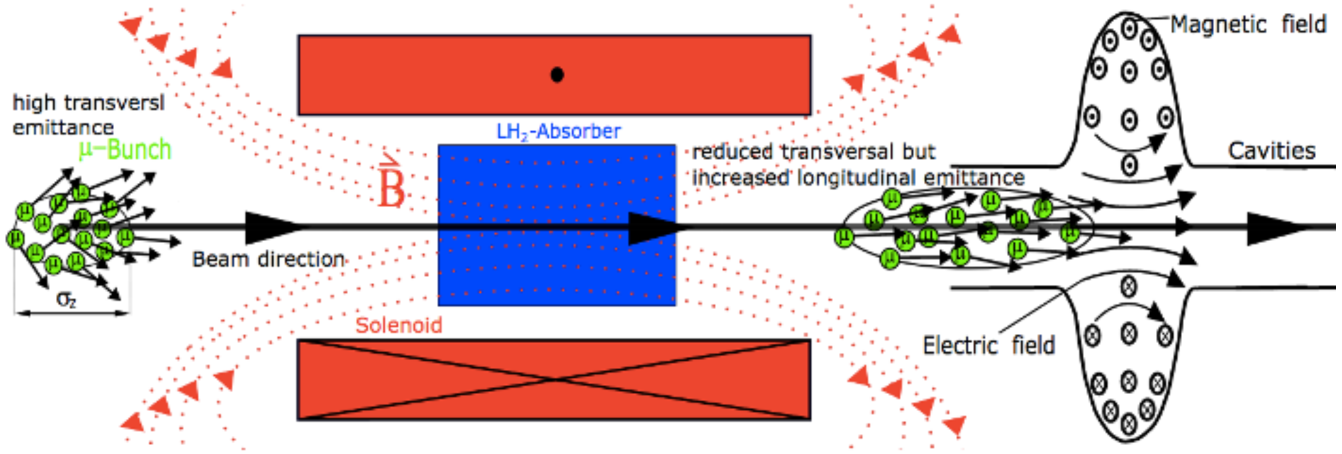
- alternative Low-EMittance Muon Accelerator (LEMMA) scheme: start with ~ 45 GeV e^+ beam impinging on e^- at rest ➠ threshold for $e^+e^- \to \mu^+\mu^-$ production (fully collimated in lab system)

- limitation: e^+ production $\mathcal{O}(10^{15}/\text{s})$

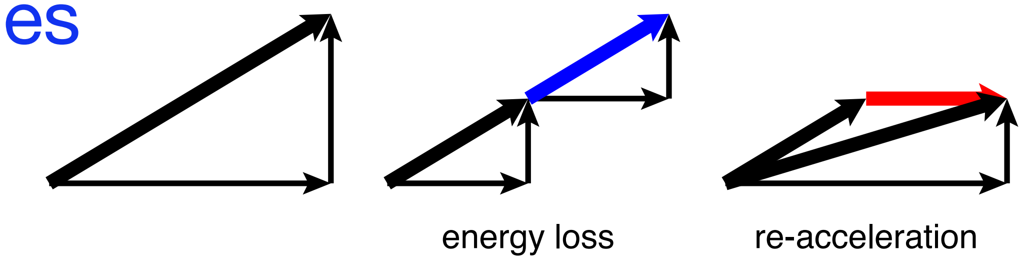
Challenge: $\mu^\pm$ cooling

In the baseline production scenario, rapid cooling is needed before acceleration is possible: ionisation cooling

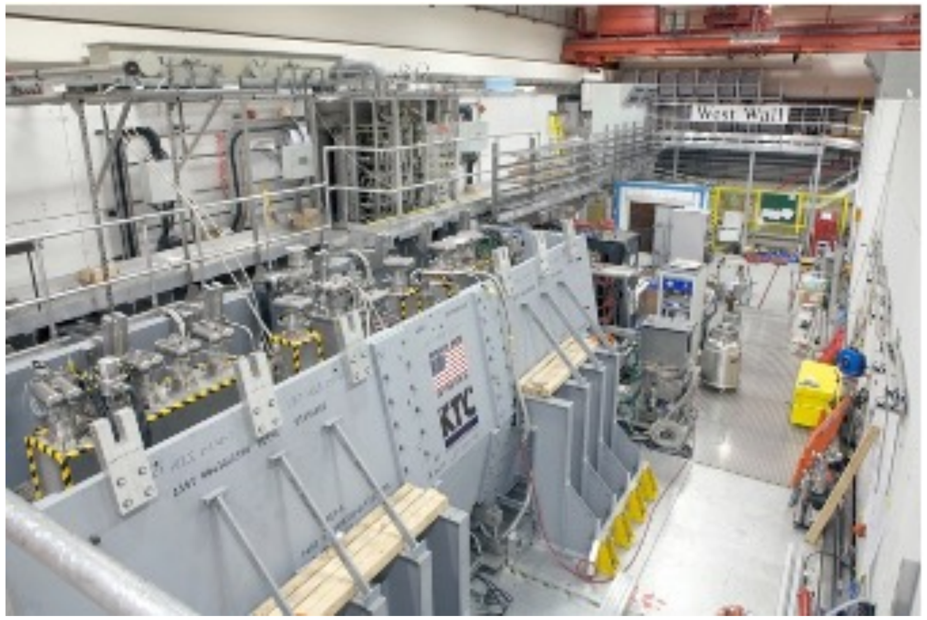
- minimise multiple Coulomb scattering by having E loss occur in low-Z material: LH_2
- all in a strong solenoidal field

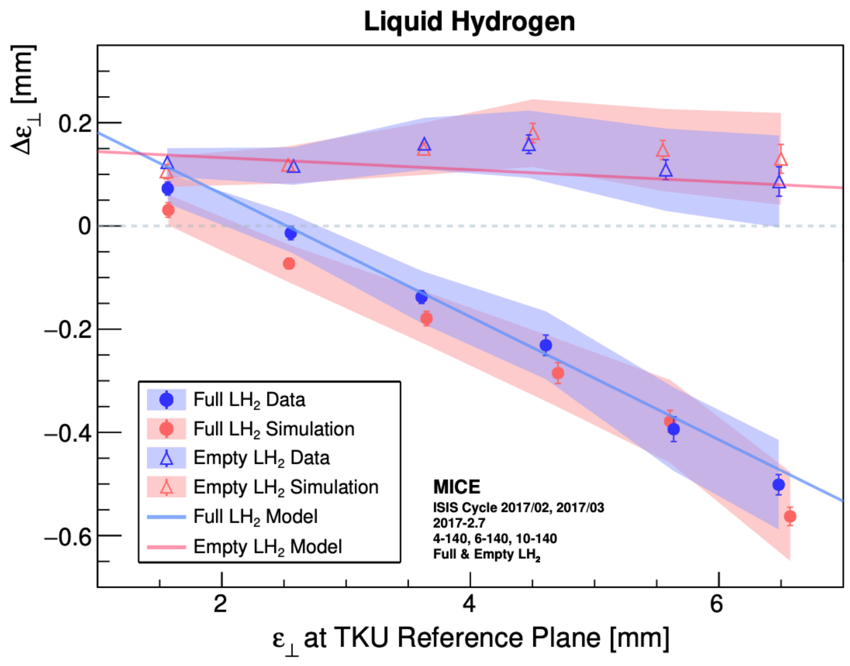


Physics of E loss by charged particles in matter is well understood, but technical challenges are significant



- demonstration (w/o RF re-acceleration): MICE, Nature 578 (2020) 53



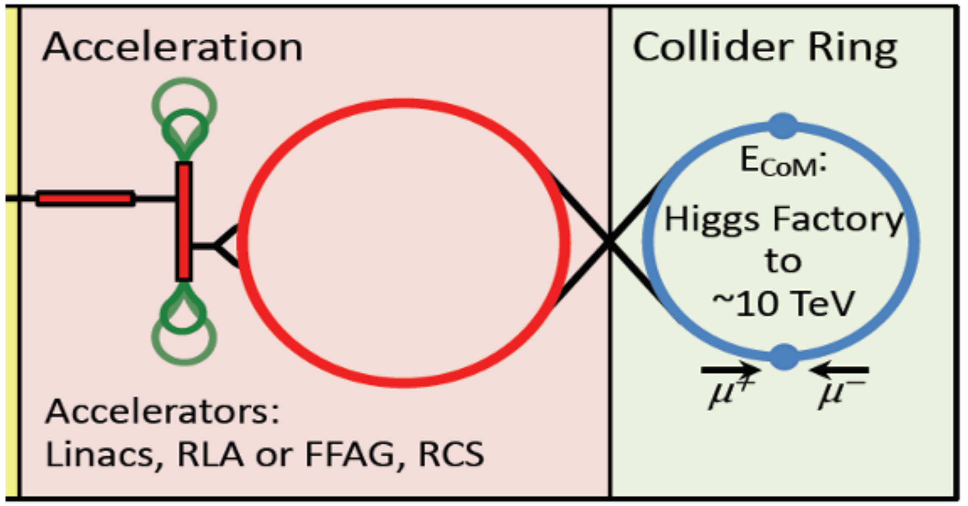


- more quantitative emittance evaluation: arXiv:2310.05669

Challenges: acceleration, ν radiation

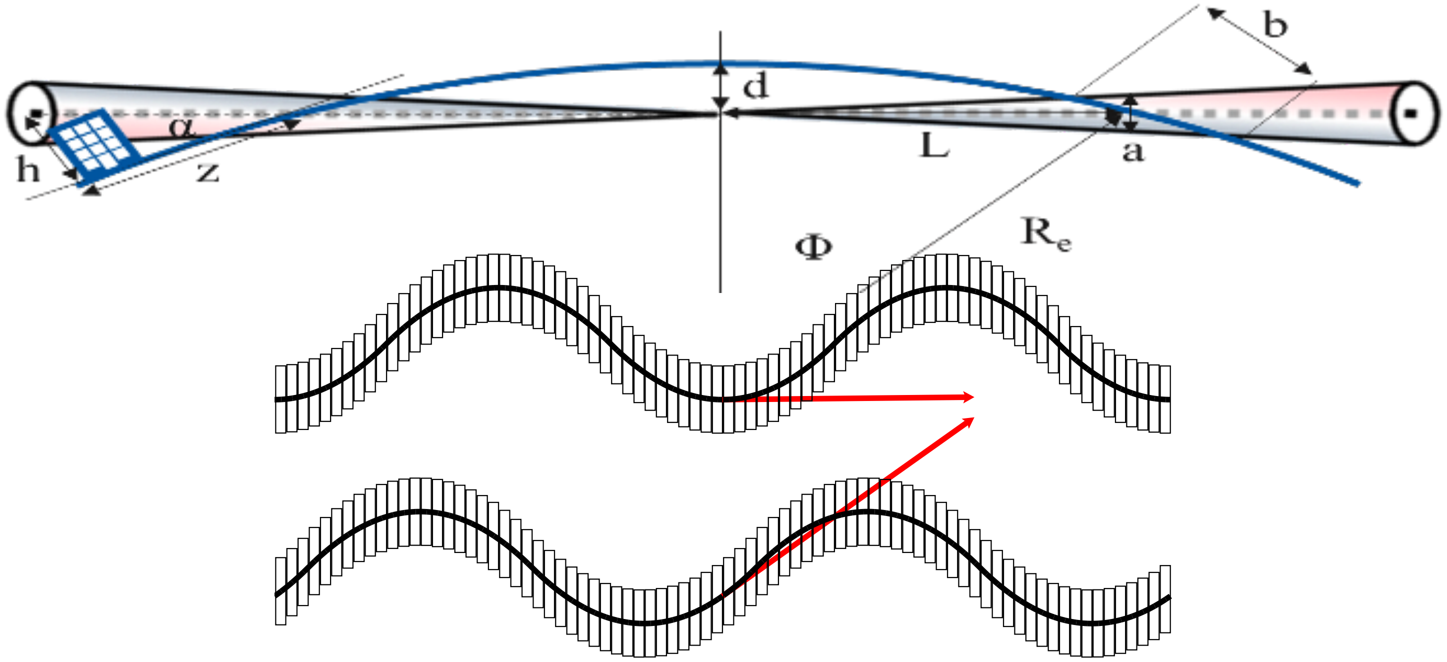
Short τ_μ also means that acceleration needs to be done very rapidly (perhaps 100 μs) ➠ cost efficiency: combination of recirculating linacs + rapid-cycling synchrotron

- different CM energies require different RCS



$\nu - N$ interaction cross section $\propto E_\nu$ ➠ ν radiation from the collider is a concern

- plan: time-dependent deformation of the μ trajectory to spread radiation over a larger area
  - at 5 TeV beam energy, it may be necessary to place beam line components on movers



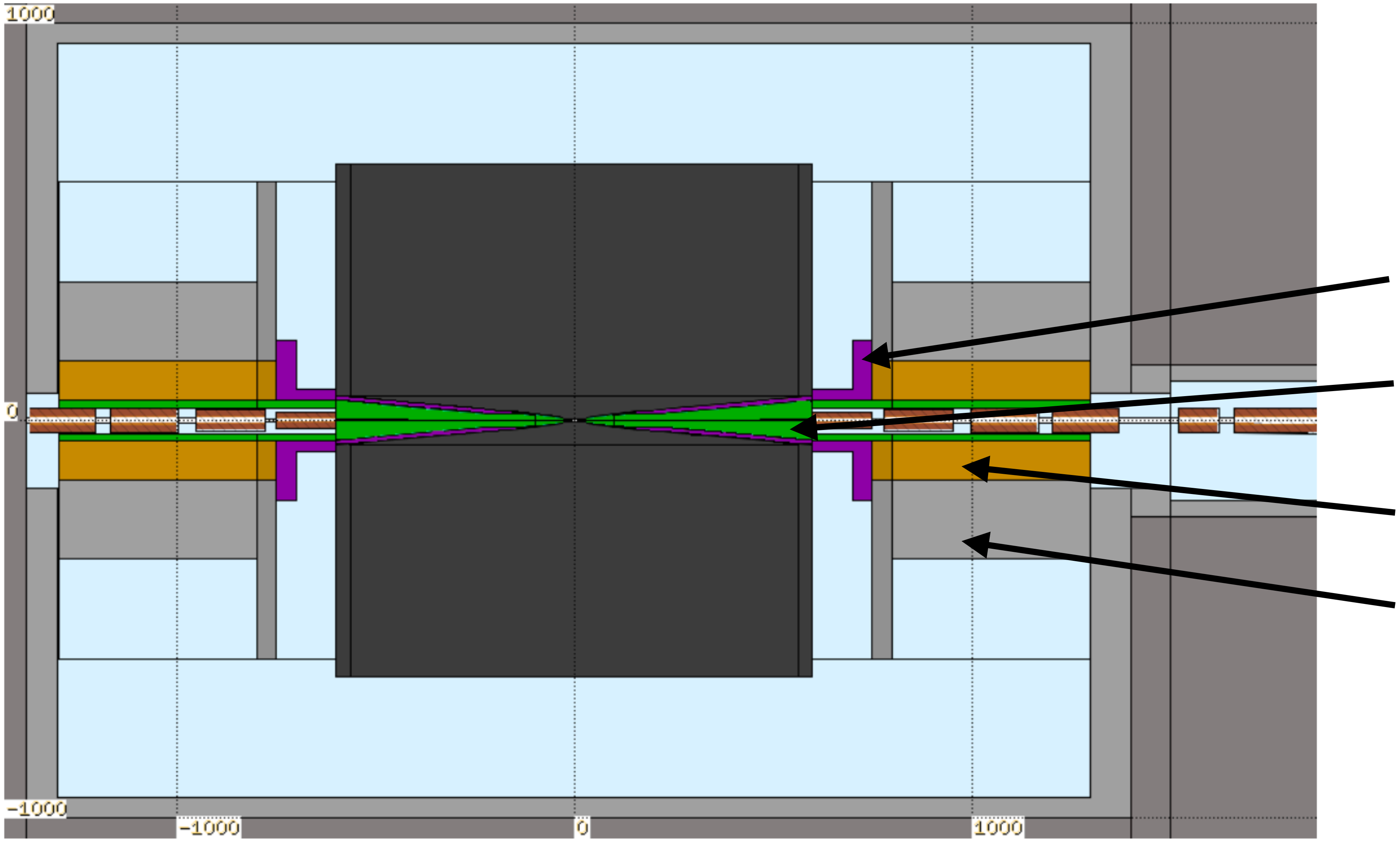
Also need to shield magnets from decay $e^\pm$

Beam-induced background

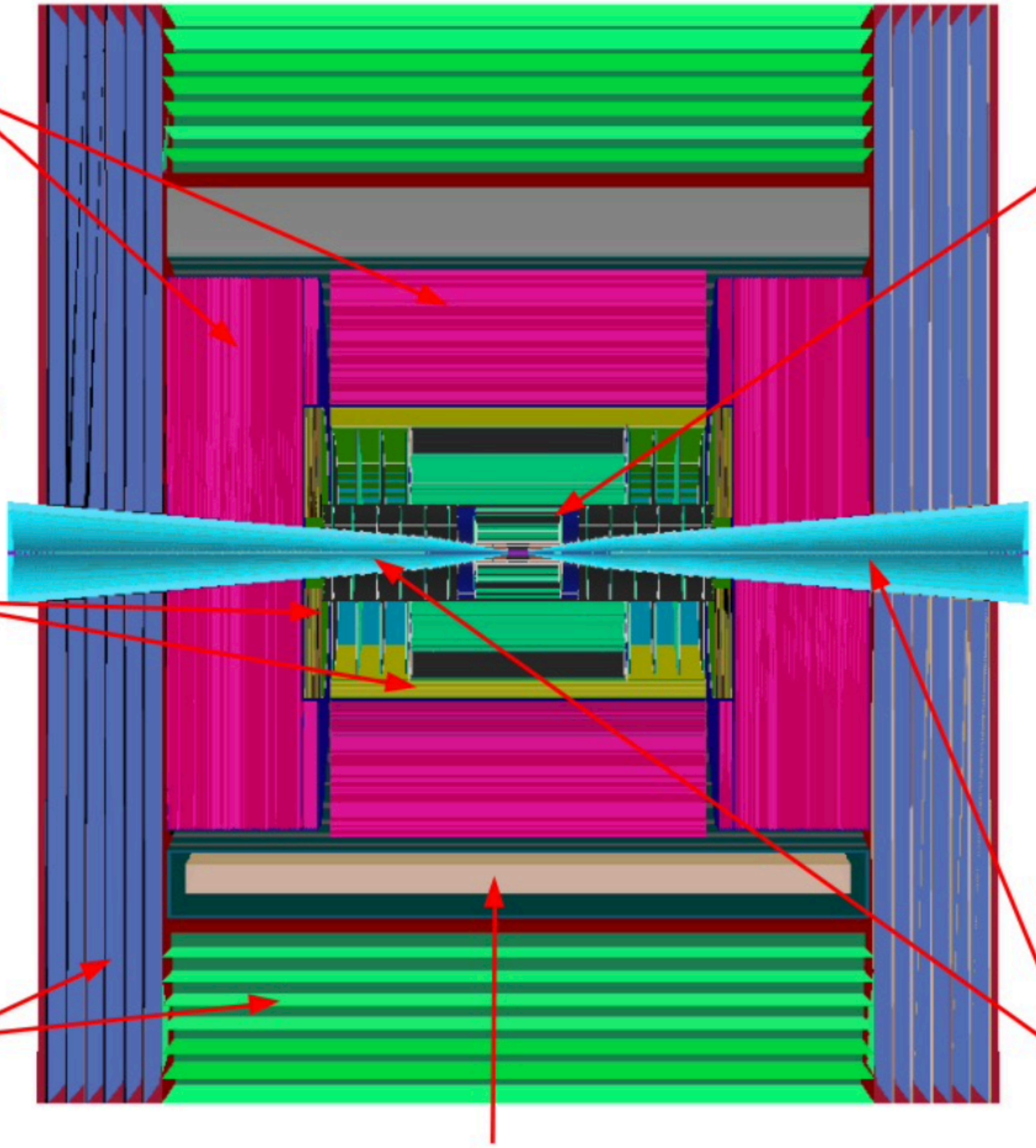
For 5 TeV μ: $\gamma = 2.4\ 10^4$ ➠ decay length in lab frame is ~ 1.6 10^7 m.

With 2 10^{12} μ / bunch: ~ 10^5 μ decays / m: challenging background!

- direct decay $e^{\pm}$ but also secondary particles from interactions with upstream accelerator elements ➠ shielding is an important consideration
  - in particular, tungsten nozzle limiting acceptance in θ, likely by 10°



Detector



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.

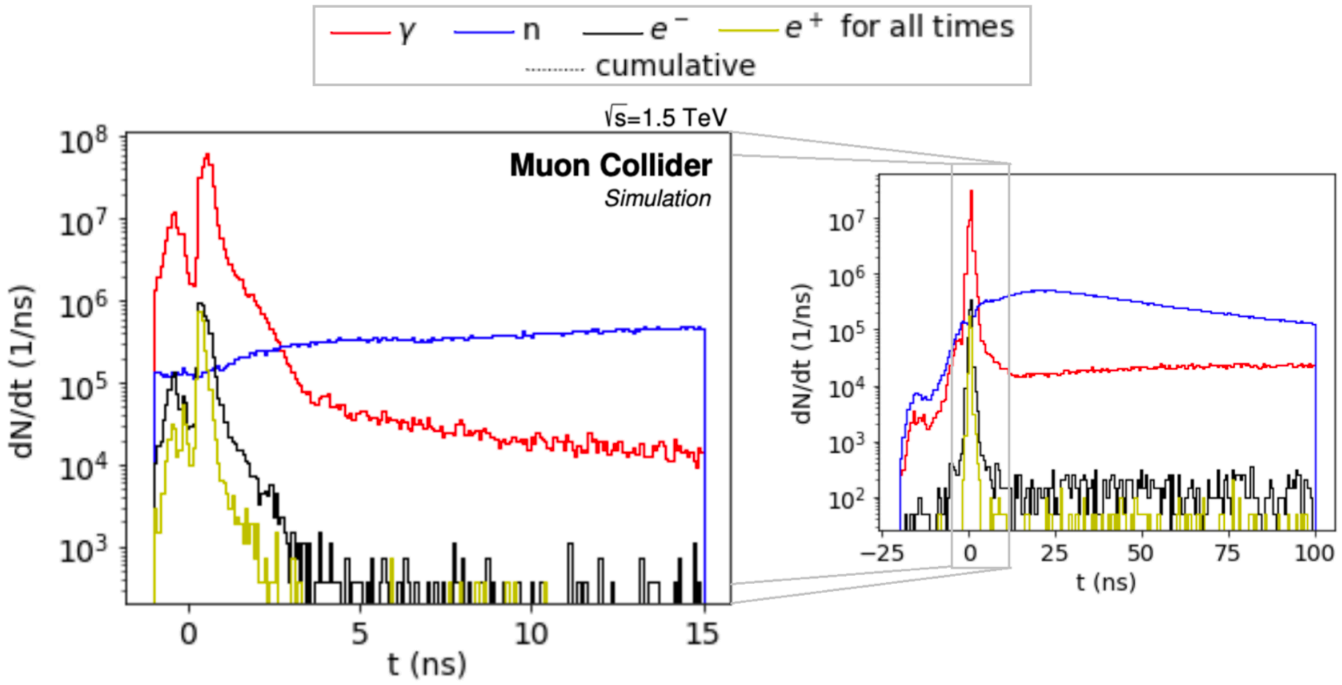
shielding nozzles

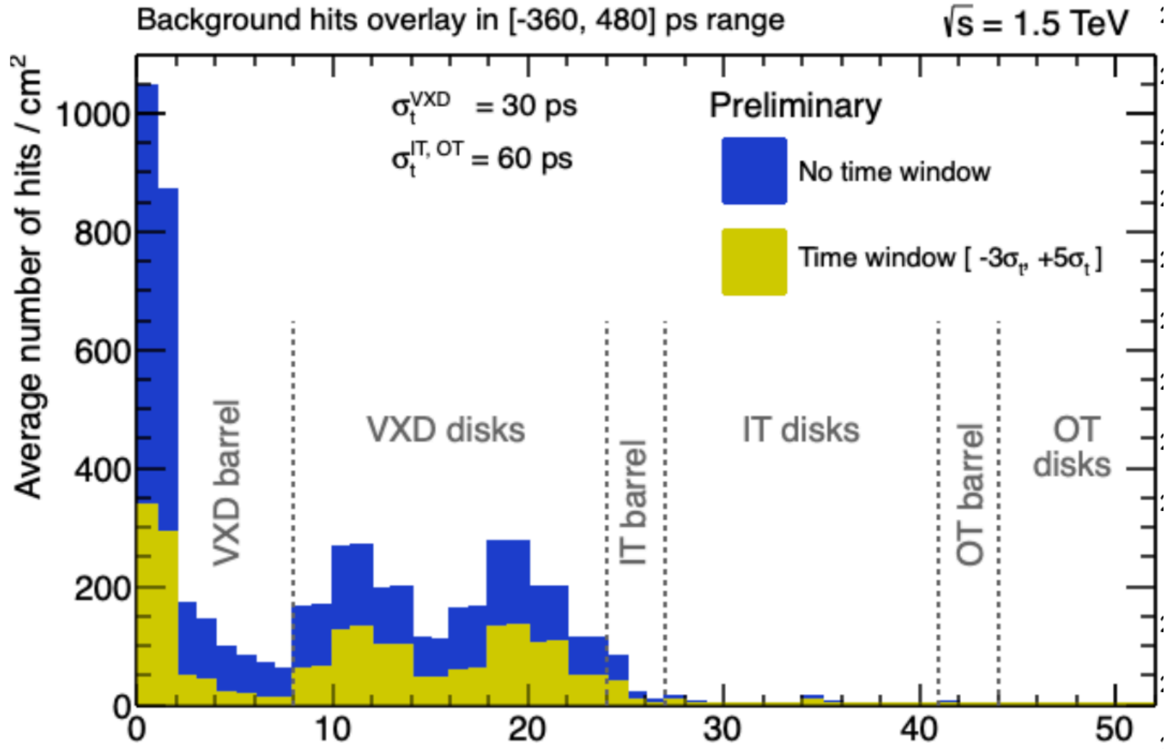
- Tungsten cones + borated polyethylene cladding.

Tracking & vertex detectors

Beam-induced background remaining after shielding is still a problem

- fine granularity to reduce occupancy
- precise timing (30 ps for vertexing, 60 ps for tracking assumed)
- challenge for the vertex detector, especially for small pixel size ($25\ \mu m \times 25\ \mu m$)
- need for “4D tracking”





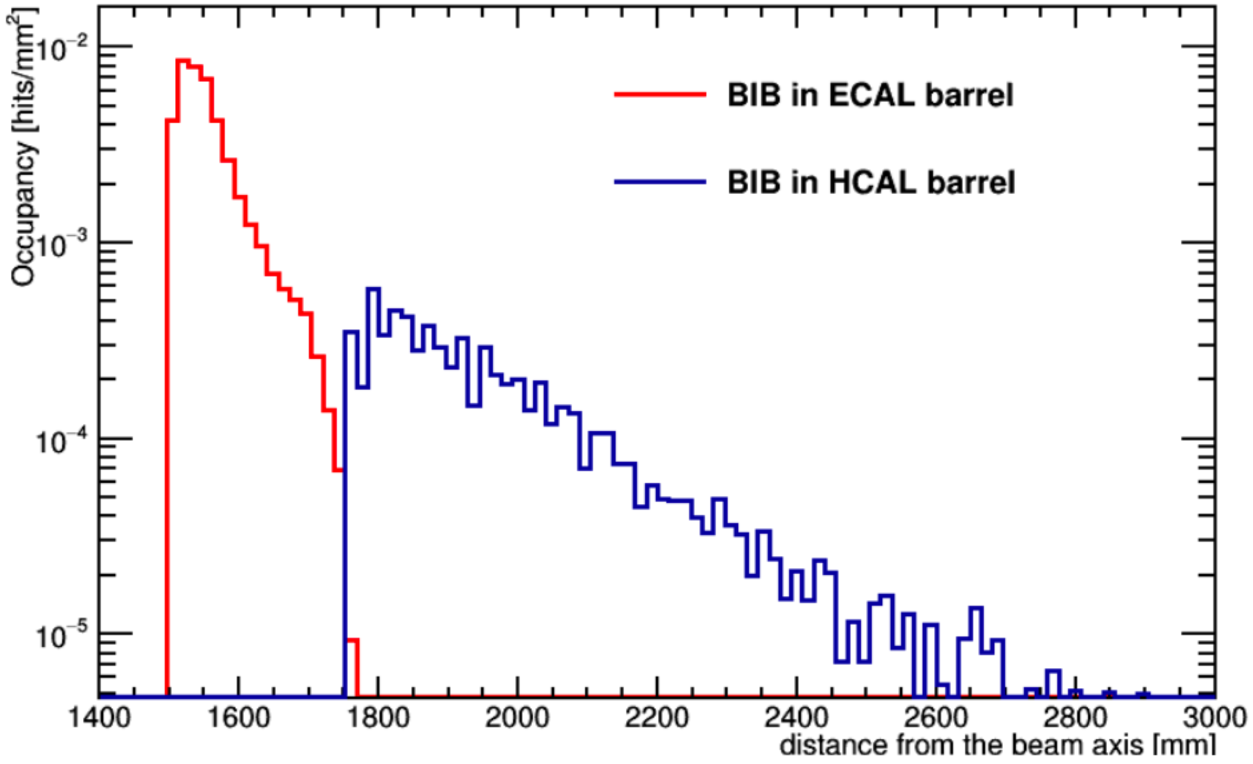
Calorimeters

Goal: resolve jet substructure in highly collimated high-momentum jets

- high granularity needed (5 mm × 5 mm in ECAL: Si + W)
  - performance studies to date mainly focus on jets with $p_\mathrm{T} < 200$ GeV

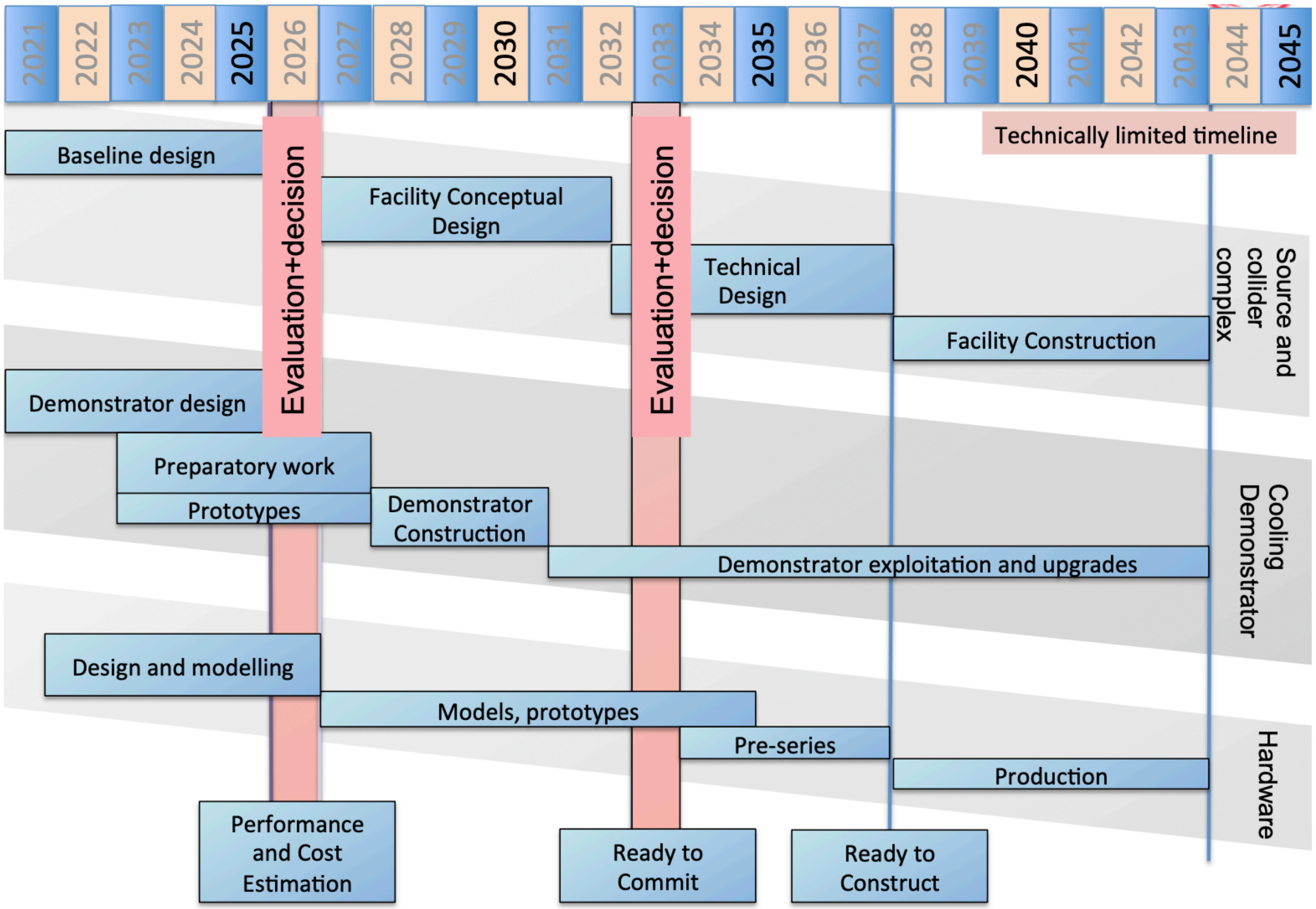
Beam-induced background is an issue especially in the ECAL

- good timing again should help to suppress this (aiming at 300 ps window)
- aided further by fine longitudinal sampling (ECAL: 40 layers)



Technically limited timeline

Ignoring funding issues and assuming good progress



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Source and collider complex

Baseline design

Evaluation+decision

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Models, prototypes

Pre-series

Production

Performance and Cost Estimation

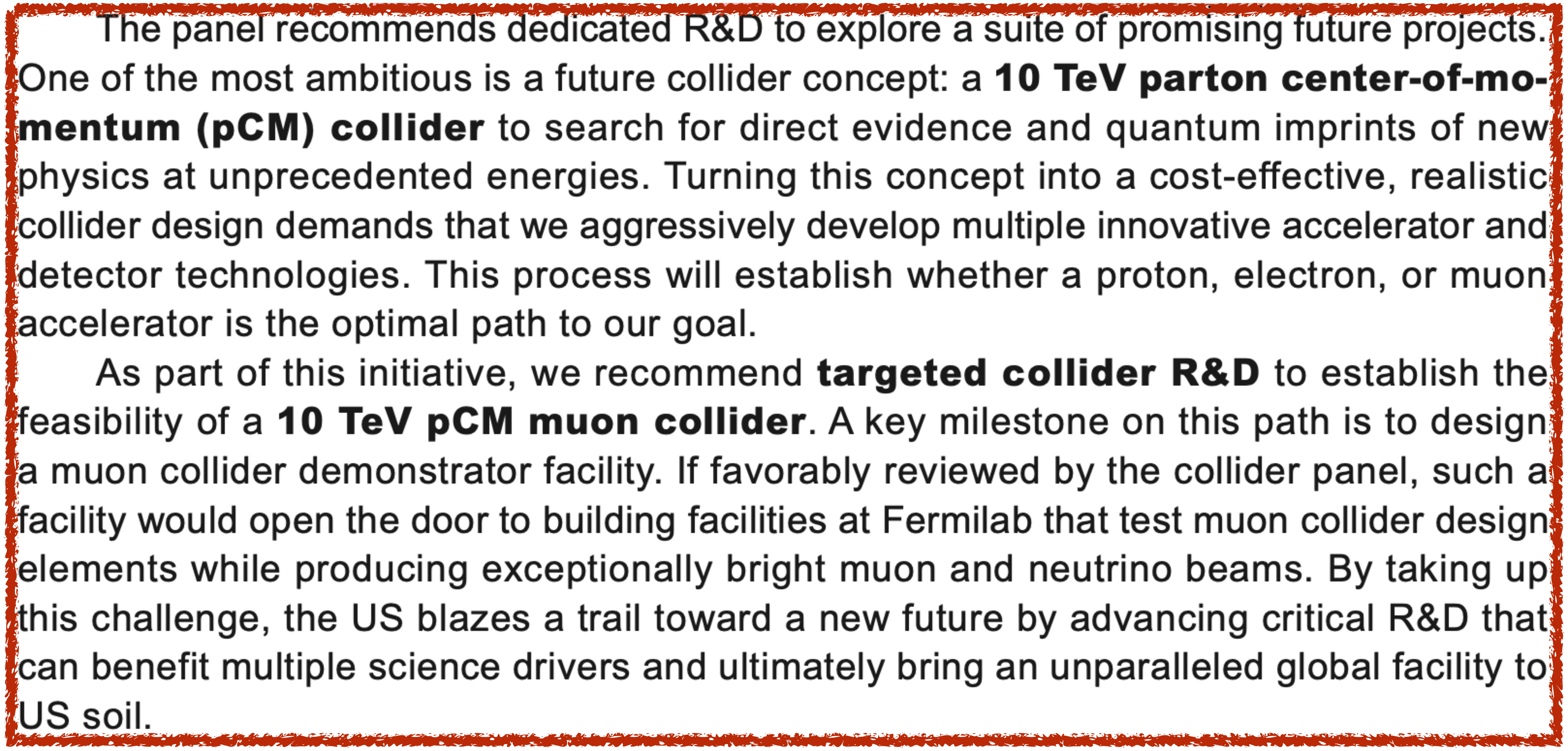
Ready to Commit

Ready to Construct

Technically limited timeline

Ignoring funding issues and assuming good progress

Report from the Particle Physics Project Prioritisation Panel:



The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM) collider** to search for direct evidence and quantum imprints of new physics at unprecedented energies. Turning this concept into a cost-effective, realistic collider design demands that we aggressively develop multiple innovative accelerator and detector technologies. This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.

Summary & outlook

A Muon Collider offers a promising (even if challenging) avenue to probe the high-energy frontier on a manageable timescale

There is still significant work to be done to

- assess its physics capabilities
- optimise its accelerator parameters and detector configuration

You are very welcome to join the effort!

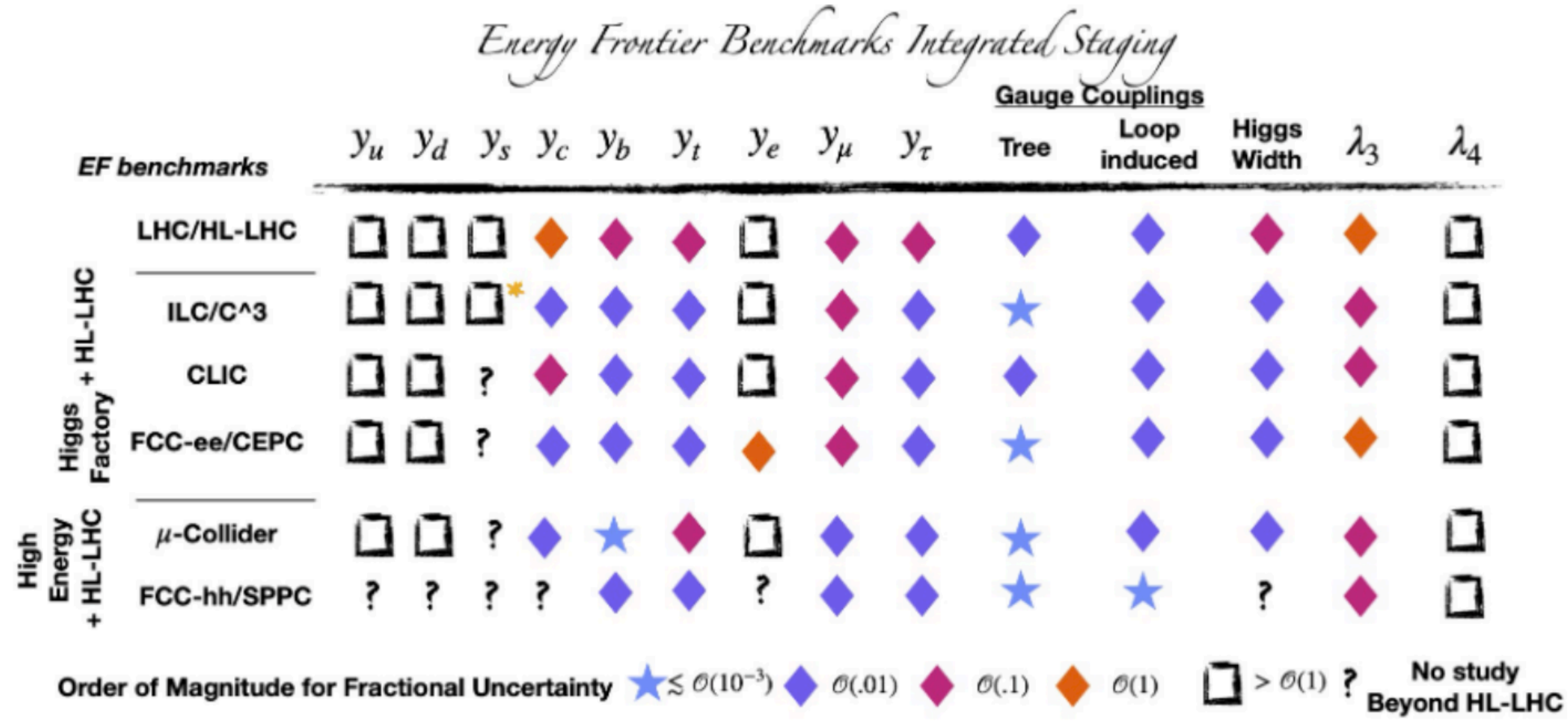
References

General references:

- EPJC paper to be submitted
- arXiv: 2103.14043

Higgs self-couplings: arXiv:2012.11555

Physics capabilities



Energy Frontier Benchmarks Integrated Staging

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings Tree	Gauge Couplings Loop induced	Higgs Width	λ_3	λ_4
Higgs Factory + HL-LHC	LHC/HL-LHC	☐	☐	☐	🔶	◆	◆	☐	◆	◆	🔷	🔷	◆	🔶	☐
	ILC/C^3	☐	☐	☐*	🔷	🔷	🔷	☐	◆	🔷	★	🔷	🔷	◆	☐
	CLIC	☐	☐	?	◆	🔷	🔷	☐	◆	🔷	🔷	🔷	🔷	◆	☐
	FCC-ee/CEPC	☐	☐	?	🔷	🔷	🔷	🔶	◆	🔷	★	🔷	🔷	🔶	☐
High Energy + HL-LHC	μ-Collider	☐	☐	?	🔷	★	◆	☐	🔷	🔷	★	🔷	🔷	◆	☐
	FCC-hh/SPPC	?	?	?	?	🔷	🔷	?	🔷	🔷	★	★	?	◆	☐

Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ 🔷 $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ 🔶 $\mathcal{O}(1)$ ☐ $> \mathcal{O}(1)$? No study Beyond HL-LHC