BSM perspective on Future Colliders (including a Muon Collider)

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Refs: my personal view, FCC-CDR, Muon collider studies for Snowmass 2021,

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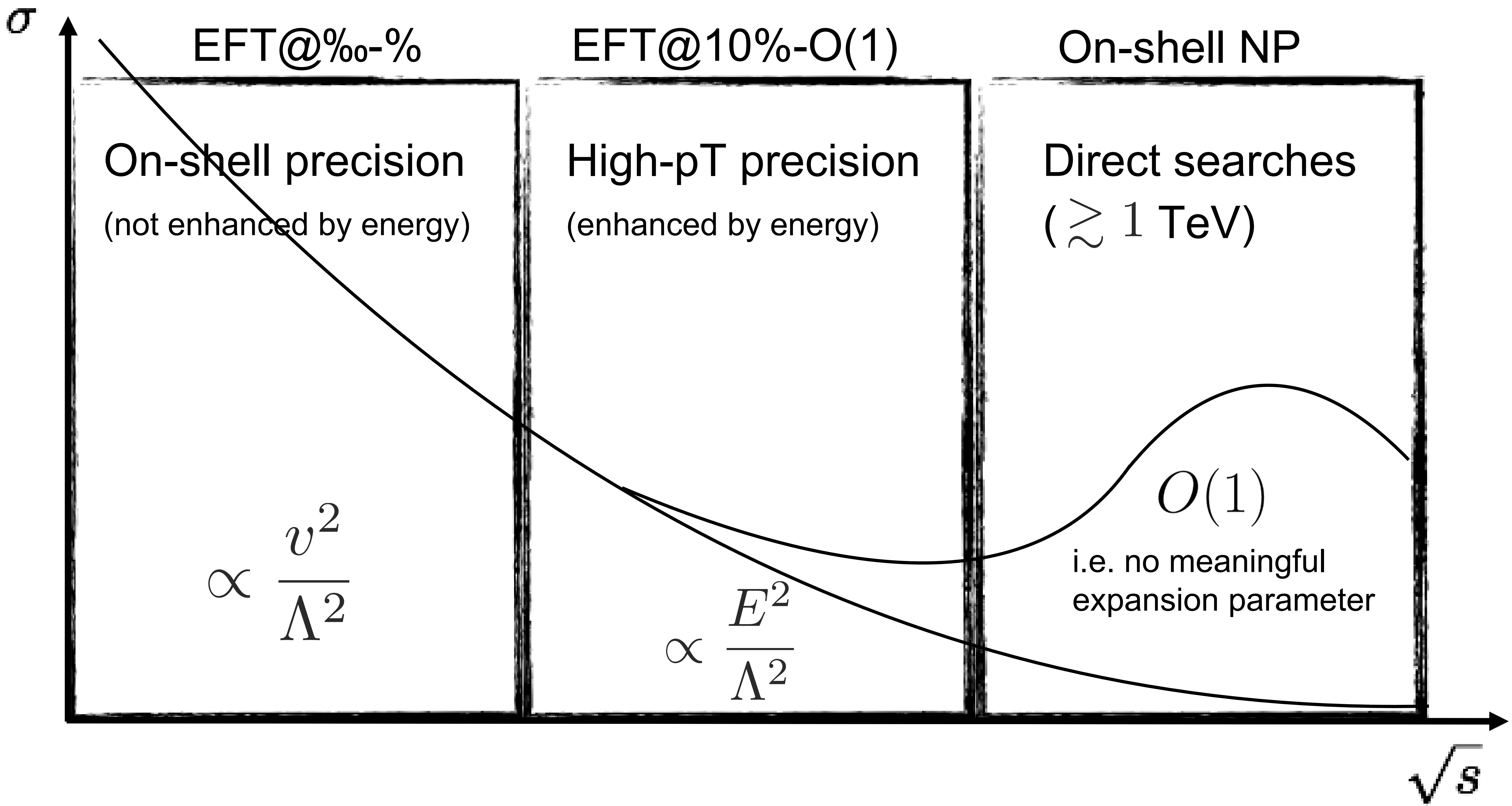
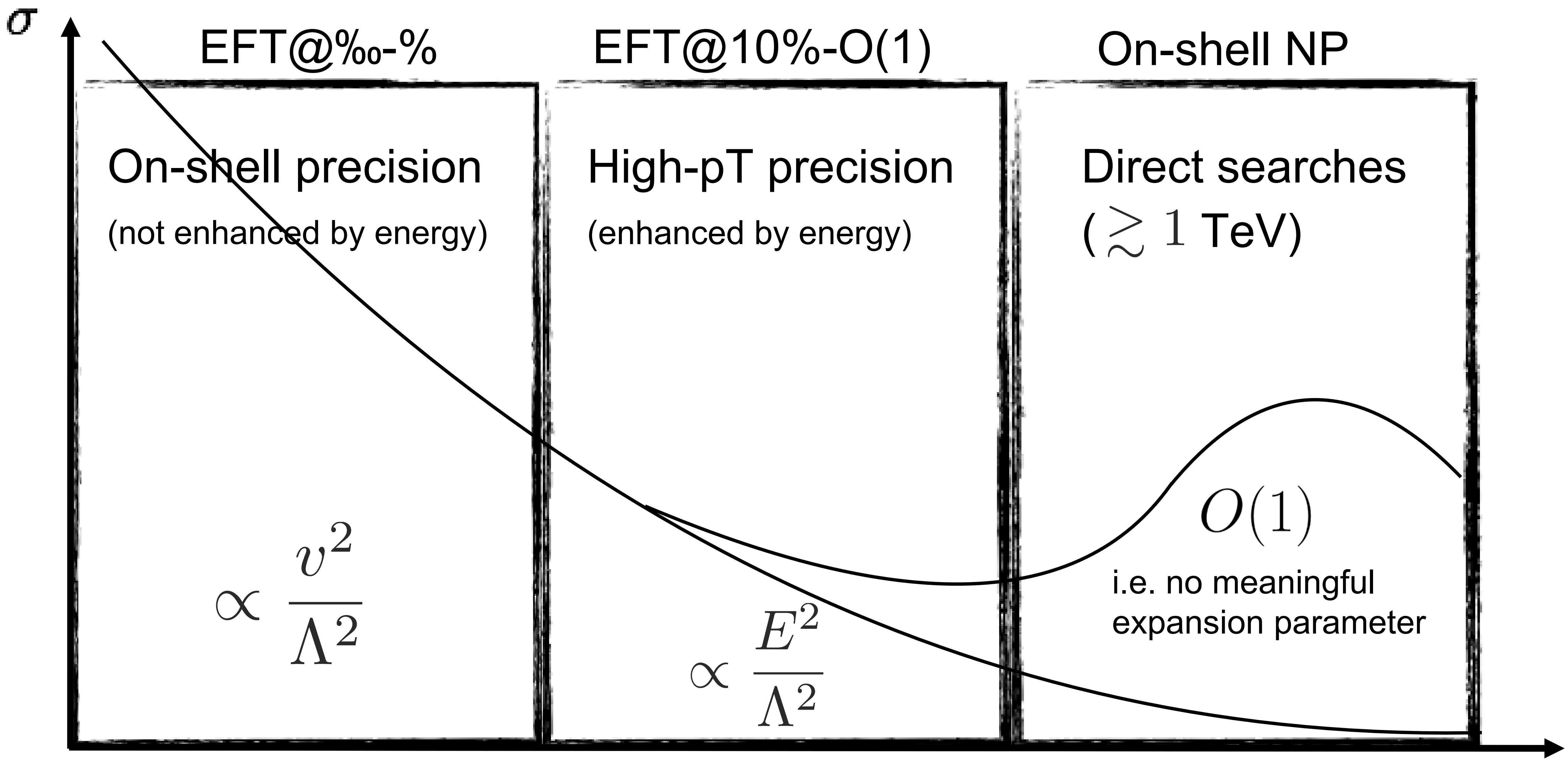
INTRODUCTION

Which BSM?



σ
EFT@‰-%
EFT@10%-O(1)
On-shell NP
On-shell precision
(not enhanced by energy)
High-pT precision
(enhanced by energy)
Direct searches
($\gtrsim 1$ TeV)
$\propto \frac{v^2}{\Lambda^2}$
$\propto \frac{E^2}{\Lambda^2}$
$O(1)$
i.e. no meaningful
expansion parameter
$\sqrt{s}$

Which BSM?

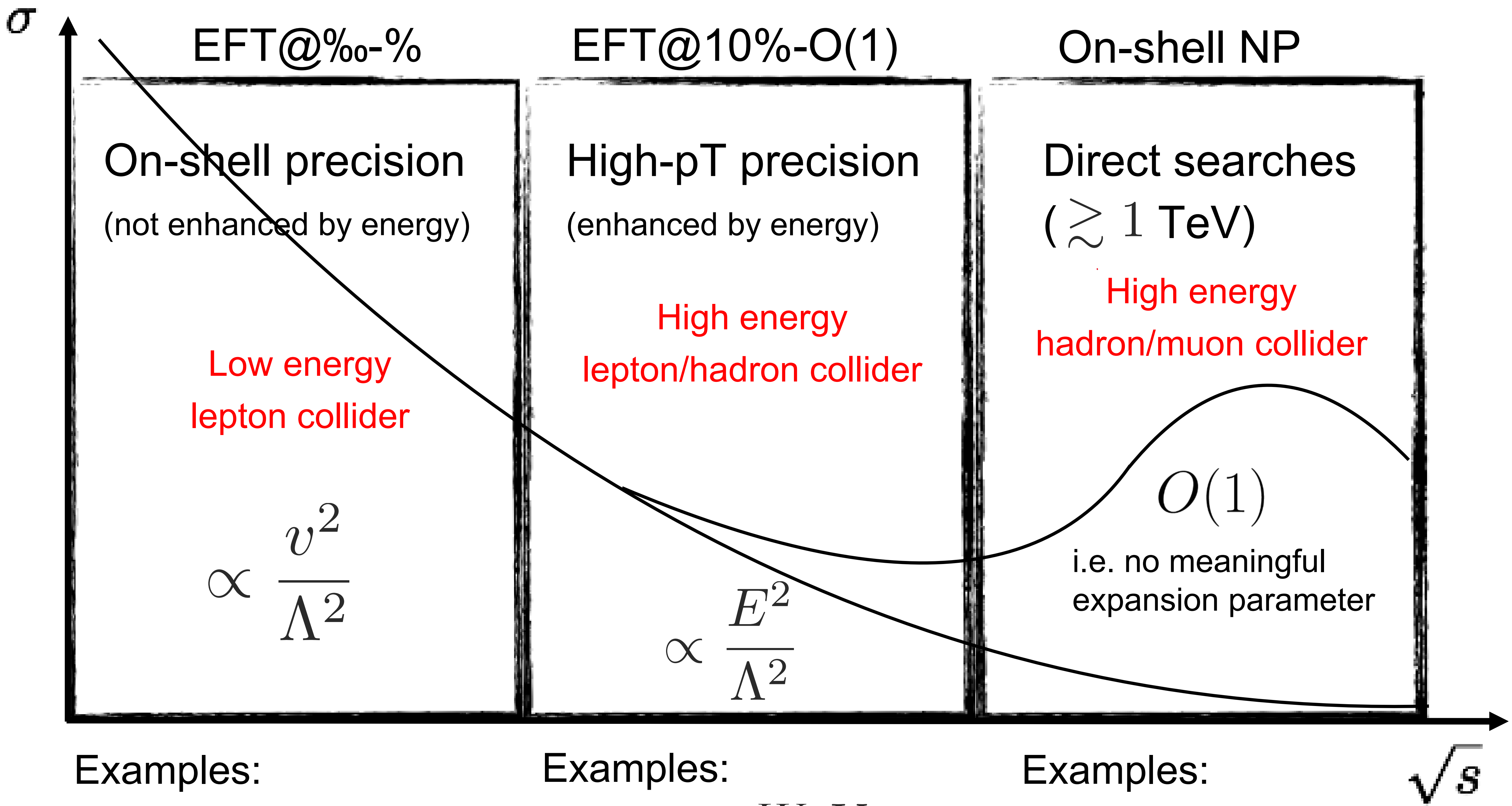


Examples:
- SM parameters
- Pole observables e.g. $\hat{S}$, $\hat{T}$, etc.
- Higgs observables

Examples:
- DY (e.g. W, Y, etc.)
- Di-bosons
- Di-jets
- Heavy quarks ($t\bar{t}$,…)

Examples:
- SUSY
- Top partners
- Resonances

Which BSM?



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On-shell vs off-shell precision

Compare for instance LEP and LHC sensitivity to interactions of the form

Z-pole observable

$$-\frac{\hat{S}}{4m_W^2}(H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu}$$

LEP	**LHC**
Energy: ~100 GeV	Energy: ~1 TeV
Accuracy: ~‰-%	Accuracy: ~10%
New physics effects not enhanced by energy	New physics effects not enhanced by energy

LHC "cannot" compete with LEP

off Z-pole observable

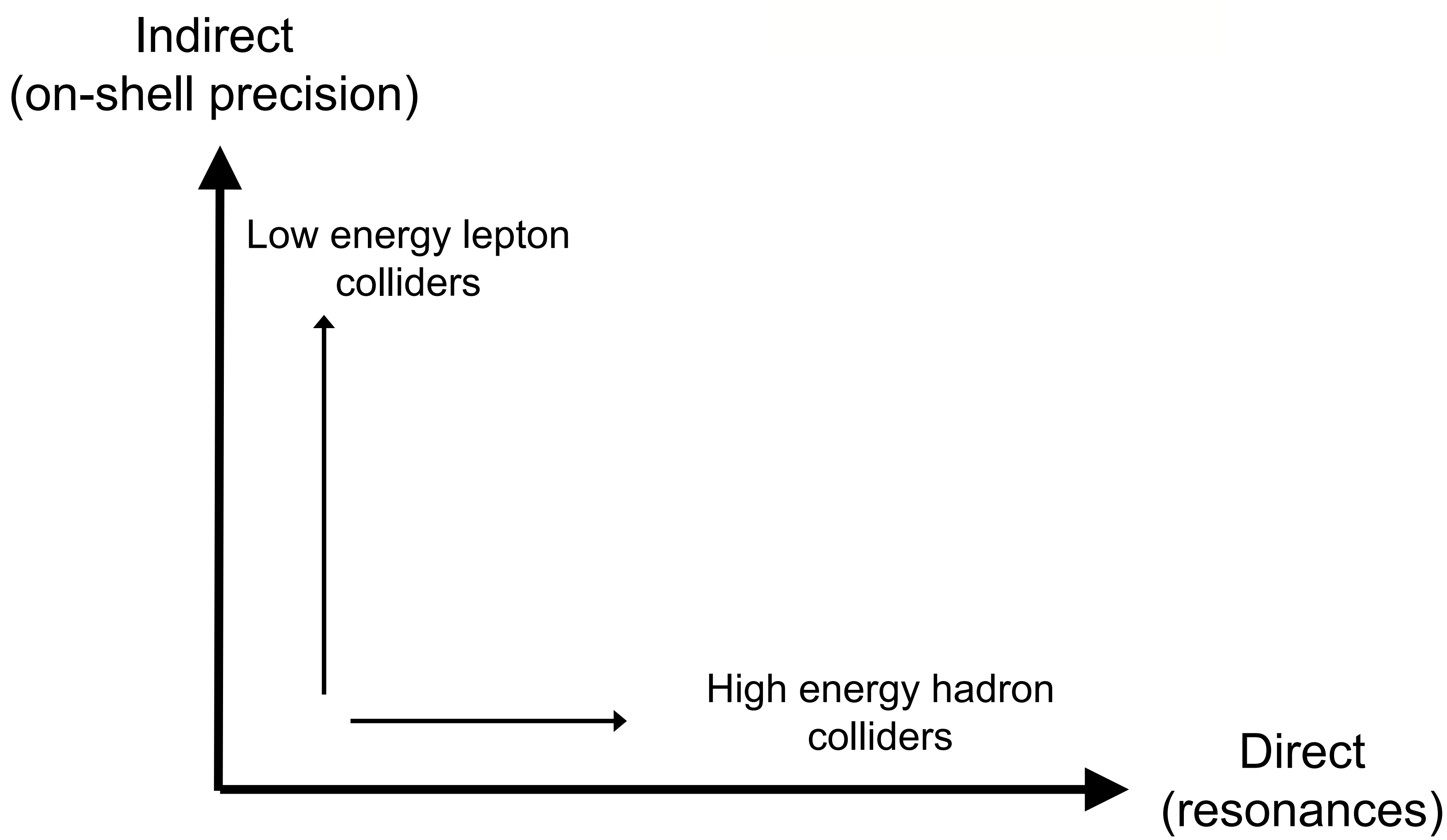
$$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

LEP	**LHC**
Energy: ~100 GeV	Energy: ~1 TeV
Accuracy: ~‰-%	Accuracy: ~10%
New physics effects not enhanced by energy	New physics effects enhanced by $E^2_{\rm LHC}/E^2_{\rm LEP} \sim 100$

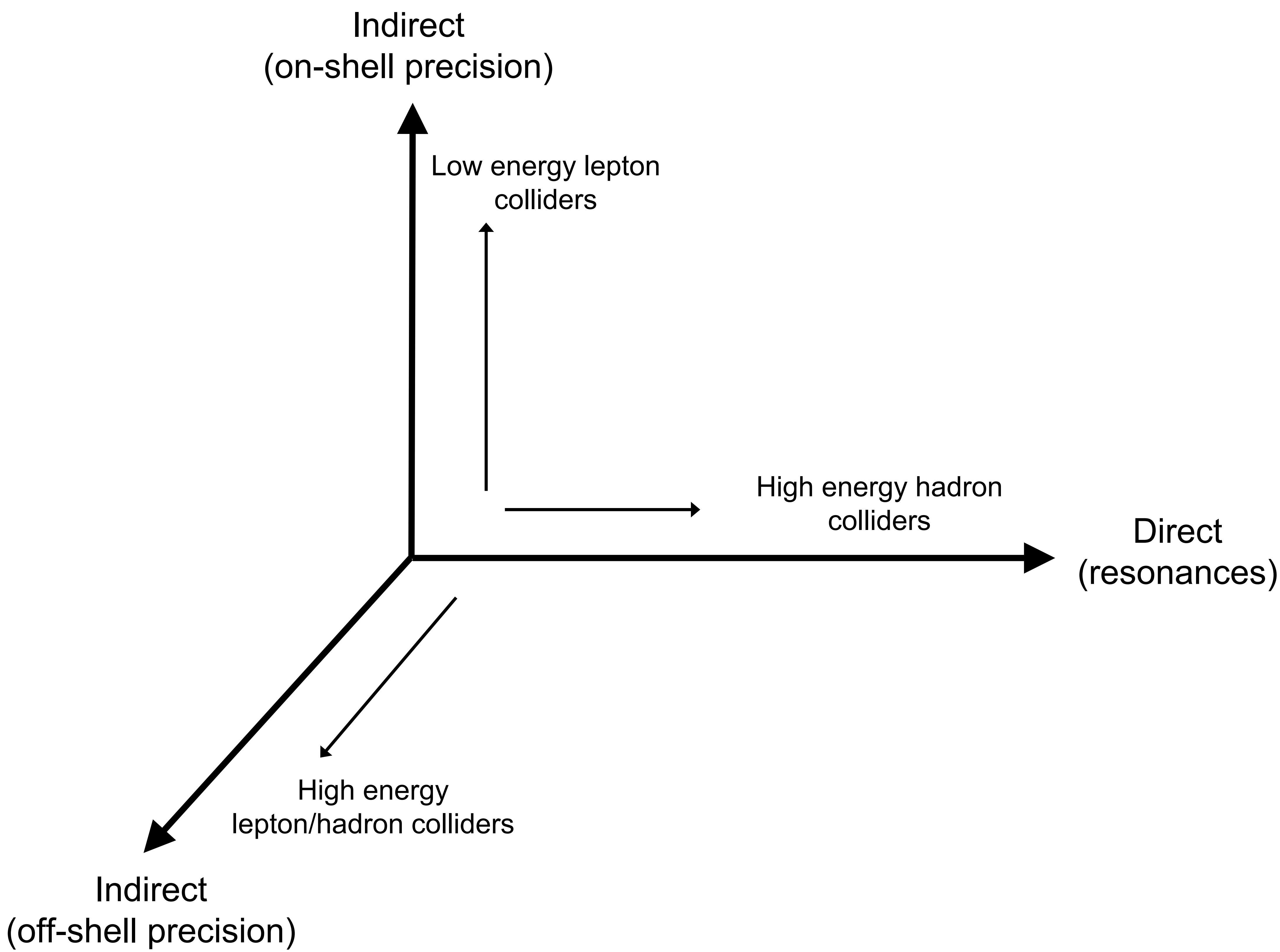
LHC comparable with (or better than) LEP

This comparison defines two orthogonal directions in the "precision program"

Future colliders



Future colliders in 3D



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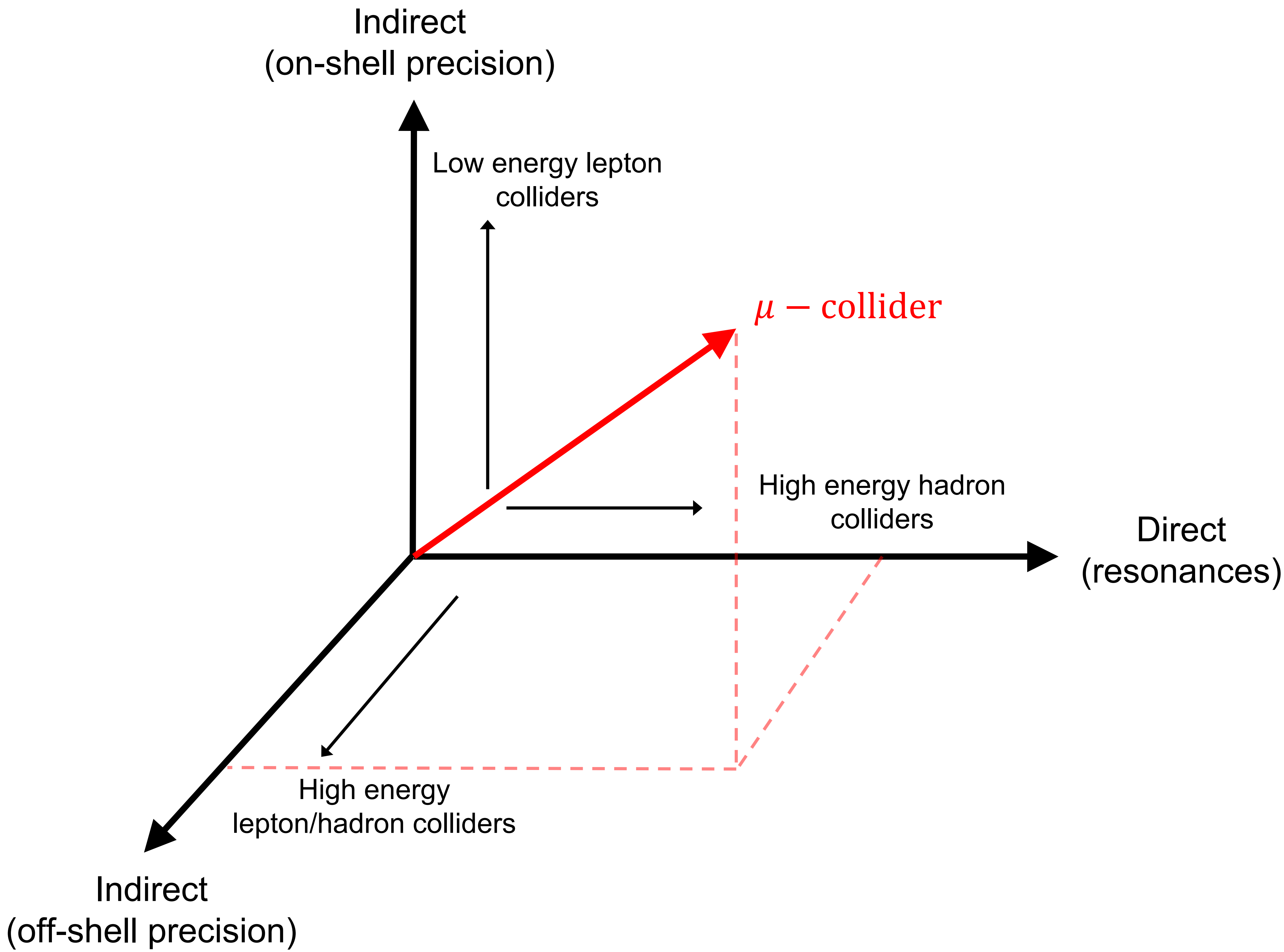

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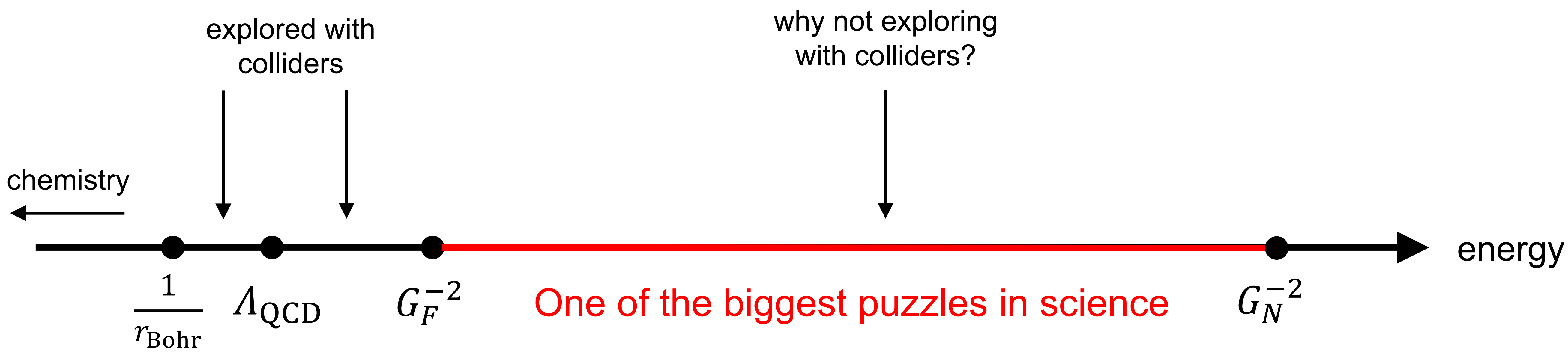

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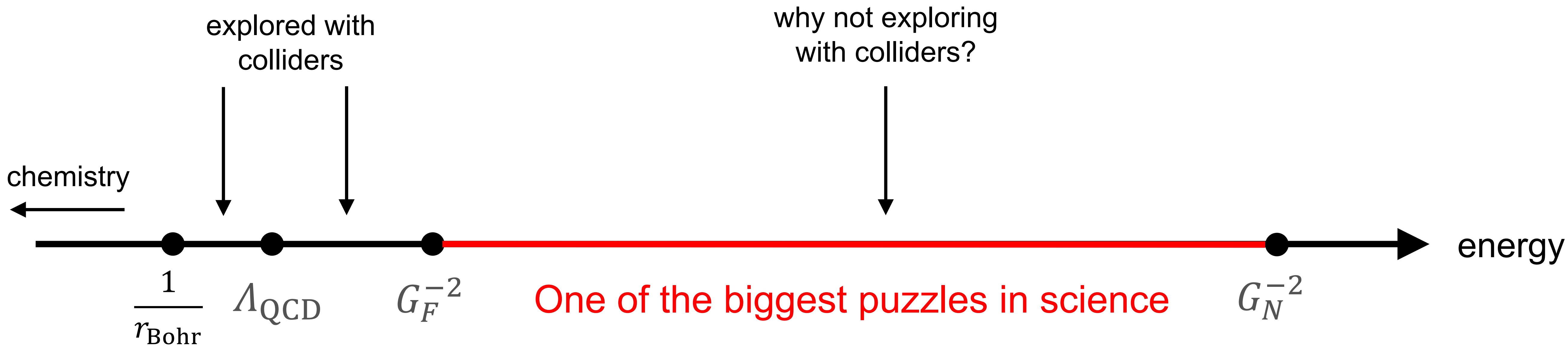
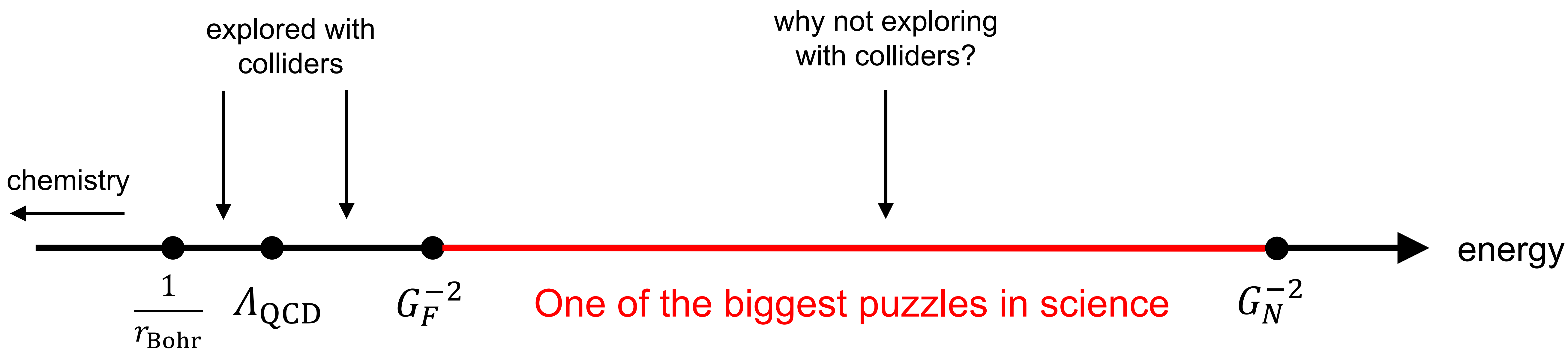


PROS

- only technique to directly probe higher energies
- experimenter defined experimental setup
- repeatable (experimental ≠ observational)
- exploration of unknown territory
- measurement of the SM in a new energy regime and to unprecedented precision
- answer to well posed BSM questions (aka limits) on EFT, on-shell new physics, etc

Why colliders?



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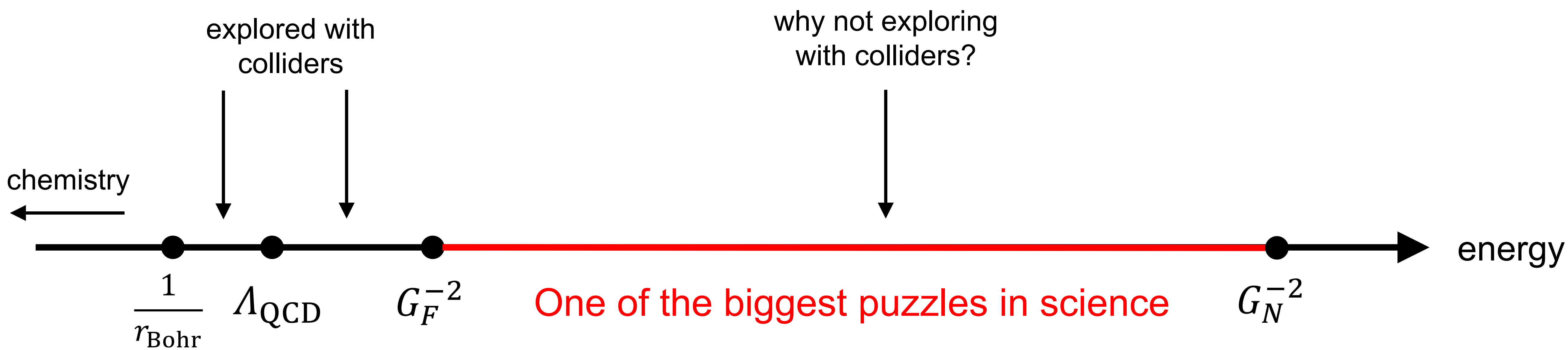
CONS (difficulties)

- energy increases very slowly with time/money (driven by technological evolution, but not only)
- need to convince funding agencies (the physics case is as simple as above, but it requires a good understanding of the scientific method and "infinite funds"; reality is different)
- long term planning is becoming more and more difficult due to the increasing speed of technological advance
- keep community engaged (or even alive)

Why colliders?



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We have no guarantee of any discovery, but
guarantees cannot be a criterion for fundamental research.
There is anyway the guarantee of a spectacular physics program

Are particle colliders observatories?

Some colleagues suggested the analogy of colliders with observatories, defining the former “particle observatories” (a very smart analogy to discuss with funding agencies!)

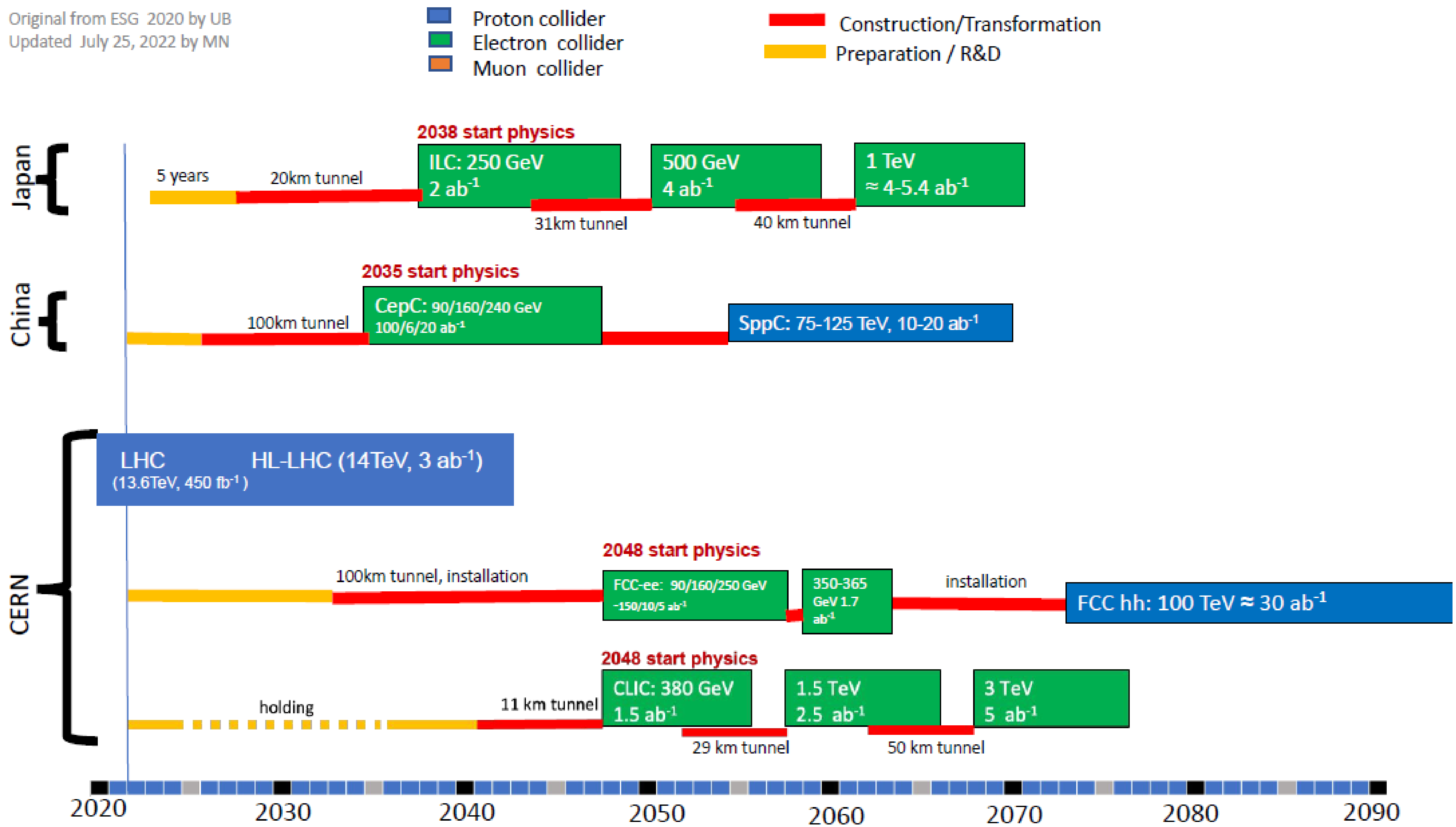
I would argue colliders are much more than observatories, because respect the basic requirement of experimental science (compared to observational science), that is the possibility for the experimenter to set up the experiment (including the system under study), to repeat it, and to decide when to stop it

Collider physics is the only
general-purpose
experimental research field
in fundamental science

and the only one who delivered
revolutionary results

* Evidence for neutrino masses may be an exception, even though neutrino physics is not studied with general-purpose experiments.

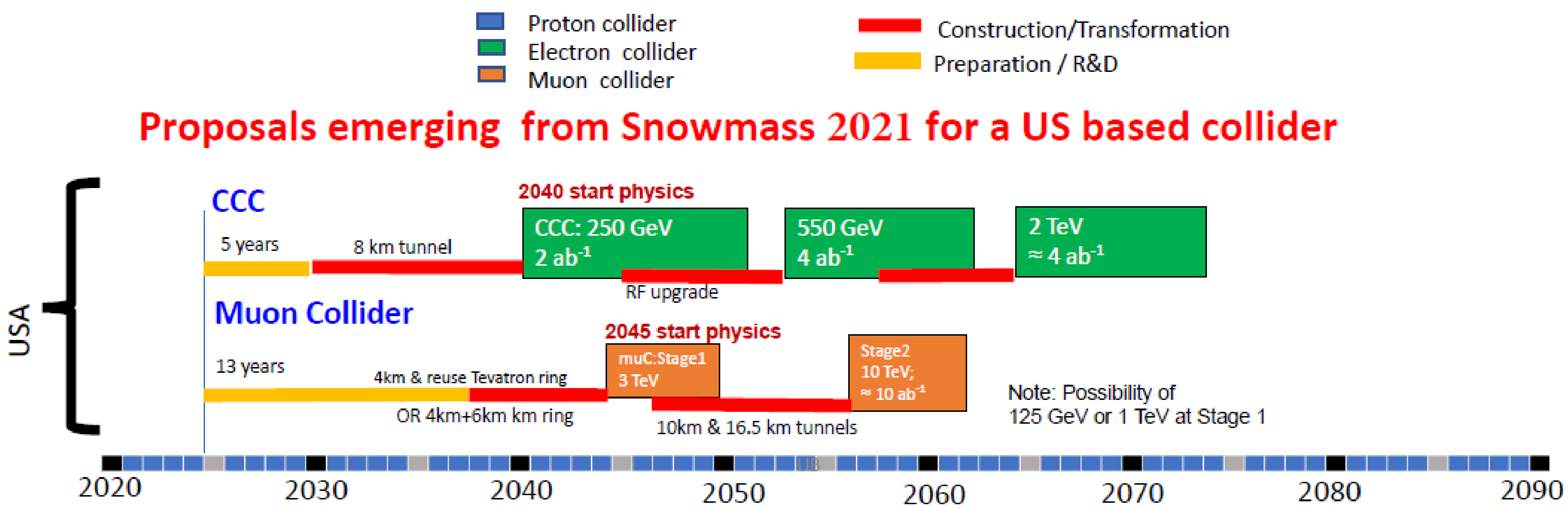
Which colliders?

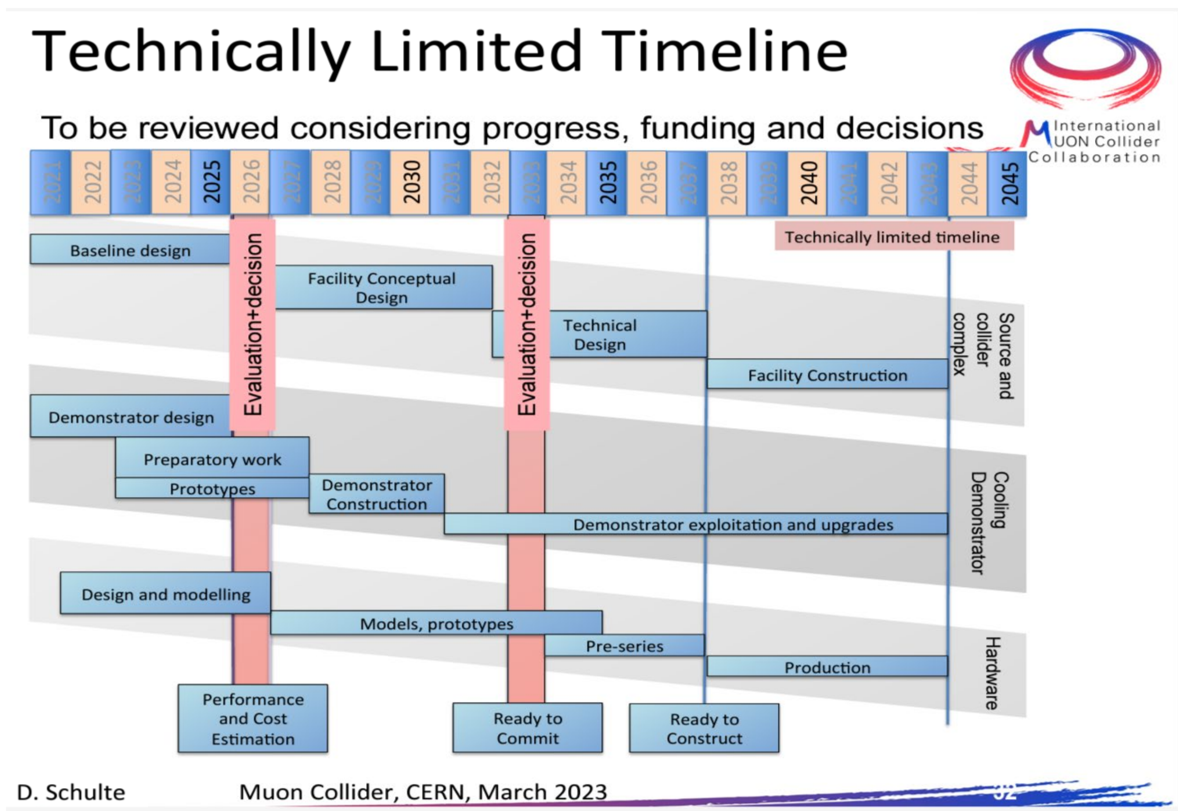


Snowmass Energy Frontier summary, 2211.11084

An “outsider” would argue that the more time-efficient strategy is to finalize CepC and ILC while CERN works to make FCC-hh real…

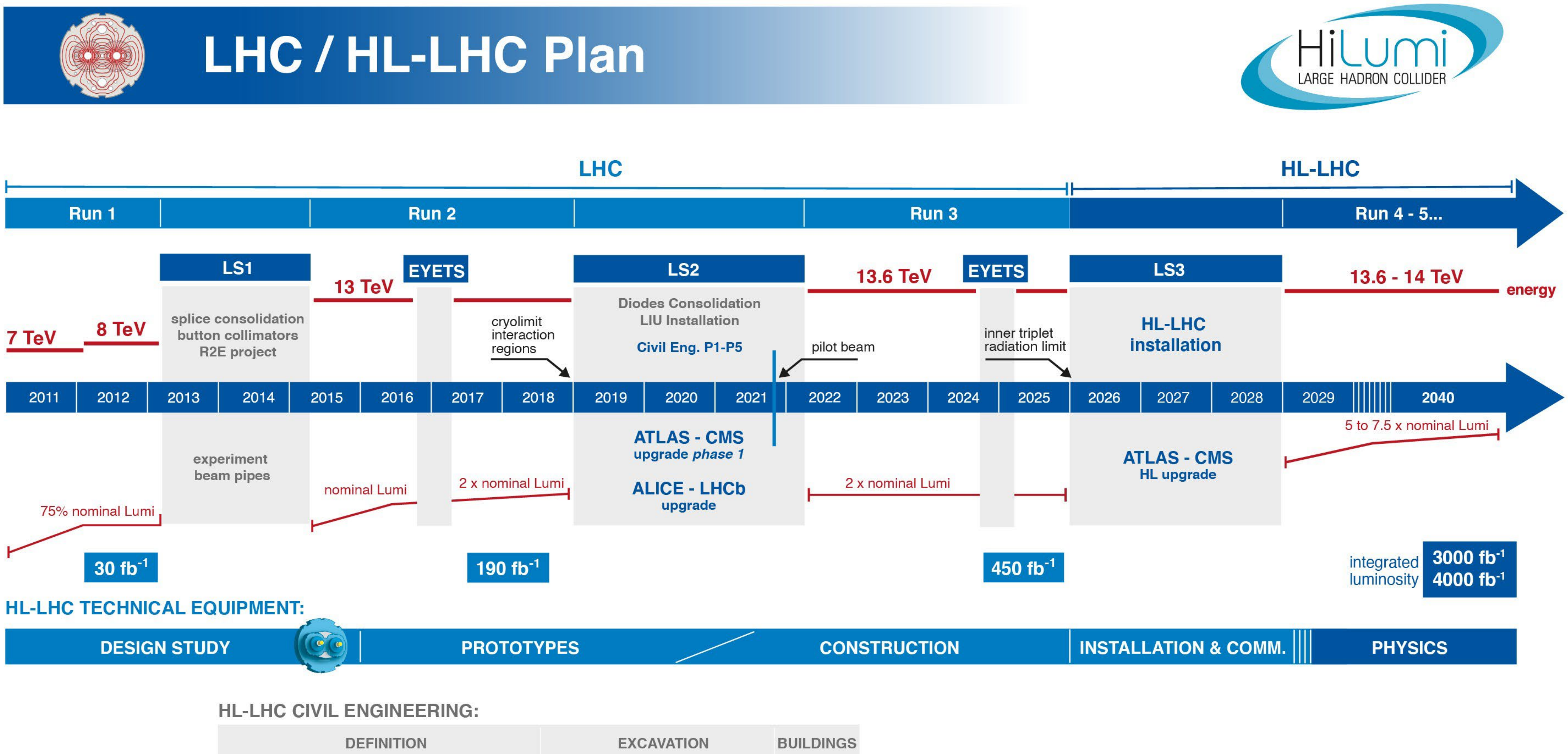
Which colliders?





or, even better, while CERN works to make a muon collider real!
However, reality is different.

Where do we start from?



Main goal: Find signs of New Physics

- directly: probing on-shell new physics → direct searches
- indirectly: probing the effect of new physics on SM observables → precision physics

SOME PERSPECTIVE

Measurements, searches, and global fits: a statistical perspective

Measurement

- What is usually called a “measurement” can be defined as **parameter estimation** within the SM hypothesis
- This quantifies precisely “what you see” (SM), but says nothing about “what you do not see” (NP)
- Used to extract SM inputs to searches and global fits

Search (or direct search)

- This usually refers to “direct searches” where, through a statistical **hypothesis test**, the SM is confronted with a specific alternative hypothesis
- It gives some information on how much your data prefer the SM vs a well-defined alternative model

Fit (or global fit or indirect search)

- This consists of either **parameter estimation** beyond the SM or a **hypothesis test** with a general enough alternative hypothesis (e.g. EFT)
- It gives information on “what you see” and “what you do not see”
- Notice that usually only BSM parameters are fit, while SM ones are taken from **measurements**

The (HL-)LHC legacy

"BSM measurements" (aka global fit v2.0: SM+EFT)

- It is known that uncertainties on some SM inputs is what limits the extraction of BSM parameters and, conversely, the presence of NP may affect extraction of SM parameters

  Examples: PDFs vs DY, multi-jet vs alphaS, etc.

- As the knowledge of the SM increases (better predictions and more analyses become available) and the large EFT parameter space gets a "good coverage" (several channels are measured and can be combined with each others) one can build a combined likelihood for SM+EFT
- Analyses that were targeting direct searches need to be turned into "measurements", which require a higher level of precision (e.g. di-bosons)
- A simple (and interesting) example is given by fitting EFT and PDFs together using DY data (see e.g. Greljo et al. 2104.02723)

The LHC legacy (in ~20 years) is to design and accomplish the final BSM measurement (which includes the SM!)

(New) Challenges

- **Combination and correlation**: combining experimental analyses is still a big issue at the LHC, where uncertainties are parametrized differently, and correlations are not known (there is a slow progress but huge work ahead)
- **Defining observables**: observables related to precision measurements are often targeted on “SM measurements”. It is necessary to extend and optimize them towards multi-differential “BSM measurement” oriented observables (e.g. recent triple differential DY cross section). Multivatiate and ML could also provide a solution.
- **Large parameter space**: when the number of parameters > a few, many studies become unfeasible (a lot of work in this direction: MEM, ML techniques, MadMiner, analytic reweighting, etc.)
- **EFT in backgrounds**: EFT effects may be relevant, especially for reducible BGs
- **Theory errors**: a further complication arises when statistical uncertainties become “negligible” and theory errors start to dominate (e.g. PDFs, HO, etc.). Including theory errors in statistical analysis presents conceptual issues that need to be addressed
- **Result presentation**: not only experimental analyses, but also theory results are still shown in an ad-hoc and incomplete way (e.g. 2D contours, etc). For experiments the issue is more severe, but theorists should try to get used to always deliver the full likelihood leading to their fits, that could be used by others and as input to global fits

Still a long way to go, but the path is clear

The EFT direction(s)

EFT for the SM seems like a rather "new" (~10 years) topic for theorists

Many theorists have abandoned model building in favor of EFT

This is not a psychological effect due to the absence of new physics

Absence of new physics (and the existence of precision measurements) is a requirement for EFT to be interesting, relevant, and applicable!

EFT is the simplest and most consistent way of parametrizing the different directions in which deviations from the SM can appear (SM deformations)

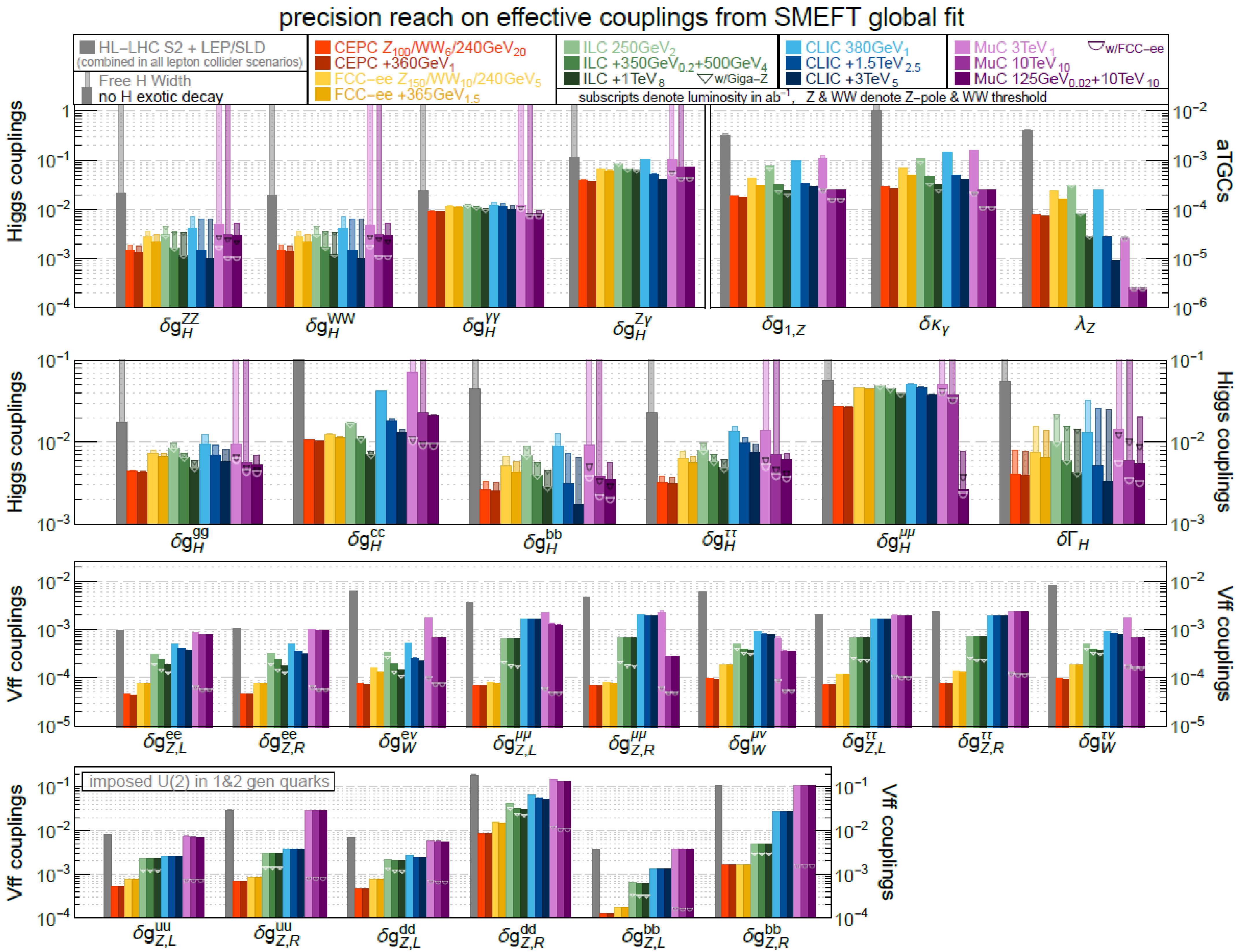
It is incredibly powerful at determining what "is possible", what "is impossible", what "is likely" and what "is unlikely"

Measurements (and especially precision measurements) in high energy physics have little meaning if one cannot quantify the above in a consistent way

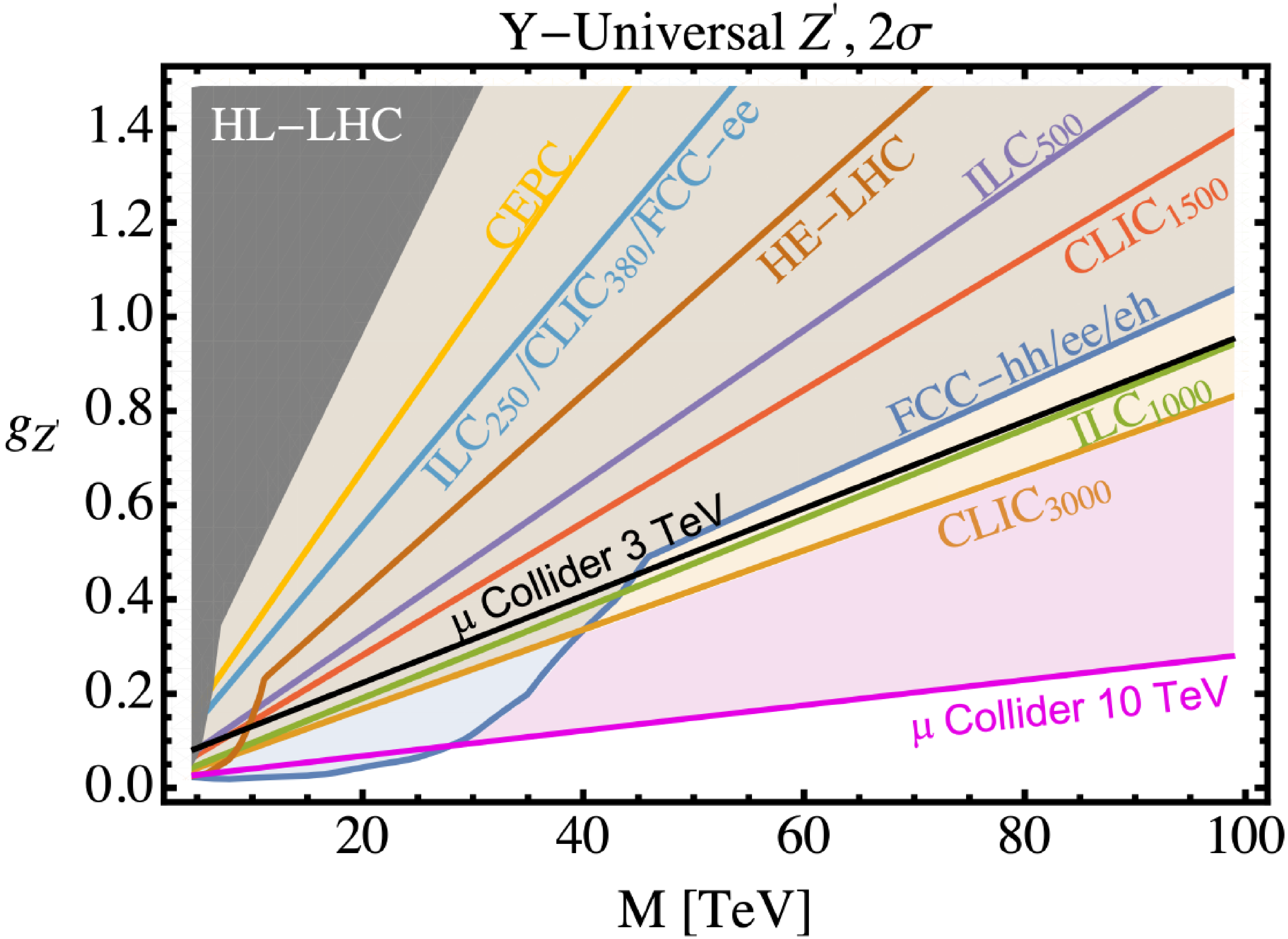
In other words, EFT provides the "alternative hypothesis" necessary for a robust statistical hypothesis test of the SM

SOME BSM PROJECTIONS
(INCLUDING A MUON COLLIDER)

Precision physics (EFT)



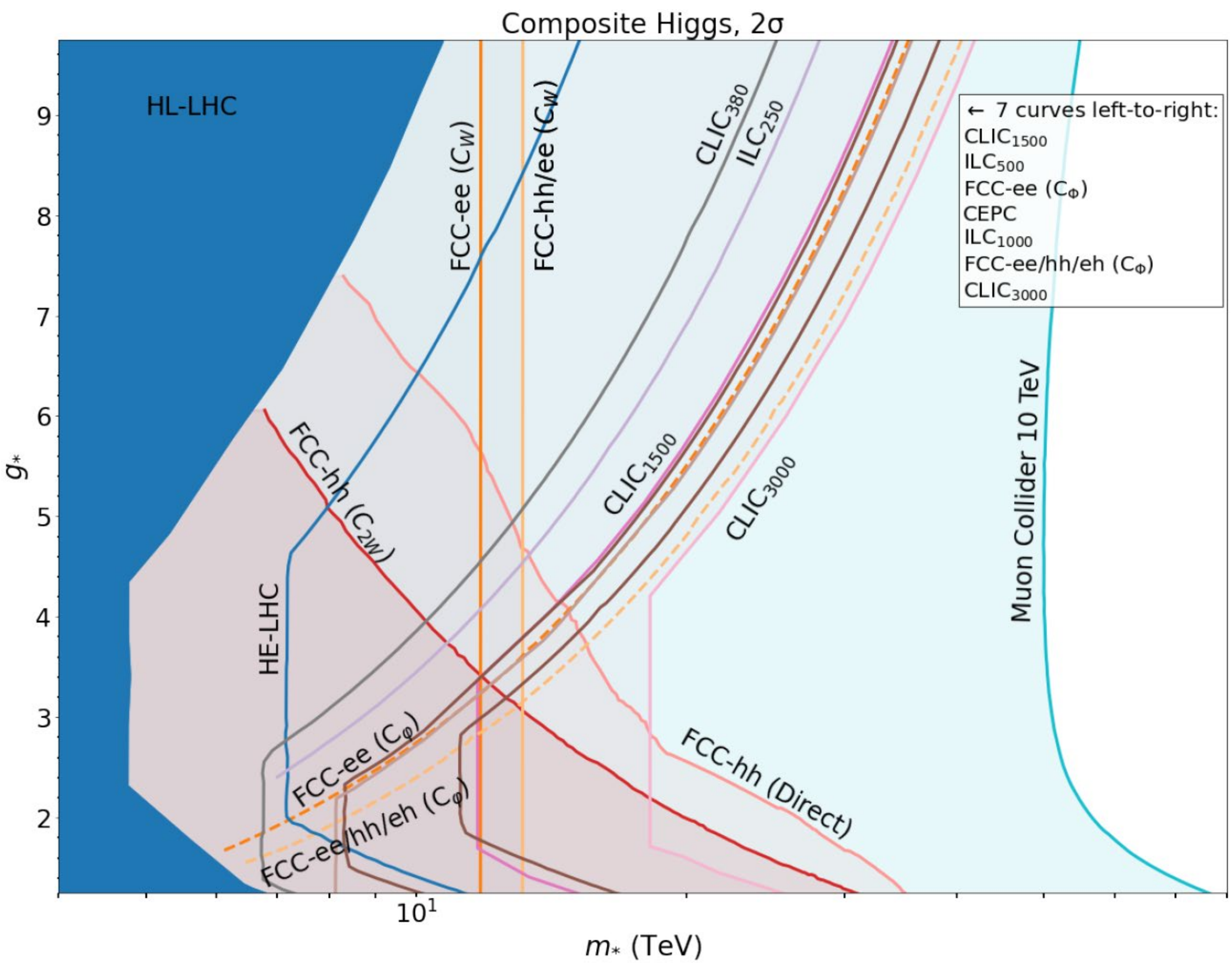
Direct vs indirect: universal Z’



Bound coming from the study of Drell-Yan at high invariant mass (Y-parameter)
Direct searches may be more relevant only in a small corner at low masses and coupling

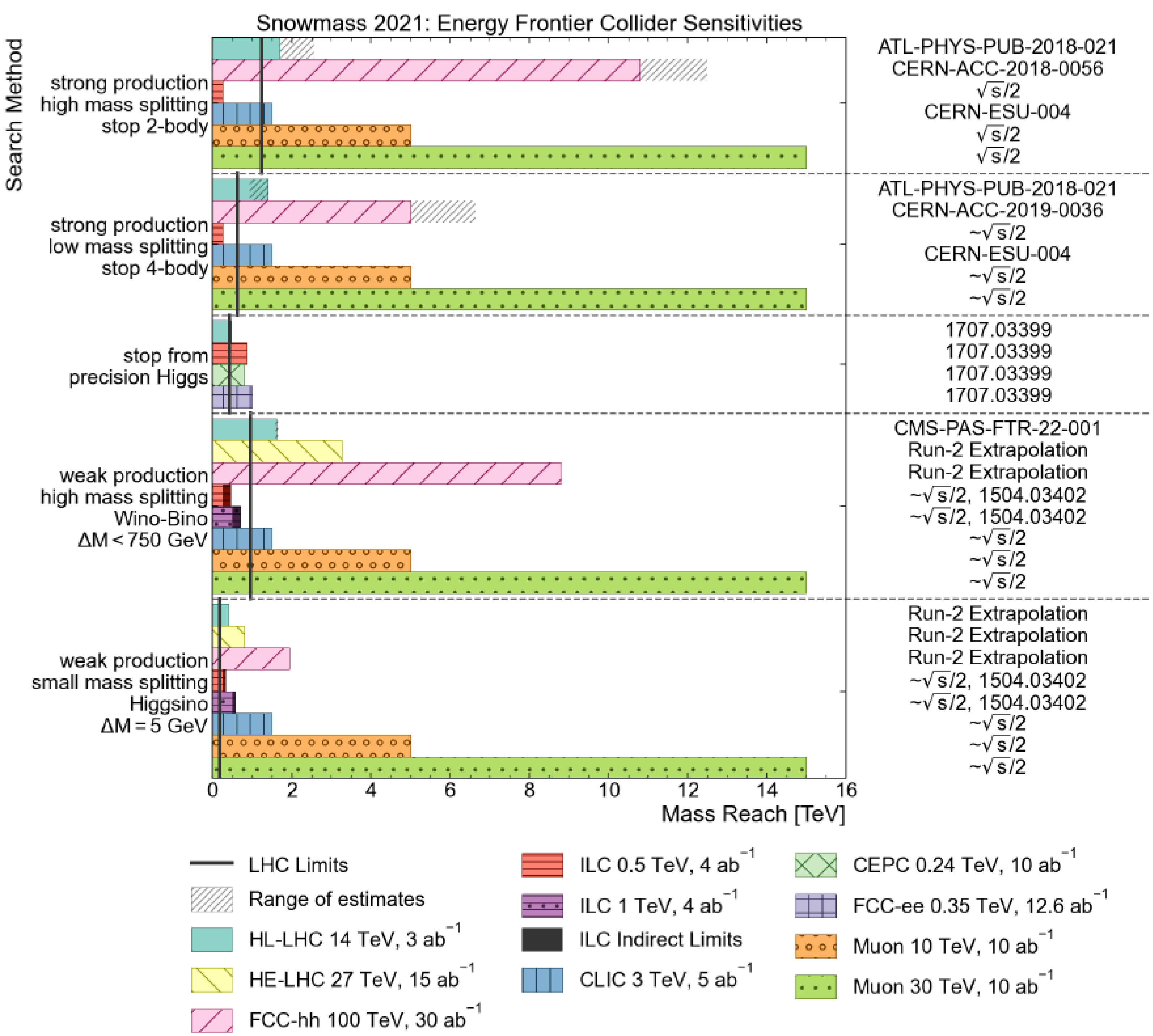
Direct vs indirect: Composite Higgs

CH models lead to several signatures that can be put into a parameter space corresponding to typical strong sector resonances mass and coupling
Different signatures, from direct production of resonances, to generated HDO set constraints in different directions



SUSY

This plots is slightly “unfair” in the way it compares FCC-hh (extrapolation from LHC) with muon collider (just taking energy into account, no analysis)



Universal Z'

Universal Z' models offer a useful benchmark to compare different collider options

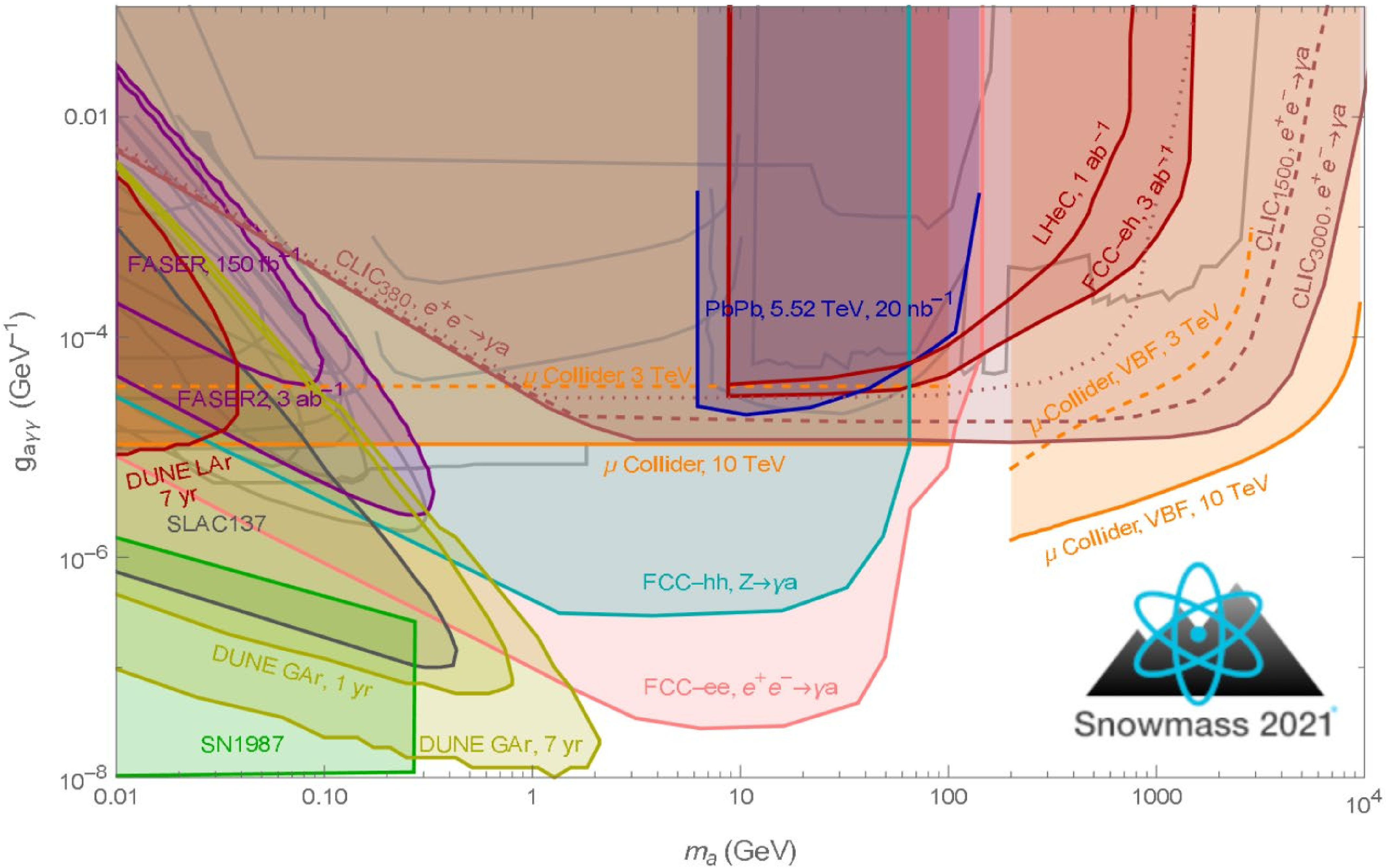
Here bounds from direct sensitivity plus indirect EFT sensitivity are combined

Machine	Type	$\sqrt{s}$ (TeV)	$\int$ Ldt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	pp	14	3	RH [424]	$Z'_{SSM} \to$ dijet	4.2	**5.2**
				ATLAS [425]	$Z'_{SSM} \to l^+l^-$	6.4	**6.5**
				CMS [426]	$Z'_{SSM} \to l^+l^-$	–	**6.8**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**6**
ILC250, CLIC380 or FCC-ee	e^+e^-	0.25	2	ILC [427]	$Z'_{SSM} \to f^+f^-$	4.9	**7.7**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**7**
HE-LHC	pp	27	15	EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**11**
				ATLAS [425]	$Z'_{SSM} \to e^+e^-$	12.8	**12.8**
ILC	e^+e^-	0.5	4	ILC [427]	$Z'_{SSM} \to f^+f^-$	8.3	**13**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**13**
CLIC	e^+e^-	1.5	2.5	EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**19**
Muon Collider	$\mu^+\mu^-$	3	1	IMCC [421]	$Z'_{Univ}(g_{Z'} = 0.2)$	10	**20**
ILC	e^+e^-	1	8	ILC [427]	$Z'_{SSM} \to f^+f^-$	14	**22**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**21**
CLIC	e^+e^-	3	5	EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**24**
FCC-hh	pp	100	30	RH [424]	$Z'_{SSM} \to$ dijet	25	**32**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**35**
				EPPSU [428]	$Z'_{SSM} \to l^+l^-$	43	**43**
Muon Collider	$\mu^+\mu^-$	10	10	IMCC [421]	$Z'_{Univ}(g_{Z'} = 0.2)$	42	**70**

ALPs

Axion like particles coupling to photons are a standard benchmark for the class of feebly interacting particles

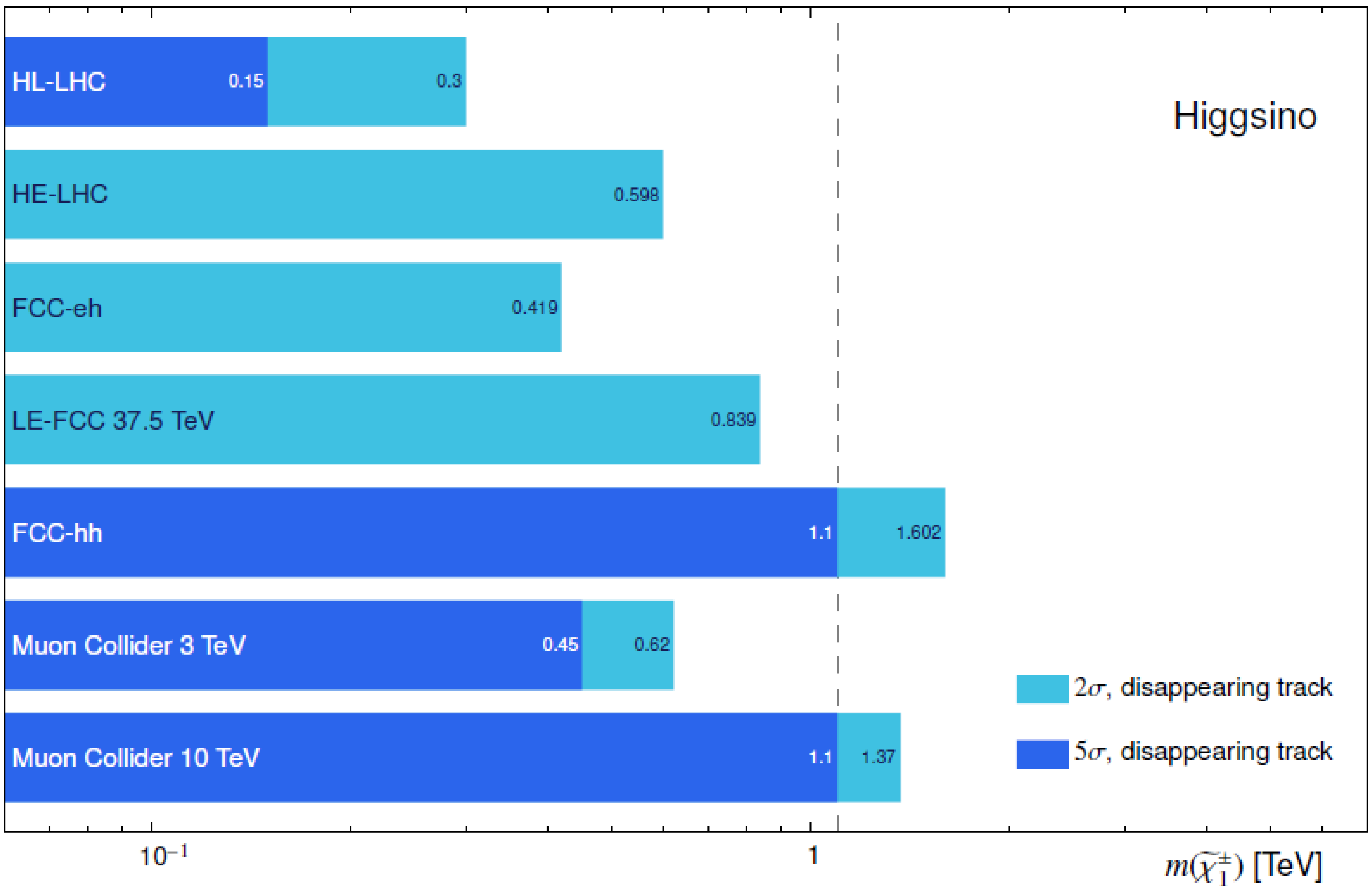
They can emerge in a wide range of masses and their parameter space needs several different experiments to be covered efficiently



Long lived (pure higgsino)

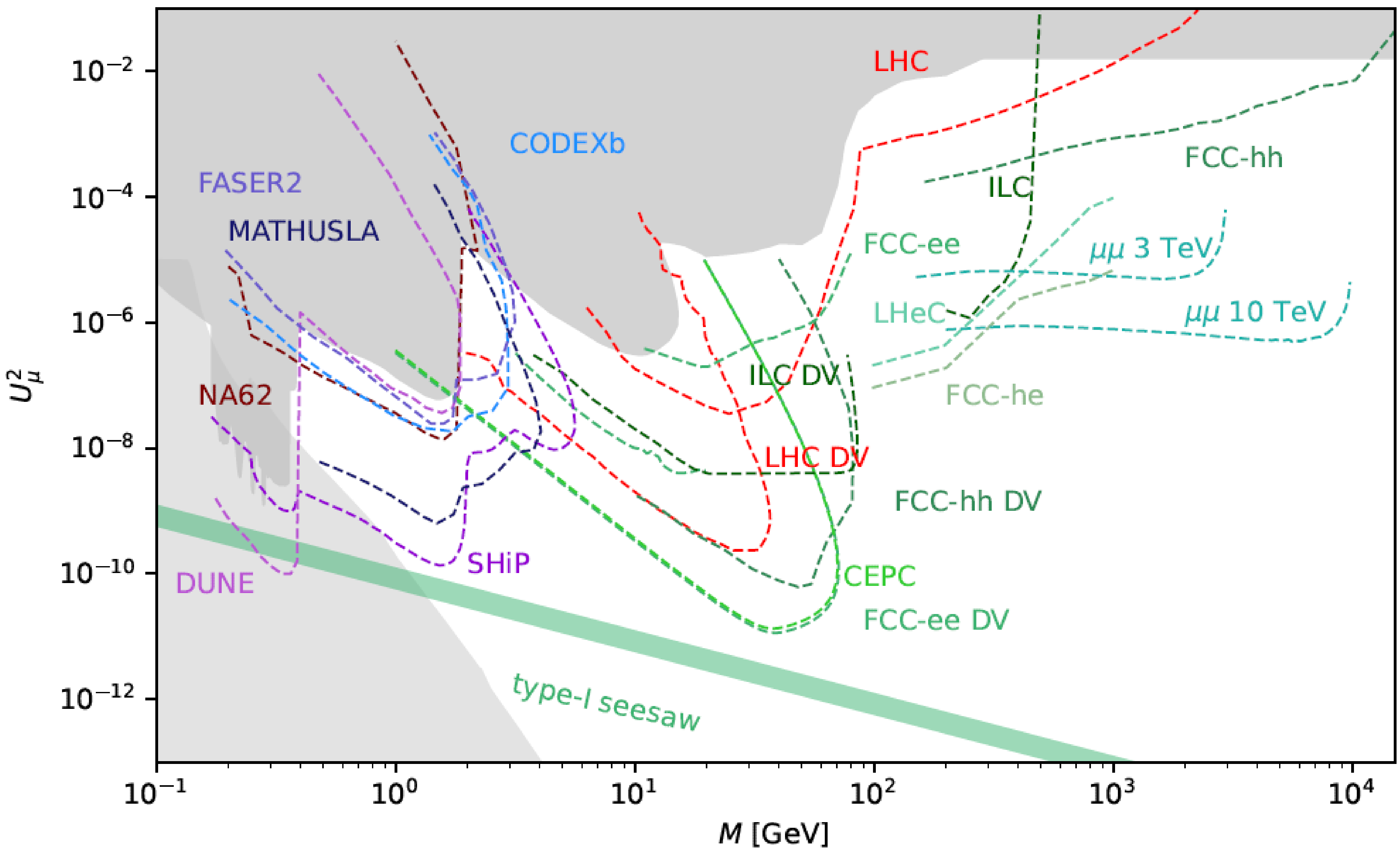
Another example of weekly interacting particles is long lived particles, usualy constrained through searches of disappearing tracks

The pure higgsino scenario is a useful benchmark to compare different collider options, but the understanding of the detector is crucial for robust estimates



Heavy Neutral Lepton

New neutral leptons (like sterile neutrinos) are another challenging signature
For instance one can consider a HNL with a small coupling to muons as a benchmark signature for collider performance comparison



Conclusions

- Collider physics is the only general-purpose experimental research field in fundamental science and the only one who delivered revolutionary results
- Astroparticle/cosmology cannot replace collider, neither can tens of “smaller” particle physics experiments (they are all complementary to colliders)
- Collider physics established the SM, the best theory of Nature we have so far, and is the only experimental research direction that can guarantee a frontier scientific program (even without guaranteeing any discovery)
- The (HL)-LHC legacy may be given by “BSM measurements” which extend the concepts of SM measurement, NP search, and global fit
- There are several issues to be addressed on top of building the next collider (precise theory predictions, combination of experimental analyses, definition of observables, large parameter space and signal generation, EFT in backgrounds, treatment of TH uncertainties, etc.) but the path is clear
- Optimized schedule would suggest CepC+ILC+FCC-hh (or CepC+ILC+muon-collider) but too many other considerations are in place (political/economical/sociological)
- A high energy muon collider is the most challenging, but also most fascinating option

THANK YOU