Physics requirements for future colliders

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EF restart workshop. AF+EF discussion. Sept. 2, 2021

This talk

- Basic physics case for future colliders, and what's required to get there.
- Focusing on general considerations (not on specific collider proposals)
  - Physics briefing book + other studies + order of magnitude estimates and scaling.
- Both the bare minimal requirement, and what's needed for a more comprehensive program.

Many more detailed studies still needed to be done.
I hope to give the impression of the order of magnitude here.

Main physics cases center around

- The electroweak scale
    - Hierarchy/naturalness.
    - Other related new physics: extended Higgs etc.
    - Higgs self-coupling. Electroweak phase transition.
- Dark matter (WIMP, dark sector)
- Could have a rich physics program in addition. But the two above typically frame the basic physics case.

How to get there

- Two possible routes
  - Lepton: e^+e^-, μ^+ μ^-
    - $\gamma\gamma$ similar, but somewhat narrower physics program.
  - Hadron, pp.
- Two approaches
  - Direct production of new physics particles. Need high energy colliders.
  - Precision measurement. Can be sensitive to new physics beyond collider energy.

Electroweak

Precision coupling measurement

Deviation from SM coupling $\delta \sim c\frac{m_W^2}{\Lambda^2}, \quad c \sim \mathcal{O}(1)$

LHC: $\delta \sim$ a few $\% \rightarrow \Lambda \sim$ TeV

$\delta \sim \mathcal{O}(10^{-3})$ (per mil) needed to reach up to $\Lambda \sim 10$ TeV

Statistics limited (lepton collider): $\delta \propto \frac{1}{\mathcal{L}^{1/2}}$

For example:
Higgs coupling measurement needs 10^6 Higgs at proposed Higgs factories

Energy = precision

For heavy new physics parameterized by (EFT)

$$\frac{1}{\Lambda^2}\mathcal{O}^{(6)}, \quad \frac{1}{\Lambda^4}\mathcal{O}^{(8)}, \ldots$$

Effect of new physics larger at higher energy scales

$$(\delta\sigma/\sigma)_{\text{higher E}} \sim \frac{E^2}{\Lambda^2},$$ $\delta\sigma$ deviation due to $\mathcal{O}^{(6)}$

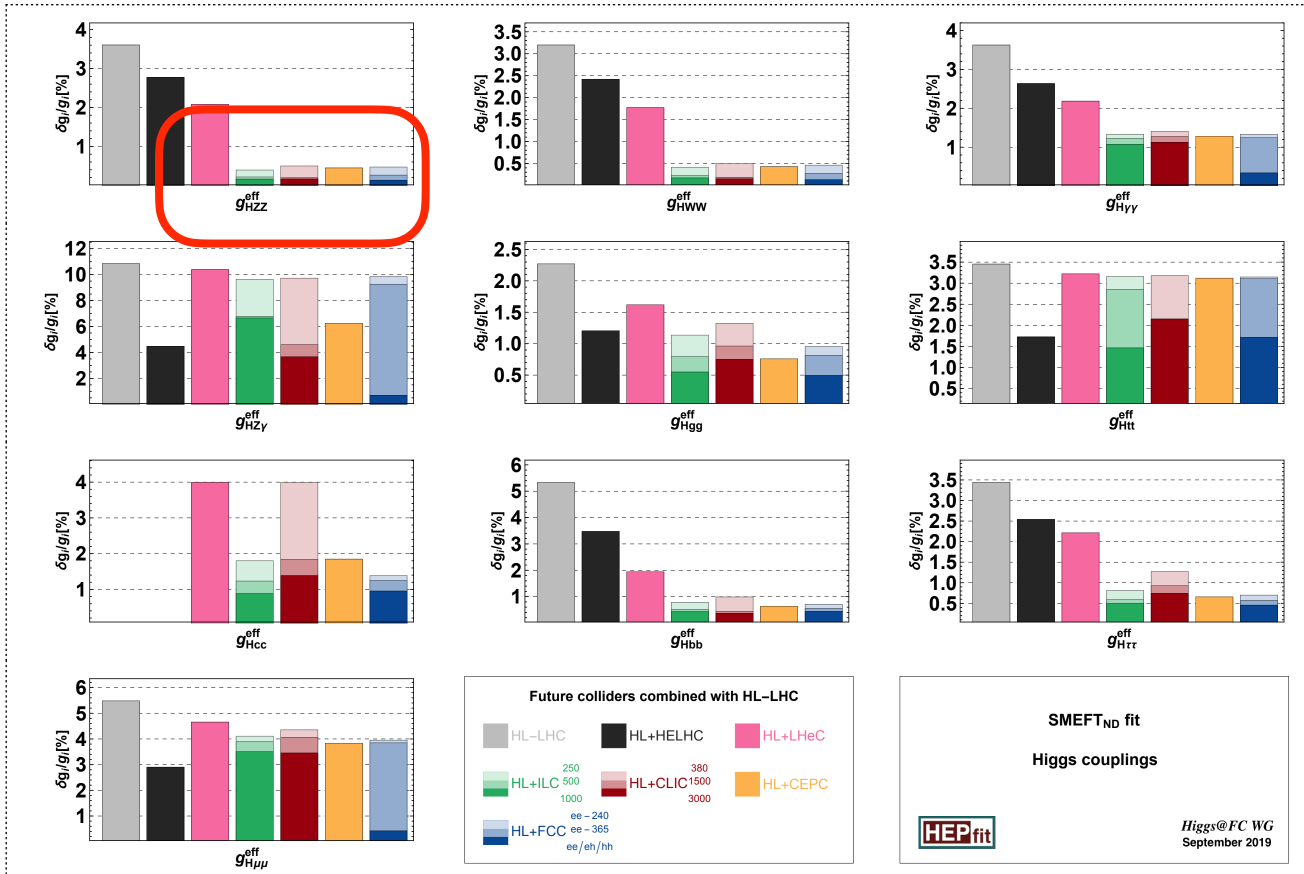
Good reach if we can measure the process at higher energies.

Lepton collider reach about $10 \times E_{CM}$

Hadron collider reach about E_{CM}

Higgs coupling

European Strategy Physics Briefing book



Muon smasher's guide

	Fit Result [%]	
	10 TeV Muon Collider	with HL-LHC
κ_W	0.06	0.06
κ_Z	0.23	0.22
κ_g	0.15	0.15
κ_γ	0.64	0.57
$\kappa_{Z\gamma}$	1.0	1.0
κ_c	0.89	0.89
κ_t	6.0	2.8
κ_b	0.16	0.16
κ_μ	2.0	1.8
κ_τ	0.31	0.30

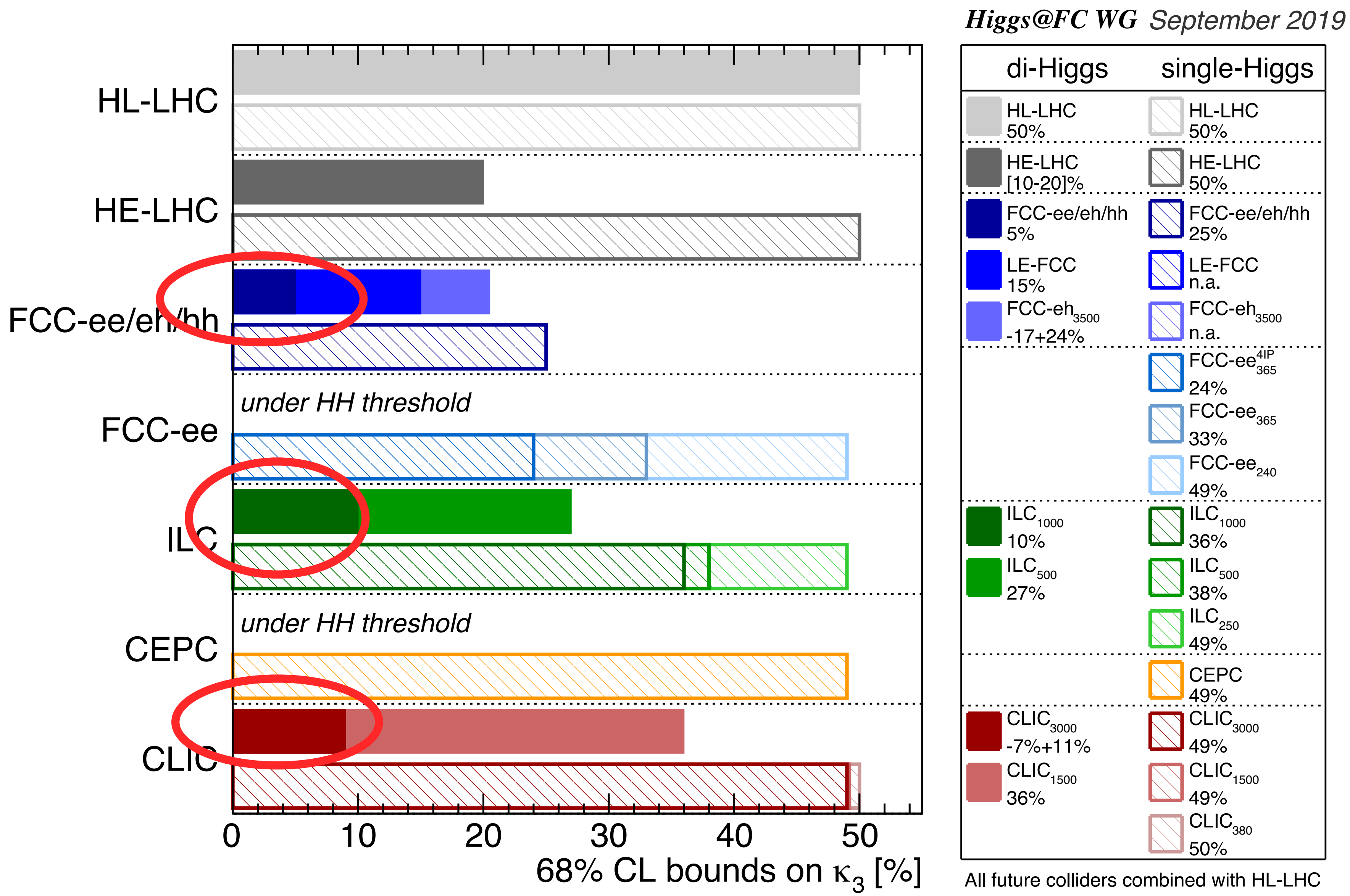
10^{-3} or better possible

Precision scale (roughly) with (# of Higgs)$^{-1/2}$

Low energy Higgs factories (Zh)
High energy (> 600 GeV) lepton colliders (WW fusion)
Sensitive to different couplings.

Measurement at lepton collider more model independent: width, Zh coupling, ...
Tera Z (and ttbar threshold) can improve significantly other EW precision measurements.

Higgs self-coupling

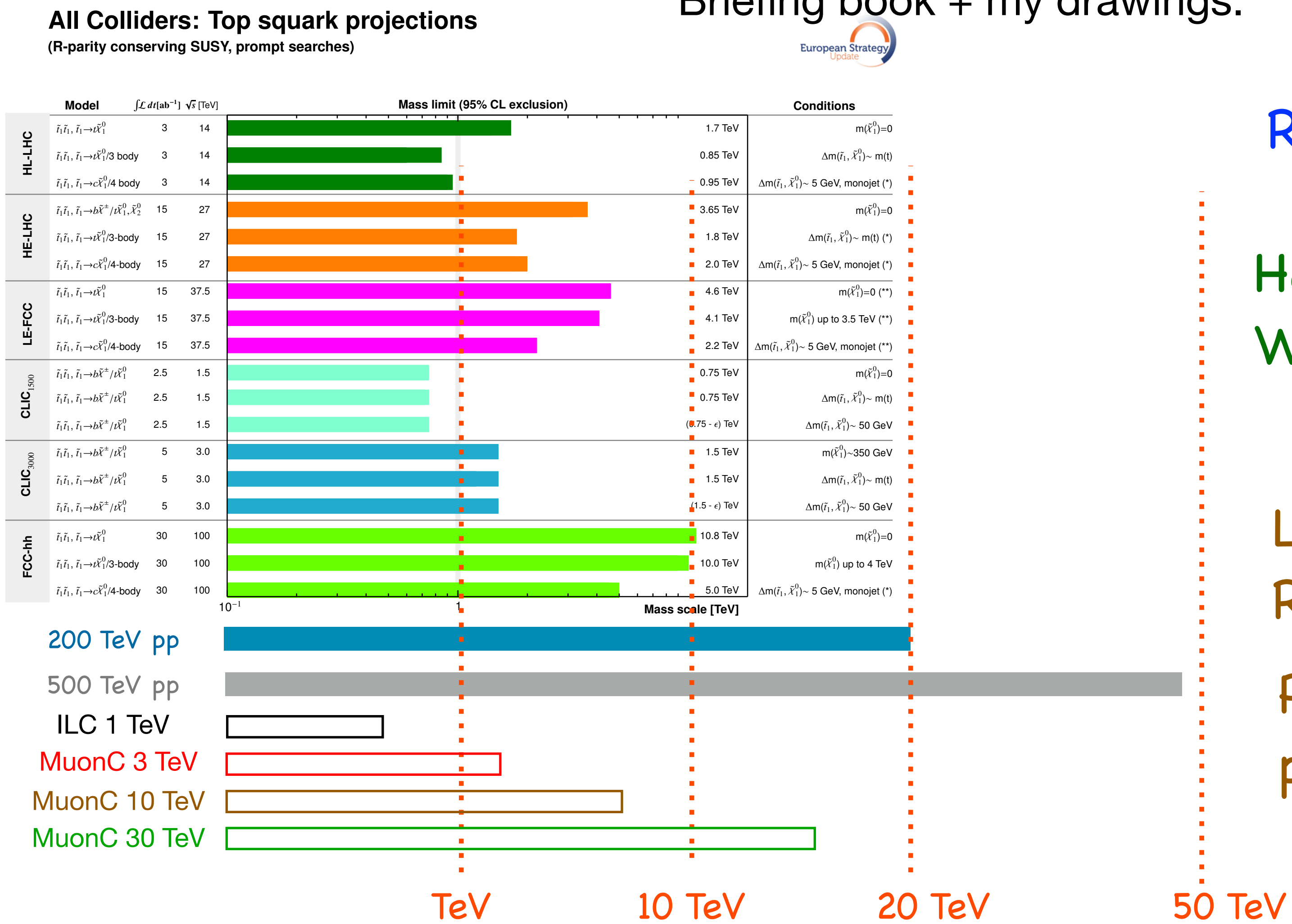


A few percent accuracy would cover most of the ground.

Higher energy collider needed:
TeV lepton collider, 100 TeV pp collider

Reach of SUSY stop

Briefing book + my drawings.



Reach for other top partners similar

Hadron collider reach ≈ 10% of E_{CM}

Weaker if new physics without strong int.

Lepton collider reach ≈ $0.5 \times E_{CM}$

Reach for other new physics similar.

Photon collider similar, but only for produce charged particles.

Scale of new physics:

Fine-tuning $\approx m_h^2 : \frac{1}{16\pi^2} M_{\rm NP}^2$, Fine-tuning small → bad

Scale to aim at? Only a theoretical expectation (extremely well motivated). However, not a firm prediction.

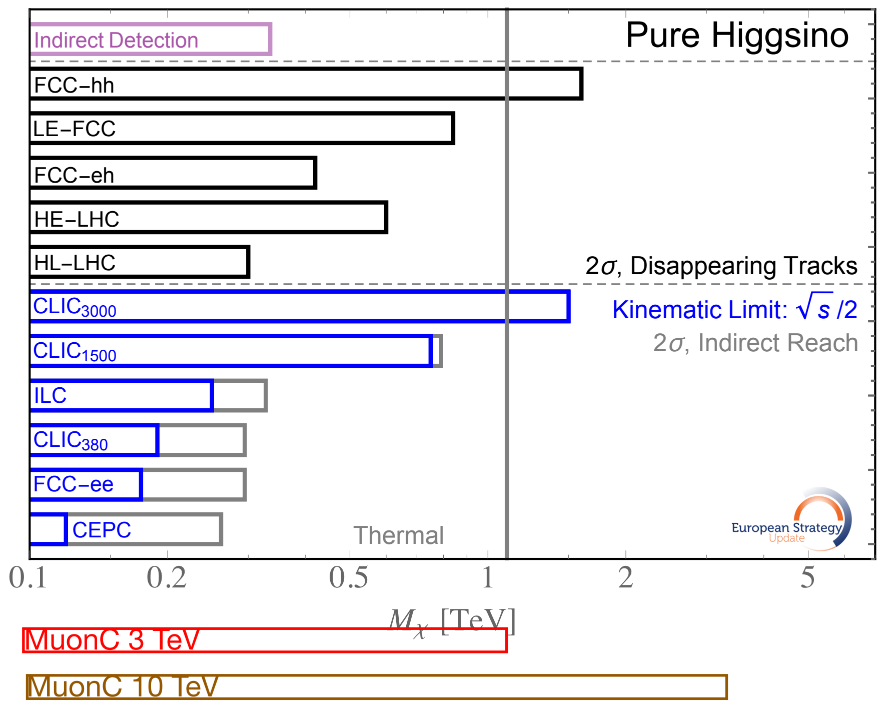
A possible measure: % good theory ideas left ~ (Fine-tuning)

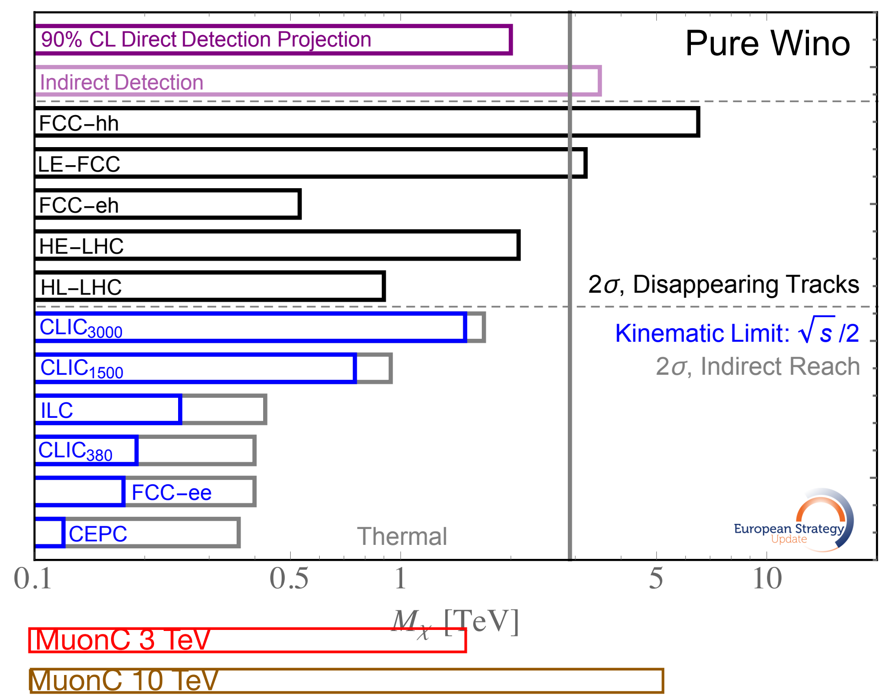
Current status: $M_{NP} \approx$ TeV(s), Fine-tuning ≈ a few - 10%. "uncomfortable"

Next milestone: $M_{NP} \approx$ 10(s) TeV, Fine-tuning < 10^{-3} . "definitive" test.

Dark matter

Dark matter reach





briefing book + my drawings for muon (or lepton) colliders.

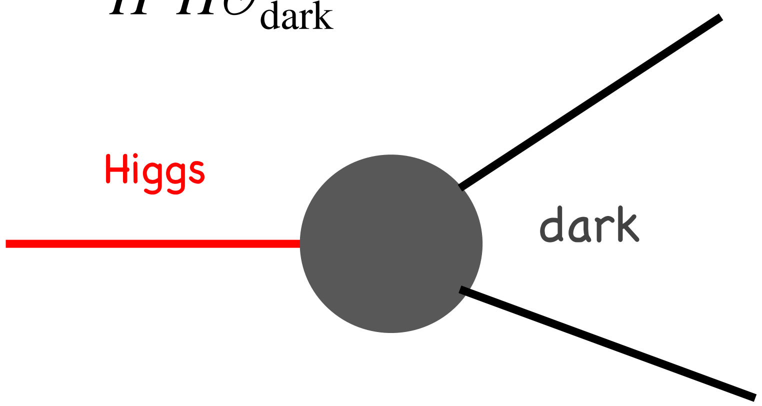
Simplest WIMP model, very predictive, definitive target mass ≈ TeVs.
Out of reach for LHC, difficult for direct detection.

Lepton collider reach close to $0.5 \times E_{CM}$ (a little less), need 10(s) TeV and hi lumi
Hadron collider ≈ a few percent x E_{CM} , need 100 (or more) TeV

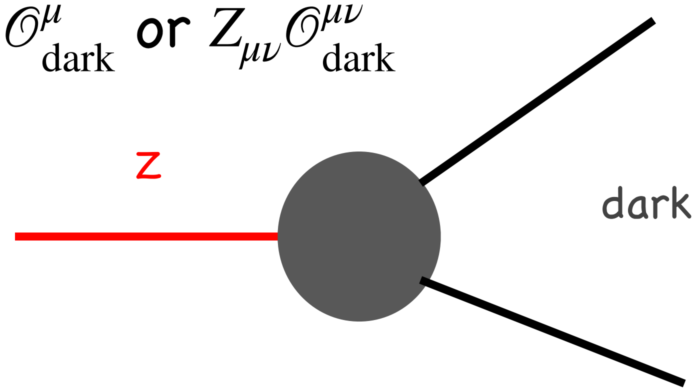
Windows into dark sector: portals

- SM particle can in principle have small couplings to dark matter/ dark sector. In particular:

$H^\dagger H \mathcal{O}_{\text{dark}}$



$Z_\mu \mathcal{O}^\mu_{\text{dark}}$ or $Z_{\mu\nu} \mathcal{O}^{\mu\nu}_{\text{dark}}$



Higgs/Z factories, sensitivity to Higgs/Z rare decays determined by the number of Higgs/Z produced.

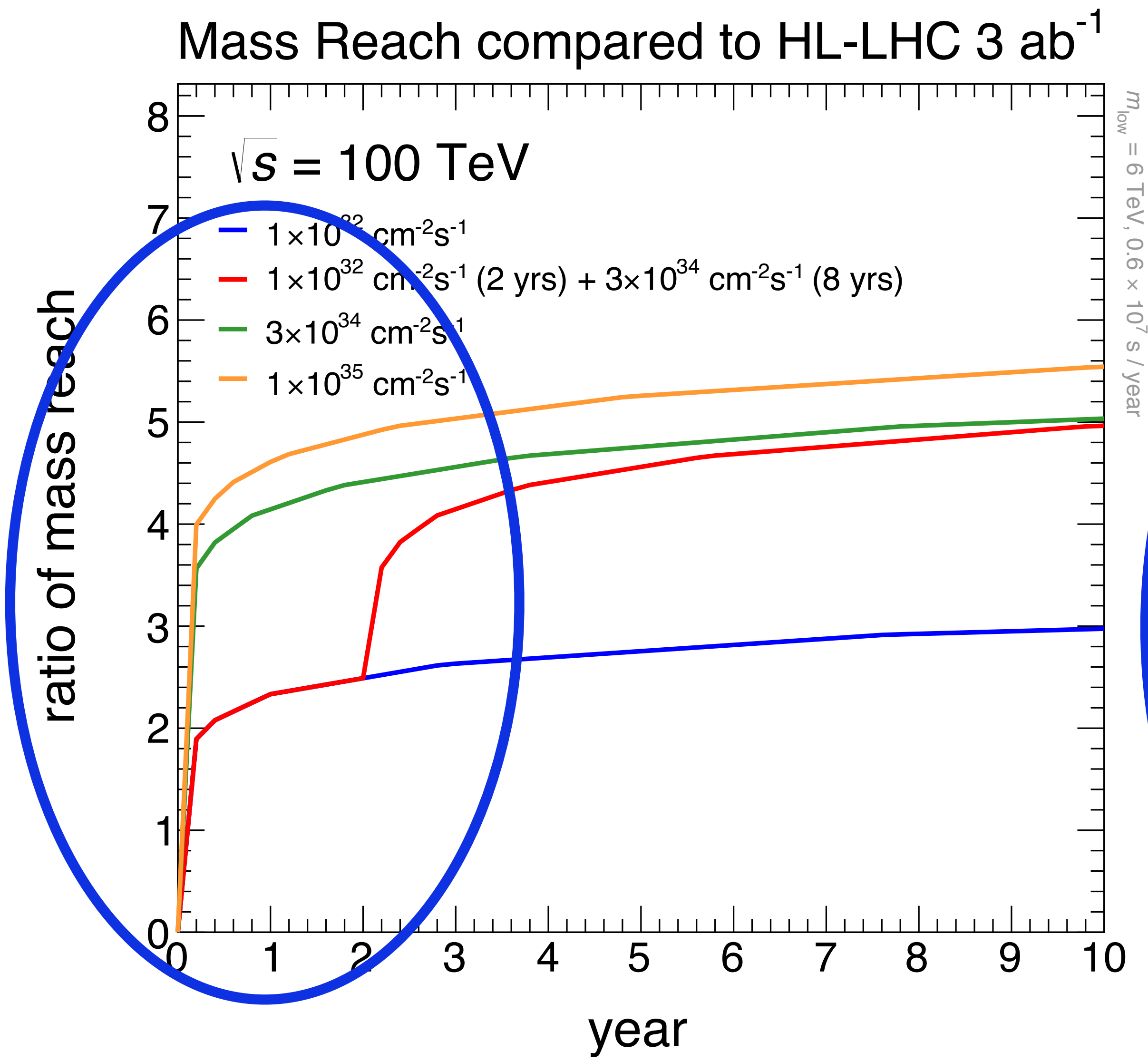
Rough estimates, if interaction is mediated by some 10(s) TeV new physics

Br(h→dark) $\sim 10^{-2}$ to 10^{-3}. Higgs factory sensitivity up to 10^{-5}. Hadron collider produces much more Higgses (better potential if decay distinct).

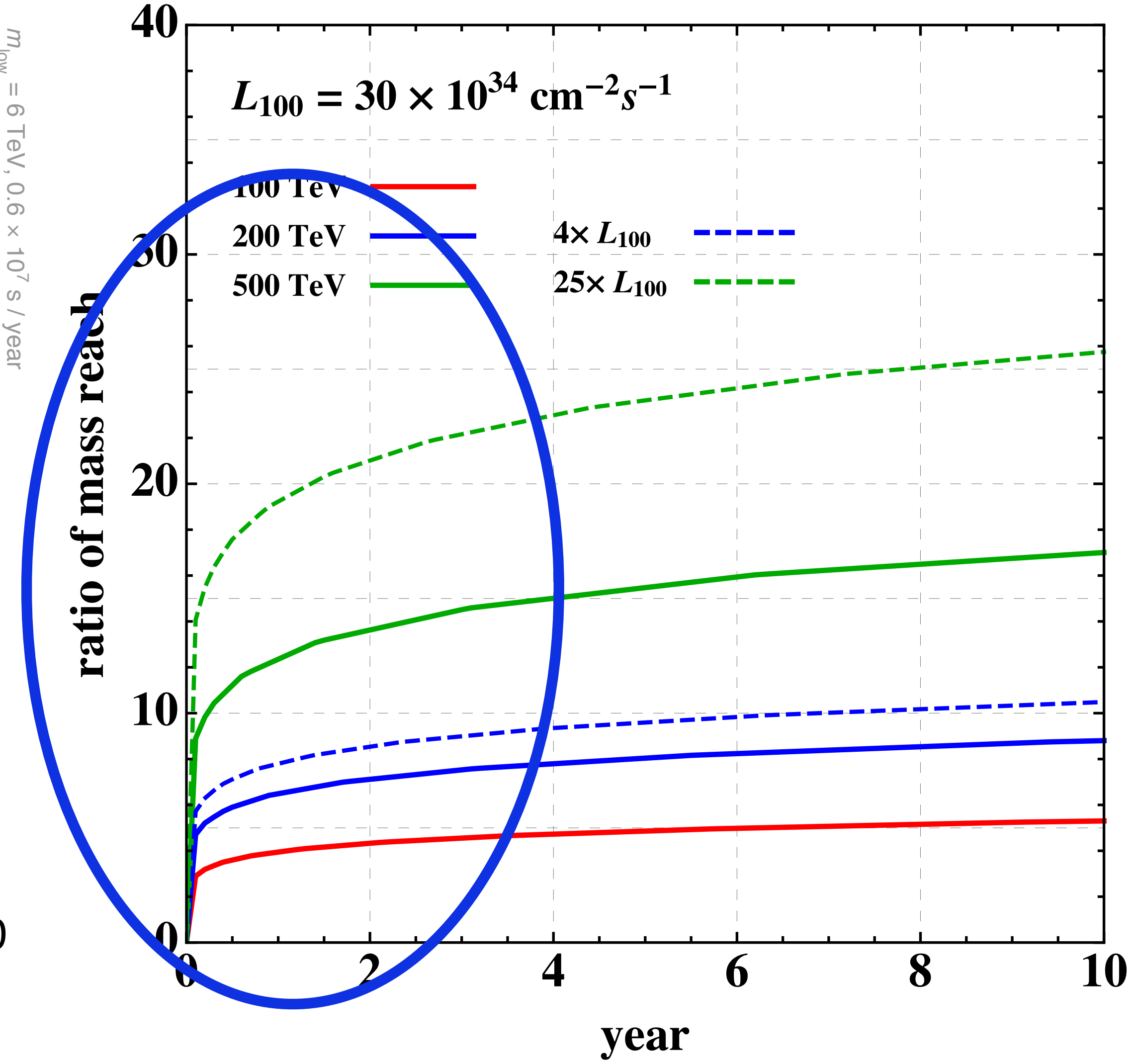
Br(Z→dark) $\sim 10^{-4}$ to 10^{-5}. Tera-Z sensitivity up to 10^{-11} .

Luminosity

Hadron collider scenarios



M. Low



Rapid gain in mass reach

10^{34} cm^{-2}s^{-1} doing a reasonable job for 100 TeV.
Need higher luminosity for Higgs self-coupling.
10^{35}–10^{36} cm^{-2}s^{-1} may be needed for higher energies.

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Lepton collider scenarios

A possible minimal scenario: can produce at least 10 signal event for weak scale cross section. Can do "basic" new physics searches and cover interesting scenarios.
Will miss some important physics. Maybe only a good starting point.

"Optimal" scenario: can cover as many difficult cases as possible, such as the dark matter searches.

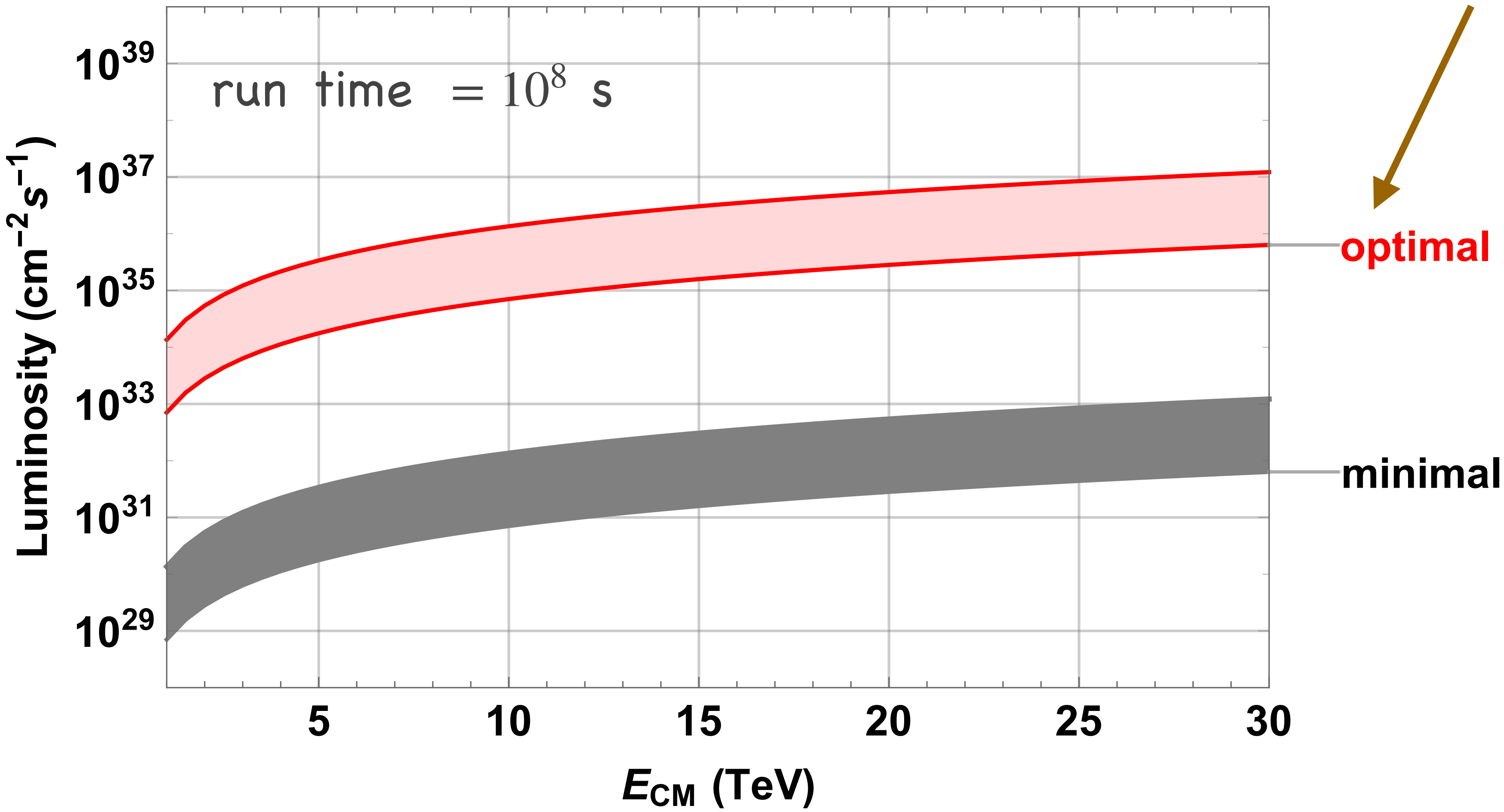
Some choices needed here, but the basic wishlist is quite commonly accepted.

Lepton collider luminosities

- For both muon and electron (photon collider similar)

Based on electroweak cross section.
Bands represent O(10) variation in signal rate

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



Both scales as $\mathscr{L} \propto E_{\mathrm{CM}}^2$, minimal $\sim 10^{-4}\times$ optimal

Summary

Higgs:

Precision measurement: 10^6 Higgs at lepton collider or above need to achieve 10^{-3} accuracy.
Tera-Z (also ttbar) can help a lot.

Self coupling, percent measurement.
TeV lepton collider, 100 TeV pp collider

New physics, aiming at 10s TeV.
10(s) TeV lepton collider and/or 100(s) TeV pp collider

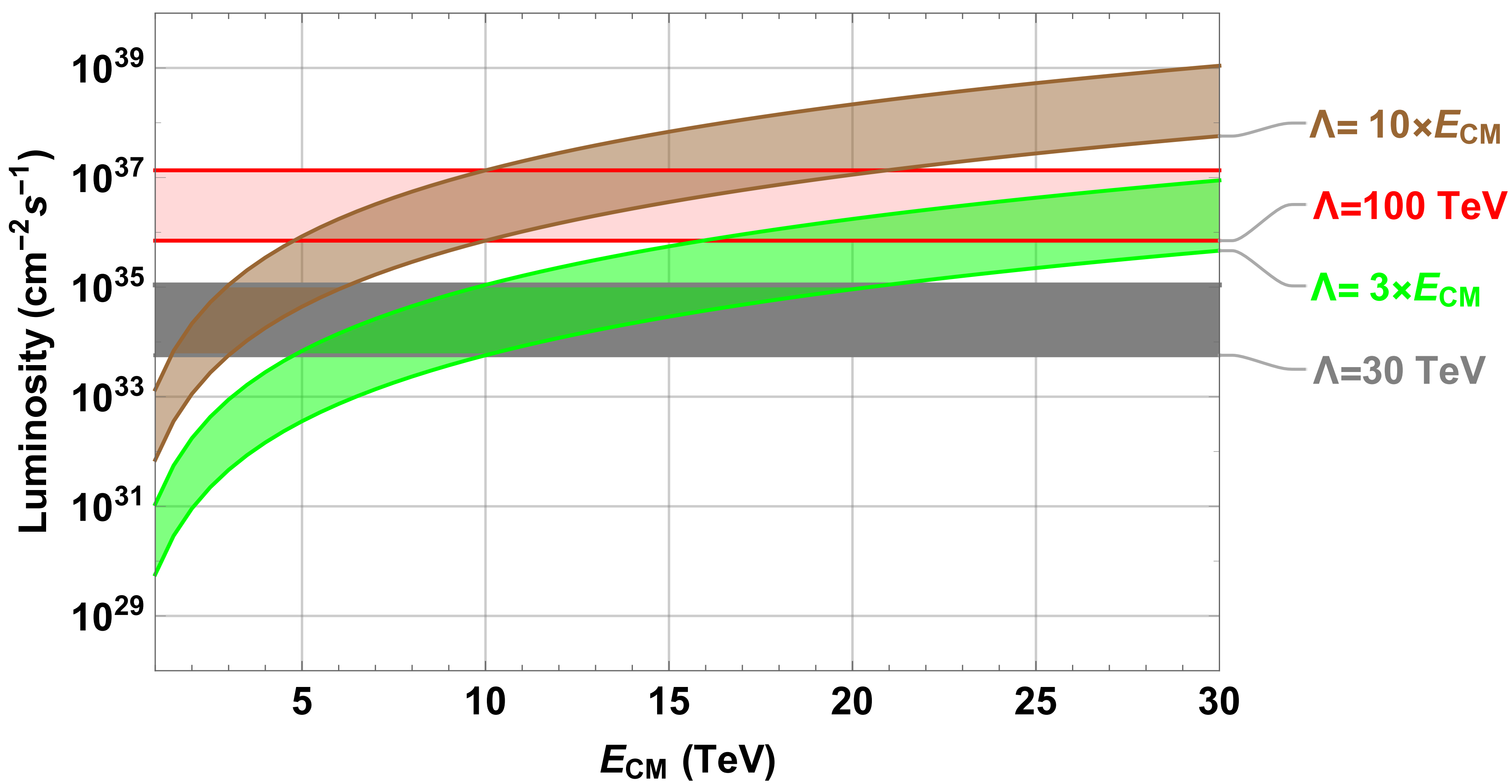
Dark matter:

WIMP, target mass TeV(s)
10(s) TeV lepton collider, 100(s) TeV pp collider

Dark sector.
rare decay of Higgs (br $< 10^{-3}$) and Z (br $< 10^{-4}$).
Sensitivity proportional to # of Higgs/Z produced.
Higgs factories, Tera Z, and hadron colliders

Extra

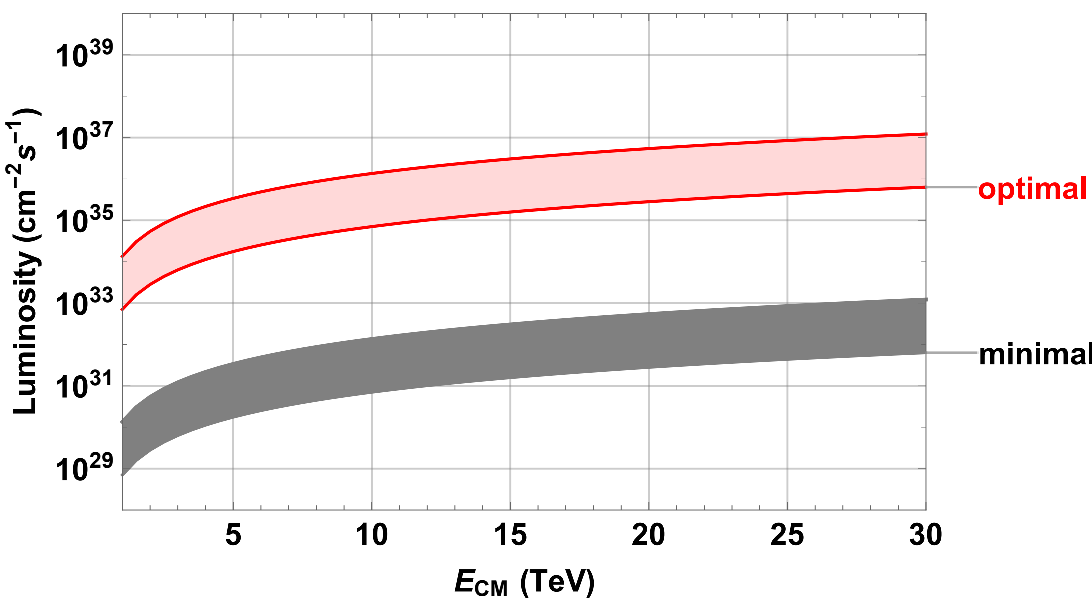
Luminosity need for precision

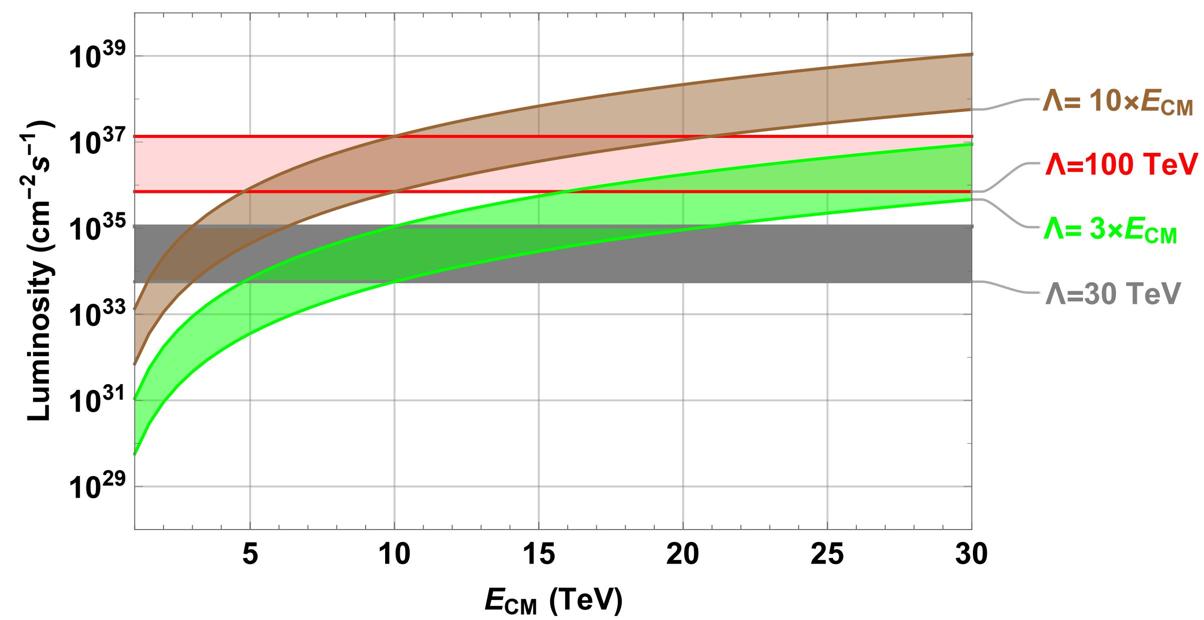


Minimally, we hope to reach new physics scale $\Lambda \approx 3\ E_{CM}$

Optimally, we would like to reach new physics scale $\Lambda \approx 10\ E_{CM}$
Also cover potential difficult cases.

Lepton collider summary

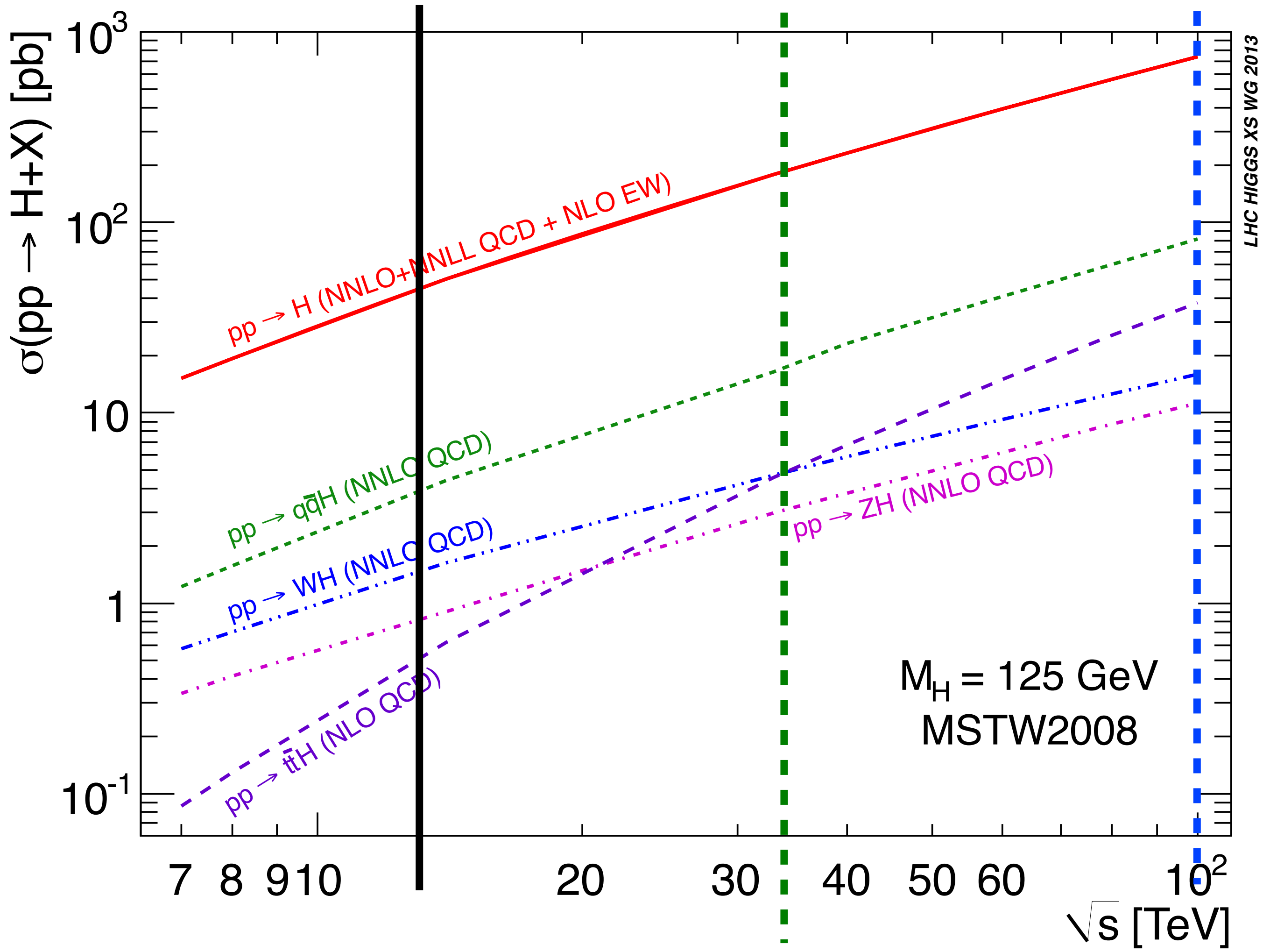




Luminosity $cm^{-2}\ s^{-1}$	1.5 TeV	3 TeV	6 TeV	10 TeV	14 TeV	30 TeV	100 TeV
Direct search minimal	3×10^{29}	10^{30}	5×10^{30}	2×10^{31}	5×10^{31}	2×10^{32}	2×10^{33}
Direct search optimal	3×10^{33}	10^{34}	5×10^{34}	2×10^{35}	5×10^{35}	2×10^{36}	2×10^{37}
Precision minimal	3×10^{30}	8×10^{31}	2×10^{33}	10^{34}	5×10^{34}	10^{36}	2×10^{37}
Precision optimal	7×10^{32}	10^{34}	2×10^{35}	2×10^{36}	5×10^{36}	10^{38}	2×10^{39}

Hadron collider

- The "ultimate" Higgs factories



# of Higgses in 3 ab^{-1}

14 TeV > 150 million

33 TeV > 500 million

100 TeV > 2 billion

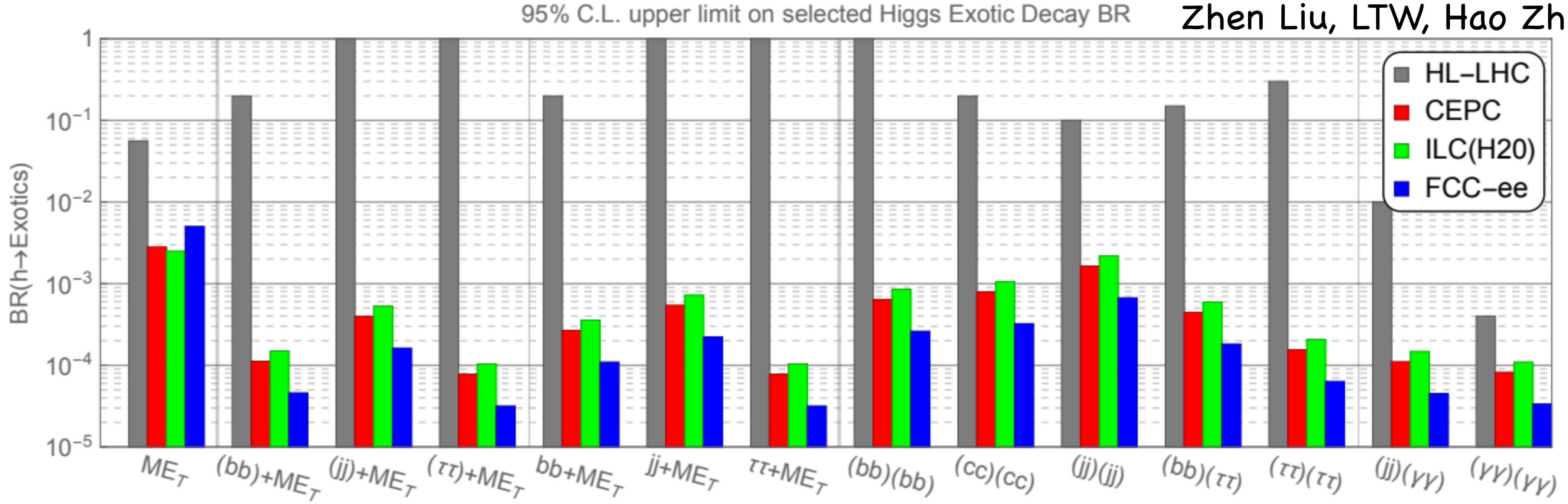
In comparison, O(million) Higgs at ee Higgs factories

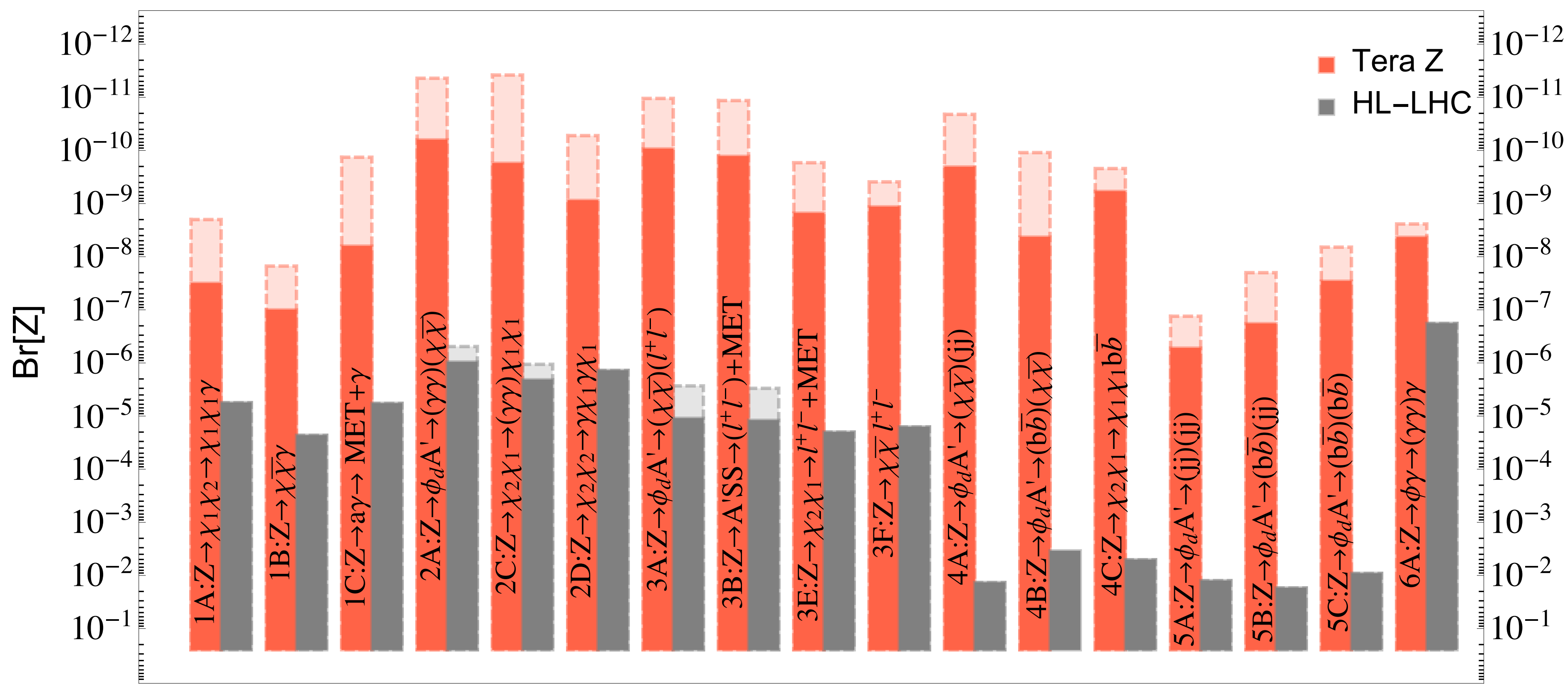
Hadron collider good for rare but clean signal

In principle, can be sensitive to BR ≈ 10^{-7}

Higgs/Z factories.

Zhen Liu, LTW, Hao Zhang





Jia Liu, Xiaoping Wang, Wei Xue, LTW

Particle statistics

	FCC-ee	ILC	CLIC	CEPC	MuonC	photon C
Higgs	10^6	$(0.6_{250}+1_{500})\text{x}10^6$	10^5	10^6	$2\text{x}10^5_{(3TeV)}$ $+10^7_{(10TeV)}$	
Z	$3\text{x}10^{12}$	a few $\text{x}10^9_{(250+90)}$	a few $\text{x}10^9_{(380+90)}$	$7\text{x}10^{11}$		
W	10^8	a few $\text{x}10^7$	$10^7_{(380)}$	$2\text{x}10^7$		
Top	10^6	$2\text{x}10^5$				

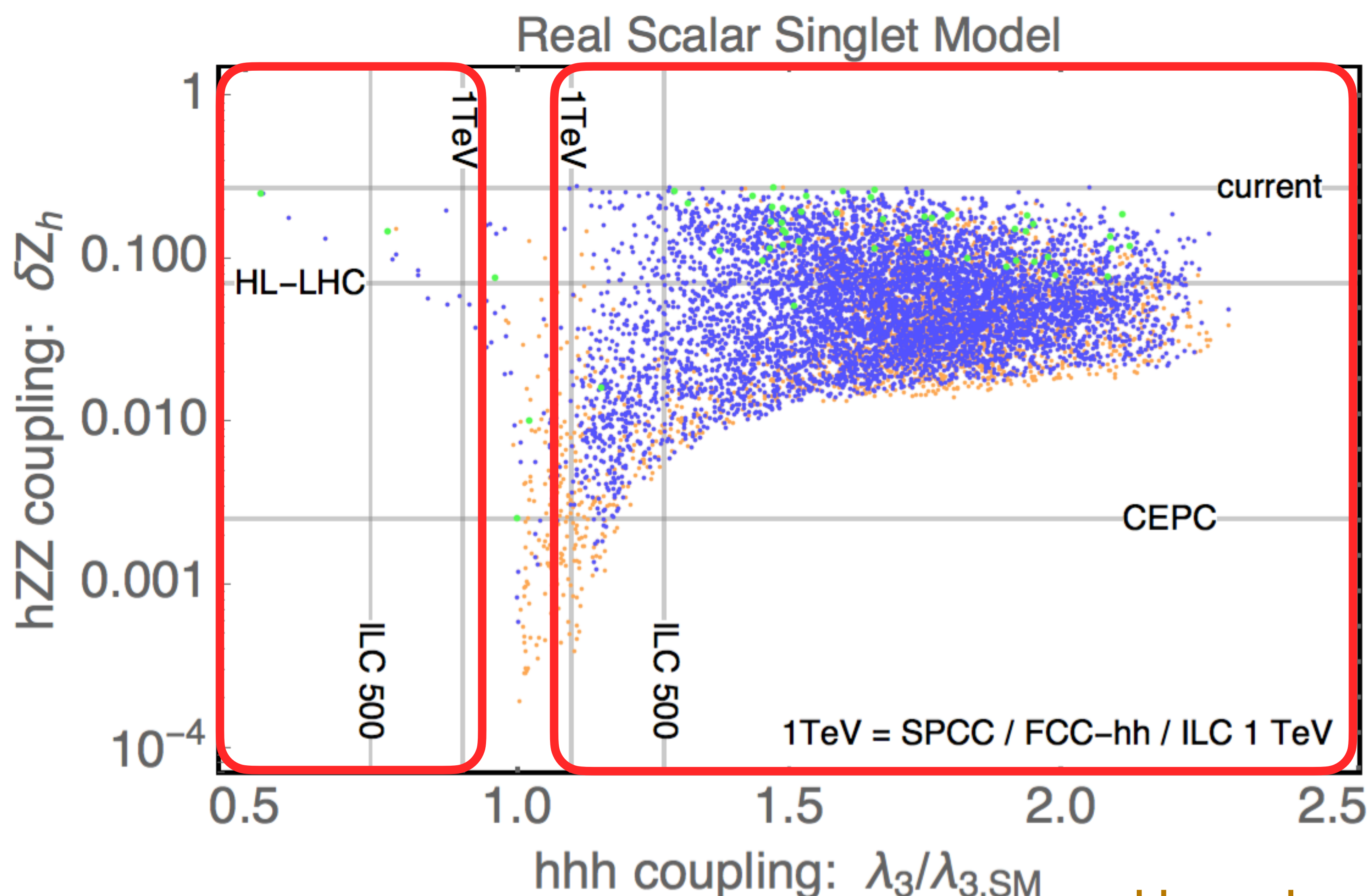
This is a draft of a table of statistics for particles important for precision measurements.

There are missing entries (no relevant study, also no concrete run plan), and the other numbers also not quite final.

Subscript labels different run options.

The statistics for hadron collider can also be shown, but it can't be quite compared with the lepton colliders since the measurement are typically systematics dominated (not determined by statistics).

Probing EW phase transition

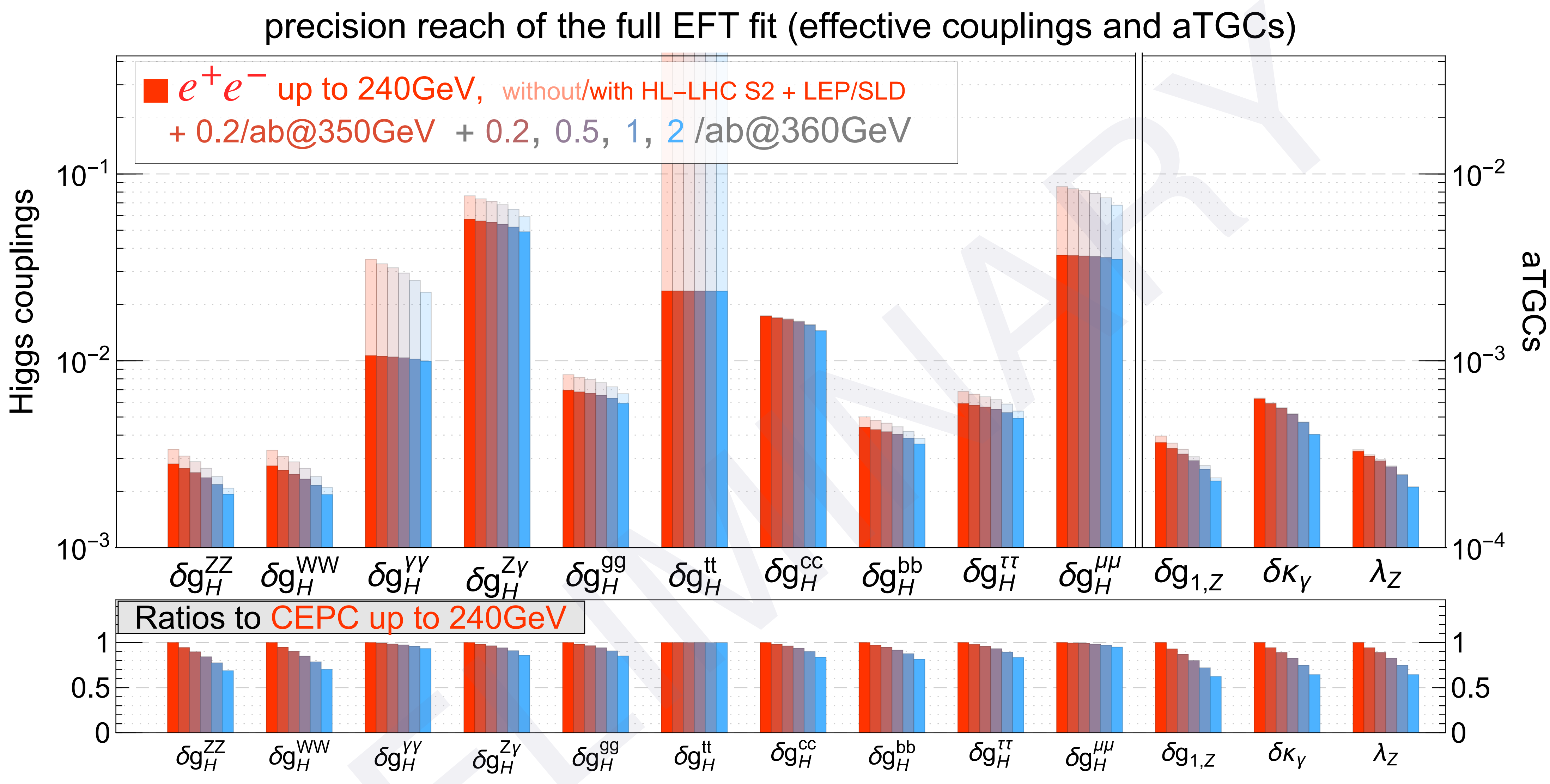


FCC-hh/SppC

Huang, Long, LTW, 1608.06619

Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

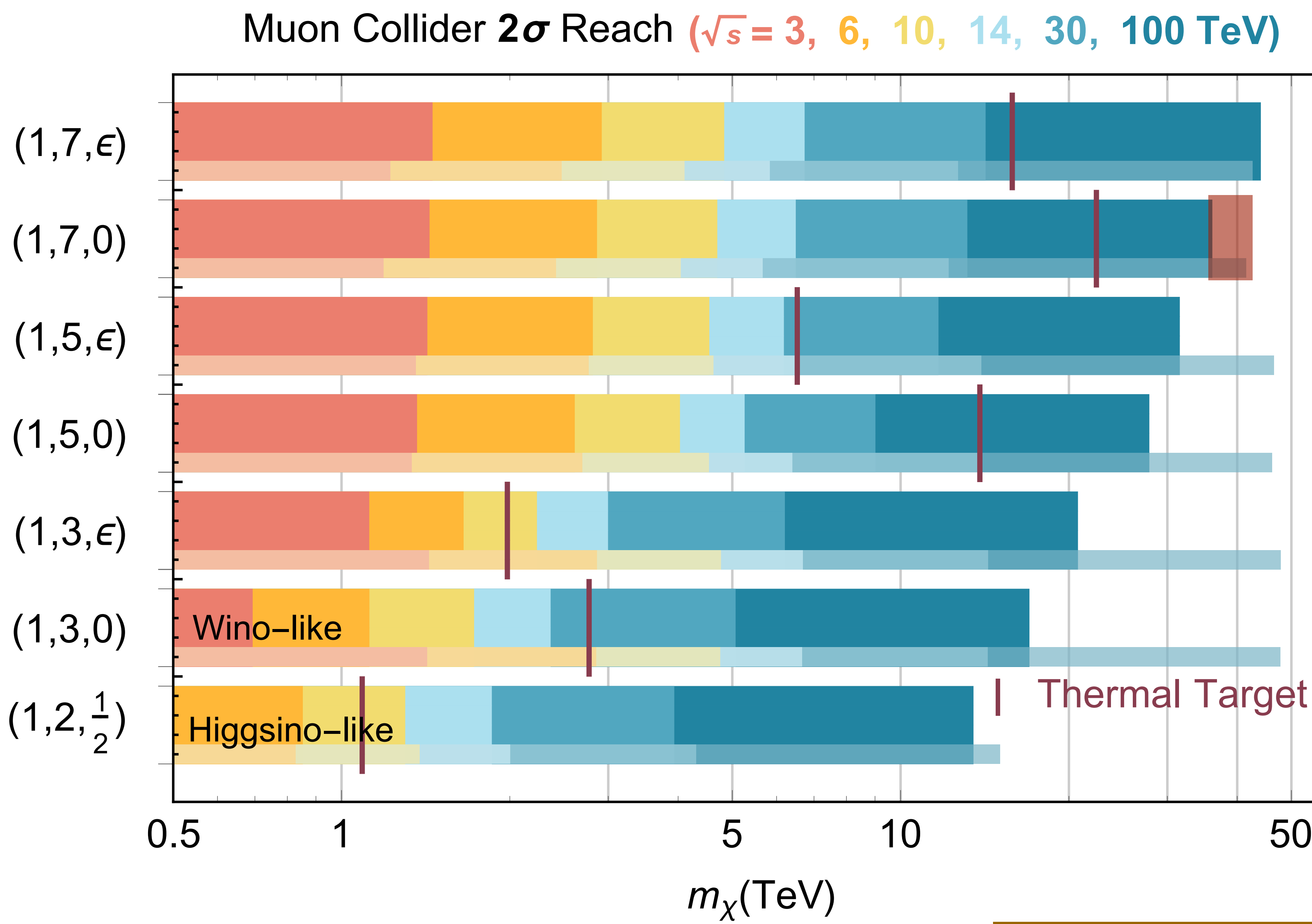
Gains of running at higher energies



Gain up to a factor of a few

Even better if one can run at even higher energies.

Harder case, dark matter



assumed luminosity:

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Really need the large luminosity to get there.