Muon collider:
Physics case studies and benchmarks

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Making the physics cases

Target:
Addressing important physics questions.
A significant step beyond FCC-x, CLIC etc.

"bread and butter"

- Higgs couplings.
- Heavy new physics.

Showcasing rich physics

- Exotic Higgs decays
- Dark sector. FIPs. Portals, long lived particles.
- ...

Higgs

Single Higgs

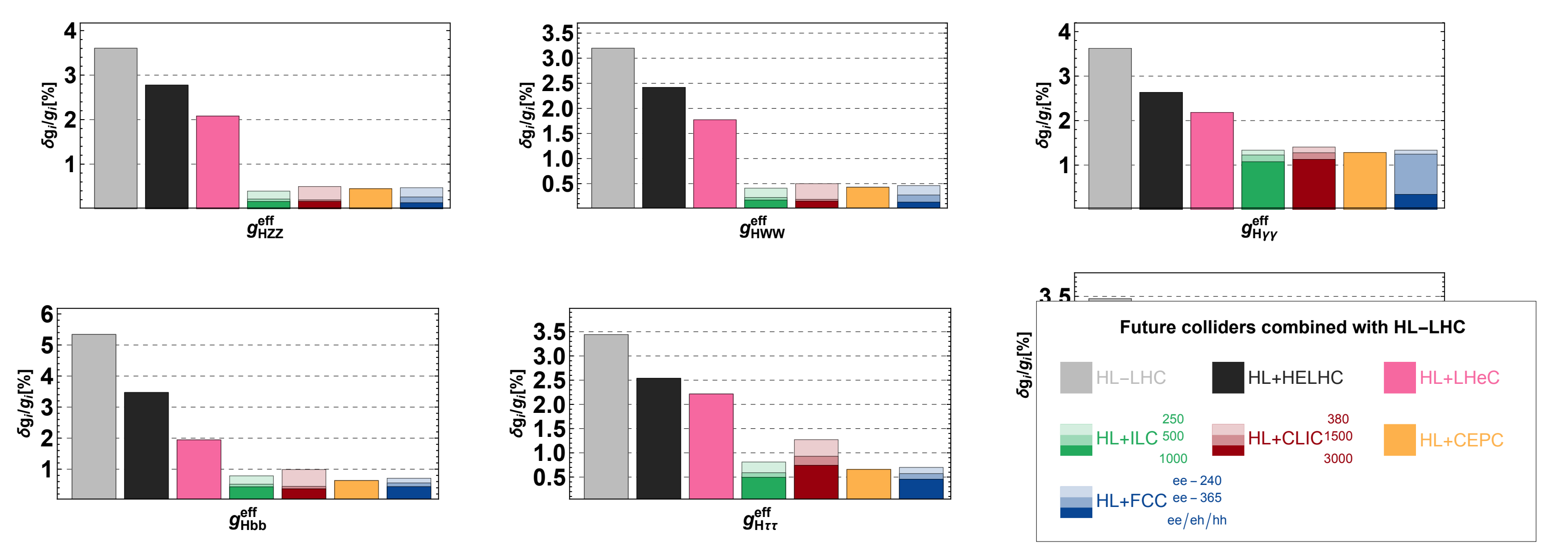
muon collider: $$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

E_{CM} (TeV):	1.5 TeV	3 TeV	6 TeV	10 TeV	30 TeV
Higgs production/10^7s	37,500	200,000	820,000	10^7	10^8

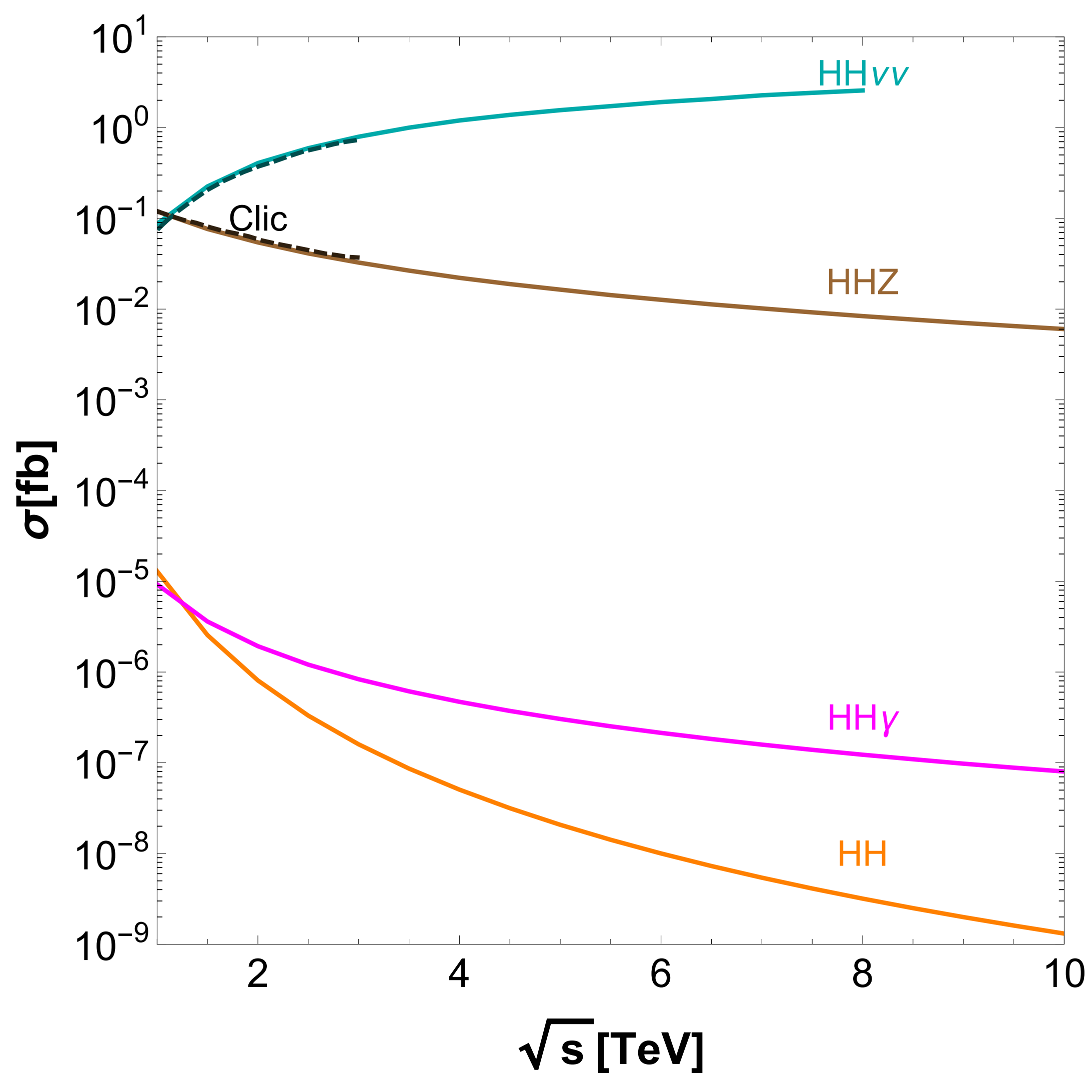
In comparison, 250 GeV Higgs factories (FCC-ee/ILC/CEPC) produces ≈ 10^6 Higgses

To have a clear edge, needs to run at 10+ TeV, with corresponding higher luminosity

Target: better than



Higgs self coupling: double Higgs



CLIC projection:

$$\delta_{hhh} \in (-7\,\%\,, 11\%) \text{ at } 5 \text{ ab}^{-1}$$

Naive scaling, for muon collider:

$$\delta_{hhh} \sim 7\,\% \text{ at } 6 \text{ TeV}$$
$$\sim 3.5\,\% \text{ at } 10 \text{ TeV}$$
$$\sim 1\,\% \text{ at } 30 \text{ TeV}$$

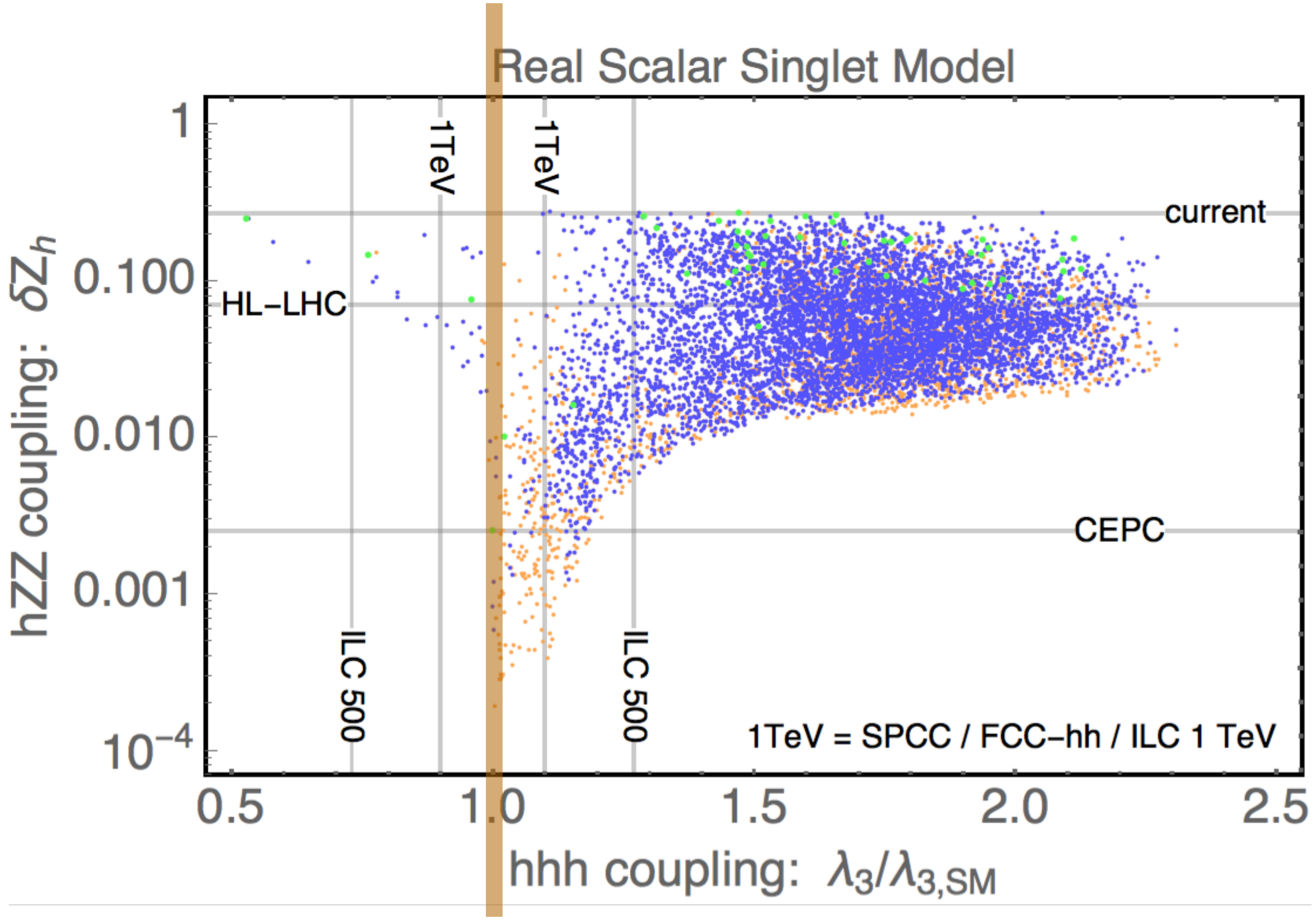
In comparison:
100 TeV pp collider, 30 ab^{-1}, ~ 5%

Enough statistics to have good precision at 10 TeV already.

10 times more statistics → significantly better than 100 TeV pp.

Run at higher energy, or longer for higher lumi?

A dream precision



A typical benchmark:

Higgs+singlet models with strong 1st order phase transition

≈ 1% or better. Goal of muon collider

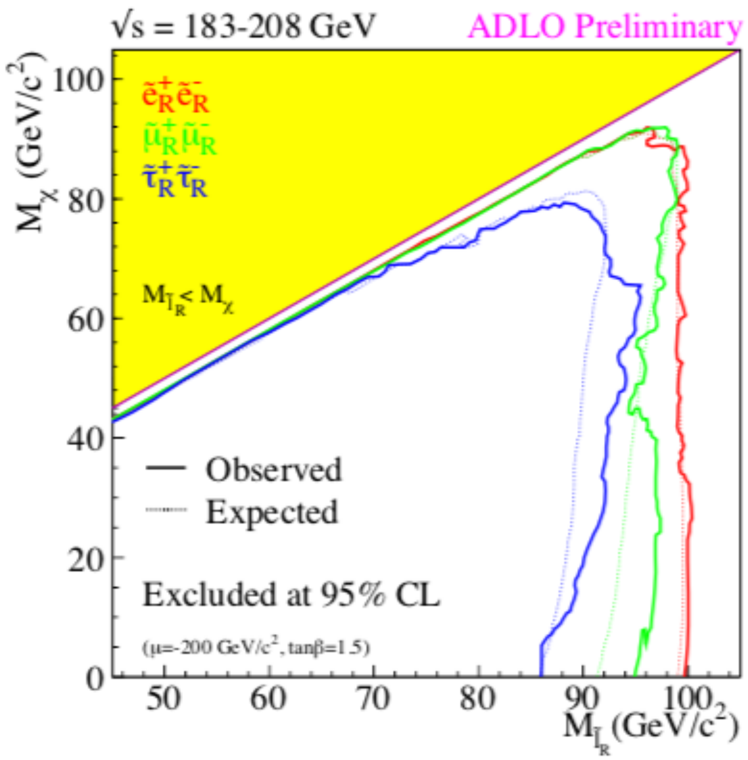
Goal of muon collider studies on Higgs measurements

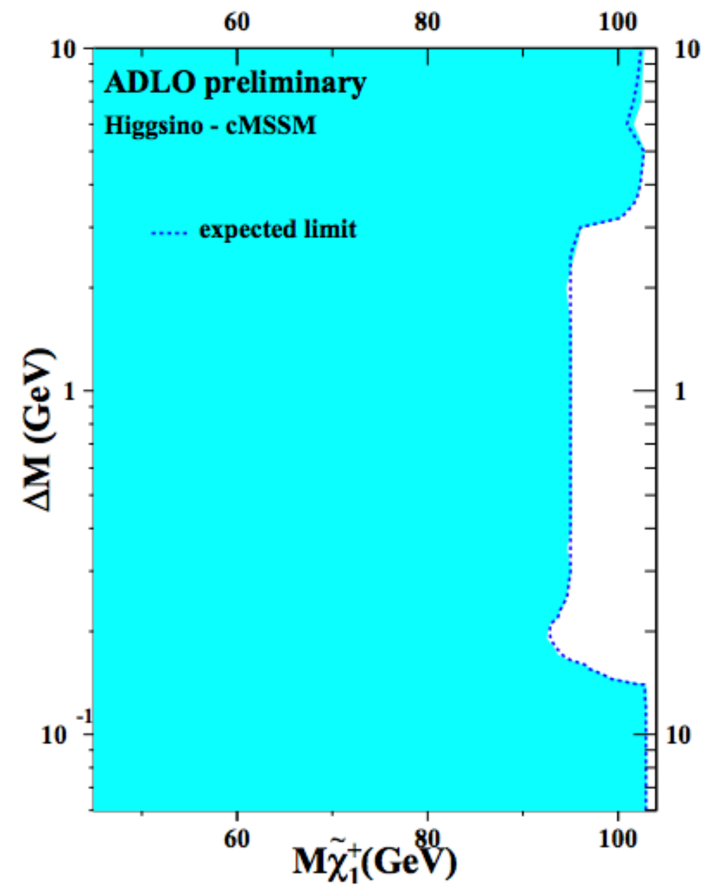
- Validate or refine these simple estimates based on statistics and simple scaling.
  - Identify main systematics, potential show stoppers.
- Good progress have been made. 2001.04431, talk by Donatella Lucchesi
  - More cases to be studied.

Heavy new physics

Example: pair production

Estimating the reach for New physics pair production





LEP has excellent reach,

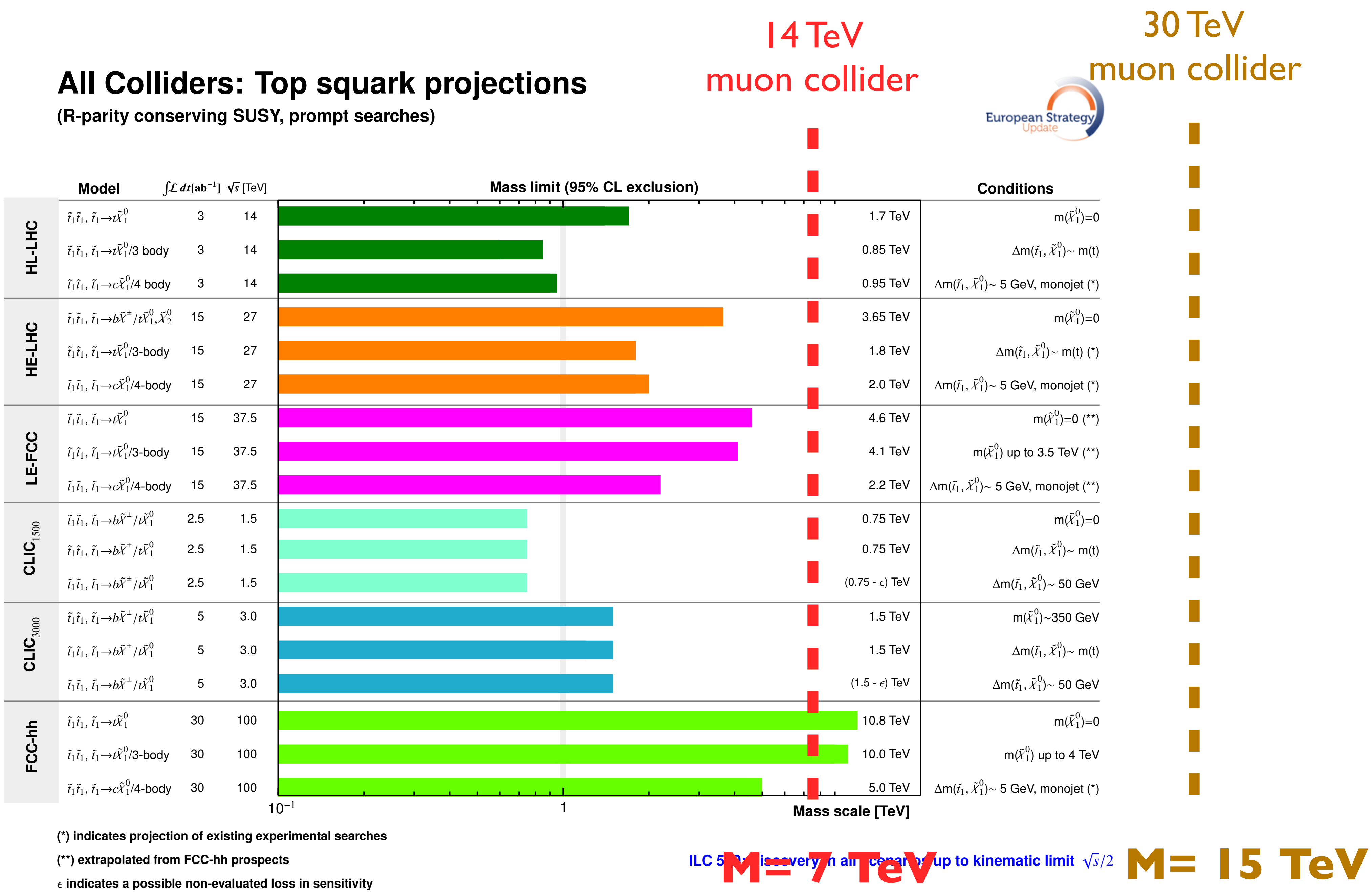
setting limit almost at its kinematical limit = $\frac{E_{CM}}{2}$

Soft particle, ISR photon, ….

At muon collider, expect similar performance

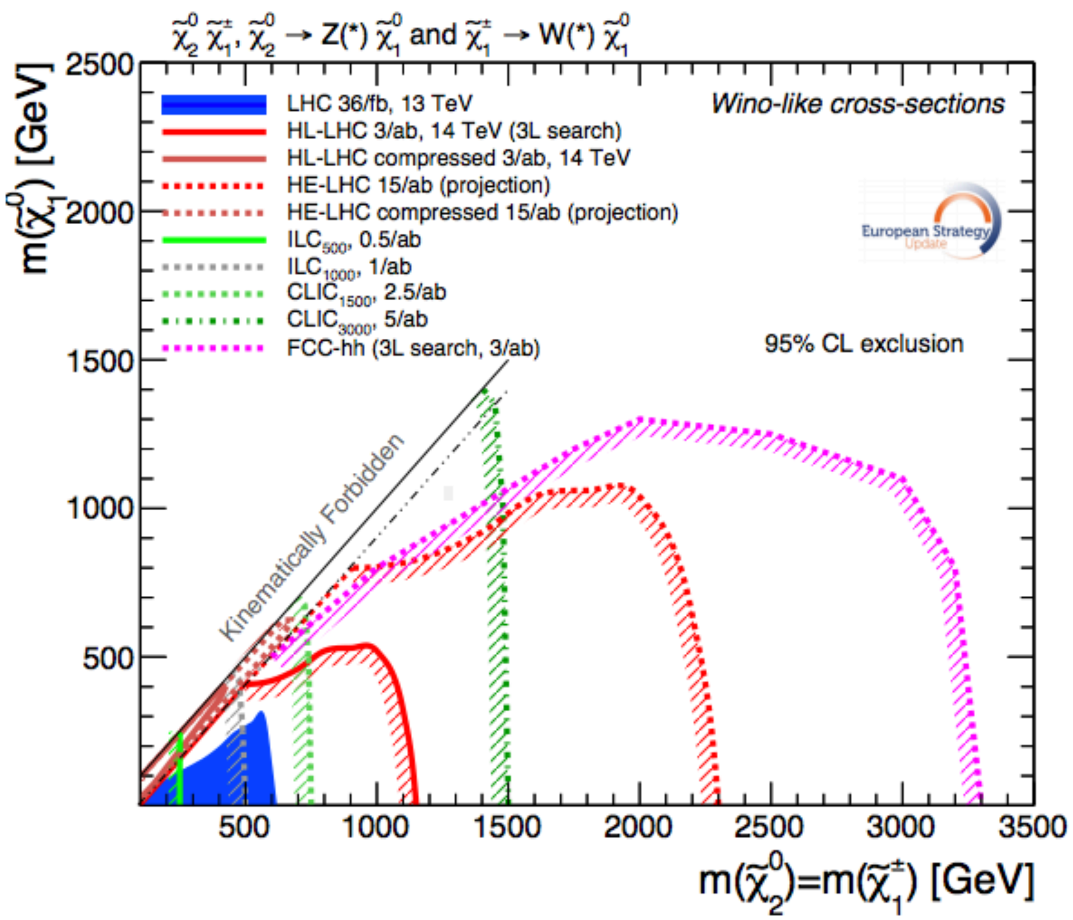
(More detailed study needed)

Direct search for new physics: pair production



stop in supersymmetry

Direct search for new physics: pair production



14 TeV
muon collider

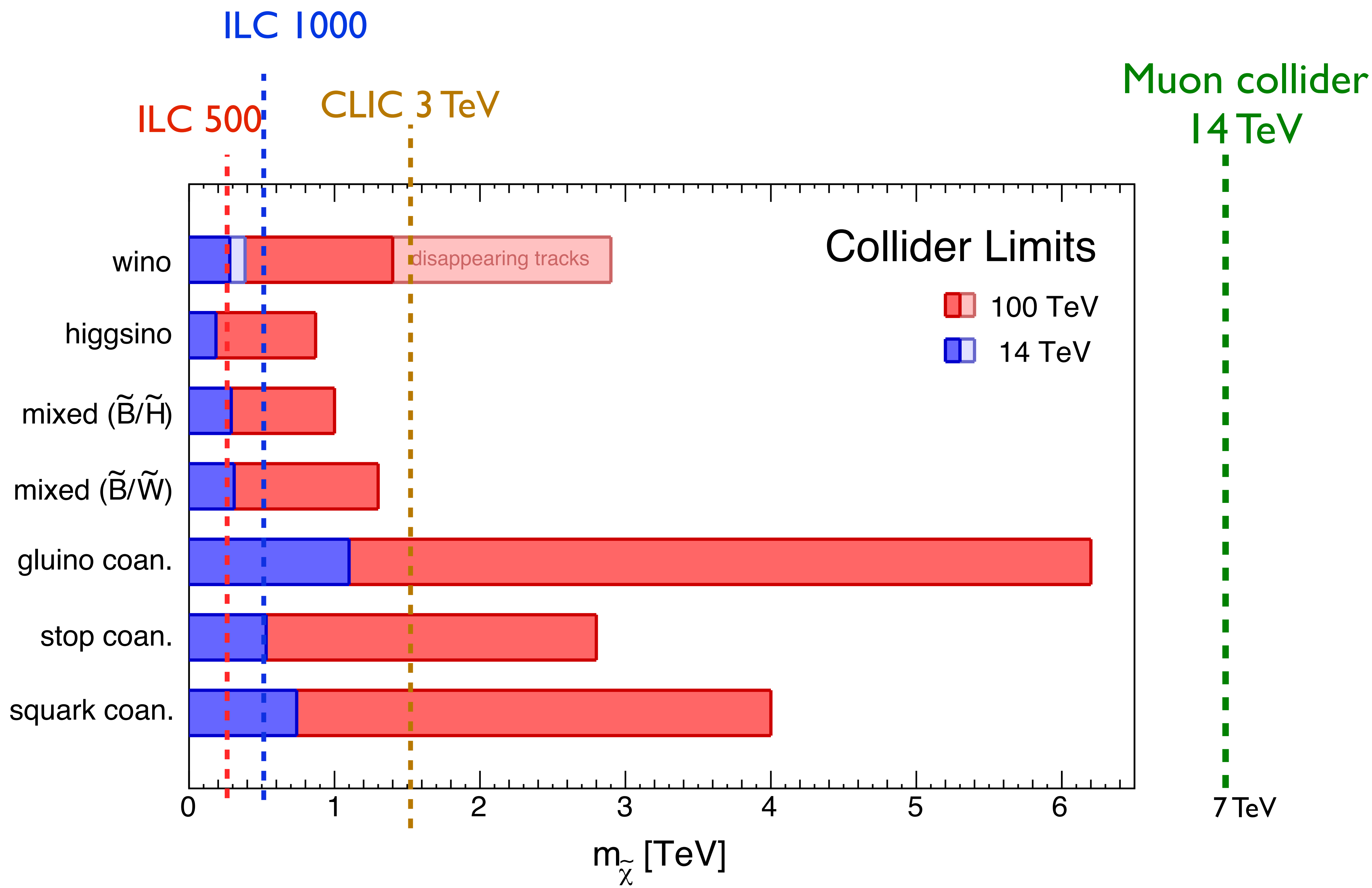
M= 7 TeV

30 TeV
muon collider

M= 15 TeV

electroweak charged particle

Dark matter



ILC 1000
ILC 500
CLIC 3 TeV
Muon collider
14 TeV
Collider Limits
100 TeV
14 TeV
wino
higgsino
mixed (B̃/H̃)
mixed (B̃/W̃)
gluino coan.
stop coan.
squark coan.
disappearing tracks
0
1
2
3
4
5
6
7 TeV
$m_{\tilde{\chi}}$ [TeV]

Goals of studies

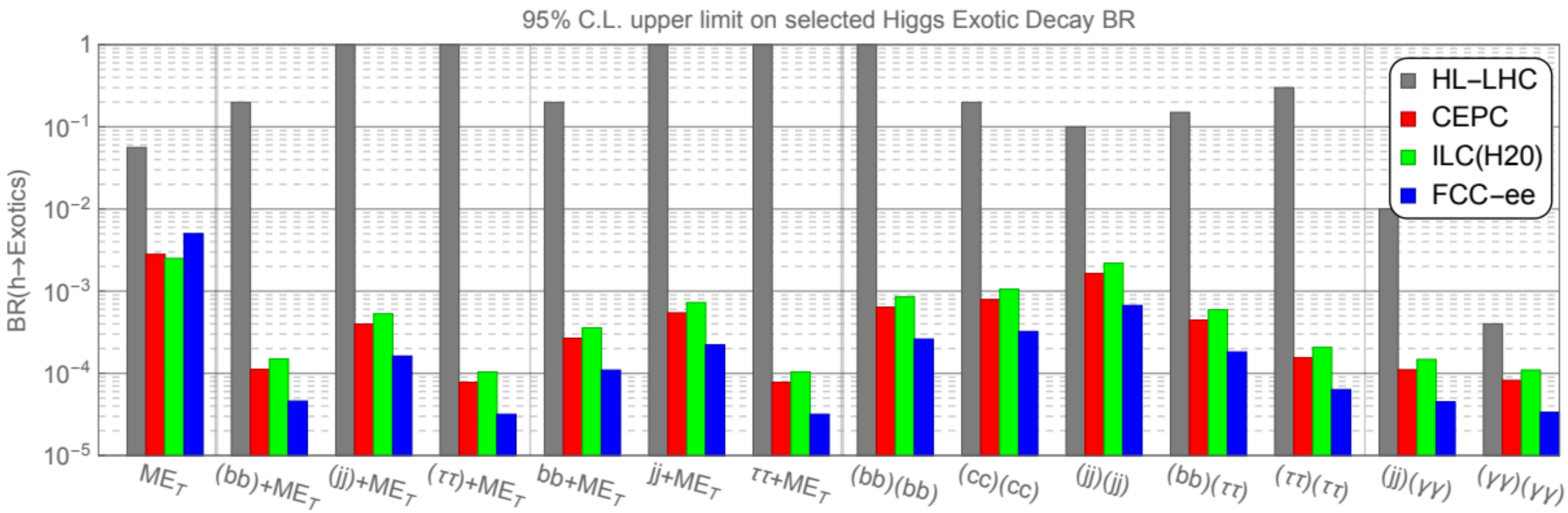
- Map out how we get to the maximal mass reach.
- NP decaying to energetic SM particles
  - Such as: $\tilde{t} \to t + \chi, \quad T' \to Wb/Zt, \ldots$ Easy (?)
- More compressed spectrum
  - DM in EW multiplet, coannhilation region...
  - Compressed spectrum.
  - Soft objects, kinks/stubs, more difficult, needs full simulation to study.
  - More inclusive searches, such as mono-X?
  - Much more study needed.

Rich exotic physics

Many many scenarios:
Dark sector, portals, etc.

Featuring (very)weakly coupled (light) particles, long life times (some stable), other non-standard signals…

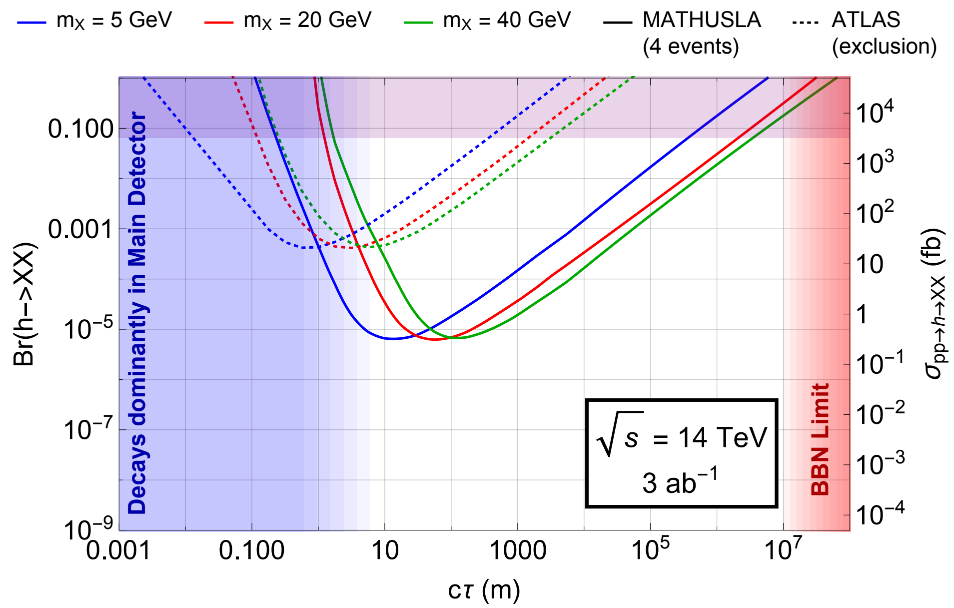
Example: Higgs exotic decays

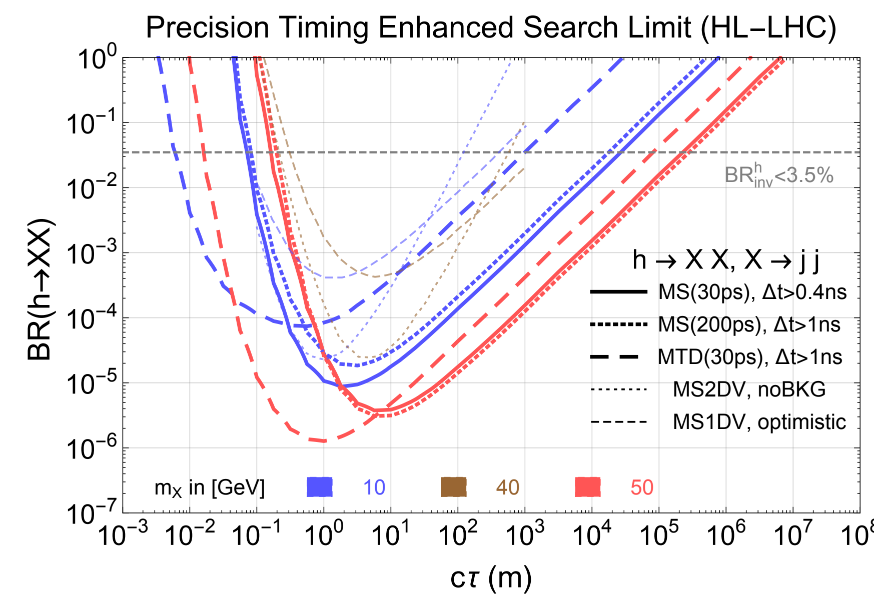


Hao Zhang, Zhen Liu, LTW

- Muon collider can produce 10^7 - 10^8 Higgses (with higer energy/lumi runs). Cleaner environment.
- Should be 1 or 2 orders better than Higgs factories.

Example: Higgs portal. $h \to XX$, $X \to$ jets (long-lived)





- LHC (ATLAS/CMS, MATHUSLA…), Br(h→XX) ≈ 10^{-5} – 10^{-6}.
- FCC-hh: probably better by 1-2 orders.
  - However, hadron collider needs to trigger on something else + large background…
- Muon collider can produce 10^7 - 10^8 Higgses (with higer energy/lumi runs). Cleaner environment. Could have a chance.

Exotica, Dark sector, etc

- Statistics crucial for reach weak coupling
  - Arguing for higher luminosity.
- Generic signal with objects still quite energetic.
  - e.g. exotic Higgs decay; LLP $h \to XX$, $X \to jj$
  - Perhaps not too challenging at muon collider.
- Can have soft tracks, very displaced and out of time...
  - e.g. Very compressed $\to$ long-lived
  - More detailed detector simulation needed.

Thoughts on simulation.

- Delphes card would be very useful.
  - Several obvious cases not too sensitive to soft/out-of-time objects.
  - Facilitates the community involvement in studies tremendously.
- MC simulation.
  - VBF is likely the workhorse for most NP productions.
  - MC4VBF (especially with photon) further improved?

Thoughts on run scenarios for studies.

- Recommended scenarios should include
  - 3, 10, 14, 30 TeV (included in snowmass benchmarks).
  - Explore luminosities different from

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

- Open to new scenarios (if not too crazy) if there is a strong physics case to be made.

Thoughts on Snowmass input

- Useful to have a document outlining open and urgent questions to be addressed.
  - Can either be an LoI or just as a separate input to the Snowmass (e.g. EF and AF).
  - e.g. FCC memo to Snowmass
- LoI (deadline Aug 31st, but ASAP)
  - Express interests for individual studies.
  - Also have less formal EoI forms.
  - To be followed by a write-up summarizing findings before summer 2021.

Let's get started!