Future High-Energy Colliders Physics

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Ideology

HEP before the LHC

HEP before the F.C.

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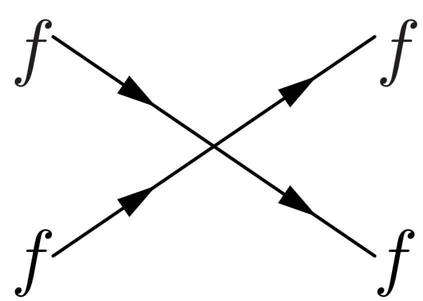
HEP before the F.C.

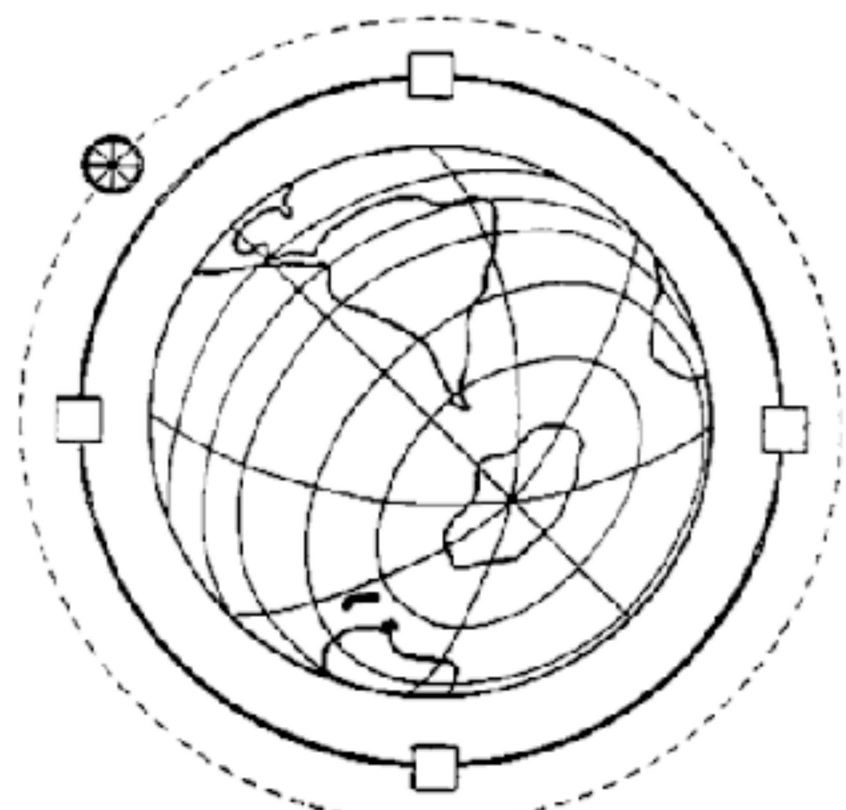


$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$

Ultimate Accelerator.

Drawn by Fermi in the ’50 to reach 3 TeV.

The manifesto of HEP!



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Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

* Not necessarily a bad thing. Columbus left for his trip just because he had no idea of where he was going !!

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HE colliders are the best systematic exploration strategy:

- Exploring **Energy Frontier** (Directly or Indirectly)
- **Multi-purpose** program
- **Reliable Old Physics** (SM) **predictions**
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HE colliders are **Expensive**.

Hence, the next one **will exist only if** capable to **explore many directions**, and be **conclusive** on some of those.

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[even better if constructed with **revolutionary technology**…]

Naturalness

"Is m_H Unnatural?" $=$ "Is m_H Unpredictable?"

$$\left(m_H^2\right)_{Phys.} = \int_0^\infty F_{true}(E;\, g_{true})$$

UV Contribution

$$c\,{\Lambda_{\rm SM}}^2$$

$$= \int_0^{\Lambda_{\rm SM}} (\ldots) + \int_{\Lambda_{\rm SM}}^\infty (\ldots)$$

SM Contribution

$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}{\Lambda_{\rm SM}}^2$$

Fine Tuning: $\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,\mathrm{GeV}}\right)^2$

Measures how much Unpredictable m_H is.

Unnaturalness is a challenge to **Reductionism**

Dramatic paradigm shift. E.g. Anthropic or Dynamical

Naturalness

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LHC may push conventional Natural models to

$$\Lambda_{\mathrm{SM}} \gtrsim 2\ \mathrm{TeV} \longrightarrow \Delta \gtrsim 10$$

Still Naturalness might be there in the form of:

Partial Unnaturalness

$$\Delta \sim 100$$

$$\downarrow$$

$$\Lambda_{\mathrm{SM}} \sim 5\ \mathrm{TeV}$$

Neutral Naturalness

$$\Delta \sim \mathrm{few} \longrightarrow \Lambda_{\mathrm{SM}}^{\mathrm{col.}} \sim 5\ \mathrm{TeV}$$

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$$\Lambda_{\mathrm{SM}}^{\mathrm{neut.}} \lesssim 1\ \mathrm{TeV}$$

Need **5 TeV** reach on ordinary Top Partners

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Still, the higher the reach, the better

Dark Matter

The FC should be capable to tell if DM is **WIMP** *

* Here I mean thermal relics with annihilation due to **SM Weak Force**

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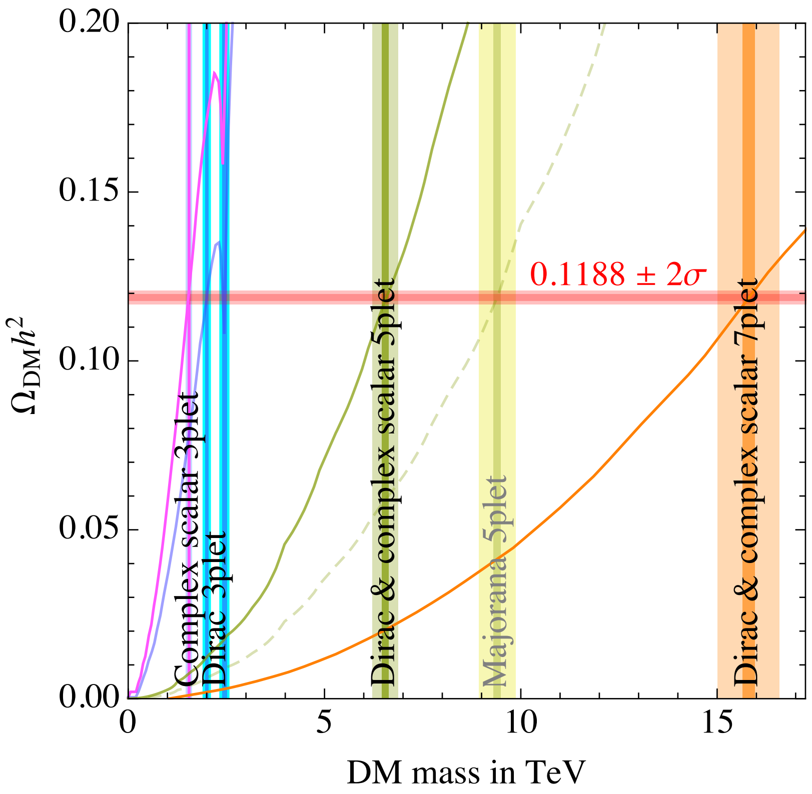
Accidental DM: stability from **accidental symmetries**

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$ *	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$ **	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16



EW Baryogenesis

Our knowledge of the Higgs sector is so **limited** that **we cannot tell** if EW phase transition was first order

This requires BSM states (possibly neutral) coupled to Higgs. Typically connected with trilinear Higgs.

The FC should be conclusive on this possibility

Measurements

The FC must allow for extensive measurements program:

- **Guaranteed outcome**
- **Indirect BSM** (reach above collider threshold)
- **Characterise discoveries**

Higgs couplings are **central**, but there is more

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EFT

$\mathcal{L}^{d=6}$

Low-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\mathrm{EW}}^2/\Lambda^2$

- require **accuracy:** large lumi, low syst. and th. err

High-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- benefit from high **energy and** high **accuracy**

If high-energy, we **can learn already from 1% measur.**

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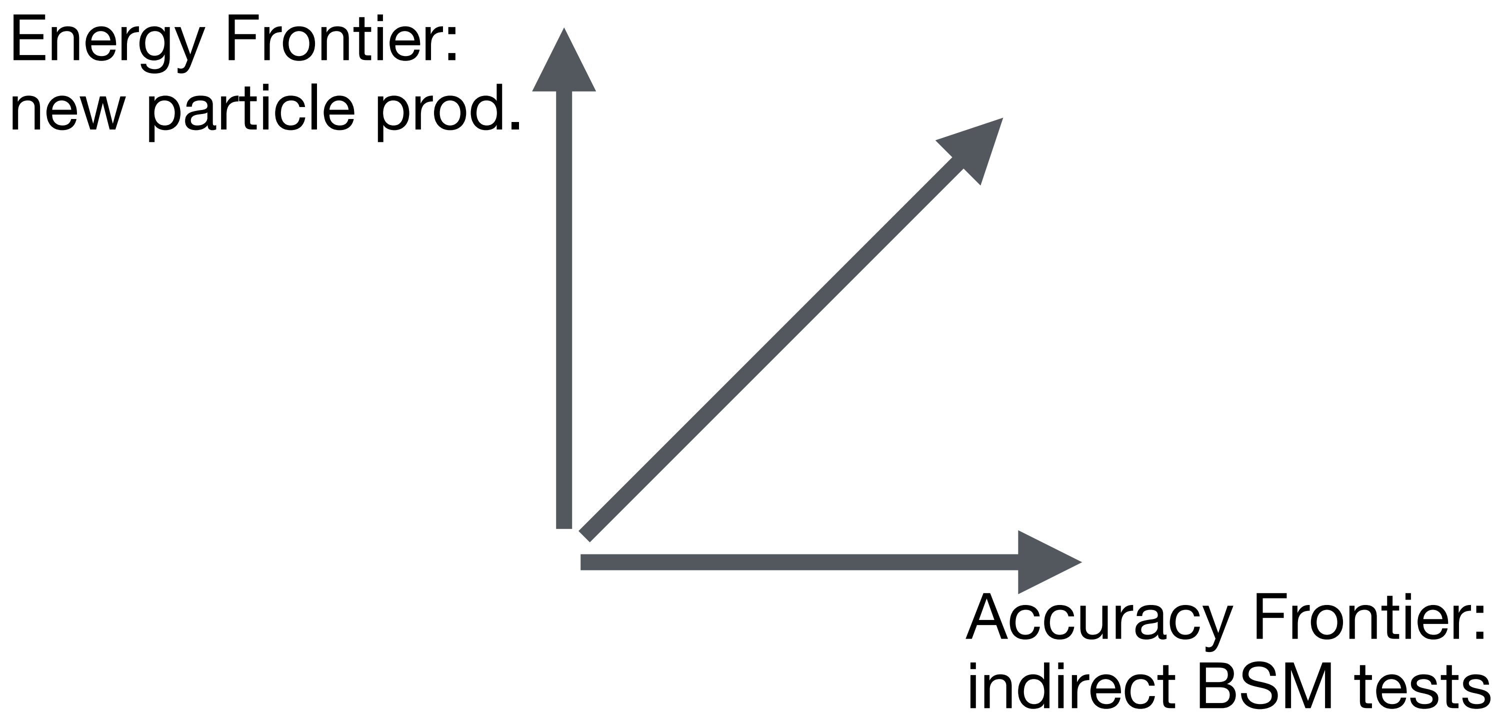
ccuracy

The Energy and Accuracy Frontier



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The FCC Project: (ee+hh+he)

CLIC: (380+1.5+3)

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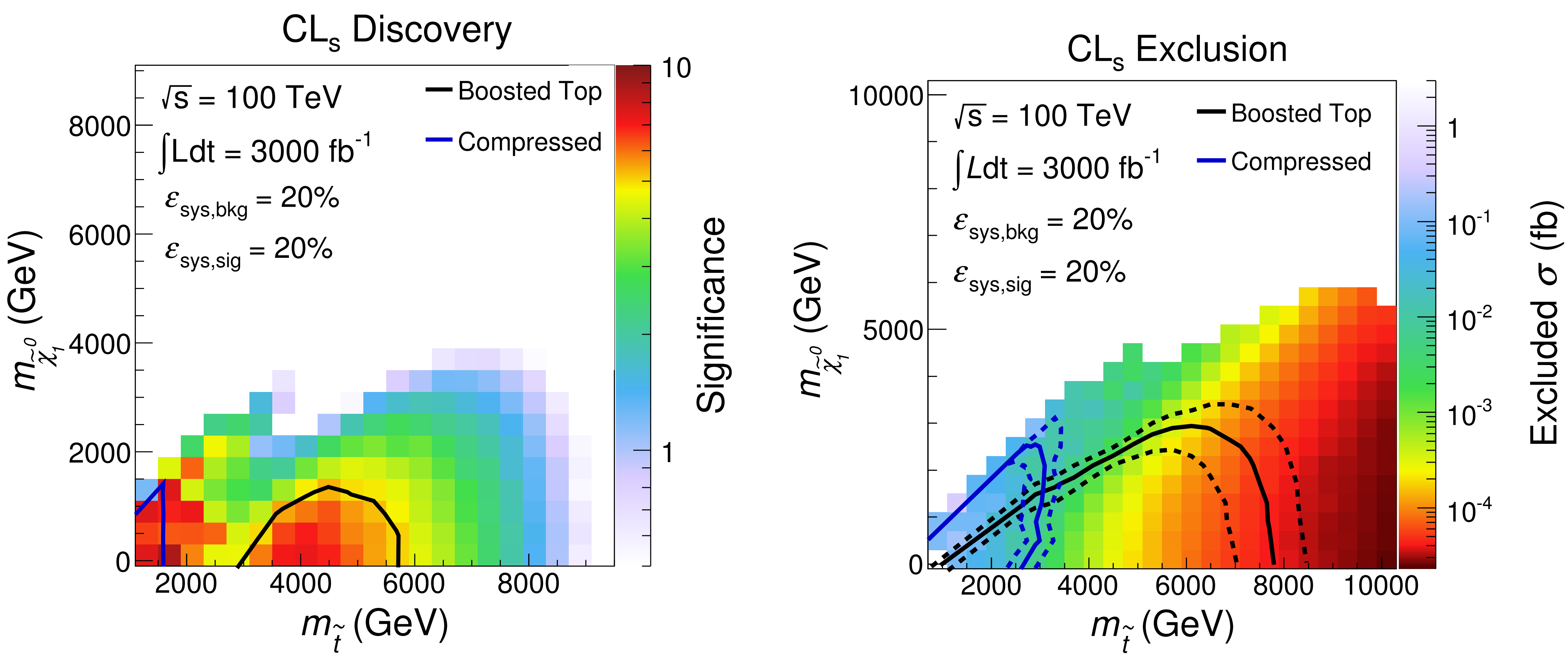
Stop to top + Neutralino:



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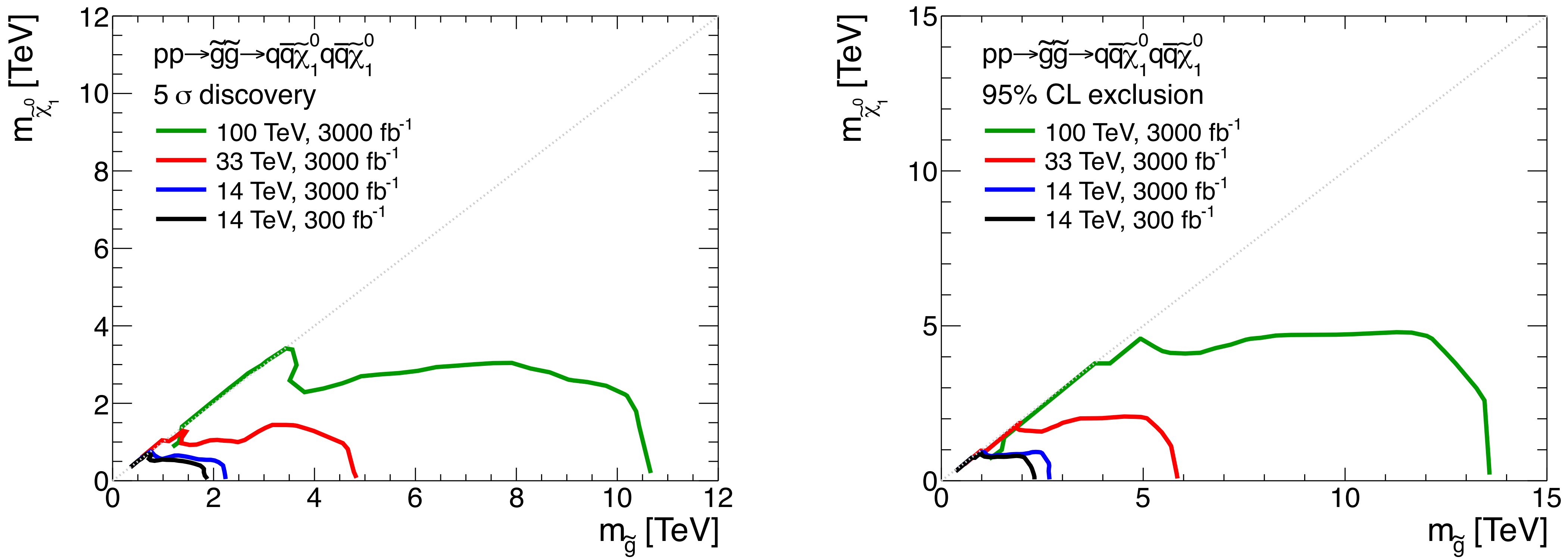
Gluino to Neutralino + q:



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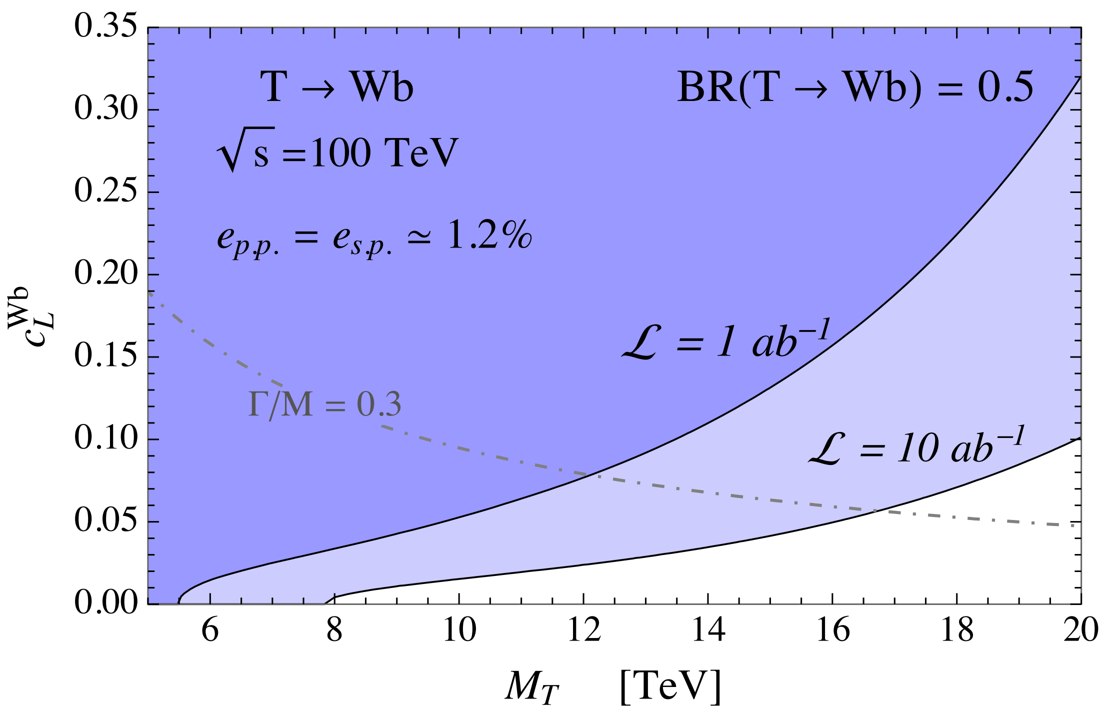
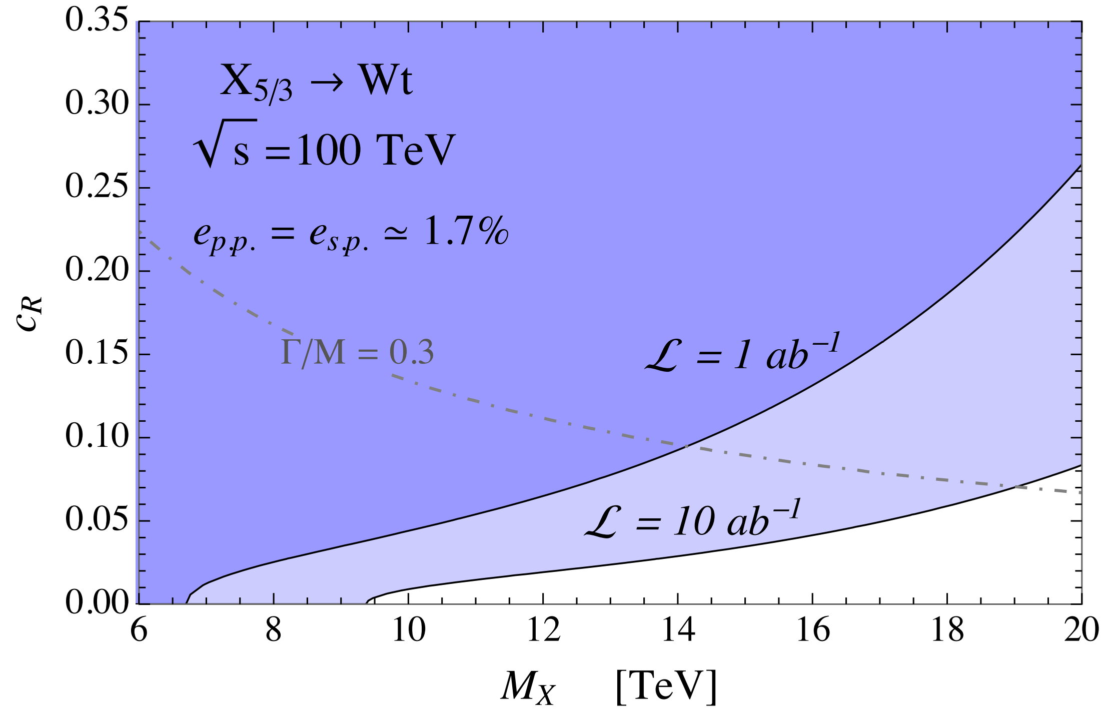
Fermionic Top Partners





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Higgs Compositeness @ FCC

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \quad \Rightarrow \quad \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

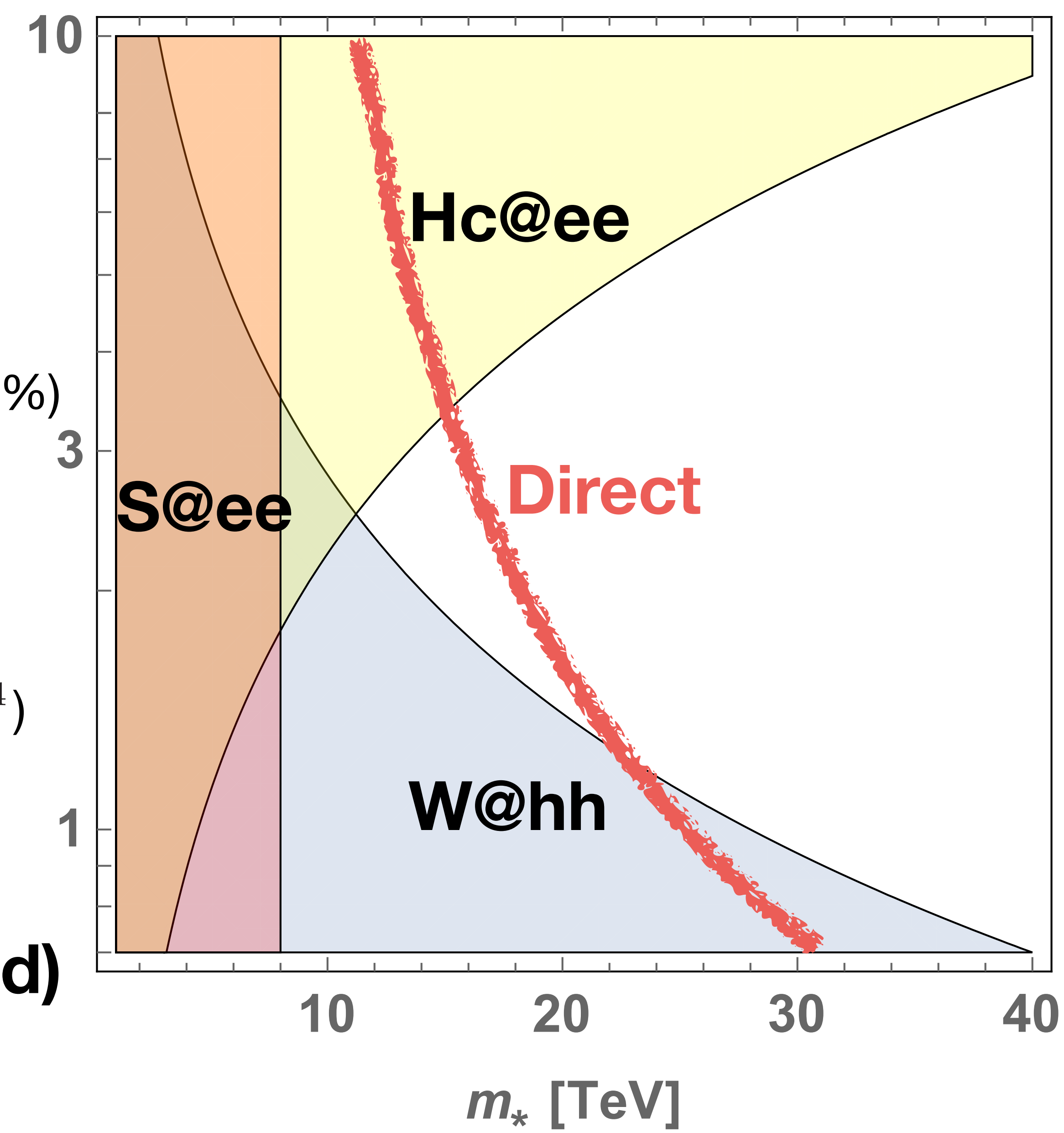
Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2} \partial_\mu |H|^2 \partial^\mu |H|^2 \quad \Rightarrow \quad \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

W @hh: (energy + accuracy) (HL-LHC$<10^{-4}$)

$$\frac{g_w^2}{g_*^2 m_*^2} (D_\mu W_{\nu\rho})^2 \quad \Rightarrow \quad W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < 4\,10^{-6}$$

Direct searches: (once model specified)



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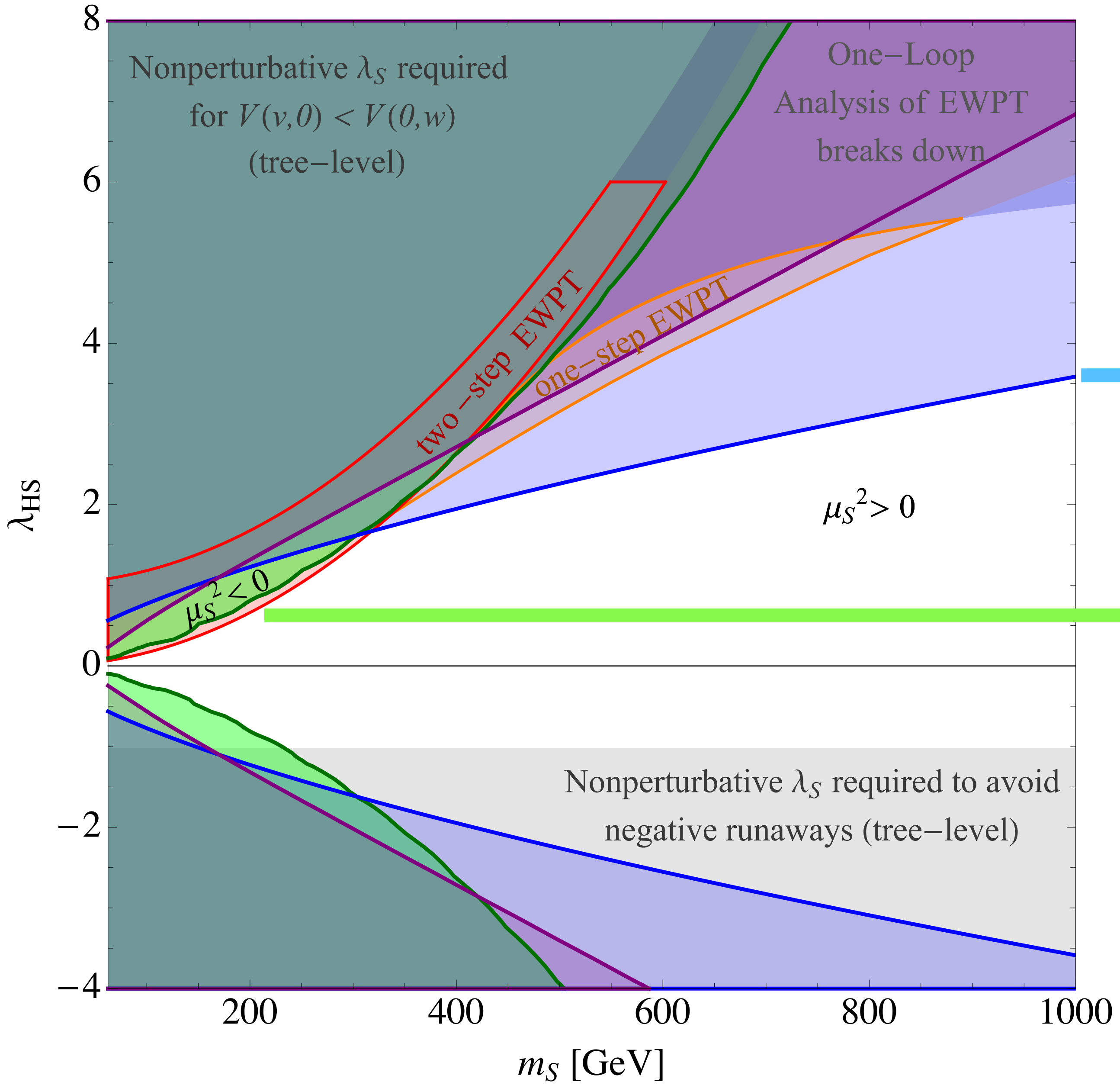
“Nightmare” strong 1st order @ FCC: [Z_2-odd singlet]



$$\delta g_{3H}/g_{3H} \sim 3, 4\%$$

Direct singlet search
(VBF h*->SS)

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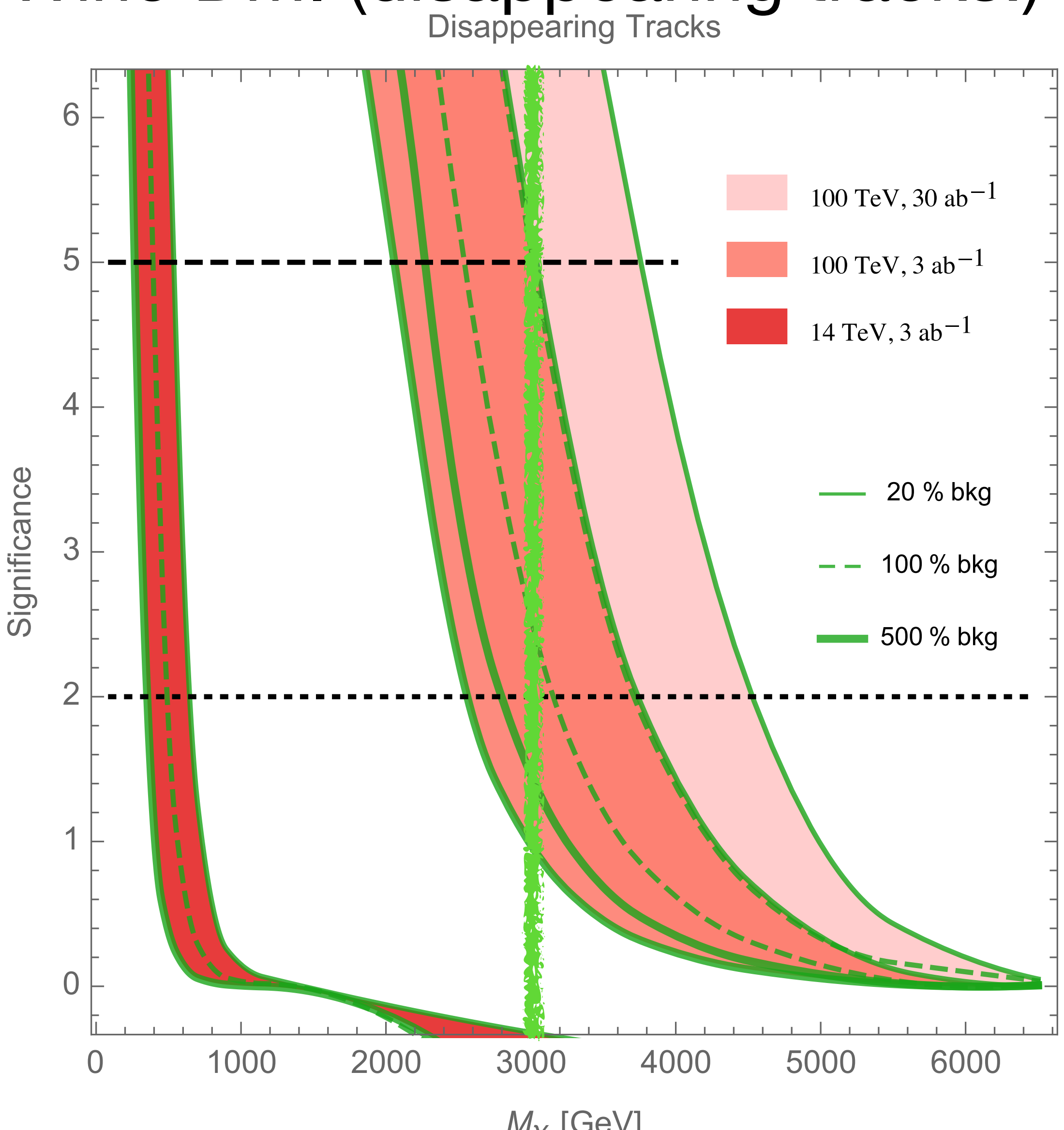
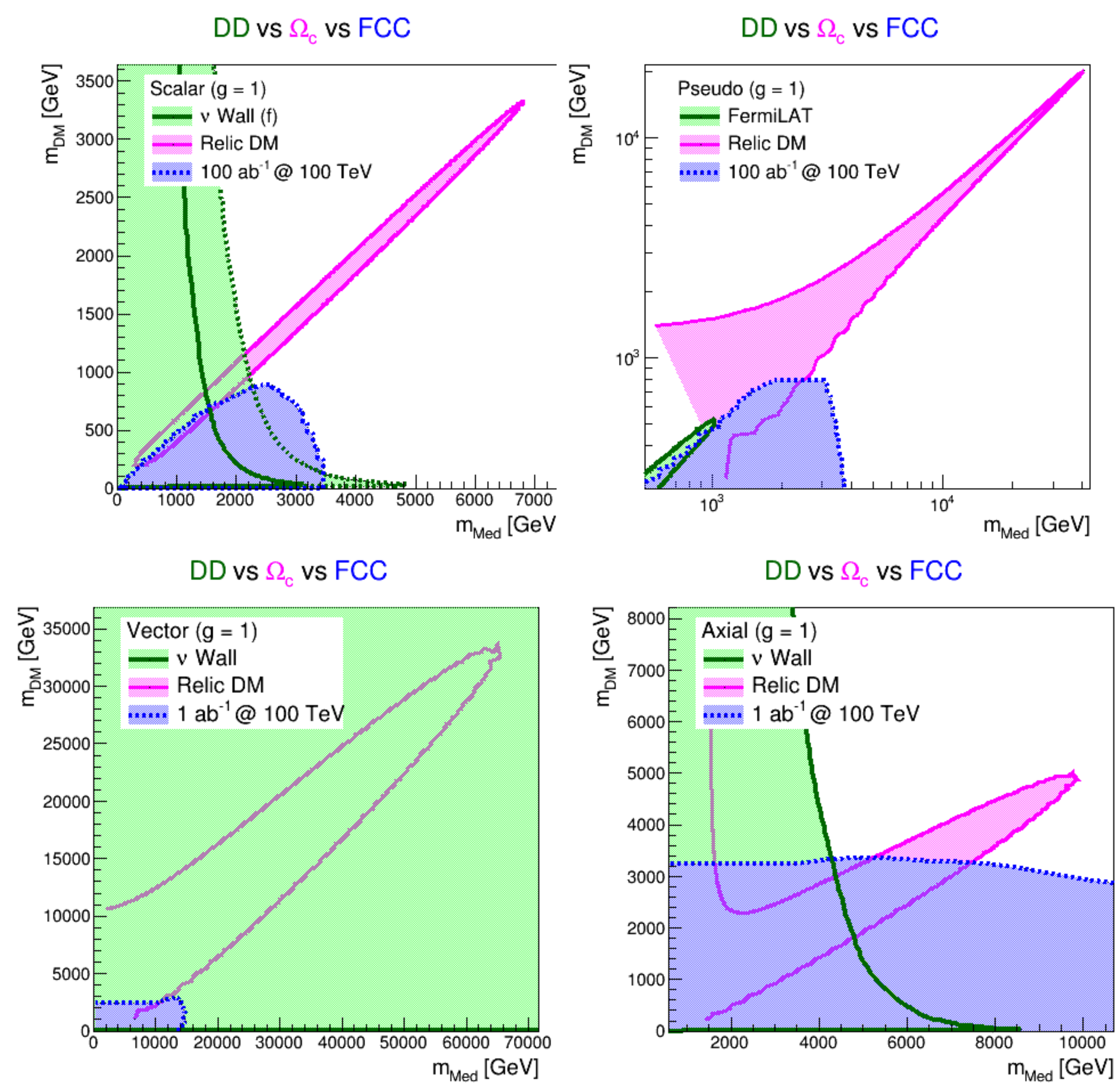
WIMP DM @ FCC: [invisible to DD]

Wino DM. (disappearing tracks:)



Crossing neutrino wall:



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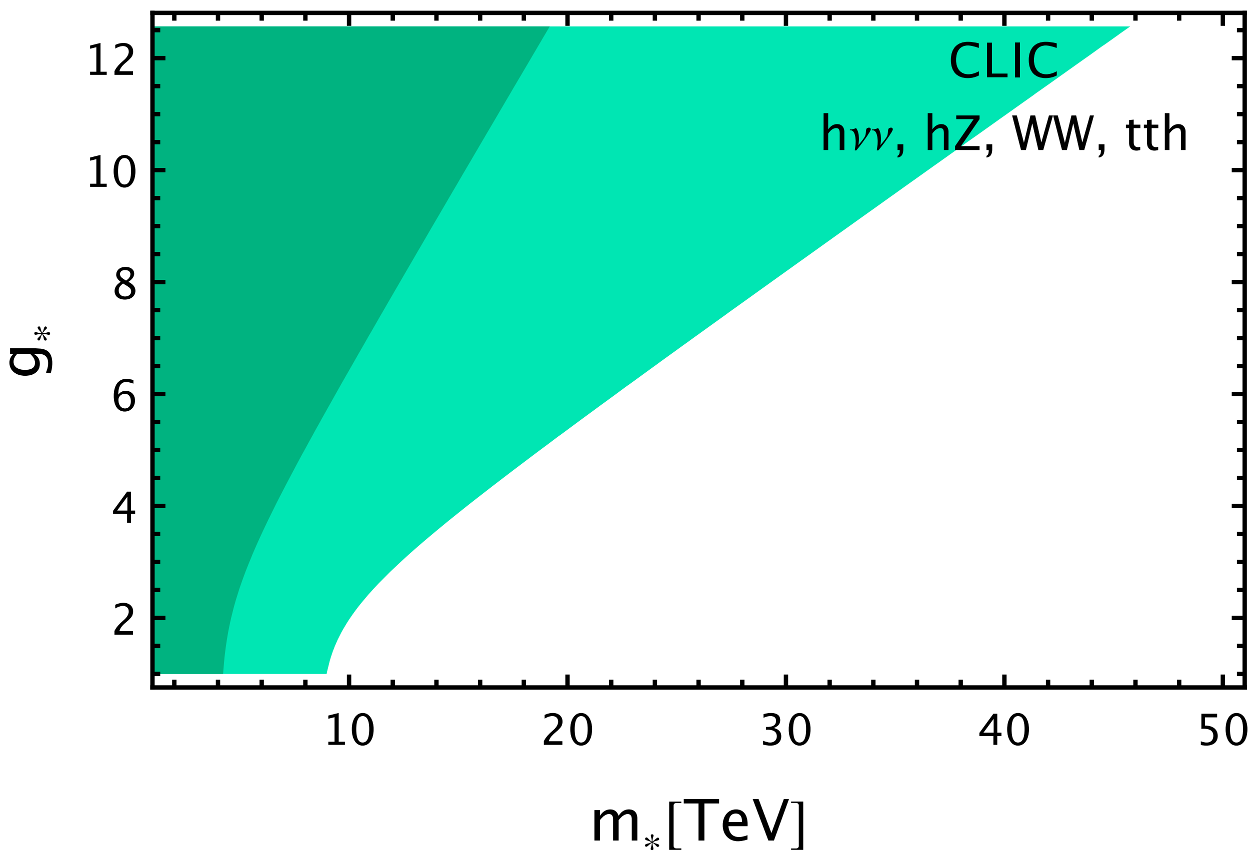
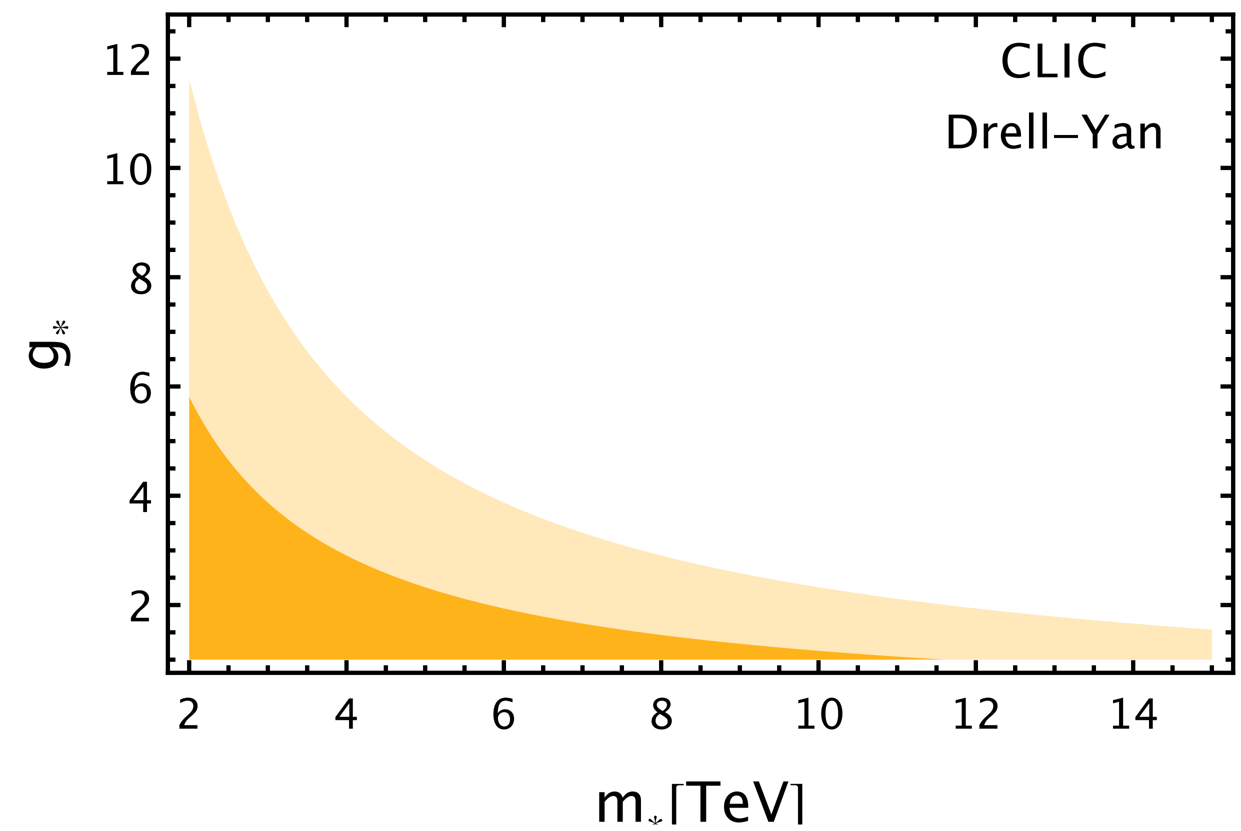
Higgs Compositeness @ CLIC: [discovery]





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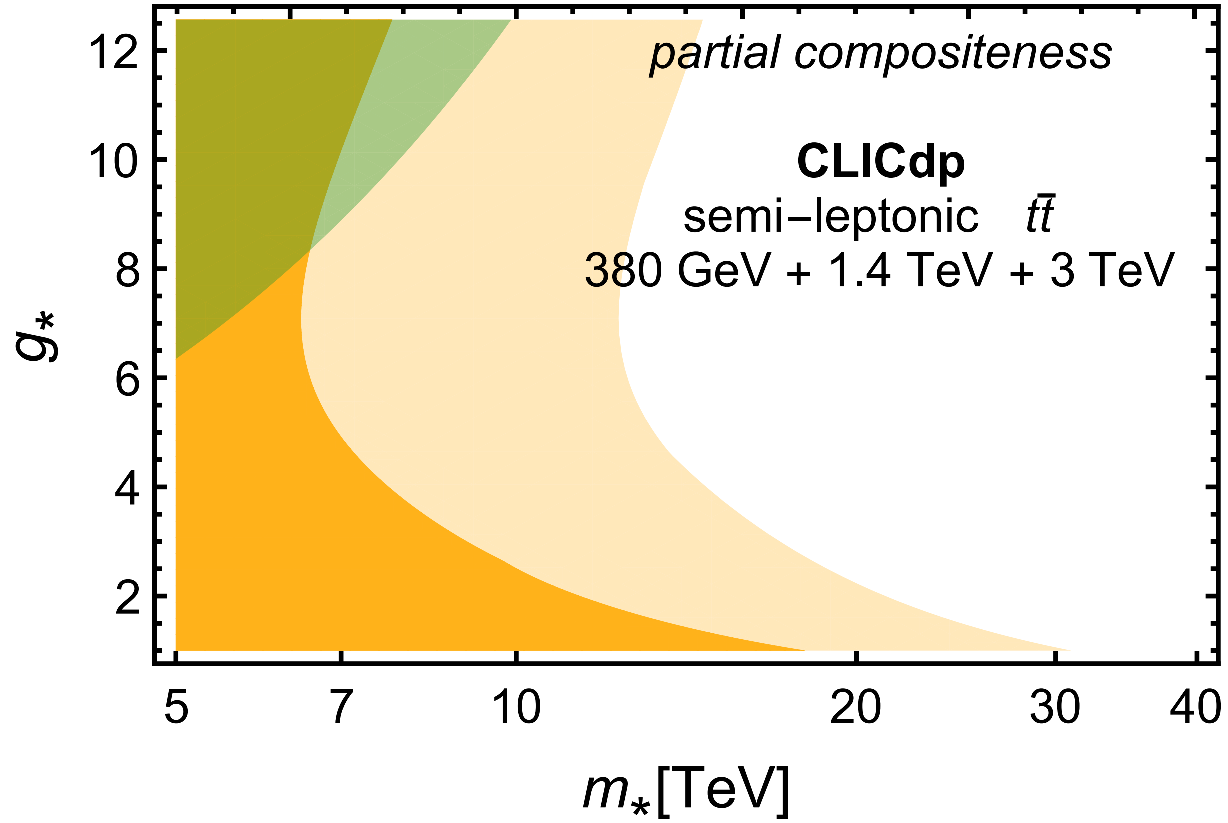
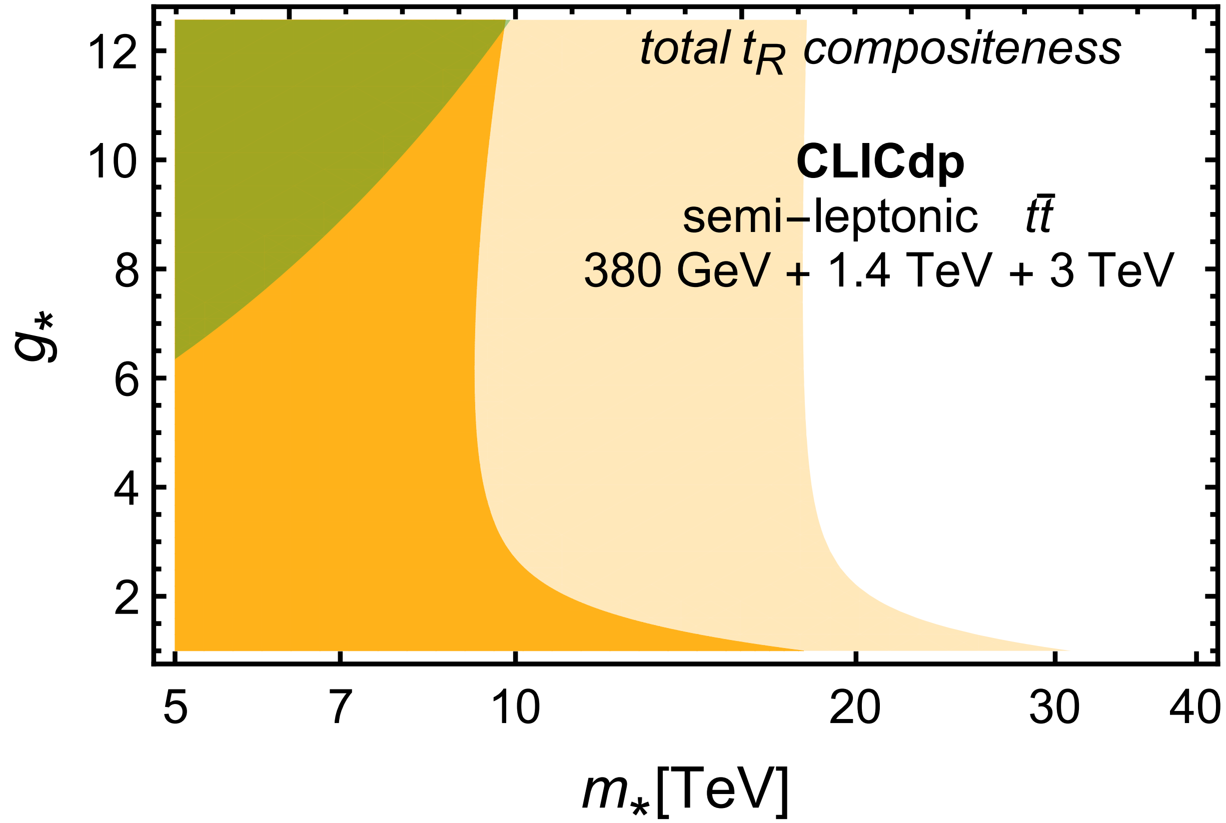
Top Compositeness @ CLIC: [discovery]





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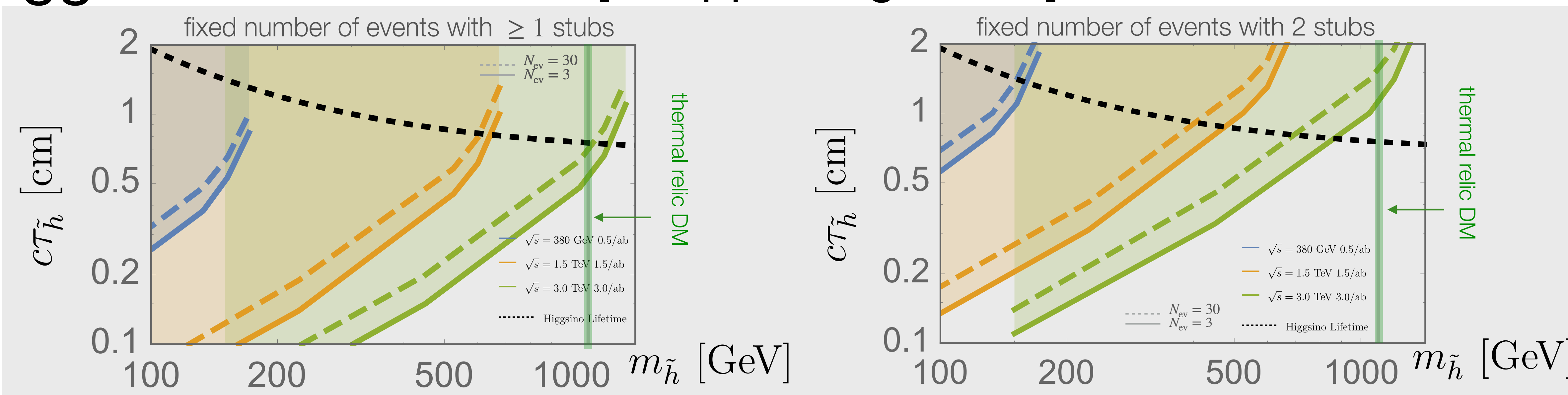
Higgsino DM @ CLIC: [disappearing tracks]



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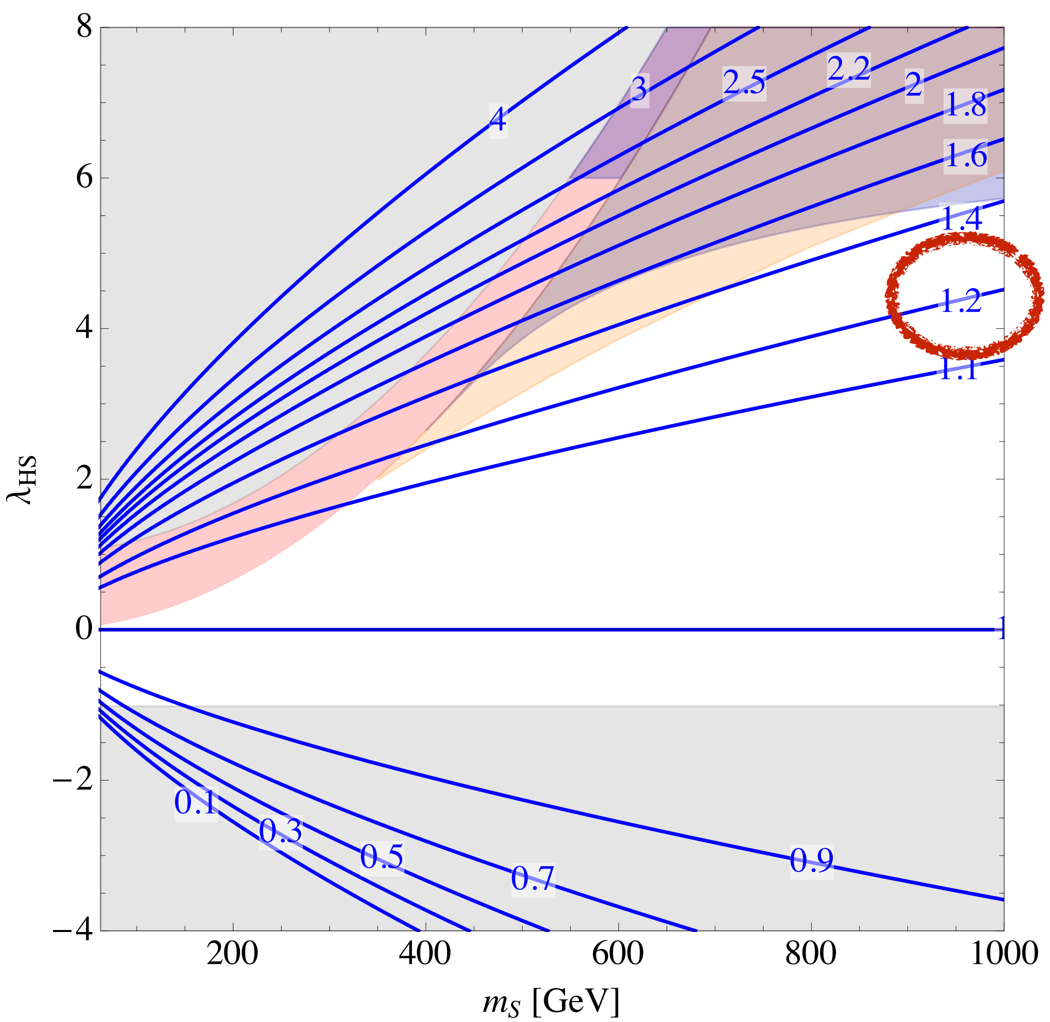
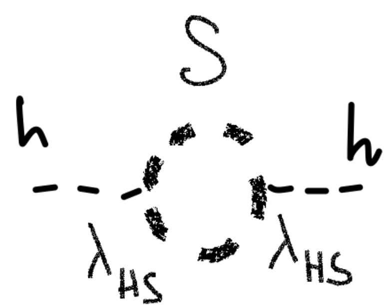
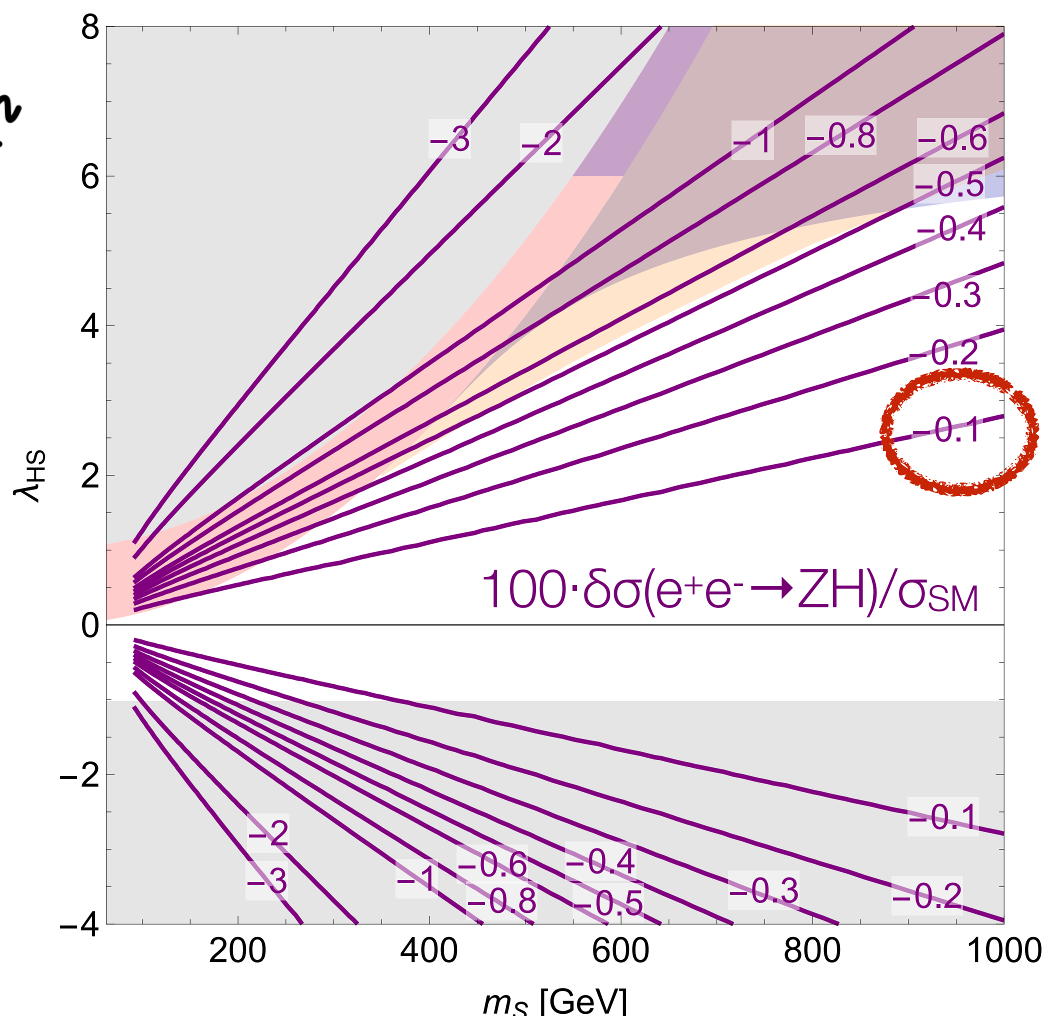
“Nightmare” strong 1st order @ CLIC: [using 1H]

$\Delta g(HXX)$ = 0.12% 95%CL @ CLIC 0.38+1.5+3 TeV







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- Covers SUSY holes [in case you care about]

Muon Colliders

Much better direct reach than hadron colliders !

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Lepton coll. operating at energy $\sqrt{s_L}$.
Cross section for reaction at $E\sim\sqrt{s_L}$
(e.g., production of BSM with $M\sim\sqrt{s_L}$)

$$\sigma_L(s_L) = \frac{1}{s_L}\left[\hat{s}\hat{\sigma}\right]_L$$

Hadron coll. operating at energy $\sqrt{s_H}$.
Cross section for reaction at E.
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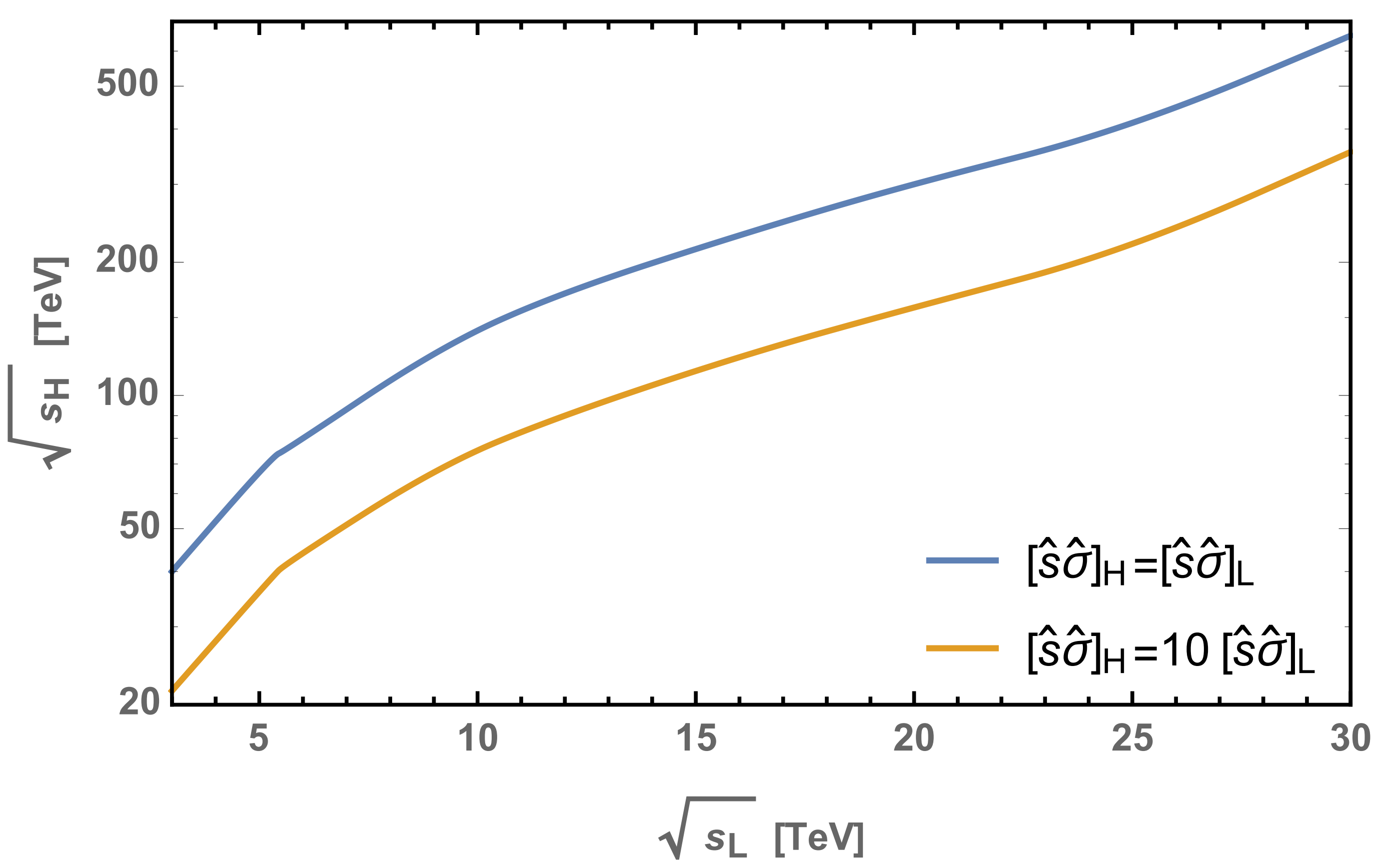
Find **equivalent $\sqrt{s_H}$** for Had. Coll. have **same cross-section** as Lep. Coll. for reactions at $E\sim\sqrt{s_L}$. Use that $\left[\hat{s}\hat{\sigma}\right]$ is nearly constant in τ.



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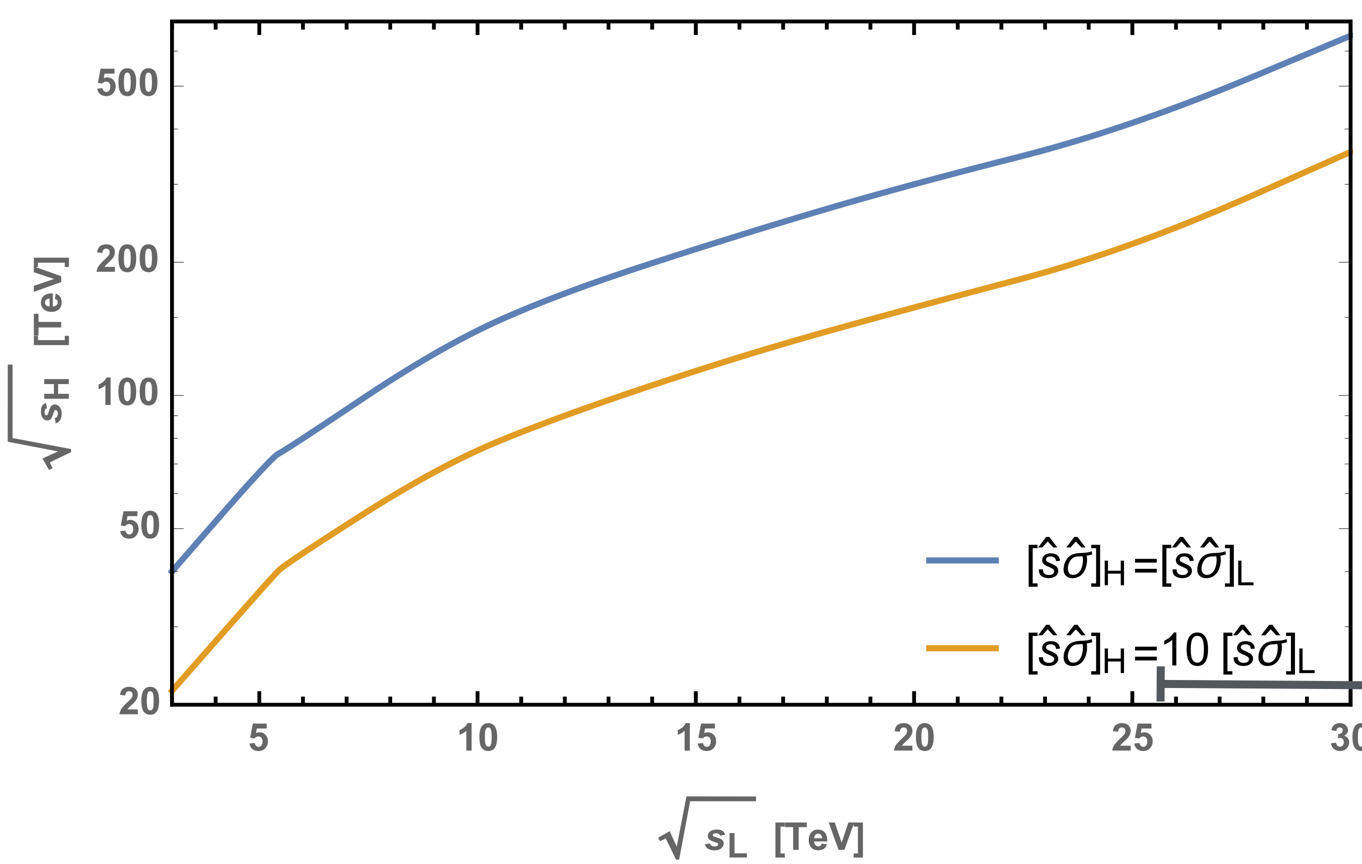

QCD-coloured BSM can easily have much larger partonic XS.

Comparison even more favourable for **QCD-neutral BSM**

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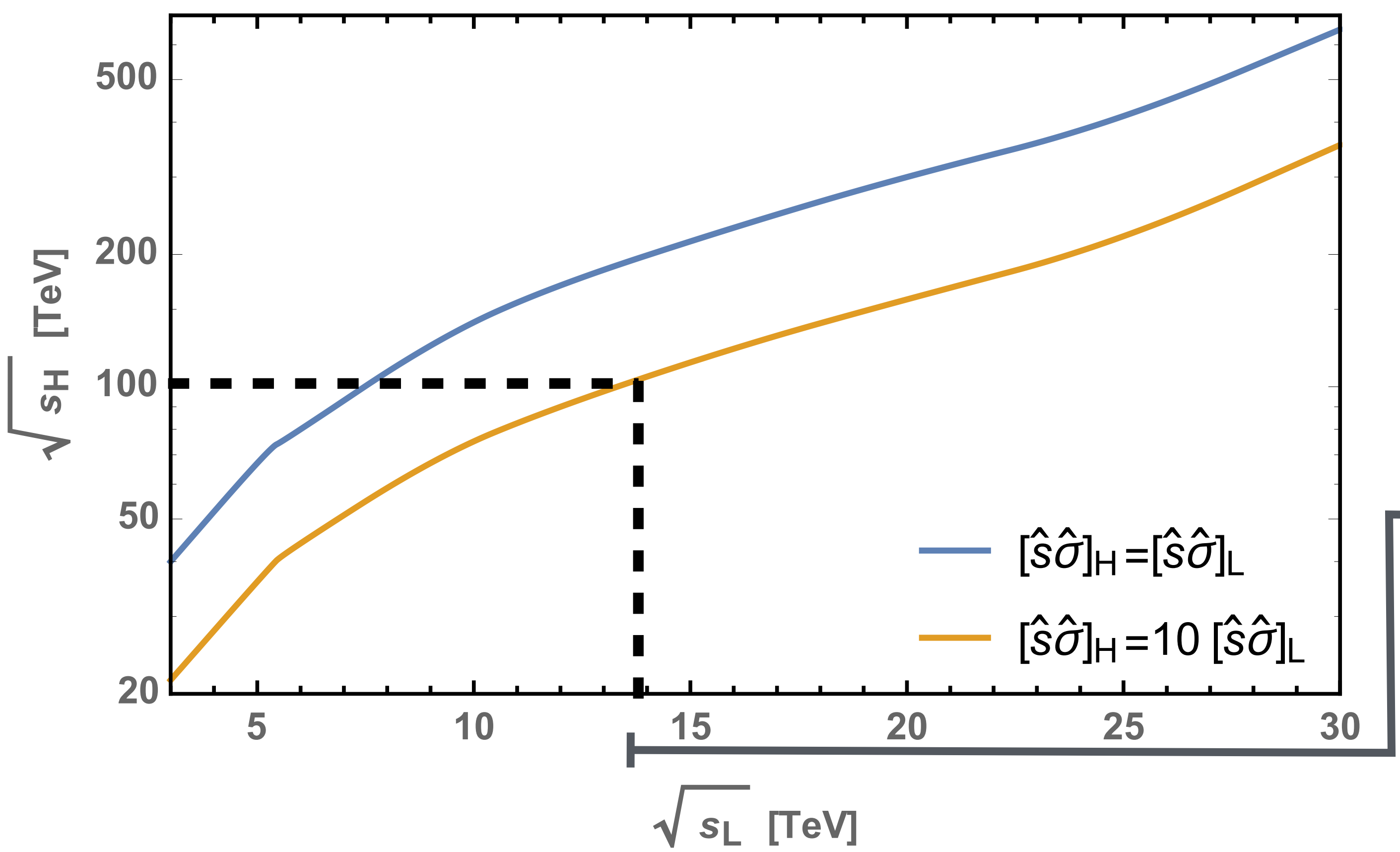

QCD-coloured BSM can easily have much larger partonic XS.

Comparison even more favourable for **QCD-neutral BSM**

14 TeV μ-collider nearly as good as the FCC at 100 TeV?

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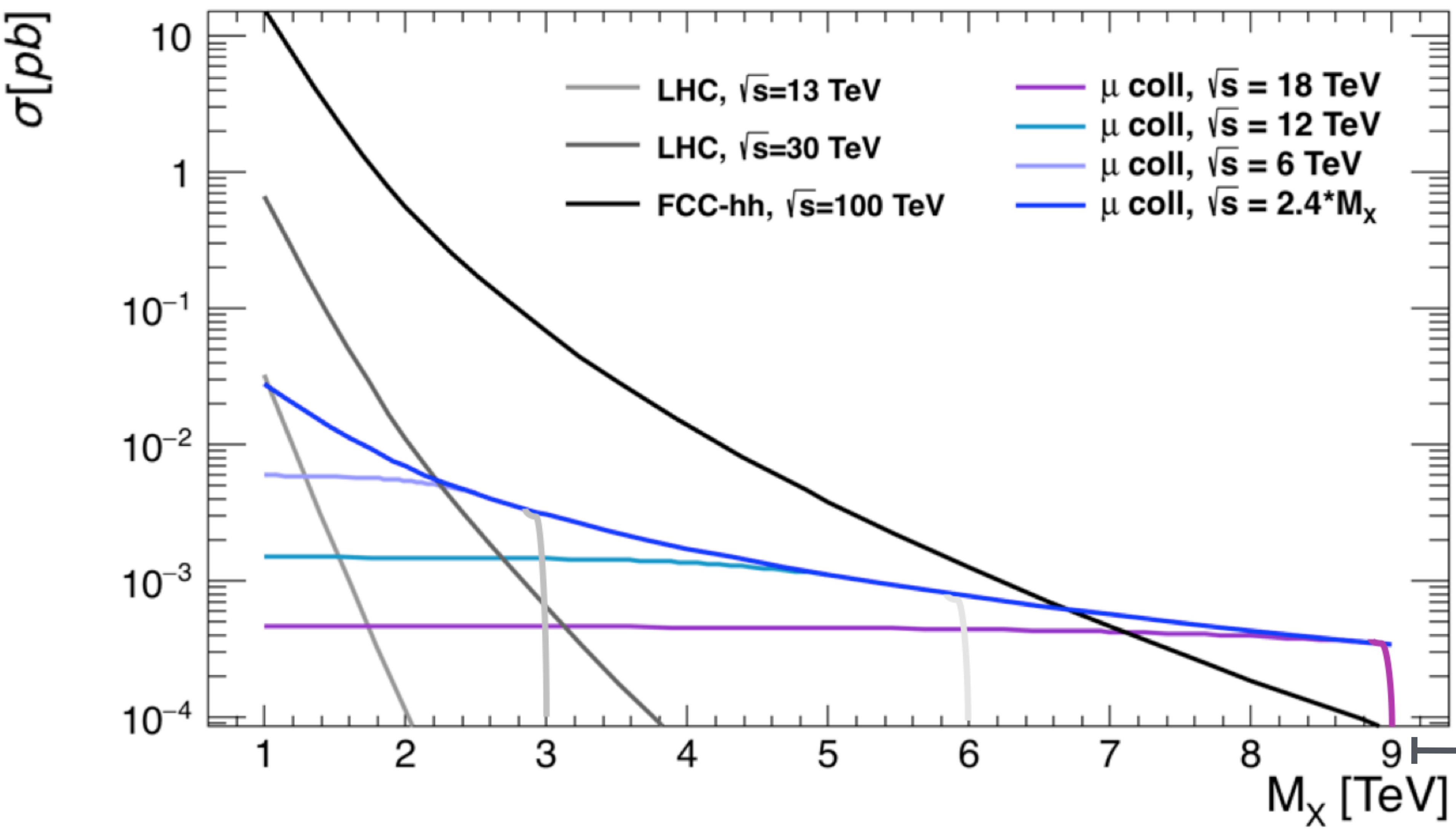
Plenty of examples can be made to refine the claim

Fermionic top partners in Composite Higgs:



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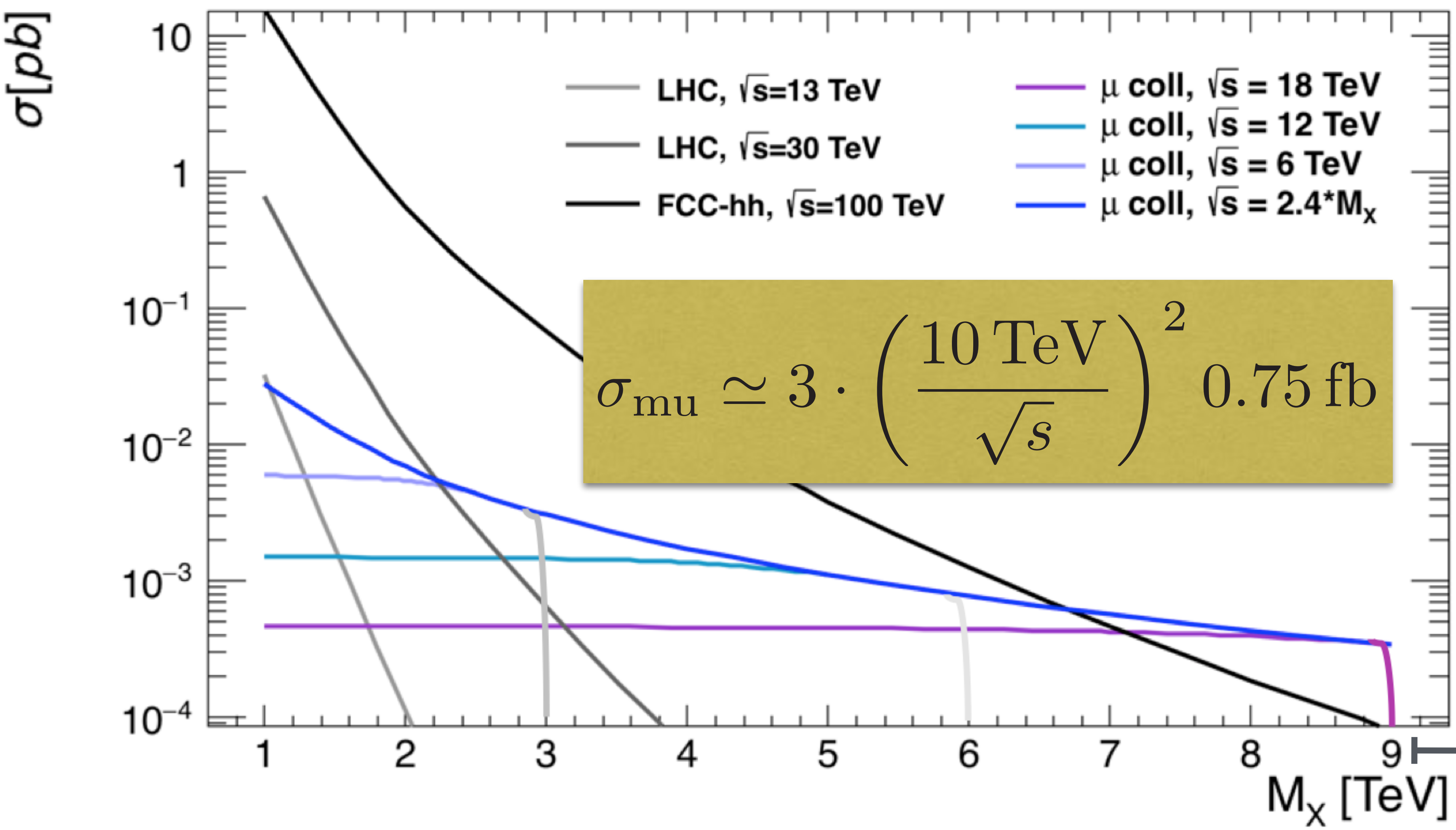

$$\sigma_{\rm mu} \simeq 3 \cdot \left(\frac{10\,\mathrm{TeV}}{\sqrt{s}}\right)^2 0.75\,\mathrm{fb}$$

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0) Reach interesting energies:
   10 TeV >> LHC; 14 TeV ~ FCC-hh; 30 TeV = amazing
1) Run for a reasonable time: 10^{34}cm^{-2}s^{-1} = 500fb^{-1}/(5yrs)
   "reasonable" for FC means 5yrs. Much less than other projects!

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   10 TeV >> LHC; 14 TeV ~ FCC-hh; 30 TeV = amazing

1) Run for a reasonable time: $10^{34}\text{cm}^{-2}\text{s}^{-1}$ = 500fb^{-1}/(5yrs)
   "reasonable" for FC means 5yrs. Much less than other projects!

2) Pair produce more than 100 EW particles:
   sufficient to probe "**easy**" decay modes (e.g., for top partners/stops)

$$N = 400\,\frac{\text{yrs}}{5}\left(\frac{10\,\text{TeV}}{\sqrt{s}}\right)^2 \frac{L}{10^{34}\text{cm}^{-2}s^{-1}} \quad \Rightarrow \quad L > \frac{1}{4}\frac{5}{\text{yrs}}\left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2 10^{34}\text{cm}^{-2}s^{-1}$$

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3) Measure SM cross-sections: 1% needs N=10000
   simple estimate for 2 → 2, **much less for** WW>HH (3H). Systematics??

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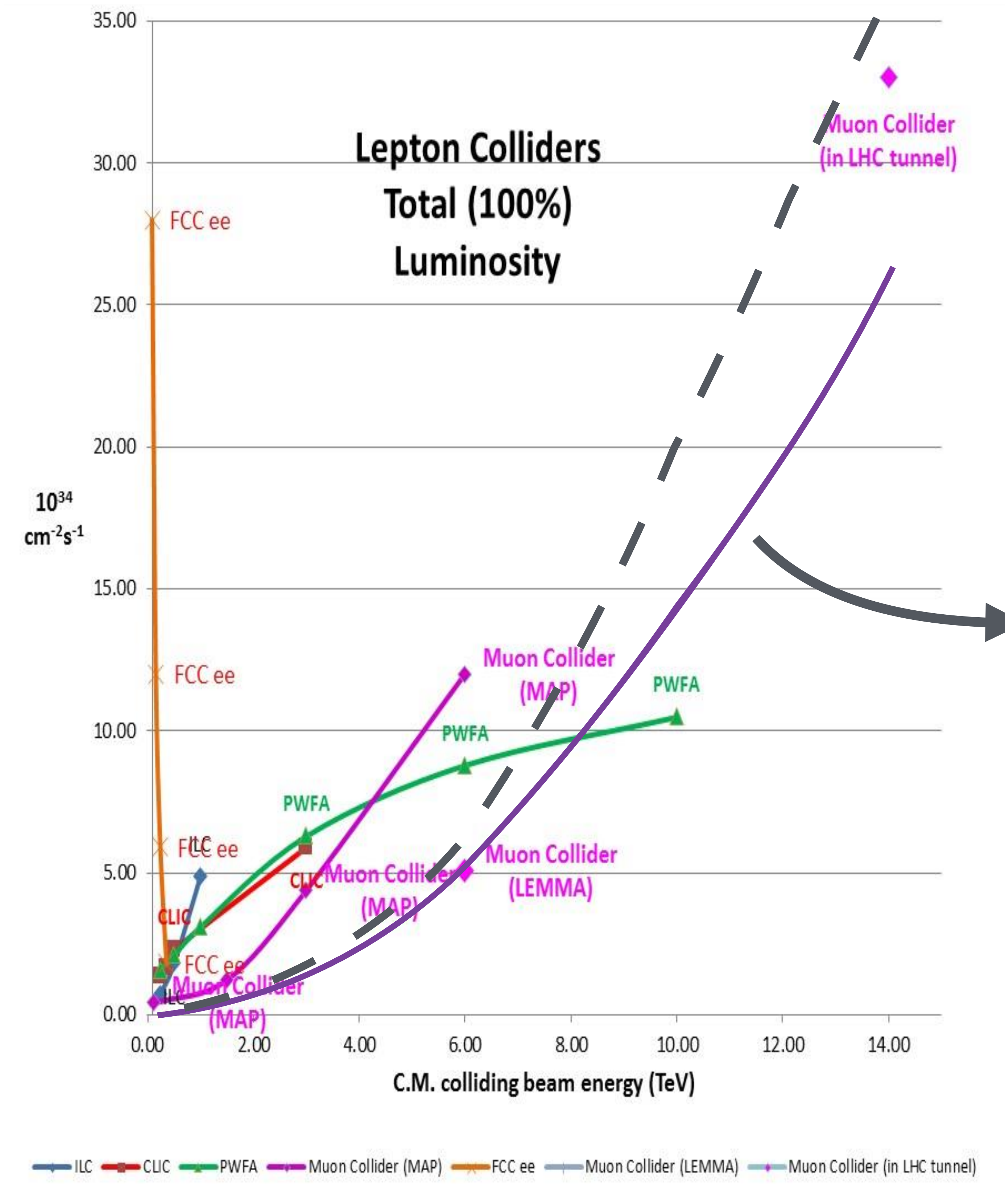
4) Probe DM in mono-γ/W/Z, EW singlets, **L>**?

Muon Colliders Requirements Specification



Both MAP and LEMMA claim they can make it

Low
Emittance
Muon
Muon
Accelerator

Muon Colliders Requirements Specification

But also:

5) Comply with radiation limit from neutrino flux
   lower emittance = less ν = less radiation

6) Produce low enough background level
   again pointing towards low emittance

Conclusions

CLIC: (380+1.5+3)

- **Ready to be built!**
- **Remarkable Exploration Potential**
- Suffers from limited energy
- Possibly expensive

The FCC Project: (ee+hh+he)

- Challenging, definitely expensive
- **Does everything!**
- **The Dream Machine**

HE-LHC:

- LHC < HE-LHC < FCC
- **Better than nothing**

Muon collider: [or Plasma]

- 10 TeV >> LHC; 14 TeV ~ FCC-hh; 30 TeV = amazing
- **Not yet clear we can dream of it!**
- **I discourage focusing on Higgs pole** [ask me why]

Backup

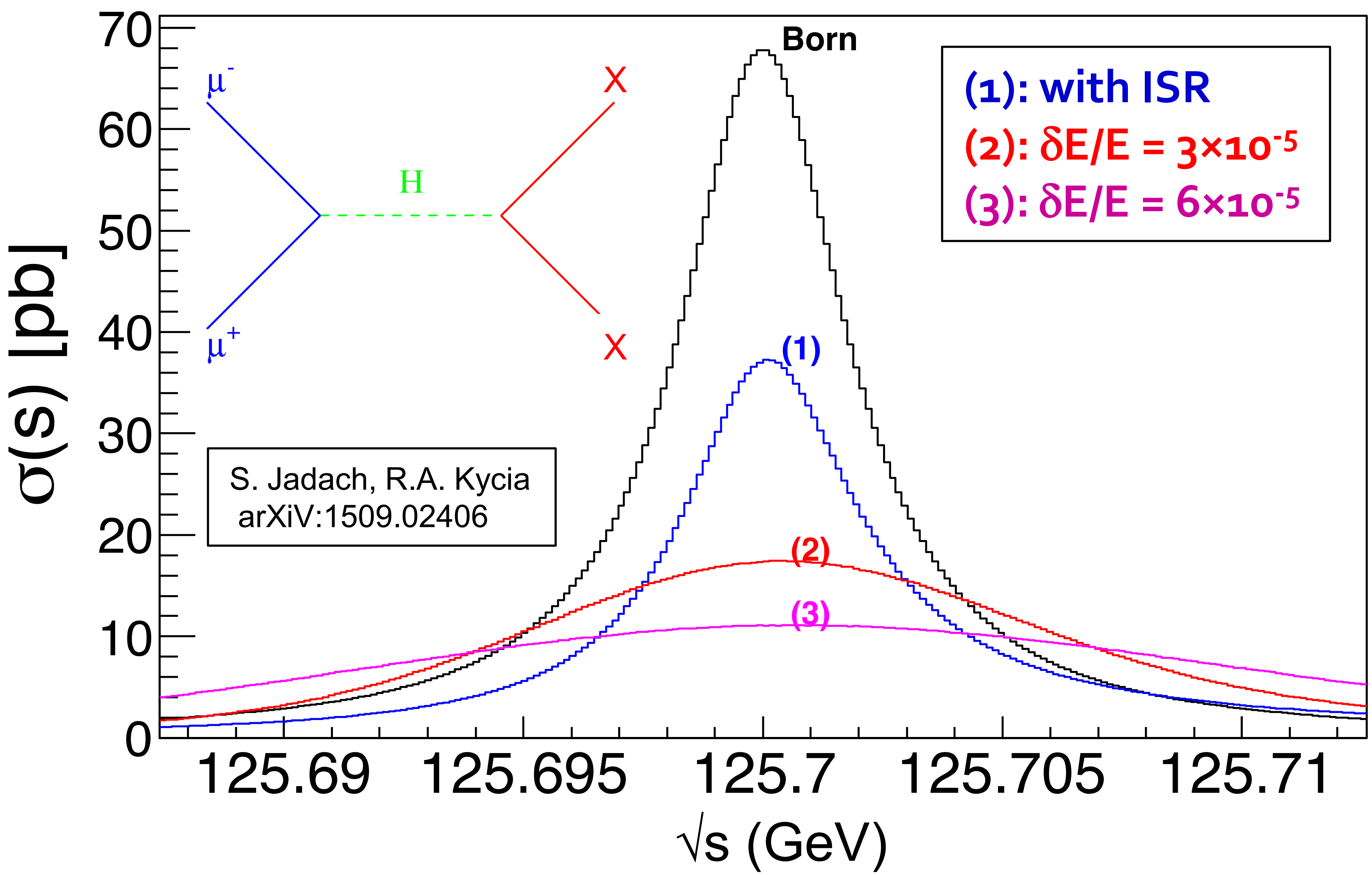
Result of the coupling (a.k.a. κ) fit

- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

13	μ Coll_{125}	ILC_{250}	CLIC_{380}	LEP3_{240}	CEPC_{250}	FCC-ee_{240}	FCC-ee_{365}
Years	6	15	5	6	7	3	+4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5
δm_H (MeV)	0.1	t.b.a.	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.70
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.82
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	4.2
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
Br_{invis} $(\%)_{95\%CL}$	SM	<0.3	<0.6	<0.5	<0.15	<0.3	<0.25
BR_{EXO} $(\%)_{95\%CL}$	–	<1.8	<3.0	<1.6	<1.2	<1.2	<1.1

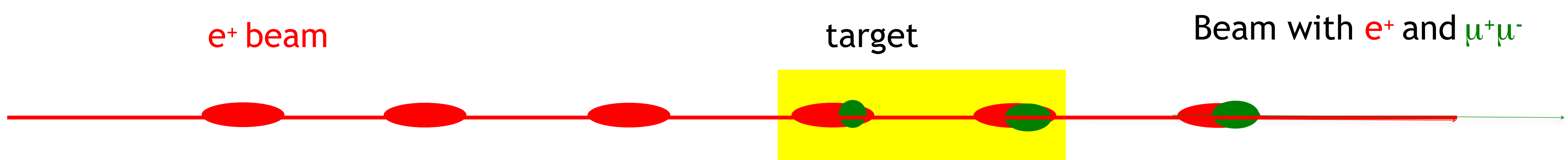
(*) Green = best
Red = worst

Backup



σ(s) [pb]
√s (GeV)
0
10
20
30
40
50
60
70
125.69
125.695
125.7
125.705
125.71
Born
(1)
(2)
(3)
(1): with ISR
(2): δE/E = 3×10-5
(3): δE/E = 6×10-5
μ-
μ+
H
X
X
S. Jadach, R.A. Kycia
arXiV:1509.02406

Backup



Ideally muons will *copy* the positron beam

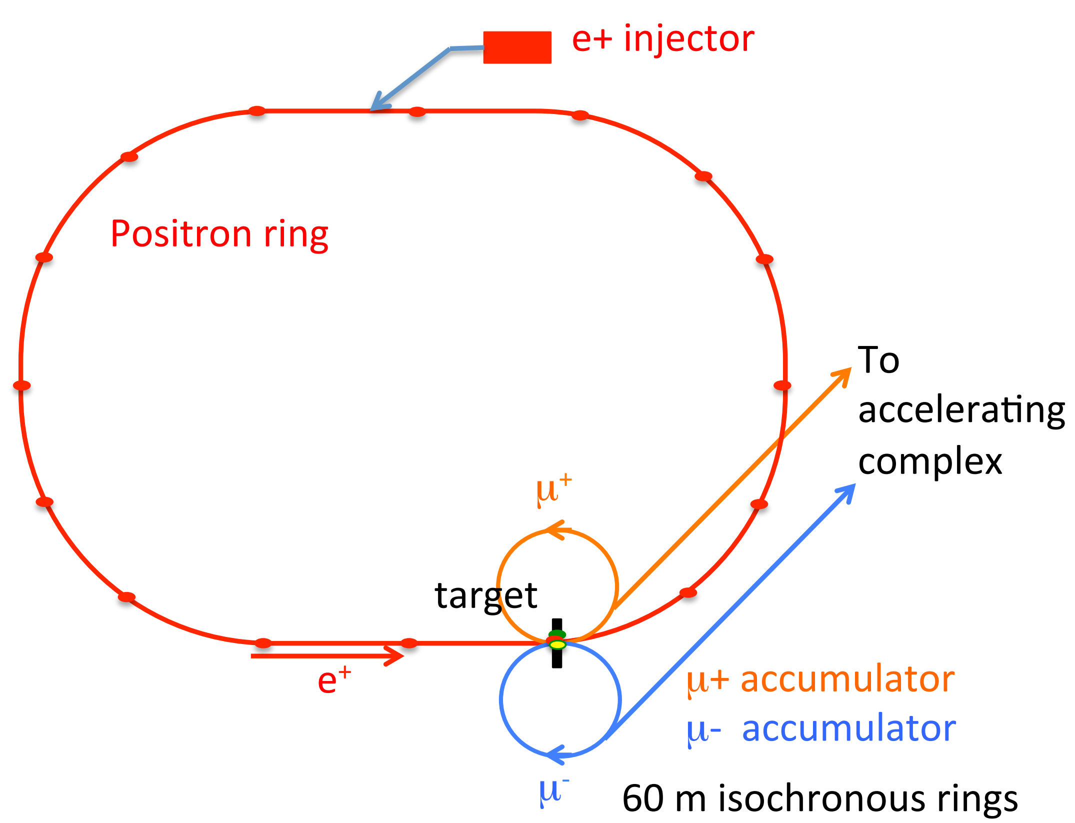
Low emittance μ from e^+ on target

[Antonelli, Boscolo, di Nardo, Raimondi, 2016]

- avoids cooling
- few circulating μ → little radiological hazard and machine bckg.

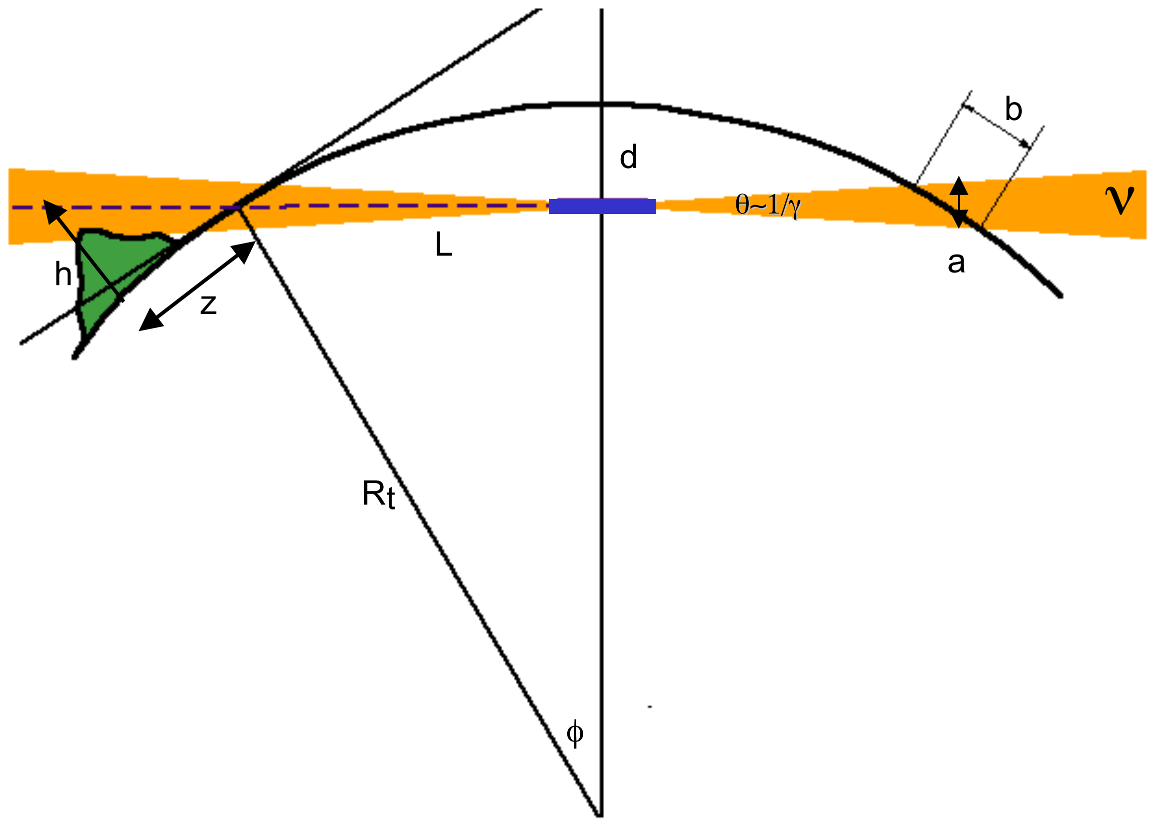
Challenges:

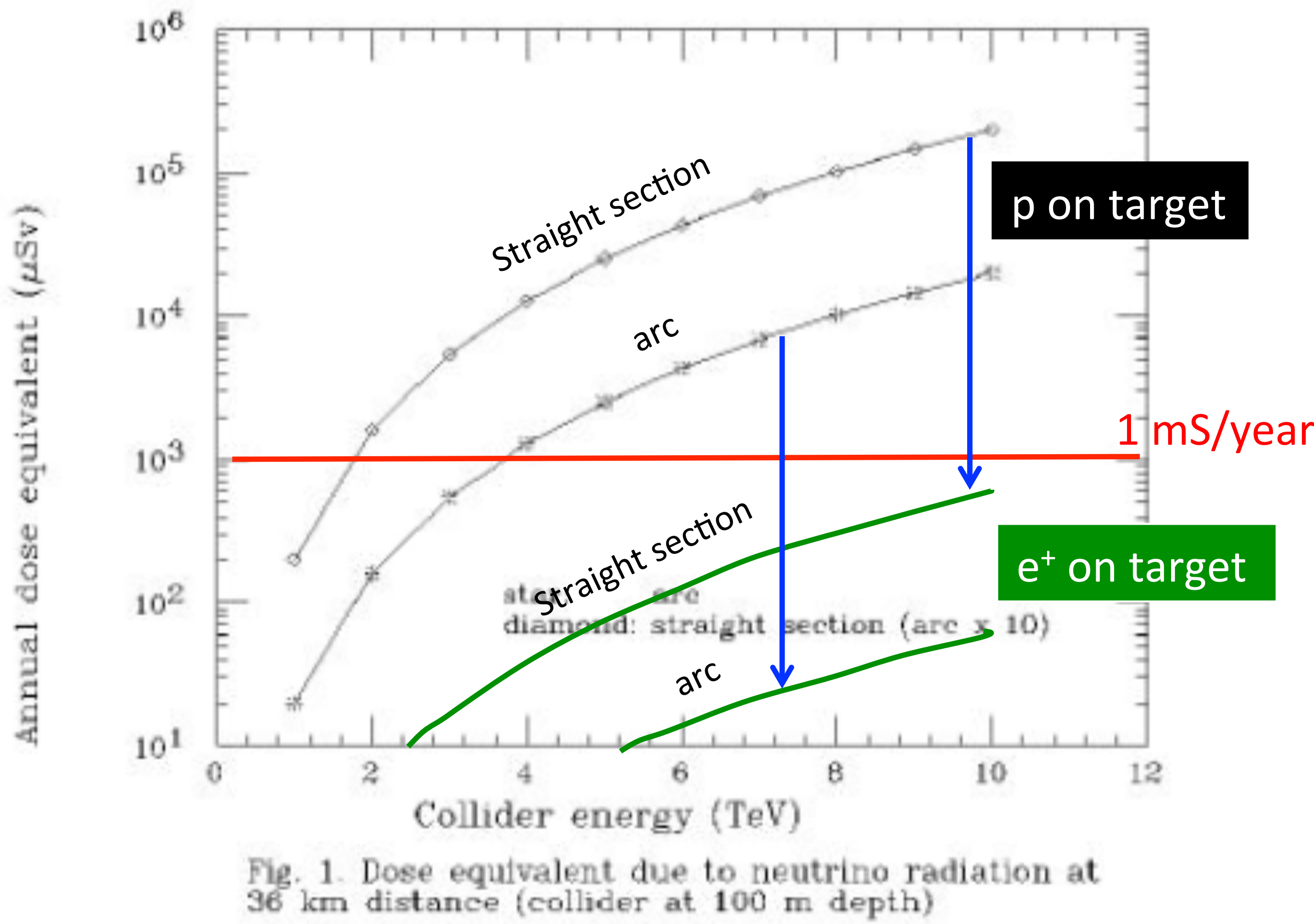
- e^+ source (embedded?)
- target breakdown
- top up muons?



Backup

Radiological Hazard





Helicoidal Orbits??

Rolandi's pipe??