Future High-Energy Colliders Physics

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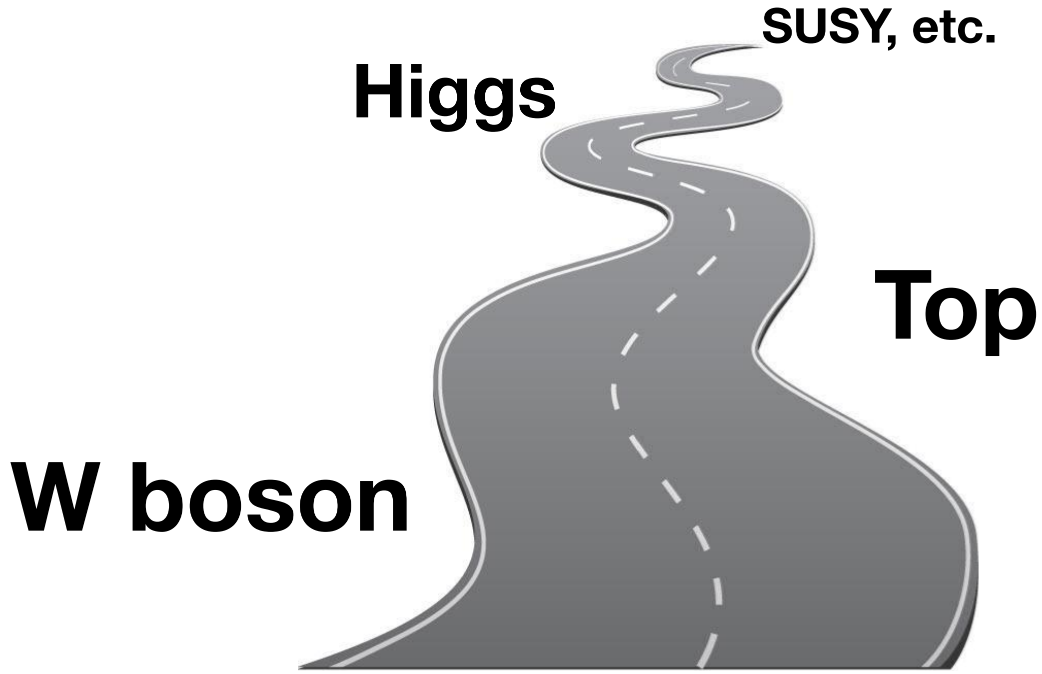
Ideology

HEP before the LHC



HEP before the F.C.

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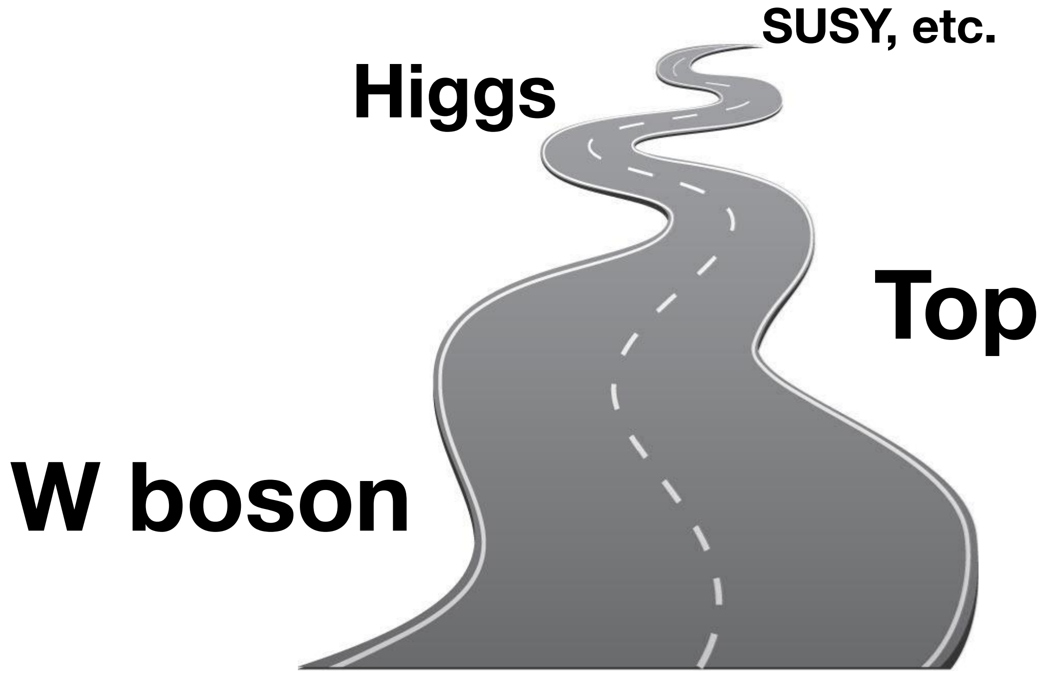
HEP before the LHC



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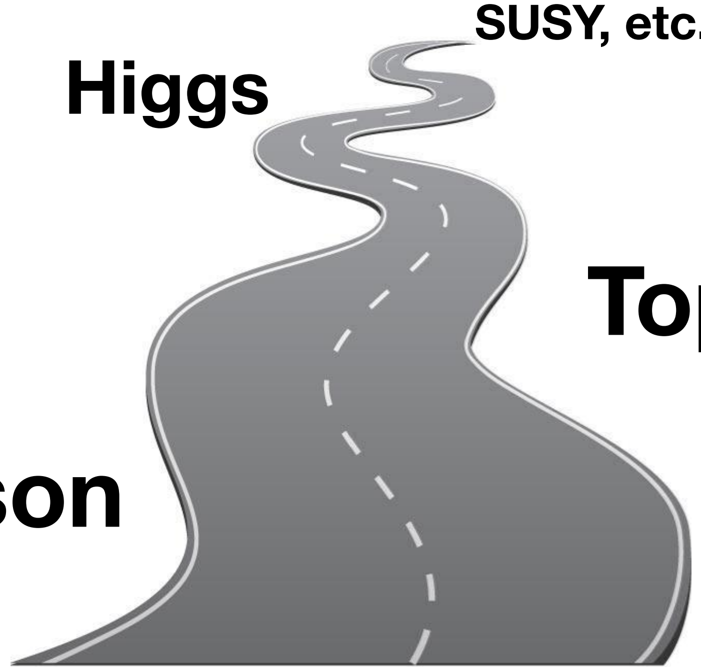

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This is **good:**

next discovery will be **revolutionary**

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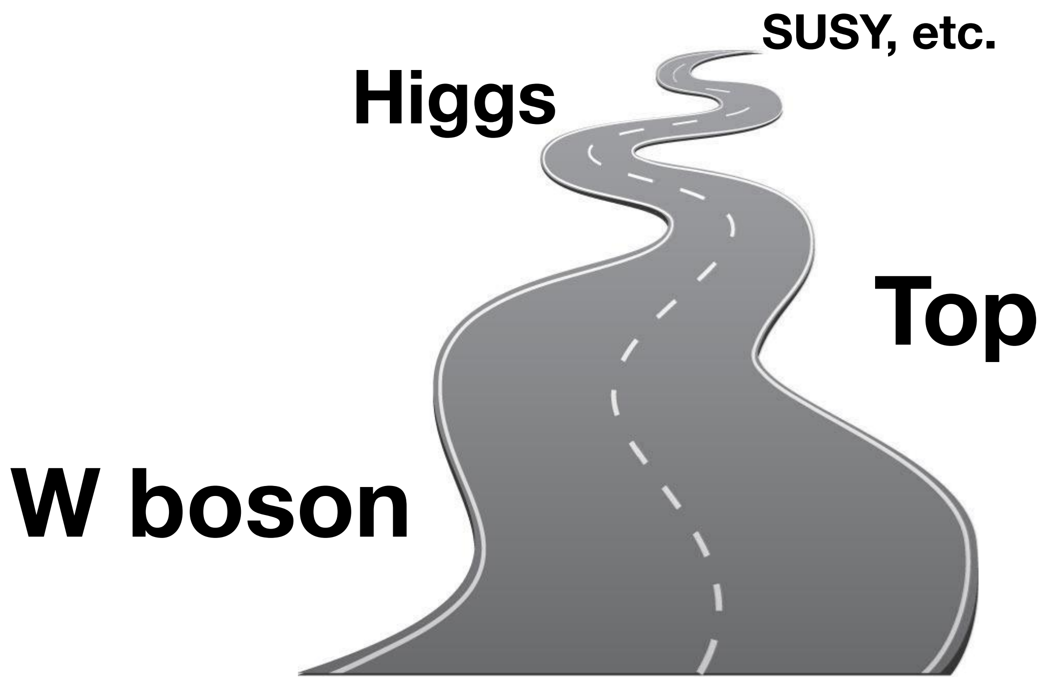


HEP before the F.C.

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

This is **good:**

next discovery will be **revolutionary**

This is **bad:**

F.C. potential cannot be evaluated on few uniquely identifiable benchmarks (e.g., Higgs for LHC).

We must assess F.C. capabilities to answer questions we consider relevant today, being aware that are most likely missing the right one!

Some Questions

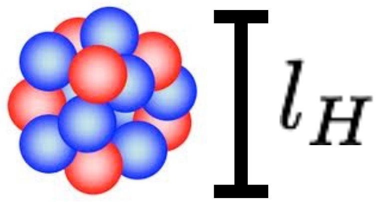
[from the BSM WG in Granada]

A New Gauge Force?

Is there a new (very) short-distance force on top of EW+Strong?

A Composite Higgs?

Is the Higgs point-like? If not, how big is it?



A **Natural** Composite (or Supersymmetric) Higgs?

Can compositeness explain the microscopic origin of the EW scale?

Is DM a WIMP?

Plausible minimal option, even when detached from SUSY

Is the Higgs Alone?

Recurrent in many contexts, from EWBG, to SUSY, even Anthropic

Feebly Interacting Exotic Particles?

We must also explore low-coupling frontier more broadly

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

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

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

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

$$\downarrow$$

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

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

Still, the higher the reach, the better

Dark Matter

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

WIMP models up to **16 TeV** mass (large EW multiplets)

WIMP invisible to DD if **inelastic** (automatic if Q=Y=0)

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

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WIMP models up to **16 TeV** mass (large EW multiplets)

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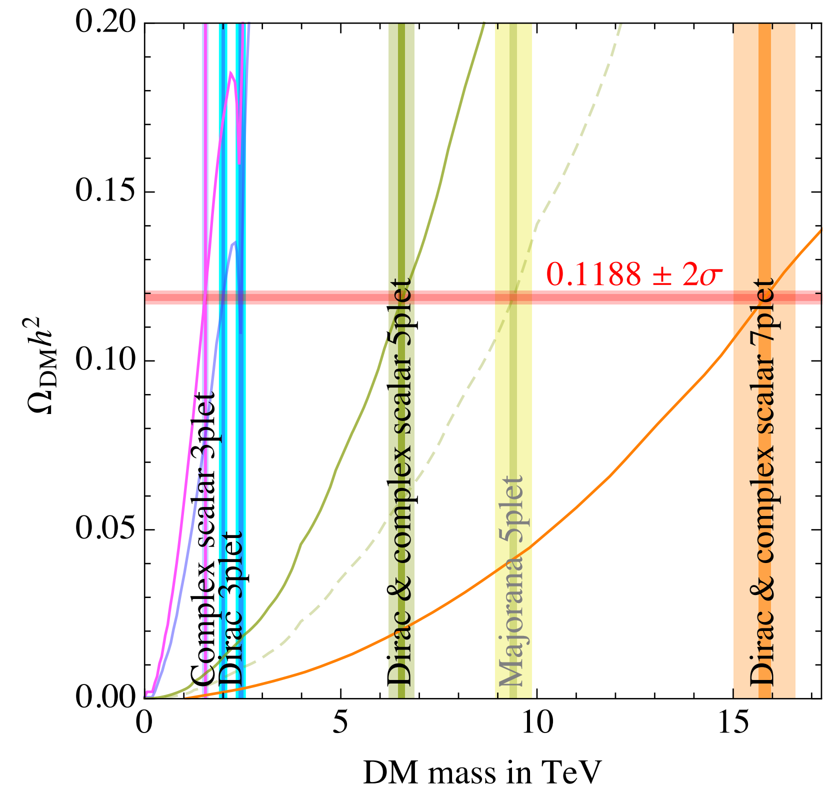
Accidental DM: stability from **accidental symmetries**

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: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\rm EW}^2/\Lambda^2$

- 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.**

Measurements

The FC must allow for extensive measurements program:

- **Guaranteed outcome**
- **Indirect**
- **Char**

Higgs

EFT

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Λ^2

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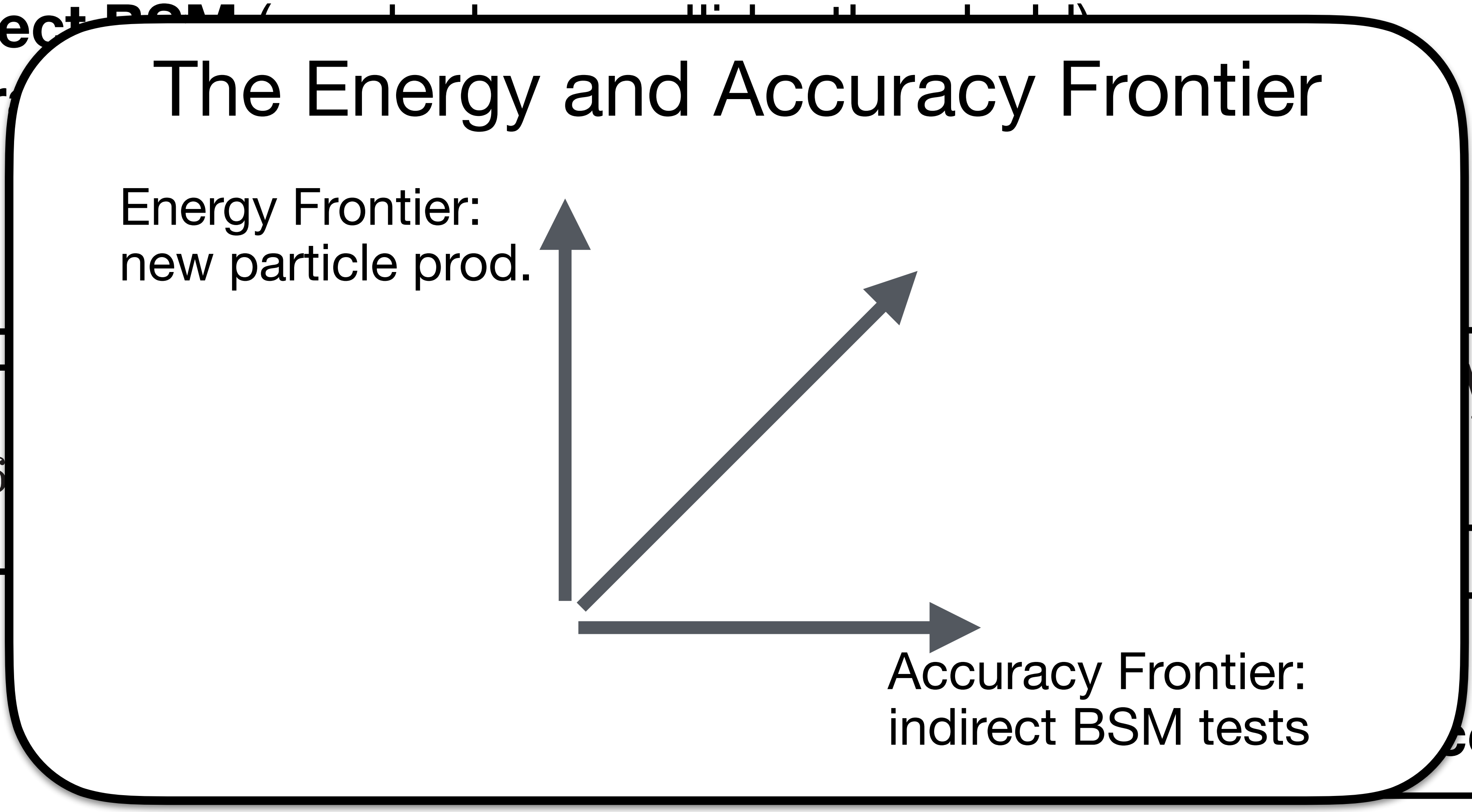
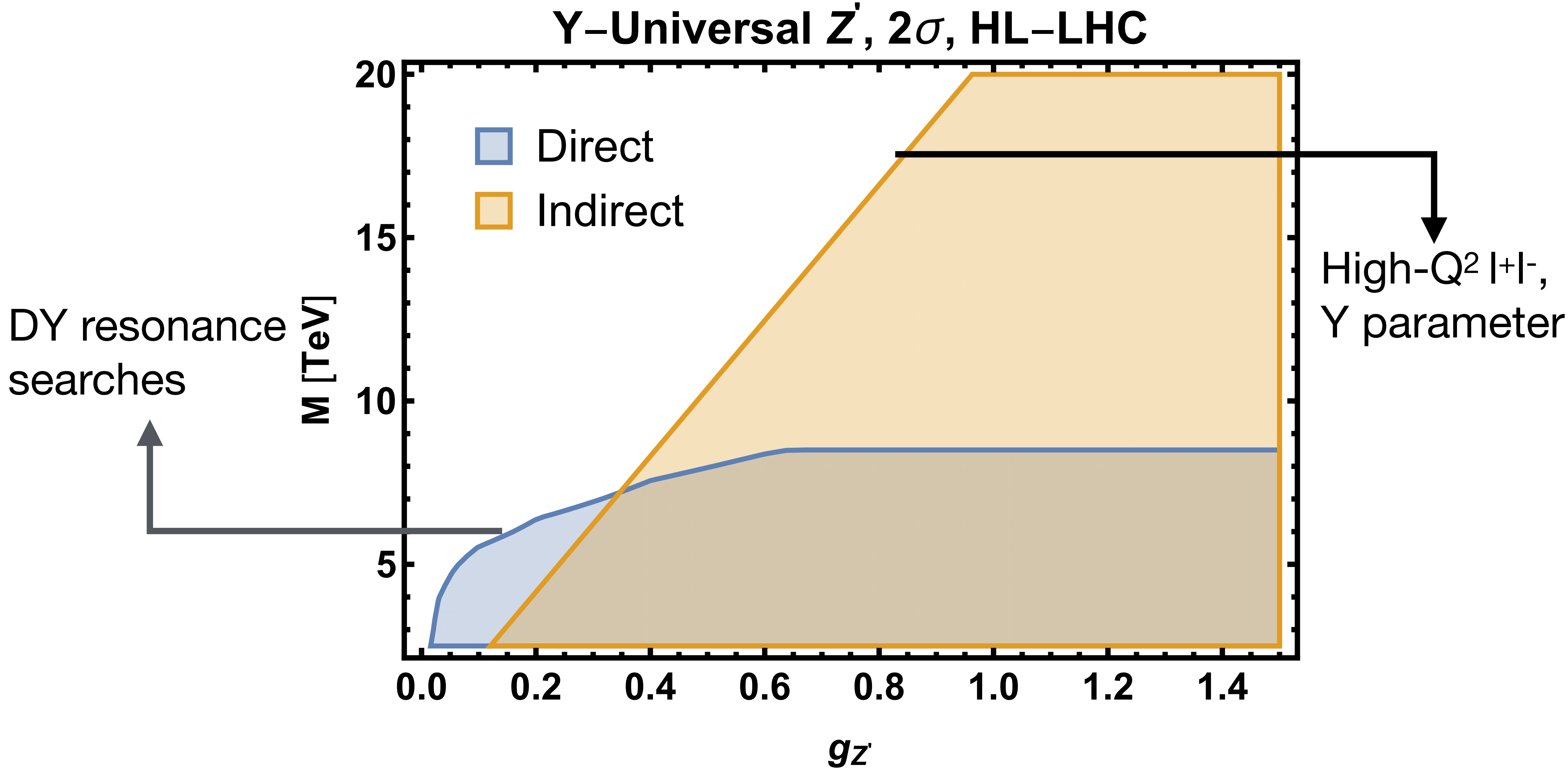


If high-energy, we **can learn already from 1% measur.**

Example: a simple Z’

Direct/Indirect complementarity at hadron colliders



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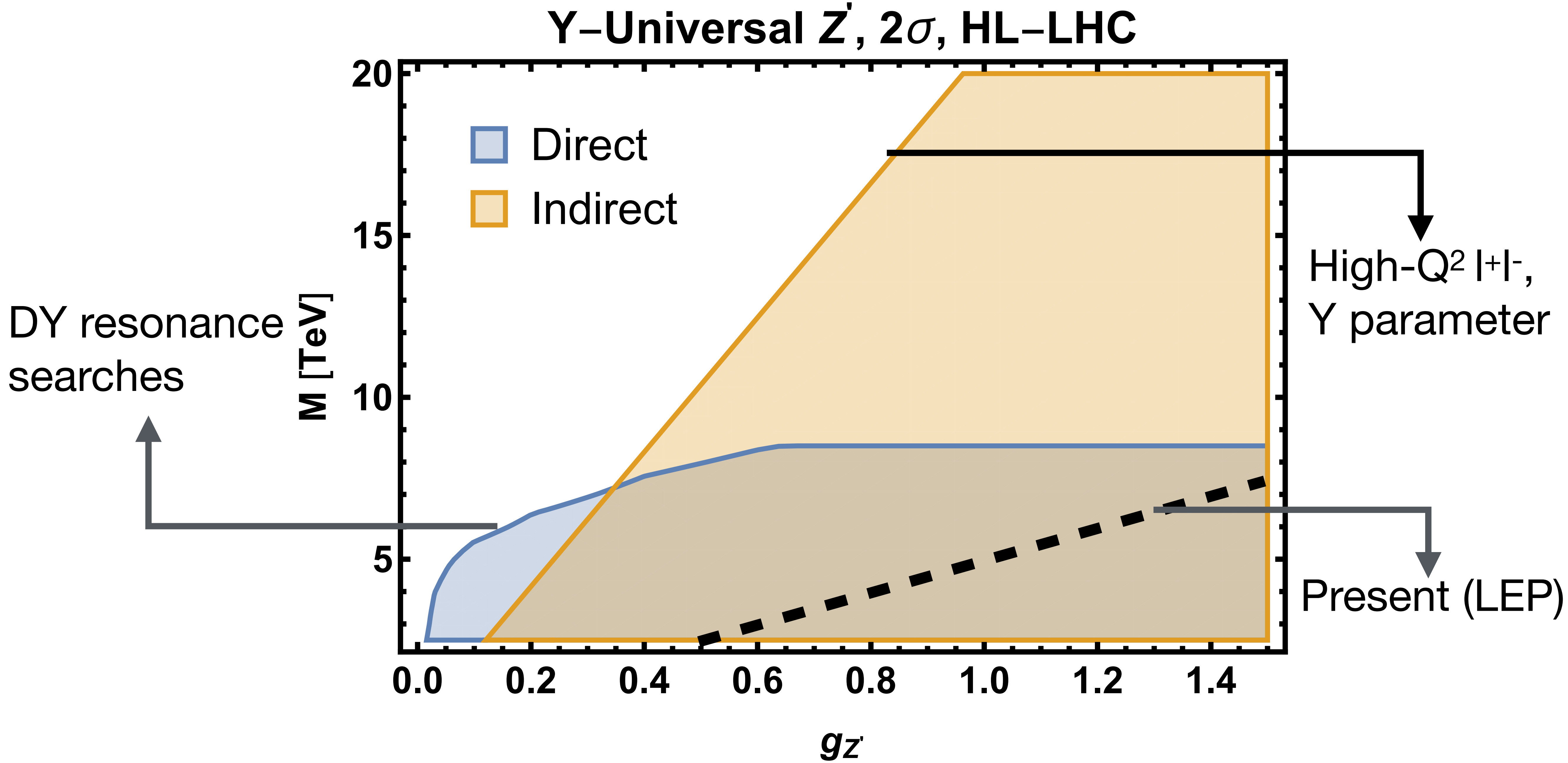
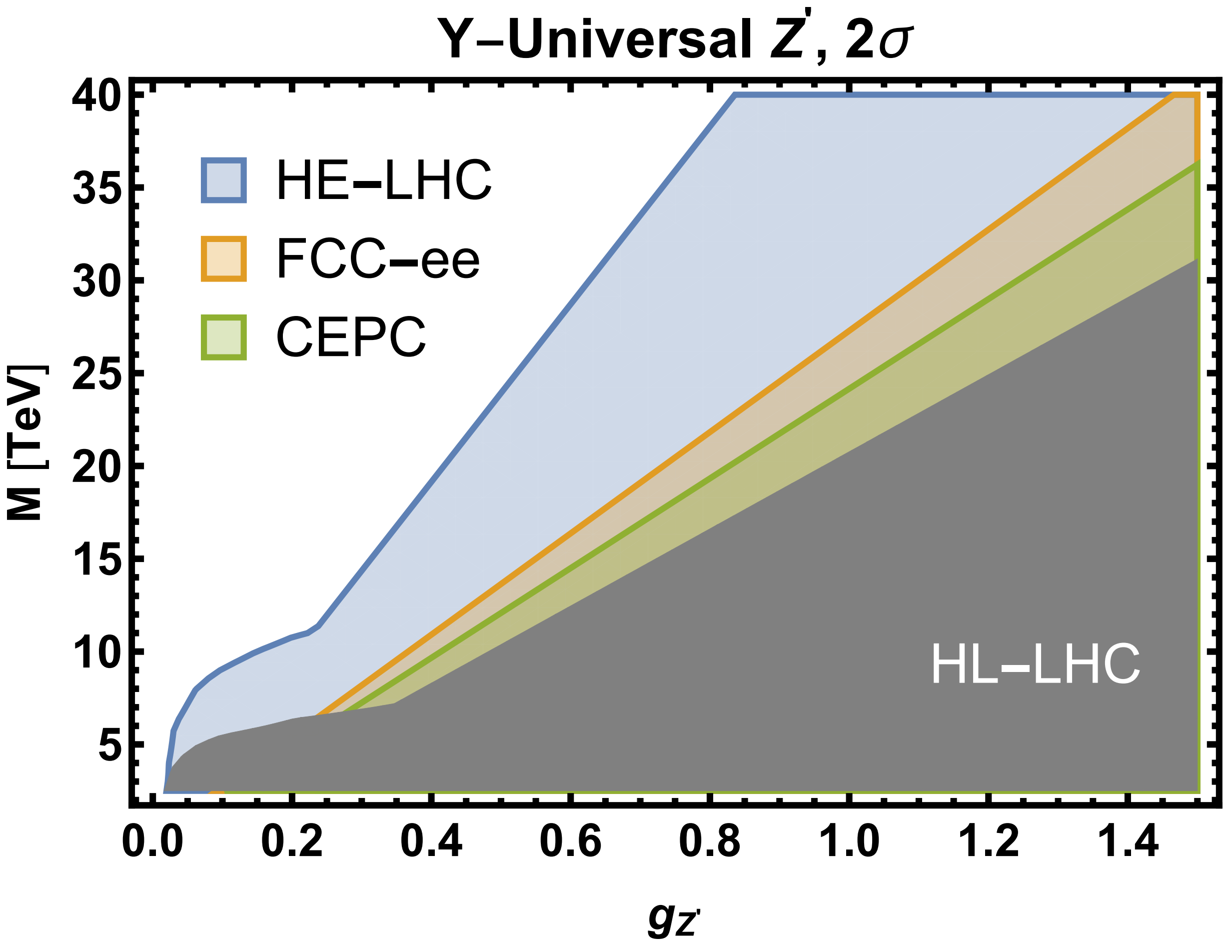
Direct/Indirect complementarity at hadron colliders

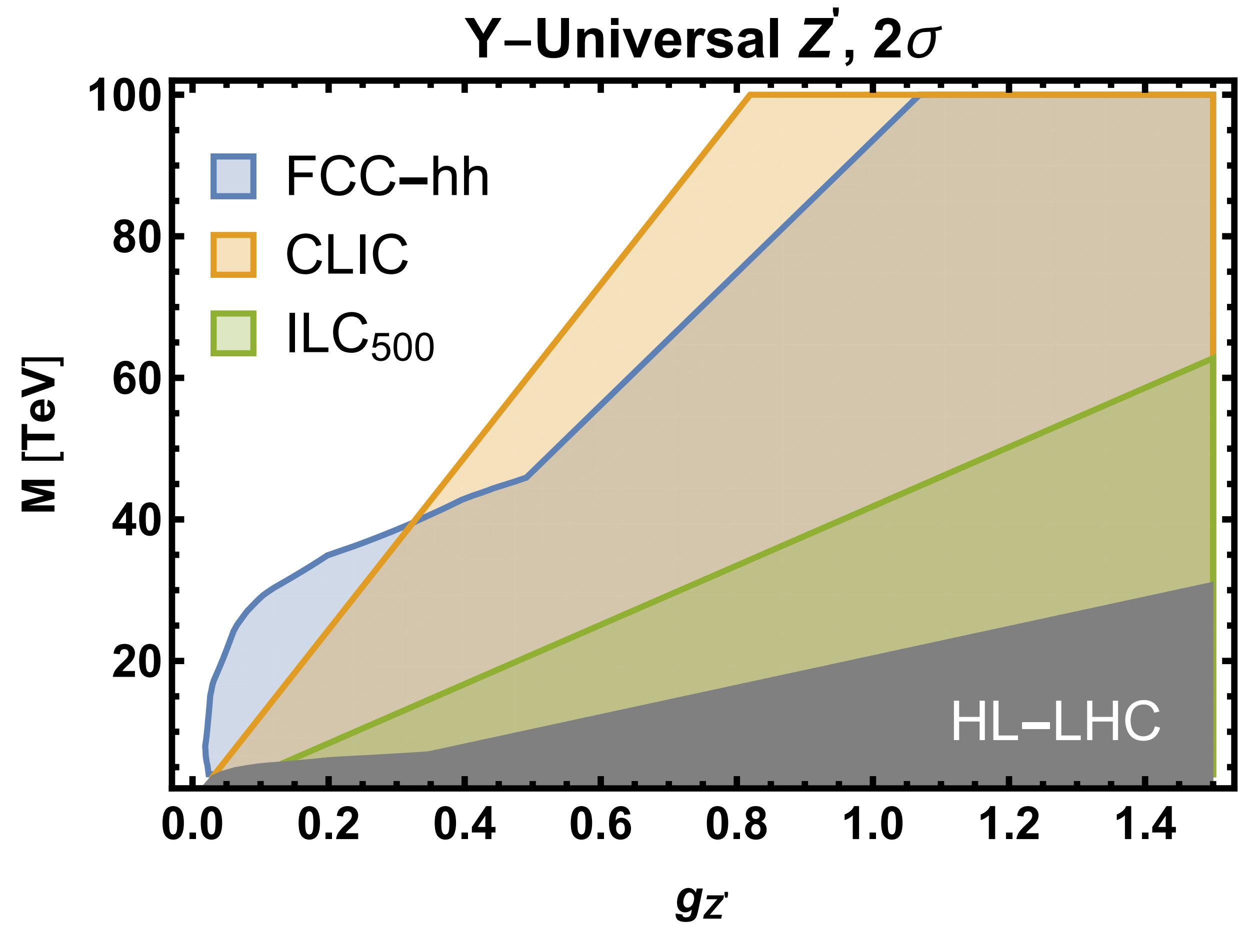


Notice how much improvement is possible at (HL-)LHC!

Example: a simple Z’

Future Colliders Reach compilation:

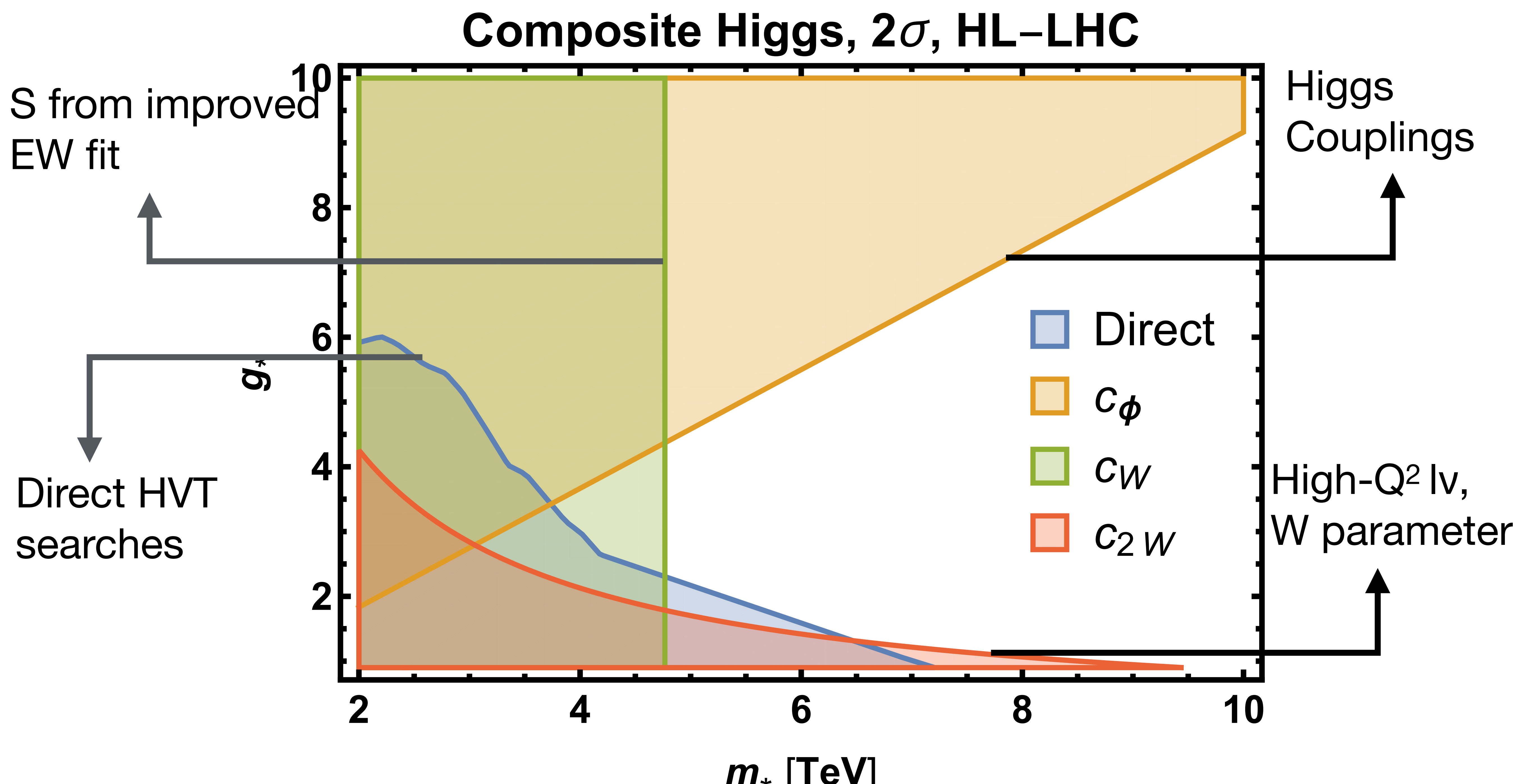




Only CLIC can compete with Had.Coll, because of large En.

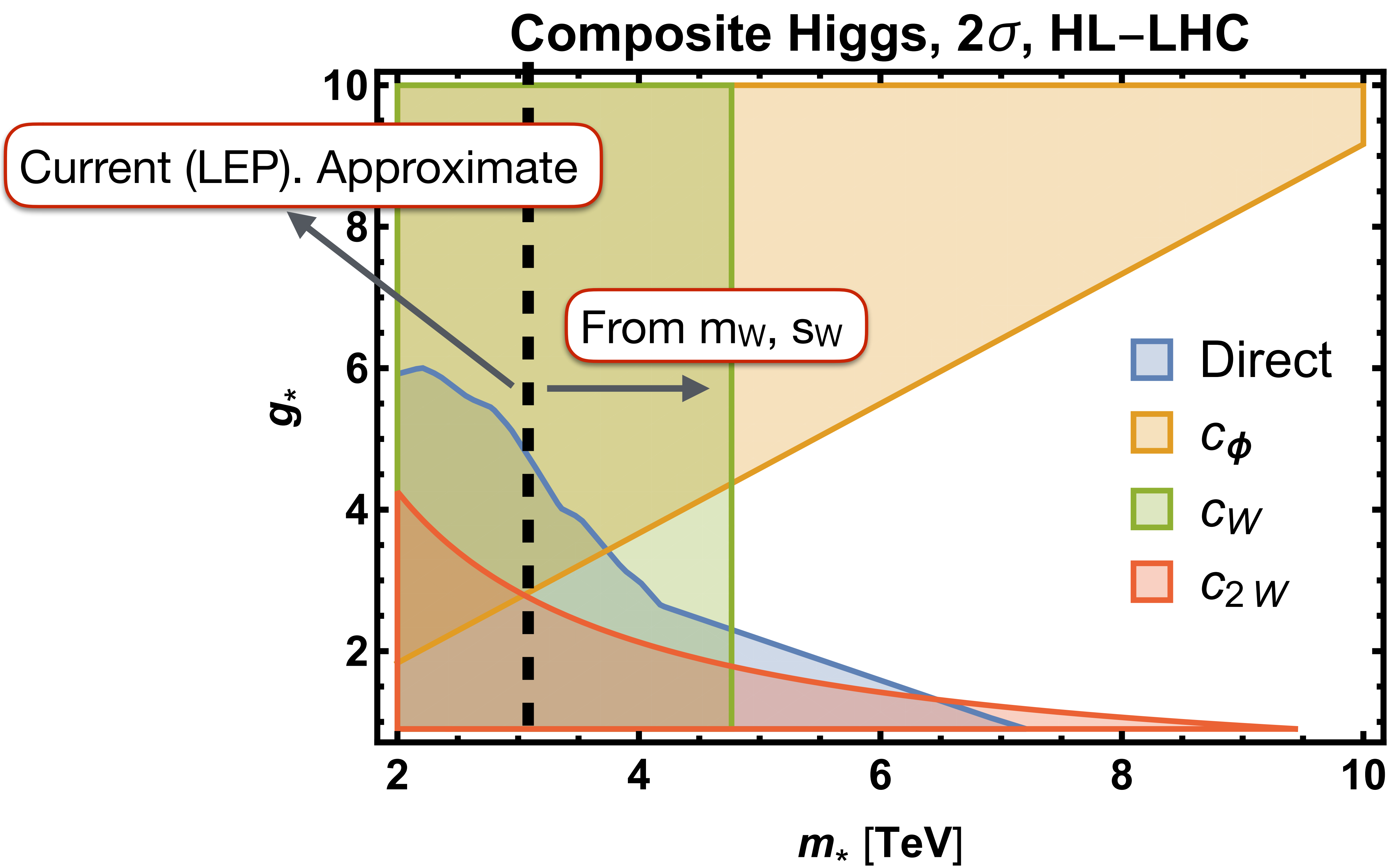
Composite Higgs

From a variety of direct and indirect probes



Composite Higgs

Notice potential improvement from LEP + m_W, s_W @HL-LHC



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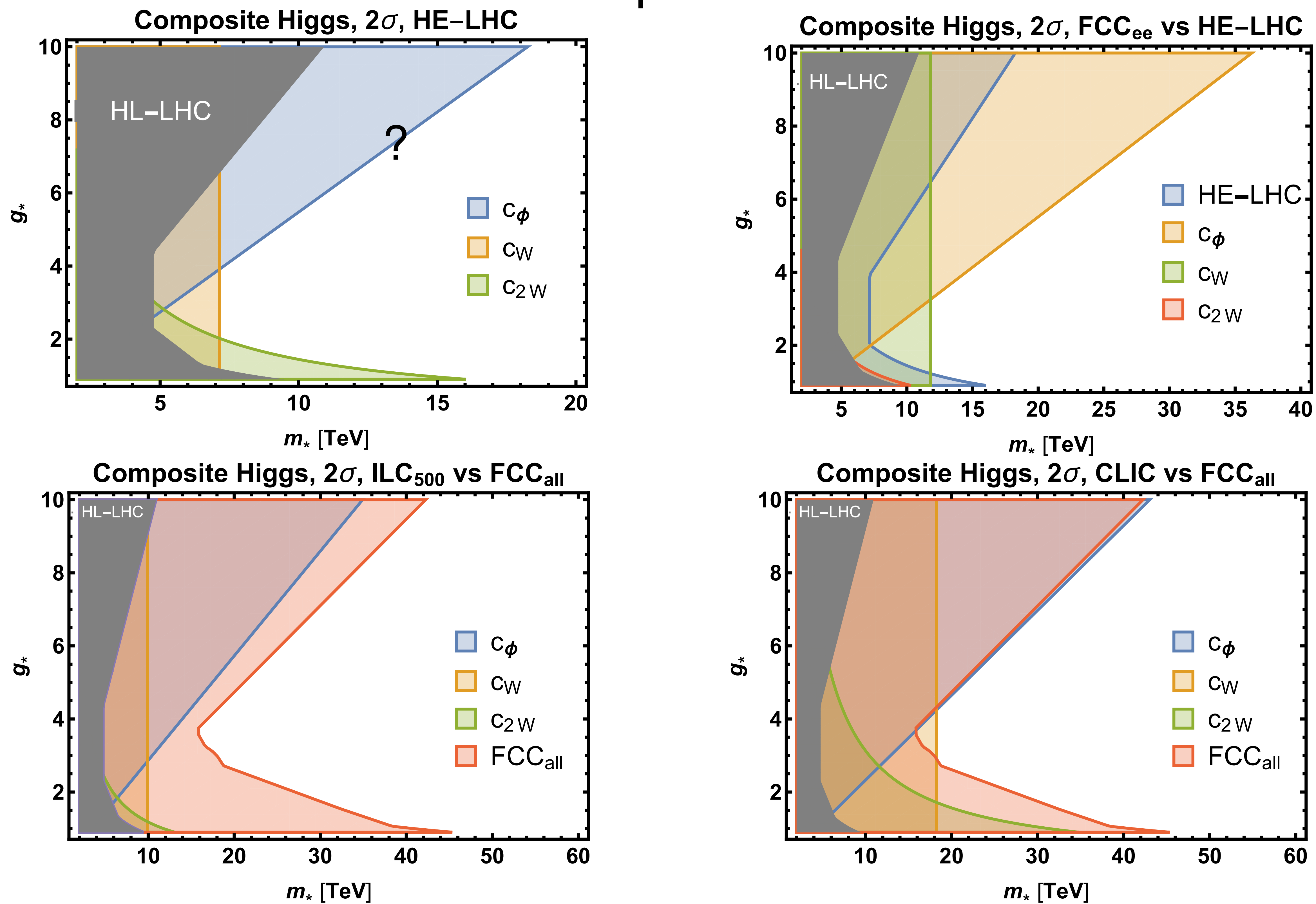
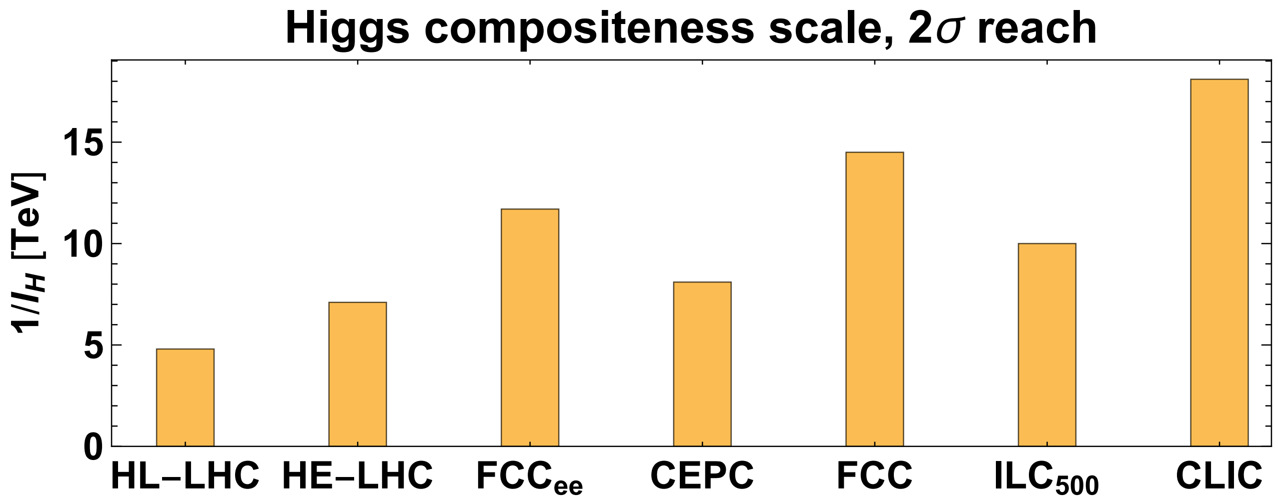


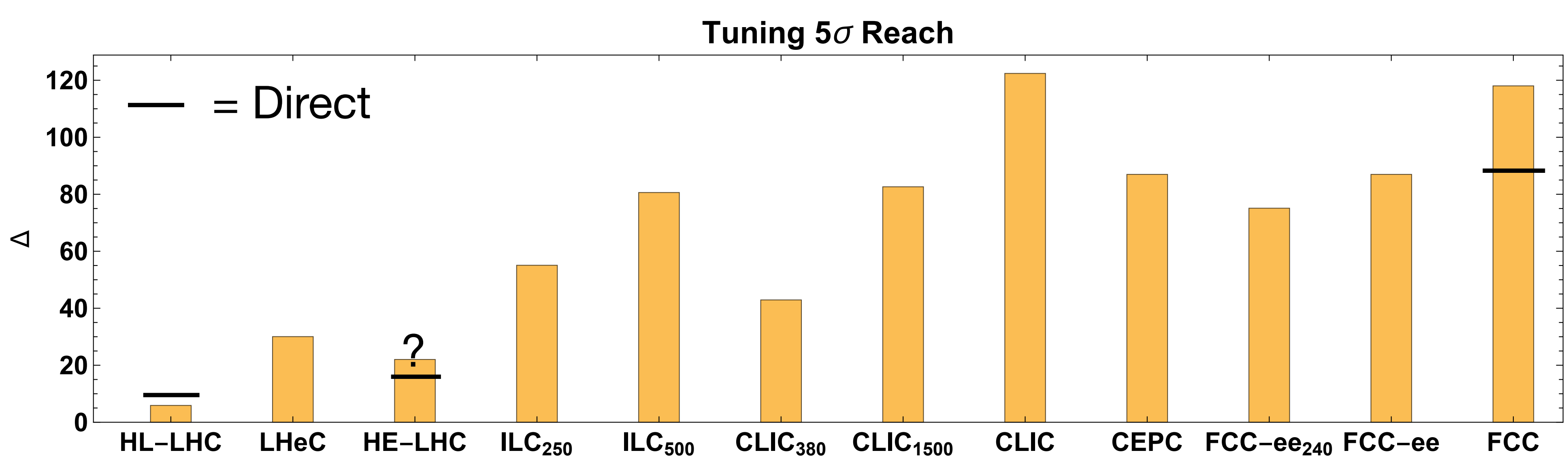
Composite Higgs

Future Colliders Reach compilation:

Higgs Compositeness scale: [max $\mathbf{m_*=1/l_H}$ the collider is sensitive to]



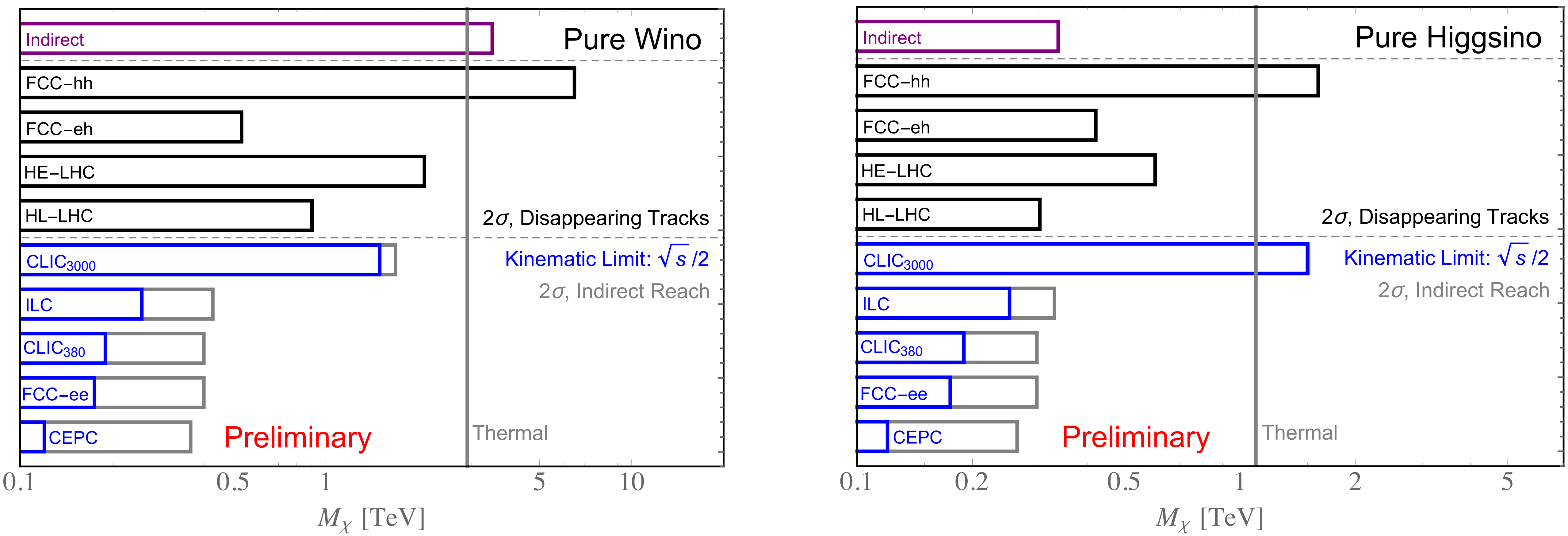
Natural Higgs Compositeness: [H coup., or direct top-partners reach]



$$\Delta > \left(\frac{M_{\rm T.P.}}{500\,{\rm GeV}}\right)^2 > \frac{1}{\xi}$$

Minimal WIMP DM

Main tools are disappearing tracks and indirect loop effects

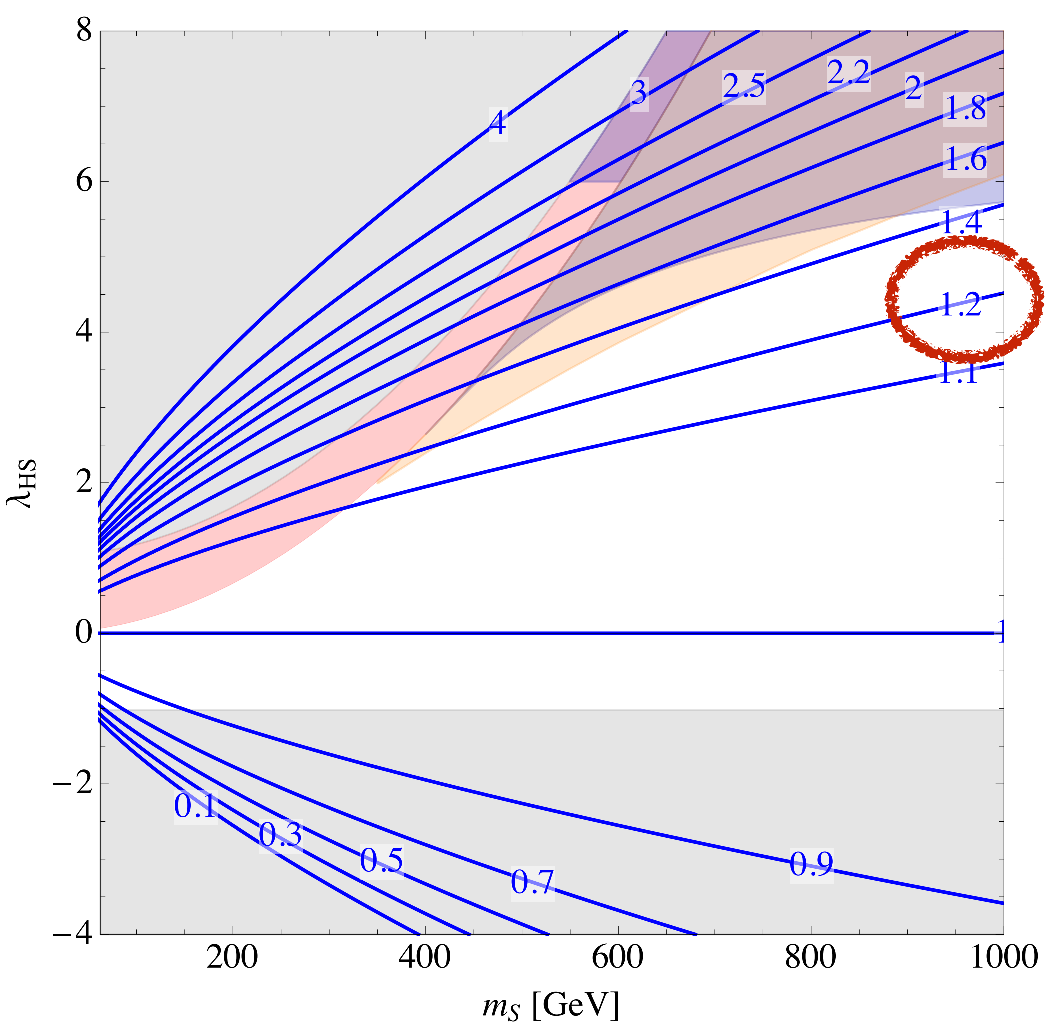


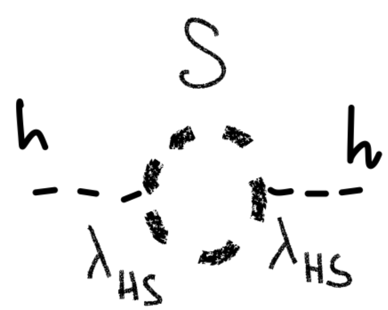
FCC can reach thermal Higgsino and Wino
CLIC, only thermal Higgsino.

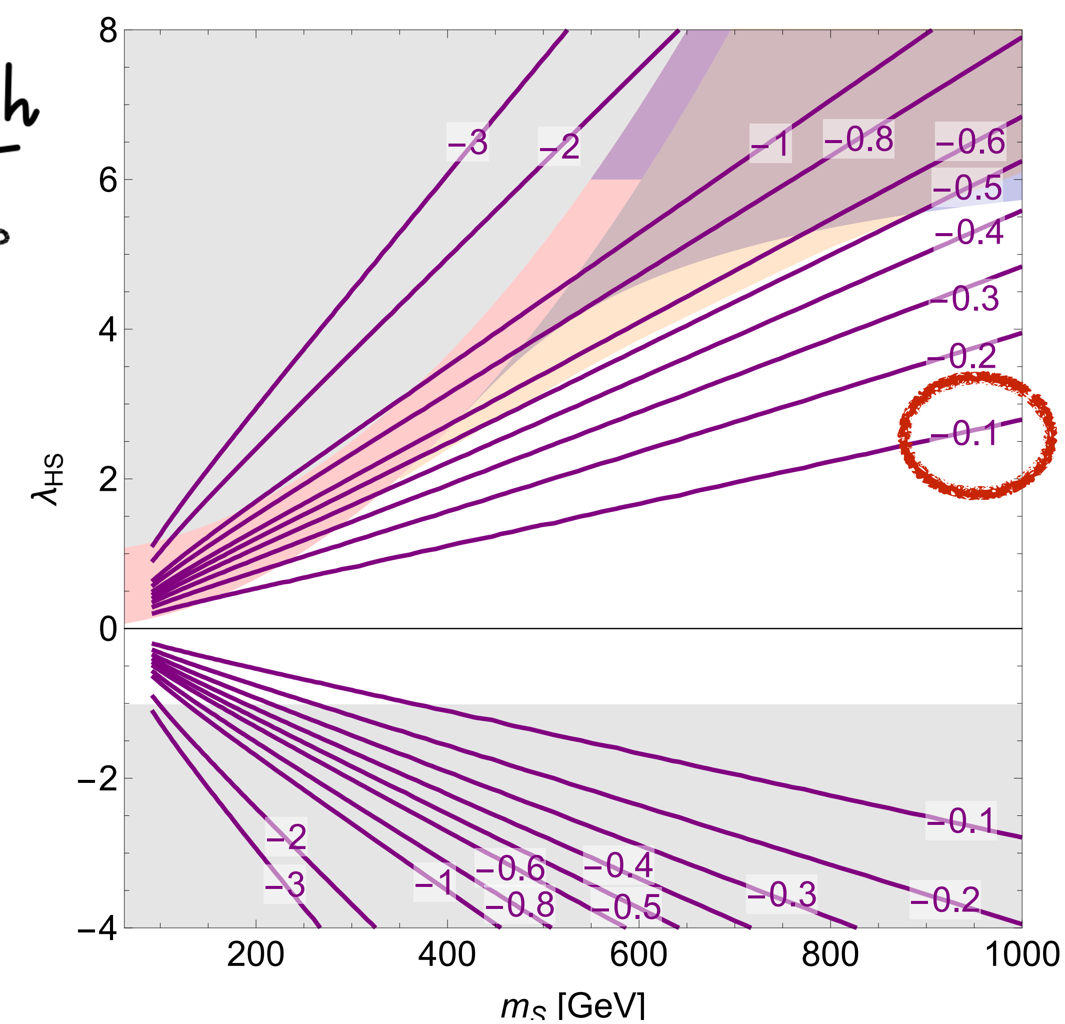
Only the muon collider could cover the entire WIMP space

EW Phase Transition

Direct probes of extra scalar only at CLIC and FCC-ee
Indirect from H 3-linear **and single Higgs couplings**



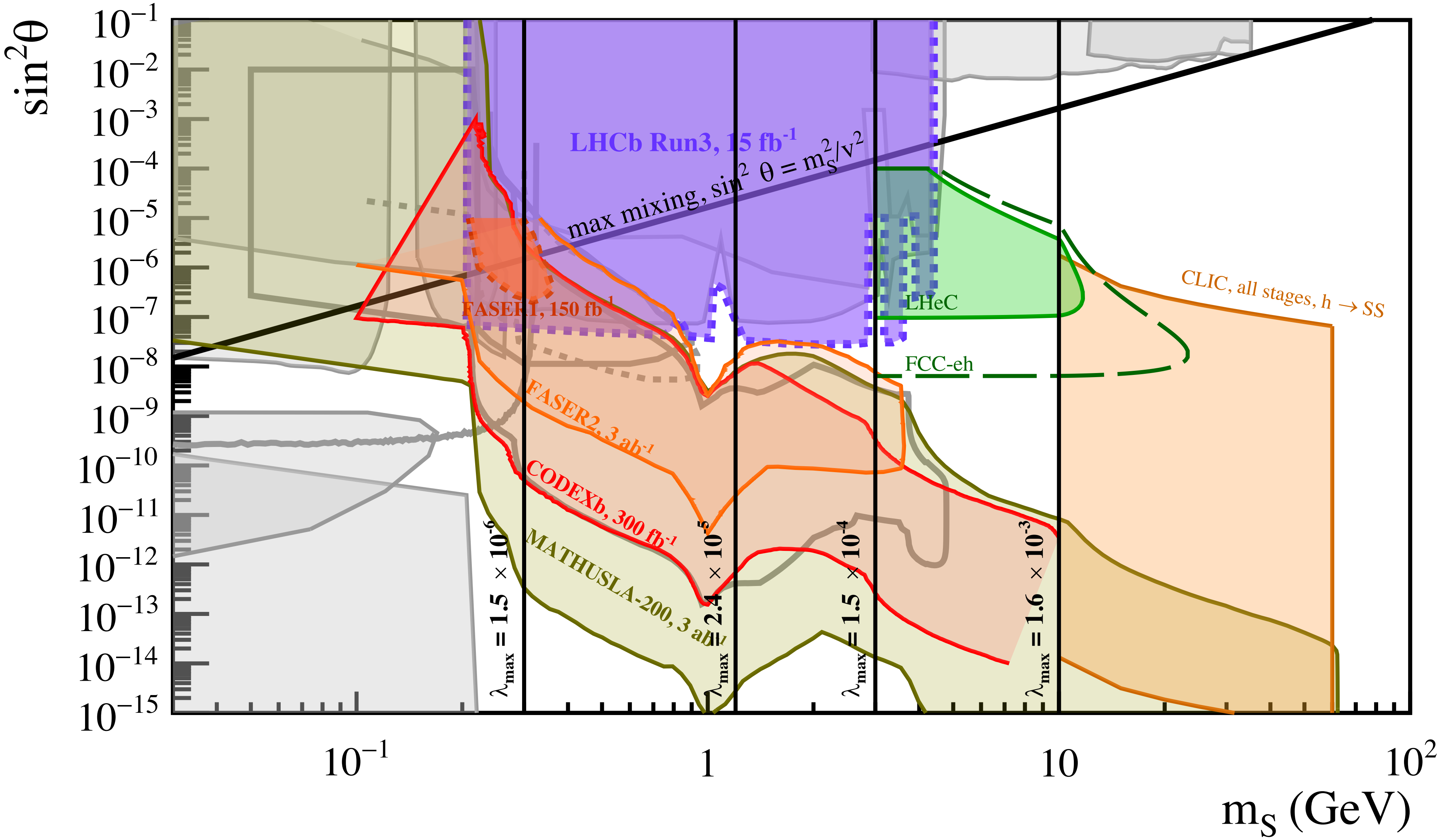




The scenario will be first and better probed by 1-H.
Role of 3-H (as usual) overemphasised.

FIPS

Main probes are long-lived particle searches, and invisible/ untagged Higgs decays.

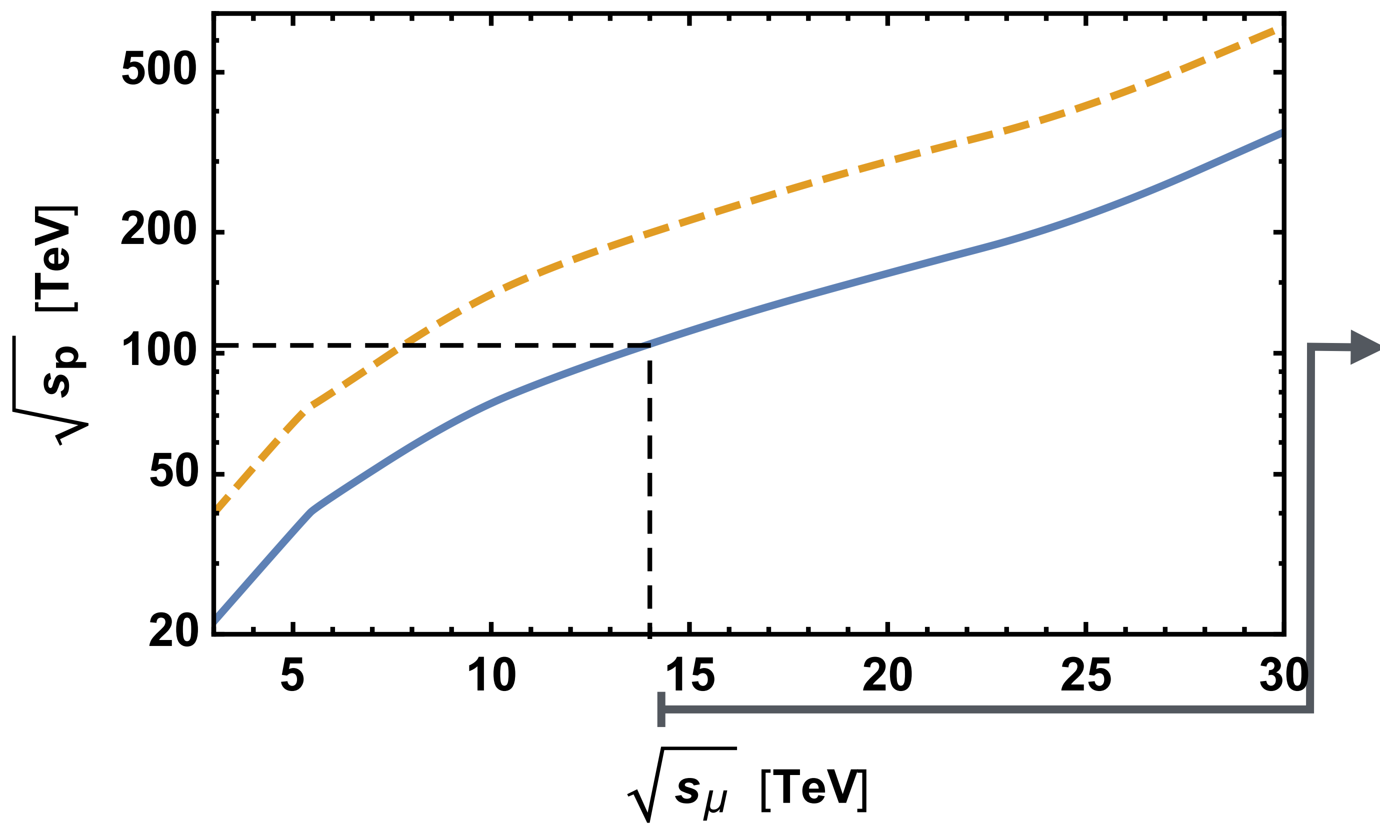


Advantage of hadron colliders of high rate to be exploited with dedicated detectors. The 10^{12} Z bosons at FCC_{ee} are also very useful.

Very High Energy Lepton Collider

Muon collider, or $e^+ e^-$ plasma (?), from 10 to 30 TeV.

Great **direct** reach, no waste due to pdf!



14 TeV VHEL as good as 100 TeV pp

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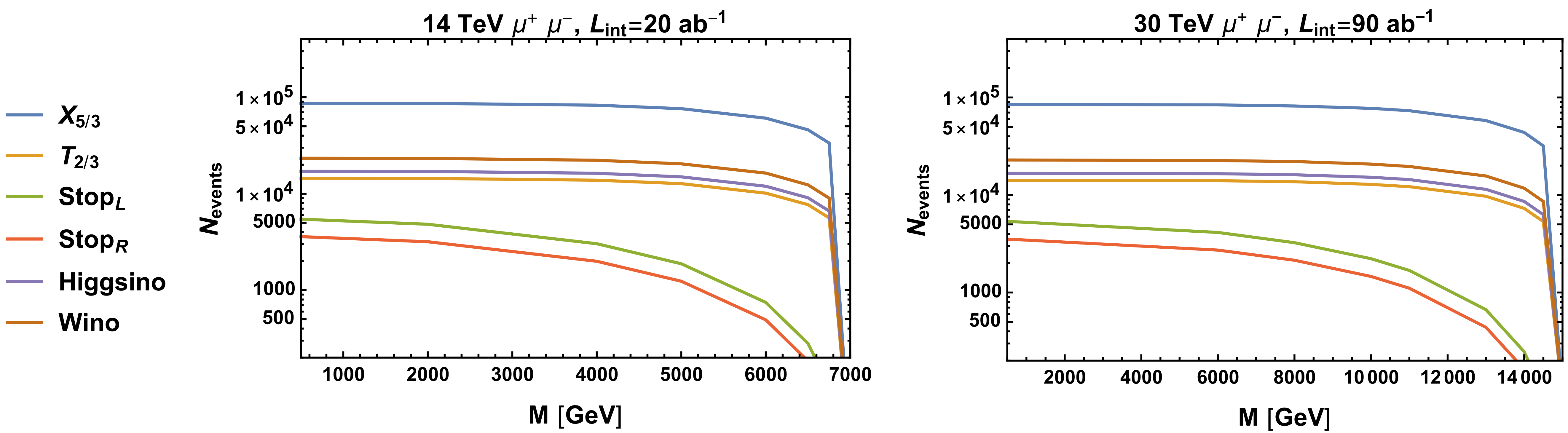

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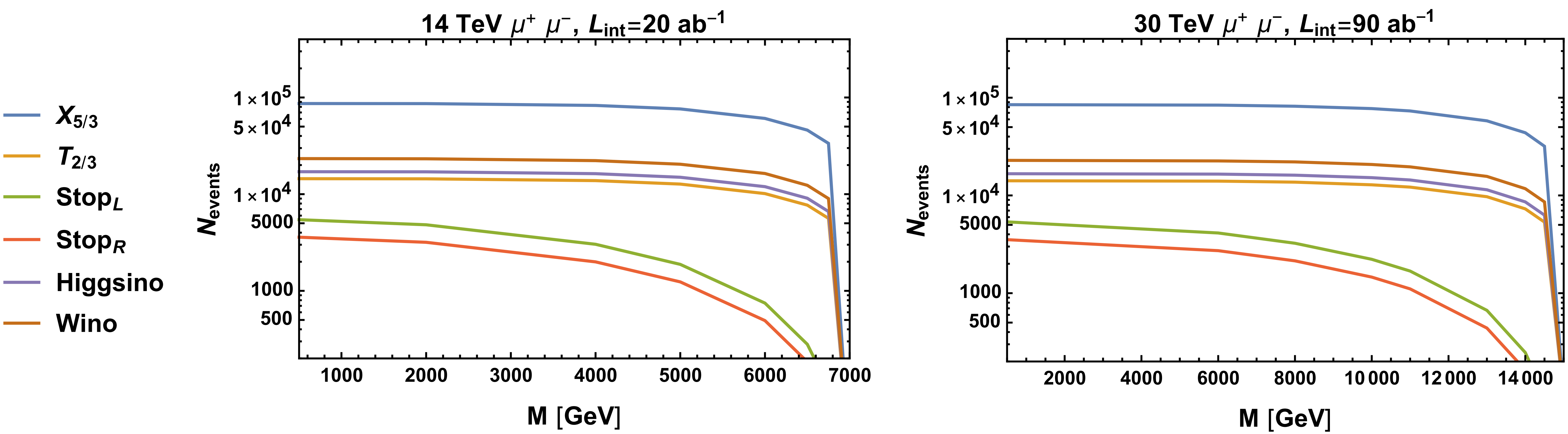
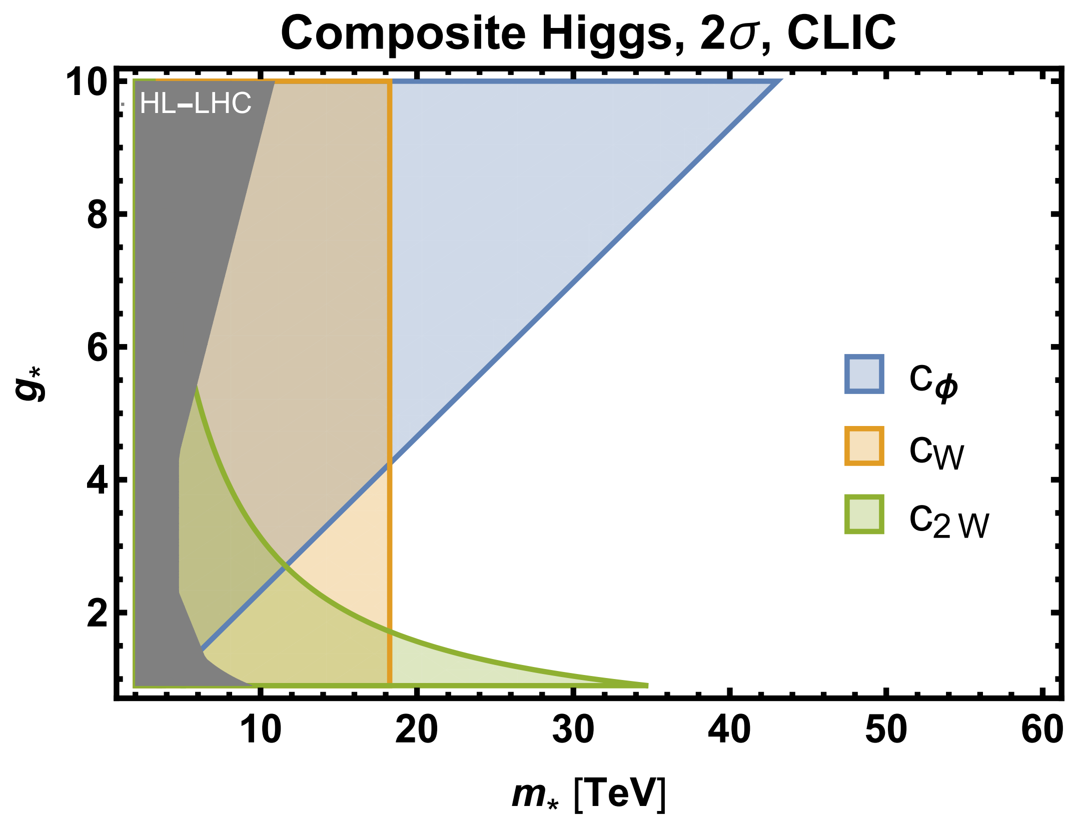


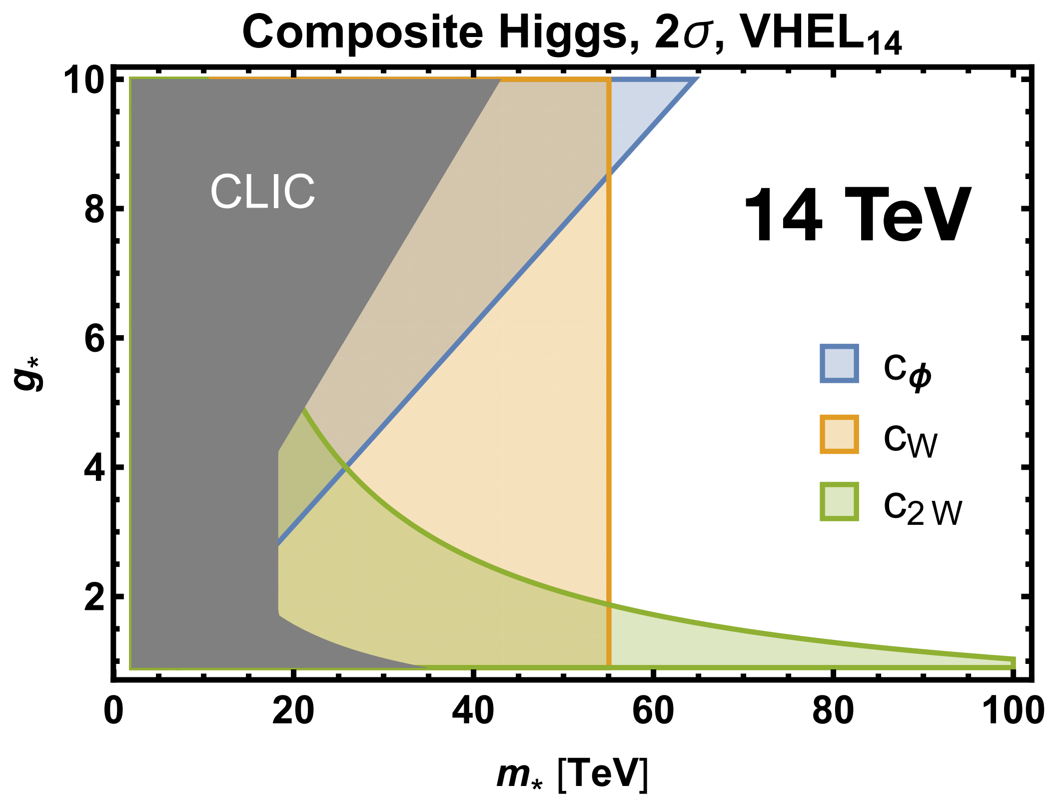
Amazing **indirect** reach, by high energy measurements. Like CLIC, but 10 times better!

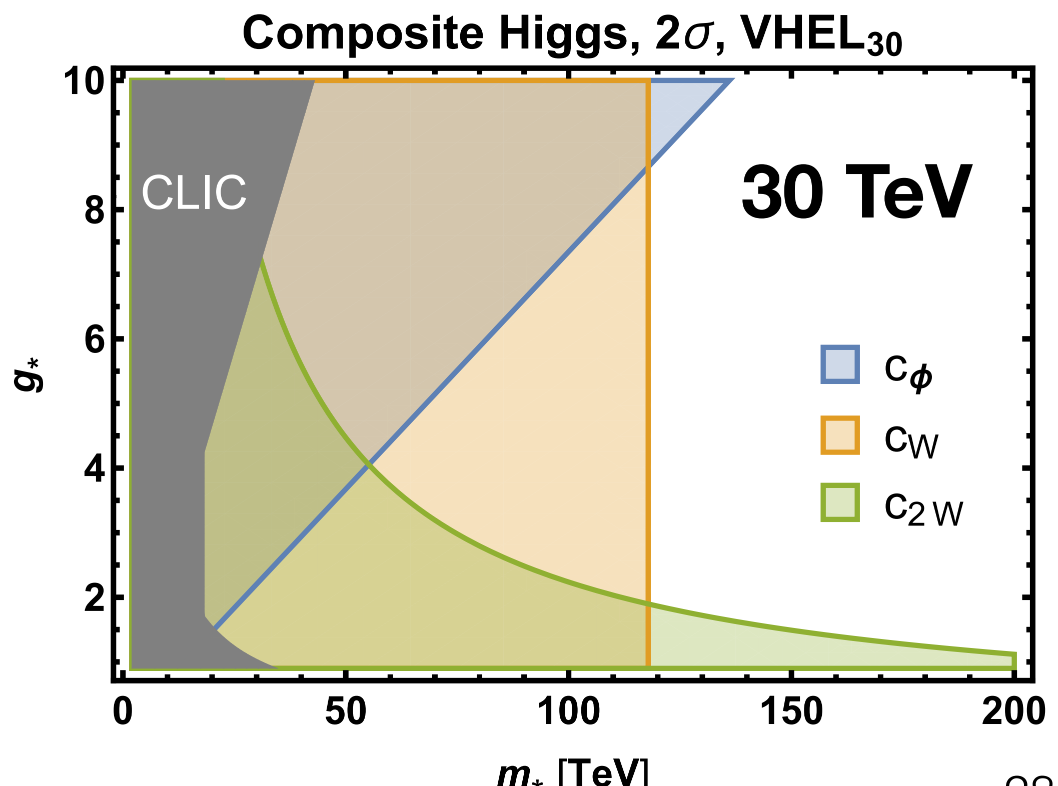
Very High Energy Lepton Collider

Reach on Higgs Compositeness:

(very) tentative [Buttazzo, Franceschini, AW. in prog.]



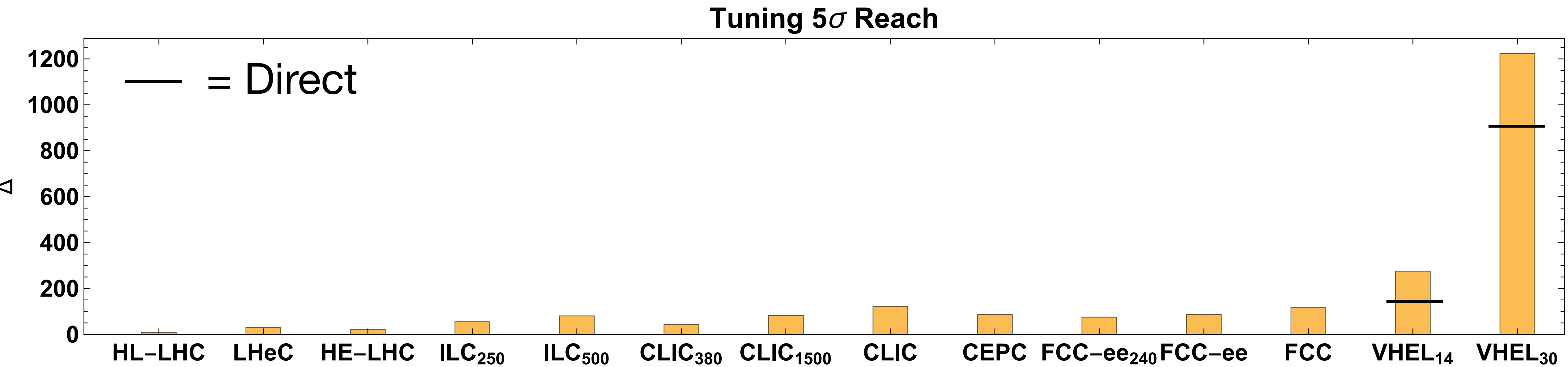




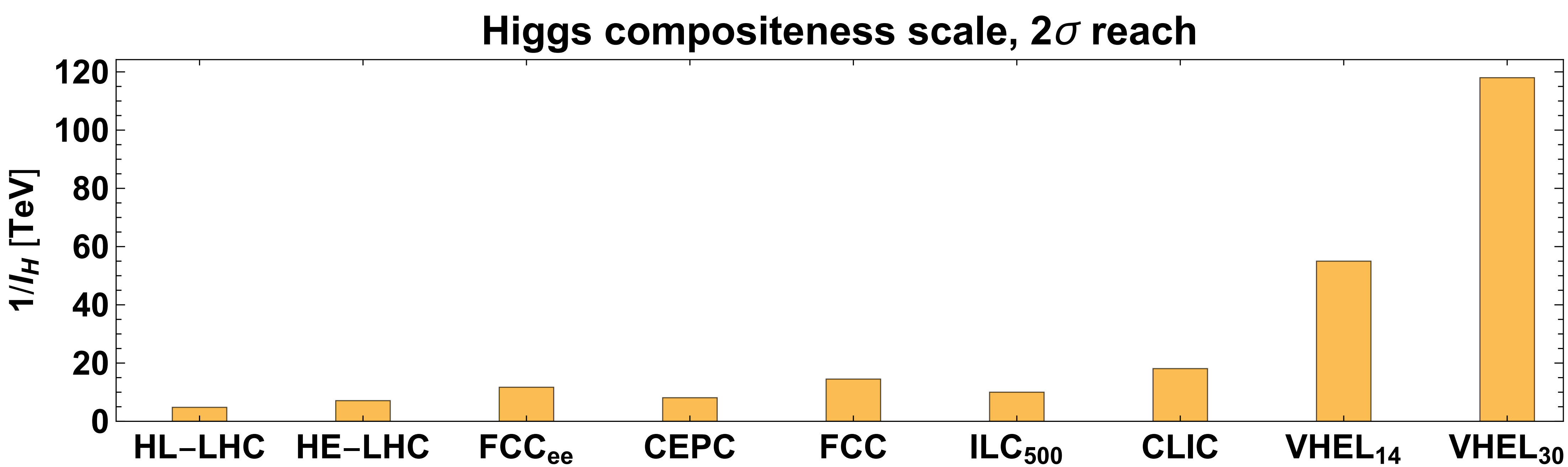
Very High Energy Lepton Collider

Tuning Reach:

(very) tentative [Buttazzo, Franceschini, AW. in prog.]



Compositeness Reach:



Conclusions

The physics case of the F.C. must be **broad and varied**

Weak theory guidance leads us to proceed in “exploratory” mode

Only a **very limited subset** could be covered here

Also not touching at all crucial issues like **characterisation** of discoveries

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Measurements (i.e., indirect BSM) will also be central

Combining Higgs, EW, top, Z-pole, **High-Energy Probes**

Abandon artificial separation and adopt common language

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Which Future Collider?

Several options for a groundbreaking Higgs program [ILC/CEPC/…]

$CLIC_{all}$ and FCC_{all} do more for BSM searches

Many advantages of $FCC_{all=ee+hh\_eh}$: direct reach; 10^{12}Z; high FIP rate; …

Also, it serves a broader user community [e.g., flavour, QGP]

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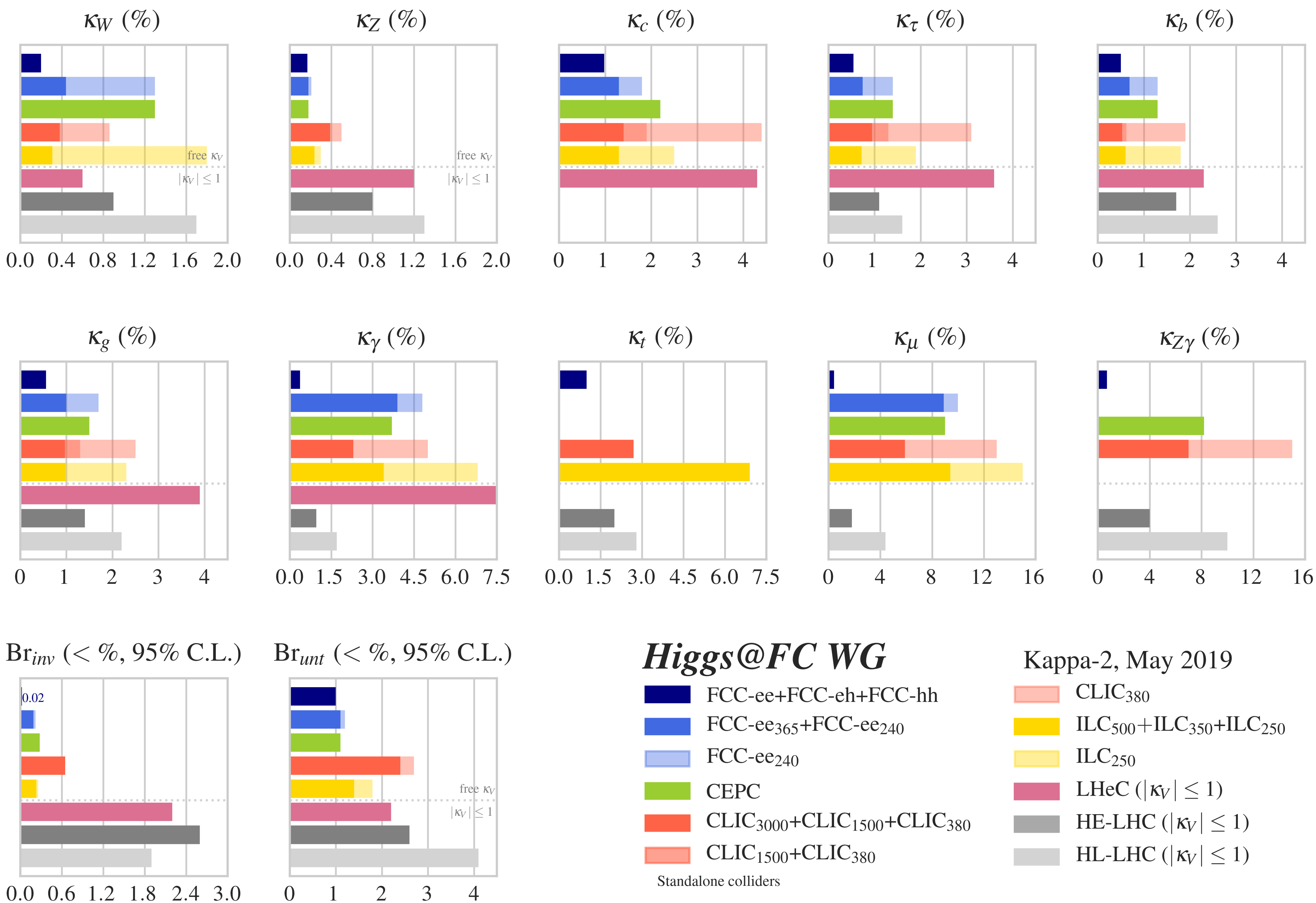
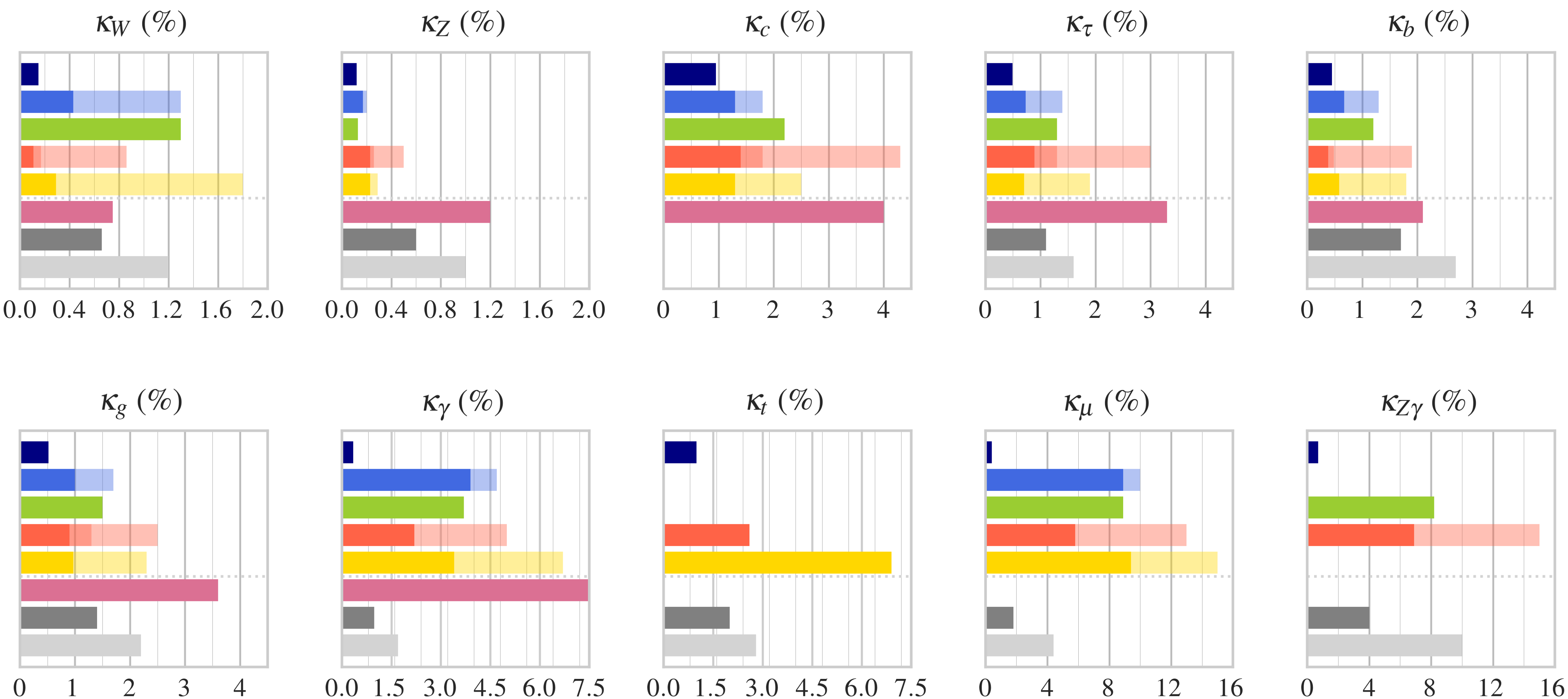
A Very High Energy **Muon Collider** is a **Dream!**

Could it become reality? **Requires R&D!!**

Kappa-2: allowing BSM and Invisible



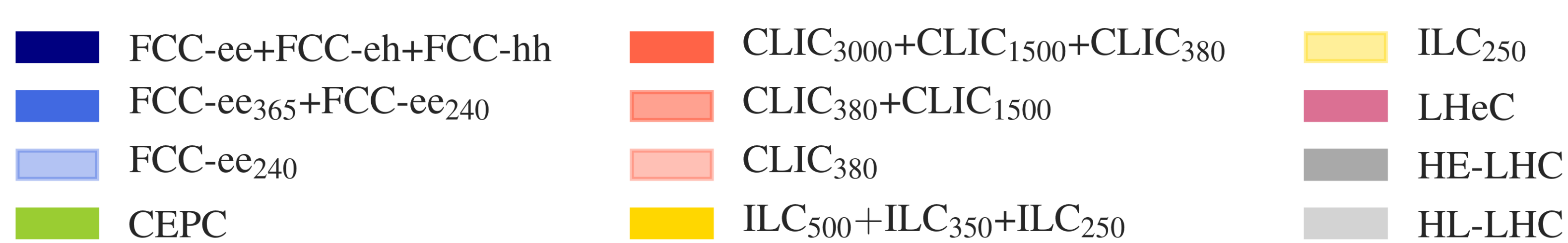
Kappa-0: No BSM Width



Zooming in for visibility - different x ranges per parameter

Higgs@FC WG

Kappa-0
May 2019



Backup

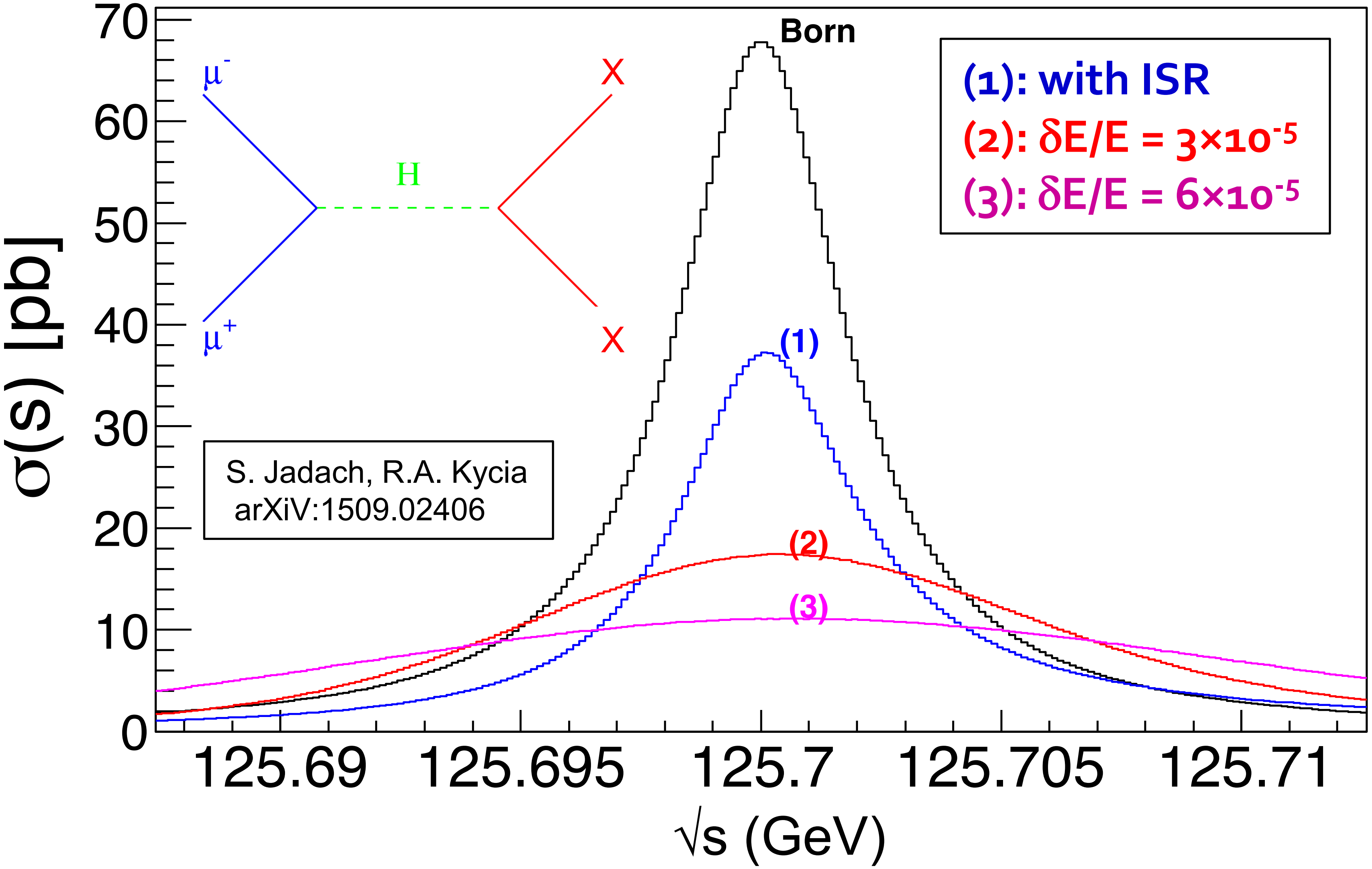
Result of the coupling (a.k.a. κ) fit

- 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

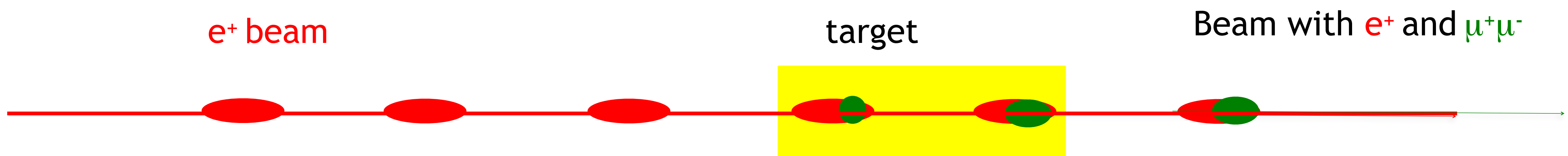
(*) Green = best
Red = worst

Backup



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

Backup



Ideally muons will *copy* the positron beam

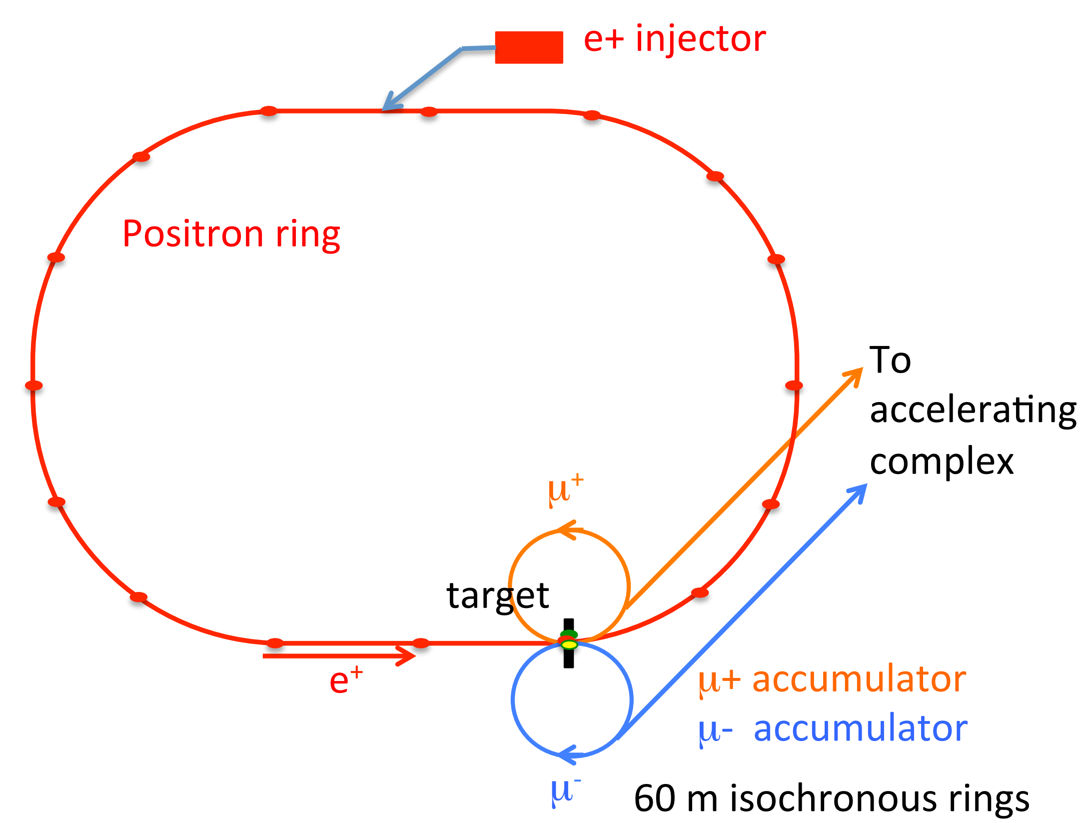
Low emittance μ from e^+ on target

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

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

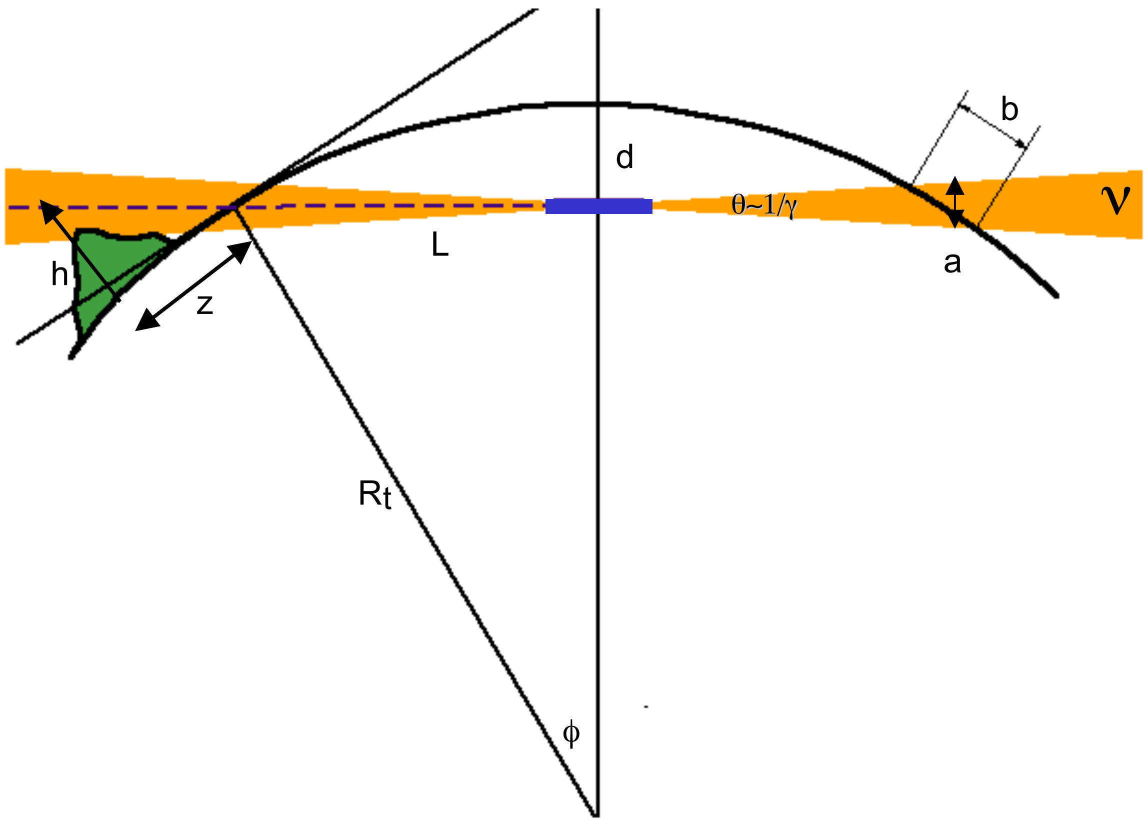
Challenges:

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



Backup

Radiological Hazard



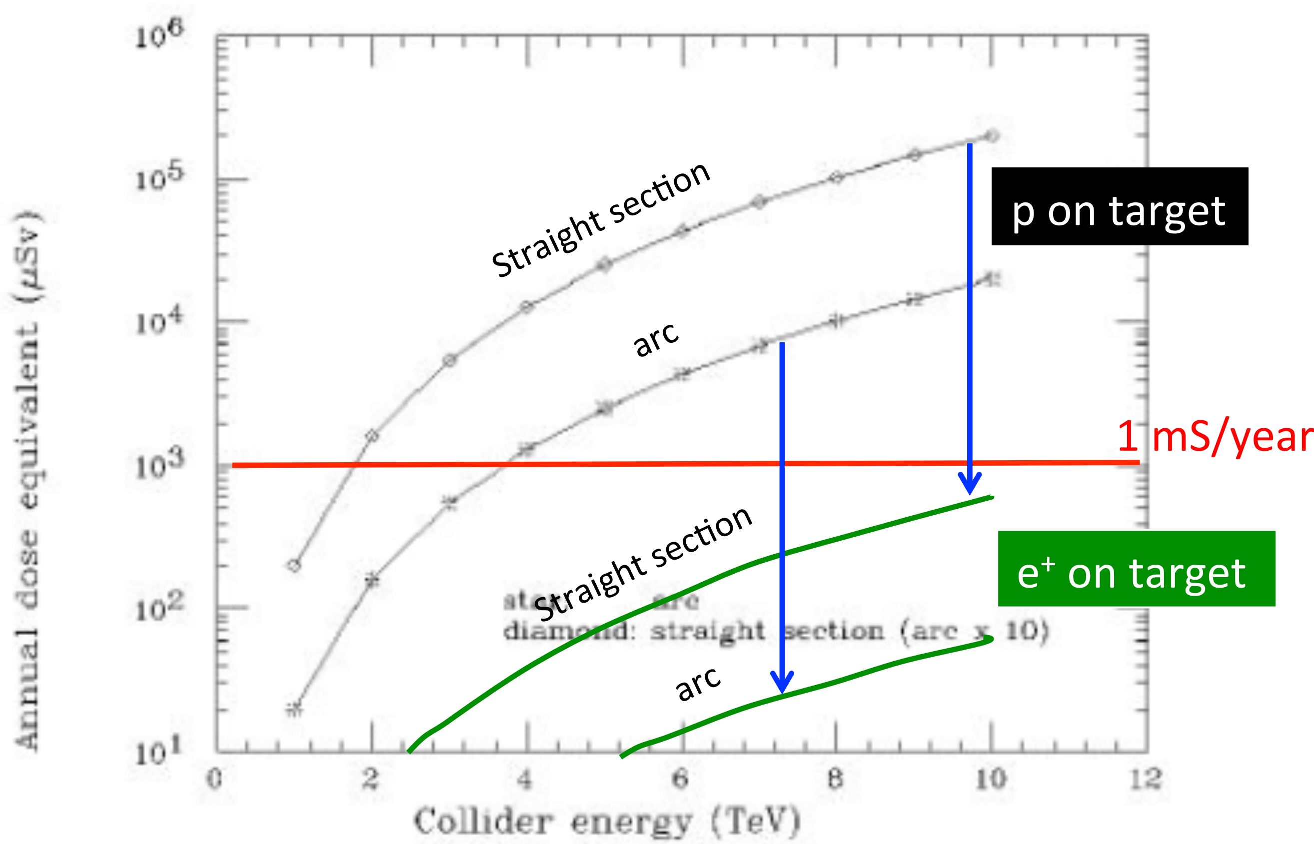


Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

Helicoidal Orbits??
Rolandi's pipe??