BSM-Part 1: Behind the SM

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Ideology

HEP before the LHC

HEP before the F.C.

Ideology

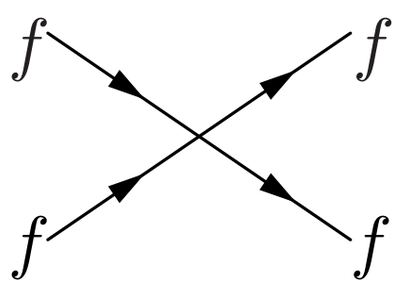
HEP before the LHC

HEP before the F.C.

SUSY, etc.

Higgs

W boson

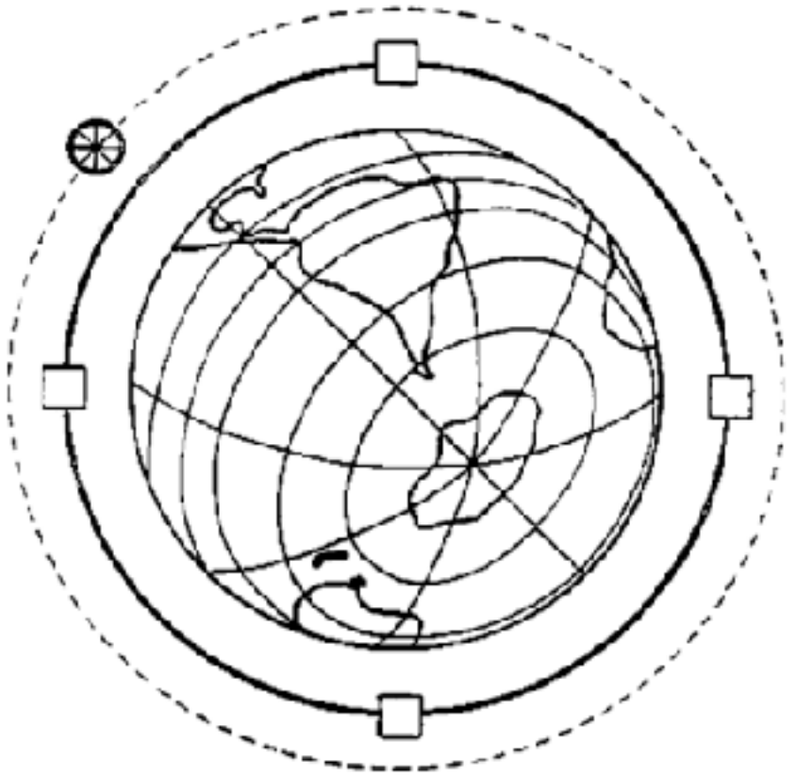


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \longrightarrow m_W < 4\pi v$$

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 !!

Ideology

No single experiment can explore all directions at once …

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but **many directions** explored by the **FCC project**

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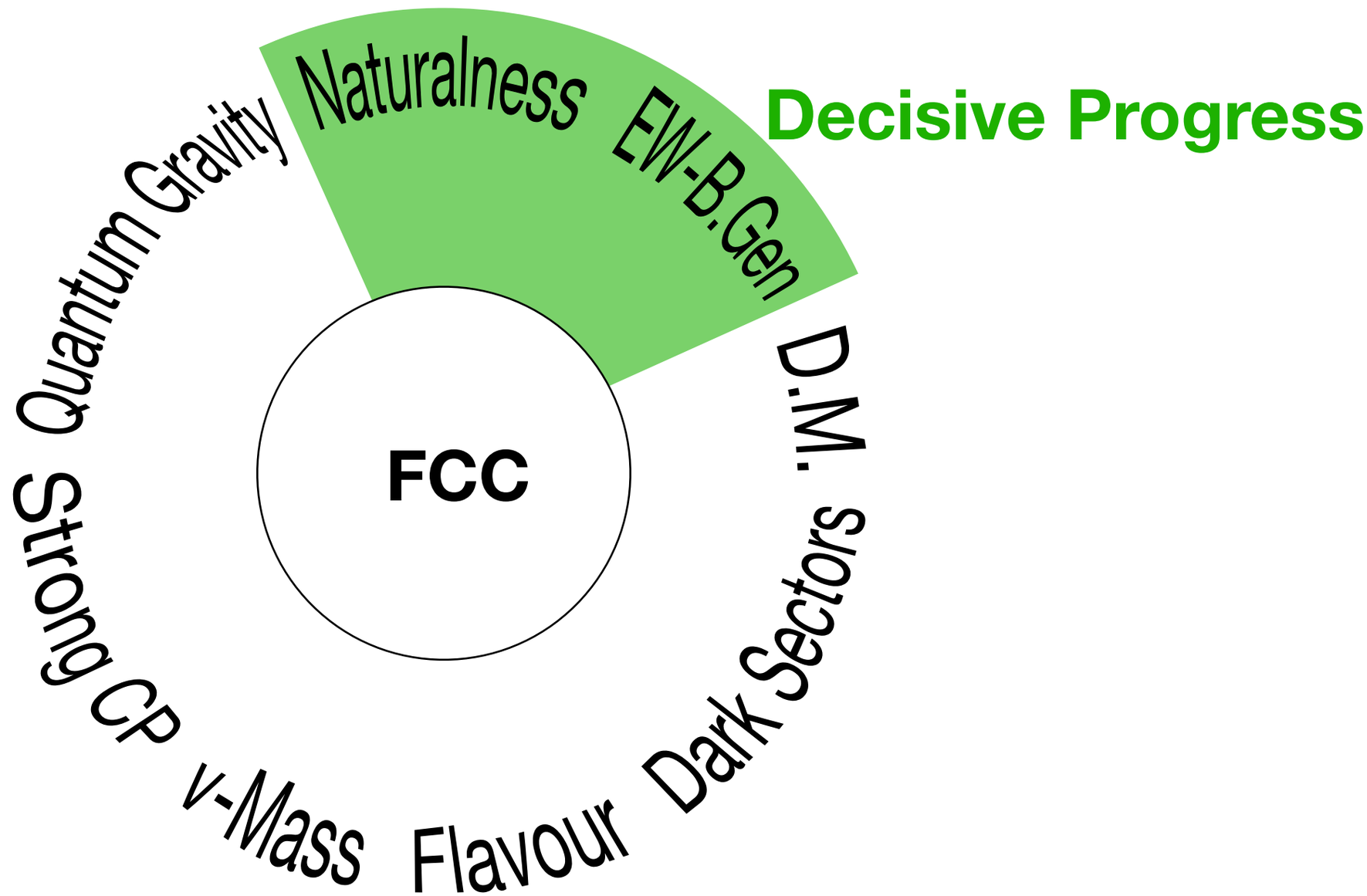

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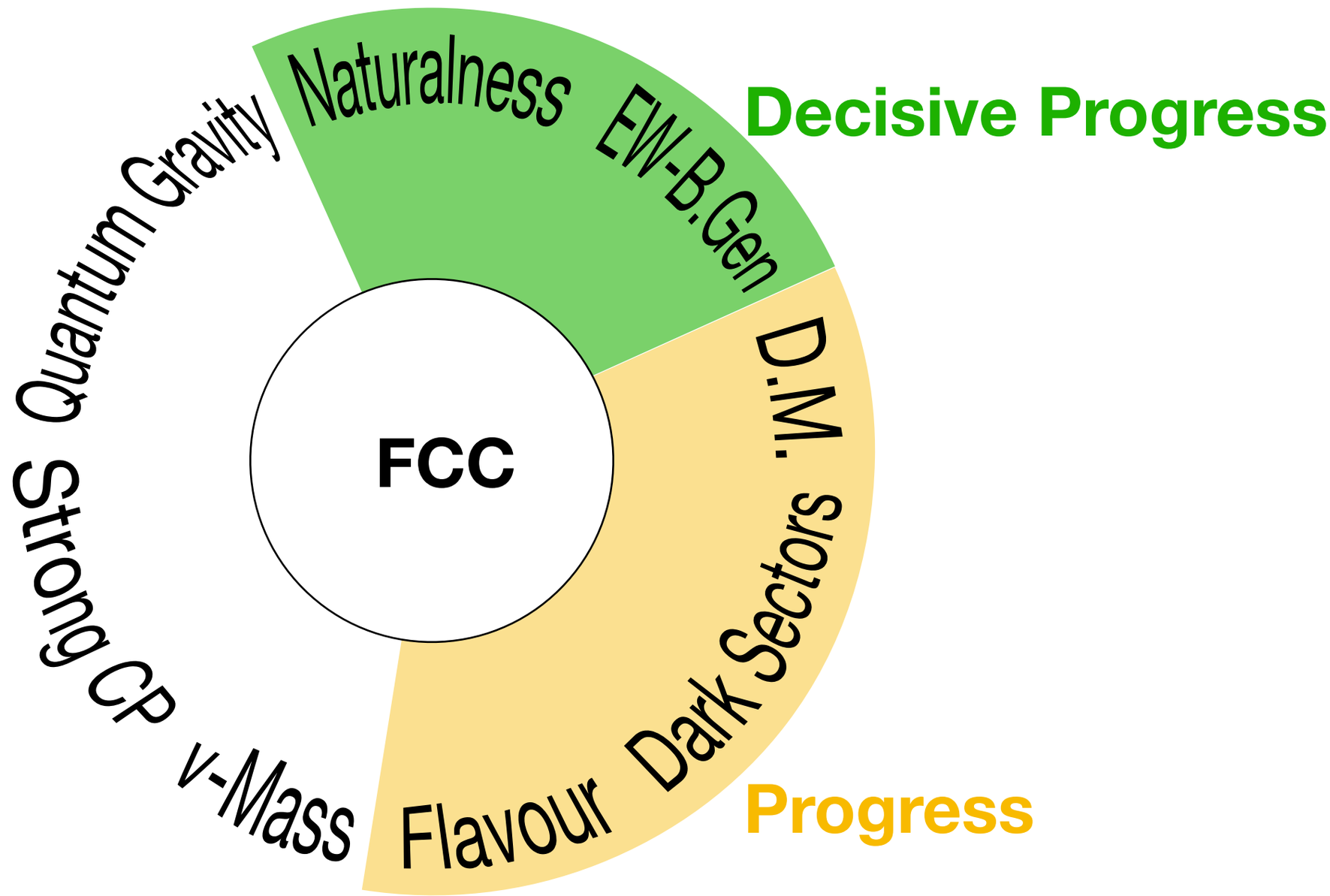

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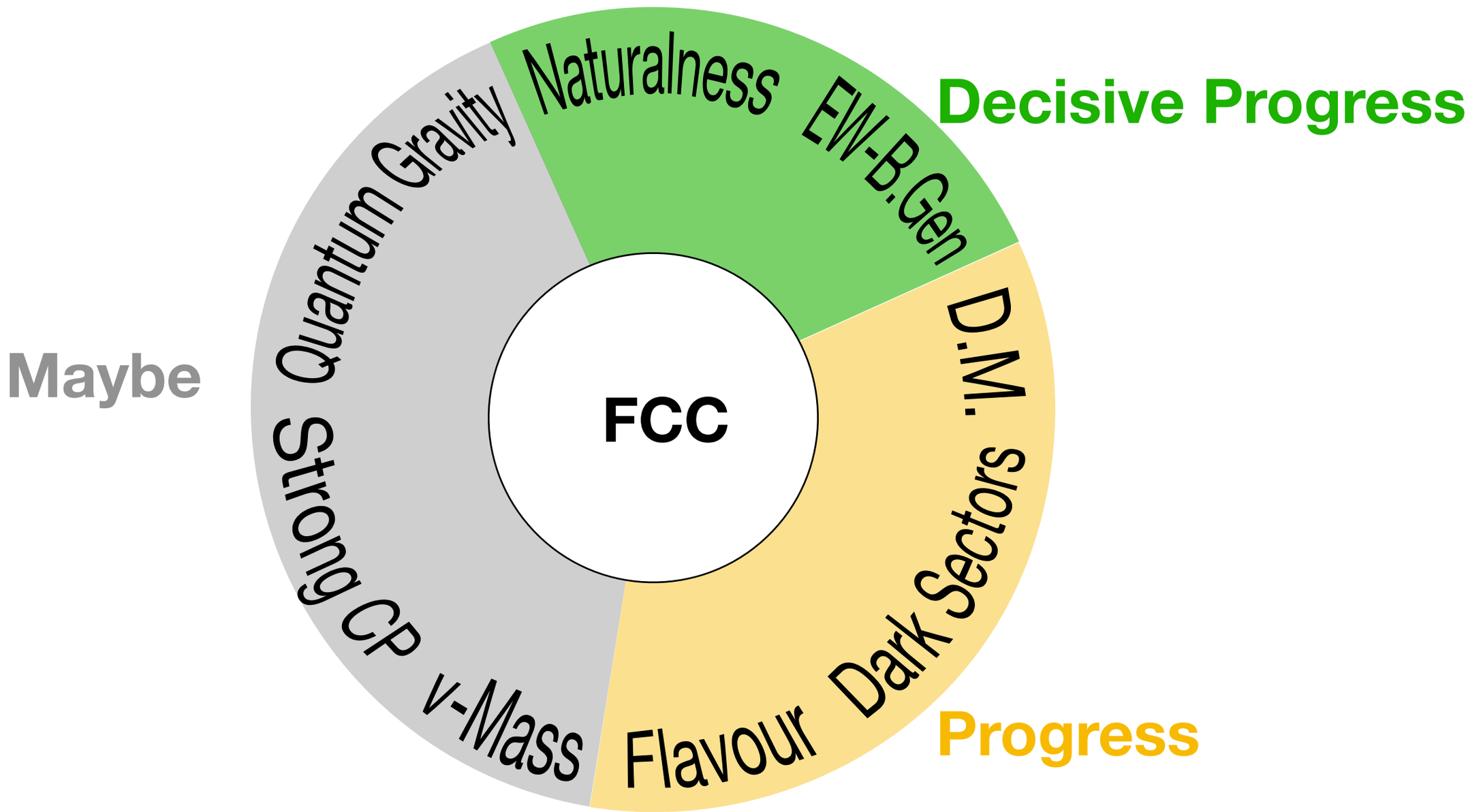

Ideology

This talk:

BSM = Behind the SM

aiming at explaining SM mysteries

Next talk:

BSM = Beyond the SM

question is what could be there, that we can probe

Naturalness

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

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

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

SM Contribution

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

UV Contribution

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

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

Measures how much Unpredictable m_H is.

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Unnaturalness is a challenge to **Reductionism**

Dramatic paradigm shift. E.g. Anthropic or Dynamical

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LHC may push conventional Natural models to

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

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Partial Unnaturalness

$$\Delta \sim 100$$

$$\downarrow$$

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Neutral Naturalness

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

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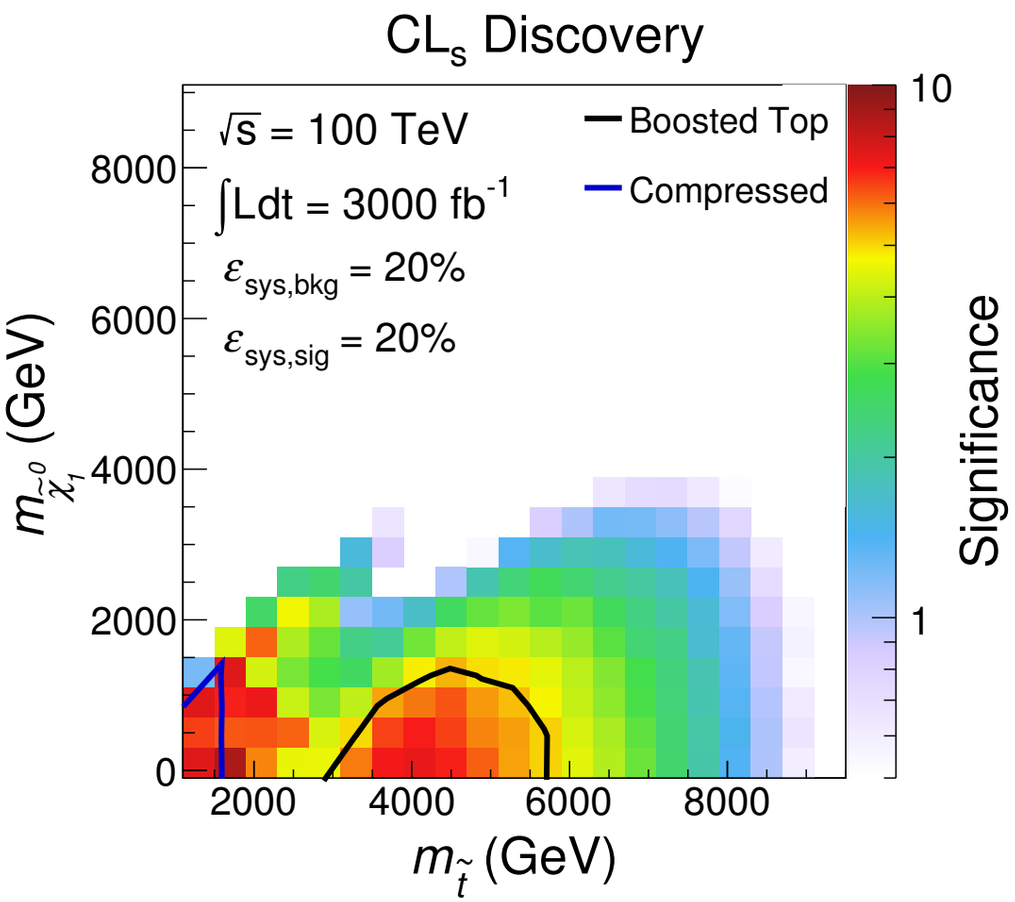
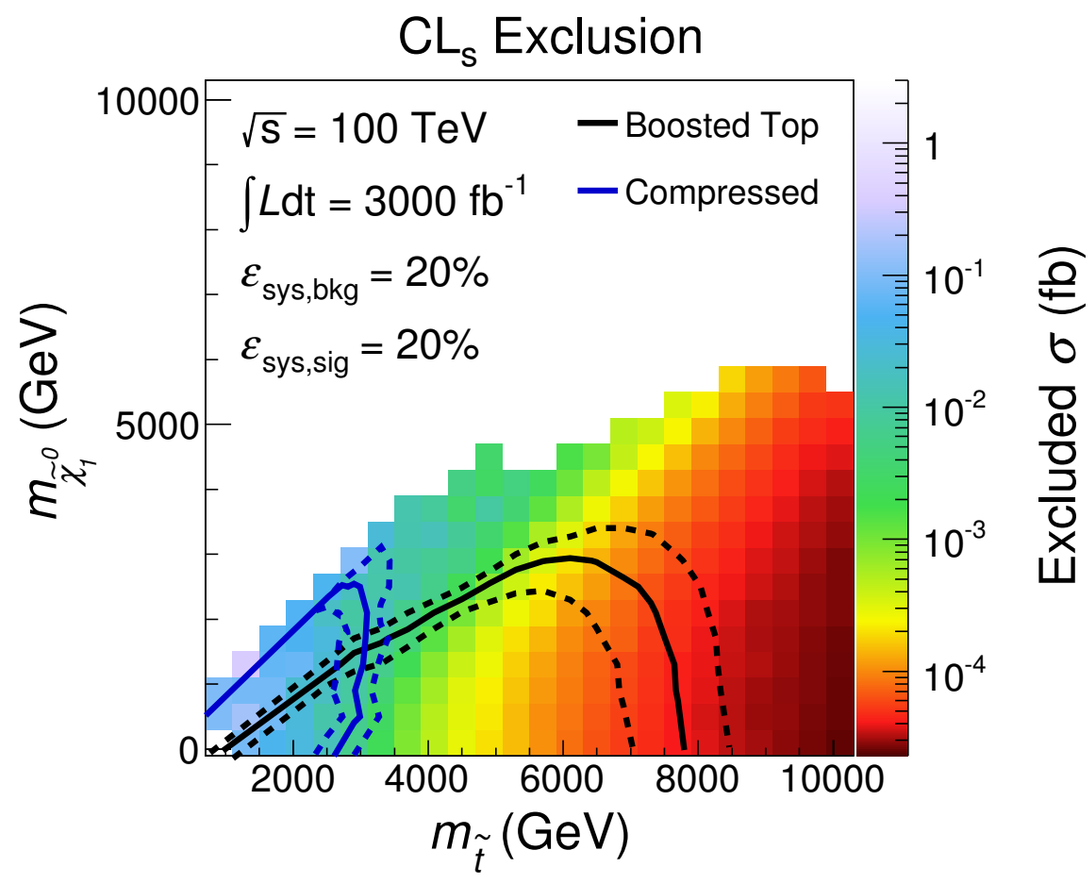
Need 5 TeV reach on ordinary Top Partners

Naturalness

Stop to top + Neutralino:

[arXiv:1406.4512]





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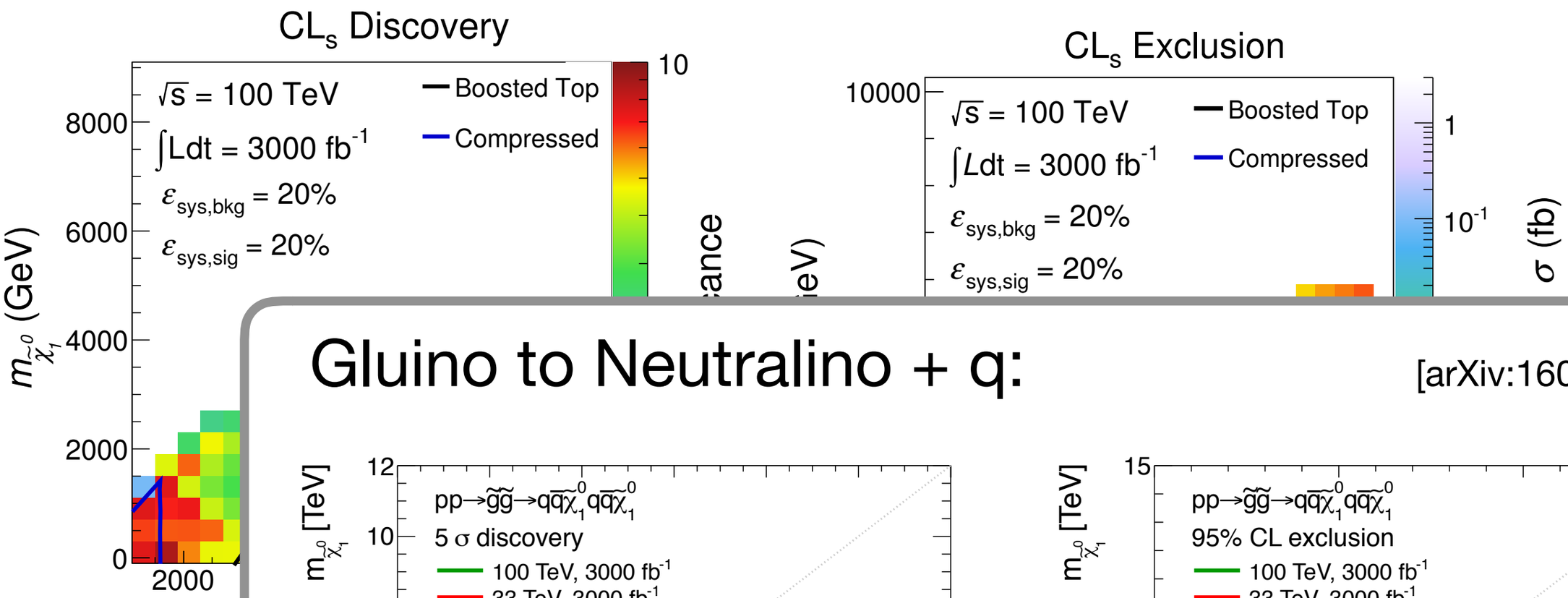
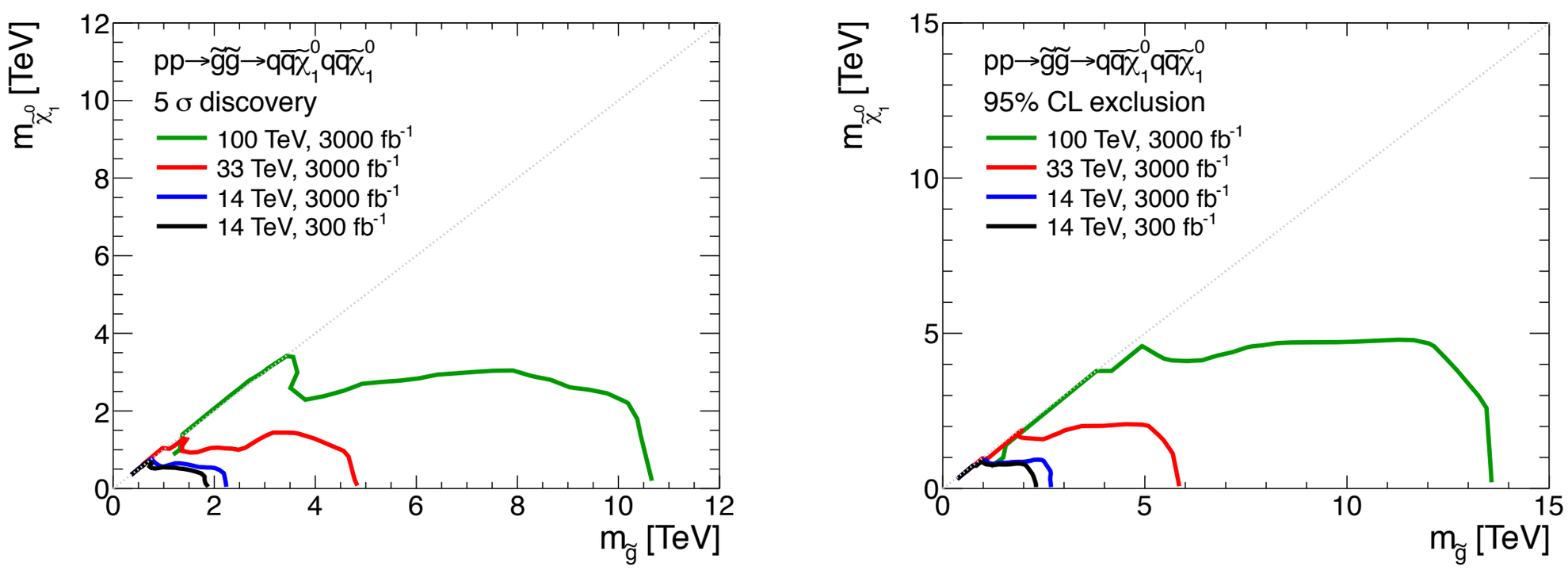


Gluino to Neutralino + q:

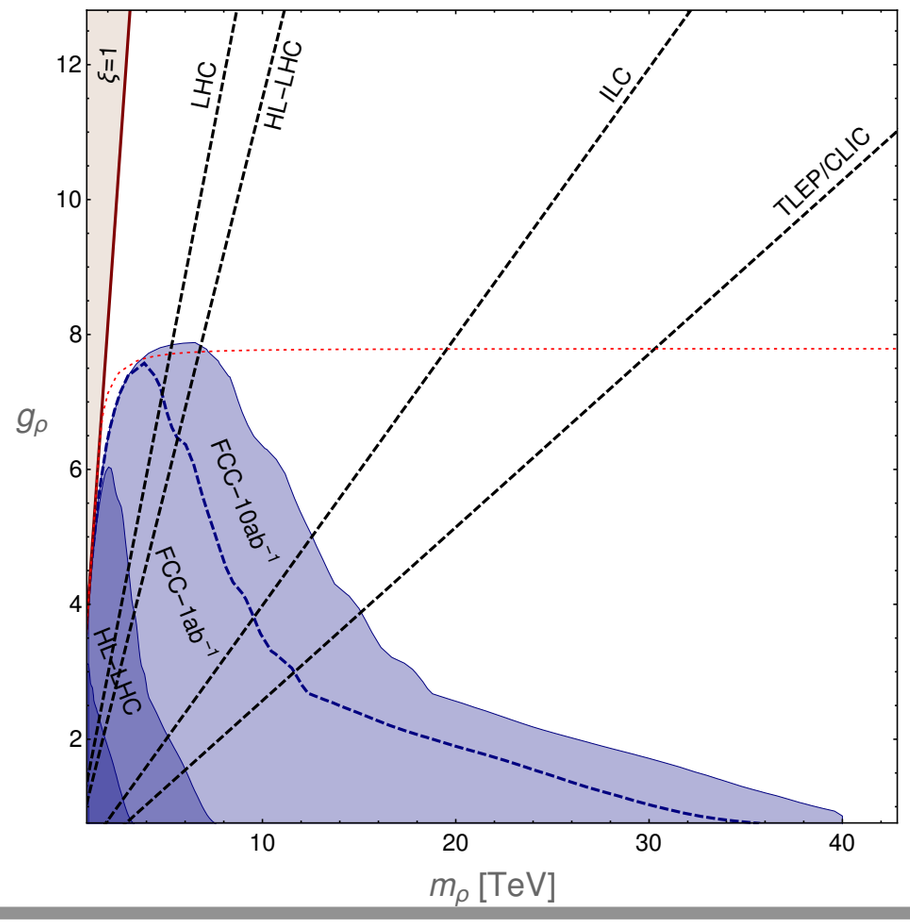
[arXiv:1606.00947]

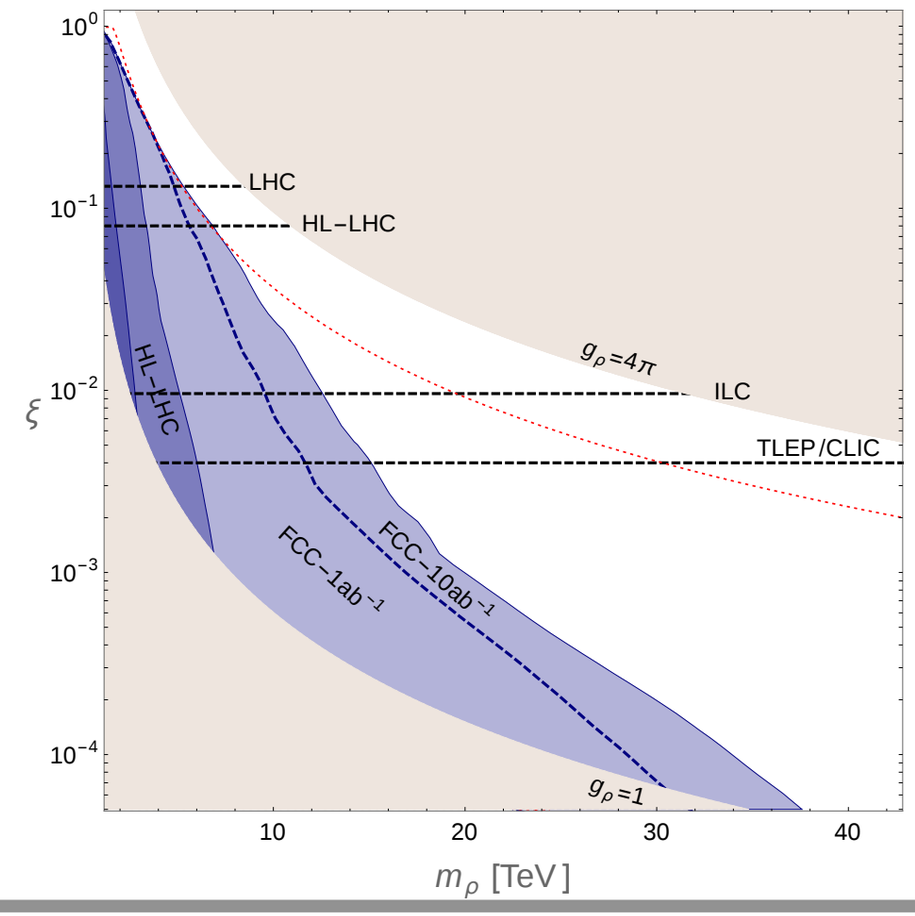


Naturalness

Spin-1 CH resonances (or V'):

[arXiv:1502.01701]





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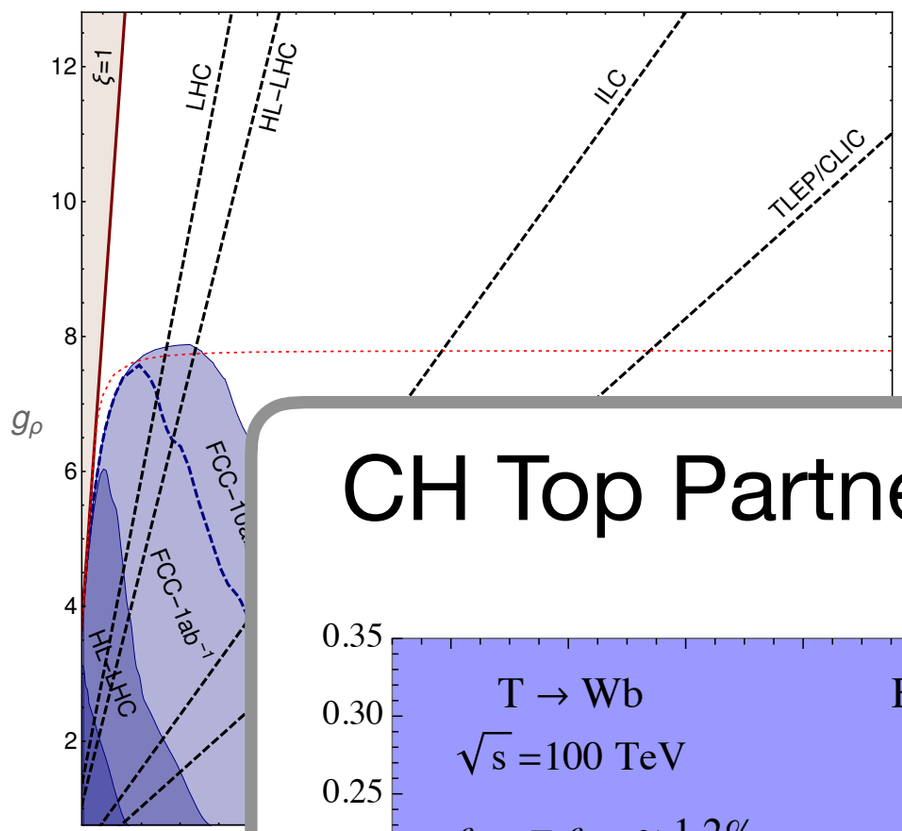
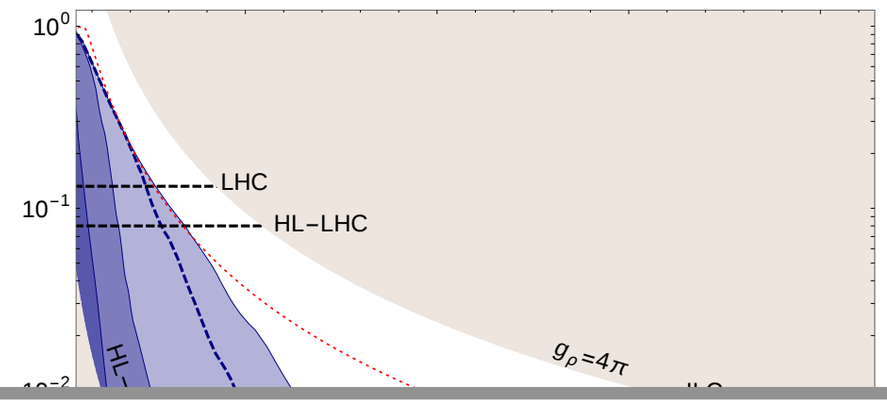
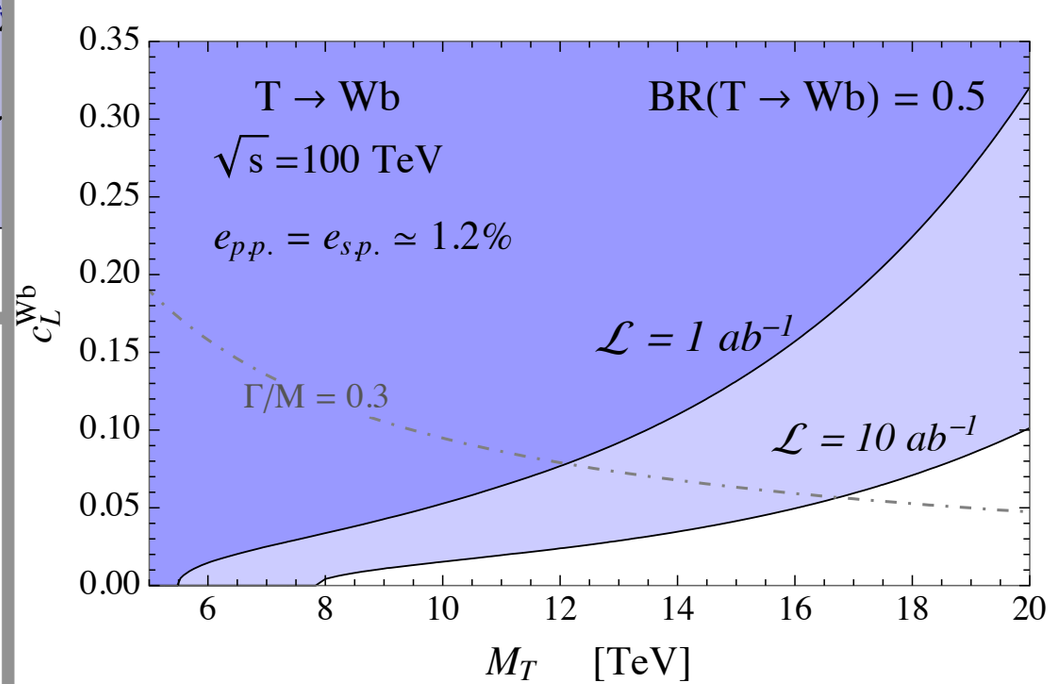
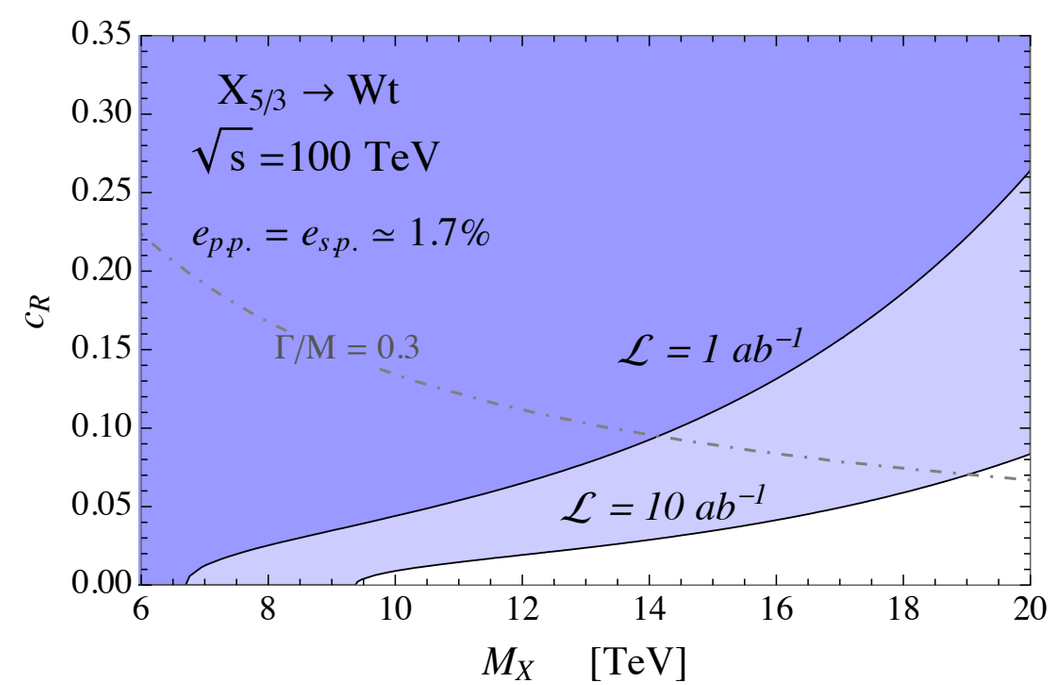




CH Top Partners:

[arXiv:1409.0100]

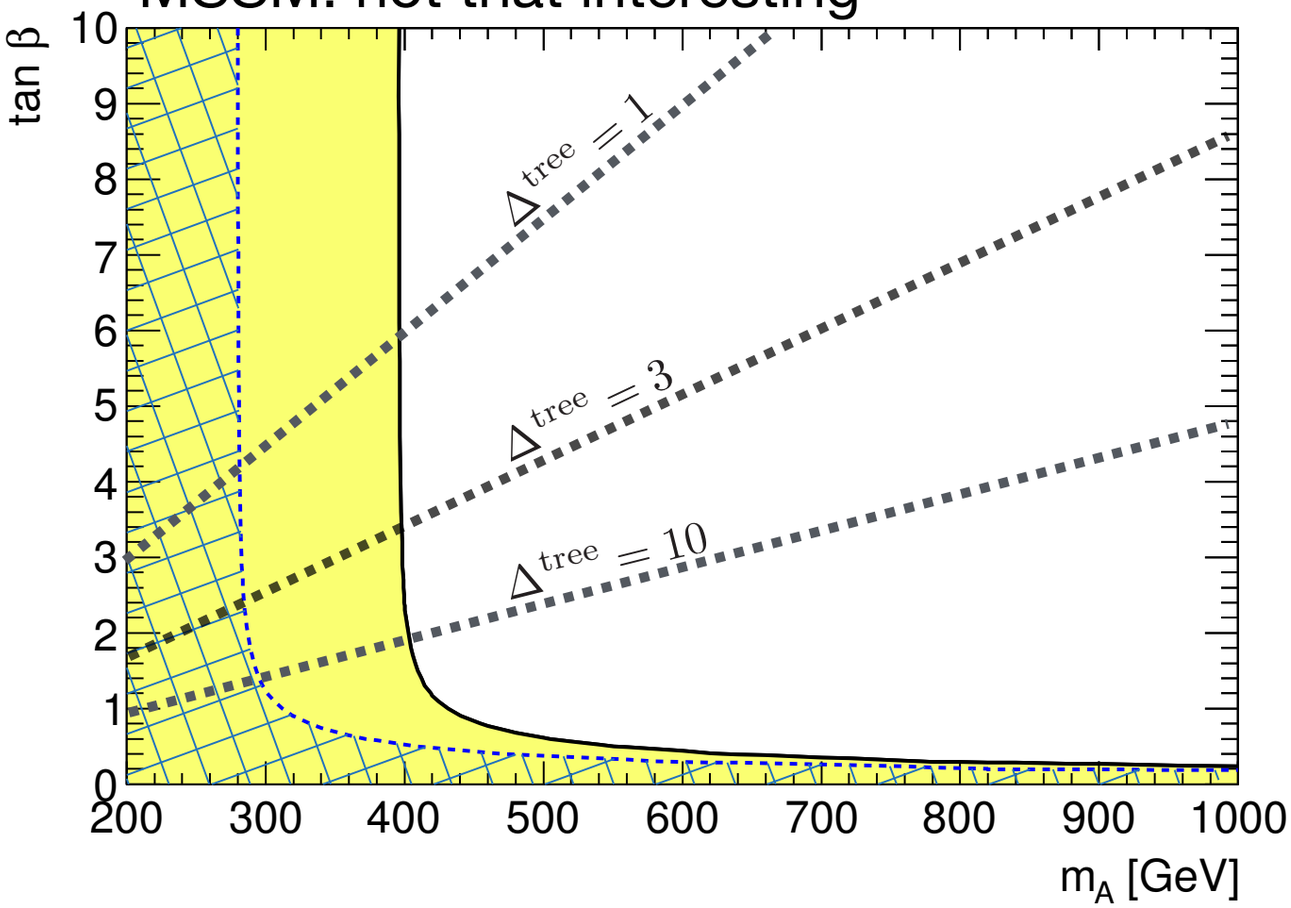




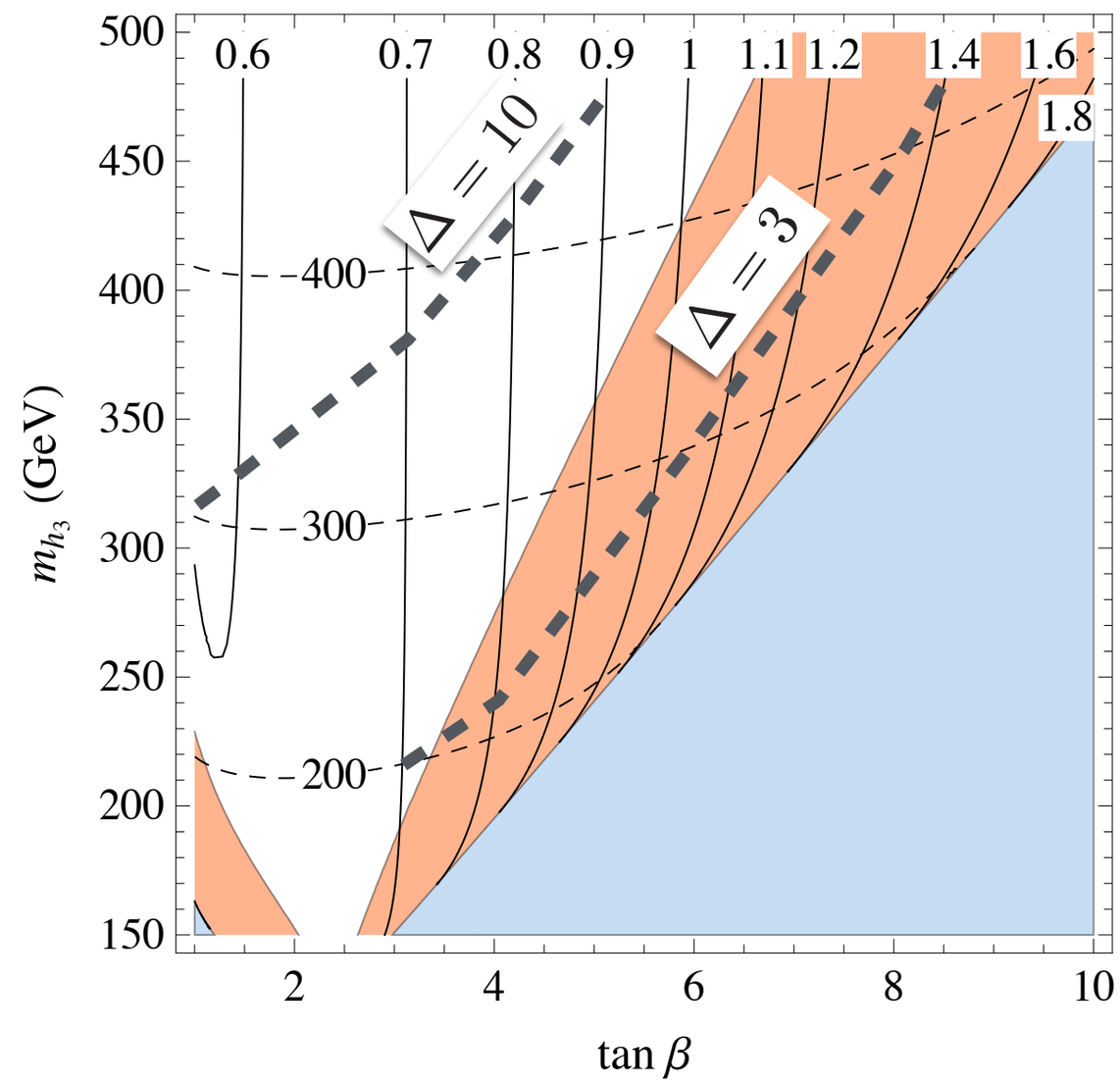
The EW Plus Higgs Sector

Higgs couplings probe many Natural scenarios, among which **SUSY** and **Composite Higgs**

MSSM: not that interesting



NMSSM: better



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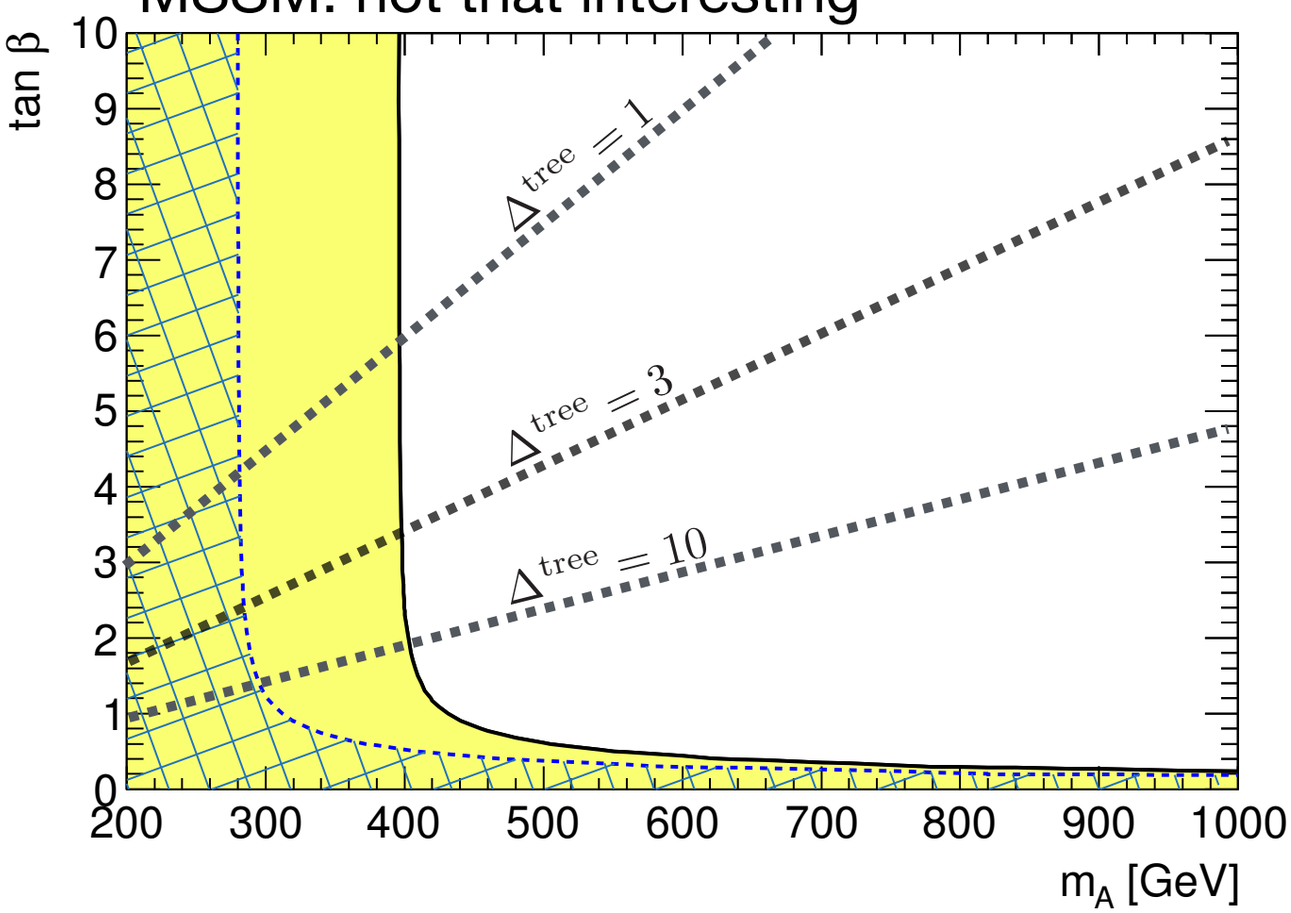
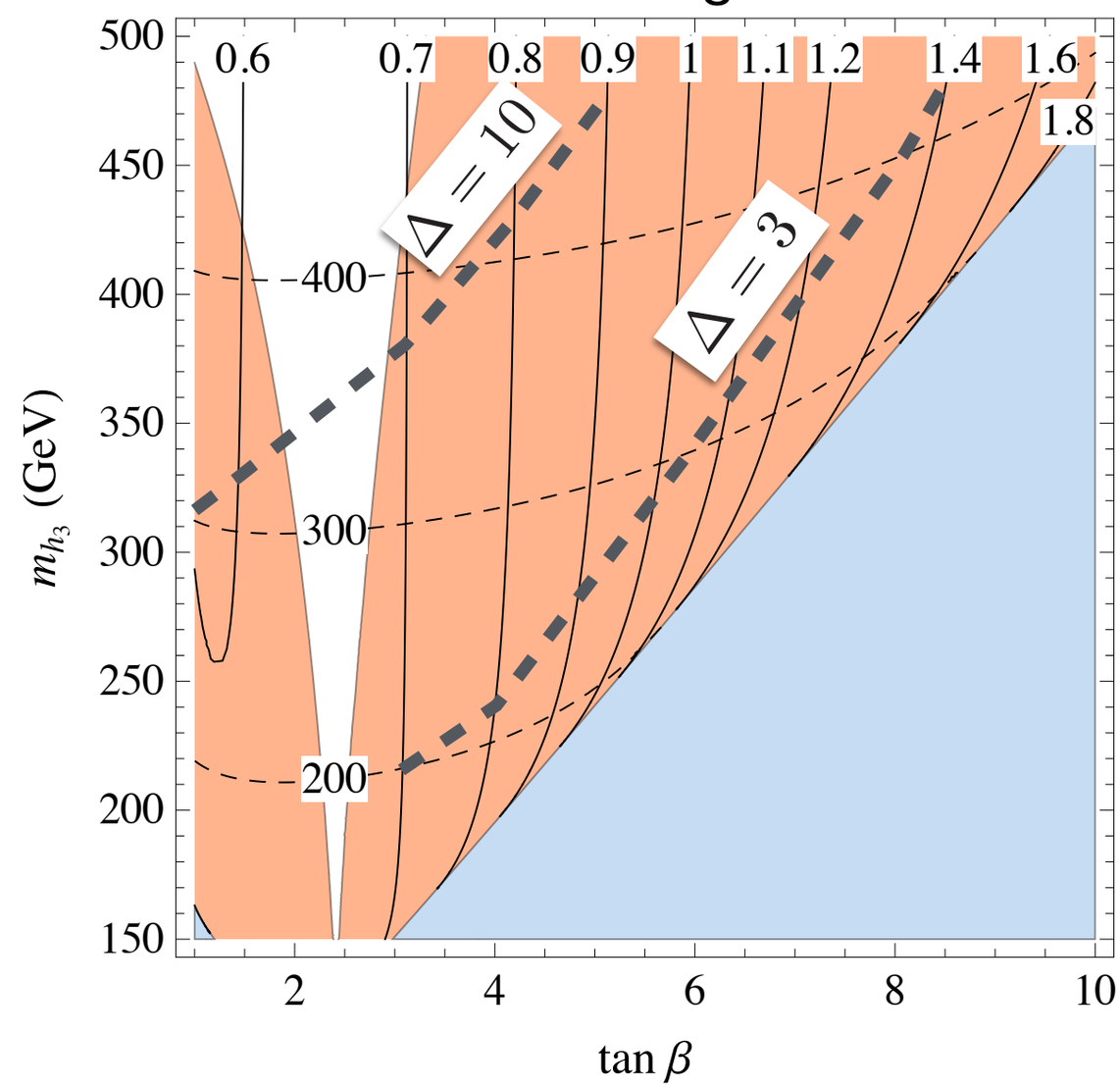


NMSSM: better. Progress @HL-LHC



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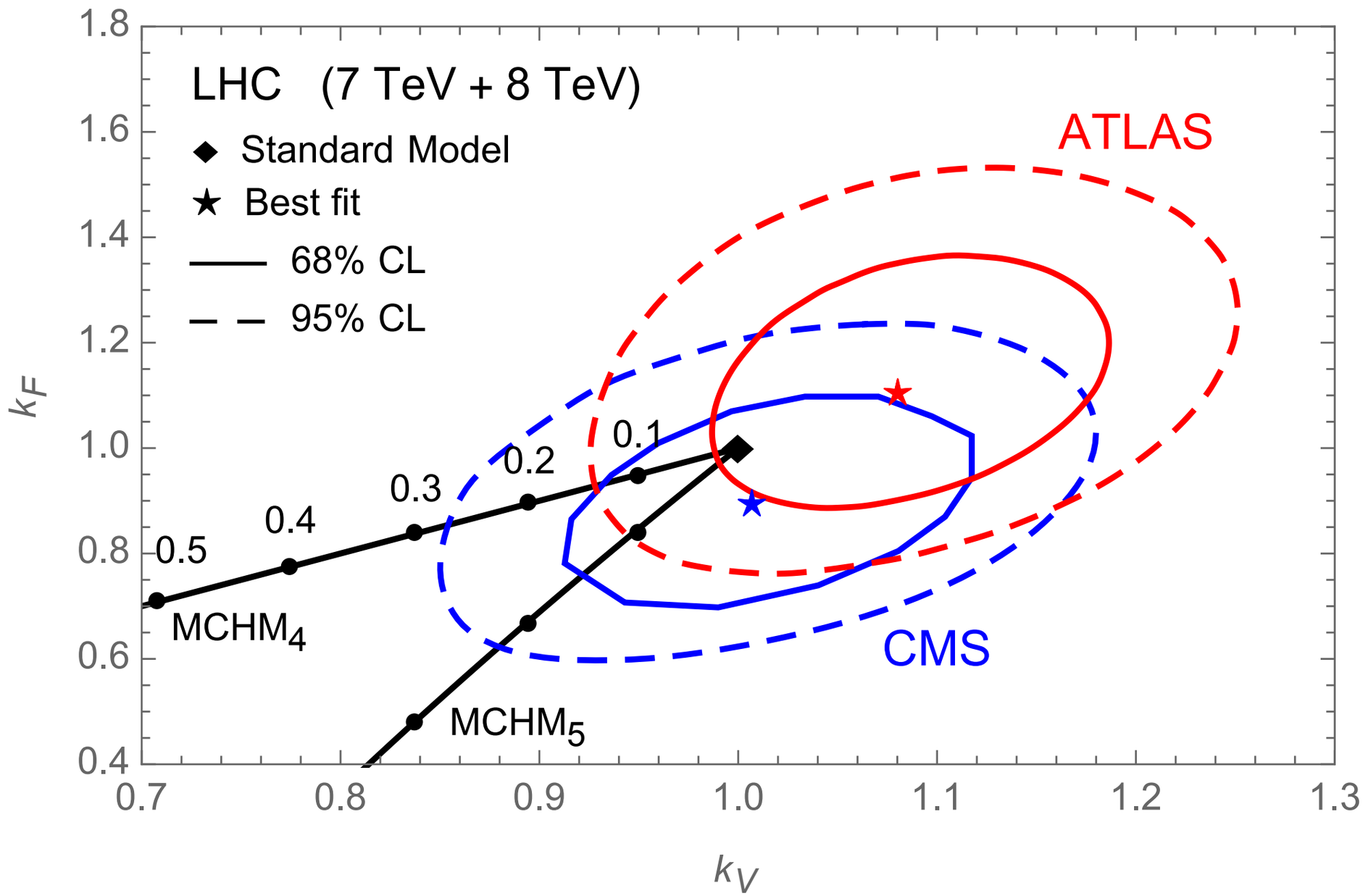

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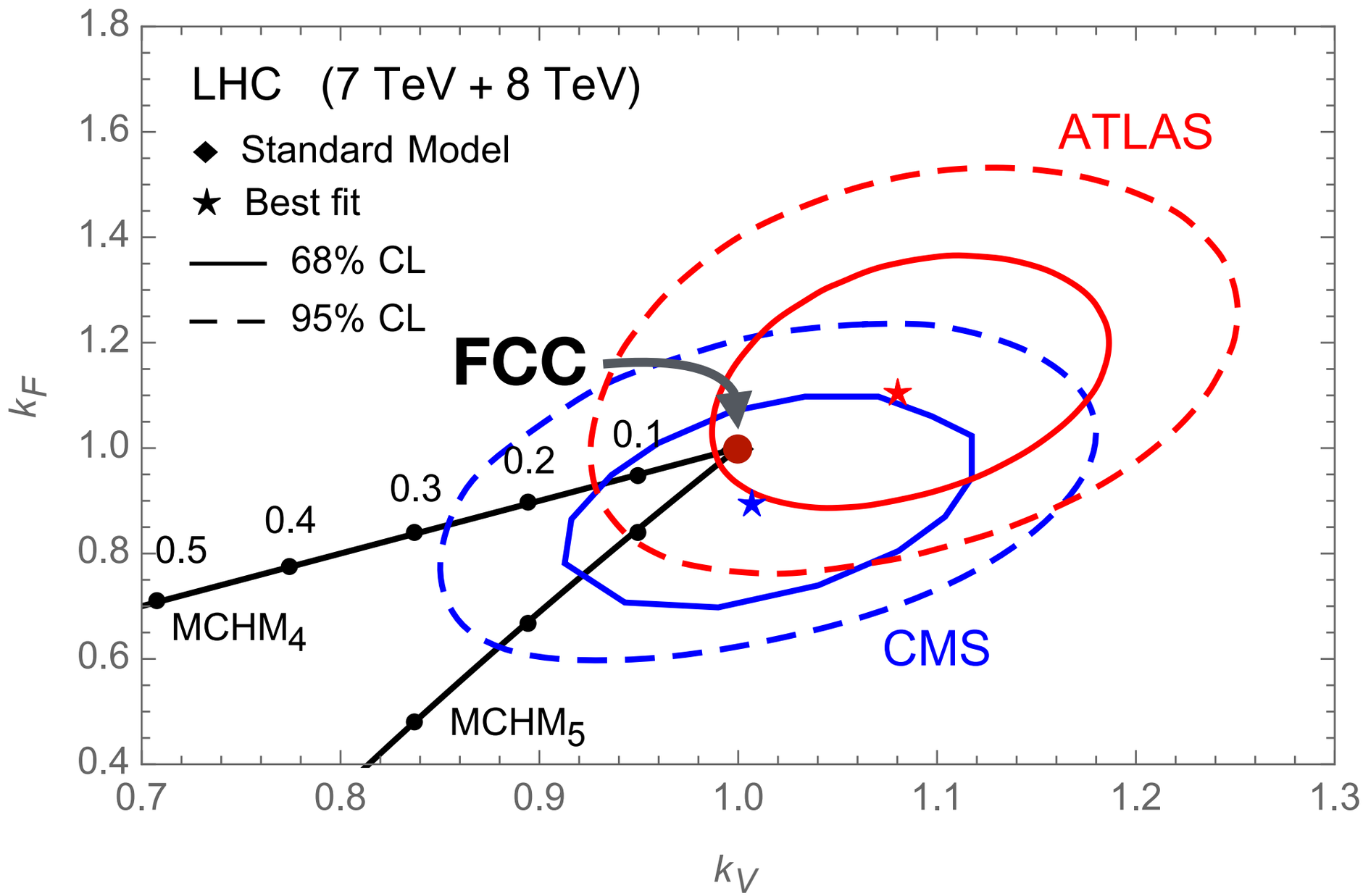

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Physics modifying couplings also affects other EW obs.

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SM EFT for **complete exploration** of EW+EWSB sector

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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**

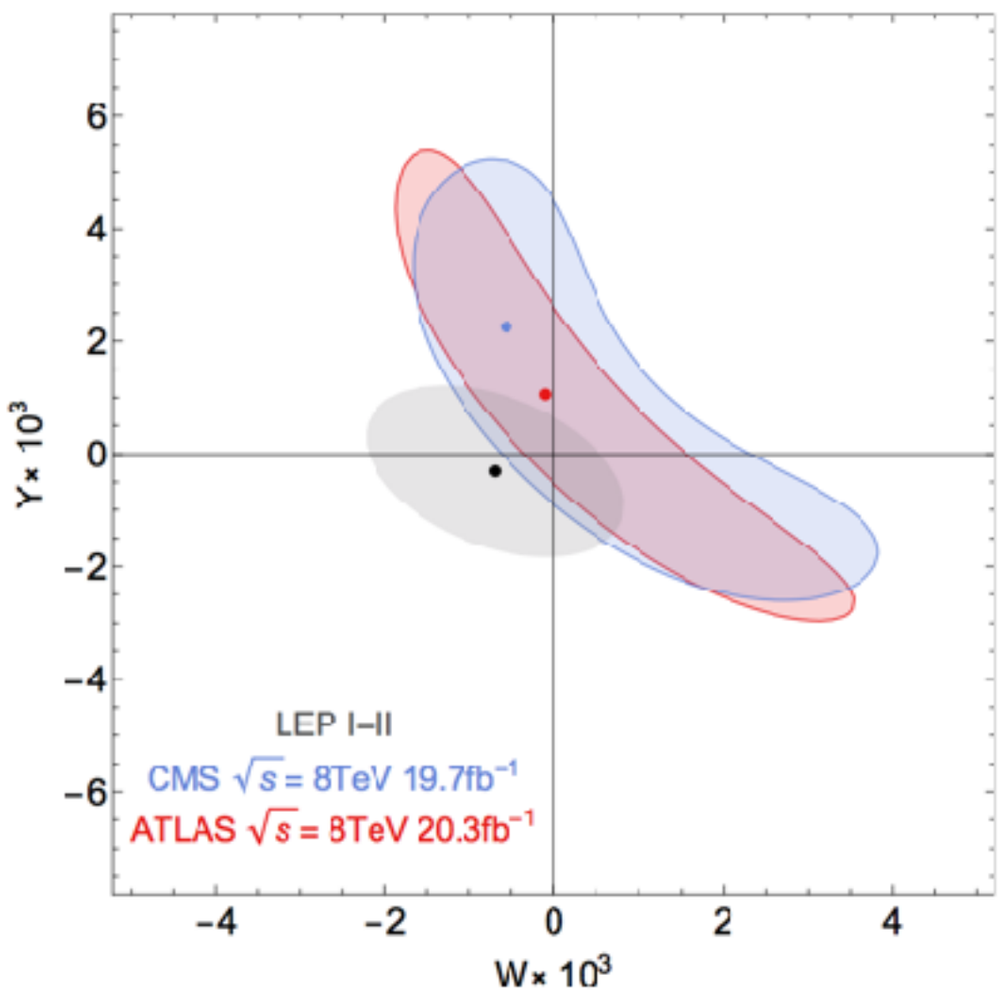
L.E. and H.E. FCC stages offer **complementary** probes!

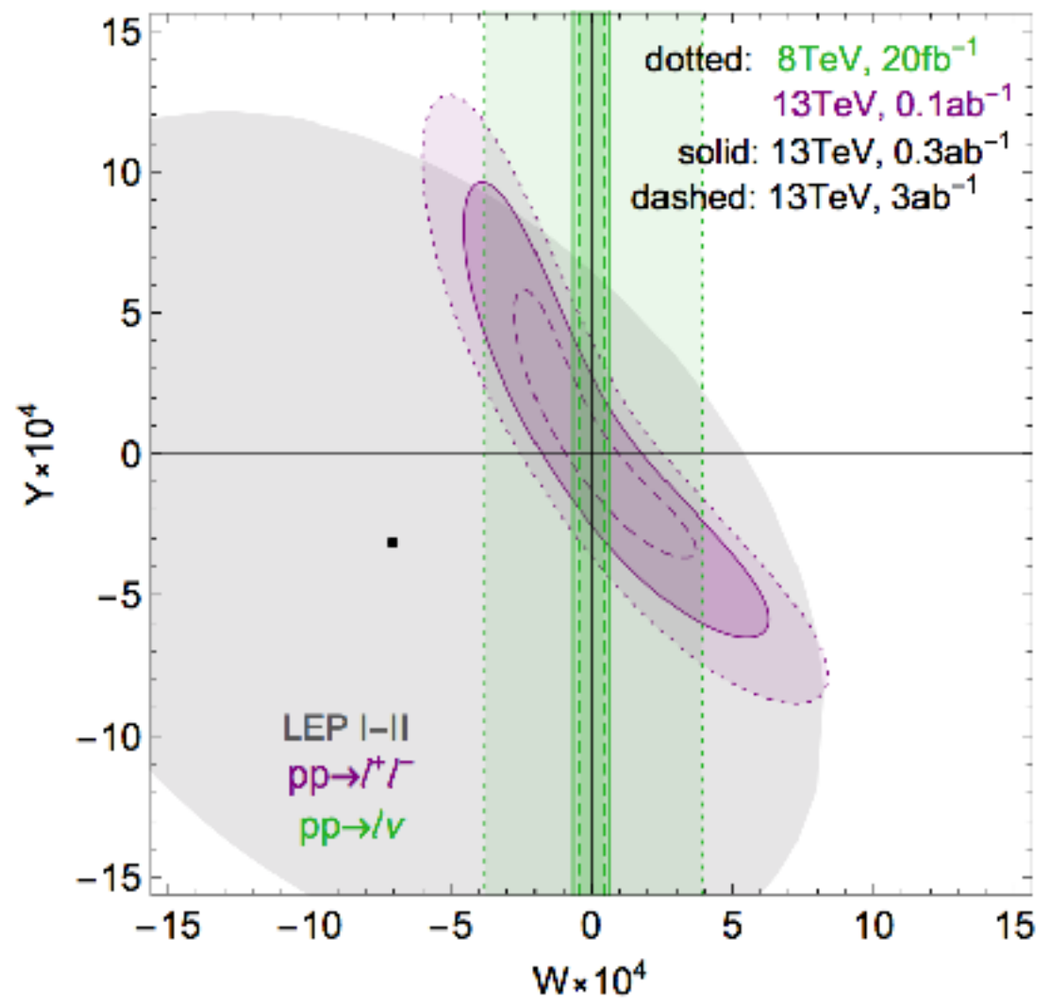
The EW Plus Higgs Sector

Enhanced indirect NP effects in high mass tails

No need of extreme accuracy for indirect NP probe

EWPT @ hadron colliders: (W and Y oblique par.s) [arXiv:1609.08157]





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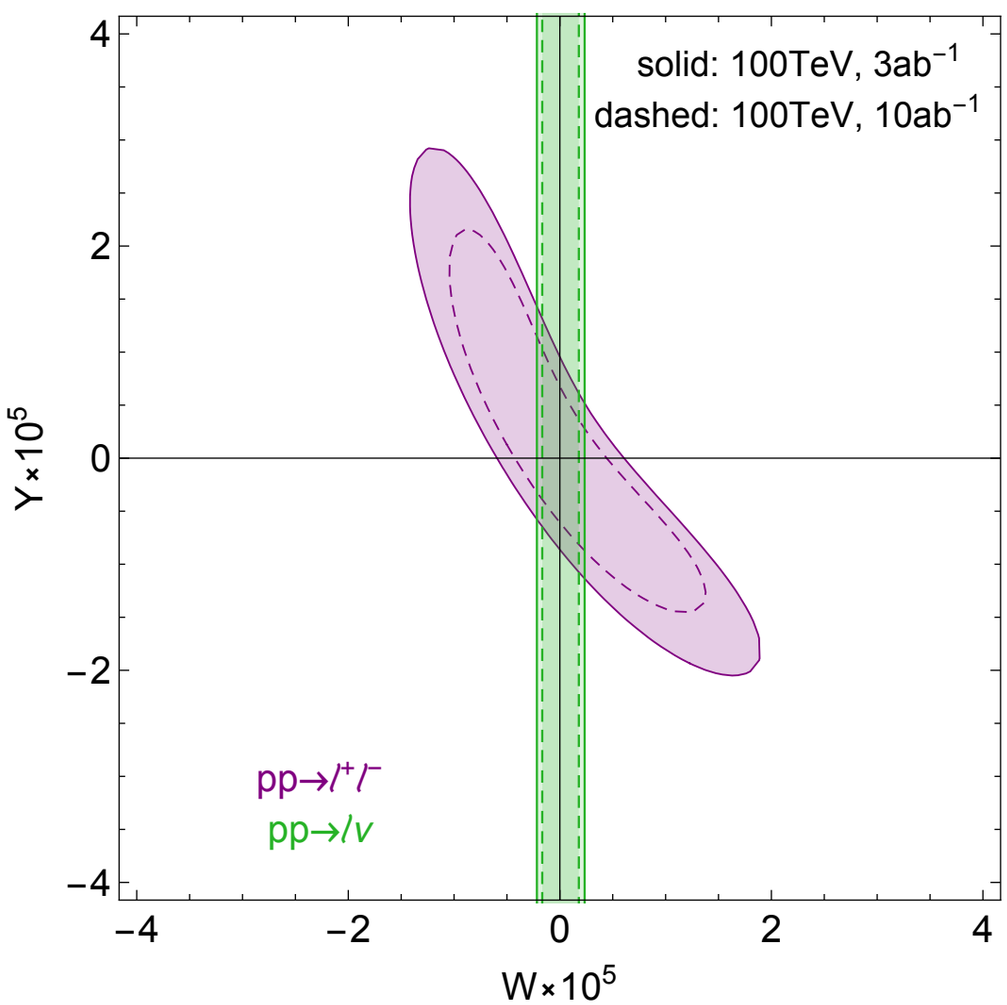

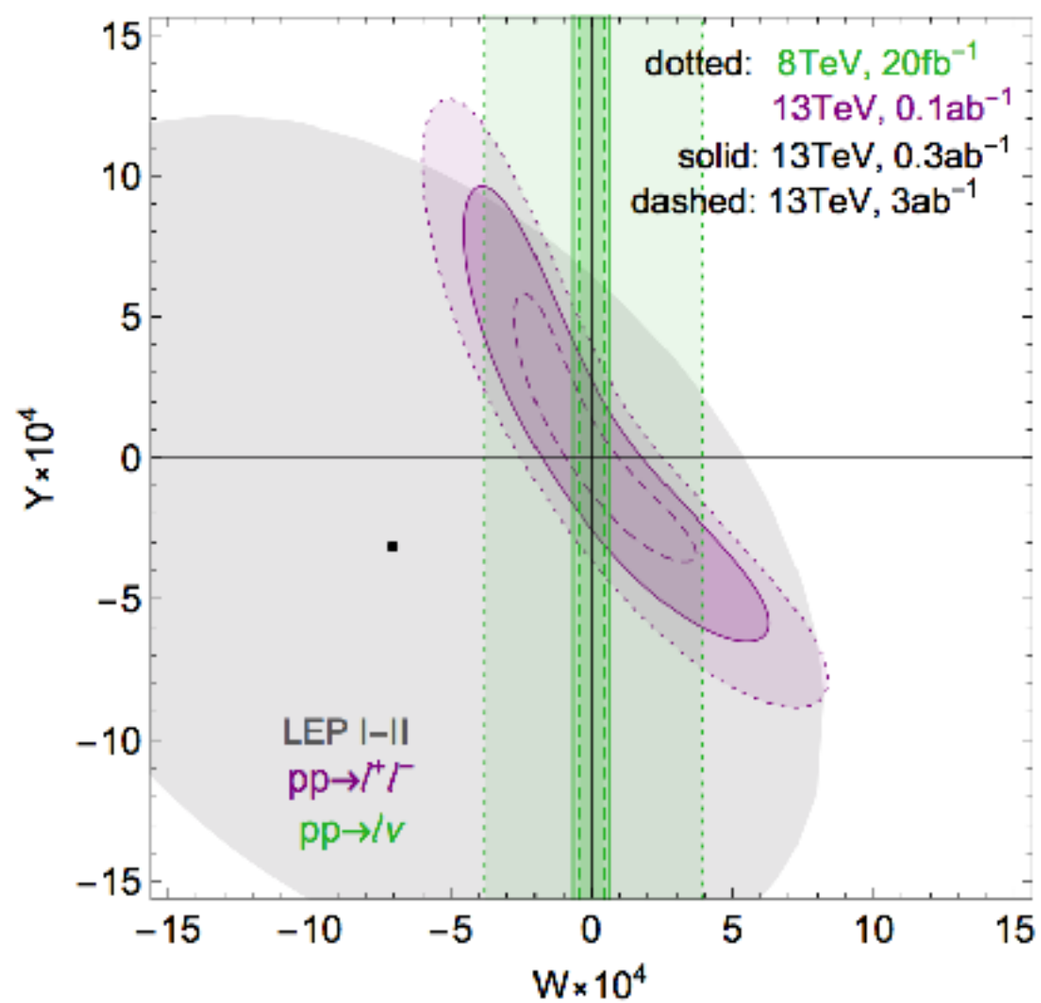

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Only CLIC@3TeV can be competitive:

		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2 \times 10^7\ Z$	$19.7\,\mathrm{fb}^{-1}$	$20.3\,\mathrm{fb}^{-1}$	$0.3\,\mathrm{ab}^{-1}$	$3\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$10^9\ Z$	$10^{12}\ Z$	$3\,\mathrm{ab}^{-1}$
NC	$\mathrm{W}\times10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	±1.5	±0.8	±0.04	±3	±0.7	±0.3
	$\mathrm{Y}\times10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	±2.3	±1.2	±0.06	±4	±1	±0.2
CC	$\mathrm{W}\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—	—	—

waiting for updates from global fit by J. de Blas

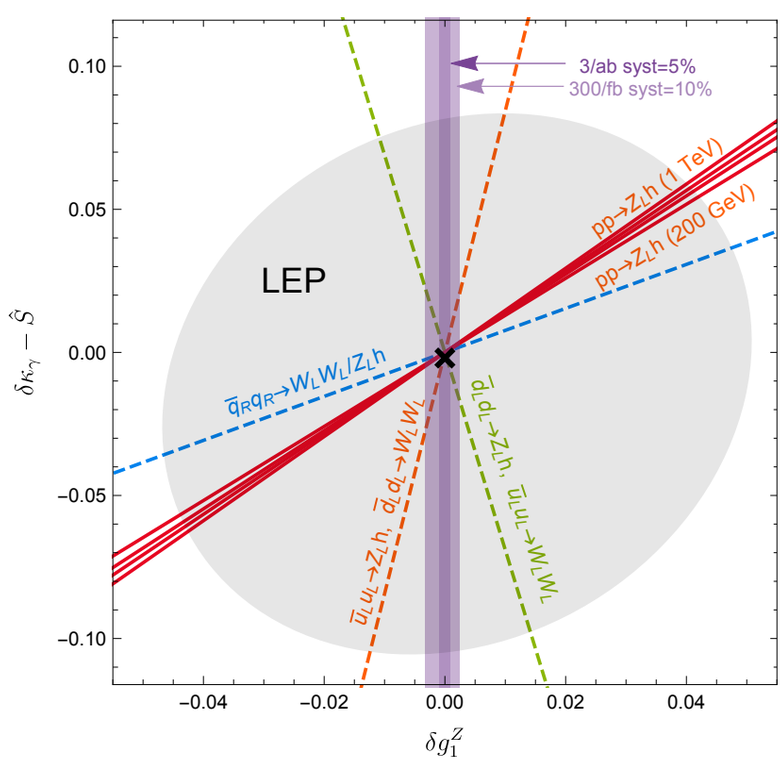
The EW Plus Higgs Sector

Enhanced indirect NP effects in high mass tails

No need of extreme accuracy for indirect NP probe

- EWPT @ hadron colliders: (W and Y oblique par.s) [arXiv:1609.08157]
- Other example is top couplings from HE ttW/ttZ [arXiv:1511.03674]
- Similar conclusions for Diboson production [arXiv:1712.01310]

LHC vs LEP (Univ. Th.)



F.C.

HL-LHC: $a_q^{(3)} \sim \pm 5 \times 10^{-2}\mathrm{TeV}^{-2}$

CLIC: $a \sim \pm 3 \times 10^{-3}\mathrm{TeV}^{-2}$

HE-LHC: $a_q^{(3)} \sim \pm 2 \times 10^{-2}\mathrm{TeV}^{-2}$

FCC-pp: $a_q^{(3)} \sim \pm 6 \times 10^{-3}\mathrm{TeV}^{-2}$

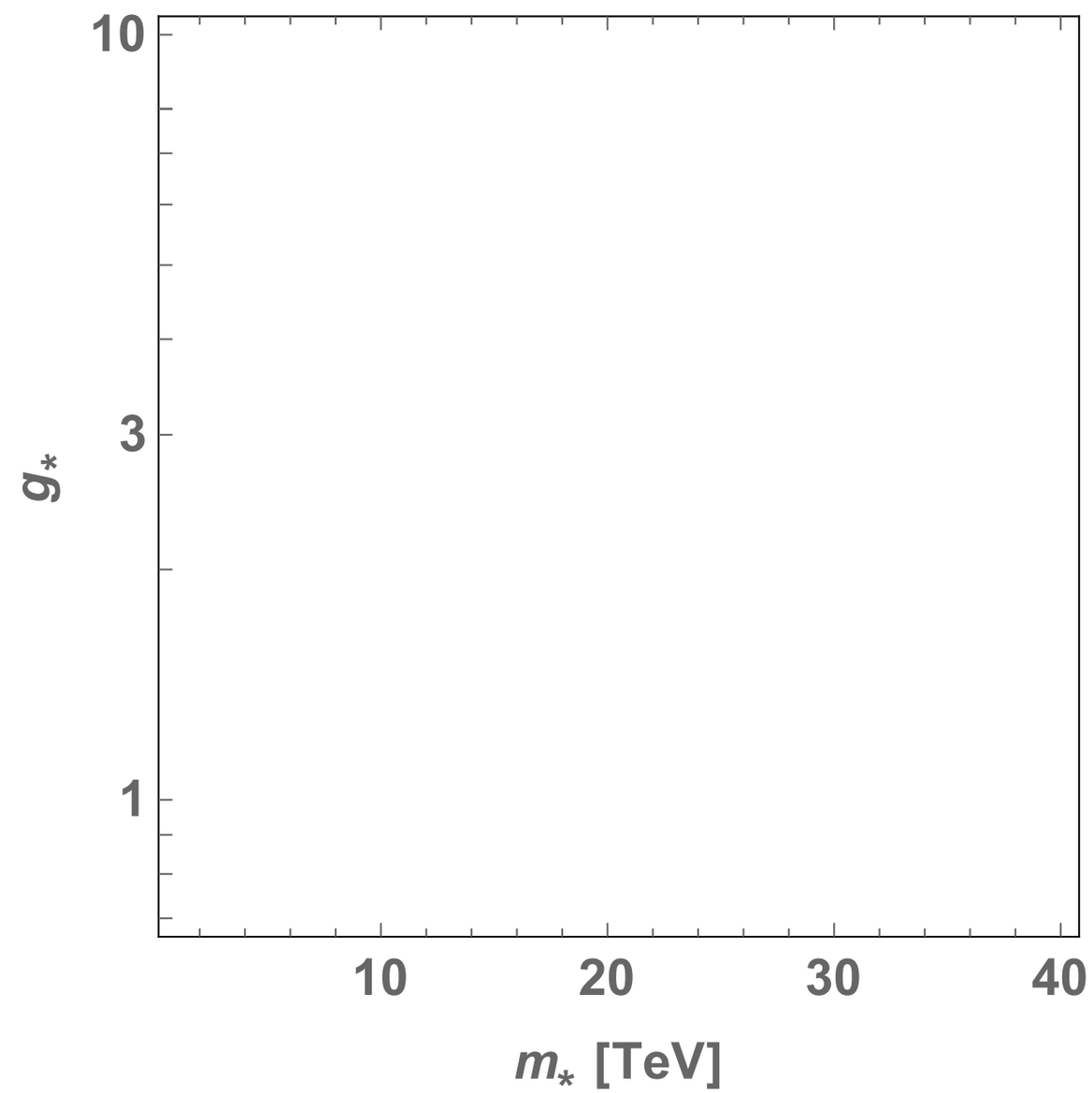
FCC-ee: $a \sim 6 \times 10^{-2}\mathrm{TeV}^{-2}$

[aTGC @ ‰]

A Rough Summary

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}_{\rm BSM}^{d=6} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$



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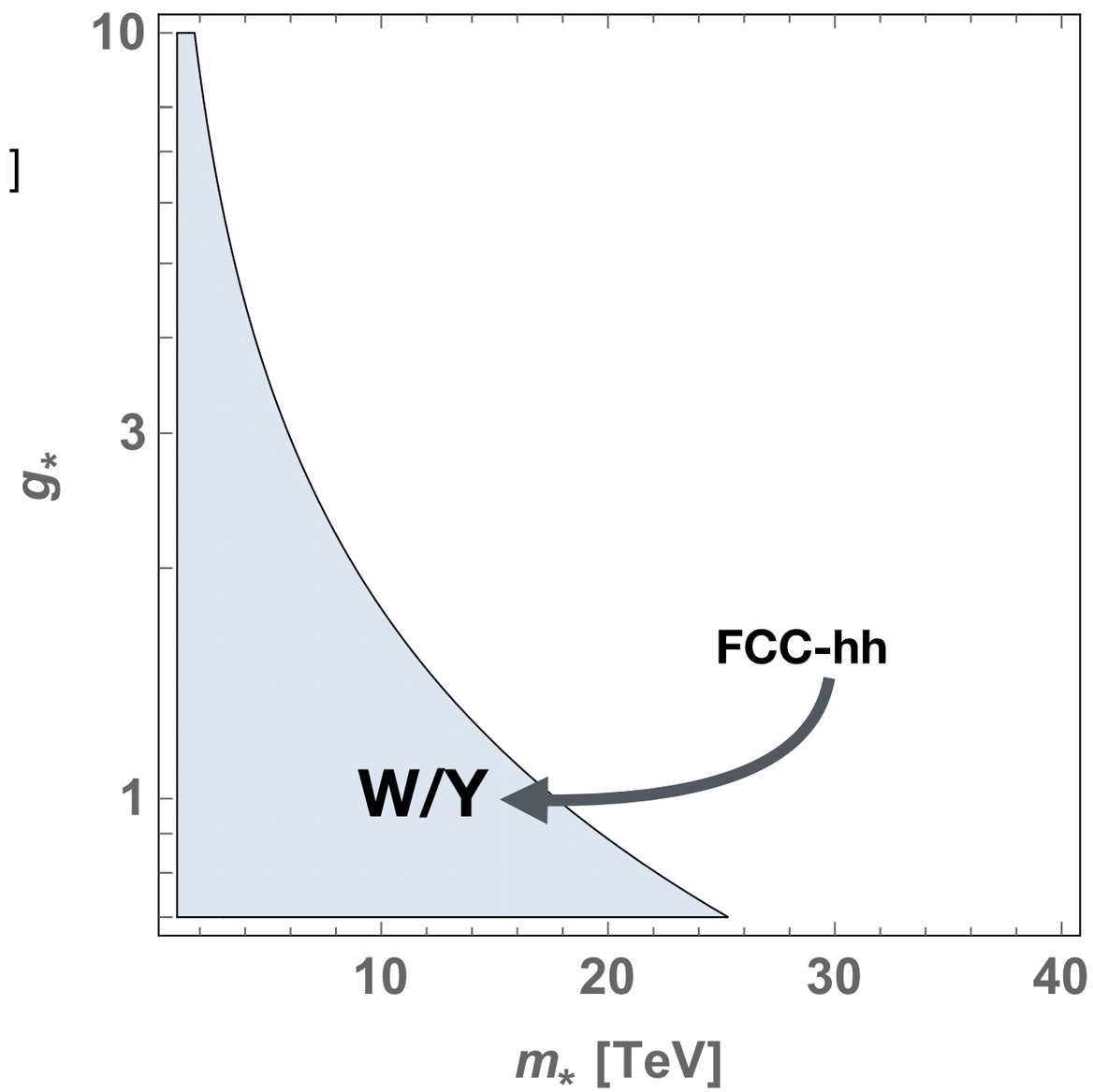
W/Y: (high energy probe) [HL-LHC $< 10^{-4}$]

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \quad \Rightarrow \quad W = \frac{g_W^2 m_W^2}{g_*^2 m_*^2} < 10^{-5}$$



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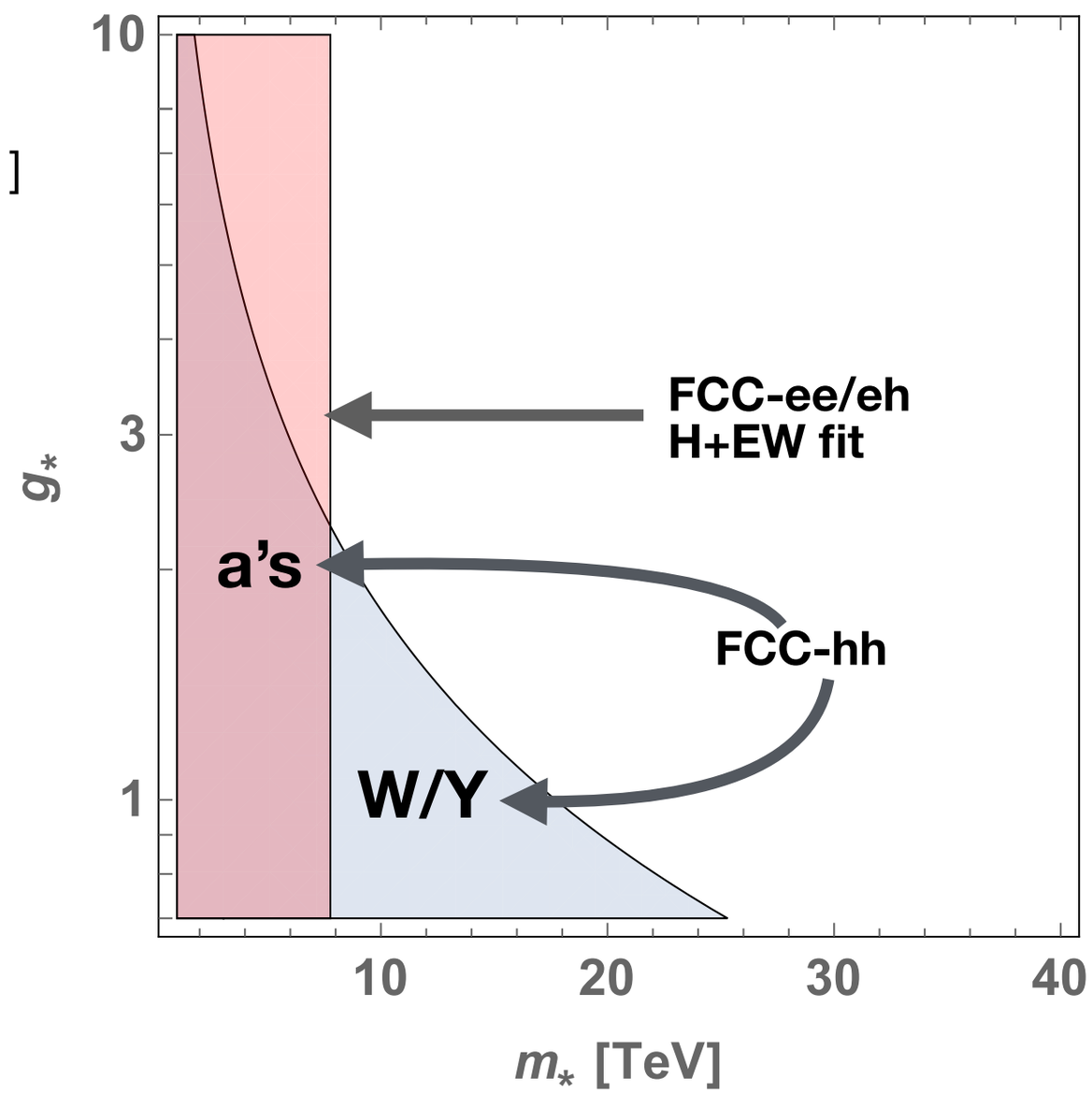

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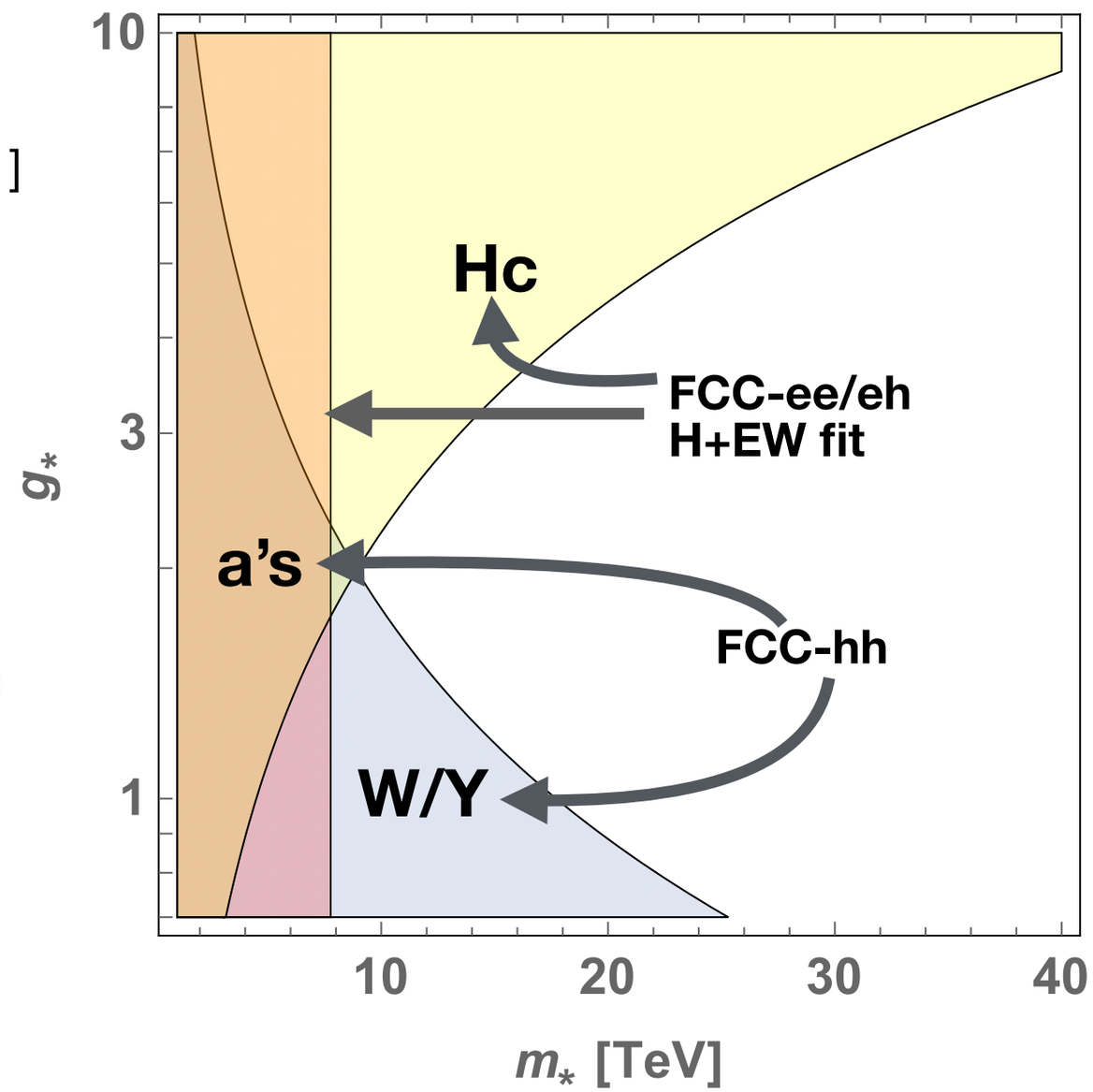
Higgs Couplings: (low energy probe)

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



Conclusions

- Naturalness or Un-Naturalness

  Conclusive FCC results

  Direct (hh) and Indirect (ee/he) complementary

- Probing the EW plus Higgs Sector

  Energy/Accuracy interplay (high q^2 measurements)

  Valuable high energy probes at FCC-hh (high q^2 measurements)

  FCC “package” robustly tests 10 TeV scale

Conclusions

- Naturalness or Un-Naturalness
  Conclusive FCC results
  Direct (hh) and Indirect (ee/he) complementary

- Probing the EW plus Higgs Sector
  Energy/Accuracy interplay (high q^2 measurements)
  Valuable high energy probes at FCC-hh (high q^2 measurements)
  FCC “package” robustly tests 10 TeV scale

- Broadband Exploration
  Next talk