SUSY and Electroweak Precision Tests at Tera-Z Colliders

Kevin Langhoff

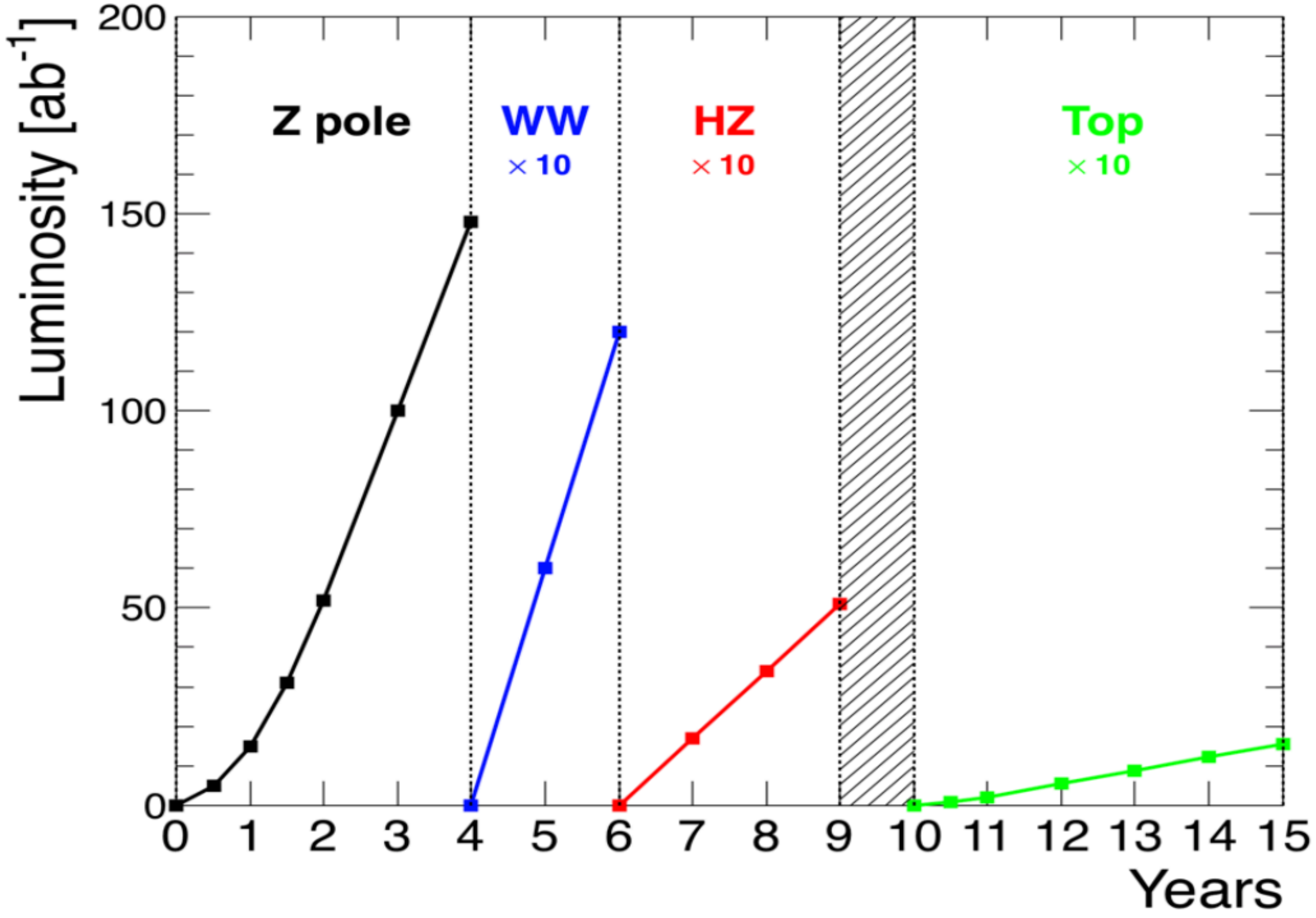
(Work in progress with Simon Knapen and Zoltan Ligeti)

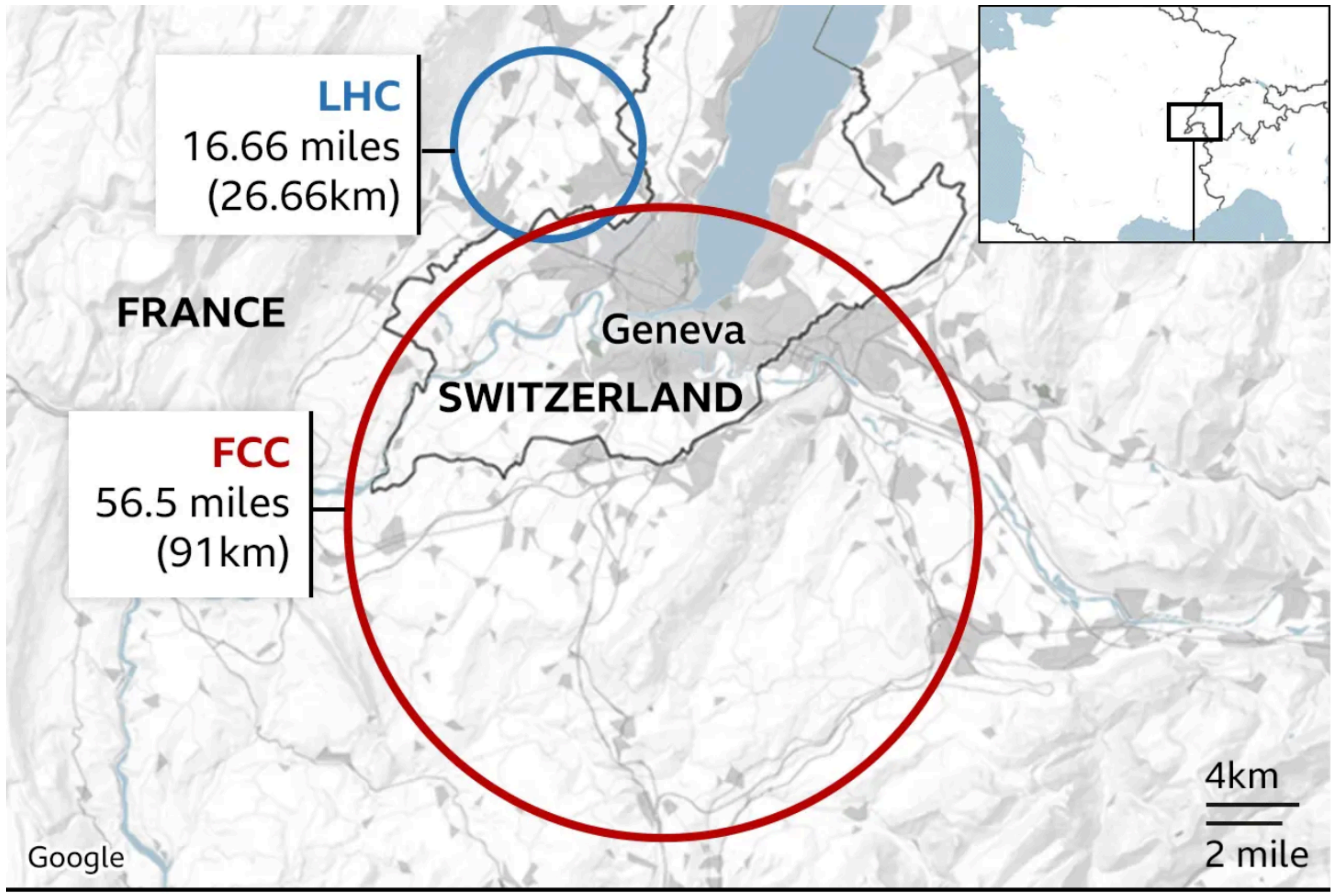
DPF Pheno (May 17th, 2024)

Berkeley UNIVERSITY OF CALIFORNIA BERKELEY LAB

Looking to the Future

[FCC CDR Vol. 2]





[Figure from BBC]

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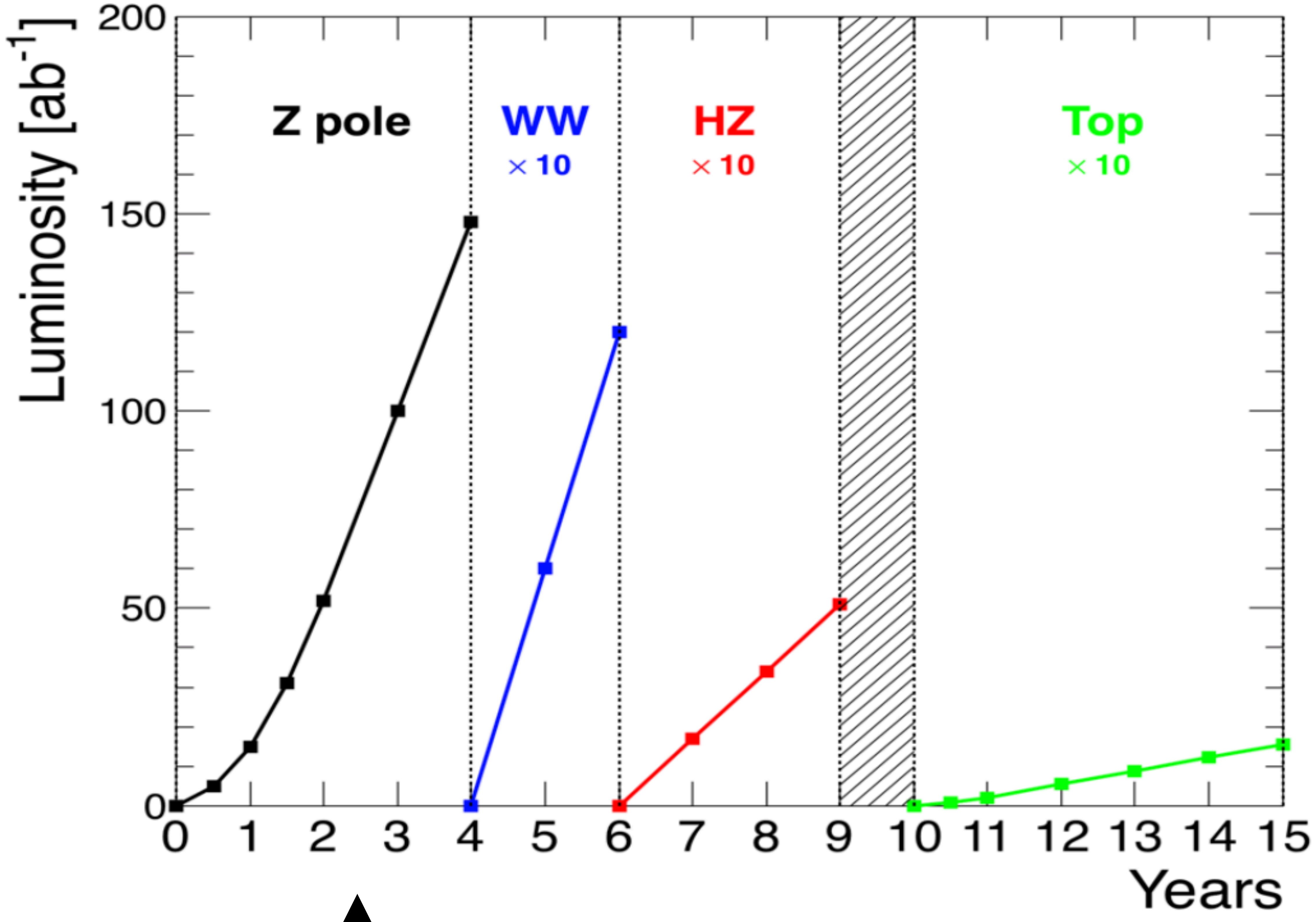
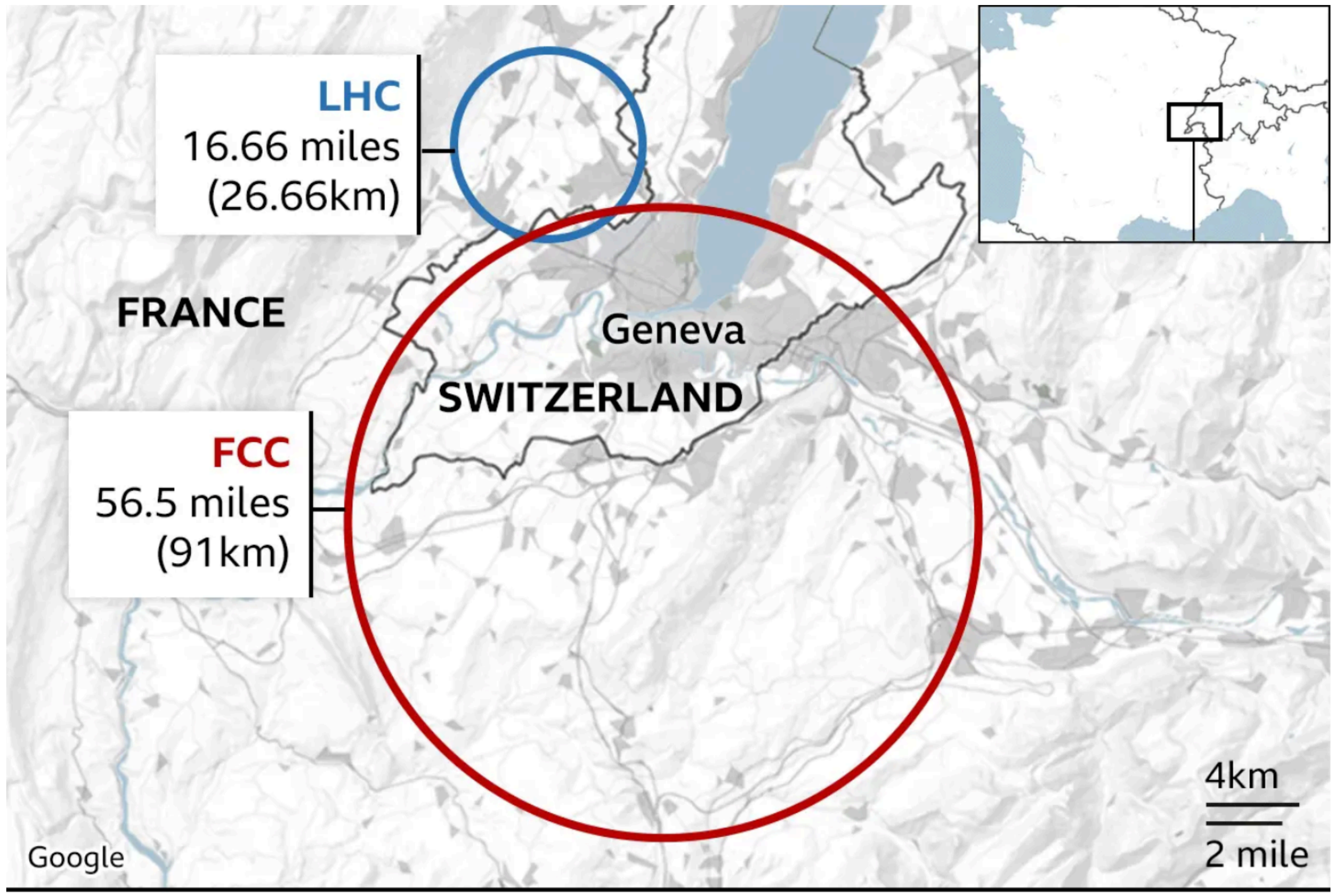


Will produce roughly 5×10^{12} Z-bosons!
(Roughly 10^5 times that produced at LEP)



[Figure from BBC]

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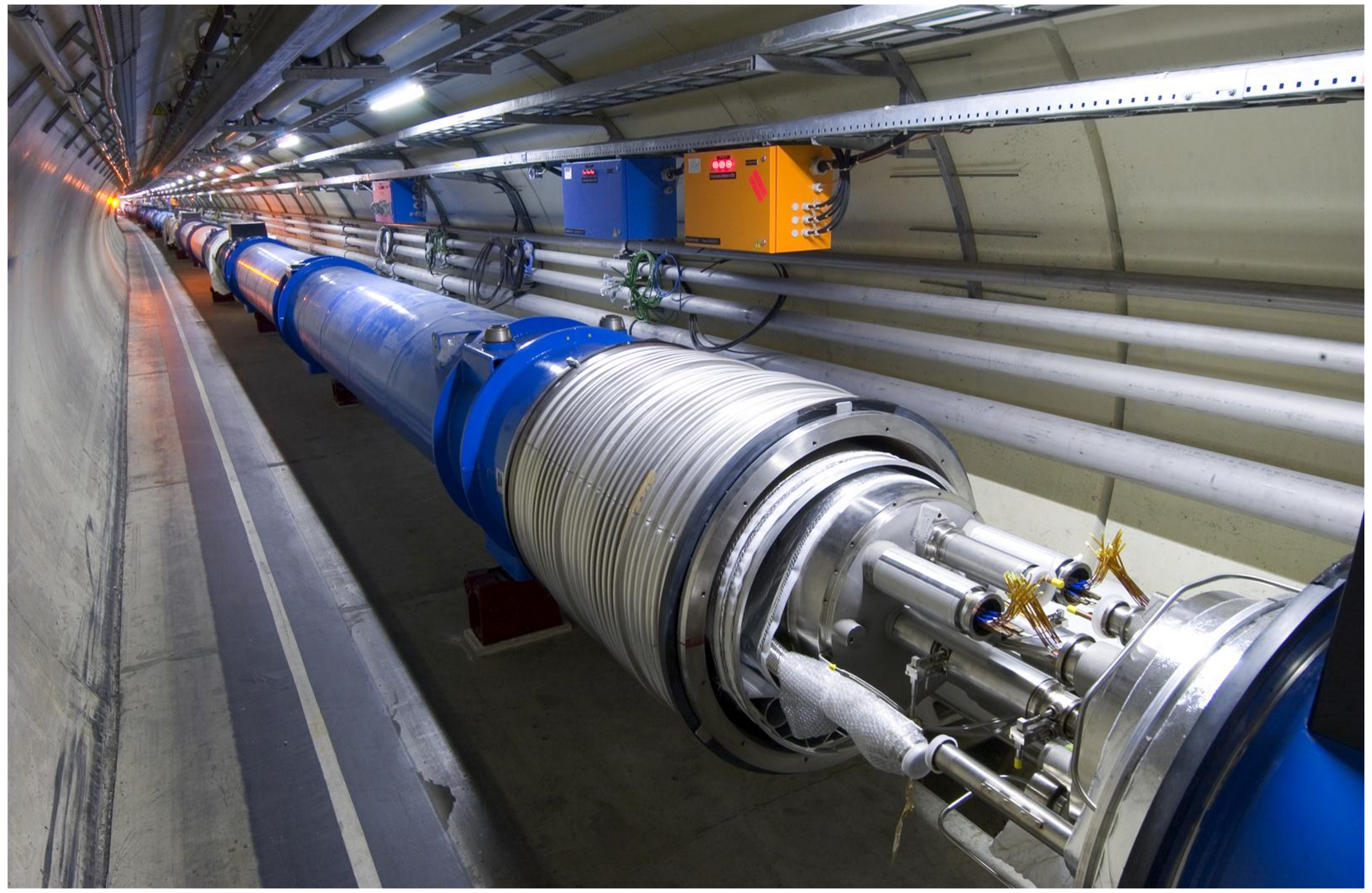
LHC?



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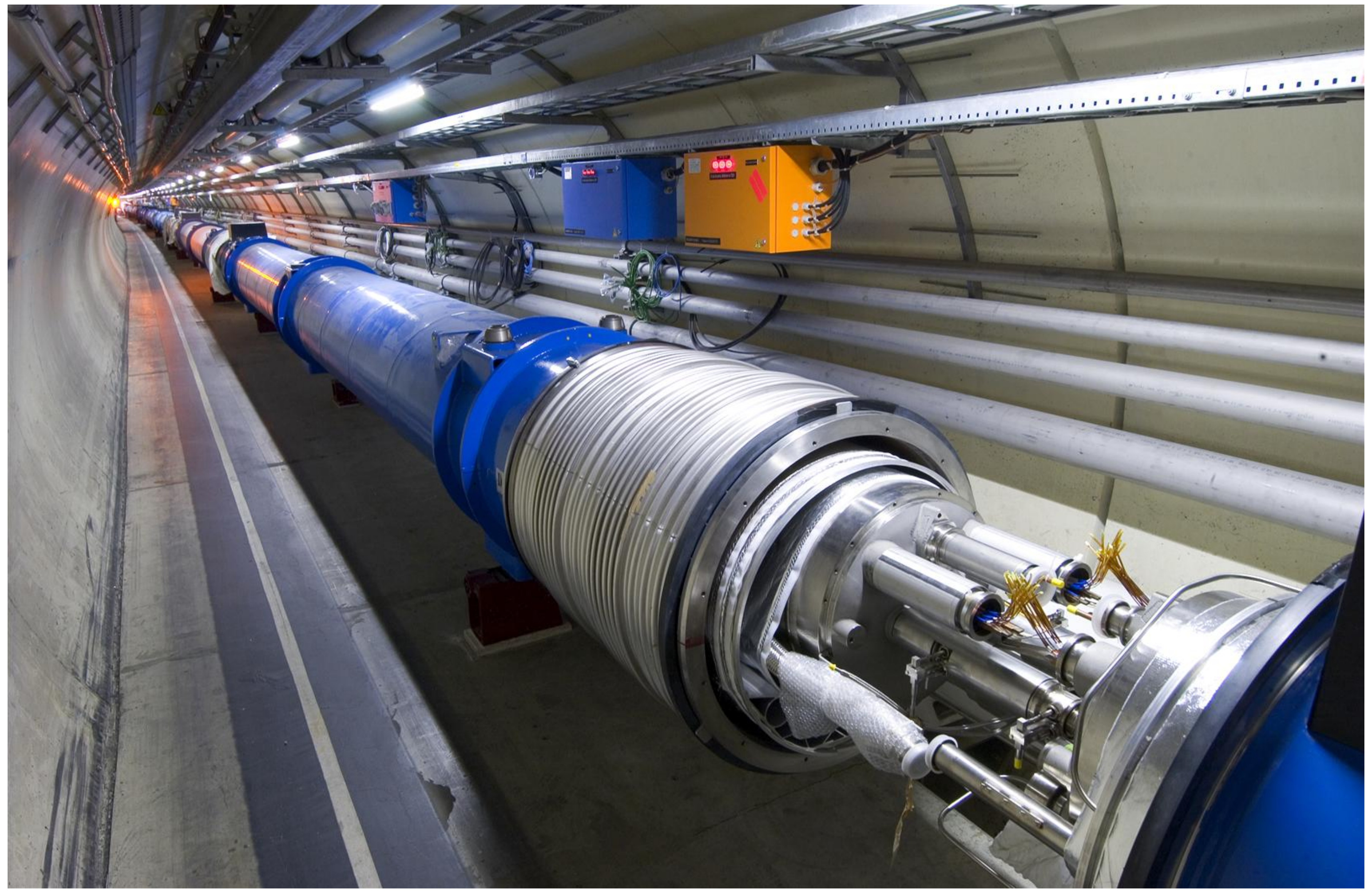
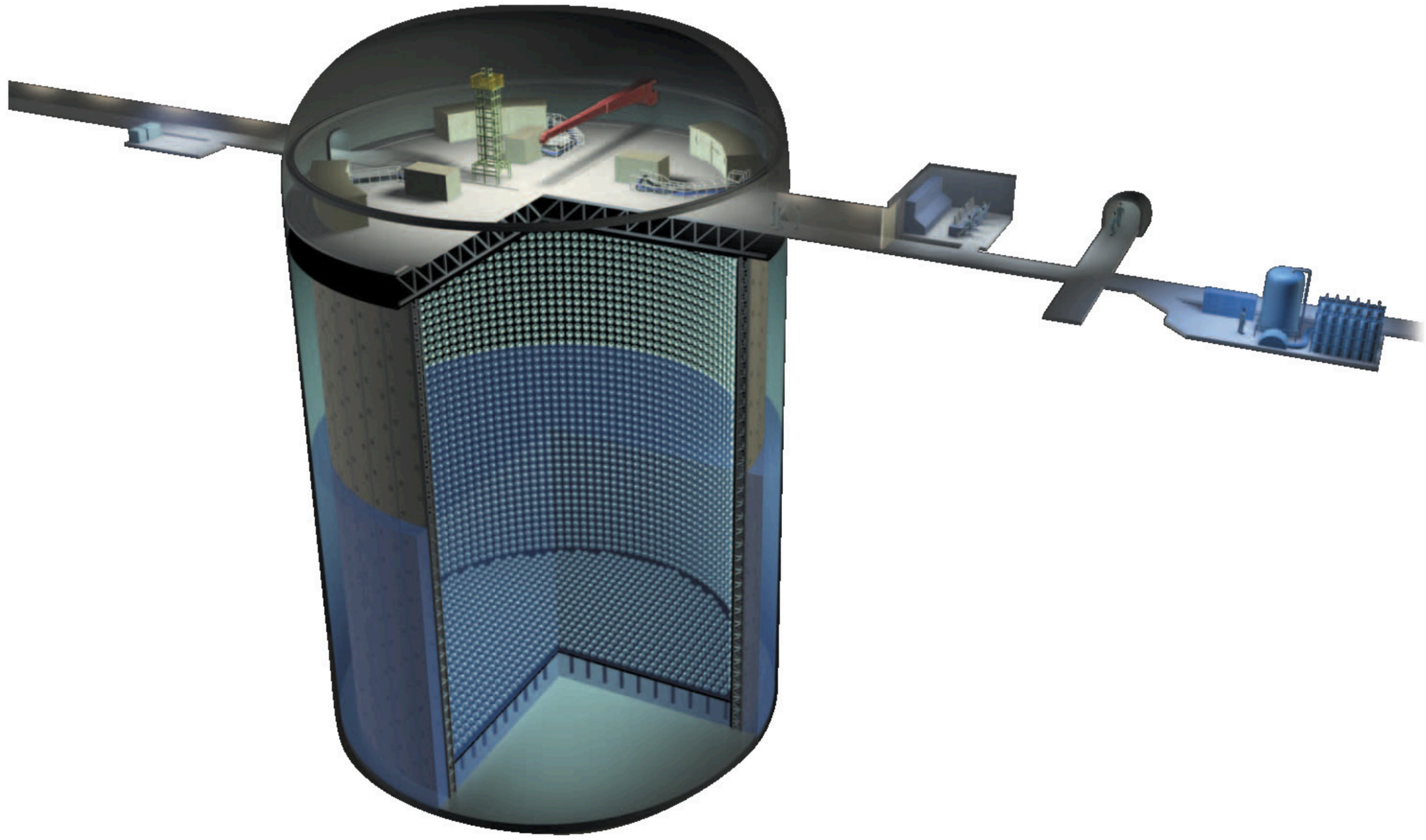


Super-Kamiokande



Directly explores energy scales $\Lambda \sim 10^3$ GeV.

Using 10^{34} protons, indirectly explores baryon violating Dim-6 operators at scales $\Lambda \sim 10^{16}$ GeV.

How can we use the FCC-ee to search for heavy new physics?

Electroweak Precision Tests (EWPTs)

- SM has many more observables than parameters $\Longrightarrow$ Predictions!

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Observables

1. $G_F = \left(\sqrt{2}v^2\right)^{-1}$
2. $m_W = \frac{1}{2}gv$
3. $m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\;v$
4. $\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$

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(At tree level)

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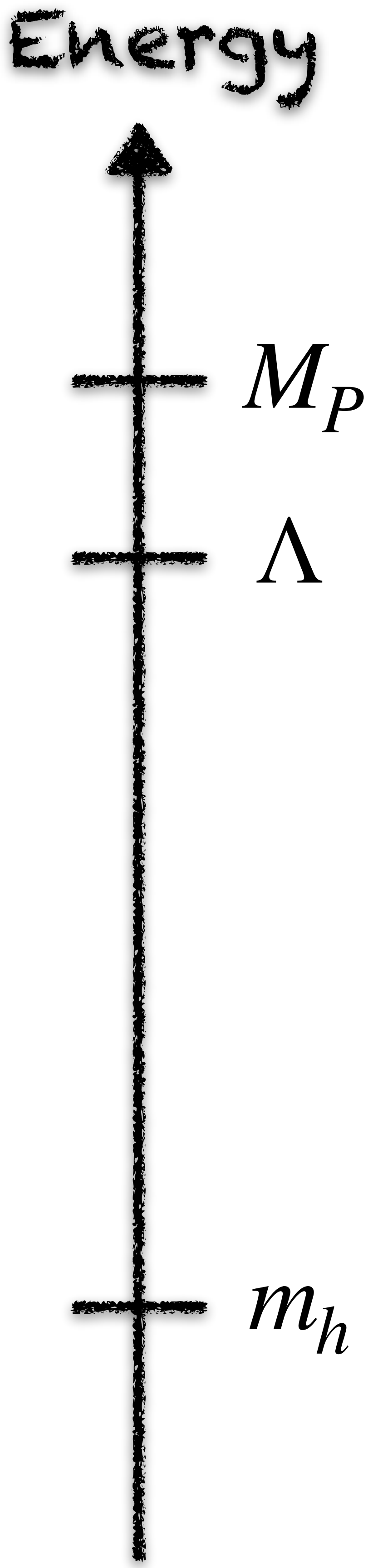
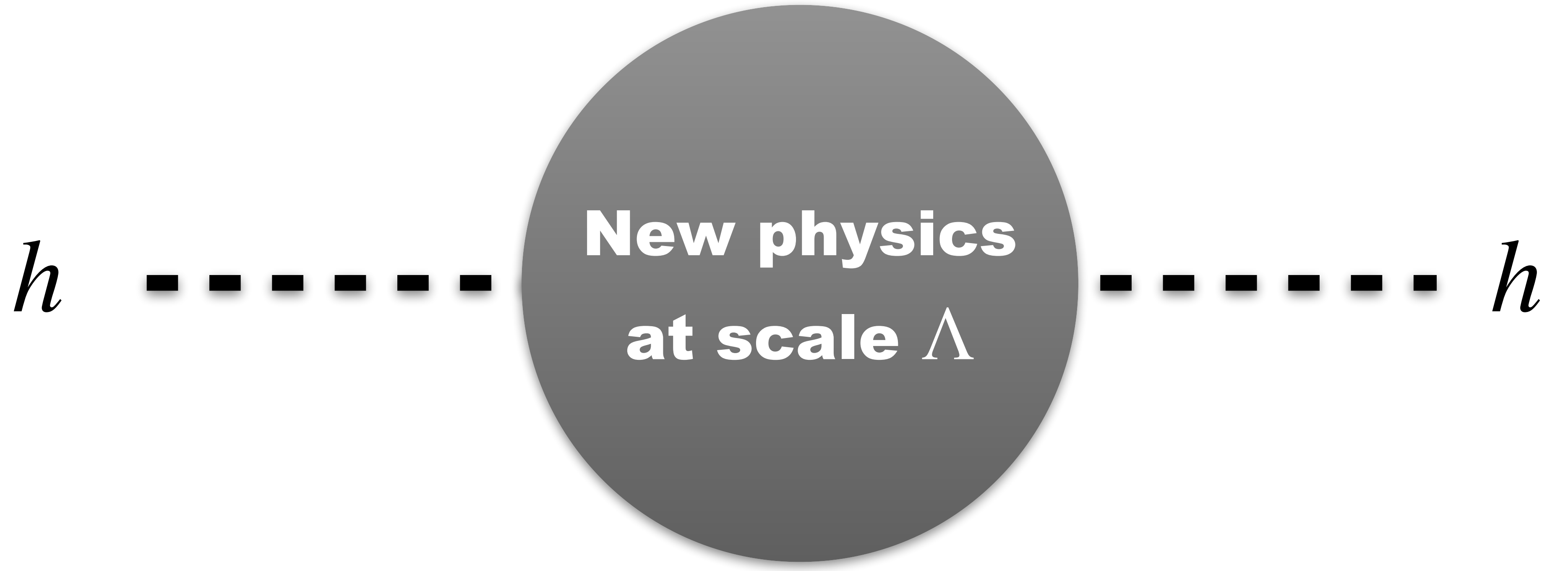
- Checks like this give us a method of indirectly discovering new physics!

What mysteries can we explore using these methods?

The Higgs Hierarchy Problem





$\delta m_h \sim \Lambda$

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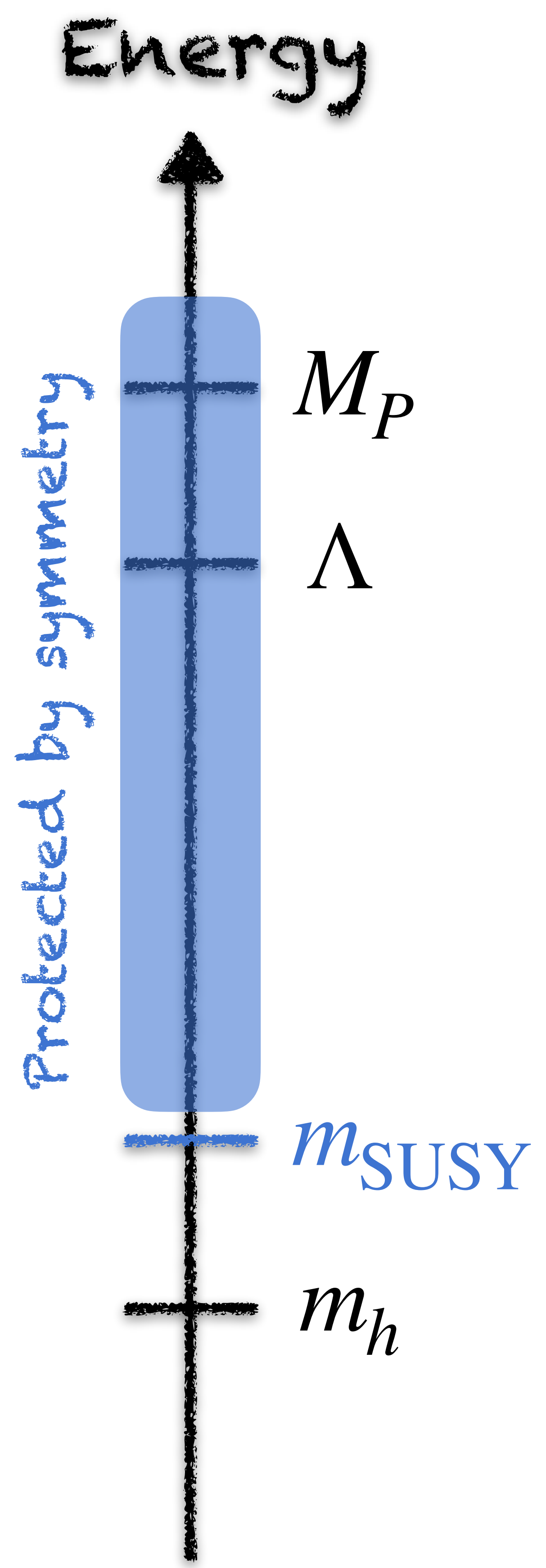

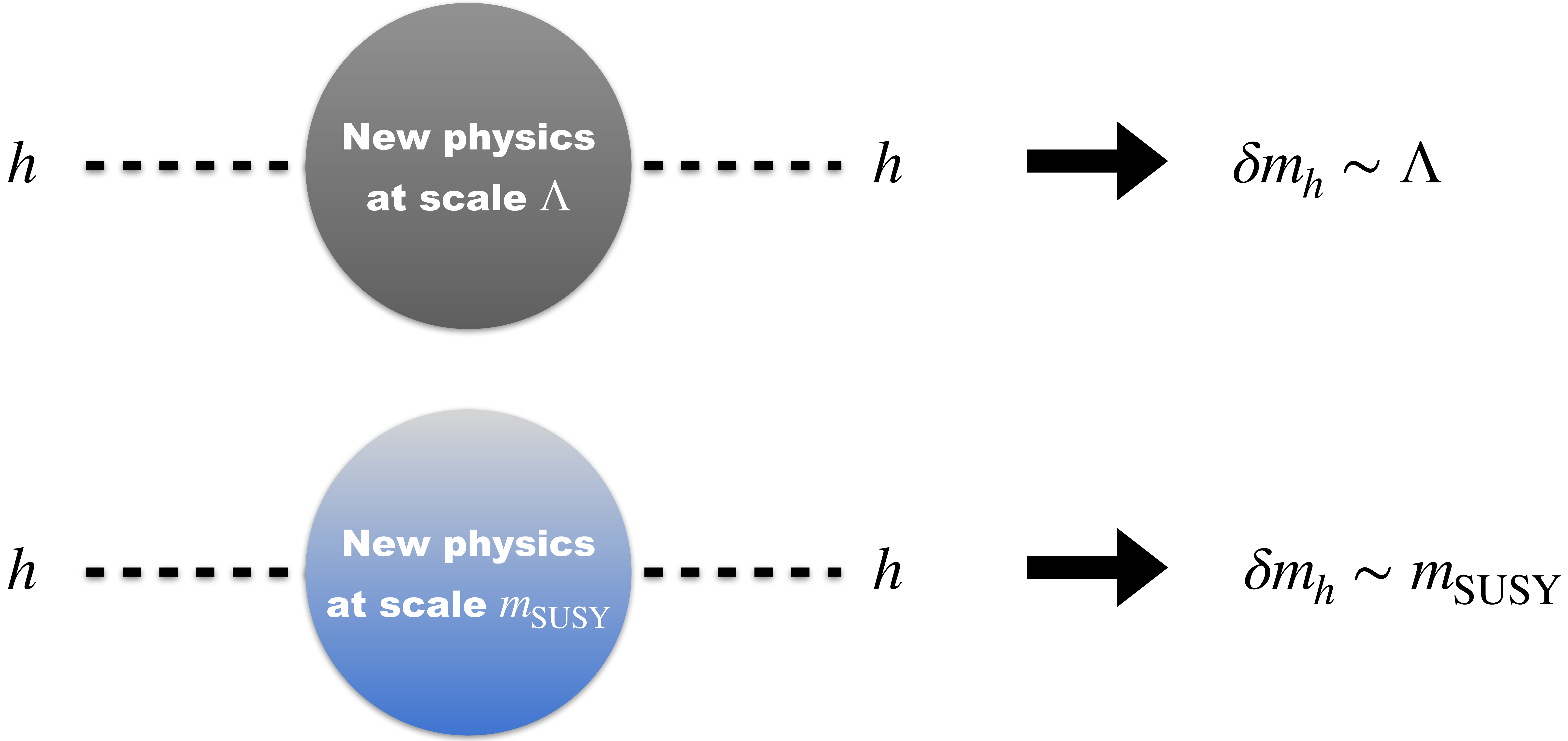

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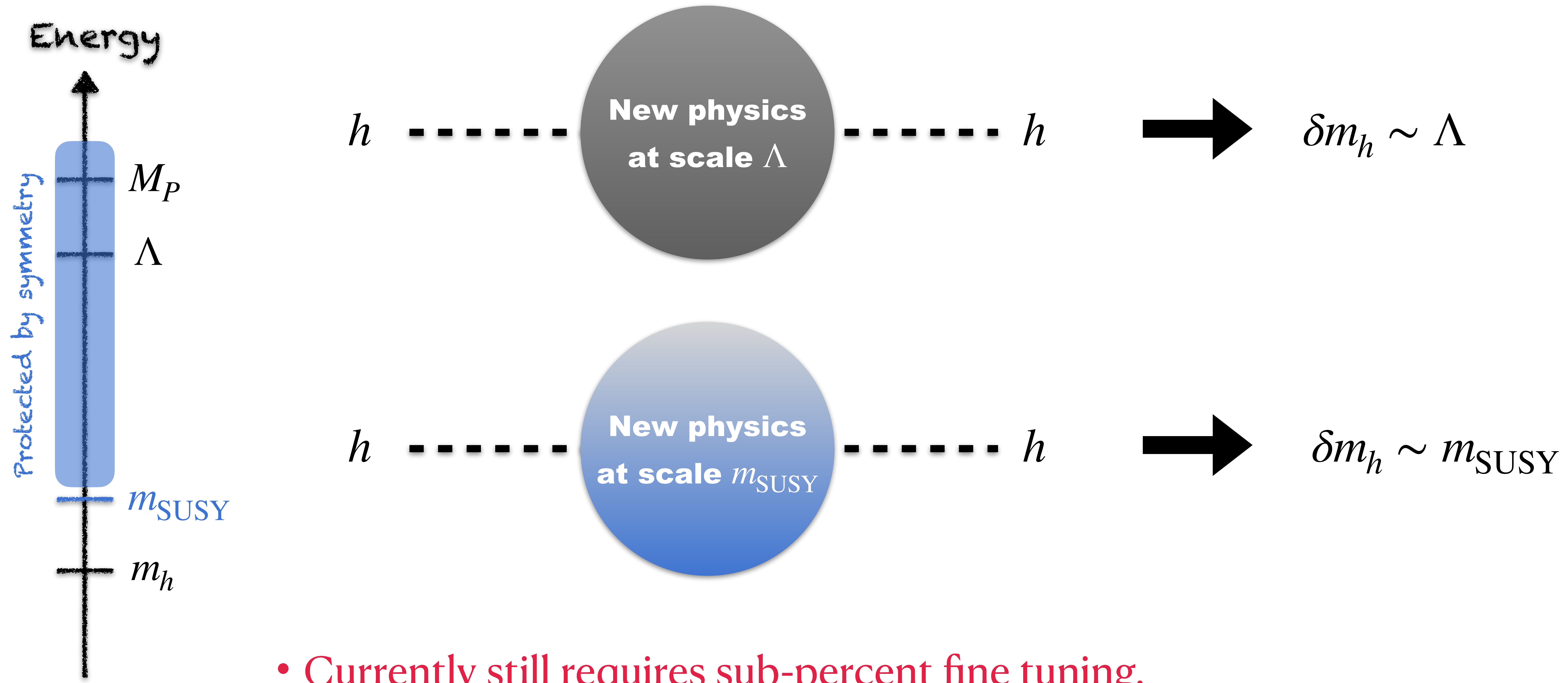
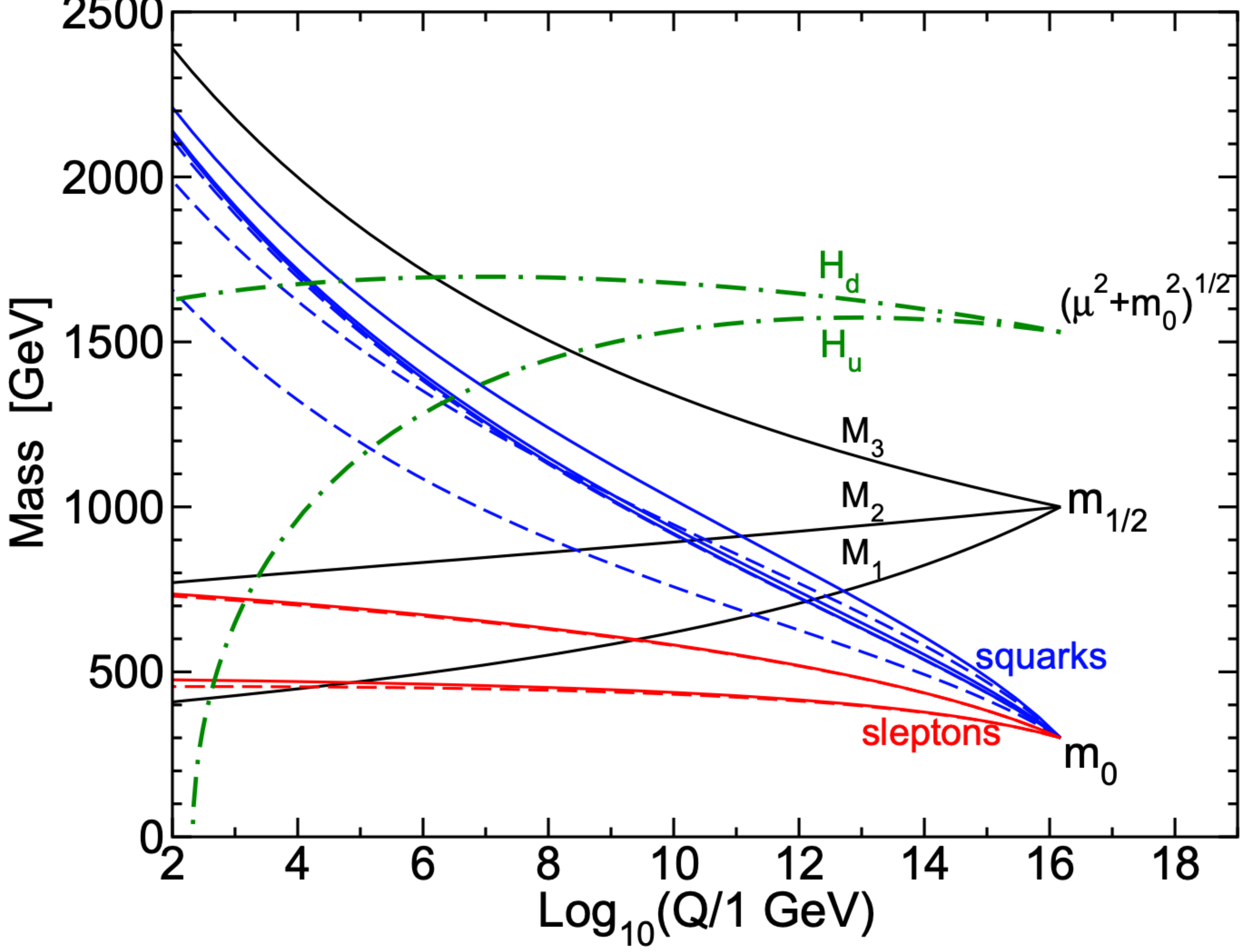


- Currently still requires sub-percent fine tuning.
- Strongest constraints are on colored sparticles (e.g. gluinos and squarks).

Can the FCC-ee See What The LHC Can't?

[Martin, 9709356]



- Running motivates $m_{\text{colored}} > m_{\text{uncolored}}$.

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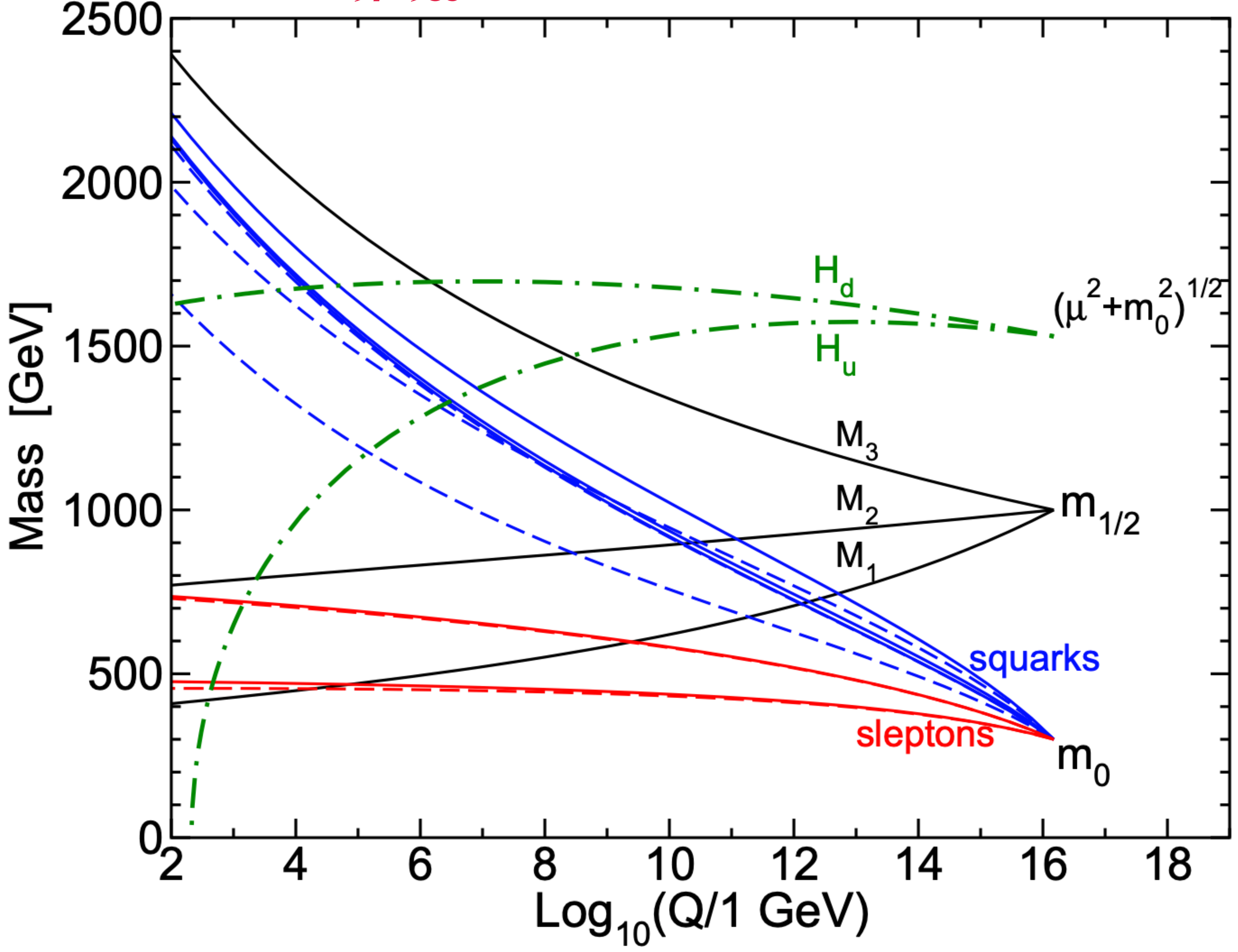

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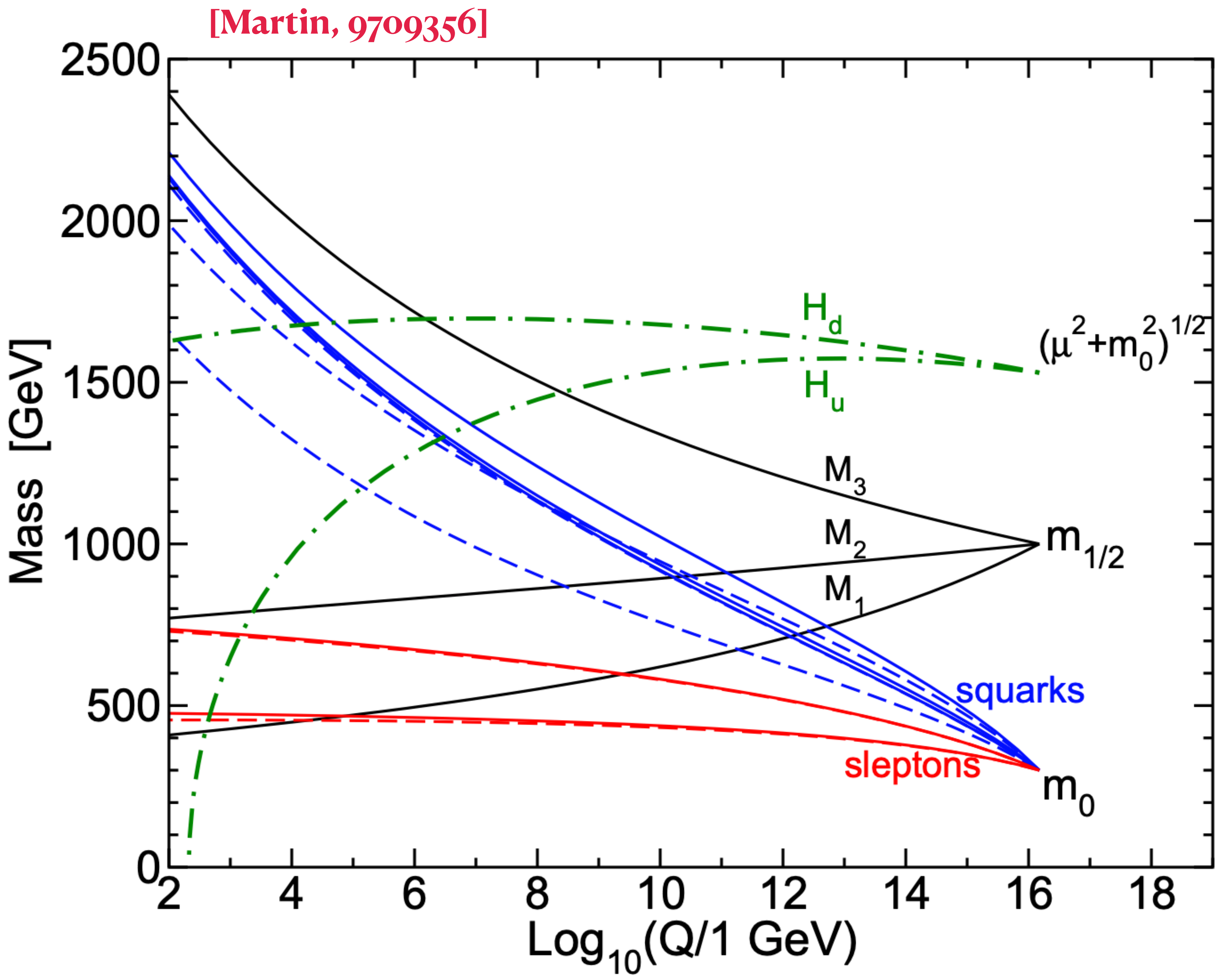

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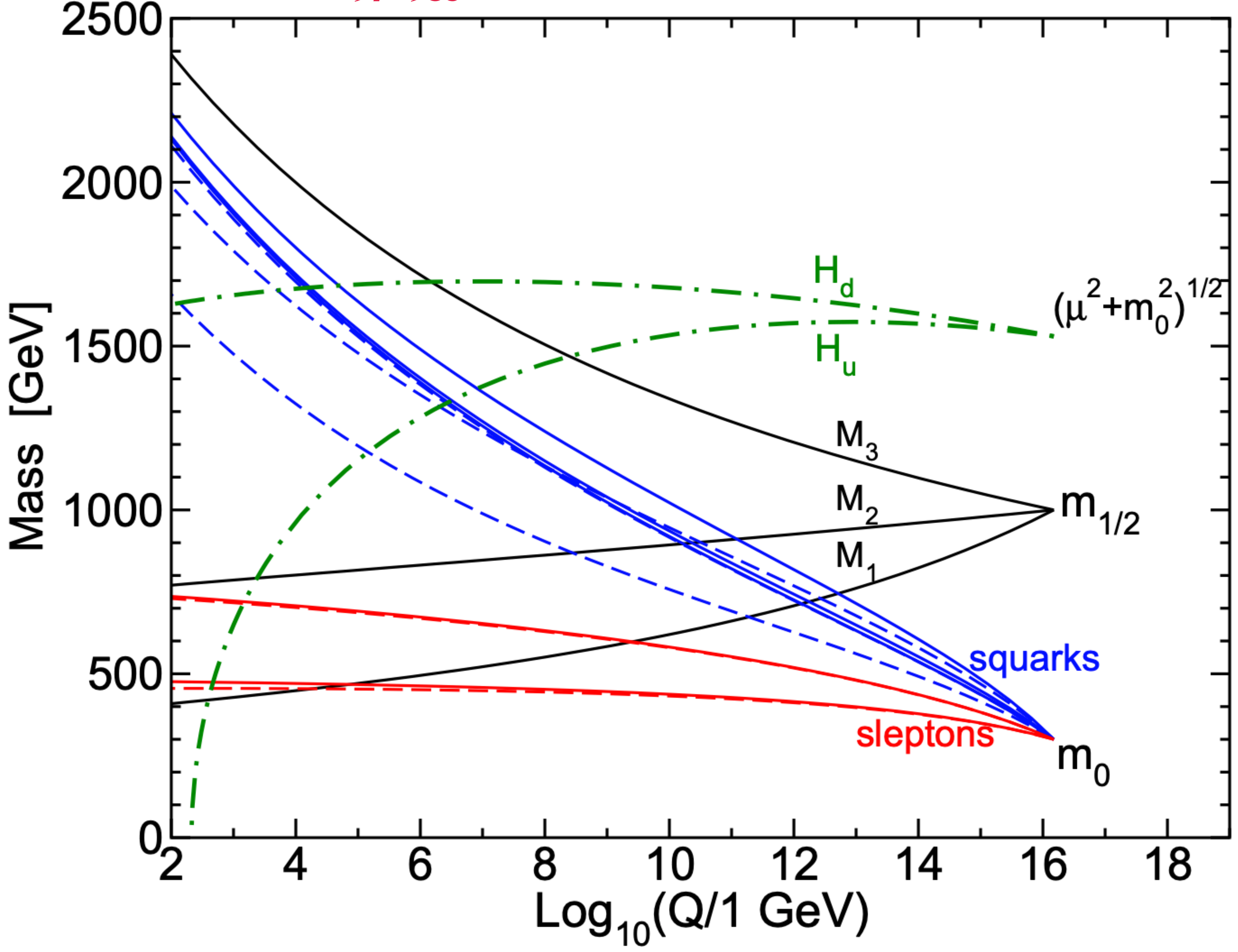
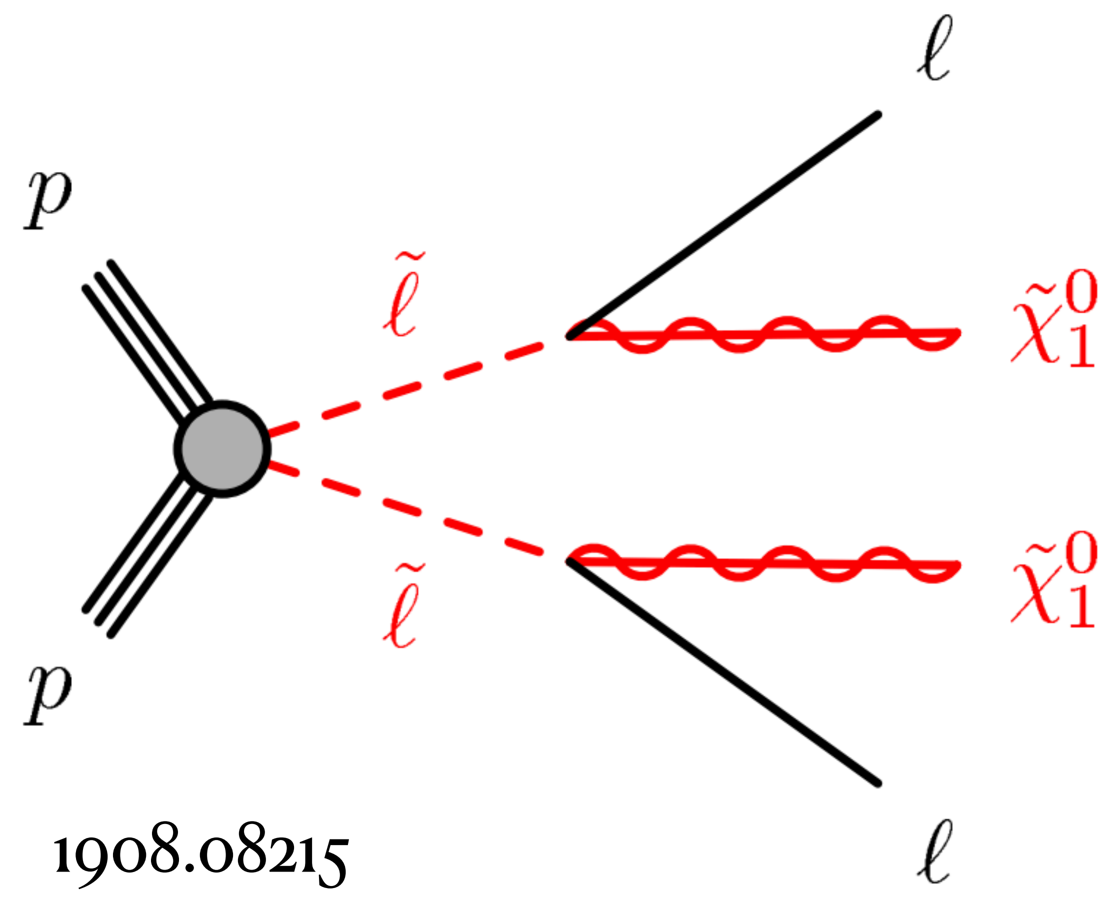


- Running motivates $m_{\text{colored}} > m_{\text{uncolored}}$.
- Colored sparticles may not be produced at the LHC.
- Dominant effect on EWPTs may come from color neutral sparticles.

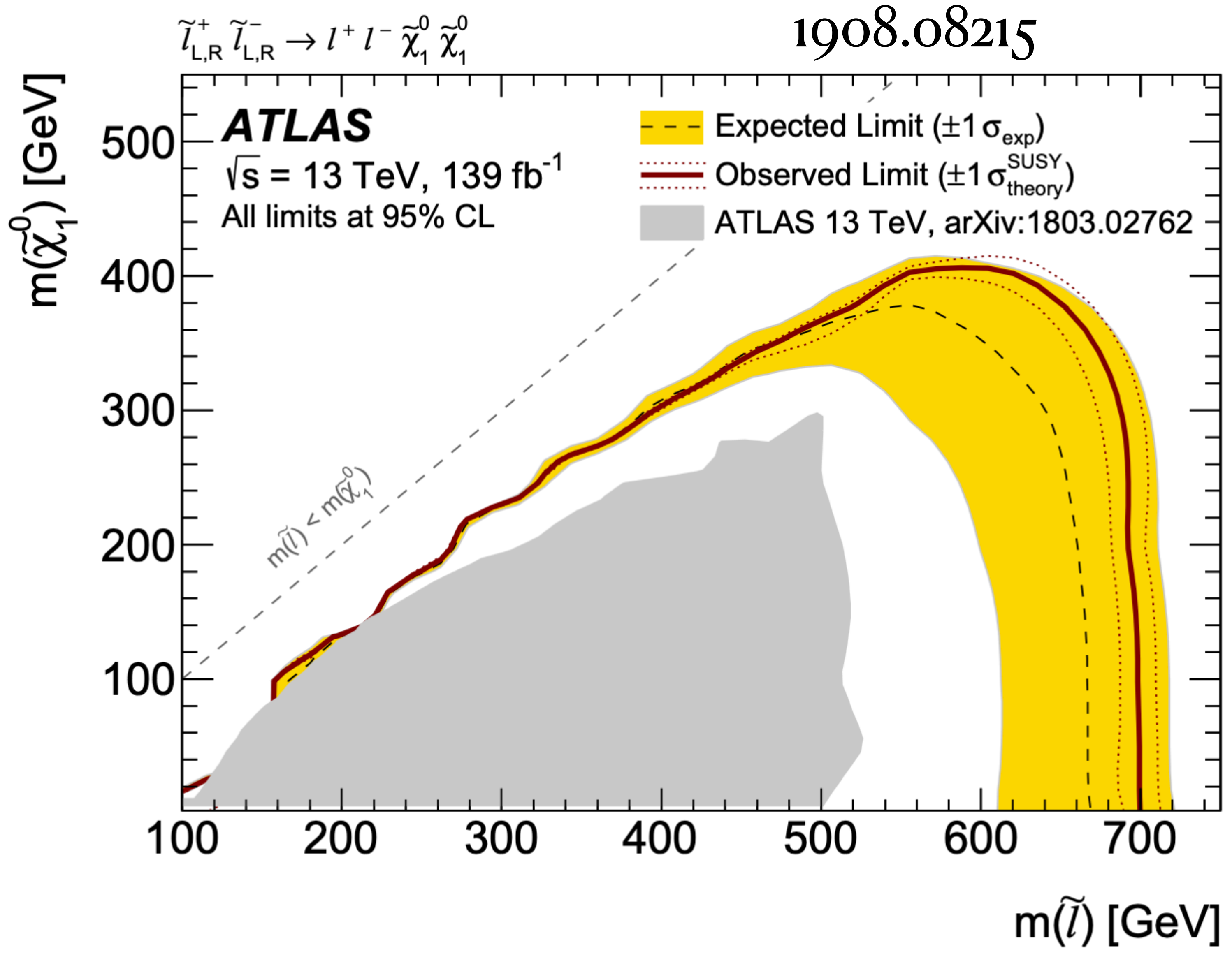
$\Longrightarrow$ FCC-ee may indirectly see SUSY using EWPTs even if the LHC sees nothing.

Simplified SUSY Models

LHC SUSY searches often consider representative simplified models.



1908.08215



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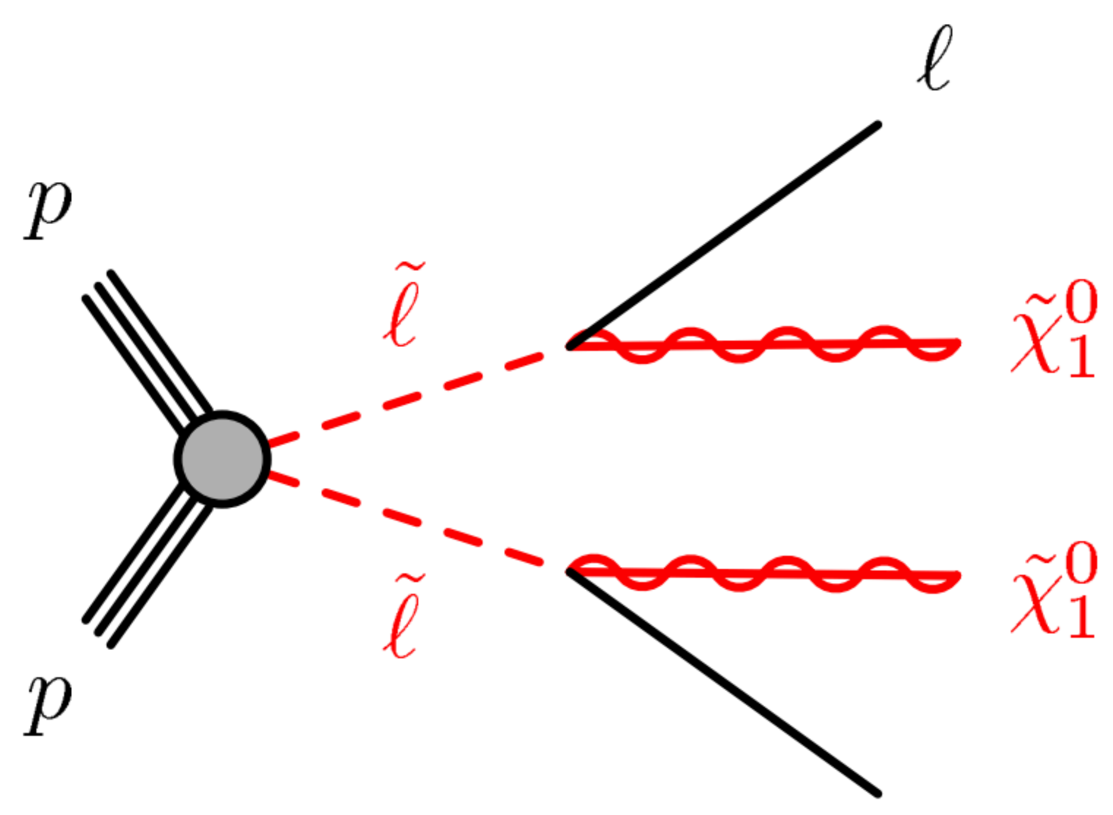

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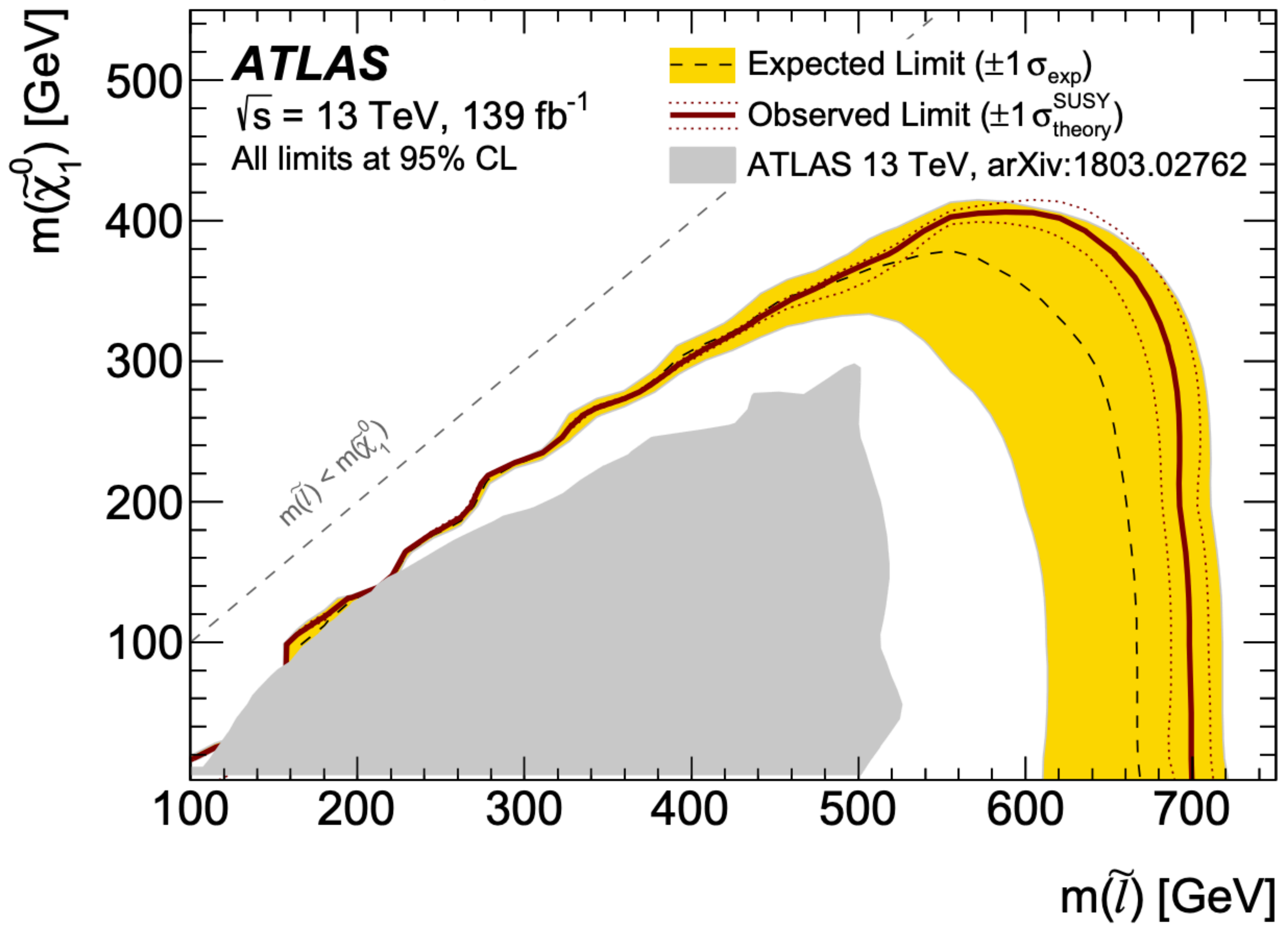

1908.08215

For simplicity we will do the same:

1. Pure Bino + RH Slepton model $\supset (\tilde{B}, \tilde{e})$
2. Pure Wino + LH Slepton model $\supset (\tilde{W}, \tilde{L})$.

How might SUSY show up in EWPTs?

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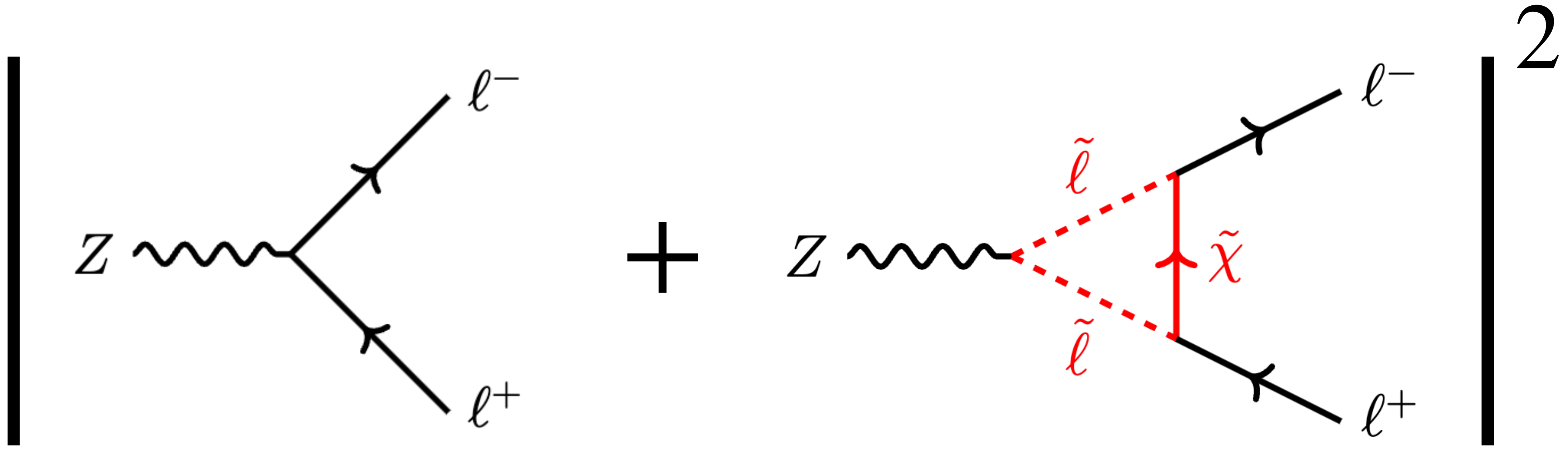
$\Gamma_{Z\to\ell\ell} \propto$



(Just one of several diagrams)

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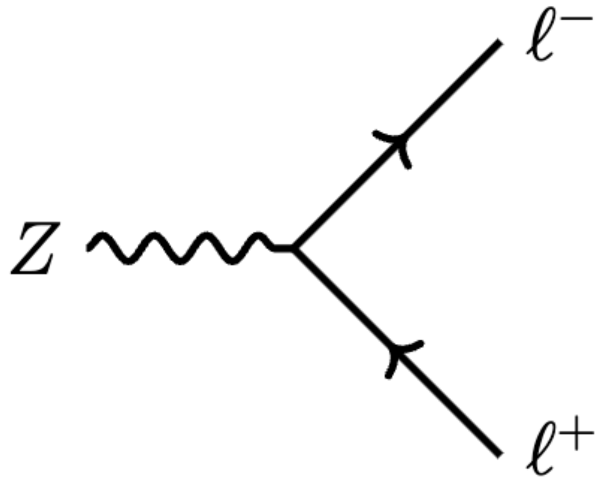
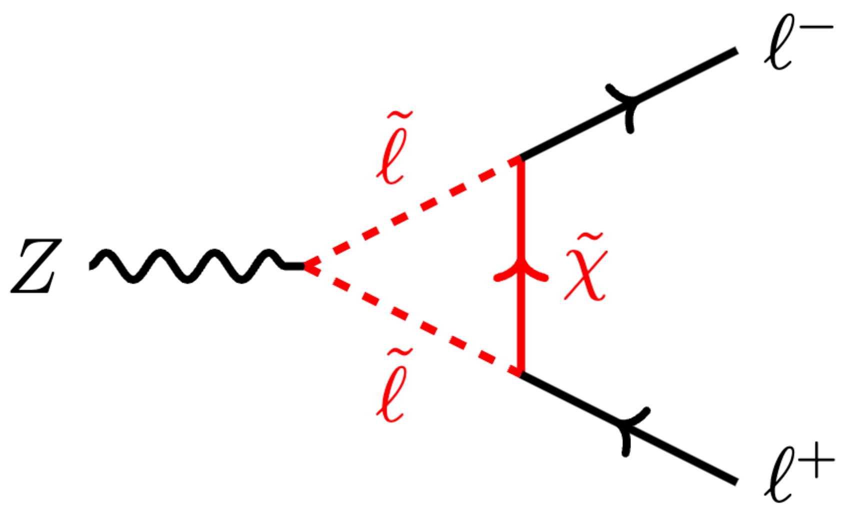
$\Gamma_{Z\to\ell\ell} \propto \Big|$  $+$  $\Big|^2$

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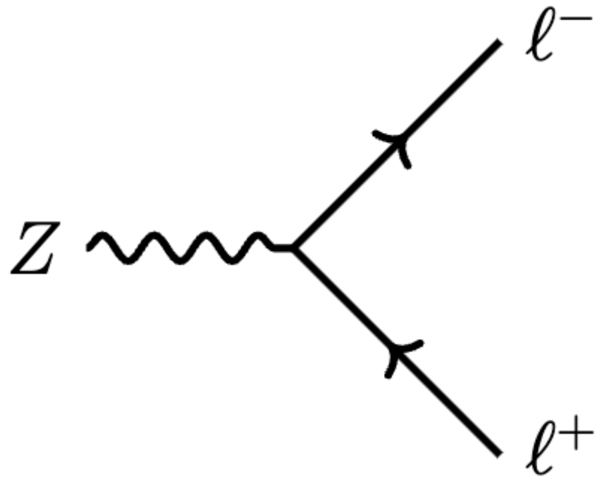
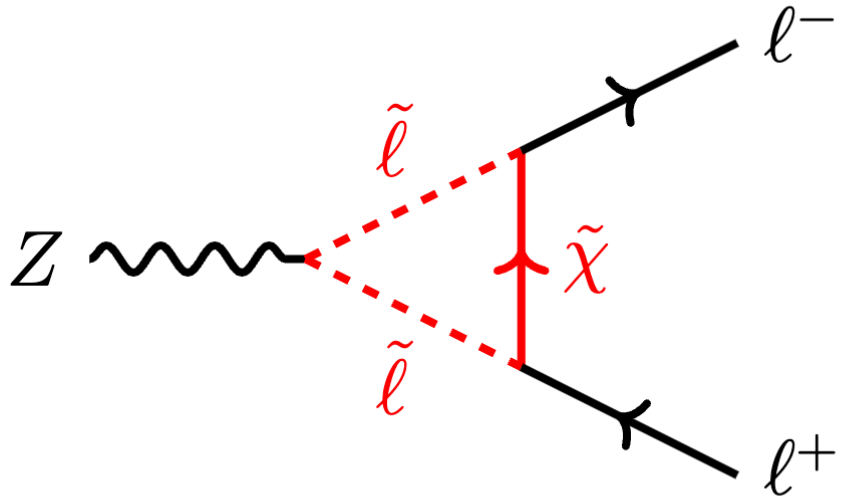
$\Gamma_{Z\to\ell\ell} - \Gamma^{(SM)}_{Z\to\ell\ell} \propto \mathrm{Re}\Big($  $\times$  $\Big)$

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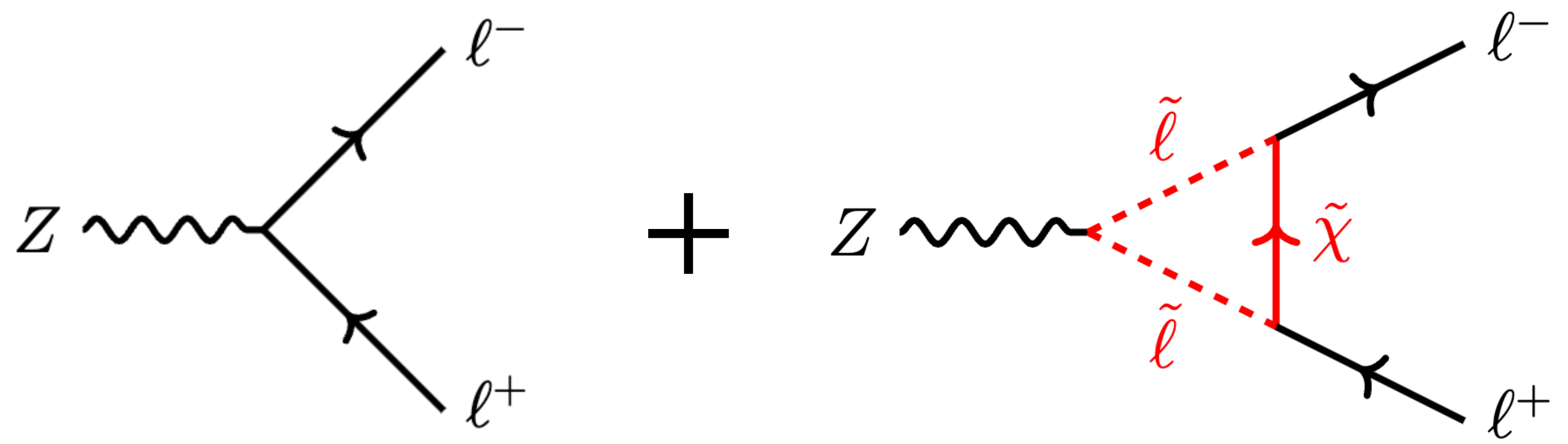
$\Gamma_{Z\to\ell\ell} \propto \Big|$  $\Big|^2$

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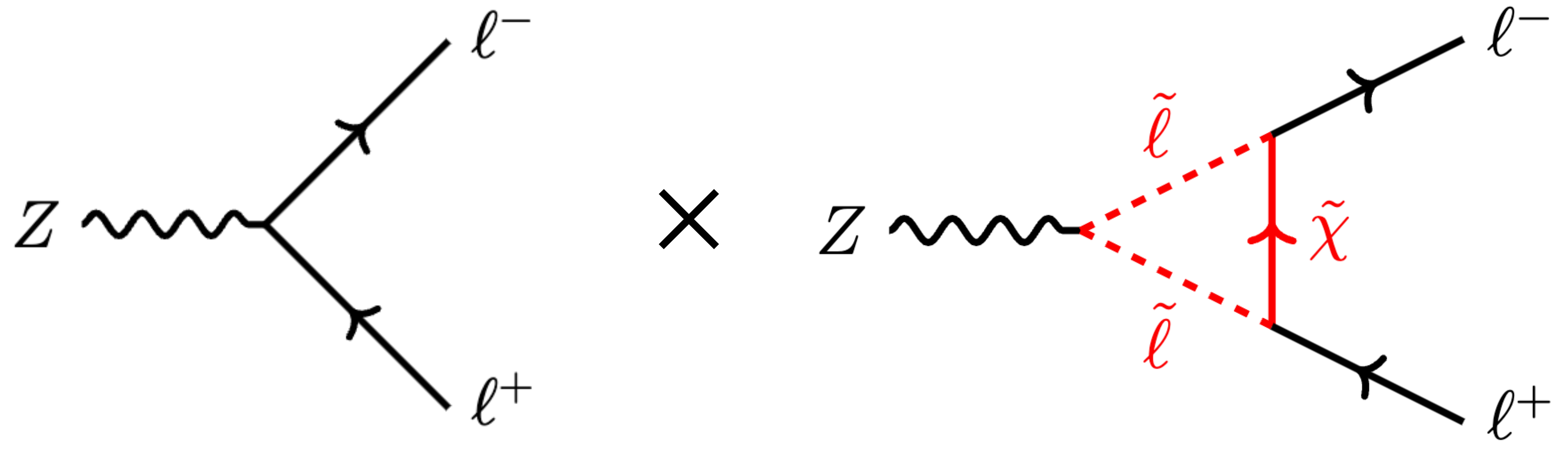
$\Gamma_{Z\to\ell\ell} - \Gamma^{(SM)}_{Z\to\ell\ell} \propto \mathrm{Re}\Big($  $\Big)$

$$\frac{\Gamma_{Z\to\ell\ell} - \Gamma^{(SM)}_{Z\to\ell\ell}}{\Gamma^{(SM)}_{Z\to\ell\ell}} \propto \frac{g^2}{16\pi^2}\left(\frac{m_Z}{M_{\mathrm{SUSY}}}\right)^2 \longrightarrow$$

$$M^{\mathrm{probed}}_{SUSY} \sim 1\ \mathrm{TeV} \times \left(\frac{\delta\Gamma/\Gamma}{10^{-5}}\right)$$

Some details

$\Gamma(Z \to \ell\bar{\ell})$ is not the best observable. Instead we use

$$R_\ell \equiv \frac{\Gamma(Z \to \text{ hadrons })}{\Gamma(Z \to \ell\bar{\ell})}$$

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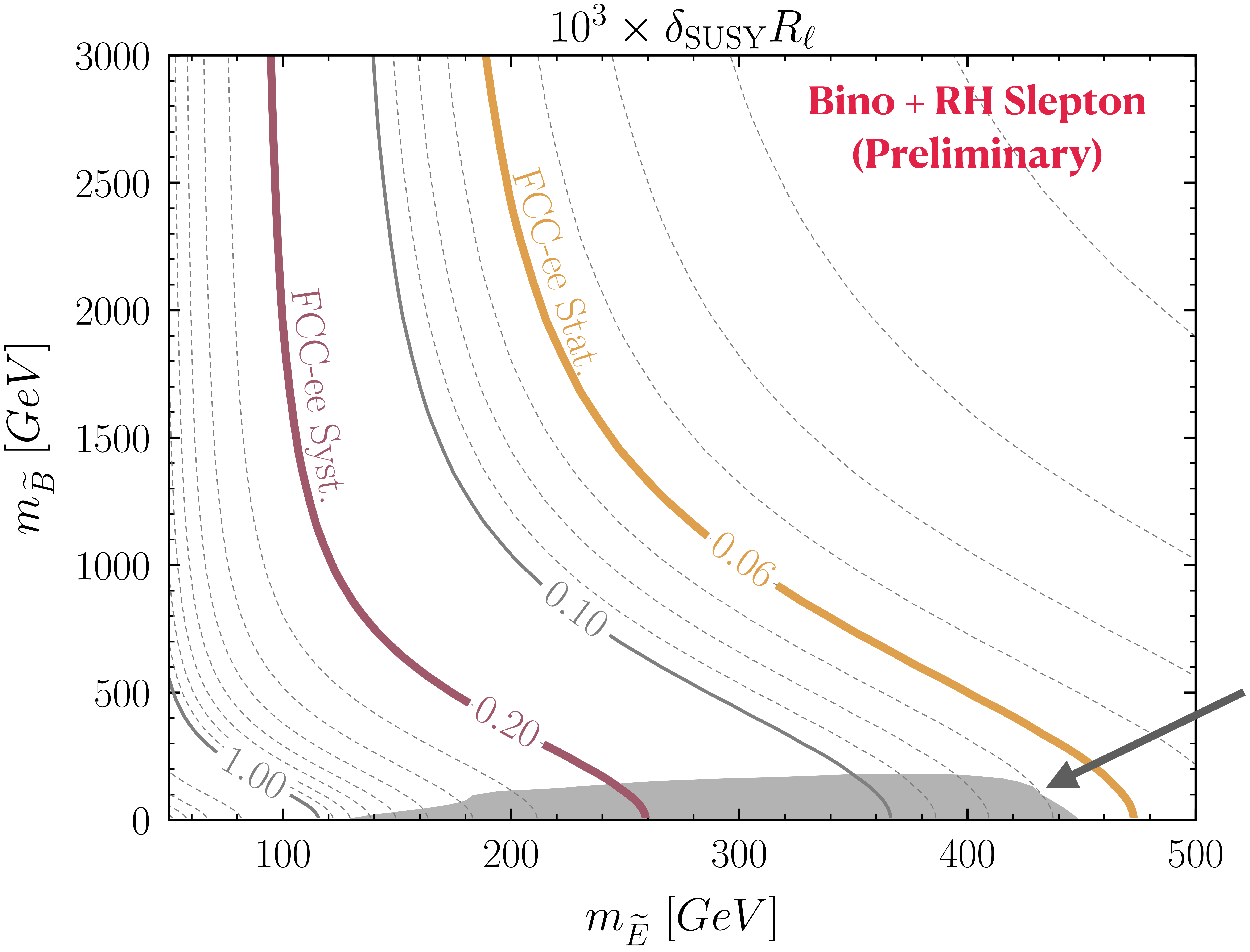
Still depends on θ_W and $\alpha_s(M_Z)$. These must be determined by other measurements.

Results



"Representative" LHC Constraints [1908.08215]

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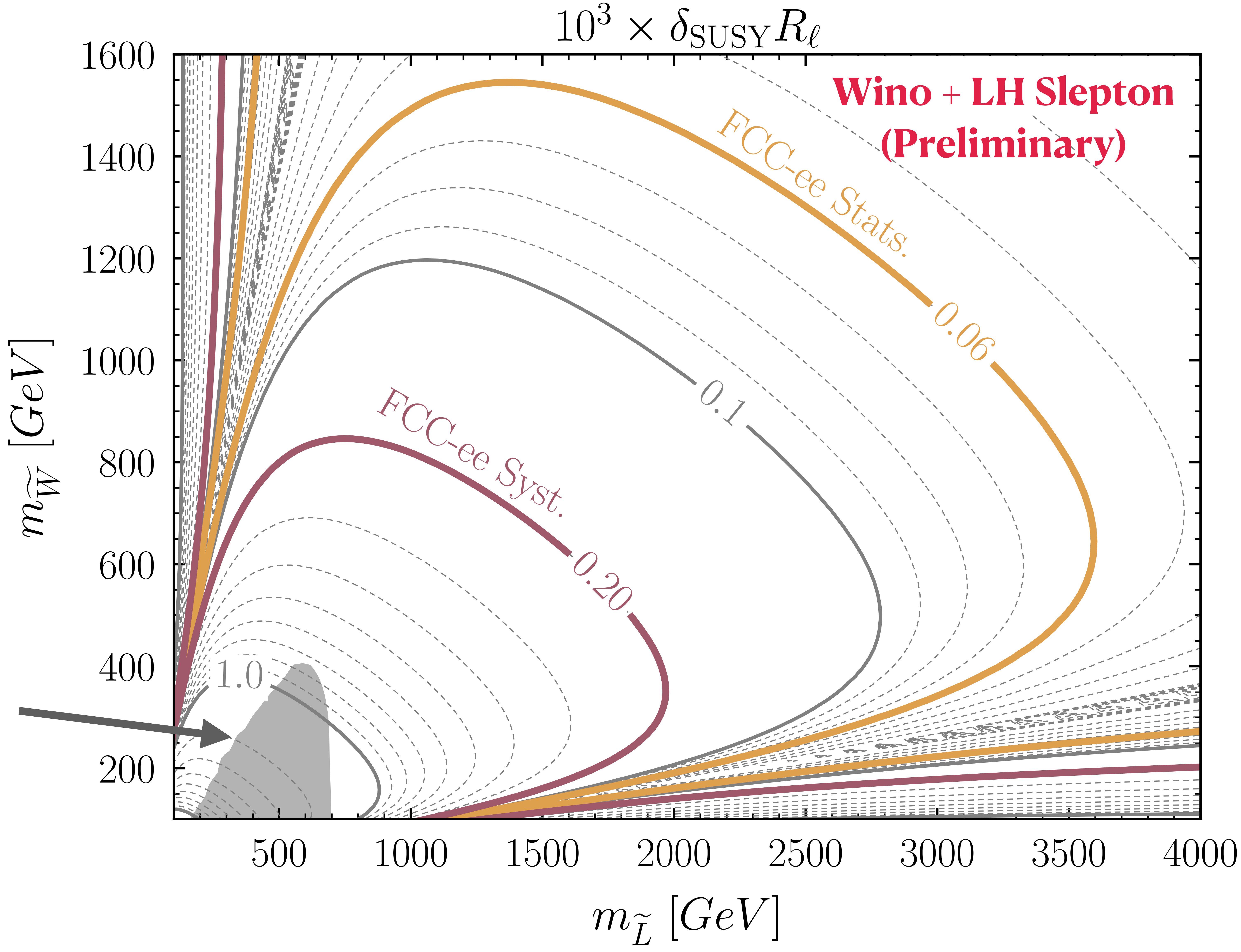
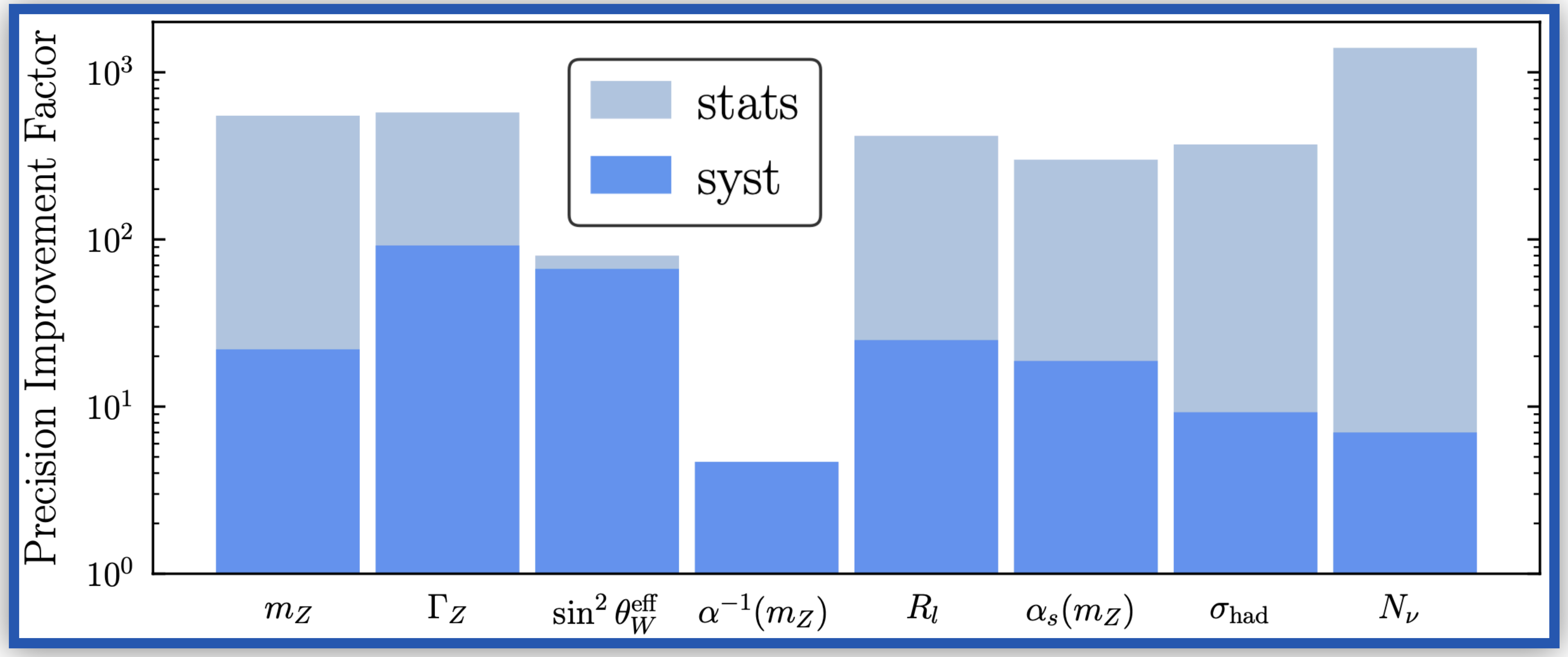


“Representative” LHC Constraints [1908.08215]

Conclusion

- EWPTs at the FCC-ee are interesting ways to search for new physics.
- These searches can be complimentary to direct searches at the LHC.
- There exists some SUSY parameter space which may be explored at the FCC-ee.
- A more thorough investigation into which observables/signatures are motivated by various models may motivate further dedication to the reduction of certain systematics.



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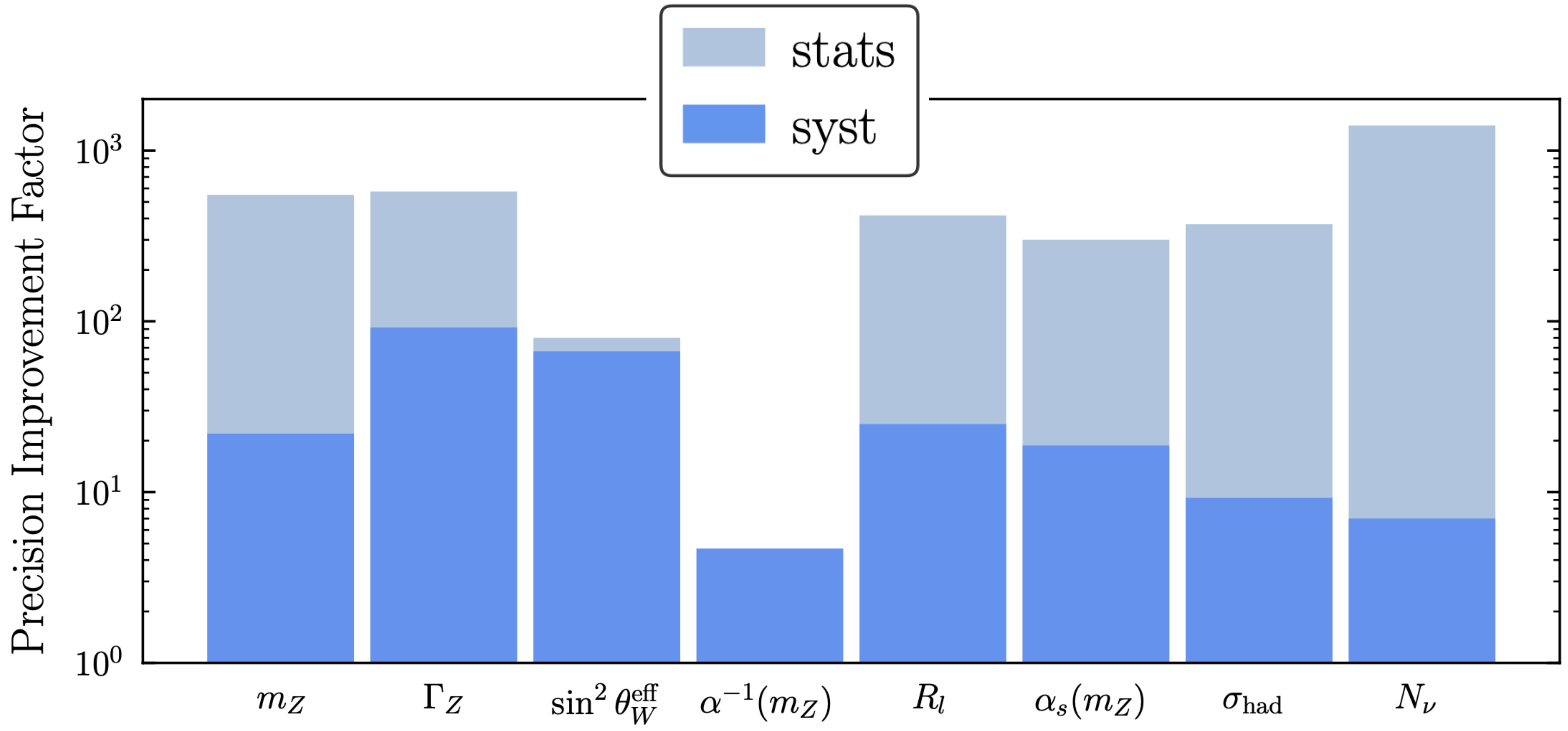
Backup Slides

Electroweak Precision Tests at the Z-pole

There are many measurements which can be performed at the Z-pole.



Many measurements are systematics limited!

Which systematics should we prioritize reducing?

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.
m_Z (keV)	$91,186,700 \pm 2200$	5	100
Γ_Z (keV)	$2,495,200 \pm 2300$	8	100
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2–1.0
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60
$\sigma^0_{\rm had}$ ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4
N_ν ($\times 10^3$)	2991 ± 7	0.005	1
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	$231,480 \pm 160$	3	2–5
$1/\alpha_{\rm QED}$ (m_Z) ($\times 10^3$)	$128,952 \pm 14$	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2
m_W (MeV)	$80,350 \pm 15$	0.5	0.3
Γ_W (MeV)	2085 ± 42	1.2	0.3
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small
$m_{\rm top}$ (MeV)	$172,740 \pm 500$	17	Small
$\Gamma_{\rm top}$ (MeV)	1410 ± 190	45	Small
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	0.1	Small
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small

[FCC CDR]

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

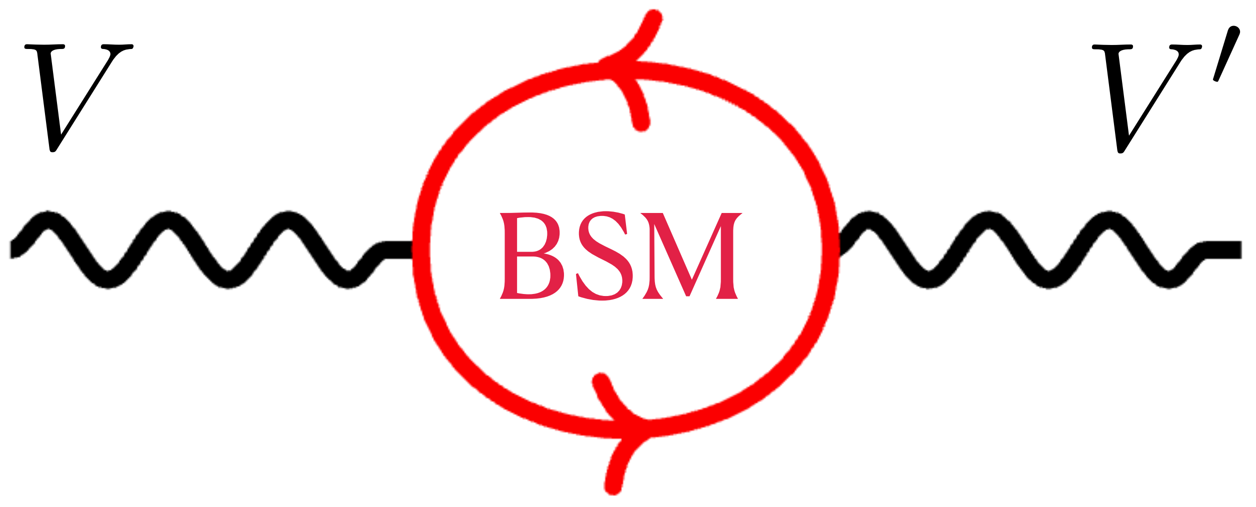
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit	Conditions	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [10× Degen.] 1.9	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$ 2.35	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		139	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$ 1.97	m($\tilde{\chi}_1^0$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$ Forbidden 0.74	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1909.08457
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$ 1.25	m($\tilde{\chi}_1^0$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ 0.44-0.59	m($\tilde{\chi}_1^0$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_2^0, \tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$ 0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	3 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.64	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 0.42	m($\tilde{\chi}_1^0$)=0	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 0.74	m($\tilde{\chi}_1^0$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$ 0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\to bbs$		$\geq$ 4b		139	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Oblique Corrections

- Assuming heavy new physics dominantly modifies SM gauge boson propagators, corrections from heavy new physics can be quantified by a set of oblique parameters.



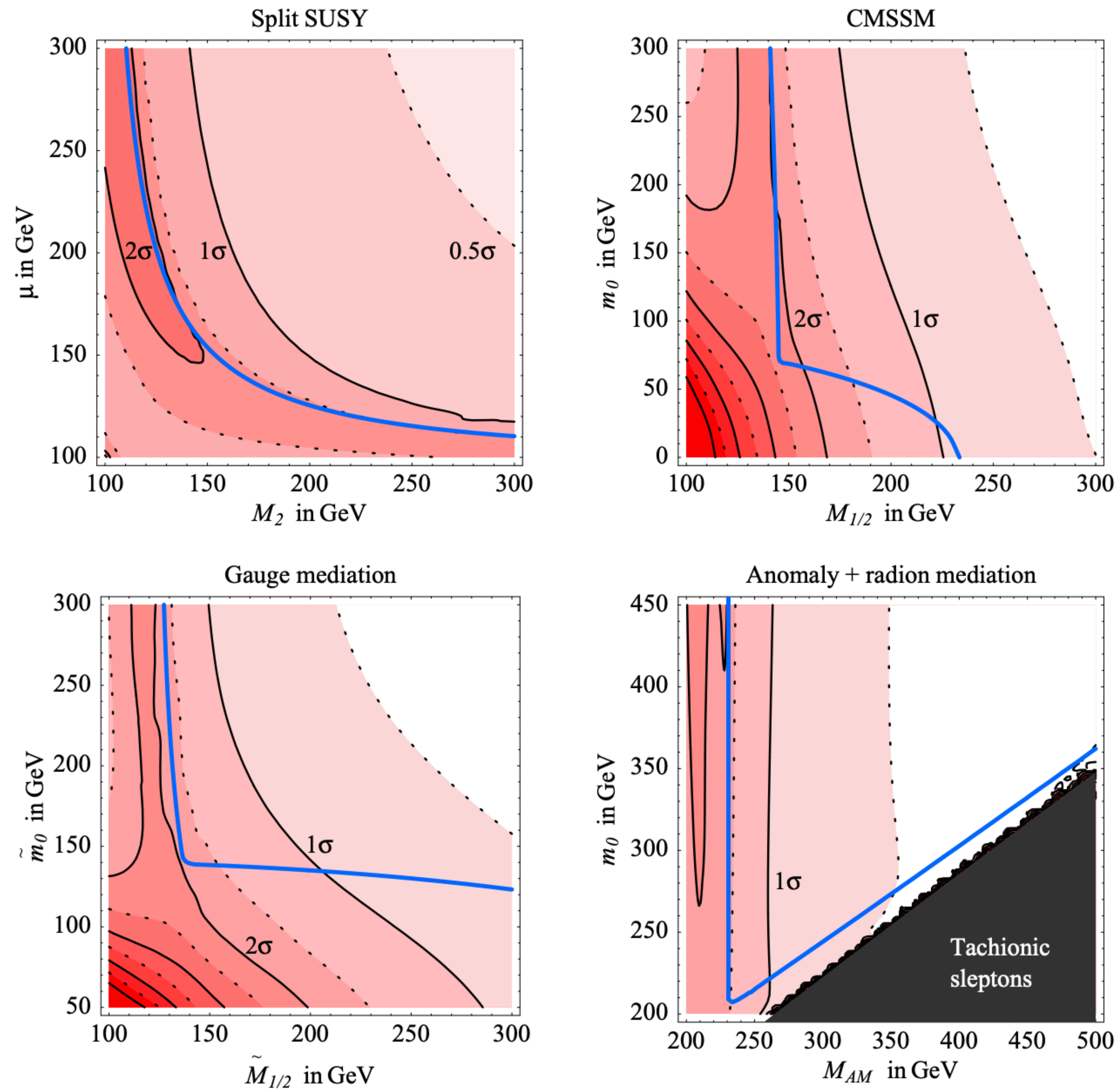
Oblique parameter	Corresponding dim-6 operator
$\widehat{S} = \frac{g}{g'}\Pi'_{W^3B}(0)$	$\mathcal{O}_S = H^\dagger \tau^a H W^a_{\mu\nu} B^{\mu\nu}$
$\widehat{T} = m_W^{-2}\left[\Pi_{W^3W^3}(0) - \Pi_{W^+W^-}(0)\right]$	$\mathcal{O}_T = \lvert H^\dagger D_\mu H\rvert^2$
$W = \frac{1}{2}m_W^2 \Pi''_{W^3W^3}(0)$	$\mathcal{O}_W = \frac{1}{2}\left(D_\rho W^a_{\mu\nu}\right)^2$
$Y = \frac{1}{2}m_W^2 \Pi''_{BB}(0)$	$\mathcal{O}_Y = \frac{1}{2}\left(\partial_\rho B_{\mu\nu}\right)^2$

- Simple, but not completely general.

X	$\widehat{S} \times \left(\frac{m_X^2}{m_W^2}\right)$	$\widehat{T} \times \left(\frac{m_X^2}{m_W^2}\right)$	$W \times \left(\frac{m_X^2}{m_W^2}\right)$	$Y \times \left(\frac{m_X^2}{m_W^2}\right)$
$\widetilde{E}$	0	0	0	$\frac{\alpha_Y}{40\pi}$
$\widetilde{L}$	$-\frac{\alpha_W c_{2\beta}}{16\pi}$	$\frac{\alpha_W c_{2\beta}^2}{16\pi}$	$\frac{\alpha_W}{80\pi}$	$\frac{\alpha_Y}{80\pi}$
$\widetilde{B}$	0	0	0	0
$\widetilde{W}$	0	0	$\frac{\alpha_W}{15\pi}$	0

Supersymmetry and precision data after LEP2 [0502095]

Guido Marandella[a], Christian Schappacher[b], Alessandro Strumia[c]



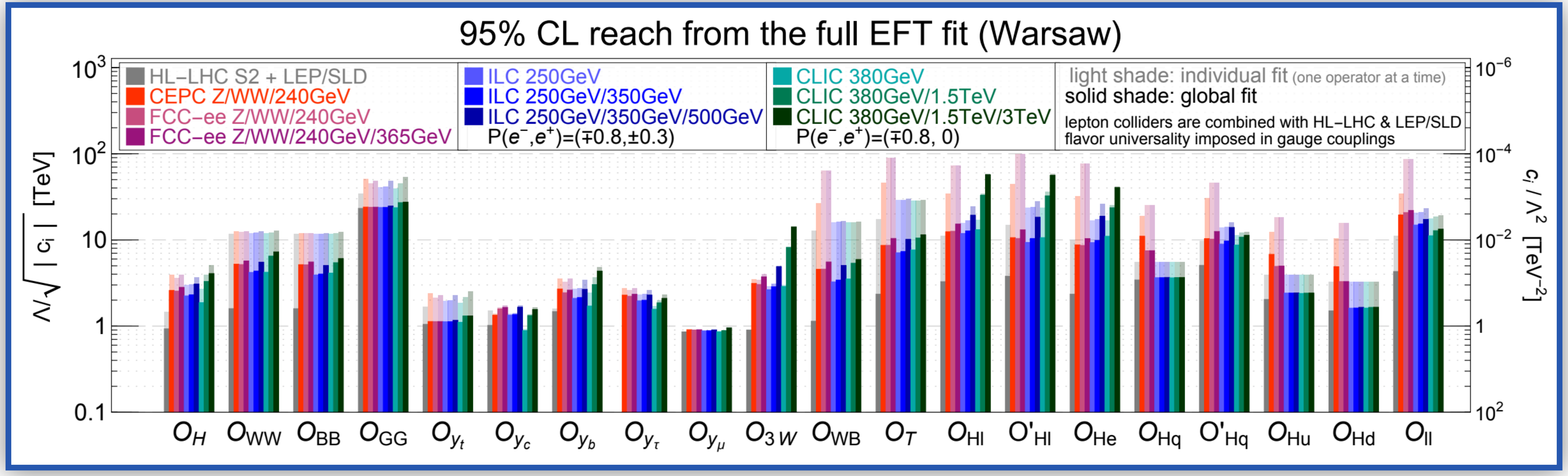
Focuses on oblique corrections

Electroweak Precision Tests

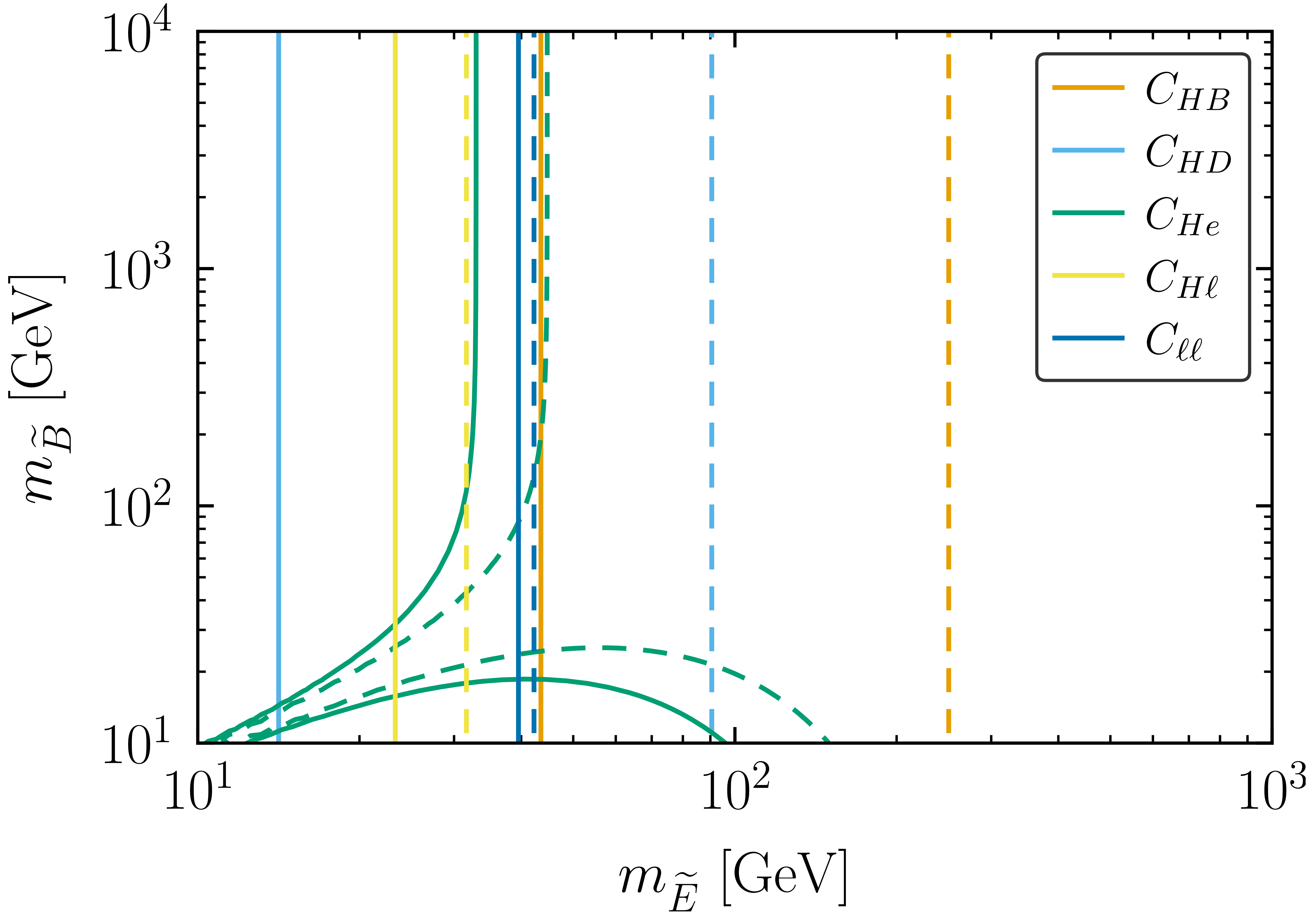
- The most general method of indirectly searching for heavy new physics is SMEFT.

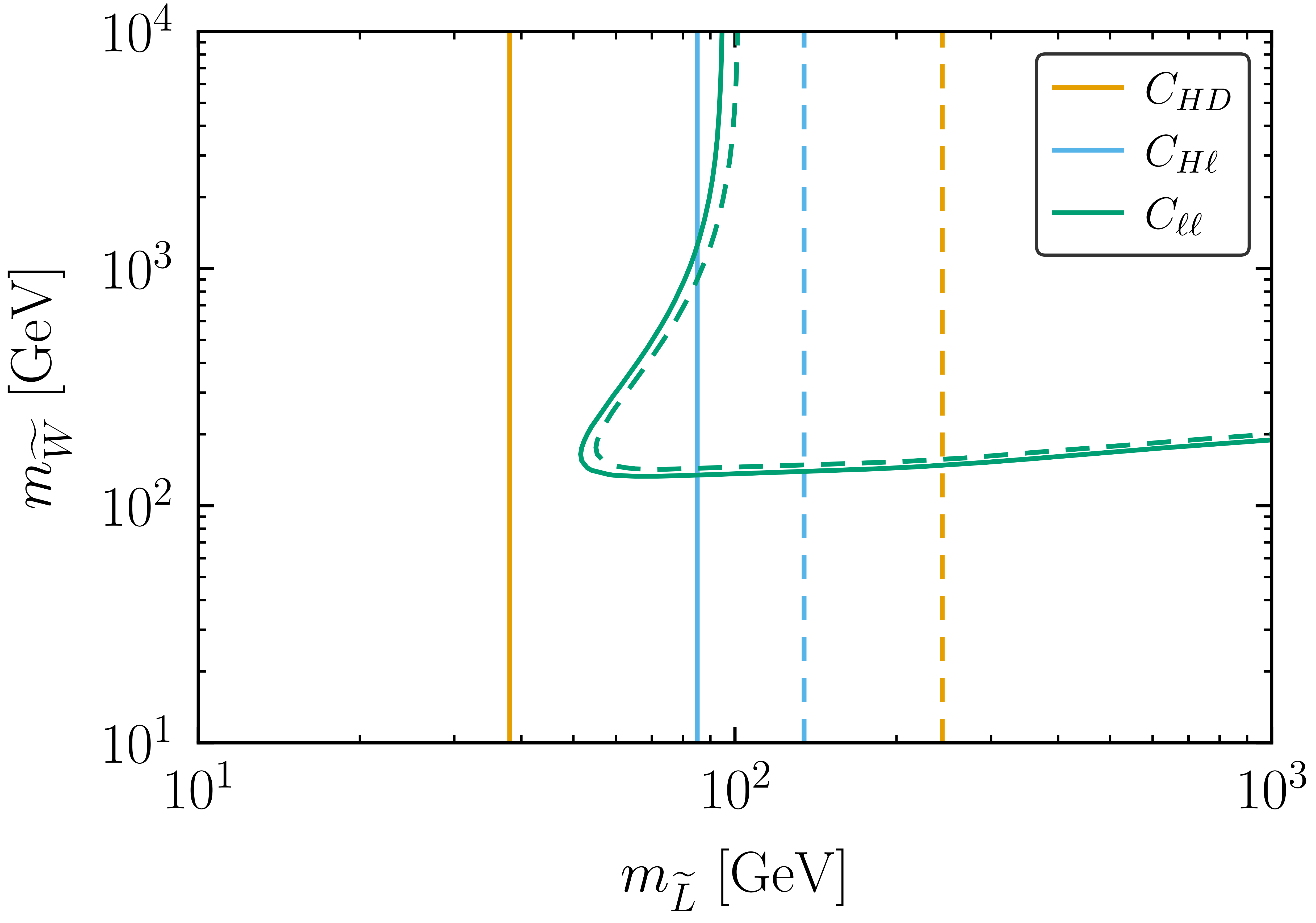
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

- Assuming CP conservation and MFV, about 20 operators are relevant for EWPTs.

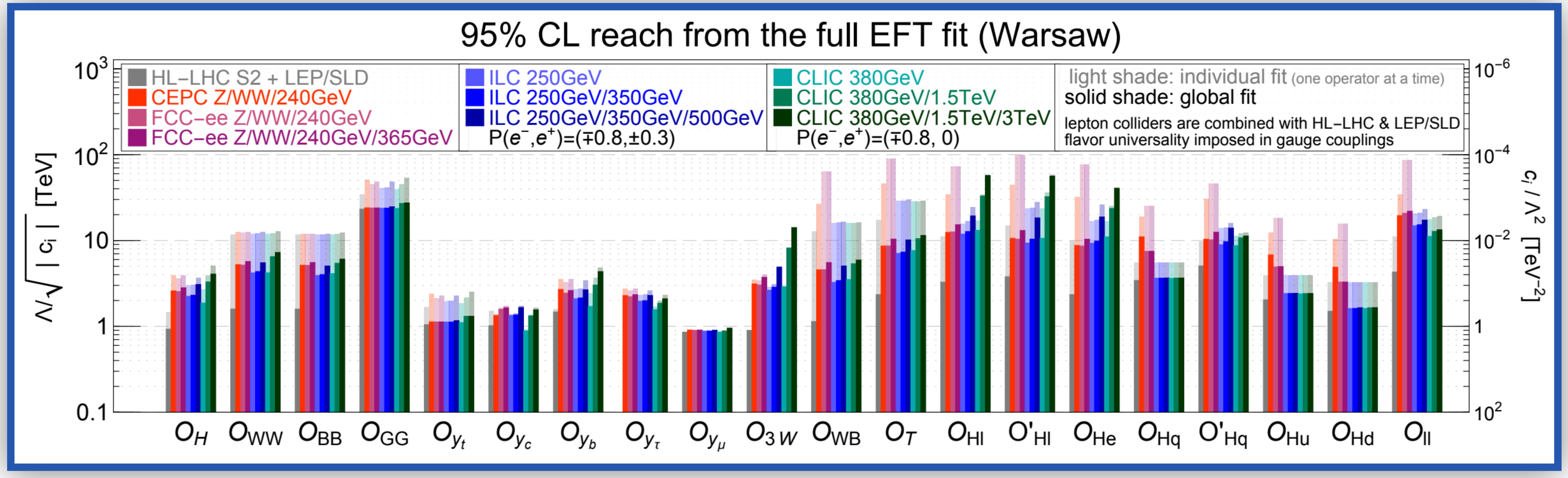


Constraints from SMEFT

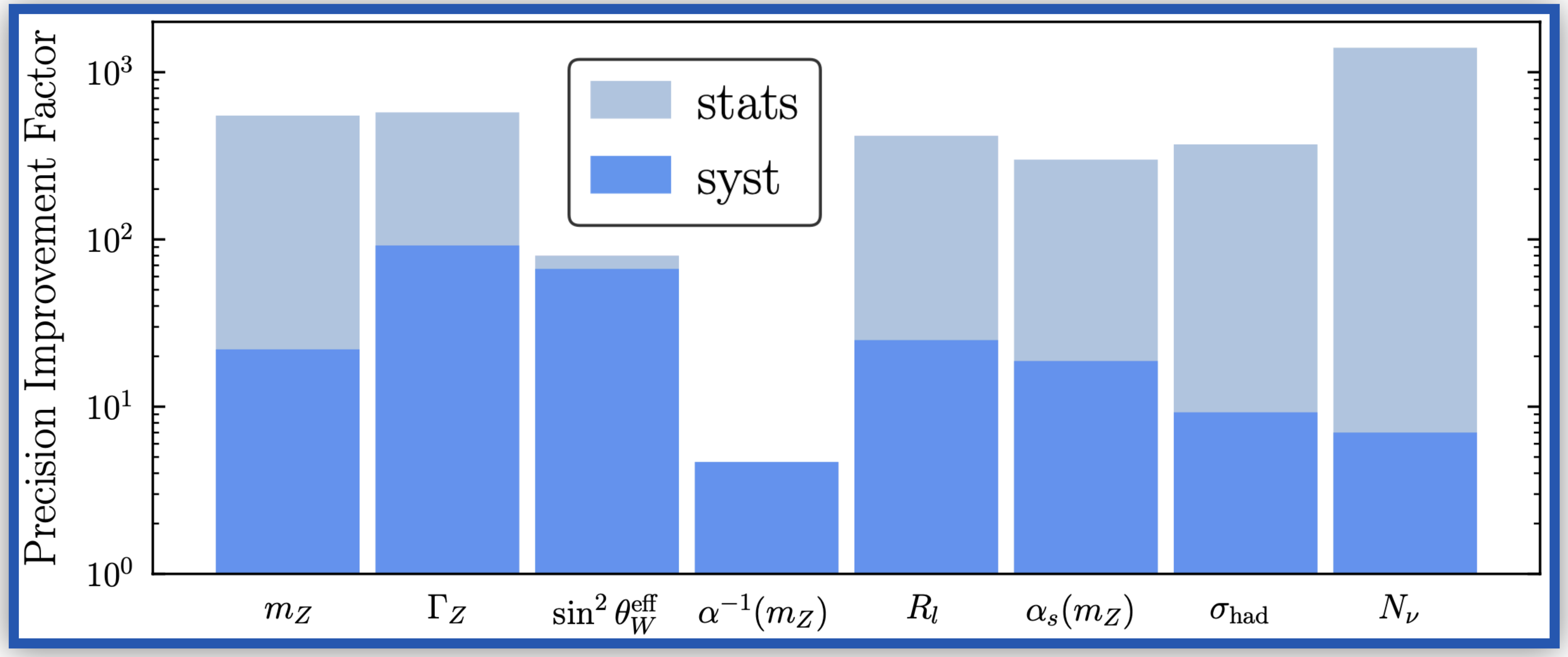




A Tale of Two Bar Plots

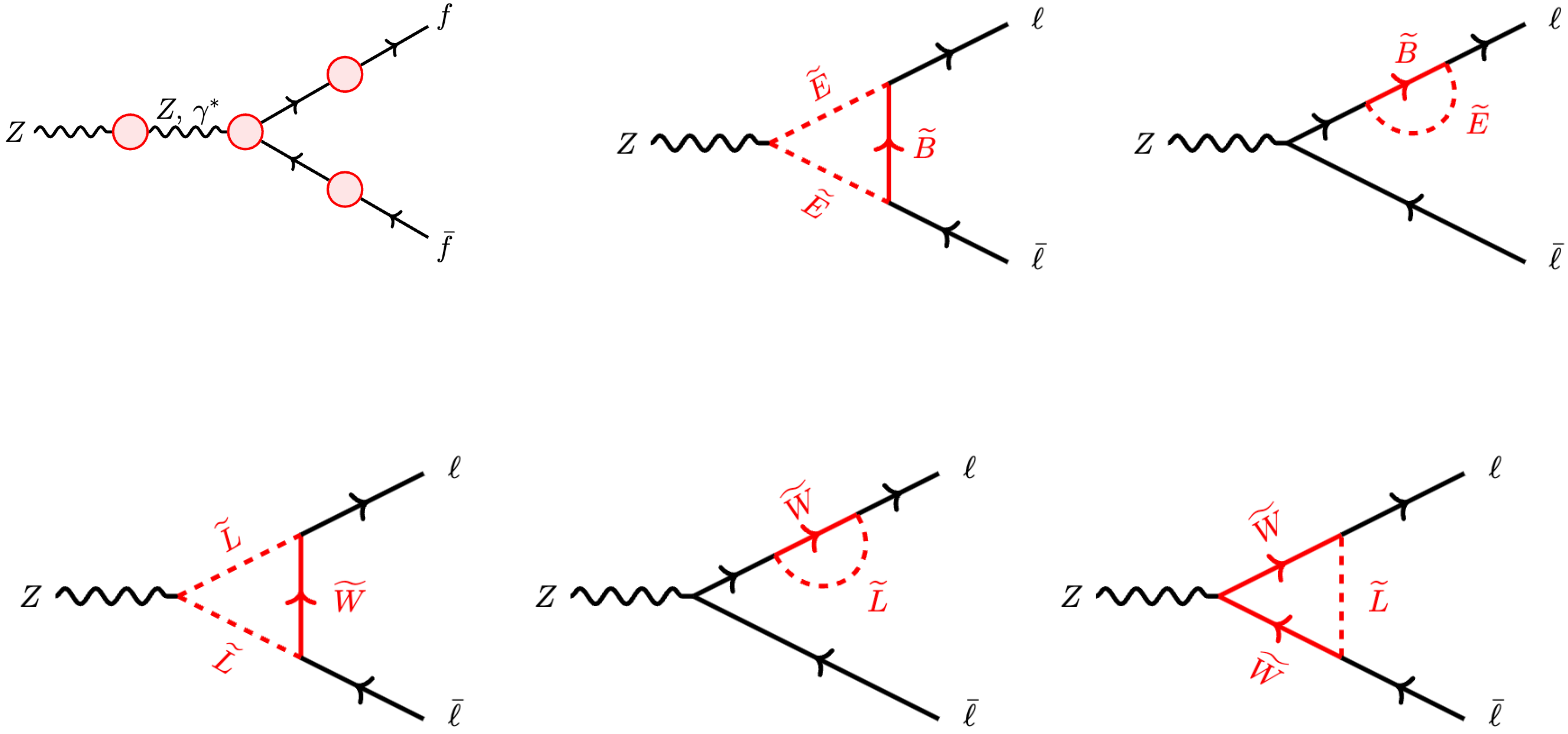


How do we interpret these?



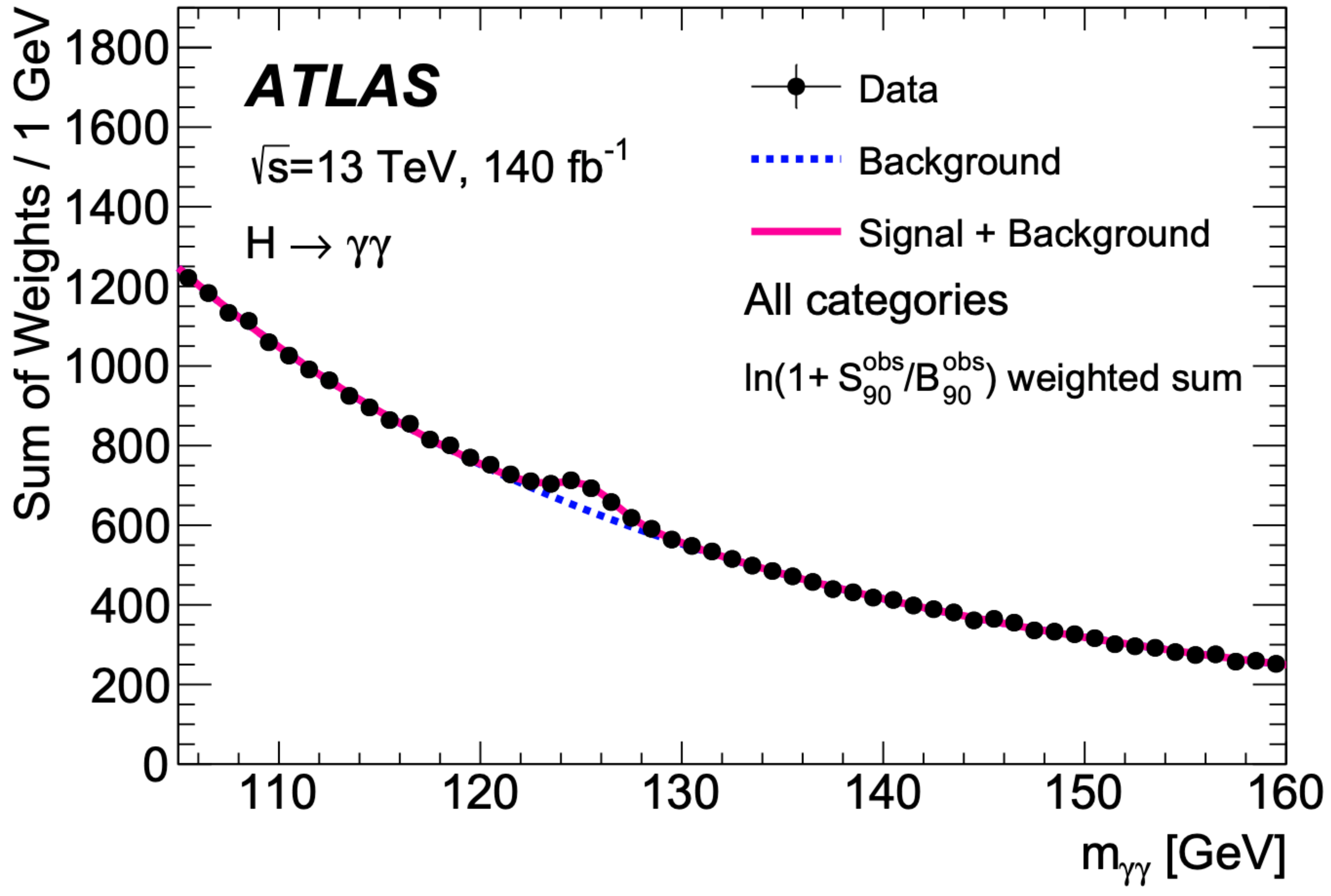
Questions

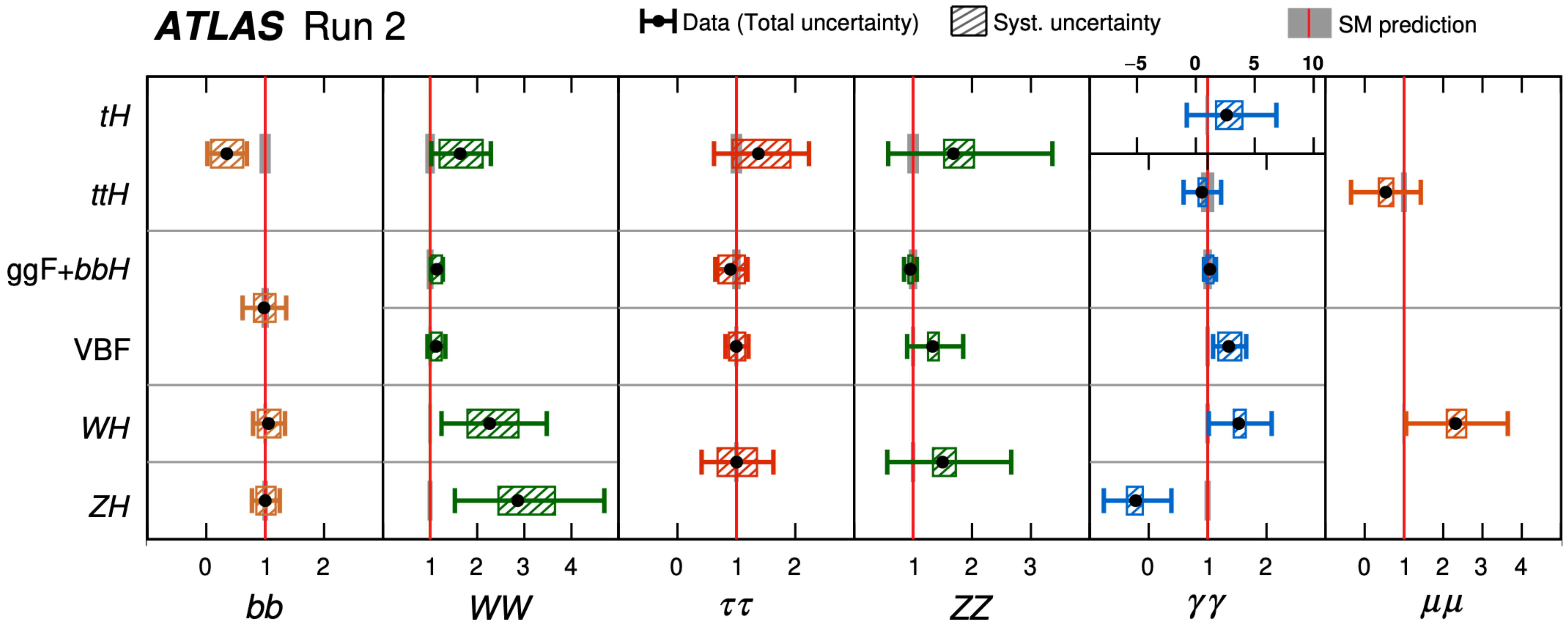
1. **Which SMEFT operators are most interesting?**
2. **Which systematics should experimentalists be most motivated to decrease?**



Z
Z, γ^*
f
$\bar{f}$
ℓ
$\bar{\ell}$
$\widetilde{E}$
$\widetilde{B}$
$\widetilde{L}$
$\widetilde{W}$

The LHC has been very successful!





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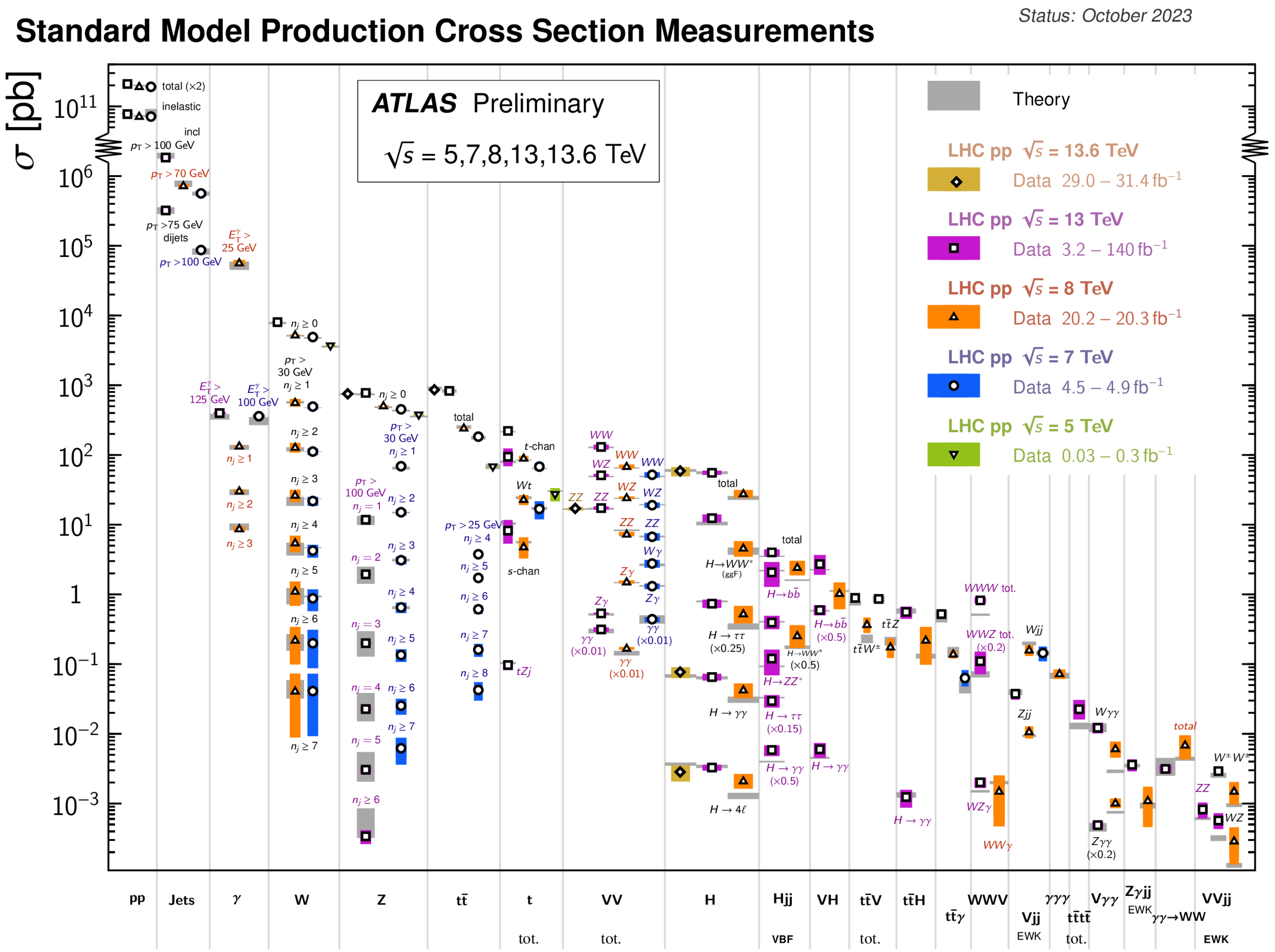

The Standard Model is extremely predictive!

Many mysteries remain!

Finding answers may require a different collider.