SUSY and Electroweak Precision Tests at Tera-Z Colliders

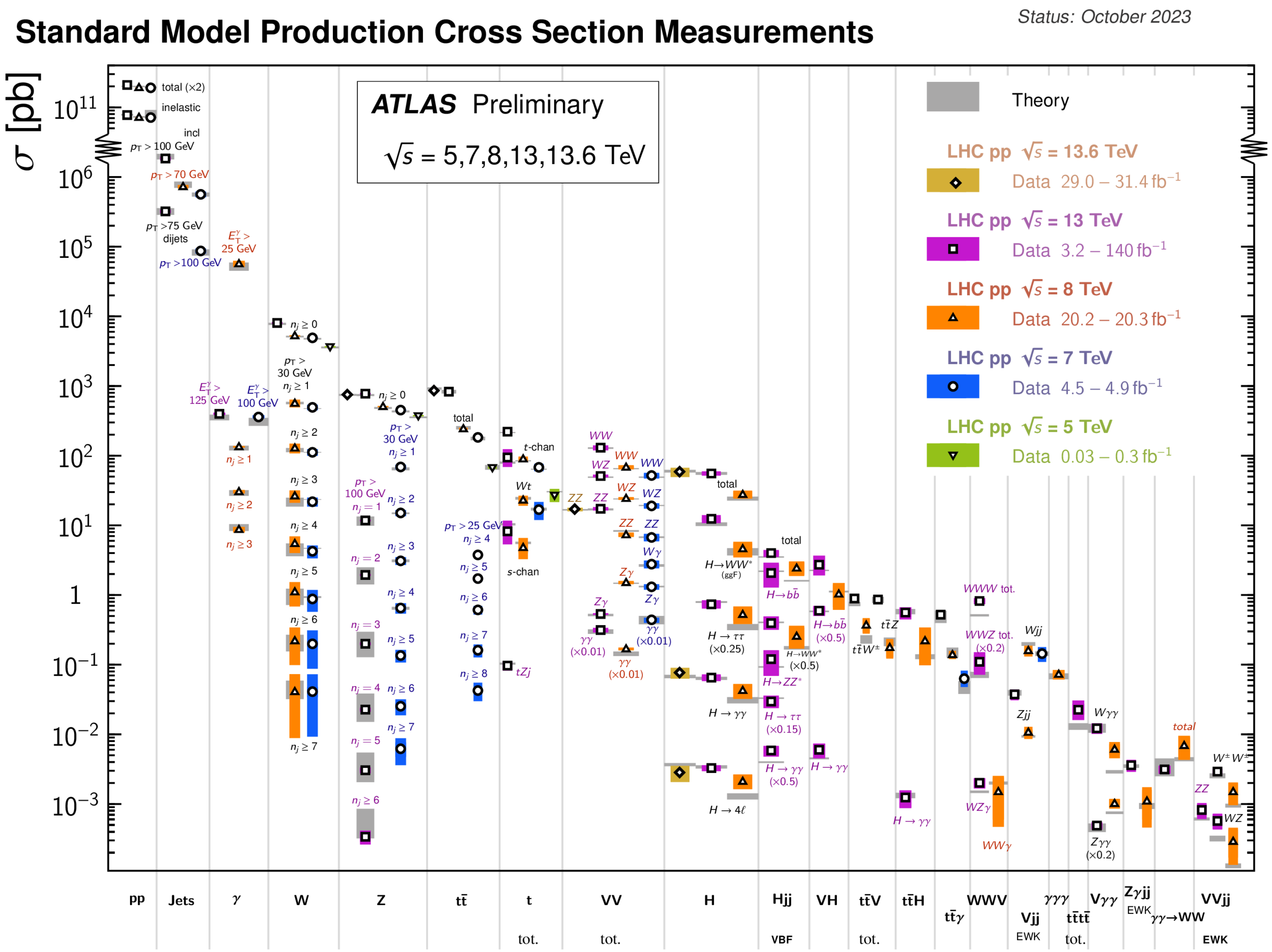
Kevin Langhoff

(Work in progress with Simon Knapen and Zoltan Ligeti)

FCC-Week (June 11th, 2024)

Berkeley
UNIVERSITY OF CALIFORNIA
BERKELEY LAB

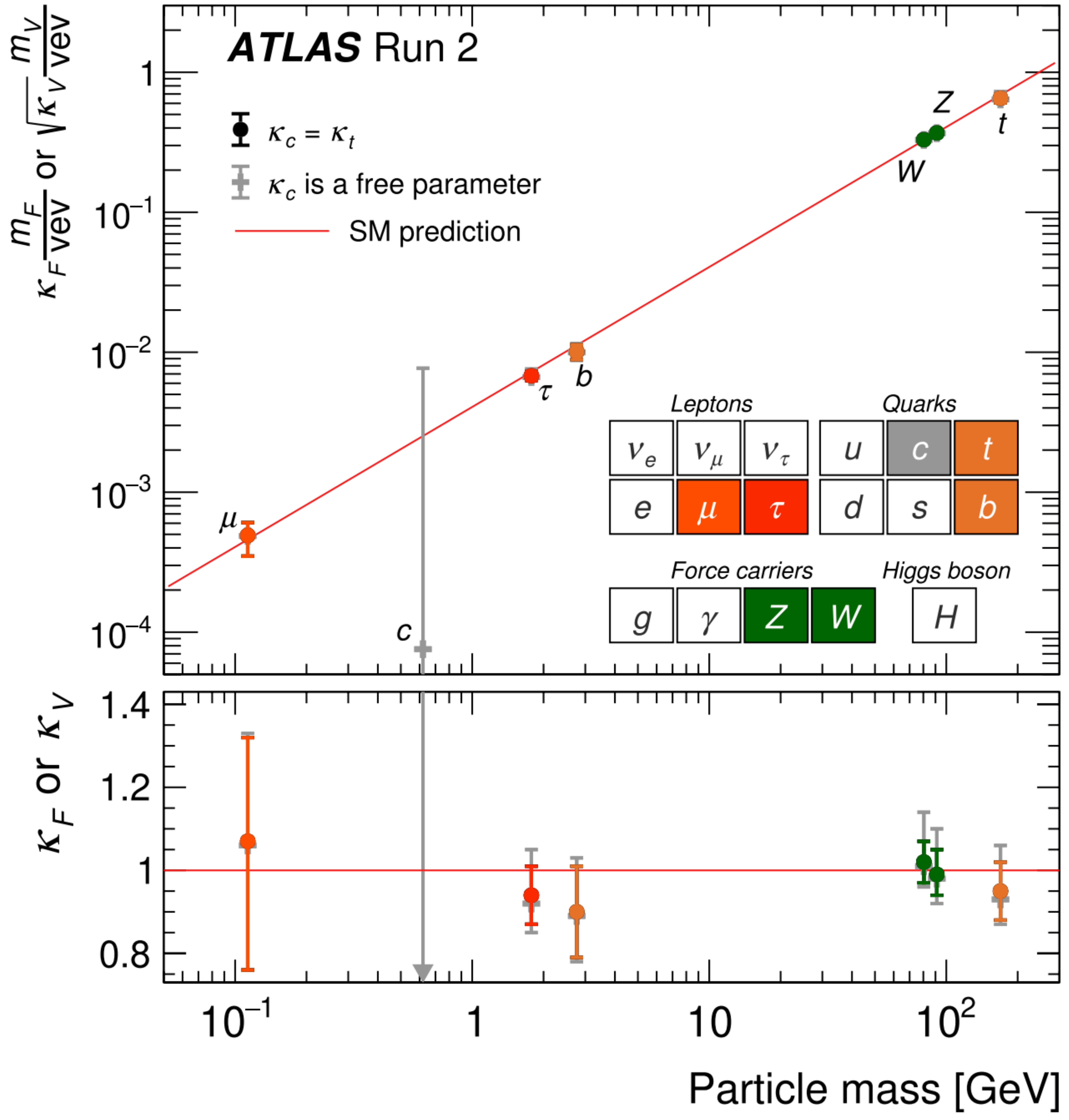
The Standard Model is extremely predictive!


Standard Model Production Cross Section Measurements

Status: October 2023

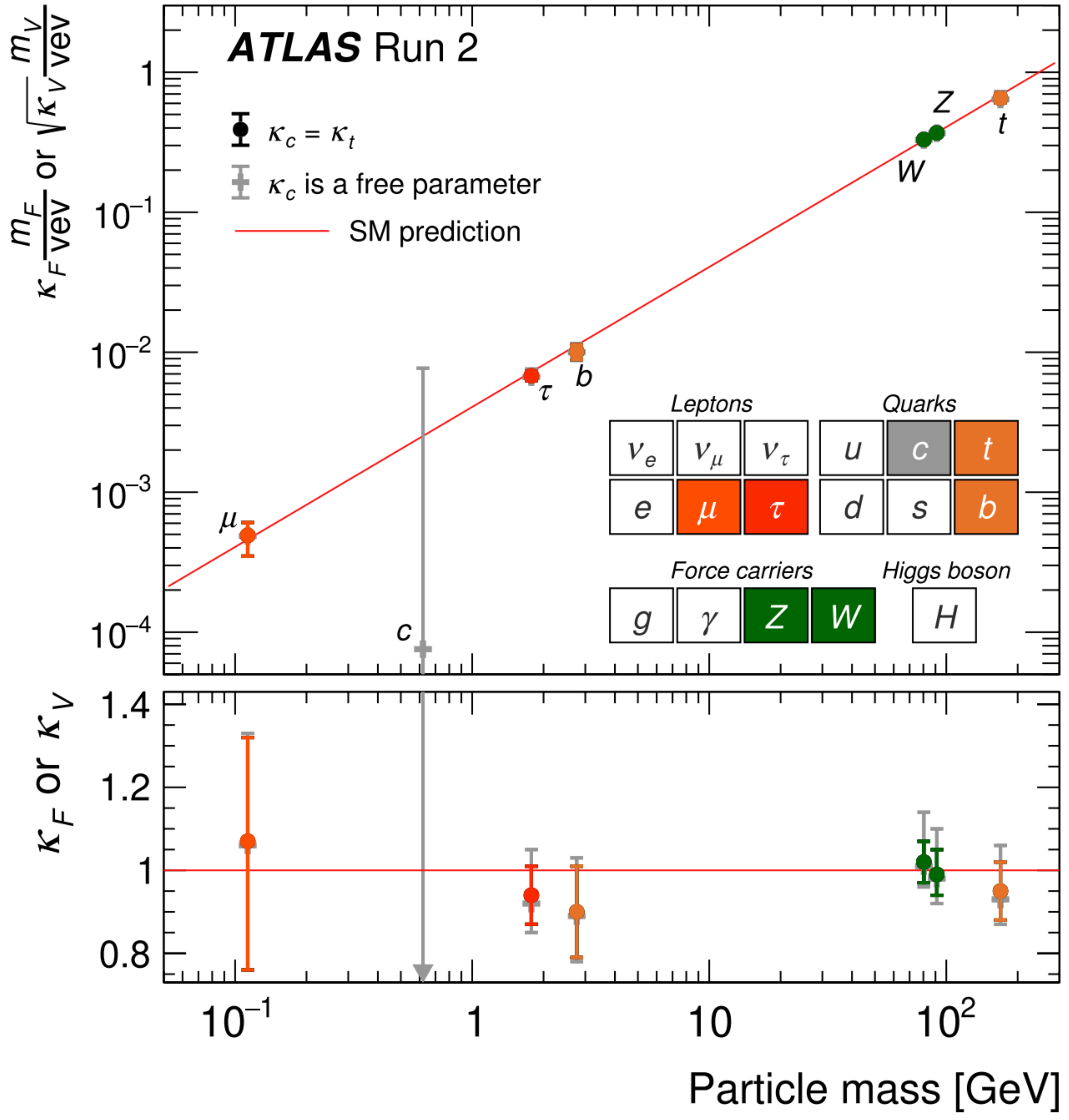
The Standard Model is extremely predictive!

Higgs couplings

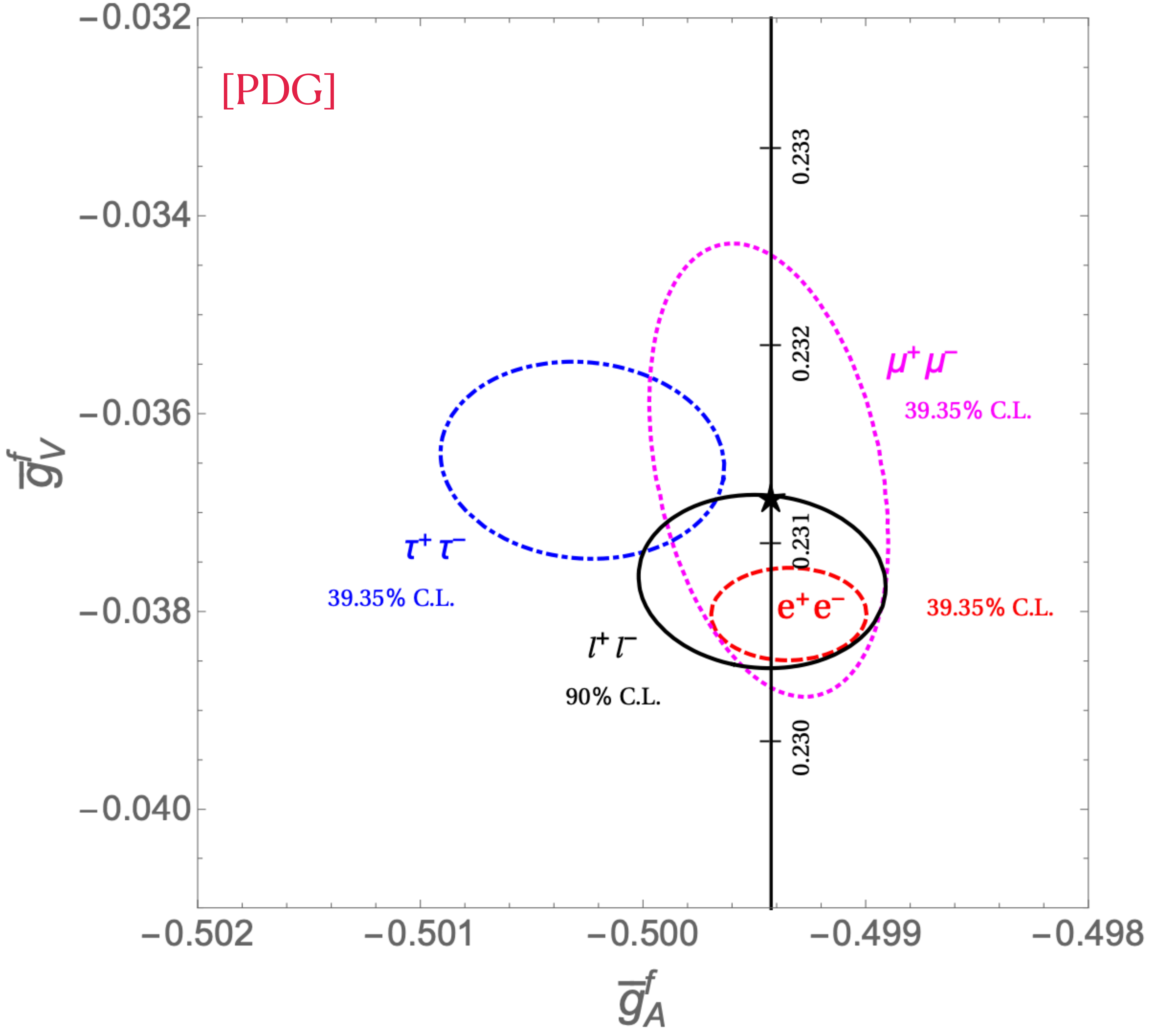


The Standard Model is extremely predictive!

Higgs couplings



Z boson couplings



Electroweak Precision Tests (EWPTs)

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

Electroweak Precision Tests (EWPTs)

- SM has many more observables than parameters ⟹ Predictions!

$$\mathcal{L} = -\frac{1}{4g'^{\,2}} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^A_{\mu\nu} W^{A\,\mu\nu} + |D_\mu H|^2 - \frac{\lambda}{4}|H|^2 \left(|H|^2 - \frac{v^2}{2} \right)$$

Electroweak Precision Tests (EWPTs)

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

$$\mathcal{L} = -\frac{1}{4g'^{\,2}}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^A_{\mu\nu}W^{A\,\mu\nu} + |D_\mu H|^2 - \frac{\lambda}{4}|H|^2\left(|H|^2 - \frac{v^2}{2}\right)$$

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. $\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$

Electroweak Precision Tests (EWPTs)

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

$$\mathcal{L} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^A_{\mu\nu}W^{A\,\mu\nu} + |D_\mu H|^2 - \frac{\lambda}{4}|H|^2\left(|H|^2 - \frac{v^2}{2}\right)$$

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. $\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$

$$\longrightarrow$$

Prediction

$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_w} = 1$$

(At tree level)

Electroweak Precision Tests (EWPTs)

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

$$\mathcal{L} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^A_{\mu\nu}W^{A\,\mu\nu} + |D_\mu H|^2 - \frac{\lambda}{4}|H|^2\left(|H|^2 - \frac{v^2}{2}\right)$$

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. $\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$

$$\longrightarrow$$

Prediction

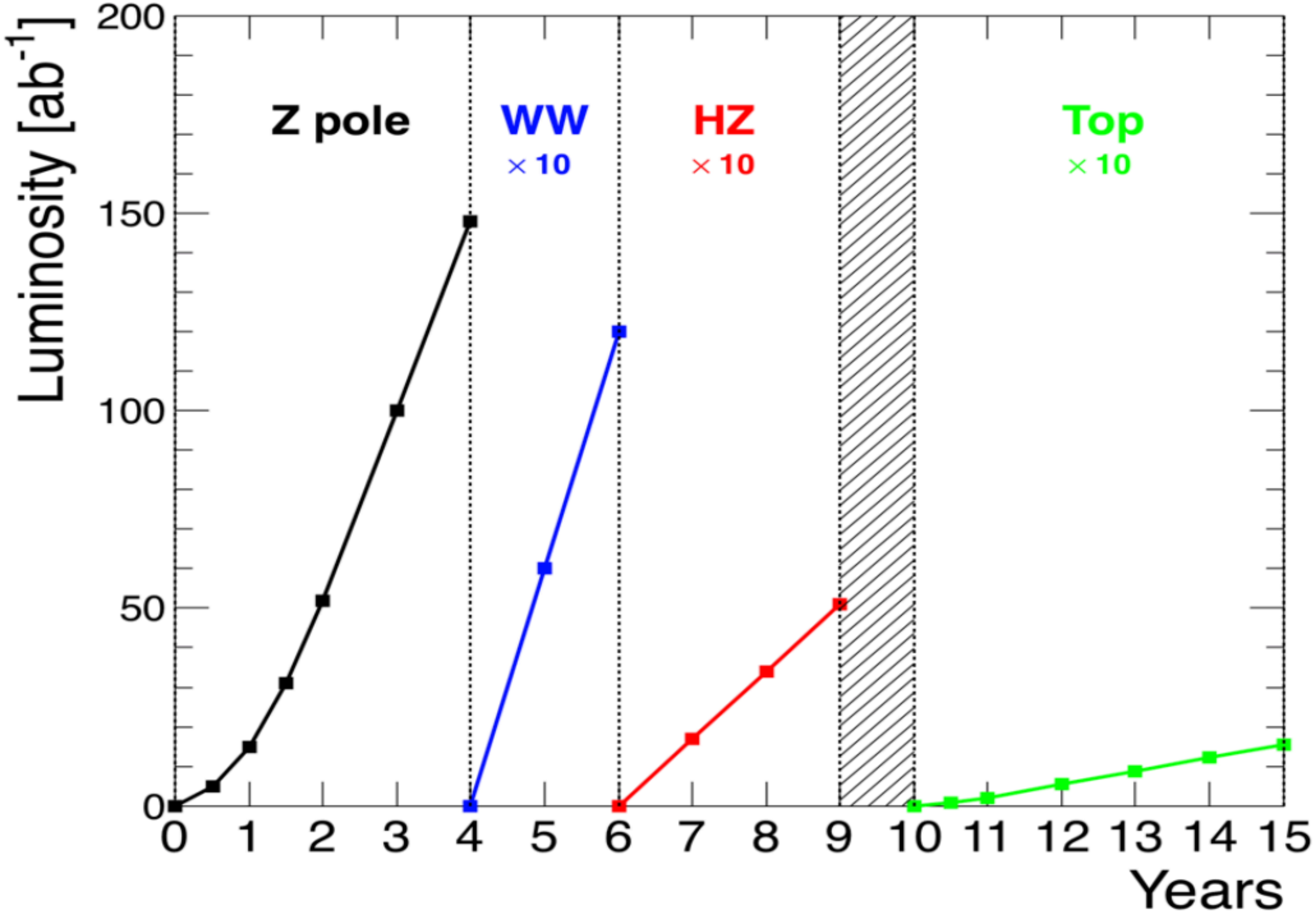
$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_w} = 1$$

(At tree level)

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

The FCC-ee is an incredible precision device!

[FCC CDR Vol. 2]

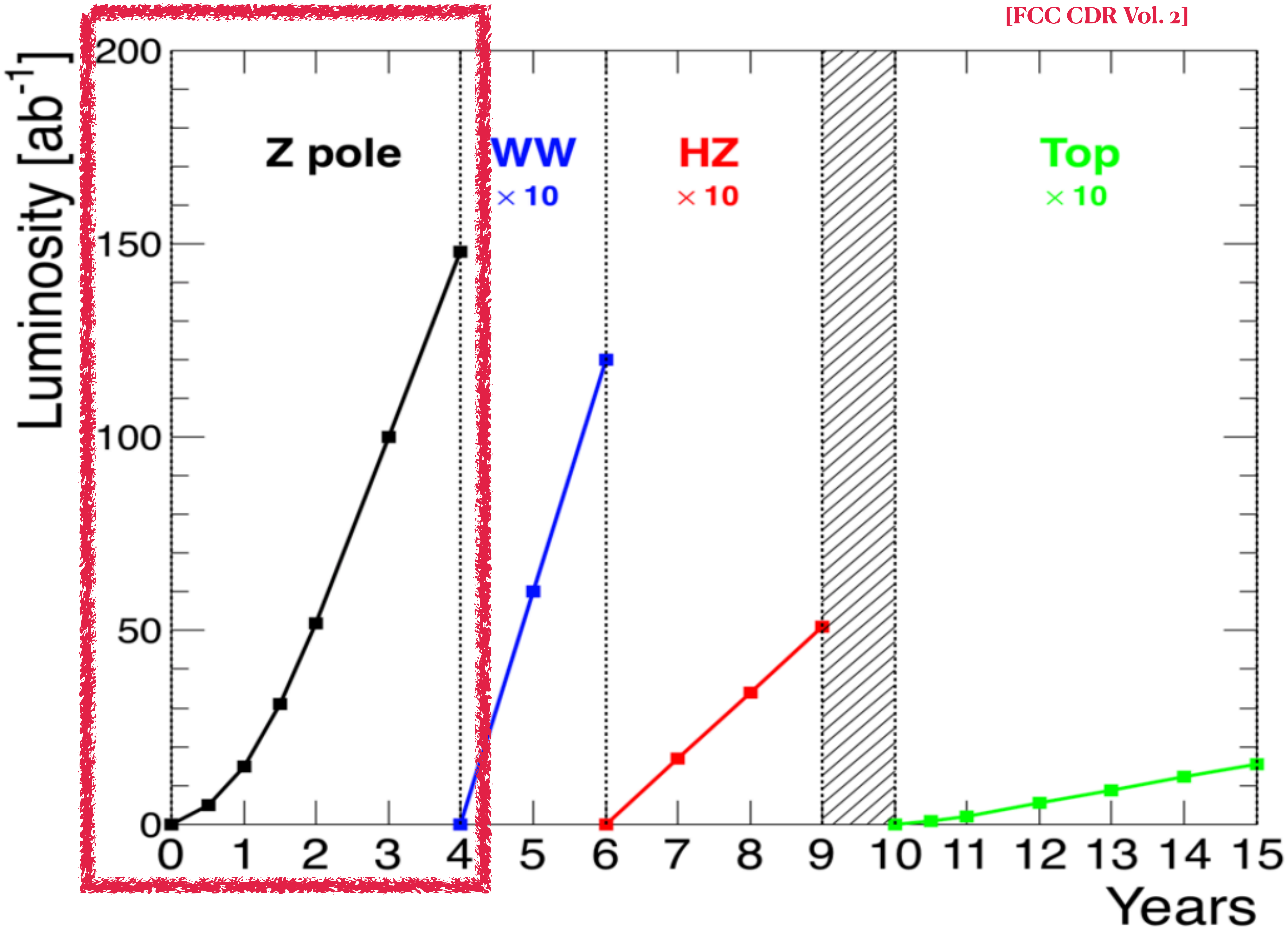


The FCC-ee is an incredible precision device!

The FCC-ee will produce roughly 5×10^{12} Z-bosons!

(Roughly a factor of 10^5 more than produced at LEP)

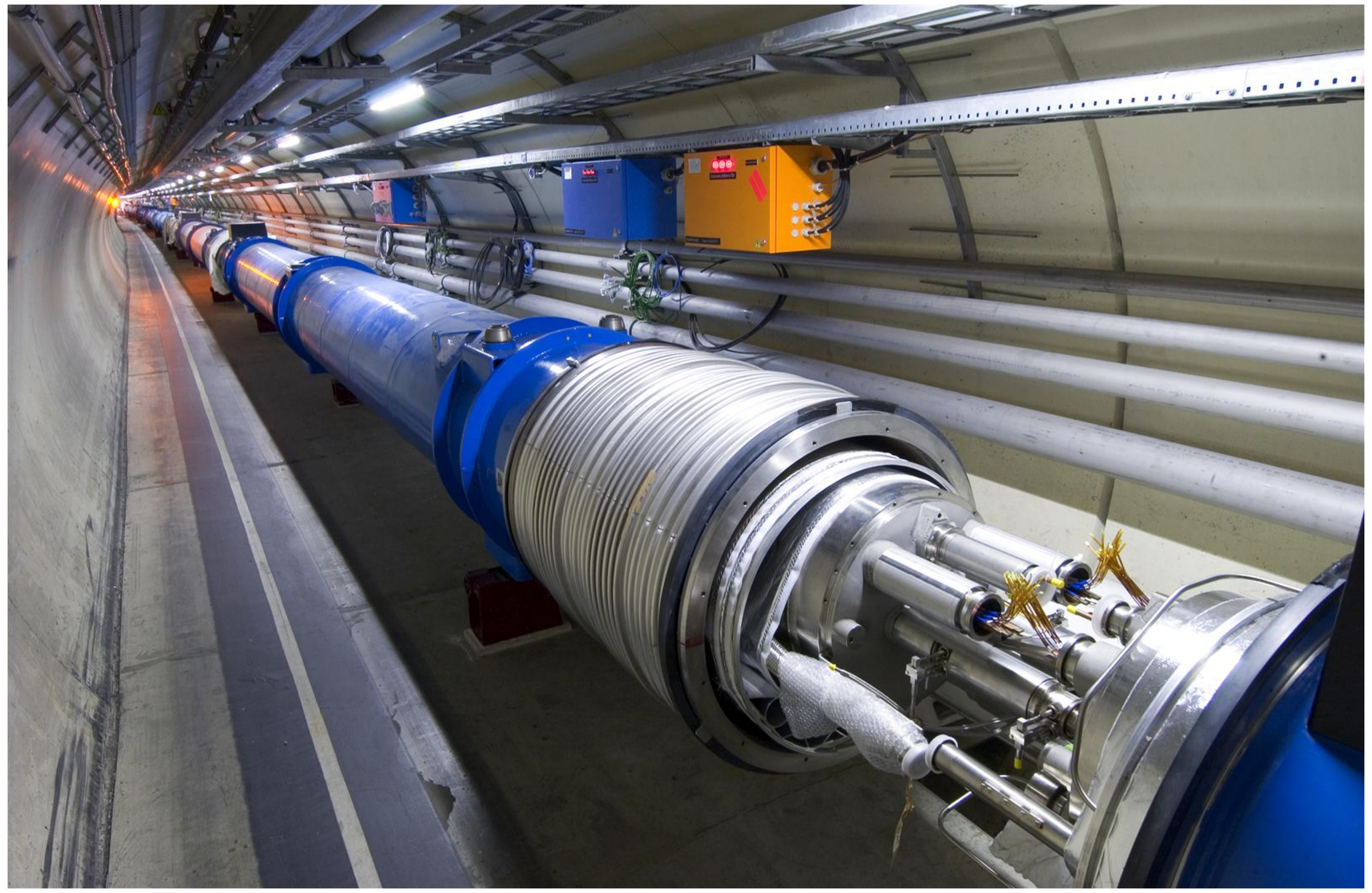
[FCC CDR Vol. 2]



What experiment explores the highest energy scales?

What experiment explores the highest energy scales?

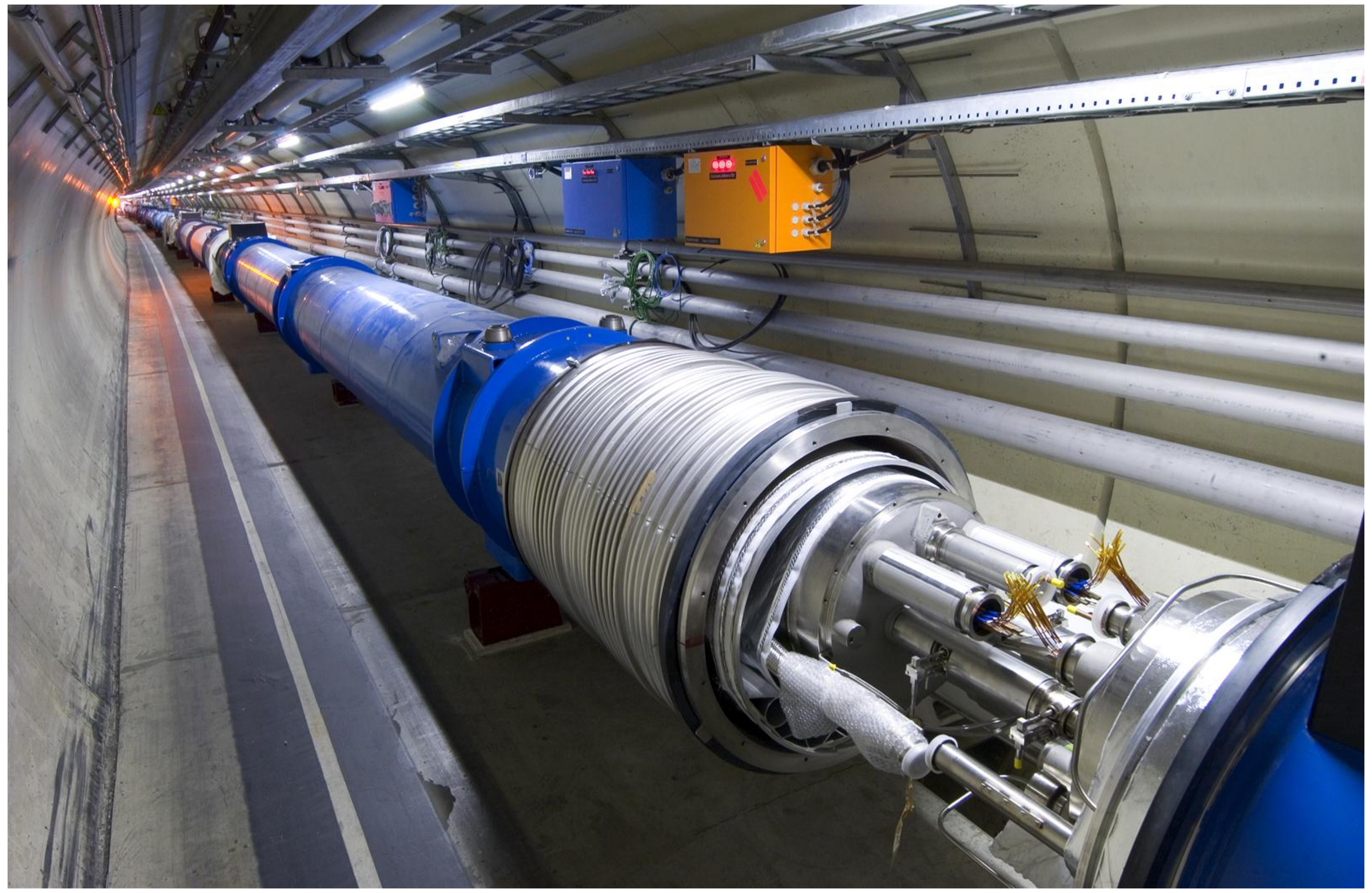
LHC?



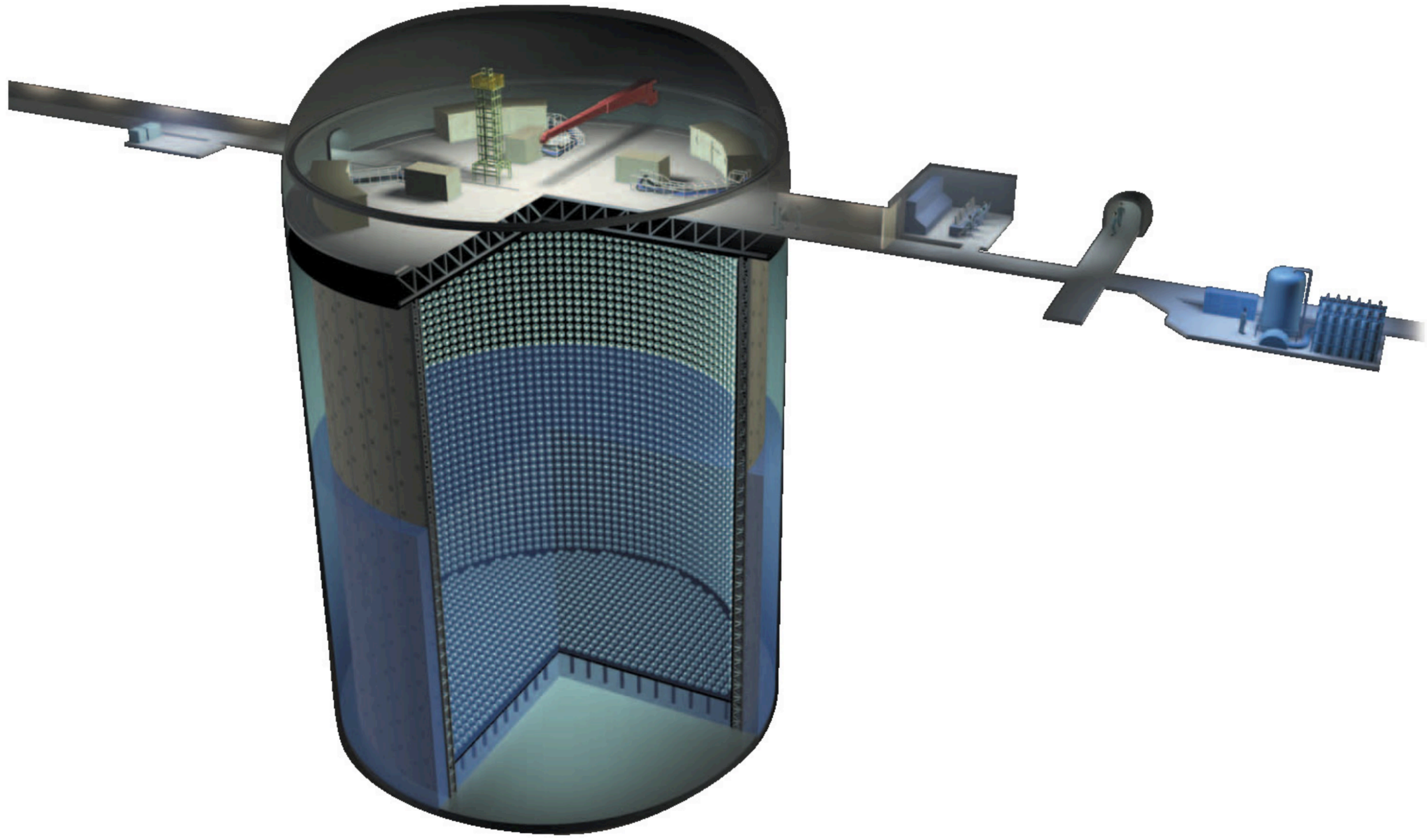
Directly explores energy scales $\Lambda \sim 10^3$ GeV.

What experiment explores the highest energy scales?

LHC?



Super-Kamiokande

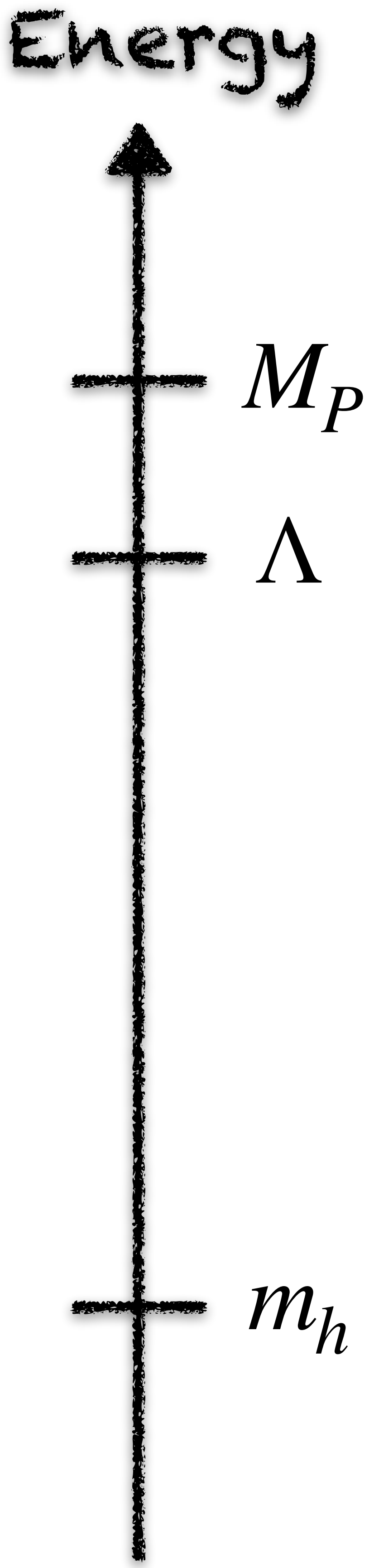


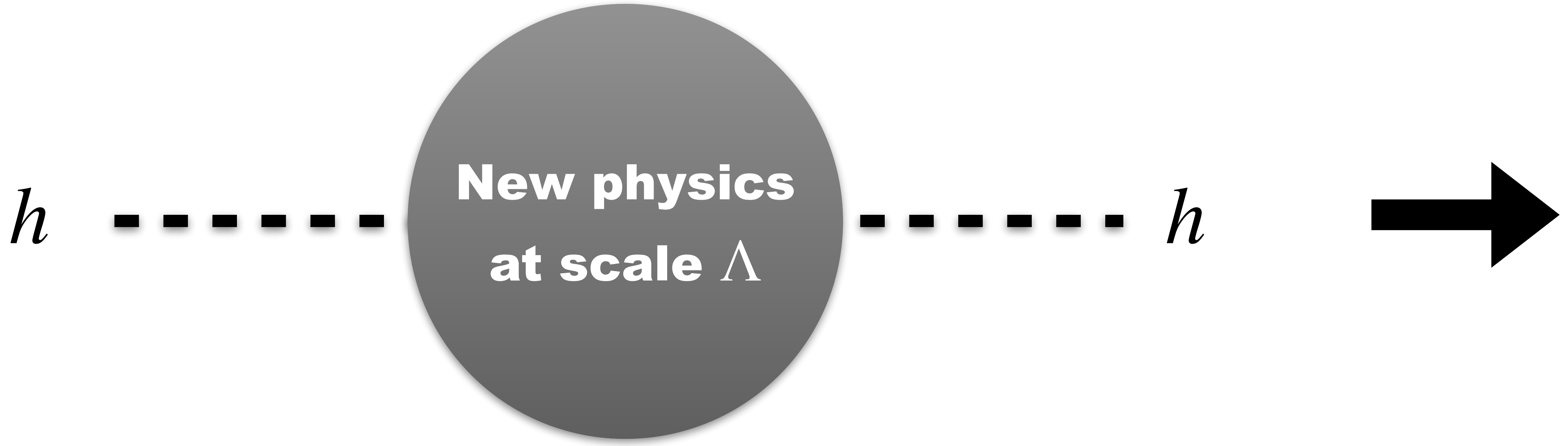
Directly explores energy scales $\Lambda \sim 10^3$ GeV.

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

What mysteries can we explore using these methods?

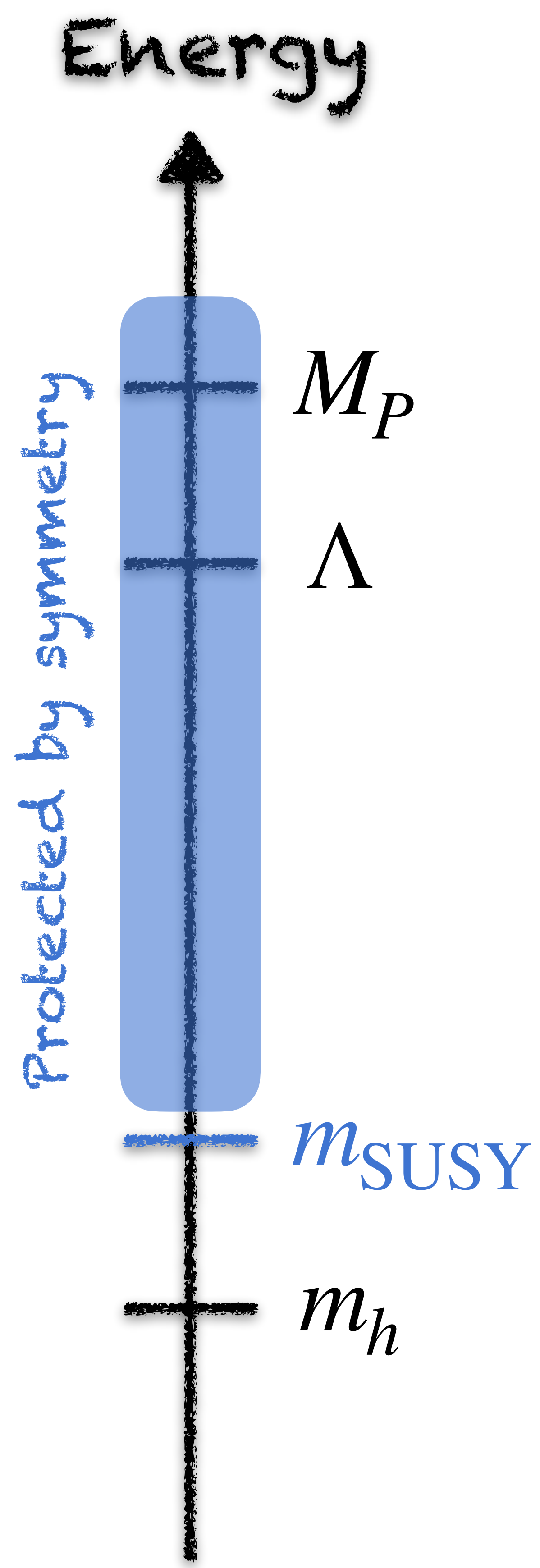
The Higgs Hierarchy Problem

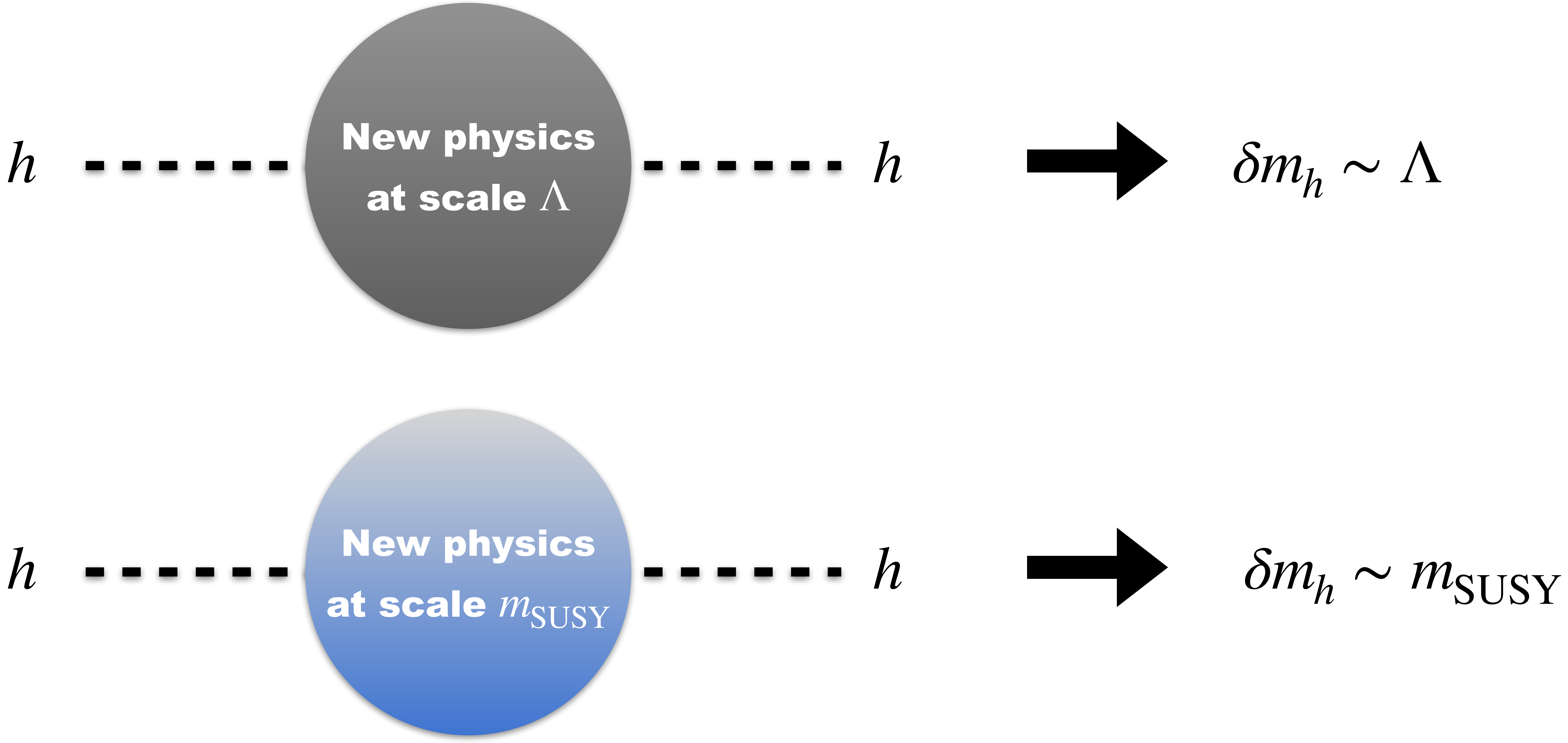




$\delta m_h \sim \Lambda$

The Higgs Hierarchy Problem

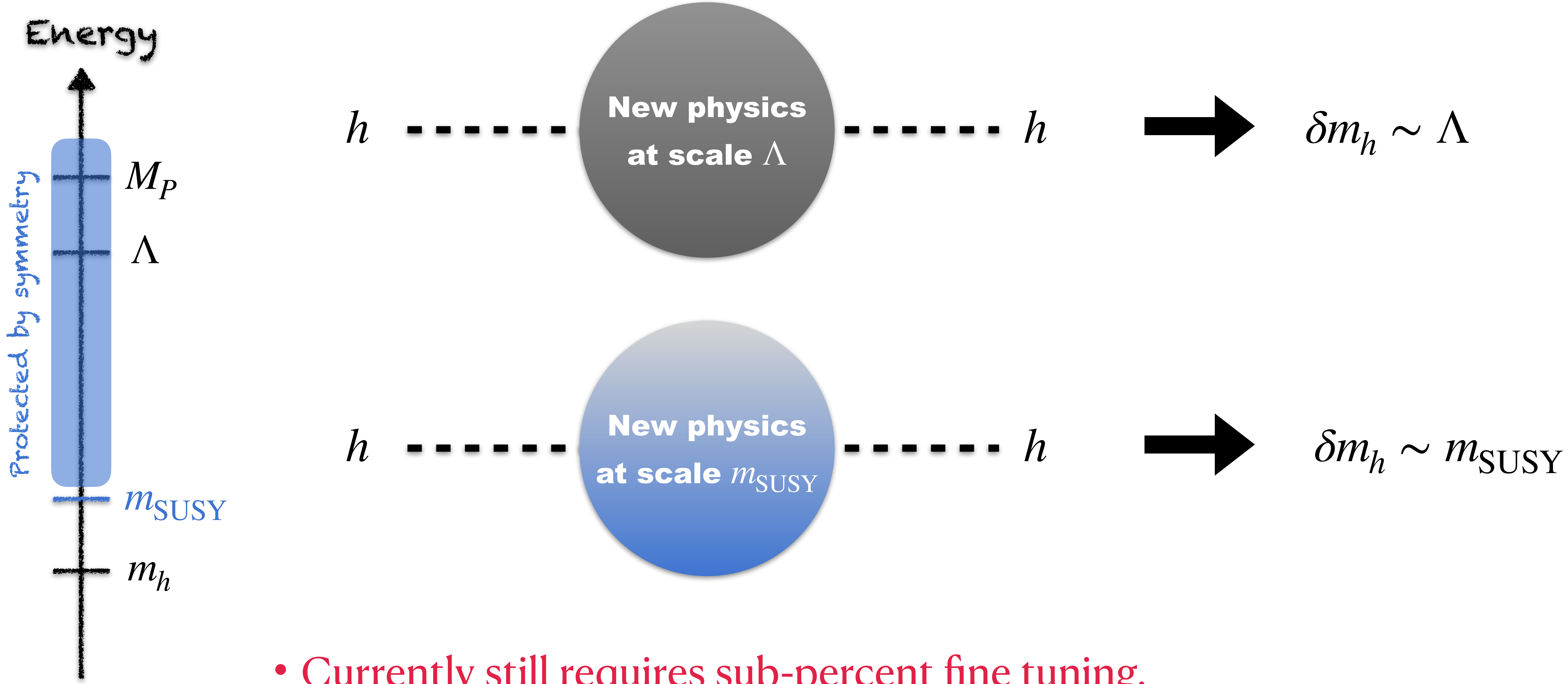




h New physics at scale Λ h $\Rightarrow$ $\delta m_h \sim \Lambda$

h New physics at scale m_{SUSY} h $\Rightarrow$ $\delta m_h \sim m_{\text{SUSY}}$

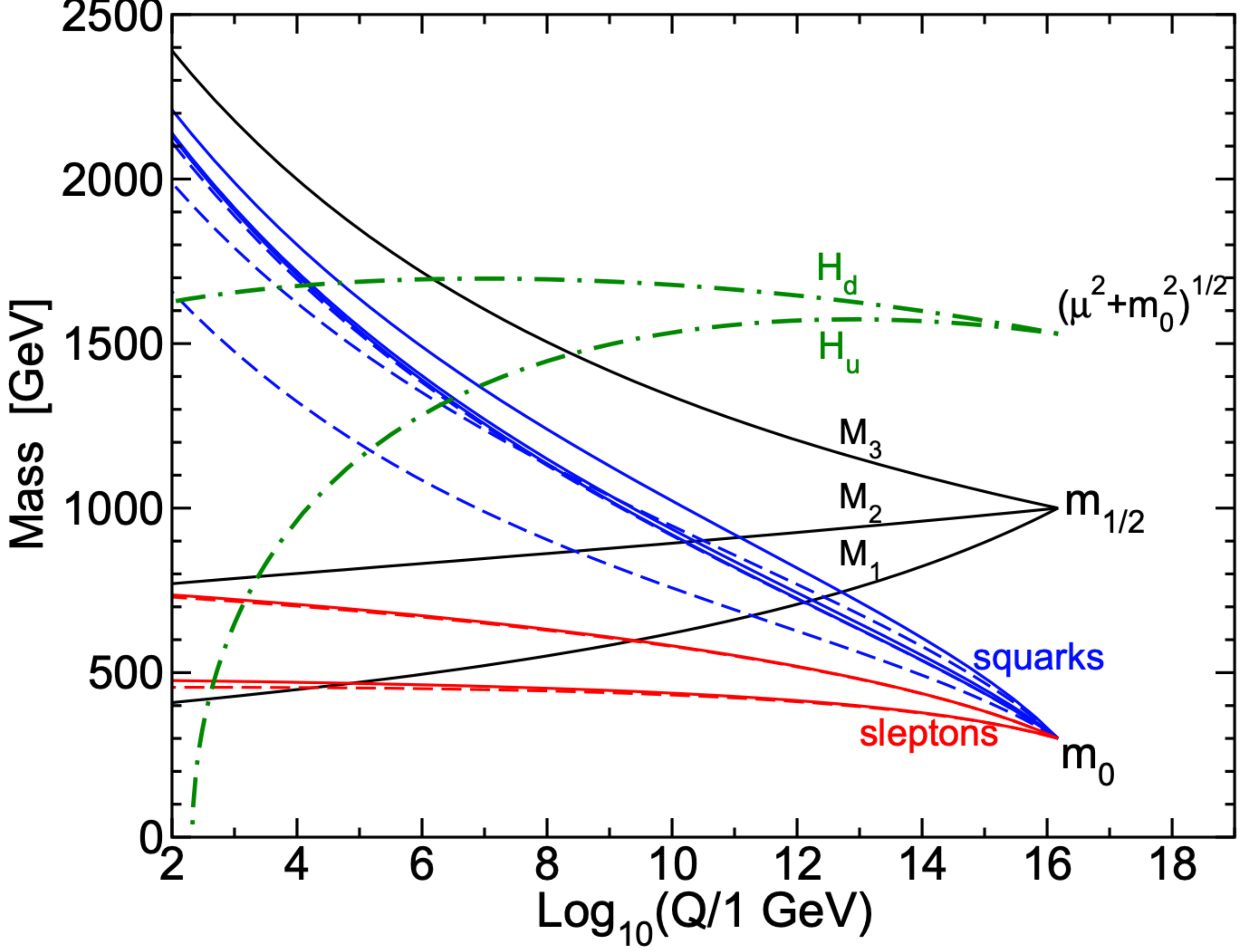
The Higgs Hierarchy Problem



- 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?

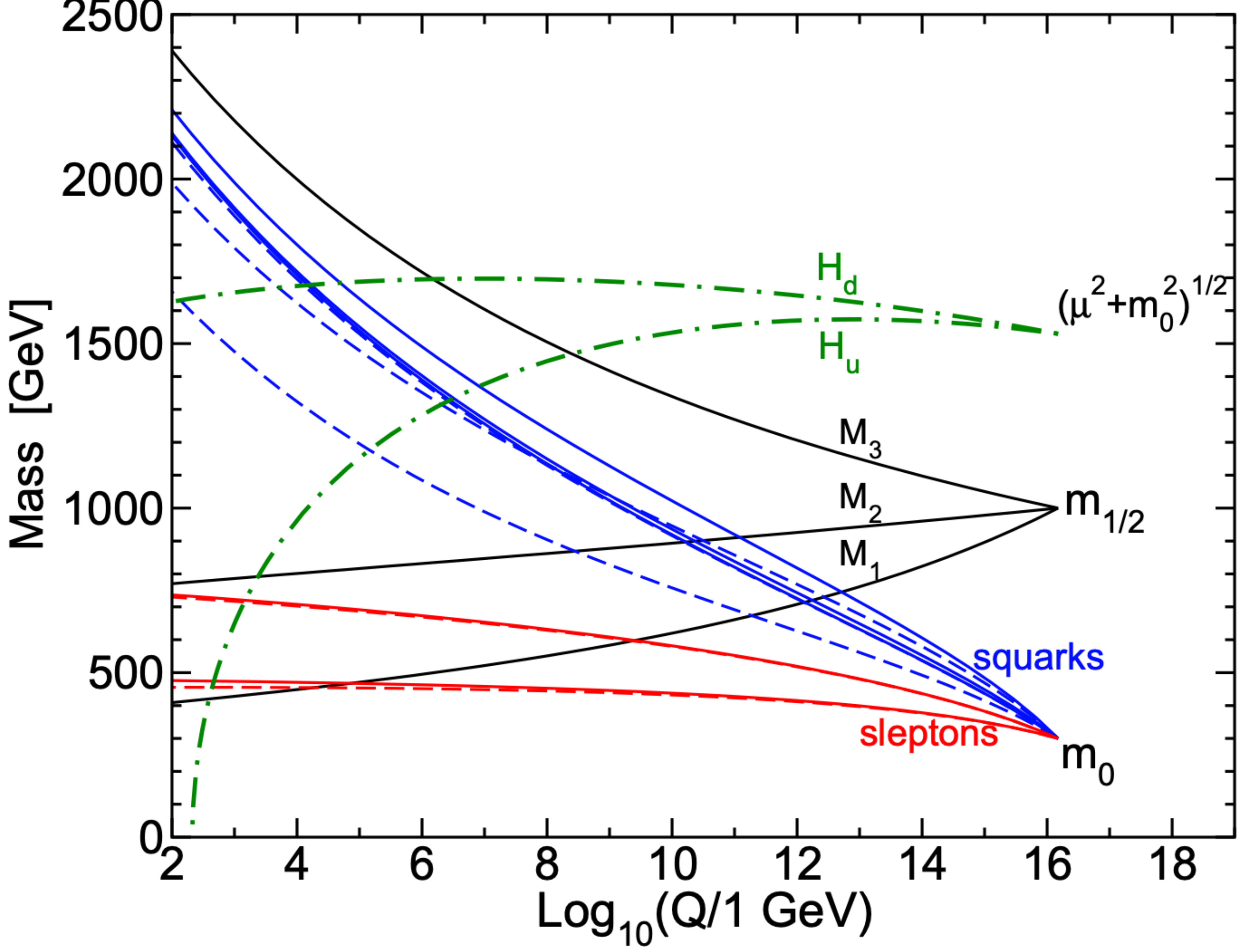
[Martin, 9709356]



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

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

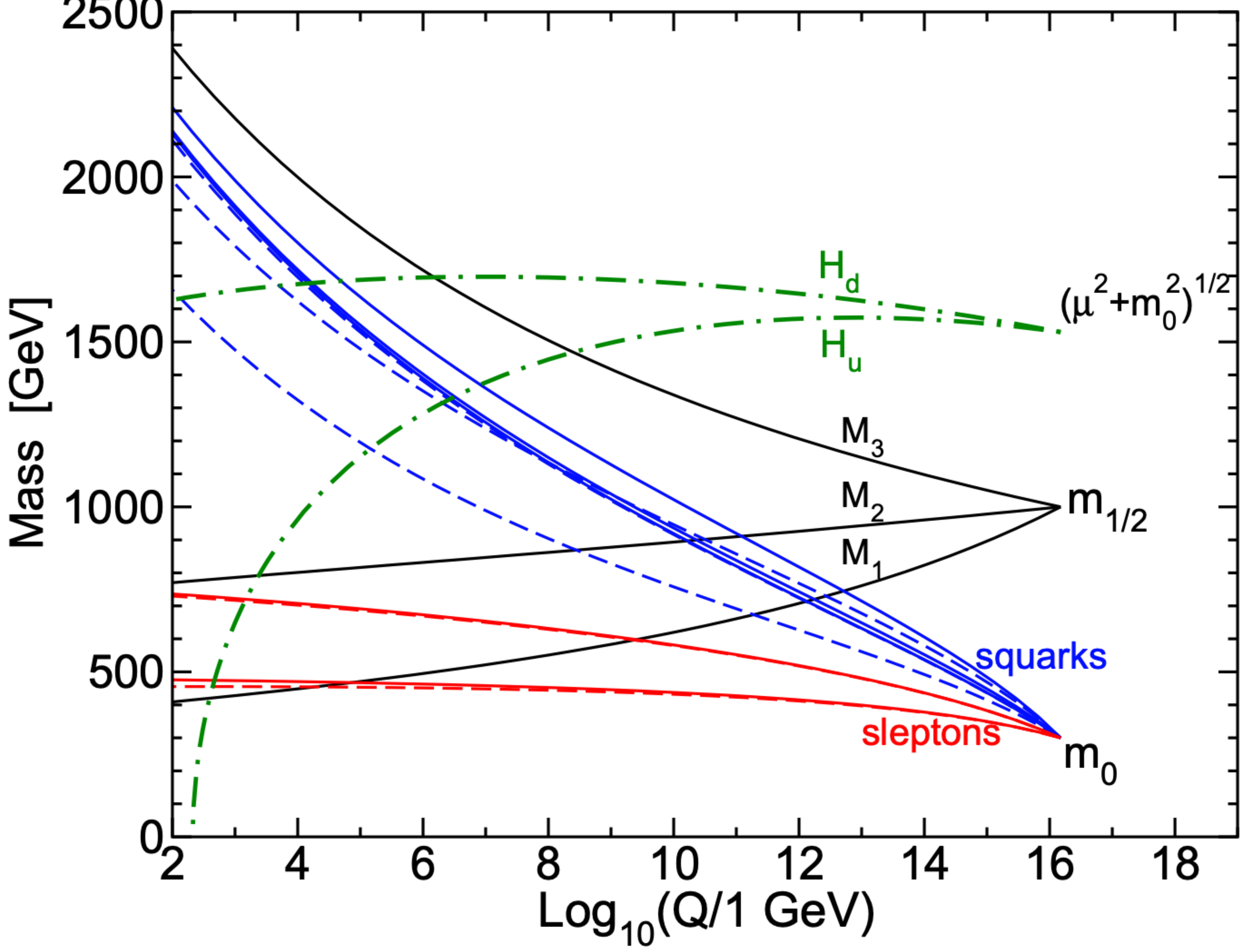
[Martin, 9709356]



- Running motivates $m_{\text{colored}} > m_{\text{uncolored}}$.
- Colored sparticles may not be produced at the LHC.

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

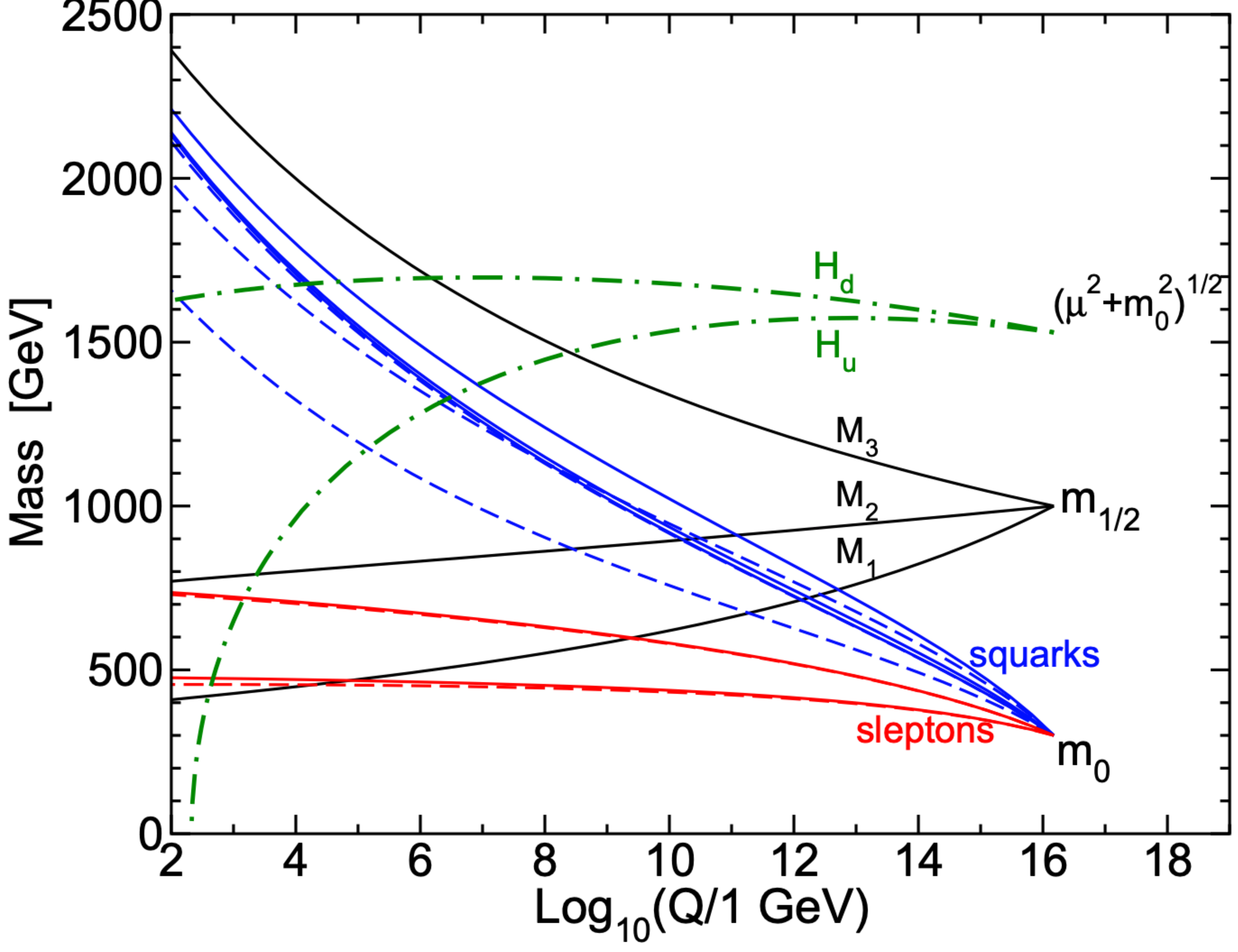
[Martin, 9709356]



- 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.

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

[Martin, 9709356]

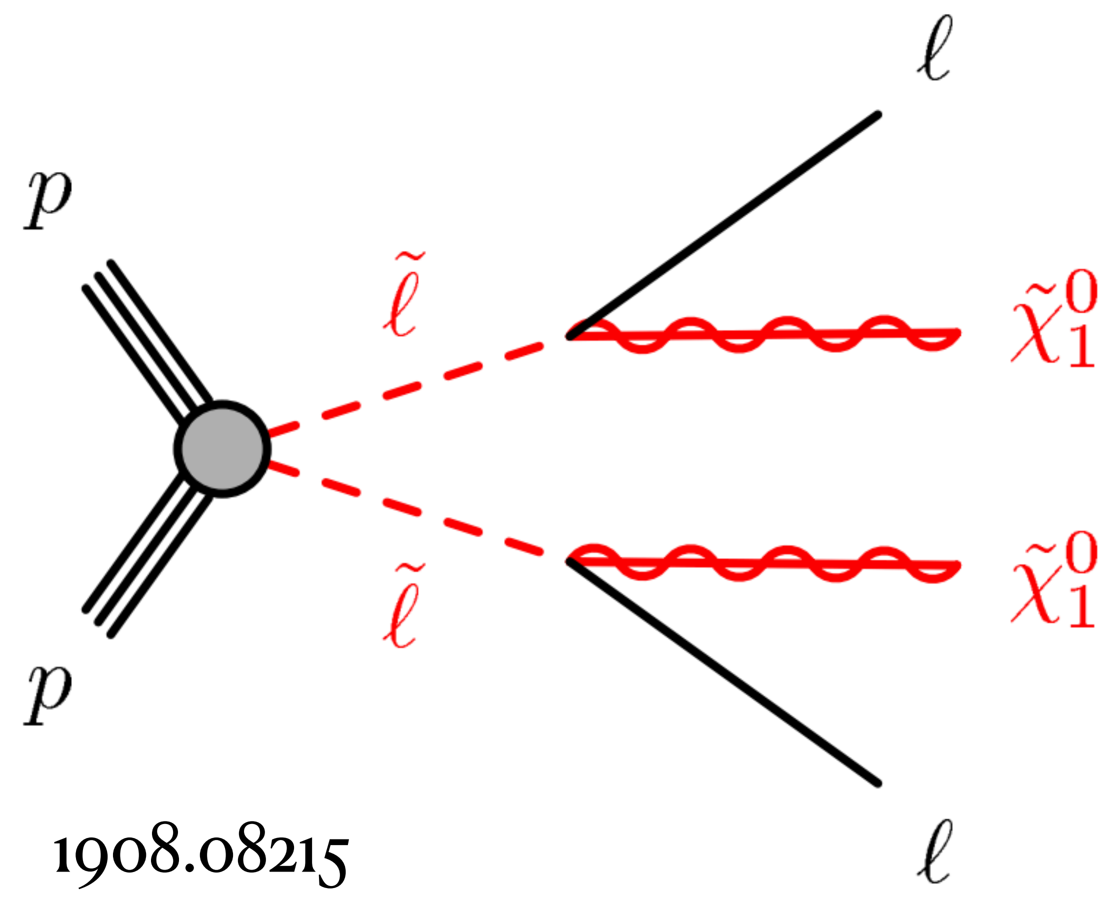


- Running motivates $m_{\text{colored}} > m_{\text{uncolored}}$.
- Colored sparticles may not be produced at the LHC.
- Dominant effect on EWPTs may come from color neutral sparticles.

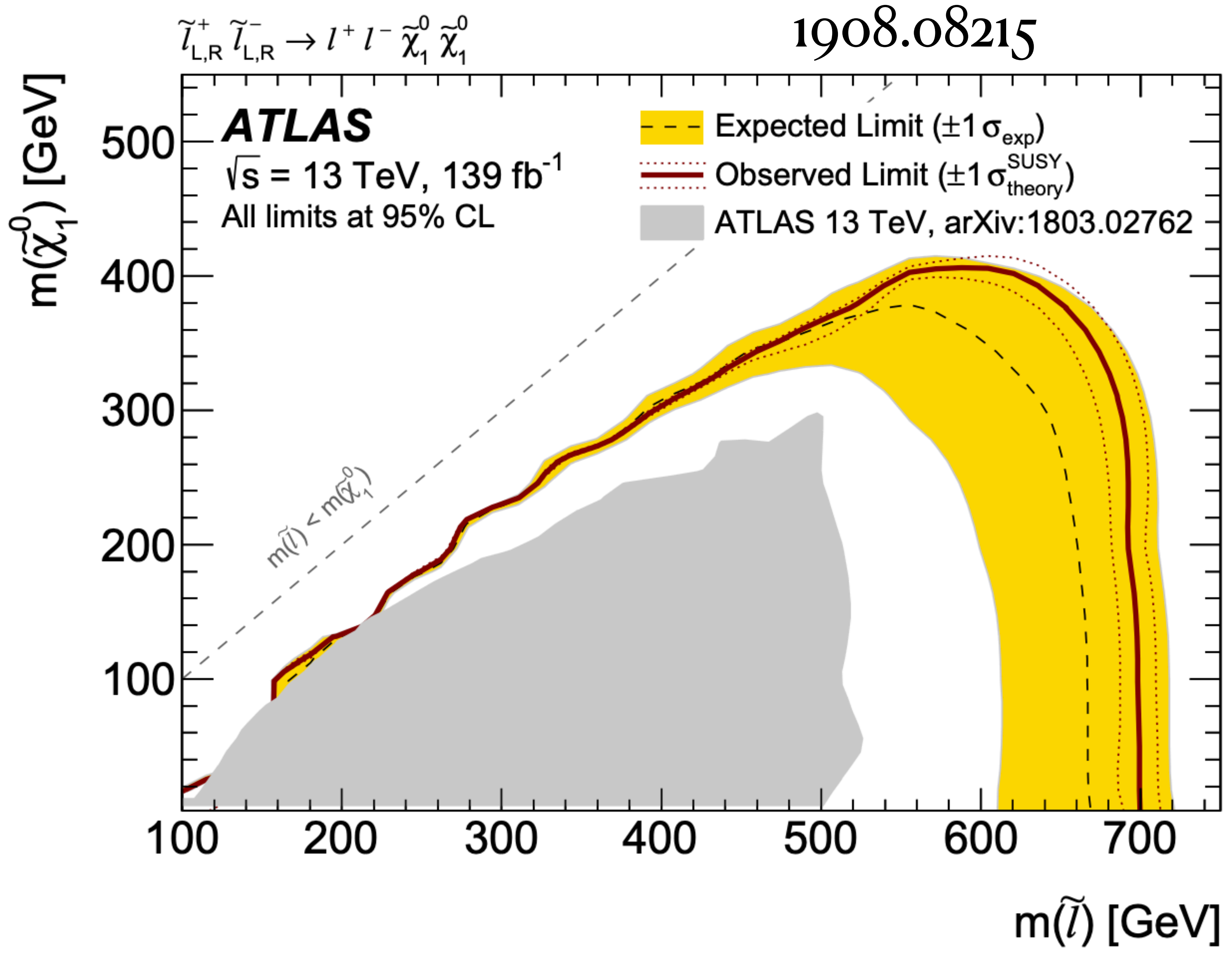
$\Longrightarrow$ FCC-ee may indirectly see SUSY using EWPTs even if the LHC sees nothing.

Simplified SUSY Models

LHC SUSY searches often consider representative simplified models.



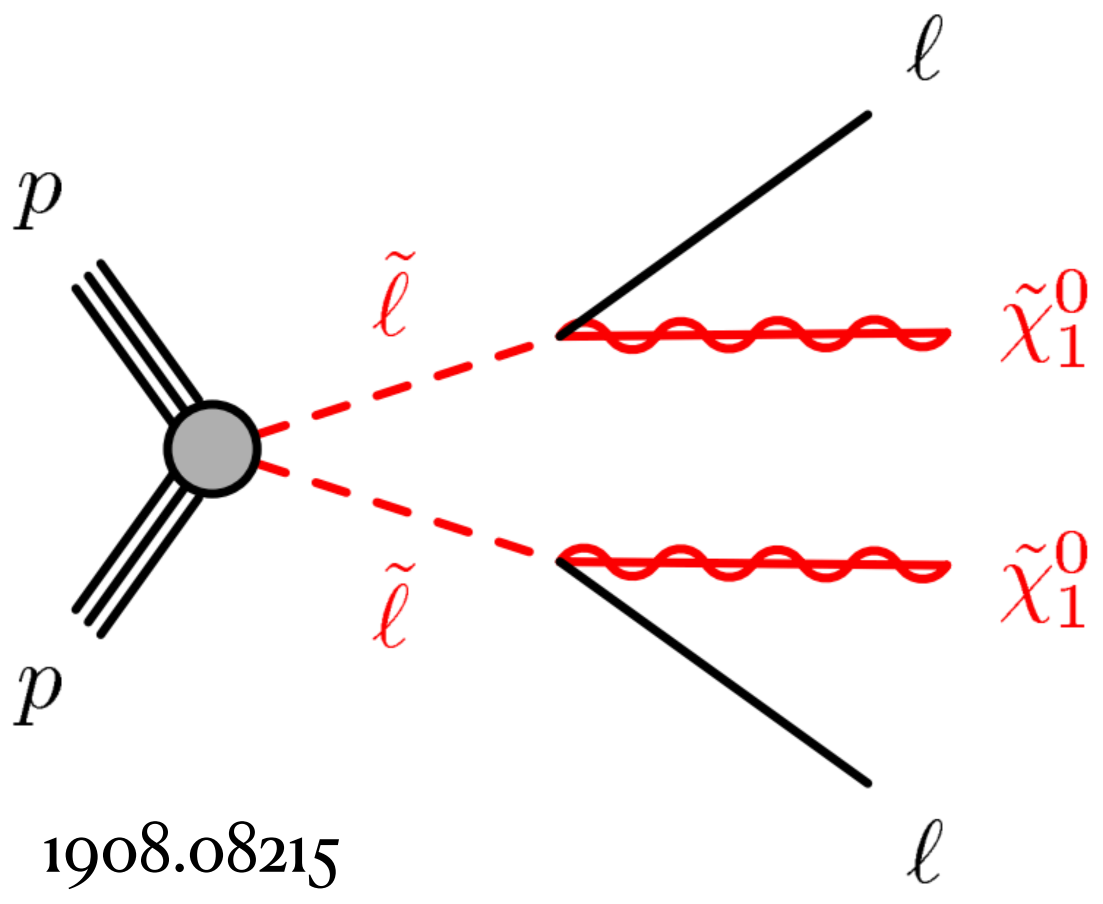
1908.08215



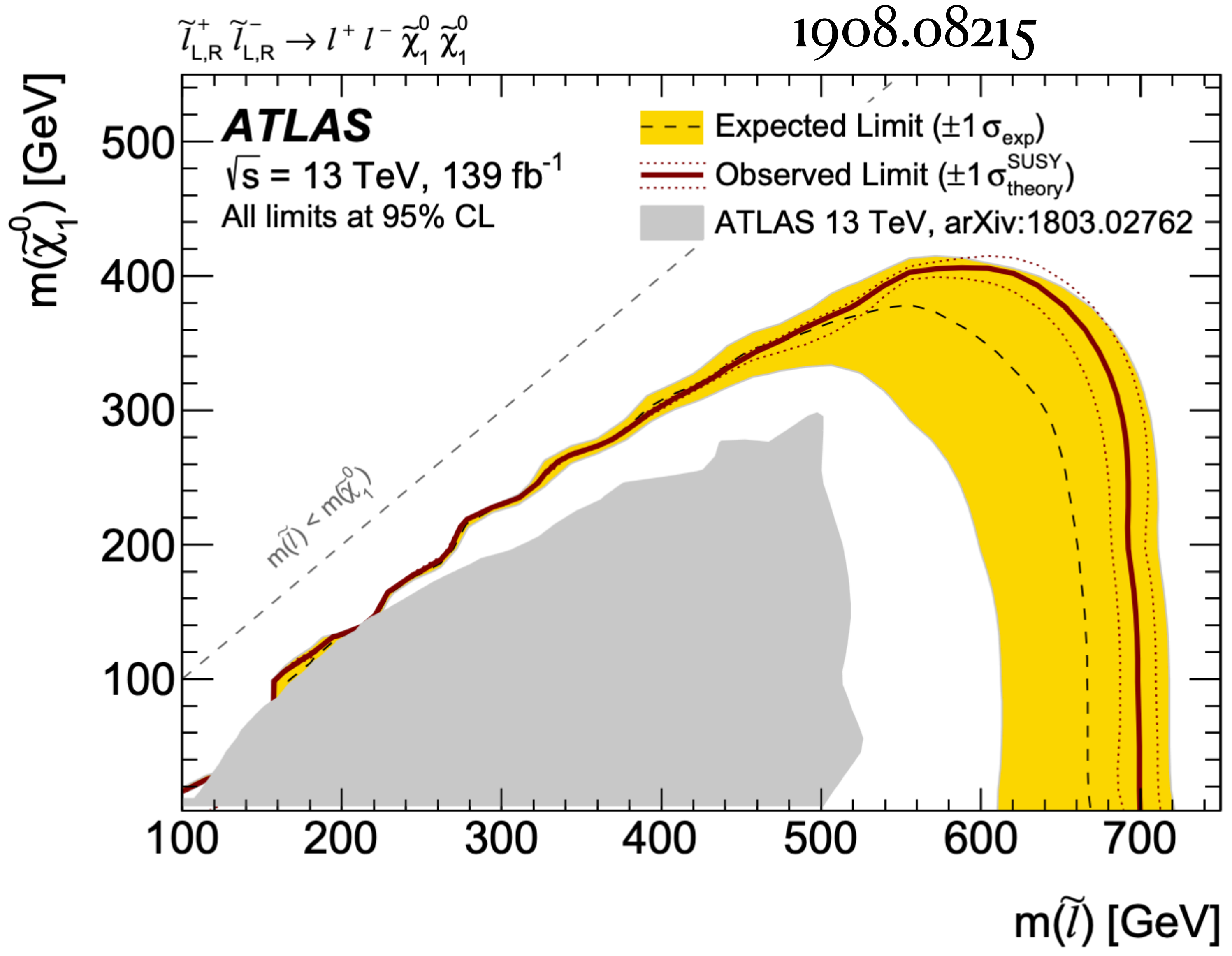
1908.08215

Simplified SUSY Models

LHC SUSY searches often consider representative simplified models.



1908.08215



1908.08215

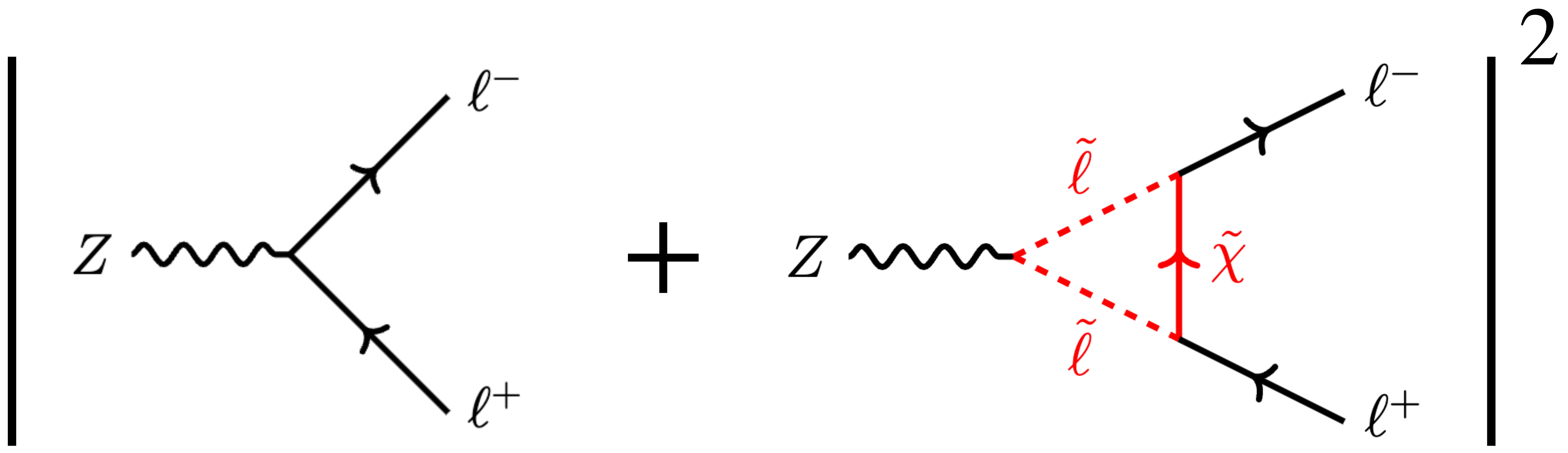
For simplicity we will do the same:

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?

Let $\tilde{\chi} = (\tilde{W}, \tilde{B})$ and $\tilde{\ell} = (\tilde{L}, \tilde{e})$.

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

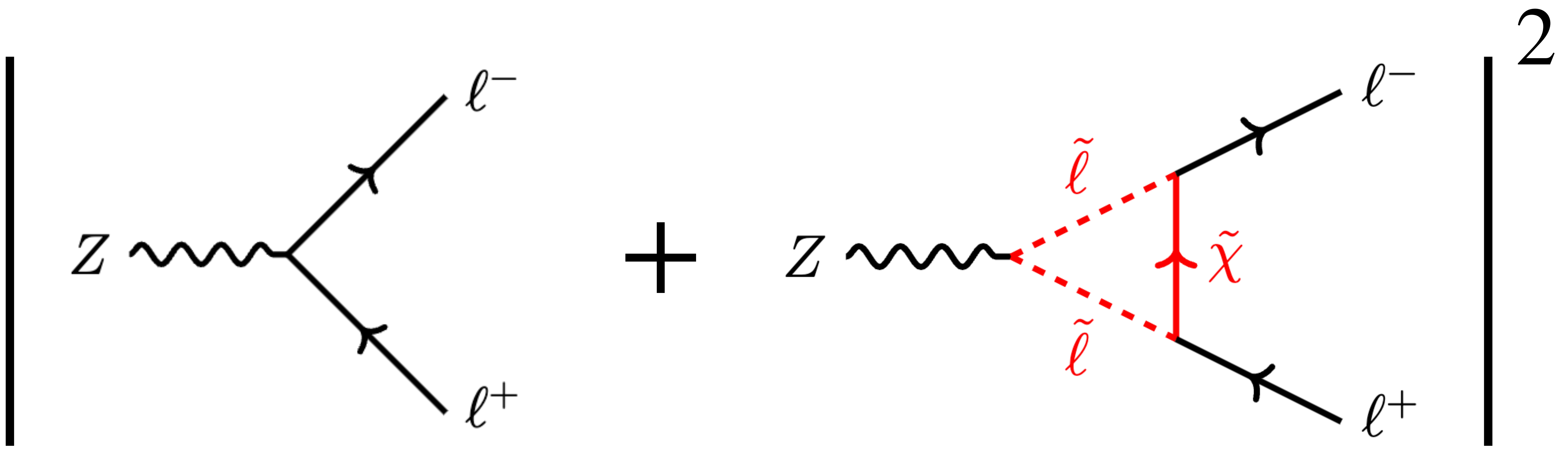


(Just one of several diagrams)

How might SUSY show up in EWPTs?

Let $\tilde{\chi} = (\tilde{W}, \tilde{B})$ and $\tilde{\ell} = (\tilde{L}, \tilde{e})$.

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



(Just one of several diagrams)

$$\frac{\Gamma_{Z\to\ell\ell} - \Gamma^{(SM)}_{Z\to\ell\ell}}{\Gamma^{(SM)}_{Z\to\ell\ell}} \propto \frac{g^2}{16\pi^2}\left(\frac{m_Z}{M_{\mathrm{SUSY}}}\right)^2 \longrightarrow \boxed{M^{\mathrm{probed}}_{SUSY} \sim 1\ \mathrm{TeV} \times \left(\frac{\delta\Gamma/\Gamma}{10^{-5}}\right)}$$

Some details

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

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

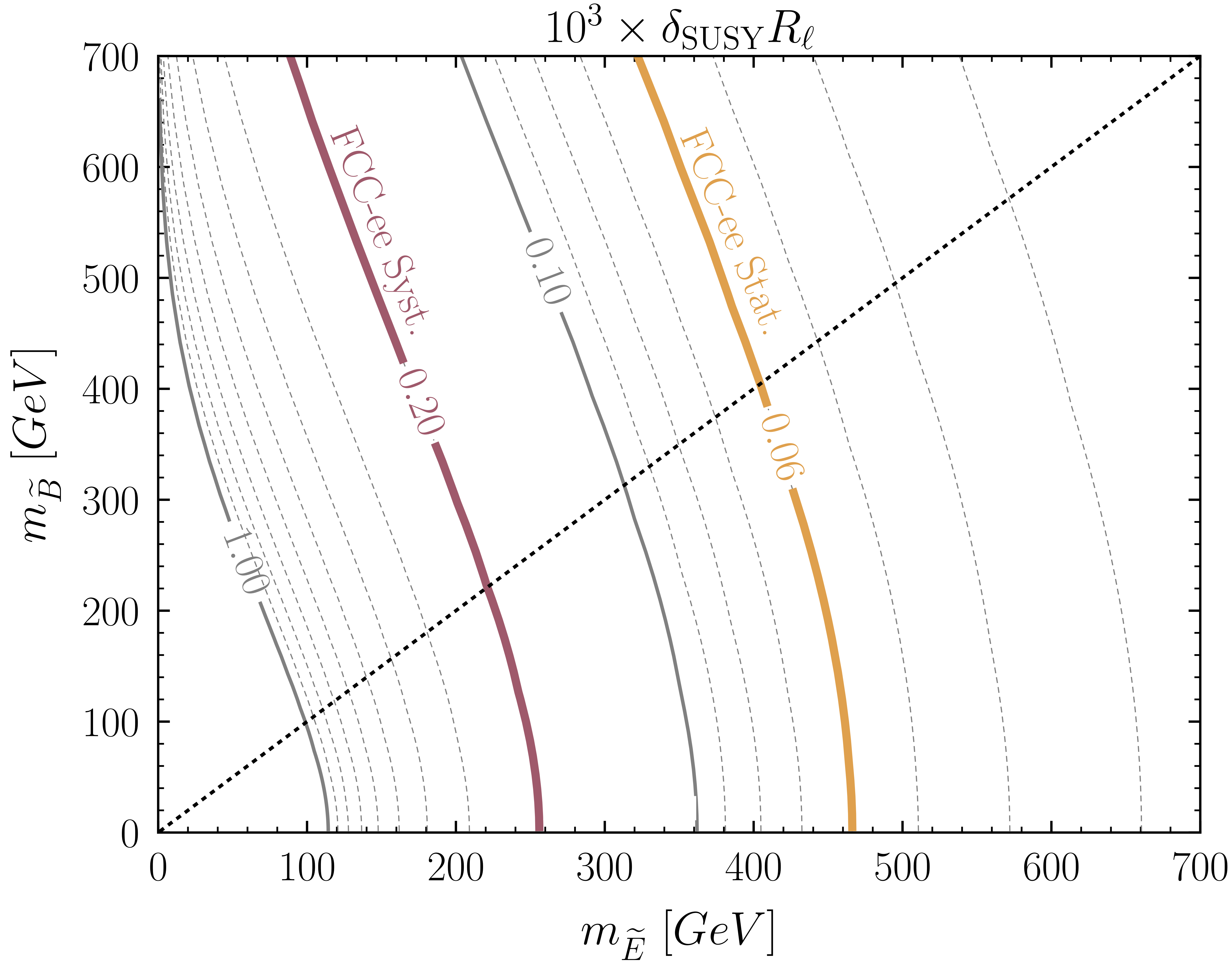
Some details

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

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

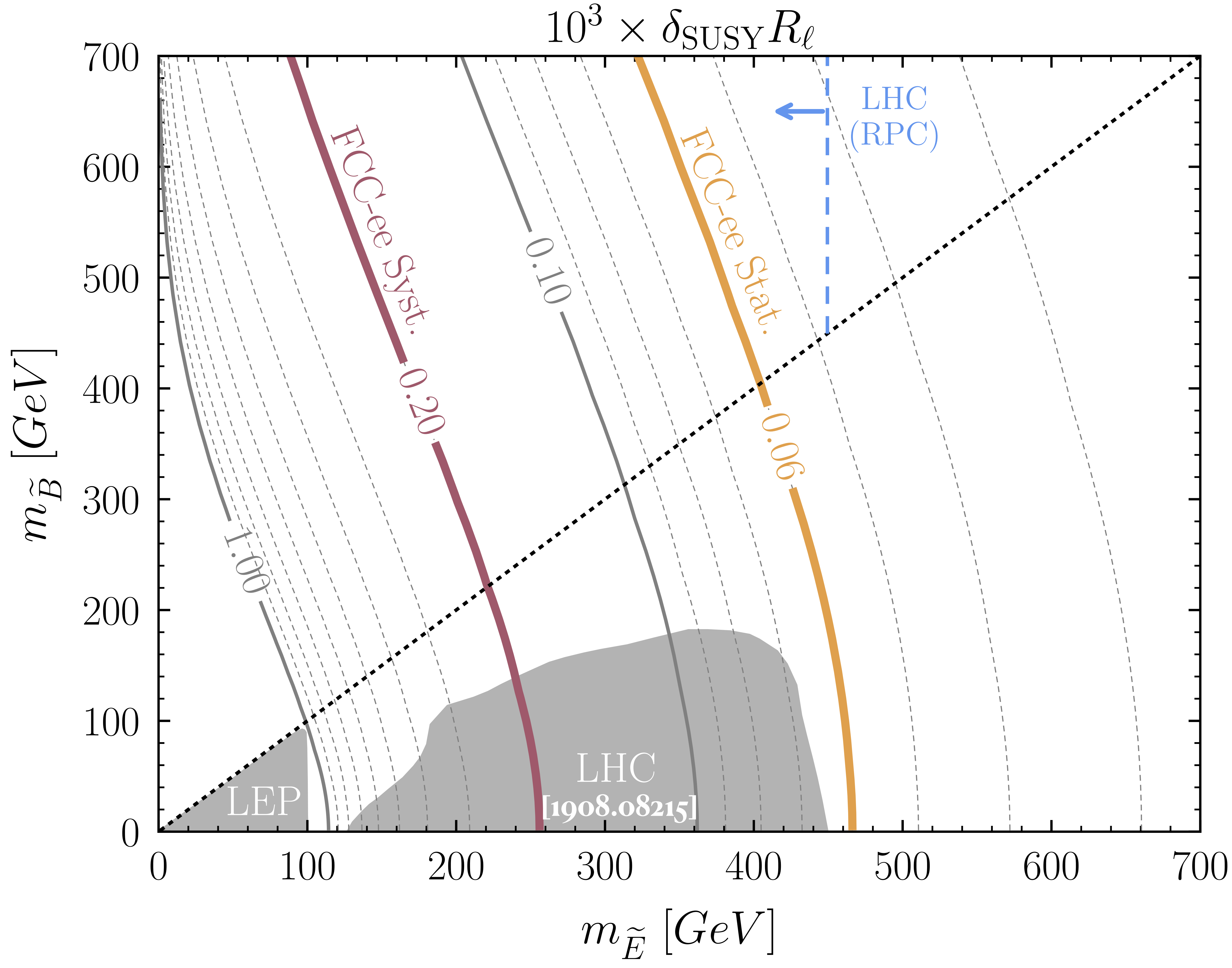
Still depends on θ_W and $\alpha_s(M_Z)$. These must be determined by other measurements.

Results



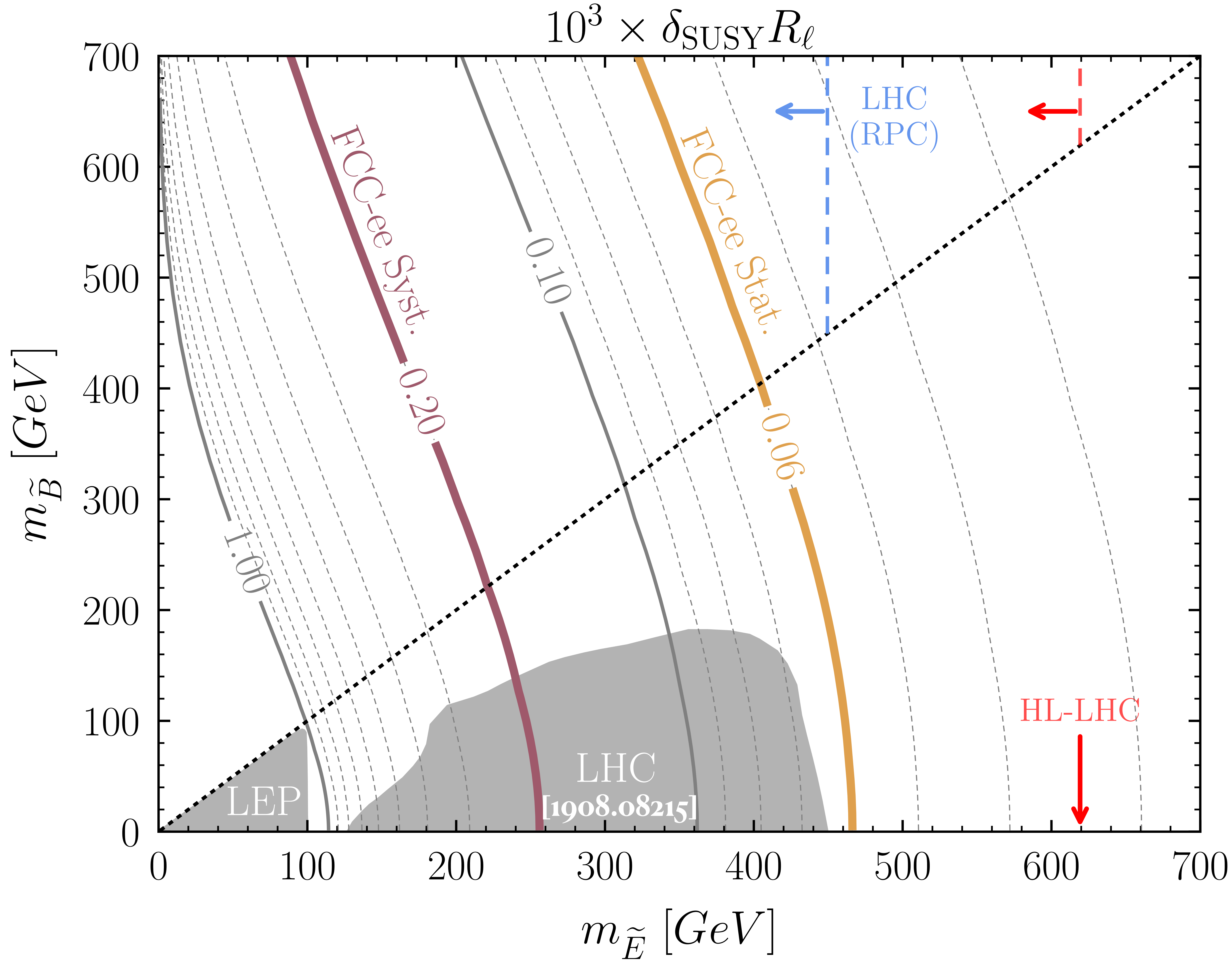
Bino + RH Slepton (Preliminary)

Results



Bino + RH Slepton (Preliminary)

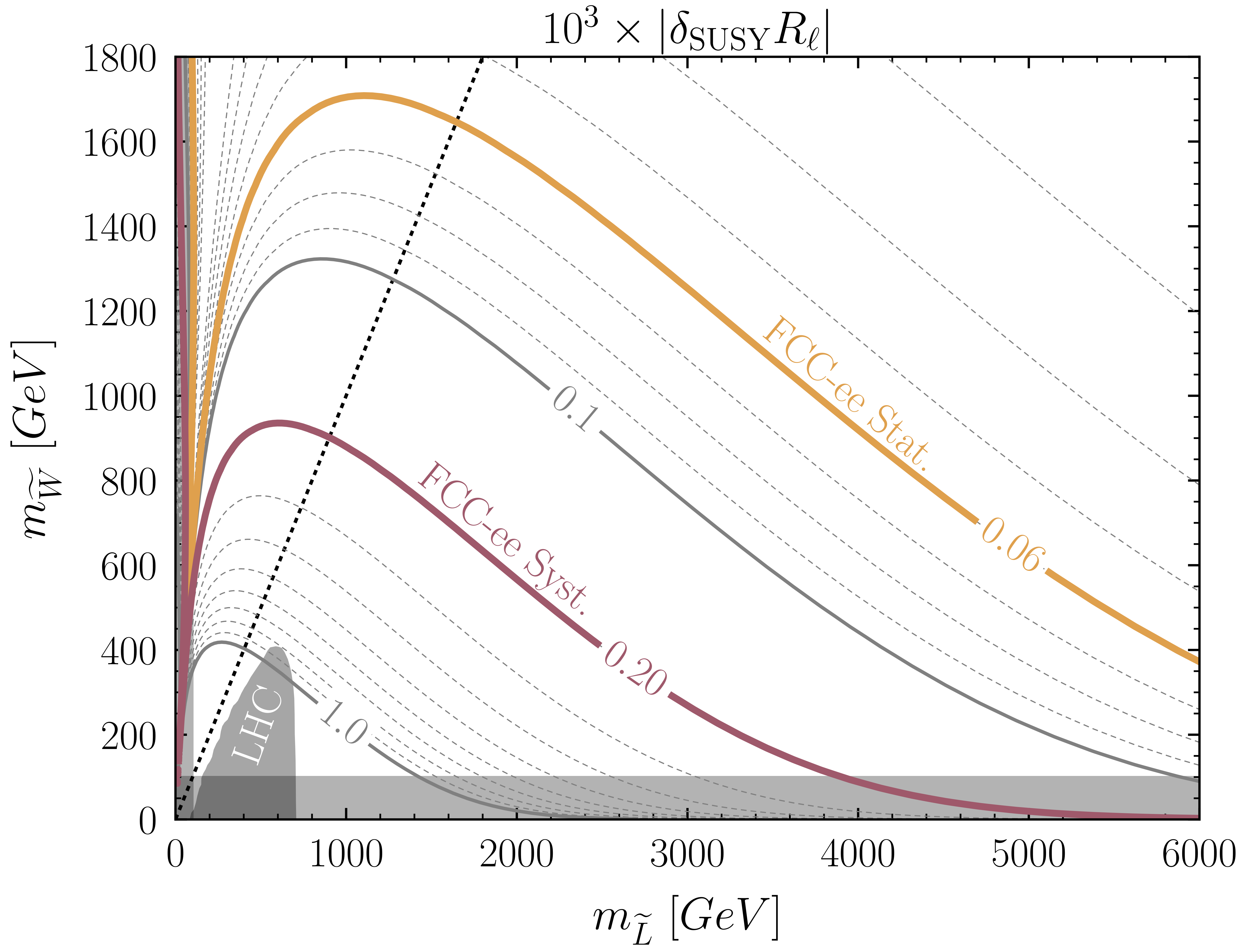
Results



Bino + RH Slepton
(Preliminary)

Results

$\cos(2\beta) = 0$

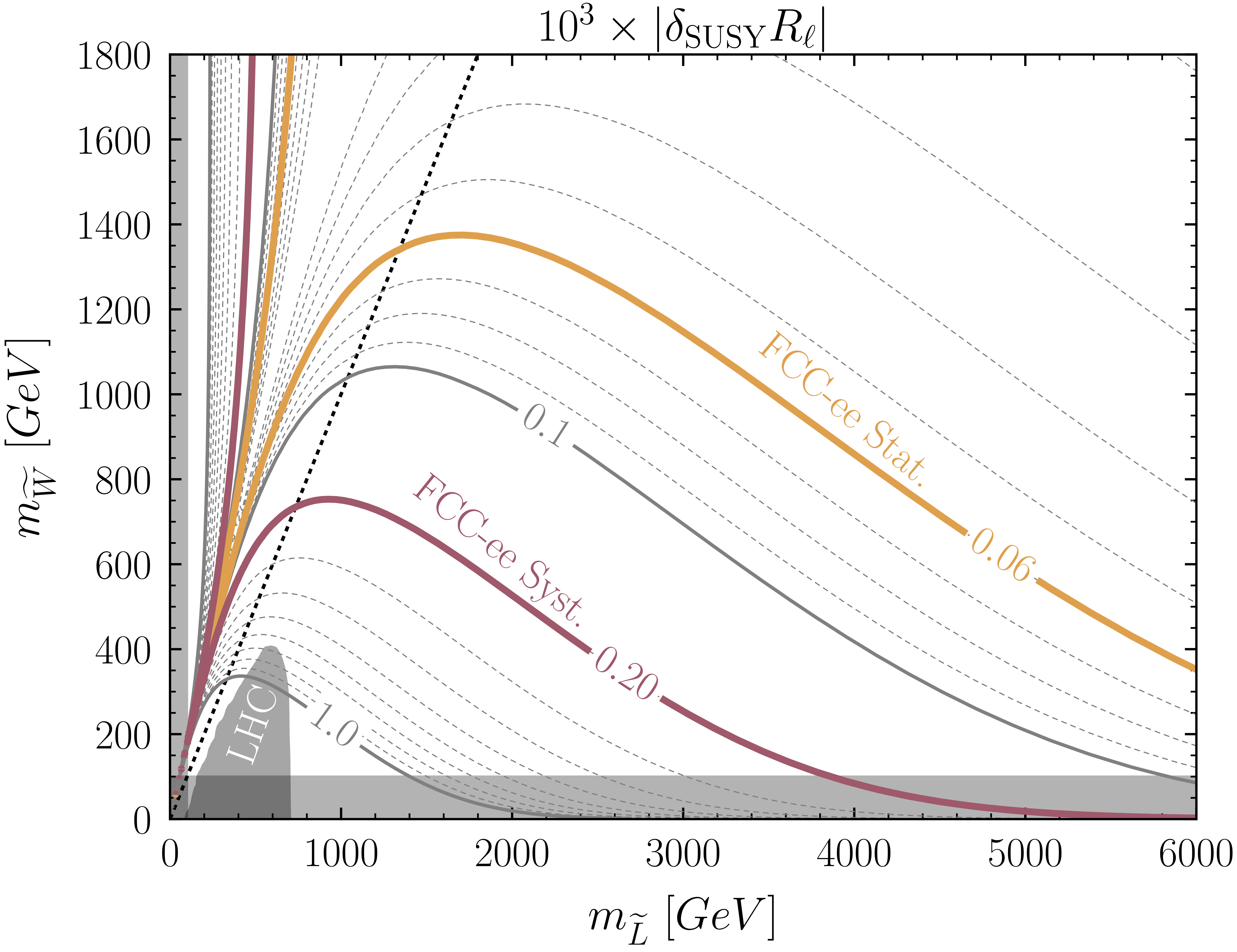


Wino + LH Slepton (Preliminary)

[1908.08215]

Results

$\cos(2\beta) = -1$

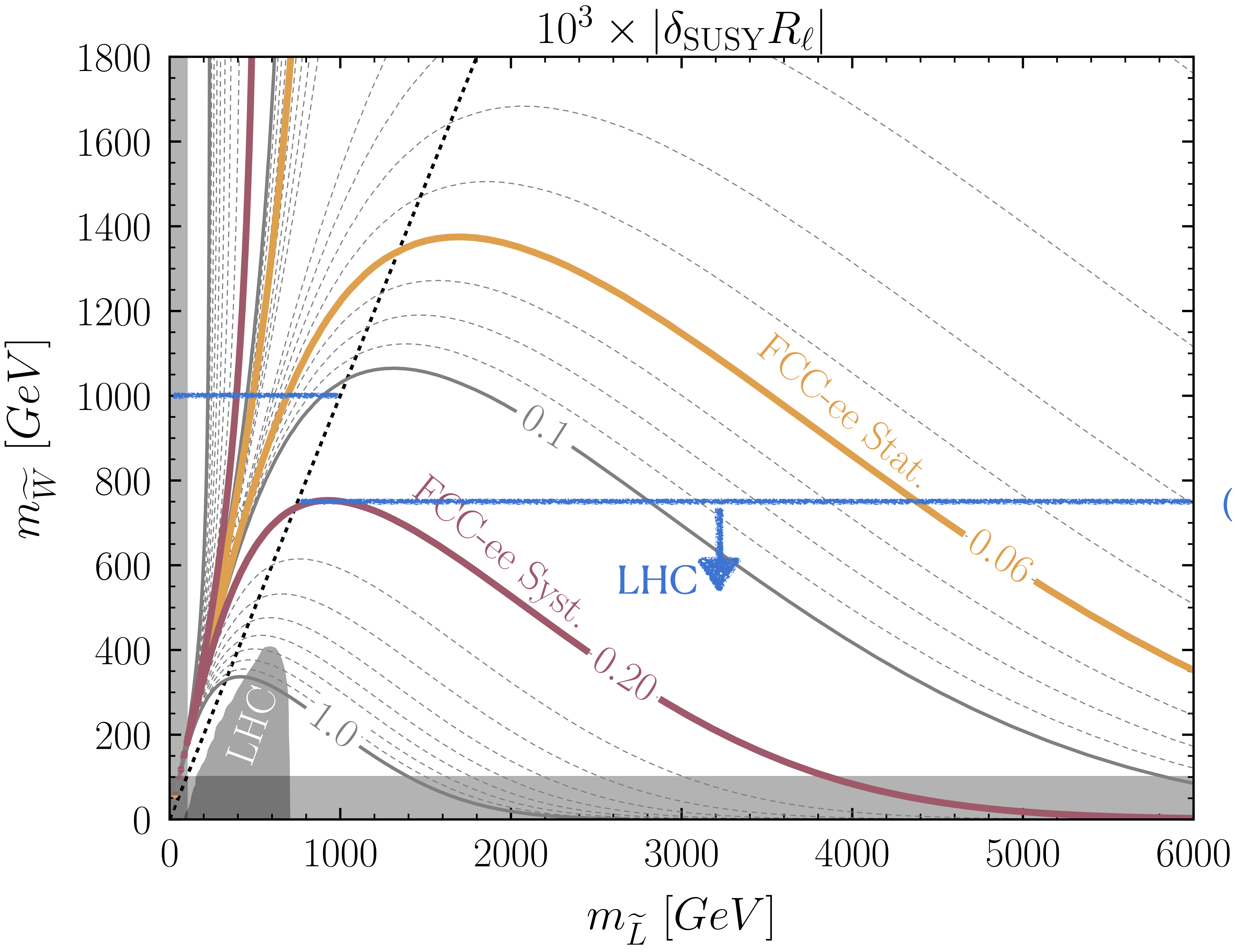


Wino + LH Slepton
(Preliminary)

[1908.08215]

Results

$\cos(2\beta) = -1$



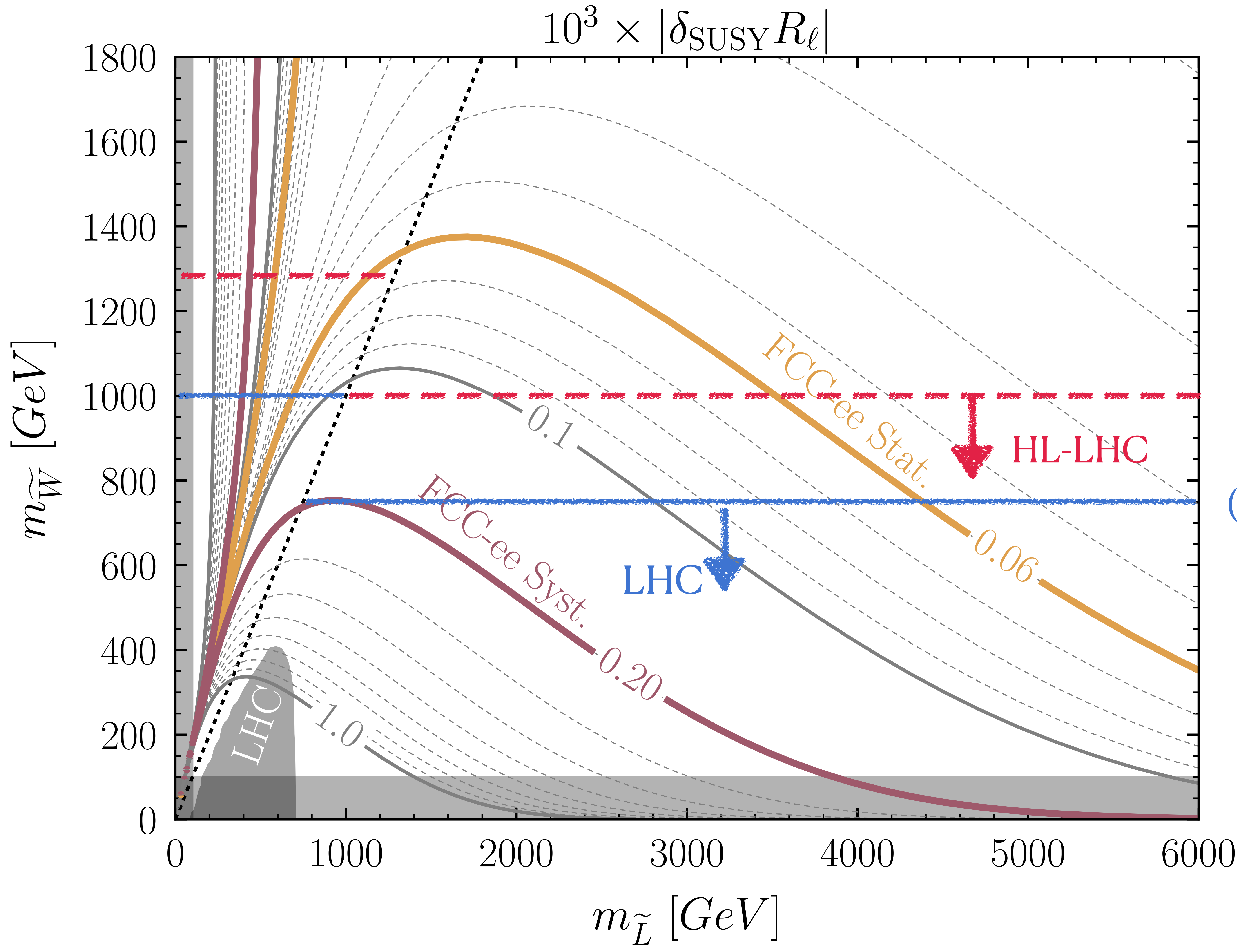
Wino + LH Slepton
(Preliminary)

(Depends on $m_{\chi_1^0}$!)

[1908.08215]

Results

$\cos(2\beta) = -1$



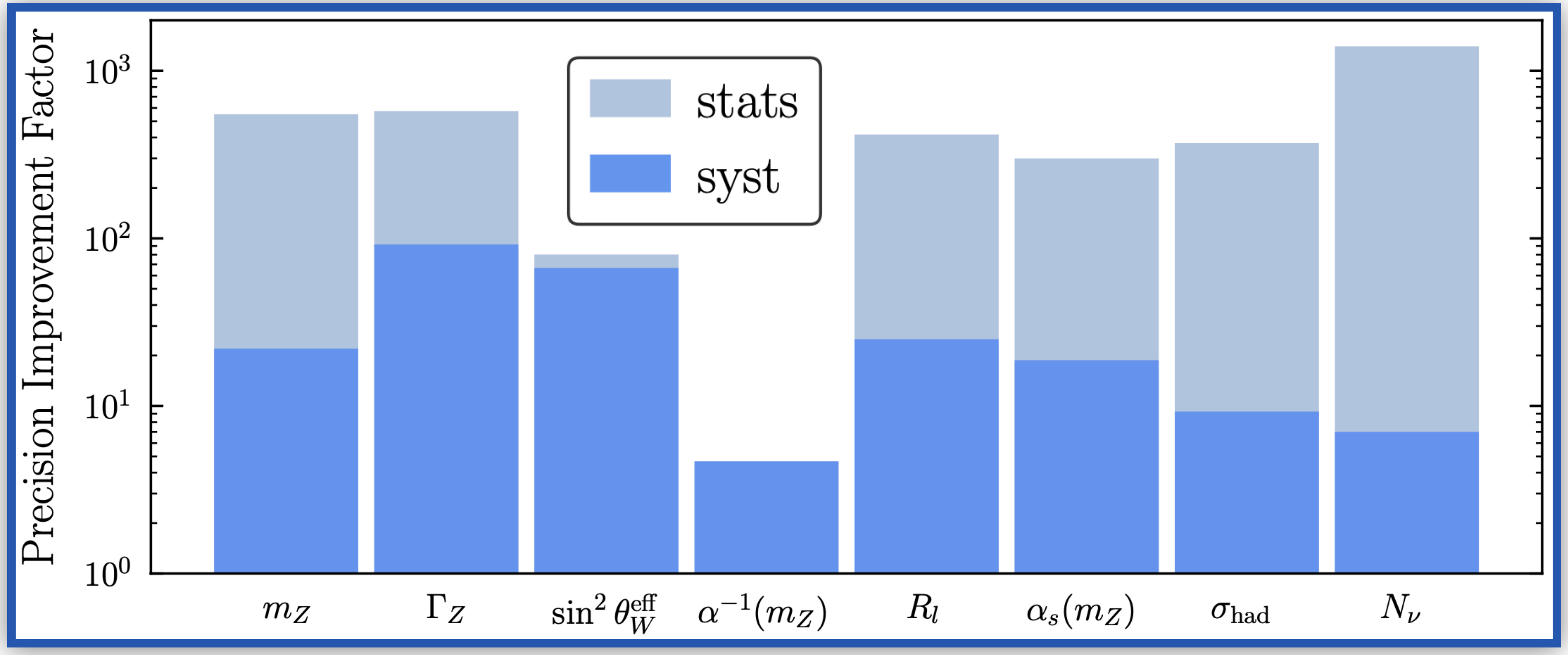
Wino + LH Slepton
(Preliminary)

(Depends on $m_{\chi_1^0}$!)

[1908.08215]

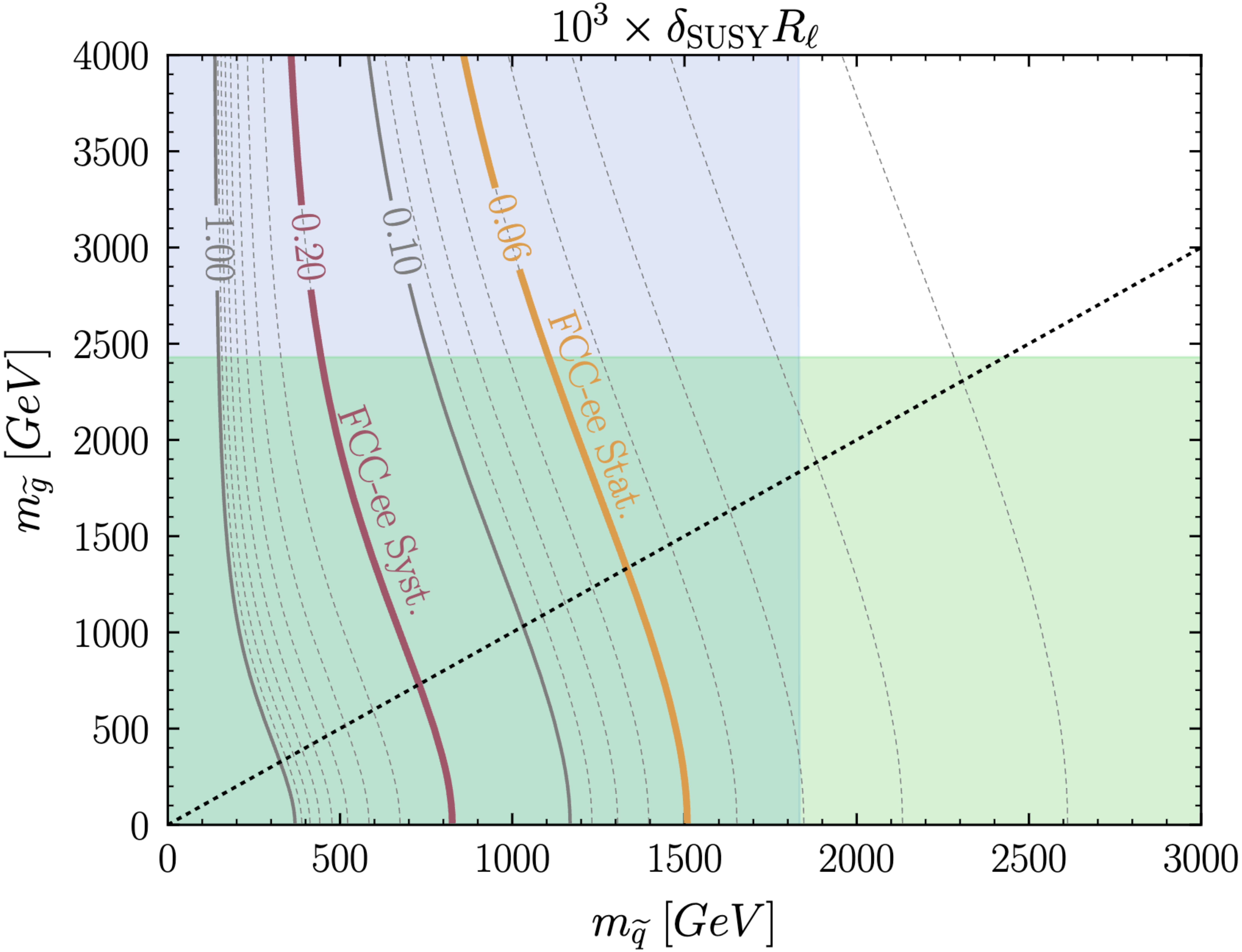
Conclusion

- EWPTs at the FCC-ee are interesting/complimentary ways to search for new physics.
- 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.



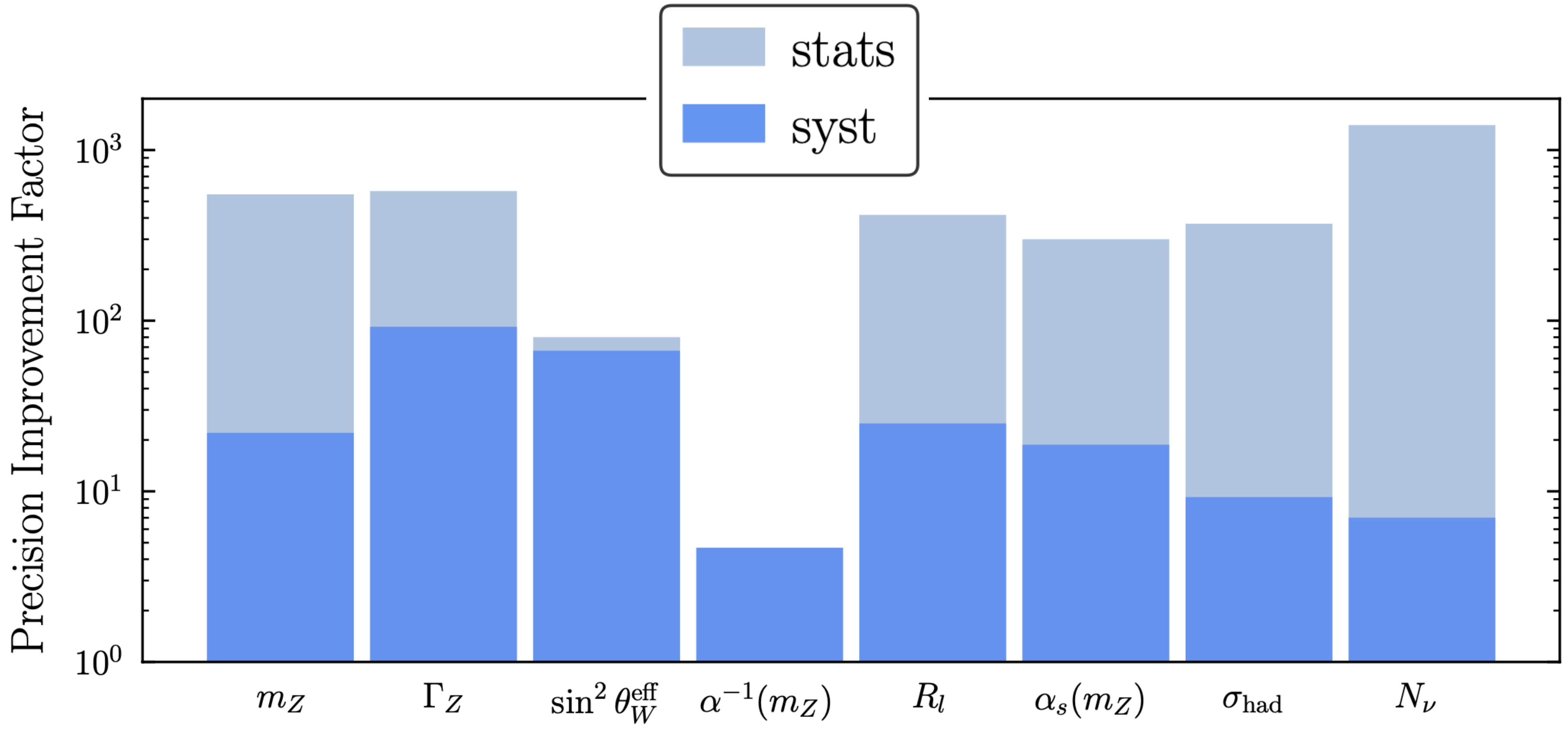
[FCC CDR Vol. 2]

Backup Slides


$10^3 \times \delta_{\mathrm{SUSY}} R_\ell$
$m_{\tilde{g}}$ [GeV]
$m_{\tilde{q}}$ [GeV]
4000
3500
3000
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
1.00
0.20
0.10
0.06
FCC-ee Syst.
FCC-ee Stat.

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

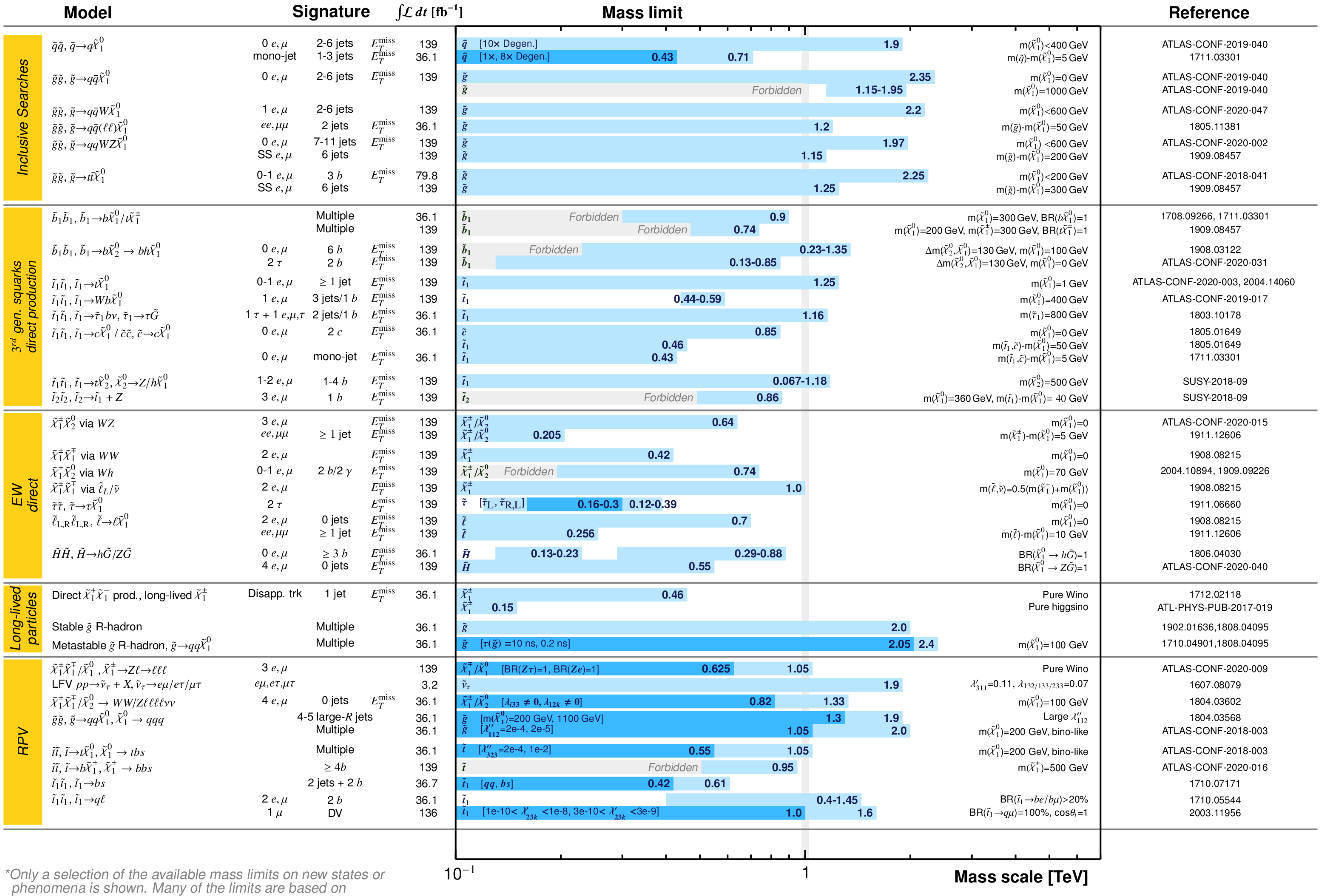
[FCC CDR]

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

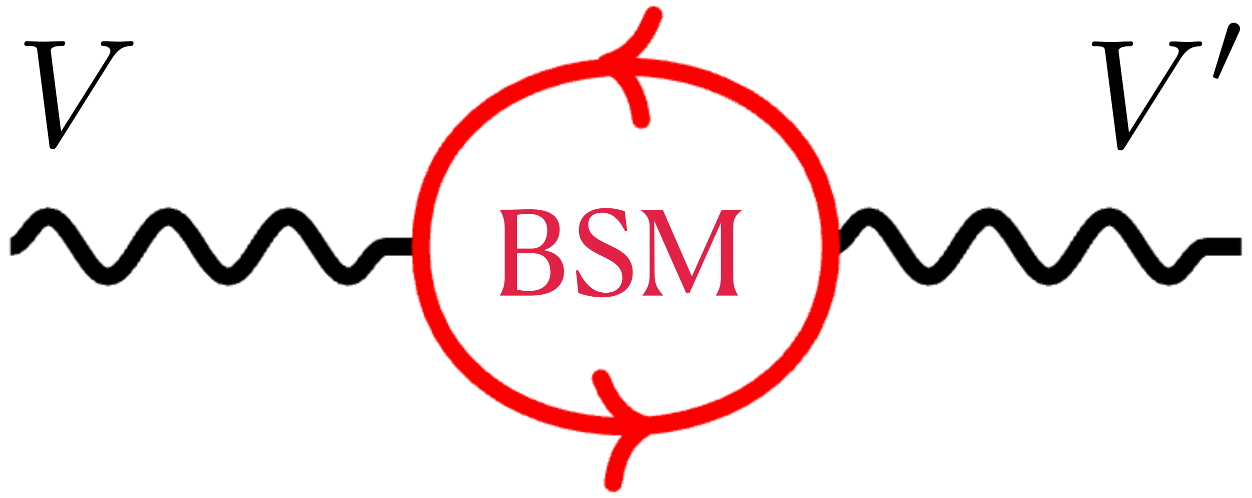


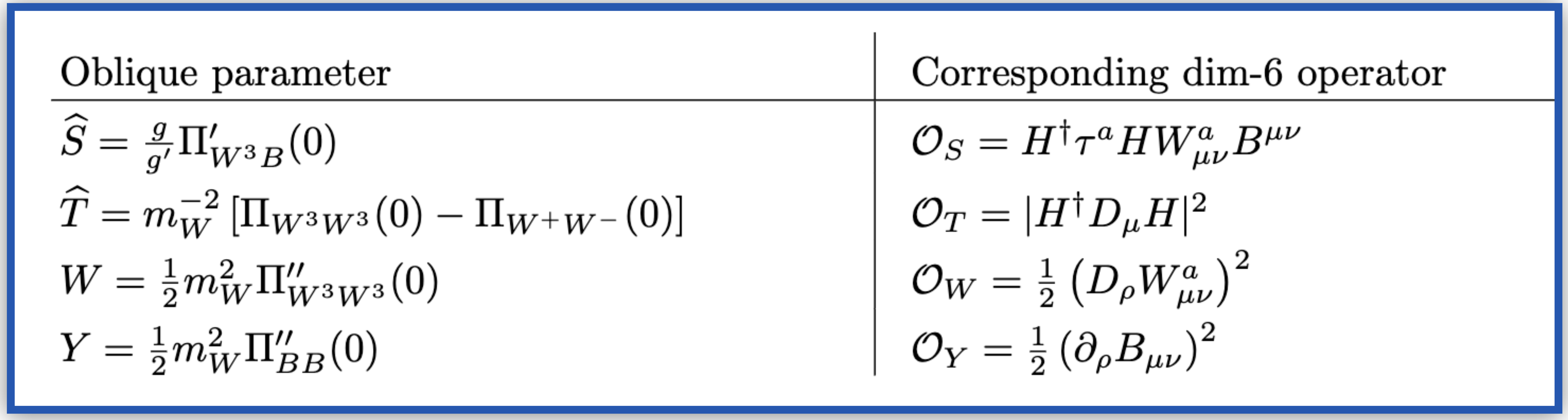
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$ [10× Degen.] **1.9**	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [1×, 8× Degen.] **0.43** **0.71**	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$ **2.35**	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$ *Forbidden* **1.15-1.95**	m($\tilde{\chi}^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$ **2.2**	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$ **1.2**	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$ **1.97**	m($\tilde{\chi}^0_1$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde{g}$ **1.15**	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$ **2.25**	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ **1.25**	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ *Forbidden* **0.9**	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$ *Forbidden* **0.74**	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1909.08457
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ *Forbidden* **0.23-1.35**	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ **0.13-0.85**	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$ **1.25**	m($\tilde{\chi}^0_1$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ **0.44-0.59**	m($\tilde{\chi}^0_1$)=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	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$ **1.16**	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$ **0.85**	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ **0.46**	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$ **0.43**	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ **0.067-1.18**	m($\tilde{\chi}^0_2$)=500 GeV	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$ *Forbidden* **0.86**	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	3 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ **0.64**	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ **0.205**	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ **0.42**	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ *Forbidden* **0.74**	m($\tilde{\chi}^0_1$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ **1.0**	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$ [$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$] **0.16-0.3** **0.12-0.39**	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$ **0.7**	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$ **0.256**	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$ **0.13-0.23** **0.29-0.88**	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$ **0.55**	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1$ **0.46**	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ **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, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] **2.05** **2.4**	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$ [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
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] **0.82** **1.33**	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=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($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] **0.55** **1.05**	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$ *Forbidden* **0.95**	m($\tilde{\chi}^\pm_1$)=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

**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

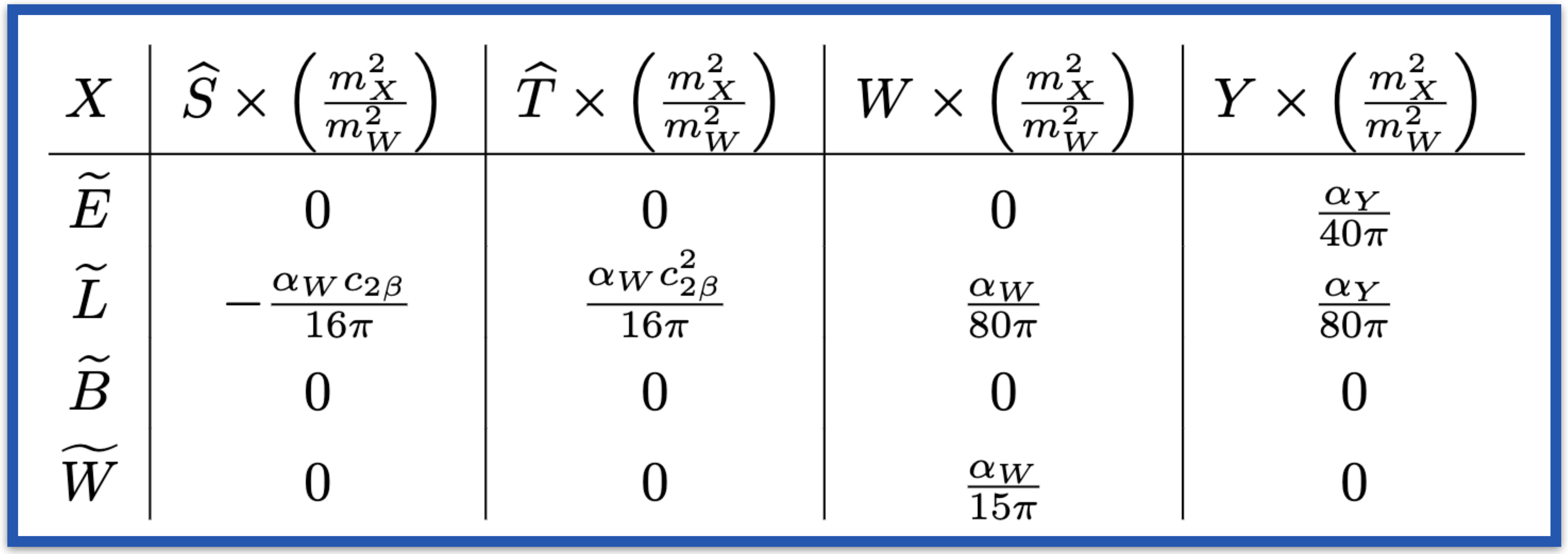
- Assuming heavy new physics dominantly modifies SM gauge boson propagators, corrections from heavy new physics can be quantified by a set of oblique parameters.





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

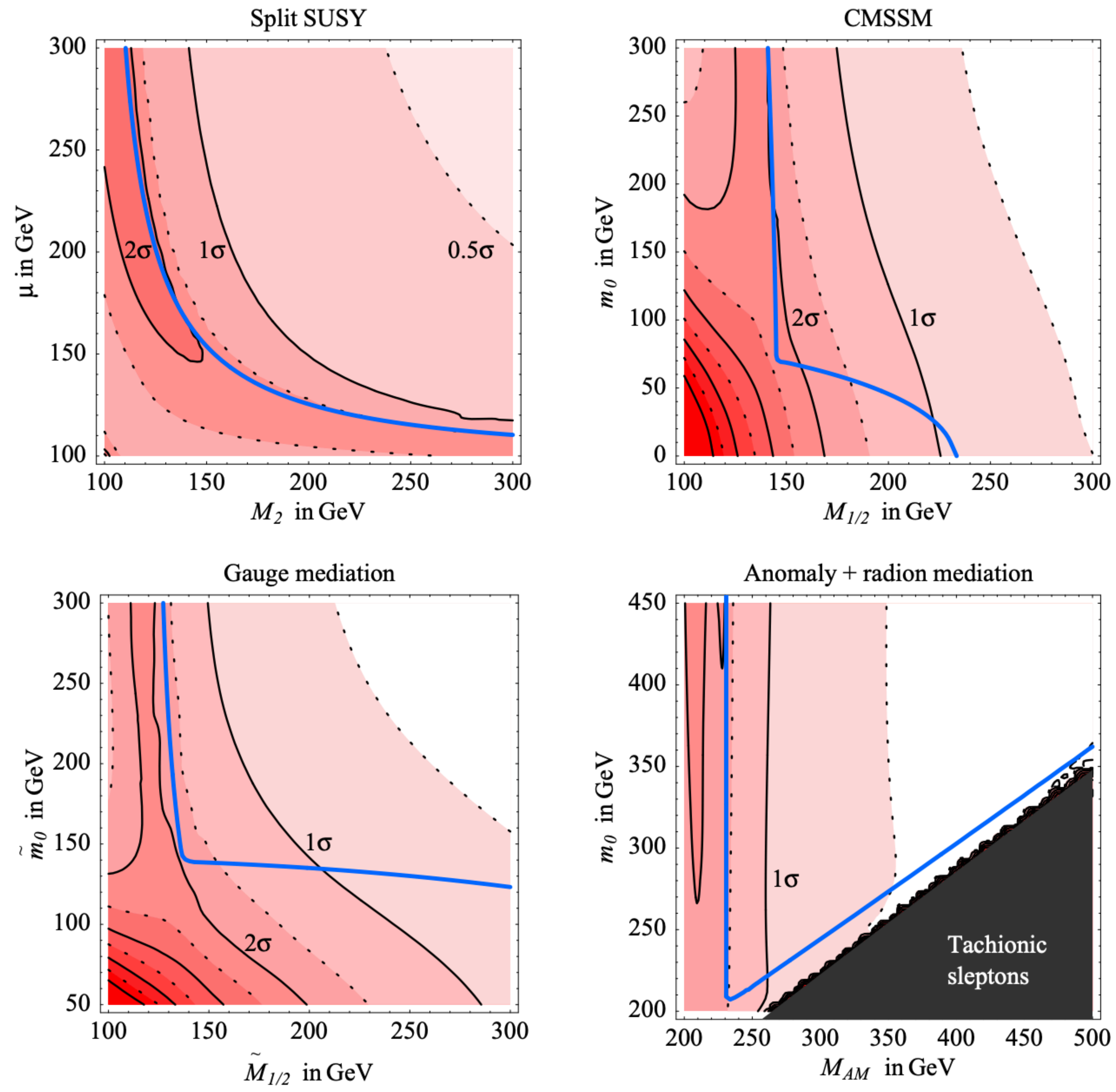
- Simple, but not completely general.



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]



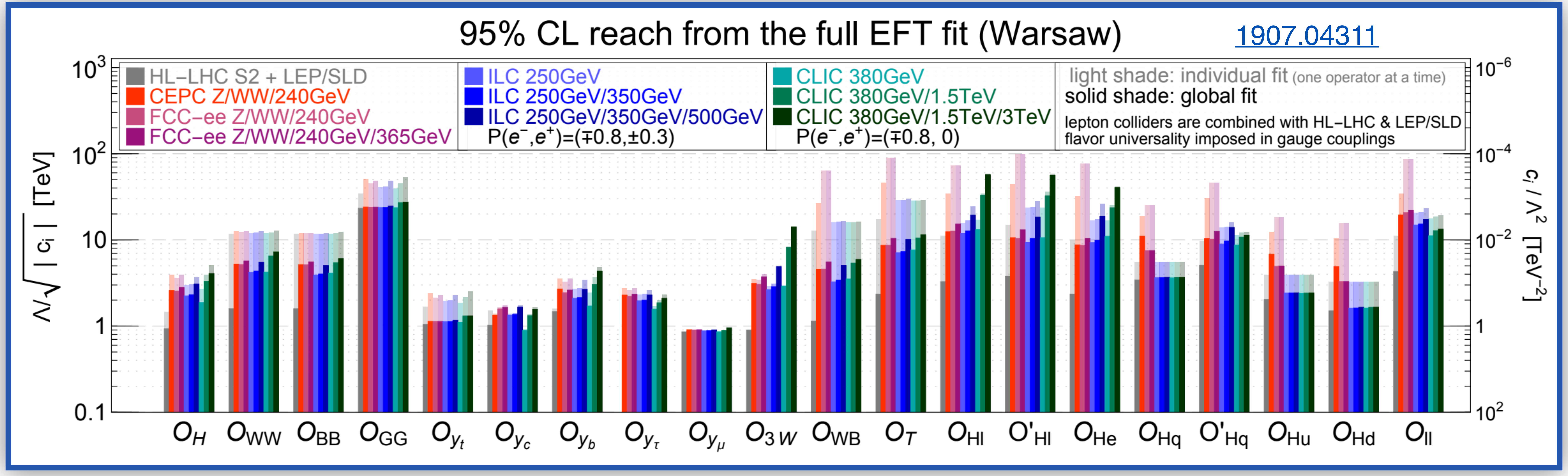
Focuses on
oblique corrections

Electroweak Precision Tests

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

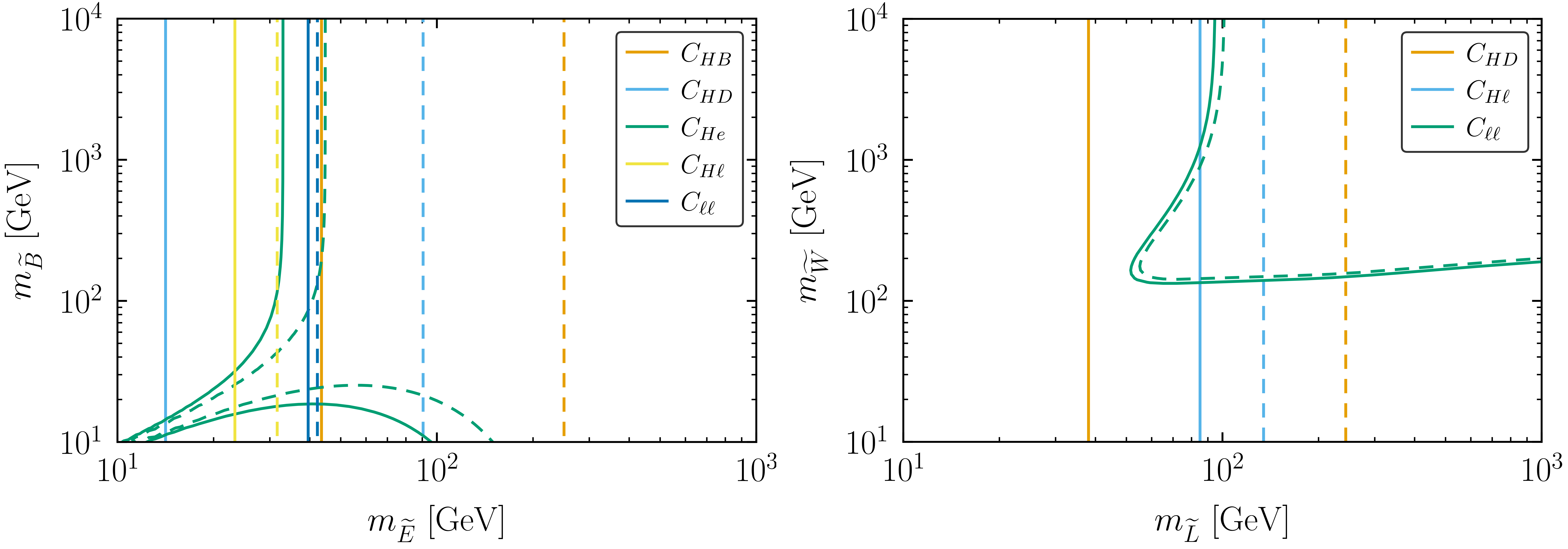
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

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

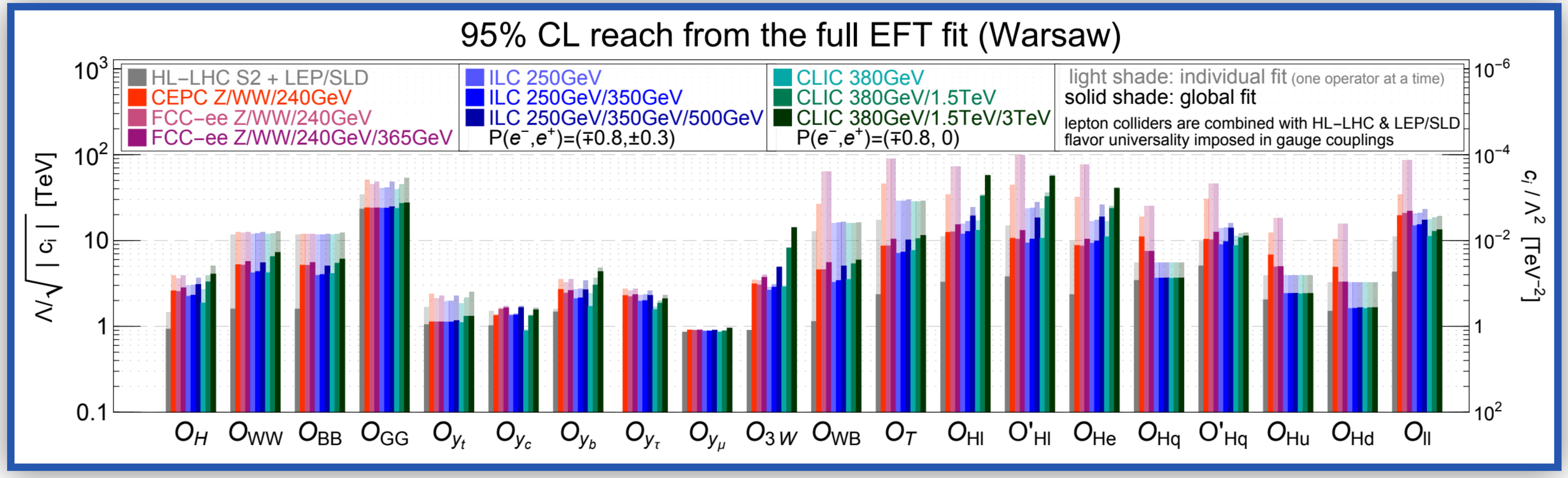


1907.04311

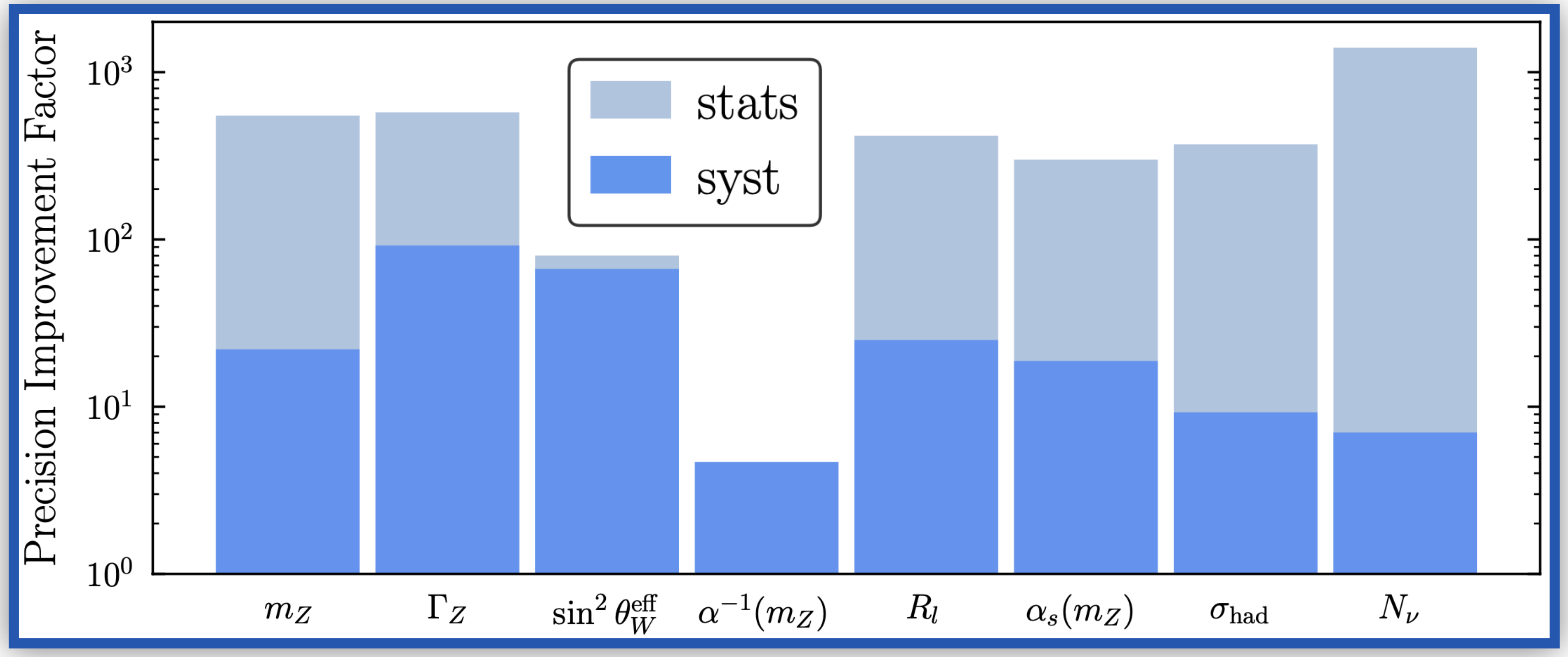
Constraints from SMEFT



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?**