Imprints of SUSY at FCC-ee

Kevin Langhoff

FCC Workshop

(Jan. 14th 2025)

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Paper: 2407.13815

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB

Isn’t SUSY dead?

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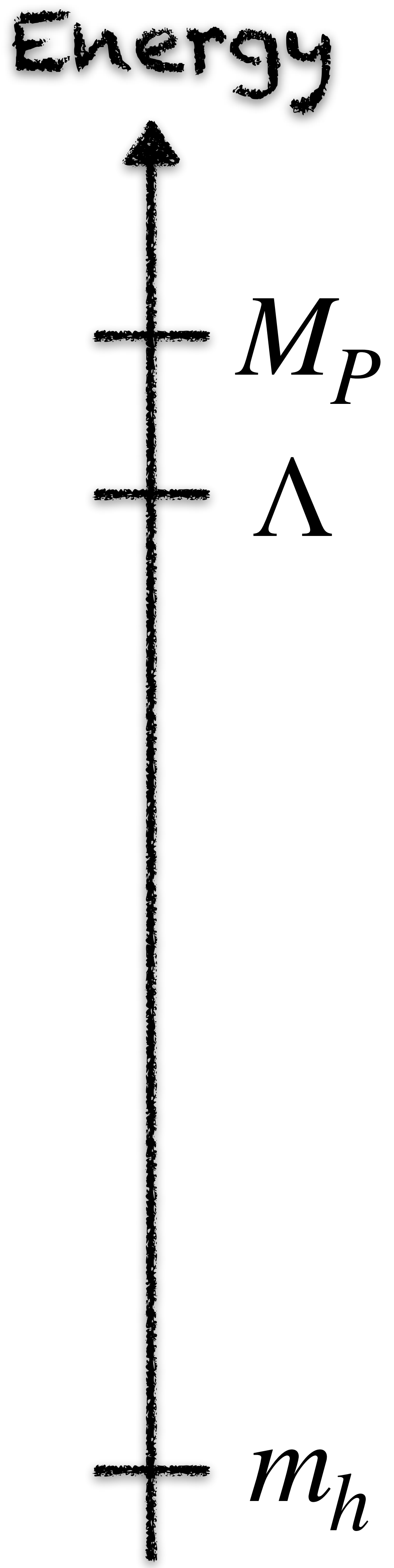
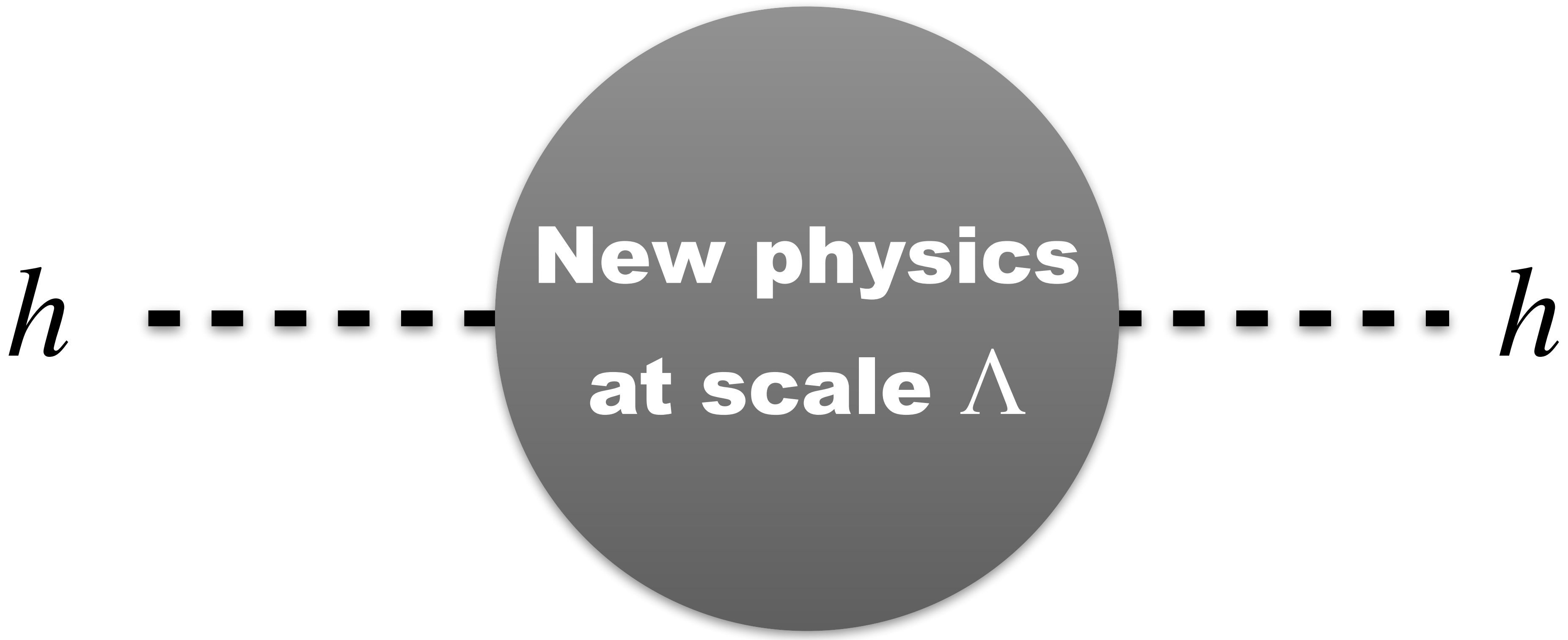
No

The Electroweak Hierarchy Problem





$\delta m_h \sim \Lambda$

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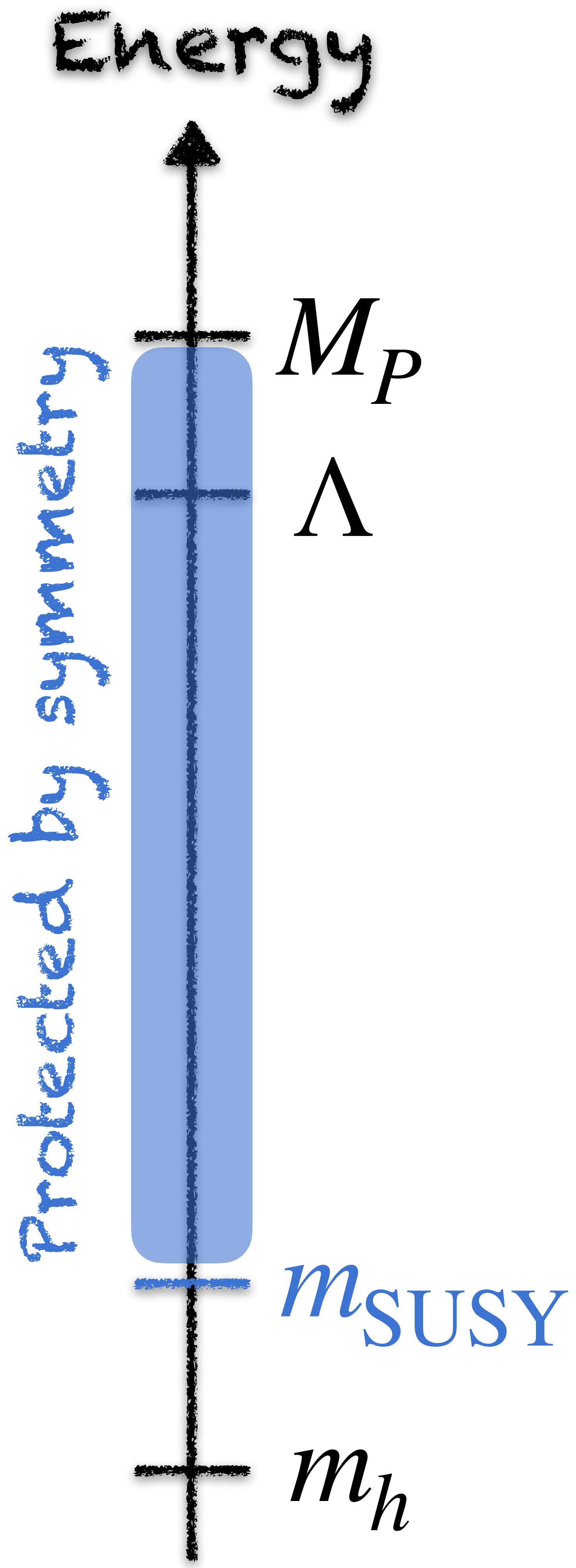

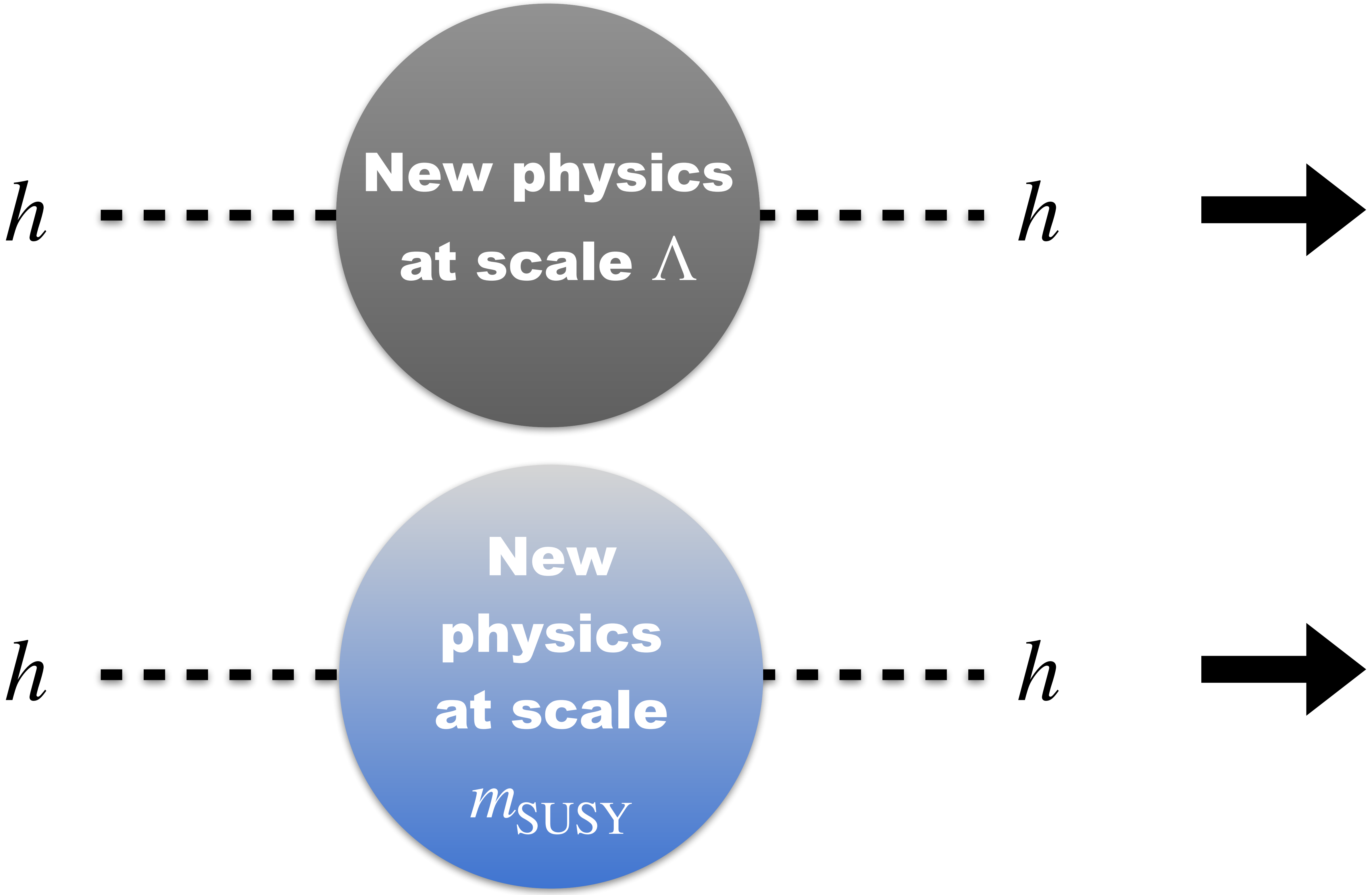

$\delta m_h \sim \Lambda$

$\delta m_h \sim m_{\text{SUSY}}$

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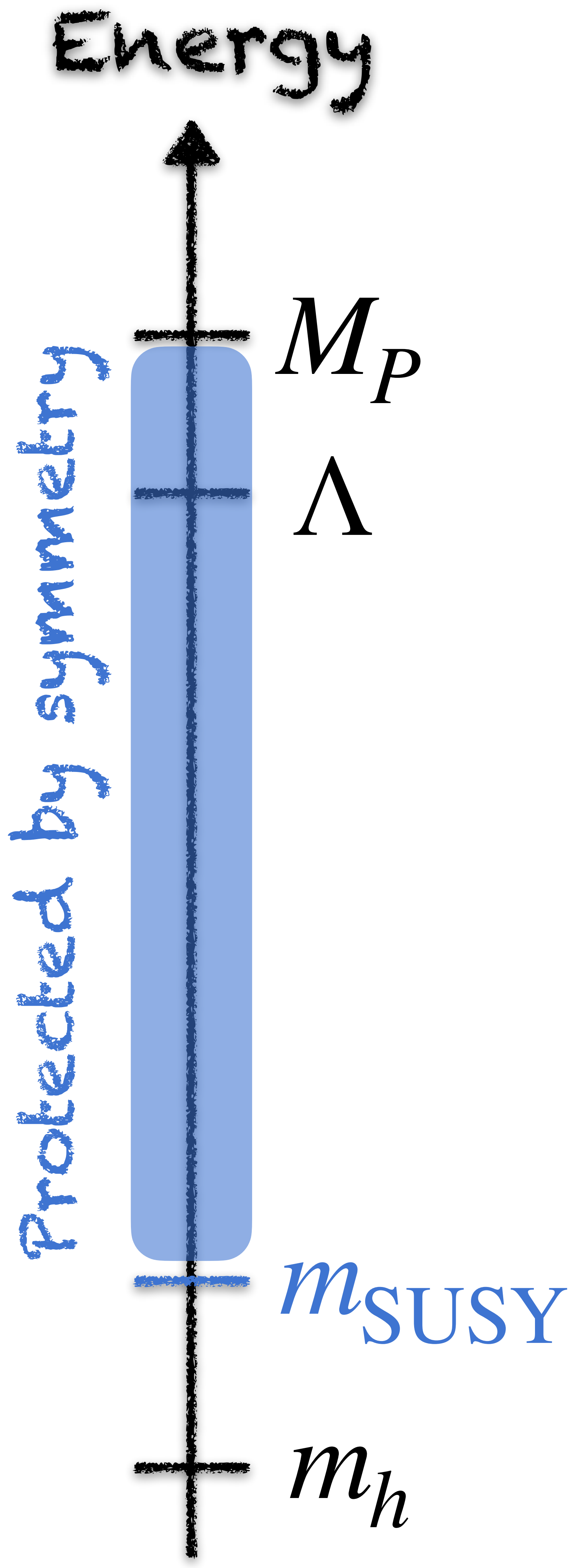
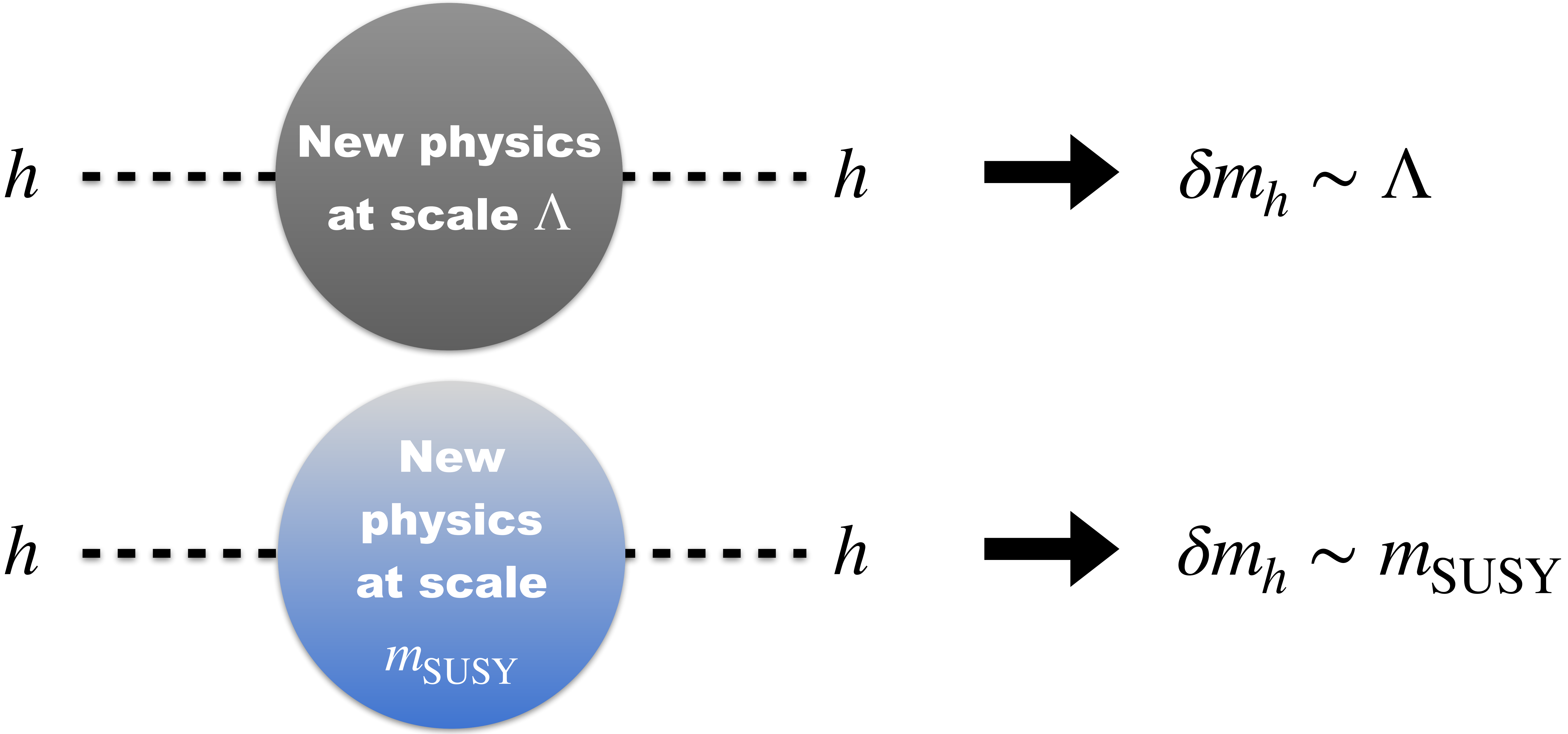




$$\delta m_h \sim \Lambda$$

$$\delta m_h \sim m_{\text{SUSY}}$$

Absence of sub-TeV sparticles $\Longrightarrow$ solution requires a lot of fine tuning.
However, nothing else prevents me from taking m_{SUSY} very large.

Why still consider SUSY in 2025?

View of the believer

- The hierarchy problem hasn't gone away; it is even more puzzling. Maybe there is fine tuning...
- SUSY is the unique extension of spacetime symmetry (for theories with *S* matrices).
- The thermal Higgsino is still a good DM candidate. Gauge coupling unification is predicted.

Should be taken seriously.

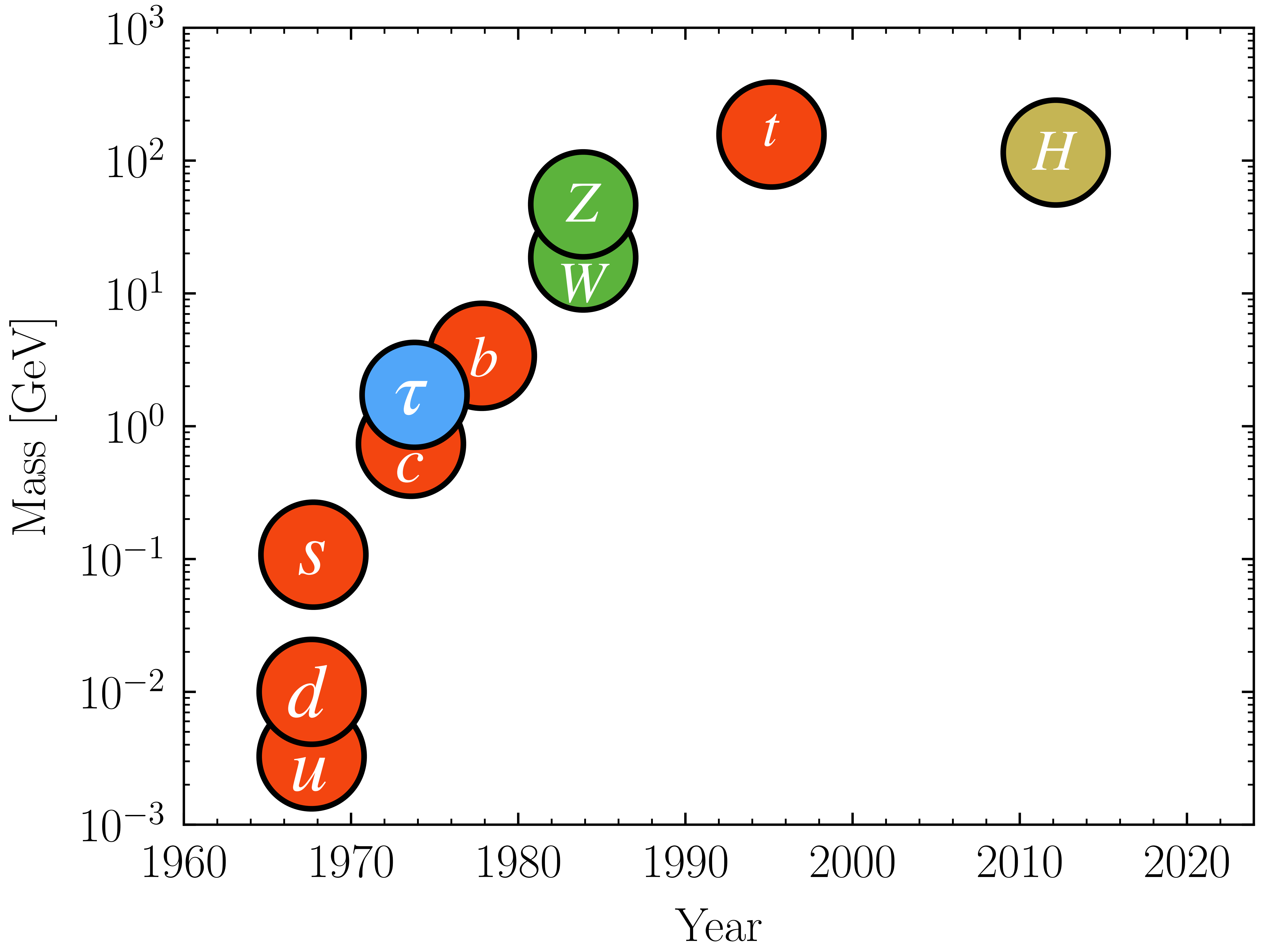
View of the skeptic

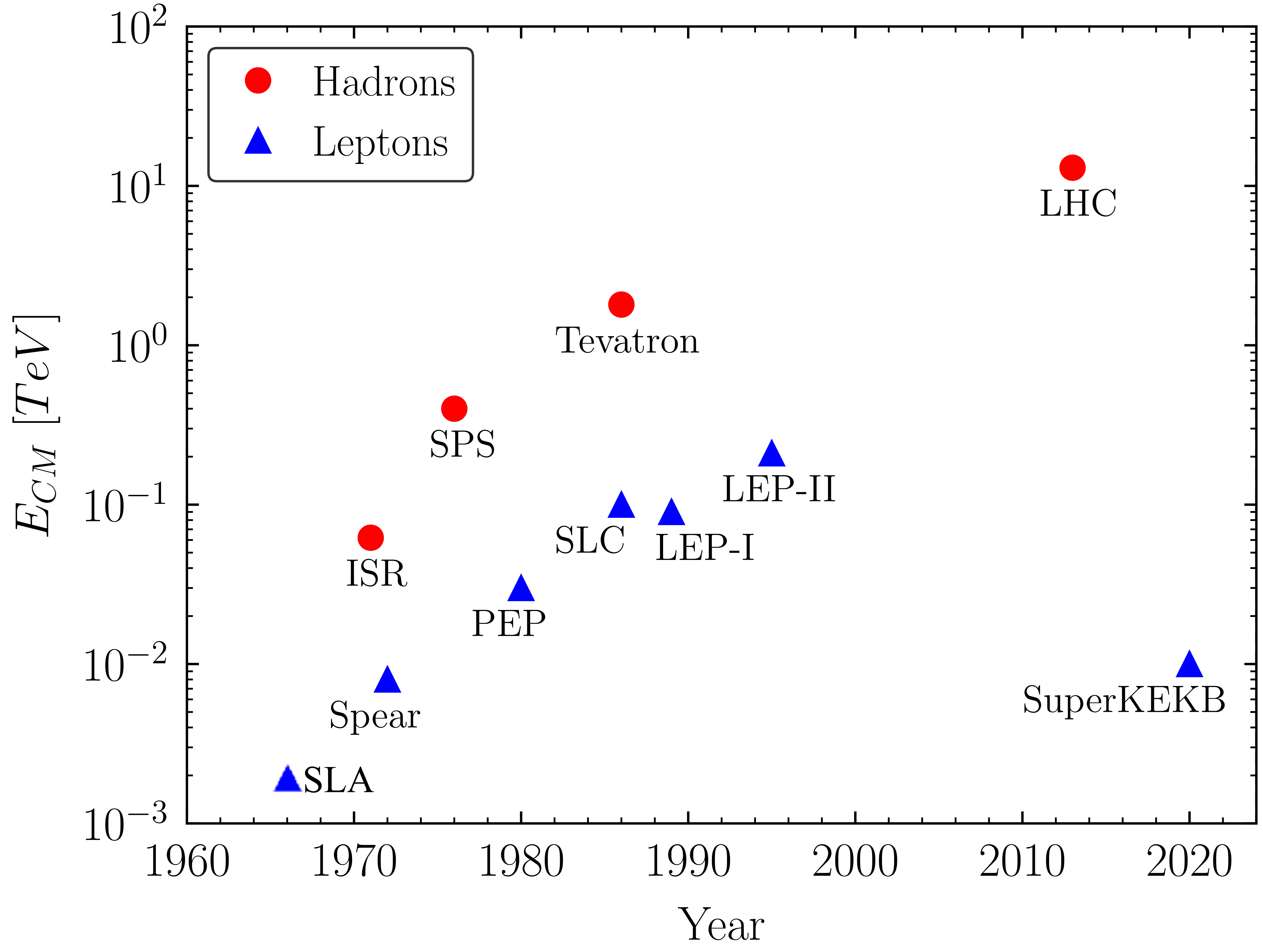
- SUSY is well defined with few parameters and represents how new physics **may** show up.
- Not too many better ideas for solving the big hierarchy problem...

SUSY is not the main motivation for FCC-ee…
But could the FCC-ee discover SUSY?

Very Obvious Statement

Discovery correlates with technological advancement.





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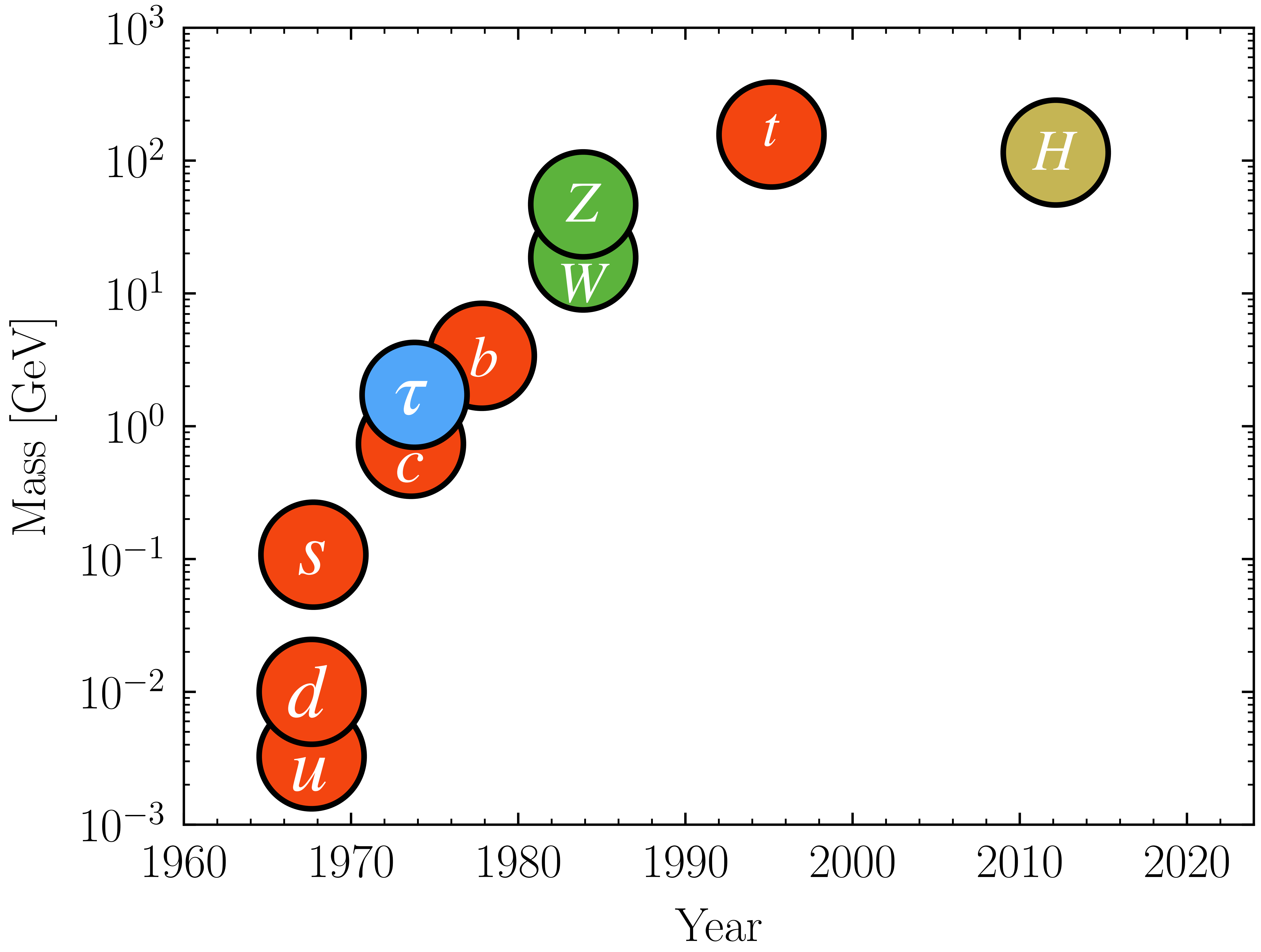
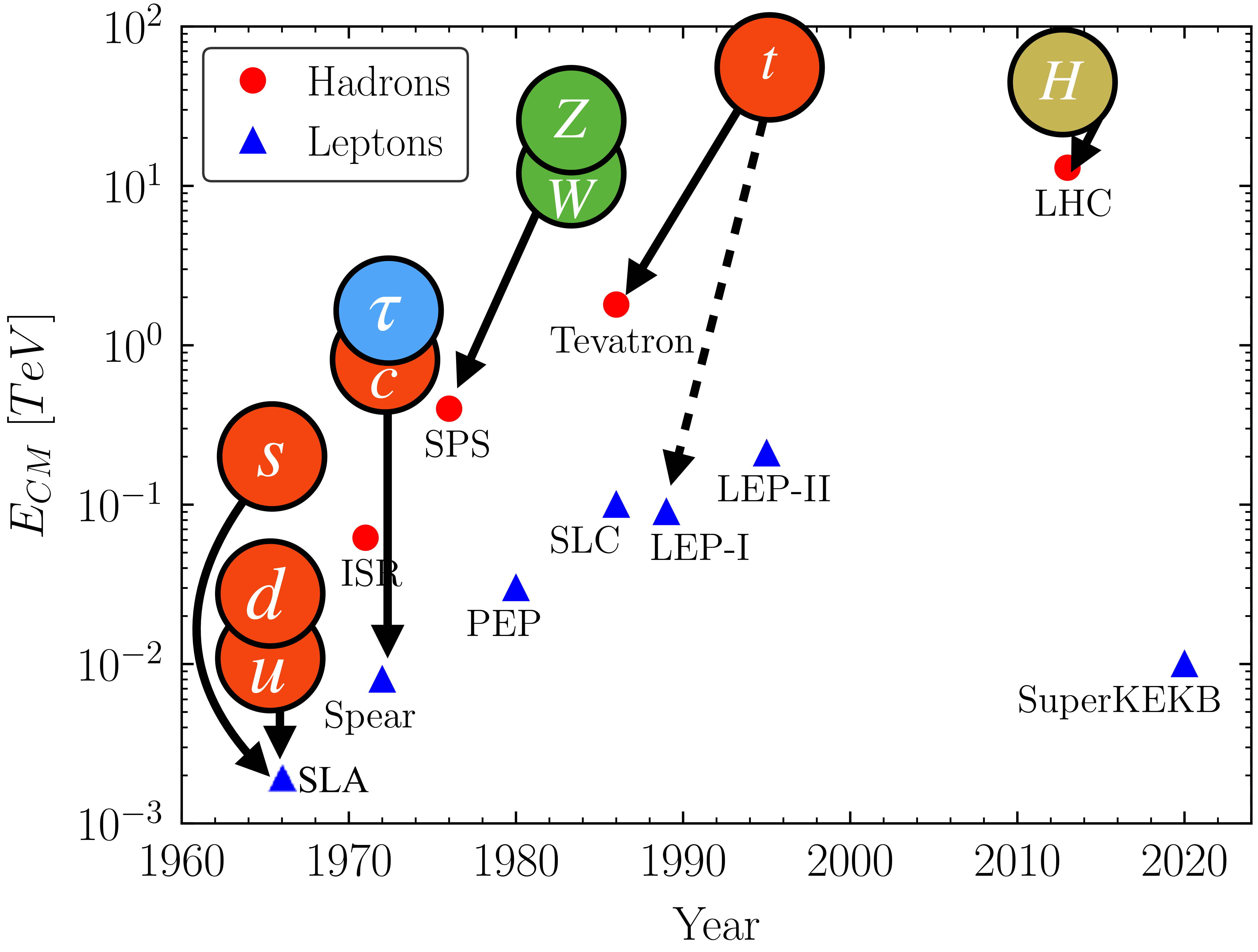
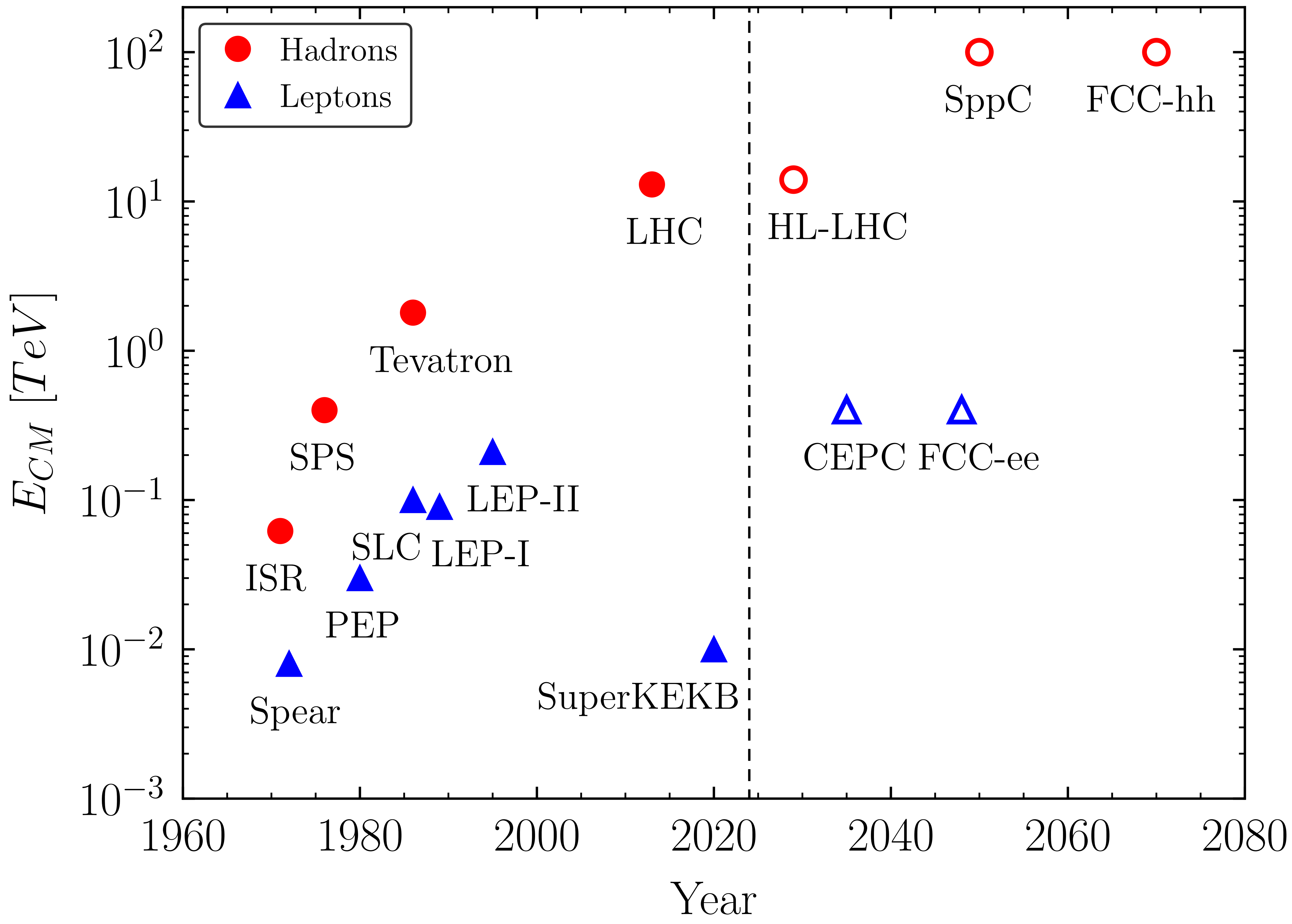




What does future technology look like?



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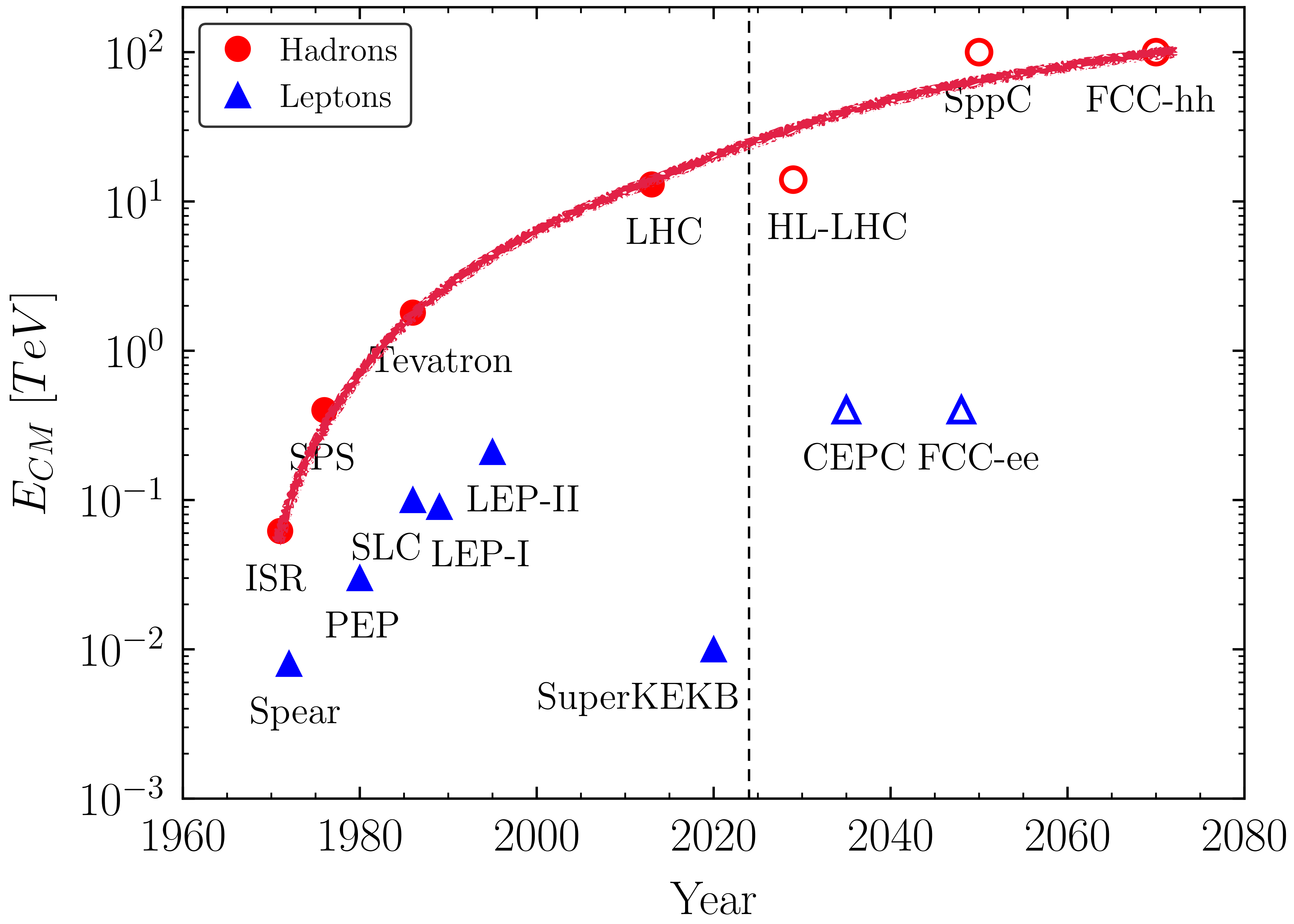

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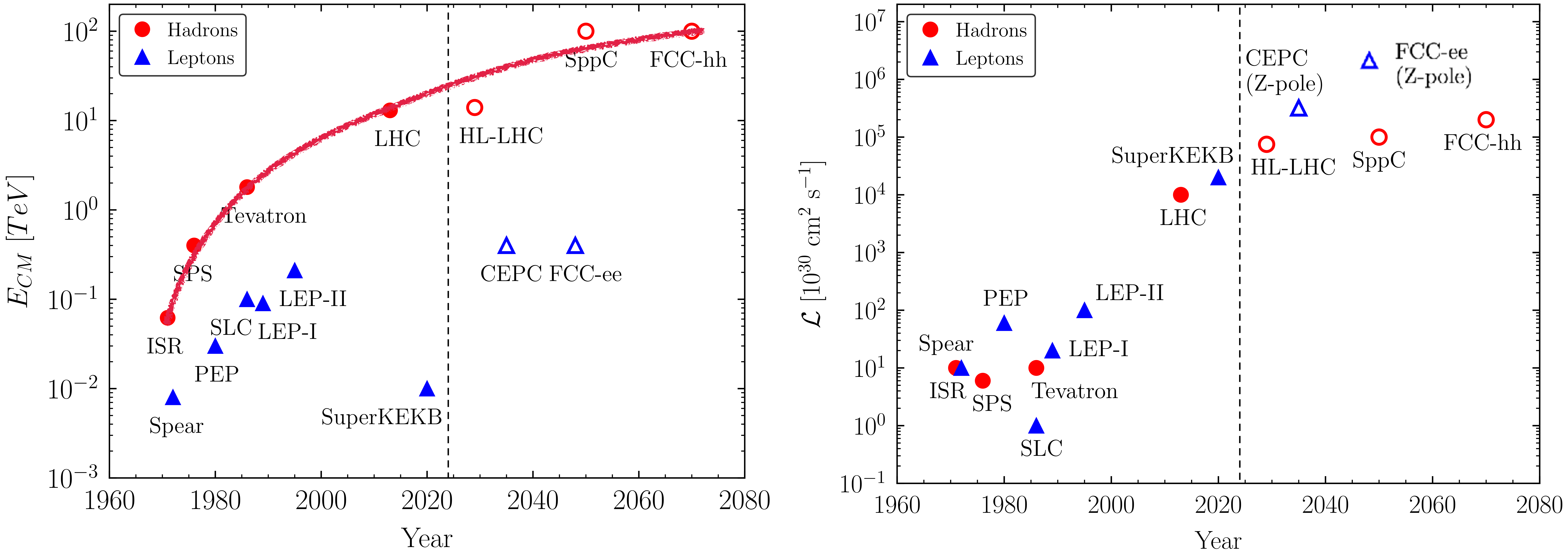

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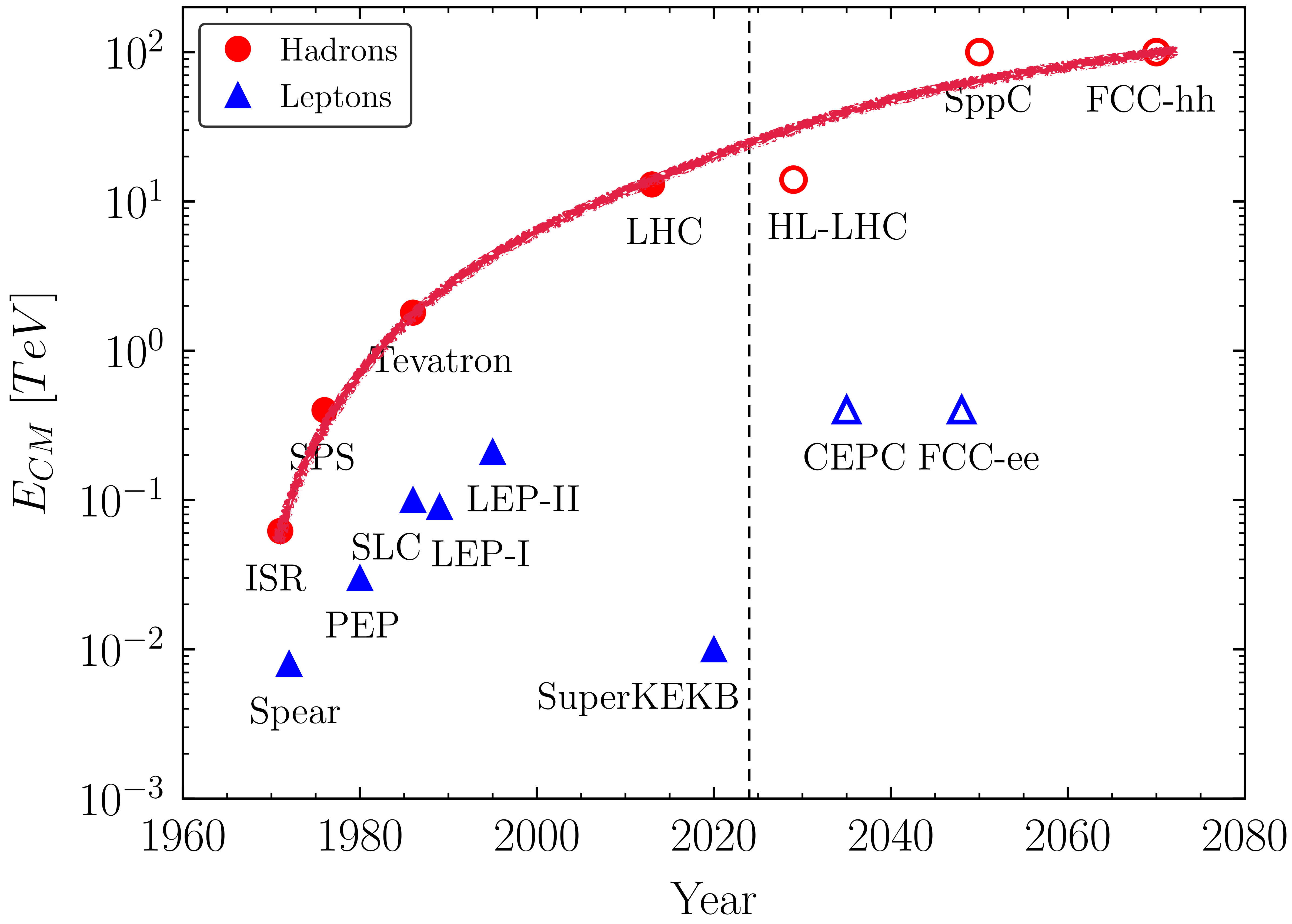

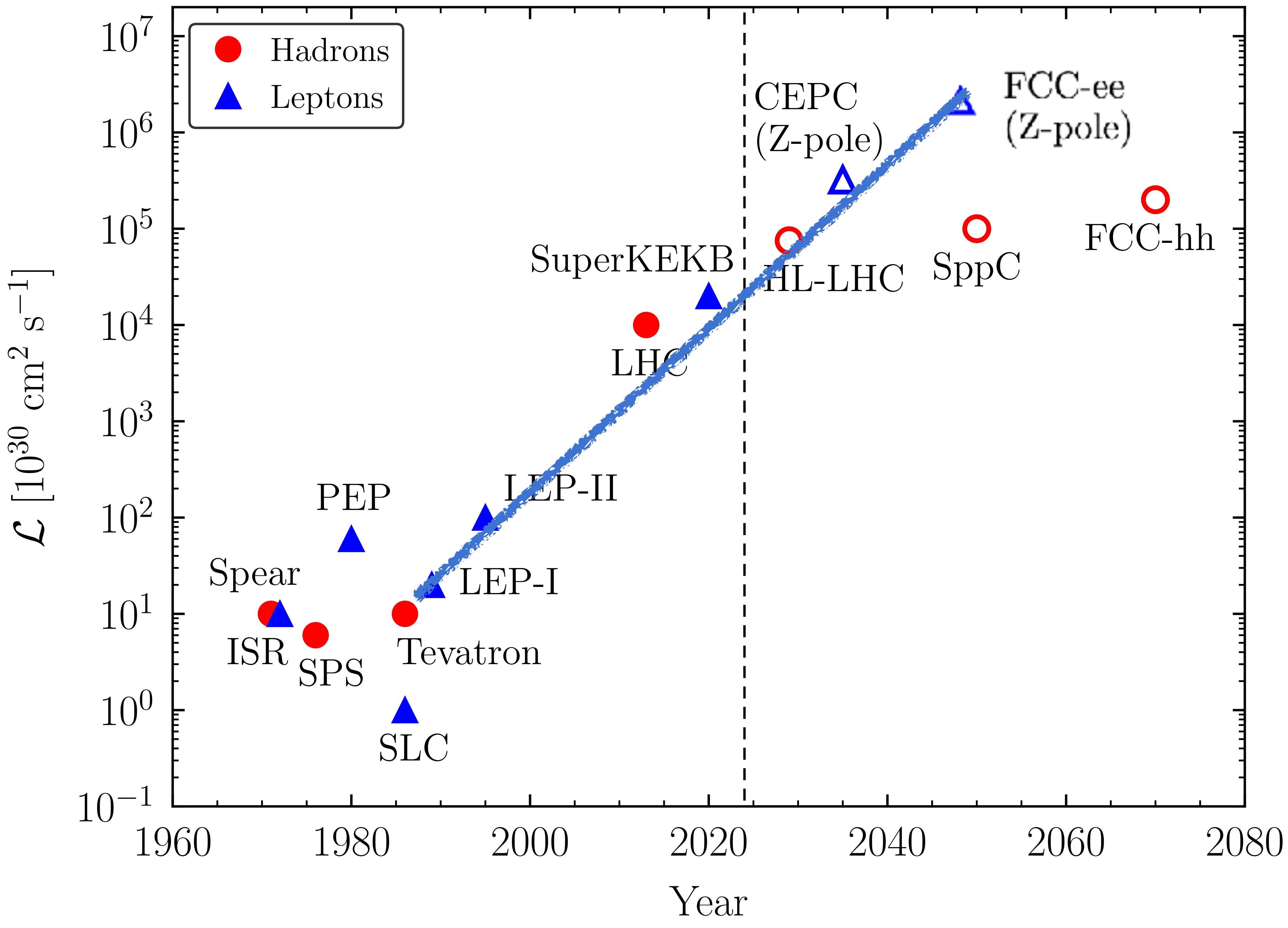

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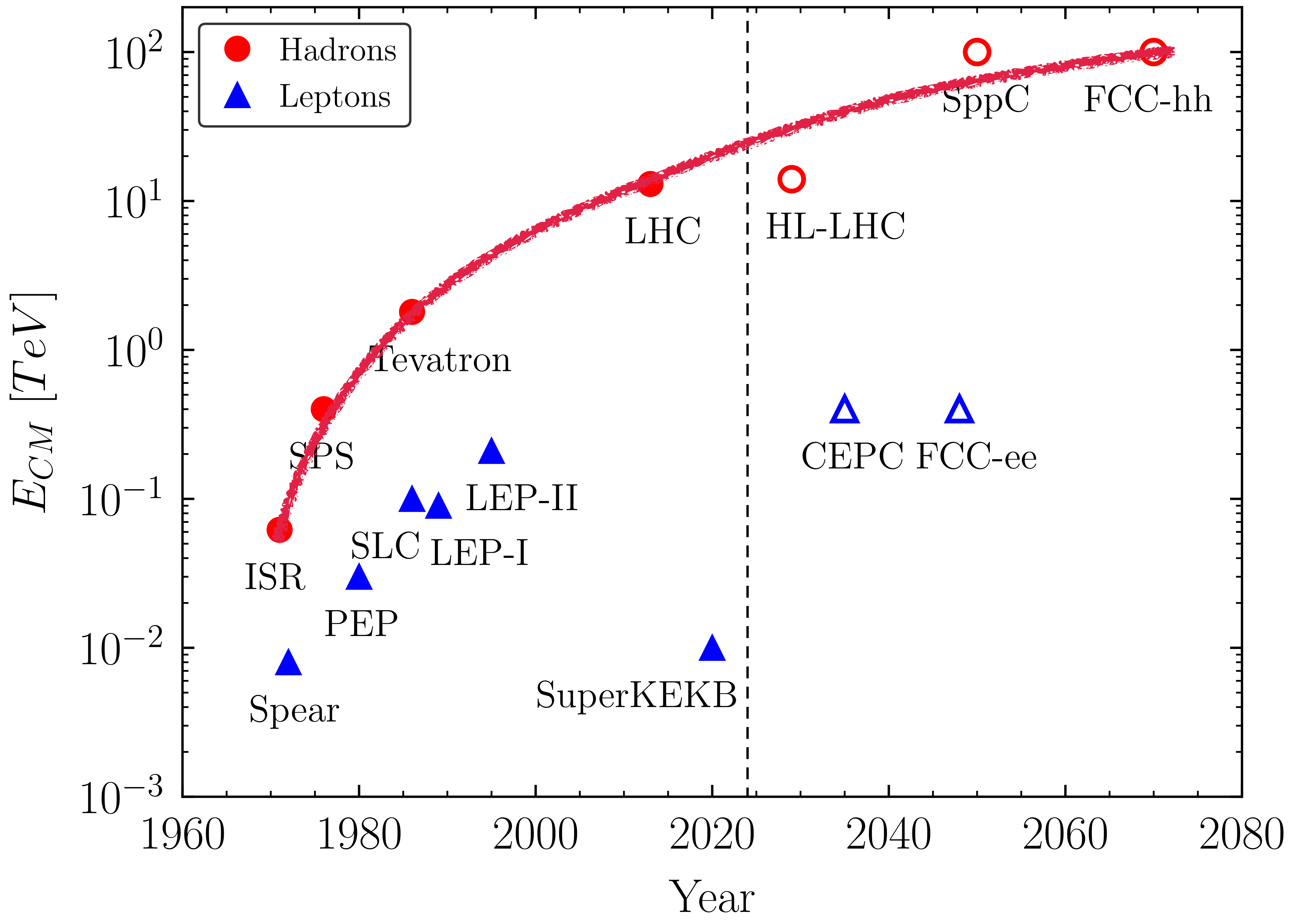

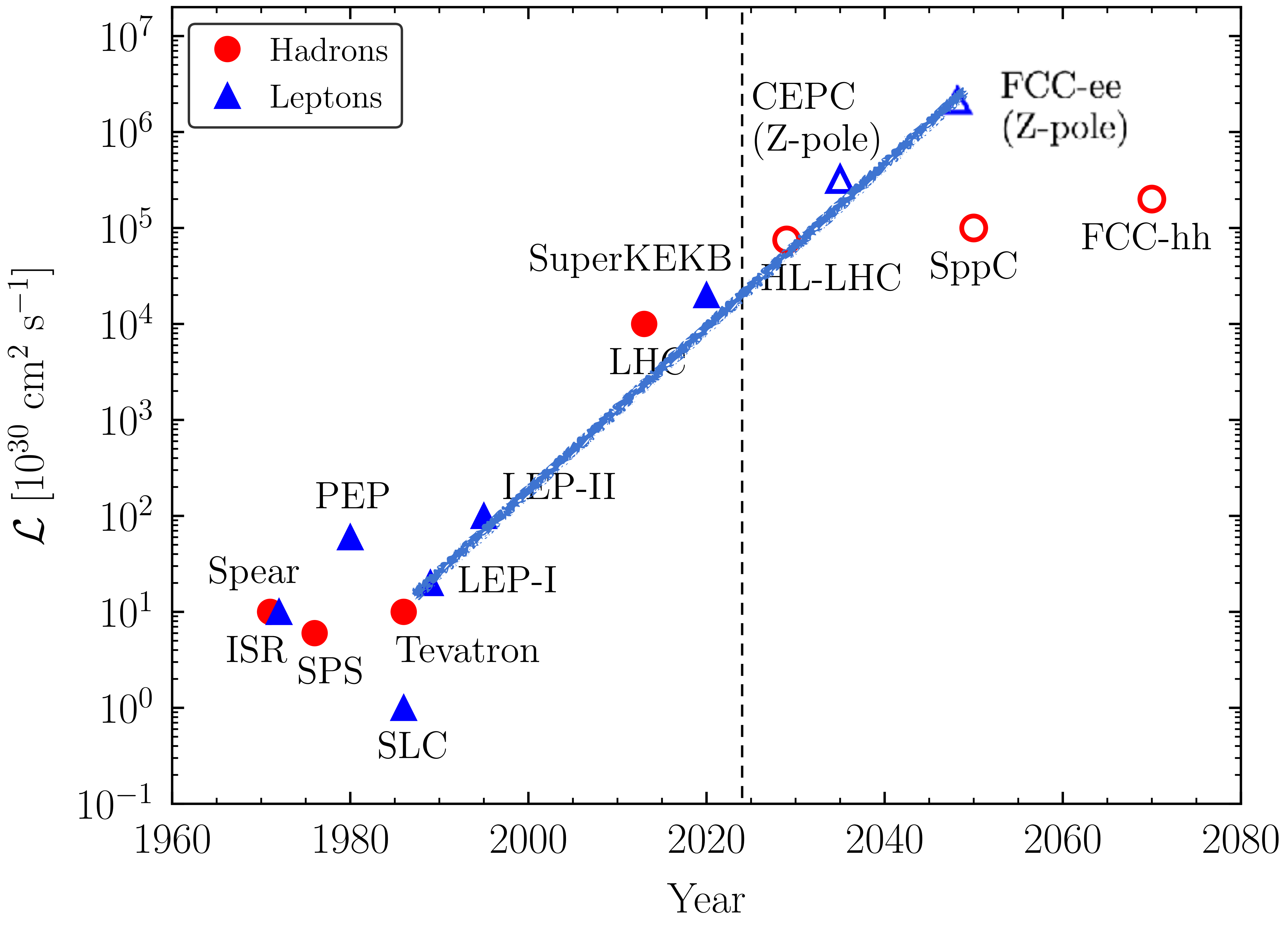

FCC-ee will produce $\sim 6 \times 10^{12}$ Z bosons ($\sim 10^5 \times$ LEP).

What experiment explores the highest energy scales?

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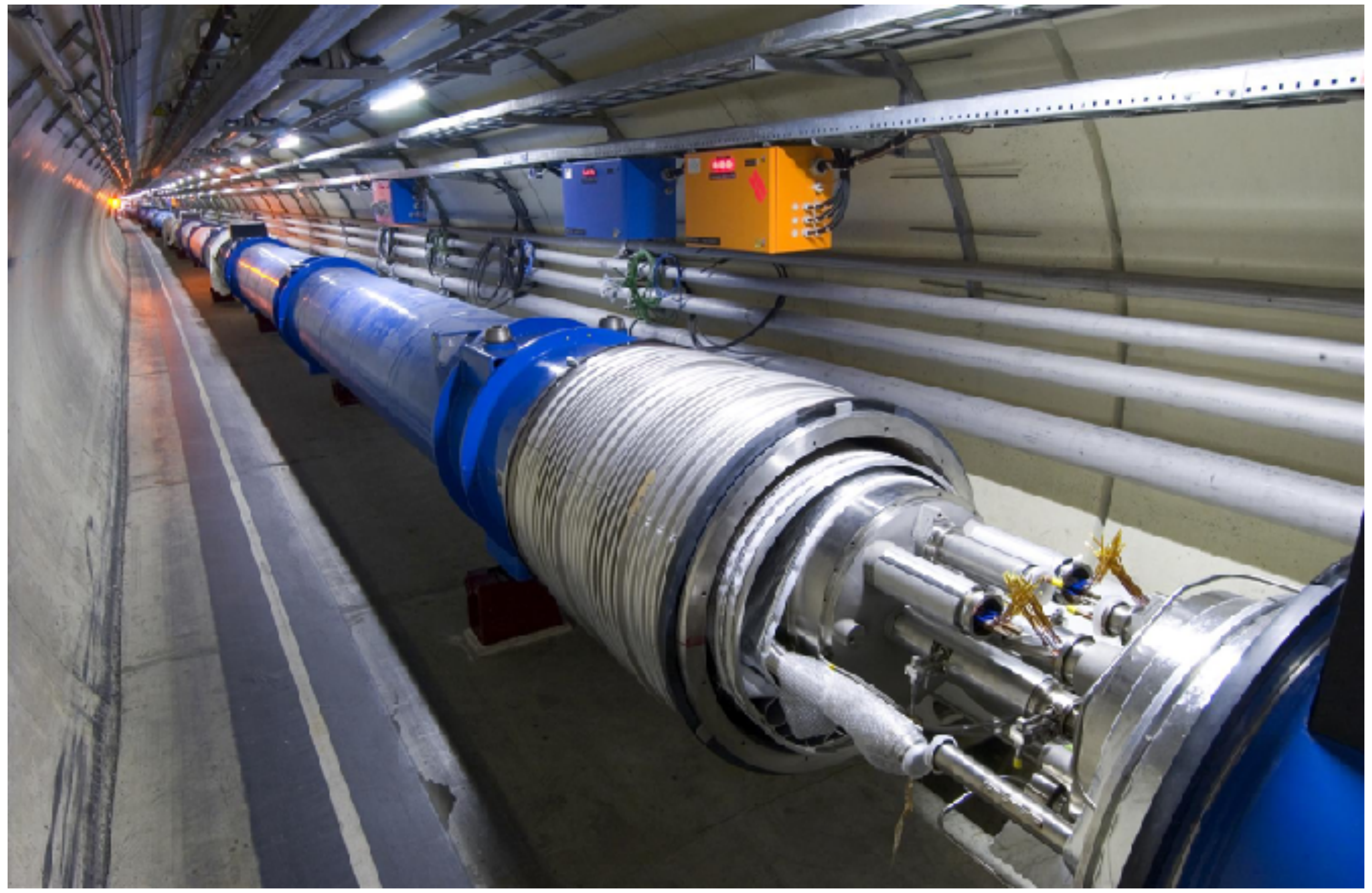
LHC?



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

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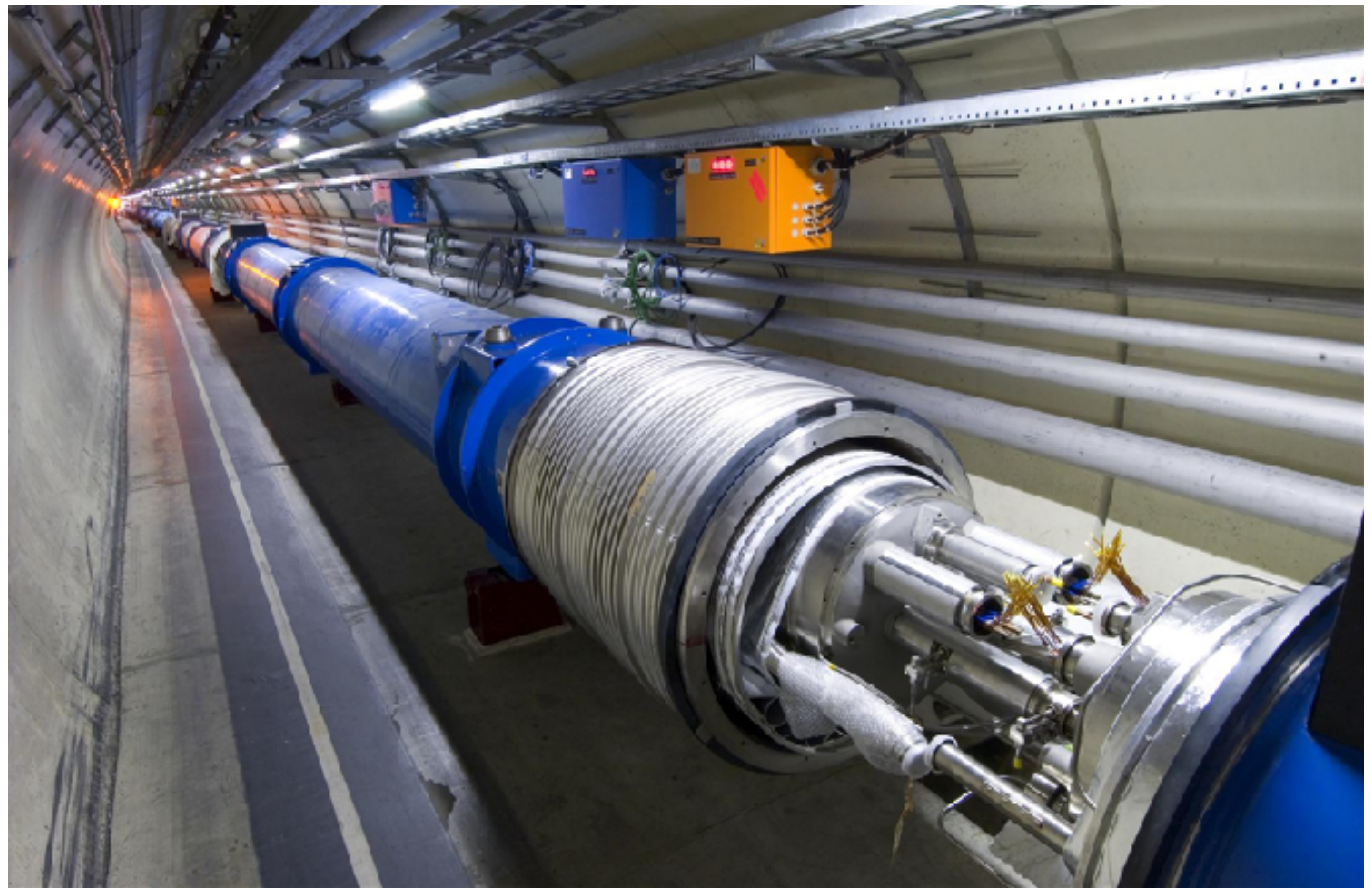
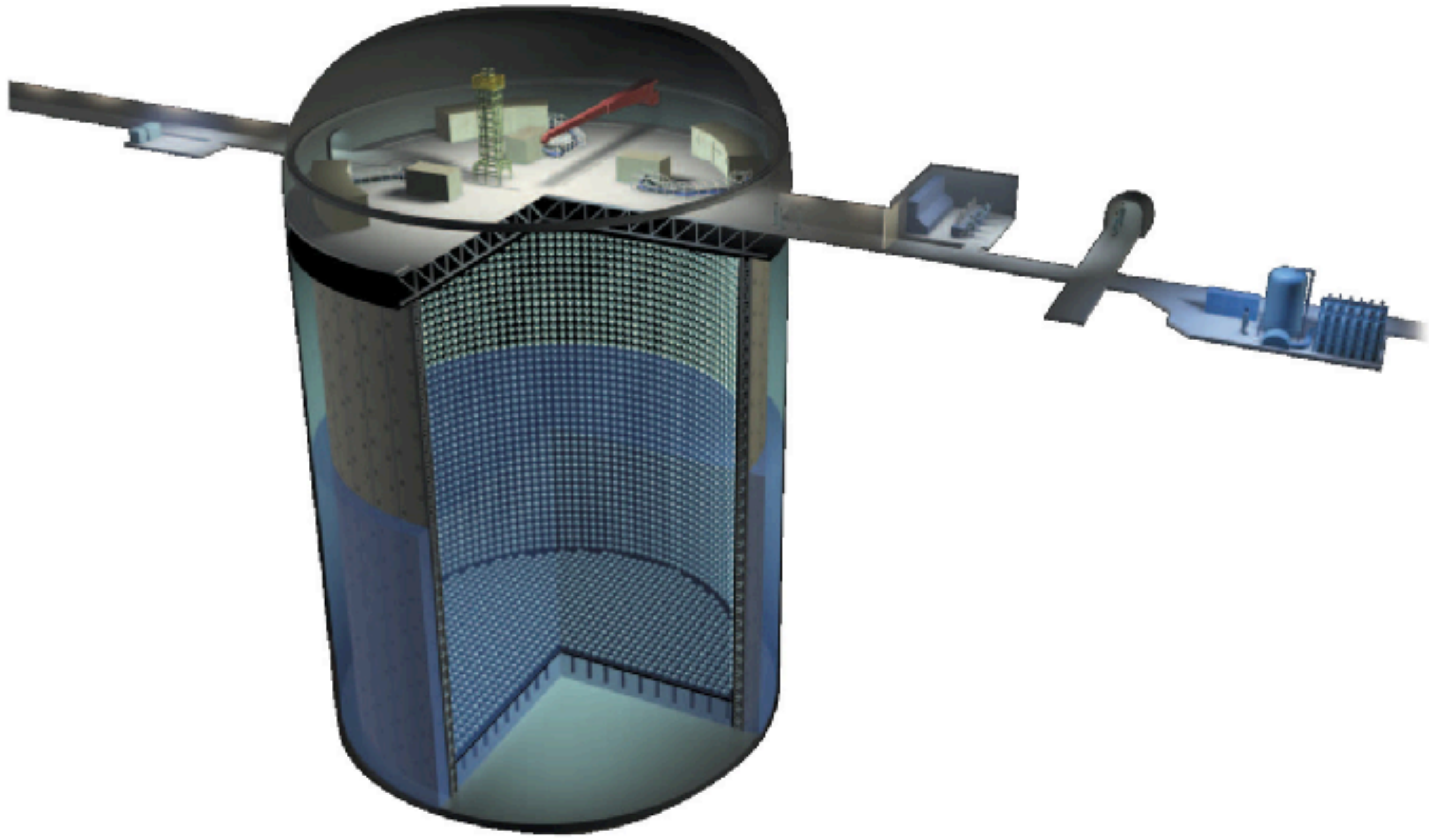


Super-Kamiokande



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

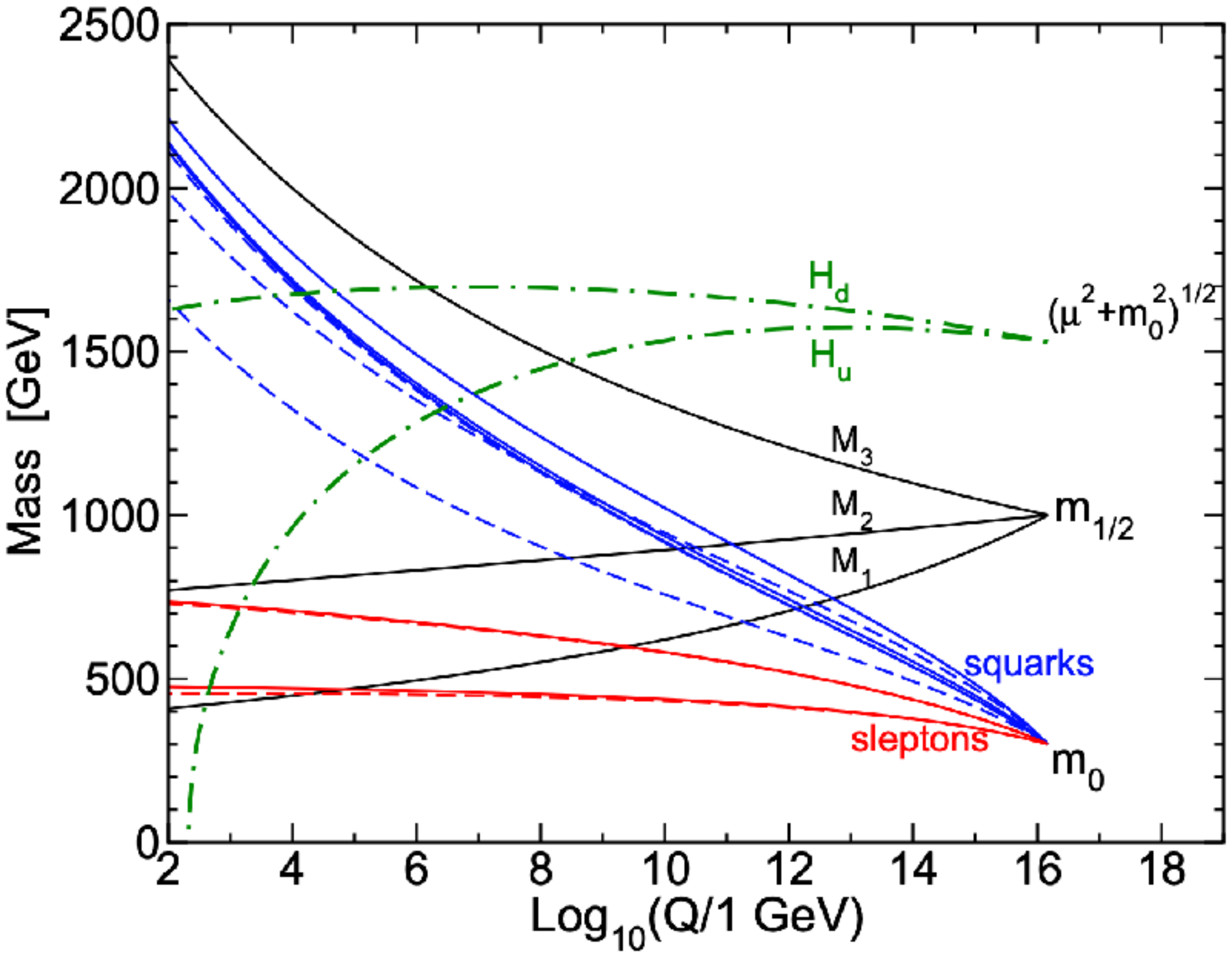
Indirectly explores energy scales $\Lambda \sim 10^{16}$ GeV.

Searching for decays using 10^{34} protons.

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

Motivation 1 : Colored sparticles may be too heavy for the LHC.

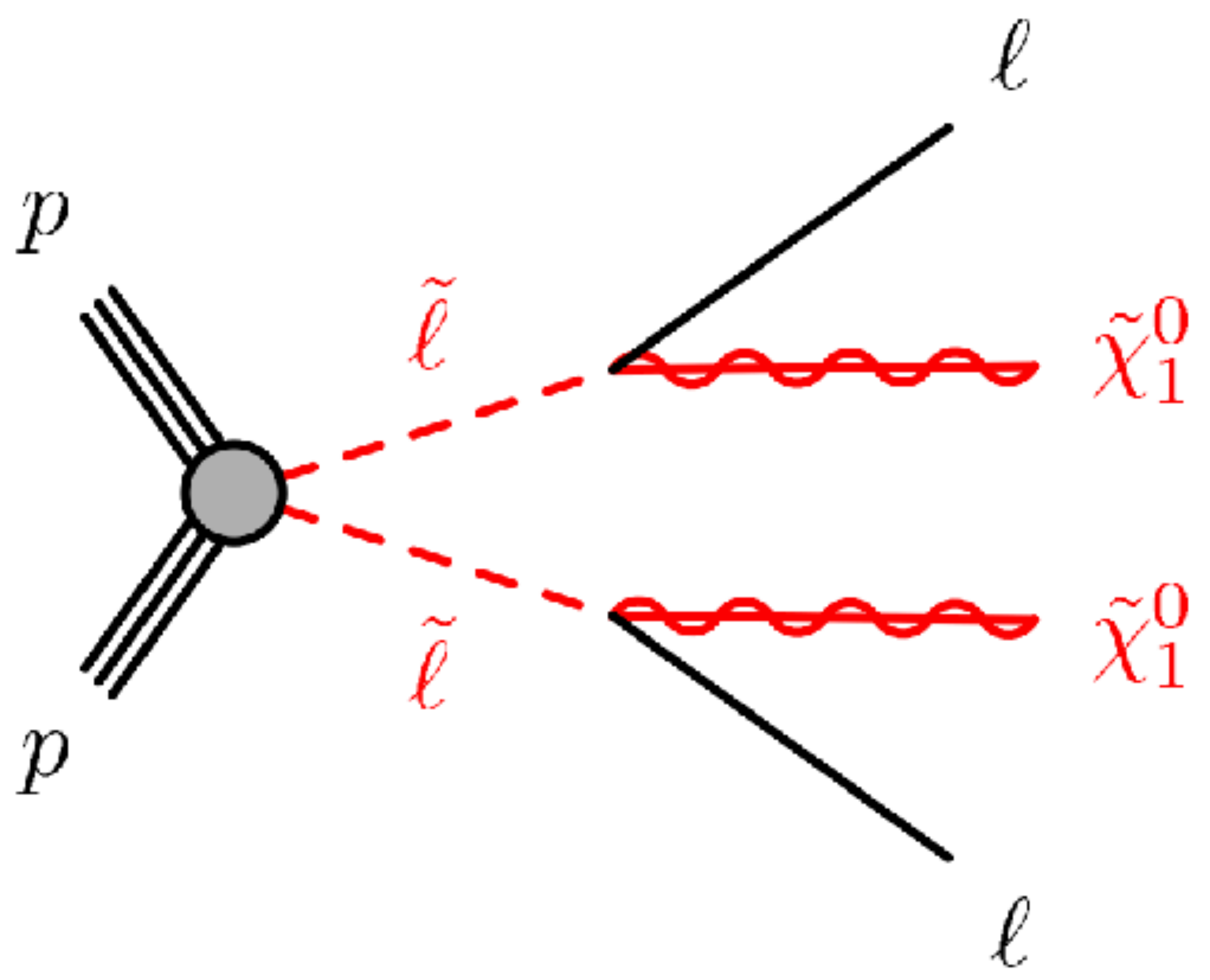
[Martin, 9709356]



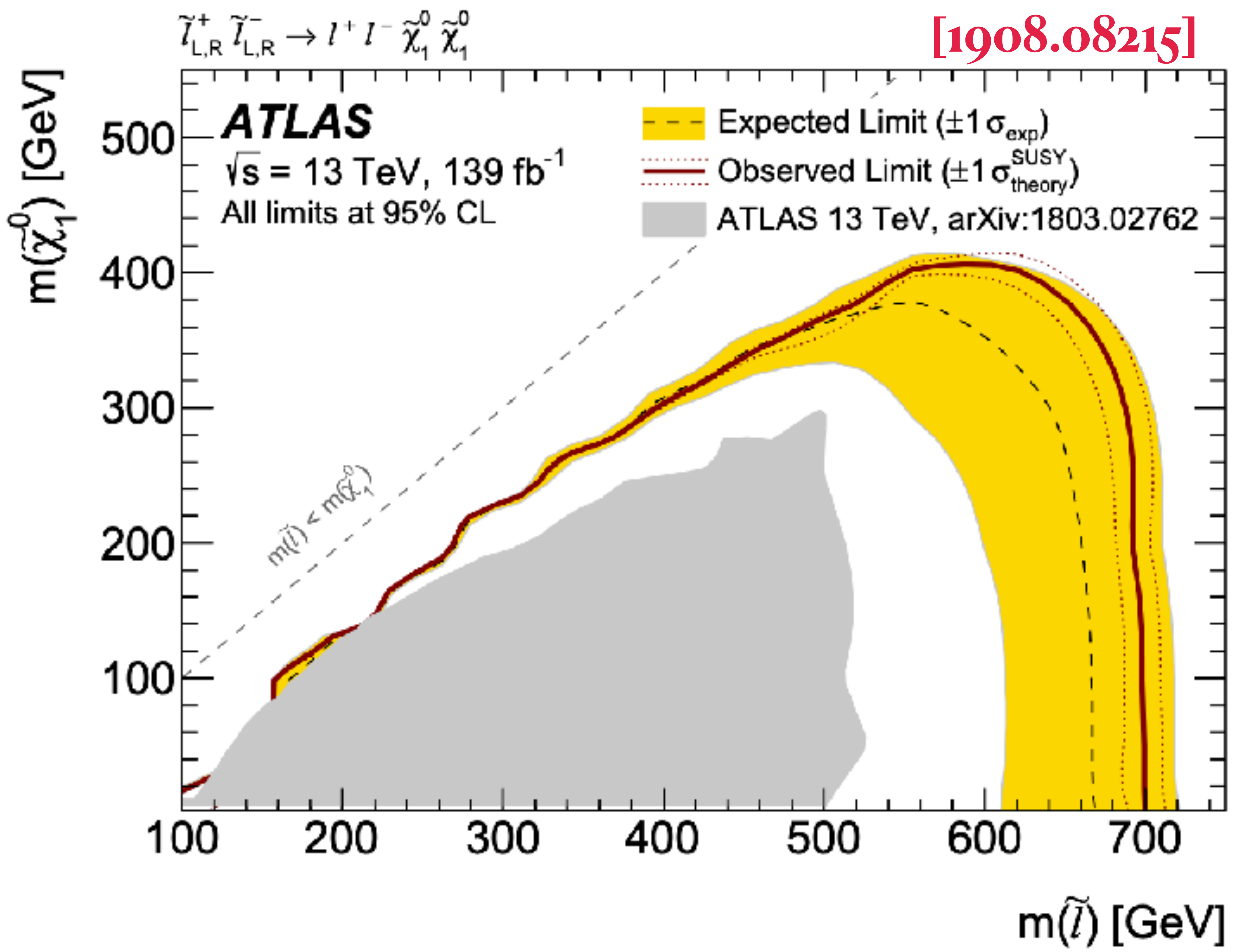
- Running motivates $m_{\text{colored}} > m_{\text{uncolored}}$.
- EWPTs are more sensitive to lighter particles.
- Alternatively, folded SUSY (for example) has no colored sparticles.

EWPTs on color neutral sparticles may beat LHC direct searches.

Motivation 2 : Blind Spots at the LHC



dilepton + MET



[1908.08215]

Direct SUSY searches often leave “gaps” in parameter space.

How could the FCC-ee see SUSY?

Simplified Models

To make progress, I will consider the following simplified models:

$U(1)_Y$ Dominated Model

$\tilde{B}(\mathbf{1},\mathbf{1})_0$	Pure Bino
$\tilde{E}(\mathbf{1},\mathbf{1})_1$	Right Handed Slepton

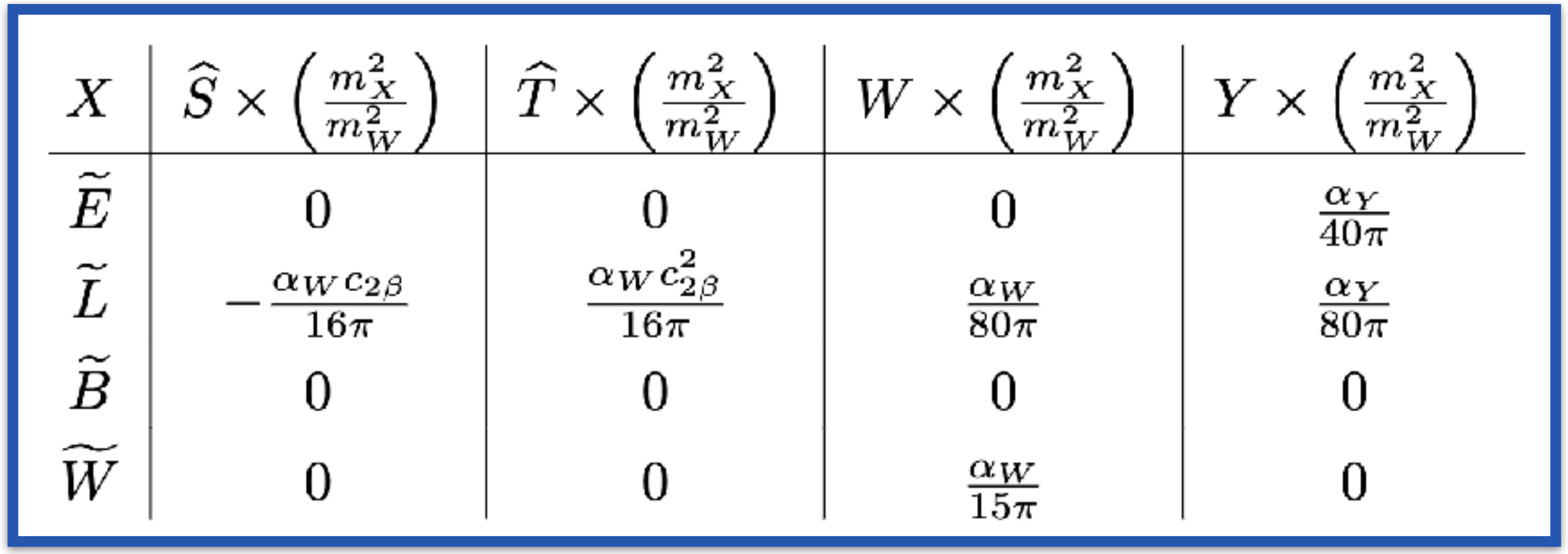
$SU(2)_L$ Dominated Model

$\tilde{W}(\mathbf{1},\mathbf{3})_0$	Pure Wino
$\tilde{L}(\mathbf{1},\mathbf{2})_{-1/2}$	Left Handed Slepton

A bit overly simplified, but gives us an idea of the sensitivity of the FCC-ee.

Corrections from SUSY (1-Sparticle Level)

- If we assume R-parity conservation, all corrections are at 1-loop.
- Dominant effects from “oblique corrections” if considering only a single sparticle.



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

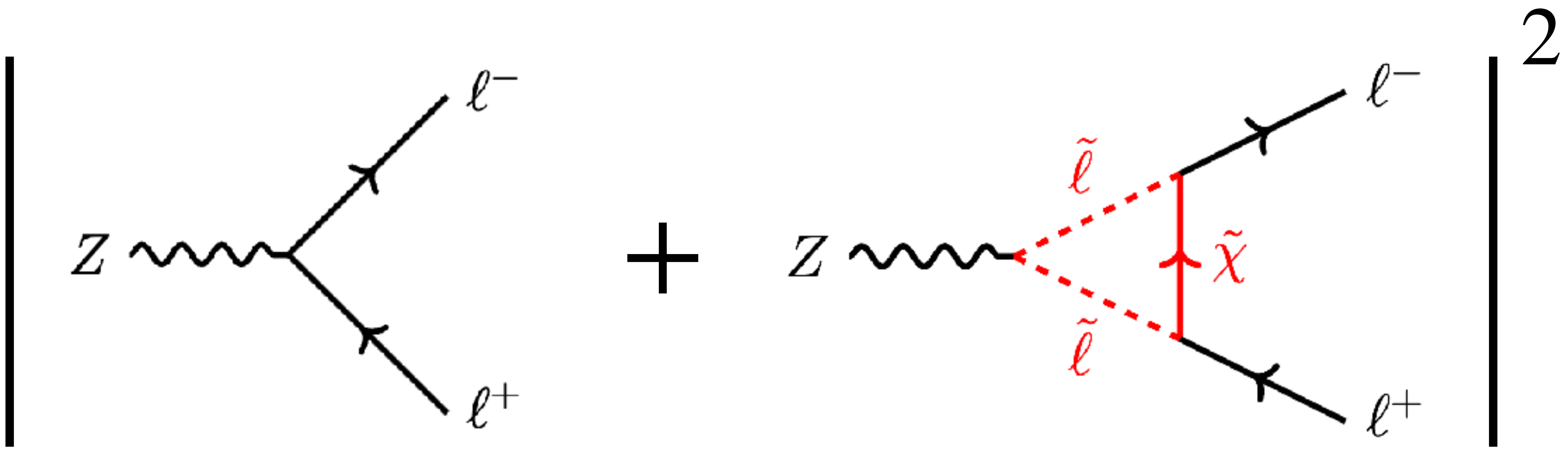
Marandella, Schappacher, Strumia [hep-ph/0502095]

- FCC sensitivity at the $\mathcal{O}($ few 100 GeV$)$ level (not the focus of this talk).

Non-Universal Corrections to Z-pole Observables

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)

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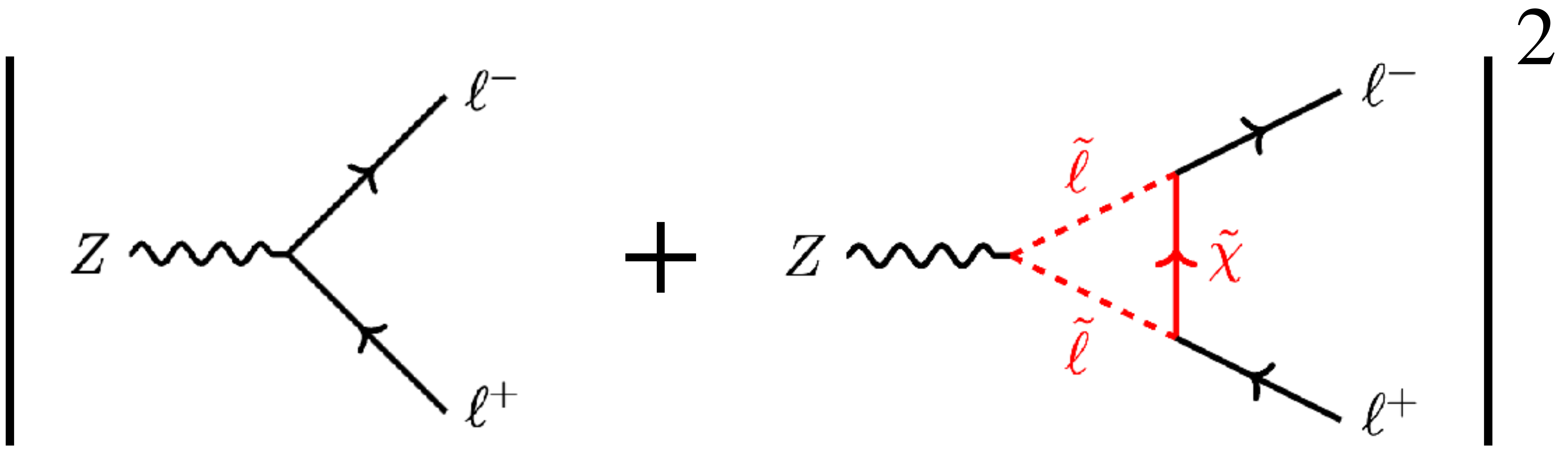


(Just one of several diagrams)

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

Finding a robust observable

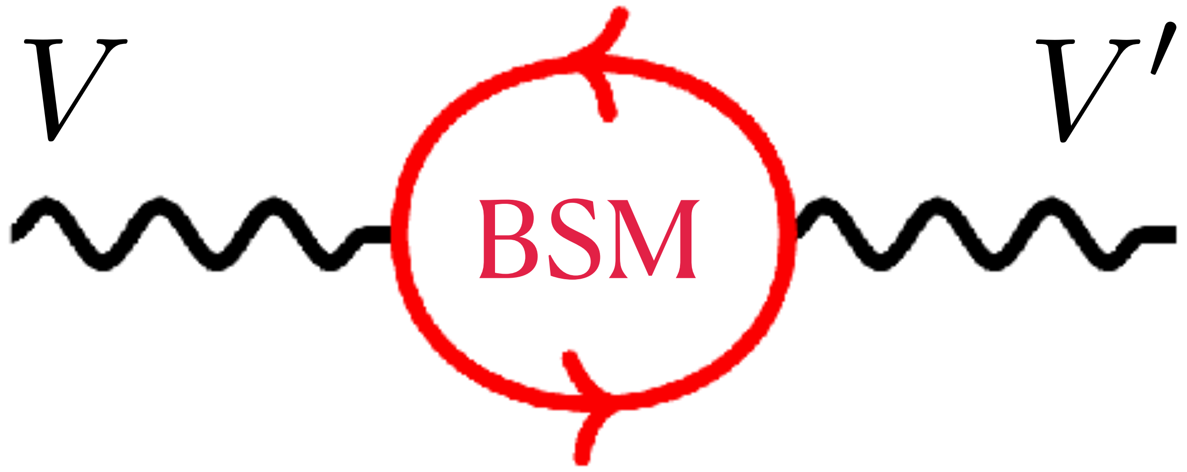
$\Gamma(Z \to \ell\bar{\ell})$ is not the best observable. Instead we use

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

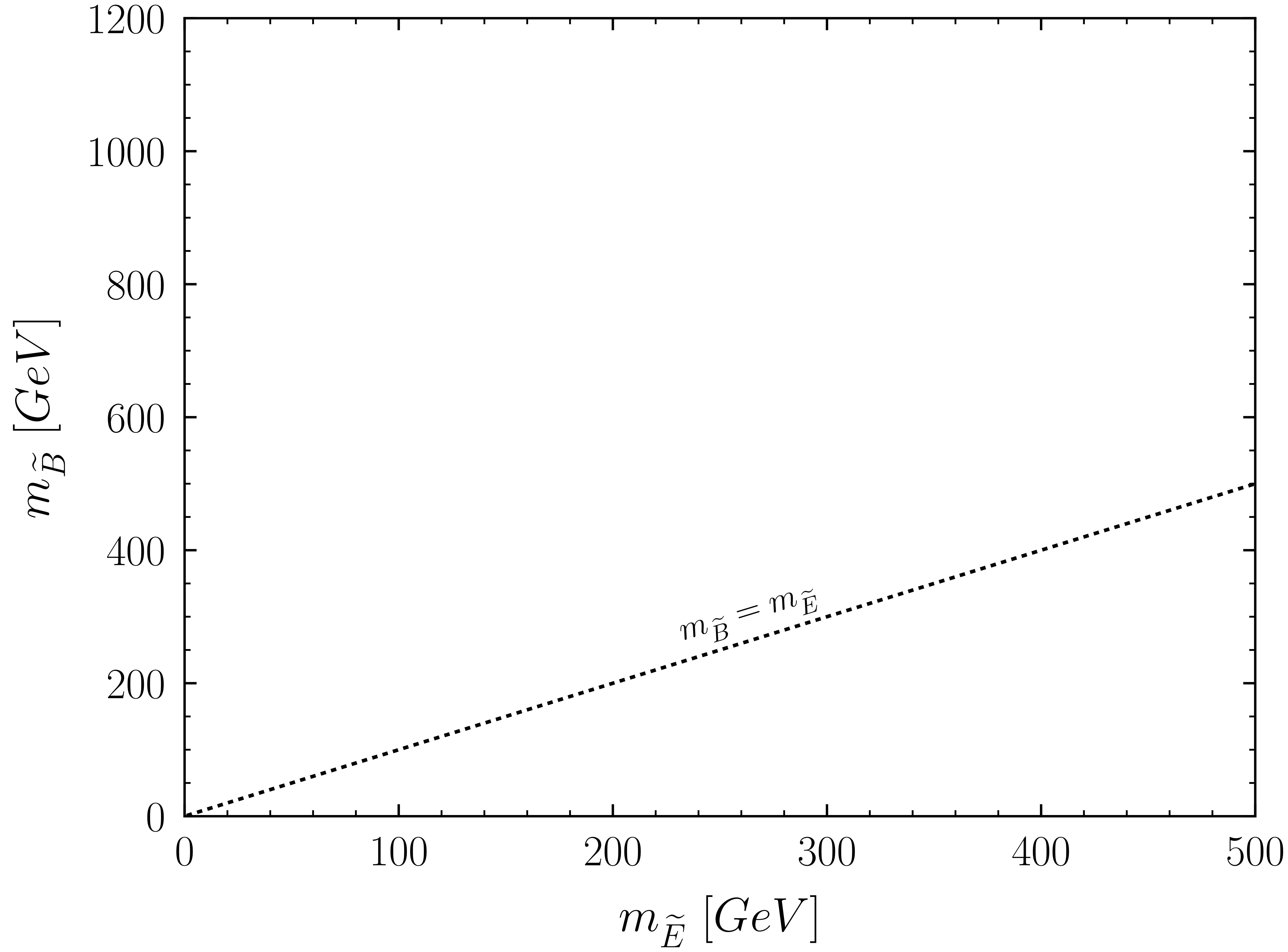
- Hadronic decay introduces $\alpha_s(M_Z)$ dependence. This must be determined by other measurements.
- Also depends on θ_W. We will identify this from

$$\sin^2 \hat{\theta}_W \cos^2 \hat{\theta}_W \equiv \frac{\pi \hat{\alpha}\left(m_Z\right)}{\sqrt{2}\hat{G}_F \hat{m}_Z^2}$$

This choice introduces modifications from oblique corrections.



Bino + RH Slepton



Knapen, KL, Ligeti, [2407.13815]

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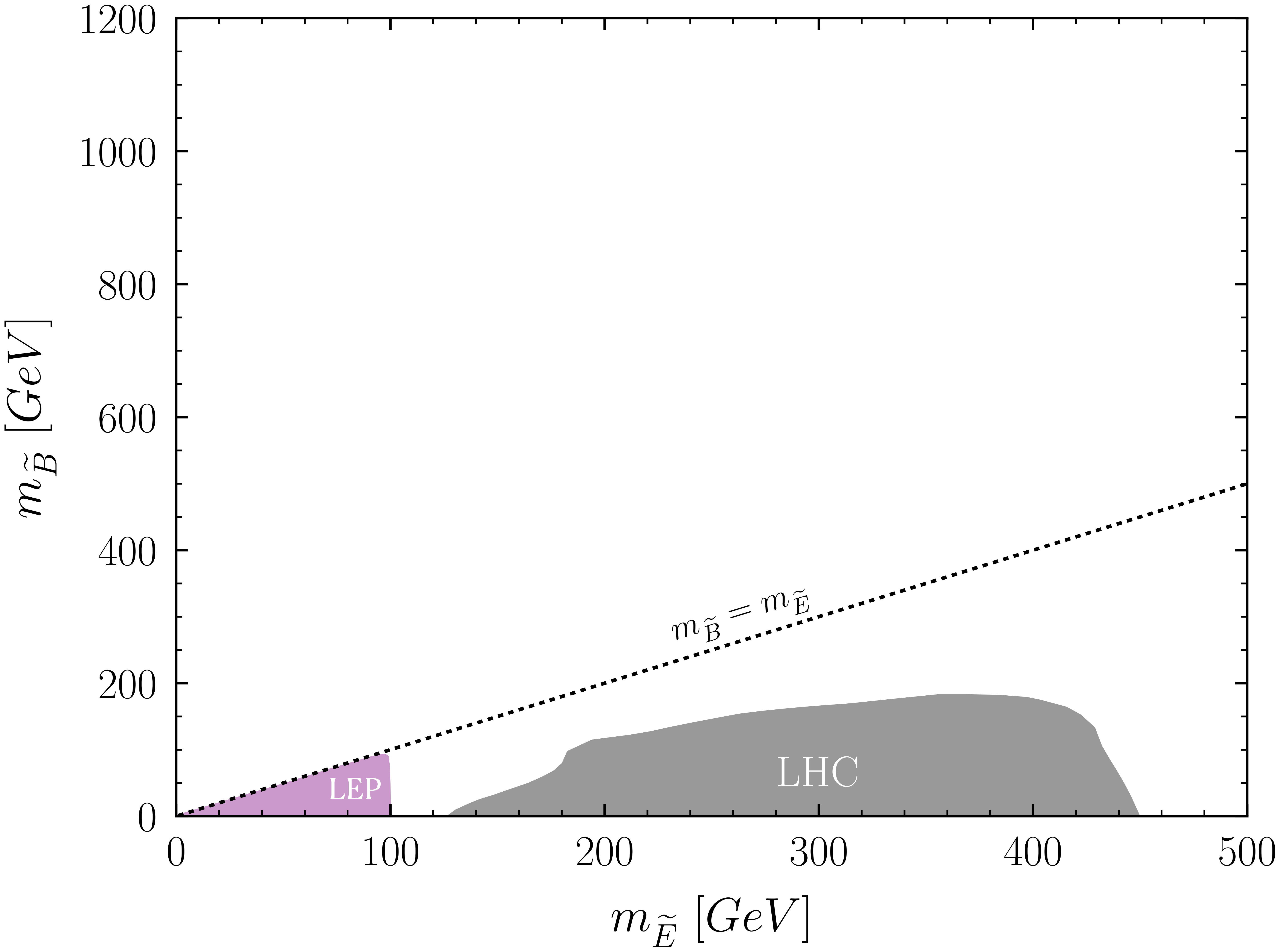

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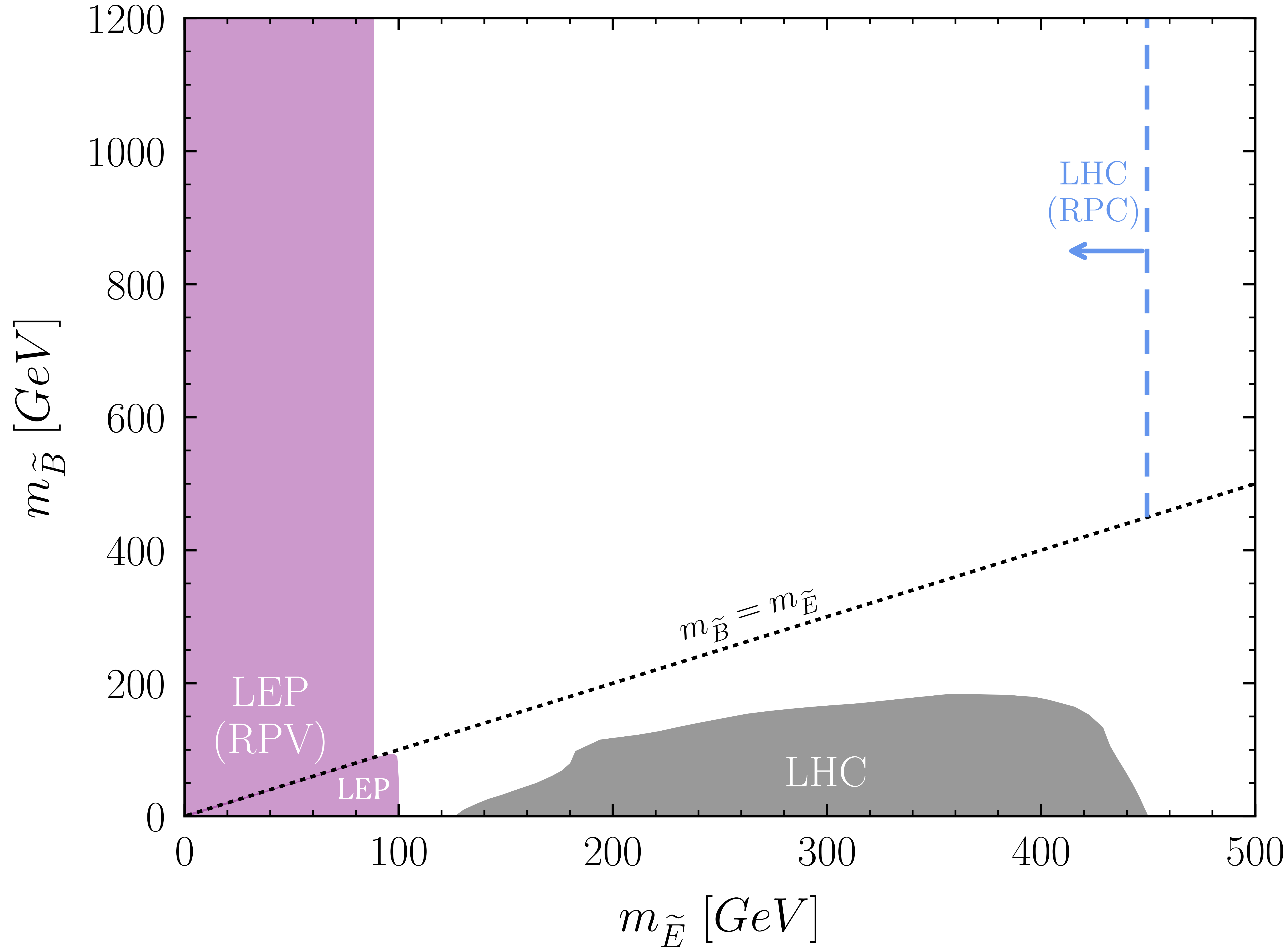

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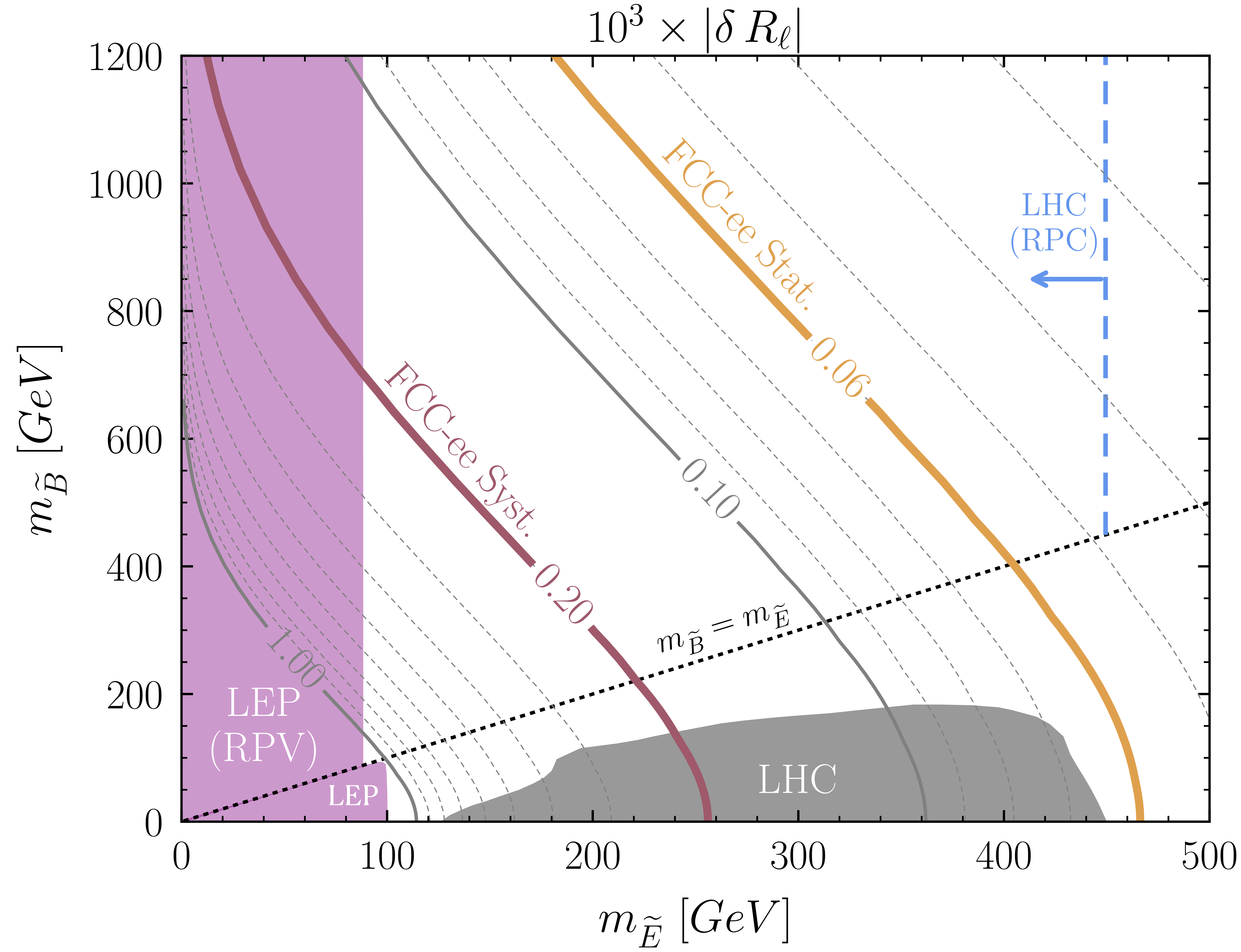

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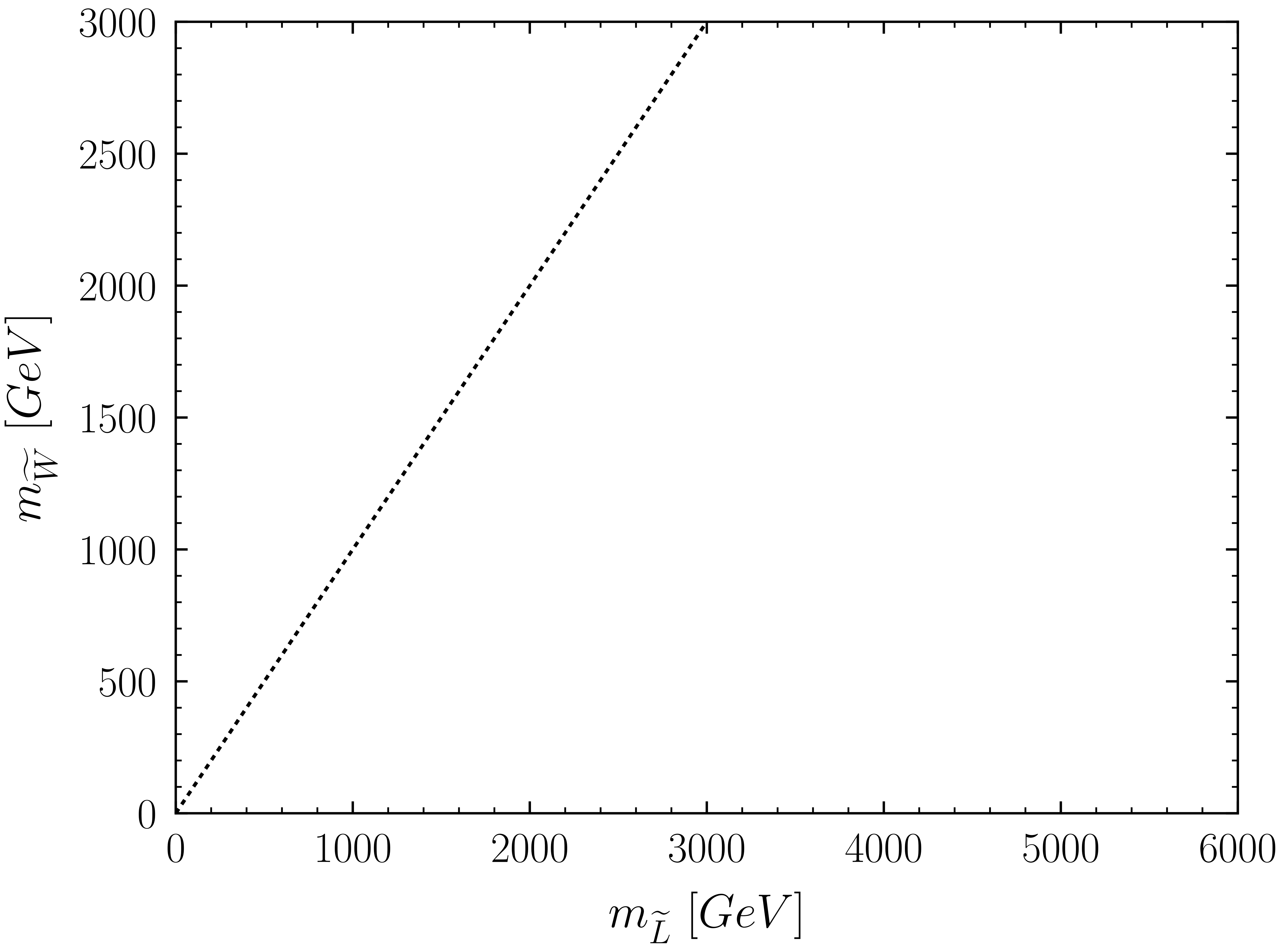
Wino + LH Sleptons



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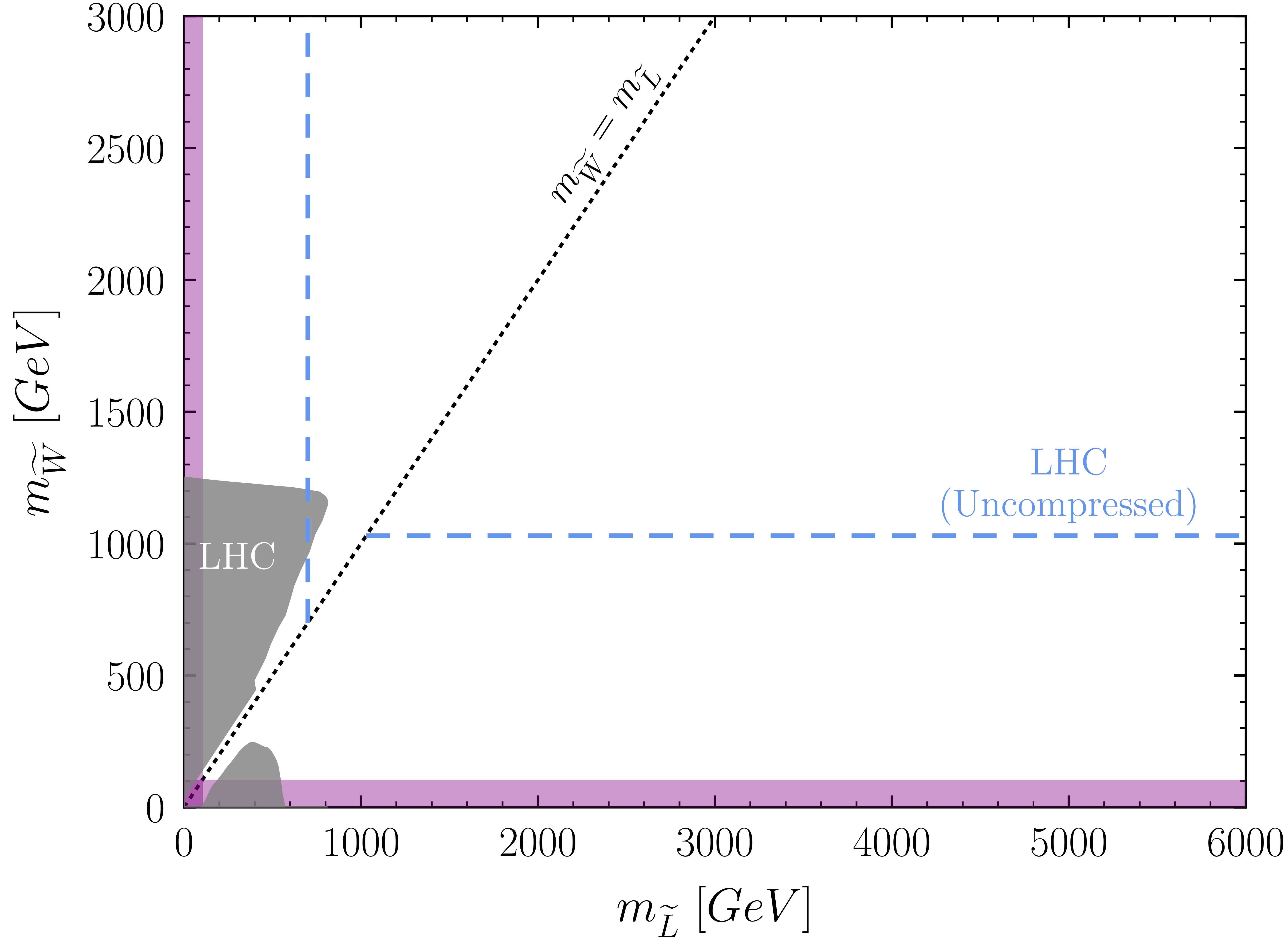

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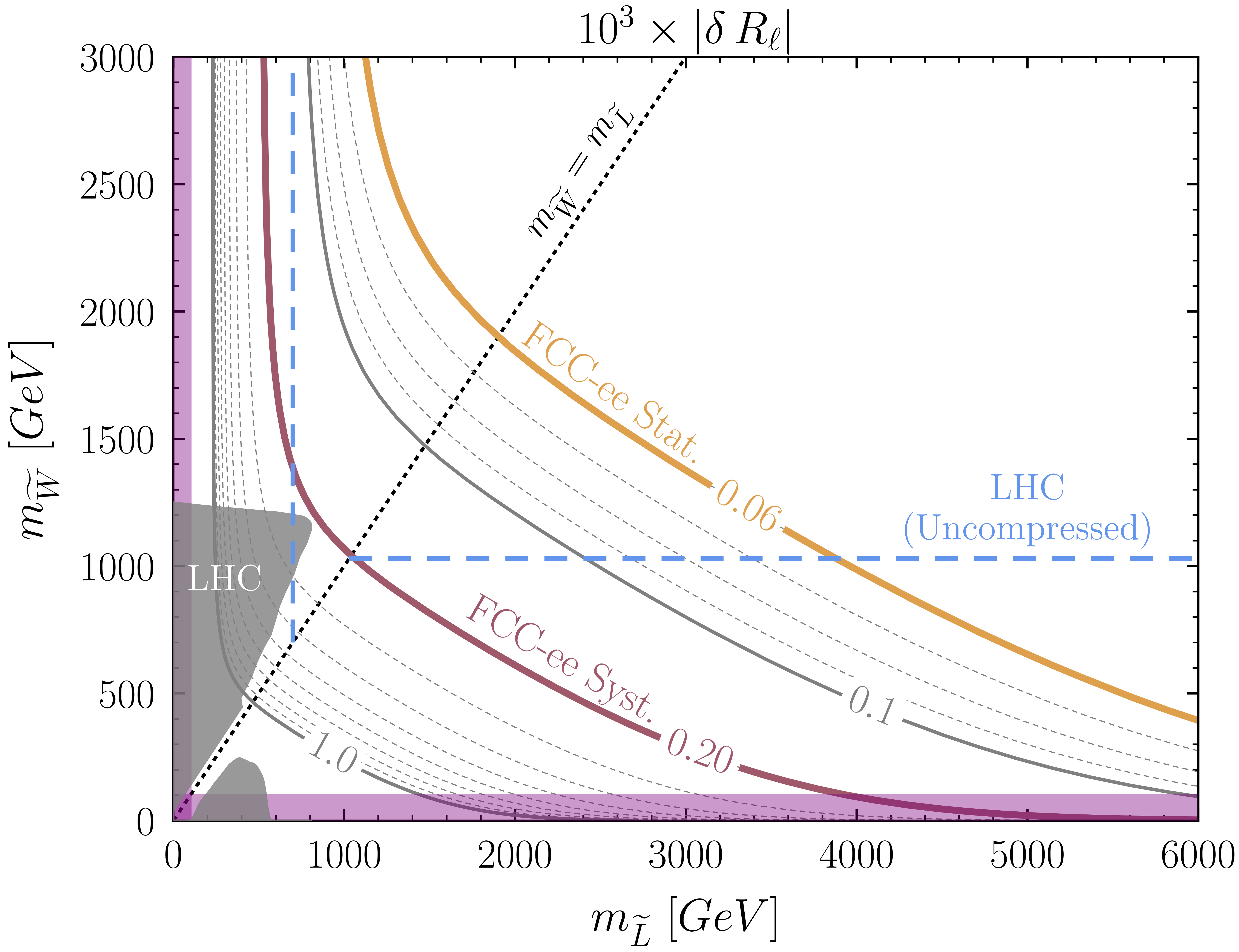

Knapen, KL, Ligeti, [2407.13815]

Conclusion

- EWPTs are complimentary searches for new physics.
- SUSY parameter space exists which may be explored at the FCC-ee.
- Motivates investigating which observables give the greatest reach to new physics.

Thanks!

Backup Slides

Electroweak Precision Tests (EWPTs)

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

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

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Observables

1. $G_F = \left(\sqrt{2}v^2\right)^{-1}$
2. $m_W = \frac{1}{2} g v$
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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$\longrightarrow$

Prediction

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

(At tree level)

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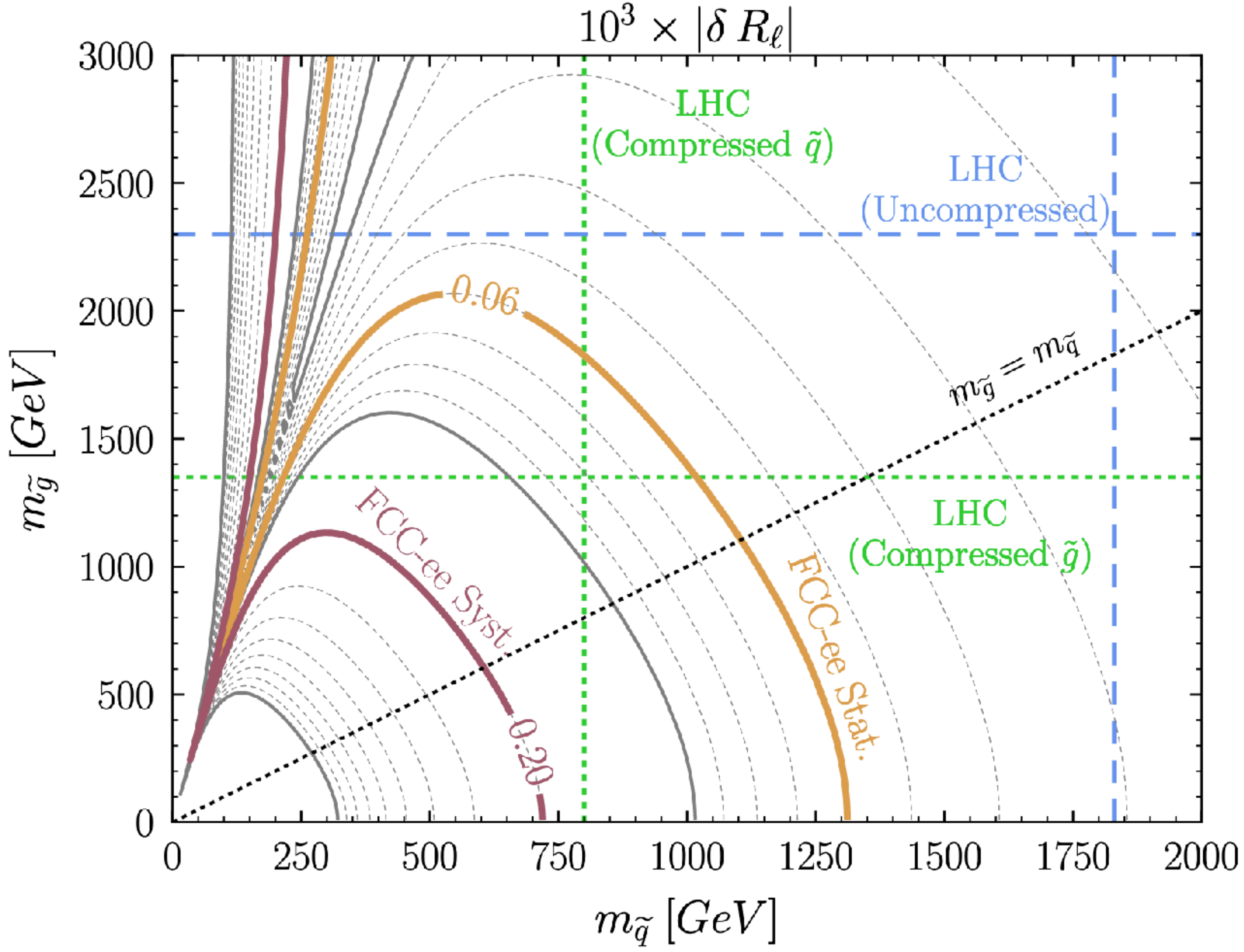
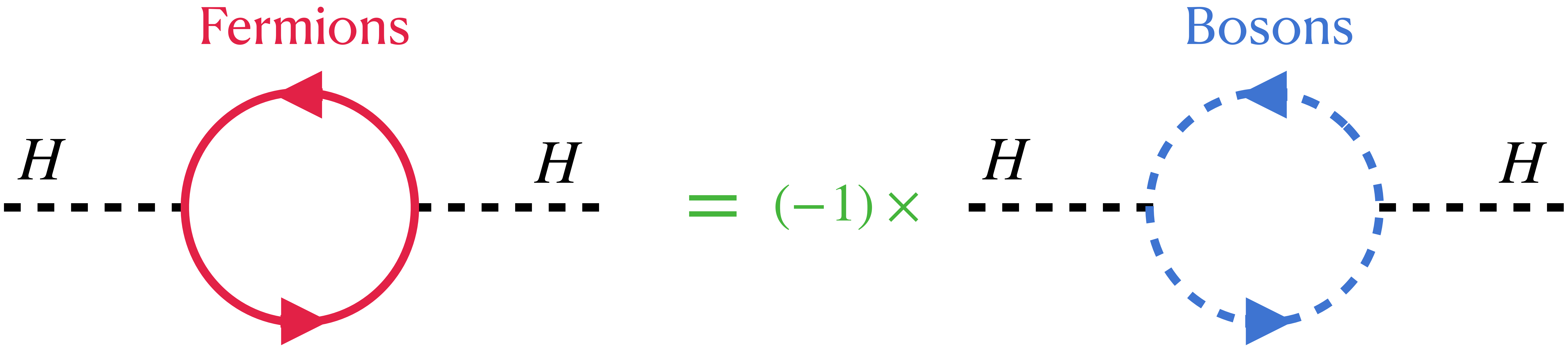
- Checks like this give us a method of indirectly discovering new physics!


$10^3 \times |\delta R_\ell|$
LHC
(Compressed $\tilde{q}$)
LHC
(Uncompressed)
0.06
$m_{\tilde{g}} = m_{\tilde{q}}$
LHC
(Compressed $\tilde{g}$)
FCC-ee Syst
FCC-ee Stat.
0.20
$m_{\tilde{g}}$ $[GeV]$
$m_{\tilde{q}}$ $[GeV]$
0
500
1000
1500
2000
2500
3000
0
250
500
750
1000
1250
1500
1750
2000

Supersymmetry

The diagrams for Higgs boson mass corrections are the following:



$$\boxed{\Delta m_H = \Delta m_{H,fermions} + \Delta m_{H,bosons} = 0}$$

If SUSY is exact. But it is broken...

Supersymmetry

When SUSY is broken, the Higgs gets corrections

$$\boxed{\Delta m_H^2 = \Delta m_{H,fermions}^2 + \Delta m_{H,bosons}^2 \propto \frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2} \log(m_{\tilde{t}}/m_t)}$$

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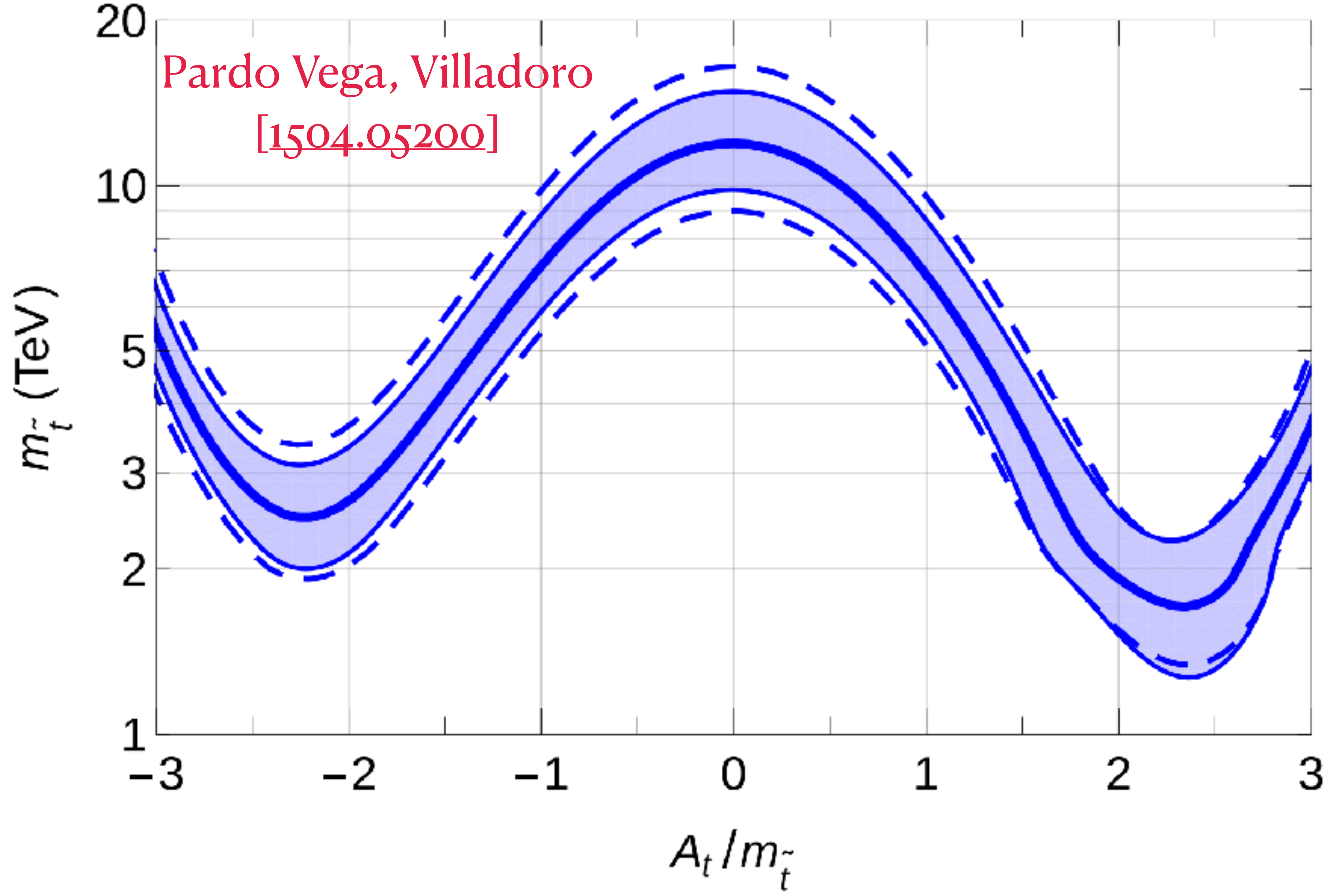

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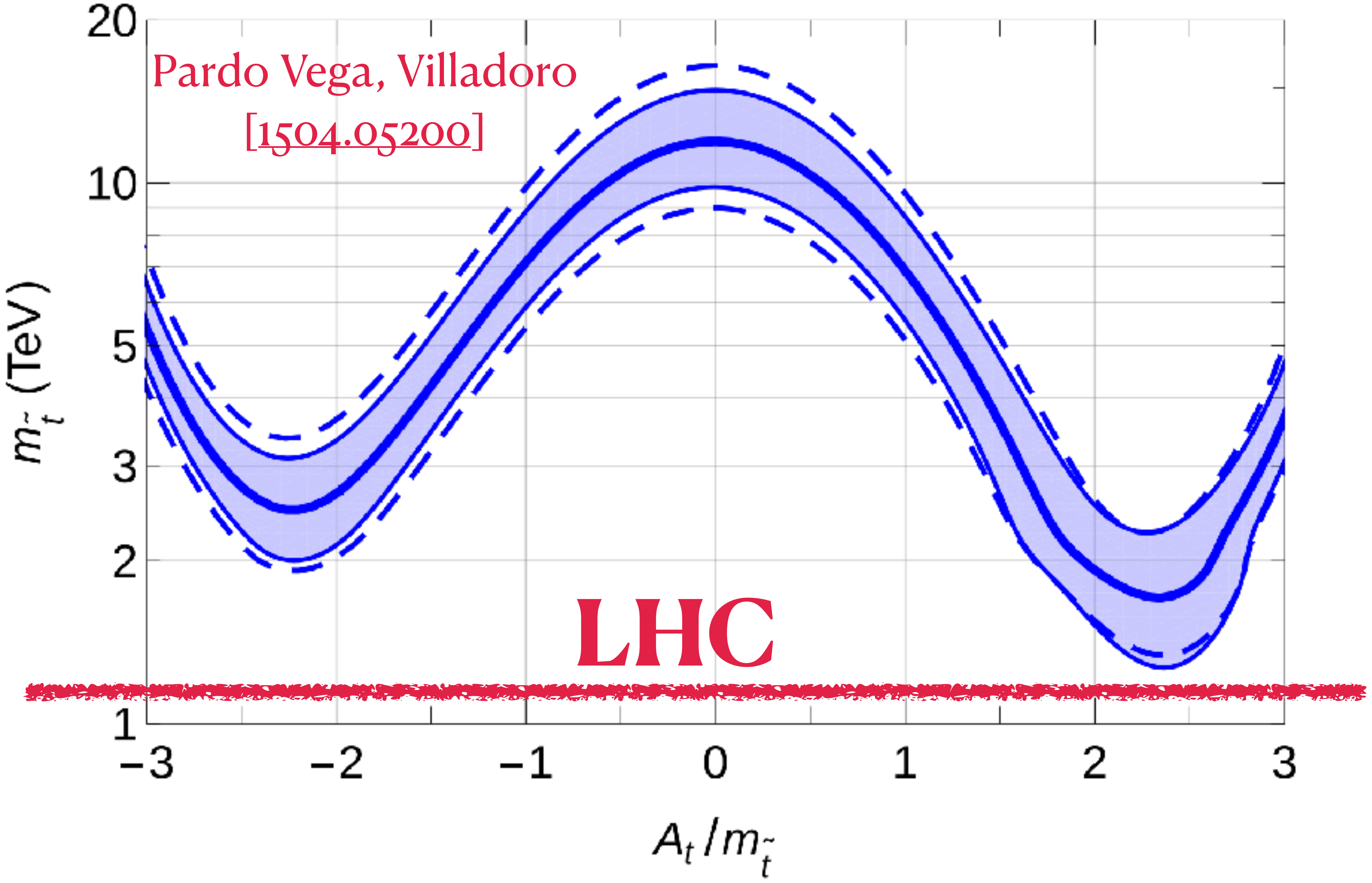

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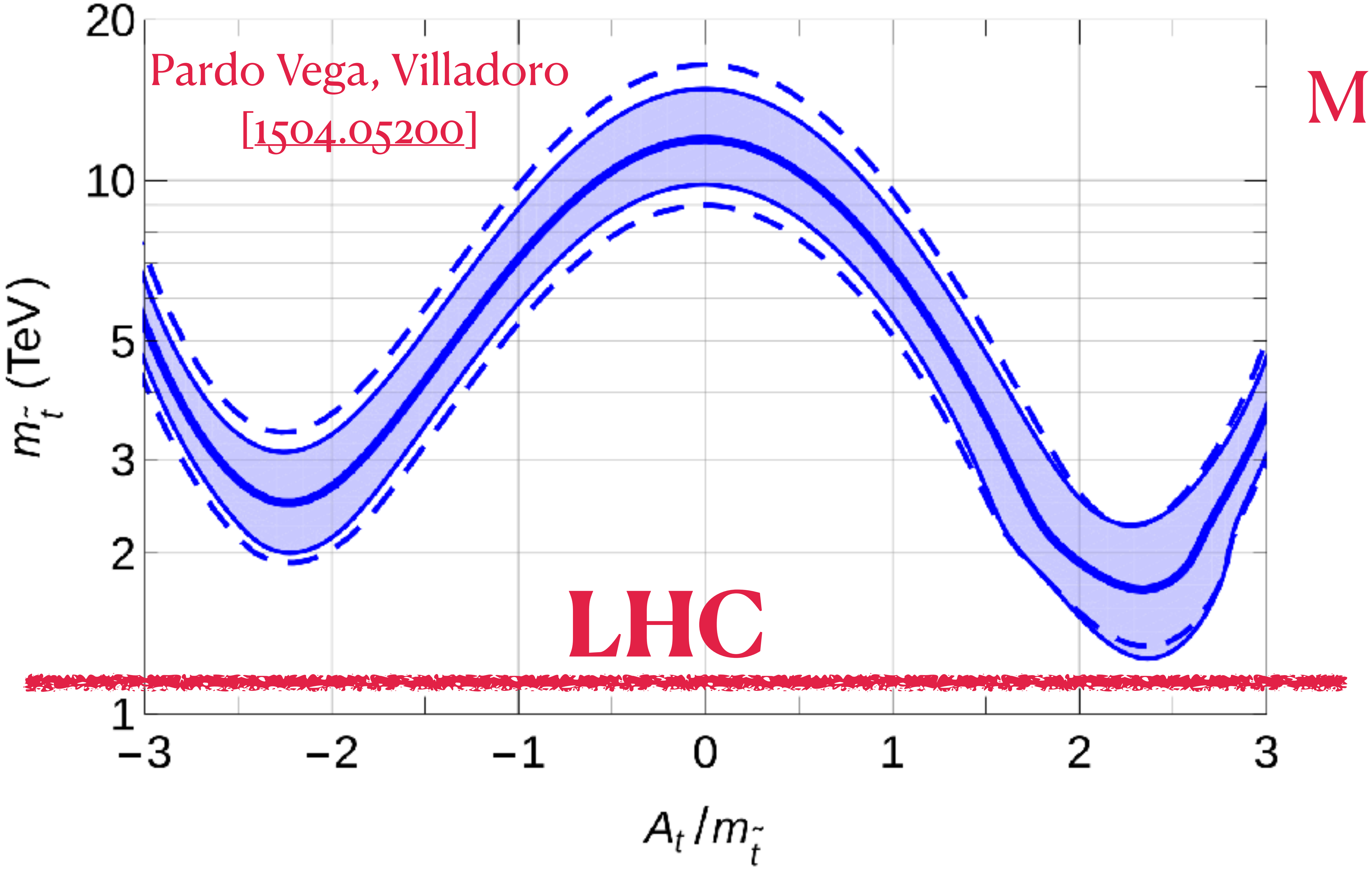

Pardo Vega, Villadoro [1504.05200]

Might be just out of reach...

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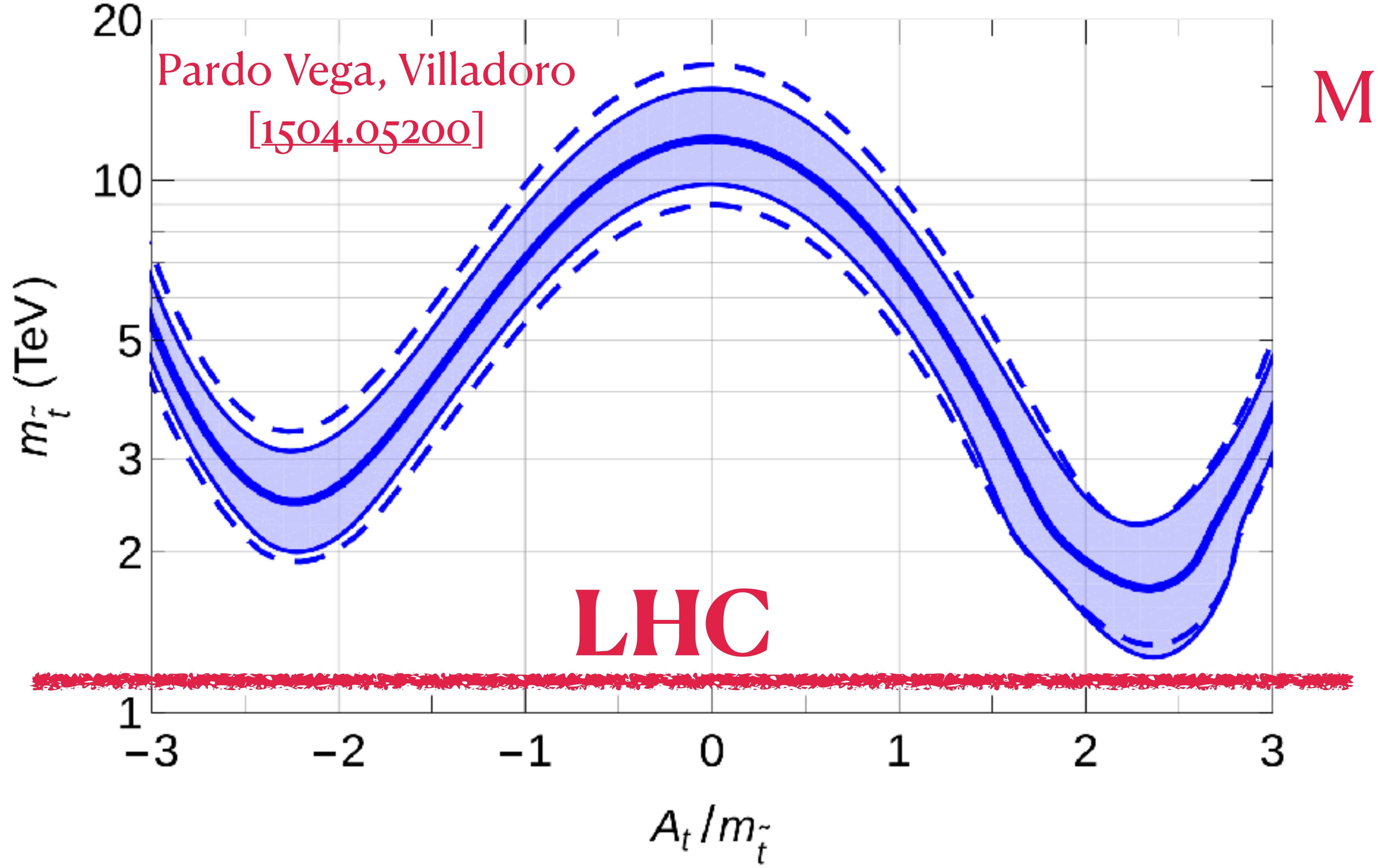

Pardo Vega, Villadoro [1504.05200]

LHC

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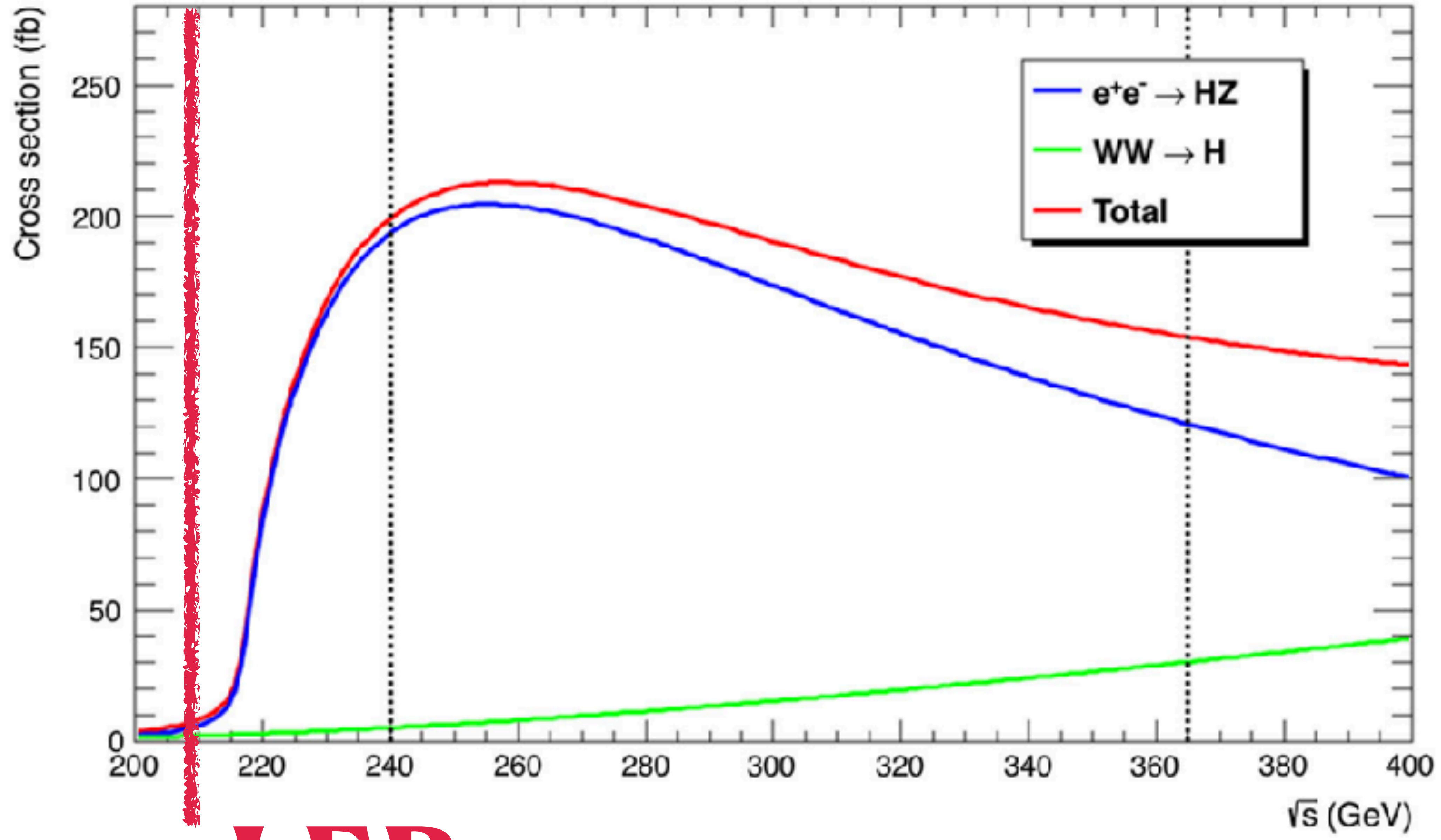
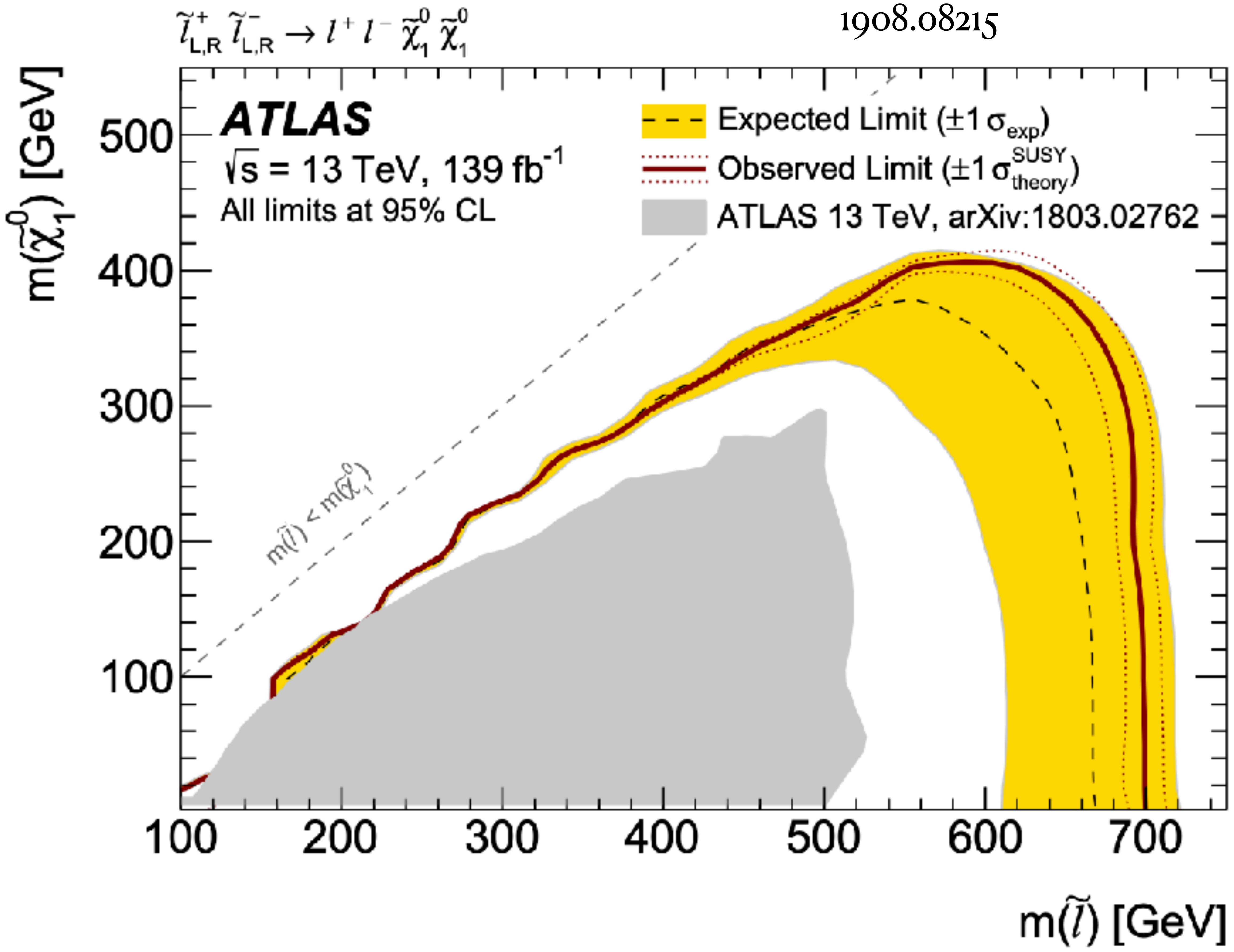
[FCC-CDR]



LEP

Simplified SUSY Models



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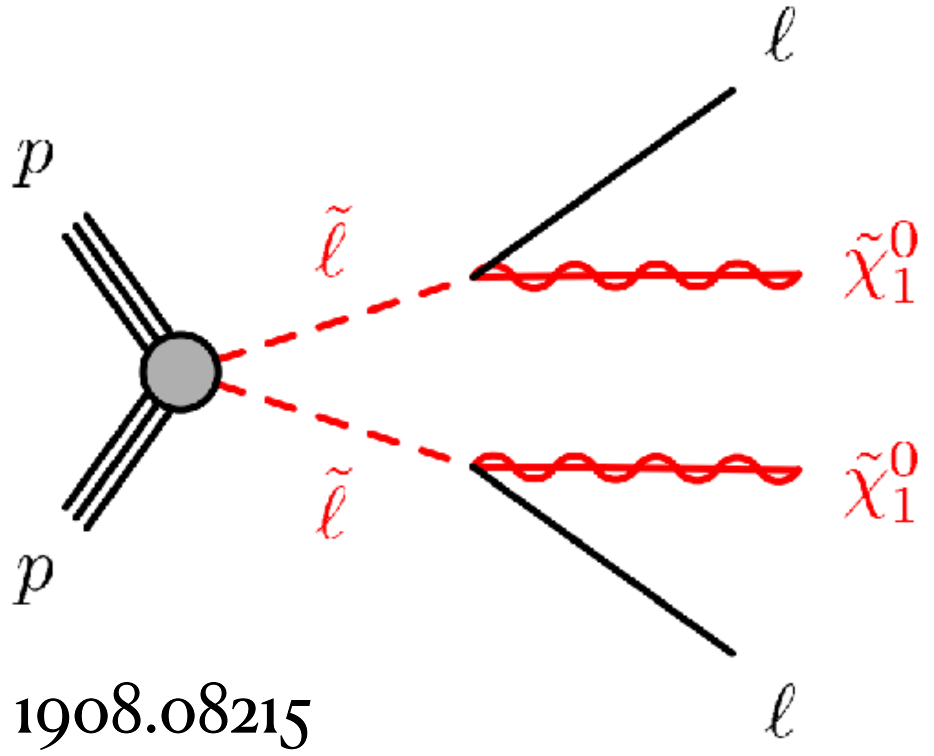

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Simplified SUSY Models

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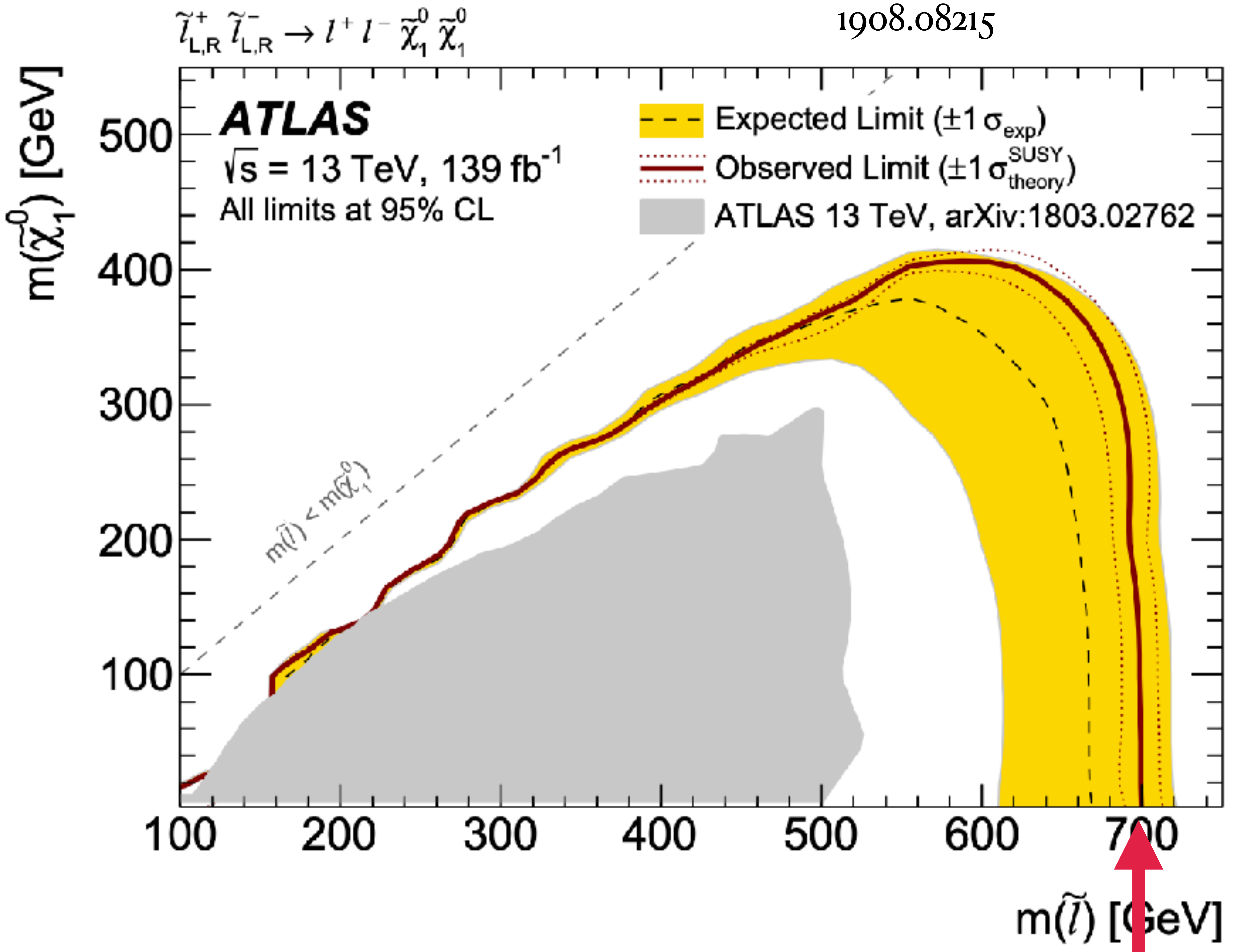

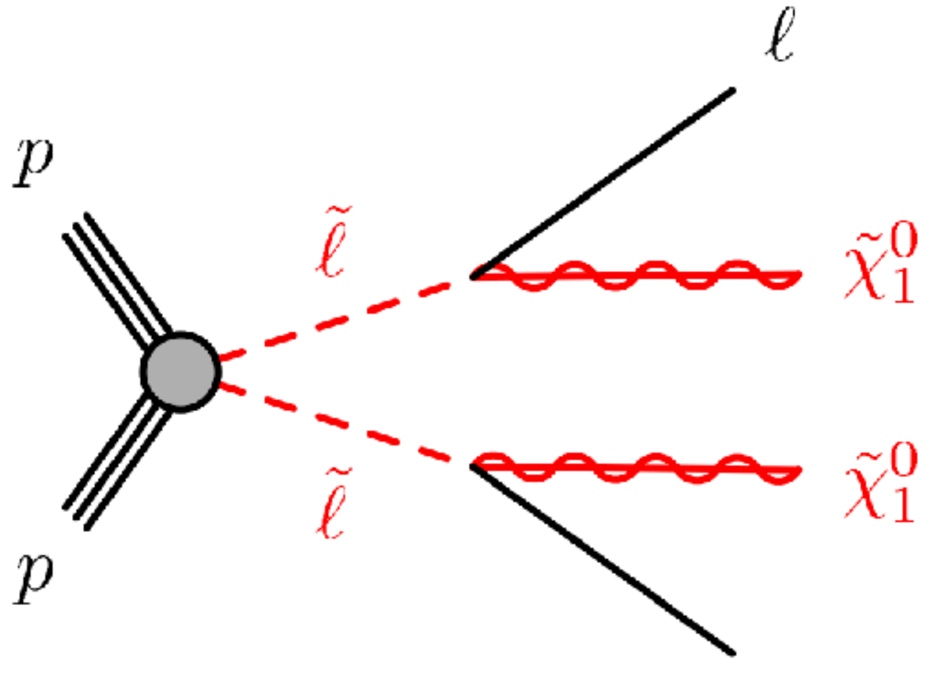

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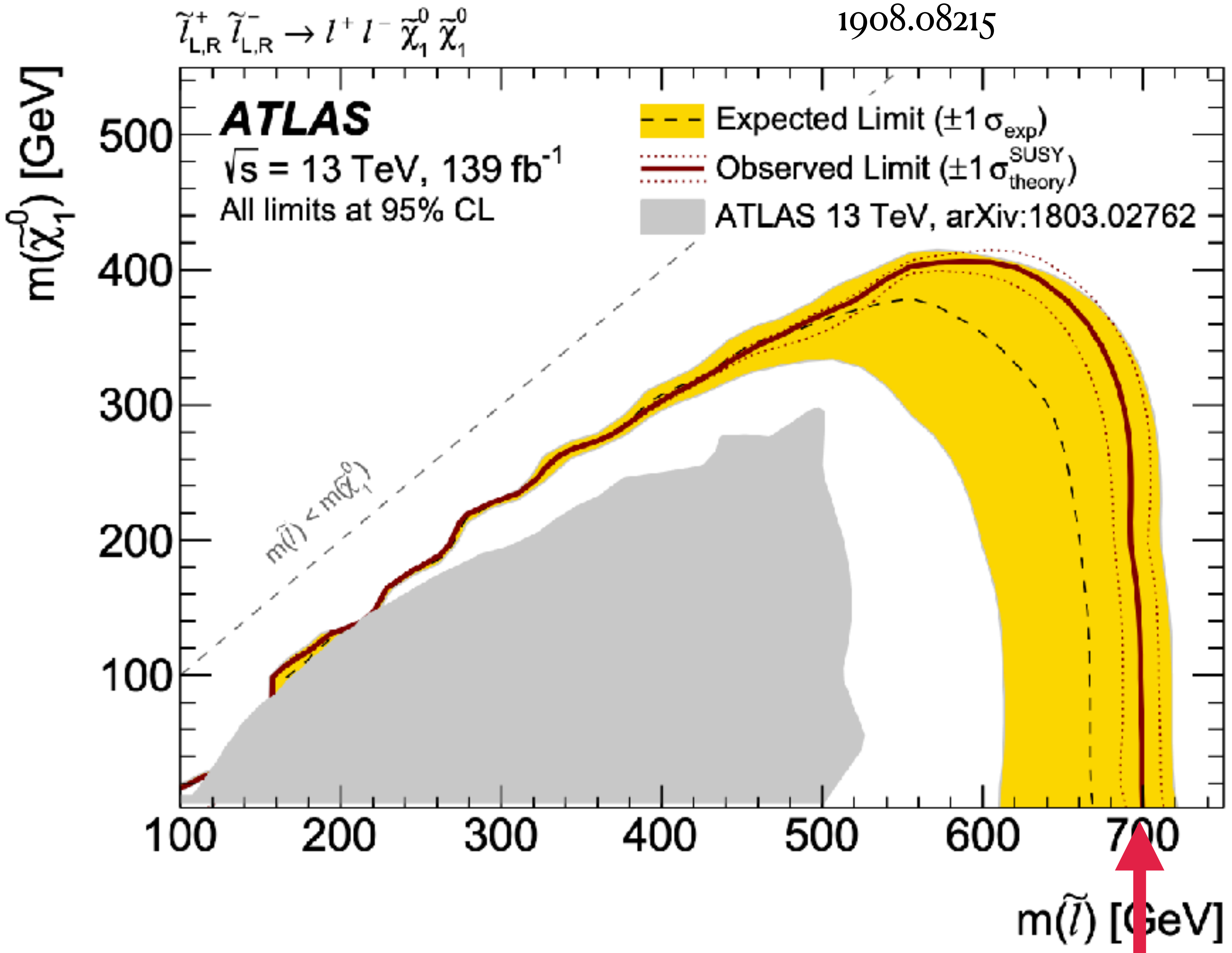
Constrained by cross section.

Simplified SUSY Models



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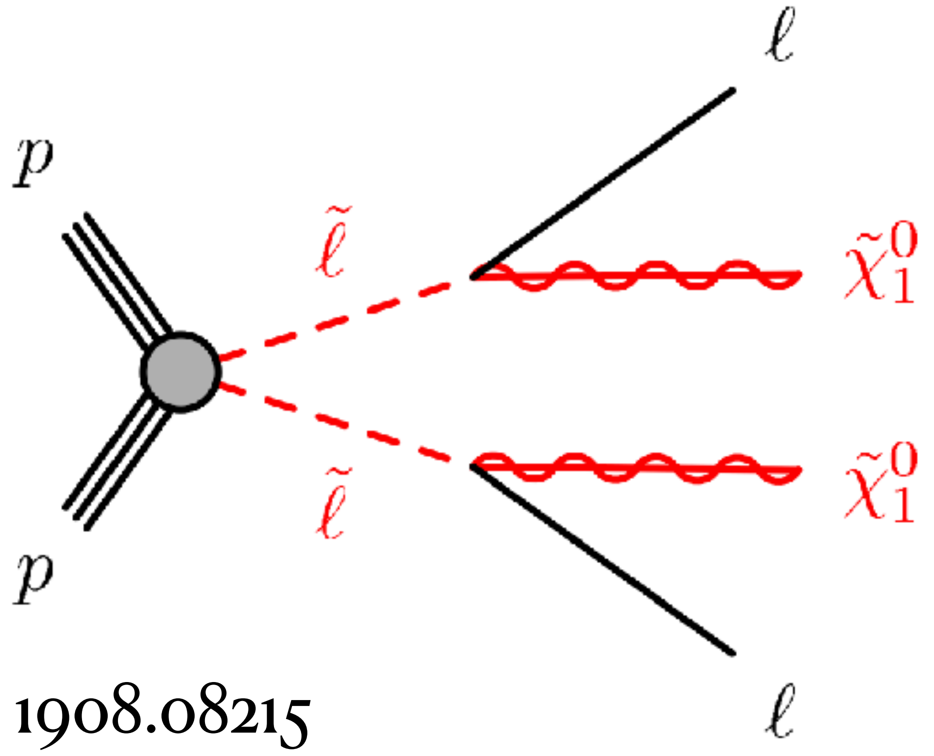
Constrained by cross section.



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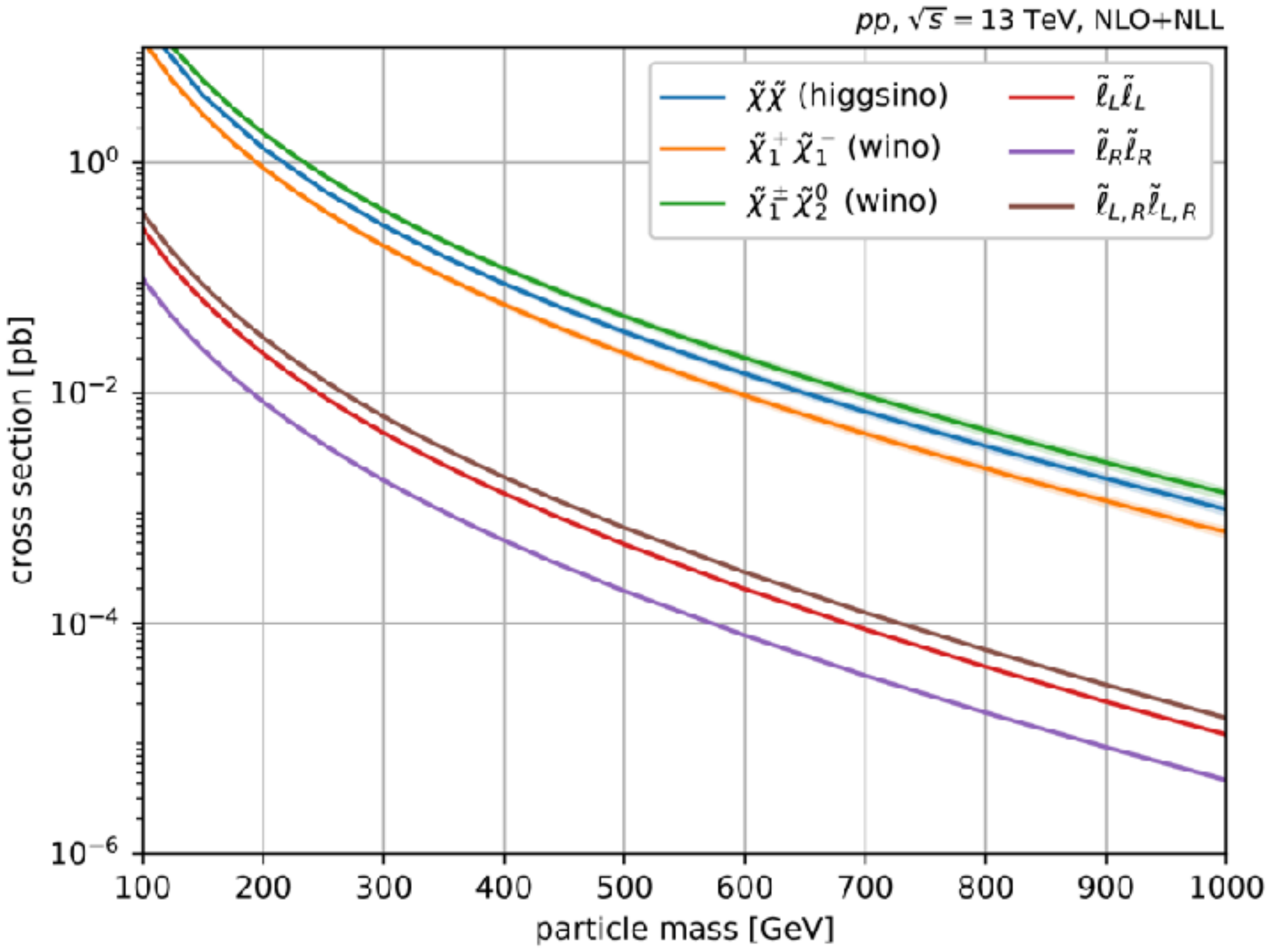
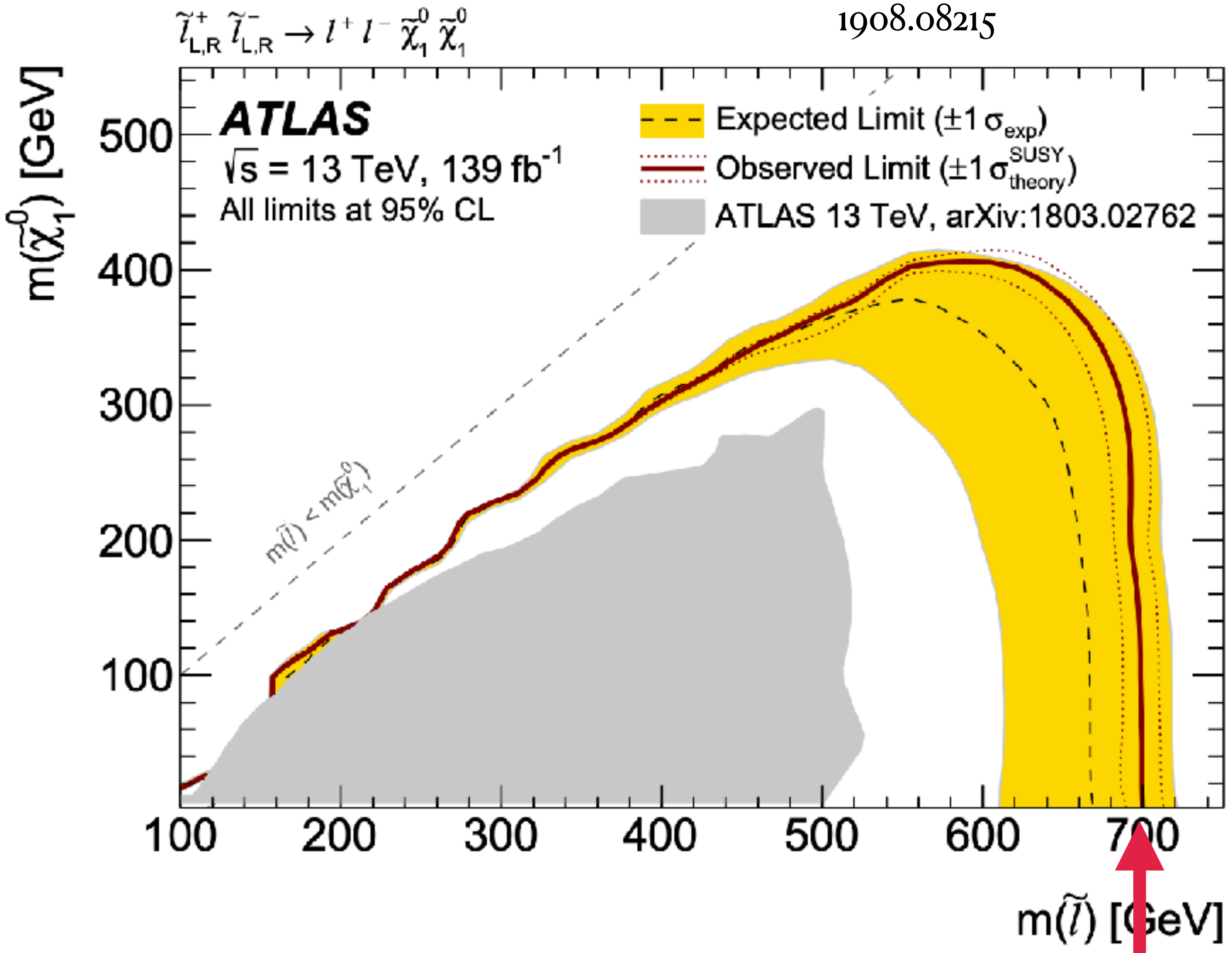


Simplified SUSY Models



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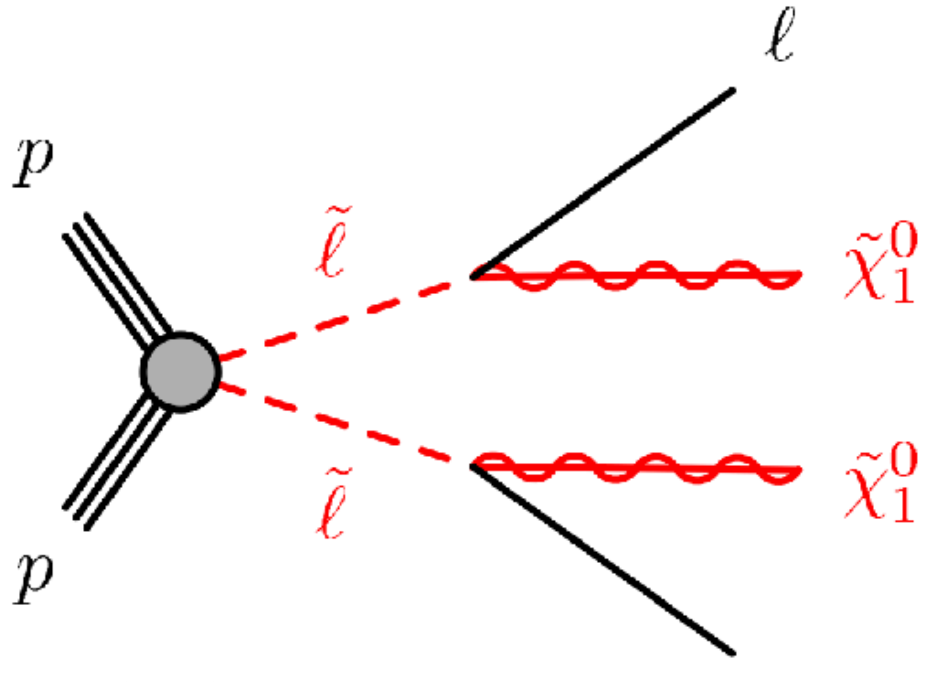

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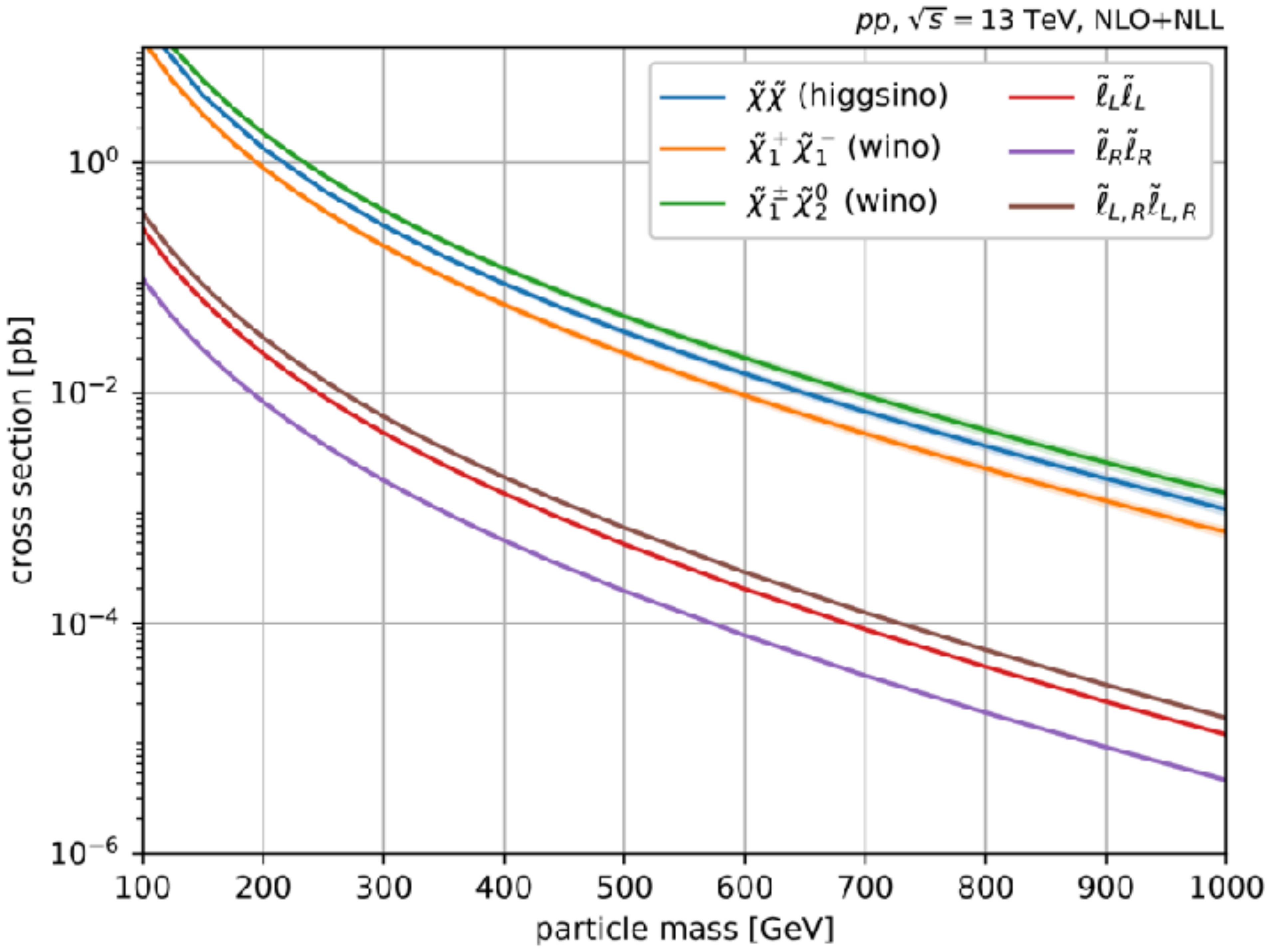
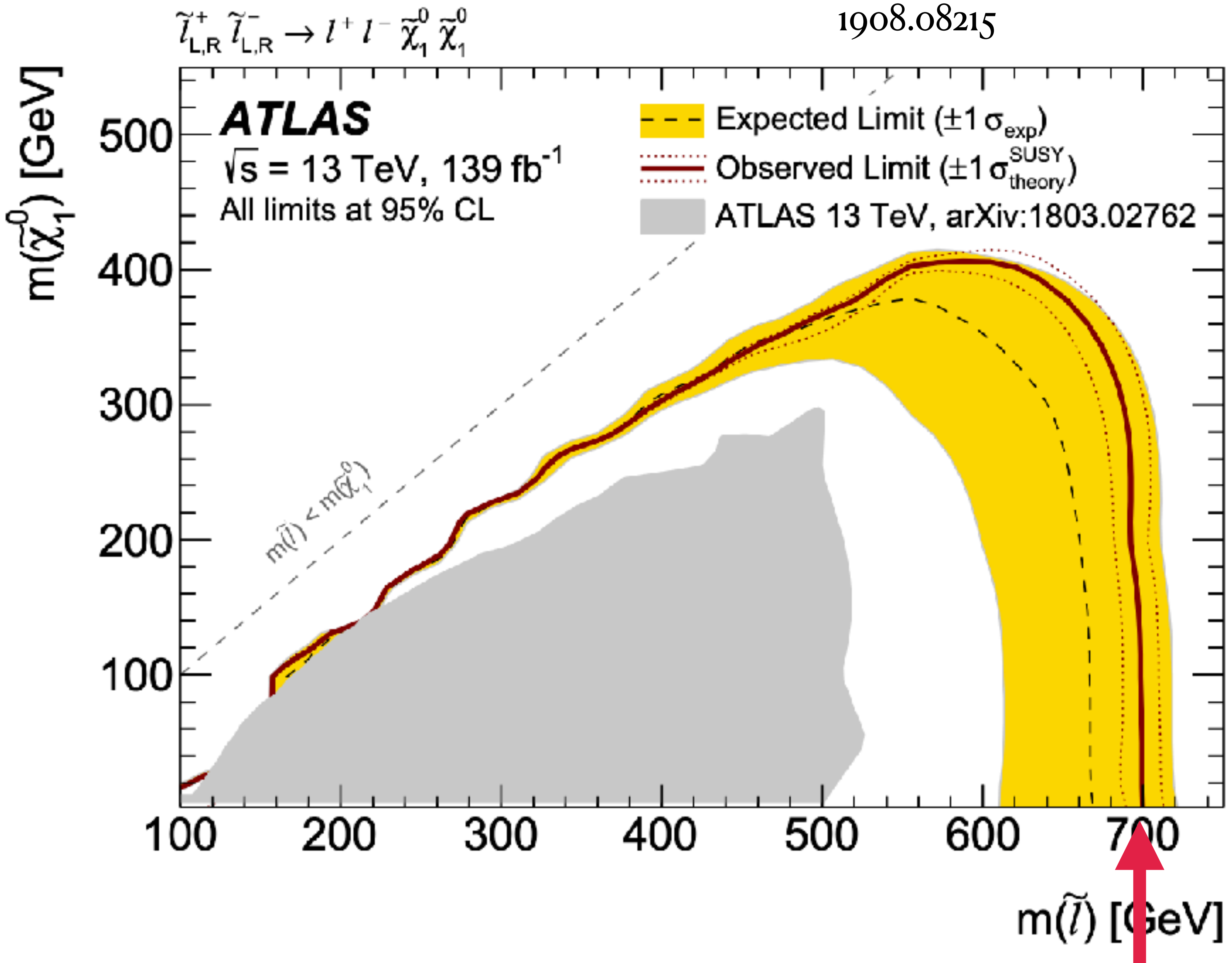
$$\boxed{N_{\text{events}} = \mathscr{L}_{\text{int}} \times \sigma}$$



Constrained by cross section.

Simplified SUSY Models



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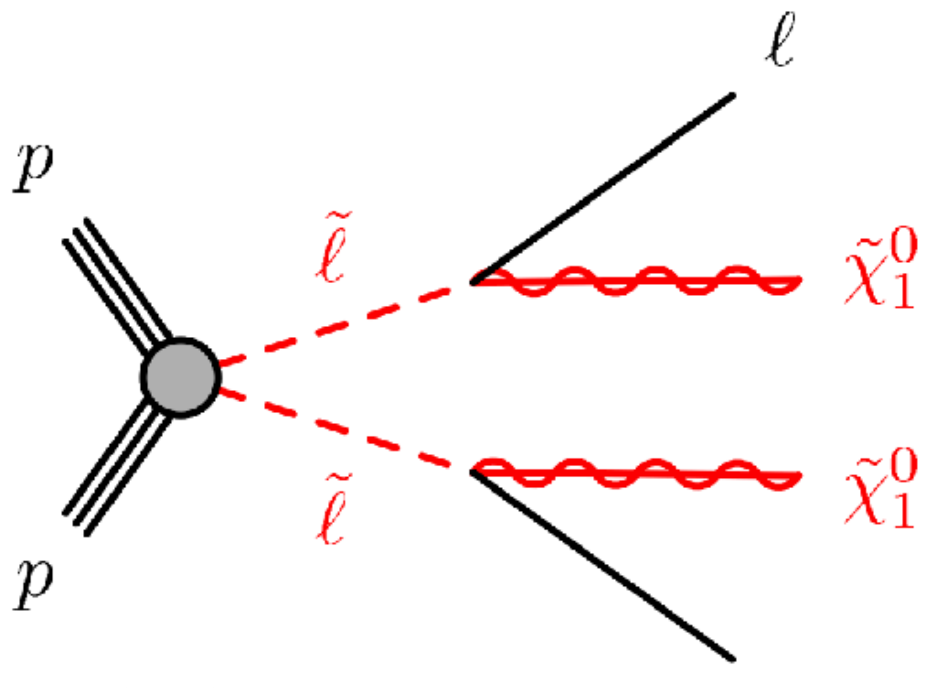
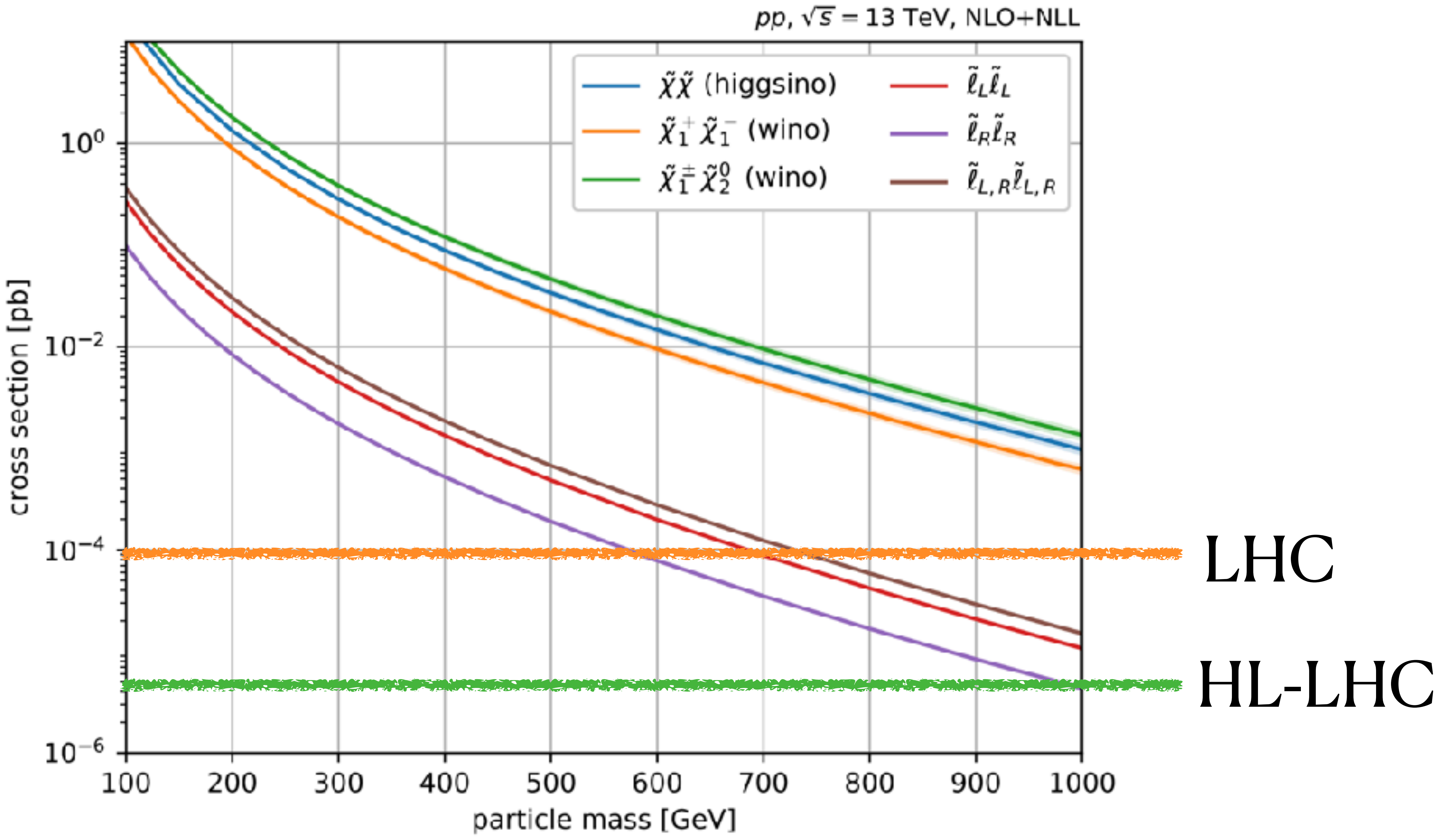
Constrained by cross section.



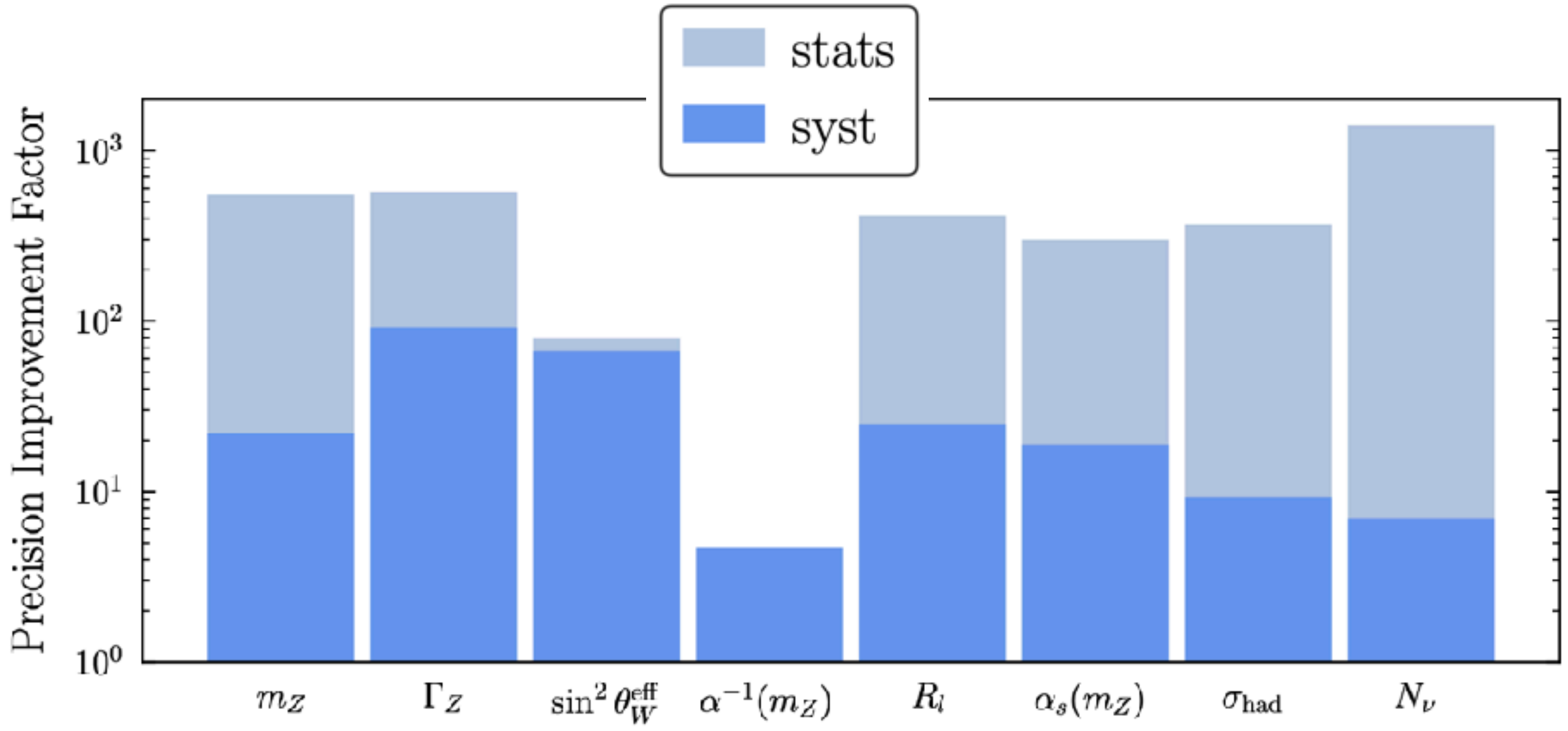
1908.08215

$$\boxed{N_{\text{events}} = \mathscr{L}_{\text{int}} \times \sigma}$$



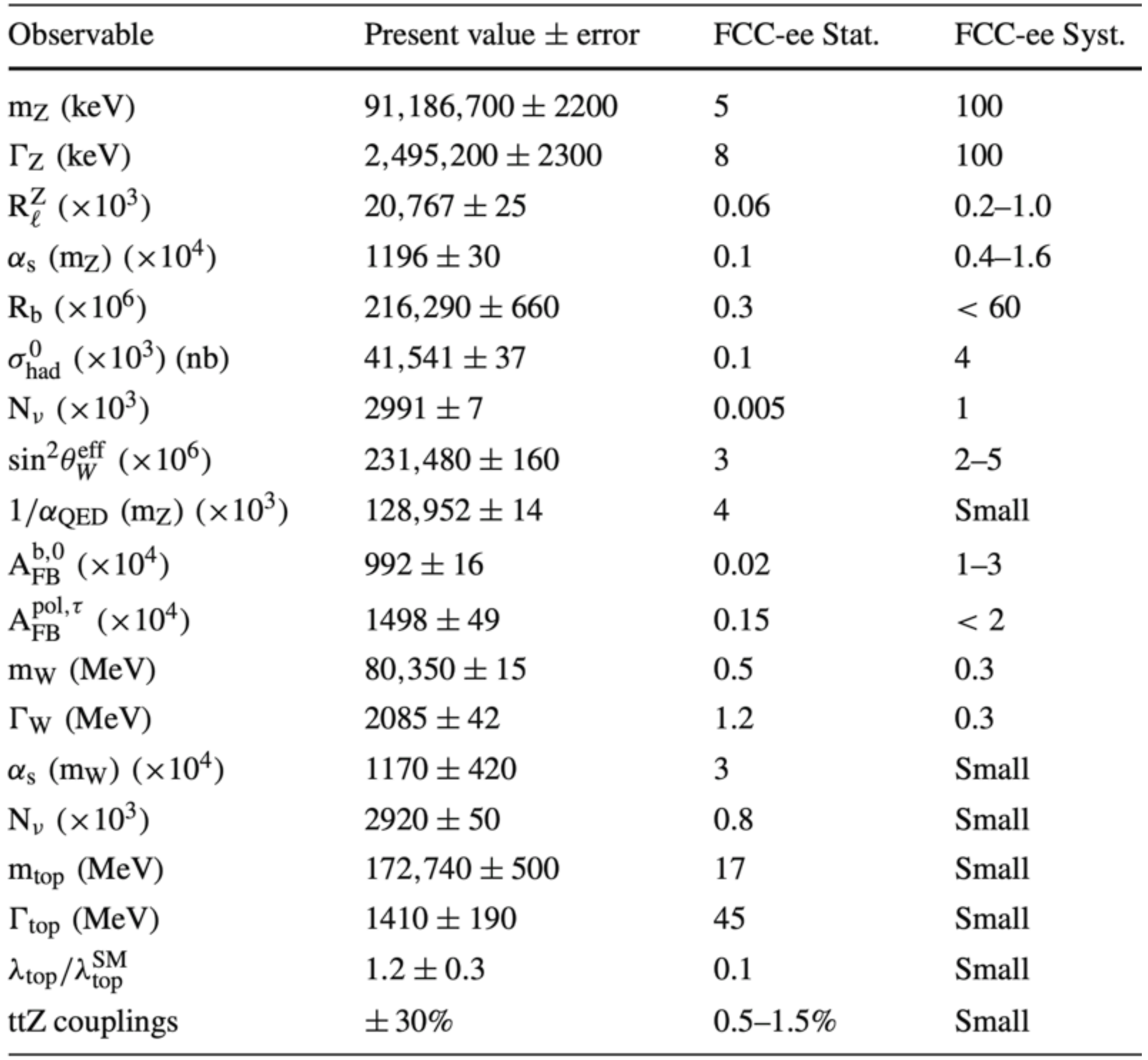
Electroweak Precision Tests at the Z-pole

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
σ_{had}^0 ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4
N_ν ($\times 10^3$)	2991 ± 7	0.005	1
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5
$1/\alpha_{\text{QED}}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3
$A_{FB}^{\text{pol},\tau}$ ($\times 10^4$)	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_{top} (MeV)	$172{,}740 \pm 500$	17	Small
Γ_{top} (MeV)	1410 ± 190	45	Small
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2 ± 0.3	0.1	Small
ttZ couplings	± 30%	0.5–1.5%	Small

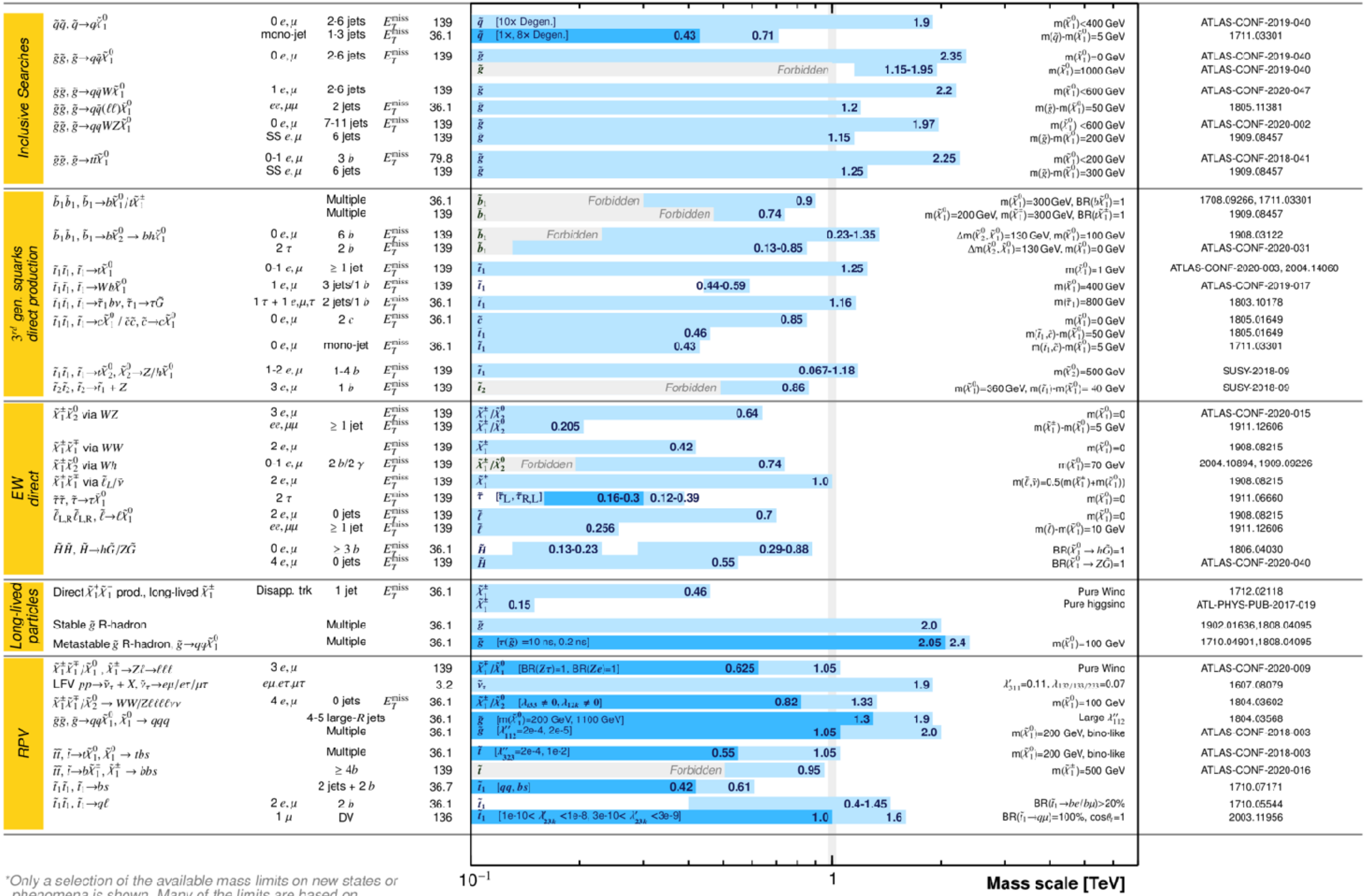
[FCC CDR]

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^{miss}	139	$\tilde{q}$ [10x Degen.]	1.9	m($\tilde{\chi}^0_1$)<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($\tilde{\chi}^0_1$)=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^{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^{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^{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^{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($\tilde{\chi}^0_1$)=300GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$ Forbidden	0.74	m($\tilde{\chi}^0_1$)=200GeV, m($\tilde{\chi}^\pm_1$)=300GeV, 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^{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^{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^{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^{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^{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^{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^{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^{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^{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^{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^{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^{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^{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^{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^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_{\mathrm{L}}, \tilde{\tau}_{\mathrm{R,L}}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{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^{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^{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^{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	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_1$ [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^{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

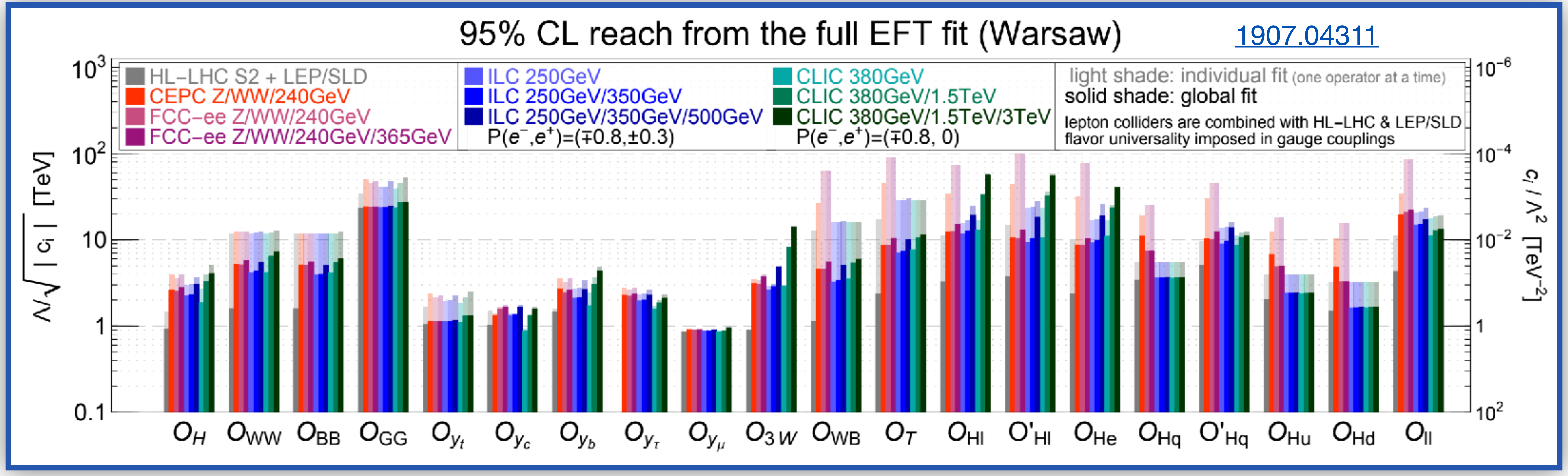
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Electroweak Precision Tests

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

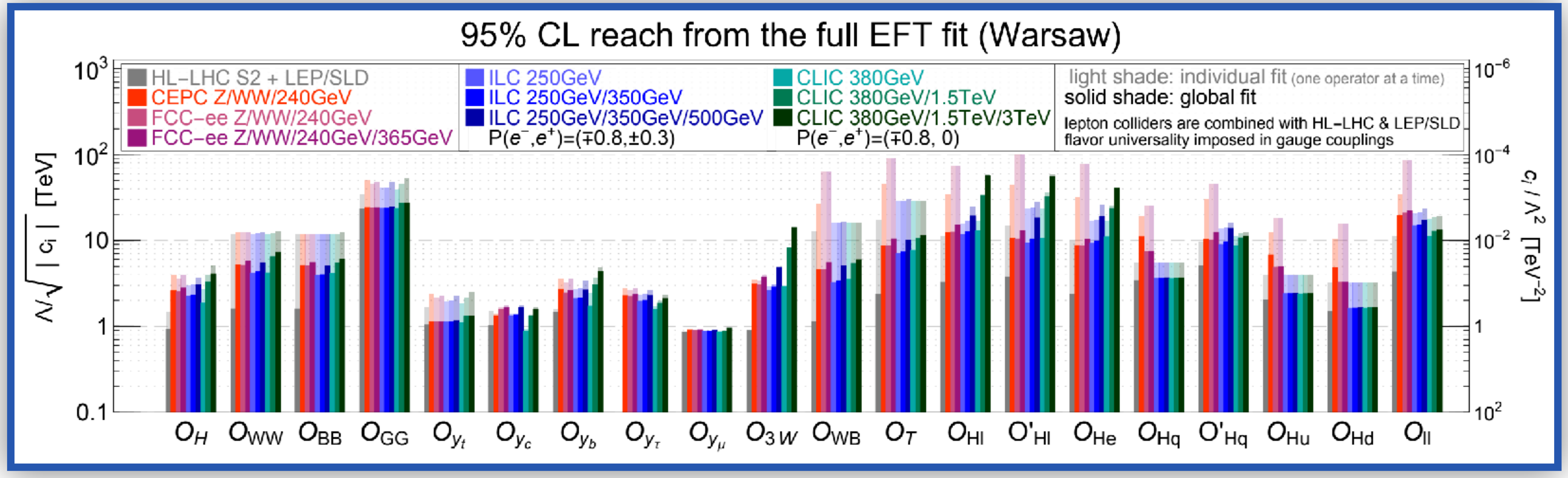
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

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



1907.04311

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?