

SUSY at Future Colliders



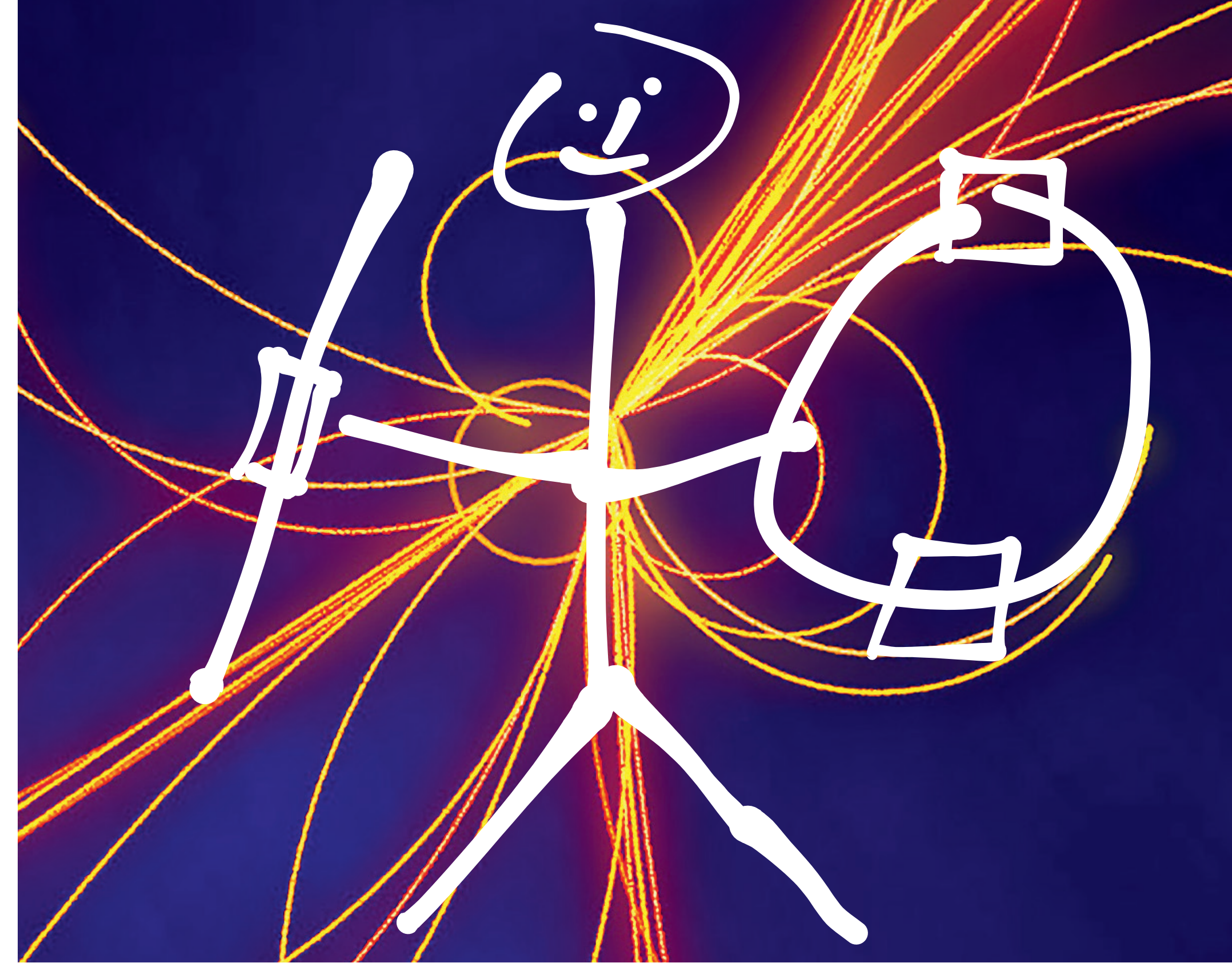
Jenny List (DESY)
SUSY2024
10-14 June 2024
Madrid

HELMHOLTZ

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SUSY at the next Future Colliders



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Outline

Today's menu

- **Setting the scene: from (HL-)LHC to our next collider**
- **Direct SUSY searches at future e^+e^- colliders**
 - **Experimental Conditions**
 - **Ex 1: scalar leptons**
 - **Ex 2: higgsinos**
- **Conclusions**

Many thanks to all who contributed material!
(with and without being asked ;)

Setting the Scene: From (HL-)LHC to our next collider

An e^+e^- Higgs factory is the highest-priority next collider

A clear message from last EPPSU — and Snowmass

=> e^+e^- Higgs factory as highest priority next collider re-emphasized in the Snowmass process in the US (2022)

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

<https://europeanstrategyupdate.web.cern.ch/welcome>

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High-priority future initiatives

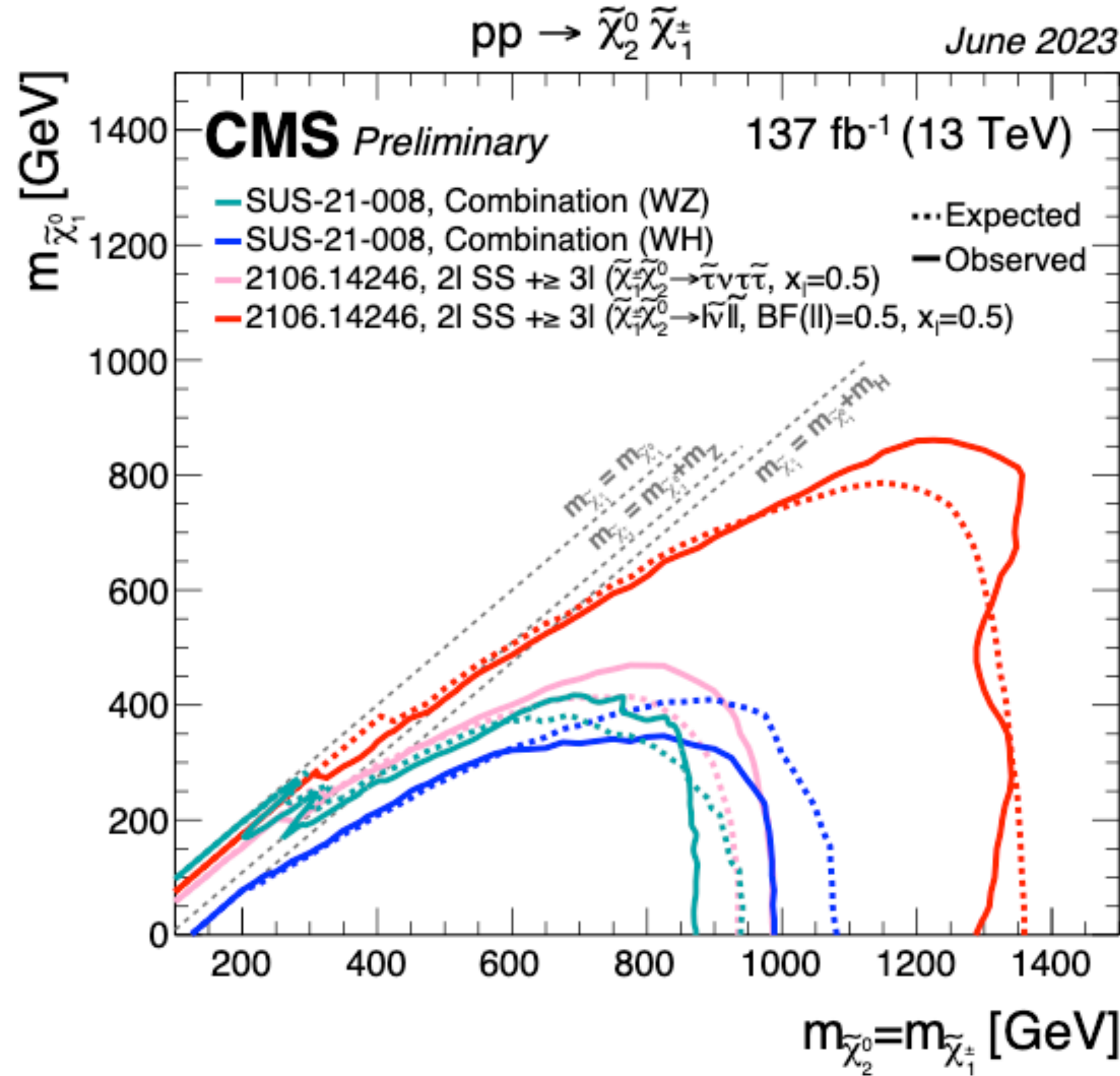
A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Can a Higgs Factory contribute to SUSY searches?

... in view of LHC exclusions?



ATLAS SUSY Searches* - 95% CL Lower Limits August 2023

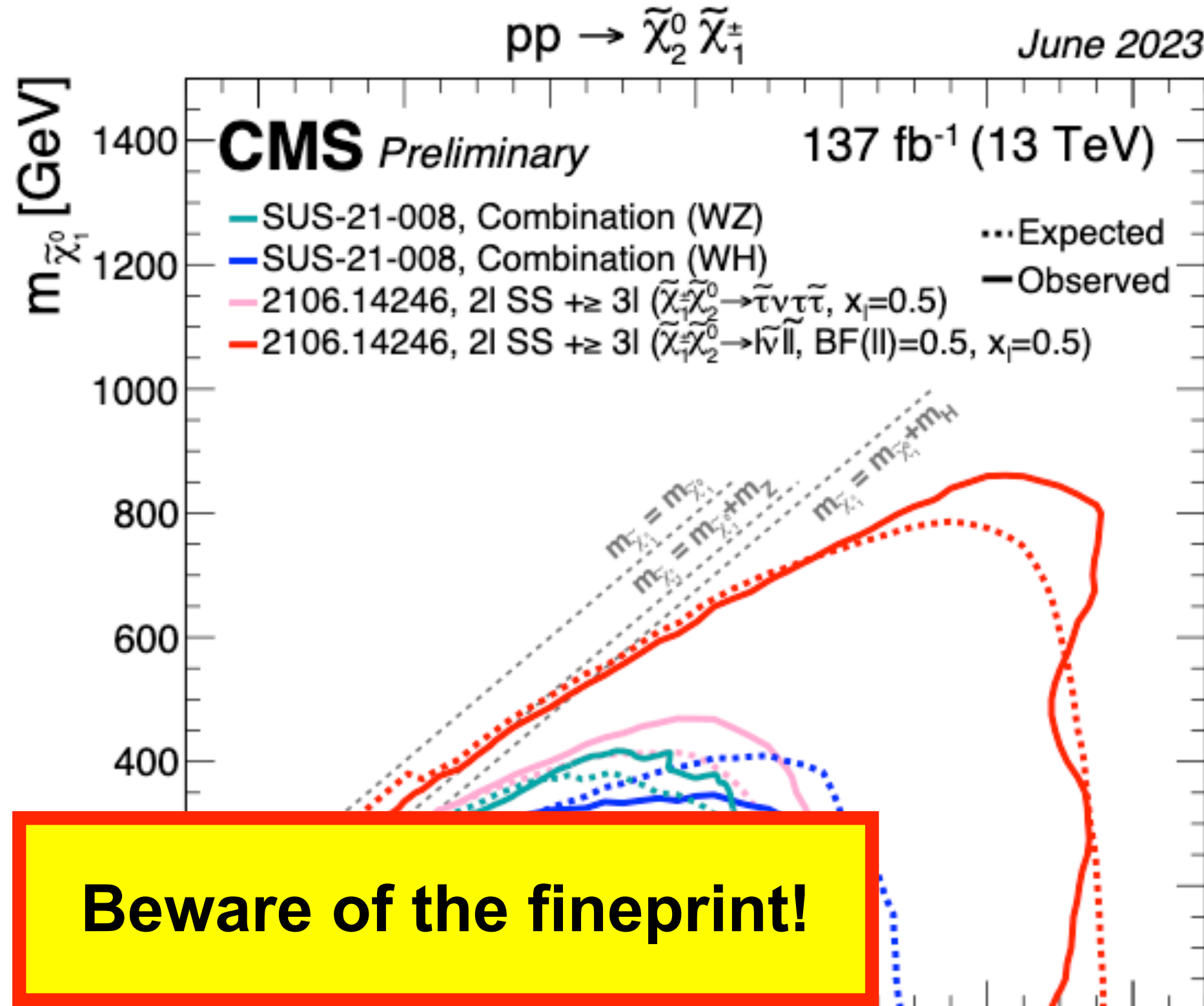
ATLAS Preliminary $\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets E_T^{miss} 140	\tilde{q} [1x, 8x Degen.] 1.0 1.85	$m(\tilde{\chi}_1^0) < 400$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0$	0 e, μ 2-6 jets	E_T^{miss} 140	\tilde{g} [8x Degen.] 0.9	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 5$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}W\tilde{\chi}_1^0$	1 e, μ 2-6 jets	E_T^{miss} 140	\tilde{g} 2.3	$m(\tilde{\chi}_1^0) = 0$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	ee, $\mu\mu$ 2 jets	E_T^{miss} 140	Forbidden 1.15-1.95	$m(\tilde{\chi}_1^0) = 1000$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ 7-11 jets	E_T^{miss} 140	\tilde{g} 2.2	$m(\tilde{\chi}_1^0) < 600$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}WZ\tilde{\chi}_1^0$	SS e, μ 6 jets	E_T^{miss} 140	\tilde{g} 1.97	$m(\tilde{\chi}_1^0) < 700$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ 3 b	E_T^{miss} 140	\tilde{g} 1.15	$m(\tilde{\chi}_1^0) < 600$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\tilde{t}\tilde{\chi}_1^0$	SS e, μ 6 jets	E_T^{miss} 140	\tilde{g} 2.45	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ 3 b	E_T^{miss} 140	\tilde{g} 1.25	$m(\tilde{\chi}_1^0) < 500$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\tilde{t}\tilde{\chi}_1^0$	SS e, μ 6 jets	E_T^{miss} 140	\tilde{g} 1.25	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ 2 b	E_T^{miss} 140	\tilde{b}_1 1.255	$m(\tilde{\chi}_1^0) < 400$ GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$	0 e, μ 6 b	E_T^{miss} 140	Forbidden 0.68	$10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$	2 τ 2 b	E_T^{miss} 140	\tilde{b}_1 0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ ≥ 1 jet	E_T^{miss} 140	\tilde{t}_1 1.25	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ 3 jets/1 b	E_T^{miss} 140	Forbidden 1.05	$m(\tilde{\chi}_1^0) = 1$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ 2 jets/1 b	E_T^{miss} 140	\tilde{t}_1 1.4	$m(\tilde{\chi}_1^0) = 500$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ 2 c	E_T^{miss} 36.1	Forbidden 0.85	$m(\tilde{\tau}_1) = 800$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} 140	\tilde{t}_1 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} 140	\tilde{t}_1 0.85	$m(\tilde{\tau}_1, \tilde{\nu}) - m(\tilde{\chi}_1^0) = 5$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} 140	\tilde{t}_1 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} 140	\tilde{t}_1 0.85	$m(\tilde{\tau}_1, \tilde{\nu}) - m(\tilde{\chi}_1^0) = 5$ GeV	
EW direct	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets ee, $\mu\mu$	E_T^{miss} ≥ 1 jet 140	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ 0.205	$m(\tilde{\chi}_1^0) = 0$, wino-bino
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via WW	2 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^\pm$ 0.42	$m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via Wh	Multiple ℓ /jets	E_T^{miss} 140	Forbidden 1.06	$m(\tilde{\chi}_1^0) = 0$, wino-bino
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ 1.0	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ	E_T^{miss} 140	$\tilde{\tau}$ [FR, FR.L] 0.34 0.48	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^0))$
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ 0 jets	E_T^{miss} 140	$\tilde{\ell}$ 0.7	$m(\tilde{\chi}_1^0) = 0$
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	ee, $\mu\mu$ ≥ 1 jet	E_T^{miss} 140	$\tilde{\ell}$ 0.26	$m(\tilde{\chi}_1^0) = 0$
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ ≥ 3 b	E_T^{miss} 140	\tilde{H} 0.94	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	4 e, μ 0 jets	E_T^{miss} 140	\tilde{H} 0.55	BR($\tilde{\chi}_1^0 \rightarrow h\tilde{G}$)=1
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ ≥ 2 large jets	E_T^{miss} 140	\tilde{H} 0.45-0.93	BR($\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$)=1
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	2 e, μ ≥ 2 jets	E_T^{miss} 140	\tilde{H} 0.77	BR($\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$)=BR($\tilde{\chi}_1^0 \rightarrow h\tilde{G}$)=0.5	
Long-lived particles	Direct $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet	E_T^{miss} 140	$\tilde{\chi}_1^\pm$ 0.21 0.66	Pure Wino
	Stable \tilde{g} R-hadron	pixel dE/dx	E_T^{miss} 140	\tilde{g} 2.05	Pure higgsino
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx	E_T^{miss} 140	\tilde{g} [τ(ḡ) = 10 ns] 2.2	$m(\tilde{\chi}_1^0) = 100$ GeV
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep	E_T^{miss} 140	$\tilde{\ell}$ 0.7	$\tau(\tilde{\ell}) = 0.1$ ns
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	pixel dE/dx	E_T^{miss} 140	$\tilde{\ell}$ 0.34 0.36	$\tau(\tilde{\ell}) = 0.1$ ns
RPV	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp / \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$ [BR(Zτ)=1, BR(Ze)=1] 0.625 1.05	Pure Wino
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp / \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow WWZ\ell\ell\ell\nu\nu$	4 e, μ 0 jets	E_T^{miss} 140	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ [$\lambda_{333} \neq 0, \lambda_{124} \neq 0$] 0.95 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	≥ 8 jets	E_T^{miss} 140	\tilde{g} [$m(\tilde{\chi}_1^0) = 50$ GeV, 1250 GeV] 1.6 2.25	Large $\lambda'_{1,2}$
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	E_T^{miss} 36.1	\tilde{t}_1 [$\lambda'_{323} = 2e-4, 1e-2$] 0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like
	$\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bbs$	$\geq 4b$	E_T^{miss} 140	Forbidden 0.95	$m(\tilde{\chi}_1^0) = 500$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	E_T^{miss} 36.7	\tilde{t}_1 [qq, bs] 0.42 0.61	1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, μ 2 b	E_T^{miss} 36.1	\tilde{t}_1 0.4-1.45	BR($\tilde{t}_1 \rightarrow b\ell$)/BR($\tilde{t}_1 \rightarrow b\mu$) > 20%
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	1 μ DV	E_T^{miss} 136	\tilde{t}_1 [$1e-10 < \lambda'_{234} < 1e-8, 3e-10 < \lambda'_{236} < 3e-9$] 1.0 1.6	BR($\tilde{t}_1 \rightarrow q\mu$) = 100%, $\cos\theta = 1$
	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0 / \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow tbs, \tilde{\chi}_1^0 \rightarrow bbs$	1-2 e, μ ≥ 6 jets	E_T^{miss} 140	$\tilde{\chi}_1^\pm$ 0.2-0.32	Pure higgsino
	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0 / \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow tbs, \tilde{\chi}_1^0 \rightarrow bbs$	1-2 e, μ ≥ 6 jets	E_T^{miss} 140	$\tilde{\chi}_1^\pm$ 0.2-0.32	2106.09609

*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.

Can a Higgs Factory contribute to SUSY searches?

... in view of LHC exclusions?



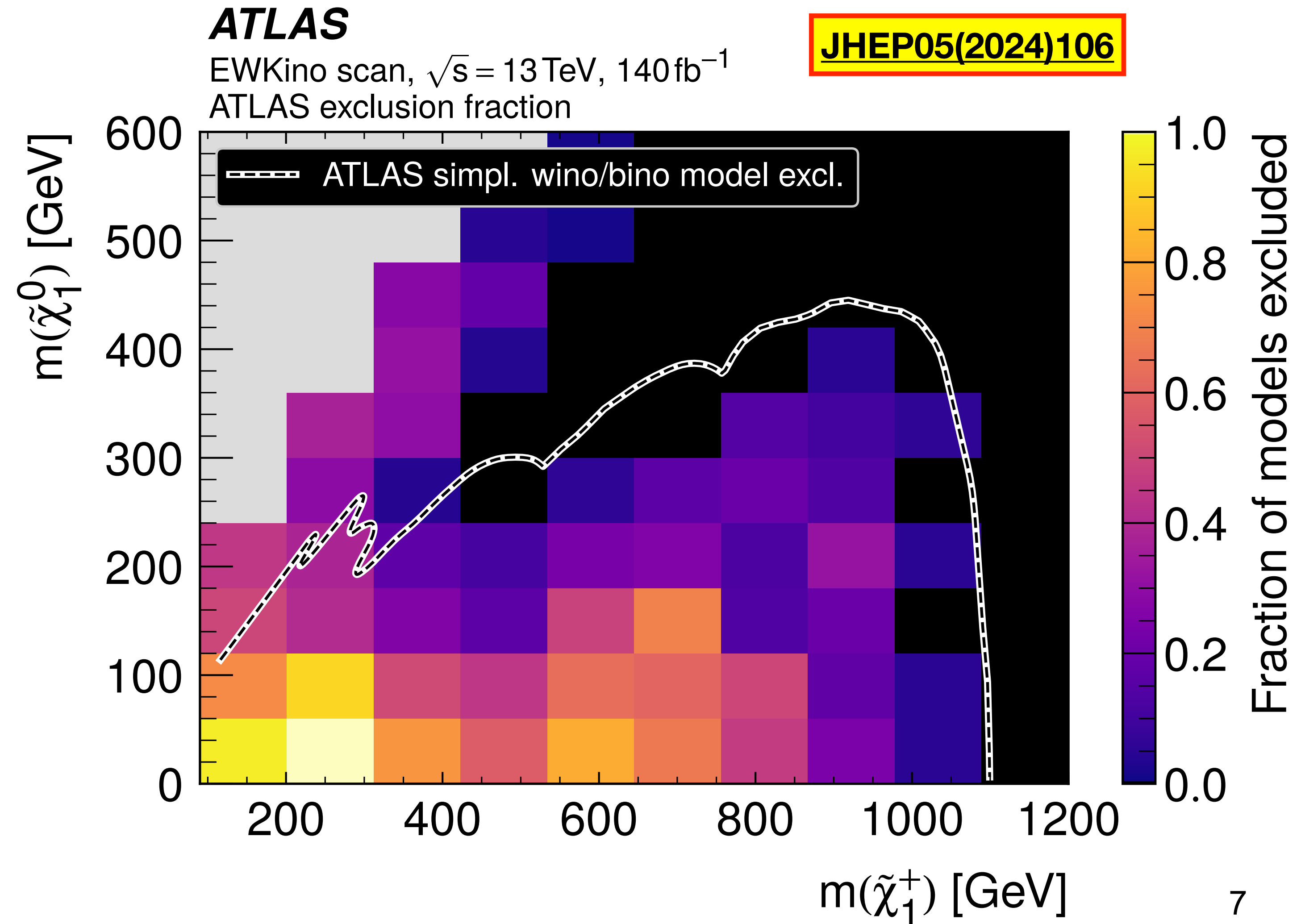
ATLAS SUSY Searches* - 95% CL Lower Limits
AUGUST 2023

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference							
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	140	\tilde{q} [1x, 8x Degen.] \tilde{q} [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets	E_T^{miss}	140	\tilde{g} \tilde{g}	Forbidden	2.3 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{\chi}_1^0) = 1000$ GeV	2010.14293 2010.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets	E_T^{miss}	140	\tilde{g}		2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	E_T^{miss}	140	\tilde{g}		2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	2204.13072	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ	7-11 jets	E_T^{miss}	140	\tilde{g}		1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}W\tilde{\chi}_1^0$	SS e, μ	6 jets	E_T^{miss}	140	\tilde{g}		1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	2307.01094	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} E_T^{miss}	140 140	\tilde{g} \tilde{g}		2.45 1.25	$m(\tilde{\chi}_1^0) < 500$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	2211.08028 1909.08457	
	3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	140	\tilde{b}_1 \tilde{b}_1		1.255 0.68	$m(\tilde{\chi}_1^0) < 400$ GeV $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
		$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$	0 e, μ 2 τ	6 b 2 b	E_T^{miss} E_T^{miss}	140 140	\tilde{b}_1 \tilde{b}_1	Forbidden	0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	≥ 1 jet	E_T^{miss}	140	\tilde{t}_1		1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 e, μ	3 jets/1 b	E_T^{miss}	140	\tilde{t}_1	Forbidden	1.05	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799, ATLAS-CONF-2023-043	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$		1-2 τ	2 jets/1 b	E_T^{miss}	140	\tilde{t}_1	Forbidden	1.4	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$		0 e, μ 0 e, μ	2 c mono-jet	E_T^{miss} E_T^{miss}	36.1 140	\tilde{t}_1 \tilde{t}_1		0.85 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$		1-2 e, μ	1-4 b	E_T^{miss}	140	\tilde{t}_1		0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$		3 e, μ	1 b	E_T^{miss}	140	\tilde{t}_2	Forbidden	0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct		$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet	E_T^{miss} E_T^{miss}	140 140	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ $\tilde{\chi}_1^+/\tilde{\chi}_2^0$		0.96 0.205	$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
		$\tilde{\chi}_1^+\tilde{\chi}_1^0$ via WW	2 e, μ		E_T^{miss}	140	$\tilde{\chi}_1^+$		0.42	$m(\tilde{\chi}_1^0) = 0$, wino-bino	1908.08215
	$\tilde{\chi}_1^+\tilde{\chi}_1^0$ via Wh	Multiple ℓ /jets		E_T^{miss}	140	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$	Forbidden	1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586	
	$\tilde{\chi}_1^+\tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ		E_T^{miss}	140	$\tilde{\chi}_1^+$		1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_R, \tilde{\tau}_{R,L}$]		0.34 0.48	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2023-029	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	140 140	$\tilde{\ell}$ $\tilde{\ell}$		0.7 0.26	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	1908.08215 1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ 0 e, μ	≥ 3 b 0 jets ≥ 2 large jets	E_T^{miss} E_T^{miss} E_T^{miss}	140 140 140	\tilde{H} \tilde{H} \tilde{H}		0.94 0.55 0.45-0.93	$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	To appear 2103.11684 2108.07586	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	2 e, μ	≥ 2 jets	E_T^{miss}	140	\tilde{H}		0.77	$\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = \text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 0.5$	2204.13072	
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$		0.66 0.21	Pure Wino Pure higgsino	2201.02472 2201.02472	
	Stable \tilde{g} R-hadron	pixel dE/dx		E_T^{miss}	140	\tilde{g}		2.05	$m(\tilde{\chi}_1^0) = 100$ GeV	2205.06013	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	140	\tilde{g} [$\tau(\tilde{g}) = 10$ ns]		2.2		2205.06013	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{\ell}, \tilde{\mu}$ $\tilde{\tau}$		0.7 0.34	$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 0.1$ ns	2011.07812 2011.07812	
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell}) = 10$ ns	2205.06013	
								0.625 0.95	Pure Wino $m(\tilde{\chi}_1^0) = 200$ GeV	2011.10543 2103.11684	
							1.05 1.55	Large λ'_{12}	To appear		
							0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003		
							0.95	$m(\tilde{\chi}_1^0) = 500$ GeV	2010.01015		
							0.61		1710.07171		
							1.0 0.4-1.45	$\text{BR}(\tilde{\tau}_1 \rightarrow b\ell/b\nu) > 20\%$ $\text{BR}(\tilde{\tau}_1 \rightarrow q\mu) = 100\%$, $\cos\theta_1 = 1$	1710.05544 2003.11956		
							1.6	Pure higgsino	2106.09609		

Summary of the most stringent limits obtained by CMS searches for the production of pairs of the lightest chargino and the second-lightest neutralino, of chargino pairs, and of slepton pairs. The models for the first category are described above. The same assumptions are made for chargino pair production. For slepton production, the four states corresponding to left- and right-handed leptons of the first two generations are assumed to be mass degenerate.

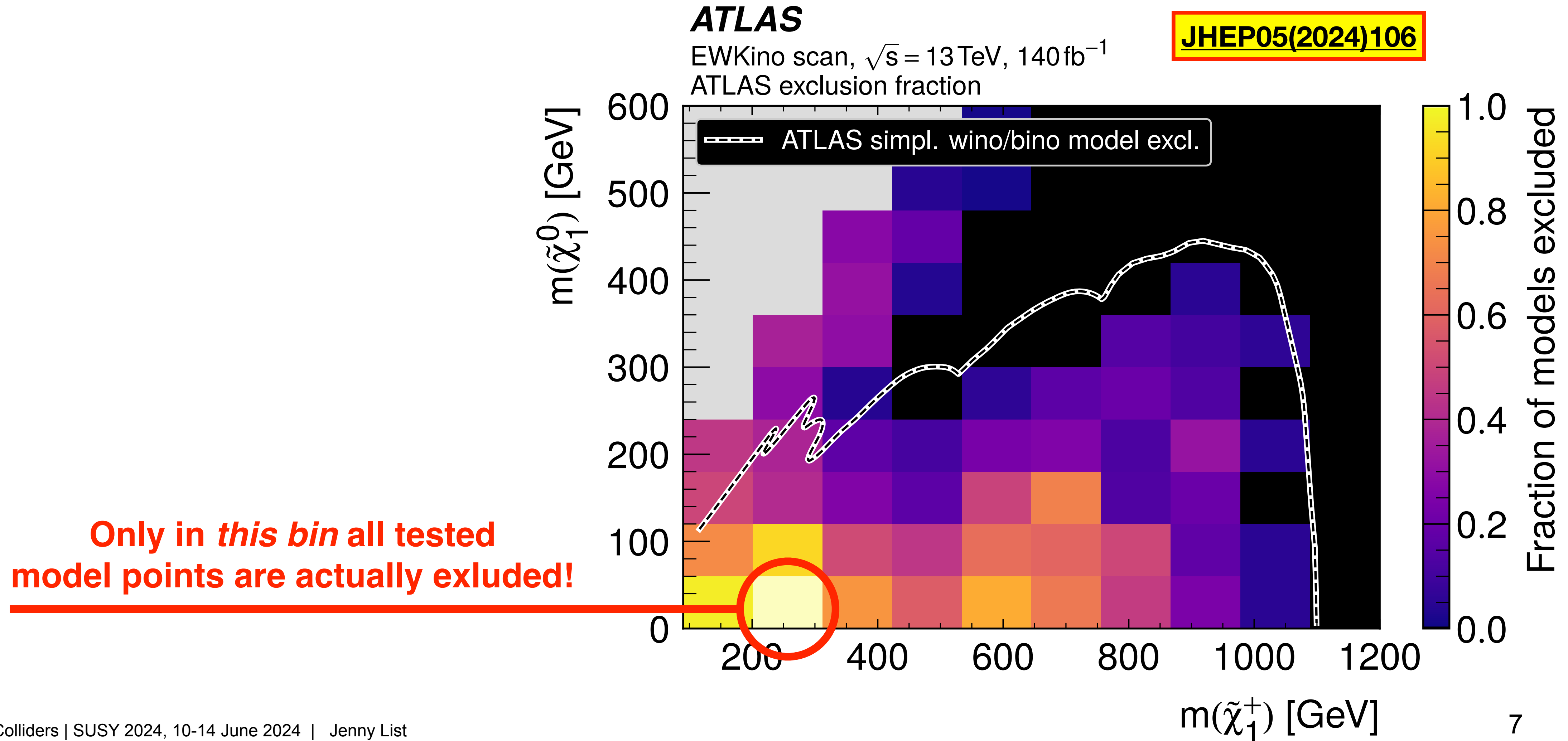
The ATLAS pMSSM scan

Don't get depressed by simplified models and Manhattan plots...



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Food for thought:

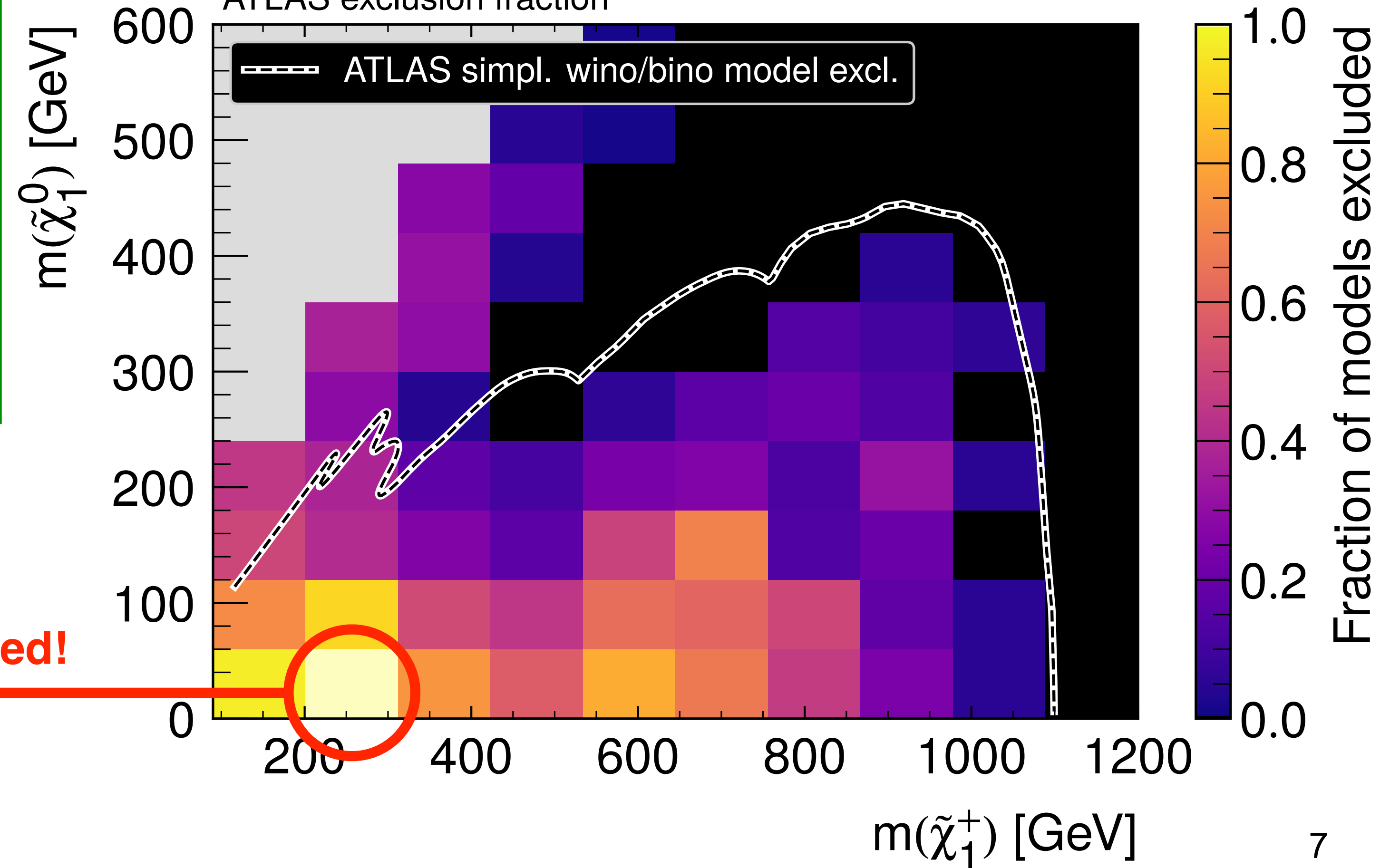
- How can we communicate the huge impact of LHC on exploring and constraining vast parameter spaces...
- ...but without oversimplifying the message and depressing ourselves too much about the up-to-now absence of SUSY particles?

Only in *this bin* all tested model points are actually excluded!

ATLAS

EWKino scan, $\sqrt{s} = 13 \text{ TeV}$, 140 fb^{-1}
ATLAS exclusion fraction

JHEP05(2024)106



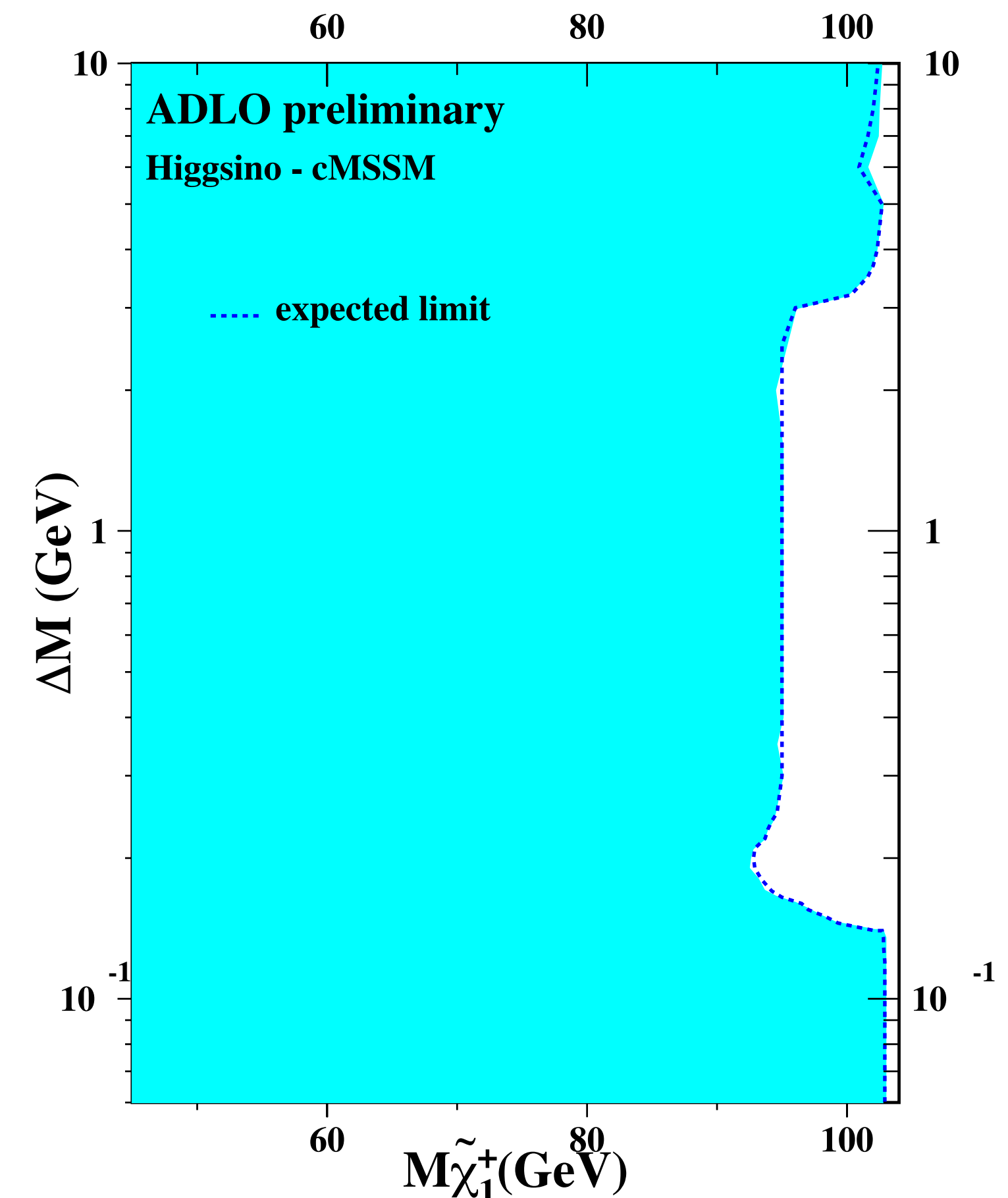
In contrast: remember LEP limit setting

Very little fingerprint

Cross sections and branching ratios have been calculated in the framework of the MSSM. Two cases were considered:

1. The unification of gaugino masses at the GUT scale is assumed, leading to the relation $M_1 = (5/3)\tan^2(\theta_W) M_2$ at the electroweak scale, which implies that low values of DM are reached in the higgsino-like region, where $\mu \ll M_2$.

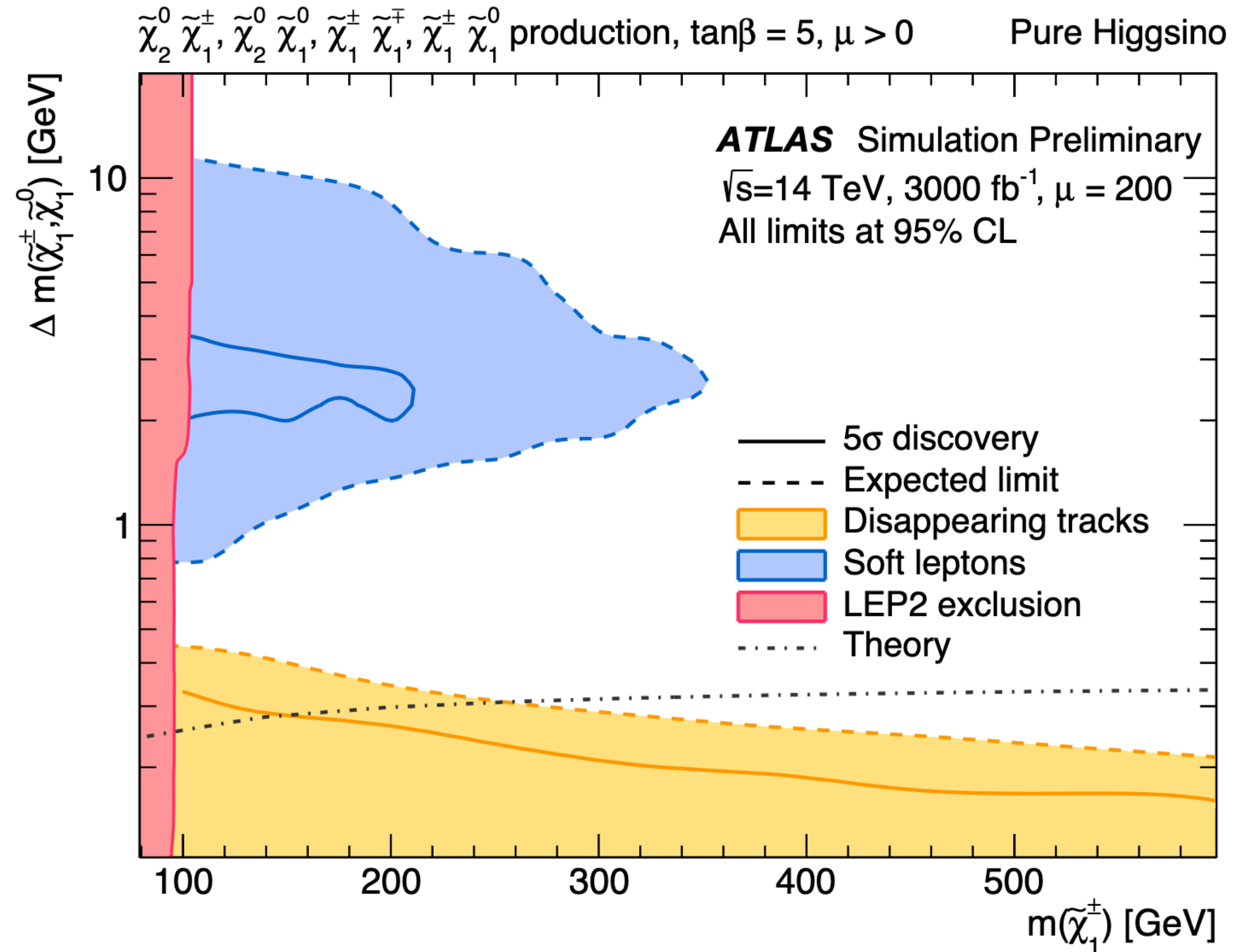
A mass point is marked as excluded if (and only if) it is excluded for *any choice* of the underlying not-shown parameters (within the above definition)



What do we expect HL-LHC to add here?

Beware of apples and bananas....

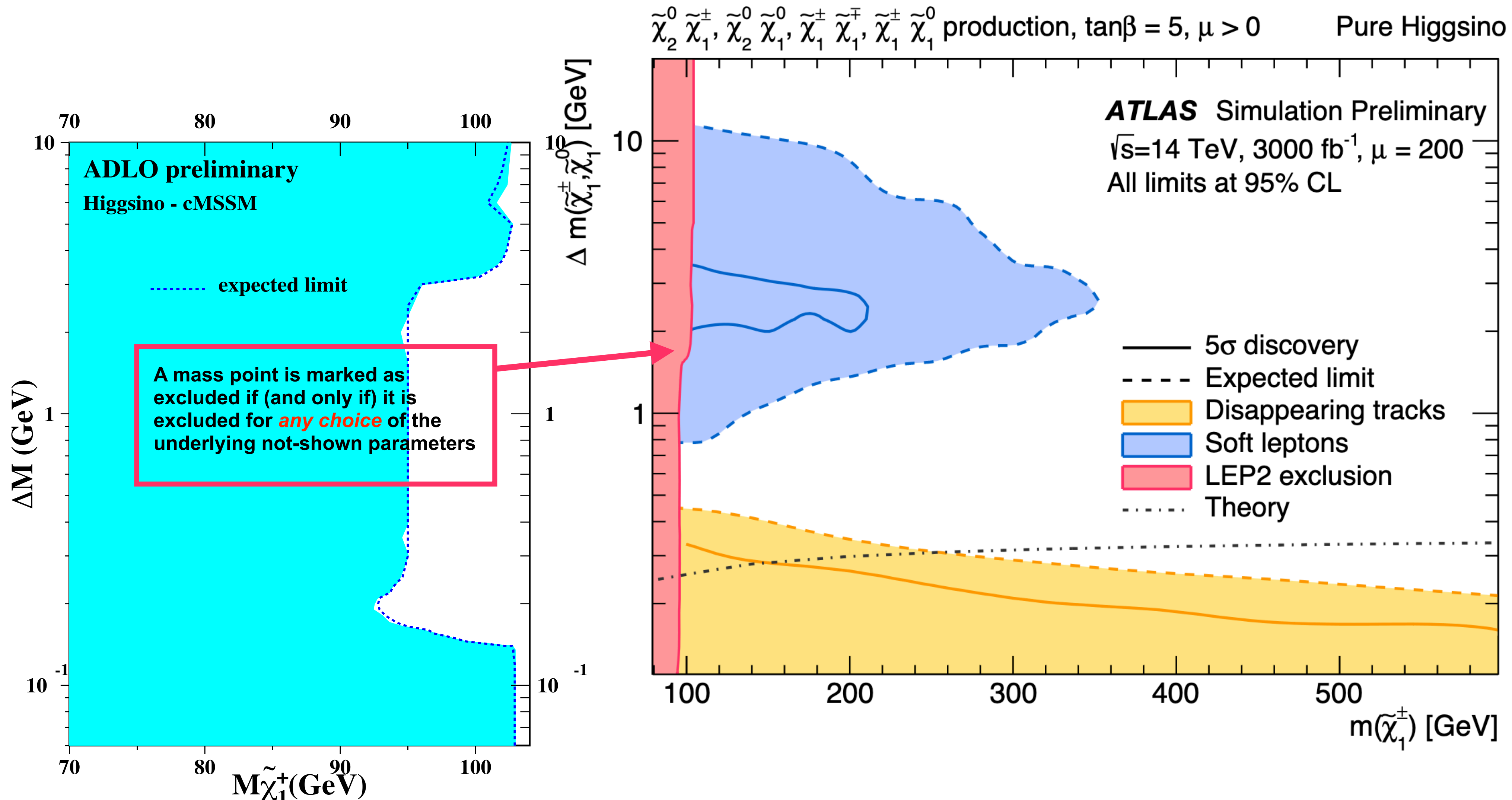
ATL-PHYS-PUB-2022-018



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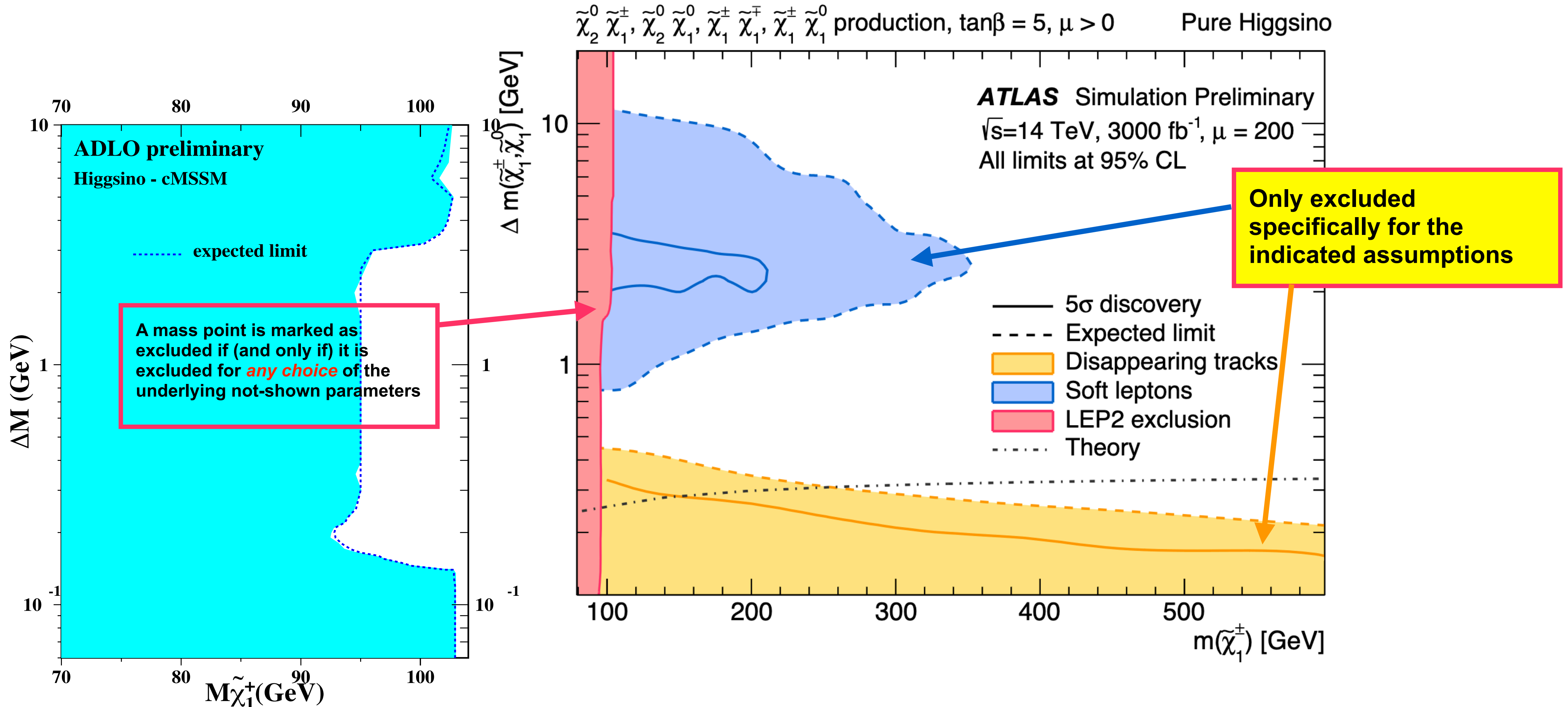
ATL-PHYS-PUB-2022-018



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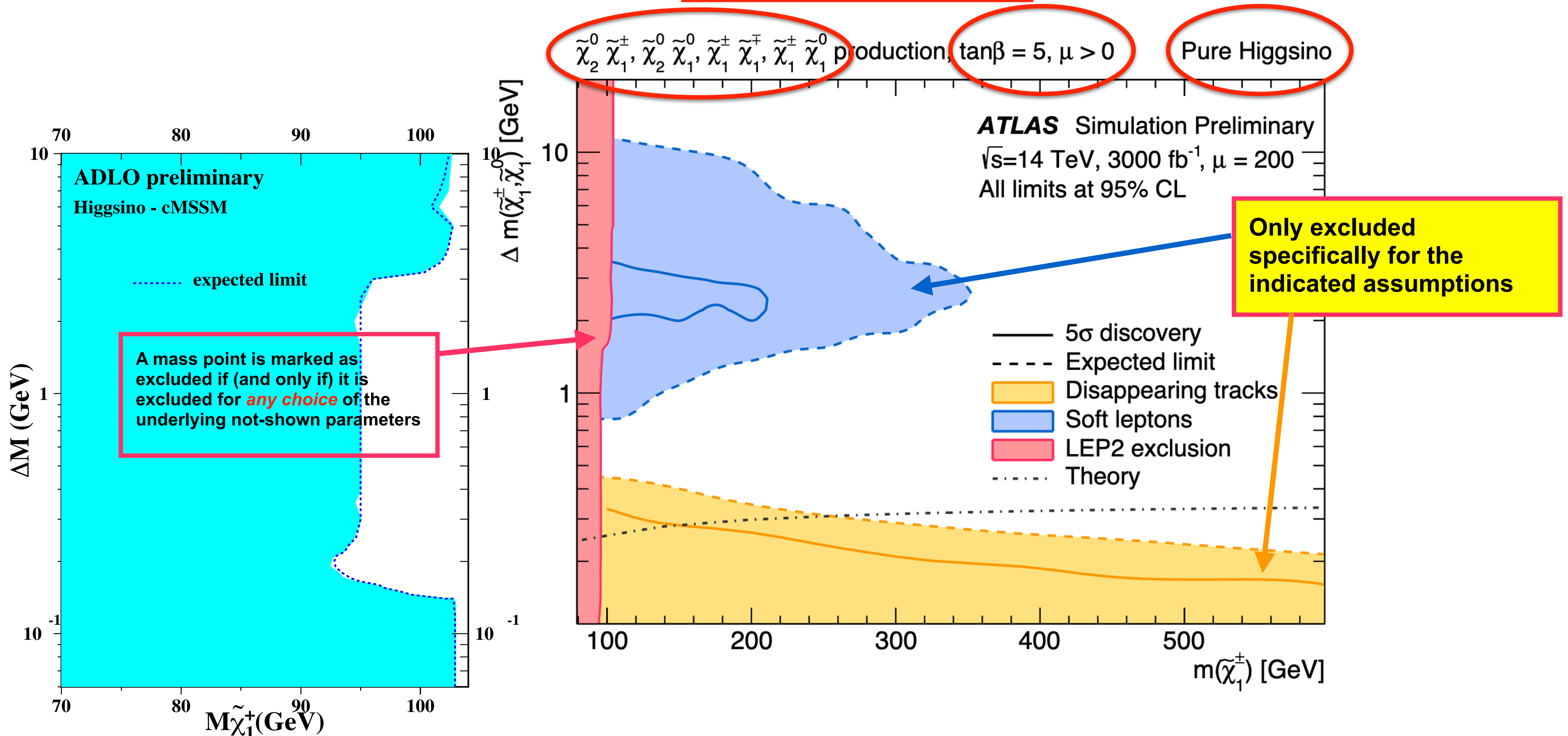
ATL-PHYS-PUB-2022-018



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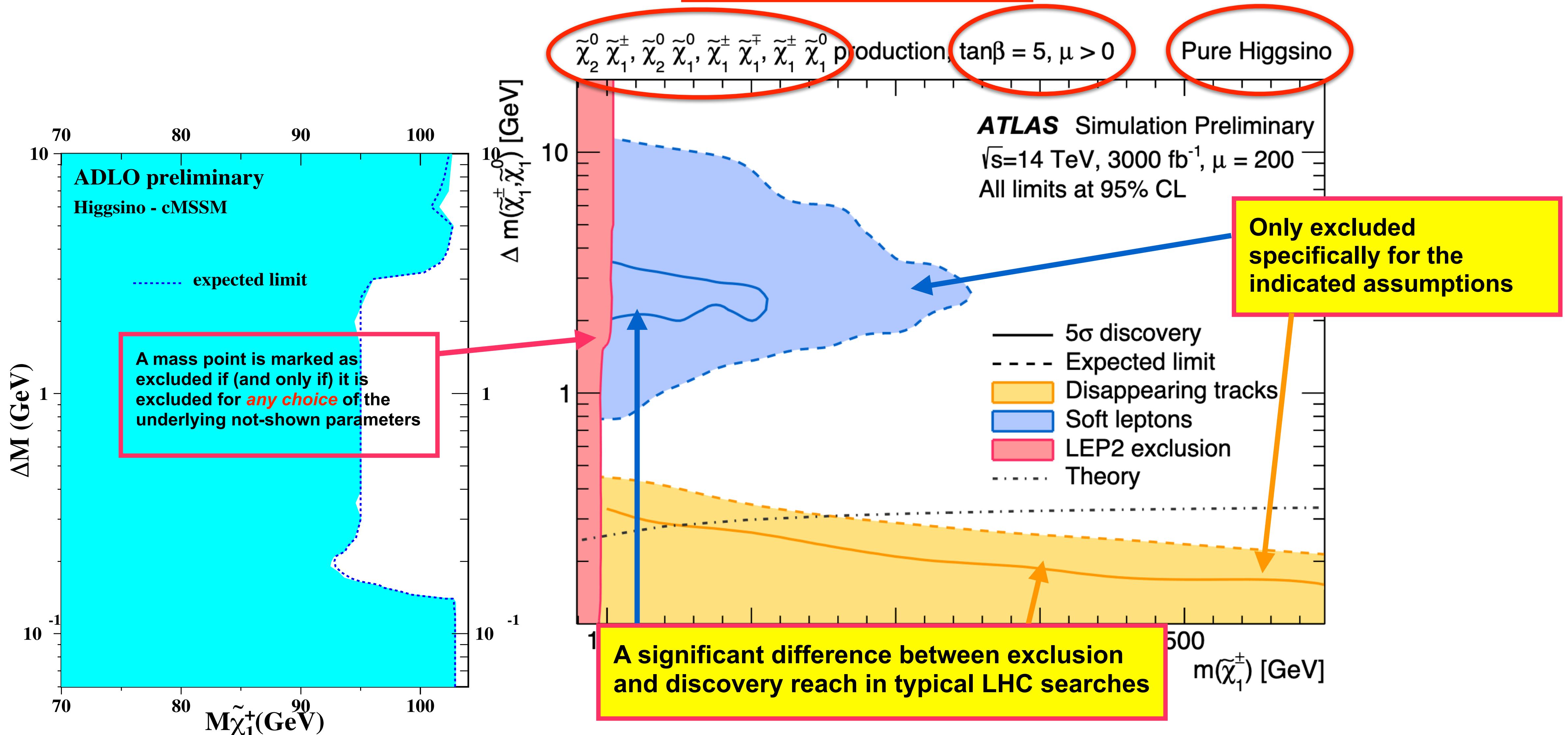
ATL-PHYS-PUB-2022-018



What do we expect HL-LHC to add here?

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ATL-PHYS-PUB-2022-018



Discovery Potential and Discovery Stories

or: the dilemma in “selling” the BSM case of future machines

- There is no known no-loose theorem for direct discovery of new particles
=> **we cannot “promise” discoveries**
 - But discussing only exclusion limits does not at all convey the excitement and opportunities of exploration
 - **The bread&butter physics case of the next collider is given by using Higgs, top, Z, W as magnifying glasses to look into the early universe
=> important progress independently of direct discoveries**
 - Still, there could be the possibility to actually also find new particles, even at quite low energies
=> **discovery *potential*, complementary to HL-LHC**
 - **Snowmass 2013 had the concept of “discovery stories”**
 - a collection of hypothetical scenarios
 - in each telling the story of a hypothetical discovery, and what would follow after the discovery - how different colliders & non-collider experiments would play together to find out what the new particle actually is - and the underlying model
- => something to consider for the upcoming EPPSU?**

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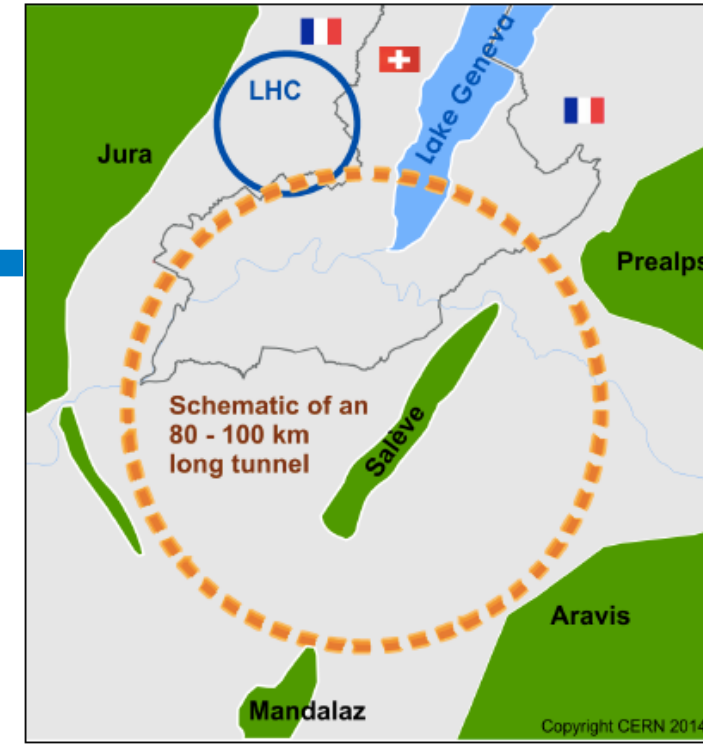
[arXiv:1311.0299](https://arxiv.org/abs/1311.0299)

- ▼ 1.3 Discovery Stories
 - 1.3.1 Higgs Beyond the Standard Model
 - ▶ 1.3.2 WIMP Dark Matter
 - ▶ 1.3.3 New gauge bosons
 - 1.3.4 Discovery in Jets + MET: `Simple' Supersymmetry
 - 1.3.5 SUSY with a light stop
 - 1.3.6 Discovery in Leptons+MET
 - 1.3.7 R-parity violating SUSY
 - 1.3.8 Long-lived Heavy Particles
 - 1.3.9 Top Partners
 - 1.3.10 Fermion Compositeness
 - 1.3.11 Warped Extra Dimensions and Flavor
 - ▶ 1.3.12 `Only' the Standard Model

Direct SUSY searches at future e^+e^- colliders

Two complementary approaches

Each has its advantages



Circular e+e- Colliders

- FCCee, CEPC
- length 250 GeV: 90...100km
- high luminosity & power efficiency at **low energies, limited to ~365 GeV**
- **multiple interaction regions**
- very clean: little beamstrahlung etc

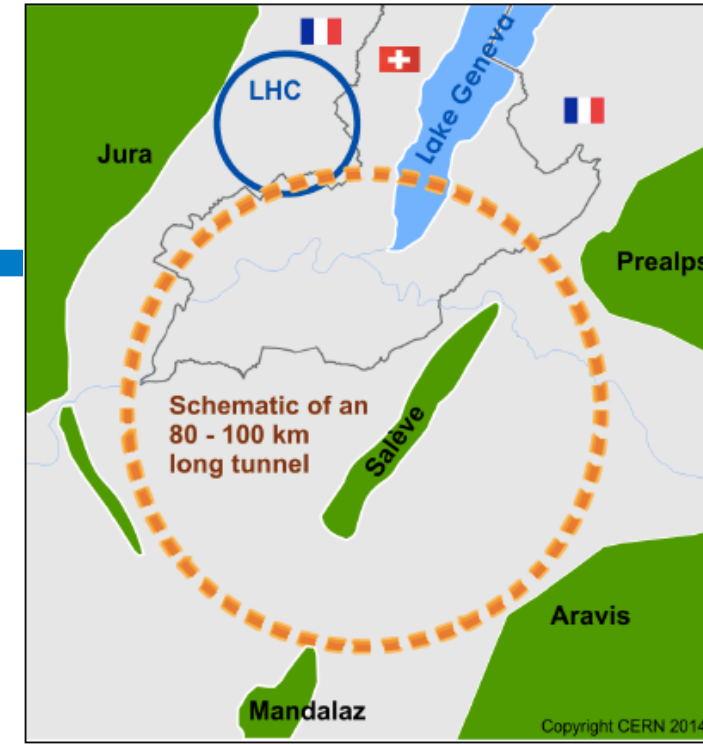
Linear Colliders

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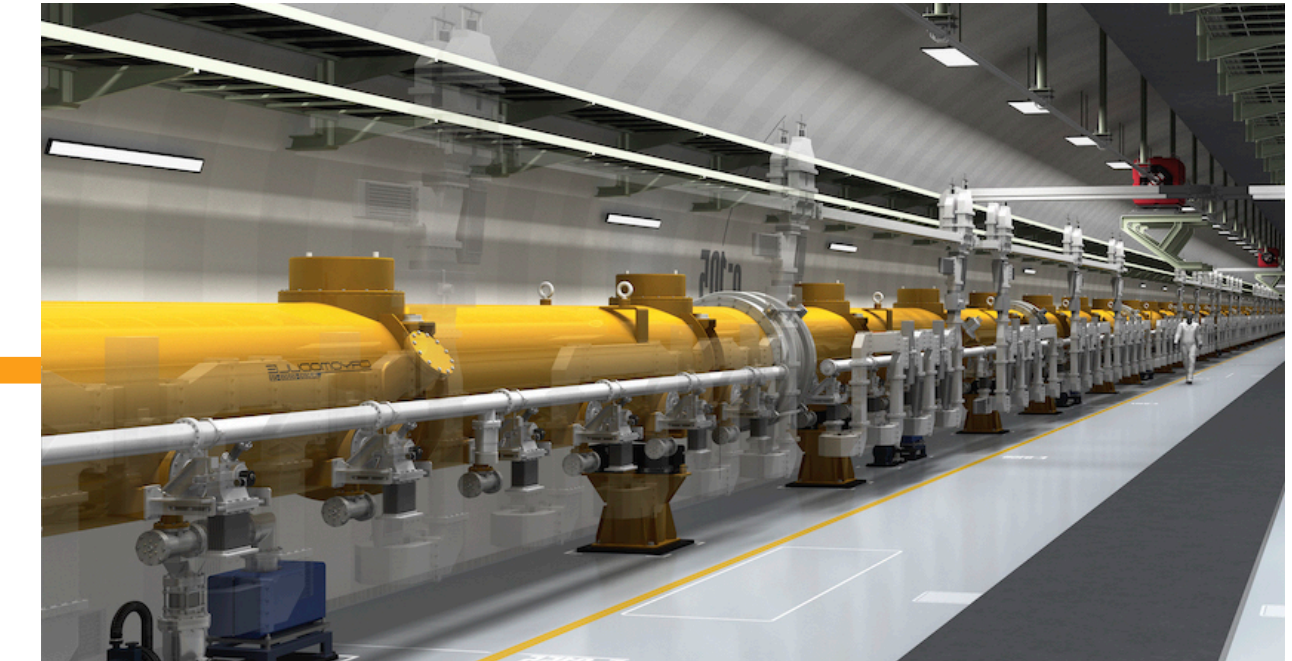
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Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge

Linear Colliders

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Long-term upgrades: energy extendability

- same technology: by increasing length
- **or by replacing accelerating structures with advanced technologies**
 - RF cavities with high gradient
 - plasma acceleration ?

Physics benefits of polarised beams

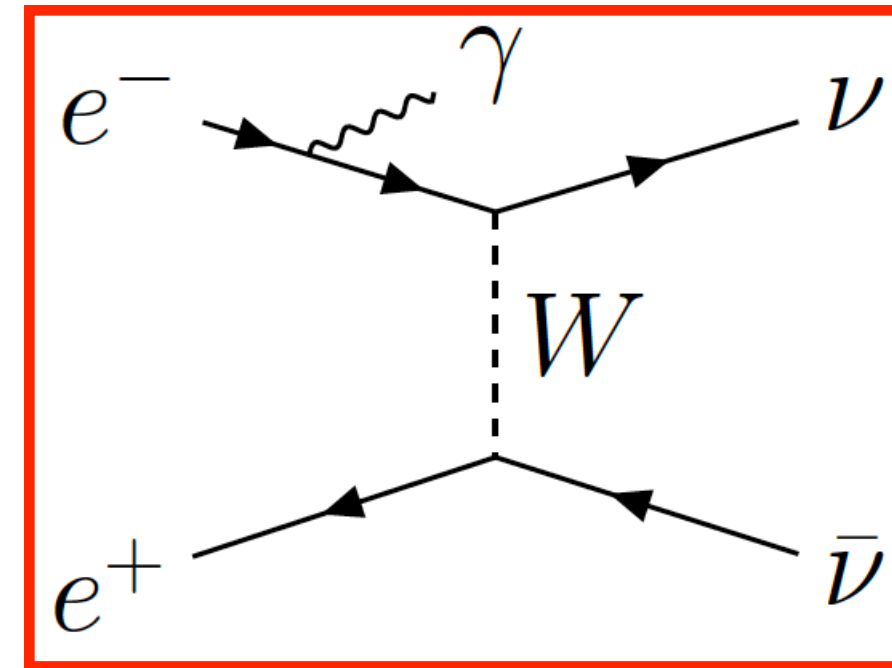
Much more than statistics - especially for SUSY!!!

General references on polarised e^+e^- physics:

- [arXiv:1801.02840](https://arxiv.org/abs/1801.02840)
- [Phys. Rept. 460 \(2008\) 131-243](#)

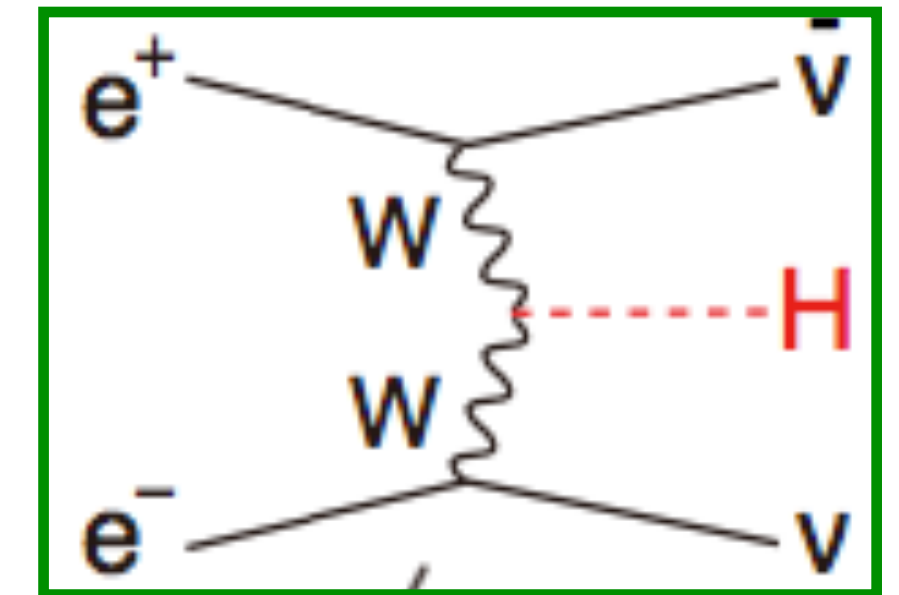
background suppression:

- $e^+e^- \rightarrow WW / \nu_e \nu_e$
strongly P-dependent
since t-channel only
for $e^-_L e^+_R$



signal enhancement:

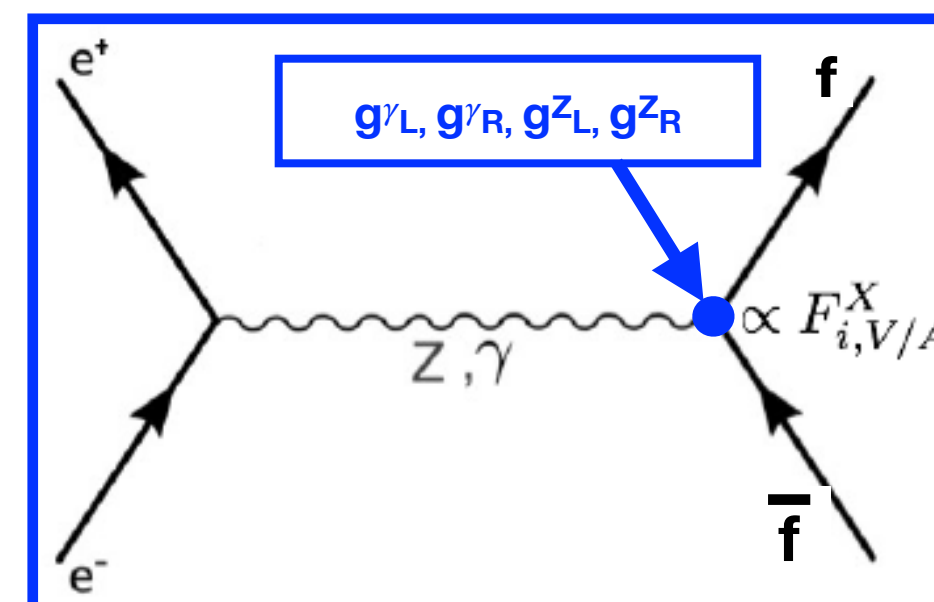
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions
- BSM:
chiral structure unknown, needs to be determined!

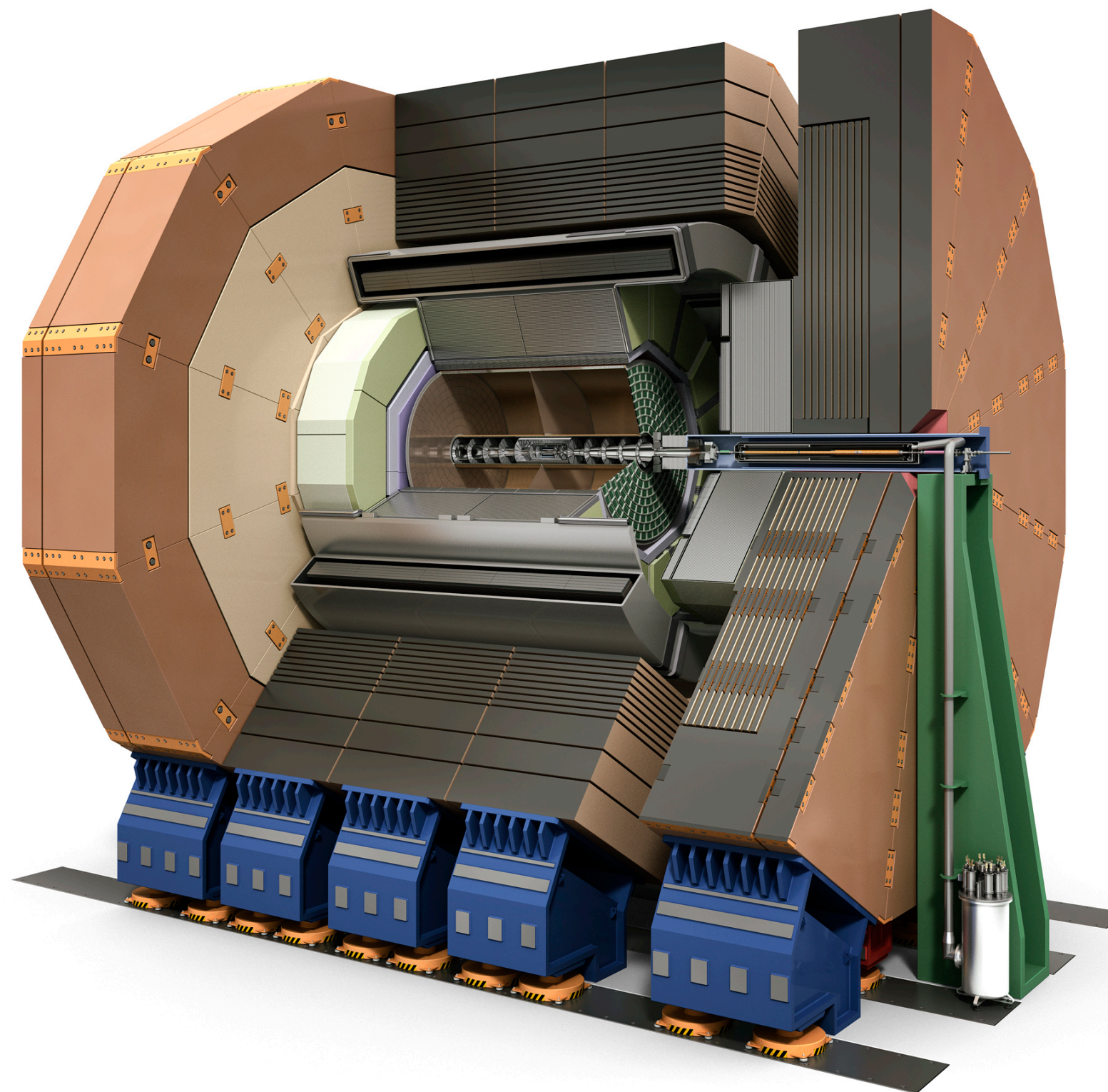
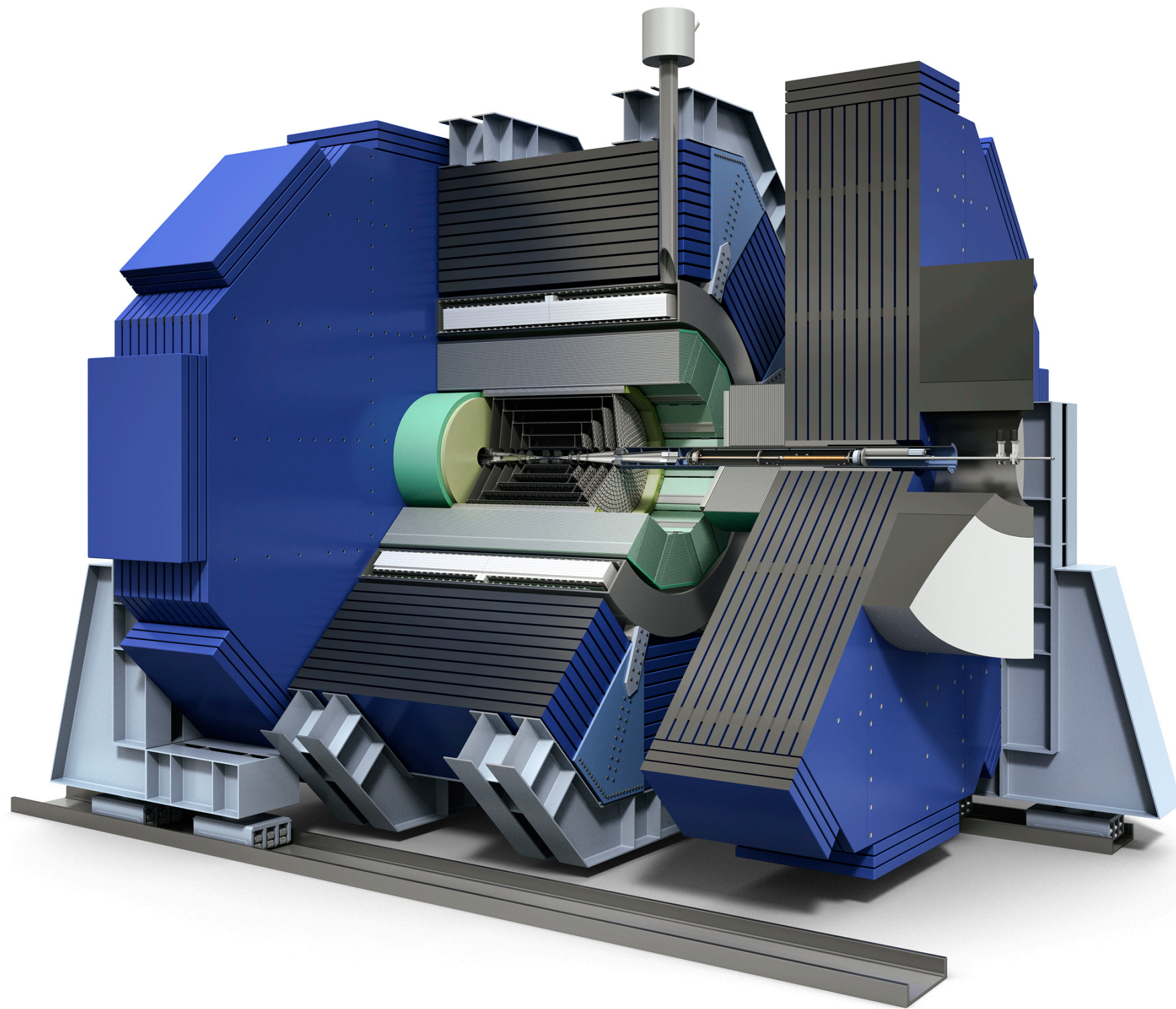


redundancy & control of systematics:

- “wrong” polarisation yields “signal-free” control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

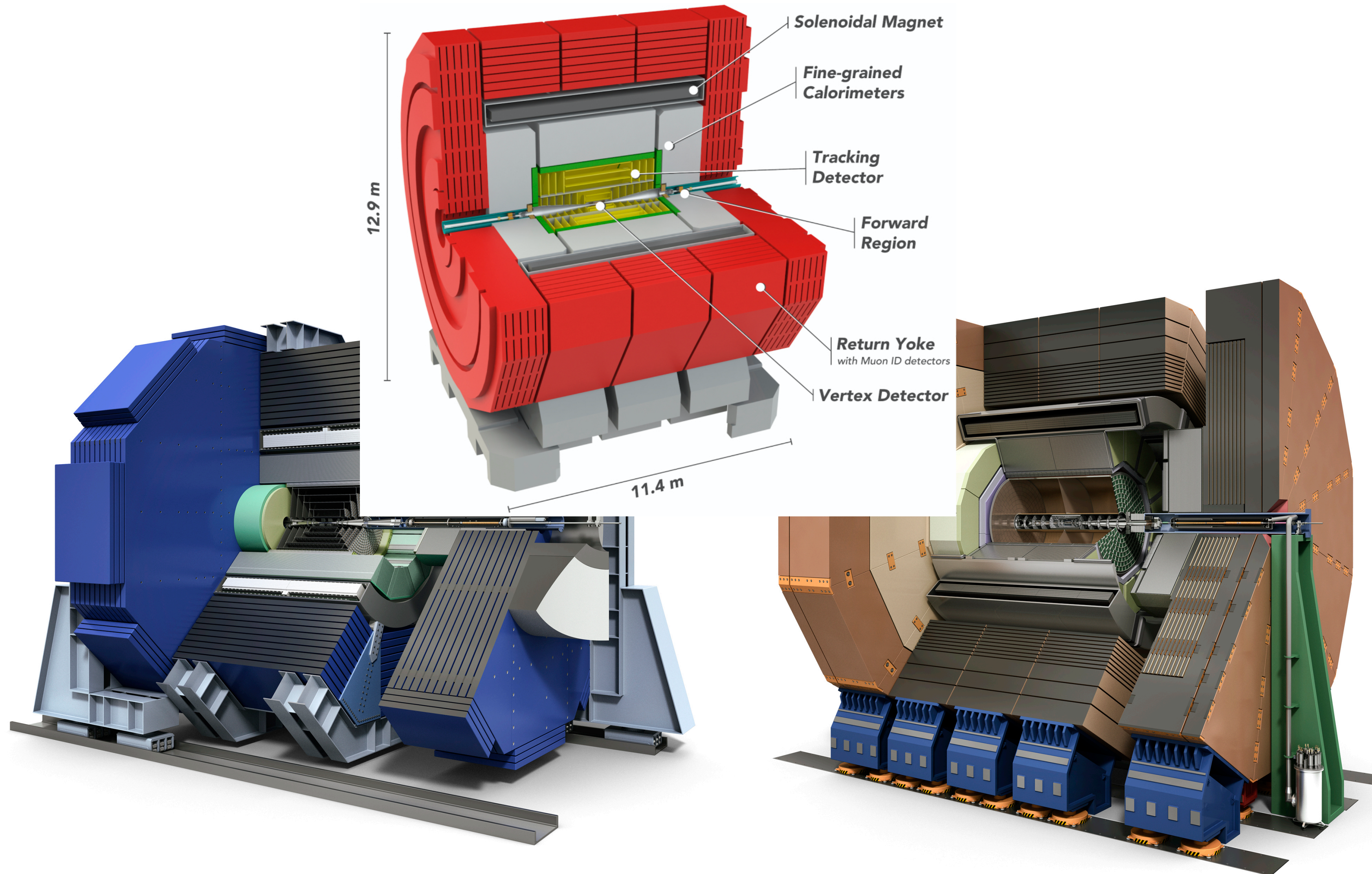
Higgs Factory Detector Concepts

for linear & circular



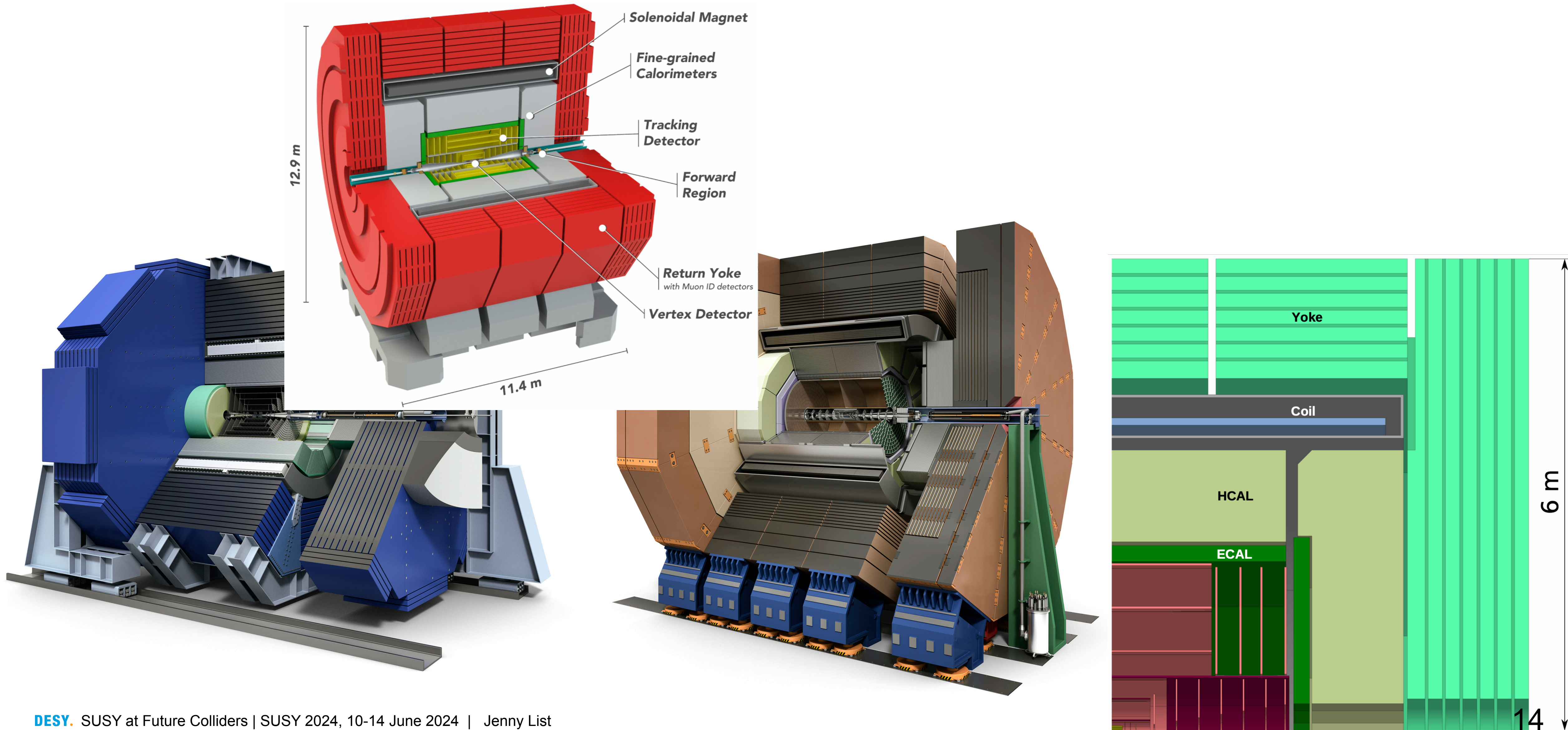
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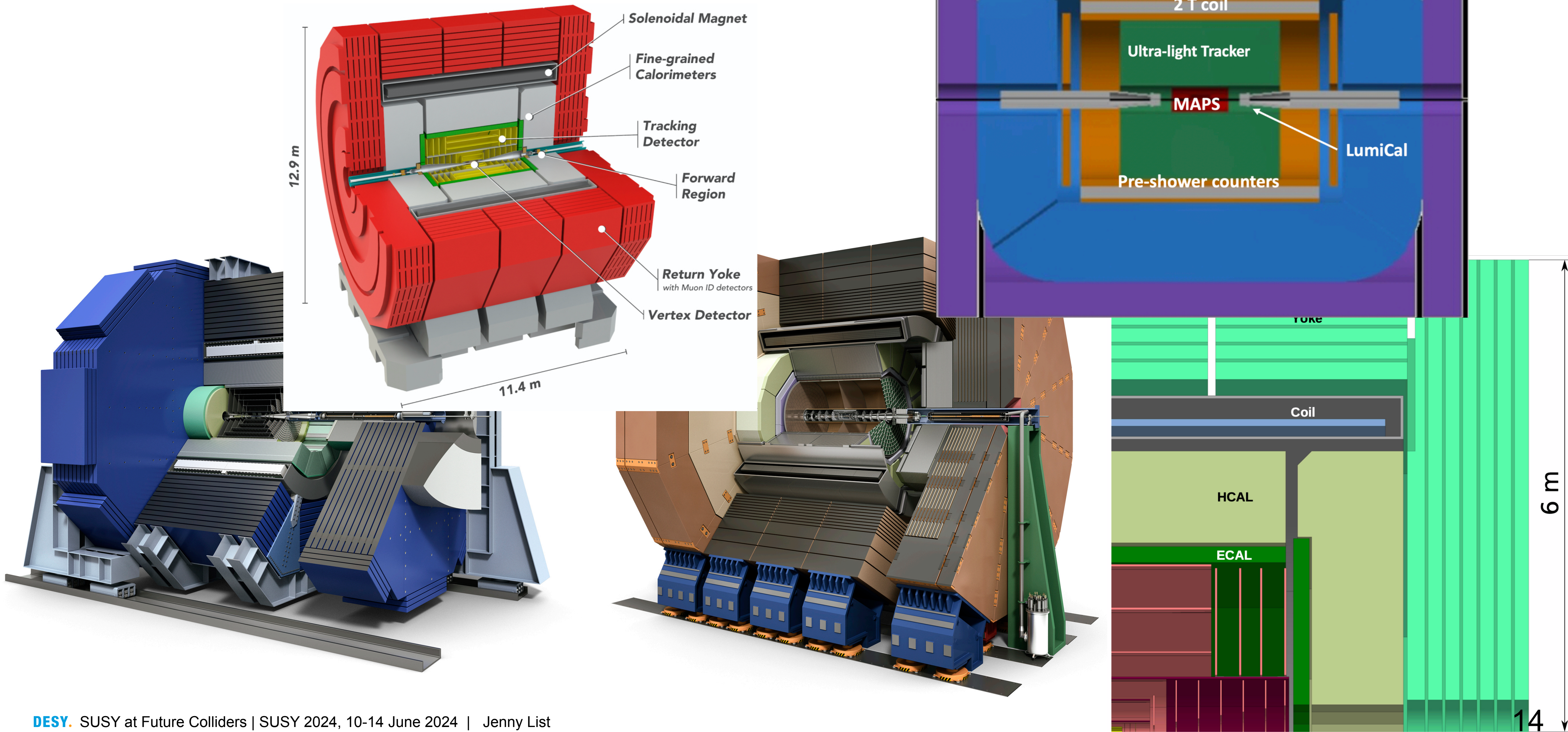
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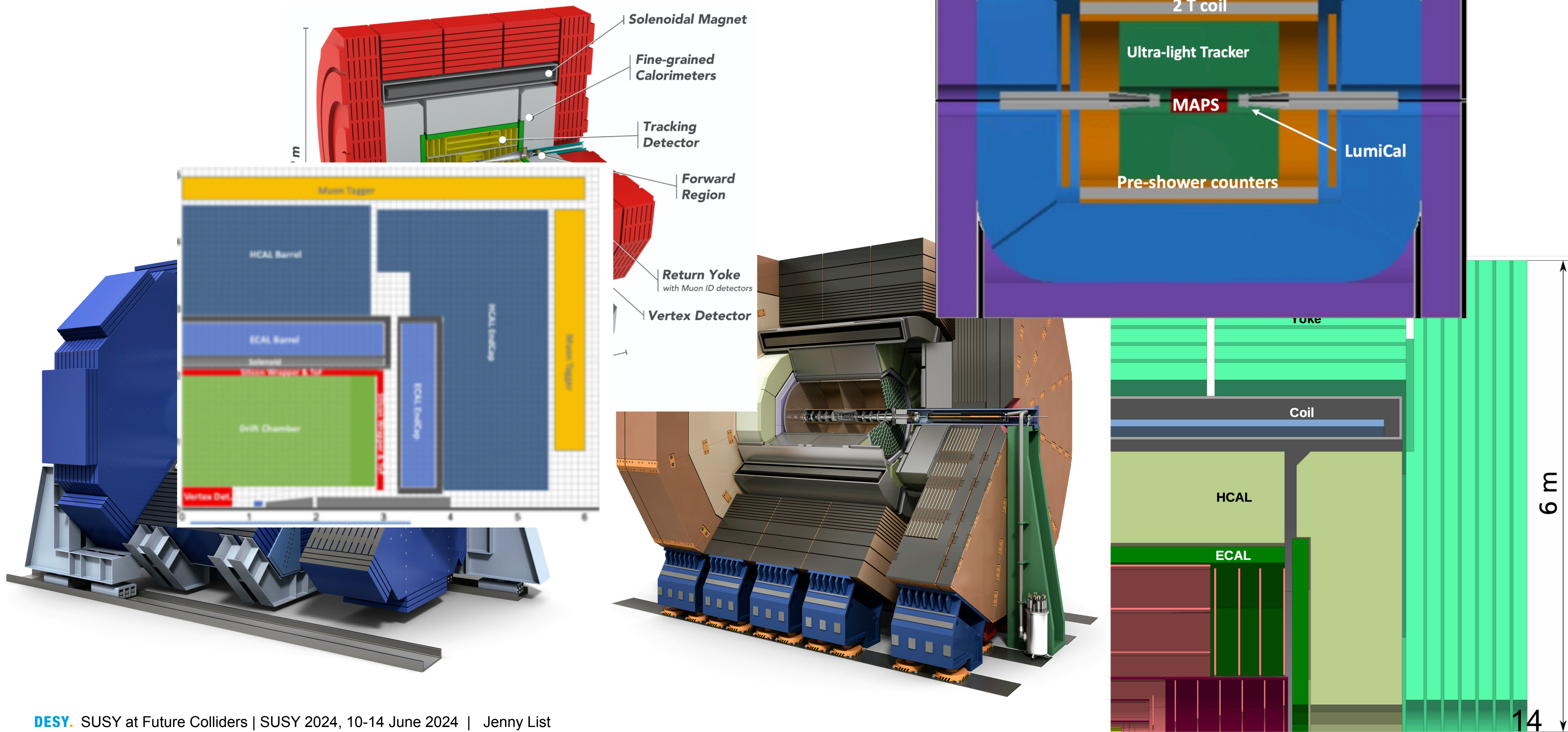
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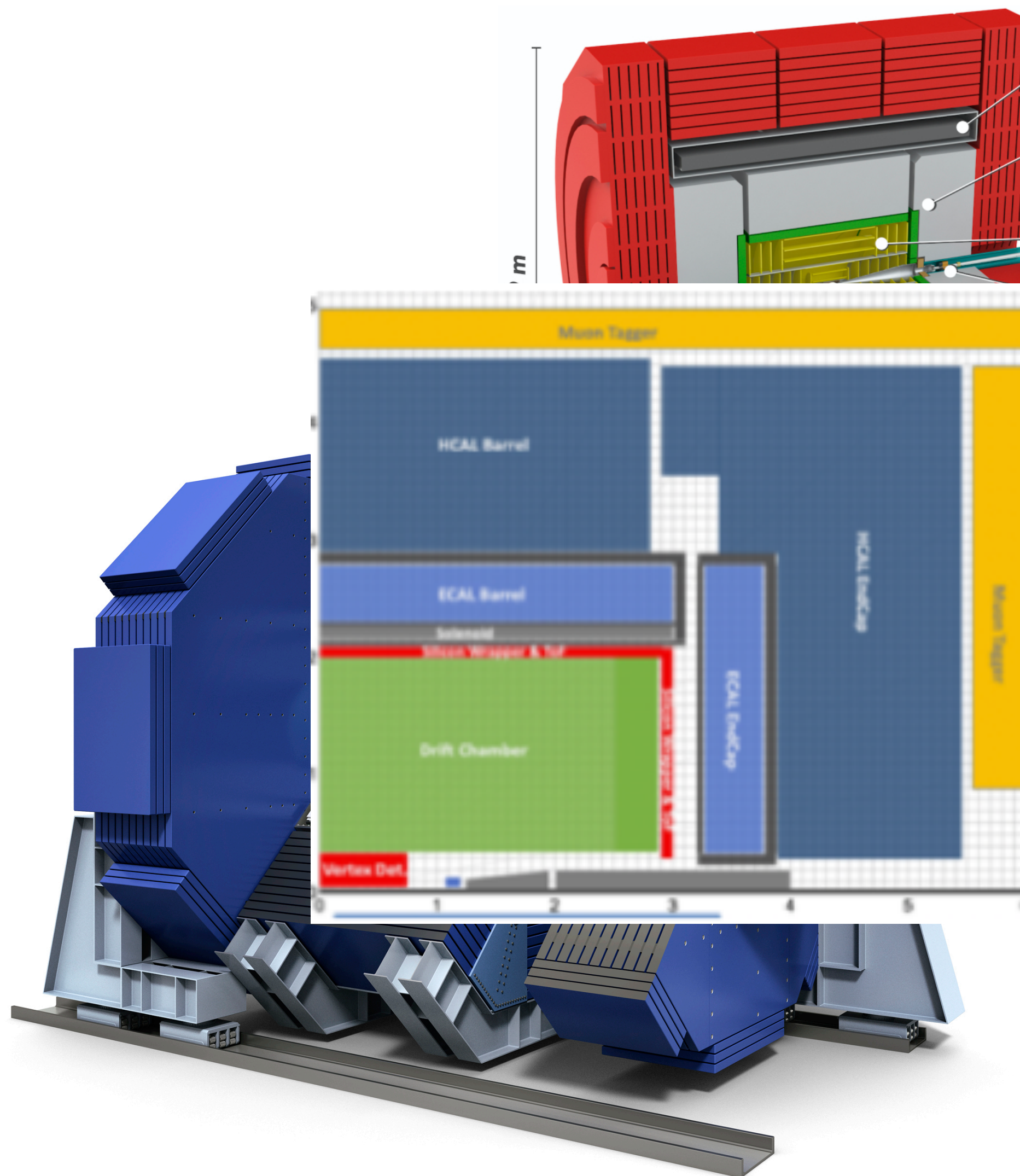
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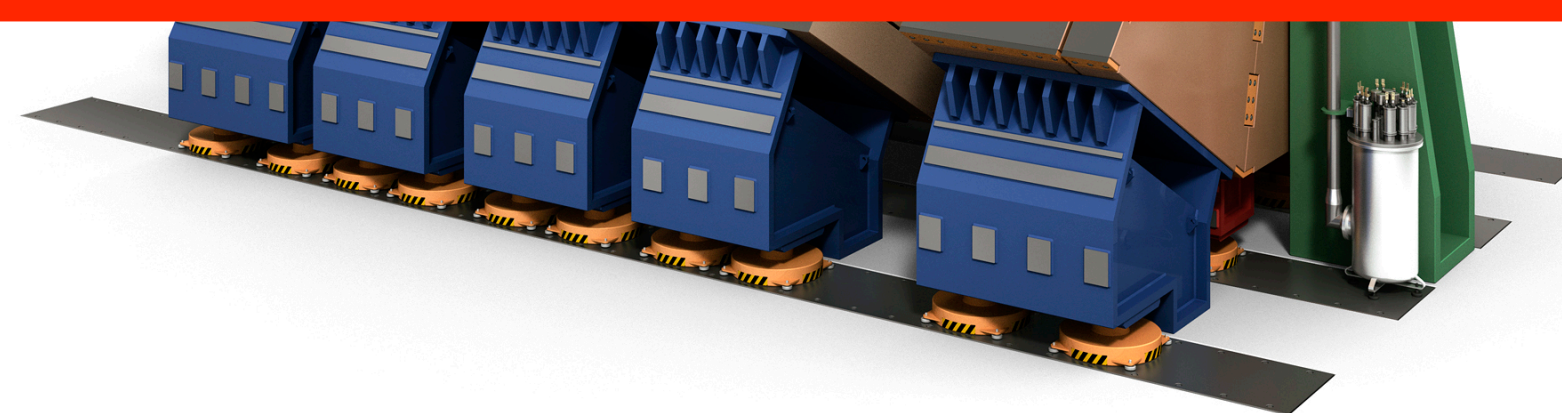
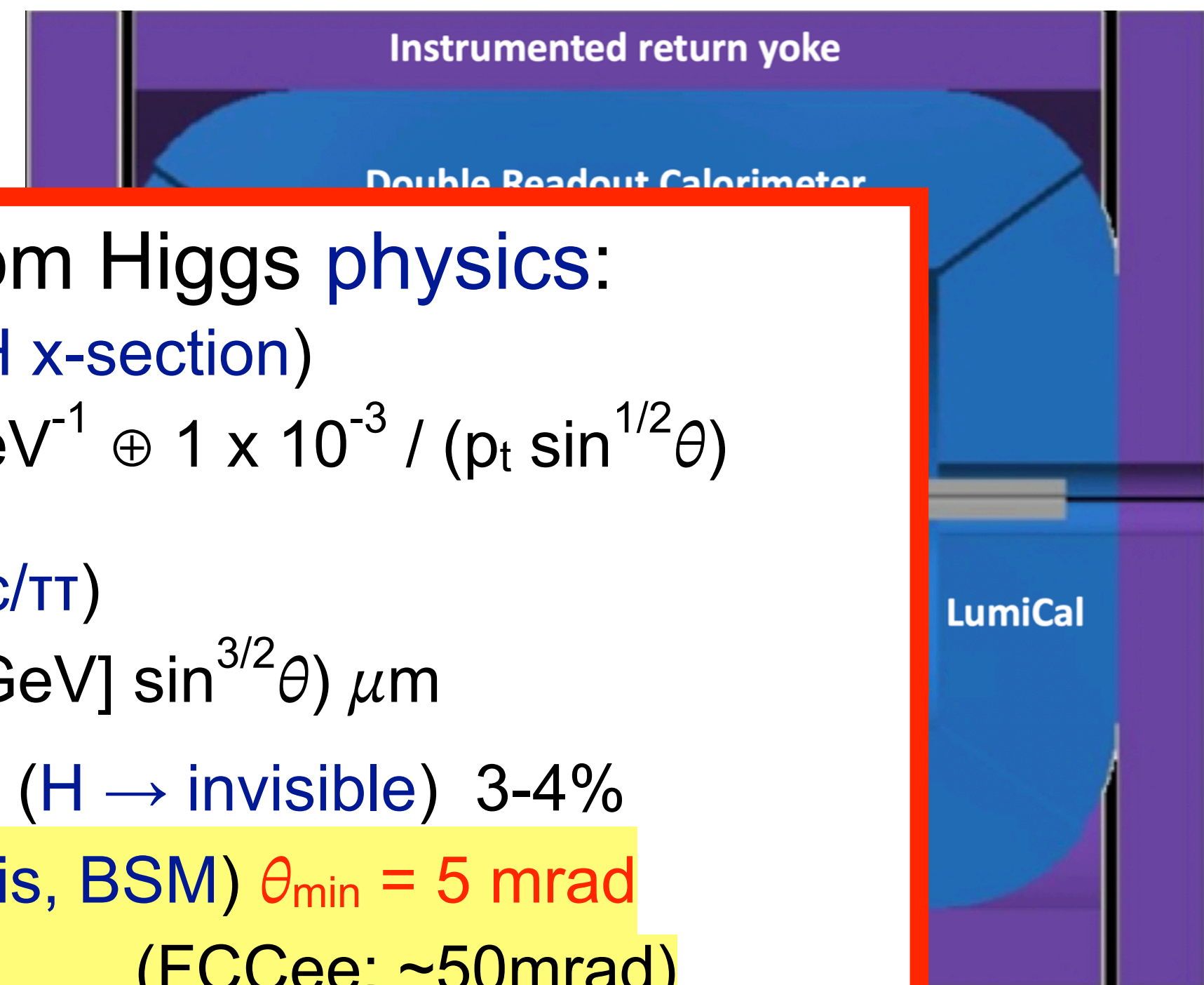


Key requirements from Higgs physics:

- **p_t resolution (total ZH x-section)**
 $\sigma(1/p_t) = 2 \times 10^{-5} \text{ GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2} \theta)$
- **vertexing ($H \rightarrow bb/cc/\tau\tau$)**
 $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2} \theta) \mu\text{m}$
- **jet energy resolution ($H \rightarrow \text{invisible}$) 3-4%**
- **hermeticity ($H \rightarrow \text{invis, BSM}$) $\theta_{\text{min}} = 5 \text{ mrad}$**
(FCCee: $\sim 50 \text{ mrad}$)

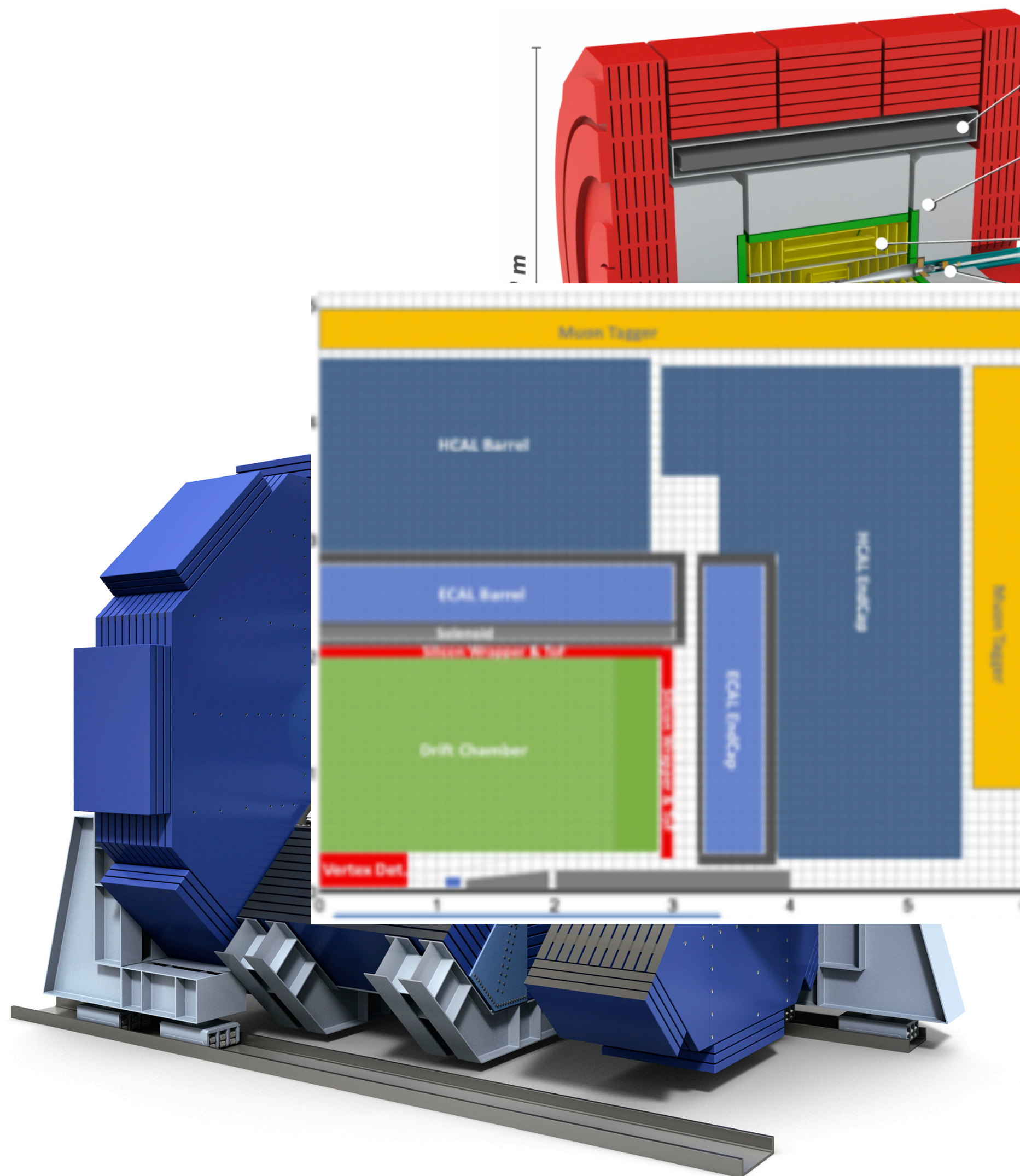
Determine to key features of the **detector**:

- **low mass tracker:**
eg VTX: 0.15% rad. length / layer)
- **calorimeters**
 - **highly granular**, optimised for particle flow
 - or dual readout, LAr, ...



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(FCCee: ~50mrad)

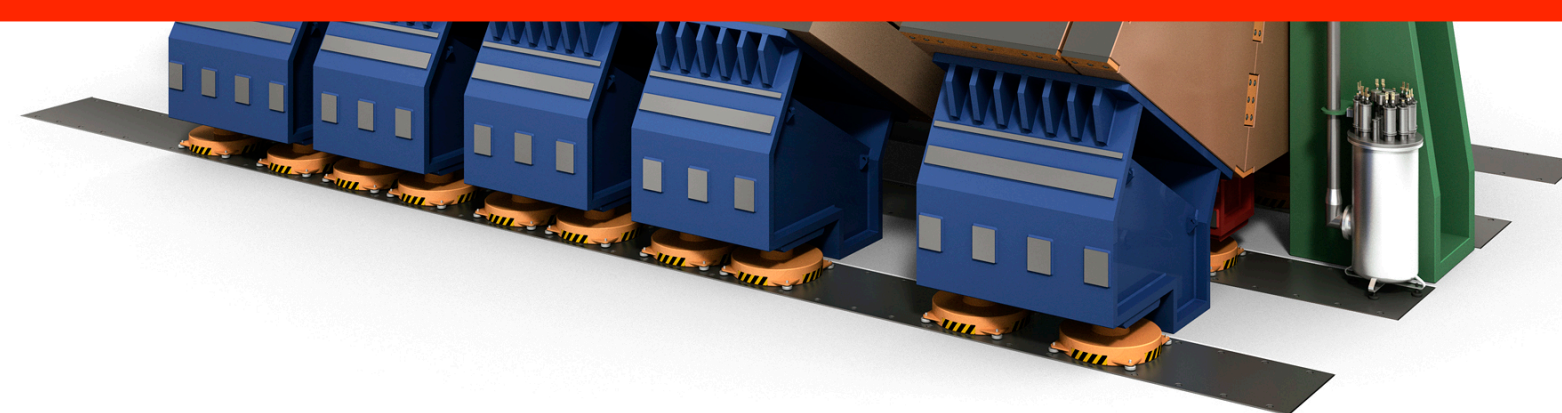
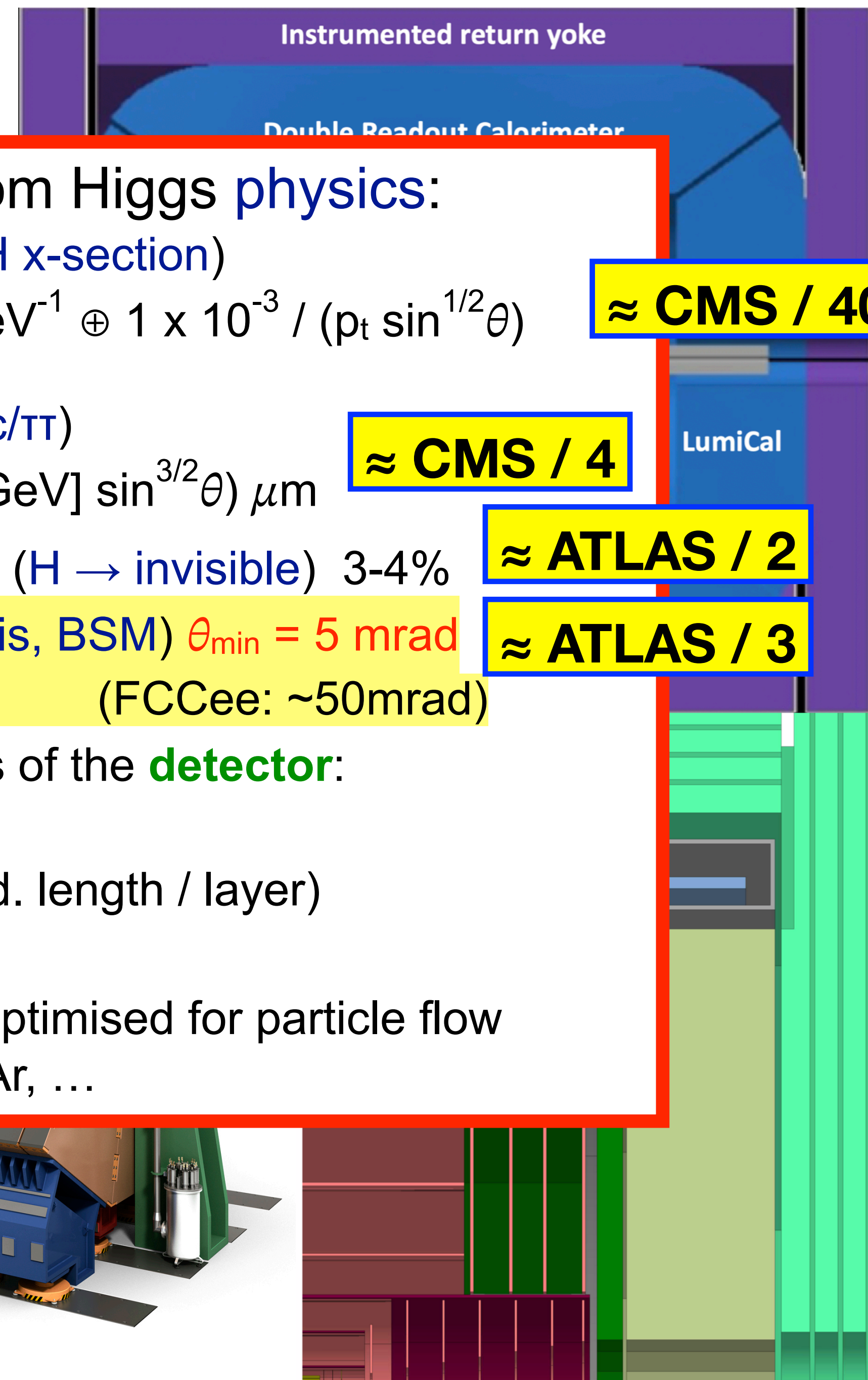
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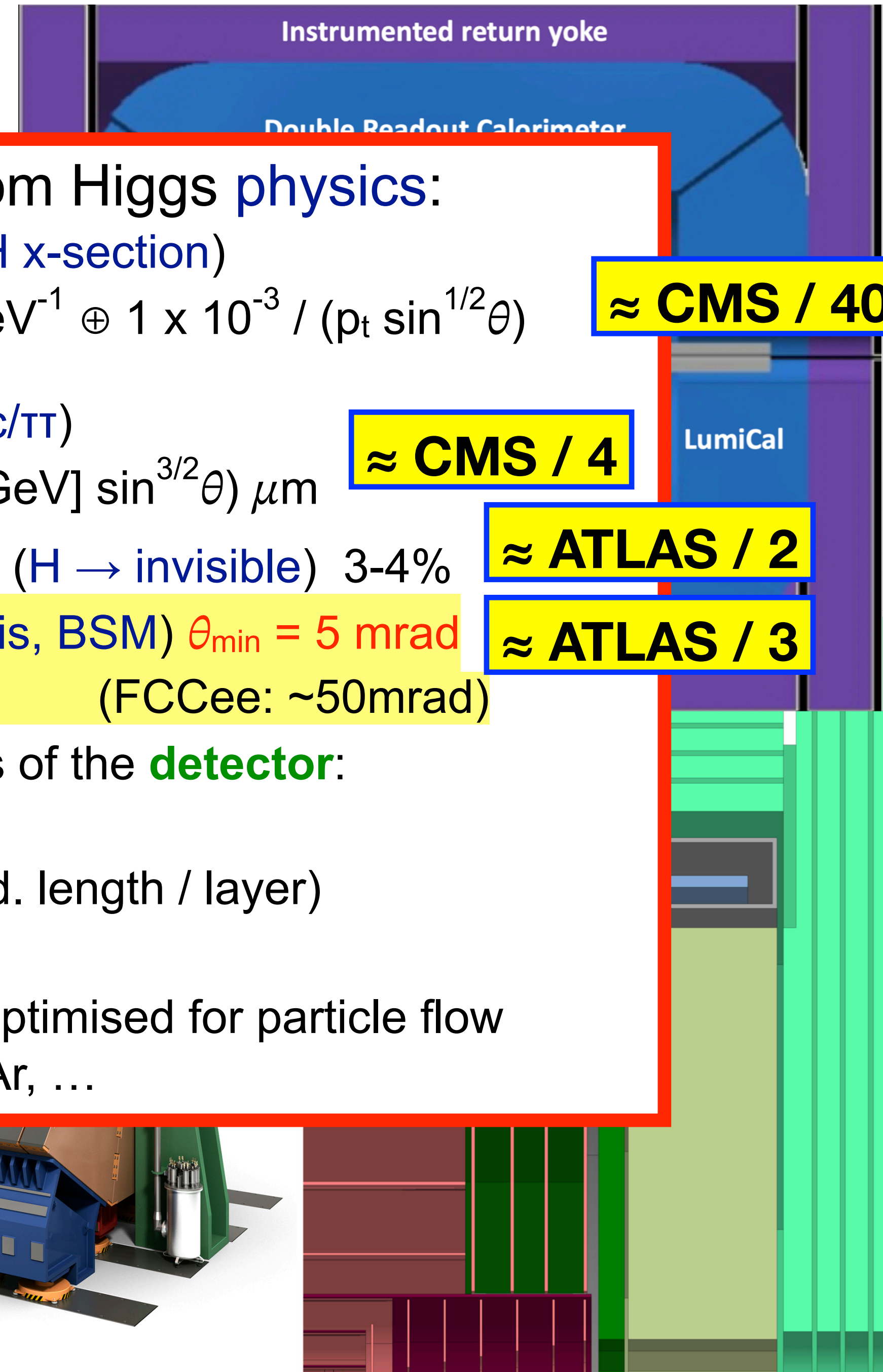
• **readout**, LAr, ...

Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

only Linear Colliders: lower collision rate enables

- **passive cooling only => low material budget**
- **triggerless operation**

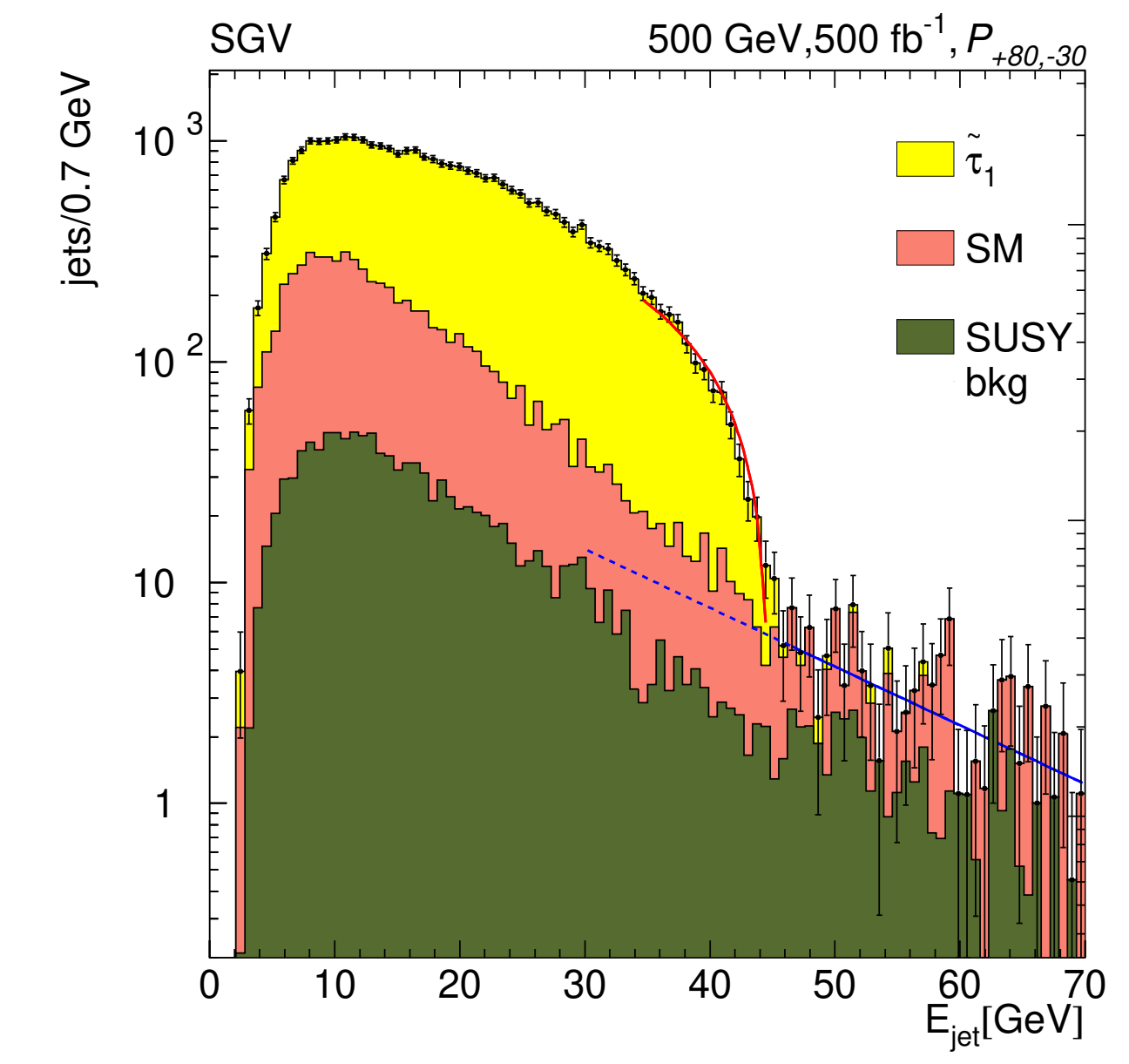
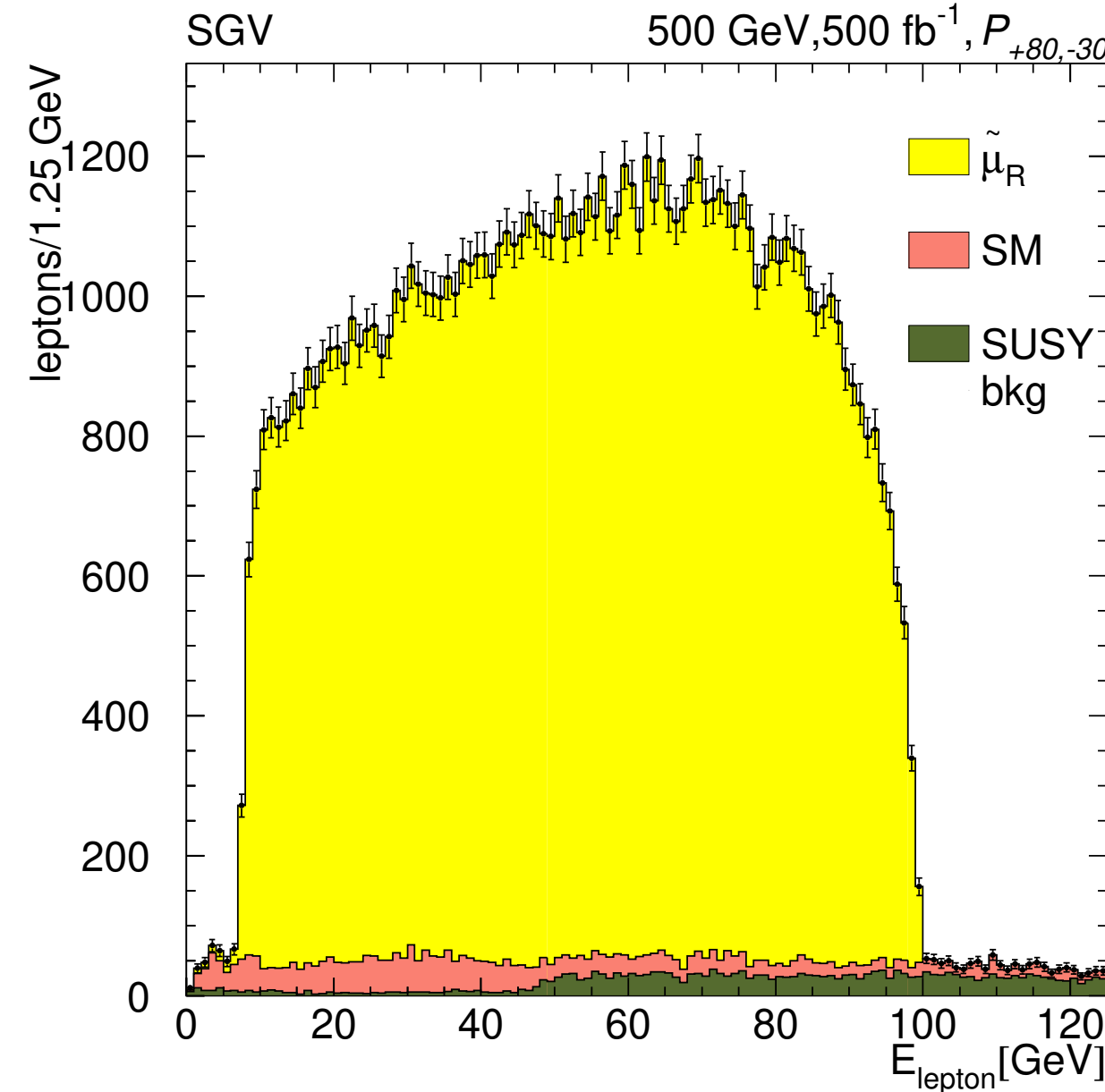
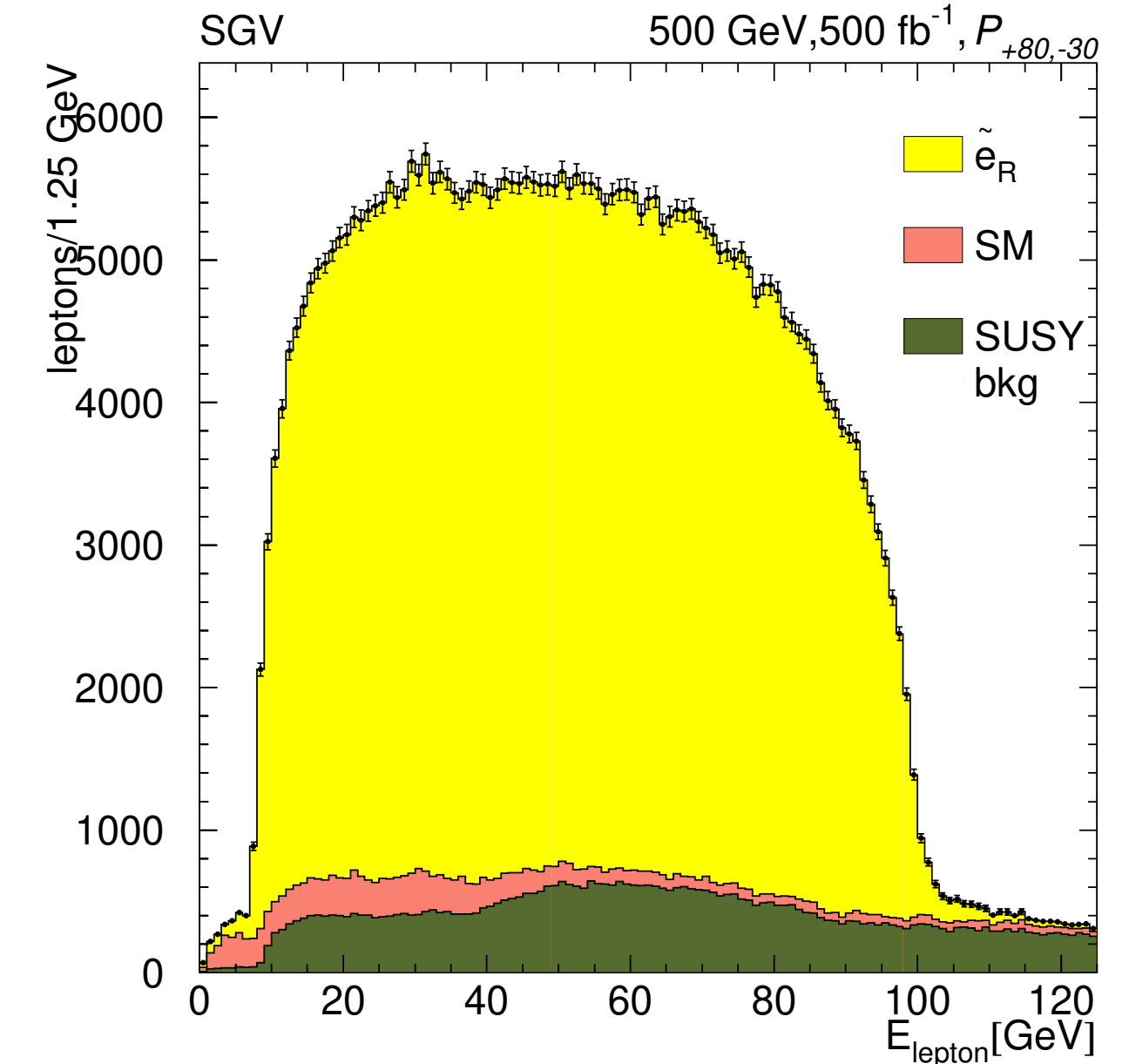
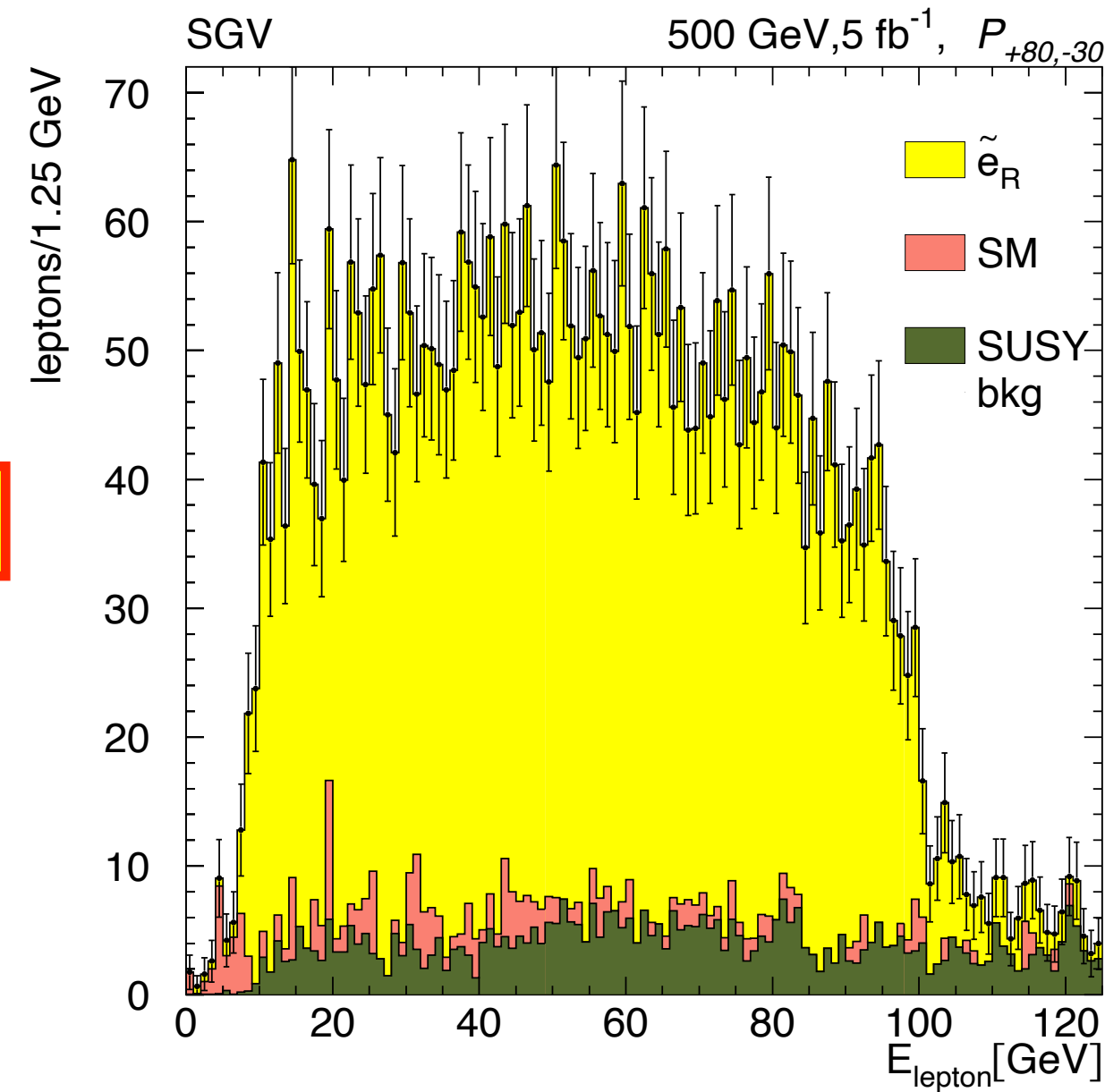


Example 1: Scalar Leptons

SUSY jumping into your eye at a lepton collider

- s-electrons after
 - a week (5fb⁻¹)
 - 2-3 years (500fb⁻¹)
- s-muons, s-taus
- permille-level mass and cross-section measurement
- SUSY parameter determination

Eur.Phys.J.C 76 (2016) 4, 183



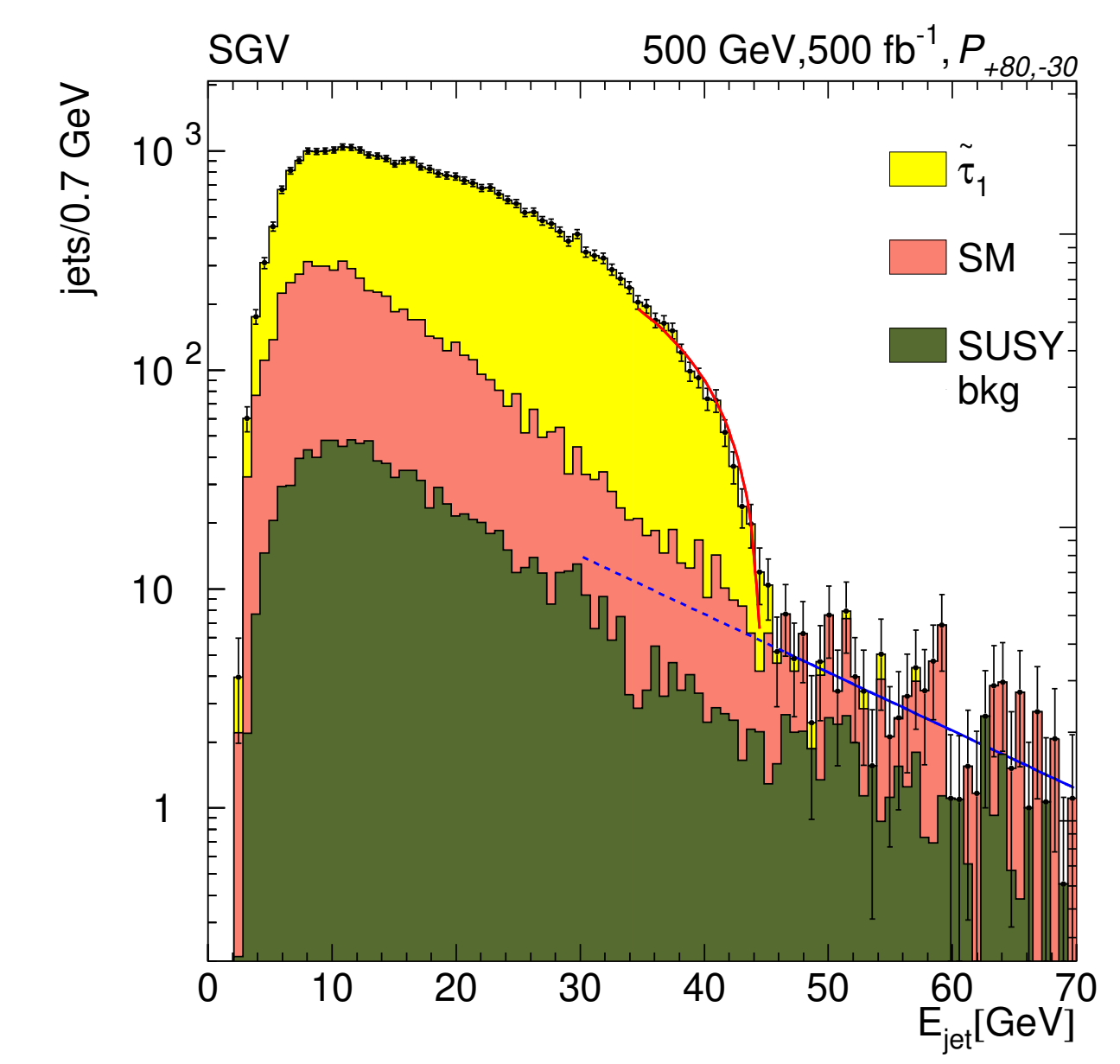
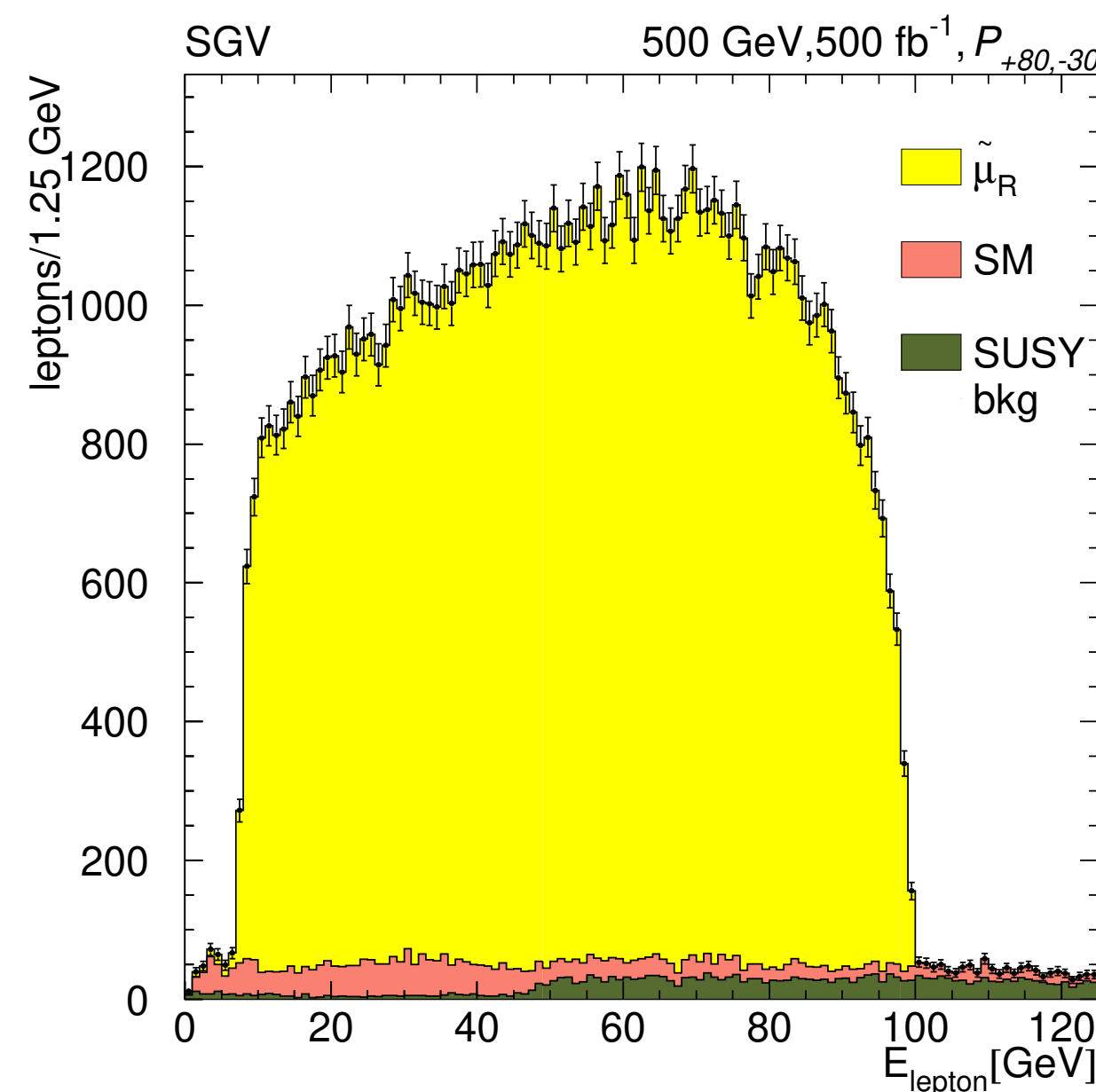
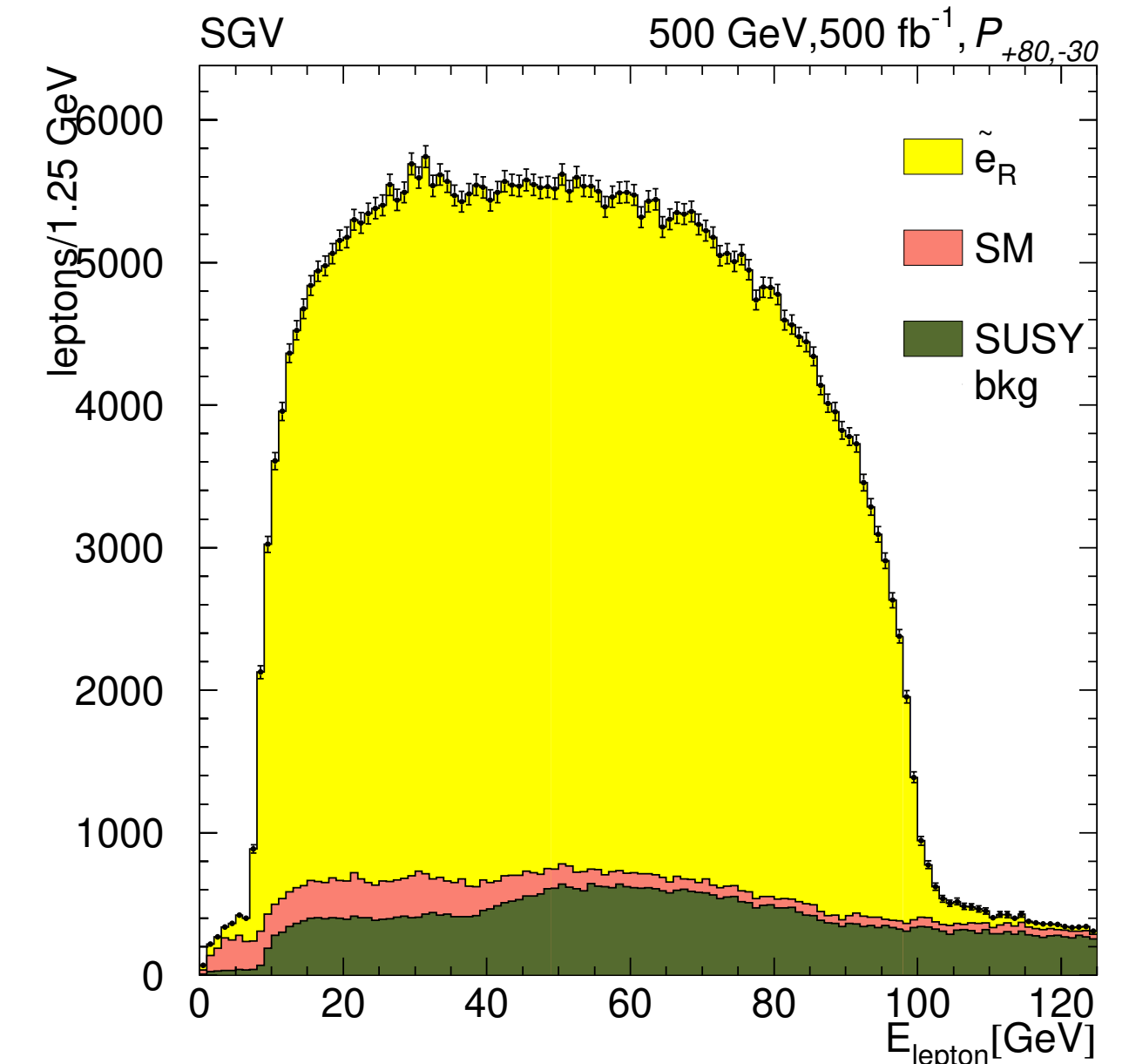
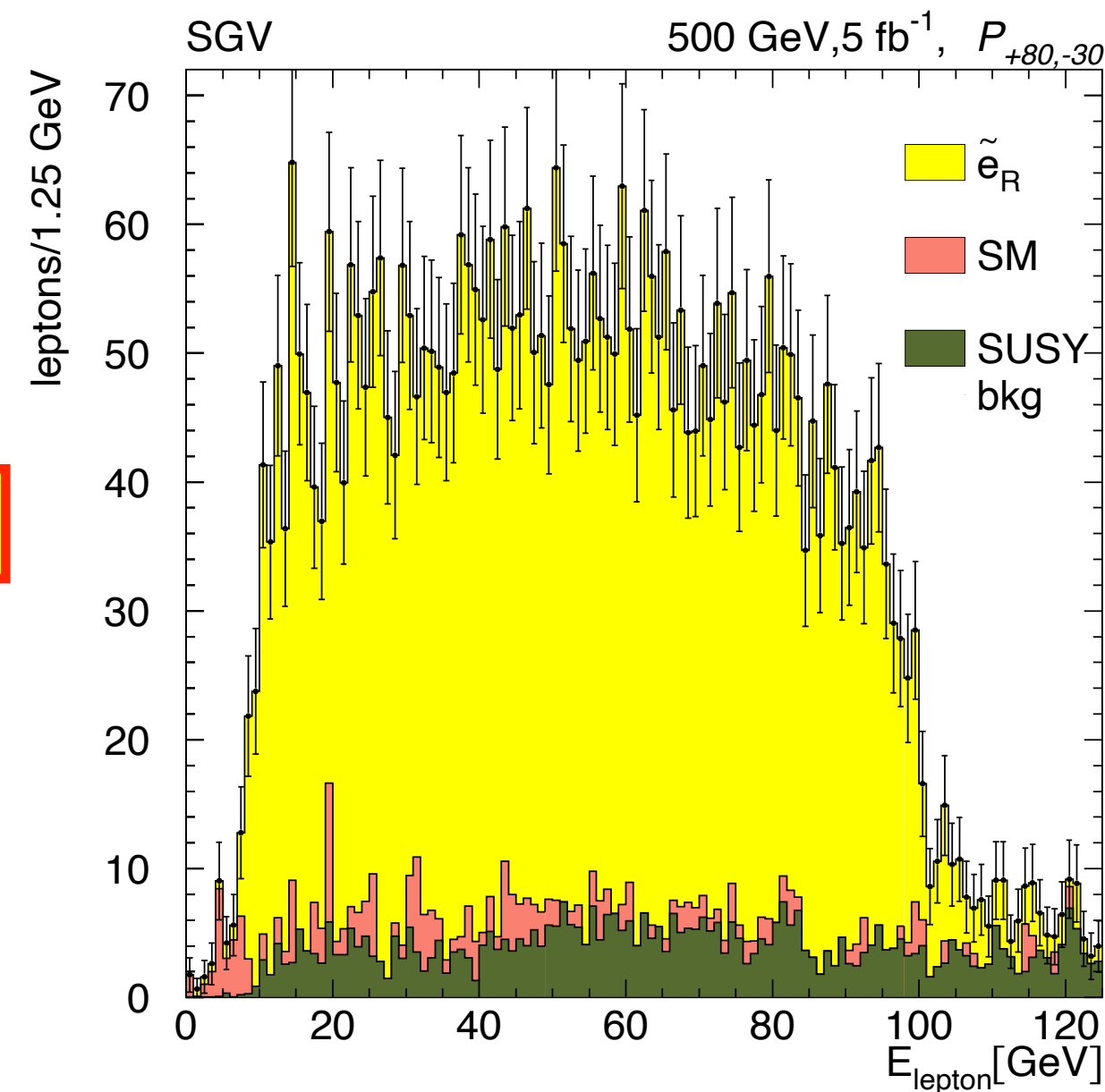
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Eur.Phys.J.C 76 (2016) 4, 183

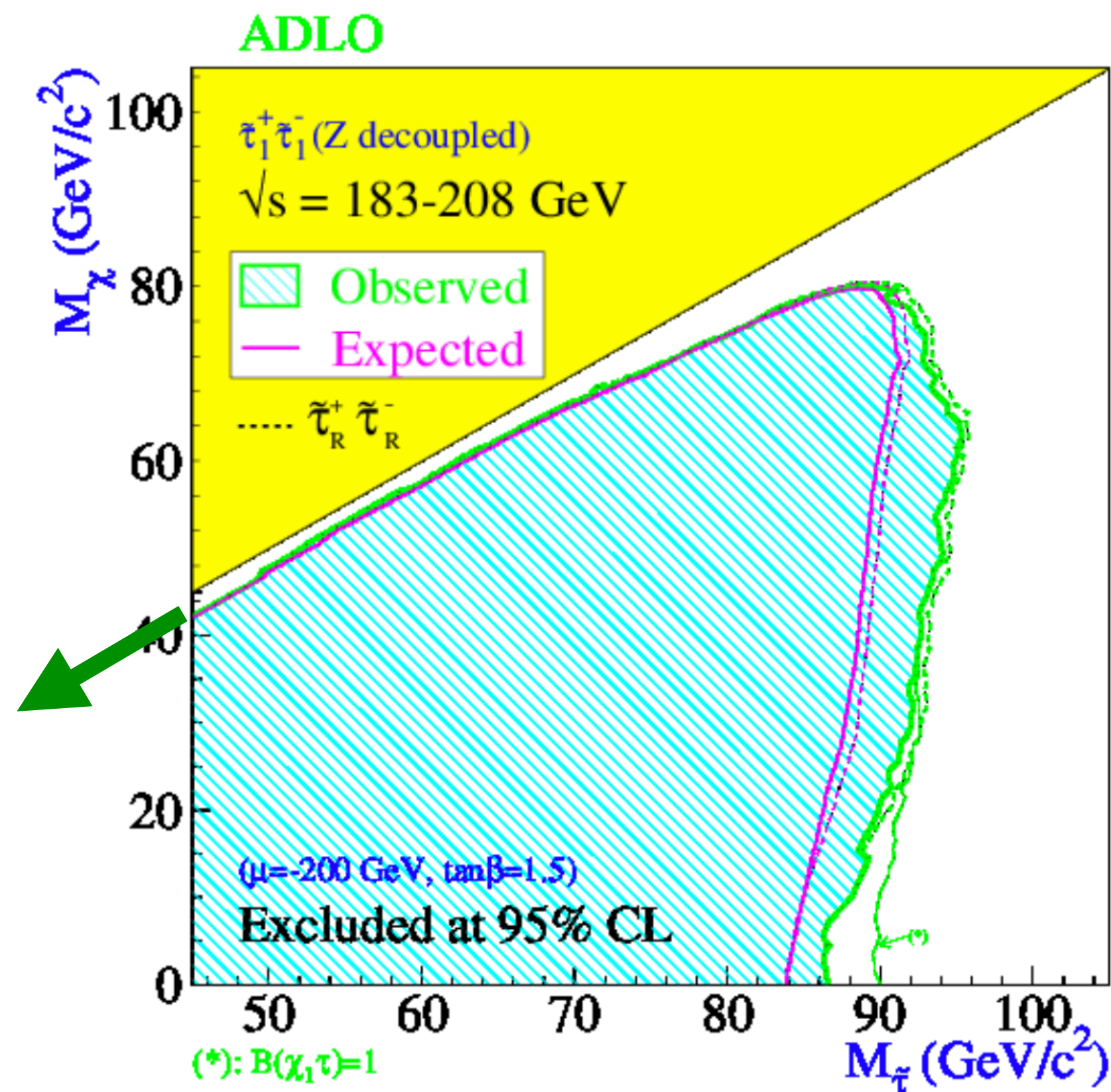
- what is the generically 'worst case'?
- parameter scan for staus - low mass splitting, mixing such that cross-section minimal,



Scalar Taus

A closer look at the difficult case

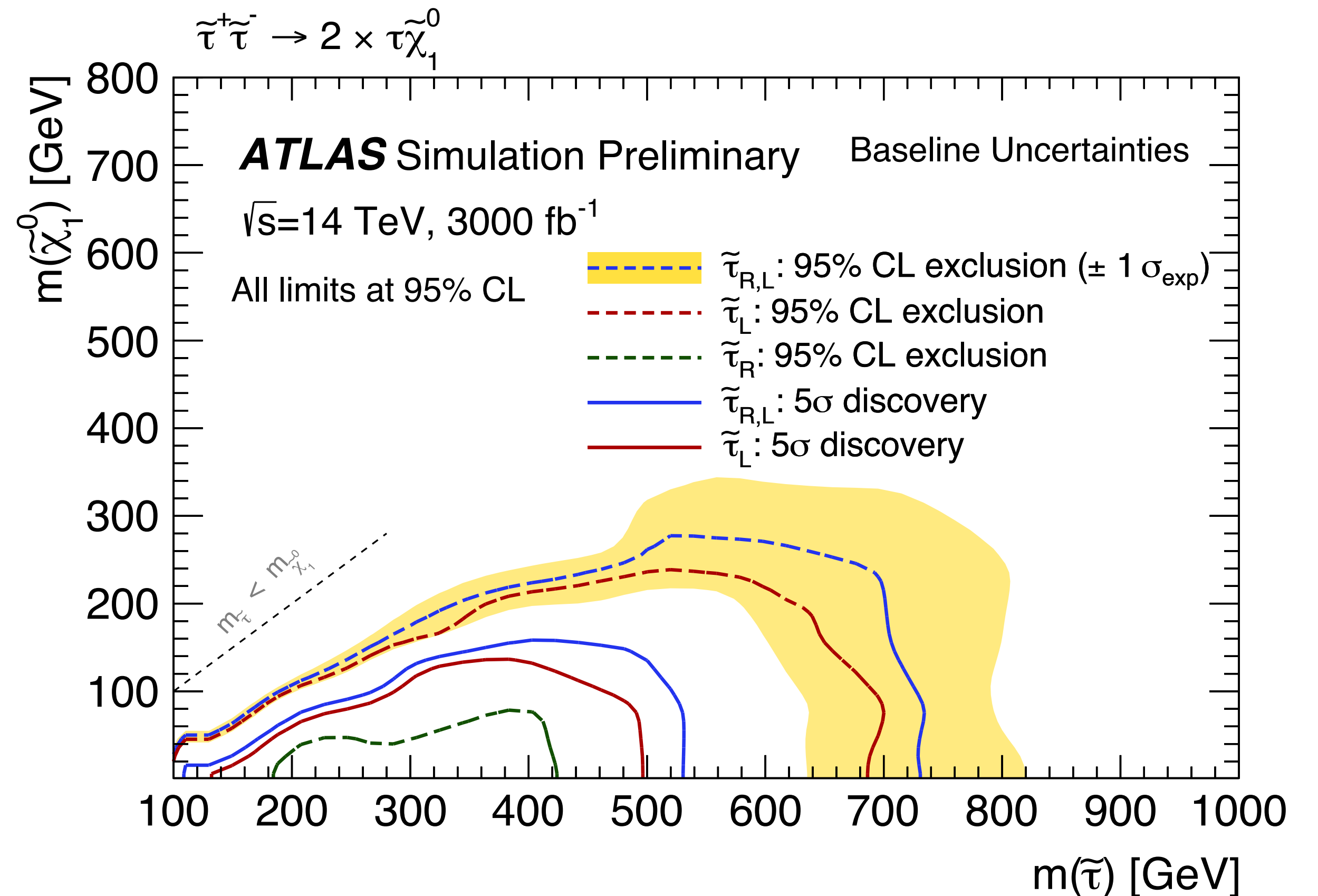
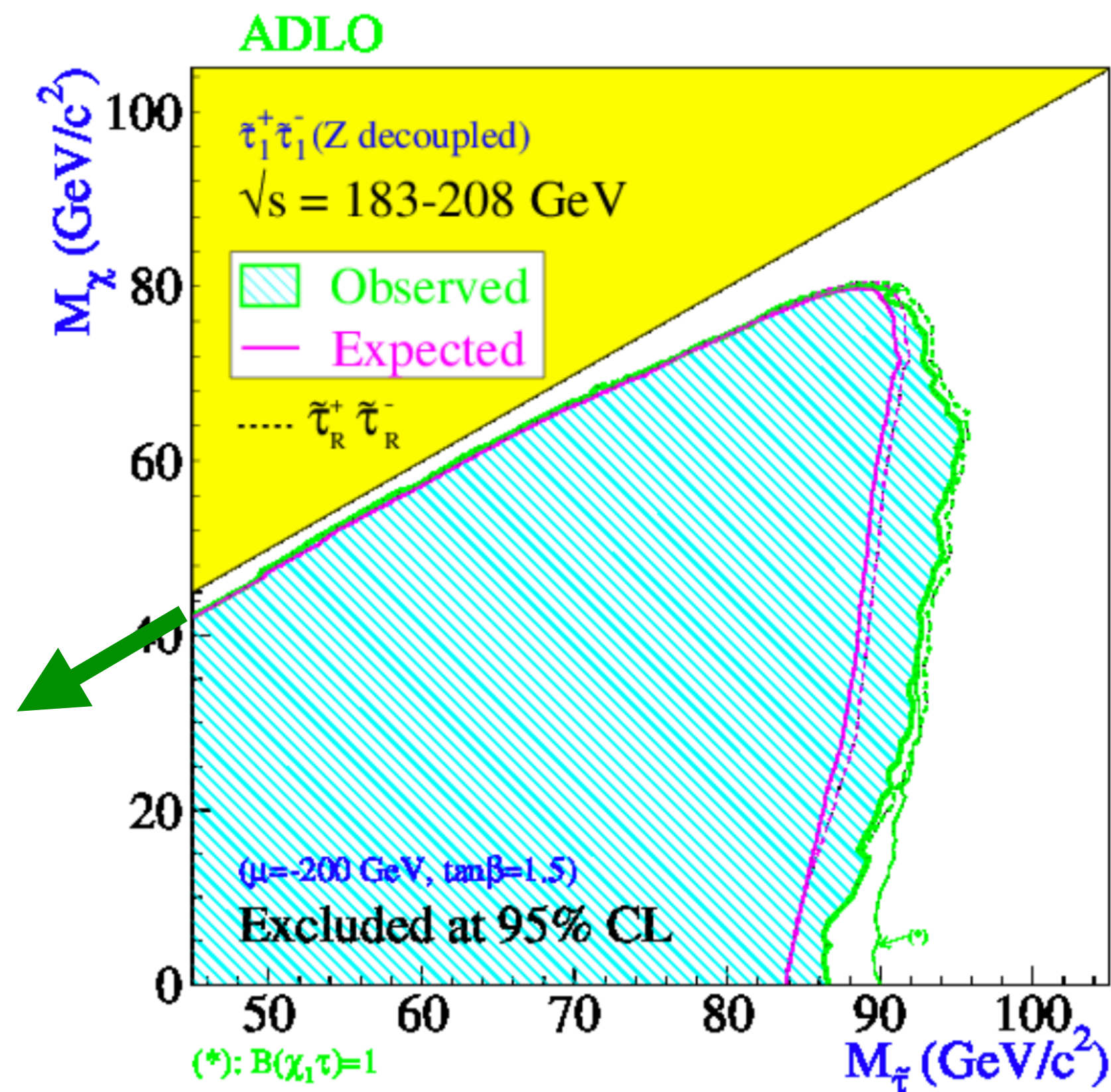
- current general lower mass limit on staus (any mass splitting $> m(\tau)$, any mixing, ...): **26.3 GeV** (DELPHI, Eur. Phys. J. C 31 (2003), 421-479)
- extremely difficult at HL-LHC - especially in realistic cases with $M_{\text{stauR}} < M_{\text{stauL}}$



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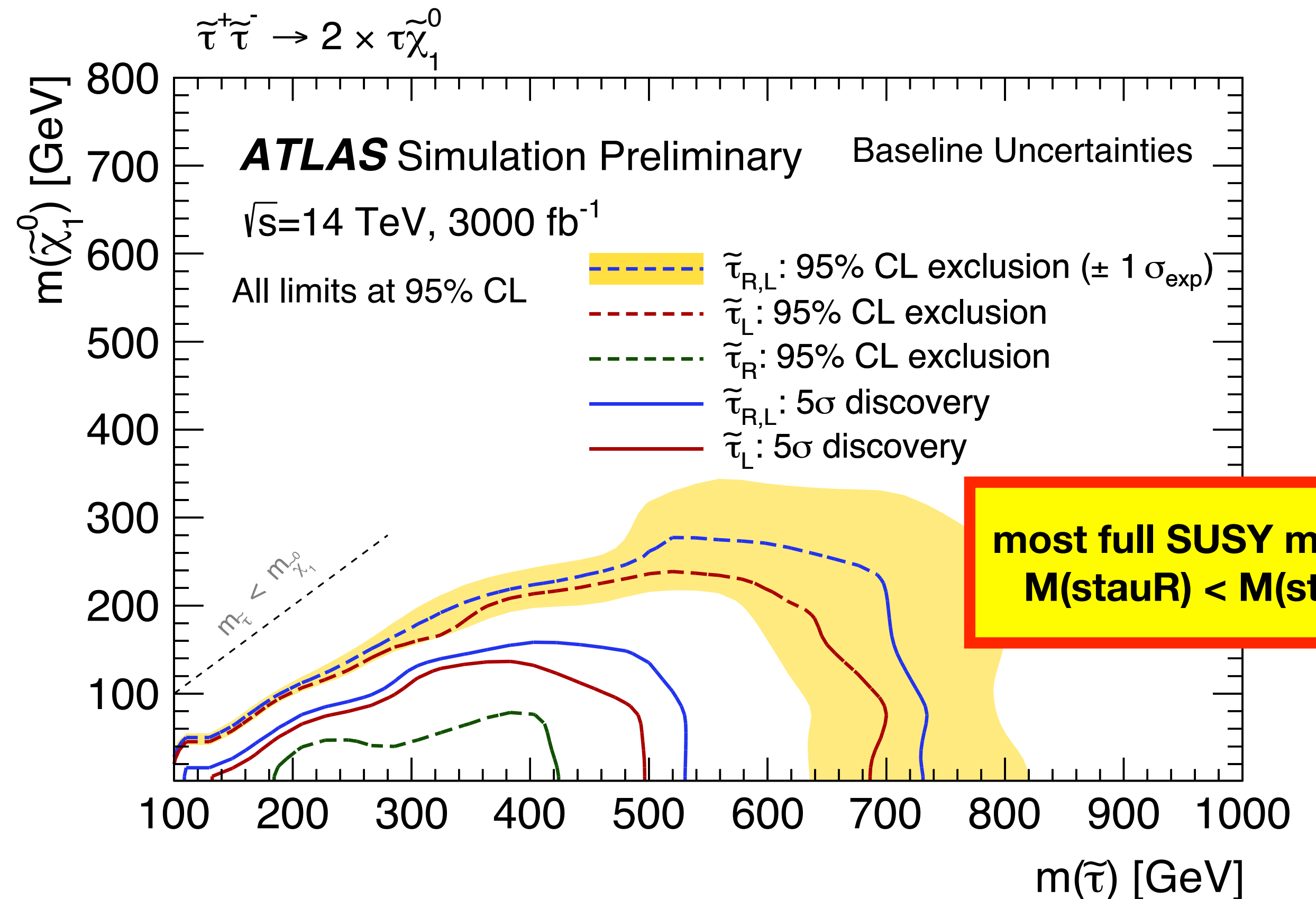
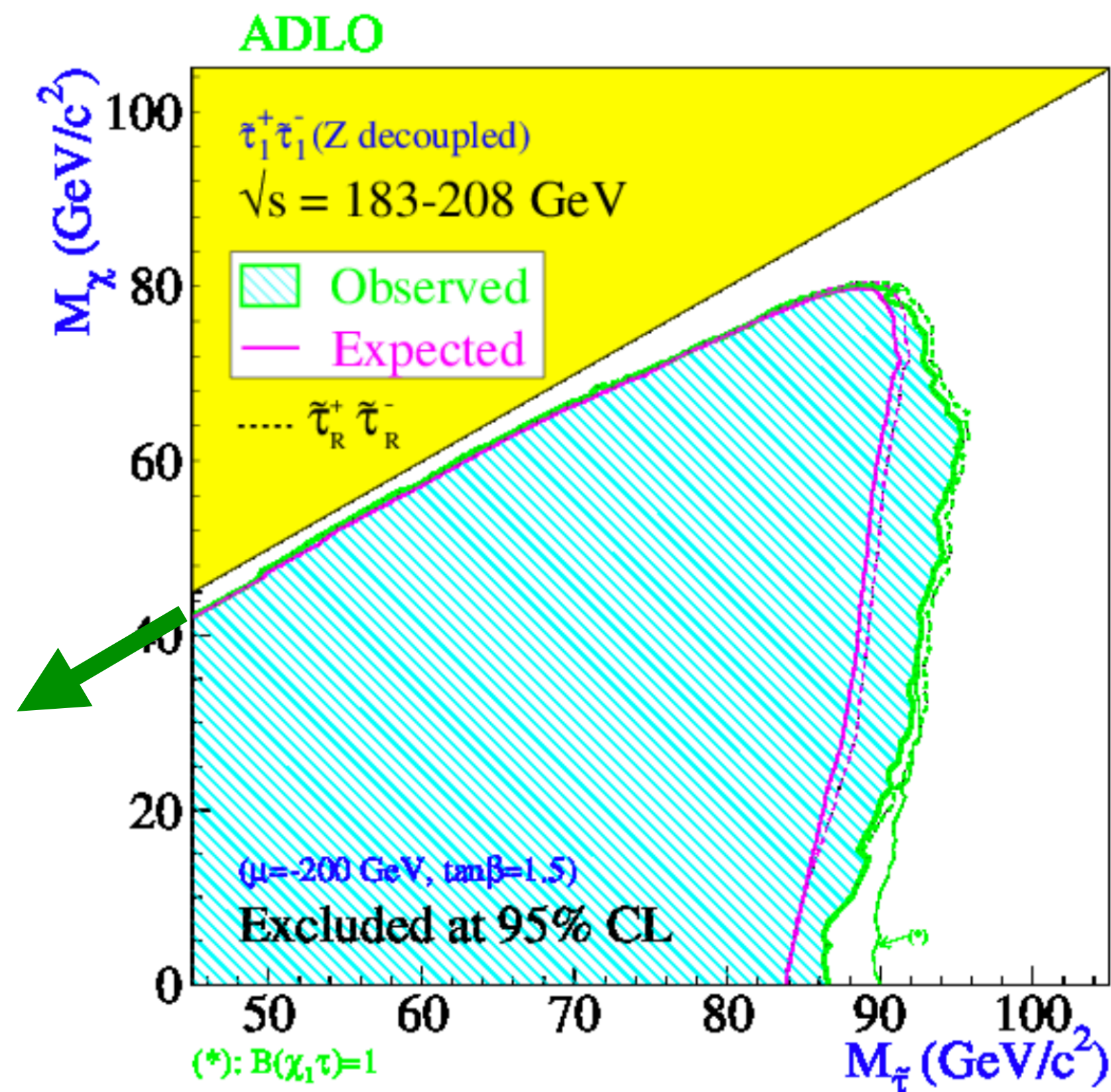
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Scalar Taus

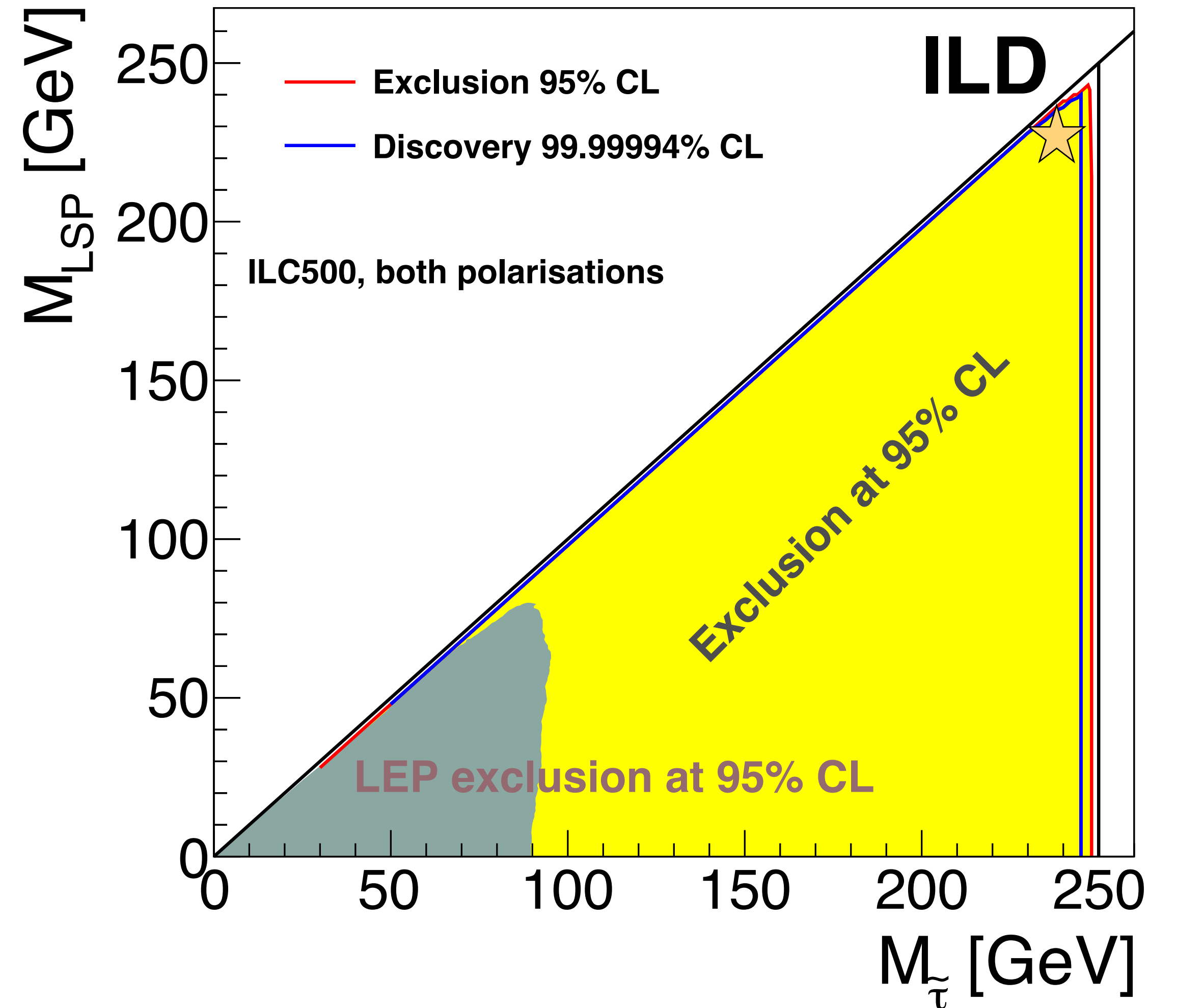
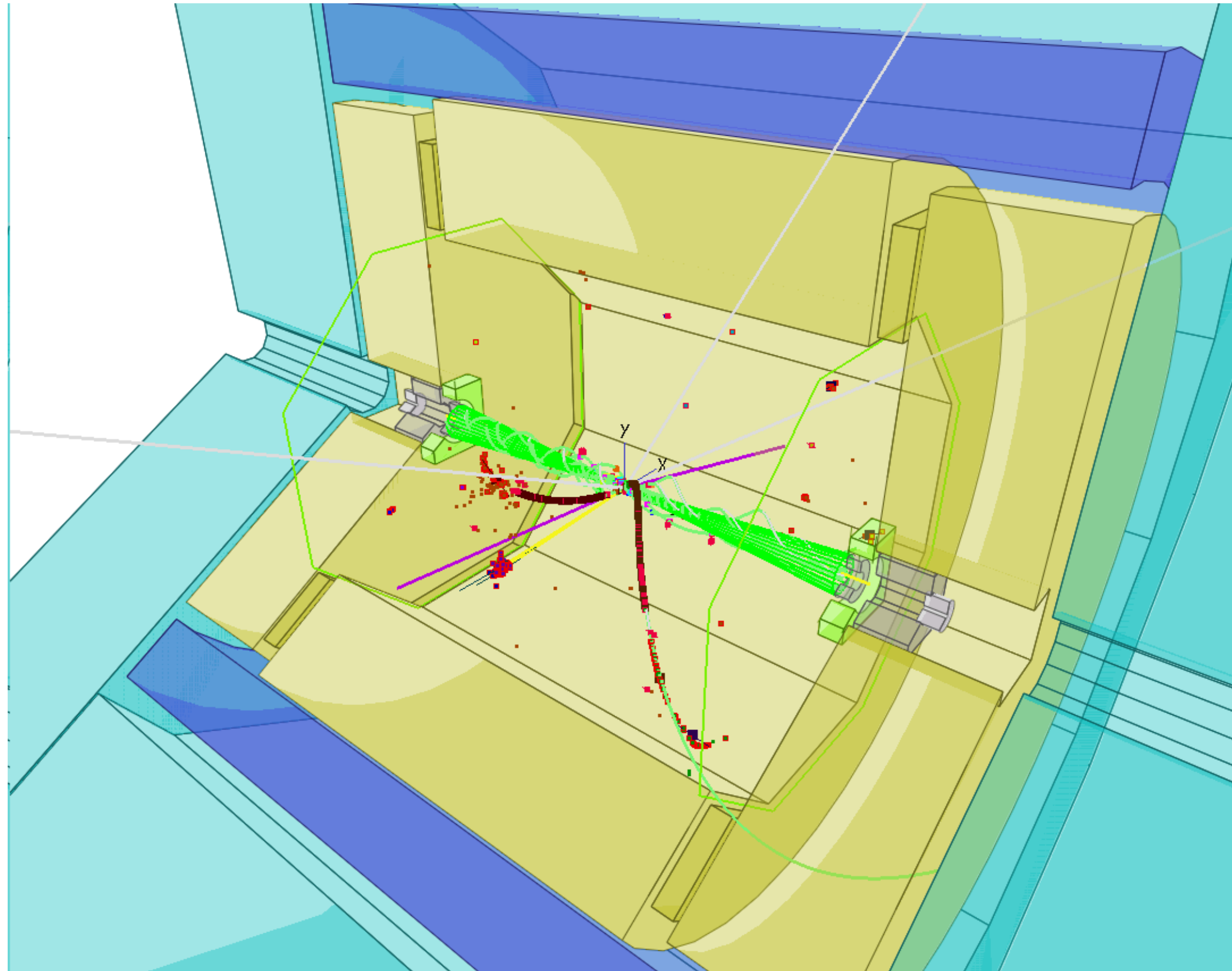
A closer look at the difficult case

- current general lower mass limit on staus (any mass splitting $> m(\tau)$, any mixing, ...): **26.3 GeV** (DELPHI, Eur. Phys. J. C 31 (2003), 421-479)
- extremely difficult at HL-LHC - especially in realistic cases with $M_{\text{stauR}} < M_{\text{stauL}}$



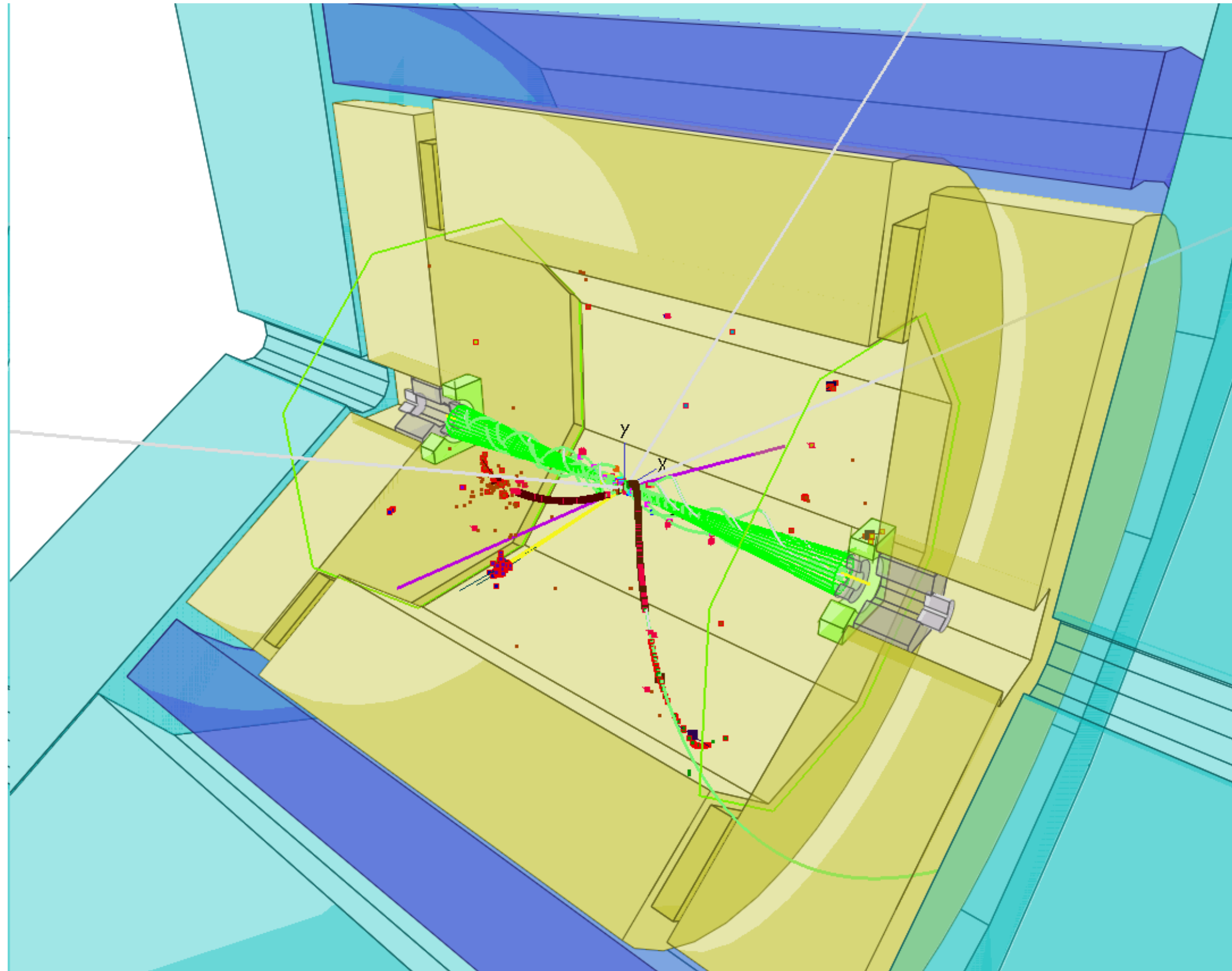
Scalar Tau Prospects at ILC

picking the worst-case choice for non-shown parameters

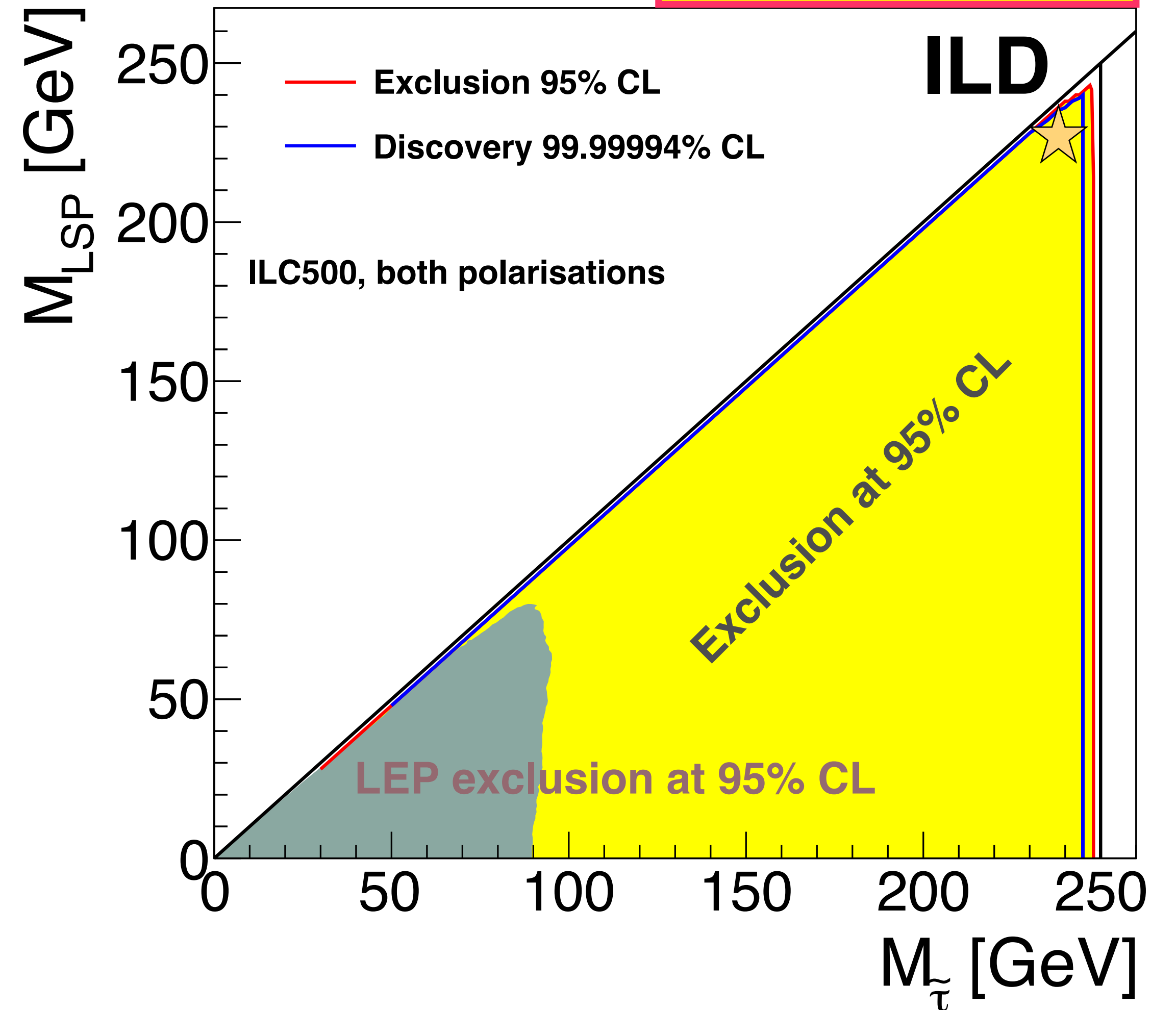


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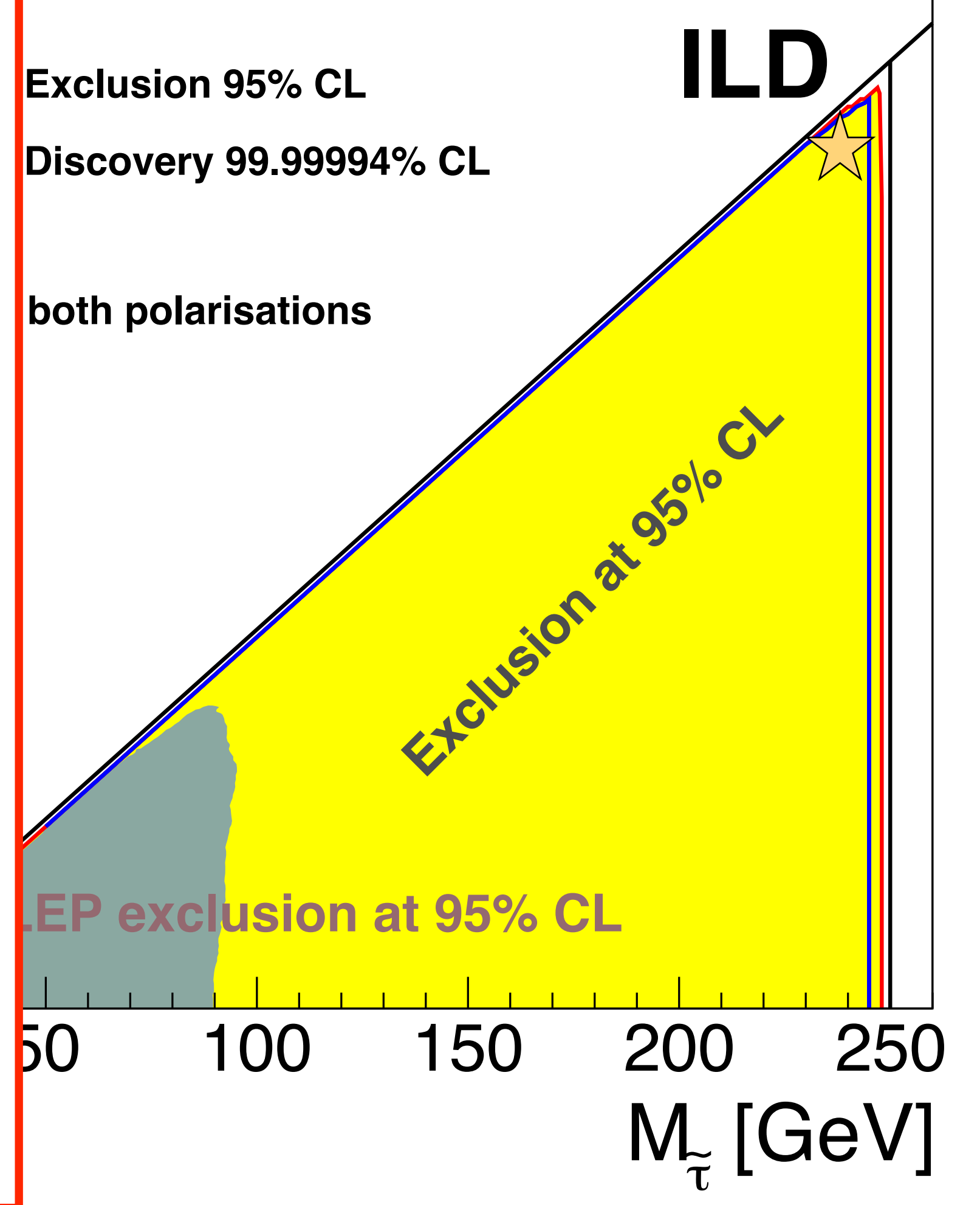
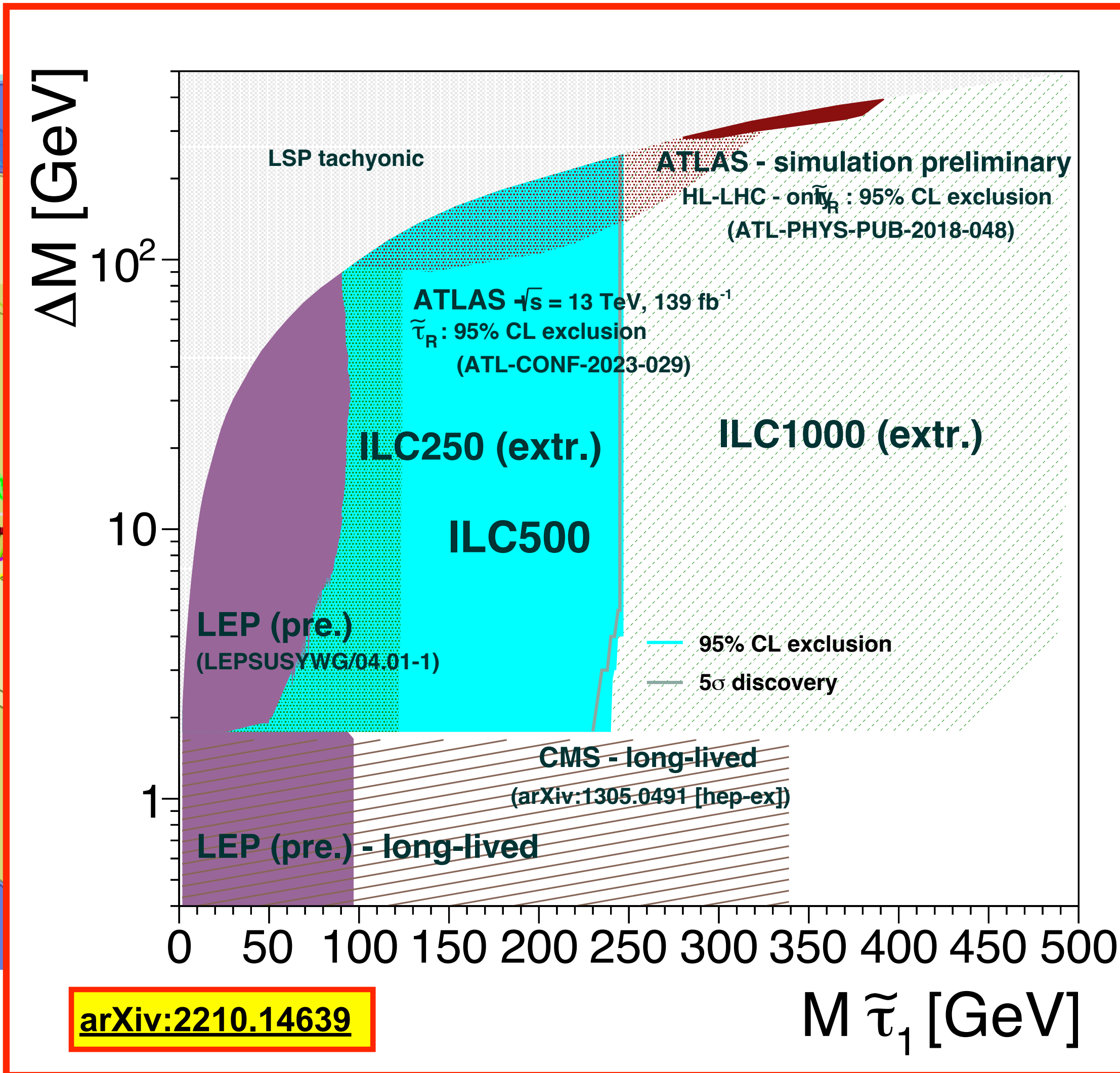
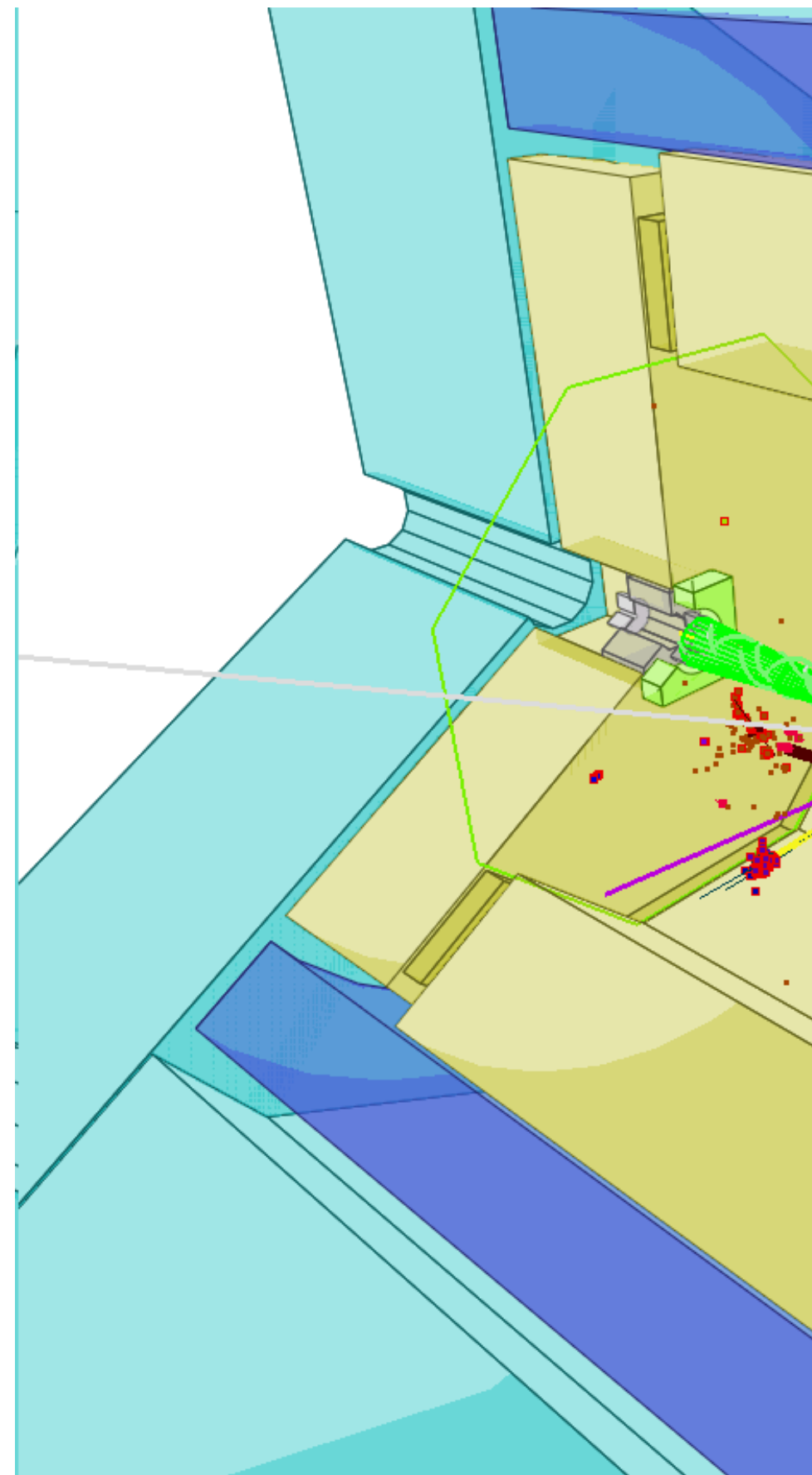
Note: difference between discovery and exclusion reach very small!



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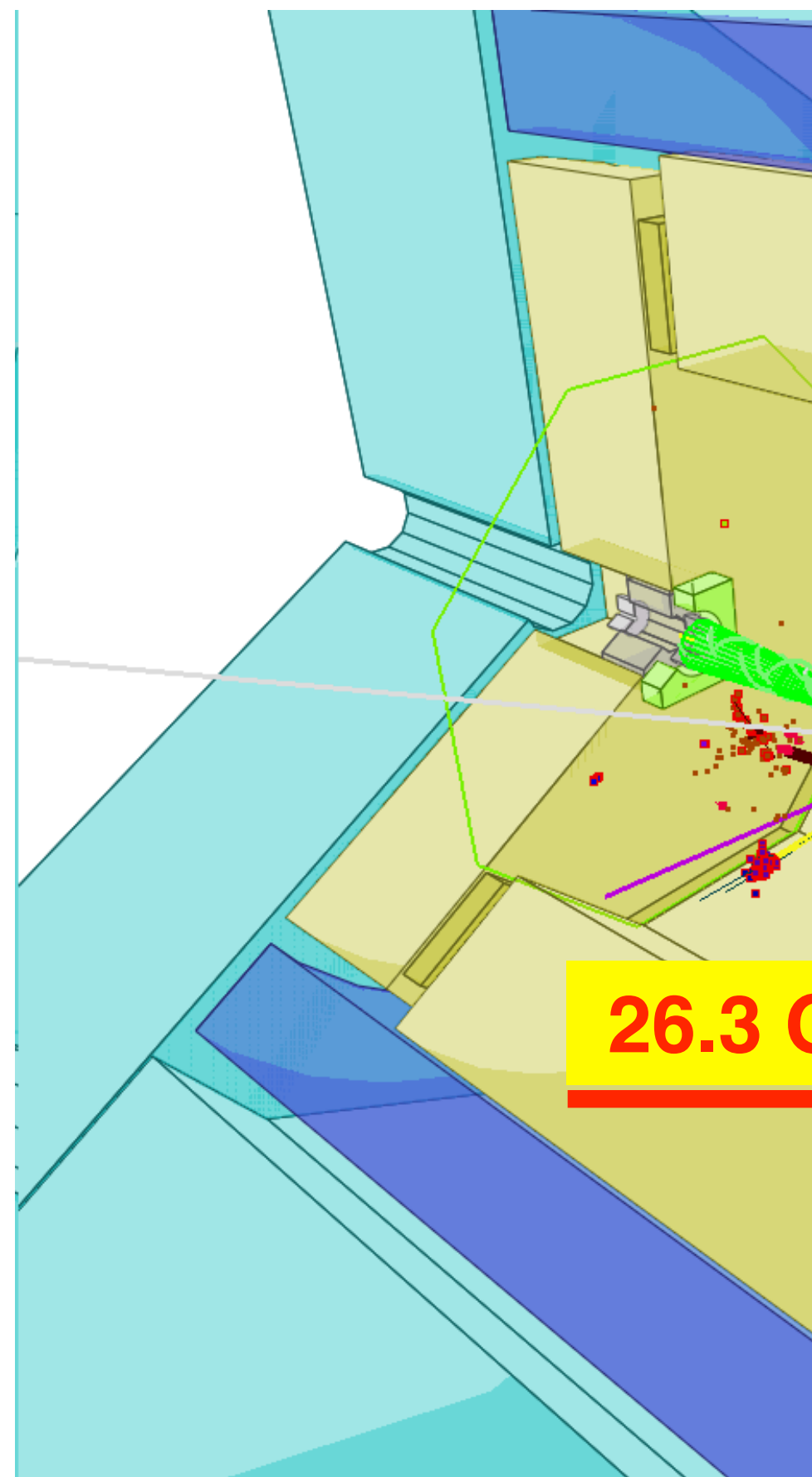
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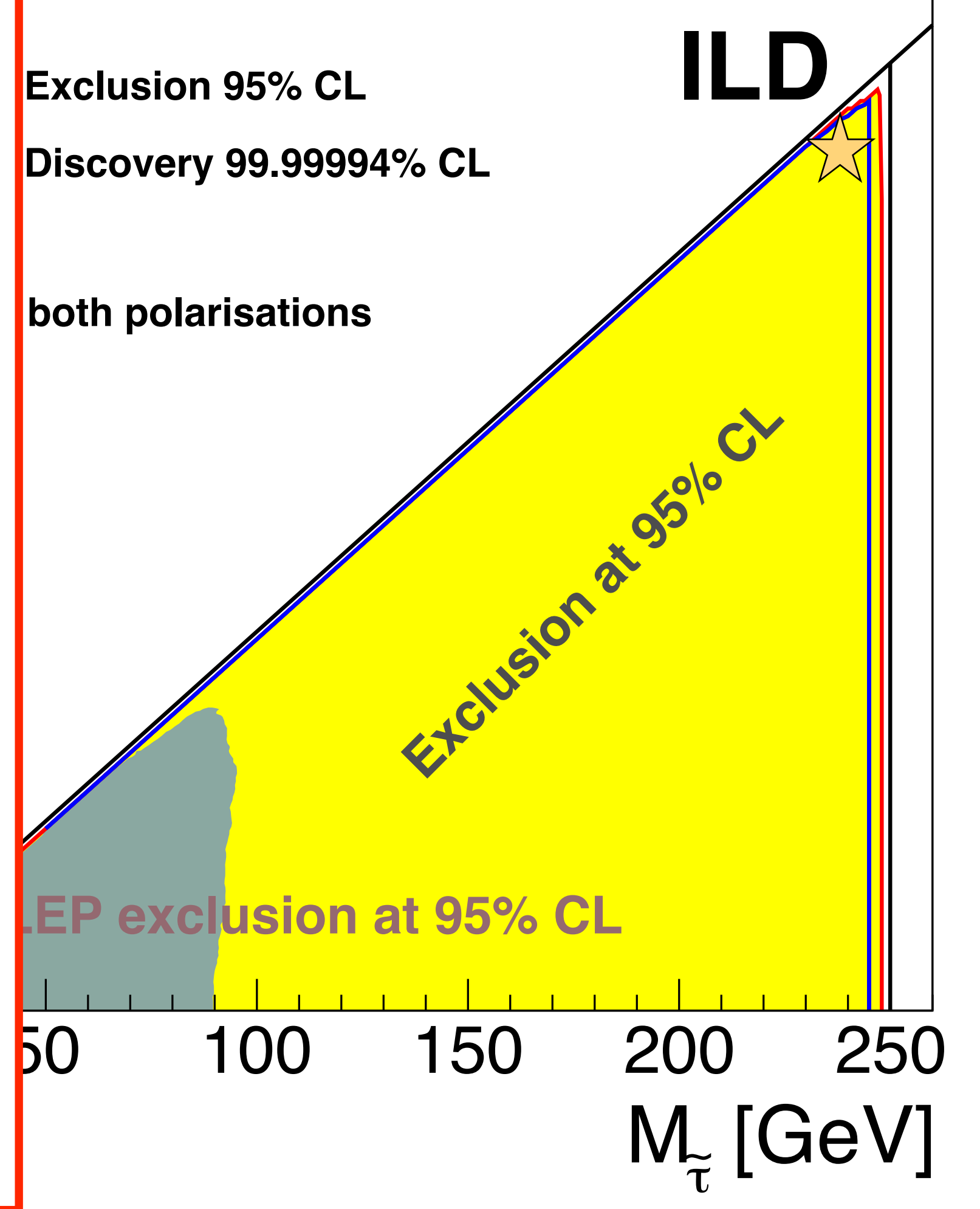
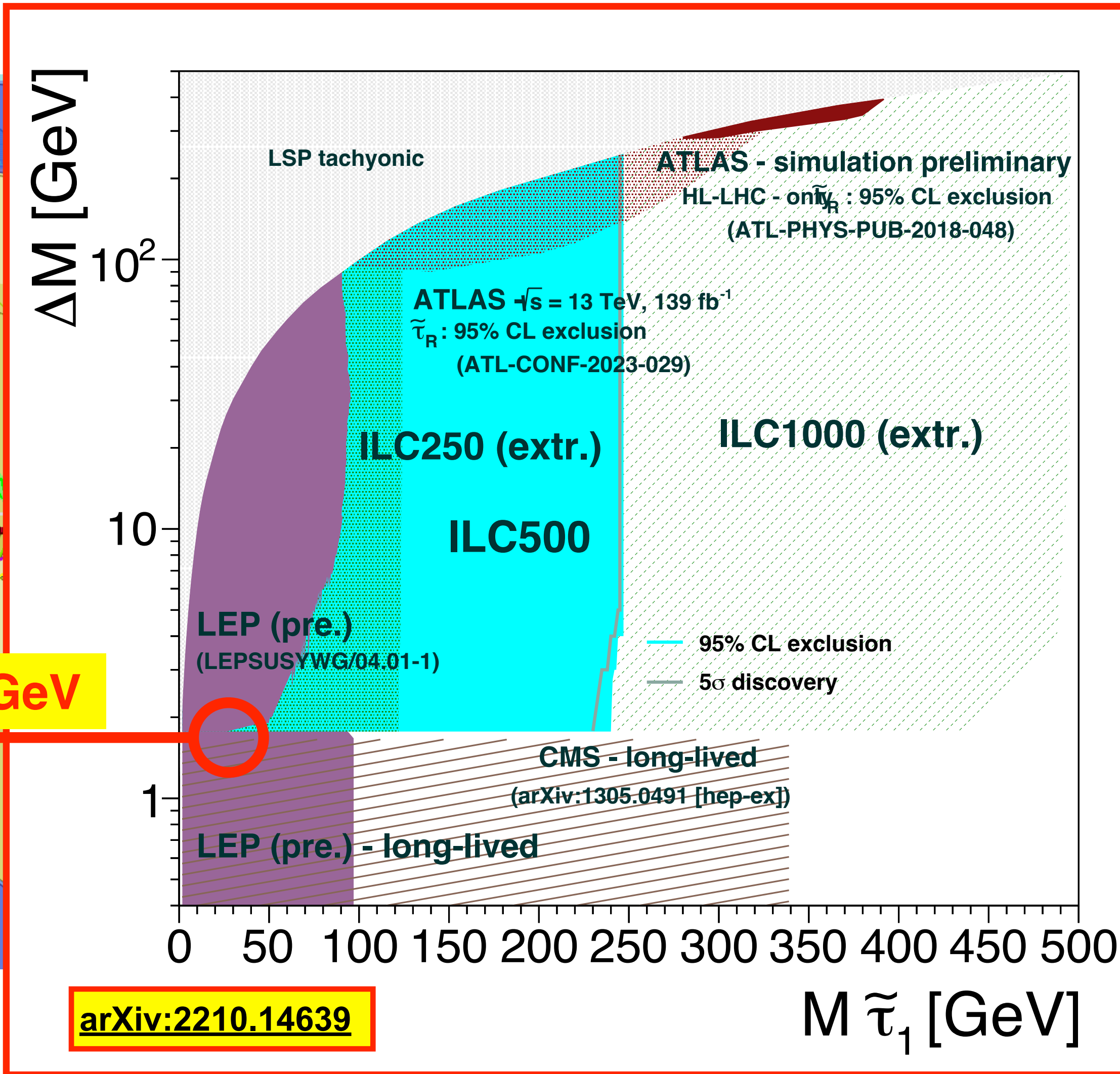
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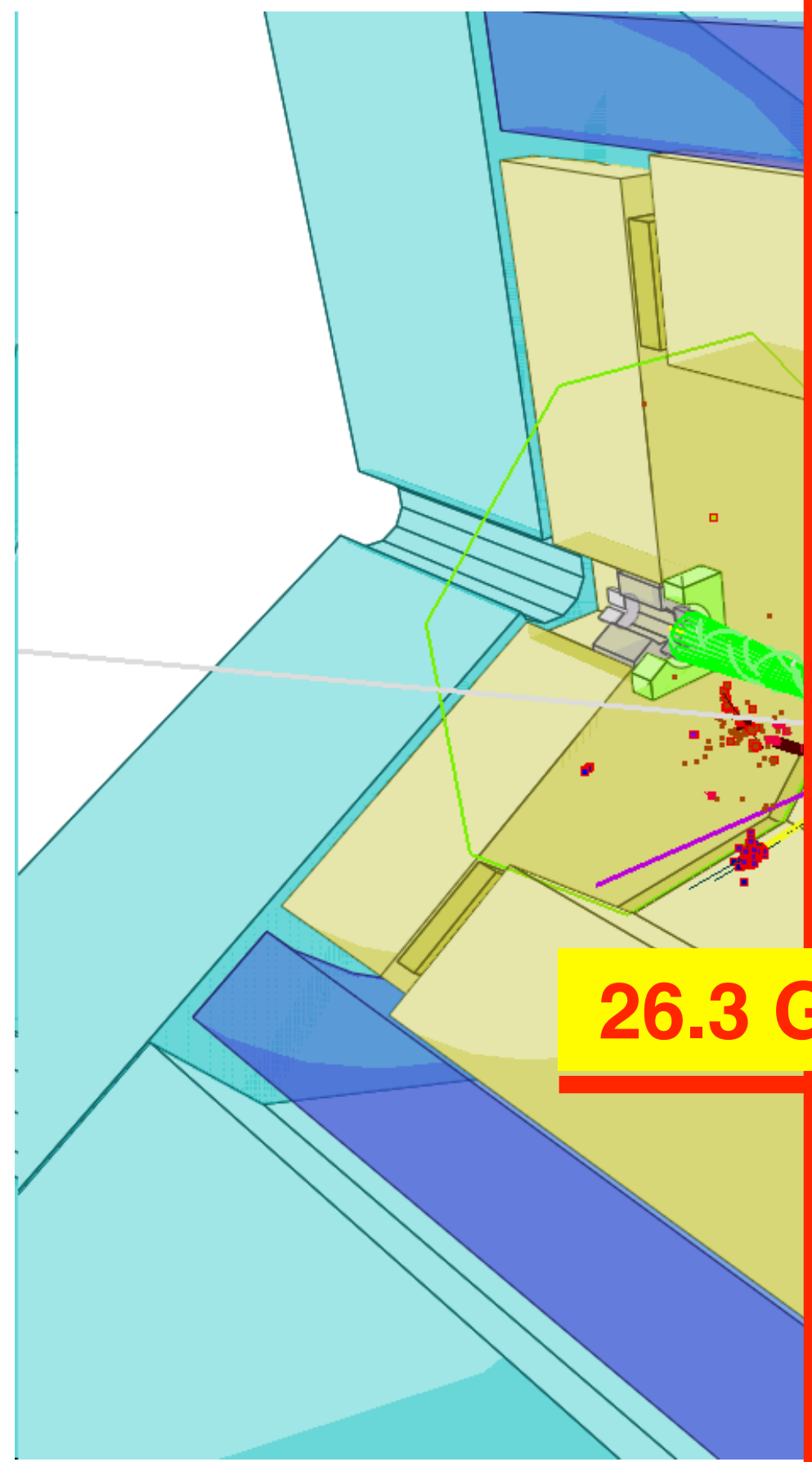
26.3 GeV



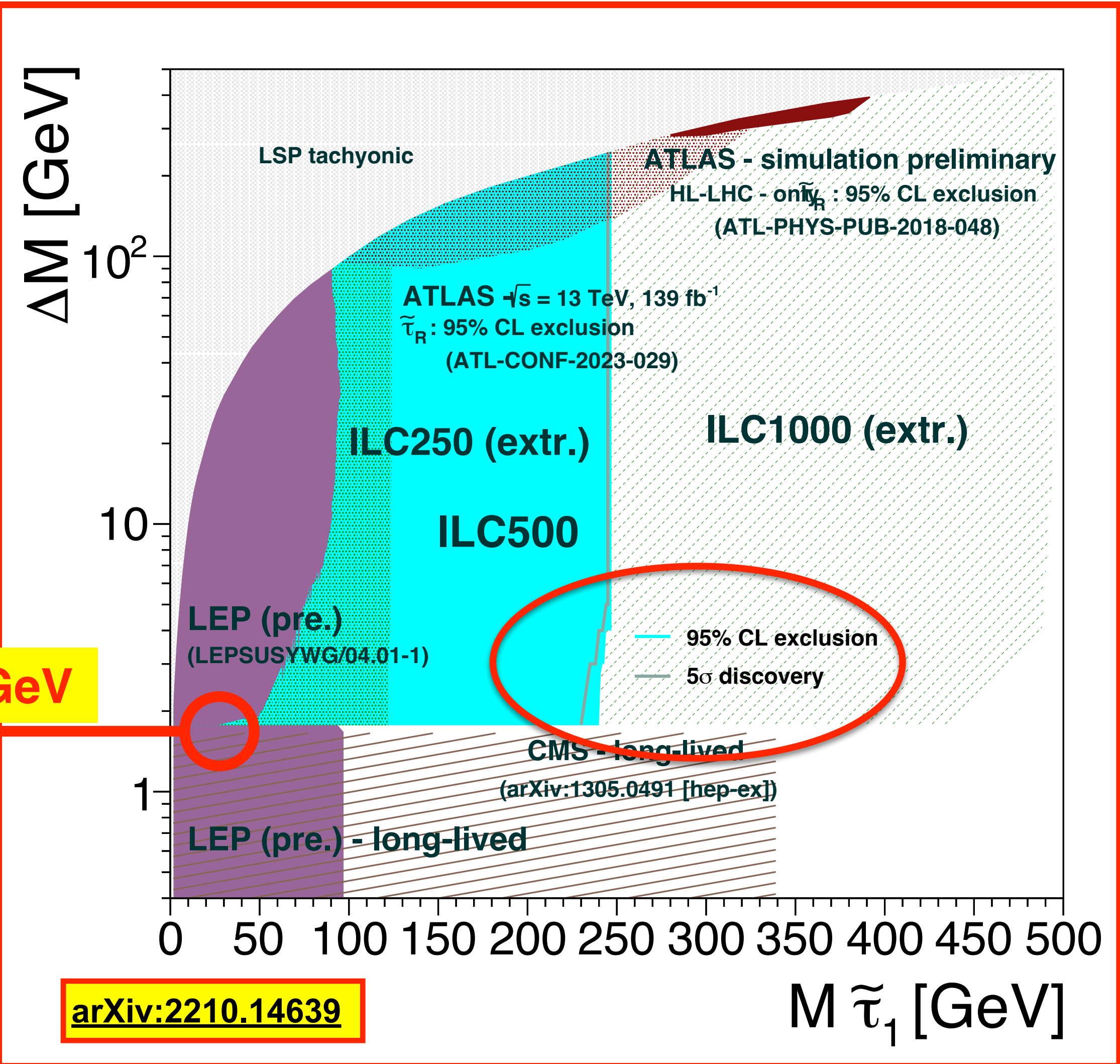
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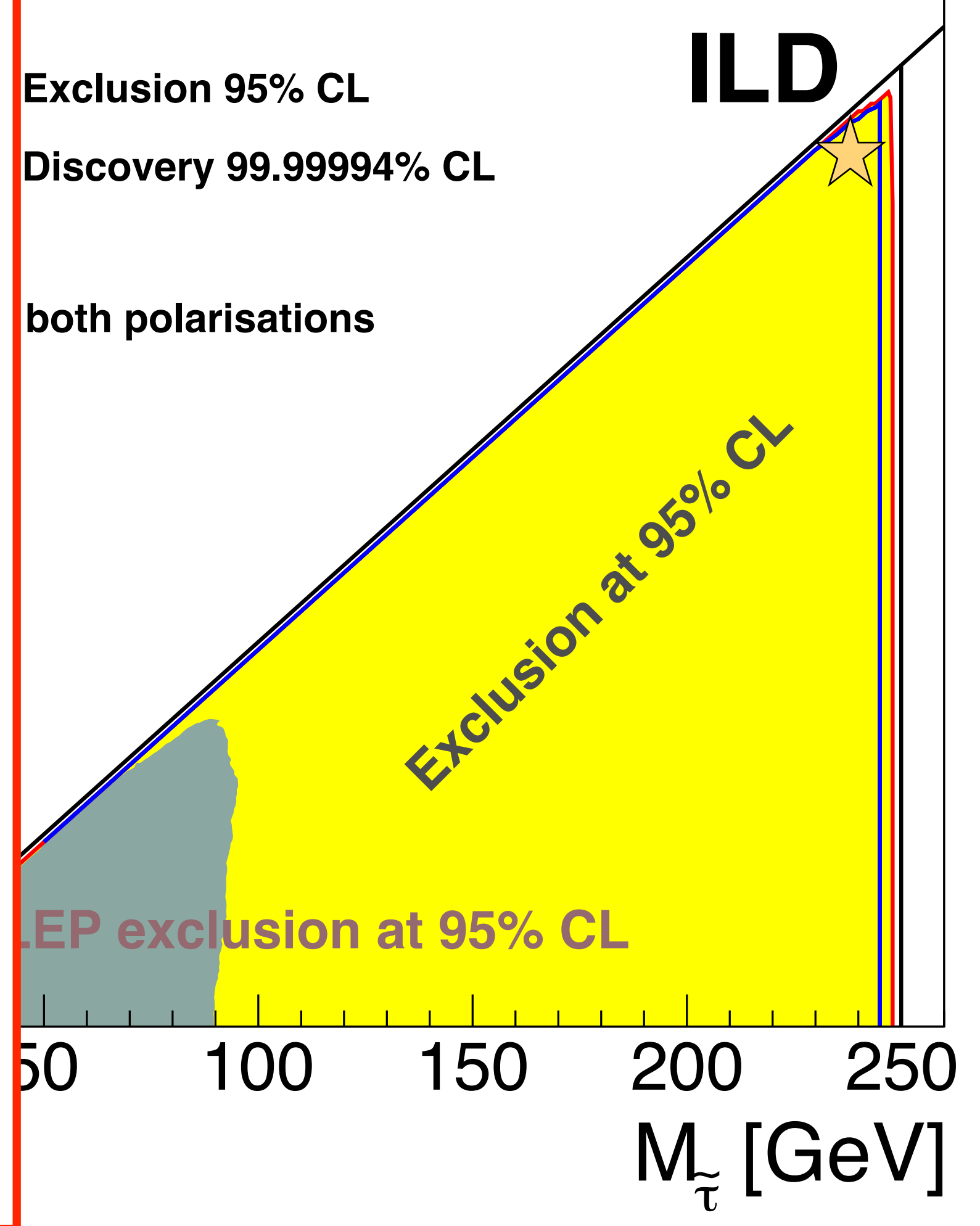
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26.3 GeV



arXiv:2210.14639



Example 2: Electroweakinos

Definition of “worst case” for e^+e^- collider => defines the benchmark for “LEP-style” definition of sensitivity

- MSSM, R-parity conservation (R-parity violation *always easier* at e^+e^-)
 - Caveat: also CP-conservation. The experimental implication of CP violation needs study
- sfermions not NLSP (*idem*, except $\tilde{\tau}$ but even worse for FCChh...)
- Then: LSP is *Bino, Wino, or Higgsino* (more or less pure), same for the NLSP
- M_1, M_2 and μ are the main-players.
- Consider *any values*, and combinations of signs, *up to values that makes the bosinos out-of-reach* for any new facility \sim a few TeV.
- Also vary other parameters ($\beta, M_A, M_{sfermion}$) with less impact.
- *No other prejudice.*

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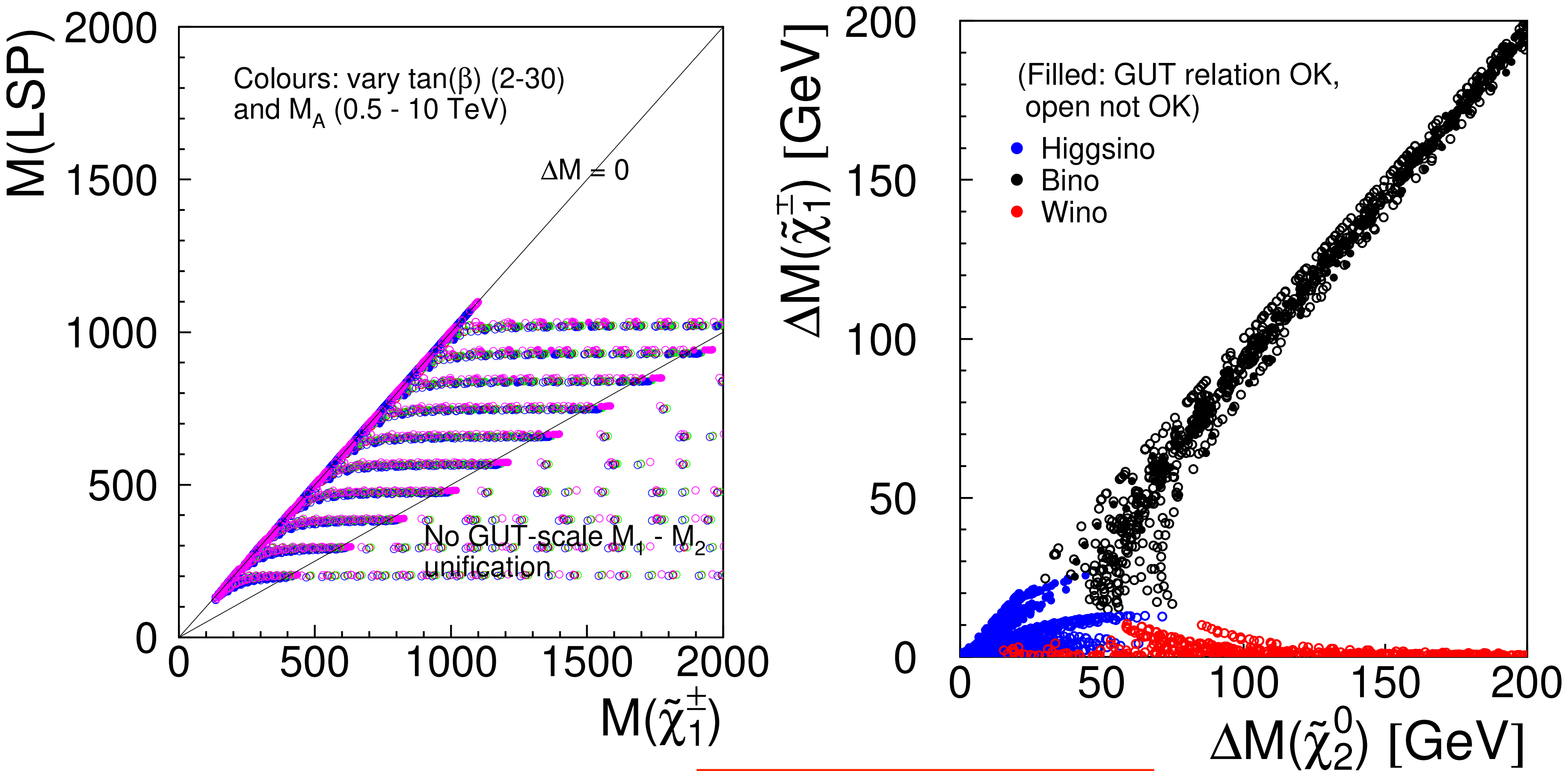
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- with this definition even more generic than LEP:
- no GUT-scale gaugino mass unification enforced!

Electroweakino parameter space with this definition

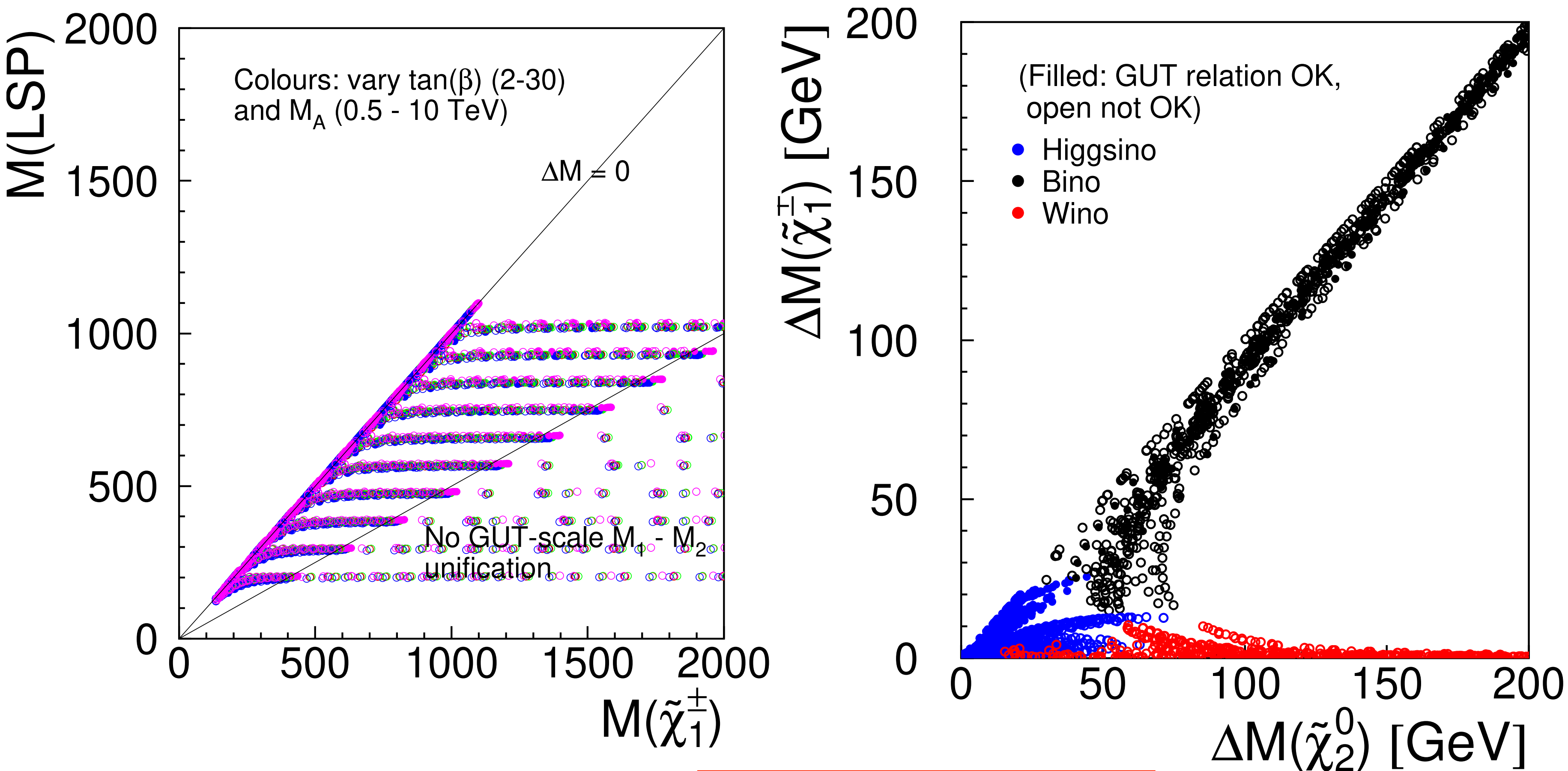
Definition of “worst case” for e+e- collider => defines the benchmark for “LEP-style” definition of sensitivity



arXiv:2003.12391

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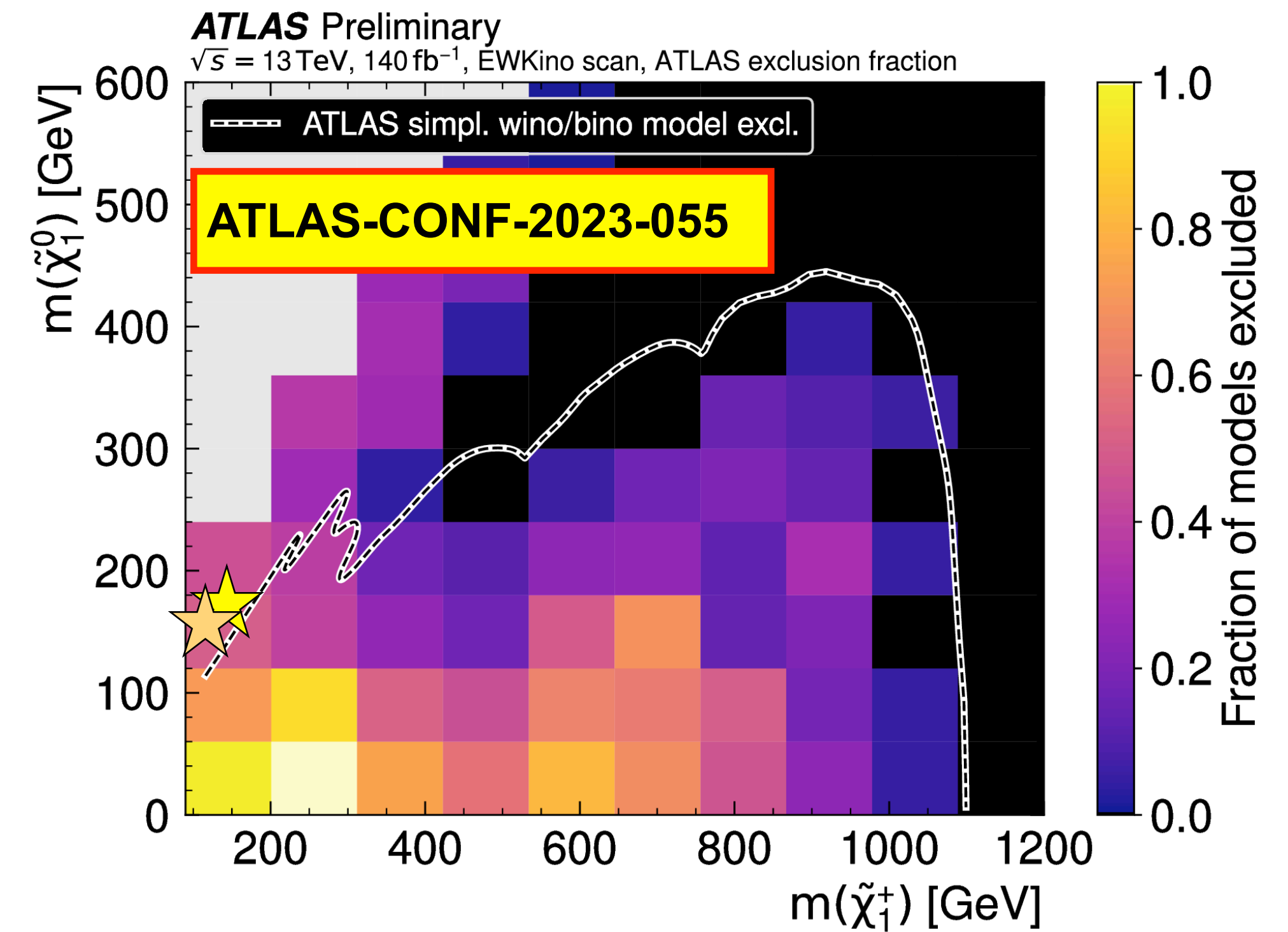


arXiv:2003.12391

- assumption of $M(\text{cha1})=M(\text{neu2})$ often not fulfilled
- even for Higgsinos-like cases
- beware of simplified models with this assumption

Light Higgsinos

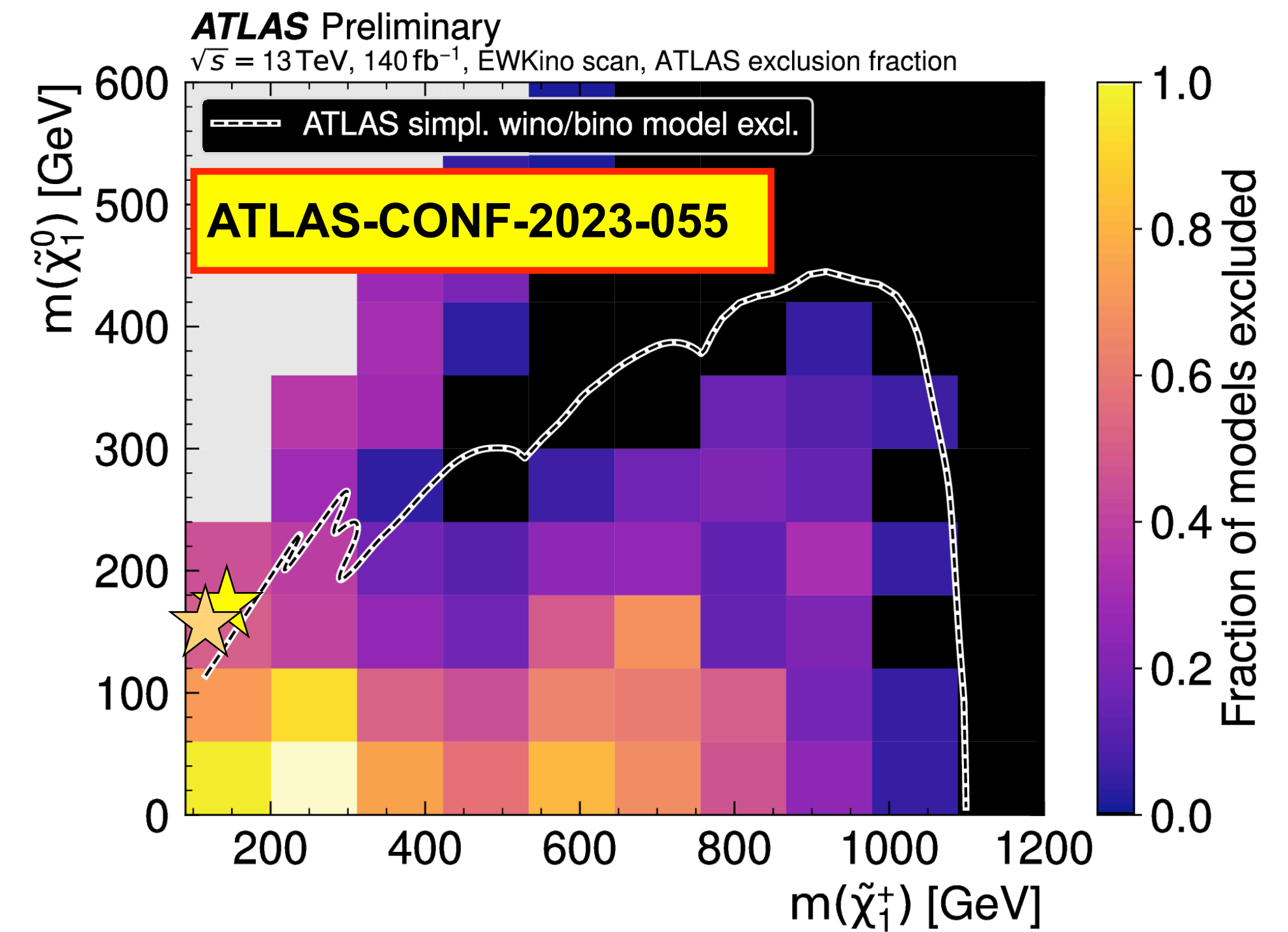
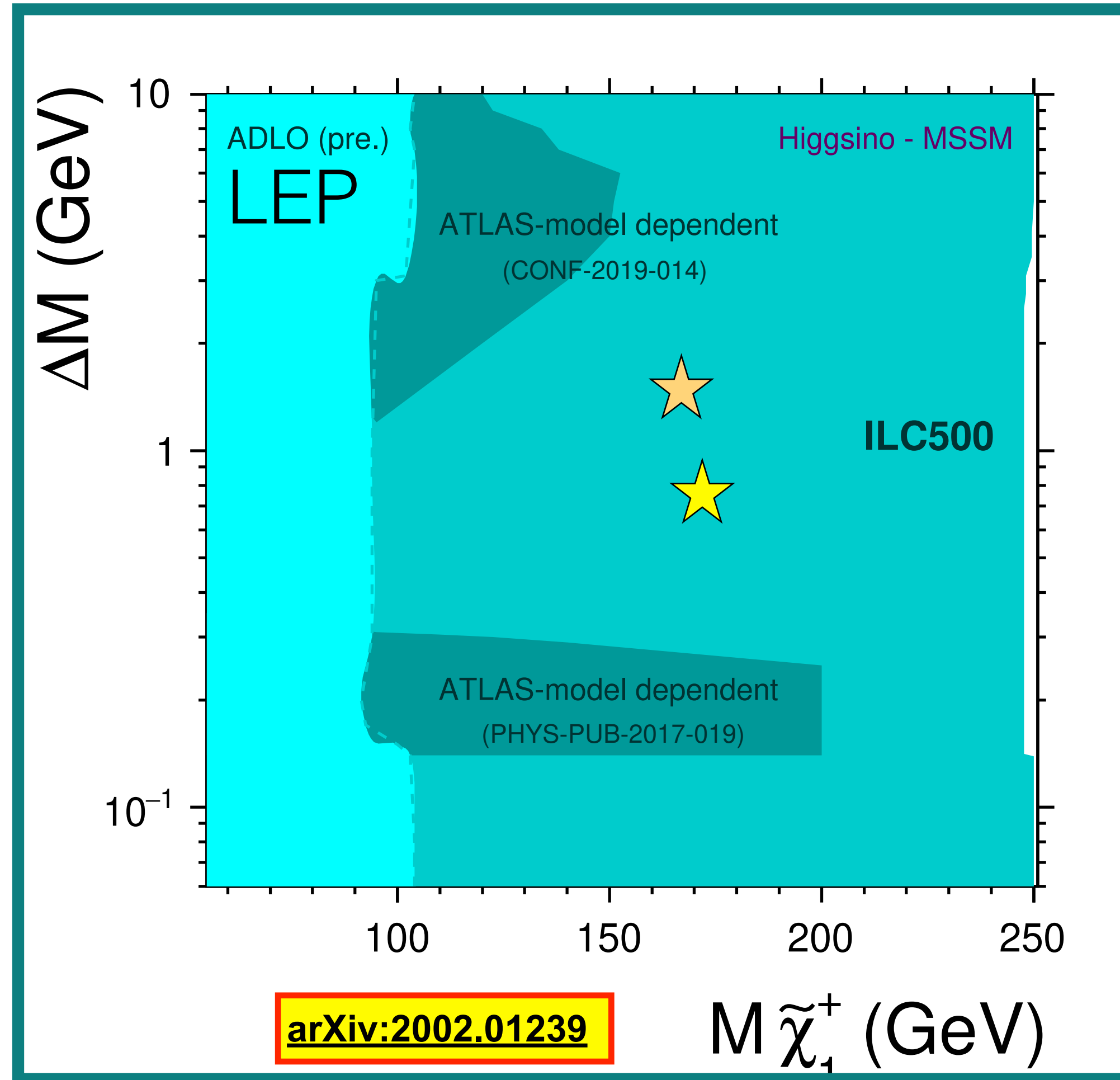
Detailed simulation studies with ILD detector for ILC



- ILD study of full detector simulation for various benchmark points
 - E.g. ★ ★ motivated by leptogenesis & gravitino DM - and extrapolation to full plane
 - Fast-simulation and LEP-data informed extrapolation to whole parameter plane
- => “loop-hole free” discovery / exclusion potential up to \sim half E_{CM}

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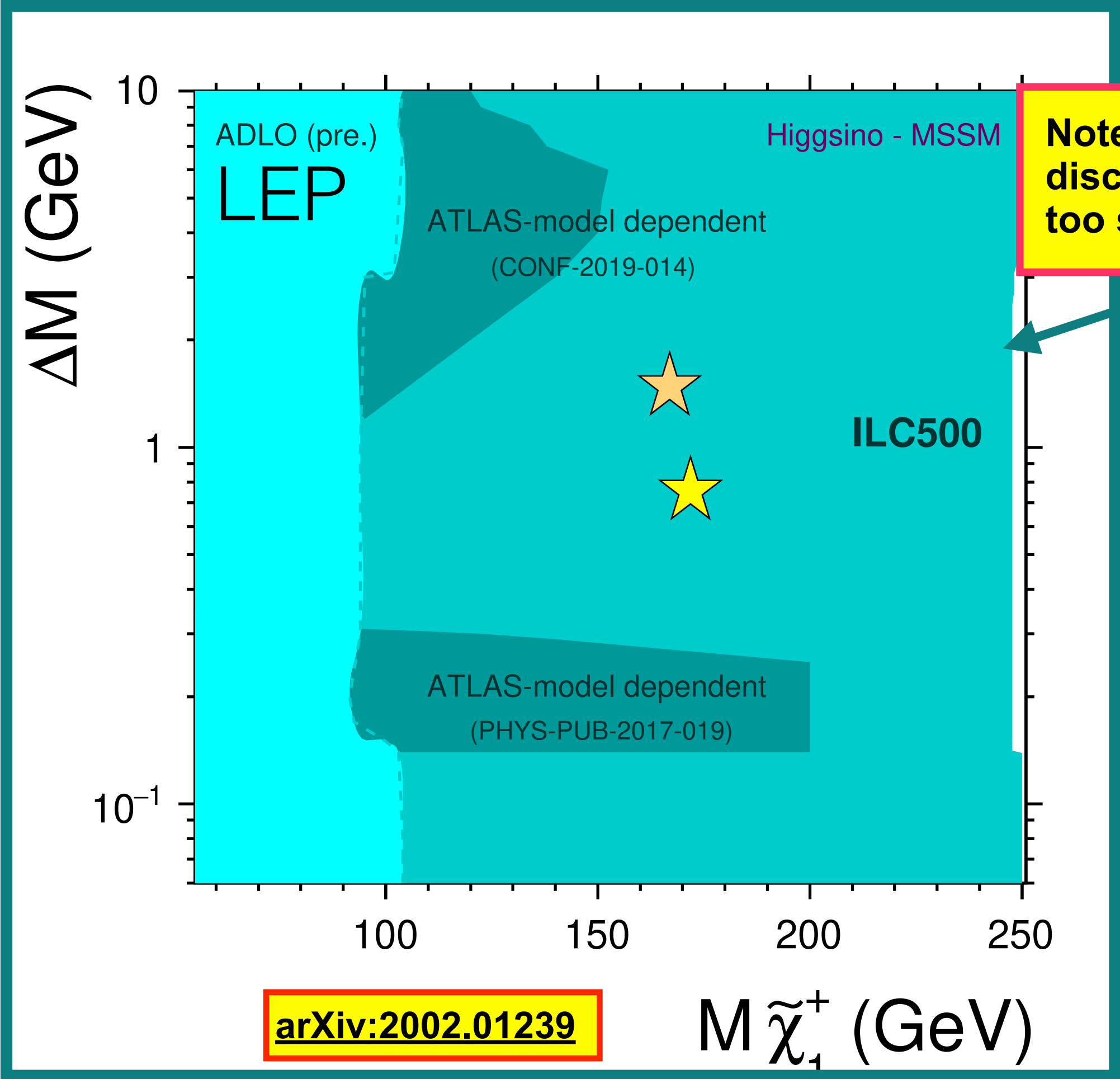
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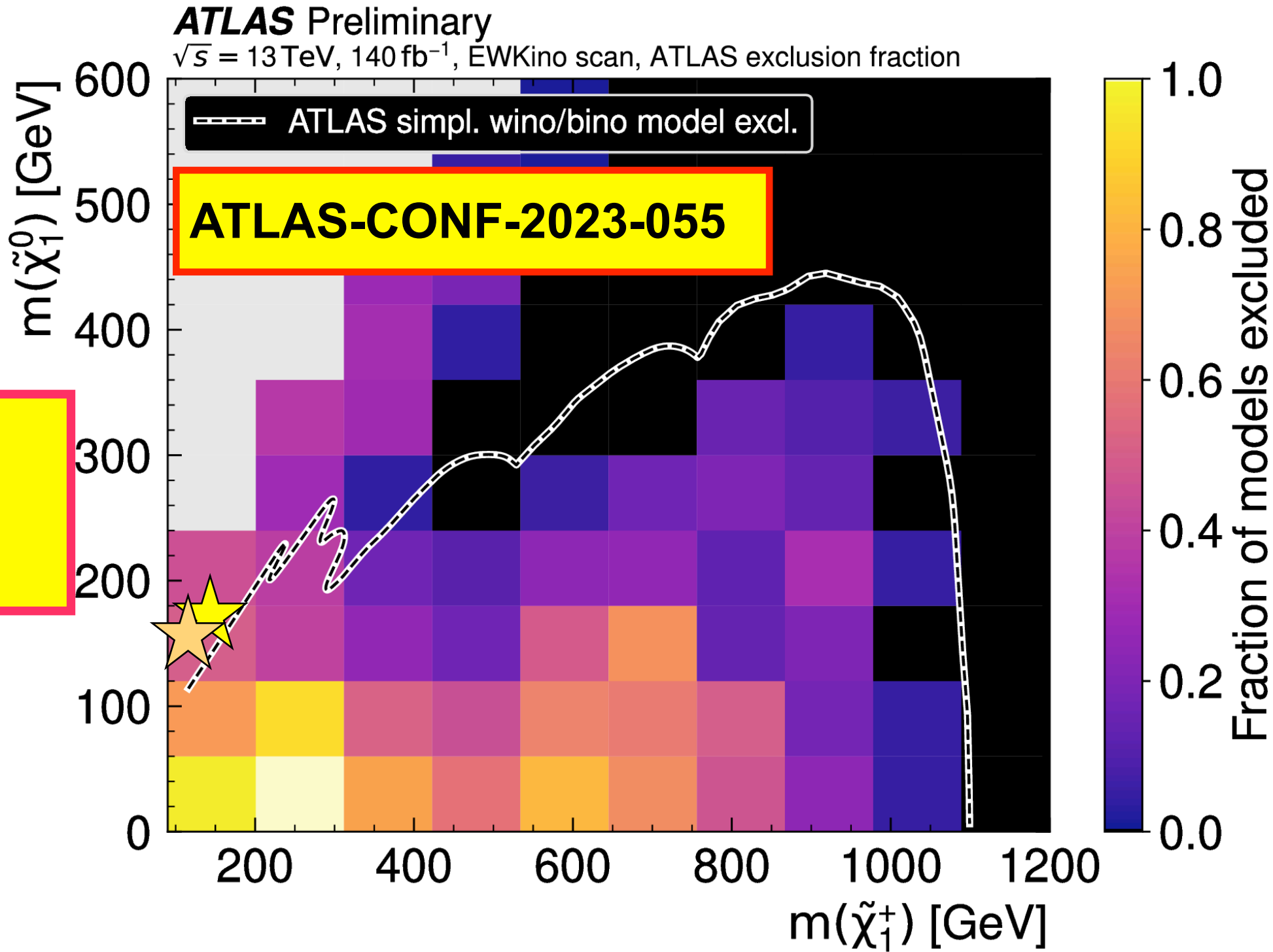
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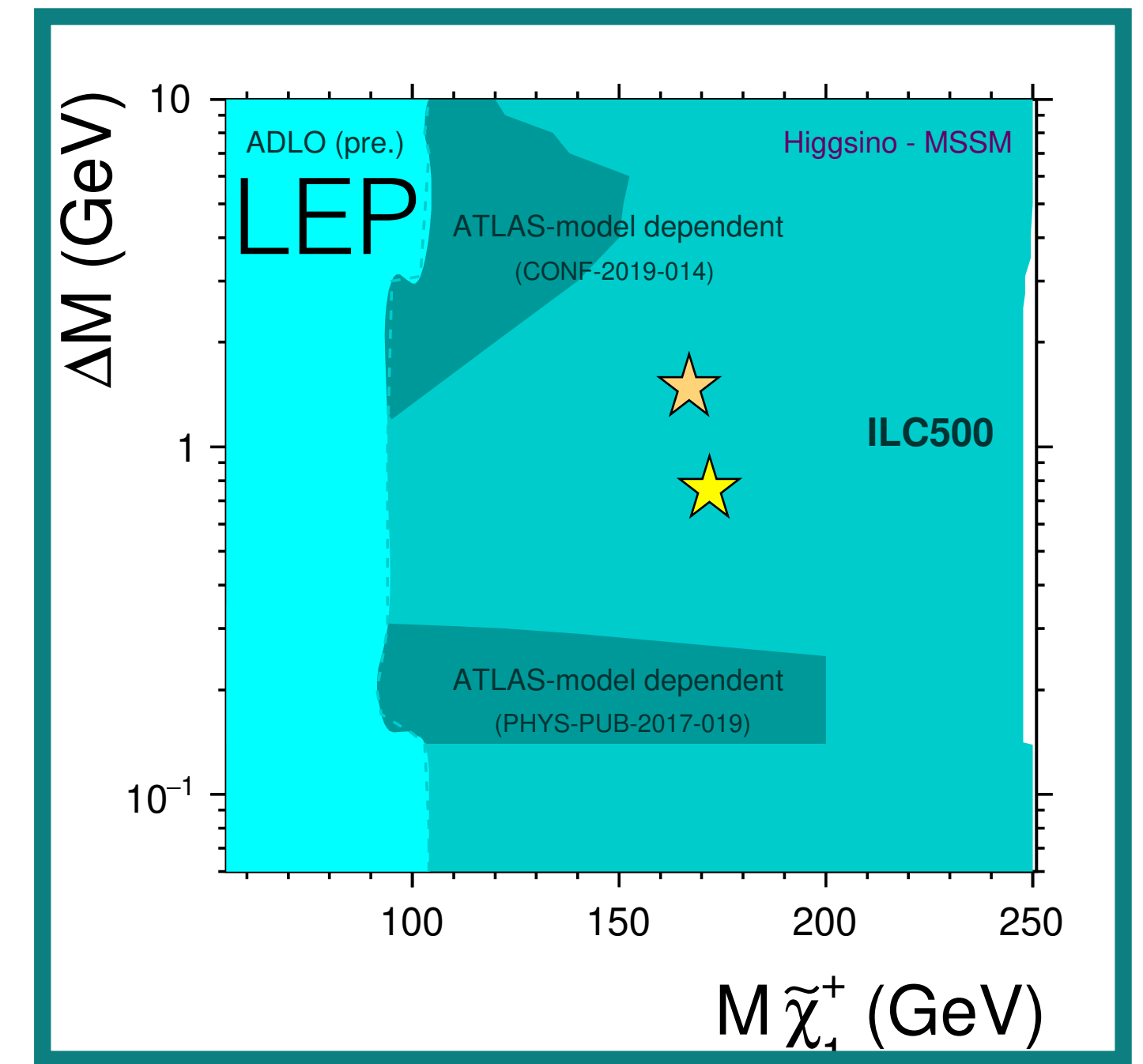
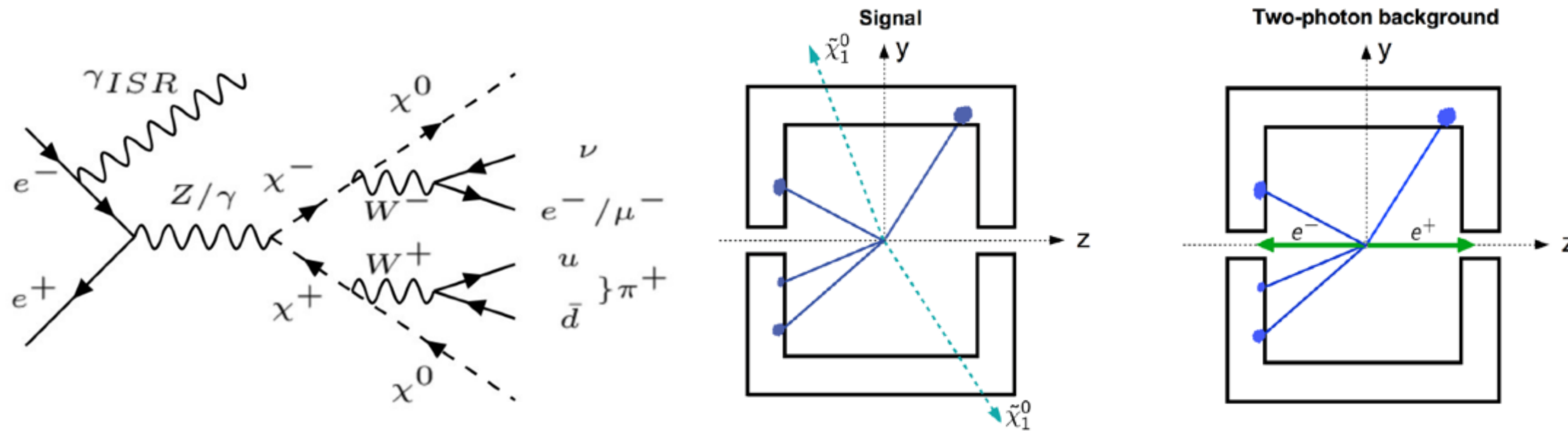
Note: difference between discovery and exclusion reach too small to be visible here!



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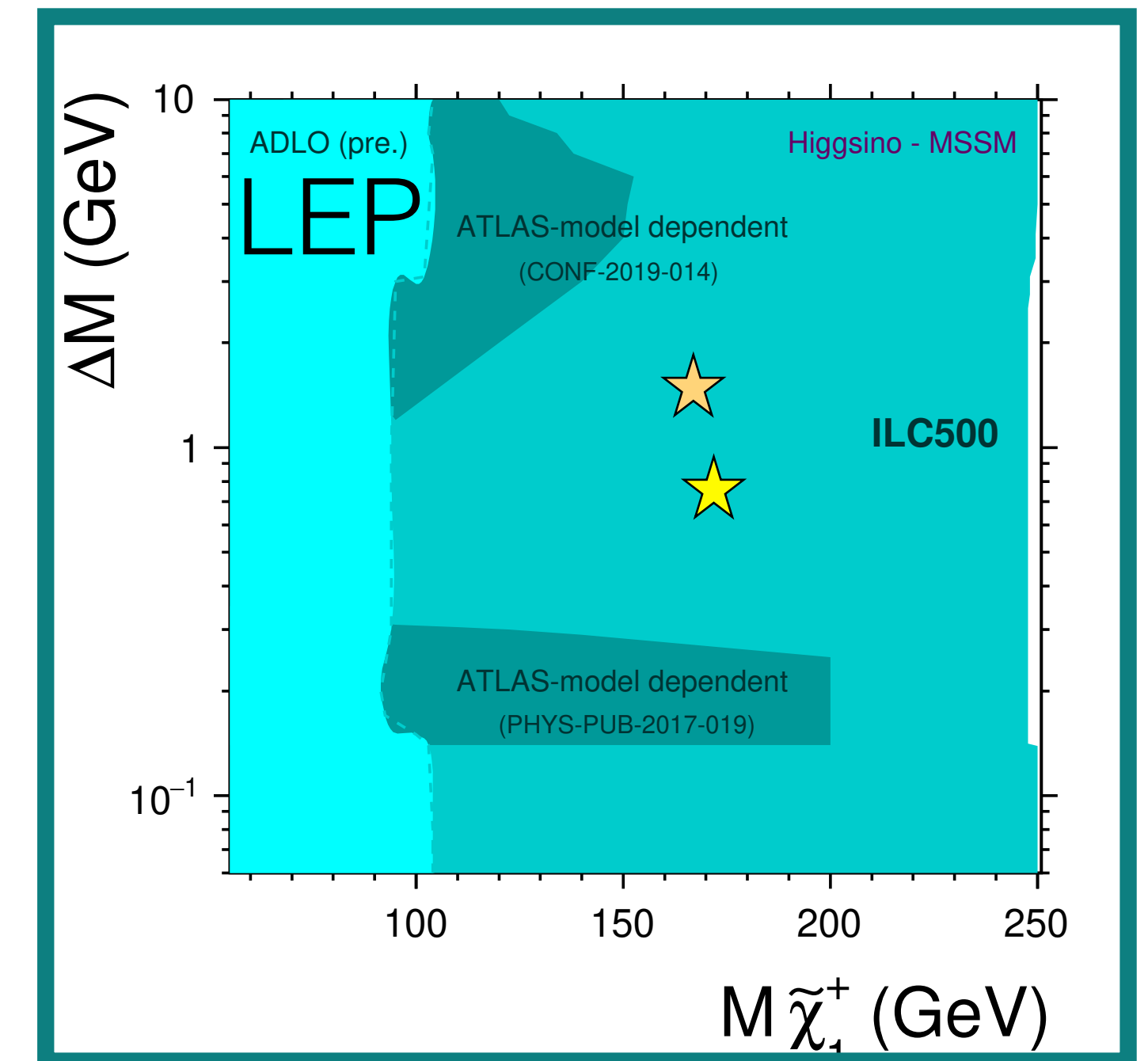
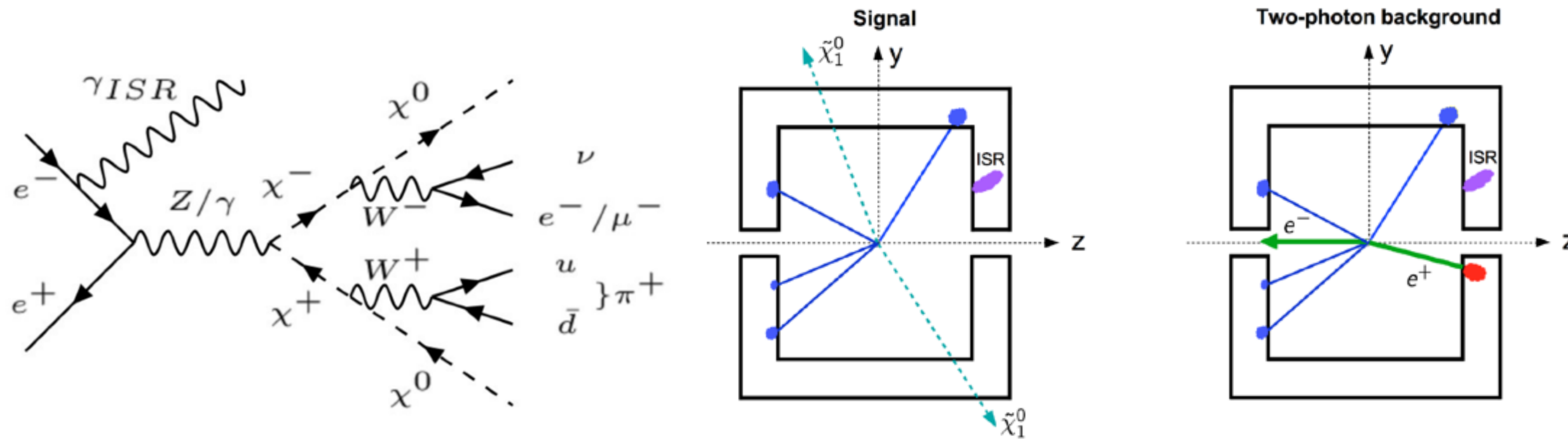
From mass and cross-section measurements to SUSY parameters



- $\Delta M \sim 1$ GeV: charginos decay to single, very soft $\pi^\pm / \mu / e$
- $p_t < 2 \dots 4$ GeV
- ISR photon required to distinguish from two-photon processes
- even in these most challenging cases:
 - few % precision on masses & cross-sections
 - SUSY parameter determination, cross-check with cosmology
- **prediction of gaugino masses**
 => **energy scale for next pp collider!**

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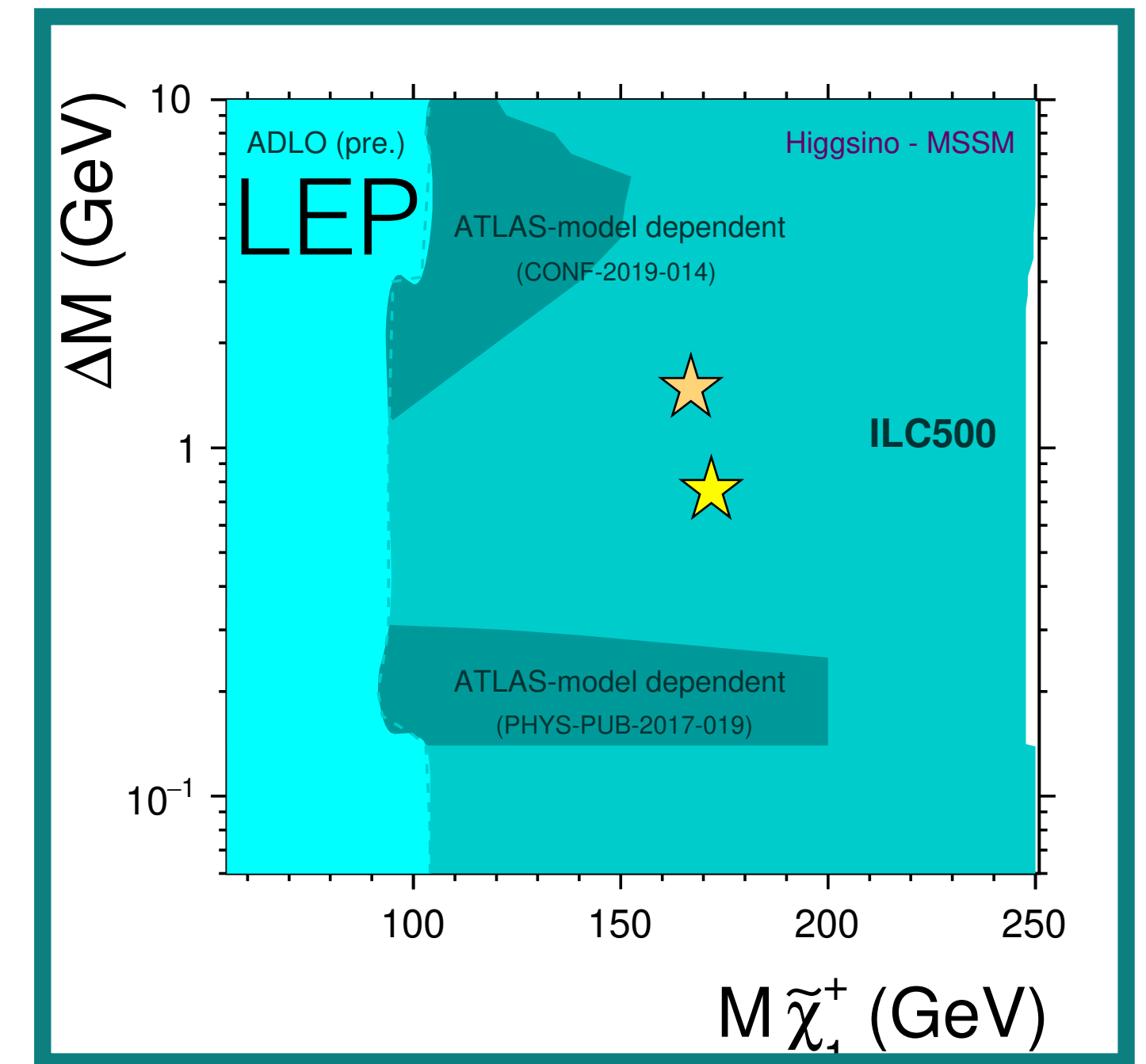
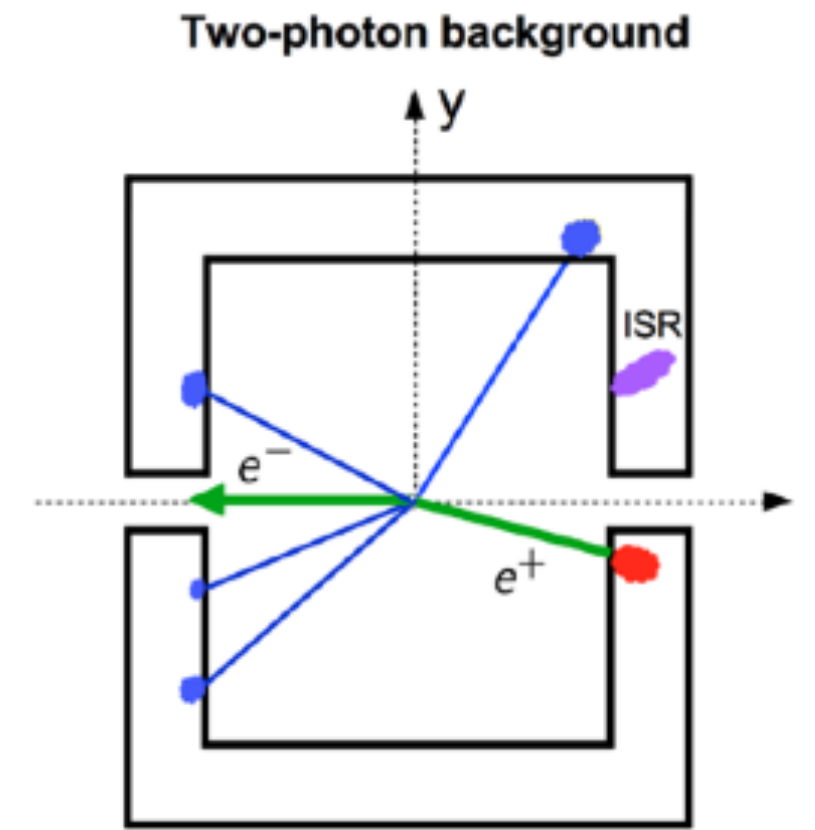
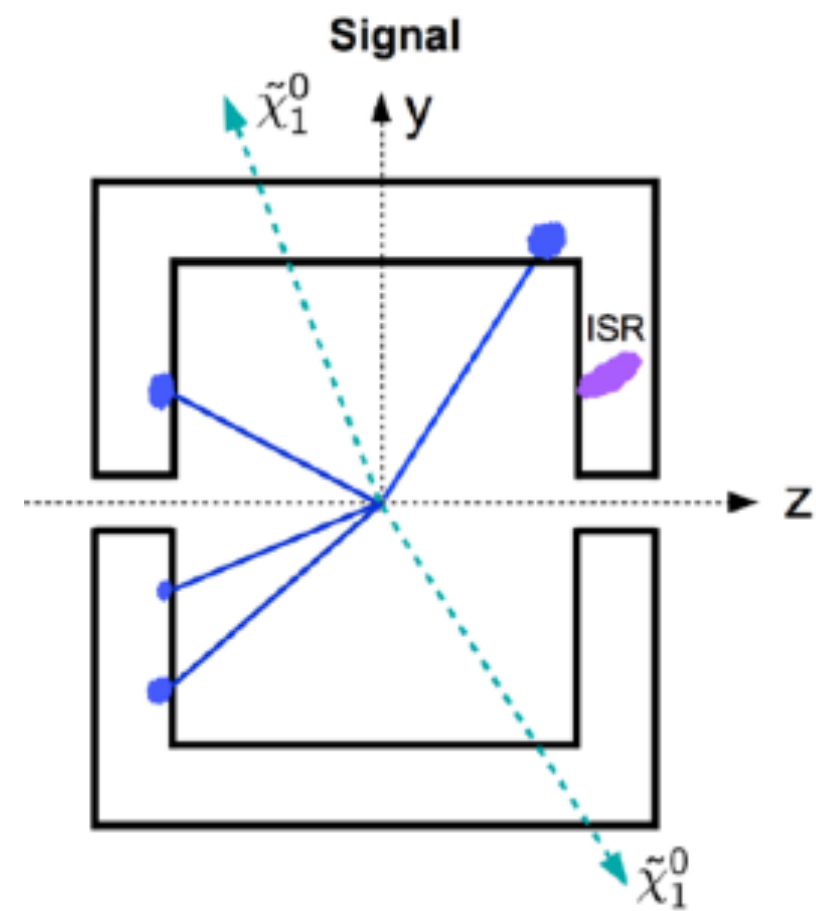
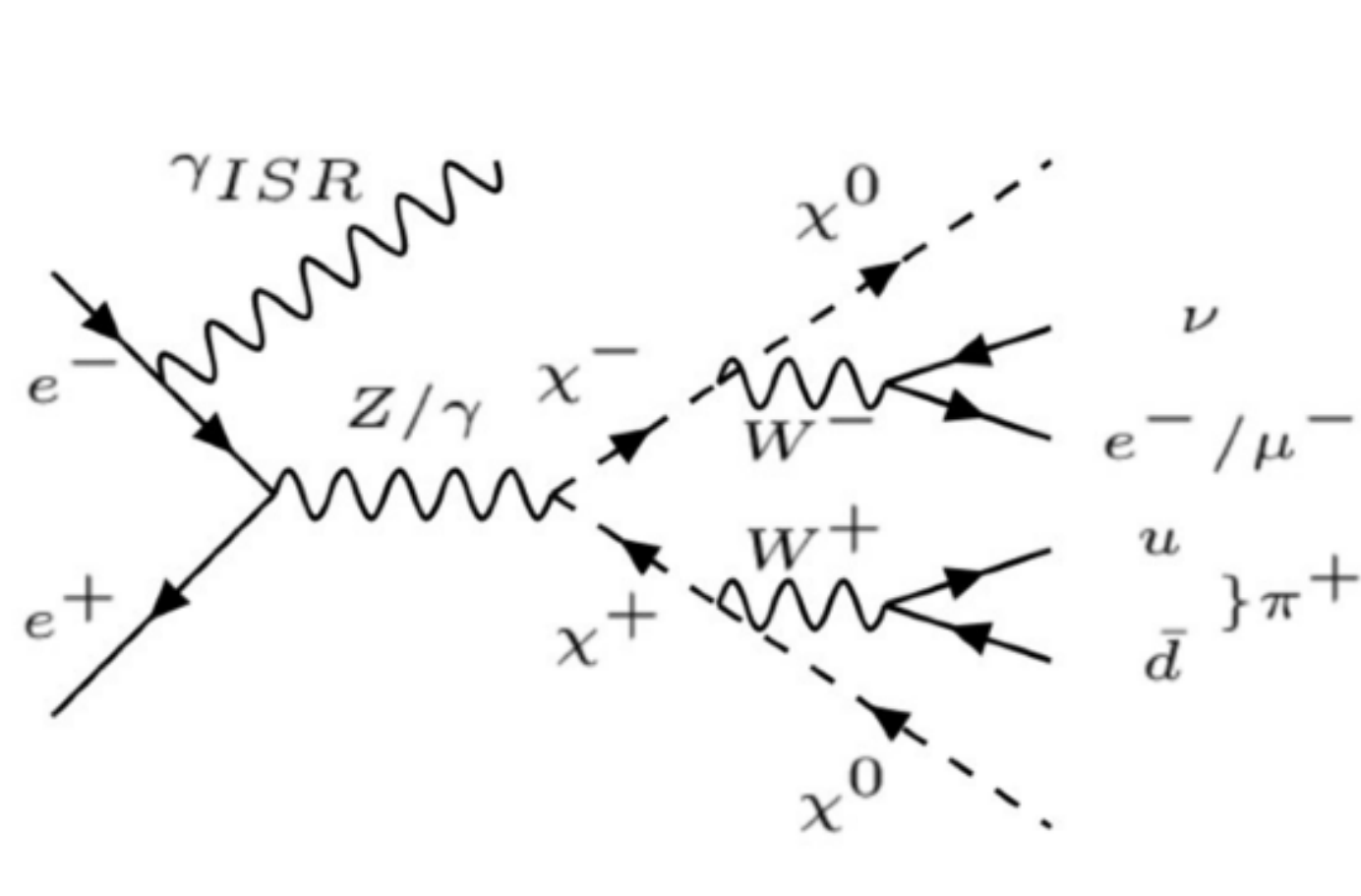


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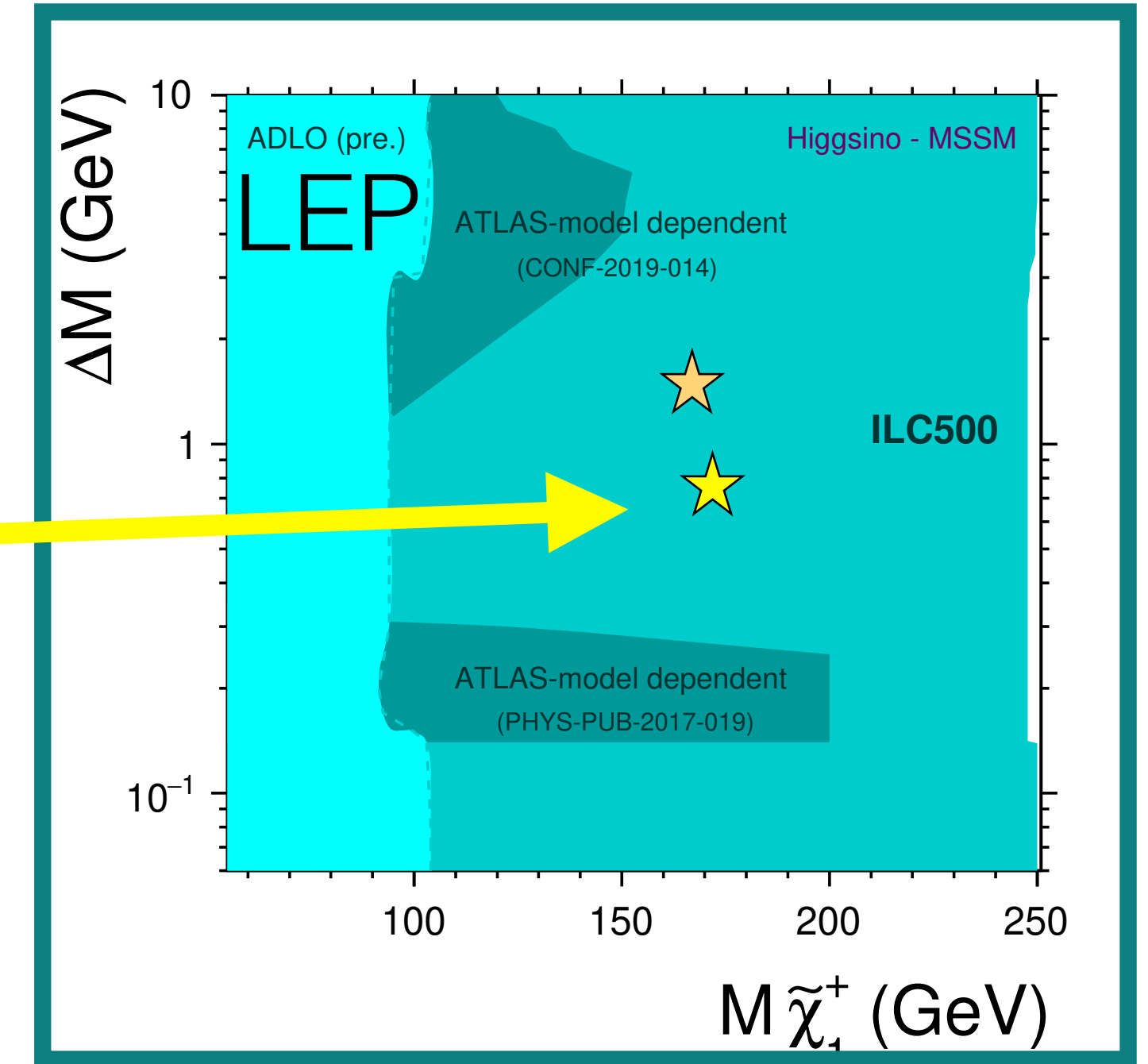
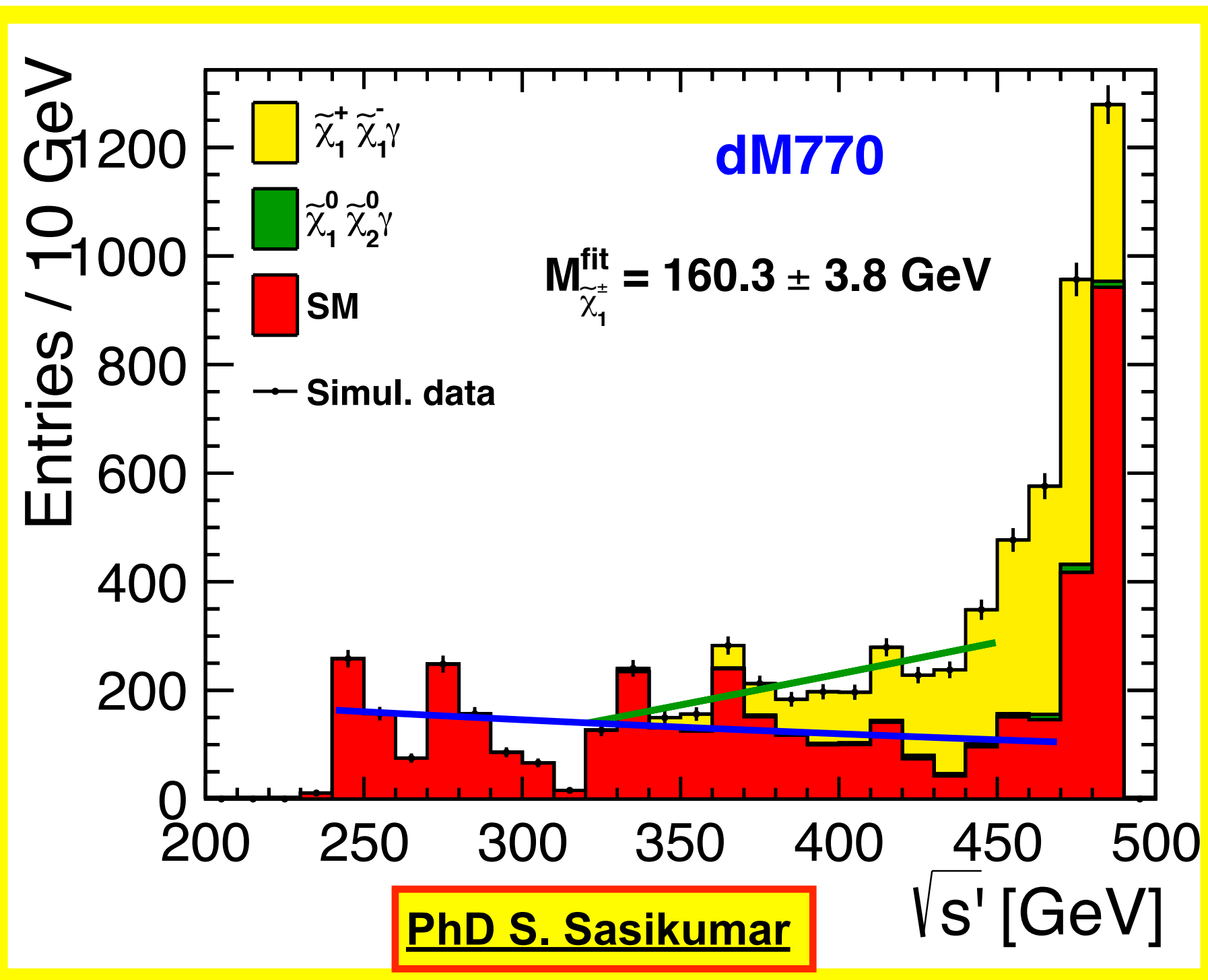
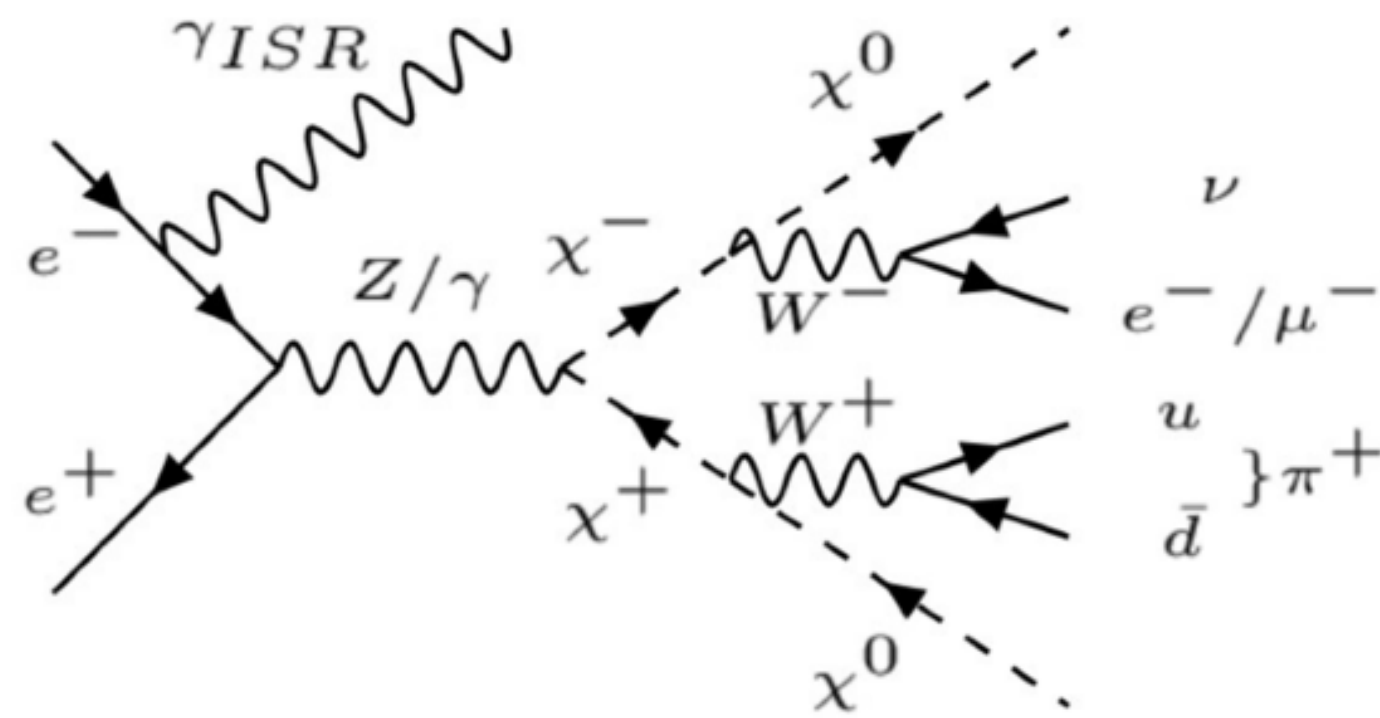
detector hermeticity is crucial!



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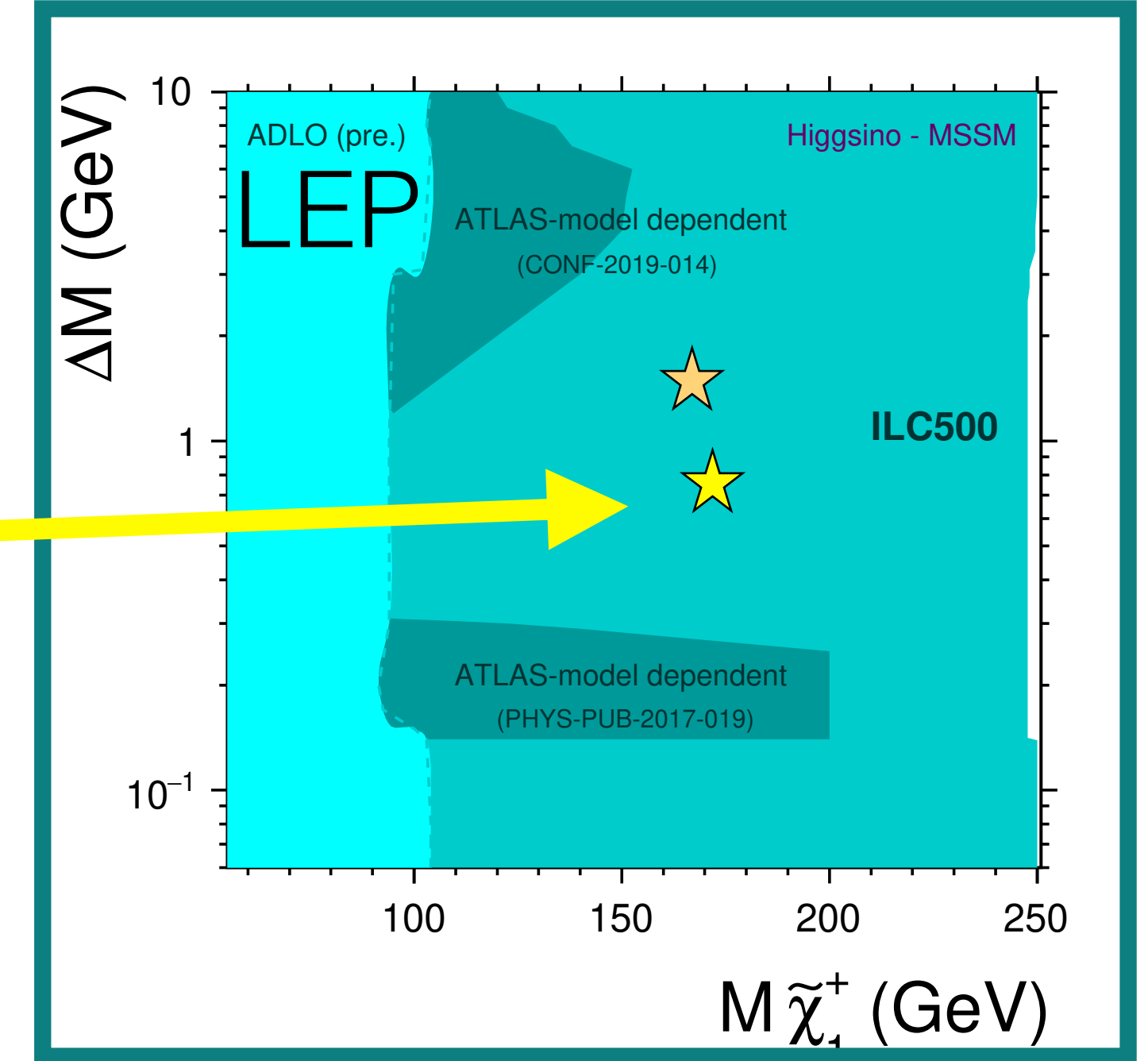
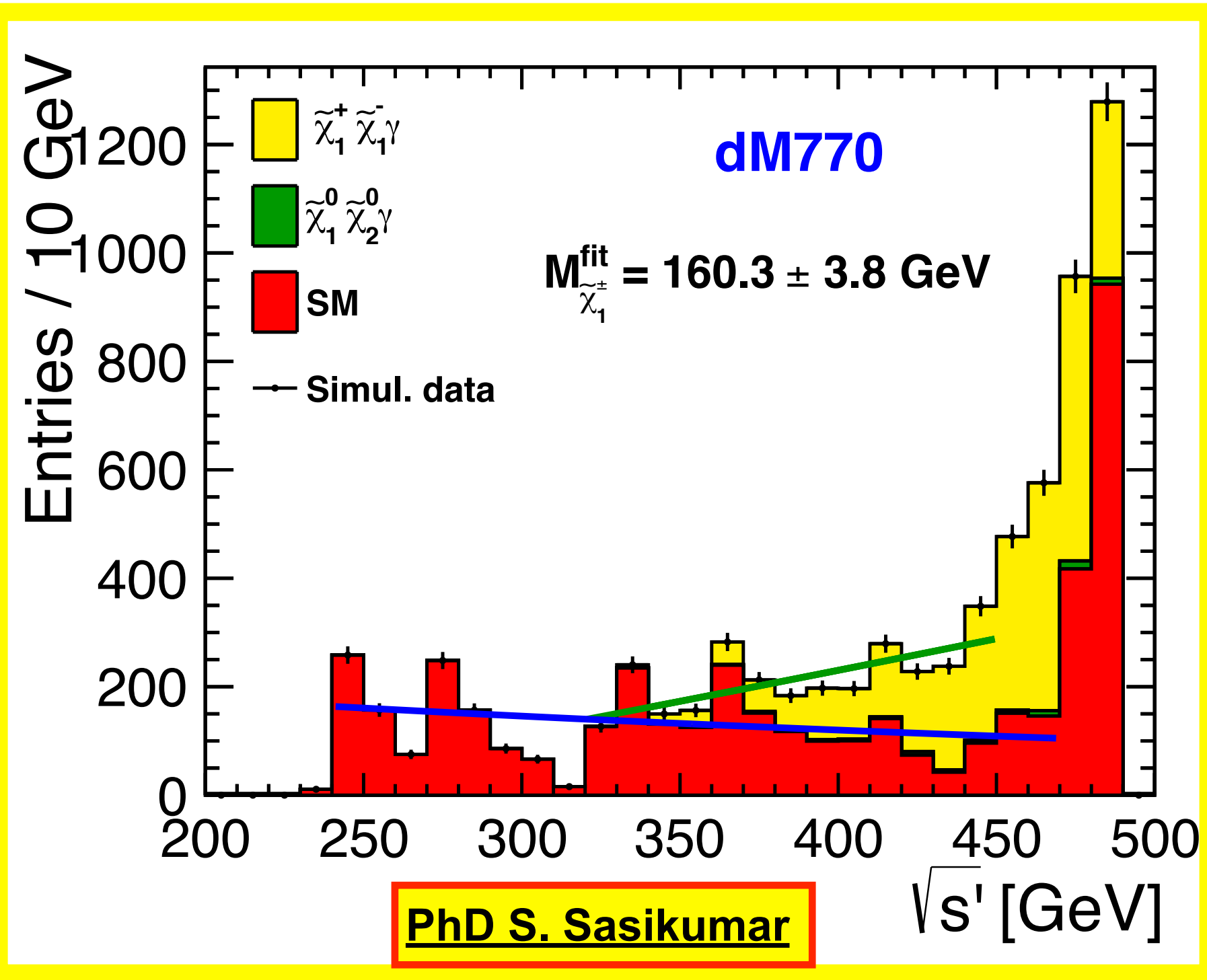
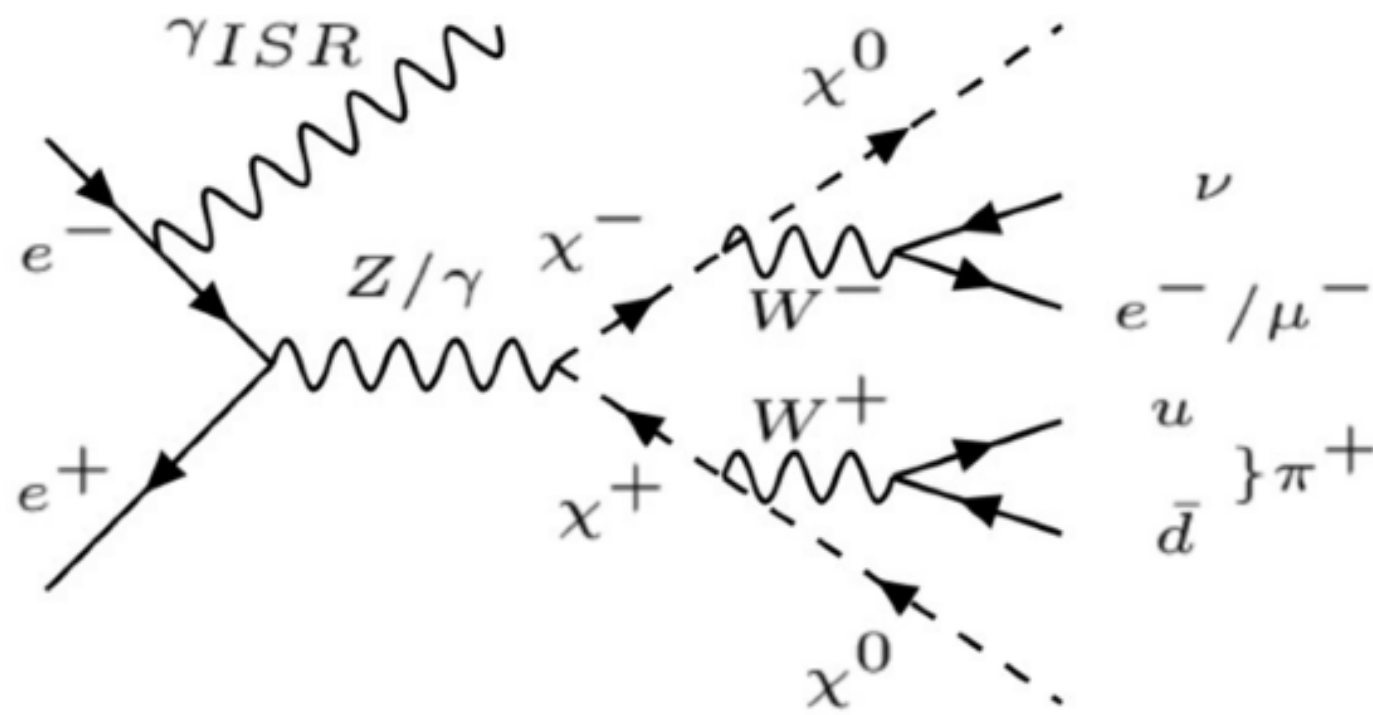
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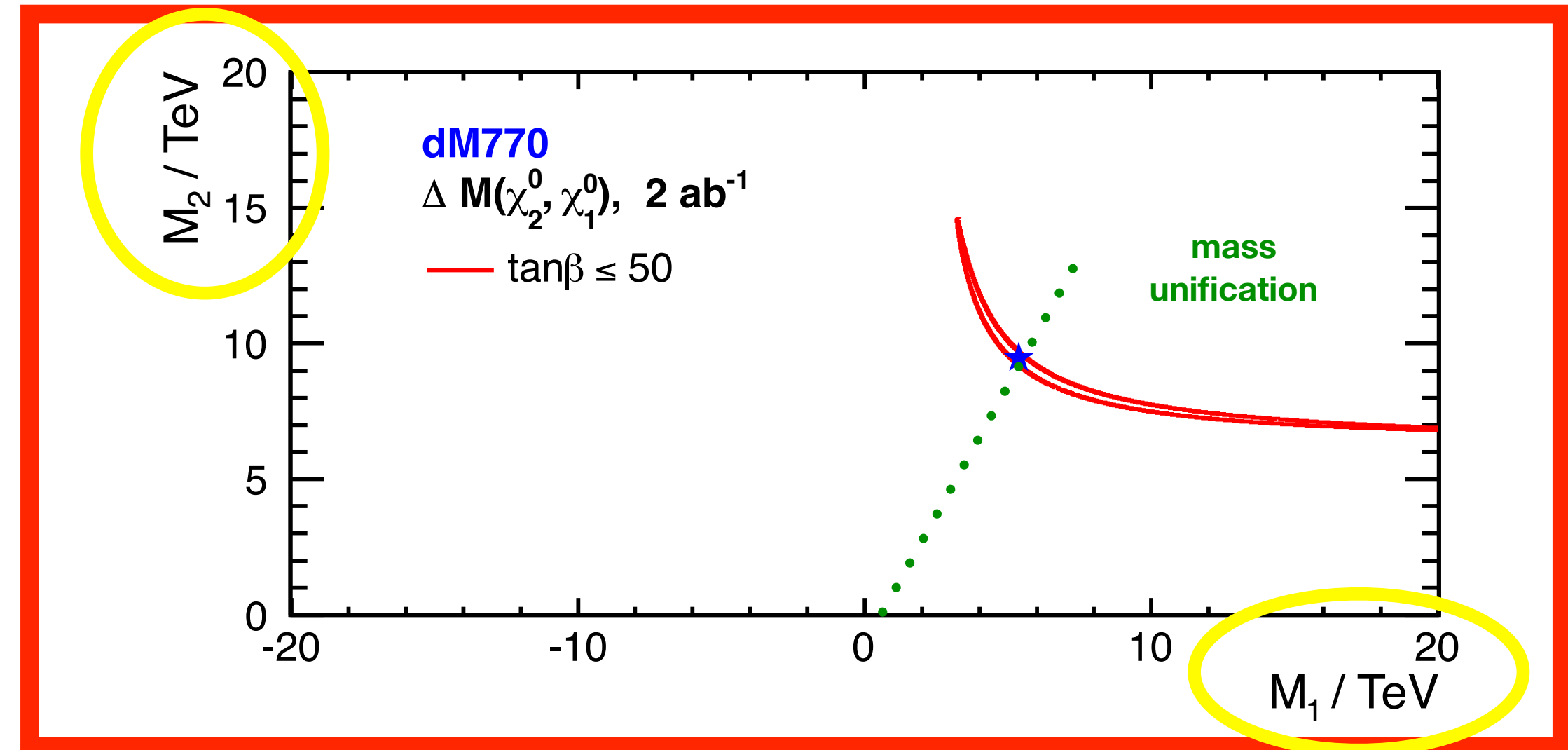
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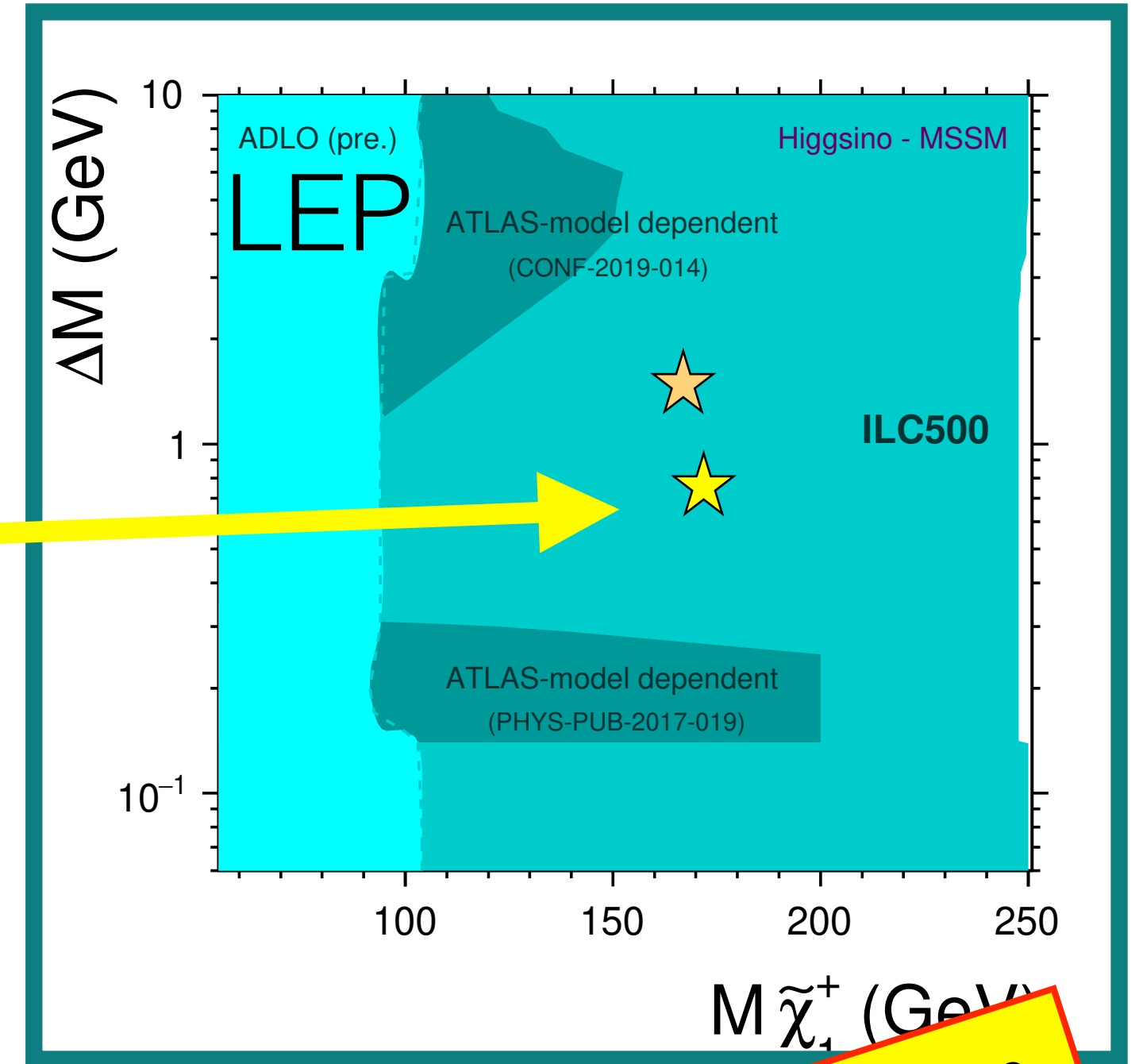
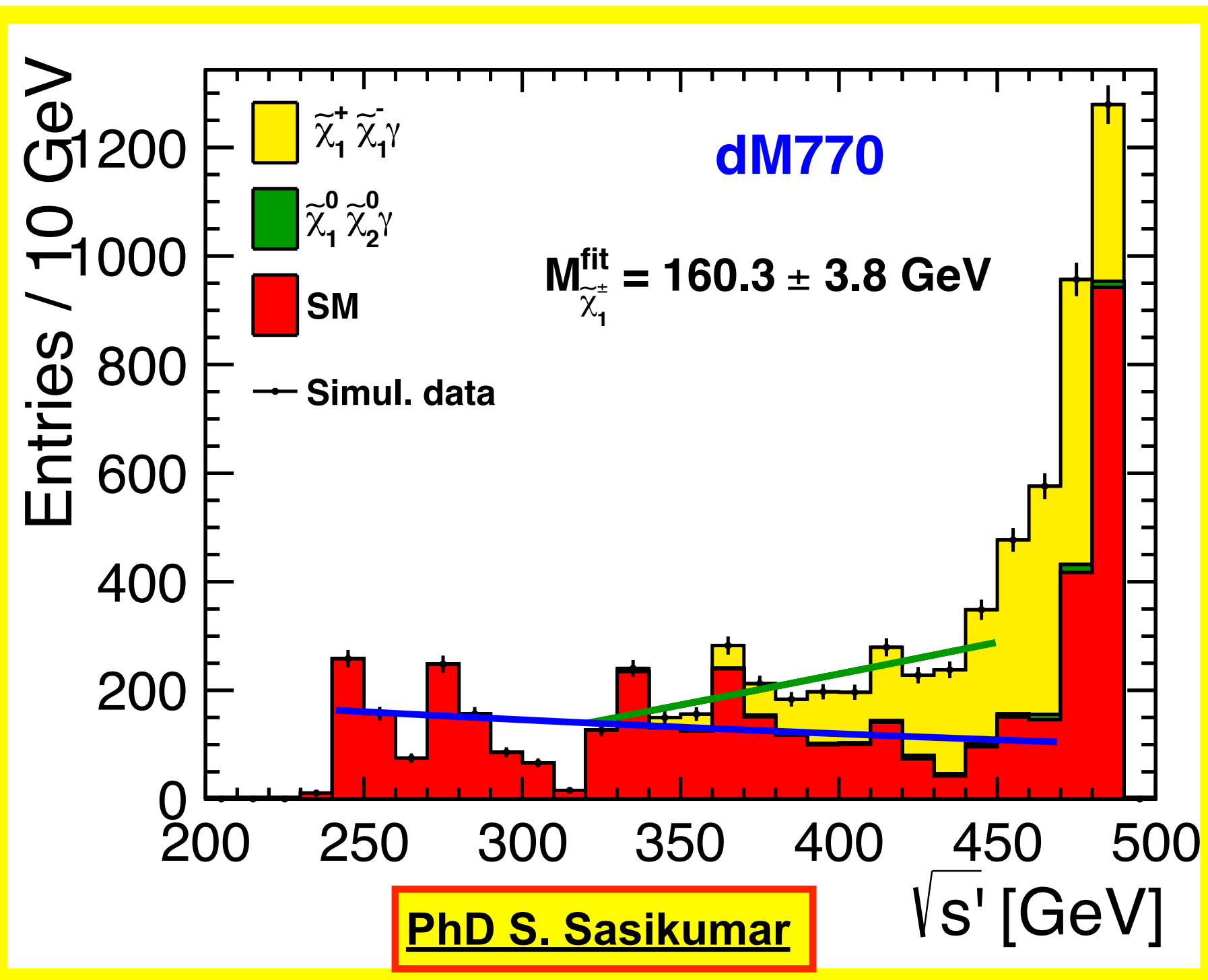
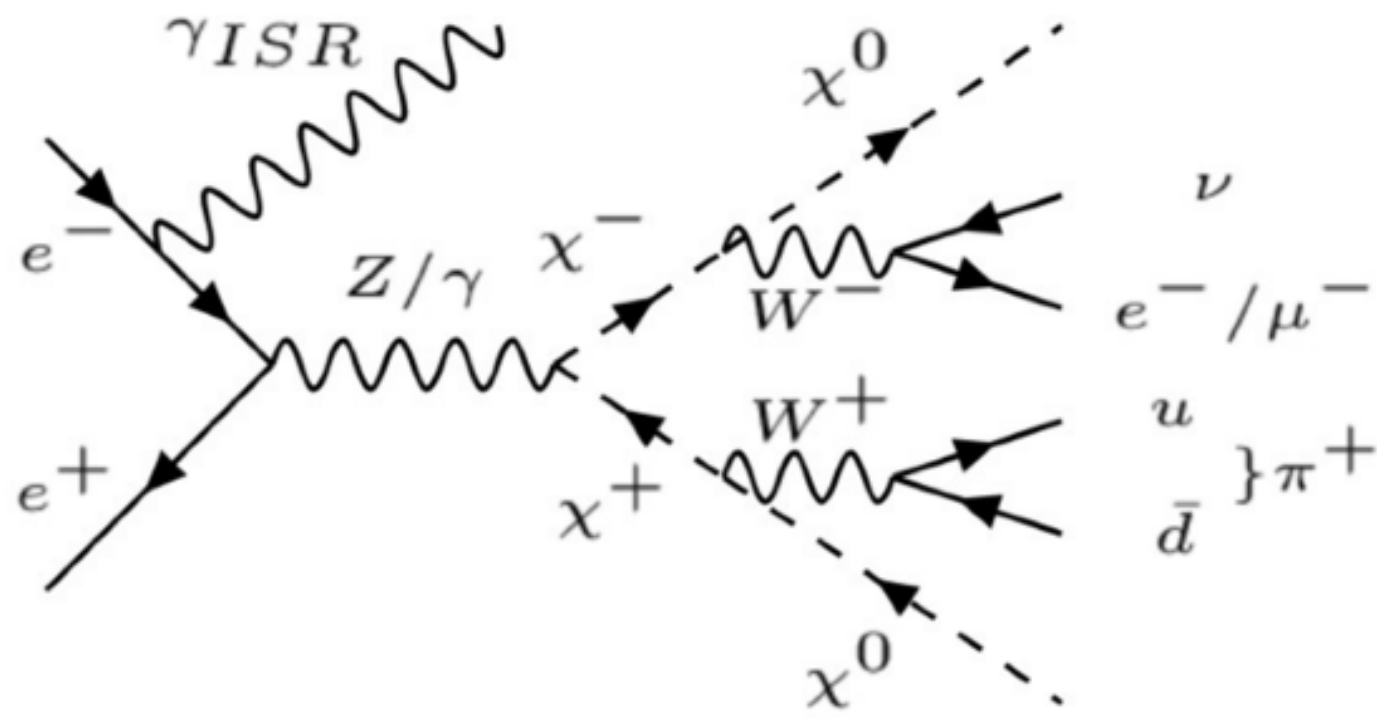


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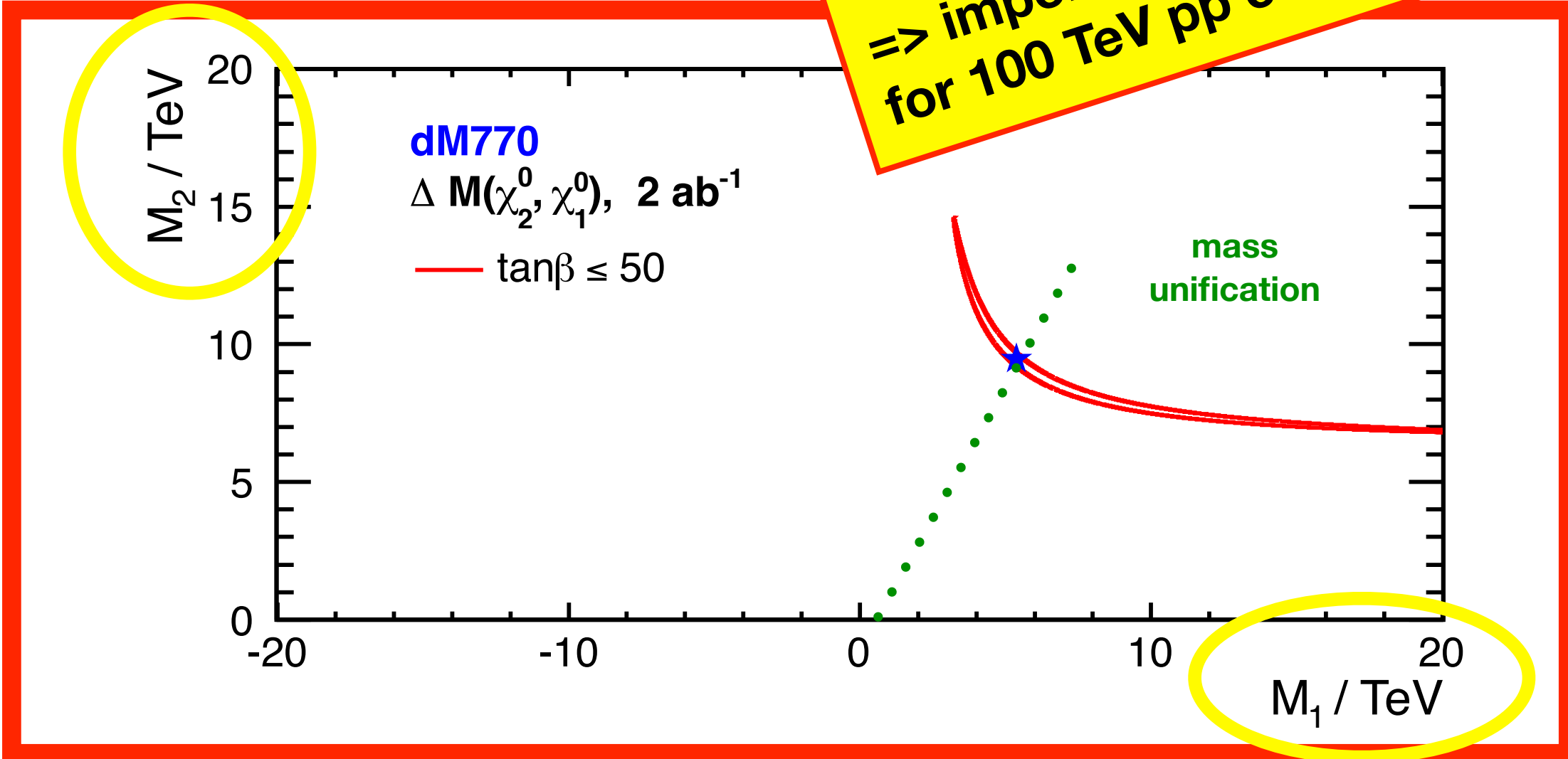
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=> important guidance for 100 TeV pp collider!

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Conclusions

And personal remarks

- **weak scale SUSY is by far not excluded - e.g. general MSSM limits on $M(\text{stau})$ still from LEP**
 - beware of the fine-print - and let's do not depress ourselves by simplified exclusion plots
 - return to LEP-style limit setting? At least for main NLSP candidates? More pMSSM scans?
- **SUSY searches at e^+e^- colliders are very complementary to those at hadron colliders**
 - electroweakinos, sleptons, low- ΔM , ... “easy”
 - triggerless operation, single-particle acceptance from $p_t = 100$ MeV, nearly hermetic detectors,...
 - much less fine-print required => **turn all the stones which are difficult for hadron colliders!**
 - beam polarisation for background suppression and chiral analysis of signal
 - precision spectroscopy allows to predict mass ranges of heavier sparticles => energy scale for pp collider ?
- **e^+e^- from SUSY perspective: the higher the ECM the better!**
 - but even a minimal “Higgs Factory” at 240/250 GeV has direct SUSY discovery potential
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Most importantly:

**Any Future Collider can only happen based on broad support within HEP community
=> get engaged and make it happen!**

Backup

Ready to take on one of these challenges?

How to contribute

- **Get involved**

- **ECFA set up a workshop series on Physics, Experiments and Detectors at a Higgs, Top and Electroweak factory cf <https://indico.cern.ch/event/1044297/>**

- address topics in common between all e^+e^- colliders, i.e. theory prediction, assessment of systematic uncertainties, software tools
- will give important input to next update of European Strategy

**you don't want to commit to a specific collider project ?
=> this is your way to contribute => get in touch!**

- **All Higgs factories are using the same software framework ([Key4HEP](#)):**

- share algorithmic developments
- share / exchange data sets for comparable analyses etc

=> anybody who'd like to shape the experiments of the next collider would be wise to build up expertise on Key4HEP now

Straight to the Future

An adaptable e⁺e⁻ LC facility for the world



- A LC facility can be extended in length for higher energies, using the same or improved versions of the same technology, e.g. as suggested for ILC, CLIC, C3 and HALHF
- It is also possible and realistic to change to more performant (usually higher gradient) technologies in an upgrade, e.g. from ILC to CLIC or C3, maybe even plasma
- Starting point for fast implementation: ILC has the most mature linac technology for large scale implementation, that is also well established in all regions and in industry - it is based on a ~20 km long tunnel
- The physics at higher energies – Higgs sector and extended models with increased reach and precision, top in detail well above threshold, searches and hopefully new physics – will open for a very exciting long term e⁺e⁻ programme
- Such a programme can run in parallel with future hadron and/or muon colliders that can be developed, optimised and implemented as their key technologies mature

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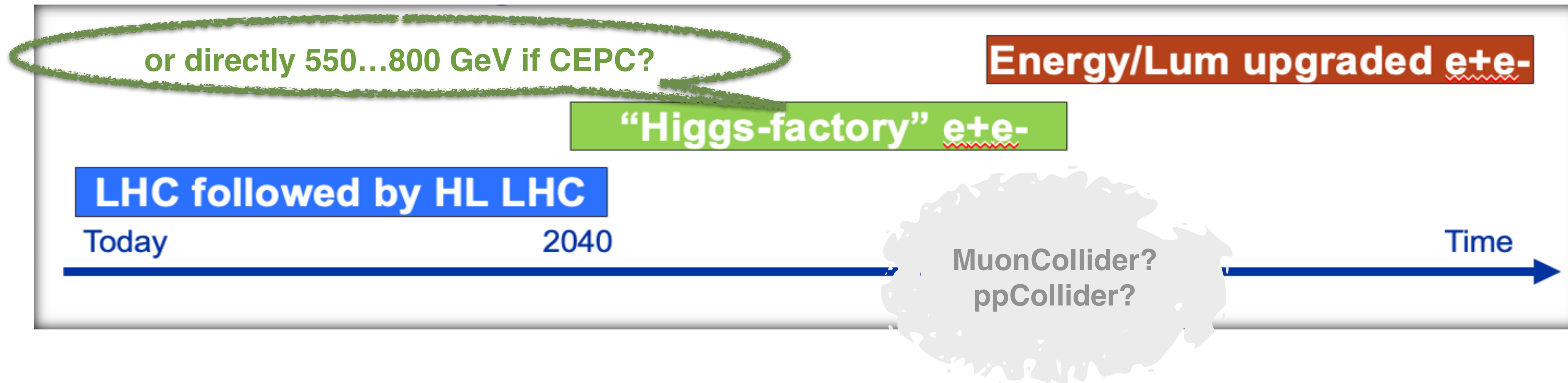
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Polarisation & Electroweak Physics

let's first recall at the Z pole situation

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

$$\Rightarrow A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

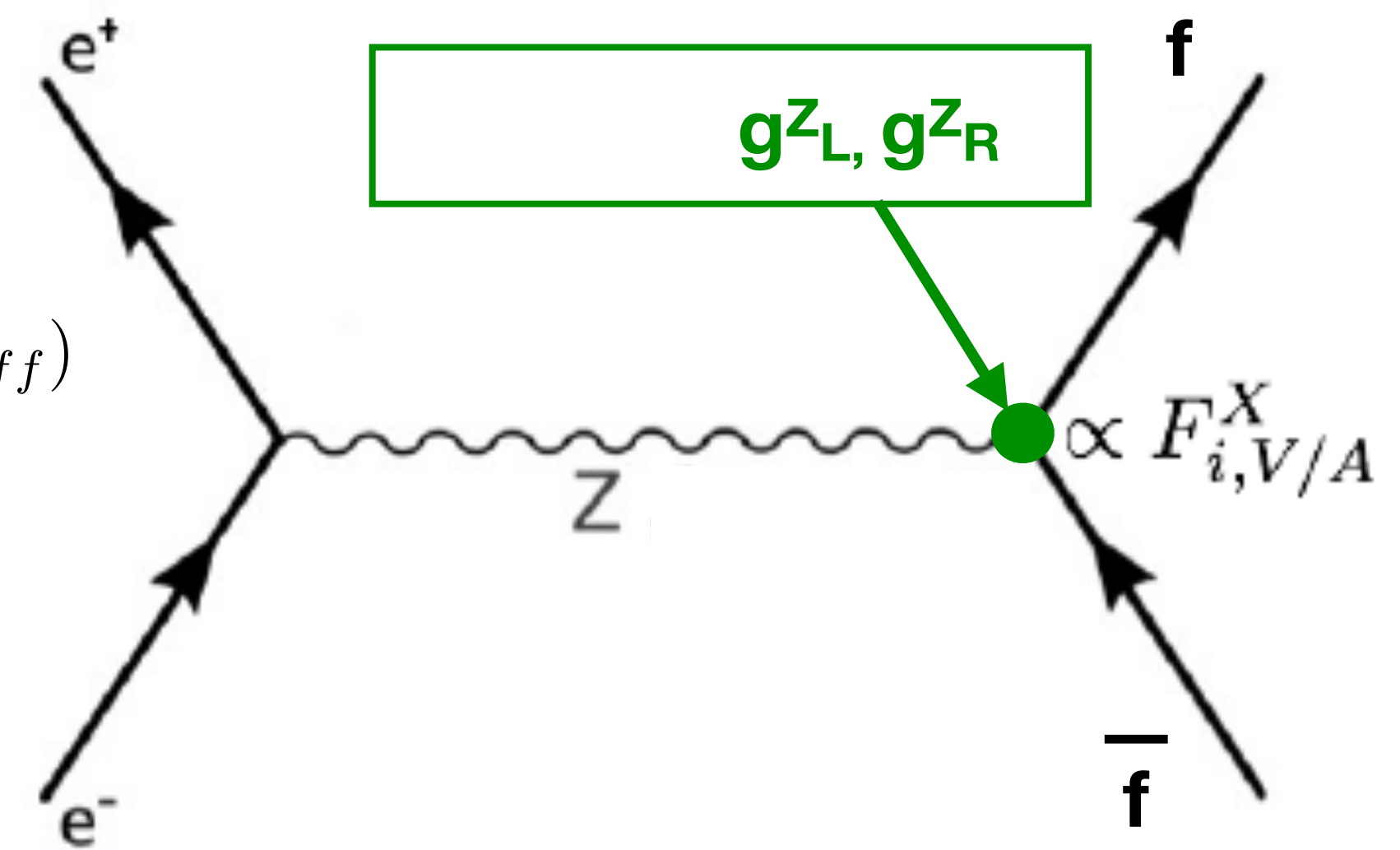
specifically for the electron: $A_e = \frac{(\frac{1}{2} - \sin^2 \theta_{eff})^2 - (\sin^2 \theta_{eff})^2}{(\frac{1}{2} - \sin^2 \theta_{eff})^2 + (\sin^2 \theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2 \theta_{eff})$

at an *unpolarised* collider:

$$A_{FB}^f \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f \quad \Rightarrow \text{no direct access to } A_e, \text{ only via tau polarisation}$$

While at a *polarised* collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)} \quad \text{and} \quad A_{FB,LR}^f \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$



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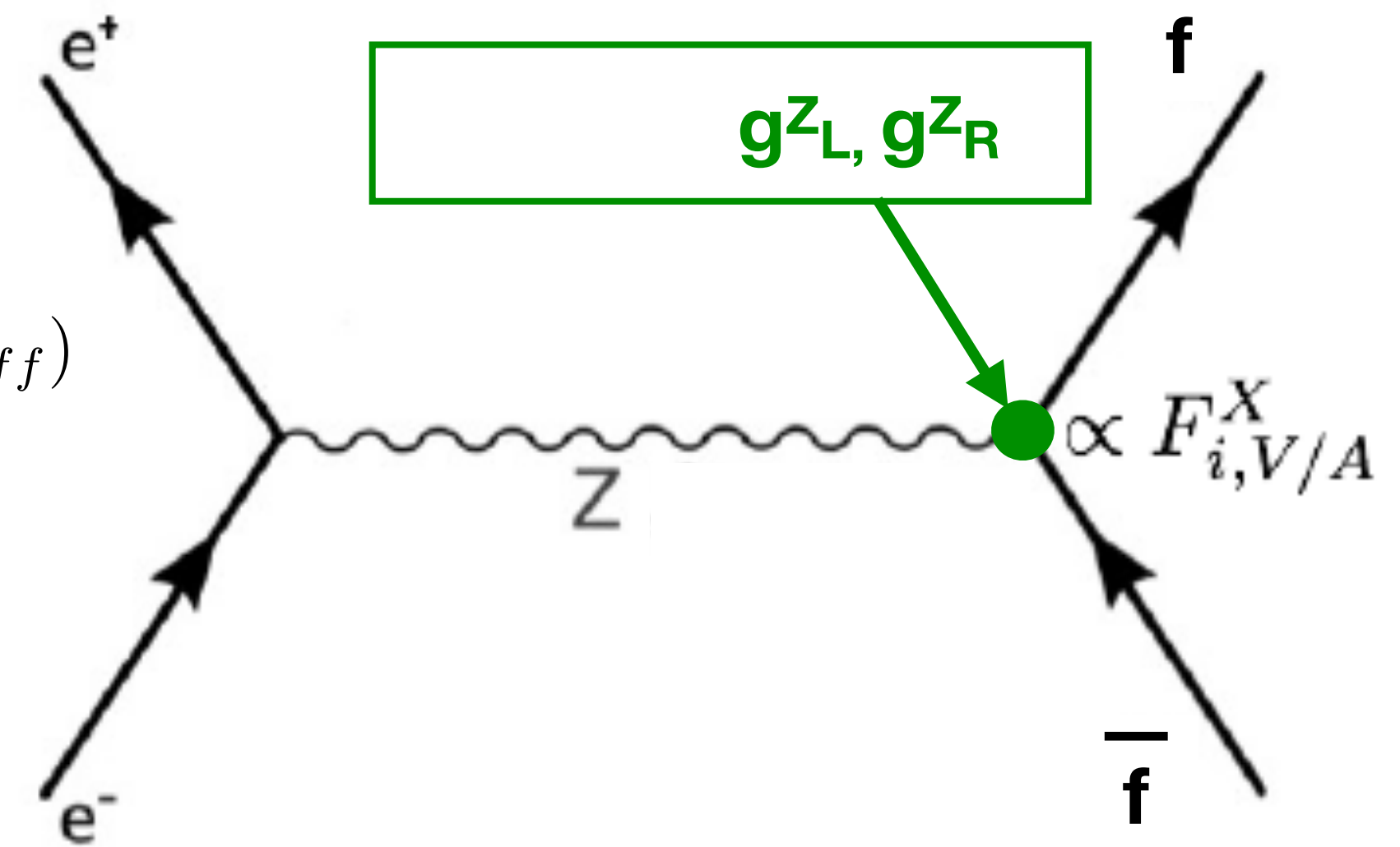
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trading theory uncertainty:

the **polarised** $A_{FB,LR}^f$ receives 7 x smaller radiative corrections than the **unpolarised** A_{FB}^f !



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at an **unpolarised** collider:

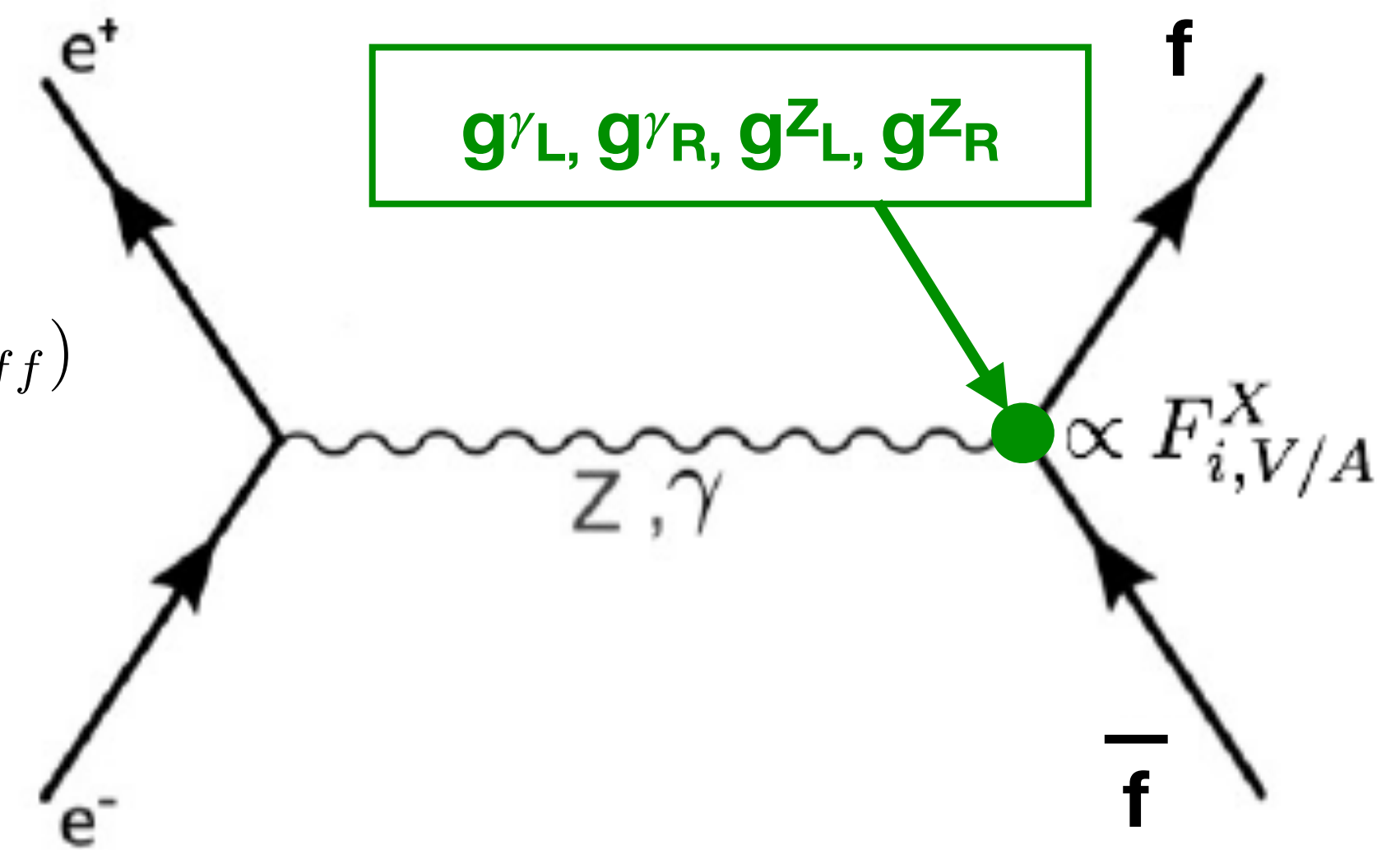
$$A_{FB}^f \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f \quad \Rightarrow \text{no direct access to } A_e, \text{ only via tau polarisation}$$

While at a **polarised** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)} \quad \text{and} \quad A_{FB,LR}^f \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

trading theory uncertainty:

the **polarised** $A_{FB,LR}^f$ receives 7 x smaller radiative corrections than the **unpolarised** A_{FB}^f !



Polarisation & Electroweak Physics

let's first recall at the Z pole situation

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

$$\Rightarrow A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

specifically for the electron: $A_e = \frac{(\frac{1}{2} - \sin^2 \theta_{eff})^2 - (\sin^2 \theta_{eff})^2}{(\frac{1}{2} - \sin^2 \theta_{eff})^2 + (\sin^2 \theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2 \theta_{eff})$

at an **unpolarised** collider:

$$A_{FB}^f \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f \quad \Rightarrow \text{no direct access to } A_e, \text{ only via tau polarisation}$$

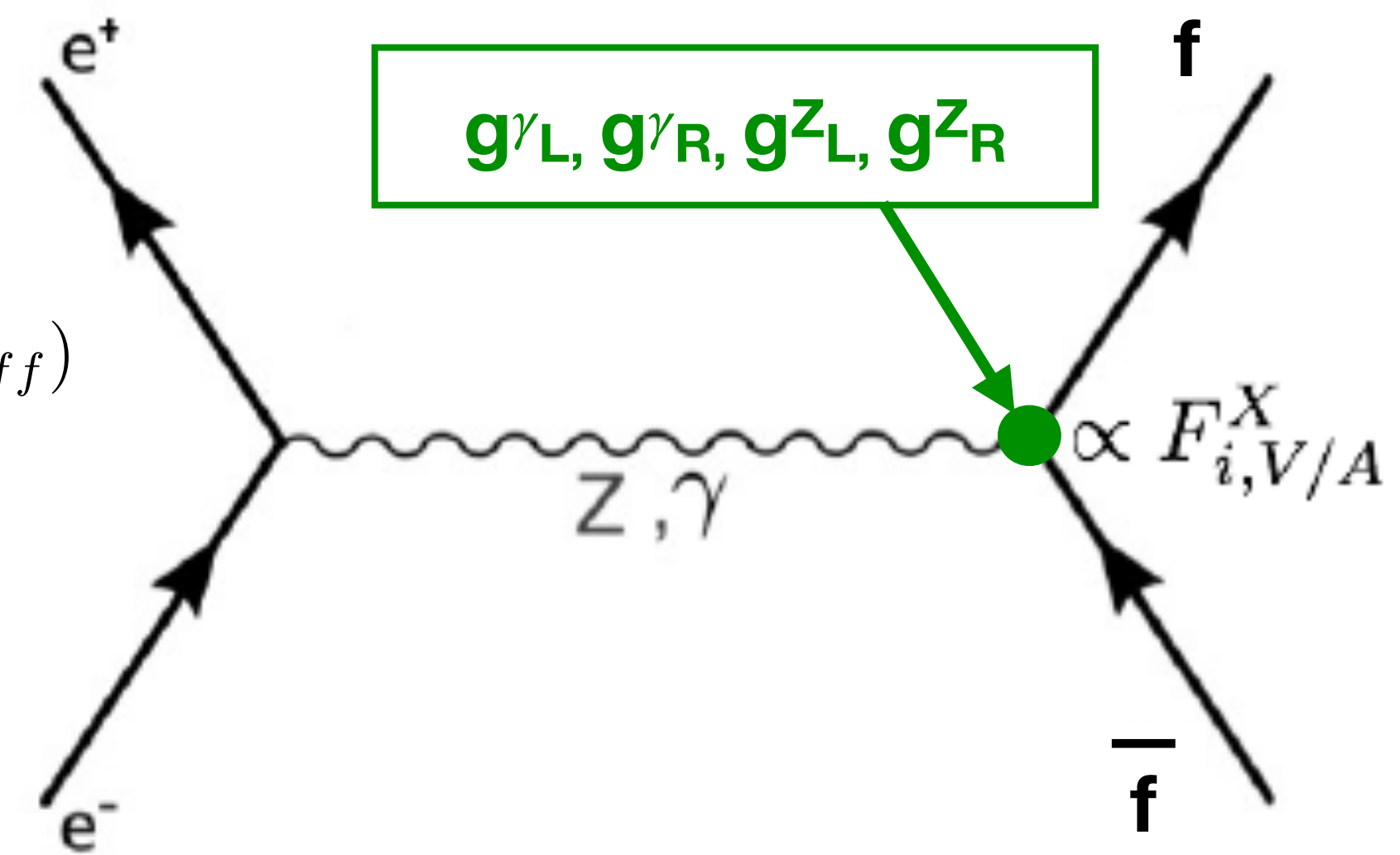
While at a **polarised** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)} \quad \text{and} \quad A_{FB,LR}^f \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

trading theory uncertainty:

the **polarised** $A_{FB,LR}^f$ receives 7 x smaller radiative corrections than the **unpolarised** A_{FB}^f !

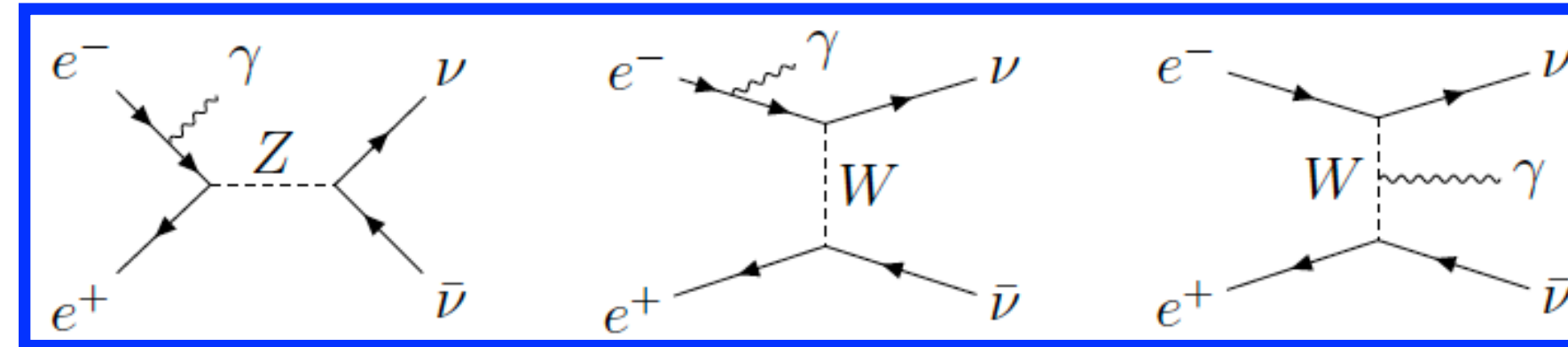
above Z pole, polarisation essential to disentangle Z / γ exchange in $e^+e^- \rightarrow f\bar{f}$



Polarisation & Beyond the SM: Dark Matter

Background reduction & Systematics

- mono-photon search $e^+e^- \rightarrow \chi\chi\gamma$
- main SM background: $e^+e^- \rightarrow \nu\nu\gamma$



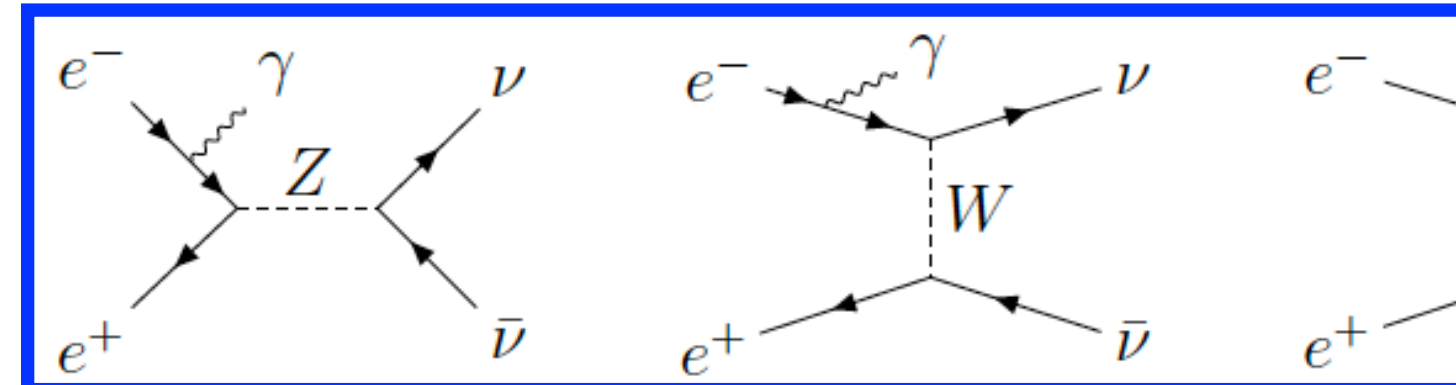
reduced $\sim 10x$ with polarisation

- shape of observable distributions changes with **polarisation** sign
 \Rightarrow combination of samples with $\text{sign}(P) = (-,+), (+,-), (+,+), (-,-)$
beats down the effect of **systematic uncertainties**

Polarisation & Beyond the SM: Dark Matter

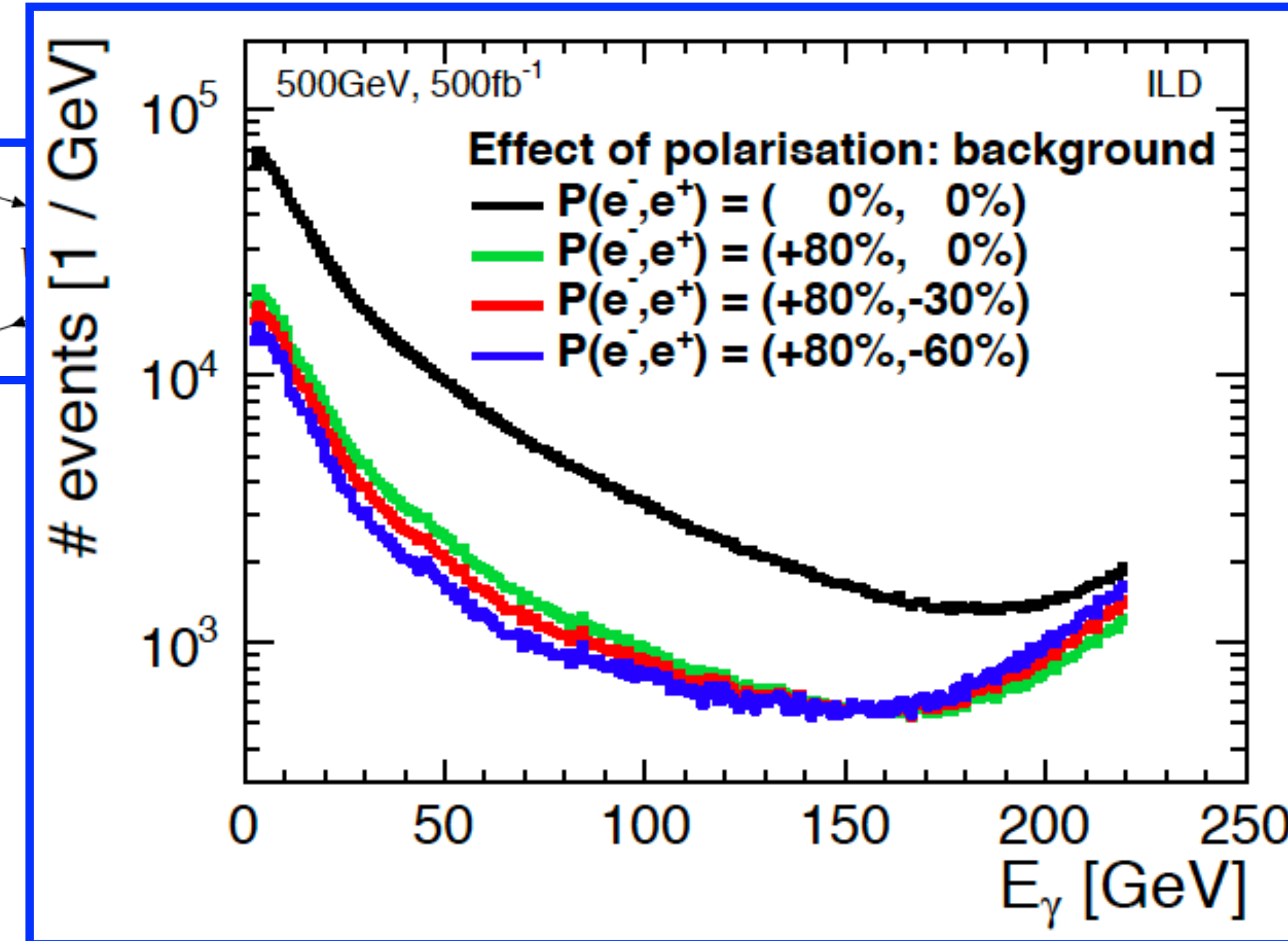
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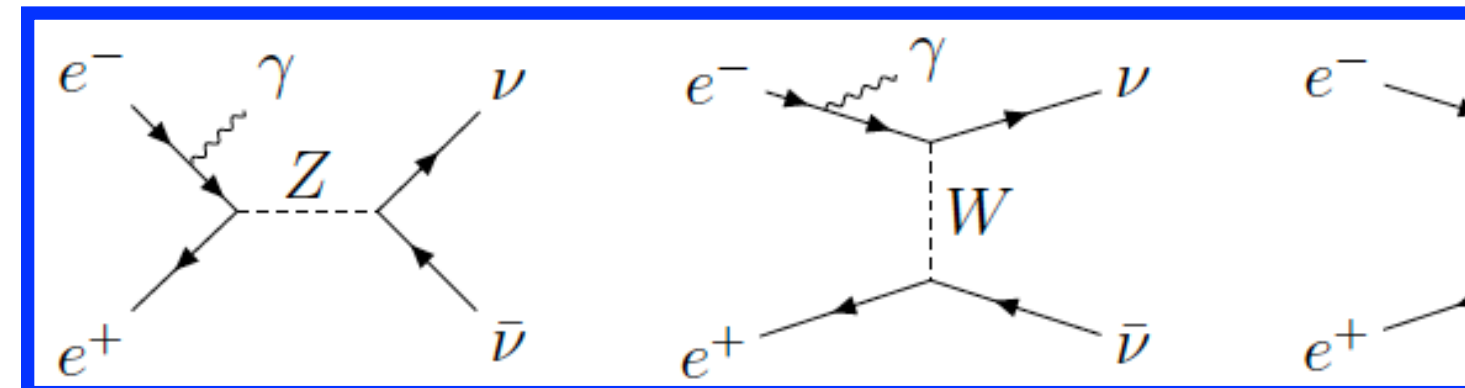
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Polarisation & Beyond the SM: Dark Matter

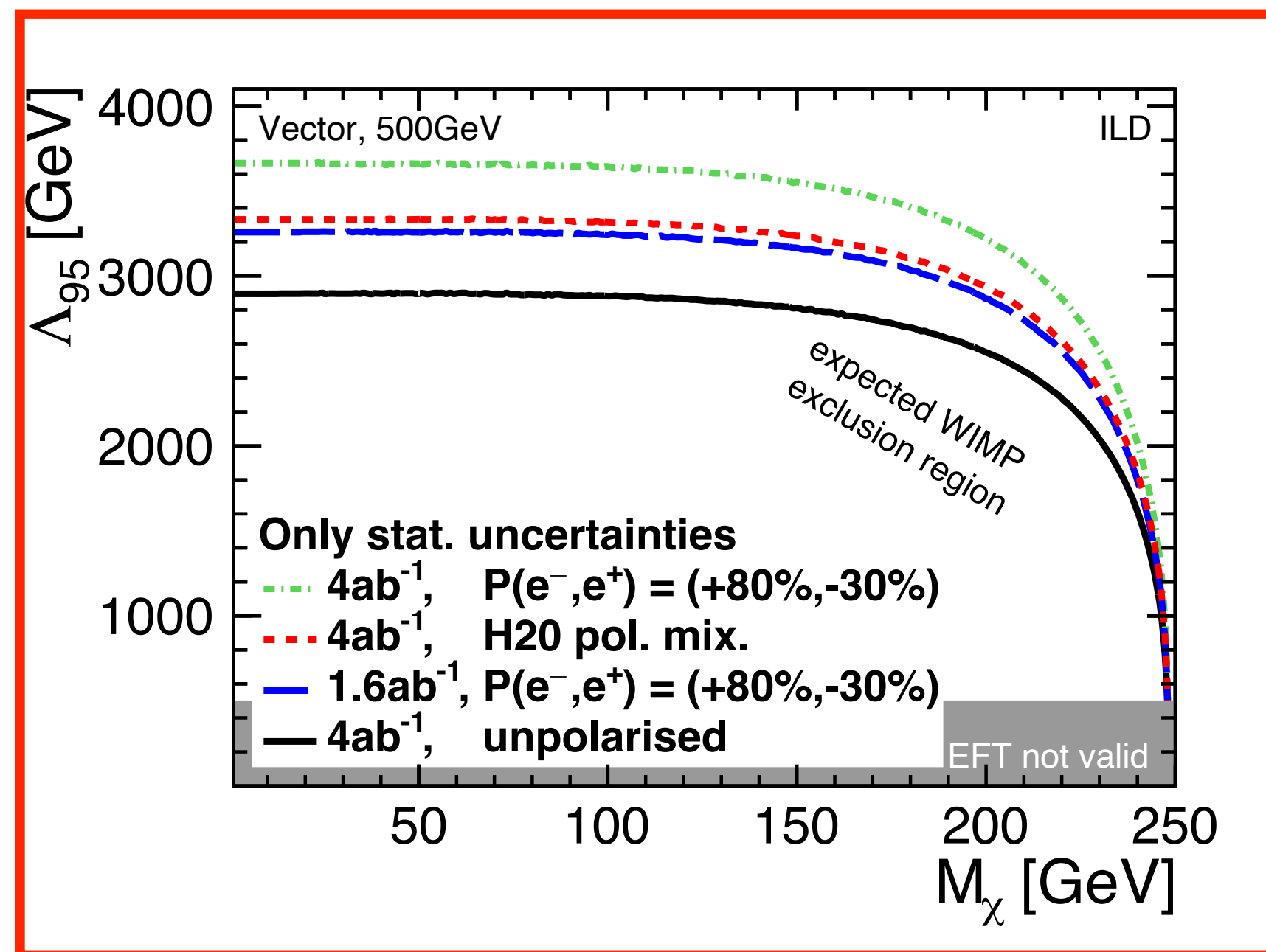
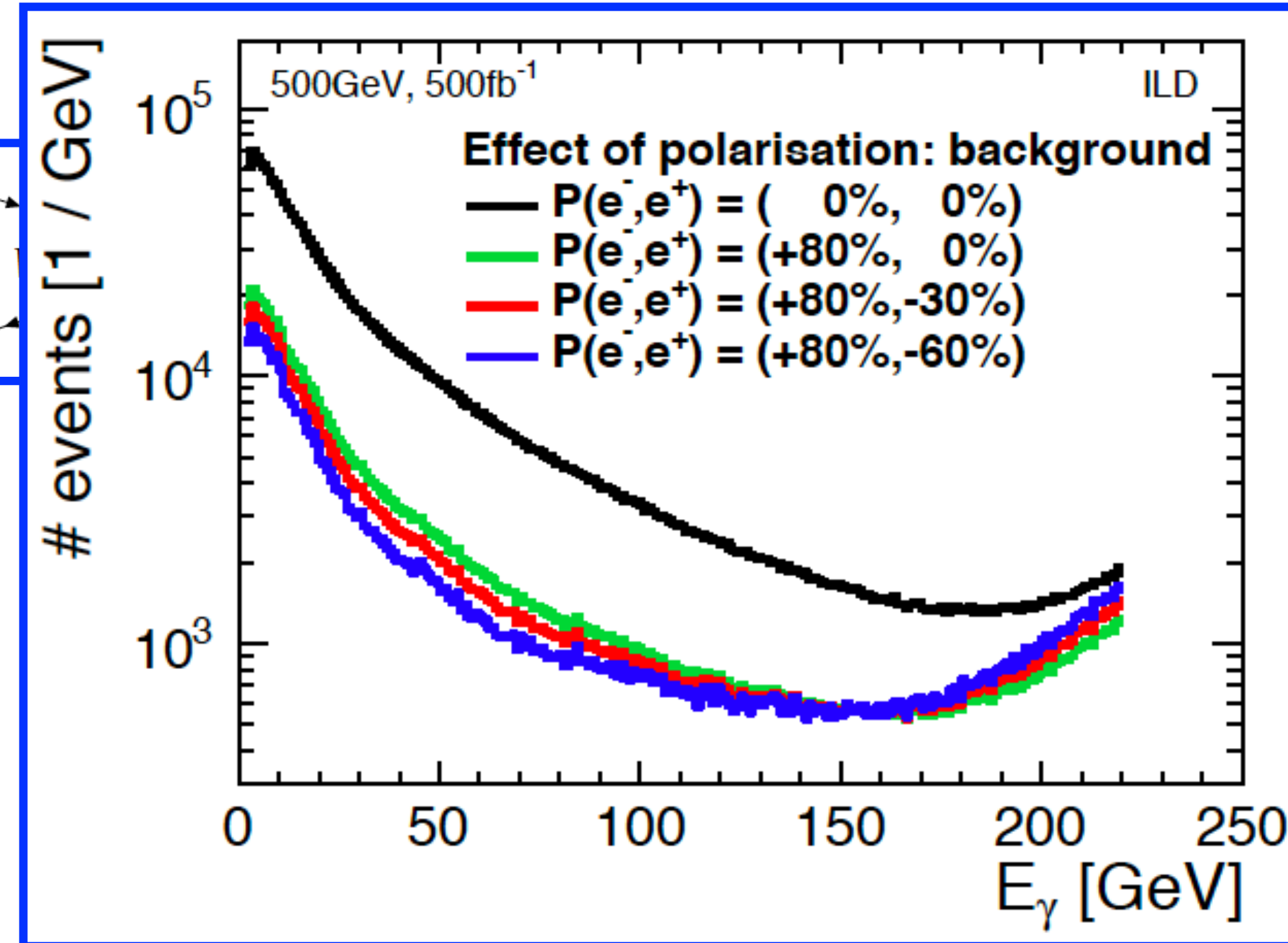
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- mono-photon search $e^+e^- \rightarrow \chi\chi\gamma$
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reduced ~10x with polarisation

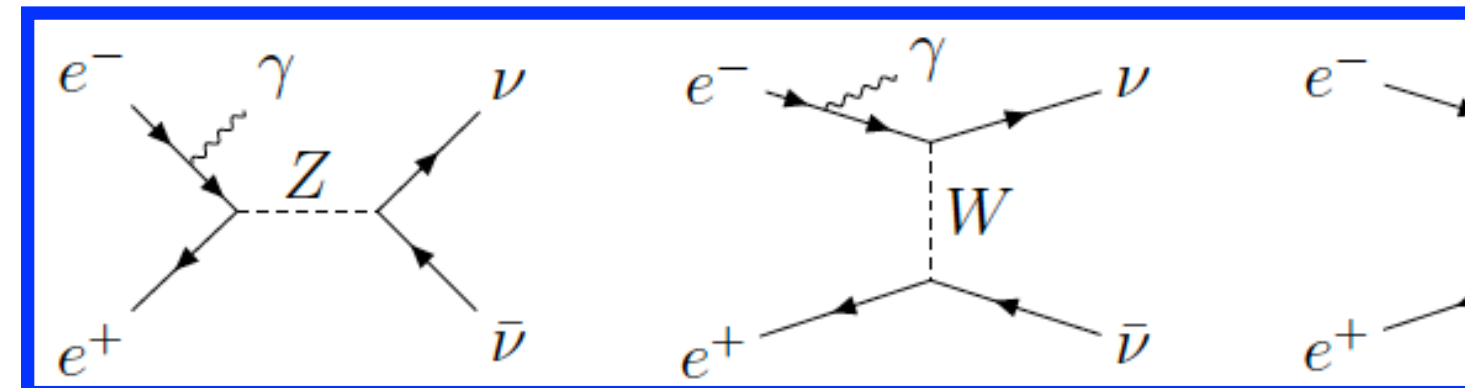
- shape of observable distributions changes with **polarisation** sign
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Polarisation & Beyond the SM: Dark Matter

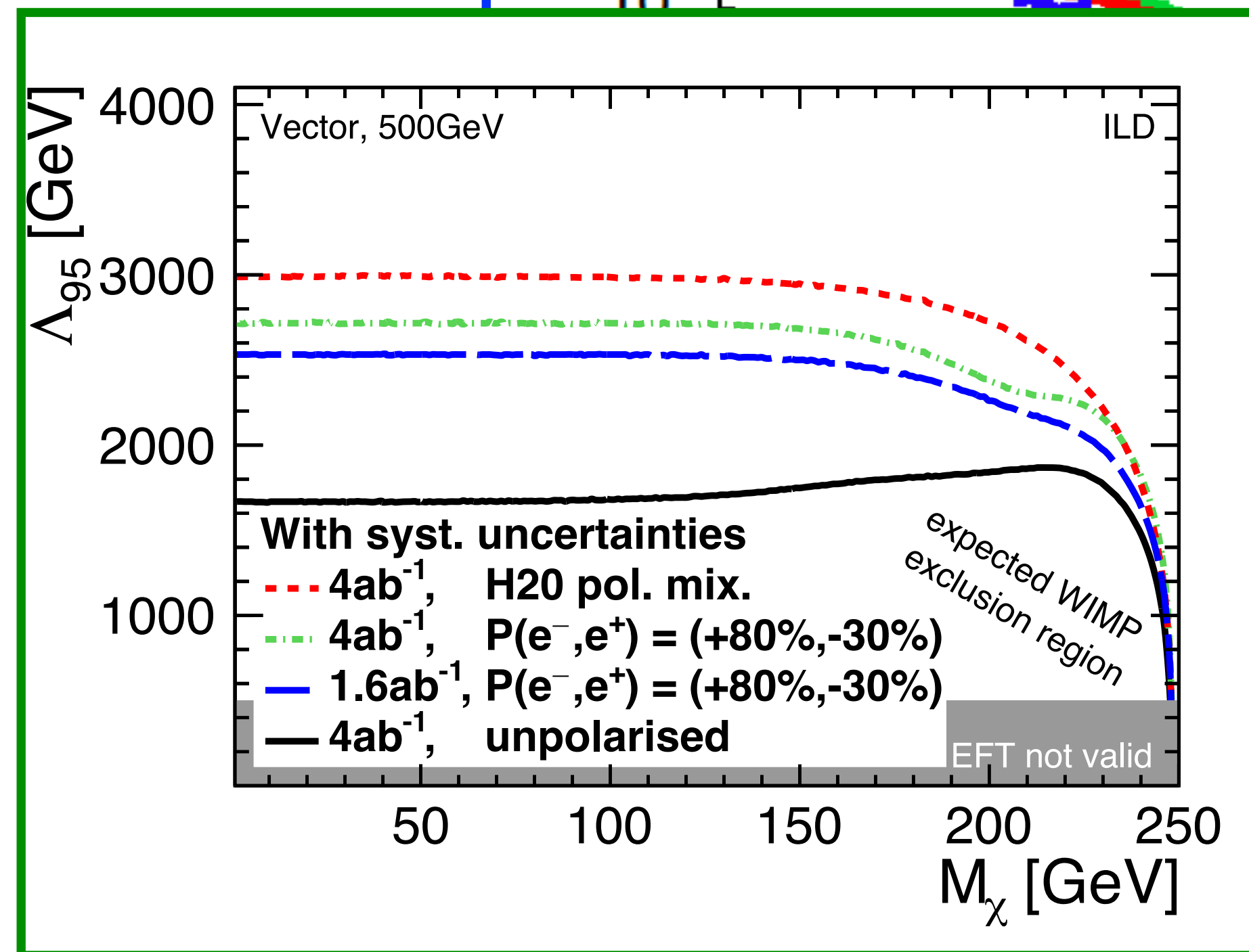
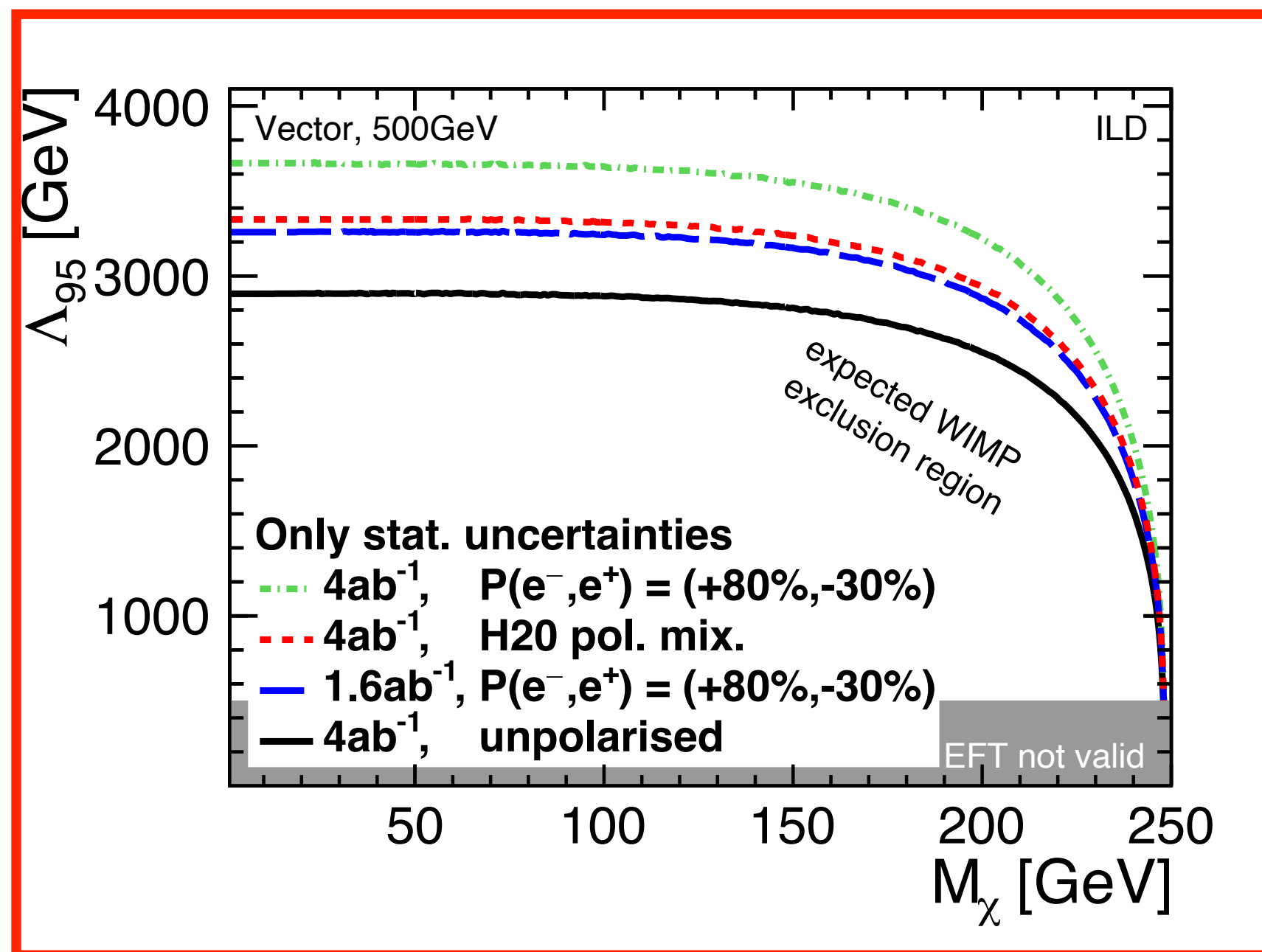
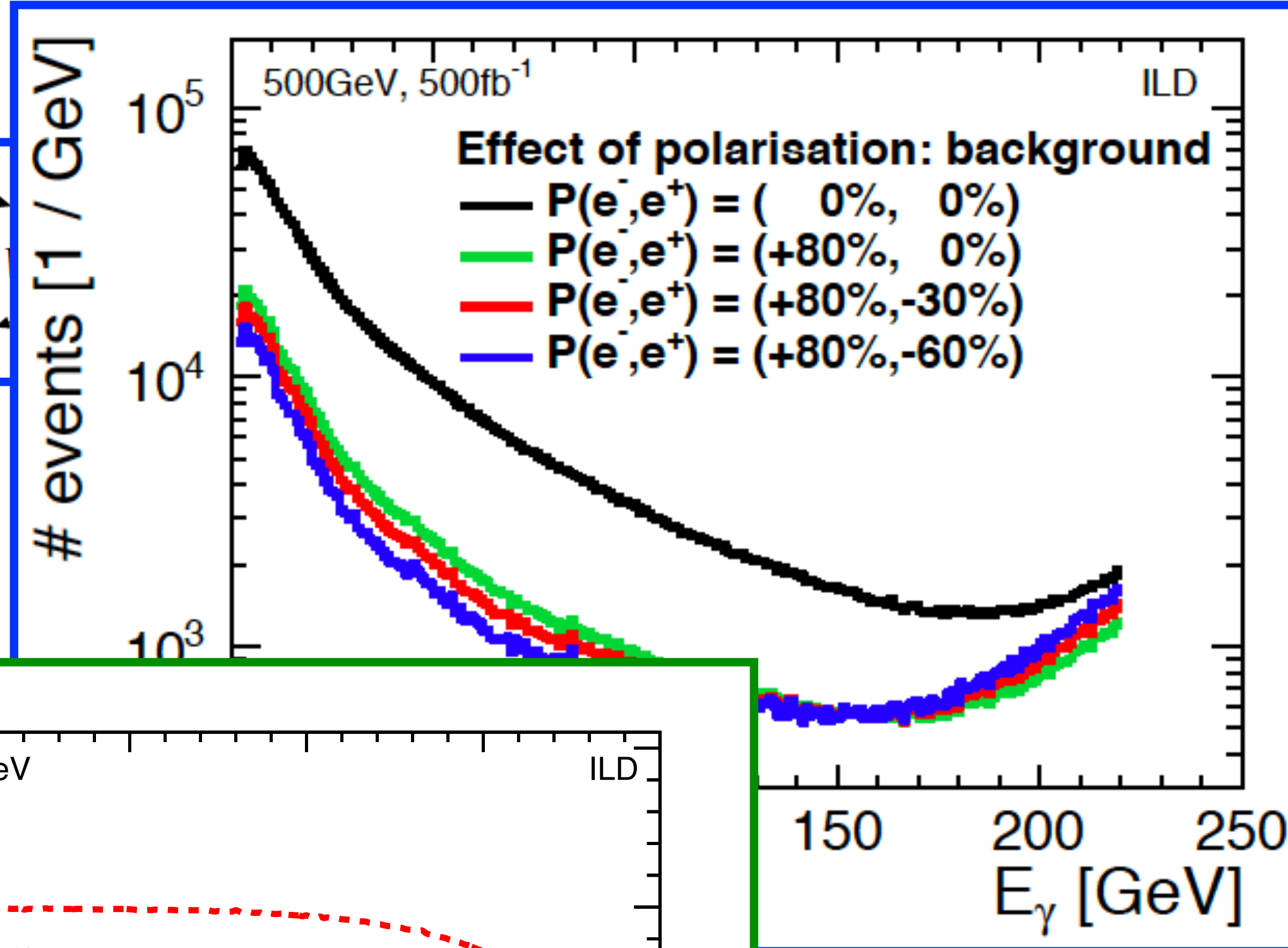
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reduced $\sim 10x$ with polarisation

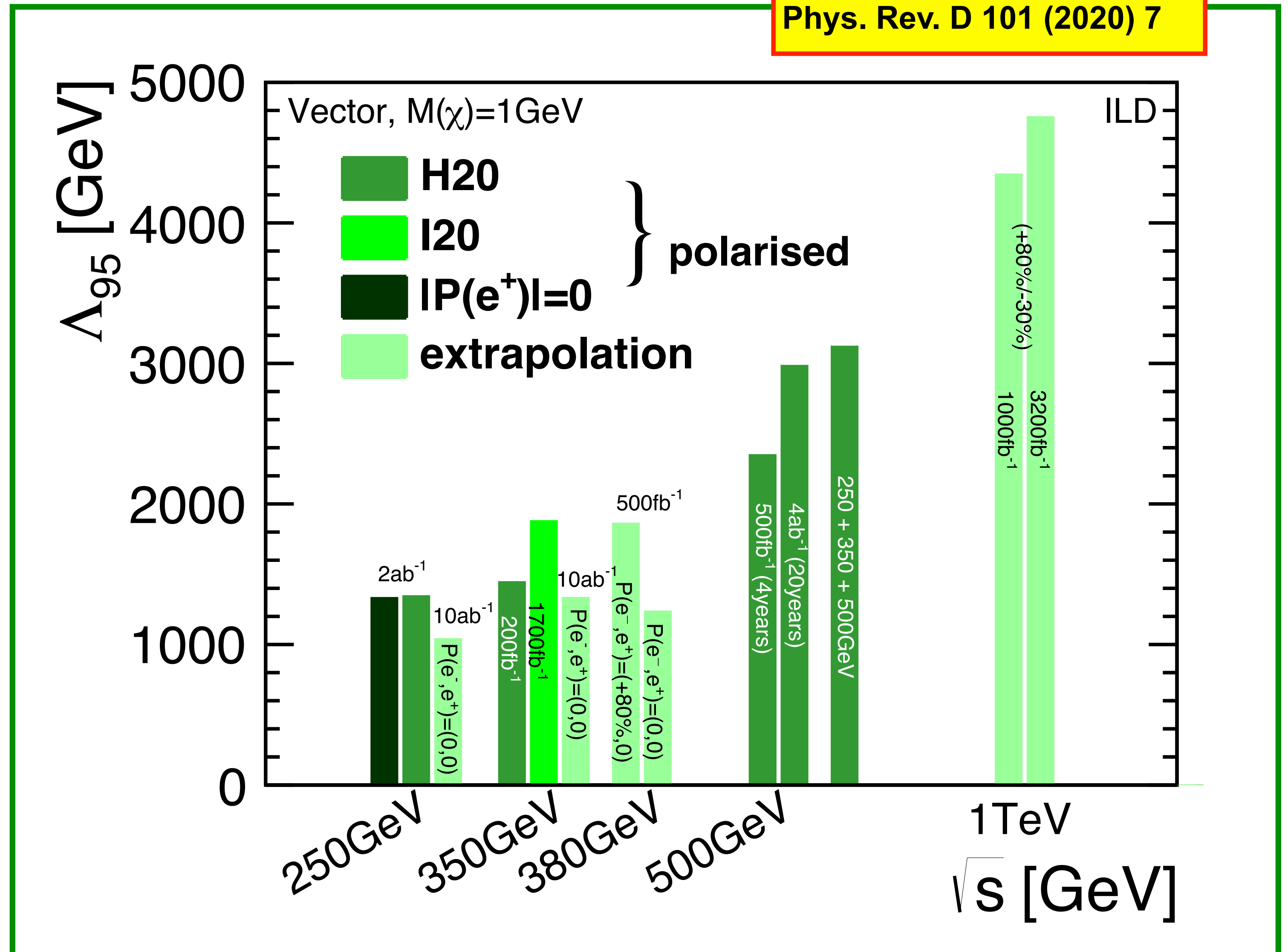
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Polarisation & Beyond the SM: Dark Matter

Example: Impact on reach in vector mediator case

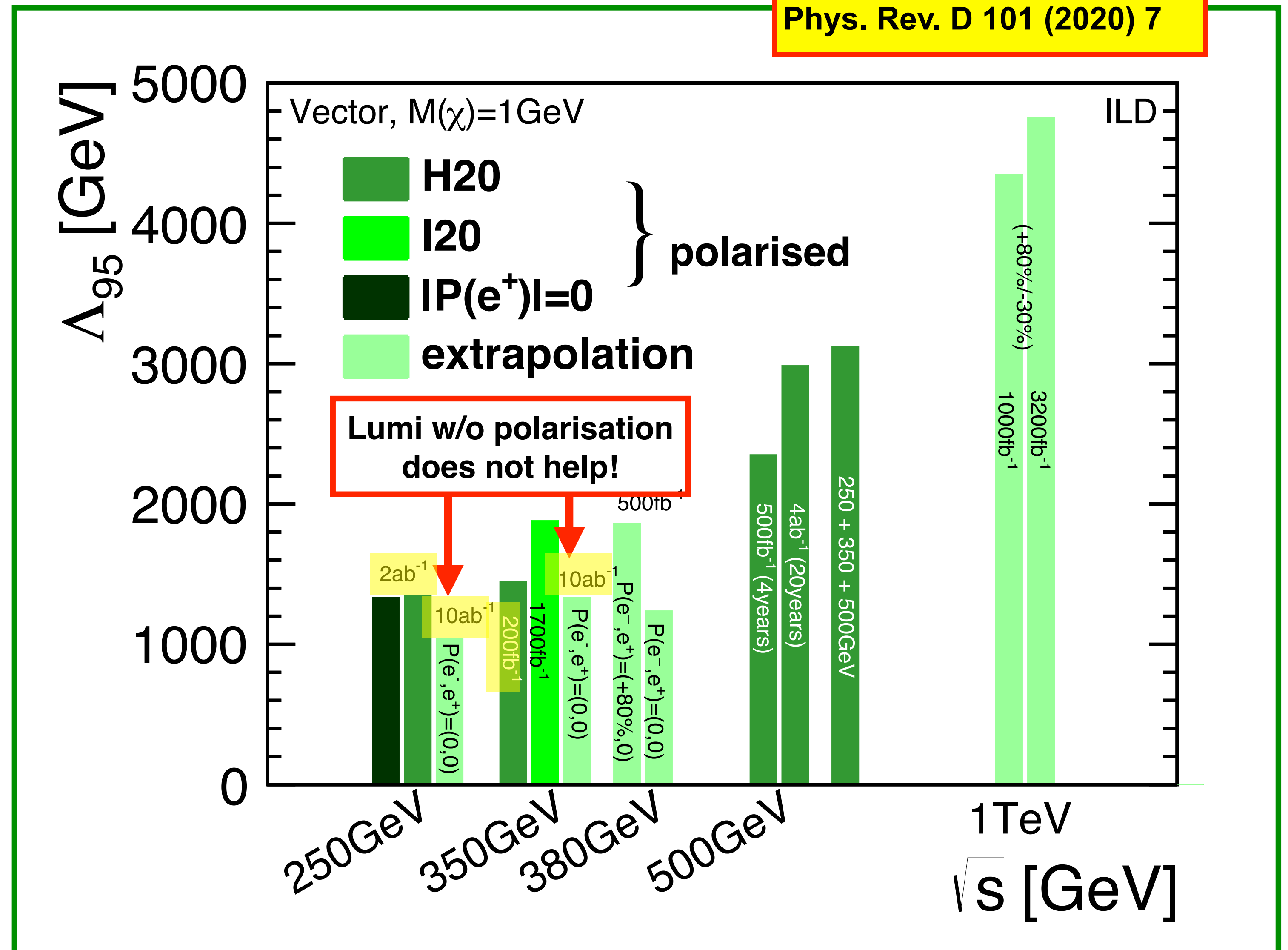
Phys. Rev. D 101 (2020) 7



Polarisation & Beyond the SM: Dark Matter

Example: Impact on reach in vector mediator case

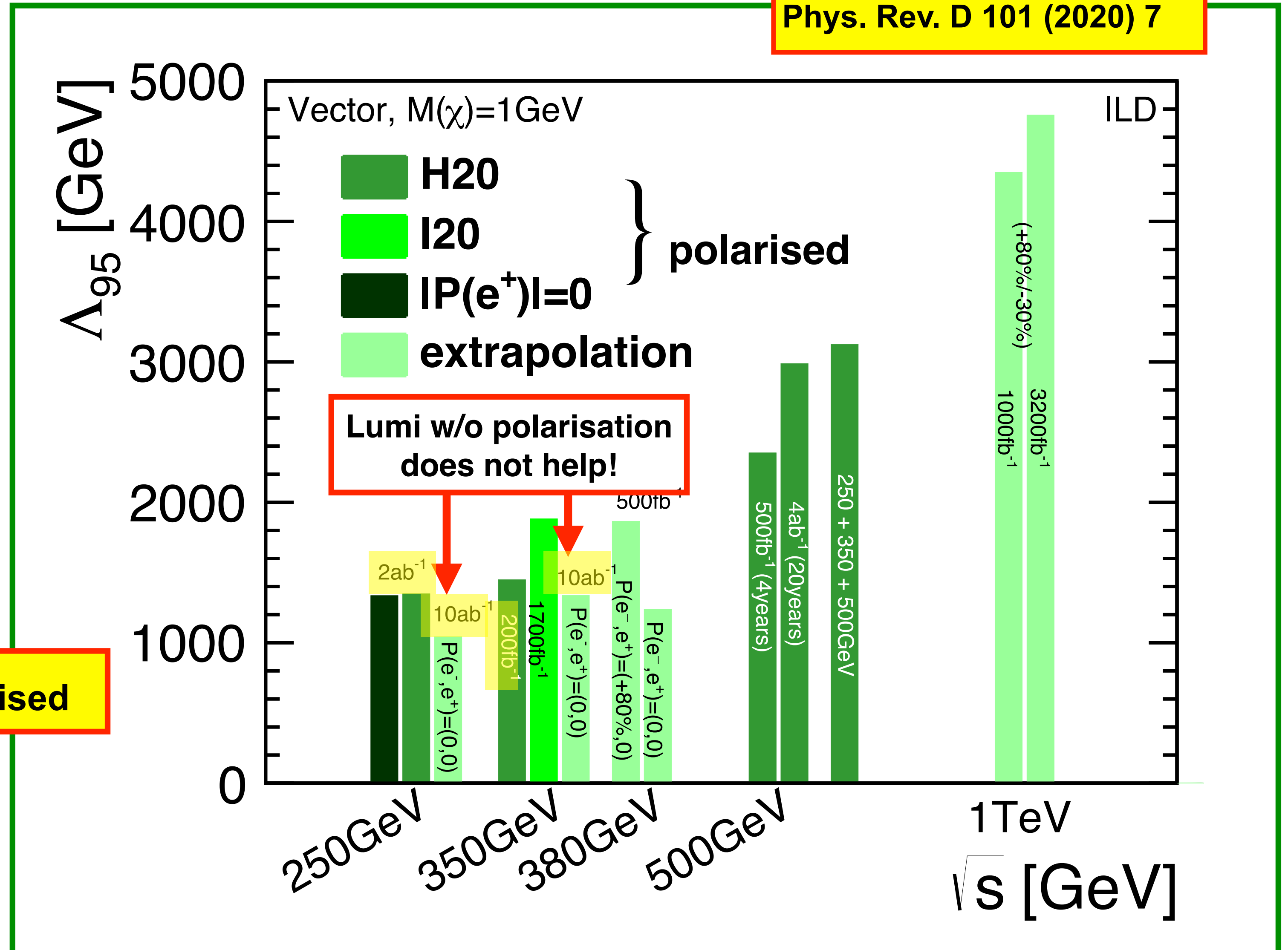
Phys. Rev. D 101 (2020) 7



Polarisation & Beyond the SM: Dark Matter

Example: Impact on reach in vector mediator case

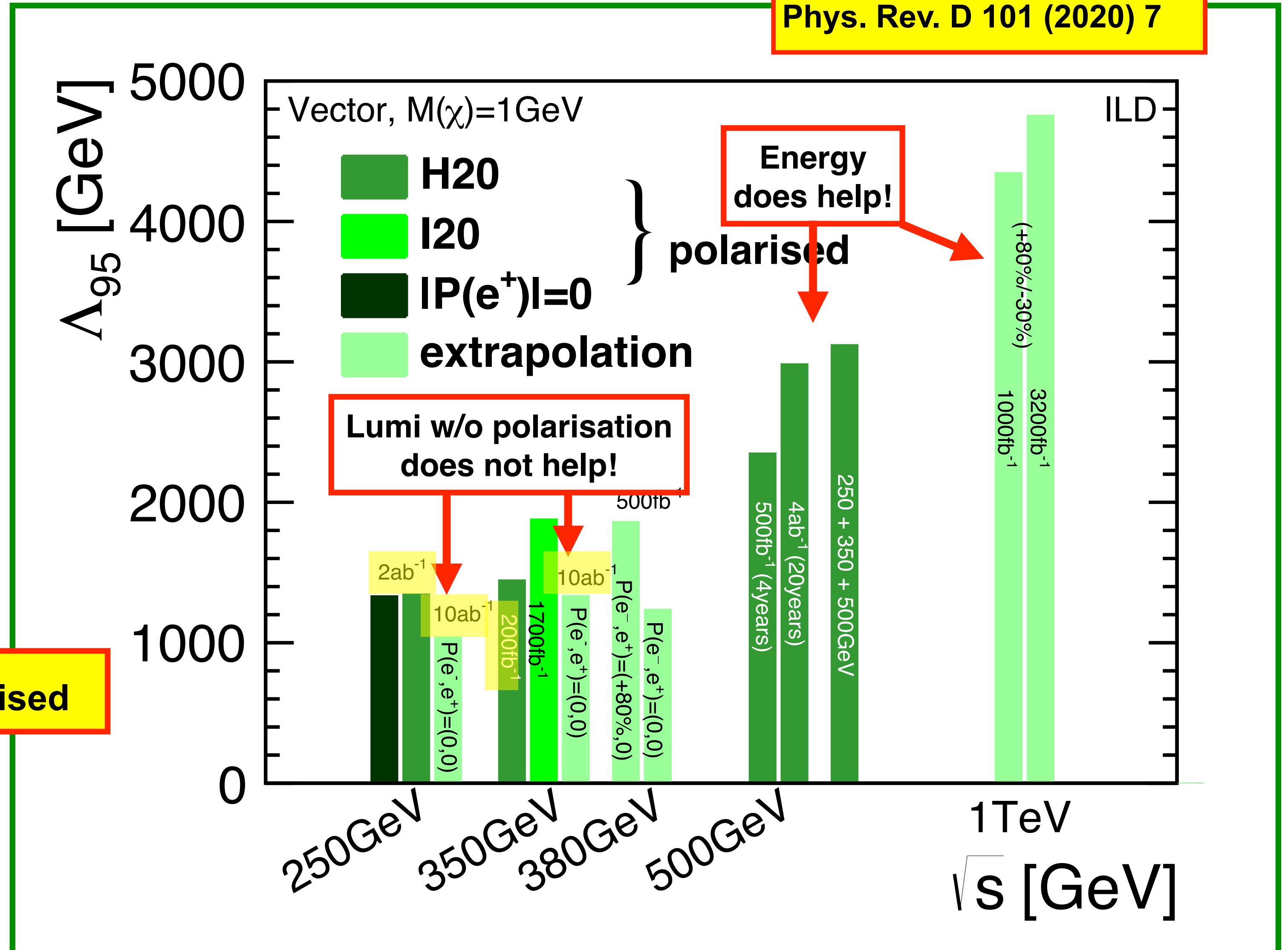
Phys. Rev. D 101 (2020) 7



Polarisation & Beyond the SM: Dark Matter

Example: Impact on reach in vector mediator case

Phys. Rev. D 101 (2020) 7



200 fb⁻¹ polarised \approx 10 ab⁻¹ unpolarised

BSM reach of $ee \rightarrow cc / bb$

arXiv:2403.09144

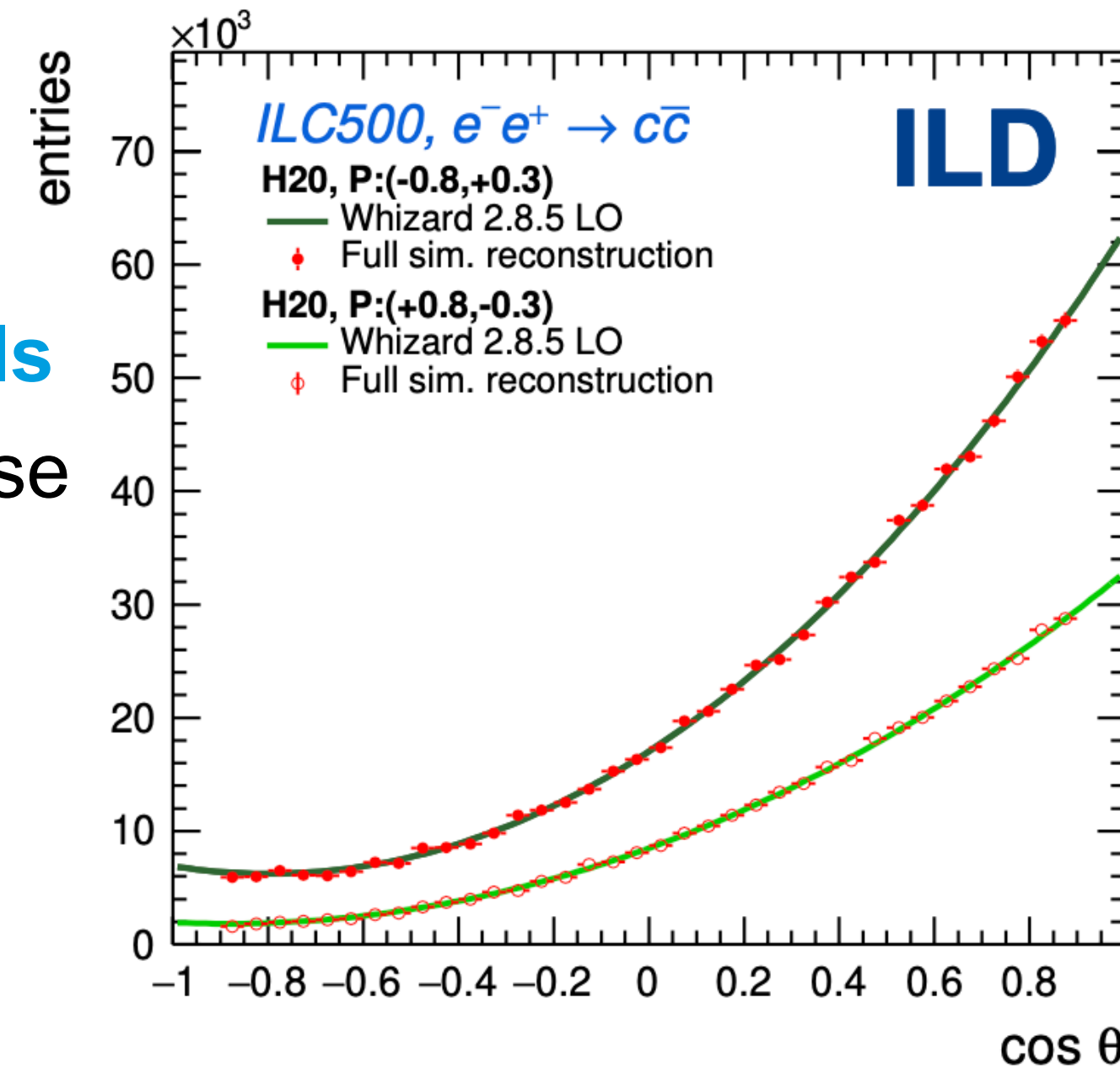
Forward-backward and left-right asymmetries above the Z pole

Study of $ee \rightarrow cc / bb$

- full Geant4-based simulation of **ILD**

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
- Z' as Kaluza-Klein excitations of γ , Z , Z_R
- various model point with $M_{Z'} = 7 \dots 20$ TeV



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Forward-backward and left-right asymmetries above the Z pole

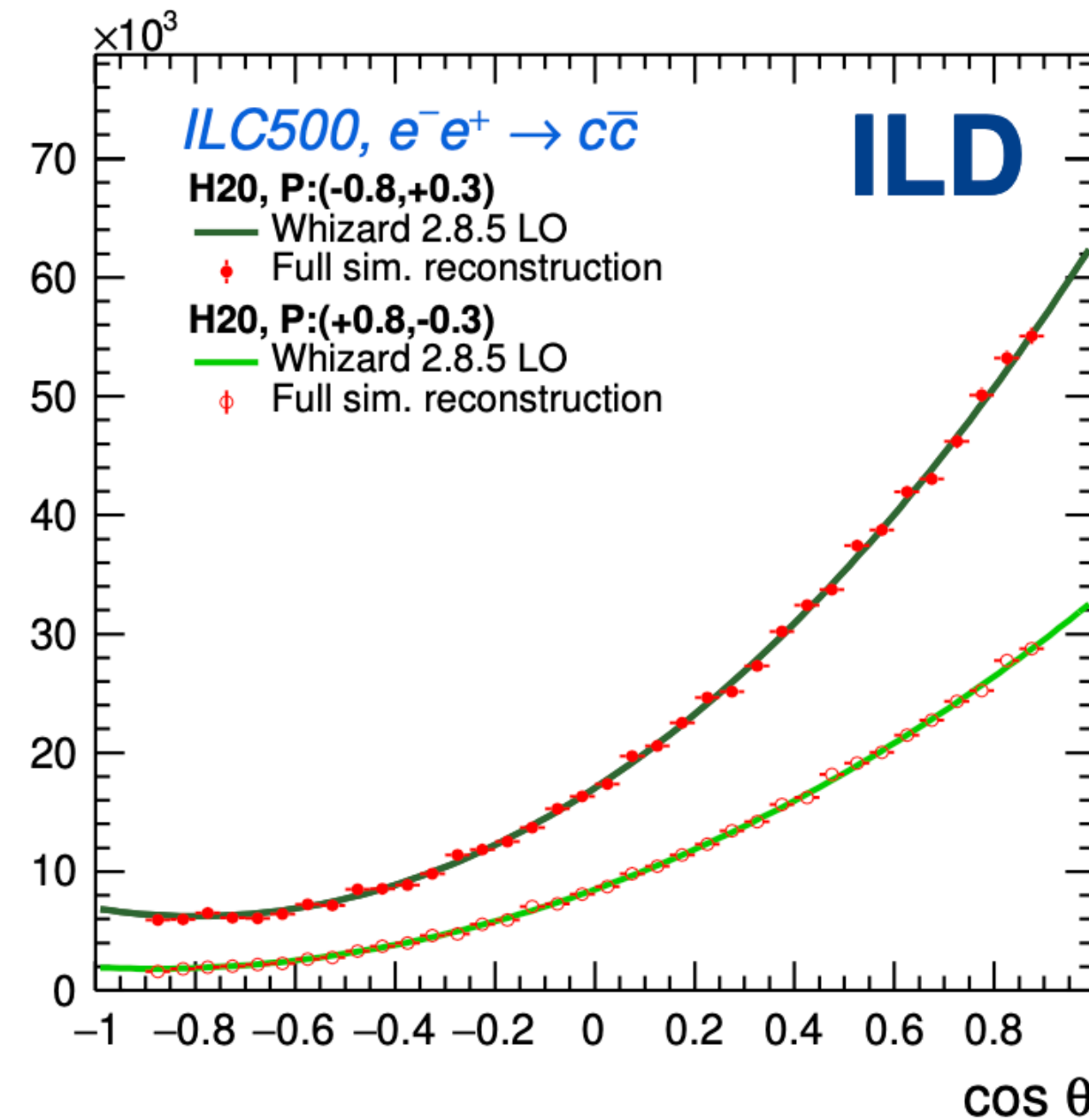
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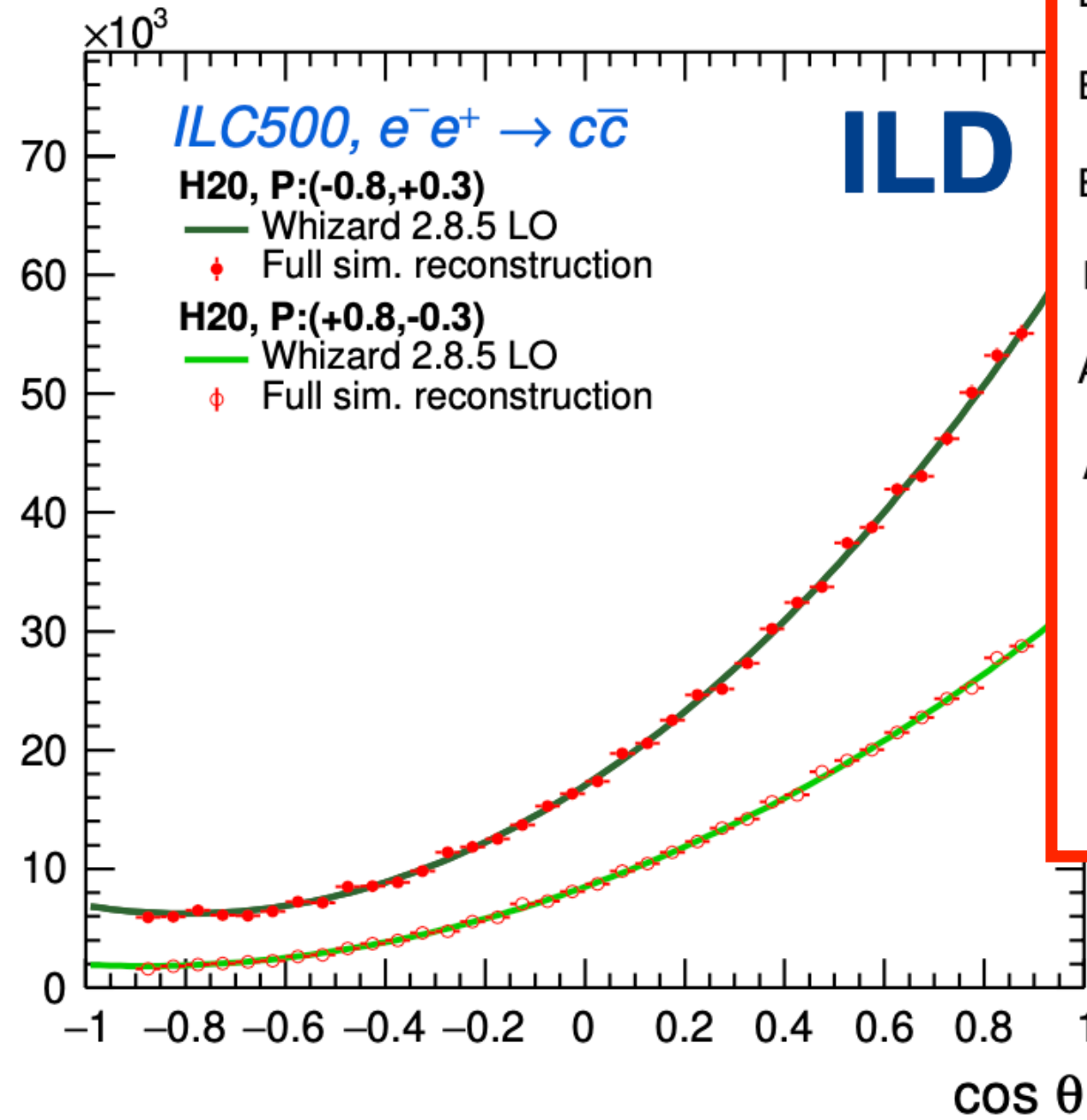
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- various model point with $M_{Z'} = 7 \dots 20$ TeV



GHU vs SM discrimination power (σ -level)

	ILC250 [*] (no pol.)			ILC250 +500			ILC250 +500			ILC250 +1000 [*]		
	O	E	N	O	E	N	O	E	N	O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

Legend for σ -level:
 < 3 σ
 3-4 σ
 4-5 σ
 > 5 σ

Ch. had. PID
 • O: No PID
 • E: $\frac{dE}{dx}$
 • N: $\frac{dN}{dx}$

BSM reach of $ee \rightarrow cc / bb$

arXiv:2403.09144

Forward-backward and left-right asymmetries above the Z pole

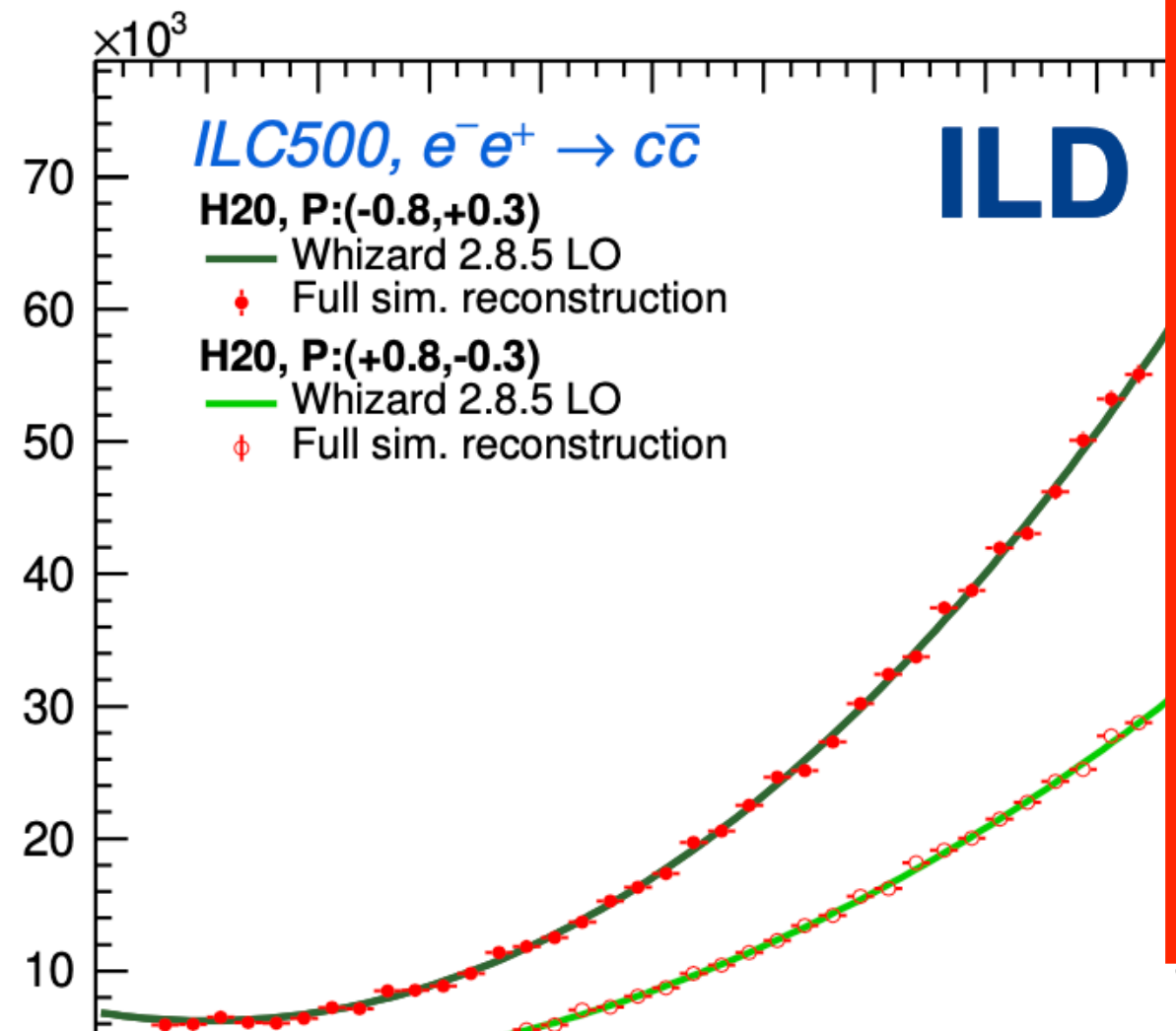
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GHU vs SM discrimination power (σ -level)

B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10
	O	E	N	O	E	N	O	E	N	O	E	N

Legend: Ch. had. PID
 • O: No PID
 • E: $\frac{dE}{dx}$
 • N: $\frac{dN}{dx}$

σ -level: $< 3\sigma$ (dark green), $3-4\sigma$ (medium green), $4-5\sigma$ (light green), $> 5\sigma$ (very light green)

ILC250* (no pol.) ILC250 +500 ILC250 +500 ILC250 +1000*

Between-model discrimination power (σ -level)

B_3^+	3.9	3.2	1.5	1.3	0.9	0.4	0.5
B_3^-	4.1	3.4	1.1	1.4	0.4	0.7	
B_2^+	3.6	2.9	1.6	1.0	1.0		
B_2^-	4.1	3.5	0.7	1.6			
B_1^+	2.7	2.0	1.9				
B_1^-	4.2	3.7					
A_2	0.8						
A_1							

Legend: $< 3\sigma$ (dark green), $3-4\sigma$ (medium green), $4-5\sigma$ (light green), $> 5\sigma$ (very light green)

ILC250* (no pol.) (2000 fb^{-1})

Between-model discrimination power (σ -level)

B_3^+	5.0	4.7	2.5	2.8	1.4	0.9	0.9
B_3^-	5.4	5.1	2.1	3.1	0.7	1.4	
B_2^+	4.3	4.1	2.5	2.1	1.7		
B_2^-	5.4	5.1	1.6	3.1			
B_1^+	2.7	2.4	3.4				
B_1^-	5.3	5.1					
A_2	0.5						
A_1							

Legend: $< 3\sigma$ (dark green), $3-4\sigma$ (medium green), $4-5\sigma$ (light green), $> 5\sigma$ (very light green)

ILC250 (2000 fb^{-1})

Between-model discrimination power (σ -level)

B_3^+	>10	>10	>10	3.9	4.9	1.3	2.9
B_3^-	>10	>10	7.6	5.1	2.4	3.4	
B_2^+	>10	>10	>10	3.0	5.2		
B_2^-	>10	>10	5.4	6.4			
B_1^+	>10	>10	>10				
B_1^-	>10	>10					
A_2	2.9						
A_1							

Legend: $< 3\sigma$ (dark green), $3-4\sigma$ (medium green), $4-5\sigma$ (light green), $> 5\sigma$ (very light green)

ILC250+500 (2000 fb^{-1} + 4000 fb^{-1})

Between-model discrimination power (σ -level)

B_3^+	>10	>10	>10	5.4	>10	2.7	7.6
B_3^-	>10	>10	>10	>10	6.7	8.6	
B_2^+	>10	>10	>10	4.1	>10		
B_2^-	>10	>10	>10	>10			
B_1^+	>10	>10	>10				
B_1^-	>10	>10					
A_2	>10						
A_1							

Legend: $< 3\sigma$ (dark green), $3-4\sigma$ (medium green), $4-5\sigma$ (light green), $> 5\sigma$ (very light green)

ILC250+500+1000* (2000 fb^{-1} + 4000 fb^{-1} + 8000 fb^{-1})

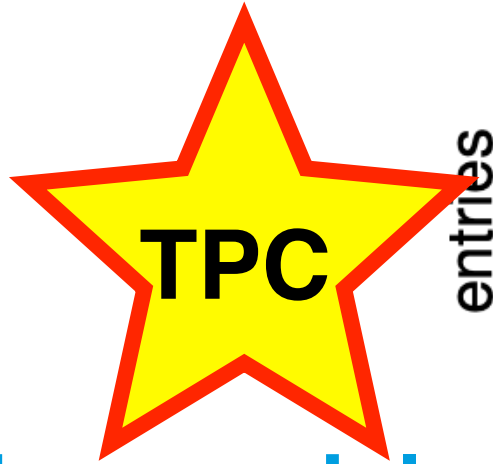
BSM reach of $ee \rightarrow cc / bb$

arXiv:2403.09144

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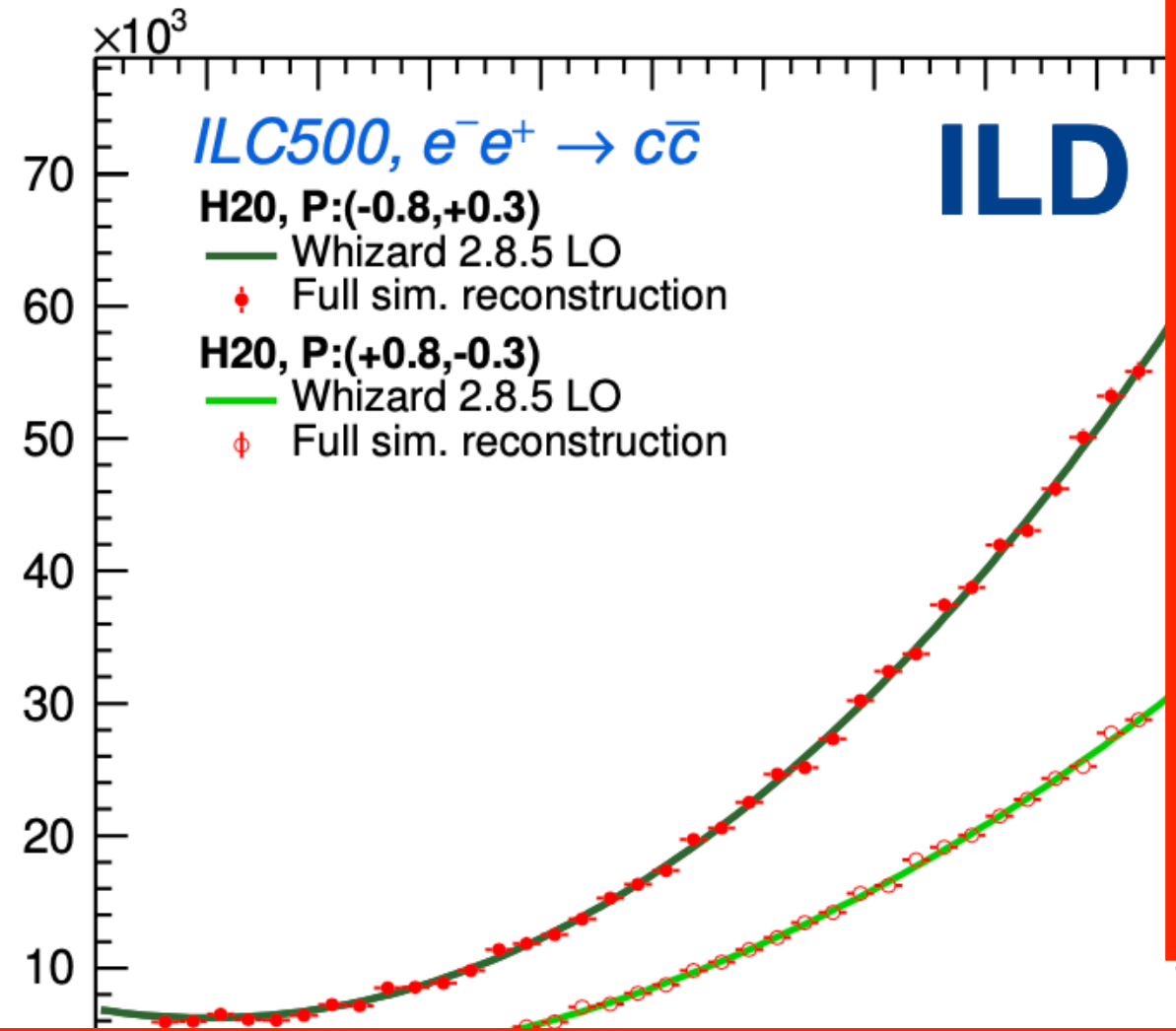
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- Z' as Kaluza-Klein excitations of γ, Z, Z_R
- various model point with $\sqrt{s} = 7 \dots 20$ TeV



GHU vs SM discrimination power (σ -level)

B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10
	O	E	N	O	E	N	O	E	N	O	E	N

Ch. had. PID
 • O: No PID
 • E: $\frac{dE}{dx}$
 • N: $\frac{dN}{dx}$

Legend:
 3σ (dark green)
 3-4 σ (medium green)
 4-5 σ (light green)
 > 5 σ (very light green)

ILC250* (no pol.) ILC250 +500 ILC250 +500 ILC250 +1000*

polarisation

Between-model discrimination power (σ -level)

B_3^+	3.9	3.2	1.5	1.3	0.9	0.7
B_3^-	4.1	3.4	1.1	1.4	0.4	0.7
B_2^+	3.6	2.9	1.6	1.0	1.0	
B_2^-	4.1	3.5	0.7	1.6		
B_1^+	2.7	2.0	1.9			
B_1^-	4.2	3.7				
A_2	0.8					
A_1						

Legend:
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 > 5 σ (very light green)

ILC250* (no pol.)
(2000 fb^{-1})

Between-model discrimination power (σ -level)

D_3	5.4	5.1	2.1	3.1	0.7	1.4
B_2^+	4.3	4.1	2.5	2.1	1.7	
B_2^-	5.4	5.1	1.6	3.1		
B_1^+	2.7	2.4	3.4			
B_1^-	5.3	5.1				
A_2	0.5					
A_1						

Legend:
 3σ (dark green)
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 > 5 σ (very light green)

ILC250
(2000 fb^{-1})

Between-model discrimination power (σ -level)

B_3^+	>10	>10	>10	3.9	4.9	1.3	2.9
B_3^-	>10	>10	7.6	5.1	2.4	3.4	
B_2^+	>10	>10	>10	3.0	5.2		
B_2^-	>10	>10	5.4	6.4			
B_1^+	>10	>10	>10				
B_1^-	>10	>10					
A_2	2.9						
A_1							

Legend:
 3σ (dark green)
 3-4 σ (medium green)
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ILC250+500
(2000 fb^{-1} + 4000 fb^{-1})

Between-model discrimination power (σ -level)

B_3^+	>10	>10	>10	5.4	>10	2.7	7.6
B_3^-	>10	>10	>10	>10	6.7	8.6	
B_2^+	>10	>10	>10	4.1	>10		
B_2^-	>10	>10	>10	>10			
B_1^+	>10	>10	>10				
B_1^-	>10	>10					
A_2	>10						
A_1							

Legend:
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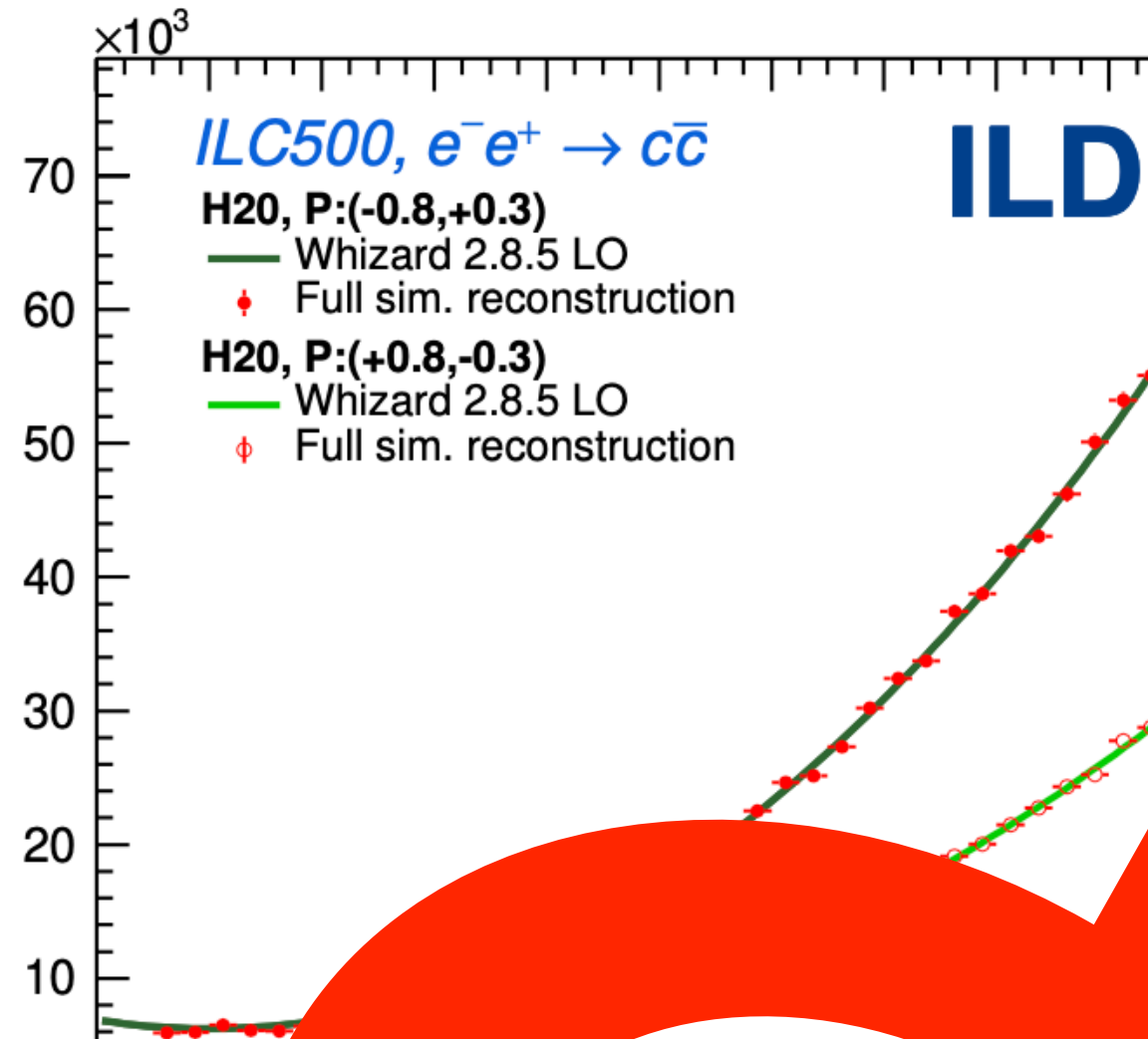
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B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
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B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10
	O	E	N	O	E	N	O	E	N	O	E	N

Legend: \bullet O: No PID, \bullet E: $\frac{dE}{dx}$, \bullet N: $\frac{dN}{dx}$

σ -level: \blacksquare < 3 σ , \square 3-4 σ , \square 4-5 σ , \square > 5 σ

ILC250* (no pol.) ILC250 +500 ILC250 +500 ILC250 +1000*

Between-model discrimination power (σ -level)

B_3^+	3.9	3.2	1.5	1.3	0.9	0.7	2.5	2.8	1.4	0.9	0.9	
B_3^-	4.1	3.4	1.1	1.4	0.4	0.7	5.4	5.1	2.1	3.1	0.7	1.4
B_2^+	3.6	2.9	1.6	1.0	1.0	4.3	4.1	2.5	2.1	1.7		
B_2^-	4.1	3.5	0.7	1.6	5.4	5.1	1.6	3.1				
B_1^+	2.7	2.0	1.9	2.7	2.4	3.4						
B_1^-	4.2	3.7	5.3	5.1								
A_2	0.8	0.5										
A_1												

Legend: \blacksquare < 3 σ , \square 3-4 σ , \square 4-5 σ , \square > 5 σ

ILC250* (no pol.) (2000 fb^{-1}) ILC250 (2000 fb^{-1})

energy

Between-model discrimination power (σ -level)

B_3^+	>10	>10	>10	4.9	1.3	2.9
B_3^-	>10	>10	7.6	5.1	2.4	3.4
B_2^+	>10	>10	>10	3.0	5.2	
B_2^-	>10	>10	5.4	6.4		
B_1^+	>10	>10	>10			
B_1^-	>10	>10				
A_2	2.9					
A_1						

Legend: \blacksquare < 3 σ , \square 3-4 σ , \square 4-5 σ , \square > 5 σ

ILC250+500 (2000 fb^{-1} + 4000 fb^{-1})

Between-model discrimination power (σ -level)

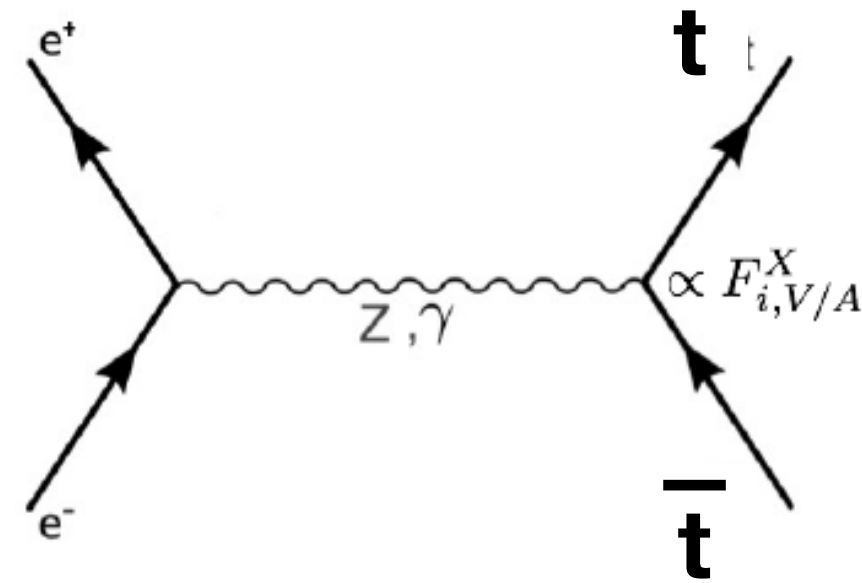
B_3^+	>10	>10	>10	5.4	>10	2.7	7.6
B_3^-	>10	>10	>10	>10	6.7	8.6	
B_2^+	>10	>10	>10	4.1	>10		
B_2^-	>10	>10	>10	>10			
B_1^+	>10	>10	>10				
B_1^-	>10	>10					
A_2	>10						
A_1							

Legend: \blacksquare < 3 σ , \square 3-4 σ , \square 4-5 σ , \square > 5 σ

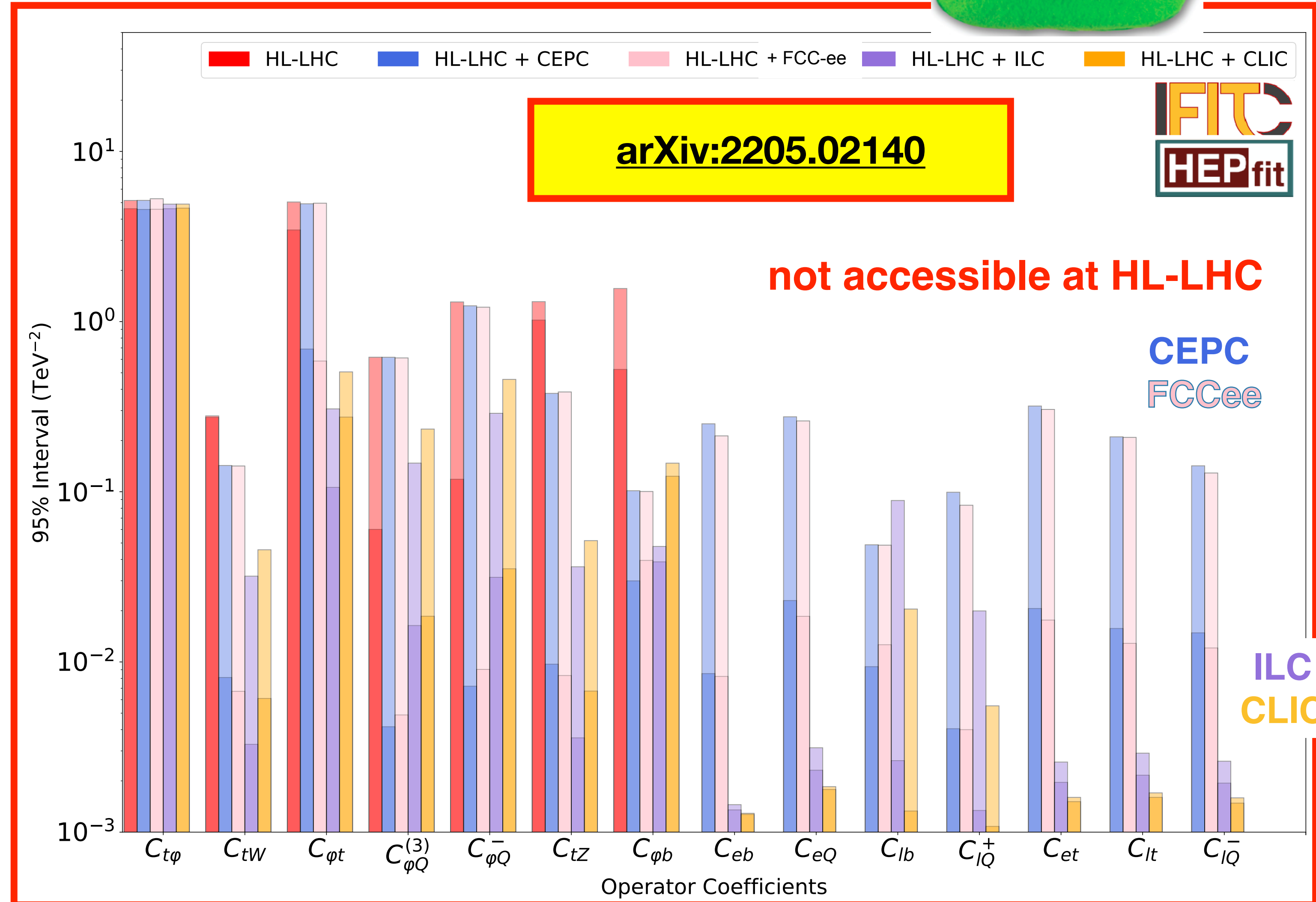
ILC250+500+1000* (2000 fb^{-1} + 4000 fb^{-1} + 8000 fb^{-1})

Full SMEFT analysis of Top Quark sector

Essential to understand special relation of top quark and Higgs boson

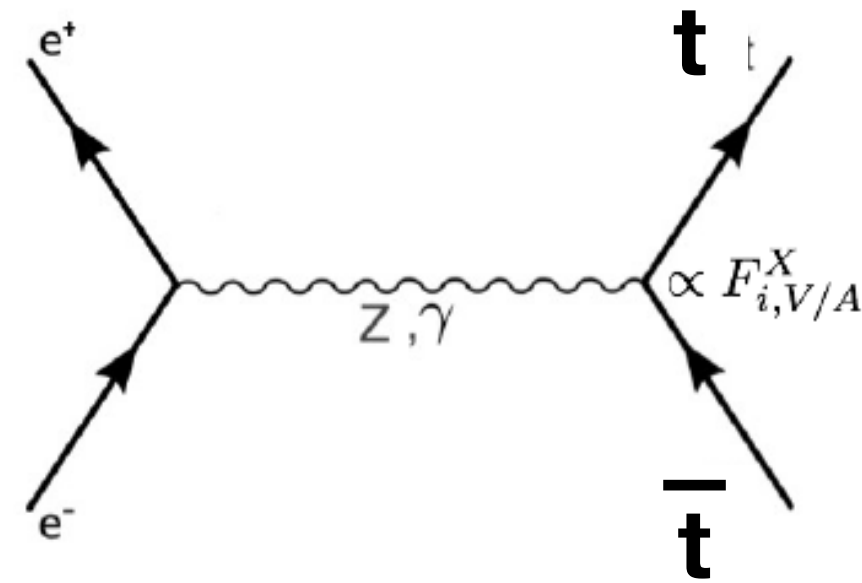


- expected precision on Wilson coefficients for HL-LHC alone and combined with various e+e- proposals
- e+e- at **high center-of-mass energy** and with **polarised beams** lifts degeneracies between operators



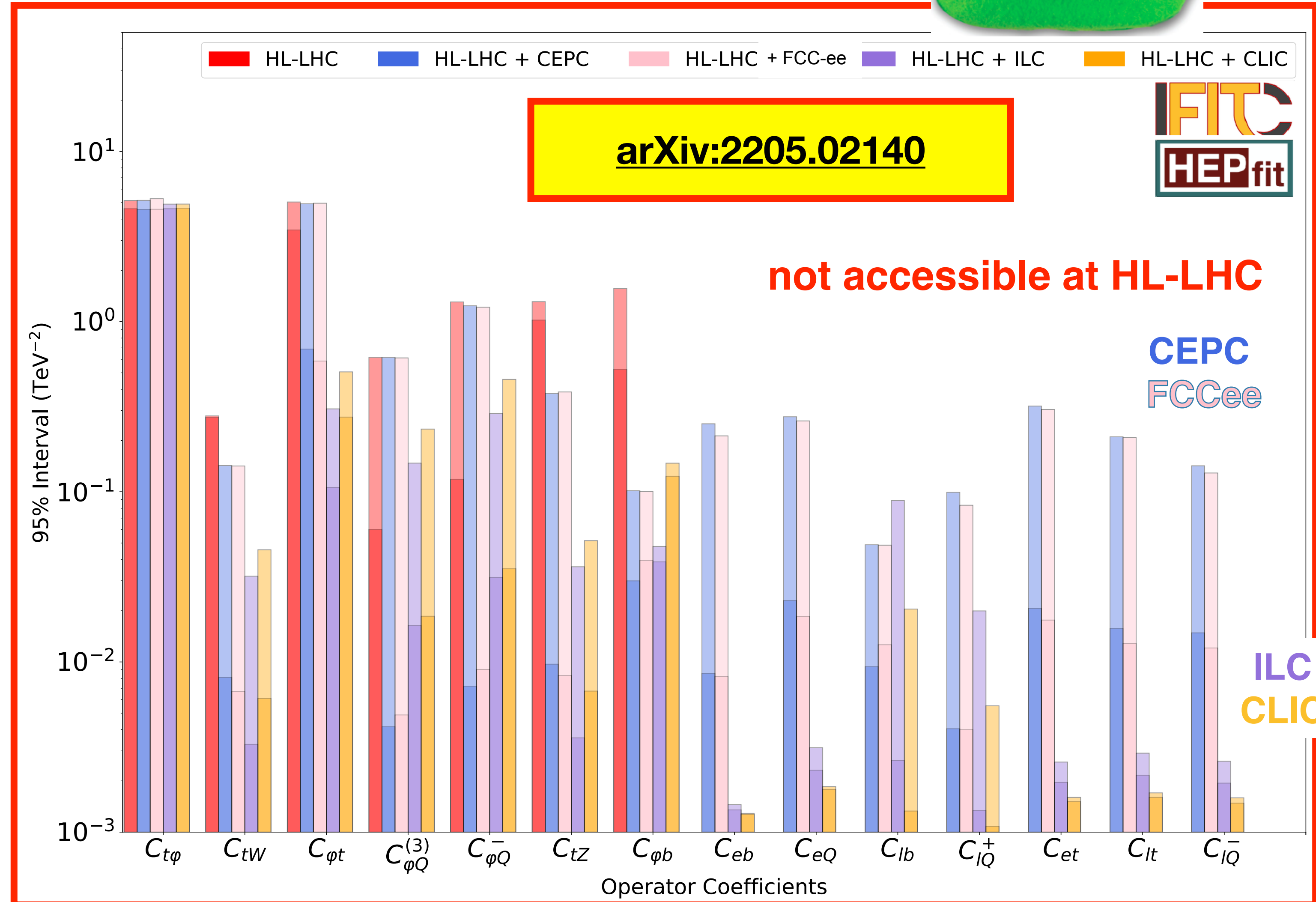
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top-quark physics requires high center-of-mass energy AND polarised beams

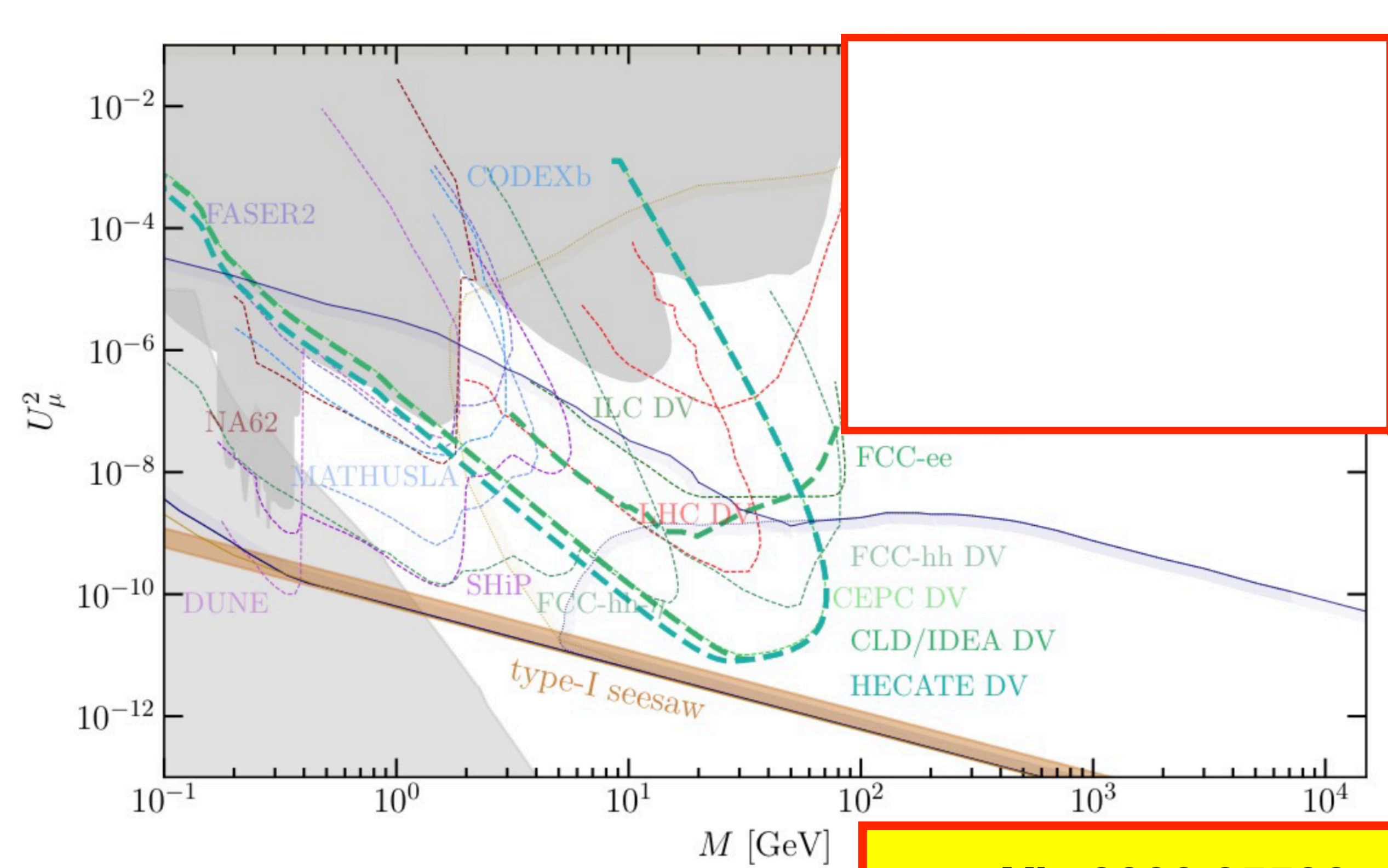


Heavy Neutral Leptons

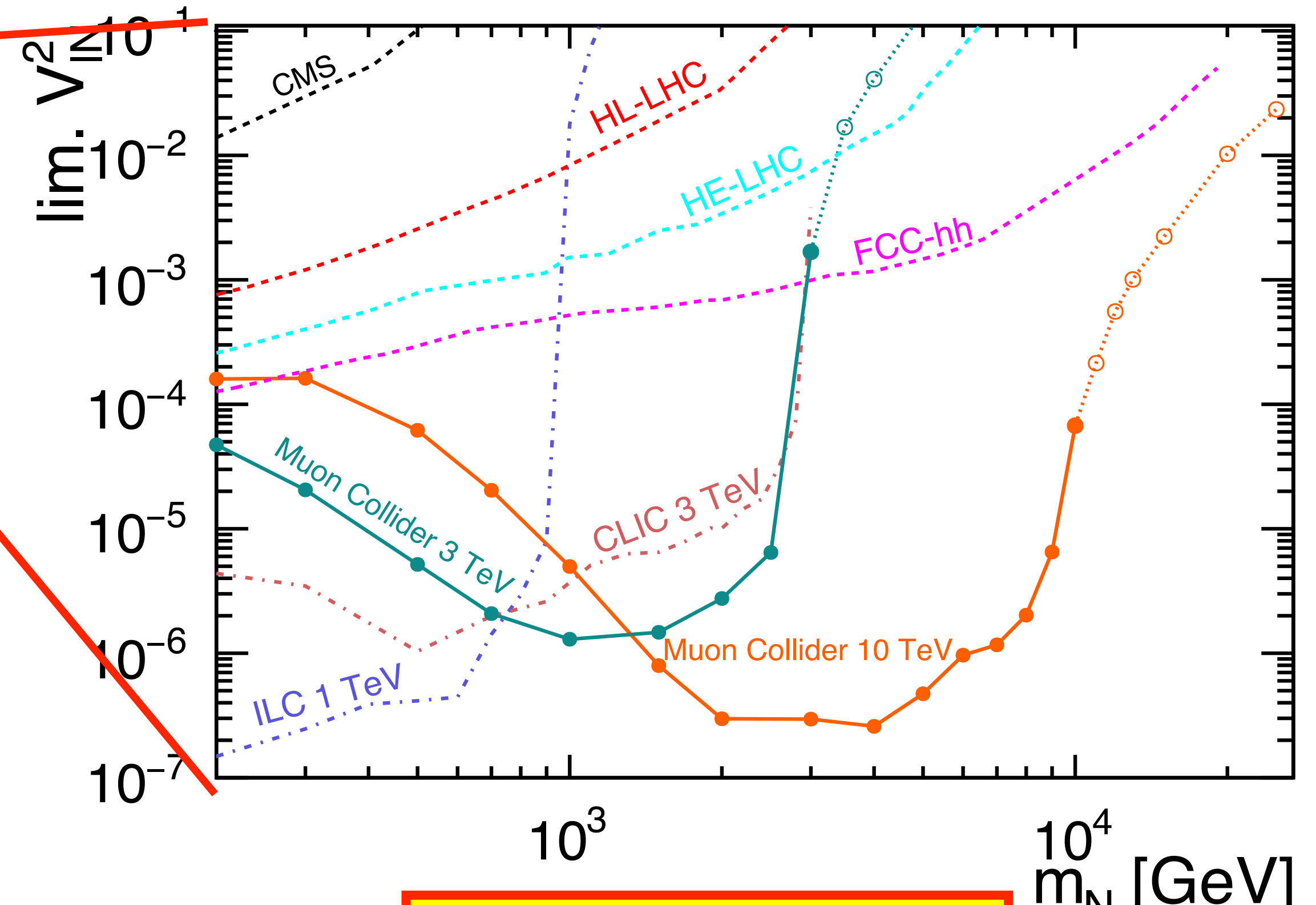
Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices...

...and at high masses in prompt decays



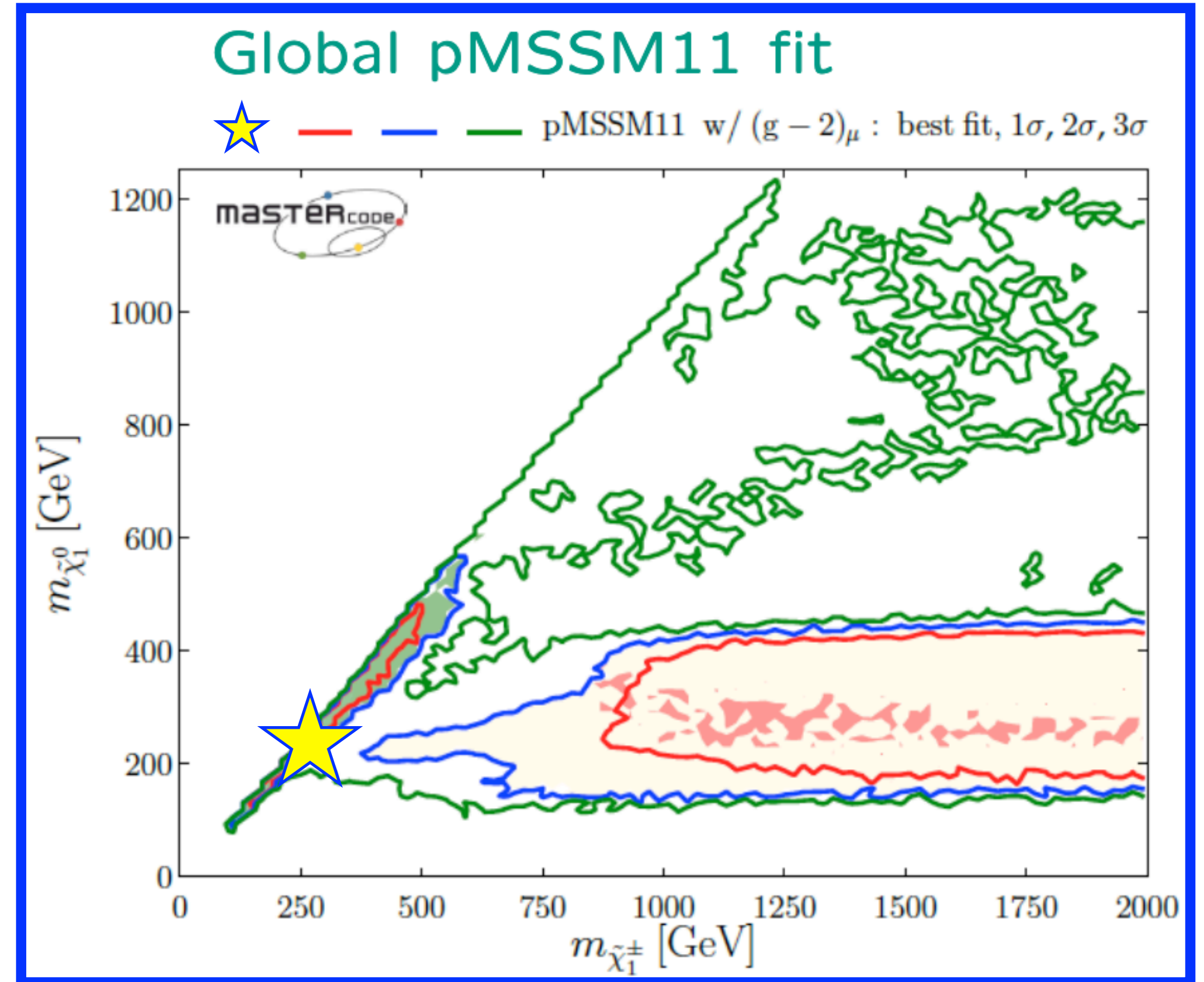
[arXiv:2203.05502](https://arxiv.org/abs/2203.05502)



[arXiv:2301.02602](https://arxiv.org/abs/2301.02602)

Higgsinos ?

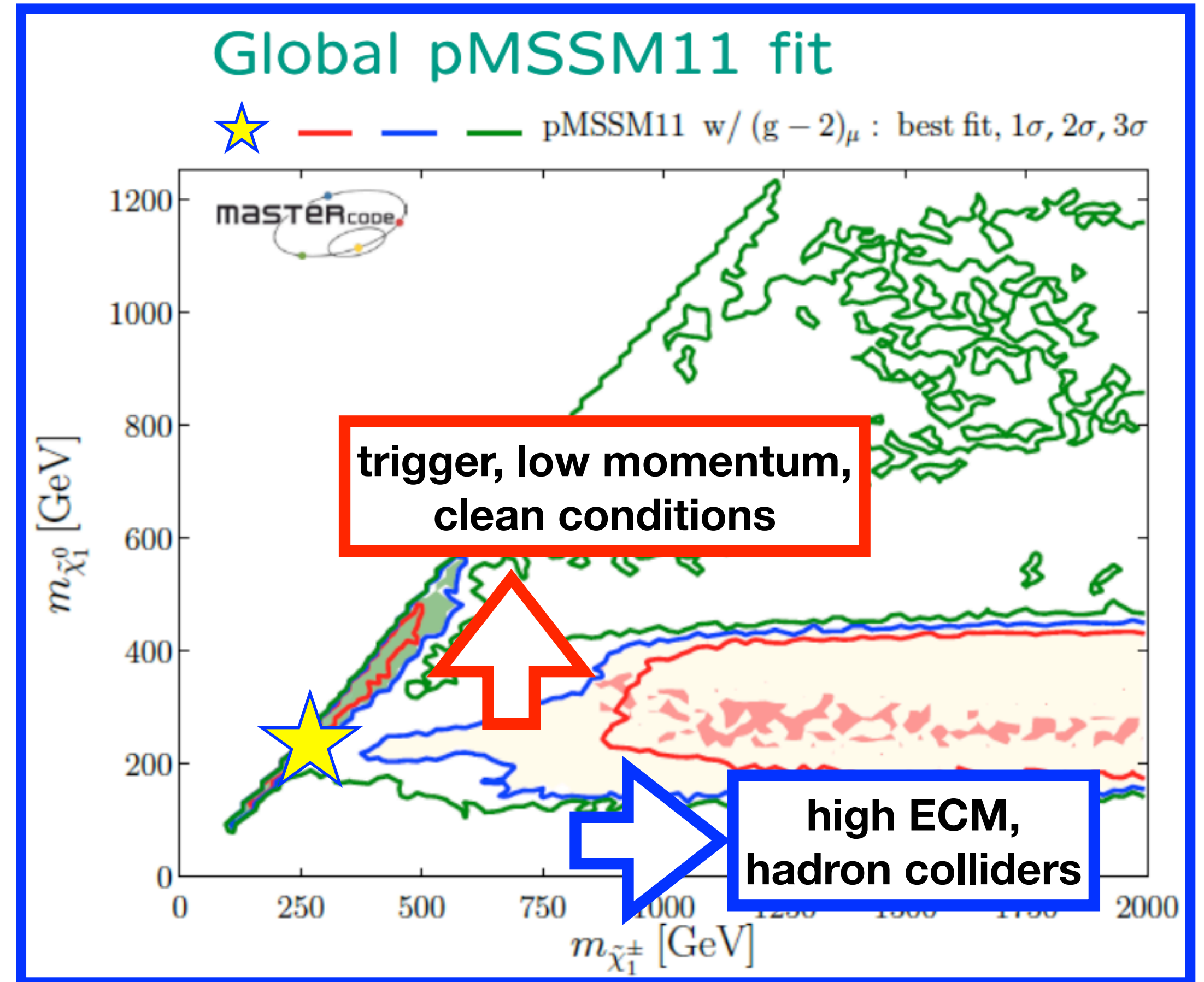
- lowish ΔM is THE region preferred by data, e.g. for charginos & neutralinos
=> no *general* limit above LEP



Eur.Phys.J. C78 (2018) no.3, 256

Higgsinos ?

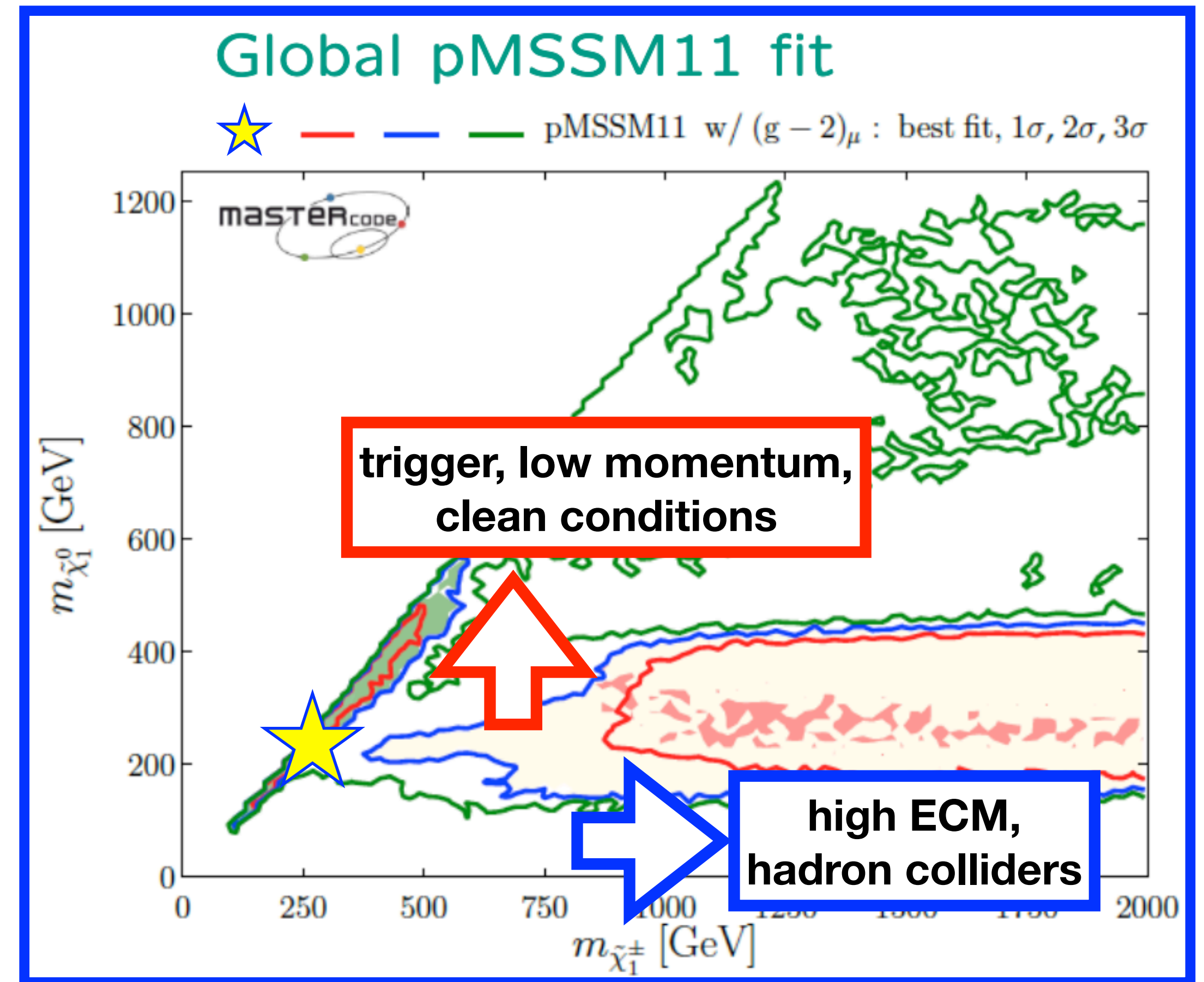
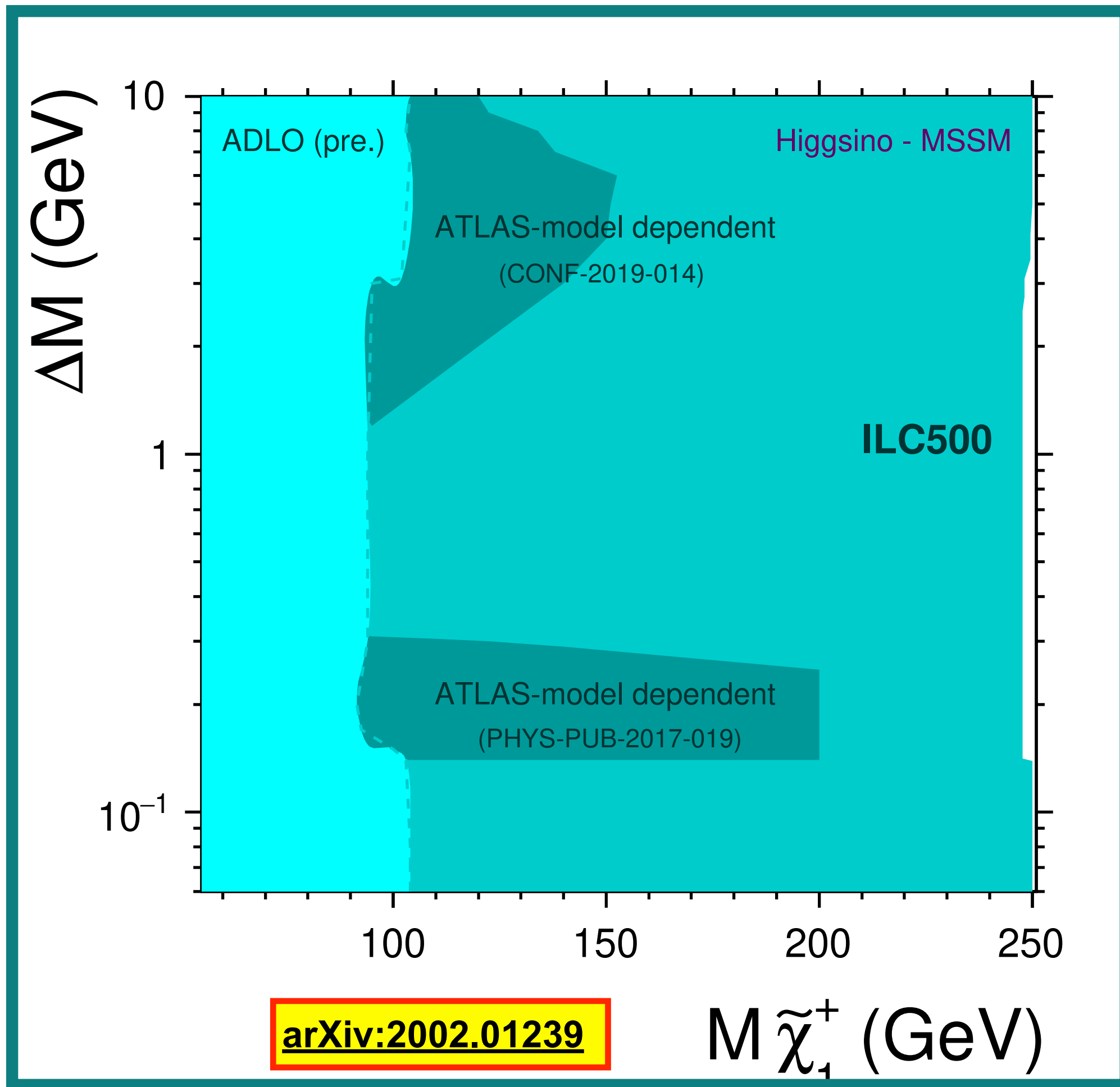
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Eur.Phys.J. C78 (2018) no.3, 256

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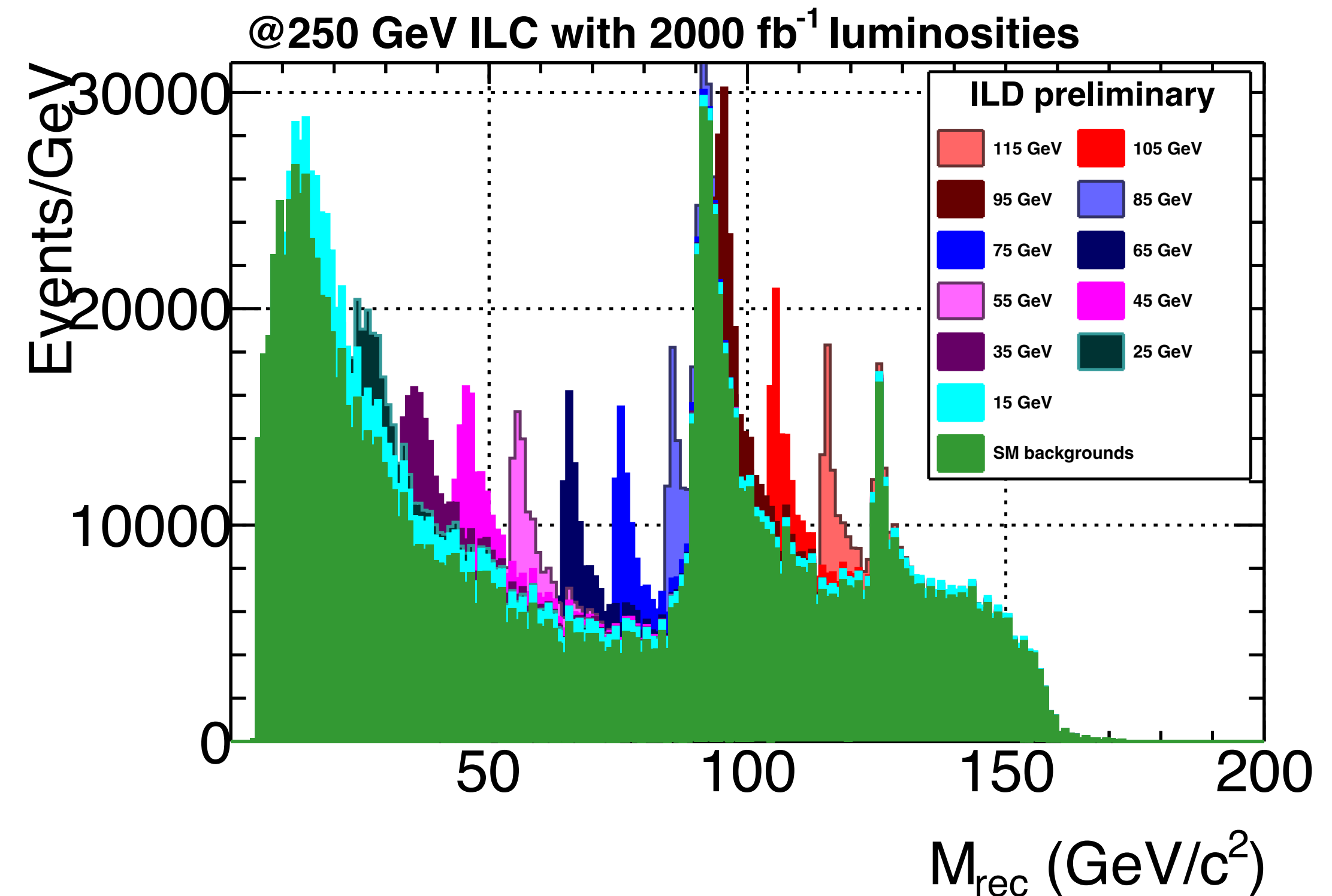
Eur.Phys.J. C78 (2018) no.3, 256

Extra Higgs Bosons ?

Siblings of the Higgs

- must “share” coupling to the Z with the 125-GeV guy:
 - $g_{HZZ}^2 + g_{hZZ}^2 \leq 1$
 - 250 GeV Higgs measurements:
 $g_{hZZ}^2 < 2.5\% g_{SM}^2$ excluded at 95% CL
- probe smaller couplings by **recoil of h against Z**
=> decay mode independent!

- fully complementary to measurement of ZH cross section
- other possibility: $ee \rightarrow bbh$ (via Yukawa coupling)

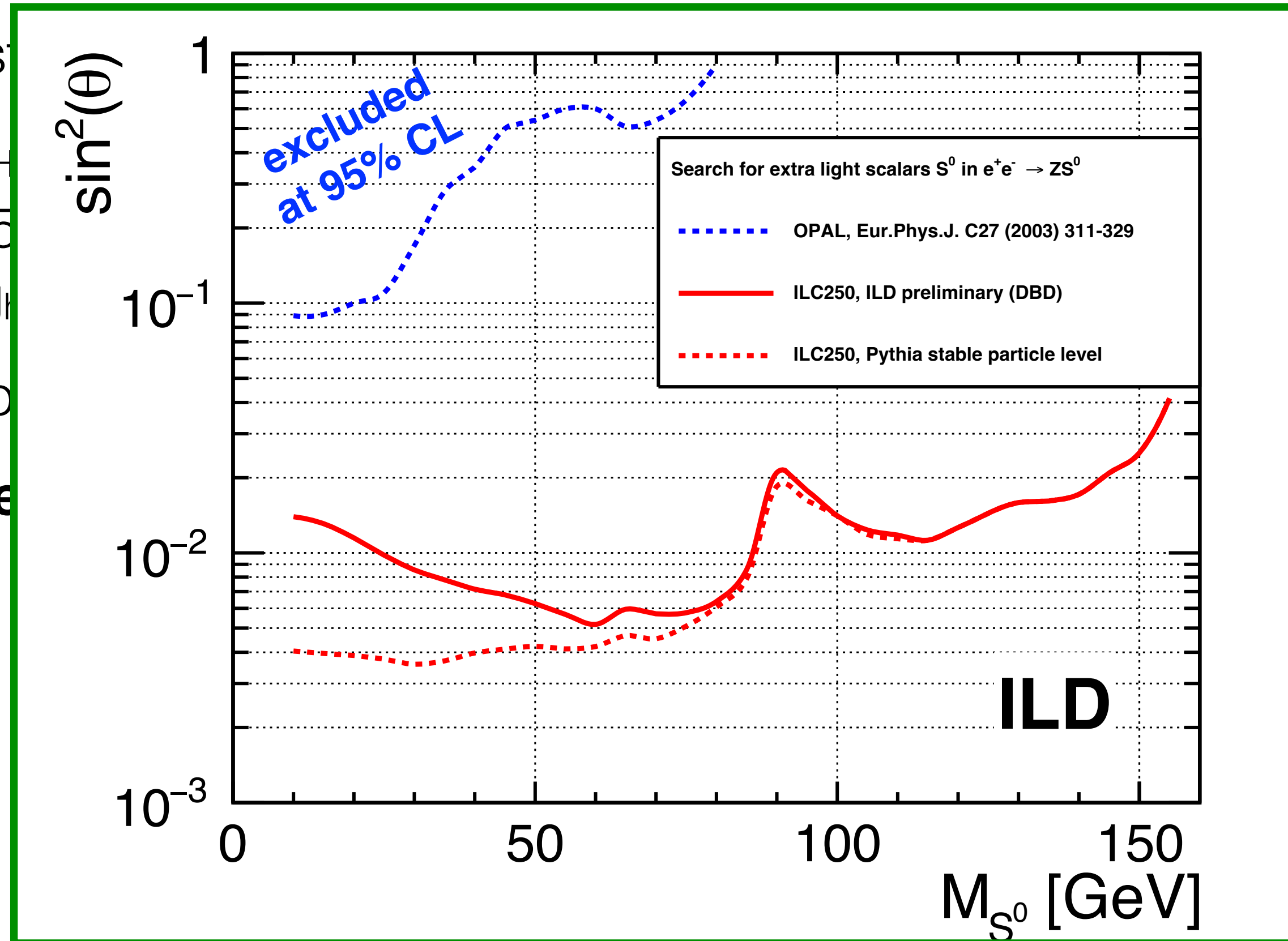


ILD full detector simulation
@ ILC 250 GeV & 500 GeV,
[arxiv:2005.06265](https://arxiv.org/abs/2005.06265)

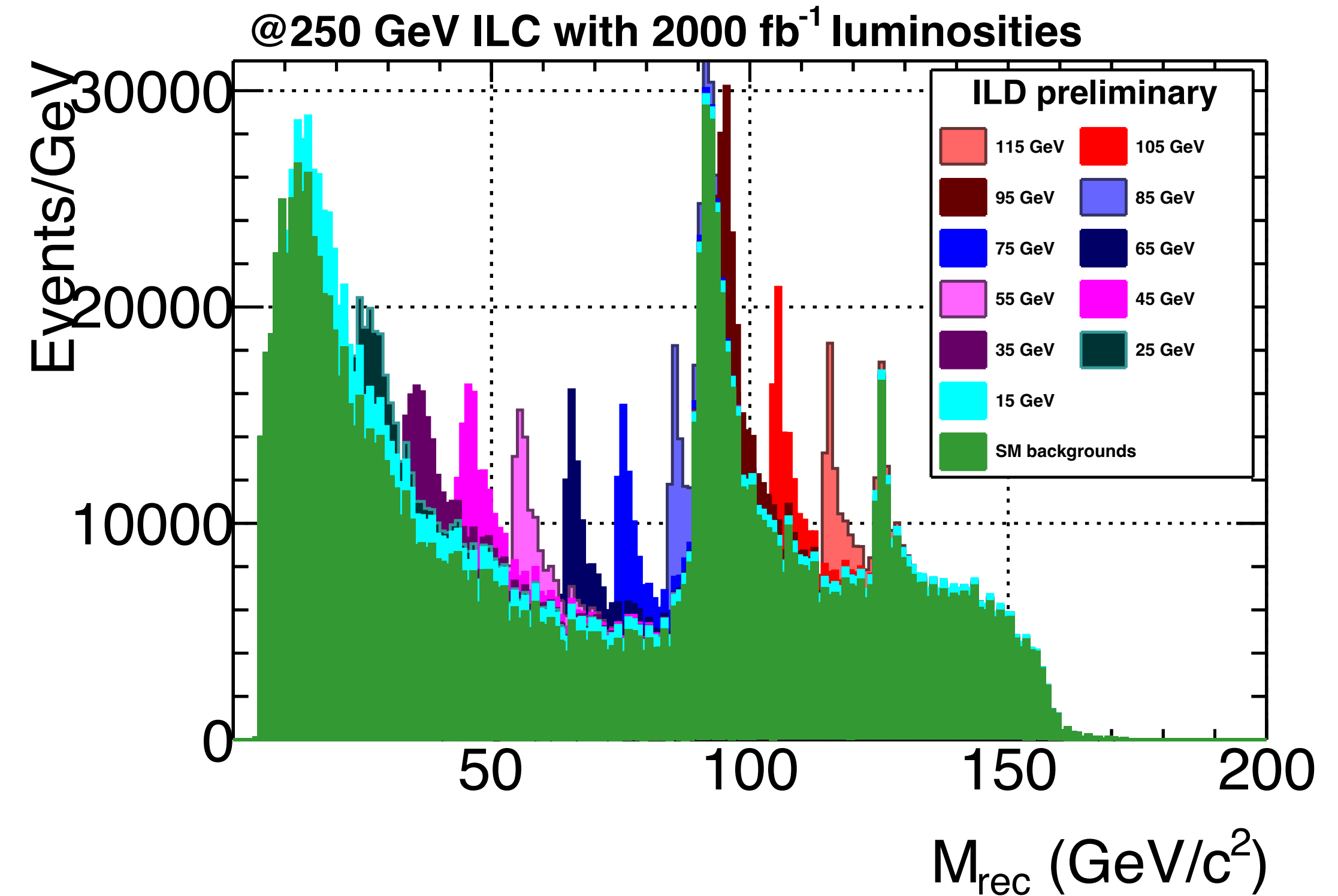
Extra Higgs Bosons ?

Siblings of the Higgs

- μ_{S^0}
- $g_{H^0 S^0 S^0}$
- 25
- $g_{H^0 S^0 S^0}$
- prob
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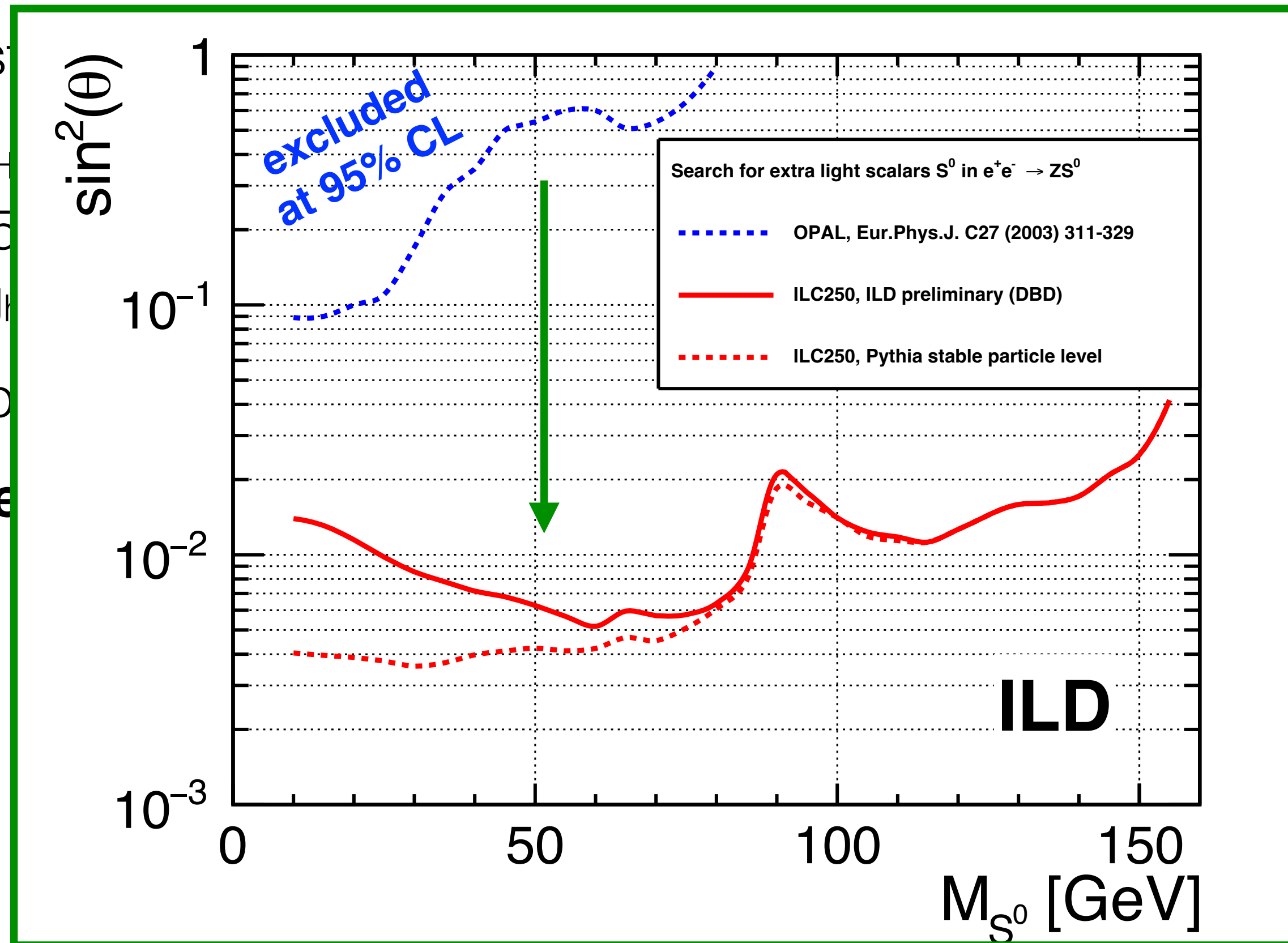


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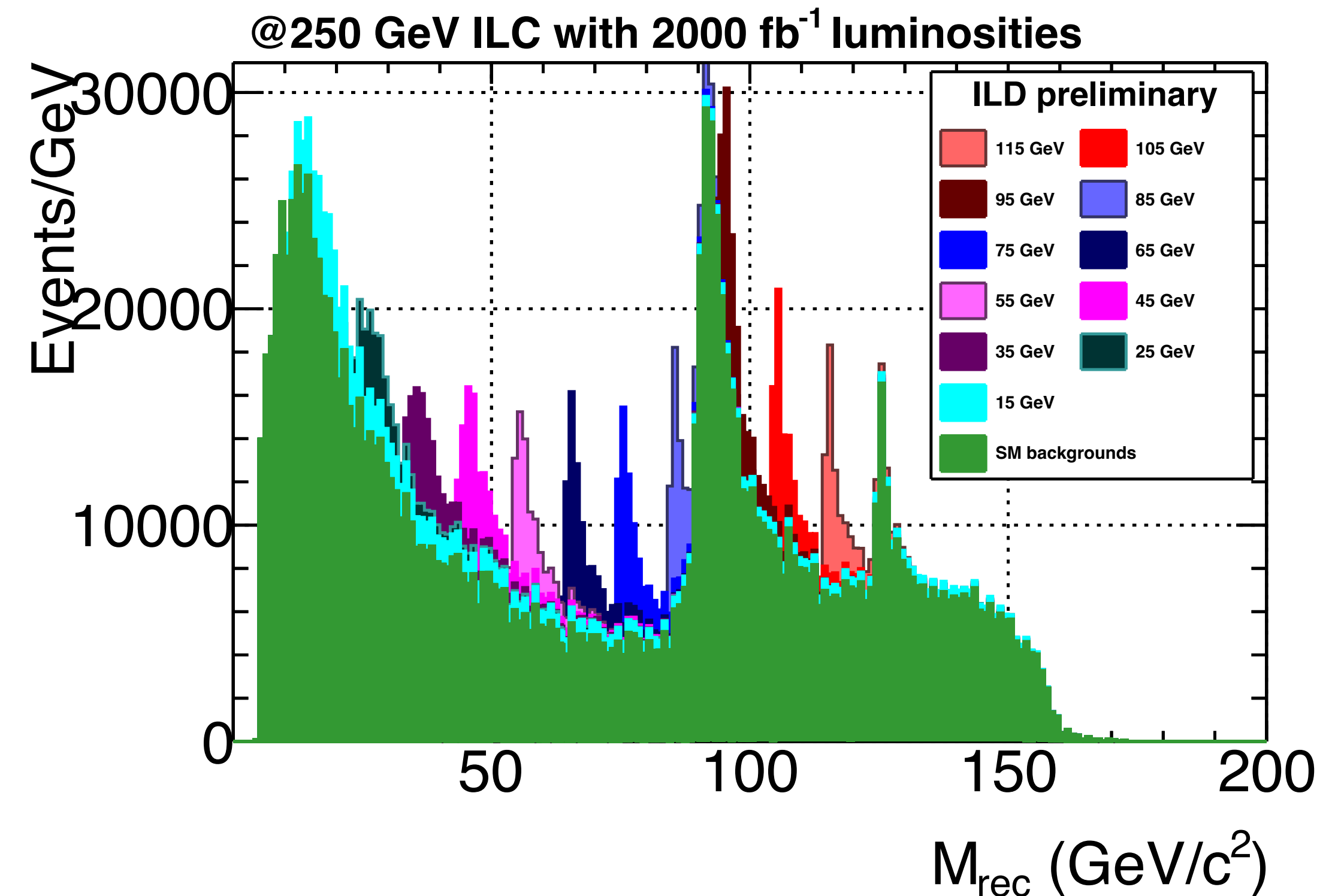
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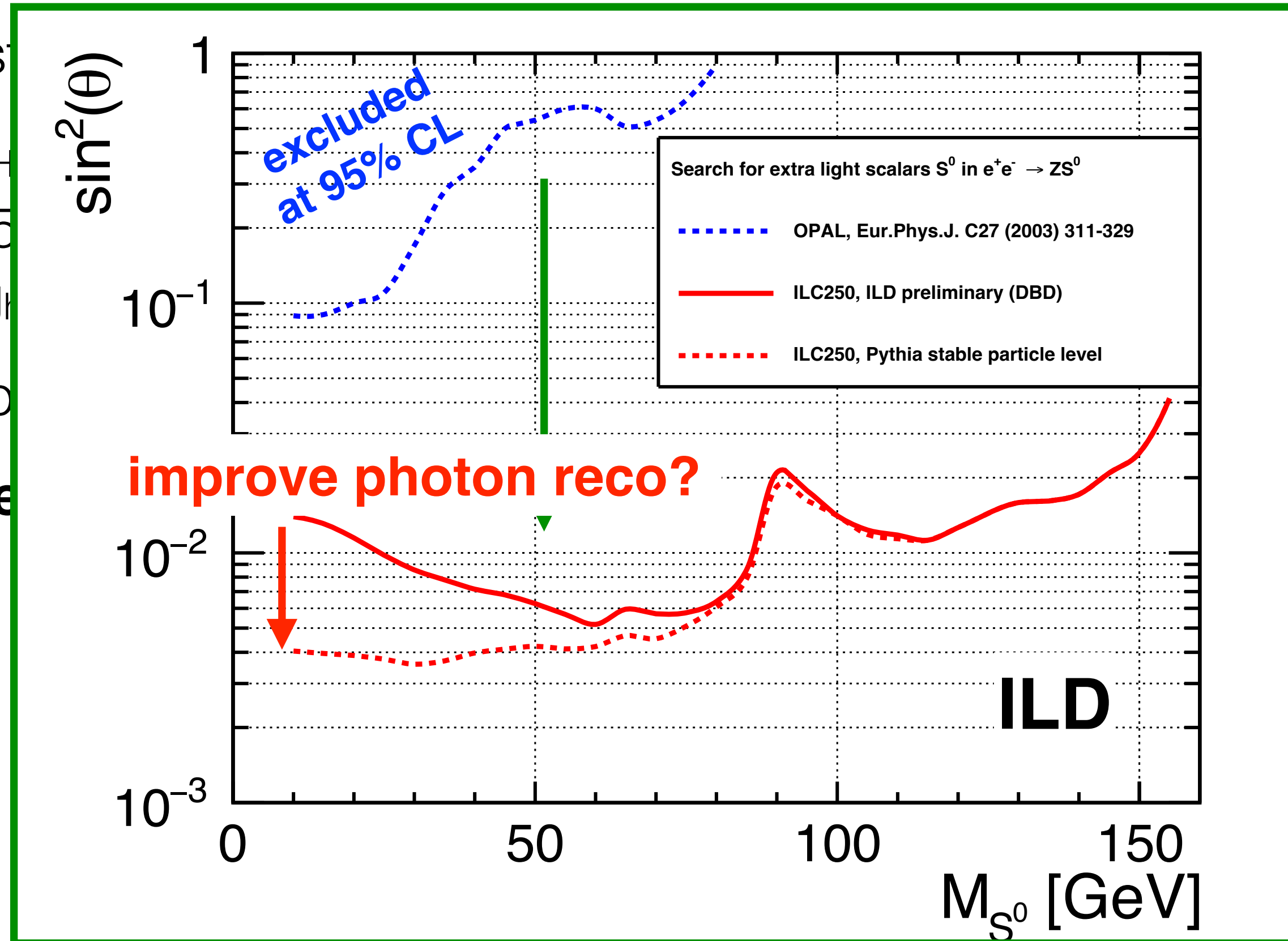


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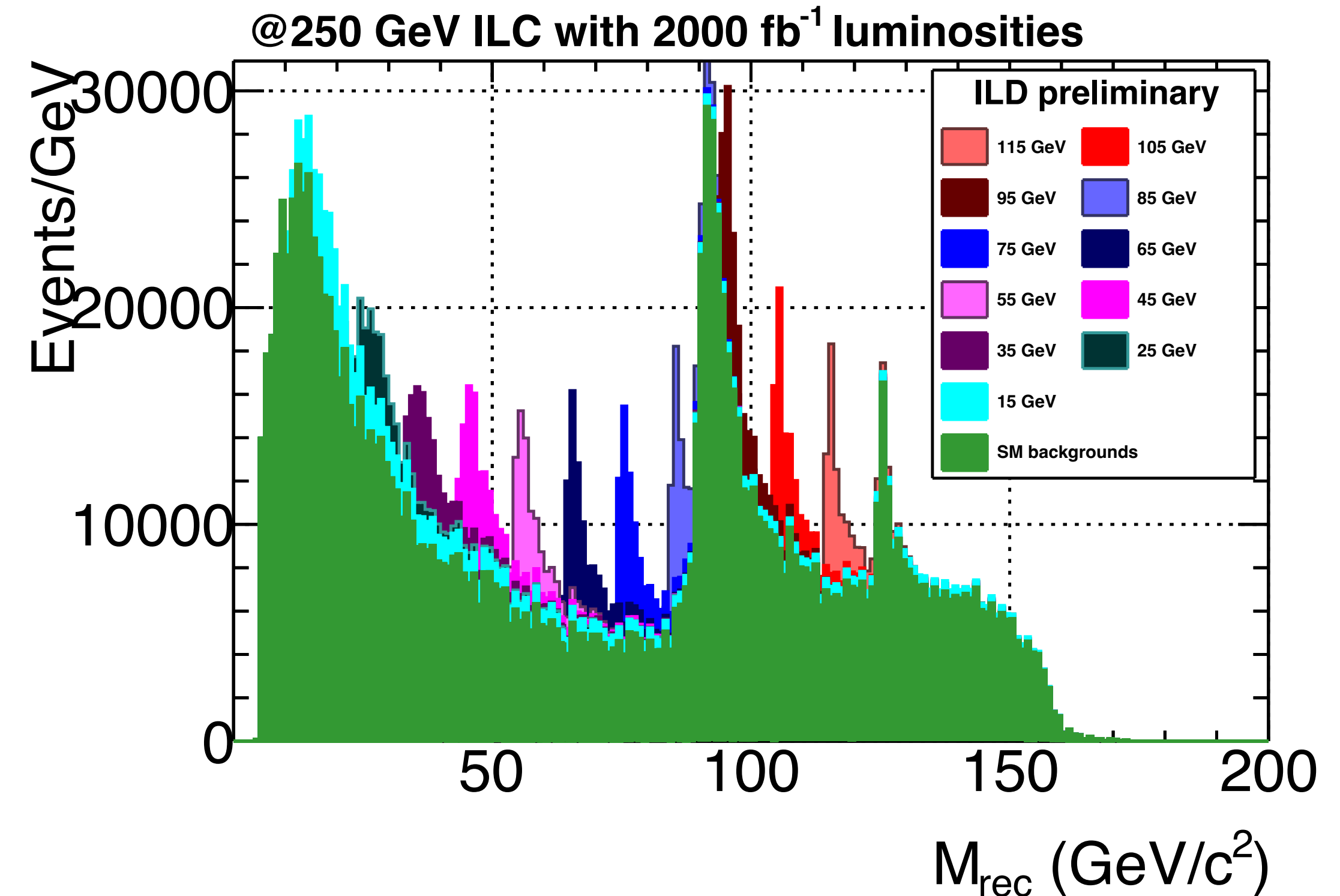
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Why do we need to know the couplings of the Higgs boson?

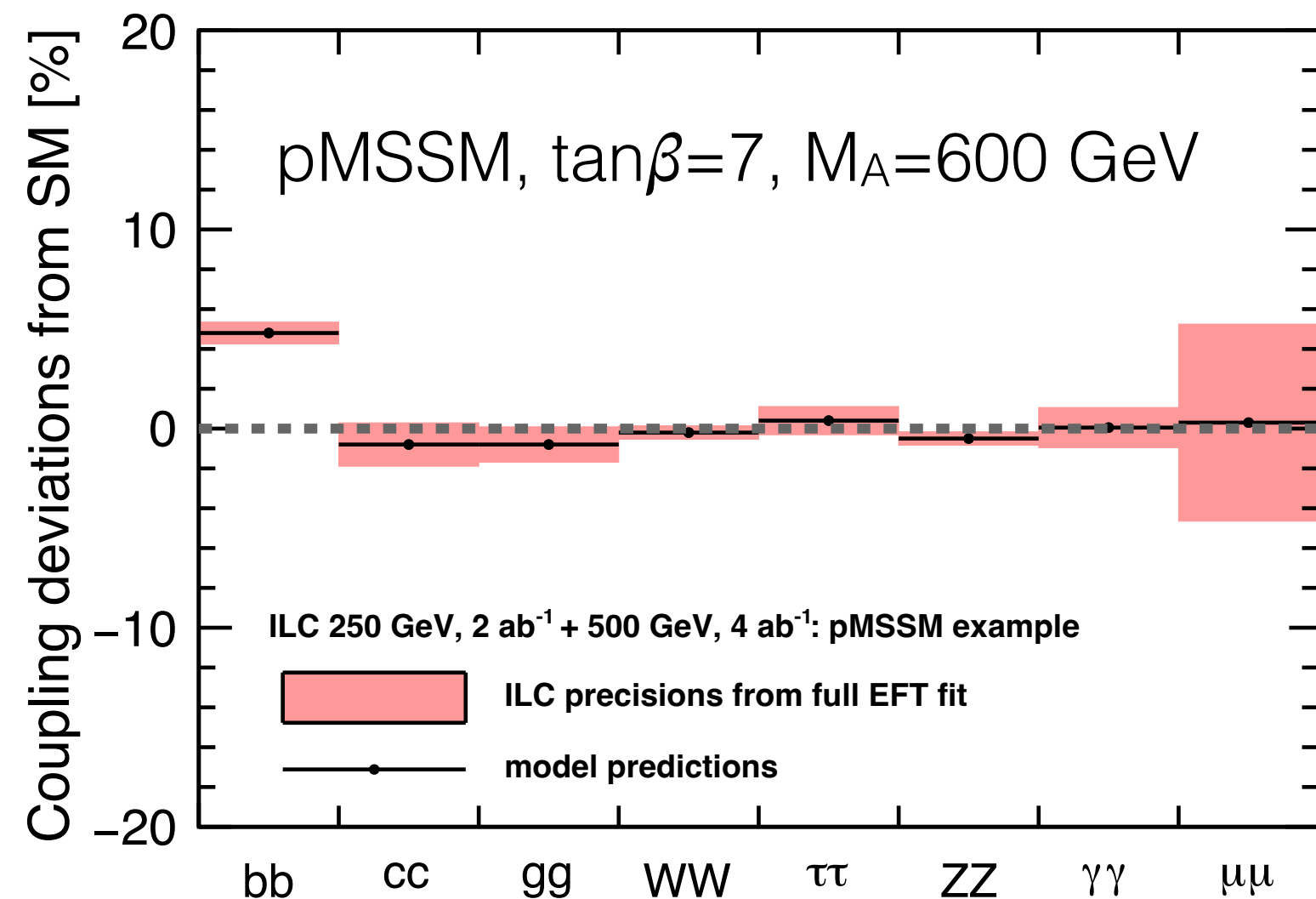
Discovering new phenomena

- Any deviation from the SM prediction is a discovery of a new phenomenon
- Higgs couplings allow finger-printing new phenomena via their different *patterns* of deviations
- *size* of deviations depends on energy scale of new particles:
the more precise the measurement, the larger the discovery potential
- need at least 1%-level of precision for Higgs couplings
- **all proposed Higgs factories can deliver this program - (HL-)LHC cannot do this**

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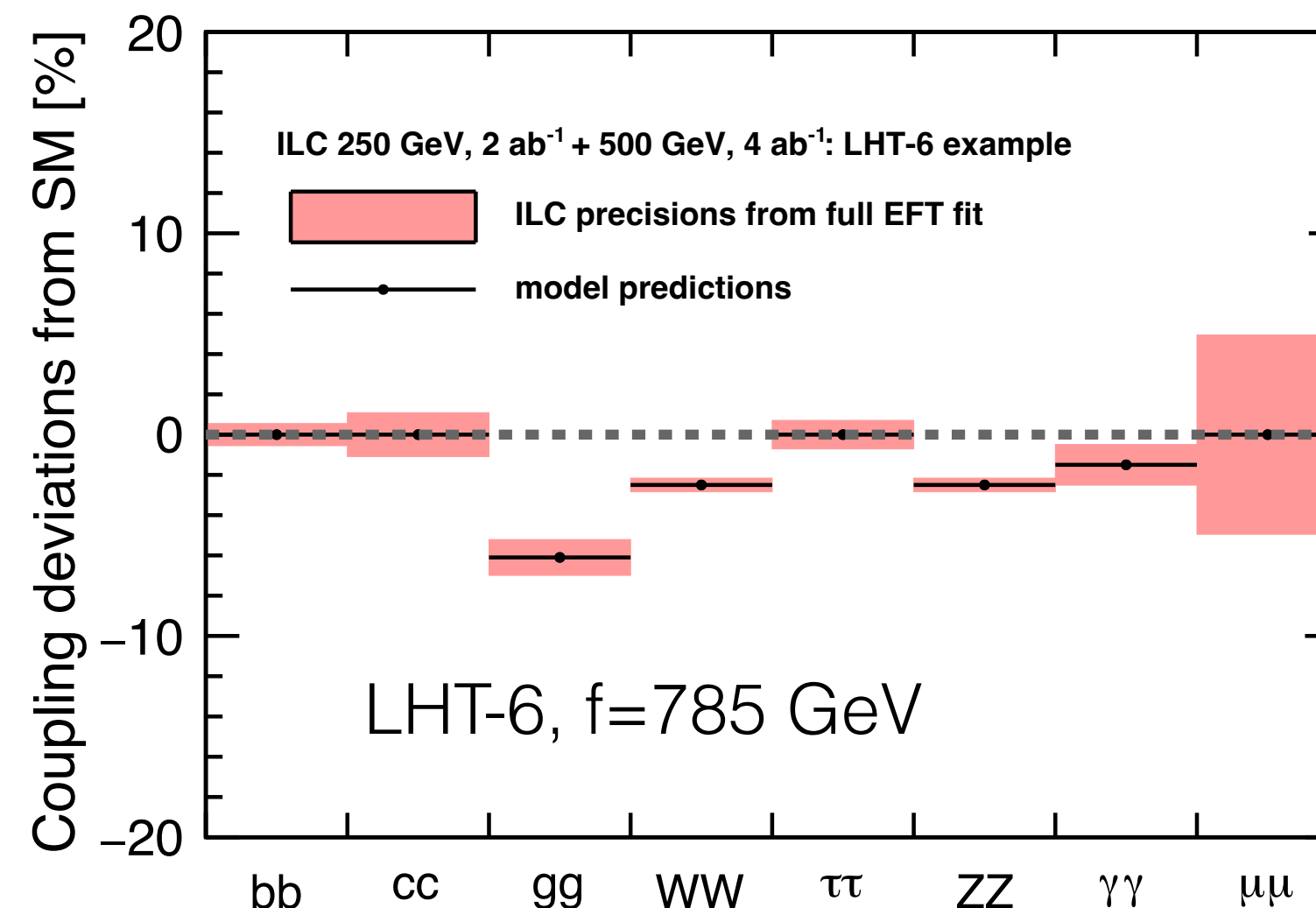
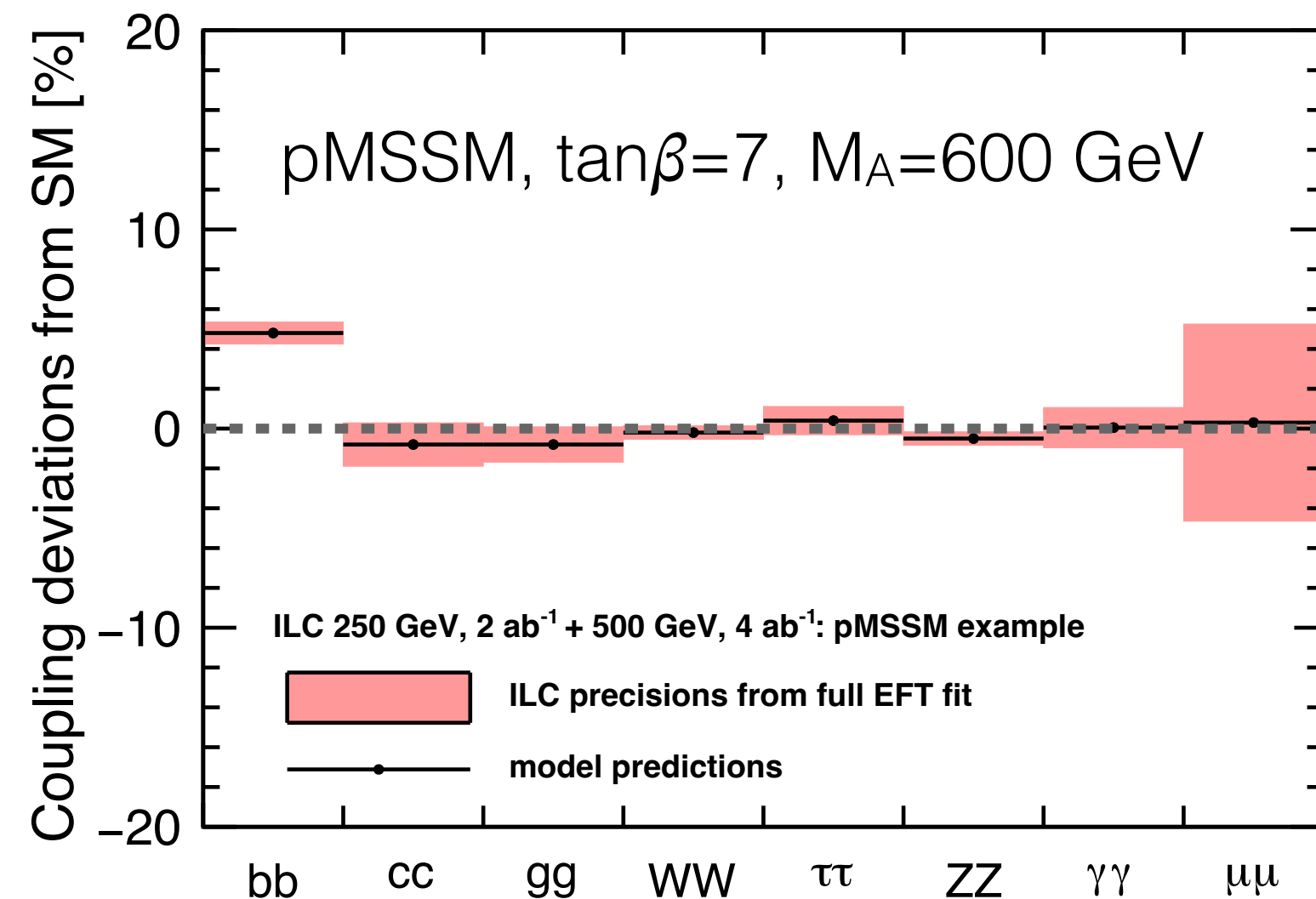
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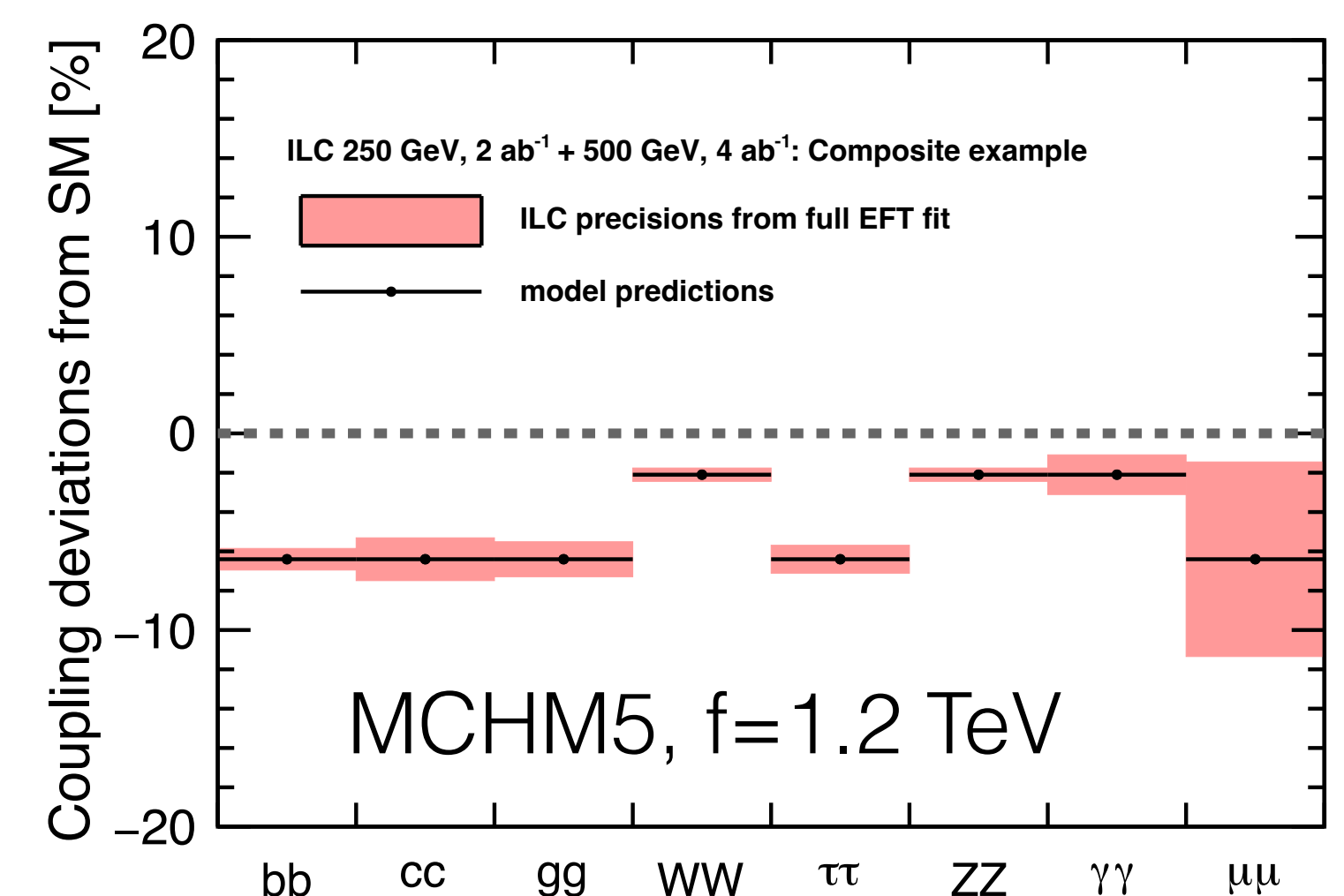
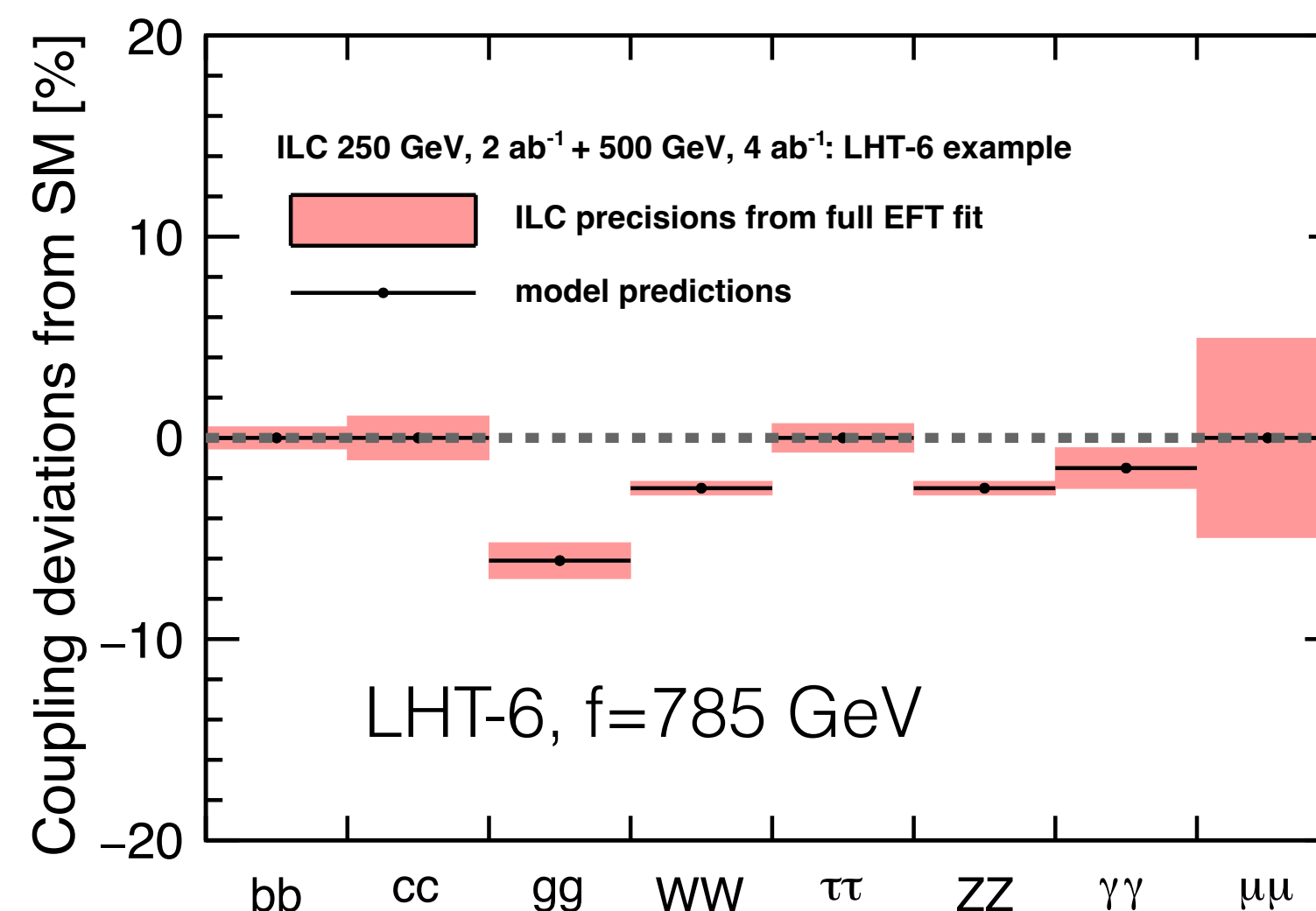
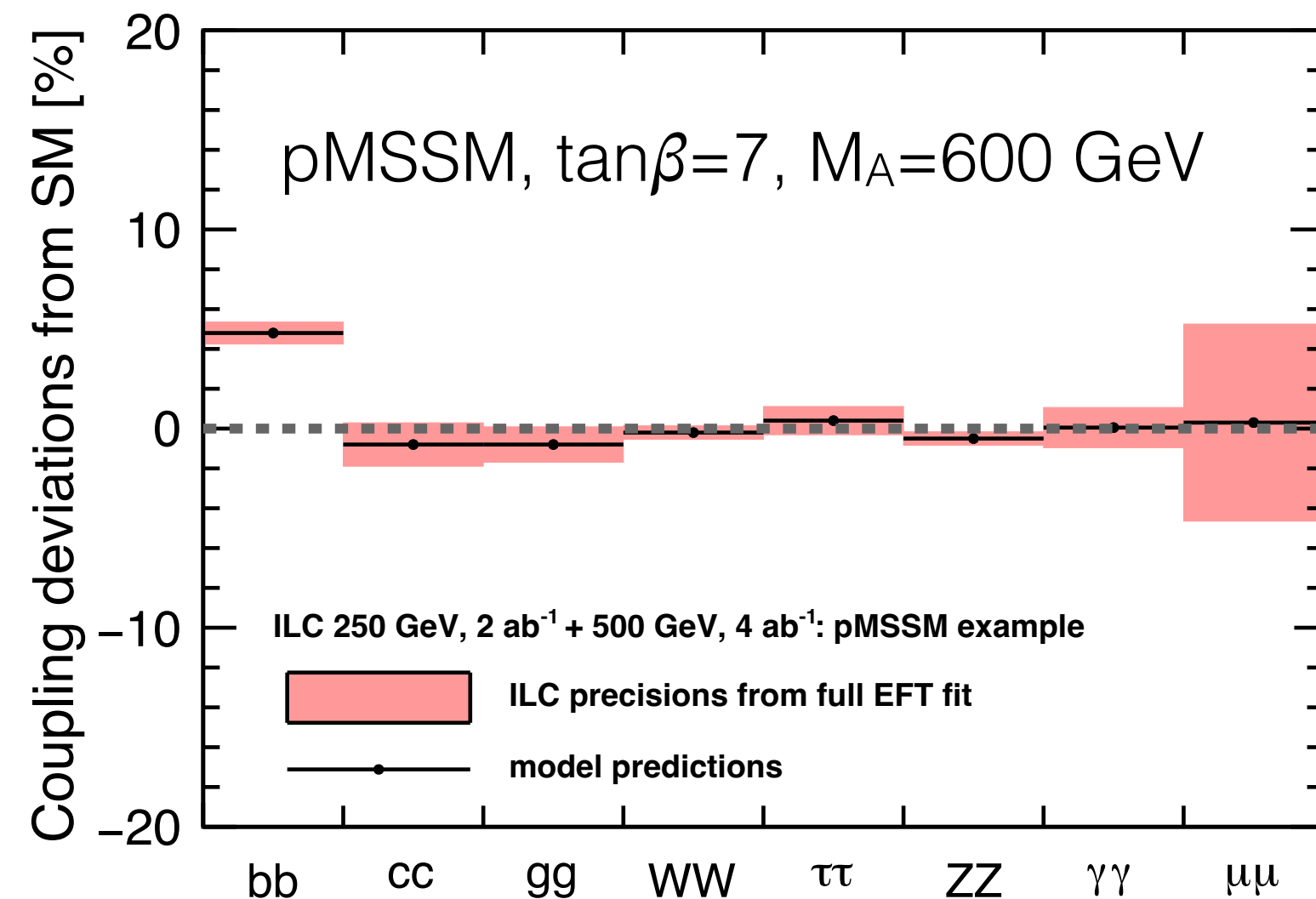
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New Physics Interpretation of Higgs & EW

Illustrating the principle - based on older fit!

**Test various example BSM points -
all chosen such that
no hint for new physics at HL-LHC**

Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1 MSSM [36]	+4.8	-0.8	-0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2 Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3 Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4 Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5 Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6 Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7 Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8 Higgs-Radion [40]	-1.5	-1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9 Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era (3 ab^{-1} of integrated luminosity). From [15].

arXiv:1708.08912

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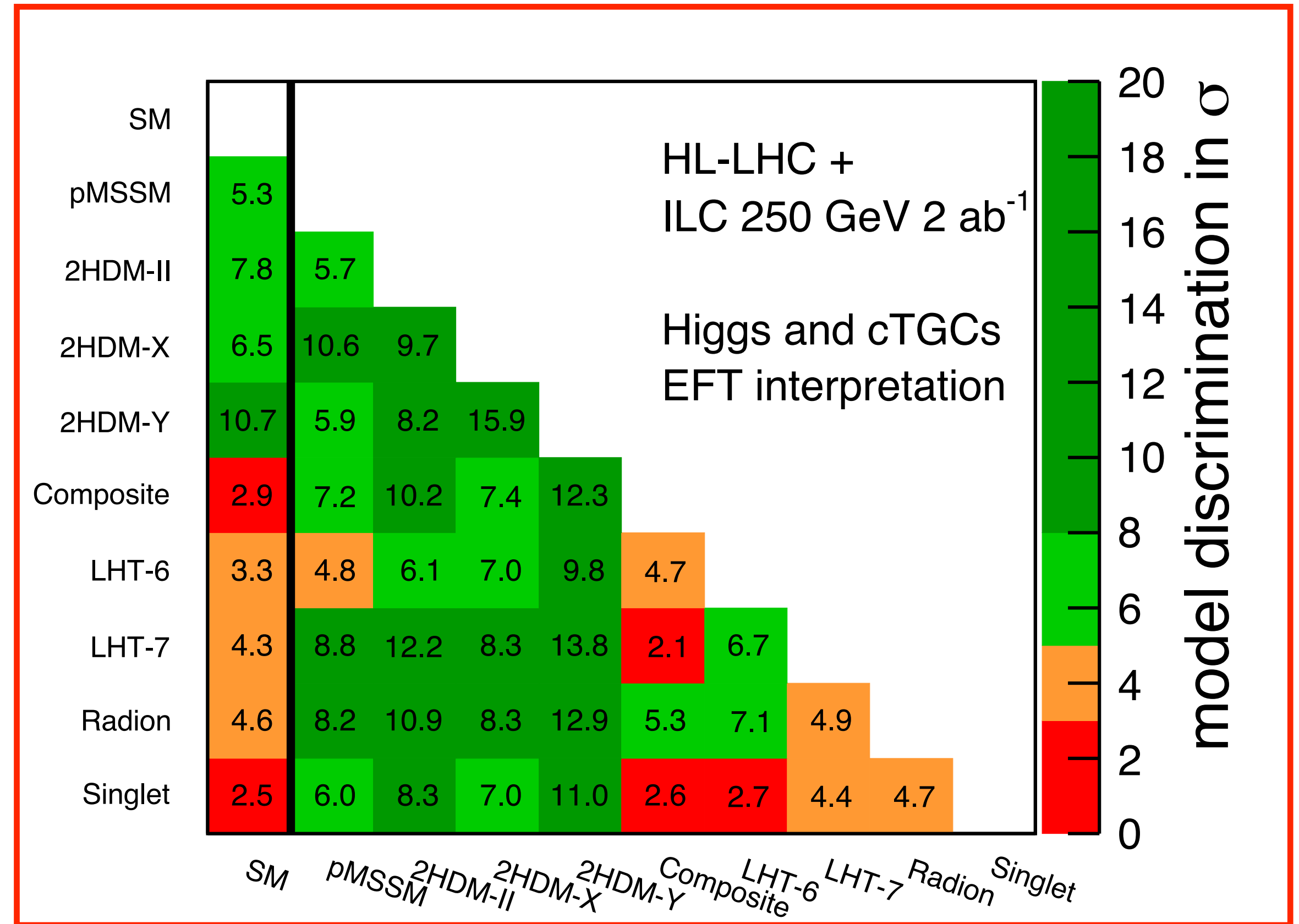
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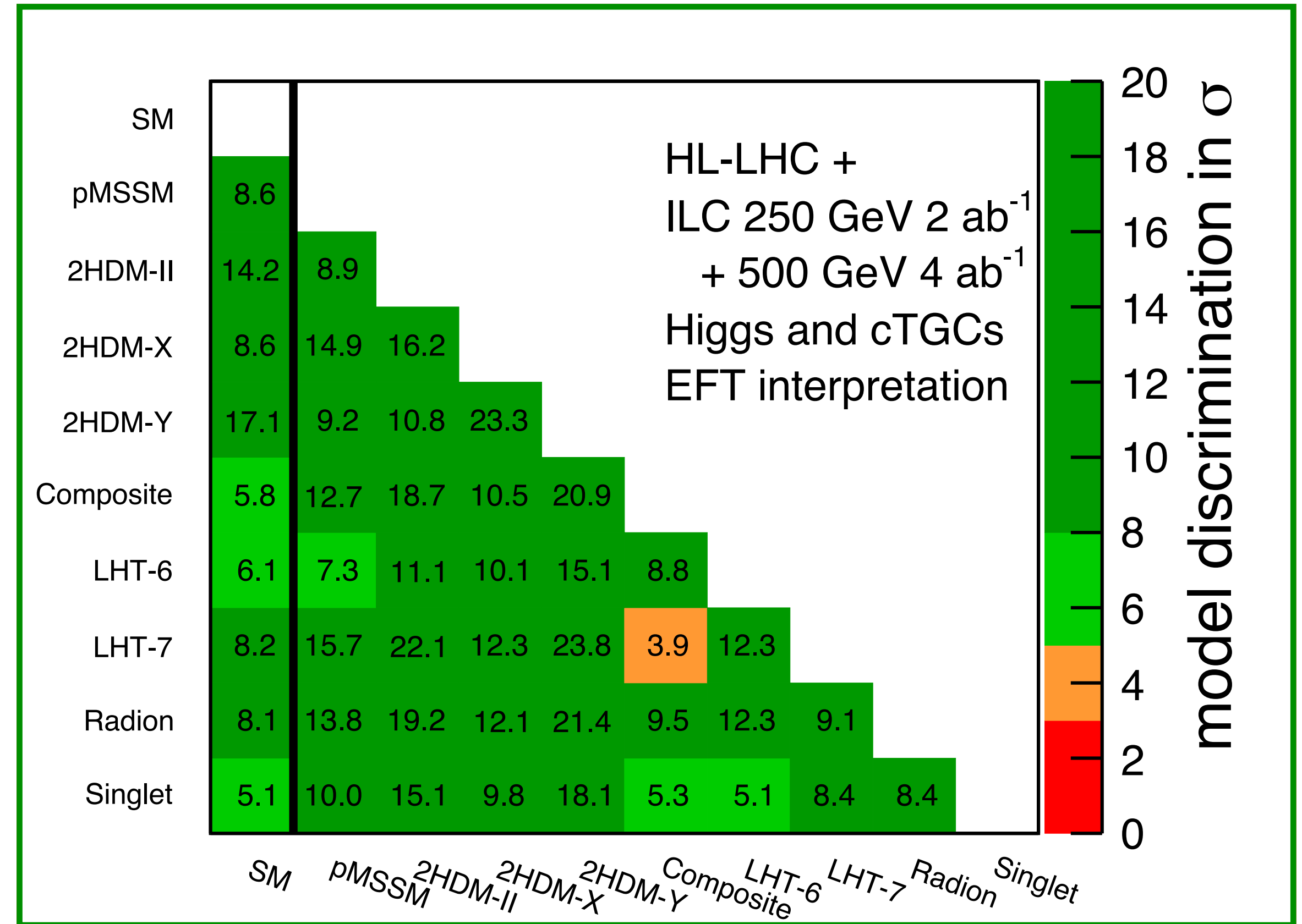
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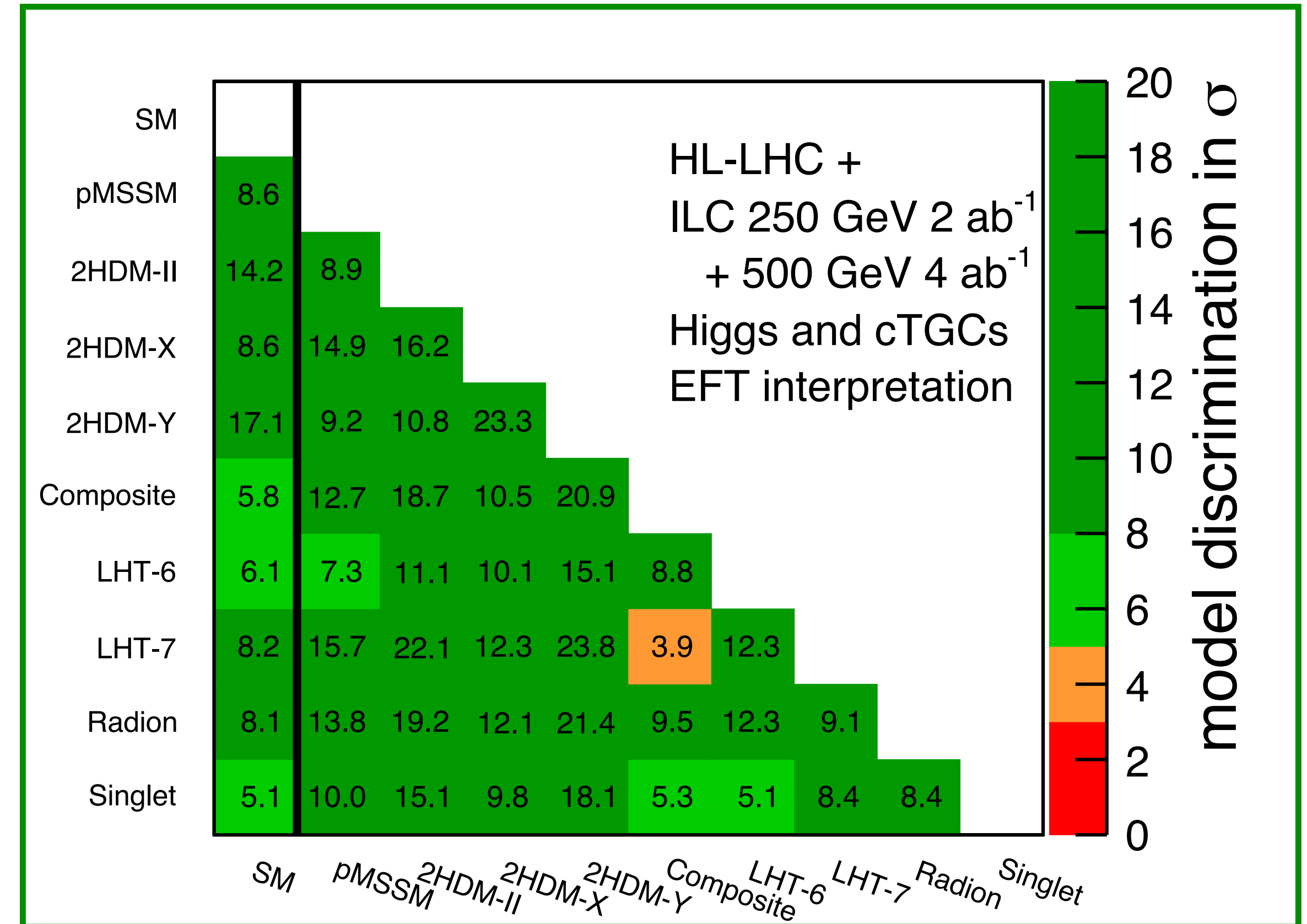
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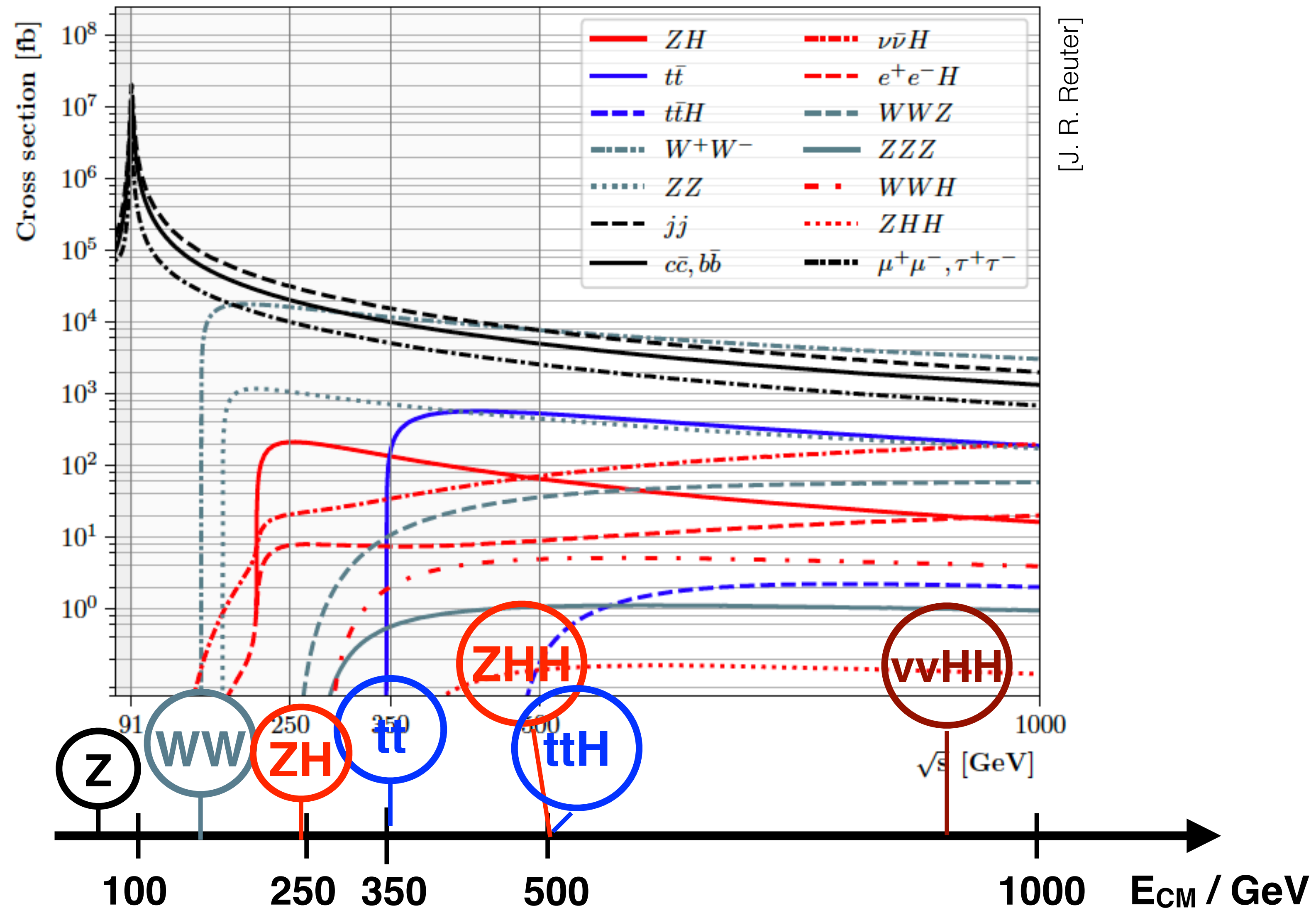


arXiv:1708.08912

illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

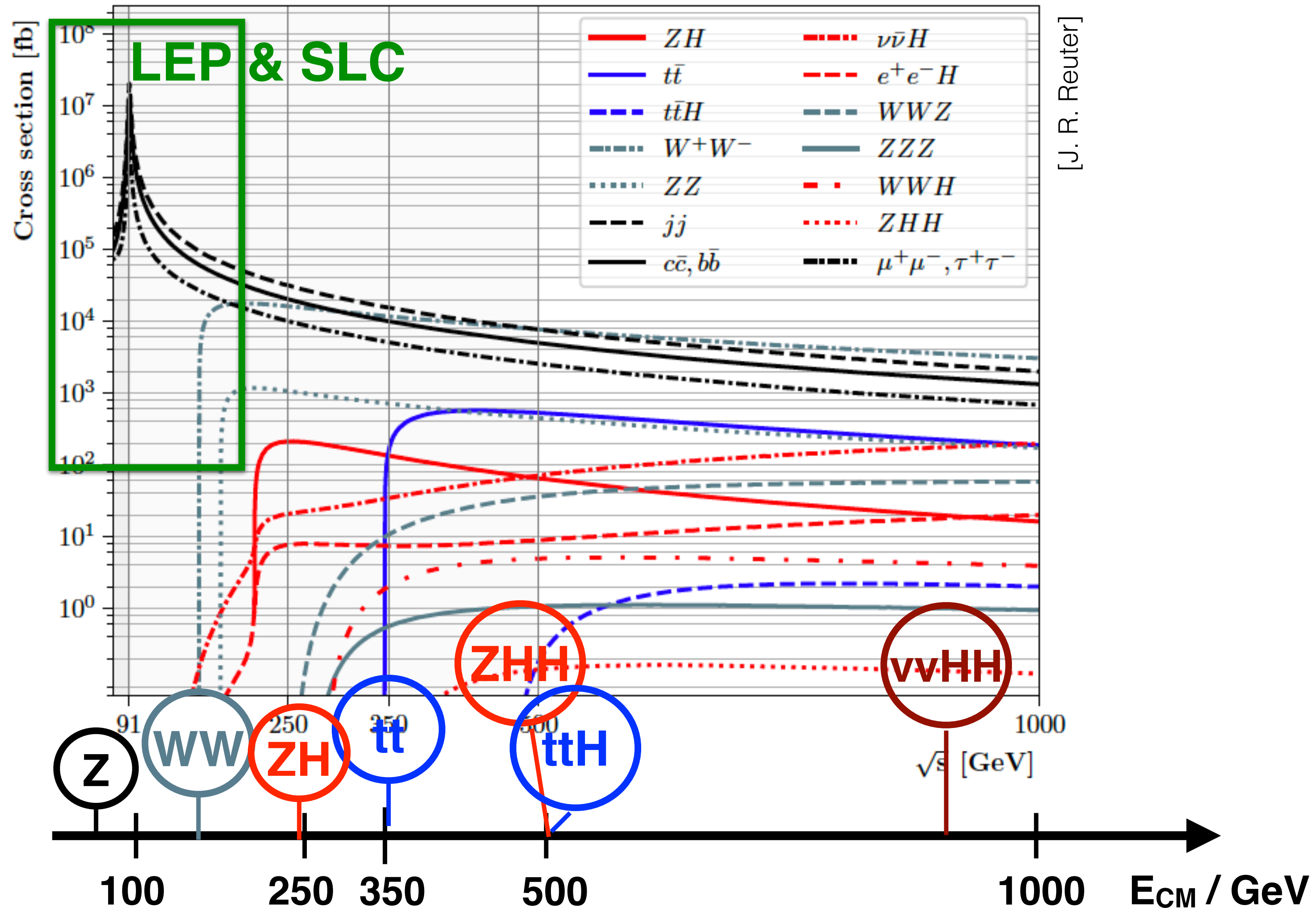
The key physics at a Higgs Factory

Production rates vs collision energy



The key physics at a Higgs Factory

Production rates vs collision energy

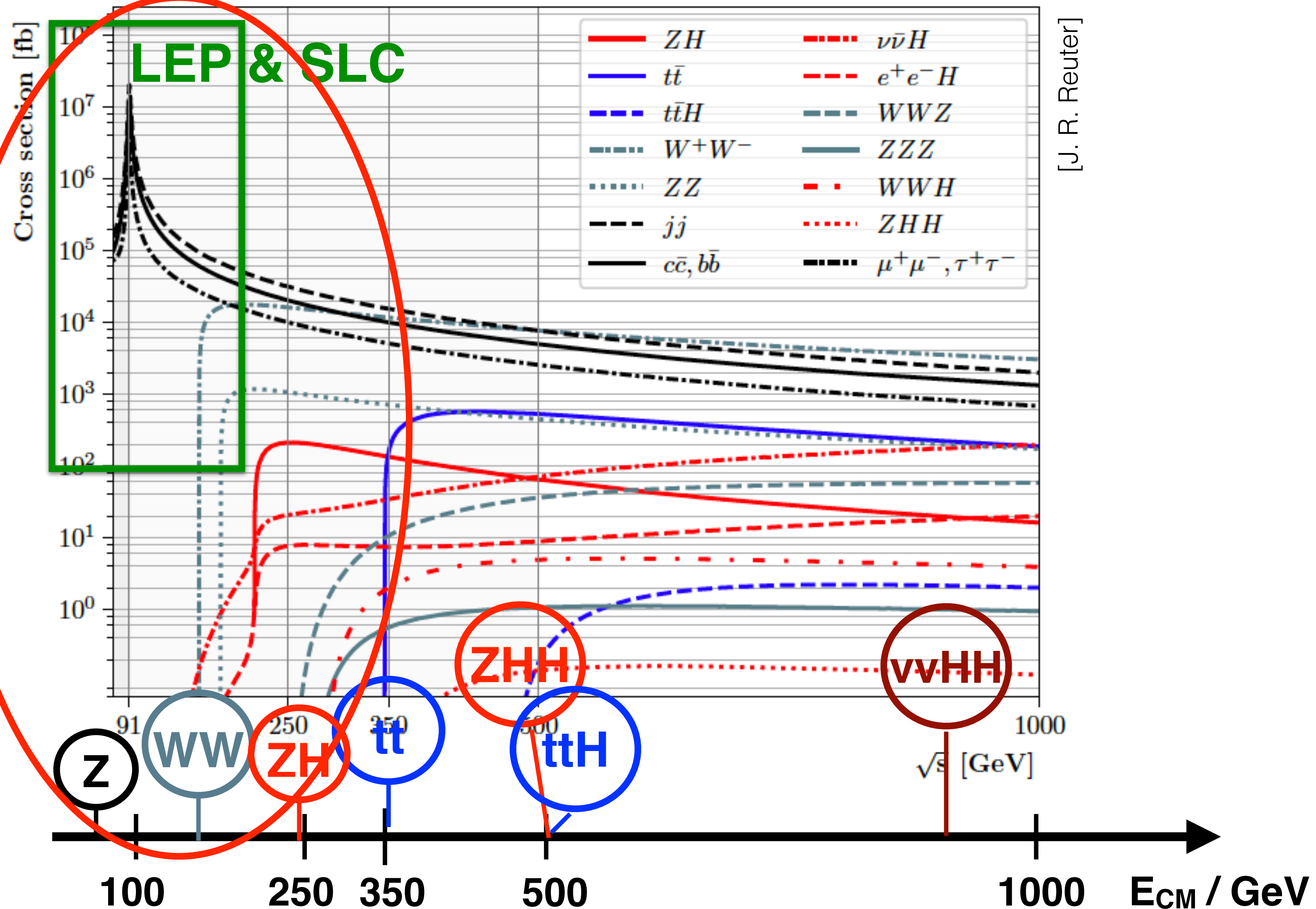


[J. R. Reuter]

The key physics at a Higgs Factory

Production rates vs collision energy

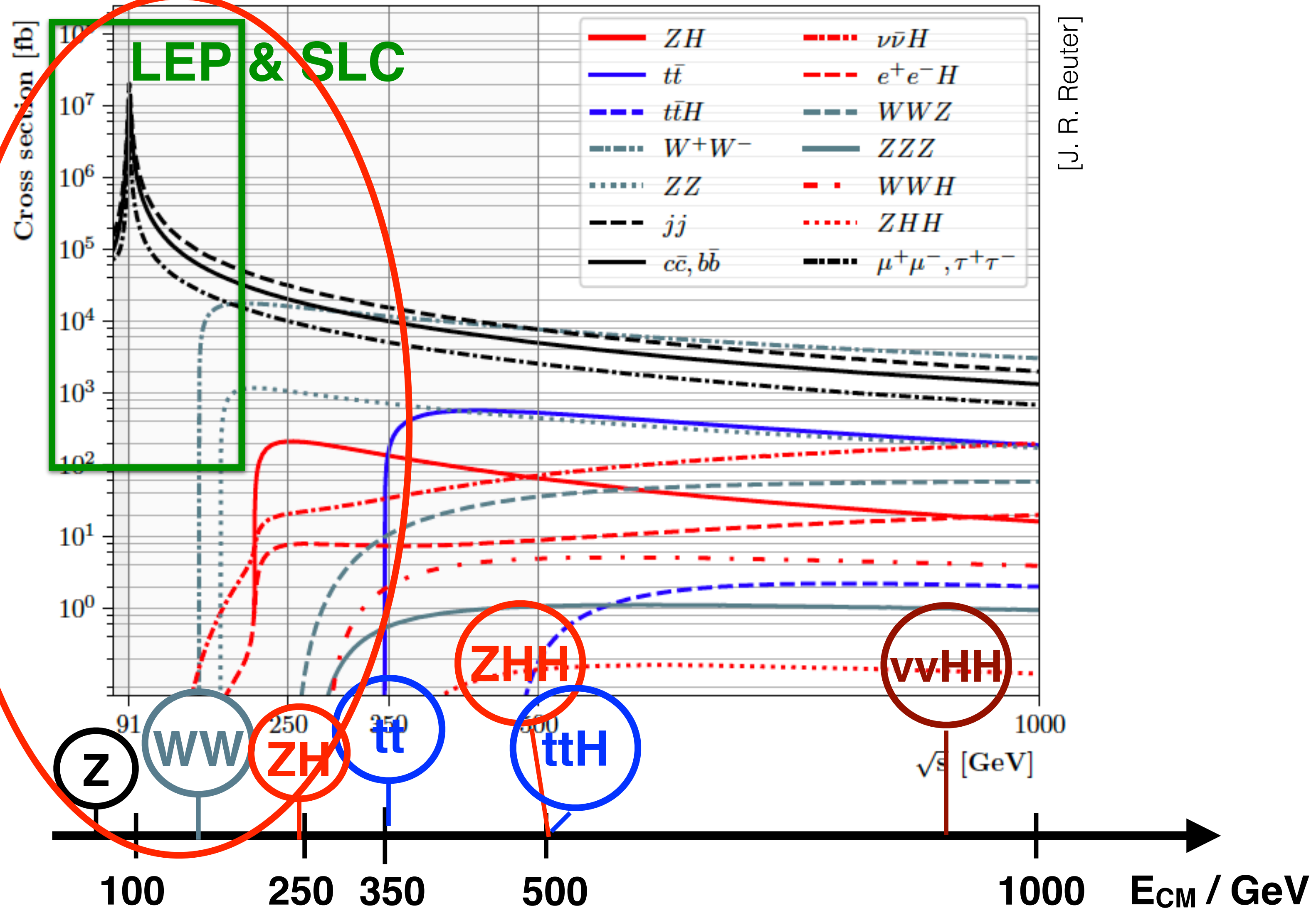
considered by all proposed e+e- projects



[J. R. Reuter]

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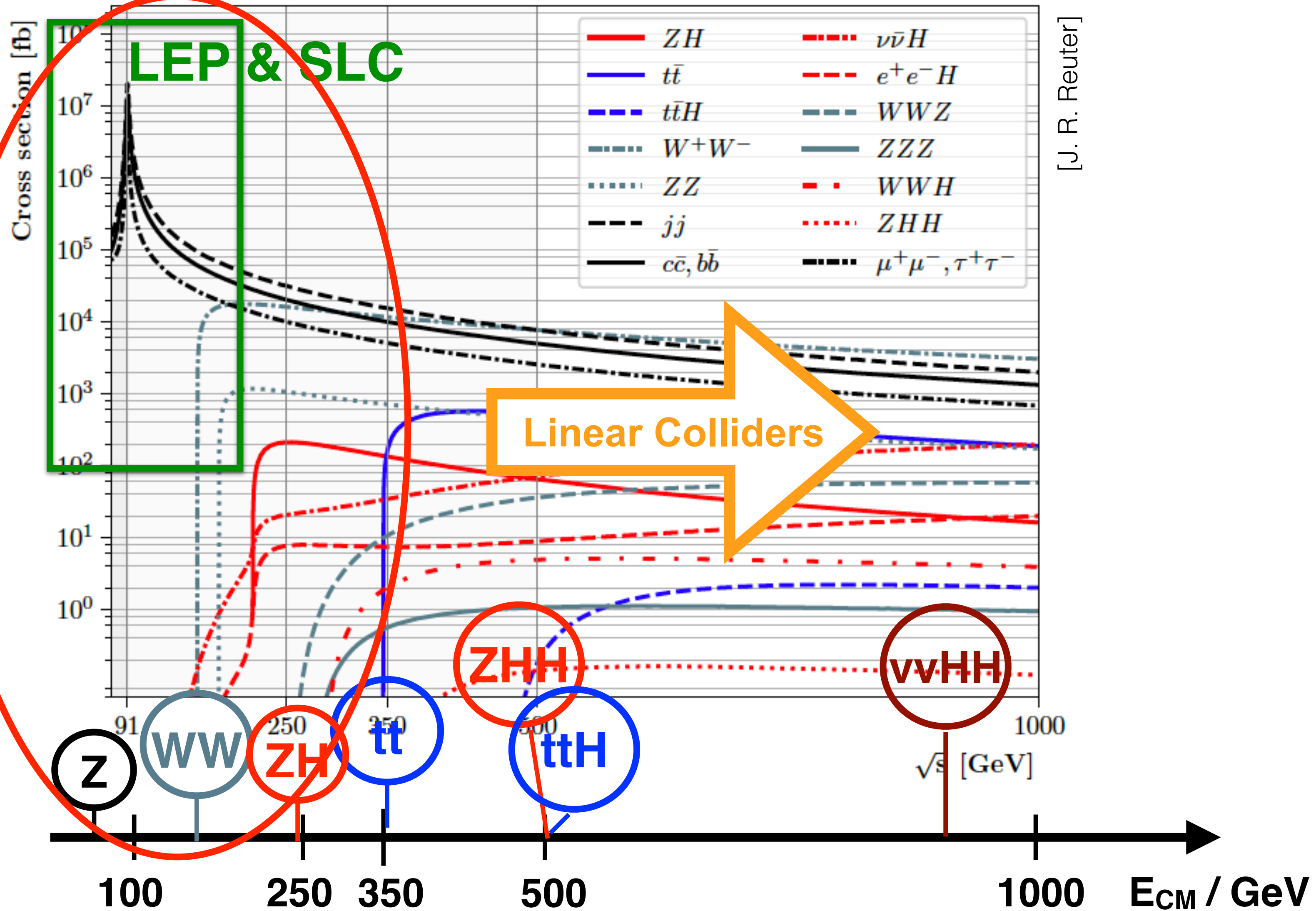
Circular Colliders

The key physics at a Higgs Factory

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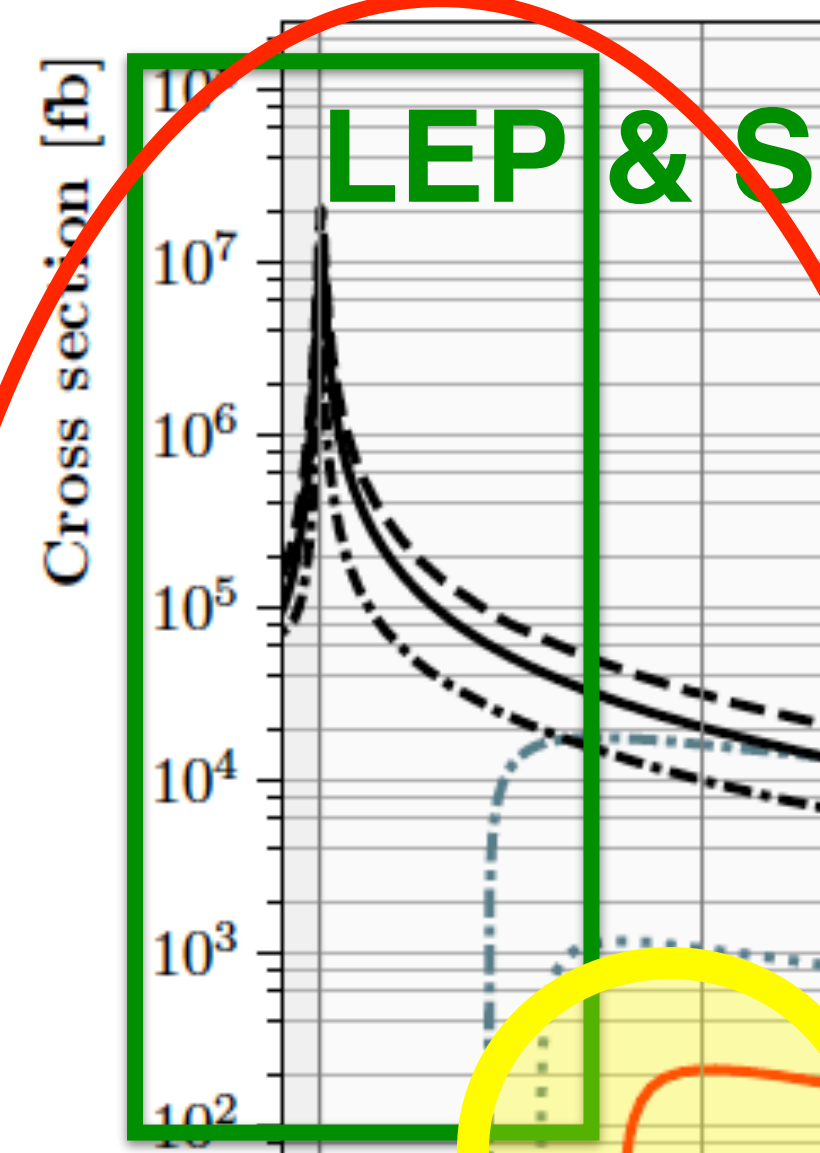
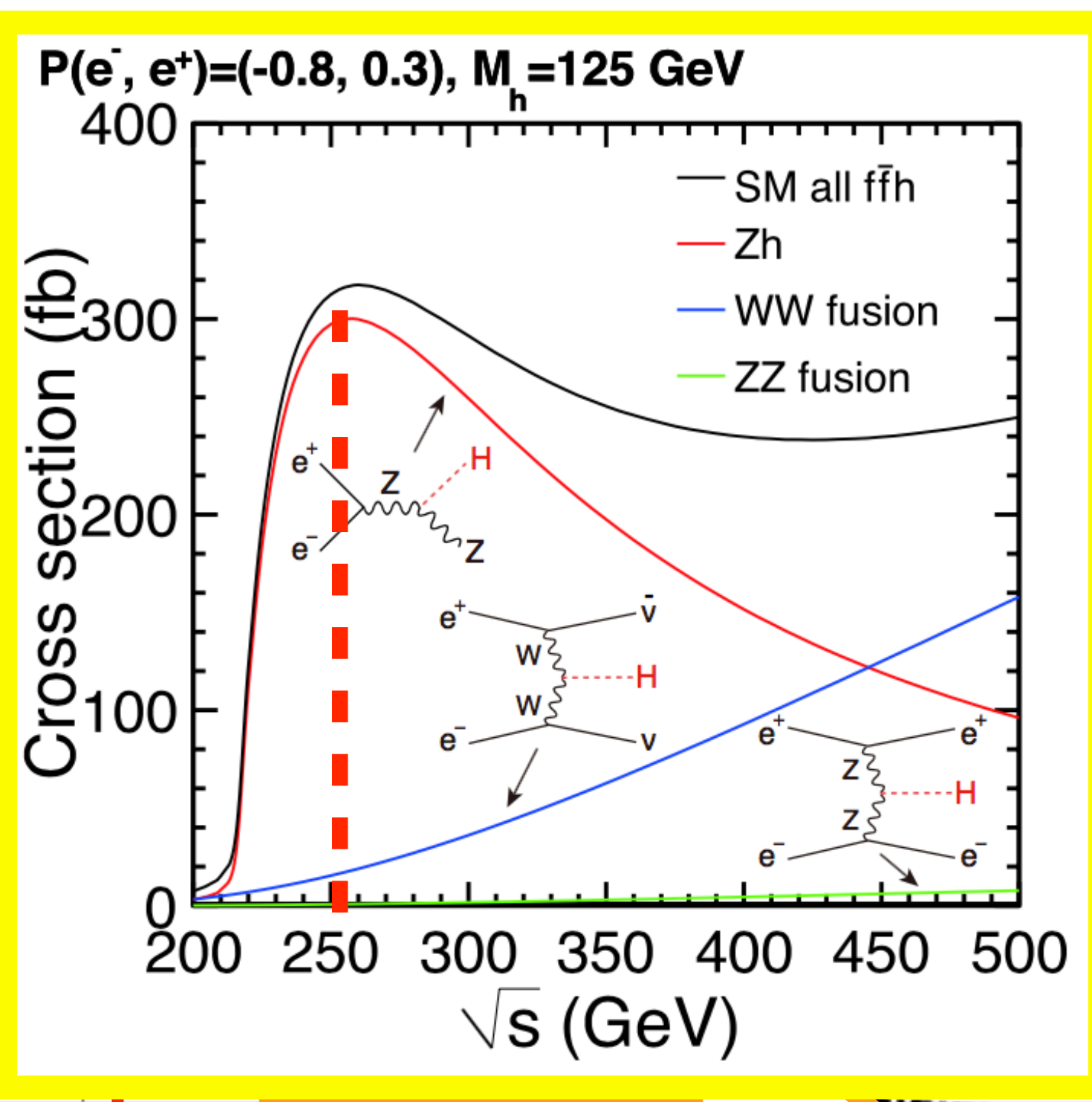
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[J. R. Reuter]

The key physics at a $\mu\mu$ collider

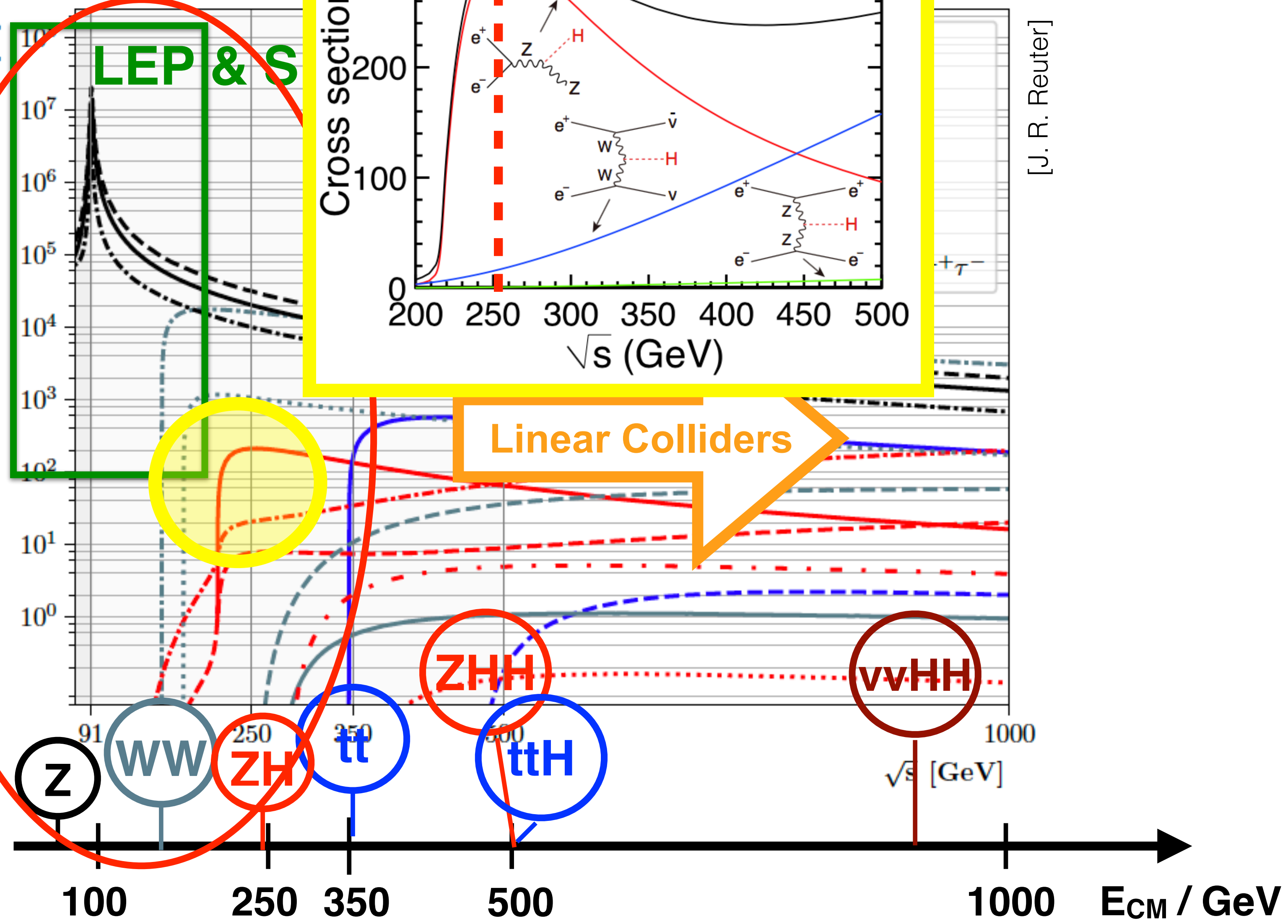
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Circular Colliders

Linear Colliders



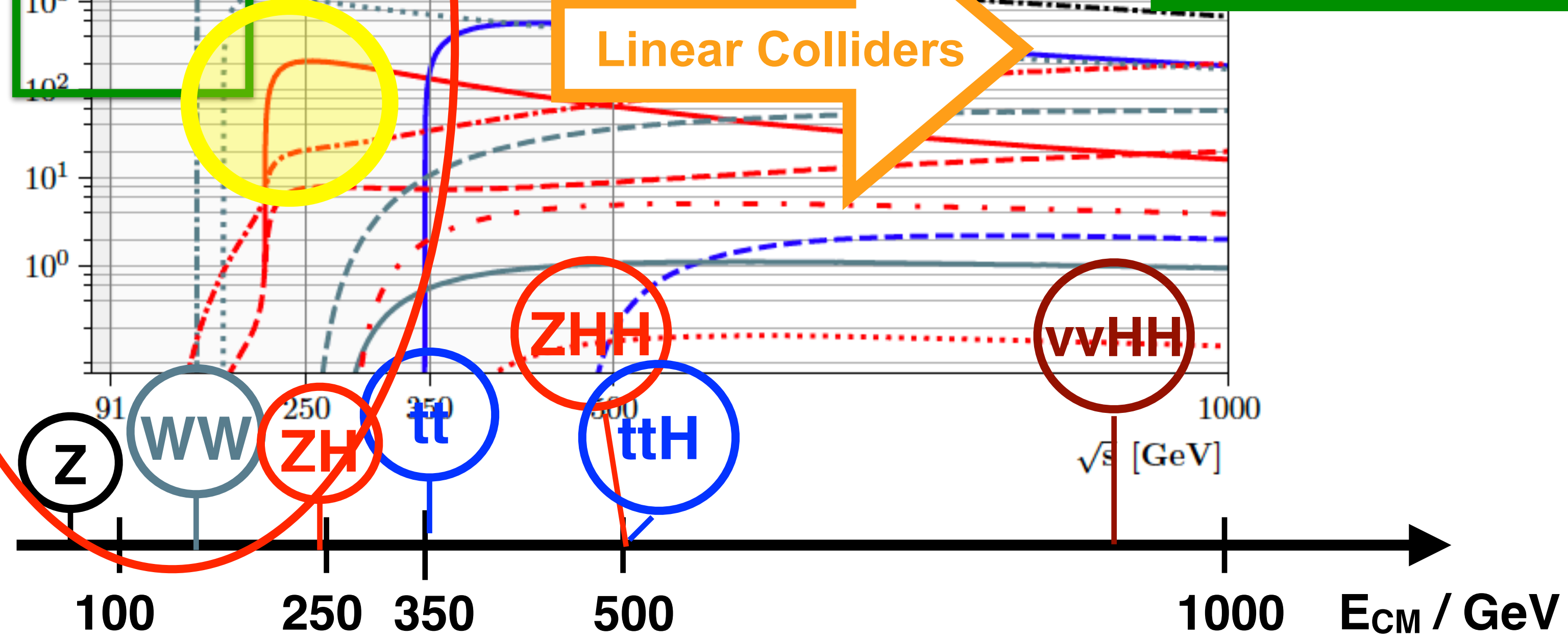
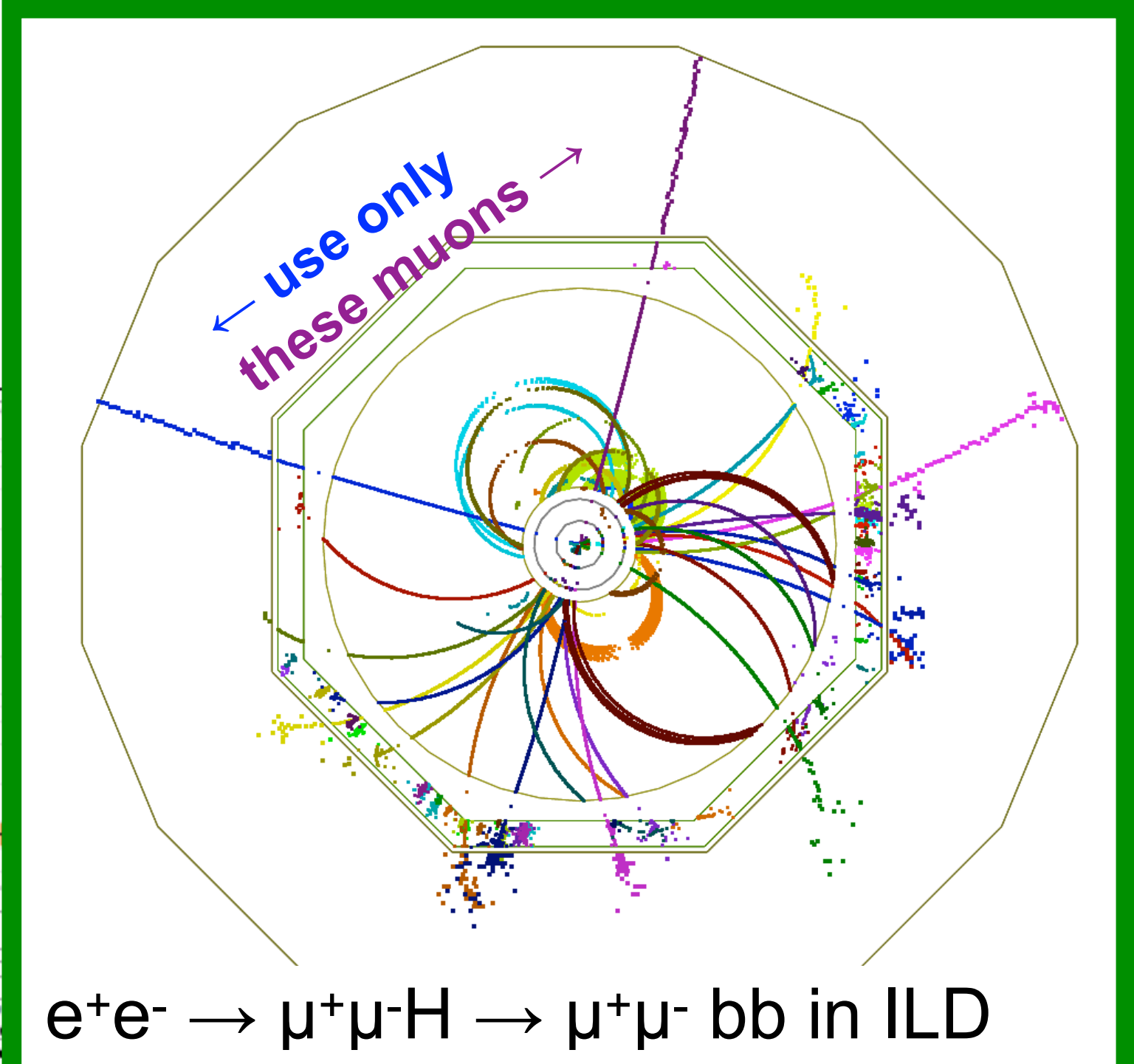
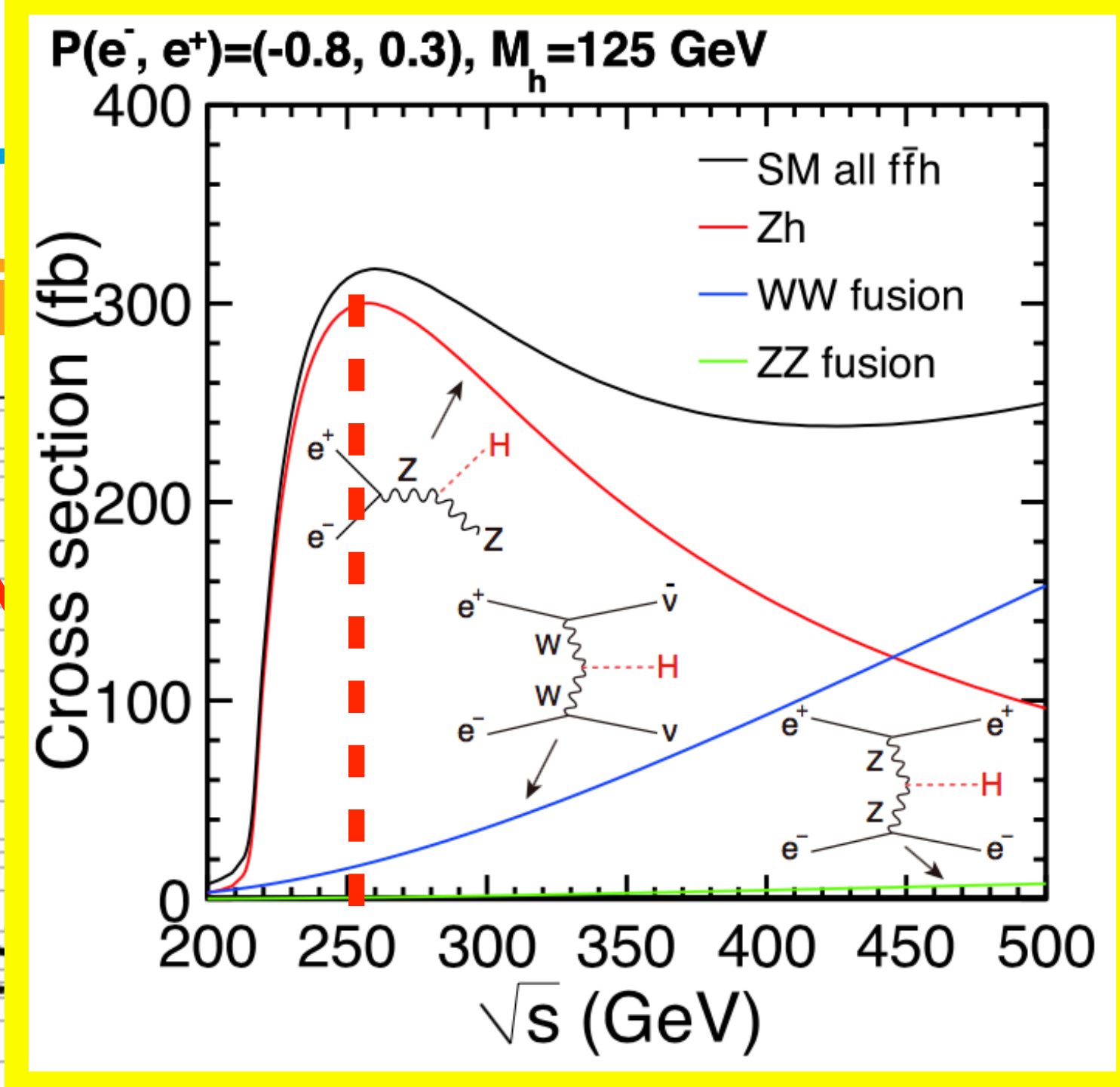
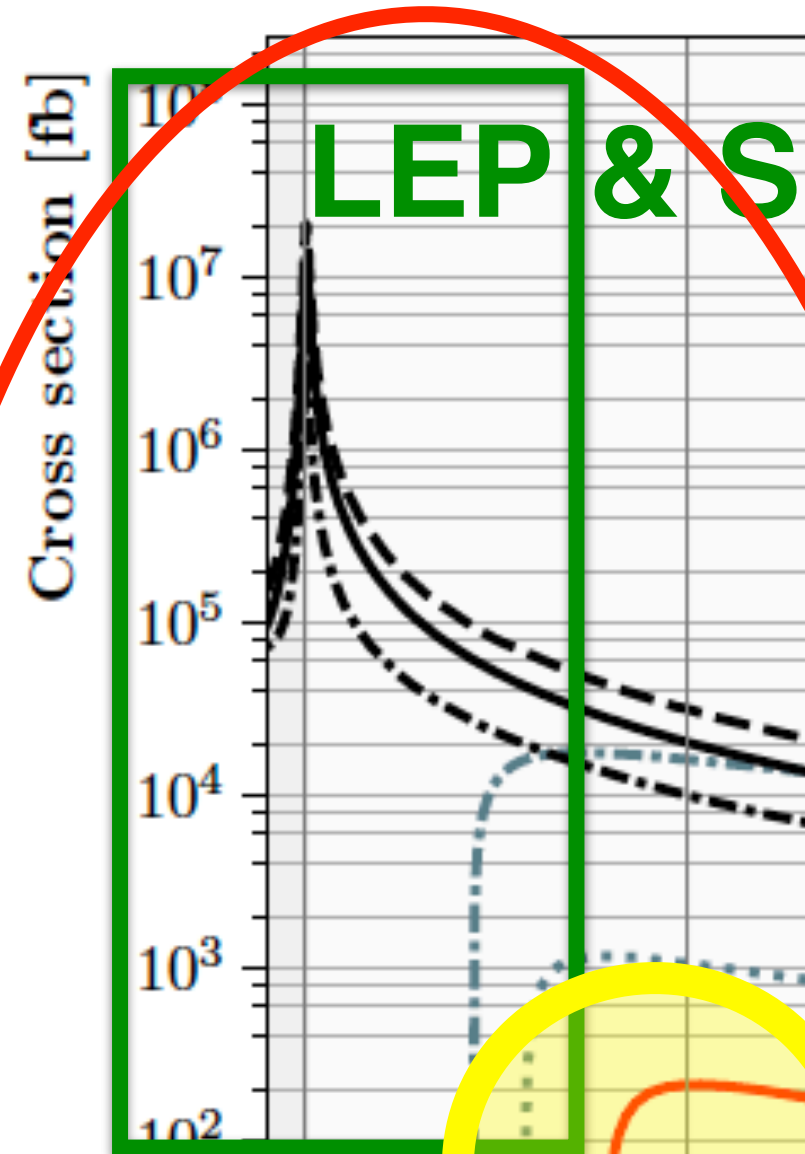
[J. R. Reuter]

The key physics at a Higgs factory

Production rates vs collision energy

considered by all proposed e+e- projects

Circular Colliders

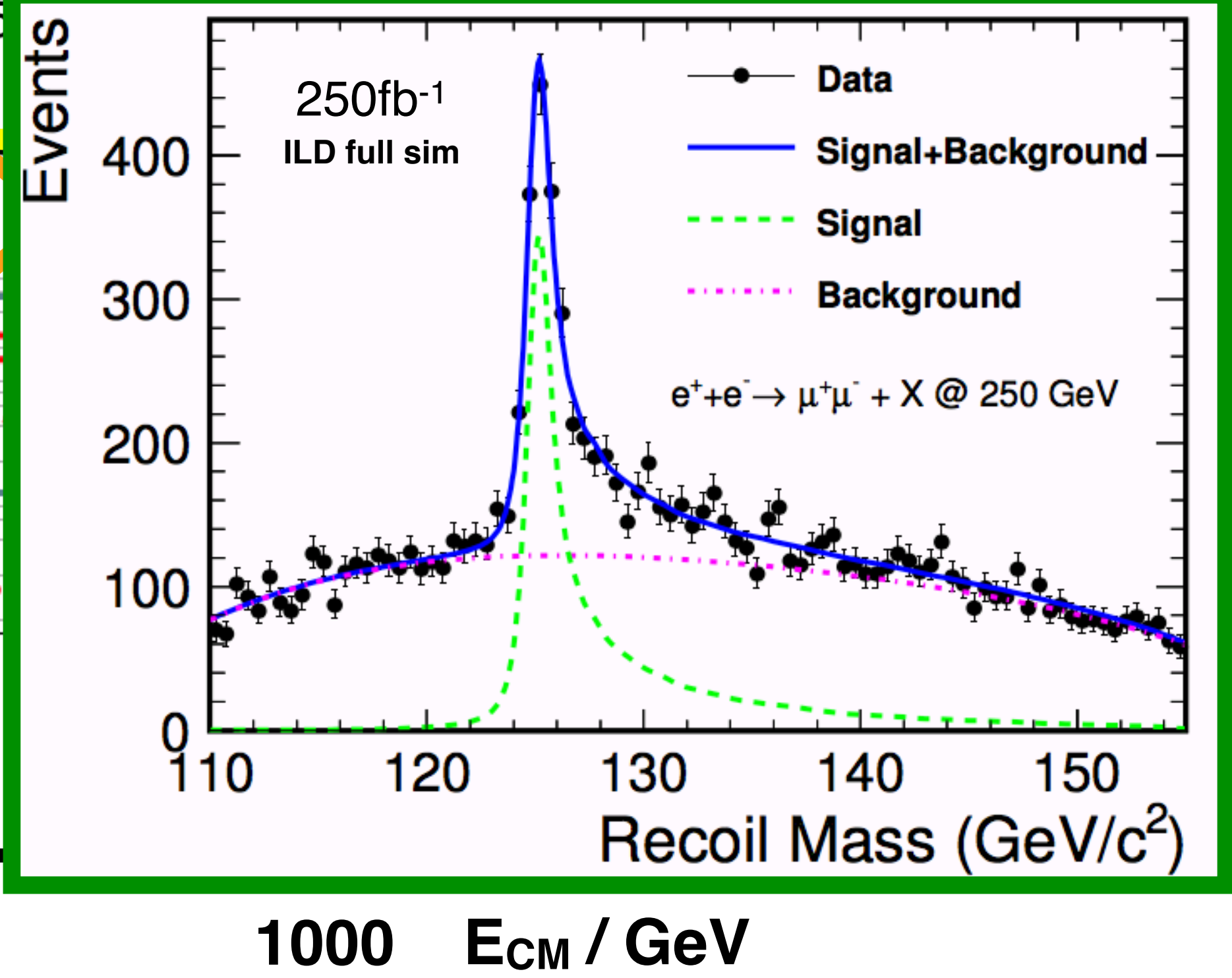
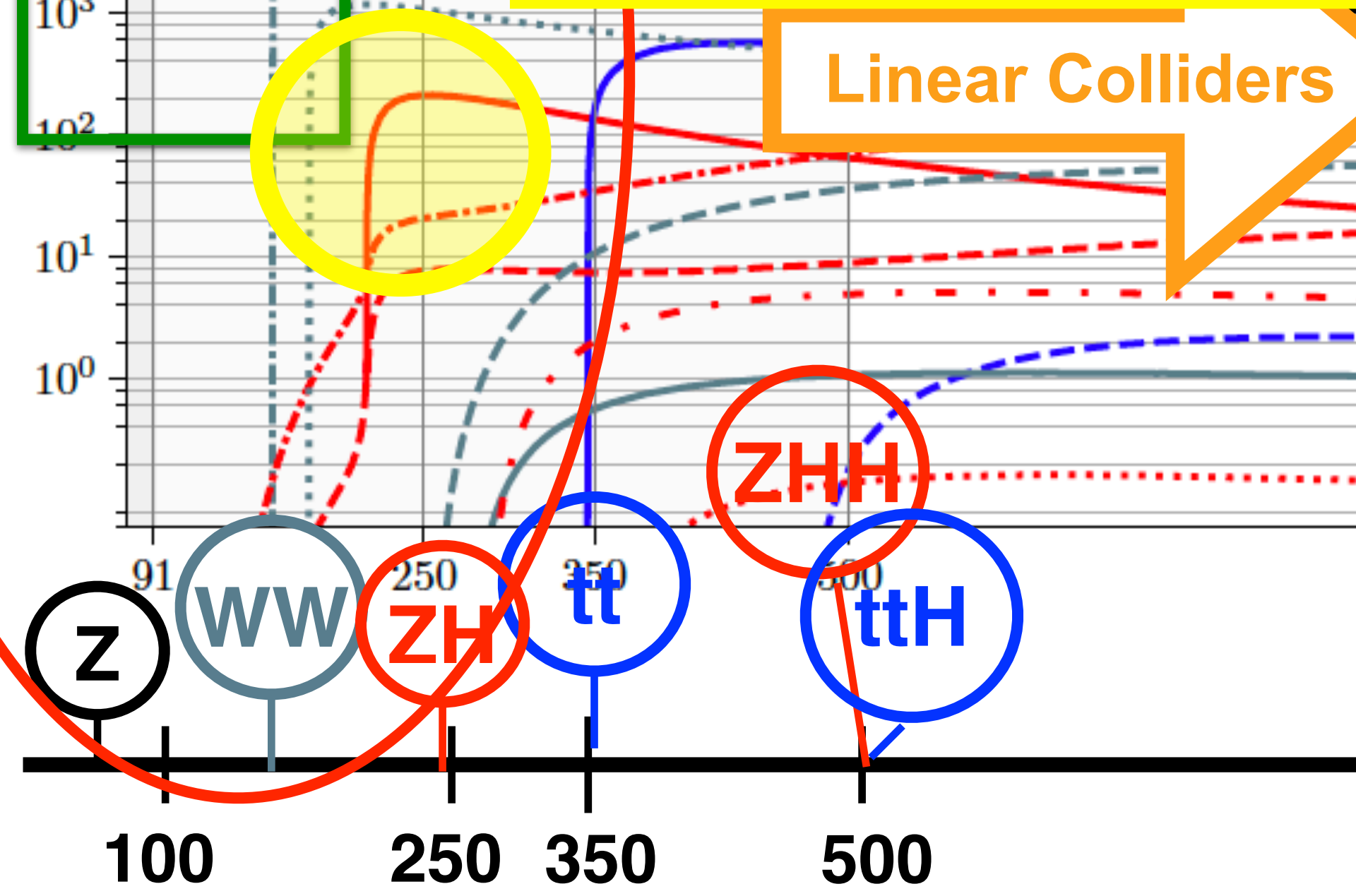
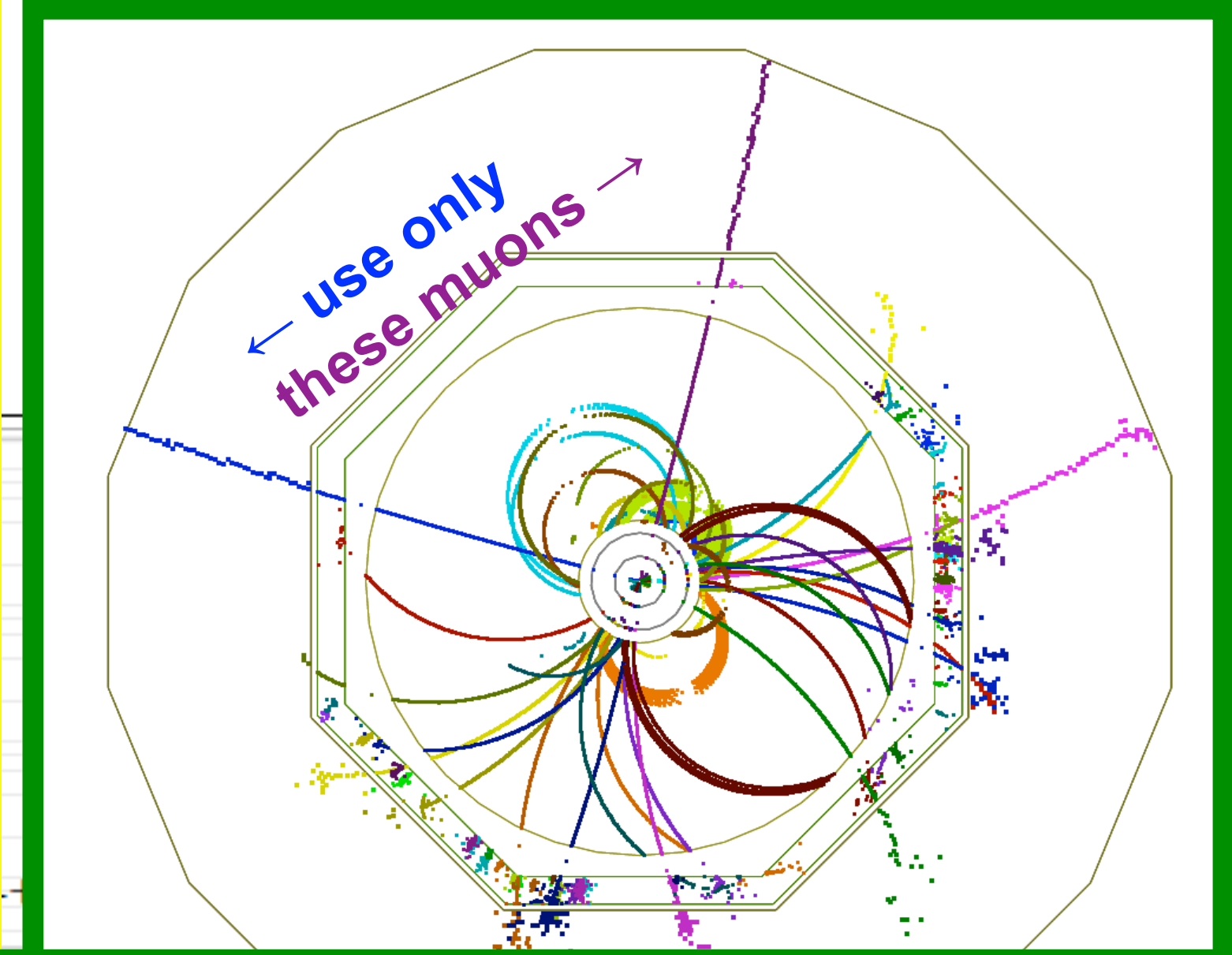
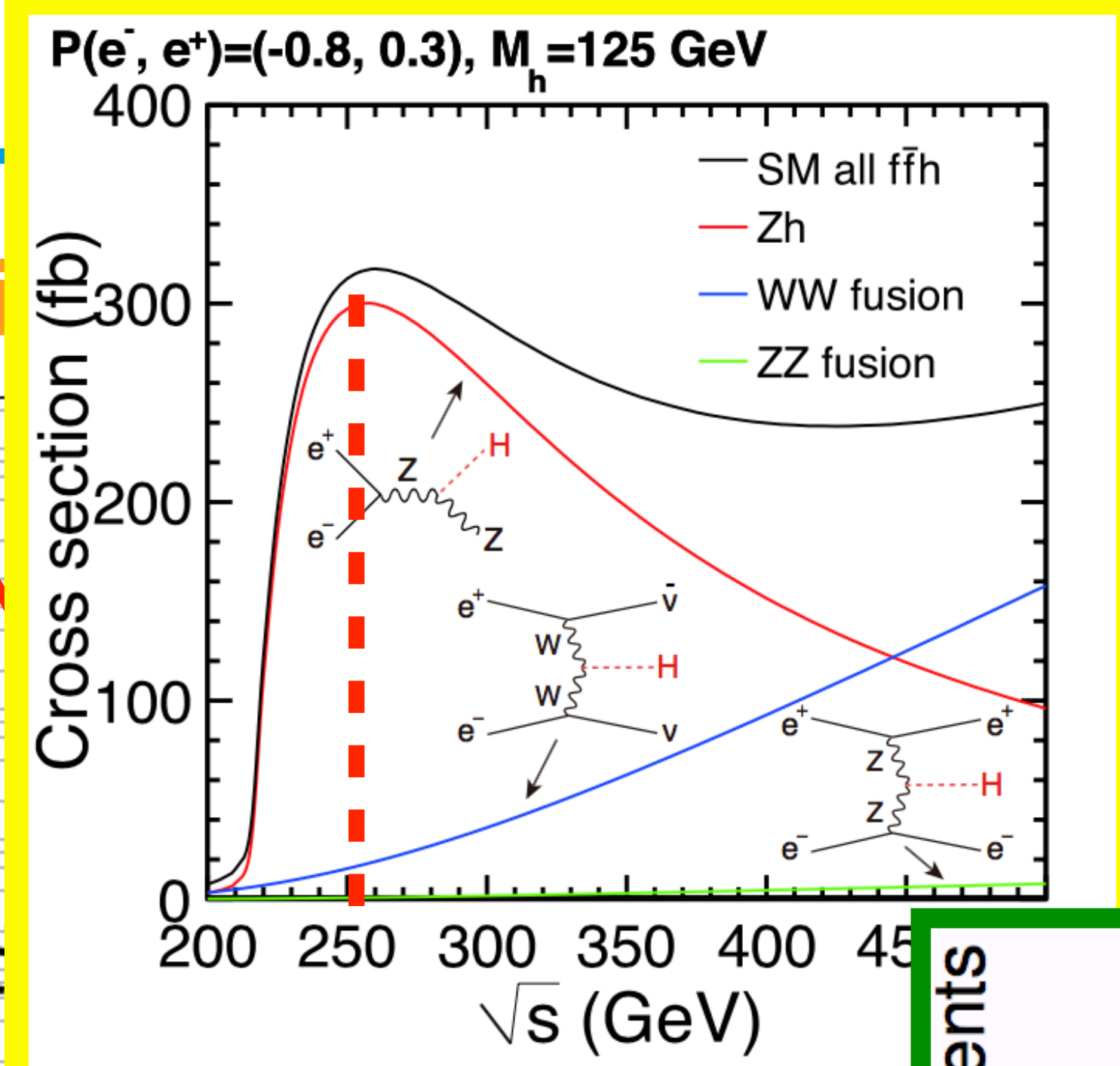
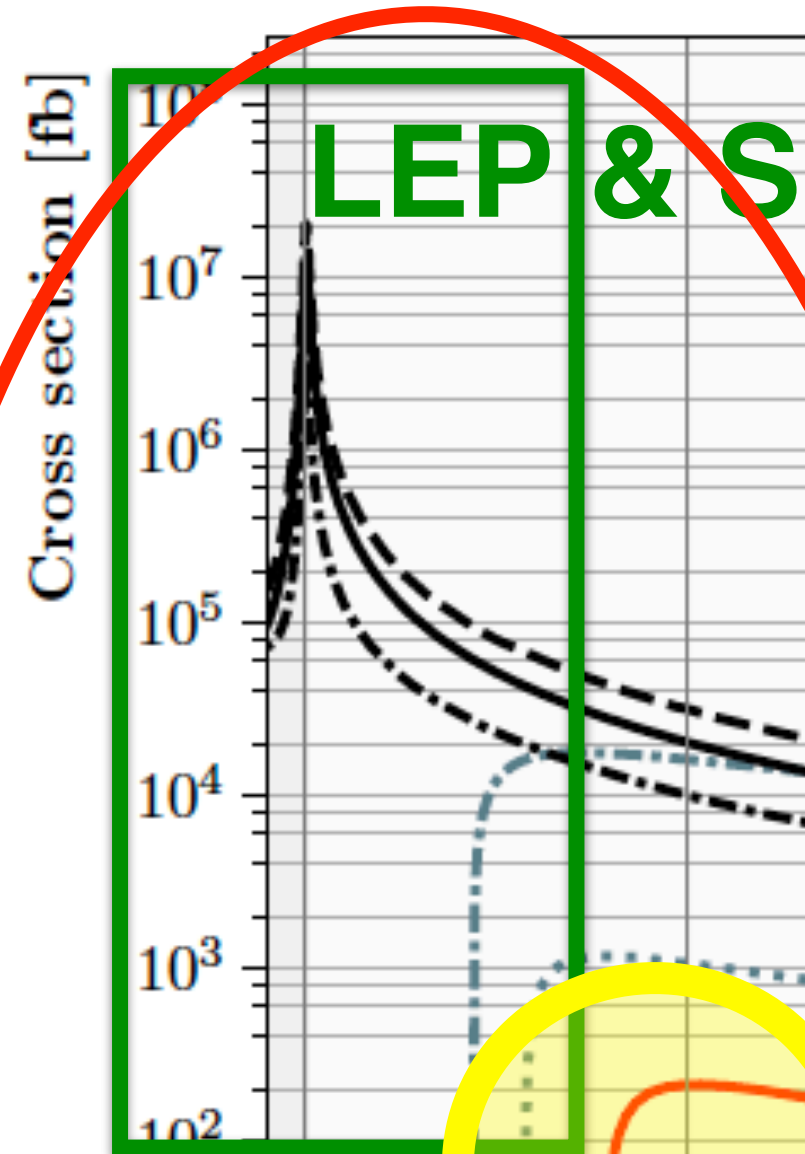


The key physics at a $\mu\mu$ collider

Production rates vs collision energy

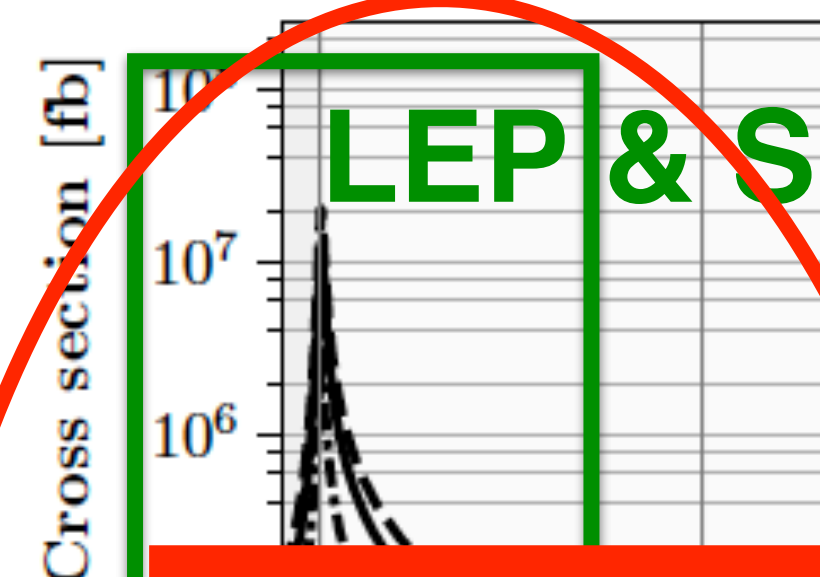
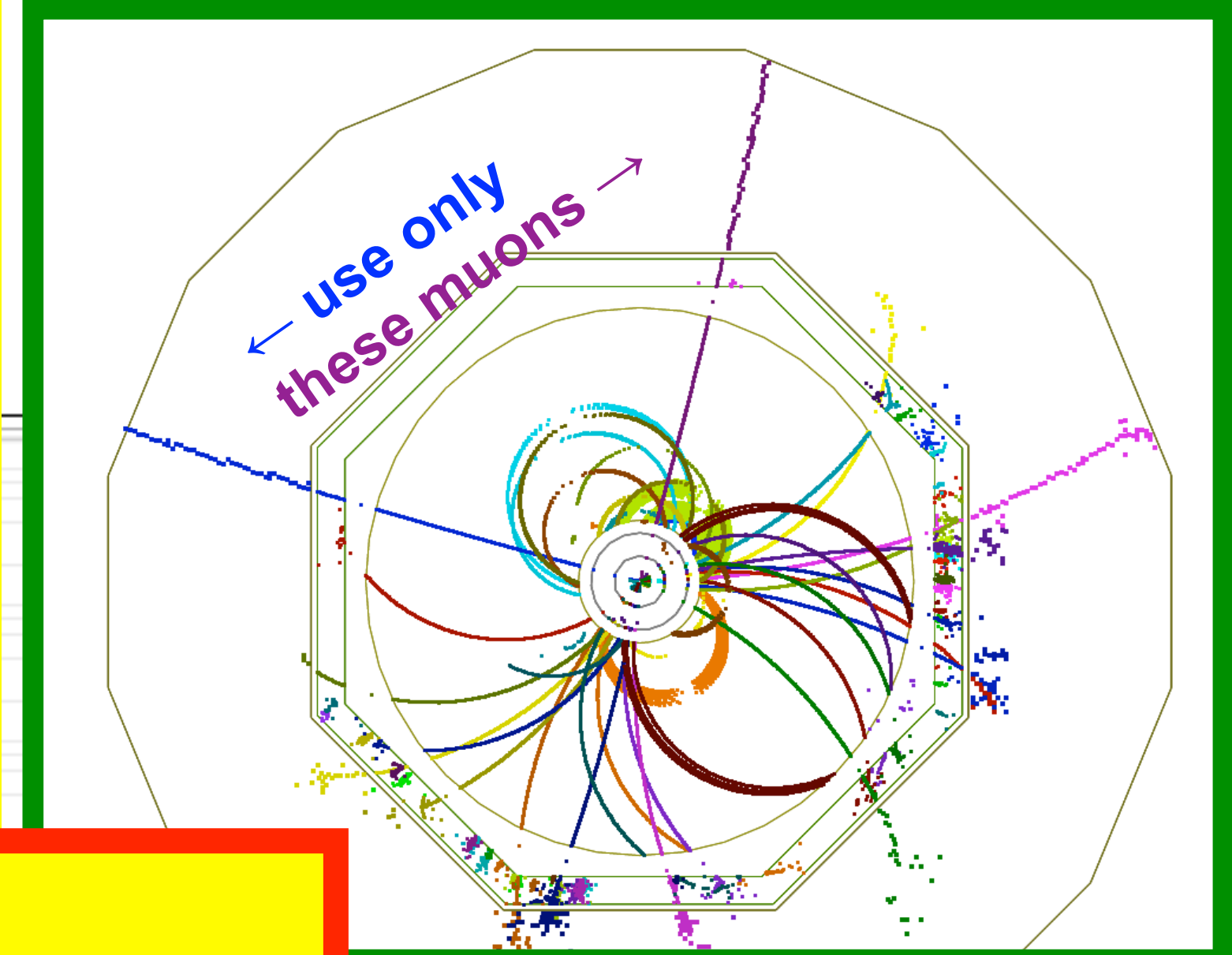
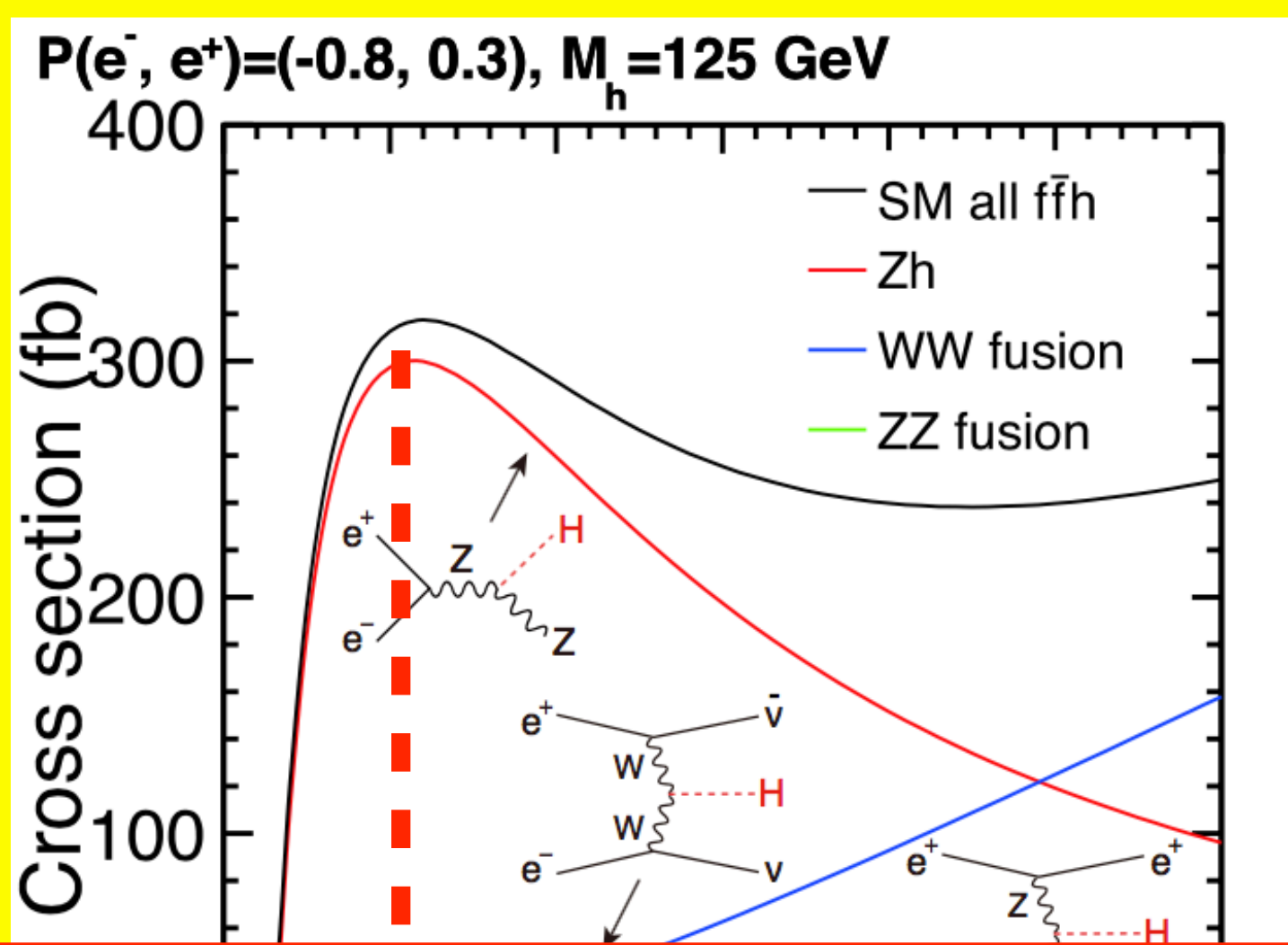
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Circular Colliders

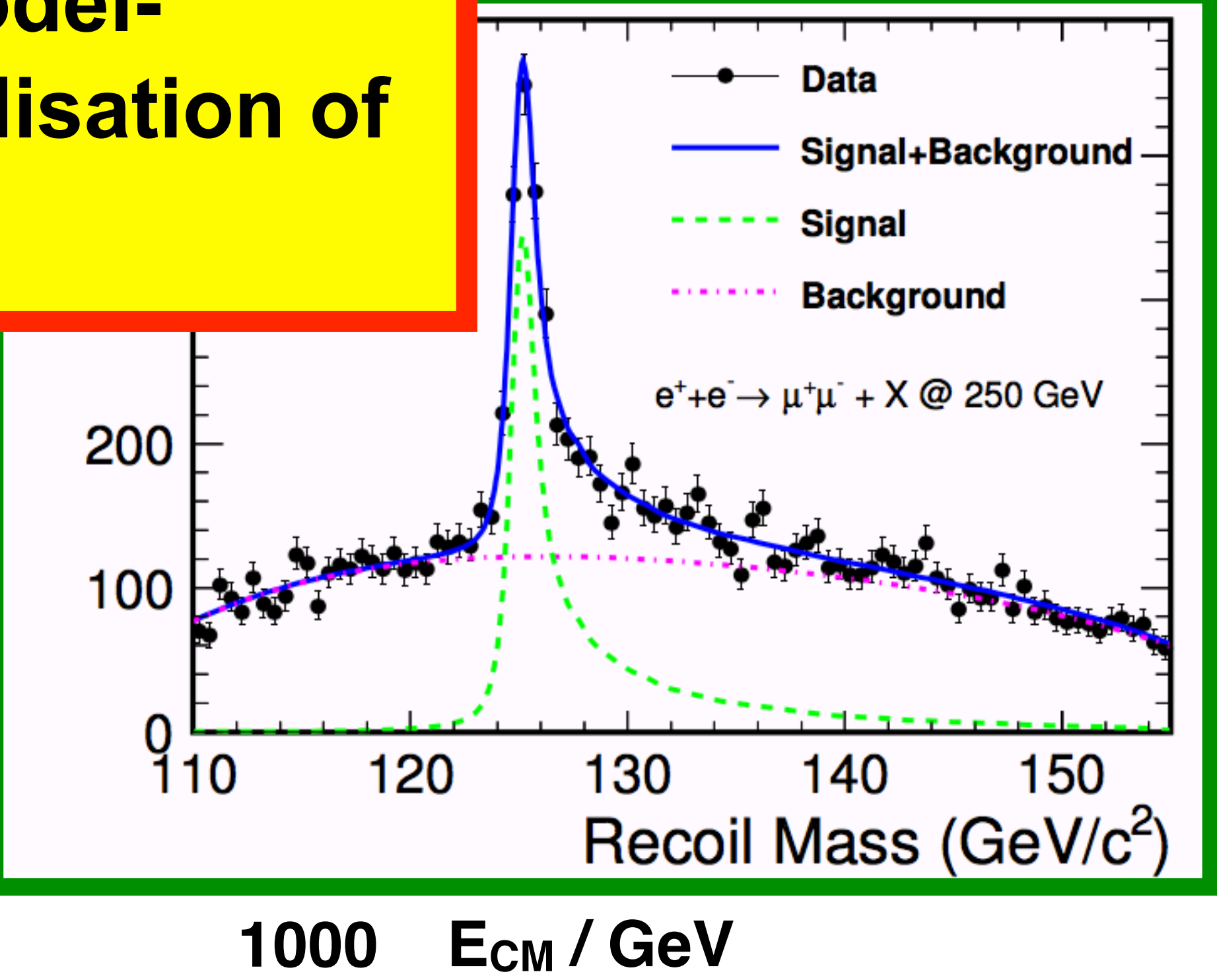
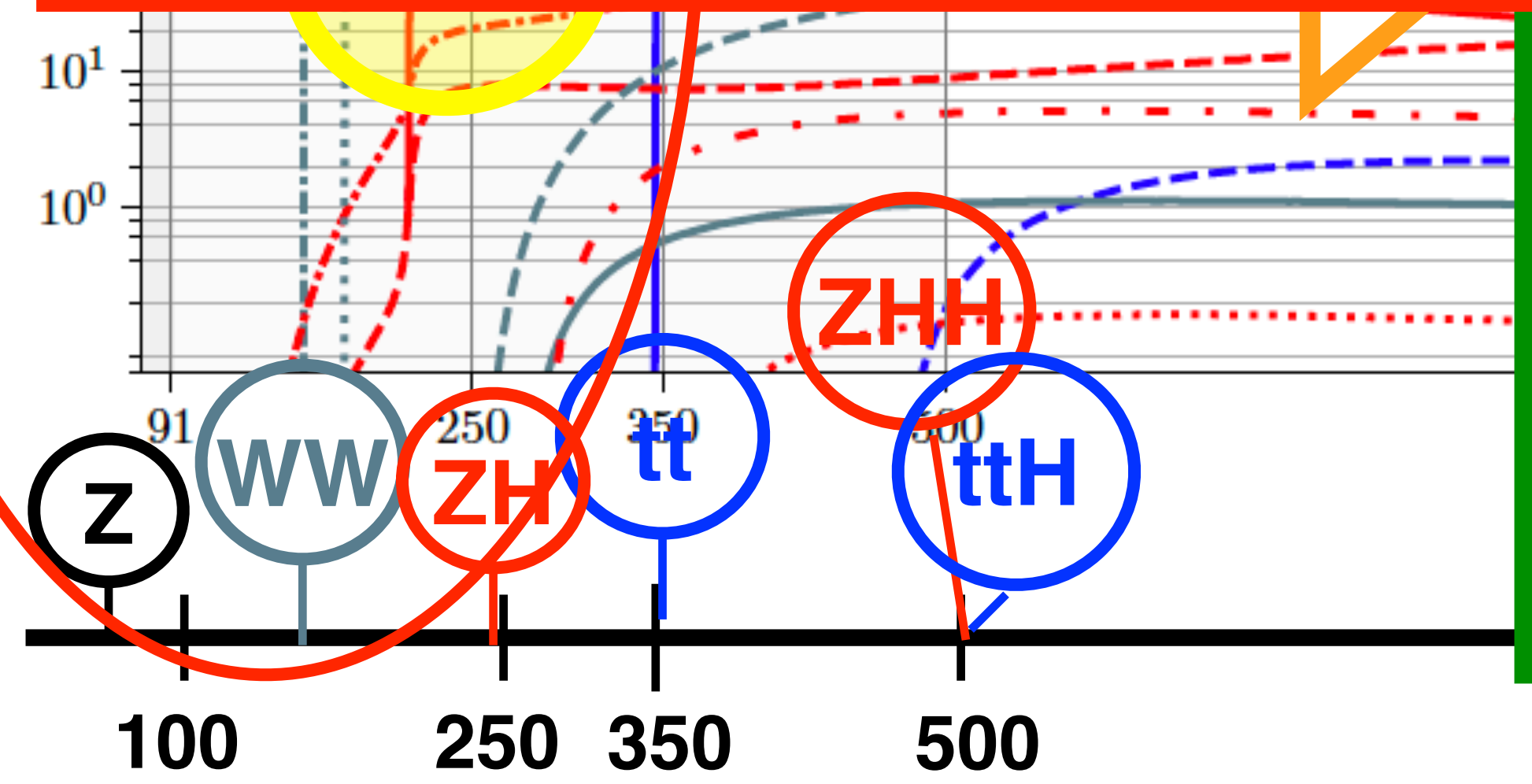


The key physics at a Higgs factory

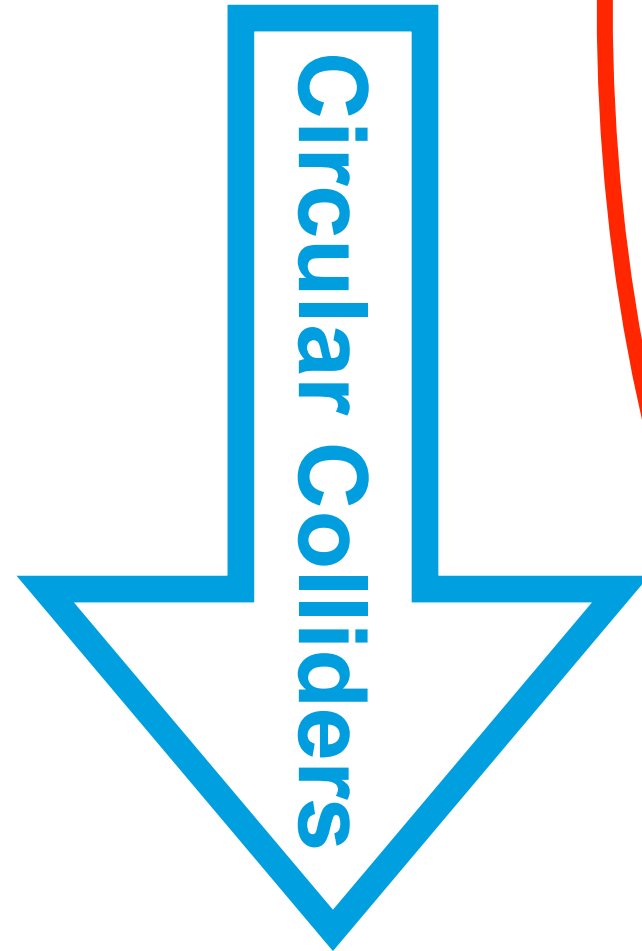
Production rates vs collision energy



This is THE key to a model-independent absolute normalisation of all Higgs couplings



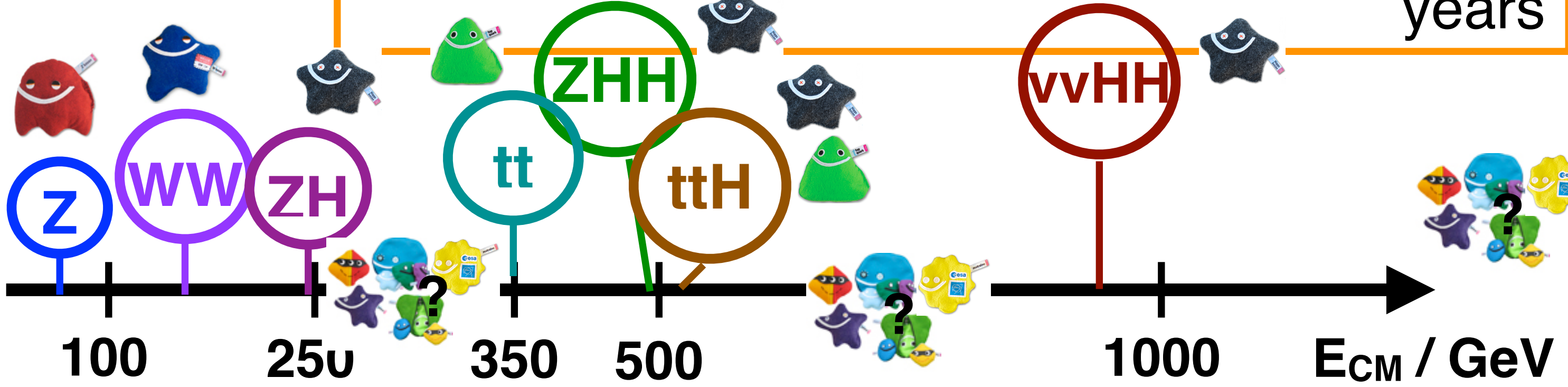
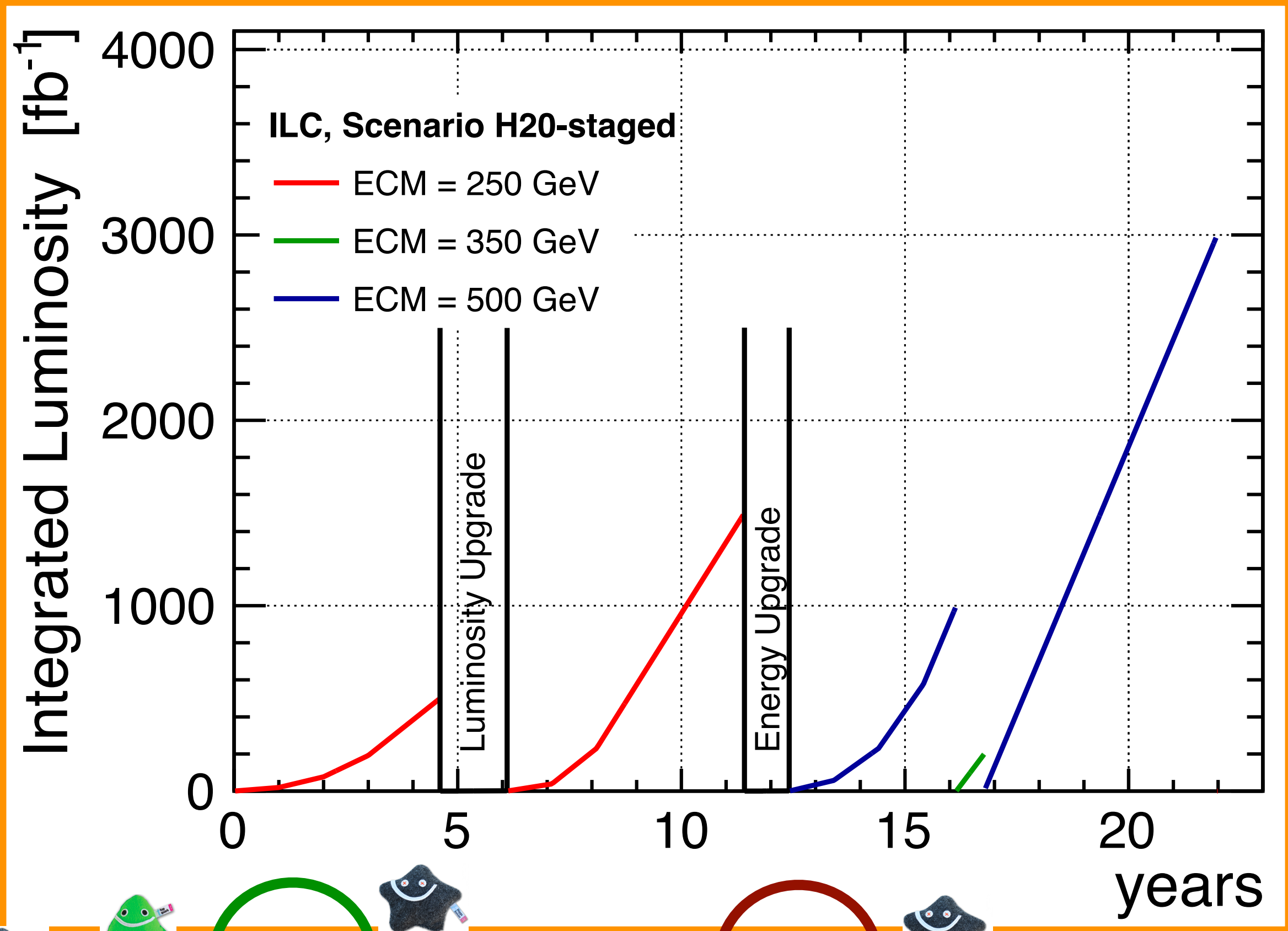
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A physics-driven operating scenario for a Linear Collider

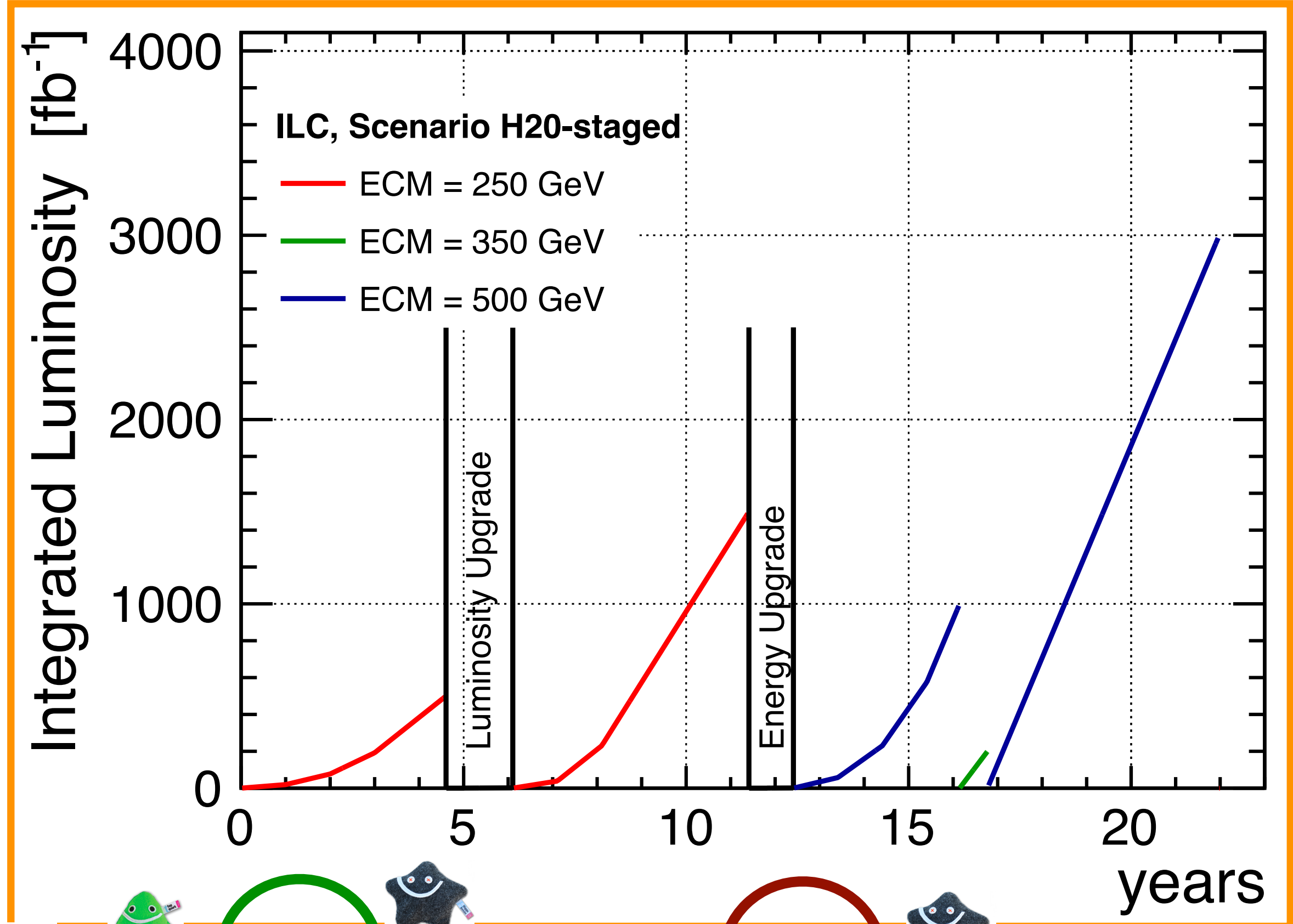
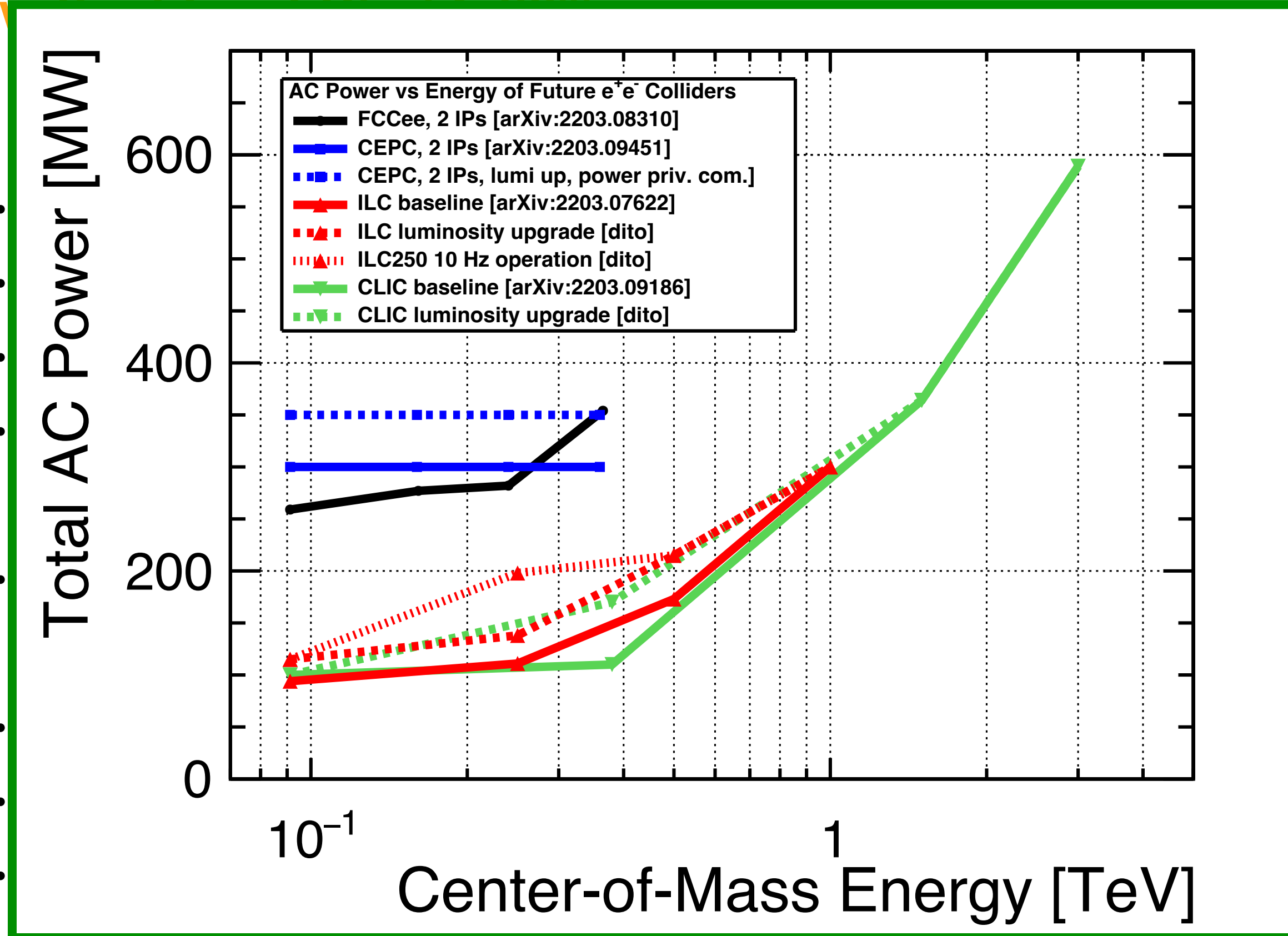
All with at least $P(e^-) > 80\%$

- **250 GeV, 2ab-1:**
 - precision Higgs mass and total ZH cross-section
 - basic ffb̄ and WW program
 - incl Z pole run with $O(10^3)\times$ LEP for EWPOs
 - optional: WW threshold scan
- **350 GeV, 200 fb-1:**
 - precision top mass from threshold scan
- **500...600 GeV, 4 ab-1:**
 - Higgs self-coupling in ZHH
 - top quark ew couplings
 - top Yukawa coupling incl CP structure
 - improved Higgs, WW and ffb̄
- **1...1.5 TeV, 8ab-1:**
 - Higgs self-coupling in VBF
 - further improvements in tt, ff, WW,

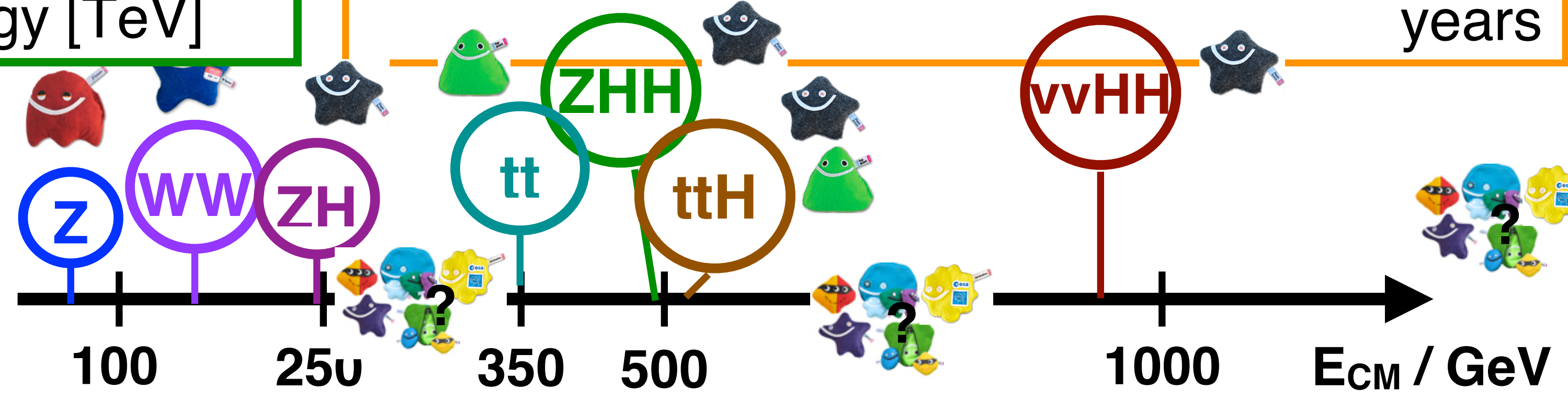


A physics-driven operating scenario for a Linear Collider

All with $\epsilon_{eff} > 99\%$

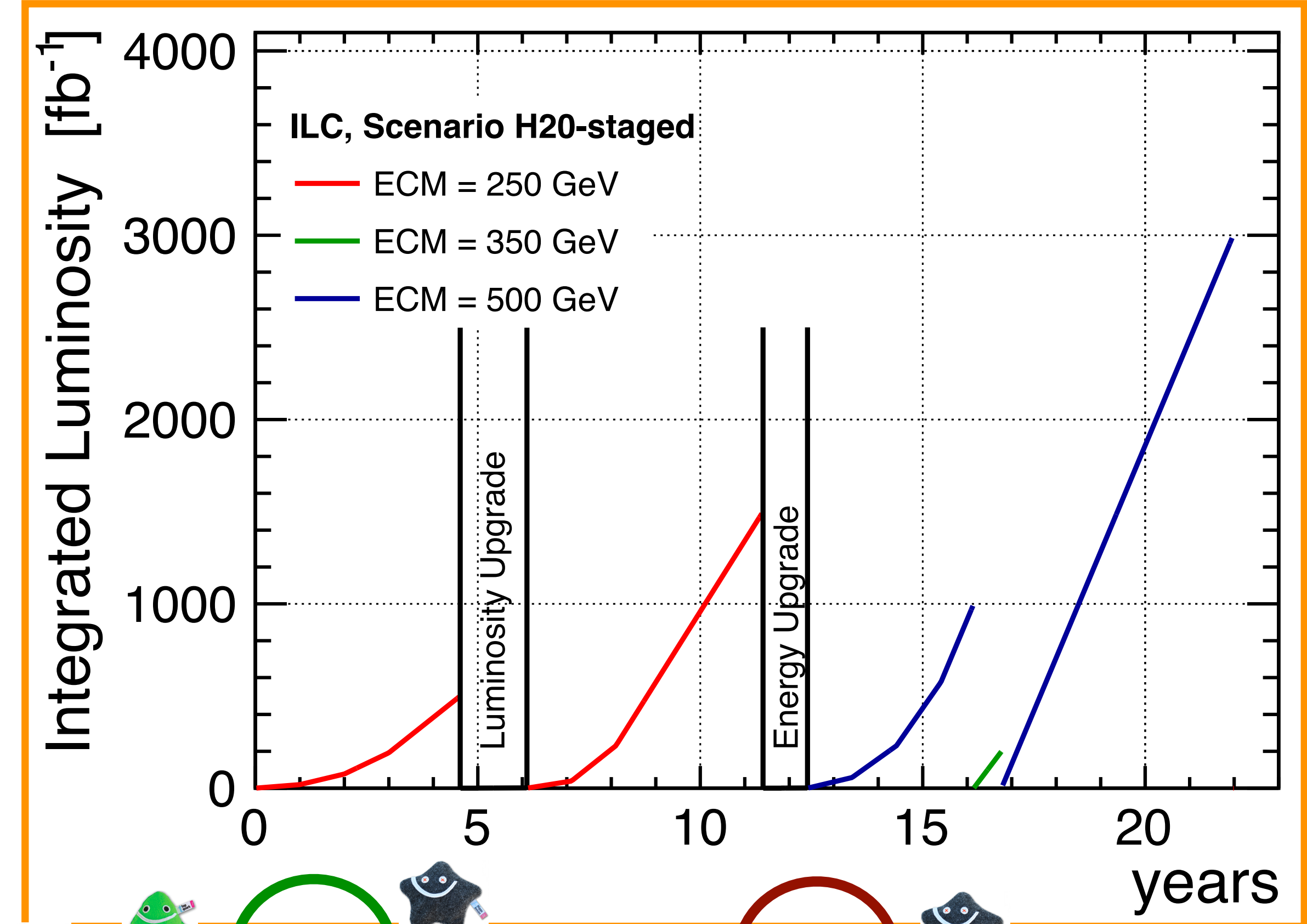
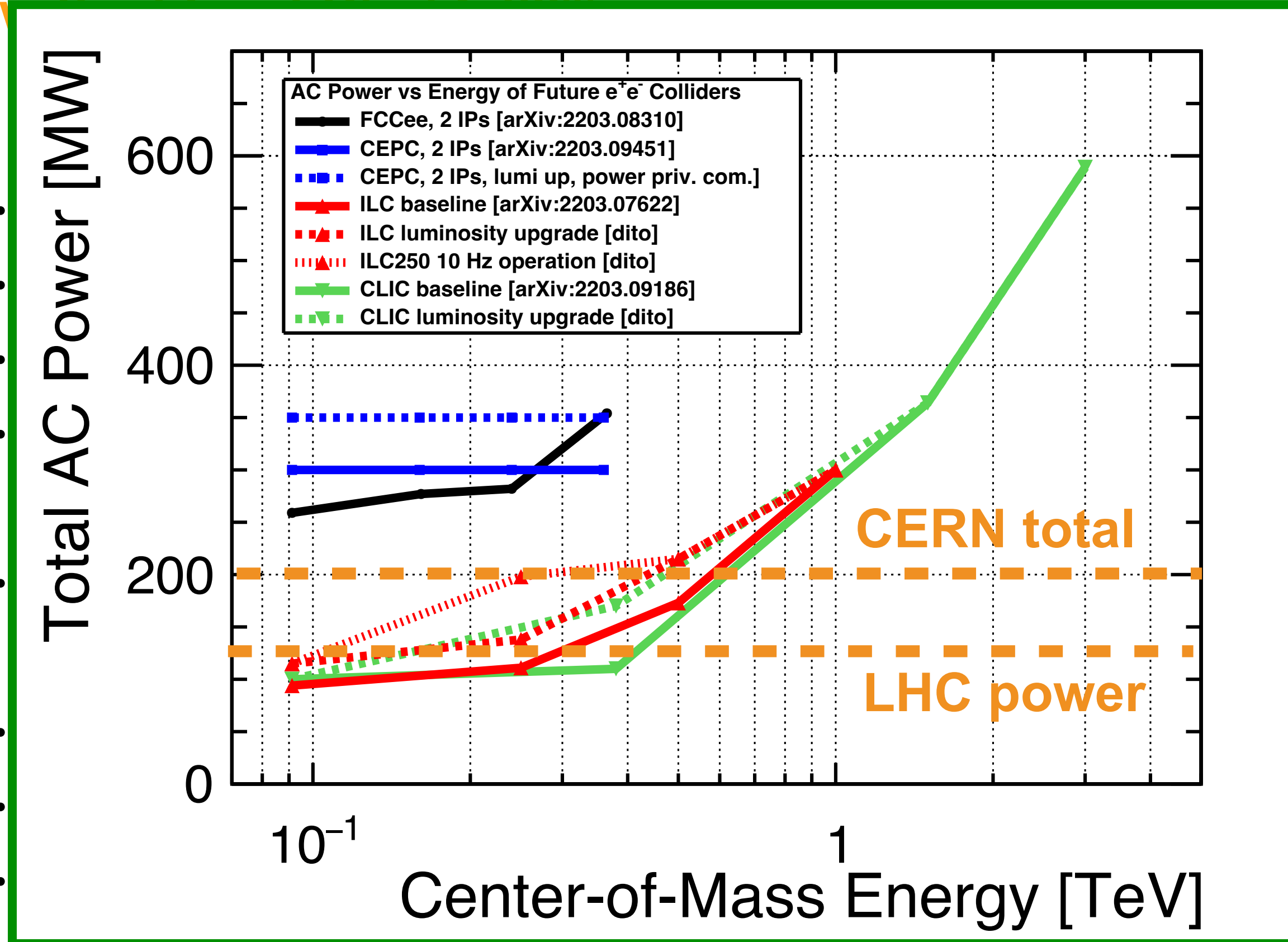


- Improved Higgs, W W and $t\bar{t}$
- 1...1.5 TeV, 8ab⁻¹:**
 - Higgs self-coupling in VBF
 - further improvements in $t\bar{t}$, $f\bar{f}$, W W ,

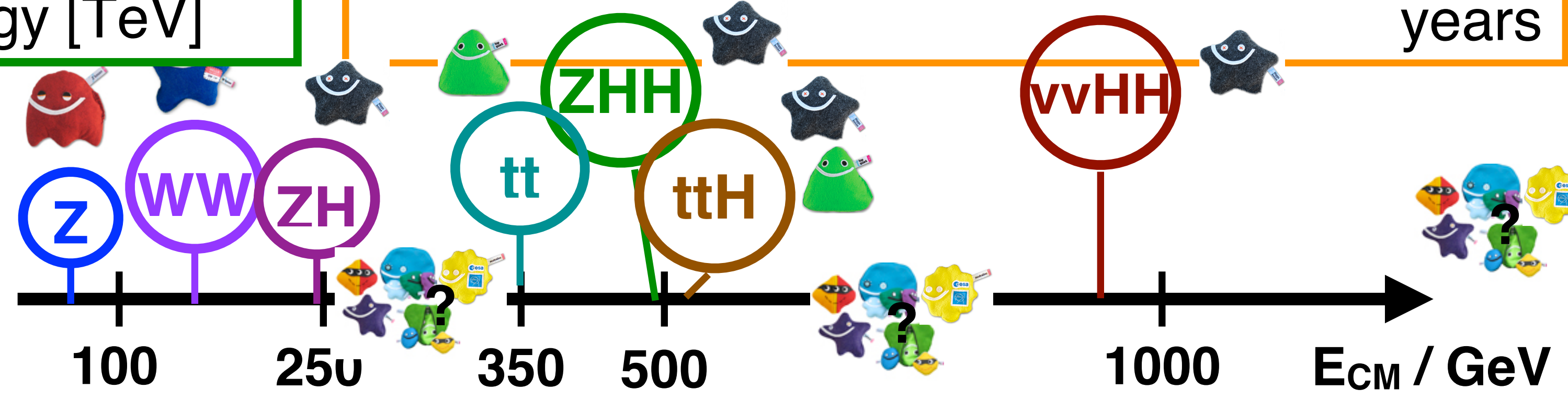


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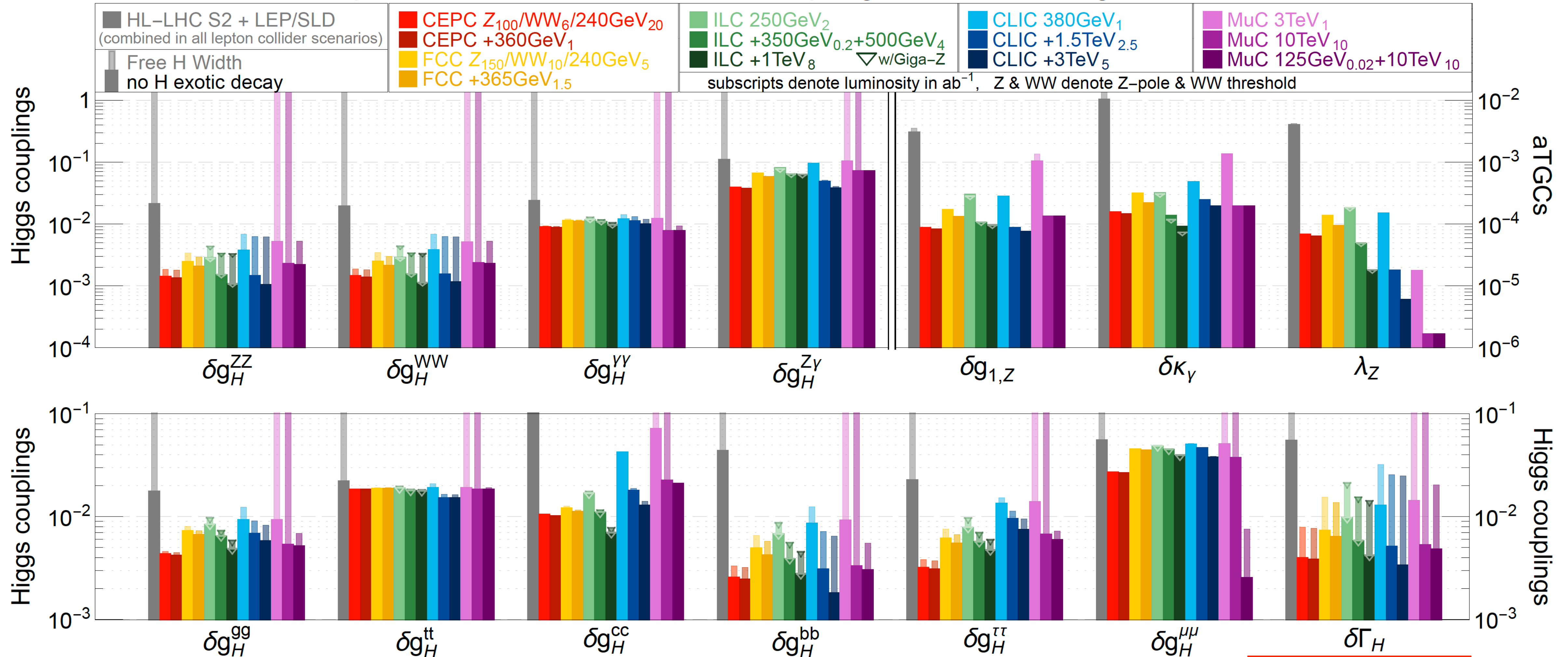
- Improved Higgs, WV and $t\bar{t}b\bar{c}$
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Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans

precision reach on effective couplings from SMEFT global fit

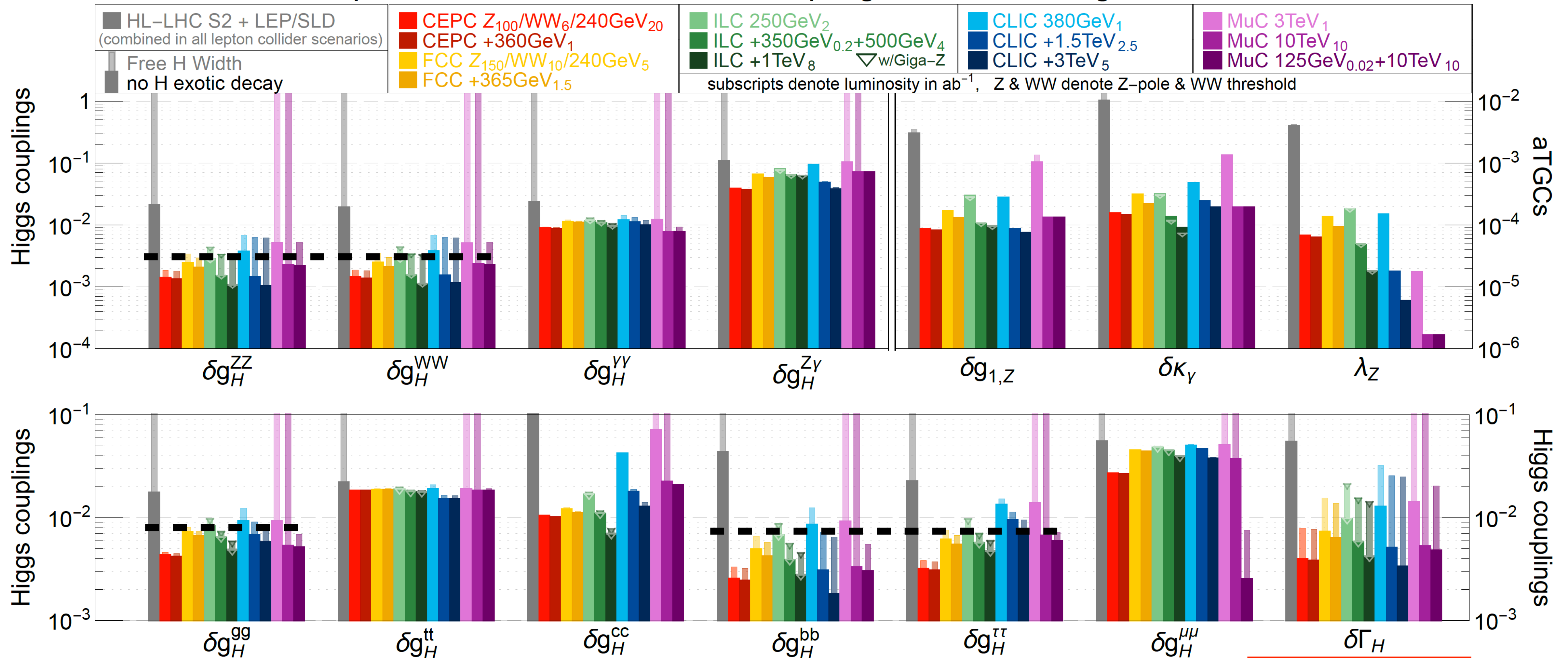


arXiv:2206.08326

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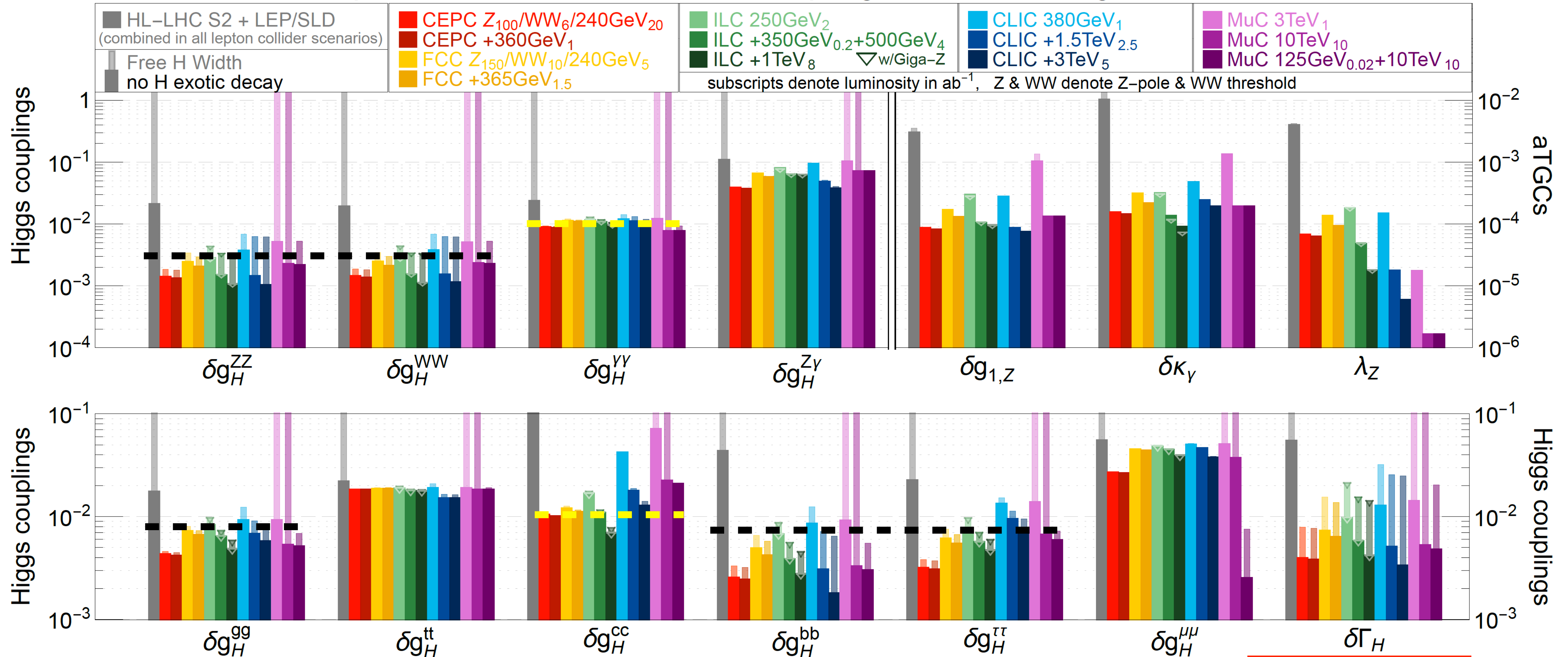


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Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans

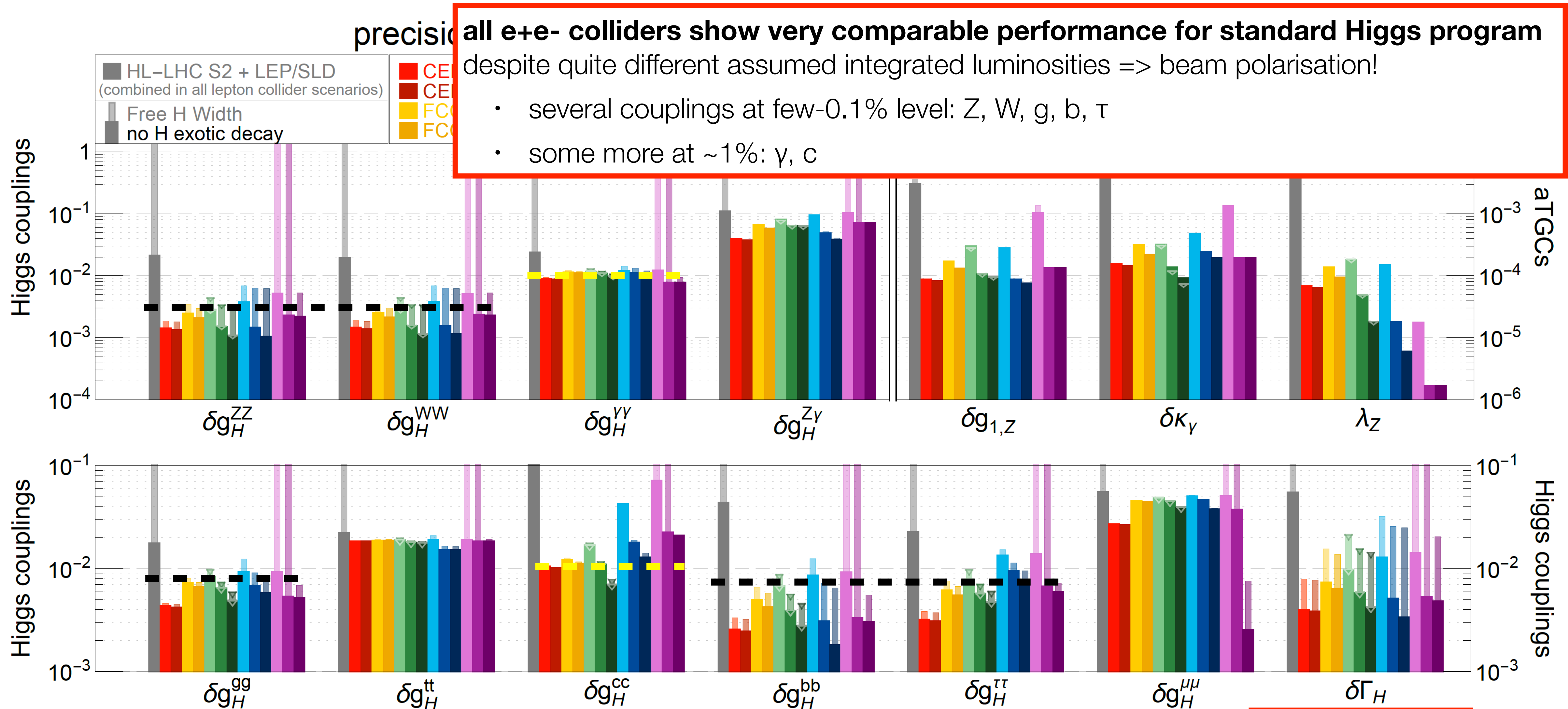
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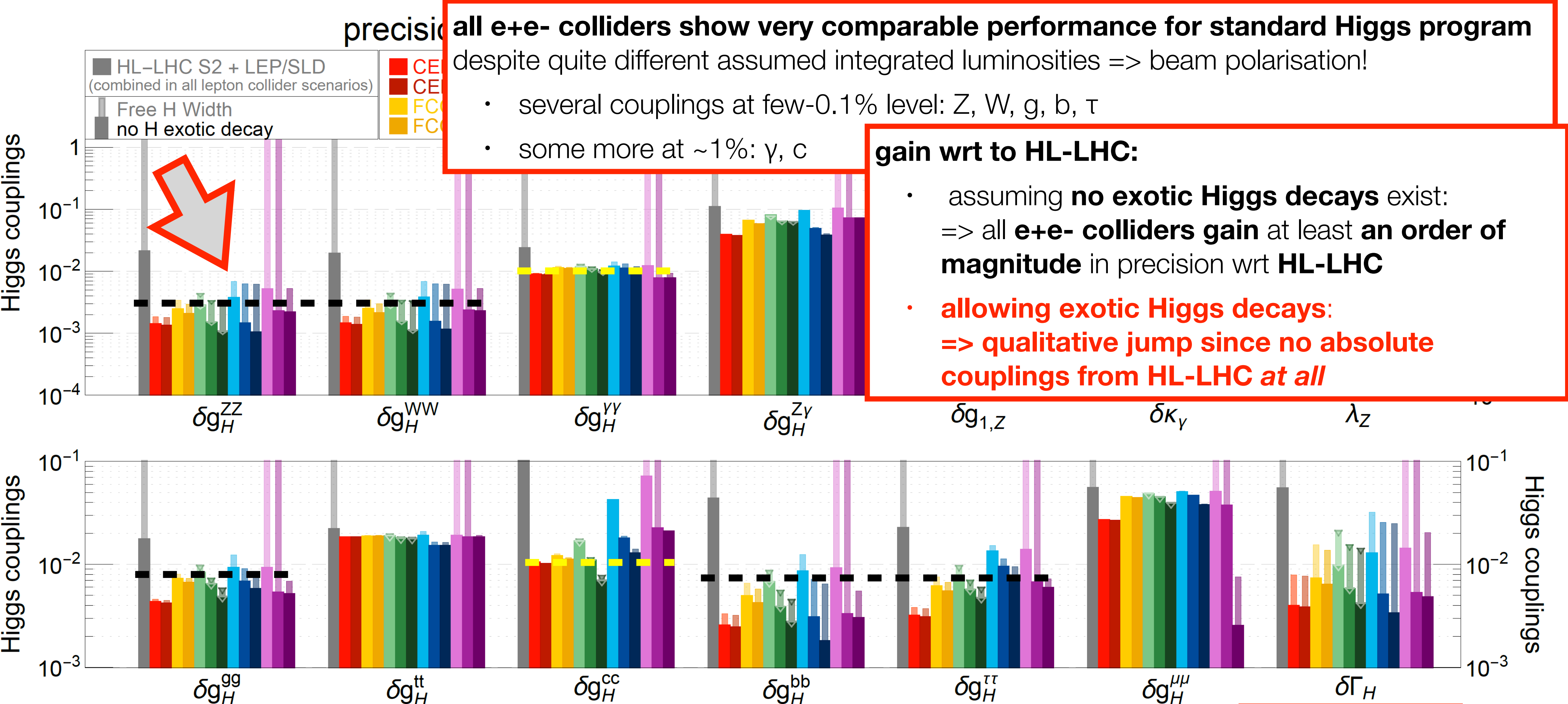
Rainbow-Manhattans



arXiv:2206.08326

Higgs Couplings: The Snowmass SMEFT fit

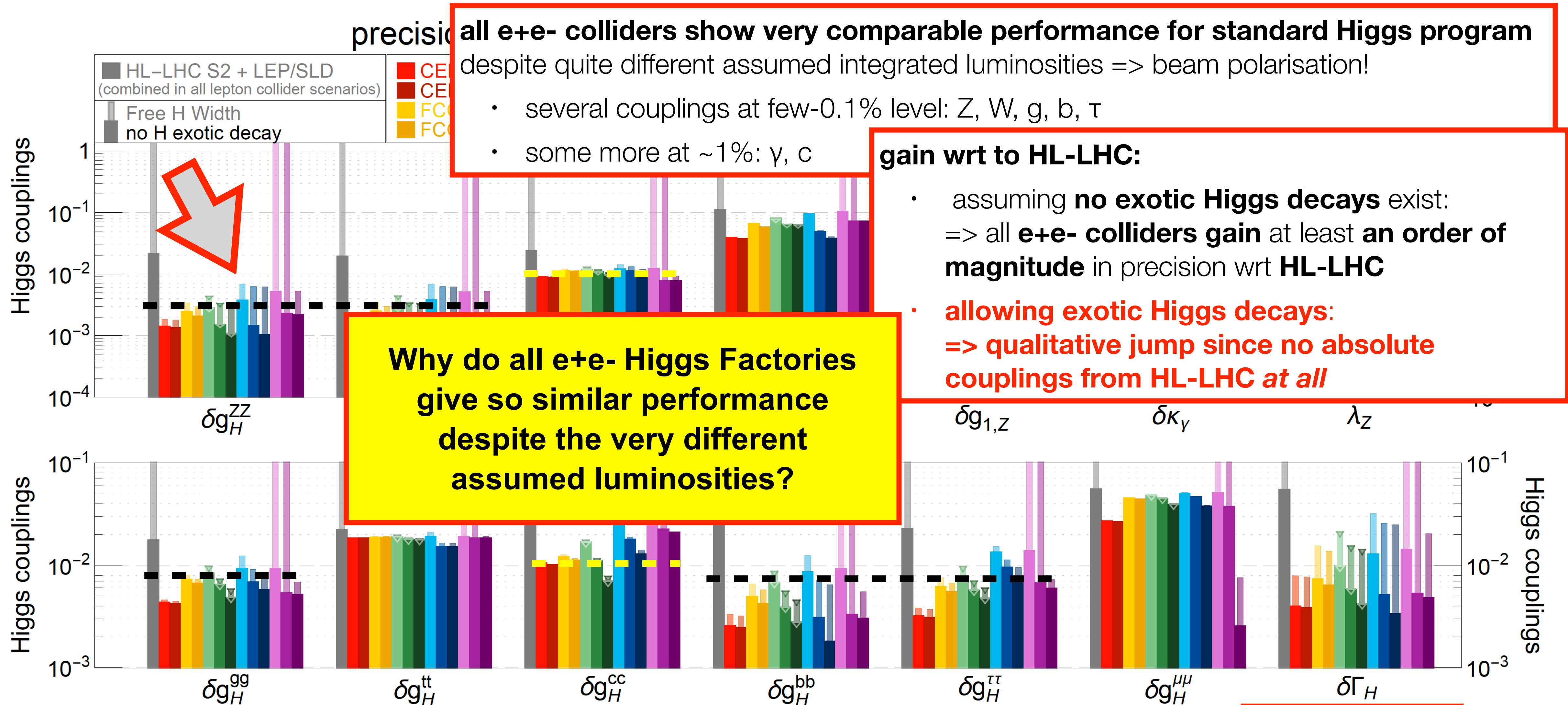
Rainbow-Manhattans



arXiv:2206.08326

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



precision **all e+e- colliders show very comparable performance for standard Higgs program**
 despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ , c

gain wrt to HL-LHC:

- assuming **no exotic Higgs decays** exist:
=> all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays:**
=> **qualitative jump** since **no absolute couplings from HL-LHC at all**

Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

Interlude: Chirality in Particle Physics

Just a quick reminder...

- Gauge group of weak x electromagnetic interaction: $SU(2)_L \times U(1)$
- L: left-handed, spin anti- \parallel momentum*
R: right-handed, spin \parallel momentum*
- **left-handed particles are fundamentally different from right-handed ones:**
 - only left-handed fermions (e^-) and right-handed anti-fermions (e^+) take part in the charged weak interaction, i.e. couple to the W bosons
 - there are (in the SM) no right-handed neutrinos
 - right-handed quarks and charged leptons are singlets under $SU(2)_L$
 - also couplings to the Z boson are different for left- and right-handed fermions
- **checking whether the differences between L and R are as predicted in the SM is a very sensitive test for new phenomena!**



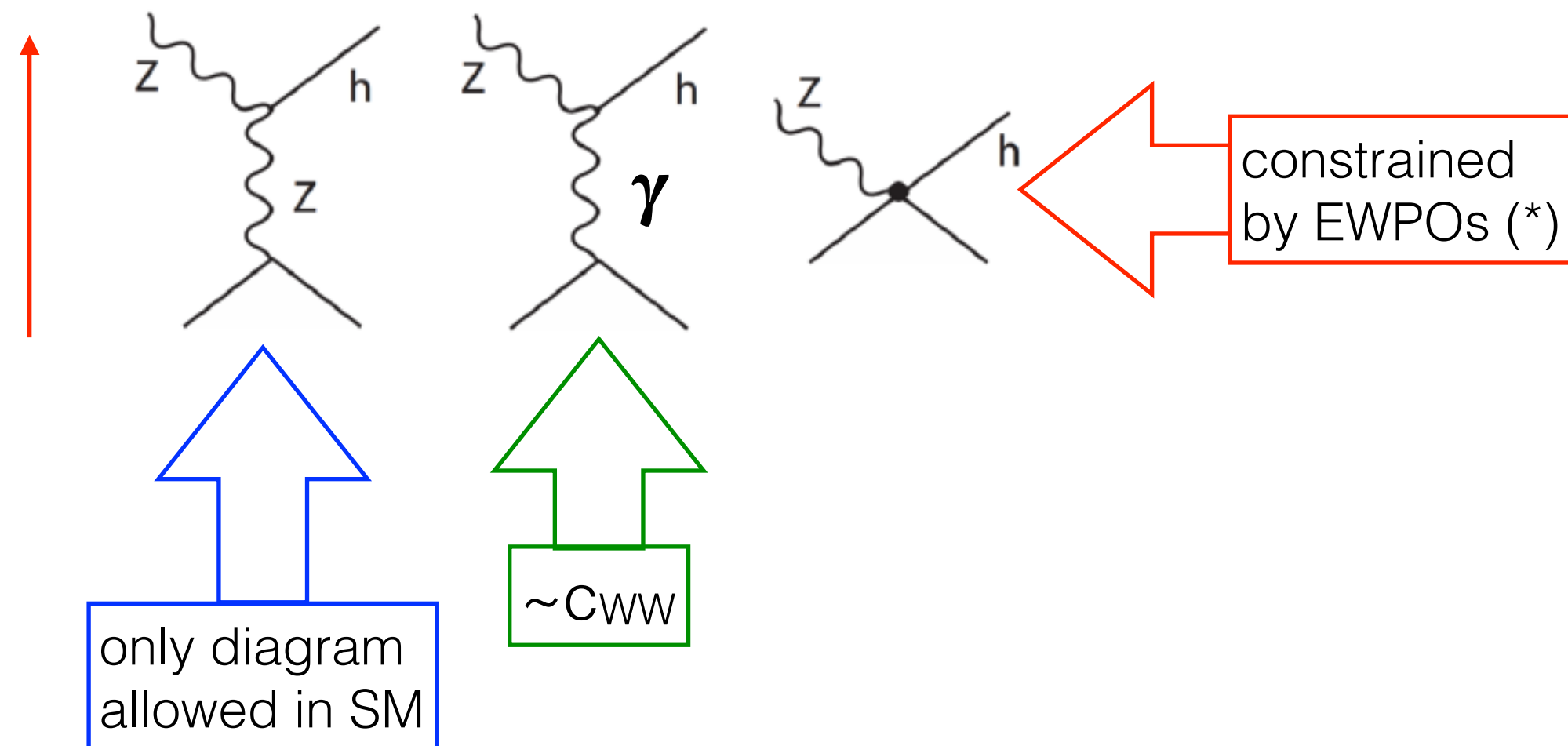
$$P = \frac{N_R - N_L}{N_R + N_L}$$

* for massive particles, there is of course a difference between chirality and helicity, no time for this today, ask at the end in case of doubt!

Polarisation & Higgs Couplings

A relationship only appreciated a few years ago...

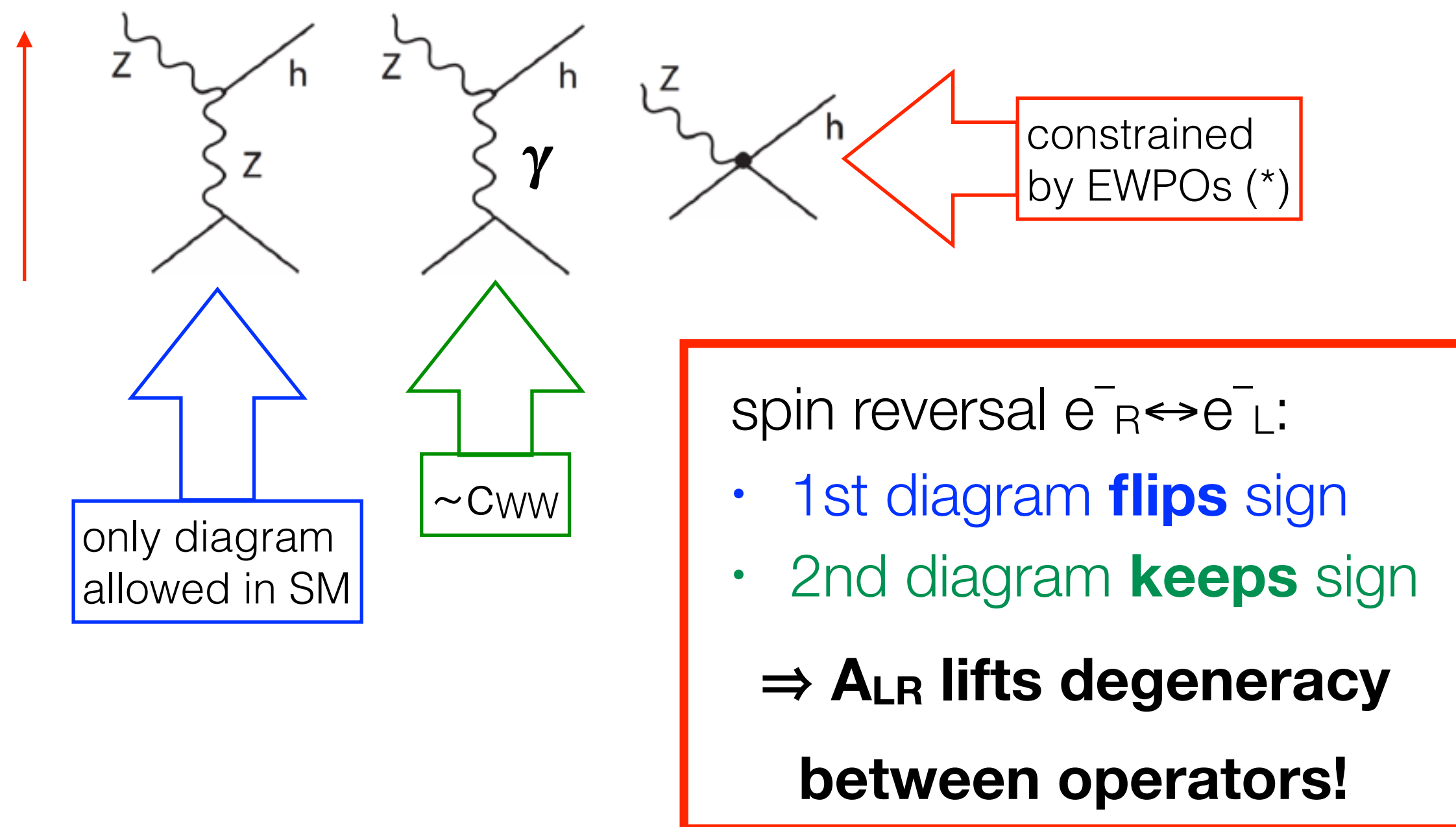
- **THE key process** at a Higgs factory:
Higgsstrahlung $e^+e^- \rightarrow Zh$
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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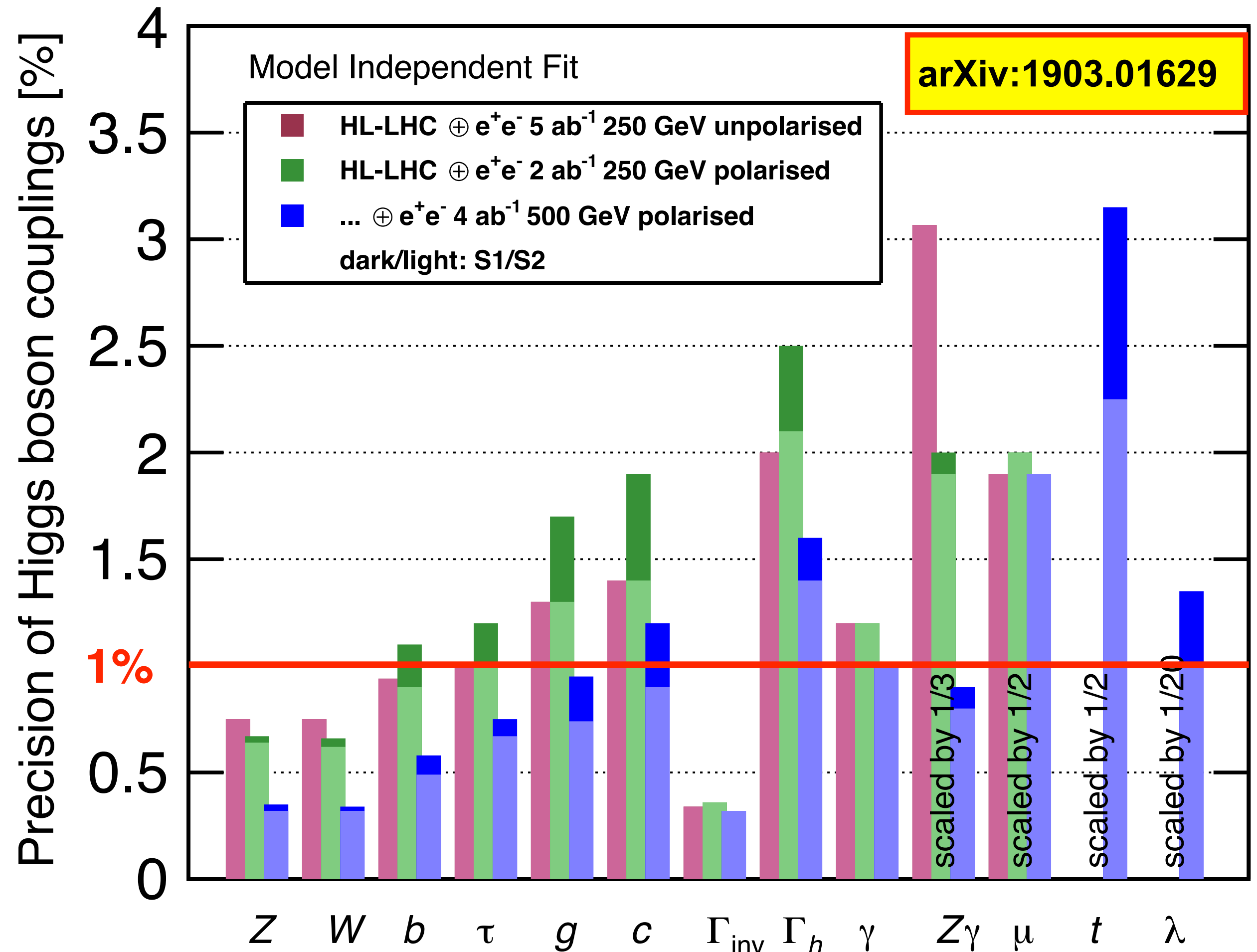
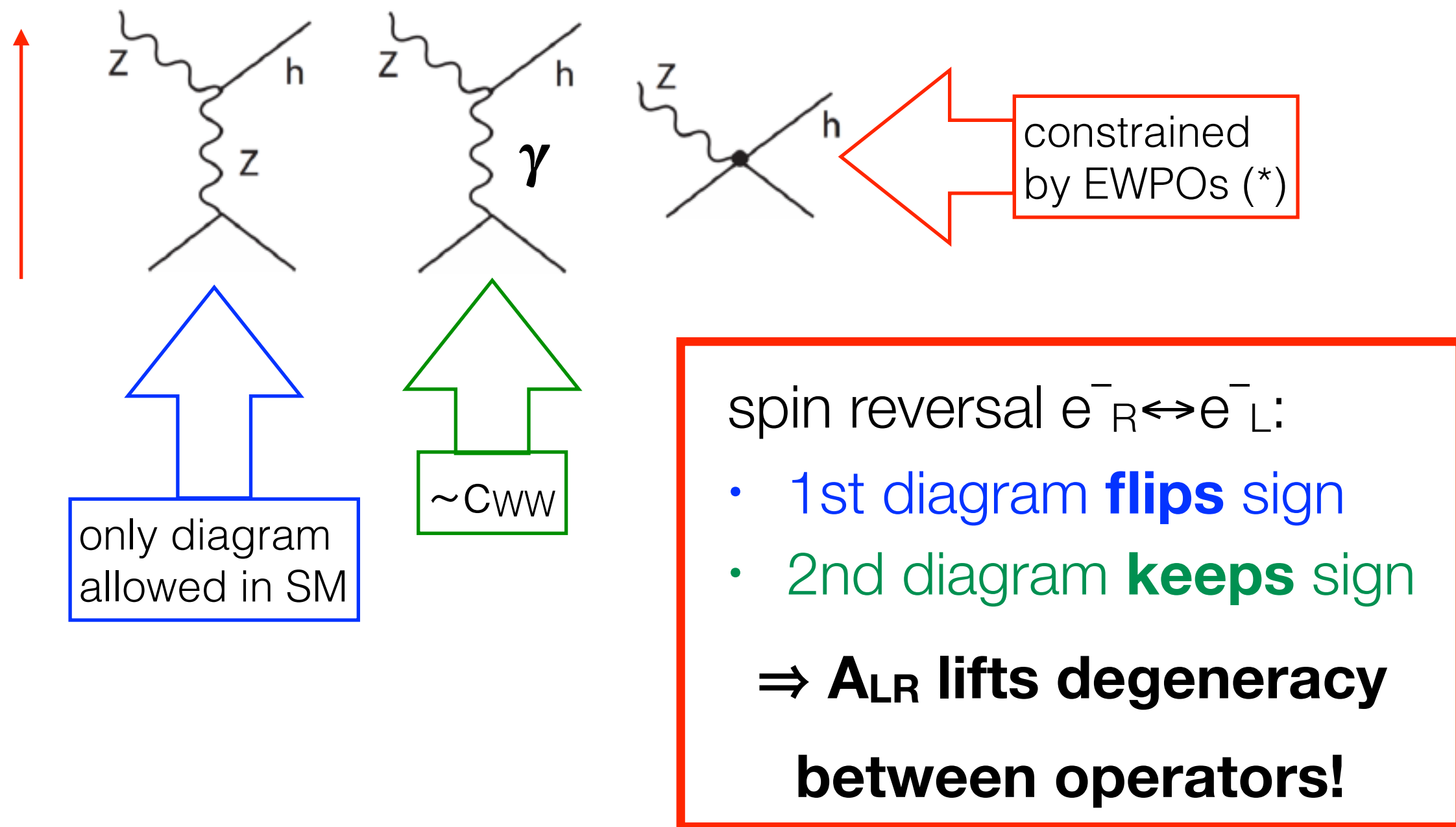
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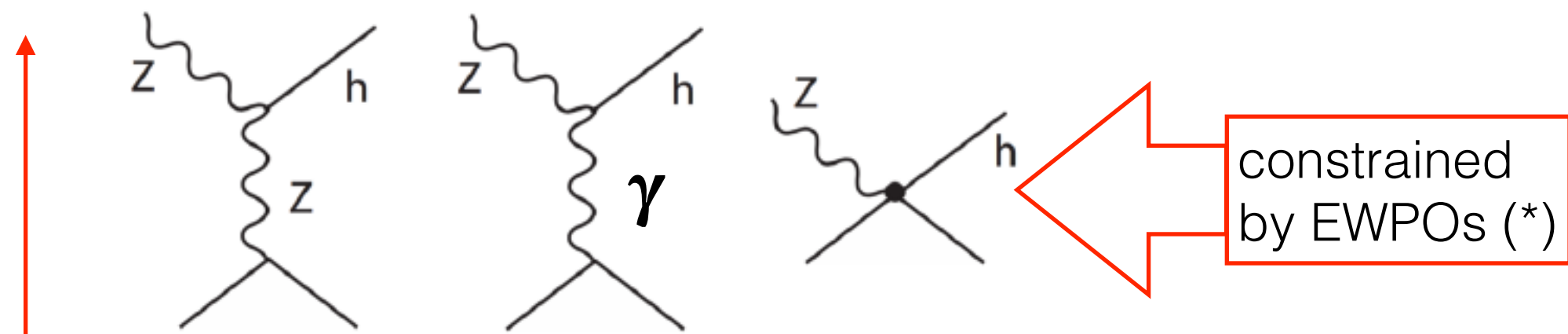
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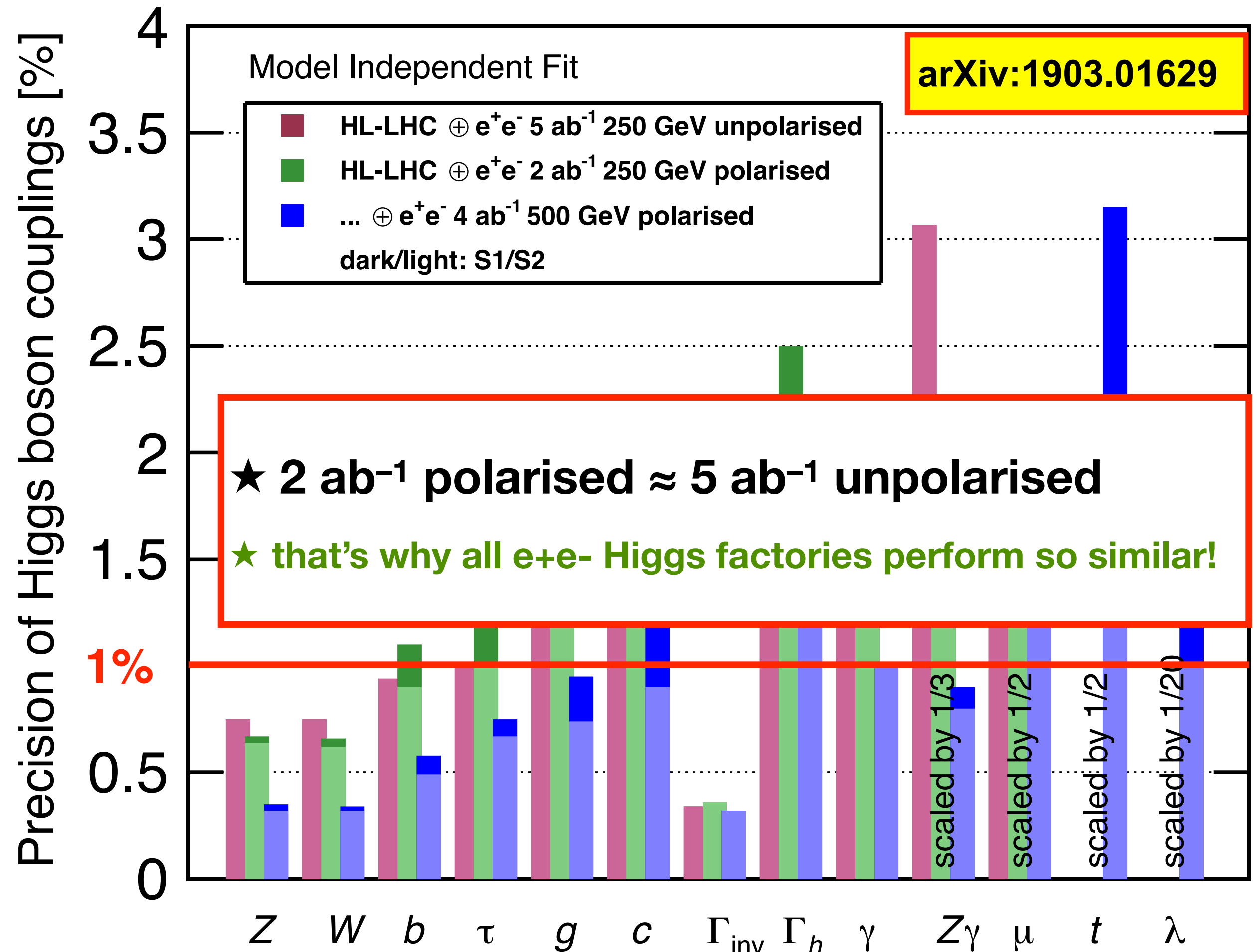
only diagram allowed in SM

$\sim C_{WW}$

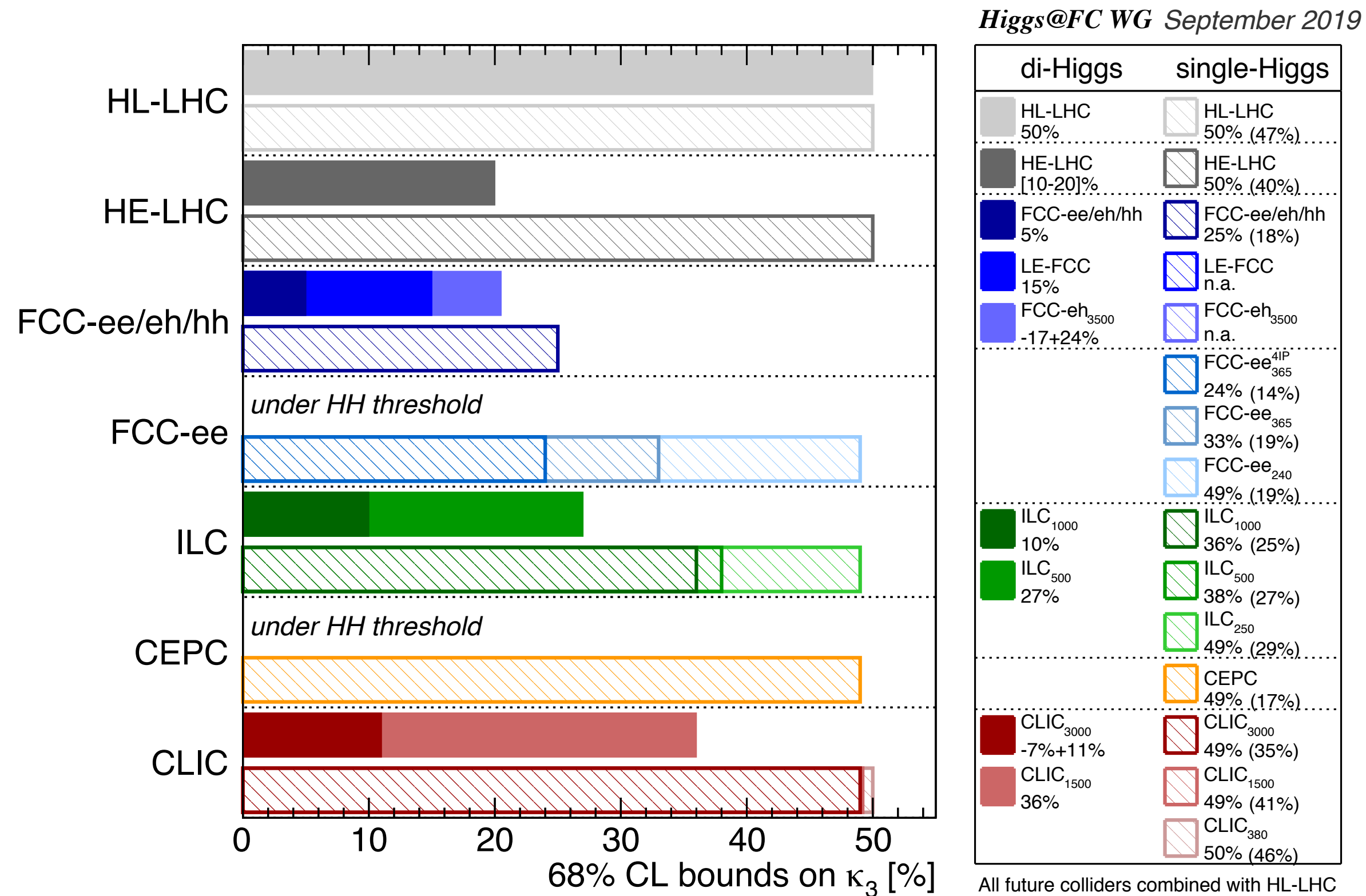
spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

\Rightarrow **ALR lifts degeneracy between operators!**



The ECFA Higgs@Future Report



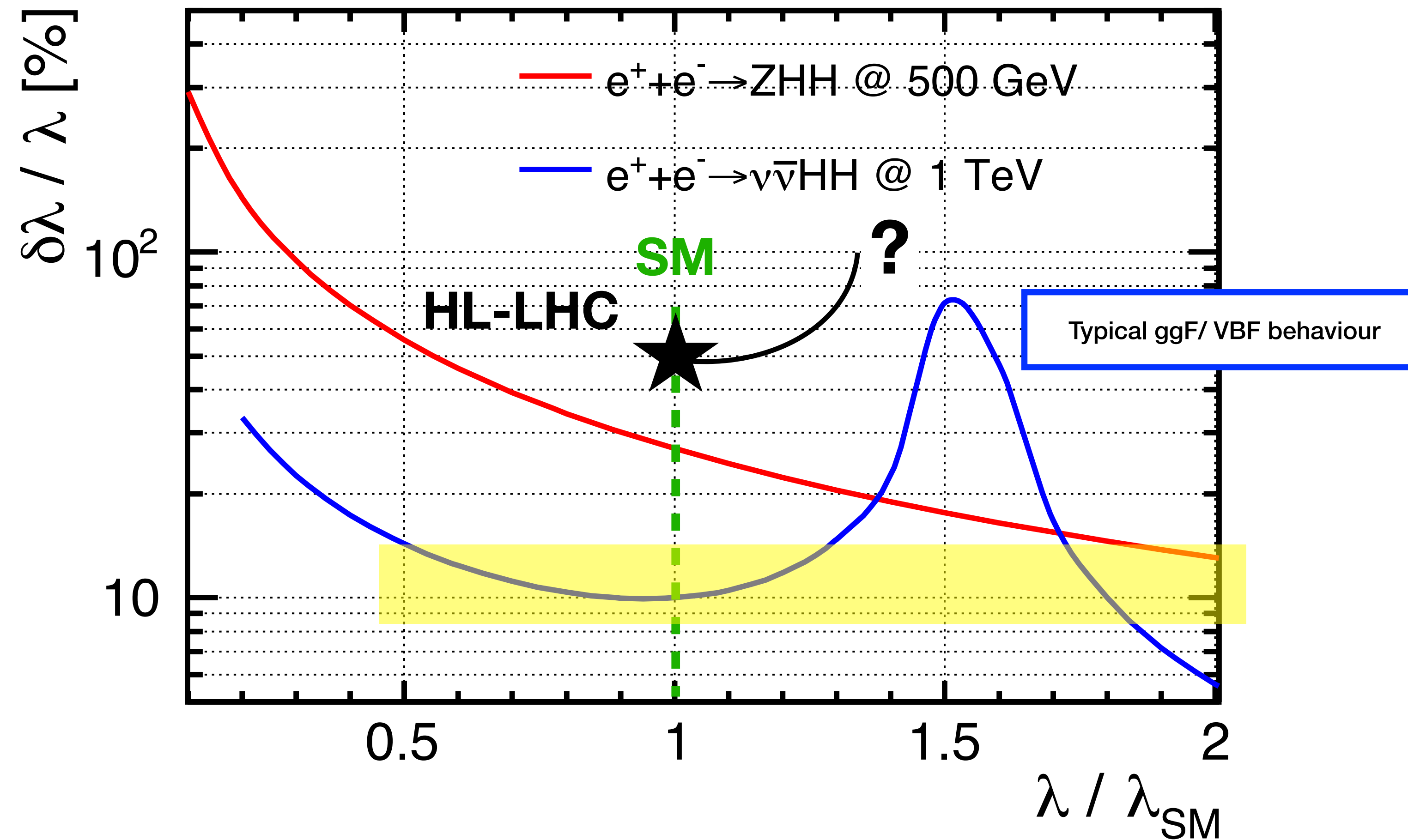
At lepton colliders, double Higgs-strahlung, $e^+e^- \rightarrow ZHH$, gives stronger constraints on positive deviations ($\kappa_3 > 1$), while VBF is better in constraining negative deviations, ($\kappa_3 < 1$). While at HL-LHC, values of $\kappa_3 > 1$, as expected in models of strong first order phase transition, result in a smaller double-Higgs production cross section due to the destructive interference, at lepton colliders for the ZHH process they actually result in a larger cross section, and hence into an increased precision. For instance at ILC₅₀₀, the sensitivity around the SM value is 27% but it would reach 18% around $\kappa_3 = 1.5$.

**This figure applies ONLY for $\lambda = \lambda_{SM}$
no studies of BSM case apart from ILC**

ILC Sensitivity vs Lambda

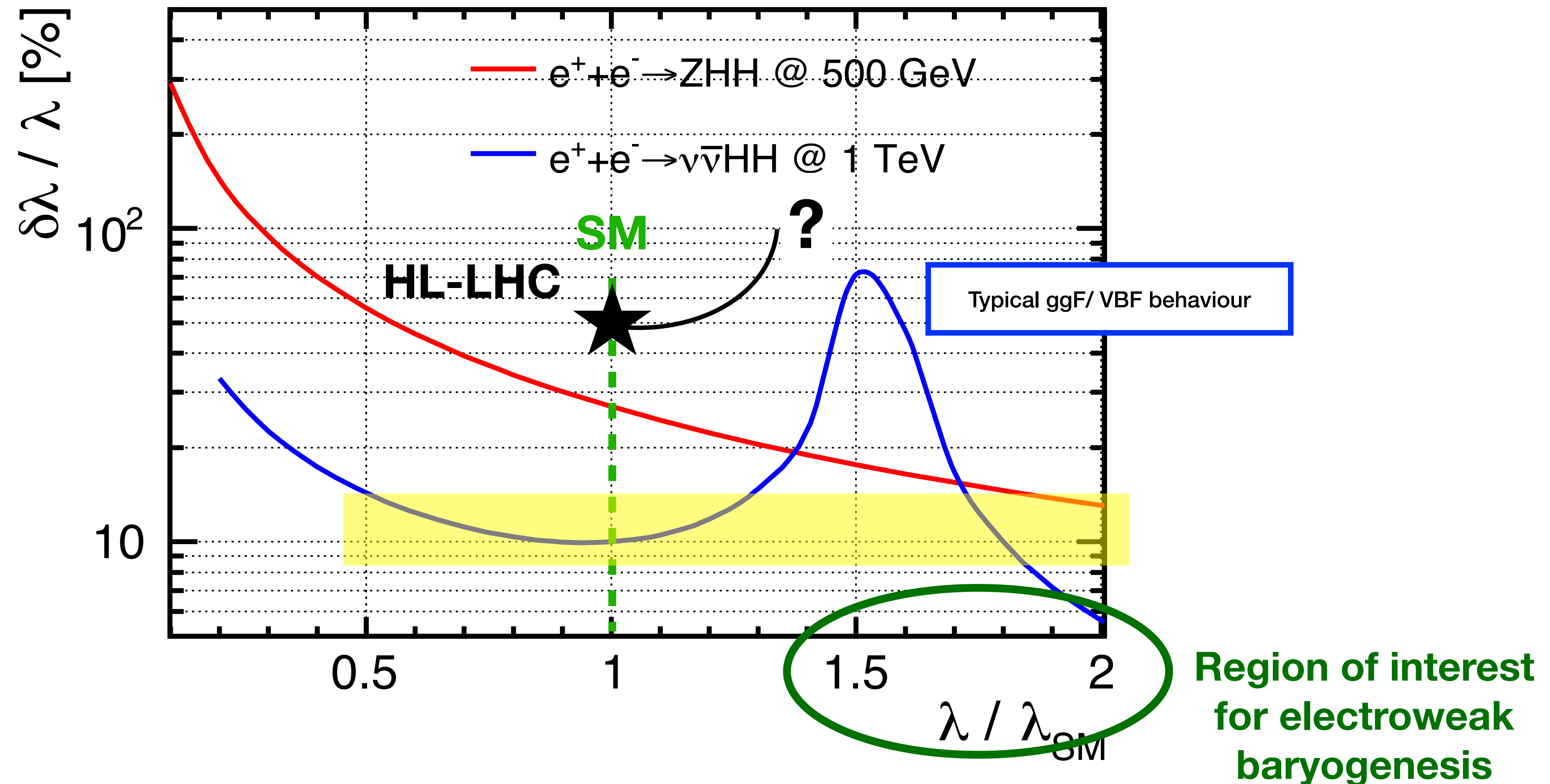
ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]



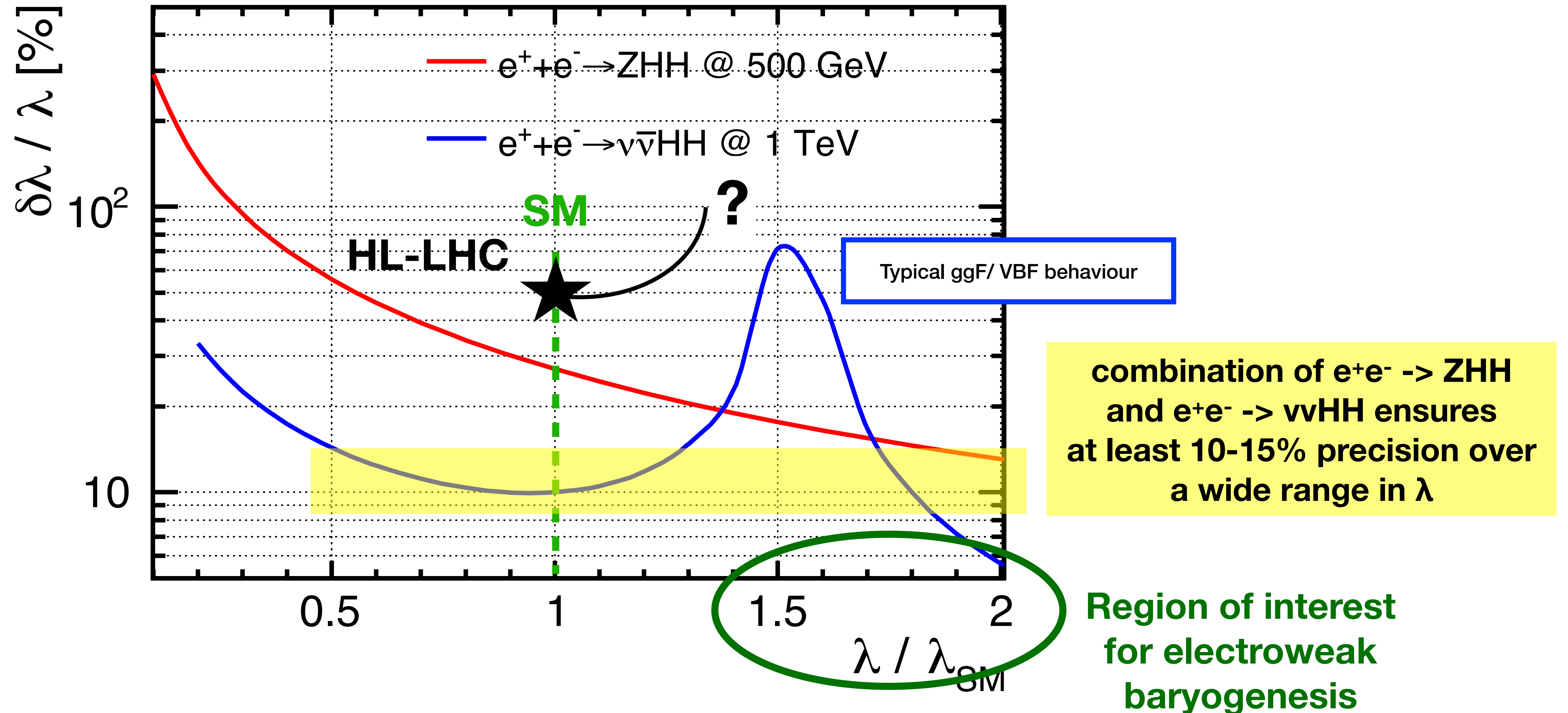
ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]



ILC Sensitivity vs Lambda

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Higgs self-coupling

Electroweak Baryogenesis?

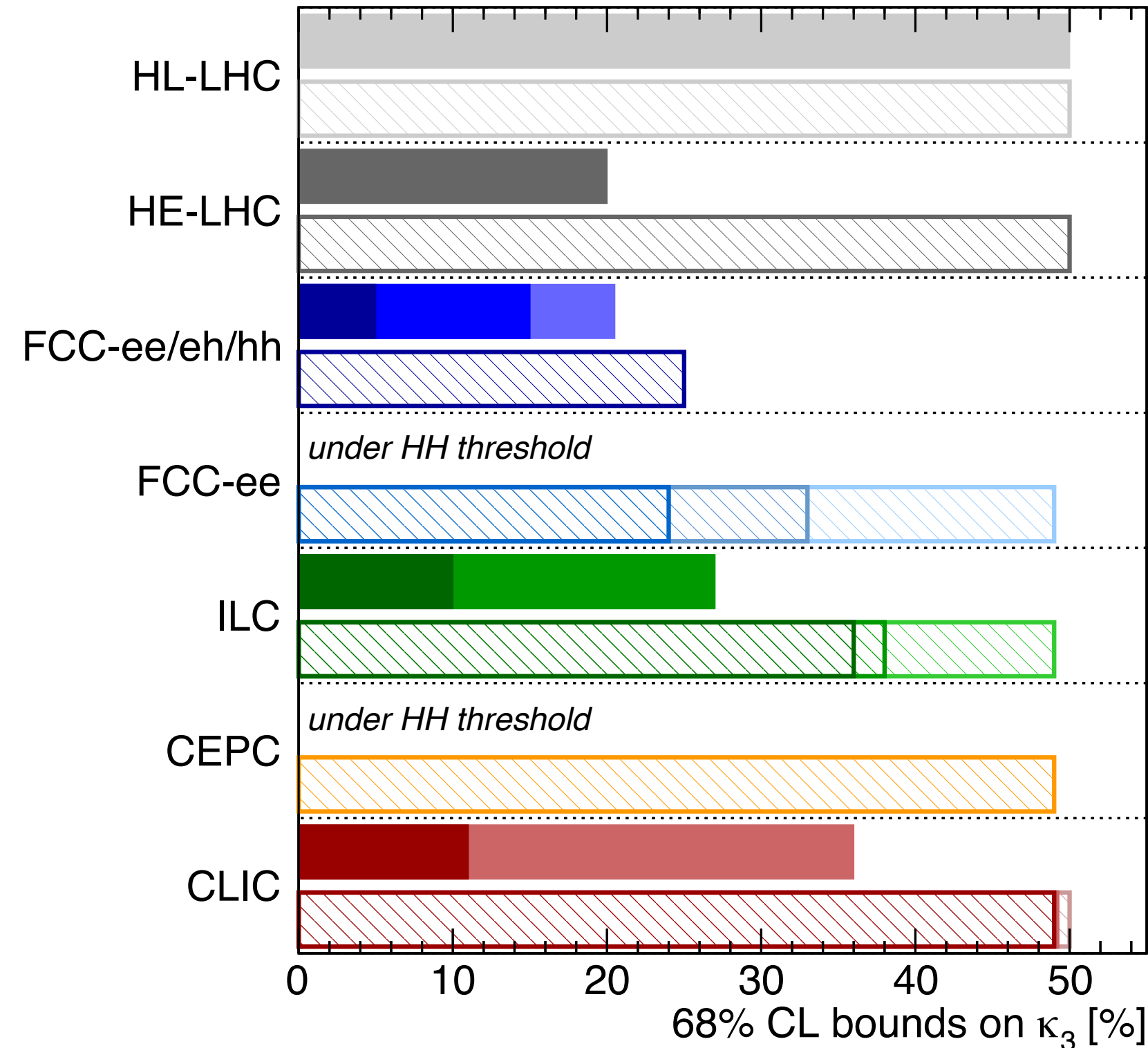


The Higgs Boson

The Higgs Boson

...and the universe

Higgs@FC WG September 2019



di-Higgs	single-Higgs
HL-LHC 50%	HL-LHC 50% (47%)
HE-LHC [10-20]%	HE-LHC 50% (40%)
FCC-ee/eh/hh 5%	FCC-ee/eh/hh 25% (18%)
LE-FCC 15%	LE-FCC n.a.
FCC-eh ₃₅₀₀ -17+24%	FCC-eh ₃₅₀₀ n.a.
	FCC-ee ^{4IP} ₃₆₅ 24% (14%)
	FCC-ee ₃₆₅ 33% (19%)
	FCC-ee ₂₄₀ 49% (19%)
ILC ₁₀₀₀ 10%	ILC ₁₀₀₀ 36% (25%)
ILC ₅₀₀ 27%	ILC ₅₀₀ 38% (27%)
	ILC ₂₅₀ 49% (29%)
	CEPC 49% (17%)
CLIC ₃₀₀₀ -7%+11%	CLIC ₃₀₀₀ 49% (35%)
CLIC ₁₅₀₀ 36%	CLIC ₁₅₀₀ 49% (41%)
	CLIC ₃₈₀ 50% (46%)

All future colliders combined with HL-LHC

most detailed ILC ref: PhD Thesis C.Dürig
Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

Higgs self-coupling

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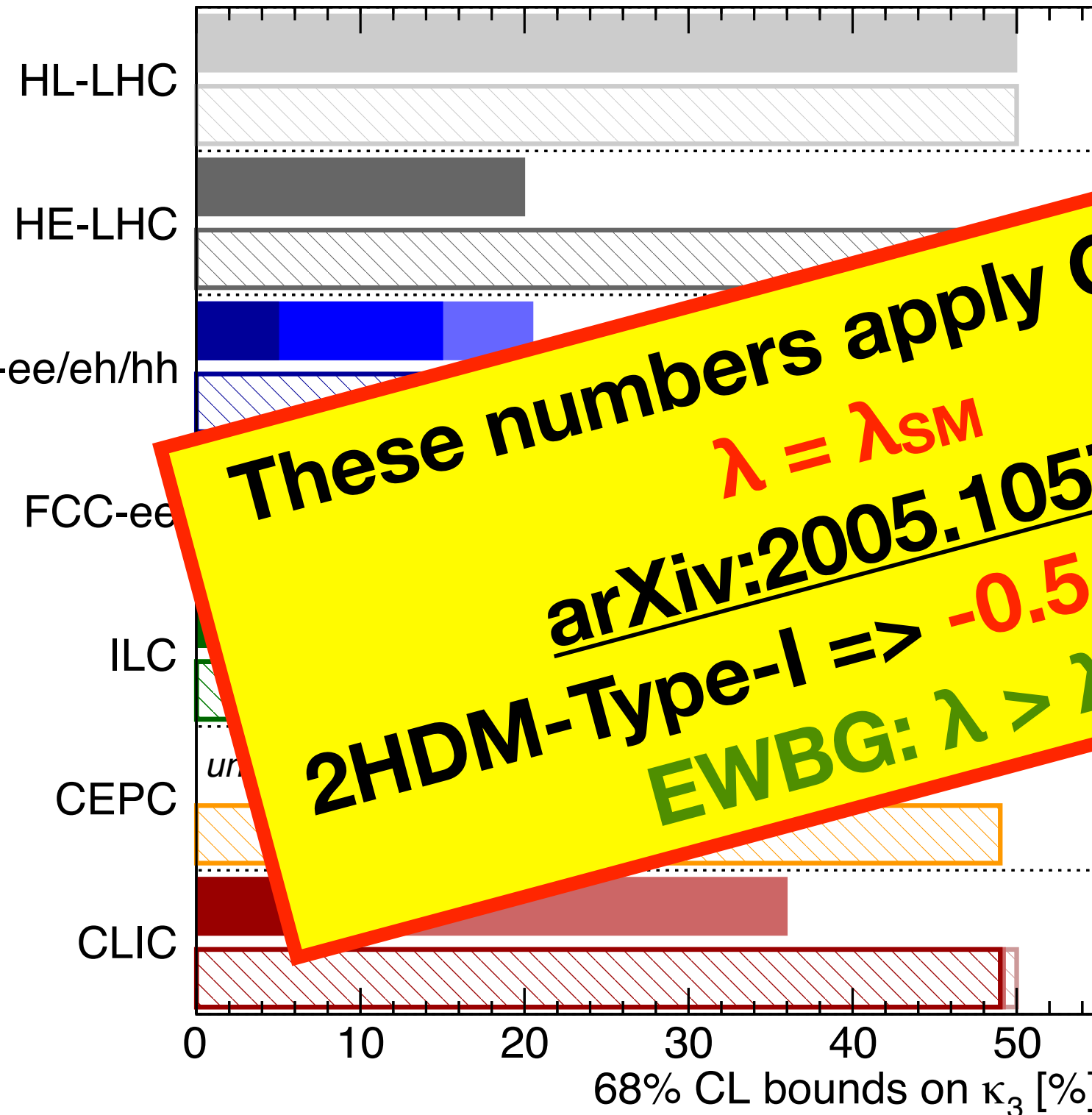
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All future colliders combined with HL-LHC



These numbers apply ONLY for
 $\lambda = \lambda_{SM}$
 arXiv:2005.10576:
 2HDM-Type-I => $-0.5 \dots 1.5 \times \lambda_{SM}$
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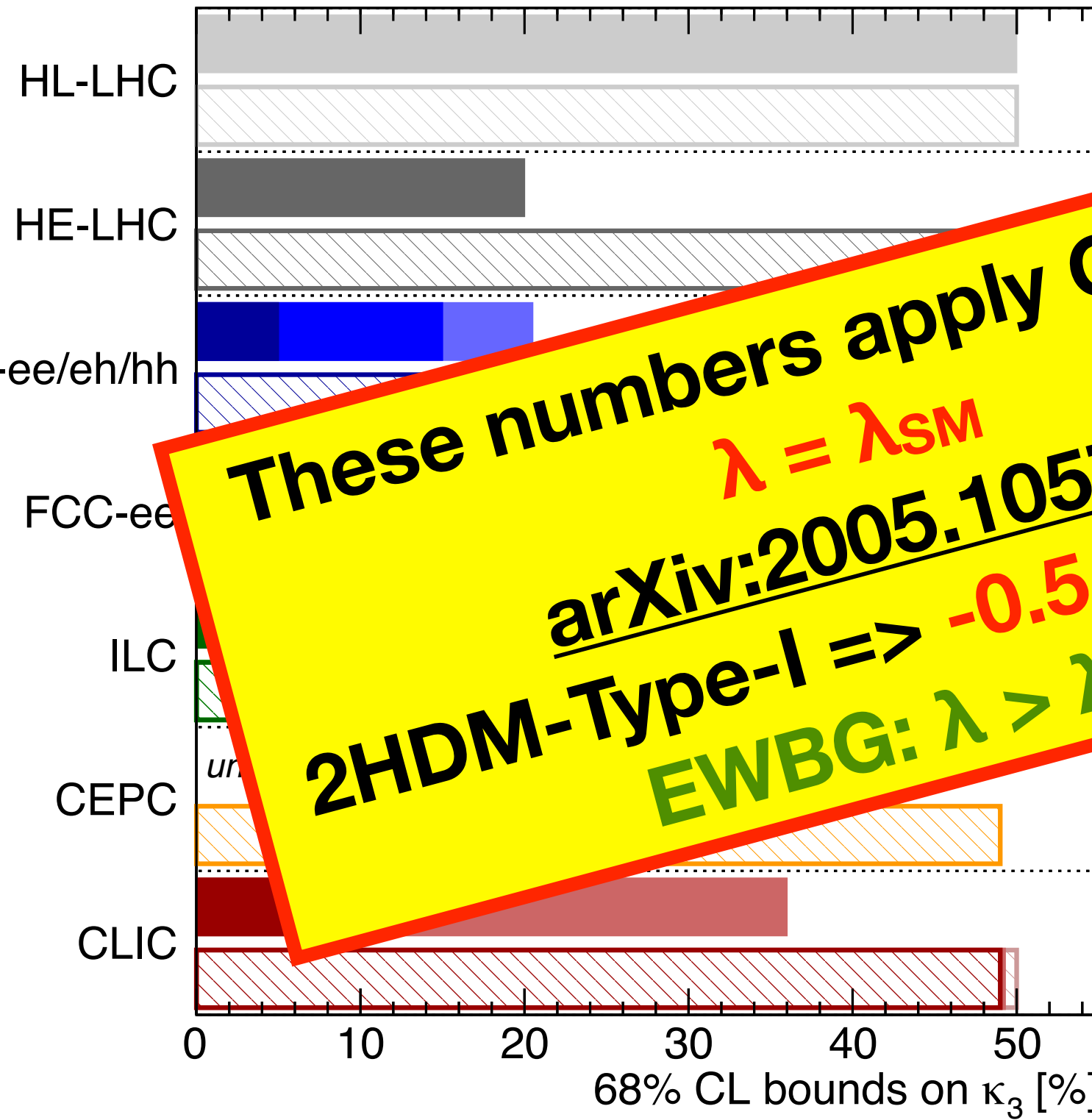
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Higgs@FC WG September 2019

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$\lambda > \lambda_{SM}$:
 • pp cross section drops
 • ee cross section rises

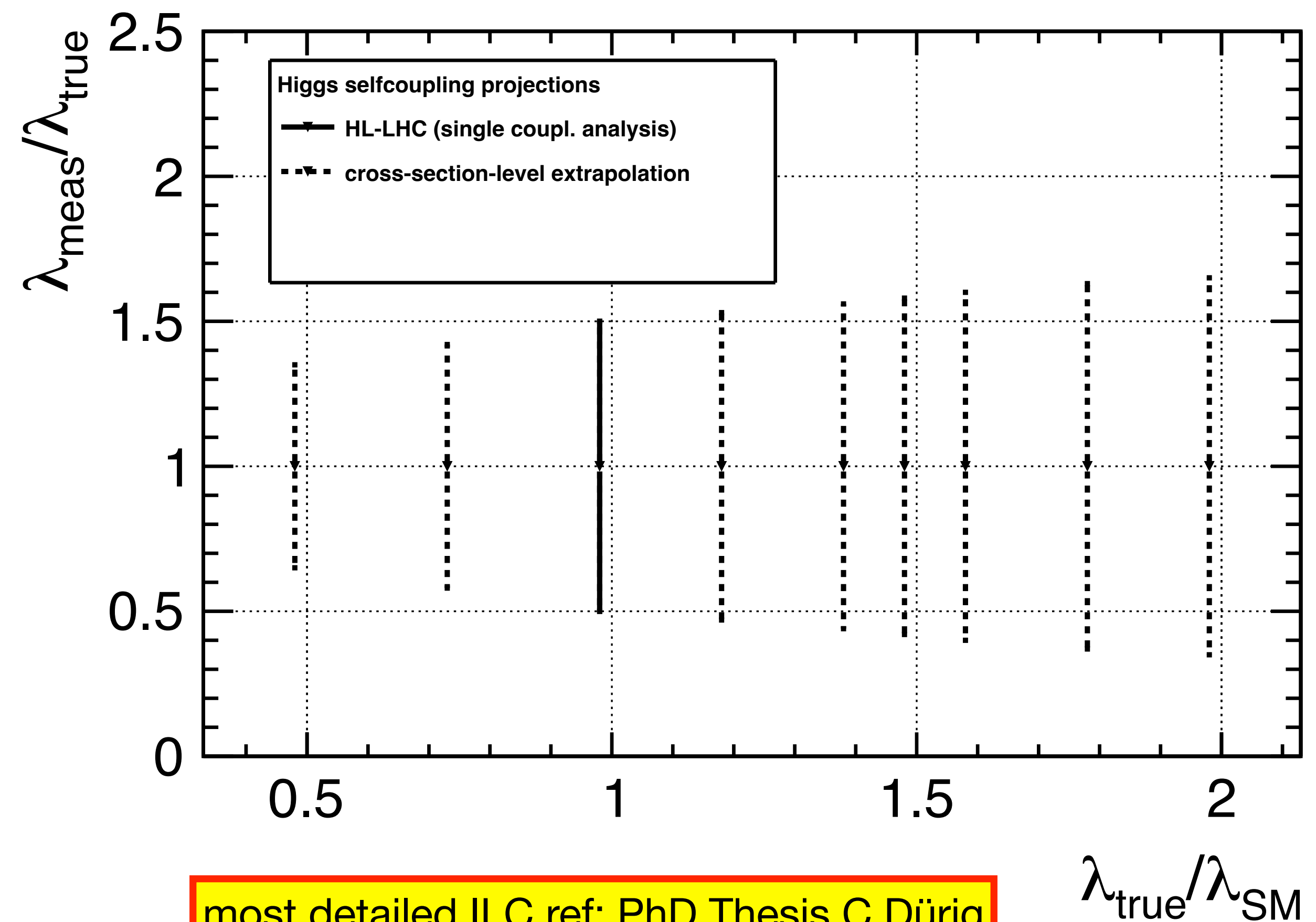
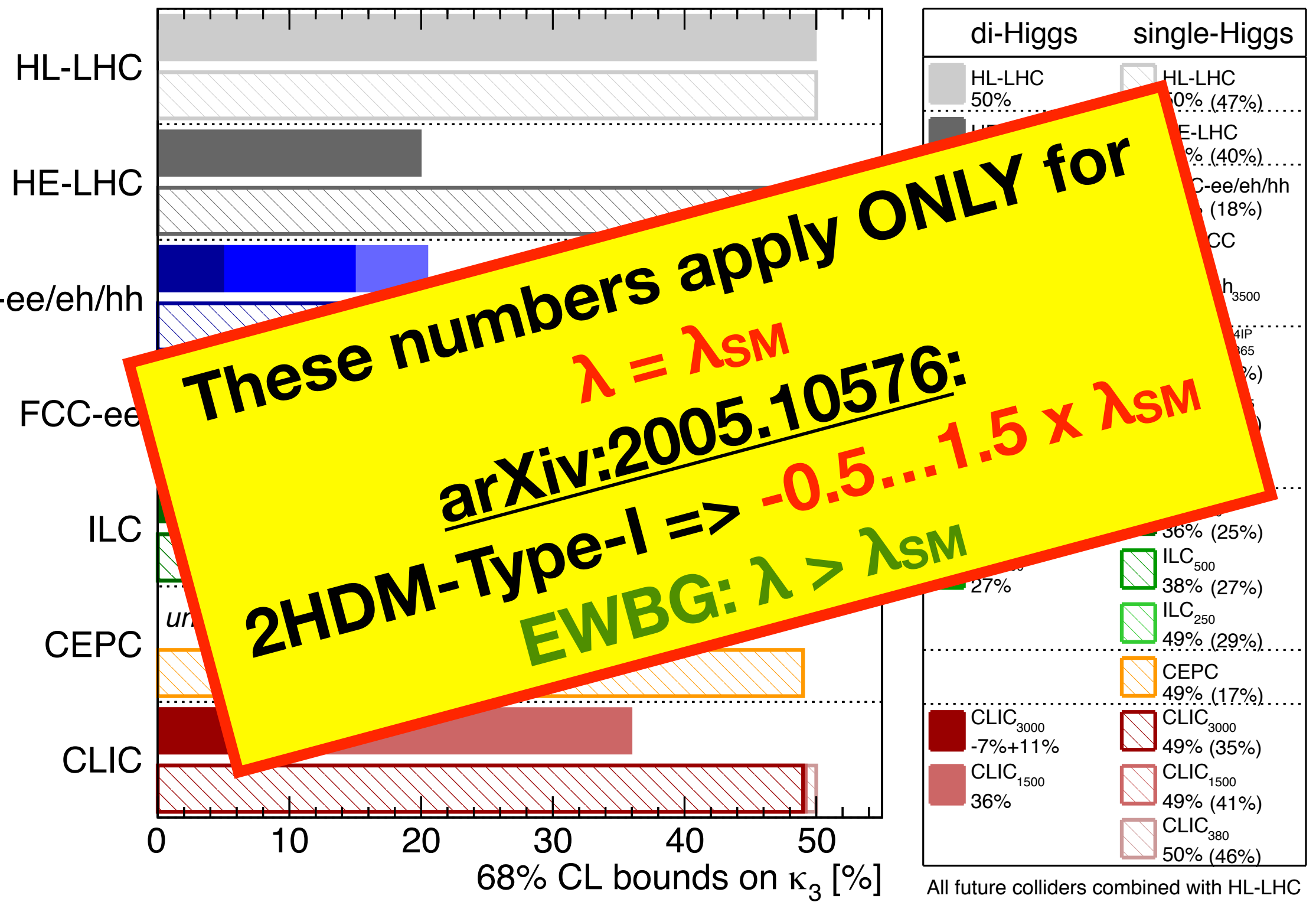
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Higgs self-coupling

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Higgs@FC WG September 2019



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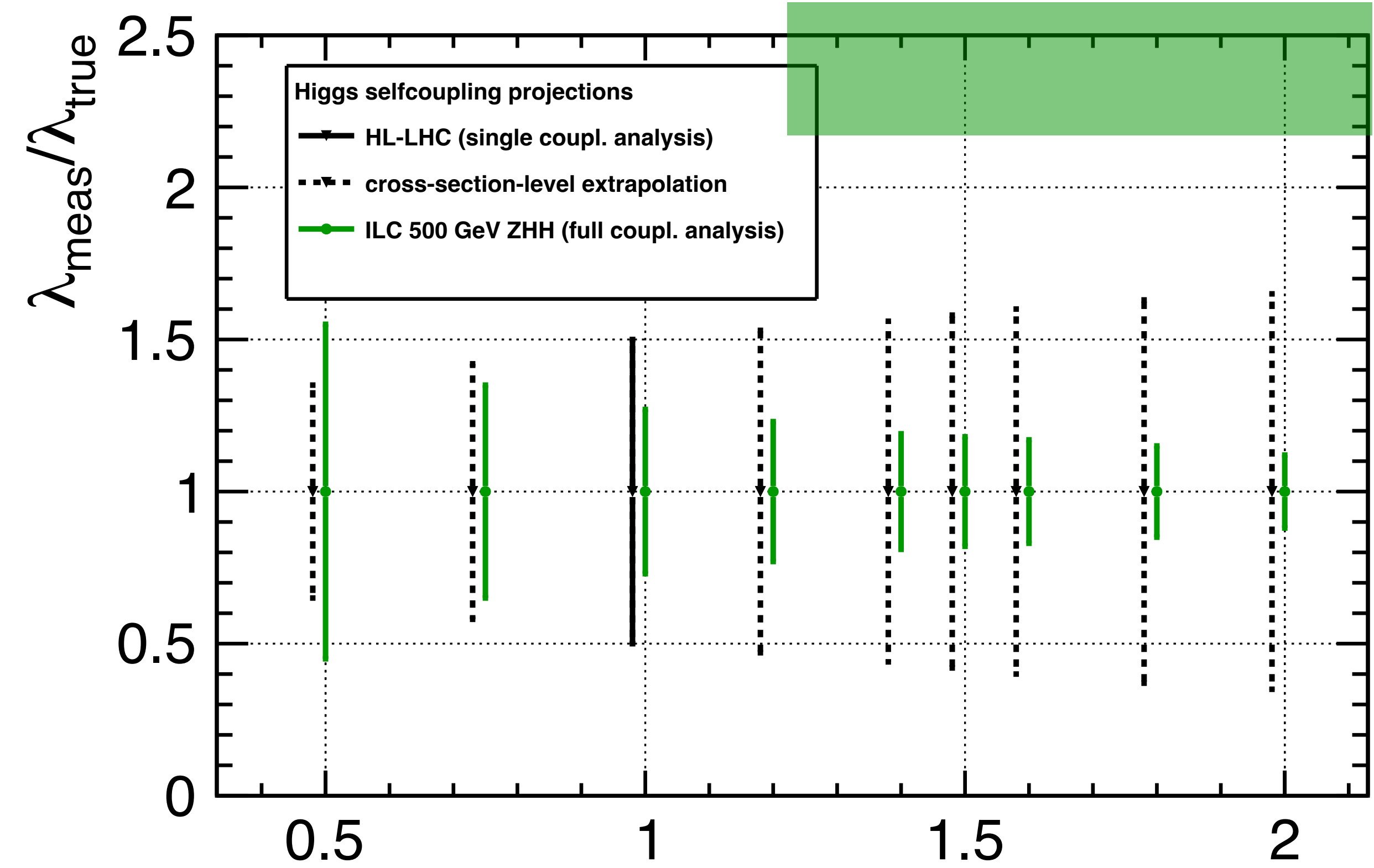


Region of interest for electroweak baryogenesis

Higgs@FC WG September 2019

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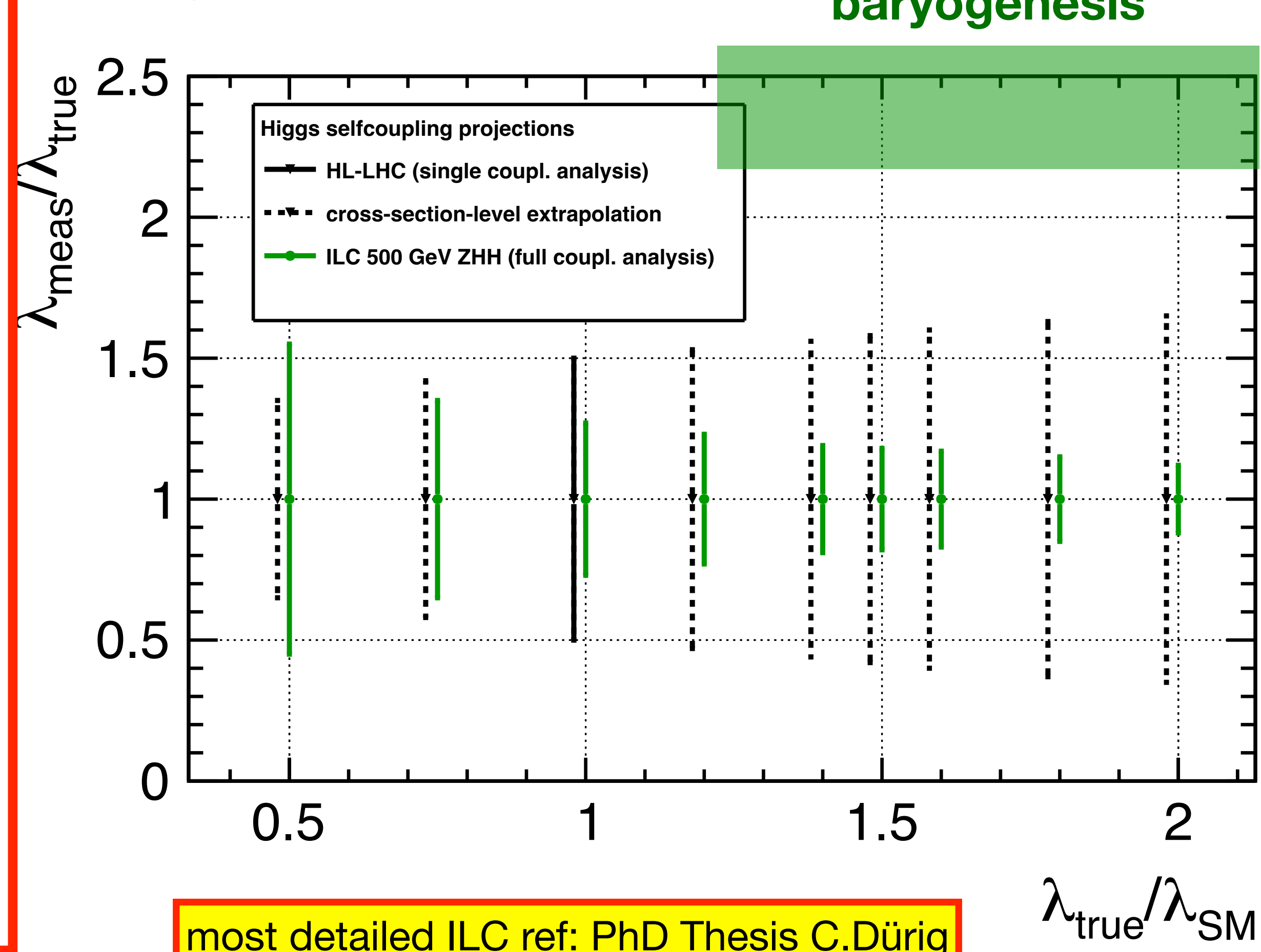
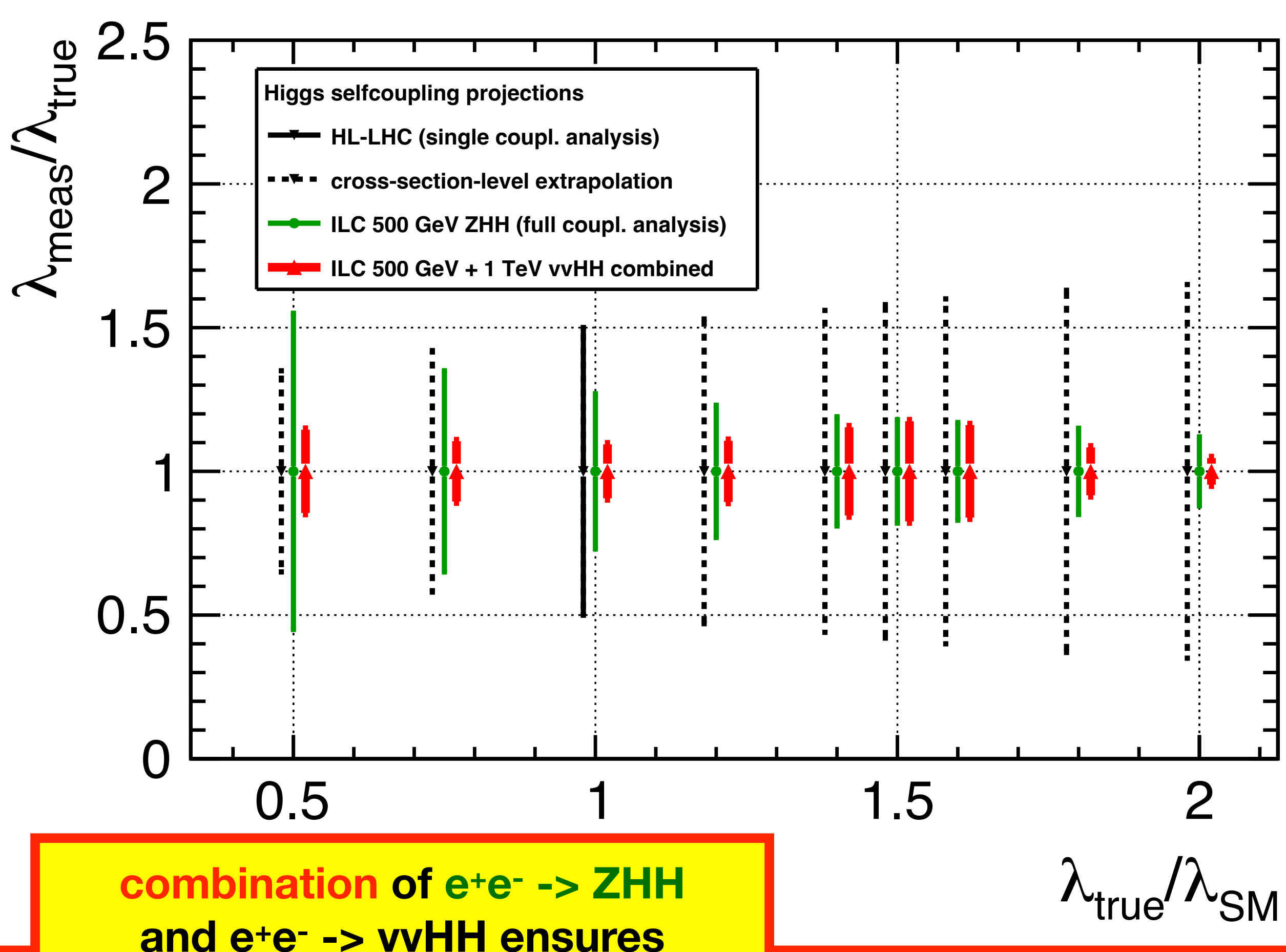
$\lambda_{true}/\lambda_{SM}$

Higgs self-coupling

Electroweak Baryogenesis?



Region of interest for electroweak baryogenesis



combination of $e^+e^- \rightarrow ZHH$ and $e^+e^- \rightarrow \nu\nu HH$ ensures at least 10-15% precision for all λ

most detailed ILC ref: PhD Thesis C.Dürig Uni Hamburg, **DESY-THESIS-2016-027** **UPDATE ONGOING!**