

# Degenerate scalar scenario in a singlet scalar extension of the Standard Model

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in collaboration with

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based on  
PRD104, 035023, PLB 823, 136787, PRD106,115012, PLB 839, 137757  
arXiv:2101.04887, 2105.11830, 2205.12046, 2212.13029)

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# Search for BSM particles (heavy)

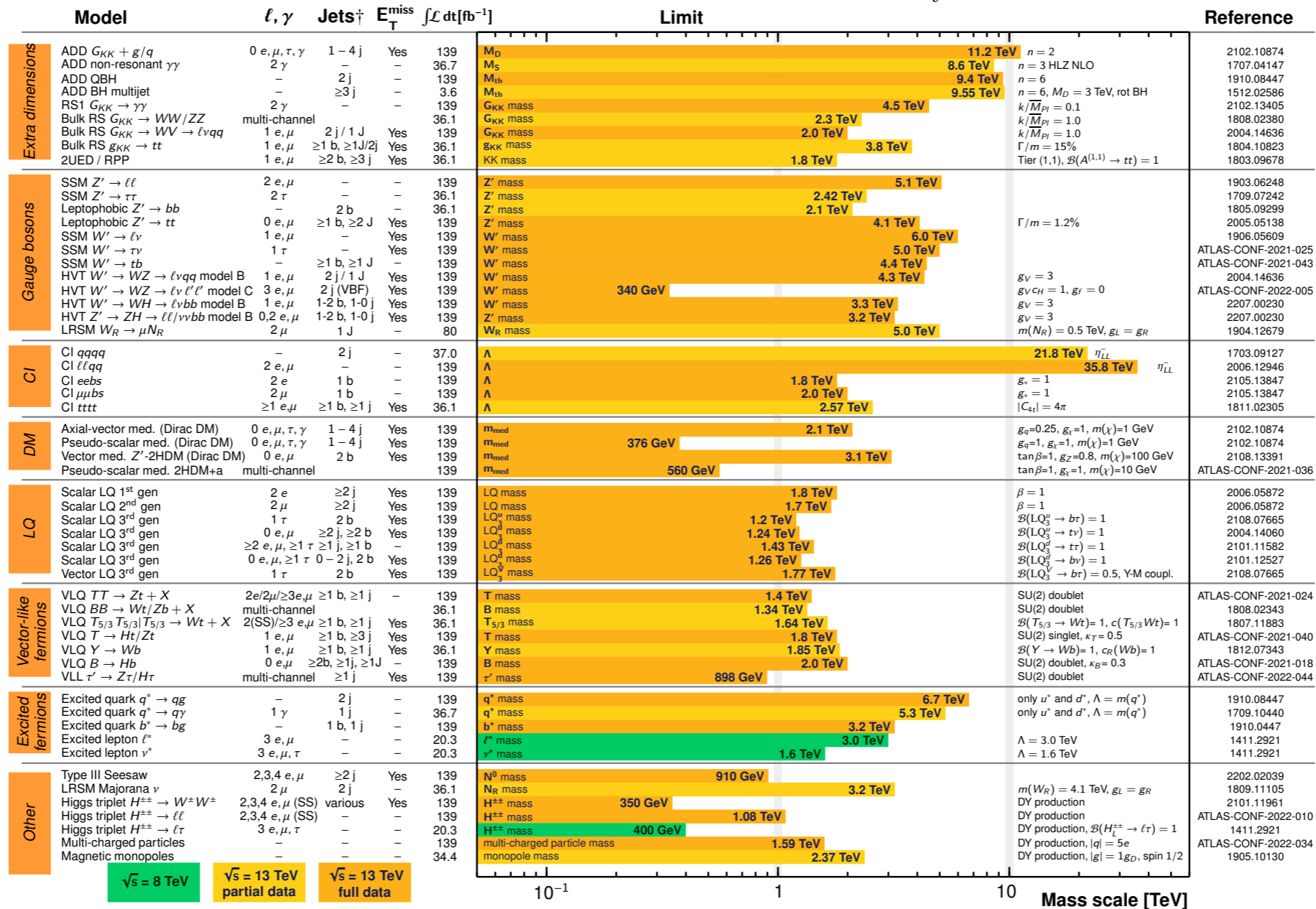
## ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

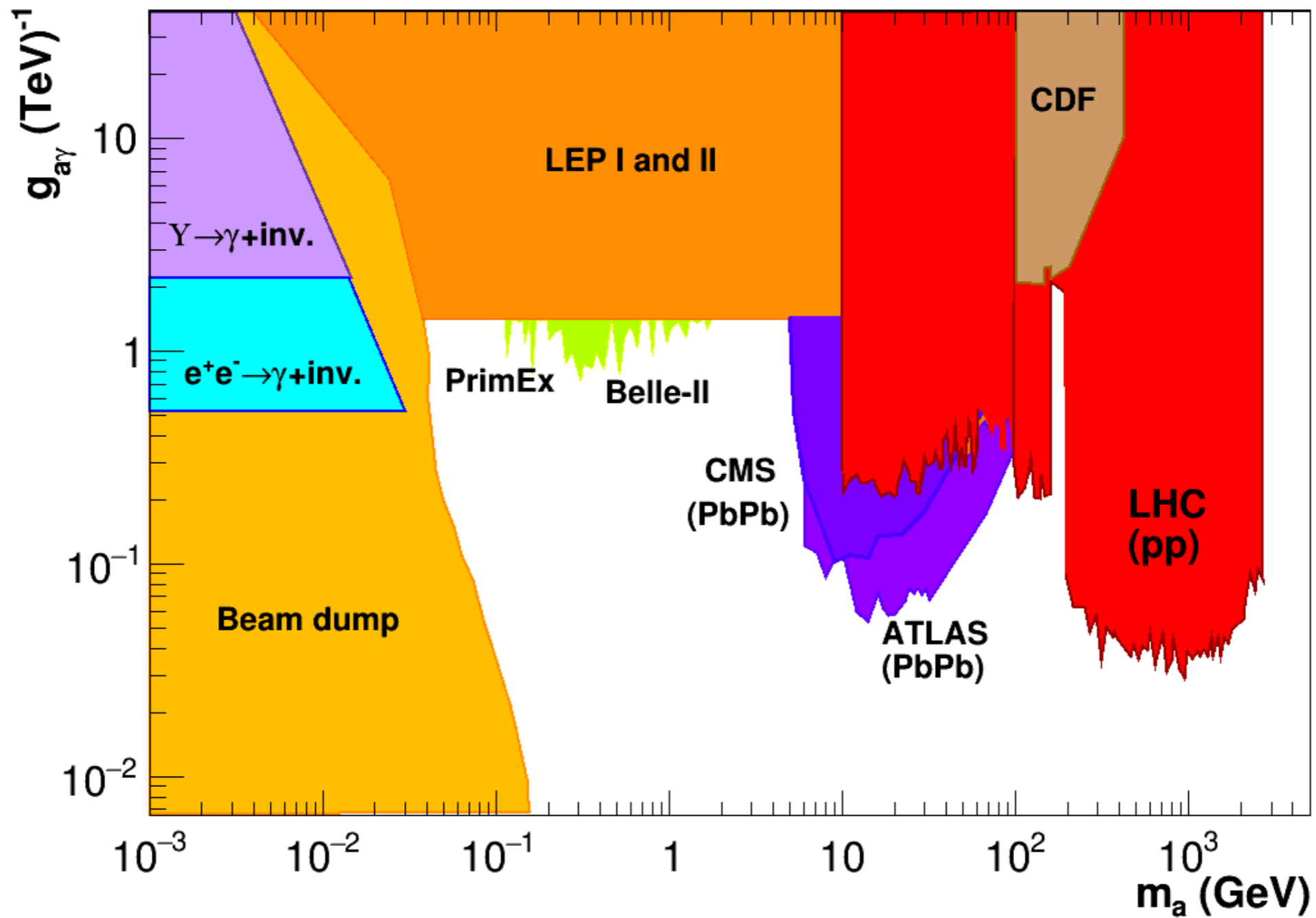


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†Small-radius (large-radius) jets are denoted by the letter j (J).

ATL-PHYS-PUB-2022-034

# Search for BSM particles (light)



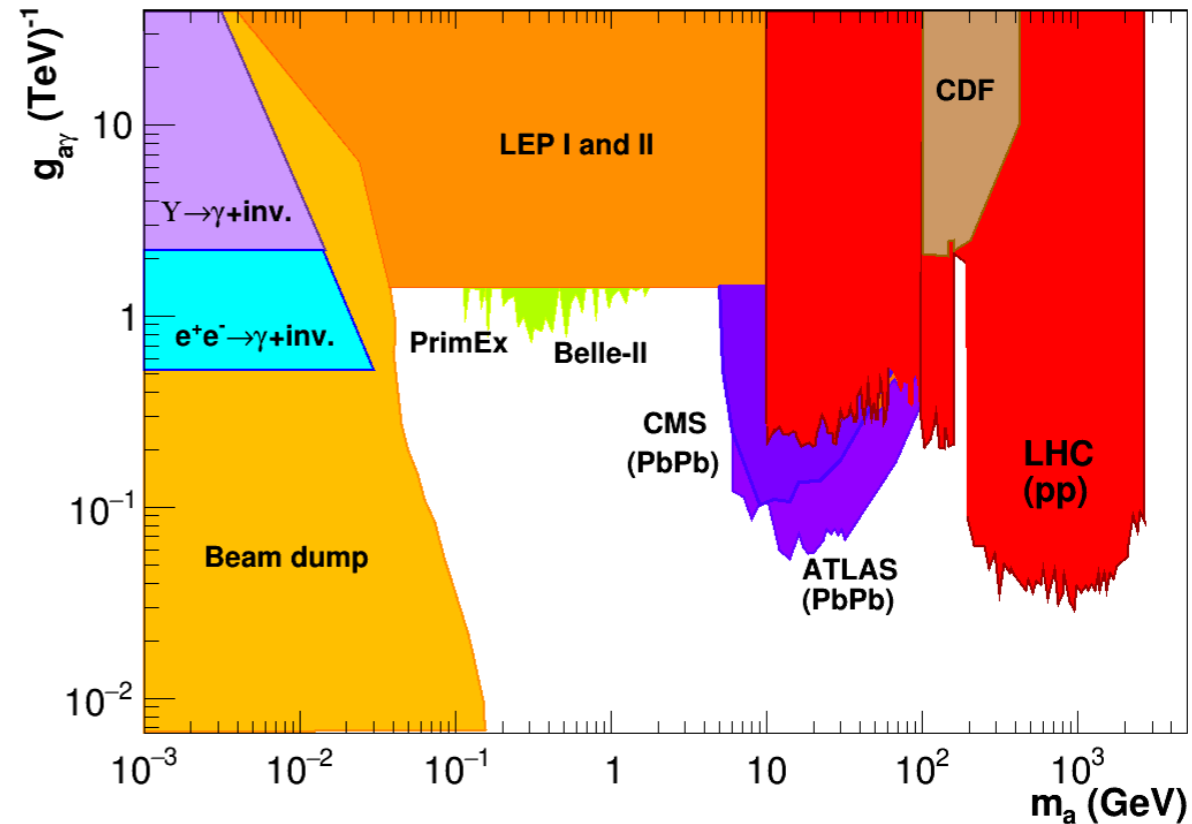
d'Enterria, 2102.08971

# Current status

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits  
Status: July 2022

ATLAS Preliminary  
 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$   $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets†	$E_{\text{miss}}^{\dagger}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} \rightarrow g/g$	$0, \mu, \tau, \gamma$	1-4 j	Yes	139	$M_{KK}$ mass 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	$2, \gamma$	-	-	36.7	$M_{KK}$ mass 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	2 j	-	139	$M_{BH}$ mass 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{BH}$ mass 9.55 TeV $n=6, M_0 = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2, \gamma$	-	-	139	$G_{KK}$ mass $k/M_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV $k/M_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1, e, \mu$	2 j / 1 j	Yes	139	$G_{KK}$ mass 2.0 TeV $k/M_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow \tau\tau$	$1, e, \mu$	$\geq 1 b, \geq 2 j$	Yes	36.1	$G_{KK}$ mass 3.8 TeV $\Gamma/m = 15\%$
	2UED / RPP	$1, e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{R}(A^{(1)} \rightarrow \tau\tau) = 1$
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	139
SSM $Z' \rightarrow \tau\tau$		$2, \tau$	-	-	36.1	$Z'$ mass 2.42 TeV
Leptophobic $Z' \rightarrow bb$		$0, e, \mu$	2 b	-	36.1	$Z'$ mass 2.1 TeV
Leptophobic $Z' \rightarrow tt$		$0, e, \mu$	$\geq 1 b, \geq 2 j$	Yes	139	$Z'$ mass 4.1 TeV $\Gamma/m = 1.2\%$
SSM $W' \rightarrow \ell\nu$		$1, e, \mu$	-	-	139	$W'$ mass 6.0 TeV
SSM $W' \rightarrow \tau\nu$		$1, \tau$	-	-	139	$W'$ mass 5.0 TeV
SSM $W' \rightarrow tb$		-	$\geq 1 b, \geq 1 j$	-	139	$W'$ mass 4.4 TeV
HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B		$1, e, \mu$	2 j / 1 j	Yes	139	$W'$ mass 4.3 TeV
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C		$3, e, \mu$	2 j (VBF)	Yes	139	$W'$ mass 3.3 TeV
HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B		$1, e, \mu$	1-2 b, 1-0 j	Yes	139	$W'$ mass 3.2 TeV
CI	CI $q\bar{q}q$	-	2 j	-	37.0	A $21.8 \text{ TeV}$ $g_{\ell}^{\pm} = 1$
	CI $\ell\ell qq$	$2, e, \mu$	-	-	139	A $35.8 \text{ TeV}$ $g_{\ell}^{\pm} = 1$
	CI $e\bar{e}bb$	$2, e$	1 b	-	139	A $1.8 \text{ TeV}$ $g_{\ell}^{\pm} = 1$
	CI $\mu\bar{\mu}bb$	$2, \mu$	1 b	-	139	A $2.0 \text{ TeV}$ $ C_{\ell}^{\pm}  = 4\tau$
DM	Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4 j	Yes	139	$\mu_{\text{had}}$ mass 376 GeV $g_{\ell} = 0.25, g_{\ell} = 1, m(\chi) = 1 \text{ GeV}$
	Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4 j	Yes	139	$\mu_{\text{had}}$ mass 560 GeV $g_{\ell} = 1, g_{\ell} = 1, m(\chi) = 1 \text{ GeV}$
	Vector med. $Z'$ -2HDM (Dirac DM)	$0, e, \mu$	2 b	Yes	139	$\mu_{\text{had}}$ mass 3.1 TeV $\tan\beta = 1, g_{\ell} = 0.8, m(\chi) = 100 \text{ GeV}$
LQ	Scalar LQ 1 <sup>st</sup> gen	$2, e$	$\geq 2 j$	Yes	139	$LQ$ mass 1.8 TeV $\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	$2, \mu$	$\geq 2 j$	Yes	139	$LQ$ mass 1.7 TeV $\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$1, \tau$	2 b	Yes	139	$LQ$ mass 1.2 TeV $\mathcal{B}(LQ \rightarrow b\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0, e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	$LQ$ mass 1.24 TeV $\mathcal{B}(LQ \rightarrow \tau\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$\geq 2, e, \mu, \tau$	$\geq 1 j, \geq 1 b$	-	139	$LQ$ mass 1.43 TeV $\mathcal{B}(LQ \rightarrow \tau\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0, e, \mu, \tau$	0-2 j, 2 b	-	139	$LQ$ mass 1.26 TeV $\mathcal{B}(LQ \rightarrow b\tau) = 1$
Vector-like fermions	VLO $T \rightarrow Zt + X$	$2e/2\mu/3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.4 TeV SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLO $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3, e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$
	VLO $T \rightarrow Ht/Zt$	$1, e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$
	VLO $Y \rightarrow Wb$	$1, e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$
	VLO $B \rightarrow Hb$	$0, e, \mu$	$\geq 2 b, \geq 1 j, \geq 1 j$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	$q^*$ mass 910 GeV only $q'$ and $d'$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1, \gamma$	1 j	-	36.7	$q^*$ mass 5.3 TeV only $q'$ and $d'$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow b\gamma$	-	1 b, 1 j	-	139	$b^*$ mass 3.2 TeV
	Excited lepton $\ell^*$	$3, e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$
Other	Type III Seesaw	$2, 3, 4, e, \mu$	$\geq 2 j$	Yes	139	$N^c$ mass 350 GeV $m(W_2) = 4.1 \text{ TeV, } g_{\ell} = g_{\tau}$
	LRSM Majorana $\nu$	$2, \mu$	2 j	-	36.1	$N_{\mu}$ mass 1.08 TeV $\nu$ production
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4, e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \tau\tau) = 1$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.59 TeV DY production, $ \mathcal{L}  = 5e$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3, e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 2.37 TeV DY production, $ \mathcal{L}  = 1g_{\ell}, \text{ spin } 1/2$
	Multiphysics particles	-	-	-	139	monopole mass



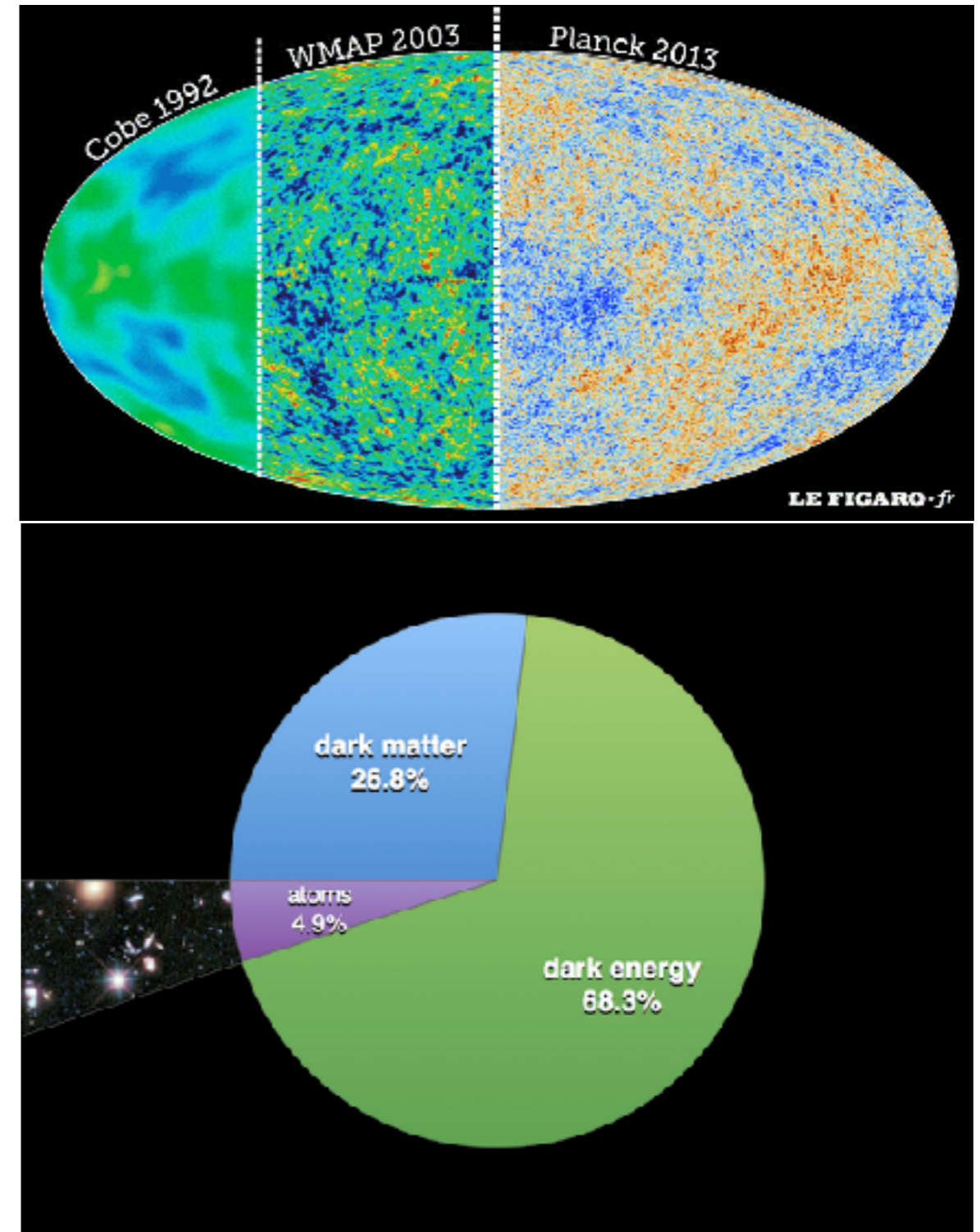
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BSM particles  $\rightarrow$  decoupled from the SM?  
(1) too heavy  
(2) light but tiny coupling

# Introduction

dark matter in the universe

→ direct evidence of physics beyond the SM



# Introduction

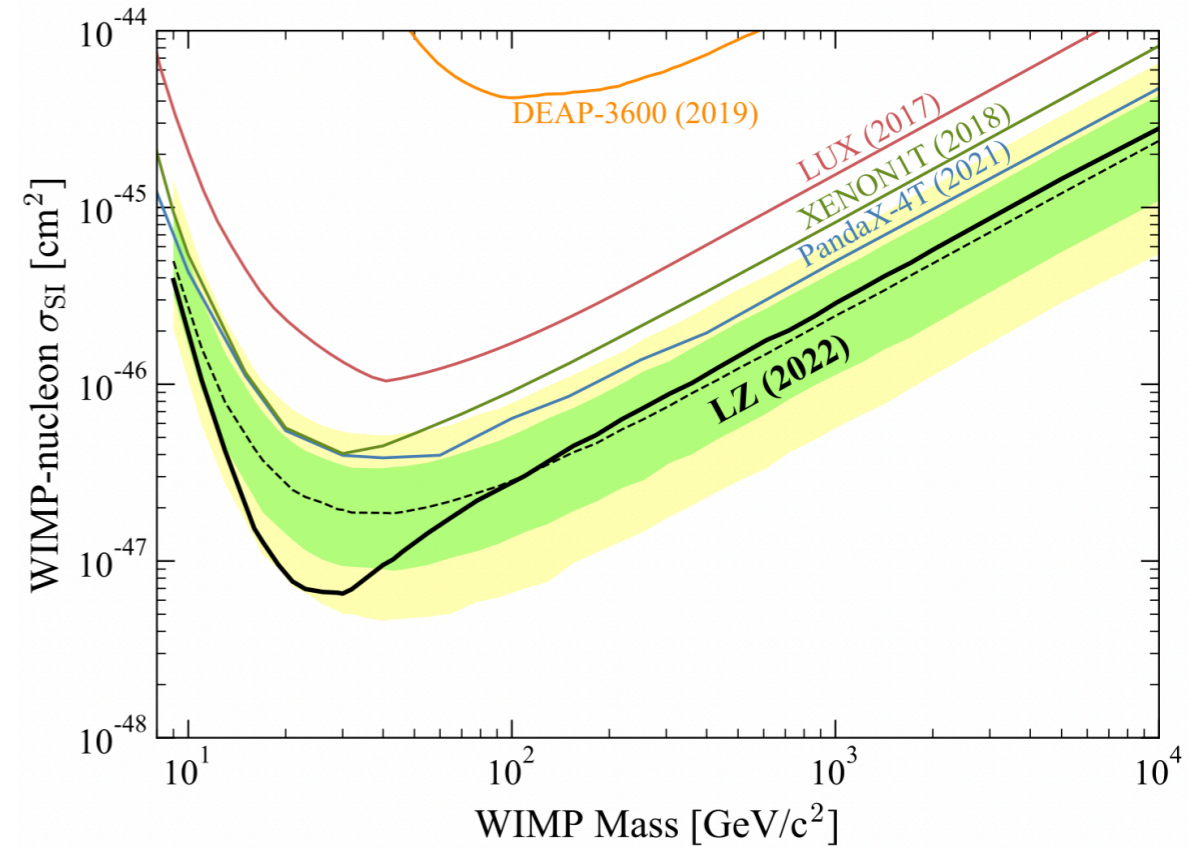
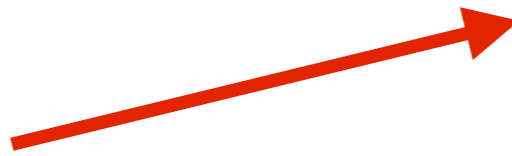
However...

no DM signature has been found yet at

colliders

direct detections

indirect detections



arXiv: 2207.03764

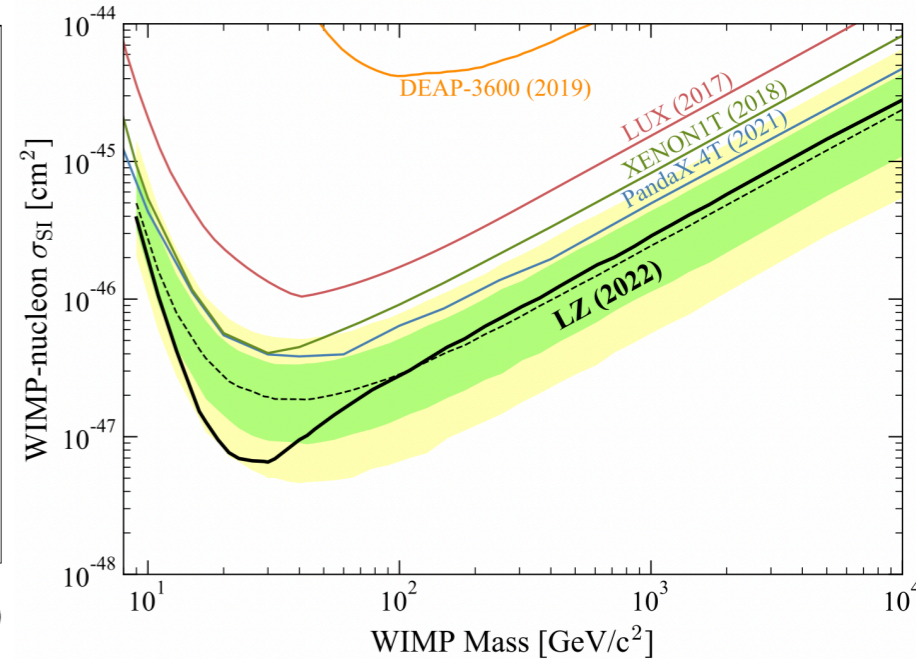
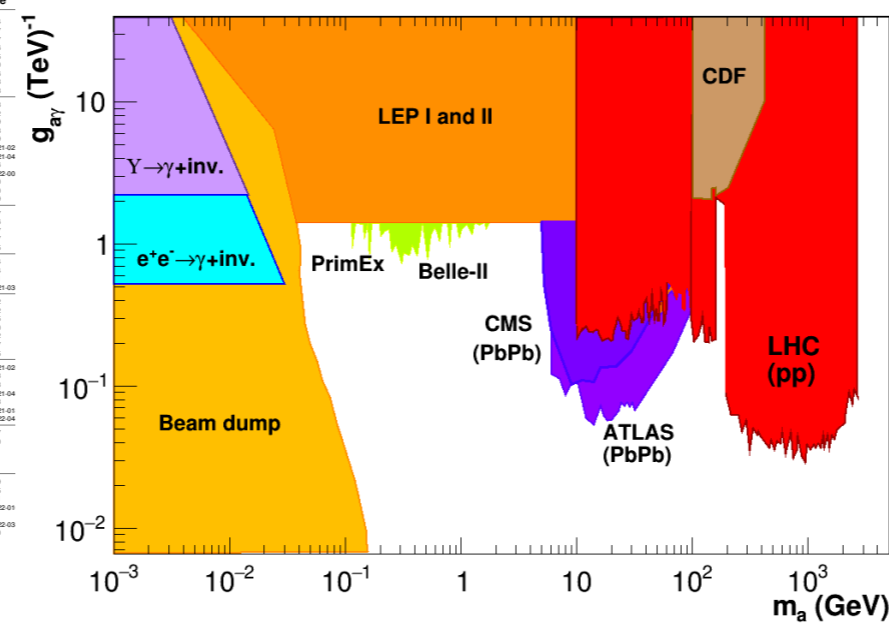
why is DM not observed at those experiments,  
although it is found in astronomical observations?

# Introduction

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 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_{\text{miss}}^{\text{min}}$	$ \mathcal{L}_{\text{eff}} [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{XX} + g/\eta$	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	11.2 TeV $n=2$		
	ADD non-resonant $\gamma\gamma$	$2, \gamma$	-	36.7	8.8 TeV $n=3, 4, 5, 6$	1307.08447		
	ADD OSH	$2, \gamma$	-	1.9	3.4 TeV $n=6$	1910.08447		
	ADD BH multijet	$2, \gamma$	-	3.6	3.4 TeV $n=6$	1912.08595		
Gauge bosons	RS1 $G_{XX} \rightarrow \gamma\gamma$	$2, \gamma$	-	1.39	3.8 TeV	2102.15405		
	Bulk RS $G_{XX} \rightarrow WW, ZZ$	$2, \gamma$	-	36.1	2.3 TeV	1802.02295		
	Bulk RS $G_{XX} \rightarrow WW \rightarrow \ell\nu$	$1, e, \mu$	$2, 1, J$	Yes	139	3.8 TeV	2004.14686	
	Bulk RS $G_{XX} \rightarrow \ell\ell$	$1, e, \mu$	$\geq 1b, \geq 1J$	Yes	36.1	3.8 TeV	1804.19282	
	UED1 (PPP)	$1, e, \mu$	$\geq 1b, \geq 1J$	Yes	36.1	3.8 TeV	1803.08978	
	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	139	5.1 TeV	1903.06348	
	SSM $Z' \rightarrow \tau\tau$	$2, \tau$	-	-	36.1	5.1 TeV	1708.07242	
	Leptophobic $Z' \rightarrow \ell\ell$	$2, e, \mu$	$\geq 1b, \geq 1J$	Yes	139	2.1 TeV	1805.05059	
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	-	139	4.1 TeV	2005.05138	
	SSM $W' \rightarrow \tau\nu$	$1, \tau$	-	-	139	4.0 TeV	1906.05669	
CI	CI $e\mu\mu$	$2, e, \mu$	-	-	37.0	21.8 TeV $\kappa_1$	1703.05127	
	CI $e\mu b$	$2, e, \mu$	-	-	139	2.0 TeV	2005.03646	
	CI $e\mu s$	$2, e, \mu$	-	-	139	1.8 TeV	2105.13847	
	CI $\mu\mu s$	$2, \mu$	-	-	139	2.0 TeV	2105.13847	
	CI $\tau\tau s$	$\geq 1, e, \mu$	$\geq 1b, \geq 1J$	Yes	36.1	2.57 TeV	1811.02305	
	DM	Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	176 GeV	2102.15874
		Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	560 GeV	2102.15874
		Vector med. $Z'$ -2HDM (Dirac DM)	$0, e, \mu$	2b	Yes	139	3.1 TeV	2108.15391
		Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	3.1 TeV	ATLAS-COUP-2021-03
	LO	Scalar LQ 1 <sup>st</sup> gen	$2, e, \mu$	$\geq 1, 2, b$	Yes	139	1.8 TeV	2006.05872
Scalar LQ 2 <sup>nd</sup> gen		$2, \mu$	$\geq 1, 2, b$	Yes	139	1.7 TeV	2008.05872	
Scalar LQ 3 <sup>rd</sup> gen		$1, \tau$	$\geq 1, 2, b$	Yes	139	1.2 TeV	2108.07665	
Scalar LQ 3 <sup>rd</sup> gen		$0, e, \mu$	$\geq 1, 2, b$	Yes	139	1.24 TeV	2004.14080	
Scalar LQ 3 <sup>rd</sup> gen		$\geq 2, e, \mu, \tau$	$\geq 1, 2, 1, 2, b$	Yes	139	1.23 TeV	2101.15182	
Vectorlike fermions	Vector LQ 3 <sup>rd</sup> gen	$0, e, \mu, \tau$	$0, 2, 1, 2, b$	Yes	139	1.26 TeV	2101.15287	
	Vector LQ 3 <sup>rd</sup> gen	$1, \tau$	$2, b$	Yes	139	1.97 TeV	2108.07665	
	VLO $T \rightarrow Z + X$	$2e, 2\mu, 2\tau, \gamma, \geq 1b, \geq 1J$	-	-	139	1.4 TeV	SU(2) doublet	
	VLO $BB \rightarrow WZ + X$	multi-channel	-	-	36.1	1.34 TeV	SU(2) doublet	
	VLO $T \rightarrow WZ + X$	$2e, 2\mu, 2\tau, \gamma, \geq 1b, \geq 1J$	-	-	36.1	1.24 TeV	$W_{L,R} \rightarrow WZ, \tau \rightarrow T_{L,R} \nu_{\tau}$	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1, \gamma$	1	-	139	3.3 TeV	1910.08447	
	Excited quark $q^* \rightarrow q\gamma$	$1, \gamma$	1	-	36.7	3.3 TeV	1709.15440	
	Excited quark $q^* \rightarrow q\gamma$	$3, e, \mu, \tau$	-	-	139	3.0 TeV	1910.08447	
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$3, e, \mu, \tau$	-	-	20.3	1.8 TeV	1411.2921	
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$3, e, \mu, \tau$	-	-	20.3	1.8 TeV	1411.2921	
Other	Type III Seesaw	$2, 3, 4, \mu, \tau$	$\geq 1, 2, b$	Yes	139	910 GeV	2202.00039	
	LRSM Majorana $\nu$	$2, \mu, \tau$	$\geq 1, 2, b$	Yes	36.1	3.2 TeV	1809.11105	
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	$2, 3, 4, e, \mu, \tau$	various	Yes	139	350 GeV	DY production	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu, \tau$	various	Yes	139	1.08 TeV	DY production	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3, e, \mu, \tau$	-	-	20.3	400 GeV	DY production	

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<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter J (L).



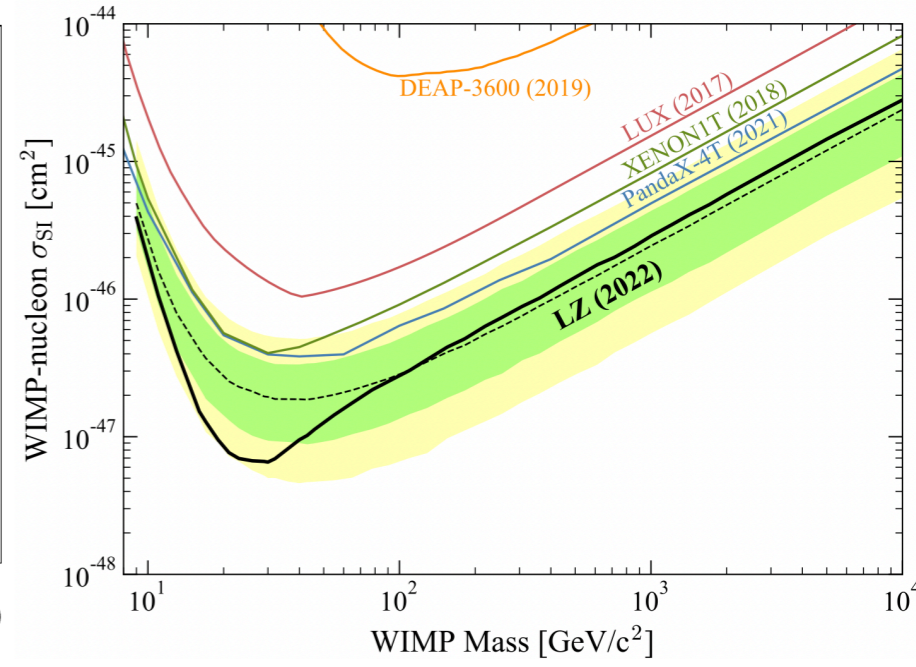
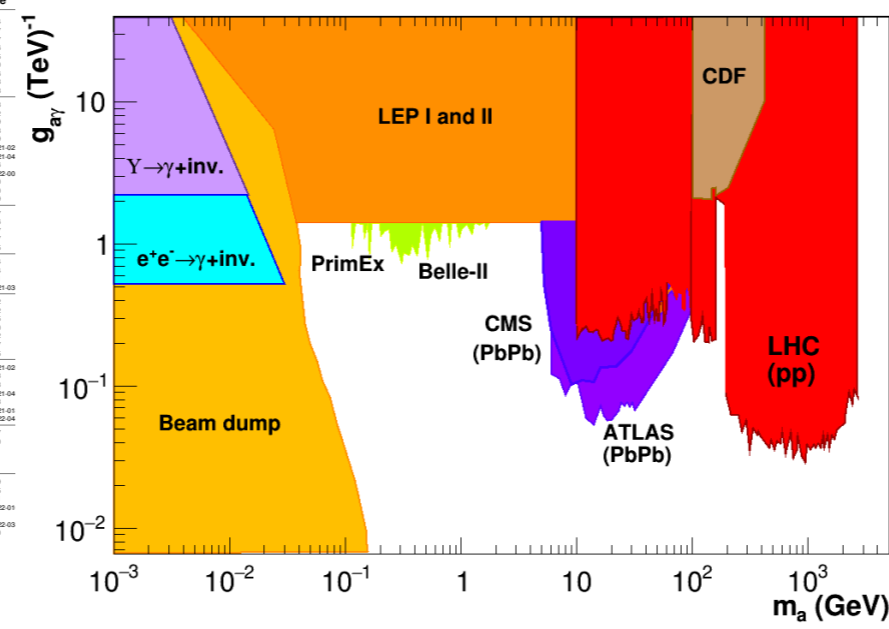
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 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets†	$E_{\text{miss}}^{\text{jet}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{XX} + g/\eta$	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	11.2 TeV $n=2$	
	ADD non-resonant $\gamma\gamma$	$2, \gamma$	-	36.7	8.8 TeV $n=3, 4, 5, 6$	1307.08447	
	ADD OSH	$2, \gamma$	-	3.6	3.4 TeV $n=6$	1910.08447	
	ADD BH multijet	$2, \gamma$	-	3.6	3.4 TeV $n=6$	1912.08590	
Gauge bosons	RS1 $G_{XX} \rightarrow \gamma\gamma$	$2, \gamma$	-	139	3.0 TeV $n=1, 2, 3, 4, 5, 6$	2102.15405	
	Bulk RS $G_{XX} \rightarrow WW, ZZ$	$2, \gamma$	-	36.1	2.0 TeV $n=1, 2, 3, 4, 5, 6$	1802.02090	
	Bulk RS $G_{XX} \rightarrow WW \rightarrow \ell\nu$	$2, \gamma$	1, J	Yes	36.1	2.0 TeV $n=1, 2, 3, 4, 5, 6$	2004.14836
	Bulk RS $G_{XX} \rightarrow \ell\ell$	$2, \gamma$	-	36.1	1.8 TeV $n=1, 2, 3, 4, 5, 6$	1804.19323	
CI	CI $e\mu\mu$	$2, \mu$	-	37.0	1.8 TeV $n=1, 2, 3, 4, 5, 6$	1703.09127	
	CI $e\mu\tau$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2005.03646	
	CI $e\mu b$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2105.13847	
	CI $e\mu s$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2105.13847	
DM	Scalar med. $Z'$ -2HDM (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	176 GeV $n=1, 2, 3, 4, 5, 6$	2102.15874
	Vector med. $Z'$ -2HDM (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	560 GeV $n=1, 2, 3, 4, 5, 6$	2102.15874
	Pseudo-scalar med. 2HDM+a	multi-channel	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2108.15391	
	Scalar med. $Z'$ -2HDM (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2108.15391
LO	Scalar LQ 1 <sup>st</sup> gen	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2006.05872	
	Scalar LQ 2 <sup>nd</sup> gen	$2, \mu$	-	139	1.7 TeV $n=1, 2, 3, 4, 5, 6$	2006.05872	
	Scalar LQ 3 <sup>rd</sup> gen	$2, \mu$	-	139	1.2 TeV $n=1, 2, 3, 4, 5, 6$	2008.07665	
	Scalar LQ 3 <sup>rd</sup> gen	$2, \mu$	-	139	1.2 TeV $n=1, 2, 3, 4, 5, 6$	2004.14080	
Vectorlike fermions	VLL $T \rightarrow WZ$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2101.15327	
	VLL $T \rightarrow W\ell$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2101.15327	
	VLL $T \rightarrow W\tau$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2101.15327	
	VLL $T \rightarrow Wb$	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2101.15327	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1, \gamma$	1	36.7	3.3 TeV $n=1, 2, 3, 4, 5, 6$	1910.08447	
	Excited quark $q^* \rightarrow q\ell$	$1, \ell$	1	36.7	3.3 TeV $n=1, 2, 3, 4, 5, 6$	1709.15440	
	Excited quark $q^* \rightarrow q\gamma$	$1, \gamma$	1	36.7	3.3 TeV $n=1, 2, 3, 4, 5, 6$	1910.08447	
	Excited quark $q^* \rightarrow q\ell$	$1, \ell$	1	36.7	3.3 TeV $n=1, 2, 3, 4, 5, 6$	1709.15440	
Other	Type III Seesaw	$2, \mu$	-	139	1.8 TeV $n=1, 2, 3, 4, 5, 6$	2202.00009	
	LRSM Majorana $\nu$	$2, \mu$	-	36.1	350 GeV $n=1, 2, 3, 4, 5, 6$	1809.11105	
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	$2, \mu$	-	139	1.08 TeV $n=1, 2, 3, 4, 5, 6$	2511.19191	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, \mu$	-	139	1.08 TeV $n=1, 2, 3, 4, 5, 6$	2511.19191	

\*Only a selection of the available mass limits on new states or phenomena is shown.  
 †Small-radius (large-radius) jets are denoted by the letter (J).



BSM particles → decoupled from the SM?

- (1) too heavy
- (2) light but tiny coupling
- (3) accessible, but...



# Introduction

## Suppression mechanisms of DM-quark scattering

fermion DM + pseudo scalar portal model  
(coupling vanishes at low E. )

Ipek, McKeen, Nelson (2014)

Escudero, Berlin, Hooper, Lin (2016)

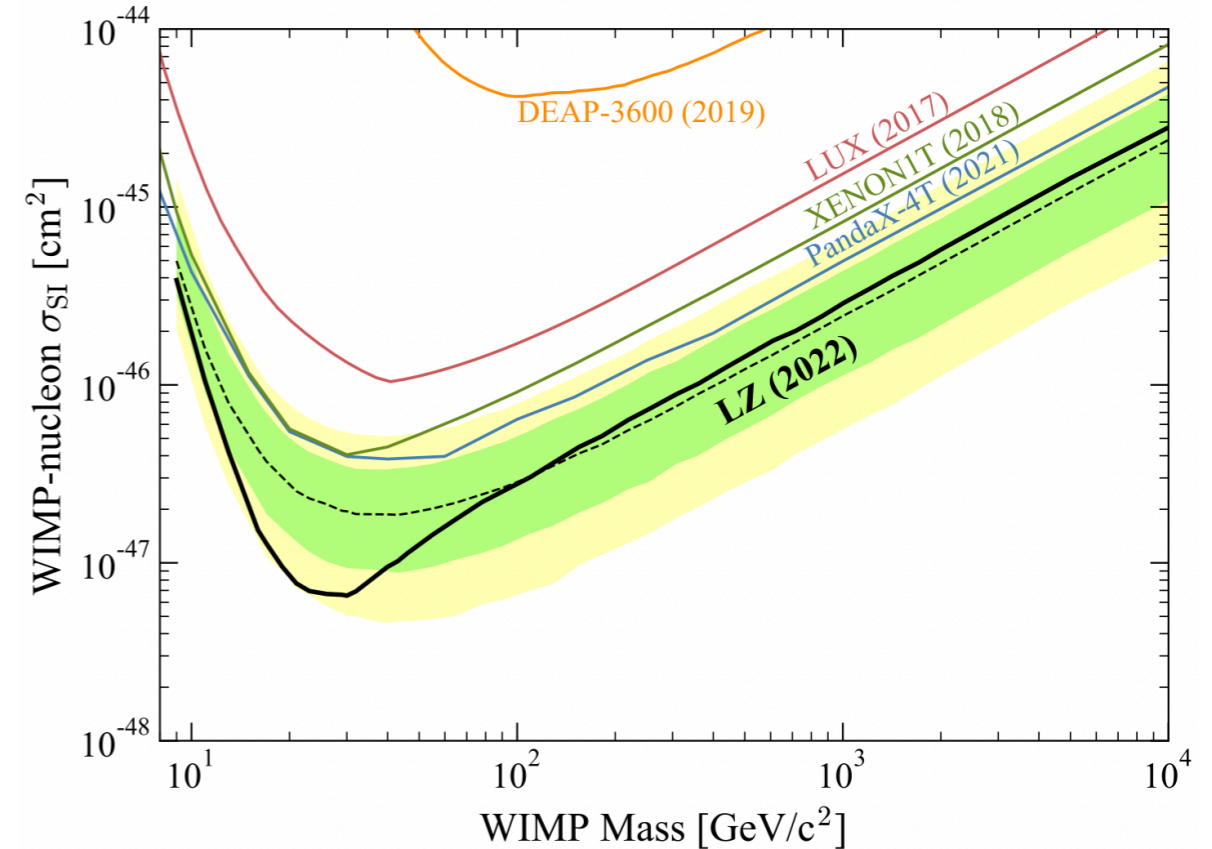
Abe, Fujiwara, Hisano (2019)

pseudo Nambu-Goldstone DM

Gross, Lebedev, Toma (2017)

pNG DM with degenerate scalars

Abe, GCC, Mawatari (2021)



arXiv: 2207.03764

# Plan

Introduction

Degenerate scalar scenario in CxSM

Singlet scalar extension of the SM

Suppression of DM-quark scattering

Bounds on degenerate scalar scenario

Search for degenerate scalars@ILC

EW phase transition and gravitational waves (→ Idegawa's talk)

phenomenological implication  
of degenerate scalar scenario

Multi-critical point principle and the degenerate  
scalar scenario

attempt to understanding  
degenerate scalar scenario

Origin of the suppression mechanism

Summary

# Singlet scalar extension of the SM

SM + complex S (CxSM)

Barger et al, arXiv:0811.0393

$$V = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left( a_1 S + \frac{b_1}{4} S^2 + \text{c.c.} \right)$$

$\uparrow$   
 (pNG DM:  $S \rightarrow -S$ )

global U(1) and soft breaking terms

(minimal set of operators to realize pNG DM w/o domain wall)

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = (v_S + s + i\chi)/\sqrt{2}$$

$\uparrow$  DM (DM stability  $\leftrightarrow$  CP sym.)

# Singlet scalar extension of the SM

$$V = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + \text{c.c.}\right)$$

mass matrix  $(h, s)$

$$M^2 = \begin{pmatrix} \frac{\lambda}{2}v^2 & \frac{\delta_2}{2}vv_S \\ \frac{\delta_2}{2}vv_S & \Lambda^2 \end{pmatrix} \quad \Lambda^2 \equiv \frac{d_2}{2}v_S^2 - \sqrt{2}\frac{a_1}{v_S}$$

mass eigenvalues

$$m_{h_1} \rightarrow m(125)\text{@LHC}$$

$(h_1, h_2)$

$$m_{h_1, h_2}^2 = \frac{1}{2} \left( \frac{\lambda}{2}v^2 + \Lambda^2 \mp \sqrt{\left(\frac{\lambda}{2}v^2 - \Lambda^2\right)^2 + 4\left(\frac{\delta_2}{2}vv_S\right)^2} \right)$$

(DM)

$$m_\chi^2 = -b_1 - \sqrt{2}\frac{a_1}{v_S}$$

mass eigenstates  $(h_1, h_2) \leftrightarrow (h, s)$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

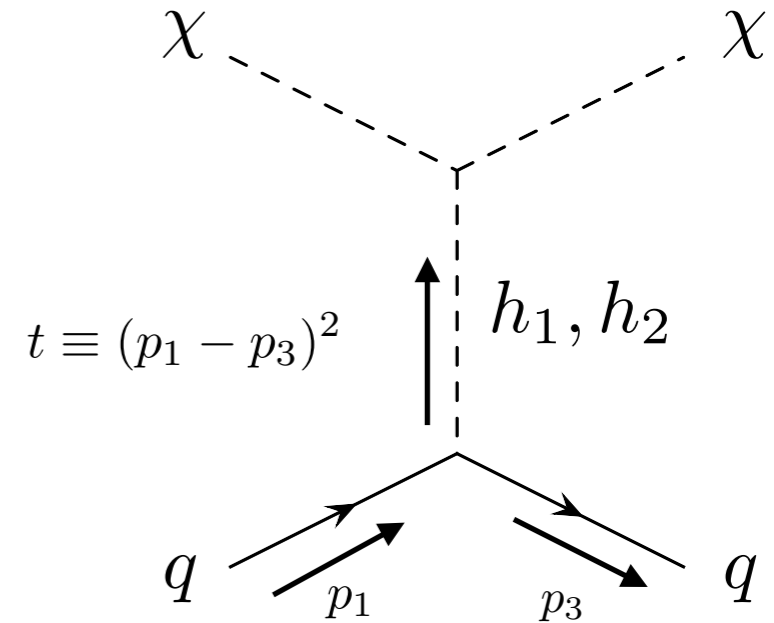
# Suppression of DM-quark scattering

scalar trilinear interactions

$$\mathcal{L}_S = g_{h_1\chi\chi} h_1 \chi^2 + g_{h_2\chi\chi} h_2 \chi^2$$

$$g_{h_1\chi\chi} \equiv \frac{m_{h_1}^2 + \frac{a_S}{2v_S}}{2v_S} \boxed{\sin \alpha}$$

$$g_{h_2\chi\chi} \equiv \boxed{-} \frac{m_{h_2}^2 + \frac{a_S}{2v_S}}{2v_S} \boxed{\cos \alpha}$$



Yukawa interactions

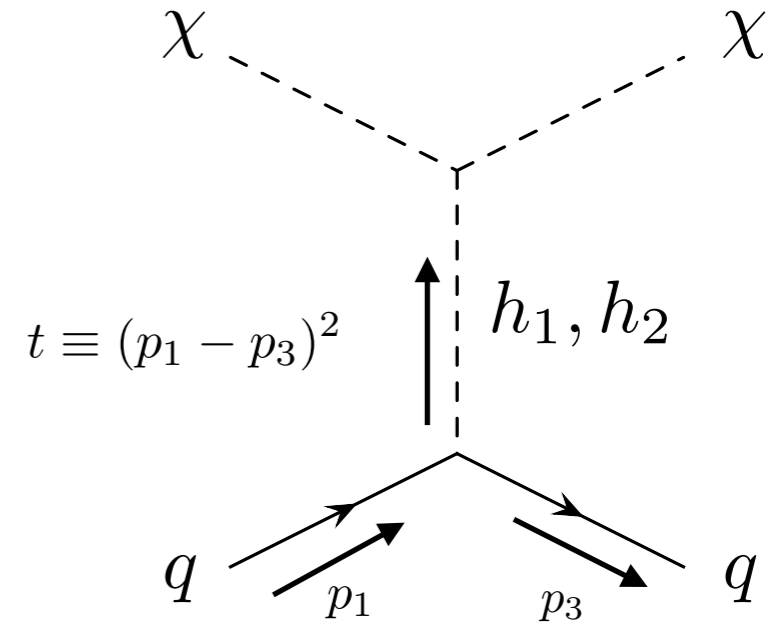
$$\mathcal{L}_Y = \frac{m_f}{v} \bar{f} f (h_1 \boxed{\cos \alpha} + h_2 \boxed{\sin \alpha})$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

# Suppression of DM-quark scattering

$$i\mathcal{M}_{h_1} = -i \frac{m_f}{vv_S} \frac{m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_1}^2} \sin \alpha \cos \alpha \bar{u}(p_3)u(p_1),$$

$$i\mathcal{M}_{h_2} = +i \frac{m_f}{vv_S} \frac{m_{h_2}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_2}^2} \sin \alpha \cos \alpha \bar{u}(p_3)u(p_1),$$



sum of scatt. amplitudes:

$$i(\mathcal{M}_1 + \mathcal{M}_2) = i \frac{m_f}{vv_S} \bar{u}(p_3)u(p_1) \sin \alpha \cos \alpha$$

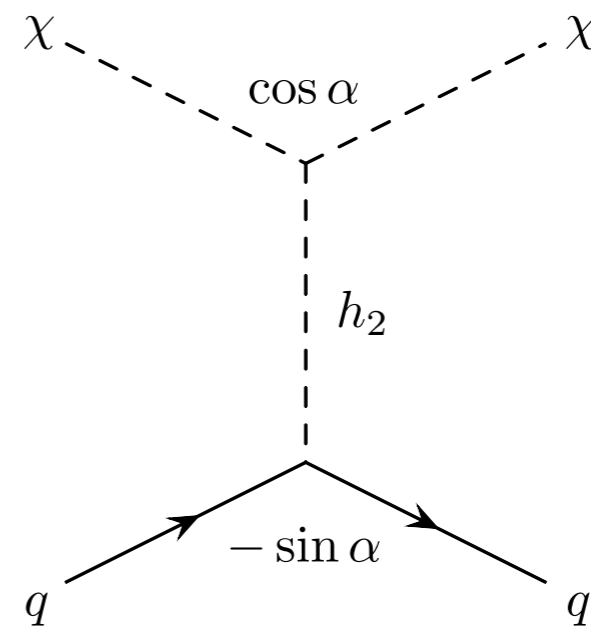
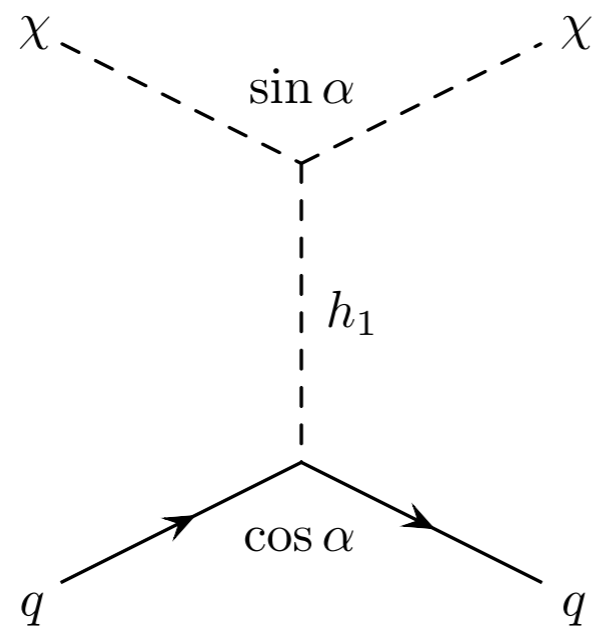
$$\times \left\{ \left( -\frac{m_{h_1}^2}{t - m_{h_1}^2} + \frac{m_{h_2}^2}{t - m_{h_2}^2} \right) \right\} \simeq 0 \quad @t \rightarrow 0$$

Gross, Lebedev, Toma (2017)

$$+ \frac{\sqrt{2}a_1}{v_S} \left( -\frac{1}{t - m_{h_1}^2} + \frac{1}{t - m_{h_2}^2} \right) \right\} \simeq 0 \quad @m_{h_1} \sim m_{h_2}$$

Abe, GCC, Mawatari (2021)

# Suppression of DM-quark scattering



$$i(\mathcal{M}_1 + \mathcal{M}_2) = i \frac{m_f}{vv_S} \bar{u}(p_3) u(p_1) \sin \alpha \cos \alpha$$

$$\times \left\{ \left( -\frac{m_{h_1}^2}{t - m_{h_1}^2} + \frac{m_{h_2}^2}{t - m_{h_2}^2} \right) + \frac{\sqrt{2}a_1}{v_S} \left( -\frac{1}{t - m_{h_1}^2} + \frac{1}{t - m_{h_2}^2} \right) \right\} \simeq 0 \quad @m_{h_1} \sim m_{h_2}$$

a la GIM mechanism

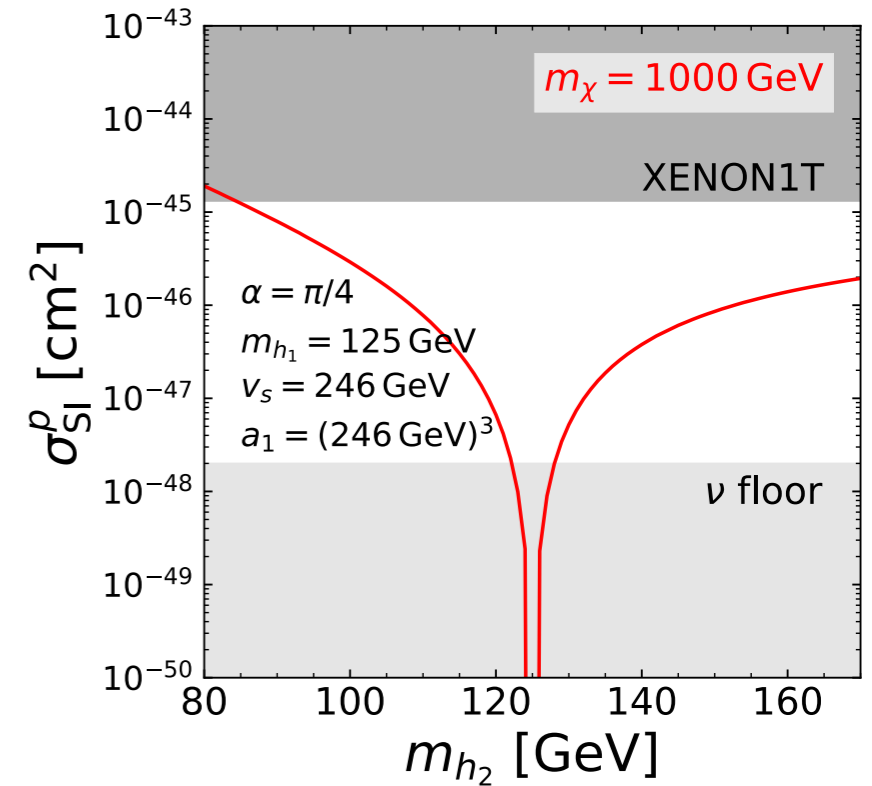
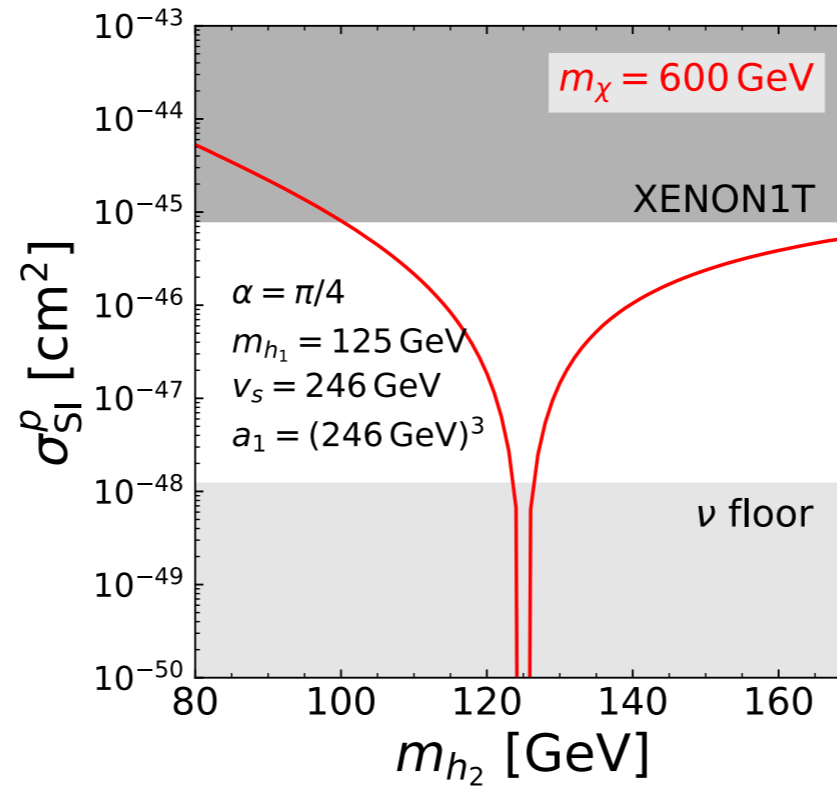
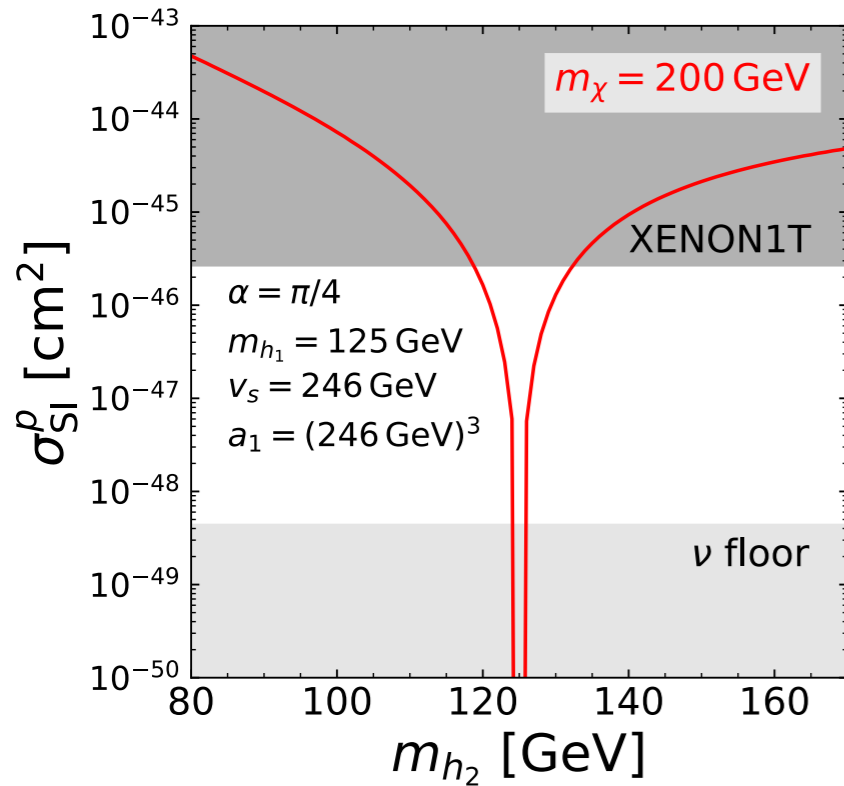


degenerate scalar scenario

# Bounds on degenerate scalar scenario

$\sigma_{SI}^p$  vs.  $m_{h_2}$

Abe, GCC, Mawatari (2021)



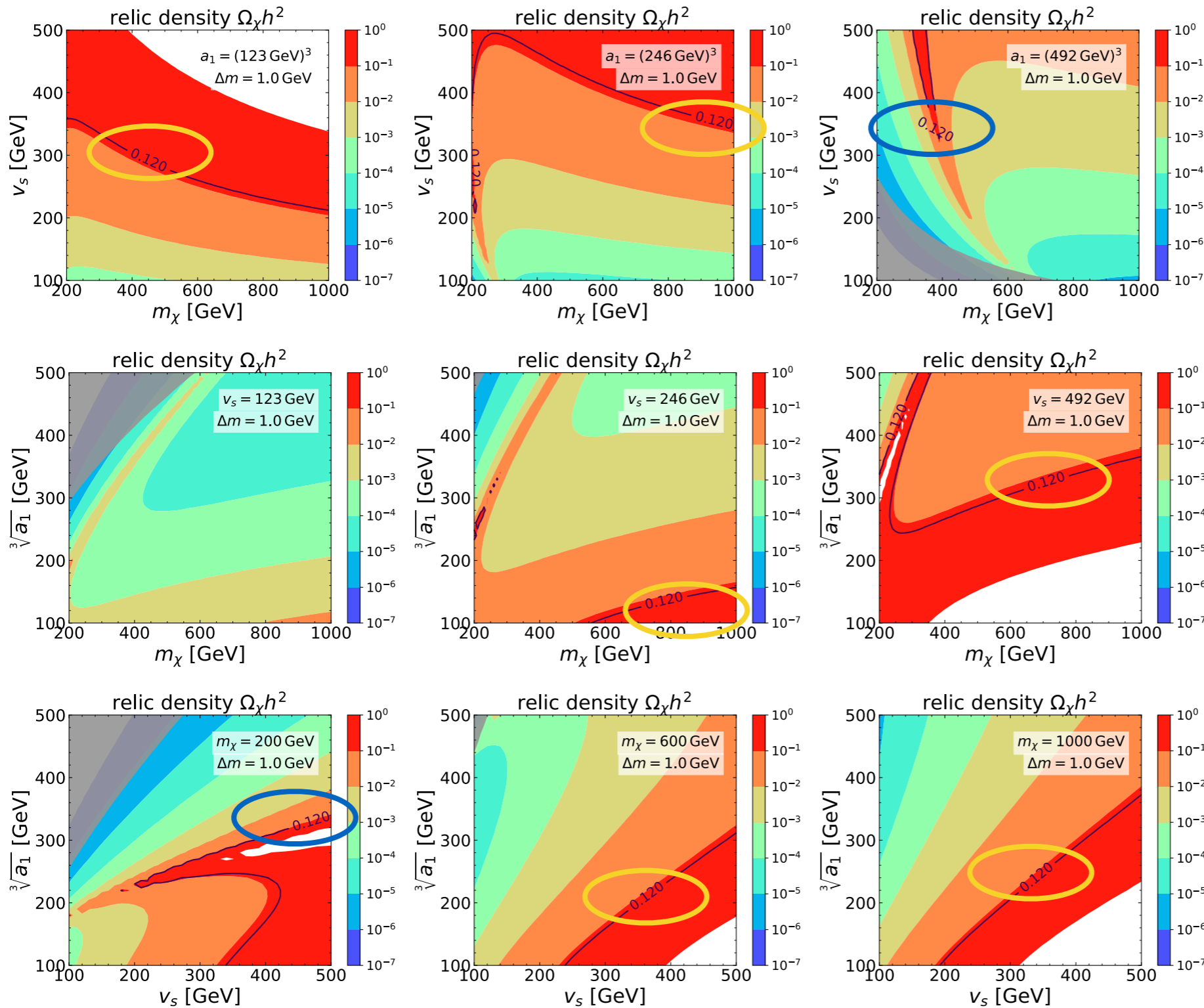
$$\alpha = \frac{\pi}{4}, v = v_S = 246 \text{ GeV}, a_1 = (246 \text{ GeV})^3$$

perturbativity  $\lambda, d_2 < \frac{16\pi}{3}$

stability  $\lambda \left( d_2 + \frac{2\sqrt{2}a_1}{v_S^3} \right) > \delta_2^2$



# Bounds on degenerate scalar scenario



$(a_1, v_s, m_\chi)$

$\Omega_{\text{DM}} h^2 = 0.120$

gray: XENON1T

Abe, GCC, Mawatari (2021)

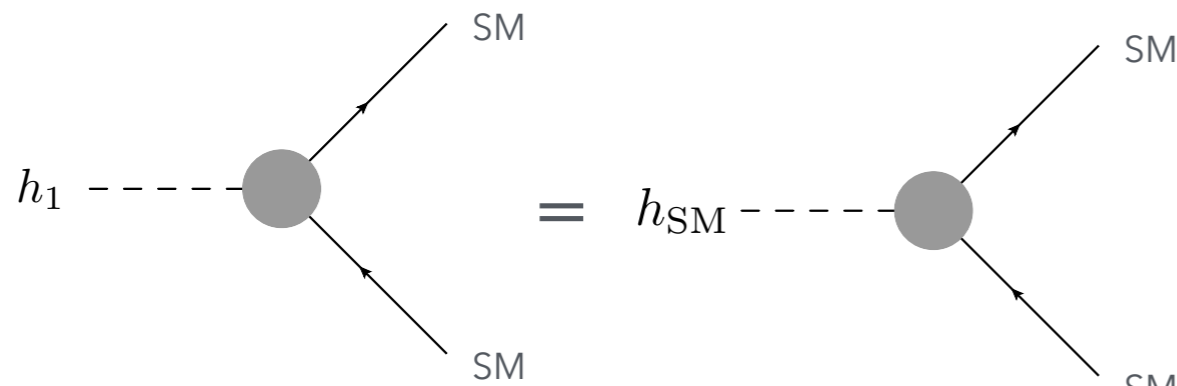
# Bounds on degenerate scalar scenario

$$h_1 = h_{\text{SM}} \cos \alpha - s \sin \alpha$$

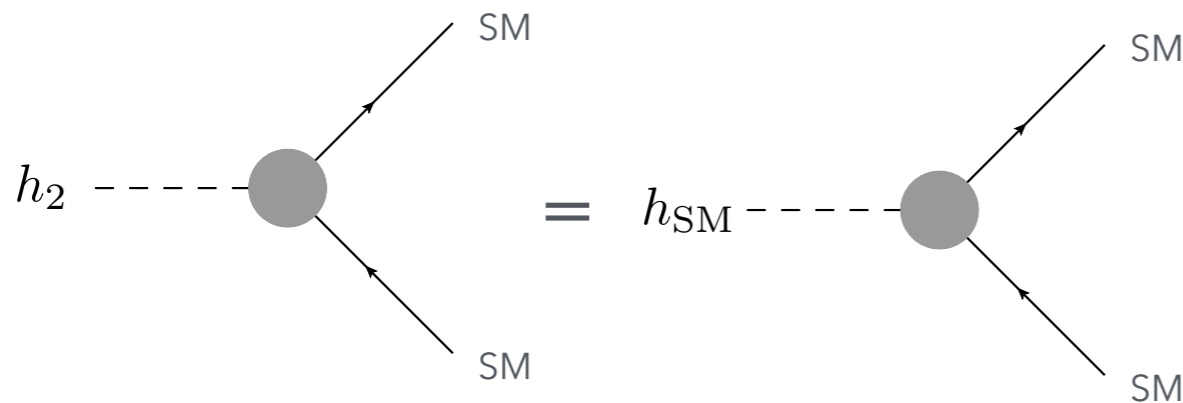
(125 GeV)

$$h_2 = -h_{\text{SM}} \sin \alpha + s \cos \alpha$$

(invisible)



$\times \cos \alpha$



$\times -\sin \alpha$

# Bounds on degenerate scalar scenario

$$h_1 = h_{\text{SM}} \cos \alpha - s \sin \alpha \quad h_2 = -h_{\text{SM}} \sin \alpha + s \cos \alpha$$

$$\Gamma(h_1 \rightarrow \text{SM}) = \Gamma(h_{\text{SM}} \rightarrow \text{SM})(m_{h_1}) \times \cos^2 \alpha$$

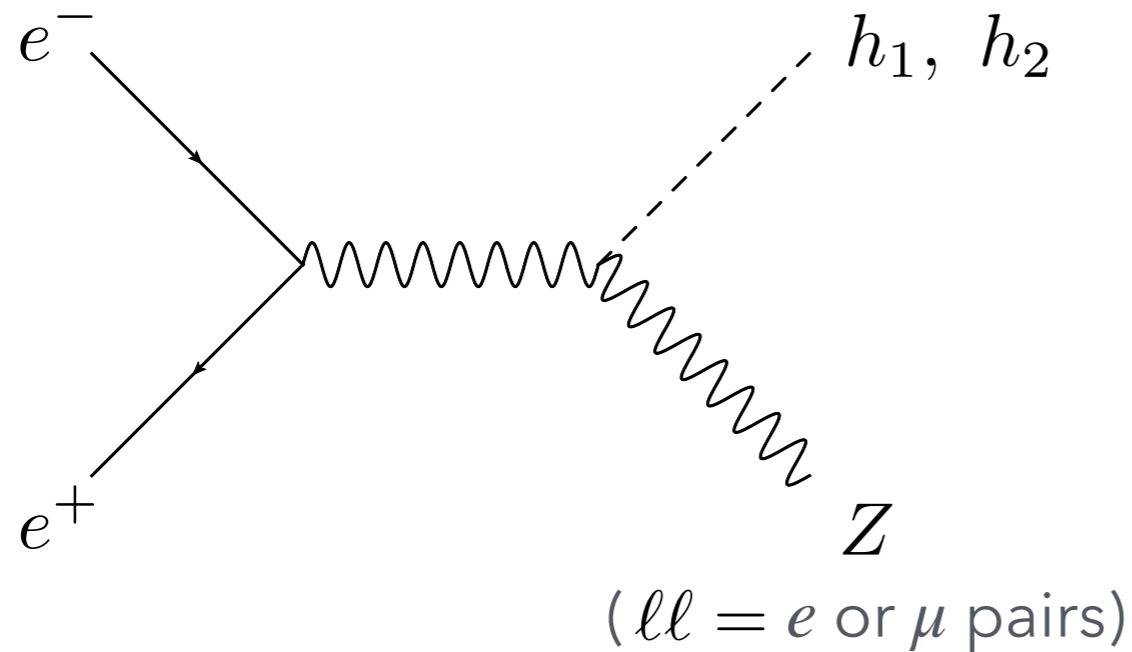
$$\Gamma(h_2 \rightarrow \text{SM}) = \Gamma(h_{\text{SM}} \rightarrow \text{SM})(m_{h_2}) \times \sin^2 \alpha$$

$$\Gamma(h_1 \rightarrow \text{SM}) + \Gamma(h_2 \rightarrow \text{SM}) \simeq \Gamma(h_{\text{SM}} \rightarrow \text{SM}) \quad \text{for } m_{h_1} \simeq m_{h_2}$$

# Search for degenerate scalars@ILC

LHC@Run-I:  $\Delta m \geq 3$  GeV

CMS, arXiv:1407.0558



recoil mass

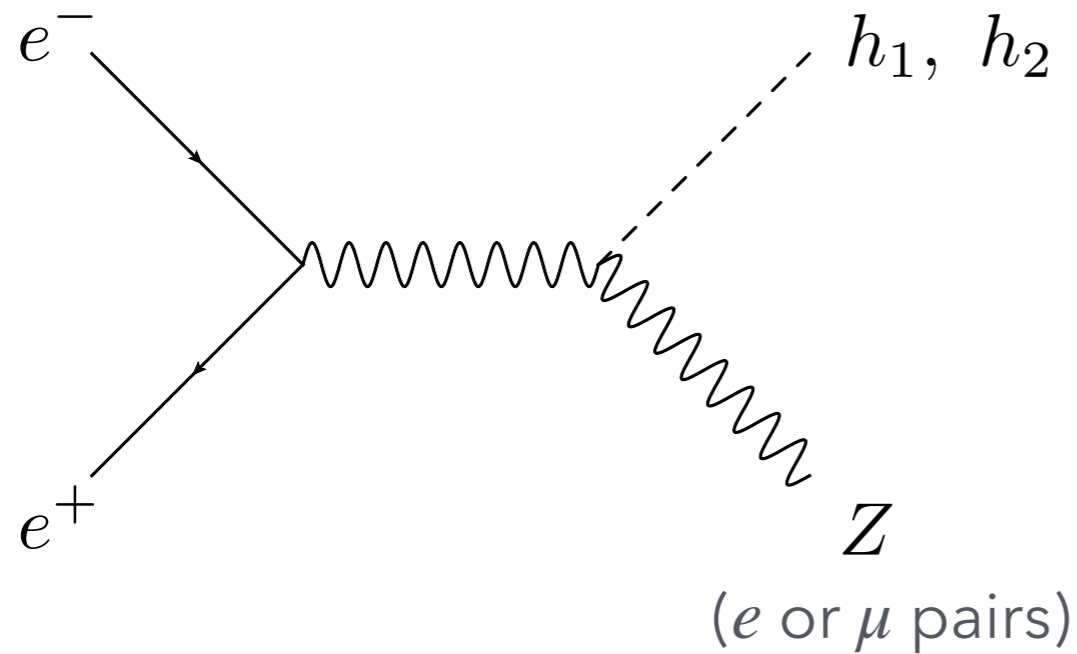
$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

$$m_{h_1, h_2} = \left(125 \pm \frac{\Delta m}{2}\right) \text{ GeV}$$

$$\alpha = \pi/4$$

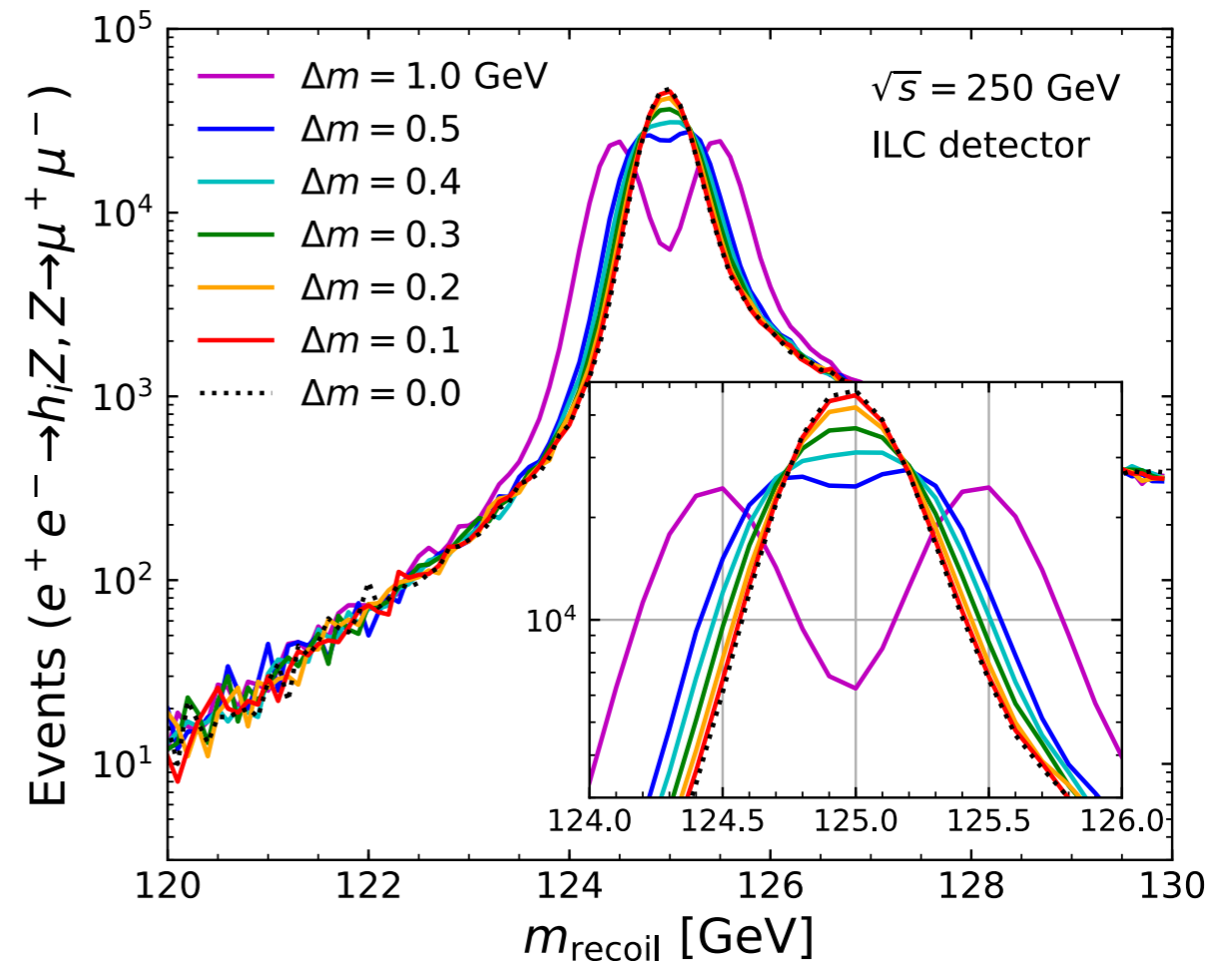
# Search for degenerate scalars@ILC

Abe, GCC, Mawatari (2021)



$$m_{h_1, h_2} = \left(125 \pm \frac{\Delta m}{2}\right) \text{ GeV}$$

$$\alpha = \pi/4$$



recoil mass

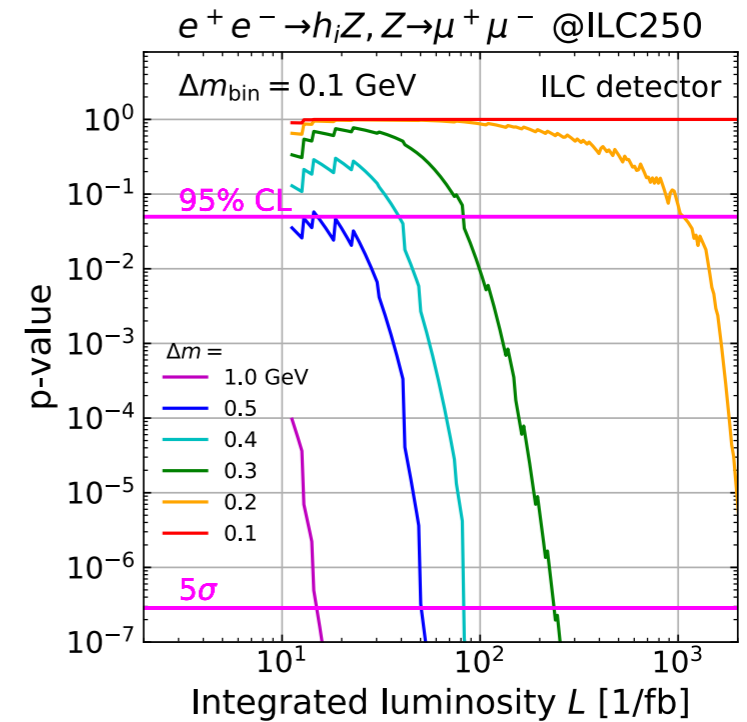
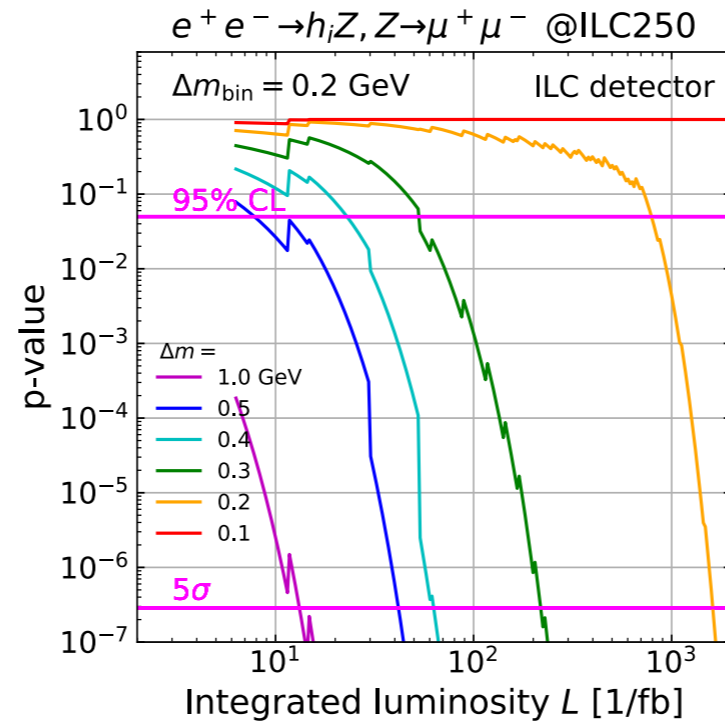
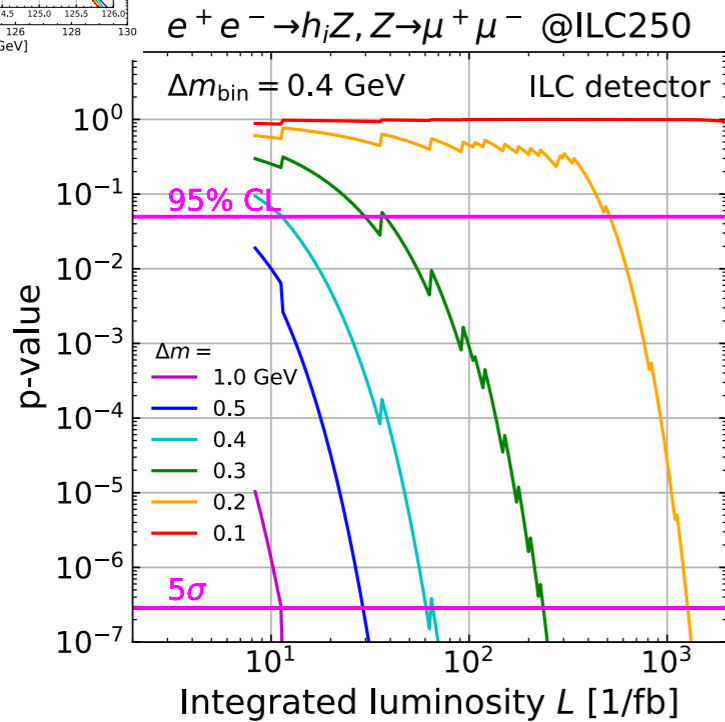
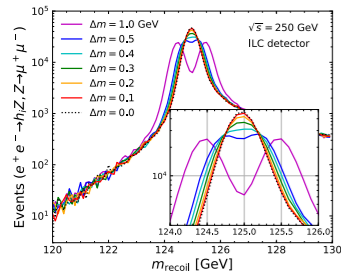
$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

MadGraph5\_aMC@NLO

Pythia 8.2

Delphes (ILCDelphes card)

# Search for degenerate scalars@ILC



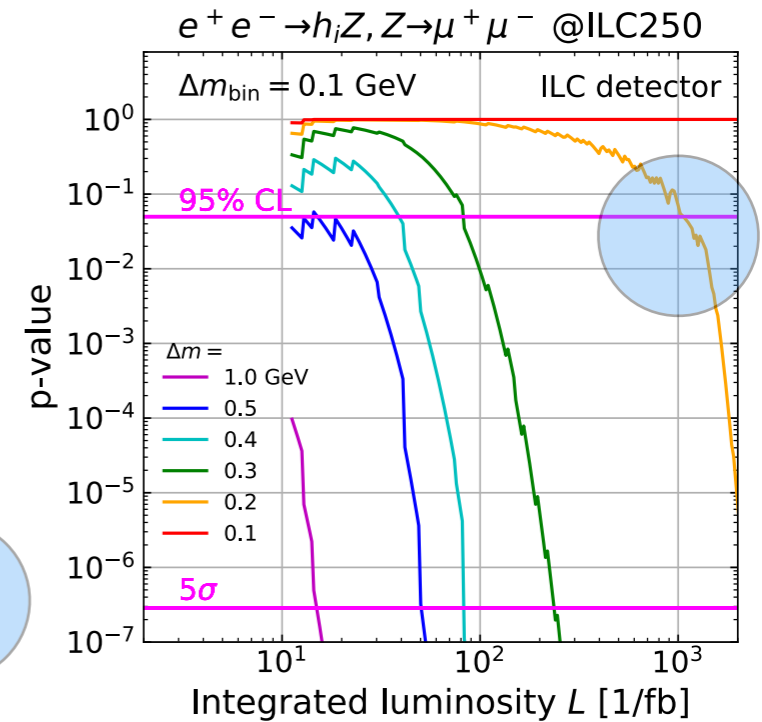
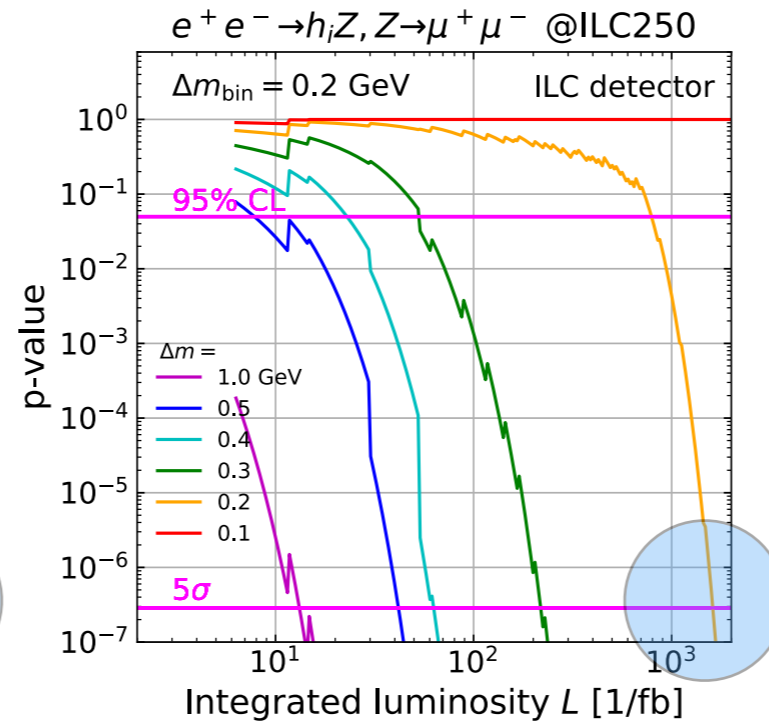
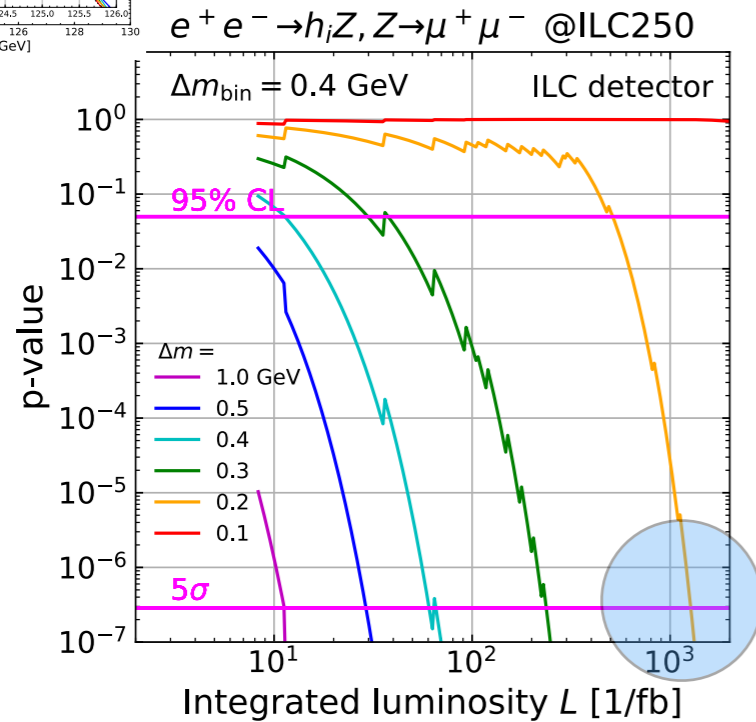
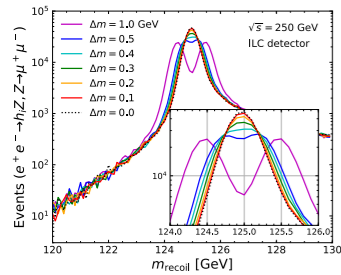
(large) ← bin size → (small)

total # of events = int.L x 10 fb ( $\sigma(e^+e^- \rightarrow hZ) \times \text{Br}(Z \rightarrow \mu^+ \mu^-)$ )

for  $m_h = 125$  GeV w/  $P(e^-, e^+) = (-0.8, 0.3)$

$$\chi^2 = \sum_{i=1}^N \frac{(n^i - n_{\text{SM}}^i)^2}{n_{\text{SM}}^i} \quad \text{w/ } n^i \text{ (\# of events in the } i\text{-th bin)} \geq 10$$

# Search for degenerate scalars@ILC



(large) ← bin size → (small)

degenerate scalar scenario w/  $\Delta m \geq 0.2$  GeV might be tested at ILC with  $2 \text{ ab}^{-1}$

\* Interference effects could be important when  $|m_{h_1} - m_{h_2}| \lesssim \Gamma_{h_1} + \Gamma_{h_2}$

Fuchs, Thewes, Weiglein, 1411.4652

Das, Moretti, Munir, Poulou, 1704.02941

Sakurai, Yin, 2204.01739

# Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)

Multi-critical point principle (MPP)

...Nature fine-tunes couplings to their values at the multiple point

@SM

$$V_{\text{eff}}(\phi) = \mu^2(\phi)\phi^2 + \frac{\lambda(\phi)}{8}\phi^4$$

$$V_{\text{eff}}(\langle\phi\rangle_1) = V_{\text{eff}}(\langle\phi\rangle_2)$$

$M_{\text{EW}}$

$M_{\text{pl}}$



$$0 = \left. \frac{dV_{\text{eff}}(\phi)}{d\phi} \right|_{\langle\phi\rangle_2} \approx \left. \frac{1}{8}\beta_\lambda\phi^3 \right|_{\langle\phi\rangle_2}$$



$$m_t \approx 173 \text{ GeV}, m_h \approx 135 \text{ GeV}$$

Application

2HDM: Froggatt etal (2004), Maniatis etal (2020)

SM+singlet scalars: Haruna, Kawai (2019), Hamada etal (2022)

Froggatt, Nielsen, PLB368 (1996) 96



# Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)

Tree-level MPP Kannike, Koivunen, Raidal, NPB968 (2021) 115441

...multiple vacua@tree level in multi scalar models

However, pNG-DM model does not have degenerate vacua

$$V = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left( a_1 S + \frac{b_1}{4}S^2 + \text{c.c.} \right)$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = (v_S + s + i\chi)/\sqrt{2}$$

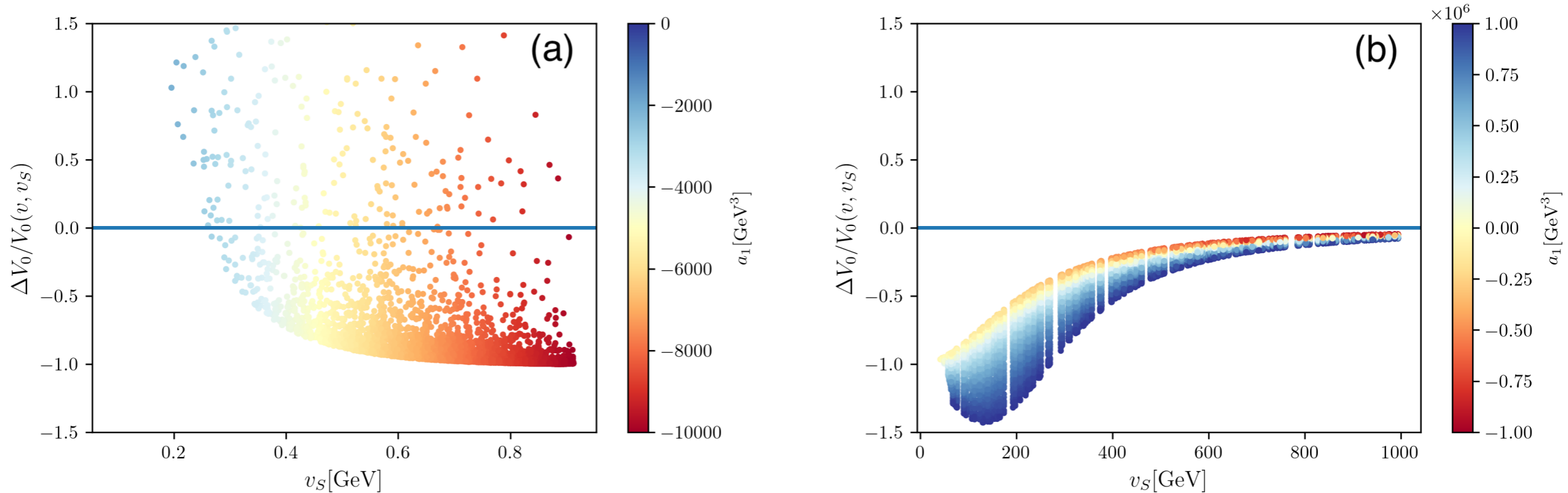
$$\longrightarrow V(v, v_S) \neq V(0, v'_S)$$

No Multi-critical point (when  $a_1 \neq 0$ )

How about in the degenerate scalar scenario?

# Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)



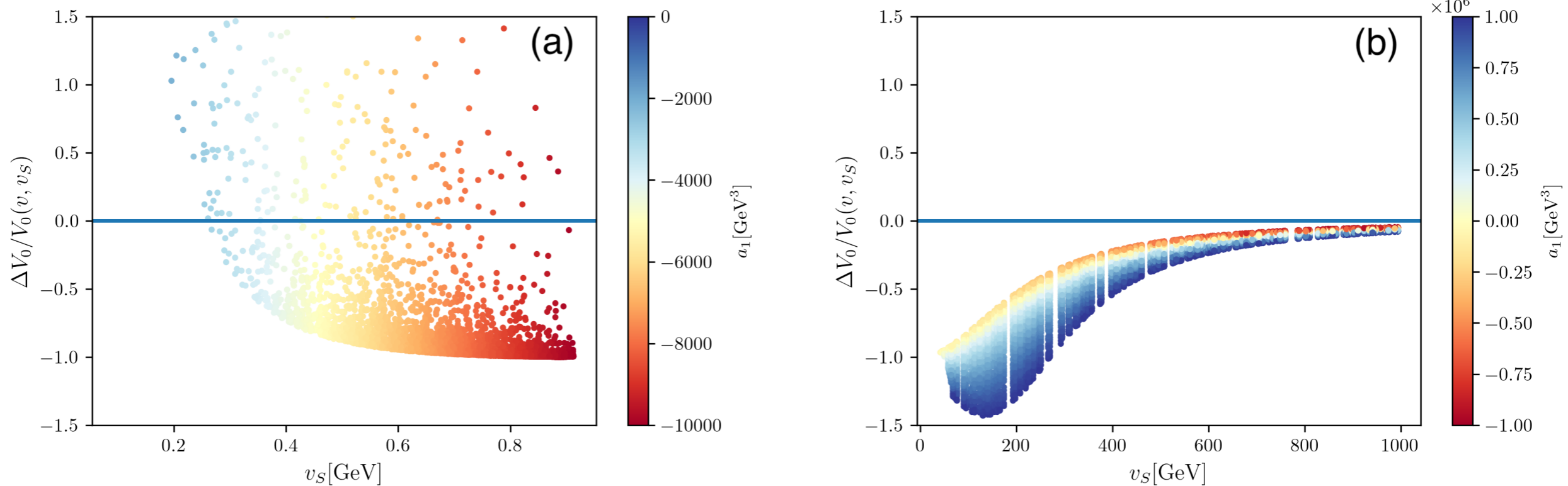
$$\Delta V_0 \equiv V_0(v, v_S) - V_0(0, v'_S)$$

$$= \frac{m^2}{8} v^2 + \frac{3\sqrt{2}a_1}{4} (v_S - v'_S) + \frac{b_1 + b_2}{8} (v_S^2 - v'^2_S)$$

$$\left( \propto -\frac{1}{\lambda d_2 - \delta_2^2} \frac{1}{d_2} \times [\delta_2 (b_2 + b_1) - d_2 b_2]^2 < 0 \quad \text{for } a_1 = 0 \right)$$

# Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)



$$\Delta V_0 \equiv V_0(v, v_S) - V_0(0, v'_S)$$

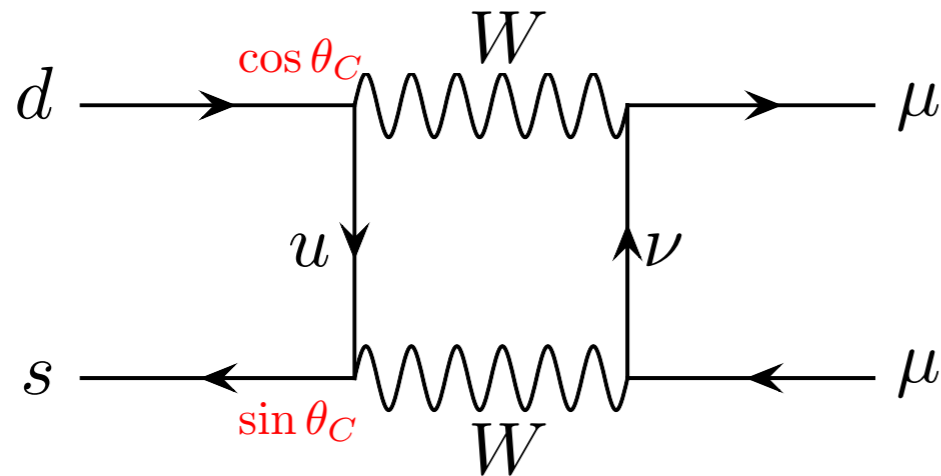
$$= \frac{m^2}{8} v^2 + \frac{3\sqrt{2}a_1}{4} (v_S - v'_S) + \frac{b_1 + b_2}{8} (v_S^2 - v'^2_S)$$

For compatibility of 1st order EWPT and tree-level MPP → Idegawa's talk

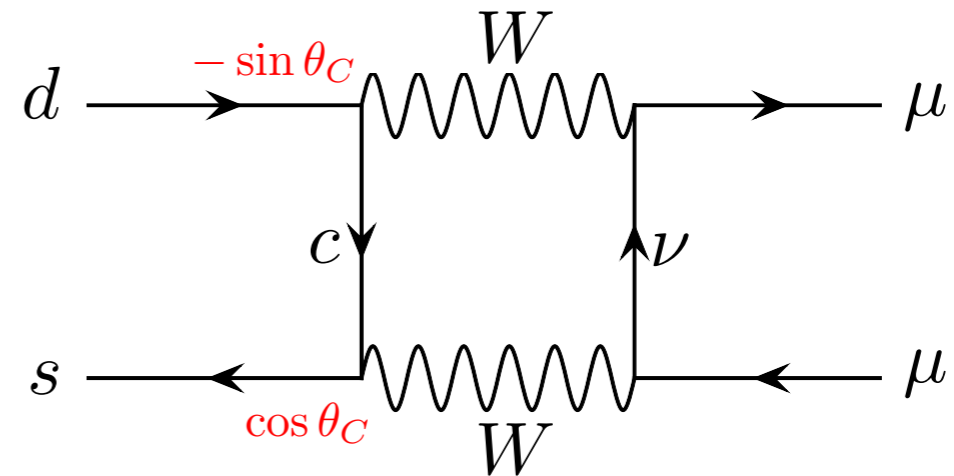
# Origin of the suppression mechanism

Lesson from the GIM mechanism

$$K \rightarrow \mu^+ \mu^-$$



$$\sim \cos \theta_C \sin \theta_C f(m_u)$$



$$\sim -\cos \theta_C \sin \theta_C f(m_c)$$

$$\text{amp} \sim \cos \theta_C \sin \theta_C \{f(m_u) - f(m_c)\} \simeq 0 \quad @m_u \sim m_c$$

\*3generation  $\rightarrow$  unitarity of CKM matrix

# Origin of the suppression mechanism

GCC, Idegawa, in progress

Origin of the cancellation of DM-quark amplitudes at the degenerate limit of scalar masses

Formulation 
$$-\mathcal{L}_{\text{int}} = C_{ijkl}\phi_i\phi_j\phi_k\phi_l$$

$$\begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} C_{hh} & C_{hs} \\ C_{hs} & C_{ss} \end{pmatrix} \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} = \begin{pmatrix} C_{h_1h_1} & 0 \\ 0 & C_{h_2h_2} \end{pmatrix}$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$-\mathcal{L}_{\text{Yukawa}} = C_{h_1ff}\bar{\psi}_L\psi_R h_1 + C_{h_2ff}\bar{\psi}_L\psi_R h_2 + \text{h.c.}$$

# Origin of the suppression mechanism

GCC, Idegawa, in progress

amplitudes@tree-level

$$i(\mathcal{M}_1 + \mathcal{M}_2) \propto \sum_{i=1,2} C_{h_i\chi\chi} C_{h_i f f} \frac{1}{t - m_{h_i}^2}$$

cancellation@ $t \rightarrow 0$

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2} \cos \alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2} \sin \alpha = 0$$

$$C_{h_1\chi\chi} = C_{h\chi\chi} \cos \alpha + C_{s\chi\chi} \sin \alpha$$

$$C_{h_2\chi\chi} = -C_{h\chi\chi} \sin \alpha + C_{s\chi\chi} \cos \alpha$$

$$C_{h\chi\chi} = \frac{A}{v_s} (C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s} (C_{ss} + \Delta_s)$$

( $H - S$  mixing)

# Origin of the suppression mechanism

GCC, Idegawa, in progress

$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

( $H - S$  mixing)

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2} \cos \alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2} \sin \alpha = \frac{A}{v_s} \left[ \sin \alpha \cos \alpha \left\{ \frac{m_{h_1}^2 + \Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2 + \Delta_s}{m_{h_2}^2} \right\} + \Delta_h \left( \frac{\cos^2 \alpha}{m_{h_1}^2} + \frac{\sin^2 \alpha}{m_{h_2}^2} \right) \right]$$

$$= 0 \quad \text{if } \Delta_h = 0 \text{ at } m_{h_1} = m_{h_2}$$

**mixing term of  $H$  and  $S$  is important**

(In addition,  $\Delta_s = 0$  is necessary in the pNG-DM model)

# Origin of the suppression mechanism

GCC, Idegawa, in progress

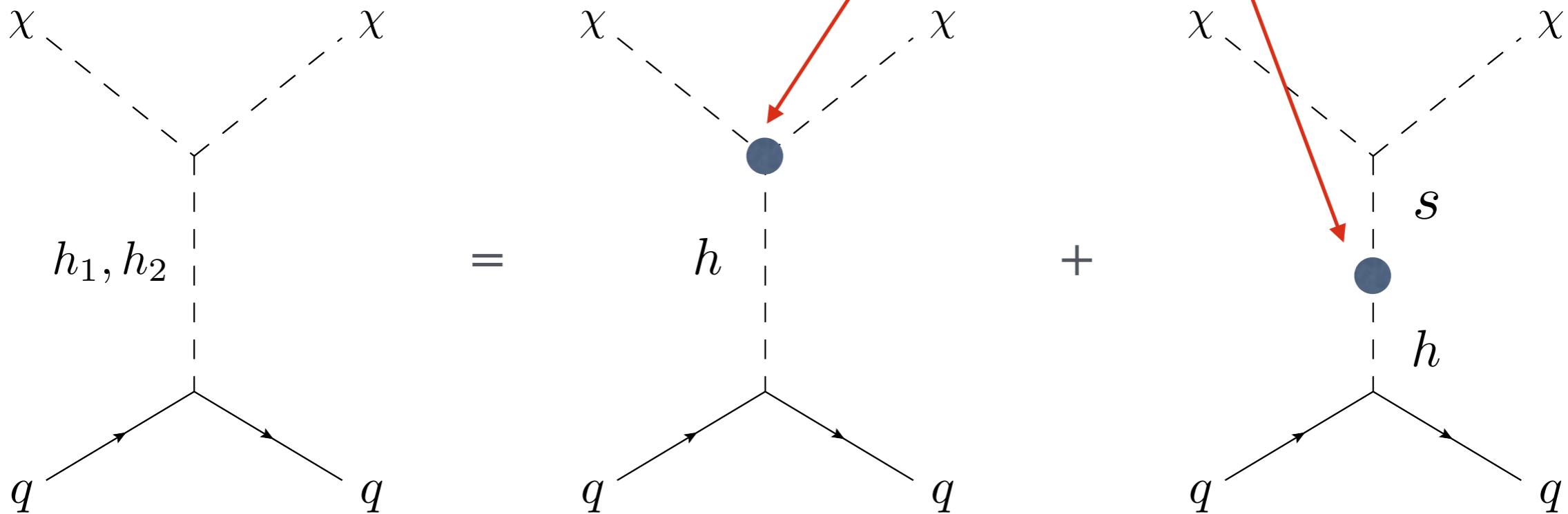
$$C_{hXX} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{sXX} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

( $H - S$  mixing)

$$\frac{C_{h1XX}}{m_{h1}^2} \cos \alpha - \frac{C_{h2XX}}{m_{h2}^2} \sin \alpha = \frac{A}{v_s} \left[ \sin \alpha \cos \alpha \left\{ \frac{m_{h1}^2 + \Delta_s}{m_{h1}^2} - \frac{m_{h2}^2 + \Delta_s}{m_{h2}^2} \right\} + \Delta_h \left( \frac{\cos^2 \alpha}{m_{h1}^2} + \frac{\sin^2 \alpha}{m_{h2}^2} \right) \right]$$

= 0 if  $\Delta_h = 0$  at  $m_{h1} = m_{h2}$

mixing term of  $H$  and  $S$  is important





# Origin of the suppression mechanism

GCC, Idegawa, in progress

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2} \cos \alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2} \sin \alpha = \frac{A}{v_s} \left[ \sin \alpha \cos \alpha \left\{ \frac{m_{h_1}^2 + \Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2 + \Delta_s}{m_{h_2}^2} \right\} + \Delta_h \left( \frac{\cos^2 \alpha}{m_{h_1}^2} + \frac{\sin^2 \alpha}{m_{h_2}^2} \right) \right]$$

$$= 0 \quad \text{if } \Delta_h = 0 \text{ at } m_{h_1} = m_{h_2}$$

$$C_{h\chi\chi} = \frac{A}{v_s} (C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s} (C_{ss} + \Delta_s)$$

( $H - S$  mixing)

In our case

$$V \supset \frac{\delta_2}{2} |H|^2 |S|^2 = C_{h\chi\chi} h\chi^2 + C_{hs} h s$$

$$C_{h\chi\chi} = \frac{\delta_2}{4} v = \frac{1}{2v_s} C_{hs} \quad \rightarrow \quad A = \frac{1}{2}, \quad \Delta_h = 0$$

# Origin of the suppression mechanism

GCC, Idegawa, in progress

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2} \cos \alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2} \sin \alpha = \frac{A}{v_s} \left[ \sin \alpha \cos \alpha \left\{ \frac{m_{h_1}^2 + \Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2 + \Delta_s}{m_{h_2}^2} \right\} + \Delta_h \left( \frac{\cos^2 \alpha}{m_{h_1}^2} + \frac{\sin^2 \alpha}{m_{h_2}^2} \right) \right]$$

$$= 0 \quad \text{if } \Delta_h = 0 \text{ at } m_{h_1} = m_{h_2}$$

$$C_{h\chi\chi} = \frac{A}{v_s} (C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s} (C_{ss} + \Delta_s)$$

( $H - S$  mixing)

most general scalar potential

soft breaking terms

$$V \supset \frac{\delta_2}{2} |H|^2 |S|^2 + \left( \frac{\delta_1}{4} |H|^2 S + \frac{\delta_3}{4} |H|^2 S^2 + \text{c.c.} \right) = C_{h\chi\chi} h\chi^2 + C_{hs} hS$$

$$C_{h\chi\chi} = \frac{\delta_2 - \delta_3}{4} v, \quad C_{hs} = \frac{v}{2} \left( \frac{\delta_1}{\sqrt{2}} + \delta_2 v_S + \delta_3 v_S \right)$$

$$\Delta_h \neq 0 \quad \text{unless } \delta_1 = \delta_3 = 0 \text{ or } \delta_1 = \delta_2 = 0$$

# Origin of the suppression mechanism

GCC, Idegawa, in progress

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2} \cos \alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2} \sin \alpha = \frac{A}{v_s} \left[ \sin \alpha \cos \alpha \left\{ \frac{m_{h_1}^2 + \Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2 + \Delta_s}{m_{h_2}^2} \right\} + \Delta_h \left( \frac{\cos^2 \alpha}{m_{h_1}^2} + \frac{\sin^2 \alpha}{m_{h_2}^2} \right) \right]$$

$$= 0 \quad \text{if } \Delta_h = 0 \text{ at } m_{h_1} = m_{h_2}$$

$$C_{h\chi\chi} = \frac{A}{v_s} (C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s} (C_{ss} + \Delta_s)$$

( $H - S$  mixing)

the degenerate scalar scenario works only for limited H-S mixing term (not in general)

# Origin of the suppression mechanism

GCC, Idegawa, in progress

Does cancellation of DM-quark amplitudes still work beyond the leading order?

cf. pNG DM models → suppression mechanism does not work at 1-loop level

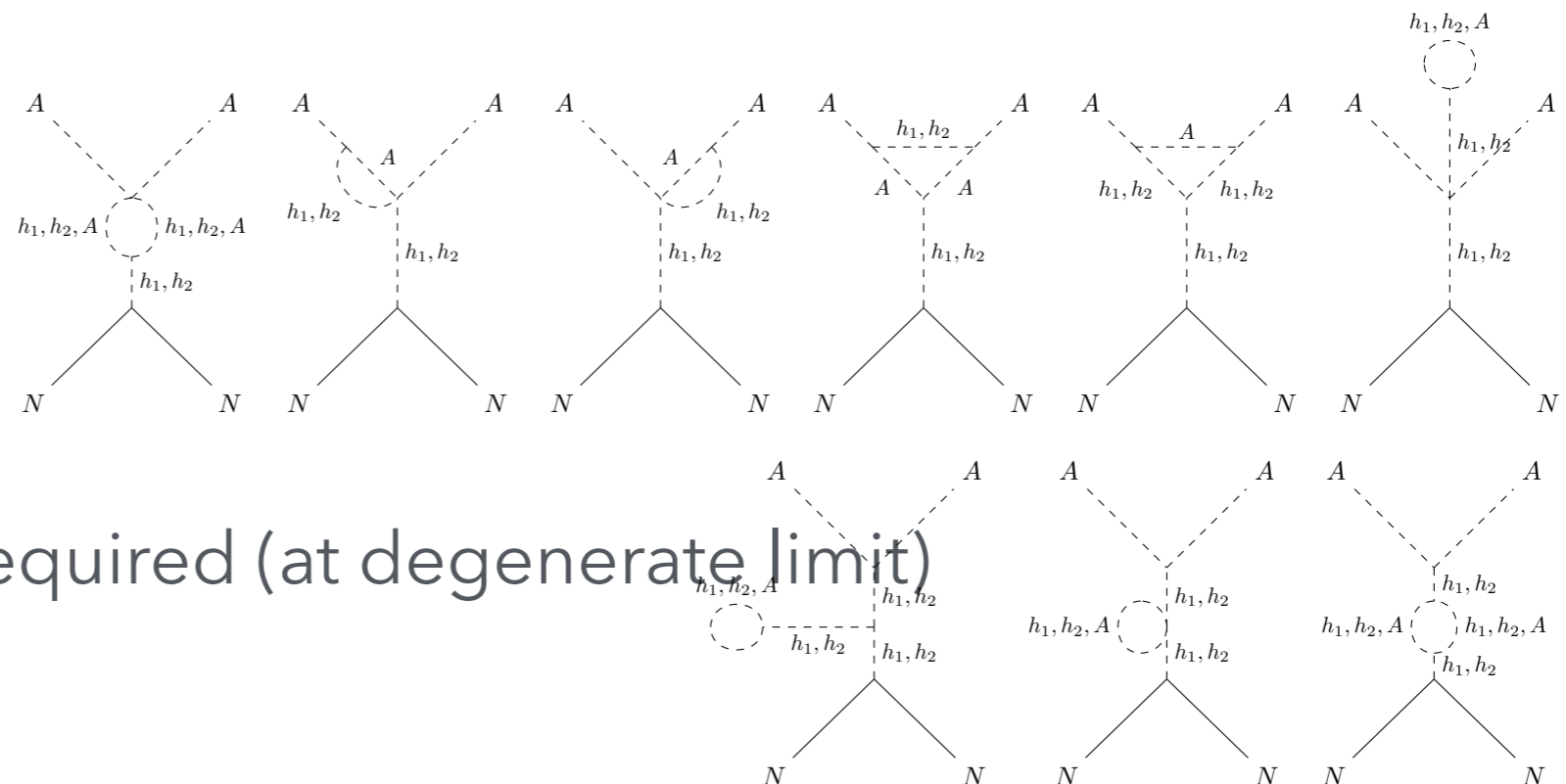
Azevedo et al, 1810.06105

Ishiwata, Toma, 1810.08139

Alanne et al, 2008.09605

Glaus et al, 2008.12985

Abe, Hamada, 2205.11919



no renormalization is required (at degenerate limit)

finite contribution?

# Summary

degenerate scalar scenario  $\rightarrow$  an alternative of "Nightmare scenario" @LHC besides super-heavy particles/ultra-weak int.

DM-quark scattering amplitudes are cancelled when  $m_{h_1} \sim m_{h_2}$

recoil mass dist. @ILC w/  $2 \text{ ab}^{-1} \rightarrow$  chance to test a degenerate scalar scenario w/  $\Delta m \geq 0.2 \text{ GeV}$

degenerate scalar scenario restricts soft breaking terms w/  $D \geq 3$   
 $(|H|^2 S, |H|^2 S^2)$

cancellation of DM-quark amplitudes in the degenerate scalar scenario @1-loop level?