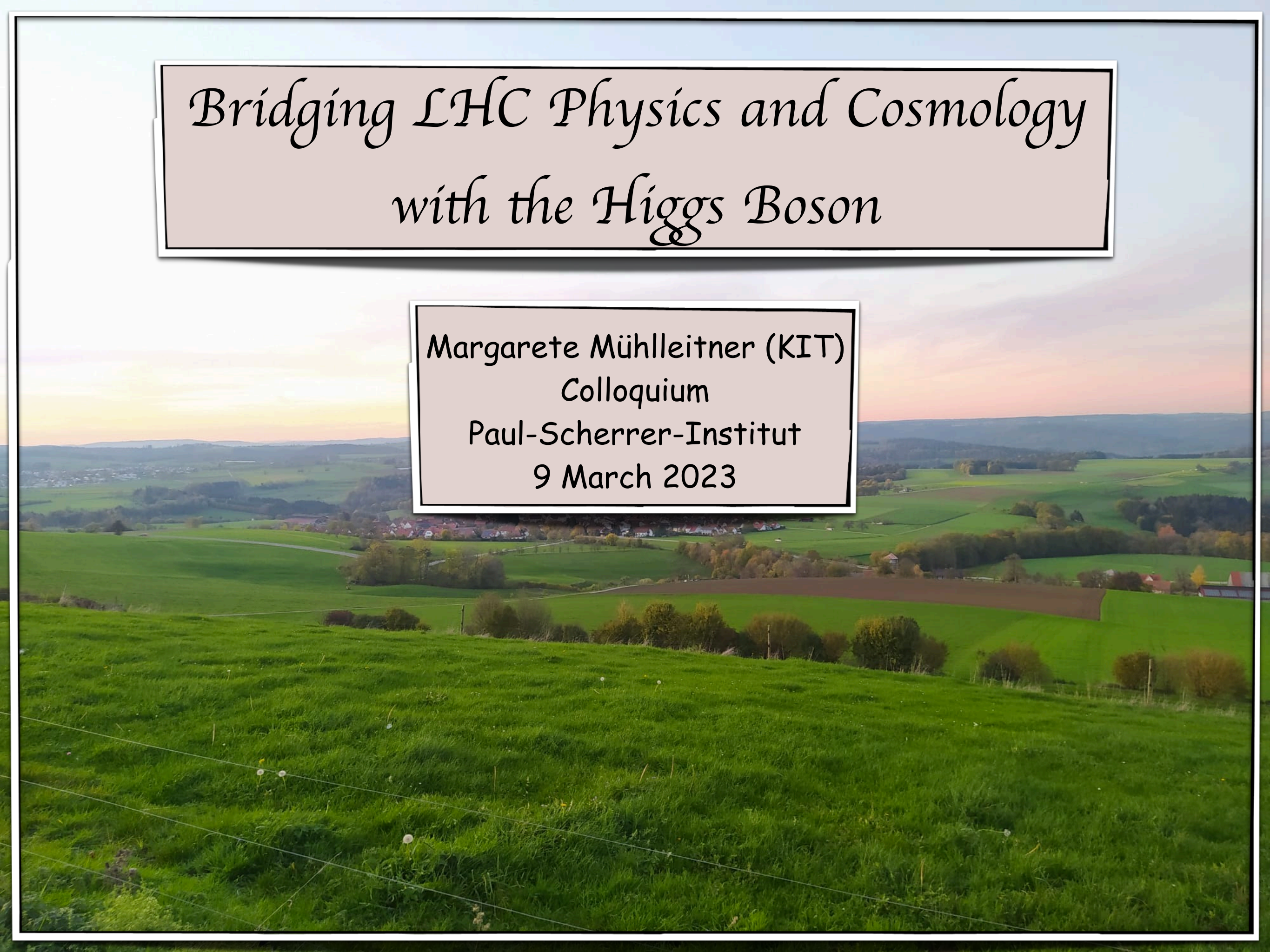
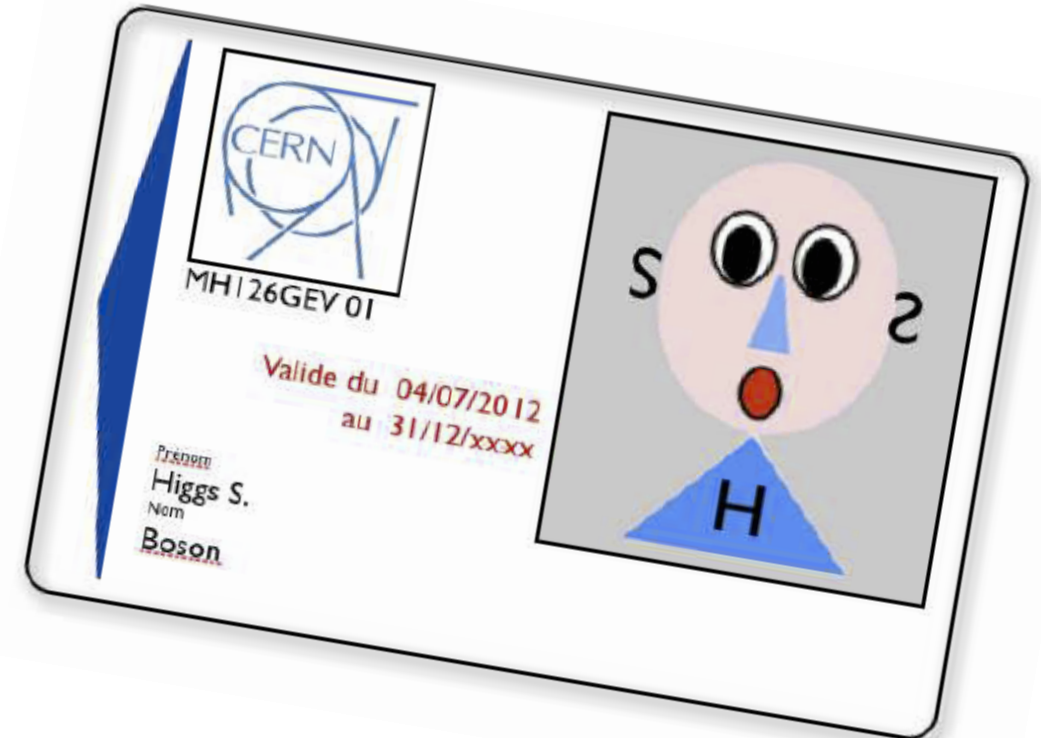




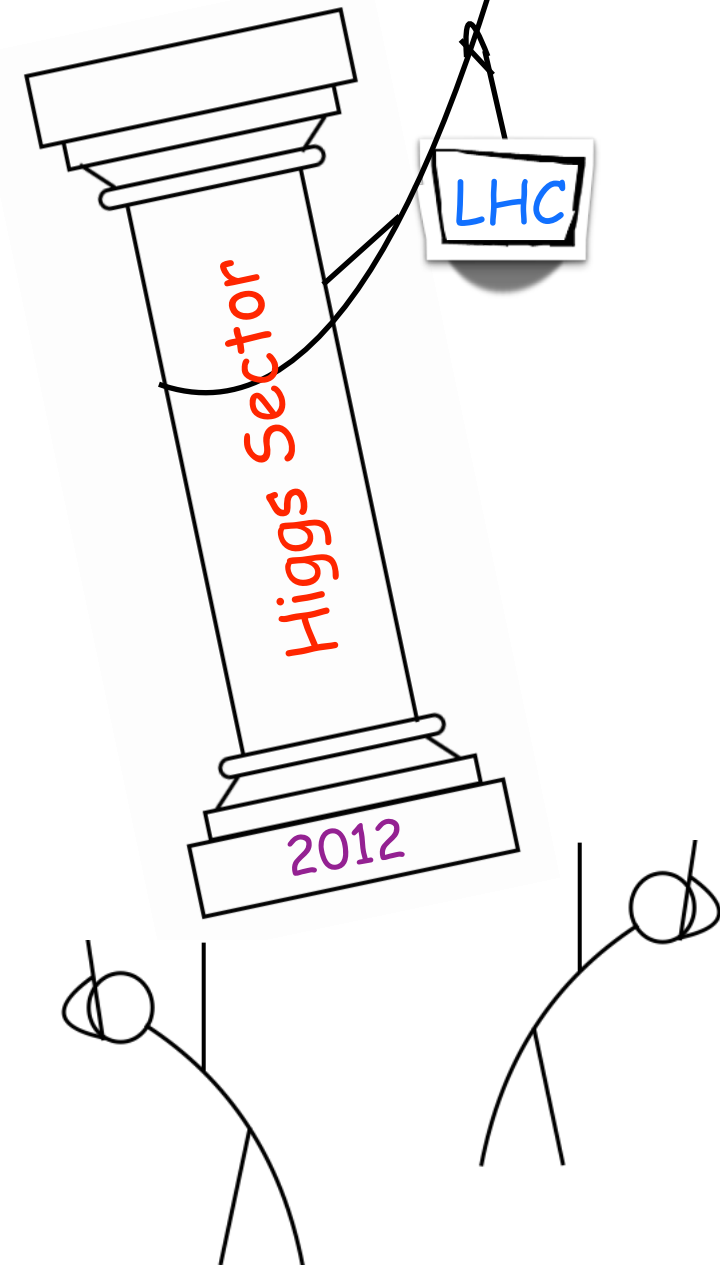
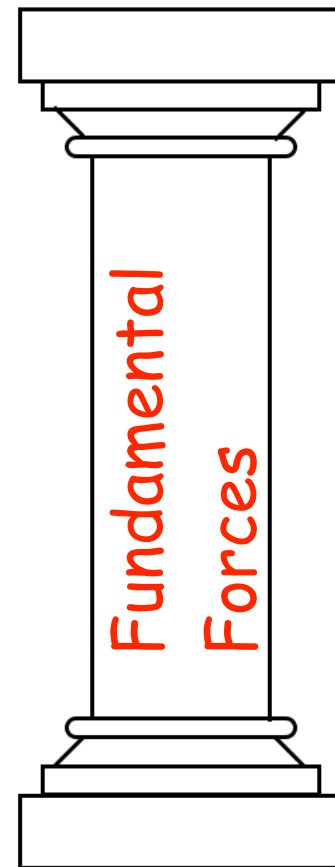
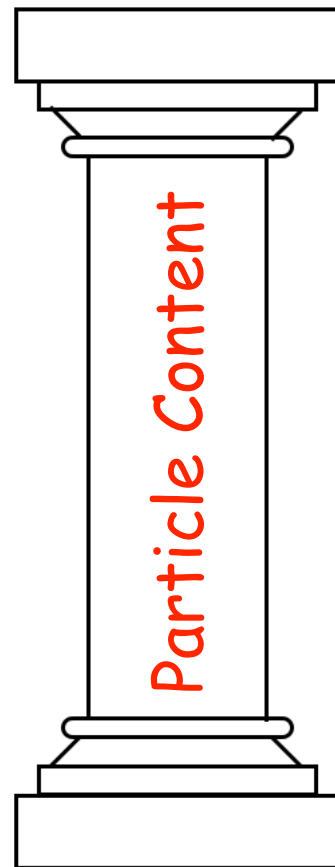
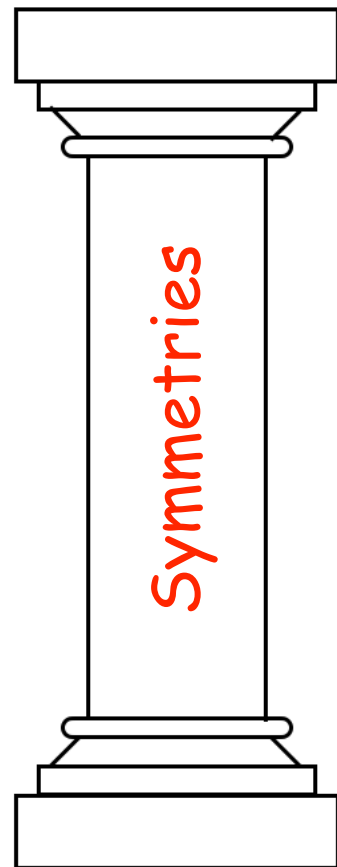
Bridging LHC Physics and Cosmology with the Higgs Boson

Margarete Mühlleitner (KIT)
Colloquium
Paul-Scherrer-Institut
9 March 2023

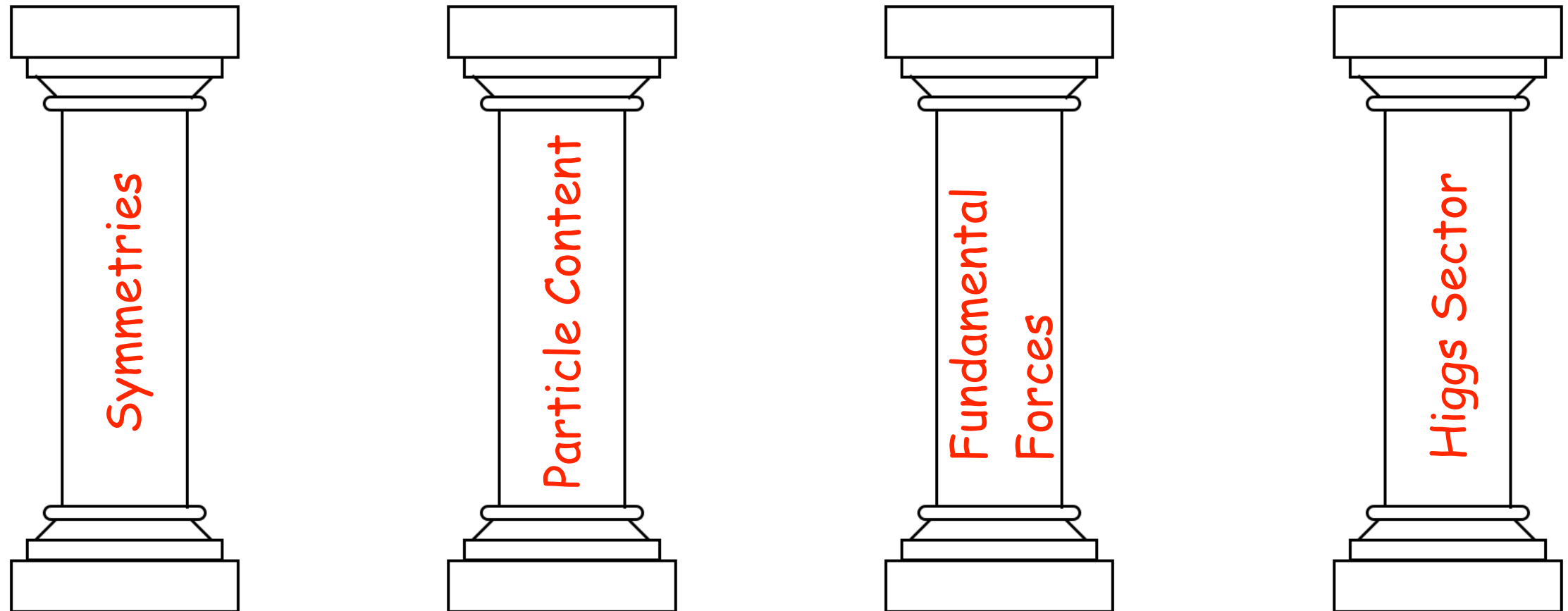
- Introduction
- The Role of the Higgs Boson Mass
- Trilinear Higgs-Self-Coupling and HH Production
 - Exp., theor. & HH constraints on BSM
 - Scan results
 - Benchmark C2HDM
- Dark Matter from the Higgs Sector
 - Higgs Portal, Higgs- $\rightarrow$ DMDM at NLO EW
 - Scalar and Vector DM models: NLO EW to indirect DM detection
- Baryogenesis in BSM Models
 - CP in the Dark
 - Impact EFT contributions
 - Size of Baroygenesis



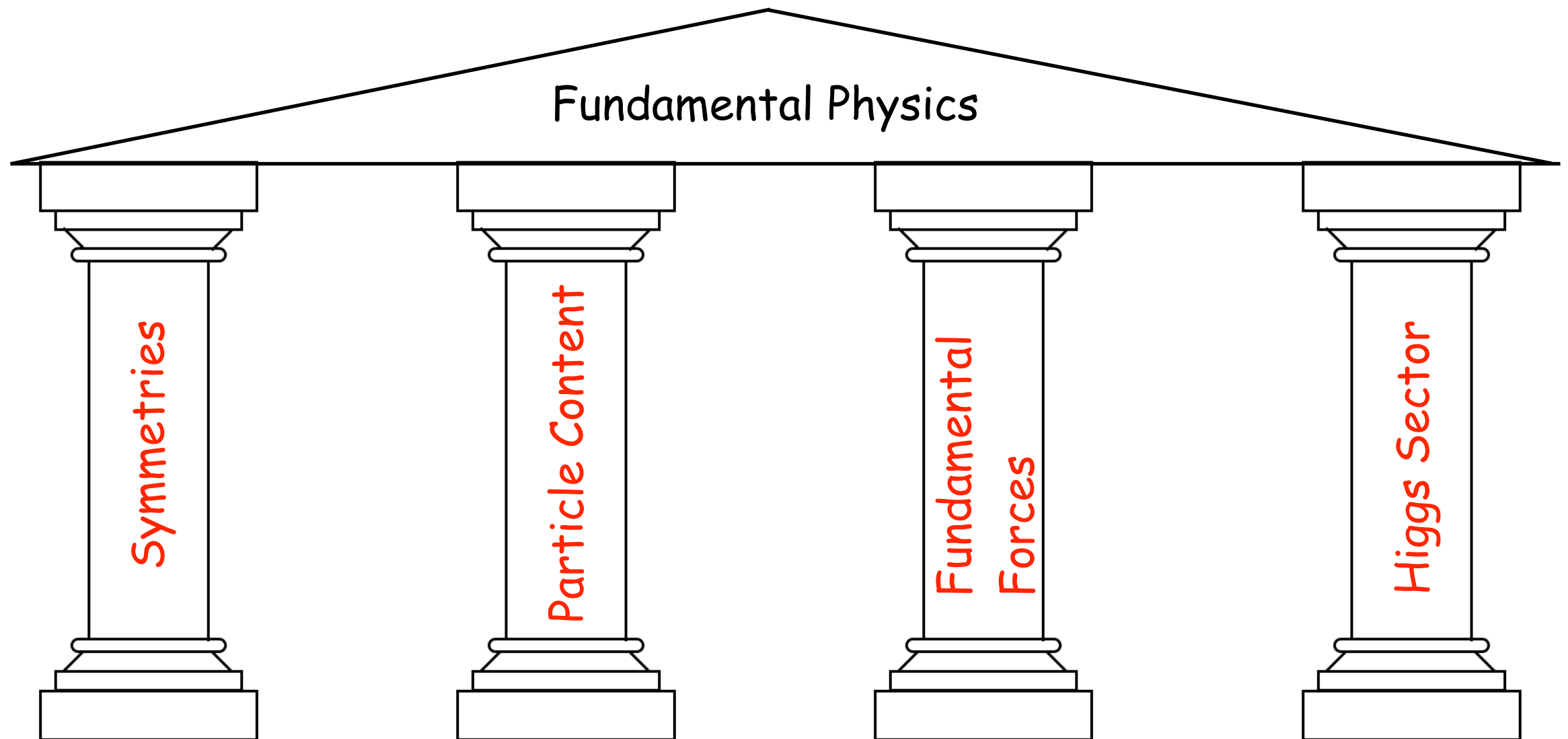
The Four Pillars of the Standard Model



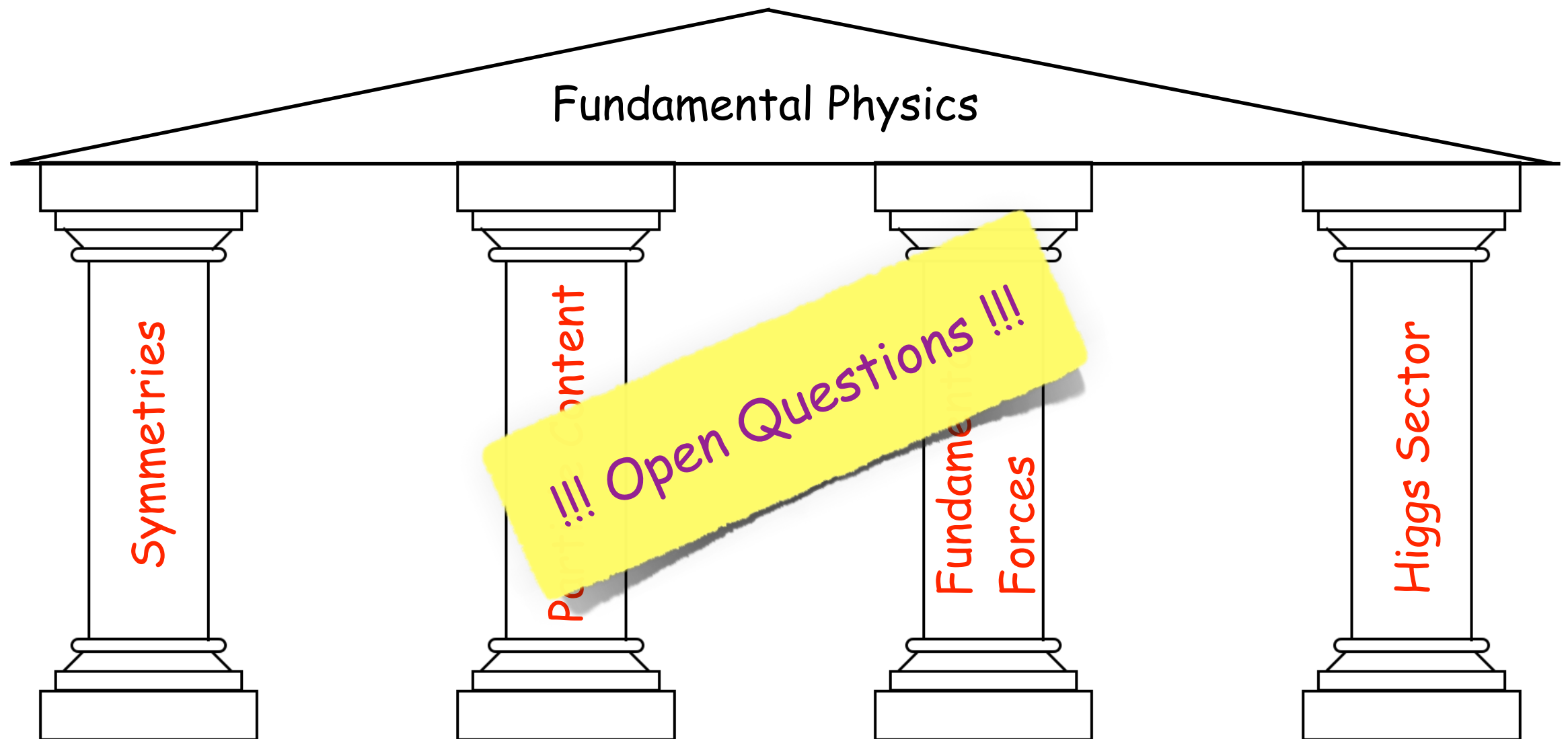
The Four Pillars of the Standard Model

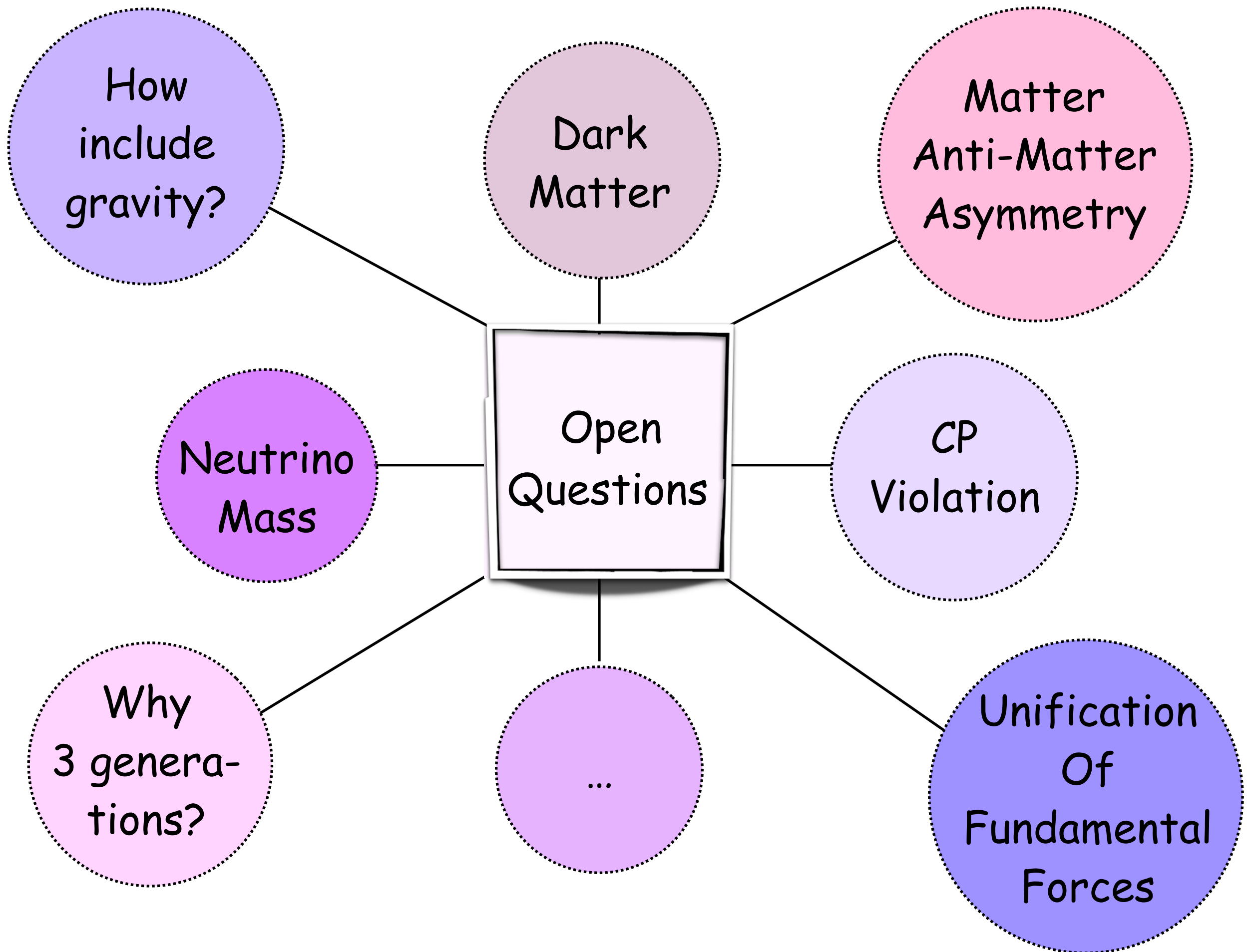


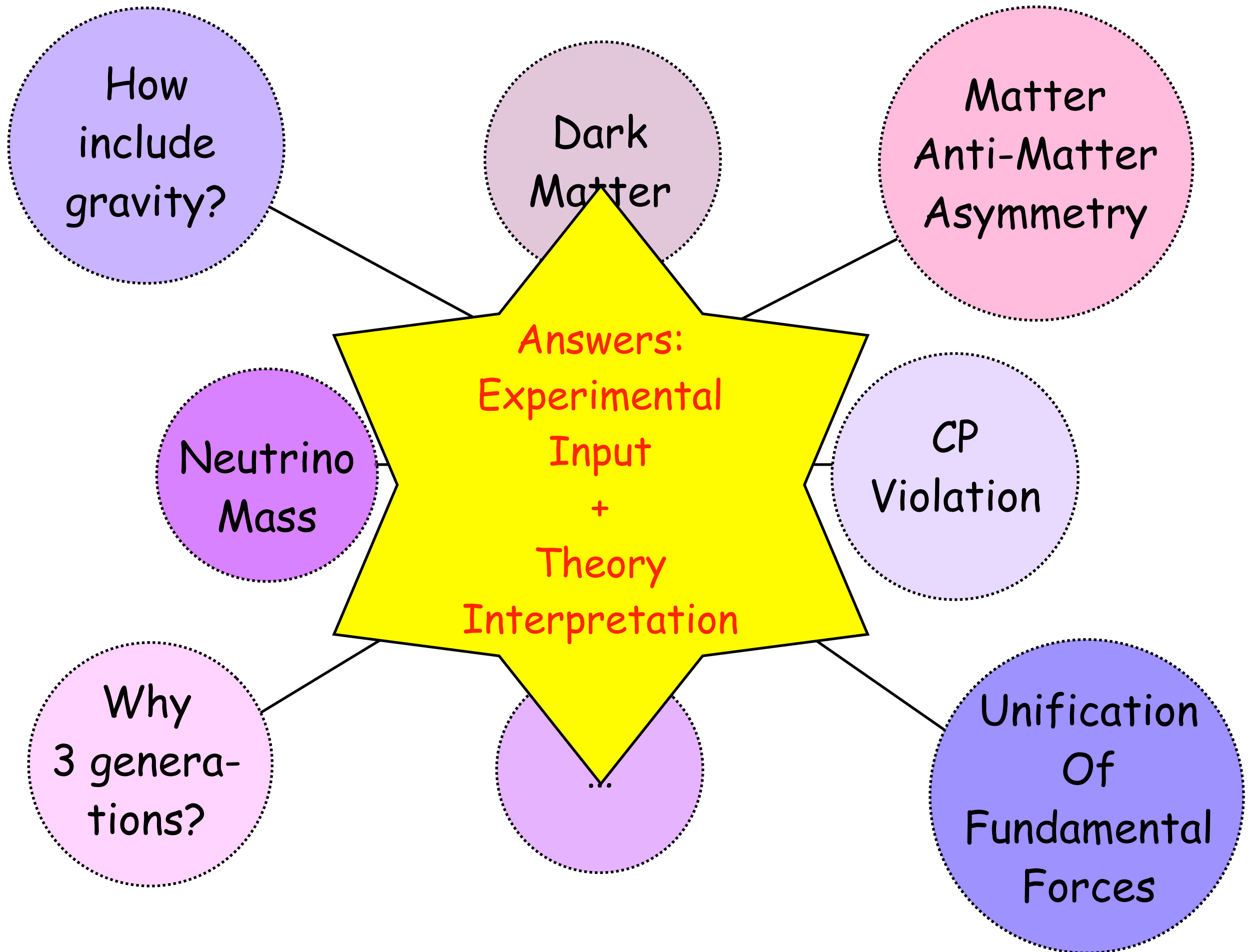
The Standard Model is Structurally Complete



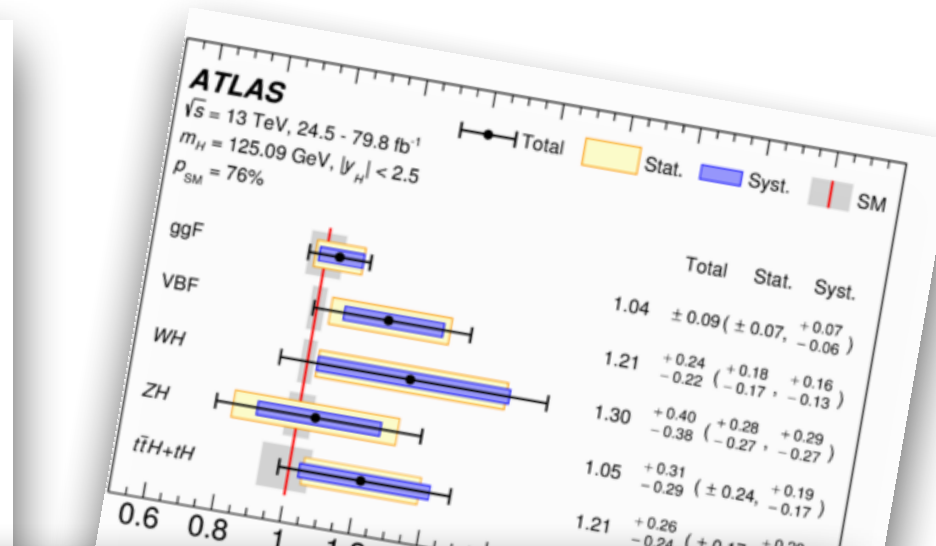
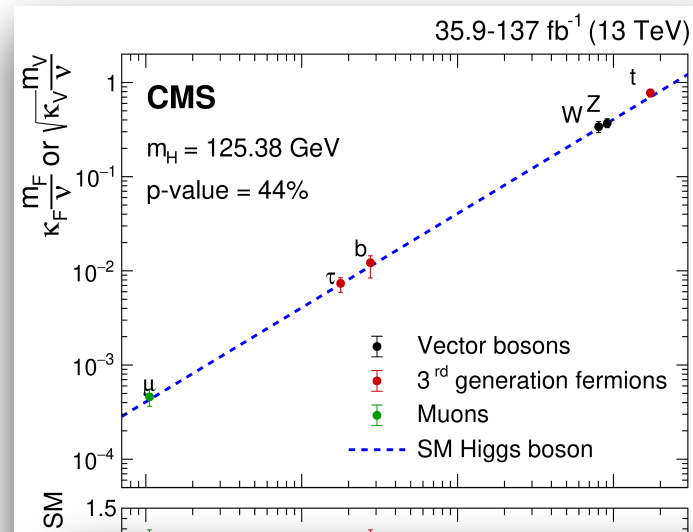
The Standard Model is Structurally Complete - But



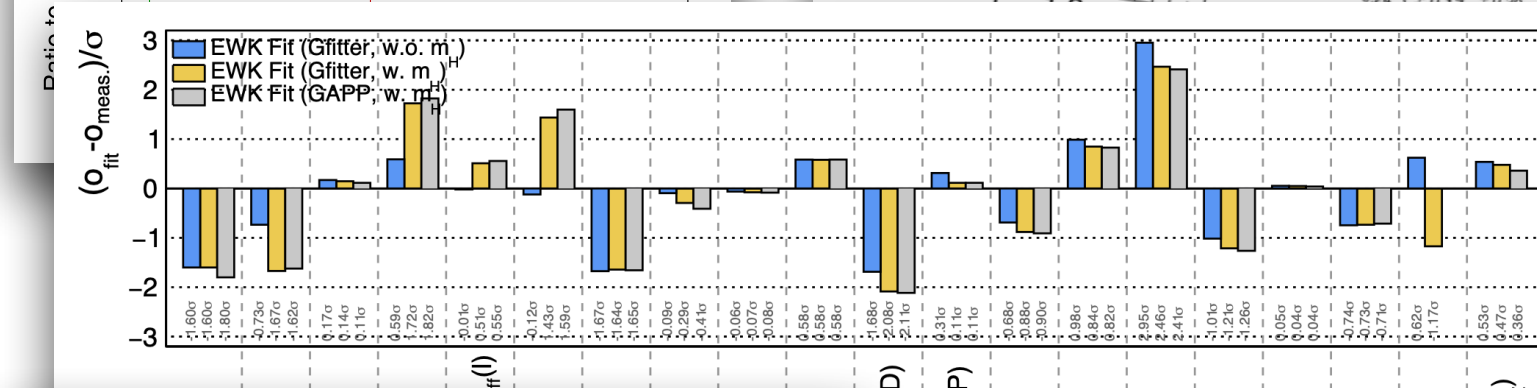




Status



Discovered Higgs Boson
behaves very SM-like



Consistency Test of the SM at the quantum level

ATLAS Heavy Particle Searches^a - 95% CL Upper Exclusion Limits

Status: July 2021

ATLAS Preliminary

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

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

	Model	ℓ, γ	Jets ^b	E_{miss}^c	$\mathcal{L} \cdot \mathcal{B} [fb^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{\mu,1} \neq 0$	$0, \mu, \tau, \gamma$	1-4 j	Yes	139	11.5 TeV $n = 2$ 8.6 TeV $n = 3$ & $3.6Z$ NLO 8.9 TeV $n = 6$ 8.9 TeV	2108 10874 1707 0417
	ADD non resonant $\gamma\gamma$	—	—	—	367	—	1709 0297
	ADD QH	—	2 j	—	370	—	1610 0206
	ADD BH multiplet	—	2 j	—	366	—	1610 0206
	RS1 $G_{\mu,1} \neq 0$	$2, \mu$	—	—	139	—	2108 13405
	BuK RS1 $G_{\mu,1} \neq 0$ WW/ZZ	multi-channel	—	—	139	2.3 TeV 4.5 TeV	1808 02380
	BuK RS1 $G_{\mu,1} \neq 0$ WW + ν eq	$1, \mu, \tau$	2 j / 1 j	Yes	139	2.0 TeV	2004 14836
	BuK RS1 $G_{\mu,1} \neq 0$ WW + ν eq	$1, \mu, \tau$	$1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 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Figure 1 displays exclusion limits for the production of light LSPs. The x-axis represents the mass scale in GeV, ranging from 0 to 2000. The y-axis lists various decay channels and their corresponding mass limits. The channels are categorized by the type of particle produced, indicated by the color of the bar: green for $A(L)S(L)$, blue for $A(L)E(L)$, orange for $A^{0,1}_{F(B)}$, red for $A^{0,2}_{F(B)}$, purple for $A^{0,1}_{F(B)}$, brown for R^0 , pink for R^0_C , grey for R^0_B , yellow for Δ^0_{had} , and light blue for $\alpha_s(m_Z)$.

The channels and their corresponding mass limits (in GeV) are as follows:

- $\tilde{q} \rightarrow q\tilde{\chi}_1^0 \rightarrow q\gamma\tilde{G}$: $\tilde{q} \rightarrow q\tilde{\chi}_1^0 \rightarrow q\gamma\tilde{G}$ (max. exclusion)
- $\tilde{q} \rightarrow (q\tilde{\chi}_1^0 \rightarrow q\gamma\tilde{G}/q\tilde{\chi}_1^+ \rightarrow qW\tilde{G})$: $\tilde{q} \rightarrow (q\tilde{\chi}_1^0 \rightarrow q\gamma\tilde{G}/q\tilde{\chi}_1^+ \rightarrow qW\tilde{G})$ (max. exclusion)
- $\tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow (\gamma/Z)\tilde{G}$: $\tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow (\gamma/Z)\tilde{G}$ (max. exclusion)
- $\tilde{p} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^+, \tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}, \tilde{\chi}_1^+ \rightarrow W\tilde{G}$: $\tilde{p} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^+, \tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}, \tilde{\chi}_1^+ \rightarrow W\tilde{G}$ (max. exclusion)
- $\tilde{p} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^+, \tilde{\chi}_1^0\tilde{\chi}_1^+ \rightarrow 2 \times [(Z/h/\gamma)\tilde{G}] + X_{had}$: $\tilde{p} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^+, \tilde{\chi}_1^0\tilde{\chi}_1^+ \rightarrow 2 \times [(Z/h/\gamma)\tilde{G}] + X_{had}$ (BF(Z,H-γ) = 1:2)
- $\tilde{p} \rightarrow \tilde{\chi}_1^{0,\pm}\tilde{\chi}_j^{0,\pm} \rightarrow hh\tilde{G}\tilde{G} + X_{had}$: $\tilde{p} \rightarrow \tilde{\chi}_1^{0,\pm}\tilde{\chi}_j^{0,\pm} \rightarrow hh\tilde{G}\tilde{G} + X_{had}$
- $\tilde{p} \rightarrow \tilde{\chi}_1^{0,\pm}\tilde{\chi}_j^{0,\pm} \rightarrow (h/Z)(h/Z)\tilde{G}\tilde{G} + X_{had}$: $\tilde{p} \rightarrow \tilde{\chi}_1^{0,\pm}\tilde{\chi}_j^{0,\pm} \rightarrow (h/Z)(h/Z)\tilde{G}\tilde{G} + X_{had}$
- $\tilde{p} \rightarrow \tilde{\chi}_1^{0,\pm}\tilde{\chi}_j^{0,\pm} \rightarrow ZZ\tilde{G}\tilde{G} + X_{had}$: $\tilde{p} \rightarrow \tilde{\chi}_1^{0,\pm}\tilde{\chi}_j^{0,\pm} \rightarrow ZZ\tilde{G}\tilde{G} + X_{had}$

The mass limits are shown as horizontal bars, with the selection of channels based on 95% C.L. (theory uncertainties are not included). The plot also includes a selection of channels based on 95% C.L. (theory uncertainties are not included). The plot also includes a selection of channels based on 95% C.L. (theory uncertainties are not included).

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up** to the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM , respectively, unless indicated otherwise.

No direct discovery of
New Physics so far

Where is New Physics?

New physics is heavy, with new particles at a large mass scale

New physics may be light, but with small couplings

=> New physics is subtle:
small cross sections
novel signatures

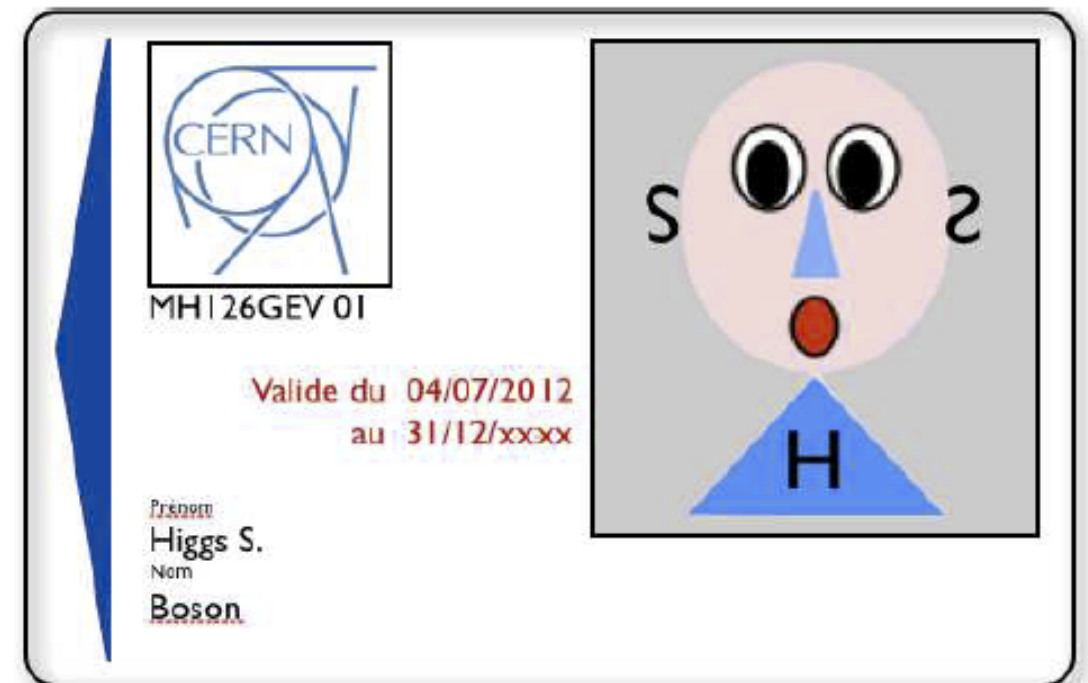
What we have

- ✦ Experimental reality: No Beyond the Standard Model Physics discovered so far!

Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate.“

- ✦ We have the SM-like Higgs boson

What can we learn from Higgs physics?



Higgs 10th Birthday!



Higgs 10th Birthday!



*The Role
of the
Higgs Boson
Mass*



The Role of the Higgs Boson Mass

♦ Present Accuracy:

[ATLAS,CMS]

$$M_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

♦ Why precision?

- * Self-consistency test of SM at quantum level
(e.g.: Higgs loop corrections to **W boson mass**)

- * $M_H \leftrightarrow$ **stability of the electroweak vacuum**

[Degrassi et al; Bednyakov et al]

- * Higgs mass uncertainty feeds back in uncertainty on **Higgs observables**

- * **Test parameter relations** in beyond-SM theories

$\Rightarrow$ **indirect constraint of viable BSM parameter space!**

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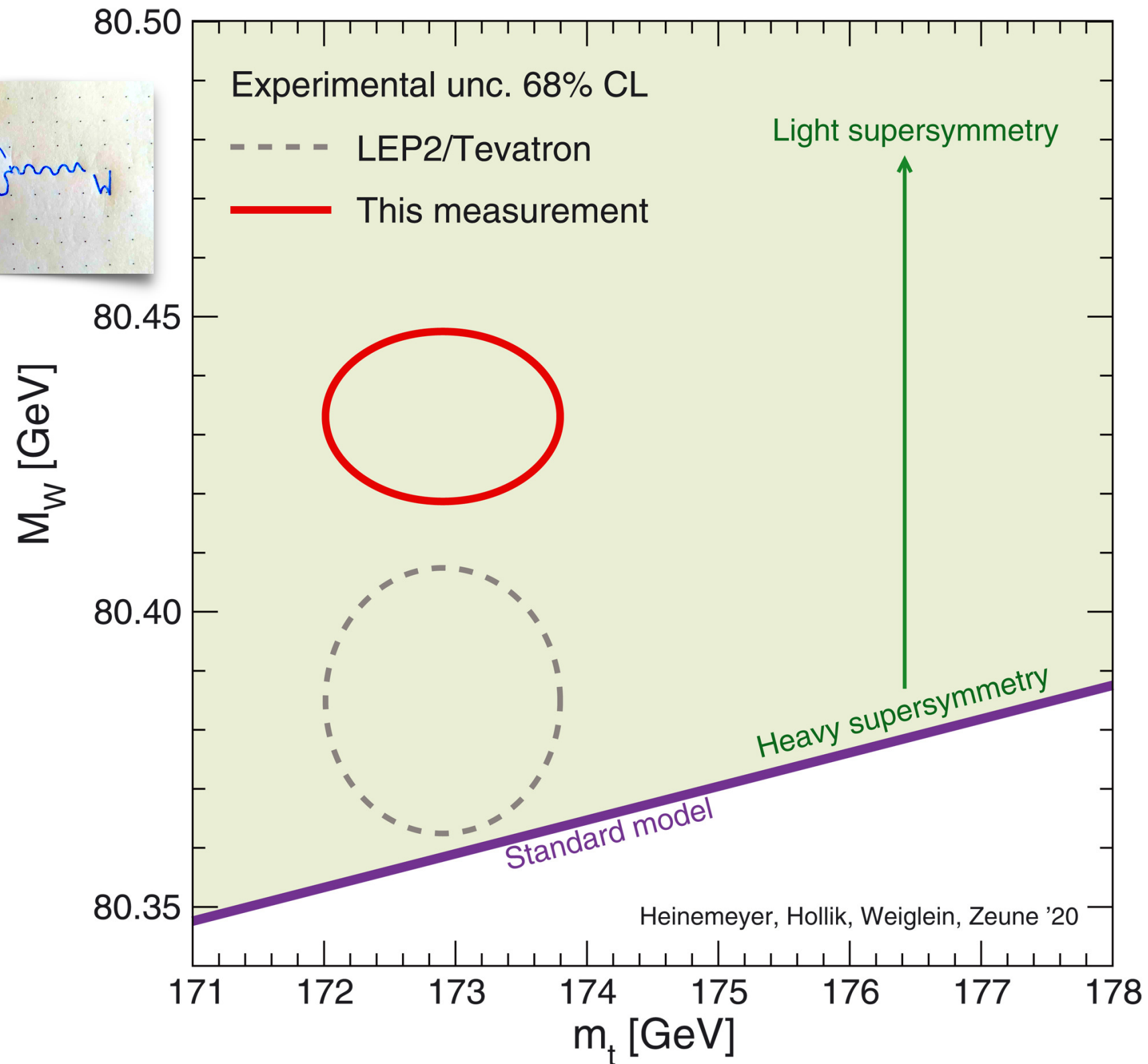
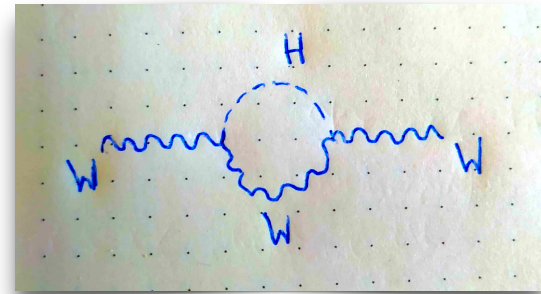
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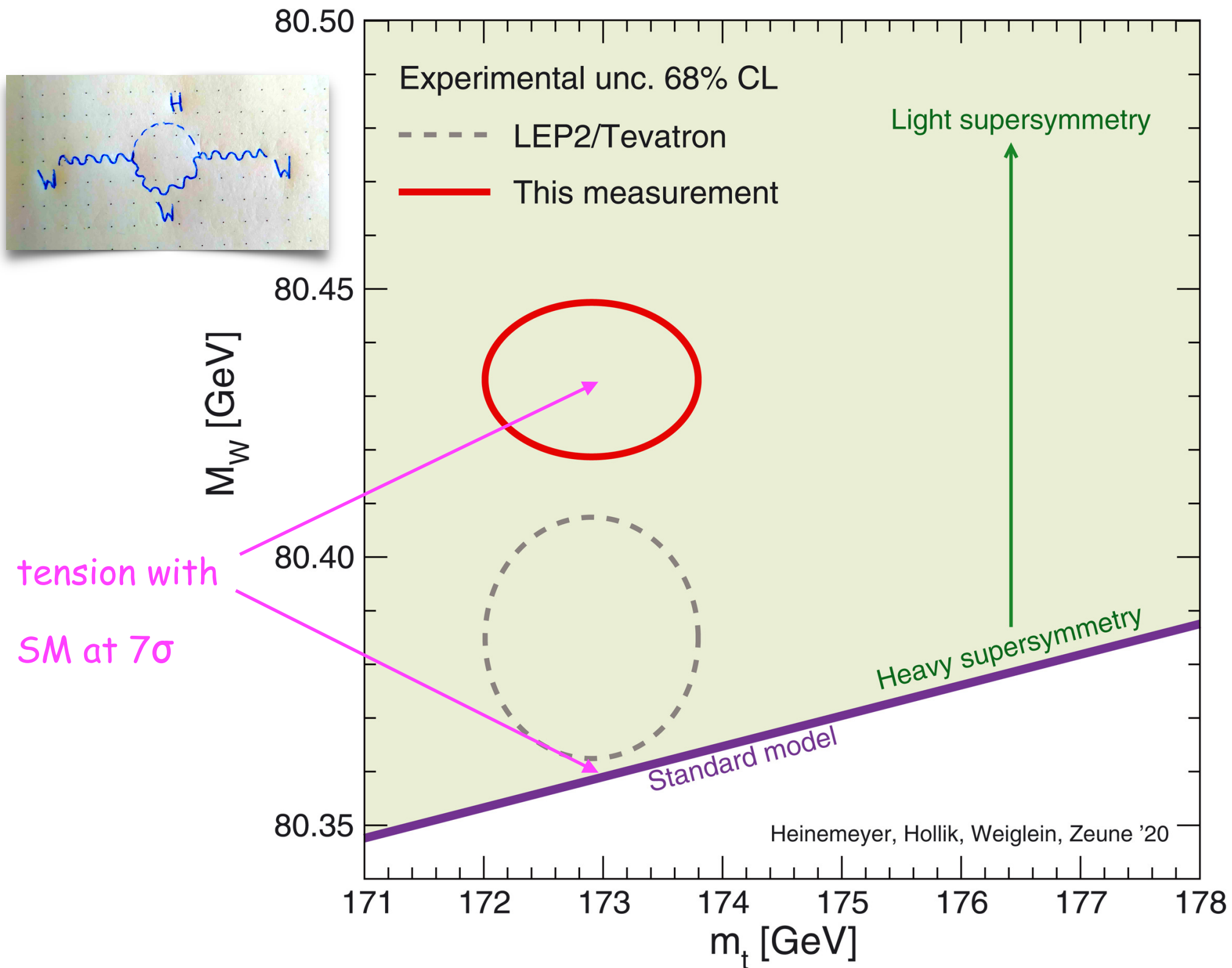
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The W Boson Mass

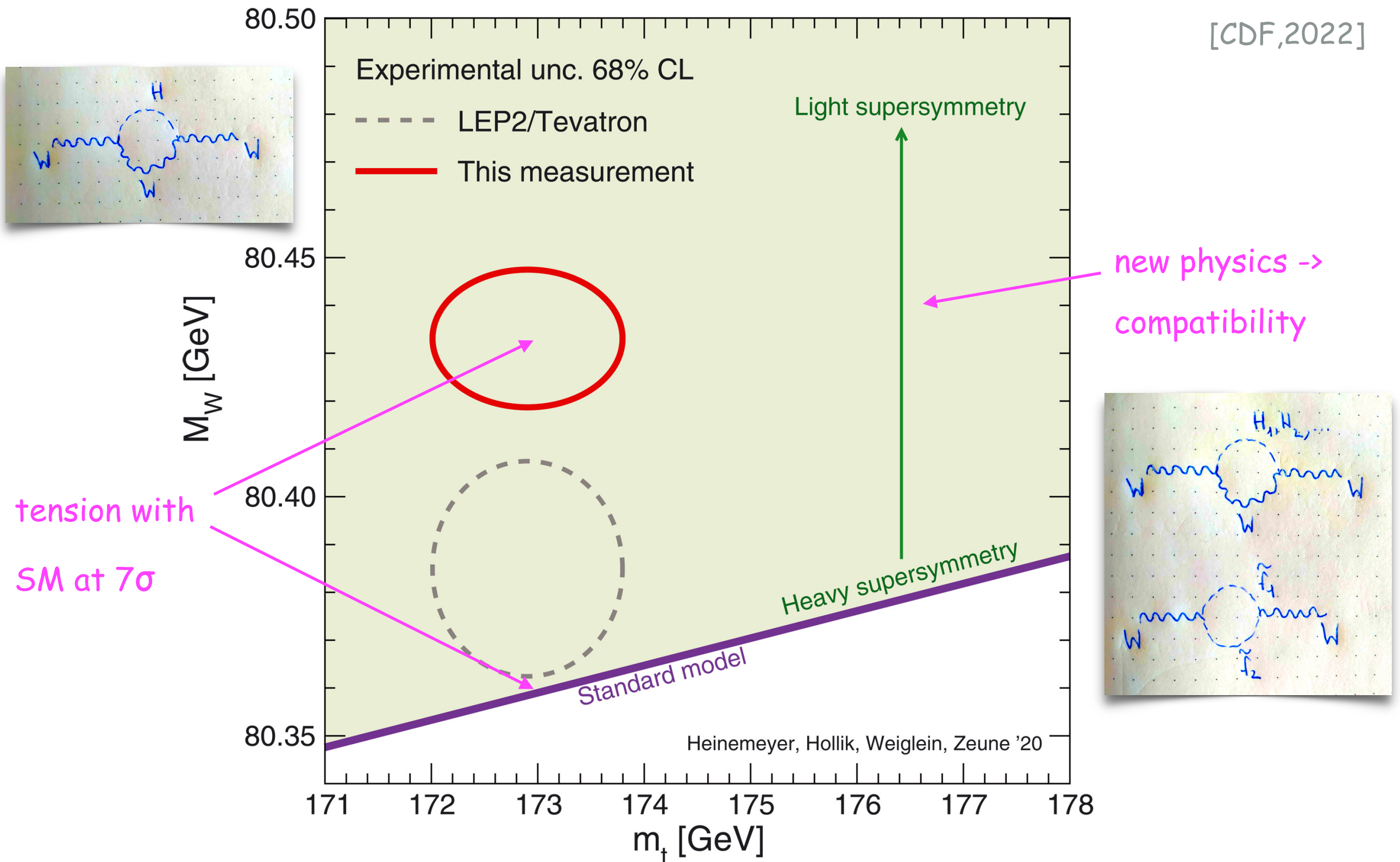


The W Boson Mass



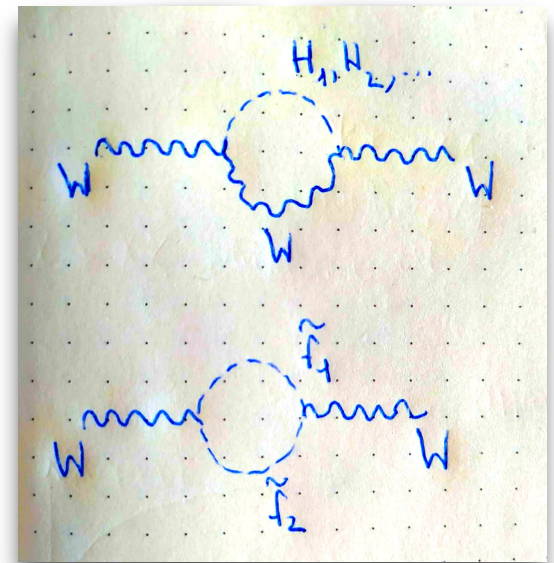
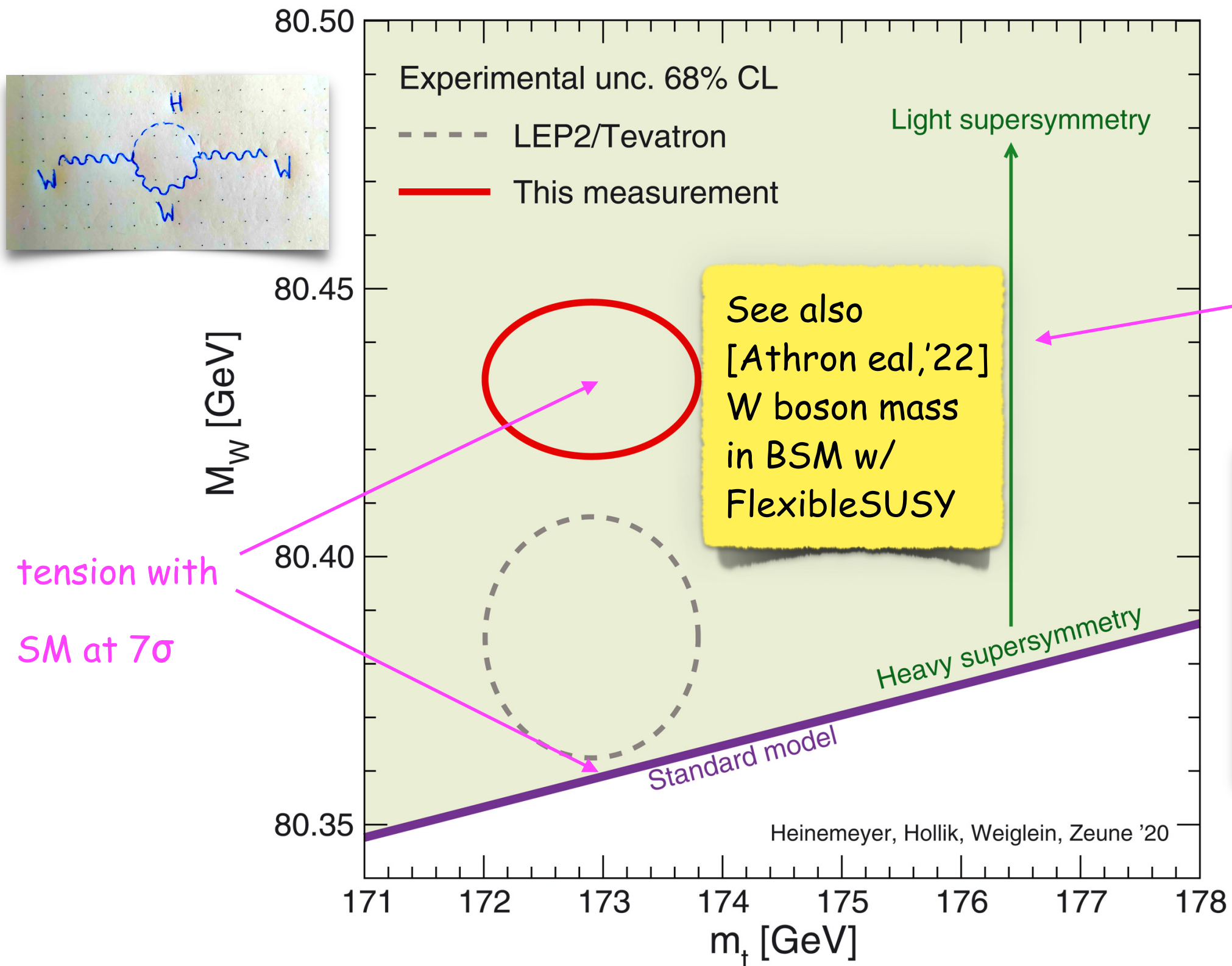
[CDF,2022]

The W Boson Mass



The W Boson Mass

[CDF,2022]



Higgs Mass in New Physics Extensions - Supersymmetry

Higgs boson mass:

- * SM: fundamental parameter, not predicted by the theory
- * Supersymmetry: calculable from input parameters;
quantum corrections Δm^2_H are important!

$$\text{MSSM: } m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_H^2 \leftarrow (85 \text{ GeV})^2 !$$

$$\text{NMSSM: } m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_H^2 \leftarrow (55 \text{ GeV})^2$$

NMSSM:

- * less important loop corrections needed compared to the MSSM
- * solves little hierarchy problem

[Kim, Nilles, '84]

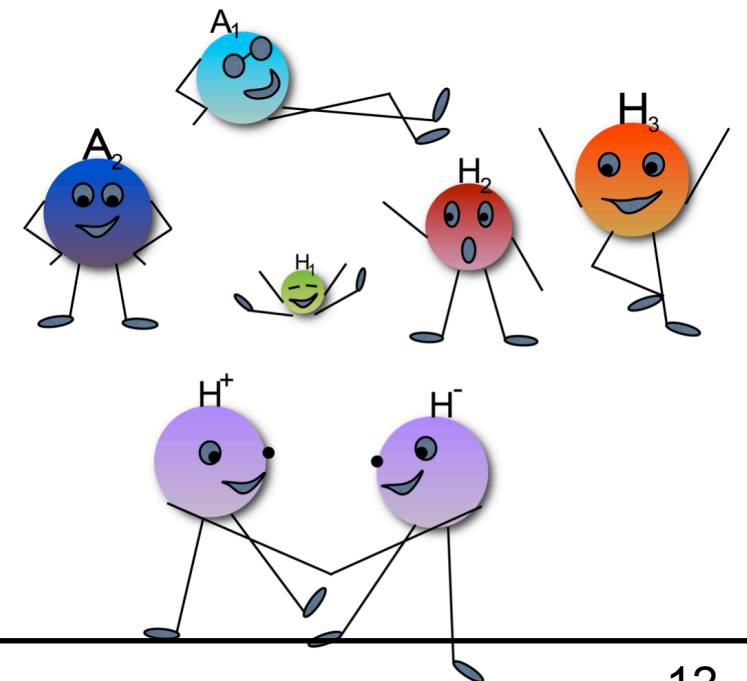
SUSY Higgs Masses

- ♦ **Supersymmetry:** requires at least 2 complex Higgs doublets
- ♦ **Minimal Supersymmetric extension (MSSM):** 2 complex Higgs doublets

5 Higgs bosons: h, H, A, H^+, H^-
4 neutralinos: $\tilde{\chi}_i^0$ ($i = 1, \dots, 4$)

- ♦ **Next-to-MSSM (NMSSM):** 2 complex Higgs doublets plus complex singlet field
- ♦ **Enlarged Higgs and neutralino sector:**

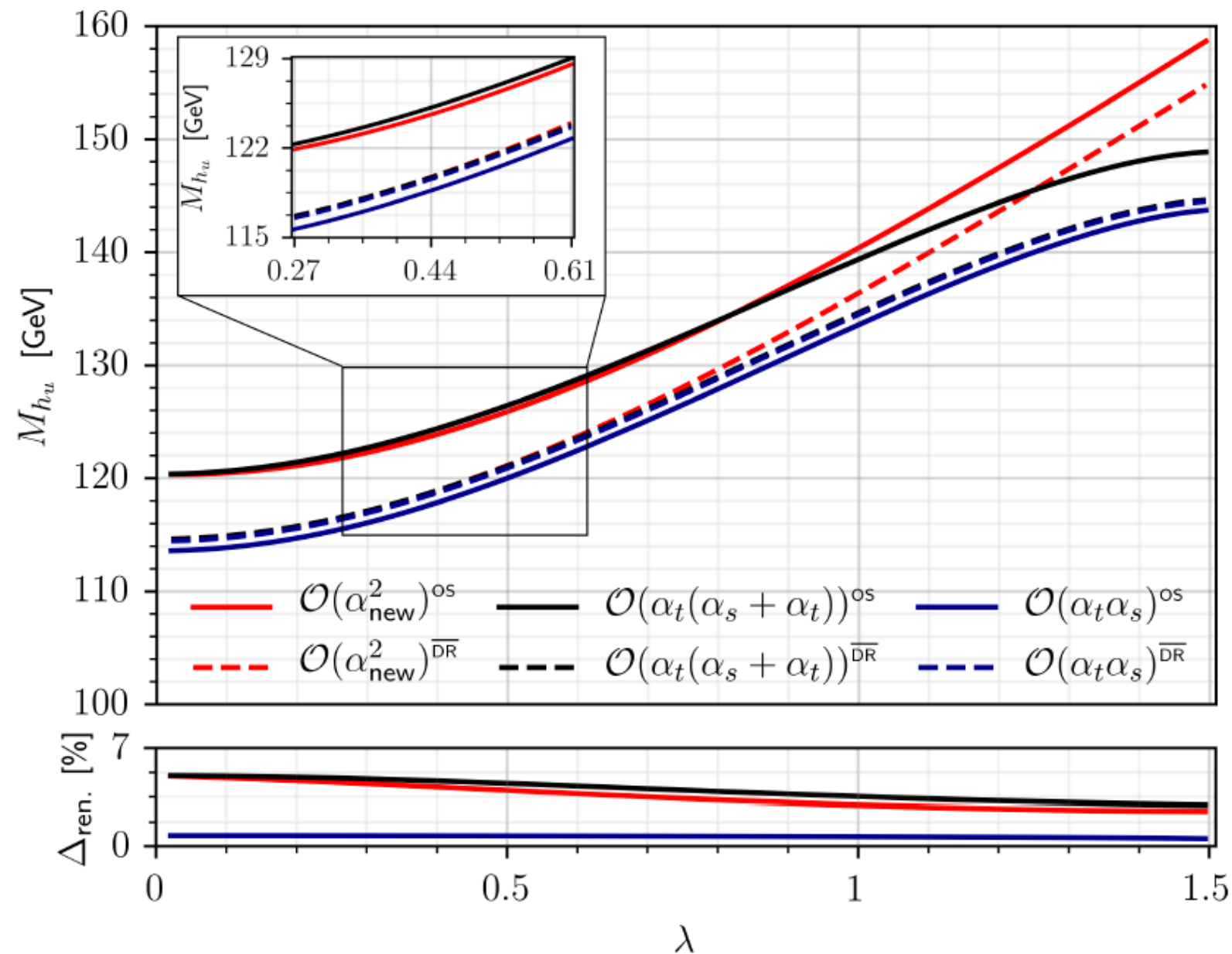
7 Higgs bosons: $H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos: $\tilde{\chi}_i^0$ ($i = 1, \dots, 5$)



$\mathcal{O}(\alpha_{\text{new}}^2) \equiv \mathcal{O}((\alpha_\lambda + \alpha_\kappa + \alpha_\tau)^2)$ Mass Corrections in the CP-Violating NMSSM

Corrections to h_u -like Higgs ($\triangleq$ SM-like Higgs)

[Dao, Gabelmann, MM, Rzehak, '21]



Remaining theoretical error: $\mathcal{O}(\text{few}\%)$

A lush garden scene featuring a pond covered in green lily pads. A small wooden bridge with a railing crosses the pond on the left. The background is filled with dense green foliage and tall trees, with sunlight filtering through the leaves. A yellow text box is overlaid in the upper right corner.

*Higgs Pair
Production*

The Higgs Self-Coupling

♦ Higgs Discovery $\leadsto$ New Era of Particle Physics: structurally completes the SM

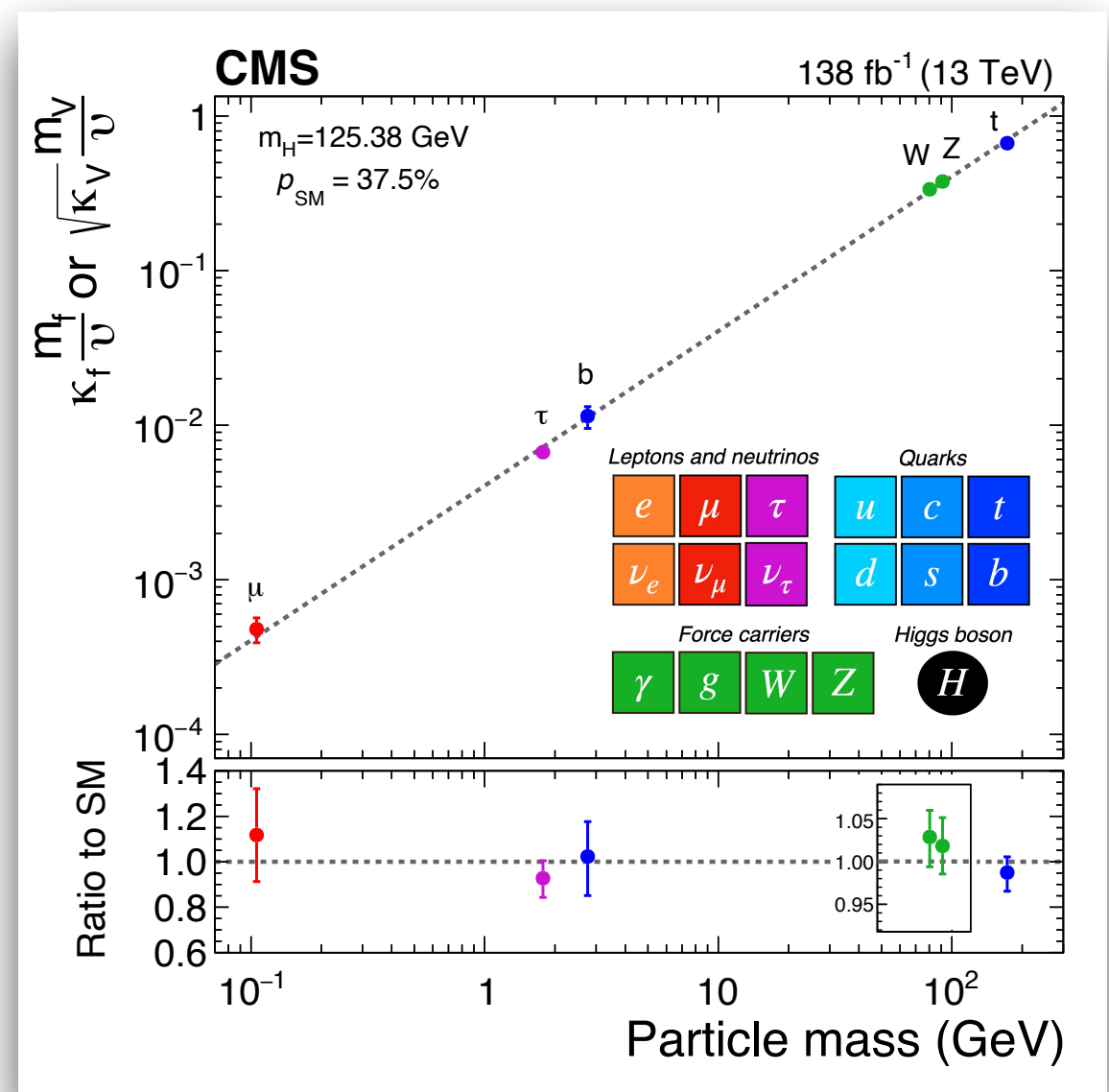
- self-consistent framework to describe physics up to cosmologically relevant scales
- extended Higgs sectors: answers to generation of baryon asymmetry, nature of DM

♦ SM Higgs couplings:

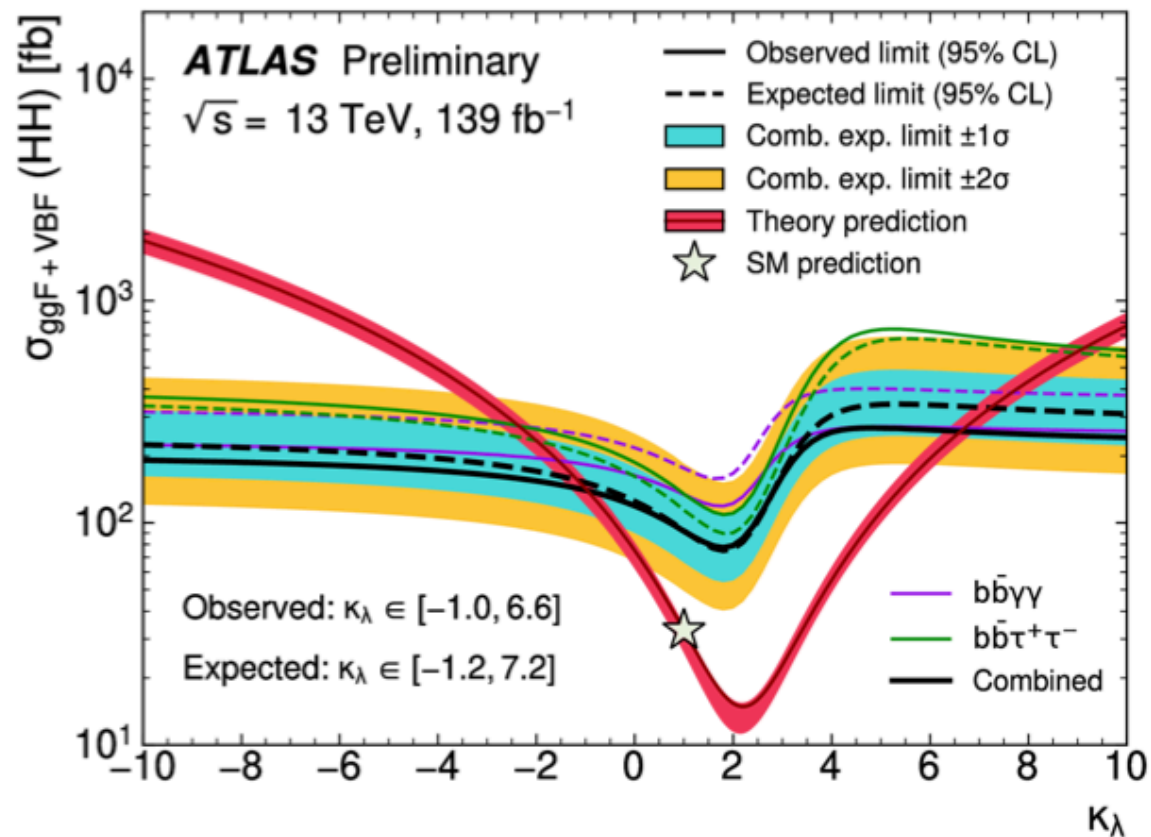
- proportional to masses/masses² of the corresponding SM particle
 $g_{hff} \sim m_f/v$, $g_{hVV} \sim m_V^2/v^2$

♦ Higgs self-coupling strength:

- still unknown



Experimental Results - Limits on Trilinear Higgs Self-Coupling

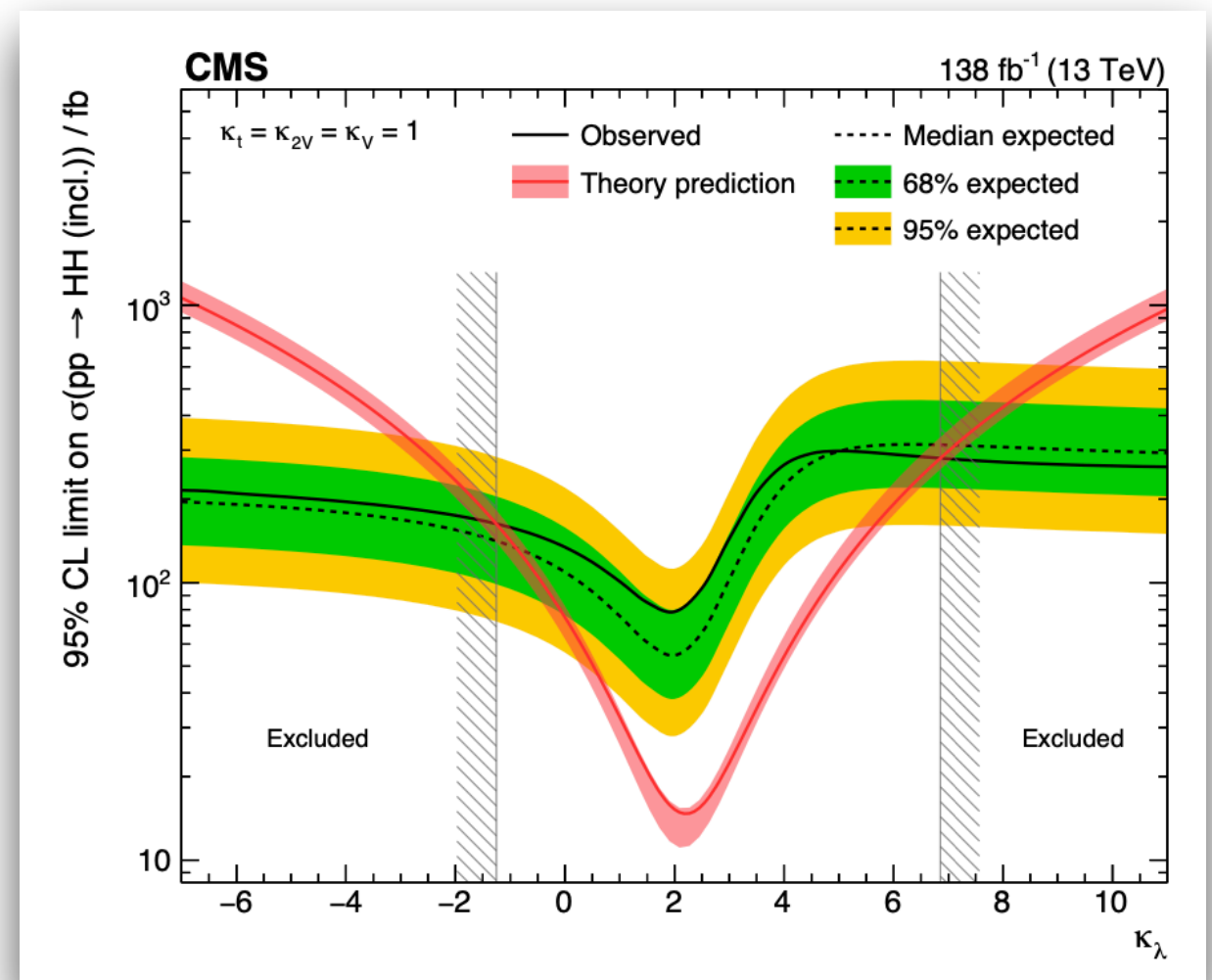


[Rui Zhang, ATLAS, HH Workshop'22]

Observed: $\kappa_\lambda \in [-1.0, 6.6]$

Expected: $\kappa_\lambda \in [-1.2, 7.2]$

[CMS,2207.00043]



$$-1.24 \leq \kappa_\lambda \leq 6.49$$

Ultimate Test of the Higgs Mechanism

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda} v$

trilinear Higgs self-coupling : $\lambda_{HHH} = 3M_H^2/M_Z^2$

quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3M_H^2/M_Z^4$

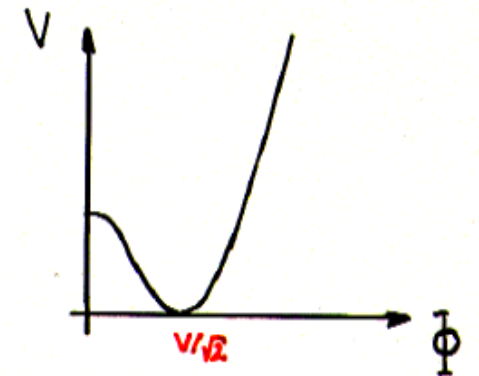
(units $\lambda_0 = 33.8 \text{ GeV}/\lambda^2$)



$$V(\Phi) = \lambda (\Phi^\dagger \Phi - \frac{v^2}{2})^2$$

$v = 246 \text{ GeV}$

$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \sim$



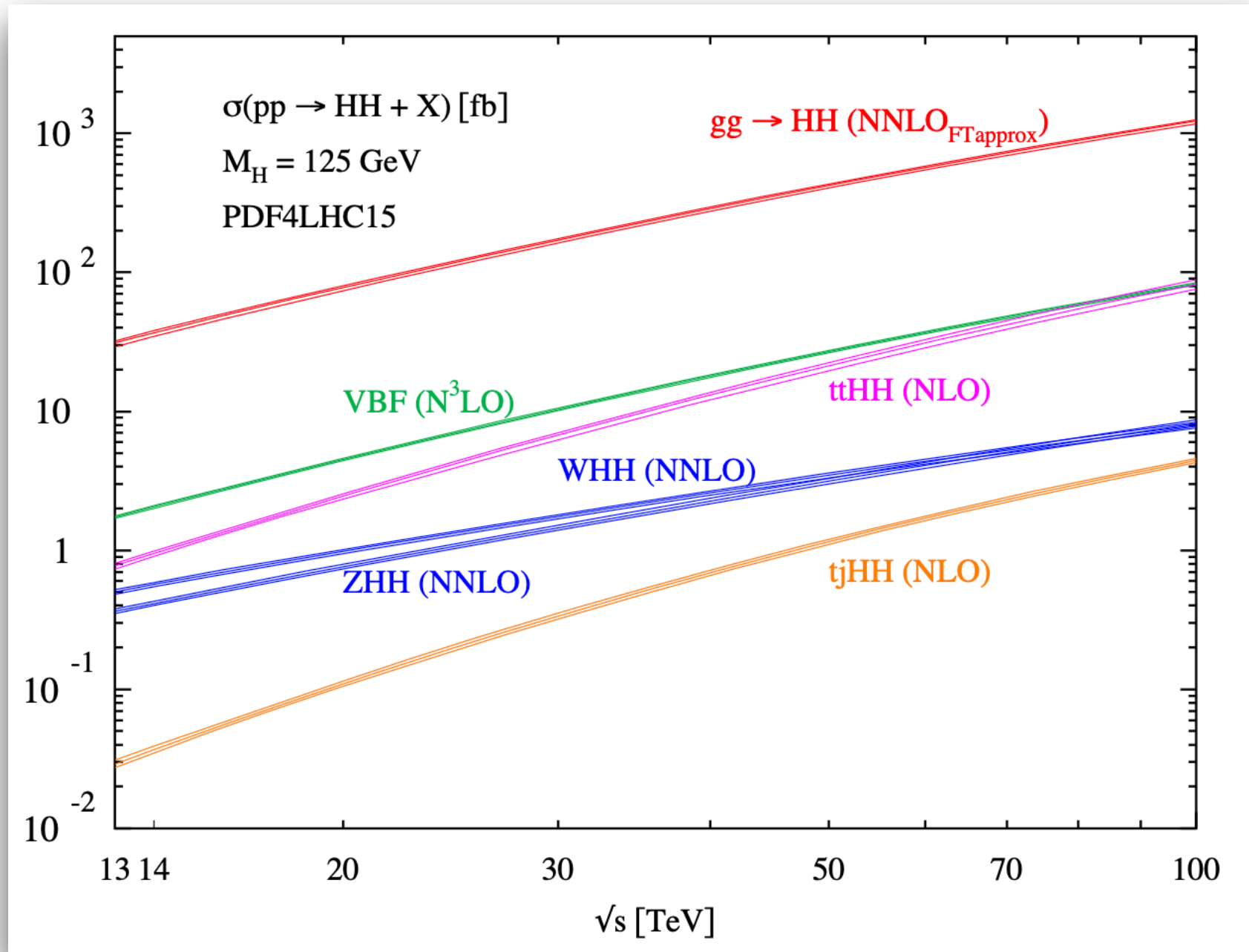
(a) trilinear coupling: via Higgs pair production

(b) quadrilinear coupling: via triple Higgs production

measurement of the Higgs self-couplings
and
reconstruction of the Higgs potential } $\Rightarrow$ establish the scalar
sector of the **Higgs mechanism**
experimentally

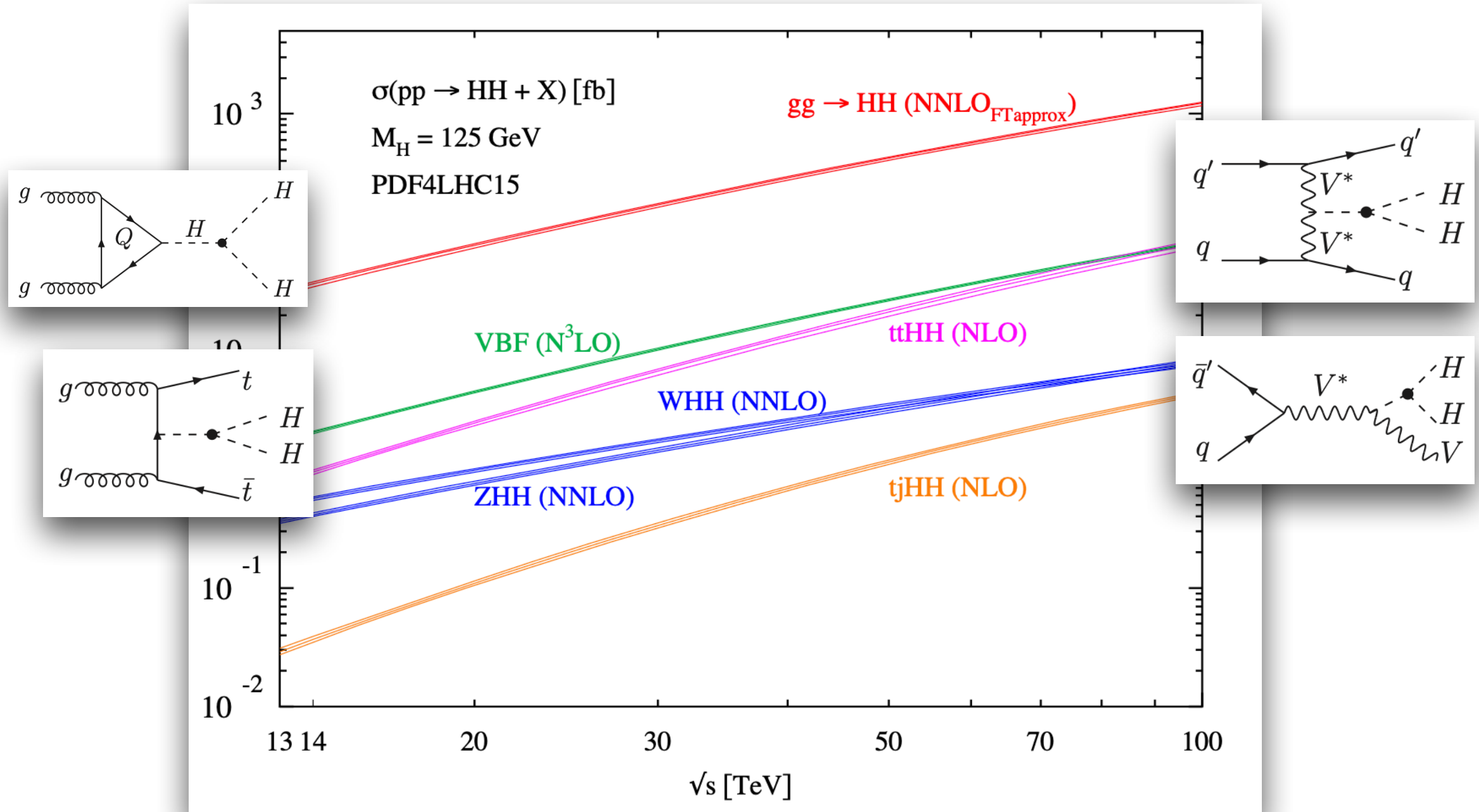
Double Higgs Production Processes

[HH, White paper]



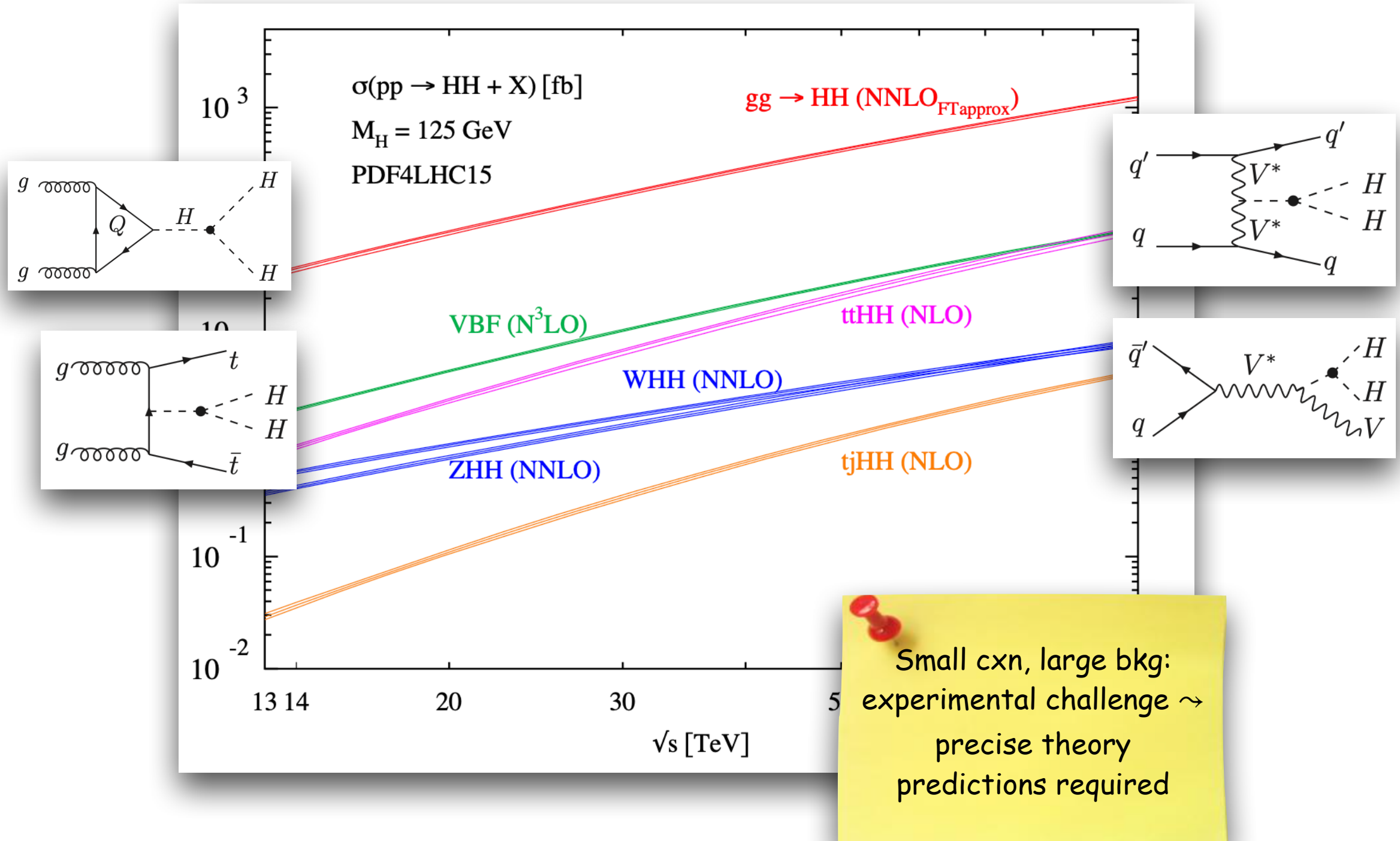
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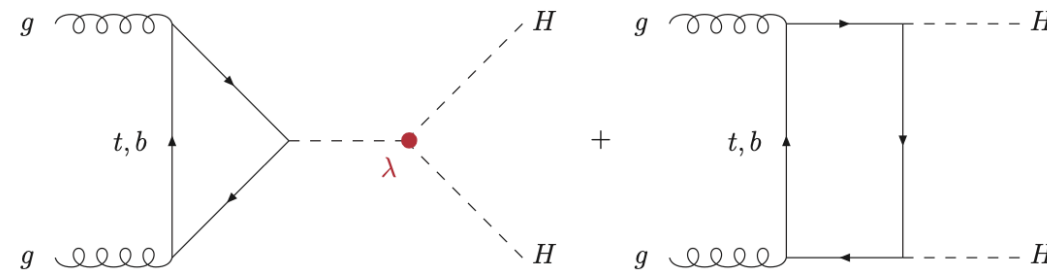
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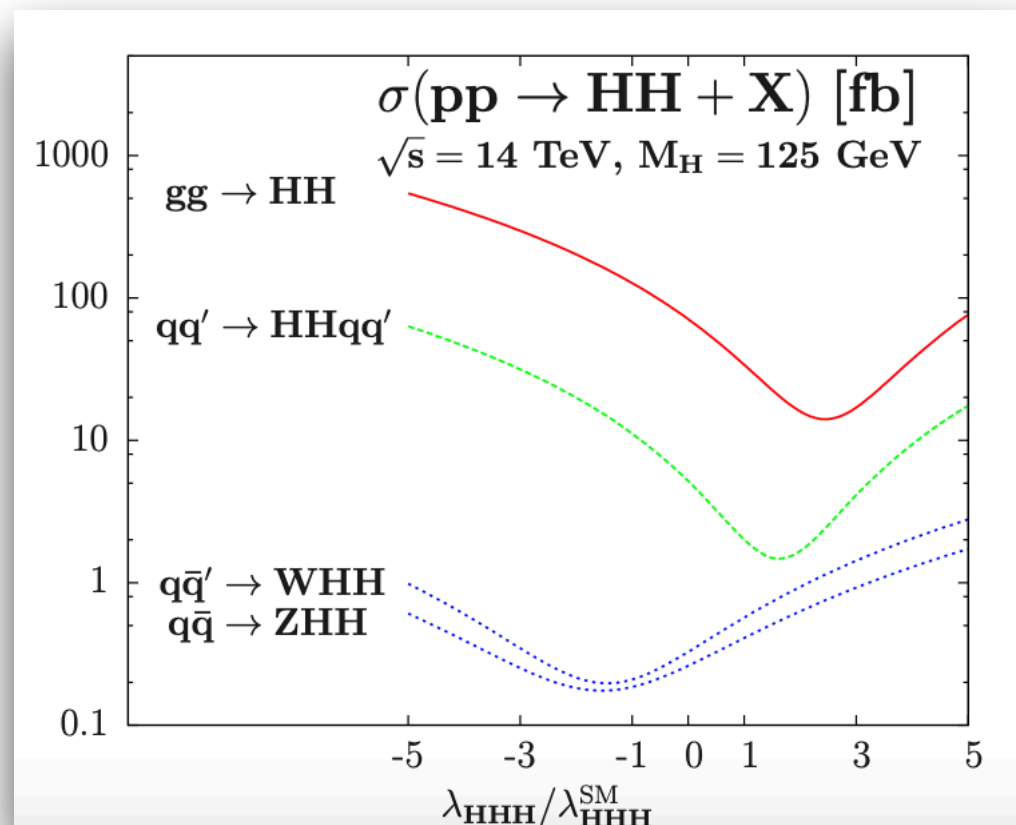


Higgs Pair Production through Gluon Fusion

- ♦ Loop mediated at leading order - SM: third generation dominant



- ♦ Sensitivity to λ :



[Baglio,Djouadi,Gröber,MM,Quévilion,Spira]

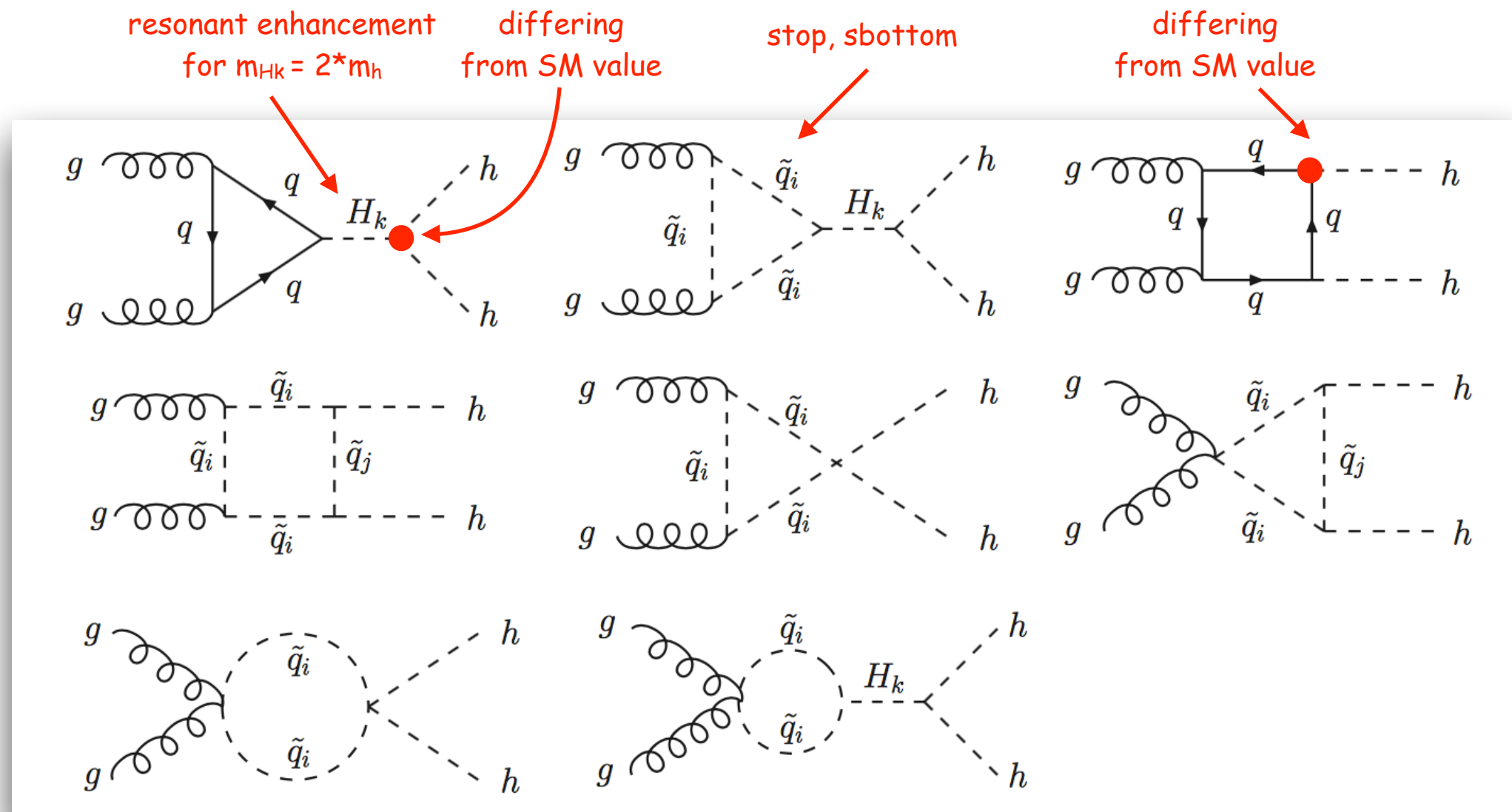
$$gg \rightarrow HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

New Physics Effects in Higgs Pair Production

- ♦ Cross section: - different trilinear couplings - different Yukawa couplings
- novel particles in the loops - resonant enhancement - novel couplings

- ♦ Example NMSSM:

[taken from Dao,MM,Streicher,Walz,'13]



*with/without SUSY
with/without singlet*

2HDM

*2 Higgs doublets
without/with CP violation*

Overview of Higgs Pair production possibilities
including theoretical and experimental
constraints in archetypical BSM Higgs sectors
including different symmetries

NMSSM

C2HDM

Provide benchmark points / lines / planes
for experiment

*singlet extensions
with/without SUSY*

N2HDM

*without/with CP violation
with/without singlet*



2 Higgs doublets

CP-violating

Singlet extension

Supersymmetry

h, H, A, H^+, H^-

H_1, H_2, H_3, H^+, H^-

H_1, H_2, H_3, H^+, H^-

$H_1, H_2, H_3, A, H^+, H^-$

SFOEWPT, DM,
plus charged Higgs

plus CP violation
baryogenesis

rich pheno, DM

a lot (DM, CPviol,
Hierarchy, ...)

Resonant Enhancement

Higgs-to-Higgs Cascade decays

♦ Following results based on:

Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, MMM, Santos, „Benchmarking Di-Higgs Production in Extended Higgs Sectors“, JHEP 09 (2022) 011



2 Higgs doublets

CP-violating

Singlet extension

Supersymmetry

h, H, A, H^+, H^-

H_1, H_2, H_3, H^+, H^-

H_1, H_2, H_3, H^+, H^-

$H_1, H_2, H_3, A, H^+, H^-$

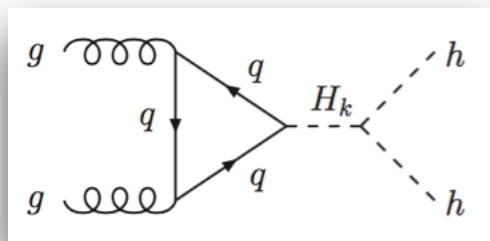
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Parameter Point Samples

♦ Scans in parameter spaces of the models w/ ScannerS:

take into account all relevant theoretical and experimental constraints

+ limits from di-Higgs searches

4b: [ATLAS-CONF-Note-2021-030, ATLAS,1804.06174], $WW\gamma\gamma$: [ATLAS,1807.08567]

$bb\gamma\gamma$: [ATLAS,1807.04873]; $bbWW$: [ATLAS,1811.04671], $bbZZ$: [CMS,2006.06391]

$bb\tau\tau$: [ATLAS,1808.00336;ATLAS-CONF-Note-2021-035;ATLAS,2007.14811], $4W$: [ATLAS,1811.11028]

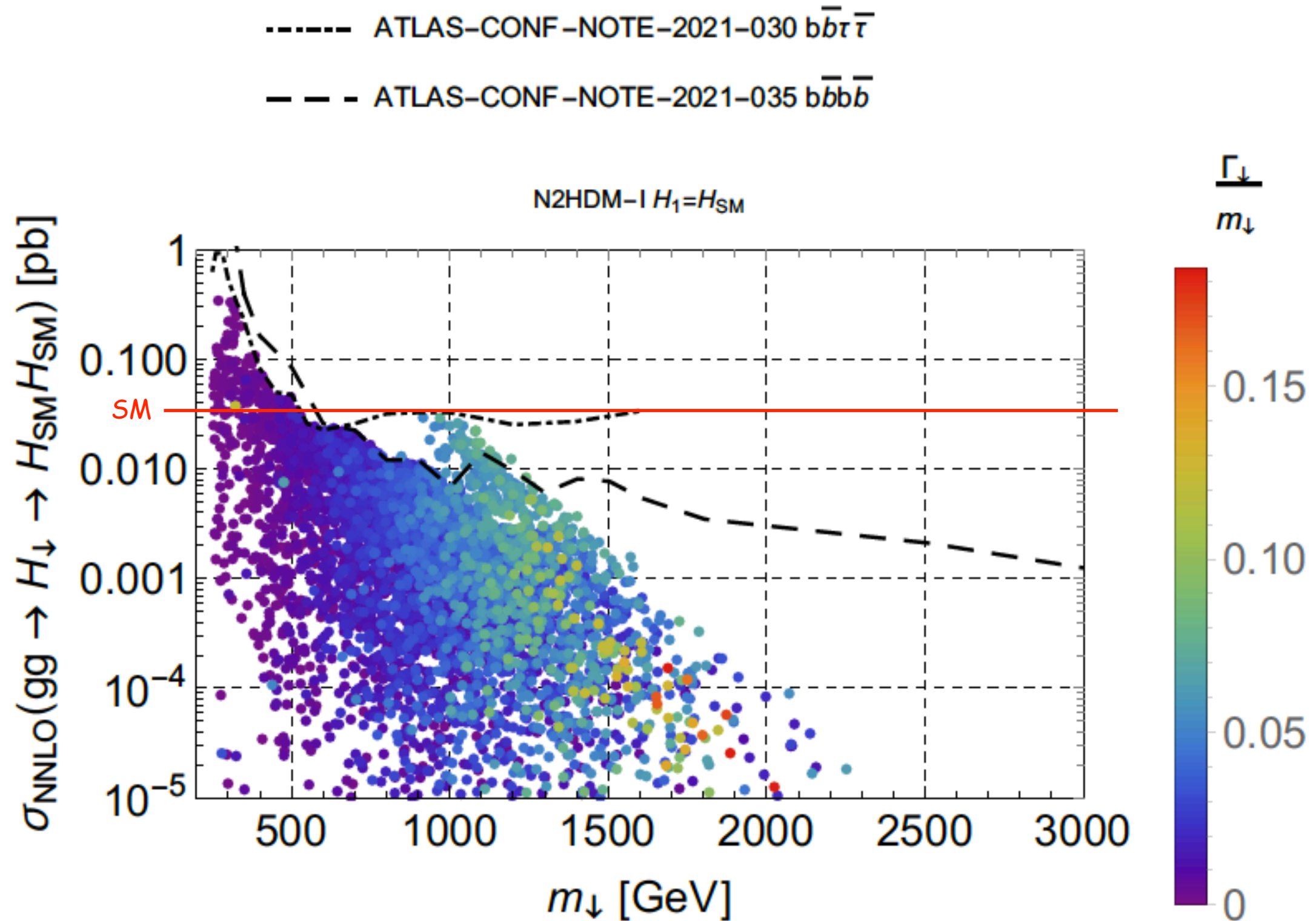
♦ Computation of Higgs pair production cxn:

HPAIR [Spira] for C2HDM [Gröber,MM,Spira,'17], NMSSM [Dao,MM,Streicher,Walz,'13],
2HDM [MM], N2HDM [MM]: Born-improved HTL cxn; K-factors 1.4-2.1

♦ Scatter plots:

LO cxn times factor 2 (to approx. account for NLO QCD), benchmark points include
NLO QCD calculated w/ HPAIR

Impact of Resonant Searches - Ex. N2HDM H1 SM-like



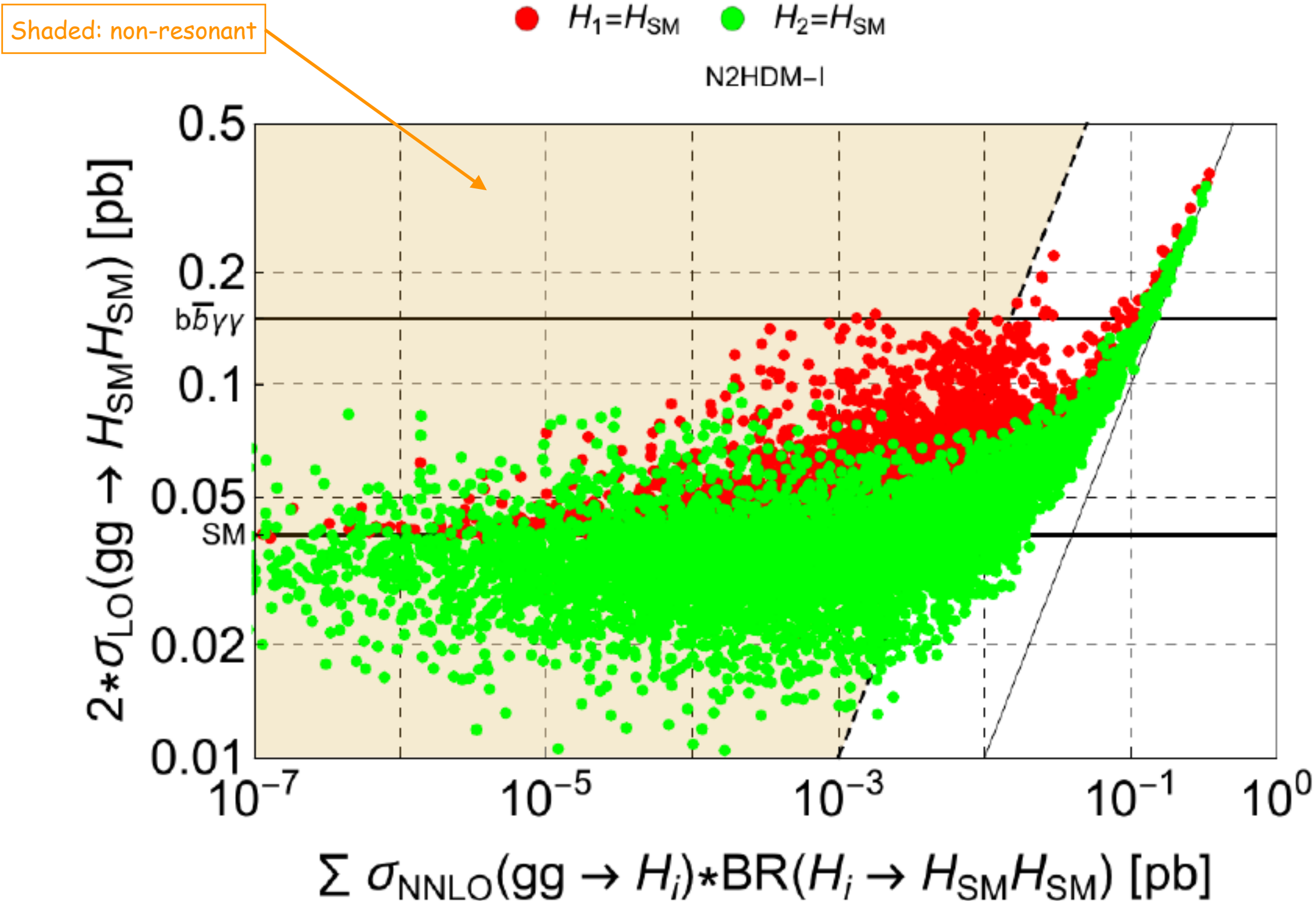
Impact of Non-resonant Searches

♦ Our definition:

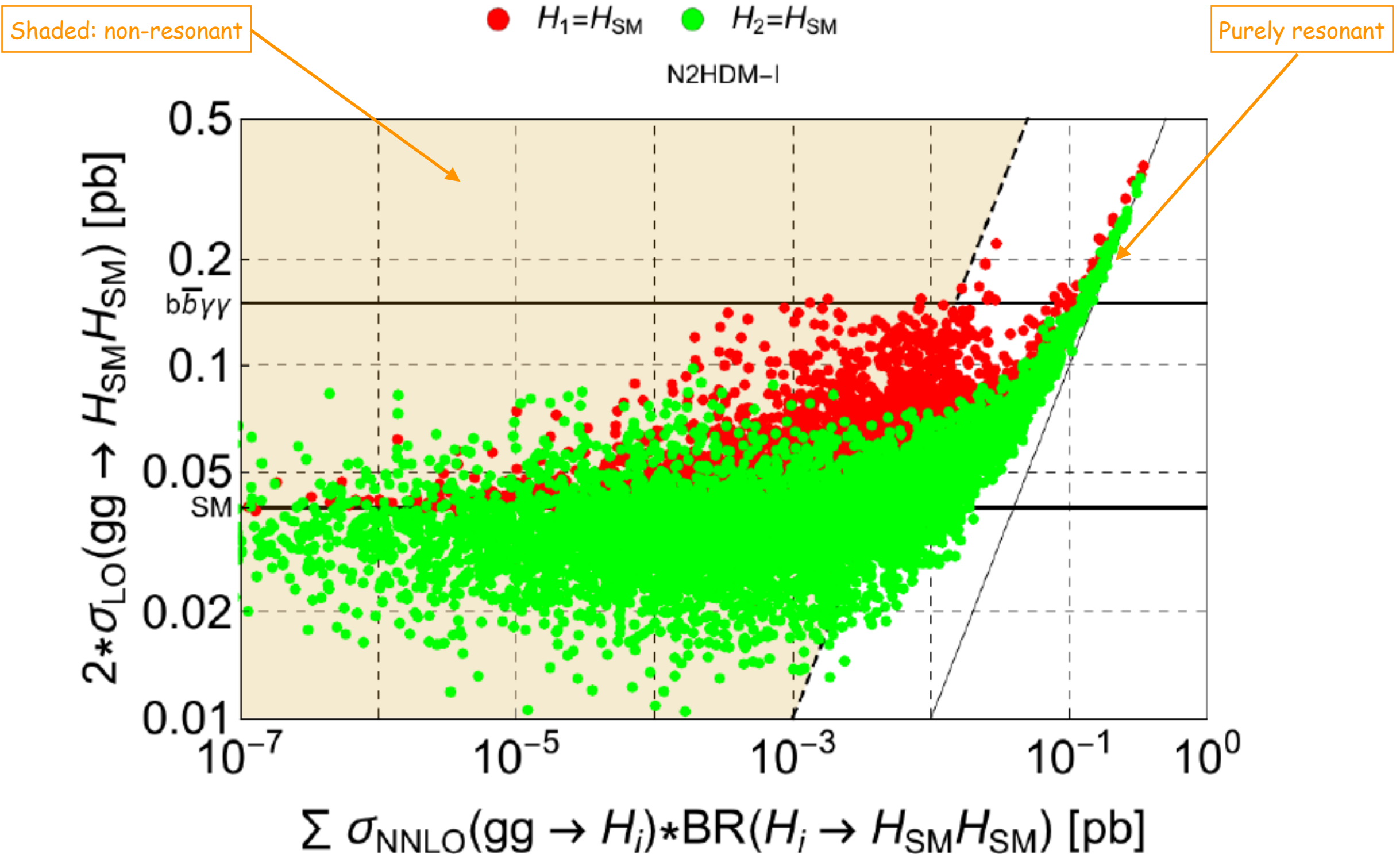
take into account all relevant theoretical and experimental constraints
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$\sigma_{\text{res}}^{\text{HH}} < 0.1 * \sigma_{\text{full}} \rightarrow \text{non-resonant production}$

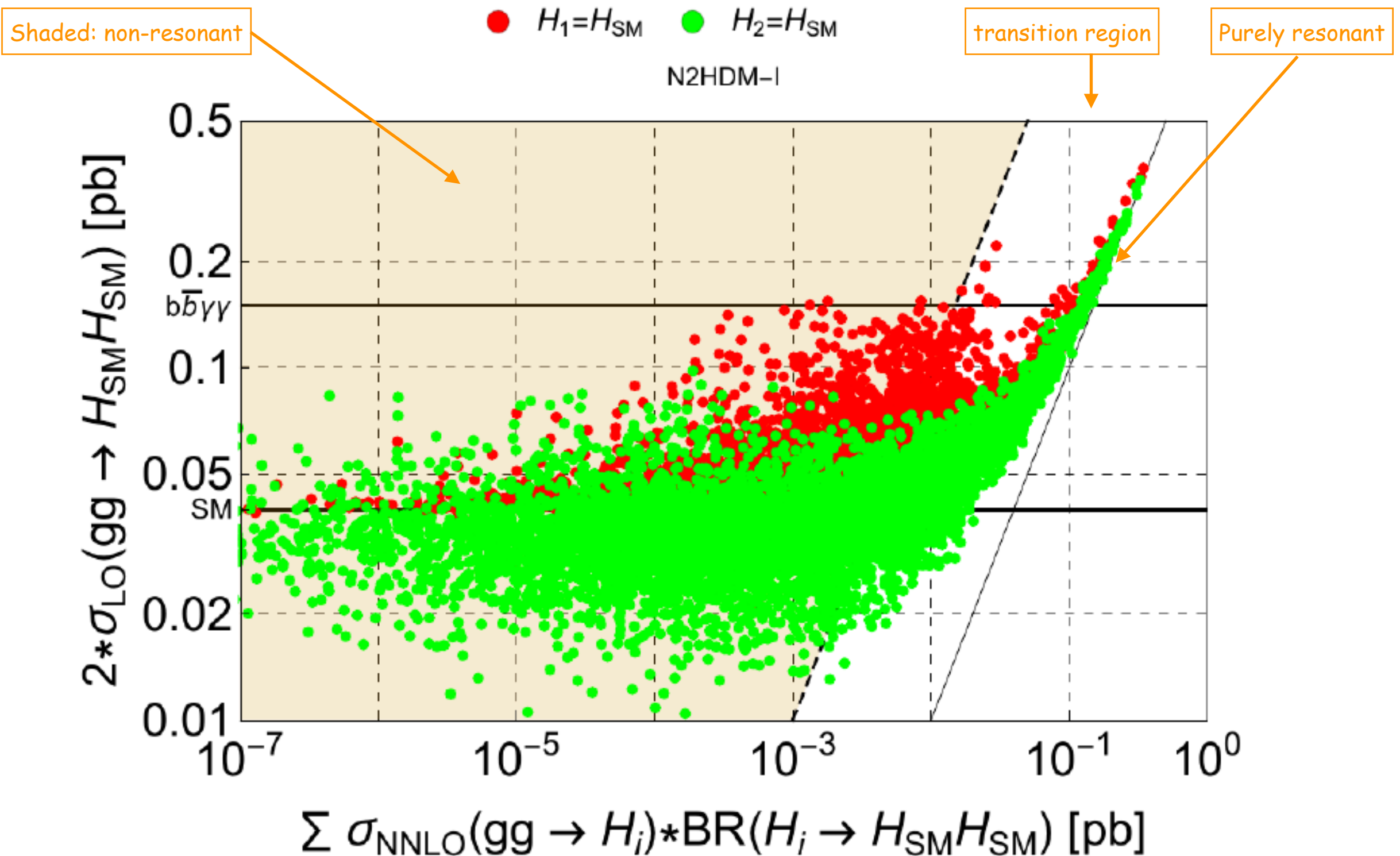
Impact of Non-resonant Searches - Example N2HDM



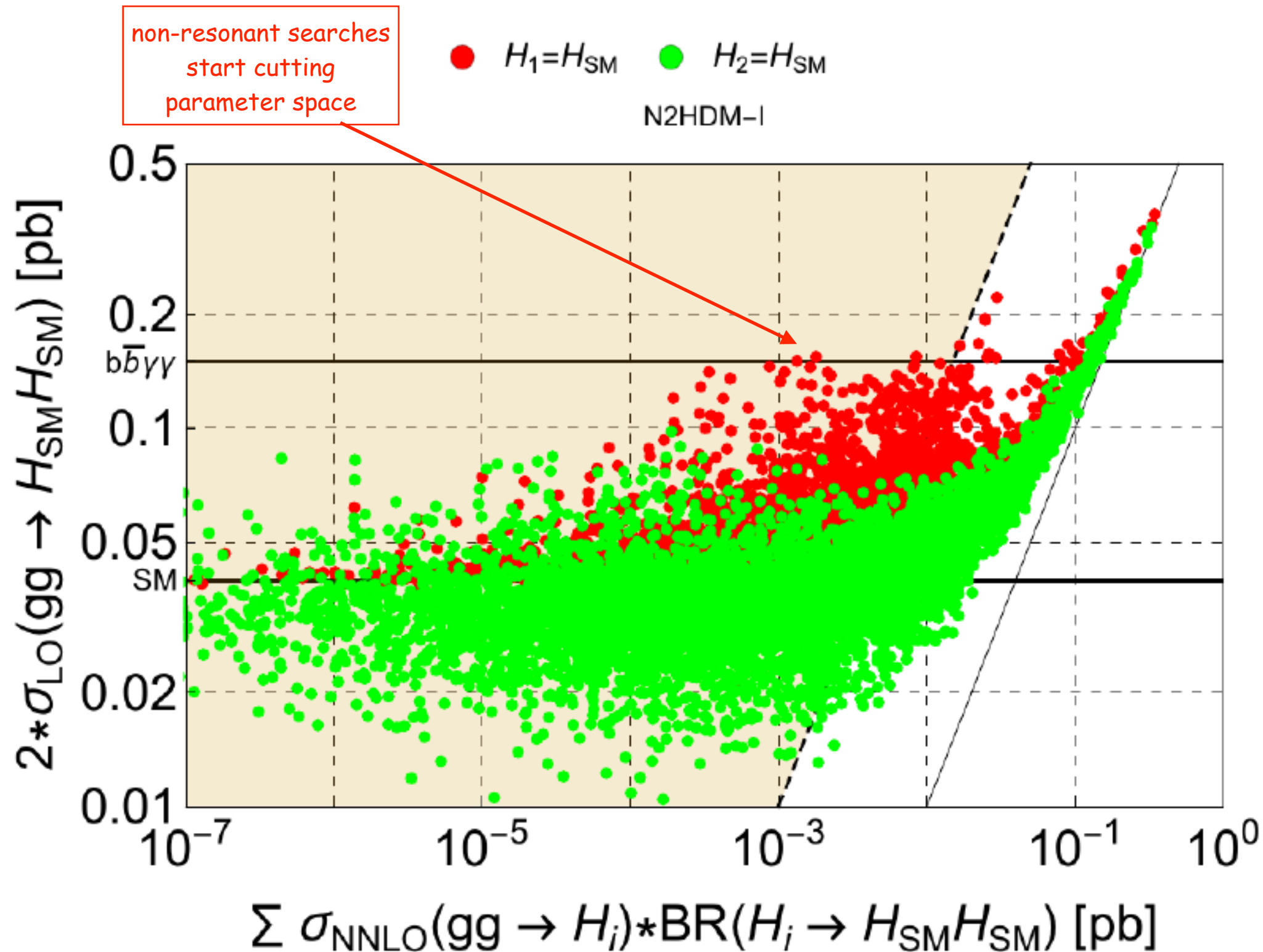
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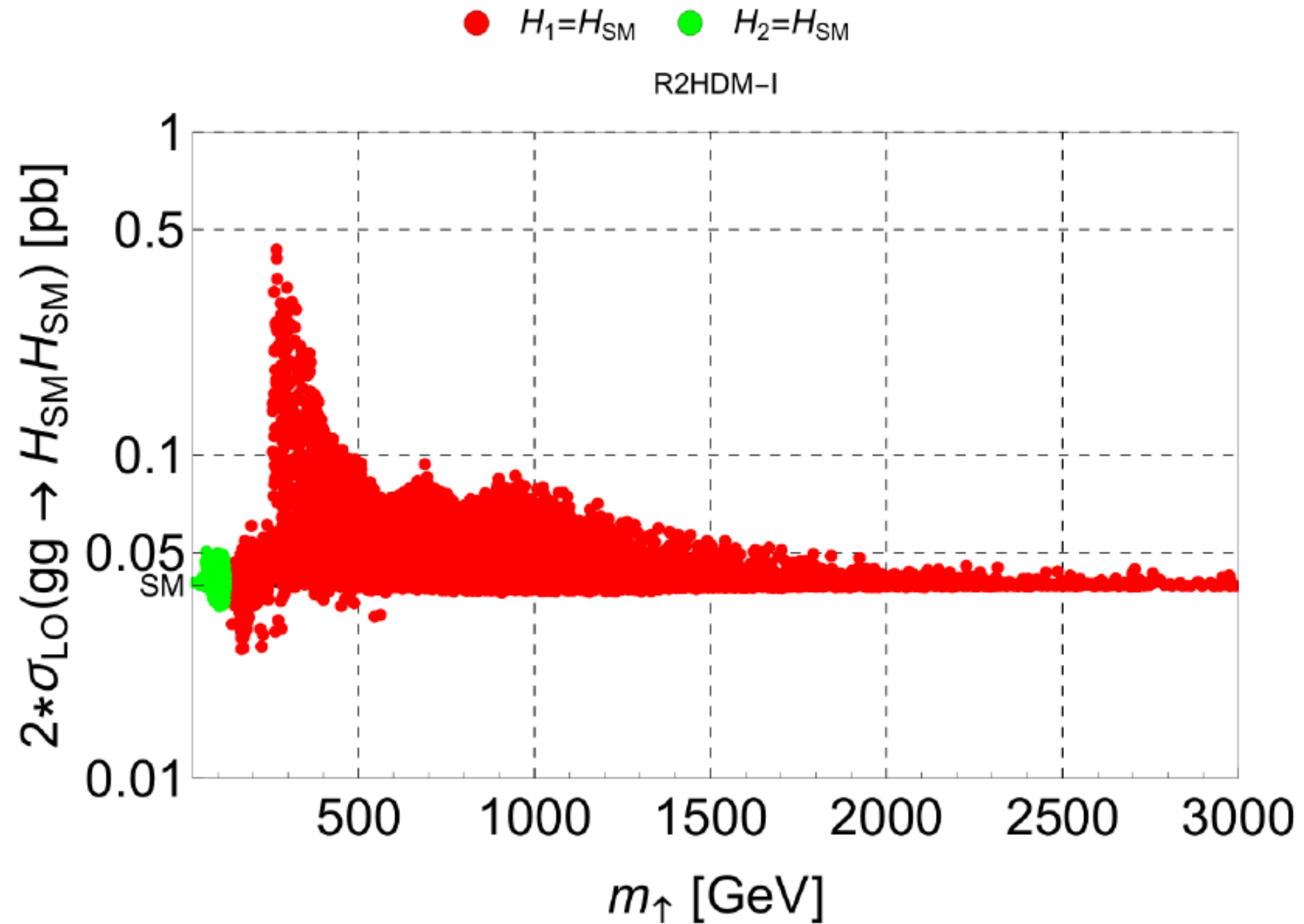
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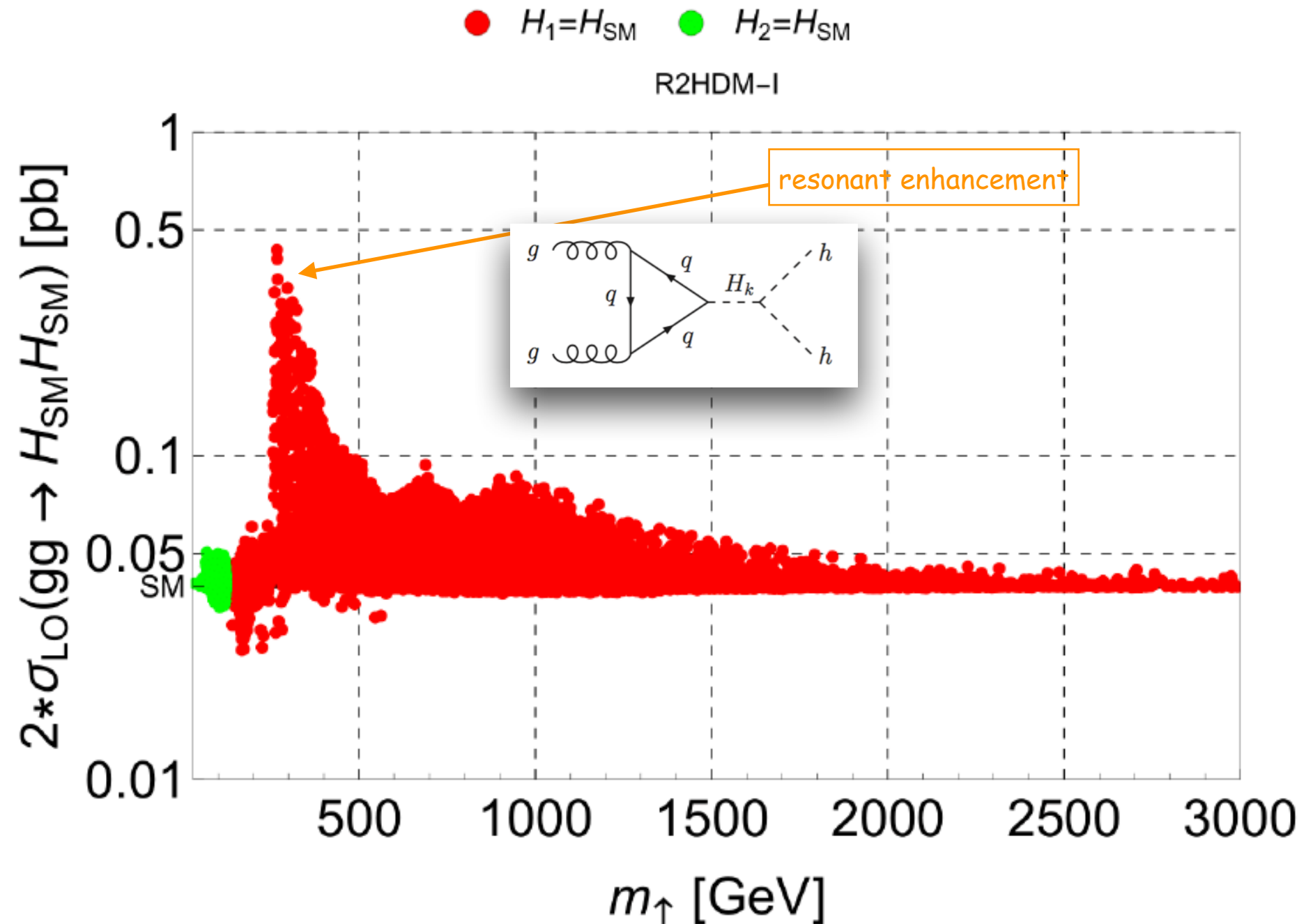
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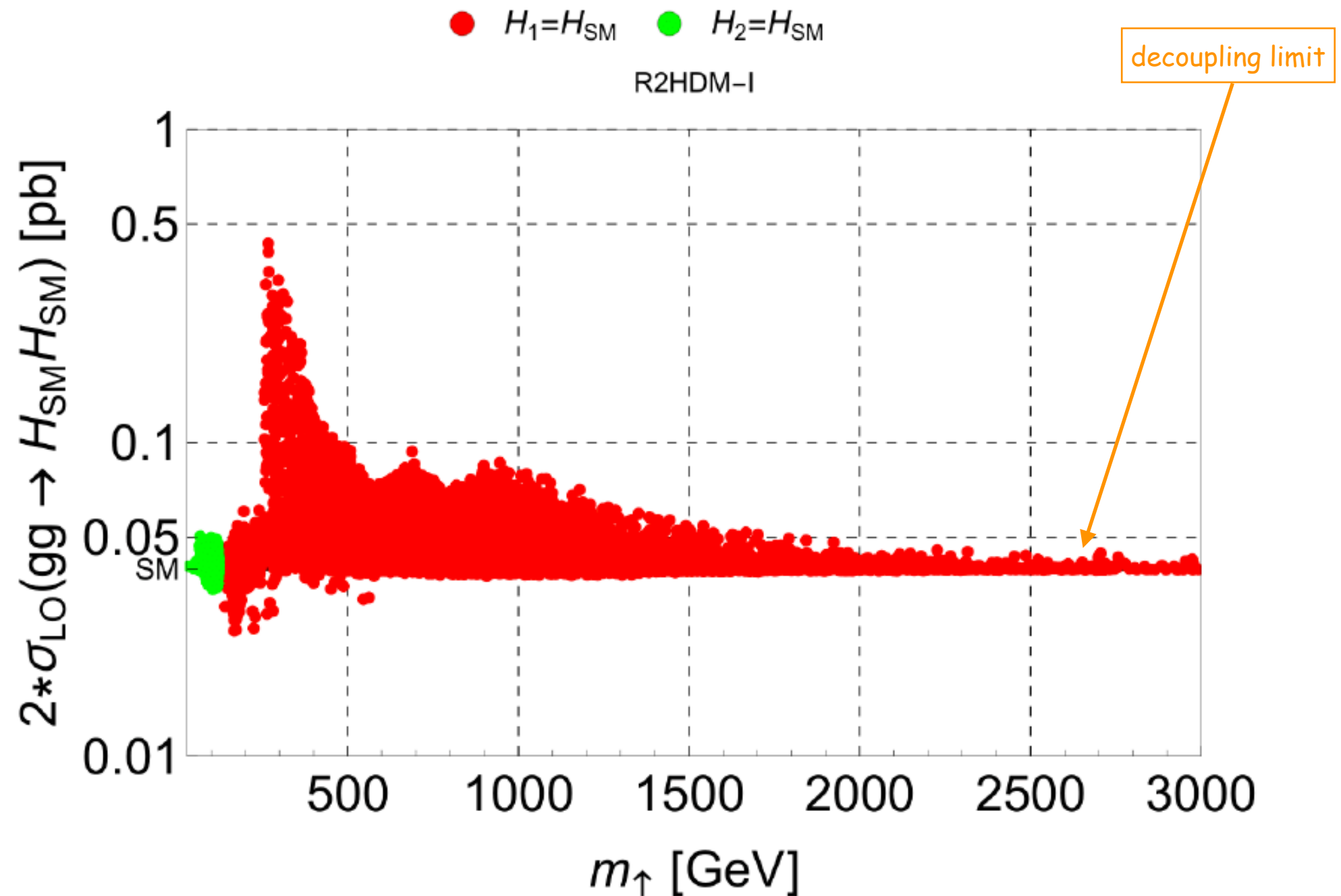
Parameter dependence - Ex. R2HDM T1



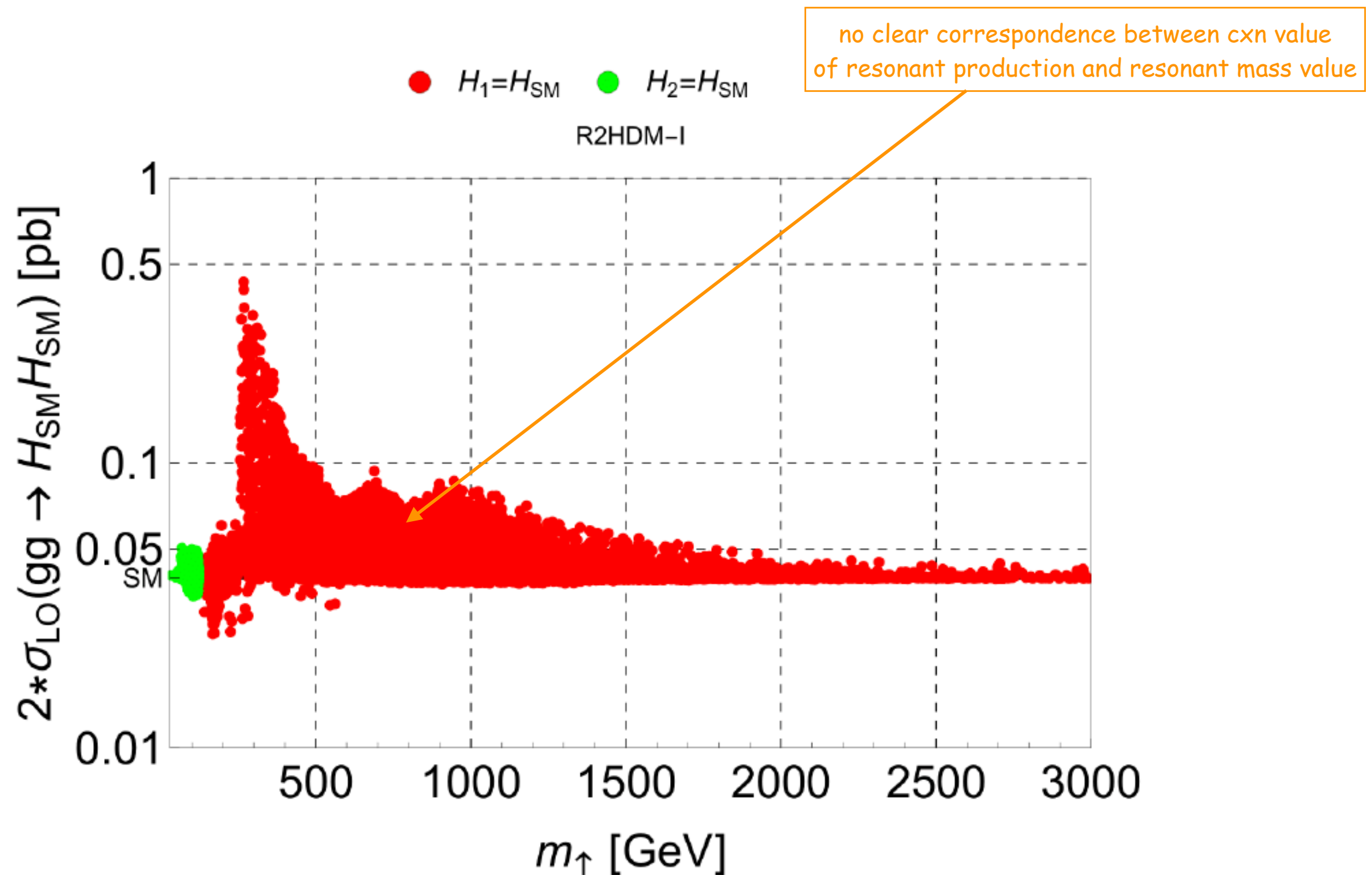
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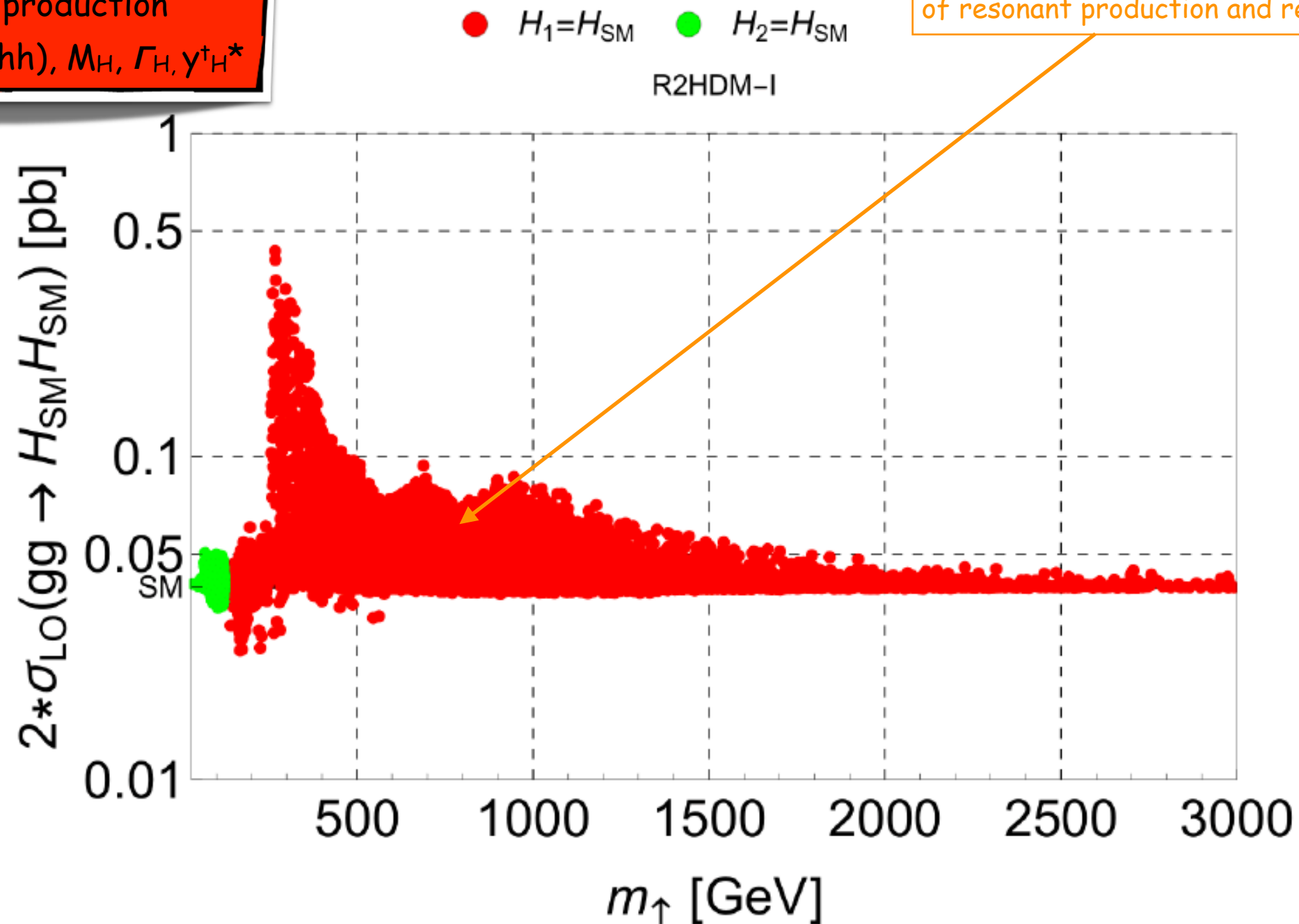


Parameter dependence - Ex. R2HDM T1



Parameter dependence - Ex. R2HDM T1

Resonant production
depends on $\lambda(Hhh)$, M_H , Γ_H , γ_H^*



*: even more in models with several resonant Higgs bosons

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
	$y_{t,H_{SM}}^{R2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{R2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{C2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{C2HDM}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	—	—
heavy II	—	—	—	—
	N2HDM		NMSSM	
	$y_{t,H_{SM}}^{N2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{N2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{NMSSM}/y_{t,H}$	$\lambda_{3H_{SM}}^{NMSSM}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	—	—	—	—

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no parameter points compatible
w/ constraints found

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
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heavy II	—	—	—	—

Experimental results cut on λ_{HHH}
and hence on the parameter space

ATLAS; $-0.4 \leq \kappa_\lambda \leq 6.3$

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
	$y_{t,H_{SM}}^{R2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{R2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{C2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{C2HDM}/\lambda_{3H}$
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Experimental results cut on λ_{HHH}
and hence on the parameter space

CMS; $-1.24 \leq \kappa_\lambda \leq 6.49$

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
	$y_{t,H_{SM}}^{R2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{R2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{C2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{C2HDM}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	—	—
heavy II	—	—	—	—
	N2HDM		NMSSM	
	$y_{t,H_{SM}}^{N2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{N2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{NMSSM}/y_{t,H}$	$\lambda_{3H_{SM}}^{NMSSM}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	—	—	—	—

some models: λ_{HHH} compatible
w/ zero still possible

CP-Violating Decays

♦ CP-violating 2HDM (C2HDM): BSM CP violation required in electroweak baryogenesis

♦ Example C2HDM T1:

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan \beta$	$\text{Re}(m_{12}^2)$ [GeV ²]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma_{H_1 H_1}^{\text{NLO}}$ [fb]	K -factor	$\Gamma_{H_1}^{\text{tot}}$ [GeV]	$\Gamma_{H_2}^{\text{tot}}$ [GeV]	$\Gamma_{H_3}^{\text{tot}}$ [GeV]	$\Gamma_{H^\pm}^{\text{tot}}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127

$\lambda_{3H_1}/\lambda_{3H}$	$y_{t,H_1}^e/y_{t,H}$	$\sigma_{H_1}^{\text{NNLO}}$ [pb]	$\sigma_{H_2}^{\text{NNLO}}$ [pb]	$\sigma_{H_3}^{\text{NNLO}}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\begin{aligned}
 \sigma(H_2) \times \text{BR}(H_2 \rightarrow H_1 H_1) &= 191 \text{ fb} , & \sigma(H_2) \times \text{BR}(H_2 \rightarrow WW) &= 254 \text{ fb} \\
 \sigma(H_2) \times \text{BR}(H_2 \rightarrow ZZ) &= 109 \text{ fb} , & \sigma(H_2) \times \text{BR}(H_2 \rightarrow ZH_1) &= 122 \text{ fb} \\
 \sigma(H_3) \times \text{BR}(H_3 \rightarrow H_1 H_1) &= 235 \text{ fb} , & \sigma(H_3) \times \text{BR}(H_3 \rightarrow WW) &= 315 \text{ fb} \\
 \sigma(H_3) \times \text{BR}(H_3 \rightarrow ZZ) &= 136 \text{ fb} , & \sigma(H_3) \times \text{BR}(H_3 \rightarrow ZH_1) &= 76 \text{ fb} .
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 \end{aligned}$$

*Dark
Matter*



The Higgs Boson as Portal to Dark Matter

- ♦ Higgs sector extensions with discrete symmetries:

Dark Matter candidate

- ♦ Example CxSM: SM extended by complex singlet field

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

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + H + iG^0) \end{pmatrix}, \quad \mathbb{S} = \frac{1}{\sqrt{2}} (v_S + S + i(v_A + A)),$$

impose two separate discrete symmetries: $S \rightarrow -S$ and $A \rightarrow -A$

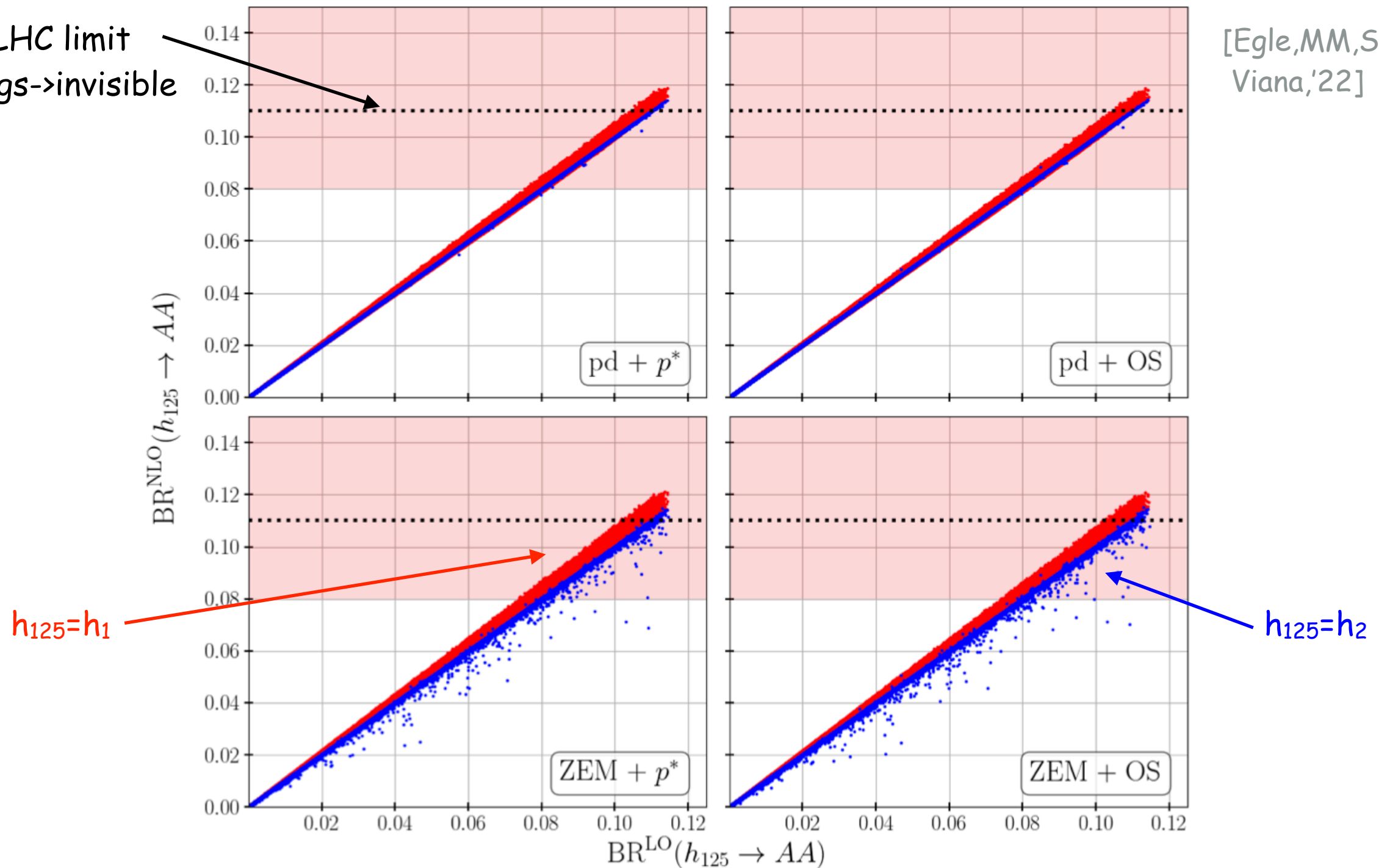
$v_A=0 \Rightarrow A \rightarrow -A$ symmetry unbroken, A is stable and becomes the Dark Matter candidate

Spectrum: h_1, h_2, A ; one of the $h_{1,2}$ is the h_{125}

LHC Test: Higgs Decay into two DM Particles, $h_{125} \rightarrow AA$

LHC limit
Higgs $\rightarrow$ invisible

[Egle, MM, Santos,
Viana, '22]



Parameter point allowed at leading order may be excluded at next-to-leading order and vice versa

A photograph of a tropical landscape. In the foreground, there is a dense cluster of palm trees with large, green, fan-shaped fronds. A thatched roof made of dried palm fronds is visible on the right side. In the background, a calm pond reflects the surrounding greenery and the sky. The water has a yellowish-green tint. The overall scene is bright and sunny, with strong shadows cast by the trees.

HH and Baroygenesis

Electroweak Baryogenesis

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]

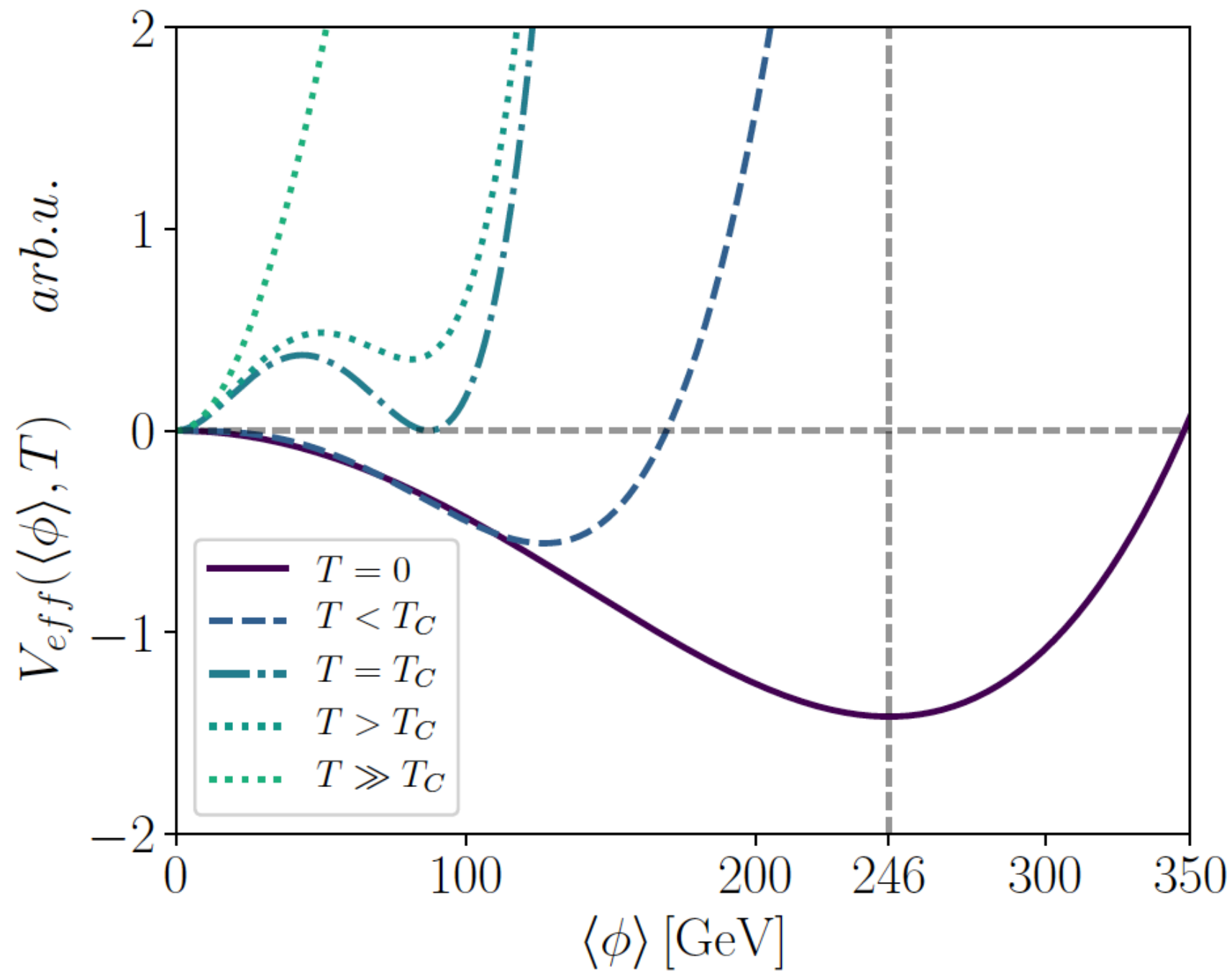
- * (i) B number violation (sphaleron processes)
- * (ii) C and CP violation
- * (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

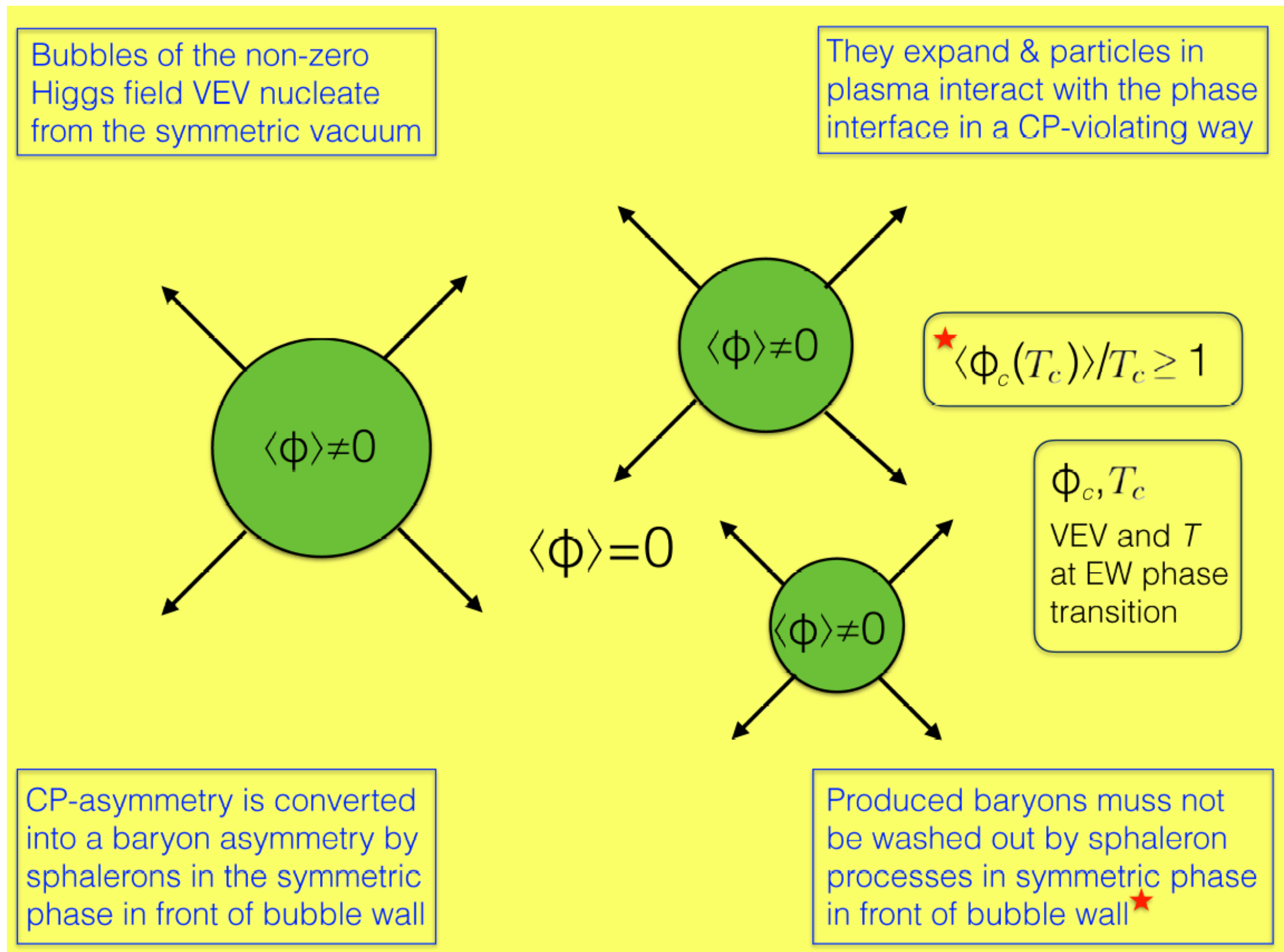
$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

Strong First Order Electroweak Phase Transition



Baryogenesis in a Nutshell



Higgs Pair Production and a 2HDM-EFT

Higgs Pair Production and a 2HDM-EFT

Higgs Pair Production and a 2HDM-EFT

Higgs Pair Production and a 2HDM-EFT

$$V_{\text{tree}}(\Phi_1, \Phi_2) = m_{11}^2(\Phi_1^\dagger \Phi_1) + m_{22}^2(\Phi_2^\dagger \Phi_2) - m_{12}^2(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_2(\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2]$$

2HDM

2 Higgs doublets

h, H, A, H^+, H^-

SFOEWPT, DM,
plus charged Higgs

Note:

- In 2HDMs we have to struggle with the possibility of so-called flavour-changing neutral currents (FCNCs)
- Can be avoided by imposing additional discrete symmetries on the model
- This leads to different 2HDM versions: type I-IV. They differ in the way how the Higgs bosons couple to the fermions

- **Effective Theory (EFT)**: parametrizes our ignorance about the New Physics model in a rather model-independent way, so that we can do calculations
- **Assumptions**:
 - * SM field content and SM gauge symmetries, no new physics at energy scale $E < \Lambda$
 - * SM deviations: higher-dimensional operators built up by the SM fields
 - * Operators = low-energy remnants of heavy new physics integrated out at Λ
 - * Operators suppressed by scale Λ
- **New interactions of SM particles**:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

- ♦ 2HDM type II struggle to reach SFOEWPT (compared to type I)

[see e.g. Basler,Krause,MM,Wittbrodt,Wlotzka,'16]

- ♦ For 2HDM type II points with $\xi_c < 1$:

What extra dynamics is required to achieve SFOEWPT?

- ♦ Our model: CP-conserving 2HDM with softly broken discrete Z_2 symmetry

$$V_{\text{tree}}(\Phi_1, \Phi_2) = m_{11}^2(\Phi_1^\dagger \Phi_1) + m_{22}^2(\Phi_2^\dagger \Phi_2) - m_{12}^2(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_2(\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2]$$

- ♦ Extended by (purely scalar) dim-6 EFT contributions to the Higgs potential

[See also Crivellin et al. , '20]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = - \sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

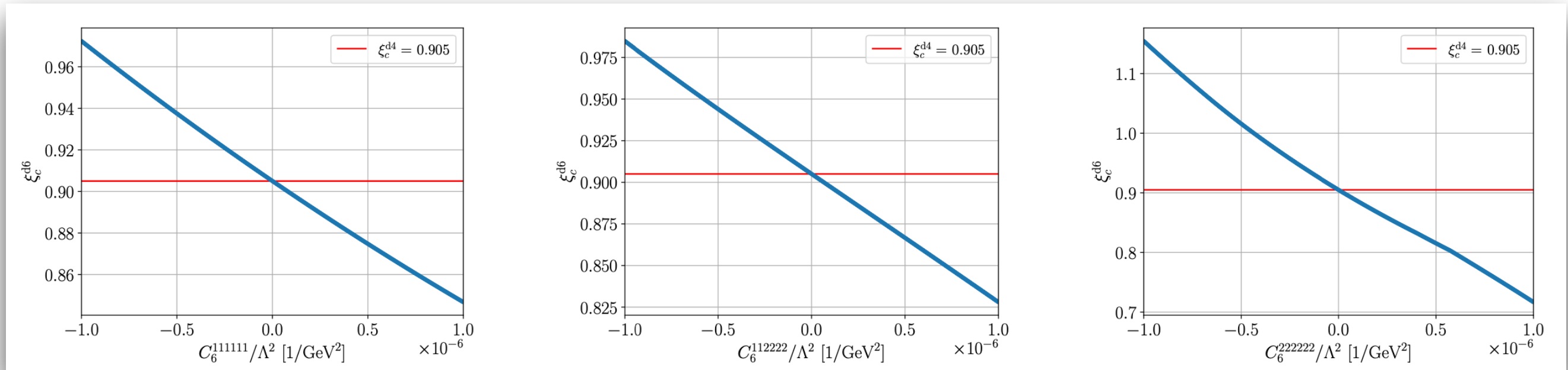
- ♦ Higgs pair production: a tool for fingerprinting an SFOEWPT?

O_6^{111111}	$(\Phi_1^\dagger \Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger \Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger \Phi_1)^2 (\Phi_2^\dagger \Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2)^2$
O_6^{122111}	$(\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) (\Phi_1^\dagger \Phi_1)$	O_6^{122122}	$(\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2)$
O_6^{121211}	$(\Phi_1^\dagger \Phi_2)^2 (\Phi_1^\dagger \Phi_1) + \text{h.c.}$	O_6^{121222}	$(\Phi_1^\dagger \Phi_2)^2 (\Phi_2^\dagger \Phi_2) + \text{h.c.}$

- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \rightarrow \lambda_i + \delta\lambda_i$, $m_{12}^2 \rightarrow m_{12}^2 + \delta m_{12}^2$
- $\Rightarrow$ scalar mass spectrum same as for dim-4 @ LO
- $\Rightarrow$ shift EFT effects into **Higgs self-couplings & multi-Higgs final states**

Effect of Dim-6 Operators

[Anisha,Biermann,Englert,MM,'22]



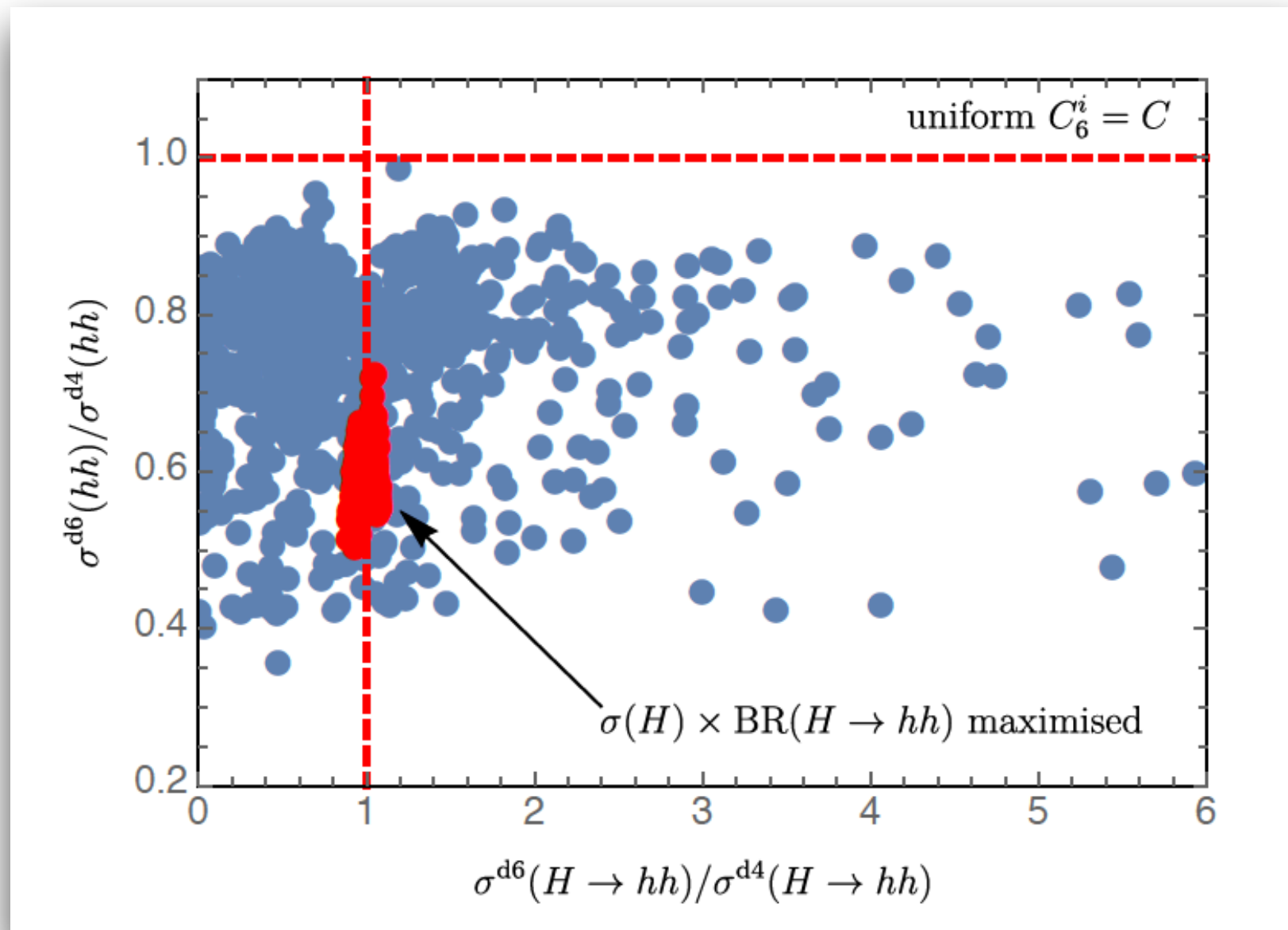
impact of individual Wilson coefficients on ξ_c^{d6} for $\xi_c^{d4} \cong 0.9$:

- linear response $\sim C_i$ $\rightarrow$ perturbativity ok
- SFOEWPT achievable in agreement with experimental constraints

interference effects in heavy Higgs production in $t\bar{t}$ final state are width dependent
 $\rightarrow$ sensitive to EFT modifications: overall effect is small after taking the Higgs data constraints into account $\Rightarrow$ hh production important tool for fingerprinting SFOEWPT

Correlation of ξ_c^{d4} , continuum and resonant hh production

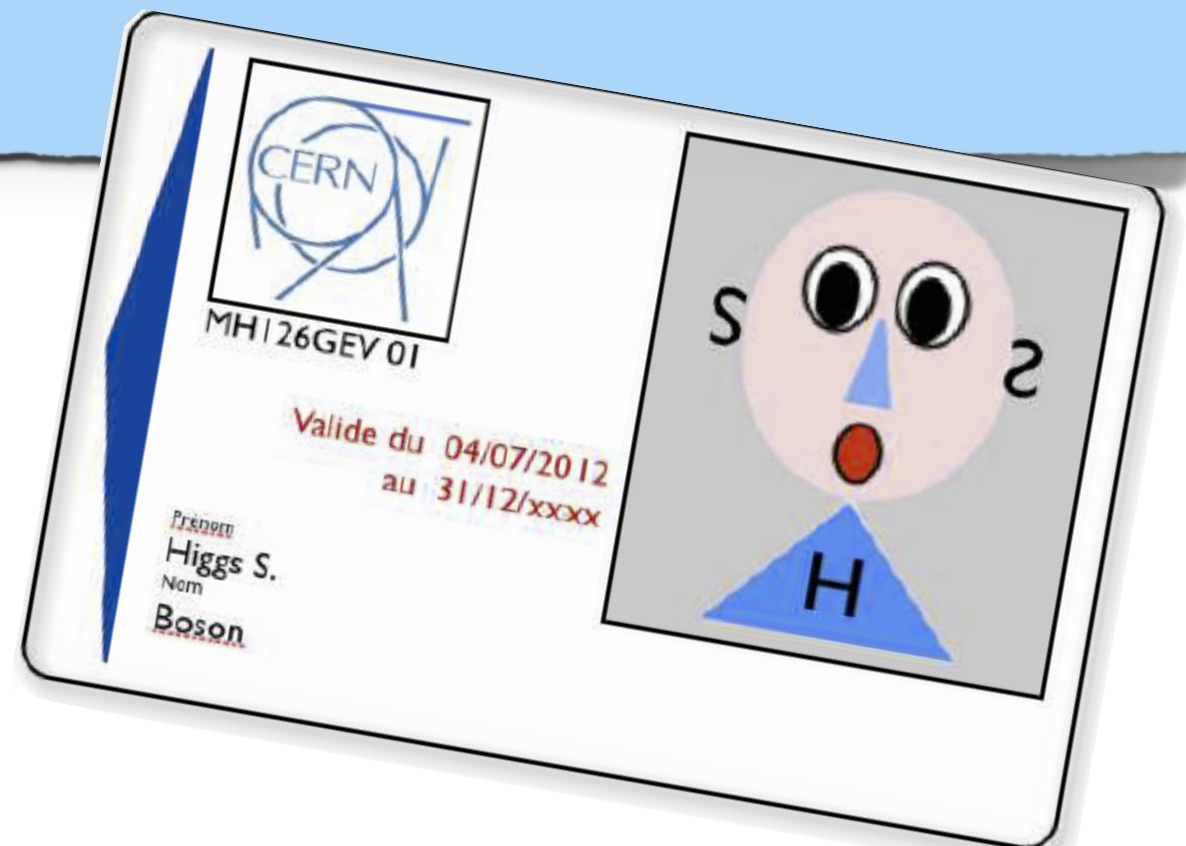
[Anisha,Biermann,Englert,MM,'22]



- Resonant $H \rightarrow hh$ production enhancement factor of 2.5 possible for cxn in fb range
- Higgs-philic points: resonance contribution modified by $\sim 5\text{-}10\%$, continuum production modified by $\sim 50\%$

Conclusions

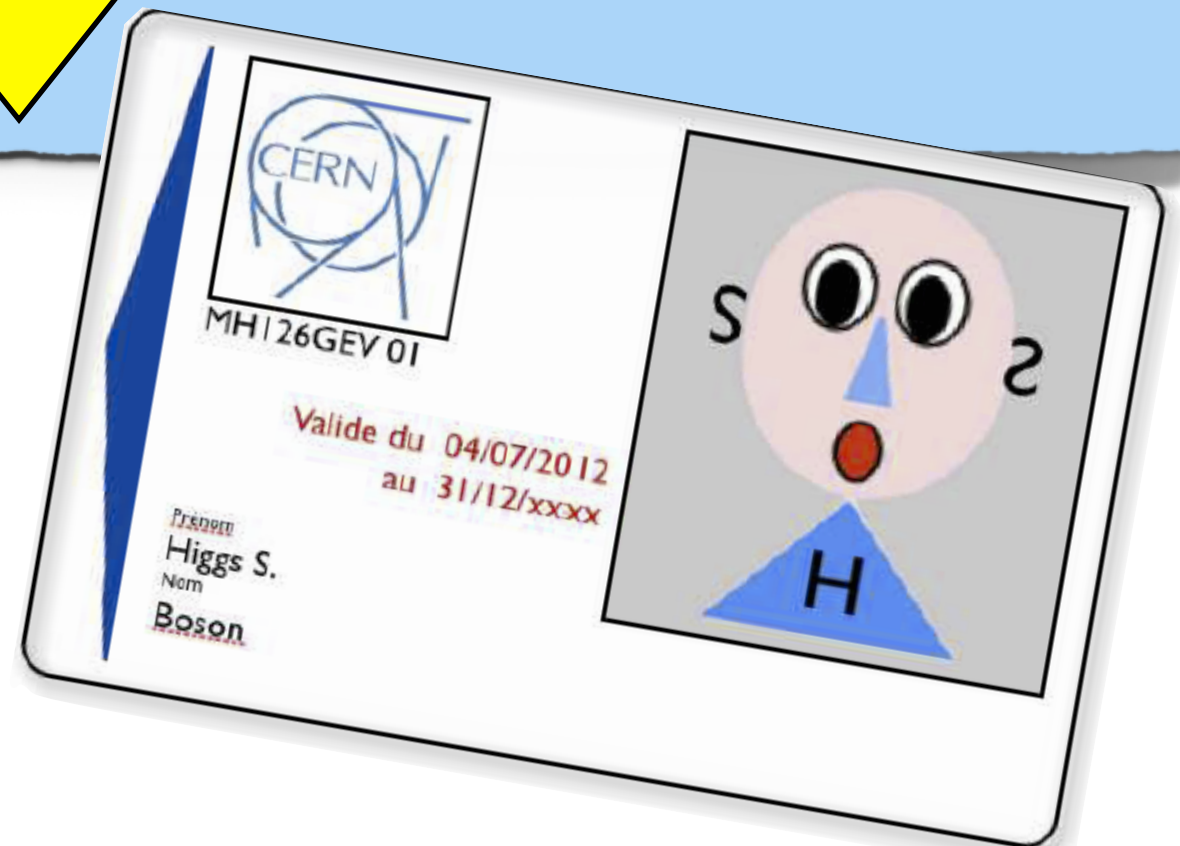
- ♦ Flaws of SM call for new physics; no direct signs of new physics => **Higgs boson**



Conclusions

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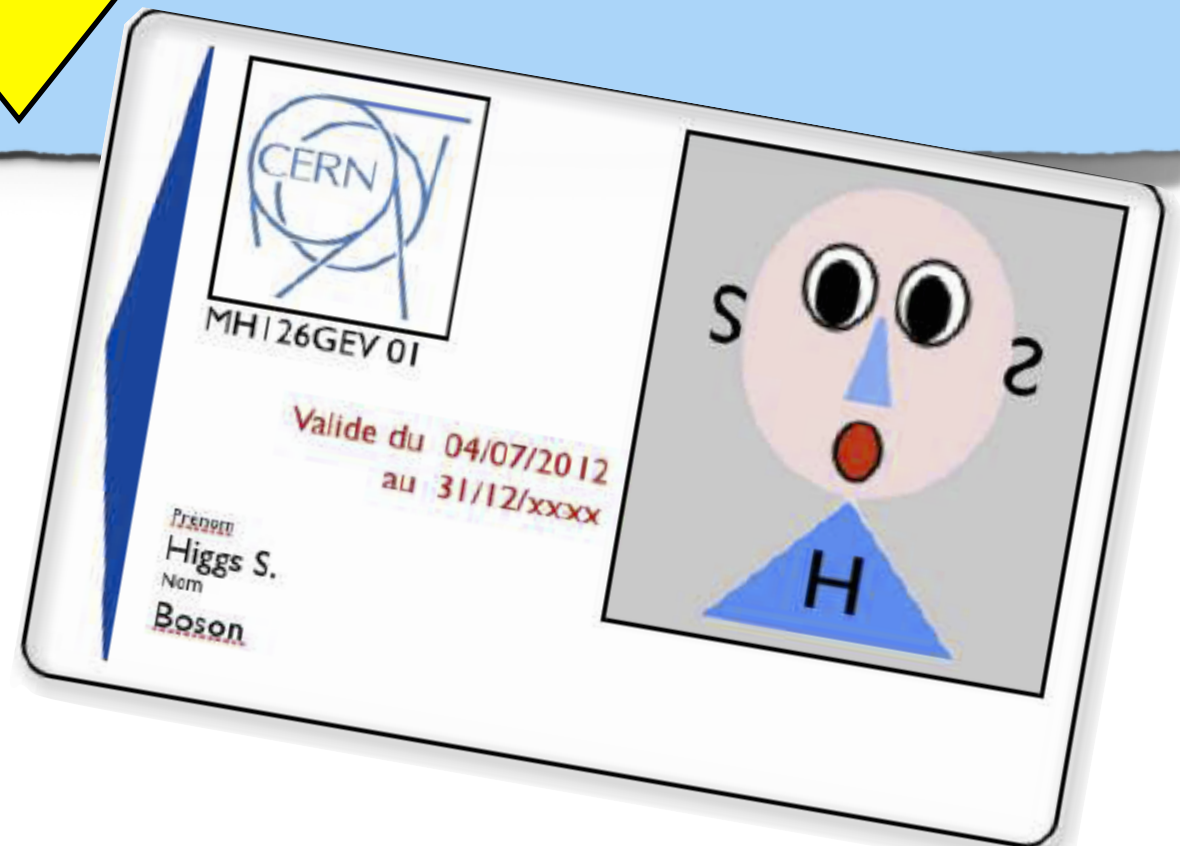
The answer to
life, the universe
and everything!



Conclusions

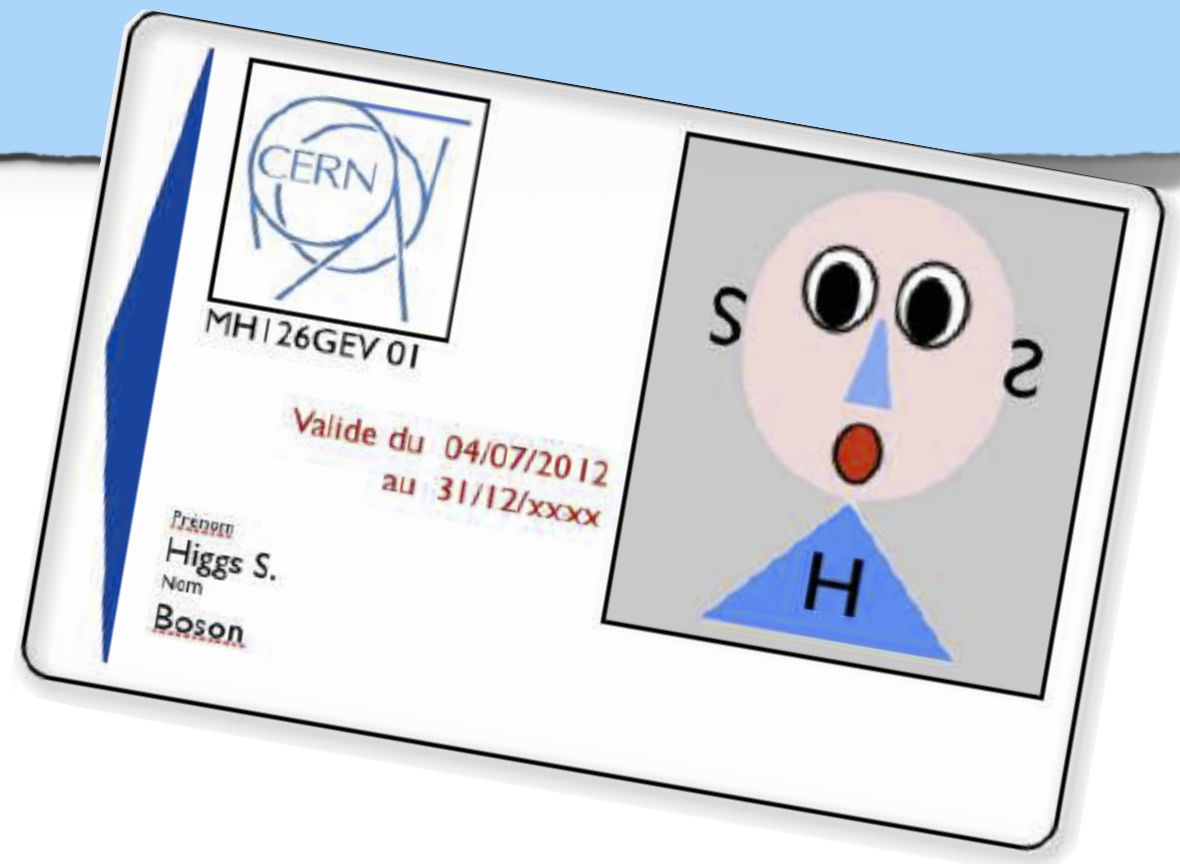
- ♦ Flaws of SM call for new physics; no direct signs of new physics => **Higgs boson**

Not quite,
but



Conclusions

- ♦ Flaws of SM call for new physics; no direct signs of new physics => **Higgs boson**
- ♦ Insights
 - in allowed parameter ranges of the BSM models, in scale of new physics
 - in mechanism of mass generation, structure & dynamics of electroweak symmetry breaking
 - in nature of Dark Matter
 - in baryogenesis
 - in flavor/CP puzzle
- ♦ Interesting times ahead!

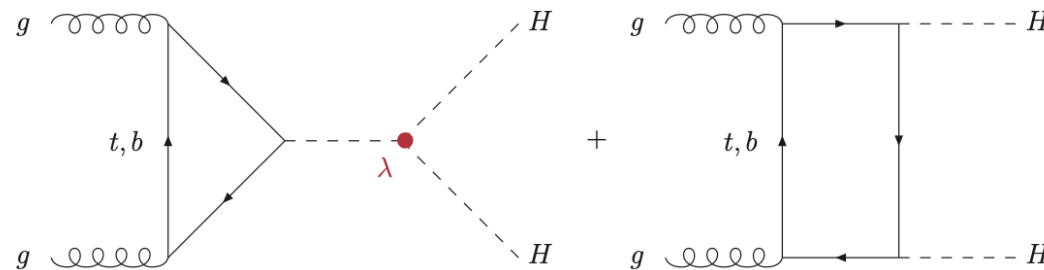




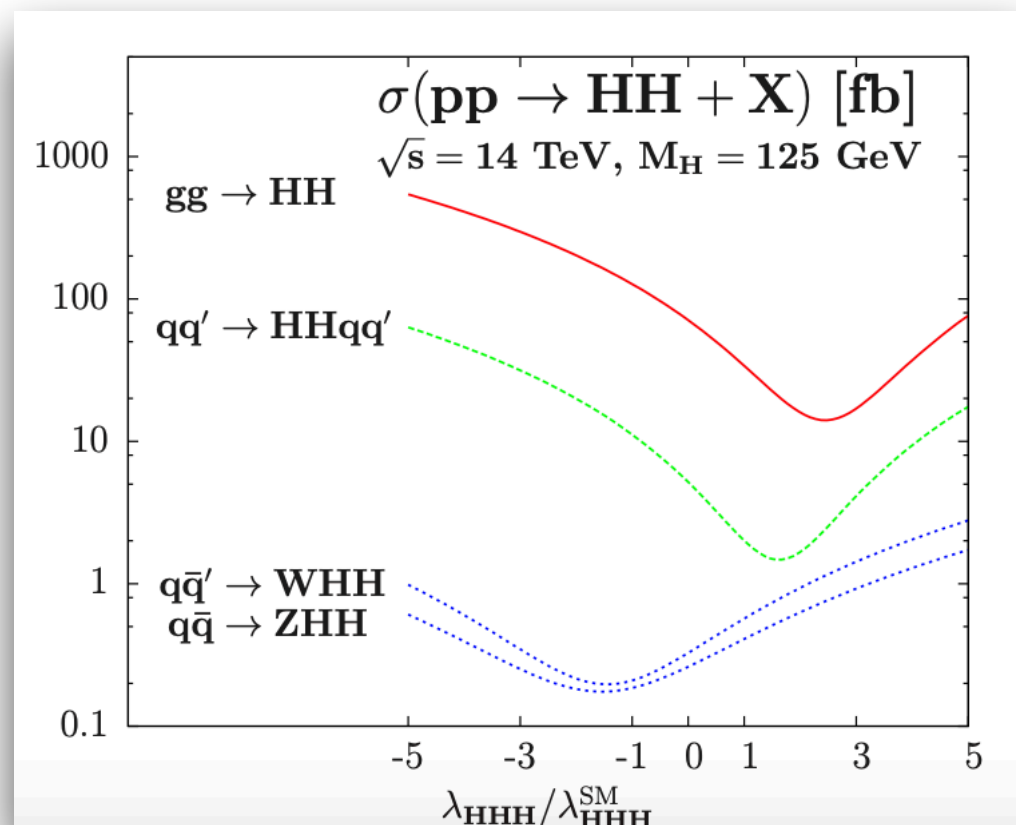
Thank you for
your attention!

Higgs Pair Production through Gluon Fusion

- ♦ Loop mediated at leading order - SM: third generation dominant



- ♦ Threshold region sensitive to λ ; large M_{HH} : sensitive to c_{tt}/c_{bb} [e.g. boosted Higgs pairs]



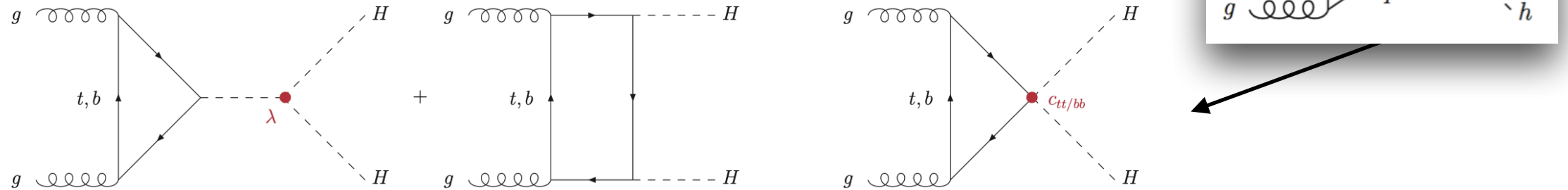
[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \rightarrow HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

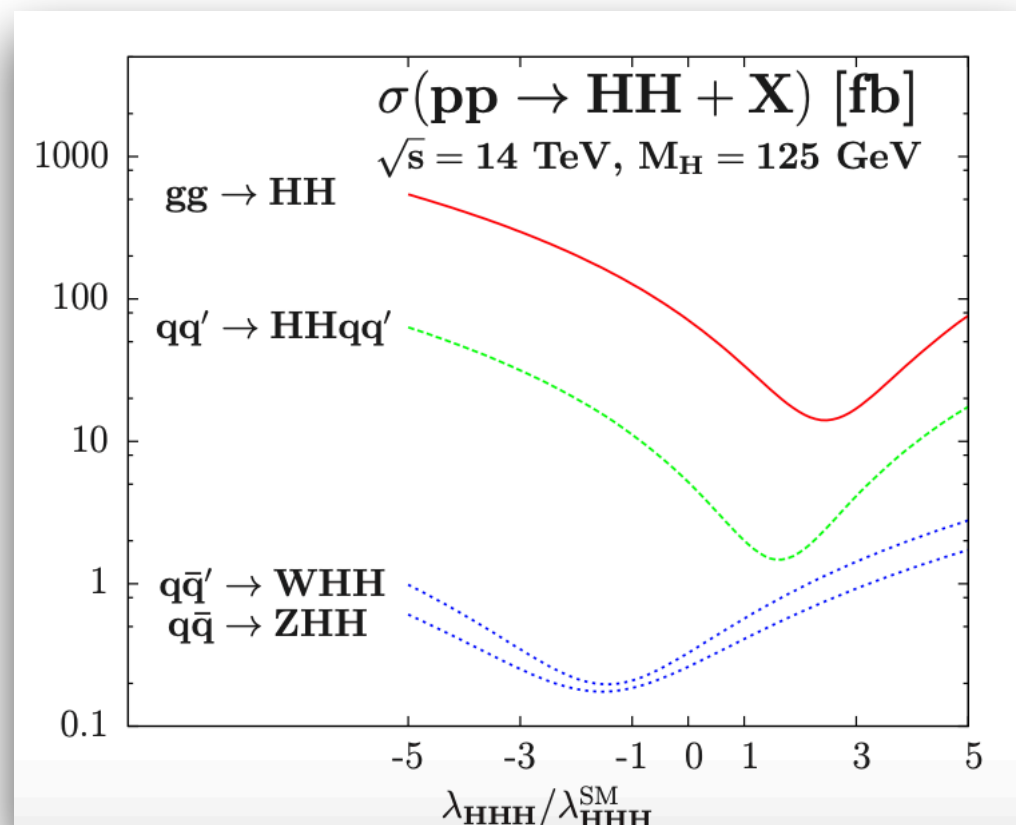
decreasing with M_{HH}

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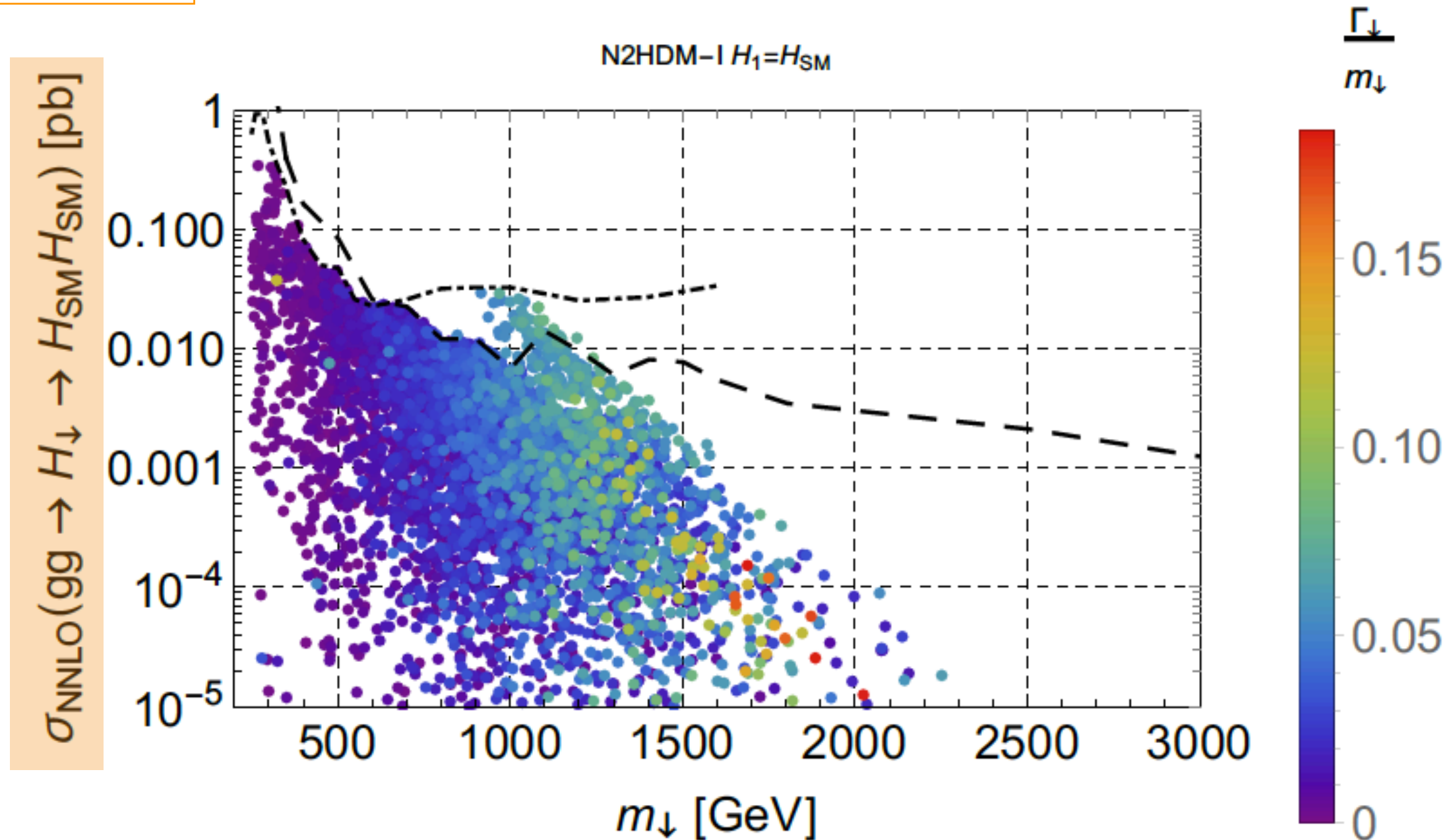
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Impact of Resonant Searches - Ex. N2HDM H1 SM-like

resonant constraint
on single Higgs times
branching ratio

----- ATLAS-CONF-NOTE-2021-030 $b\bar{b}\tau\bar{\tau}$
- - - - ATLAS-CONF-NOTE-2021-035 $b\bar{b}b\bar{b}$

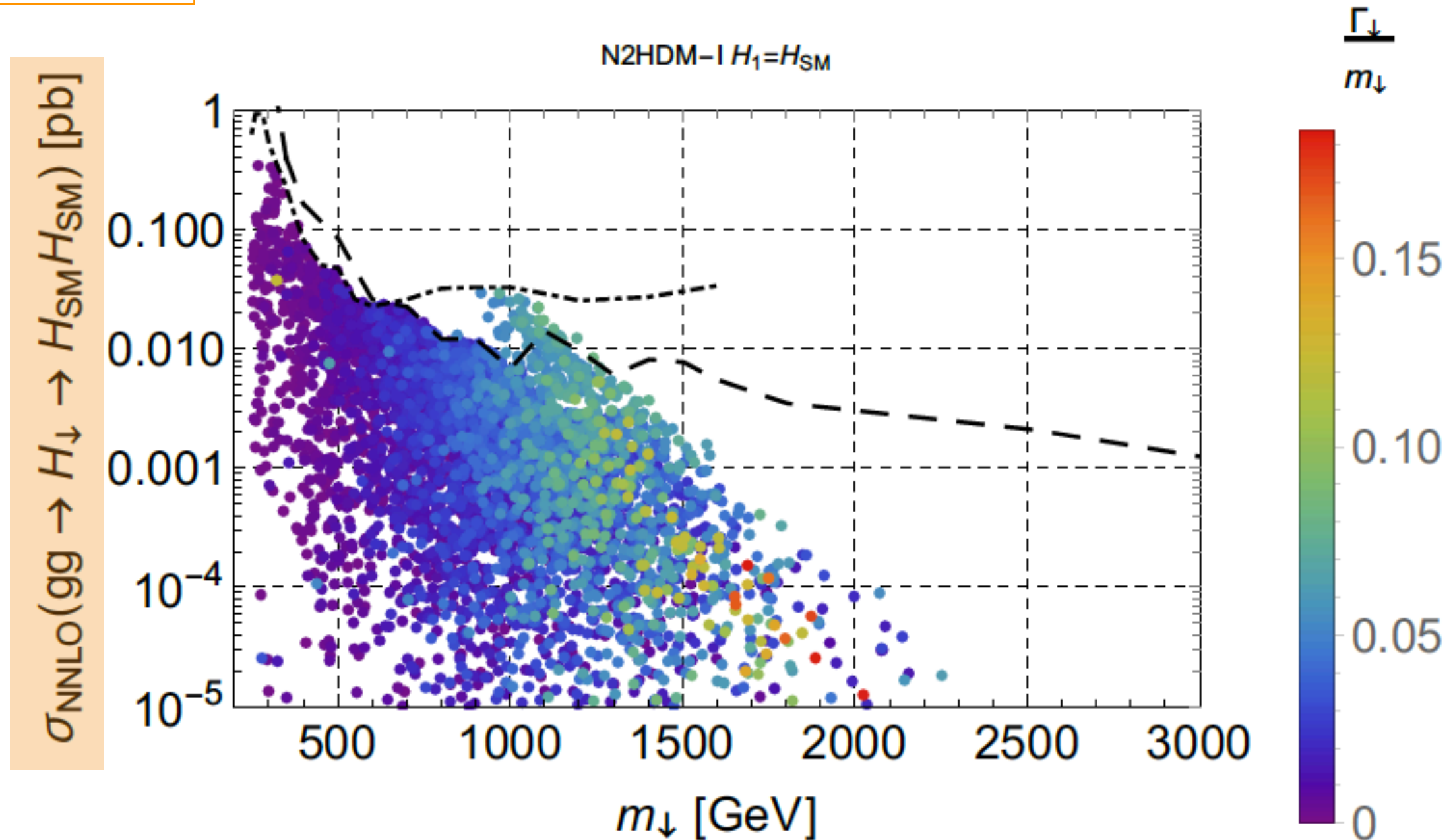


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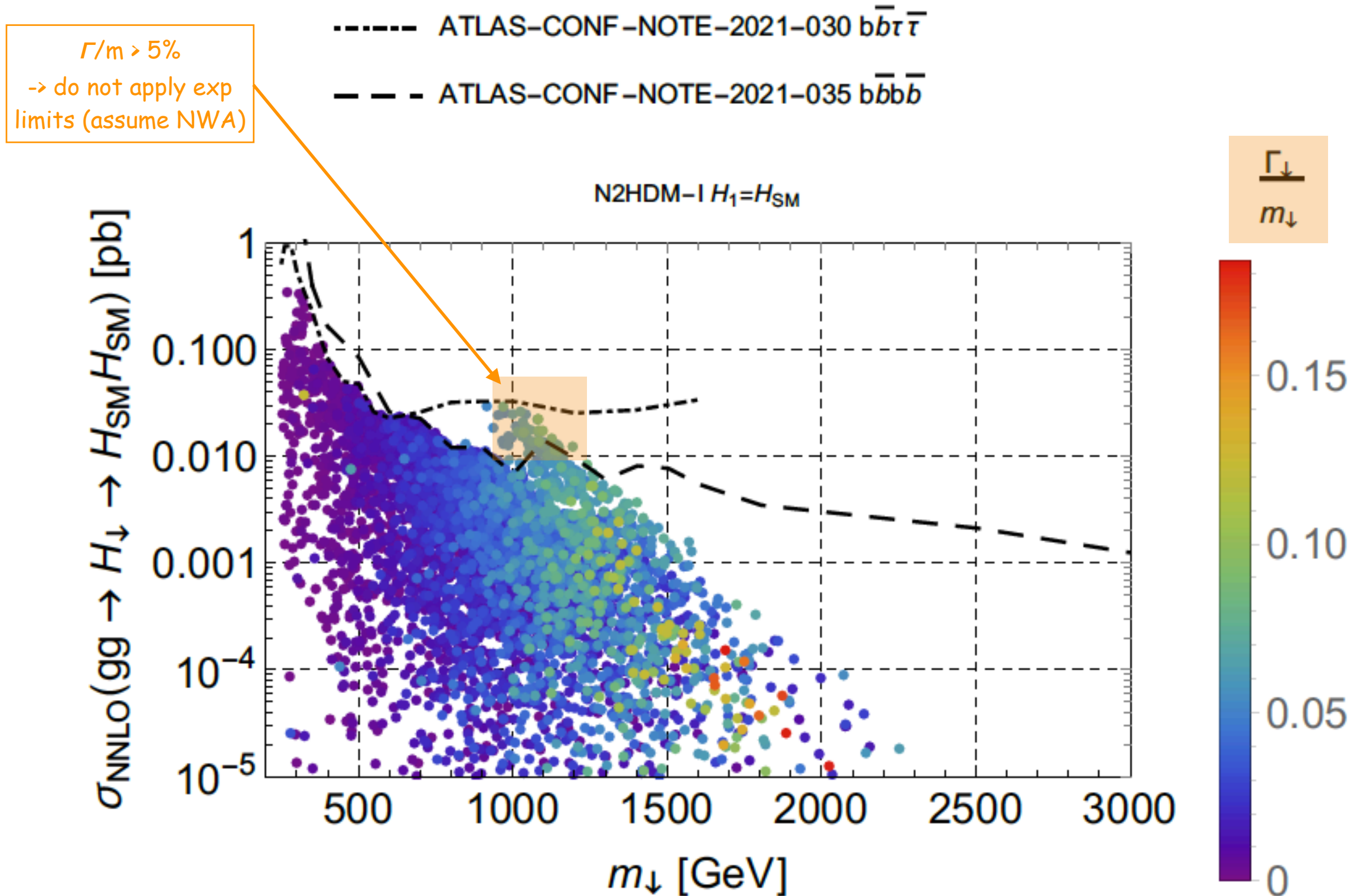
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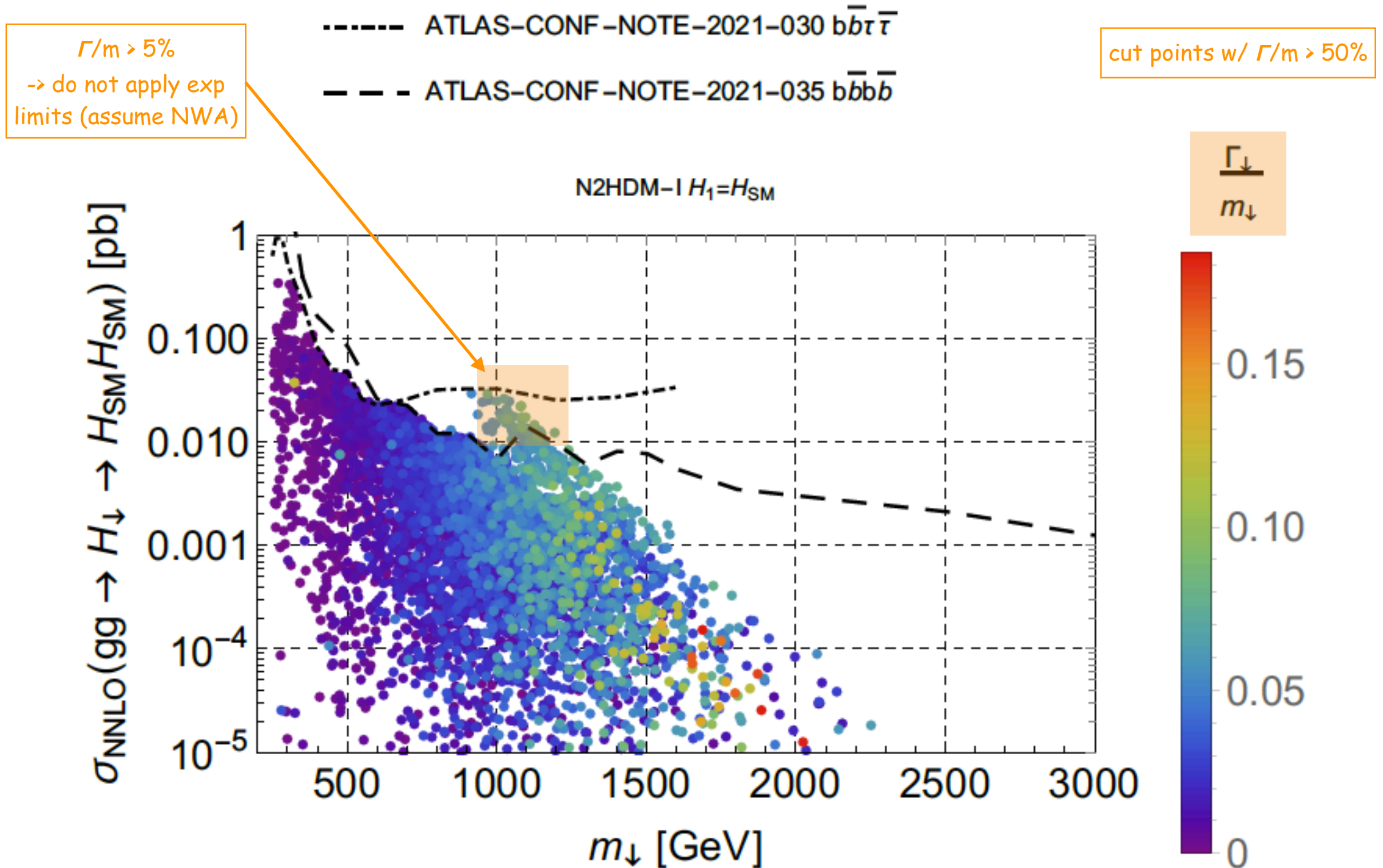
assume non-resonant contribution is SM-like
and no interference effects



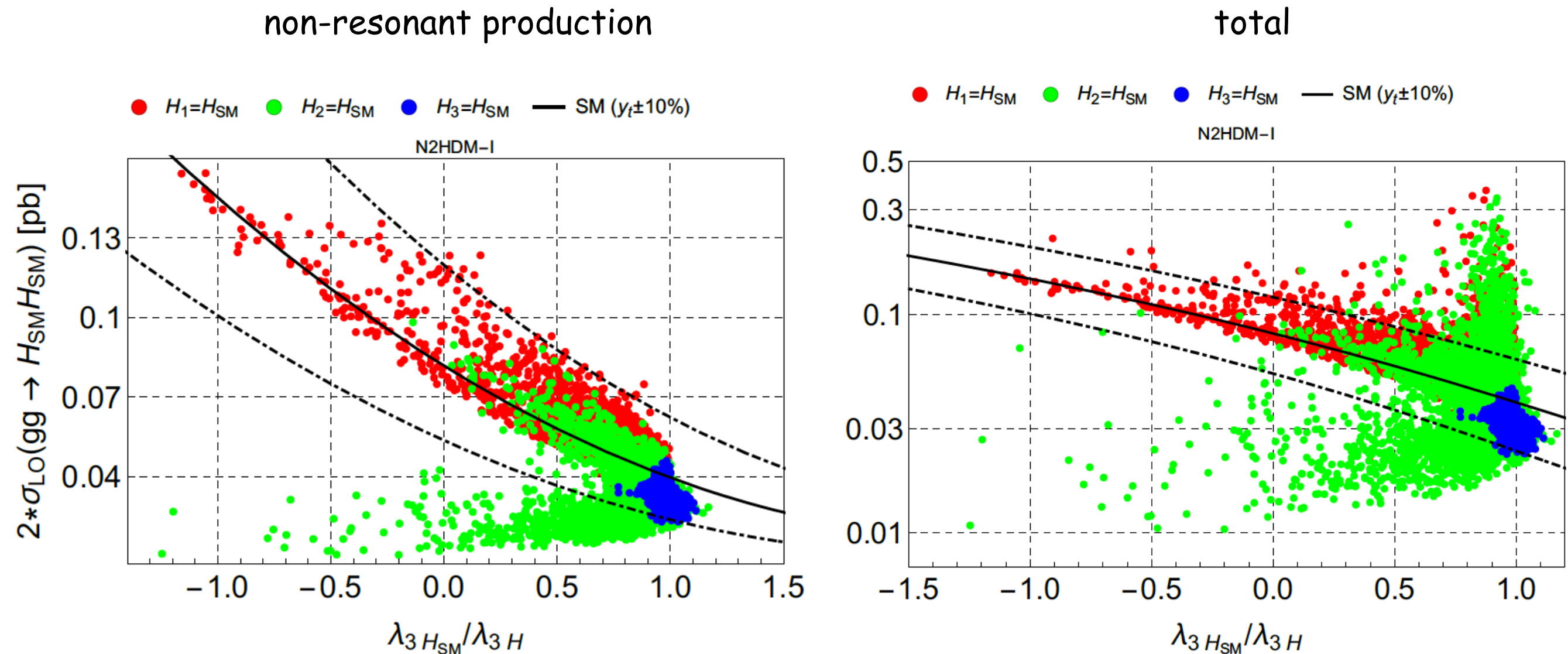
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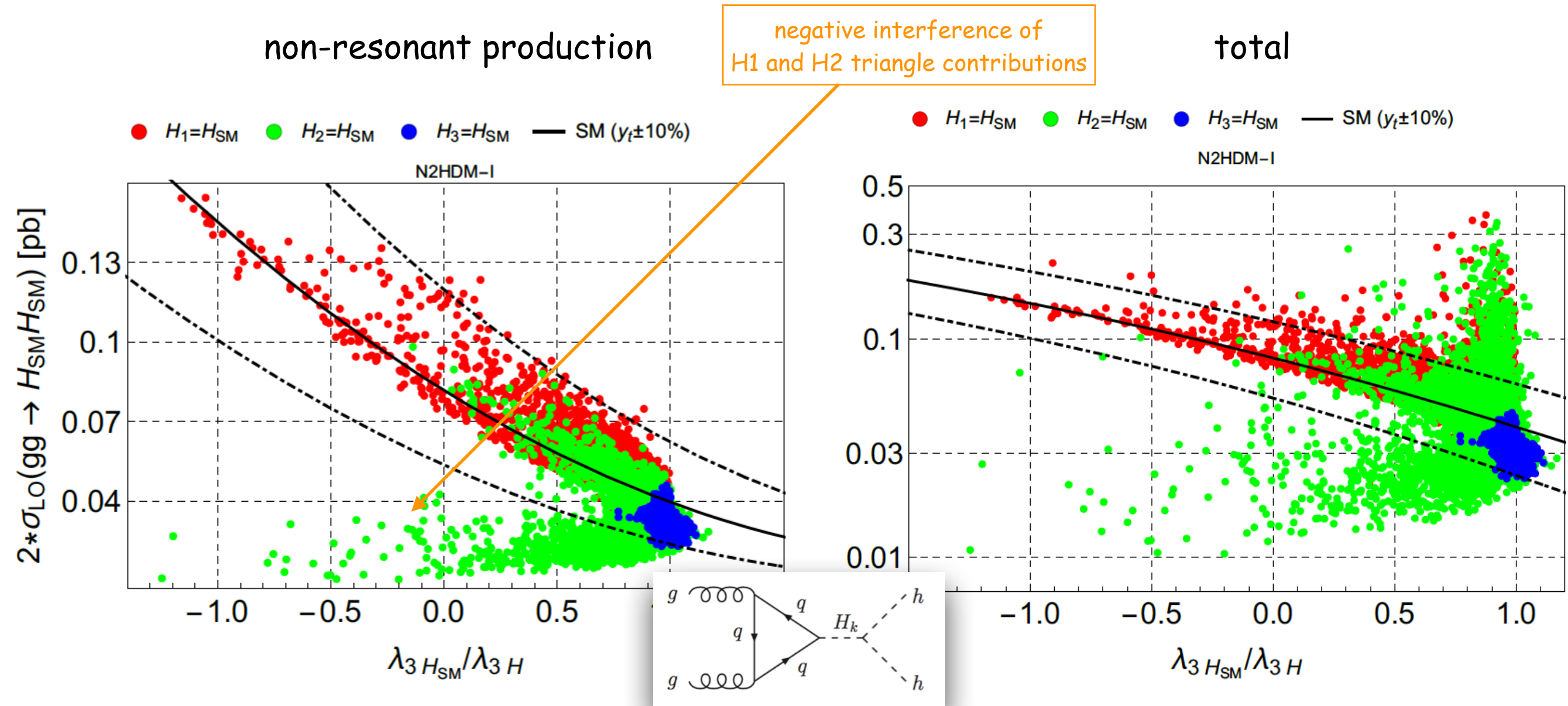


Required: combination Non-resonant and Resonant Searches



- full/dashed lines: top-Yukawa coupling = SM value/ $\pm 10\%$
- Combination of resonant and resonant searches required to constraint trilinear coupling

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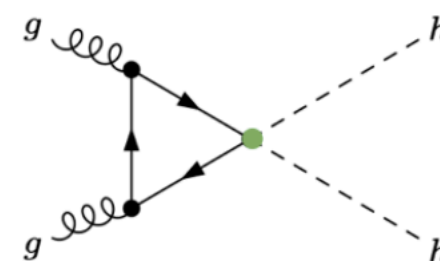
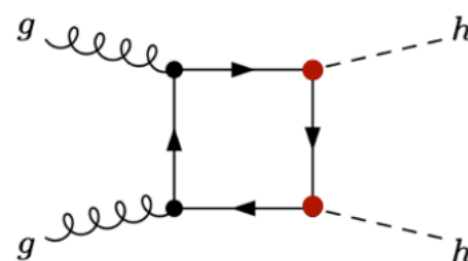
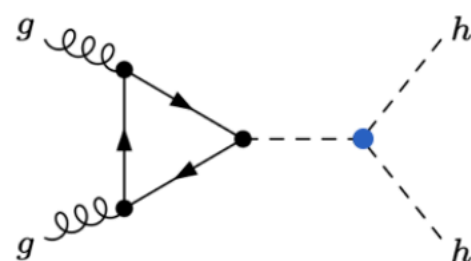
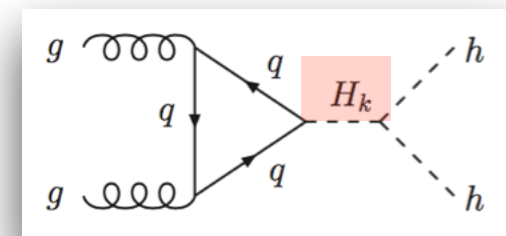
Comparison with EFT

♦ Effective Lagrangian: $\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t t\bar{t} \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \left(\frac{3M_h^2}{v} \right) h^3$

c_3 : trilinear coupling modification; c_t : top-Yukawa coupling modification;

c_{tt} : effective two-Higgs-two-fermion coupling

no c_g, c_{gg} : no new heavy colored BSM particles assumed



♦ Matching relations of our specific BSM models:

Higgs-top Yukawa coupling	:	$g_t^{H_{\text{SM}}}(\alpha_i, \beta)$	$\rightarrow$	c_t
trilinear Higgs coupling	:	$\frac{g_3^{H_{\text{SM}}H_{\text{SM}}H_{\text{SM}}}(p_i)}{3M_{H_{\text{SM}}}^2/v}$	$\rightarrow$	c_3
two-Higgs-two-top quark coupling	:	$\sum_{k=1}^{k_{\text{max}}} \left(\frac{-v}{m_{H_k}^2} \right) g_3^{H_k H_{\text{SM}} H_{\text{SM}}}(p_i) g_t^{H_k}(\alpha_i, \beta)$	$\rightarrow$	c_{tt}

2HDM versus EFT

♦ R2HDM T2 sample parameter point:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan \beta$	m_{12}^2 [GeV ²]
125.09	1131	1082	1067	-0.924	0.820	552749

♦ corresponding EFT values:

$$g_t^{H_2} = -1.126$$

$$c_3 = 0.782, \quad c_t = 0.951, \quad c_{tt} = -0.122$$

♦ goodness of approximation?:

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2 H_1 H_1}$ [GeV]	$\sigma_{\text{R2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt} \neq 0}$ [fb]	ratio
1131	78.80	-0.1222	-504.52	30.5	26.1	86%
1200	89.74	-0.1031	-479.29	27.7	24.8	90%
1500	470.2	$-4.853 \cdot 10^{-2}$	-352.42	21.8	21.4	98%

♦ Remark:

$$\sigma_{\text{R2HDM}}^{\text{w/o res}} = 18.6 \text{ fb} \quad \text{and} \quad \sigma_{\text{SMEFT}}^{c_{tt}=0} = 18.6 \text{ fb}$$

N2HDM versus EFT

♦ N2HDM T1 sample parameter point:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan \beta$
125.09	269	582	390	380	4.190
α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV ²]	
1.432	-0.109	0.535	1250	28112	

$$g_t^{H_2} = 0.179 \quad \text{and} \quad g_t^{H_3} = 2.337 \times 10^{-2}$$

♦ corresponding EFT values:

$$c_3 = 0.877, \quad c_t = 1.012, \quad c_{tt} = 4.127 \times 10^{-2}$$

♦ goodness of approximation?: (m_{H_3} kept fixed)

m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2 H_1 H_1}$	$\sigma_{\text{N2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt} \neq 0}$ [fb]	ratio
269	0.075	4.410×10^{-2}	4.127×10^{-2}	-72.42	183.70	20.56	11%
300	0.083	3.170×10^{-2}	2.877×10^{-2}	-64.80	162.80	21.28	13%
400	0.177	9.544×10^{-3}	6.721×10^{-3}	-34.68	43.33	22.60	52%
420	0.229	6.895×10^{-3}	4.063×10^{-3}	-27.62	31.70	22.76	72%
440	0.284	4.600×10^{-3}	1.767×10^{-3}	-20.22	26.26	22.90	87%
450	0.315	3.564×10^{-3}	7.323×10^{-4}	-16.39	24.84	22.96	92%
500	2.567	-7.132×10^{-4}	-3.545×10^{-3}	4.05	23.56	23.22	99%

Single Higgs versus Di-Higgs Cascade Decays

♦ **Singlet extended N2HDM, NMSSM:** non-SM Higgs is singlet-like and/or more down- than up-type like => suppressed direct production rate

♦ **Sample parameter point N2HDM T1:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan \beta$
125.09	281.54	441.25	386.98	421.81	1.990
α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV ²]	
1.153	0.159	0.989	9639	29769	

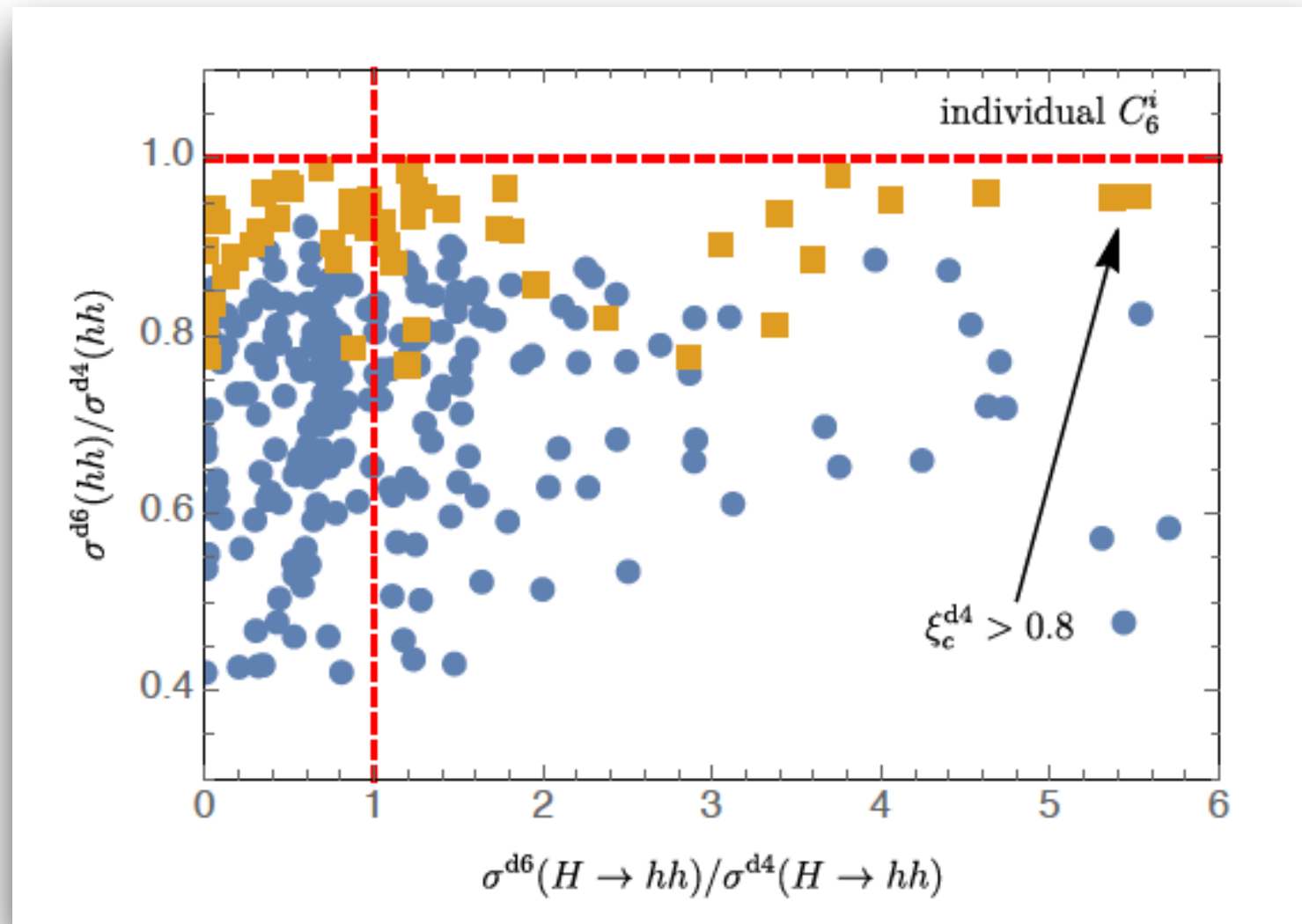
$$\sigma_{H_1 H_2}^{\text{NLO}} \times \text{BR}(H_2 \rightarrow H_1 H_1) \times \text{BR}(H_1 \rightarrow b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}$$

$$\sigma^{\text{NNLO}}(H_2) \times \text{BR}(H_2 \rightarrow H_1 H_1) \times \text{BR}(H_1 \rightarrow b\bar{b})^2 = 161 \cdot 0.37 \cdot 0.60^2 \text{ fb} = 21 \text{ fb}$$

H2 has tiny couplings to b-quarks => better chances to be discovered in di-Higgs than single Higgs channels

Strength of EWPT and hh production

[Anisha,Biermann,Englert,MM,'22]

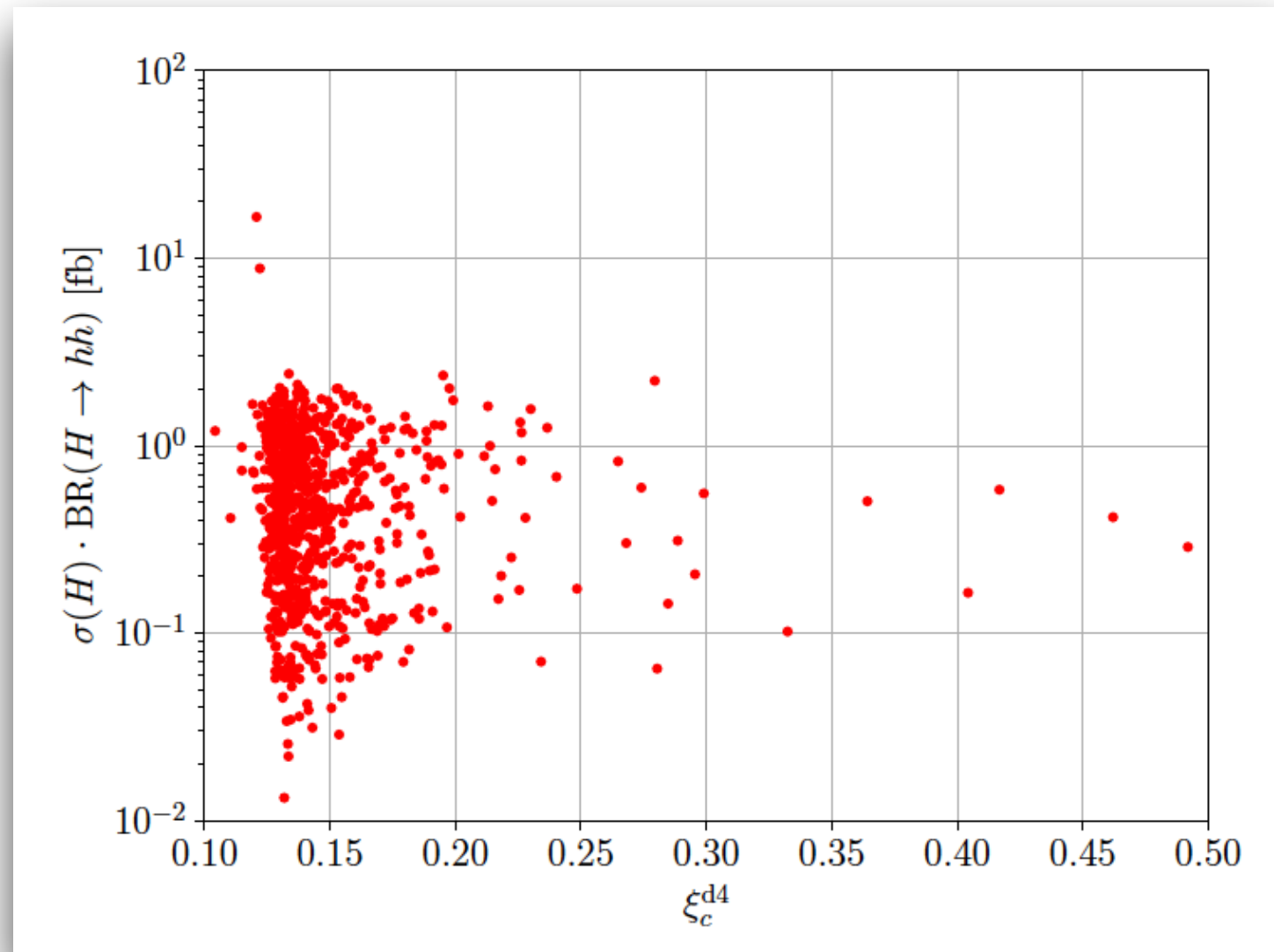


Points with $\xi_c^{d6} \cong 1$ for $\xi_c^{d4} \geq 0.3$, orange points $\xi_c^{d4} > 0.8$

- suppression of overall hh: additional potential contributions enhance λ_{hhh} by $O(50\%)$
- analysis of the separated res. production $H \rightarrow hh$ compared to hh continuum production
→ indirect constraint on $\xi_c \sim 1$

Correlation of ξ_c^{d4} and resonant $H \rightarrow hh$ Production

[Anisha,Biermann,Englert,MM,'22]



- Higgsphilic points characterized by larger distance $|1 - \xi_c^{d4}|$
 - $\leadsto$ interplay of different dim-6 operators to achieve $\xi_c \sim 1$ in a controlled way



*More on Electroweak Phase
Transition and Baryogenesis*

Model „CP in the Dark“

♦ Next-to-Minimal 2-Higgs Doublet Model:

[Azevedo,Ferreira,MM,Patel,Santos,'18]

$$\begin{aligned} V^{(0)} = & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + \frac{m_S^2}{2} \Phi_S^2 + \left(A \Phi_1^\dagger \Phi_2 \Phi_S + \text{h.c.} \right) \\ & + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2] \\ & + \frac{\lambda_6}{4} \Phi_S^4 + \frac{\lambda_7}{2} |\Phi_1|^2 \Phi_S^2 + \frac{\lambda_8}{2} |\Phi_2|^2 \Phi_S^2. \end{aligned}$$

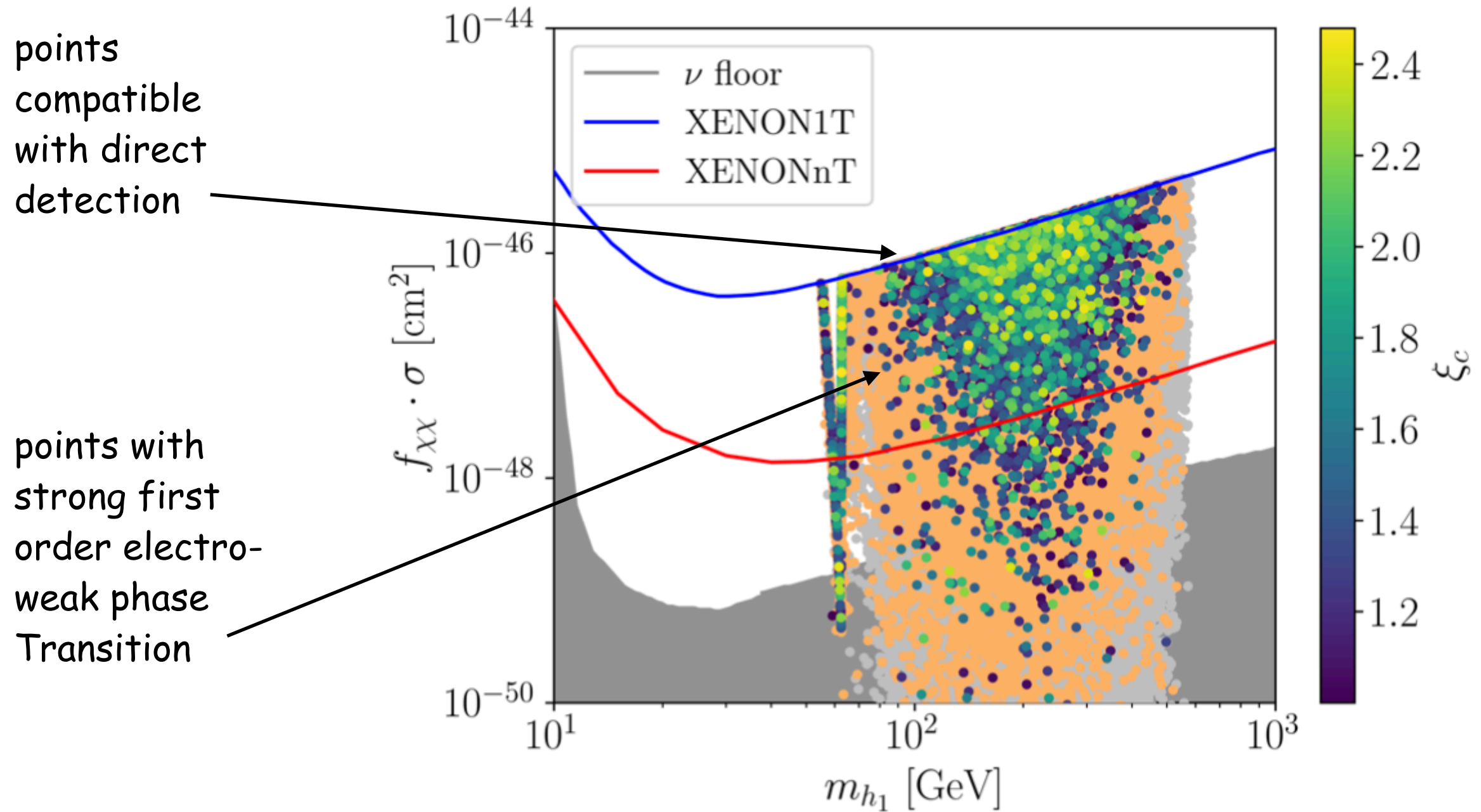
♦ with one discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2, \quad \Phi_S \rightarrow -\Phi_S$

one SM-like Higgs plus dark sector: $h_1, h_2, h_3, H^\pm$

♦ trilinear coupling A is complex: dark sector with CP violation <- not constrained by electric dipole moment

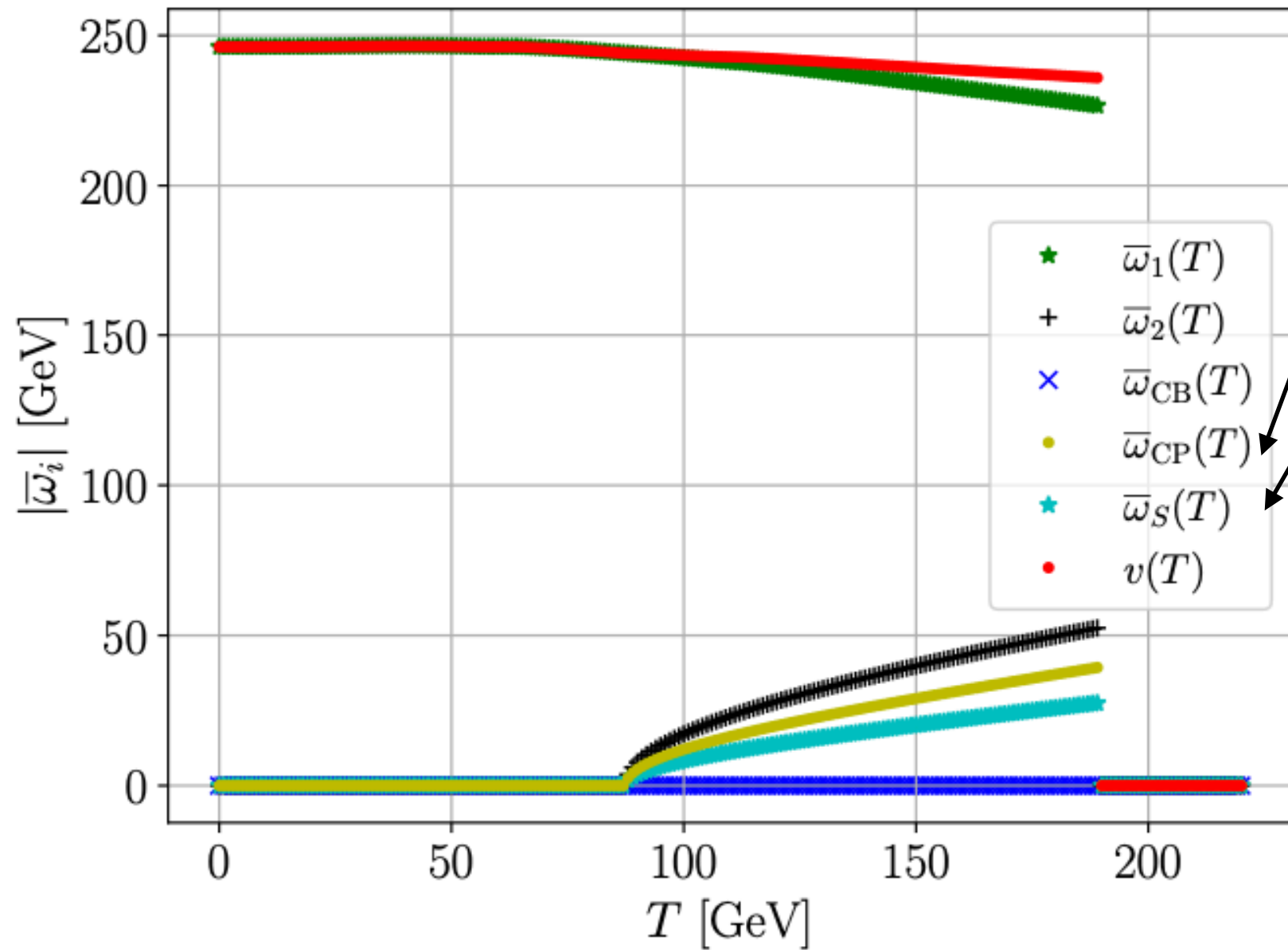
Strong First Order Phase Transition and DM Constraints

[Biermann,MM,Müller'22]



Spontaneous CP Violation

[Biermann,MM,Müller'22]

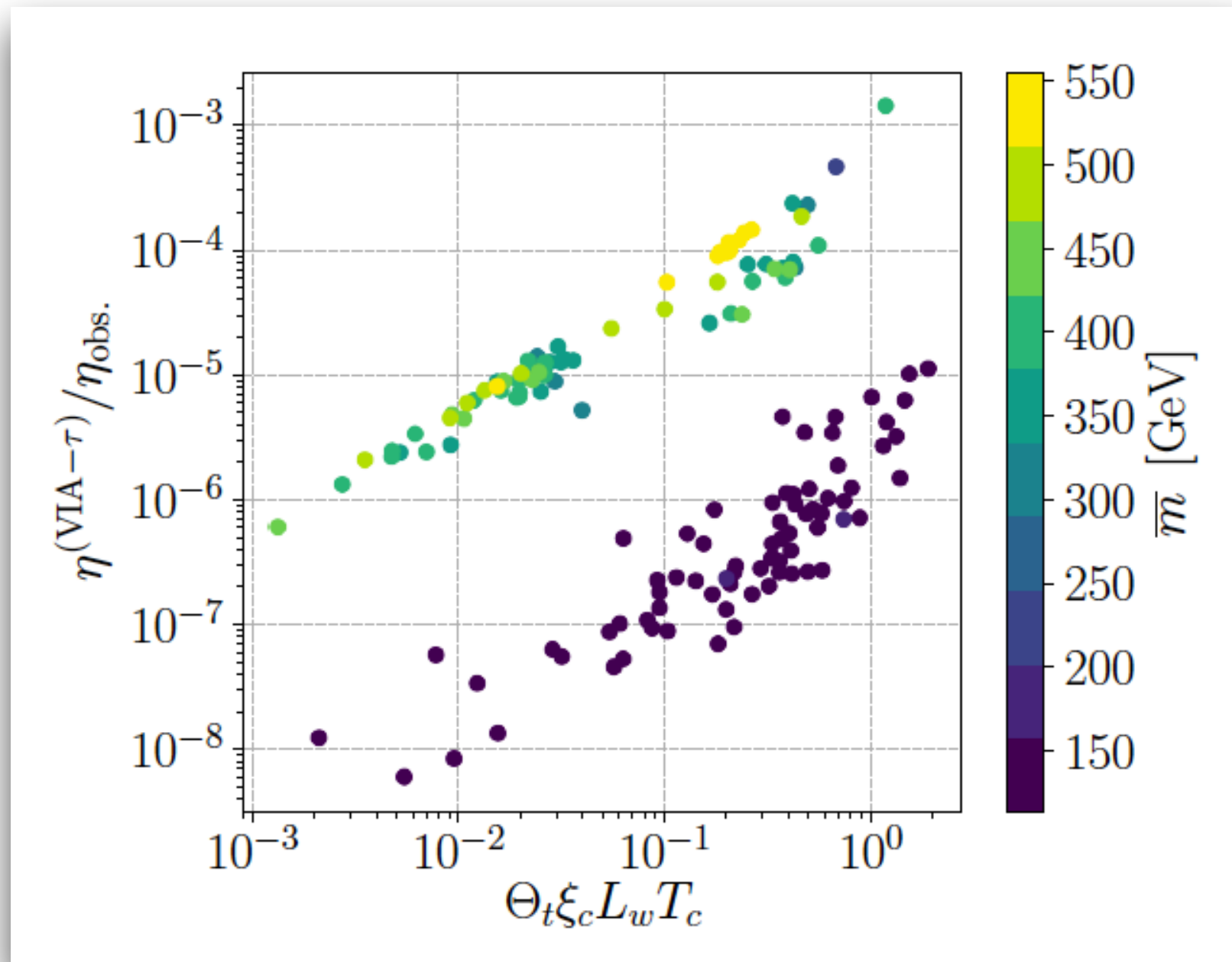


CP-violating
VEV in dark
sector plus
singlet VEV
generated
spontaneously
 $\Rightarrow$ CP violation
transferred
to visible
sector

Strong first order electroweak phase transition

Electroweak Baryogenesis - C2HDM

BSMPT [Basler,MM,Müller,'18,'20;Basler,Biermann,MM,Müller,'22]

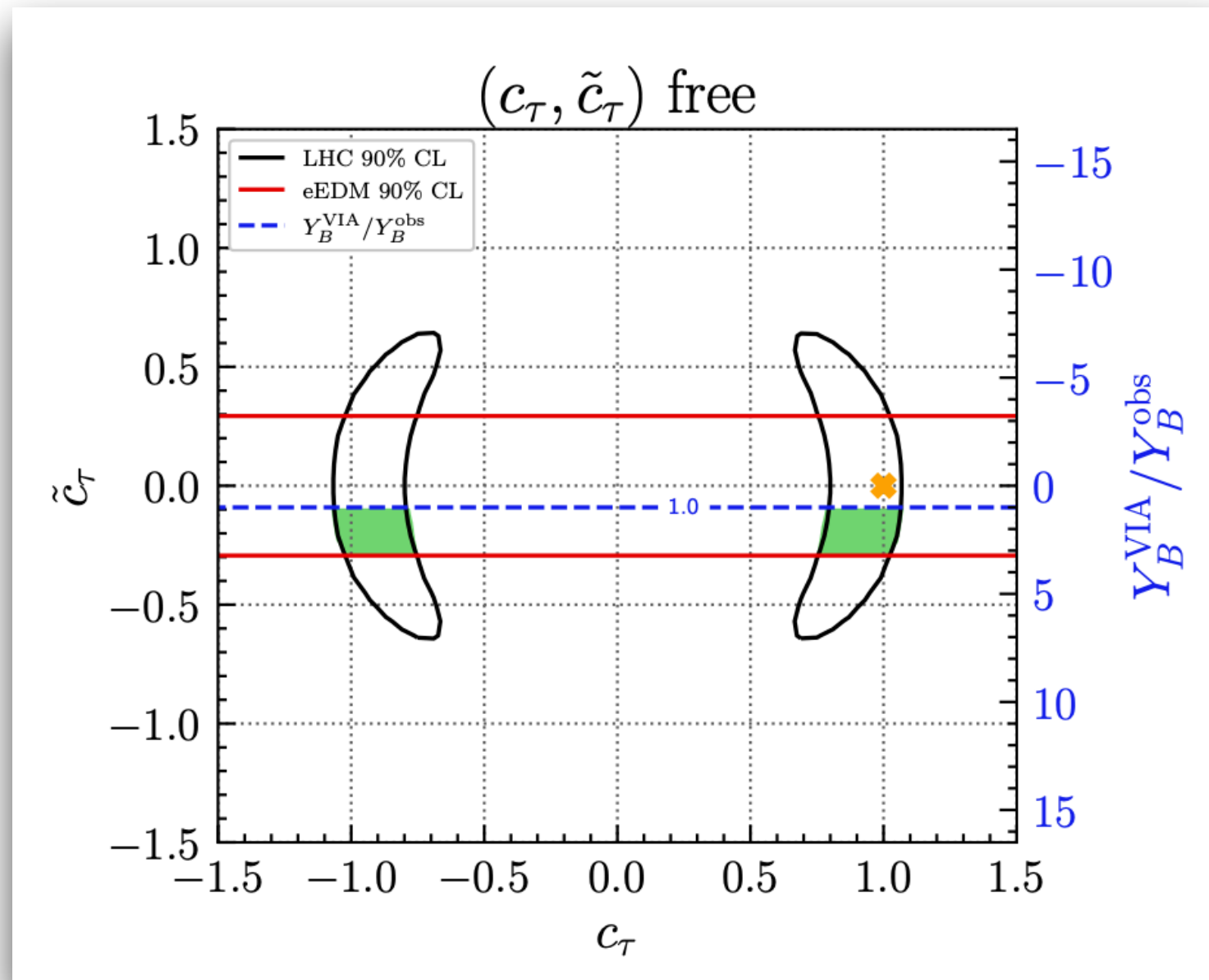


Θ_t CP-violating top-quark phase, L_w wall thickness

but with large uncertainties in the baryogenesis calculation [Postma,van de Vis,White,'22]

CP-violating Higgs-Fermion Couplings, Electron EDM and Baryogenesis

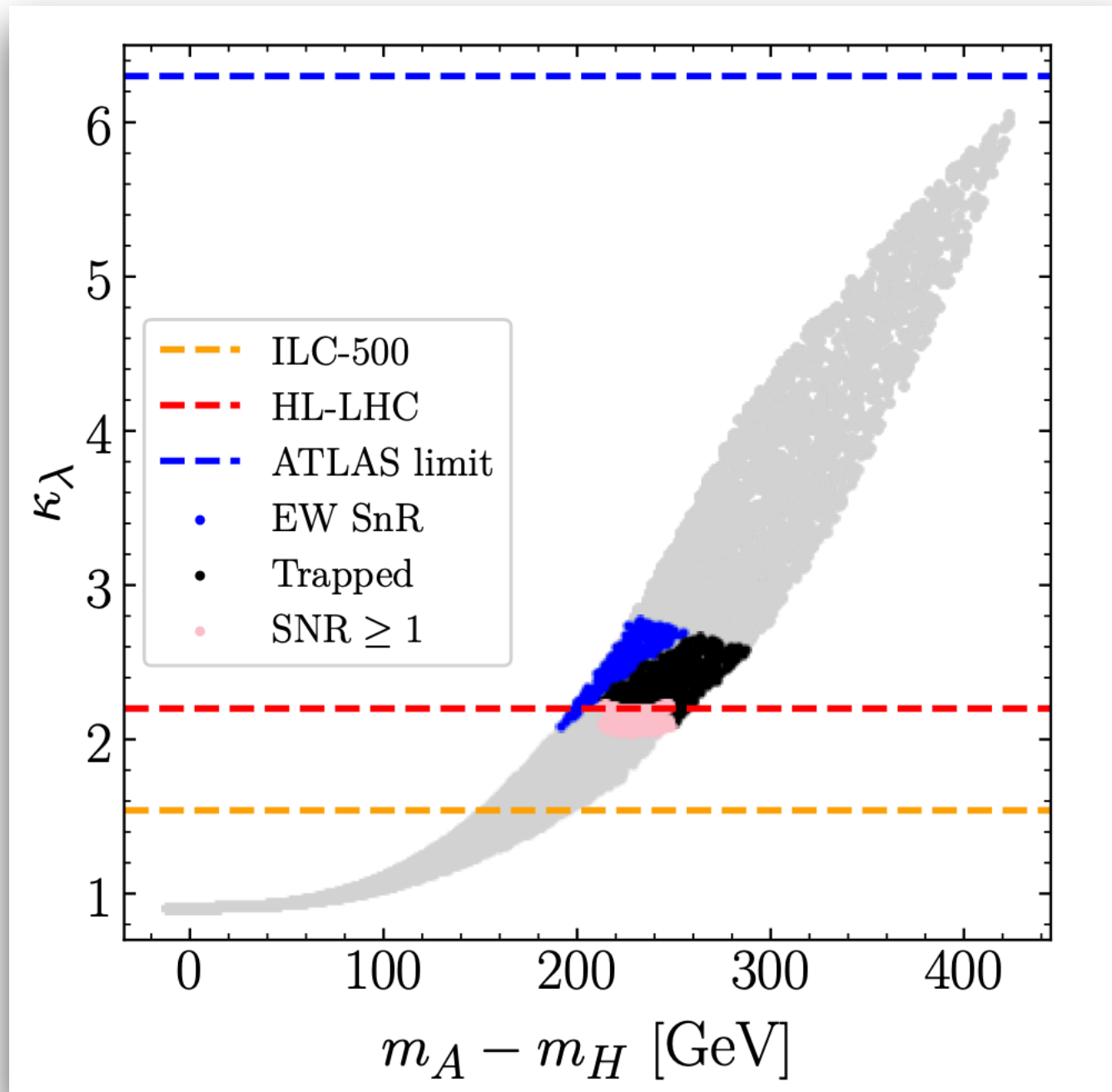
[Bahl,Fuchs,Heinemeyer,Katzy,Menen,Peters,Saimpert,Weiglein,'22]



- Complex tau Yukawa coupling can account for observed baryon asymmetry but with large uncertainties in the baryogenesis calculation [Postma, van de Vis, White, '22]

Interplay between Gravitational Waves and LHC Physics in the 2HDM

[Biekötter, Heinemeyer, No, Olea-Romacho, Weiglein, '22]



Two More DM Models



The Vector Dark Matter Model (VDM)

[Hambye, '08; Lebedev et al., '11; Farzan, Akbarich, '12; Baek et al., '12, '14; Duch et al., '15; Azevedo et al., '18]

- ♦ **The VDM:** SM extended by complex SM-gauge singlet S , charged under $U(1)_\chi$ gauge symmetry; gauged symmetry $\leadsto$ new vector boson χ_μ ; invariance under $\mathbb{Z}_2$ symmetry (under which SM particles are even) $\leadsto$ stable VDM candidate:

$$\chi_\mu \rightarrow -\chi_\mu \quad \text{and} \quad S \rightarrow S^*$$

no kinetic mixing between $U(1)_\chi$ dark gauge boson and SM $U(1)_Y$ gauge boson

- ♦ **Higgs potential:**

$$V = -\mu_H^2 |H|^2 + \lambda_H |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \kappa |S|^2 |H|^2$$

with the doublet and singlet fields

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + \Phi_H + i\sigma_H) \end{pmatrix} \quad \text{and} \quad S = \frac{1}{\sqrt{2}} (v_S + \Phi_S + i\sigma_S)$$

σ_H : neutral SM-like Goldstone boson G^0

σ_S : DM Goldstone boson G^χ

and we have the covariant derivative

$$\mathcal{D}_\mu S = (\partial_\mu + ig_\chi \chi_\mu) S$$

The Vector Dark Matter Model (VDM)

♦ Mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R_\alpha \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix} \equiv \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix}$$

Using the relations

$$\begin{aligned} \lambda_H &= \frac{m_{h_1}^2 \cos^2 \alpha + m_{h_2}^2 \sin^2 \alpha}{2v^2} \\ \kappa &= \frac{(m_{h_1}^2 - m_{h_2}^2) \cos \alpha \sin \alpha}{vv_S} \\ \lambda_S &= \frac{m_{h_1}^2 \sin^2 \alpha + m_{h_2}^2 \cos^2 \alpha}{2v_S} \\ v_S &= \frac{m_\chi}{g_\chi}. \end{aligned}$$

tadpole parameters

♦ Independent physical Higgs potential parameters:

$$m_{h_1}, m_{h_2}, m_\chi, \alpha, v, g_\chi, T_{\Phi_H}, T_{\Phi_S}$$

The Scalar Dark Matter Model (SDM)

[Silveira,Zee,'85; McDonald,'94; ...; see also Gross eal,'17; Azevedo eal,'18; Ishiwata,Toma,'18]

- ♦ **The SDM:** SM extended by complex scalar singlet S , invariant under intrinsic global dark $U(1)$ symmetry

$$S \rightarrow \exp(i\alpha S)$$

soft breaking of this $U(1)$ symmetry to residual $\mathbb{Z}_2$ symmetry: $S \rightarrow -S \leadsto$

- ♦ **Higgs potential:**

$$V = -\frac{\mu_H^2}{2} |H|^2 + \frac{\lambda_H}{2} |H|^4 - \frac{\mu_S^2}{2} |S|^2 + \frac{\lambda_S}{2} |S|^4 + \lambda_{HS} |H|^2 |S|^2 - \frac{m_\chi^2}{4} (S^2 + S^{*2})$$

with the doublet and singlet fields

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + \Phi_H + iG^0) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} (v_s + \Phi_S + i\chi)$$

- ♦ **Mass eigenstates:** χ DM particle with mass m_χ and scalar mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \equiv R(\alpha) \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix}, \quad M^2 \equiv R(\alpha) \mathcal{M}^2 R^{-1}(\alpha) = \begin{pmatrix} m_{h_1}^2 & 0 \\ 0 & m_{h_2}^2 \end{pmatrix} \quad R(\alpha) \equiv \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix}$$

soft breaking term gives mass to DM particle χ

The Scalar Dark Matter Model (SDM)

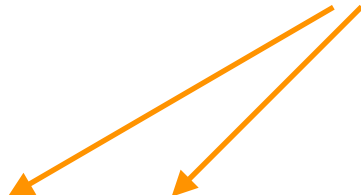
Using the relations

$$\lambda_{HS} = -\frac{m_{h_2}^2 - m_{h_1}^2}{2vv_s} \sin 2\alpha ,$$
$$\lambda_H = \frac{m_{h_2}^2 \sin^2 \alpha + m_{h_1}^2 \cos^2 \alpha}{v^2}$$
$$\lambda_S = \frac{m_{h_2}^2 \cos^2 \alpha + m_{h_1}^2 \sin^2 \alpha}{v_s^2}$$

♦Independent physical Higgs potential parameters:

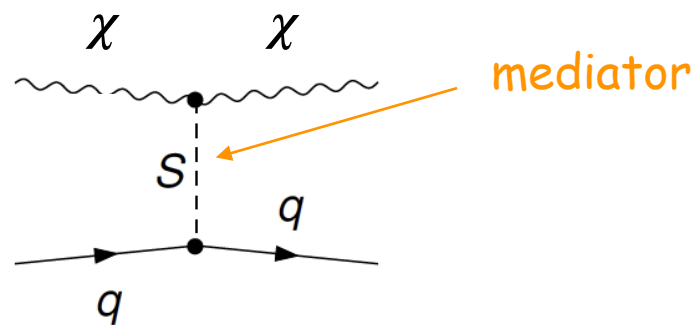
$$v, v_s, \alpha, m_{h_1}^2, m_{h_2}^2, m_\chi^2, T_H, T_S$$

tadpole parameters



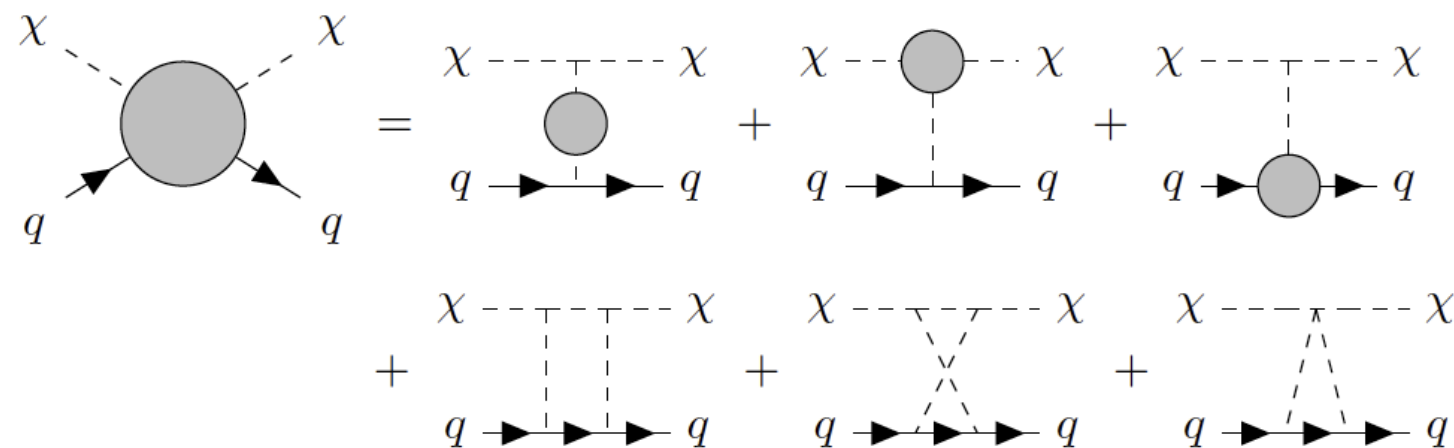
One-loop Corrections to the Spin-Independent DM-Nucleon Cross Section

- ♦ Computation of spin-independent DM-N cxx: use effective Lagrangian



$$\mathcal{L}^{\text{eff}} = \sum_{q=u,d,s} \mathcal{L}_q^{\text{eff}} + \mathcal{L}_G^{\text{eff}}$$

[Hisano,Nagai,Nasato, '15]



generic diagrams:
vertex and mediator corrections

box corrections

- ♦ Approximation:

zero momentum transfer:

incoming momentum of DM equal to outgoing momentum

- ♦ Cross section at Leading Order for the SDM:

equal to zero at vanishing momentum transfer ($\leftarrow$ U(1) symmetry)

Parameter Scan

♦ Scan with ScannerS checks for:

- theoretical constraints: EW minimum=global one, bounded from below, perturbative unitarity
- experimental constraints: EWPD, Higgs data [HiggsBounds, ATLAS,CMS '15]; BRs are computed w/ sHDECAY/anyHDECAY [Costa,MM,Sampaio,Santos,'15/MM,Sampaio,Santos,Wittbrodt,'20]

♦ Dark Matter Constraints:

- DM relic density $< (\Omega h^2)_{\text{DM}}^{\text{obs}} = 0.1186 \pm 0.002 \leadsto$ define DM fraction $f_{\chi\chi} = \frac{(\Omega h^2)_{\chi}}{(\Omega h^2)_{\text{DM}}^{\text{obs}}}$  relic density in our models
- DM annihilation strongest bounds from Fermi-LAT [FermiLAT,'15]; comparison with data through $\sigma_{\chi\chi}^{\text{eff}} = f_{\chi\chi}^2 \sigma_{\chi\chi}$, with $f_{\chi\chi}, \sigma_{\chi\chi}$ obtained from MicrOmegas [Bélanger eal]
- bound on SI DM-nucleon cross section (applied on LO value): for DM mass > 6 GeV limit by Xenon1T [Xenon1T Aprile eal,'18]; for lighter DM masses combined limits by CRESST [CRESST Angloher eal,'15] and CDMSlite [SuperCDMS Agnese eal,'15]; quantity to be compared $\sigma_{\chi N}^{\text{eff}} \equiv f_{\chi\chi} \sigma_{\chi N}$; we use $N=p$, with $m_p = 0.93827$ GeV

♦ Notation and SM parameters: non-SM-like of the h_i ($i=1,2$) called m_{Φ} , SM-like called m_h

$$\begin{array}{llll} m_W & = & 80.398 \text{ GeV} & , \\ m_e & = & 0.511 \cdot 10^{-3} \text{ GeV} & , \\ m_u & = & 0.19 \text{ MeV} & , \\ m_c & = & 1.4 \text{ GeV} & , \end{array} \quad \begin{array}{llll} m_Z & = & 91.1876 \text{ GeV} & , \\ m_\mu & = & 0.1057 \text{ GeV} & , \\ m_d & = & 0.19 \text{ MeV} & , \\ m_b & = & 4.75 \text{ GeV} & , \end{array} \quad \begin{array}{ll} \sin \theta_W & = & 0.4719 & , \\ m_\tau & = & 1.777 \text{ GeV} & , \\ m_s & = & 0.19 \text{ MeV} & , \\ m_t & = & 172.5 \text{ GeV} & . \end{array}$$

Scan Ranges

♦ VDM:

	m_ϕ [GeV]	m_χ [GeV]	v_S [GeV]	α
min	1	1	1	$-\frac{\pi}{4}$
max	1000	1000	10^7	$\frac{\pi}{4}$

with $g_\chi = m_\chi / m_S$ with $g_\chi^2 \leq 4\pi$

♦ SDM:

$$m_\phi \in [30 \text{ GeV}, 1000 \text{ GeV}]$$

$$m_\chi \in [30 \text{ GeV}, 1000 \text{ GeV}]$$

$$v_S \in [1 \text{ GeV}, 1000 \text{ GeV}]$$

$$\alpha \in [-\pi/2, \pi/2]$$

♦ Nuclear proton
matrix elements:

$$f_u^p = 0.01513, \quad f_d^p = 0.0191, \quad f_s^p = 0.0447,$$

$$f_g^p = 0.92107,$$

$$u^p(2) = 0.22, \quad c^p(2) = 0.019,$$

$$\bar{u}^p(2) = 0.034, \quad \bar{c}^p(2) = 0.019,$$

$$d^p(2) = 0.11, \quad s^p(2) = 0.026, \quad b^p(2) = 0.012,$$

$$\bar{d}^p(2) = 0.036, \quad \bar{s}^p(2) = 0.026, \quad \bar{b}^p(2) = 0.012,$$

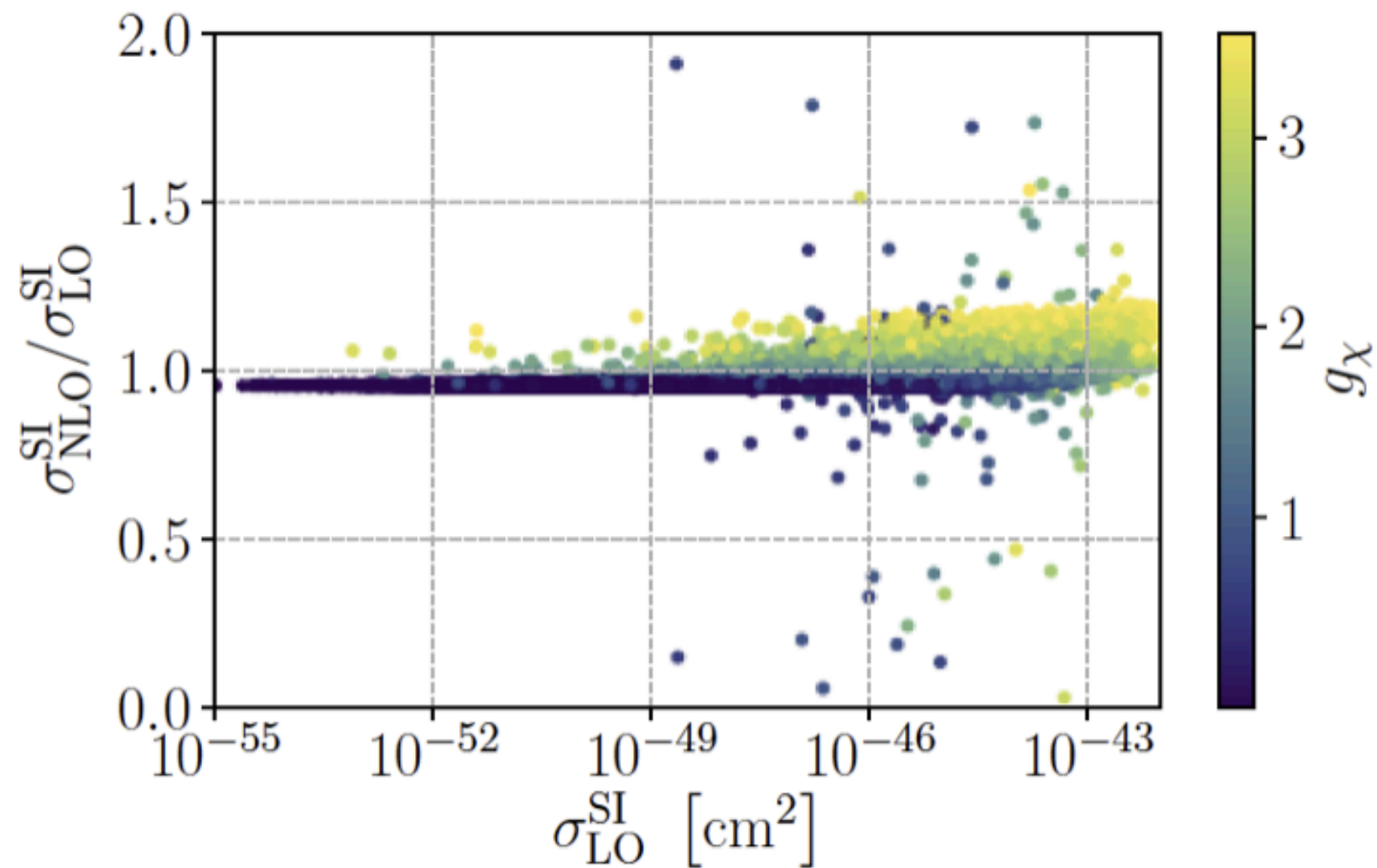
[Hisano, Ishiwata, Nagata, '12;

Young, Thomas, '09;

Shifman, Vainshtein, Zakharov, '78]

VDM: K-Factors

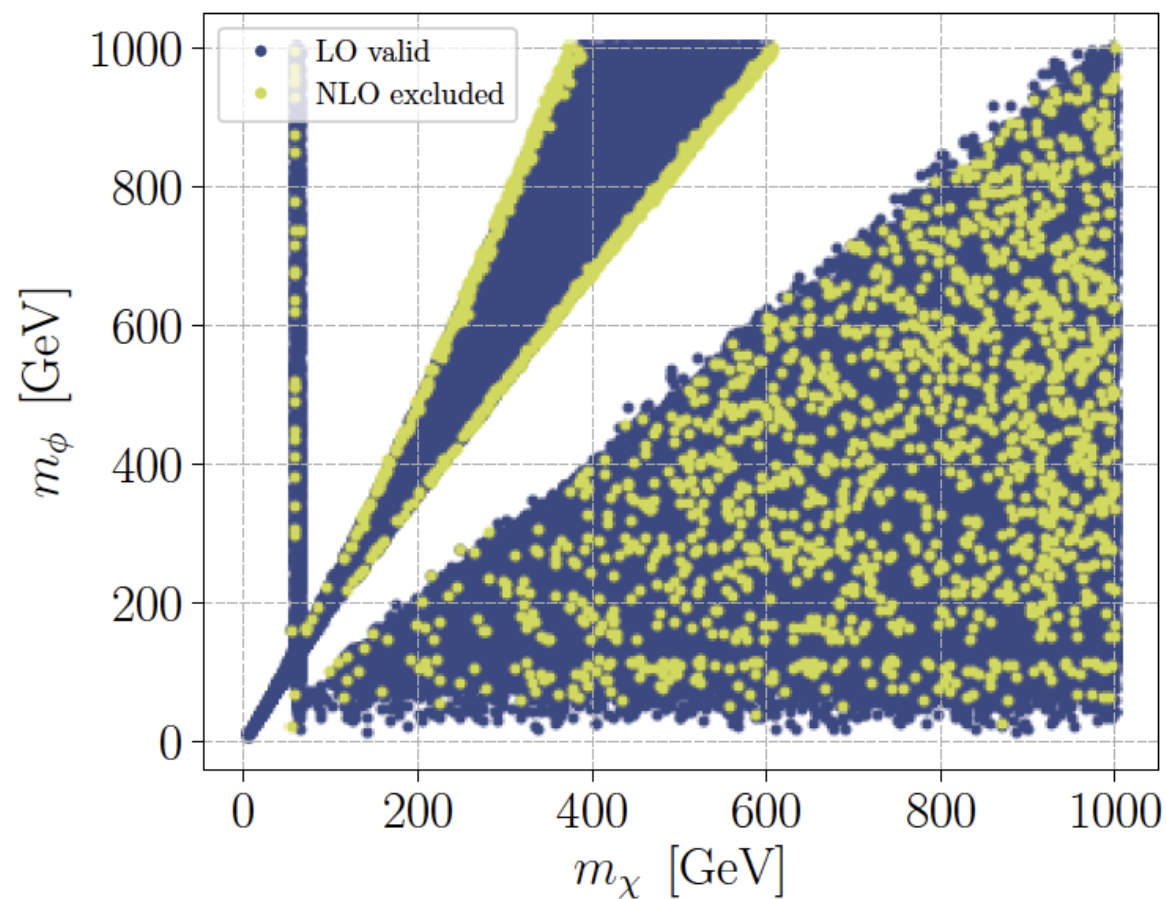
[Glaus,MM,Müller,Patel,Santos,' 20]



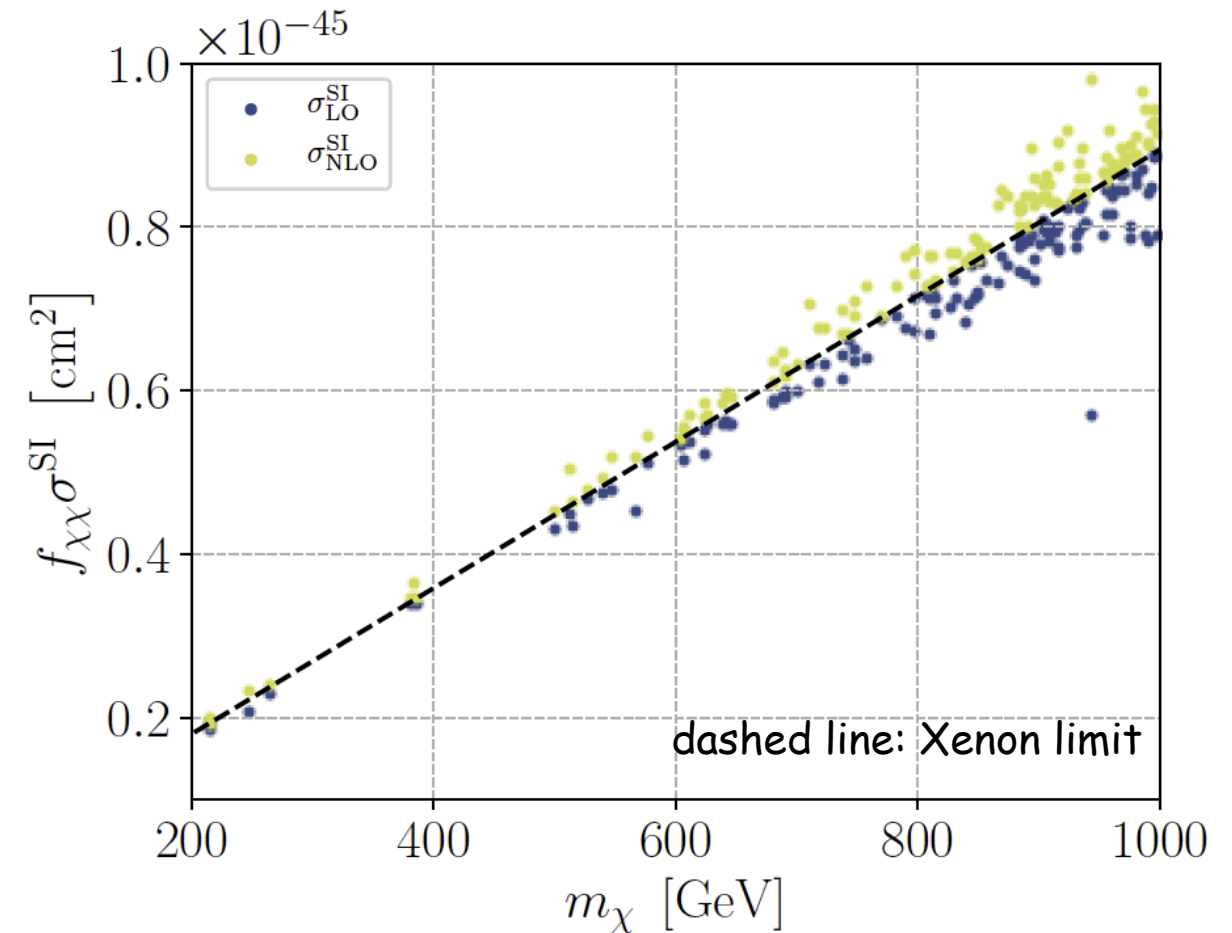
- K-factor increases with g_χ , below 30% (barring outliers)

VDM: Phenomenological Impact

[Glaus,MM,Müller,Patel,Santos,'20]



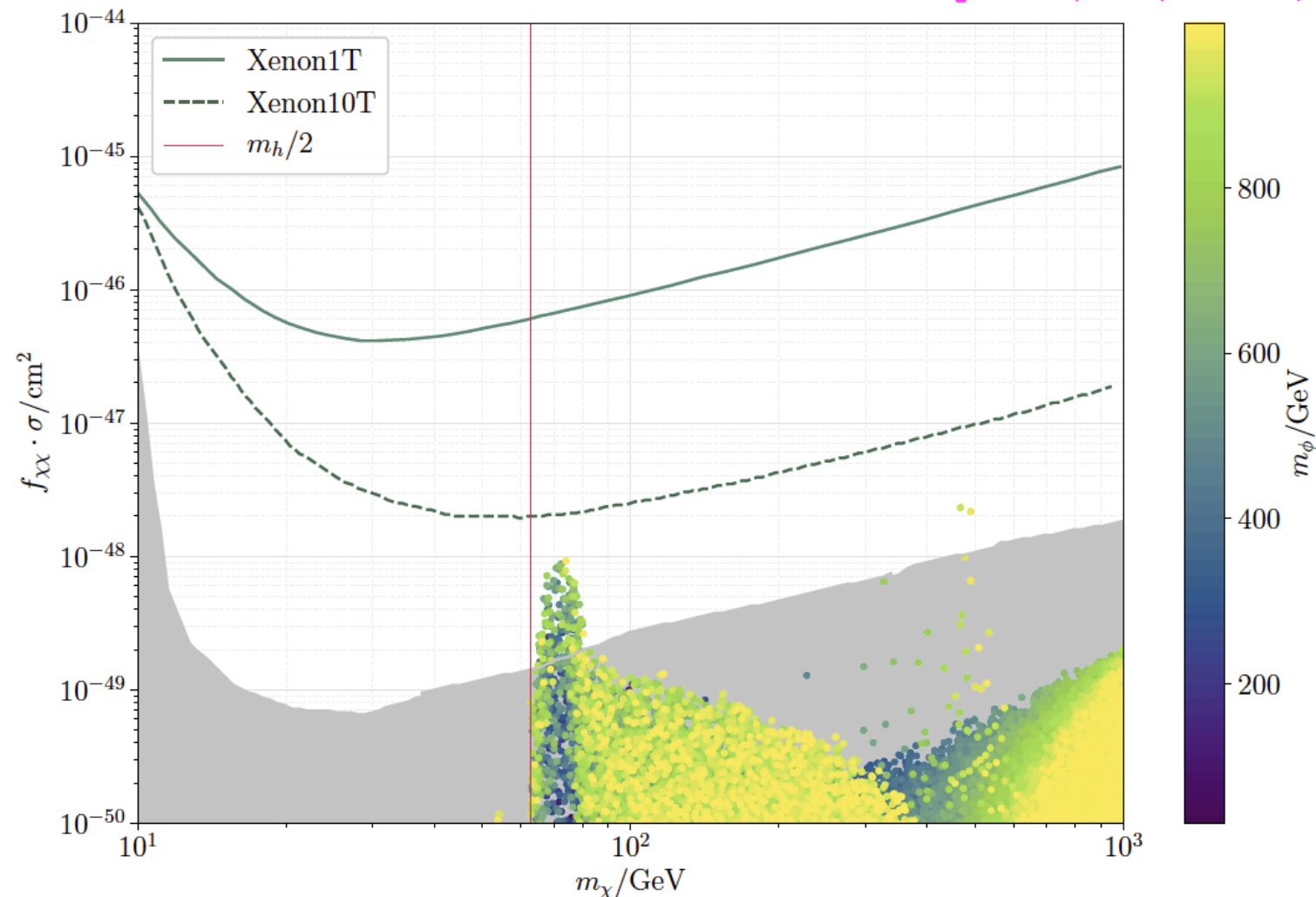
- blue: allowed at LO
- green excluded at NLO



- parameter points, allowed at LO, but excluded at NLO
 $\leadsto$ NLO corrections phenomenologically important

SDM: Impact of NLO Corrections

[Glaus,MM,Müller,Patel,Römer,Santos,'20]



- $\sigma_{\chi\chi}^{\text{LO}} = 0$ (vanishing momentum transfer), NLO corrections shift effective SI cxn above neutrino floor (grey) [Drukier,Stodolsky; COHERENT Coll. Asimov et al,'17]
- at resonances ($m_\chi \gtrsim m_h/2$, $m_\chi \approx m_\phi/2$) suppressed DM-resonance coupling ($\leftarrow$ direct detection), compensated by kinematic resonant enhancement
- $m_\chi < m_h/2$: constrained by Higgs data ($h \rightarrow \chi\chi$)

Computation of the DM-Nucleon Cross Section

♦ Effective Lagrangian:

[Hisano,Nagai,Nasato,'15; Hisano,Ishiwata,Nagata,'10,'15; Ishiwata,Toma,'18; Hisano,Ishiwata,Nagata,Yamanaka,'10]

$$\mathcal{L}^{\text{eff}} = \sum_{q=u,d,s} \mathcal{L}_q^{\text{eff}} + \mathcal{L}_G^{\text{eff}}$$

$$\mathcal{L}_q^{\text{eff}} = f_q \chi \chi m_q \bar{q} q + \frac{g_q}{m_\chi^2} \chi i \partial^\mu i \partial^\nu \chi \mathcal{O}_{\mu\nu}^q$$

$$\mathcal{O}_{\mu\nu}^q = \frac{1}{2} \bar{q} i \left(\partial_\mu \gamma_\nu + \partial_\nu \gamma_\mu - \frac{1}{2} \not{\partial} \right) q$$

$$\mathcal{L}_G^{\text{eff}} = f_G \chi \chi G_{\mu\nu}^a G^{a\mu\nu}$$

χ stands generically for scalar and vector (χ_μ) DM

♦ Nuclear Matrix elements for the partonic operators:

$$\langle N | m_q \bar{q} q | N \rangle = m_N f_{T_q}^N$$

[Shifman,Vainshtein,Zakharov,'78]

$$-\frac{9\alpha_S}{8\pi} \langle N | G_{\mu\nu}^a G^{a,\mu\nu} | N \rangle = \left(1 - \sum_{q=u,d,s} f_{T_q}^N \right) m_N = m_N f_{T_G}^N$$

$N=p,n$, m_N nucleon mass

$$\langle N(p) | \mathcal{O}_{\mu\nu}^q | N(p) \rangle = \frac{1}{m_N} \left(p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu} \right) (q^N(2) + \bar{q}^N(2))$$

$q^N(2), \bar{q}^N(2)$ second moments of (anti-)quark pdfs

♦ DM-Nucleon Cross section:

$$\sigma_N = \frac{1}{\pi} \left(\frac{m_N}{m_\chi + m_N} \right)^2 |f_N|^2.$$

$$f_N/m_N = \sum_{q=u,d,s} f_q f_{T_q}^N + \sum_{q=u,d,s,c,b} \frac{3}{4} (q^N(2) + \bar{q}^N(2)) g_q - \frac{8\pi}{9\alpha_S} f_{T_G}^N f_G$$

Treatment of Heavy Quarks

- ♦ Second momenta (contribution from quark twist-2 operator):

$$\sum_{q=u,d,s,c,b} \frac{3}{4} (q^N(2) + \bar{q}^N(2)) g_q$$

contains all quarks below
energy scale $\sim 1 \text{ GeV}$

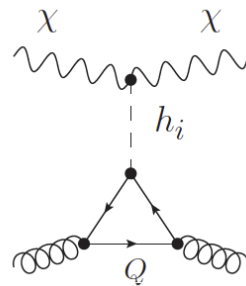
- ♦ Sum over quarks in first term:

$$\sum_{q=u,d,s} f_q f_{T_q}^N$$

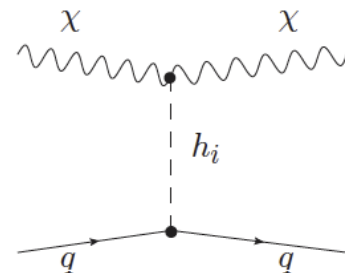
only light quarks

- ♦ Heavy quarks contribute through effective gluon interaction:

obtained from



by integrating out the heavy quarks



equivalent to calculating

w/ $Q=c,t,b$ and replacing resulting
tensor structure $m_Q \bar{Q}Q$ as:

$$m_Q \bar{Q}Q \rightarrow -\frac{\alpha_S}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}$$

and hence

$$f_G = \sum_{q=c,b,t} -\frac{\alpha_S}{12\pi} f_q \quad \text{so that at LO}$$

$$f_N/m_N = \sum_{q=u,d,s} f_q f_{T_q}^N - \frac{8\pi}{9\alpha_S} f_{T_G}^N f_G = f_q \left(\sum_{q=u,d,s} f_{T_q}^N + 3 \cdot \frac{2}{27} f_{T_G}^N \right)$$

Computation of the Wilson Coefficients

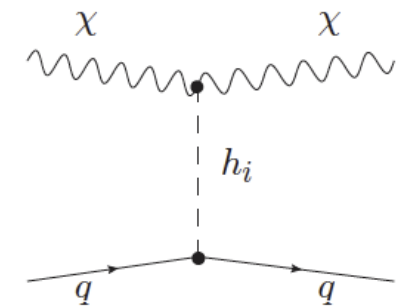
- ♦ Wilson coefficients f_q, g_q, f_G :

compute building blocks of direct detection cross section and match onto tensor structure of effective Lagrangian

- ♦ Cross section at Leading Order for the VDM:

at vanishing momentum transfer, summing over Higgs mediators $h: \sim$

$$f_q = \frac{1}{2} \frac{gg_\chi}{m_W} \frac{\sin(2\alpha)}{2} \frac{m_{h_1}^2 - m_{h_2}^2}{m_{h_1}^2 m_{h_2}^2} m_\chi$$



hence

$$\sigma^{\text{LO}} = \frac{\sin^2 2\alpha}{4\pi} \left(\frac{m_\chi m_N}{m_\chi + m_N} \right)^2 \frac{(m_{h_1}^2 - m_{h_2}^2)^2}{m_{h_1}^4 m_{h_2}^4} \frac{m_\chi^2 m_N^2}{v^2 v_S^2} \left| \sum_{q=u,d,s} f_{T_q}^N + 3 \cdot \frac{2}{27} f_{T_G}^N \right|^2$$

no contribution from twist-2 operator at LO

- ♦ Cross section at Leading Order for the SDM:

equal to zero at vanishing momentum transfer ($\leftarrow$ U(1) symmetry)

Renormalization



Renormalization of the VDM

- ♦ Parameters to be renormalized: DM and scalar fields h_i and m_χ, m_{h_i} , mixing angle α , dark coupling g_χ (dark coupling replaces singlet VEV)

- ♦ Mass and field renormalization: on-shell

$$\delta m_\chi^2 = \text{Re} \Sigma_{\chi\chi}^T(m_\chi^2) \quad \delta Z_{\chi\chi} = -\text{Re} \left. \frac{\partial \Sigma_{\chi\chi}^2(p^2)}{\partial p^2} \right|_{p^2=m_\chi^2}$$

$$\delta m_{h_i}^2 = \text{Re} [\Sigma_{h_i h_i}(m_{h_i}^2) - \delta T_{h_i h_i}] \quad \delta Z_{h_i h_i} = -\text{Re} \left[\frac{\partial \Sigma_{h_i h_i}(p^2)}{\partial p^2} \right]_{p^2=m_{h_i}^2} \quad \delta Z_{h_i h_j} = \frac{2}{m_{h_i}^2 - m_{h_j}^2} \text{Re} [\Sigma_{h_i h_j}(m_{h_j}^2) - \delta T_{h_i h_j}] , \quad i \neq j$$

- ♦ Renormalization of the dark coupling: $\overline{MS}$

$$\delta g_\chi|_\epsilon = \frac{g_\chi^3}{96\pi^2} \Delta_\epsilon \quad \text{with} \quad \Delta_\epsilon = \frac{1}{\epsilon} - \gamma_E + \ln 4\pi$$

Renormalization of the VDM

[Pilaftsis, '97; Kanemura, Okada, Senaha, Yuan, '04; Krause, Lorenz, MM, Santos, Ziesche, '16]

♦ **Mixing angle renormalization:** KOSY scheme, process-dependent scheme, $\overline{\text{MS}}$

(i) **KOSY scheme:** counterterm def. through off-diagonal wave function ren. constants

rotation from gauge
to mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha + \delta\alpha) \sqrt{Z_\Phi} \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix}$$

$$R(\alpha + \delta\alpha) \sqrt{Z_\Phi} \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix} = \underbrace{R(\delta\alpha) R(\alpha) \sqrt{Z_\Phi} R(\alpha)^T}_{\stackrel{!}{=}\sqrt{Z_H}} R(\alpha) \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix} + \mathcal{O}(\delta\alpha^2) = \sqrt{Z_H} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

expansion in α

$$\sqrt{Z_H} = R(\delta\alpha) \begin{pmatrix} 1 + \frac{\delta Z_{h_1 h_1}}{2} & \delta C_h \\ \delta C_h & 1 + \frac{\delta Z_{h_2 h_2}}{2} \end{pmatrix} \approx \begin{pmatrix} 1 + \frac{\delta Z_{h_1 h_1}}{2} & \delta C_h + \delta\alpha \\ \delta C_h - \delta\alpha & 1 + \frac{\delta Z_{h_2 h_2}}{2} \end{pmatrix}$$

on-shell conditions

$$\frac{\delta Z_{h_1 h_2}}{2} \stackrel{!}{=} \delta C_h + \delta\alpha \quad \text{and} \quad \frac{\delta Z_{h_2 h_1}}{2} \stackrel{!}{=} \delta C_h - \delta\alpha$$

$$\begin{aligned} \delta\alpha &= \frac{1}{4} (\delta Z_{h_1 h_2} - \delta Z_{h_2 h_1}) \\ &= \frac{1}{2(m_{h_1}^2 - m_{h_2}^2)} \text{Re}(\Sigma_{h_1 h_2}(m_{h_1}^2) + \Sigma_{h_1 h_2}(m_{h_2}^2) - 2\delta T_{h_1 h_2}) \end{aligned}$$

Renormalization of the VDM

(ii) $\overline{MS}$ scheme: take only divergent part of counterterm in D=4 dimensions

(iii) process dependent scheme: through SM-like h decay $h \rightarrow \tau\tau$

requirement $\mathcal{A}_{h \rightarrow \tau\tau}^{\text{NLO,weak}} \stackrel{!}{=} \mathcal{A}_{h \rightarrow \tau\tau}^{\text{LO}}$

with $\mathcal{A}_{h \rightarrow \tau\tau}^{\text{NLO,weak}} = \mathcal{A}^{\text{LO}} + \mathcal{A}^{\text{virt,weak}} + \mathcal{A}^{\text{ct}}$

leads to $\mathcal{A}^{\text{virt,weak}} + \mathcal{A}^{\text{ct}} = 0$ so that finally

$$\delta\alpha = \left(\frac{2m_W}{gm_\tau \cos \alpha} \right) \left[\mathcal{A}^{\text{virt,weak}} + \mathcal{A}^{\text{ct}} \Big|_{\delta\alpha=0} \right]$$

Note: weak corrections form UV-finite subset (electromagnetic corrs. exhibit IR divergence, to be avoided)

Renormalization of the SDM

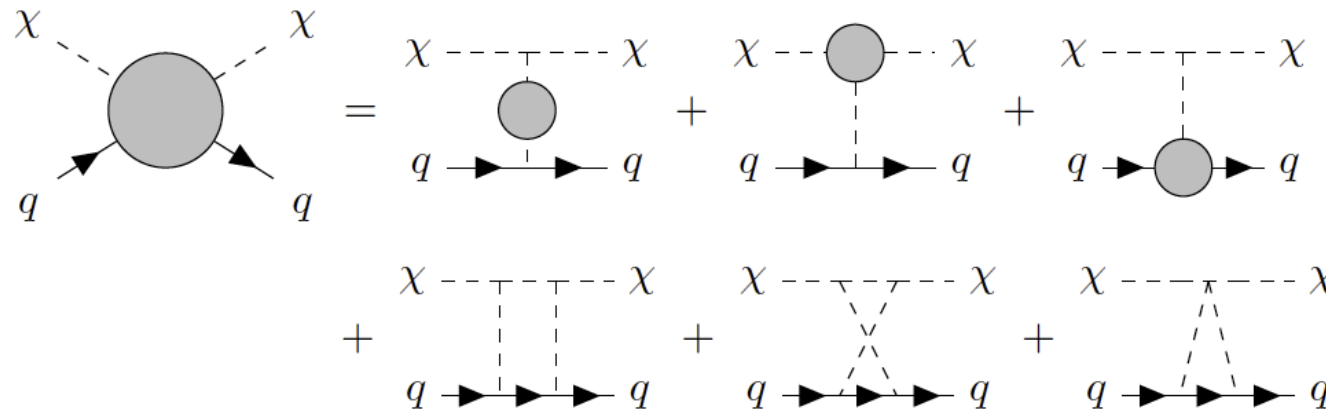
- ♦ Parameters to be renormalized: DM and scalar fields h_i and m_χ, m_{h_i} , mixing angle α , **singlet VEV v_s** (singlet VEV instead of dark coupling)
 - ♦ Mass and field renormalization: on-shell - like in VDM
 - ♦ Renormalization of the singlet VEV: we use standard tadpole scheme:
in R_ξ gauge singlet VEV does not need to be renormalized at 1-loop if scalar field obeys rigid invariance (disconnected from scalar sector $\leadsto$ invariance under global transformations)
[Sperling, Stöckinger, Voigt, '13]
 - ♦ Mixing angle renormalization: KOSY scheme
-

The NLO Cross Section



The SI Cross Section at NLO

♦ NLO contributions:



Calculation of loops including ct diagrams $\leadsto$ result can be expressed in terms of form factors of the effective Lagrangian

♦ One-loop Wilson coefficients:

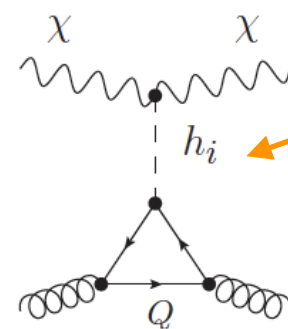
Light quark contributions

$$f_q^{\text{NLO}} = f_q^{\text{vertex}} + f_q^{\text{med}} + f_q^{\text{box}}$$

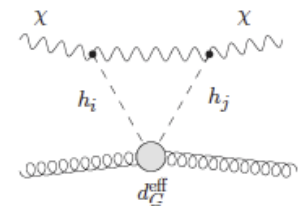
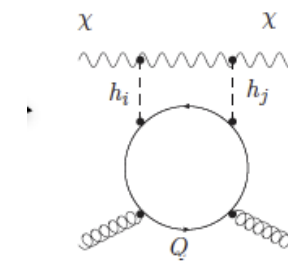
$$g_q^{\text{NLO}} = g_q^{\text{box}}$$

heavy quark contributions

$$f_G^{\text{NLO}} = -\frac{\alpha_S}{12\pi} \sum_{q=c,b,t} \left(f_q^{\text{vertex}} + f_q^{\text{med}} \right) + f_G^{\text{top}}$$

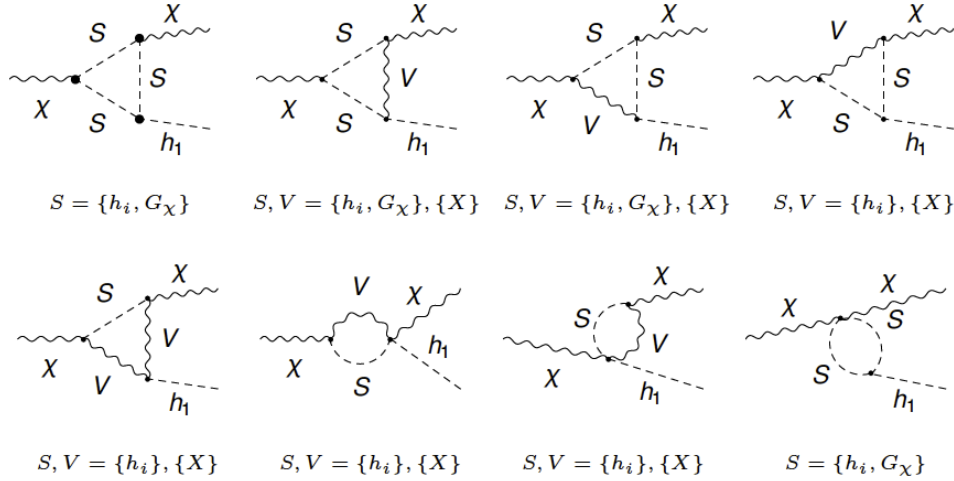


vertex&mediator corrections to this diagram

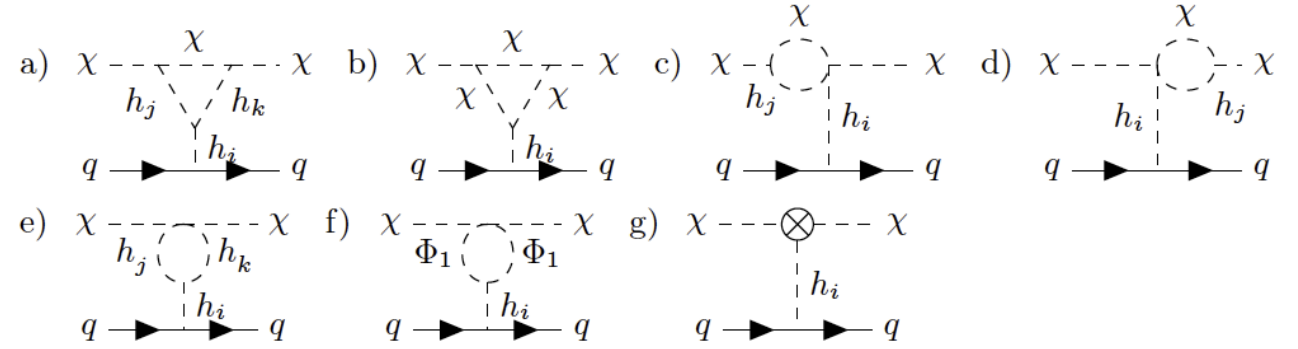


Upper Vertex Corrections

♦ Upper vertex corrections:



VDM



SDM

Computation of
with

$$i\mathcal{A}_{\chi\chi h_i}^{\text{NLO}} = i\mathcal{A}_{\chi\chi h_i}^{\text{LO}} + i\mathcal{A}_{\chi\chi h_i}^{\text{VC}} + i\mathcal{A}_{\chi\chi h_i}^{\text{CT}}$$

$$i\mathcal{A}_{\chi\chi h_i}^{\text{LO}} = g_{\chi\chi h_i} \varepsilon(p) \cdot \varepsilon^*(p) = 2g_\chi m_\chi \varepsilon(p) \cdot \varepsilon^*(p) \begin{cases} \sin \alpha, & i = 1 \\ \cos \alpha, & i = 2 \end{cases}$$

$$i\mathcal{A}_{\chi \rightarrow \chi h_1}^{\text{CT}} = \left[\frac{1}{2} (g_{\chi\chi h_2} \delta Z_{h_2 h_1} + g_{\chi\chi h_1} \delta Z_{h_1 h_1}) + g_{\chi\chi h_1} \delta Z_{\chi\chi} + \delta g_{\chi\chi h_1} \right] \varepsilon(p) \cdot \varepsilon^*(p)$$

$$i\mathcal{A}_{\chi \rightarrow \chi h_2}^{\text{CT}} = \left[\frac{1}{2} (g_{\chi\chi h_1} \delta Z_{h_1 h_2} + g_{\chi\chi h_2} \delta Z_{h_2 h_2}) + g_{\chi\chi h_2} \delta Z_{\chi\chi} + \delta g_{\chi\chi h_2} \right] \varepsilon(p) \cdot \varepsilon^*(p)$$

results in tensor structure

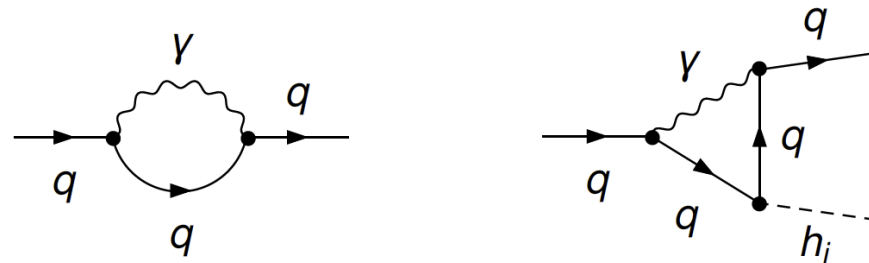
$$i\mathcal{A}^{\text{NLO}} = (\dots) \underbrace{\varepsilon(p_{\text{in}}) \cdot \varepsilon^*(p_{\text{out}})}_{\sim \text{LO}} + (\dots) \underbrace{(p_{\text{in}} \cdot \varepsilon^*(p_{\text{out}})) (p_{\text{out}} \cdot \varepsilon(p_{\text{in}}))}_{\sim \text{NLO}}$$

with our approximation $p_{\text{in}} = p_{\text{out}}$ second tensor structure vanishes

Lower Vertex Corrections

♦ Lower vertex corrections:

we encounter IR divergences in VDM from QED subset



diagrams form UV-finite subset

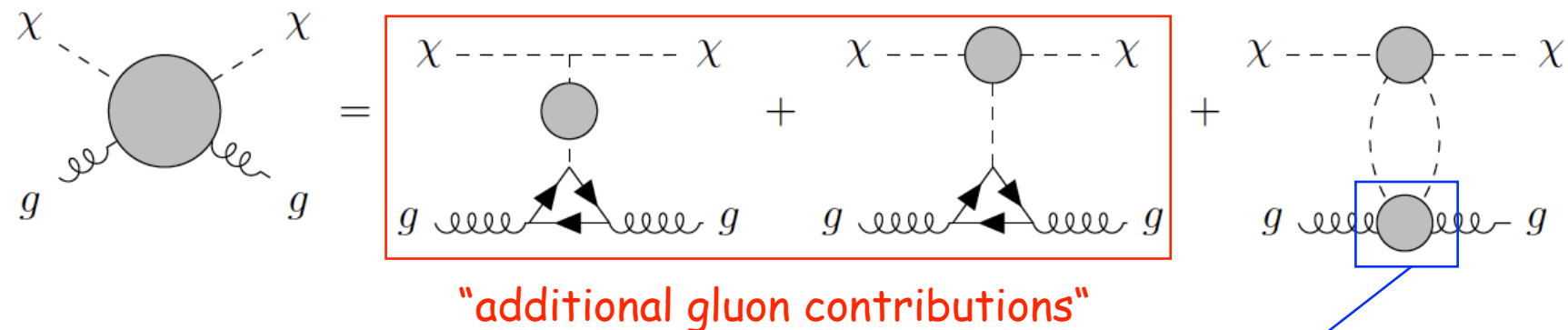
expansion for strictly vanishing external quark momentum and neglecting terms of $\mathcal{O}(p_q^2) \leadsto$ regularization of IR divergences in VDM

SDM: U(1) symmetry of the potential $\leadsto$ complete cancellation of the QED subset, hence no IR divergences

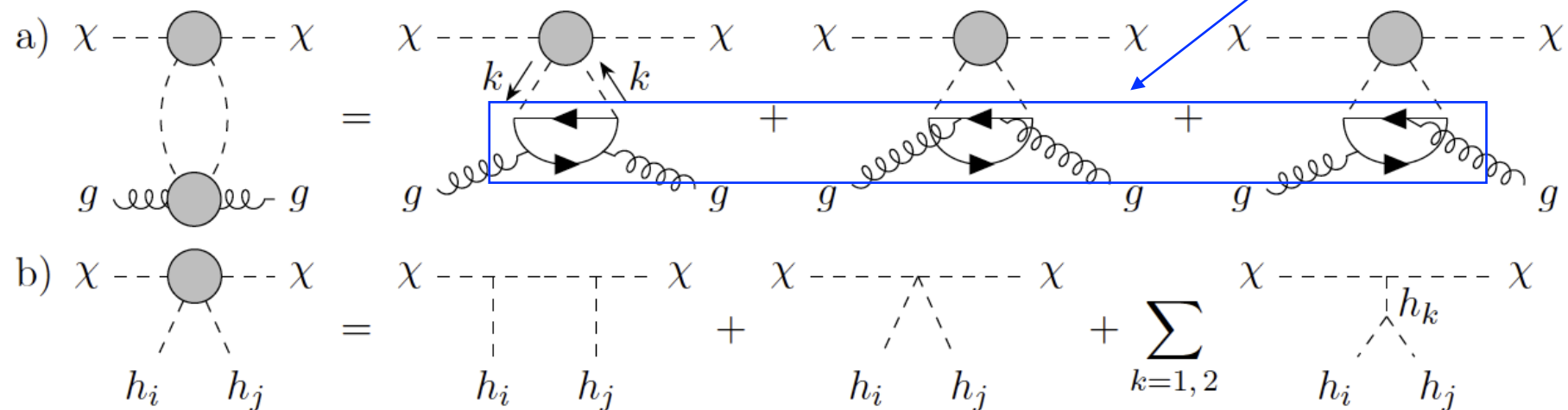
Heavy Quarks

- ♦ Inclusion of heavy quarks through replacement rule $m_Q \bar{Q}Q \rightarrow -\frac{\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}$

Inclusion of EW corrections would require two-loop matching of QCD trace anomaly!



with

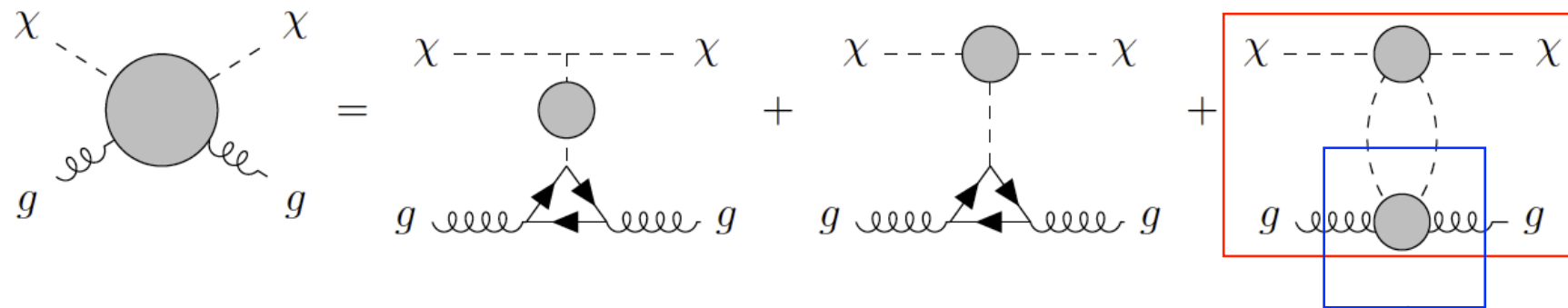


Our approach: no inclusion of EW correction to heavy quark contributions

only for comparison w/ literature we include the "additional gluon contributions"

[Ishiwata,Toma,'18]

Heavy Quarks



- ♦ Treatment of third diagram (gluon box diagrams): replace lower vertex by effective vertex

$$\approx \frac{ig_s^2}{48\pi^2 m_t^2} a_i a_j$$

[Hisano,Ishiwata,Nagata,'10;
Abe,Fujiwara,Hisano,'19;
Ertas,Kahlhoefer,'19]

produced by

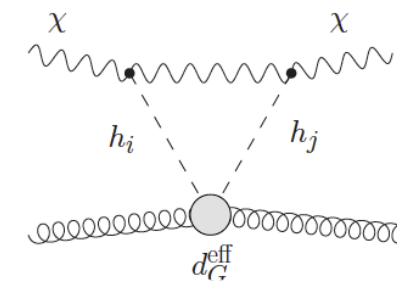
$$\mathcal{L} \supset \frac{1}{2} \frac{g_s^2}{48\pi^2 m_t^2} a_i a_j h_i h_j G_{\mu\nu}^a G^{a\mu\nu}$$

combination with

$$=$$

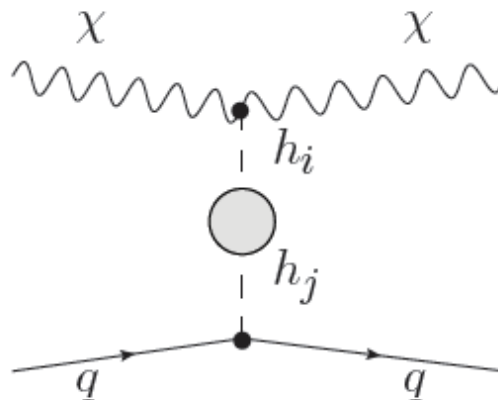
leads to

$$f_G^{\text{top}} = \left(d_G^{\text{eff}}\right)_{ij} C_{\Delta}^{ij} \frac{-\alpha_S}{12\pi}$$



Mediator Corrections

♦ Mediator corrections:



in approximation of zero momentum exchange we get

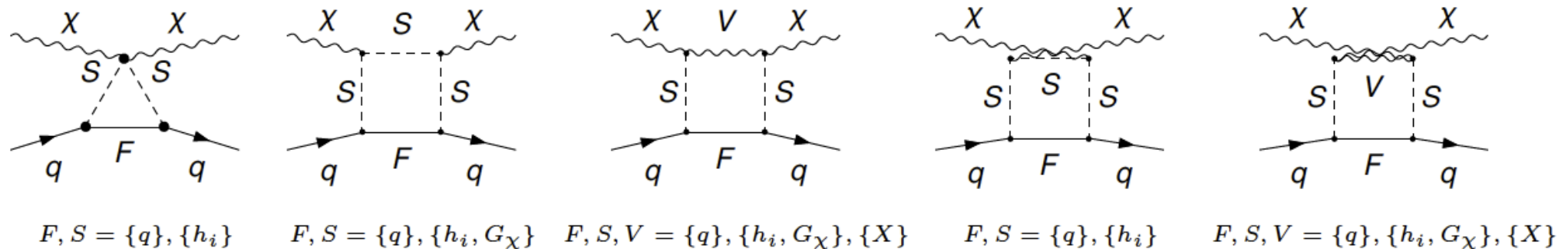
$$\Delta_{h_i h_j} = -\frac{\hat{\Sigma}_{h_i h_j}(p^2 = 0)}{m_{h_i}^2 m_{h_j}^2}$$

projection on corresponding tensor structure $\leadsto$ effective NLO correction to
Wilson coefficient of operator $m_q \chi \chi q \bar{q}$

$$f_q^{\text{med}} = \frac{g g_\chi m_\chi}{2m_W} \sum_{i,j} R_{\alpha,i2} R_{\alpha,j1} \Delta_{h_i h_j}$$

Box Corrections

♦ Box corrections:



expansion of propagator terms in small quark momentum $\leadsto$ projection onto required tensor structures $\leadsto$ we get the box contribution to the Wilson coefficients f_q^{box} and g_q^{box}

Result for SI Cross Section at NLO

♦ LO form factor:

$$\frac{f_N^{\text{LO}}}{m_N} = f_q^{\text{LO}} \left[\sum_{q=u,d,s} f_{T_q}^N + \sum_{q=c,b,t} \frac{2}{27} f_{T_G}^N \right]$$

♦ NLO form factor:

$$\frac{f_N^{\text{NLO}}}{m_N} = \sum_{q=u,d,s} f_q^{\text{NLO}} f_{T_q}^N + \sum_{q=u,d,s,c,b} \frac{3}{4} (q(2) + \bar{q}(2)) g_q^{\text{NLO}} - \frac{8\pi}{9\alpha_S} f_{T_G}^N f_G^{\text{NLO}}$$

with

$$f_q^{\text{NLO}} = f_q^{\text{vertex}} + f_q^{\text{med}} + f_q^{\text{box}}$$

$$g_q^{\text{NLO}} = g_q^{\text{box}}$$

$$f_G^{\text{NLO}} = -\frac{\alpha_S}{12\pi} \sum_{q=c,b,t} \left(f_q^{\text{vertex}} + f_q^{\text{med}} \right) + f_G^{\text{top}}$$

“additional gluon contributions”

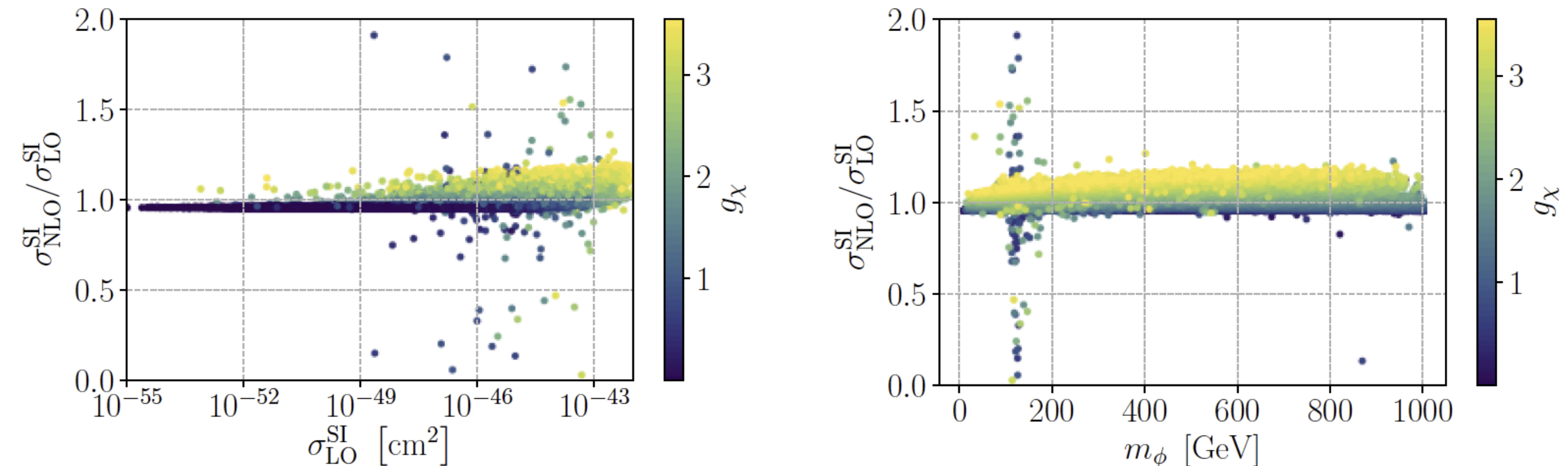
♦ NLO cross section:

$$\sigma_N = \frac{1}{\pi} \left(\frac{m_N}{m_\chi + m_N} \right)^2 \left[|f_N^{\text{LO}}|^2 + 2\text{Re} (f_N^{\text{LO}} f_N^{\text{NLO}*}) \right] \quad \text{VDM}$$

$$\sigma_N = \frac{1}{\pi} \left(\frac{m_N}{m_\chi + m_N} \right)^2 \left[|f_N^{\text{NLO}}|^2 \right] \quad \text{SDM}$$

VDM: K-Factors

[Glaus,MM,Müller,Patel,Santos,'20]



- K-factor increases with g_χ , below 30% (barring outliers)
- for $m_\phi \approx m_h$ K-factor close to 2 due to resonant behavior in vertex correction
- blind spots are the same for LO and NLO