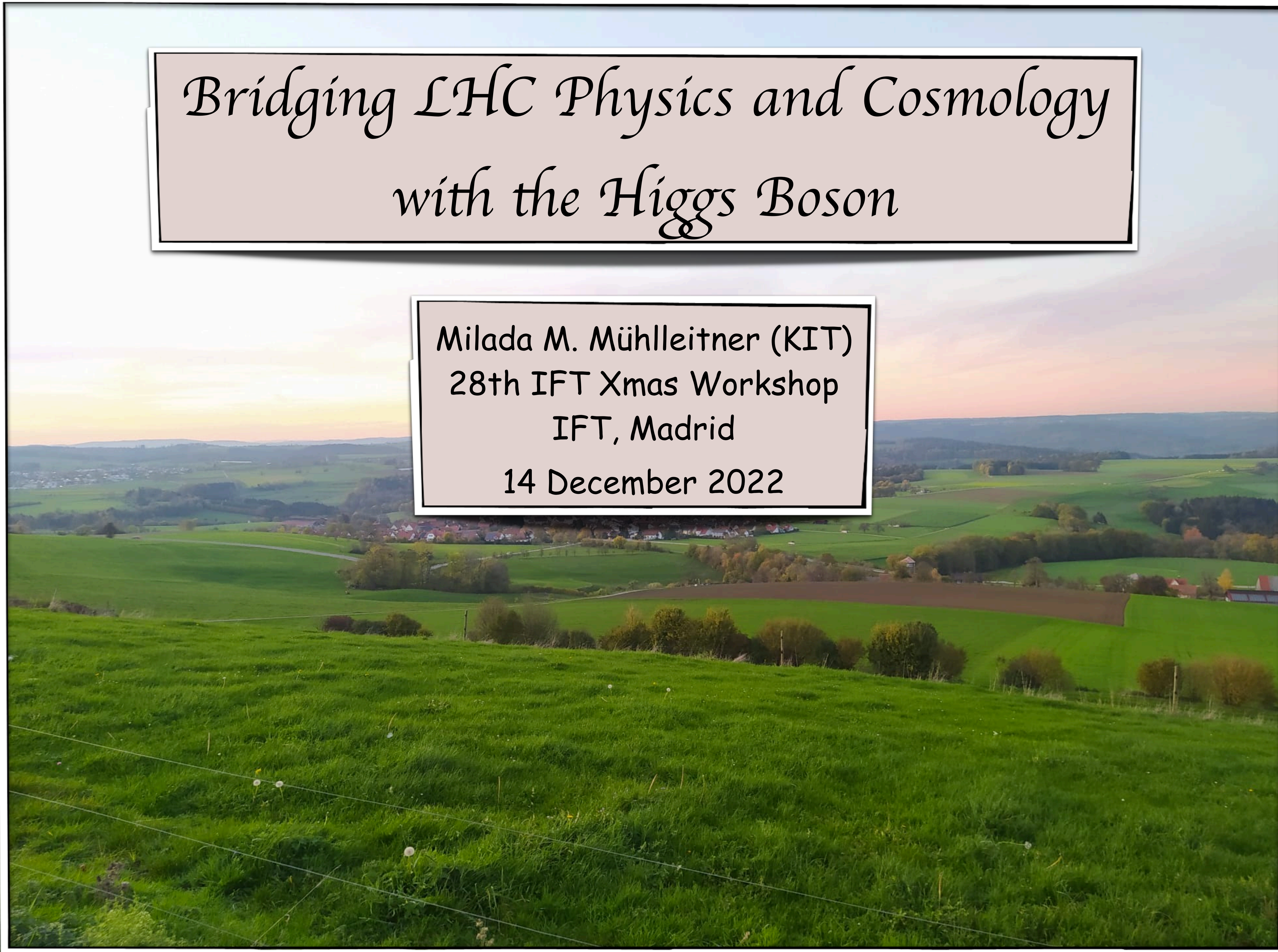
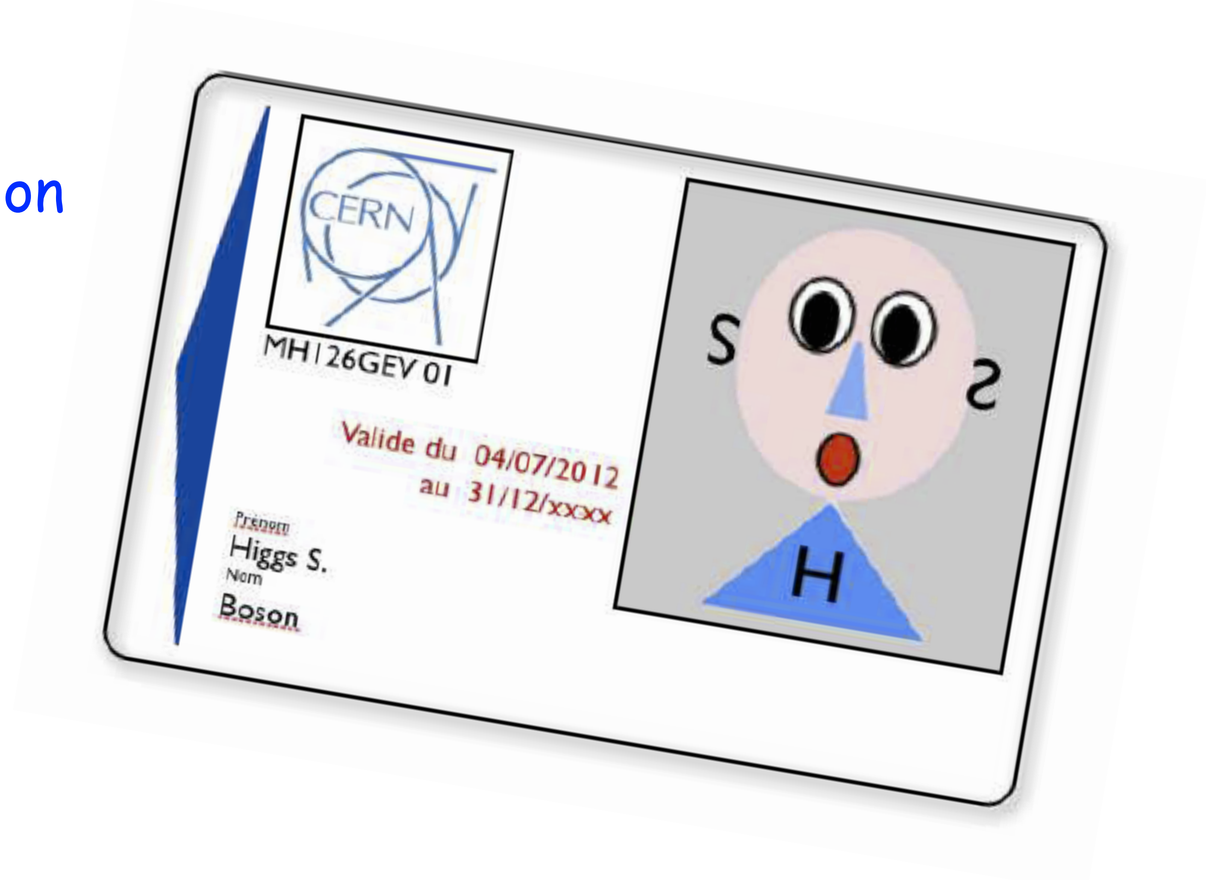
Bridging LHC Physics and Cosmology with the Higgs Boson

Milada M. Mühlleitner (KIT)
28th IFT Xmas Workshop
IFT, Madrid
14 December 2022



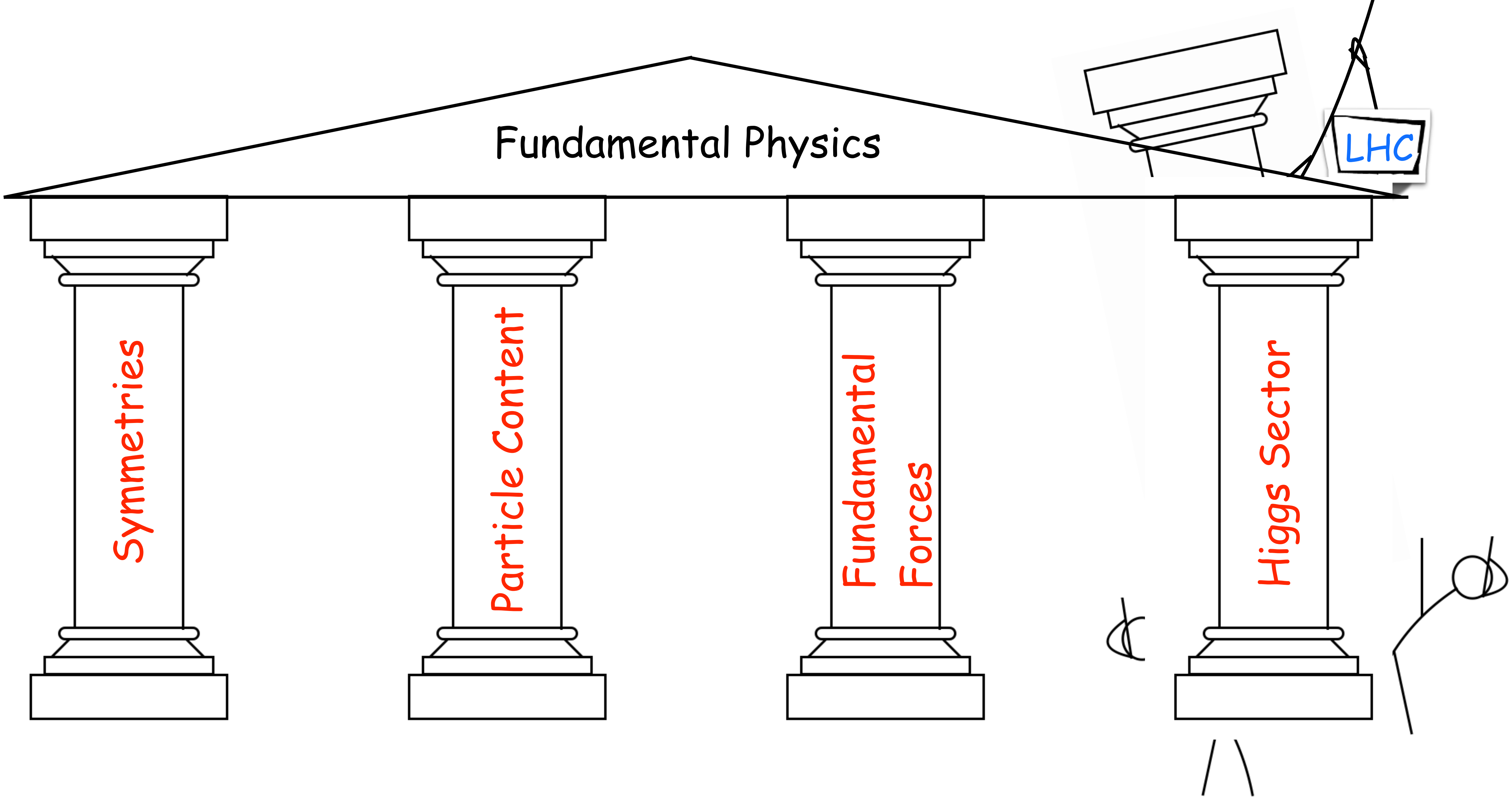
Outline

- 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->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

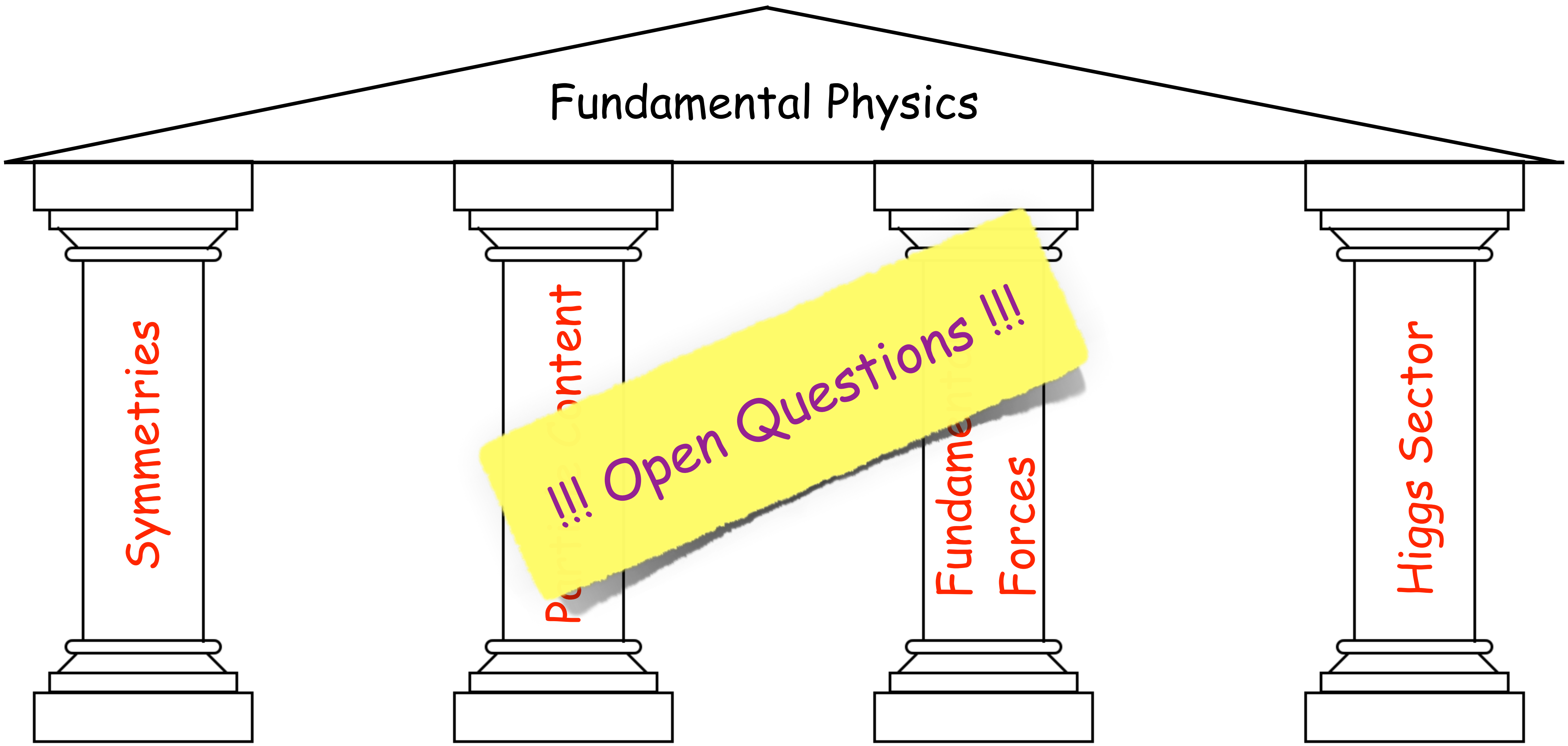


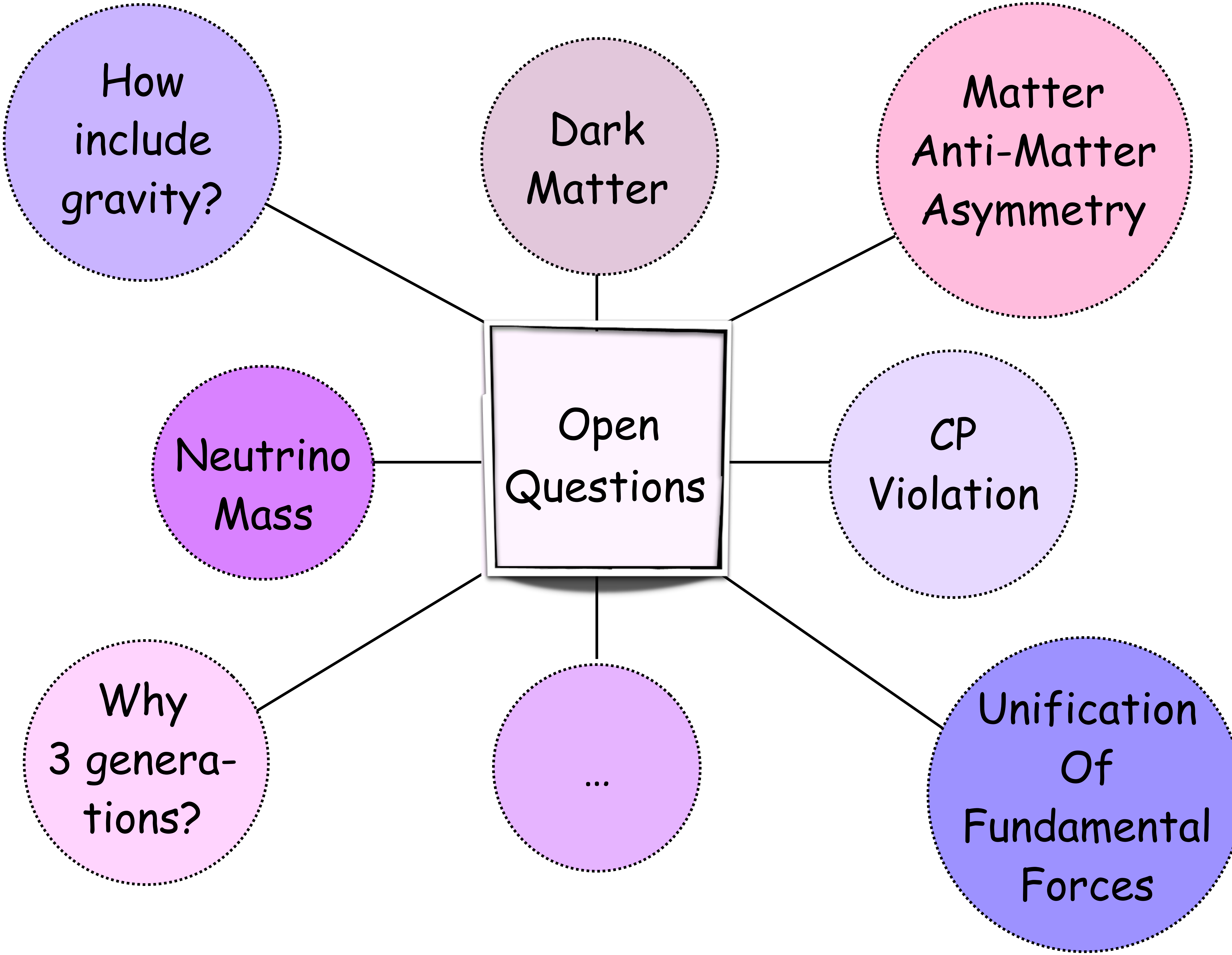
The Standard Model is Structurally Complete

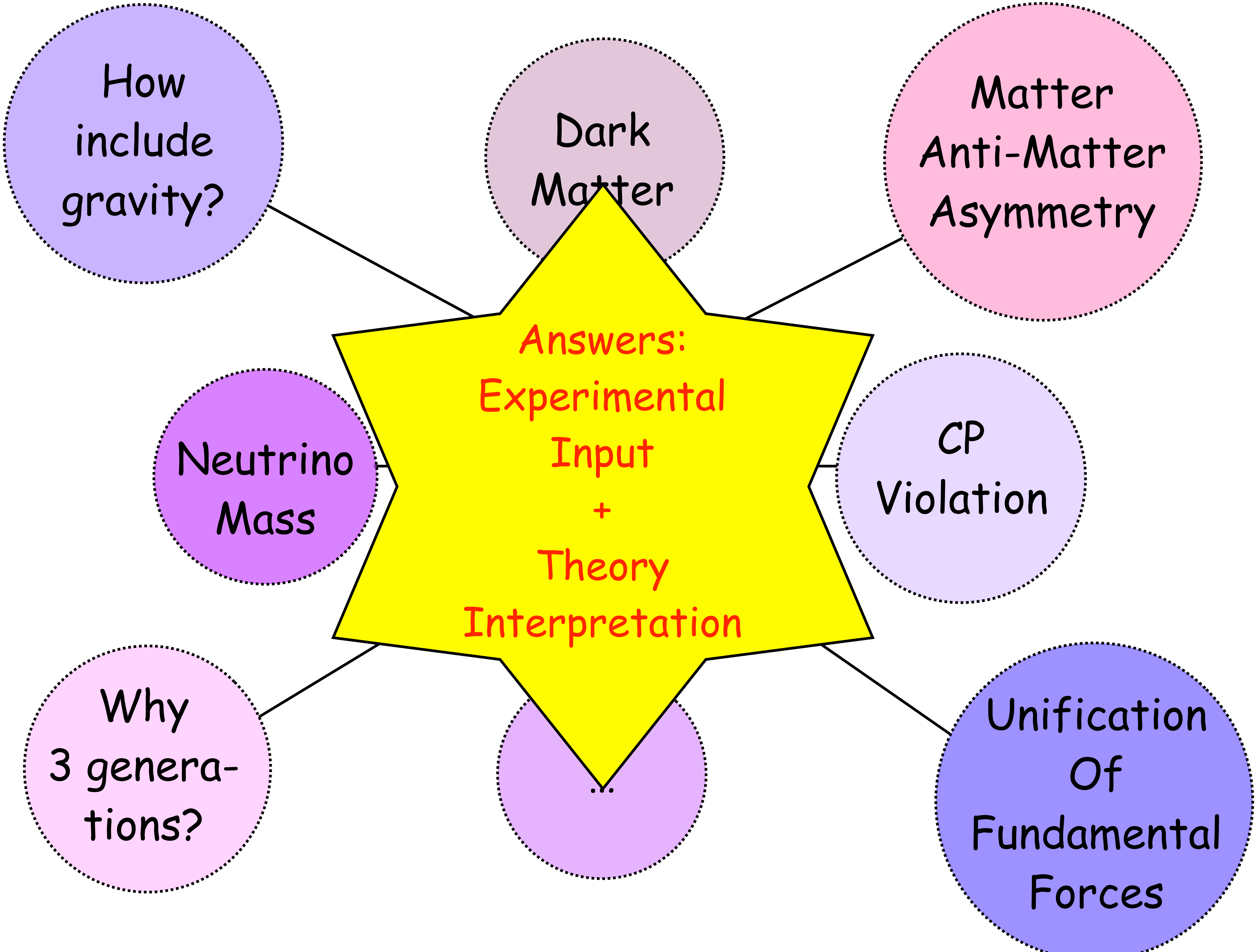
The Four Pillars of the Standard Model



The Standard Model is Structurally Complete - But




How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Open Questions
CP Violation
Why 3 genera-tions?
...
Unification Of Fundamental Forces


How include gravity?
Dark Matter
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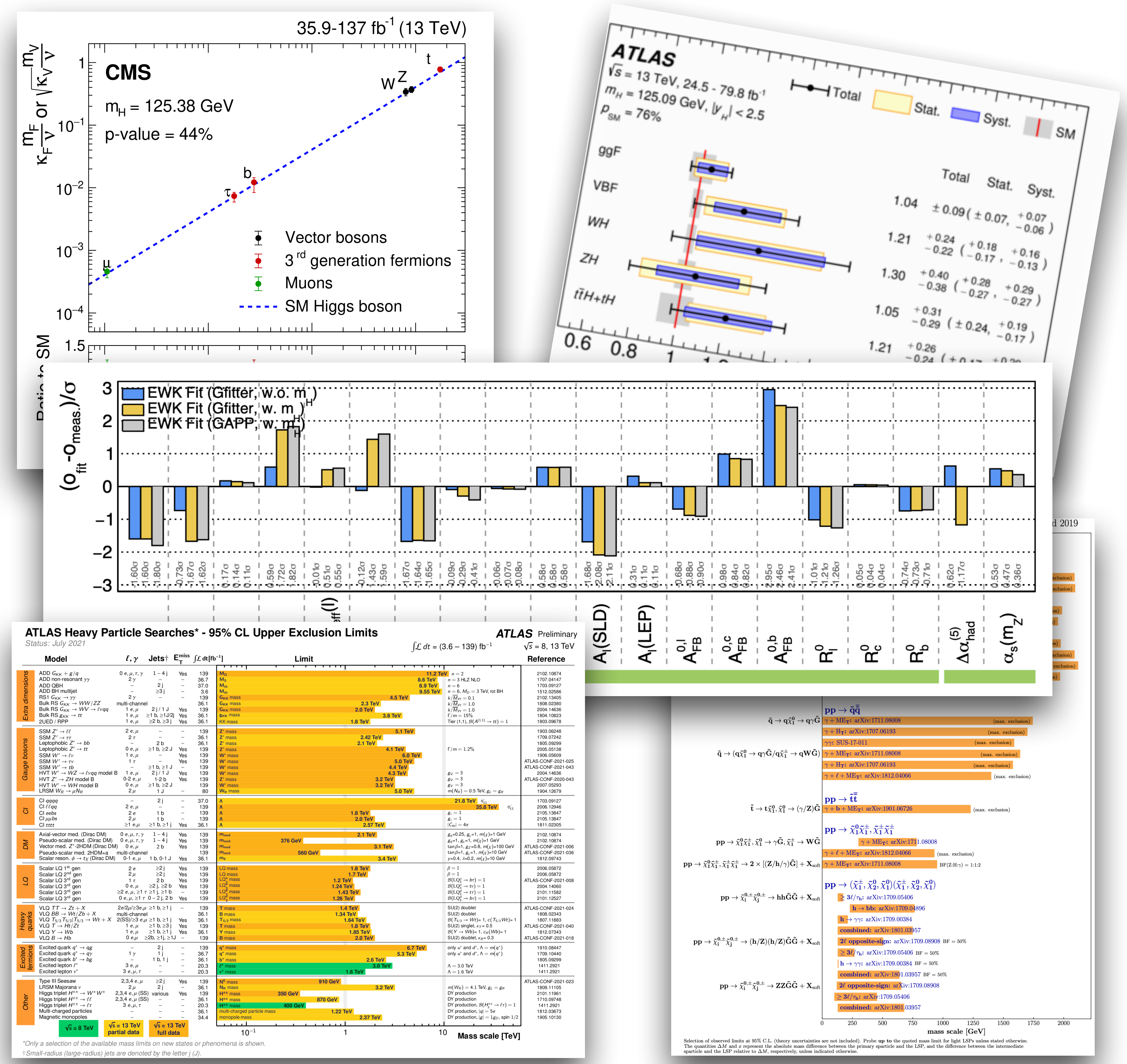
Neutrino Mass
Answers: Experimental Input + Theory Interpretation
CP Violation
Why 3 generations?
...
Unification Of Fundamental Forces

Status

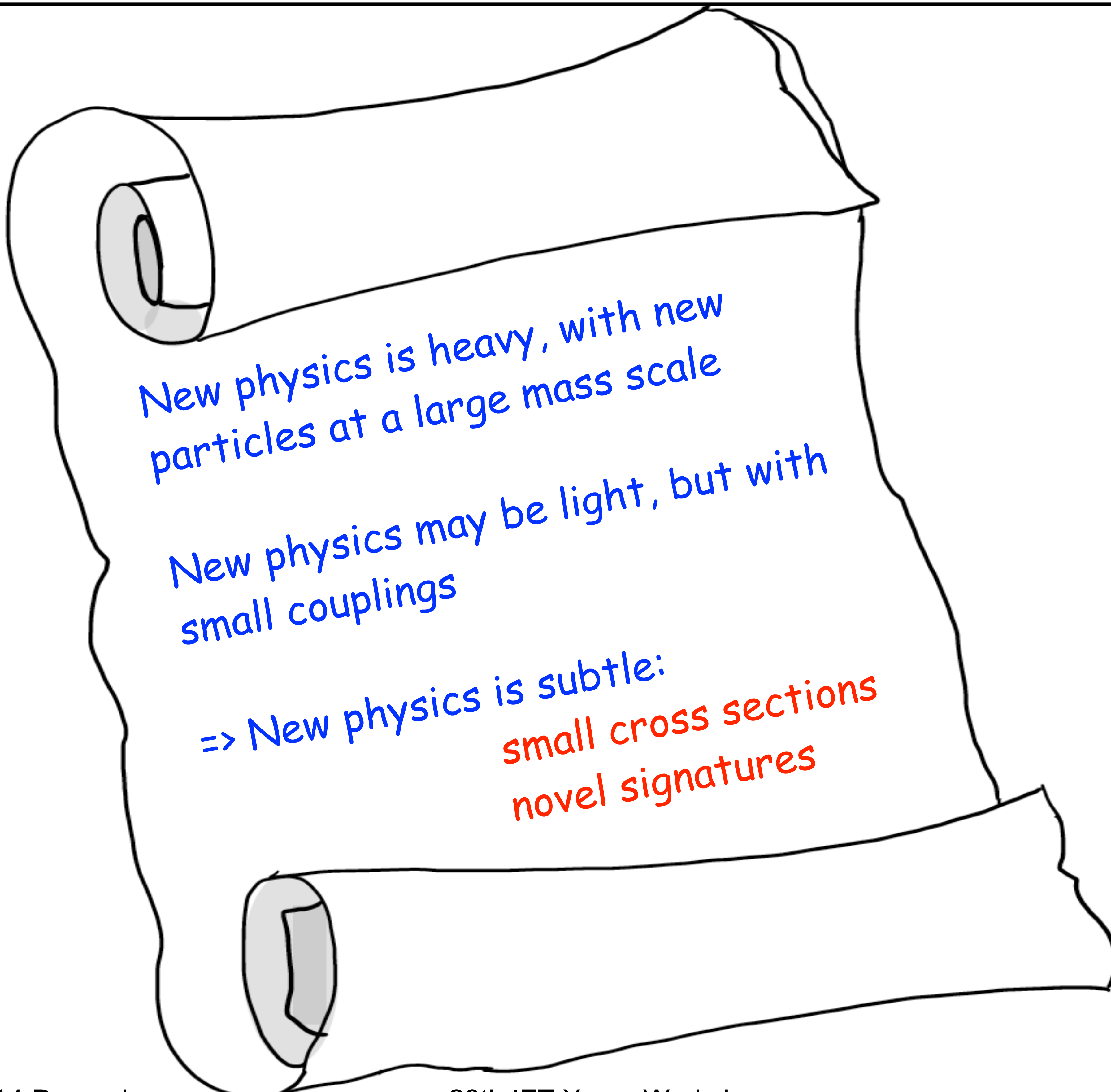


Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

Where is New Physics?



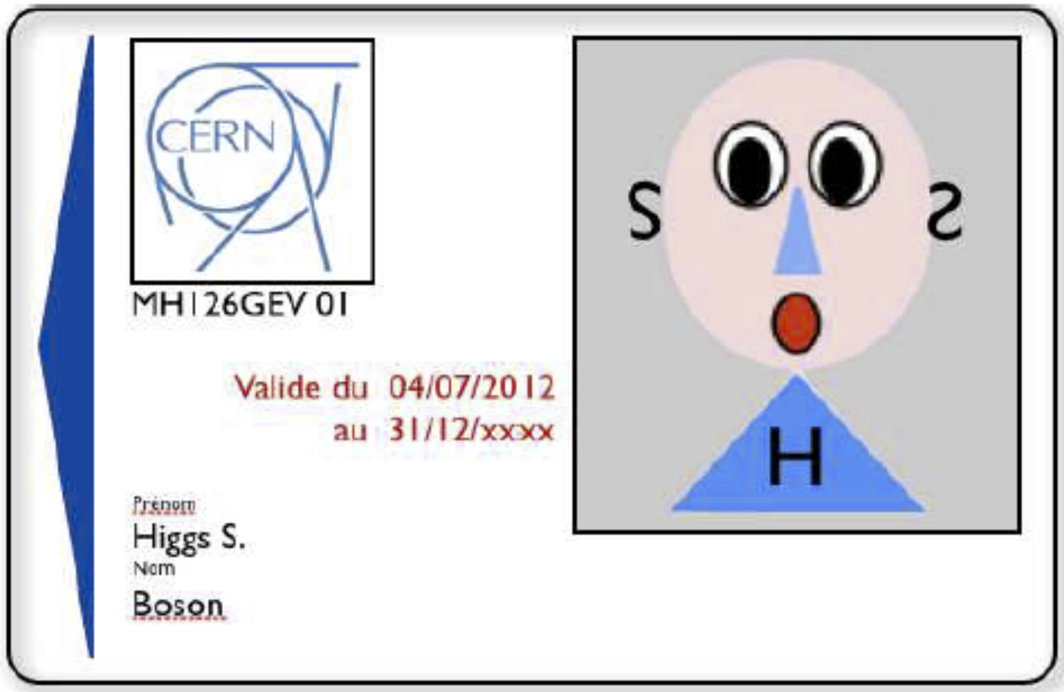
What we have

- 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!

The Role of the Higgs Boson Mass

The Role of the Higgs Boson Mass

✦ Present Accuracy: [ATLAS,CMS]

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

✦ 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 eal;Bednyakov eal]

∗ 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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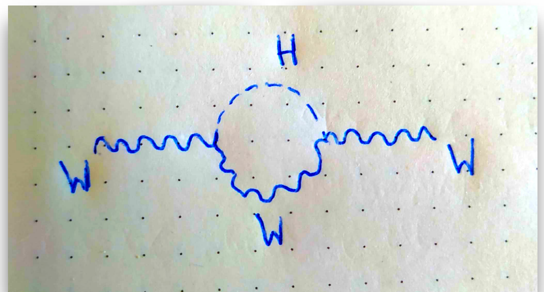
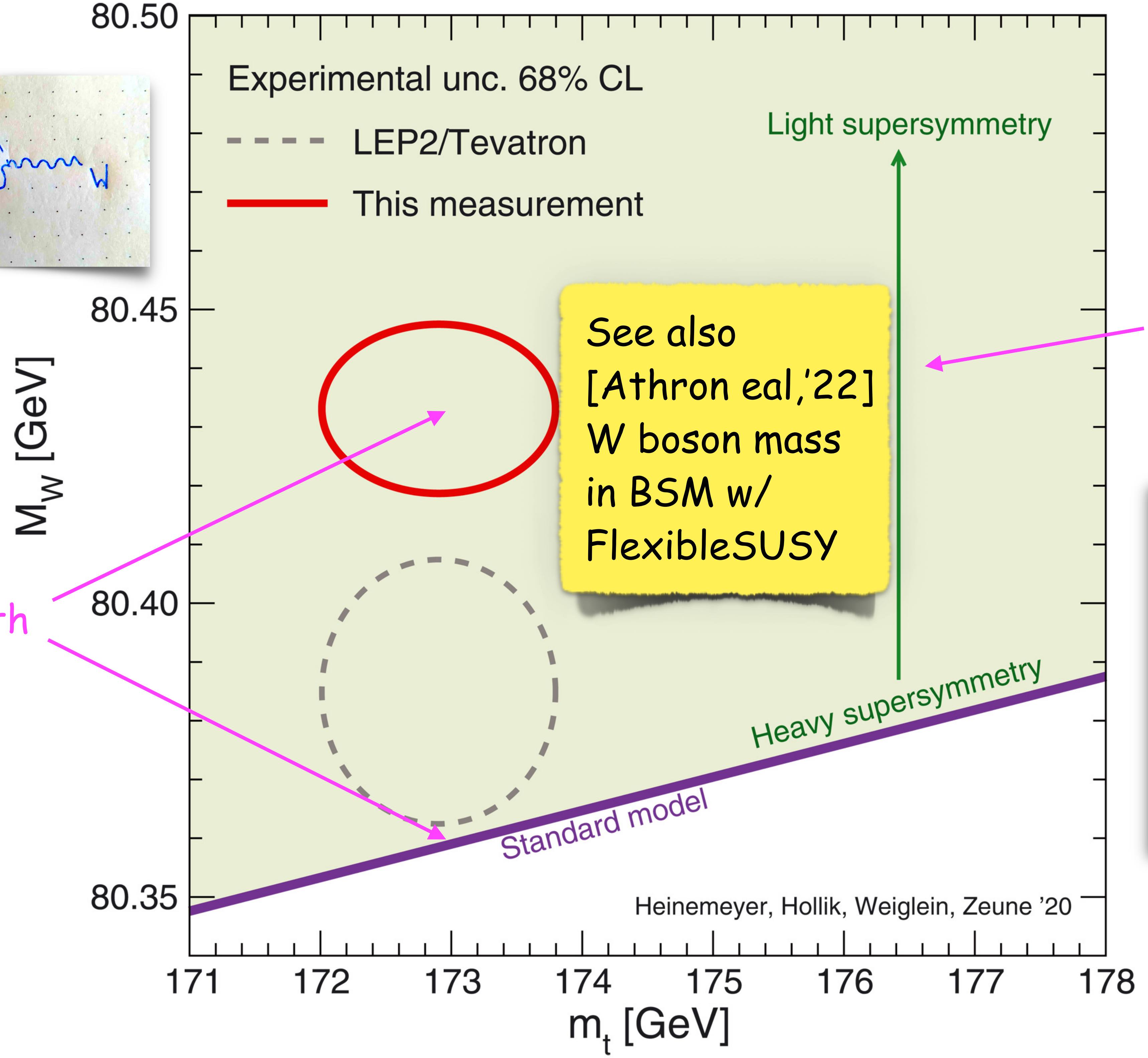
The W Boson Mass

[CDF,2022]





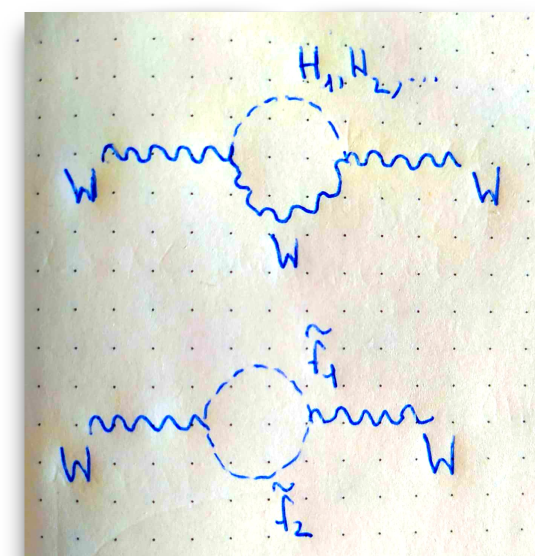
See also [Athron eal,'22] W boson mass in BSM w/ FlexibleSUSY

tension with

SM at 7σ

new physics ->

compatibility



Higgs boson mass:

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

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

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

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

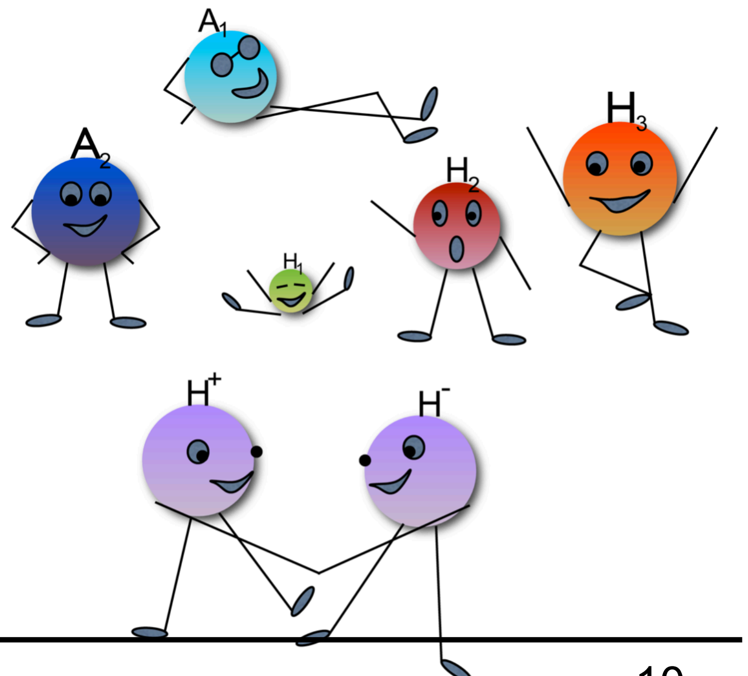
- Minimal Supersymmetric extension (MSSM): 2 complex Higgs doublets

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

- Next-to-MSSM (NMSSM): 2 complex Higgs doublets plus complex singlet field

- Enlarged Higgs and neutralino sector:

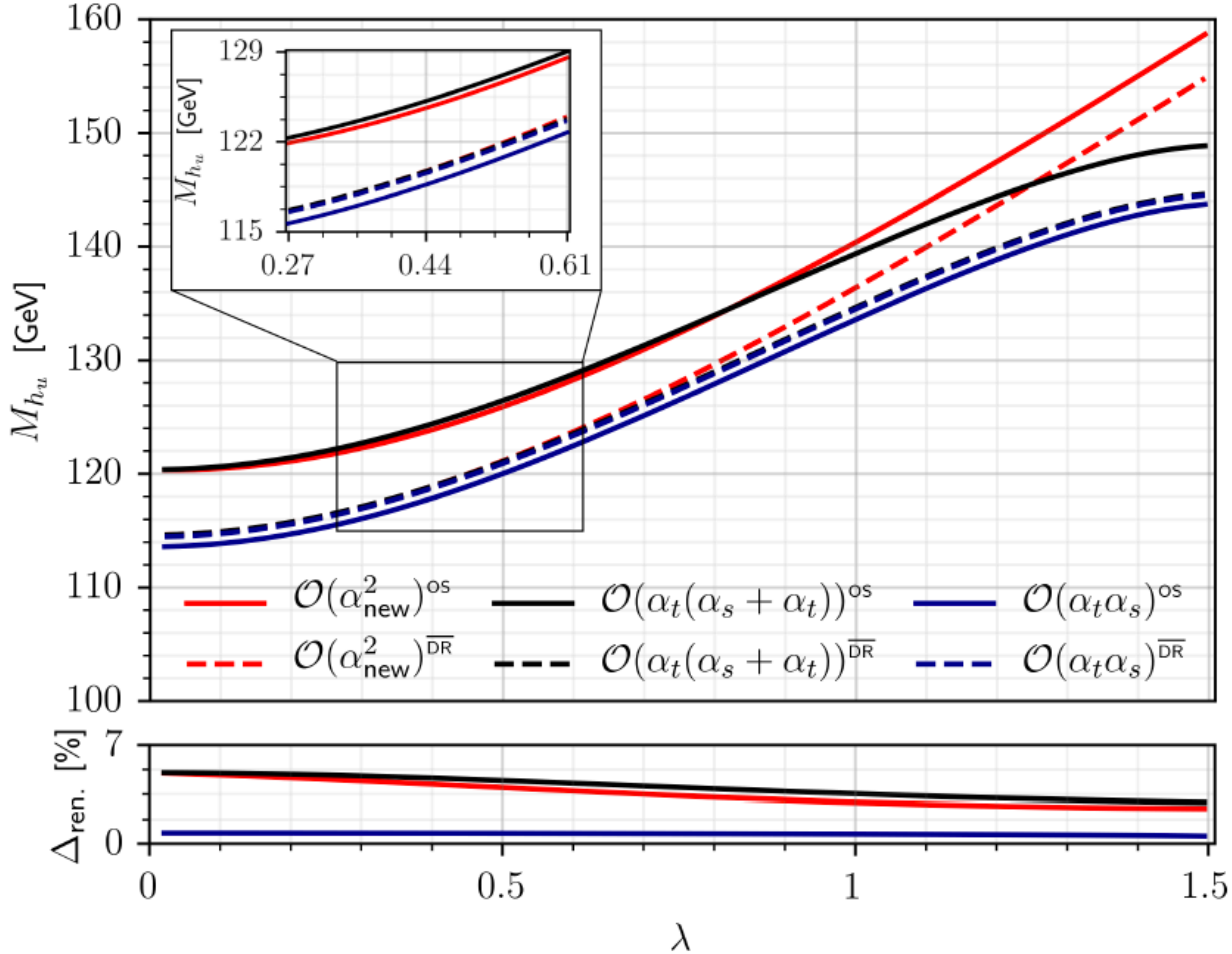
7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0 \ (i = 1, ..., 5)$



$\mathcal{O}(\alpha_{new}{}^2)\equiv\mathcal{O}((\alpha_\lambda+\alpha_\kappa+\alpha_t)^2)$ 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: $\mathcal{O}$(few%)

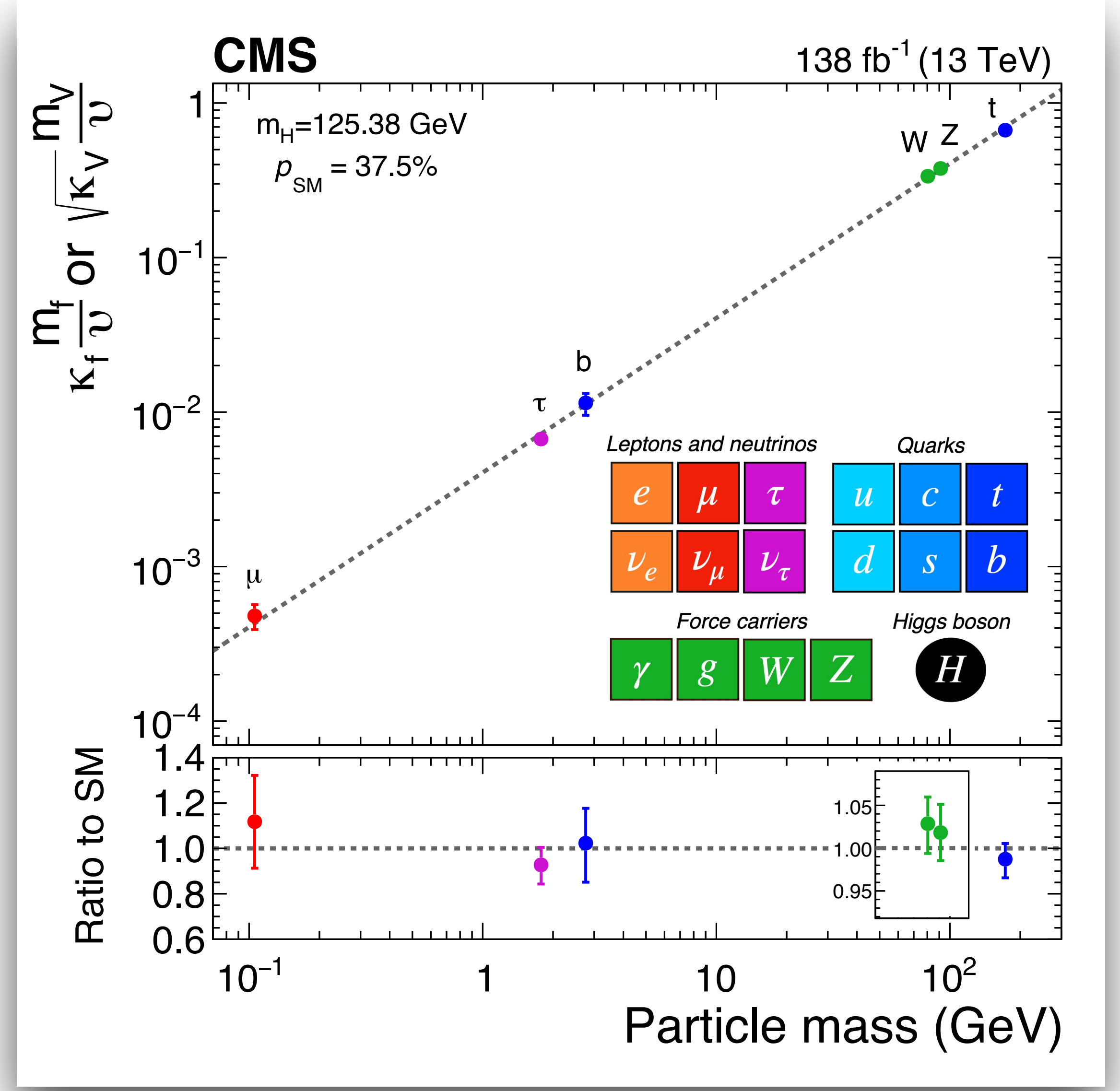

Higgs Pair
Production

The Higgs Self-Coupling

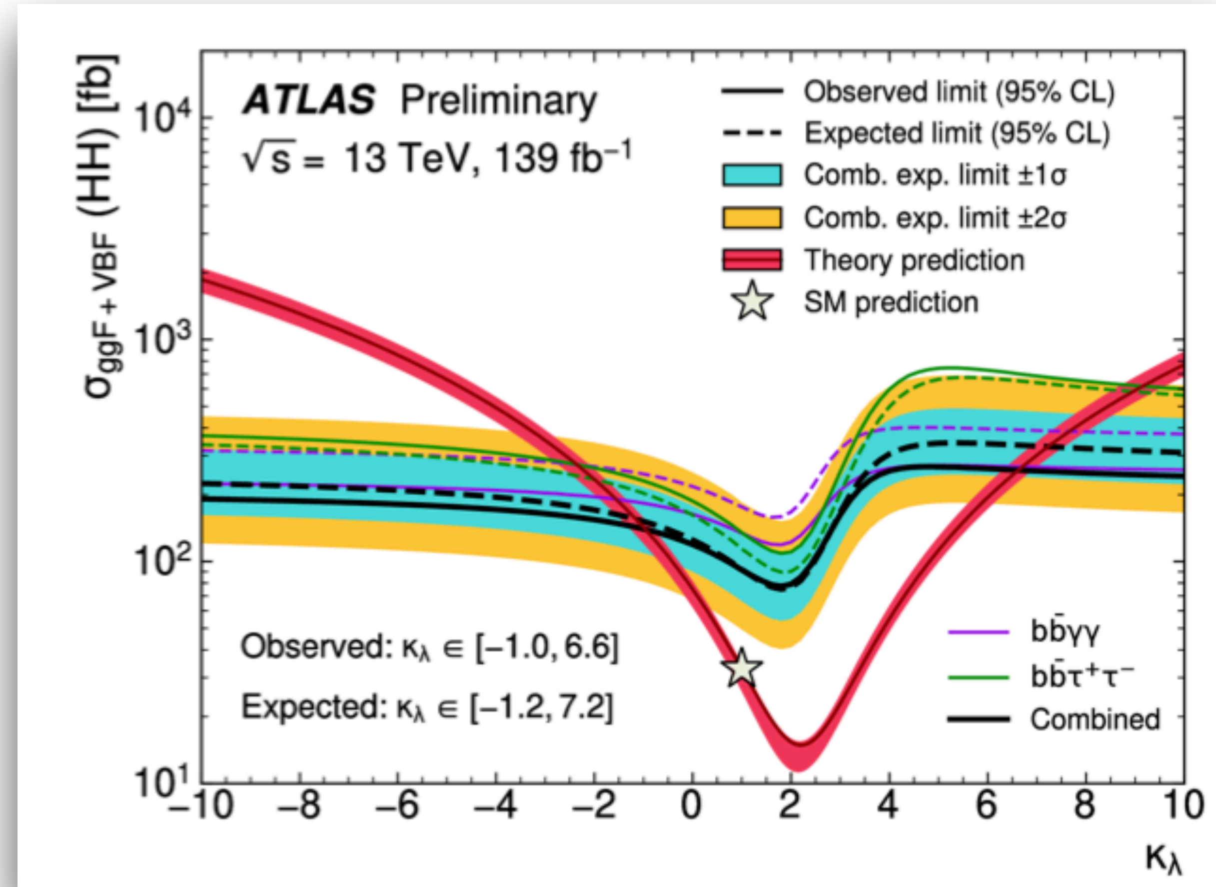
- Higgs Discovery ⇝ New Era of Particle Physics: structurally completes the SM
  - self-consistent framework to describe physics up to cosmologically relevant scales
  - extended Higgs sectors: answers to generation of baryon asymmetry, nature of DM

- 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



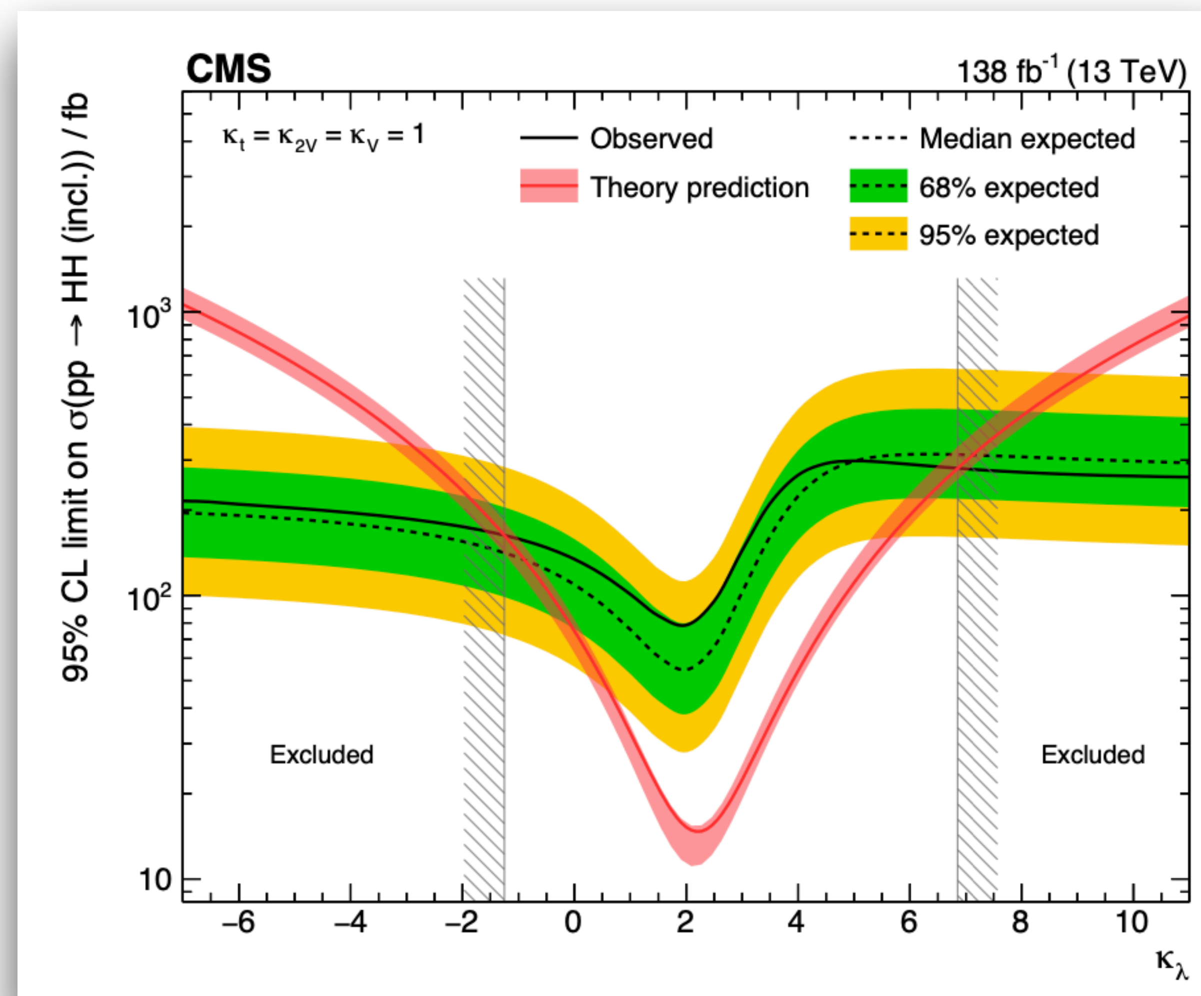
[Rui Zhang, ATLAS, HH Workshop´22]

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

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

[CMS,2207.00043]

$-1.24 \leq \boldsymbol{\kappa_\lambda} \leq 6.49$

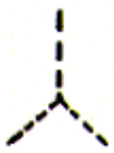


Ultimate Test of the Higgs Mechanism

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

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

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



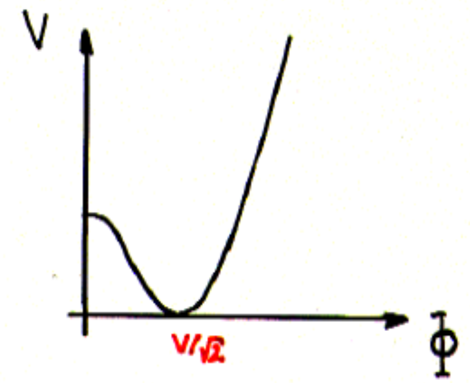
quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$

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

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

$v = 246$ GeV

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



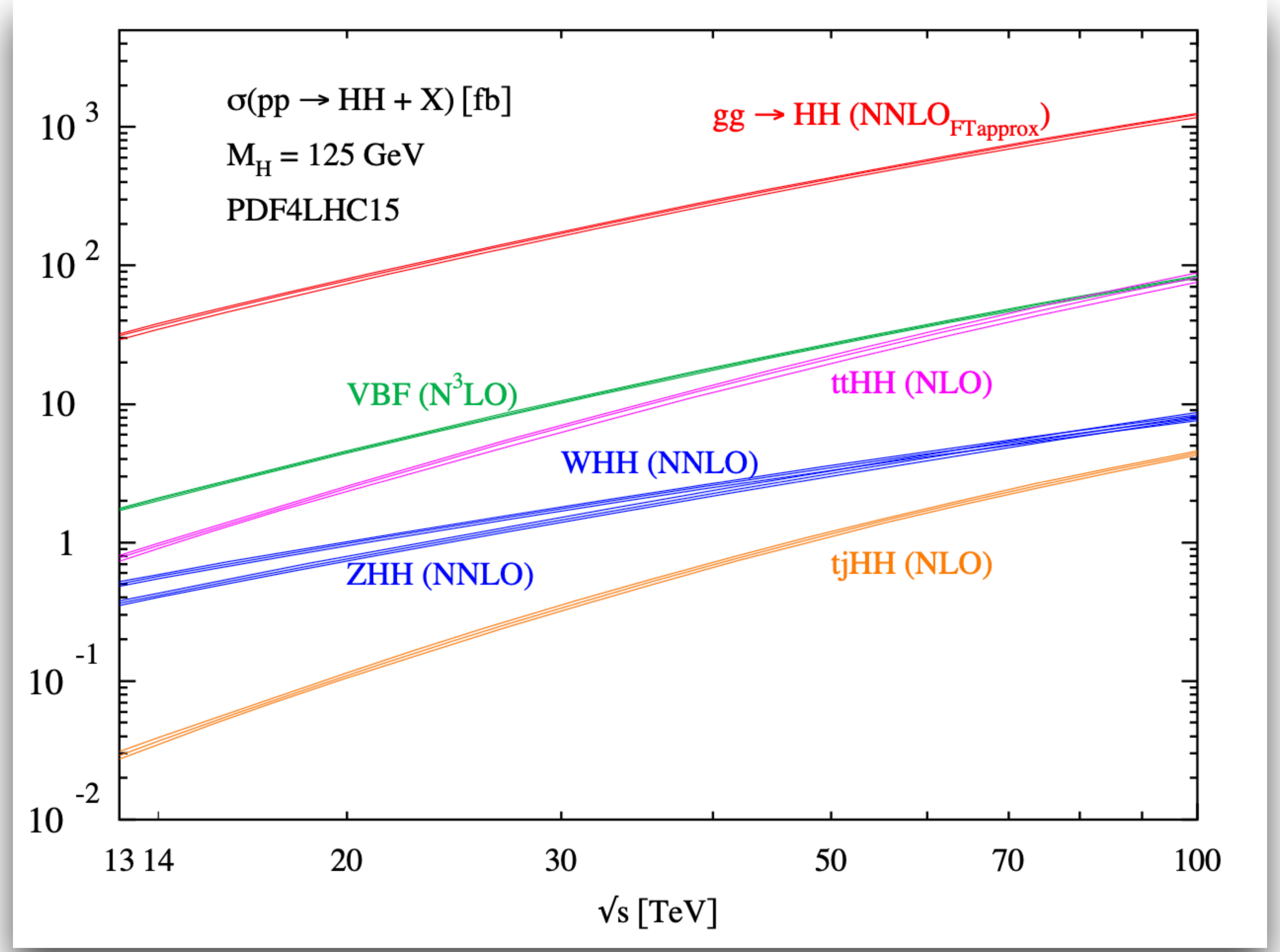
(a) trilinear coupling : via Higgs pair production

(b) quadrilinear coupling : via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential	⇒	establish the scalar sector of the Higgs mechanism experimentally

Double Higgs Production Processes

[HH, White paper]



Double Higgs Production Processes

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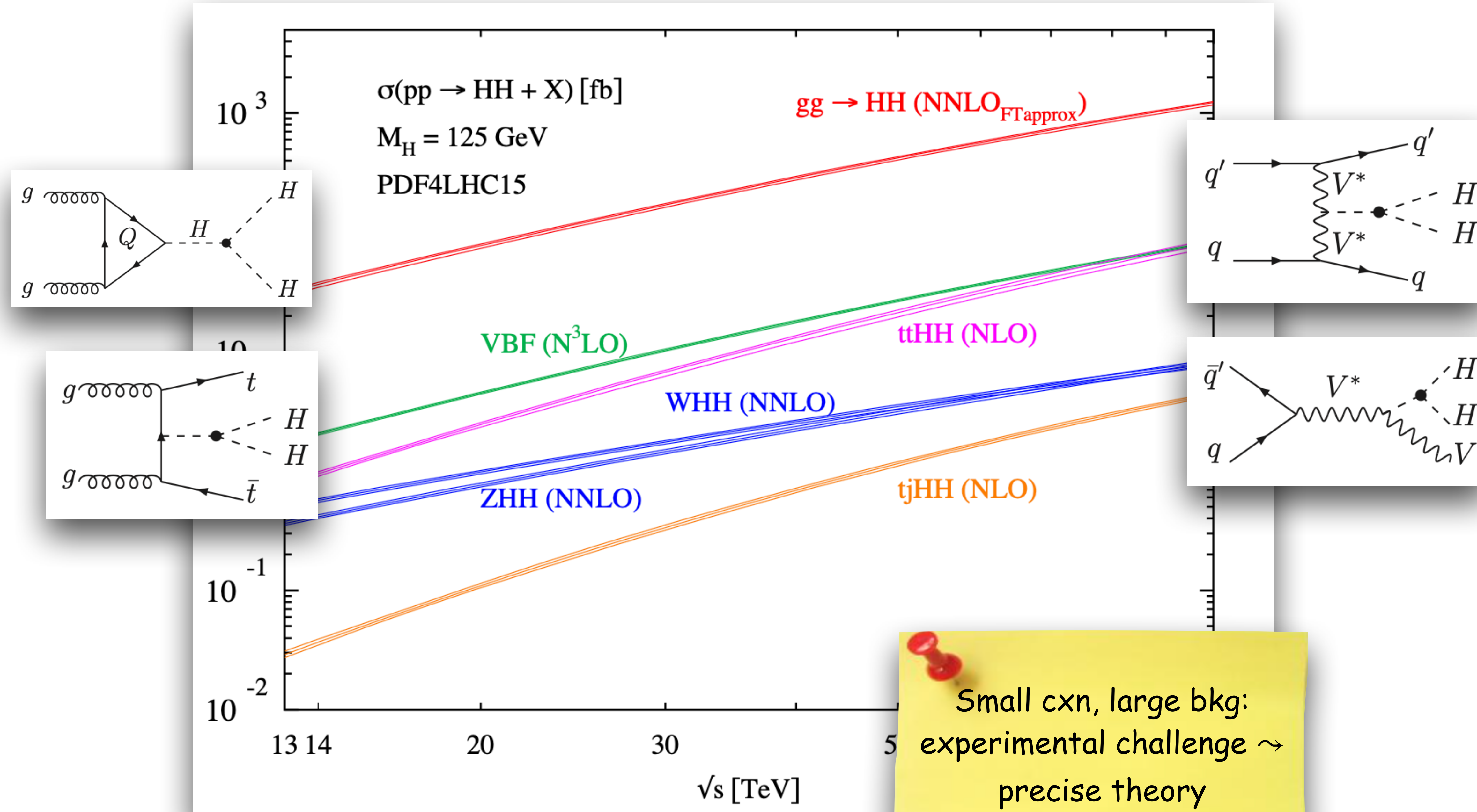
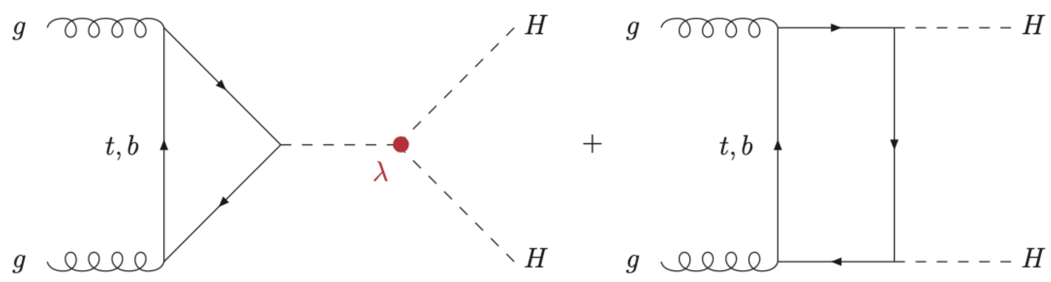


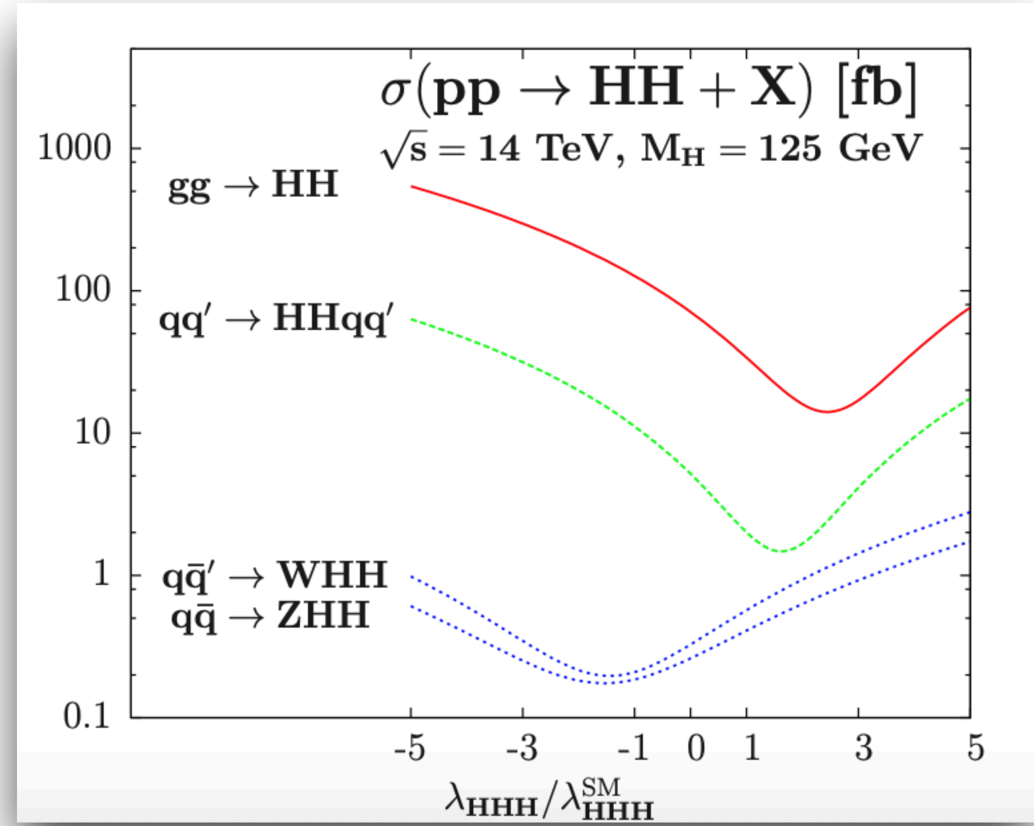
Small cxn, large bkg: experimental challenge ⇝ precise theory predictions required

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]

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

decreasing with M_{HH}

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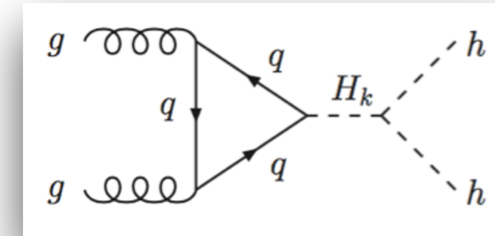

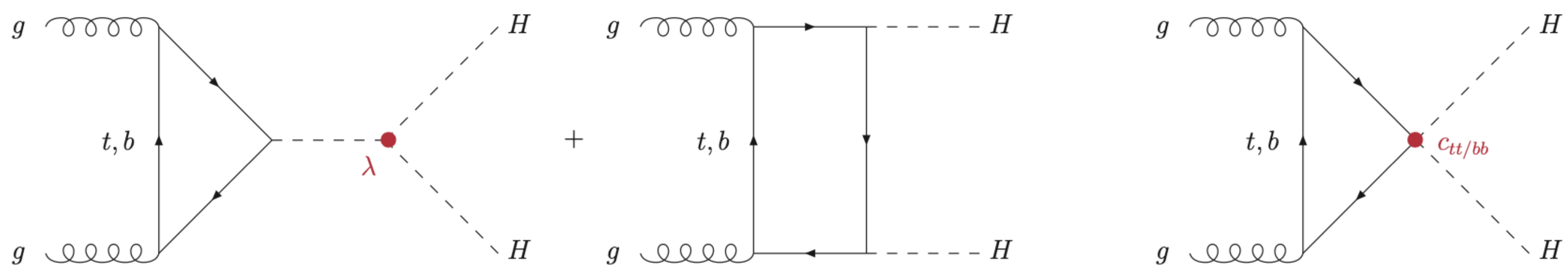

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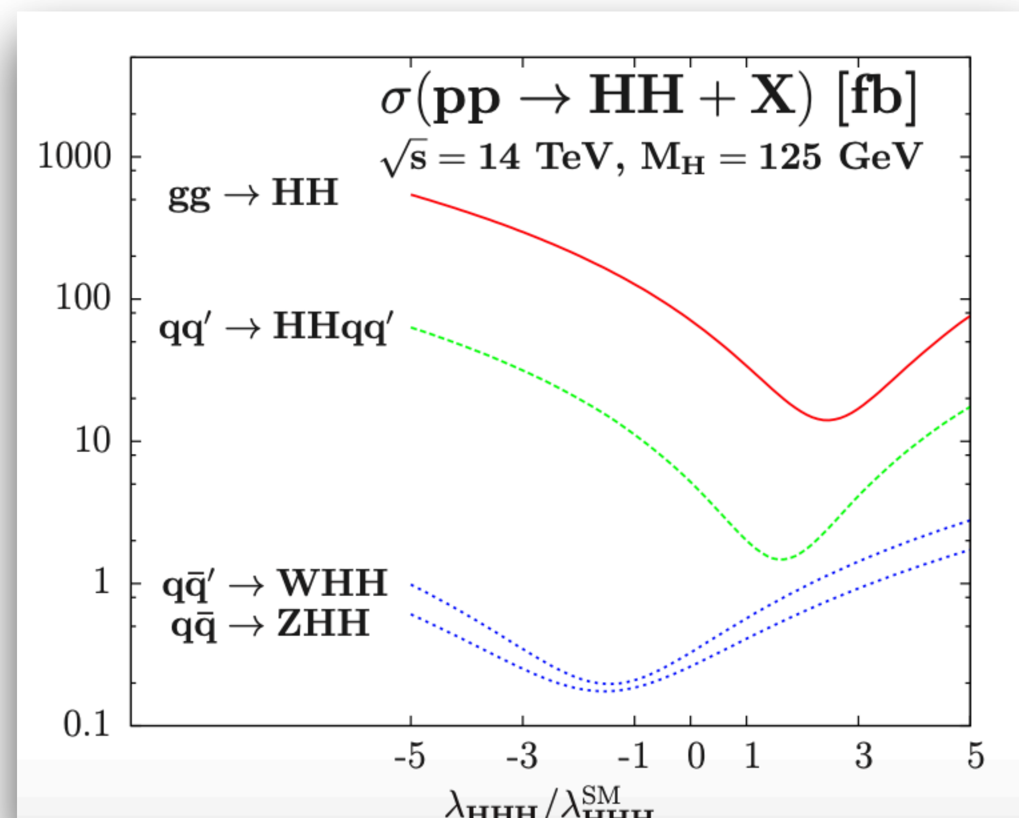

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$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

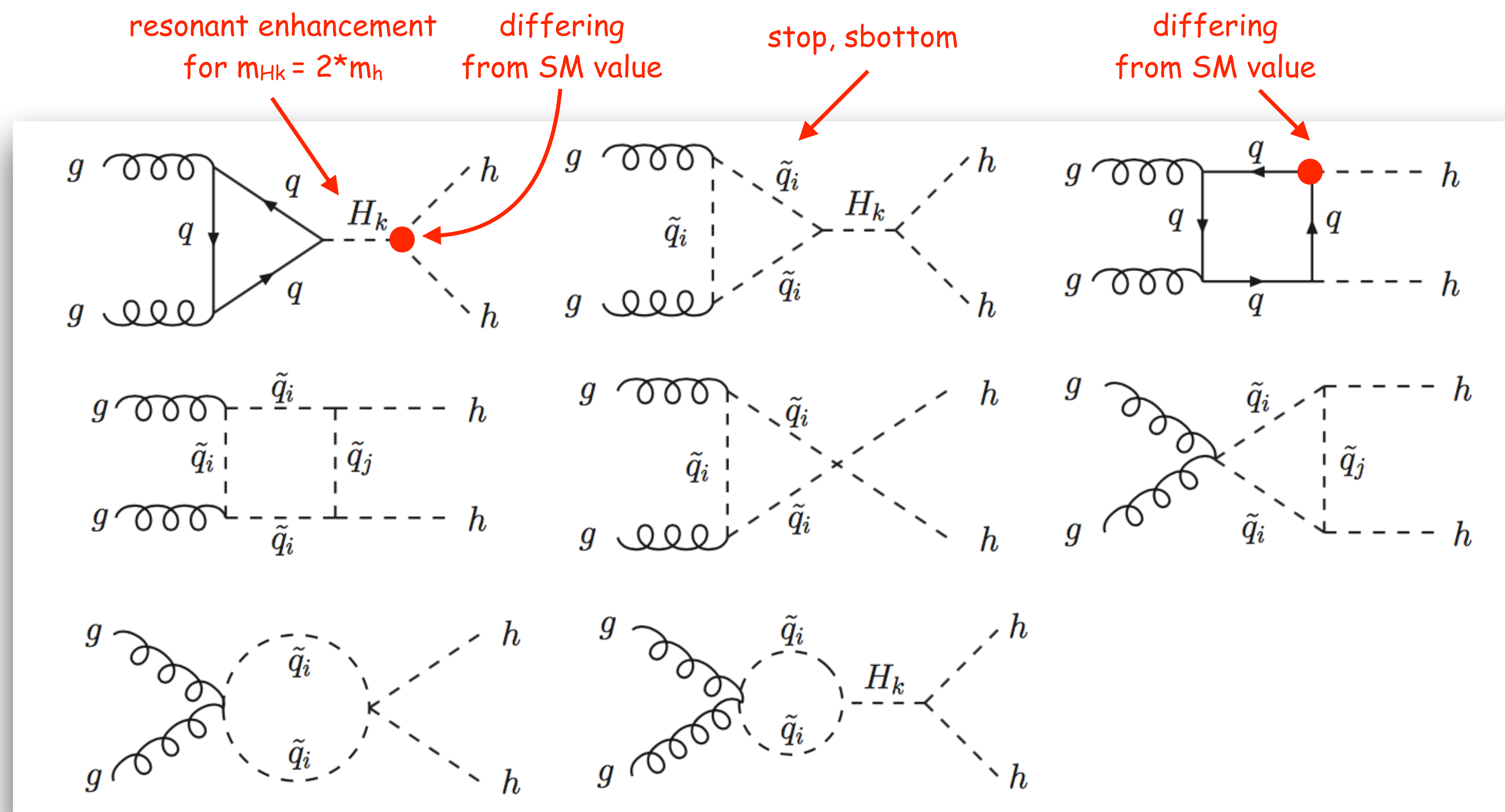
decreasing with M_{HH}

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]

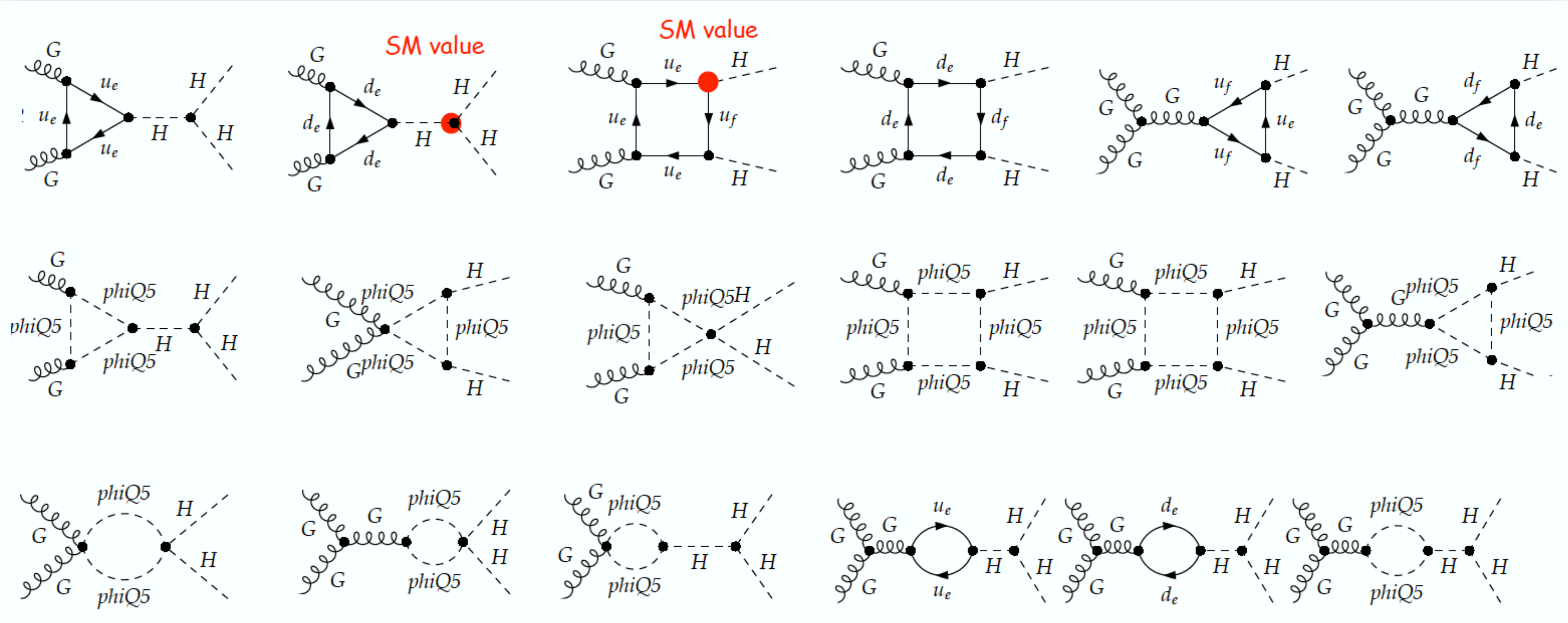


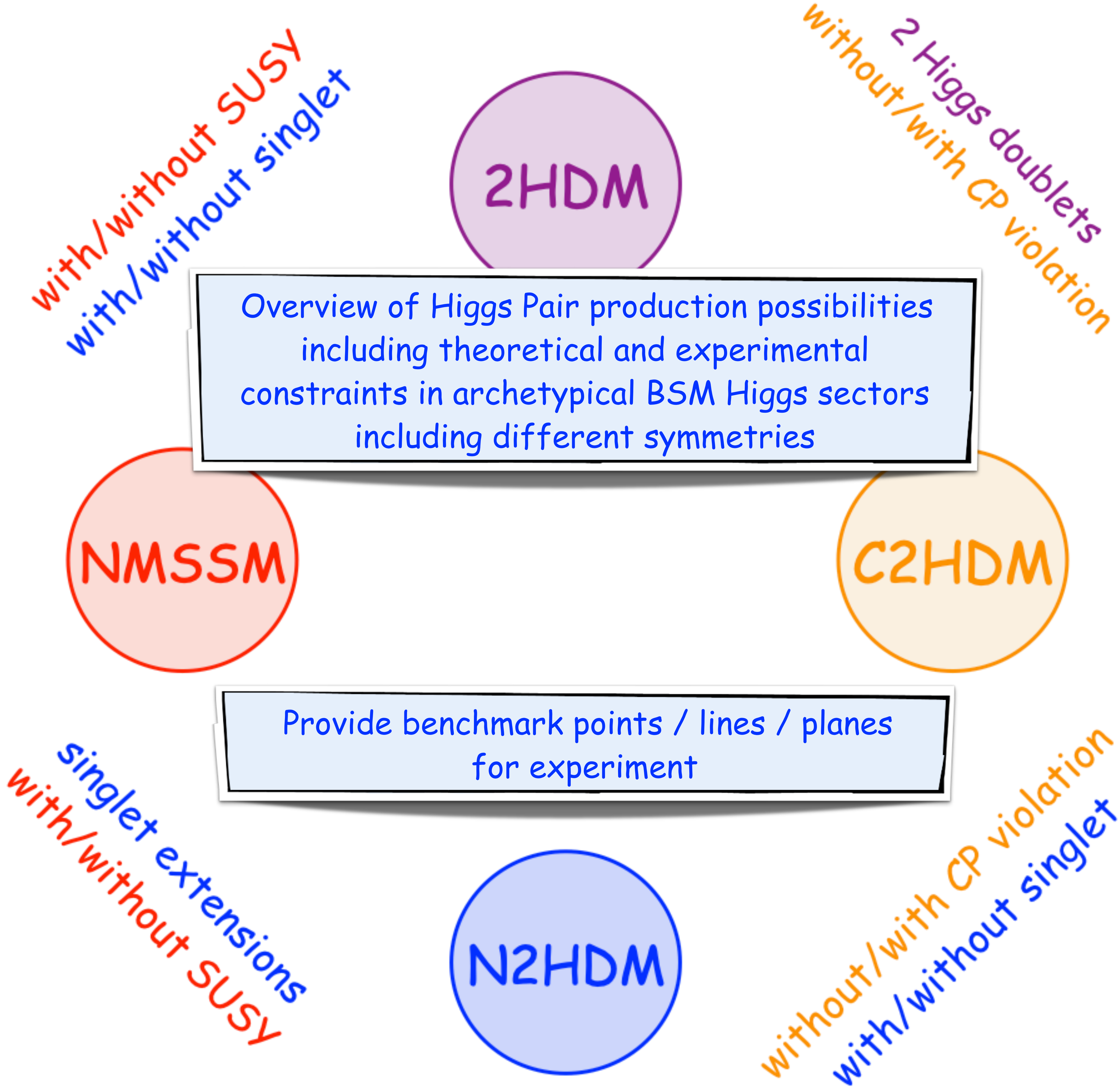
New Physics Effects in Higgs Pair Production

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

- **Example extension w/ strange Dark sector:**

[thanks to D. Neascu]




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

2HDM	C2HDM	N2HDM	NMSSM
2 Higgs doublets	CP-violating	Singlet extension	Supersymmetry
h, H, A, H^+, H^-	$H1, H2, H3, H^+, H^-$	$H1, H2, H3, H^+, H^-$	$H1, H2, H3, A, H^+, H^-$
SFOEWPT, DM, plus charged Higgs	plus CP violation baryogenesis	rich pheno, DM	a lot (DM, CPviol, Hierarychy, ...)

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

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]

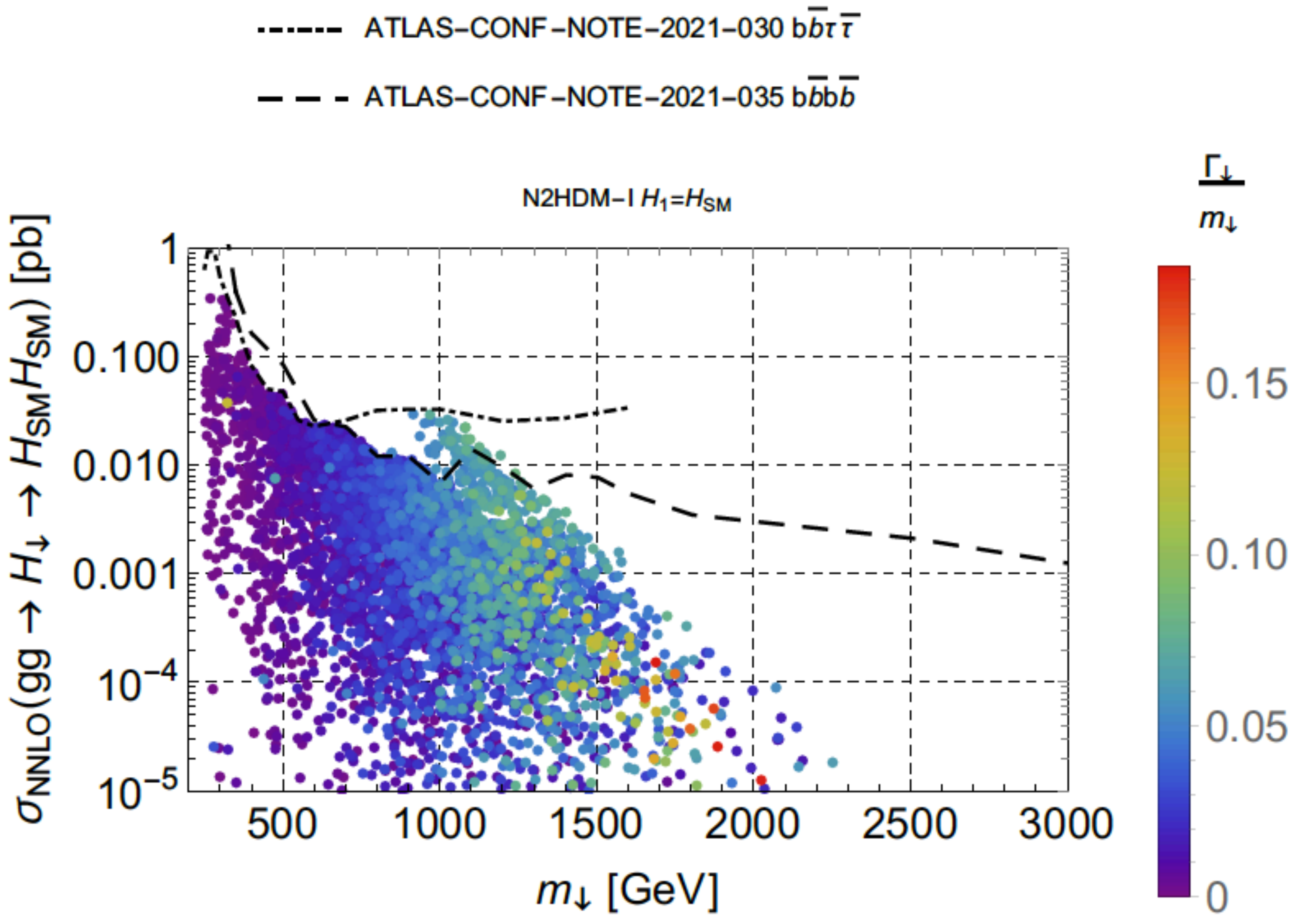
- Computation of Higgs pair production cxn:

  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:

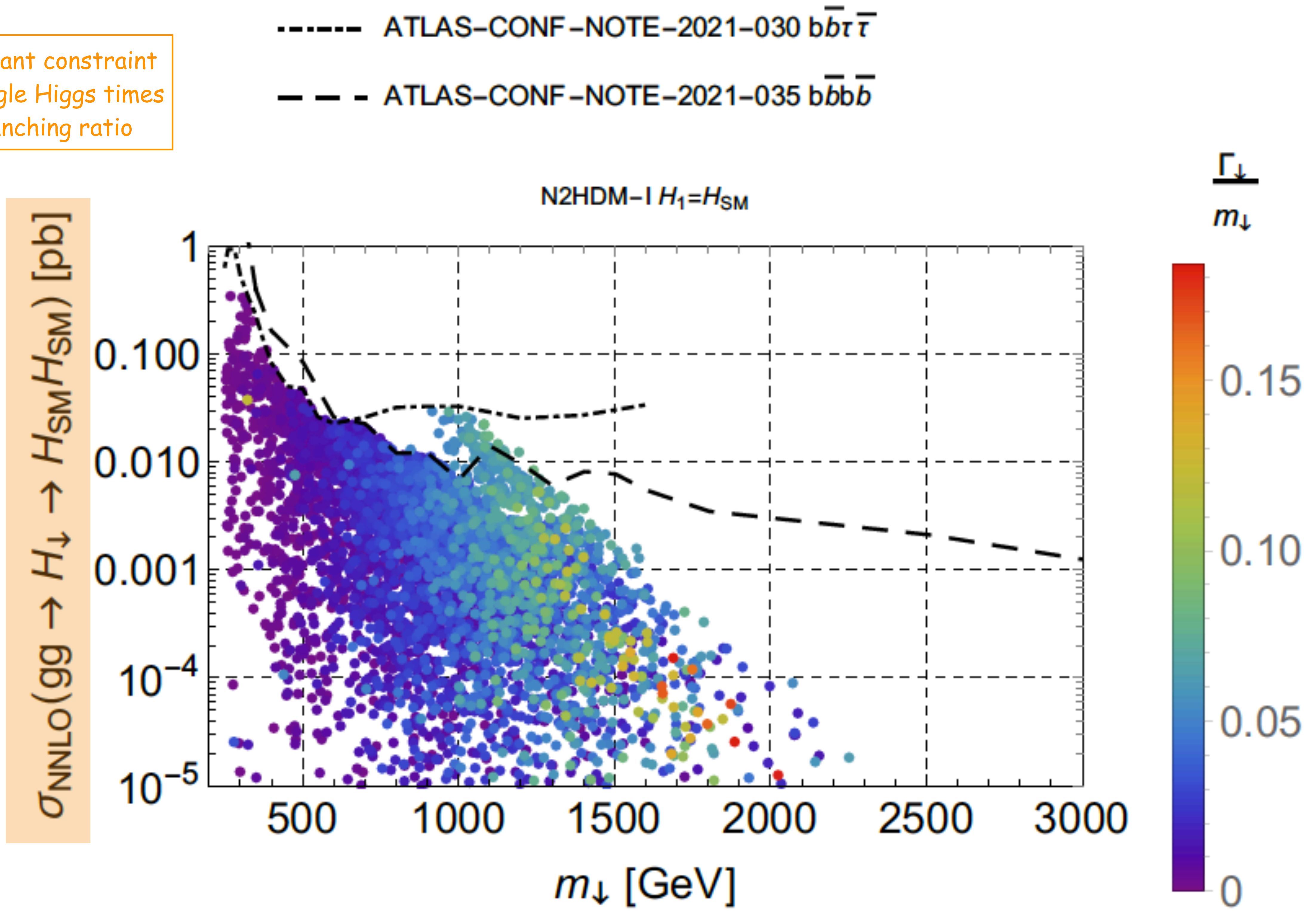
  LO cxn times factor 2 (to approx. account for NLO QCD), benchmark points include
  NLO QCD calculated w/ HPAIR

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



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

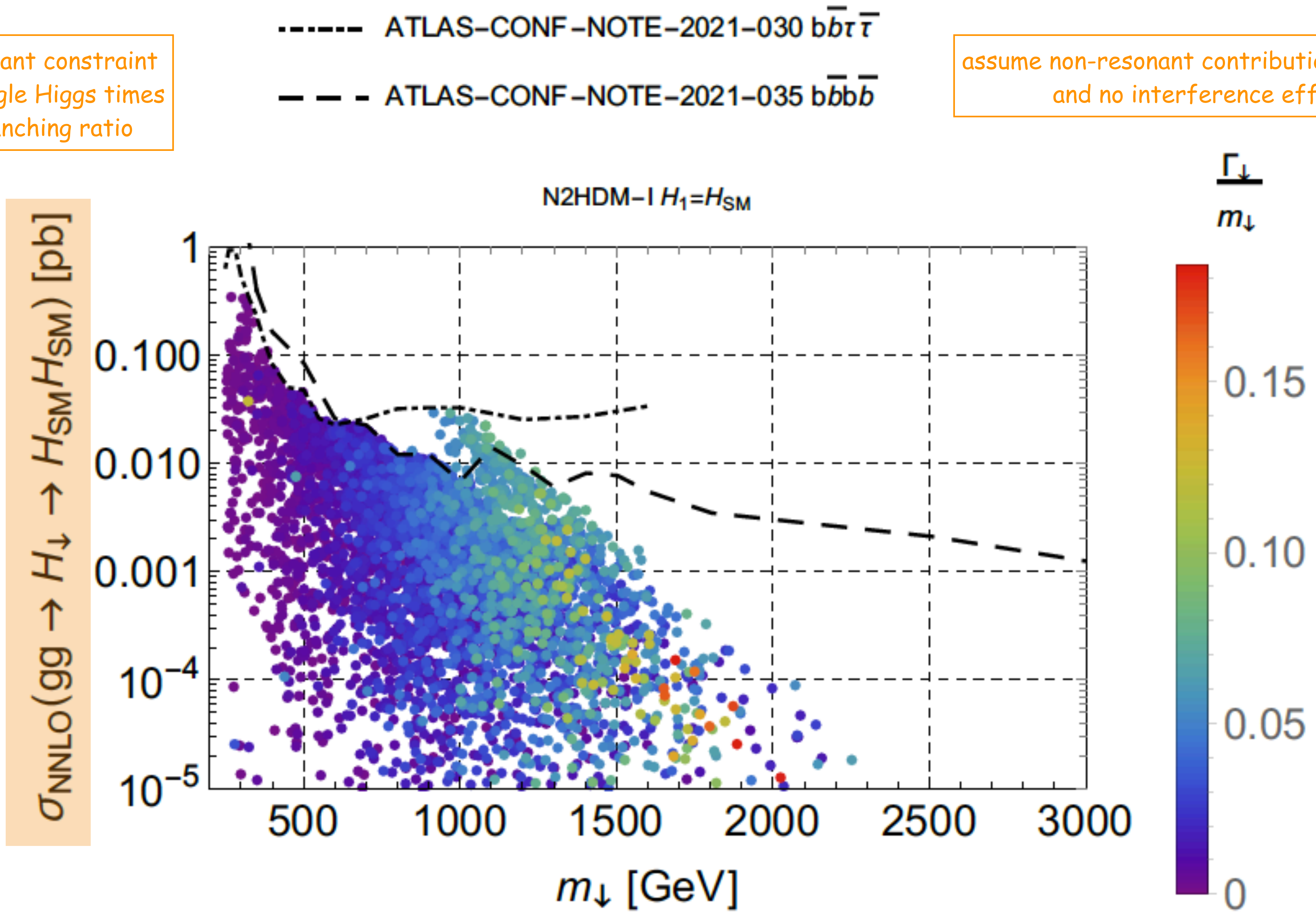
resonant constraint on single Higgs times branching ratio



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

resonant constraint on single Higgs times branching ratio

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



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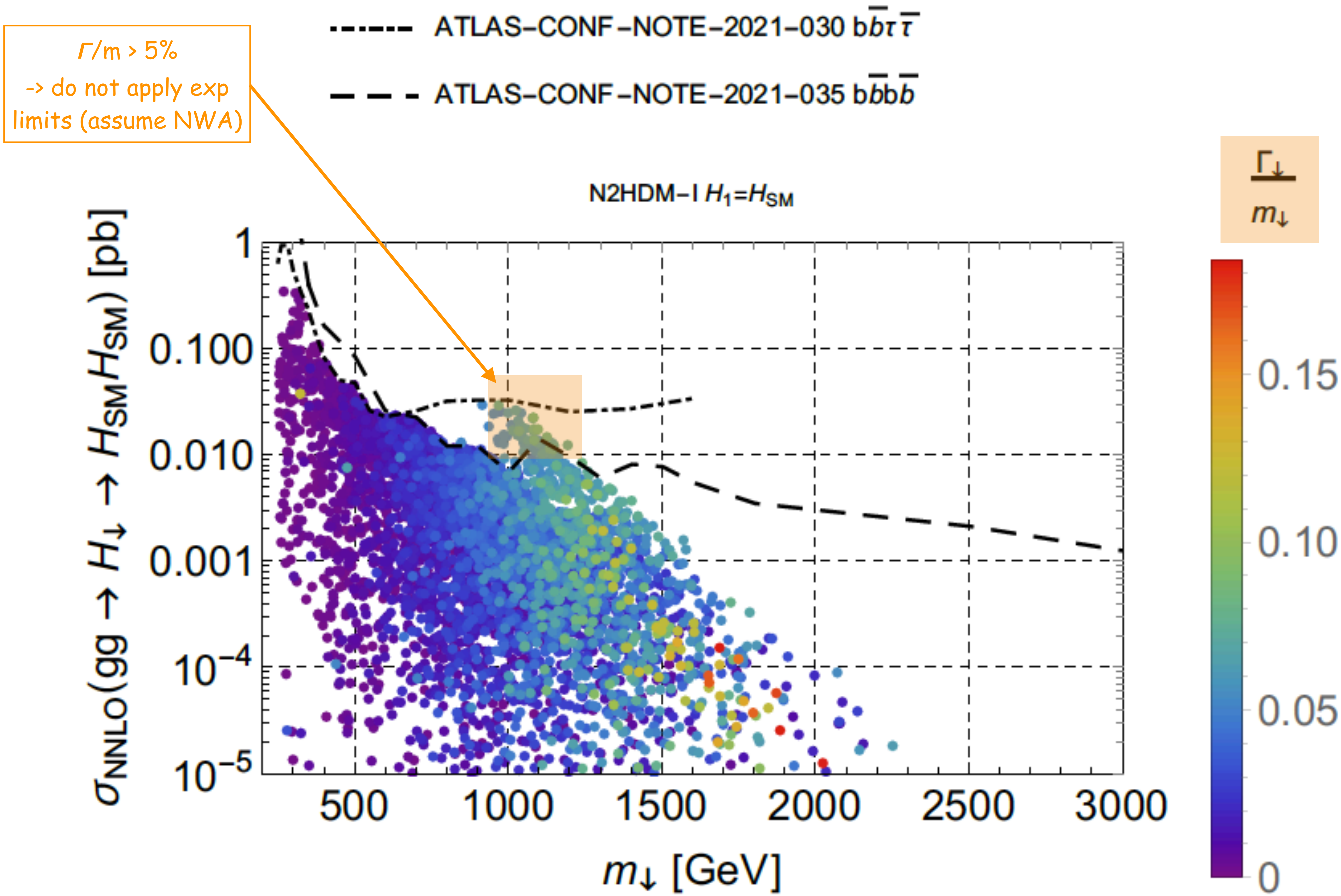
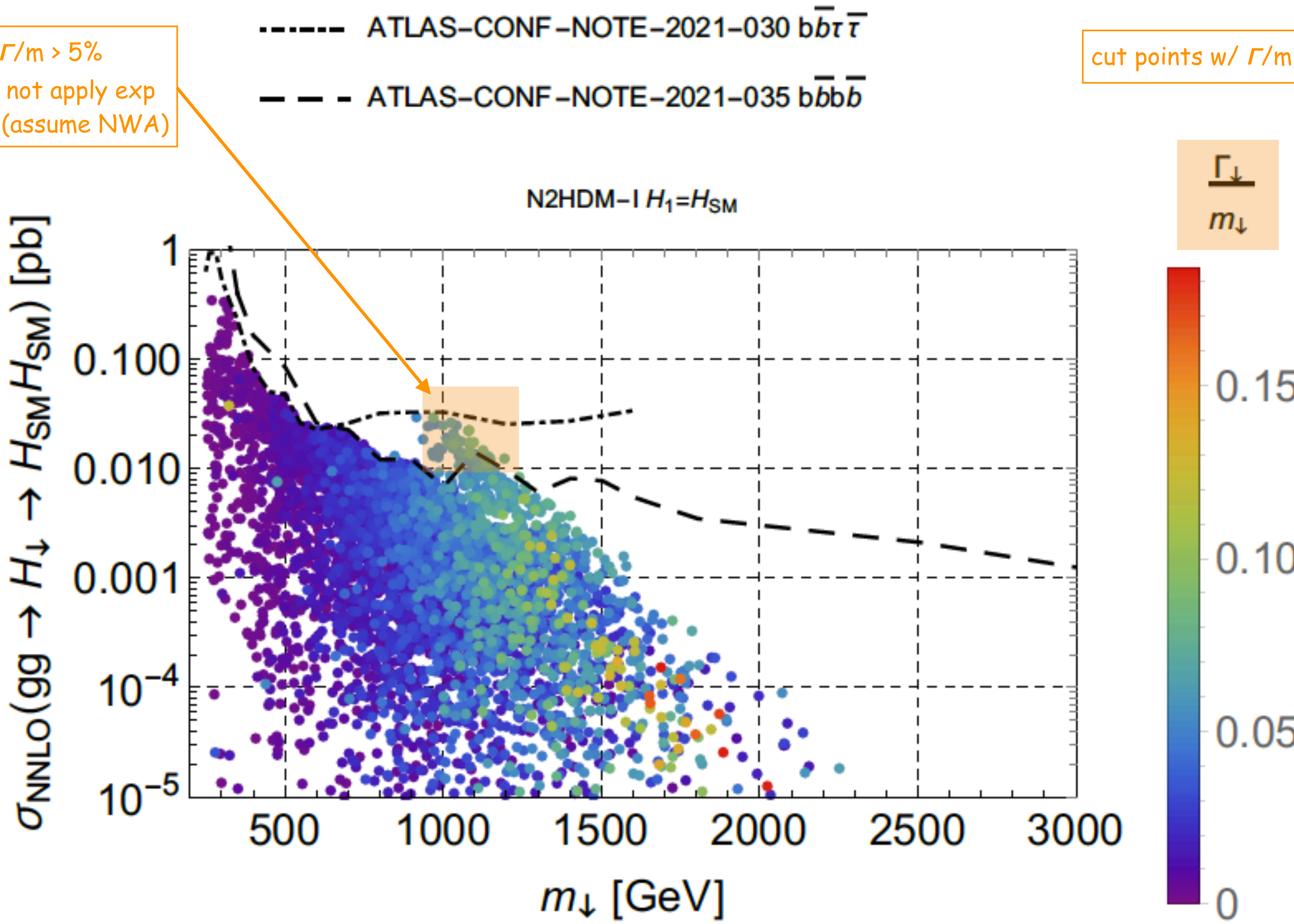


Impact of Resonant Searches - Ex. N2HDM H1 SM-like

$\Gamma/m > 5\%$
-> do not apply exp limits (assume NWA)

cut points w/ $\Gamma/m > 50\%$



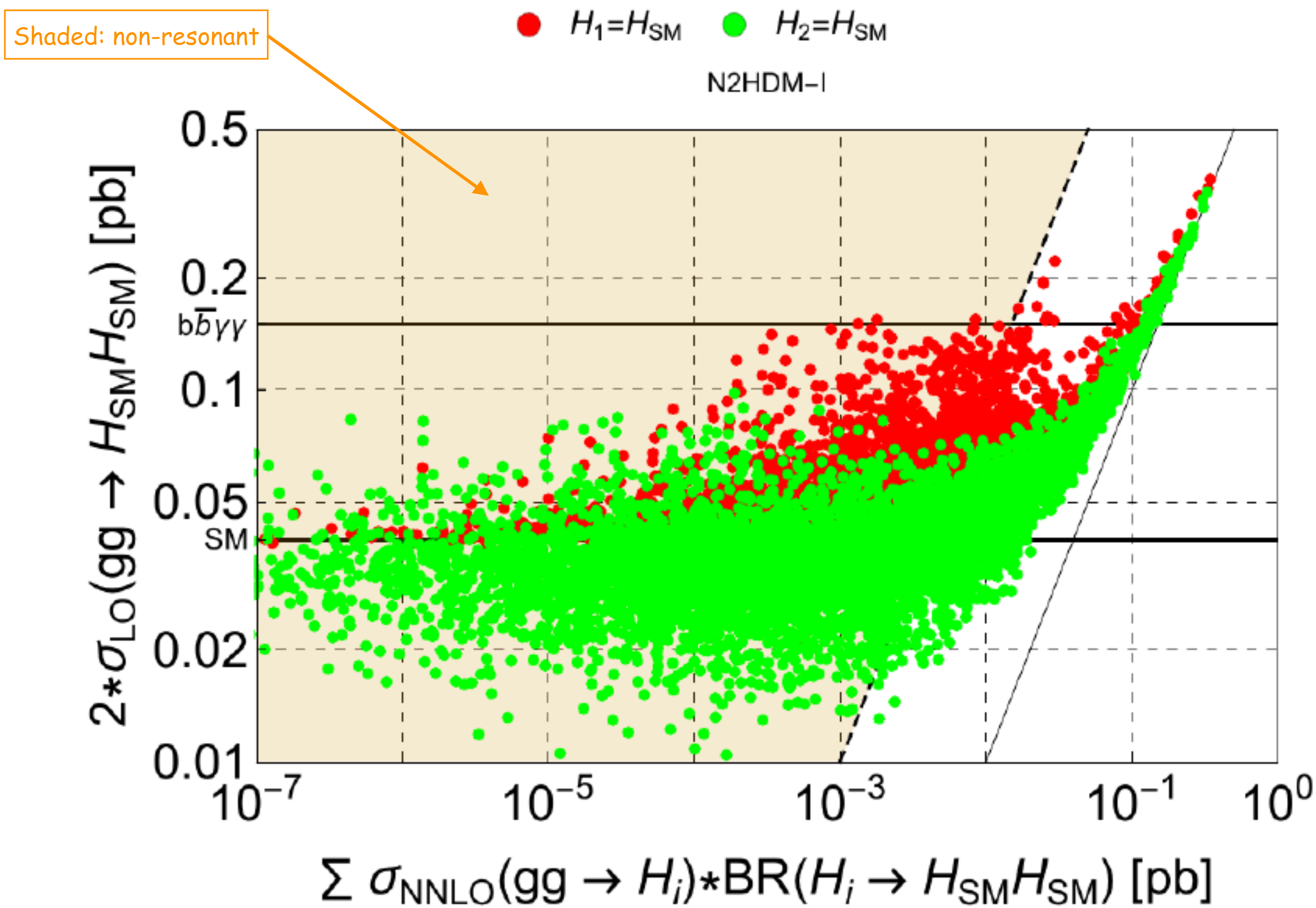
Impact of Non-resonant Searches

✦ Our definition:

take into account all relevant theoretical and experimental constraints
+ limits from di-Higgs searches

$\boldsymbol{\sigma}_{res}^{HH} < 0.1 * \boldsymbol{\sigma}_{full}$ -> non-resonant production

Impact of Non-resonant Searches - Example N2HDM



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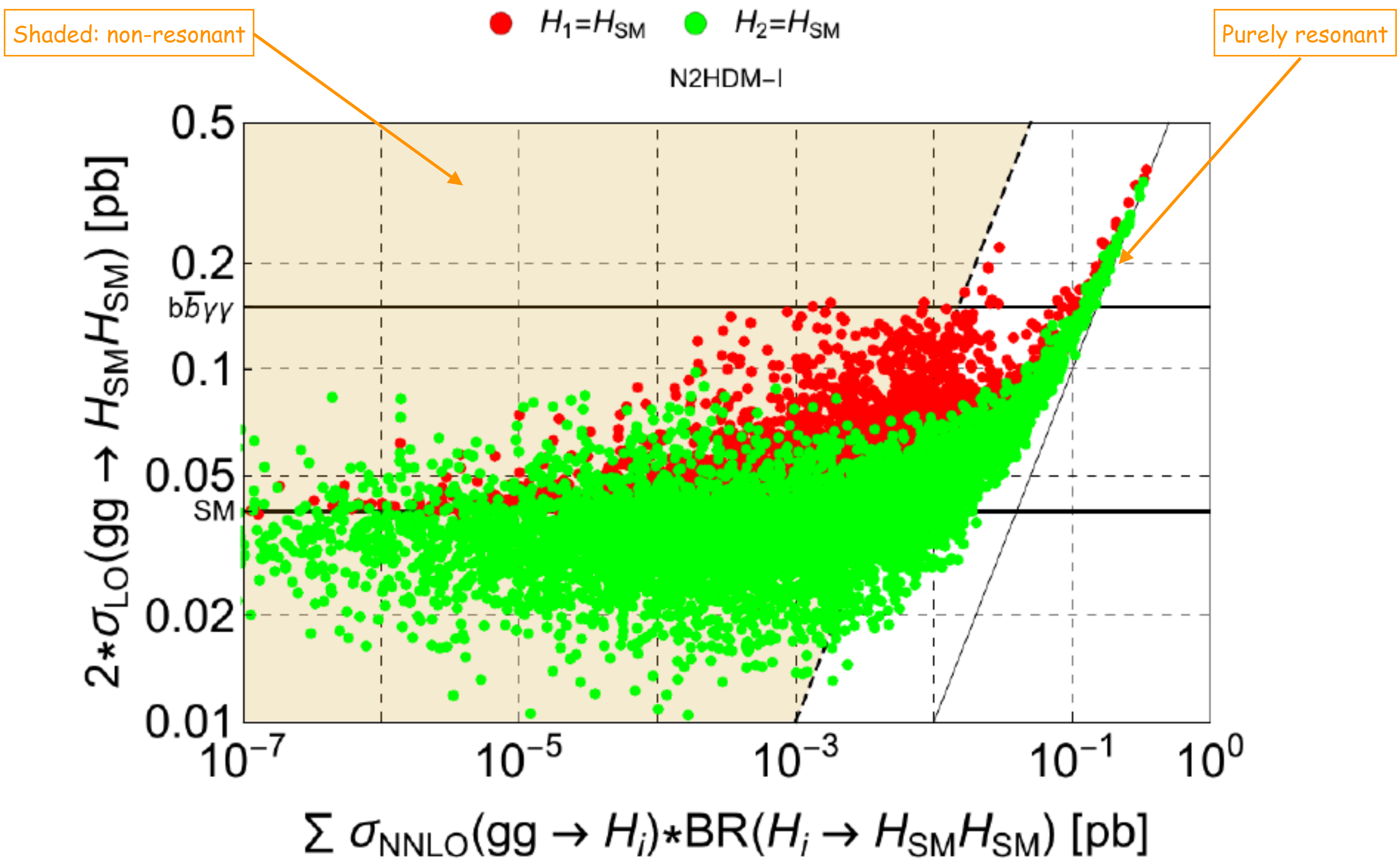

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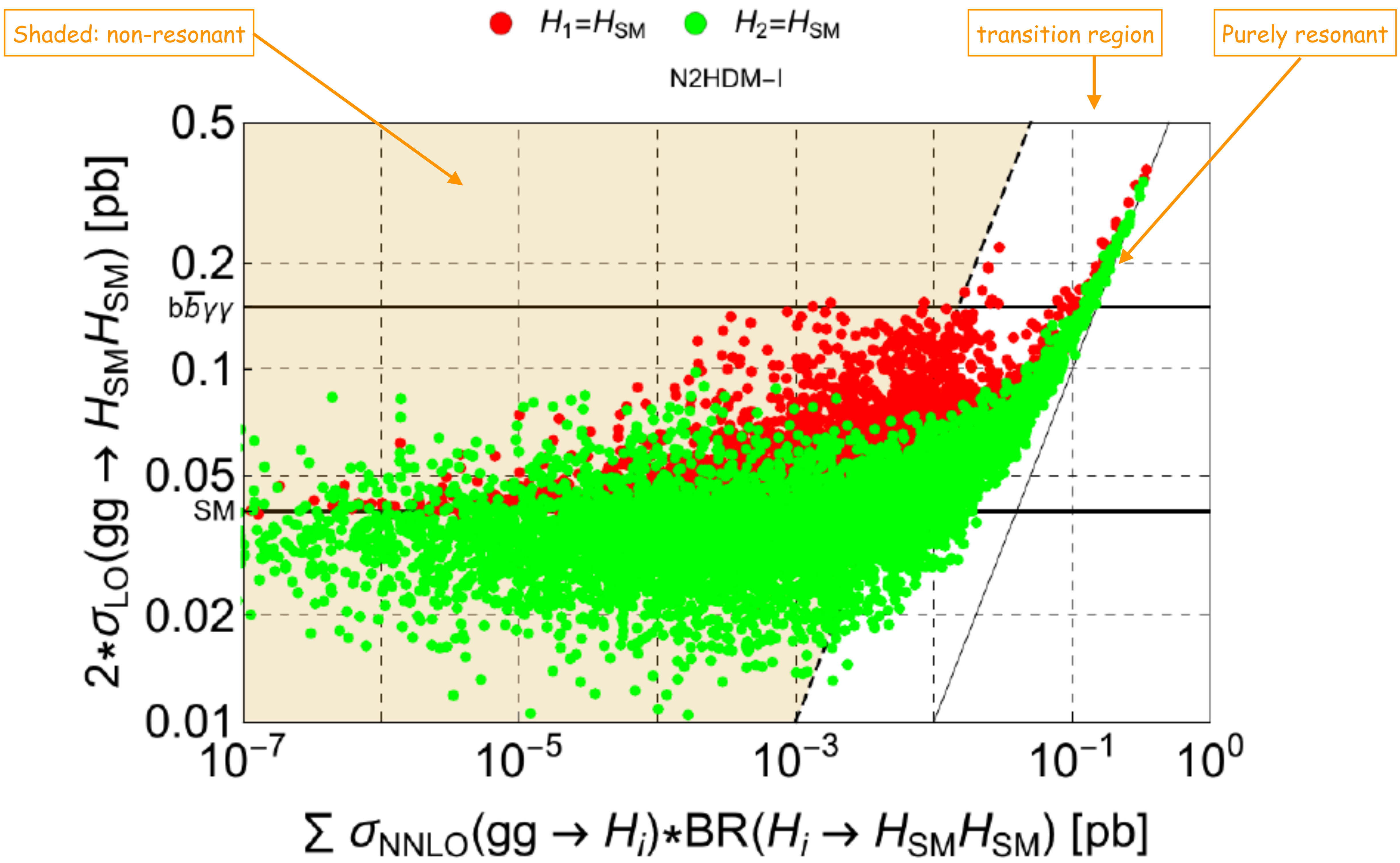
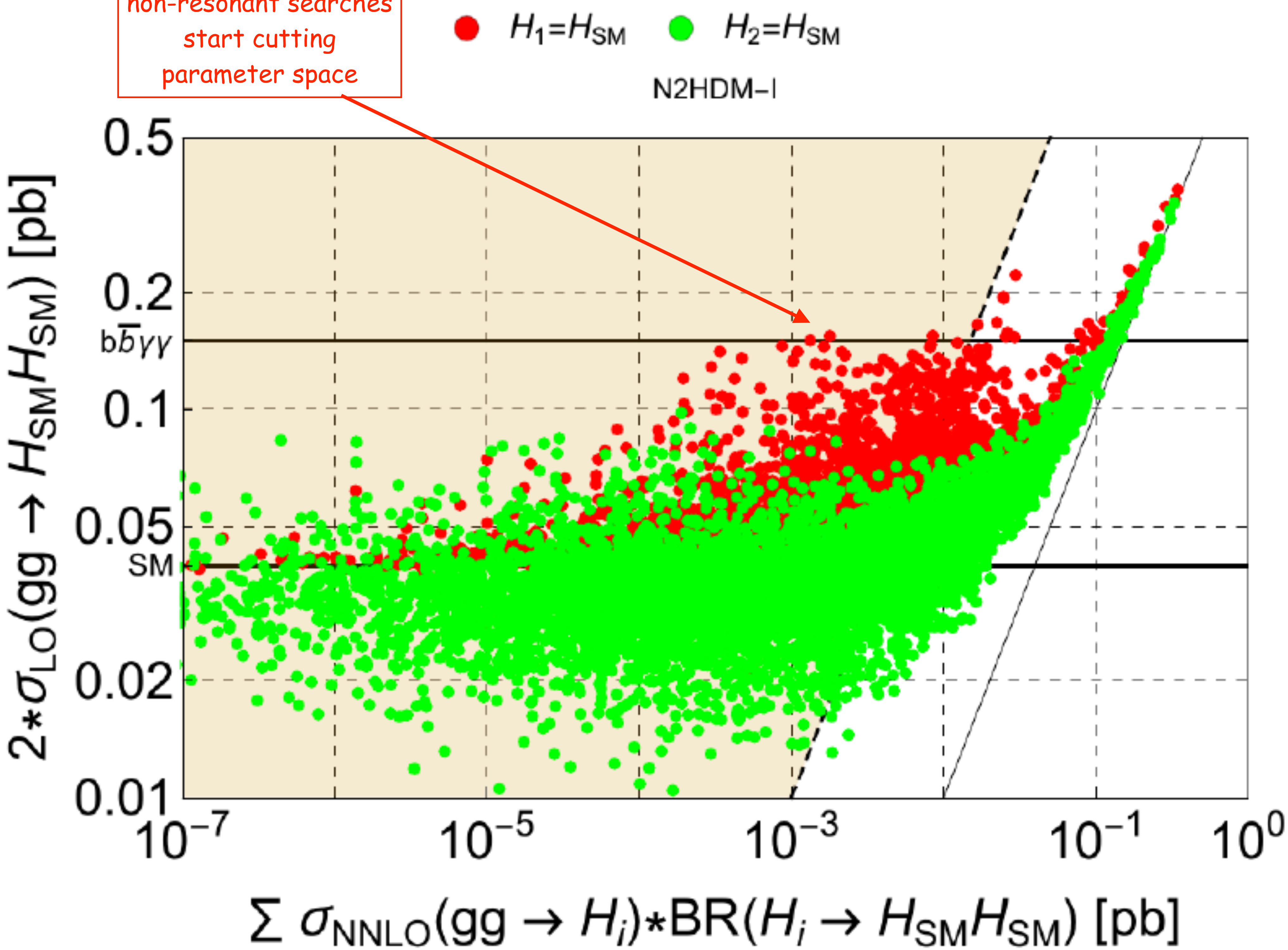


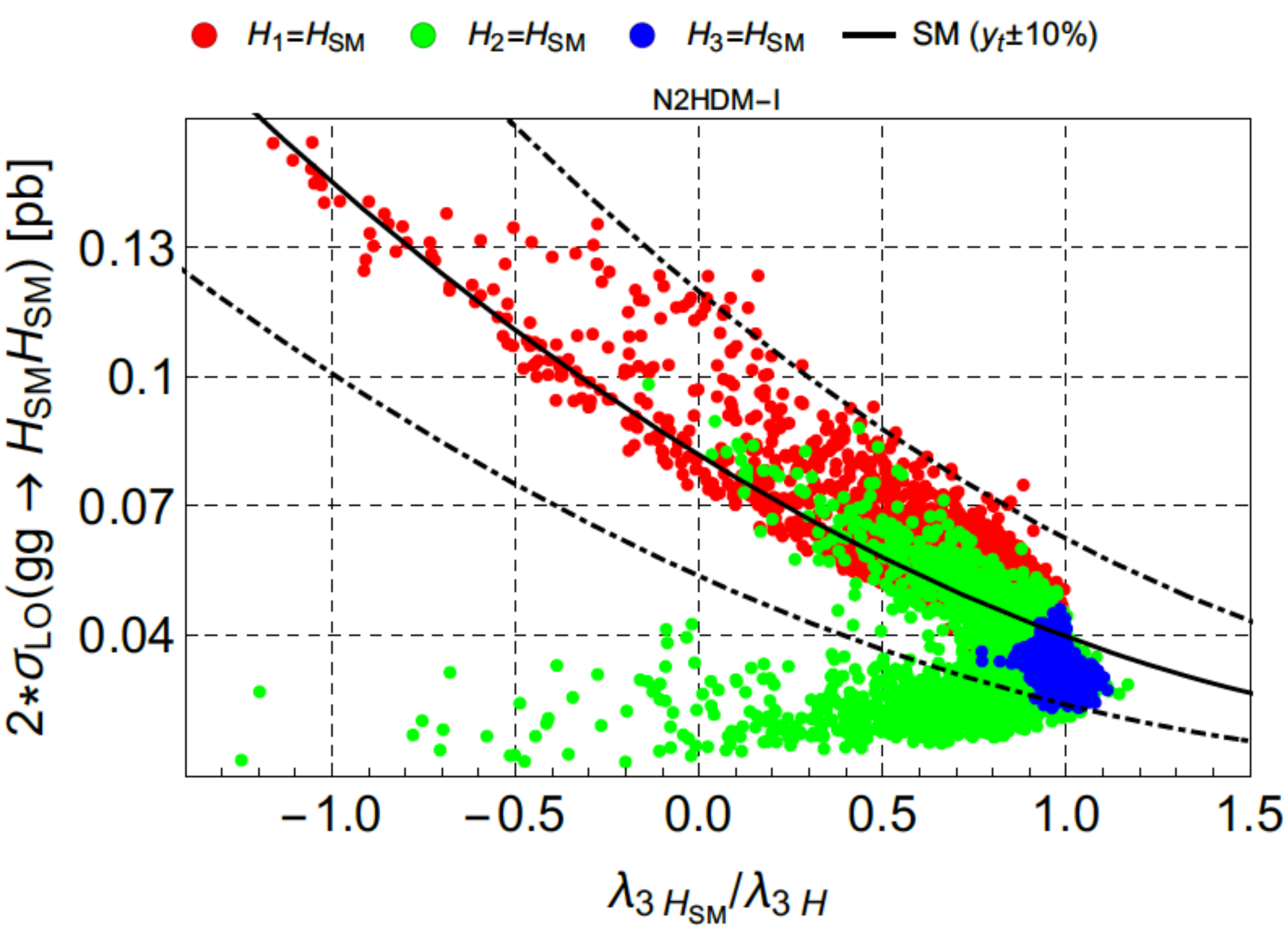
Impact of Non-resonant Searches - Example N2HDM

non-resonant searches start cutting parameter space

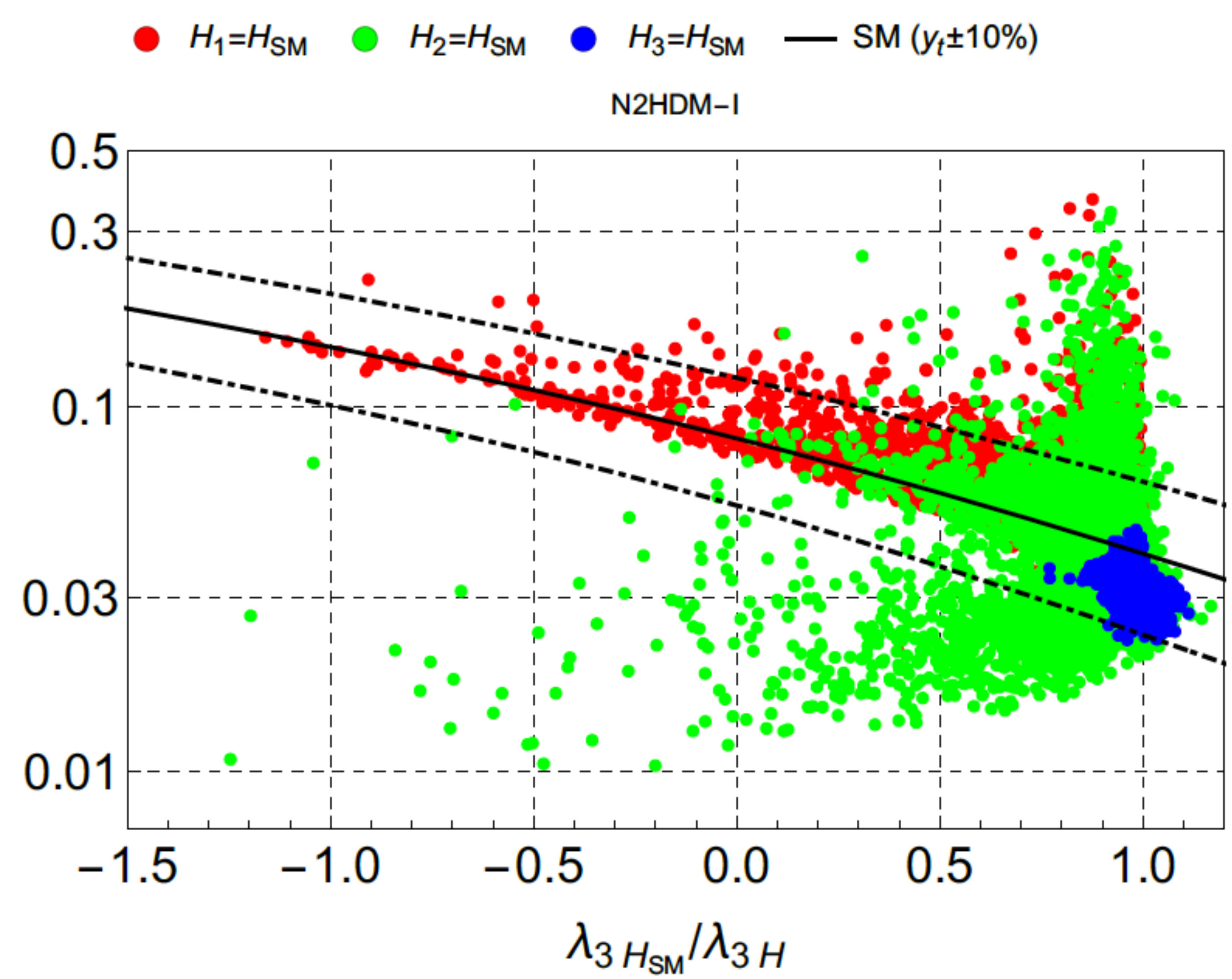


Required: combination Non-resonant and Resonant Searches

non-resonant production



total



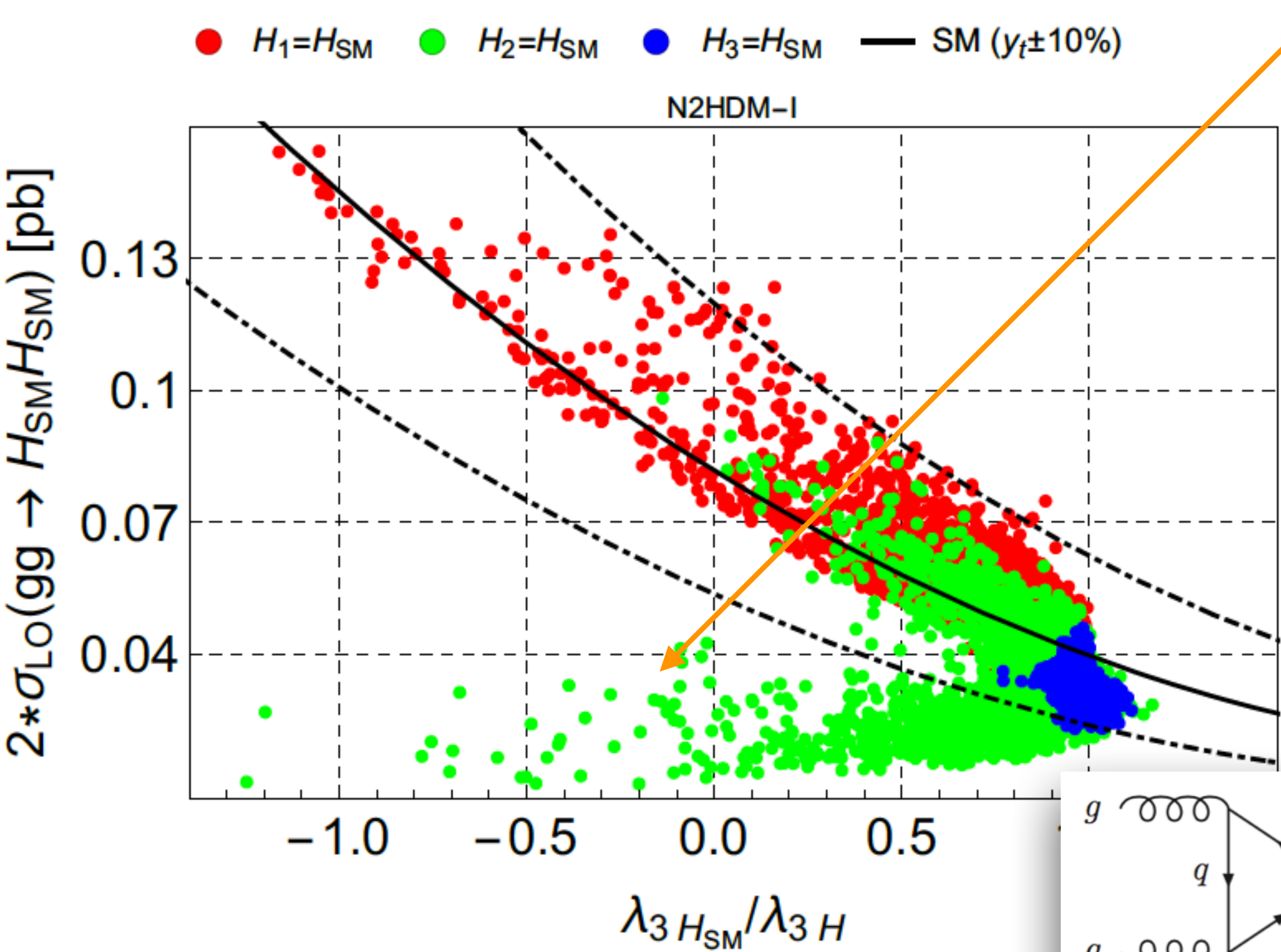
- full/dashed lines: top-Yukawa coupling = SM value/+-10%
- Combination of resonant and resonant searches required to constraint trilinear coupling

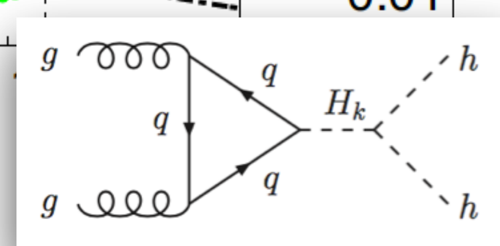
Required: combination Non-resonant and Resonant Searches

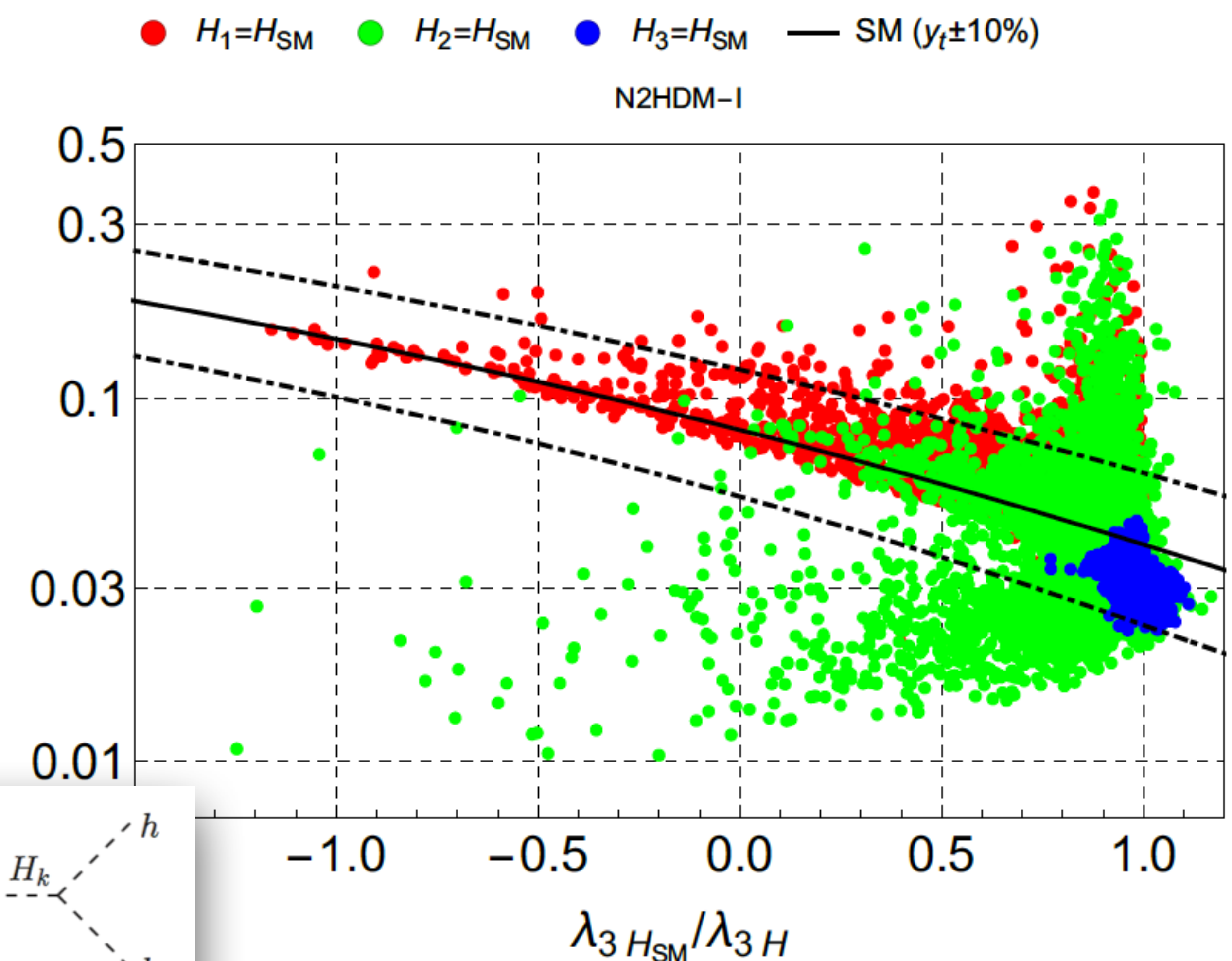
non-resonant production

negative interference of
H1 and H2 triangle contributions

total







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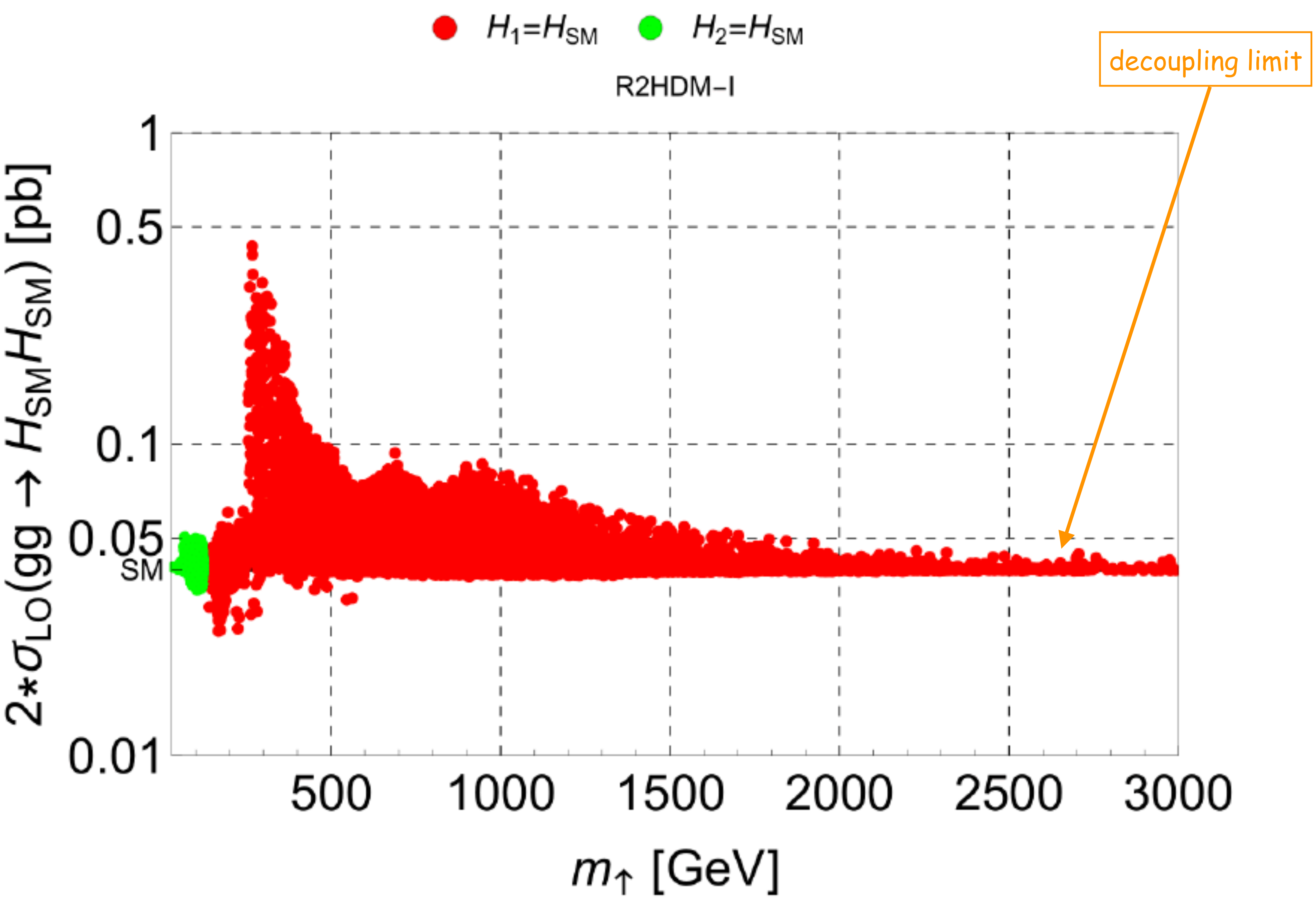
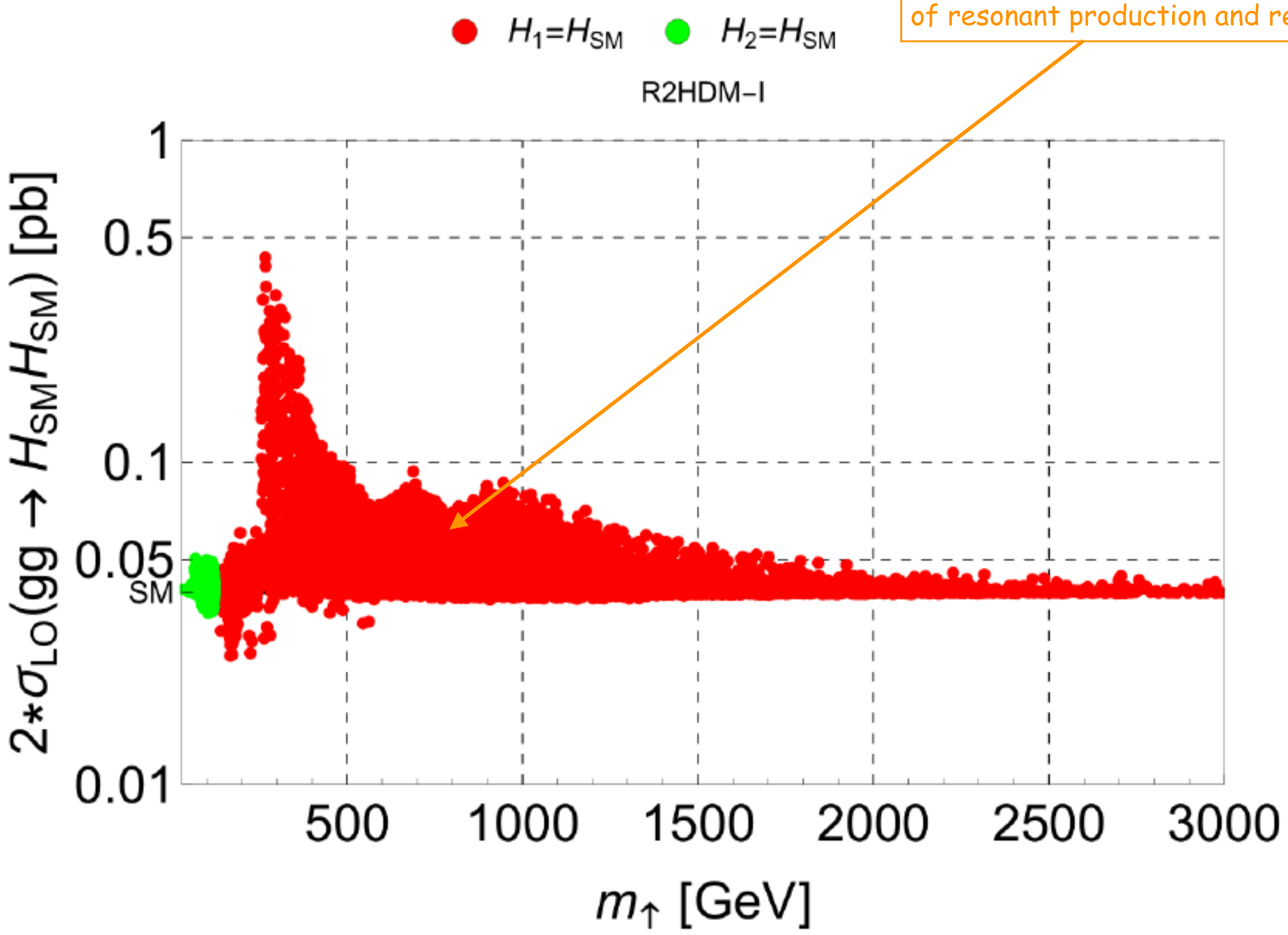
Parameter dependence - Ex. R2HDM T1



Parameter dependence - Ex. R2HDM T1

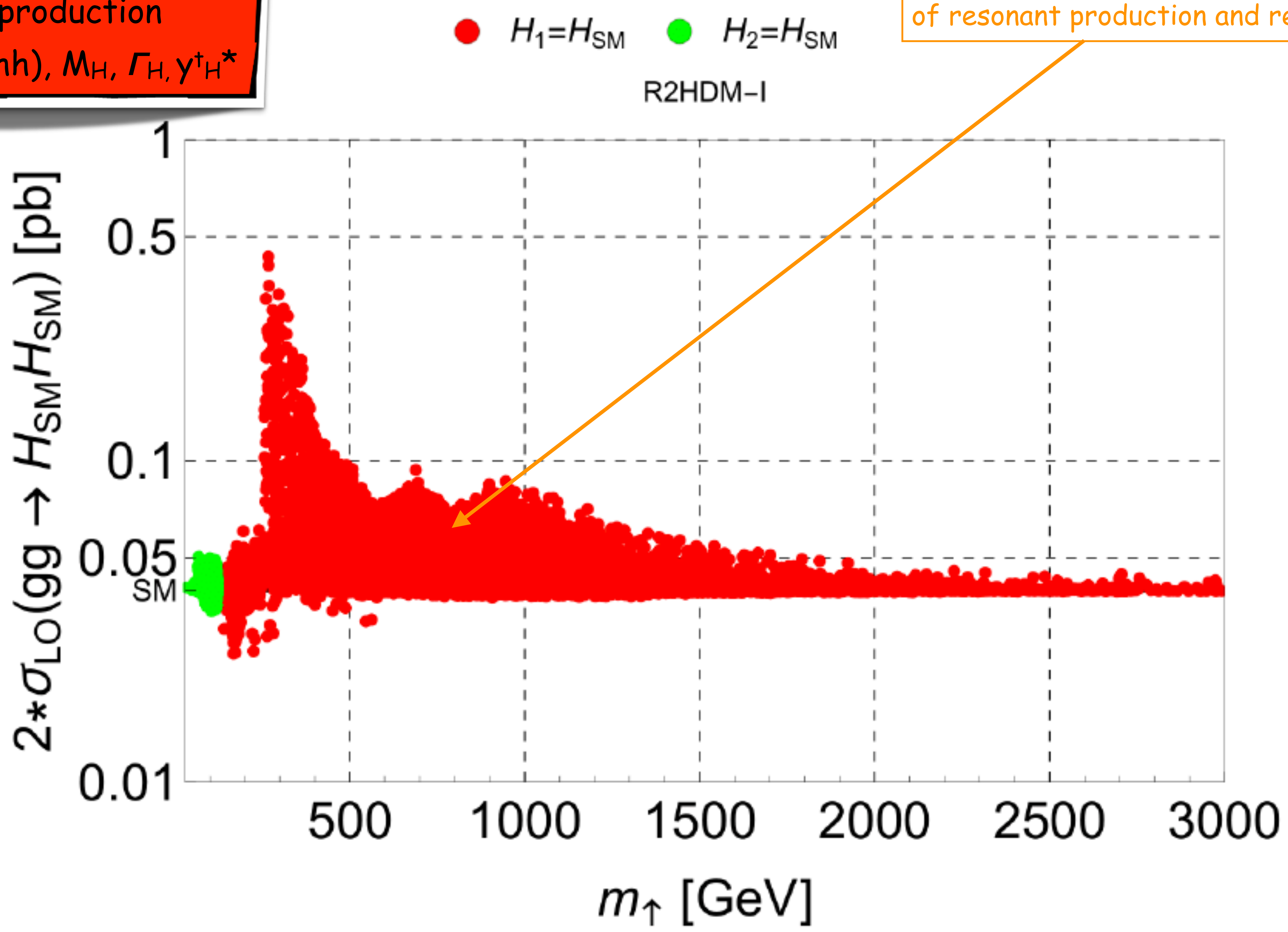
no clear correspondence between cxn value
of resonant production and resonant mass value



Parameter dependence - Ex. R2HDM T1

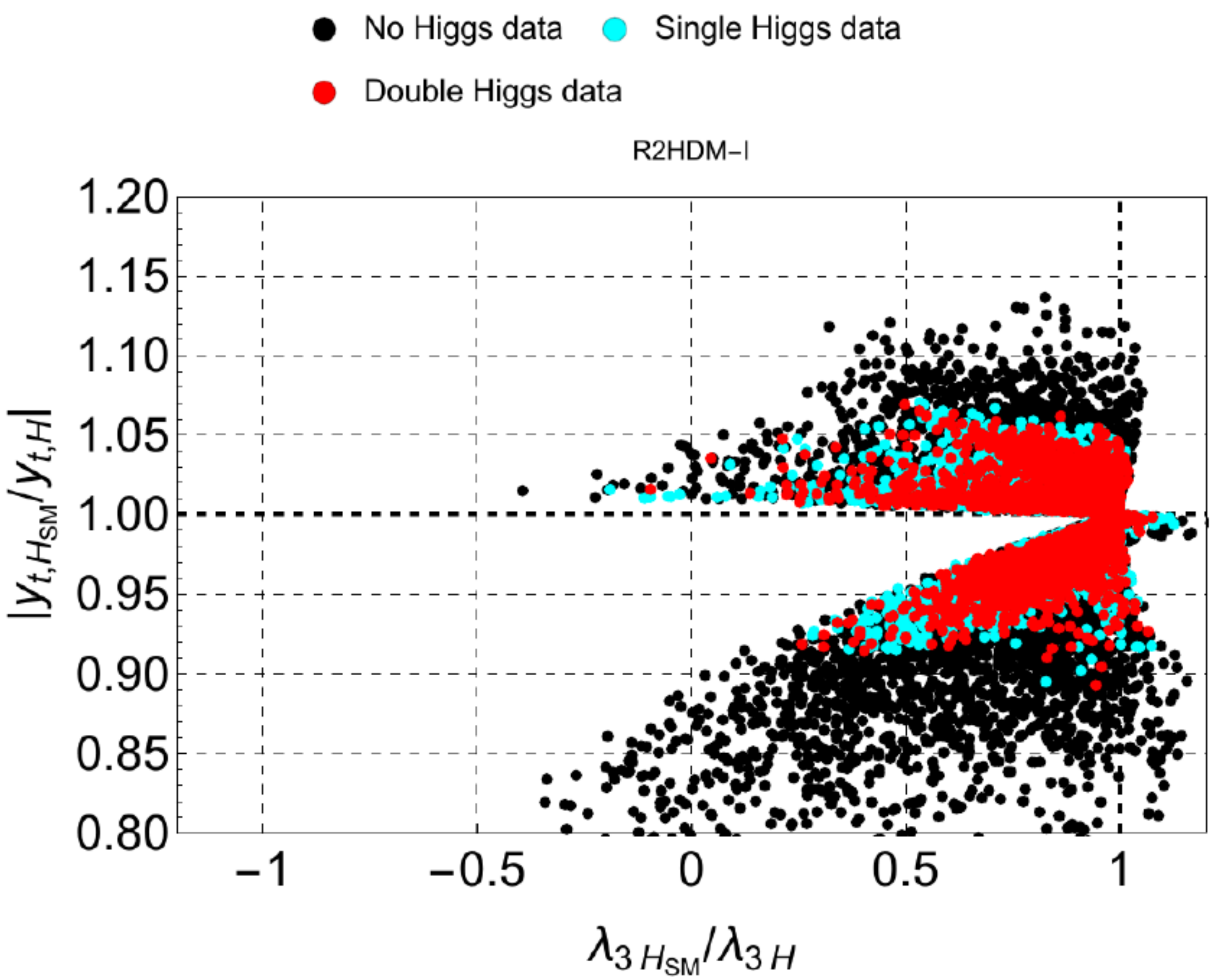
Resonant production depends on λ(Hhh), M_H, Γ_H, $y^t{}_H$*

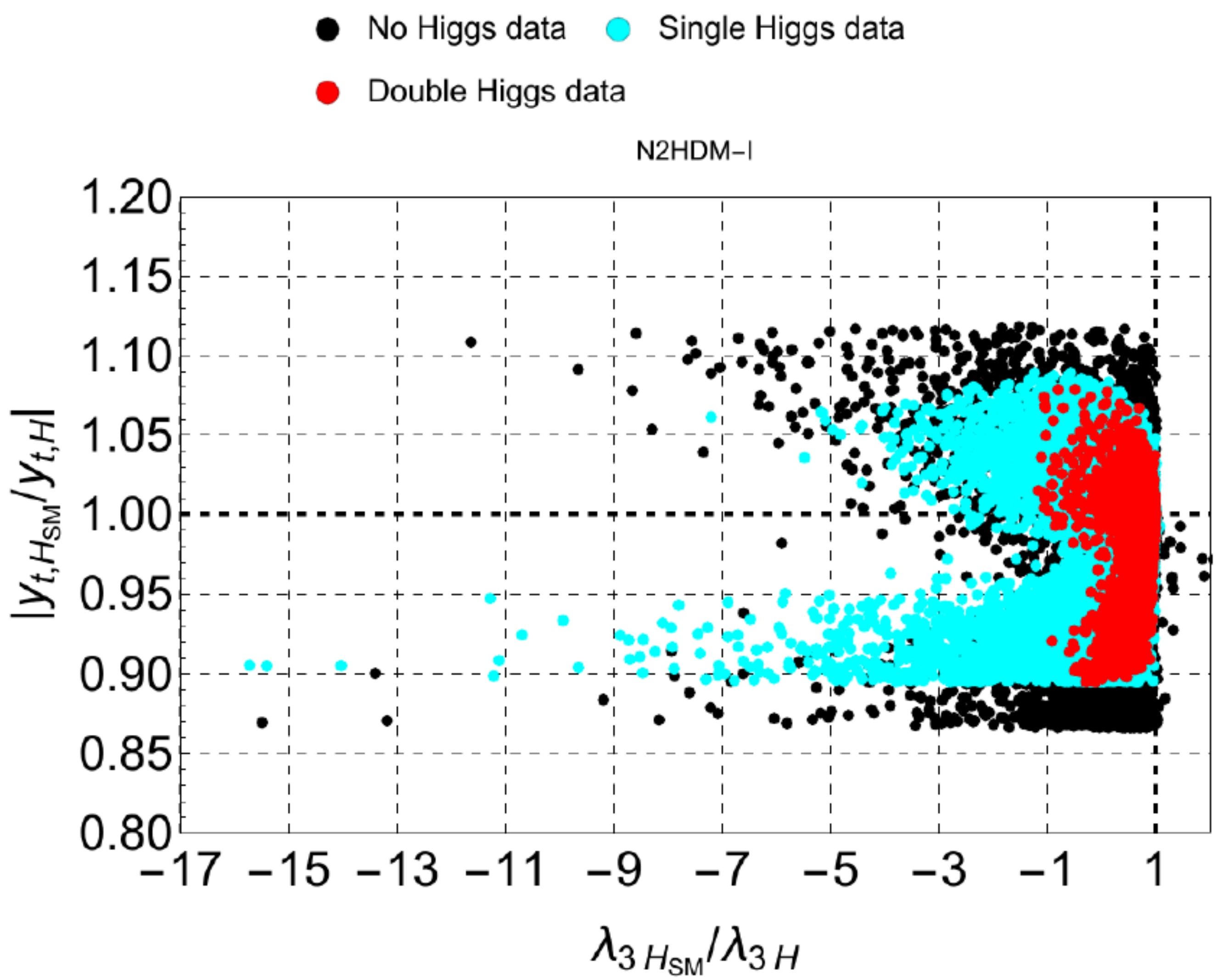
no clear correspondence between cxn value of resonant production and resonant mass value



*: even more in models with several resonant Higgs bosons

Impact of Single- & Di-Higgs Constraints on trilinear Higgs couplings





- single Higgs constrains y_t -> affects λ_{HHH}
- di-Higgs does not lead to much further restriction

- increased y_t precision affects here λ_{HHH} more strongly
- λ_{HHH} reduction mostly due to unitarity constraints (specific to N2HDM)

„wedge": non-SM λ_{HHH} comes with non-SM y_t

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
	$y_{t,H_{SM}}^{\rm R2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{\rm R2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{\rm C2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{\rm C2HDM}/\lambda_{3H}$
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	
	$y_{t,H_{SM}}^{\rm N2HDM}/y_{t,H}$	$\lambda_{3H_{SM}}^{\rm N2HDM}/\lambda_{3H}$	$y_{t,H_{SM}}^{\rm NMSSM}/y_{t,H}$	$\lambda_{3H_{SM}}^{\rm NMSSM}/\lambda_{3H}$
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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heavy II	–	–	–	–

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: $-0.4 \leqq \kappa_\lambda \leqq 6.3$

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
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Experimental results cut on λ_{HHH}
and hence on the parameter space

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

Allowed values of the trilinear Higgs self-coupling

	R2HDM		C2HDM	
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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	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\begin{aligned}
\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) &= 191 \text{ fb}\,, & \sigma(H_2)\times \mathrm{BR}(H_2\to WW) &= 254 \text{ fb}\\
\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) &= 109 \text{ fb}\,, & \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) &= 122 \text{ fb}\\
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\end{aligned}
$$


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

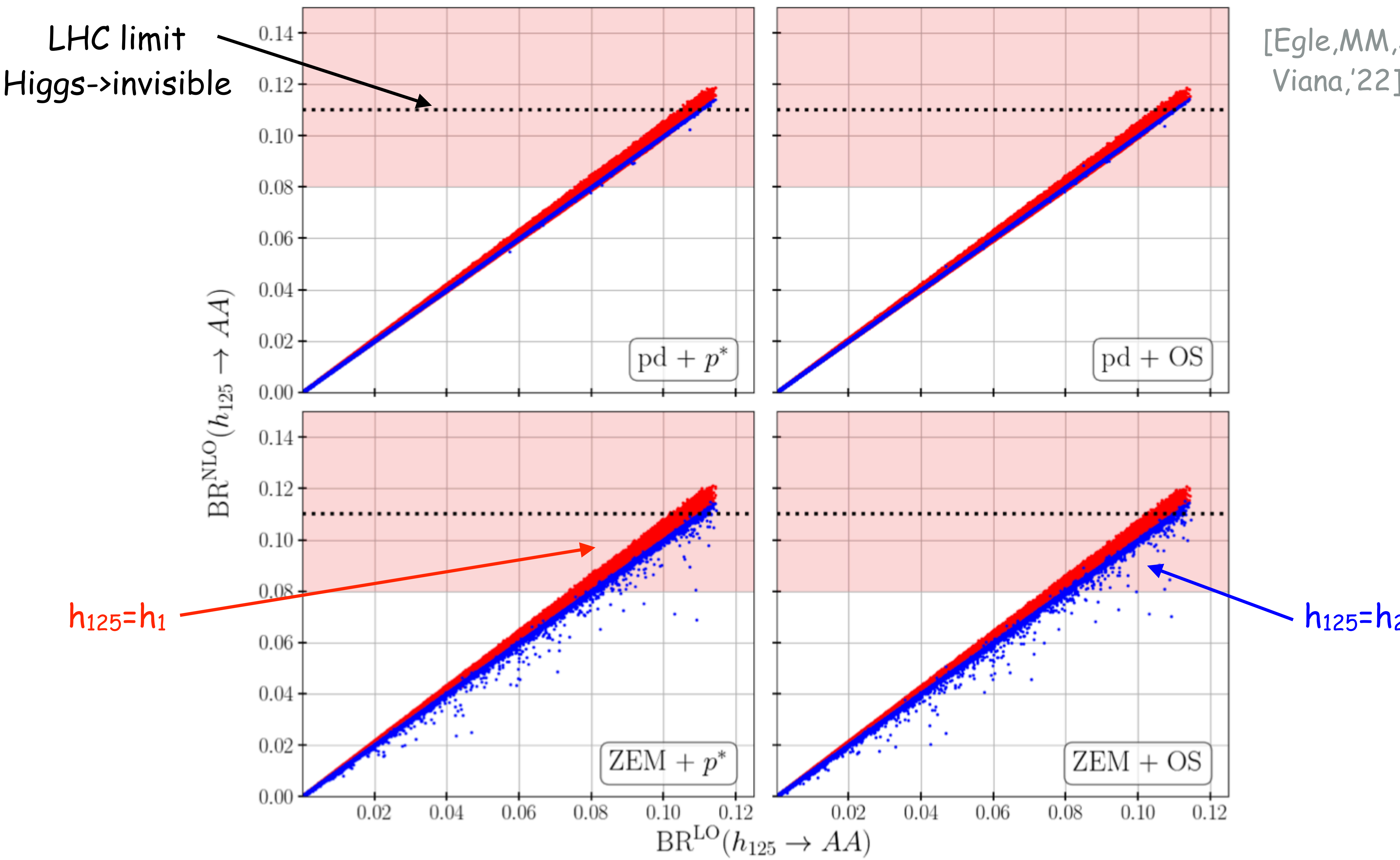
$$V = \frac{m^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \frac{\delta_2}{2}\Phi^\dagger\Phi|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + c.c.\right)$$

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

impose two separate discrete symmetries: S -> -S and A -> -A
v_A=0 => A->-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}->AA



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

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

Two More DM Models

The Vector Dark Matter Model (VDM)

[Hambye,´08; Lebedev eal,´11; Farzan,Akbarich,´12; Baek eal,´12,´14; Duch eal,´15; Azevedo eal,´18]

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

$$\chi_\mu \to -\chi_\mu \qquad \text{and} \qquad S \to S^*$$

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

σ_H: neutral SM-like Goldstone boson G^0

σ_S : DM Goldstone boson G^χ

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

and we have the covariant derivative

$$\mathcal{D}_\mu S = \left(\partial_\mu + i g_\chi \chi_\mu\right) S$$

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

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

✦ Independent physical Higgs potential parameters:

tadpole 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: $S \rightarrow -S$ $\rightsquigarrow$

- **Higgs potential:**

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

with the doublet and singlet fields

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

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

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

soft breaking term gives mass to DM particle χ

The Scalar Dark Matter Model (SDM)

Using the relations

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

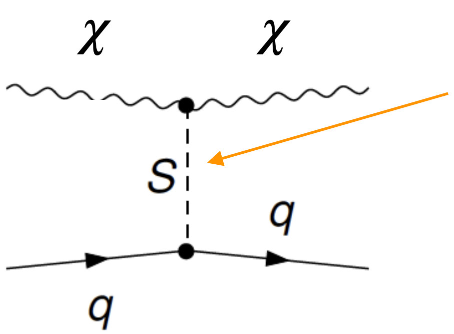
tadpole parameters

✦ Independent physical Higgs potential parameters:

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

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

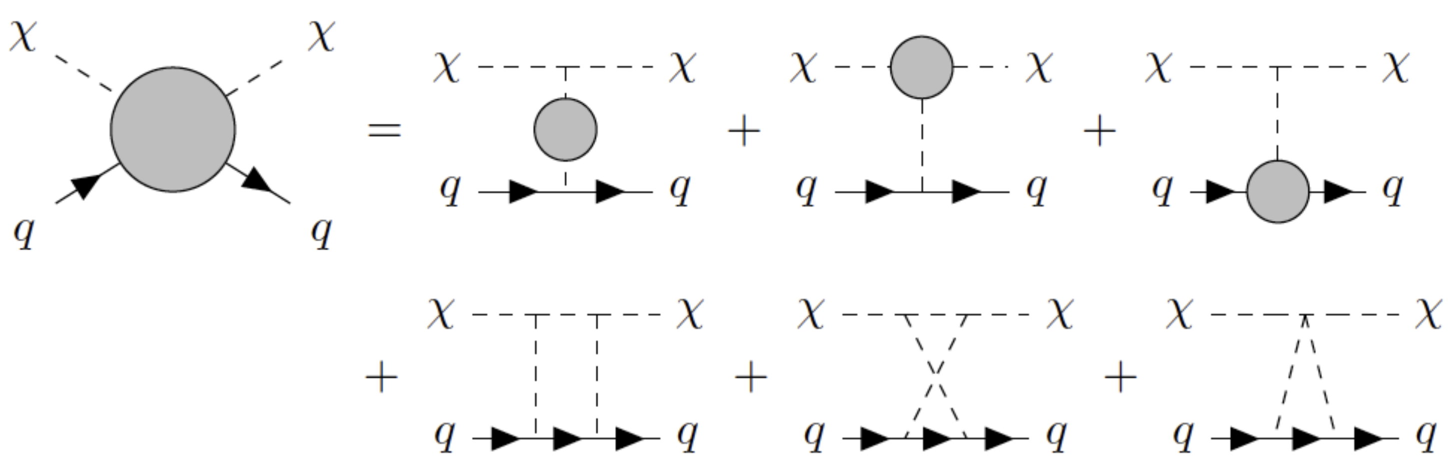
✦Computation of spin-independent DM-N cxn: use effective Lagrangian



mediator

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

[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 (←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:

relic density in our models

- DM relic density < $(\Omega h^2)^{\rm obs}_{\rm DM} = 0.1186 \pm 0.002 \rightsquigarrow$ define DM fraction $f_{\chi\chi} = \frac{(\Omega h^2)_\chi}{(\Omega h^2)^{\rm obs}_{\rm DM}}$

- DM annihilation strongest bounds from Fermi-LAT [FermiLAT,´15]; comparison with data through $\sigma^{\rm eff}_{\chi\chi} = f^2_{\chi\chi}\sigma_{\chi\chi}$, 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 $\sigma^{\rm eff}_{\chi N} \equiv f_{\chi\chi}\sigma_{\chi N}$; 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

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

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:

$$\begin{aligned} m_\phi &\in [\ 30\,\mathrm{GeV},\ 1000\,\mathrm{GeV}\ ] \\ m_\chi &\in [\ 30\,\mathrm{GeV},\ 1000\,\mathrm{GeV}\ ] \\ v_S &\in [\ 1\,\mathrm{GeV},\ 1000\,\mathrm{GeV}\ ] \\ \alpha &\in [\ -\pi/2,\ \pi/2\ ] \end{aligned}$$

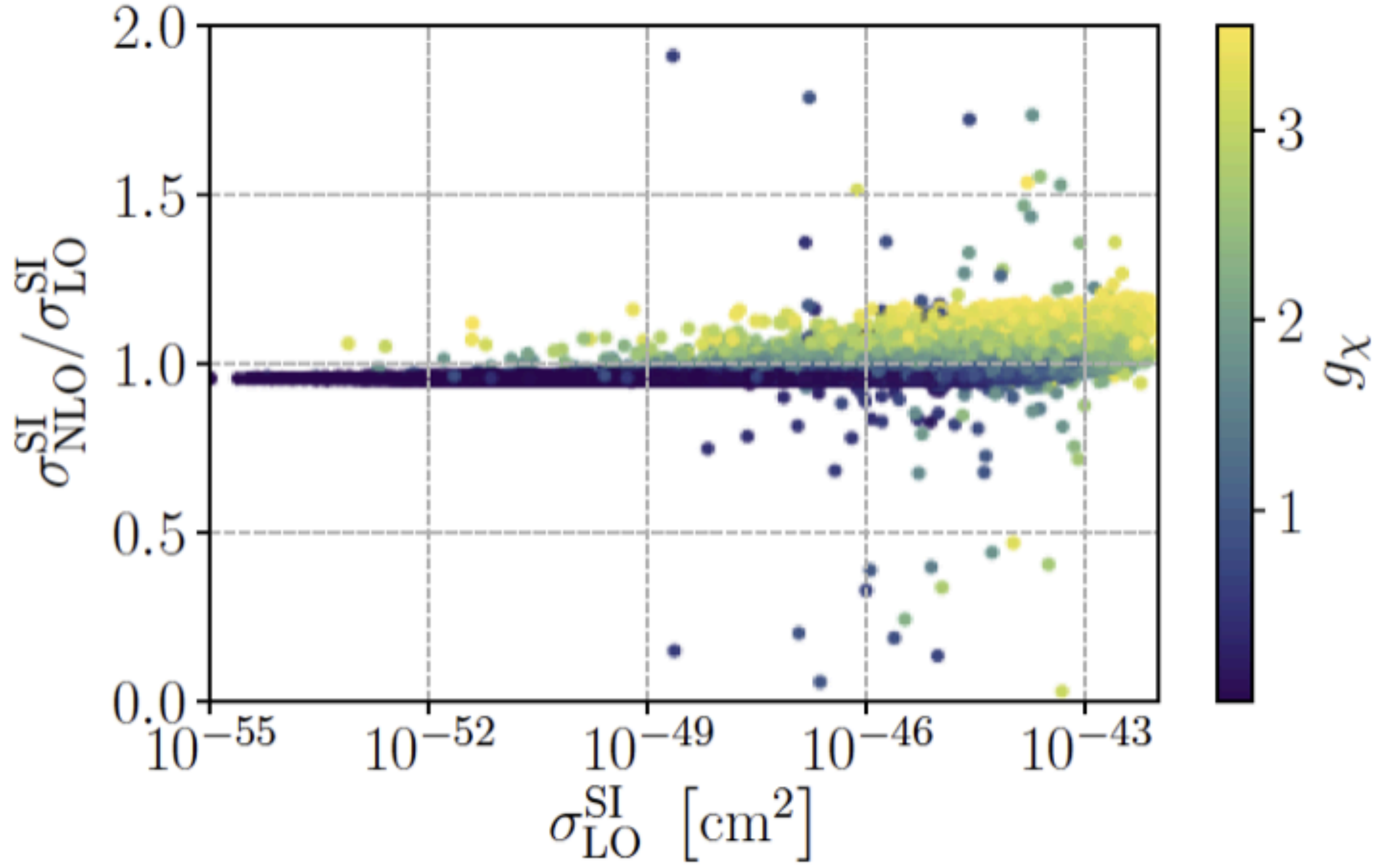
- Nuclear proton matrix elements:

[Hisano,Ishiwata,Nagata,´12; Young,Thomas,´09; Shifman,Vainshtein,Zakharov,´78]

$$f_u^p = 0.015\,13\,, \quad f_d^p = 0.0191\,, \quad f_s^p = 0.0447\,,$$
$$f_g^p = 0.921\,07\,,$$
$$u^p(2) = 0.22\,, \quad c^p(2) = 0.019\,,$$
$$\bar{u}^p(2) = 0.034\,, \quad \bar{c}^p(2) = 0.019\,,$$
$$d^p(2) = 0.11\,, \quad s^p(2) = 0.026\,, \quad b^p(2) = 0.012\,,$$
$$\bar{d}^p(2) = 0.036\,, \quad \bar{s}^p(2) = 0.026\,, \quad \bar{b}^p(2) = 0.012\,,$$

VDM: K-Factors

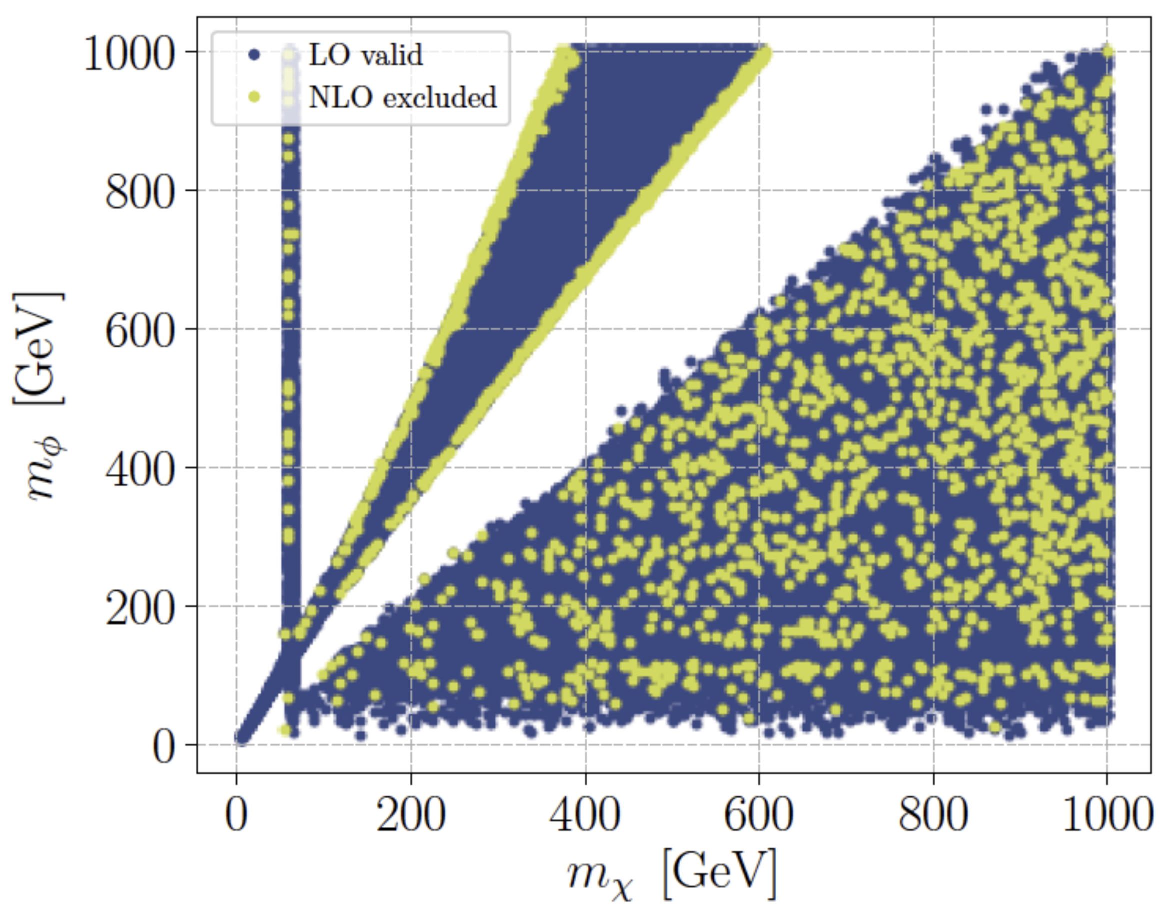
[Glaus,MM,Müller,Patel,Santos,´20]

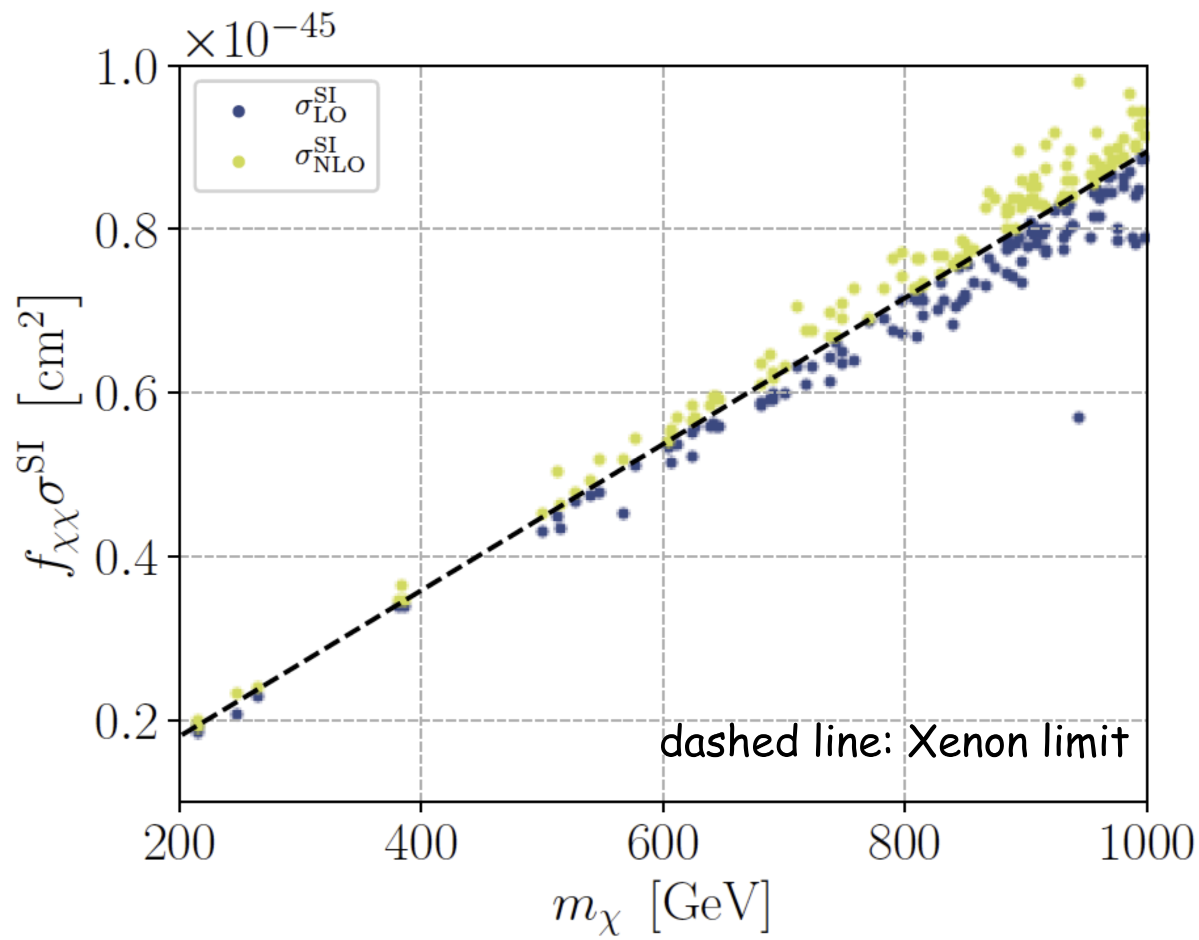


- K-factor increases with g_χ, below 30% (barring outliers)

VDM: Phenomenological Impact

[Glaus,MM,Müller,Patel,Santos,´20]



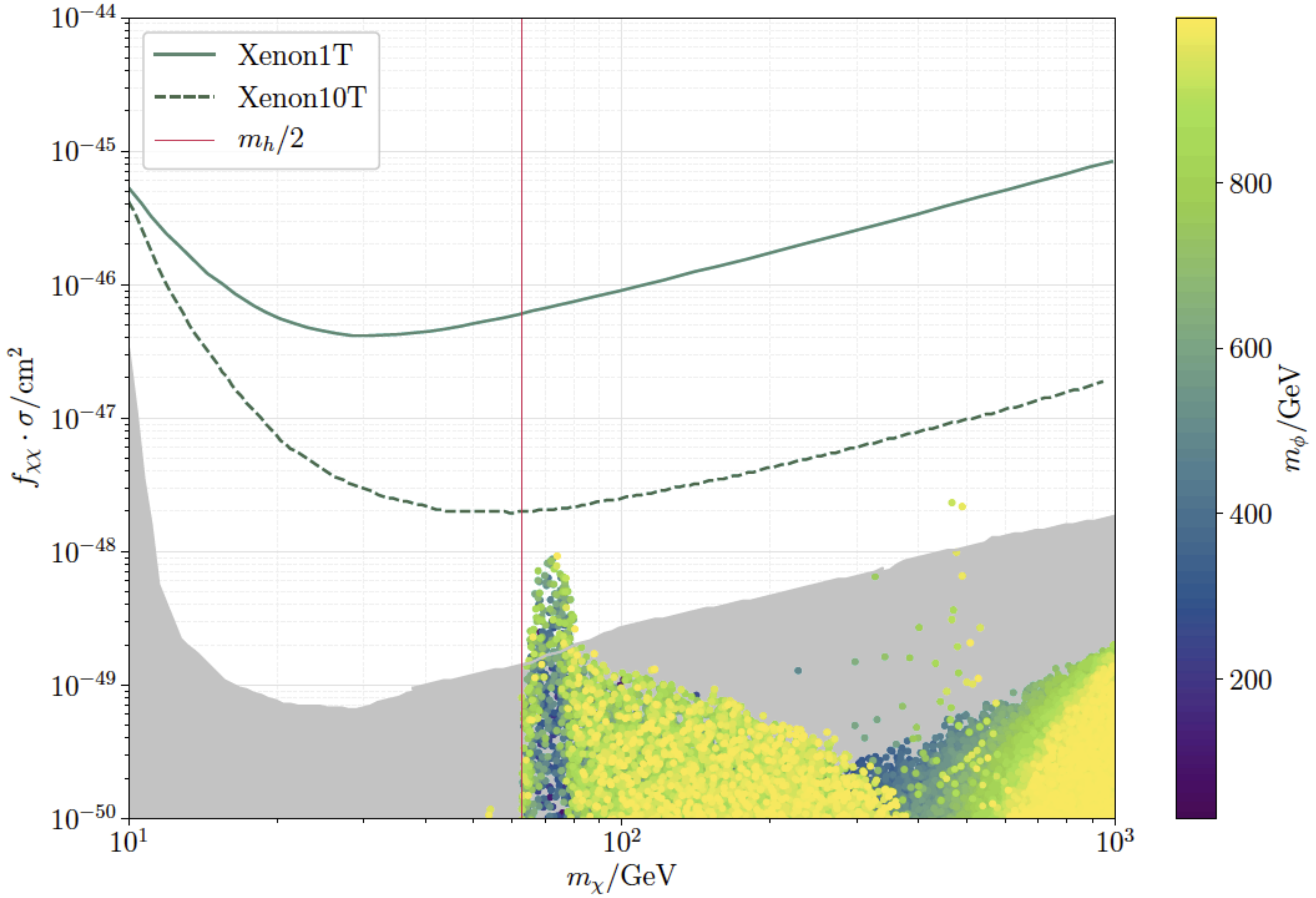


- blue: allowed at LO
  green excluded at NLO

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

SDM: Impact of NLO Corrections

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



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


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]

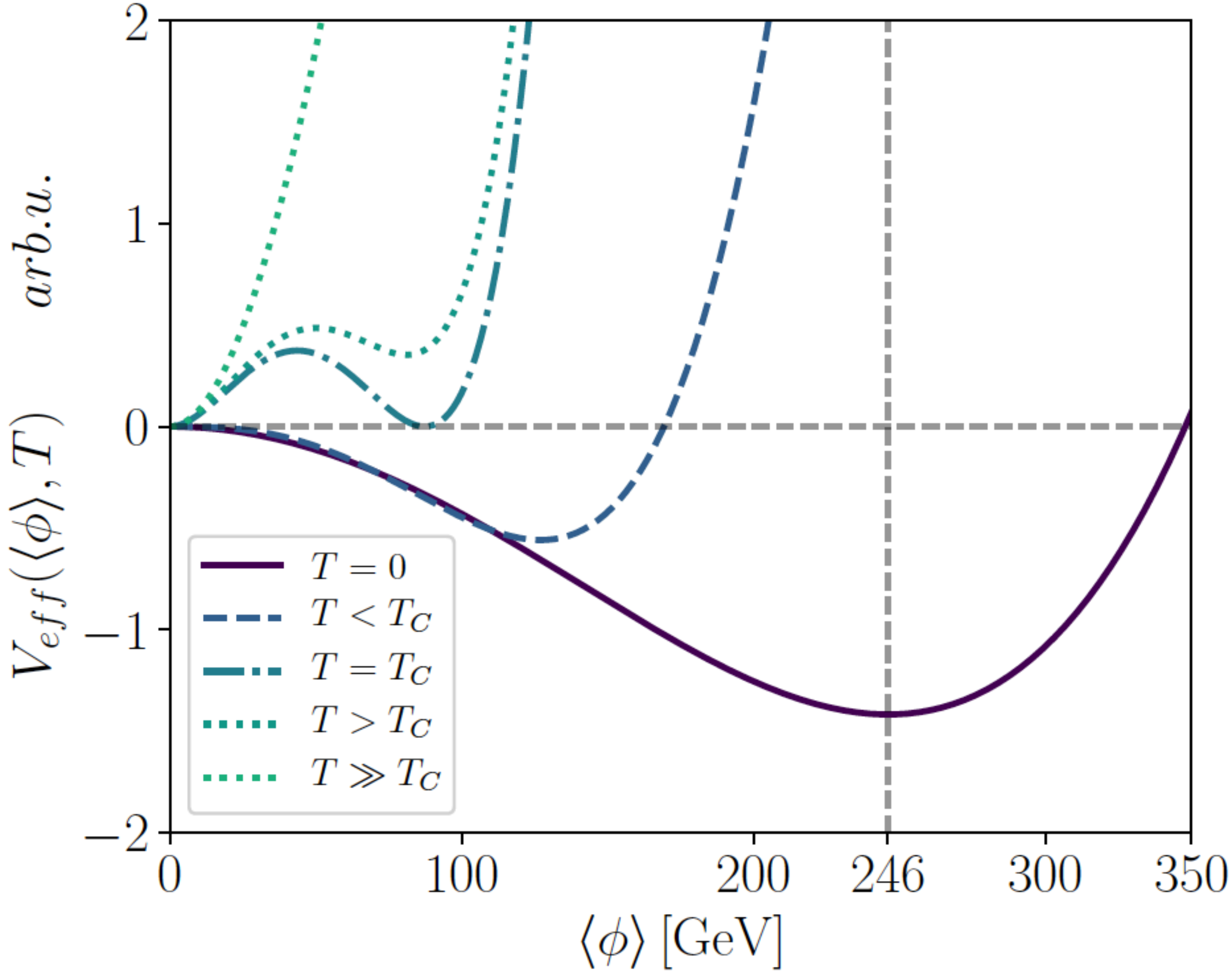
$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  * (i) B number violaton (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]

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

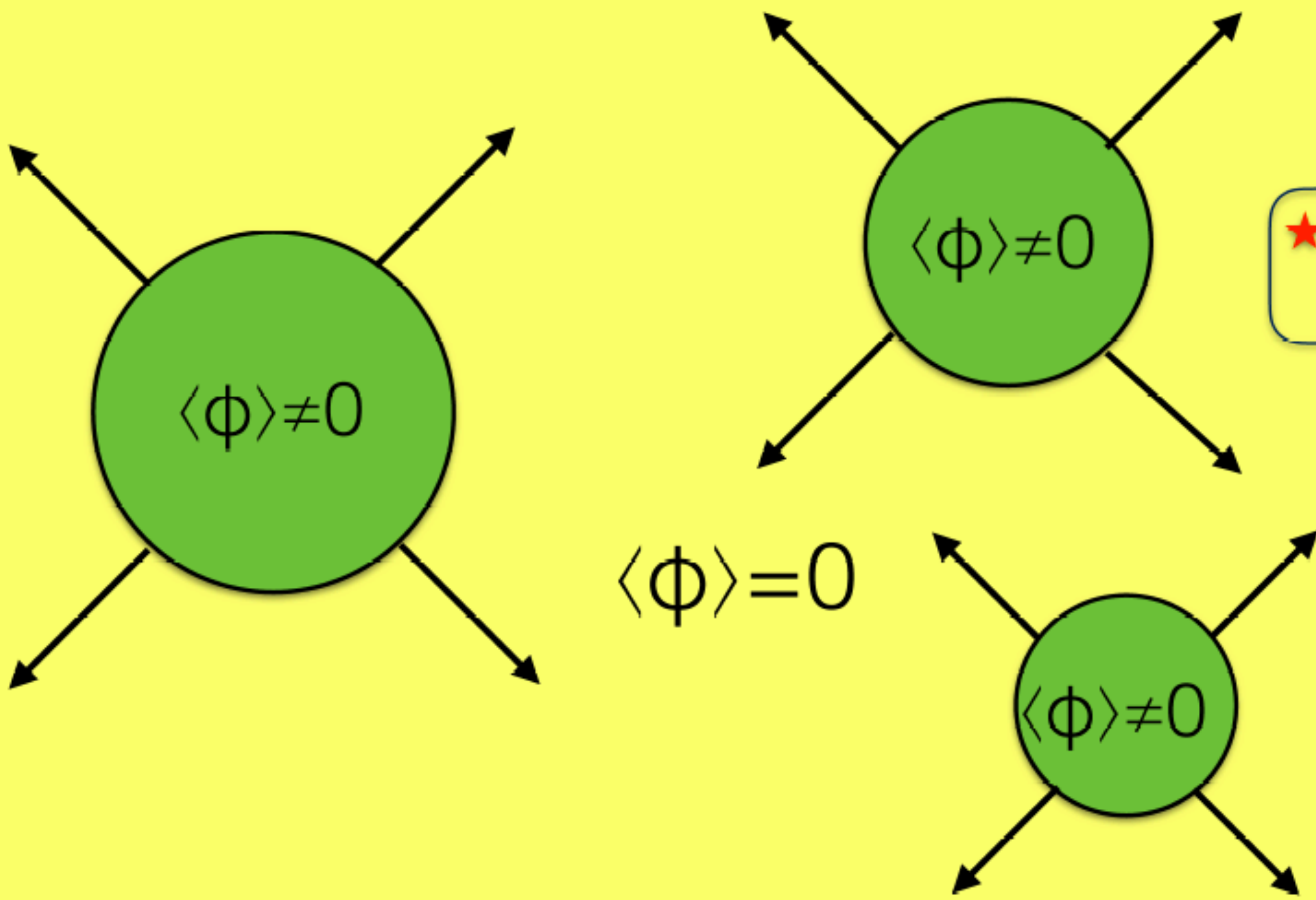
$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition


$V_{eff}(\langle\phi\rangle, T)$ arb.u.
2
1
0
−1
−2
0
100
200
246
300
350
$\langle\phi\rangle$ [GeV]
$T = 0$
$T < T_C$
$T = T_C$
$T > T_C$
$T \gg T_C$

Baryogenesis in a Nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle \phi_c(T_c) \rangle / T_c \geq 1$

ϕ_c, T_c

VEV and T at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall★

Higgs Pair Production and a 2HDM-EFT [Anisha,Biermann,Englert,MM,'22]

- 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 [Anisha eal,´19]

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

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

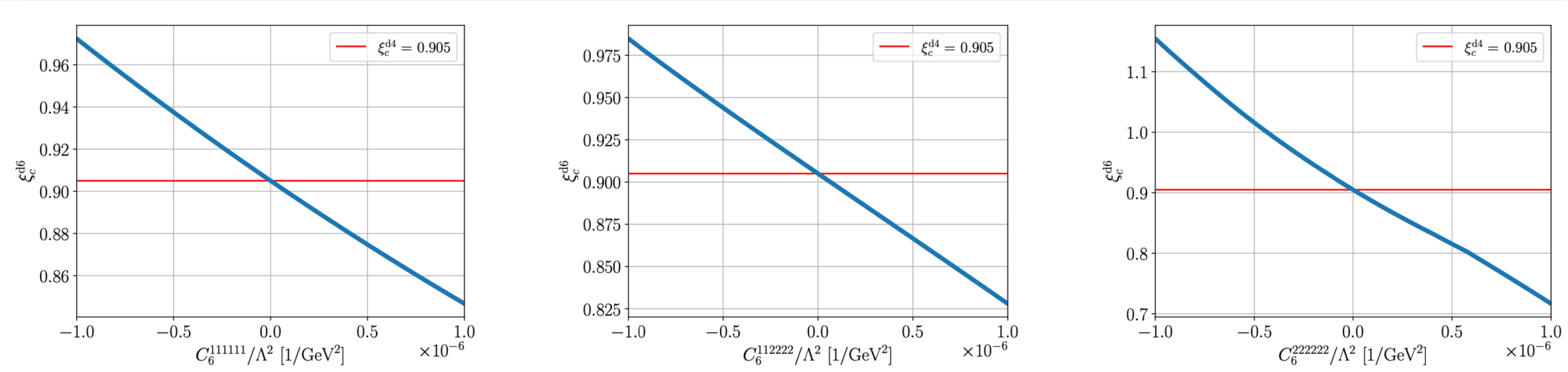
O_6^{111111}	$(\Phi_1^\dagger\Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger\Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$
O_6^{122111}	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1)$	O_6^{122122}	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_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

- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ 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]



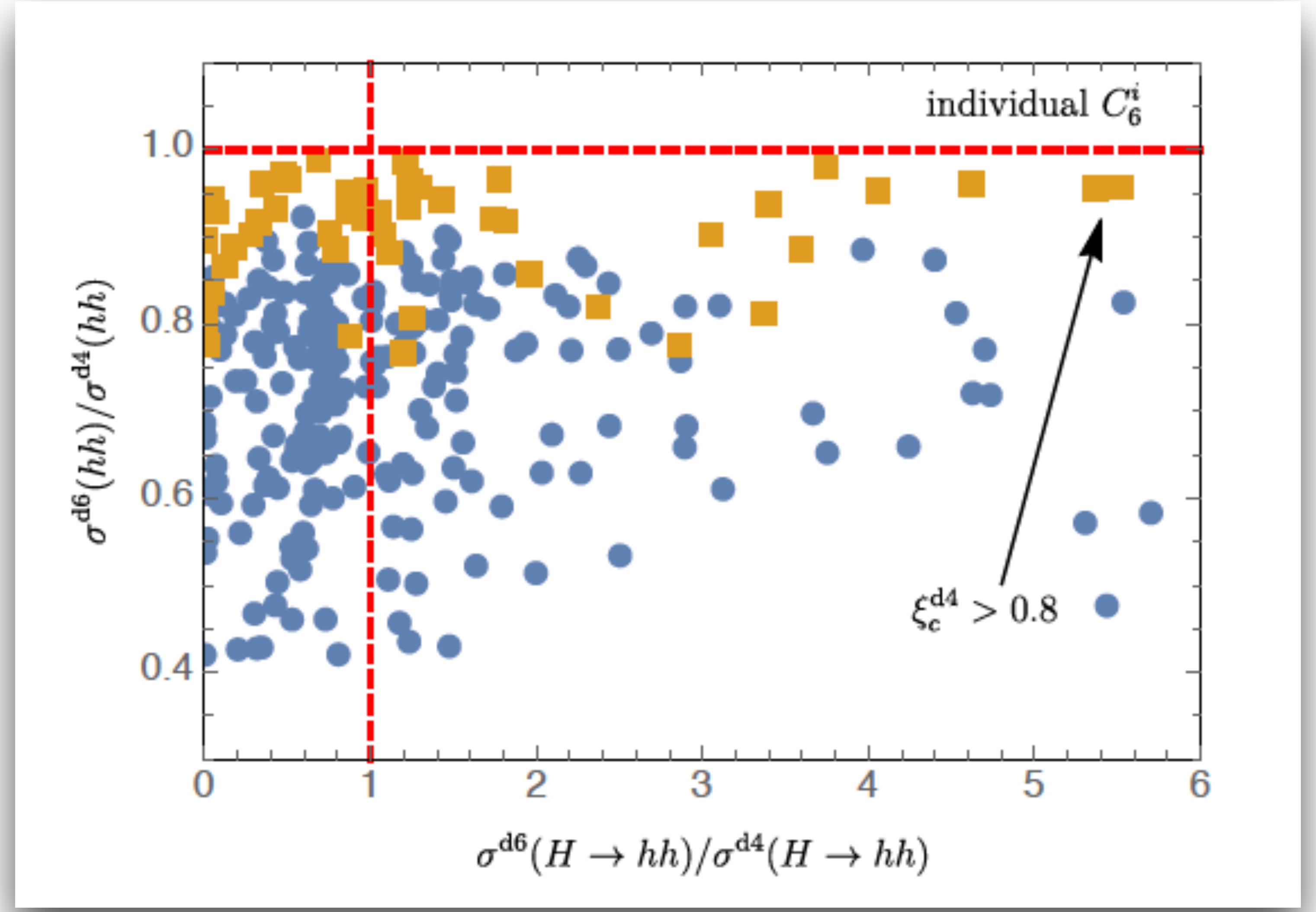
impact of individual Wilson coefficients on ξ_c^{d6} for $\xi_c^{d4} \cong 0.9$:

- linear response ~ C^i_6 -> perturbativity ok
- SFOEWPT achievable in agreement with experimental constraints

interference effects in heavy Higgs production in tt final state are width dependent
-> sensitive to EFT modifications: overall effect is small after taking the Higgs data constraints into account => hh production important tool for fingerprinting SFOEWPT

Strength of EWPT and hh production

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

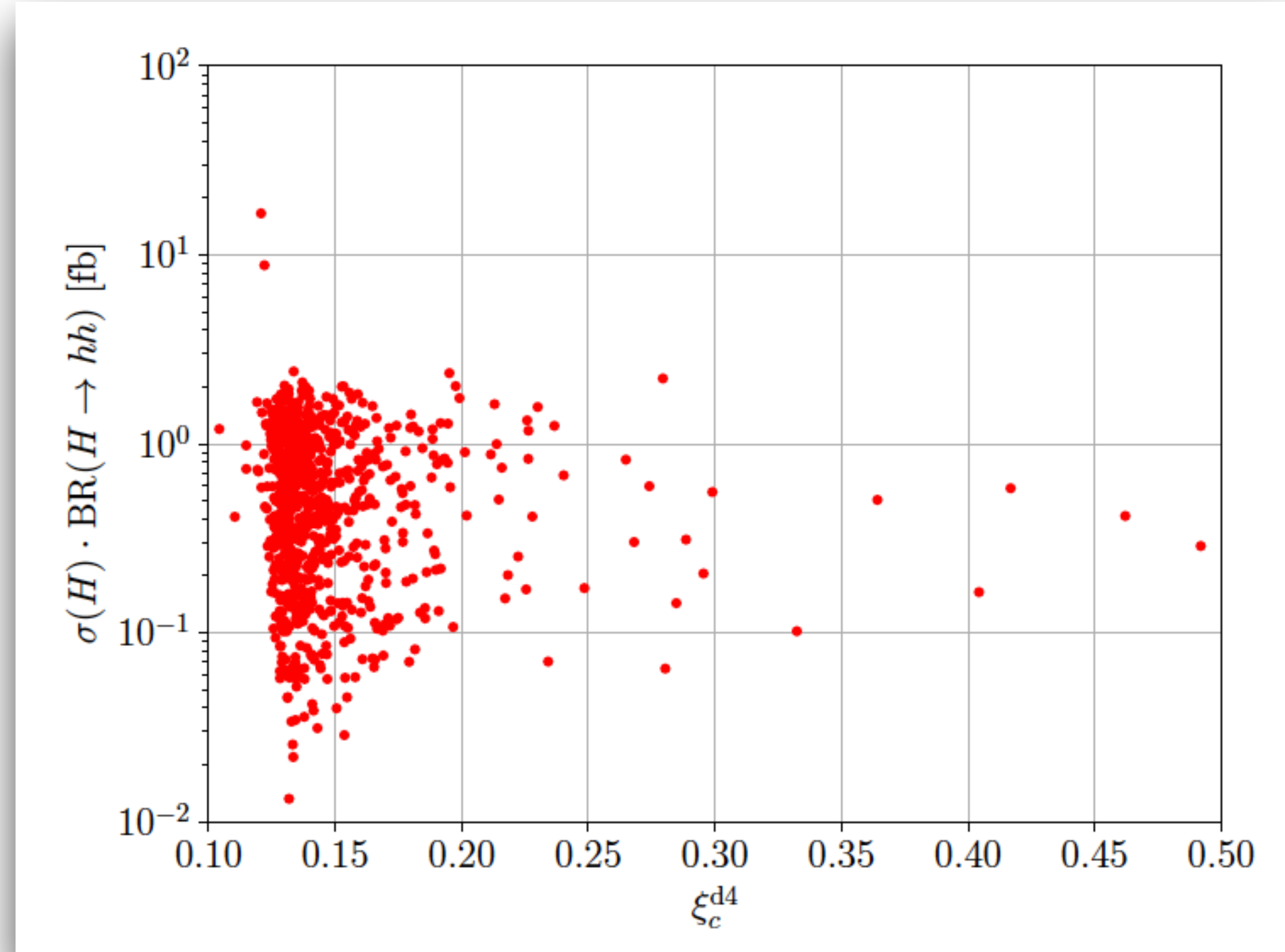


Points with $\xi_c^{d6} \cong 1$ for $\xi_c^{d4} \geqq 0.3$, orange points $\xi_c^{d4} > 0.8$

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

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

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

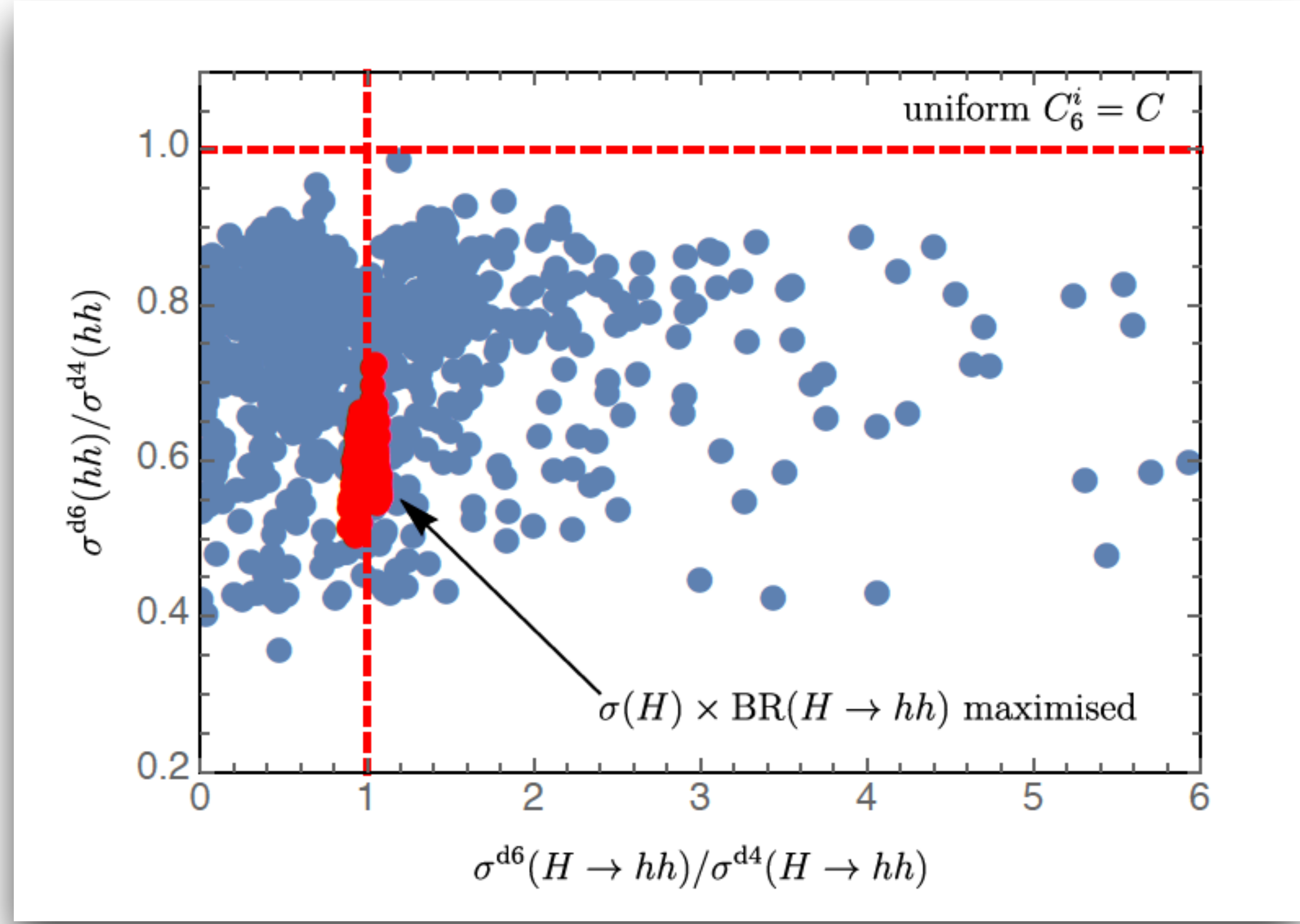


- Higgsphilic points characterized by larger distance $|1- \xi_c^{d4}|$

  $\rightsquigarrow$ interplay of different dim-6 operators to achieve ξ_c~1 in a controlled way

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

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



- Resonant H→hh production enhancement factor of 2.5 possible for cxn in fb range
- Higgs-philic points: resonance contribution modified by ~5-10%, continuum production modified by ~50%


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: $\Phi_1 \to \Phi_1 \, , \quad \Phi_2 \to -\Phi_2 \, , \quad \Phi_S \to -\Phi_S$

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

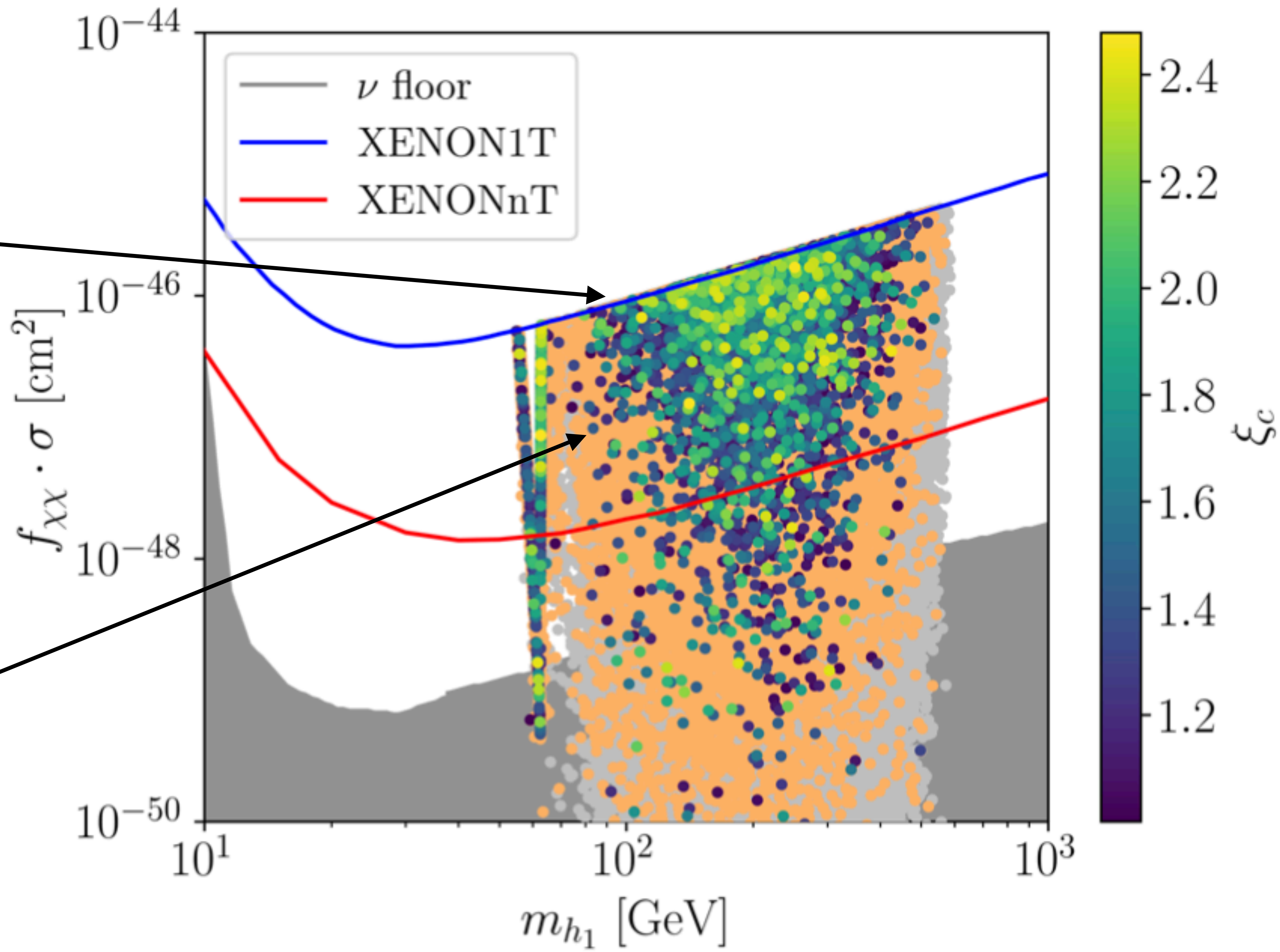
- trilinear coupling A is complex: dark sector with CP violation <- not constrained by electric dipole moment

Strong First Order Phase Transition and DM Constraints

[Biermann,MM,Müller'22]

points compatible with direct detection

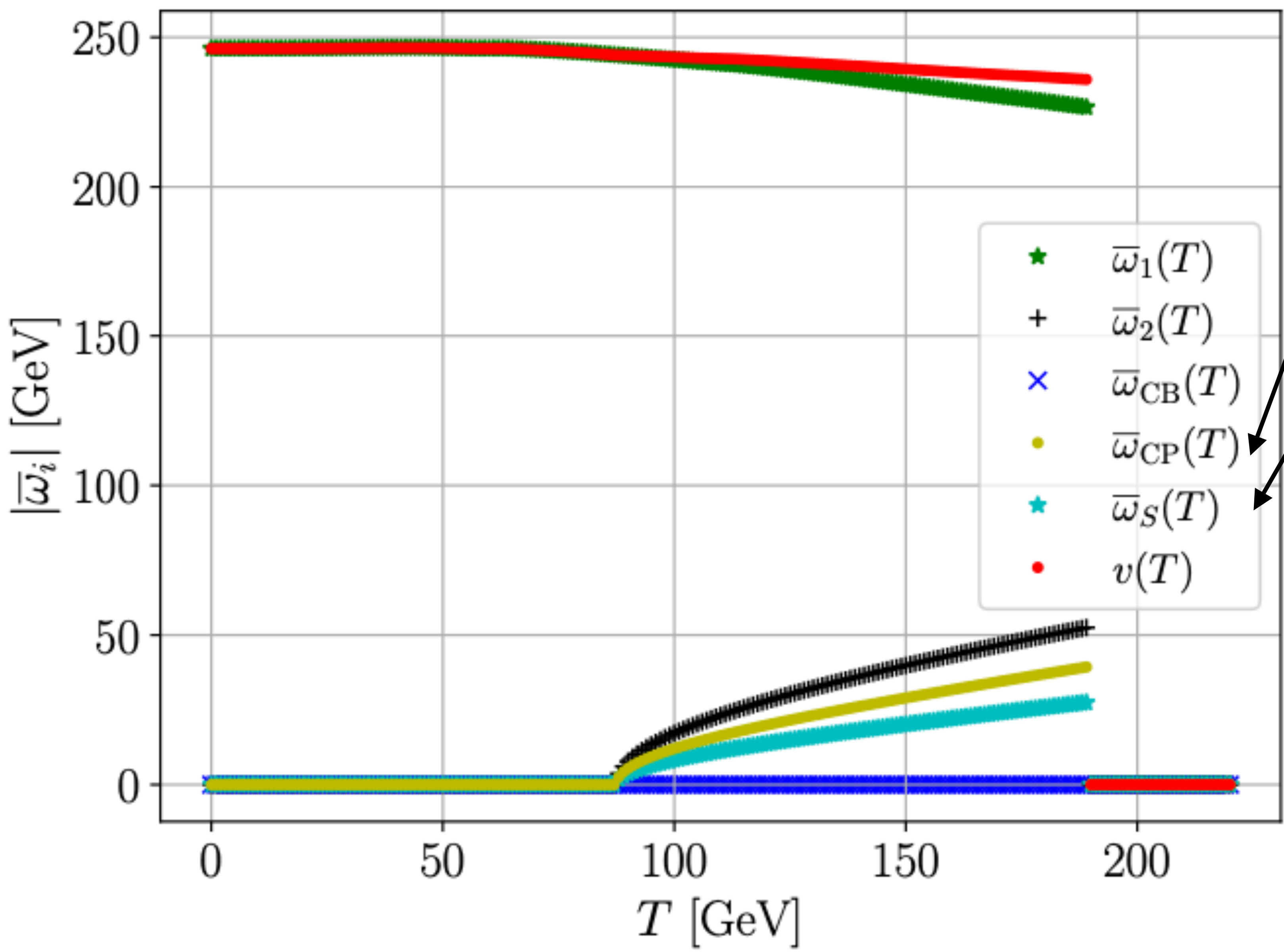
points with strong first order electro-weak phase Transition



points also compatible with DM relic density

Spontaneous CP Violation

[Biermann,MM,Müller'22]

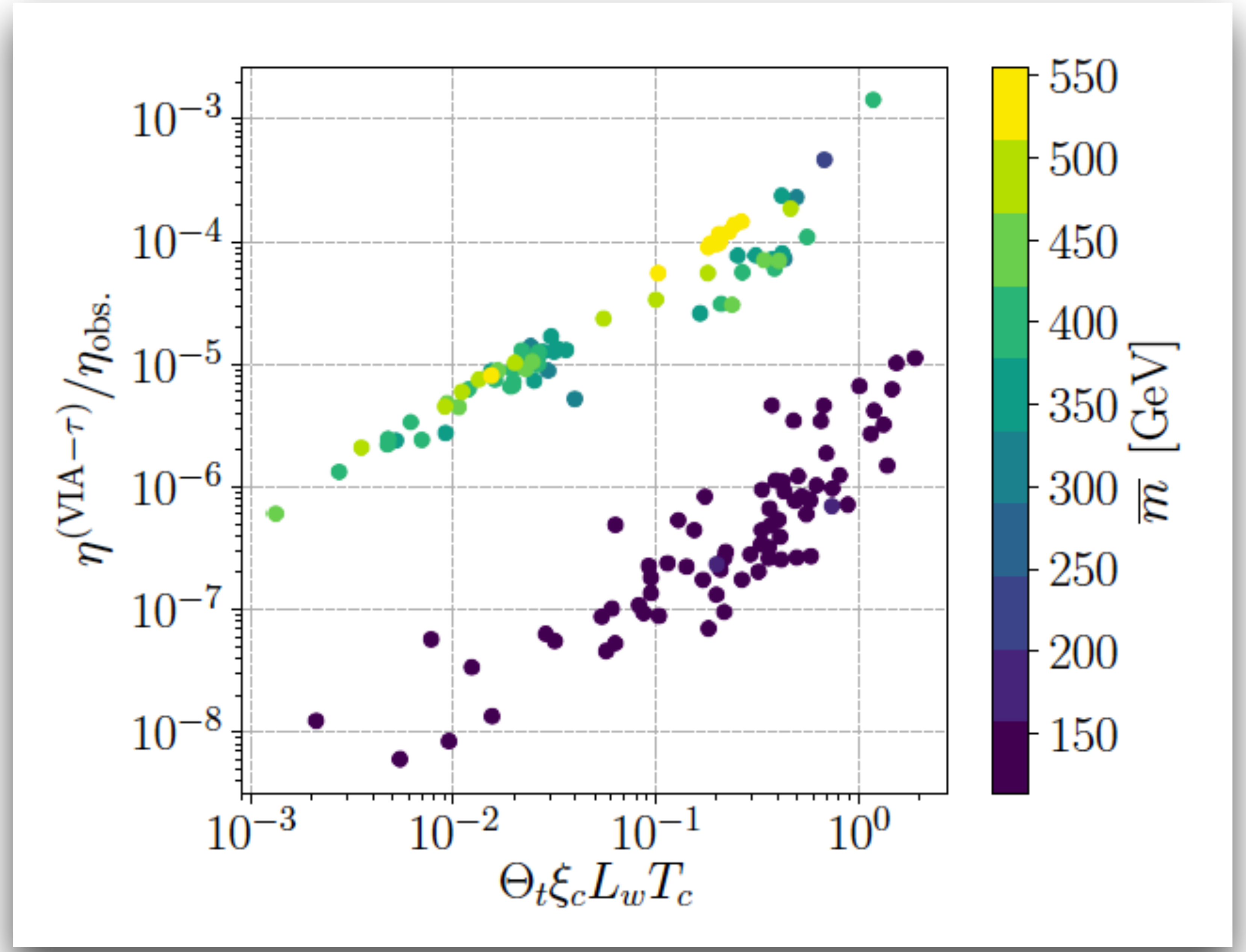


CP-violating VEV in dark sector plus singlet VEV generated spontaneously => CP violation transferred to visible sector

Strong first order electroweak phase transition

Electrweak Baroygenesis - C2HDM

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

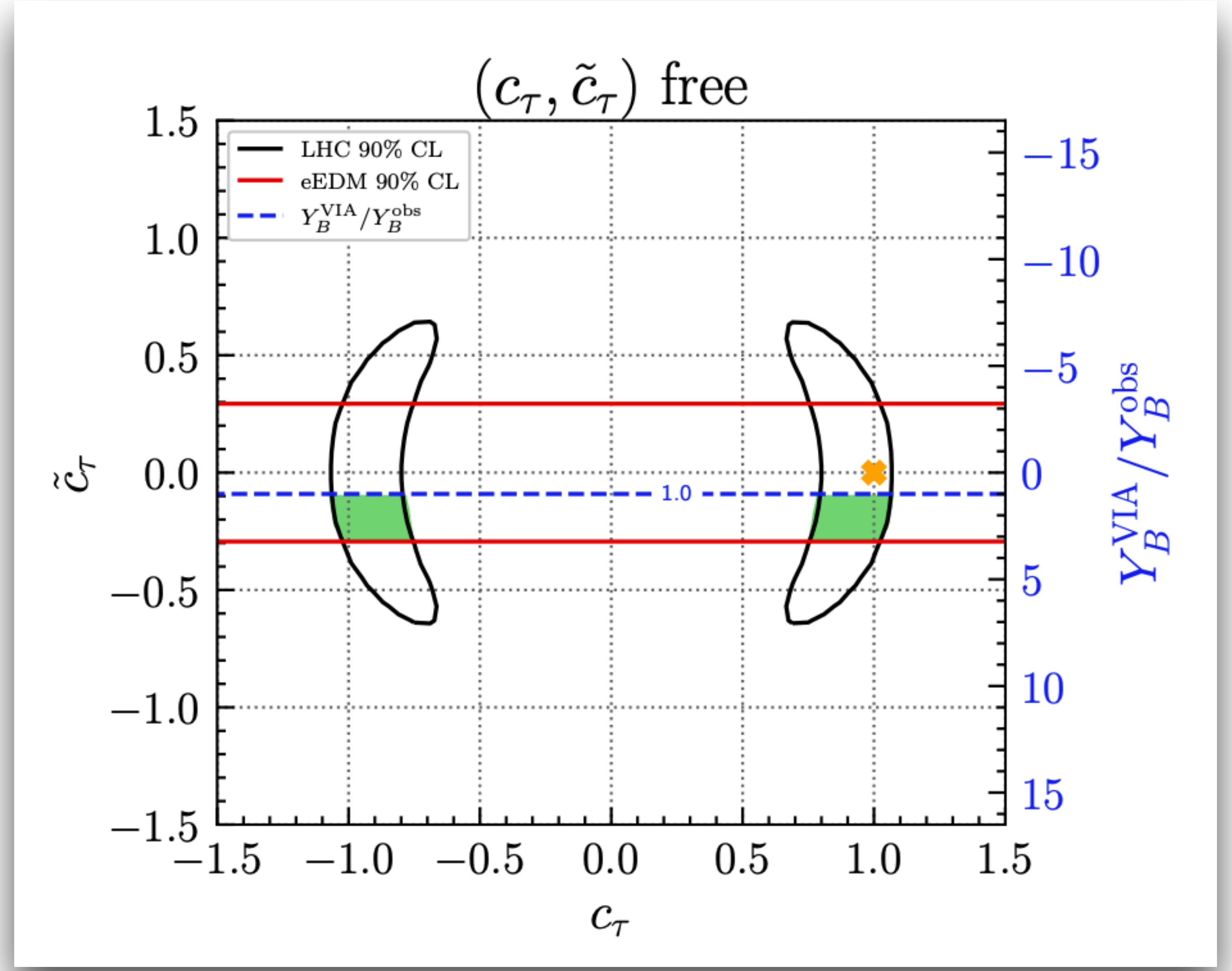


Θ_t CP-violating top-quark phase, L_W wall thickness

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

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

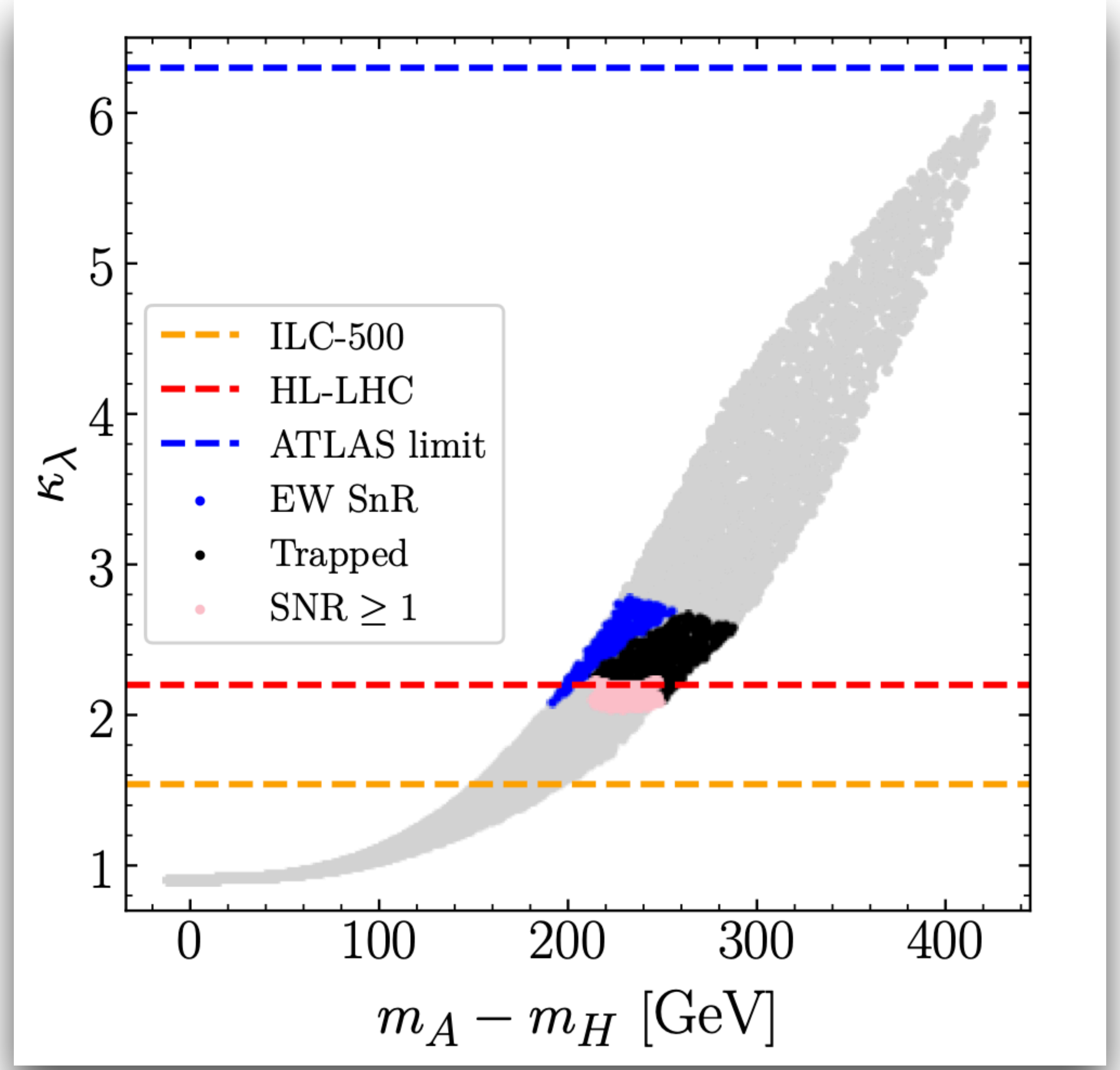
[Bahl,Fuchs,Heinemeyer,Katzy,Menen,Peters,Saimpert,Weiglein,'22]



- 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]



Conclusions

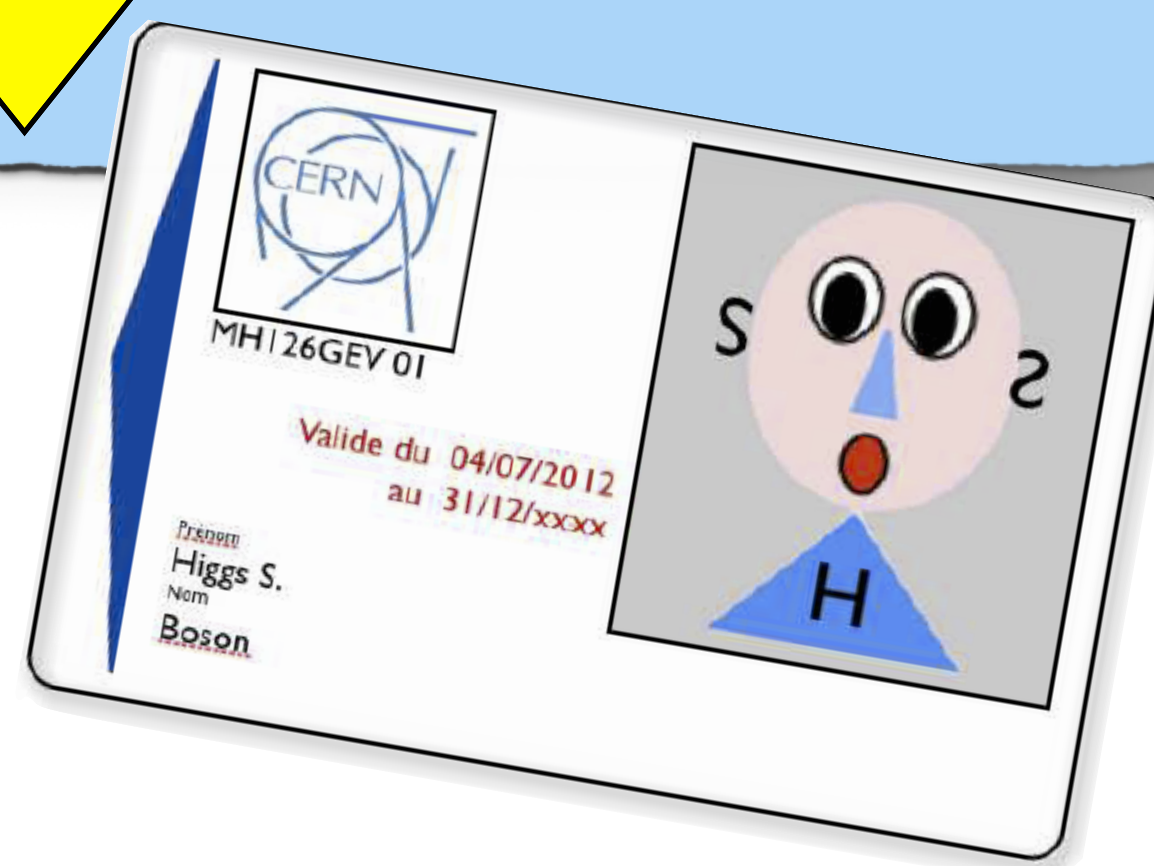
✦ **Flaws of SM call for new physics; no direct signs of new physics => Higgs boson**

✦ 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!

The answer to life, the universe and everything!

Not quite, but



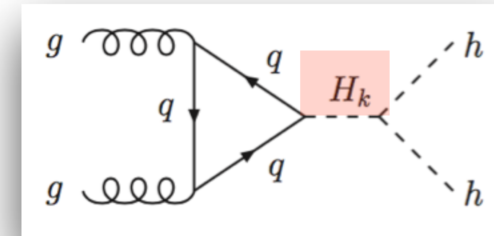
Thank you for your attention!

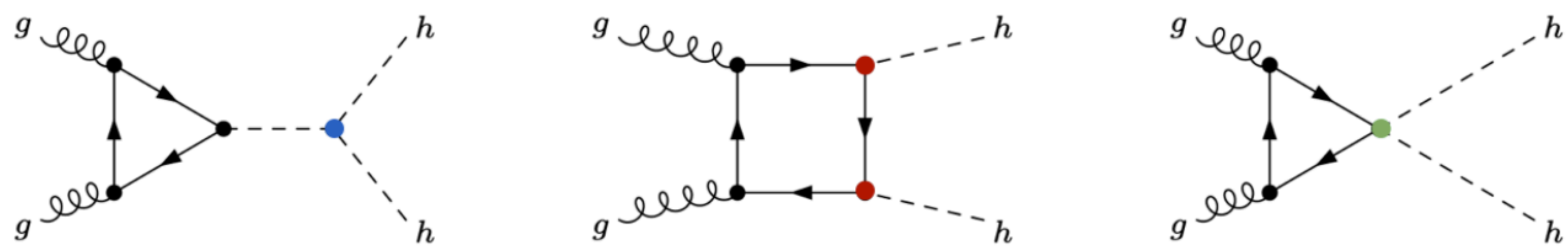
Comparison with EFT

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

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

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

✦ goodness of approximation?:

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2H_1H_1}$ [GeV]	$\sigma_{\rm R2HDM}^{\rm w/\ res}$ [fb]	$\sigma_{\rm SMEFT}^{c_{tt}\neq 0}$ [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 10^{-2}	-352.42	21.8	21.4	98%

✦ Remark:

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

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]	$\mathrm{Re}(m_{12}^2)$ [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:

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

✦ goodness of approximation?: (m_{H3} kept fixed)

m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2H_1H_1}$	$\sigma_{\text{N2HDM}}^{\text{w/ res}}$ [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]	$\mathrm{Re}(m_{12}^2)$ [GeV^2]	
1.153	0.159	0.989	9639	29769	

$$\sigma^{\mathrm{NLO}}_{H_1 H_2} \times \mathrm{BR}(H_2 \to H_1 H_1) \times \mathrm{BR}(H_1 \to b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}$$

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

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

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]

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

$$\mathcal{L}_q^{\rm eff} = f_q \chi\ \chi\ m_q \bar{q} q + \frac{g_q}{m_\chi^2} \chi\ i\partial^\mu i\partial^\nu \chi\ \mathcal{O}_{\mu\nu}^q \qquad \mathcal{O}_{\mu\nu}^q = \frac{1}{2}\bar{q} i \left(\partial_\mu \gamma_\nu + \partial_\nu \gamma_\mu - \frac{1}{2} \not{\partial} \right) q$$

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

χ stands generically for scalar and vector (χ_μ) DM

✦Nuclear Matrix elements for the partonic operators:

[Shifman,Vainshtein,Zakharov,´78]

$$\begin{aligned} \langle N | m_q \bar{q} q | N \rangle &= m_N f_{T_q}^N \\ -\frac{9\alpha_S}{8\pi} \langle N | G_{\mu\nu}^a G^{a,\mu\nu} | N \rangle &= \left(1 - \sum_{q=u,d,s} f_{T_q}^N \right) m_N = m_N f_{T_G}^N \\ \langle N(p) | \mathcal{O}_{\mu\nu}^q | N(p) \rangle &= \frac{1}{m_N} \left(p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu} \right) \left(q^N(2) + \bar{q}^N(2) \right) \end{aligned}$$

N=p,n, m_N nucleon mass

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

✦DM-Nucleon Cross section:

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

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

Treatment of Heavy Quarks

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

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

contains all quarks below energy scale ~ 1 GeV

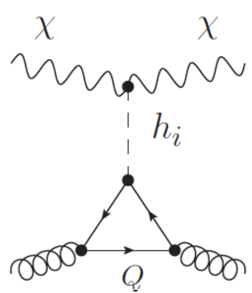
- Sum over quarks in first term:

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

only light quarks

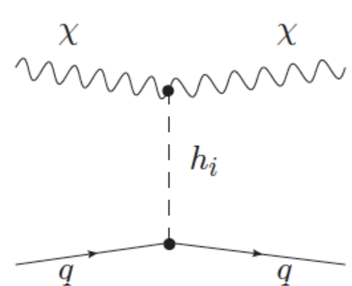
- Heavy quarks contribute through effective gluon interaction:

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:

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

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

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

Computation of the Wilson Coefficients

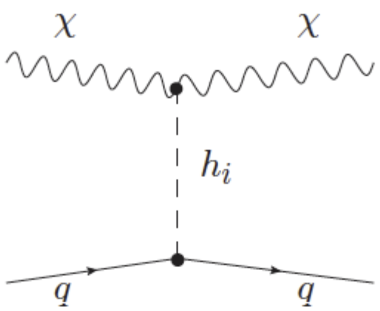
✦ Wilson coefficients f_q, g_q, f_G:

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_i $\rightsquigarrow$

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



hence

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

no contribution from twist-2 operator at LO

✦ Cross section at Leading Order for the SDM:

equal to zero at vanishing momentum transfer (←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

$$\delta m_\chi^2 = \mathrm{Re}\,\Sigma^T_{\chi\chi}\left(m_\chi^2\right) \qquad \delta Z_{\chi\chi} = -\mathrm{Re}\frac{\partial \Sigma^2_{\chi\chi}(p^2)}{\partial p^2}\bigg|_{p^2=m_\chi^2}$$

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

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

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

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

$$\sqrt{Z_H} = R(\delta\alpha)\begin{pmatrix} 1+\frac{\delta Z_{h_1h_1}}{2} & \delta C_h \\ \delta C_h & 1+\frac{\delta Z_{h_2h_2}}{2} \end{pmatrix} \approx \begin{pmatrix} 1+\frac{\delta Z_{h_1h_1}}{2} & \delta C_h + \delta\alpha \\ \delta C_h - \delta\alpha & 1+\frac{\delta Z_{h_2h_2}}{2} \end{pmatrix}$$

on-shell conditions

$$\frac{\delta Z_{h_1h_2}}{2} \stackrel{!}{=} \delta C_h + \delta\alpha \qquad \text{and} \qquad \frac{\delta Z_{h_2h_1}}{2} \stackrel{!}{=} \delta C_h - \delta\alpha$$

$$\begin{aligned} \delta\alpha &= \frac{1}{4}\left(\delta Z_{h_1h_2} - \delta Z_{h_2h_1}\right) \\ &= \frac{1}{2(m_{h_1}^2 - m_{h_2}^2)}\mathrm{Re}\big(\Sigma_{h_1h_2}(m_{h_1}^2) + \Sigma_{h_1h_2}(m_{h_2}^2) - 2\delta T_{h_1h_2}\big) \end{aligned}$$

Renormalization of the VDM

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

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

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

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

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

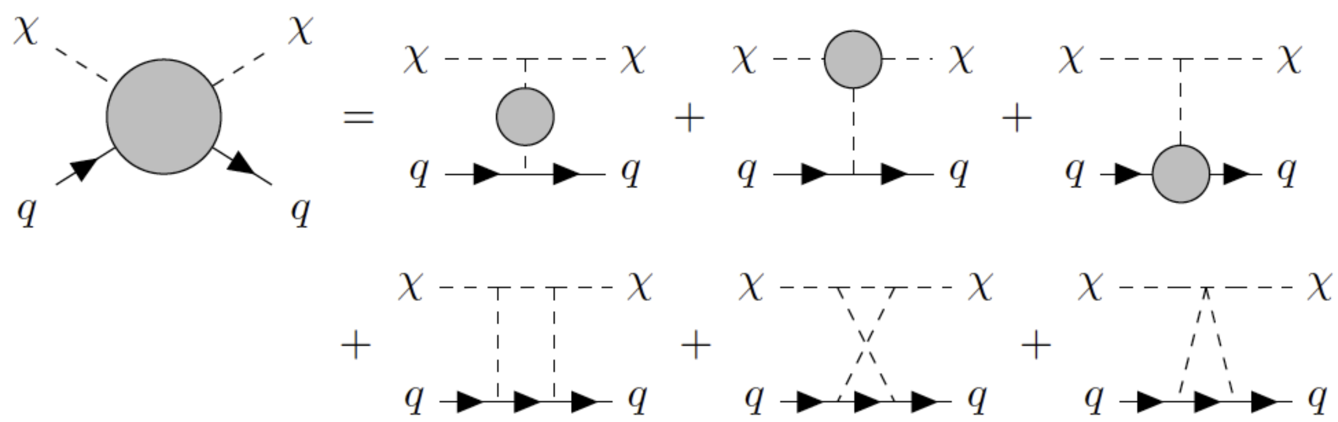
✦Renormalization of the singlet VEV: we use standard tadpole scheme:
in R_ξ gauge singlet VEV does not need to be renormalized at 1-loop if scalar field obeys rigid invariance (disconnected from scalar sector $\rightsquigarrow$ invariance unter global transformations)
[Sperling,Stöckinger,Voigt,´13]

✦Mixing angle renormalization: KOSY scheme


The NLO Cross Section

The SI Cross Section at NLO

✦NLO contributions:



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

✦One-loop Wilson coefficients:

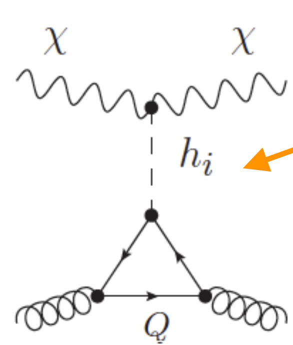
Light quark contributions

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

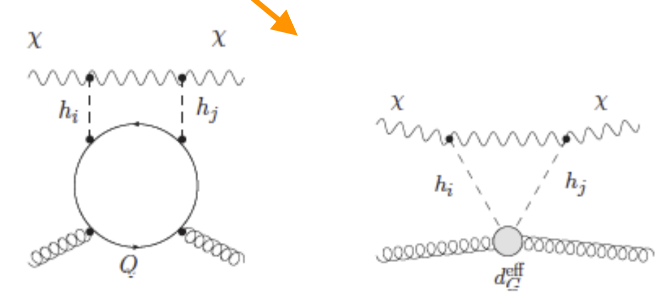
$$g_q^{\rm NLO} = g_q^{box}$$

heavy quark contributions

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

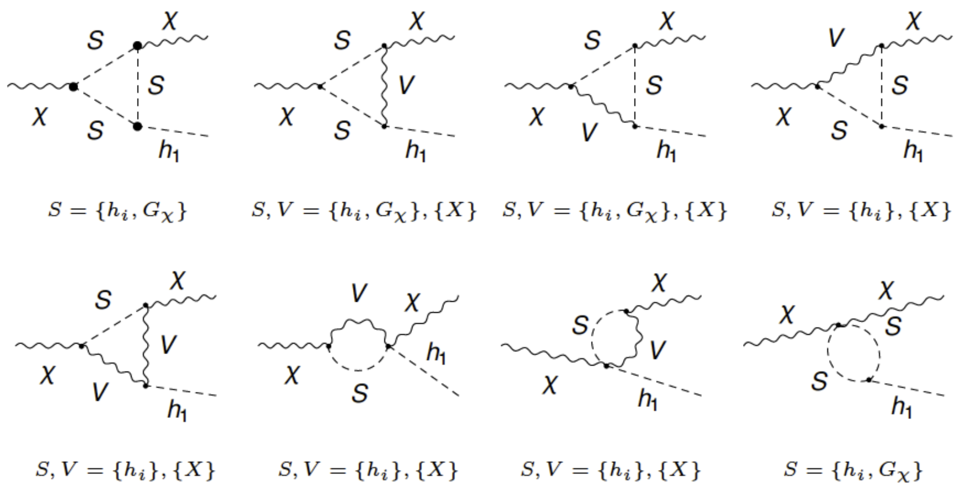


vertex&mediator corrections to this diagram

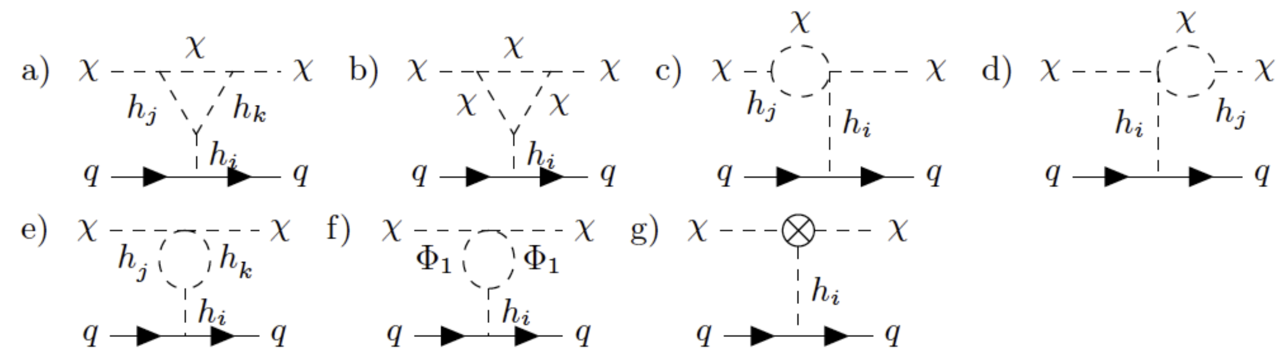


Upper Vertex Corrections

✦Upper vertex corrections:



VDM



SDM

Computation of

$$iA^{\rm NLO}_{\chi\chi h_i} = iA^{\rm LO}_{\chi\chi h_i} + iA^{\rm VC}_{\chi\chi h_i} + iA^{\rm CT}_{\chi\chi h_i}$$

with

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

$$iA^{\rm CT}_{\chi\to\chi h_1} = \left[\frac{1}{2}\left(g_{\chi\chi h_2}\delta Z_{h_2h_1} + g_{\chi\chi h_1}\delta Z_{h_1h_1}\right) + g_{\chi\chi h_1}\delta Z_{\chi\chi} + \delta g_{\chi\chi h_1}\right]\varepsilon(p)\cdot\varepsilon^*(p)$$

$$iA^{\rm CT}_{\chi\to\chi h_2} = \left[\frac{1}{2}\left(g_{\chi\chi h_1}\delta Z_{h_1h_2} + g_{\chi\chi h_2}\delta Z_{h_2h_2}\right) + g_{\chi\chi h_2}\delta Z_{\chi\chi} + \delta g_{\chi\chi h_2}\right]\varepsilon(p)\cdot\varepsilon^*(p)$$

results in tensor structure

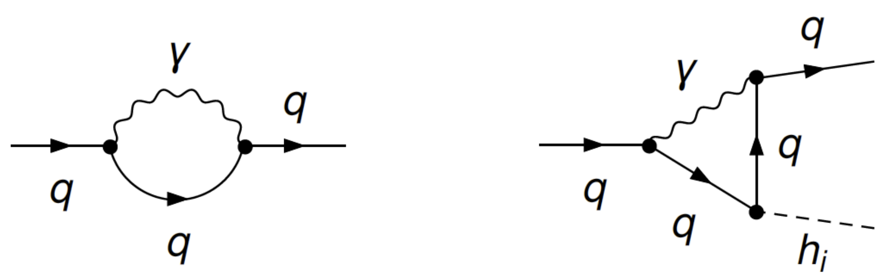
$$iA^{\rm NLO} = (\dots)\underbrace{\varepsilon(p_{\rm in})\cdot\varepsilon^*(p_{\rm out})}_{\sim\rm LO} + (\dots)\underbrace{(p_{\rm in}\cdot\varepsilon^*(p_{\rm out}))\,(p_{\rm out}\cdot\varepsilon(p_{\rm in}))}_{\sim\rm NLO}$$

with our approximation $p_{\rm in} = p_{\rm out}$ 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 $\mathcal{O}(p_q^2)$ $\rightsquigarrow$ regularization of IR divergences in VDM

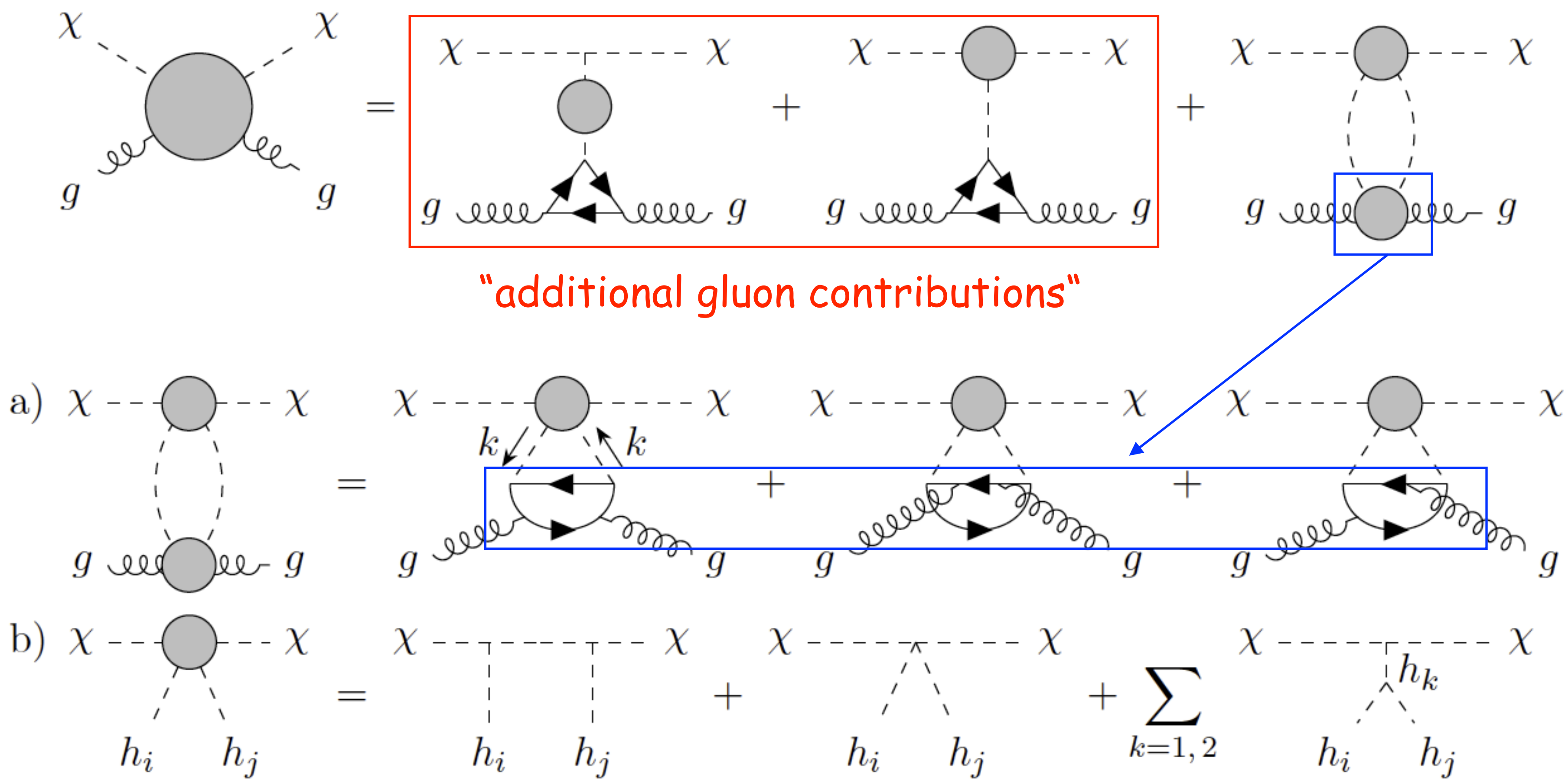
SDM: U(1) symmetry of the potential $\rightsquigarrow$ complete cancellation of the QED subset, hence no IR divergences

Heavy Quarks

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

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

with

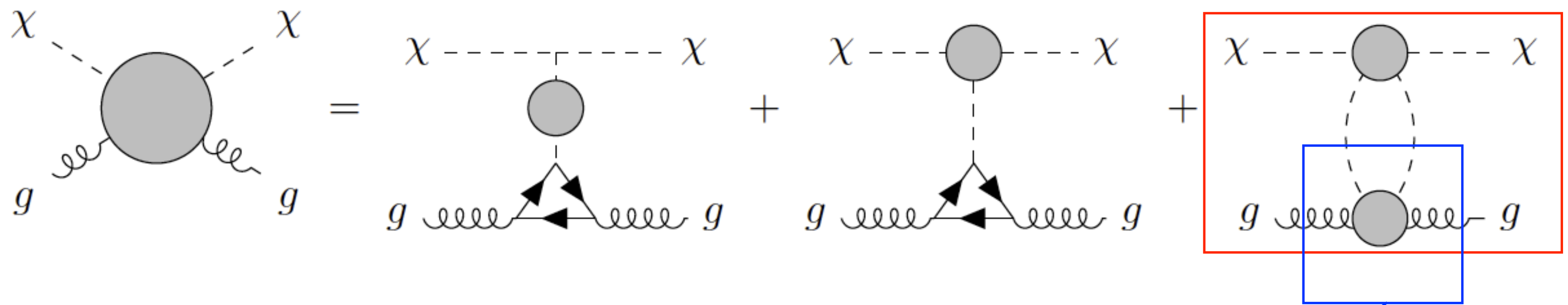


Our approach: no inclusion of EW correction to heavy quark contributions

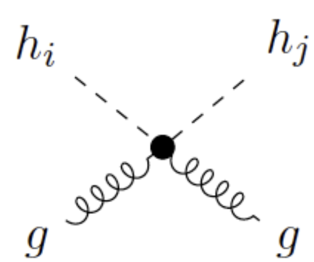
only for comparison w/ literature we include the “additional gluon contributions“

[Ishiwata,Toma,´18]

Heavy Quarks



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



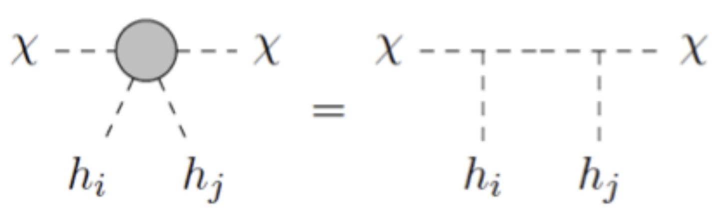
$$\approx \frac{i g_s^2}{48\pi^2 m_t^2} a_i a_j$$

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

produced by

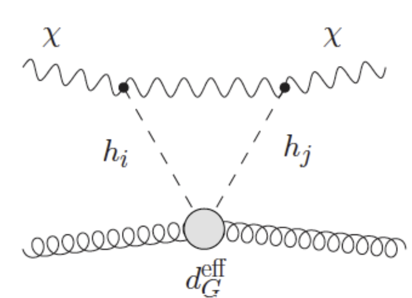
$$\mathcal{L} \supset \frac{1}{2} \frac{g_s^2}{48\pi^2 m_t^2} a_i a_j \, h_i h_j G^a_{\mu\nu} \, G^{a\mu\nu}$$

combination with



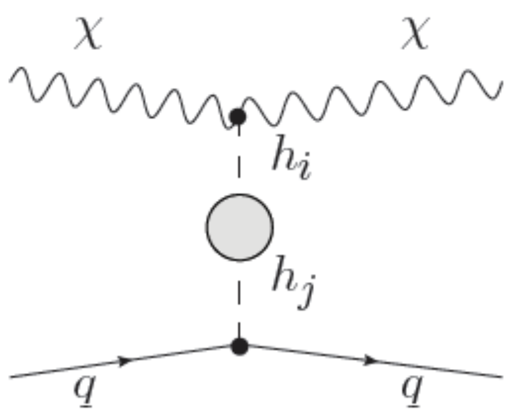
leads to

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



Mediator Corrections

✦ Mediator corrections:



in approximation of zero momentum exchange we get

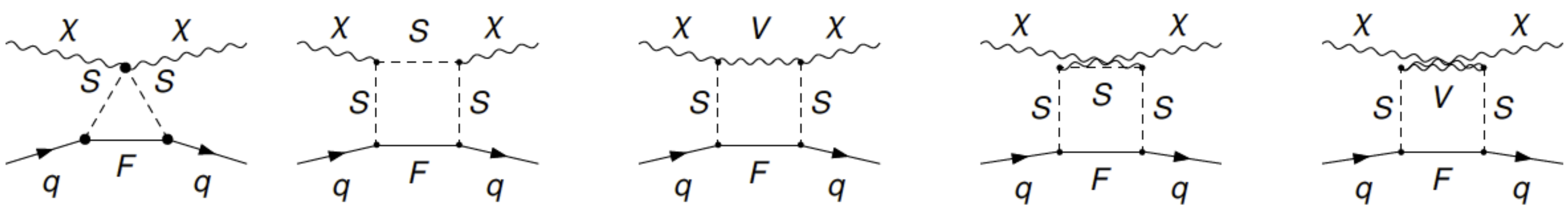
$$\Delta_{h_i h_j} = -\frac{\hat{\Sigma}_{h_i h_j}(p^2 = 0)}{m^2_{h_i} m^2_{h_j}}$$

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

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

Box Corrections

✦ Box corrections:



$F, S = \{q\}, \{h_i\}$ $F, S = \{q\}, \{h_i, G_\chi\}$ $F, S, V = \{q\}, \{h_i, G_\chi\}, \{X\}$ $F, S = \{q\}, \{h_i\}$ $F, S, V = \{q\}, \{h_i, G_\chi\}, \{X\}$

expansion of propagator terms in small quark momentum $\rightsquigarrow$ projection onto required tensor structures $\rightsquigarrow$ 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:

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

✦NLO form factor:

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

with

$$\begin{aligned} f_q^{\rm NLO} &= f_q^{\rm vertex} + f_q^{\rm med} + f_q^{\rm box} \\ g_q^{\rm NLO} &= g_q^{box} \\ f_G^{\rm NLO} &= \underbrace{\boxed{-\frac{\alpha_S}{12\pi}\sum_{q=c,b,t}\left(f_q^{\rm vertex} + f_q^{\rm med}\right)}}_{\text{“additional gluon contributions“}} + f_G^{\rm top} \end{aligned}$$

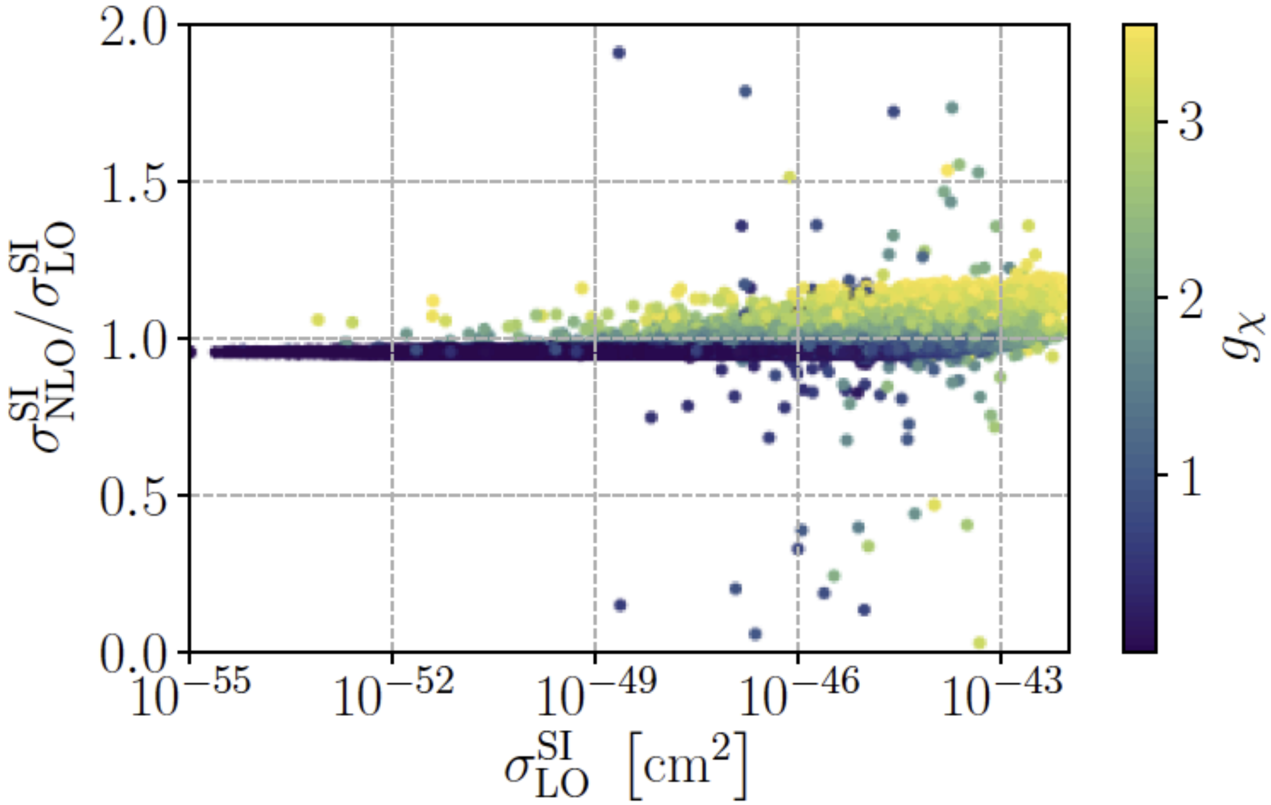
✦NLO cross section:

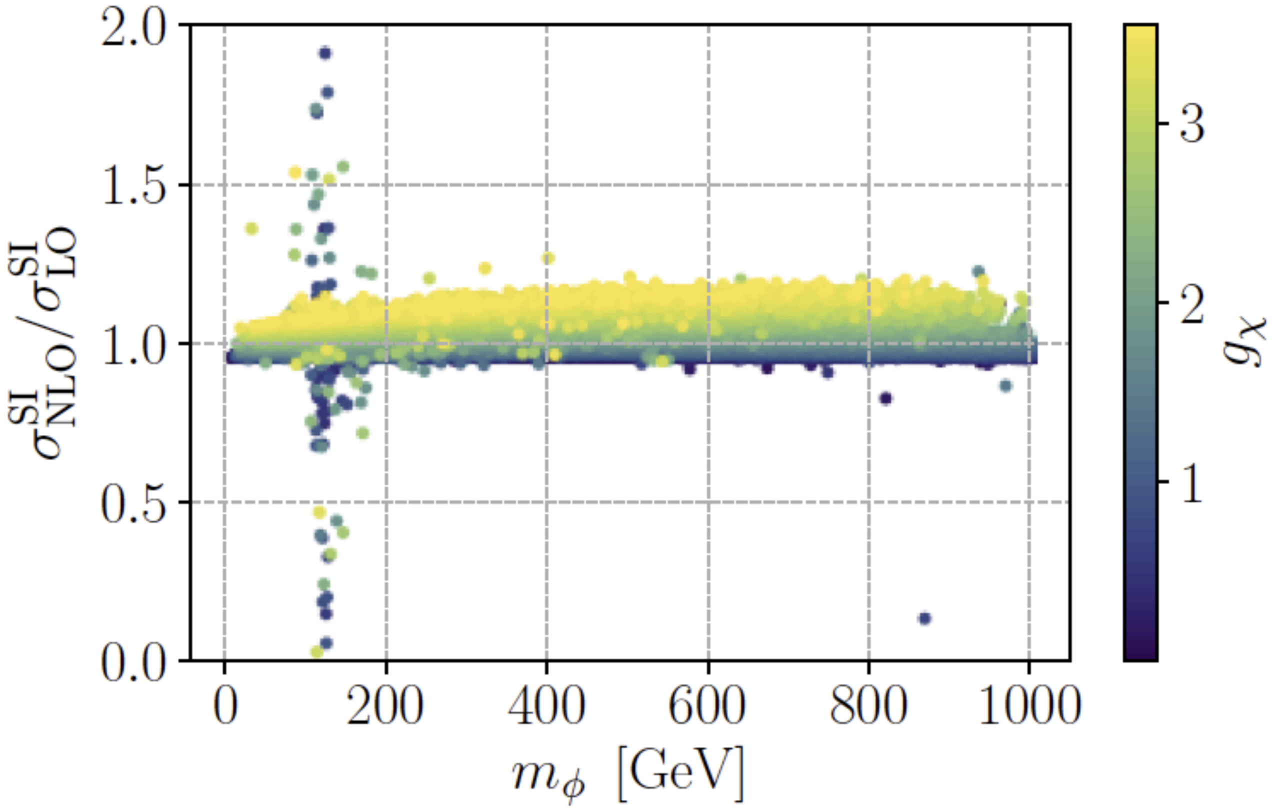
$$\sigma_N = \frac{1}{\pi}\left(\frac{m_N}{m_\chi + m_N}\right)^2 \left[|f_N^{\rm LO}|^2 + 2{\rm Re}\left(f_N^{\rm LO} f_N^{\rm NLO*}\right)\right] \qquad \text{VDM}$$

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

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