CORFU2012

Corfu 16.09.2012

The 125 GeV Higgs in 2HDM

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THE THEORY OF MATTER and STANDARD MODEL(S)

F. Wilczek, LEPFest, Nov.2000 (hep-ph/0101187)

Theory of Matter = $SU(2)_{I\ weak} \times U(1)_{Y\ weak} \times SU(3)_{color}$

Theory of Matter refers to the core concepts:
- quantum field theory
- gauge symmetry
- spontaneous symmetry breaking
- asymptotic freedom
- the assignments of the lightest quarks and leptons

Standard Models: Choose the number of Higgs (scalar) doublets
SM=1HDM, <u>2HDM</u> (MSSM), 3HDM ...
Note, that the lightest scalar is often SM-like

NonStandard Models are based on more radical assumptions.

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow U(1)_{QED}$

Standard Model

Doublet of SU(2): $\Phi = (\varphi^+, v+H+i\zeta)^T$

Masses for $W^{+/-}$, Z (tree $\rho = 1$) , no mass for the photon

Fermion masses via Yukawa interaction

Higgs particle H_{SM} - spin 0, neutral, CP even

couplings to WW/ZZ, Yukawa couplings to fermions

mass $\leftrightarrow$ selfinteraction unknown

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow$?

T.D. Lee 1973

Two Higgs Doublet Models

Two doublets of SU(2) ($Y=1$, $\rho=1$) - Φ_1, Φ_2

Masses for $W^{+/-}$, Z, no mass for photon?

Fermion masses via Yukawa interaction –

various models: Model I, II, III, IV,X,Y,...

5 scalars: H+ and H- and neutrals:

- CP conservation: CP-even h, H & CP-odd A
- CP violation: h_1,h_2,h_3 with undefinite CP parity*

Sum rules (relative couplings to SM χ)

SM-like scenarios

- In many models possible SM-like scenarios

  Higgs mass ~ 125 GeV GeV, SM tree-level couplings*

  (* up to sign)

  No other new particle seen …

  (too heavy or too weakly interacting)

- In models with two doublets:

  - MSSM with decoupling of heavy Higgses

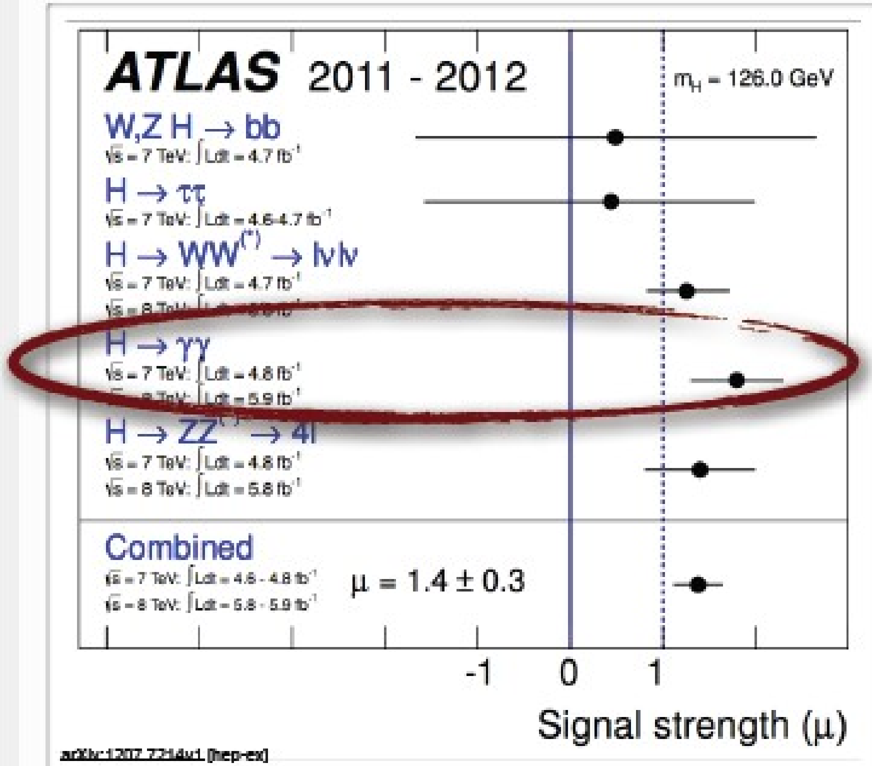
    → *LHC-wedge*

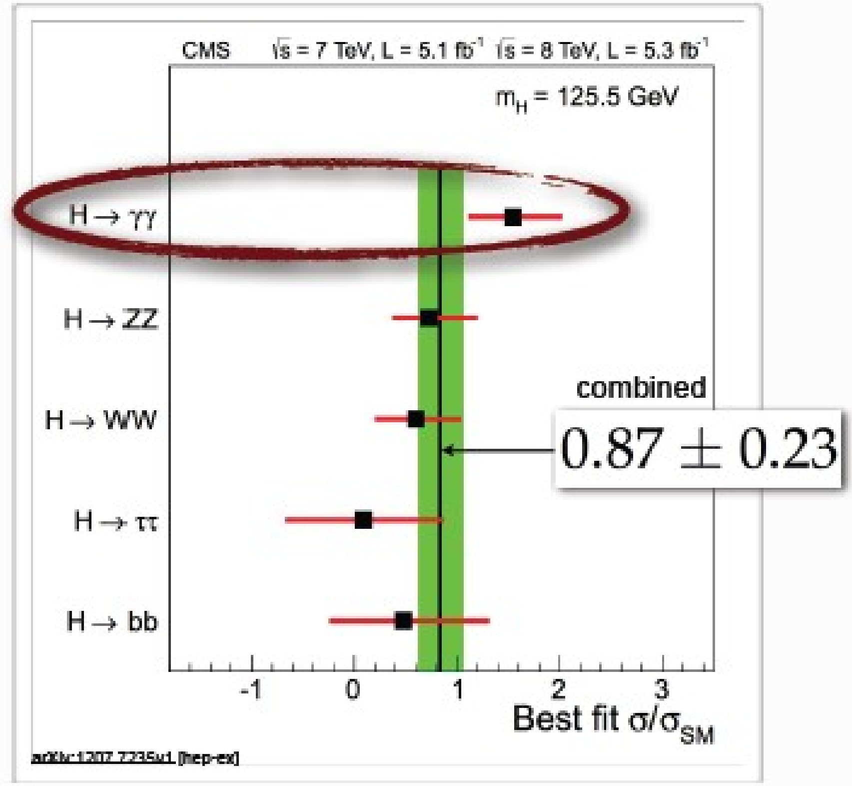
  - 2HDM (Mixed) with and without CP violation

    both h or H can be SM-like

  - Dark 2HDM (Intert Doublet Model)

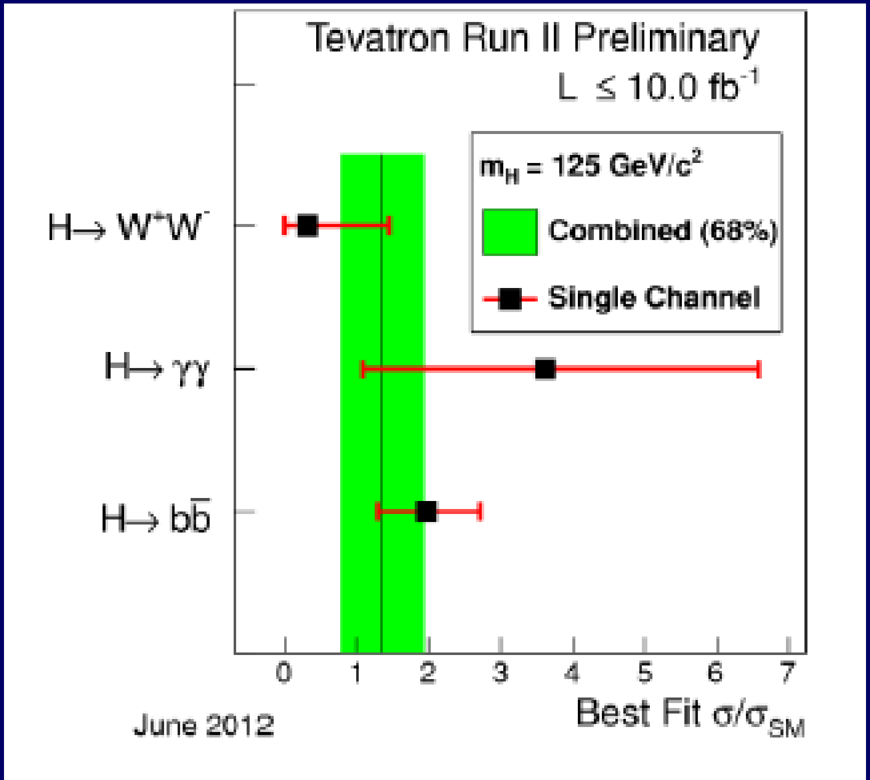
Signal strength per channel





- overall, consistency with SM
- however, most striking/interesting: **high γγ rate**, in both exps and both c.o.m. energies
  - ATLAS: 1.8 ± 0.5
  - CMS: 1.6 ± 0.4
- further data highly awaited, also to see development on the fermionic side
- interpretation in terms of couplings: see talk by Ch. Grojean

Tevatron 2012



2HDM- great laboratory of BSM

- Mixed Model with a scalar sector as in MSSM

→ the 125 GeV Higgs boson h or H (for CPconservation)

- Inert Doublet Model (IDM) contains DM, has one Higgs boson - the 125 GeV Higgs boson

If today (temp=0) the Inert phase what was in the past ?

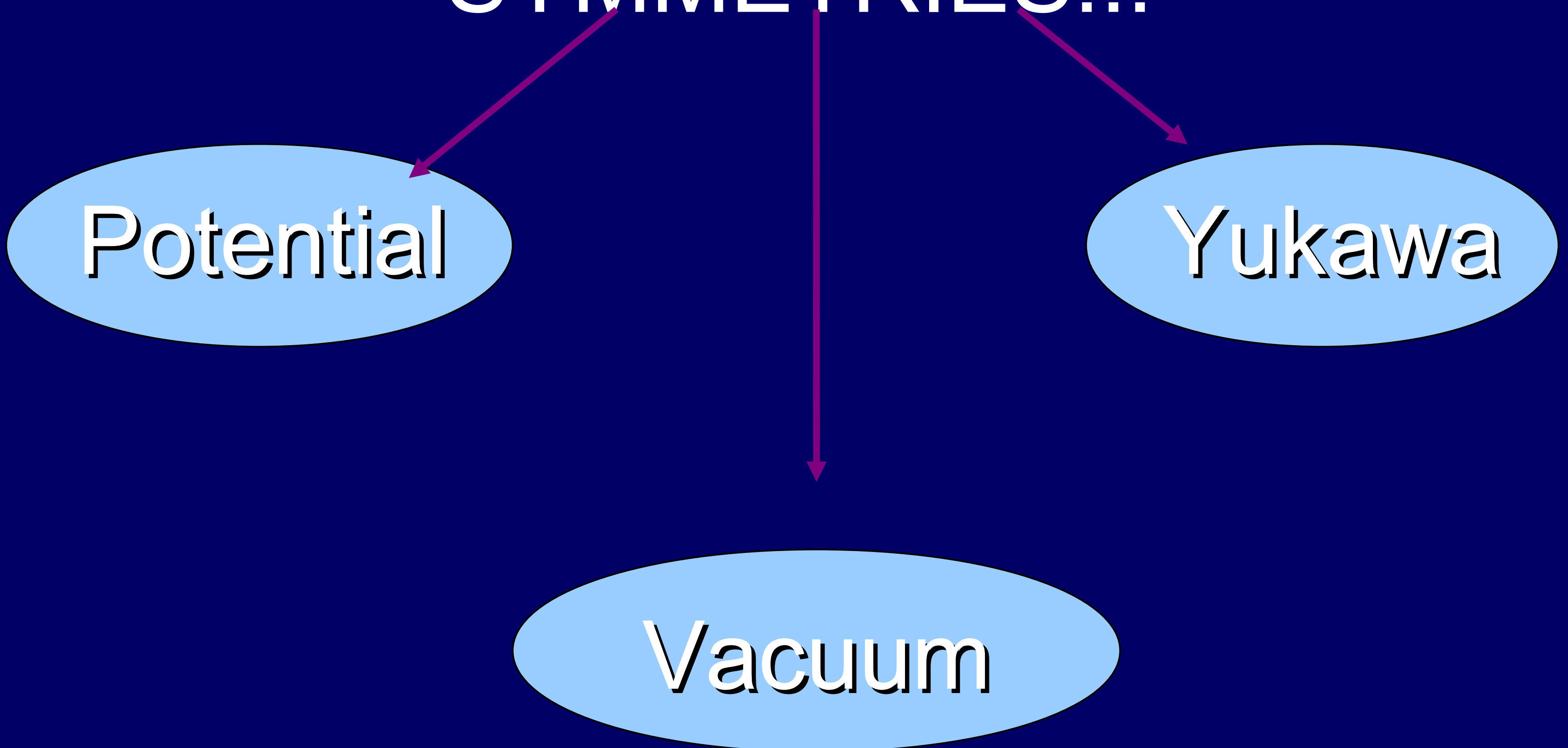
Temp. evolution of the inert vacuum and sequences of different vacua in the past (one, two and three phase transitions) *PRD 82(2010) Ginzburg, Kanishev,MK, Sokołowska*

- with leading T^2 corrections

- beyond T^2 corrections (to find strong enough first-order phase transition needed for baryogenesis)
(G. Gil Thesis'2011, G.Gil, P. Chankowski, MK 1207.0084 [hep-ph])

2HDM's

SYMMETRIES!!!



Various models of Yukawa inter.

typically with some Z2 type symmetry to avoid FCNC

Model I - only one doublet interacts with fermions

Model II – one doublet with down-type fermions d , l

other with up-type fermions u

Model III - both doublets interact with fermions

Model IV (X) - leptons interacts with one doublet, quarks with the other

Model Y - one doublet with down-type quarks d

other with up-type quarks u and leptons

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

+ Extra dim 2HDM models

2HDM Potential (Lee'73)

$$V = \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}\,[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c]$$

$$+ [(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2) + h.c]$$

$$- \tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1) - \tfrac{1}{2}m^2_{22}(\Phi_2^\dagger\Phi_2) - \tfrac{1}{2}[m^2_{12}(\Phi_1^\dagger\Phi_2) + h.c.]$$

Z_2 symmetry transformation: $\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$

(or vice versa)

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12} = \mu^2$)

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12} = 0$

Z2 symmetry

Z_2 symmetry under transformation:

$$\Phi_1 \rightarrow \Phi_1 \qquad \Phi_2 \rightarrow -\Phi_2$$

(SM → SM, eg. in Model I)

I will call D-symmetry,

and denote Φ_1 as Φ_S and $\Phi_2 \rightarrow \Phi_D$

Extrema of the 2HDM potential with explicit Z_2 (D) symmetry

Ginzburg, Kanishev, MK, Sokołowska'09

Finding extrema: $\partial V / \partial \Phi|_{\Phi = \langle\Phi\rangle} = 0$

Finding minima → global minimum = vacuum

Positivity (stability) constraints (V with real parameters)

$$\left[\quad \lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R+1>0. \quad \right]$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}.$$

Extremum fulfilling the positivity constraints

with the lowest energy = vacuum

Possible extrema (vacuum) states

The most general state **for V with explicit Z_2 (D)**

$$\langle \phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ v_D \end{pmatrix}$$

v_S, v_D, u - real

$v_S, u \geq 0$

$v^2 = v_S^2 + v_D^2 + u^2 = (246\ \text{GeV})^2$

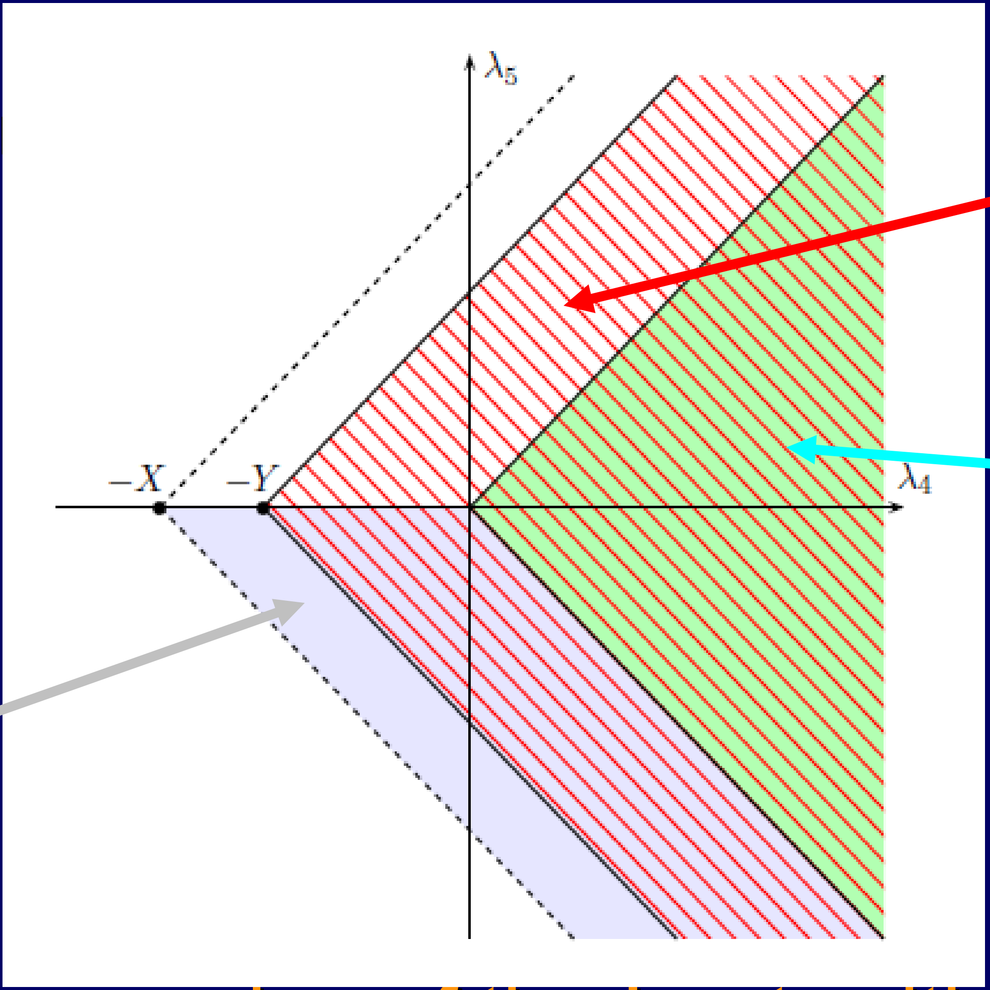
EWs	EWs	$u = 0 \quad v_D = v_S = 0$
Inert	I_1	$u = 0 \quad v_D = 0$
Inert-like	I_2	$u = 0 \quad v_S = 0$
Mixed (Normal, MSSM like)	M	$u = 0 \quad v_D \neq v_S \neq 0$
Charge Breaking	Ch	$u \neq 0 \quad v_D = 0$

Various extrema (vacua) on (λ_4 , λ_5) plane

Positivity constrains: $\lambda_4 \pm \lambda_5 > -X$ $X=\sqrt{\lambda_1 \lambda_2}+\lambda_3>0$

Inert (Inert-like)

$Y = M_{H+}^{2}\, 2/v^2$



Charge Breaking Ch

Mixed

We fix

$\lambda_4+\lambda_5<0, \lambda_5<0$

Note the overlap of the Inert with M and Ch !

TODAY

2HDM with explicit Z_2 (D) symmetry

$\Phi_S \to \Phi_S \quad \Phi_D \to - \Phi_D$

Model I (Yukawa int. with Φ_S only)

- Charge breaking phase Ch?

  photon is massive, el.charge is not conserved...

  → No

- Neutral phases:

  Mixed M ok, many data, but no DM

  Inert I1 OK! In agreement with accelerator and astrophysical data (neutral DM)

  Inert-like I2 No, all fermions massless, no DM

Mixed Model (Model II Yukawa)

Masses

$$M_{H^\pm}^2 = -\tfrac{1}{2}(\lambda_4+\lambda_5)v^2$$
$$M_A^2 = -\lambda_5 v^2,$$
$$M_H^2 = \tfrac{1}{2}\left(\lambda_1 v_S^2 + \lambda_2 v_D^2 + \sqrt{(\lambda_1 v_S^2 - \lambda_2 v_D^2)^2 + 4\lambda_{345}^2 v_S^2 v_D^2}\right),$$
$$M_h^2 = \tfrac{1}{2}\left(\lambda_1 v_S^2 + \lambda_2 v_D^2 - \sqrt{(\lambda_1 v_S^2 - \lambda_2 v_D^2)^2 + 4\lambda_{345}^2 v_S^2 v_D^2}\right).$$

Relative couplings ($\tan\beta = v_D/v_S$)

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
HW^+W^-	hW^+W^-
HZZ	hZZ

hbb, hττ $= \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,$

htt $\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,.$

Relative couplings (respect SM)

For neutral Higgs particles h_i ,i = 1,2,3

$$\chi_j^{(i)} = \frac{g_j^{(i)}}{g_j^{SM}} \quad j = V, u, d$$

there are relations among couplings, eg.

$$\Sigma_i (\chi_j^{(i)})^2 = 1, \text{ for } j = V, u, d$$

pattern relation

$$(\chi_u^{(i)} + \chi_d^{(i)})\chi_V^{(i)} = 1 + \chi_u^{(i)}\chi_d^{(i)},$$

or

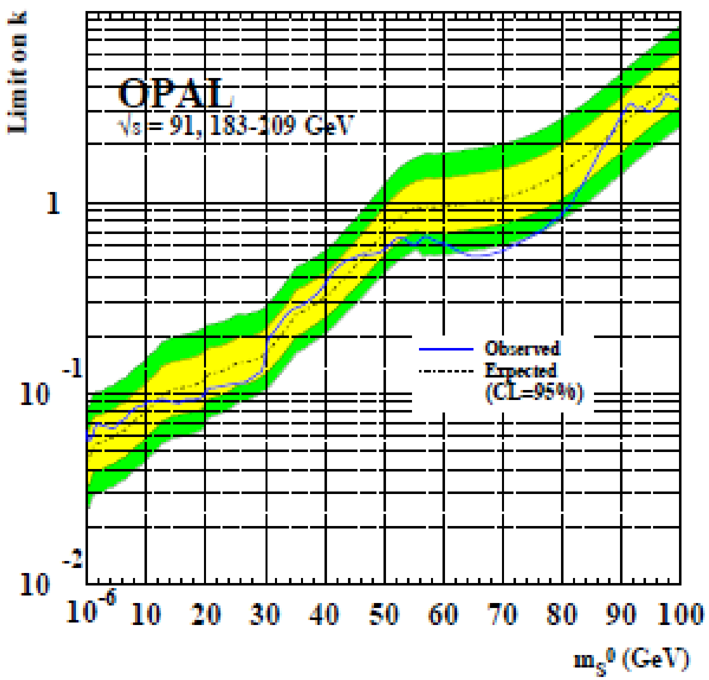
$$(\chi_u^{(i)} - \chi_V^{(i)})(\chi_V^{(i)} - \chi_d^{(i)}) = 1 - (\chi_V^{(i)})^2.$$

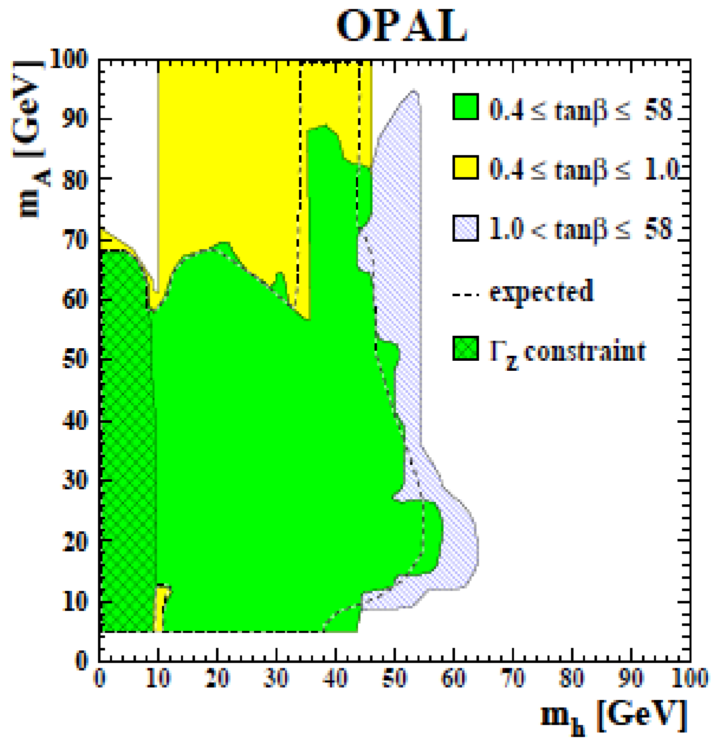
Neutral Higgs bosons - couplings to gauge boson, and mass exclusion

LEP: 2HDM with Z2 symmetry

Light h OR light A in agreement with current data

hZZ: $sin(\beta-\alpha)$ and hAZ: $cos(\beta-\alpha)$

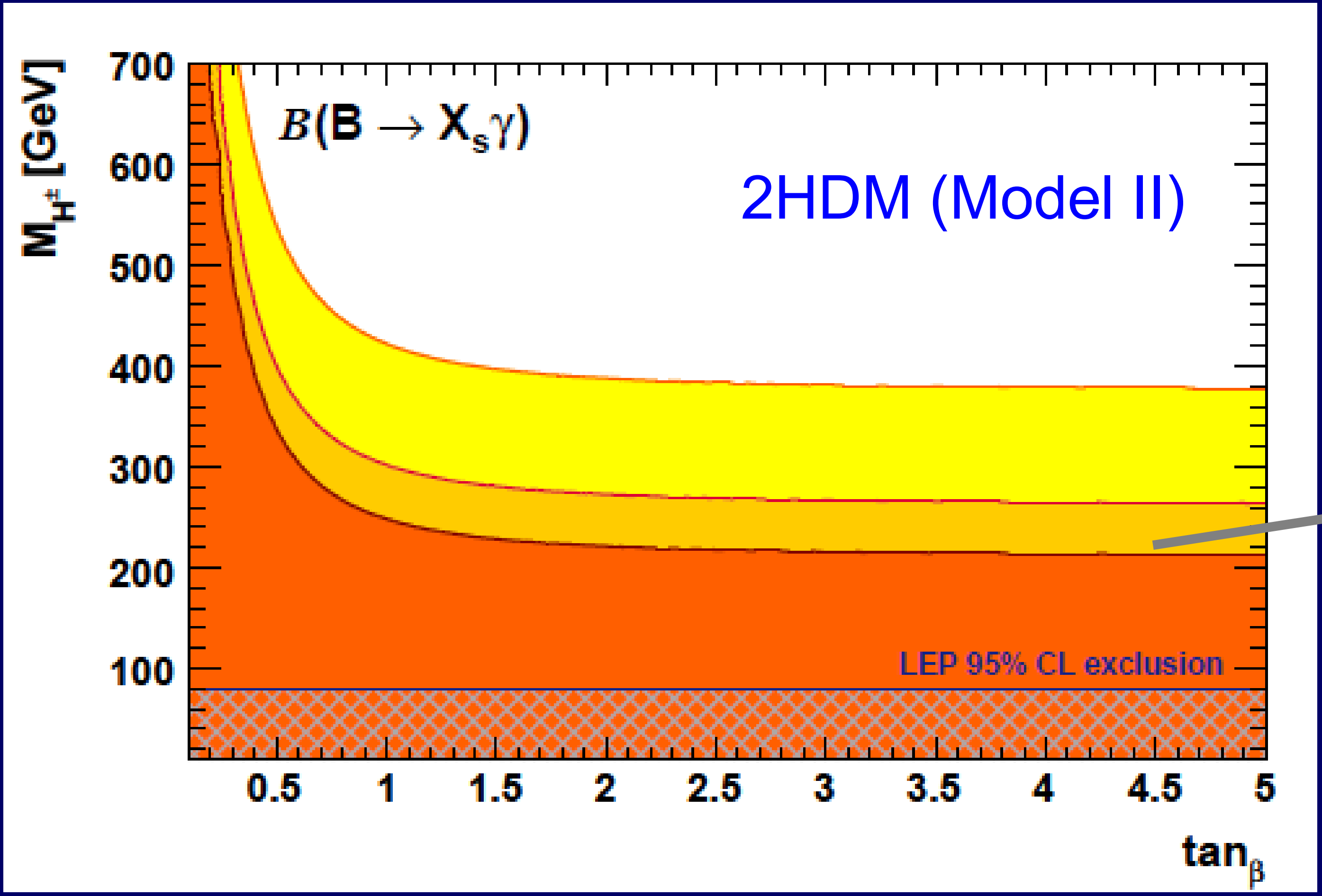




Light scalar $h \rightarrow$ small $k = sin^2(\beta-\alpha)$!

H is SM like then !

$B \to X_s$ gamma decay
M_{H+} vs tan β



95%CL

New 2012: M_{H+}> 380 GeV
Misiak

Gfitter 0811.0009[hep-ph]

Unitarity constraints on parameters of V (Z_2 symmetry)

analysis by B. Gorczyca, MSc Thesis, July 2011

Full scattering matrix macierz 25x25 for scalars (including Goldstone's)

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_1 & & & & & \\ & \mathcal{M}_2 & & & & \\ & & \mathcal{M}_3 & & & \\ & & & \mathcal{M}_4 & & \\ & & & & \mathcal{M}_5 & \\ & & & & & \mathcal{M}_6 \end{pmatrix}.$$

in high energy limit

Block-diagonal form due electric charge and CP conservation

M1: G+H-, G-H+, hA, GA, GH, hH
M2: G+G-, H+H-, GG, HH, AA, hh
M3: Gh, AH
M4: G+G, G+H, G+A, G+h, GH+, HH+,AH+,hH+
M5: G+G+, H+H+
M6: G+H+

Unitarity constraints
→ |eigenvalues|< 8 π

Constraints for lambdas

$$0 \leqslant \lambda_1 \leqslant 8.38,$$
$$0 \leqslant \lambda_2 \leqslant 8.38,$$
$$-6.05 \leqslant \lambda_3 \leqslant 16.44,$$
$$-15.98 \leqslant \lambda_4 \leqslant 5.93,$$
$$-8.34 \leqslant \lambda_5 \leqslant 0.$$

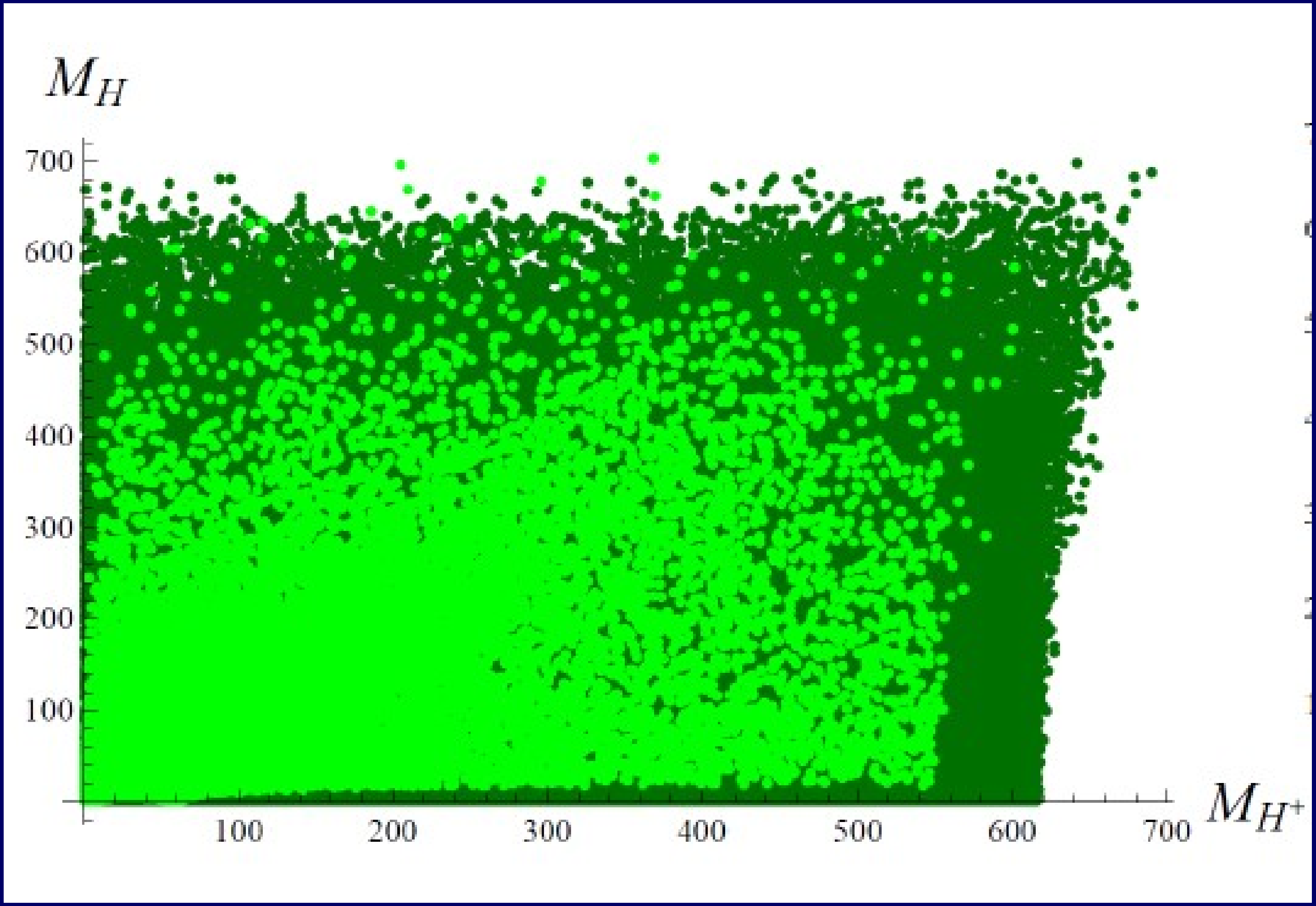
Couplings for dark particles in IDM →

$\lambda_{345}=\lambda_3+\lambda_4+\lambda_5$

$\lambda_{45}=\lambda_4+\lambda_5$

$$-8.10 \leqslant \lambda_{345} \leqslant 12.38,$$
$$-7.76 \leqslant \lambda_{\bar{3}45} \leqslant 16.45,$$
$$-8.28 \leqslant \tfrac{1}{2}\lambda_{45} \leqslant 0,$$
$$-7.97 \leqslant \tfrac{1}{2}\lambda_{\bar{4}5} \leqslant 6.08,$$

Allowed region MH vs MH+

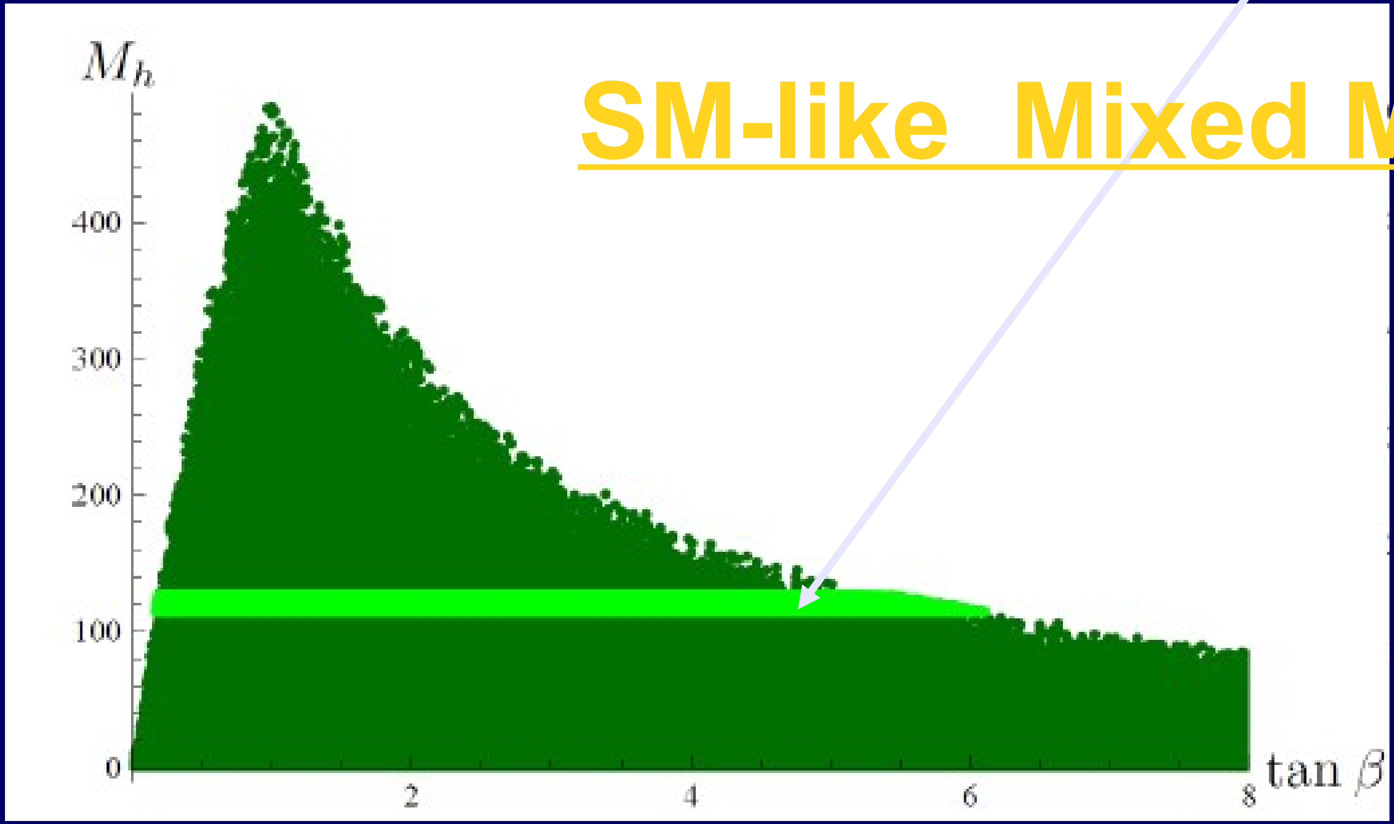


EWPT (pale regions)

M_h vs tan β

For h mass 115 -127 GeV

SM-like Mixed Model



B.Gorczyca, MK

1112.5086v2 [hep-ph]

tan β

constrained by
mass not Yukawa!

Mixed Model

B. Gorczyca, MSc Thesis, July 2011

Upper limits on masses

$$
\begin{aligned}
M_{H^\pm} &\leqslant 690\,\text{GeV},\\
M_A &\leqslant 711\,\text{GeV},\\
M_H &\leqslant 688\,\text{GeV},\\
M_h &\leqslant 499\,\text{GeV}.
\end{aligned}
$$

SM-like Mixed Model

Akeroyd, A. Arhrib, E. Naimi,

$g(hVV)=g(H_{SM}\,VV)$

V=W,Z

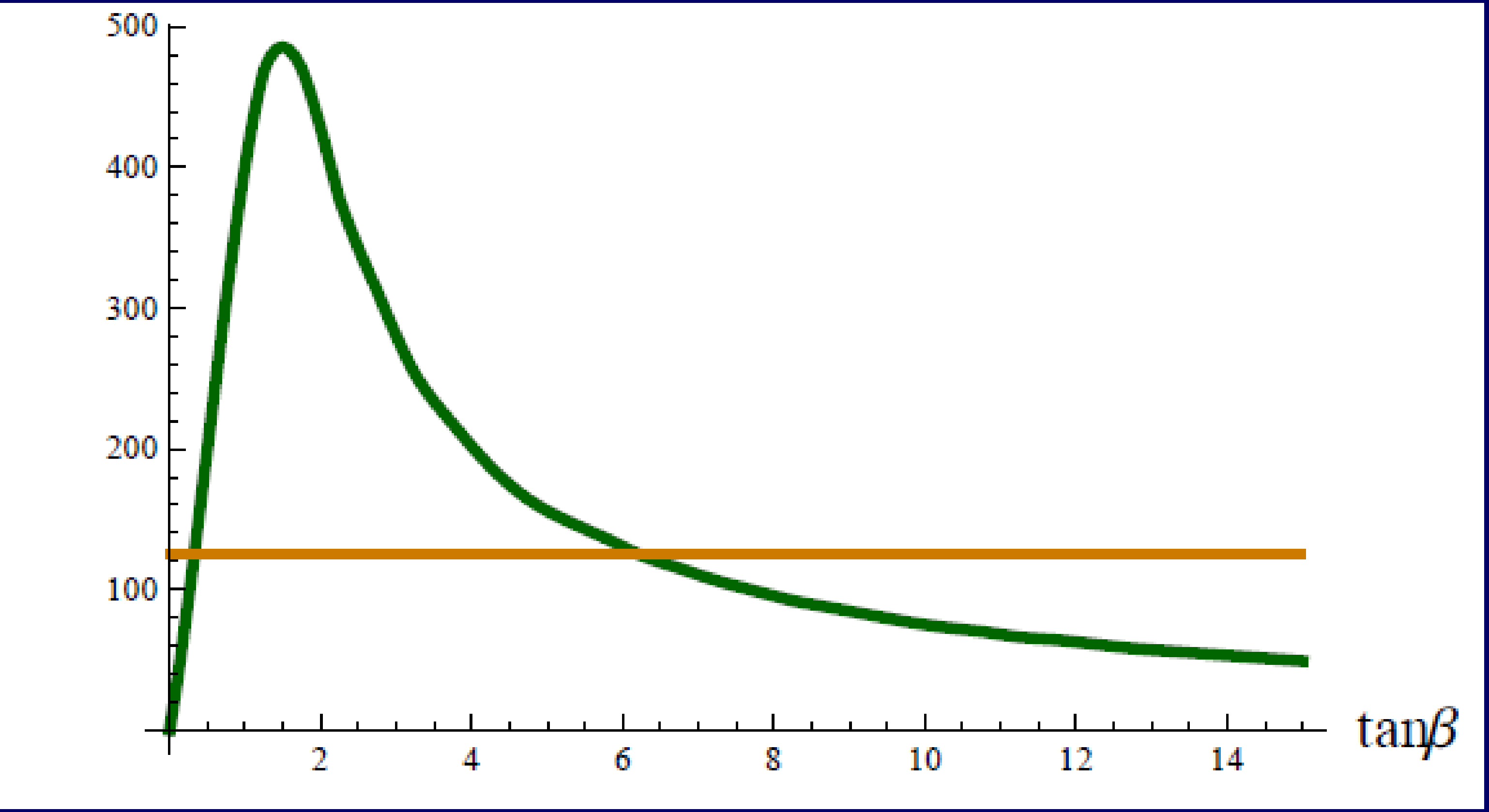
$115 \leq M_h \leq 127$ GeV

Limit on tan beta from lowest M_h value

$$
\begin{aligned}
M_{H^\pm} &\leqslant 616\,\text{GeV},\\
M_A &\leqslant 711\,\text{GeV},\\
M_H &\leqslant 609\,\text{GeV},
\end{aligned}
$$

$$0.17 \leqslant \tan\beta \leqslant 6.10.$$

Max Mh vs tan beta



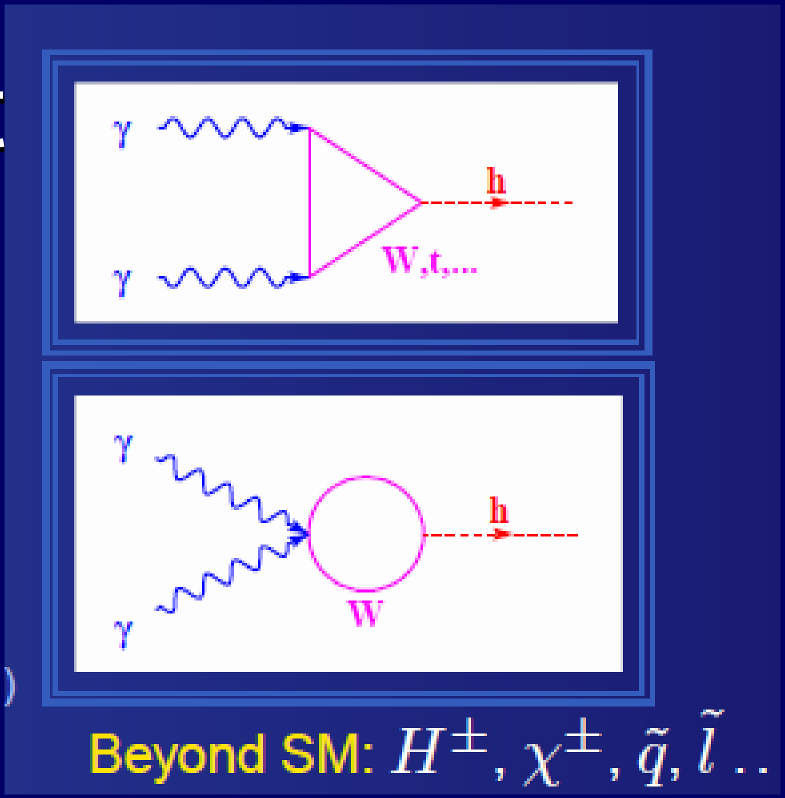
For Mh = 125 GeV

$$0.2 \lesssim \tan\beta \lesssim 6.2.$$

Loop couplings hgg and h γ γ

For hgg
- b and t important

For h γ γ
- t (b), W, H+
(in 2HDMs)



W and t destructive interference in SM, so...

LC-TH-2001-026

Identifying an SM-like Higgs particle at future colliders

LC-TH-2003-089

I. F. Ginzburg[1], M. Krawczyk [2] and P. Osland[3]

SM-like scenario. One of the great challenges at future colliders will be the SM-like scenario that no new particle will be discovered at the Tevatron, the LHC and electron-positron Linear Collider (LC) except the Higgs boson with partial decay widths, for the basic channels to fundamental fermions (up- and down-type) and vector bosons W/Z, as in the SM:

$$\left|\frac{\Gamma_i^{\rm exp}}{\Gamma_i^{\rm SM}}-1\right| \lesssim \delta_i \ll 1. \quad \text{where } i=u,d,V. \qquad (1)$$

Then for the relative couplings (vs SM)

for $i=u,d,V$.

$$\chi_i^{\rm obs}=\pm(1-\epsilon_i), \quad \text{with } |\epsilon_i|\ll 1\,.$$

$|\epsilon_i|\le\delta_i$.

Using pattern relation for 2HDM (II)

$$(\chi_u+\chi_d)\chi_V=1+\chi_u\chi_d.$$

Loop couplings ggh/H, $\gamma\gamma$h/H

$\Gamma(h/H \to gg, \gamma\gamma)$

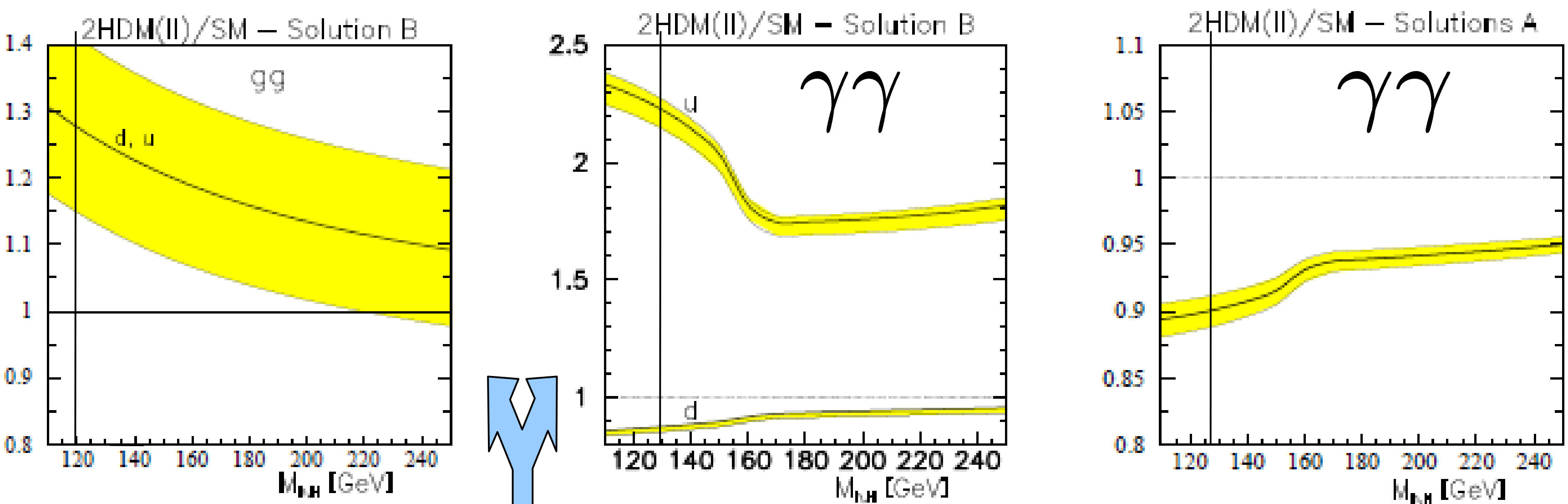
including exp. uncertainties

2HDM(Z_2) = Mixed

Ginzburg,Osland, MK '2001

Tree couplings as in SM - close to 1 (solution A)

suppression due to H+ (600GeV)



solution B → „wrong" signs of fermion couplings

Both h and H maybe SM-like

Two solutions:

A – all couplings close to 1
B – one Yukawa coupling close to -1

Loop induced couplings gg, $\gamma\gamma$, $Z\gamma$
different for A and B

MH+=600 GeV

For h or H with mass 120 GeV

solution	basic couplings	$\lvert\chi_{gg}\rvert^2$	$\lvert\chi_{\gamma\gamma}\rvert^2$	$\lvert\chi_{Z\gamma}\rvert^2$
A_{h+}/A_{H-}	$\chi_V \approx \chi_d \approx \chi_u \approx 1$	1.00	0.90	0.96
B_{h+d}/B_{H-d}	$\chi_V \approx -\chi_d \approx \chi_u \approx 1$	1.28	0.87	0.96
$B_{h\pm u}$	$\chi_V \approx \chi_d \approx -\chi_u \approx 1$	1.28	2.28	1.21

Collider. The observation of loop-induced couplings can distinguish models in the frame of the "current SM-like scenario" determined via currently measured coupling constants. Even at the Tevatron the solution B_{h+u} can easily be distinguished via a study of the process $gg \to \phi \to \gamma\gamma$ with rate about three times higher than that in the SM (the product

Inert Doublet Model

Ma'78
Barbieri'06

Symmetry under Z_2 transf. $\Phi_S \to \Phi_S$ $\Phi_D \to -\Phi_D$

both in L (V and Yukawa interaction = Model I only Φ_S)

and in the vacuum:

$<\Phi_S> = v$ $<\Phi_D> = 0$ Inert vacuum I_1

Today?

Φ_S as in SM (BEH), with Higgs boson h (SM-like)

Φ_D has <u>no vev</u>, with 4 scalars (no Higgs bosons!)

no interaction with fermions (inert doublet)

Here Z_2 symmetry exact $\to Z_2$ parity, only Φ_D has odd Z_2-parity

→ The lightest scalar stable -a dark matter candidate

(Φ_D dark doublet with dark scalars) .

$\Phi_1 \to \Phi_S$ Higgs doublet S $\Phi_2 \to \Phi_D$ Dark doublet D

Constraining Inert Doublet Model

- Positivity,extrema,vacua,pert. unitarity, S, T
- By considering properties of *(Ma'2006,..B. Świeżewska, Thesis2011, 1112.4356, 1112.5086[hep-ph] and talk)*
  - the SM-like h, $M^2_h = m_{11}^2 = \lambda_1 v^2$
  - the dark scalars D always in pairs!

$$M_{H^+}^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3}{2} v^2$$

$$M_H^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2} v^2$$

$$M_A^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2} v^2$$

λ_{345}

D couple to V = W/Z (eg. AZH, $H^- W^+ H$), not DVV!

Quartic selfcouplings D^4 proportional to λ_2

hopeless to be measured at colliders! *(→ D. Sokołowska talk)*

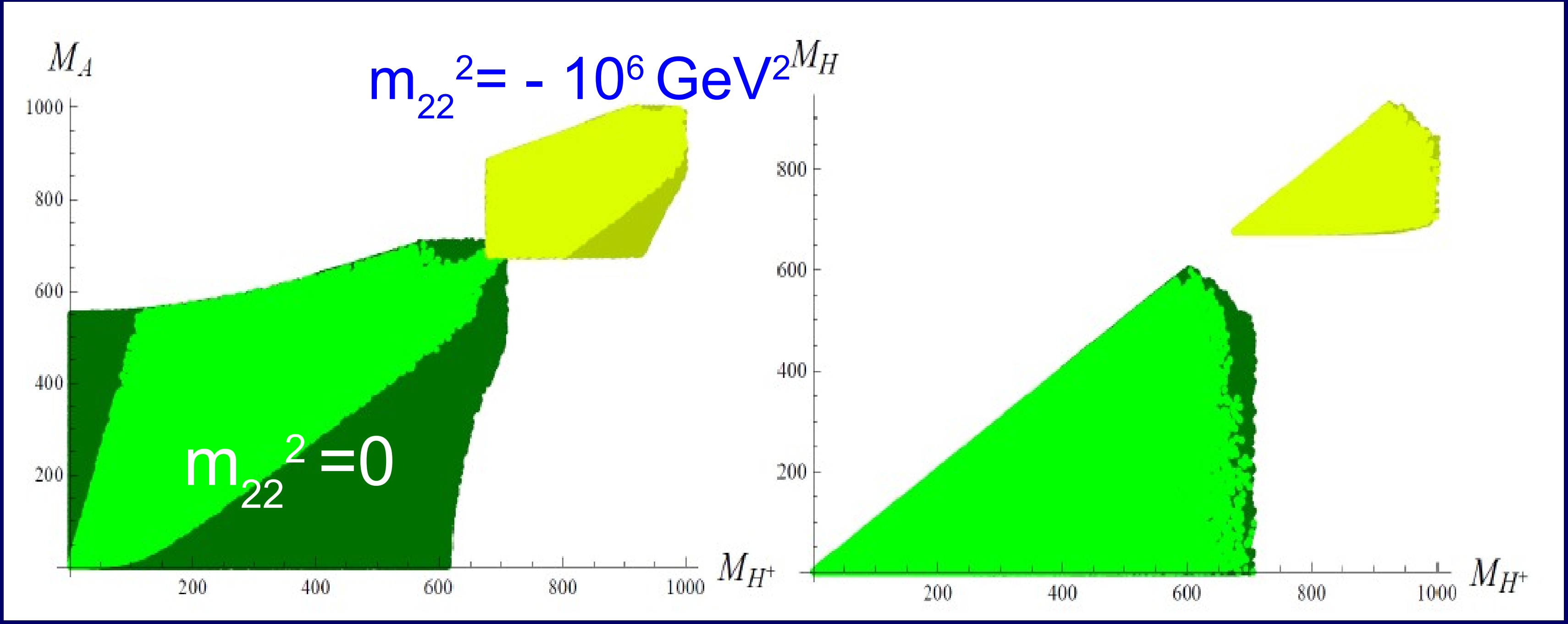
Couplings with Higgs: hHH ~ λ_{345} h H+H- = ~ λ_3

Inert Doublet Model with Mh=125 GeV

Analysis based on unitarity, positivity, EWPT constraints

Gorczyca'2011-12

$$M_H \leqslant 602\,\mathrm{GeV},$$
$$M_{H^\pm} \leqslant 708\,\mathrm{GeV},$$
$$M_A \leqslant 708\,\mathrm{GeV}.$$

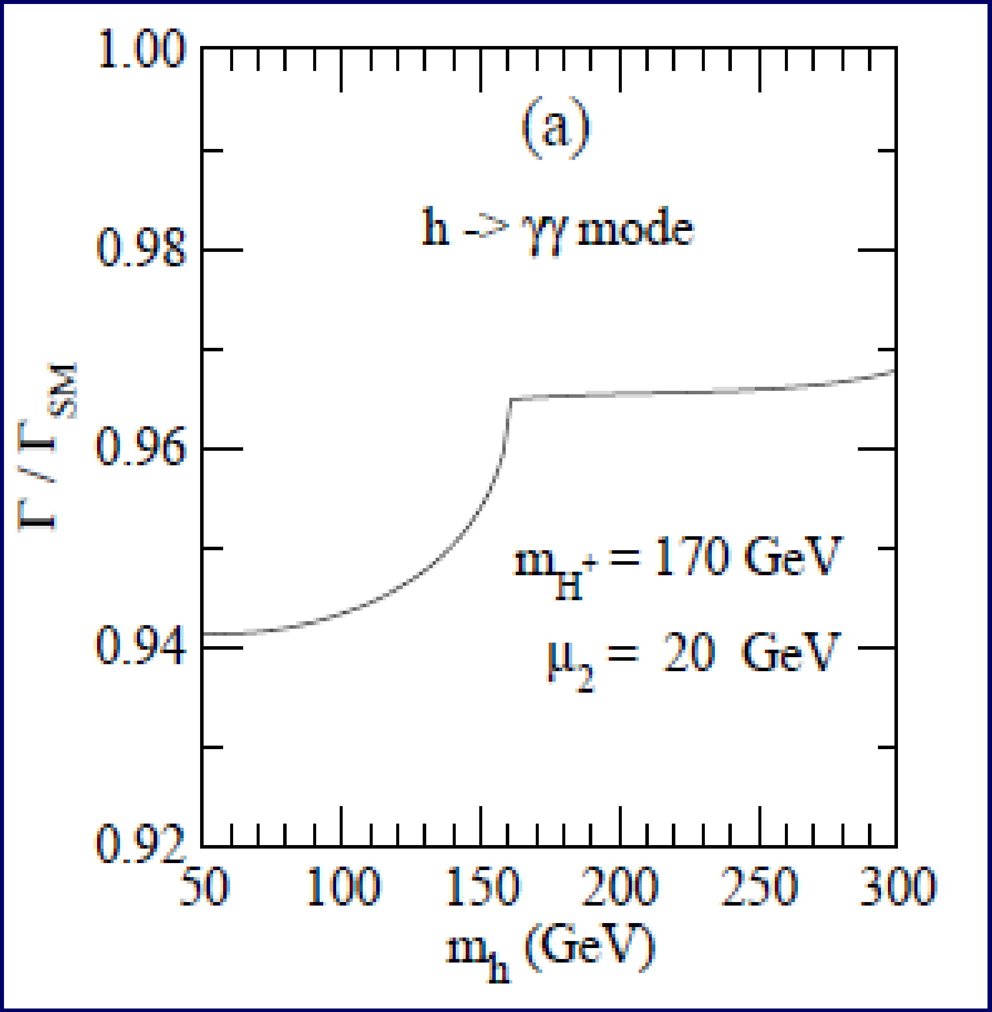


valid up to $|m_{22}^2|= 10^4$GeV^2

EWPT (pale regions)

IDM: decay width $\gamma\gamma h$

Ma'2007



For negative λ_3

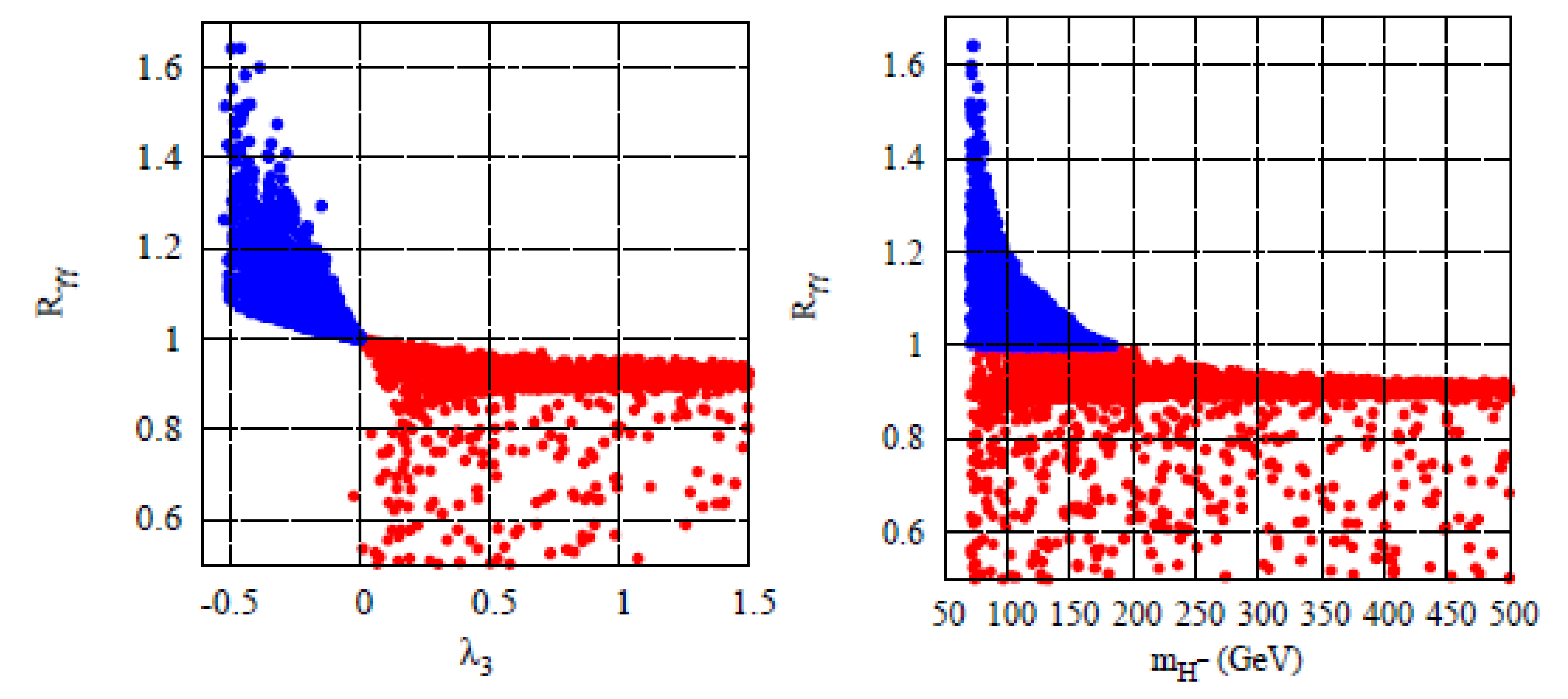
It maybe larger than in SM

$$= \frac{G_\mu \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_C Q_f^2 g_{hff} A_{1/2}(\tau_f) + g_{hWW} A_1(\tau_W) + \frac{m_{H^\pm}^2 - \mu_2^2}{\sqrt{2}\, m_{H^\pm}^2} A_0(\tau_{H^\pm}) \right|^2 ,$$

$= \lambda_3$

gg → h → γγ in IDM

$$R_{\gamma\gamma} = \frac{\sigma_h^{\gamma\gamma}}{\sigma_{h_{SM}}^{\gamma\gamma}} = \frac{\sigma(gg \to h) \times Br(h \to \gamma\gamma)}{\sigma(gg \to h)^{SM} \times Br(h \to \gamma\gamma)^{SM}} = \frac{Br(h \to \gamma\gamma)}{Br(h \to \gamma\gamma)^{SM}}$$



Arhrib at al

Blue : R > 1

When λ_3< 0 (and λ_{345} <0

Evolution of the Universe in 2HDM– through different vacua in the past

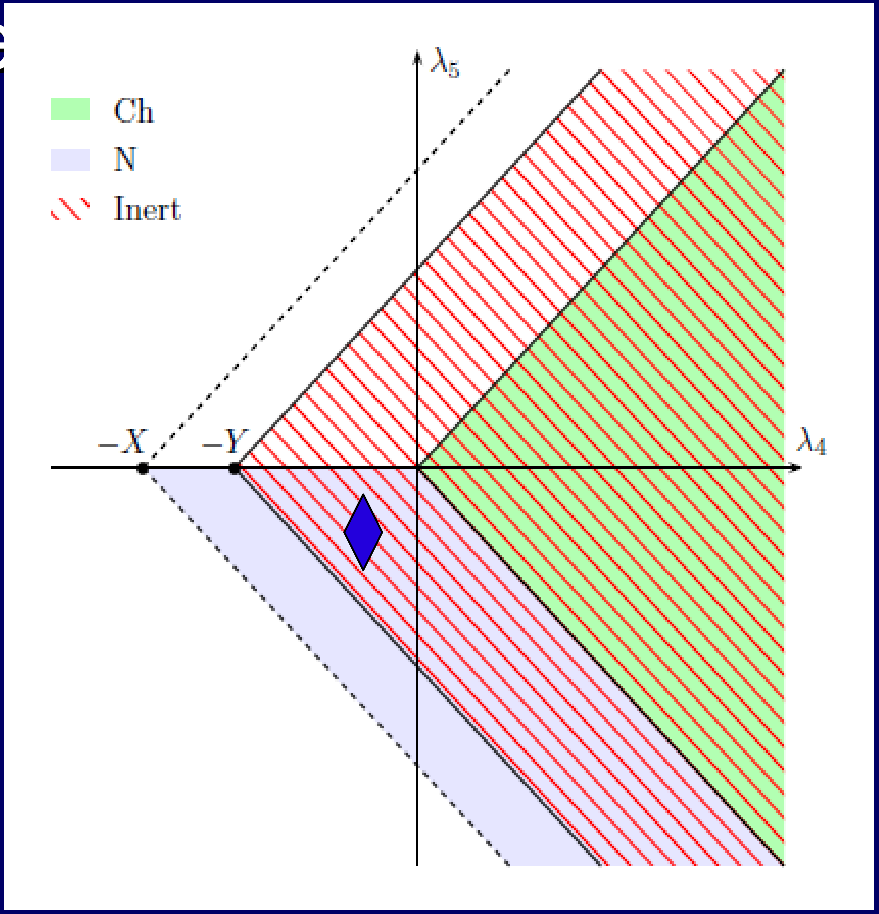
Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev, Krawczyk,
Sokołowska 2010, Sokołowska 2011

We consider 2HDM with an explicit D (Z_2) symmetry assuming that today the Inert Doublet Model describes reality

Yukawa interaction – Model I →
all fermions couple only to Φ_S

From the EW symmetric phase to the INERT phase in T2 approximation

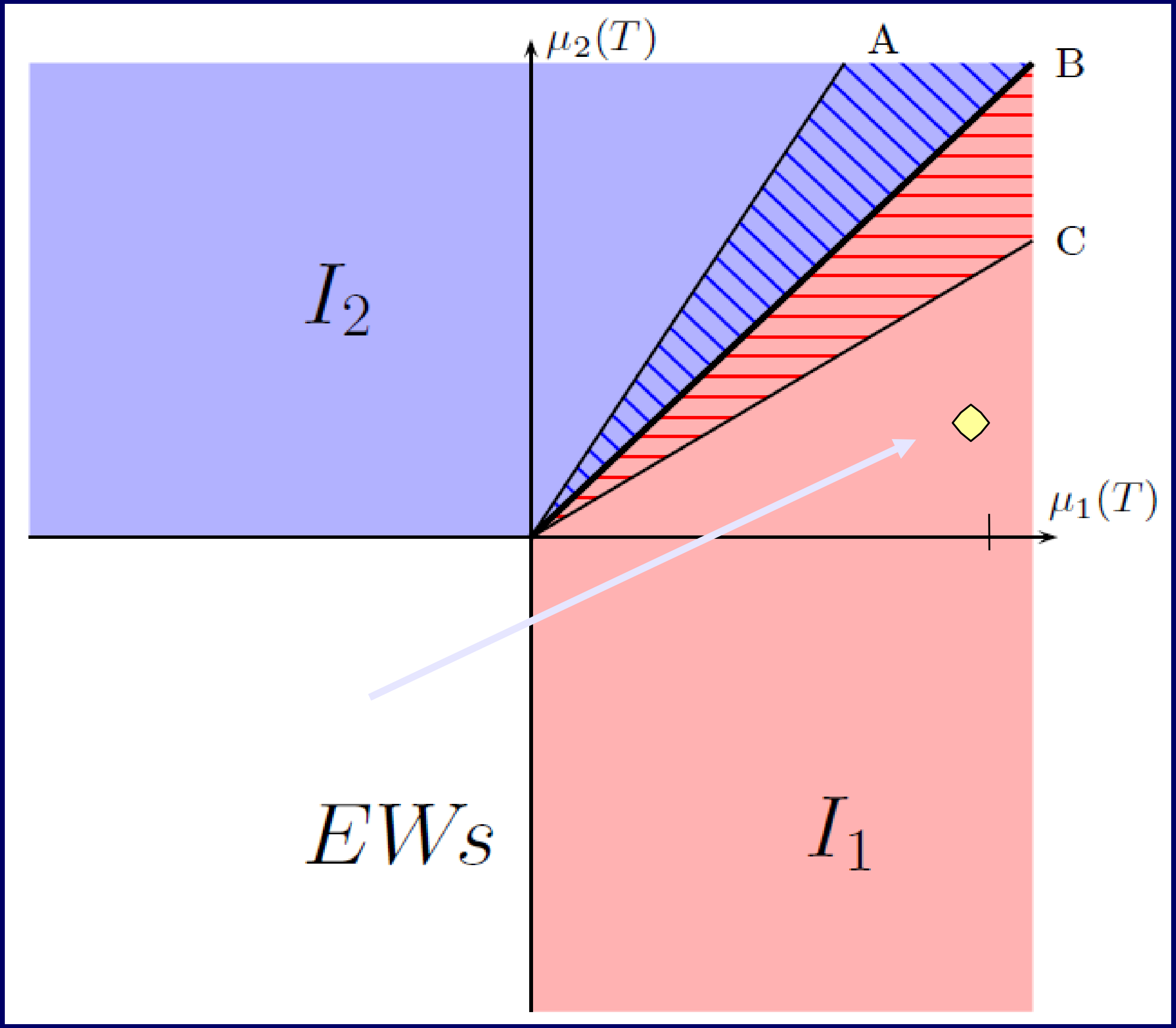
In the simplest T2 approximation only *mass terms* in V vary with temperature like T^2, while λ' are fixed



Various scenarios possible in one, two or three steps, with 1st or 2nd type phase transitions → *Sokołowska talk*

Ginzburg, Kanishev, MK, Sokołowska Phys. Rev D 2010

Phase diagram (μ_1,μ_2)



$\mu_i = m_{ii}^2/\sqrt{\lambda_i}$

$$R + 1 > 0.$$

Stability condition

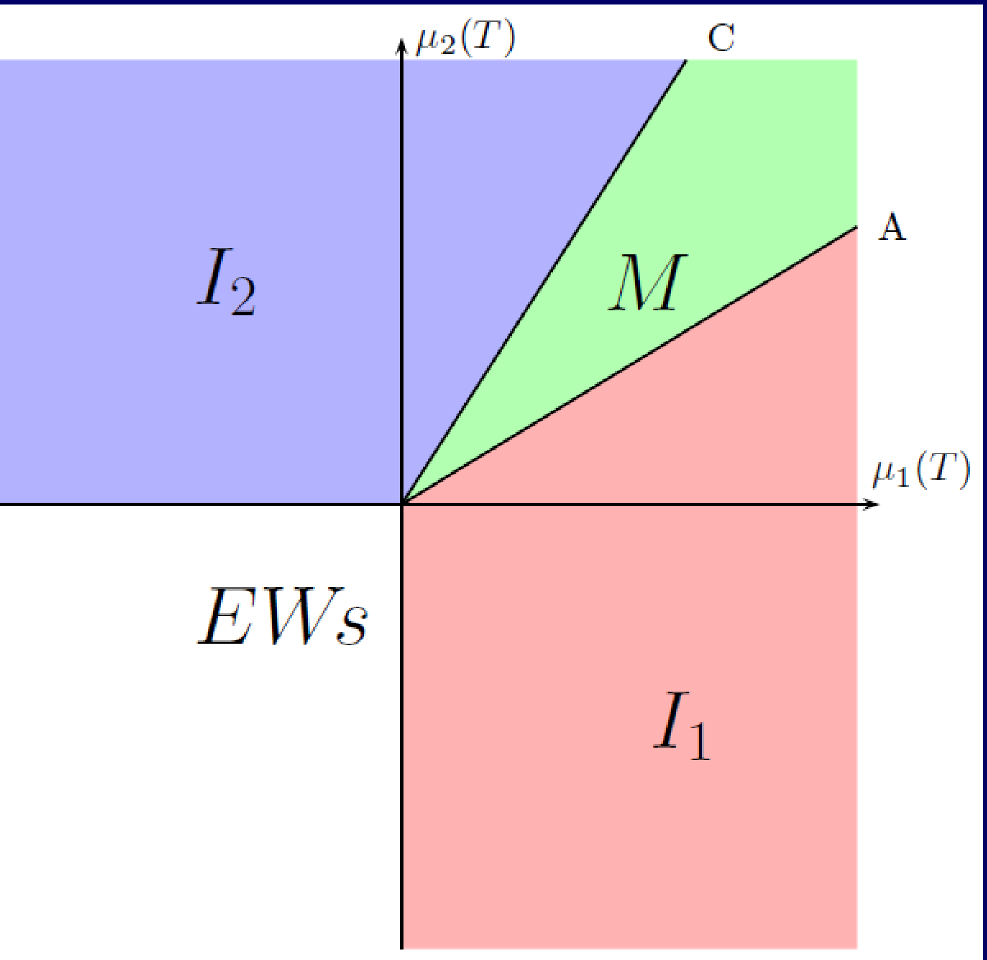
$$R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}.$$

3 regions of R

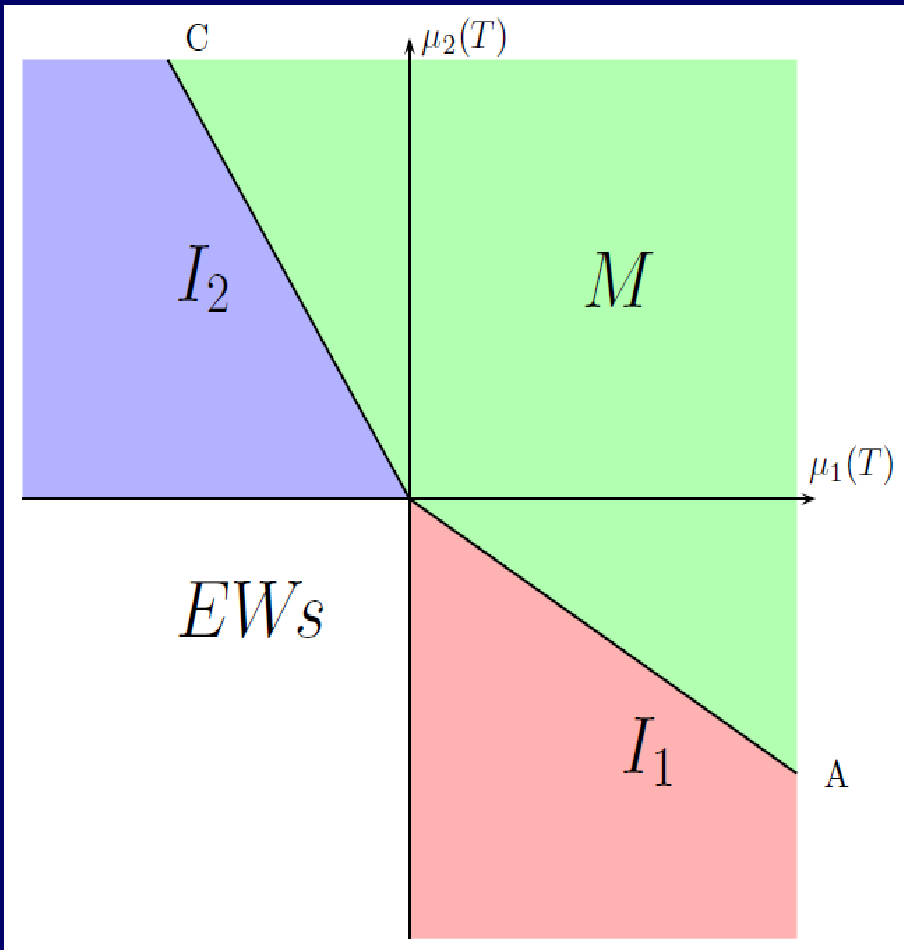
T2 corrections → rays from EW s to Inert phase

R>1

Phase diagrams



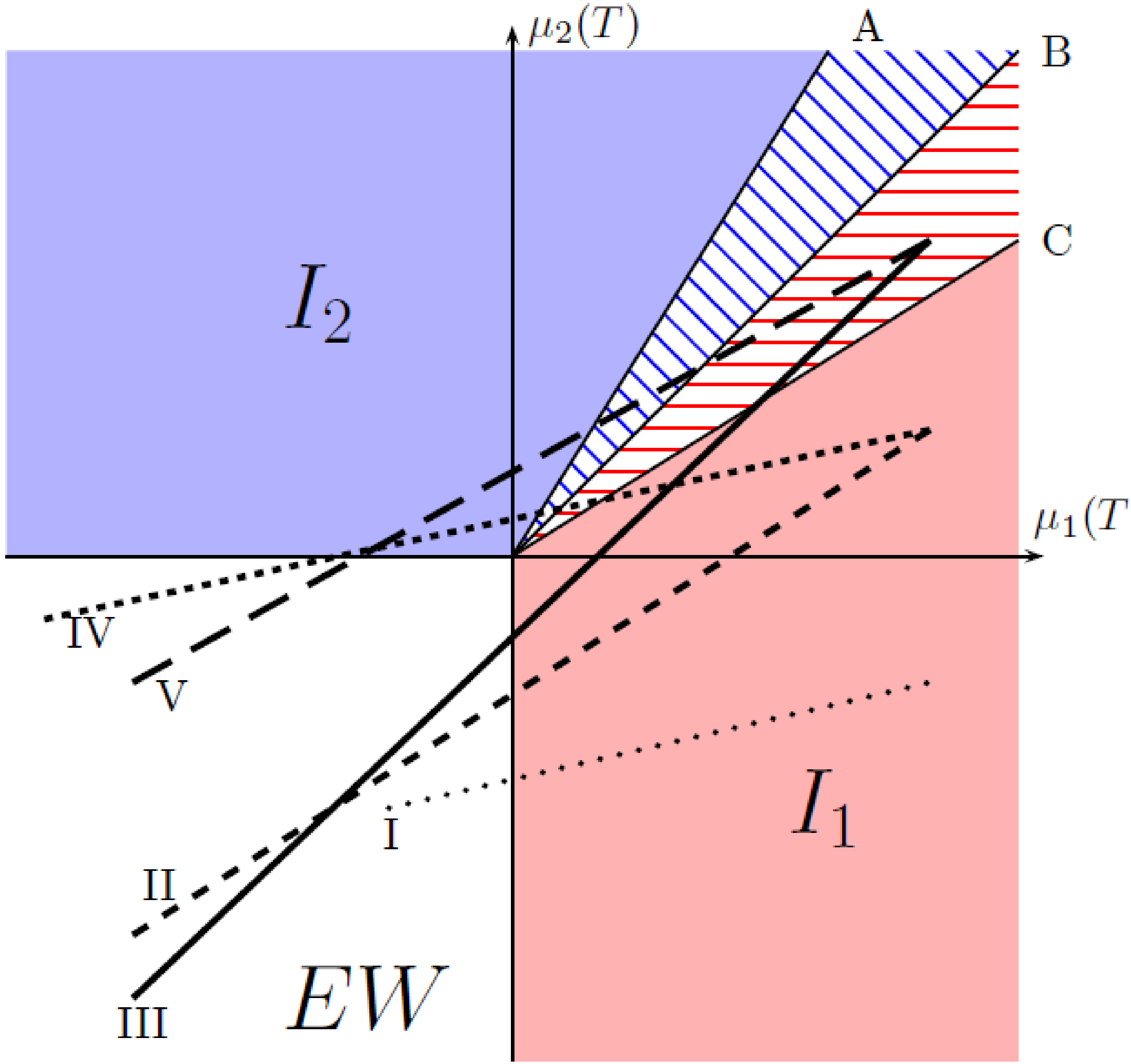
1>R>0



0>R>-1

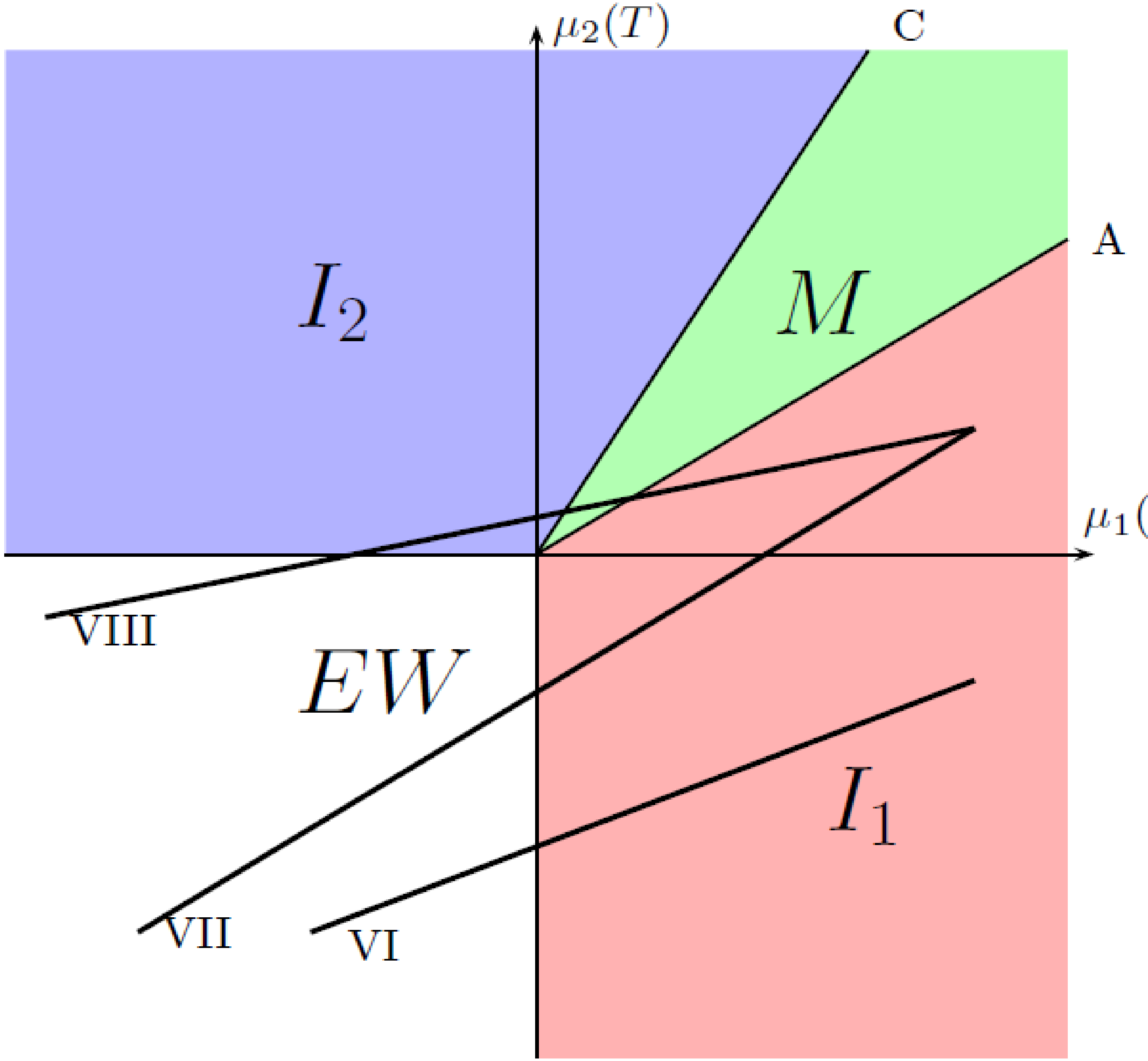
R>1

Mixed vacuum impossible



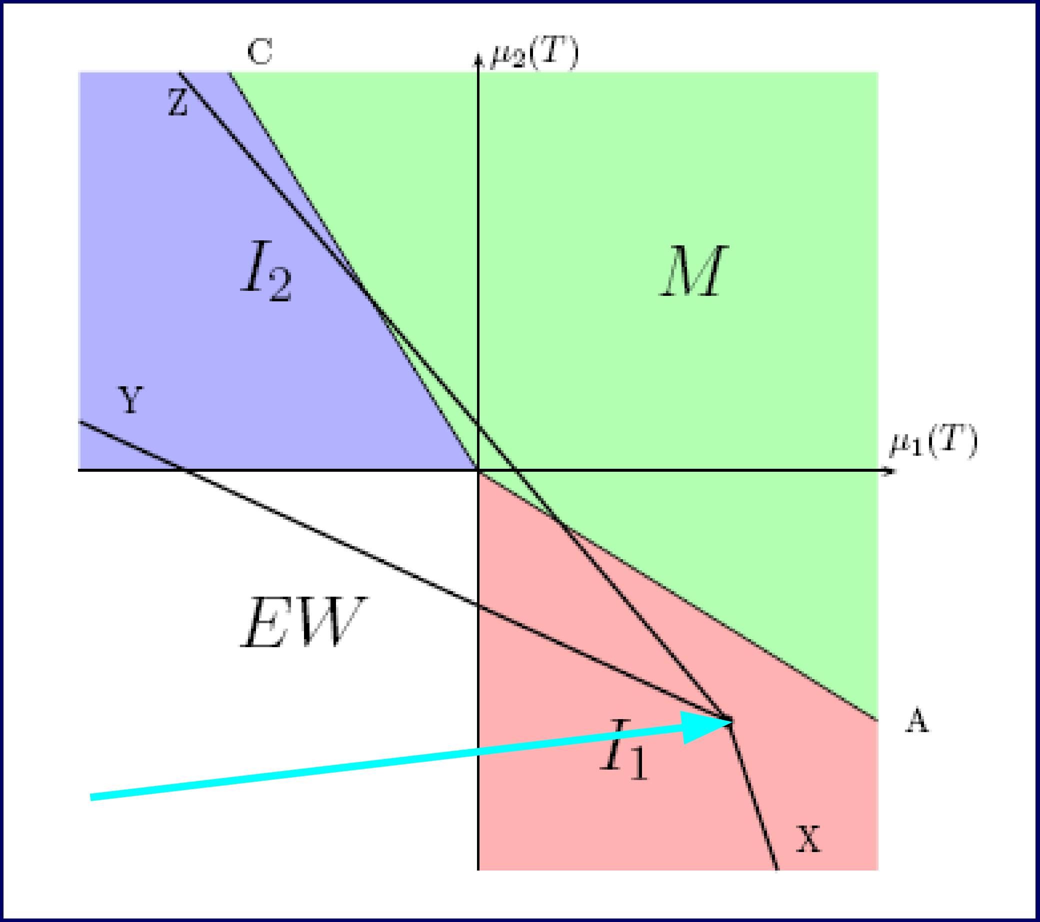
0<R<1

$0 < R\mu_1 < \mu_2 < \mu_1/R.$



Non-restoration of EW symmetry R <0

c_1 or $c_2 < 0$



The only evolution with EW restoration in the past (and $R_{\gamma\gamma} > 1$!)

Transitions to the Inert phase beyond T2 corrections

We applied one-loop effective potential at T=0 (Coleman-Wienberg term) and temperature dependent effective potential at T≠0 (with sum of ring diagrams)

$$V_T^{(1L)}(v_1, v_2) = V_{\text{eff}}^{(1L)}(v_1, v_2) + \Delta^{(1L)} V_{T\neq 0}(v_1, v_2).$$

The one-loop effective potential $V_{\text{eff}}(v_1, v_2)$ is given in the Landau gauge by standard formula

mass matrices

$$V_{\text{eff}}^{(1L)} = V_{\text{tree}} + \frac{1}{64\pi^2} \sum_{\text{fields}} C_s \left\{ \mathcal{M}_s^4 \left(\ln \frac{\mathcal{M}_s^2}{4\pi\mu^2} - \frac{3}{2} + \frac{2}{d-2} - \gamma_E \right) \right\} + \text{CT},$$

number of states

counter terms →

Fixing counterterms

We require that v1=v1(tree)
and that h field propagator has a pole for tree-level mass-squared M_h^2

Then we put conditions on λ_{345} (hHH), λ_2(HHHH)

On the other hand λ_2 cannot be directly measured in the foreseeable future[6] so its precise definition at the loop-level is not important. Here for simplicity we choose to subtract the divergences of $V_{\rm eff}^{(1L)}$ proportional to v_2^4 and $v_1^2 v_2^2$ using the $\overline{\rm MS}$ scheme. This fixes the combinations $\delta\lambda_2 + 2\lambda_2\delta Z_2$ and $\delta\lambda_{345} + \lambda_{345}(\delta Z_1 + \delta Z_2)$. Once the latter counterterm is fixed the last necessary combination $\delta m_{22}^2 + m_{22}^2 \delta Z_2$ is determined by renormalizing the H^0 propagator on-shell. The counterterms $\delta\lambda_3$ and $\delta\lambda_5$ can be then used to enforce that the tree-level masses M_{A^0} and $M_{H^\pm}$ remain unchanged by one-loop corrections (they do not need to be determined explicitly).

One-loop temperature dependent effective potential

$$\Delta^{(1L)}V_{T\neq 0} = \frac{T^4}{2\pi^2}\sum_{\text{fields}} C_s \int_0^\infty dx\, x^2 \ln\left[1-(-1)^{2s}\exp\left(-\sqrt{x^2+\mathcal{M}_s^2/T^2}\right)\right].$$

For $T^2 \gg \mathcal{M}_s^2$ the contribution of $\mathcal{M}_s^2$ to (12) can be expanded:

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_B = |C_s|\left\{-\frac{\pi^2}{90}T^4 + \frac{1}{24}T^2\mathcal{M}_s^2 - \frac{T}{12\pi}|\mathcal{M}_s^3| - \frac{\mathcal{M}_s^4}{64\pi^2}\left(\ln\frac{\mathcal{M}_s^2}{T^2} - C_B\right)\right.$$

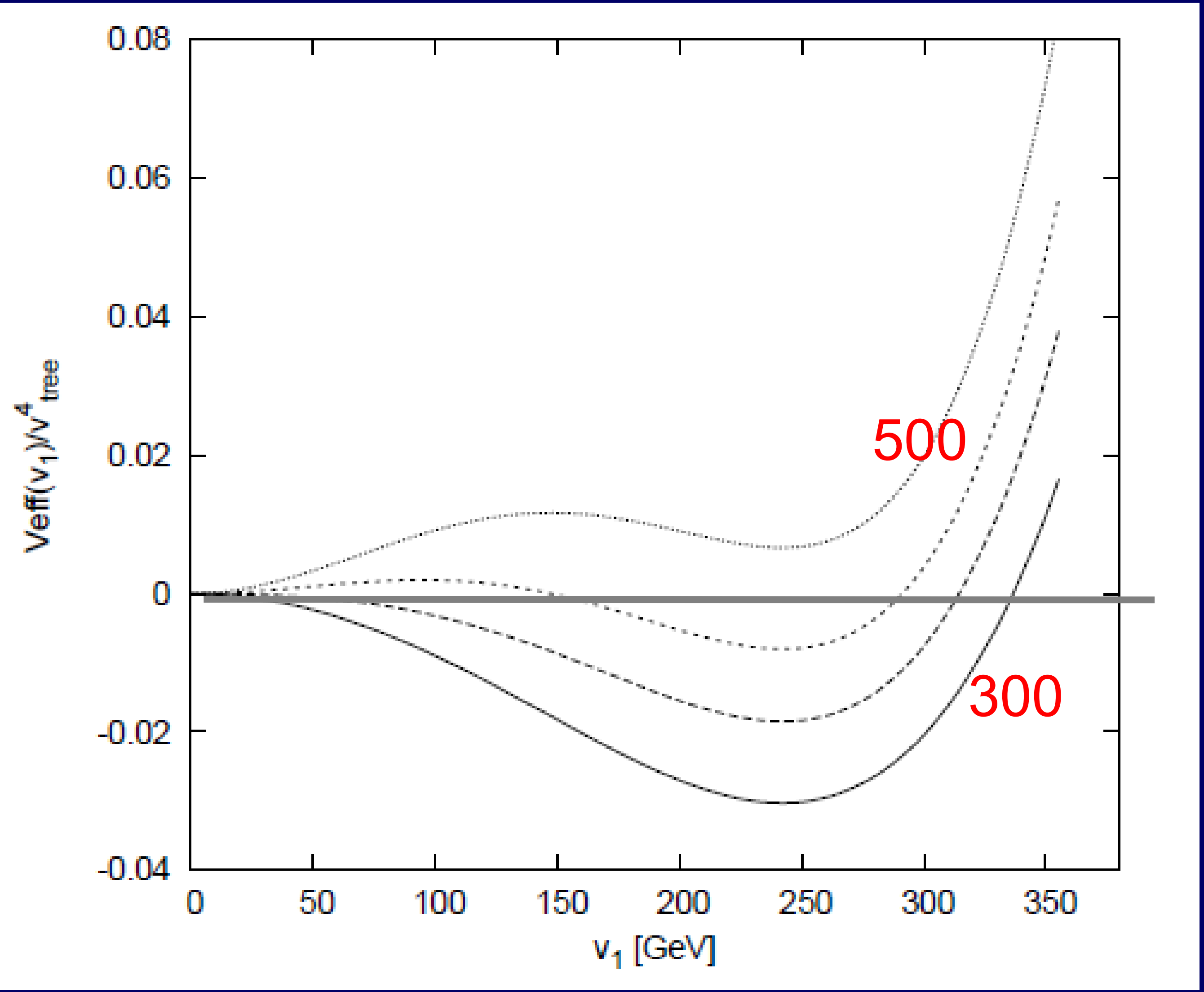
$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_F = |C_s|\left\{-\frac{7\pi^2}{720}T^4 + \frac{1}{48}T^2\mathcal{M}_s^2 + \frac{\mathcal{M}_s^4}{64\pi^2}\left(\ln\frac{\mathcal{M}_s^2}{T^2} - C_F\right)\right\}$$

($C_B = 5.40762$, $C_F = 2.63503$). In the opposite limit $T^2 \ll \mathcal{M}_s^2$ one has

$$\left(\Delta^{(1L)}V_{T\neq 0}\right)_s = -|C_s|\,T^4\left(\frac{|\mathcal{M}_s|}{2\pi T}\right)^{3/2}\left(1+\frac{15}{8}\frac{T}{|\mathcal{M}_s|}+\ldots\right)\exp\left(-\frac{|\mathcal{M}_s|}{T}\right),$$

both for B and F

Effective T=0 potential



Mh=125 GeV

MH=65 GeV

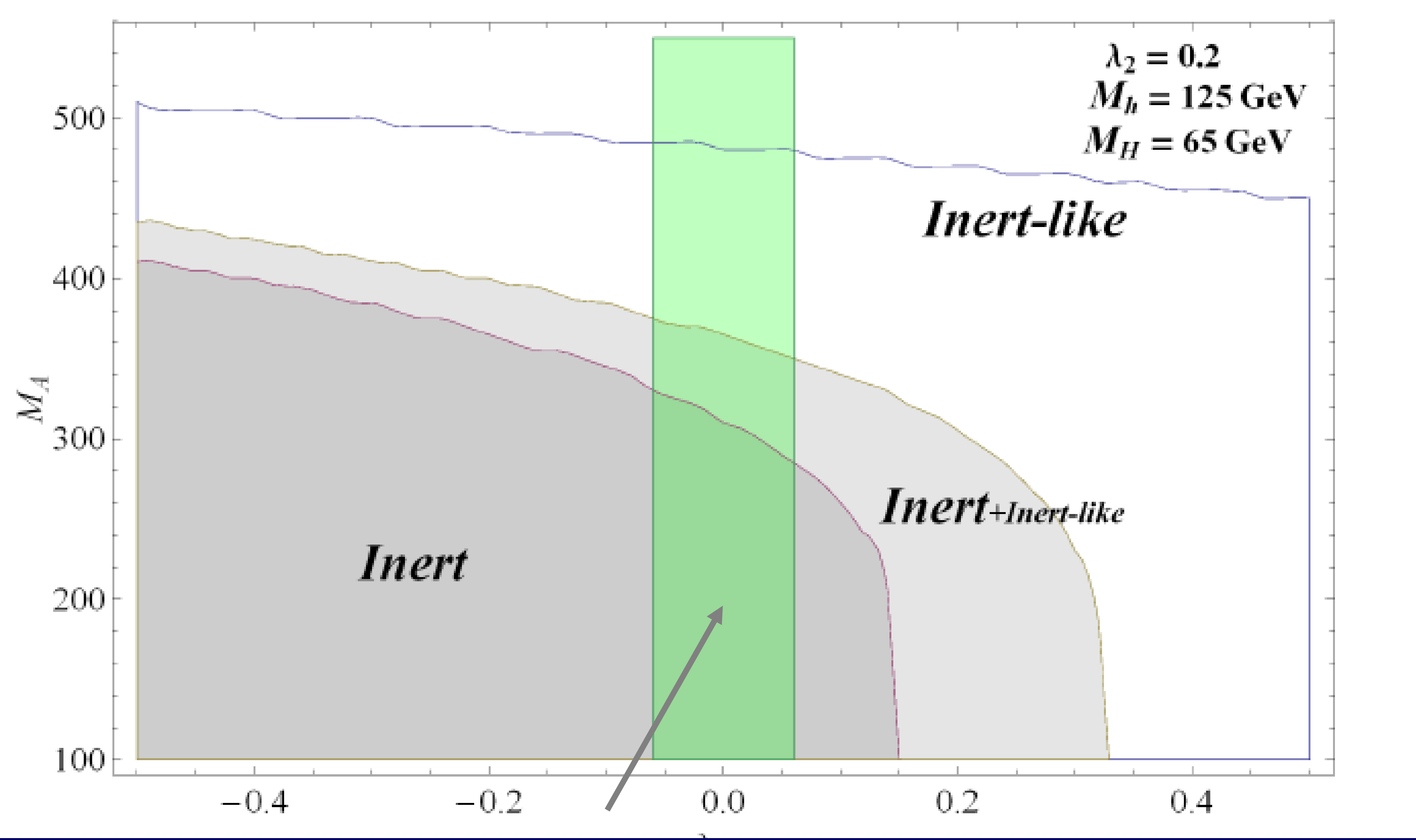
MH+=MA=
500,450,400,300
GeVṼ

λ_{345}=0.2,
λ_2=0.2

$v_{2(D)}$=0

Critical temperature T_{EW}: V at new minimum = V at $v_{1(s)}=v_{2(D)}=0$

Phases at T=0



Xenon100 bound

λ_{345}

Strength of the phase transition

$v(T_{EW})/T_{EW}$

We are looking for parameter space of IDM which allows for a strong first order phase transition

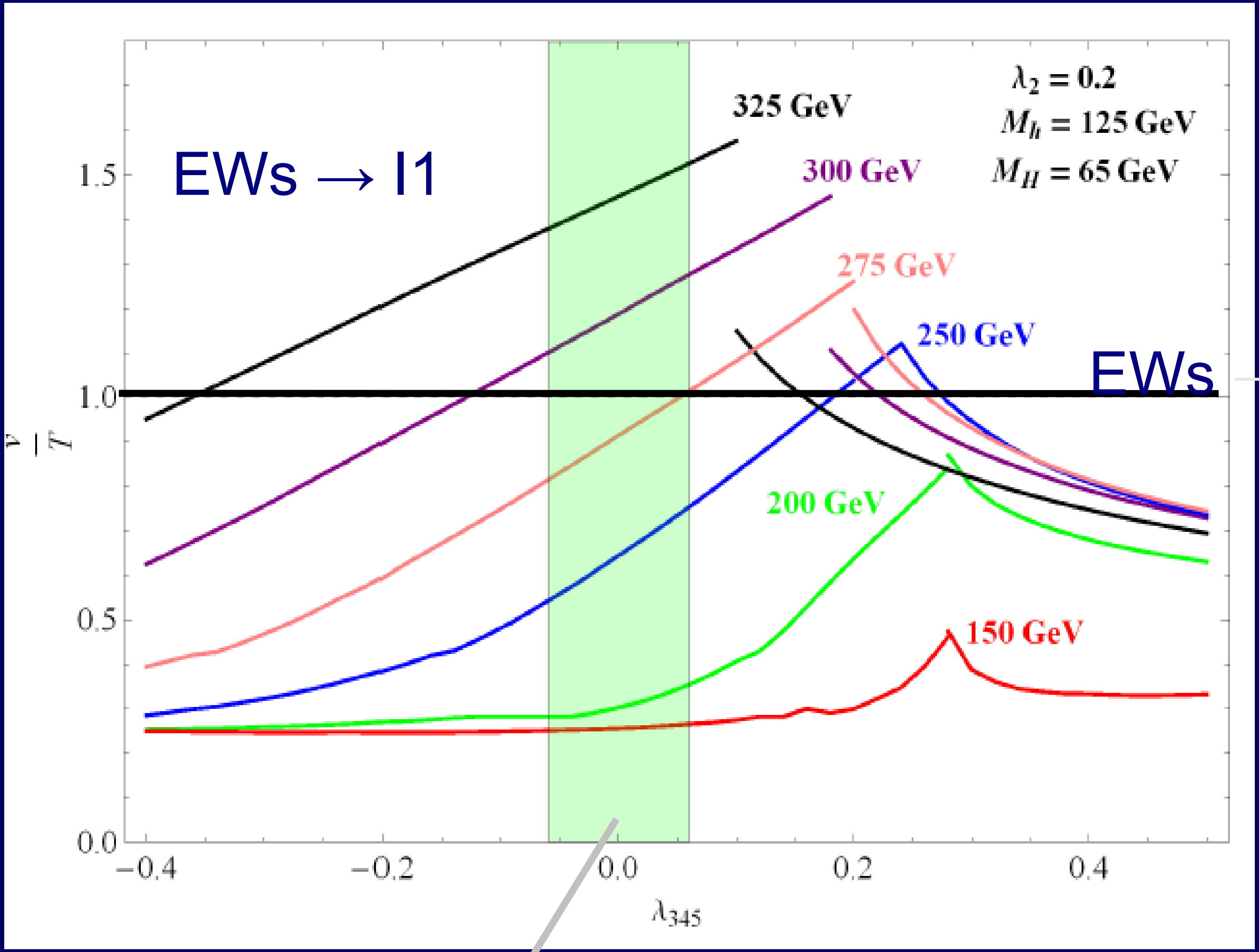
$v(T_{EW})/T_{EW} > 1$

being in agreement with collider and astro-physical data

We focus on medium DM, with MH « v,heavy degenerated A and H+ and M_h=125 GeV

Results for $v(T_{EW})/T_{EW}$

Mh=125 GeV, MH=65 GeV, λ2=0.2

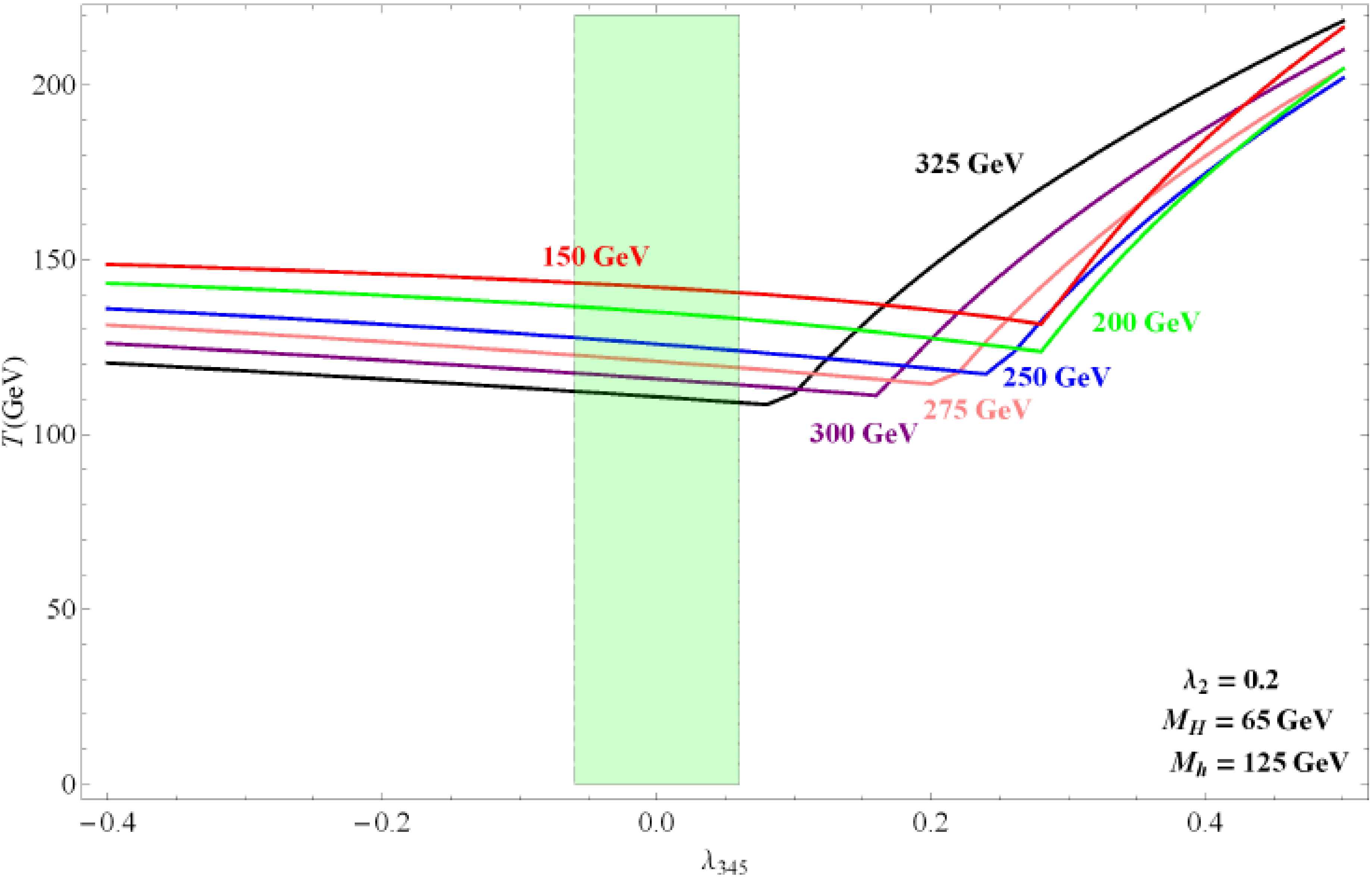


Allowed MH+=MA between 275 and 380 GeV (one step)

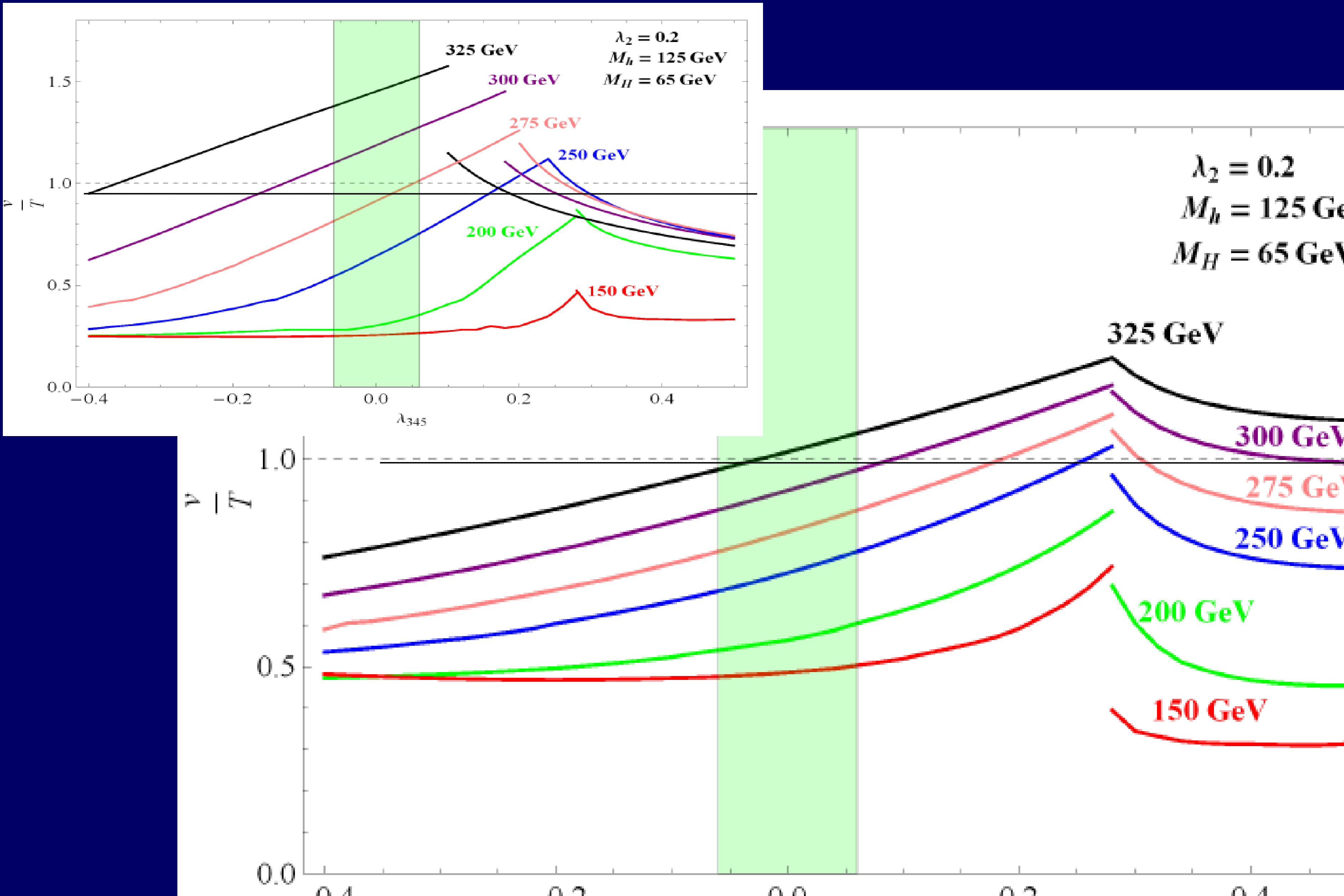
λ_{345}

Xenon100 bound

T_{EW} as a function of λ_{345}



Role of Coleman-Weinberg



Conclusion

Strong first order phase transition in IDM possible for realistic mass of Higgs boson (125 GeV)

and DM (~65 GeV) for

1/ heavy (degenerate) H+ and A with mass

275 -380 GeV

2/ low value of hHH coupling $|\lambda_{345}| < 0.1$

3/ Coleman-Weinberg term important

Our results in agreement with recent papers on IDM
Borach, Cline 1204.4722
Chowdhury et al 1110.5334 (DM as a trigger of strong EW PT)
(on 2HDM Cline et al, 1107.3559 and Kozhusko..1106.0790)

Conclusions

- 2HDM - a great laboratory for physics BSM
- In many Standard Models SM-like scenarios can be realized:

  [Higgs mass >115 GeV, SM tree-level couplings]
- In models with two scalar doublets:

- MSSM with decoupling of heavy Higgses *LHC-wedge*
- 2HDM (Mixed) where *both h or H can be SM-like*
- Intert Doublet Model *only h can be SM-like*

Evolution of Universe (Ginzburg.. 2010),
DM (Ma.. 2007), Inflation (Gong .. 2012)

Yes, Photon Linear Collider can distinguish...

PLC

$\Gamma(h \to \gamma\gamma) \sim 3\%$

$$\gamma\gamma \to h \to b\bar{b}$$

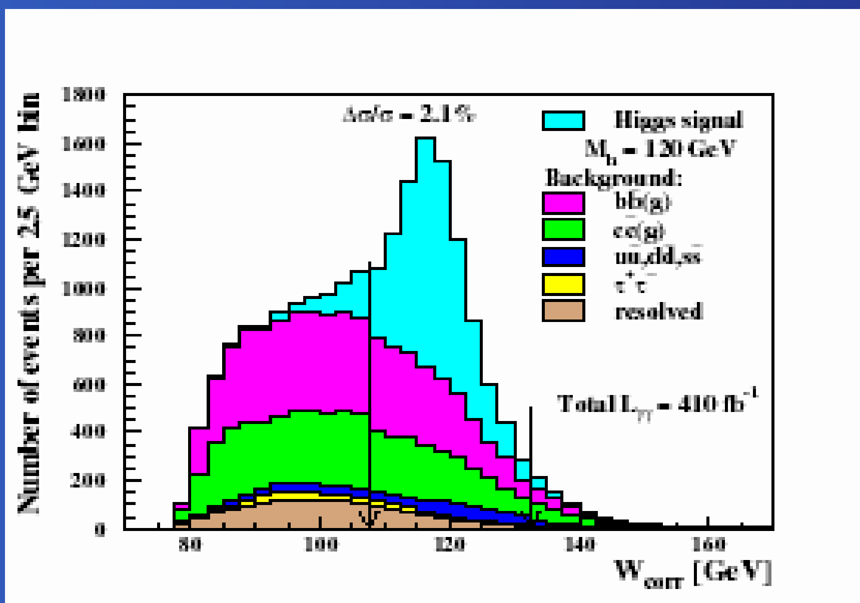
NŻK

SM summary

Niezurawski et al.,

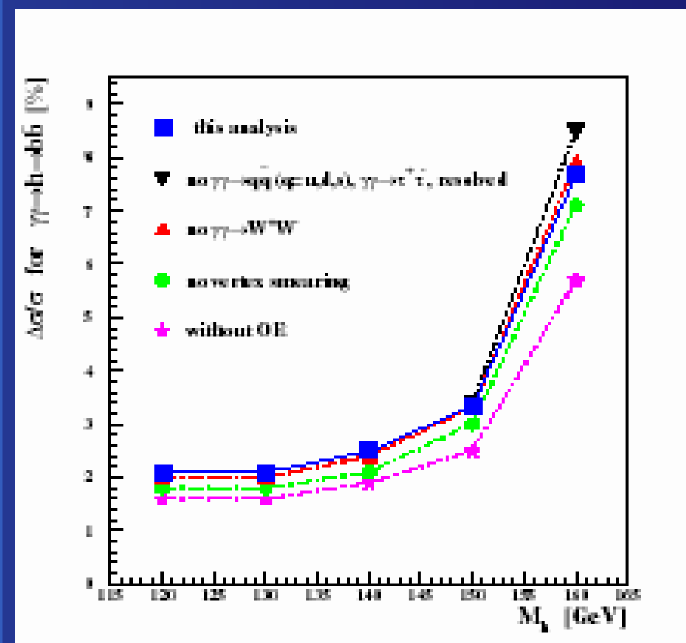
Monig, Rosca

→ Results for $M_h = 120$ GeV



Corrected invariant mass distributions for signal and background events

Results for $M_h =$ 120-160 GeV



For $M_h =$ 150, 160 GeV additional cuts to reduce $\gamma\gamma \to W^+W^-$

Backup

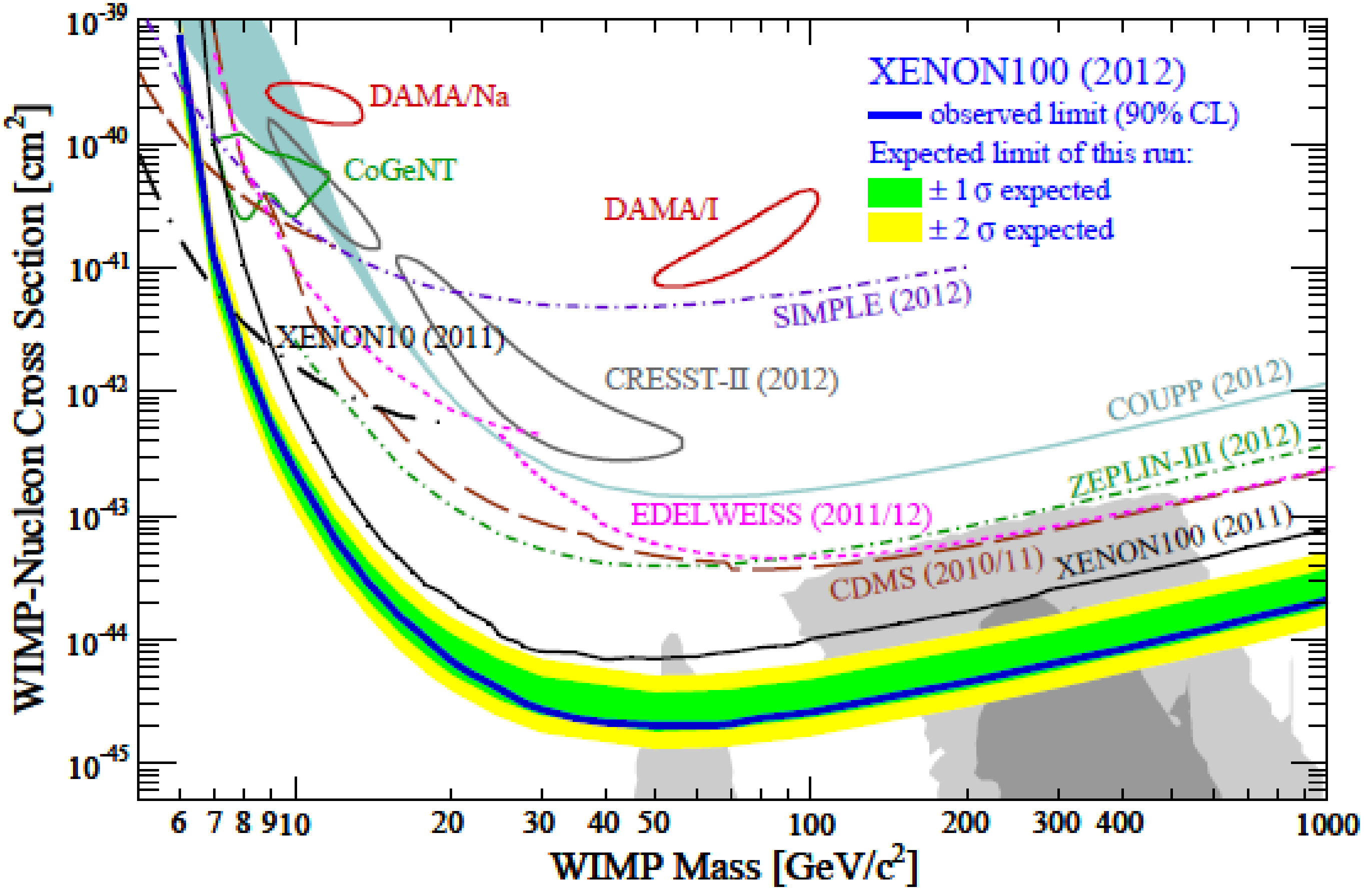


FIG. 3: New result on spin-independent WIMP-nucleon scattering from XENON100: The expected sensitivity of this run is shown by the green/yellow band ($1\sigma/2\sigma$) and the resulting exclusion limit (90% CL) in blue. For comparison, other experimental results are also shown [19–22], together with

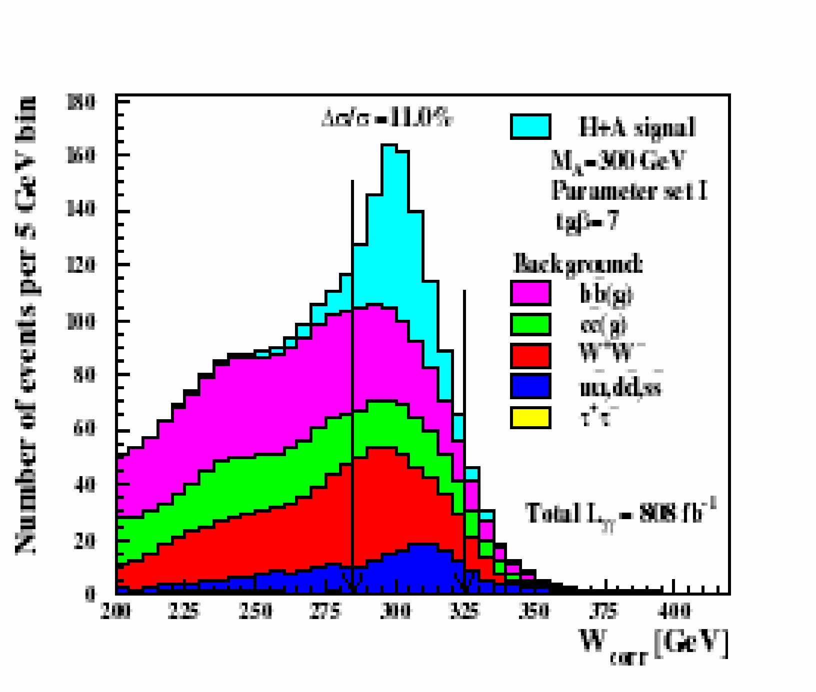
MSSM: Precision at PLC

Niezurawski et al., Spira et al

Covering the LHC wedge

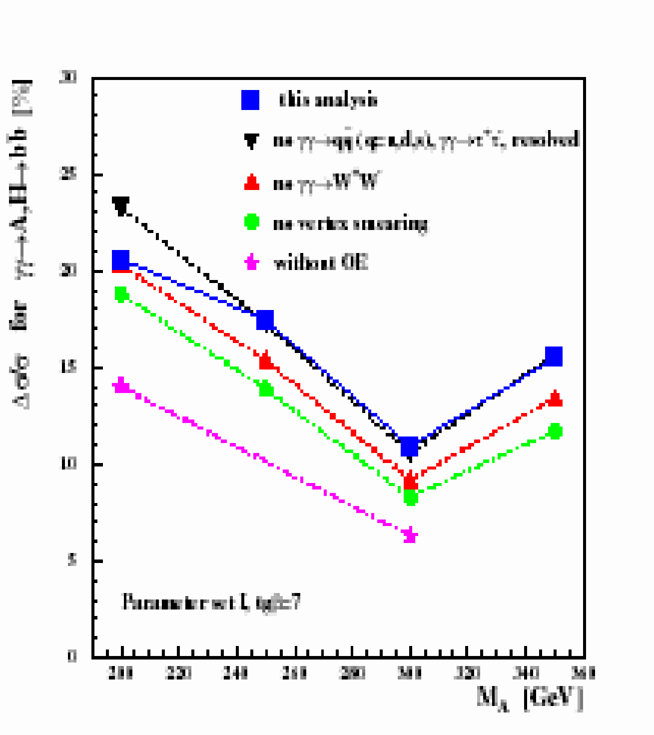
Precision of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ mesurement

Results for $M_A = 300$ GeV



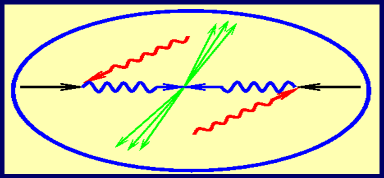
Corrected invariant mass distributions

Results for $M_A = 200$-350 GeV



our previous results compared

PLC: Photon Linear Collider
$\gamma\ \gamma$ and e γ



- Resonance production of C=+ states (eg. Higgs) Ginzburg et al
- Higher mass reach
- Polarised beams – CP filter Gunion, Grzadkowski, Godbole,Zarnecki
- H $\gamma\ \gamma$ coupling – sensitive to charged particles in theory (nondecoupling) Ginzburg et al.., Gunion..

- Direct production of charged scalars, fermions and vectors – higher cross section Monig,
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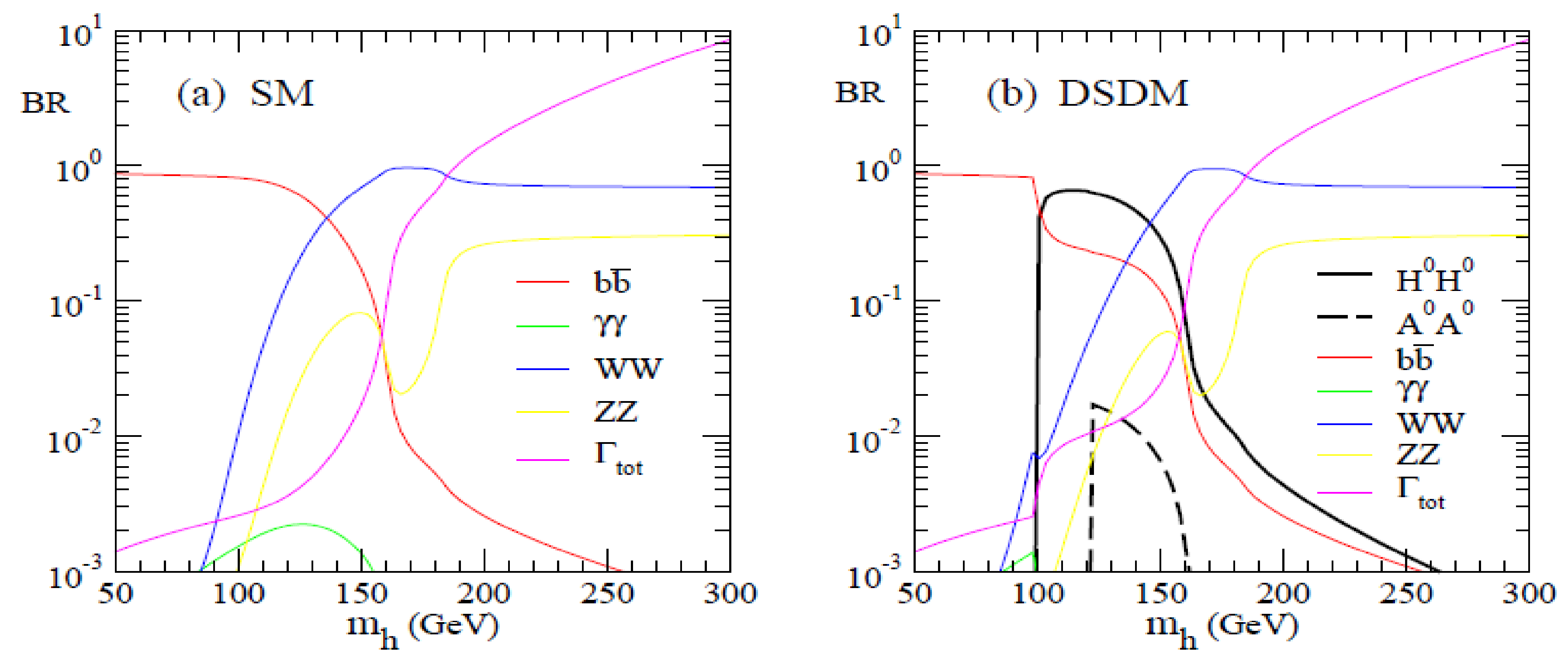
- Study of hadronic interaction of the photon Godbole,Pancheri; MK Brodsky, deRoeck,Zerwas

Colliders signal/constraints for IDM

Barbieri et al '2006 for heavy h; Cao, Ma, Rajasekaren' 2007 for a light h, *later many others*

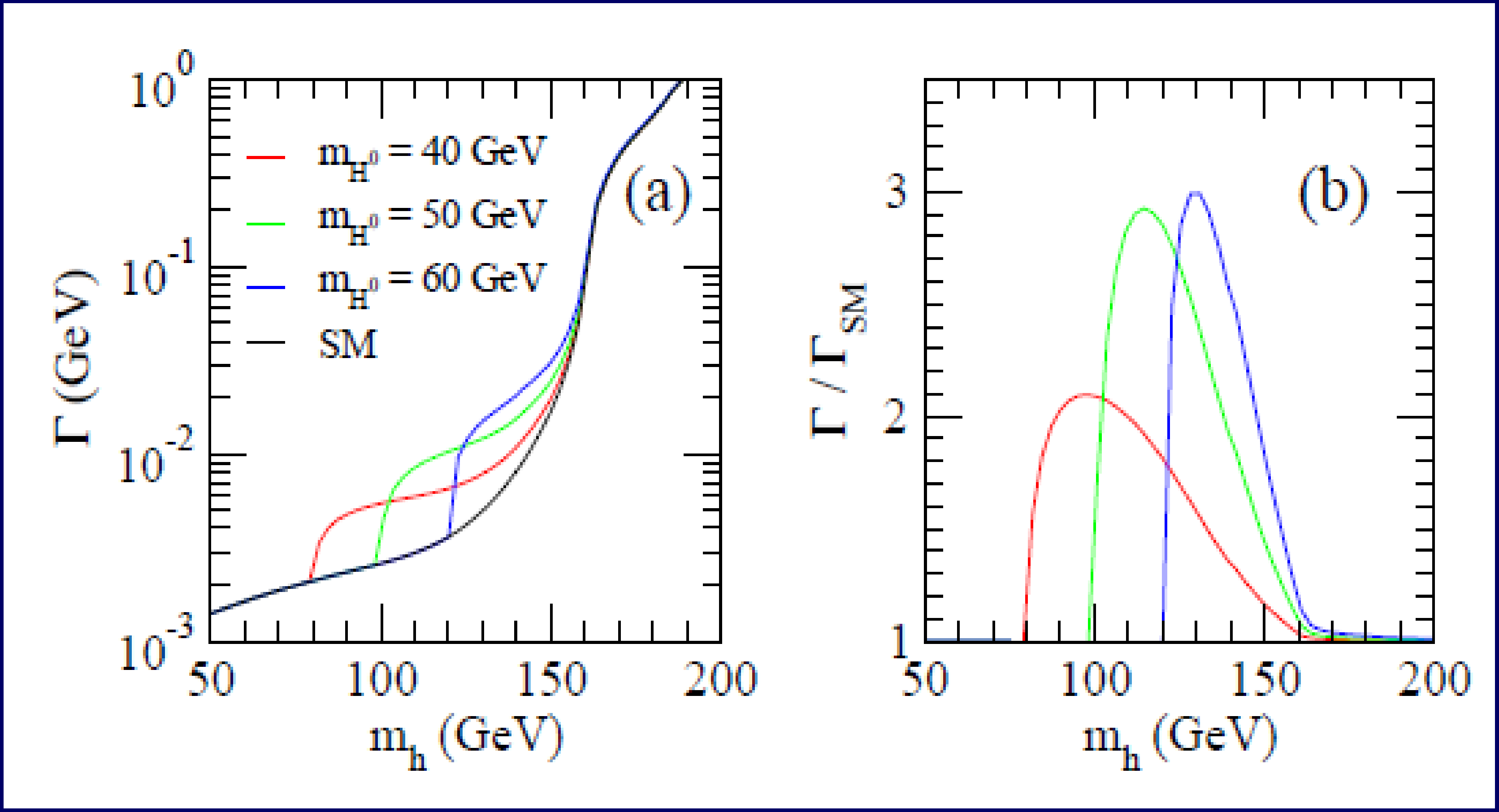
EW precision data $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

For MH=50 GeV



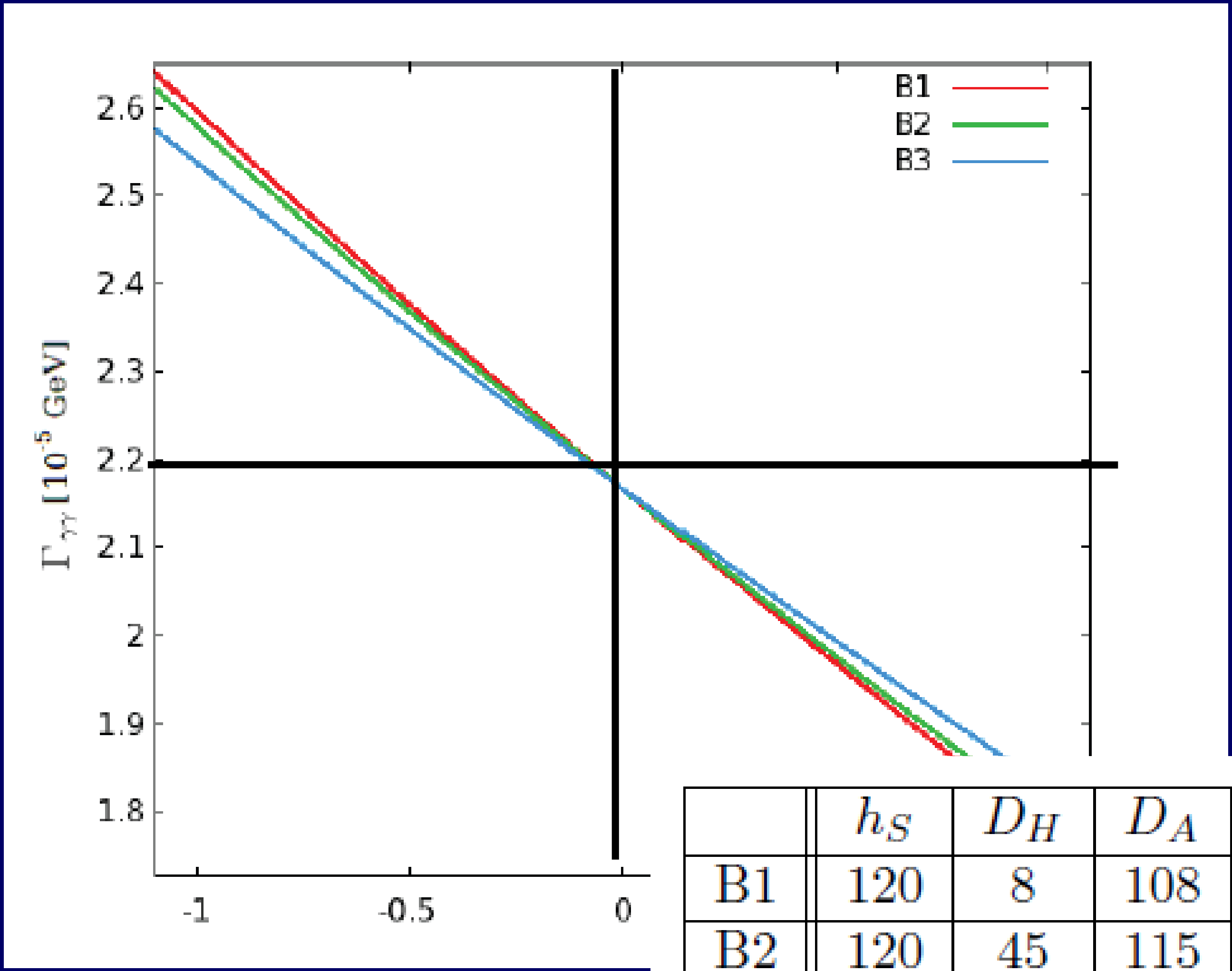
For $M_H = 50$ GeV, $\Delta(A, H)$=10 GeV, M_{H+}=170 GeV, m_{22}=20 GeV

IDM – total width of h



IDM for DM benchmarks B1-3

$\Gamma(h\gamma\gamma)$



SM

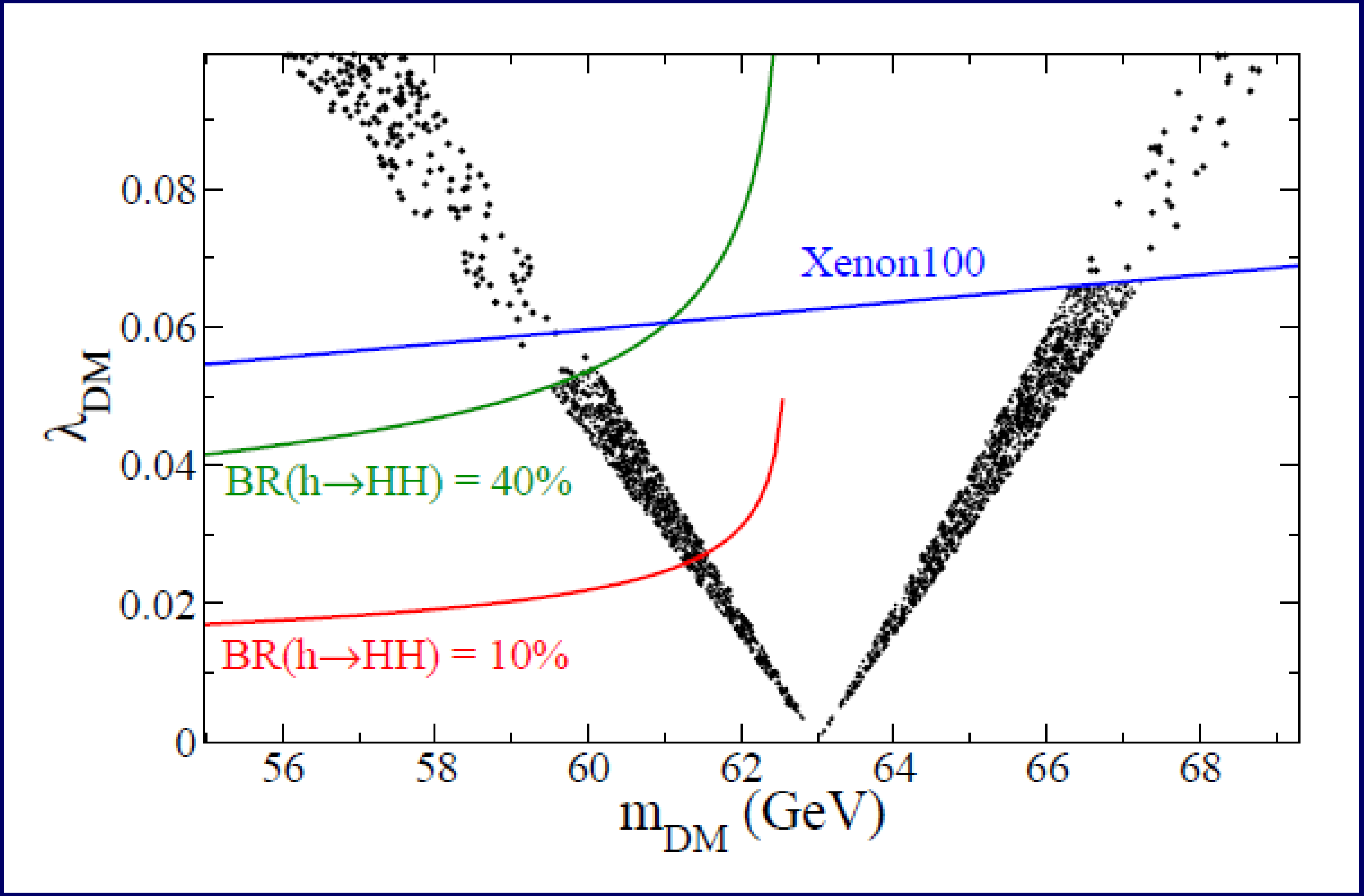
	h_S	D_H	D_A	D_{H+} i D_{H-}
B1	120	8	108	113
B2	120	45	115	115
B3	120	70	78	120

λ_3

GeV

D. Sokołowska; J. Bogdanowicz'11

D. Borach, J. Cline Inert Doublet DM with Strong EW phase transition 1204.4722[hep-ph]



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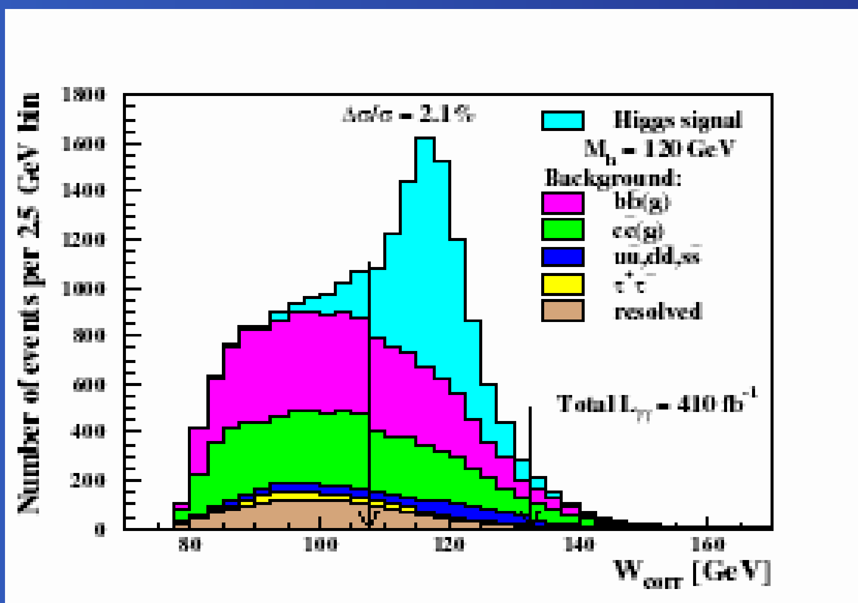

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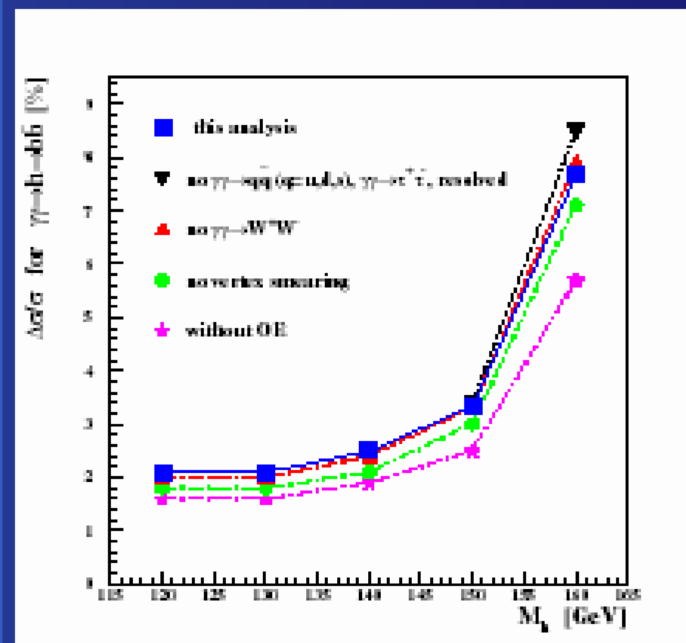

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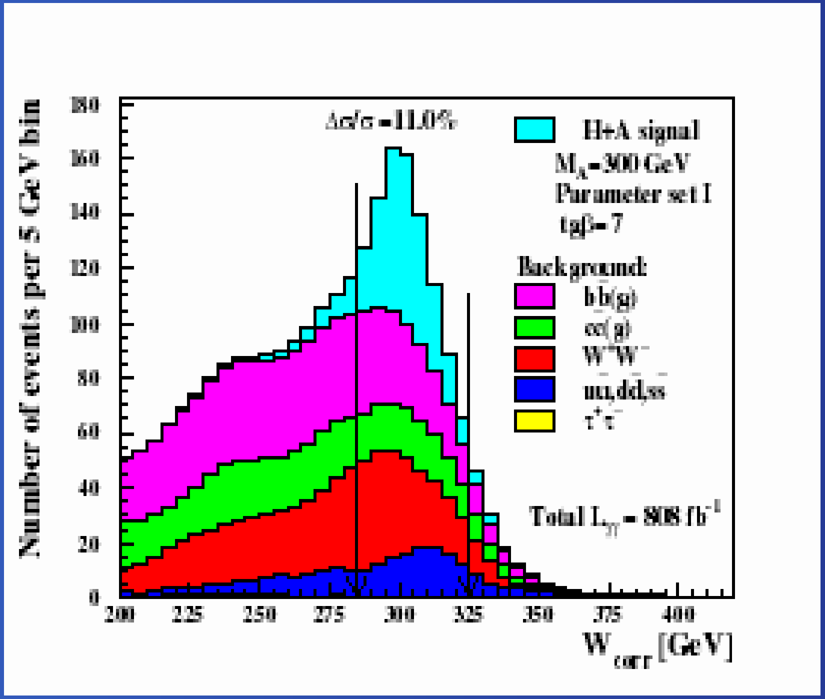

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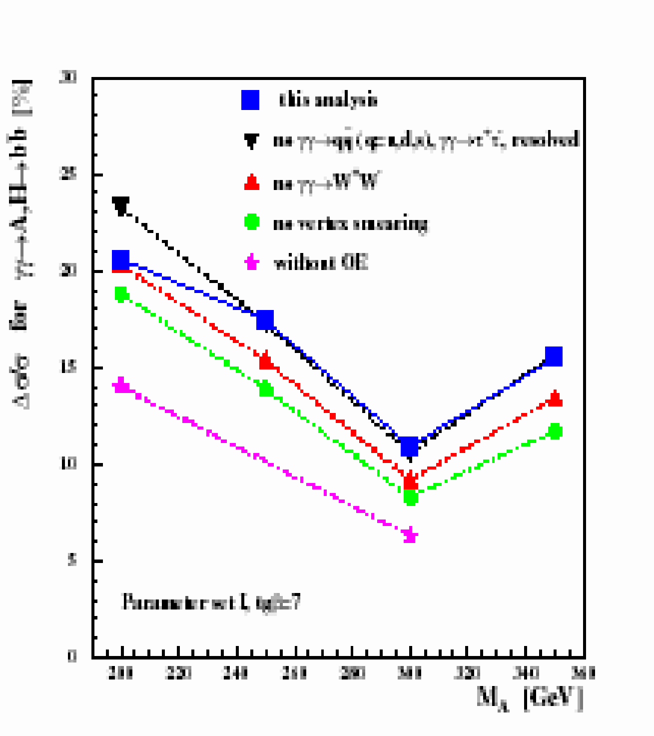
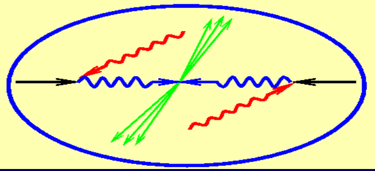


our previous results compared

PLC: Photon Linear Collider
$\gamma\,\gamma$ and e γ



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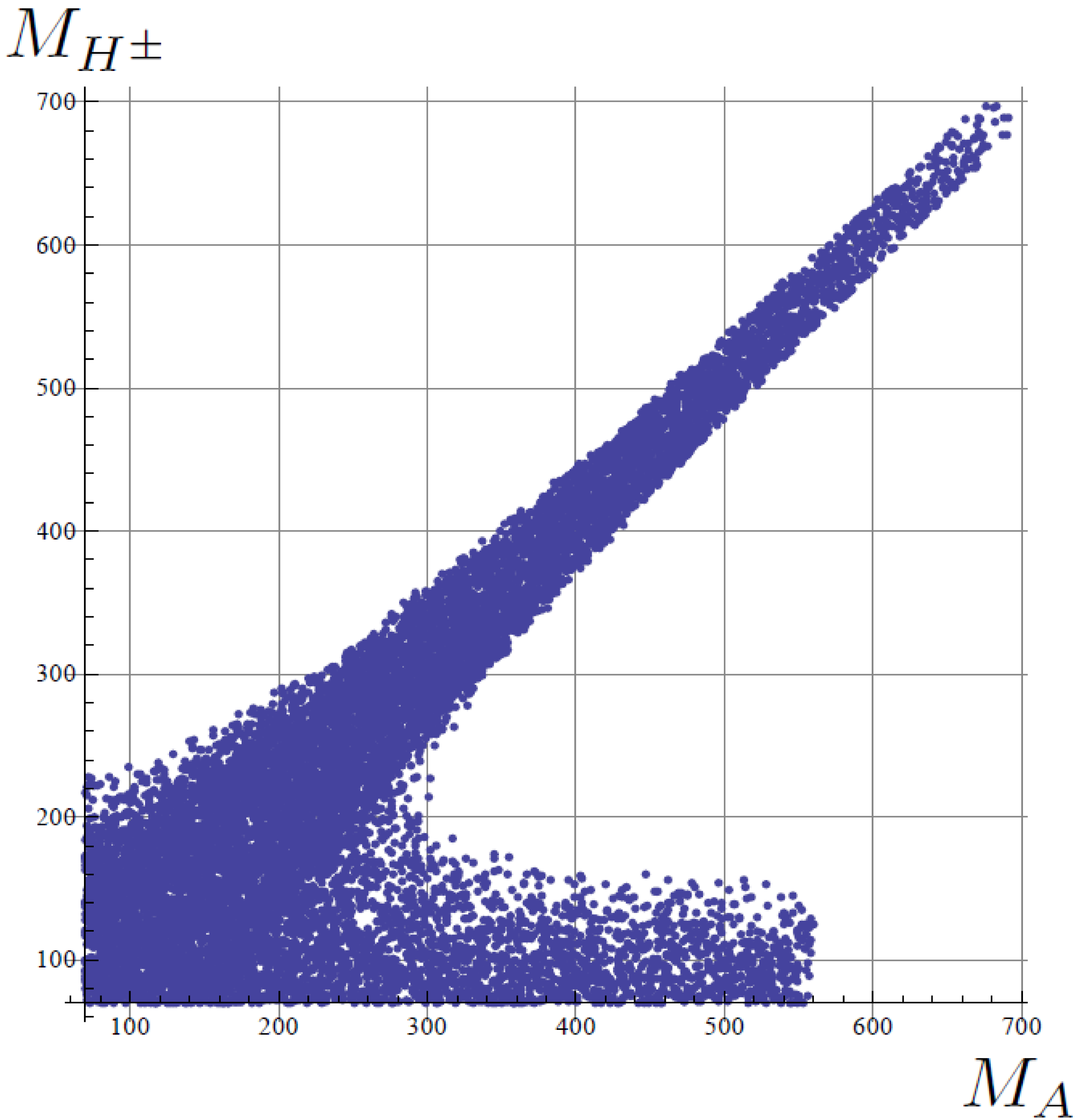

B. Gorczyca 2012 (IDM) Unitarity and S,T constraints

hγγ >1 for MH+ below 200 GeV

Also Arhrib..2012