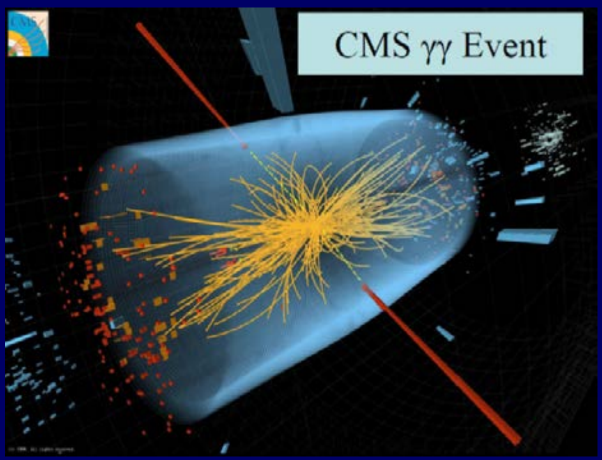
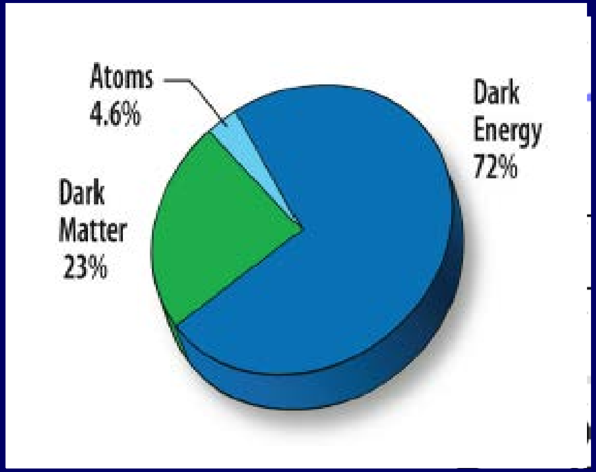
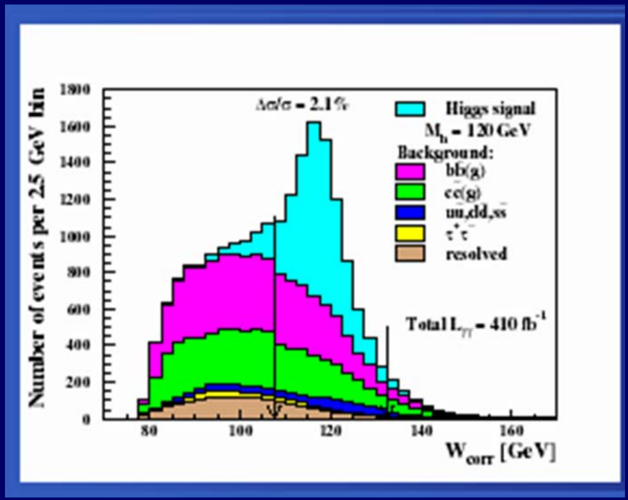
FCAL, Kraków 29.04.2013

Dark Matter and evolution of Universe







Maria Krawczyk,
U. of Warsaw

in collaboration with I. Ginzburg, K. Kanishev (Novosibirsk U.), D.Sokołowska, G. Gil, B. Gorczyca (Świeżewska) J. Bogdanowicz (U. of Warsaw)

„The theory ends here. We need help.
Experiments must clear up this mess.” **M. Veltman** 2003

Nobel 1999 "for elucidating
the quantum structure of EW interactions”

Plan

Higgs: New LHC data

SM-like scenarios at LHC

Inert Doublet Model

h->ɣɣ enhancement

Dark Matter

Temperature evolution of the Universe

Conclusion

LHC

Higgs-like particle with mass125-126 GeV observed at ATLAS+CMS (+Tevatron)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

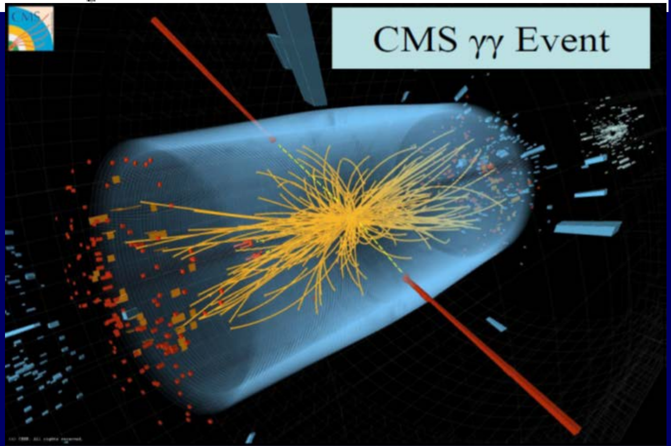
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
ceived 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

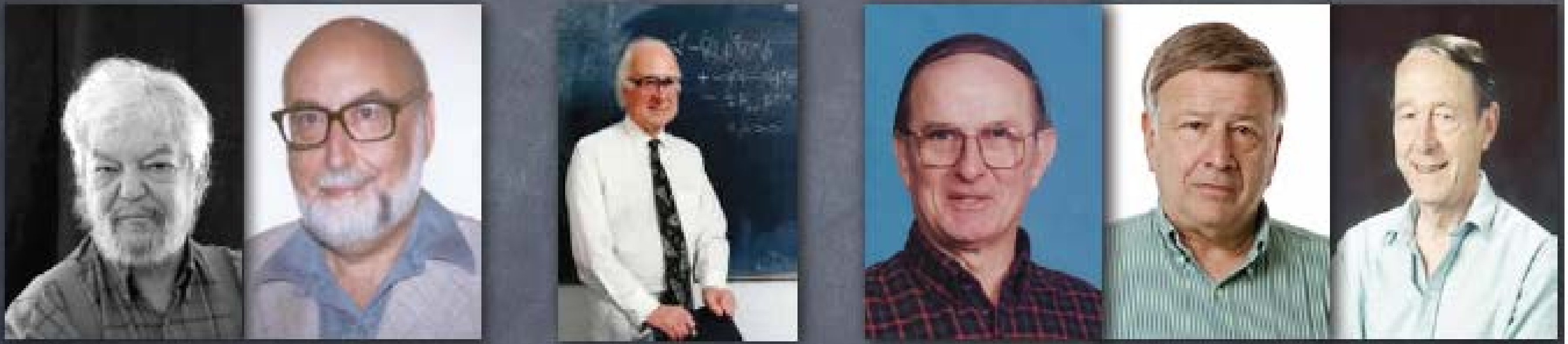
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



Important loop couplings ggH,γγH

2010 Sakurai Prize

... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."



Brout Englert Higgs Hagen Guralnik Kibble

PRL 13, 321-323 (1964) PRL 13, 508-509 (1964) PRL 13, 585-587 (1964)

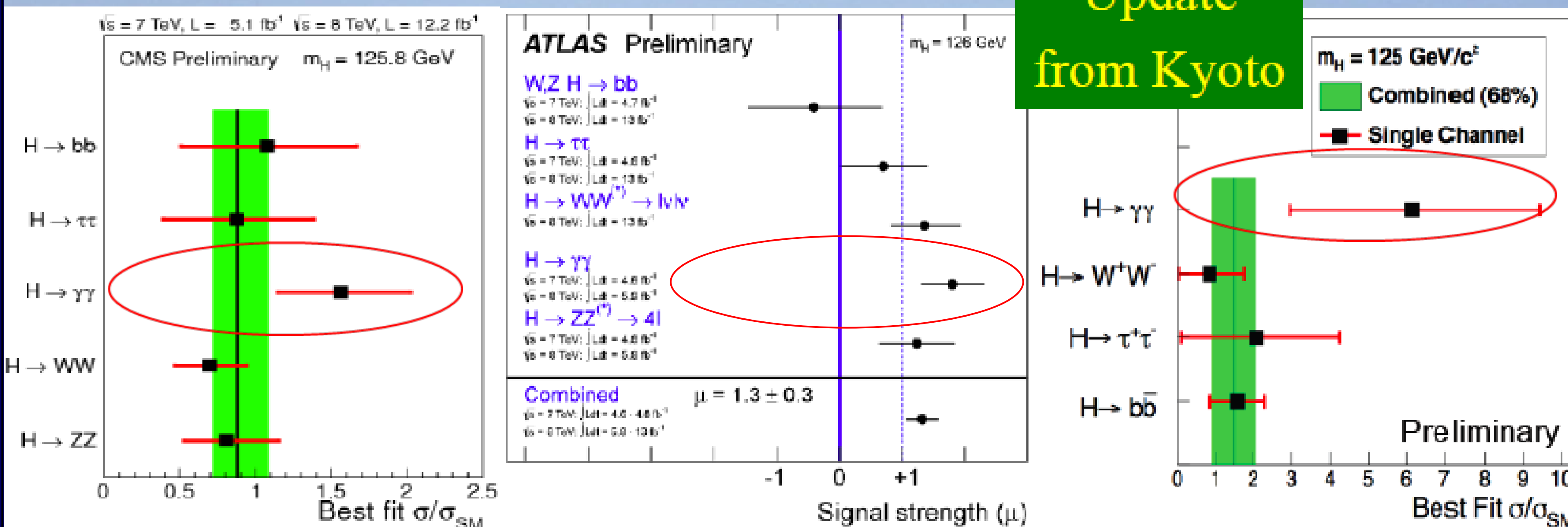
Nambu, Nobel 2008

Za wprowadzenie SSB do fizyki cząstek elementarnych

J. Ellis, 20.11.2012

Summary of the Story so far

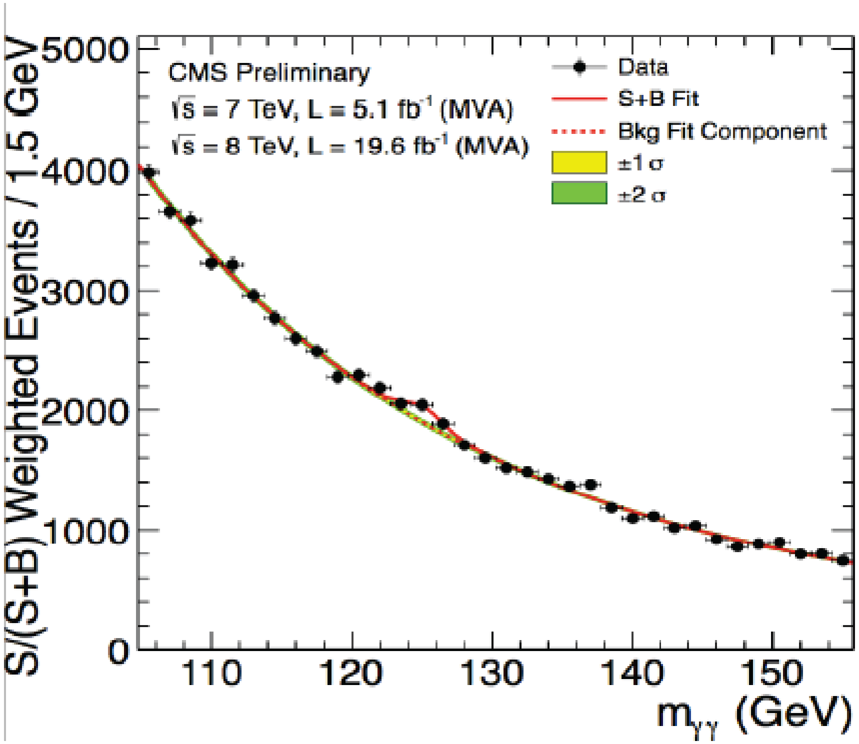
Update from Kyoto



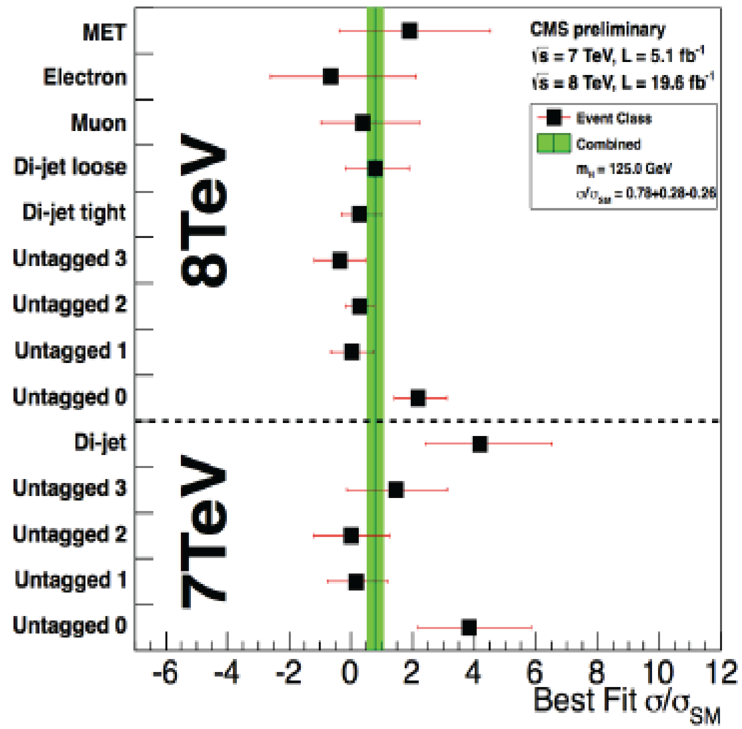
Signals compatible (so far) with the Standard Model

H→γγ: Combined mass plot: 7+8 TeV

MVA mass-factorized



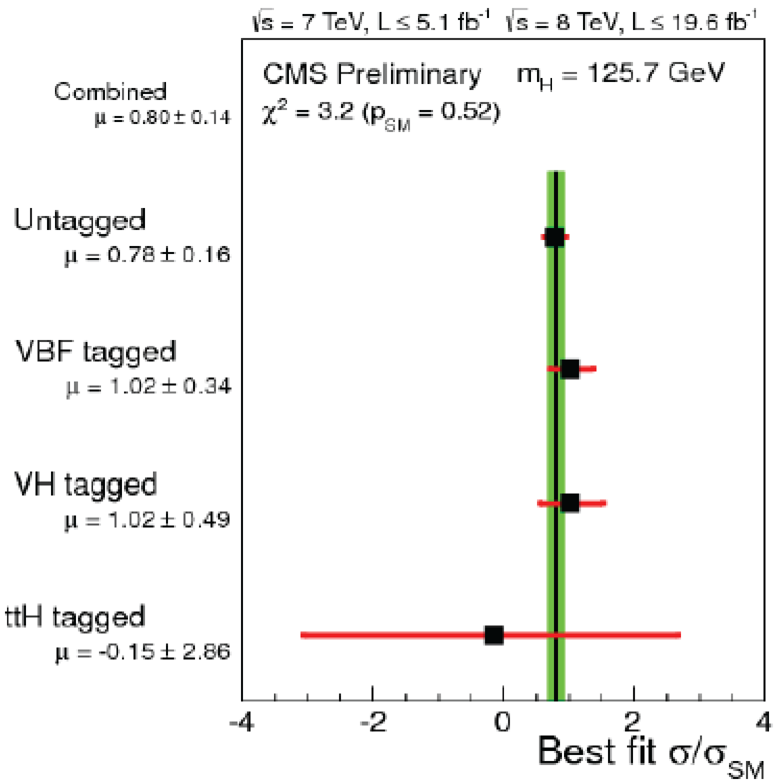
MVA mass-factorized

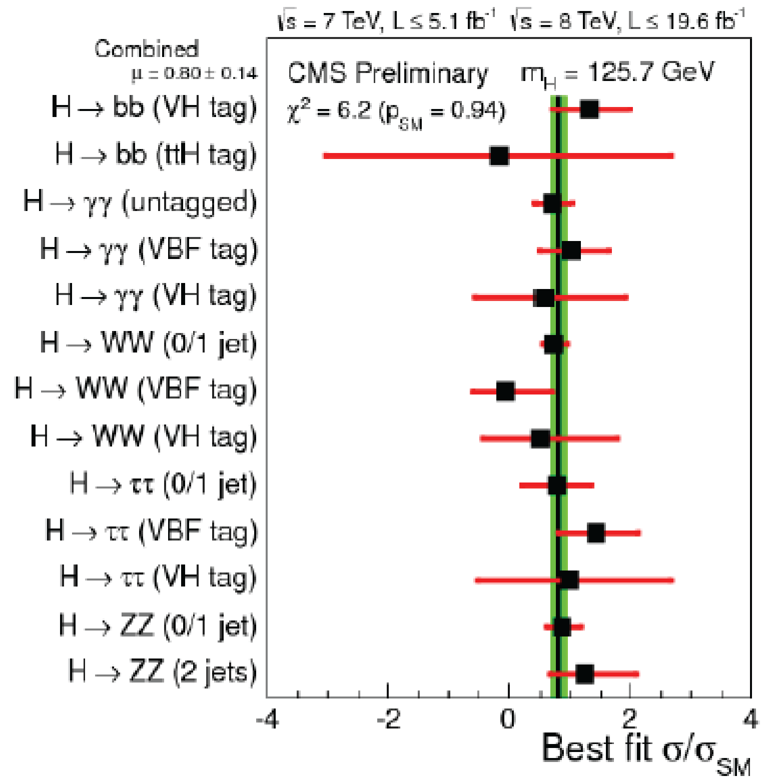


Each event category is **weighted by its S/(S+B)** only for visualization purposes

7+8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

Consistency with SM hypothesis



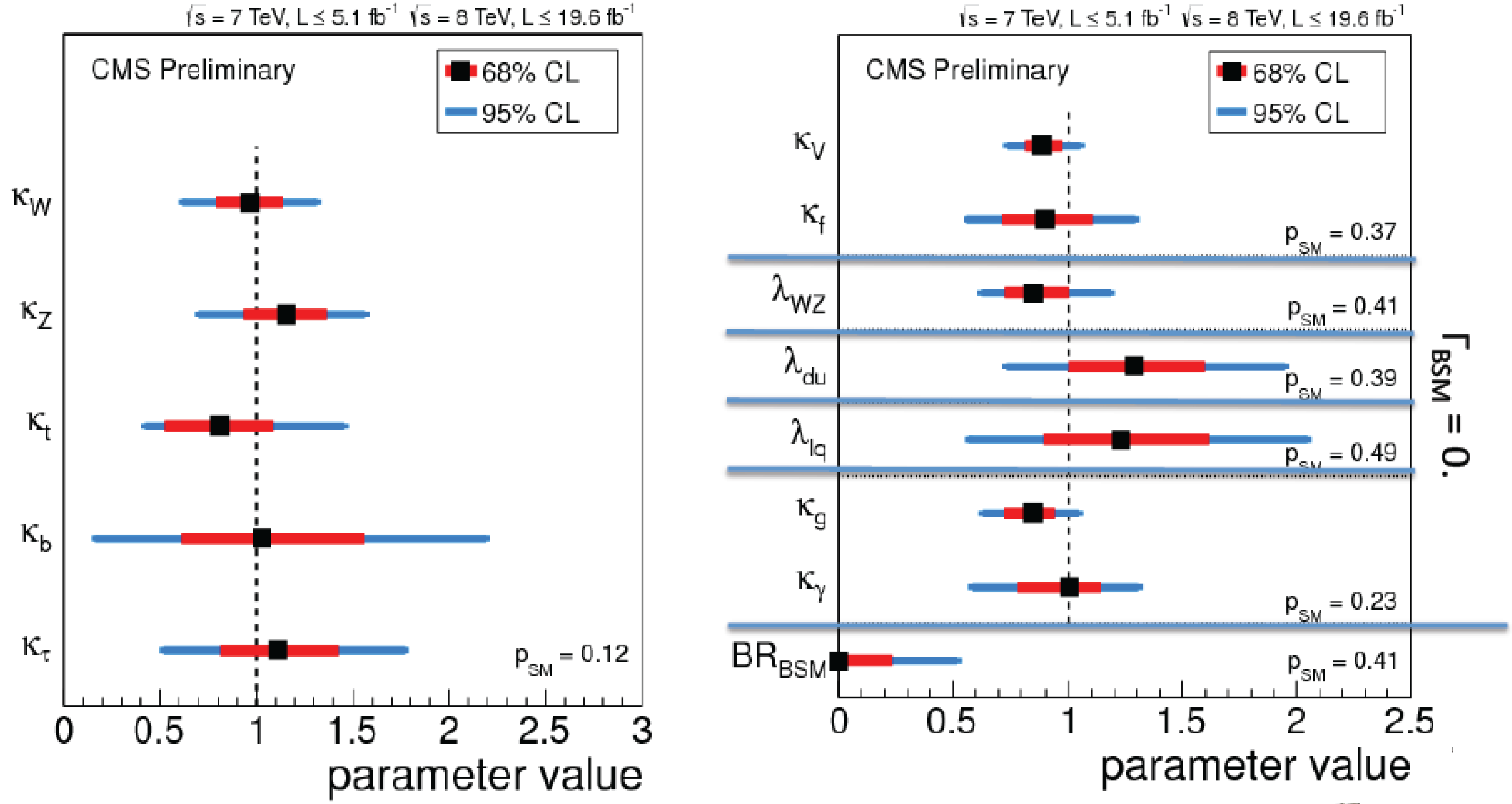


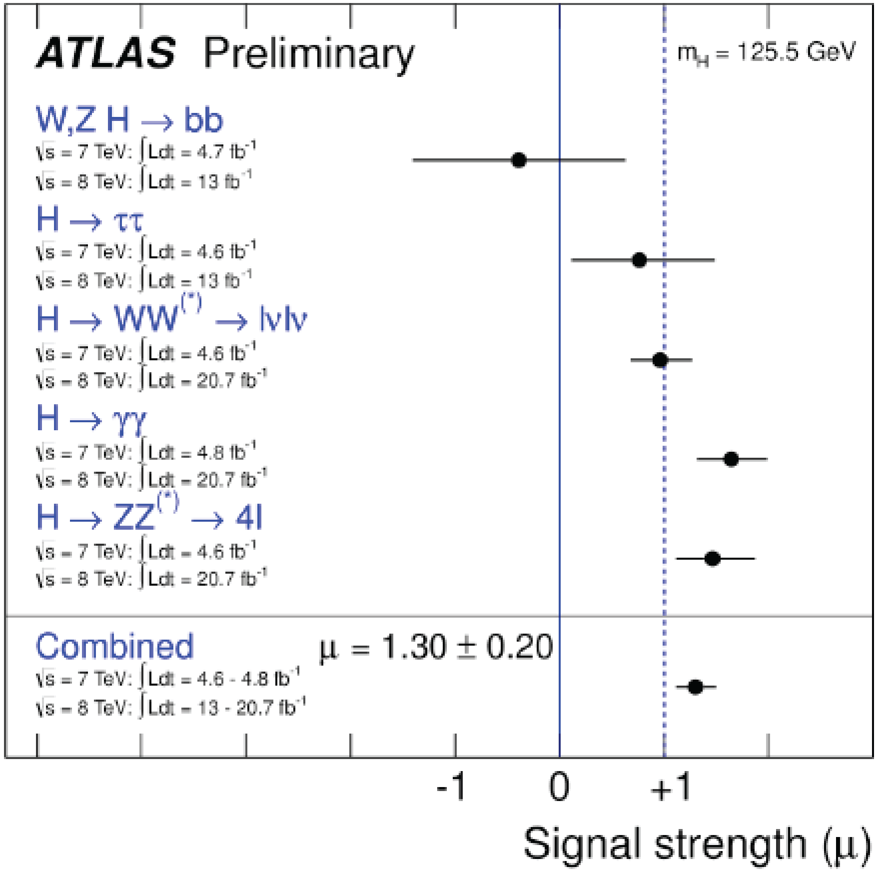
p-value= 0.52 w.r.t. $\mu=1$

$\mu=0.80\pm0.14$

p-value= 0.94 w.r.t. $\mu=1$

Summary of all searches for coupling deviations





LHC: 15.04.2013

Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \rightarrow Vbb$	-0.4 ± 1.0
$H \rightarrow \tau\tau$	0.8 ± 0.7
$H \rightarrow WW^{(*)}$	1.0 ± 0.3
$H \rightarrow \gamma\gamma$	1.6 ± 0.3
$H \rightarrow ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

Combined signal strength μ =1.30 ± 0.13 (stat) ± 0.14 (syst)

Global compatibility between the 5 channels and the SM expectation is 8%

Dependence of the combined μ on the mass is weak
(4% for 124.5 - 126.5 GeV)

SM-like scenarios

- In many models SM-like scenarios are possible

Our definition of SM-like scenario (2013):

Higgs h with mass ~ 125 GeV, SM tree-level couplings*
within exp. accuracy (* up to sign)

No other new particles seen …
(too heavy or too weakly interacting)

Note: Loops ggh, $\gamma\gamma$h, γZh may differ from the SM case

- In models with two SU(2) doublets:
  - MSSM with decoupling of heavy Higgses
  - 2HDM (Mixed), where *both* h or H can be SM-like
  - Intert Doublet Model, where one Higgs h *is* SM-like

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

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

Standard Model

$$V = \tfrac{1}{2}\lambda(\Phi^{\dagger}\Phi)^2 - \tfrac{1}{2}m^2(\Phi^{\dagger}\Phi)$$

Doublet of SU(2): $\Phi = (\varphi^{+}, v + H + i\zeta)^{T}$ $\qquad v^2 = m^2/\lambda$

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

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

SU(2) x U(1) → ?

T.D. Lee 1973

Two Higgs Doublet Models

Two doublets of SU(2) (Y=1, ρ =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 hold (for relative couplings to SM χ)

2HDM Lagrangian $L=L_{SM}+L_H+L_Y$

Potential (Lee'73)

with $L_H=T-V$

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

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

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

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

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: λ_6, λ_7, $m^2_{12}=0$ (NO CP violation)

Possible extrema (vacuua)

for V with Z_2 symmetry $\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$ (D symmetry)

The most general extremum state $\Phi_1 \to \Phi_S \quad \Phi_2 \to \Phi_D$

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

v_S, v_D, u - real

v_S, $u \geq 0$

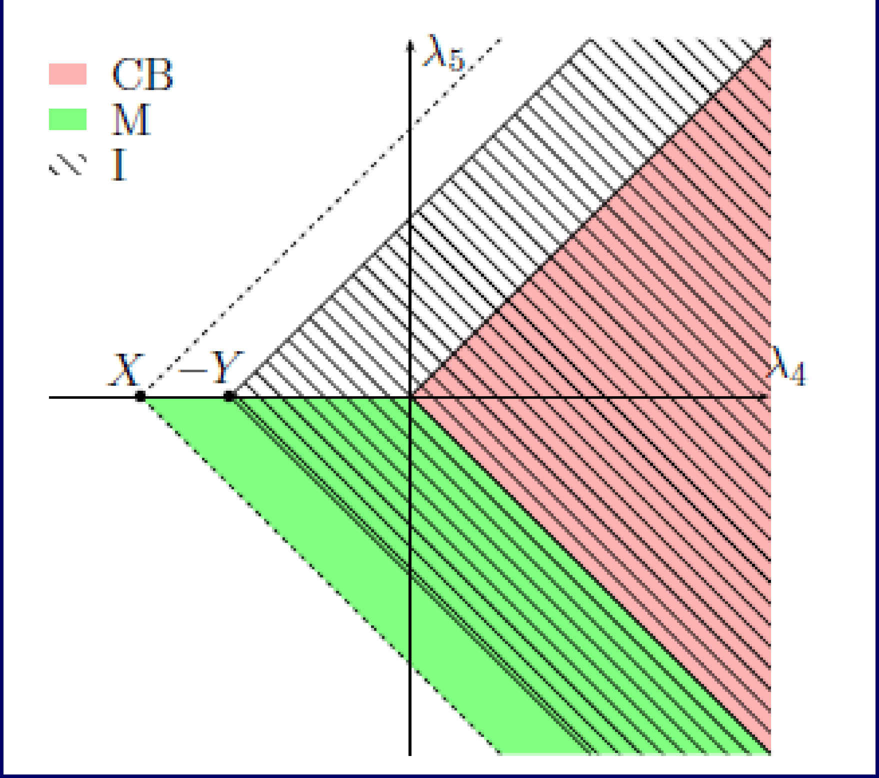
$v^2 = v_S^2 + v_D^2 + u^2$

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

D-symmetric potential - vacua

Stable vacuum (positivity) $\lambda_4 \pm \lambda_5 > - X$, $X = \sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0$

$$\lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R + 1 > 0, \quad R_3 + 1 > 0$$
$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad R = \lambda_{345}/\sqrt{\lambda_1 \lambda_2}, \quad R_3 = \lambda_3/\sqrt{\lambda_1 \lambda_2}.$$



$Y = M_{H+}^2\ 2/v^2|_{\text{Inert}}$

Neutral vacua

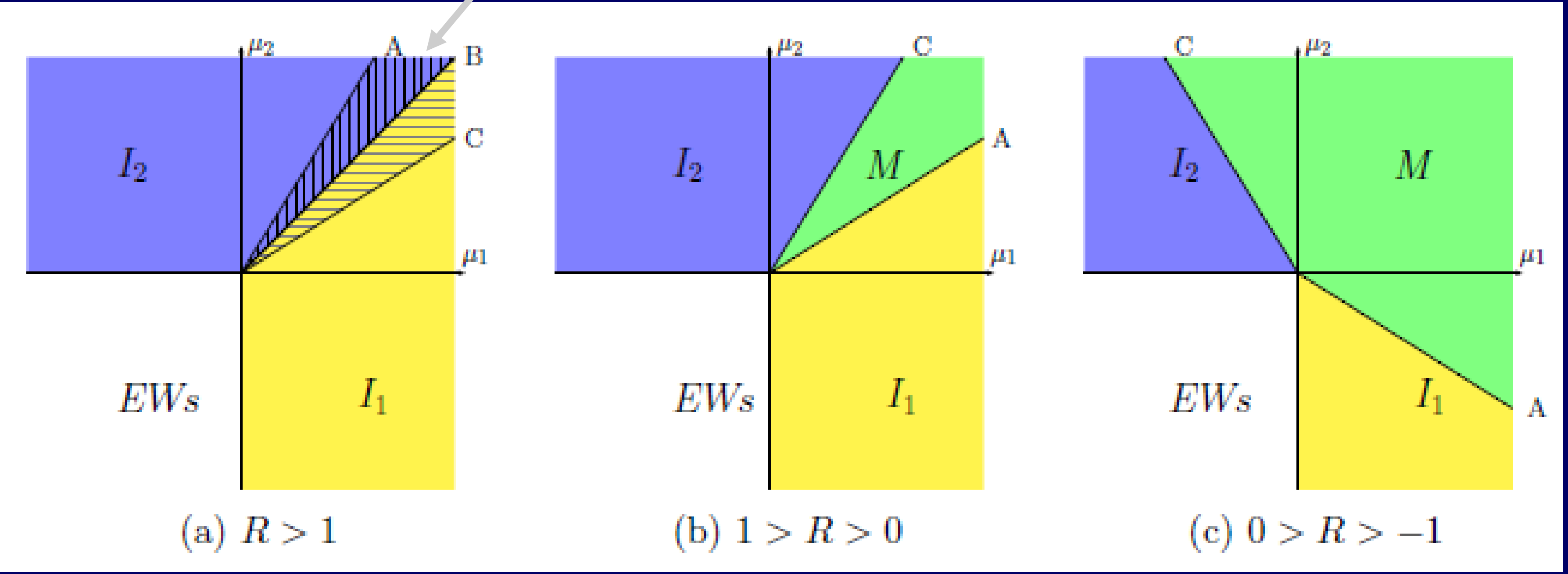
- Mixed M [v1, v2 ≠ 0]
- Inert I1 (I2) [v1(v2) ≠ 0]
- Charged breaking vacuum CB

Inert overlaps both with Mixed and CB !

Phase diagrams for D-sym. V

coexistence of minima

$$\mu_1 = \frac{m_{11}^2}{\sqrt{\lambda_1}}, \quad \mu_2 = \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$



Inert (I1) vacuum for Mh=125 GeV →

$$\mu_1 = \frac{m_{11}^2}{\sqrt{\lambda_1}},$$

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:

Today

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

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

The Inert Doublet Model: An Archetype for Dark Matter, Lopez Honorez,..Tytgat ..07

Inert Doublet Model

Ma'2006,.Barbieri 2006, Dolle,Su, Gorczyca(Świeżewska), MSc 2011 1112.4356, 1112.5086, Posch, 2011, Arhrib..2012

- SM-like h,

  $M^2_h = m_{11}^2 = \lambda_1 v^2 = (125\text{ GeV})^2$

- Dark scalars

  - masses depend on m_{22}^2
  - dark scalars D interact always in pairs!

λ_{345}

$$M^2_{H^+} = -\frac{m^2_{22}}{2} + \frac{\lambda_3}{2} v^2$$

$$M^2_H = -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2} v^2$$

$$M^2_A = -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2} v^2$$

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! *(→ DM ?)*

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

IDM – scan *(B. Świeżewska 2012)*

Constraints: M_h=125 GeV (λ_1=0.25)
pert. vacuum stability,
conditions for Inert I1 vacuum
perturbative unitarity condition
EWPT →
LEP (LHC)

H = DM
$0 > \lambda_{45} = \lambda_4 + \lambda_5$

$$S = 0.03 \pm 0.09$$
$$T = 0.07 \pm 0.08$$
$$\rho = 87\%$$

$$\begin{aligned} M_h &= 125\,\mathrm{GeV}, \\ 70\,\mathrm{GeV} \leqslant M_{H^\pm} &\leqslant 800\,\mathrm{GeV}\,(1400\,\mathrm{GeV}), \\ 0 < M_A &\leqslant 800\,\mathrm{GeV}\,(1400\,\mathrm{GeV}), \\ 5 \leqslant M_H &< M_A, M_{H^\pm}, \\ -25 \cdot 10^4\,\mathrm{GeV}^2\,(-2 \cdot 10^6\,\mathrm{GeV}^2) \leqslant m_{22}^2 &\leqslant \sqrt{\lambda_2} M_h v \lesssim 9 \cdot 10^4\,\mathrm{GeV}^2. \\ 0 < \lambda_2 &\leqslant 10. \end{aligned}$$

narrow (wide) range

condition for I_1

Pert. unitarity constraints on lambda’s

B. Gorczyca, MSc Thesis, July 2011

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

(hold for Mixed as well)

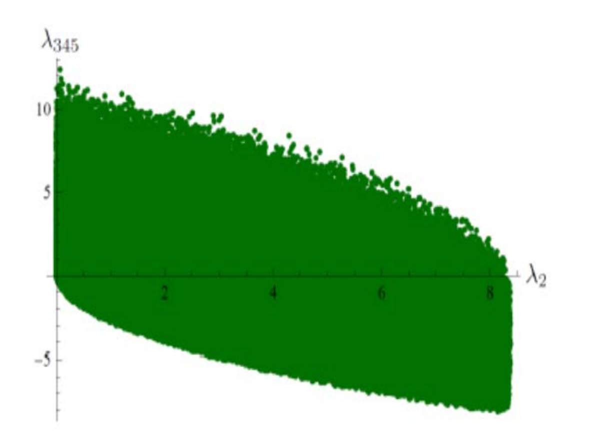
and for combinations

Couplings for dark particles in IDM

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

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

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



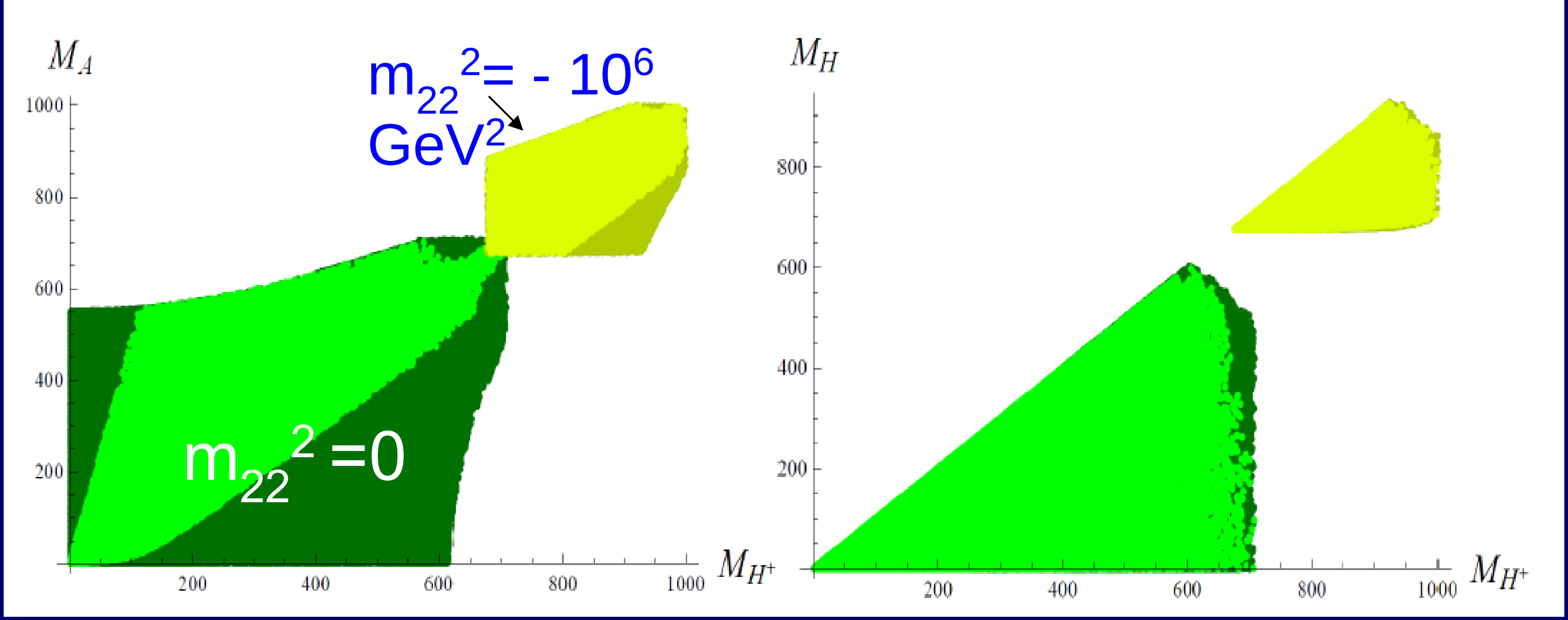
Inert Doublet Model with Mh=125 GeV

Analysis based on unitarity, positivity, EWPT constraints

Gorczyca'2011-12

$m_{22}^2 = 0$

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

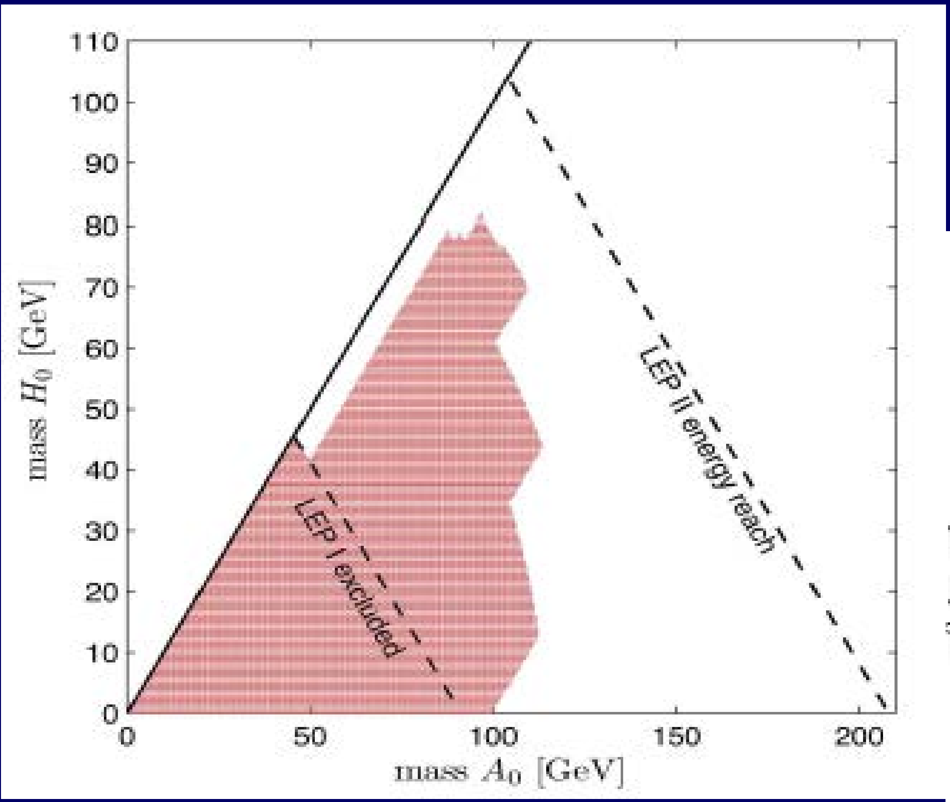


valid up to $|m_{22}^2| = 10^4 \mathrm{GeV}^2$

EWPT (pale regions)

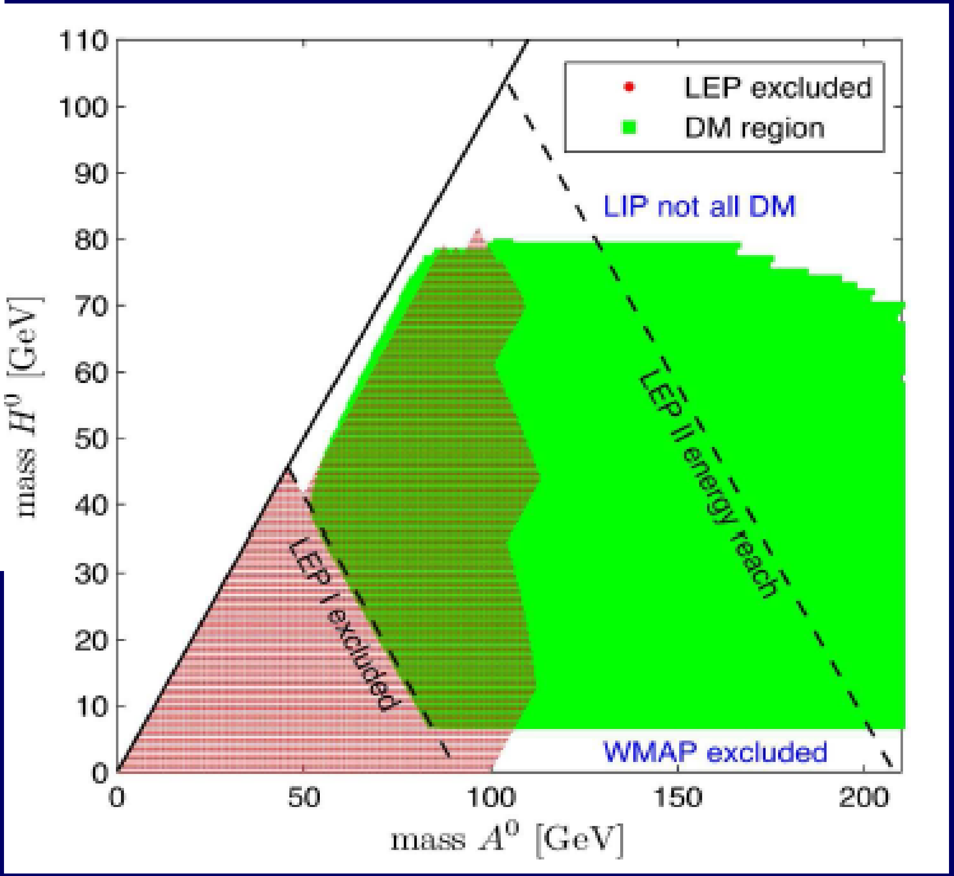
IDM: LEP II exclusion (masses H vs A)

Lundstrom... hep-ph/0810.3924

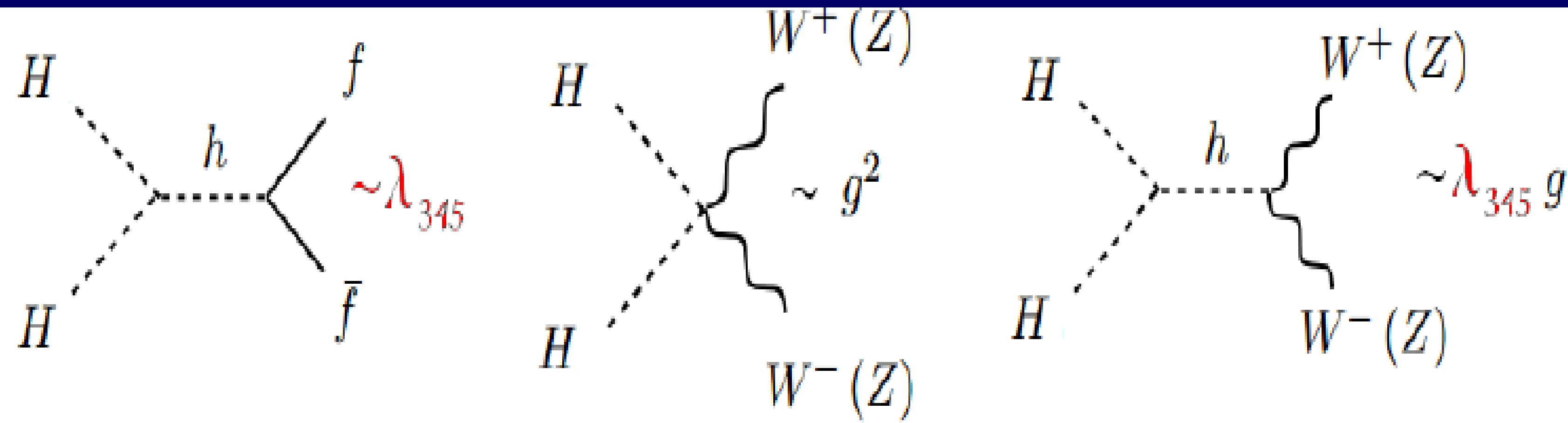


DM=H

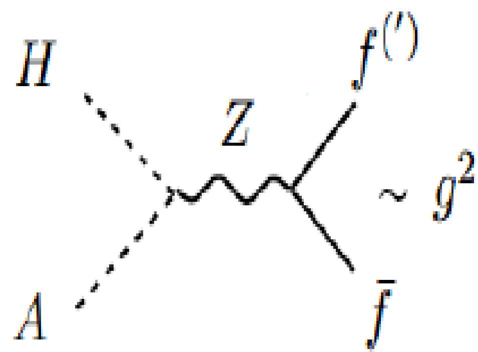
LEP II + WIMAP



Relic density - processes



- koanihilacja (gdy $M_A - M_H \lesssim 10$ GeV):



IDM constraints: LEP + S.T.U + DM relic density

3σ limit $0.1018 < \Omega_{DM} h^2 < 0.1234$

constraints for masses and $D_H D_H h_S$, $D_H D_H h_S h_S$ couplings

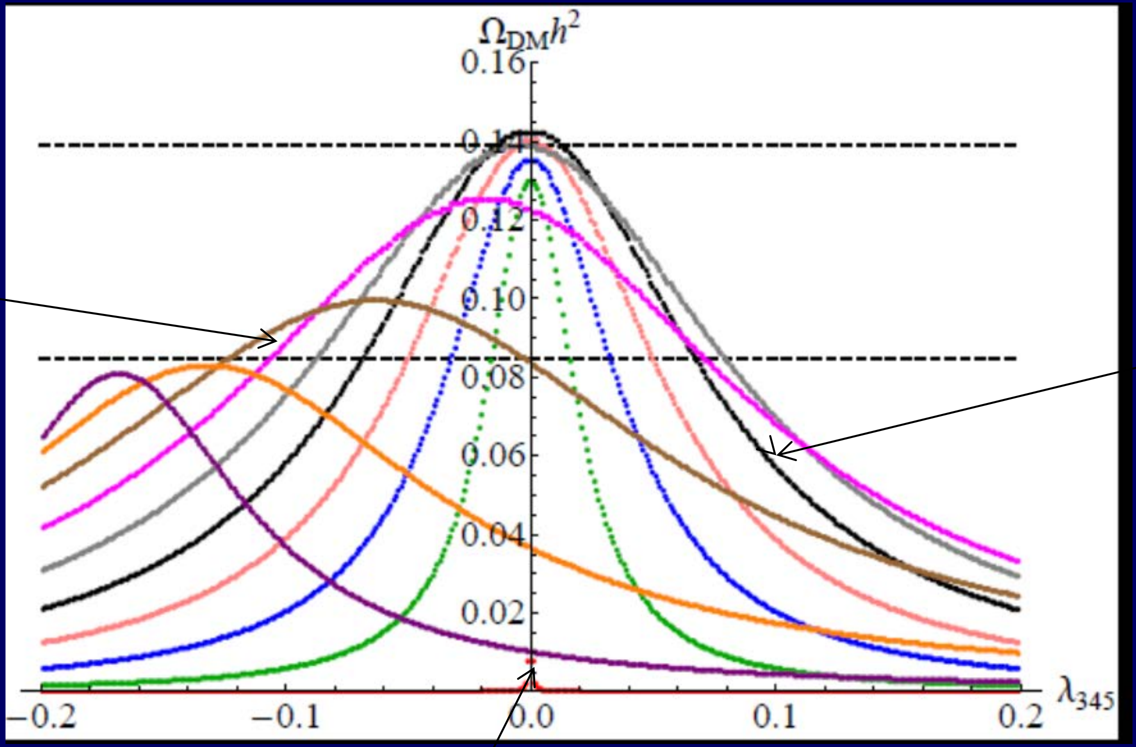
D. Sokołowska 2010
using MicroOmega's

Dark scalars:

- **low DM mass** $M_{D_H} \lesssim 10$ GeV,
  large mass splittings: $\Delta(D_A, D_H)$ and $\Delta(D^\pm, D_H)$
- **medium DM mass** $M_{D_H} \approx (40 - 160)$ GeV,
  large $\Delta(D^\pm, D_H)$, small or large $\Delta(D_A, D_H)$
- **high DM mass** $M_H \approx (500 - 1000)$ GeV,
  small $\Delta(D_A, D_H)$ and $\Delta(D^\pm, D_H)$

Lopez Honorez et al. '07, Hambye et al. '08,'09, Agrawal et al. '09, Dolle et al. '09, Arina et al. '09, ...

Relict density for DM with mass 62,64,…,80 GeV



76

HA coannihilation
Δ [50,8]

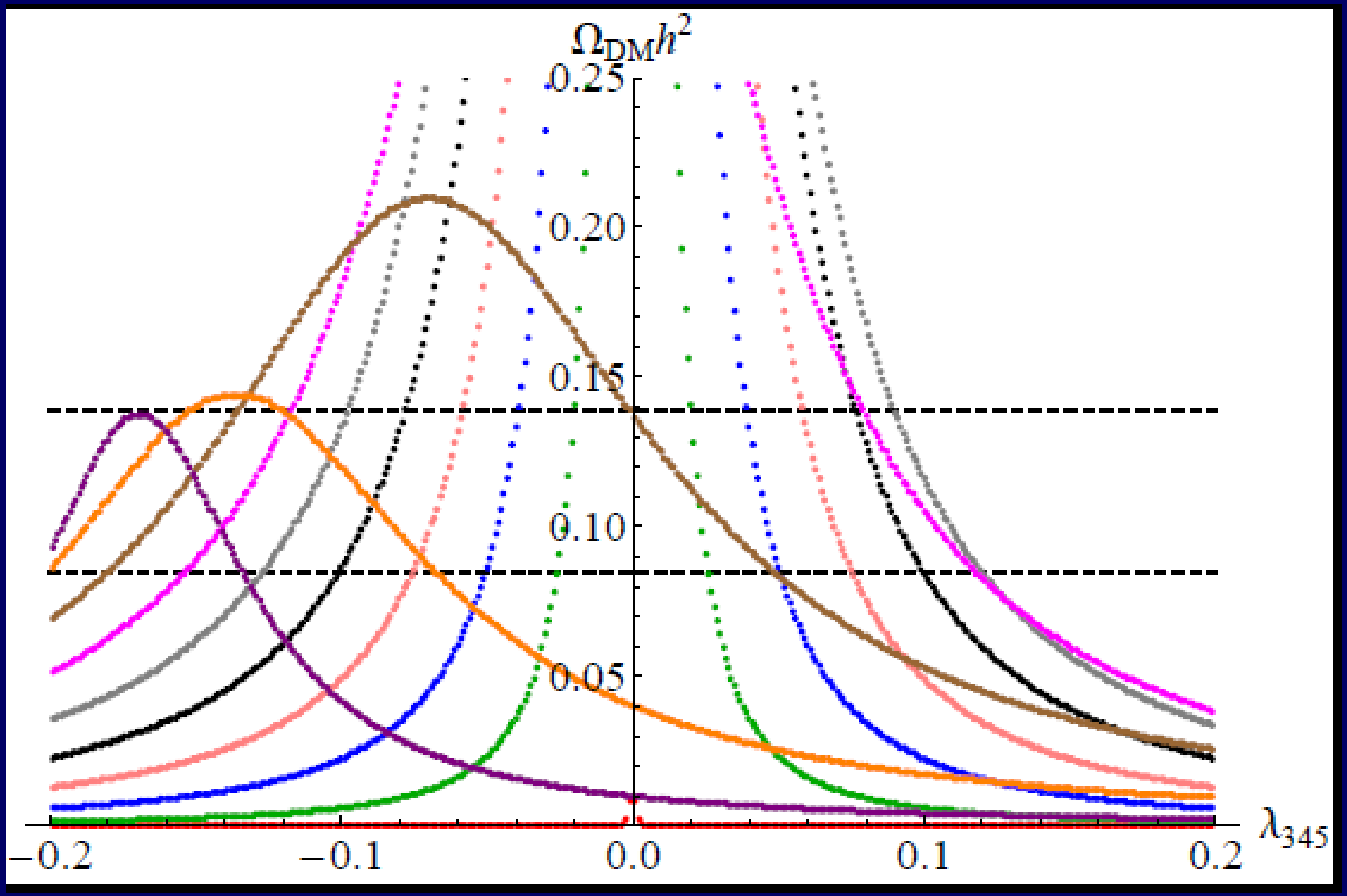
70 GeV

62 GeV

above 76 GeV asymmetry due to annihilation to gauge bosons

D. Sokołowska, 2013

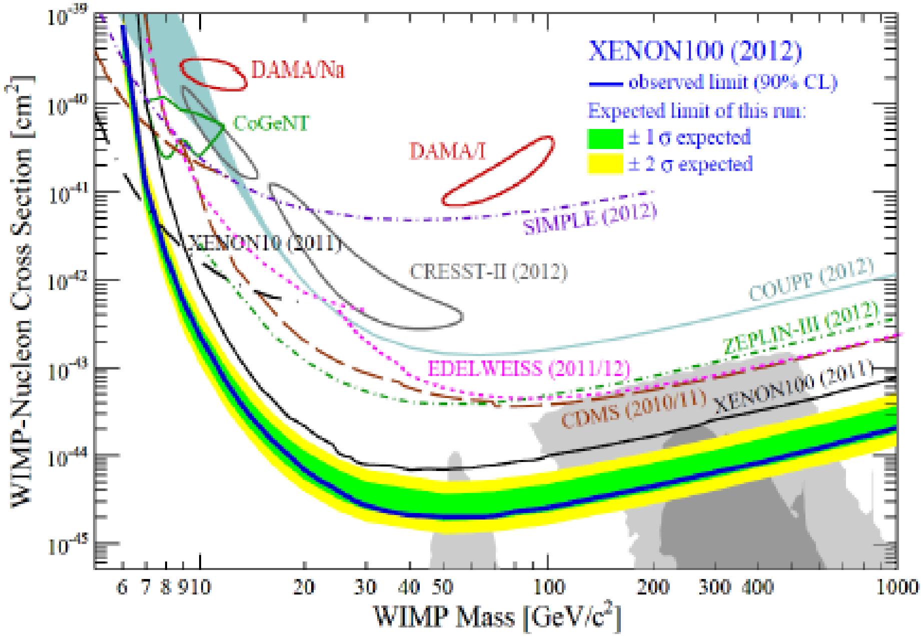
Relict density for DM with mass 62,64,…,80 GeV



no HA coannihilation
Δ= [50,50]

IDM constraints: Direct detection experiments

dark matter – nucleon stattering → DM-quark interactions



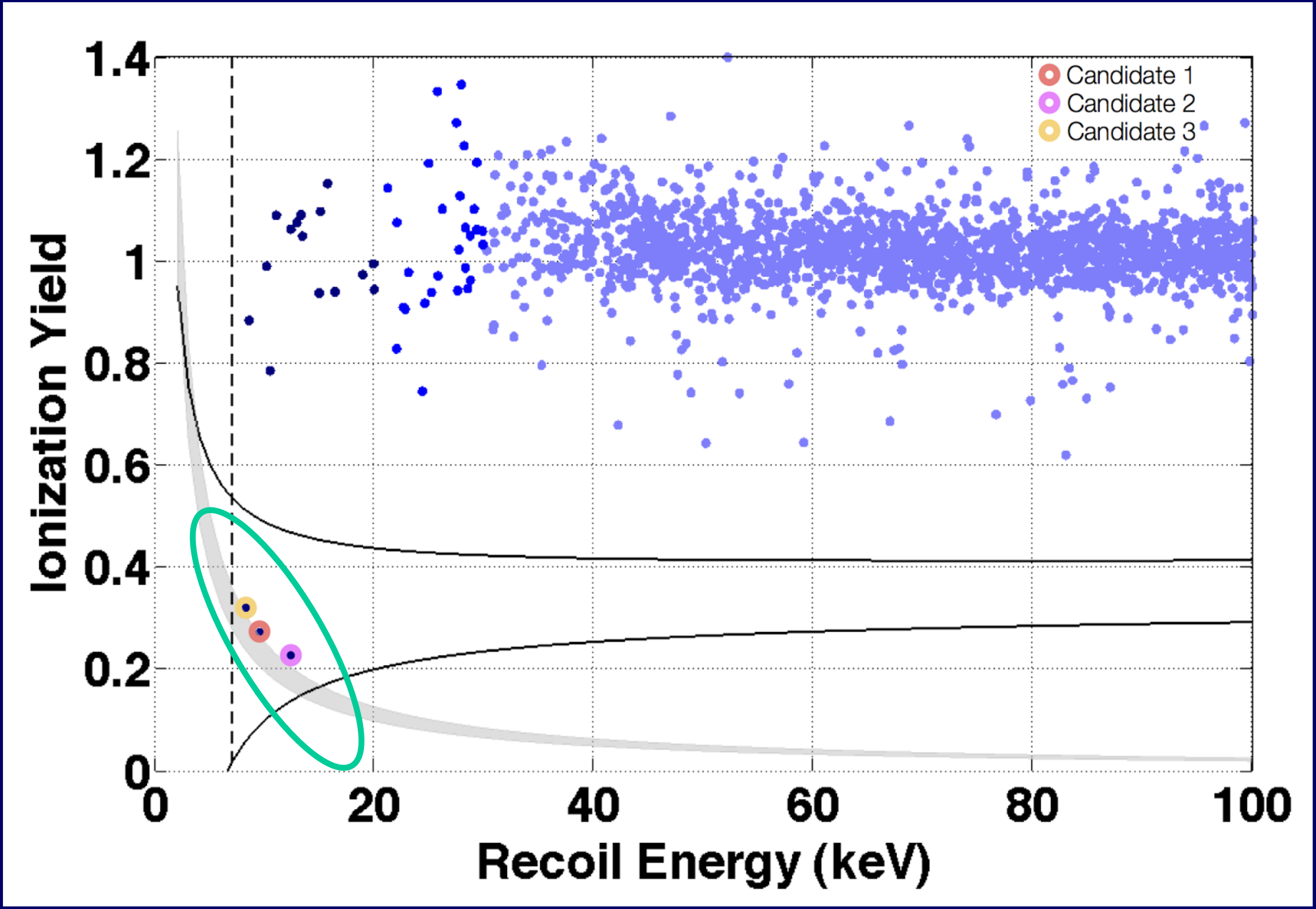
detection signals (DAMA, CoGeNT, CRESST-II) point to the light DM

but there is no agreement with

exclusion limits (XENON100, CDMS-II)

arXiv:1109.0702,1207.5988[astro-ph]

CDMS Collaboration], arXiv:1304.4279 [hep-ex]



2-photon decay rate of the SM-like scalar

[J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B 106 (1976) 292, M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, Sov. J. Nucl. Phys. 30 (1979) 711 [Yad. Fiz. 30, 1368 (1979)], P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021]

$R_{\gamma\gamma}$ – 2-photon decay rate

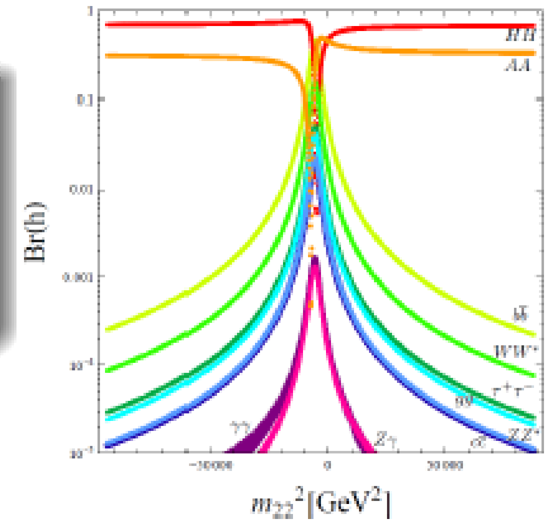
$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

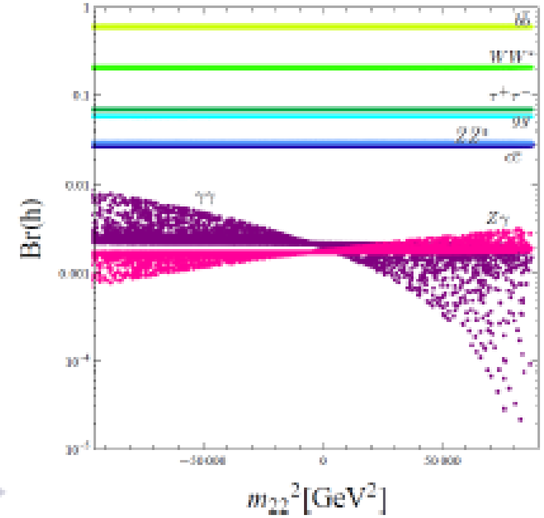
Two sources of deviation from the SM:

- invisible decays $h \to HH$, $h \to AA$ in $\Gamma(h)^{IDM}$
- charged scalar loop in $\Gamma(h \to \gamma\gamma)^{IDM}$

$\sim \lambda_3$

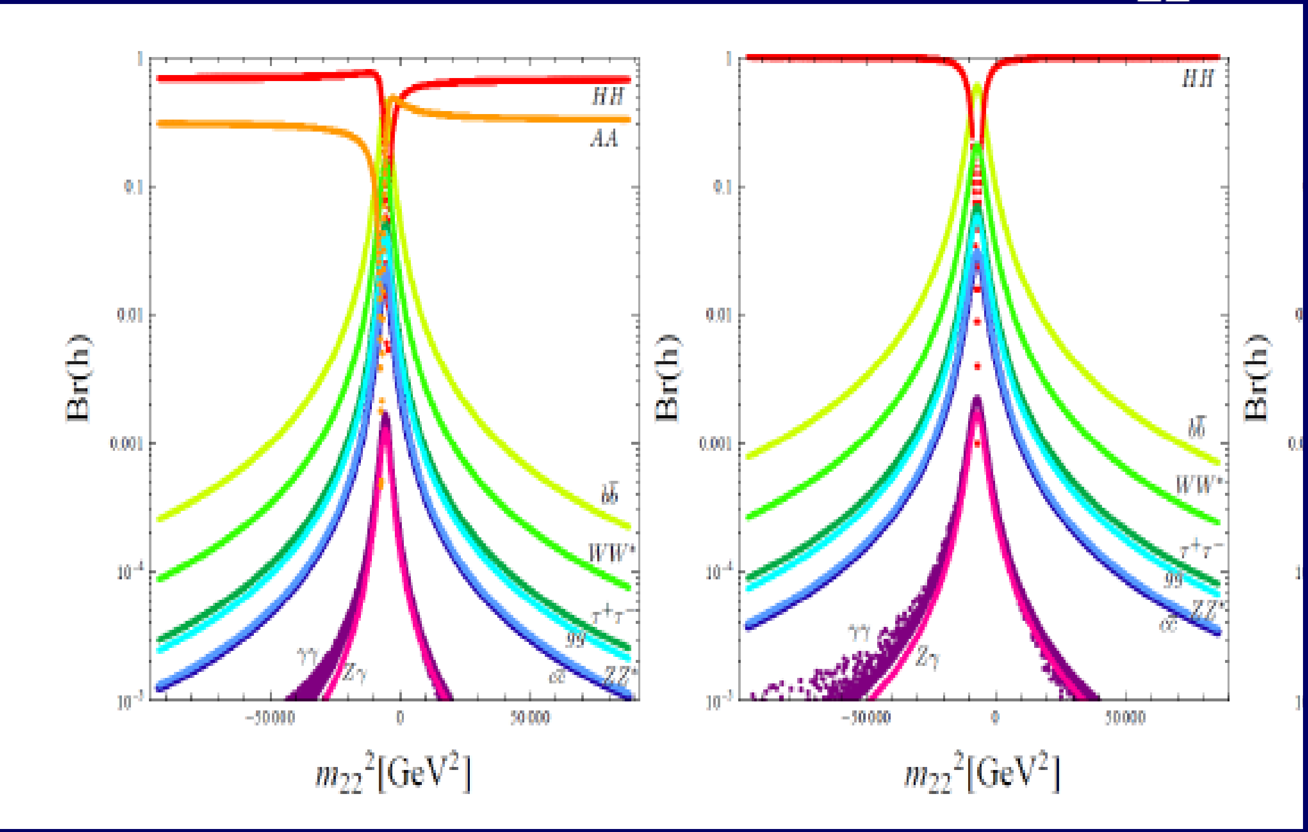
$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$





Br of Higgs boson (125 GeV)
HH and AA channels open or closed

for positive and negative m_{22}^2 *for positive as Arhrib..'12*



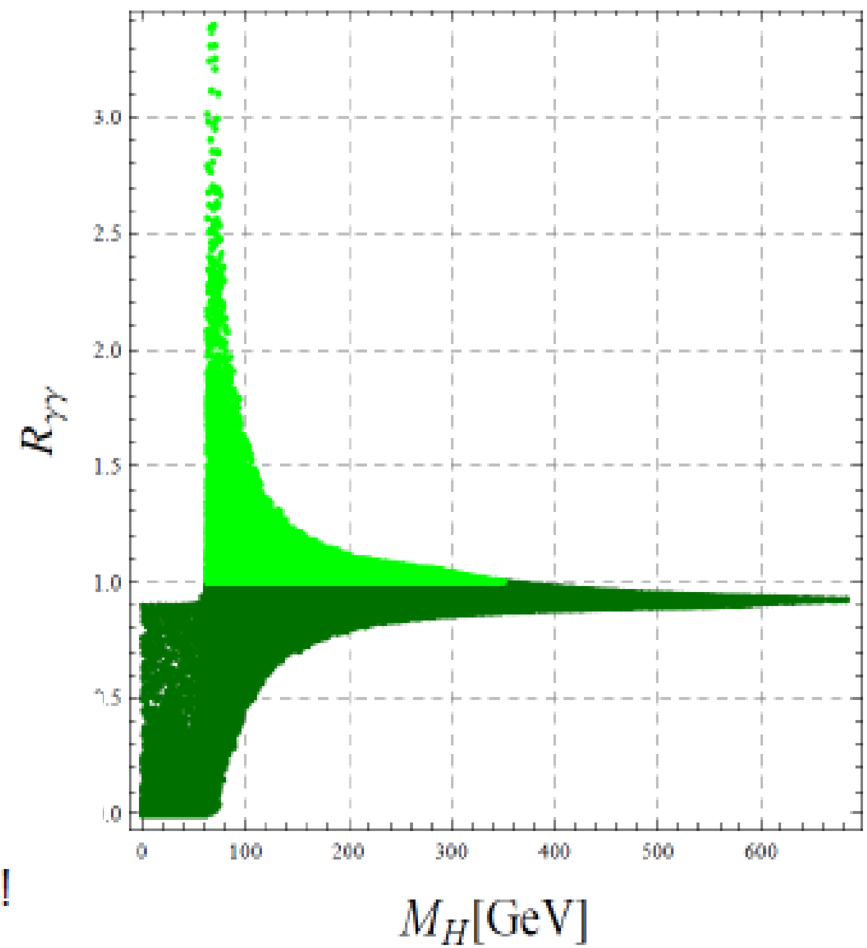
H(50 GeV),A(60 GeV) both open

H open H(60 GeV),A(>63 GeV)

$R_{\gamma\gamma}$ vs Dark Matter mass

[see also: A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021]

- Invisible channels open $\Rightarrow$ no enhancement in $h \to \gamma\gamma$ possible
- Enhanced $R_{\gamma\gamma}$ for $M_H, M_{H^\pm}, M_A > 62.5$ GeV
- If $R_{\gamma\gamma} > 1.3$
  - 62.5 GeV $< M_{H^\pm}, M_H \lesssim 135$ GeV
    $\Rightarrow$ Only medium masses of DM!
    $\Rightarrow$ Light charged scalar!
  - constrained $\lambda_{hHH}, \lambda_{hH^+H^-}$

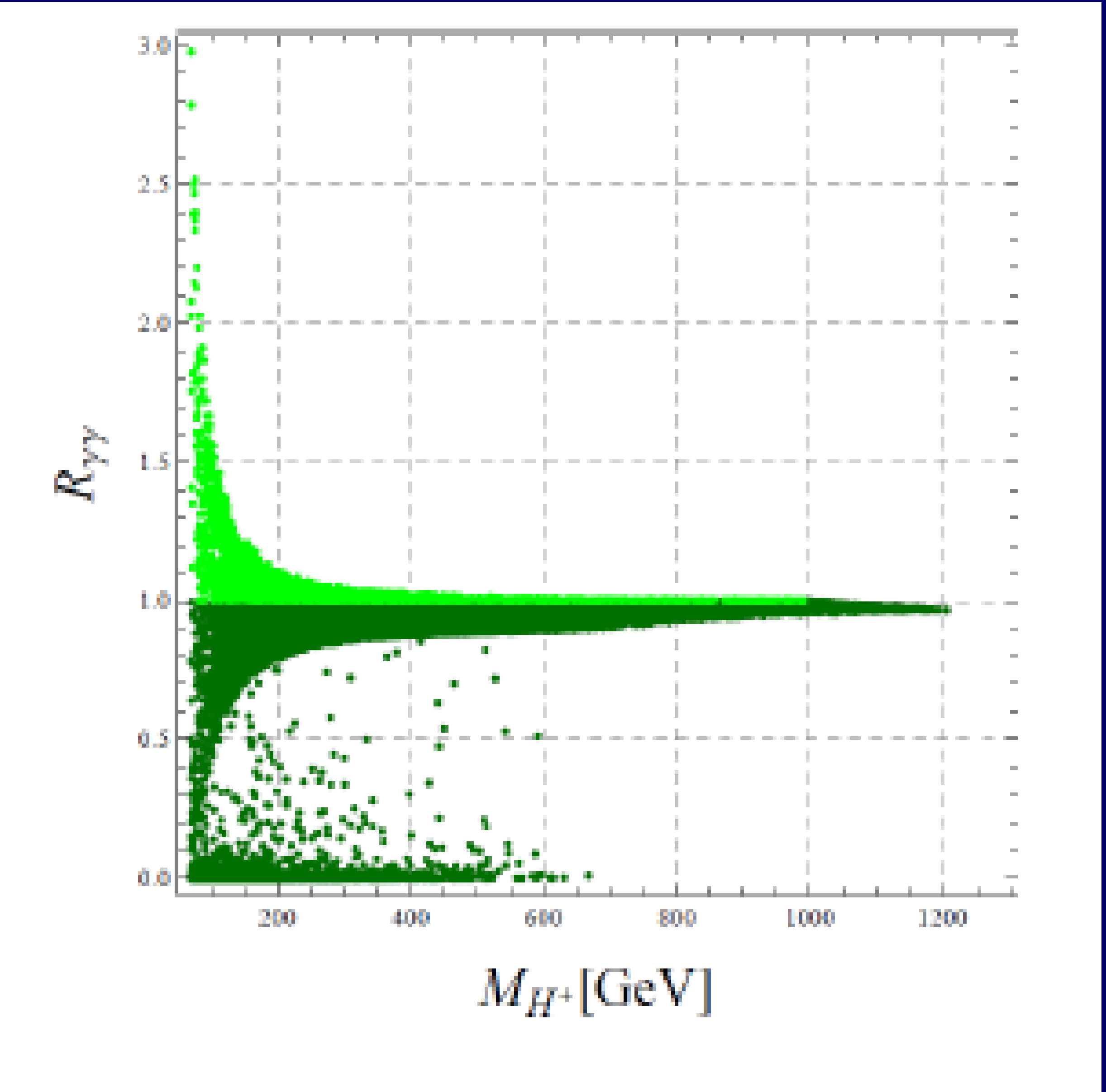


Dependence on MH+

Enhancement for negative

h H+H- ~ λ_3

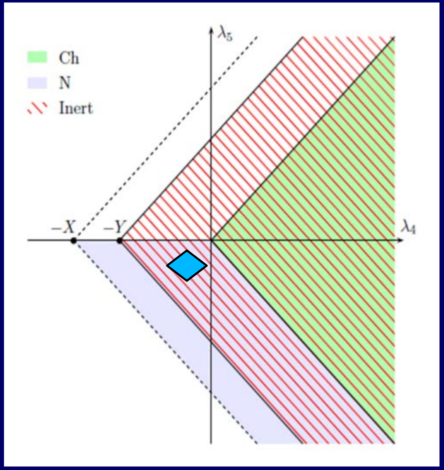
(also $\lambda_{345}<0$)



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

Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev,MK, Sokołowska PRD 2010,
Sokołowska 2011

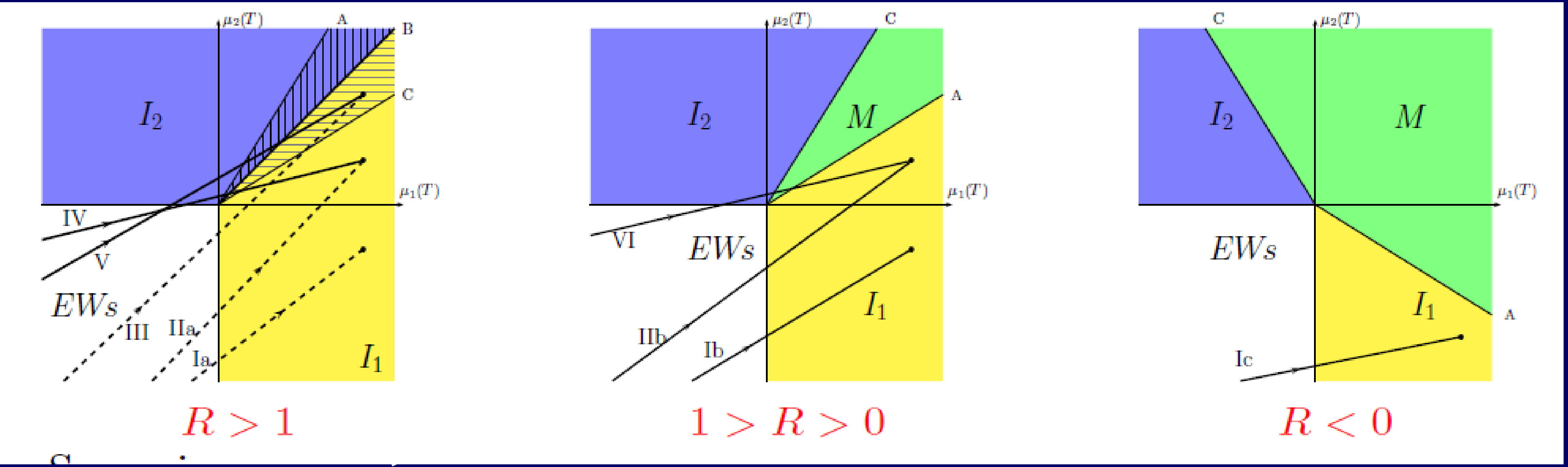
We consider 2HDM with an explicit D symmetry assuming that today the Inert Doublet Model describes reality. In the simplest approximation only *mass terms* in V vary with temperature like T^2, while λ's are fixed



Various evolution from EWs to Inert phase possible in one, two or three steps, with 1st or 2nd type phase transitions...

Evolution of vacua on phase diagram (μ_1,μ_2)

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



Tree regions of R

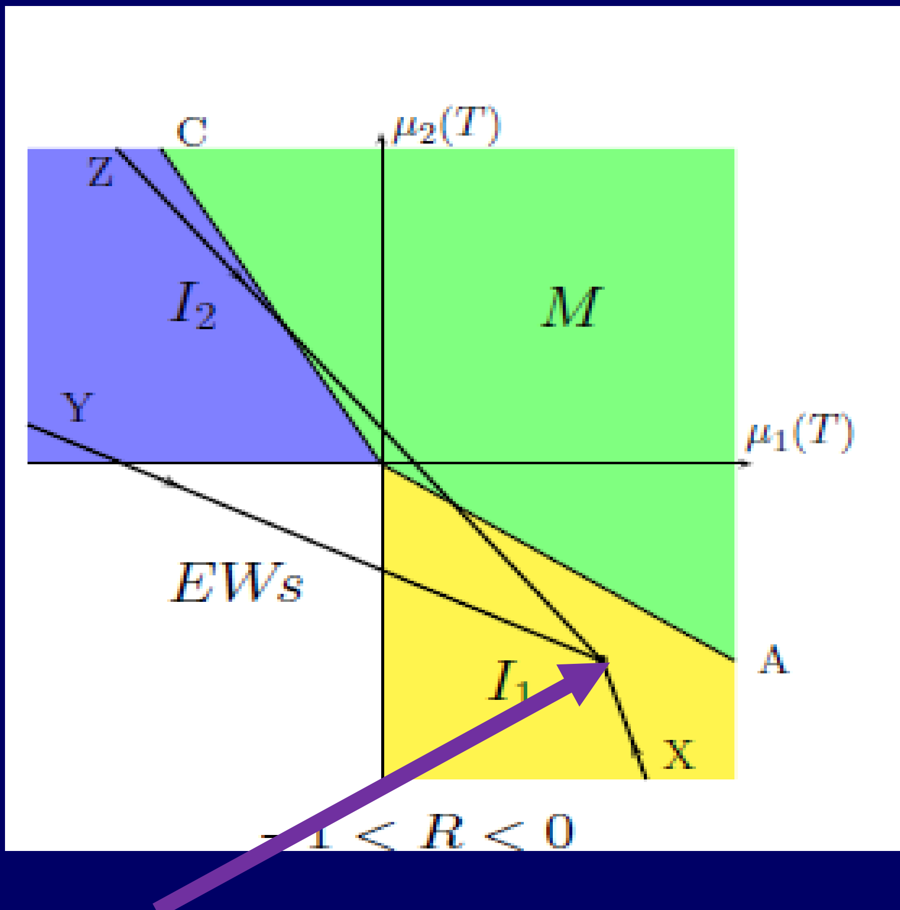
$$R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}$$

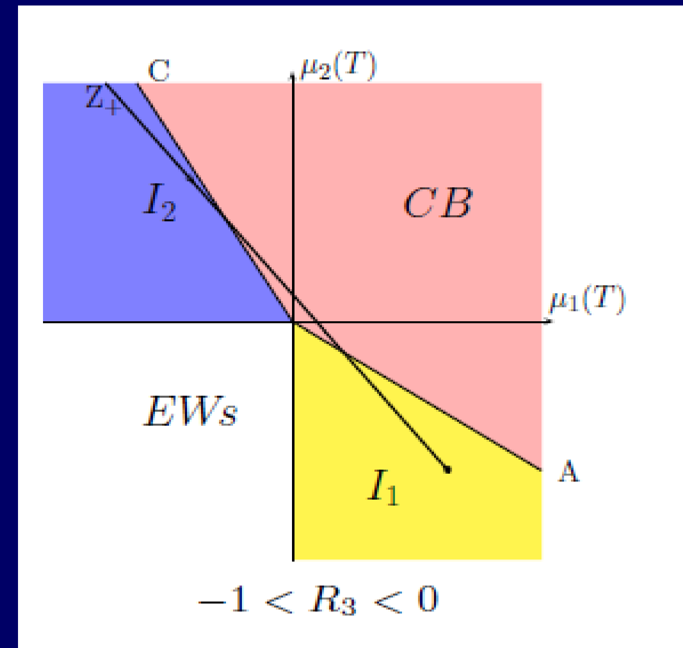
T2 corrections
→ rays from EWs phase to Inert phase

stability condition

$$R + 1 > 0$$

Nonrestoration of EW symmetry: R <0





Charged breaking phase

Only one ray with EW restoration in the past (in one step 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)

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

Can in IDM strong first -order phase transition – needed for baryogenesis ?

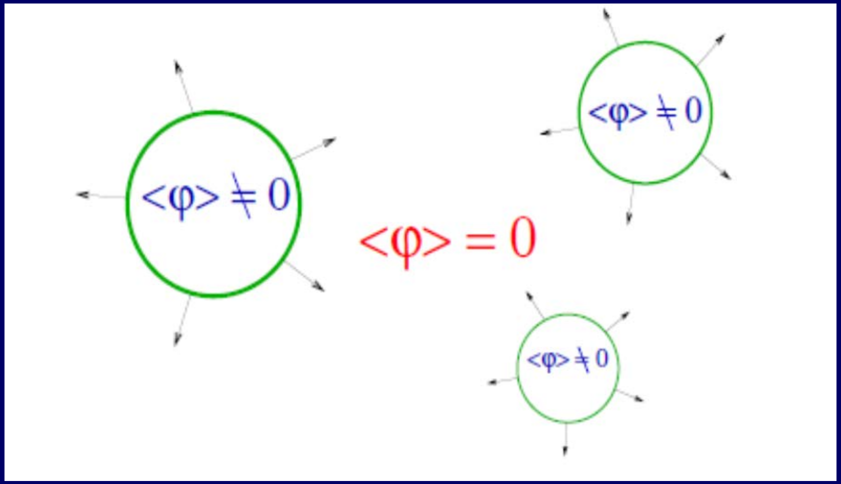
Gil,Chankowski,Krawczyk: Inert Dark Matter and Strong Electroweak Phase Transition, Phys.Lett. B717,396-402

Strength of the phase transition

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

a strong first order phase transition

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

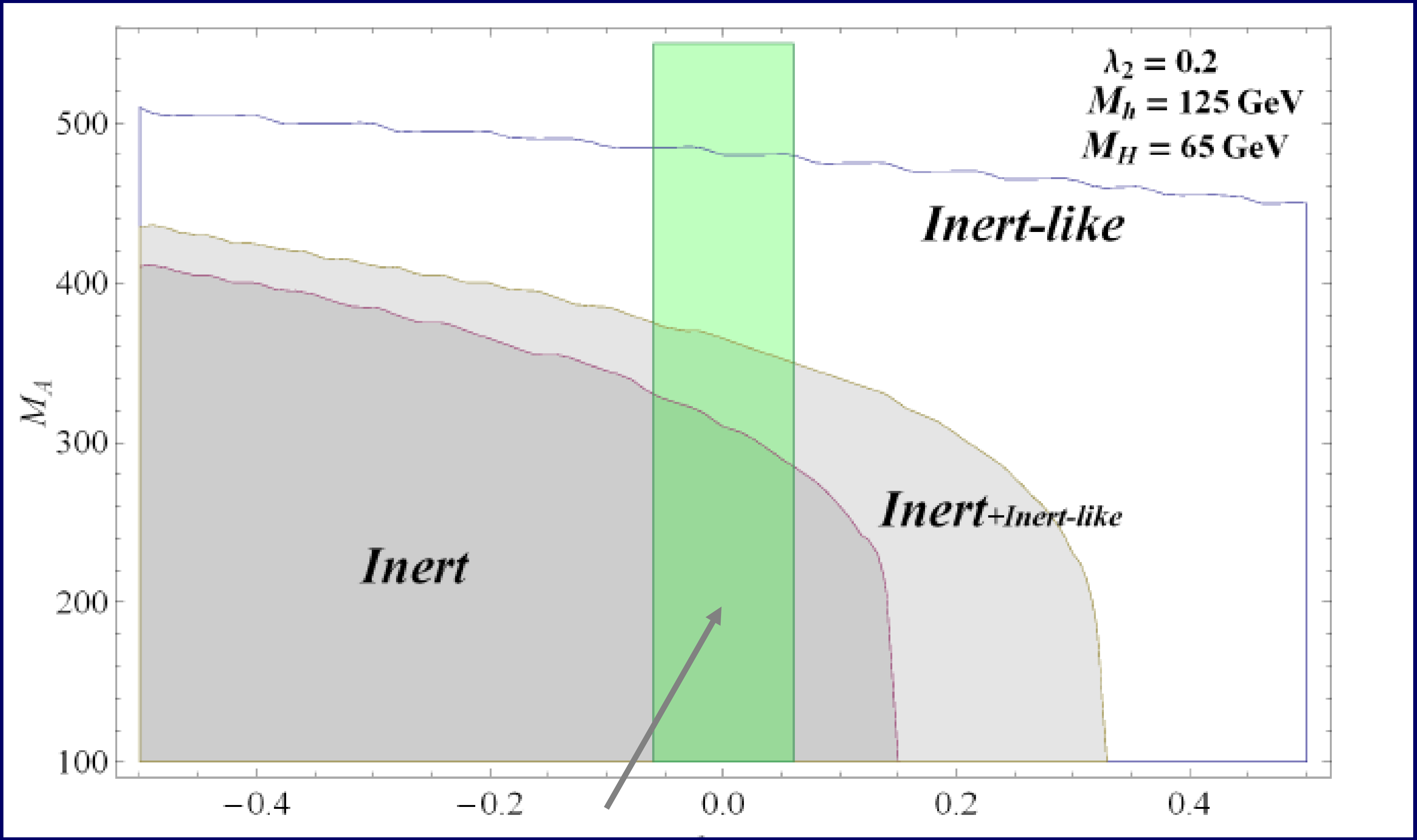


Sacharow: nonequillibrium

IDM: collider and astrophysical data

We focus on medium DM, with $M_H \ll v$, heavy degenerated A and H+ and M_h=125 GeV

Phases at T=0 (M_H+ = M_A, DM=H)



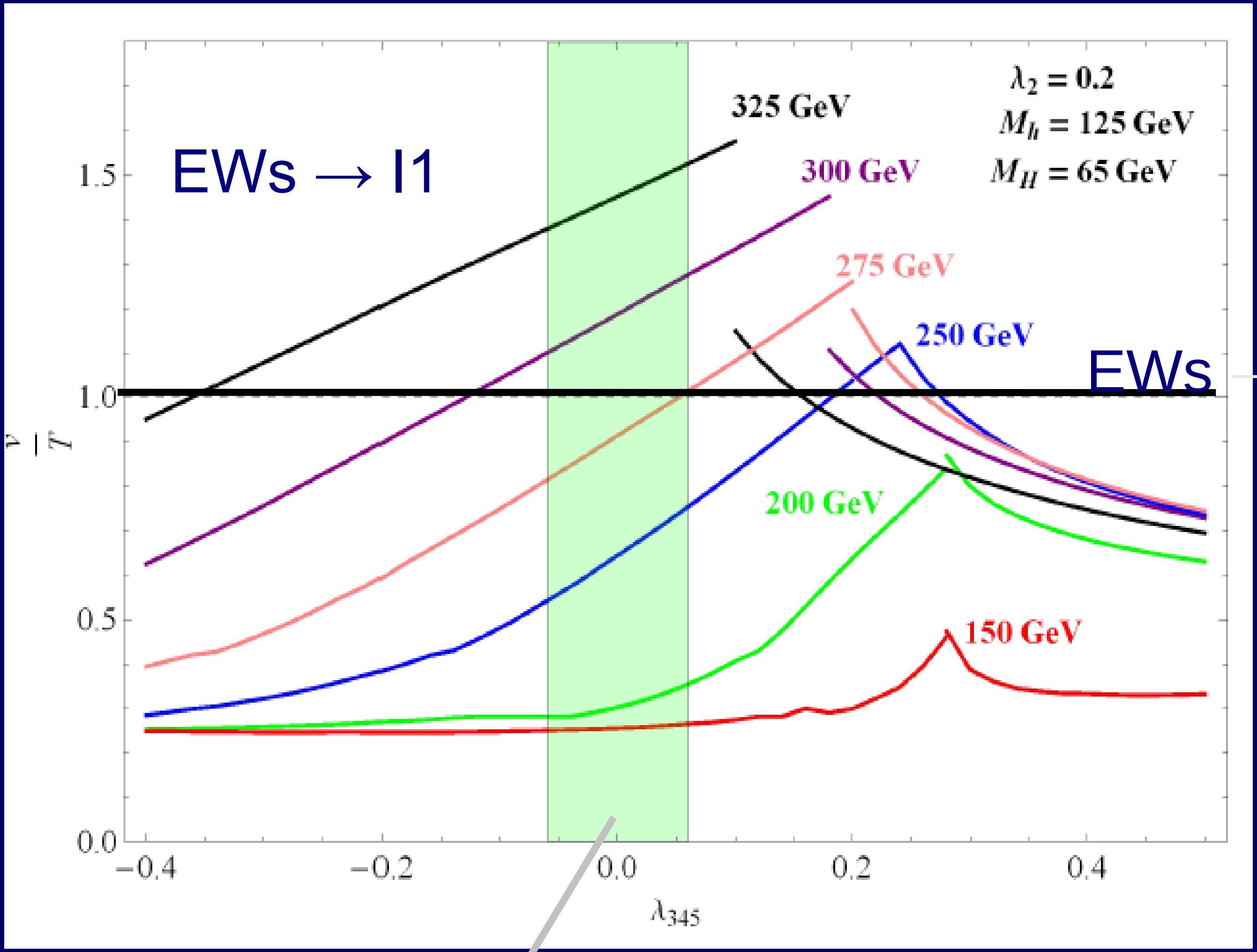
XENON100 bound

λ_{345}

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

Mh=125 GeV, MH=65 GeV, λ2=0.2

strong Ist order phase transition if ratio > 1



→ I2 → I1

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

λ_{345}

XENON100 bound

Conclusion

Inert Doublet Model with *SM-like h:*

mass of H+ below 160 (130) GeV if $R\gamma\gamma$ >1.2 (1.3)

and DM heavier than 62.5 GeV (and lighter than H+)

Various scenarios of evolution to Inert phase

$$EWs \xrightarrow{II} \begin{cases} I_1 \\ I_2 & \begin{cases} \xrightarrow{II} M \xrightarrow{II} I_1 \\ \xrightarrow{I} I_1 \end{cases} \end{cases}$$

Ch breaking in the past?-excluded if DM neutral

DM matter may appear later

Going beyond T^2 approximation – strong first order phase transition (-> baryogenesis) DM ~65 GeV H+ and A with mass 275 -380 GeV, hHH $|\lambda_{345}| < 0.1$

PLC

$\Gamma\,(h \rightarrow \gamma\,\gamma) \sim 3\ \%$

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

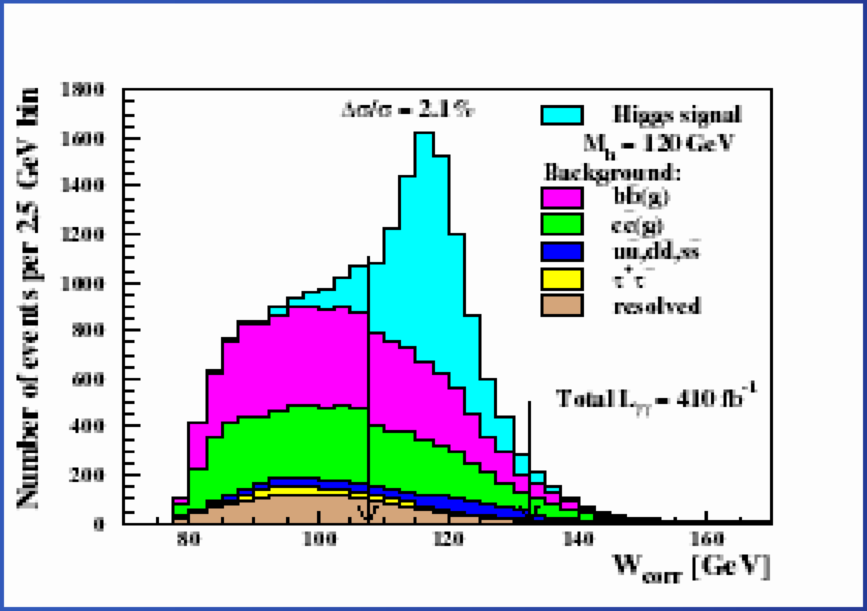
SM summary

NŻK

Niezurawski et al.,

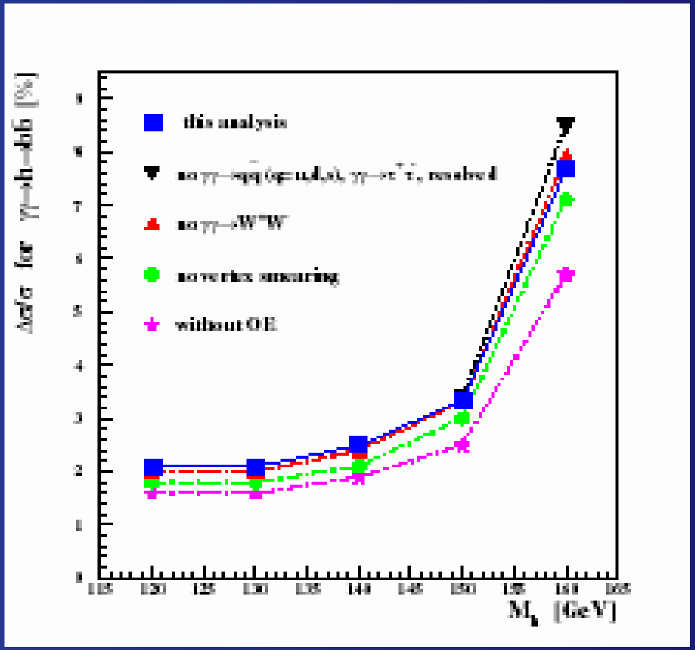
Monig, Rosca

→ Results for $M_h = 120$ GeV



Corrected invariant mass distributions for signal and background events

Results for $M_h = 120$-160 GeV

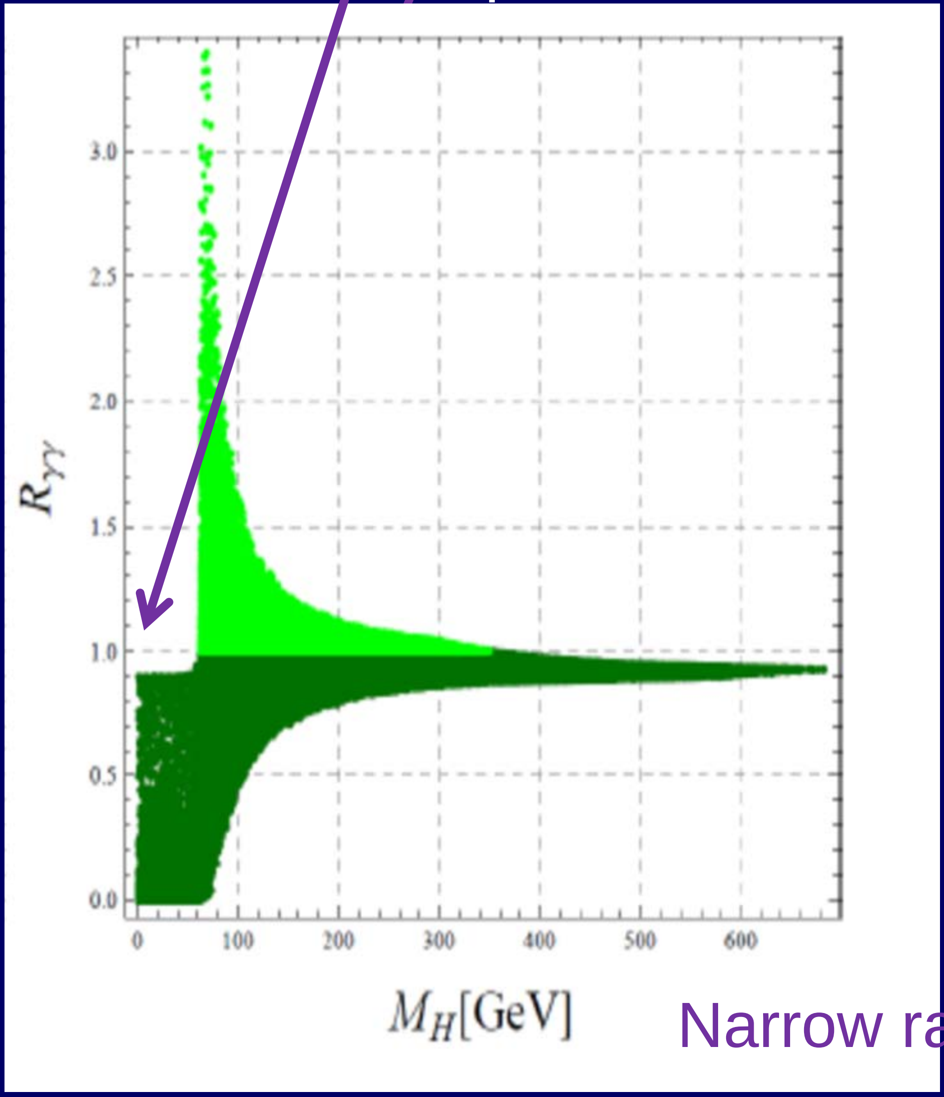


For $M_h = 150$, 160 GeV additional cuts to reduce $\gamma\gamma \rightarrow W^+W^-$

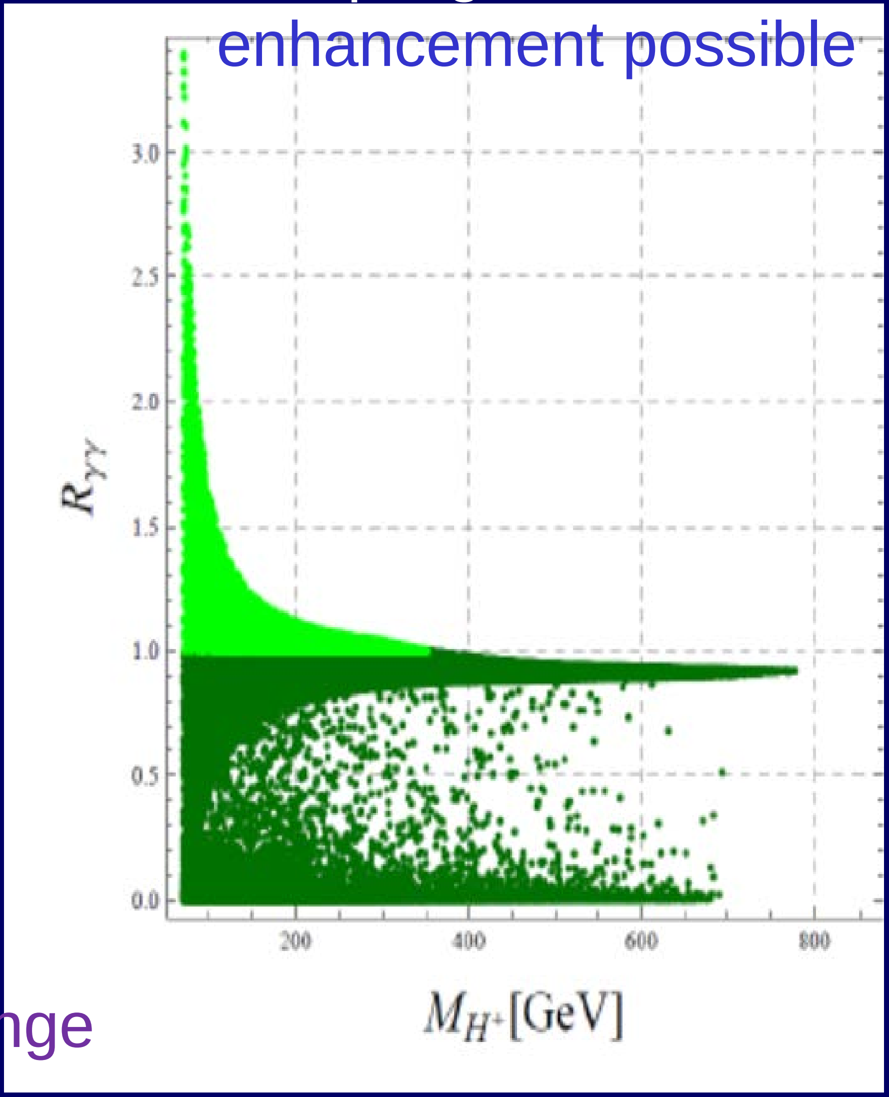
$R_{\gamma\gamma}$ as a function of mass H and H +

Invisible decays makes enhancement impossible

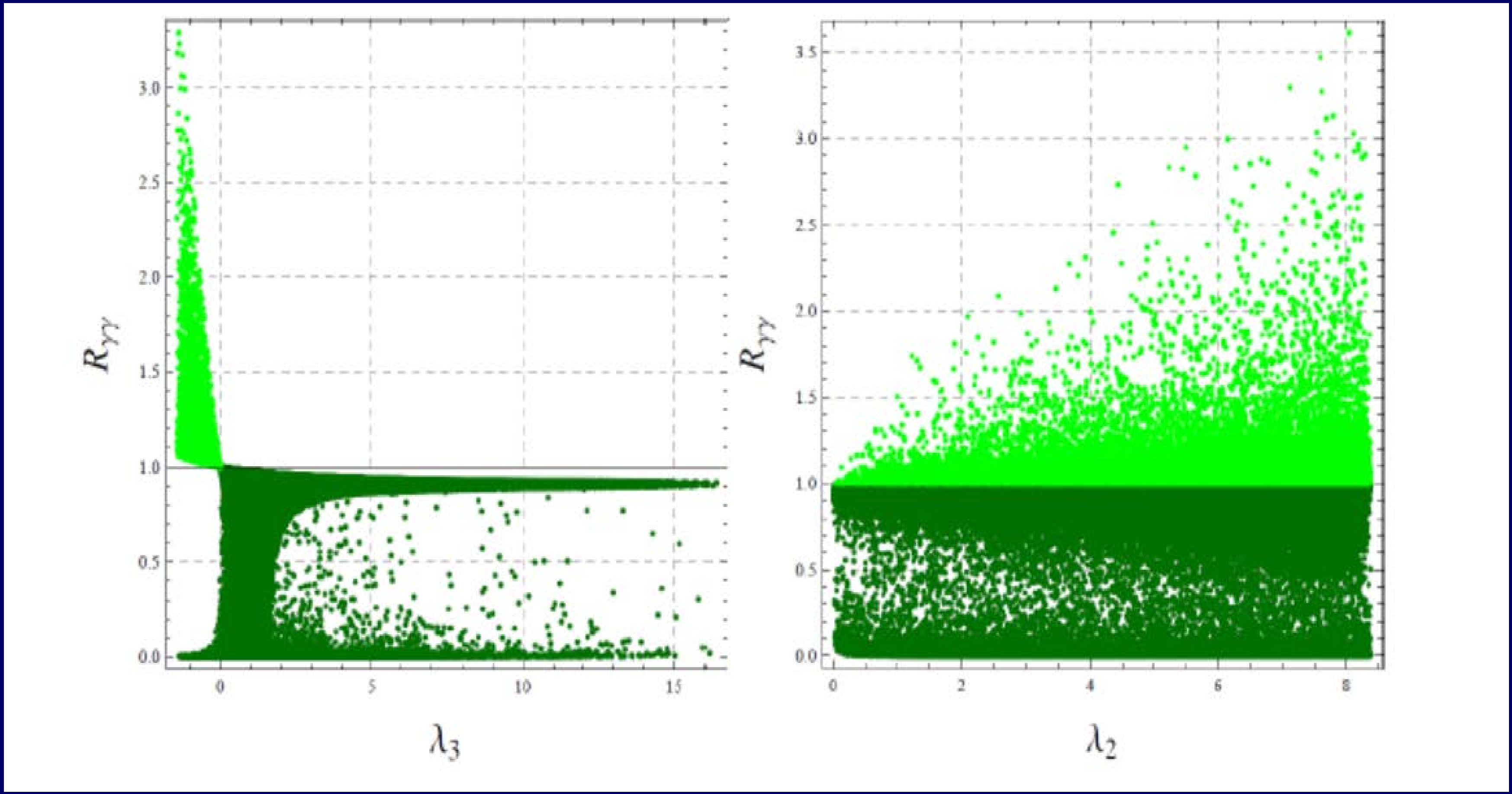
Light H+ with proper sign of hH+H- coupling makes enhancement possible



Narrow range



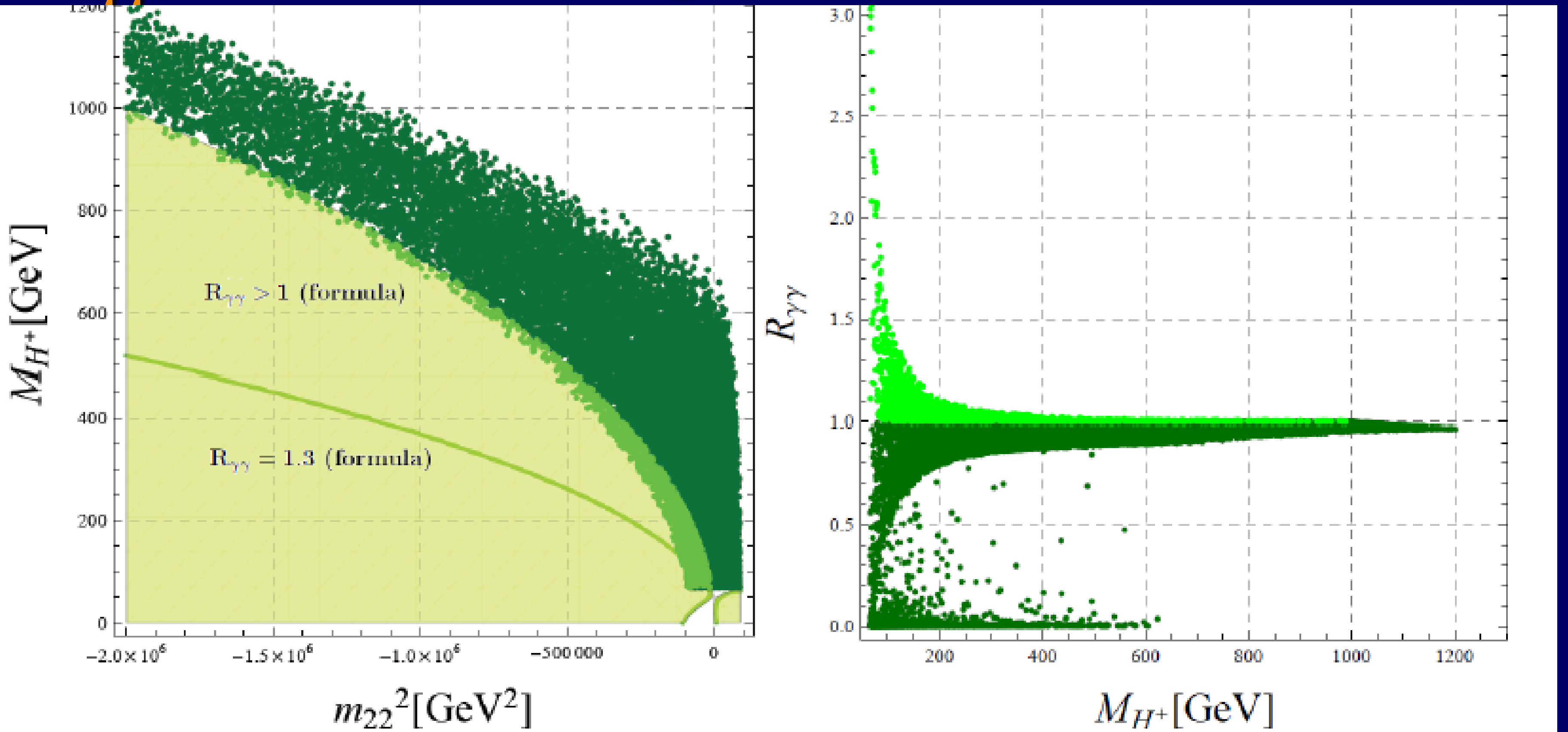
$R_{\gamma\gamma}$ as a function of λ_3 and λ_2



similar result
Arhrib at al

enhancement for negative λ_3

$R_{\gamma\gamma}$ - wide range of m_{22}^2



similar result Arhrib at al

- $R_{\gamma\gamma} \geqslant 1$ also for big $M_{H^\pm}$, e.g. $M_{H^\pm} = 1$ TeV
- Substantial enhancement, $R_{\gamma\gamma} \geqslant 1.3$, only for $M_{H^\pm} \lesssim 130$ GeV

IDM and evolution of the Universe

- Inert Doublet Model (IDM) provides DM and it is in agreement with present astrophysical and collider data including the 125 GeV Higgs boson
- If today (T=0) Universe in the Inert phase what was in the past ?
- We have studied temperature dependent Z2 sym. 2HDM potential → evolution of the Inert vacuum and sequences of different vacua in the past (one, two and three phase transitions)

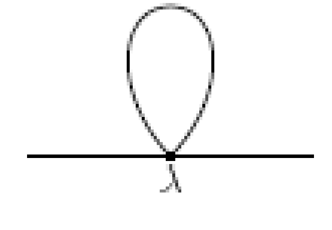
- with leading T2 corrections (only m^2_{ii} (T^2))

(*PRD 82(2010) Ginzburg, Kanishev, MK, D. Sokołowska)*

- beyond T2 corrections (to find strong enough first-order phase transition needed for baryogenesis)

(G. Gil Thesis'2011, G.Gil, P. Chankowski, MK Phys. Lett. B 2012

Termal corrections of parameters



Evolution of the Universe

Scalar, bosonic and fermionic contributions to $\Delta V \to m_{ii}^2(T)$:

$$m_{11}^2(T) = m_{11}^2 - c_1 T^2\,, \quad m_{22}^2(T) = m_{22}^2 - c_2 T^2$$

$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{6} + \frac{3g^2 + g'^2}{8} + \frac{g_t^2 + g_b^2}{2}, \quad c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{6} + \frac{3g^2 + g'^2}{8}$$

- fermionic contribution in c_1 (Model I)
- $c_1 + c_2 > 0$ from positivity constrains
- c_1 and c_2 positive to restore EW symmetry in the past

For a given T we determine:

- sign of $v_i^2\big|_{I_1, I_2, M}(T) \to$ possible existence of a given extremum
- values of λ_i (fixed) $\to$ existence of a local minimum
- value of extremum energy $\to$ global minimum

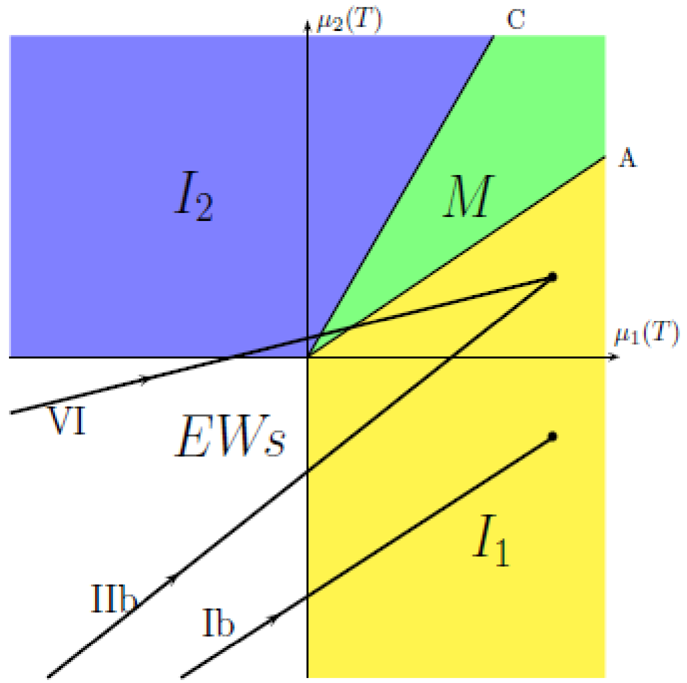
$\Rightarrow$ **sequences of possible phase transitions**

For $u = 0$ (neutral extrema) three separate cases of $EWs \to ... \to I_1$:

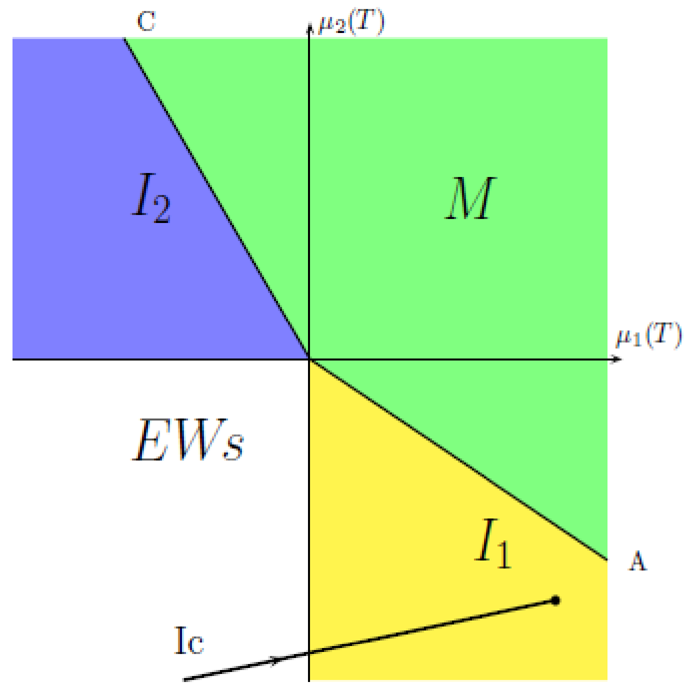
$$R = \lambda_{345}/\sqrt{\lambda_1 \lambda_2}\,: \quad R > 1, \quad 1 > R > 0, \quad 0 > R > -1$$

Phase diagrams

$0 < R < 1$



$-1 < R < 0$



$EWs \to I_2 \to M \to I_1$

$EWs \to I_1$

Sensitivity to HHHH coupling λ_2 medium DM mass - example

Medium DM mass: example

- fixed values of scalars' masses $\to$ $(\lambda_{345}, \lambda_2)$ phase space:

$$M_{D_H} = 50 \text{ GeV}, \; M_{D_A} = 120 \text{ GeV}, \; M_{D^\pm} = 120 \text{ GeV}, \; M_{h_S} = 120 \text{ GeV}$$

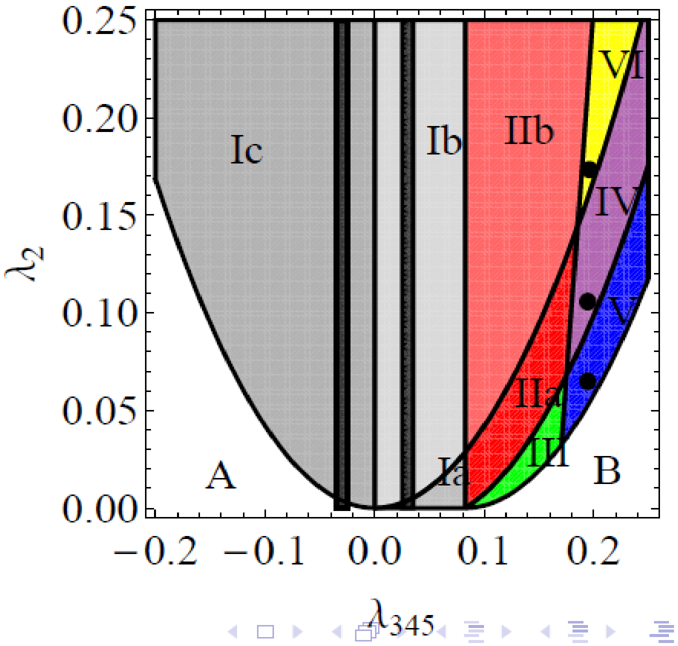
- fixed value of λ_{345}:

$$\lambda_{345} = 0.1945$$

- **rays may differ only by value of λ_2**

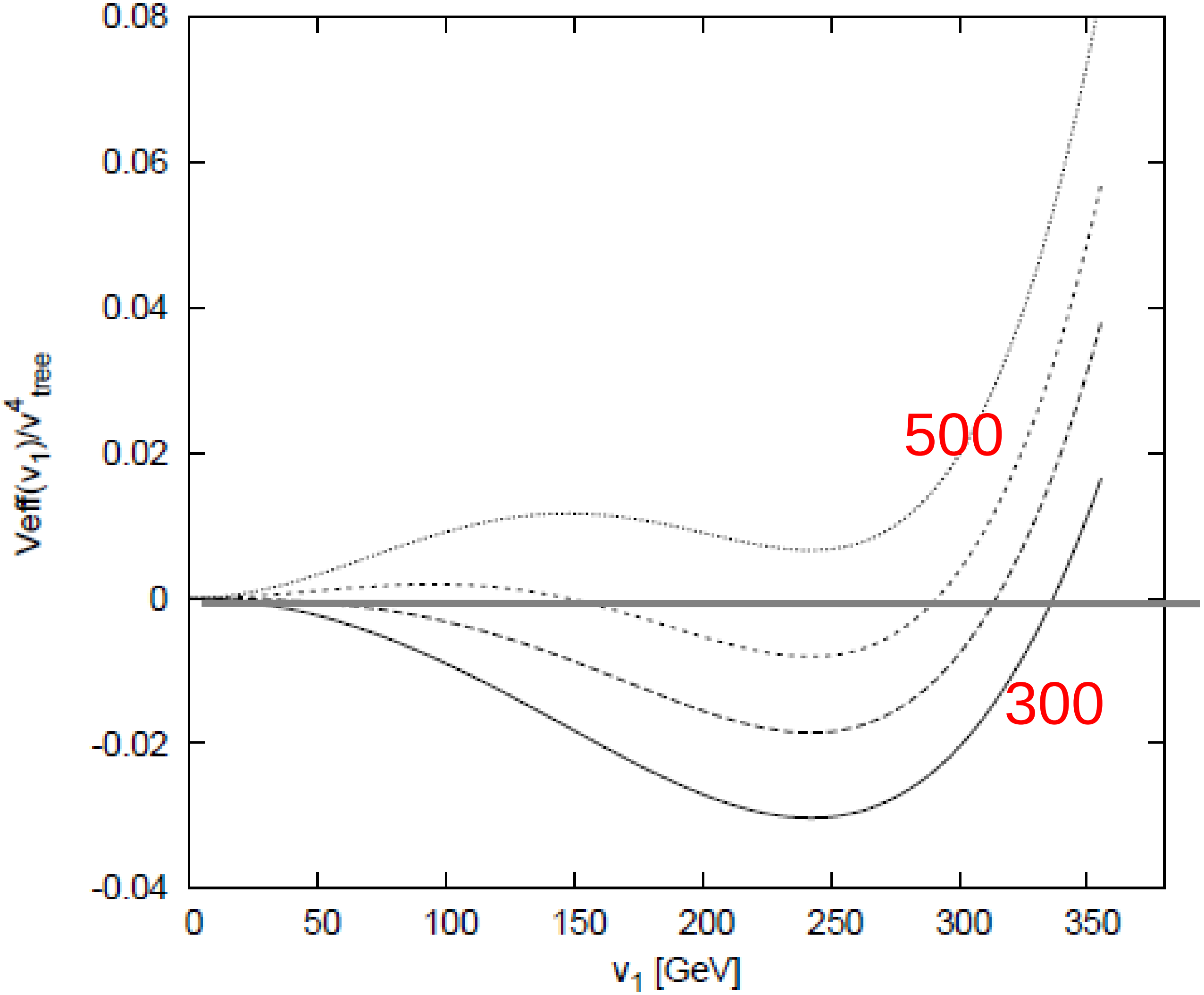
vertical bounds – WMAP-allowed region

Ray no.	λ_2
$EWs \to I_2 \to I_1$	
IV	$\lambda_2 = 0.1031$
V	$\lambda_2 = 0.0684$
$EWs \to I_2 \to M \to I_1$	
VI	$\lambda_2 = 0.1672$



limits on λ_2
- -positivity
- -Inert vacuum

Effective T=0 potential



Mh=125 GeV

MH=65 GeV

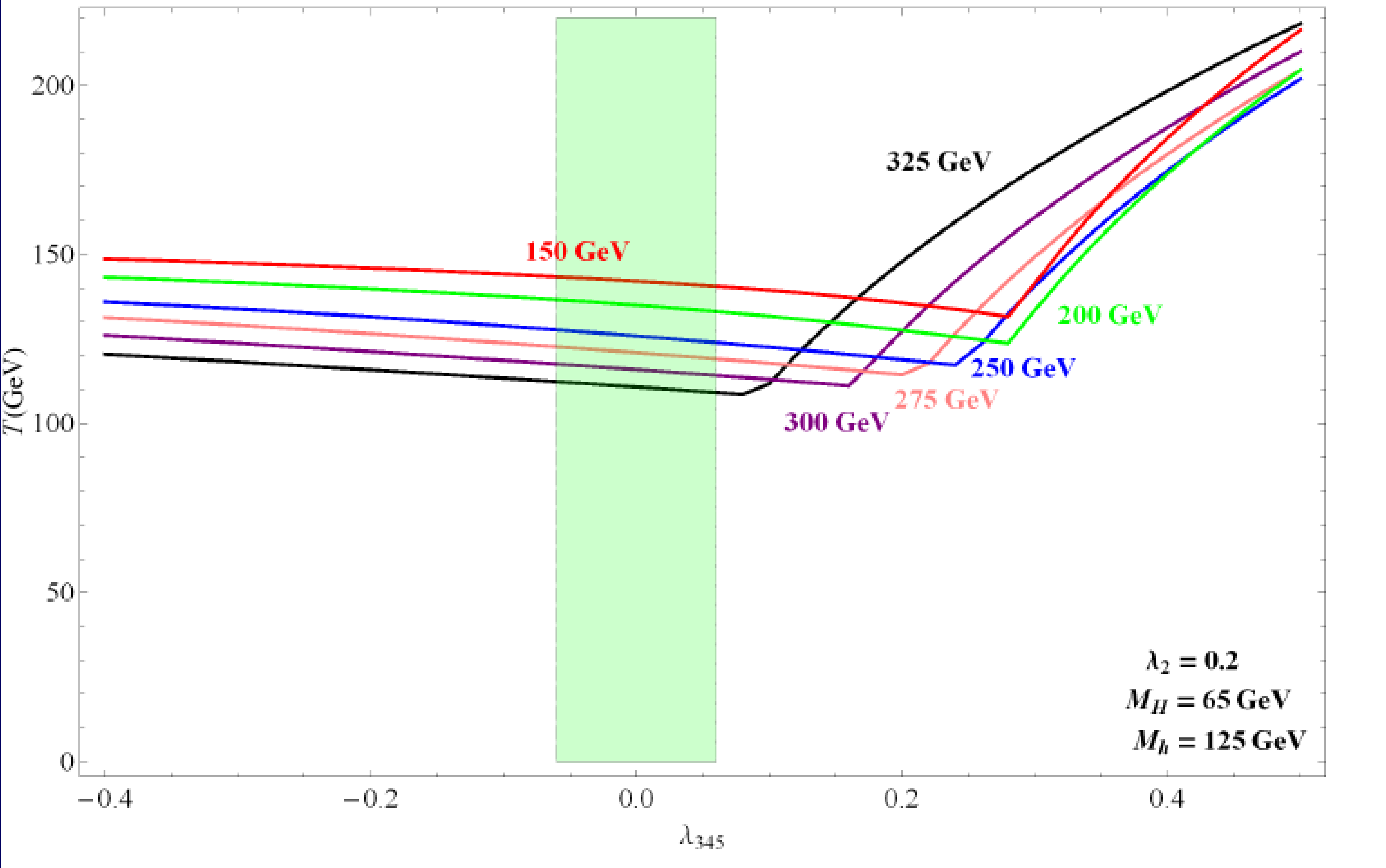
MH+=MA=
500,450,400,300
GeVṼ

λ_{345}=0.2,
λ_2=0.2

$v_{2(D)}$=0

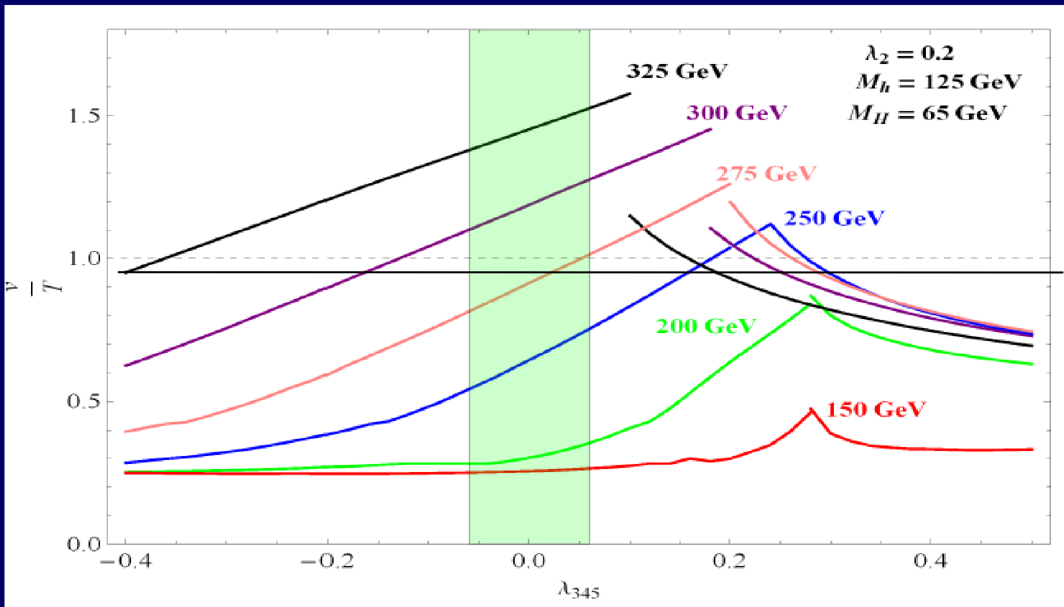
Critical temperature T_{EW}: V at new minimum = V at $v_{1(s)}=v_{2(D)}=0$

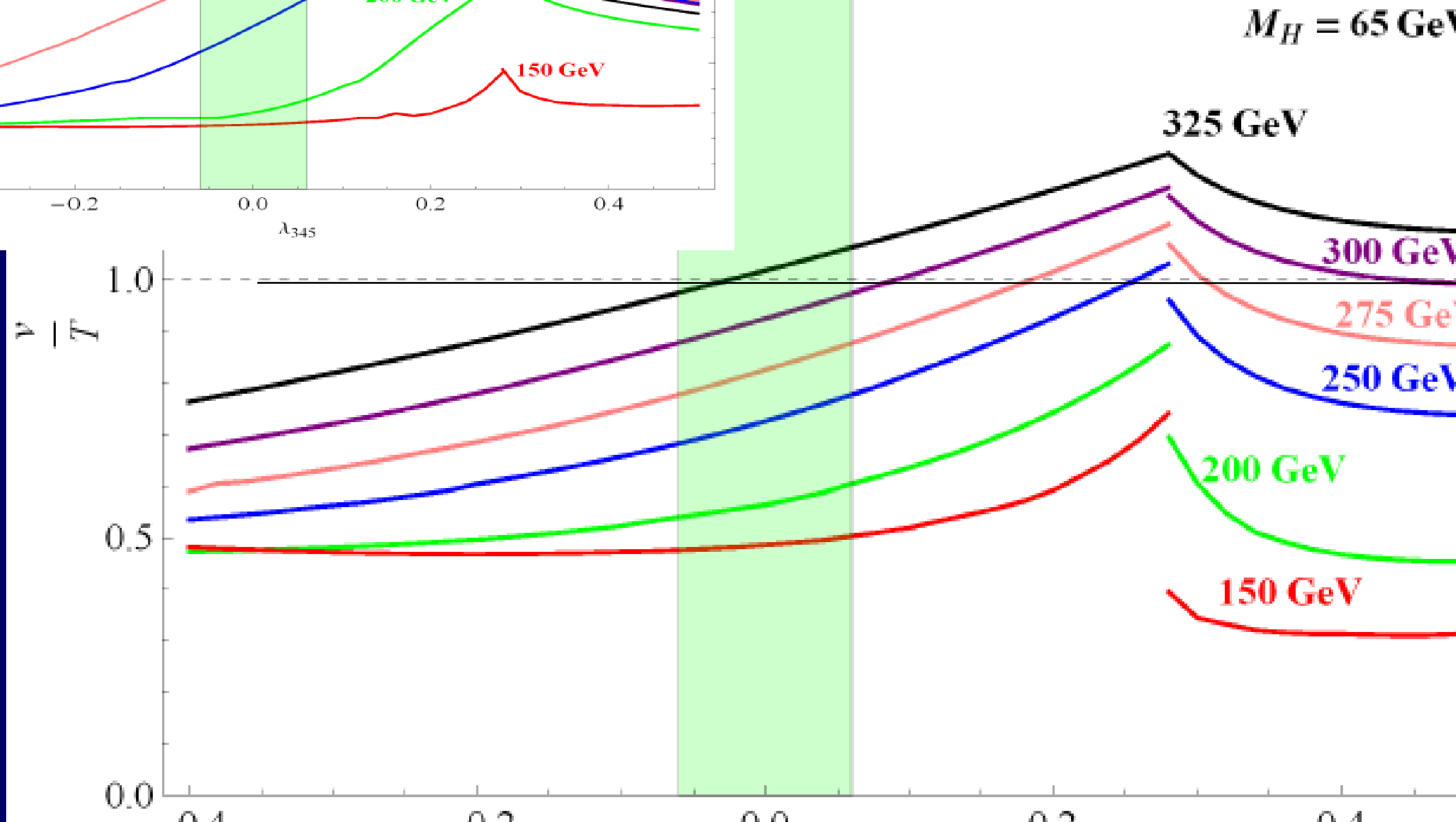
T_{EW} as a function of λ_{345}



Role of Coleman-Weinberg term

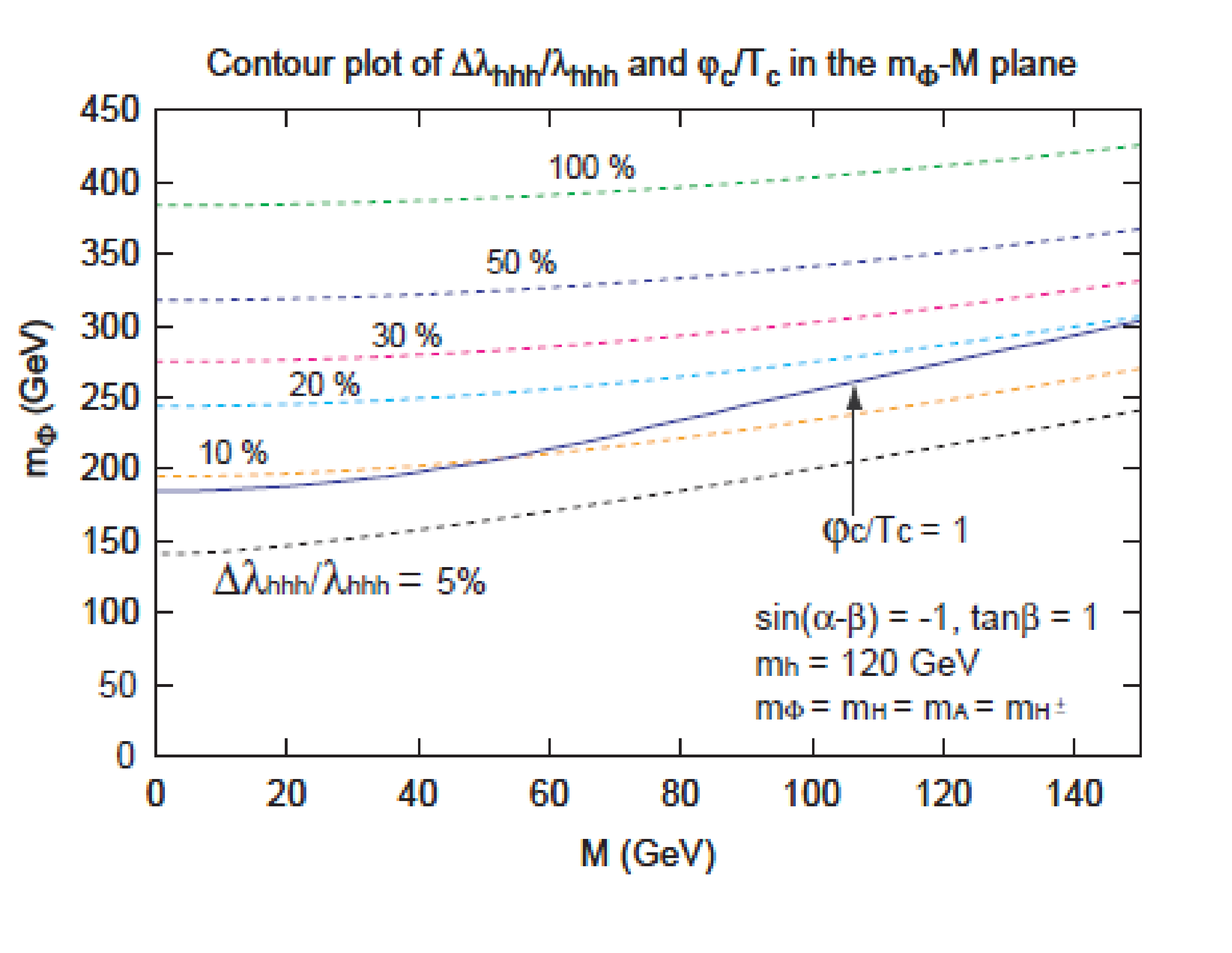
with and without CW term





Electroweak baryogenesis and quantum corrections to the triple Higgs boson coupling '2004

Shinya Kanemuraa, Yasuhiro Okada, Eibun Senahab

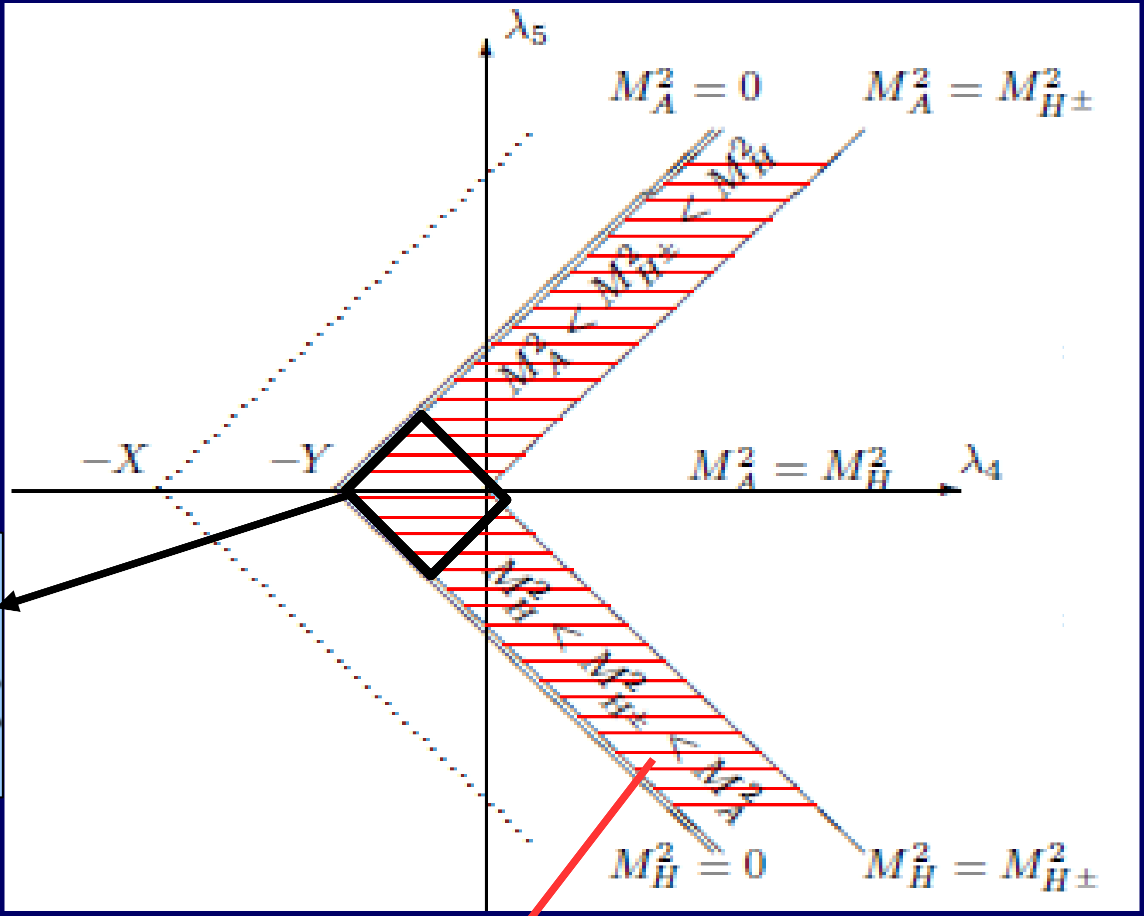


$m_H = m_A = m_{H^\pm} (\equiv m_\Phi)$

$M^2 \ (= m_3^2 / \sin\beta\cos\beta),$

Dark scalar masses

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



here H+
the heaviest

here H is the lightest ($\lambda_5 < 0$) – our DM

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

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:

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

Then for the relative basic couplings of neutral Higgses

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

$$|\epsilon_i| \le \delta_i .$$

Using pattern relation for 2HDM (II)

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

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.

Both h and H maybe SM-like

Two solutions of pattern relation:

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

„wrong" sign of coupling to top → large enhancement of hgg, h$\gamma\gamma$, h$Z\gamma$! and Hgg

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

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

Γ(h/H → gg, $\gamma\gamma$)

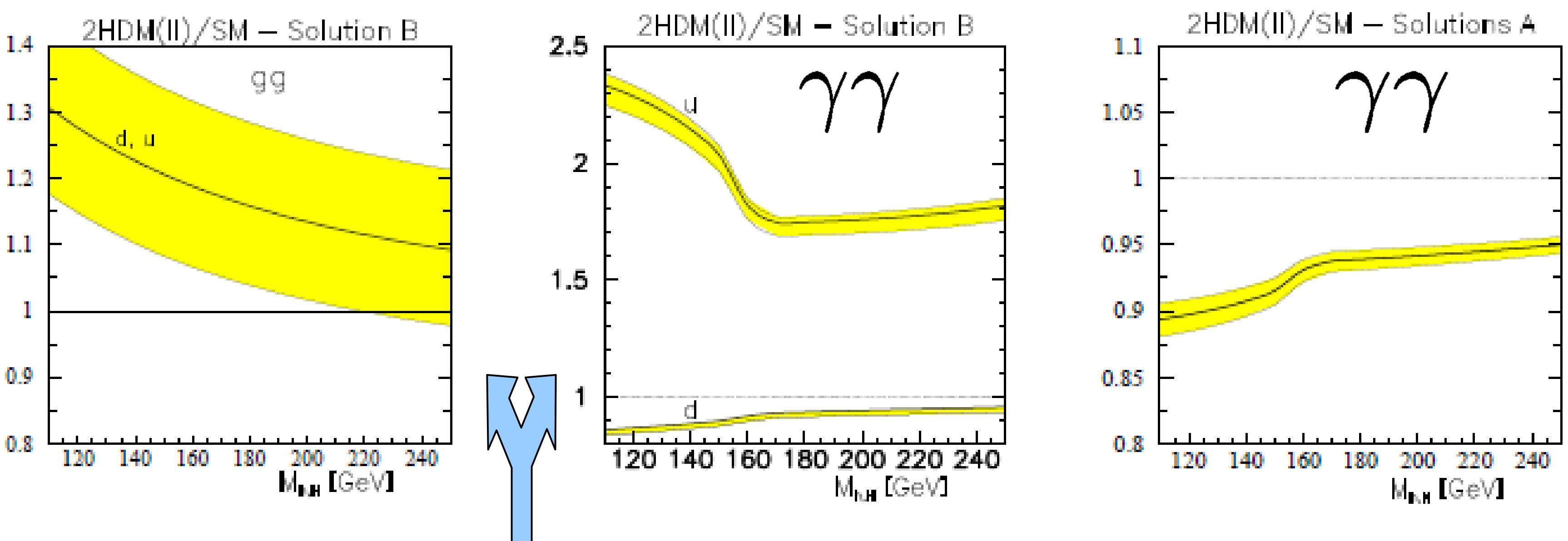
including exp. uncertainties

2HDM(Z_2) = Mixed

Ginzburg,Osland, MK '2001

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

large non-decoupling effects due to heavy $H^{\pm}$. (600 GeV)



solution B → „wrong" signs of fermion couplings

λ_{345} – **trójliniowe** i **kwartyczne** sprzężenie: $D_H D_H h_S$ i $D_H D_H h_S h_S$

- główny kanał anihilacji $D_H D_H \to h_S \to f\bar{f}$:

  $\sigma \propto \lambda_{345}^2/(4M_{D_H}^2 - M_{h_S}^2)^2 \Rightarrow$ ograniczenia z gęstości reliktowej

- rozpraszanie DM-nukleon przez wymianę h_S:

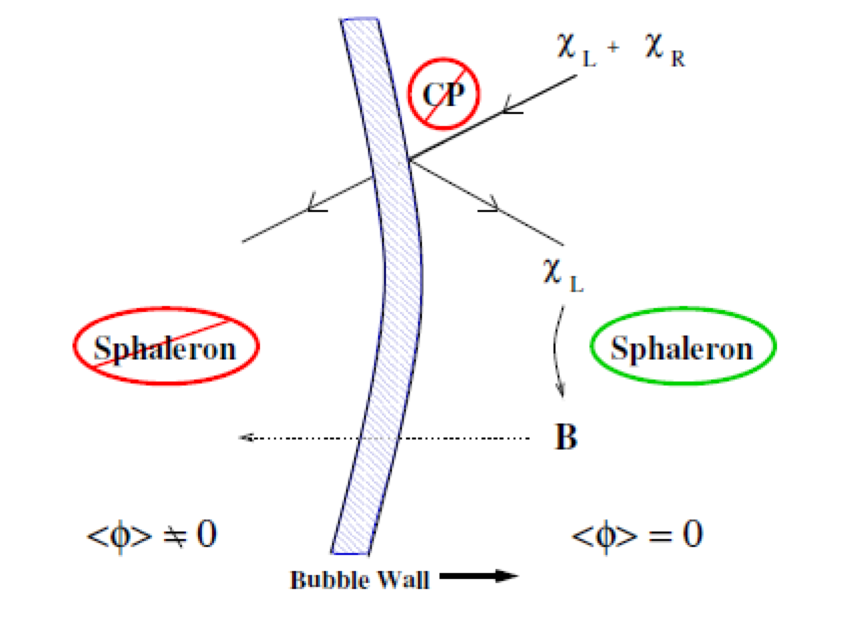
  $\sigma_{DM,N} \propto \lambda_{345}^2/(M_{D_H} + M_N)^2 \Rightarrow$ eksperymenty bezpośredniej detekcji

λ_2 – **kwartyczne** sprzężenie $D_H D_H D_H D_H$

- brak wpływu na gęstość reliktową DM
- niedostępne w akceleratorach
- związek z λ_{345} przez warunki dodatniości i istnienie próżni I_1
- wpływa na typ ewolucji

Baryon creation in EWBG takes place in the vicinity of the expanding bubble walls. The process can be divided into three steps [4]:

1. Particles in the plasma scatter with the bubble walls. If the underlying theory contains CP violation, this scattering can generate CP (and C) asymmetries in particle number densities in front of the bubble wall.
2. These asymmetries diffuse into the symmetric phase ahead of the bubble wall, where they bias electroweak sphaleron transitions [15, 16] to produce more baryons than antibaryons.
3. Some of the net baryon charge created outside the bubble wall is swept up by the expanding wall into the broken phase. In this phase, the rate of sphaleron transitions is strongly suppressed, and can
the baryons created in first two steps

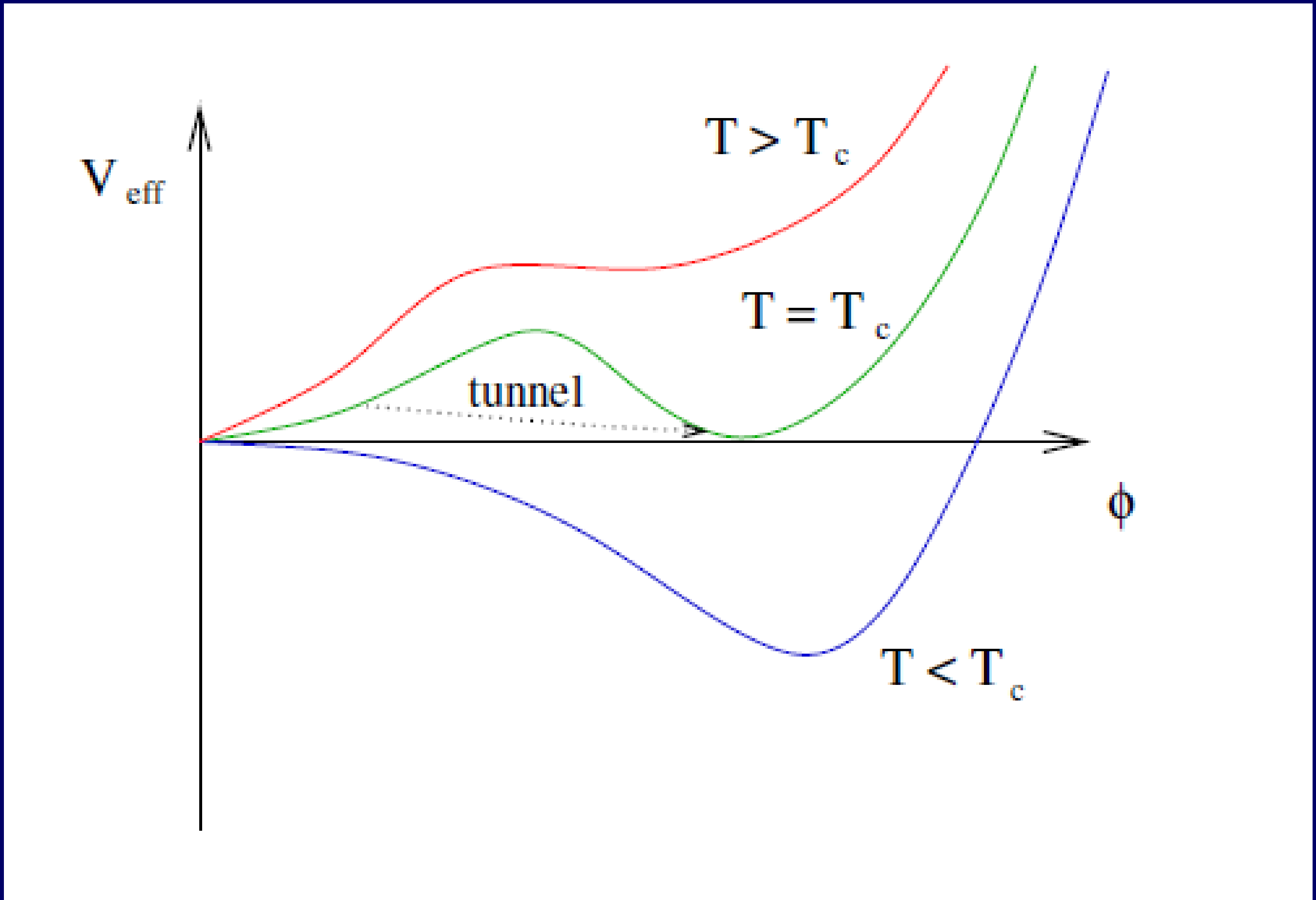


Baryon production in front of the bubble walls.

These EWBG steps satisfy explicitly the three Sakharov conditions for baryon creation [17]. First, departure from thermodynamic equilibrium is induced by the passage of the rapidly-expanding bubble walls through the cosmological plasma. Second, violation of baryon number comes from the rapid sphaleron transitions in the symmetric phase. And third, both C- and CP-violating scattering processes are needed at the phase boundaries to create the particle number asymmetries that bias the sphalerons to create more baryons than antibaryons.

All the ingredients required for EWBG are contained in the SM. Unfortunately, EWBG is unable to explain the observed baryon asymmetry within the SM alone. The

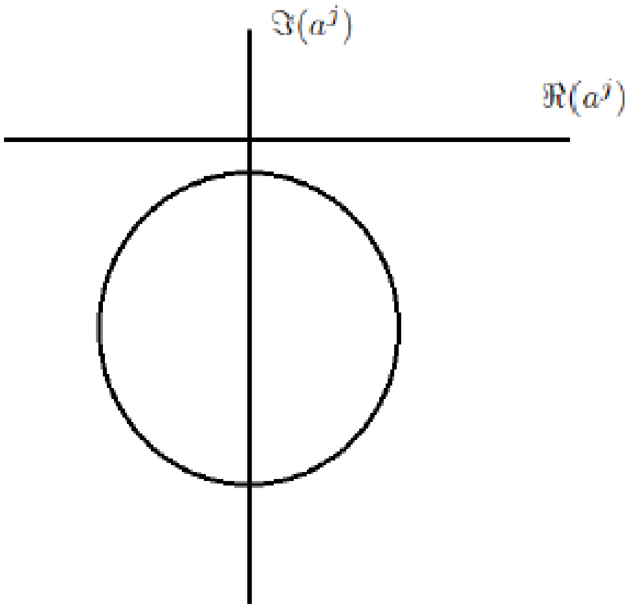
first impediment is that the SM electroweak phase transition is first-order only if the mass of the Higgs boson lies below $m_h \lesssim 70$ GeV [18, 19]. This is much less than the current experimental lower bound of $m_h > 115.5$ GeV [20, 21]. Even if the phase transition were first order, the CP violation induced by the CKM phase does not appear to be sufficient to generate large enough chiral asymmetries [22, 23, 24].



V_{eff}
$T > T_c$
$T = T_c$
tunnel
ϕ
$T < T_c$

Perturbative unitarity condition

- $SS^\dagger = 1 \Rightarrow$ partial wave amplitudes of elastic scatterings lie on the Argand circle.
- In the high energy limit: $|\Re(a^0(s))| < \frac{1}{2}$.



Confronting with data

Ma,..2006,..
*B. Gorczyca(Świeżewska), Thesis2011, 1112.4356, 1112.5086 ,
Posch..2011, Dolle, Su…
Arhrib..2012, Chang…2012

Constraints:

vacuum stability,

perturbative unitarity

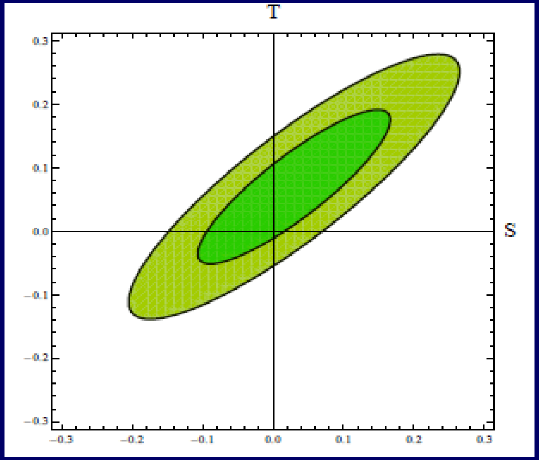
condition for a specific vacuum

Data:

EWPT (S and T)

LEP, LHC and DM data

$$S = 0.03 \pm 0.09$$
$$T = 0.07 \pm 0.08$$
$$\rho = 87\%$$



Inert Doublet Model: it's a SM-like scenario for h; H=DM

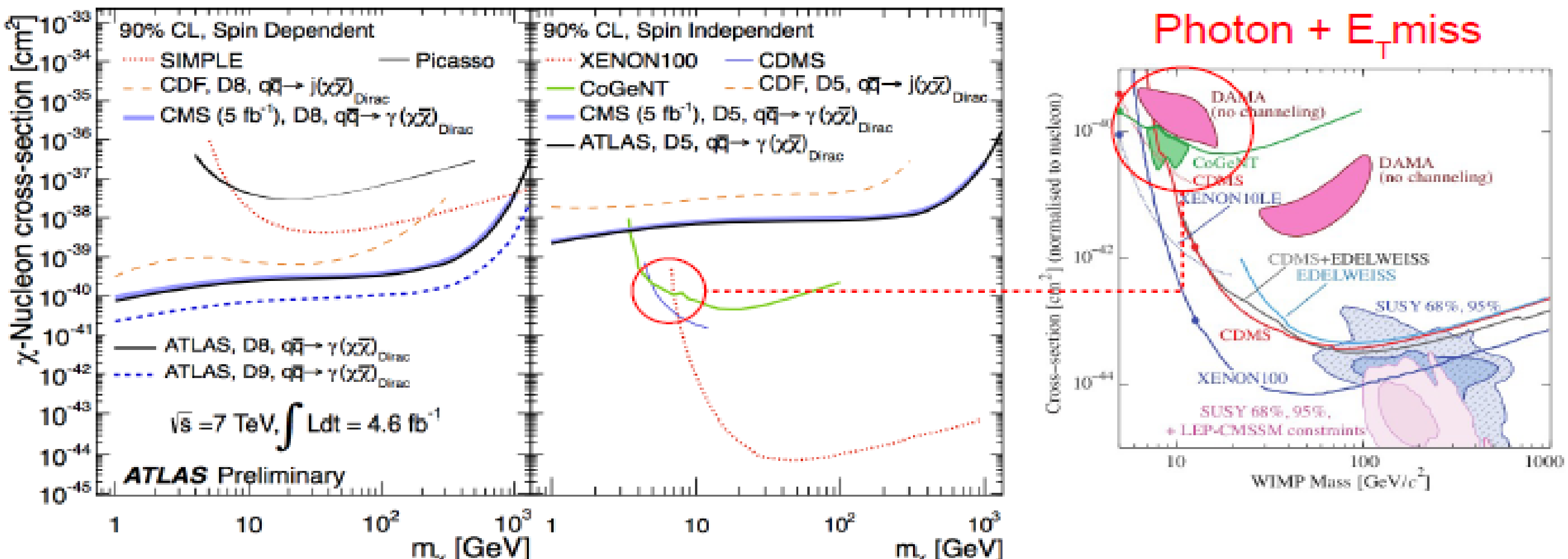
In contrast Mixed Model (II) with 5 Higgses

sum rules for relative couplings eg. $(\chi^h{}_V)^2 + (\chi^H{}_V)^2 = 1$

can have SM-like h or H (with $\chi_V = 1$) V=W/Z

DM - LHC

WIMP search



- LHC results represent a large improvement of the limits set at Tevatron
- Limits on scattering σ : ~10^{-40}-10^{-41} cm^2 (SD) and ~10^{-38} cm^2 (SI) for m_χ<100 GeV
- Not enough sensitivity yet to exclude/confirm CoGeNT/DAMA excess at ~10 GeV in case of D1/D5 models

Invisible decay

Dedicated search for ZH→ $\ell\ell$ + invisible

Select events with two exclusive leptons, large missing E_T, recoiling against the Z boson