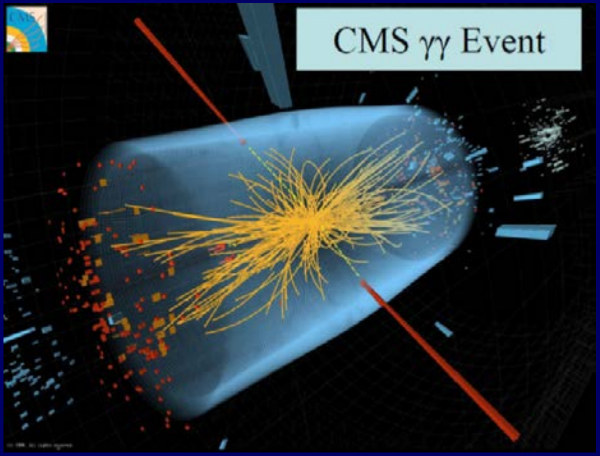
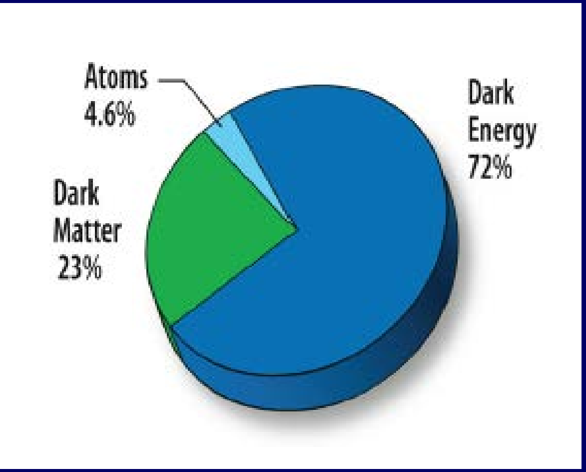
Constraining Inert Doublet Model





Maria Krawczyk
U. of Warsaw

In coll. with I. Ginzburg, K. Kanishev, D.Sokolowska, B. Świeżewska, G. Gil, P.Chankowski, M. Matej, N. Darvishi, A. Ilnicka, T. Robens, L. Diaz-Cruz, C. Bonilla

Higgs particle-the missing particle of SM

discovered (?)

The discovered ~125 GeV scalar has properties very close to predicted by the SM.

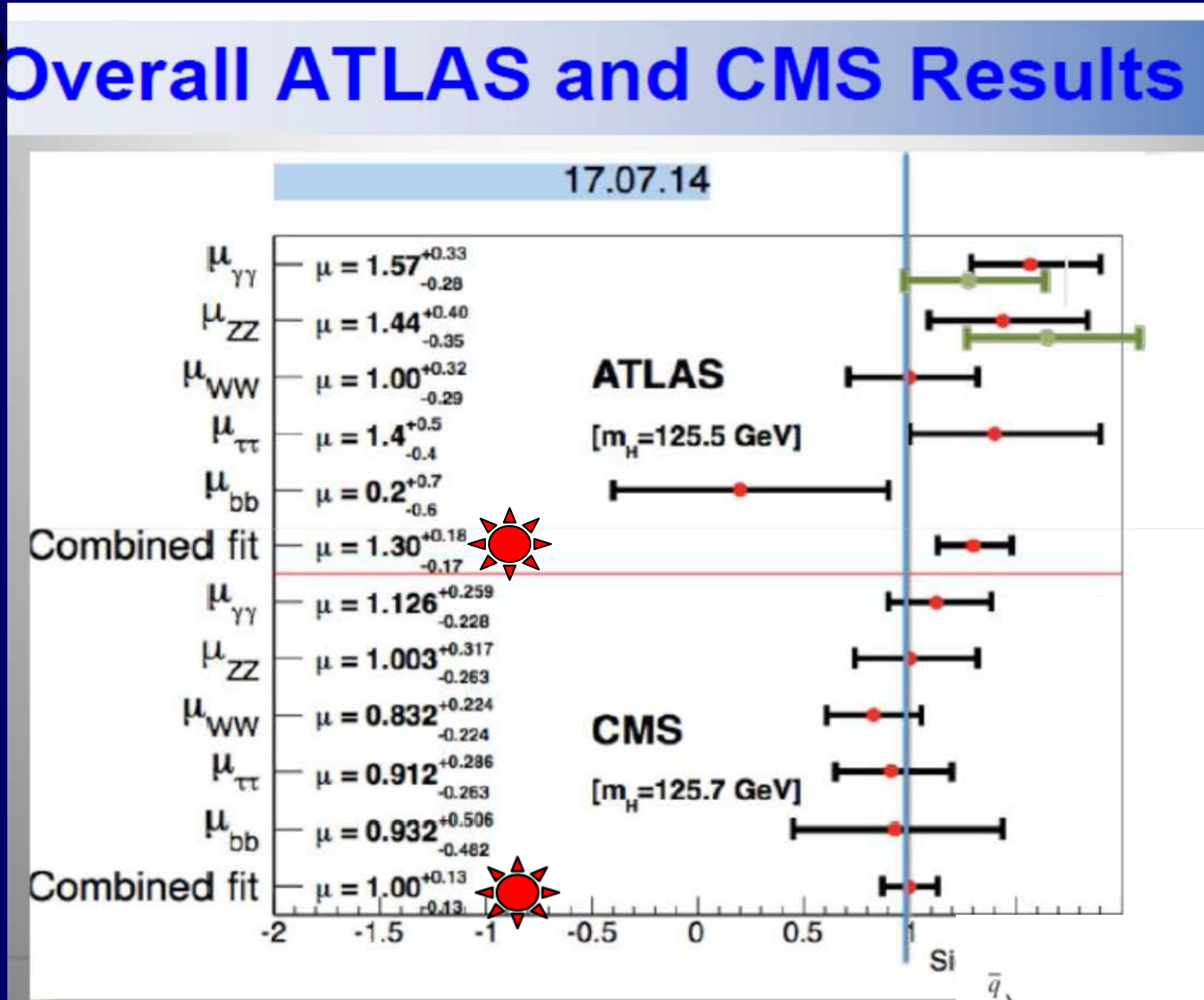
But how close?

Loop couplings ggh, $\gamma\gamma$h, γZh sensitive to new physics (new, even very heavy particles → *nondecoupling* effects)

Beyond SM (BSM) - only SM-like scenarios:

SM-like h and no other new particle seen

SM-like Higgs



old

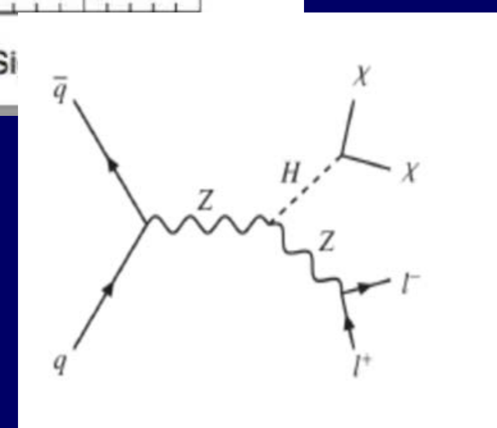
In addition:

total width

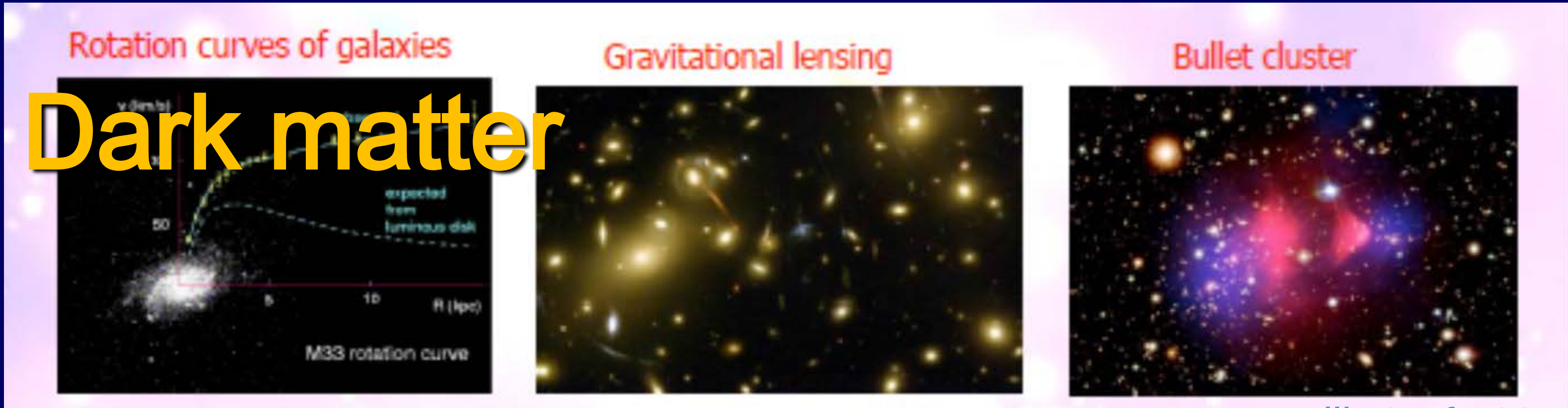
$\lesssim$ 4-5 x SM (in SM - 4.2 MeV)

decay to invisible particles

BR (inv) < 0.37 (now 0.20)



Dark matter



Morsolli, Corfu 2014

relic density

WMAP $$0.1018 < \Omega_{DM} h^2 < 0.1234$$

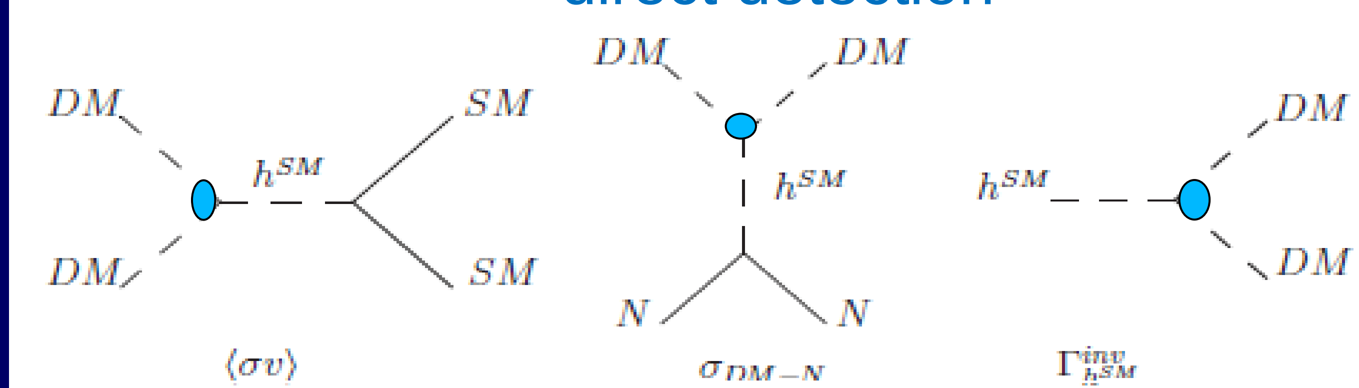
3 sigma:

PLANCK $$0.1118 < \Omega_{DM} h^2 < 0.128$$

Higgs portal models

SM-like h

direct detection



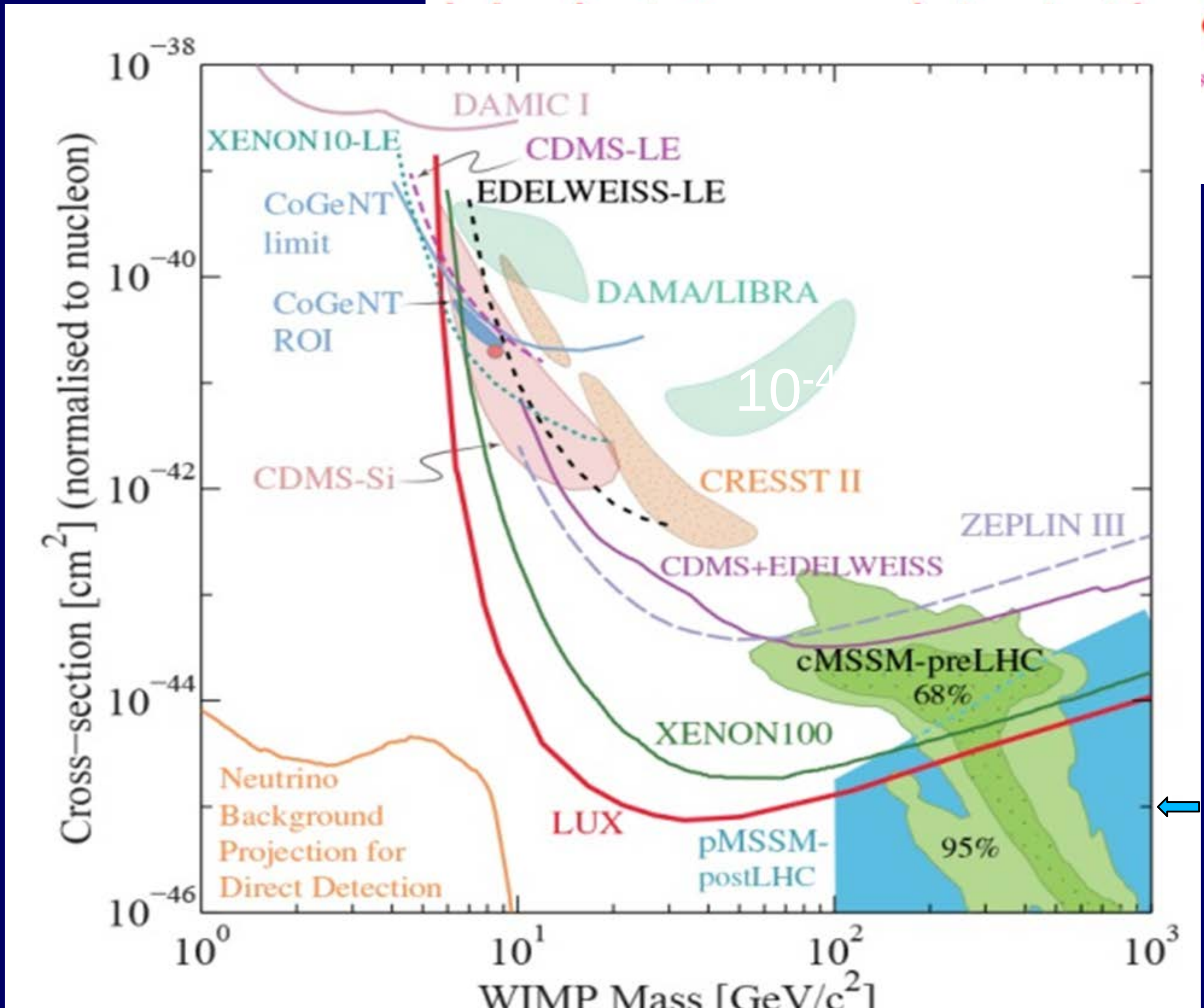
DM DATA?

Direct & indirect detection experiments do not provide a coherent picture of Dark Matter.

"One should be aware, however, that this area of investigation is at present beset with large controversies, and one should allow the dust to settle

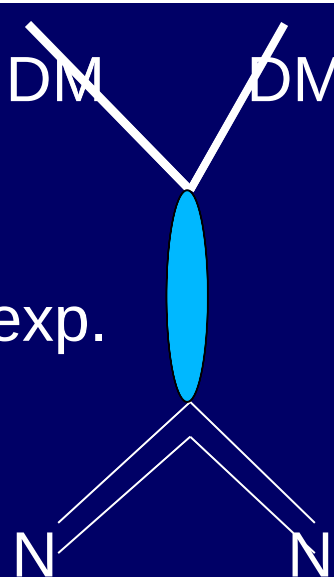
directions."

; Candidates and Detection Methods,



10^{-45} cm^2

direct exp.



Inert Doublet Model (IDM)

- a model with two SU(2) doublets with *exact* Z_2 symmetry (L & vacuum)

Today

Higgs and Dark Matter sectors in agreement with data

- Various type of evolution from EWs to Inert phase possible in one, two or three steps, with 1st or 2nd order phase transitions *(T2 evolution, Ginzburg et al..PRD 2010)*
- Strong enough first-order phase transition needed for baryogenesis *(G. Gil Msc'2011, G.Gil, P.Chankowski, MK PL.B 2012*
- Metastability of vacua in IDM *(B. Świeżewska -> poster)*
- IDM+complex singlet *Bonilla,Diaz-Cruz,Sokołowska,Darvishi, MK'14*

Z_2 symmetric 2HDM

Potential

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

$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c]$$

$$- \tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1) - \tfrac{1}{2}m^2_{22}(\Phi^\dagger\Phi_2)$$

Z_2 symmetry transf.: $\Phi_1 \rightarrow \Phi_1$ $\Phi_2 \rightarrow -\Phi_2$

Yukawa interaction

Model I – one doublet Φ_1 couples to all fermions

Types of extrema (vacua) *Ma78, Velhinho, Santos, Barroso..94*

change of notation: $\Phi_1 \to \Phi_S$ & $\Phi_2 \to \Phi_D$ (D symmetry)

real v_S, v_D, $u \geq 0$

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

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

------------------ $u=0$ ------------------

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

------------------ $u \neq 0$ ------------------

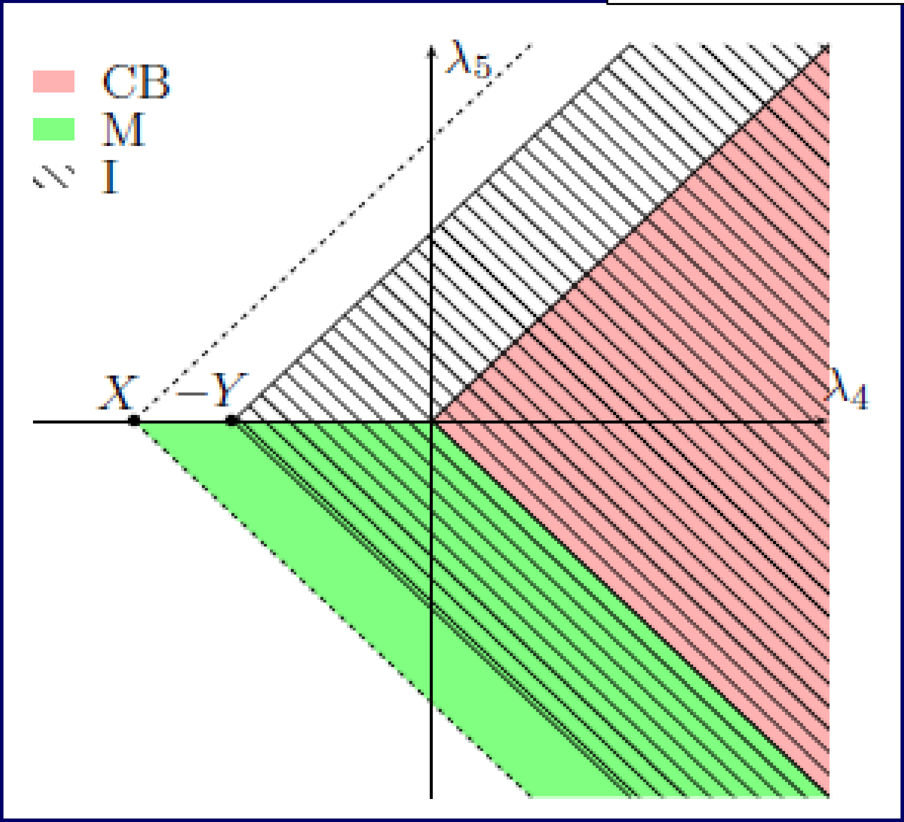
Charge Breaking	CB	$v_D = 0$

D-symmetric potential – vacua

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

$$\lambda_1 > 0\,, \quad \lambda_2 > 0, \quad \boxed{R+1>0,} \quad R_3+1>0$$

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



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

Neutral vacua

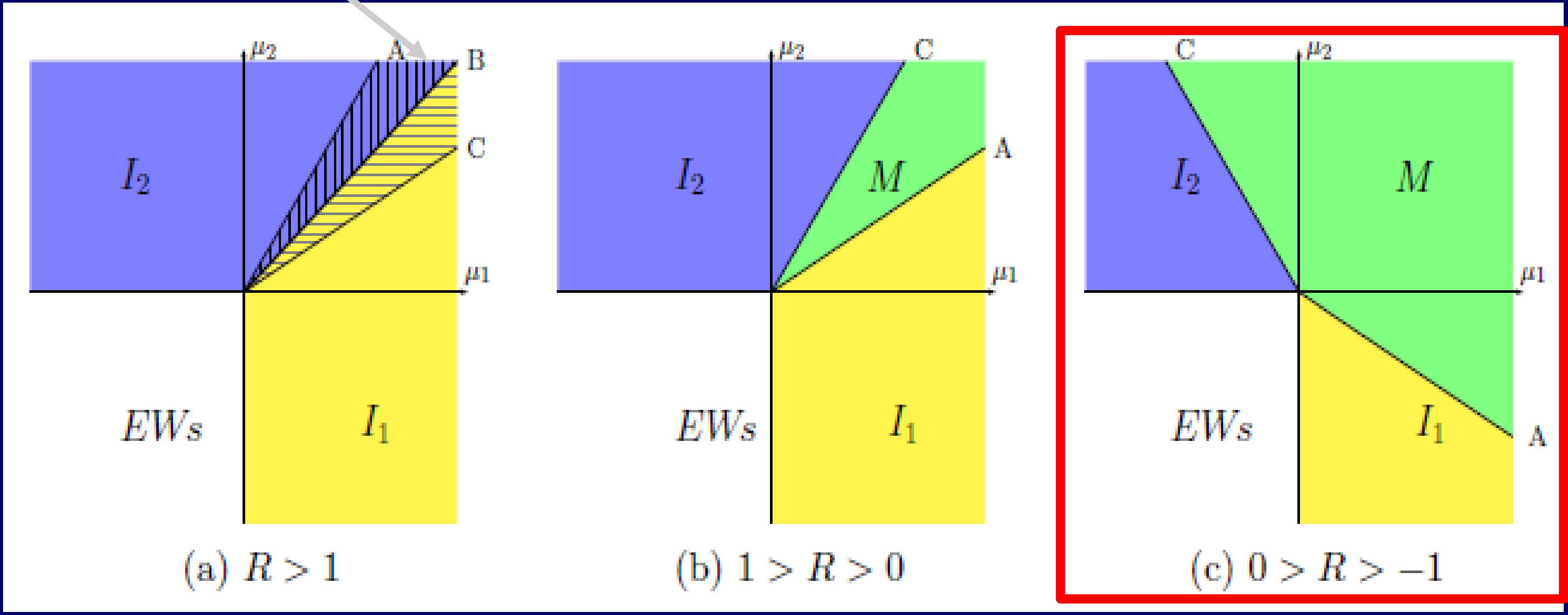
- Mixed M [v_S and $v_D \neq 0$]
- Inert I1 (I2) [v_S or $v_D \neq 0$]
- Charged breaking vacuum CB

Inert overlaps both with Mixed and CB !

Phase diagrams for D-sym. V

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

coexistence of
I1 and I2 minima



$$R = \lambda_{345}/\sqrt{\lambda_1\lambda_2},$$

preferred by new scan

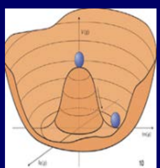
Inert (I1) vacuum

for Mh=125 GeV → fixed μ_1

Inert Doublet Model

Ma,…'78
Barbieri..'06

Φ_S as in SM (BEH) Φ_D – no vev



$$\Phi_S = \begin{pmatrix} \varphi^+ \\ \frac{V+h+i\,\zeta}{\sqrt{2}} \end{pmatrix}$$

$$\Phi_D = \begin{pmatrix} H^+ \\ H+i\,A \end{pmatrix}$$

(no Higgses!)

Higgs boson h (SM-like)

4 scalars H+,H-,H, A
no interaction with fermions

D symmetry $\Phi_S \to \Phi_S$ $\Phi_D \to -\Phi_D$ exact →
- D parity
  - only Φ_D has odd D-parity
    - the lightest scalar stable - DM candidate (H)
      - (Φ_D dark doublet with dark scalars)

IDM: An Archetype for Dark Matter, Lopez Honorez,..Tytgat..07
LHC phenomenology (Barbieri., Ma.. 2006,…)

Testing Inert Doublet Model

Ma'2006,.Barbieri 2006, Dolle,Su, Gorczyca(Świeżewska), MSc T2011, 1112.4356, ...5086, ..1305. Posch 2011, Arhrib..2012, Chang, Stal ..2013

- Detailed study of
  - the SM-like h

LHC $M^2_h = m_{11}^2 = \lambda_1 v^2$

- Study of dark scalars D
  - masses depend on m_{22}^2
  - the dark scalars D in pairs!

λ_{345}

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

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

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

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

Quartic selfcouplings D^4 proportional to λ_2 hopeless

DM data

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

IDM vs DATA

Many (scans) analyses of IDM

theor. conditions (stability(positivity),pert.unitarity.

condition for Inert vacuum)

STU parameters (some LEP data)

LHC data:

$R_{\gamma\gamma}$: sensitive to invisible decays (λ_{345}^2 and M_H)

H+ loop (λ_3 (sign !) ; if λ_3 <0, λ_{345} <0)

enhancement only if λ_3 (λ_{345}) <0

Br_inv < 20%; total Higgs h width < 22 MeV

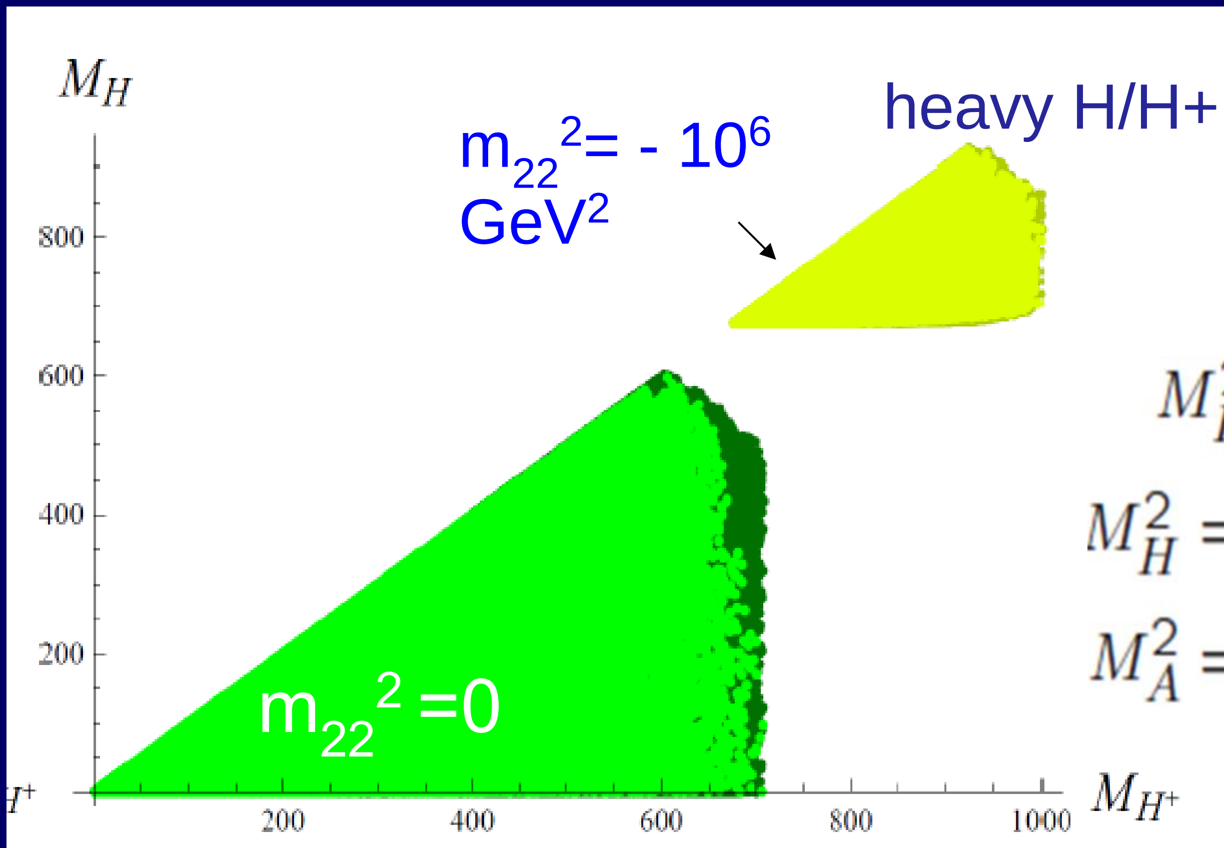
Dark matter exp: relict density

direct detection (LUX)

Inert Doublet Model with M_h=125 GeV

$m_{22}^2 = 0$

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



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

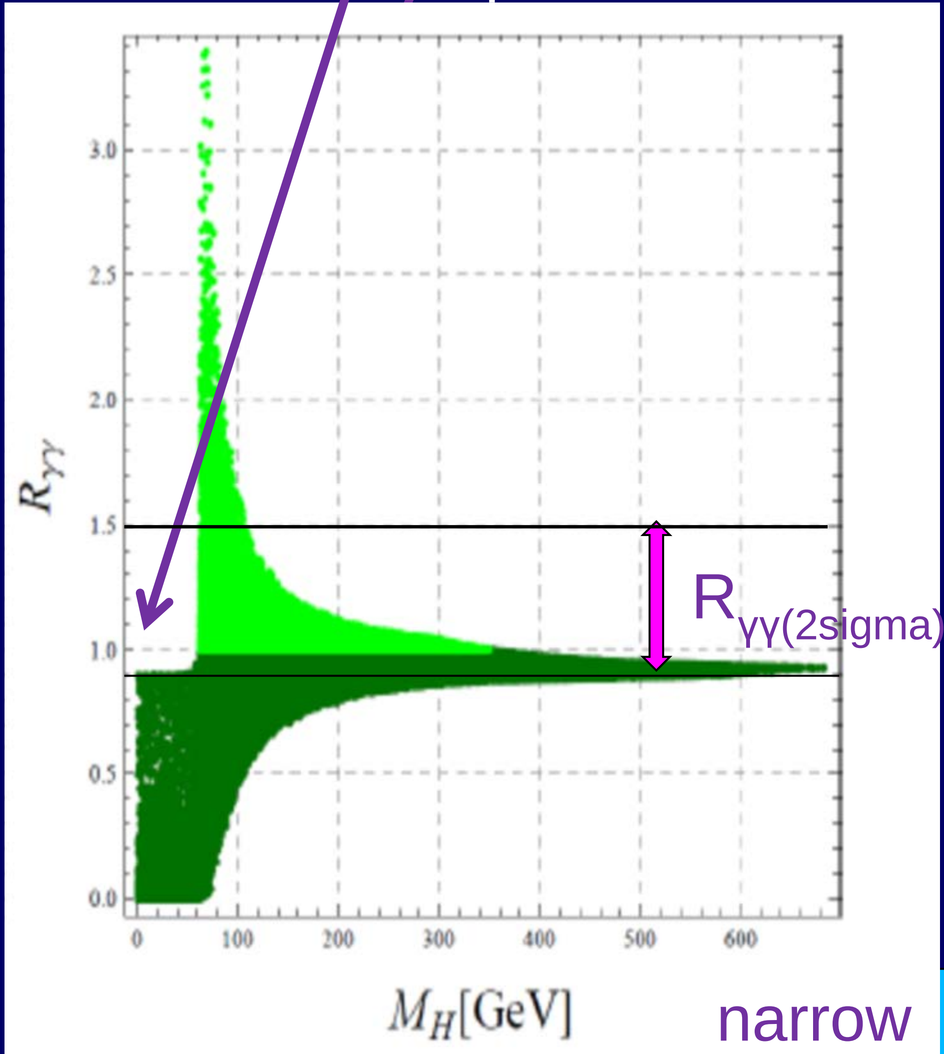
valid up to $|m_{22}^2| = 10^4\,\mathrm{GeV}^2$

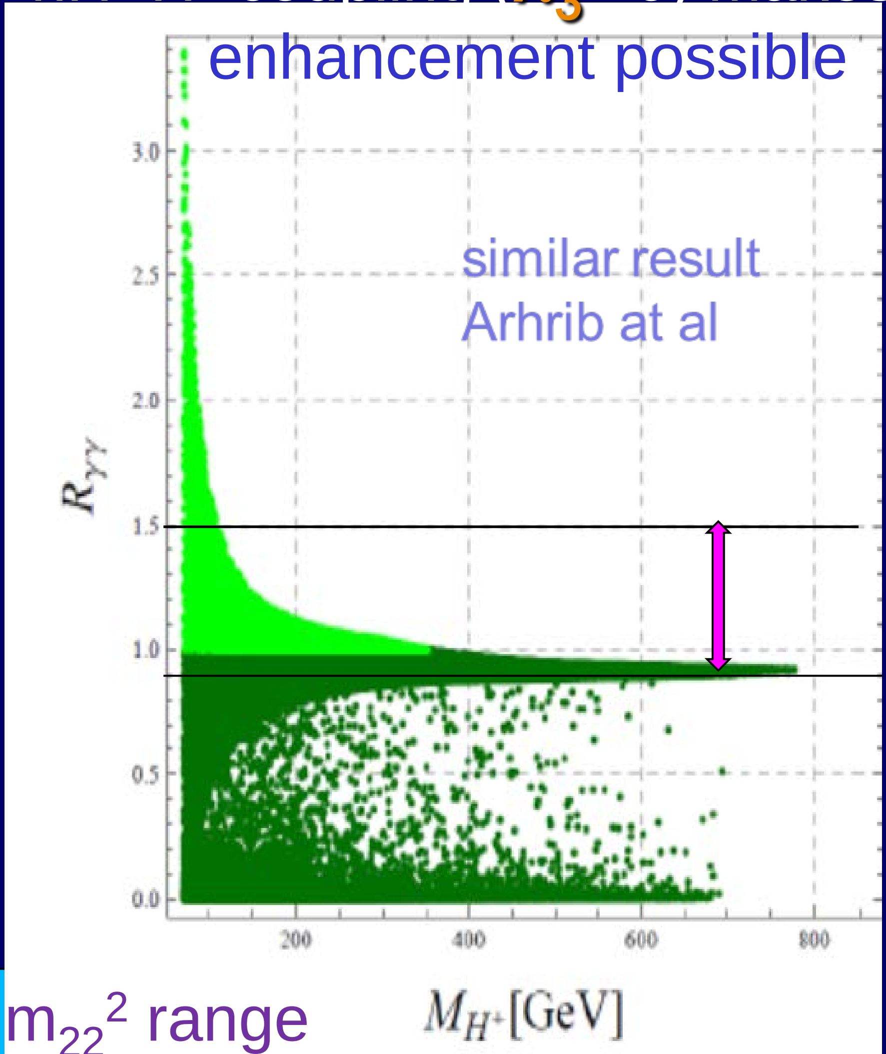
EWPT (pale regions)

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

Invisible decays makes enhancement impossible

Light H+ with proper sign of hH+H- coupling (λ_3 <0) makes enhancement possible





narrow m_{22}^2 range

Constraining **Inert** Dark Matter by $R_{\gamma\gamma}$ and WMAP data

M. Krawczyk, D. Sokolowska, P. Swaczyna, B. Swiezewska

hep-ph/ 1305.6266 JHEP 2013

Relict DM density

$$\Omega_{DM} h^2 = 0.1126 \pm 0.0036.$$

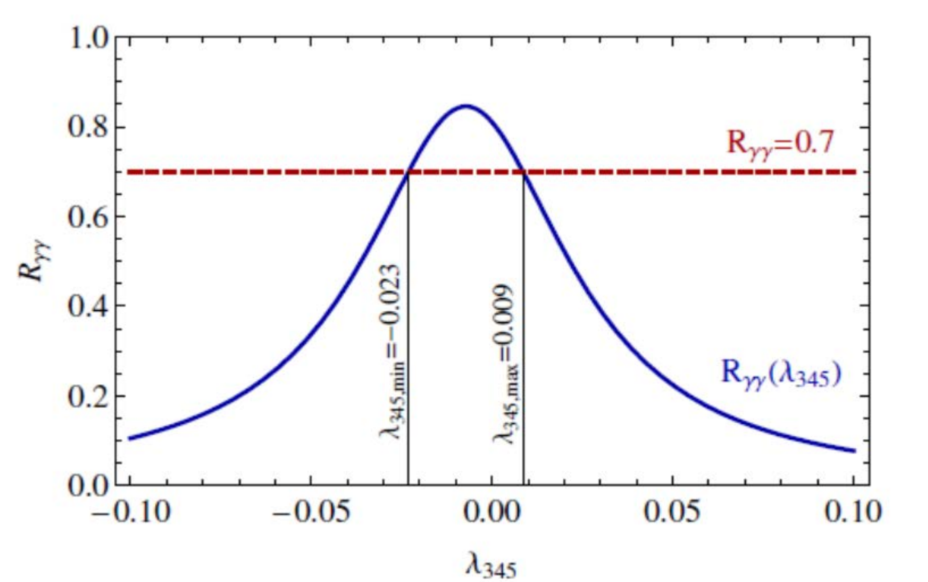
LHC data

$$\text{ATLAS} : R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$$
$$\text{CMS} : R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$$

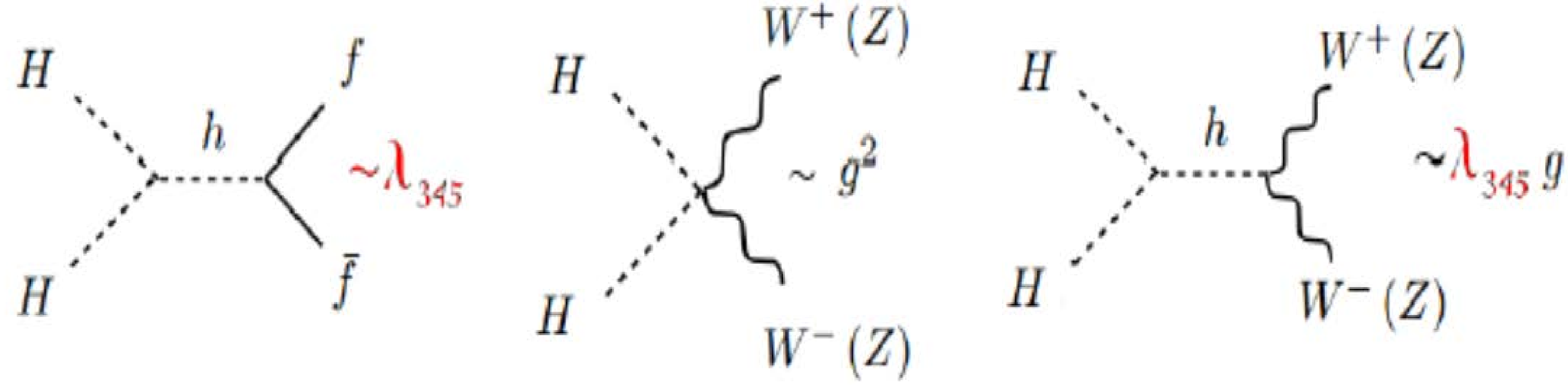
For now: $R_{\gamma\gamma} = 1.17 \pm 0.27$ (ATLAS), $R_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}$ (CMS)

$R_{\gamma\gamma} > 1$ possible
DM mass only above 62.5 GeV allowed

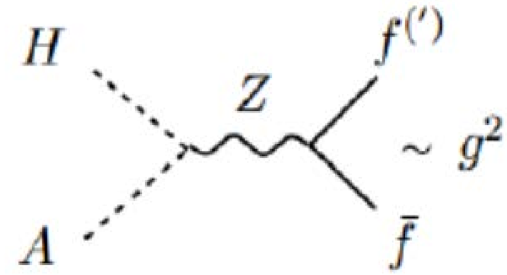
DM mass below 62.5 GeV allowed only if
$R_{\gamma\gamma} < 1$



Relic density constraints on masses and couplings of DM



Coannihilation possible for small (AH) splitting



- low DM mass $M_H \lesssim 10$ GeV, $g_{HHh} \sim \mathcal{O}(0.5)$
- medium DM mass $M_H \approx (40 - 160)$ GeV, $g_{HHh} \sim \mathcal{O}(0.05)$
- high DM mass $M_H \gtrsim 500$ GeV, $g_{HHh} \sim \mathcal{O}(0.1)$

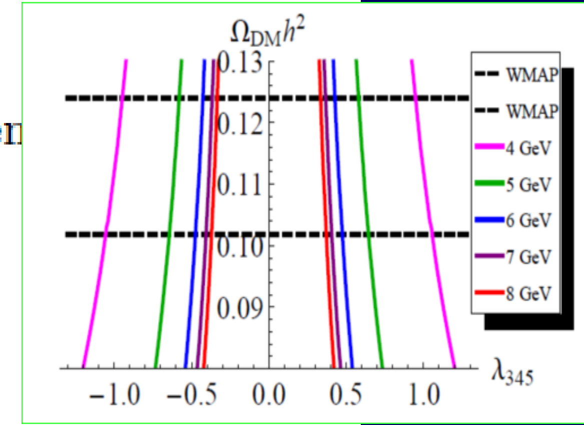
Low mass H – excluded by LHC!

$R_{\gamma\gamma}$ constraints on $\lambda_{345} \sim hHH$

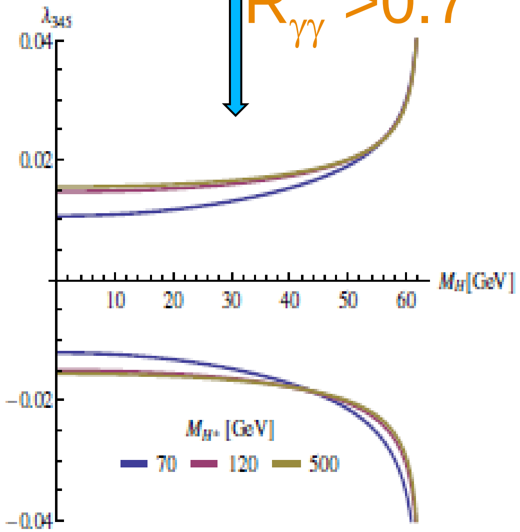
[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

$$M_H \lesssim 10\,\text{GeV}, \quad M_A \approx M_{H\pm} \approx 100\,\text{GeV}$$

$h \to AA$ channel closed, $h \to HH$ channel open



$R_{\gamma\gamma}$ >0.7



- Proper relic density

  $0.1018 < \Omega_{DM}h^2 < 0.1234 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$

- CDMS-II reported event:

  $M_H = 8.6$ GeV $\Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$

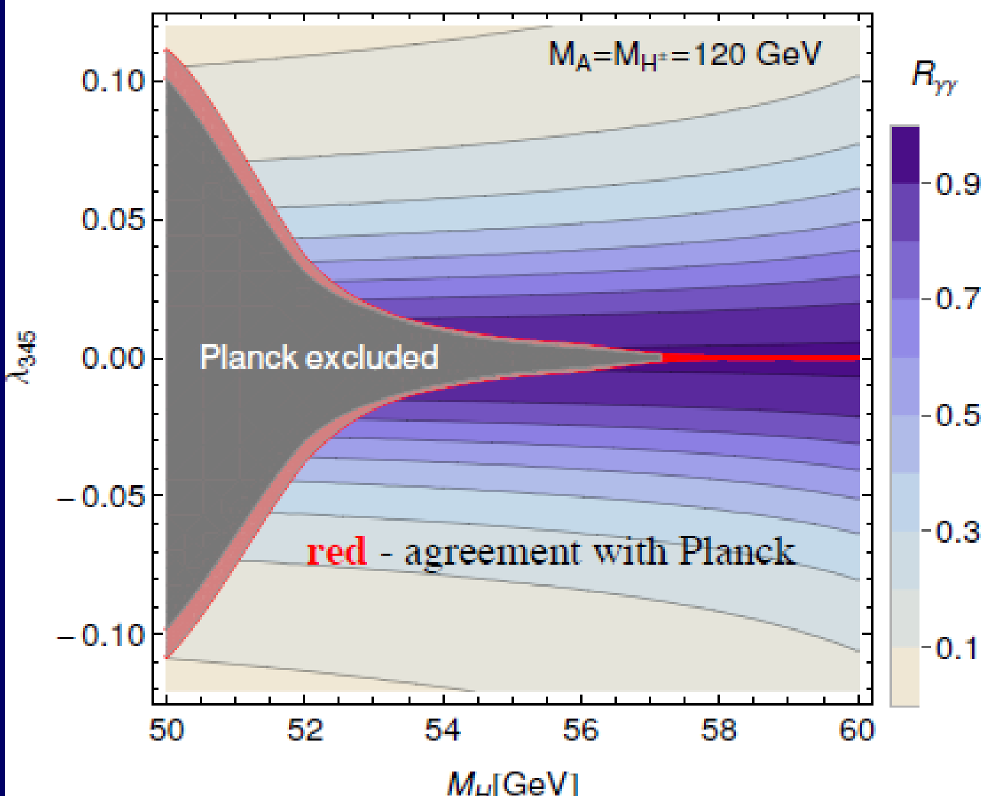
Low DM mass excluded

Sokołowska/Świeżewska

Using PLANCK data

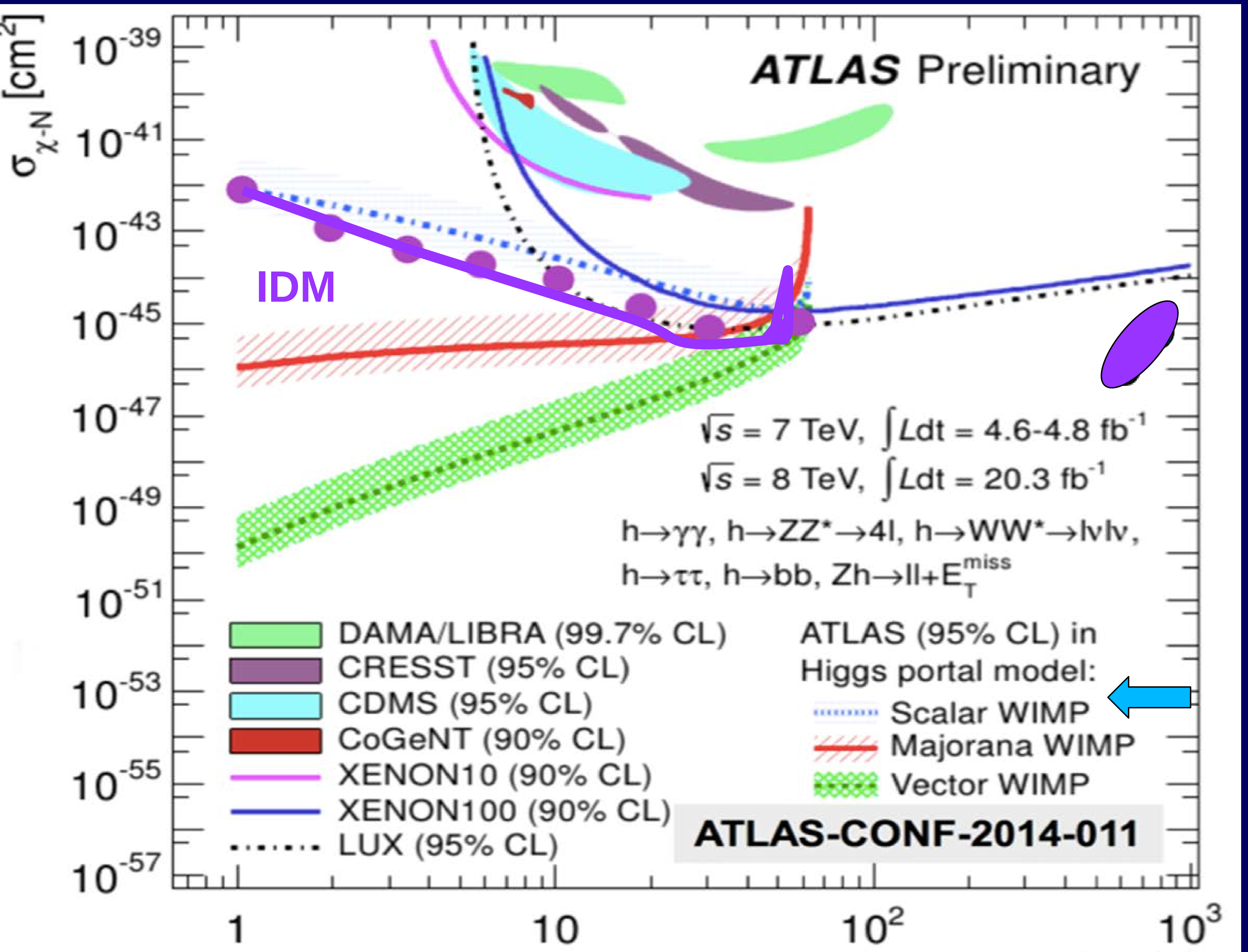
[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open



$50\,\text{GeV} < M_H < M_h/2,\ M_A = M_{H\pm} = 120\,\text{GeV}$

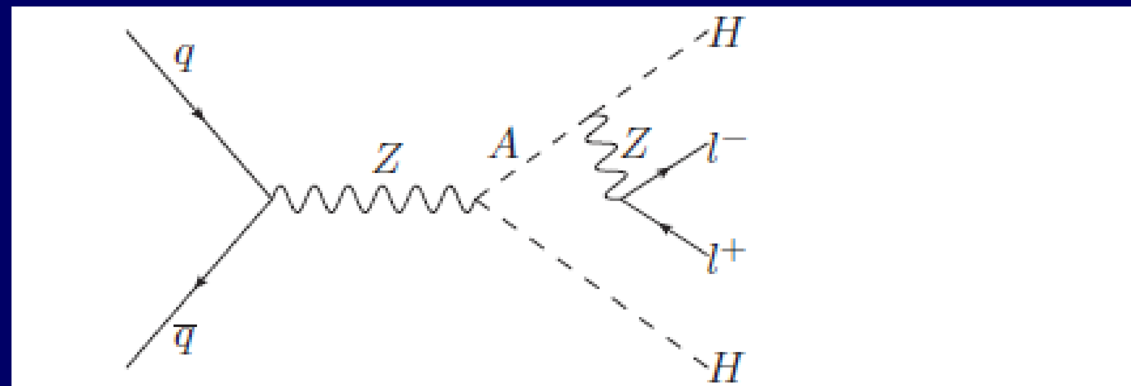
- light DM ($M_H < 10\,\text{GeV}$)
  $\Rightarrow$ excluded
- intermediate DM 1
  ($50\,\text{GeV} < M_H < M_H/2$)
  $\Rightarrow M_H > 53\,\text{GeV}$
- intermediate DM 2
  ($M_h/2 < M_H \lesssim 82\,\text{GeV}$)
  $\Rightarrow R_{\gamma\gamma} < 1$
- heavy DM
  ($M_H > 500\,\text{GeV}$)
  $\Rightarrow R_{\gamma\gamma} \approx 1$



$\sigma_{\chi\text{-}N}$ [cm^2]
ATLAS Preliminary
IDM
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 20.3 fb^{-1}
h→γγ, h→ZZ*→4l, h→WW*→lνlν,
h→ττ, h→bb, Zh→ll+E_T^{miss}
DAMA/LIBRA (99.7% CL)
CRESST (95% CL)
CDMS (95% CL)
CoGeNT (90% CL)
XENON10 (90% CL)
XENON100 (90% CL)
LUX (95% CL)
ATLAS (95% CL) in
Higgs portal model:
Scalar WIMP
Majorana WIMP
Vector WIMP
ATLAS-CONF-2014-011
10^{-39}
10^{-41}
10^{-43}
10^{-45}
10^{-47}
10^{-49}
10^{-51}
10^{-53}
10^{-55}
10^{-57}
1
10
10^2
10^3

IDM: DM production at LHC

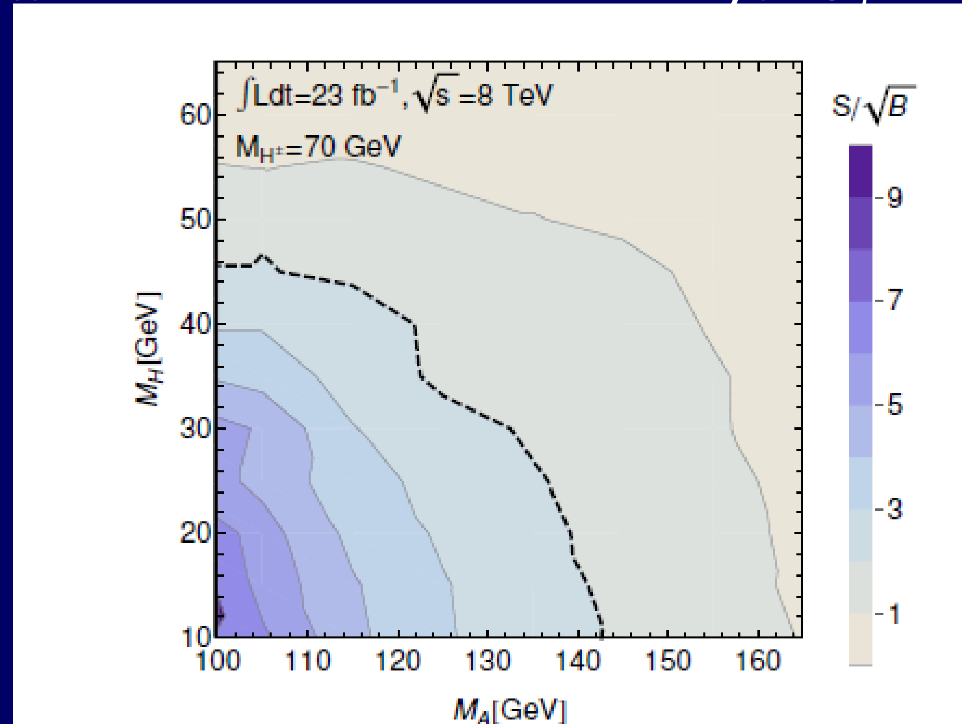
LHC at 8 TeV



P. Swaczyna
MSc, May 2013

SM background WW,ZZ, tt

Pythia, 2HDMC



$S/\sqrt{B}$ above 2

M_H+M_A< 145 GeV
M_A>100 GeV

work in progress
Bach,Ilnicka,Robens,MK

New scan for IDM (2015)

A. Ilnicka, T. Robens, MK

Theor. constraints -
stability(positivity),pert.unitarity, condition for Inert vacuum

STU

Higgssignal/Higgs bounds (summer 2014)

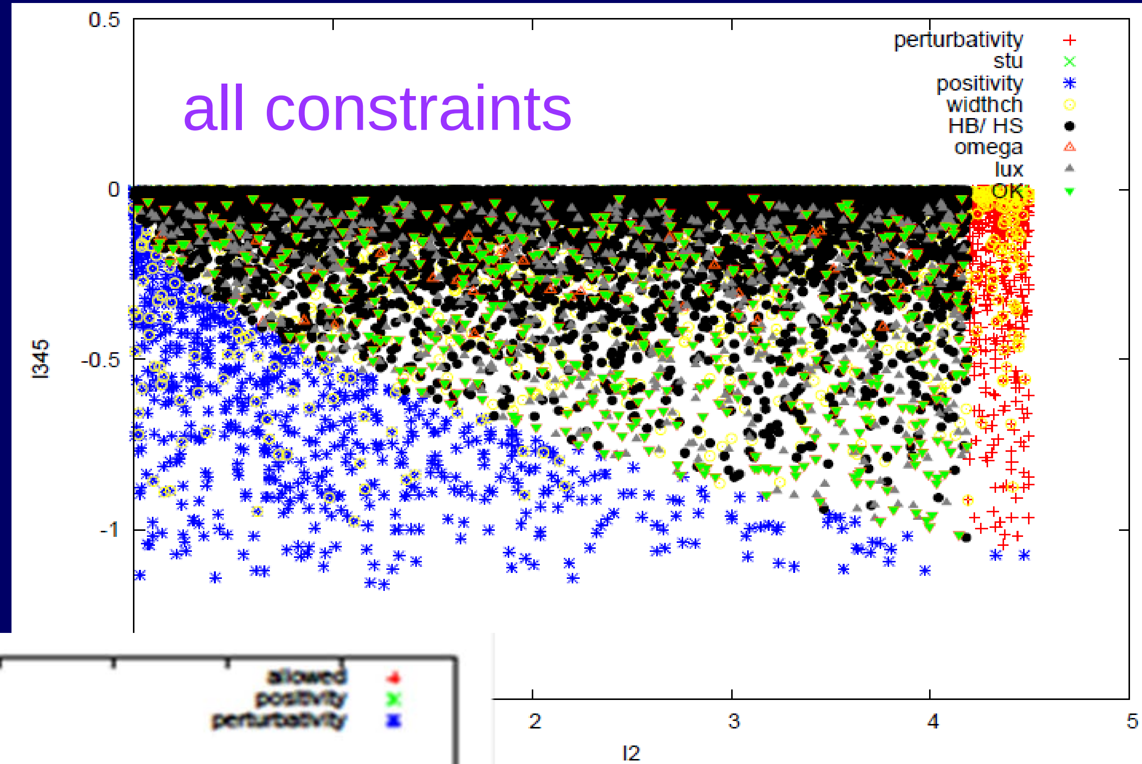
Lifetime of H+

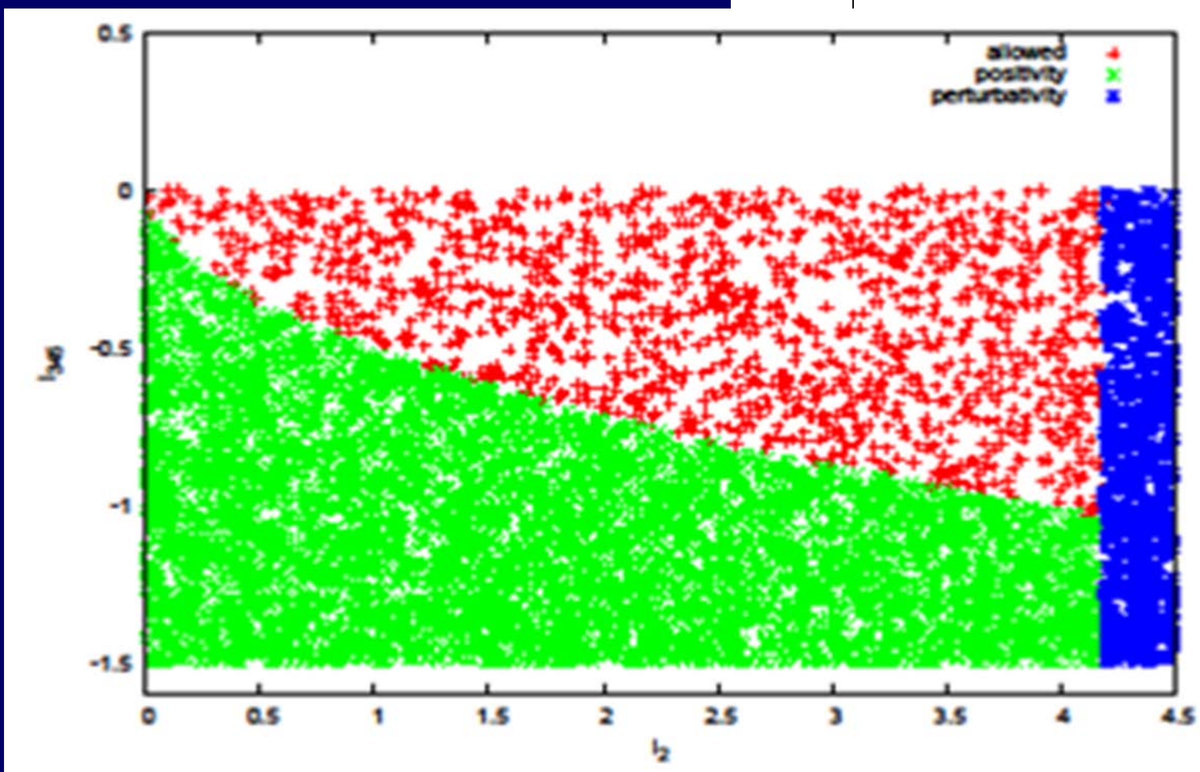
Relict density

LUX

--> scan over M_H up to1 TeV

λ_{345} vs λ_2



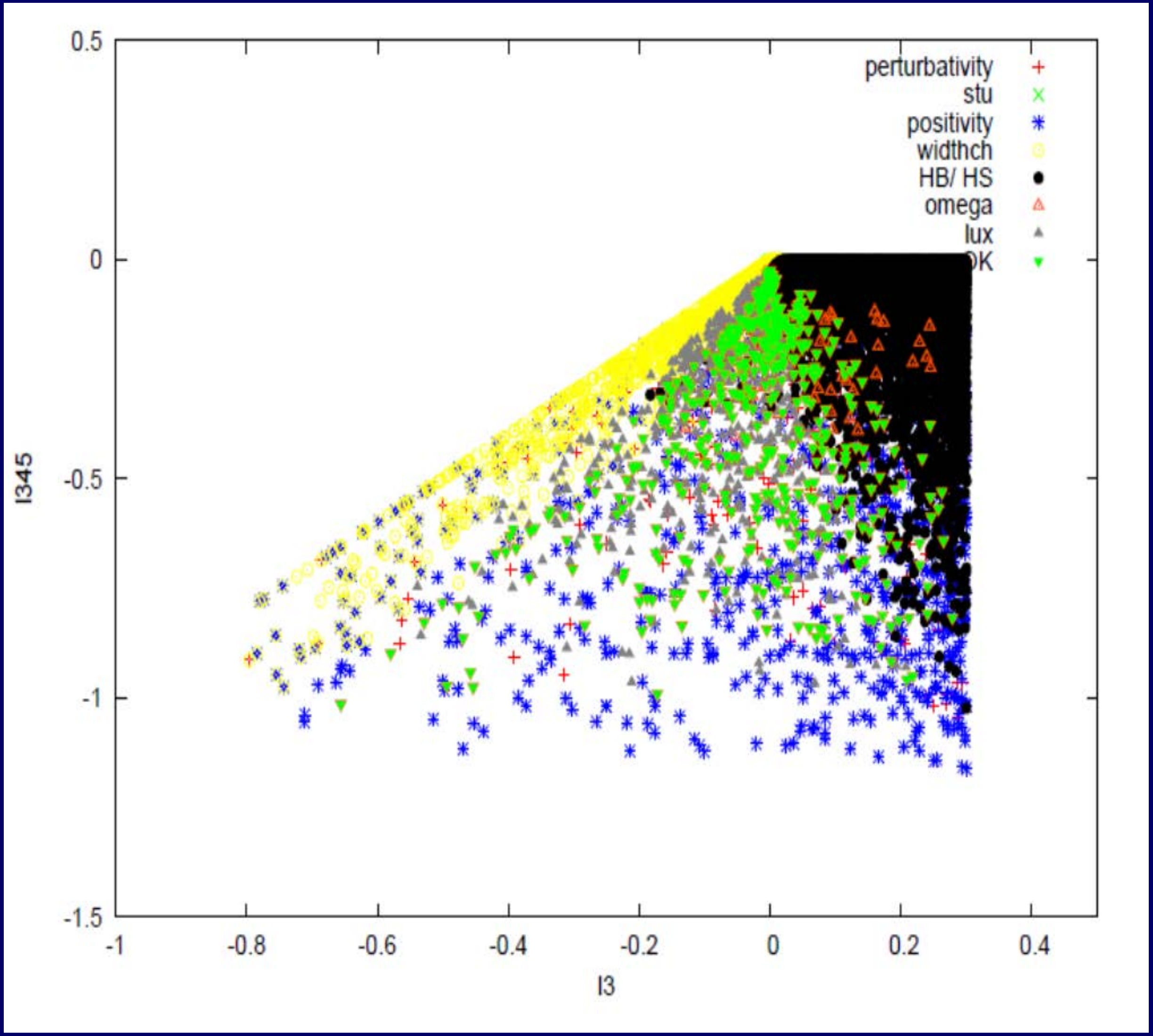


$-1 < \lambda_{345} < 0$,

$\lambda_2 < 4.2$

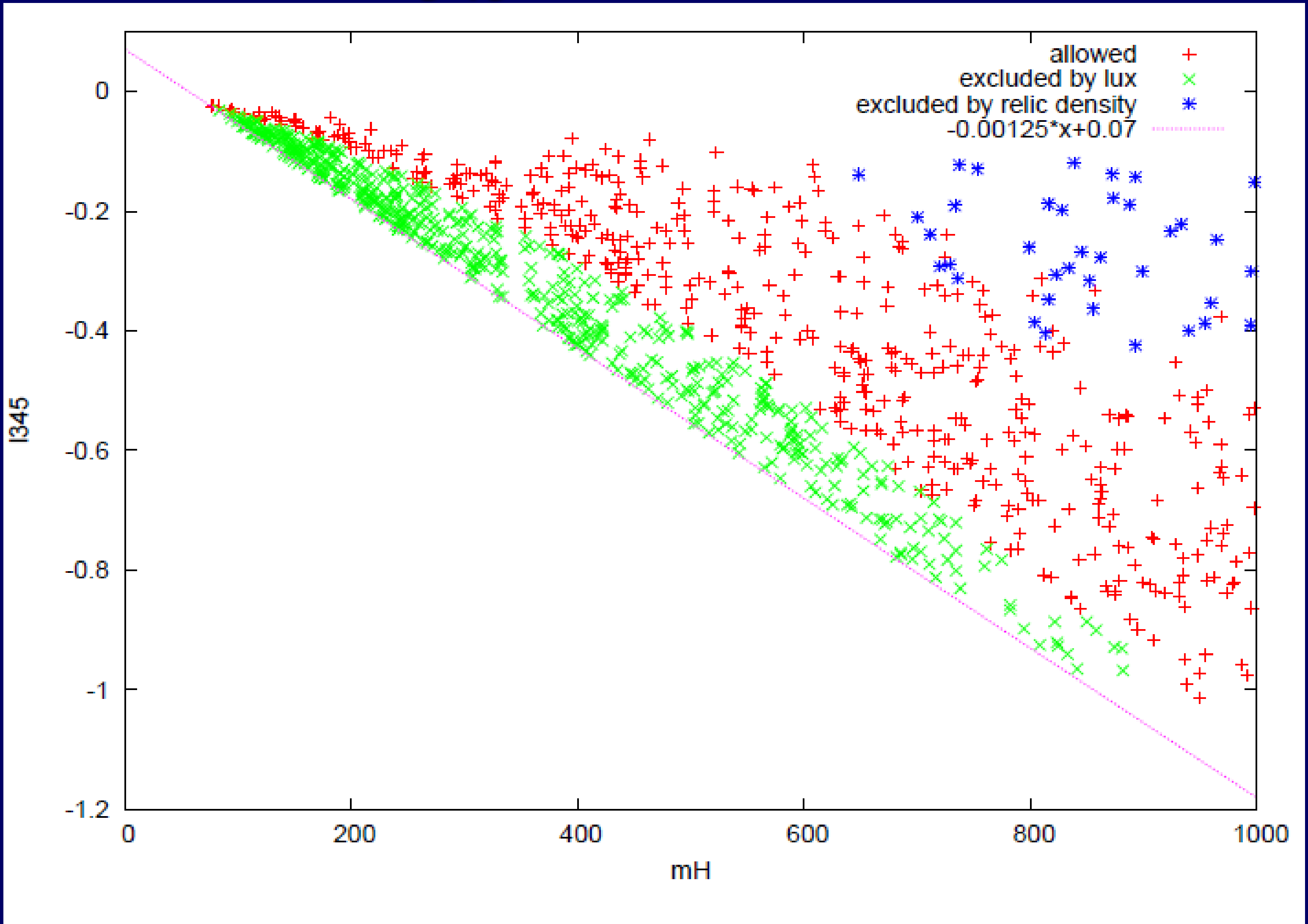
with DM constraints, no HS/HB

λ_{345} vs λ_3

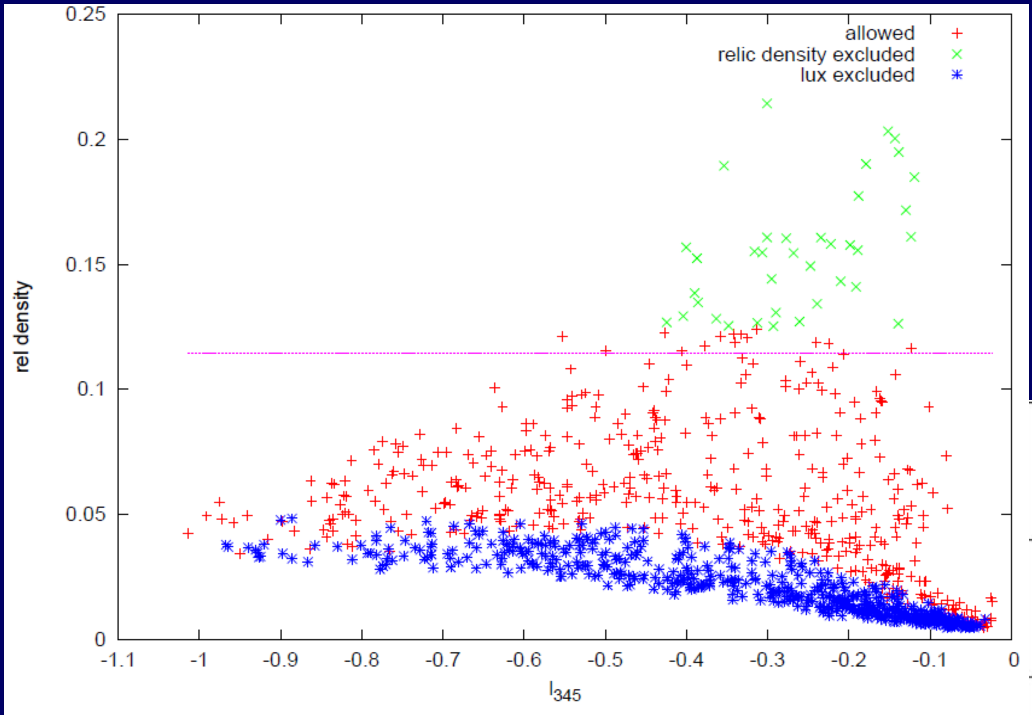


dominantly $\lambda_3 < 0$

Coupling λ_{345} vs M_H

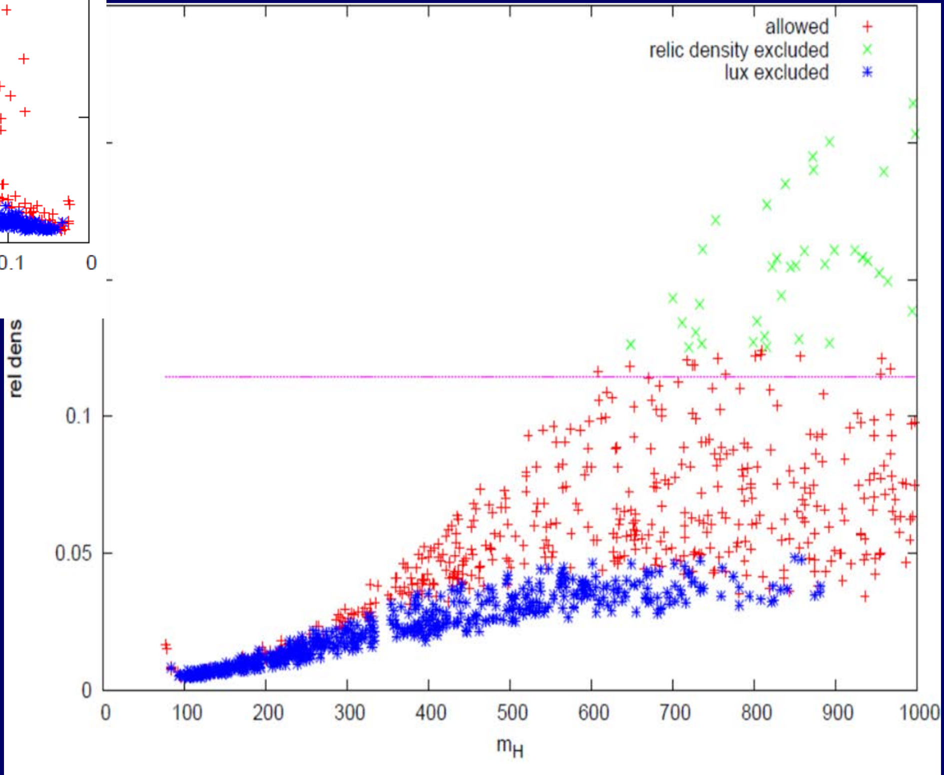


Relic density (and LUX) vs λ_{345}



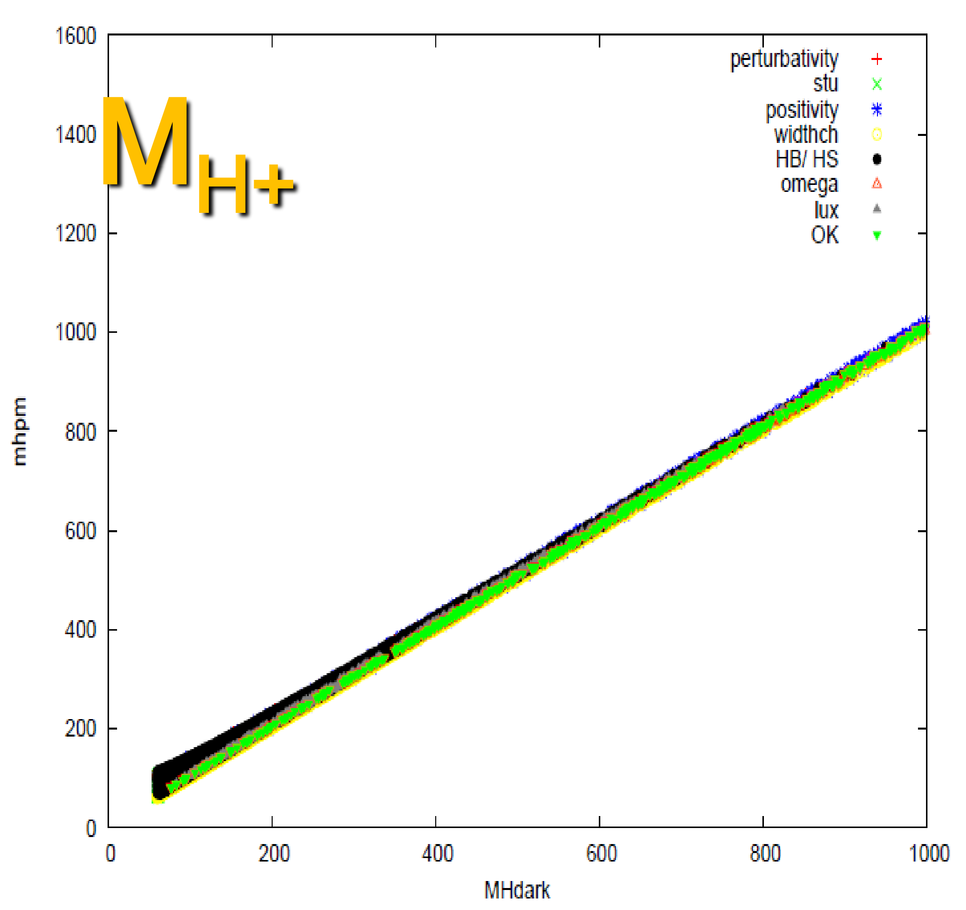
other constraints satisfied

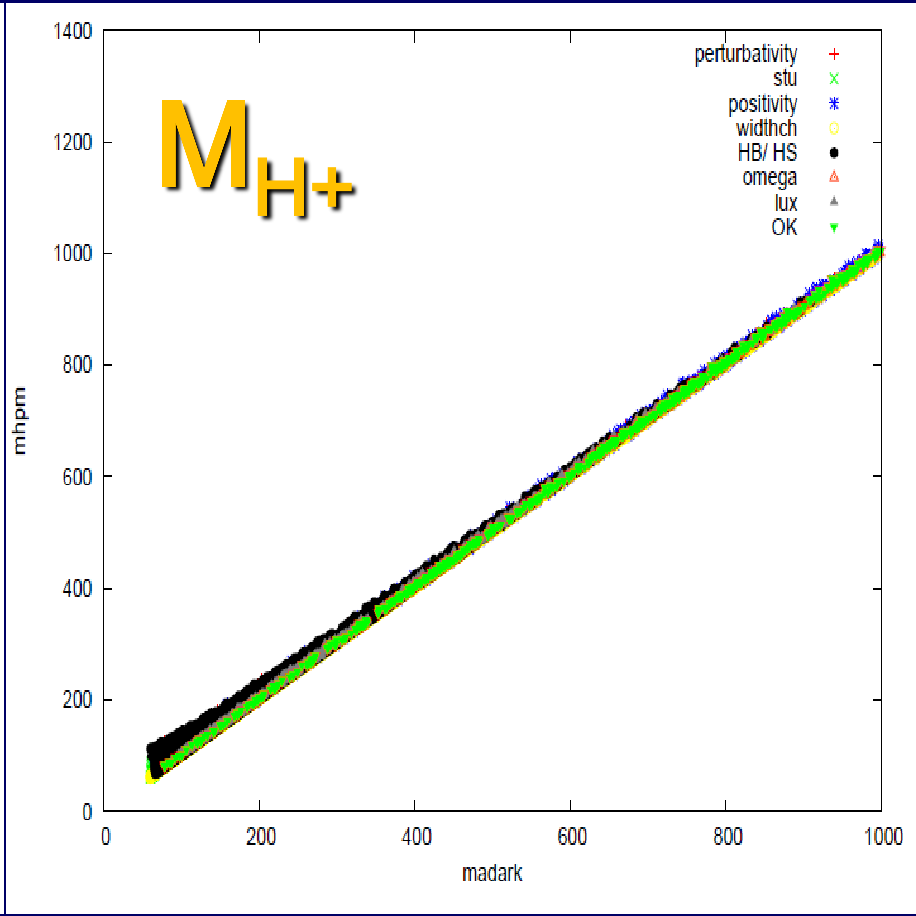
vs M_H



No solution for DM mass below 60 GeV

M_{H+} vs M_H (or M_A) – degeneracy!





M_H

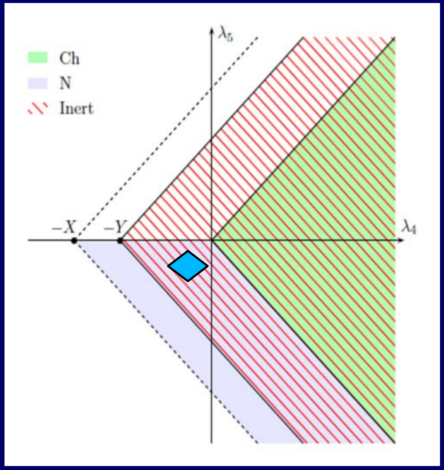
M_A

CONSEQUENCES?

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

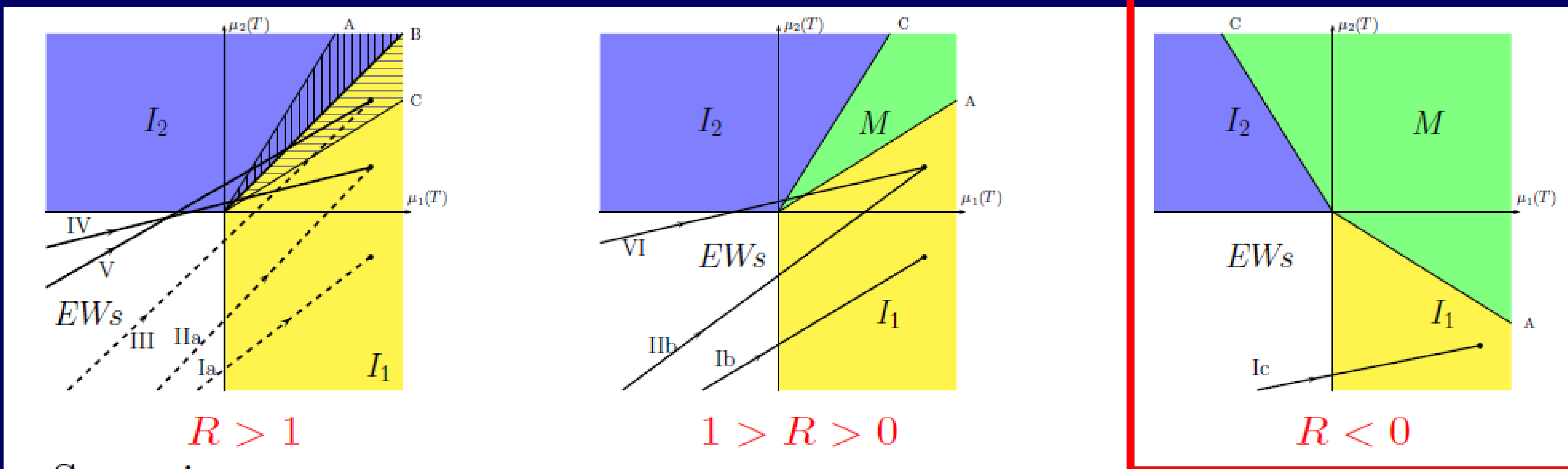


Various evolution from EWs to Inert phase possible in one, two or three steps, with 1st or 2nd order phase transitions...

Evolution of vacua on phase diagram (μ_1, μ_2)

$\lambda_{345} < 0$!!

$EWs \rightarrow I_2 \rightarrow I_1$



$EWs \rightarrow I_1$

stability condition

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

$$R + 1 > 0$$

T2 corrections

→ rays from EWs phase to Inert phase
one, two or three stages of Universe
(II order phase transitions, one I order)

Beyond T^2 corrections – strong 1st order phase transition in IDM? EW bariogenesis?

G. Gil MsThesis'2011, G.Gil, P. Chankowski, MK 1207.0084 [hep-ph] PLB 2012

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

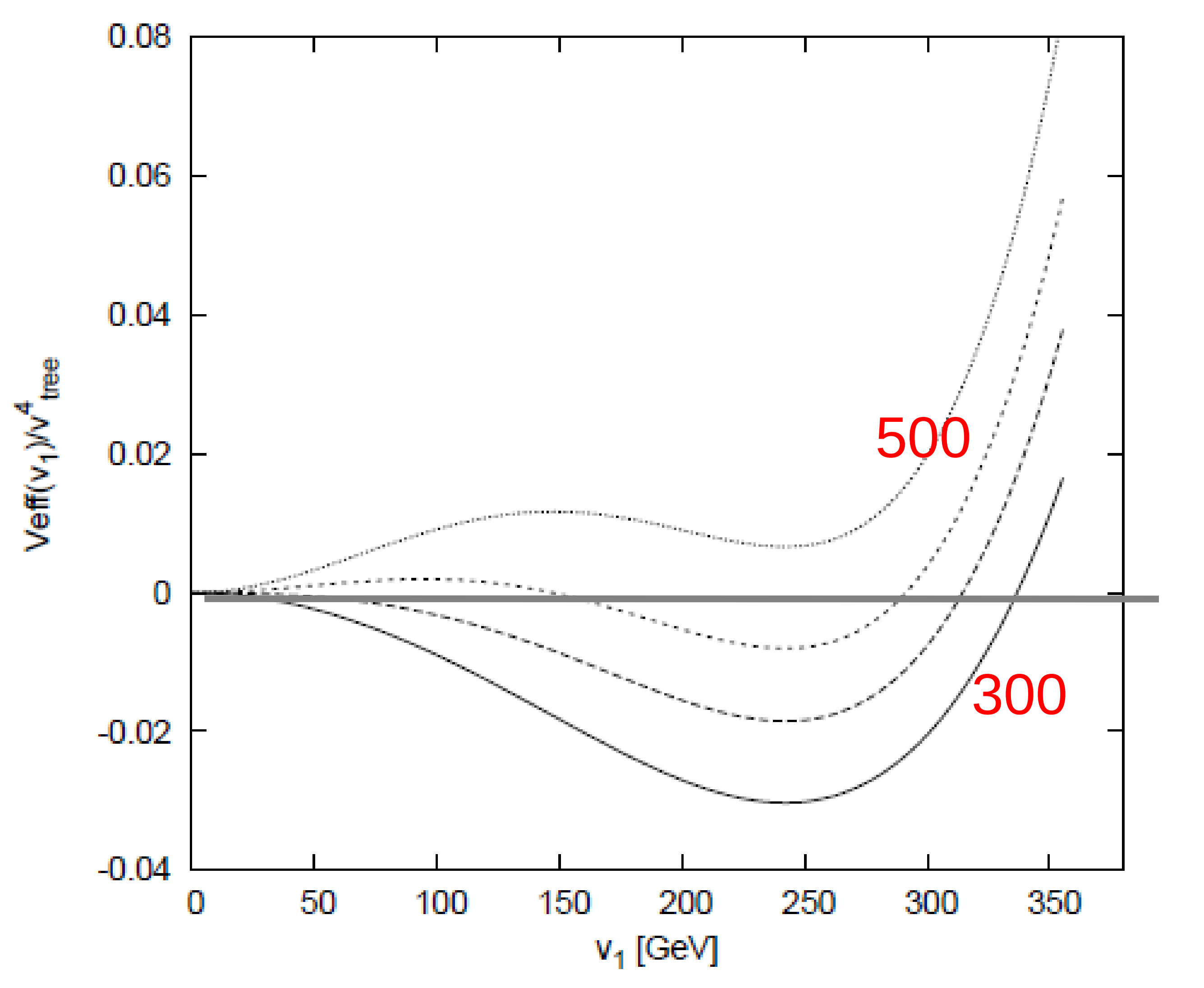
mass matrices

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

number of states

counter terms →

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 $v_{1(s)}=v_{2(D)}=0$

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

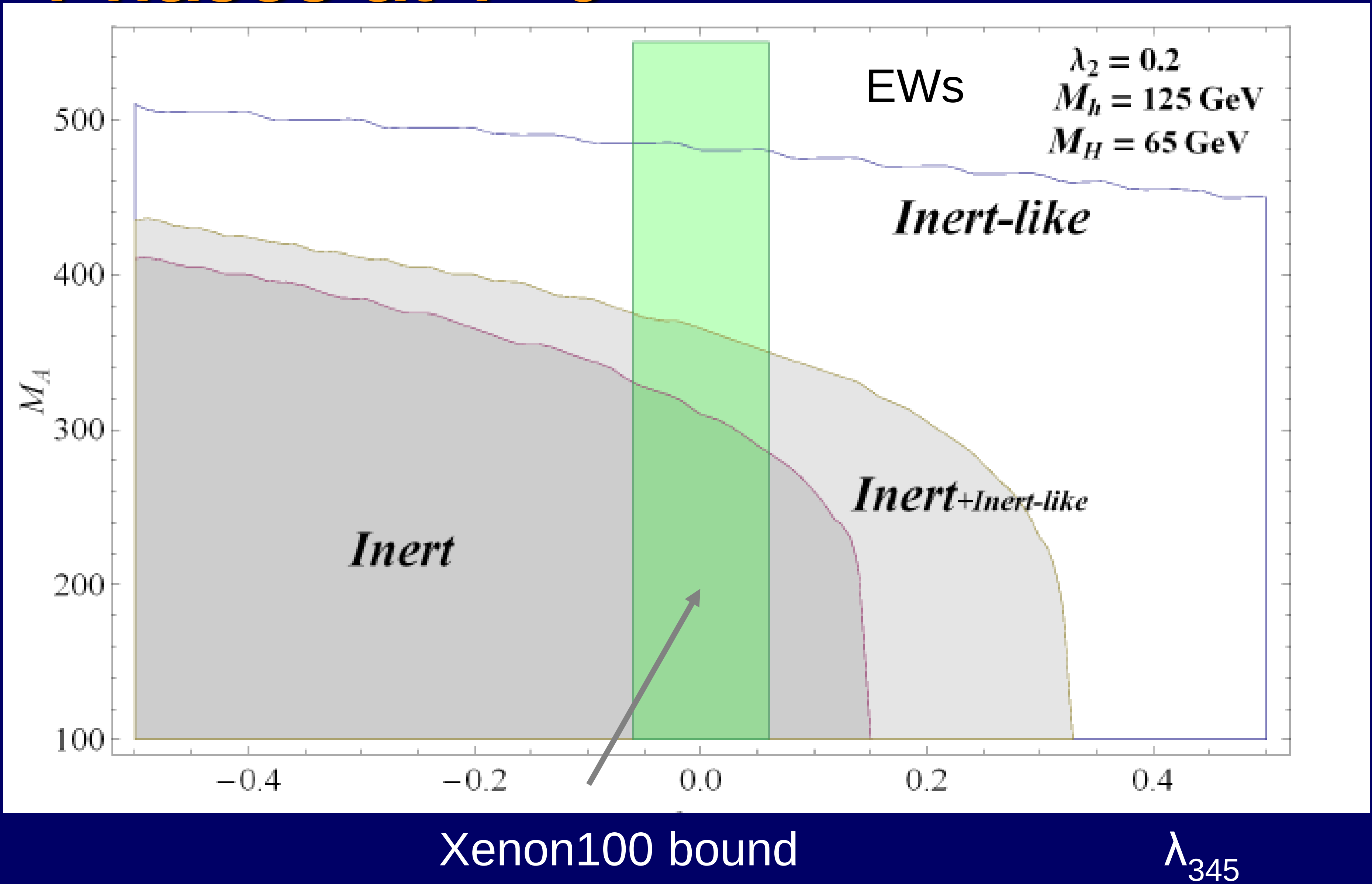
$$v(T_{EW})/T_{EW} > 1$$

being in agreement with collider and astrophys. 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

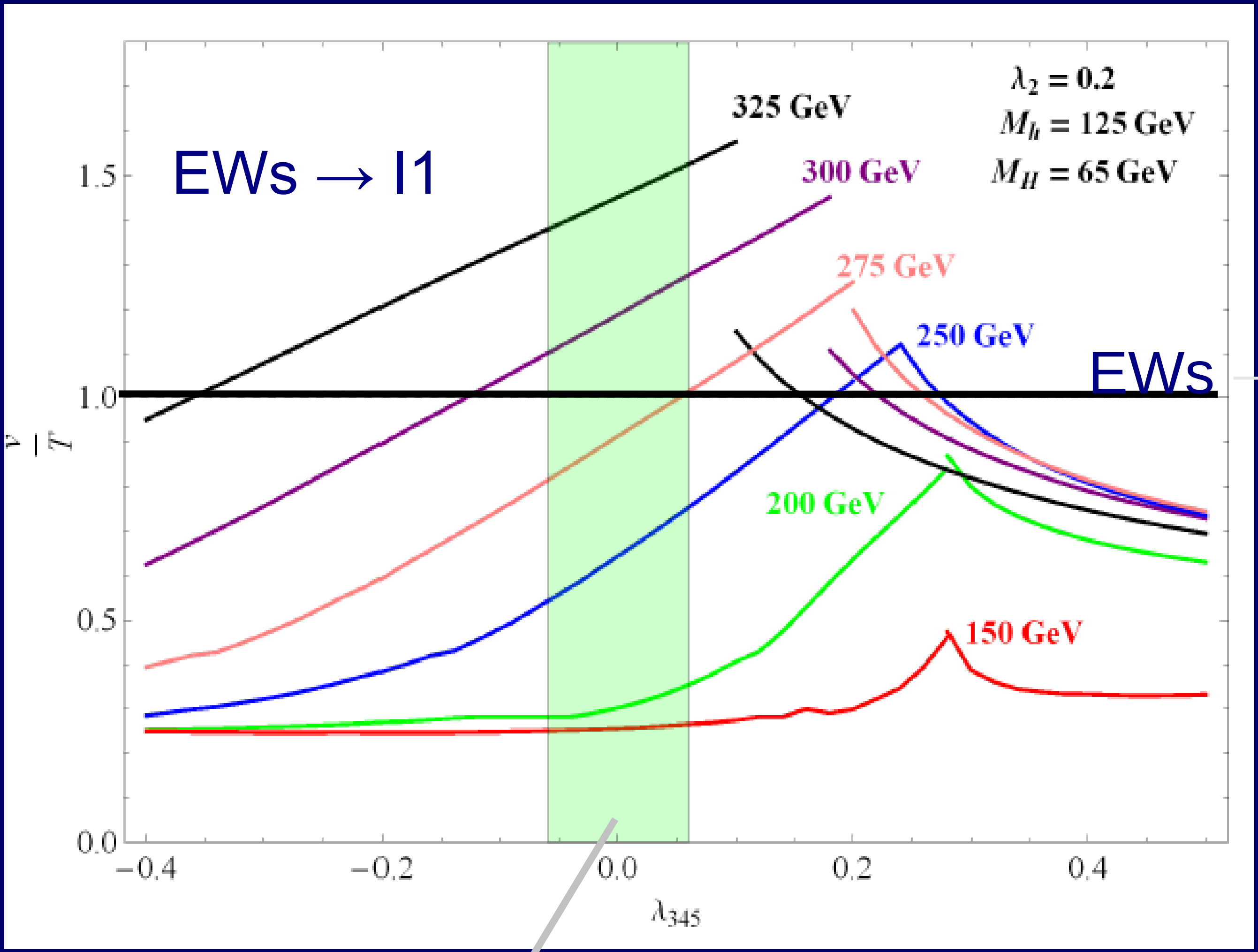


EWs
λ2 = 0.2
Mh = 125 GeV
MH = 65 GeV
Inert-like
Inert+Inert-like
Inert
MA
500
400
300
200
100
−0.4
−0.2
0.0
0.2
0.4
Xenon100 bound
λ345

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

Mh=125 GeV, MH=65 GeV, λ2=0.2

strong 1st order phase transition if ratio > 1



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

λ_{345}

R<0

Xenon100 bound

R>0

Conclusion (beyond T^2)

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: mass 275-380 GeV
2/ low value of hHH coupling $|\lambda_{345}| < 0.1$
3/ Coleman-Weinberg term important

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)

Vacuum (meta)stability

[D. Buttazzo et al., JHEP 1312 (2013) 089, V. Branchina, E. Messina, PRL 111 (2013) 241801, C. Callan, S. Coleman, PRD 16 (1977) 1762]

- stable vacuum = global minimum of the potential
- matastable vacuum = local minimum with $\tau > 1$,
  τ – relative (w.r.t. to the age of the Universe) lifetime

SM vacuum – long-lived, metastable state

QUESTION: How do additional scalars affect vacuum stability?

B. Świeżewska, in preparation

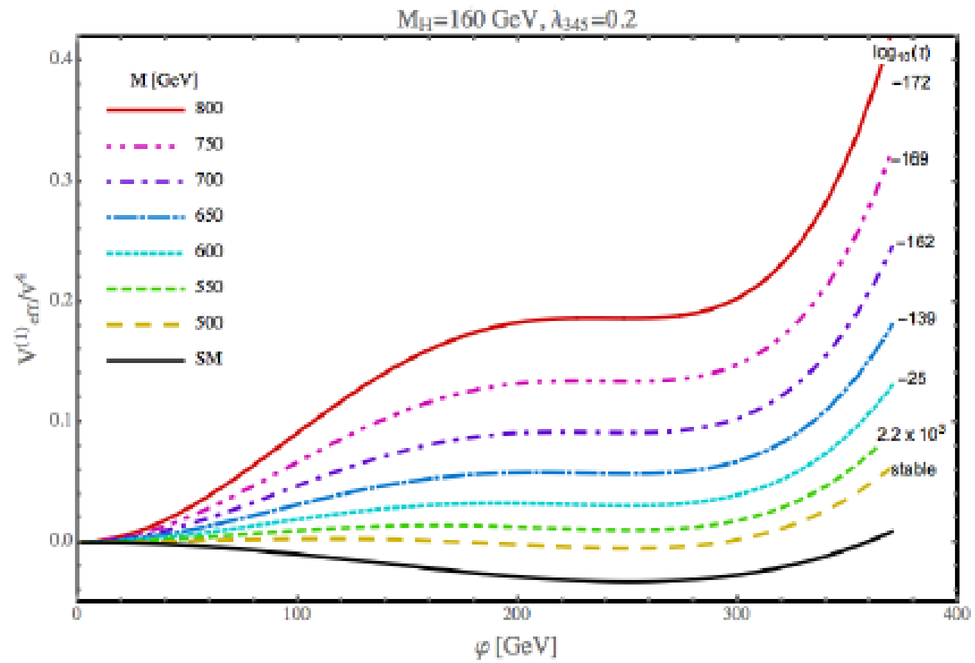
Metastbility at EW scale

B. Świeżewska

[A. Goudelis, B. Herrmann, O. Stål, JHEP 09 (2013) 106, P. Chankowski, G. Gil, M. Krawczyk, PLB 717 (2012) 396-402]

Due to additional scalars

- improved stability at large field values (Higgs self-coupling crosses zero later)
- the EWSB minimum can become a local one
- for heavy scalars the lifetime of EWSB minimum is very short



⟶ See the poster of B. Świeżewska

Are we approaching a new era?

Spring 2015 at LHC…

Higgs data → Dark Matter

Dedicated DM analysis at LHC

What about ILC ?

(NB. IDM analysis, by Kanemura et al. is ready)

International Linear Collider ILC

Origin of the Linear Collider Idea

M. Tigner,
Nuovo Cimento **37** (1965) 1228

A Possible Apparatus for Electron-Clashing Experiments (

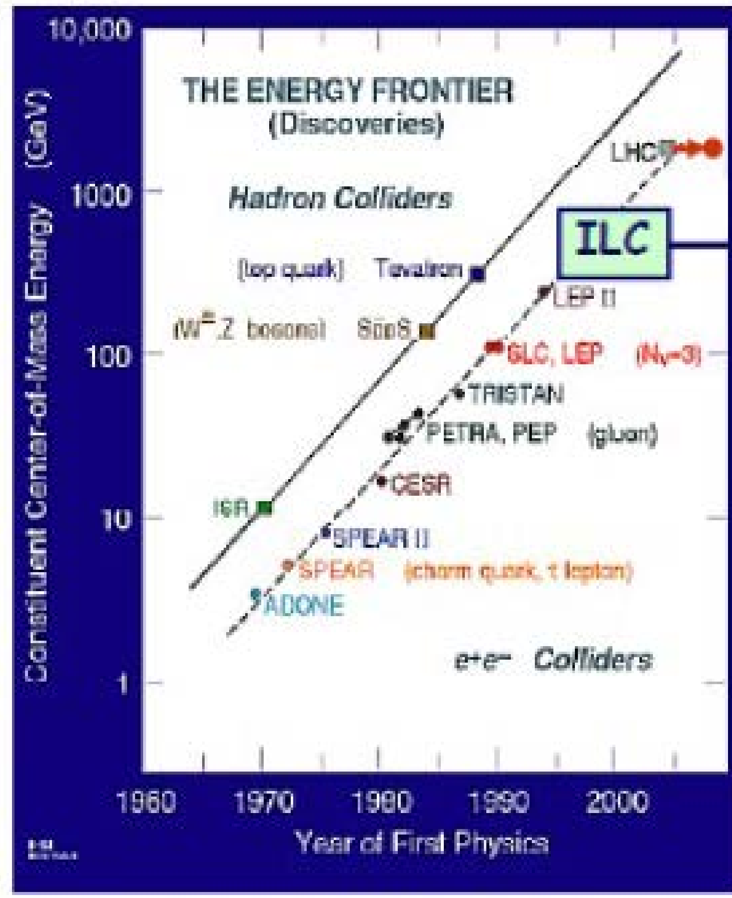
M. Tigner

Laboratory of Nuclear Studies. Cornell University - Ithaca, N.Y.

"While the storage ring concept for providing clashing-beam experiments ([1]) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant and superficially more complex may prove more tractable."

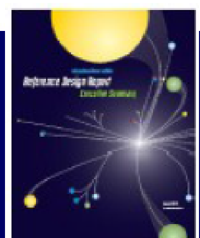
Daniele Sertore

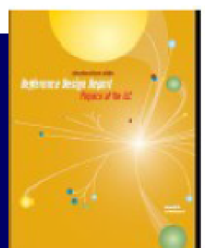
50 years!



RDR Design Parameters

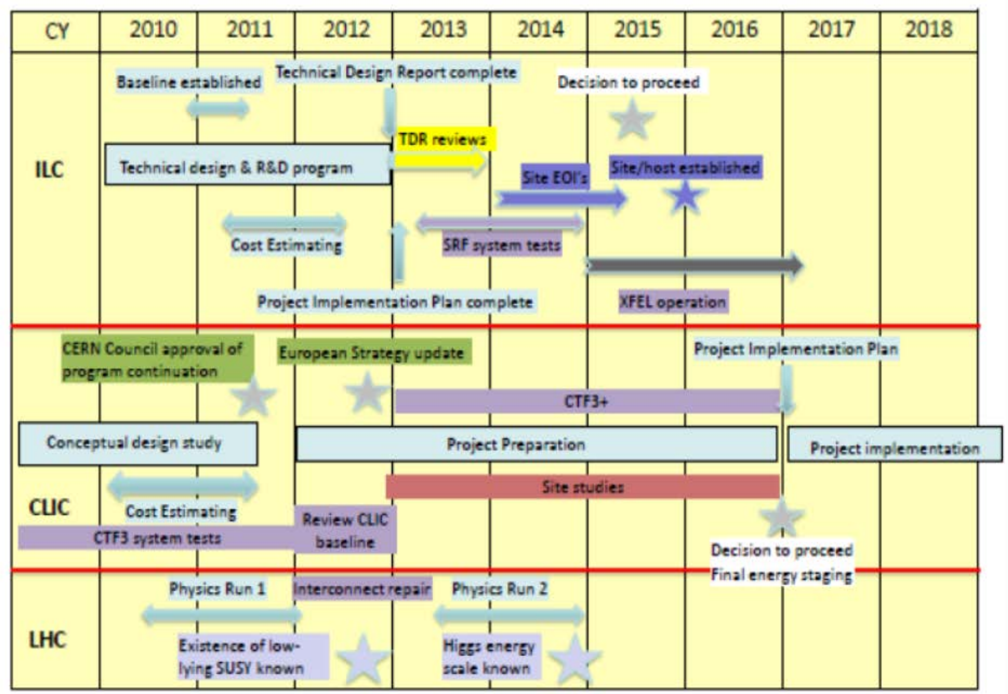
Max. Center-of-mass energy	500	GeV
Peak Luminosity	~2x10[34]	1/cm[2]s
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MV





2007

CLIC & ILC roadmaps



Ph.Lebrun

125 GeV *Higgs* at PLC ?

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

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

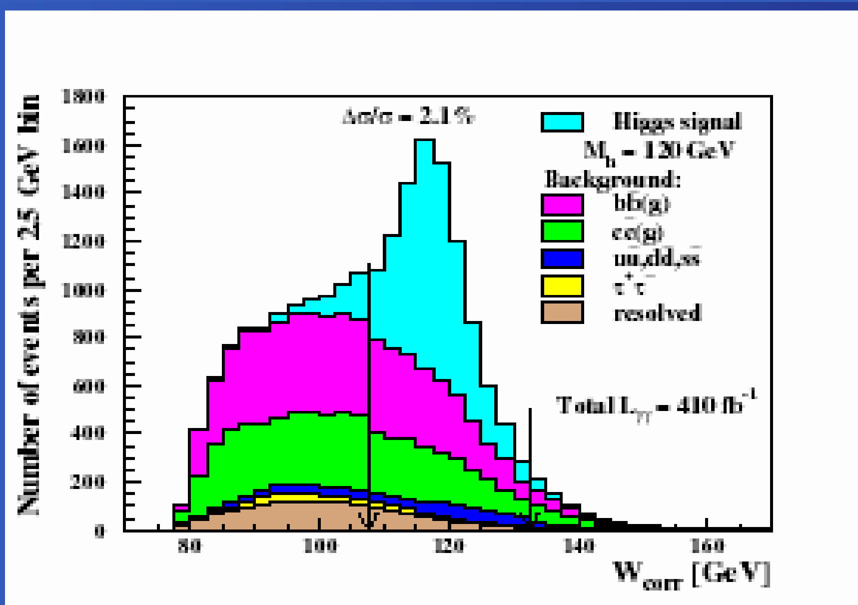
SM summary

NŻK

Niezurawski et al.,

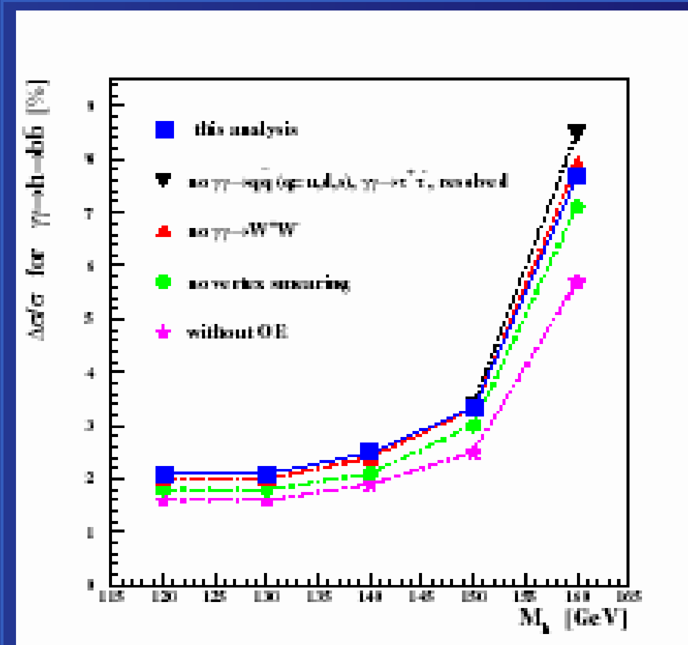
Monig, Rosca

→ 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 $\gamma\gamma \to W^+W^-$

M.Peskin (SLAC) in 2010

one final point:

There is a significant opportunity for the discovery of new particles in the 2011 LHC run at 7 TeV. In this case, the magic moment of discovery will come in 2011 or 2012.

Presidents, legislators, and journalists have an attention span of years, not decades. We should be ready with a case for a new collider that addresses the physics questions raised by this discovery and can be implemented immediately.

In 2012, the only LC technology on the table will be ILC. To take advantage of the opportunity, we have be ready, as a community, to go forward with the ILC.

Final conclusion

Near future 2015-16

looks

very interesting