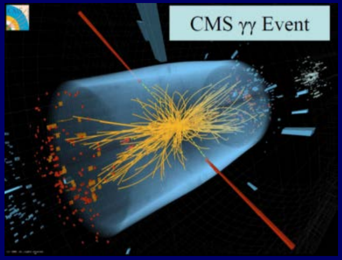
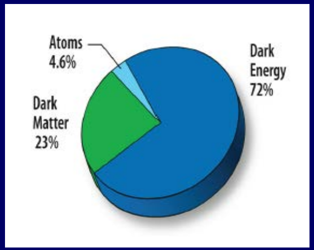
PHOTON2015, Novosibirsk ,15.6. 2015

Higgs(es) and photons



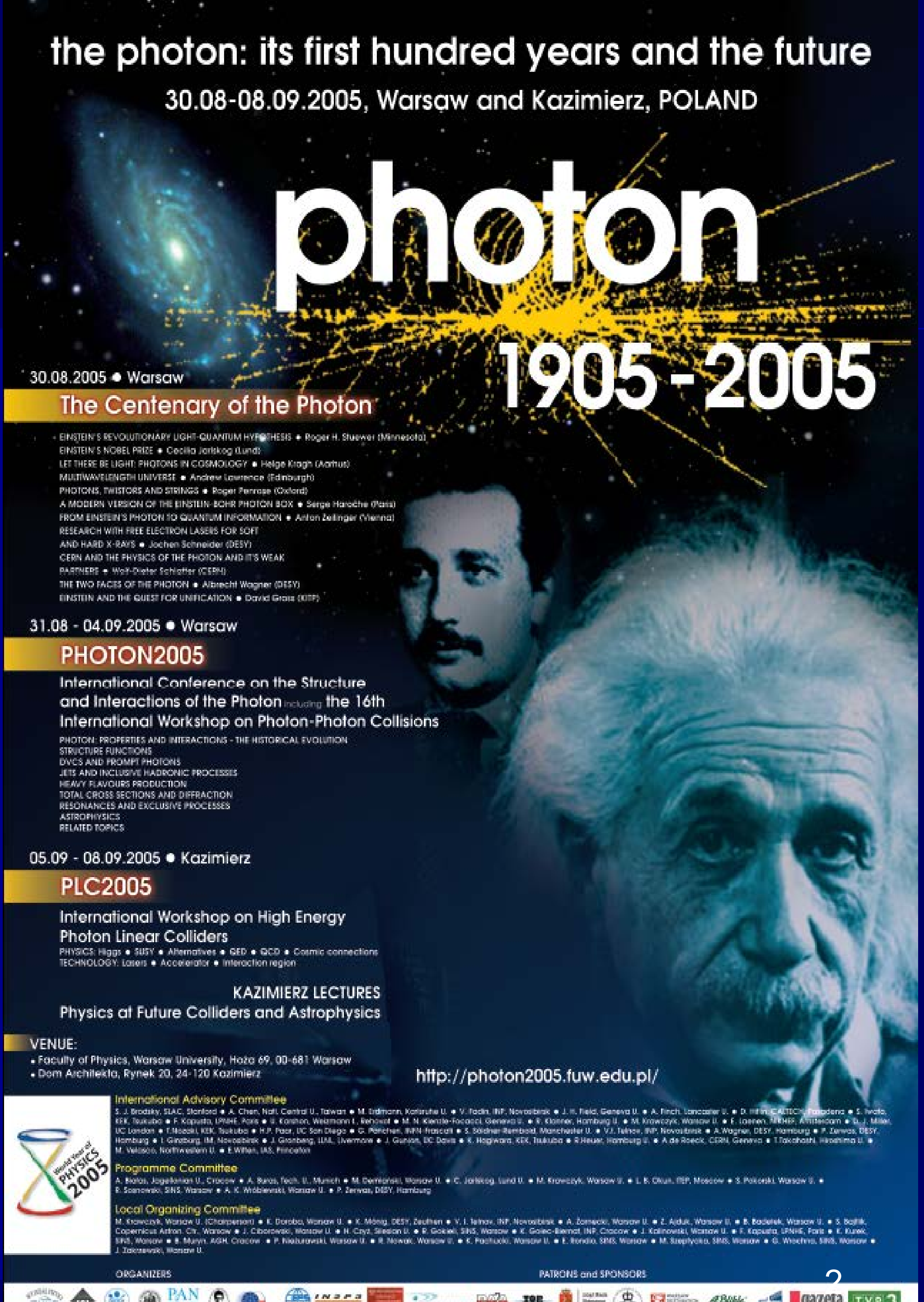


Maria Krawczyk
Dept of Physics, U. of Warsaw

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

Year of Physics 2005

Warsaw



2015: International Year of Light PHOTON2015

INTERNATIONAL YEAR OF LIGHT 2015

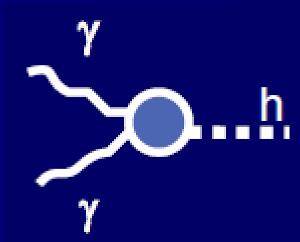
- Optics -Ibn Al Haytham 1015
- Wave nature of light - Fresnel 1815
- Electromagnetic waves - Maxwell 1865
- Photoelectric effect (photon) -Einstein 1905
- Special relativity (space-time, velocity of light c) - Einstein 1915
- Cosmic microwave radiation - Penzias, Wilson -1965
- Use of optical fiber in telecommunication – Kao 1965

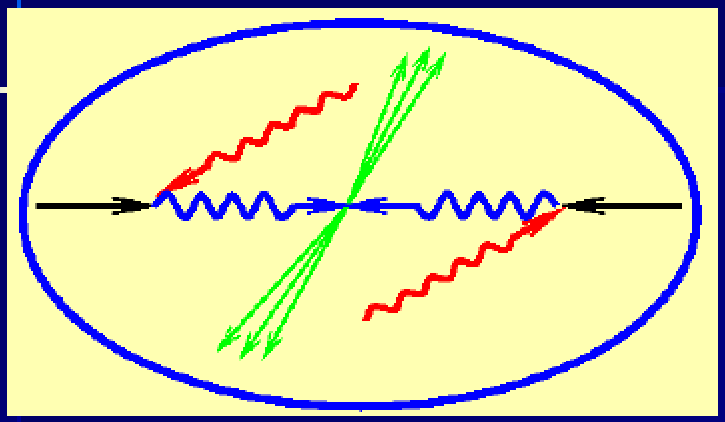
http://www.unesco.pl/644/

My perspective

- From the structure of photon to the Higgs
- From the structure of photon to the photon (linear) collider PLC: $\gamma\gamma$ and eγ modes

- Higgs resonance at the PLC

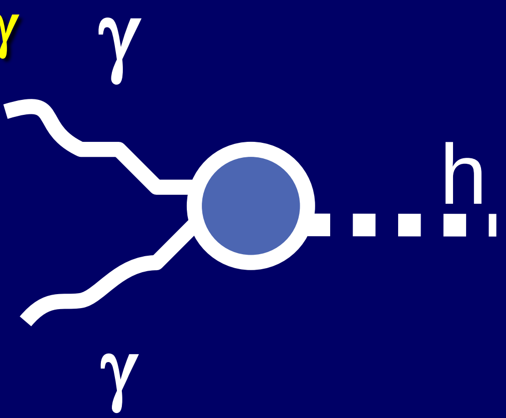




I. Ginzburg, V. Telnov

SM Higgs-resonance decaying in bb

→ extracting $\Gamma_{\gamma\gamma}$



Studies (simulations) for Mh=120 GeV:

- Ohgaki, Takahashi, Watanabe 1997
- Jikia, Soldner-Rembold 1999
- Asner, Gronberg, Gunion 2001
- Niezurawski, Zarnecki, MK 2002
- Moenig, Rosca 2003

Cross section x Br ~ 2 %

(+Br to bb from e+e-) → 3 % accuracy for $\Gamma_{\gamma\gamma}$

$\Gamma_{\gamma\gamma}$ sensitive to SUSY particles, charged Higgs bosons charged new particles (new generations..).

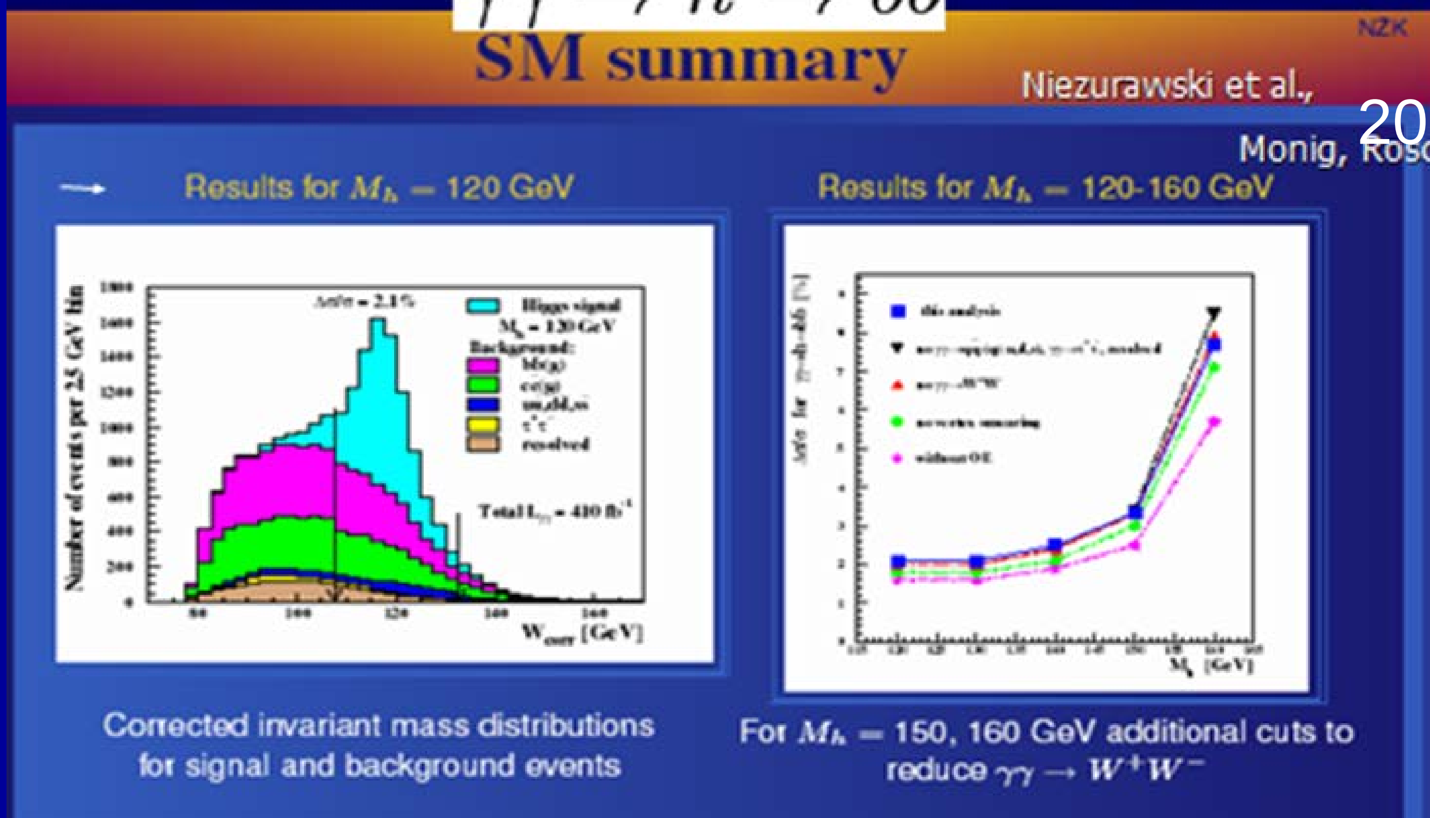
Distinguishing SM-like scenarios possible

Note that hγγ vertex has a phase !!

SM Higgs at PLC

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

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

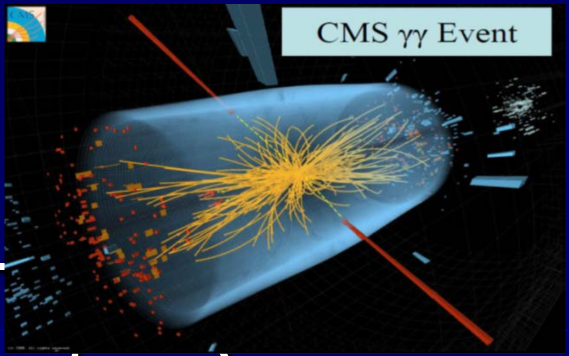


2002

LHC 4.07.2012

Higgs-like particle with mass125 –

observed by 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)

26.06.1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

27.07.1964

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

(Received 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)

12.10.1964

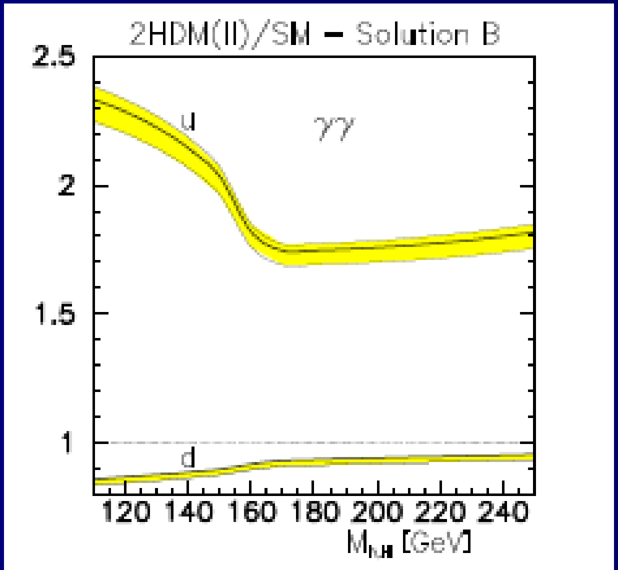
125 GeV particle $\mathcal{H}$

What it is?

- H_{SM} - Higgs boson of SM ?
- h or H of CP-conserving 2HDM ?
- other scalar particle ?

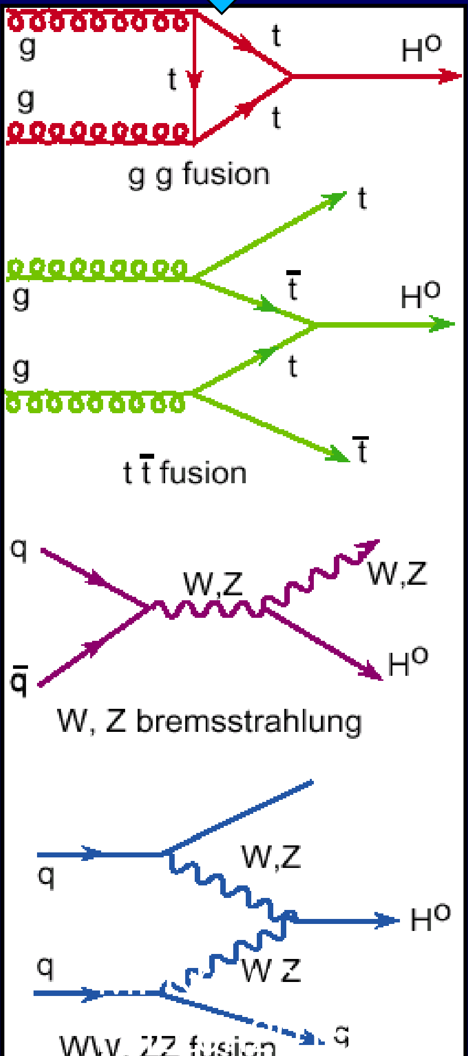
SM-like scenario observed *negative tth*

all measured $\mathcal{H}$ couplings are close to the SM-prediction for *absolute value*



2001 I. Ginzburg, P. Osland MK

Production and decay of Higgs particle at LHC



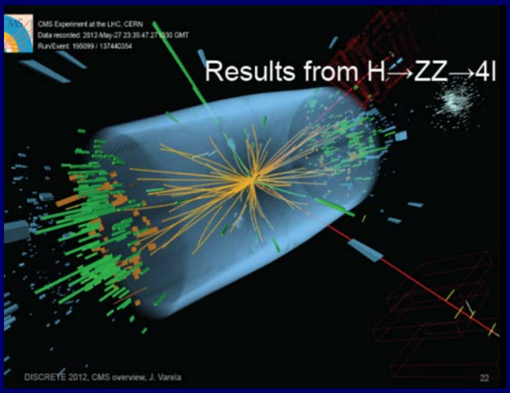
~ SM

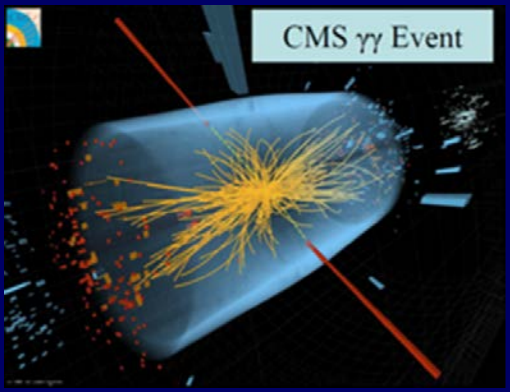
main decays

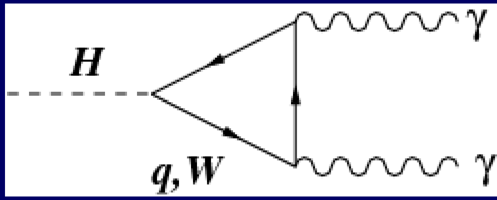
1) $H \to \gamma\gamma$
2) $H \to$ tau tau
3) $H \to$ bb
4) $H \to WW \to l\nu l\nu$
5) $H \to ZZ \to 4l$

decay to $\gamma\gamma$

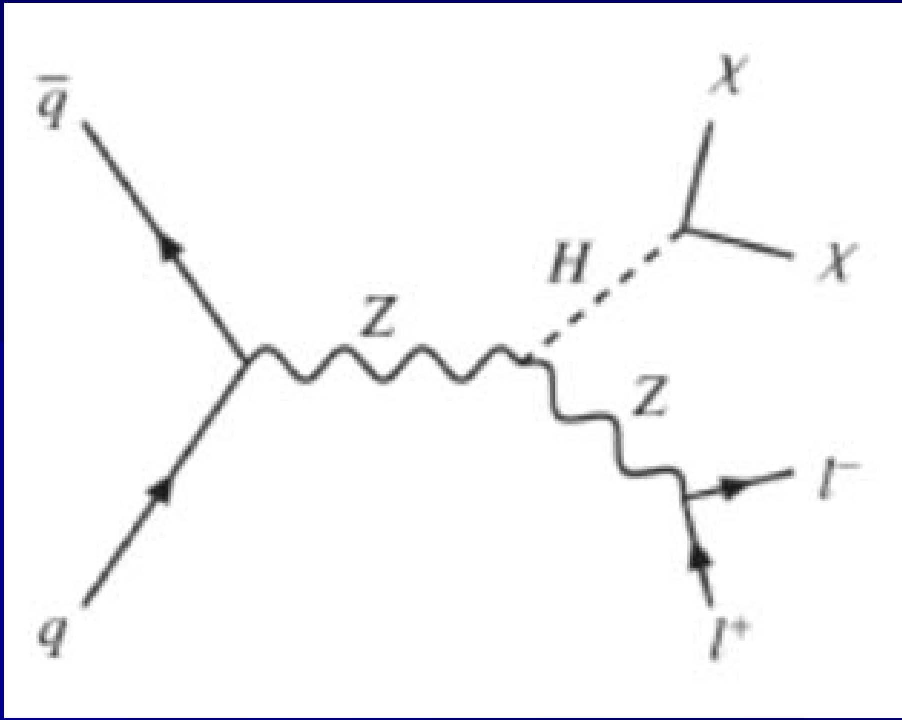
loop t,b,W...







Invisible decay (Dark Matter)



- ATLAS
  BR < 0.27 (95% CL)

- CMS
  BR < 0.32 (95% CL)

Dark matter

Morsolli, Corfu 2014

relic density

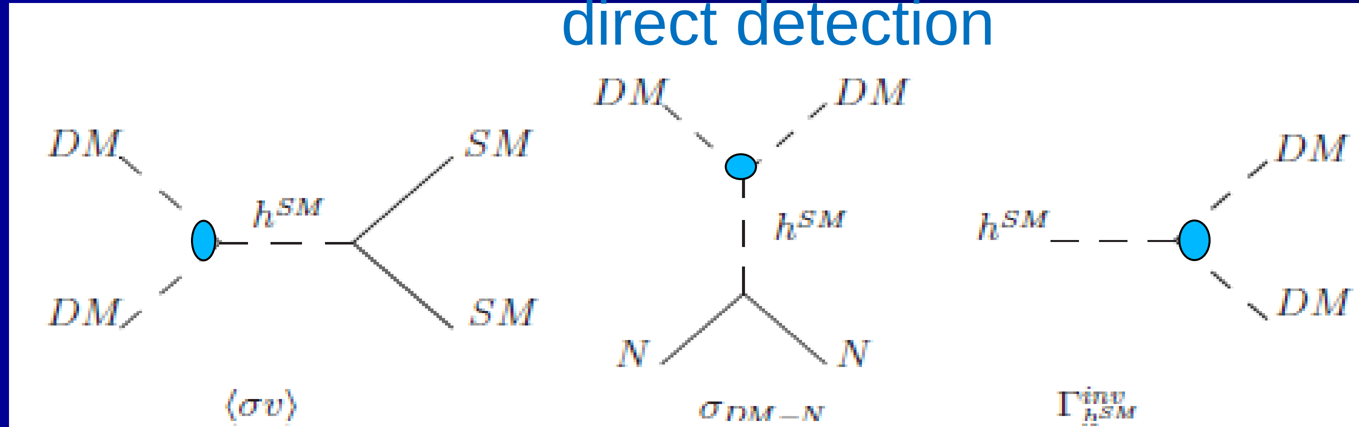
WMAP $0.1018 < \Omega_{DM} h^2 < 0.1234$

3 sigma:

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

Higgs portal models

SM-like h

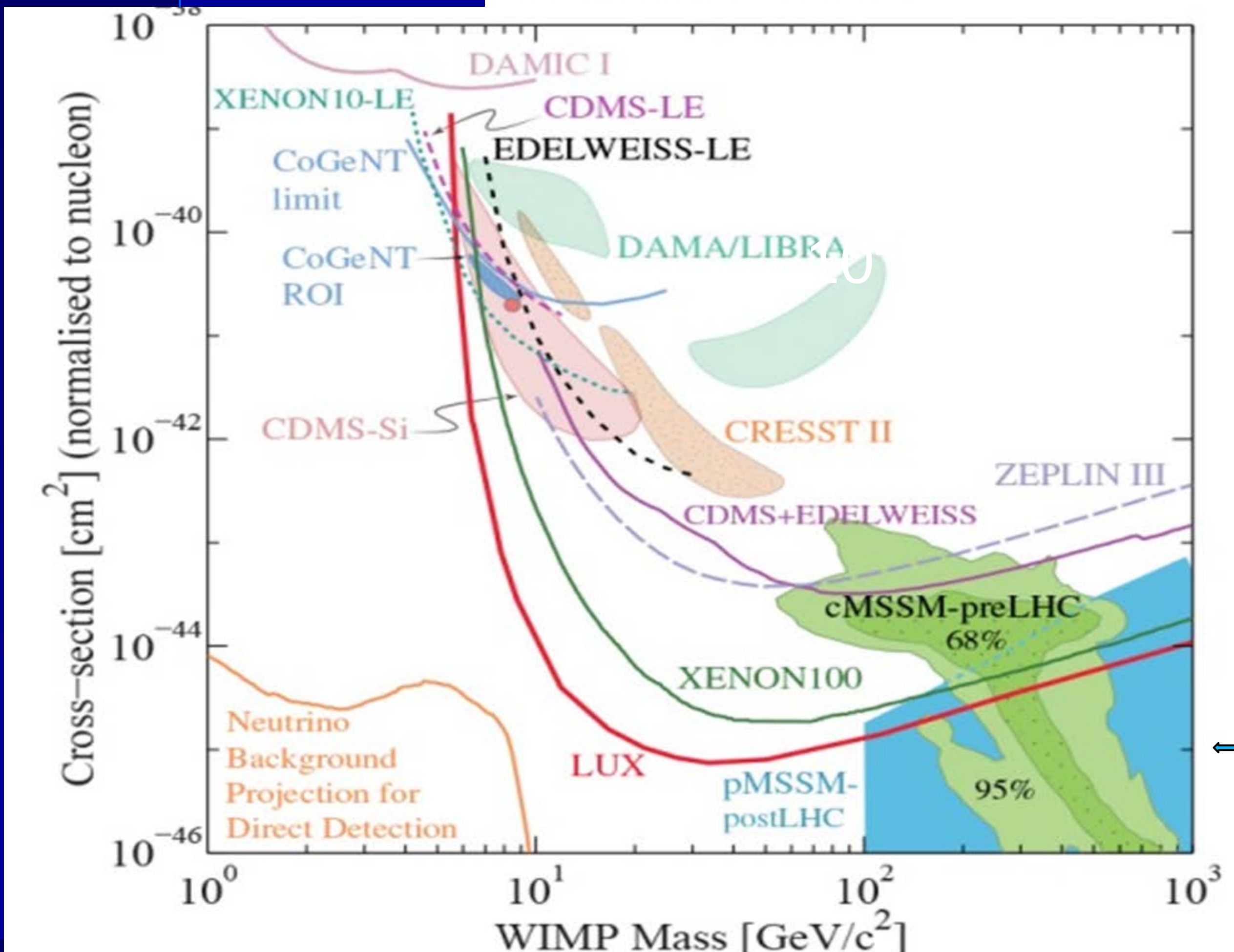


DM DATA?

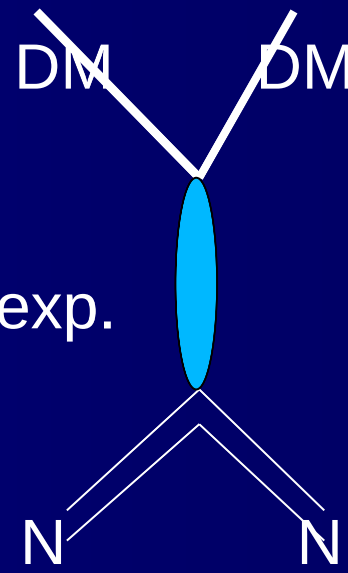
Direct & indirect detection experiments do not provide a coherent picture of Dark Matter.

"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 before drawing strong conclusions in either directions."

Lars Bergstrom, *Dark Matter Evidence, Particle Physics Candidates and Detection Methods*, arXiv:1205.4882 [astro-ph.HE]



direct exp.



10^{-45} cm^2

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 ,15)*
- IDM+complex singlet *Bonilla,Diaz-Cruz,Sokołowska,Darvishi,MK'14*

Z_2 symmetric 2HDM

Potential

$$V = \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c]$$
$$-\tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1) - \tfrac{1}{2}m^2_{22}(\Phi^\dagger\Phi_2)$$

λ_{345}

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

Yukawa interaction

Model I – one doublet Φ_1 couples to all fermions

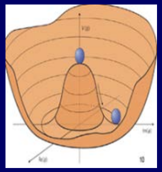
Vacuum state ? Various possible

Inert Doublet Model

Ma,…'78
Barbieri..'06

$\Phi_1 \to \Phi_S$ & $\Phi_2 \to \Phi_D$ (D symmetry)

Φ_S as in SM (BEH) $\qquad$ Φ_D – no vev



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

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

λ_{345}

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

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

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 $\lambda_3 <0$ also $\lambda_{345} <0$)
enhancement only if λ_3 (λ_{345}) <0

$Br_{inv} < 20\%$; total Higgs h width < 22 MeV

Dark matter exp: relic density
direct detection (LUX)

$\gamma\gamma$ and $Z\gamma$ decay rates of the Higgs boson

[Q.-H. Cao, E. Ma, G. Rajasekaran, Phys. Rev. D 76 (2007) 095011, P. Posch, Phys. Lett. B696 (2011) 447, A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021, BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019]

signal strength μ

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

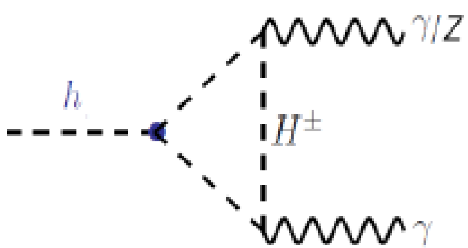
$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

$R_{Z\gamma}$ – treated analogously

- Largest contribution from gg fusion narrow width approx
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$ (not true in other 2HDMs)

Two sources of deviation from $R_{\gamma\gamma} = 1$:

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

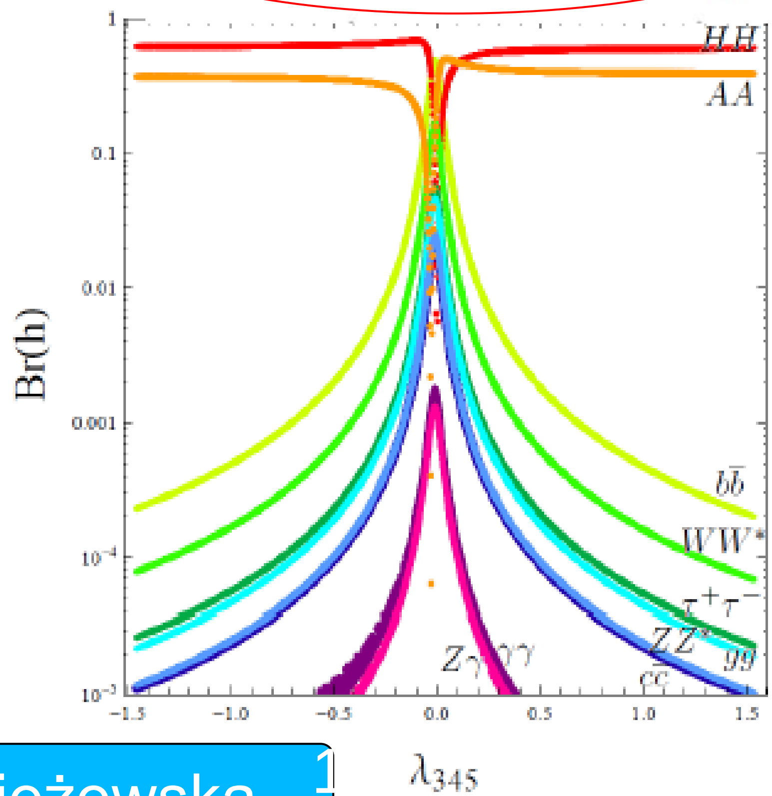


Invisible decays

$$\Gamma(h) = \Gamma(h \to b\bar{b}) + \Gamma(h \to WW^*) + \Gamma(h \to \tau^+\tau^-) + \Gamma(h \to gg)$$
$$+ \Gamma(h \to ZZ^*) + \Gamma(h \to c\bar{c}) + \Gamma(h \to Z\gamma) + \Gamma(h \to \gamma\gamma)$$
$$+ \Gamma(h \to HH) + \Gamma(h \to AA)$$

$$\Gamma(h \to HH) = \frac{\lambda_{345}^2 v^2}{32\pi M_h} \sqrt{1 - \frac{4M_H^2}{M_h^2}},$$

- Controlled by: M_H, M_A, $\lambda_{345} \sim hHH$, $\bar{\lambda}_{345} \sim hAA$
- Invisible decays, if kinematically allowed, dominate over SM channels.
- Plot for $M_A = 58$ GeV, $M_H = 50$ GeV

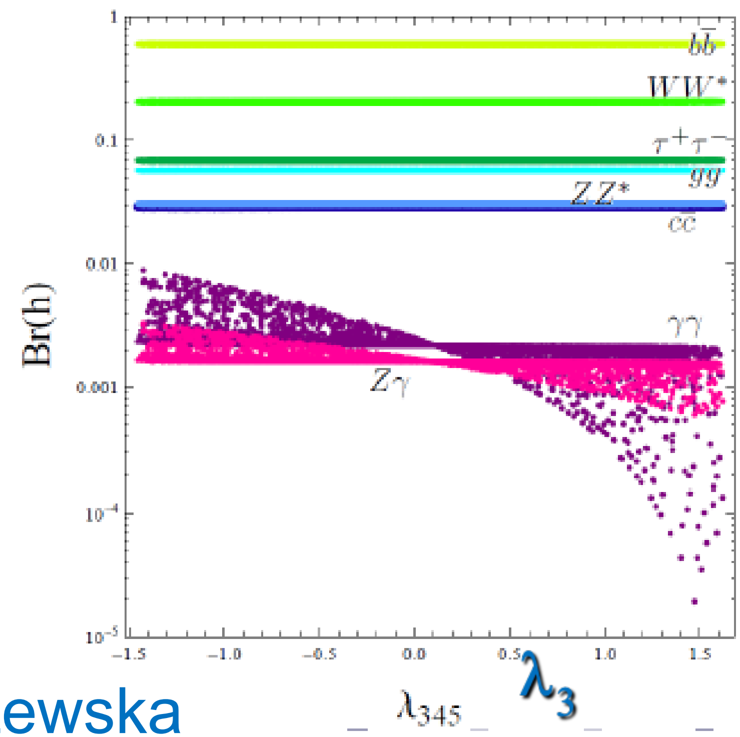


Charged scalar $H^{\pm}$ loop

[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)]

$$\Gamma(h \to \gamma\gamma)^{IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \mathcal{A}^{SM} + \overbrace{\frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2}}^{\lambda_3} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) \right|^2$$

- Constructive or destructive interference between SM and $H^{\pm}$ contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- Invisible channels closed $\Rightarrow H^{\pm}$ contribution visible

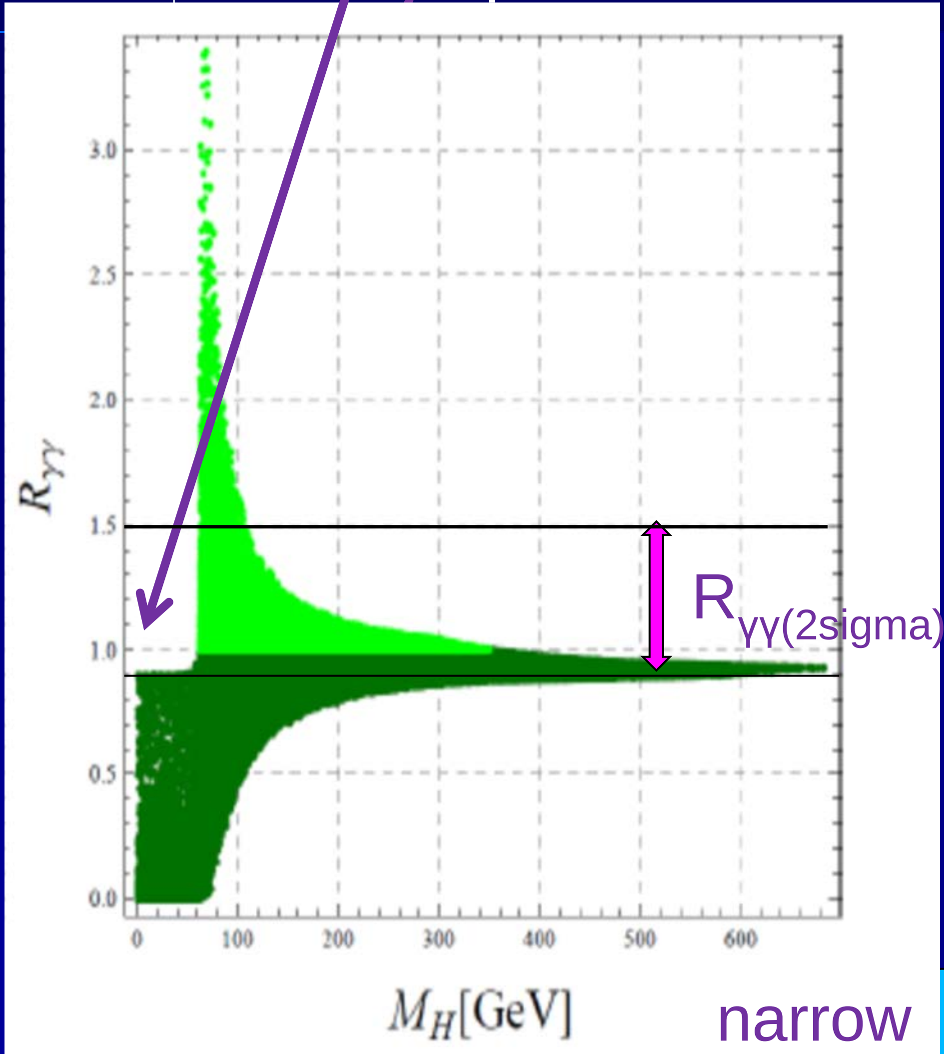


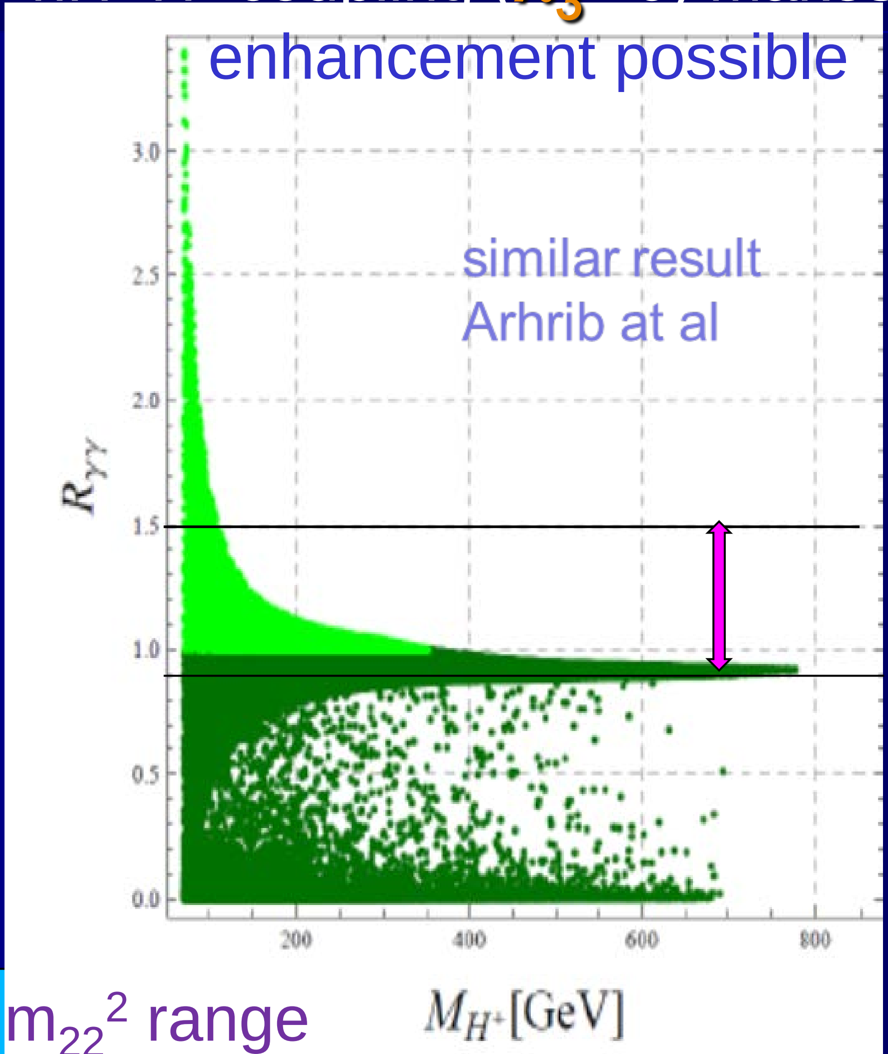
B. Świeżewska

$R_{\gamma\gamma}$ 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

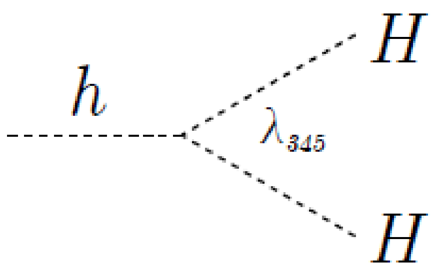




narrow m_{22}^2 range

Invisible decay in IDM constraining coupling hHH

- $h \to HH$ – invisible decay (H is stable)
- augmented total width of the Higgs boson, $\Gamma(h \to HH) \sim \lambda_{345}^2$

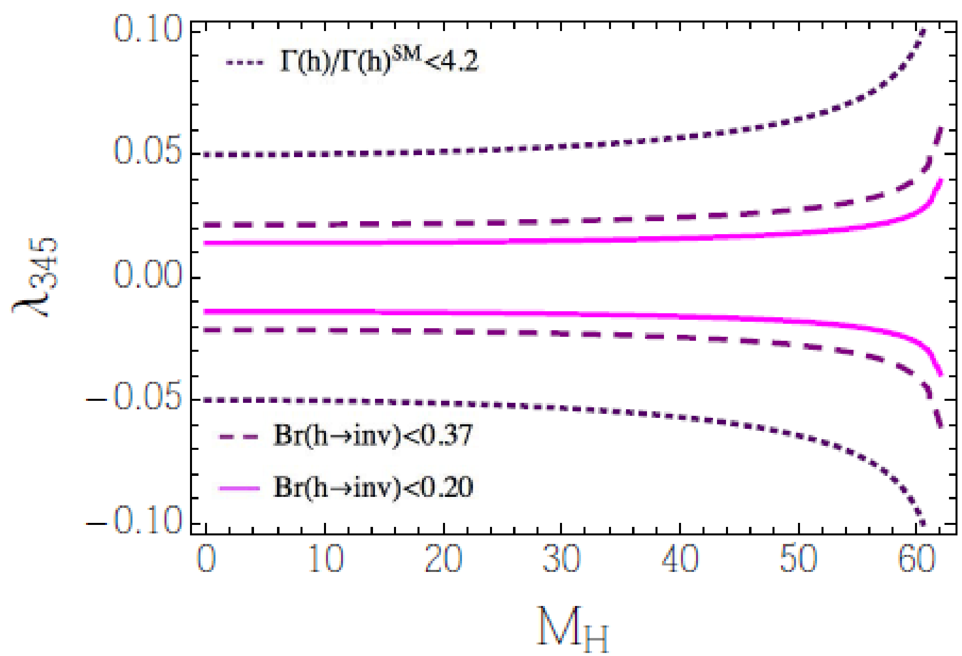


LHC:

- $\mathrm{Br}(h \to \mathrm{inv}) < 37\%$,
- $\Gamma(h)/\Gamma(h)^{SM} < 4.2$

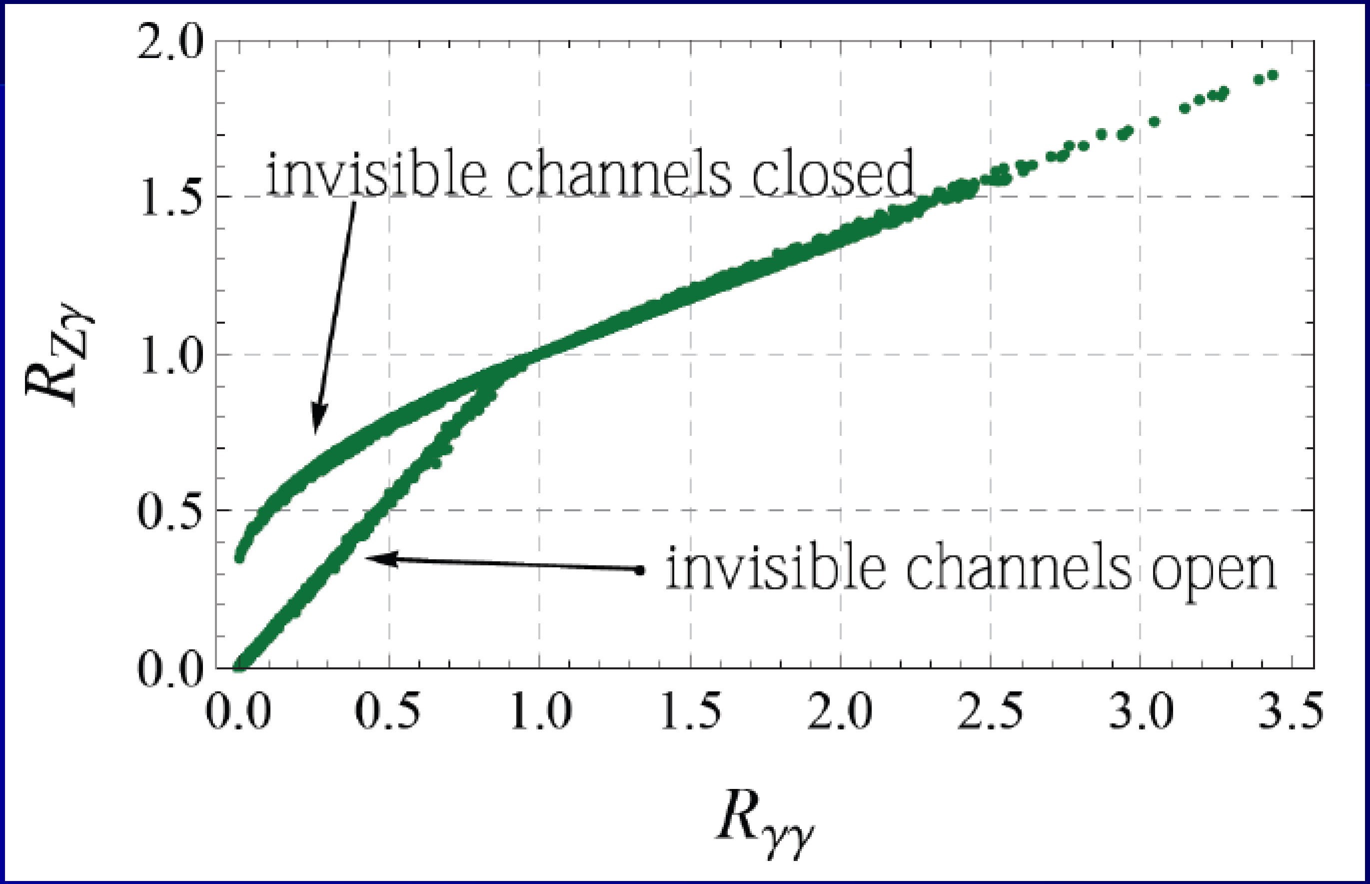
global fit:

- $\mathrm{Br}(h \to \mathrm{inv}) \lesssim 20\%$



[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010, 2014; CMS-PAS-HIG-14-002]

Zgamma vs gamma gamm



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

Relic DM density

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

LHC data

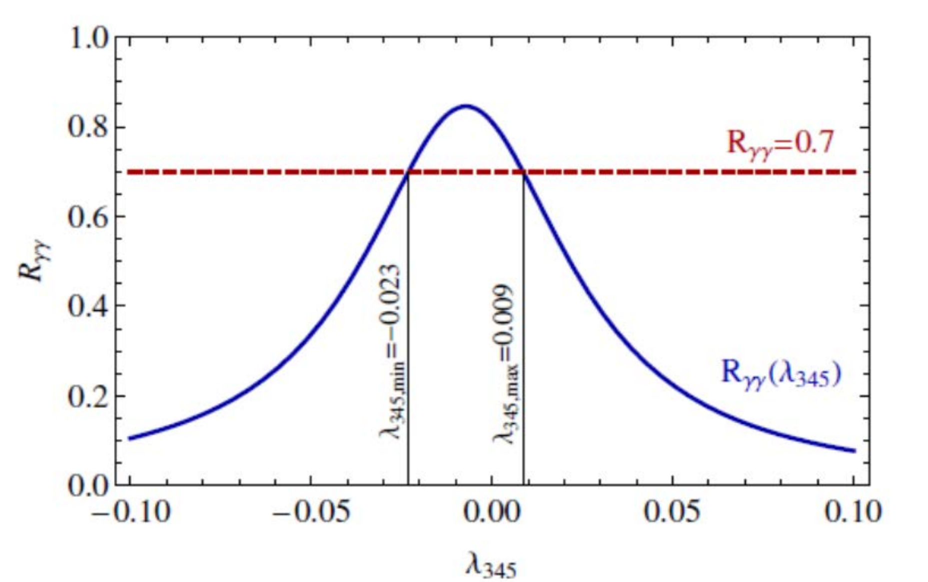
$$\text{ATLAS} : R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$$
$$\text{CMS} : R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$$

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

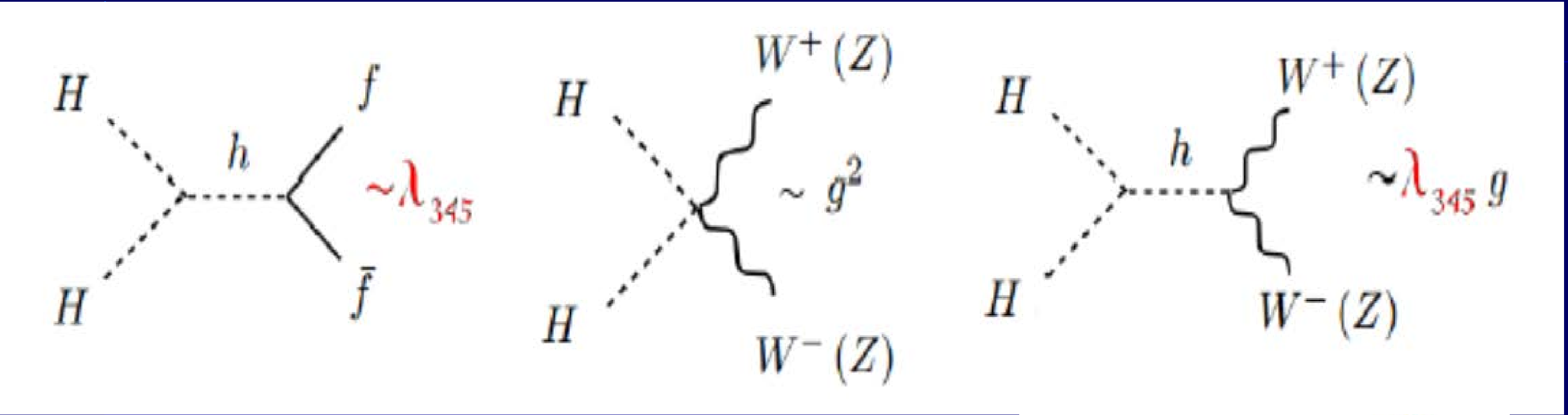
1.12 ± 0.24

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

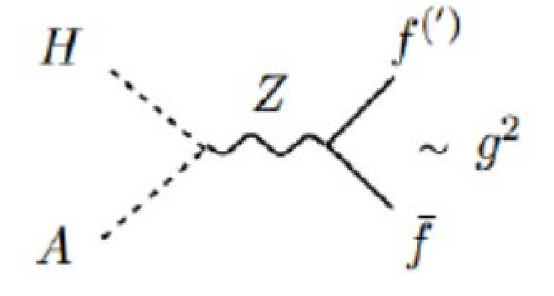
DM mass below 62.5 GeV allowed only if
$R_{\gamma\gamma} < 1$



Relic density constraints on masses and couplings of DM

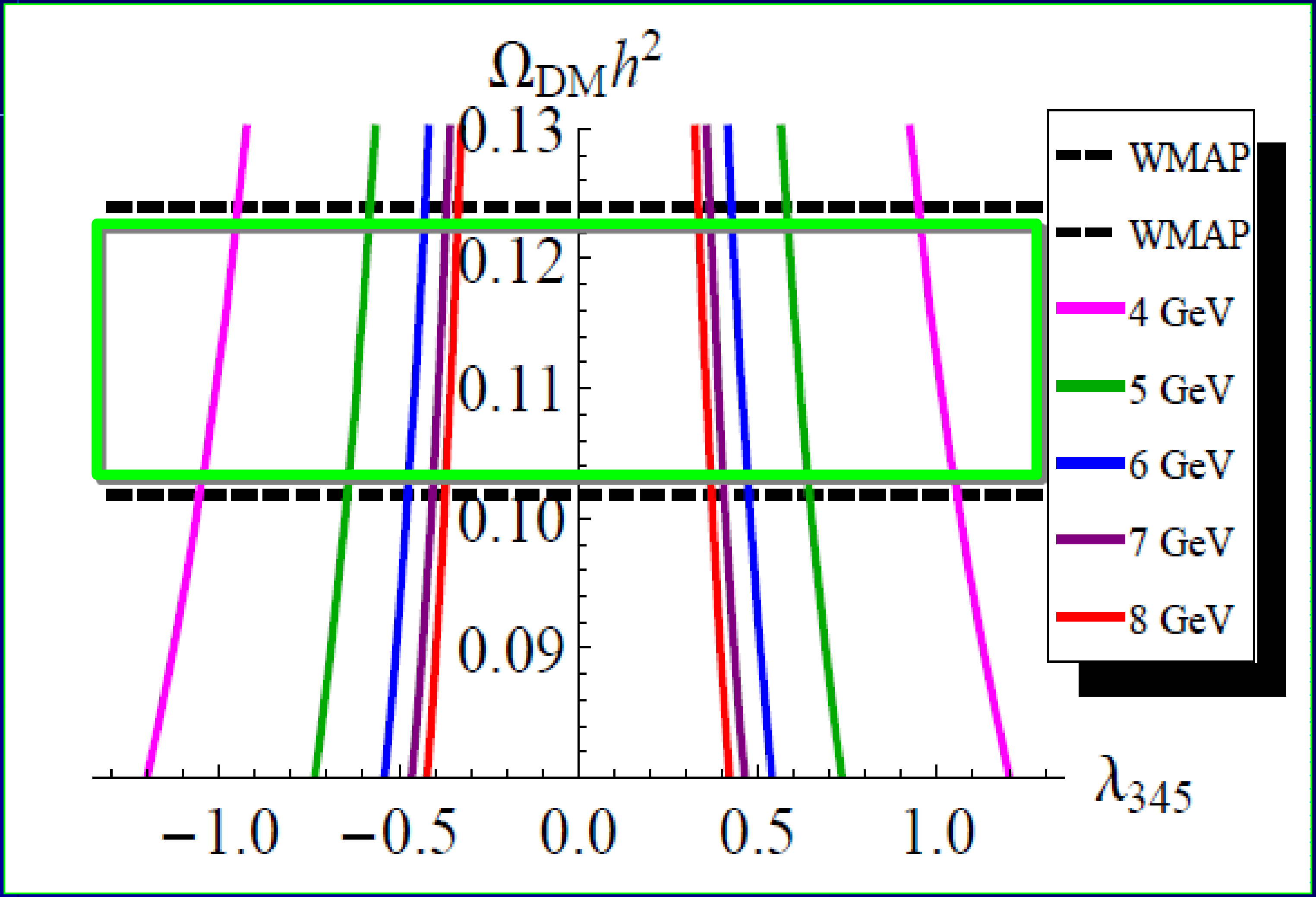


Coannihilation possible for small (AH) splitting



- 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, $g_{HHh} \sim \mathcal{O}(0.1)$

WMAP window for light H (DM)



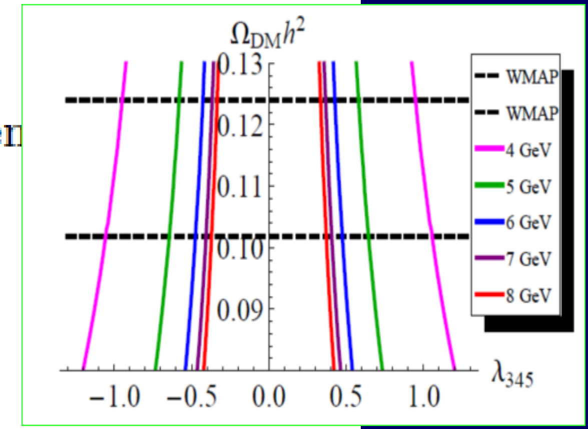
Low mass H – excluded by LHC!

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

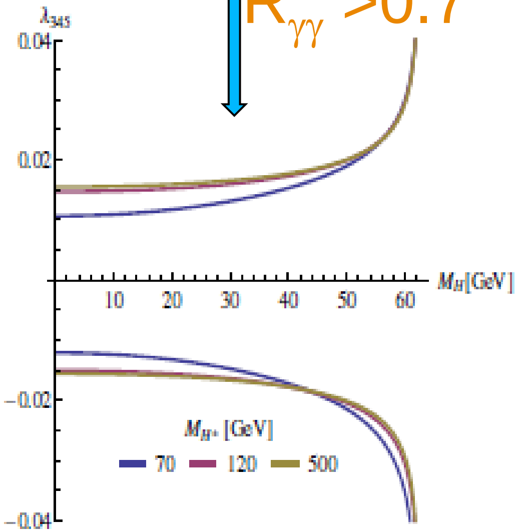
[M. Krawczyk, D. Sokołowska, P. Swaczyna, BŚ, arXiv:1305.6266 [hep-ph], JHEP 2013]

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

$h \to AA$ 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

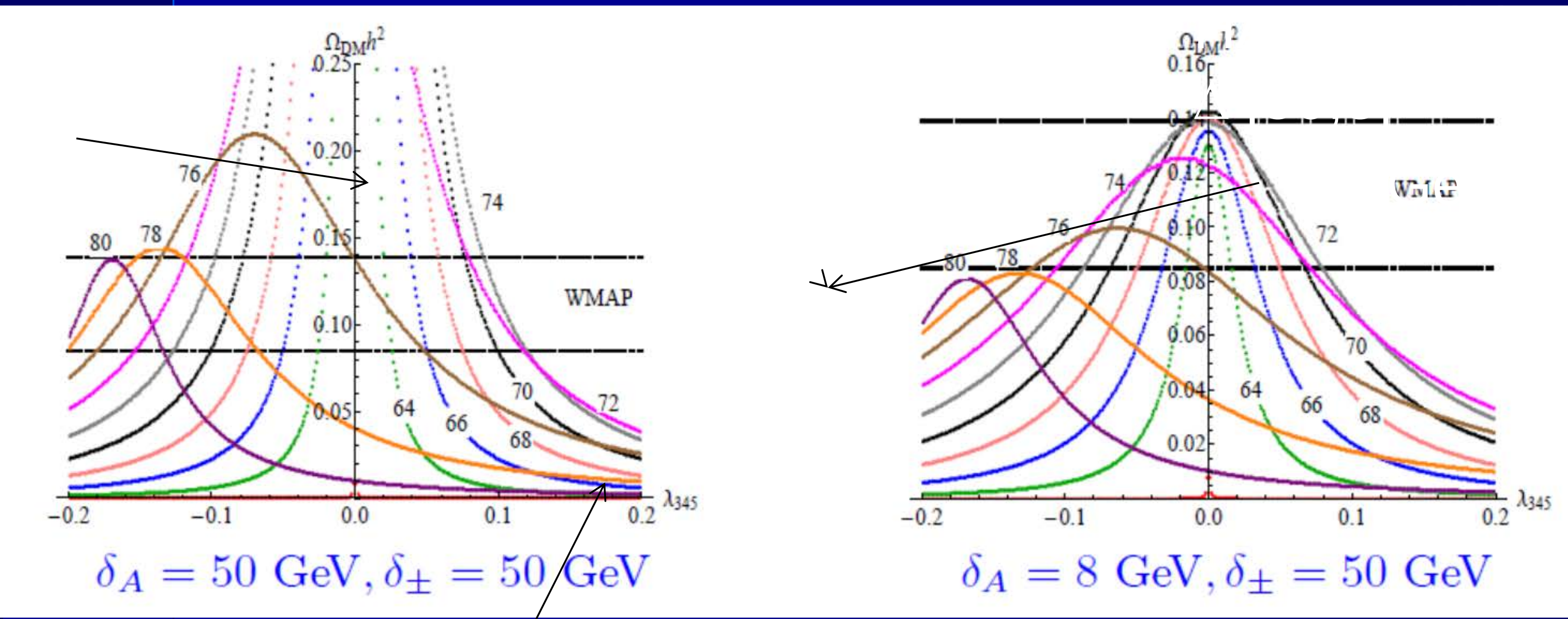
Sokołowska/Świeżewska

Relic density for DM with mass 64,…,80 GeV

D. Sokołowska, 2013

$$M_{A,H^\pm} = M_H + \delta_{A,\pm}$$

on

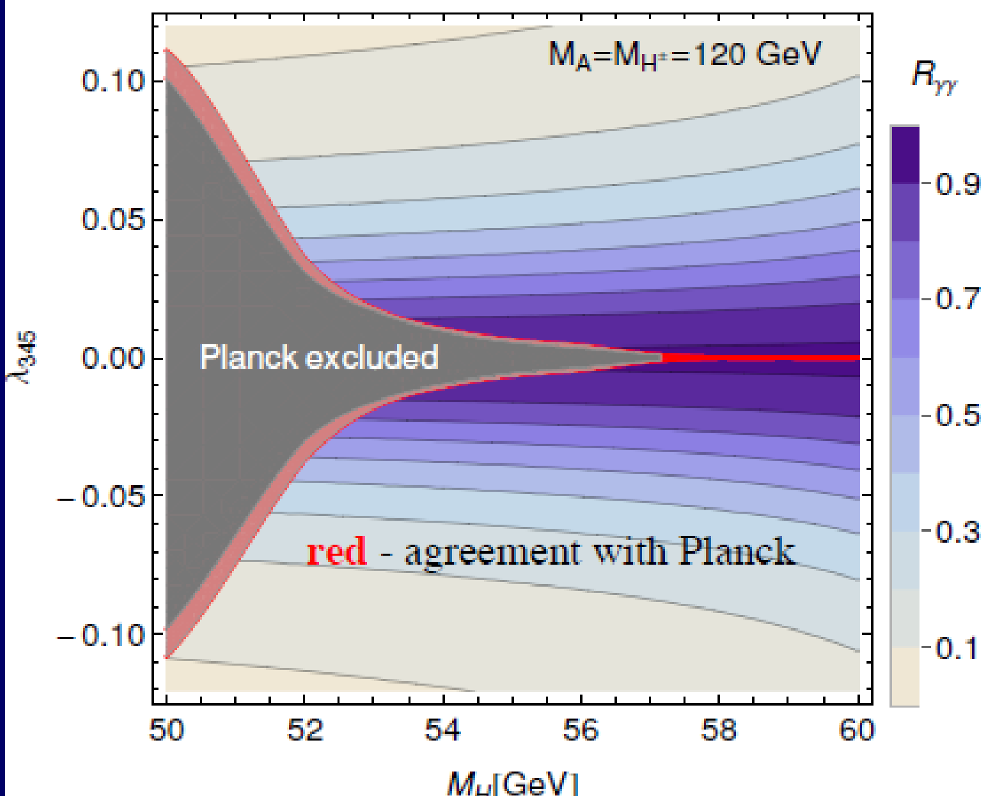


above 76 GeV asymmetry due to annihilation to gauge bosons

Using PLANCK data

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

$h \to HH$ open

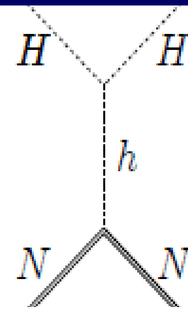


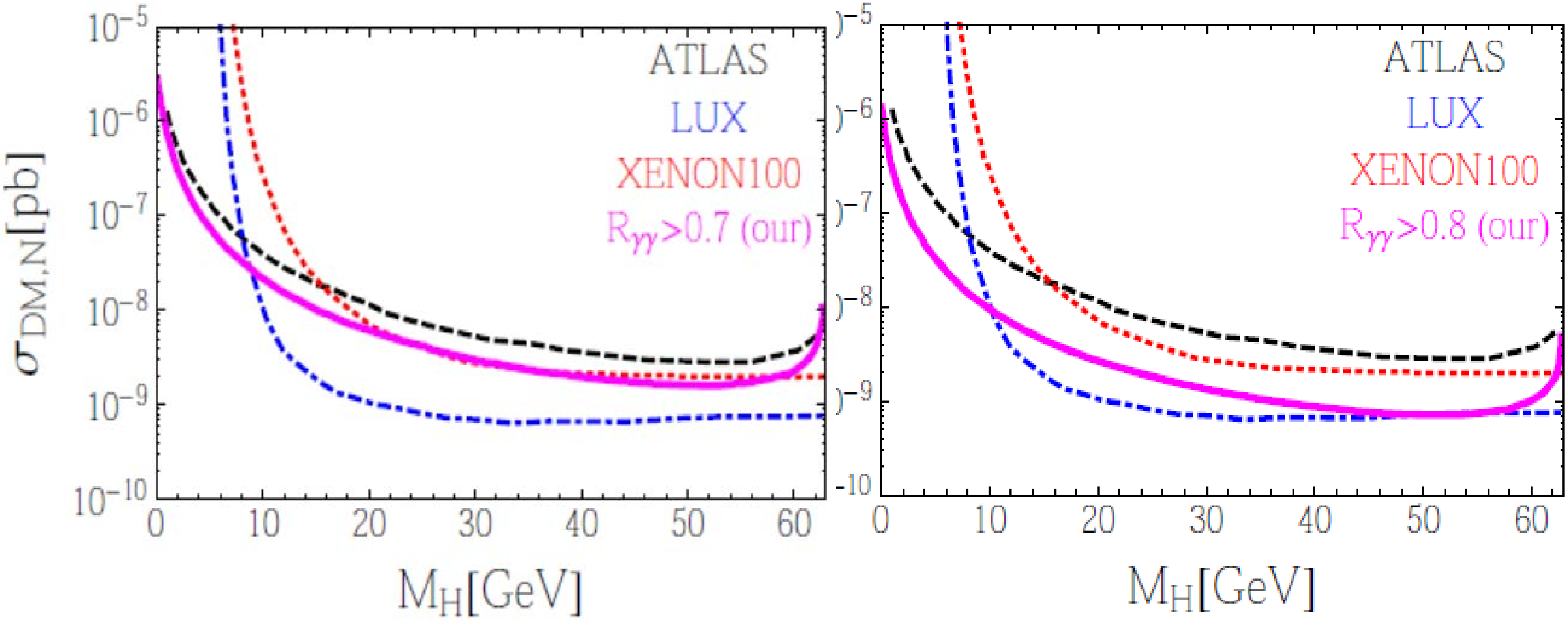
$50\,\mathrm{GeV} < M_H < M_h/2$, $M_A = M_{H^\pm} = 120\,\mathrm{GeV}$

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

Direct detection – comparison with LHC, Xenon 100 and LUX

- DM-nucleon scattering cross section $\sigma_{\mathrm{DM,N}} \sim \lambda_{345}^2$
- $R_{\gamma\gamma}$ bounds on λ_{345} translated to $(M_H,\ \sigma_{\mathrm{DM},N})$ plane





… stronger than the dedicated DM experiments

Photons are perfect tools to study BSM

" The study of light has resulted in achievements of insight,

imagination and ingenuity unsurpassed in any field of mental activity;

it illustrates, too, better than any other branch of physics,

the Vicissitudes of theories." -

Sir J. J. Thomson, 1925.