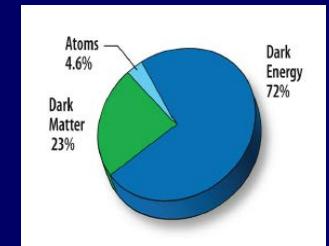
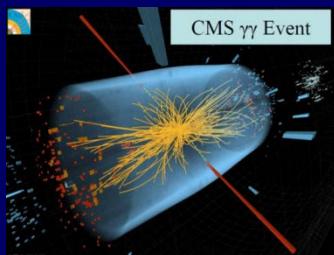


Higgs(es) and photons



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

the photon: its first hundred years and the future

30.08-08.09.2005, Warsaw and Kazimierz, POLAND

photon

1905-2005

30.08.2005 • Warsaw

The Centenary of the Photon

- EINSTEIN'S REVOLUTIONARY LIGHT-QUANTUM HYPOTHESIS • Roger H. Stuewer (Minnesota)
- EINSTEIN'S NOBEL PRIZE • Cecilia Jonsson (Lund)
- LET THERE BE LIGHT: PHOTONS IN COSMOLOGY • Helge Kragh (Aarhus)
- MULTIWAVELENGTH UNIVERSE • Andrew Lawrence (Edinburgh)
- PHOTONS, TWISTORS AND STRINGS • Roger Penrose (Oxford)
- A MODERN VERSION OF THE EINSTEIN-BEHR PHOTON BOX • Serge Haroche (Paris)
- FROM EINSTEIN'S PHOTON TO QUANTUM INFORMATION • Anton Zeilinger (Vienna)
- RESEARCH WITH FREE ELECTRON LASERS FOR SOFT AND HARD X-RAYS • Jochen Schmieder (DESY)
- CERN AND THE PHYSICS OF THE PHOTON AND ITS WEAK PARTNER • Wulf-Dieter Schnüter (CERN)
- THE TWO FACES OF THE PHOTON • Albrecht Wagner (DESY)
- EINSTEIN AND THE QUEST FOR UNIFICATION • David Gross (KITP)

31.08 - 04.09.2005 • Warsaw

PHOTON2005

International Conference on the Structure
and Interactions of the Photon including the 16th
International Workshop on Photon-Photon Collisions

- PHOTON PROPERTIES AND INTERACTIONS - THE HISTORICAL EVOLUTION
- STRUCTURE FUNCTIONS
- DVCS AND PROMPT PHOTONS
- JETS AND INCLUSIVE HADRONIC PROCESSES
- HEAVY FLAVOURS PRODUCTION
- TOTAL CROSS SECTIONS AND DIFFRACTION
- RESONANCES AND EXCLUSIVE PROCESSES
- APPENDIX: PAPERS PRESENTED
- RELATED TOPICS

05.09 - 08.09.2005 • Kazimierz

PLC2005

International Workshop on High Energy
Photon Linear Colliders

- PHYSICS: Higgs • SUSY • Alternatives • GED • IQCD • Cosmic connections
- TECHNOLOGY: Lasers • Accelerators • Interaction region

KAZIMIERZ LECTURES Physics at Future Colliders and Astrophysics

VENUE:

- Faculty of Physics, Warsaw Univ., Hoza 69, 00-681 Warsaw
- Dom Architekta, Rynek 20, 24-120 Kazimierz

<http://photon2005.fuw.edu.pl/>



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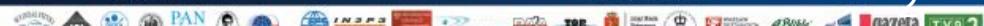
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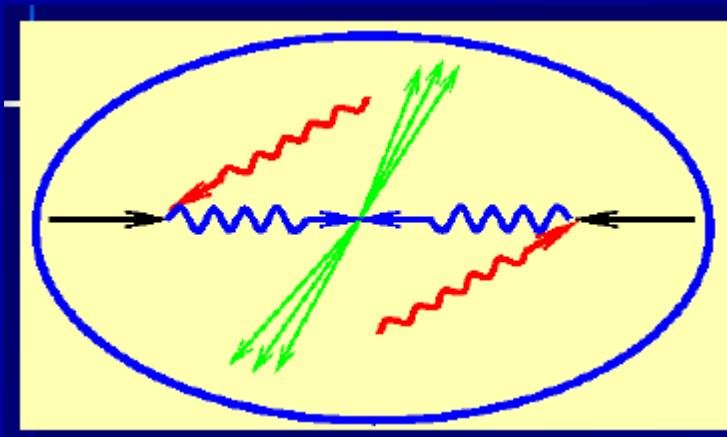
2015: International Year of Light PHOTON2015



- 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

My perspective

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



I. Ginzburg, V. Telnov

SM Higgs-resonance decaying in bb

→ extracting $\Gamma_{\gamma\gamma}$

Studies (simulations) for $M_h=120$ GeV:

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

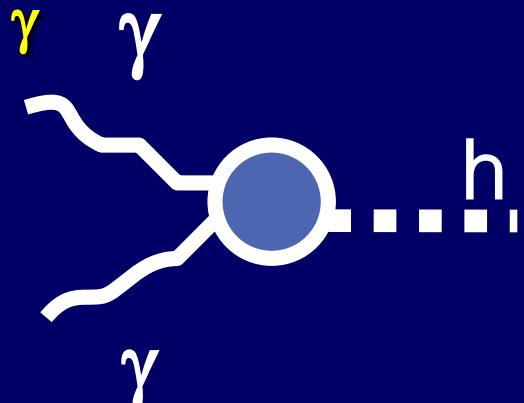
Cross section \times Br $\sim 2\%$

(+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

M. Krawczyk,
Photon2015



Note that $h\gamma\gamma$ vertex⁵ has a phase !!

SM Higgs at PLC

PLC

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

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

SM summary

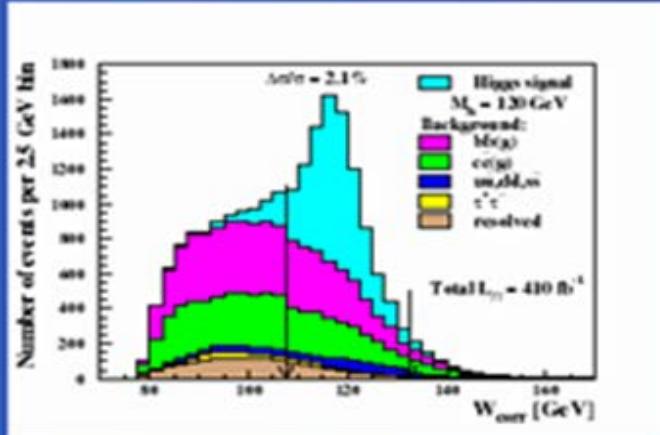
NZK

Niezurawski et al.,

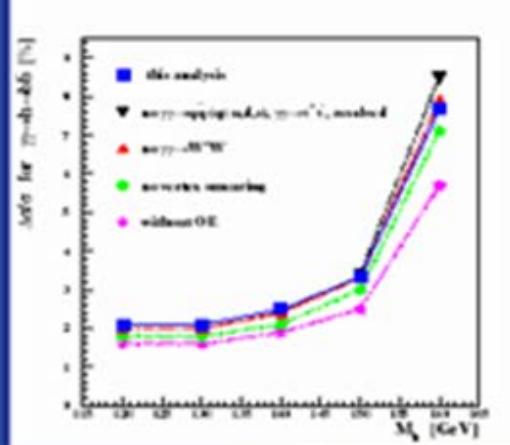
2002

Monig, Rosca

→ Results for $M_h = 120$ GeV



Results for $M_h = 120-160$ GeV

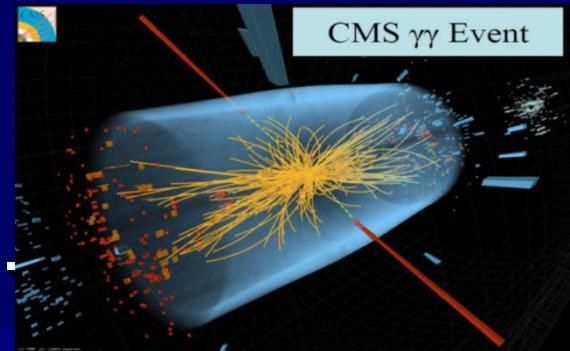


Corrected invariant mass distributions
for signal and background events

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

LHC 4.07.2012

Higgs-like particle with mass 125 GeV 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)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

26.06.1964

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 ?

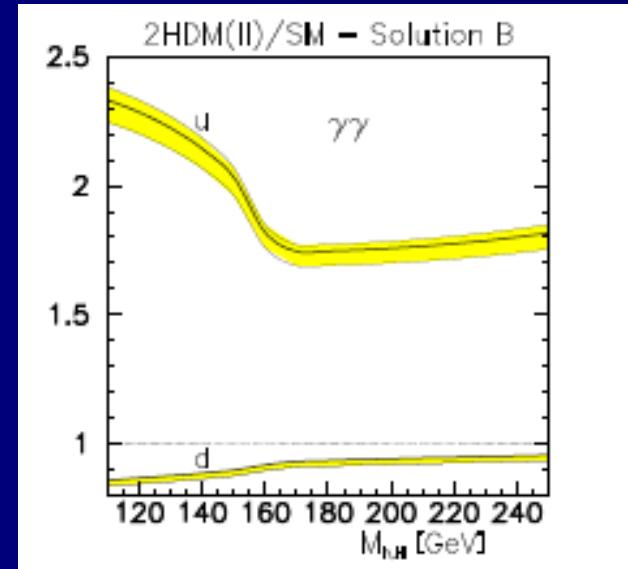
SM-like scenario observed

all measured \mathcal{H} couplings

are close to the SM-prediction for *absolute value*

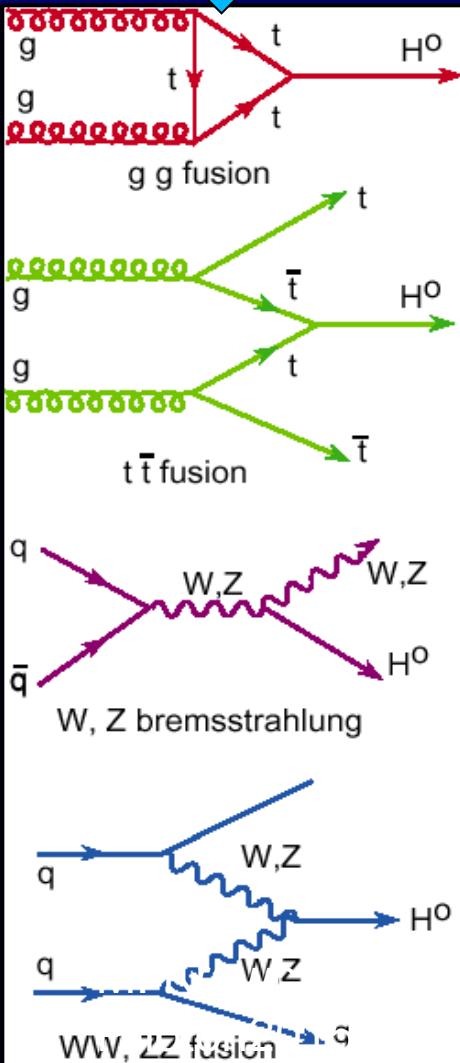
2001 I. Ginzburg, P. Osland MK

negative $t\bar{t}h$



Production and decay of Higgs particle at LHC

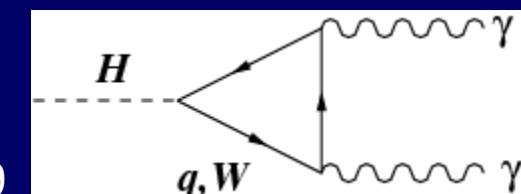
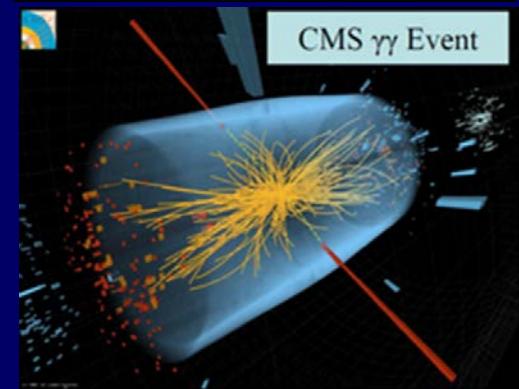
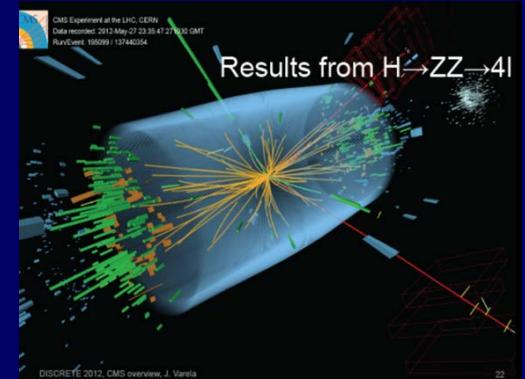
~ SM



main decays

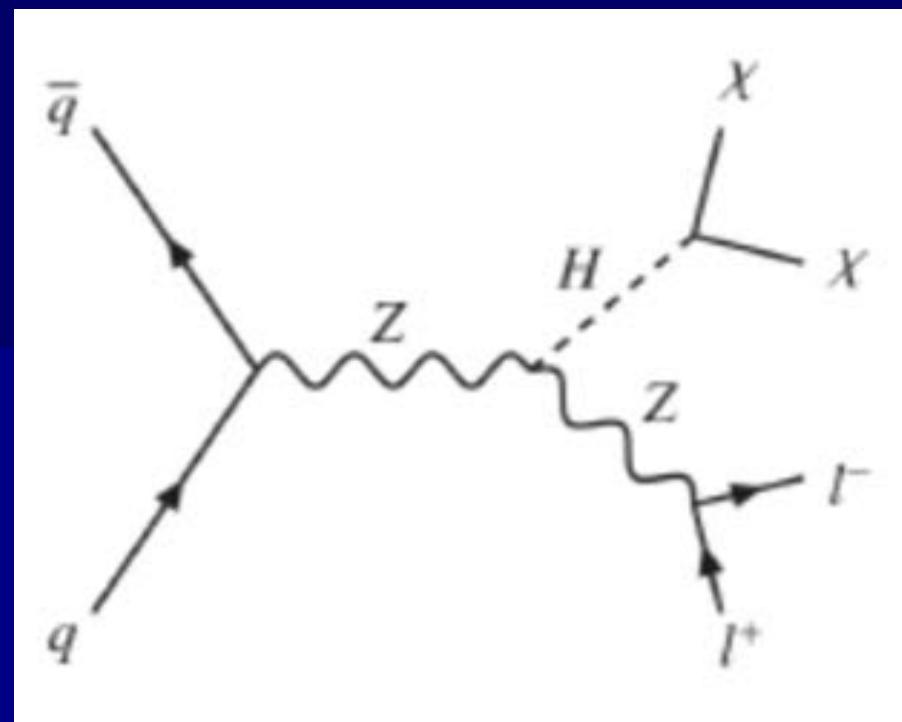
- 1) $H \rightarrow \gamma\gamma$
- 2) $H \rightarrow \tau\tau$
- 3) $H \rightarrow bb$
- 4) $H \rightarrow WW \rightarrow l\nu l\nu$
- 5) $H \rightarrow ZZ \rightarrow 4l$

decay to $\gamma\gamma$
loop t,b,W...



Invisible decay (Dark Matter)

- ATLAS
BR < 0.27 (95% CL)
- CMS
BR < 0.32 (95% CL)

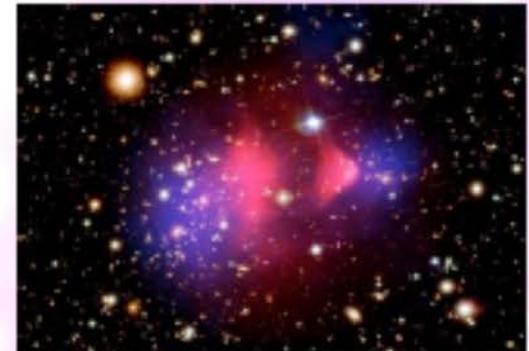
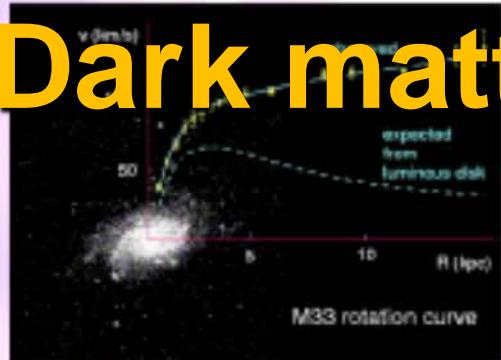


Rotation curves of galaxies

Gravitational lensing

Bullet cluster

Dark matter



Morsolli, Corfu 2014

relic density

WMAP

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

3 sigma:

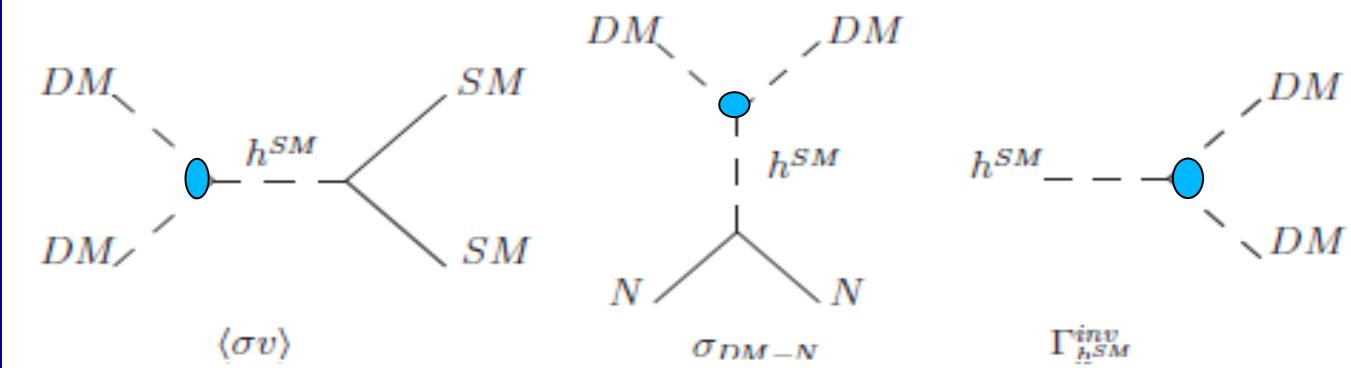
PLANCK

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

Higgs portal models

SM-like h

direct detection

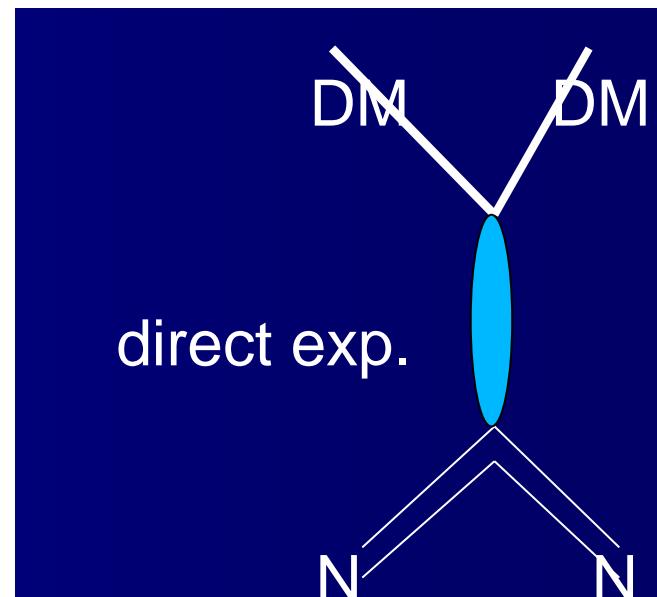
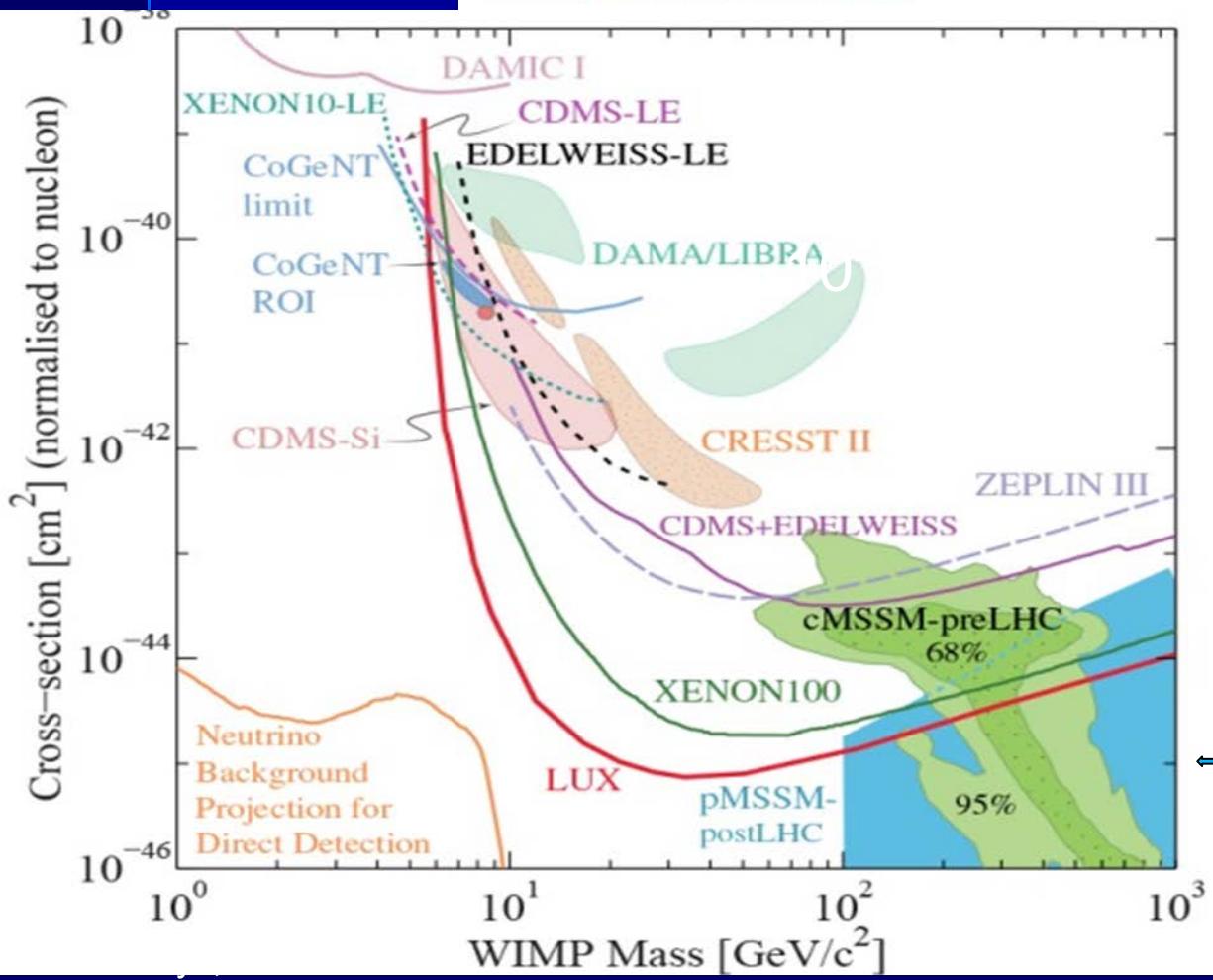


DM DATA?

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 before drawing strong conclusions in either directions."

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



Inert Doublet Model (IDM)

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

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,MK¹³14*

Z_2 symmetric 2HDM

Potential

$$\begin{aligned} V = & \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c] \\ & - \frac{1}{2}m_{11}^2(\Phi_1^\dagger\Phi_1) - \frac{1}{2}m_{22}^2(\Phi_2^\dagger\Phi_2) \end{aligned}$$

λ_{345}

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

Vacuum state ? Various possible

Inert Doublet Model

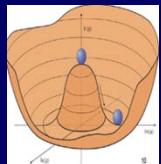
Ma,... '78

Barbieri..'06

$\Phi_1 \rightarrow \Phi_S \text{ & } \Phi_2 \rightarrow \Phi_D$ (D symmetry)

Φ_S as in SM (BEH)

Φ_D – no vev



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

Higgs boson h (SM-like)

$$\Phi_D = \begin{pmatrix} H^+ \\ H+iA \end{pmatrix}$$

(no Higgses!)

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

D symmetry $\Phi_S \rightarrow \Phi_S \quad \Phi_D \rightarrow -\Phi_D$ exact \rightarrow

► 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



$$M_h^2 = m_{11}^2 = \lambda_1 v^2$$

- ❖ Study of dark scalars D

- masses depend on m_{22}^2

- the dark scalars D in pairs!

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

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

Quartic selfcouplings D^4 proportional to λ_2 -hopeless



DM data

Couplings with Higgs: $hHH \sim \lambda_{345}$ $hH+H- \sim \lambda_3$

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]

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

signal strength μ

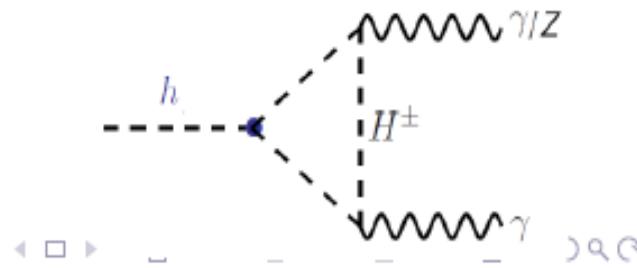
$$R_{\gamma\gamma} = \frac{\sigma(pp \rightarrow h \rightarrow \gamma\gamma)^{IDM}}{\sigma(pp \rightarrow h \rightarrow \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \rightarrow \gamma\gamma)^{IDM}}{\Gamma(h \rightarrow \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

$R_{Z\gamma}$ – treated analogously

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

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

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

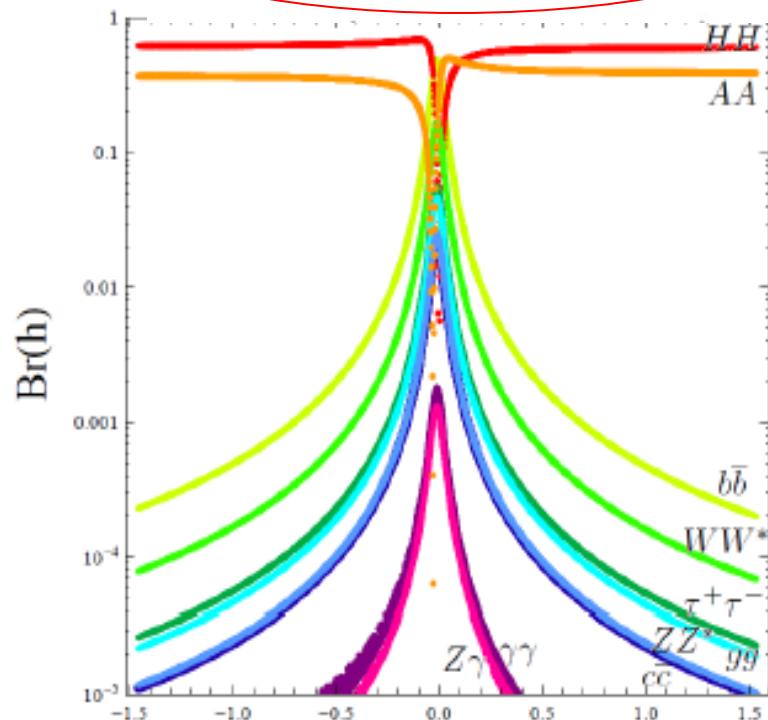


Invisible decays

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

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

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

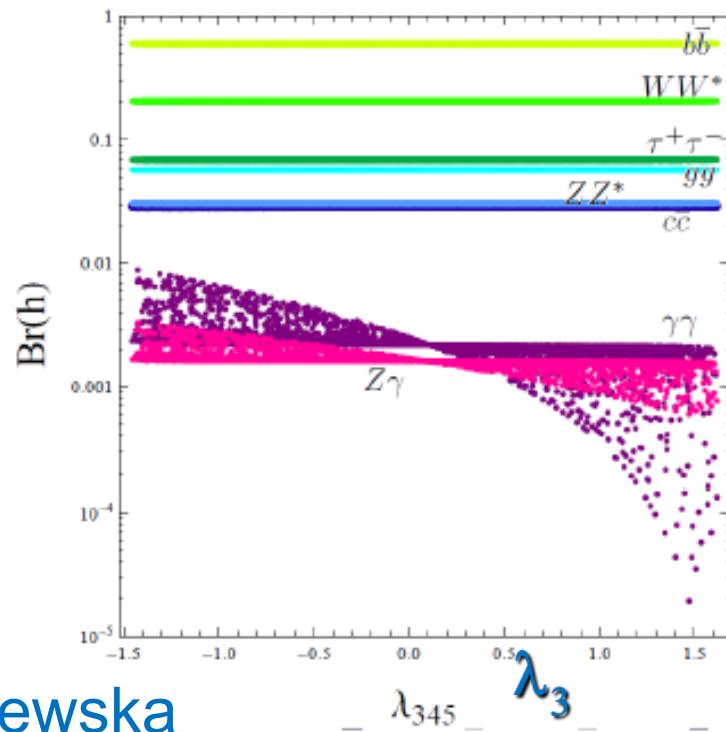


Charged scalar H^\pm loop

[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)]

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

- 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

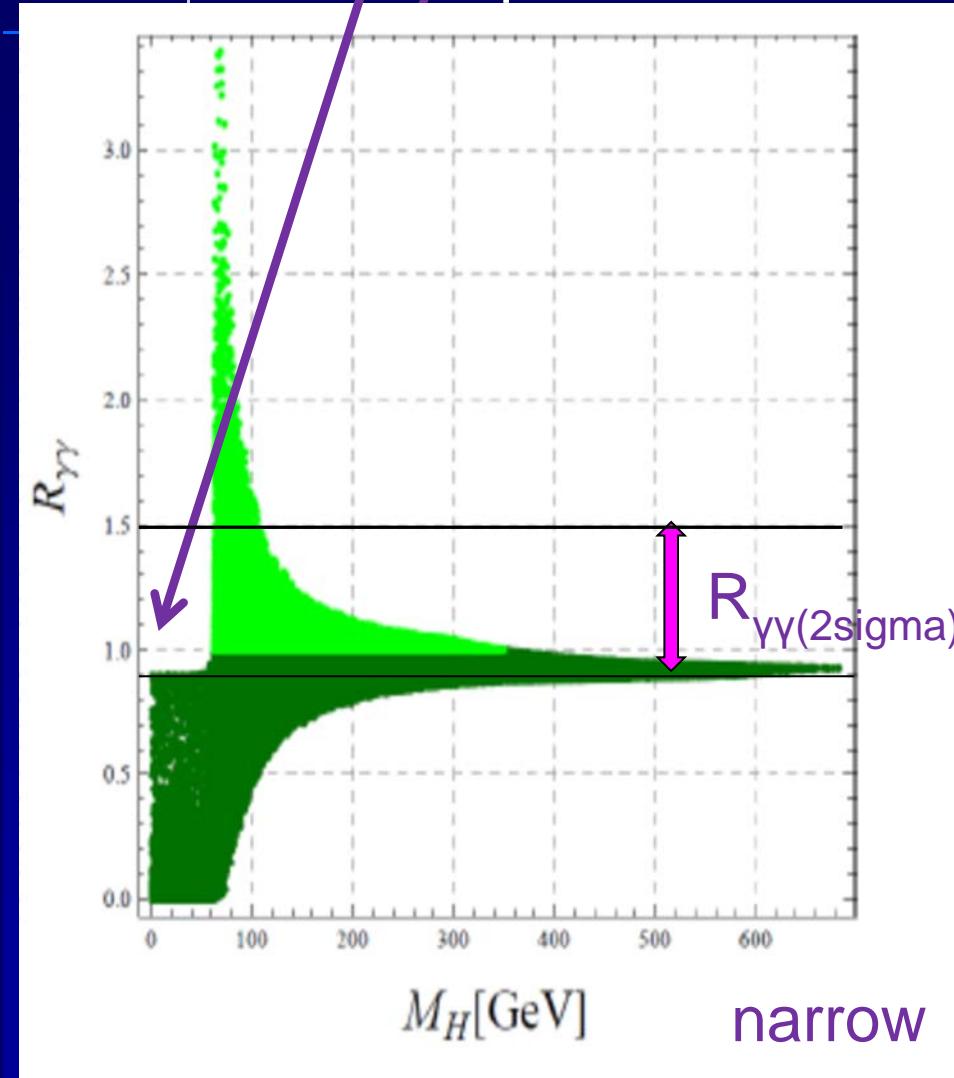


B. Świeżewska

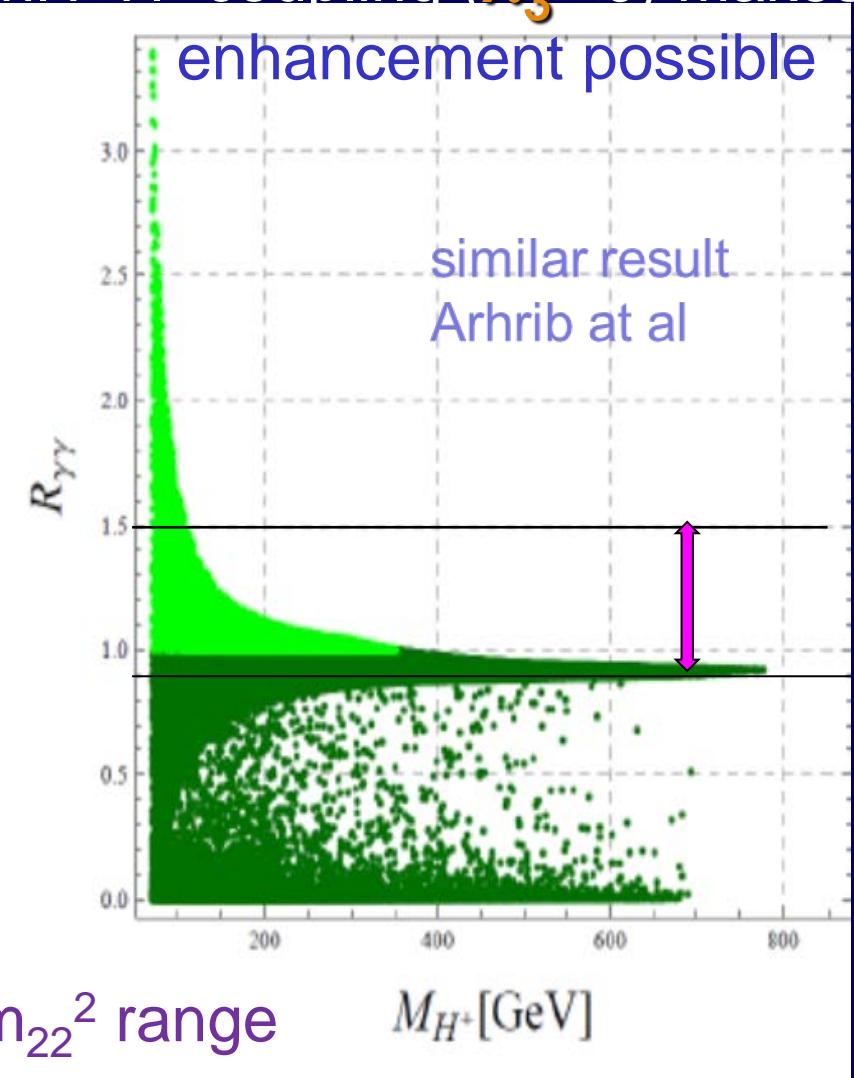
λ_{345}

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

Invisible decays makes enhancement impossible

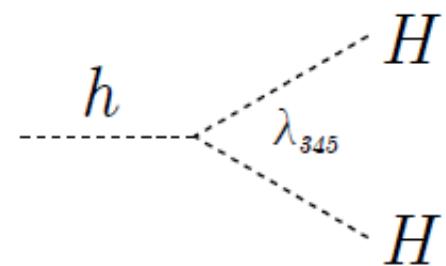


Light H^+ with proper sign of hH^+H^- coupling ($\lambda_3 < 0$) makes enhancement possible



Invisible decay in IDM constraining coupling hHH

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

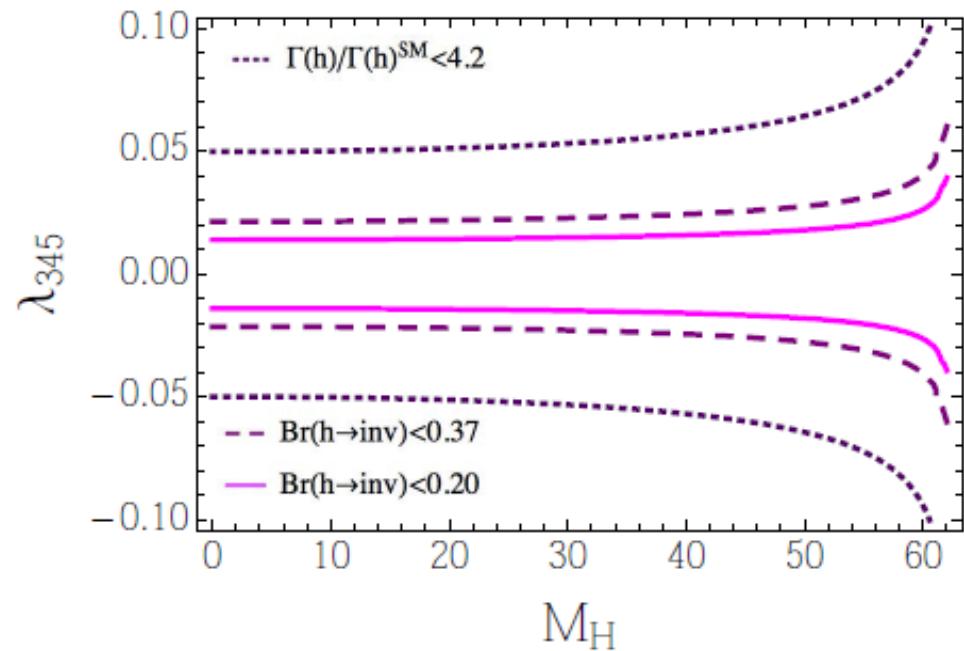


LHC:

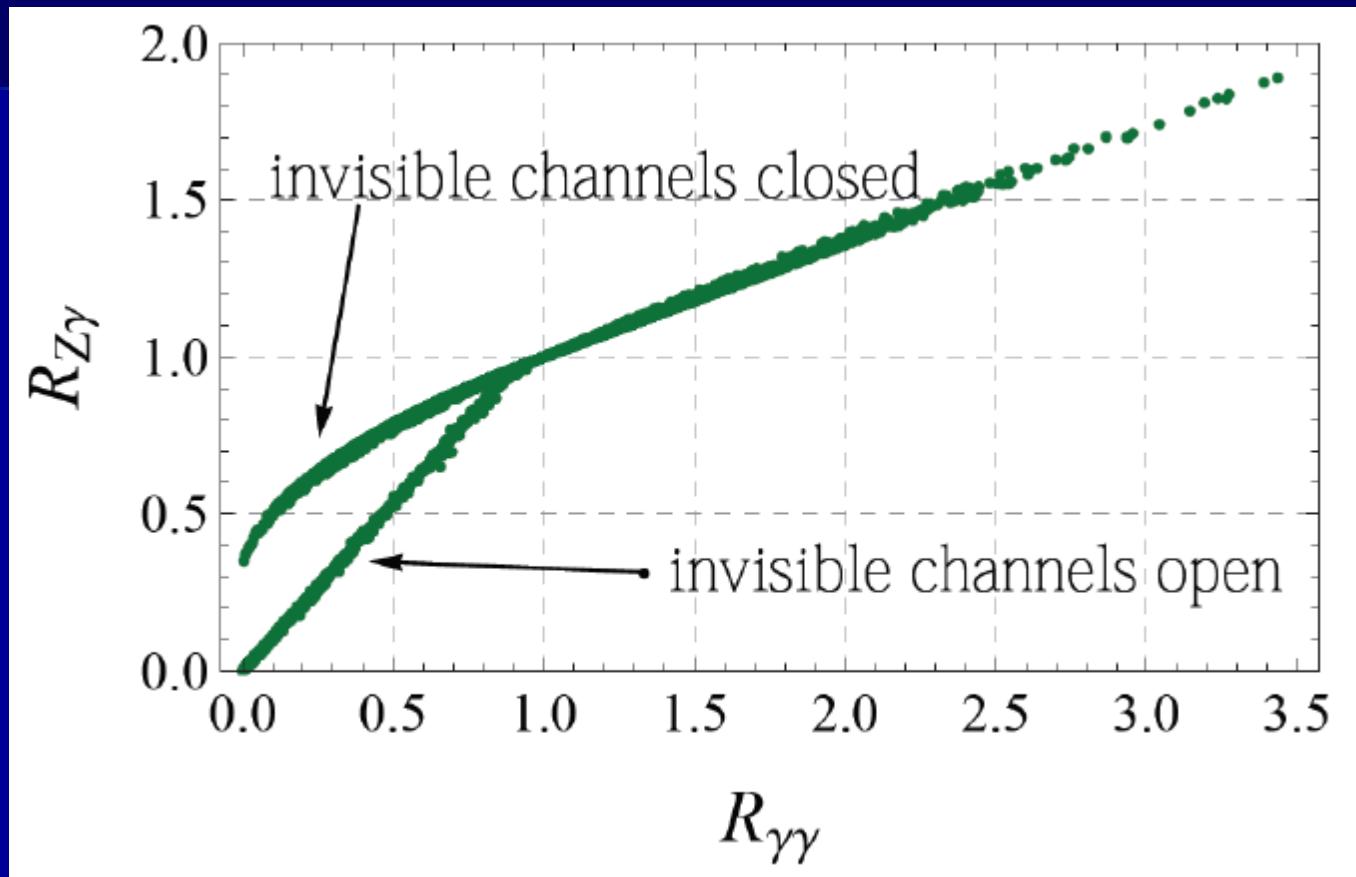
- $\text{Br}(h \rightarrow \text{inv}) < 37\%$,
- $\Gamma(h)/\Gamma(h)^{\text{SM}} < 4.2$

global fit:

- $\text{Br}(h \rightarrow \text{inv}) \lesssim 20\%$



Zgamma vs gamma gamm



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

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

Relic DM density

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

LHC data

hep-ph/
1305.6266
JHEP 2013

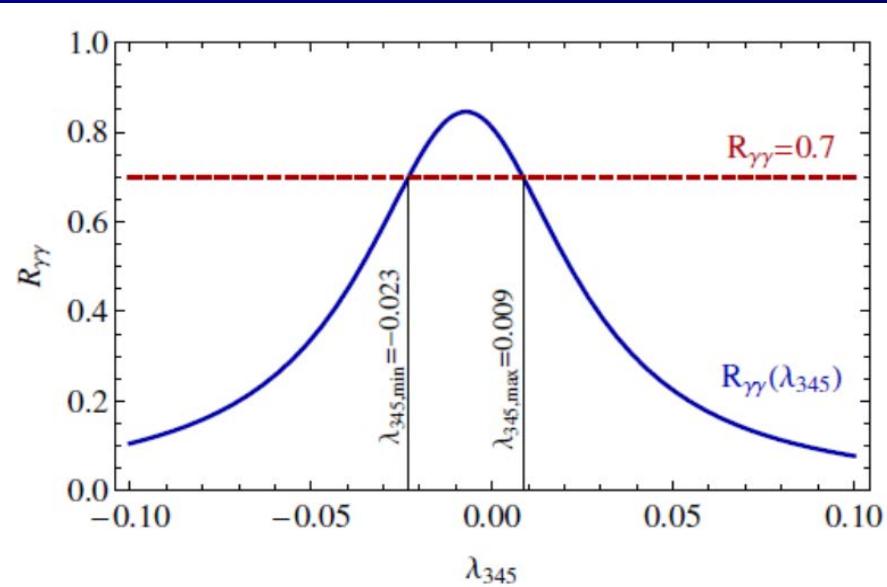
ATLAS : $R_{\gamma\gamma} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst}),$
CMS : $R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26}.$

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

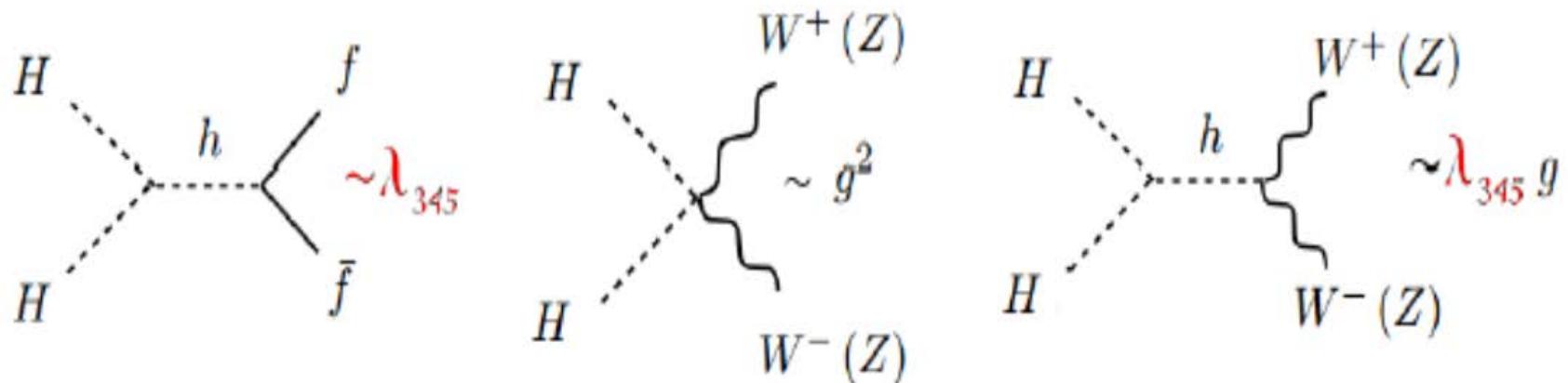
1.12 ± 0.24

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

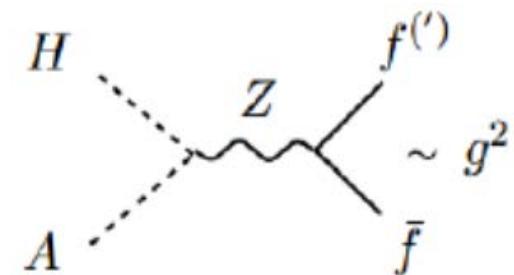
DM mass below 62.5 GeV
allowed only if
 $R_{\gamma\gamma} < 1$



Relic density constraints on masses and couplings of DM

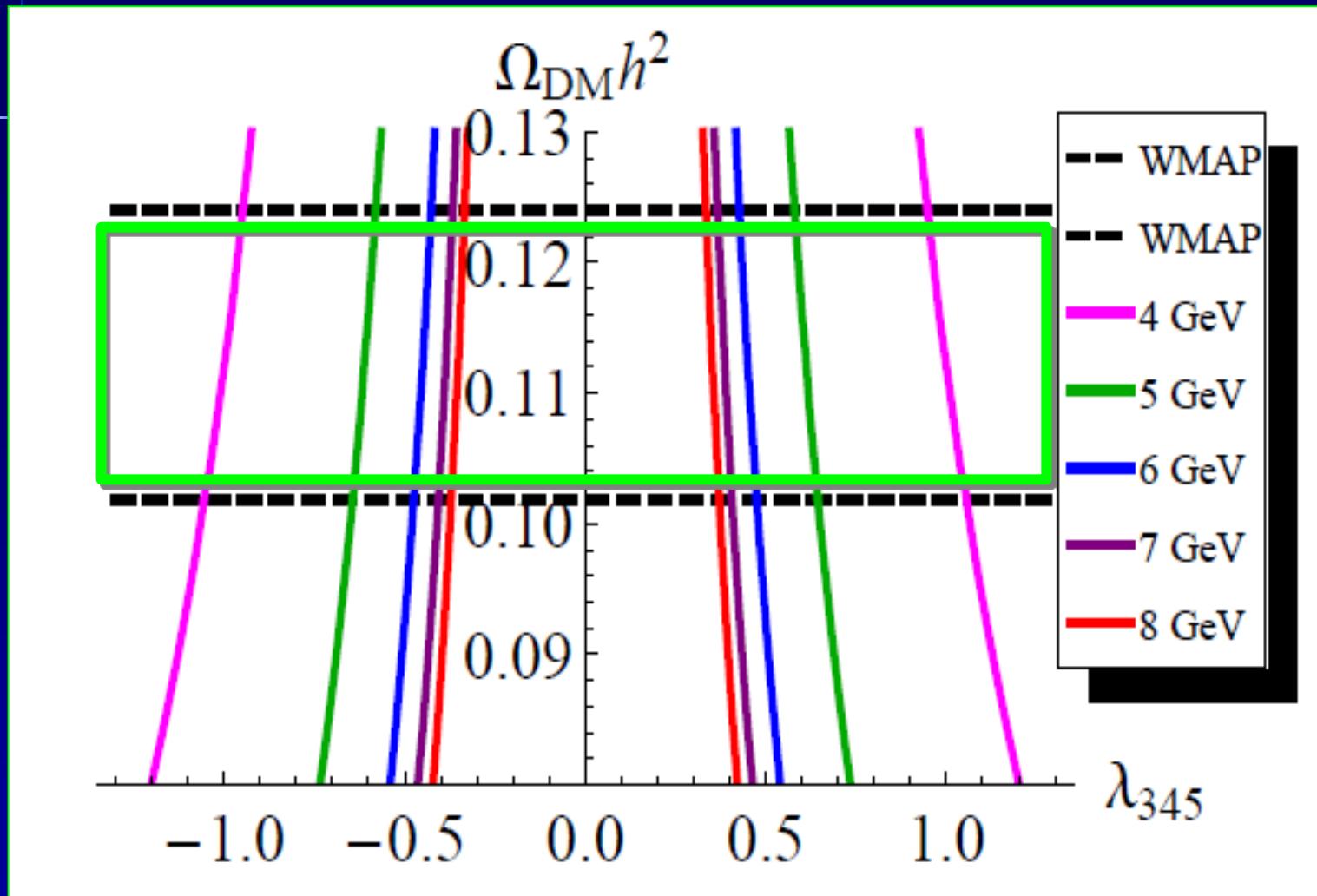


Coannihilation possible
for small (AH) splitting



- 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)

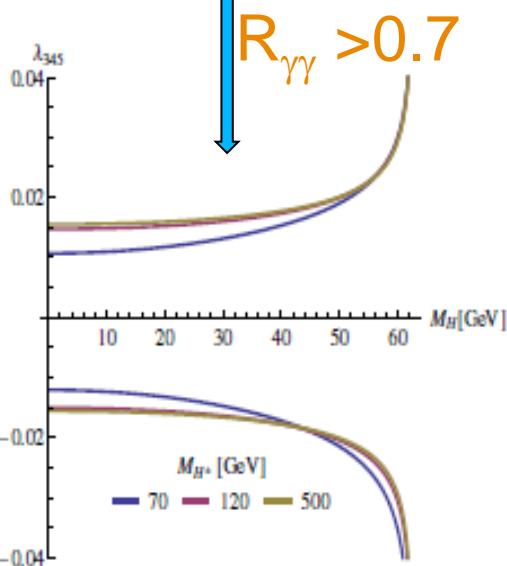


Low mass H – excluded by LHC!

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

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

$M_H \lesssim 10 \text{ GeV}, \quad M_A \approx M_{H^\pm} \approx 100 \text{ GeV}$
 $h \rightarrow AA$ channel closed, $h \rightarrow HH$ channel open



- Proper relic density

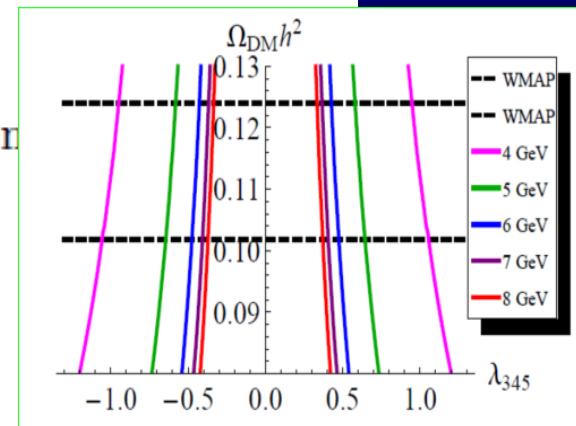
$$0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$$

- CDMS-II reported event:

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

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

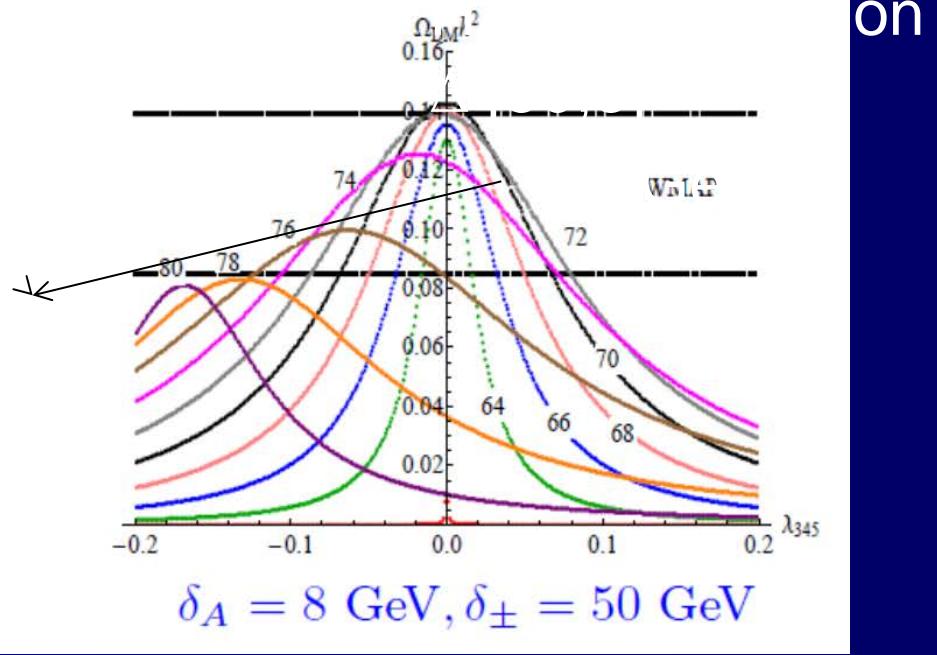
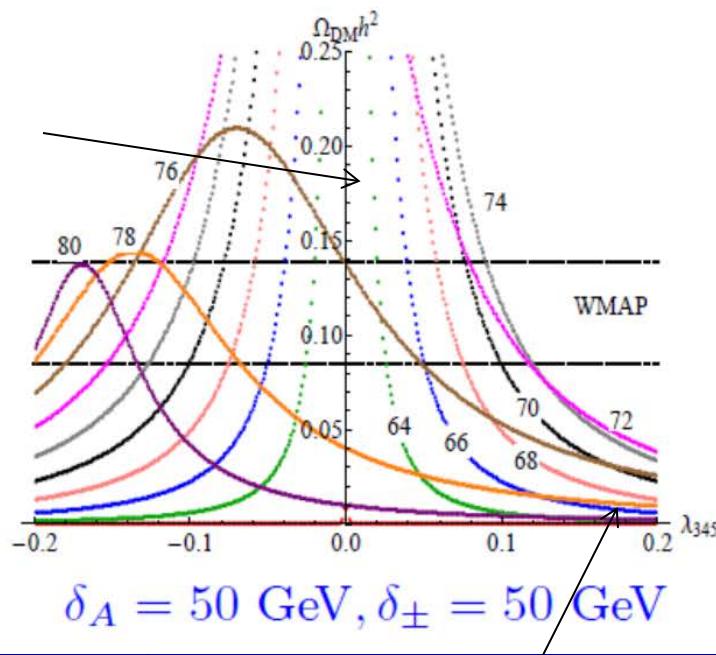
Low DM mass excluded



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

D. Sokołowska, 2013

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

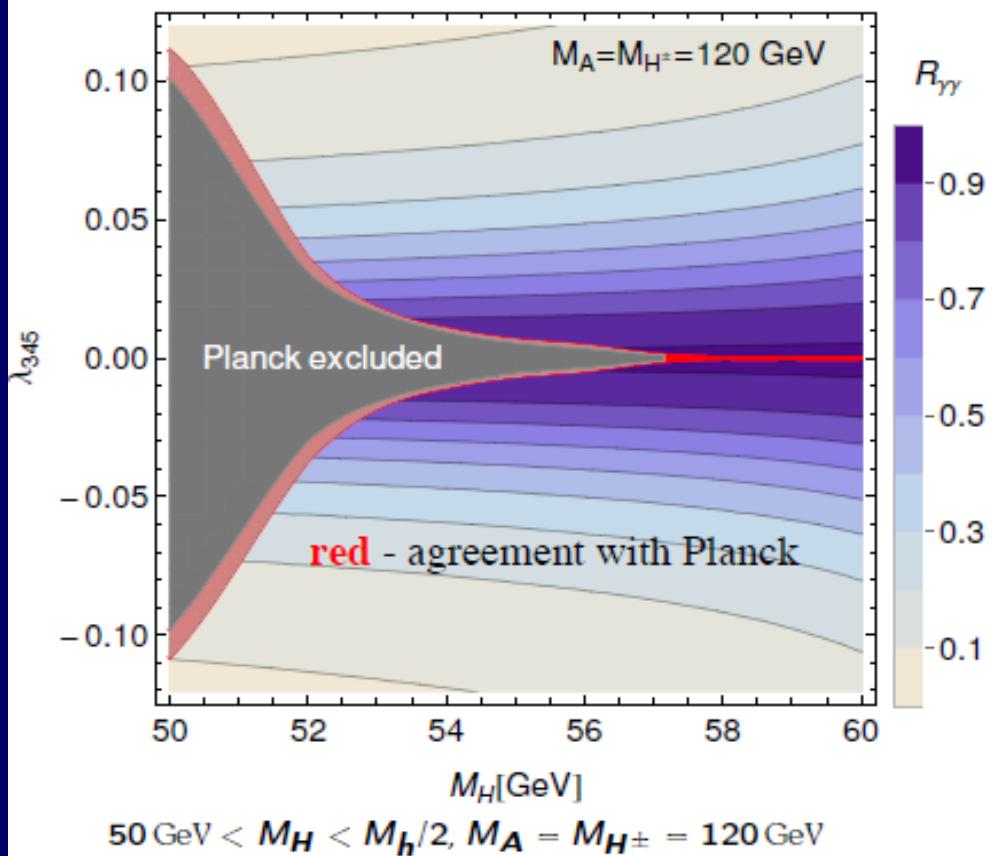


above 76 GeV asymmetry due to annihilation to gauge bosons

Using PLANCK data

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

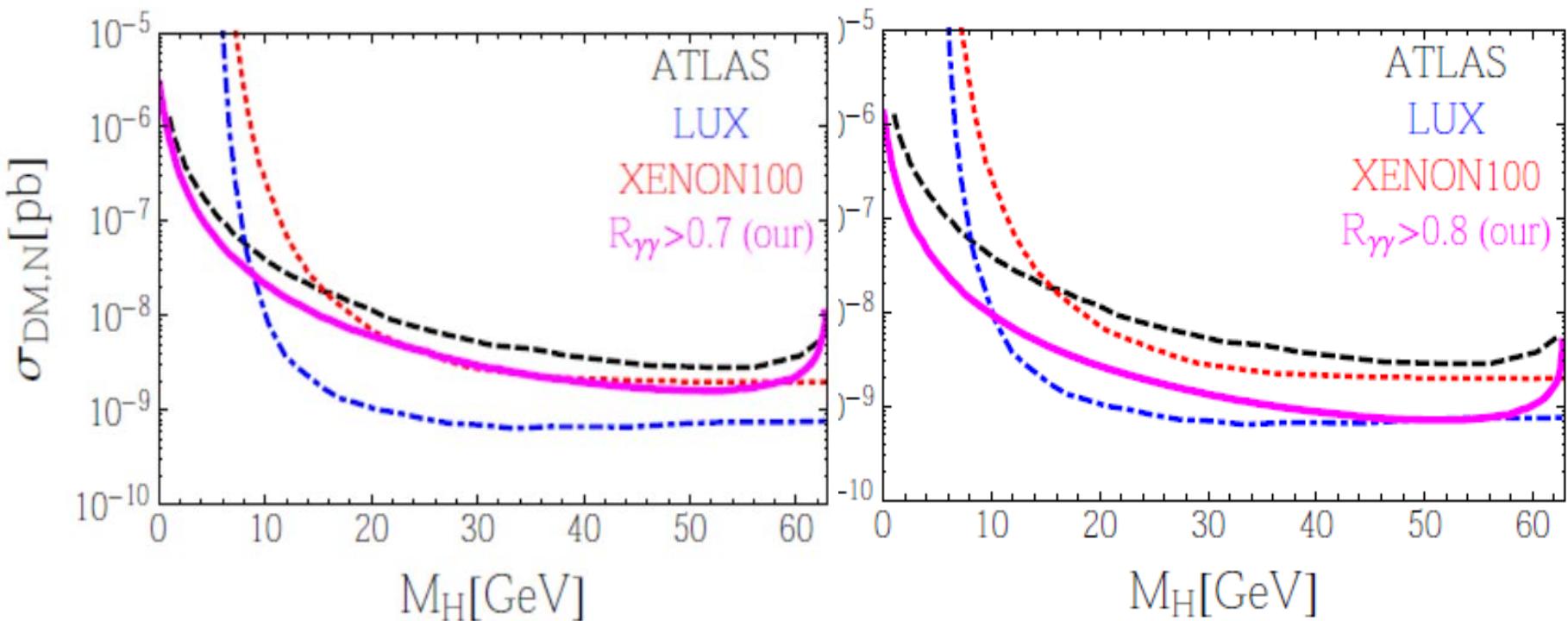
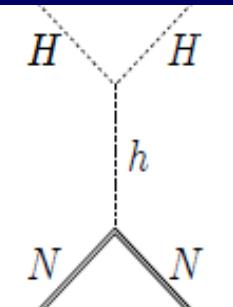
$h \rightarrow HH$ open



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

Direct detection – comparison with LHC, Xenon 100 and LUX

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