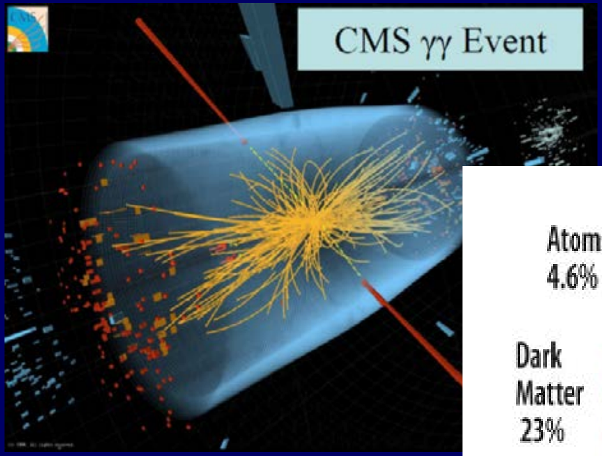
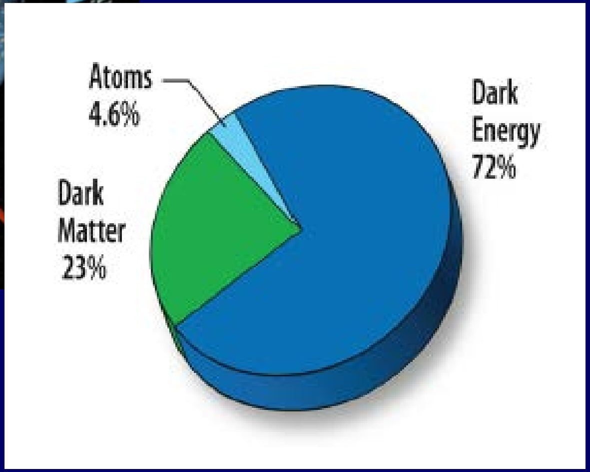
II Syposium on applied nuclear physics,
Kraków 26.09.2014

# Universe in the light of LHC data



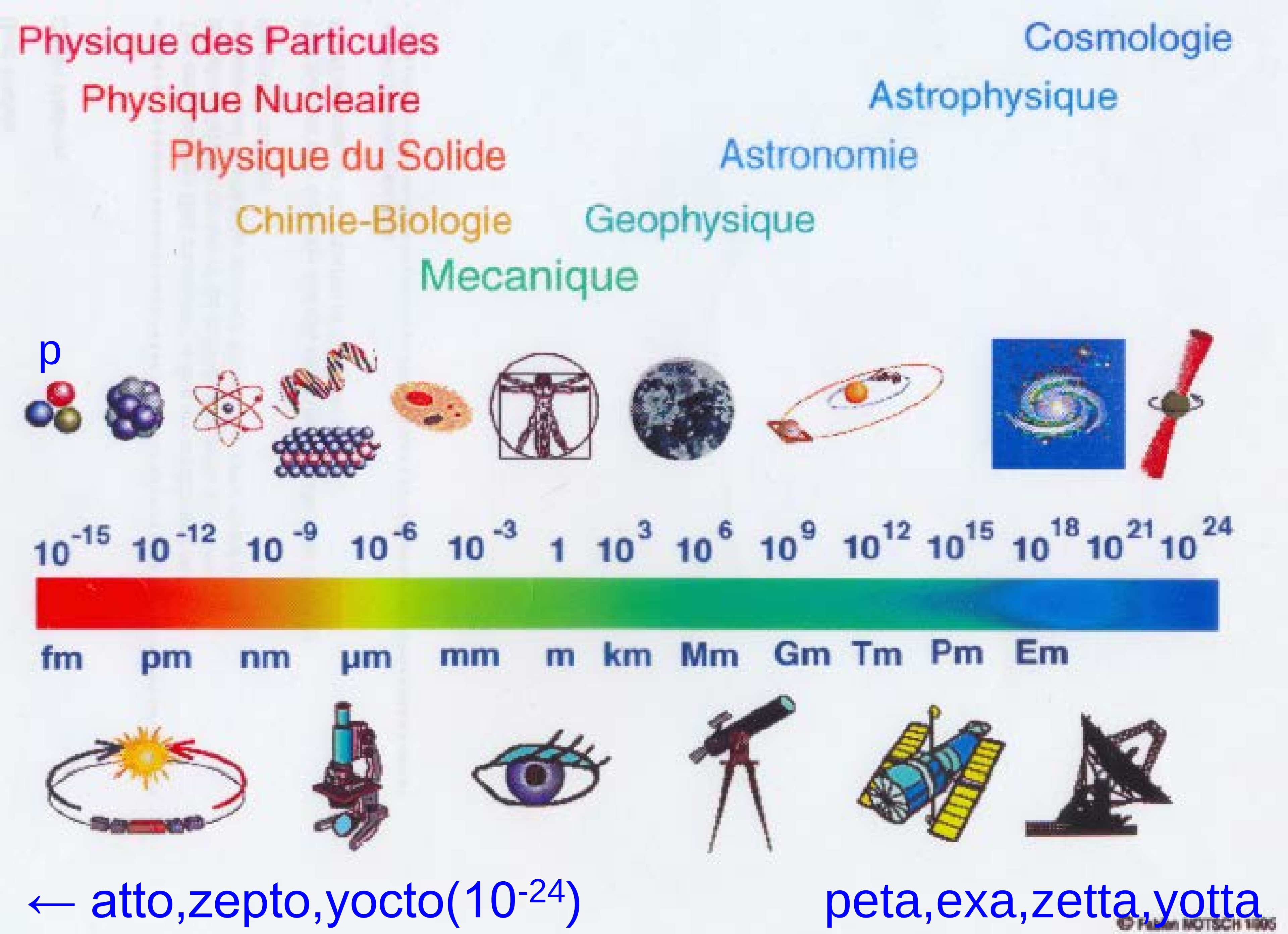




Plan

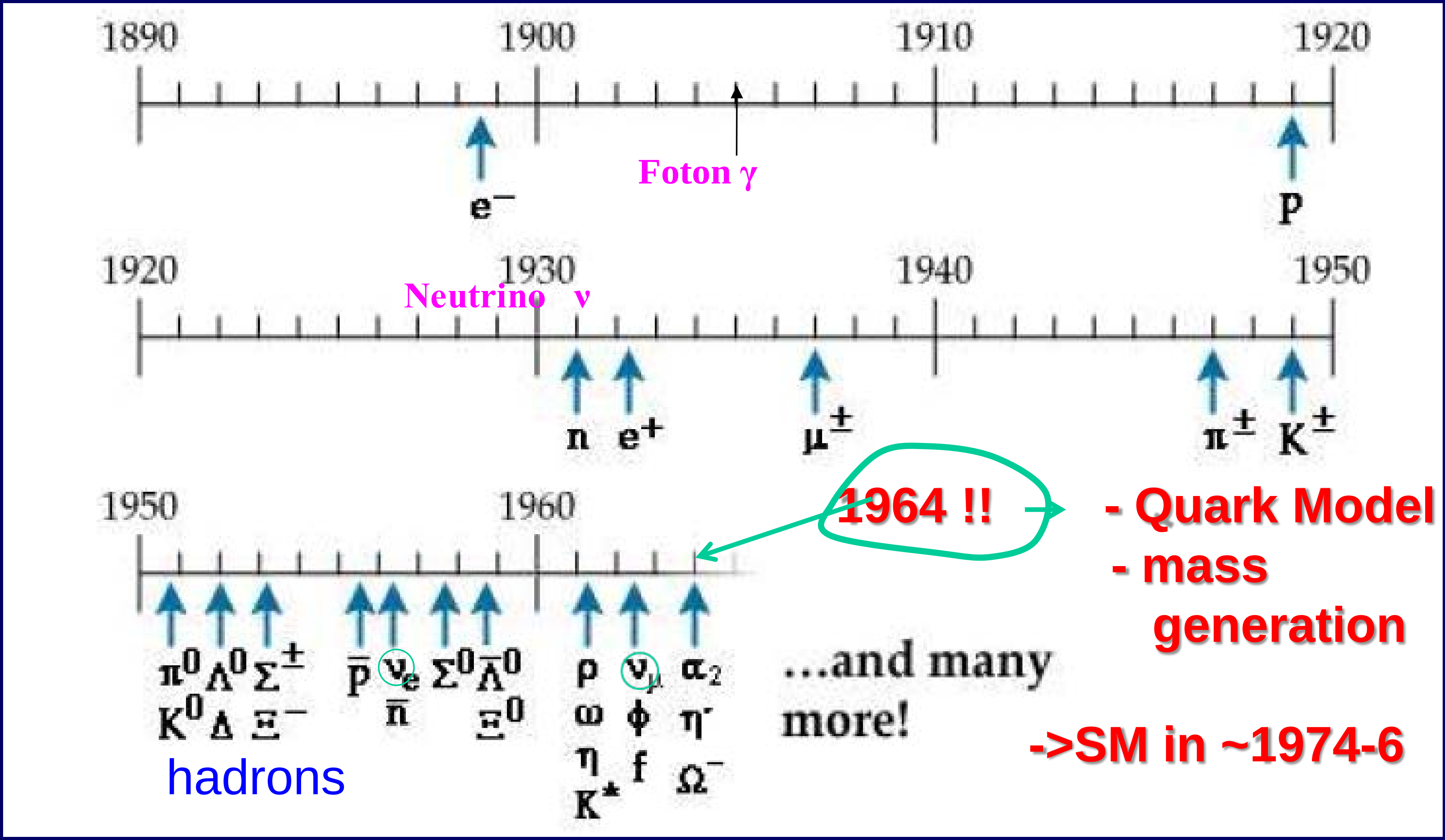
- Standard Model
- Higgs: LHC data
- SM-like scenarios at LHC
- Higgs-portal to dark matter
- Temperature evolution of the Universe

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)


Physique des Particules
Physique Nucleaire
Physique du Solide
Chimie-Biologie
Mecanique
Geophysique
Astronomie
Astrophysique
Cosmologie
p
$10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$ $10^{24}$
fm pm nm µm mm m km Mm Gm Tm Pm Em
← atto,zepto,yocto($10^{-24}$)
peta,exa,zetta,yotta

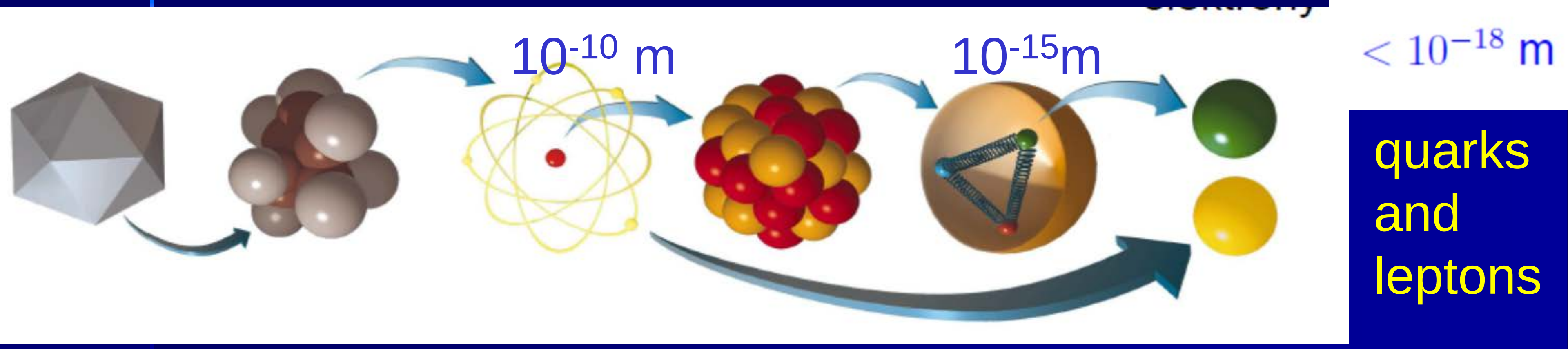
# Discoveries of elementary particles - ‚flood' in years 1950-60



# Structure of matter

**Molecules> atoms>nuclei>nucleons>quarks**

**subquarks?? – probabbly no (confinement)**




**Forces**: electro-mag, gravity, strong and weak

strong (nuclear) between nucleons (exchange of pions) in nucleus range $10^{-15}$ m

- <u>strong (nuclear) fundamental (color)between quarks and gluons</u>

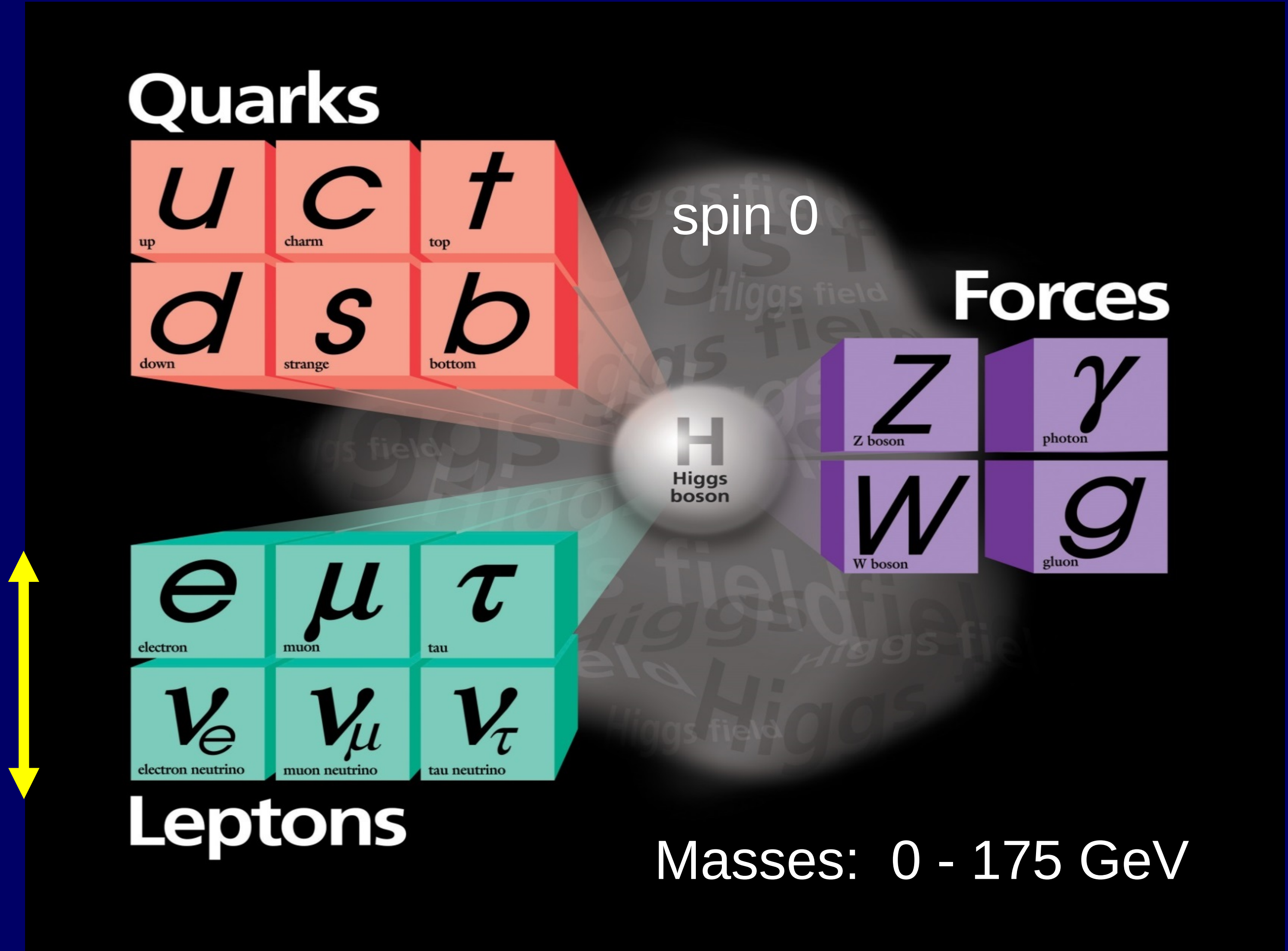
weak (eg. decay of neutron), range < $10^{-18}$ m (point-like)

- <u>weak fundamental between quarks and leptons (exchange of W+,W-, Z with masses 80-90 GeV)</u>

# Fundamental particles in SM

spin 1/2 ħ

spin 1




Masses: 0 - 175 GeV

# STANDARD MODEL (SM)

Description of the fundamental level

- quarks and leptons
- strong, electromagnetic, weak forces

*electroweak (EW)*

Symmetry as a basic principle –

local (gauge) symmetry used to describe dynamics!

**SU(3) x SU(2) x U(1)**

carriers of interactions –> gauge bosons

all should be massless (as well matter particle) ?!

We need a special symmetry breaking …(SSB)

# Year 1964

## -> LHC 4.07.2012

Higgs-like particle with mass125 -126 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)

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

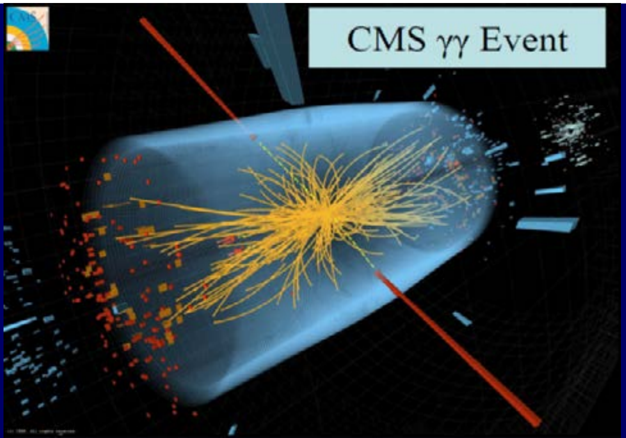
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

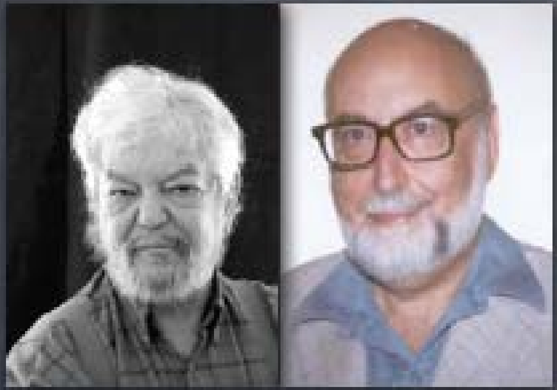
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

12.10.1964

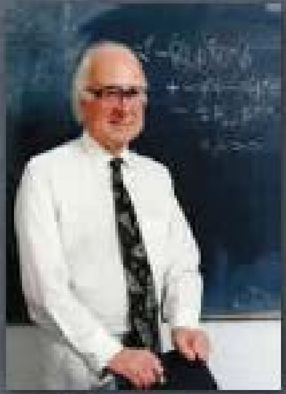


# 2010 Sakurai Prize

... 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

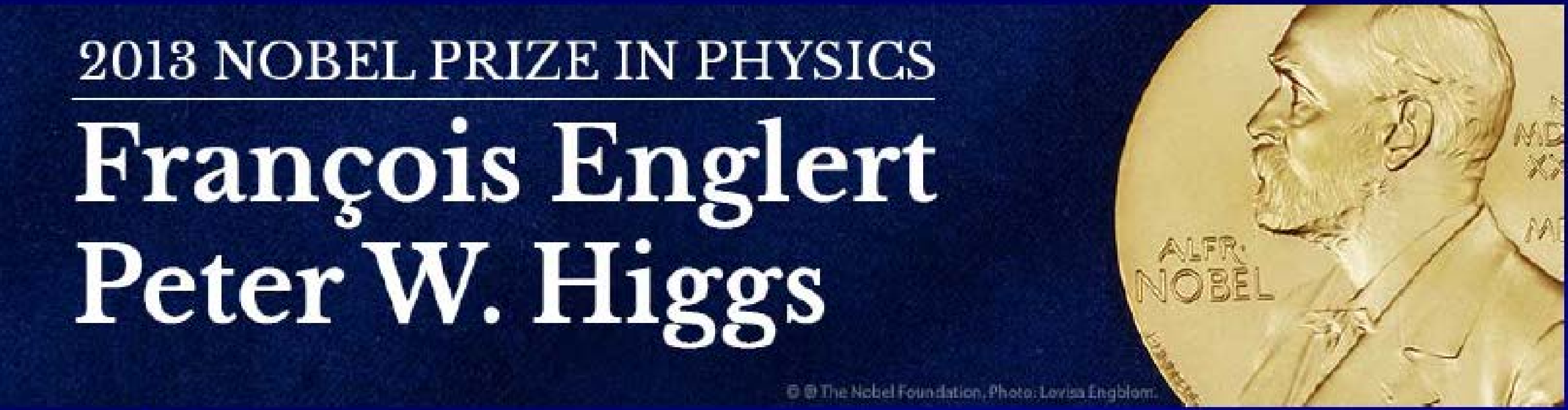
PRL 13, 321-323 (1964)

PRL 13, 508-509 (1964)

PRL 13, 585-587 (1964)

Nambu, Nobel 2008

For introducing SSB to elementary particle physics




The Nobel Prize in Physics 2013

François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

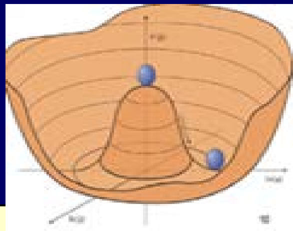
October 2013

# 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): $\Phi = (\varphi^{+}, v+h+i\zeta)^{T}$ $v^2 = m^2/\lambda$ (vev)

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

Generation of mass of gauge boson: $M_W = g\, v$

Fermion masses via Yukawa int. (add. parameters)

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

h couplings prop. to masses for WW/ZZ, fermions

only unknown was Higgs mass $\leftrightarrow$ selfinteraction

# Higgs particle-the missing particle of SM

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

But how close? Loop couplings ggh, $\gamma\gamma$h, $\gamma$Zh sensitive to new physics (new even very heavy particles - *nondecoupling* effects)

Beyond SM (BSM) – only models with SM-like scenarios:

*SM-like h and no other new particle seen*

are relevant.

# 1. The Higgs in the SM and beyond

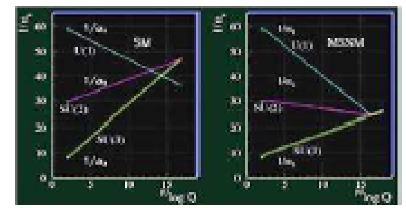
**There are major theoretical and experimental problems in the SM:**

- does not incorporate masses for the neutrinos (there is no $\nu_R$ in SM);
- does not explain baryon asymmetry (baryogenesis?) in the universe;
- does not incorporate the fourth fundamental interaction, gravity;
- does not explain why $\mu^2 < 0$ and has too many (19!) free parameters.

- **No real unification of the interactions:**

– $3 \neq$ gauge groups with $3 \neq$ couplings,

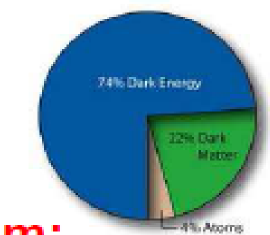
– no meeting of the couplings in SU(5).




- **No solution to the Dark Matter problem:**

– 25% of the universe made by Dark Matter,

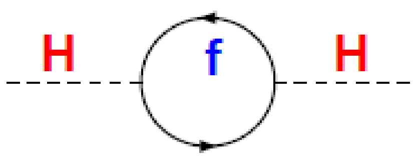
– no stable, neutral, weak, massive particle.




- **Above all: there is the hierarchy or naturalness problem:**

radiative corrections to $M_H$ in SM with a cut–off $\Lambda = M_{NP} \approx M_P$

$$\Delta M_H^2 \equiv$$




$$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2!$$

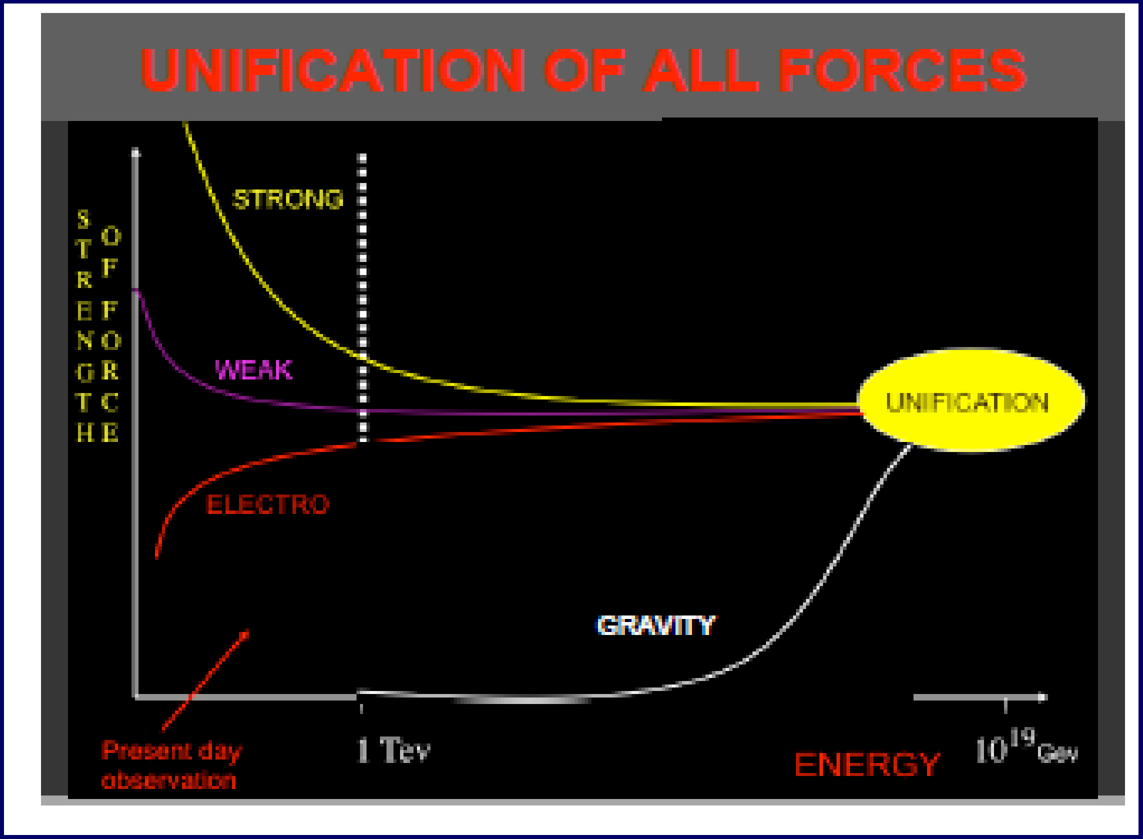
$M_H$ prefers to be close to the high scale than to the EWSB scale...

# Unification with gravitation

David Gross: The Coming Revolutions in Theoretical Physics

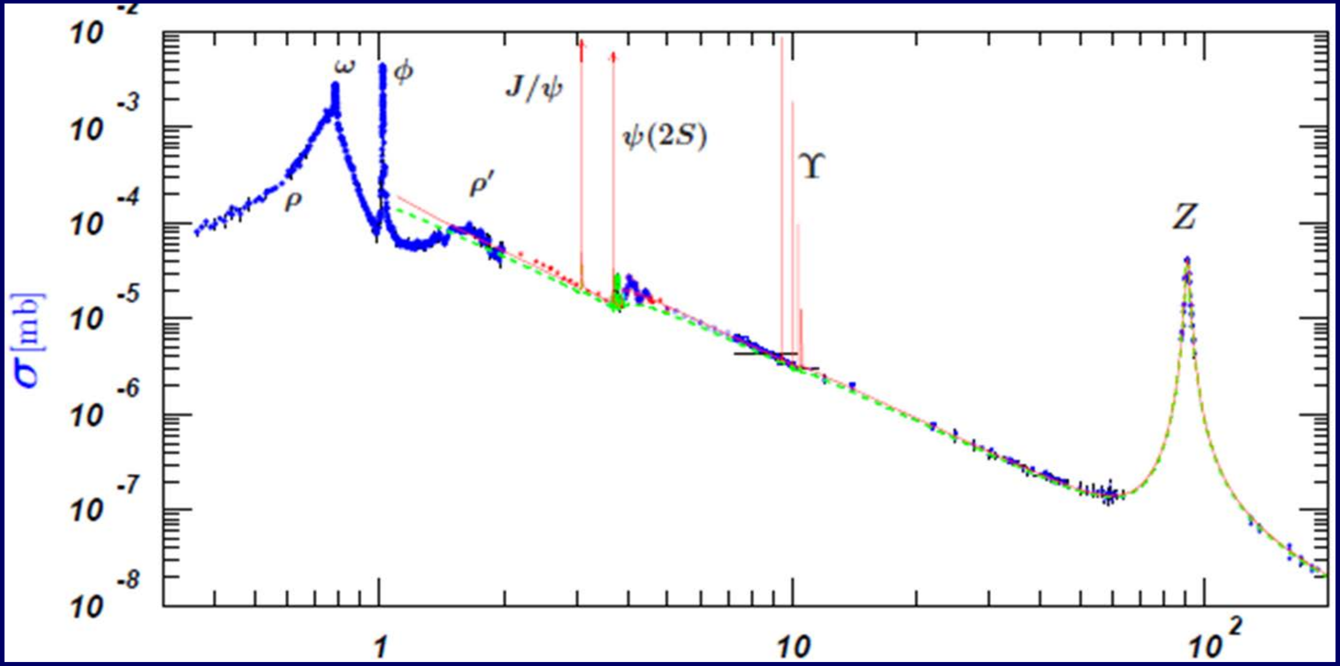
*http://www.youtube.com/watch?v=AM7SnUlw-DU&feature=channel*

running coupling constants

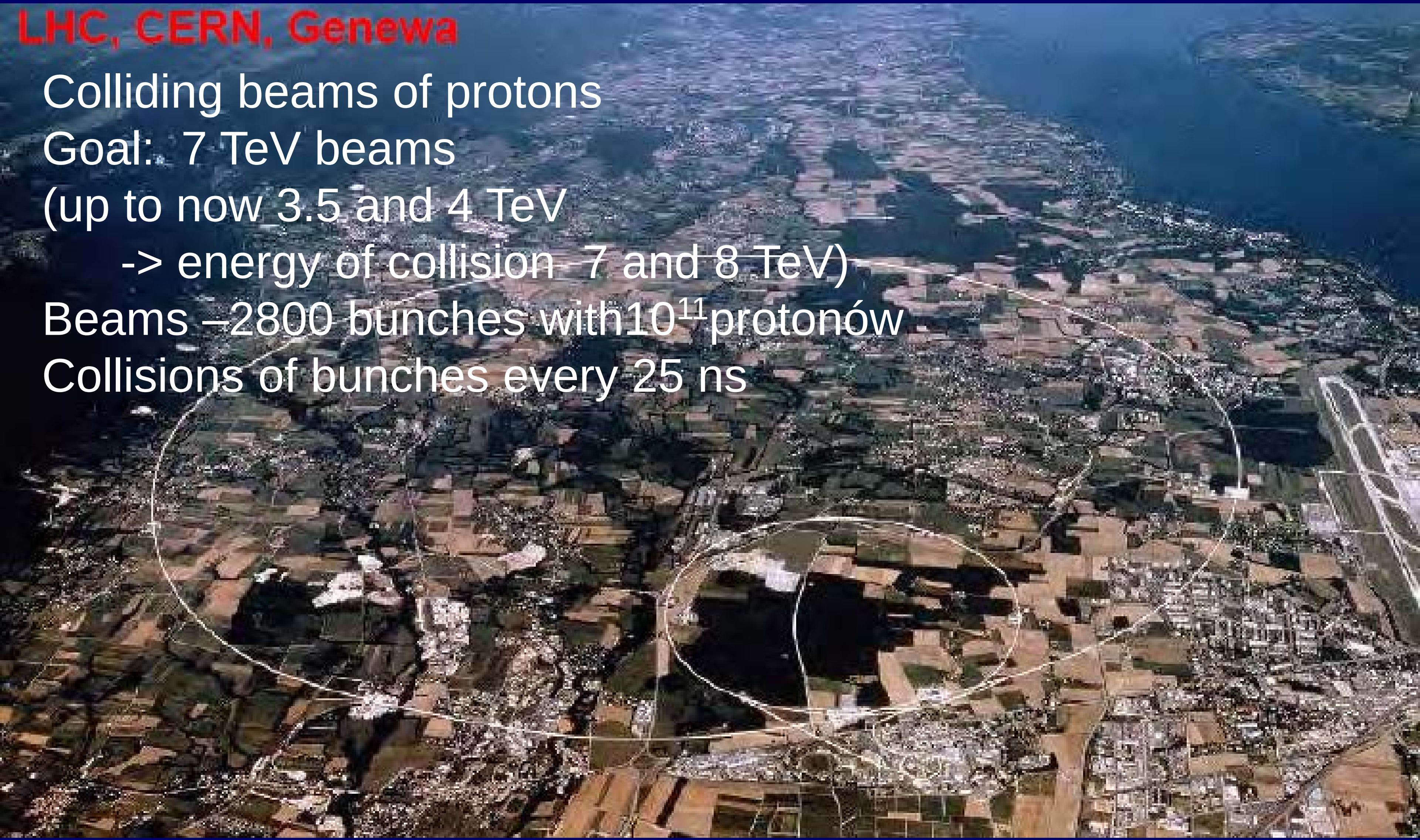



**„Strenght" of gravity F~ $M^2$ ~ $E^2$ i therfore is rising so fast for large E**

e+e-
LEP




# LHC DATA

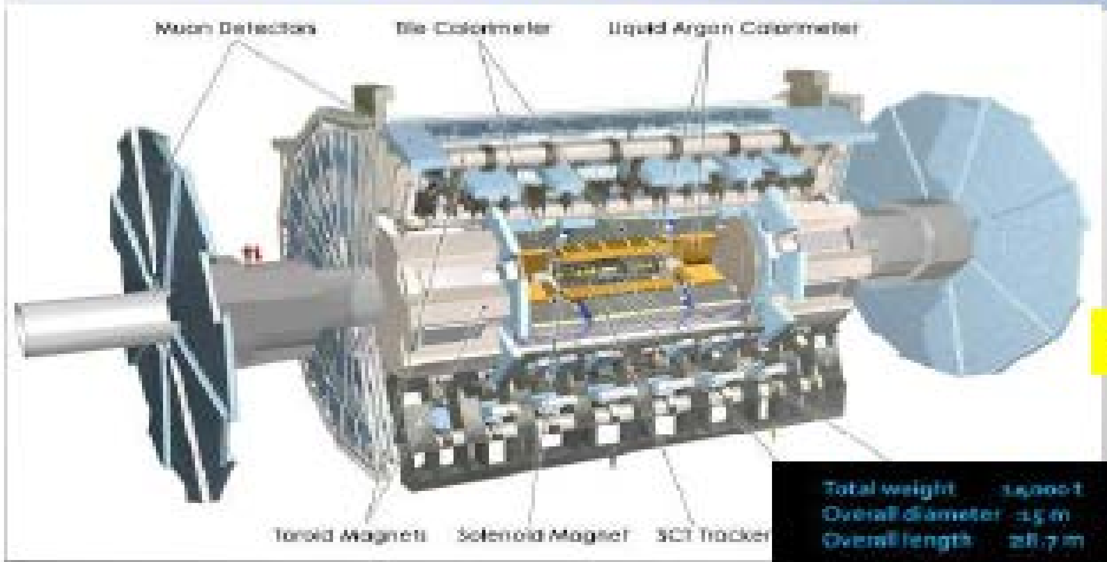



Colliding beams of protons
Goal: 7 TeV beams
(up to now 3.5 and 4 TeV
-> energy of collision 7 and 8 TeV)
Beams –2800 bunches with $10^{11}$ protonów
Collisions of bunches every 25 ns

Large Hadron Collider –
4 experiments (detectors) ATLAS,CMS..

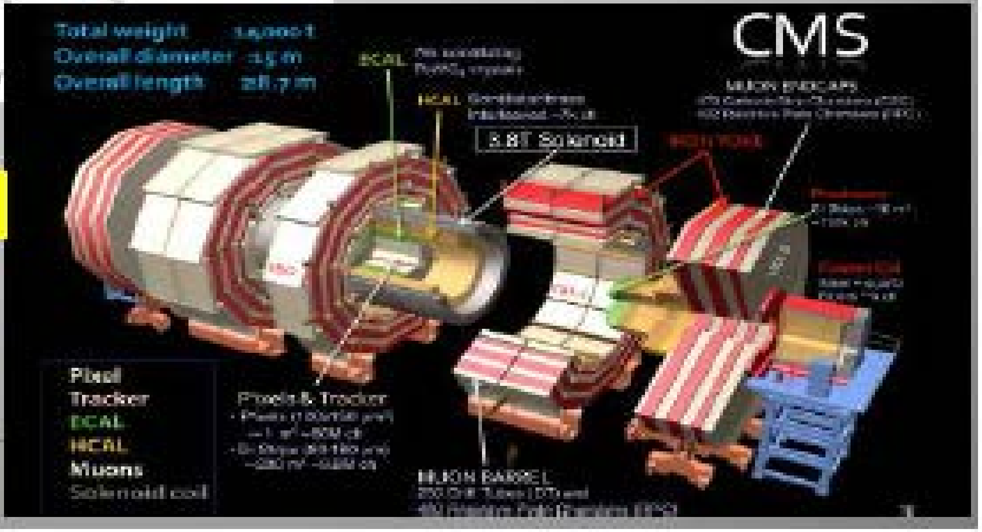
break till spring 2015

# The Higgs Hunters @ the LHC




LHC: pp collisions
Luminosity:
$5\ fb^{-1}$ @ 7 TeV
$20\ fb^{-1}$ @ 8 TeV

The ATLAS experiment



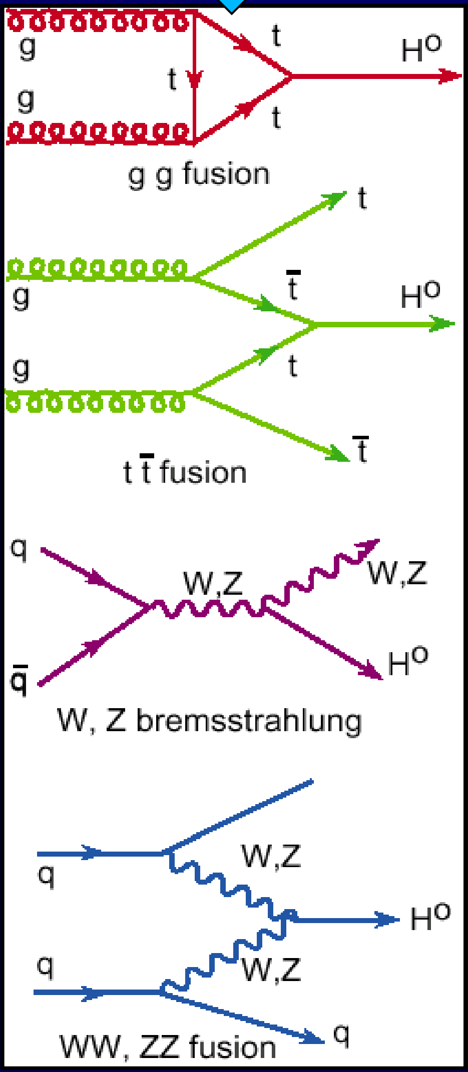

The CMS experiment

And LHCb...?

The Higgs is the new playground: Room for new experimental/theoretical ideas!!
Remember: we have already ~1 Million Higgses produced at the LHC

deRoeck, 13.09.2014

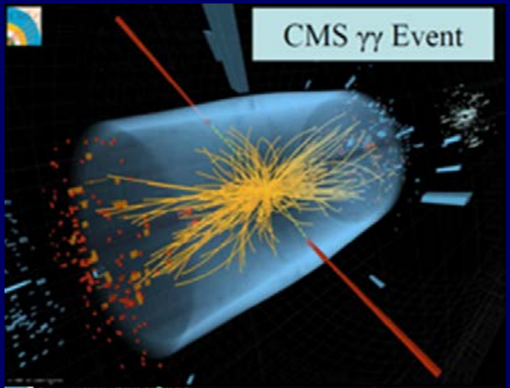
# Production and decay of Higgs particle at LHC

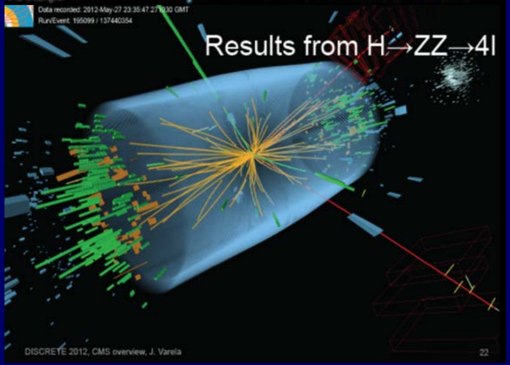


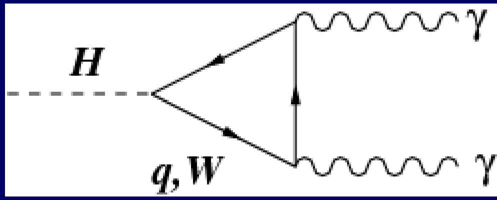

## main decays

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...

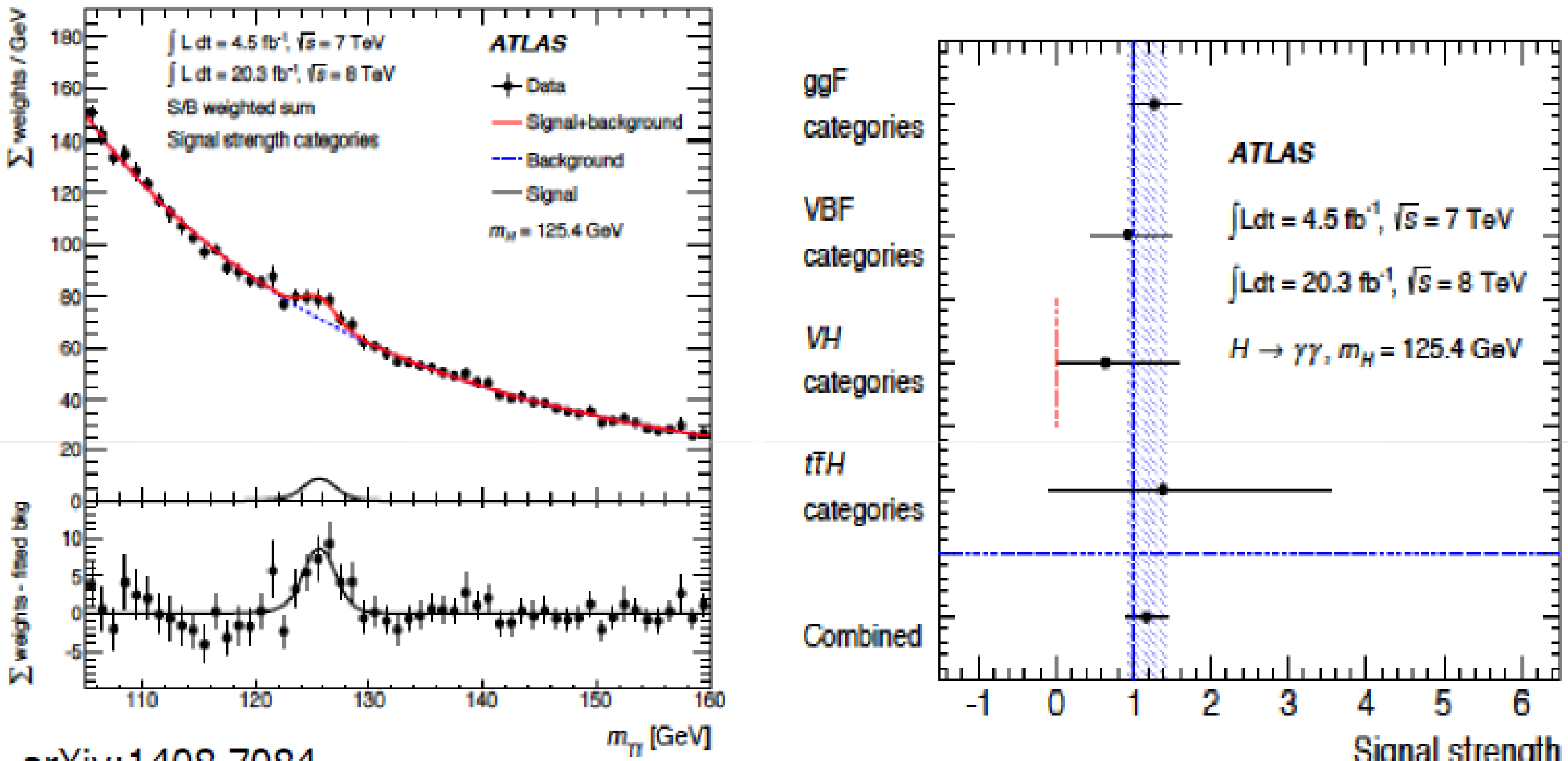


# ATLAS: Higgs → γγ

deRoeck, 13.09.2014




arXiv:1408.7084

$\mu = 1.17 \pm 0.27$

For $M_H$=125.4 GeV

Signal strength $\mu = \dfrac{\sigma_{measured}}{\sigma_{SM}}$

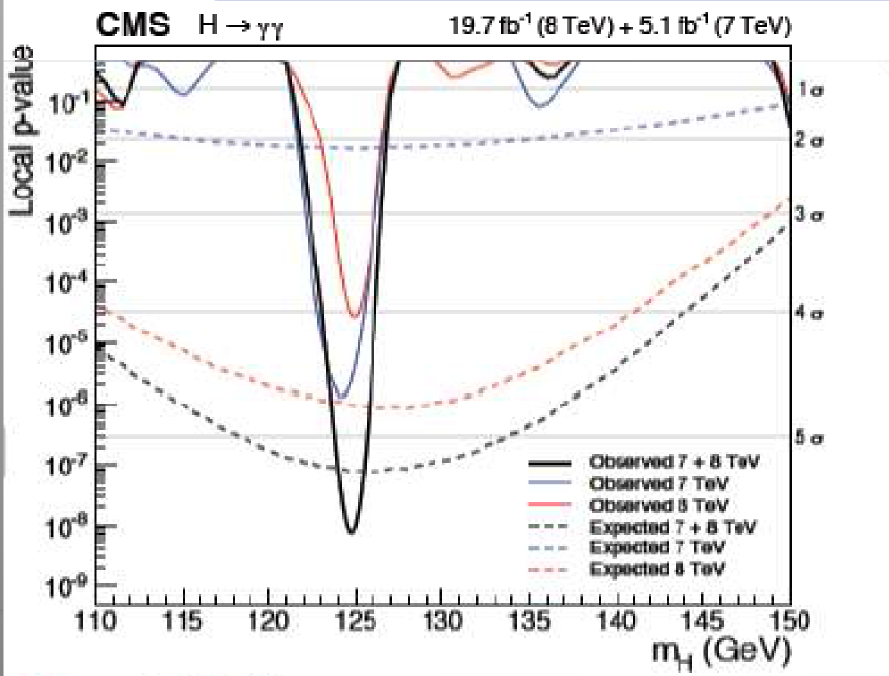
# CMS: Higgs → γγ

Signal Strength:

arXiv:1407.0558

| Dataset | Significance (obs) | $\sigma/\sigma_{SM}$ | $m_H$ (GeV) |
|---|---|---|---|
| 7 TeV | 4.7σ | $2.22^{+0.62}_{-0.55}$ | 124.2 |
| 8 TeV | 4.0σ | $0.90^{+0.26}_{-0.23}$ | 124.9 |
| 7 + 8 TeV | 5.7σ | $1.14^{+0.26}_{-0.23}$ | 124.7 |

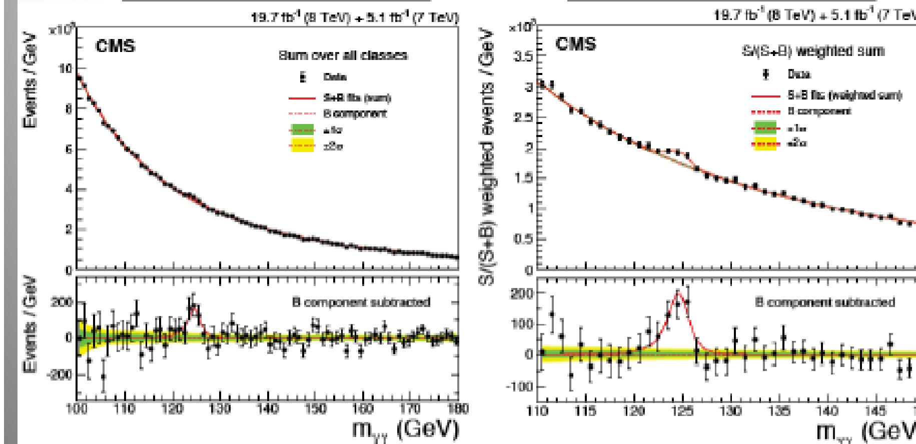
$$\sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23}\left[{}^{+0.21}_{-0.21}(\text{stat.})^{+0.09}_{-0.05}(\text{syst.})^{+0.13}_{-0.09}(\text{th.})\right]$$




## CMS: Higgs → γγ

Inclusive sum of all events chosen

Sum weighted by sensitivity



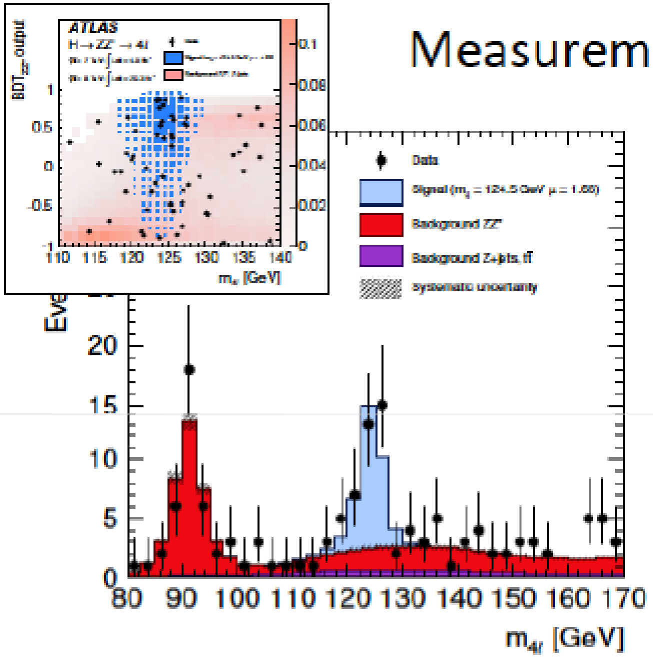

arXiv:1407.0558

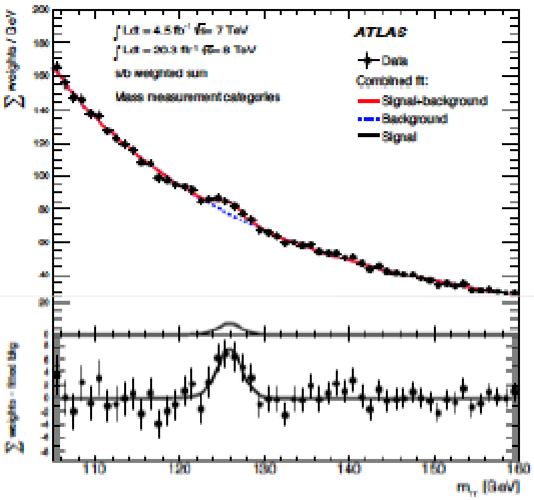
deRoeck, 13.09.2014

# ATLAS: Higgs Mass

Use of BDT ZZ

## Measurement of the Higgs boson mass




Old

$124.3\ ^{+0.6}_{-0.5}\ \text{(stat)}\ ^{+0.5}_{-0.3}\ \text{(syst)}\ \text{GeV}$

$124.51 \pm 0.37\ \text{(stat)} \pm 0.06\ \text{(syst)}\ \text{GeV}$

- Analyses improvements
  - Categories for mass in the diphoton
  - BDT-ZZ, far FSR corrections

Old

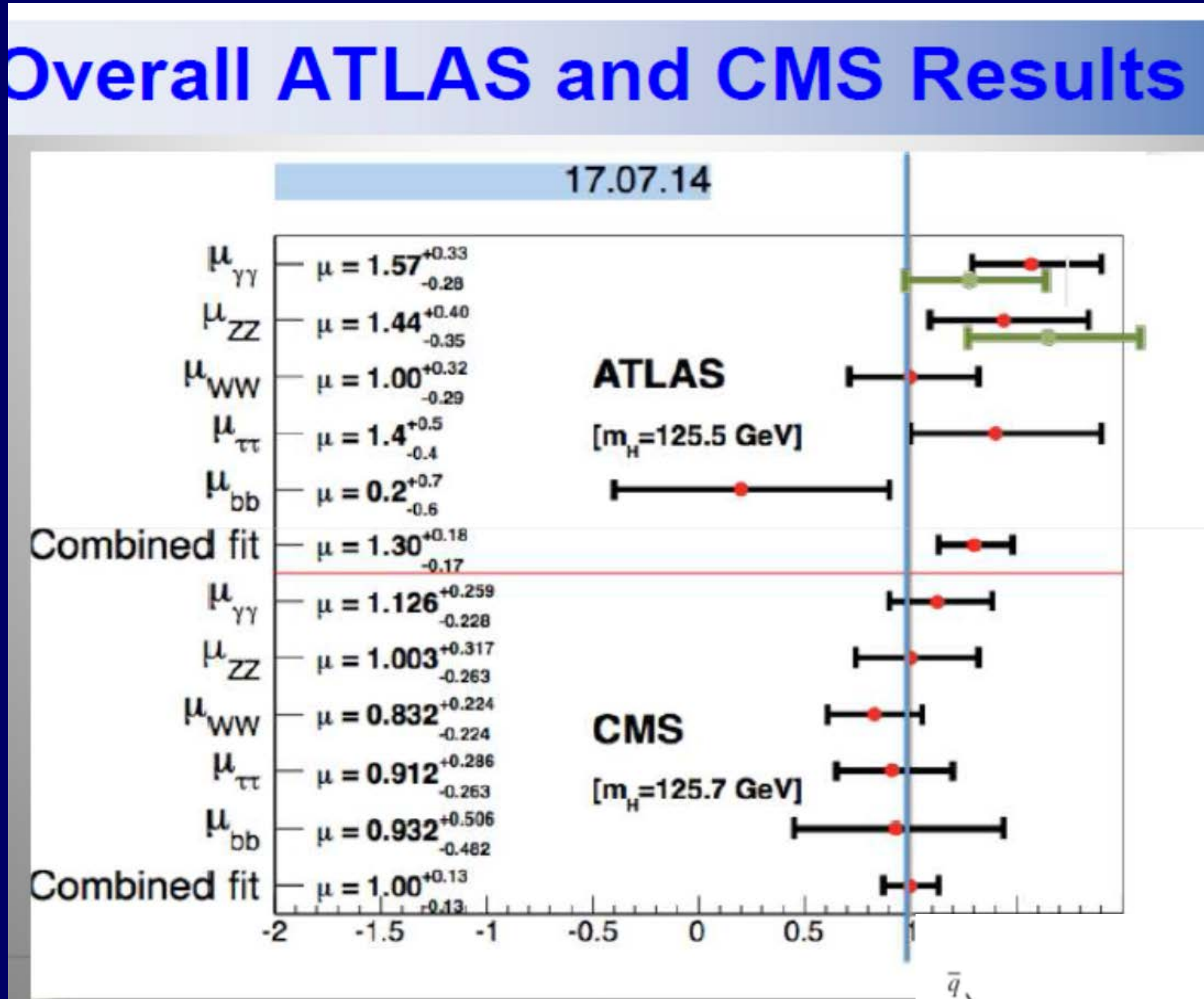
$126.8 \pm 0.2\ \text{(stat)} \pm 0.7\ \text{(syst)}\ \text{GeV}$

Expected mass shift -450 +/- 350 MeV

$125.98 \pm 0.42\ \text{(stat)} \pm 0.28\ \text{(syst)}\ \text{GeV}$

- Large improvement on systematics
- Increase in stat uncertainty in diphoton:
  - Lower signal rate
  - Fluctuation of the error (exp. 0.35 GeV)

# SM-like Higgs

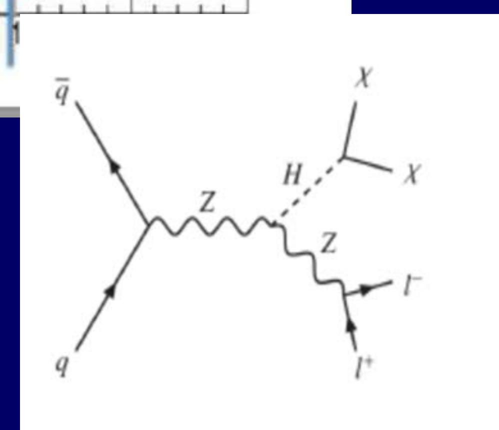



Total width

< 4 x SM (in SM 4,2 MeV)

Decay to invisible particles

BR (inv) < 0.37



# HIGGS PORTAL TO DM

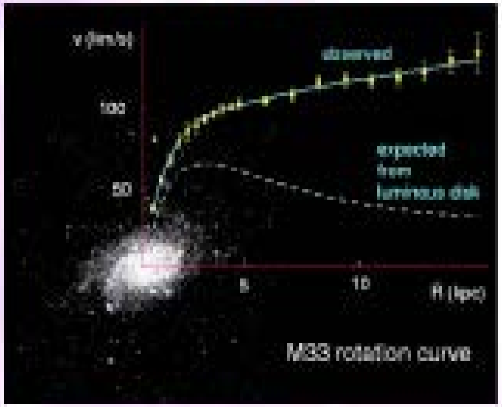
# Dark Matter EVIDENCES

Morsolli, Sept. 2014

- In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:

- Since then, many other evidences:

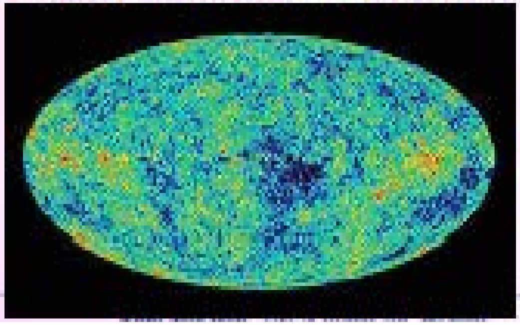
Rotation curves of galaxies




Gravitational lensing

Bullet cluster

Structure formation as deduced from CMB



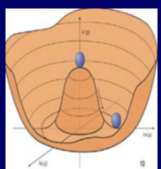
Data by WMAP imply:


$\Omega_b h^2 \approx 0.02$

$\Omega_{DM} h^2 \approx 0.1$

# Inert Doublet Model

$\Phi_S$ as in SM (BEH) $\Phi_D$ – 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 $\Phi_D$ has odd D-parity
    - the lightest scalar stable - DM candidate (H)
      - ($\Phi_D$ dark doublet with dark scalars)

*IDM: An Archetype for Dark Matter, Lopez Honorez,..Tytgat..07*

*LHC phenomenology (Barbieri., Ma.. 2006)*

# 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!

$\lambda_{345}$

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

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

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

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

Quartic selfcouplings $D^4$ proportional to $\lambda_2$

hopeless to be measured at colliders! *(→ DM ?)*

Couplings with Higgs: hHH ~ $\lambda_{345}$ h H+H- ~ $\lambda_3$

# IDM – scan

*(B. Świeżewska 2012)*

Constraints: M_h=125 GeV ($\lambda_1$=0.25)

pert. vacuum stability,

conditions for Inert I1 vacuum

perturbative unitarity condition

EWPT ~~(other data)~~ →

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

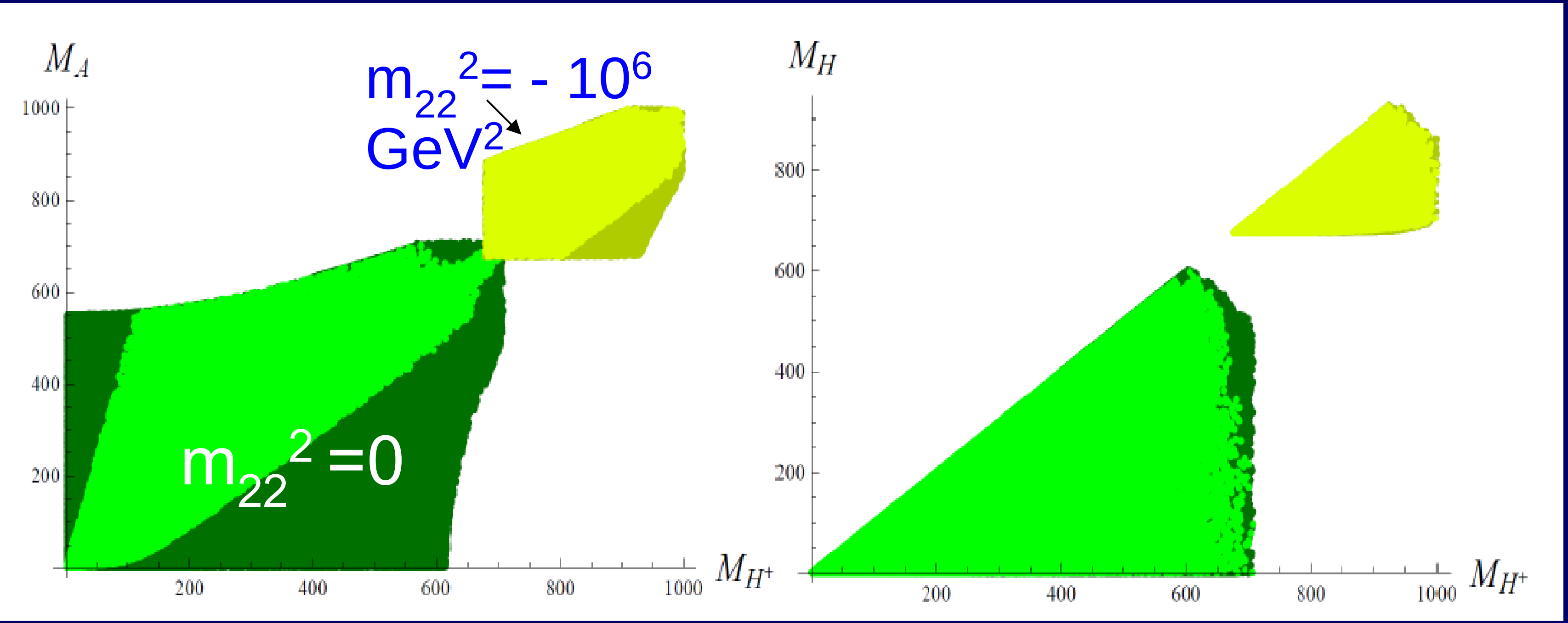
# Inert Doublet Model with Mh=125 GeV

Analysis based on unitarity, positivity, EWPT constraints

*Gorczyca'2011-12*

$m_{22}^2 = 0$

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




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

EWPT (pale regions)

# $\gamma\gamma$ 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**

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

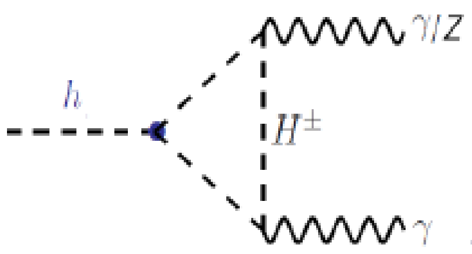
$R_{Z\gamma}$ – treated analogously

narrow width approx

- Largest contribution from $gg$ fusion
- $\sigma(gg \to h)^{SM} = \sigma(gg \to h)^{IDM}$ (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 $\Gamma(h \to \gamma\gamma)^{IDM}$

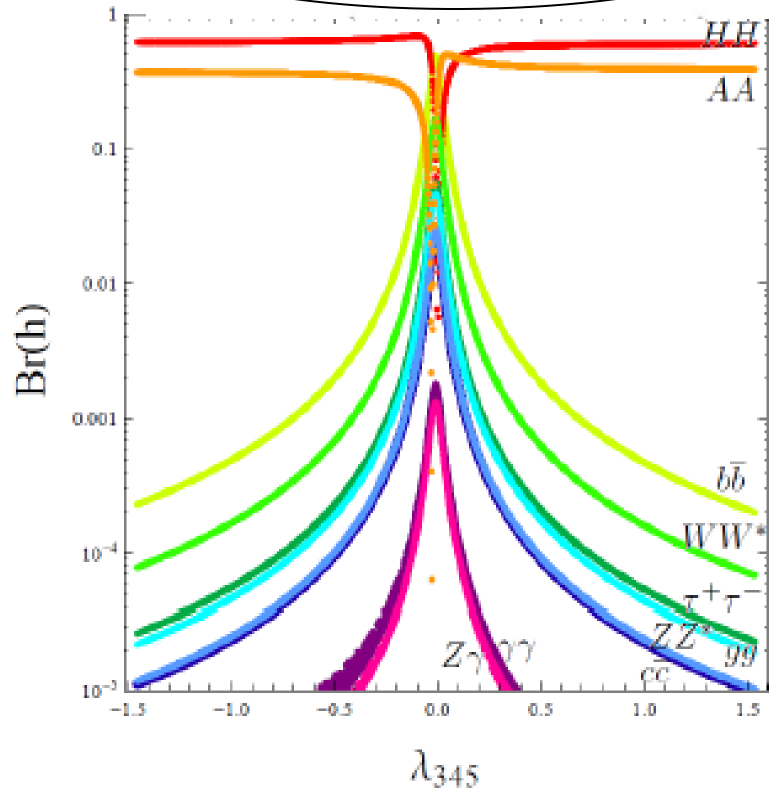


# Invisible decays

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

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

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

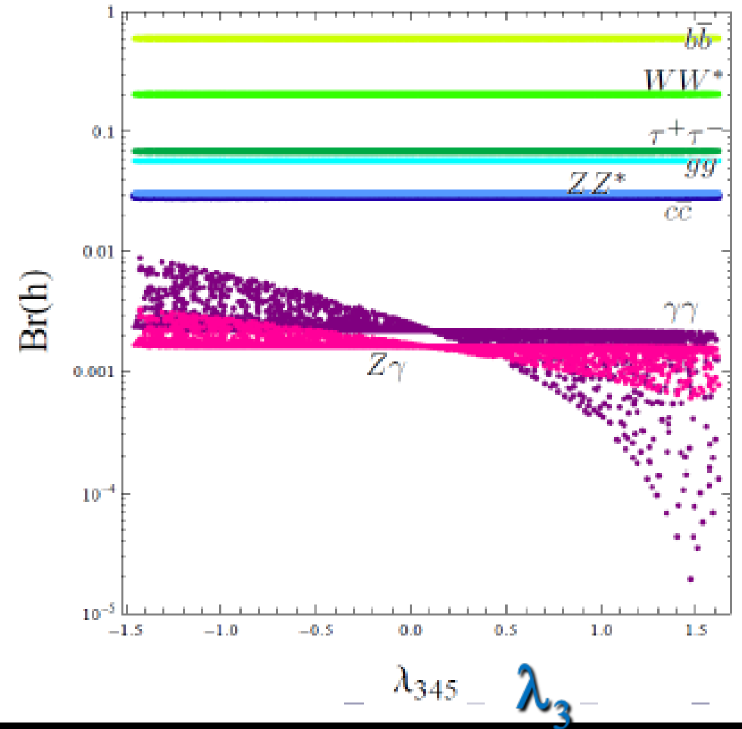


# Charged scalar $H^{\pm}$ loop

[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)]

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

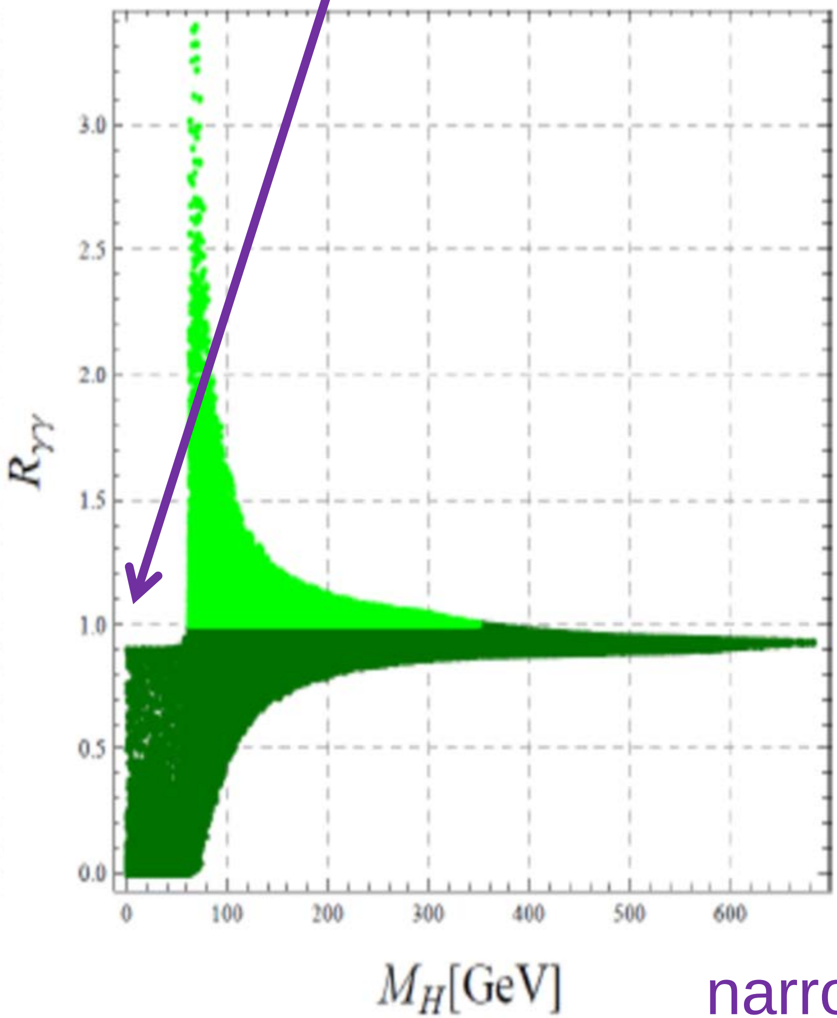
- Constructive or destructive interference between SM and $H^{\pm}$ contributions
- Controlled by $M_{H^\pm}$ and $2M_{H^\pm}^2 + m_{22}^2 \sim \lambda_3 \sim hH^+H^-$
- Invisible channels closed $\Rightarrow H^{\pm}$ contribution visible

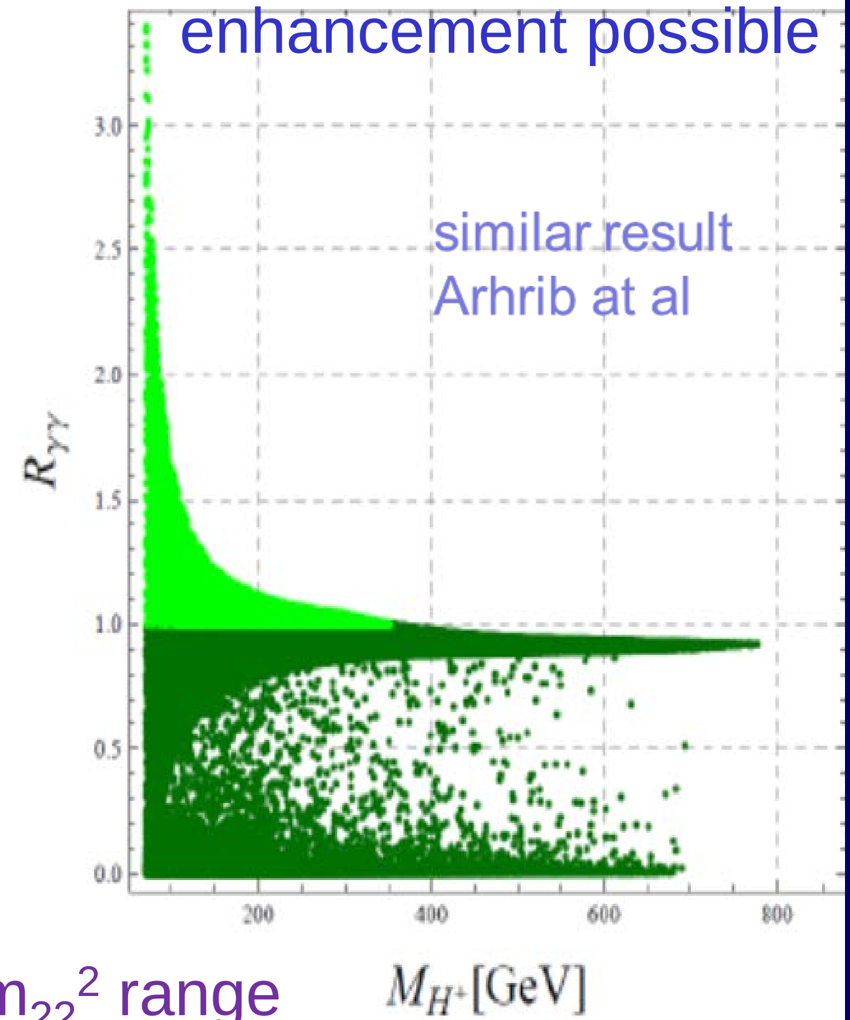


# $R_{\gamma\gamma}$ as a function of mass H and H +

Invisible decays makes enhancement impossible

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



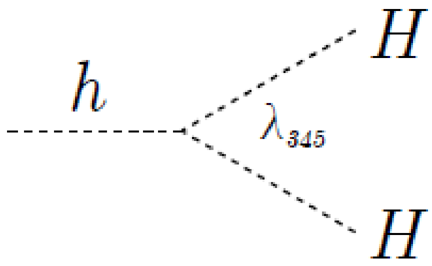




similar result Arhrib at al

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, $\Gamma(h \to HH) \sim \lambda_{345}^2$

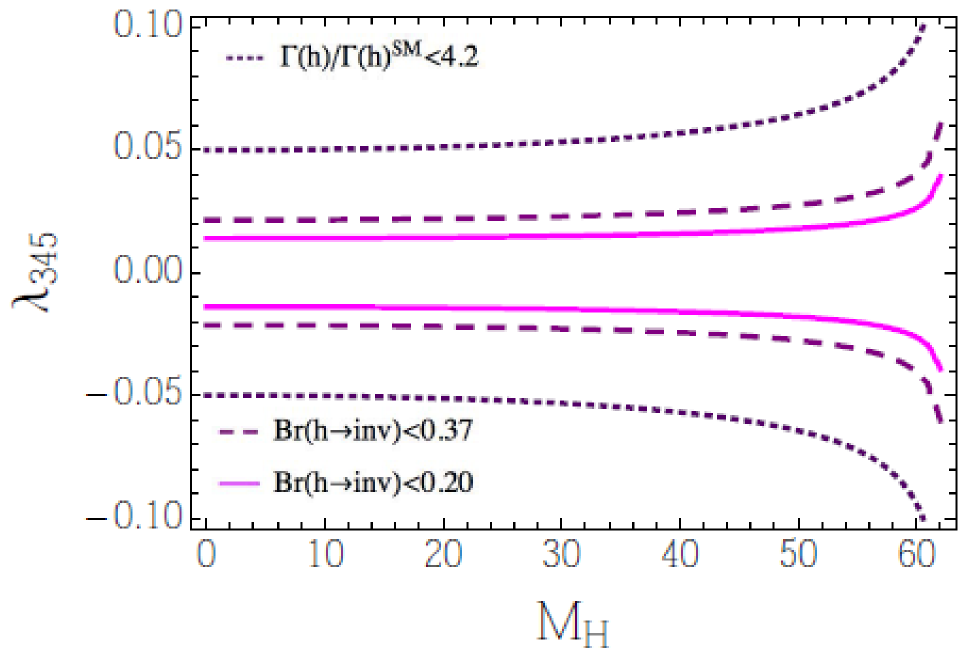



LHC:

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

global fit:

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



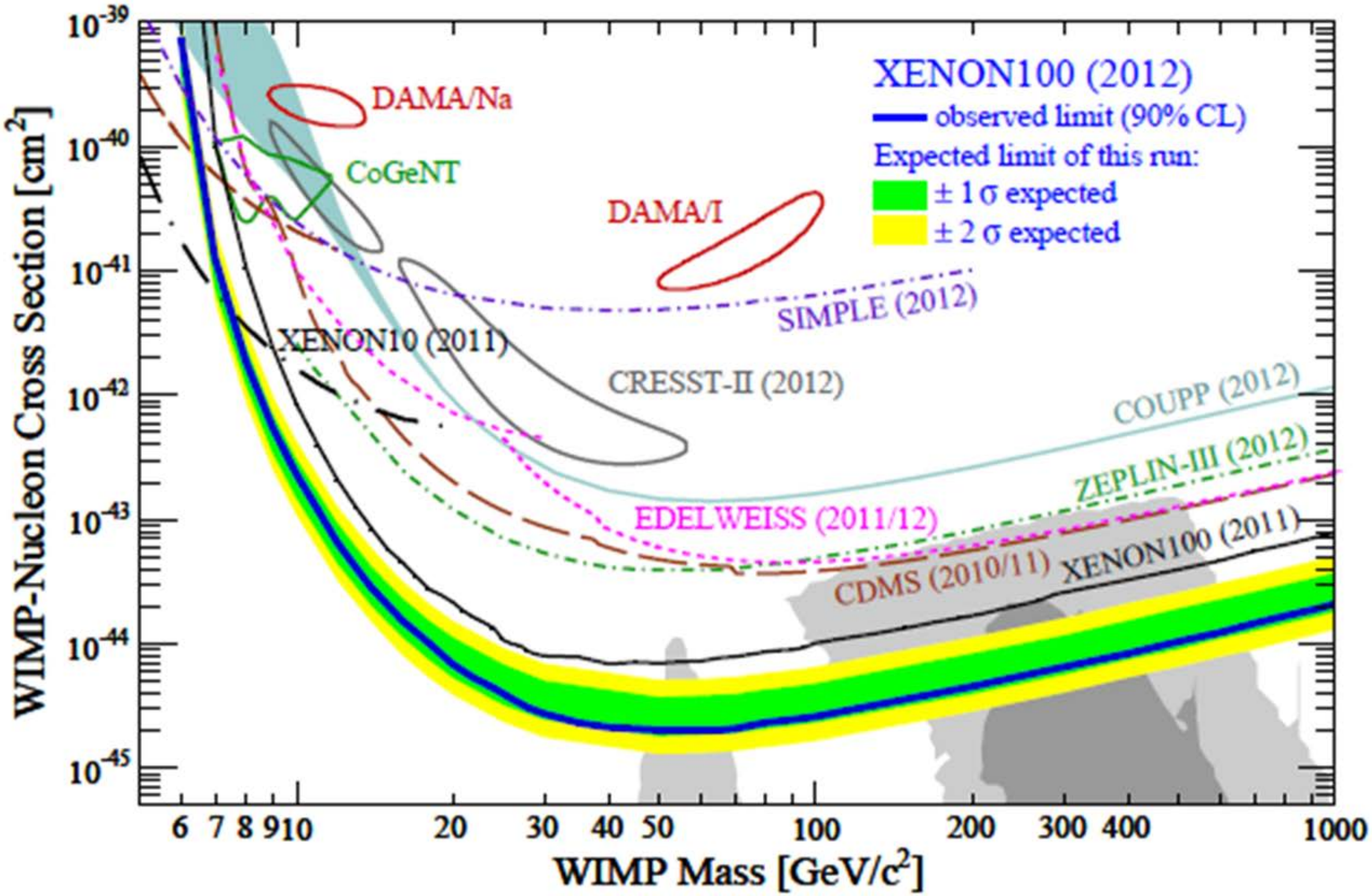

[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010, 2014; CMS-PAS-HIG-14-002]

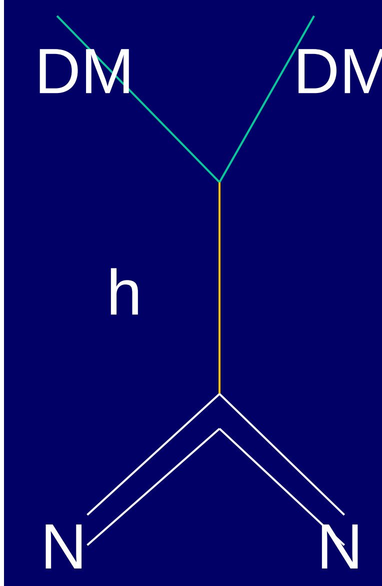
# DM DATA?

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."

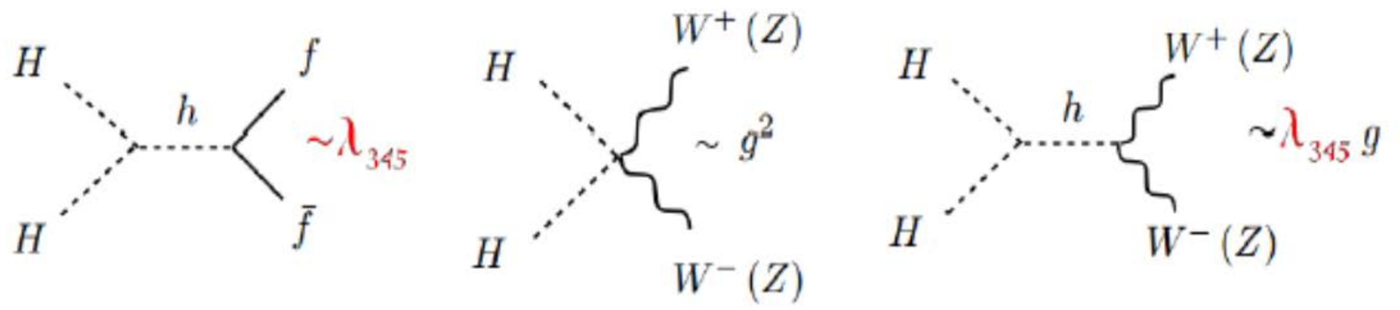
Lars Bergstrom, *Dark Matter Evidence, Particle Physics Candidates and Detection Methods*, arXiv:1205.4882 [astro-ph.HE]



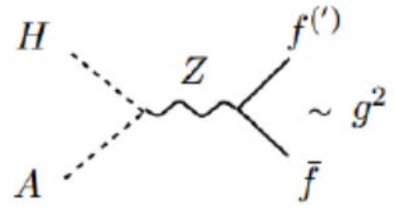
# Relic density constraints on masses and couplings - OK

## Relic density constraints




$$0.1018 < \Omega_{DM} h^2 < 0.1234 \Rightarrow \lambda_{345}^{\min}, \lambda_{345}^{\max}$$

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

# 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**

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

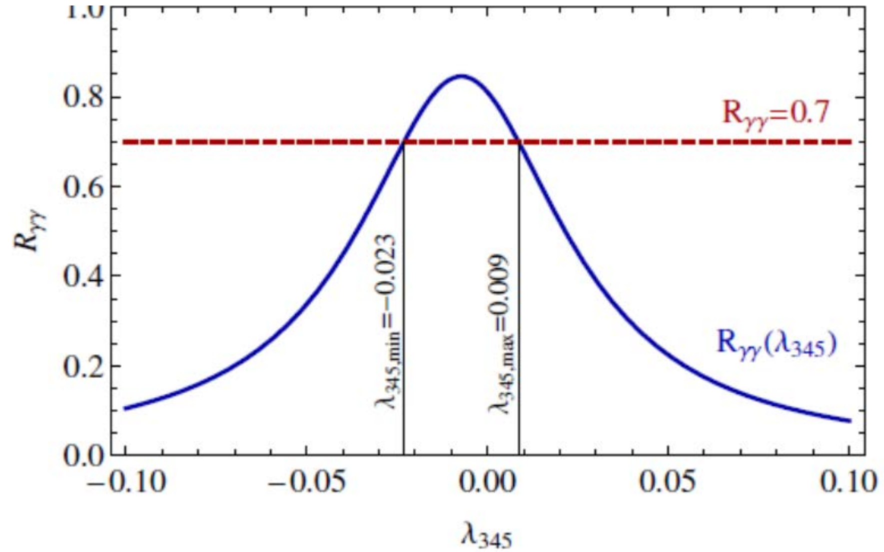
**LHC data**

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

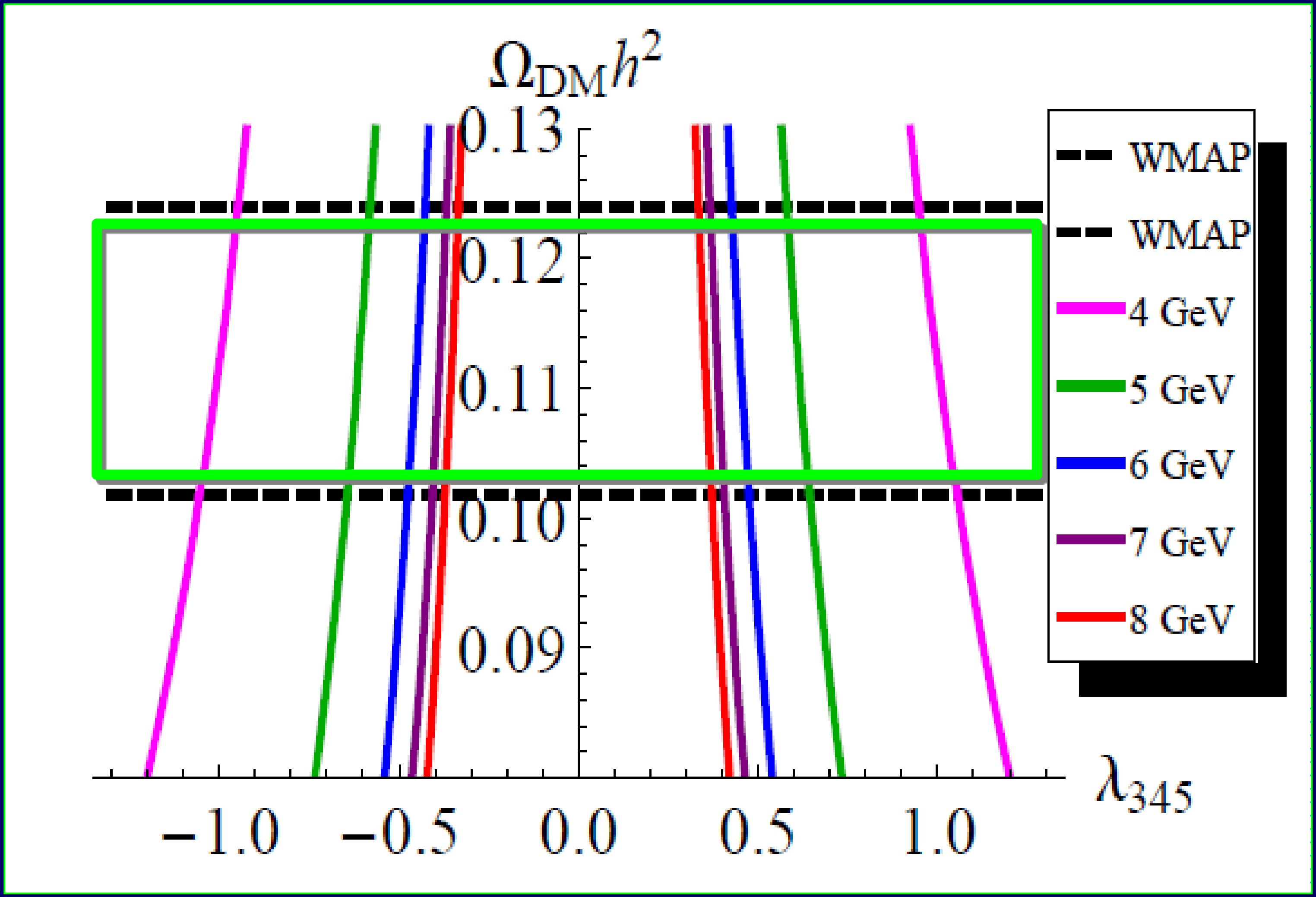
For now: $R_{\gamma\gamma} = 1.17 \pm 0.27$ (ATLAS), $R_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}$ (CMS)

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

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



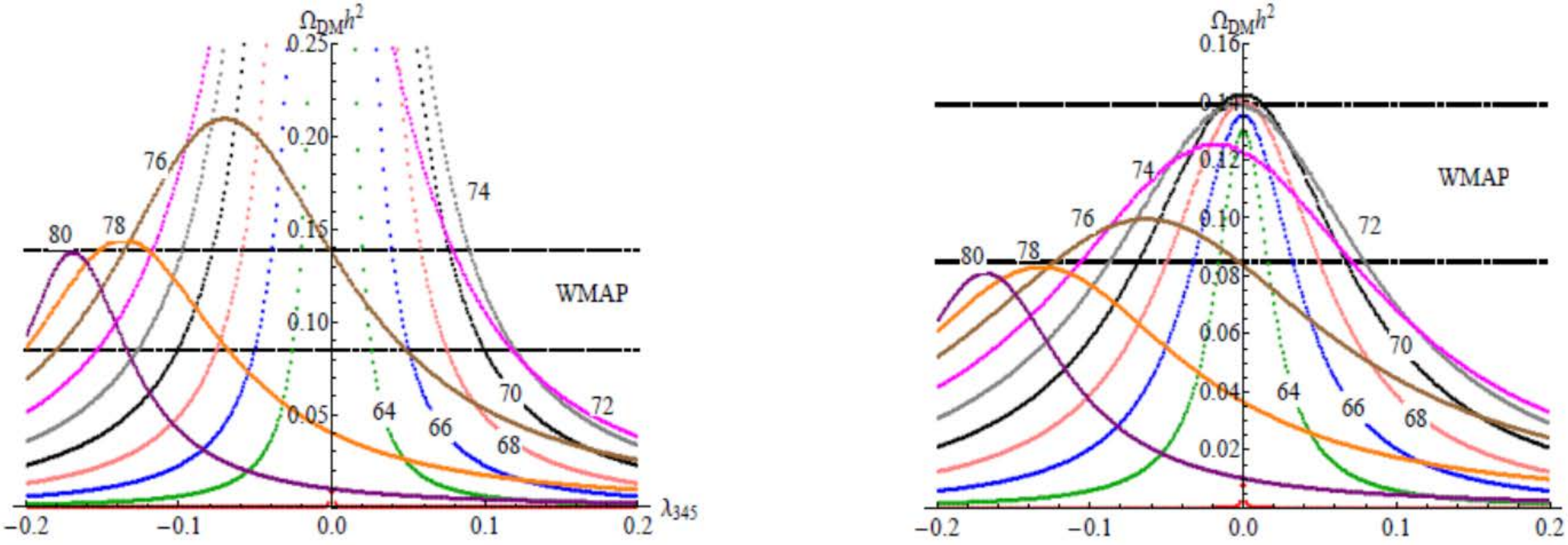
# WMAP window for light H (DM)



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

D. Sokołowska, 2013

$$M_H = (62, ..., 80)\ \text{GeV},\ M_{A,H^\pm} = M_H + \delta_{A,\pm}$$




$\delta_A = 50\ \text{GeV}, \delta_\pm = 50\ \text{GeV}$  $\delta_A = 8\ \text{GeV}, \delta_\pm = 50\ \text{GeV}$

above 76 GeV asymmetry due to annihilation to gauge bosons

# Low mass H – excluded by LHC!

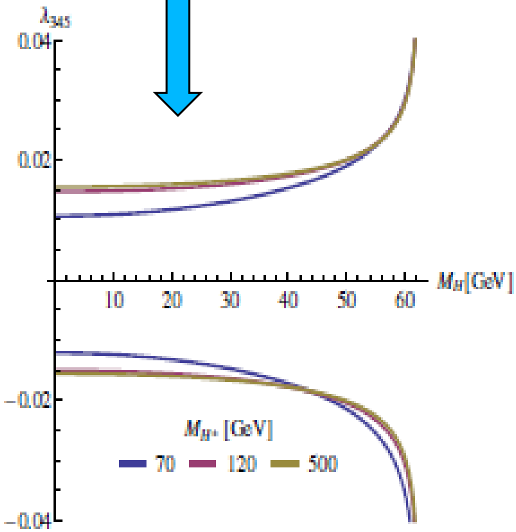
## $R_{\gamma\gamma}$ constraints on $\lambda_{345} \sim hHH$

[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>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 $\Rightarrow |\lambda_{345}| \approx (0.35 - 0.41)$

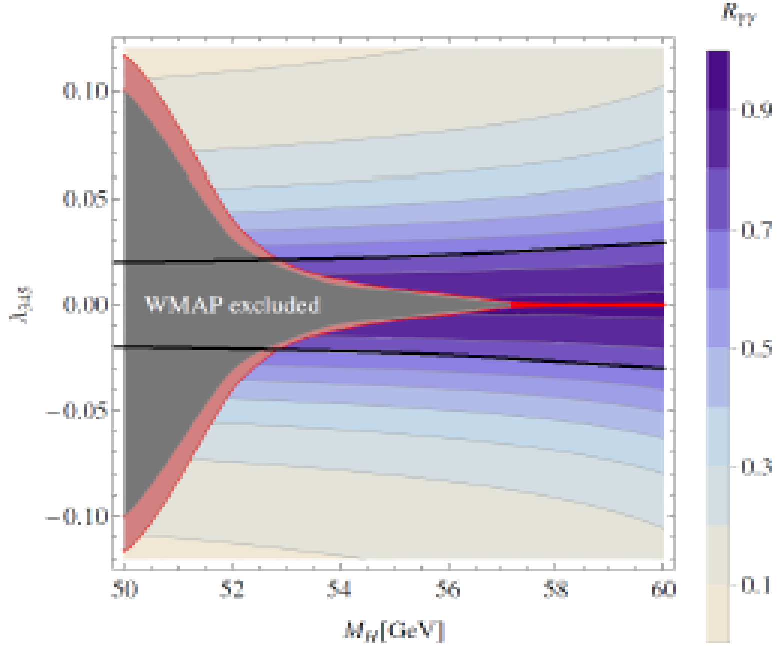
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow$

Low DM mass excluded

Sokołowska

# Medium DM mass (1) – $HH$ channel open

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

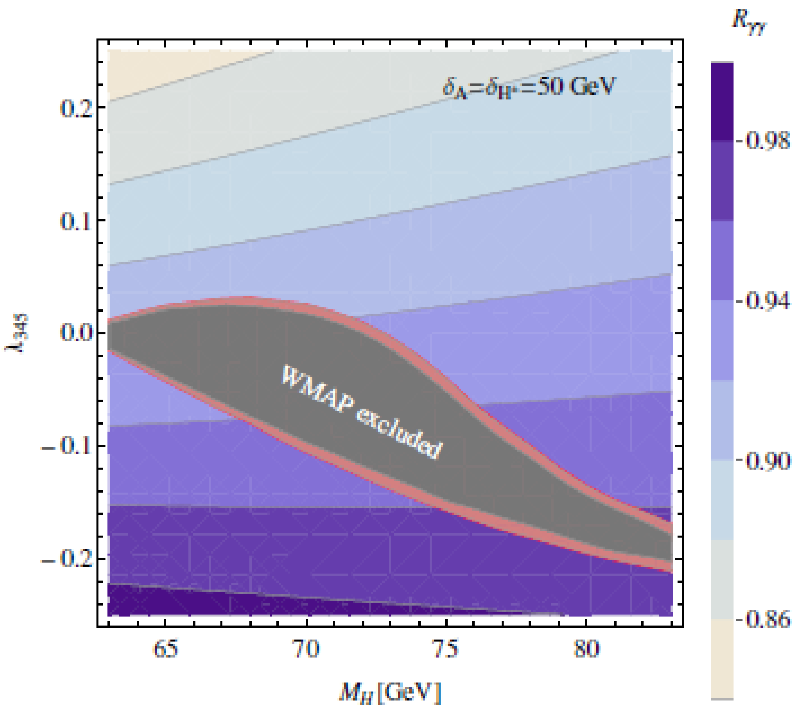


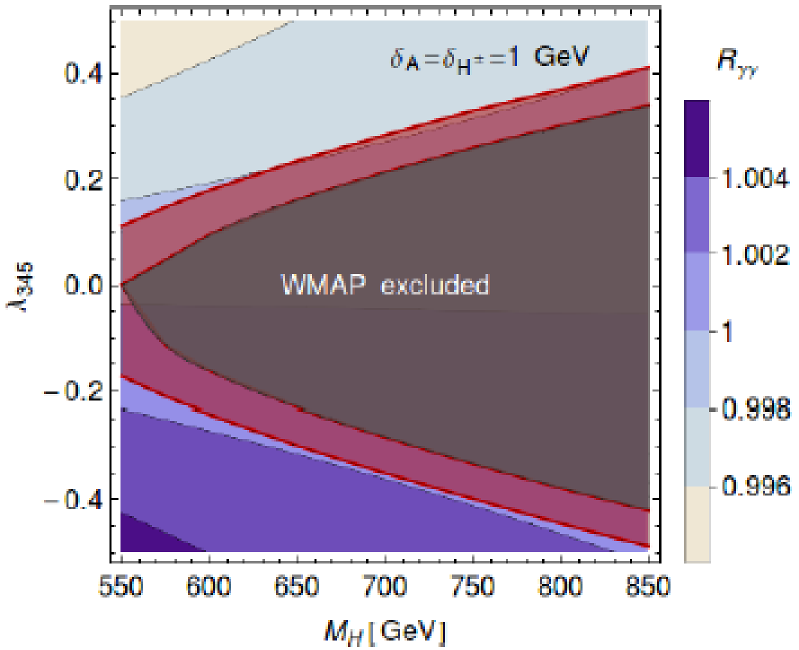

Red bound: $\Omega_{DM} h^2$ in agreement with WMAP

Black line: $R_{\gamma\gamma} = 0.7$

- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| \lesssim 0.02 \Rightarrow M_H \lesssim 53\,\text{GeV}$ excluded
- $53\,\text{GeV} \lesssim M_H \lesssim M_h/2 \Rightarrow R_{\gamma\gamma} \approx (0.8 - 0.9)$

# Intermediate and heavy DM



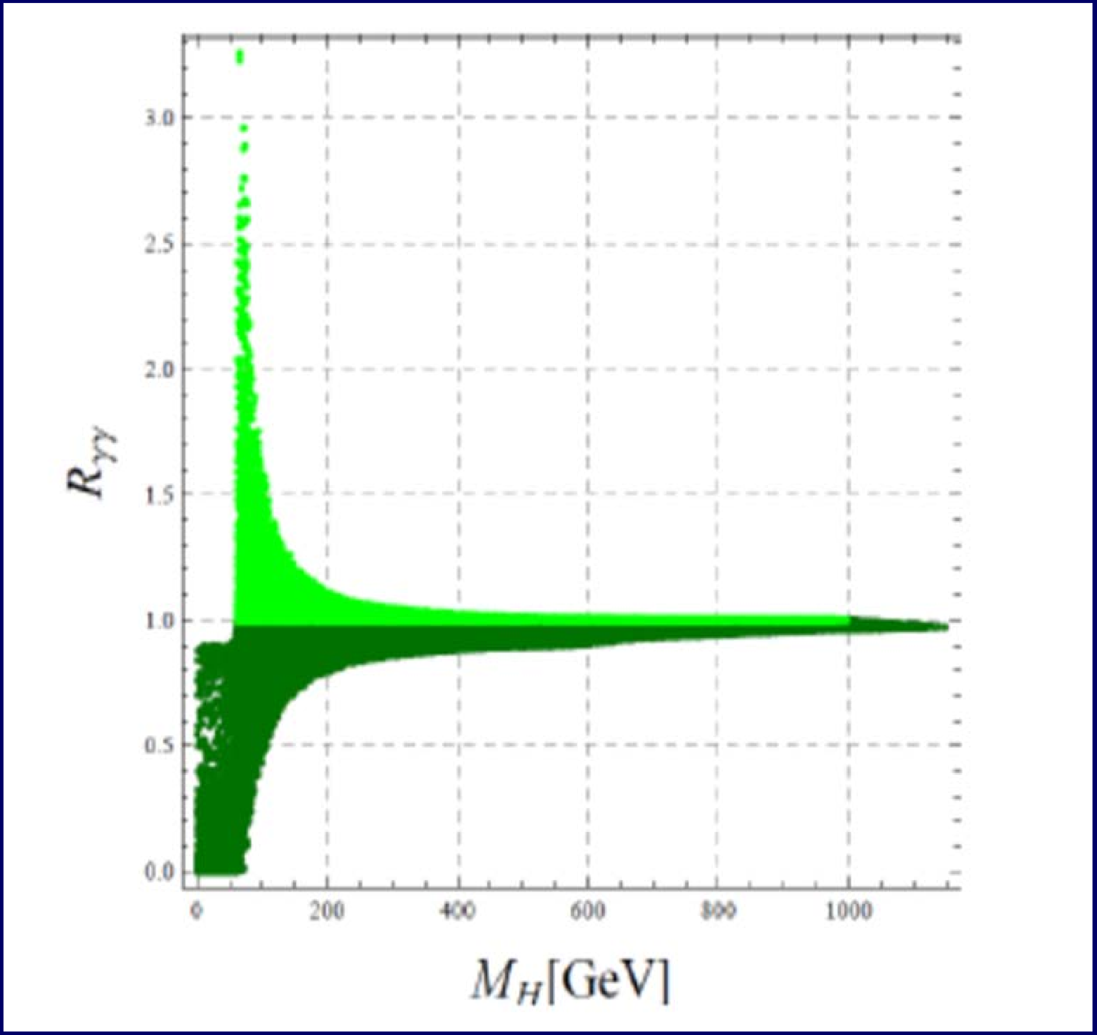




- H of intermediate mass can constitute 100% of DM
- H constituting 100% DM inconsistent with $R_{\gamma\gamma} > 1$

- For heavy DM $R_{\gamma\gamma} \approx 1$ only very small deviations allowed

D. Sokołowska, EPS HEP 2013

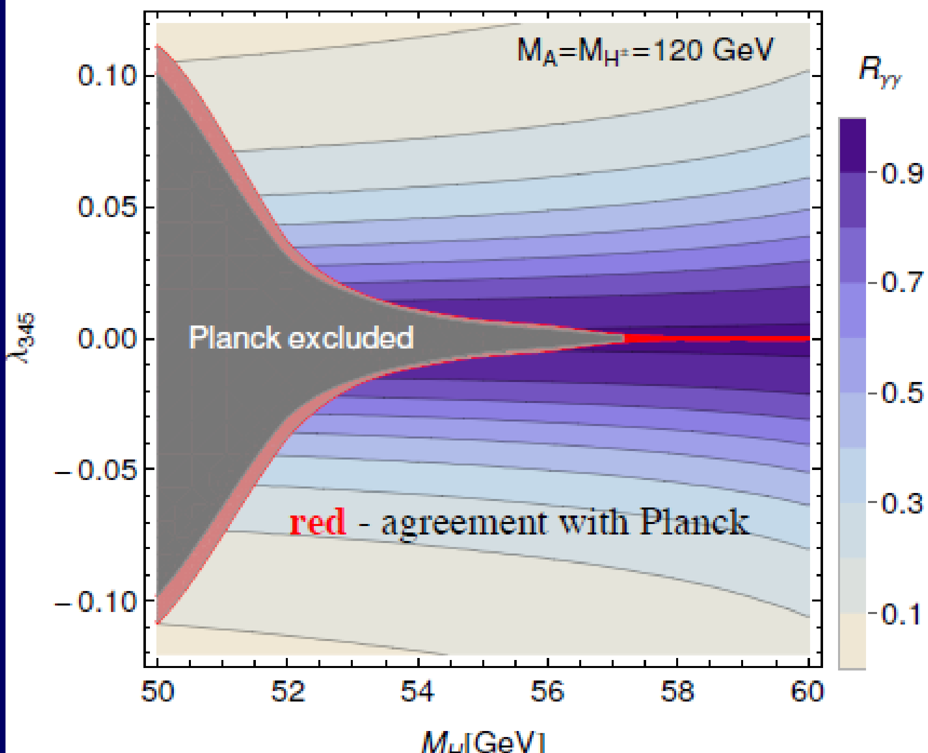
# Very heavy DM



# New (Planck)

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

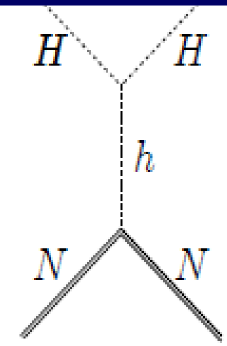
$h \to HH$ open



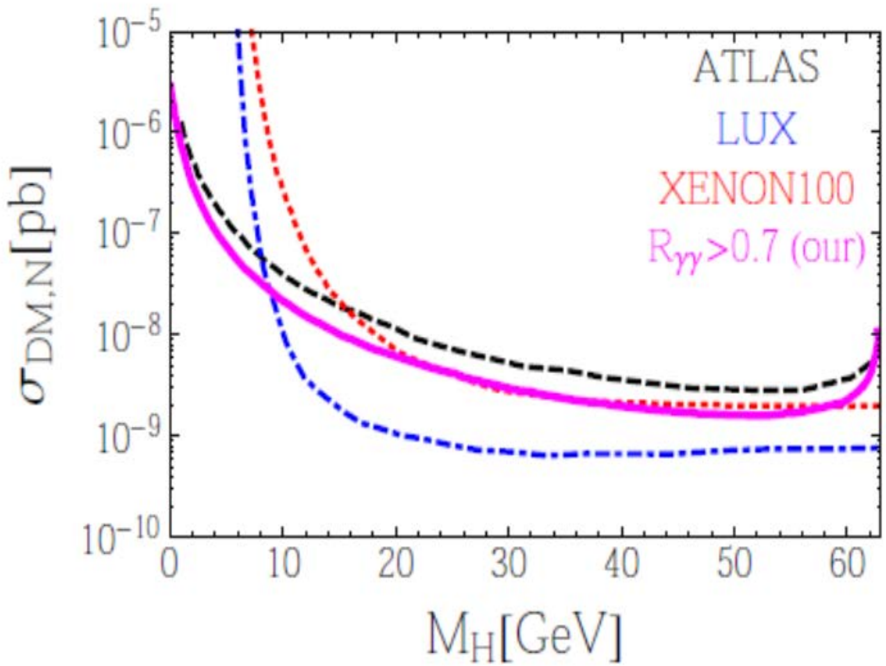

$50\,\text{GeV} < M_H < M_h/2$, $M_A = M_{H^\pm} = 120\,\text{GeV}$

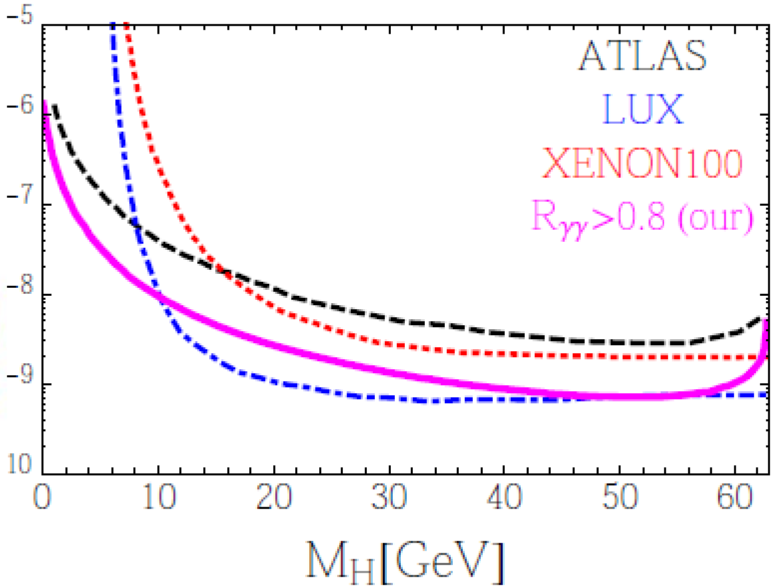
- light DM ($M_H < 10\,\text{GeV}$)
  $\Rightarrow$ excluded
- intermediate DM 1
  ($50\,\text{GeV} < M_H < M_H/2$)
  $\Rightarrow M_H > 53\,\text{GeV}$
- intermediate DM 2
  ($M_h/2 < M_H \lesssim 82\,\text{GeV}$)
  $\Rightarrow R_{\gamma\gamma} < 1$
- heavy DM
  ($M_H > 500\,\text{GeV}$)
  $\Rightarrow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

# 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 $\lambda_{345}$ translated to $(M_H,\ \sigma_{\mathrm{DM},N})$ plane



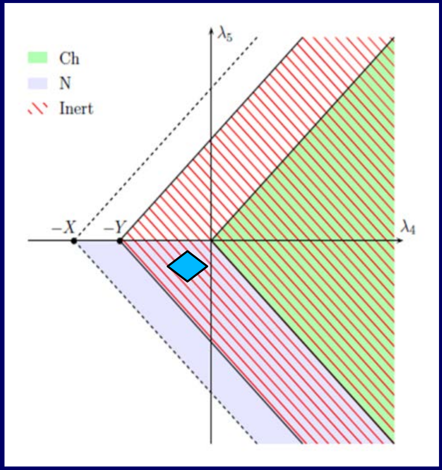




… stronger than the dedicated DM experiments

# 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 $\lambda$'s are fixed




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

# 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 I1

$$EW s \xrightarrow{II} \begin{cases} I_1 \\ I_2 \begin{cases} \xrightarrow{II} M \xrightarrow{II} I_1 \\ \xrightarrow{I} I_1 \end{cases} \end{cases}$$

Ch breaking in the past?-excluded if DM neutral

DM matter may appear later (only in I1)

Going beyond $T^2$ approximation – strong first order phase transition (→ baryogenesis) DM ~65 GeV

H+ and A with mass 275 -380 GeV, hHH $|\lambda_{345}| < 0.1$

# Are we approaching a new era?

Spring 2015 at LHC

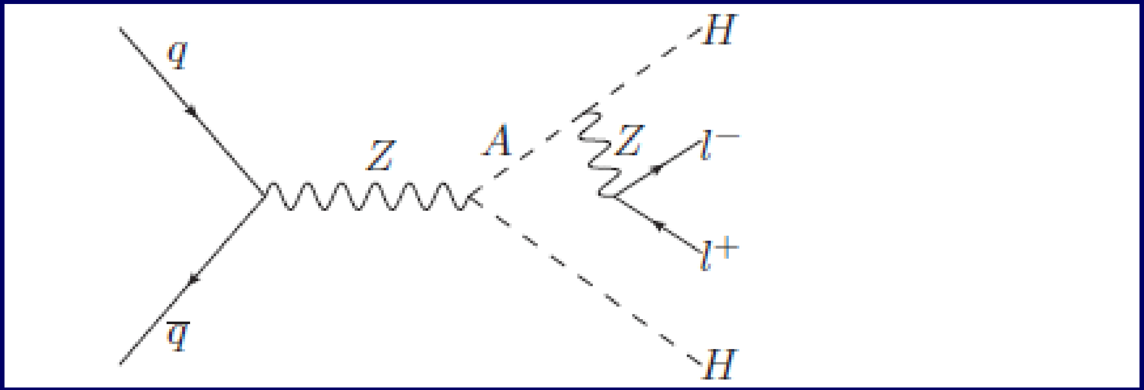
Higgs data -> Dark Matter

Dedicated DM analysis at LHC

# DM production at LHC

LHC at 8 TeV

P. Swaczyna
MSc, May 2013

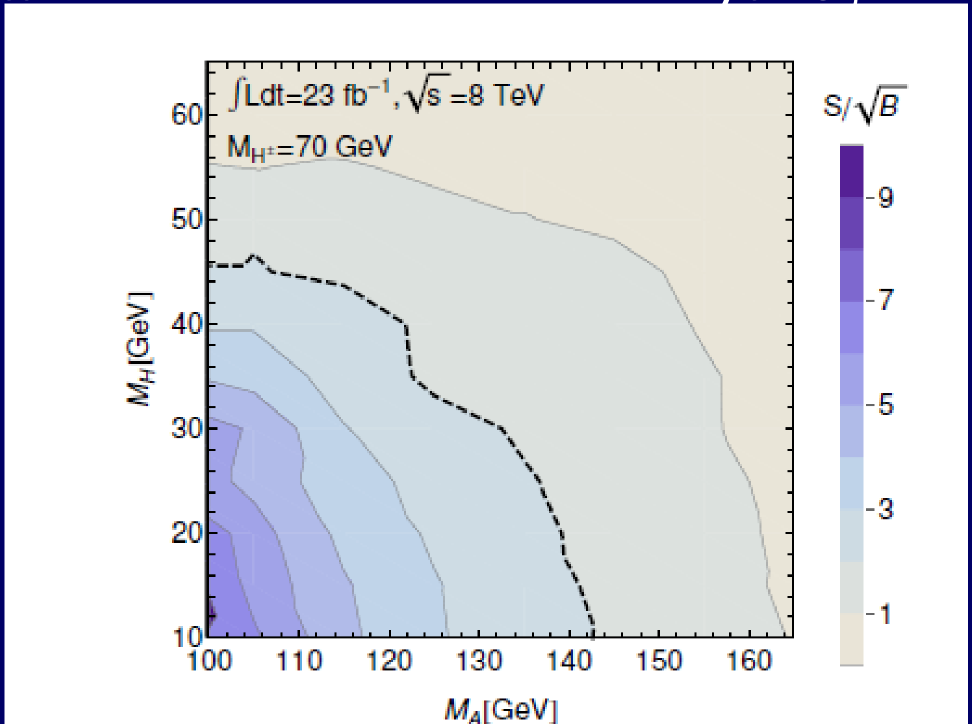



SM background WW,ZZ, tt

Pythia, 2HDMC

$S/\sqrt{B}$ above 2

M_H+M_A< 145 GeV
M_A>100 GeV



# 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)

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

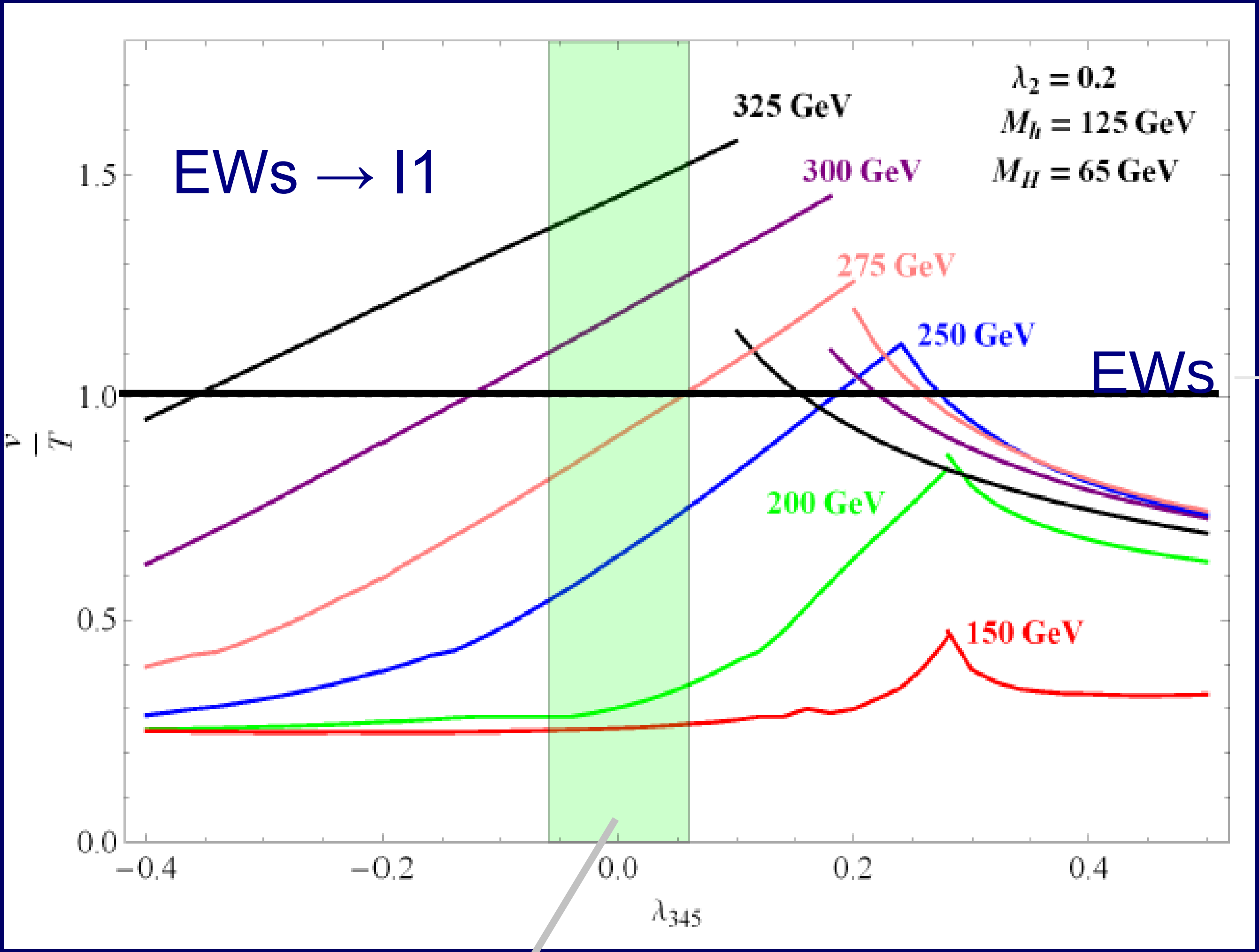
Can in IDM strong first -order phase transition – needed for baryogenesis ?

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

# 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

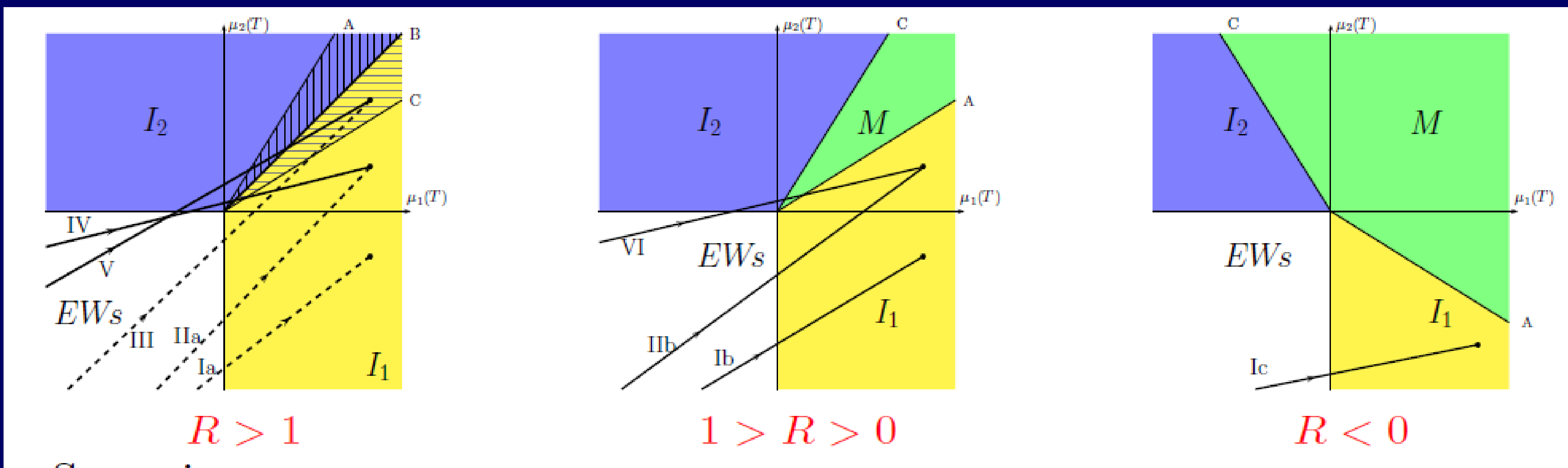
Allowed MH+=MA between 275 and 380 GeV (one step)

$\lambda_{345}$

XENON100 bound

# Evolution of vacua on phase diagram $(\mu_1,\mu_2)$

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




three regions of R

stability condition

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

$$R + 1 > 0$$

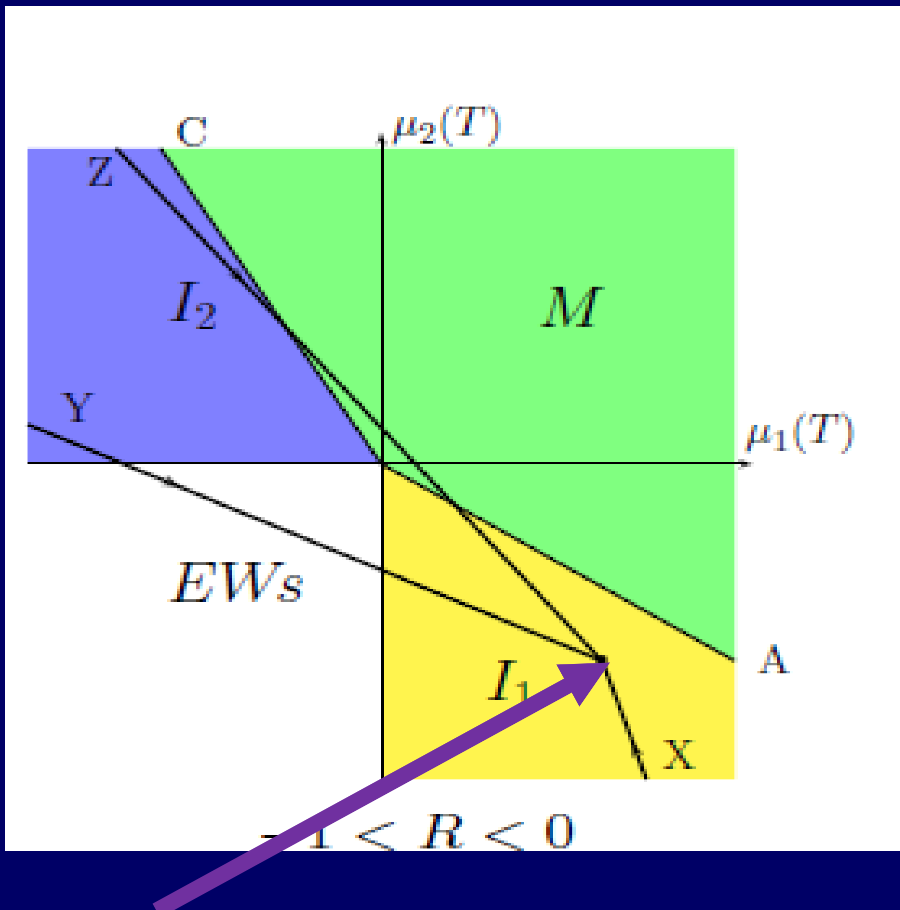
T2 corrections

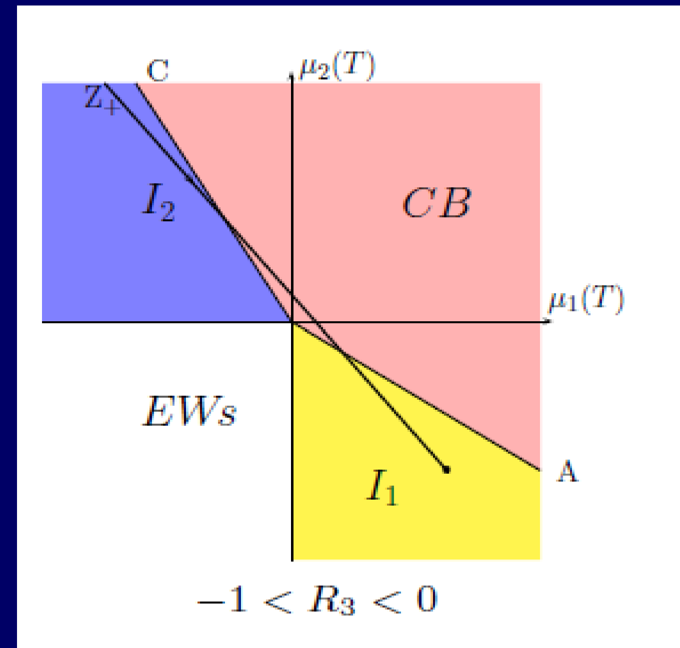
→ rays from EWs phase to Inert phase

one, two or three stages of Universe

(II order phase transitions, one I order)

# 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!)

# Extrema -> vacua

(v=246 GeV)

$$\mathrm{EWs}: \quad v_D = 0, \quad v_S = 0, \qquad \mathcal{E}_{EWs} = 0;$$

$$\mathrm{I}_1: \quad v_D = 0, \quad v_S^2 = v^2 = \frac{m_{11}^2}{\lambda_1}, \quad \mathcal{E}_{I_1} = -\frac{m_{11}^4}{8\lambda_1};$$

$$\mathrm{I}_2: \quad v_S = 0, \quad v_D^2 = v^2 = \frac{m_{22}^2}{\lambda_2}, \quad \mathcal{E}_{I_2} = -\frac{m_{22}^4}{8\lambda_2};$$

$$\mathrm{M}: \quad v_S^2 = \frac{m_{11}^2\lambda_2 - \lambda_{345}m_{22}^2}{\lambda_1\lambda_2 - \lambda_{345}^2}, \quad v_D^2 = \frac{m_{22}^2\lambda_1 - \lambda_{345}m_{11}^2}{\lambda_1\lambda_2 - \lambda_{345}^2};$$

$$\mathcal{E}_M = -\frac{m_{11}^4\lambda_2 - 2\lambda_{345}m_{11}^2m_{22}^2 + m_{22}^4\lambda_1}{8(\lambda_1\lambda_2 - \lambda_{345}^2)}.$$

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

$$\mu_2 = \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$

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

$$R + 1 > 0,$$

$$\mathcal{E}_{I_1} - \mathcal{E}_M = \frac{\left(m_{11}^2\lambda_{345} - m_{22}^2\lambda_1\right)^2}{8\lambda_1^2\lambda_2(1 - R^2)}.$$

$$\mathrm{CB}: \quad v_S^2 = \frac{m_{11}^2\lambda_2 - \lambda_3 m_{22}^2}{\lambda_1\lambda_2 - \lambda_3^2}, \quad v_D = 0, \quad u^2 = \frac{m_{22}^2\lambda_1 - \lambda_3 m_{11}^2}{\lambda_1\lambda_2 - \lambda_3^2},$$

$$\mathcal{E}_{CB} = -\frac{m_{11}^4\lambda_2 - 2\lambda_3 m_{11}^2 m_{22}^2 + m_{22}^4\lambda_1}{8(\lambda_1\lambda_2 - \lambda_3^2)}.$$

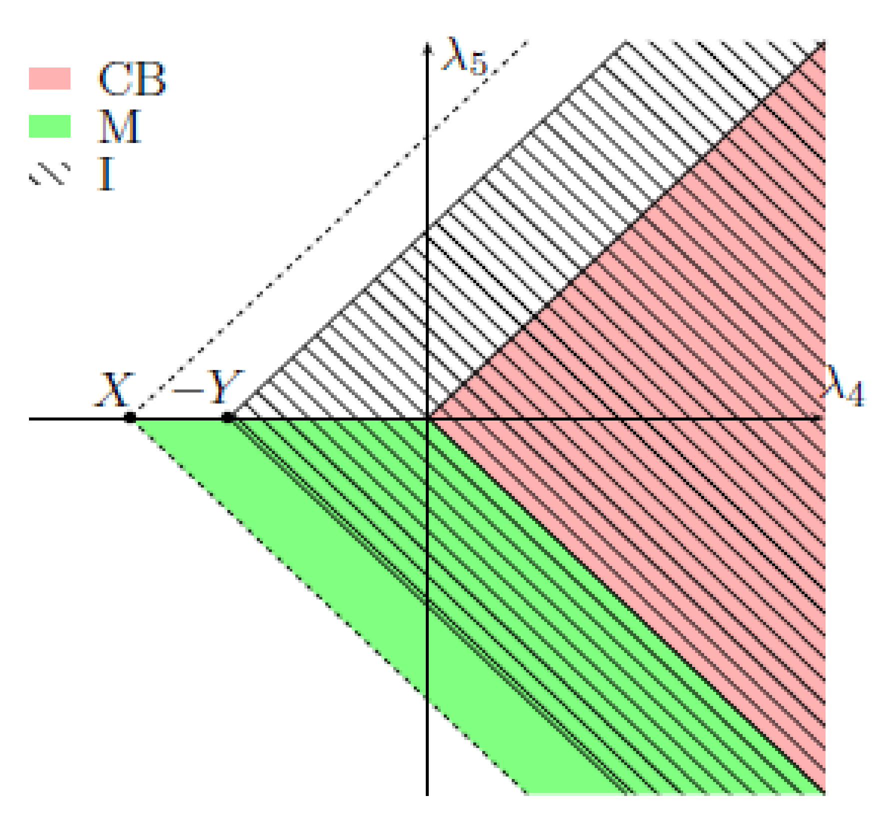
$\sim 1/(1-R_3^2)$

# 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 [$v_S$ 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 !