LCWS2011

29.09. 2011

New results for the 2HDM

BSM → 2HDMs

Various: potentials

Yukawas

vacua

The Inert Doublet Model

SM-like Higgs scenarios at ...

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(University of Warsaw)

PLC

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

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

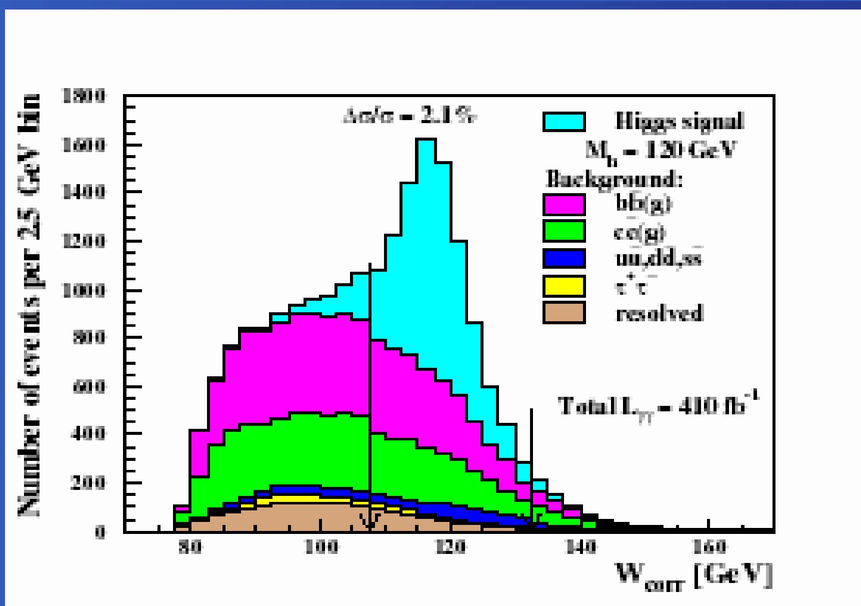
SM summary

NŻK

Niezurawski et al.,

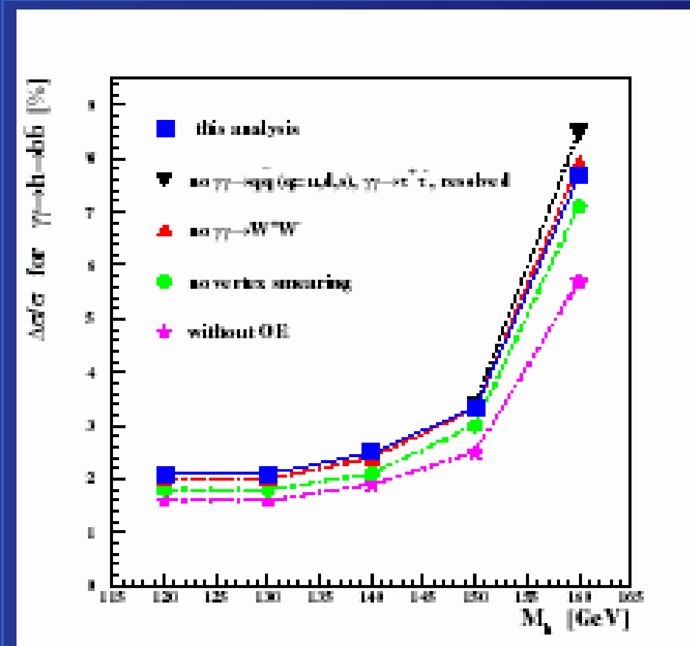
Monig, Rosca

→ Results for $M_h = 120$ GeV



Corrected invariant mass distributions for signal and background events

Results for $M_h = 120$-160 GeV



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

THE THEORY OF MATTER and STANDARD MODEL(S)

F. Wilczek, LEPFest, Nov.2000 (hep-ph/0101187)

Theory of Matter = $SU(2)_{I\ weak}$ x $U(1)_{Y\ weak}$ x $SU(3)_{color}$

The core concepts:

quantum field theory-gauge symmetry-spontaneous symmetry breaking-asymptotic freedom- the assignments of the lightest quarks and leptons

Brout-Englert-Higgs mechanism SSB of SU(2)xU(1)

Standard Models of scalar sector:

Choose the number of Higgs (scalar) doublets

SM=1HDM, 2HDM (as in MSSM), 3HDM ...

The lightest neutral scalar is often SM-like...

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

SU(2) x U(1) → ?

T.D. Lee 1973

Two Higgs Doublet Models

Two doublets of SU(2) (Y=1, ρ =1) - Φ_1 , Φ_2

Masses for $W^{+/-}$, Z , no mass for photon?

Fermion masses via Yukawa interaction –

various models: Model I, II, III, IV,X,Y,...

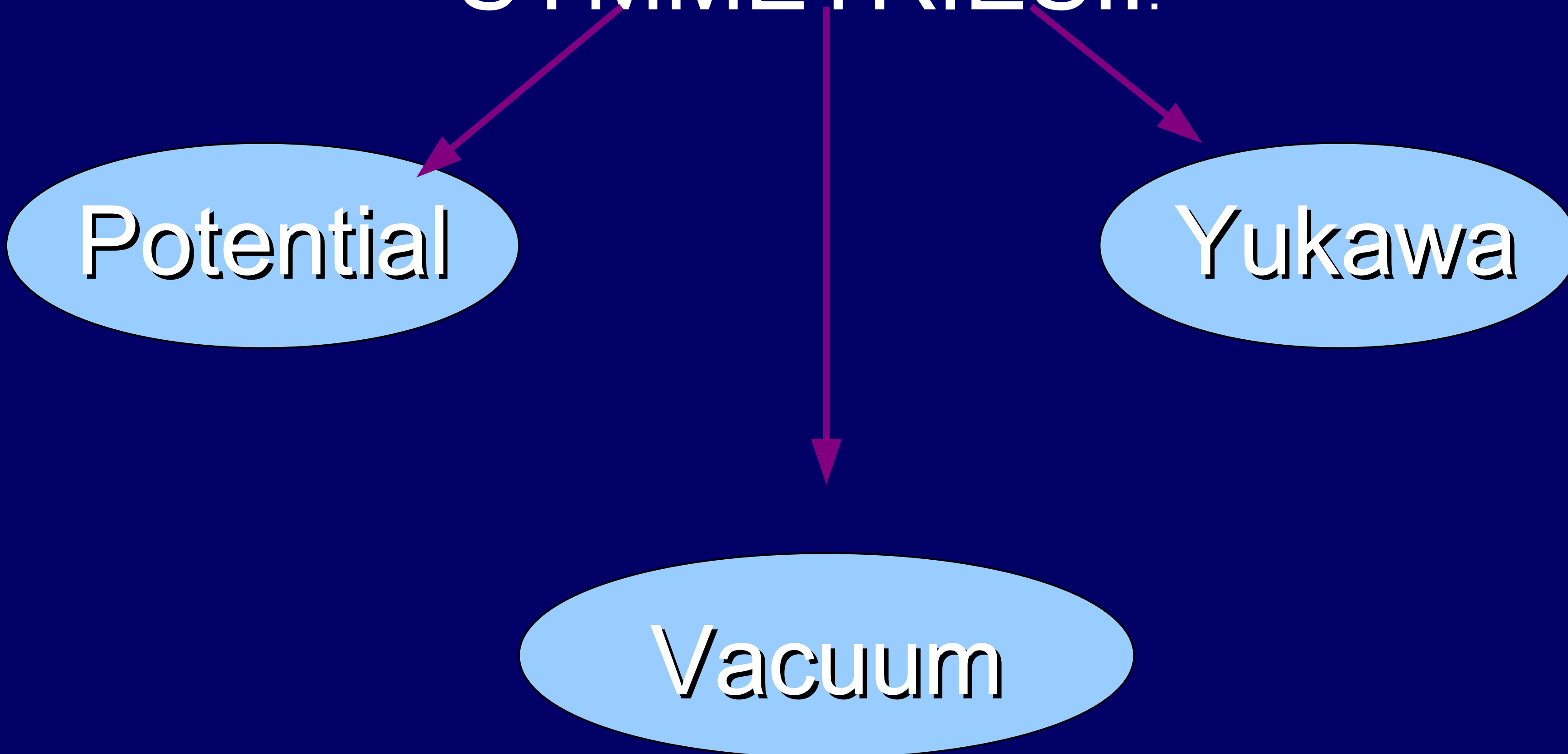
5 scalars: H+ and H- and neutrals:

- CP conservation: CP-even h, H & CP-odd A
- CP violation: h_1,h_2,h_3 with undefinite CP parity*

Sum rules (relative couplings to SM χ)

2HDMs

SYMMETRIES!!!



Various models of Yukawa inter.

typically with some Z2 type symmetry to avoid FCNC

<u>Model I</u> - only one doublet interacts with fermions

<u>Model II</u> – one doublet with down-type fermions d , l

other with up-type fermions u

Model III - both doublets interact with fermions

Model IV (X) - leptons interacts with one doublet, quarks with the other

Model Y - one doublet with down-type quarks d

other with up-type quarks u and leptons

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

+ Extra dim 2HDM models

2HDM Potential

Lee, Haber, Gunion, Glashow, Weinberg, Paschos, Despande, Ma, Wudka, Branco, Rebelo, Lavoura, Ferreira, Barroso, Santos, Bottela, Silva, Diaz-Cruz, Grimus, Ecker, Ivanov, Ginzburg, Krawczyk, Osland, Nishi, Pilaftsis, Nachtmann, Maniatis,Akeroyd, Kanemura, Kalinowski, Grządkowski ,Hollik, Rosiek..

$$V = \lambda_1(\Phi_1^\dagger\Phi_1)^2+\lambda_2(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+ [\lambda_5(\Phi_1^\dagger\Phi_2)^2+h.c]$$

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

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

Z_2 symmetry transformations:

$\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$ $\qquad$ $\Phi_1 \to -\Phi_1 \quad \Phi_2 \to \Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12}=\mu^2$)

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12}=0$

• Symmetries of the 2HDM Potential

Pilaftsis, Scalars 2011

[R. A. Battye, G. D. Brawn, A.P., JHEP08 (2011) 020.]

$$V = -\frac{1}{2} M_A R^A + \frac{1}{4} L_{AB} R^A R^B .$$

• Symmetries of the $U(1)_Y$-Invariant 2HDM Potential

SO(5)-diagonally reduced basis: $\mathrm{Im}\,\lambda_5 = 0$ and $\lambda_6 = \lambda_7$.

The 2HDM potential exhibits a total of $\underline{13} = \underline{6} + \underline{7}$ accidental Higgs-Family (HF) and CP symmetries:

Symmetry	μ_1^2	μ_2^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	$\mathrm{Re}\,\lambda_5$	$\lambda_6 = \lambda_7$
$(Z_2)^2 \times SO(2)$	–	–	0	–	–	–	–	–	0
$O(2) \times O(2)$	–	–	0	–	–	–	–	0	0
$O(3) \times O(2)$	–	μ_1^2	0	–	λ_1	–	$2\lambda_1 - \lambda_3$	0	0
$Z_2 \times O(2)$	–	–	Real	–	–	–	–	–	Real
$(Z_2)^3 \times O(2)$	–	μ_1^2	0	–	λ_1	–	–	–	0
$Z_2 \times [O(2)]^2$	–	μ_1^2	0	–	λ_1	–	–	$2\lambda_1 - \lambda_{34}$	0
SO(5)	–	μ_1^2	0	–	λ_1	$2\lambda_1$	0	0	0
$Z_2 \times O(4)$	–	μ_1^2	0	–	λ_1	–	0	0	0
SO(4)	–	–	0	–	–	–	0	0	0
$O(2) \times O(3)$	–	μ_1^2	0	–	λ_1	$2\lambda_1$	–	0	0
$(Z_2)^2 \times SO(3)$	–	μ_1^2	0	–	λ_1	–	–	λ_4	0
$Z_2 \times O(3)$	–	μ_1^2	Real	–	λ_1	–	–	λ_4	Real
SO(3)	–	–	Real	–	–	–	–	λ_4	Real

This talk

Inert Doublet Model

Ma'78
Barbieri'06

Symmetry under Z_2 transf. $\Phi_1 \to \Phi_1 \quad \Phi_2 \to - \Phi_2$

both in L (V and Yukawa interaction = Model I)

and in the vacuum:

$$<\Phi_1> = v \qquad <\Phi_2> = 0$$

Today?

→ Φ_1 as in SM (BEH), with Higgs boson h (SM-like)

→ Φ_2 has <u>no vev</u>, with 4 scalars (no Higgs bosons!)
no interaction with fermions (inert doublet)

Here Z_2 symmetry exact →Z_2 parity, only Φ_2 has odd Z_2-parity

→ The lightest scalar stable -a dark matter candidate
(Φ_2 dark doublet with dark scalars) .

$\Phi_1 \to \Phi_S$ Higgs doublet S $\qquad$ $\Phi_2 \to \Phi_D$ Dark doublet D

Extrema of the 2HDM potential with explicit Z_2 symmetry

Ginzburg, Kanishev, MK, Sokołowska'09

Finding extrema: $\partial V / \partial \Phi|_{\Phi = \langle\Phi\rangle} = 0$

Finding minima → global minimum = vacuum

Positivity (stability) constraints (V with real parameters)

$$\left[\ \lambda_1 > 0\,, \quad \lambda_2 > 0, \quad R + 1 > 0.\ \right]$$

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

Extremum fulfilling the positivity constraints

with the lowest energy = vacuum

Possible extrema (vacuum) states

for V with explicit Z_2

The most general extremum state

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

v_S, v_D, u - real

v_S, $u \geq 0$

$v^2 = v_1{}^2 + v_2{}^2 + u^2 = (246\ \text{GeV})^2$

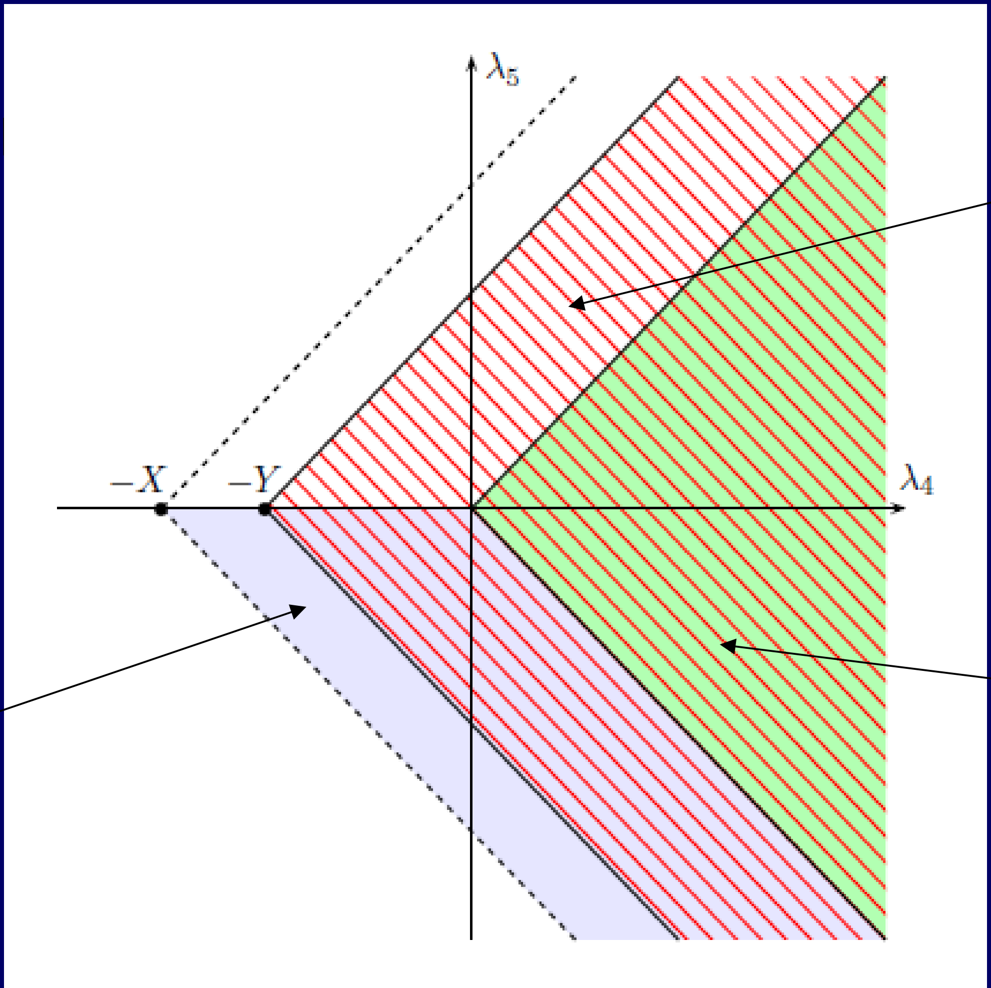
EWs	EWs	$u = v_D = v_S = 0$
Inert	I_1	$u = v_D = 0$
Inert-like	I_2	$u = v_S = 0$
Mixed (Normal, MSSM like)	M	$u = 0$
Charge Breaking	Ch	$u \neq 0 \quad v_D = 0$

Various extrema (vacua) on (λ_4 , λ_5) plane

Positivity constrains: $\lambda_4 \pm \lambda_5 > -X$ $X=\sqrt{\lambda_1\lambda_2}+\lambda_3>0$

Inert (Inert-like)

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



Charge Breaking

Ch

Mixed

Note the overlap of the Inert with M and Ch !

TODAY

2HDM with explicit Z_2 (D) symmetry

$\Phi_S \to \Phi_S \quad \Phi_D \to -\Phi_D$

Model I (Yukawa int. with Φ_S only)

- Charge breaking phase Ch?

  photon is massive, el.charge is not conserved...

  → No

- Neutral phases:

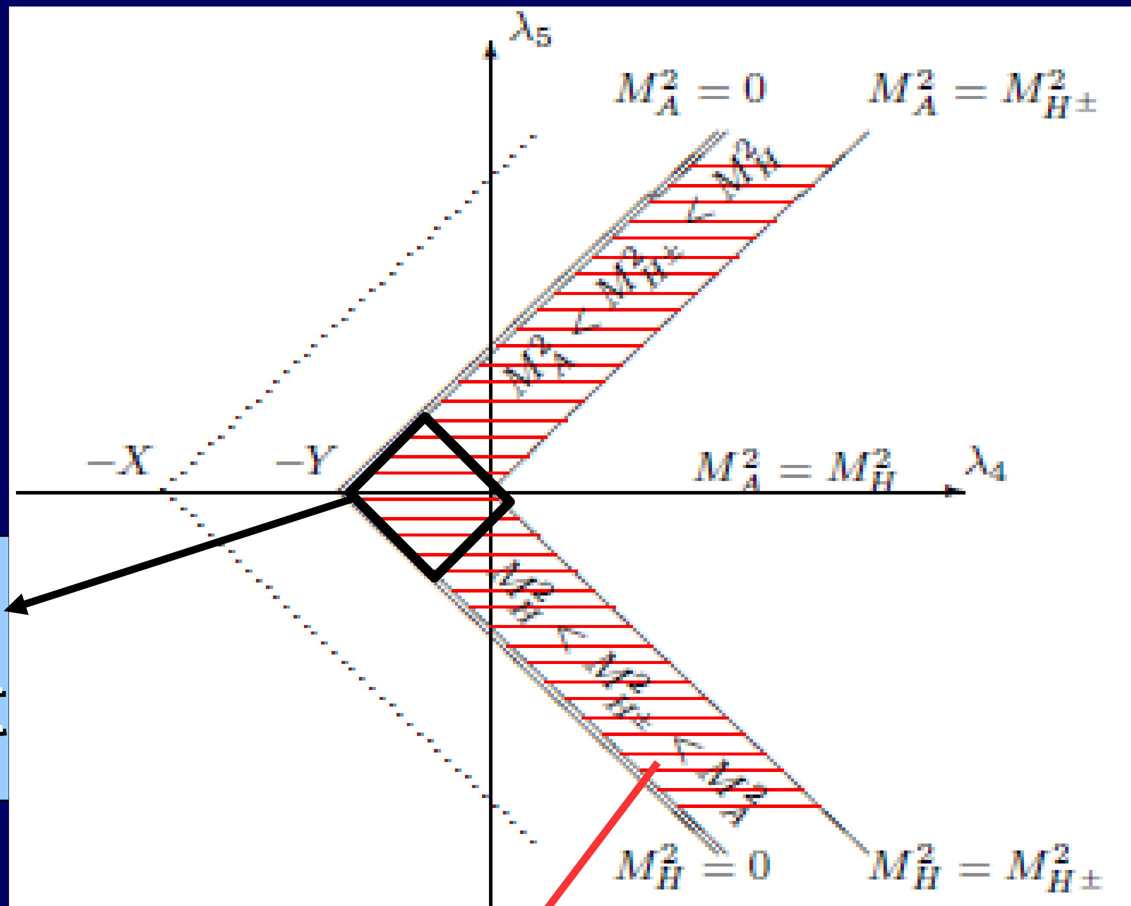
  Mixed M ok, many data, but no DM

  Inert I1 OK! In agreement with accelerator and astrophysical data (neutral DM)

  Inert-like I2 No, all fermions massless, no DM

Dark scalar masses

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



here H+
the heaviest

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

Constraining Inert Doublet Model

- Positivity, extrema, vacua, unitarity, perturbativity
- By considering properties of

  - the SM-like h, $M^2_h = m_{11}^2 = \lambda_1 v^2$ (light and heavy)

  - the dark scalars D always in pairs!

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

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

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

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

Quartic selfcouplings D^4 proportional to λ_2

hopeless to be measured at colliders!

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

Unitarity constraints on parameters of V (Z_2 symmetry)

analysis by B. Gorczyca, MSc Thesis, July 2011

Full scattering matrix macierz 25x25 for scalars (including Goldstone's)

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_1 & & & & & \\ & \mathcal{M}_2 & & & & \\ & & \mathcal{M}_3 & & & \\ & & & \mathcal{M}_4 & & \\ & & & & \mathcal{M}_5 & \\ & & & & & \mathcal{M}_6 \end{pmatrix}.$$

in high energy limit

Block-diagonal form due electric charge and CP conservation

M1: G+H-, G-H+, hA, GA, GH, hH
M2: G+G-, H+H-, GG, HH, AA, hh
M3: Gh, AH
M4: G+G, G+H, G+A, G+h, GH+, HH+,AH+,hH+
M5: G+G+, H+H+
M6: G+H+

Unitarity constraints
→ |eigenvalues|< 8 π

Constraints for lambdas

$$0 \leqslant \lambda_1 \leqslant 8.38$$
$$0 \leqslant \lambda_2 \leqslant 8.38$$
$$-13.64 \leqslant \lambda_3 \leqslant 16.52$$
$$-16.13 \leqslant \lambda_4 \leqslant 16.53$$
$$-8.24 \leqslant \lambda_5 \leqslant 0$$

Couplings for dark particles in IDM →

$\lambda^-_{345} = \lambda_3 + \lambda_4 - \lambda_5$

$\lambda^-_{45} = \lambda_4 - \lambda_5$

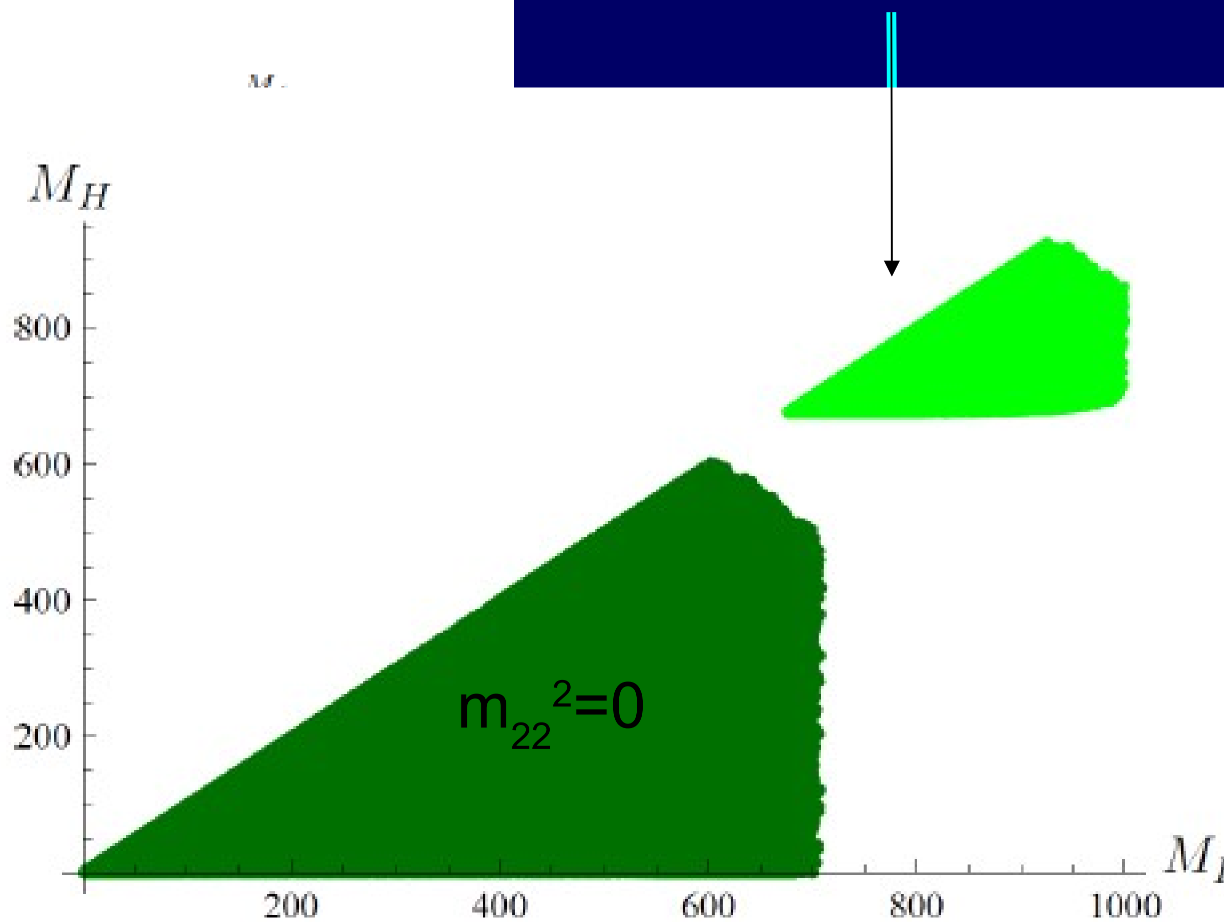
$$-8.19 \leqslant \lambda_{345} \leqslant 15.54,$$
$$-7.65 \leqslant \lambda^-_{345} \leqslant 16.46,$$
$$-16.66 \leqslant \lambda_{45} \leqslant 16.50,$$
$$-15.80 \leqslant \lambda^-_{45} \leqslant 16.71.$$

Unitarity bounds for IDM

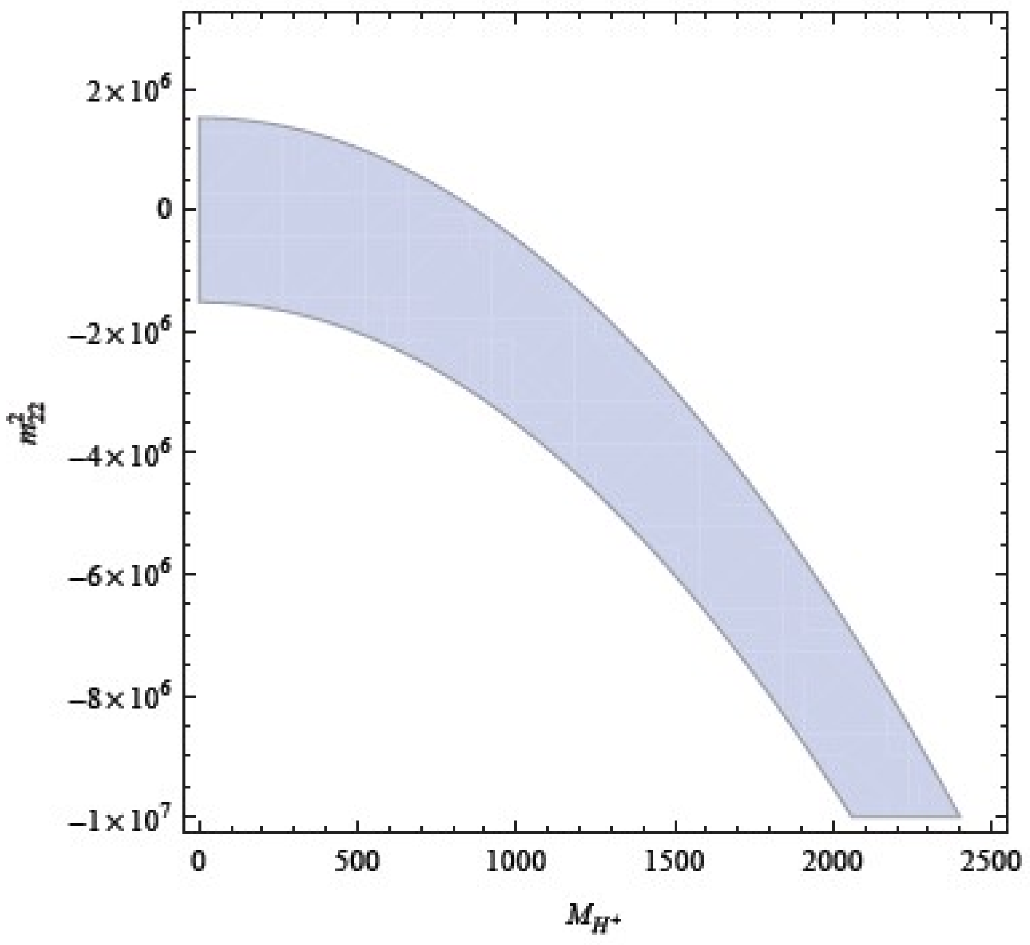
$m_{22}^2 = -10^6\ \mathrm{GeV}^2$

Bounds for the case
$m_{22}^2 = 0$,
$M_h = 120\,\mathrm{GeV}$ and
$M_h \in [114,\ 145]\,\mathrm{GeV}$:

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



MH+, GeV



IDM

Simplified unitarity condition
|lambda 3| < 8 pi

Mixed Model=Mixed vacuum and Yukawa Model II

Bounds for the Mixed Model

For the general case:

$$M_{H\pm} \leqslant 690\,\mathrm{GeV},$$
$$M_A \leqslant 702\,\mathrm{GeV},$$
$$M_H \leqslant 698\,\mathrm{GeV},$$
$$M_h \leqslant 501\,\mathrm{GeV}$$

(Compare Kanemura et al. (1993

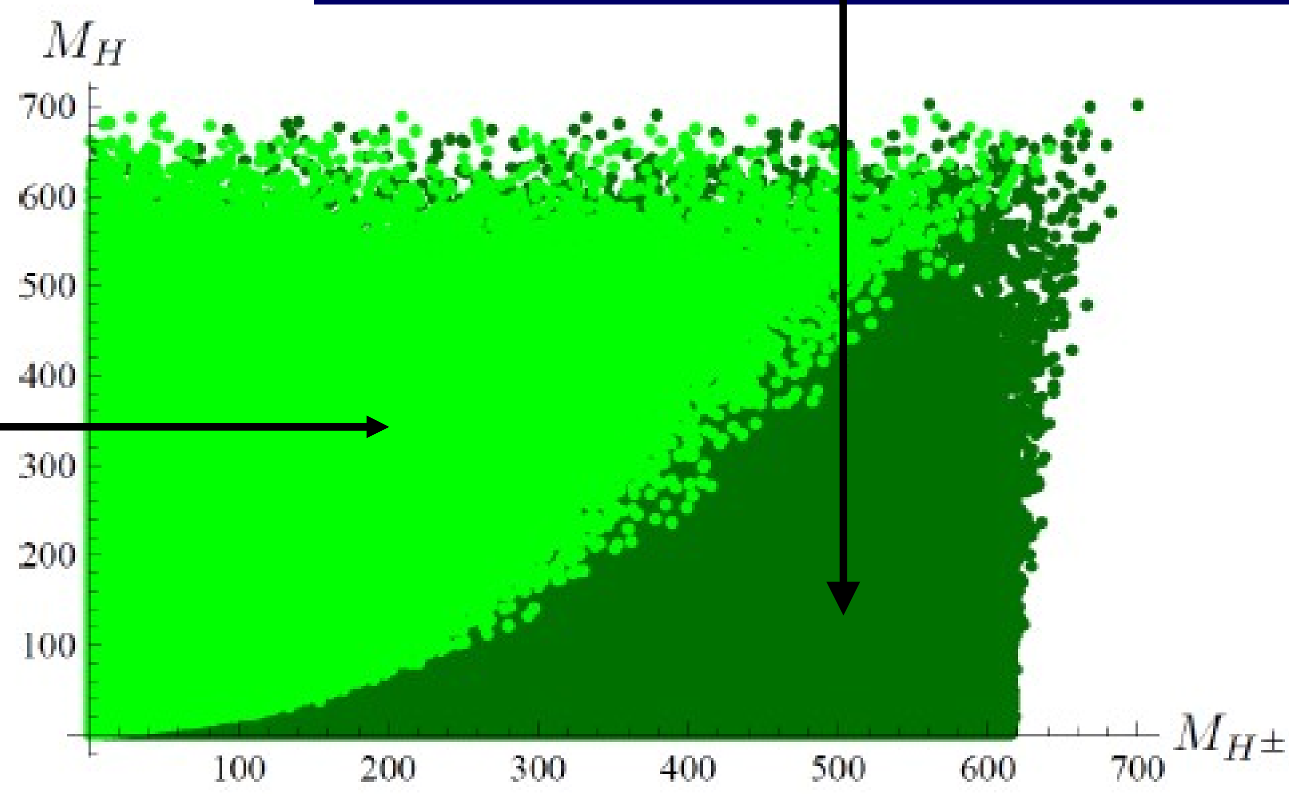
Hořejši & Kladiva (2006).)

Akeroyd, A. Arhrib, E. Naimi,

MSSM type

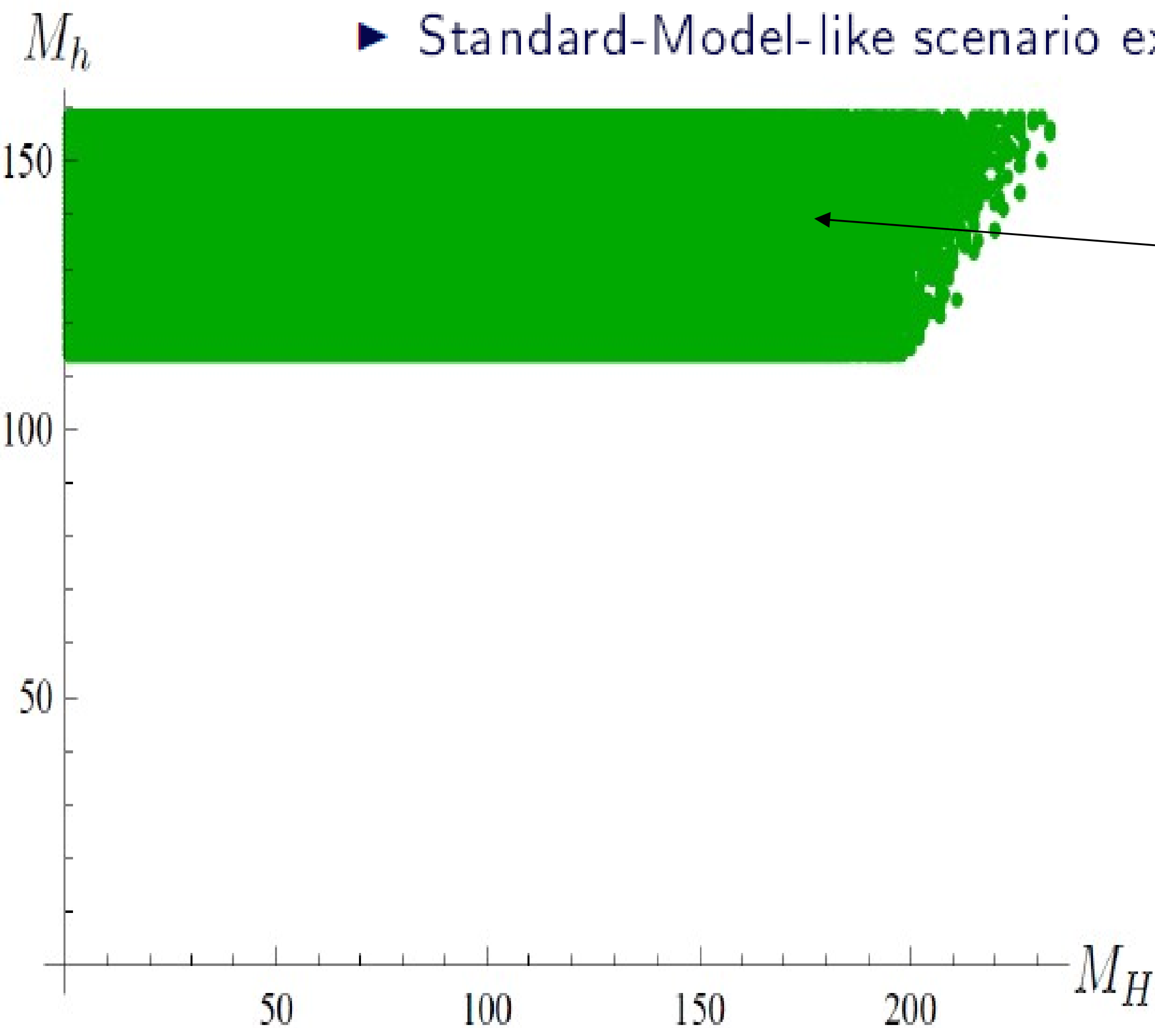
Dark region - not allowed for Mixed vacuum !!!

Light green = true allowed region



For the SM-like Mixed Model (h couples like the standard Higgs boson and $M_h \in [114, 145]\,\mathrm{GeV}$):

- unitarity: $M_H^{\pm} \leqslant 224\,\mathrm{GeV}$.
- $b \to s\gamma$: $M_{H\pm} \geqslant 300\,\mathrm{GeV}$ (Misiak *et al.* (2007)).
- Standard-Model-like scenario excluded.



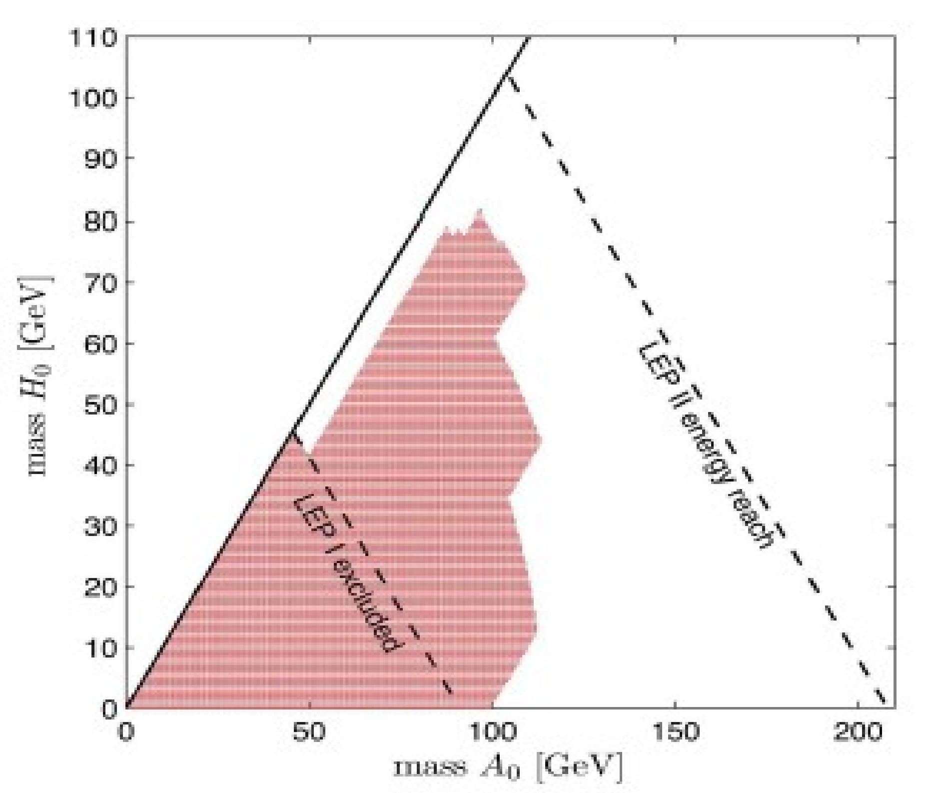
allowed region by unitarity

$$M_{H\pm} \leqslant 233\,\mathrm{GeV},$$
$$M_A \leqslant 618\,\mathrm{GeV},$$
$$M_H \leqslant 611\,\mathrm{GeV},$$
$$M_h \leqslant 158\,\mathrm{GeV}.$$

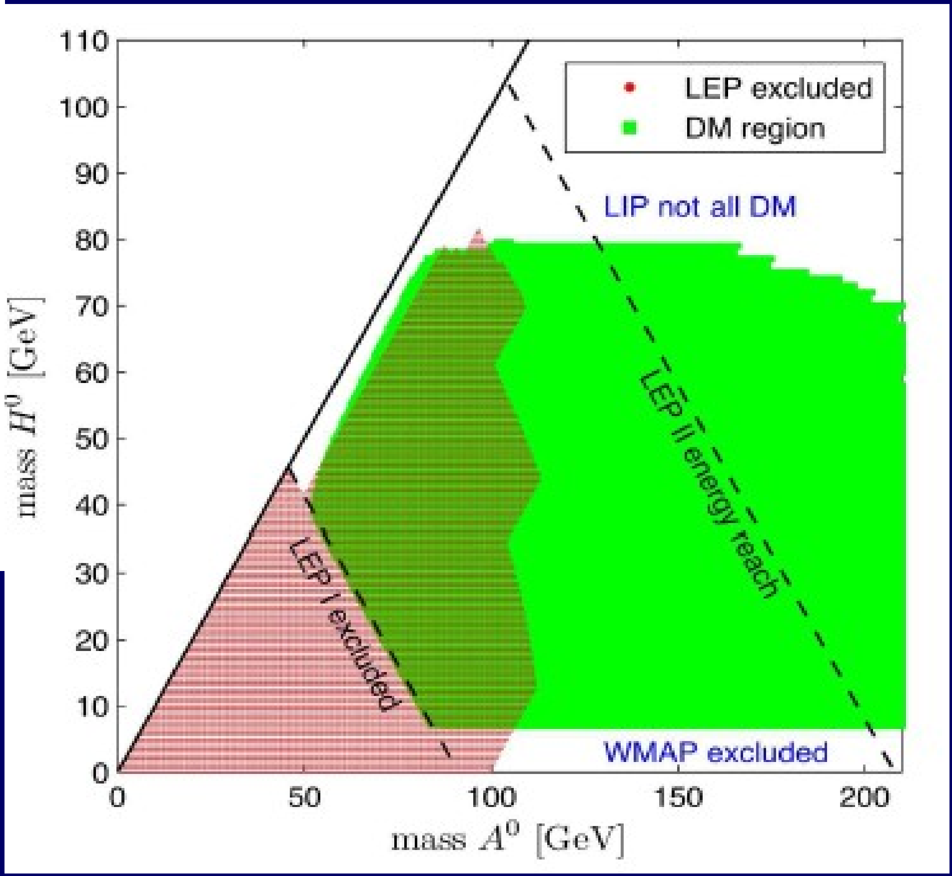
$$-0.96 \leqslant \sin\alpha \leqslant -0.17,$$
$$0.29 \leqslant \tan\beta \leqslant 6.16.$$

IDM: LEP II exclusion (massesH vs A)

Lundstrom... hep-ph/0810.3924



LEP II + WIMAP



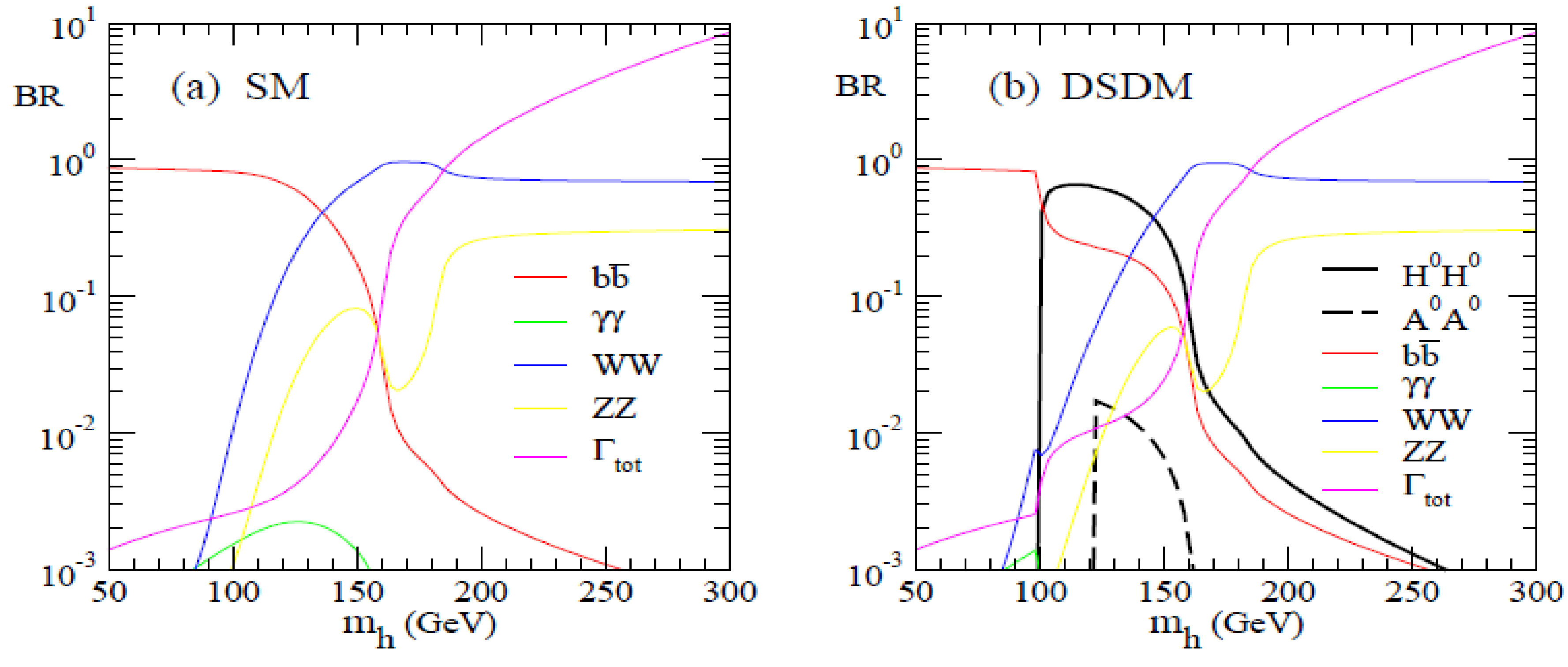
DM = low, medium, high mass

Colliders signal/constraints for IDM

Barbieri et al '2006 for heavy h; Cao, Ma, Rajasekaren' 2007 for a light h, *later many others*

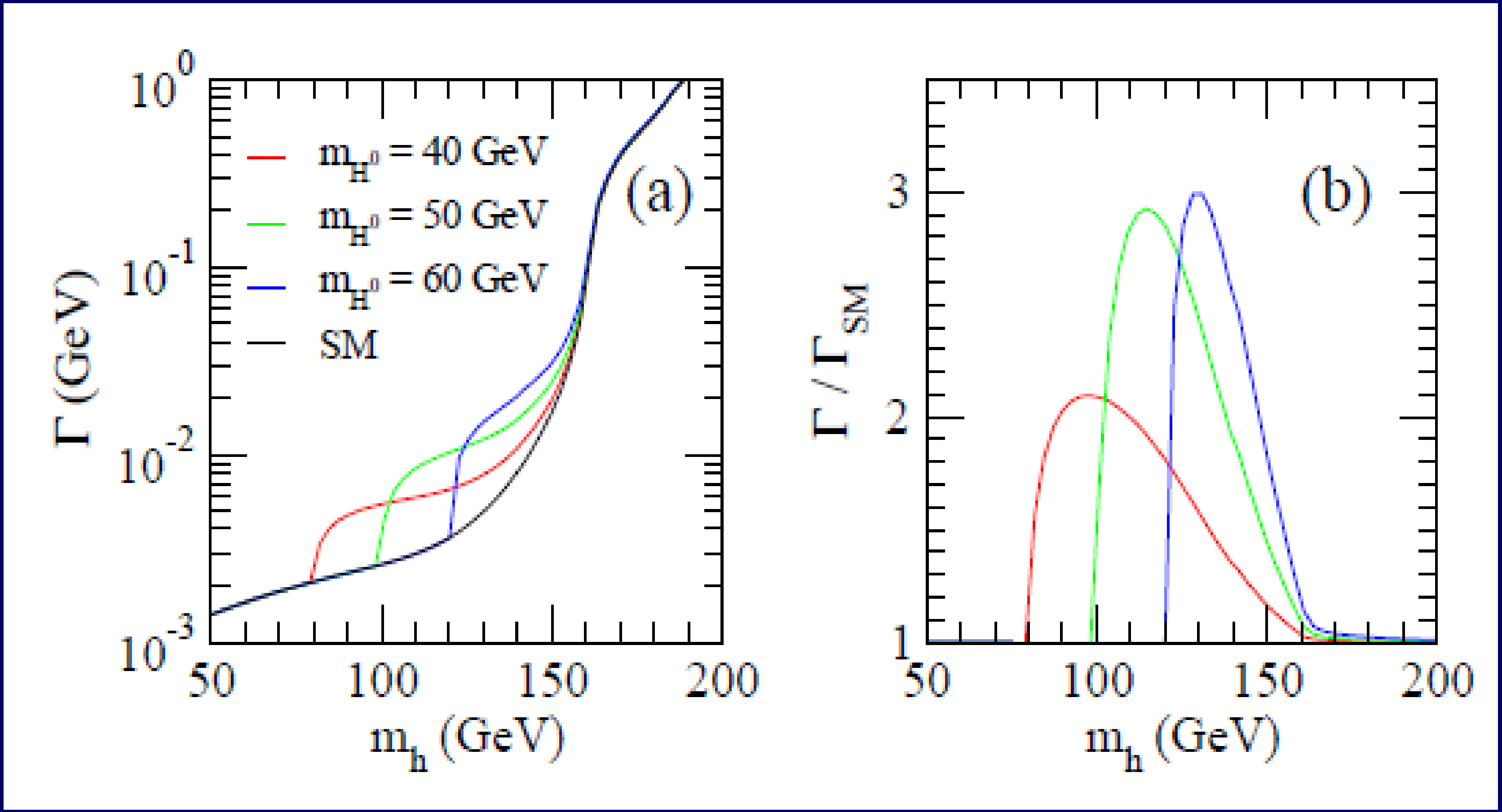
EW precision data $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

For MH=50 GeV

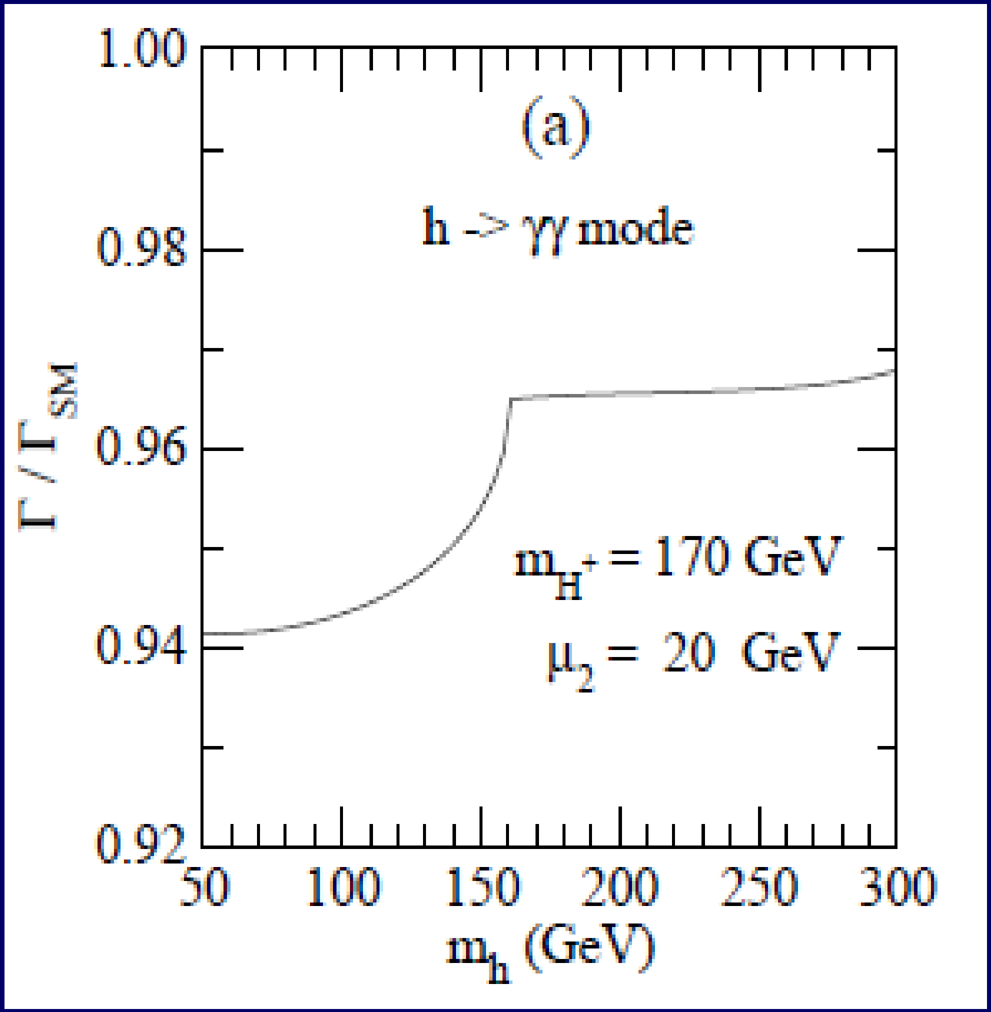


For $M_H = 50$ GeV, $\Delta(A,H)$=10 GeV, M_{H+}=170 GeV, m_{22}=20 GeV

IDM – total width of h



IDM: $\gamma\gamma h$



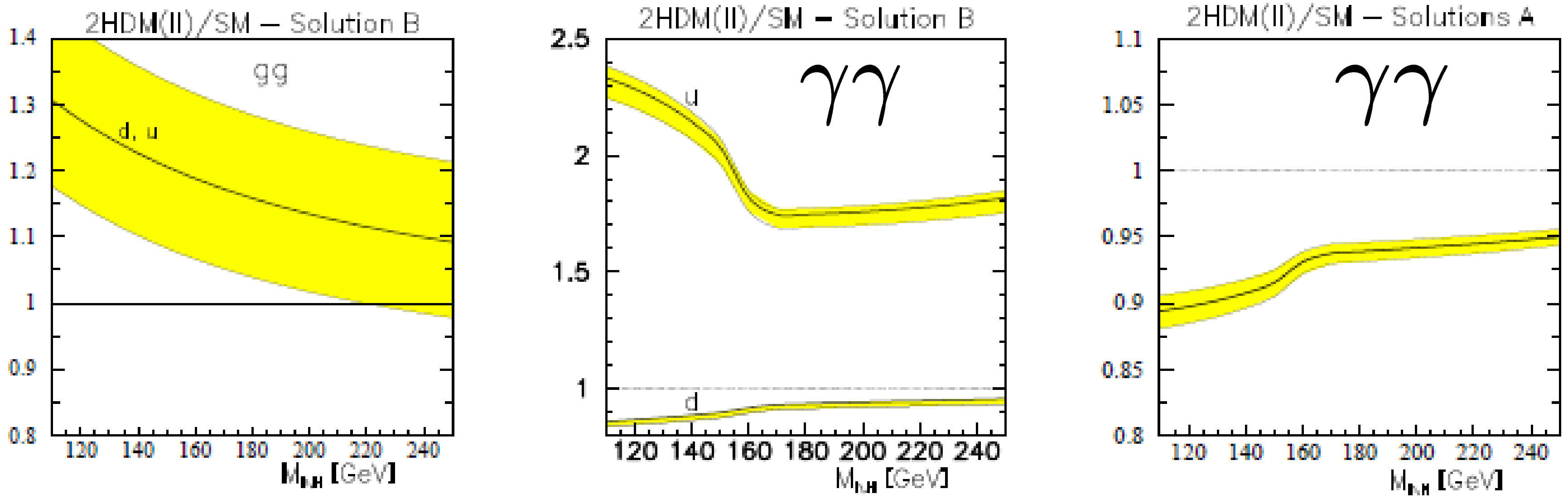
Loop couplings ggh, $\gamma\gamma$h in Z_2 2HDM

(Mixed)

$\Gamma(h \to gg, \gamma\gamma)$
including exp. uncertainties

Ginzburg,Osland, MK '2001

Even when hVV and hff as in SM , (SM-like scenario A) →
large non-decoupling effects due to heavy $H^{\pm}$. 600 GeV



ggh - solution B „wrong" signs of fermion couplings

Conclusions

- 2HDM - a great laboratory for physics BSM
- In many Standard Models SM-like scenarios can be realized:

  [Higgs mass >114 GeV, SM tree-level couplings]
- In models with two doublets:

  - MSSM with decoupling of heavy Higgses $\rightarrow$ *LHC-wedge*

  - 2HDM (Mixed) with and without CP violation *both h or H can be SM-like*

  - Intert Doublet Model

Yes, Photon Linear Collider can distinguish...

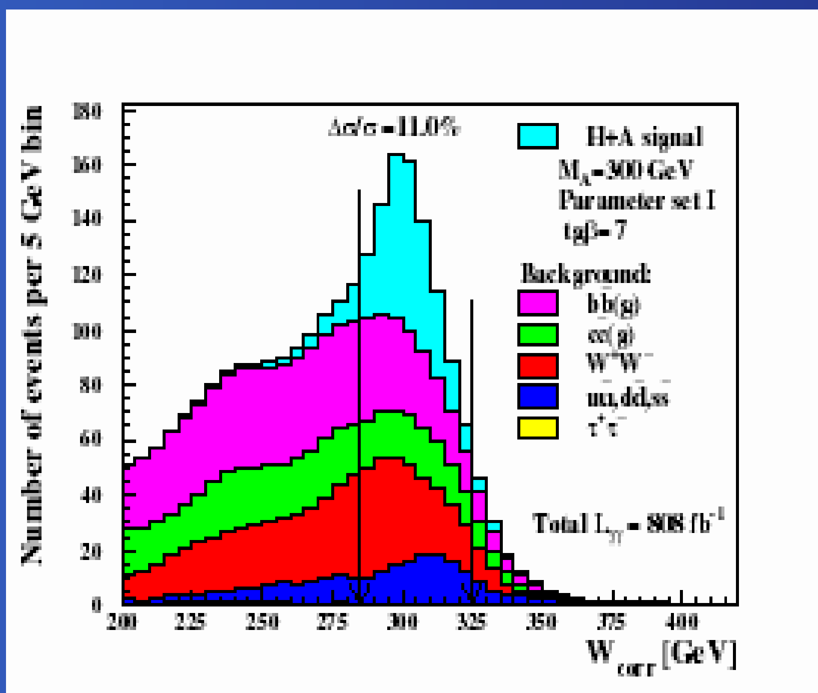
MSSM: Precision at PLC

Niezurawski et al., Spira et al

Covering the LHC wedge

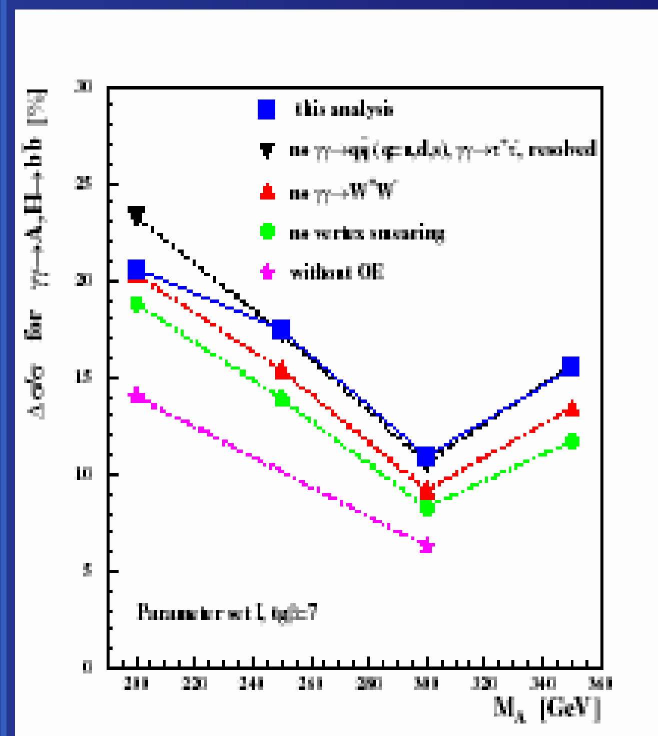
Precision of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ mesurement

Results for $M_A = 300$ GeV



Corrected invariant mass distributions

Results for $M_A = 200$-350 GeV

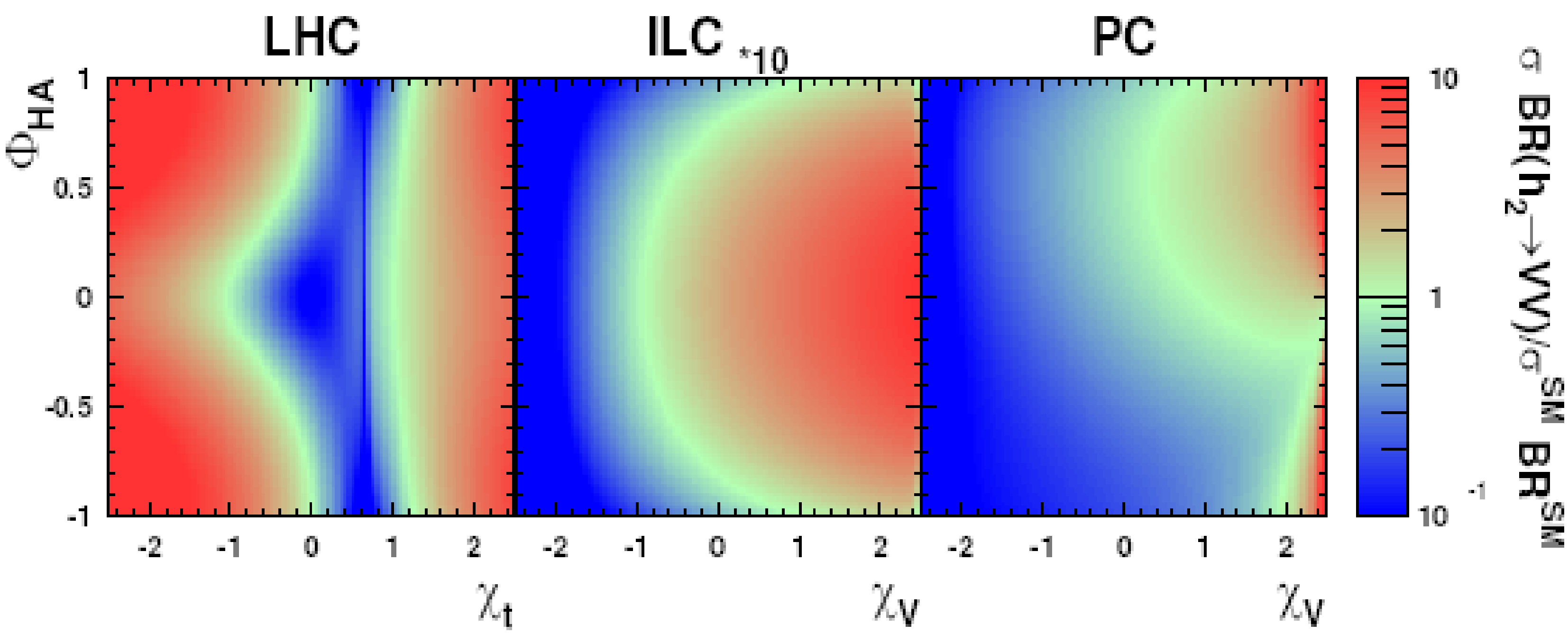


our previous results compared

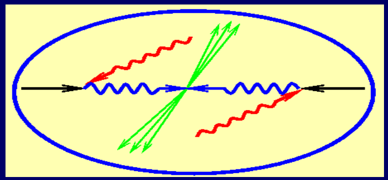
LHC $\oplus$ ILC $\oplus$ PC

Sensitivity of LHC, ILC and Photon Collider measurements
to CP-violating mixing phase Φ_{HA}

Cross sections $\times$ BR relative to SM $\qquad M_H = 250 GeV$



PLC: Photon Linear Collider
$\gamma\,\gamma$ and e γ



- Resonance production of C=+ states (eg. Higgs) Ginzburg et al
- Higher mass reach
- Polarised beams – CP filter Gunion, Grzadkowski, Godbole,Zarnecki
- H $\gamma\,\gamma$ coupling – sensitive to charged particles in theory (nondecoupling) Ginzburg et al.., Gunion..

- Direct production of charged scalars, fermions and vectors – higher cross section Monig,
- Pair production of neutral particles (eg. light-on-light) via loops Jikia, Gounaris…
- Study of hadronic interaction of the photon Godbole,Pancheri; MK Brodsky, deRoeck,Zerwas