Dark CP violation through the Z portal

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In praise of the Standard Model

Current formulation finalised in the 70's predicted:

- the W & Z (1983)
- the top quark (1995)
- the tau neutrino (2000)
- "a" Higgs boson (2012)

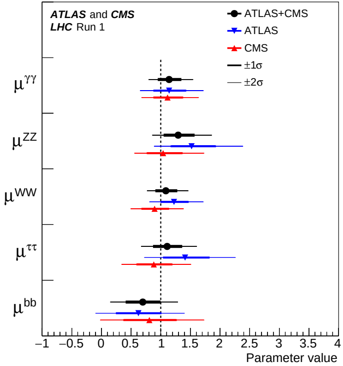
In criticism of the Standard Model

At the LHC:

- Higgs looks SM-like
- No signs of new physics

What is missing:

- Explanation for the fermion mass hierarchy
- EW vacuum stability
- Sufficient amount of CP violation
- Suitable candidate(s) for Dark Matter



[JHEP 08 (2016) 045]

Scalars to the rescue!

SM + singlet scalar extensions

ϕ S

real singlet

complex singlet

extra singlets

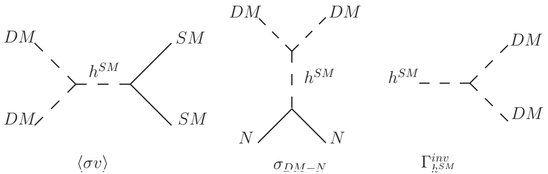
SM + real singlet (DM, ~~CPV~~)

DM protected by a Z_2 symmetry $(+,-)$: $\quad \mathrm{SM} \to \mathrm{SM}, \quad S \to -S$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 + \frac{1}{2}\mu_s^2 S^2 - \lambda_s S^4 - \lambda_{hs}\Phi^2 S^2$$

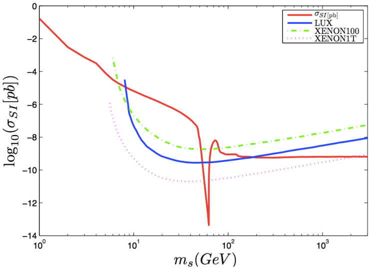
Z_2 symmetric Lagrangian, respected by the vacuum

$$\phi = \begin{pmatrix} G^+ \\ \frac{v_h + h + iG^0}{\sqrt{2}} \end{pmatrix}, \quad S = \left(\frac{s}{\sqrt{2}} \right)$$



SM + real singlet (DM, $\cancel{\text{CPV}}$)

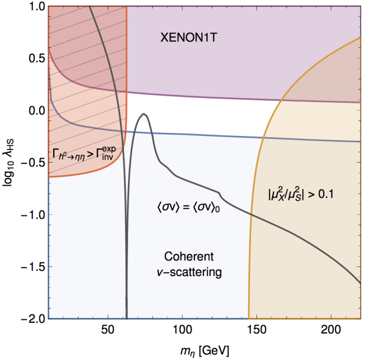
- Bounded from below potential: $h, s \to \infty \;\; \Rightarrow V > 0$
- Vacuum stability: $E_{v_{EW}} < E_{v_i}$ or $\tau_{v_{EW}} >$ age of the universe
- Perturbative unitarity: $|\lambda_i| \leq 4\pi, \; |\Lambda_i| \leq 8\pi$
- Higgs decays: $BR(h \to inv.) < 20\% \;\; \Rightarrow \lambda_{hs}$ small
- Relic density: λ_{hs} large
- Direct and indirect detection: λ_{hs} small

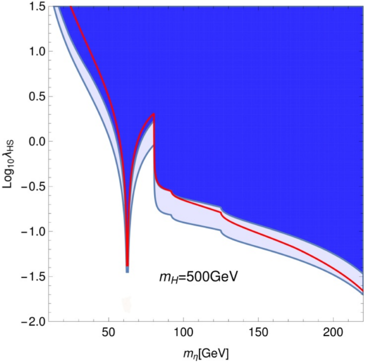


[JHEP 12, 044 (2015)]

SM + complex singlet (DM, ~~CPV~~)

$$S = (v_s + s + i\chi)$$





[Phys.Rev. D99 (2019) no.7, 075028]

Further singlet extensions (DM, ~~CPV~~)

SM+ 2 singlet scalars:

$S_1 \to -S_1, \quad S_2 \to -S_2, \quad \text{SM fields} \to \text{SM fields}$

- DM: the lightest particle from the dark sector s_1, s_2
- Introducing coannihilation channels: $s_1 s_2 \to h \to SM$
- Mixing in the dark sector $s_1, \chi_1, s_2, \chi_2 \to d_1, d_2, d_3, d_4$

does not result in CPV

[Phys.Rev.D. 83 (2011)]

Scalars to the rescue!

2 Higgs doublet model (2HDM)

$\phi_1,\ \phi_2$

CPC-2HDM

CPV-2HDM

IDM

The generic 2HDM

The general scalar potential:

$$
\begin{aligned}
V &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \left[\mu_3^2(\phi_1^\dagger\phi_2) + h.c.\right] \\
&+ \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\
&+ \left[\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + h.c.\right].
\end{aligned}
$$

Dangerous FCNCs appear

$$\mathcal{L}_Y = y_{ij}^1 \bar{\psi}_i \psi_j \phi_1 + y_{ij}^2 \bar{\psi}_i \psi_j \phi_2$$

Z_2 symmetry $(\phi_1 \to +\phi_1,\ \phi_2 \to -\phi_2) \Rightarrow \lambda_6 = \lambda_7 = 0$

The CP-conserving 2HDM (~~DM~~, ~~CPV~~)

The doublets compositions:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix}, \quad \tan\beta = \langle\phi_2\rangle / \langle\phi_1\rangle$$

Mass eigenstates:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} a_1^0 \\ a_2^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

More constraints

Electroweak precision observables:

$$S,\ \ T,\ \ U\text{parameters}$$

Flavour observables:

$$BR(B \to X_s\gamma), \quad B^0 - \bar{B}^0\text{mixing}$$
$$D_s \to \tau\nu_\tau, \quad D_s \to \mu\nu_\mu, \quad B \to D\tau\nu_\tau$$

LEP bounds:

$$m_{H^\pm} + m_{H,A} > m_{W^\pm}, \qquad m_H + m_A > m_Z, \qquad 2m_{H^\pm} > m_Z$$

$$m_{H^\pm} \gtrsim 70 - 90\ \mathrm{GeV}$$

$$\text{if } M_H < 80\ \mathrm{GeV} \text{ and } M_A < 100\ \mathrm{GeV} \Rightarrow M_A - M_H < 8\ \mathrm{GeV}$$

LHC bound on the total decay signal strength:

$$\mu_{tot} = \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h_{\mathrm{SM}} \to XX)} = 1.17 \pm 0.17$$

2HDM with CP-violation (CPV, ~~DM~~)

The scalar potential with softly broken Z_2 symmetry:

$$\begin{aligned} V &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \mu_3^2(\phi_1^\dagger\phi_2) + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + h.c. \end{aligned}$$

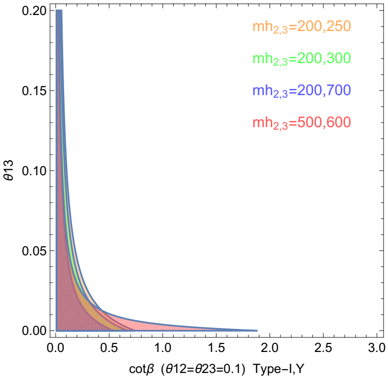
The only source of CPV-violation:

$$\mathrm{Im}\mu_3^2 = \frac{v^2}{2}\mathrm{Im}\lambda_5 \sin\beta\cos\beta$$

The CP mixed mass eigenstates in the *Higgs basis*:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} 1 & \theta_{12} & \theta_{13} \\ -\theta_{12} & 1 & \theta_{23} \\ -\theta_{13} & -\theta_{23} & 1 \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ \phi_3^0 \end{pmatrix}$$

CPV angles constrained by EDM data



[JHEP 1809 (2018) 059]

The Inert Doublet Model (DM, ~~CPV~~)

Scalar potential with an exact Z_2 symmetry:

$$Z_2: \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}$$

$$\begin{aligned} V &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 \end{aligned}$$

The vacuum respects the Z_2 symmetry:

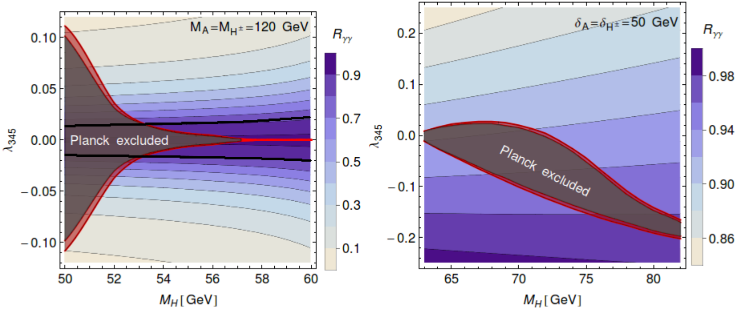
$$\langle\phi_1\rangle = v, \quad \langle\phi_2\rangle = 0$$

DM is the lightest neutral particle from the inert doublet: H, A

More constraints

Higgs invisible decays: $\mathrm{BR}(h \to S_i S_j) < 0.23 - 0.36$

$h \to \gamma\gamma$ signal strength: $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$



[JHEP 09, 055 (2013)]

Scalars to the rescue!

3-Higgs doublet models

I(1+2)HDM

$(0, v, v)$

I(2+1)HDM

$(0, 0, v)$

The scalar potential with explicit CPV (DM, CPV)

$$
\begin{aligned}
V_{3HDM} &= V_0 + V_{Z_2} \\
V_0 &= \sum_i^3 \left[-\mu_i^2 (\phi_i^\dagger \phi_i) + \lambda_{ii} (\phi_i^\dagger \phi_i)^2 \right] \\
&+ \sum_{i,j}^3 \left[\lambda_{ij} (\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij} (\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right] \\
V_{Z_2} &= -\mu_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_1 (\phi_1^\dagger \phi_2)^2 + \lambda_2 (\phi_2^\dagger \phi_3)^2 + \lambda_3 (\phi_3^\dagger \phi_1)^2 + h.c.
\end{aligned}
$$

The Z_2 symmetry

$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3, \quad \text{SM fields} \to \text{SM fields}$$

The CP-mixed mass eigenstates

The doublet compositions

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

The mass eigenstates

$$m^2_{S_1^\pm} = -\mu_2^2 - \mu_{12}^2 + \frac{1}{2}\lambda_{23} v^2, \quad m^2_{S_2^\pm} = -\mu_2^2 + \mu_{12}^2 + \frac{1}{2}\lambda_{23} v^2$$

$$m^2_{S_{1,2}} = -\mu_2^2 + \frac{v^2}{2}(\lambda'_{23} + \lambda_{23}) \mp \Lambda^-, \quad m^2_{S_{3,4}} = -\mu_2^2 + \frac{v^2}{2}(\lambda'_{23} + \lambda_{23}) \mp \Lambda^+$$

$$\Lambda^\mp = \sqrt{(\mu_{12}^2)^2 + v^4|\lambda_2|^2 \mp 2v^2\mu_{12}^2|\lambda_2| \cos\theta_{CPV}}$$

S_1 is assumed to be the DM candidate

[JHEP 1612 (2016) 014]

Setting Higgs portal couplings to zero

- **annihilation processes:**

$$S_1 S_1 \to VV, \qquad S_1 S_1 \to VV^* \to Vff', \qquad S_1 S_1 \to V^* V^* \to ff' ff'$$

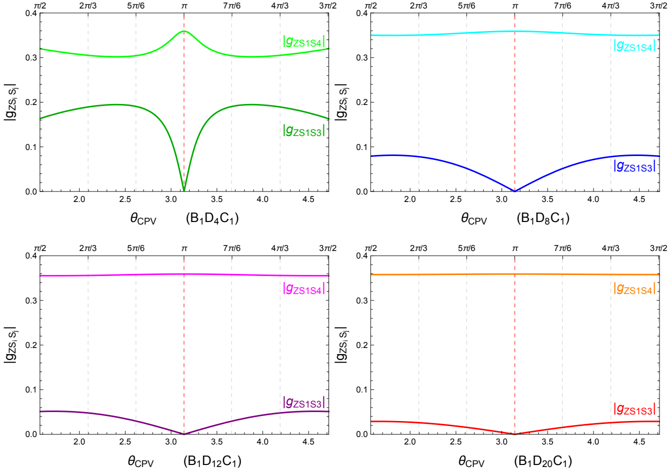
- **co-annihilation processes:**

$$S_1 S_{2,3,4} \to Z^* \to f \bar{f}, \qquad S_1 S^{\pm}_{1,2} \to W^{\pm *} \to ff'$$

- **(co)annihilation of other dark states:**

$$S_i S_i \to VV, \quad S_i S_i \to VV^* \to Vff',$$
$$S_i S_i \to V^* V^* \to ff' ff', \quad S_i S_j \to V^* \to ff'$$

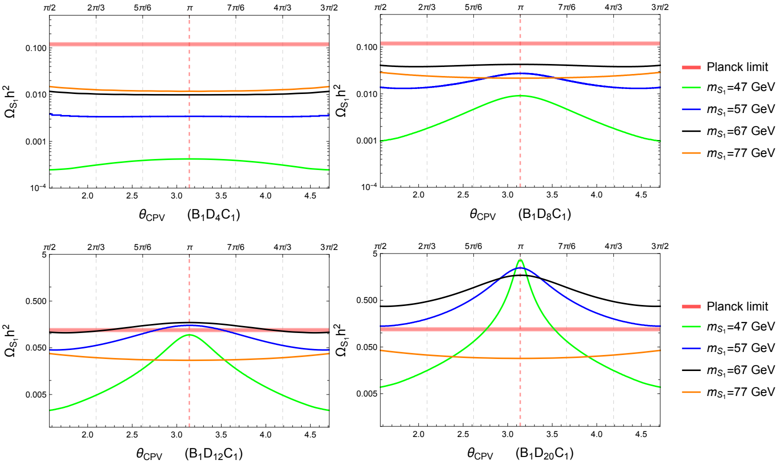
Type 1 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm} \sim m_{S_2^\pm}$



$$\mathbf{B_1D_4C_1}: \ \delta_{12} = 4 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV},$$

$$\mathbf{B_1D_8C_1}: \ \delta_{12} = 8 \text{ GeV}, \quad \mathbf{B_1D_{12}C_1}: \ \delta_{12} = 12 \text{ GeV}, \quad \mathbf{B_1D_{20}C_1}: \ \delta_{12} = 20 \text{ GeV}$$

Type 1 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm} \sim m_{S_2^\pm}$



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$$\mathbf{B_1D_8C_1}: \ \delta_{12} = 8 \text{ GeV}, \quad \mathbf{B_1D_{12}C_1}: \ \delta_{12} = 12 \text{ GeV}, \quad \mathbf{B_1D_{20}C_1}: \ \delta_{12} = 20 \text{ GeV}$$

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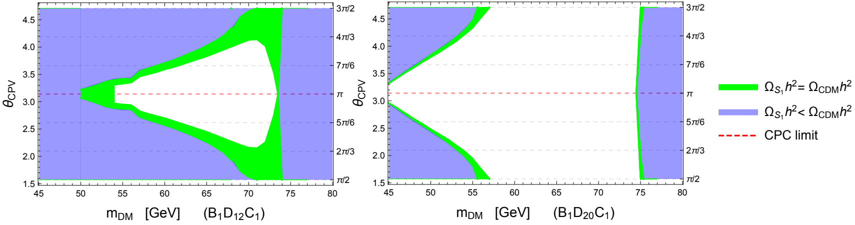
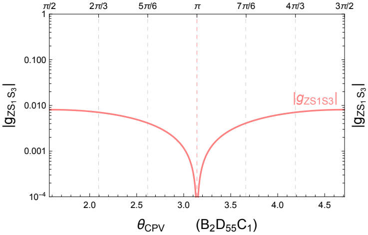
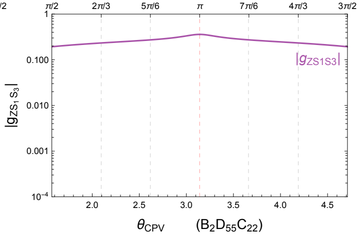


$$\mathbf{B_1D_4C_1}: \ \delta_{12} = 4 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV},$$
$$\mathbf{B_1D_8C_1}: \ \delta_{12} = 8 \text{ GeV}, \quad \mathbf{B_1D_{12}C_1}: \ \delta_{12} = 12 \text{ GeV}, \quad \mathbf{B_1D_{20}C_1}: \ \delta_{12} = 20 \text{ GeV}$$

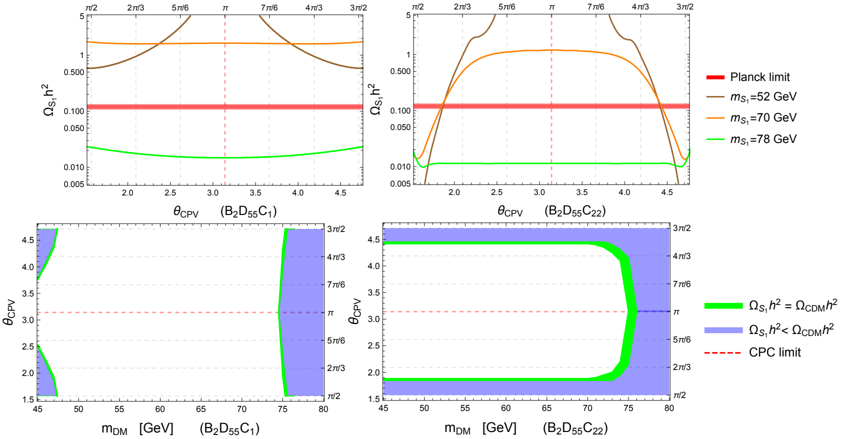
Type 2 benchmarks: $m_{S_1} \sim m_{S_3} \ll m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$





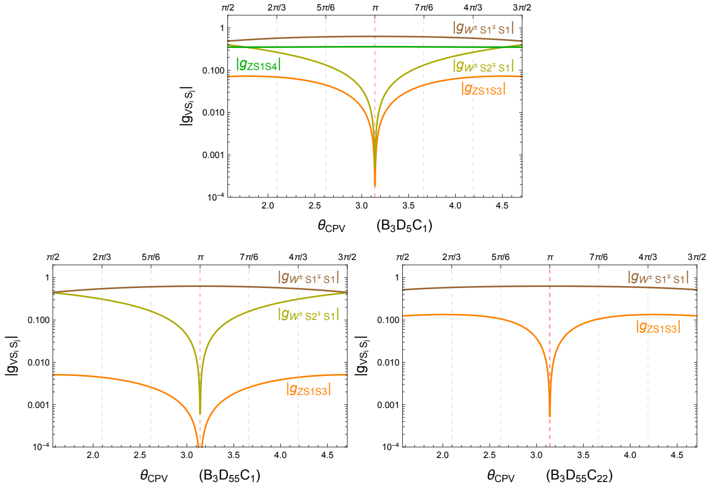
$$\mathbf{B_2D_{55}C_1}: \ \delta_{12} = 55 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV},$$
$$\mathbf{B_2D_{55}C_{22}}: \ \delta_{12} = 55 \text{ GeV}, \quad \delta_c = 22 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV}$$

Type 2 benchmarks: $m_{S_1} \sim m_{S_3} \ll m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$



$$\mathbf{B_2D_{55}C_1}: \ \delta_{12} = 55 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV},$$
$$\mathbf{B_2D_{55}C_{22}}: \ \delta_{12} = 55 \text{ GeV}, \quad \delta_c = 22 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV}$$

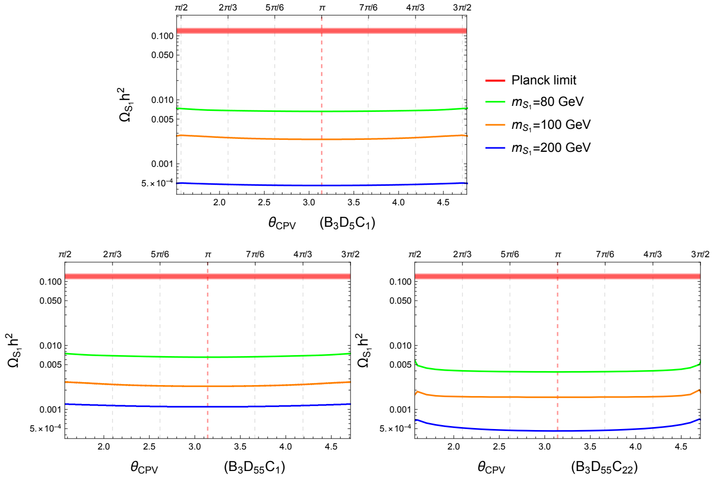
Type 3 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$



$\mathbf{B_3D_5C_1}$: $\delta_{12} = 5$ GeV, $\delta_c = 1$ GeV, $\delta_{1c} = 1$ GeV,

$\mathbf{B_3D_{55}C_1}$: $\delta_{12} = 55$ GeV, $\delta_c = 1$ GeV, $\mathbf{B_3D_{55}C_{22}}$: $\delta_{12} = 55$ GeV, $\delta_c = 22$ GeV

Type 3 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$

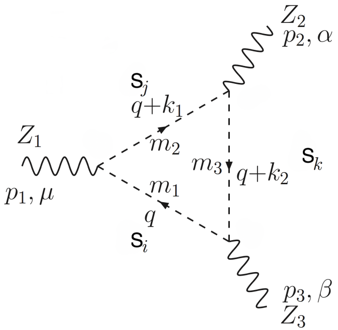


$$\mathbf{B_3D_5C_1}: \ \delta_{12} = 5 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \delta_{1c} = 1 \text{ GeV},$$

$$\mathbf{B_3D_{55}C_1}: \ \delta_{12} = 55 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \mathbf{B_3D_{55}C_{22}}: \ \delta_{12} = 55 \text{ GeV}, \quad \delta_c = 22 \text{ GeV}$$

Dark CPV observables: the ZZZ vertex

$$e\Gamma^{\alpha\beta\mu}_{ZZZ} = ie\frac{q^2 - M_Z^2}{M_Z^2}[f_4(q^\alpha g^{\mu\beta} + q^\beta g^{\mu\alpha}) + f_5\epsilon^{\mu\alpha\beta\rho}(p_1 - p_2)_\rho]$$



$$f_4 = \frac{M_Z^2|g_{ZS_2S_3}|\,|g_{ZS_1S_3}|\,|g_{ZS_1S_2}|}{2\pi^2 e(q^2 - M_Z^2)} \sum_{i,j,k}^{4} \epsilon_{ijk} C_{002}(M_Z^2, M_Z^2, q^2, m_i^2, m_j^2, m_k^2)$$

JHEP1605,025(2016)

Summary

Scalar extensions with or without a Z_2 symmetry:

- SM + scalar singlet(s)
  - $\phi_{SM}, \; S \quad \Rightarrow \quad$ DM, $\cancel{\text{CPV}}$
  - $\phi_{SM}, \; S_1, \; S_2 \quad \Rightarrow \quad$ DM, $\cancel{\text{CPV}}$
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1, \; \phi_2 \quad \Rightarrow \quad$ CPV, $\cancel{\text{DM}}$
  - IDM - I(1+1)HDM: $\phi_1, \; \phi_2 \quad \Rightarrow \quad$ DM, $\cancel{\text{CPV}}$
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: $\phi_1, \; \phi_2, \; \phi_3 \quad \Rightarrow \quad$ CPV, $\cancel{\text{DM}}$
  - I(1+2)HDM: $\phi_1, \; \phi_2, \; \phi_3 \quad \Rightarrow \quad$ DM, CPV
  - I(2+1)HDM: $\phi_1, \; \phi_2, \; \phi_3 \quad \Rightarrow \quad$ CPV, DM

BACKUP SLIDES

The CP-mixed mass eigenstates

The doublet compositions

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

The mass eigenstates

$$S_1 = \frac{\alpha H_1^0 + \alpha H_2^0 - A_1^0 + A_2^0}{\sqrt{2\alpha^2+2}}, \quad S_2 = \frac{-H_1^0 - H_2^0 - \alpha A_1^0 + \alpha A_2^0}{\sqrt{2\alpha^2+2}}$$

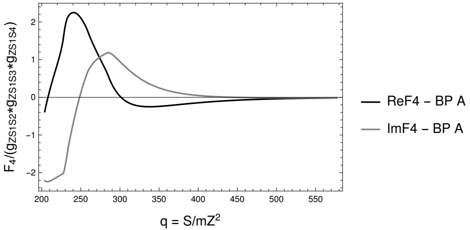
$$S_3 = \frac{\beta H_1^0 - \beta H_2^0 + A_1^0 + A_2^0}{\sqrt{2\beta^2+2}}, \quad S_4 = \frac{-H_1^0 + H_2^0 + \beta A_1^0 + \beta A_2^0}{\sqrt{2\beta^2+2}}$$

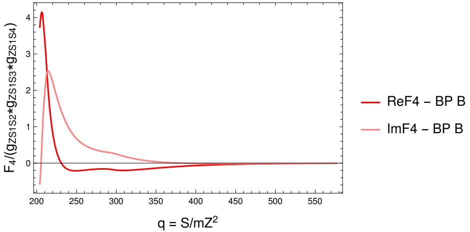
$$S_1^\pm = \frac{H_2^\pm + H_1^\pm}{\sqrt{2}}, \quad S_2^\pm = \frac{H_2^\pm - H_1^\pm}{\sqrt{2}}$$

S_1 is assumed to be the DM candidate

[JHEP 1612 (2016) 014]

f_4 values for exemplary benchmark points

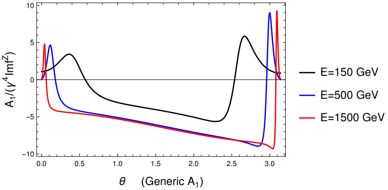


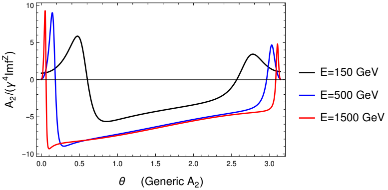


Assuming the momenta and helicities of ZZ are known:

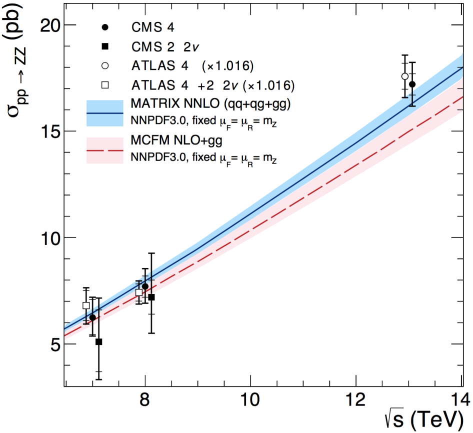
$$A_1^{ZZ} \equiv \frac{\sigma_{+,0} - \sigma_{0,-}}{\sigma_{+,0} + \sigma_{0,-}}, \quad A_2^{ZZ} \equiv \frac{\sigma_{0,+} - \sigma_{-,0}}{\sigma_{0,+} + \sigma_{-,0}},$$

$\sigma_{\lambda,\bar{\lambda}}$: unpolarized-beam cross sections for ZZ production with helicities λ and $\bar{\lambda}$





$pp \to ZZ$ at CMS



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Typical cross sections for DD and ID experiments