Dark CP-Violation in the Three Higgs Doublet Model

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Shortcomings of SM and the need of BSM

No sign of New Physics at the LHC

- No viable DM candidate
- Insufficient amount of CP violation
- An unstable vacuum
- No explanation for the fermion mass hierarchy
- ...

Scalar extensions aiming to provide a solution:

- Higgs portal models: ϕ, S
- 2HDM: ϕ_1, ϕ_2
- IDM - I(1+1)HDM: ϕ_1, ϕ_2
- 3HDM - I(1+2)HDM: ϕ_1, ϕ_2, ϕ_3, I(2+1)HDM: ϕ_1, ϕ_2, ϕ_3

Dark matter

Evidence for Dark Matter at diverse scales:

- galaxy scales: rotational speed of galaxies
- cluster scales: gravitational lensing at galaxy clusters
- horizon scales: anisotropies in the CMB

$\Rightarrow$ **around 25 % of the Universe is:**

- cold
- non-baryonic
- neutral
- very weakly interacting

$\Rightarrow$ **Weakly Interactive Massive Particle**

- stable due to the discrete symmetry

$$\underbrace{\text{DM DM} \to \text{SM SM}}_{\text{pair annihilation}}, \qquad \underbrace{\text{DM} \nrightarrow \text{SM}, \ldots}_{\text{stable}}$$

- annihilation cross section $\langle \sigma v \rangle \propto$ EW interaction
- thermal evolution of DM density - a fixed value after freeze-out

- Richer symmetry groups than the 2HDMs [Keus et al., JHEP 1401 (2014) 051]
- Richer particle spectrum
- Possible update to 6HDM
- It resembles the 3 generation of fermions ⇒ Interesting for flavour physics
- Different DM pheno: CPV-DM, multi-components, . . .
- Two inert possibilities:
    - Two inert plus One Higgs doublet, I(2+1)HDM
    - One inert plus Two Higgs doublets, I(1+2)HDM
    - CPC and CPV versions

The scalar potential

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

The Z_2 symmetry

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

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

$$\begin{aligned} m^2_{S_1^\pm} &= -\mu_2^2 - \mu_{12}^2 + \frac{1}{2}\lambda_{23} v^2 \\ m^2_{S_2^\pm} &= -\mu_2^2 + \mu_{12}^2 + \frac{1}{2}\lambda_{23} v^2 \\ m^2_{S_{1,2}} &= -\mu_2^2 + \frac{1}{2}(\lambda_{23} + \lambda'_{23}) v^2 \mp \Lambda^- \\ m^2_{S_{3,4}} &= -\mu_2^2 + \frac{1}{2}(\lambda_{23} + \lambda'_{23}) v^2 \mp \Lambda^+ \end{aligned}$$

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

S_1 is assumed to be the DM candidate

Parameters of V: $\mu_2^2, |\lambda_2|, |\mu_{12}^2|, \lambda_{23}, \lambda'_{23}, \theta_{CPV}$

DM mass:

m_{S_1}

mass splittings:

$\delta_{12} = m_{S_2} - m_{S_1}$

$\delta_{1c} = m_{S_1^\pm} - m_{S_1}$

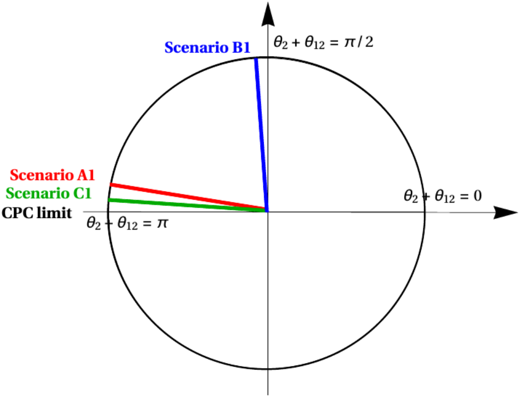
$\delta_c = m_{S_2^\pm} - m_{S_1^\pm}$

Higgs-DM coupling:

$g_{S_1 S_1 h}$

CPV phase:

$\theta_{CPV} = \theta_{12} + \theta_2$



We recover CPC when $\theta_{CPV} = \pi$, where $\cos\theta_{CPV} = -1$ and $\Lambda = v^2|\lambda_2| + |\mu_{12}^2|, \Lambda = v^2|\lambda_2| - |\mu_{12}^2|$ and $\alpha, \beta \to \infty$.

Benchmark scenarios

A1: $\delta_{12} = 125$ GeV, $\delta_{1c} = 50$ GeV, $\delta_c = 50$ GeV, $\theta_2 = \theta_{12} = 0.5$

$m_{S_1} < m_{2,3,4}, m_{S^\pm_{1,2}}$ (no co-annihilation)

B1: $\delta_{12} = 125$ GeV, $\delta_{1c} = 50$ GeV, $\delta_c = 50$ GeV, $\theta_2 = \theta_{12} = 0.82$

$m_{S_1} \approx m_{S_3} < m_{2,4}, m_{S^\pm_{1,2}}$

C1: $\delta_{12} = 12$ GeV, $\delta_{1c} = 100$ GeV, $\delta_c = 1$ GeV, $\theta_2 = \theta_{12} = 1.57$

$m_{S_1} \approx m_{S_2} \approx m_{S_3} \approx m_{S_4} < m_{S^\pm_{1,2}}$

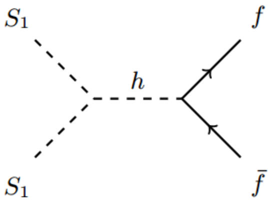
G1: $\delta_{12} = 2$ GeV, $\delta_{1c} = 1$ GeV, $\delta_c = 1$ GeV, $\theta_2 = \theta_{12} = 0.82$

$m_{S_1} \approx m_{S_2} \approx m_{S_3} \approx m_{S_4} \approx m_{S^\pm_1} \approx m_{S^\pm_2}$

H1: $\delta_{12} = 50$ GeV, $\delta_{1c} = 1$ GeV, $\delta_c = 50$ GeV, $\theta_2 = \theta_{12} = 0.82$

$m_{S_1} \approx m_{S_3} \approx m_{S^\pm_1} < m_{S_4} \approx m_{S_2} \approx m_{S^\pm_2}$

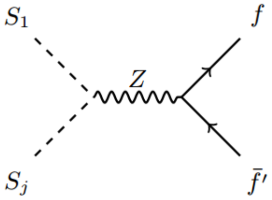
A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. F. King, S. Moretti, DRC and D. Sokoowska, JHEP **1612**, 014 (2016)



Higgs-mediated annihilation

depends on m_{S_1} and $g_{S_1 S_1 h}$

[Cordero et al., JHEP 1612 (2016) 014]



Z-mediated coannihilation

depends on $m_{S_j} - m_{S_1}$:

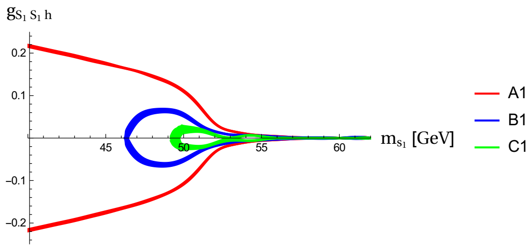
A1: no coannihilation

B1: $S_1 S_3$ coannihilation only

C1: $S_1 S_3, S_2 S_4, S_1 S_4, S_2 S_3$ coannihilation

depends on $Z S_1 S_j$ couplings

Low DM mass

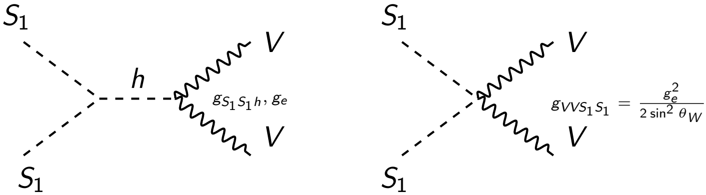


A1: mainly Higgs annihilation, large $g_{S_1 S_1 h}$

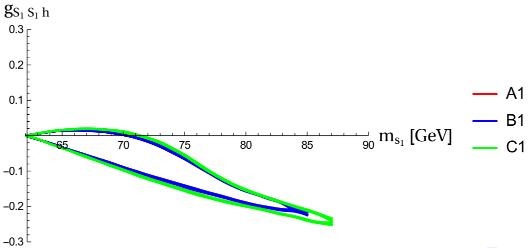
B1: Higgs annihilation (smaller $g_{S_1 S_1 h}$)
 $+$ ZS_1S_3 coannihilation (reduced with respect to the CPC case)

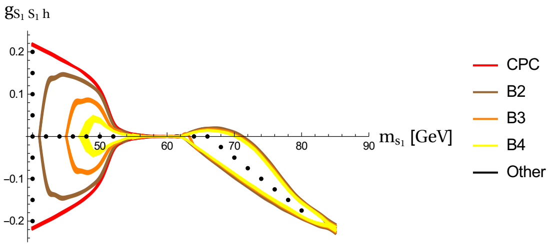
C1: mainly ZS_1S_4 coannihilation ($\chi_{ZS_1S_4} \approx -1$)
 $+$ Higgs annihilation

Tools used in calculation: LanHEP, arXiv:1412.5016 [physics.comp-ph]; CalcHEP, Comput. Phys. Commun. 184 (2013) 1729; micrOMEGAs 4.2 arXiv:1407.6129 [hep-ph]



no dependence on the benchmarks





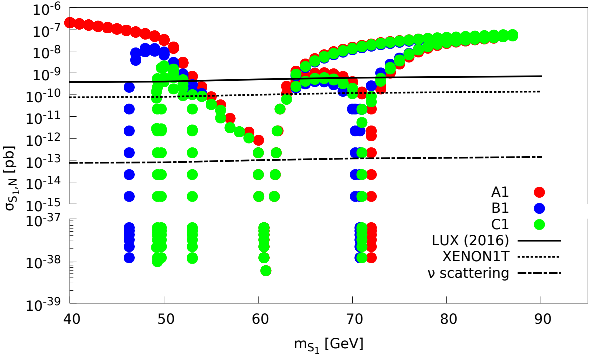
$m_{S_1} < m_h/2$: many new solutions:

different mass splittings + ZS_iS_j interaction strength

$m_{S_1} > m_h/2$: less freedom but still new solutions:

Higgs mediated coannihilations + sign of hS_3S_3 coupling

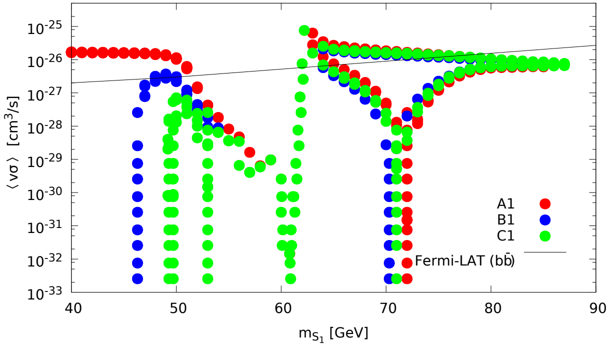
Direct detection



$$\sigma_{S_1,N} \propto \frac{g^2_{S_1 S_1 h}}{(m_{S_1} + m_N)^2}$$

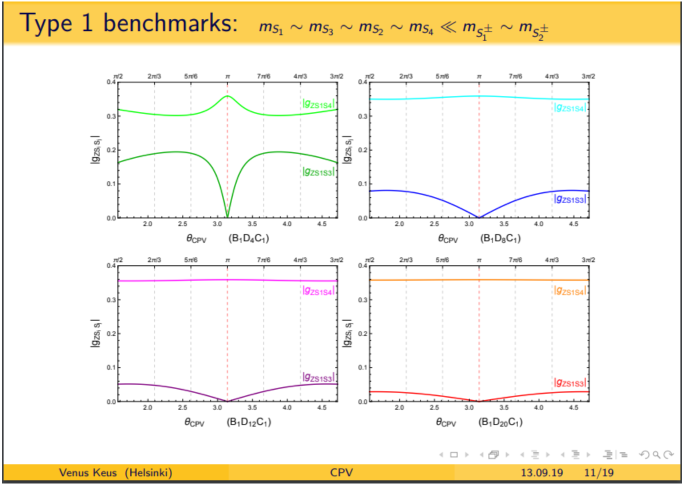
- Case Case A1: mostly excluded (large $g_{S_1 S_1 h}$)

Indirect detection



Most of the parameter space in agreement with Planck

Z-portal version (From arXiv: 1909.09234 [hep-ph])

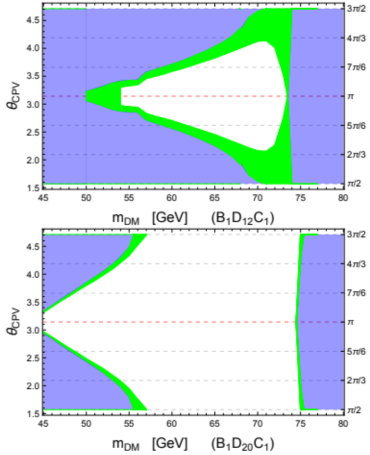


$B_1 D_4 C_1$: $\delta_{12} = 4$ GeV, $\delta_c = 1$ GeV, $\delta_{1c} = 50$ GeV, $B_1 D_8 C_1$: $\delta_{12} = 8$ GeV,
$B_1 D_1 2 C_1$: $\delta_{12} = 12$ GeV, $B_1 D_8 C_1$: $\delta_{12} = 20$ GeV

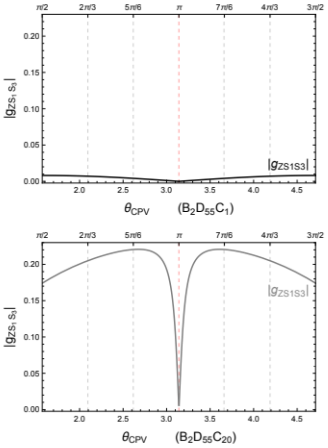
*Slides from Scalars 2019 - Venus Keus talk

Z-portal version (From arXiv: 1909.09234 [hep-ph])

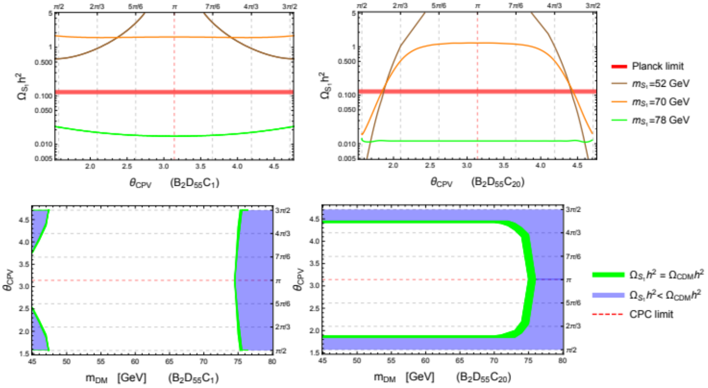
Type 1 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm} \sim m_{S_2^\pm}$



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

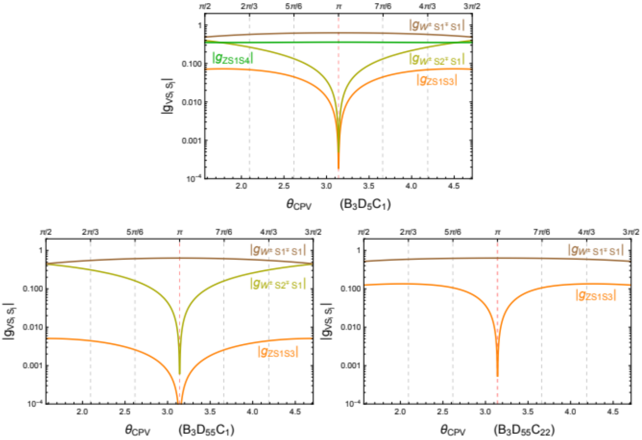


Type 2 benchmarks: $m_{S_1} \sim m_{S_3} \ll m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$



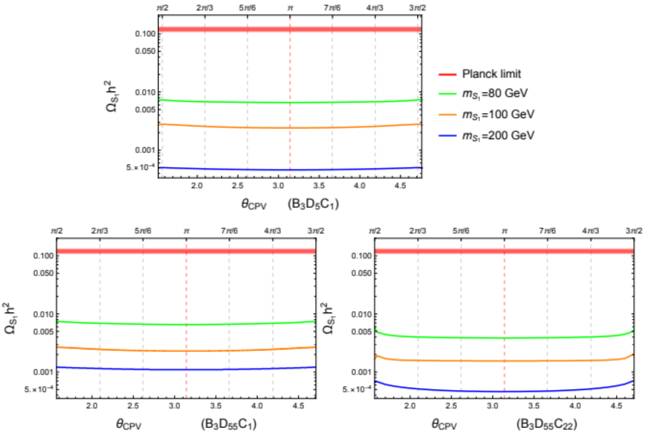
Z-portal version (From arXiv: 1909.09234 [hep-ph])

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



Venus Keus (Helsinki) | CPV | 13.09.19 | 16/19

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



Collider

signatures

Collider signatures

- $e^+e^- \to Z^* \to S_iS_j \ (i,j = 1,\ldots,4)$
  - if CPC 4 final states:

$$H_1A_{1,2},\ H_2A_{1,2}$$

  - if CPV 6 final states:

$$S_1S_{2,3,4},\ S_2S_{3,4},\ S_3S_4$$

- cross-section of few pb for $\sqrt{s}$ at future e^+e^- colliders
- different BPs: the proximity of thresholds can test dark mass spectrum
- complementary to XENON*n*T searches

A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. Moretti, DR-C and D. Sokolowska, Eur. Phys. J. C 80 (2020) no.2, 135 [arXiv:1812.00820 [hep-ph]].

Testing CPV in e^+e^- colliders

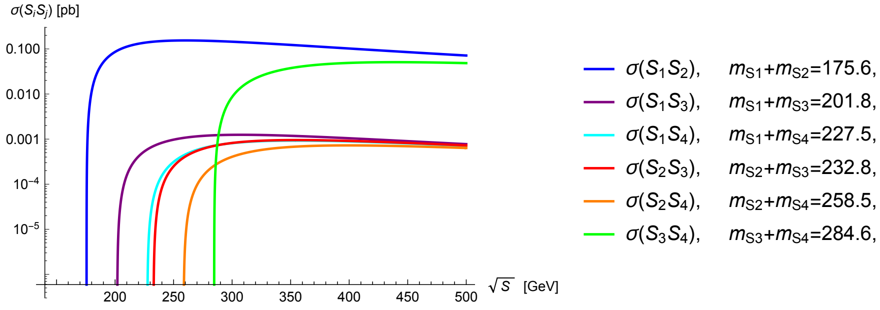


Figure: The $e^+e^- \to Z^* \to S_iS_j$ cross section for BP A with masses in GeV.

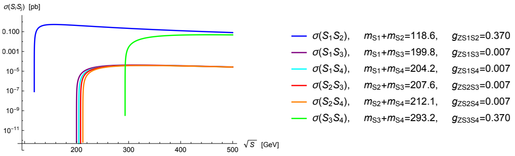


Figure: The $e^+e^- \to Z^* \to S_i S_j$ cross section for BP B with masses in GeV.

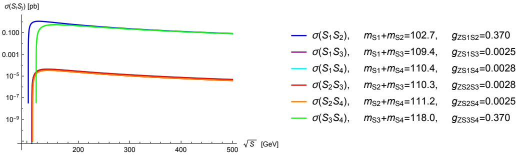


Figure: The $e^+e^- \to Z^* \to S_i S_j$ cross section for BP C with masses in GeV.

Dark CPV observables: the ZZZ vertex

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

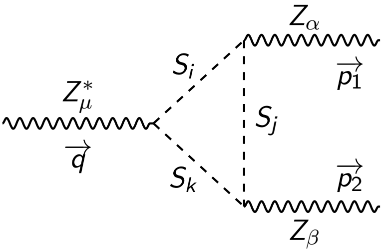
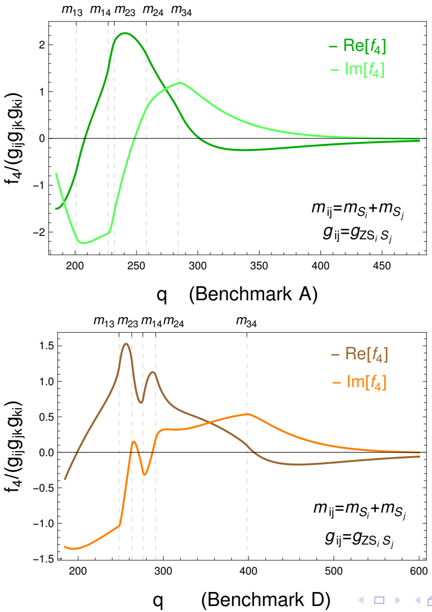


Figure: The one-loop triangle diagram contributing to the f_4^Z factor in the ZZZ vertex, mediated by non-identical scalars S_i, S_j, S_k.

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

f_4 values for exemplary benchmark points



The $f\bar{f} \to Z^* \to ZZ$ cross section

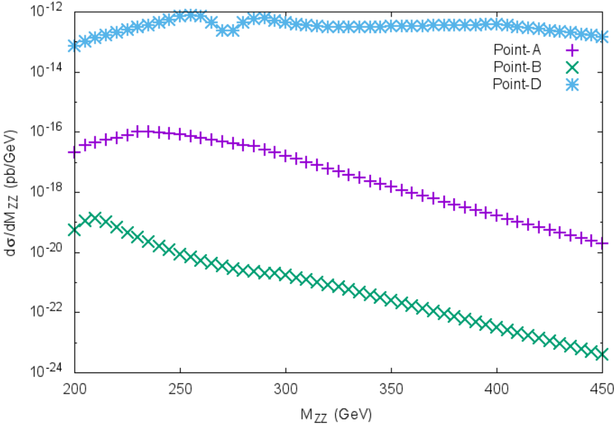


Figure: The differential cross section $d\sigma/dM_{ZZ}$ versus M_{ZZ} for the $q\bar{q} \to Z^* \to ZZ$ process for BPs A, B and D at the 14 TeV LHC.

A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. Moretti, DR-C and D. Sokolowska, [arXiv:2002.04616 [hep-ph]],

(accepted in PRD)

The $f\bar{f} \to Z^* \to ZZ$ cross section

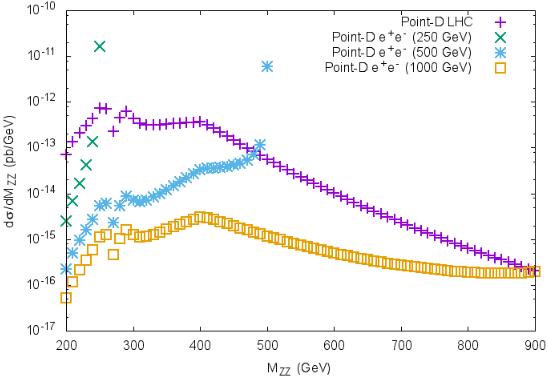


Figure: The differential cr Rojas-Ciofalooss section $d\sigma/dM_{ZZ}$ versus M_{ZZ} for the $f\bar{f} \to Z^* \to ZZ$ process for BP D at the 14 TeV LHC $(f = q)$ and a lepton collider $(f = e)$ with different energies.

A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. Moretti, DR-C and D. Sokolowska, [arXiv:2002.04616 [hep-ph]], (accepted in PRD)

CP-violating asymmetries

- In an $f\bar{f} \to ZZ$ process, the helicities/polarizations of the ZZ pair can be measured statistically from the angular distributions of their decay products.
- With this one can define observables to test CPV at future colliders

One can express the cross-section as:

$$\sigma(f_\delta \bar{f}_{\bar{\delta}} \to Z_\eta Z_{\bar{\eta}}) \;\equiv\; \sigma_{\eta,\bar{\eta}} = \sum_{\delta,\bar{\delta}} \mathcal{M}^{\delta,\bar{\delta}}_{\eta,\bar{\eta}}\,[\Theta]\,\mathcal{M}^{\star\,\delta,\bar{\delta}}_{\eta,\bar{\eta}}\,[\Theta], \qquad (1)$$

where $\delta, \bar{\delta}$ are the helicities of the incoming $f, \bar{f}$ and $\eta, \bar{\eta}$ are the helicities of the outgoing ZZ pair, respectively.
The helicity amplitude is:

$$\mathcal{M}_{f\bar{f}\to ZZ} = \frac{1}{q^2 - M_Z^2}\,\Gamma^{\mu\alpha\beta}_{ZZZ}\,\epsilon^{\alpha}(p_1)\,\epsilon^{\beta}(p_2) j^{\mu}(q) \qquad (2)$$

In the limit of massless fermions: $q_\mu j^\mu = 0$.

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The angle Θ is the angle between the e^- beam and the Z whose helicity is η. For hadron collider $\to$ use of the event boost to define the incoming quark direction.

CP-violating asymmetries

- In an $f\bar{f} \to ZZ$ process, the helicities/polarizations of the ZZ pair can be measured statistically from the angular distributions of their decay products.
- With this one can define observables to test CPV at future colliders
- We introduce the three asymmetries: $A^{ZZ}, \widetilde{A}^{ZZ}$ and A''^{ZZ}
- Since the ZZ are indistinguishable:
  - A_1: forward hemisphere
  - A_2: backward hemisphere
- If the asymmetries in the two hemispheres are not equal, i.e. $A_1 - A_2 \neq 1$, one can confidently claim that the model is CP-violating

Asymmetries

Assuming the momenta and helicities of ZZ are known:

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

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

To lowest order in f_4:

$$A_1^{ZZ} = -4\beta\gamma^4[(1+\beta)^2 - (2\beta\cos\Theta)^2]\mathcal{F}_1(\beta,\Theta)\mathrm{Im}f_4$$

where $\gamma = \sqrt{s}/(2M_Z)$, $\beta = 1 - \gamma^2$.

Assuming the momenta and helicities of ZZ are known:

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

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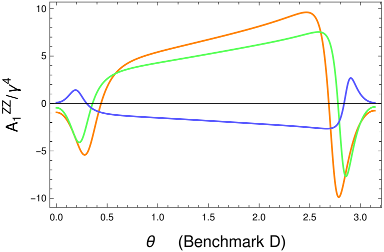
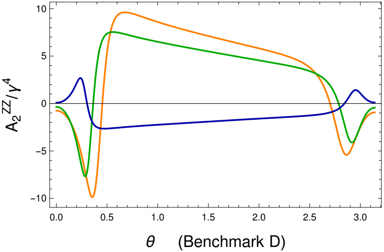
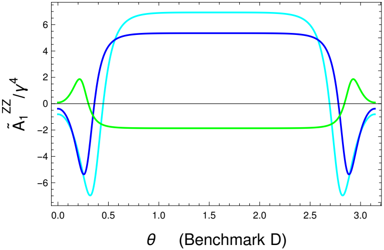
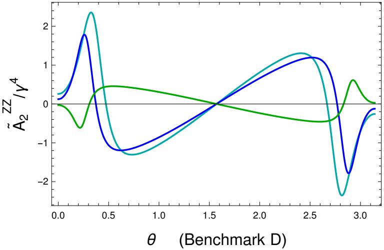




$$A^{ZZ} \equiv \frac{\sigma_{+,0} + \sigma_{0,+} - \sigma_{0,-} - \sigma_{-,0}}{\sigma_{+,0} + \sigma_{0,+} + \sigma_{0,-} + \sigma_{-,0}}, \qquad \tilde{A}^{ZZ} \equiv \frac{\sigma_{+,0} - \sigma_{0,+} - \sigma_{0,-} + \sigma_{-,0}}{\sigma_{+,0} + \sigma_{0,+} + \sigma_{0,-} + \sigma_{-,0}}$$





In the low energy limit, these become:

$$A^{ZZ} \rightarrow \frac{-2\beta(1 - 3\cos^2\Theta)\xi \mathrm{Im} f_4}{1 - 3\cos^2\Theta + 4\cos^4\Theta},$$

$$\tilde{A}^{ZZ} \rightarrow \frac{-2\beta\cos^3\Theta\tilde{\xi}\mathrm{Im} f_4}{1 - 3\cos^2\Theta + 4\cos^4\Theta}.$$

Asymmetries $A_1''^{ZZ}$ and $A_2''^{ZZ}$

Instead of analysing the complicated event topology of the 4-fermion final state from the decays of the Z boson pairs $\rightarrow$ just focus on the decay of one outgoing Z boson and study its density matrix[1]

$$\rho(\Theta)_{\eta,\bar{\eta}} = \frac{1}{\mathcal{N}(\Theta)} \sum_{\delta,\bar{\delta},\eta\prime} \mathcal{M}^{\delta,\bar{\delta}}_{\eta,\eta\prime}(\Theta)\, \mathcal{M}^{*\,\delta,\bar{\delta}}_{\bar{\eta},\eta\prime}(\Theta), \tag{1}$$

where again, $\delta, \bar{\delta}$ are the helicities of incoming $f, \bar{f}$ beam, and the $\eta, \bar{\eta}$ are the helicities of the outgoing Z bosons. $\mathcal{N}$ is a normalisation factor which ensures $\mathrm{Tr}(\rho) = 1$.

[1] D. Chang, W. Y. Keung and P. B. Pal, Phys. Rev. D **51**, 1326 (1995) [hep-ph/9407294].

Asymmetries $A_1''^{ZZ}$ and $A_2''^{ZZ}$

Since the $(+,-)$ or $(-,+)$ components of the spin-density matrix ρ receive the largest CP violating contribution, another observable CP-odd asymmetry is defined as

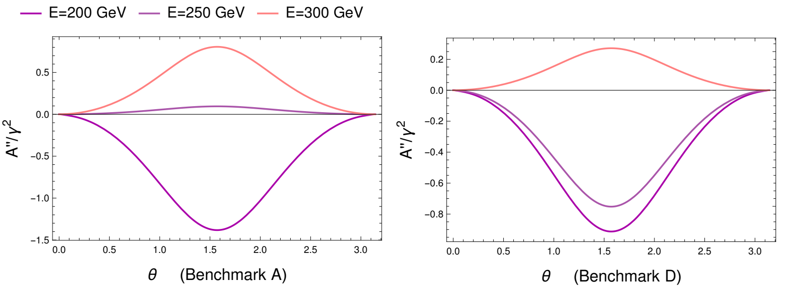
$$A_1'' = -\frac{1}{\pi}[\mathrm{Im}\rho(\Theta)_{+,-}], \qquad A_2'' = \frac{1}{\pi}[\mathrm{Im}\rho(\pi - \Theta)_{-,+}]. \qquad (2)$$

$$\mathcal{A}'' = -\frac{1}{\pi}[\mathrm{Im}\rho(\Theta)_{+,-} - \mathrm{Im}\rho(\pi - \Theta)_{-,+},]$$

which in the low-energy limit simplifies to:

$$\mathcal{A}'' \to \frac{\beta \sin^2 \Theta \xi \mathrm{Re} f_4}{2\pi}.$$

Asymmetries $A_1''^{ZZ}$ and $A_2''^{ZZ}$



$$\mathcal{A}'' = -\frac{1}{\pi}[\mathrm{Im}\rho(\Theta)_{+,-} - \mathrm{Im}\rho(\pi - \Theta)_{-,+},]$$

$$\mathcal{A}'' \to \frac{\beta \sin^2 \Theta \xi \mathrm{Re} f_4}{2\pi}.$$

Summary and Conclusions

- 3HDM can accommodate both a DM candidate and unconstrained CPV source
- The lightest inert is stable due to a Z_2 symmetry
- New regions of DM relic density are opened up by the dark CPV source
- Process $e^+e^- \to Z^* \to S_iS_j$ is a CPV smoking-gun signature that can test also the inert spectrum
- CPV can be analysed through the vertex ZZZ $\Rightarrow$ largest in the 3HDM than in other models
- CPV can be tested by measuring different asymmetries in colliders related to the ZZZ vertex

Thanks for

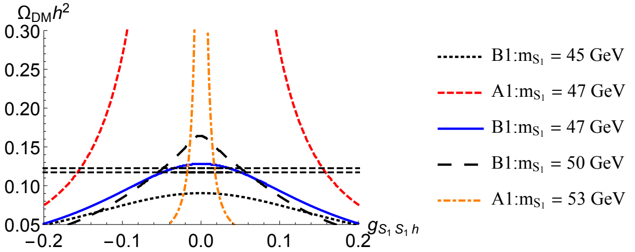
your attention!

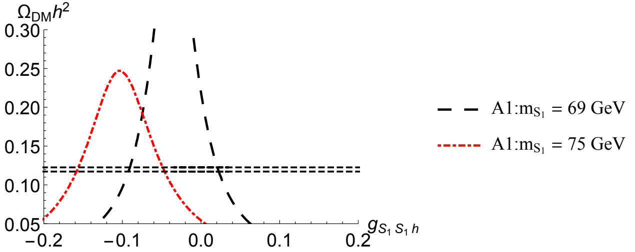
BACKUP

SLIDES

Constraints

- Bounded from below potential $\phi_i \to \infty \Rightarrow V > 0$
- Vacuum stability $E_{v_{EW}} < E_{v_i}$, or $\tau_{V_{EW}} >$ age of universe
- Perturbative unitarity $|\lambda_i| \leq 4\pi$, $|\Lambda_i| \leq 8\pi$
- Electroweak precision observables S, T, U
- Relic density $\Omega_{DM} h^2 = 0.1197 \pm 0.0022$
- Direct and indirect detection $\sigma_{DM,N} \lesssim 10^{-11}$ pb, $\langle \sigma v \rangle \lesssim 10^{-27}$ cm^3/s
- Flavour observables $BR(B \to X_s \gamma)$, $B^0 - \bar{B}^0$ mixing $D_s \to \tau \nu_\tau$, $D_s \to \mu \nu_\mu$, $B \to D \tau \nu_\tau$
- LEP bounds $m_{H^\pm} + m_{H,A} > m_{W^\pm}$, $m_H + m_A > m_Z$, $2m_{H^\pm} > m_Z$, $m_{H^\pm} \gtrsim 70 - 90$ GeV if $m_H < 80$ GeV and $m_A < 100$ GeV $\Rightarrow m_A - m_H < 8$ GeV
- LHC bound total decay signal strength $\frac{BR(h \to XX}{BR(h_{SM} \to XX} = 1.17 \pm 0.17$
- $h \to \gamma\gamma$ signal strength $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$
- Higgs invisible decays $BR(h \to S_i S_j) < 0.23 - 0.36$

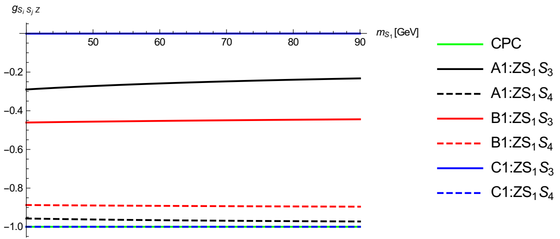

$\Omega_{DM}h^2$
0.30
0.25
0.20
0.15
0.10
0.05
−0.2
−0.1
0.0
0.1
0.2
$g_{S_1 S_1 h}$
B1:m$_{S_1}$ = 45 GeV
A1:m$_{S_1}$ = 47 GeV
B1:m$_{S_1}$ = 47 GeV
B1:m$_{S_1}$ = 50 GeV
A1:m$_{S_1}$ = 53 GeV


$\Omega_{DM}h^2$
0.30
0.25
0.20
0.15
0.10
0.05
−0.2
−0.1
0.0
0.1
0.2
$g_{S_1 S_1 h}$
A1:m$_{S_1}$ = 69 GeV
A1:m$_{S_1}$ = 75 GeV

Z-inert couplings

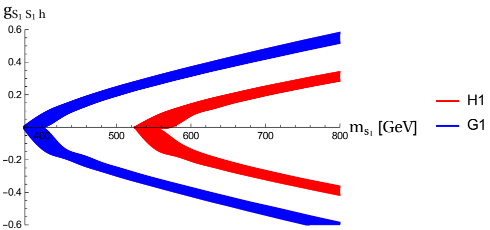
$$\chi_{ZS_1S_3} = \chi_{ZS_2S_4} = \frac{\alpha+\beta}{\sqrt{\alpha^2+1}\sqrt{\beta^2+1}}, \qquad \chi_{ZS_1S_4} = \chi_{ZS_2S_3} = \frac{\alpha\beta-1}{\sqrt{\alpha^2+1}\sqrt{\beta^2+1}}$$

$$\chi^2_{ZS_1S_3} + \chi^2_{ZS_1S_4} = 1, \qquad \chi^2_{ZS_2S_3} + \chi^2_{ZS_2S_4} = 1$$



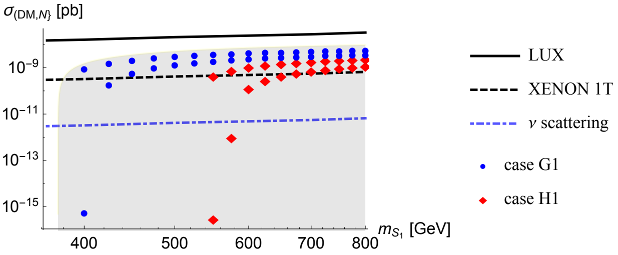
- mass order: $m_{S_1} < m_{S_3} < m_{S_4} < m_{S_2}$
- CPC limit: $\chi_{ZS_1S_3} = -1$, $\chi_{ZS_1S_4} = 0$
- $\chi_{ZS_1S_3}$: reduced for A1 and B1
- $\chi_{ZS_1S_4}$: close to CPC value, dominant channel for C1

Heavy Dark Matter in the I(2+1)HDM



- $g_{S_1 S_1 h}$ in case G $>$ $g_{S_1 S_1 h}$ in case H
- The same behaviour in both cases
- Lower m_{S_1} for case G
- Not really different from the CPC case

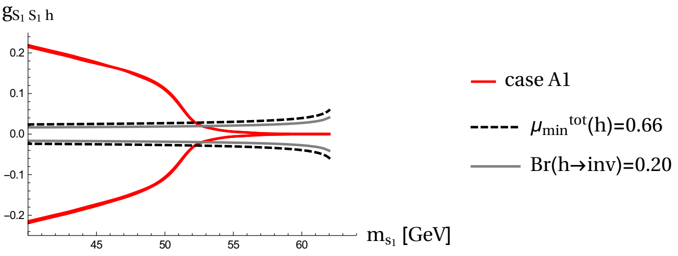
Direct detection CPV model - heavy case

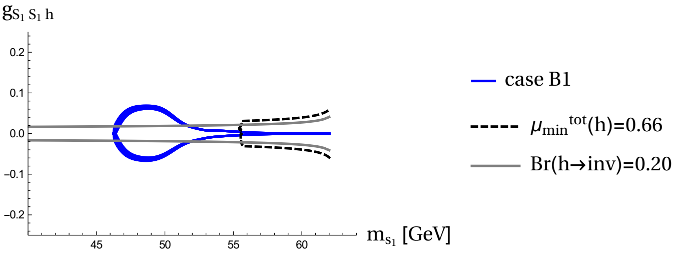


$$\sigma_{DM,N} \propto \frac{g^2_{S_1 S_1 h}}{(M_{S_1} + M_N)^2}$$

- In agreement with LUX
- Within the reach of XENON-1T
- case G (bigger couplings) easier to see/exclude than case H (smaller couplings)

Planck vs LHC





If the only invisible channel is $h \to S_1 S_1$:

$$Br(h \to inv.) = \frac{\Gamma(h \to S_1 S_1)}{\Gamma_h^{\mathrm{SM}} + \Gamma(h \to S_1 S_1)}. \tag{2}$$

If particles $S_{2,3,4}$ are long-lived enough (i.e with $\Gamma_{\text{tot}} \leq 6.58 \times 10^{-18}$ GeV $\Leftrightarrow \tau \geq 10^{-7}\, s$), they will not decay inside the detector, therefore seen as Higgs decays $h \to S_i S_i$, then

$$Br(h \to inv.) = \frac{\sum_i \Gamma(h \to S_i S_i)}{\Gamma_h^{\mathrm{SM}} + \sum_i \Gamma(h \to S_i S_i)}. \tag{3}$$

Searches at the LHC for neutral, long-lived particles have historically relied on the detection of displaced particles produced by their decay *within* the detector.
But we can use a recent study [ref] in where the case of the particle decaying *outside* the detector is included.