Dark CP violation through the Z portal

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Based on [arXiv:1909.XXXX]

Scalars, 13 Sep 2019

1. Introduction and motivation
2. 3 Higgs doublet models (3HDM)
3. CP violating DM
4. CP violating observables
5. Summary

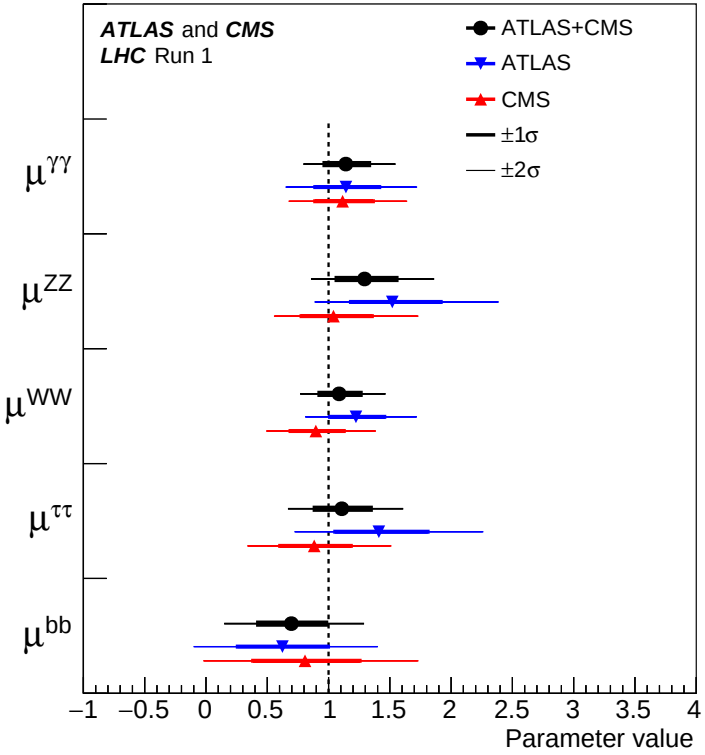
Standard Model and beyond

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!

Scalar extensions with or without a Z_2 symmetry:

- SM + scalar singlet(s)
  - ϕ_{SM}, S $\Rightarrow$ DM, ~~CPV~~
  - ϕ_{SM}, S_1, S_2 $\Rightarrow$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: ϕ_1, ϕ_2 $\Rightarrow$ CPV, ~~DM~~
  - IDM - I(1+1)HDM: ϕ_1, ϕ_2 $\Rightarrow$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: ϕ_1, ϕ_2, ϕ_3 $\Rightarrow$ CPV, ~~DM~~
  - I(1+2)HDM: ϕ_1, ϕ_2, ϕ_3 $\Rightarrow$ DM, CPV
  - I(2+1)HDM: ϕ_1, ϕ_2, ϕ_3 $\Rightarrow$ CPV, DM

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)

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

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]

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 the universe
- Perturbative unitarity: $|\lambda_i| \leq 4\pi,\; |\Lambda_i| \leq 8\pi$
- Electroweak precision observables: $S,\; T,\; U$parameters
- Relic density: $\Omega_{DM}\, h^2 \;=\; 0.1197 \pm 0.0022$
- Direct and indirect detection: $\sigma_{DM,N} \lesssim 10^{-11}$ pb

  $\langle \sigma v \rangle \lesssim 10^{-27}\, cm^3/s$

Constraints

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

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

  if $M_H < 80$ GeV and $M_A < 100$ GeV $\Rightarrow M_A - M_H < 8$ GeV

- LHC bound on the total decay signal strength:

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

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

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

Setting Higgs portal couplings to zero

- **annihilation processes:**

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

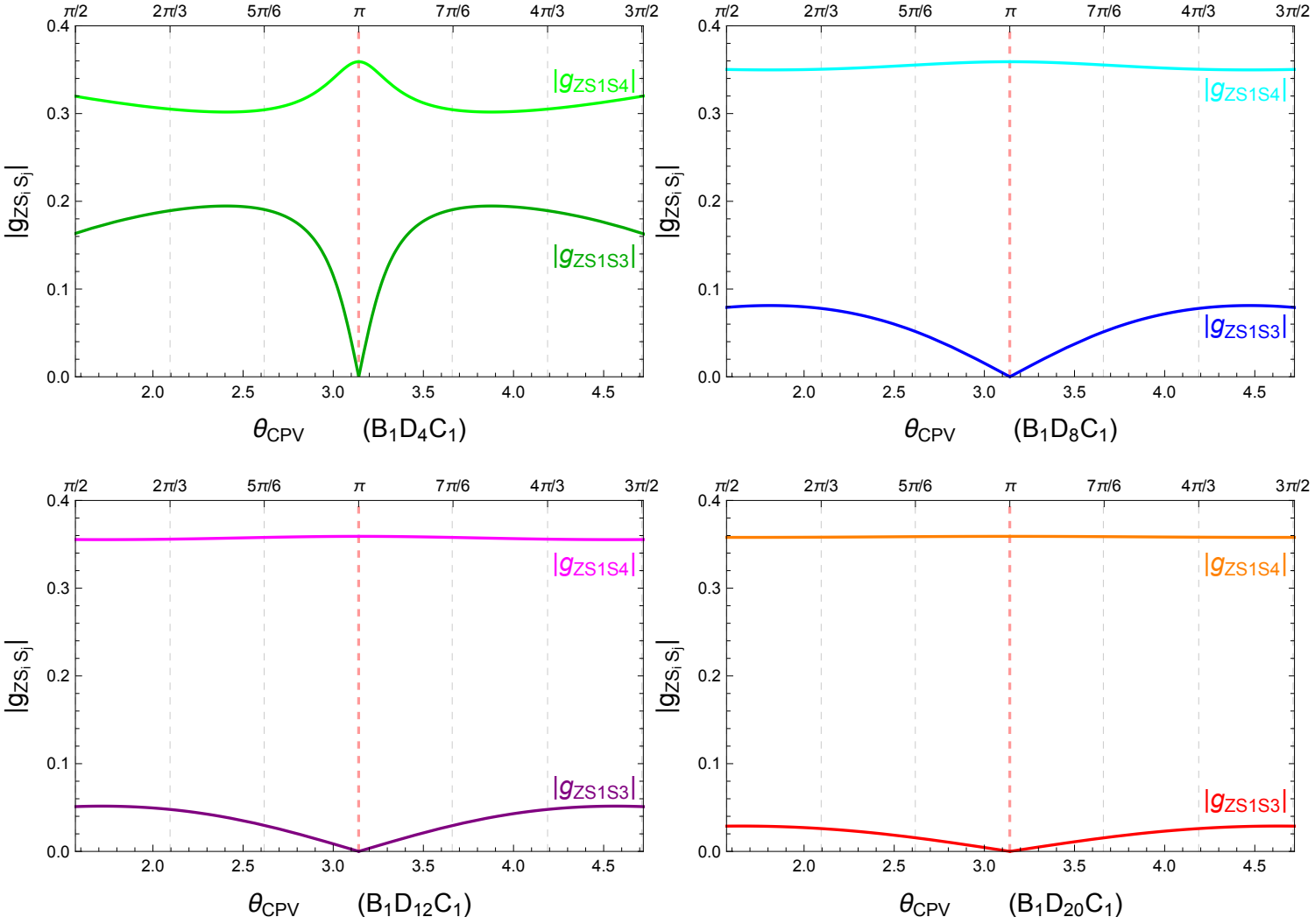
- **co-annihilation processes:**

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

- **(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: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm} \sim m_{S_2^\pm}$



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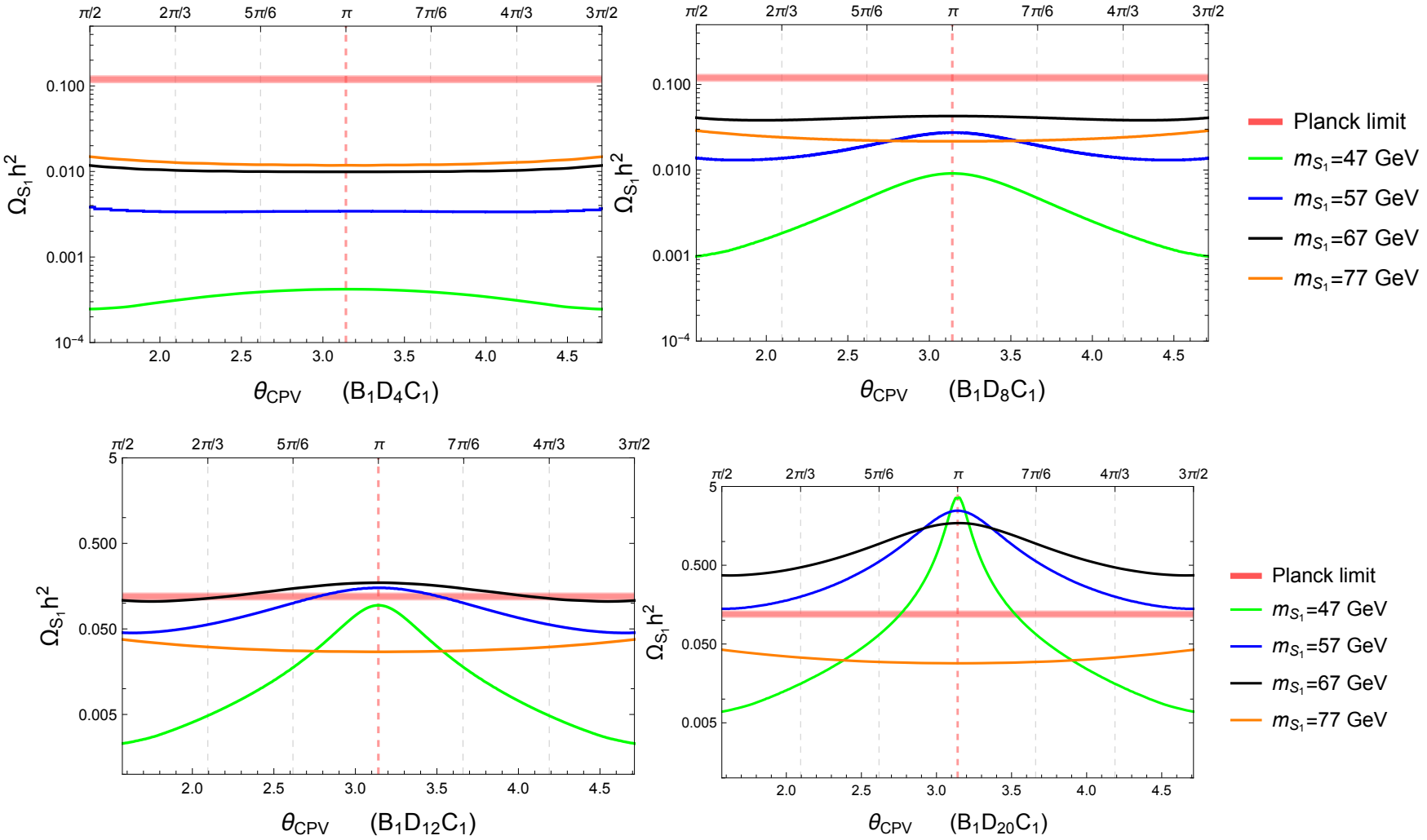

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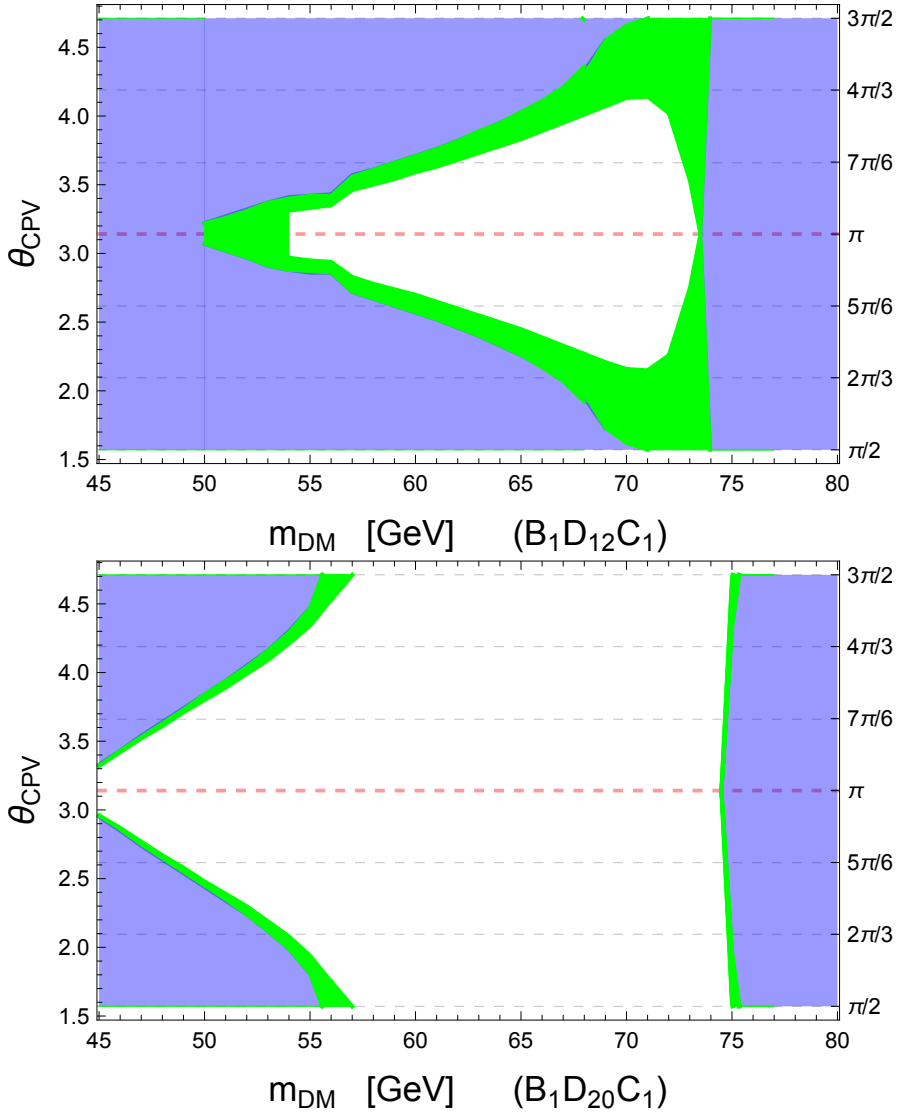
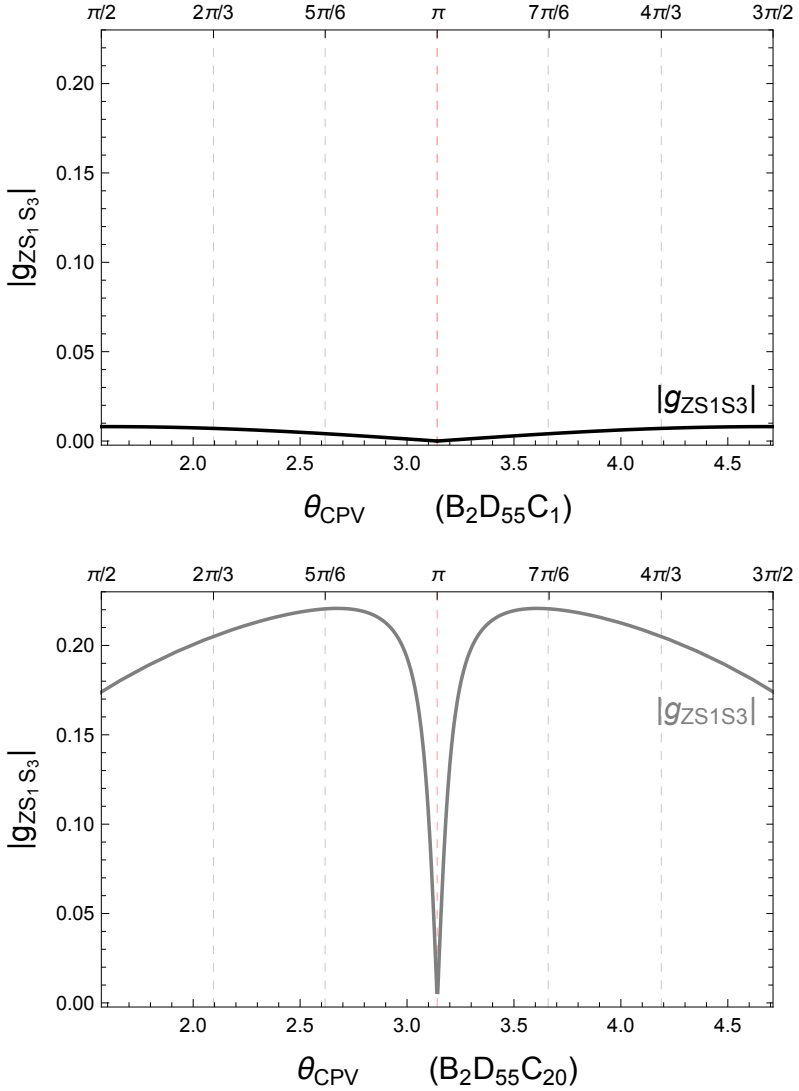


Type 2 benchmarks: $m_{S_1} \sim m_{S_3} \ll m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$



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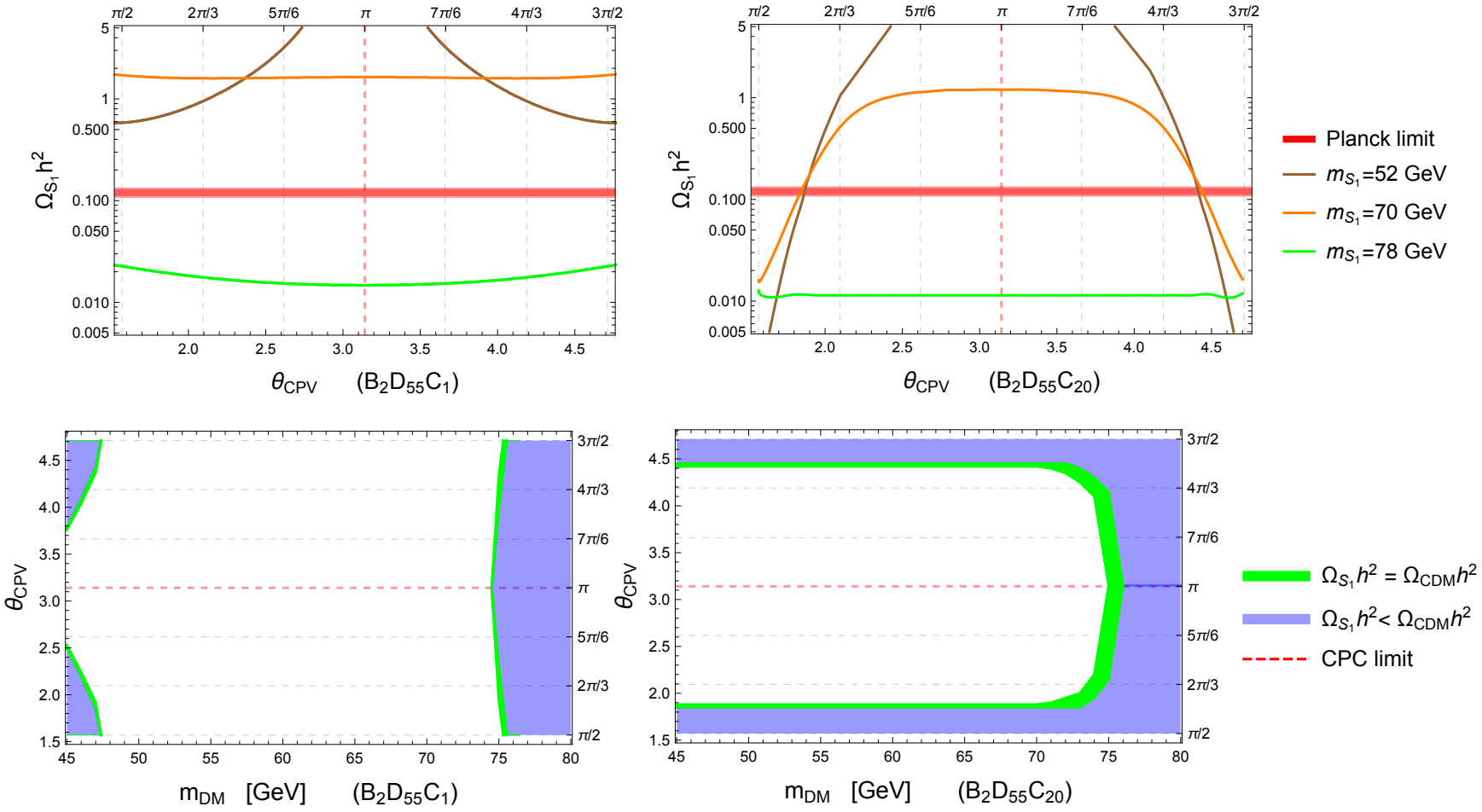
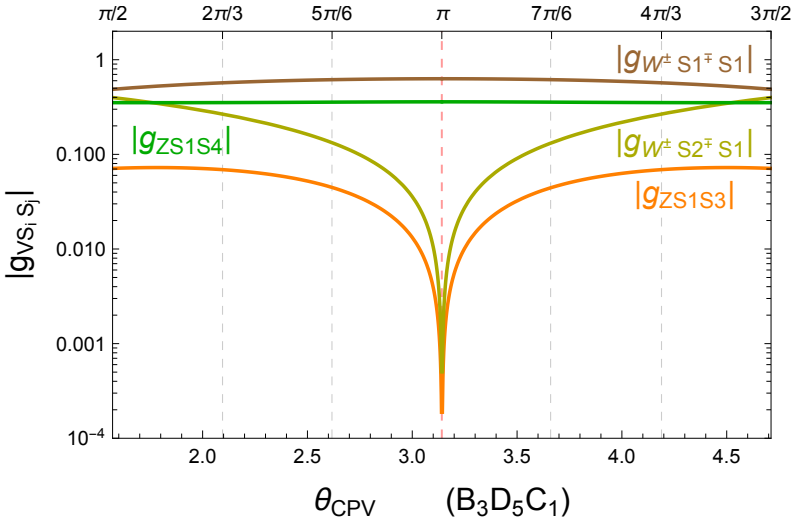
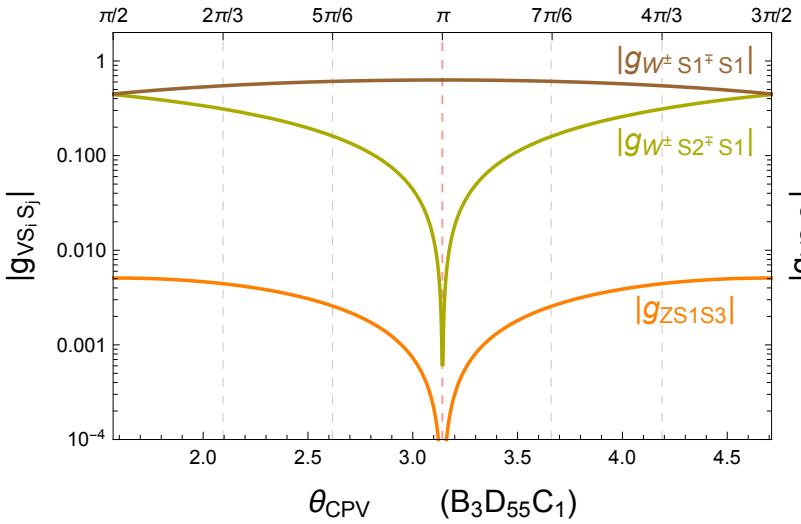
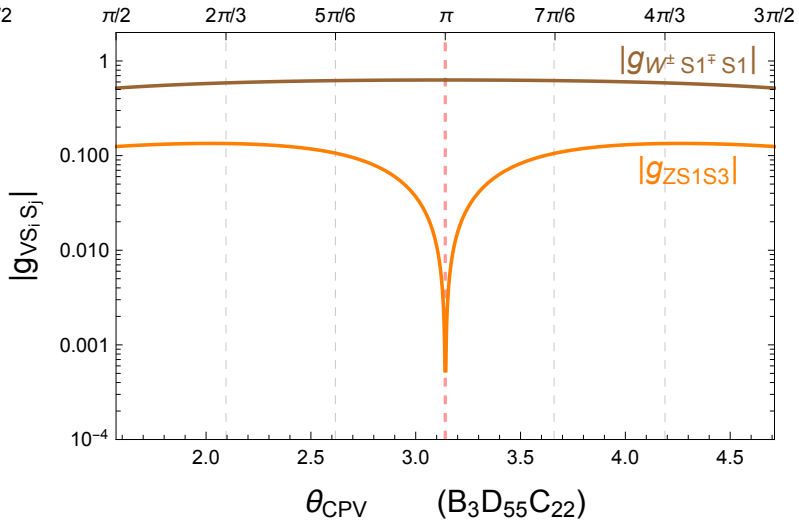


Type 3 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \sim m_{S_1^\pm} \sim m_{S_2^\pm}$







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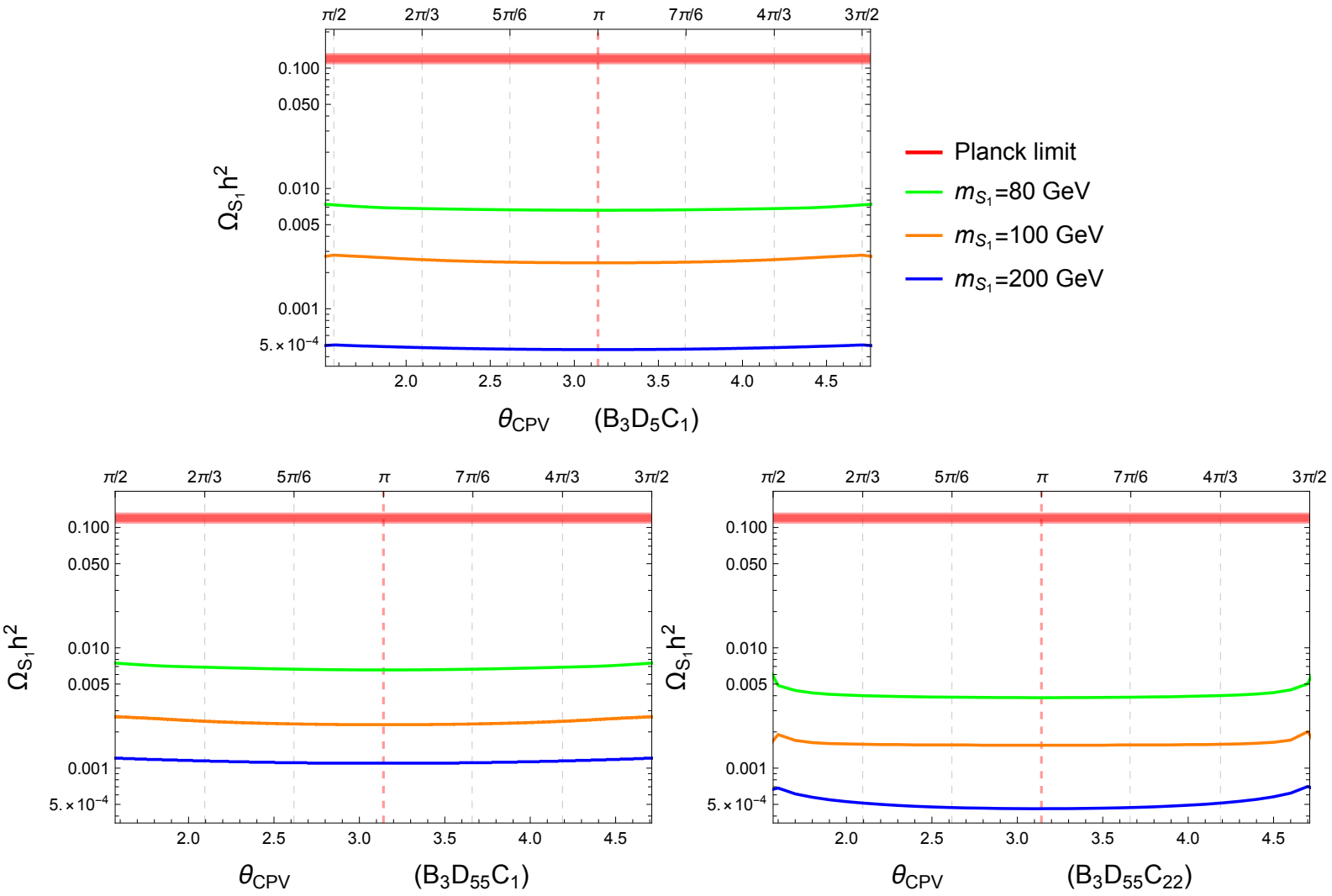
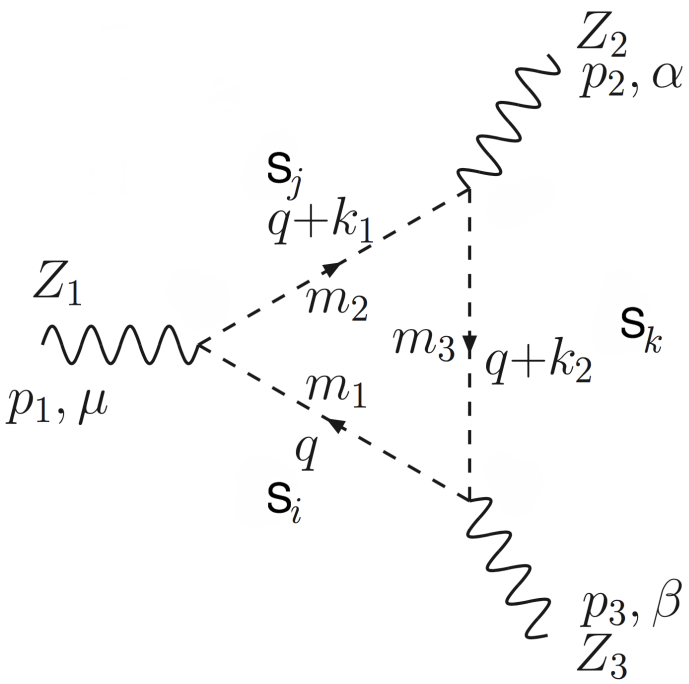


Dark CPV observables: the ZZZ vertex

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



$$f_4 = \frac{M_Z^2|g_{Zs_2s_3}|\,|g_{Zs_1s_3}|\,|g_{Zs_1s_2}|}{2\pi^2 e(q^2 - M_Z^2)} \sum_{i,j,k}^{4} \epsilon_{ijk} C_{002}(M_Z^2, M_Z^2, q^2, m_i^2, m_j^2, m_k^2)$$

JHEP1605,025(2016)

Summary

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BACKUP SLIDES

The CP-mixed mass eigenstates

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The mass eigenstates

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

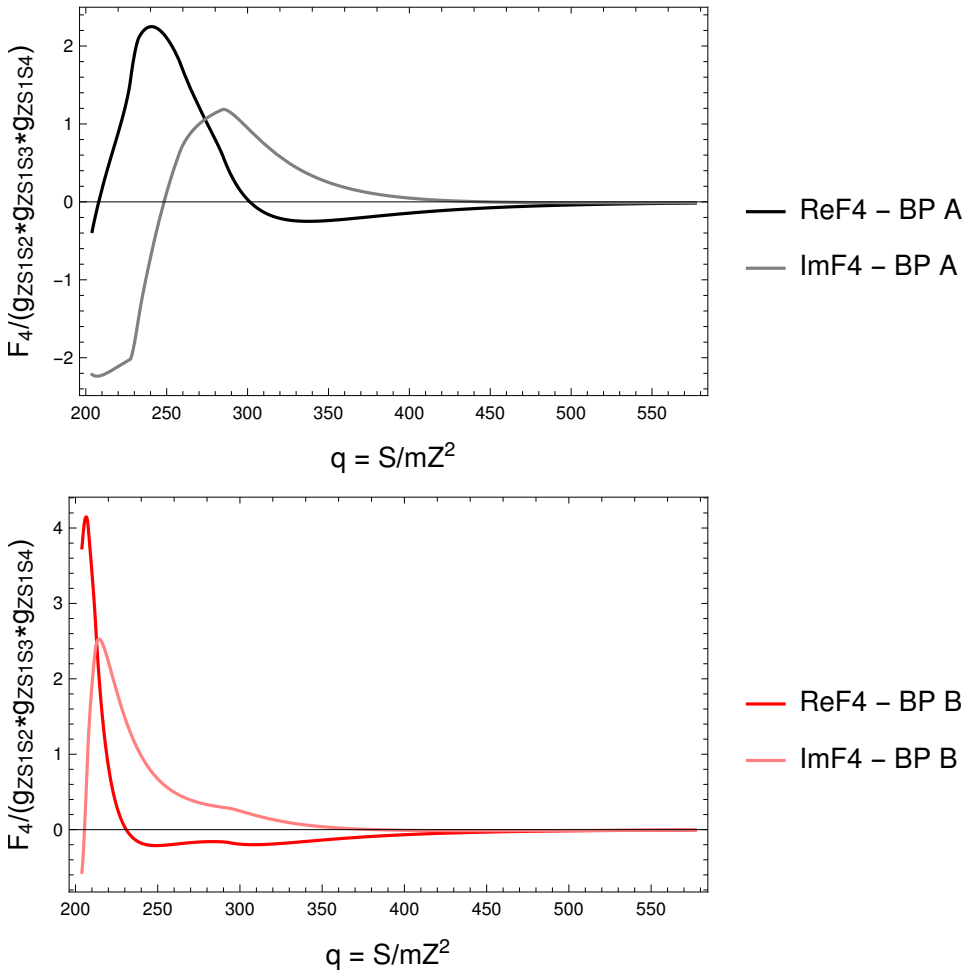
$$S_3 = \frac{\beta H_1^0 - \beta H_2^0 + A_1^0 + A_2^0}{\sqrt{2\beta^2+2}}, \quad S_4 = \frac{-H_1^0 + H_2^0 + \beta A_1^0 + \beta A_2^0}{\sqrt{2\beta^2+2}}$$

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

S_1 is assumed to be the DM candidate

[JHEP 1612 (2016) 014]

f_4 values for exemplary benchmark points

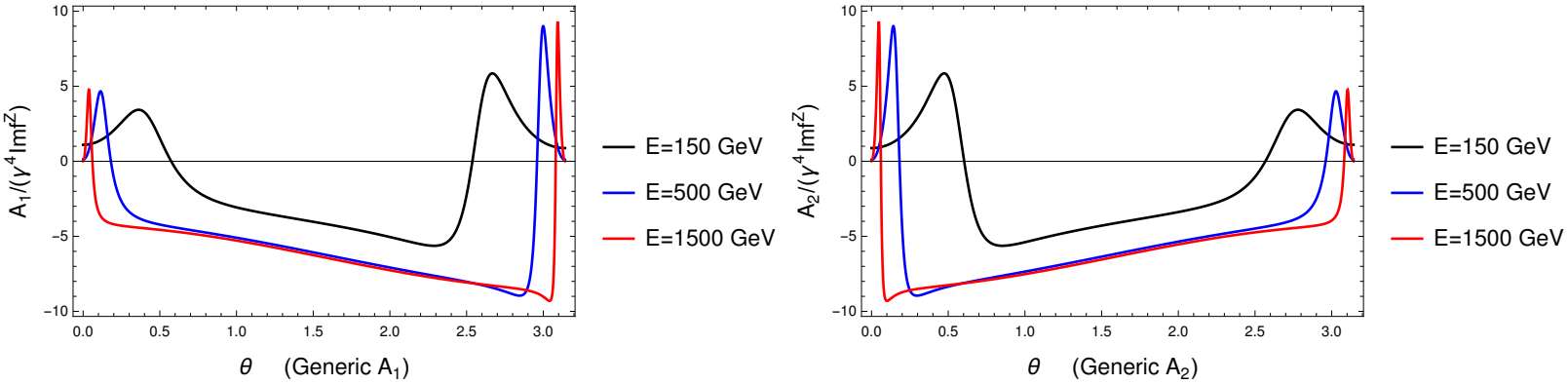


A_1 and A_2 asymmetries in $f\bar{f} \to ZZ$

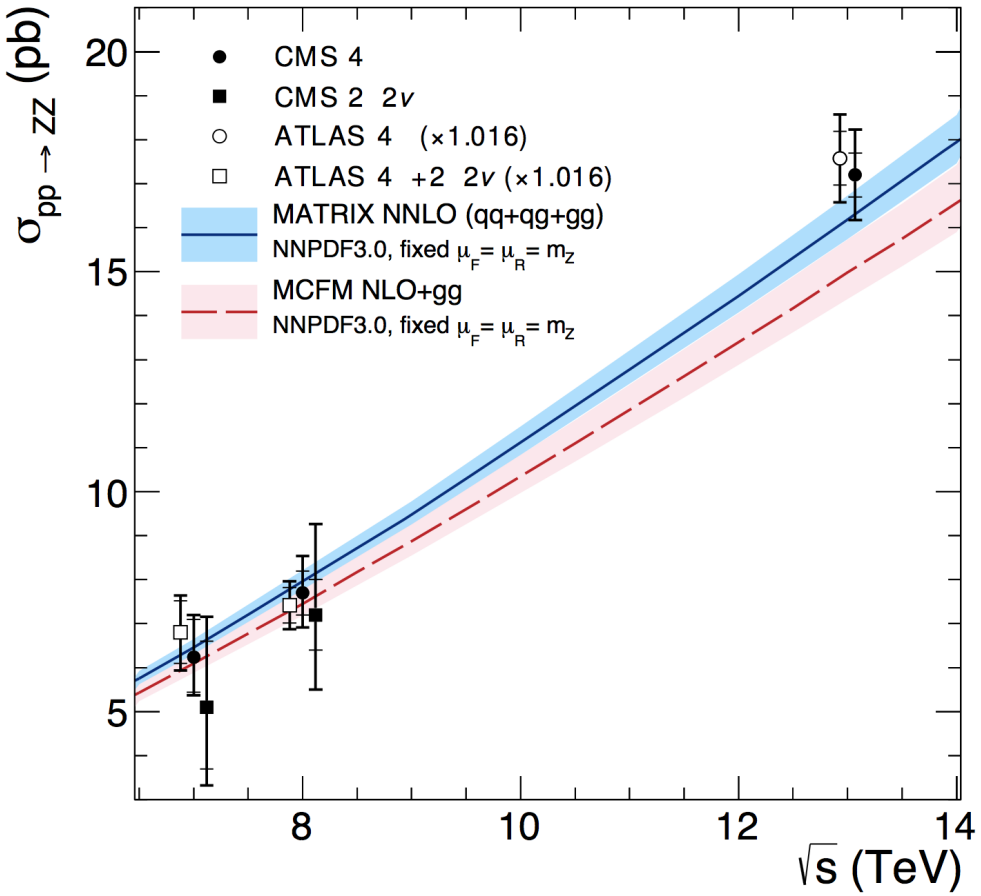
Assuming the momenta and helicities of ZZ are known:

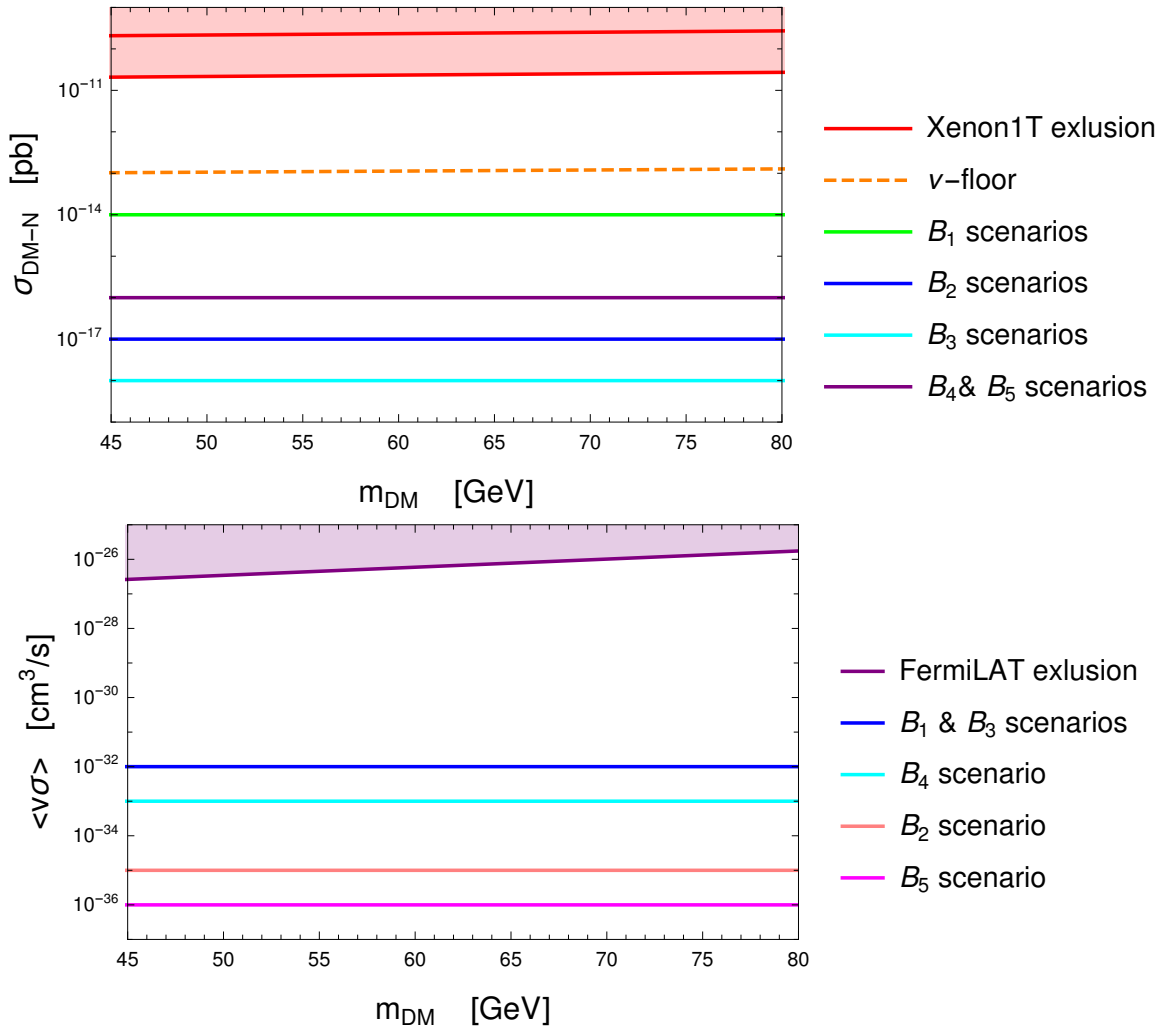
$$A_1^{ZZ} \equiv \frac{\sigma_{+,0} - \sigma_{0,-}}{\sigma_{+,0} + \sigma_{0,-}}, \quad A_2^{ZZ} \equiv \frac{\sigma_{0,+} - \sigma_{-,0}}{\sigma_{0,+} + \sigma_{-,0}},$$

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



$pp \to ZZ$ at CMS



[Eur.Phys.J. C78 (2018) 165]

Typical cross sections for DD and ID experiments