Probing Extended Higgs Sectors through Zh production

Juhi Dutta

based on

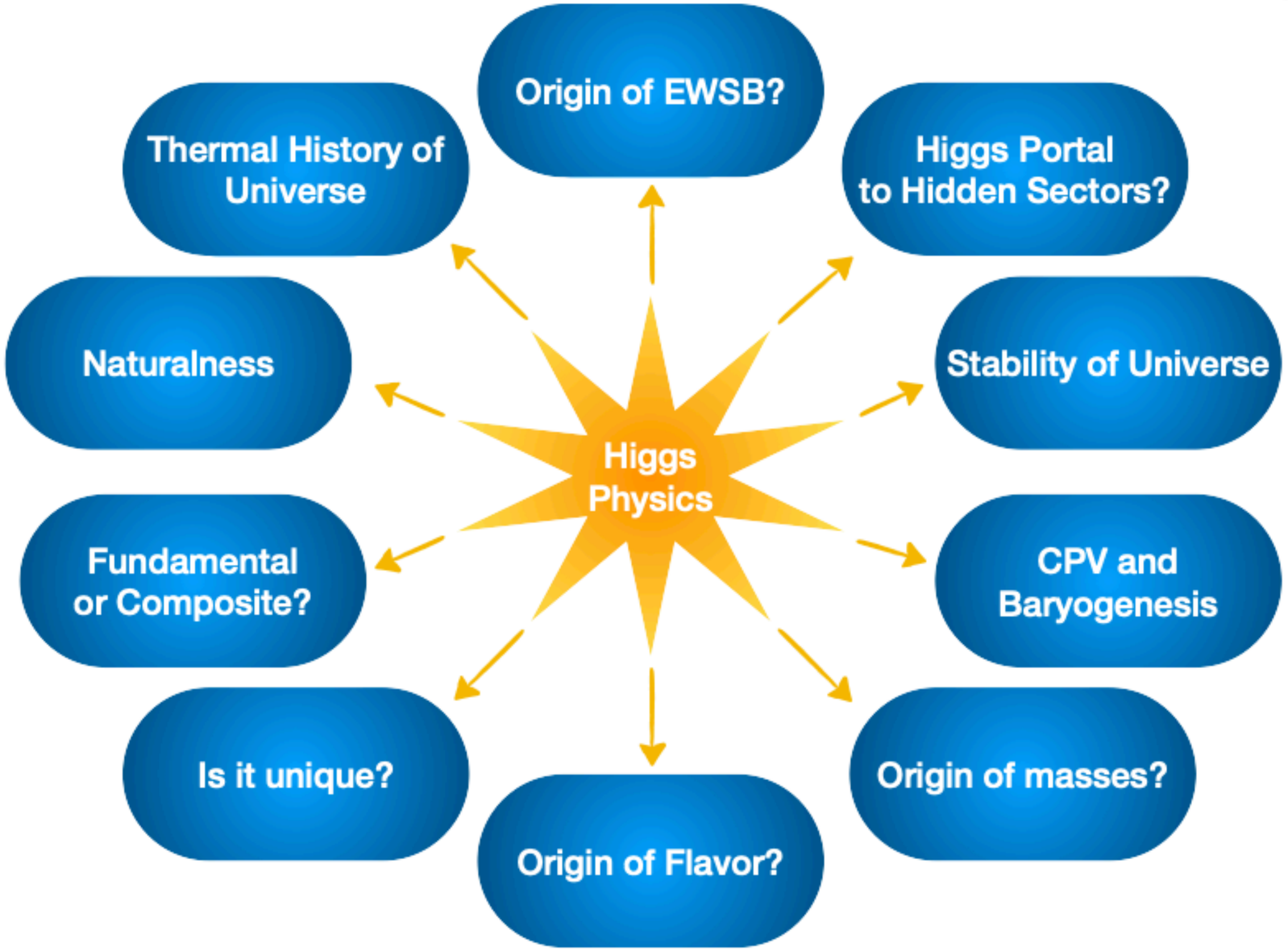
Eur. Phys. J. C 86, 1295 (2026)

with P.M.Ferreira, S.Heinemeyer

International Workshop on Future Linear Colliders 2026 (LCWS2026), KEK, Japan

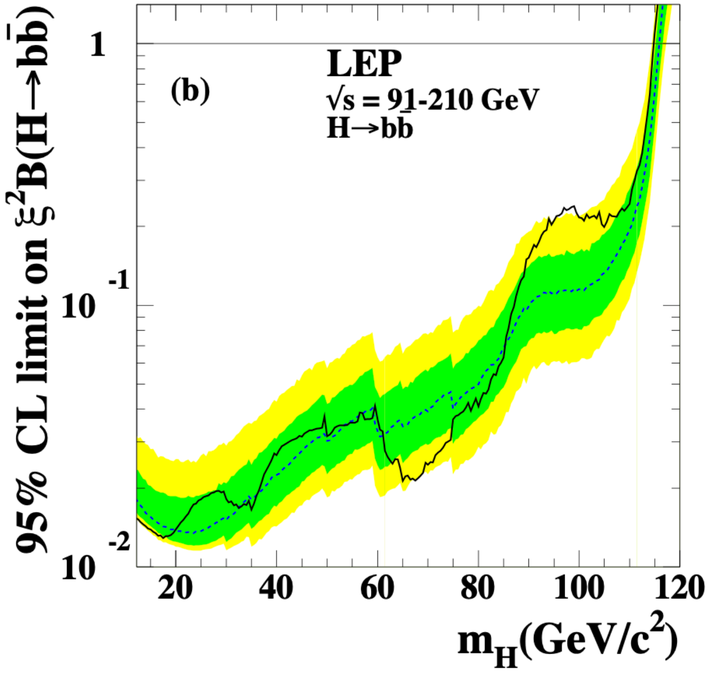
November 12, 2026

Higgs(es) as a window to New Physics?



Snowmass 2021
arXiv:2209.07510

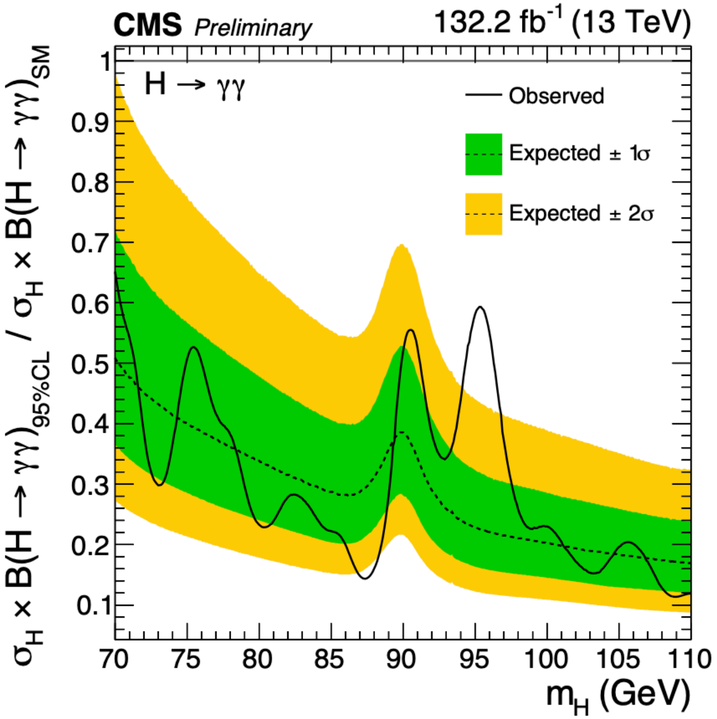
A ~95 GeV excess



$$\xi^2 = (g_{\mathrm{HZZ}}/g^{\mathrm{SM}}_{\mathrm{HZZ}})^2$$

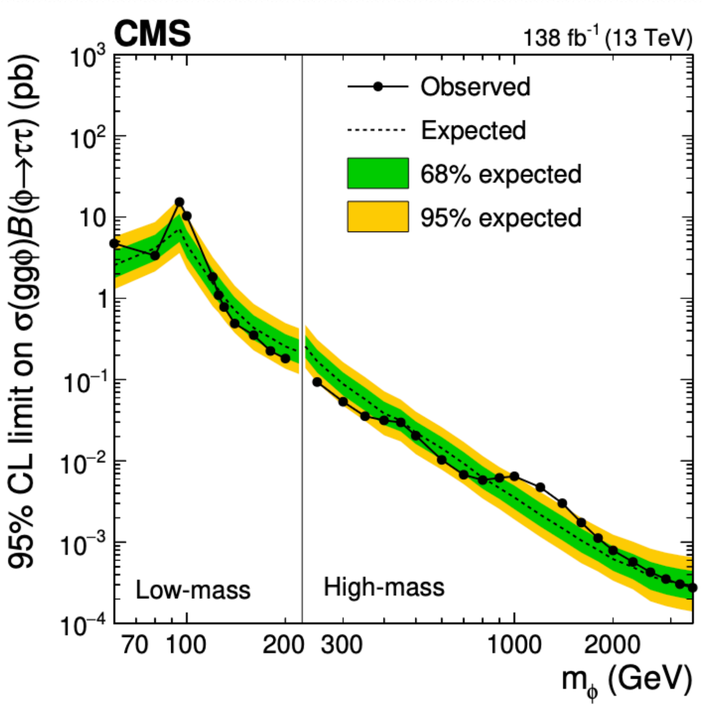
~2 σ excess in $b\bar{b}$ mode around 95 GeV

$$\mu^{b\bar{b}}_{\mathrm{LEP}} = 0.117^{+0.057}_{-0.057},$$



$$\mu^{\mathrm{CMS}}_{\gamma\gamma} = \frac{\sigma^{\mathrm{exp}}\,(pp \to \phi \to \gamma\gamma)}{\sigma^{\mathrm{SM}}\,(pp \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

~2.9 σ excess in $\gamma\gamma$ mode.



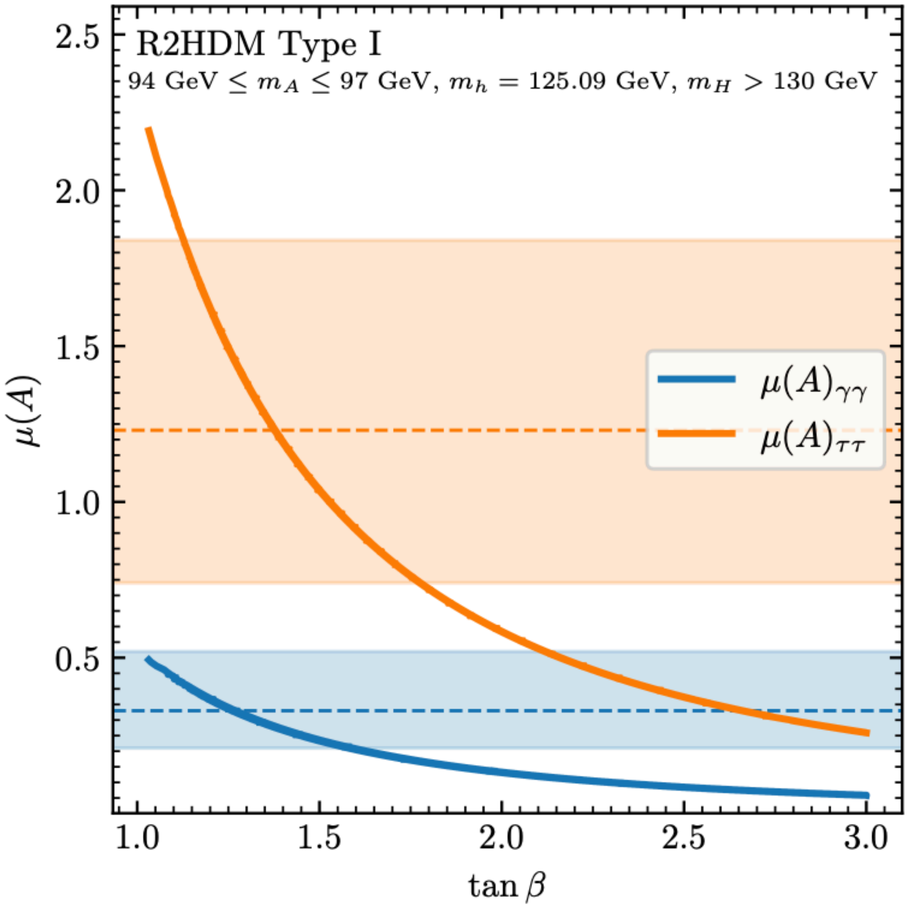
$$\mu^{exp}_{\tau\tau} = 1.2 \pm 0.5.$$

~2.6 σ excess in $\tau\tau$ mode.

- CMS observed a 2.9σ local excess at 95.4 GeV in di-photon searches. CMS-PAS-HIG-20-002
- ATLAS found a 1.7σ excess at 95.4 GeV in their full Run 2 result. ATLAS-CONF-2023-035
- Combined results show a 3.1σ local significance with the signal strength $\mu_{\gamma\gamma}^{exp} = 0.24^{+0.09}_{-0.08}$. Phys.Rev.D 109 (2024) 3, 035005
- Di-tau excess observed at 2.6σ local significance at CMS at 95.4 GeV with the signal strength $\mu_{\tau\tau}^{exp} = 1.2 \pm 0.5$. https://doi.org/10.1007/JHEP07(2023)073
- Extra pseudoscalar as in extended Higgs sector models may address the di-photon and di-tau excess.

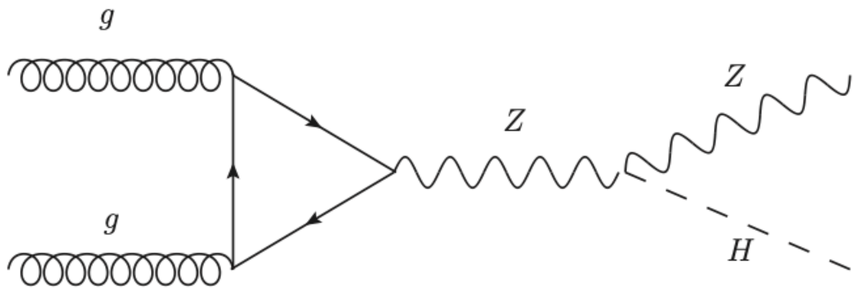
Signal rates for the diphoton and ditau excesses vs tan β for a 95 GeV pseudoscalar within the Type I 2HDM.

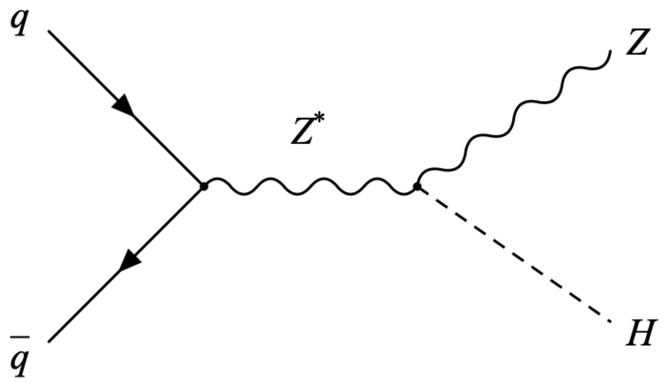
***JHEP* 11 (2023) 017**

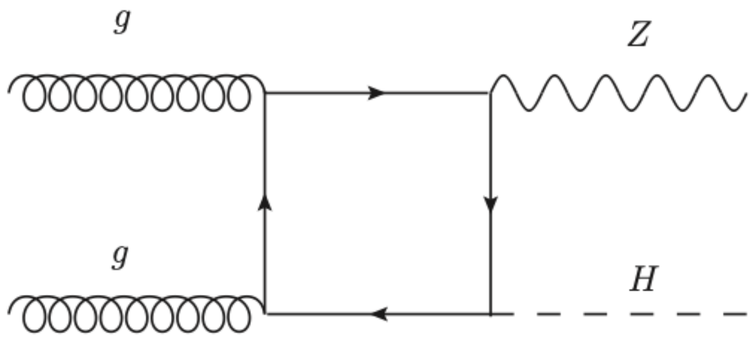


Can a pseudoscalar show up indirectly via known SM processes, such as Zh?

Zh process in the Standard Model







ATLAS measurement of Zh cross-section at 13 TeV : $\sigma(pp \to Zh)^{\text{ATLAS}} = 0.80 \pm 0.14\,\text{pb}$,

ATLAS-CONF-2025-006

HL-LHC predicts ~7% precision at 14 TeV. https://cds.cern.ch/record/2927842

The Model

- Consider a softly broken Z_2 (to avoid FCNC) symmetric Type I 2HDM.

$$
\begin{aligned}
V_{\text{2HDM}} = & \, m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\
& + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
& + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right]
\end{aligned}
$$

$$
\Phi_i = \begin{pmatrix} \phi_i^\pm \\ \frac{1}{\sqrt{2}} (v_i + \rho_i + i\eta_i) \end{pmatrix}
$$

$$
\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2
$$

$$
\mathcal{L}_{\text{Yukawa}}^{I} = -(y_u^{ij} Q_i \tilde{\Phi}_2 u_j + y_d^{ij} Q_i \Phi_2 d_j + y_l^{ij} L_i \Phi_2^{ij} l_j) + \text{ h.c.}
$$

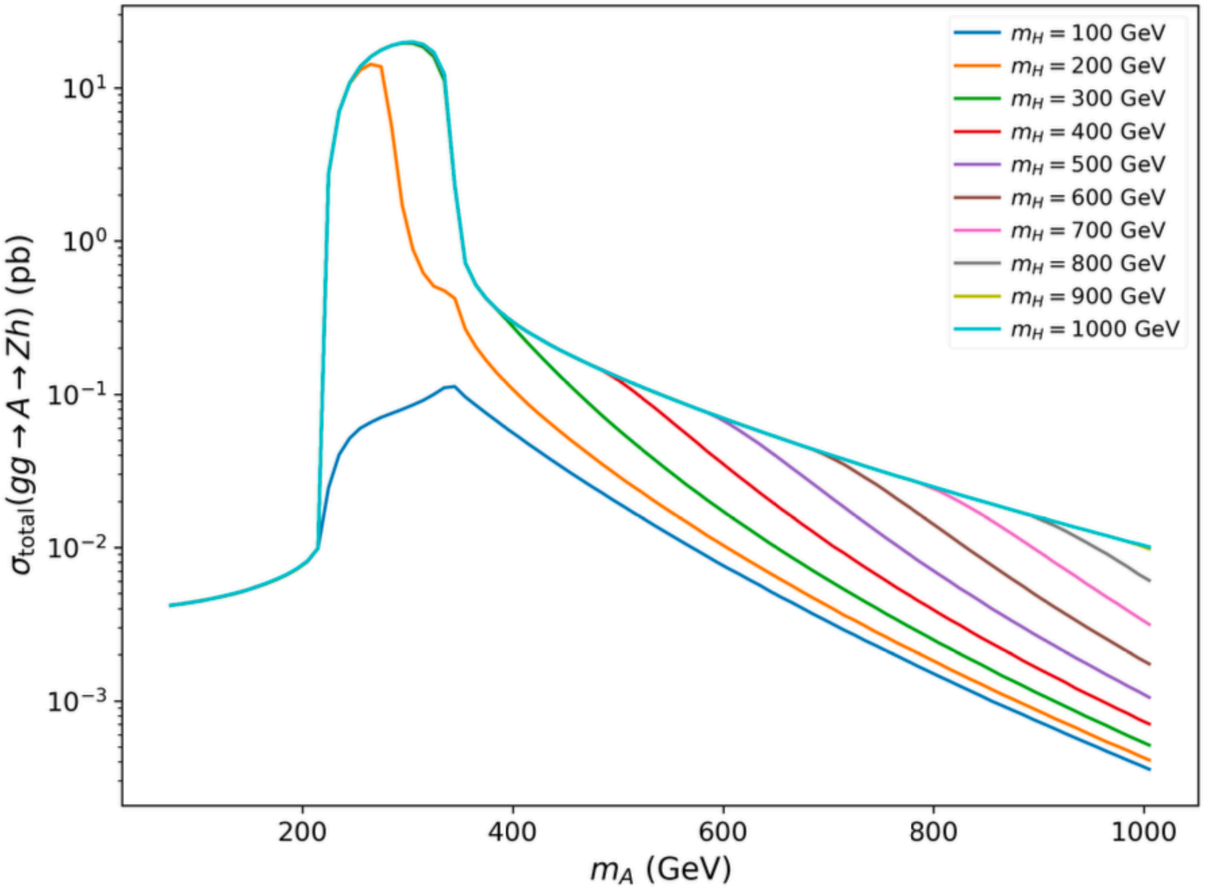
$$
\mathcal{L}_{\text{Yukawa}}^{II} = -(y_u^{ij} Q_i \tilde{\Phi}_2 u_j + y_d^{ij} Q_i \Phi_1 d_j + y_l^{ij} L_i \Phi_1^{ij} l_j) + \text{ h.c.}
$$

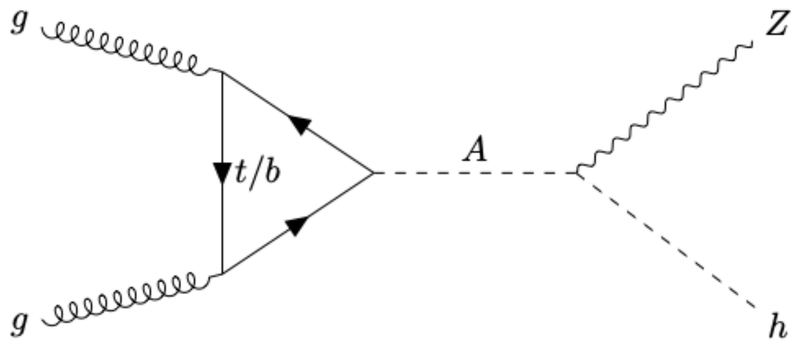
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1

- **Particle Spectra:** $h, H, A, H^\pm$
- **Free parameters:** $\tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}, m_{12}^2$

Production cross-section gg -> A -> Zh

$gg \to A \to Zh$





$$A\,\overline{f}\,\gamma_5\,f : \xi_A^f\,\frac{m_f}{v},$$

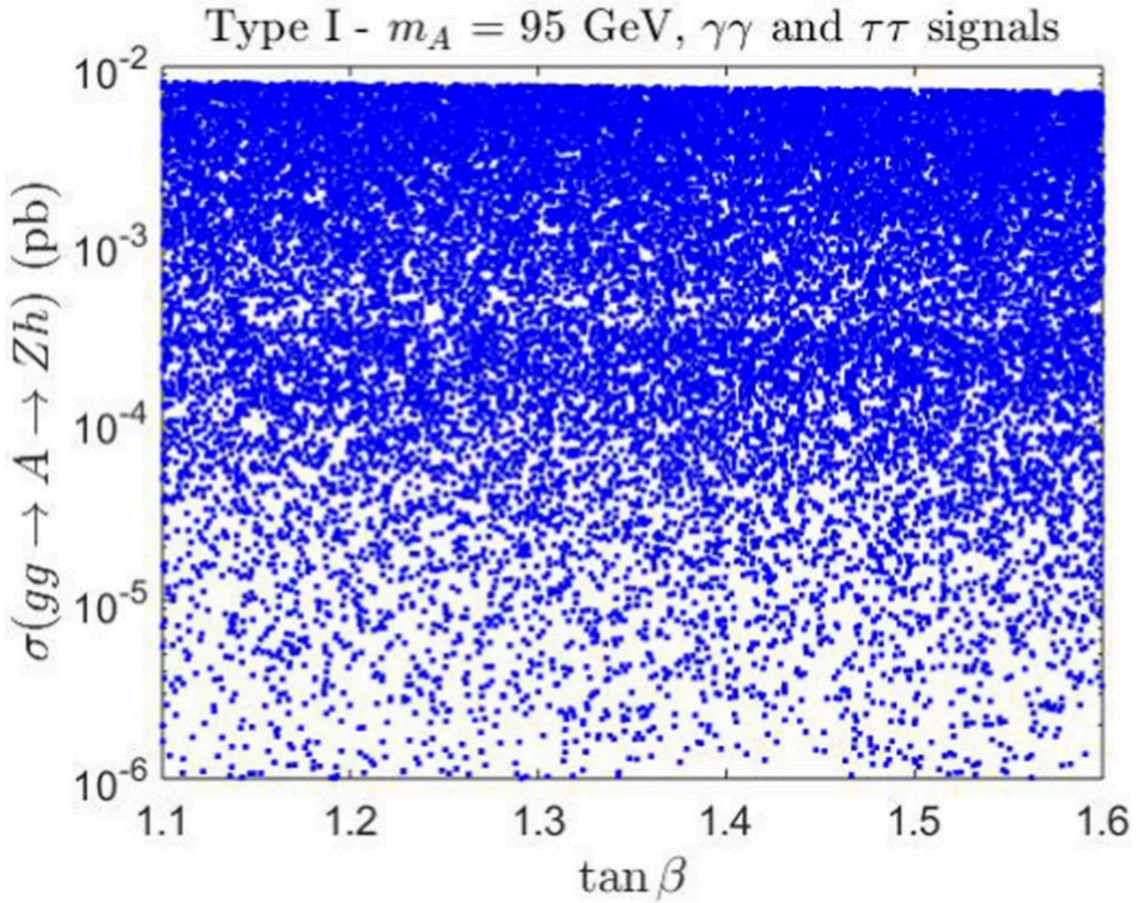
$$A\,h\,Z_\mu : \frac{g}{2\cos\theta_W}\,\xi_A^{Zh}\,(p_h - p_A)_\mu$$

$$\xi_A^{Zh} = \cos(\beta - \alpha)$$

for $\tan\beta = 1, \cos(\beta - \alpha) = 0.1$

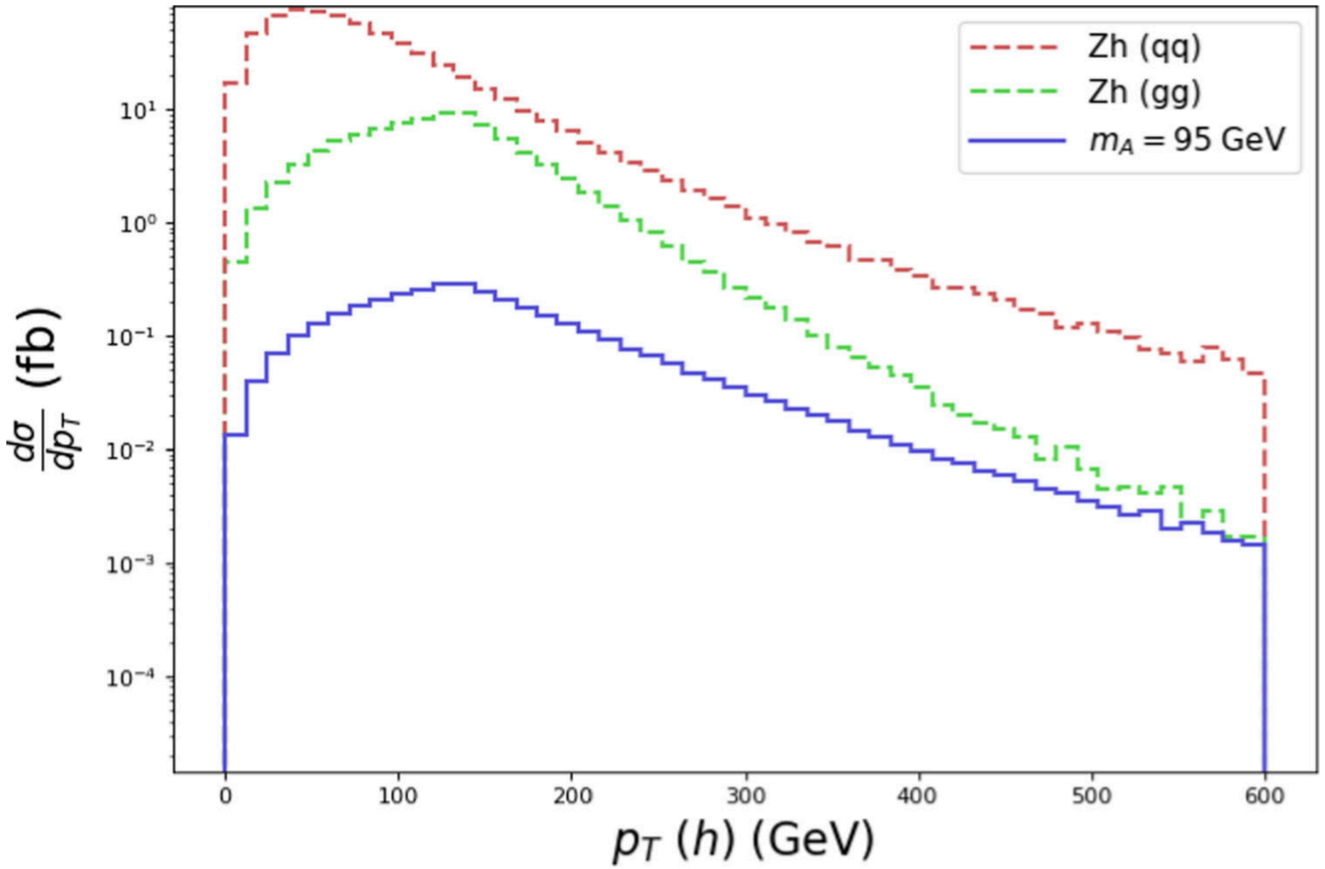
$$\sigma(gg \to A \to Zh) = 100\left(\sigma_t\,\xi_A^{t\,2} + \sigma_b\,\xi_A^{b\,2} + \sigma_i\,\xi_A^t\xi_A^t\right)\xi_A^{Zh\,2}$$

Can a pseudoscalar at 95 GeV affect Zh?



Contribution to Zh production via gluon fusion to a pseudoscalar at LHC, for m A = 95 GeV, as a function of tan β. The cross section is computed at NNLO.

Kinematic distributions



Distributions of the transverse momentum of the Higgs (identical at LO to that of Z) from the signal and background for mA = 95 GeV.

2HDMS: The model

- Consider a softly broken Z_2 and Z_3 symmetric Type II 2HDM.

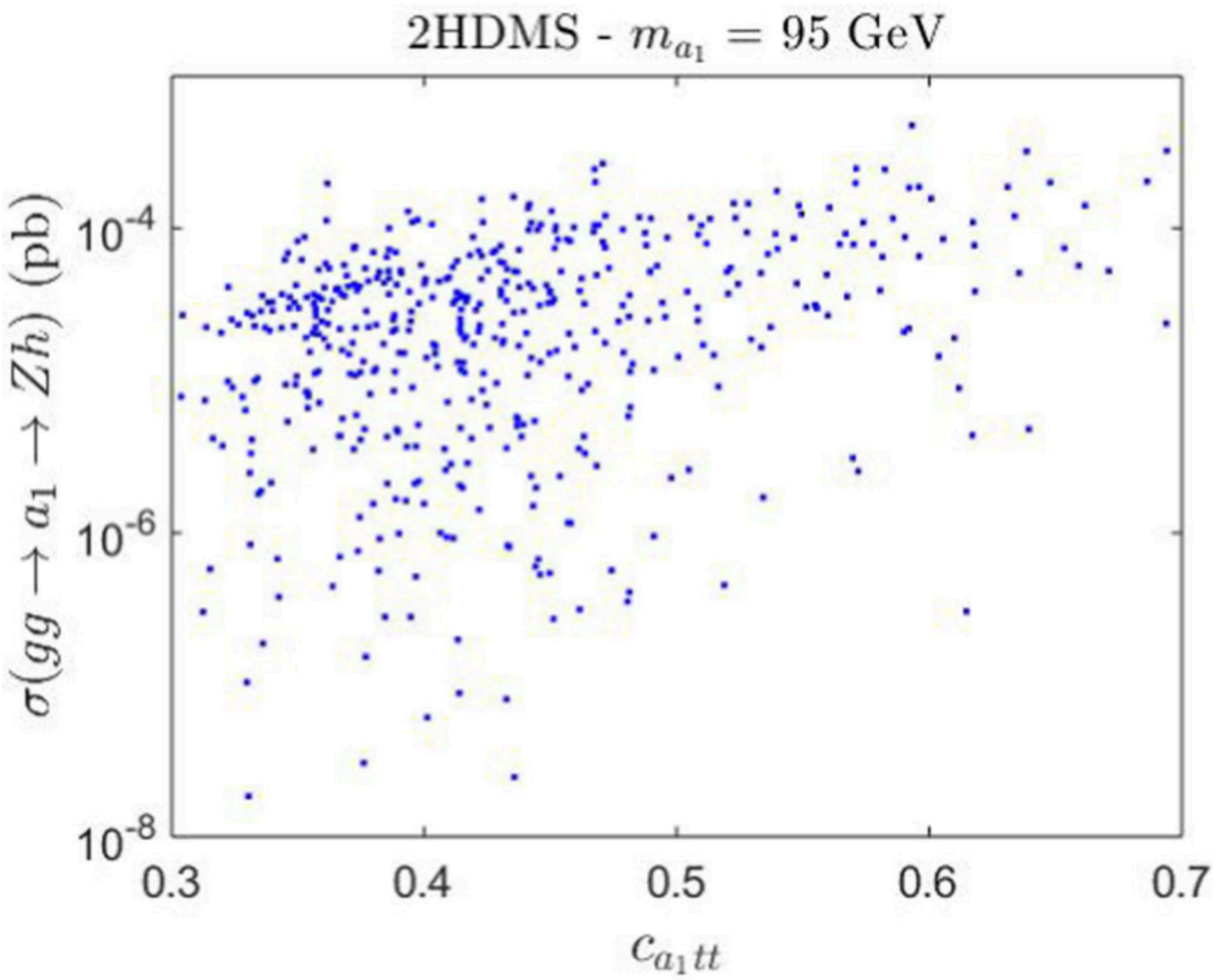
$$
\begin{aligned}
V_{\text{2HDMS}} &= m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) \\
&+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
&+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + m_S^2(S^\dagger S) \\
&+ \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2) \\
&+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \left(- m_{12}^2\Phi_1^\dagger\Phi_2 + \frac{\mu_{S1}}{6}S^3 + \mu_{12}S\Phi_1^\dagger\Phi_2 + \text{h.c.}\right).
\end{aligned}
$$

$$
\begin{aligned}
Z_2 &: \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad S \to S, \\
Z_3 &: \begin{pmatrix}\Phi_1\\ \Phi_2\\ S\end{pmatrix} \to \begin{pmatrix}1 & & \\ & e^{i2\pi/3} & \\ & & e^{-i2\pi/3}\end{pmatrix}\begin{pmatrix}\Phi_1\\ \Phi_2\\ S\end{pmatrix}
\end{aligned}
$$

$$
\Phi_1 = \begin{pmatrix}\chi_1^+\\ \phi_1\end{pmatrix} = \begin{pmatrix}\chi_1^+\\ v_1 + \dfrac{\rho_1 + i\eta_1}{\sqrt{2}}\end{pmatrix},
$$

$$
\Phi_2 = \begin{pmatrix}\chi_2^+\\ \phi_2\end{pmatrix} = \begin{pmatrix}\chi_2^+\\ v_2 + \dfrac{\rho_2 + i\eta_2}{\sqrt{2}}\end{pmatrix}, S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}}
$$

- **Particle Spectra:** $h_1, h_2, h_3, a_1, a_2, H^\pm$
- **Free parameters:** $\tan\beta, \quad \alpha_{1,2,3,4}, \quad m_{h_1}, \quad m_{h_2}, \quad m_{h_3}, \quad m_{a_1}, \quad m_{a_2}, \quad m_{H^\pm}, \quad v_S$

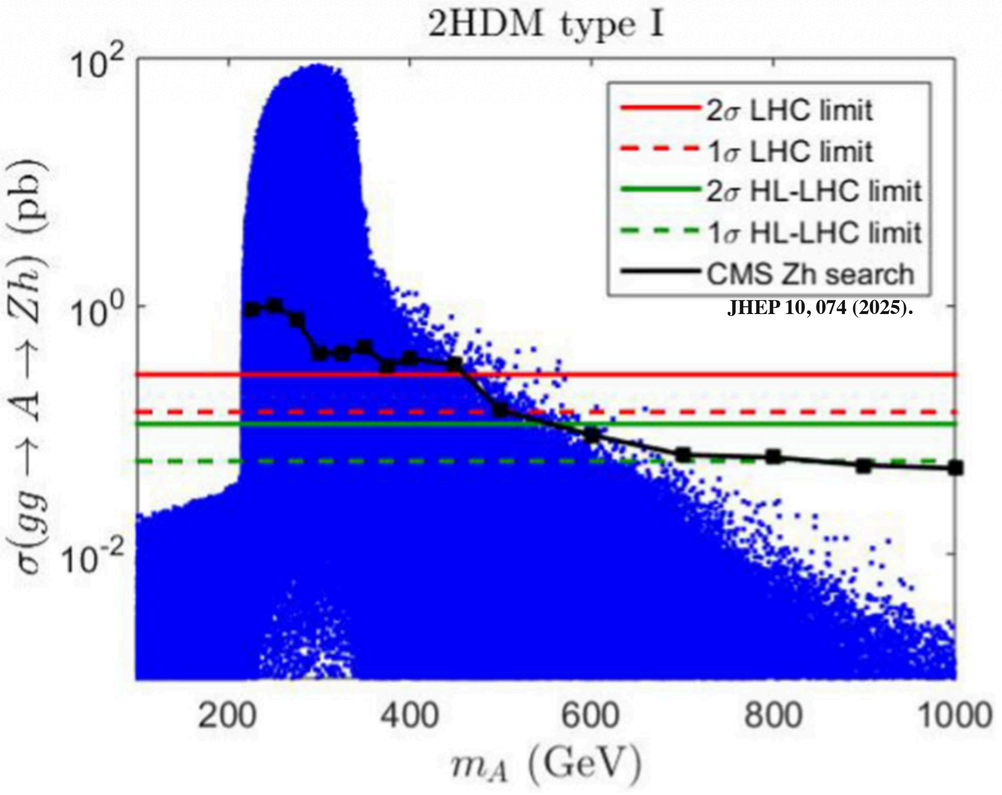


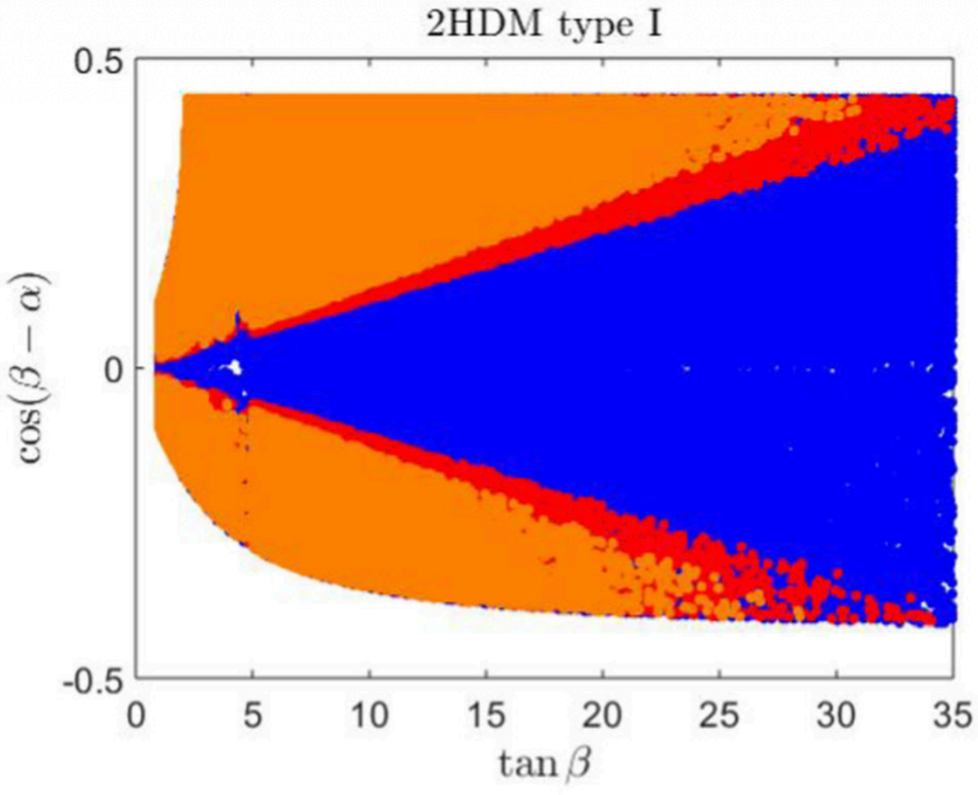
	Type I	Type II
$c_{h_i tt}$	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i2}}{\sin\beta}$
$c_{h_i bb}$	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i1}}{\cos\beta}$
$c_{h_i \tau\tau}$	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i1}}{\cos\beta}$

$$\xi_A^{Zh} = c_{\alpha_4}\left(c_{\beta-\alpha_1} c_{\alpha_3} + s_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3}\right)$$

Contribution to *Z h* production via gluon fusion to a pseudoscalar at LHC within the 2HDMS type II, for m_{a_1} = 95 GeV, as a function of the lightest pseudoscalar top coupling modifier $c_{a_{1tt}}$. The cross section is computed at NNLO.

Can heavy pseudoscalars affect Zh production?

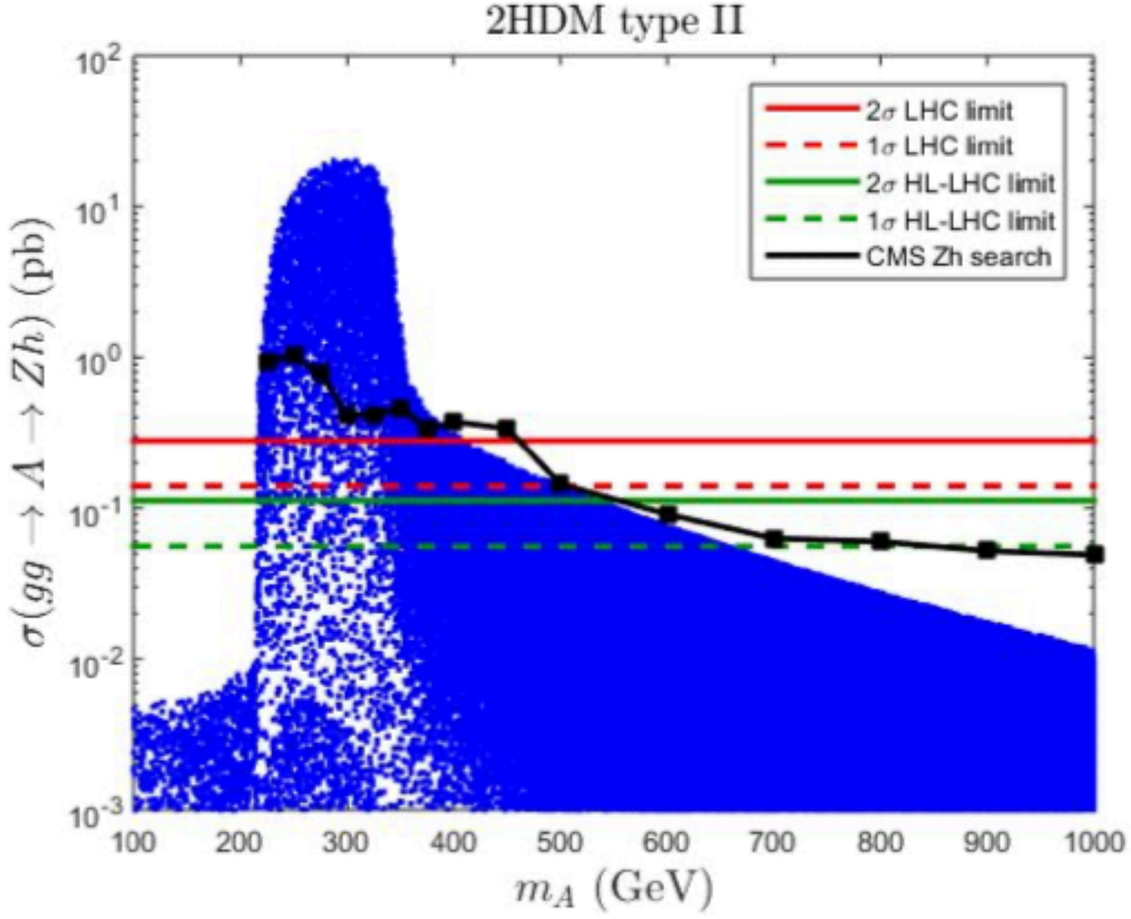


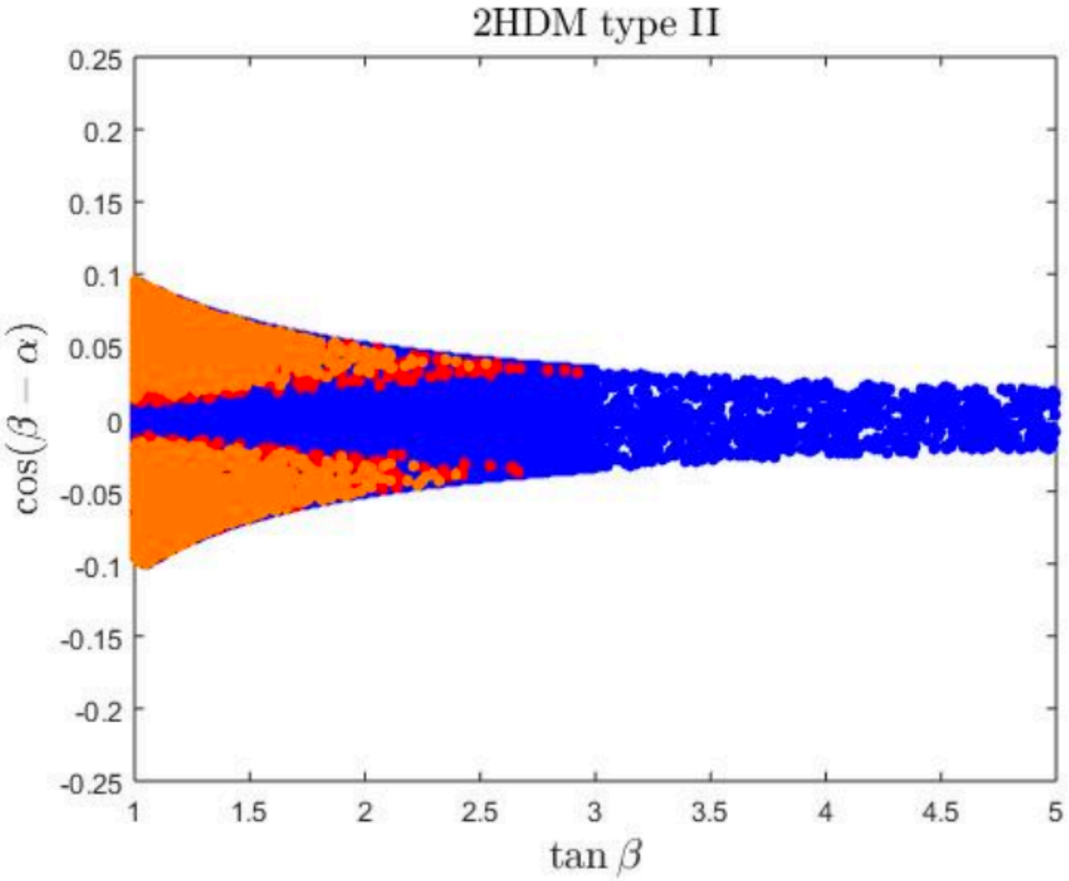


Substantial constraints from ~260-550 GeV from CMS Zh searches for pseudoscalar masses in 2HDM Type I.

Coupling modifiers:

$$\kappa_t = \kappa_b = \kappa_l = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta} \quad , \quad \kappa_V = \sin(\beta-\alpha) \, ,$$



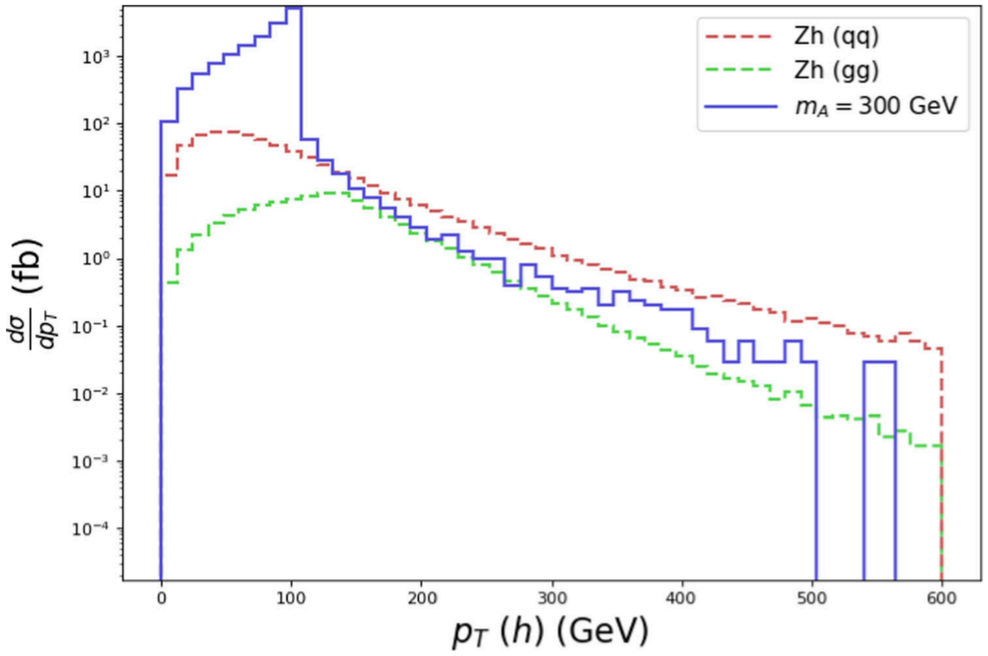


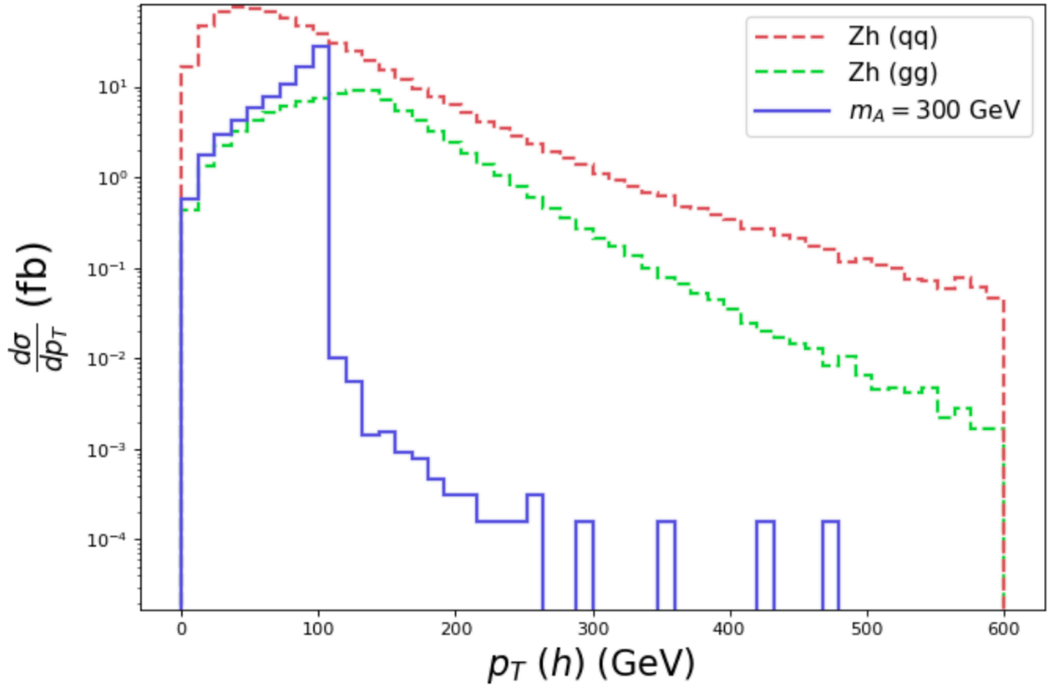
Substantial constraints from ~260-375 GeV from CMS searches on pseudoscalar masses in Type II 2HDM.

Coupling modifiers:

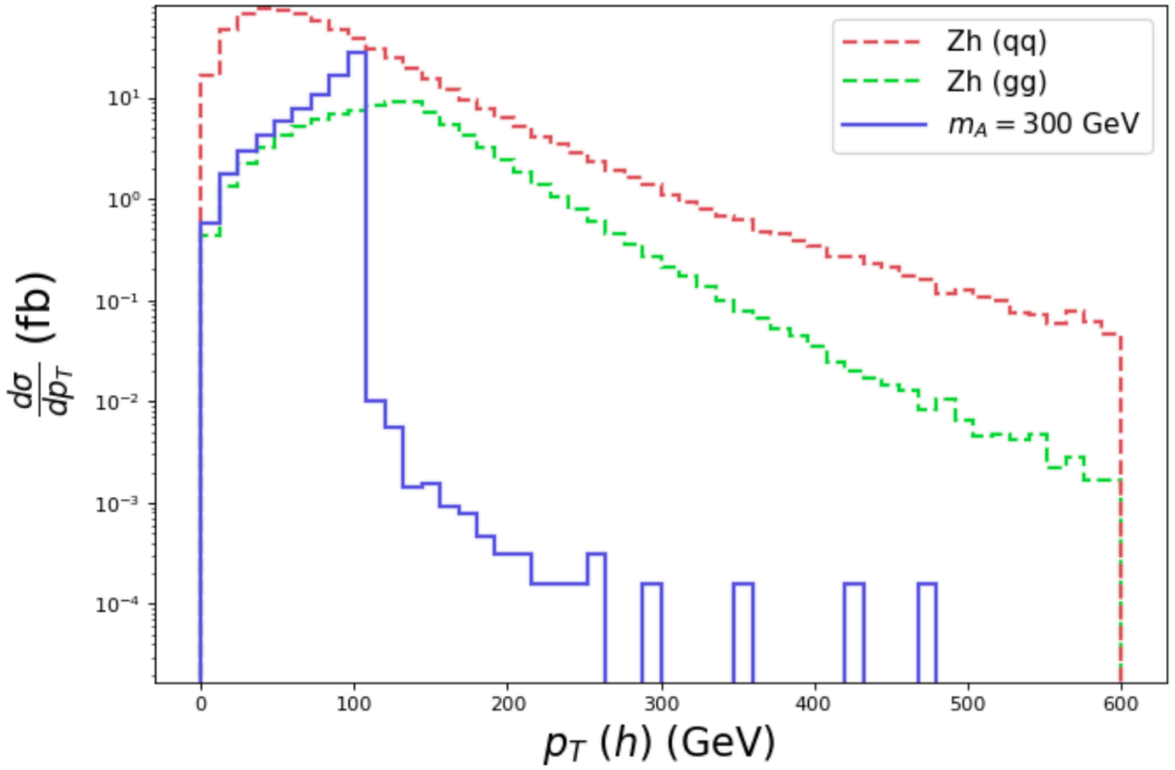
$$\kappa_t = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta},$$
$$\kappa_b = \kappa_l = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta,$$
$$\xi_A^t = \frac{1}{\tan\beta},$$
$$\xi_A^b = \xi_A^l = \tan\beta,$$

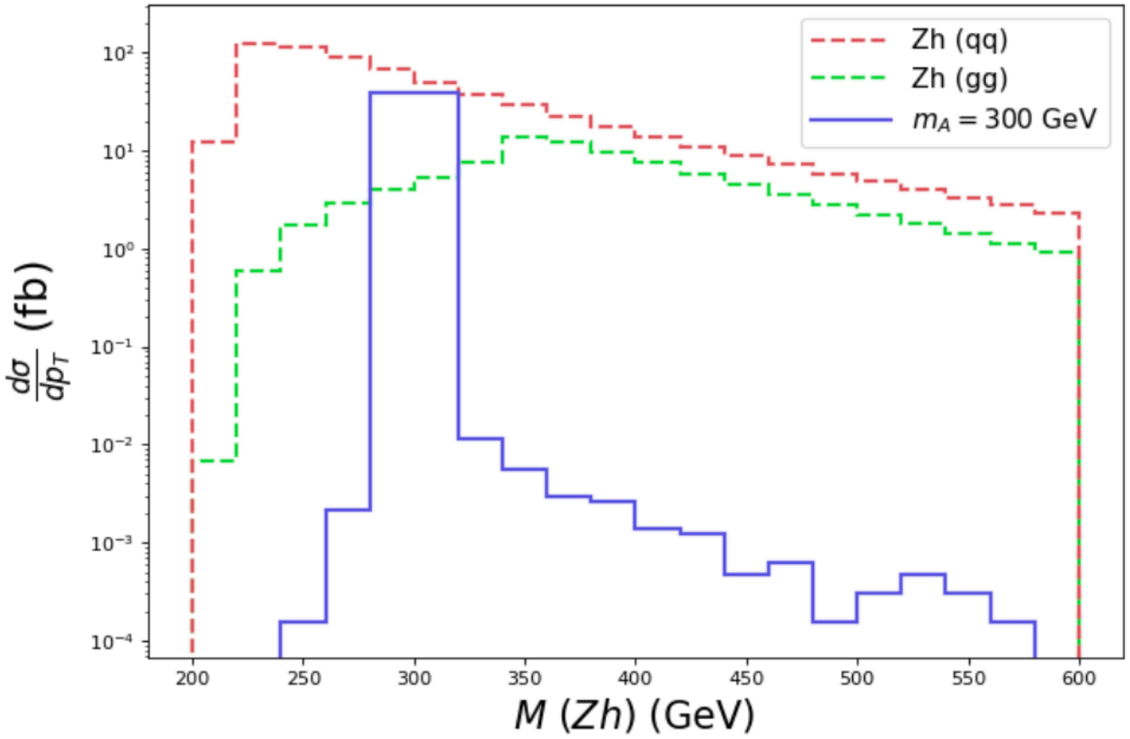
Kinematic distributions





Distributions of the transverse momentum of the Higgs (identical at LO to that of Z) from the signal and background for mA = 300 GeV for $\tan\beta = 1.1,\ \cos(\beta-\alpha) = 0.4, 0.005$ respectively. The former is excluded and latter is allowed from current LHC data.





Allowed benchmark with $m_A = 300$ GeV, $\tan\beta = 1.1,\ \cos(\beta - \alpha) = 0.005$ allowed from 13 TeV STXS analysis in Zh channel.

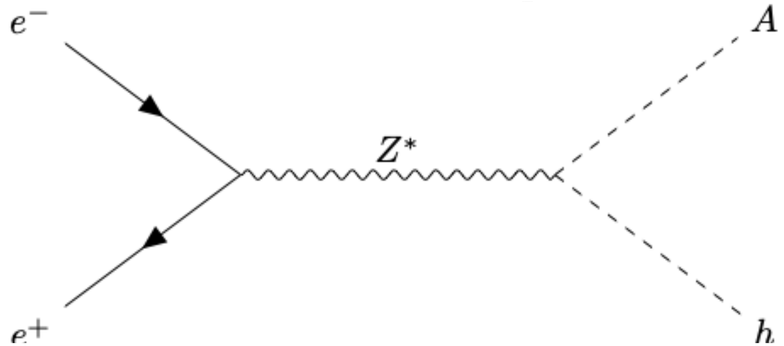
p_T [GeV]	Total $\sigma(Zh)$ at 14 TeV [fb] (LO) ($\|y_h\| < 2.5$) for			
m_A [GeV]	95	300 (above)	300 (below)	SM
< 150	1.93	13806.74	73.25	542.03
$150 - 250$	1.09	30.65	3.58×10^{-3}	76.93
> 250	0.43	5.61	0.93×10^{-3}	18.53
p_T [GeV]	Total $\sigma(Zh)$ at 14 TeV [fb] (with K-factors) ($\|y_h\| < 2.5$) for			
m_A [GeV]	95	300 (above)	300 (below)	SM
< 150	3.86	27613.48	146.49	726.96
$150 - 250$	2.17	61.3	7.15×10^{-3}	103.18
> 250	0.85	11.22	1.87×10^{-3}	24.85

STXS cross-section values in different pT (h) bins at the parton level at $\sqrt{s}$ = 14 TeV with a cut on the Higgs-boson rapidity of $|y_h| < 2.5$ at LO (NNLO) in the upper (lower) part

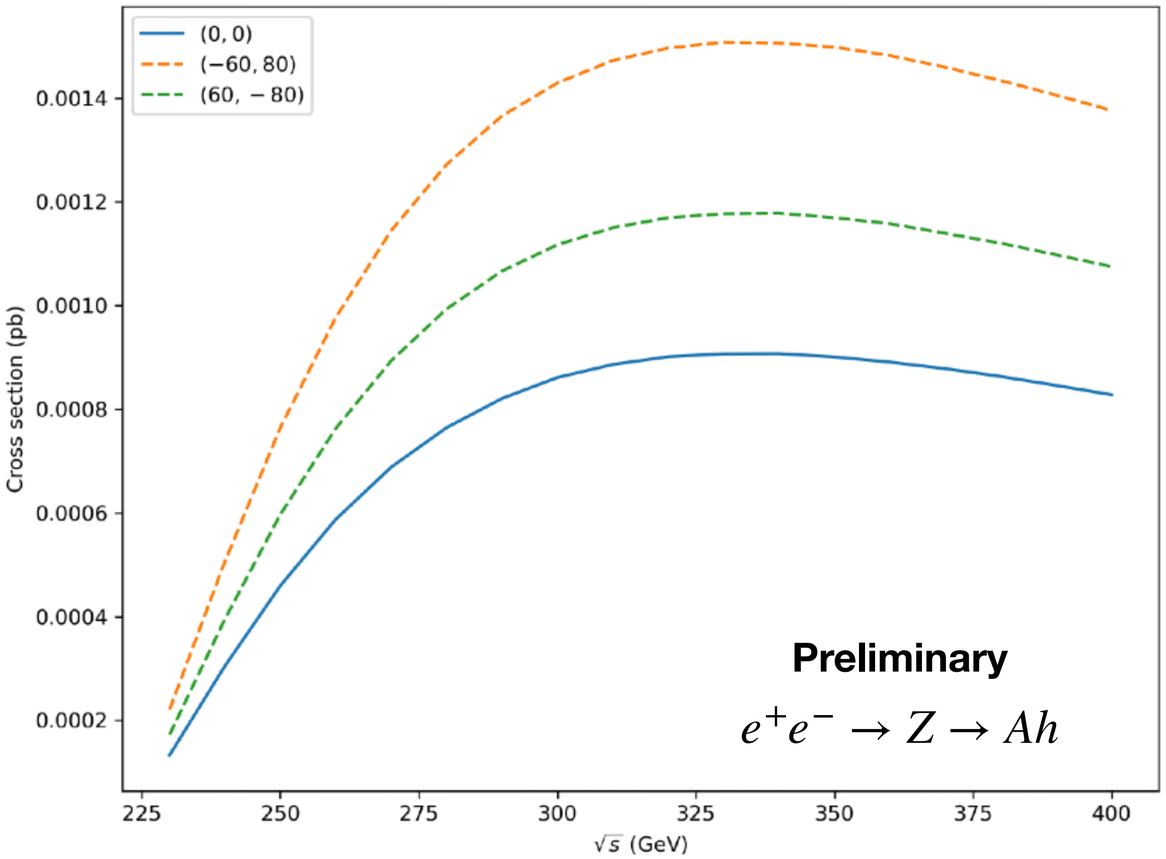
p_T [GeV]	$\sigma(Z(\to \ell\ell, \nu\nu)h)$ at 13 TeV [fb] ($\|y_h\| < 2.5$) for				Exp. measurements [fb]
m_A [GeV]	95	300 (above)	300 (below)	SM	(CMS) [79]
< 150	1.025	5919.59	39.31	205.42	200
$150 - 250$	0.570	1.81	0.003	28.38	32
> 250	0.214	0.25	0.00025	6.76	9.99

STXS cross-section values in different pT (h) bins at the parton level at $\sqrt{s}$ = 13 TeV with a cut on the Higgs-boson rapidity of $|y_h| < 2.5$ at LO (NNLO).

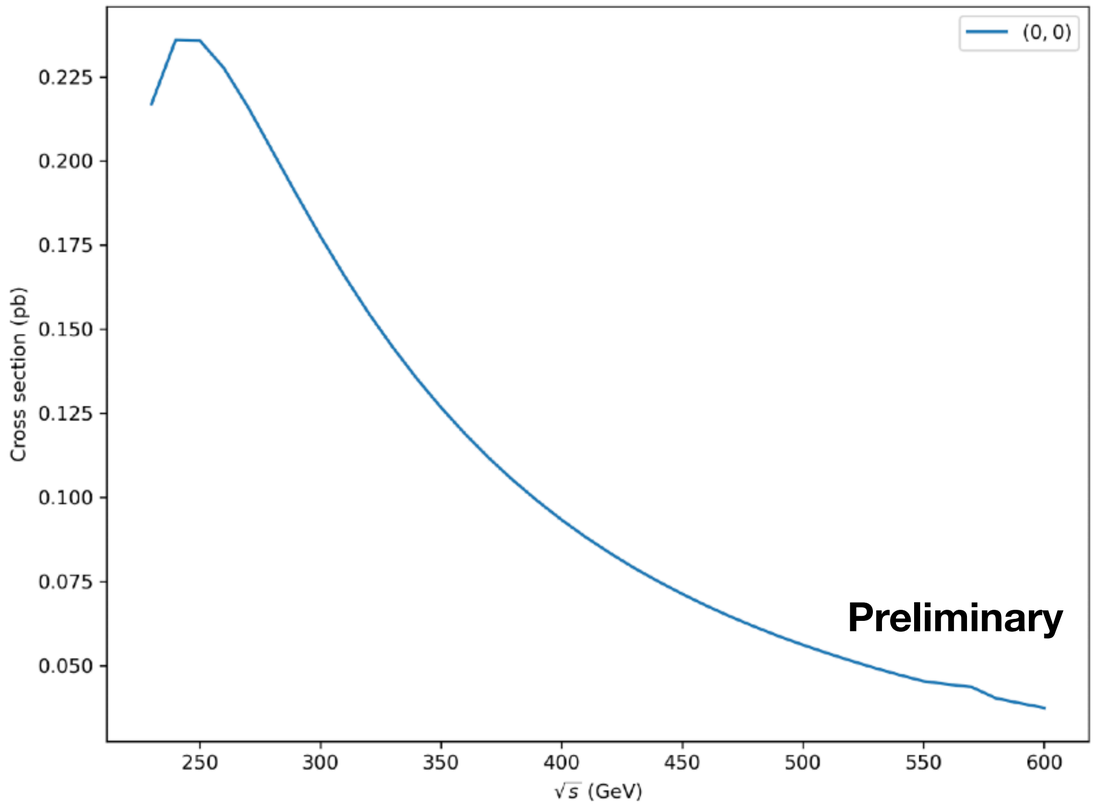
Prospects of a light pseudoscalar at linear colliders



for $\tan\beta = 1.1, \cos(\beta - \alpha) = 0.13$

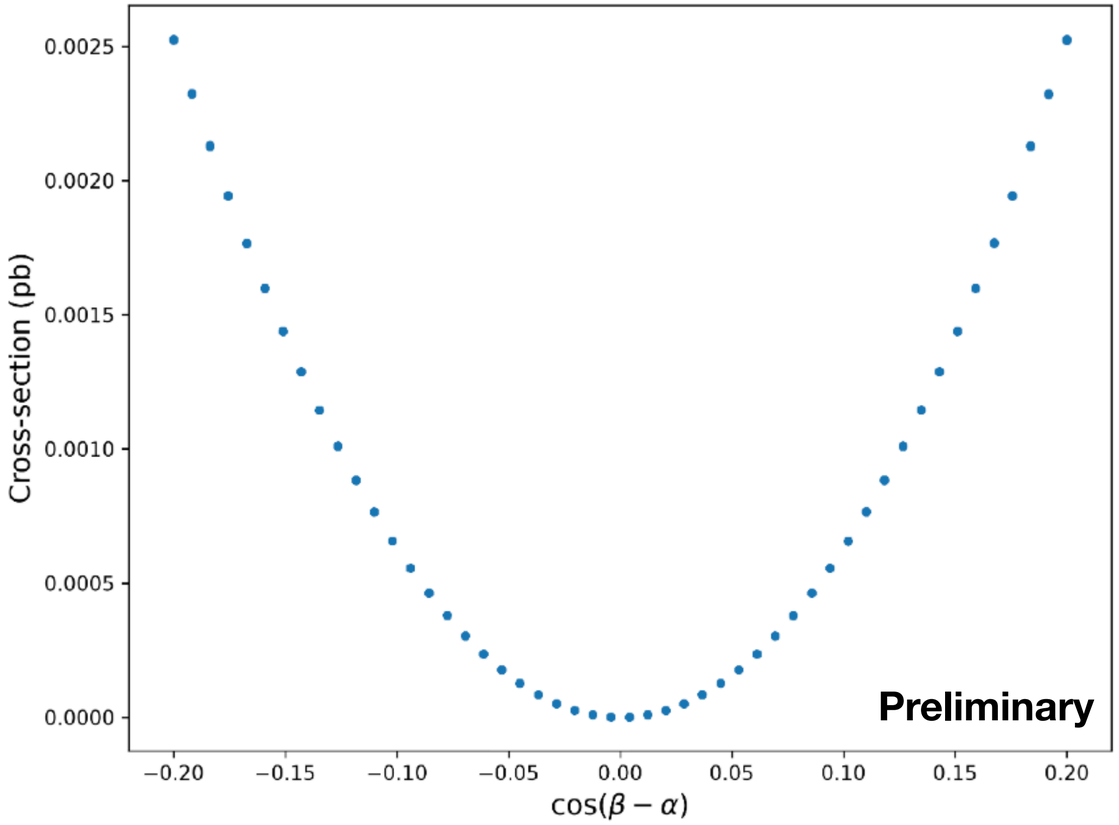


$e^+e^- \to Zh$

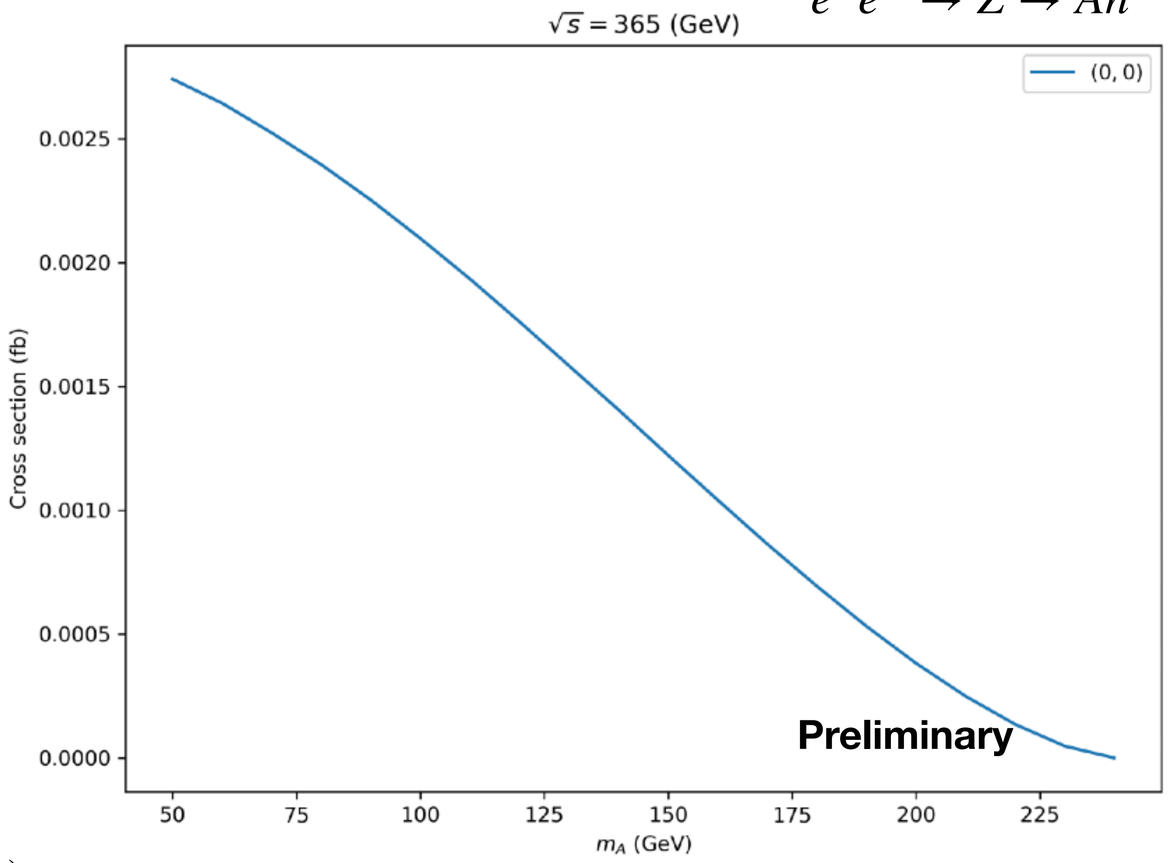


Cross-sections for Zh at different $\sqrt{s}$ values.

$\sqrt{s} = 365$ **GeV** $e^+e^- \to Z \to Ah$



$e^+e^- \to Z \to Ah$



Cross-sections for signal for $\tan\beta = 1.1 - 1.6$ **and varying** $\cos(\beta - \alpha)$

Cross-sections for various different values of m_A **at** $\sqrt{s} = 365$ **GeV.**

Summary and Outlook

- 95 GeV pseudoscalars affect the Zh cross-section via off-shell effects negligibly and escape detection at HL-LHC.
- Stronger constraints from heavier pseudoscalars.
- Current LHC constraints on Zh already constrain large parts of the parameter space for 2HDM.
- Ongoing work to detect possible prospects for detection of light pseudoscalars at linear colliders.

Thank You