Unveiling the CP-odd Higgs boson in a generalized 2HDM at future colliders

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Outline

Based on: PRD 111(2025) 1, 015035

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- Motivation
- Model
- Muon g-2 and lepton flavor violation(LFV)
- Constraints
- Collider searches
- Conclusion

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- Muon anomaly has been one of the long-standing motivations for the particle physicists to look for BSM physics scenarios since last two decades.

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- International Muon Collider Collaboration (IMCC) is a very important and interesting development in recent time [muoncollider.web.cern.ch] ⇒ offers the advantage of both the ee and pp collider.
- In the context of a 2HDM model, we propose a unique signal that can serve as a complementary channel to look for the light pseudoscalar at the LHC.

Model

[1912.08533]

$$
\begin{aligned}
V(\Phi_1,\Phi_2) &= m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - [m_{12}^2(\Phi_1^\dagger\Phi_2) + \text{H.C.}] \\
&+ \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
&+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1)\right. \\
&+ \left.\lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + \text{H.C.}\right\}
\end{aligned}
$$

$$
\begin{pmatrix}\phi_1^\pm\\ \phi_2^\pm\end{pmatrix} = \begin{pmatrix}\cos\beta & \sin\beta\\ \sin\beta & -\cos\beta\end{pmatrix}\begin{pmatrix}G^\pm\\ H^\pm\end{pmatrix}
$$

$$
\begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix} = \begin{pmatrix}-\sin\alpha & \cos\alpha\\ \cos\alpha & \sin\alpha\end{pmatrix}\begin{pmatrix}h\\ H\end{pmatrix}
$$

$$
\begin{pmatrix}\eta_1\\ \eta_2\end{pmatrix} = \begin{pmatrix}\cos\beta & \sin\beta\\ \sin\beta & -\cos\beta\end{pmatrix}\begin{pmatrix}G_0\\ A\end{pmatrix}
$$

Model

$$
\begin{aligned}
-\mathcal{L}_{\text{Yukawa}} &= \bar{Q}_L(Y_1^d\Phi_1 + Y_2^d\Phi_2)d_R + \bar{Q}_L(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)u_R \\
&+ \bar{L}_L(Y_1^l\Phi_1 + Y_2^l\Phi_2)e_R + H.C.
\end{aligned}
$$

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$$

$$
\begin{aligned}
-\mathcal{L}_{\text{Yukawa}} &= \bar{u}_L\Big[\Big(\frac{c_\alpha m^u}{vs_\beta} - \frac{c_{\beta-\alpha}\Sigma^u}{\sqrt{2}s_\beta}\Big)h + \Big(\frac{s_\alpha m^u}{vs_\beta} + \frac{s_{\beta-\alpha}\Sigma^u}{\sqrt{2}s_\beta}\Big)H\Big]u_R \\
&+\bar{d}_L\Big[\Big(\frac{c_\alpha m^d}{vs_\beta} - \frac{c_{\beta-\alpha}\Sigma^d}{\sqrt{2}s_\beta}\Big)h + \Big(\frac{s_\alpha m^d}{vs_\beta} + \frac{s_{\beta-\alpha}\Sigma^d}{\sqrt{2}s_\beta}\Big)H\Big]d_R \\
&+\bar{e}_L\Big[\Big(-\frac{s_\alpha m^l}{vc_\beta} + \frac{c_{\beta-\alpha}\Sigma^l}{\sqrt{2}c_\beta}\Big)h + \Big(\frac{c_\alpha m^l}{vc_\beta} - \frac{s_{\beta-\alpha}\Sigma^l}{\sqrt{2}c_\beta}\Big)H\Big]e_R \\
&+i\Big[\bar{u}_L\Big(\frac{m^u}{vt_\beta} - \frac{\Sigma^u}{\sqrt{2}s_\beta}\Big)u_R + \bar{d}_L\Big(-\frac{m^d}{vt_\beta} + \frac{\Sigma^d}{\sqrt{2}s_\beta}\Big)d_R \\
&+\bar{e}_L\Big(\frac{m^l t_\beta}{v} - \frac{\Sigma^l}{\sqrt{2}c_\beta}\Big)e_R\Big]A + \text{H.C.}
\end{aligned}
$$

Model

[PhysRevD.35.3484]

$$\Sigma_{ij}^{f} = \sqrt{m_i^f m_j^f}\,\frac{\chi_{ij}}{v}$$

For three generations of leptons, the leptonic non-diagonal couplings (χ_{ij}) would be noted as $y_{\mu e}$, $y_{\tau\mu}$ and $y_{\tau e}$ respectively.

Muon “g-2” and Lepton Flavor Violation(LFV)

$a_\mu^{SM} = 116591810(43) \times 10^{-11}$

$a_\mu^{FNAL} = 116592055(24) \times 10^{-11}$

$a_\mu^{exp\text{-}combined} = 116592059(22) \times 10^{-11}$

[hep-ex/0602035]

$\triangle a_\mu = 249(48) \times 10^{-11}$

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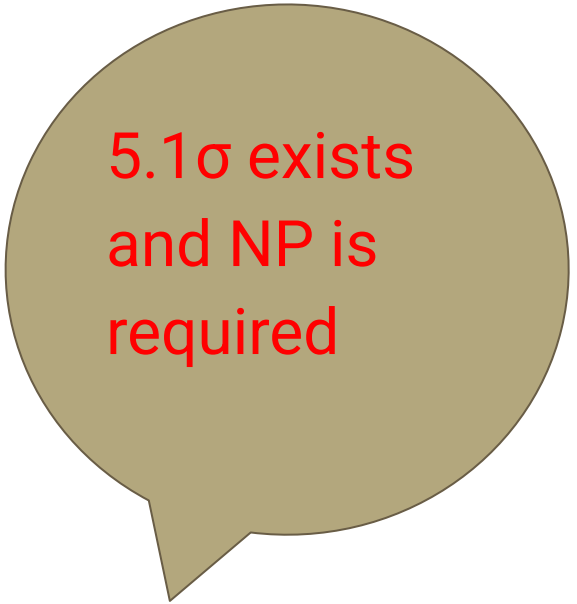
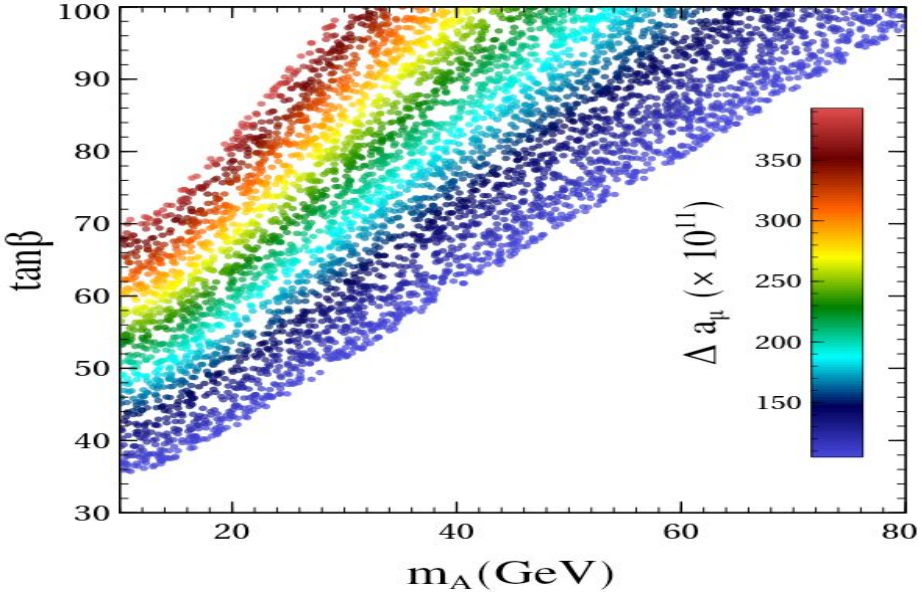


Muon “g-2” and Lepton Flavor Violation(LFV)

Contribution from both 1-loop and 2-loop Bar-Zee diagram [1502.04199]



Muon “g-2” and Lepton Flavor Violation(LFV)

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}, \quad \mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8},$$

$$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}.$$

$y_{e\mu}$, $y_{e\tau}$ and $y_{\mu\tau}$ respectively to be $O(10^{-5})$, $O(10^{-4})$ and $O(10^{-5})$ or lesser.

Constraints:

$$
\begin{aligned}
m_{12}^2 &\in [-500, 500]\ \mathrm{GeV}^2, m_A \in [10.0, 60.0]\ \mathrm{GeV}, \\
m_H &\in [62.5, 125.0]\ \mathrm{GeV}, m_H^{\pm} \in [89.0, 190.0]\ \mathrm{GeV}, \\
\tan\beta &\in [10, 100], \quad |\cos(\beta - \alpha)| \in [0.99, 1], \\
\lambda_6 &\in [0, 0.1], \quad \lambda_7 \in [0, 0.1]
\end{aligned}
$$

Vacuum stability and perturbative unitarity :

The set of stability conditions required

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 - \lambda_5 > \sqrt{\lambda_1 \lambda_2}$$

Alongwith, one needs the $\lambda \lesssim 4\pi$

To keep λ_1 to be within perturbative limit

$$m_{12}^2 \simeq \frac{m_H^2}{\tan\beta}$$

Electroweak constraints :

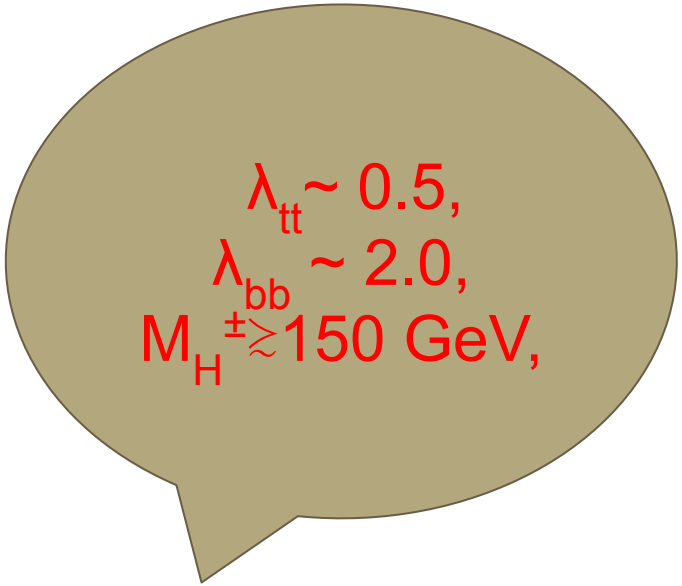
[1803.01853]

$$S = 0.04 \pm 0.11,\ T = 0.09 \pm 0.14,\ U = -0.02 \pm 0.11$$

EW observables are satisfied at 2σ ✅

B-Physics constraints :

- $B \rightarrow X_s \gamma$ [1710.05898]
- $B^{\pm} \rightarrow \tau^{\pm} \nu_{\tau}$ [1611.06676]
- ΔM_B [0907.1791]
- $B_s \rightarrow \mu^+ \mu^-$ [1706.07414]



Constraints from collider searches :

Charged Higgs

- LEP bound $M_{H^\pm} \gtrsim 80$ GeV [1301.6065]

- At LHC, when $M_{H^\pm} < m_t$, Upper limit on BR($t \rightarrow bH^\pm$) [1807.07915 ,1302.3694]

  For $M_{H^\pm} > m_t$, Upper limit on $pp \rightarrow tbH^\pm$ [1603.09203]

Constraints from collider searches :

Non-standard neutral Higgs

- h/H → Z(ℓℓ)A(τ τ) [1603.02991] and h/H → Z(ℓℓ)A(bb̄) [1911.03781] relevant only for masses ≳ 200 GeV.

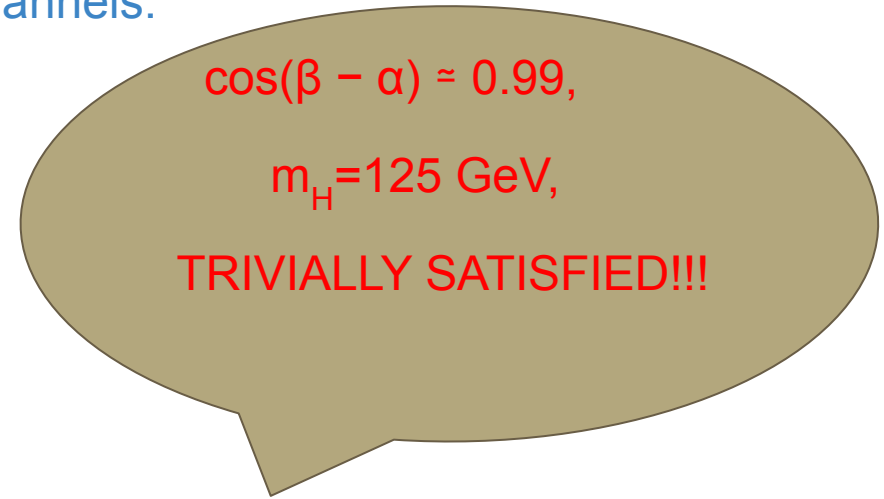
- low-mass pseudoscalar produced in association with b quarks and decaying into a τ τ final state [1903.10228]

- low-mass (pseudo)scalars produced in association with bb̄ and decaying into bb̄ [CMS-PAS-HIG-16-025]

Constraints from collider searches :

125 GeV Higgs

CMS and ATLAS have a series of searches of the decay of 125 GeV Higgs at various final states, namely, τ τ [2312.02394], μμ [CMS-PAS-HIG-19-006], ee [CMS-PAS-HIG-21-015] and also lepton flavor violating eτ,μτ [2302.05225], and τ τ [1911.10267] channels.



Constraints from collider searches :

125 GeV Higgs

The strongest constraint come from H → AA decay.

$$
\begin{aligned}
g_{HAA} &= \frac{1}{2v}[(2m_A^2 - m_H^2)\frac{\cos(\alpha-3\beta)}{\sin 2\beta} + (8m_{12}^2 \\
&\quad - \sin 2\beta(2m_A^2 + 3m_H^2))\frac{\cos(\beta+\alpha)}{\sin^2 2\beta}] \\
&+ v\Big[\sin 2\beta \cos 2\beta(\lambda_6 - \lambda_7)\cos(\beta-\alpha) \\
&+ (\lambda_6 \sin\beta \sin 3\beta + \lambda_7 \cos\beta \cos 3\beta)\sin(\beta-\alpha)\Big]
\end{aligned}
$$

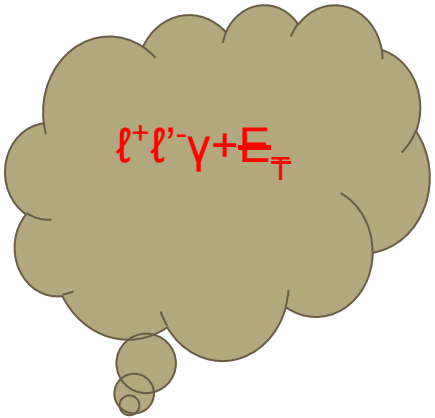
g_{HAA} can be made very small

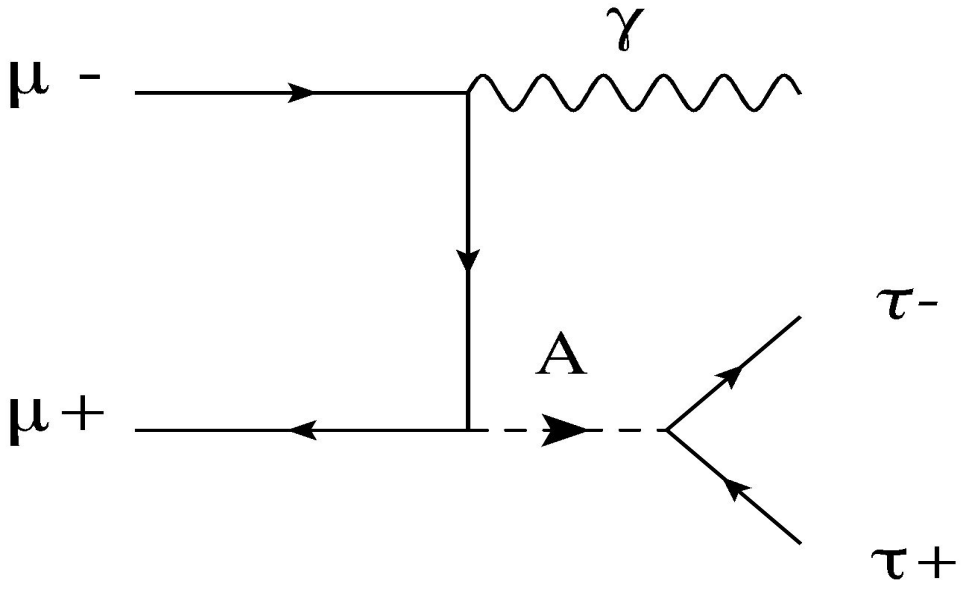
m_h = 110 GeV, m_H = 125 GeV, $m^{\pm}_H$ = 165 GeV,
$m_A \in$ [30, 50] GeV, tan β ∈ [50, 80]

Collider Searches:

Followed by leptonic decay of τ s

So our signal of interest is:





Collider Searches:

BP	$\tan\beta$	m_A(GeV)	m_h(GeV)	$m_{H^\pm}$(GeV)	$m_{12}^2(GeV^2)$	λ_6	λ_7	$\lvert s_{\beta\alpha}\rvert$	$\sigma_{prod}(fb)$
BP1	54.96	30	110	165	284.27	0.004	0.0004	0.01	0.43
BP2	58.94	35	110	165	265.08	0.003	0.0007	0.01	0.49
BP3	68.84	40	110	165	226.97	0.01	0.0006	0.01	0.67
BP4	74.66	50	110	165	209.27	0.004	0.0005	0.01	0.78

The SM background that can mimic the signal comes from γW^+W^- , γZZ and $\gamma\tau^+\tau^-$

$$|\eta(\gamma)| < 2.5; \qquad |\eta(l)| < 2.5;$$
$$p_T(l) > 10 \text{ GeV}; \qquad p_T(\gamma) > 10 \text{ GeV}.$$

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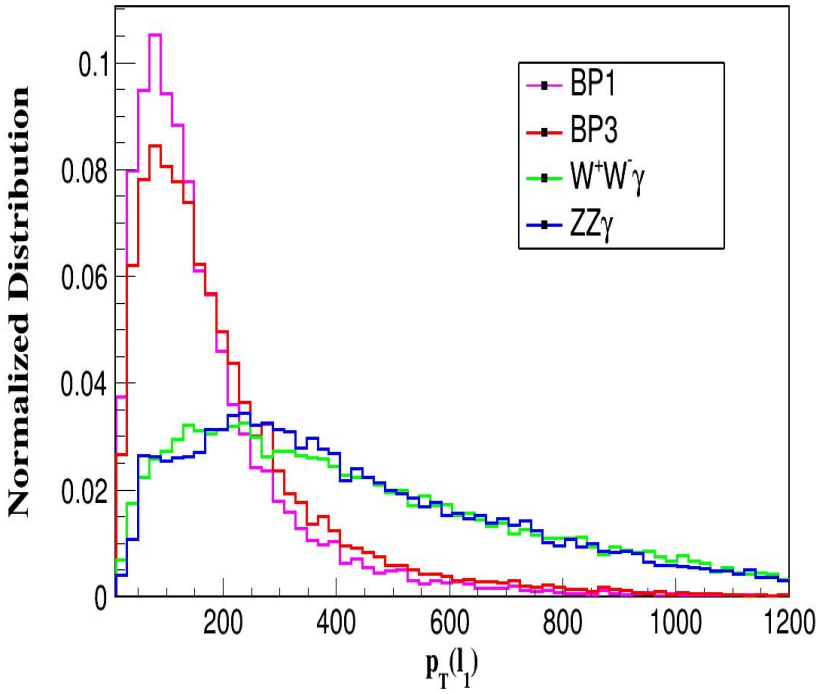

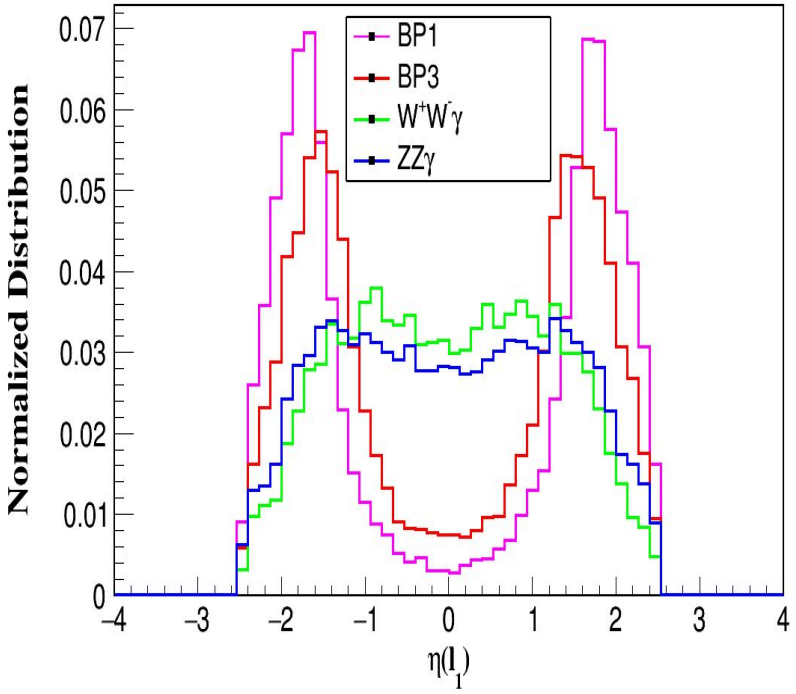

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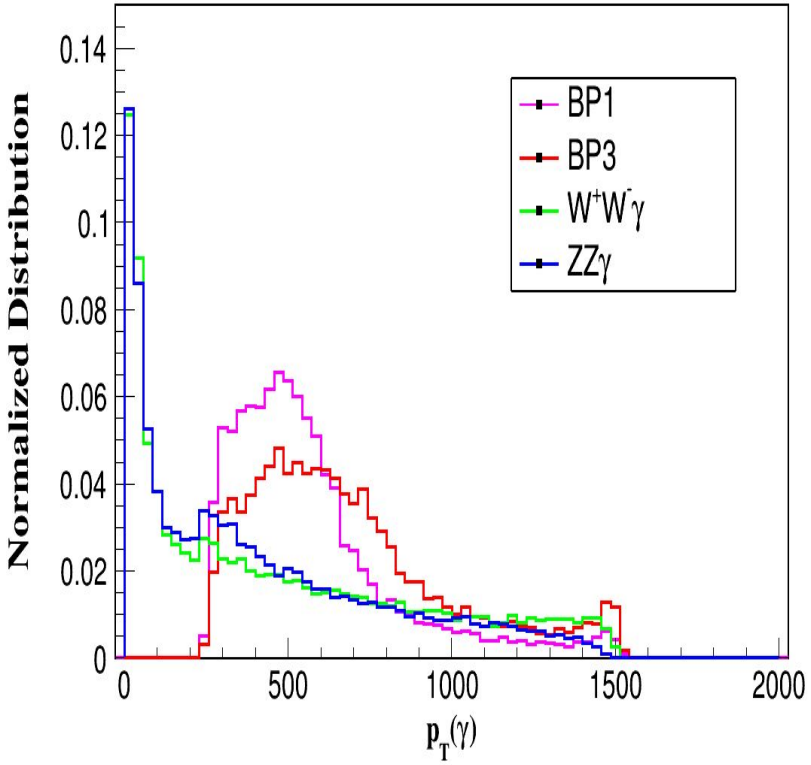

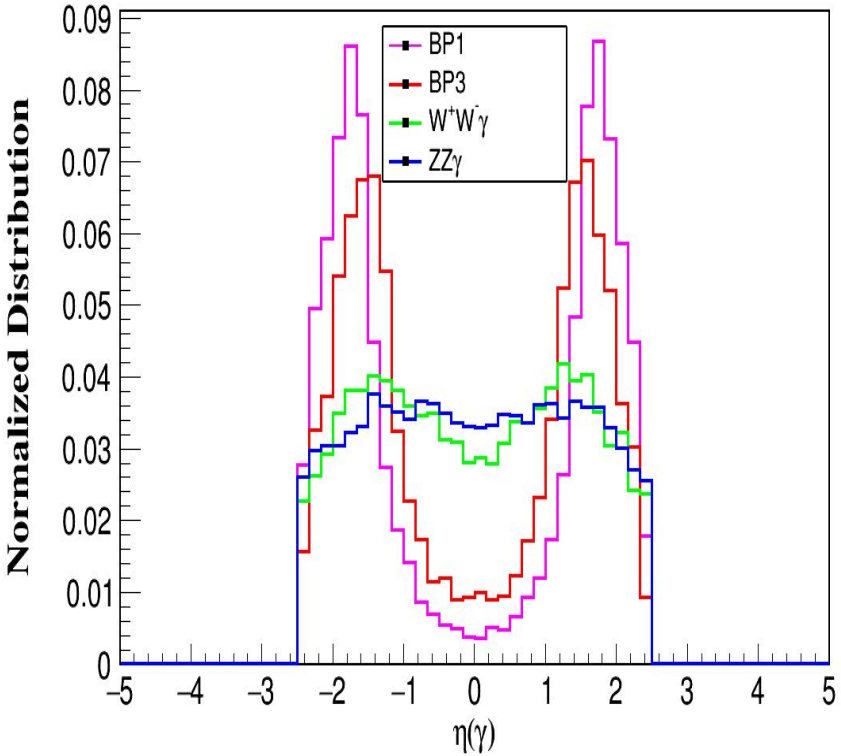

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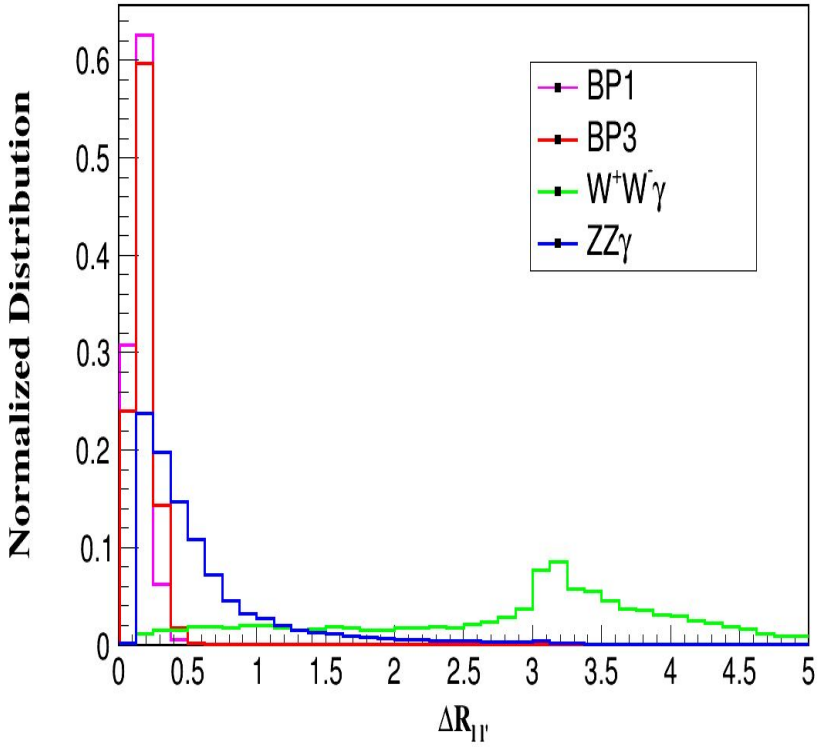

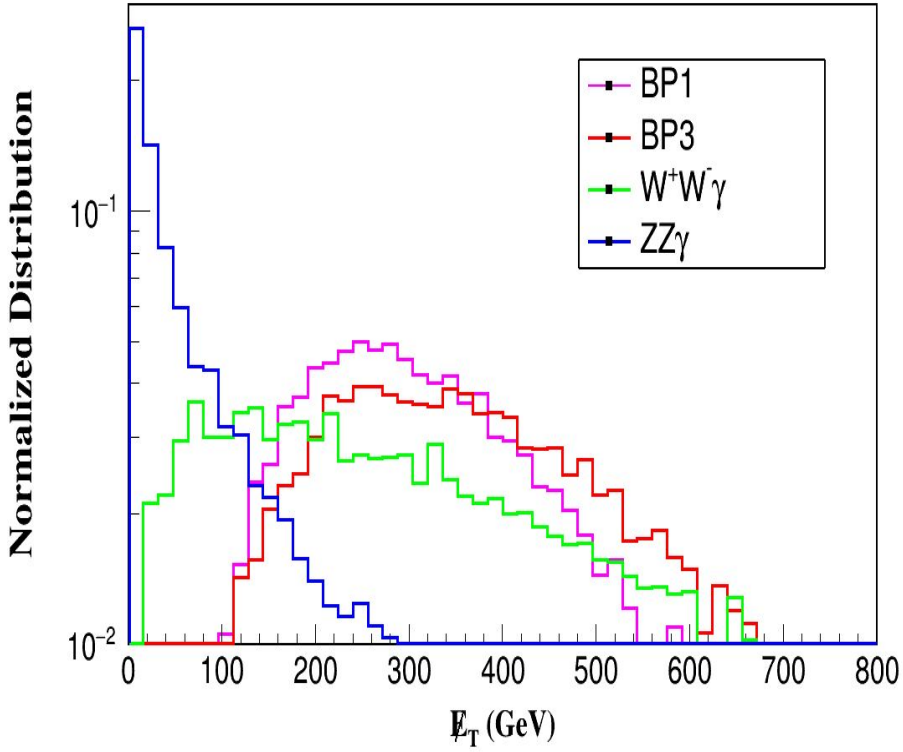

Collider Searches:

Number of events after cut ($\mathcal{L} = 1ab^{-1}$)						
SM-background	Preselection cuts	$p_T(\ell_1) < 300$ GeV	$\lvert\eta_{\ell_1}\rvert > 1.5$	$p_T(\gamma) > 200$ GeV	$\lvert\eta_\gamma\rvert > 1.5$	$\Delta R_{ll'} < 0.35$
$\gamma\ W^+W^-$	966	369	171	123	98	2
γZZ	136	51	27	15	7	0
Signal						
BP1	12	10	8	8	8	8
BP2	17	14	10	10	10	10

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$\gamma\ W^+W^-$	966	369	260	187	172	5
γZZ	136	51	36	24	16	0
Signal						
BP3	27	22	20	20	20	19
BP4	40	30	25	25	25	22

Collider Searches:

$$\mathcal{S} = \sqrt{2[(S+B)\ln(1+\frac{S}{B}) - S]}.$$

Signal	Significance(S)
BP1	4.0 σ
BP2	4.8 σ
BP3	6.1 σ
BP4	6.9 σ

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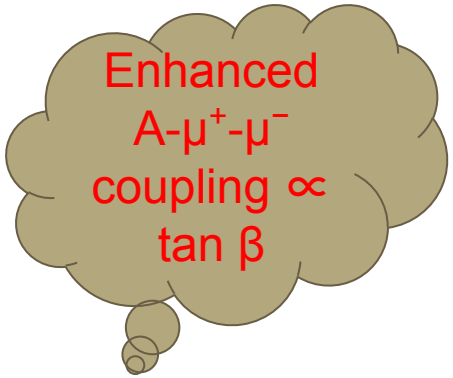
Comparing with the 14 TeV LHC, the cross-sections for BP1 and BP4 are 1.8×10^{-3} fb and 8.9×10^{-4} fb, which are at least a factor of 200(800) less than a 3 TeV muon collider.



Conclusion:

- Low mass pseudoscalar scalar explaining $(g-2)_\mu$ anomaly at 3σ as well as LFV constraints.
- Satisfied all the theoretical as well as experimental constraints.
- Looked for a unique channel at 3 TeV muon collider that would have a smaller cross-section to be probed even at HL-LHC due to the suppressed coupling of the pseudoscalar with quarks for the parameter space favored by muon (g−2) anomaly data.
- After a simple cut-based analysis, we have shown that the pseudoscalar having a mass range of 30 to 50 GeV can be probed with significance $\gtrsim 4\sigma$.

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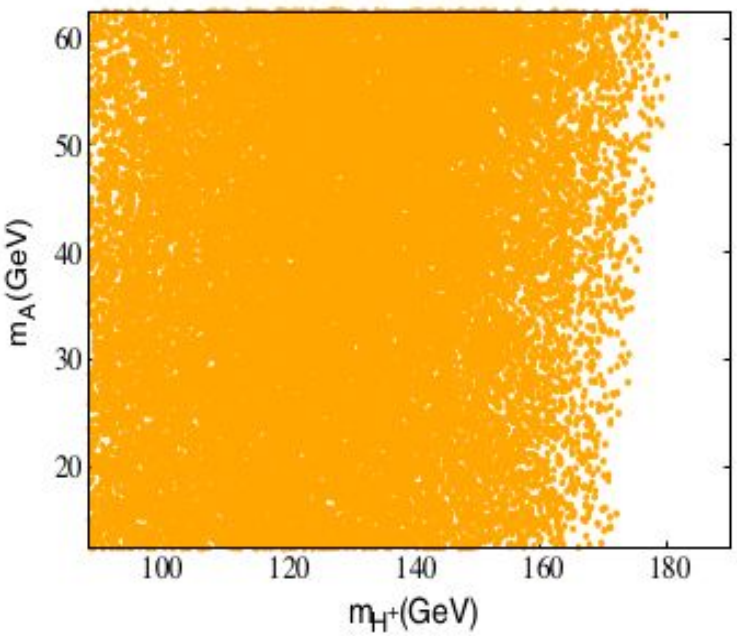
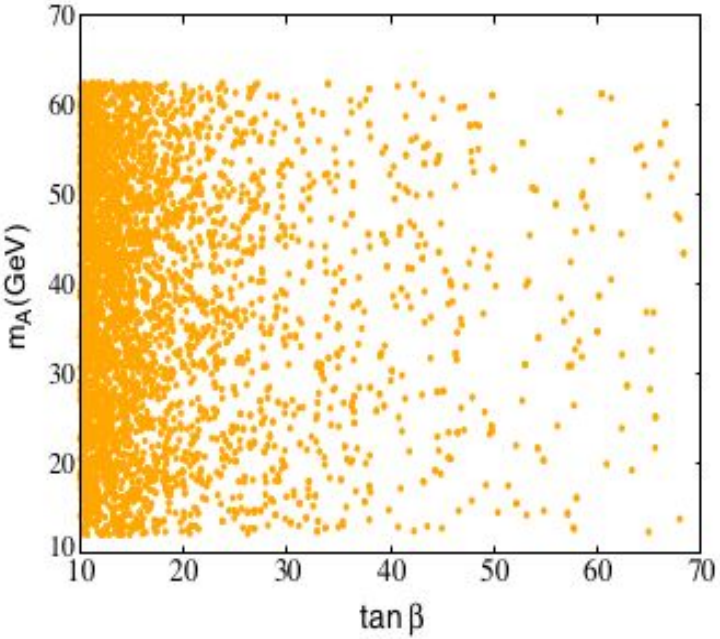
Thank you !!!

Backup Slides





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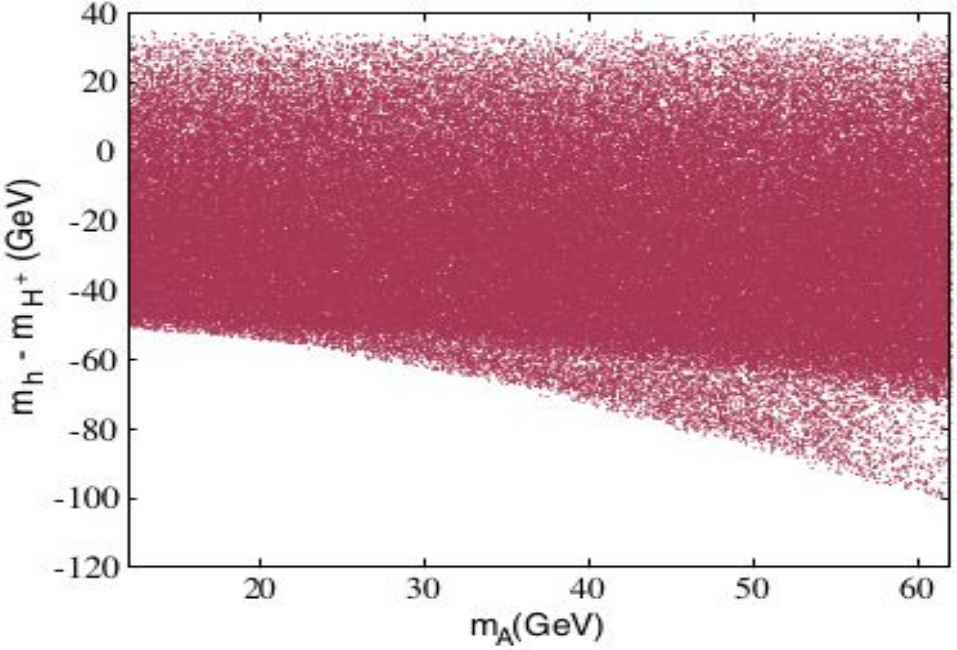
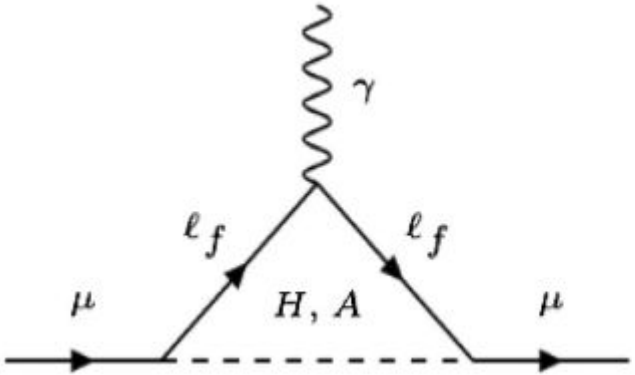
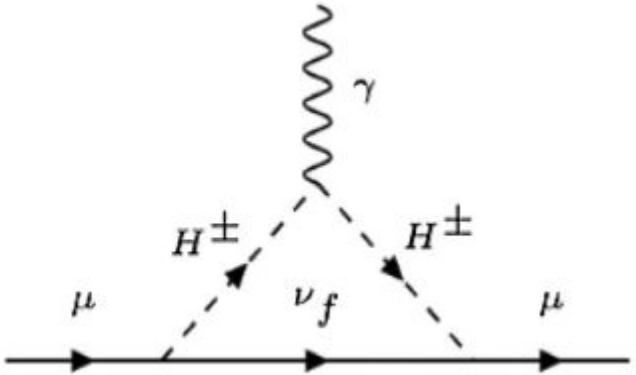


Muon “g-2” and Lepton Flavor Violation(LFV)





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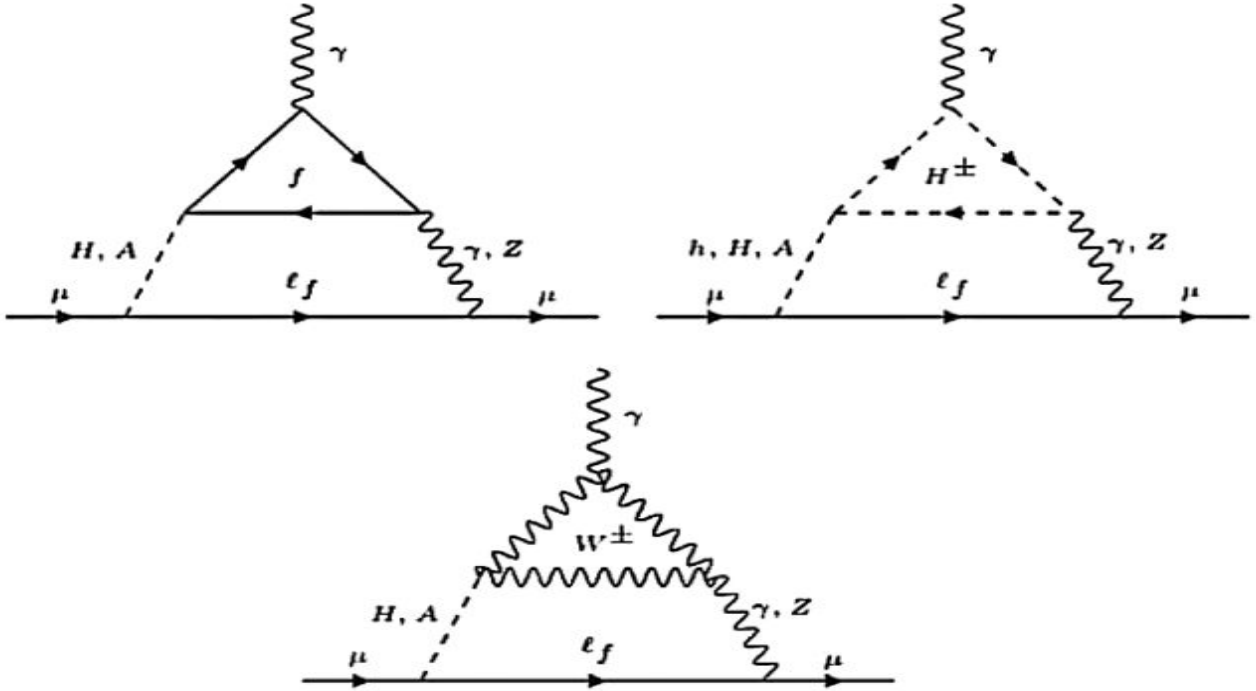

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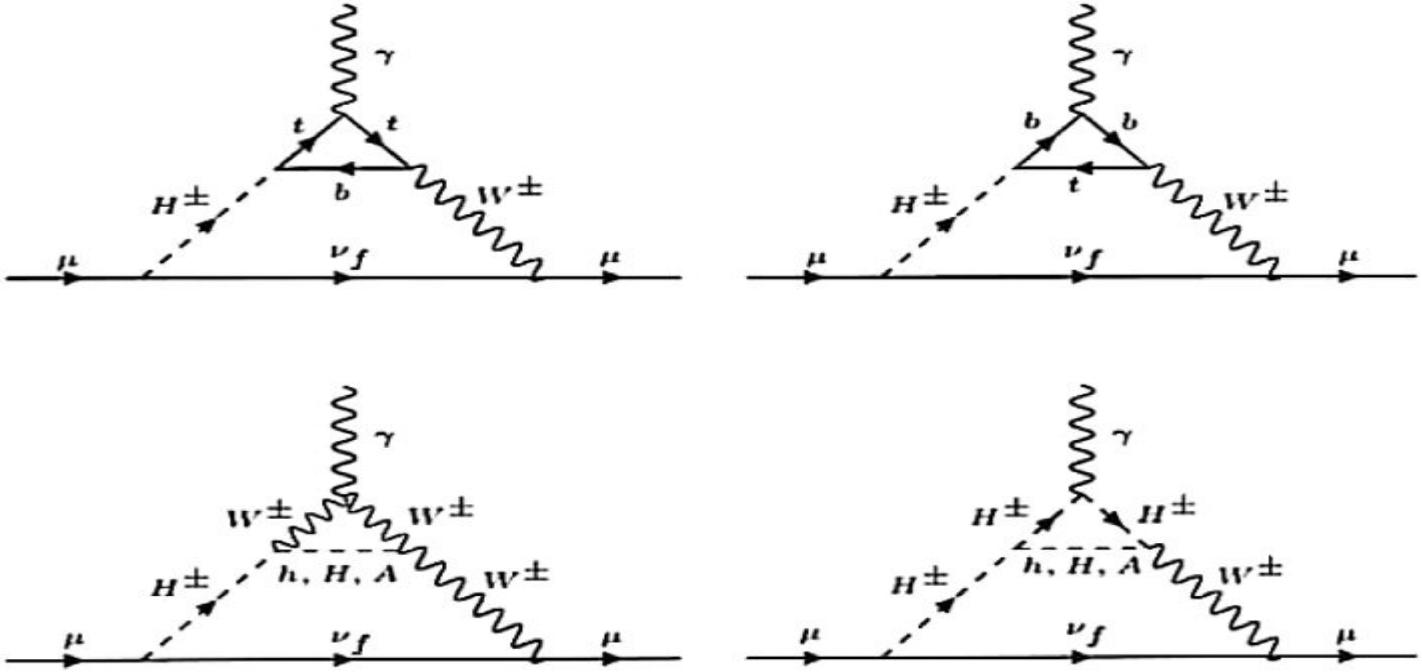
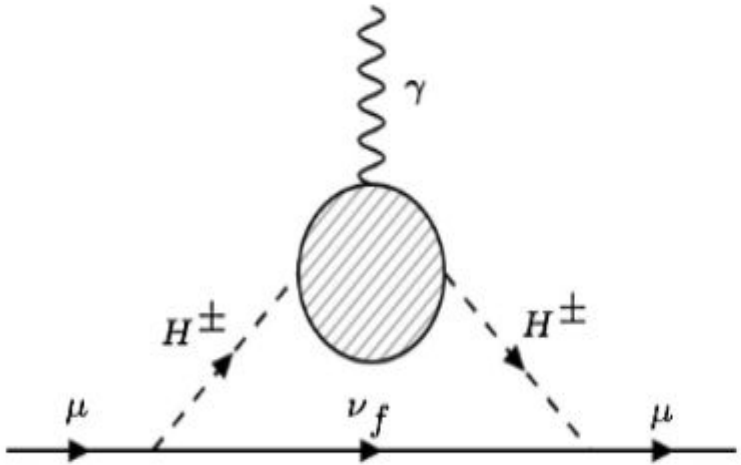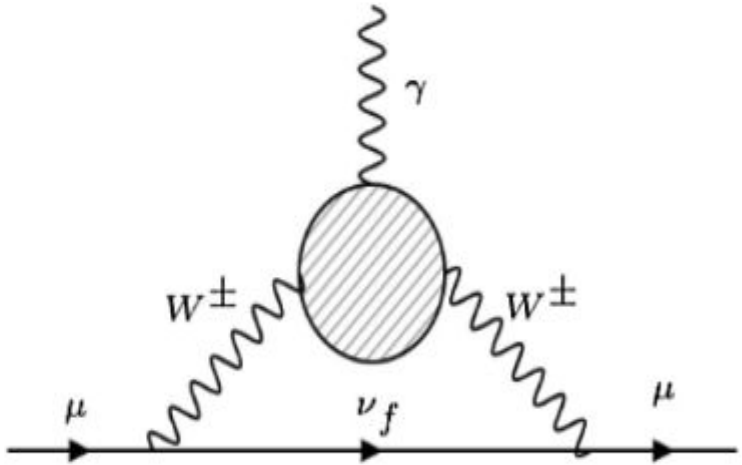
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