LHC Higgs Working Group WG3 (BSM) -- Extended Higgs Sector subgroup meeting

Jul 6, 2021, 3:00 PM → Jul 7, 2021, 6:00 PM Europe/Zurich

CERN

Searches for a light pseudoscalar in L2HDM

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On behalf of Eung Jin Chun

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Outline

- Limited parameter space for muon g-2 in L2HDM

  FNAL: $\Delta a_\mu = (251 \pm 59) \times 10^{-11}$

  Updated from 1409.3199, 1605.06298

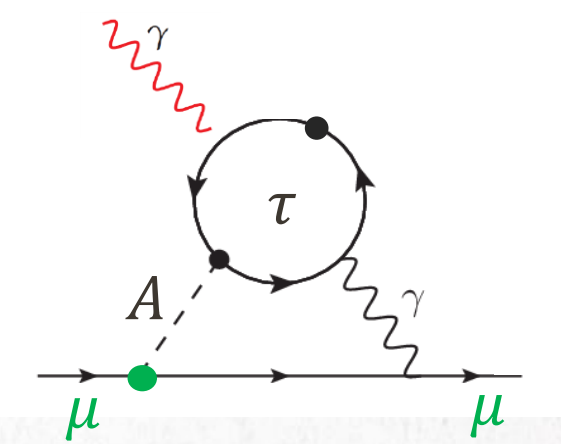
- LHC searches yet to be explored

  $pp \to H^\pm(H)A \to \tau^\pm\nu(\tau^+\tau^-)\,\tau^+\tau^-$ 1507.08067

  $pp \to h \to A(\tau\tau)A(\mu\mu)$ 1707.07928

  $pp \to H^\pm(H)A \to W^\pm(Z)A(\tau\tau)A(\mu\mu)$ 1807.05379

  $pp \to \tau^+\tau^- A(\tau\tau)$??



Leptophilic 2HDM

- 2HDM of type-X:

$$\mathcal{L}_Y = y_u \overline{q_L} \Phi_2^* u_R + y_d \overline{q_L} \Phi_2 d_R + y_l \overline{l_L} \Phi_1 e_R + h.c.$$

- 2HDM Higgs bosons: $h(125), H, H^{\pm}, A$
- In the alignment limit: $\sin(\beta-\alpha) \to 1;\ \cos(\beta-\alpha) \to 0, \text{or } 2/t_\beta$

$$\begin{cases} \Phi_2 \to s_\beta (v+h) - c_\beta H - i c_\beta A \\ \Phi_1 \to c_\beta (v+h) + s_\beta H + i s_\beta A \end{cases}$$

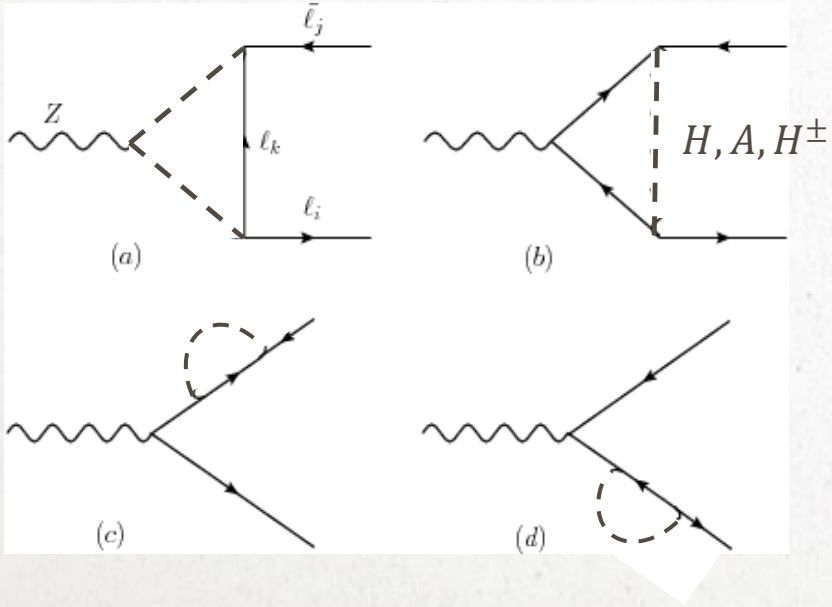
$$\mathcal{L}_Y = \kappa_f \frac{m_f}{v} \bar{f} h f + \frac{m_q}{v} \frac{1}{t_\beta} \bar{q}(H \pm i\gamma_5 A) q + \frac{m_l}{v} t_\beta \bar{l}(H + i\gamma_5 A) l \rightarrow \text{ Leptophilic at large tan}\beta$$

- Muon g-2 favored (2σ): $m_H \approx m_{H^\pm} \gg m_A = (10-50)\text{GeV}, t_\beta = (35-70)$

Lepton Universality in $Z \to ll$

- One-loop corrections mediated by extra Higgs bosons.

Hollik, Kuehn, 1991



LEP EWWG, 0509008

$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028\,,$$
$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}} = 1.0019 \pm 0.0032\,,$$

with correlation +0.63

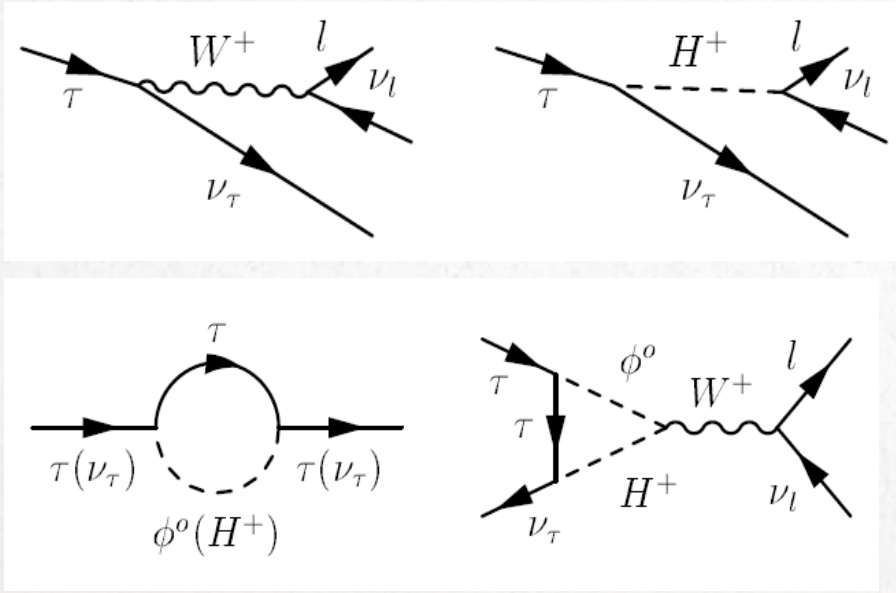
$$\delta_{\mu\mu} \simeq 0\,,$$
$$\delta_{\tau\tau} = \frac{2g_L^e \mathrm{Re}(\delta g_L^{2\mathrm{HDM}}) + 2g_R^e \mathrm{Re}(\delta g_R^{2\mathrm{HDM}})}{g_L^{e\,2} + g_R^{e\,2}}\,,$$

Constraining large tanβ
and big hierarchy:
$m_A \ll m_H \approx m_{H^\pm}$ and $m_\phi \gg m_Z$

Lepton Universality in τ/μ Decays

- Tree-level contribution from $H^{\pm}$.
- One-loop corrections mediated by $A, H, H^{\pm}$.

Krawczyk, Temes, 0410248



HFAG, 1612.07233

$$\frac{\tau \to e\nu\nu}{\mu \to e\nu\nu}, \frac{\tau \to \mu\nu\nu}{\mu \to e\nu\nu}, \frac{\tau \to \mu\nu\nu}{\tau \to e\nu\nu} \quad \frac{(\tau \to \nu\pi/K)}{(\pi/K \to \mu\nu)}$$

$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0011 \pm 0.0015$$

$$\left(\frac{g_\tau}{g_e}\right) = 1.0029 \pm 0.0015$$

$$\left(\frac{g_\mu}{g_e}\right) = 1.0018 \pm 0.0014$$

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9963 \pm 0.0027$$

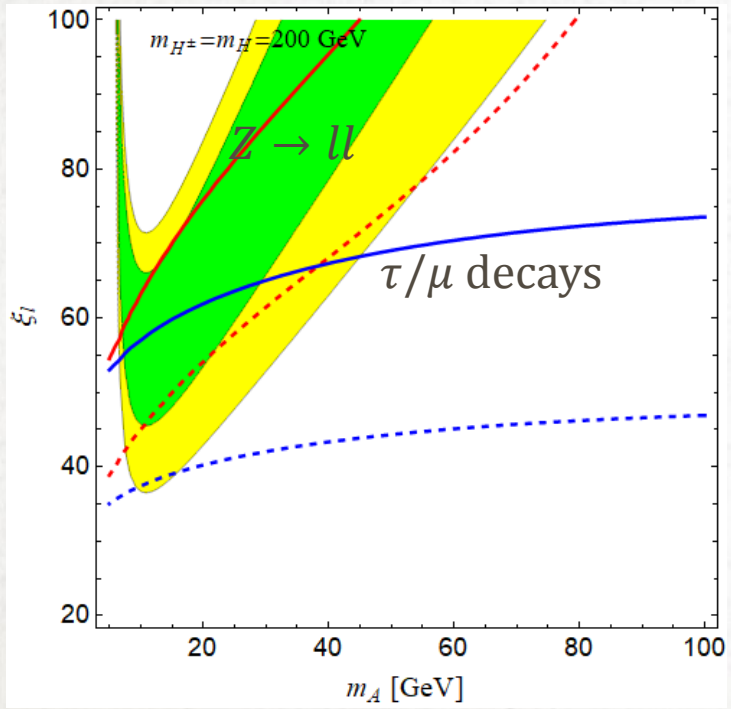
$$\left(\frac{g_\tau}{g_\mu}\right)_K = 0.9858 \pm 0.0071$$

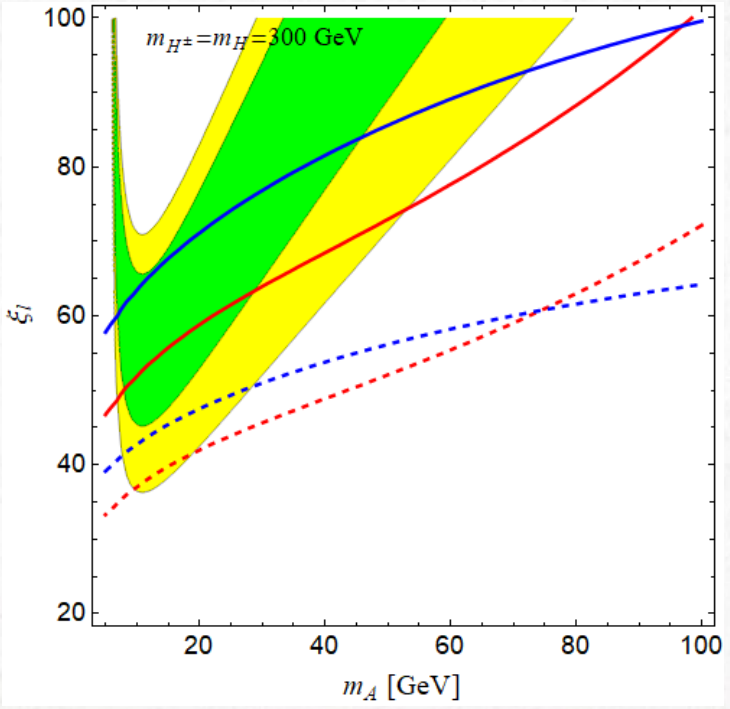
$$\delta_{\text{tree}} = \frac{m_\tau^2 m_\mu^2}{8 m_{H^\pm}^4} t_\beta^4 - \frac{m_\mu^2}{m_{H^\pm}^2} t_\beta^2 \frac{g(m_\mu^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)},$$

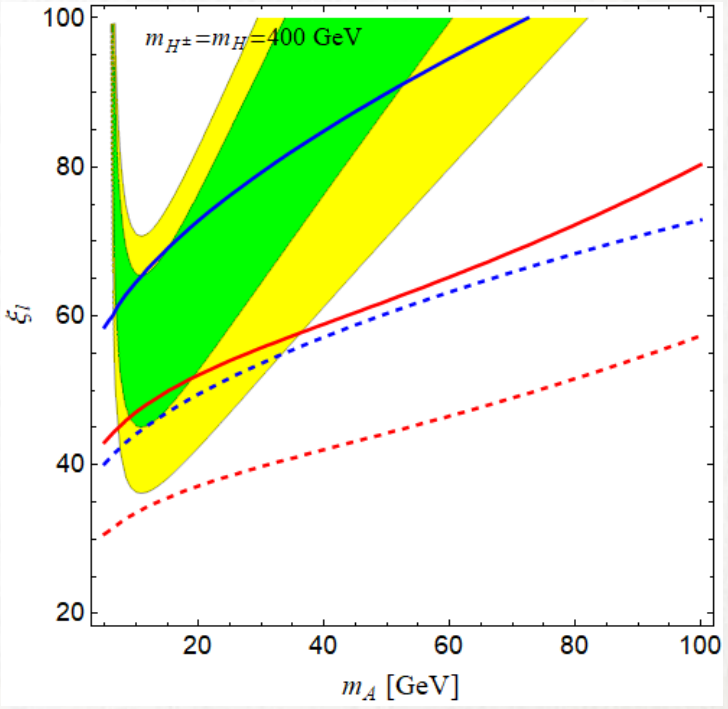
$$\delta_{\text{loop}} = \frac{1}{16\pi^2} \frac{m_\tau^2}{v^2} t_\beta^2 \left[1 + \frac{1}{4}\left(H(x_A) + s_{\beta-\alpha}^2 H(x_H) + c_{\beta-\alpha}^2 H(x_h)\right)\right]$$

Muon g-2 in L2HDM

FNAL: $\Delta a_\mu = (251 \pm 59) \times 10^{-11}$



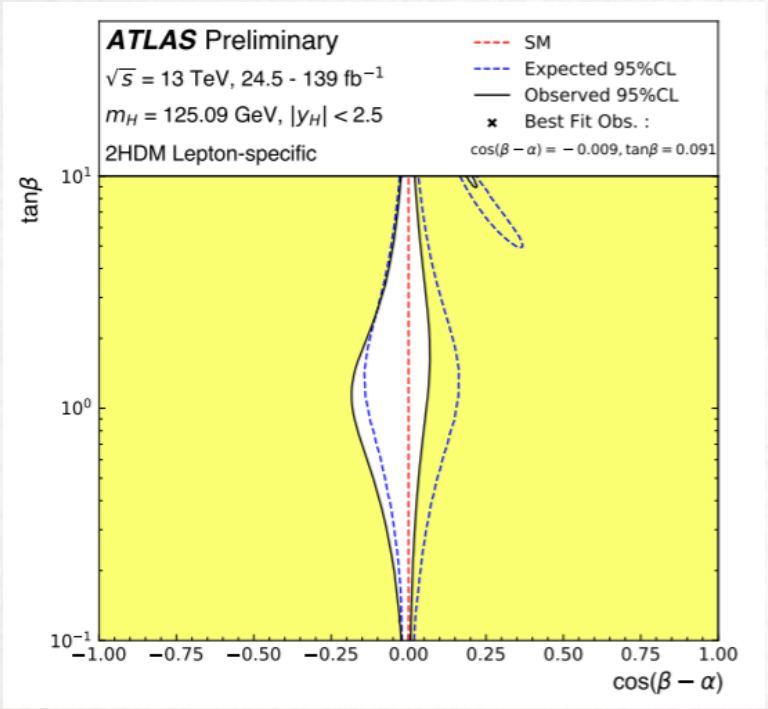


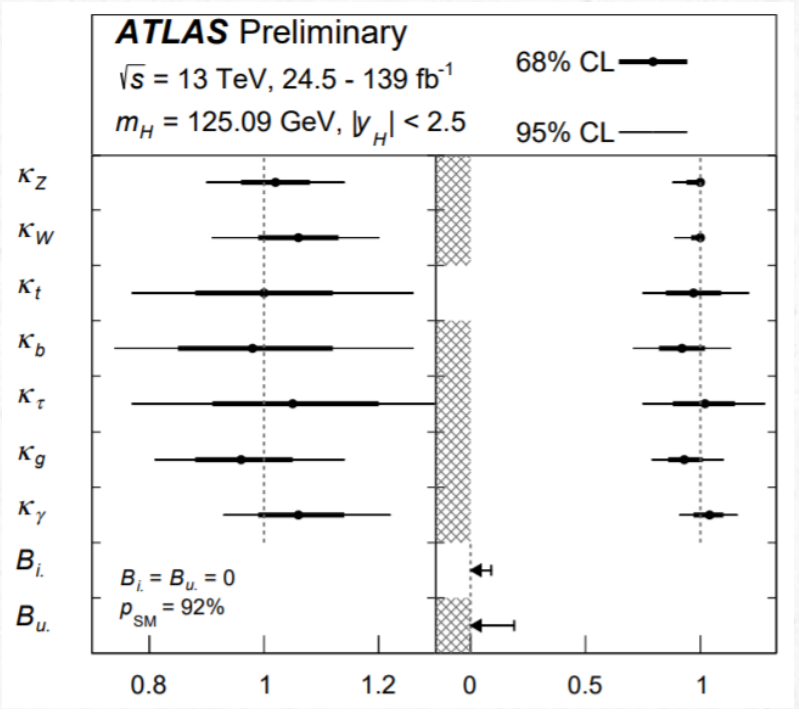


(*) $m_A \gtrsim 10\text{GeV}$ for $\text{B}(B_s \to \mu\mu)$

EJC, Jinsu Kim, JHEP 07 (2016) 110

Higgs precision at LHC





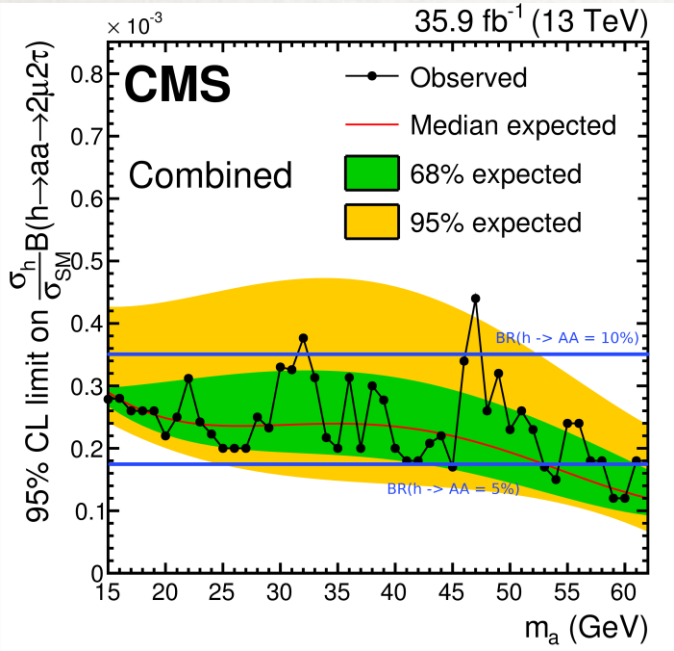
ATLAS-CONF-2020-027

$$c_{\beta-\alpha} \to 0; \quad \text{or } \frac{2}{t_\beta}$$

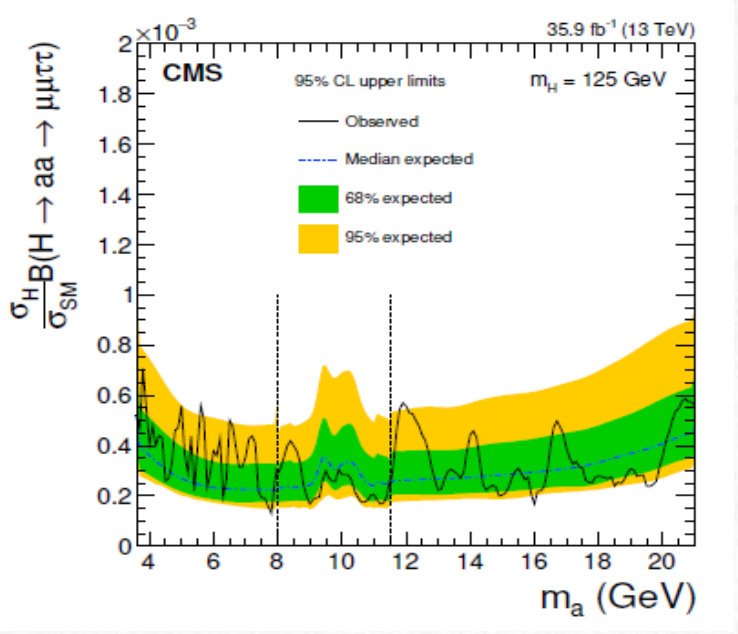
$$\kappa_q = +\frac{c_\alpha}{s_\beta} = s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta} \to 1$$

$$\kappa_l = -\frac{s_\alpha}{c_\beta} = s_{\beta-\alpha} - c_{\beta-\alpha} t_\beta \to \pm 1$$

LHC Search: $pp \to h \to AA \to \mu\mu\tau\tau$



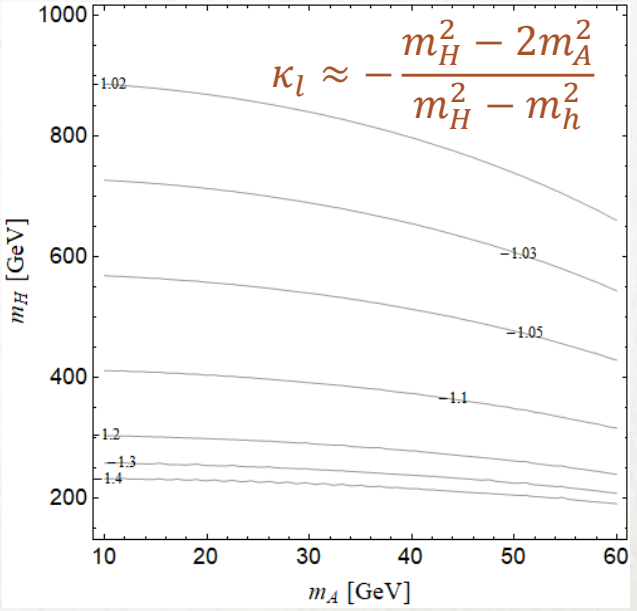
CMS 1805.04865



CMS 2005.08694

$$\frac{g_{hAA}}{v} = \lambda_3 + \lambda_4 - \lambda_5 + O\left(\frac{1}{t_\beta^2}\right) \approx -(1+\kappa_l)m_H^2 + \kappa_l m_h^2 + 2m_A^2$$

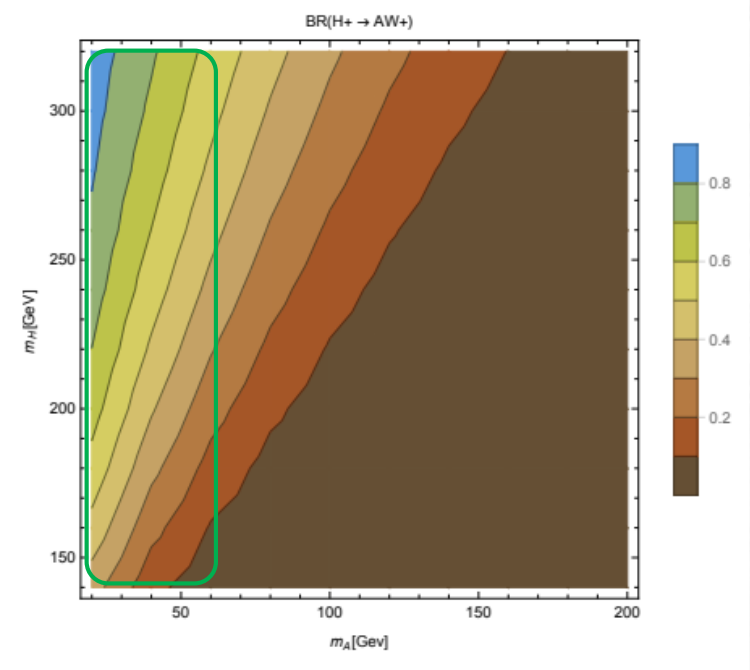
$$\frac{g_{hAA}}{v} \approx 0 \Rightarrow \kappa_l \approx -\frac{m_H^2 - 2m_A^2}{m_H^2 - m_h^2}$$

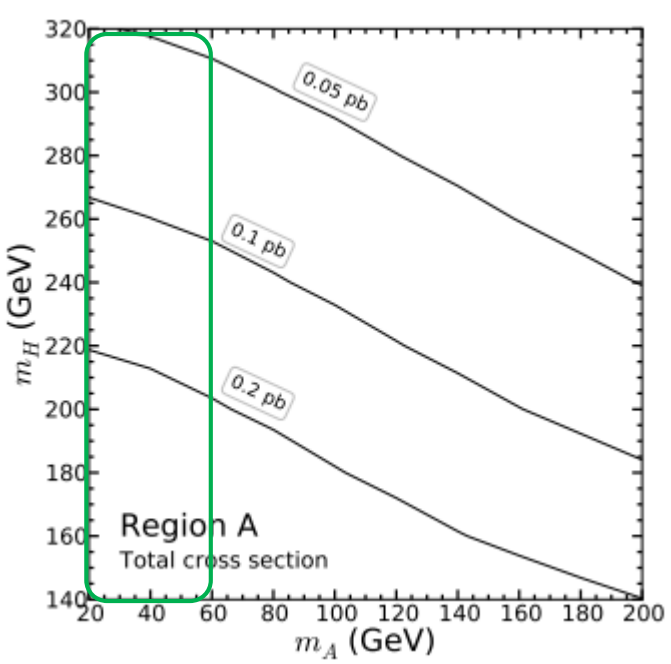


$$\mathrm{B}(h \to AA \to \mu\mu\tau\tau) = 0.35\%\,\mathrm{B}(h \to AA)$$

$$\mathrm{B}(h \to AA) = 6\%\left(\frac{g_{hAA}}{0.007v}\right)^2\sqrt{1-4\,\frac{m_A^2}{m_h^2}}$$

LHC Search: $pp \to AH, AH^{\pm} \to 4\tau, 3\tau$





	point A	point B	point D
m_A [GeV]	20	40	40
m_H [GeV]	200	200	260
total $\sigma_{\rm gen}$ [fb]	270.980	241.830	100.430
$n_\ell \geq 3$	6.606	16.681	7.110
$n_\tau \geq 3$	0.894	2.602	0.888
$\not{E}_T > 100$ GeV	0.201	0.547	0.209
$n_b = n_j = 0$	0.098	0.314	0.121
S/B	0.1	0.5	0.2
$S/\sqrt{B}_{25\text{fb}^{-1}}$	0.6	1.9	0.7

$H^{\pm} \to A\, W^{\pm}, \tau\nu$

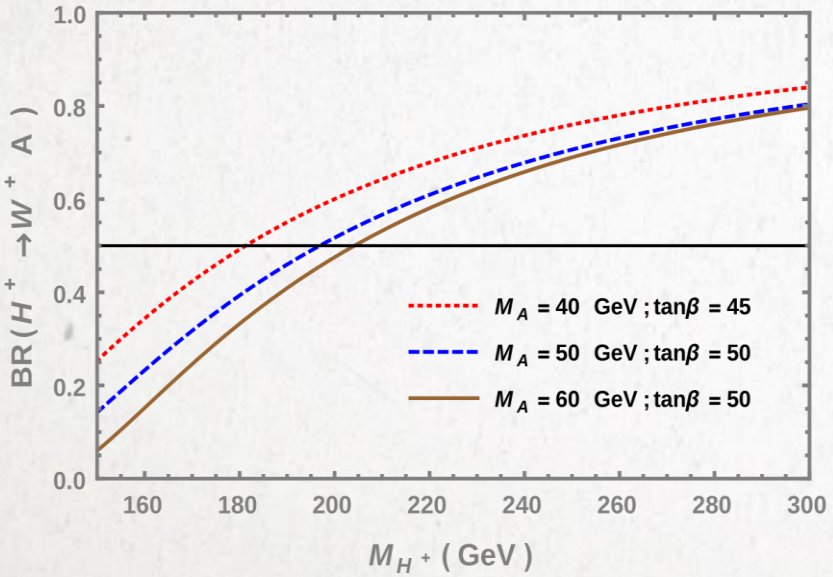
$H \to A\, Z, \tau\tau$

EJC, Z. Kang, M. Takeuchi, Y-L S. Tsai, 1507.08067

LHC Search: $pp \to AH/AH^{\pm} \to A(\mu\mu)A(\tau\tau)Z/W^{\pm}$

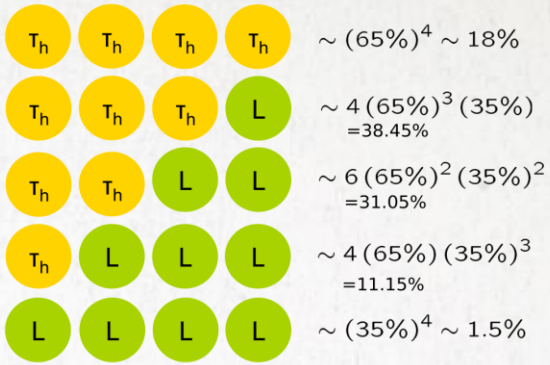
$$\Gamma(H^{\pm} \to W^{\pm} A) \sim \frac{m_{H^{\pm}}}{16\pi}\left(\frac{m_{H^{\pm}}}{v}\right)^2$$

$$\Gamma(H^{\pm} \to \tau^{+}\nu_{\tau}) \sim \frac{m_{H^{\pm}}}{16\pi}\left(\frac{\sqrt{2}m_{\tau}}{v}\tan\beta\right)^2$$



Possible Signatures

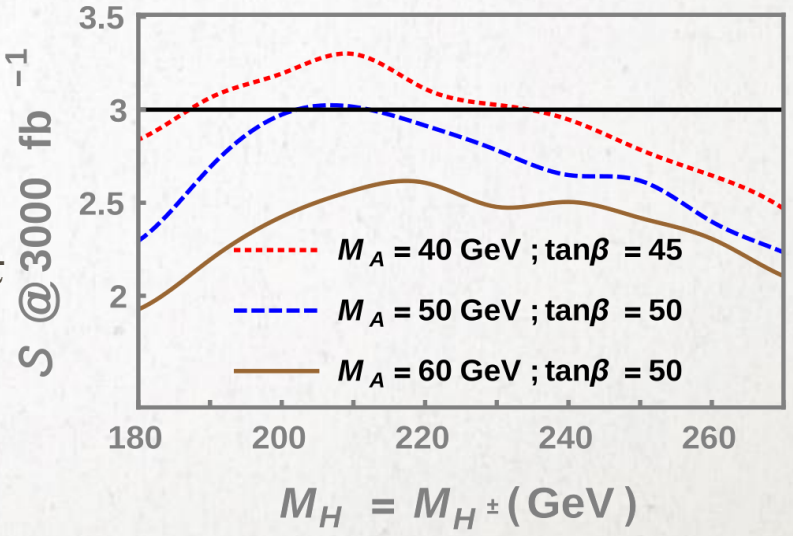
- p p > $H^{\pm}$ A > ($W^{\pm}$ A) A > 1L + **4** τ
- p p > H A > (Z A) A > 2L + **4** τ



Also : Z/W > j j & A > μ μ

- p p > $H^{\pm}$ A > ($W^{\pm}$ A) A > j j μμ + 2 τ
- p p > H A > (Z A) A > j j μμ + 2 τ

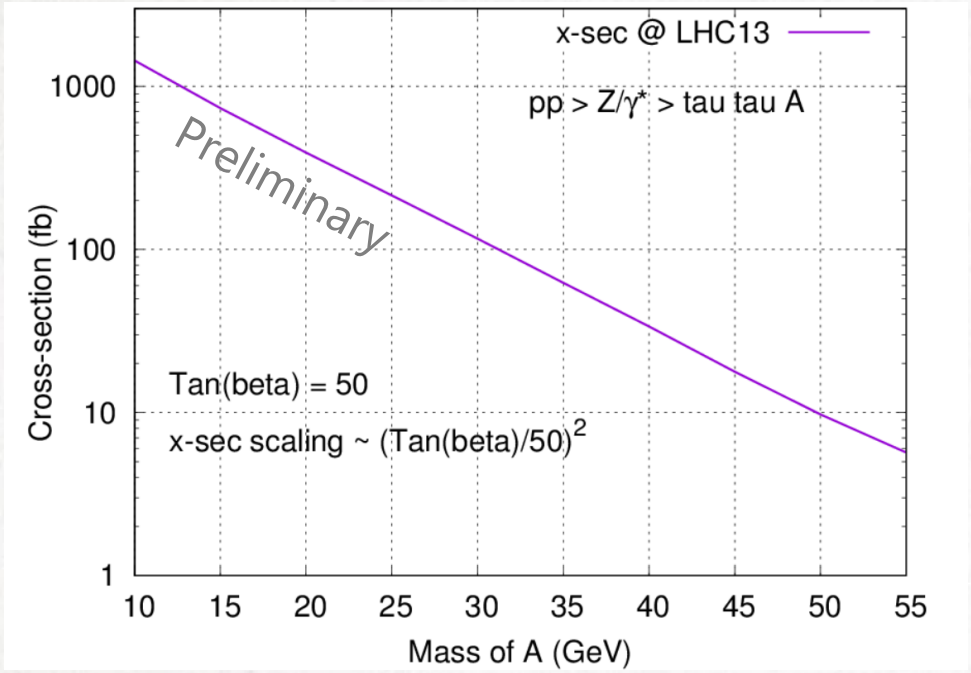
IM(j j μμ) = $m_{H^{\pm}}$

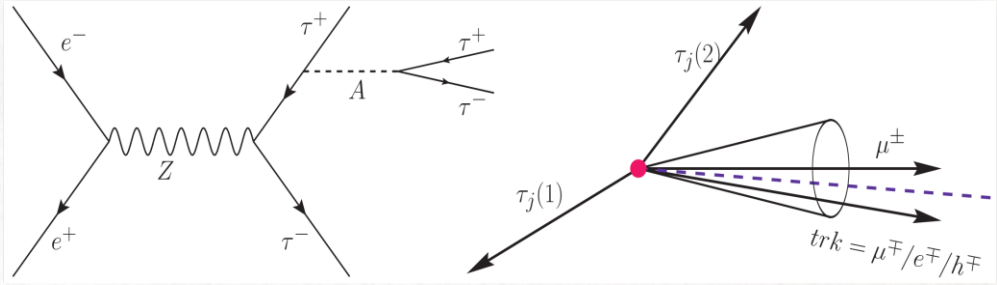


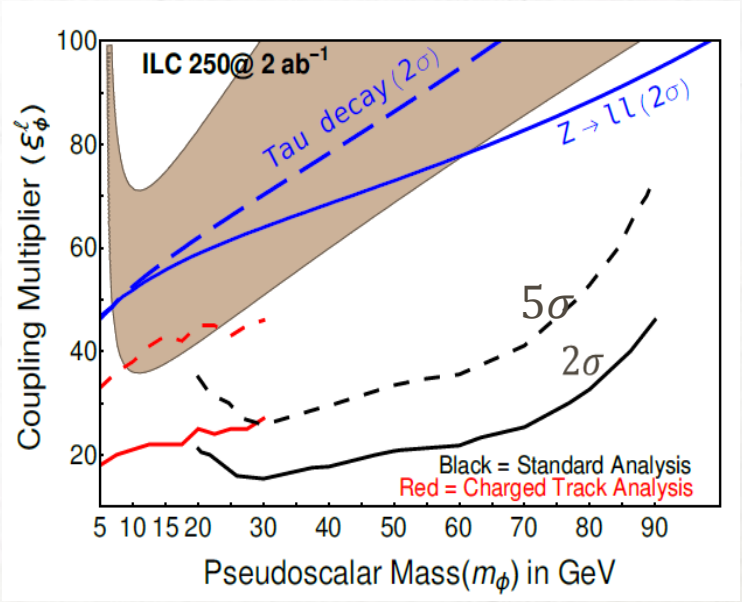
EJC, Dwivedi, TM, Mukhopadhyaya, Rai PRD 98 (2018) 7

LHC Search: $pp \to \tau\tau A(\tau\tau)$?

(*) Lepton collider can cover all the region







EJC, T. Mondal, 1909.09515; 2104.03701

Summary

- The muon g-2 explanation in L2HDM requires $m_{H^\pm} \approx m_H \gg m_A = (10-50)\text{GeV}, \tan\beta = 35-70$.
- Precision determination of the (wrong-sign) tau-Yukawa coupling will provide an additional limit on the spectrum.
- Stay tuned for the current search $pp \to h \to AA(\mu\mu\tau\tau)$ depending on g_{hAA}.
- Dedicated search for $pp \to AH^\pm, AH \to 3\tau, 4\tau$ & $3\tau, 4\tau + \text{W/Z}$
- A direct probe with $pp \to \tau\tau A(\tau\tau)$ should be studied carefully.

BACP UP

2HDM

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

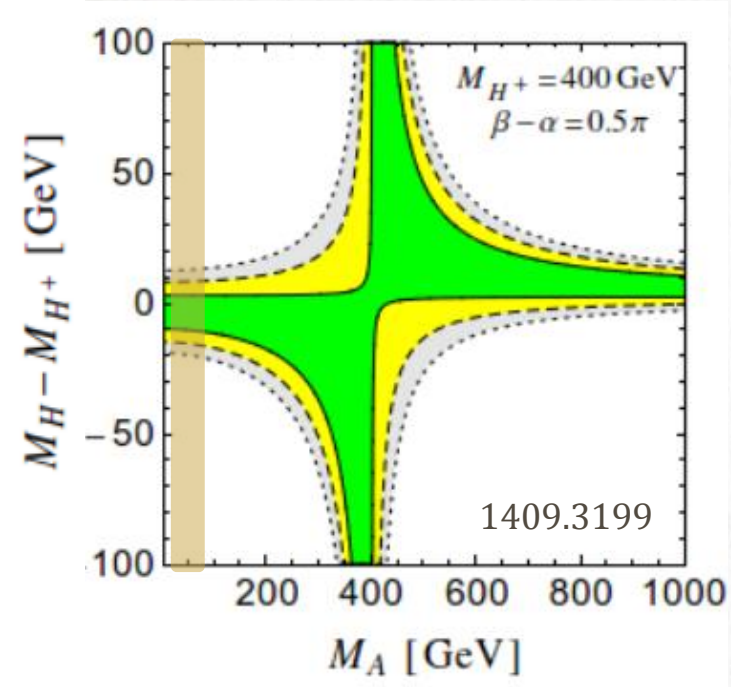
Tau decay in 2HDM

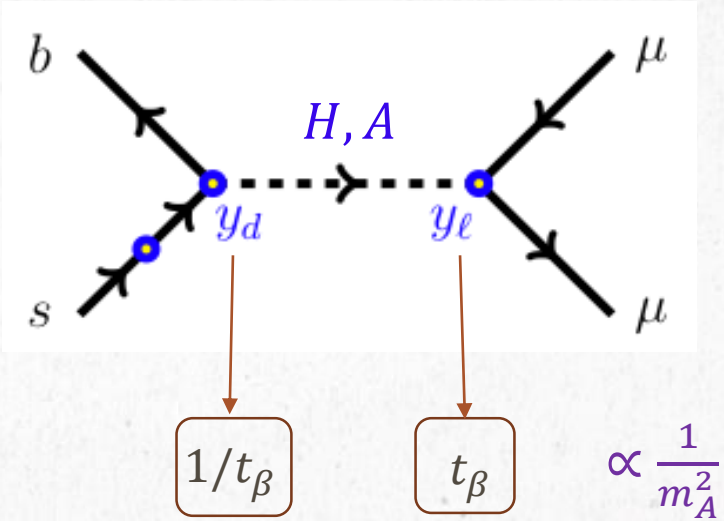
$$\delta_{\text{tree}} = \frac{m_\tau^2 m_\mu^2}{8 m_{H^\pm}^4} t_\beta^4 - \frac{m_\mu^2}{m_{H^\pm}^2} t_\beta^2 \frac{g(m_\mu^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)},$$

$$\delta_{\text{loop}} = \frac{1}{16\pi^2}\frac{m_\tau^2}{v^2} t_\beta^2 \left[1 + \frac{1}{4}\left(H(x_A) + s_{\beta-\alpha}^2 H(x_H) + c_{\beta-\alpha}^2 H(x_h)\right)\right],$$

where $f(x) \equiv 1 - 8x + 8x^3 - x^4 - 12x^2\ln(x)$, $g(x) \equiv 1 + 9x - 9x^2 - x^3 + 6x(1+x)\ln(x)$ and $H(x_\phi) \equiv \ln(x_\phi)(1+x_\phi)/(1-x_\phi)$ with $x_\phi = m_\phi^2/m_{H^\pm}^2$.

EWPT and $B_s \to \mu^+\mu^-$





$\propto \frac{1}{m_A^2} \Rightarrow m_A \gtrsim 10$ GeV

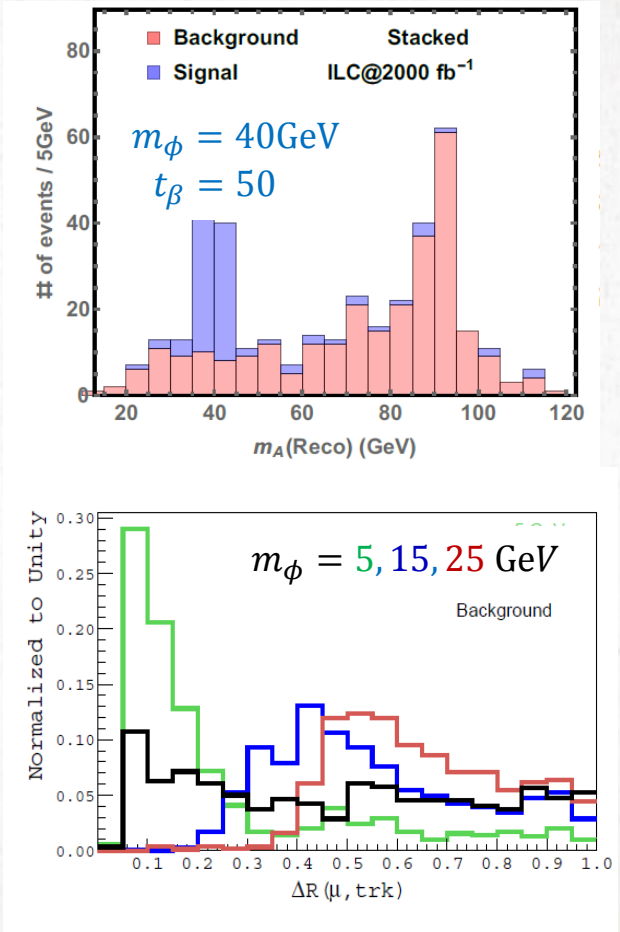
ILC Study

- $e^+e^- \to \tau^+\tau^-\phi \to \tau^+\tau^-(\tau^+\tau^-)$

  1909.09515

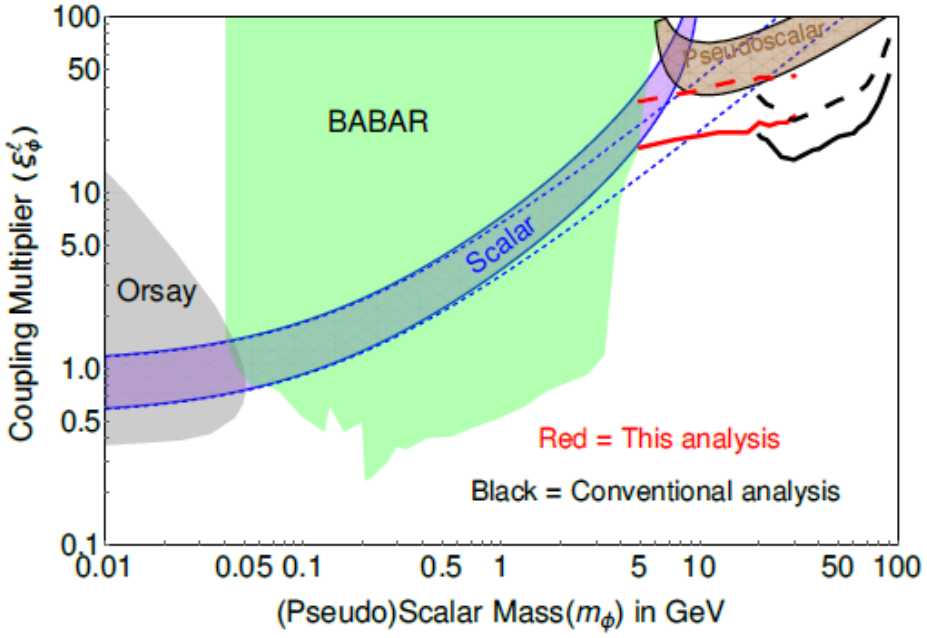
- $e^+e^- \to \tau^+\tau^-\phi(\tau\tau)$ 2104.03701

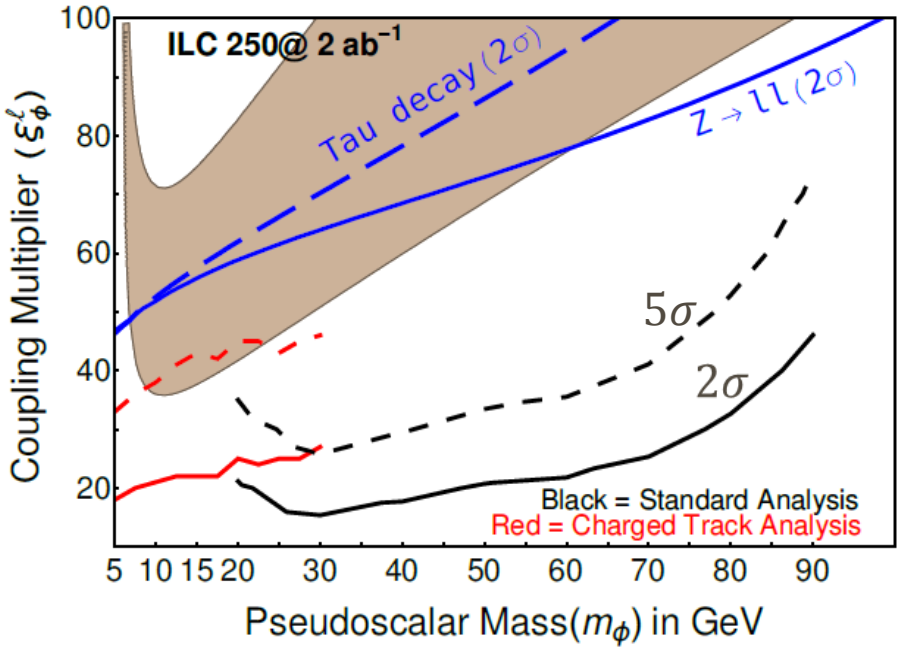
  $\phi(\tau\tau) = \mu^{\pm} + trk^{\mp}(\mu^{\mp}/\, e^{\mp}/h^{\mp})$



ILC Reach

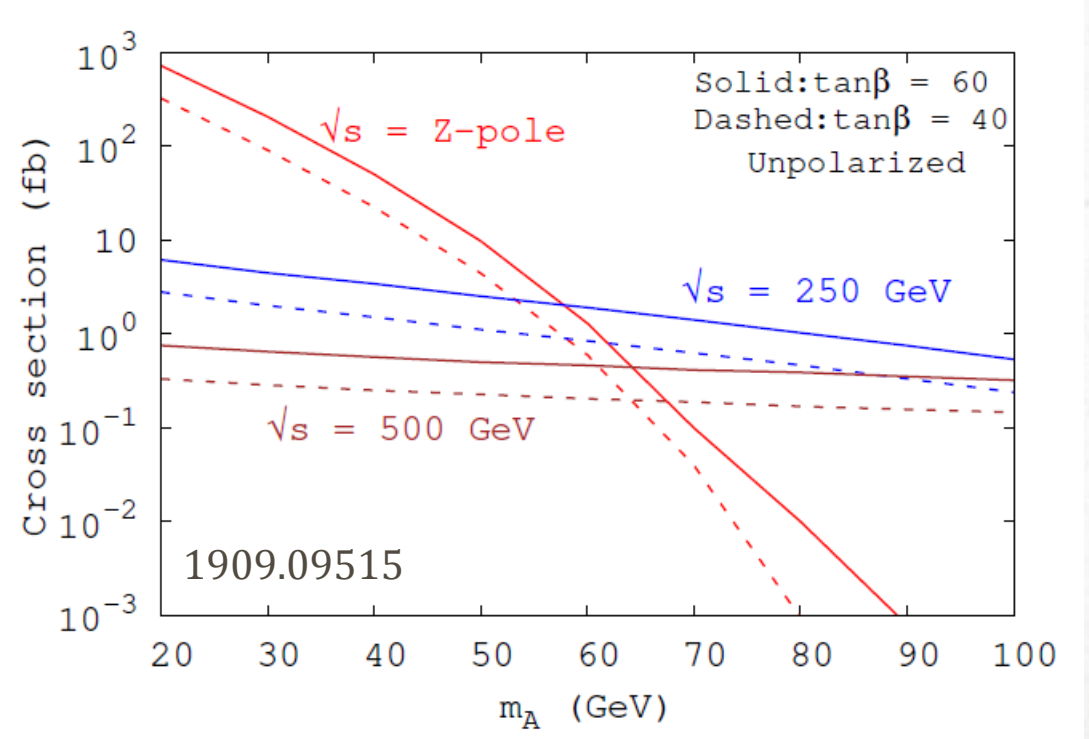
2104.03701





Yukawa production at ILC

$$y_\tau \, \phi\bar{\tau}\tau \;\text{ where } y_\tau = \frac{m_\tau}{v}\xi_l \quad (\xi_l = \tan\beta\sin\theta)$$

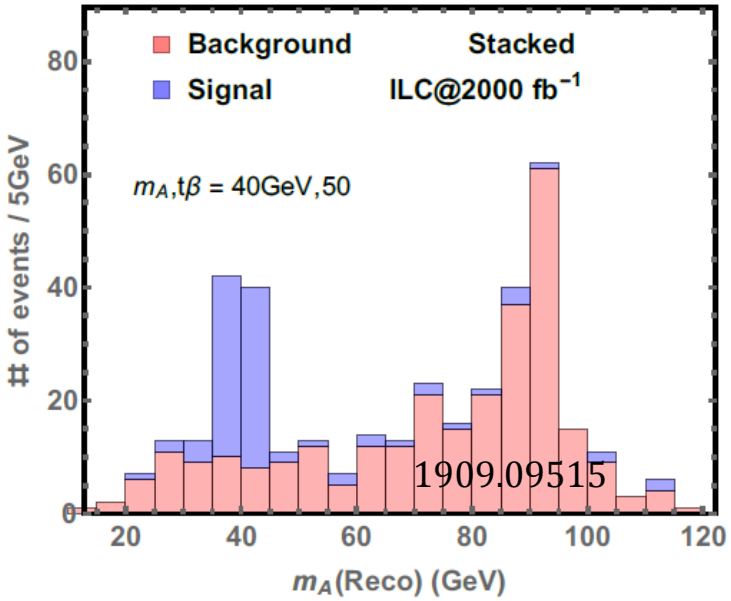


ILC search (I)

- Signal: $e^+e^- \to Z^*(\gamma^*) \to \tau^+\tau^-\ \phi(\tau^+\tau^-)$
- Background: $e^+e^- \to ZZ \to 4\tau, 2\tau 2j$
- Events: $4\tau = 3j_\tau + X(j_\tau/j/l_\tau)$ with $E > 20$ GeV
- Mass reconstruction: $m(j_{\tau 1}j_{\tau 2})$ from $E_{j_{\tau 1}} < E_{j_{\tau 2}} < E_{j_{\tau 3}}$

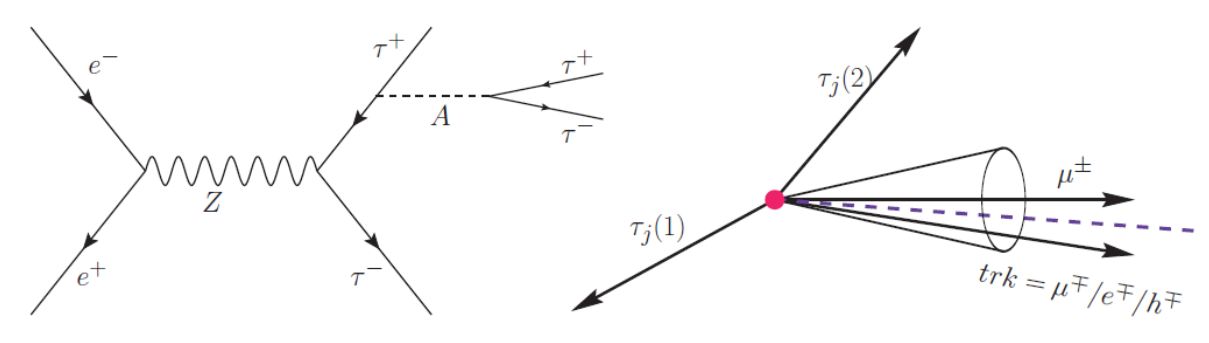
Pre-selection cut : Energy > 20 GeV. $\lvert\eta\rvert$ < 2.3				
$\mathcal{L} = 2000\ fb^{-1}$	Signal	Background		Significance
		4τ	2τ 2 j	
Pre-selection cut	106 [100%]	242 [100%]	98[100%]	5.5
Collinear approx $0 < z_i < 1.1$	91 [86.0%]	217[89.7%]	69[70.4%]	5.1
$m_A \pm 10$GeV	66 [62.3%]	32 [14.9%]	10[10.2%]	8.5

Table 2. Cut flow for $m_A = 40$ GeV and $\tan\beta = 50$ with integrated luminosity of 2000 fb^{-1}.

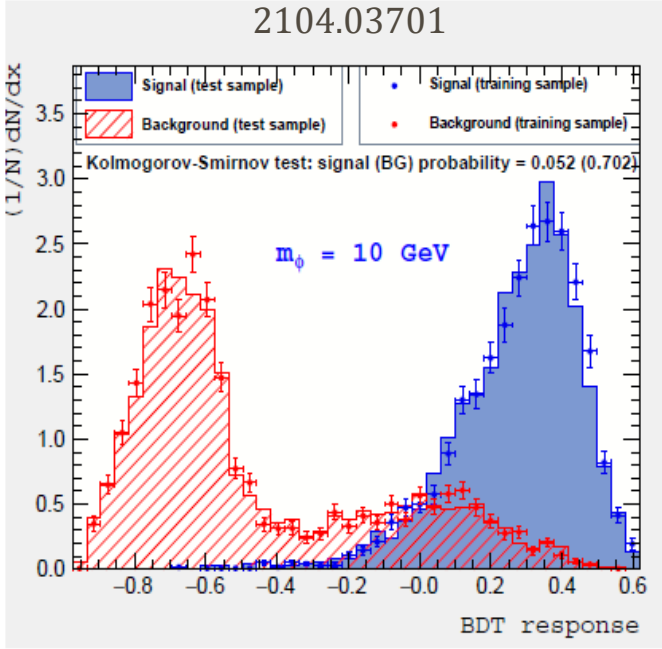


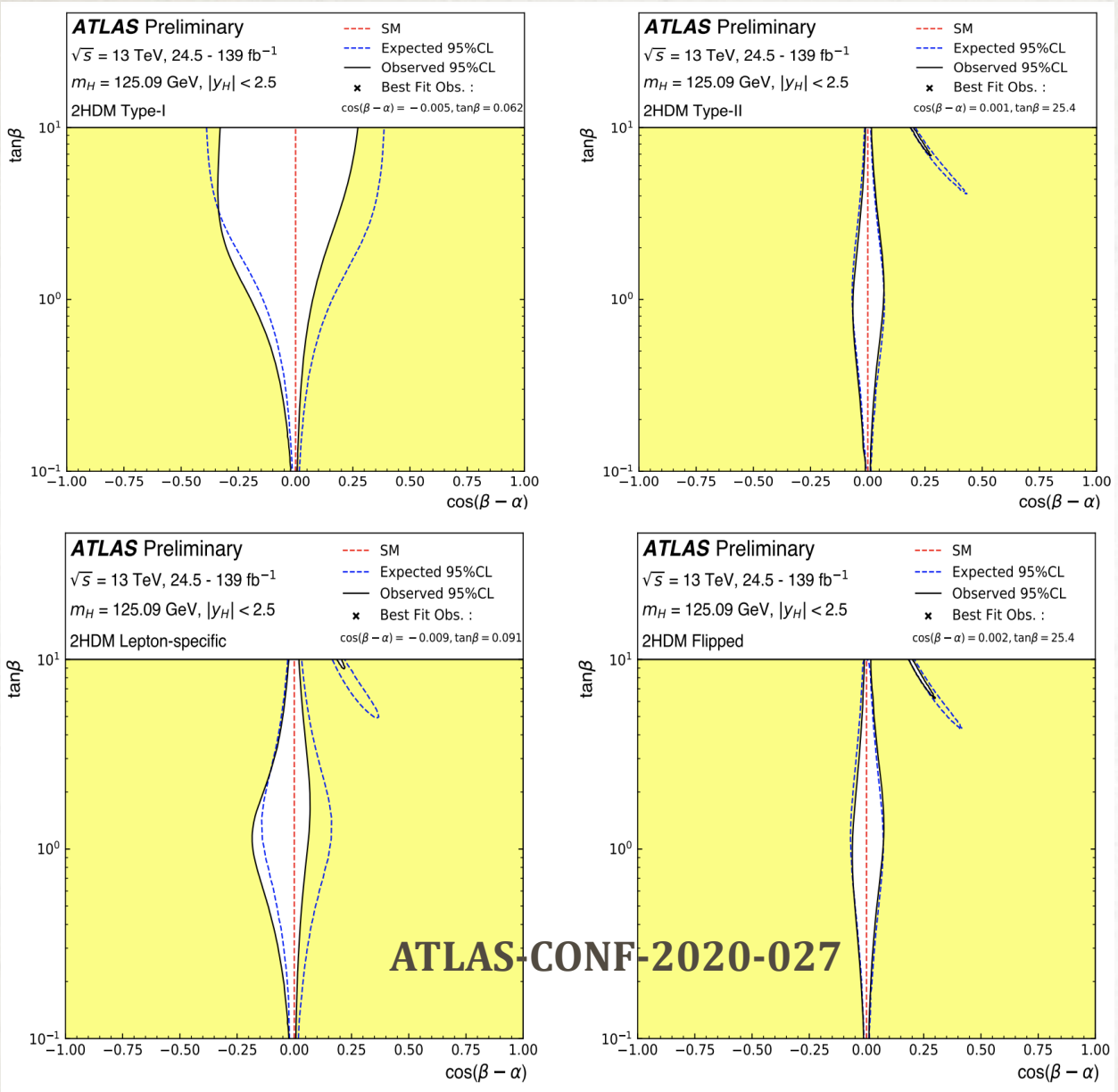
ILC search (II)

- Can we go down to see a lighter particle?
- $\phi(\tau\tau)$ becomes too energetic/collimated.
- Signal events: $\phi(\tau\tau) = \mu^{\pm} + trk^{\mp}(\mu^{\mp}/\, e^{\mp}/h^{\mp})$



- Background: $e^+e^- \to Z(\gamma^*)\, Z(\gamma^*) \to 2\mu 2\tau, 4\tau$





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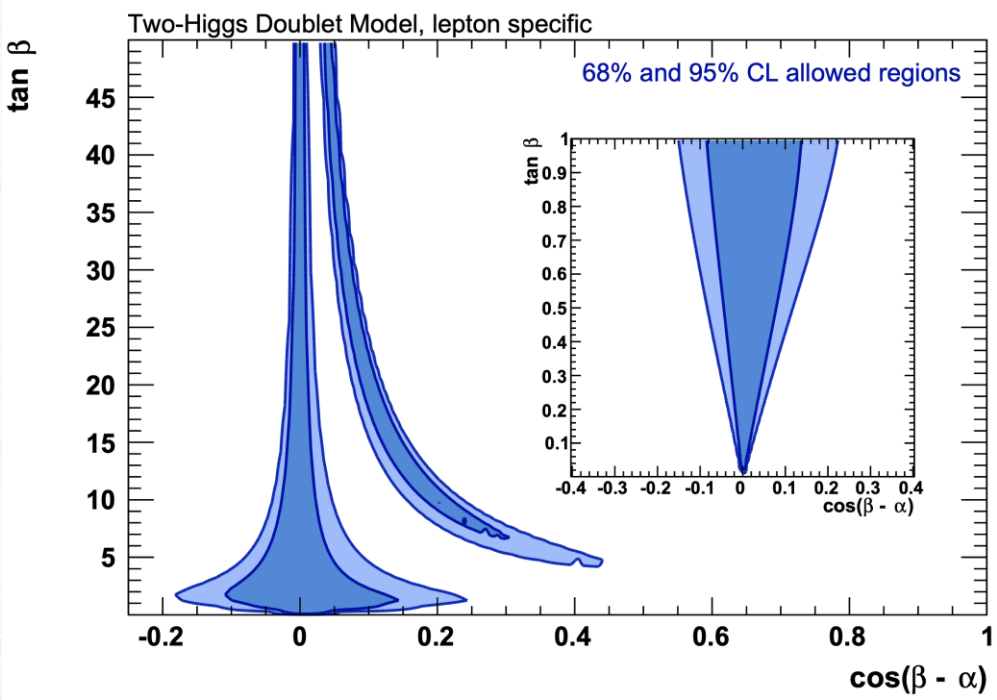

arXiv:1803.01853
GFitter