Exploring doubly charged Higgs bosons collider signals in light of low energy constrains

Magdalena Kordiaczyńska

University of Silesia

in collaboration with
Tripurari Srivastava, Janusz Gluza

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Plan:

1. Extensions of the Standard Model
2. Higgs Triplet Model
3. $H^{\pm\pm} - l - l'$ coupling (LFV)
4. Experimental constraints
5. $H^{\pm\pm}$ decay (HTM and LRSM)
6. Pair production and collider signals
7. Summary

Extensions of the Standard Model

- Higgs Triplet Model (HTM)
  One additional triplet:

$$\Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} w_{\Delta}^{+} & \sqrt{2}\delta^{++} \\ v_{\Delta} + h_{\Delta} + iz_{\Delta} & -w_{\Delta}^{+} \end{pmatrix}$$

- Doubly charged scalar particles exist in other Standard Model's extention, for example Left Right Symmetric Model (LRSM)

Extensions of the Standard Model

HTM	MLRSM
Type II See-Saw	Three heavy neutrinos
$SU(2) \times U(1)$	$SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ $W_1,\ W_2,\ Z_1,\ Z_2,\ \gamma$
$h, H, A, H^{\pm},\ H^{\pm\pm}$	$h, H_1, H_2, H_3, A_1, A_2$ $H_1^{\pm}, H_2^{\pm},\ H_1^{\pm\pm}, H_2^{\pm\pm}$

HTM - Lagrangian

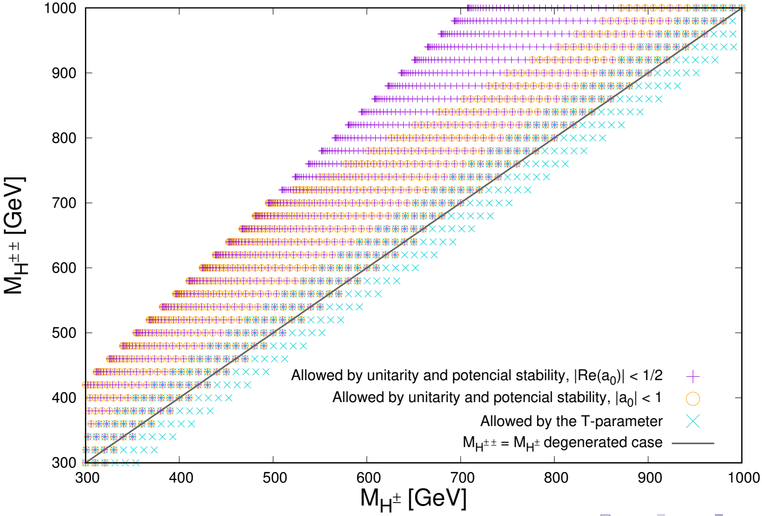
$$
\begin{aligned}
V = & -m_\Phi^2\left(\Phi^\dagger\Phi\right) + M^2 \mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \left\{\mu\left(\Phi^T i\sigma_2\Delta^\dagger\Phi\right) + \mathrm{h.c.}\right\} \\
& + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \lambda_1\left(\Phi^\dagger\Phi\right)\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \lambda_2\left\{\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right\}^2 \\
& + \lambda_3 \mathrm{Tr}\left[\left(\Delta^\dagger\Delta\right)^2\right] + \lambda_4\left(\Phi^\dagger\Delta\Delta^\dagger\Phi\right)
\end{aligned}
$$

- Potential stability
- Unitarity

HTM - Lagrangian

$$
\begin{aligned}
M_A^2 &= \frac{\mu}{\sqrt{2}v_\Delta}(v_\Phi^2 + 4v_\Delta^2) \\
M_h^2 &= \lambda v_\Phi^2 \cos^2\alpha + \left(\frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} + 2v_\Delta^2(\lambda_2 + \lambda_3)\right)\sin^2\alpha \\
&\quad +2\left(v_\Phi v_\Delta(\lambda_1 + \lambda_4) - \sqrt{2}\mu v_\Phi\right)\cos\alpha\sin\alpha \\
M_H^2 &= \lambda v_\Phi^2 \sin^2\alpha + \left(\frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} + 2v_\Delta^2(\lambda_2 + \lambda_3)\right)\cos^2\alpha \\
&\quad -2\left(v_\Phi v_\Delta(\lambda_1 + \lambda_4) - \sqrt{2}\mu v_\Phi\right)\cos\alpha\sin\alpha \\
M_{H^\pm}^2 &= \frac{(2\sqrt{2}\mu - \lambda_4 v_\Delta)}{4v_\Delta}(v_\Phi^2 + 2v_\Delta^2) \\
M_{H^{\pm\pm}}^2 &= \frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} - \frac{\lambda_4}{2}v_\Phi^2 - \lambda_3 v_\Delta^2
\end{aligned}
$$

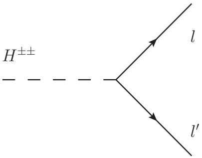
Unitarity, stability



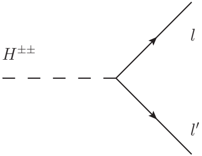
$H^{\pm\pm} - l - l'$ coupling

$$\mathcal{L}_Y = \frac{1}{2} f_{\ell\ell'} L_\ell^T C^{-1} i\sigma_2 \Delta L_{\ell'} + \mathrm{h.c.}$$

$$\mathcal{L}_\nu = \frac{1}{2}\, \bar{\nu}_\ell\, \frac{v_\Delta}{\sqrt{2}}\, f_{\ell\ell'}\, \nu_{\ell'}$$



$H^{\pm\pm} - l - l'$ coupling



$$f = \frac{1}{\sqrt{2}v_\Delta} \; V^*_{PMNS} \, D_\nu \, V^\dagger_{PMNS} \qquad\qquad D_\nu = \frac{1}{2}\,\mathrm{diag}\{m_1, m_2, m_3\}$$

Neutrino parameters

$$v_\Delta \iff f_{ll'} \iff \theta_{12},\ \theta_{23},\ \theta_{13},\ \delta_{\mathrm{CP}}$$

$$m_1,\ m_2,\ m_3$$

$f_{ll'}$ coupling and parameter's constraints

- $10^{-7} \leq f_{ll'} \leq \sqrt{4\pi}$ [hep-ex/0309076]
- $v_\Delta \sim 1\,\mathrm{GeV}$ [Phys.Rev. D21 (Mar, 1980) 1404-1409], [arXiv:0712.4053]

$$\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W} = \frac{1 + 2\frac{v_\Delta^2}{v_\phi^2}}{1 + 4\frac{v_\Delta^2}{v_\phi^2}} = 1.00040 \pm 0.00024$$

- $\sum m_i \leq 2$ eV - Tritium decay [PDG]
  $\sum m_i \leq 0.23$ eV - astrophysics [arXiv:1303.5076]

Neutrino oscillation data

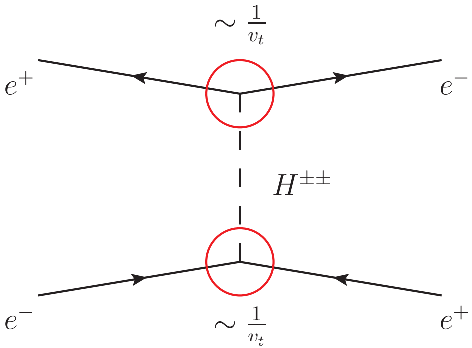
	Normal hierarchy			Inverted hierarchy		
	Best fit:	σ	bfp$\pm 2\sigma$	Best fit:	σ	bfp$\pm 2\sigma$
$\sin^2\theta_{12}$	0.306	${}^{+0.012}_{-0.012}$	0.282 $\div$ 0.330	0.306	${}^{+0.012}_{-0.012}$	0.282 $\div$ 0.330
$\sin^2\theta_{23}$	0.441	${}^{+0.027}_{-0.021}$	0.399 $\div$ 0.495	0.587	${}^{+0.020}_{-0.024}$	0.539 $\div$ 0.627
$\sin^2\theta_{13}$	0.02166	${}^{+0.00075}_{-0.00075}$	0.02016 $\div$ 0.02316	0.02179	${}^{+0.00076}_{-0.00076}$	0.02027 $\div$ 0.02331
$\delta_{CP}[^o]$	261	${}^{+51}_{-59}$	143 $\div$ 363	277	${}^{+40}_{-46}$	185 $\div$ 357
$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2}$	7.50	${}^{+0.19}_{-0.17}$	7.16 $\div$ 7.88	7.50	${}^{+0.19}_{-0.17}$	7.16 $\div$ 7.88
$\frac{\Delta m^2_{3l}}{10^{-3}\mathrm{eV}^2}$	+2.524	${}^{+0.039}_{-0.040}$	2.445 $\div$ 2.602	-2.514	${}^{+0.038}_{-0.041}$	-2.596 $\div$ -2.438

[www.nu-fit.org , arXiv:1611.01514]

Experimental constraints

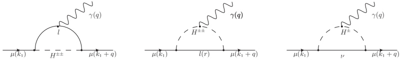
- High energy:
  - Bhabha scattering: $f_{ee}^2 \leq 6.0 \times 10^{-6} M_{H^{\pm\pm}}$

[Phys.Rev. D40 (1989) 1521] , [hep-ph/0304069]

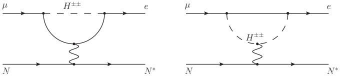


Experimental constraints

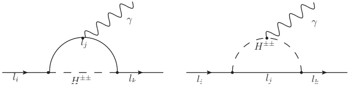
- Low energy:
  - $(g-2)_\mu$ contribution:



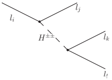
  - μ to e conversion:



  - Radiative LFV decays:



  - LFV three body decays :



Experimental constraints

- $(g-2)_\mu$

$$\Delta a_{(muong-2)} = (29.3 \pm 9.0) \times 10^{-10}$$

- μ to e (for Au)

$$\text{BR}(\mu N \to e N^*) < 7.0 \times 10^{-13}$$

- Radiative LFV decays

$$\text{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

$$\text{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

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

- LFV three body decays

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

$$\text{BR}(\tau \to 3\mu) < 2.1 \times 10^{-8}$$

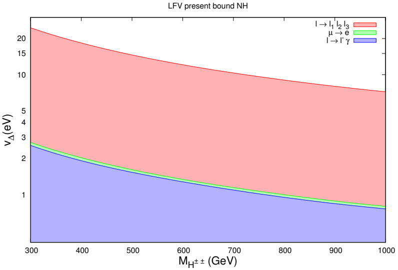
$$\text{BR}(\tau \to e\mu^+\mu^-) < 2.7 \times 10^{-8}$$

$$\text{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$$

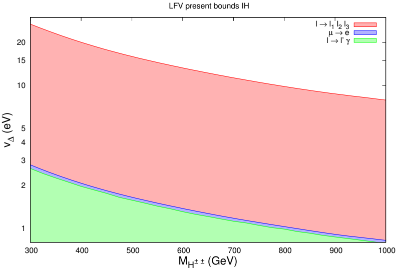
[arXiv:1512.03581] , [Nucl. Phys. B299 (1988) 1-6]

v_Δ vs $M_{H^{\pm\pm}}$

NH

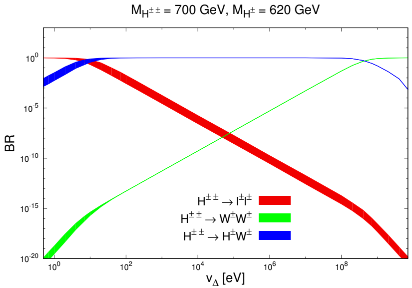


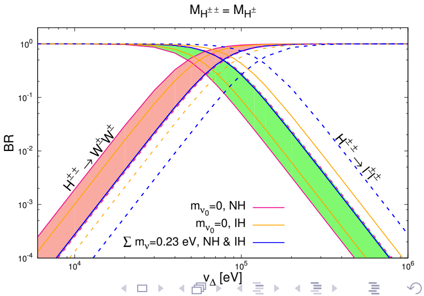
IH



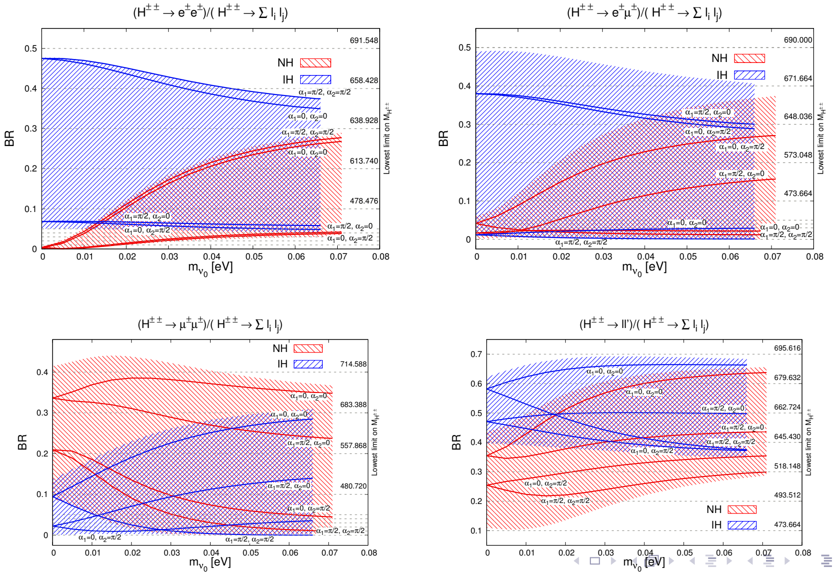
$H^{\pm\pm}$ decay

- $H^{\pm\pm} \to l_i l_j$
- $H^{\pm\pm} \to W^{\pm} W^{\pm}$
- $H^{\pm\pm} \to H^{\pm} W^{\pm}$
- $H^{\pm\pm} \to H^{\pm} H^{\pm}$



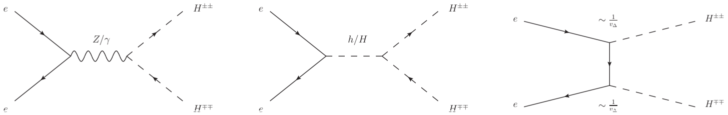


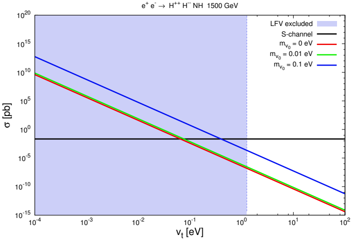
$H^{\pm\pm}$ decay

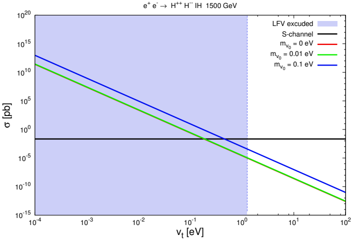


(H±± → e±e±)/(H±± → Σ li lj)
(H±± → e±μ±)/(H±± → Σ li lj)
(H±± → μ±μ±)/(H±± → Σ li lj)
(H±± → ll')/(H±± → Σ li lj)
BR
mν0 [eV]
NH
IH
Lowest limit on MH±±
α1=π/2, α2=π/2
α1=0, α2=0
α1=π/2, α2=0
α1=0, α2=π/2
691.548
658.428
638.928
613.740
478.476
690.000
671.664
648.036
573.048
473.664
714.588
683.388
557.868
480.720
695.616
679.632
662.724
645.430
518.148
493.512
473.664

$H^{\pm\pm}$ pair production in lepton colliders

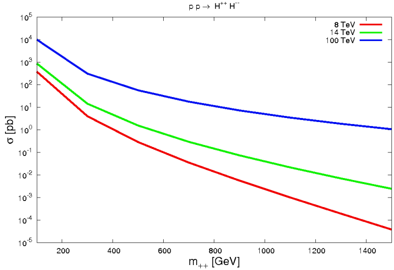






$H^{\pm\pm}$ pair production in hadron colliders

HTM



For MLRSM see `arXiv:1311.4144`

$pp \to H^{++}H^{--} \to$ 4-leptons signal

Luminosity $25fb^{-1}$, $\sqrt{s} = 14$ TeV

$M_{H^{\pm\pm}}$	SM	MLRSM	HTM			
			NH		IH	
			$\alpha_1 = 0,\ \alpha_2 = 0$	$\alpha_1 = 0,\ \alpha_2 = \frac{\pi}{2}$	$\alpha_1 = 0,\ \alpha_2 = 0$	$\alpha_1 = 0,\ \alpha_2 = \frac{\pi}{2}$
400	2.9	30	7.3	2.6	33	20
600		4.4	1.0	0.4	4.9	2.9

Summary

- $H^{\pm\pm}$ pair production in colliders gives possibility for clean BSM 4l signals
- For $\theta_{13} \neq 0$ the strongest limit on v_t comes from the $\mu \to 3e$ LFV process
- T channel contribution to the $H^{\pm\pm}$ pair production in lepton colliders is negligible due to the low energy constraints
- Heavy gauge bosons (RH currents) do not influence the total number of event for the 4-lepton signal in hadron colliders

Thank you for your attention

mkordiaczynska@us.edu.pl

U_{PMNS}

$$V_{PMNS} = \begin{bmatrix} c_{12}c_{13}e^{i\alpha_1} & s_{12}c_{13}e^{i\alpha_2} & s_{13}e^{-i\delta_{CP}} \\ (-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & s_{23}c_{13} \\ (s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & c_{23}c_{13} \end{bmatrix} \quad (1)$$

ρ and T parameters

$$\Delta\rho = \frac{\prod_{WW}(0)}{M_W^2} - \frac{\prod_{ZZ}(0)}{M_Z^2}$$

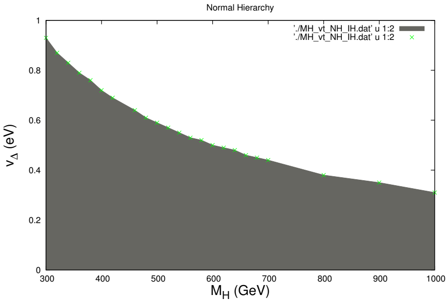
$$T = \frac{1}{\alpha}\left(\frac{\prod_{WW}(0)}{M_W^2} - \frac{\prod_{ZZ}(0)}{M_Z^2}\right) = \frac{\rho - 1}{\alpha} = 0.05 \pm 0.12$$

$$\Delta T = \frac{1}{4\pi \sin\theta_W{}^2 M_W^2}\left(F(M_{H^\pm}^2, M_A^2) + F(M_{H^{\pm\pm}}^2, M_{H^\pm}^2)\right)$$

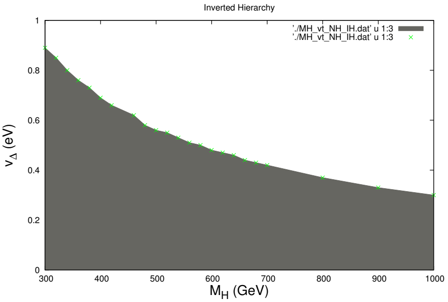
$$\Delta T < 0.2$$

$$F(x,y) = \frac{x+y}{2} - \frac{xy}{x-y}\ln\left(\frac{x}{y}\right)$$

$(g-2)_\mu$

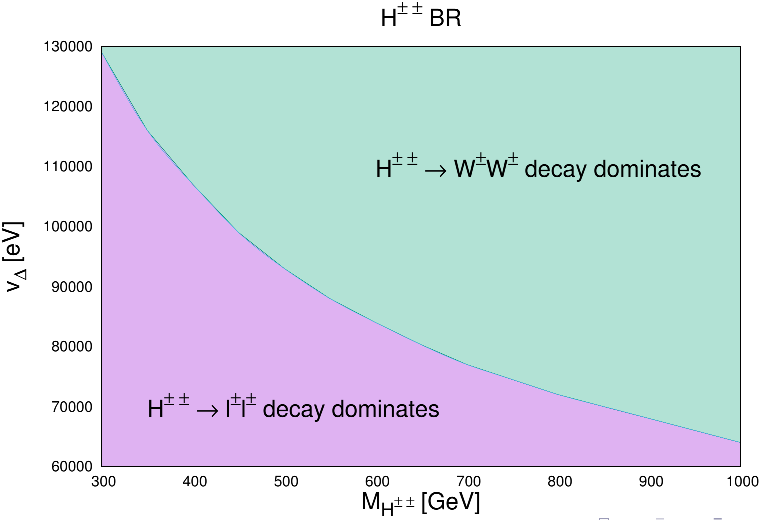


Normal Hierarchy
'./MH_vt_NH_IH.dat' u 1:2
'./MH_vt_NH_IH.dat' u 1:2
v_Δ (eV)
M_H (GeV)

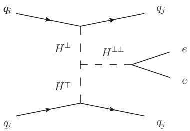


Inverted Hierarchy
'./MH_vt_NH_IH.dat' u 1:3
'./MH_vt_NH_IH.dat' u 1:3
v_Δ (eV)
M_H (GeV)

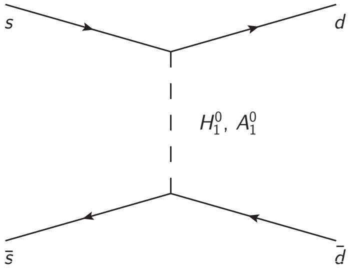
$H^{\pm\pm}$ decay


$H^{\pm\pm}$ BR
130000
120000
110000
100000
90000
80000
70000
60000
v_Δ [eV]
300
400
500
600
700
800
900
1000
$M_{H^{\pm\pm}}$ [GeV]
$H^{\pm\pm} \to W^{\pm}W^{\pm}$ decay dominates
$H^{\pm\pm} \to l^{\pm}l^{\pm}$ decay dominates

$0\nu\beta\beta$



FCNC



Potential stability

$$
\begin{aligned}
\lambda &> 0 \\
\lambda_2 + \lambda_3 &\geq 0 \\
\lambda_2 + \frac{\lambda_3}{2} &\geq 0 \\
\lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} &\geq 0 \\
\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} &\geq 0
\end{aligned}
$$

$$
\left[\begin{aligned}
|\lambda_4|\sqrt{\lambda_2 + \lambda_3} - \lambda_3\sqrt{\lambda} &\geq 0 \\
\text{or} \quad 2\lambda_1 + \lambda_4 + \sqrt{(2\lambda\lambda_3 - \lambda_4^2)\left(\frac{2\lambda_2}{\lambda_3} + 1\right)} &\geq 0
\end{aligned} \right]
$$

Unitarity

$$\begin{aligned}
\left|(\lambda + 4\lambda_2 + 8\lambda_3) \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}\right| &\leq 64\pi \\
\left|(3\lambda + 16\lambda_2 + 12\lambda_3) \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}\right| &\leq 64\pi \\
|\lambda| &\leq 32\pi \\
|2\lambda_1 + 3\lambda_4| &\leq 32\pi \\
|2\lambda_1 - \lambda_4| &\leq 32\pi \\
|\lambda_1| &\leq 16\pi \\
|\lambda_1 + \lambda_4| &\leq 16\pi \\
|2\lambda_2 - \lambda_3| &\leq 16\pi \\
|\lambda_2| &\leq 8\pi \\
|\lambda_2 + \lambda_3| &\leq 8\pi
\end{aligned}$$