LHC explores what LEP hinted at: CP-violating type-I 2HDM

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Technische Universität Dresden

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"Physics at the Terascale"
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Based on

- JhP, JHEP10(2006)077
- Mader, JhP, Pruna, Stöckinger, Straessner, JHEP09(2012)125

Lepton universality in charged current interactions

- SM predicts lepton universality
- W boson couplings to e, μ, τ are determined by SU(2) gauge invariance

$$\mathscr{L}_{\rm CC} = \frac{g}{\sqrt{2}} \sum_{l=e,\mu,\tau} W_\mu^\dagger \, \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2} \right) l + \text{h.c.}$$

- Thoroughly tested in $\mu \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to e\nu\nu$, $\pi \to e\nu$, $\pi \to \mu\nu$, $\tau \to \pi\nu$, ...
  All tests confirm lepton universality

Test of lepton universality using $\mu \to e\nu\nu$ and $\tau \to \mu\nu\nu$

- Parametrize

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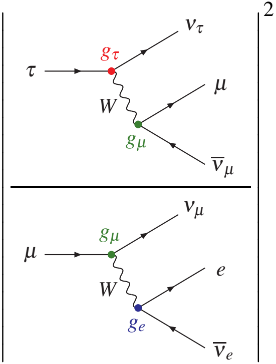
- Take ratio $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$:



$$\rightsquigarrow \quad (g_\tau/g_e)_{\tau\mu} = 1.0004 \pm 0.0022$$

Data from Loinaz, Okamura, Rayyan, Takeuchi, Wijewardhana, PRD(2004)

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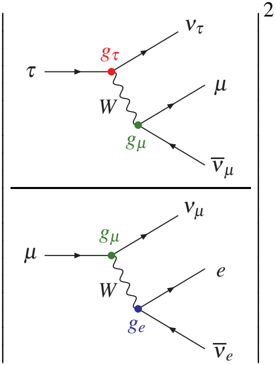

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Perfect agreement with lepton universality

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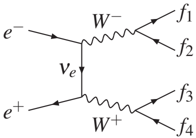
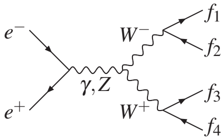
Measurement of $B(W \to l\nu)$ at LEP

LEP directly measured
$B(W \to e\nu_e)$, $B(W \to \mu\nu_\mu)$, $B(W \to \tau\nu_\tau)$,
from partial cross sections of $WW \to 4f$





$(f_1, f_2) = (e, \overline{\nu}_e), (\mu, \overline{\nu}_\mu), (\tau, \overline{\nu}_\tau), (d, \overline{u}), (s, \overline{c})$
(f_4, f_3) is a conjugate

Excess in tau mode

LEP electroweak working group, hep-ex/0612034

- LEP results

Experiment	$B(W \to e\nu_e)$ [%]	$B(W \to \mu\nu_\mu)$ [%]	$B(W \to \tau\nu_\tau)$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22

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$$\left. \frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2} \right|_{\mathrm{LEP}} = 1.077 \pm 0.026$$

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Dilemma

- A model leading to effective interactions

$$\mathscr{L}_{\mathrm{CC}} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W_\mu^\dagger \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) l + \text{h.c.},$$

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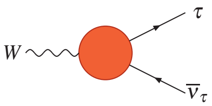

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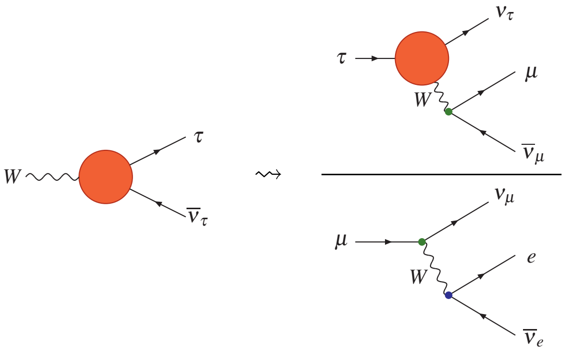

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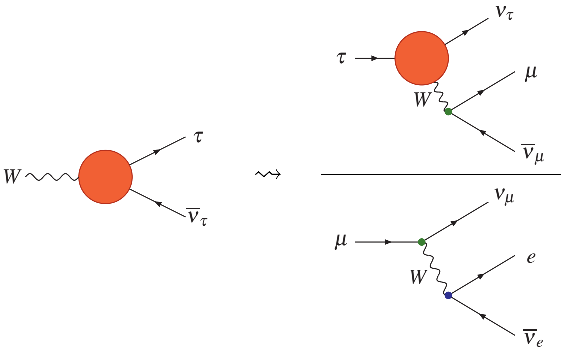

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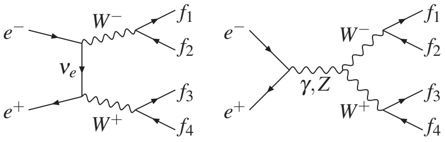
Charged Higgs solution

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP



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- σ_{HH} is a decreasing function of $M_{H^\pm}$ $\quad \rightarrow \quad$ $M_{H^\pm} \approx m_W$ desirable
- Hard to realize in MSSM due to

$$M^2_{H^\pm} = m^2_W + m^2_A \quad \text{and} \quad m_A > 93 \text{ GeV}$$

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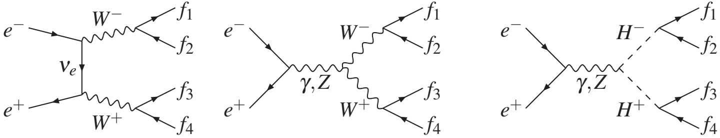

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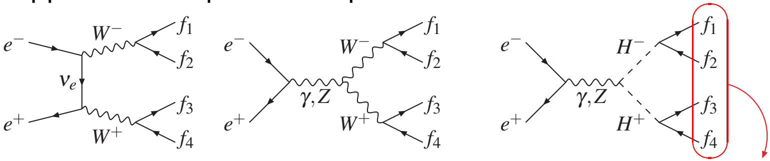

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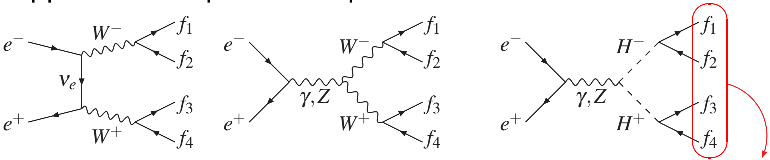

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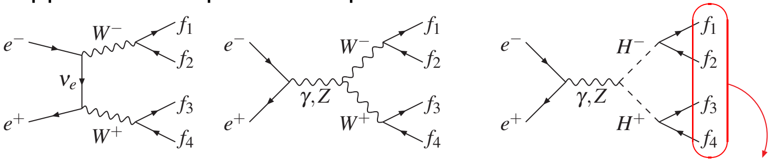

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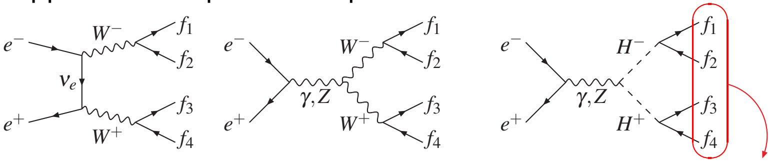

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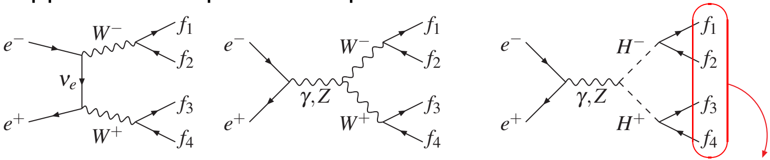

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Naturally flavour-conserving 2HDMs

- Arrange Yukawas to kill Higgs-mediated tree-level FCNC

Glashow, Weinberg, PRD(1977)

Model labels borrowed from Barger, Hewett, Phillips, PRD(1990)

Models	I		II		III		IV	
	VEV	A_f	VEV	A_f	VEV	A_f	VEV	A_f
u	Φ_2	$\cot\beta$	Φ_2	$\cot\beta$	Φ_2	$\cot\beta$	Φ_2	$\cot\beta$
d	Φ_2	$-\cot\beta$	Φ_1	$\tan\beta$	Φ_1	$\tan\beta$	Φ_2	$-\cot\beta$
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$$\tan\beta \equiv v_2/v_1$$

- $H^{\pm}$-fermion-fermion interactions

$$\mathscr{L} = \frac{g}{\sqrt{2}m_W} H^+ [V_{ij} m_{u_i} A_u \overline{u}_{Ri} d_{Lj} + V_{ij} m_{d_j} A_d \overline{u}_{Li} d_{Rj} + m_l A_l \overline{\nu}_L l_R] + \text{h.c.}$$

govern $b \to s\gamma$, $t \to H^+ b$, $H^{\pm} \to \tau\nu_\tau$, ...

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govern $b \to s\gamma$, $t \to H^+ b$, $H^{\pm} \to \tau\nu_\tau$, ...

H^+-fermion couplings in Model I are suppressed by $\cot\beta$

Requirements

- $82\ \mathrm{GeV} \leq M_{H^\pm} \lesssim 86\ \mathrm{GeV}$ $\longleftarrow$ LEP

  OPAL, EPJC(2012)

- Experimental constraints:
  FCNC, CP-violation, S, T, U, $t \to H^+ b$, $B^- \to \tau\nu$,
  other lepton universality tests

Out of four models with natural flavour conservation, only **type-I** works if $\tan\beta \gtrsim 4$

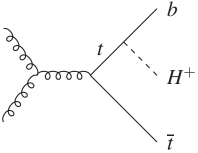
Test at ILC

- What to look for: charged Higgs with $M_{H^\pm} \approx m_W$ that couples very weakly to fermions
- Doable at ILC
- Beam polarization helps a lot

e^-/e^+ polarization	σ_{HH} [pb]	σ_{WW} [pb]	σ_{HH}/σ_{WW} [%]
0%/ 0%	0.10	7.13	1.4
80%/ 0%	0.05	1.47	3.3
90%/ 0%	0.04	0.76	5.4
80%/60%	0.06	0.65	8.7
90%/60%	0.06	0.37	15.0

for $\sqrt{s} = 500$ GeV, right-handed electron and left-handed positron beam polarizations

Standard light $H^{\pm}$ search at hadron colliders



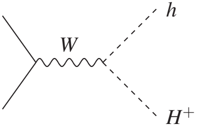
$$\propto \quad \frac{1}{\tan\beta}$$

- Escapes from Tevatron search if $\tan\beta \gtrsim 1$
- Can be relevant at the LHC for low $\tan\beta$

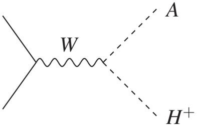
ATLAS, CMS, JHEP(2012)

Alternative channels for $H^{\pm}$ search

Djouadi, Kilian, Muhlleitner, Zerwas, EPJC(1999)



$\propto \cos(\beta-\alpha)$



$\propto 1$

- May survive even at high $\tan\beta$
- $\sigma(pp \to H^{\pm}, h|A) \sim 100$ fb

CP-violating neutral Higgs mixing

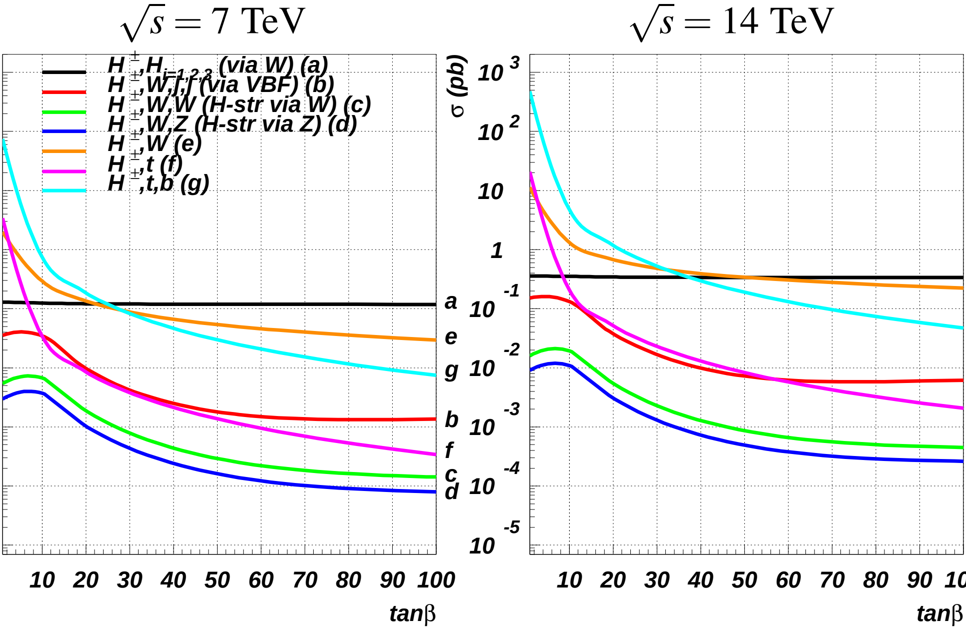
$$\begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} = \begin{bmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix}$$

$$\Phi_1 = \begin{bmatrix} i \sin\beta H^+ \\ \frac{1}{\sqrt{2}}(v_1 + \eta_1 - i \sin\beta \, \eta_3) \end{bmatrix}$$

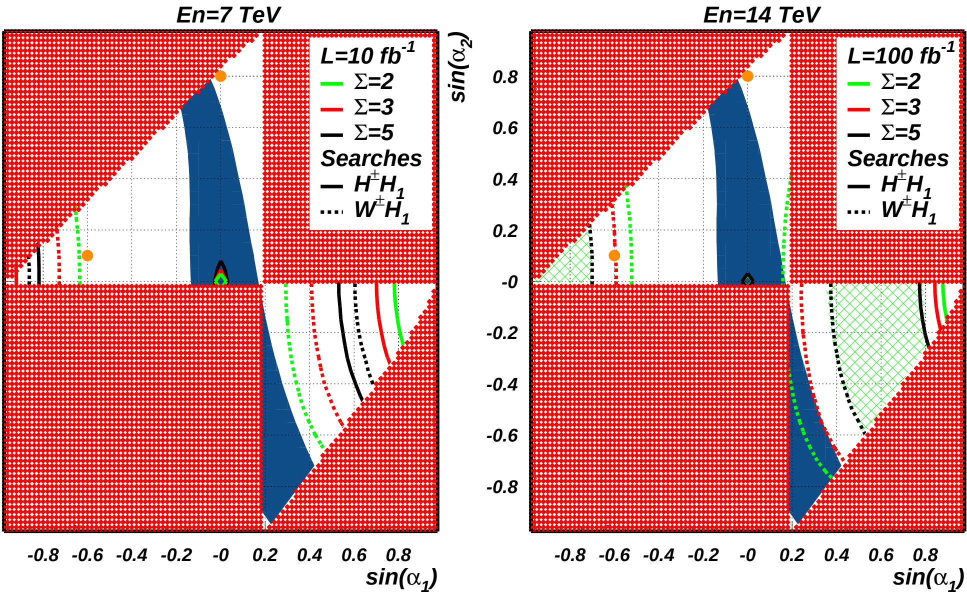
$$\Phi_2 = \begin{bmatrix} -i \cos\beta H^+ \\ \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i \cos\beta \, \eta_3) \end{bmatrix}$$

$$s_i = \sin \alpha_i, \quad c_i = \cos \alpha_i$$

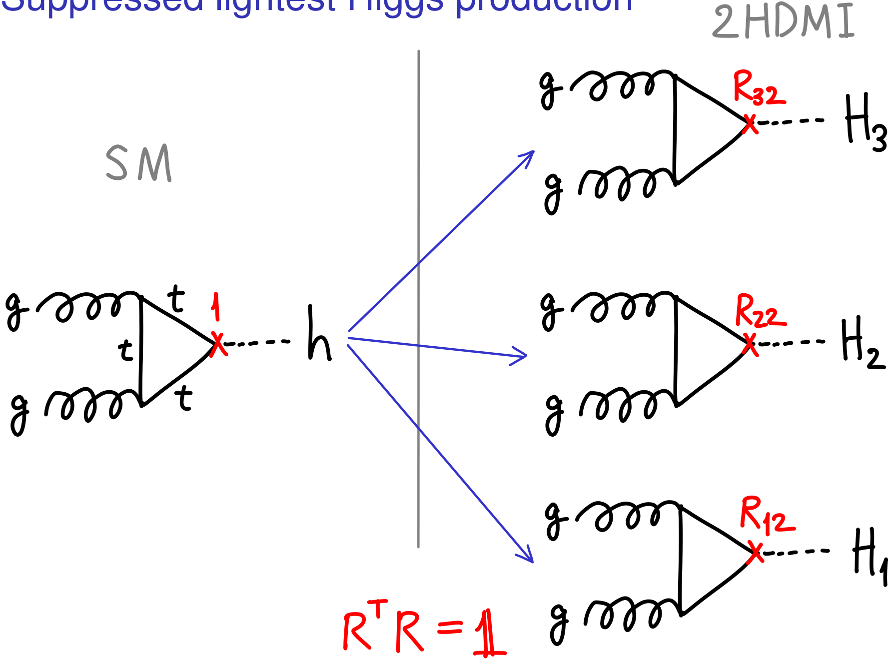
$H^{\pm}$ production at the LHC



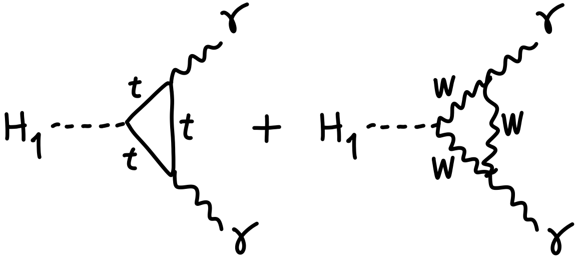
$ud \to W \to H^{\pm}H_1 \to \tau\nu b\bar{b}$



Suppressed lightest Higgs production



$H^{\pm}$-loop enhances $H_1 \to \gamma\gamma$



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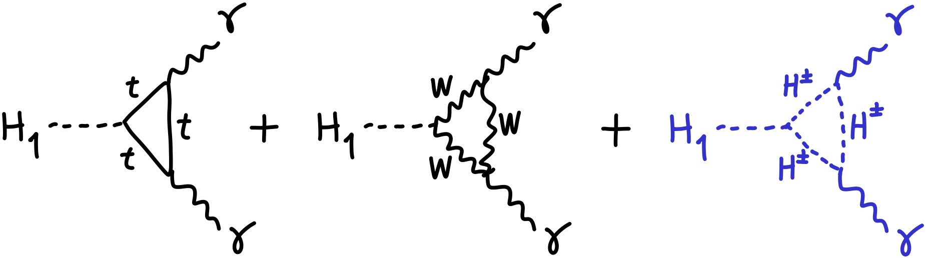
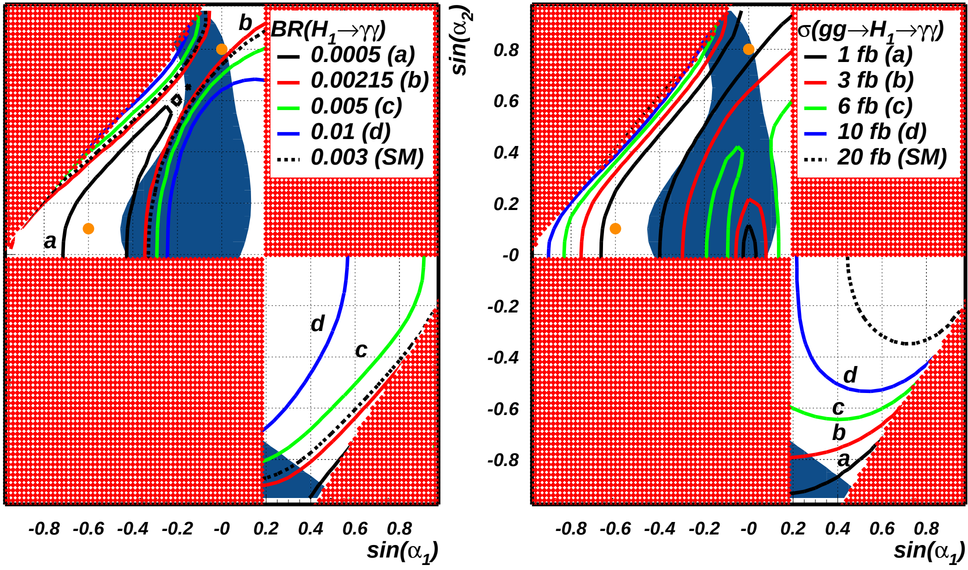


$gg \to H_1 \to \gamma\gamma$

$\sqrt{s} = 7$ TeV



Summary

- Type-I 2HDM could resolve lepton non-universality in W-pair production at LEP
- $H^{\pm}$ almost degenerate with W reduces 2.8 σ of deviation down to 1.4 σ
- LHC has excellent potential to discover H^{+} in this scenario
- Light $H^{\pm}$ loop can enhance $H_1 \to \gamma\gamma$