Probing CP Violation in Higgs physics

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disclaimer:

Not at all a thorough review,
simply a (biased) selection of facts.

not covered: flavor violating Higgs CPV couplings, → Harnik-Kopp-Zupan '13
UV theories. → arXiv.org

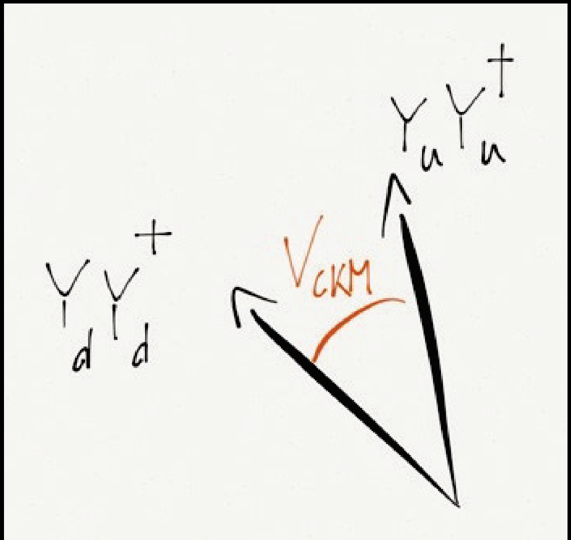
Outline

- CPV comes at a high price in the SM
  - → most CPV observables are BSM smoking guns!
- CPV Higgs EFT
- Indirect constraints on CPV-ing Higgs interactions:
  - → EDMs
  - → Higgs rates
- Probing CPV in Higgs physics at colliders:
  - → $h \to \gamma\gamma$, $h \to \tau\tau$, $h \to ZZ^*$
  - → Wh

CP within/beyond the SM

CPV is highly "screened" in the SM

- ignore neutrinos, fine-tune $\theta_{QCD}=0$ → CPV only in CKM



$$V^{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

$\rho = 0.129^{+0.0176}_{-0.0094}$
$\eta = 0.348 \pm 0.012$ [CKMfitter '13]

$\delta_{KM} \sim 70°$ → $O(1)$ phase, which dominates CPV in K, B physics!

yet CPV is suppressed by CKM hierarchies:

Jarlskog's invariant measure: $\mathrm{Im}(\det[Y_u Y_u^\dagger, Y_d Y_d^\dagger]) \propto \mathrm{Im}(J) \sim 10^{-5} \sin\delta_{KM}$

Jarlskog '85

\+ mass hierarchies suppression, as much as:

$$\prod_{j<i} (y_{u_i}^2 - y_{u_j}^2)(y_{d_i}^2 - y_{d_j}^2)\,/v^{12} \sim 10^{-17}$$

Large CPV sources beyond the SM…

Natural BSM theories introduce new symmetries broken below TeV-scale to screen the Higgs from the UV

→ new CP/flavor spurions from symmetry breaking terms

SUSY: M_{gino}, A-terms,…

CH: $\Delta_{q,u,d}$ = elem/comp mixings

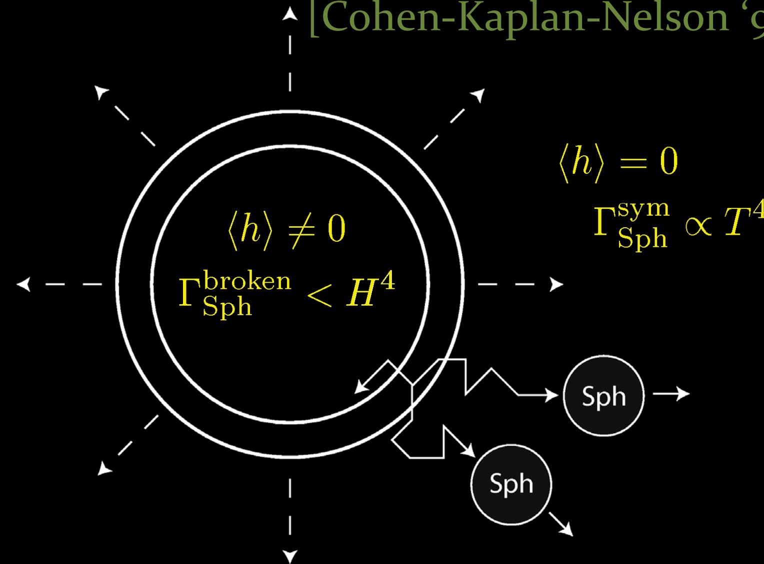
→ large CPV (unsuppressed by flavor structure) sources are possible *a priori*

...good news for EW scale Baryogenesis

[Kuzmin-Rubakov-Shaposhnikov '85]
[Cohen-Kaplan-Nelson '93]

Sakharov '67:

$$\Delta B \neq 0 \Leftrightarrow \begin{cases} \text{B violation} \\ \text{C, } \textbf{CP violation} \\ \text{out of equilibrium} \end{cases}$$



Baryon asymmetry estimate:

$$\eta_b \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{\Gamma_{sph}}{l_w T^2} \cdot \delta_{CP} \cdot e^{-M/T} \sim 10^{-10}$$

CP violation way to small in the SM: $\delta_{CP} \sim 10^{-22}$

→ *Could CPV in Higgs interactions induce EWBG?*

Higgs EFT with CPV

- assume new physics' heavy: $\Lambda \gg E_{\text{exp}} \sim m_h$

$$\mathscr{L}_{BSM} = \mathscr{L}_{SM} + \boxed{\mathscr{L}_{d=6}} + \mathscr{L}_{d>6}$$

$$\mathscr{L}_{d=6}^{CP=+1} \qquad \mathscr{L}_{d=6}^{CP=-1}$$

- 8 «Higgs only»:

$$|H|^6$$
$$|H|^2|D_\mu H|^2$$
$$g_s^2|H|^2 G_{\mu\nu}^{A\,2}$$
$$g_1^2|H|^2 B_{\mu\nu}^2$$
$$g_2^2|H|^2 W_{\mu\nu}^{a\,2}$$
$$\bar{f}_L H f_R |H|^2 + h.c.$$

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$$g_1^2|H|^2 B_{\mu\nu} B_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}$$
$$g_2^2|H|^2 W_{\mu\nu}^a W_{\rho\sigma}^a \varepsilon^{\mu\nu\rho\sigma}$$
$$g_1 g_2 H^\dagger \sigma^a H W_{\mu\nu}^a B_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}$$
$$i\bar{f}_L H f_R |H|^2 + h.c.$$

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→ Alex/Francesco talks

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$$i\bar{f}_L H f_R |H|^2 + h.c.$$

→ this talk

Higgs EFT with CPV

- more practical parameterization:

$$g_1^2|H|^2\widetilde{B_{\mu\nu}}B^{\mu\nu}$$
$$g_2^2|H|^2\widetilde{W_{\mu\nu}^a}W^{\mu\nu a}$$
$$g_1 g_2 H^\dagger\sigma^a H\widetilde{W_{\mu\nu}^a}B_{\rho\sigma}$$

$\rightarrow$ unitary gauge $h = v + h_{phys}$

$$\frac{e^2}{2}\tilde{c}_{\gamma\gamma}h^2\widetilde{F_{\mu\nu}}F^{\mu\nu}$$
$$\frac{g_2^2}{2}\tilde{c}_{WW}h^2\widetilde{W_{\mu\nu}^+}W^{\mu\nu-}$$
$$\frac{g_Z^2}{2}\tilde{c}_{ZZ}h^2\widetilde{Z_{\mu\nu}}Z^{\mu\nu}$$

(*note:* $\widetilde{Z_{\mu\nu}}F^{\mu\nu}$ combination is fixed)

- fermion couplings:

$$y_f\overline{f_L}Hf_R + h.c.$$
$$(a_f + ib_f)\overline{f_L}Hf_R|H|^2 + h.c.$$

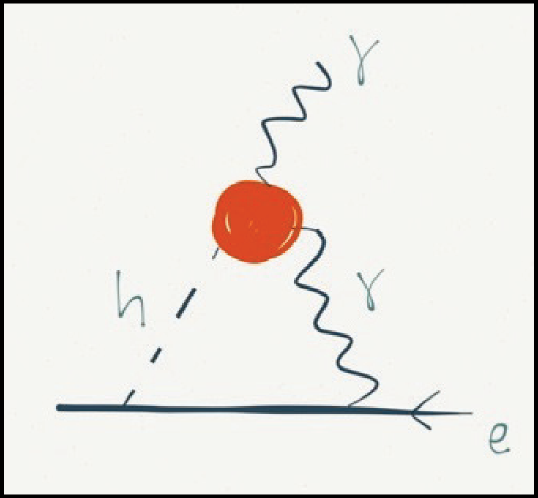
$$\rightarrow \quad |c_f|\frac{m_f}{v}\bar{f}(cos\varphi_f + i\gamma_5 sin\varphi_f)f h_{phys}$$

Indirect constraints on CP-odd Higgs operators

EDMs

= very efficient probes, linearly sensitive to $\mathscr{L}_{d=6}^{CP=-1}$

- if $h\bar{e}_L e_R$ is SM-like, CP-even → strong bound from e-EDM:



$$\frac{|d_e|}{e} \leq 8.7\times 10^{-29} cm \sim \frac{1}{10^{11}\mathrm{TeV}}$$

ACME '13

$h^2 F\tilde{F}$: $\tilde{c}_{\gamma\gamma}^{-1/2} \gtrsim 24$ TeV

updating *McKeen-Pospelov-Ritz '12*

top Yukawa phase: $\sin(2\varphi_t) \lesssim 10^{-2}$ *Brod-Haisch-Zupan '13*

(bottom/tau phase not constrained, $h^2 Z\tilde{F}$ accidentally small)

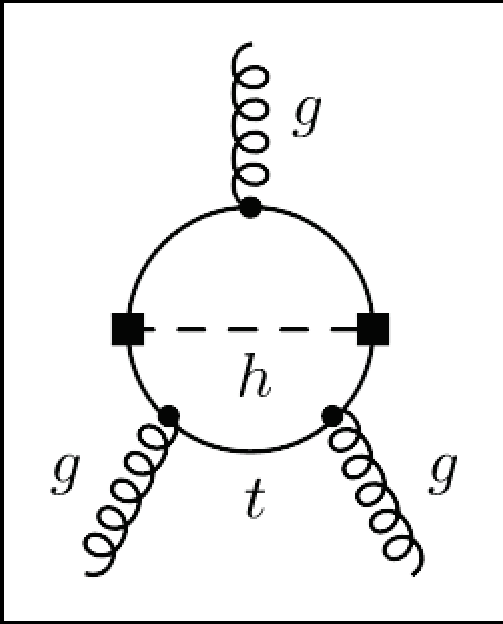
→ strong constraints, but with strong assumption on $h\bar{e}_L e_R$...

EDMs

- if $h\bar{e}_L e_R = 0$, there is a Weinberg contribution to n-EDM:

$$\frac{|d_n|}{e} \leq 2.6 \times 10^{-26} cm \sim 0.02 \text{ GeV} \times w(\mu = 1\text{GeV})$$

Baker et al. '06



$\sin(2\varphi_t) \sim o(1)$

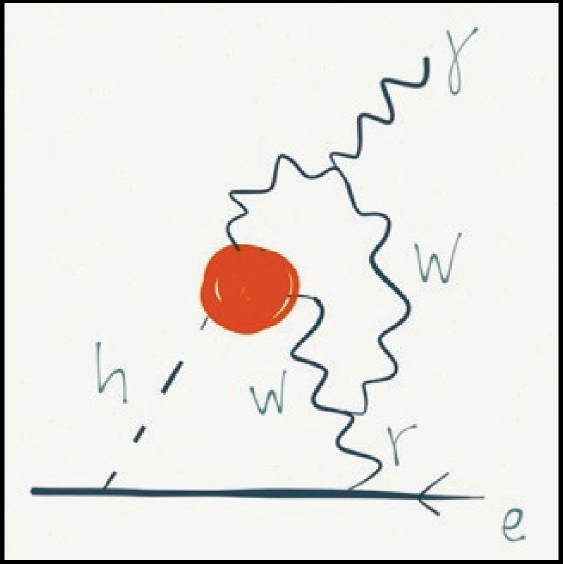
→ currently barely sensitive to maximal phase

future exp. projection: $\frac{|d_n|}{e} \sim 10^{-28} cm \rightarrow \varphi_t \lesssim o(10^{-1} - 10^{-2})$

FRMII '1x

EDMs

- $h^2 V\tilde{V}$ $(V = Z, W)$ are one-loop factor less contrained:



→ e-EDM bound: $\tilde{c}_{WW}^{-1/2} \gtrsim 600$ GeV

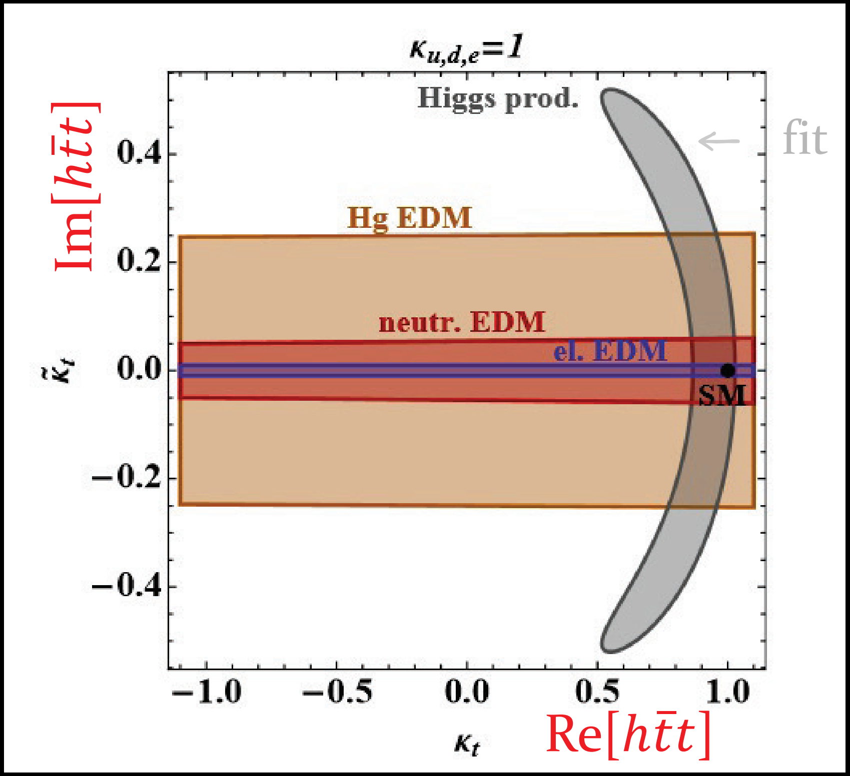
similarly for $\tilde{c}_{ZZ}$

→ could still yield sizable CPV effects in Vh production

→ *see later*

Inclusive Higgs rates

- sensitive to top phase via W/top interference in $h \to \gamma\gamma$:



← fit LHC run 1 data, assuming no other BSM effect

$\varphi_t \lesssim 0.5$

HL-LHC projection: $\varphi_t \sim 10^{-3} - 10^{-4}$
comparable to e-EDM projections

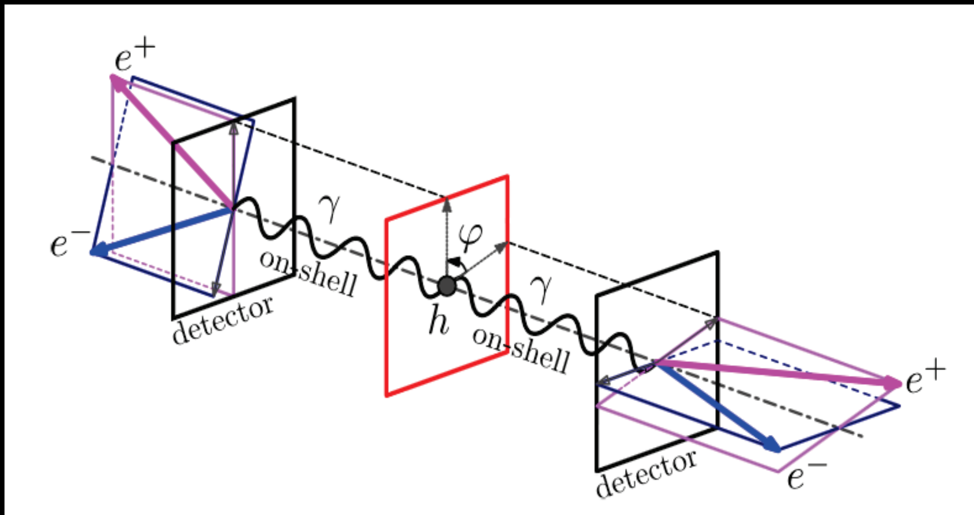
Brod-Haisch-Zupan '13

- CP-odd effects can be hidden by BSM CP-even ones:

$$\mu_{\mathrm{inclusive}} \propto |1 - \delta_{CP-\mathrm{even}}|^2 + |\delta_{CP-\mathrm{odd}}|^2 \approx 1$$

Probing Higgs CPV at colliders

Higgs to diphoton



[Voloshin '12, Bishara et al '13]

$$h^2 F^{\mu\nu} \widetilde{F_{\mu\nu}}$$

different $\gamma\gamma$ helicities interfere:
$2Re[(1-\delta_{CP-\text{even}})^* \delta_{CP-\text{odd}}]$

issue= can't measure γ polarization → e^+e^- conversion in tracker

CPV phase interferes w/ kinematical phase, which is the acoplanarity angle between the e^+e^- planes

Not clear it can be measured:

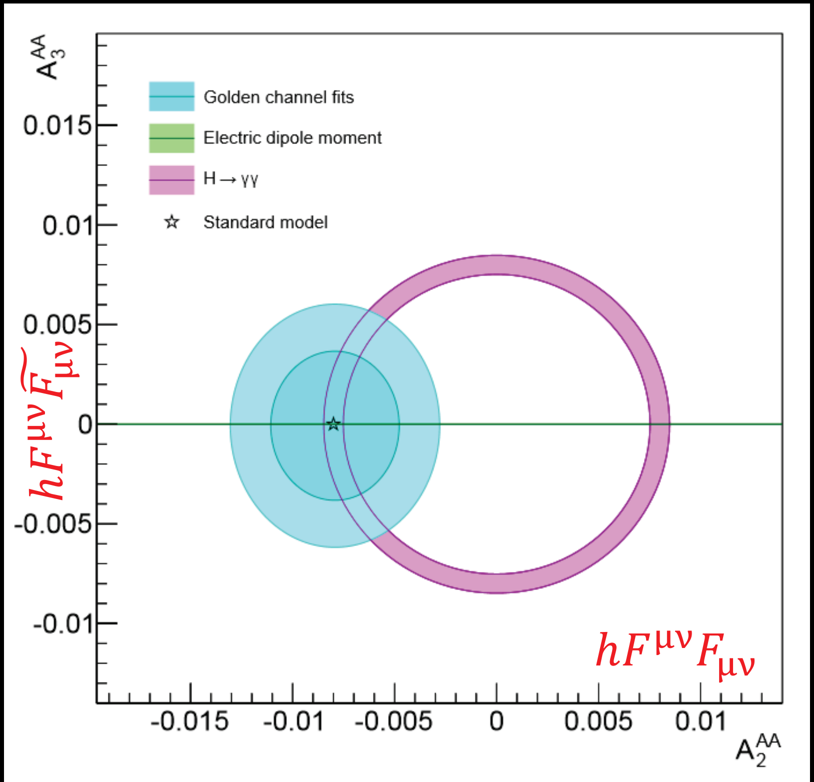
e.g. $E_\gamma \approx 60$ GeV → opening angle $\approx \frac{2m_e}{E_\gamma} \approx 10^{-5}$

Higgs to $4l$

[Chen-Harnik-VegaMorales '14]

- alternative approach to probe $h^2 F^{\mu\nu}\widetilde{F_{\mu\nu}}$:

look at inteference between $h \to ZZ^* \to 4l$ and $h \to \gamma^*\gamma^* \to 4l$



(also sensitive to $h^2 F^{\mu\nu}\widetilde{Z_{\mu\nu}}$ and $h^2 Z^{\mu\nu}\widetilde{Z_{\mu\nu}}$)

→ R. Vega-Morales talk

Higgs to $\tau\tau$

[Chen-Harnik-VegaMorales '14]

- possible to probe τ phase: $\bar{\tau}(\cos\varphi_\tau + i\gamma_5 \sin\varphi_\tau)\tau h_{phys}$,

via angular distributions of $\tau^\pm \to \rho^\pm(\pi^\pm\pi^0)\nu$ decay products:

τ_h efficiency	50%	70%
3σ	$L = 550\ \text{fb}^{-1}$	$L = 300\ \text{fb}^{-1}$
5σ	$L = 1500\ \text{fb}^{-1}$	$L = 700\ \text{fb}^{-1}$
Accuracy($L = 3\ \text{ab}^{-1}$)	11.5°	8.0°

TABLE III: The luminosity required for distinguishing the scalar and pseudoscalar couplings and the accuracy in measuring Δ with $3\ \text{ab}^{-1}$ of luminosity at the 14 TeV LHC.

Probing CPV in hVV at colliders

$\mathrm{H}-\mathrm{V}_{\mu}-\mathrm{V}_{\nu}$:

$$-i g_V m_V \left[A_V \eta_{\mu\nu} + B_V p_{1\nu} p_{2\mu} + C_V \epsilon_{\mu\nu\alpha\beta} p_1^\beta p_2^\alpha \right]$$

CP-even **CP**-odd

Lorentz invariance → A, B, C = general functions of p^2

CPV requires both A_V (or B_V) and $C_V \neq 0$ → CPV obs. □ AC

→ interference

$H - V_\mu - V_\nu$: $$-ig_V m_V \left[A_V \eta_{\mu\nu} + B_V p_{1\nu} p_{2\mu} + C_V \epsilon_{\mu\nu\alpha\beta} p_1^\beta p_2^\alpha \right]$$

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CPV requires both A_V (or B_V) and $C_V \neq 0$ → CPV obs. □ AC

→ interference

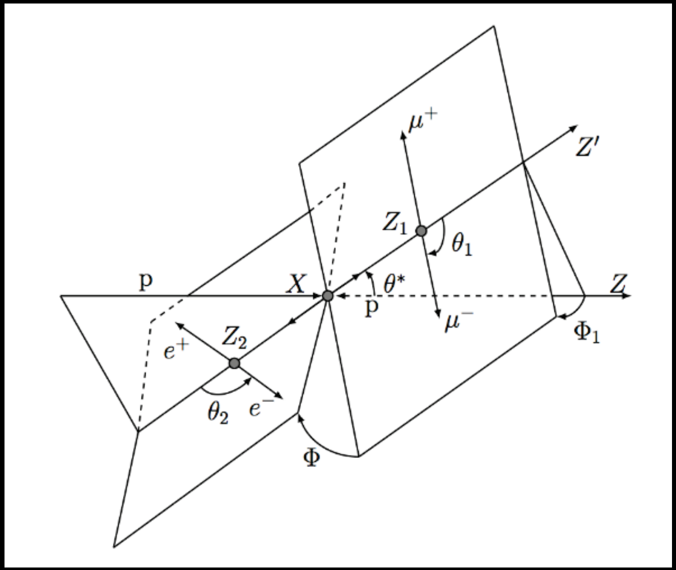
proposed ways to probe $C_V \neq 0$ in the literature:

- $H \to VV^*$ *[Gao et al. PRD '10]*
- azimuth difference between 2 forward jets in VBF *[Plehn-Rainwater-Zeppenfeld PRL '02]*
- $WH \to (l\nu)(WW^* \to l\nu qq)$ *[Desai-Ghosh-Mukhopadhyaya PRD '11]*

- $H \to VV^* \to$ leptons: [Gao et al. PRD '10]

"look at angular distributions to probe $C_V \neq 0$"

$H \to VV^* \to$ leptons: 5 physical angles



- full kinematics accessible in $ZZ^* \to 4l$

$$f_{a3} = \frac{|A_{odd}|^2}{|A_{even}|^2 + |A_{odd}|^2}$$ <58% @95%CL

[CMS-PAS-HIG-13-002]

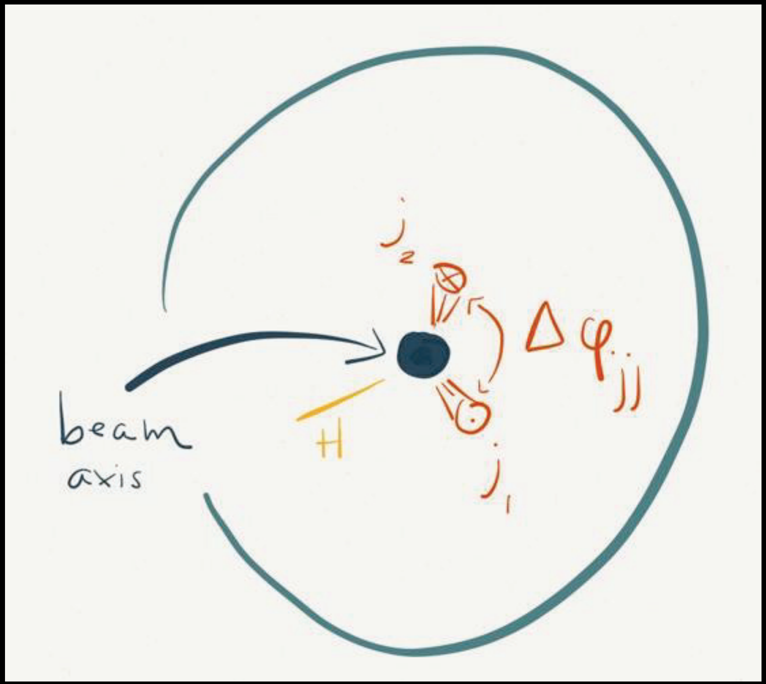
- harder in $WW^* \to 2l2\nu$ due to missing neutrinos

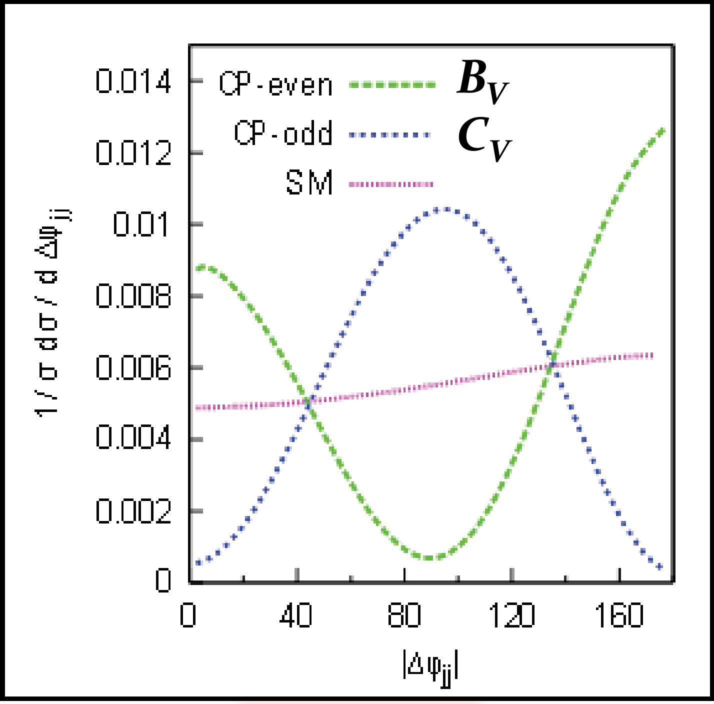
drawbacks: 1) energy is fixed, effect of $O(m_h^2/\Lambda^2)$
2) poor constraint on C_W

- azimuth difference between 2 forward jets in VBF:

[Plehn-Rainwater-Zeppenfeld PRL '02]

see also: *[Hankele PRD '06]* *[Englert et al. JHEP '13]*



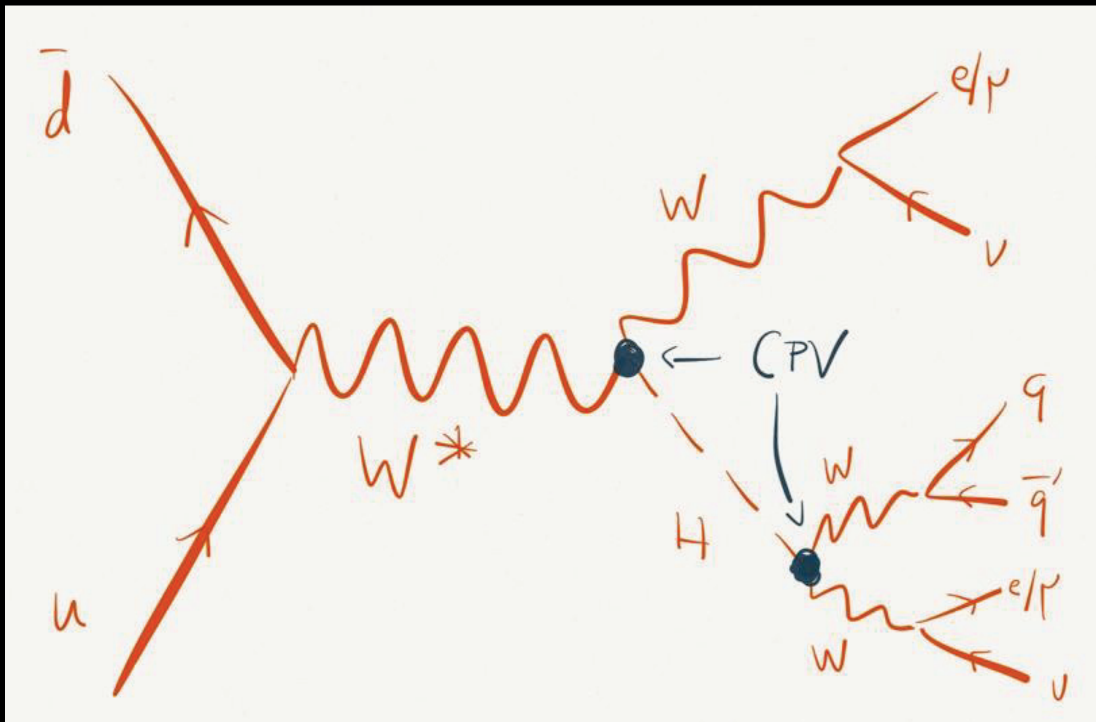


$$\varepsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2p_{T,+}p_{T,-}\sin(\phi_+ - \phi_-) = 2p_{T,+}p_{T,-}\sin\Delta\phi_{jj}$$

drawbacks:
1) effect suppressed by p_T of tagged jets
2) hard to disentable NP from SM
3) can't disentangle C_W from C_Z

- $WH \to (l\nu)(WW^* \to l\nu qq)$ *[Desai-Ghosh-Mukhopadhyaya PRD '11]*

see also in ZH:
[Christensen-Han-Li PLB '10]
[Englert et al. JHEP '13]



construct asymmetries in $\Delta\phi = \phi(l_1) - \phi(l_2)$

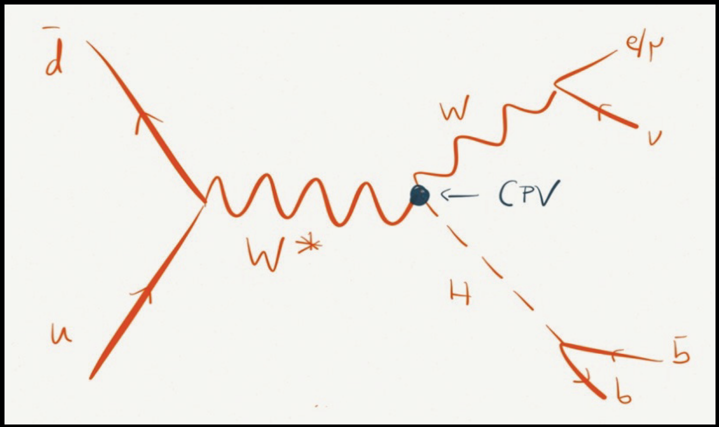
benefits: H boosted, increased sensitivity to NP scale

drawbacks: $H \to WW^*$ only 20% in SM

Consider *WH→lνbb*:

[CD-Perez-de Sandes-Skiba '13]

parton level process →



$H - V_\mu - V_\nu$: $-ig_V m_V \left[A_V \eta_{\mu\nu} + B_V p_{1\nu} p_{2\mu} + C_V \epsilon_{\mu\nu\alpha\beta} p_1^\beta p_2^\alpha \right]$

CP-even **CP**-odd

induces **P**-odd triple product

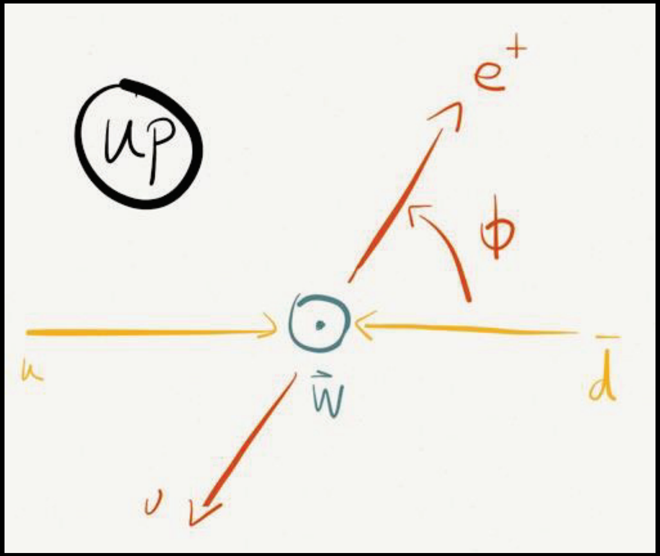
$\vec{\mathcal{E}}_W \cdot (\vec{H} \times \vec{u})$

trade W for e/μ momentum*

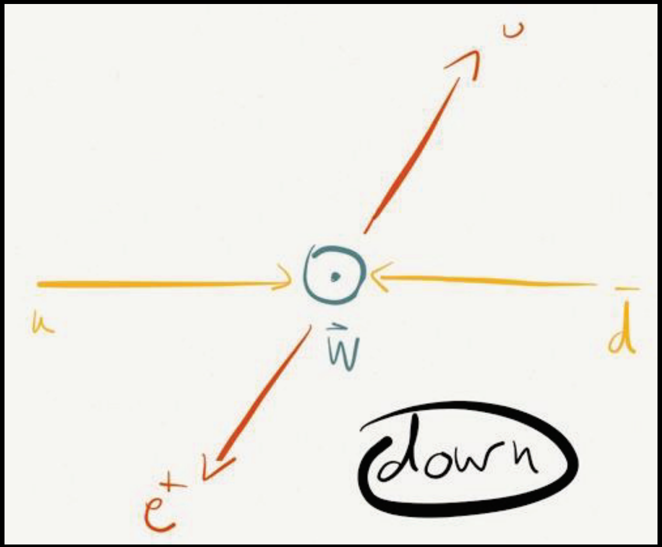
$t = \vec{\ell} \cdot (\vec{H} \times \vec{u})$ + **CP**-even couplings → asymmetry in t

*see [Goldbole et al. '13] for using reconstructed W

asymmetry in t is an up/down asymmetry in terms of l^+



vs.



$$A_{up/down} = -\frac{9\pi}{16}\sin\gamma\left(\frac{\mathcal{A}_T\mathcal{A}_L}{2\mathcal{A}_T^2+\mathcal{A}_L^2}\right)$$ @partonic level

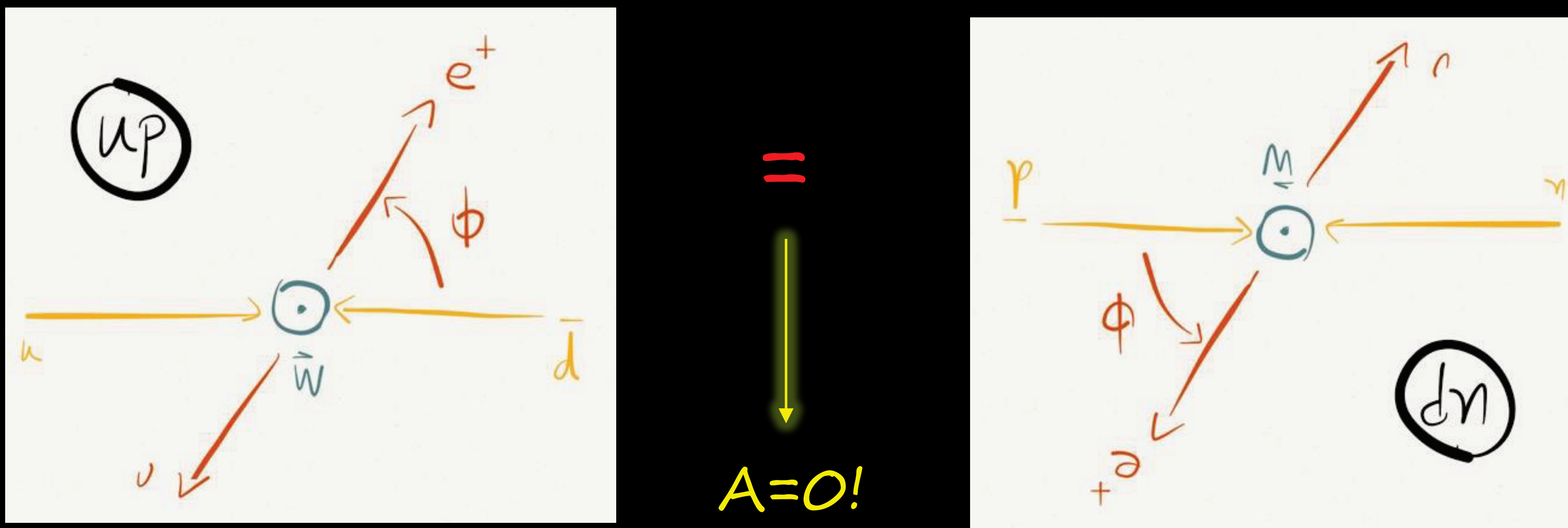
$$\tan\gamma = \frac{C_W\,\hat{s}\,\beta}{2A_W}$$

"weak" phase

"strong" phase: $M_{W_\lambda \to l^+\nu} \propto e^{i\lambda\phi}$

pp@LHC is parity invariant

→ can't tell up from down w/out notion of left/right



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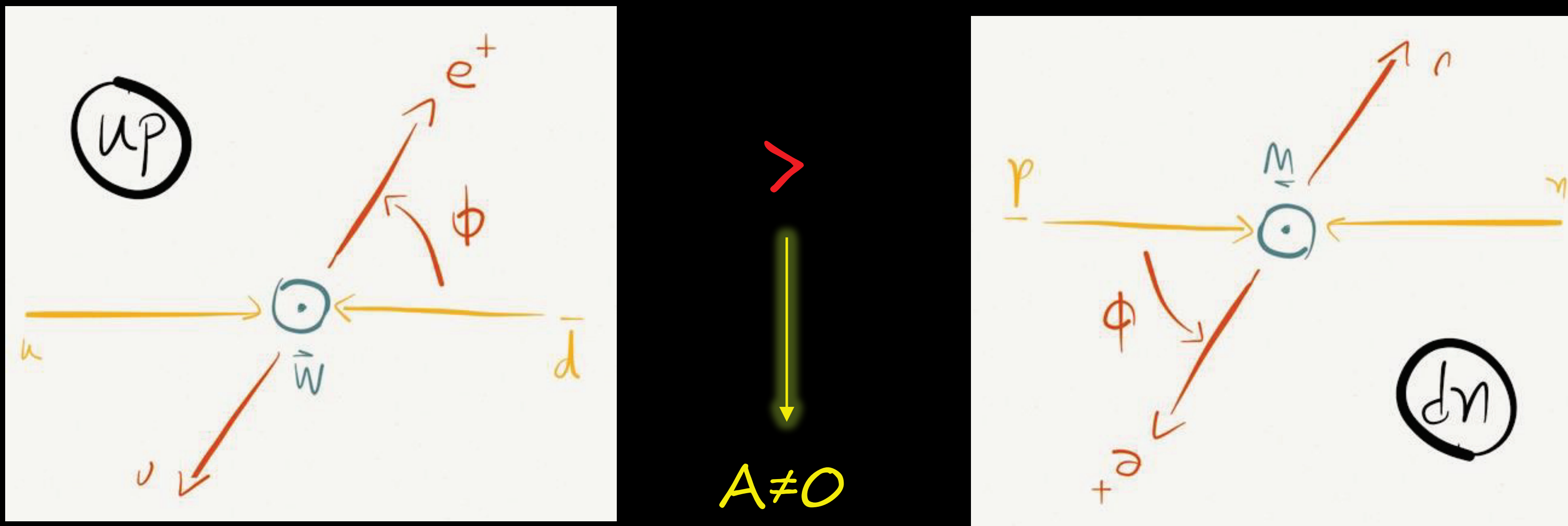


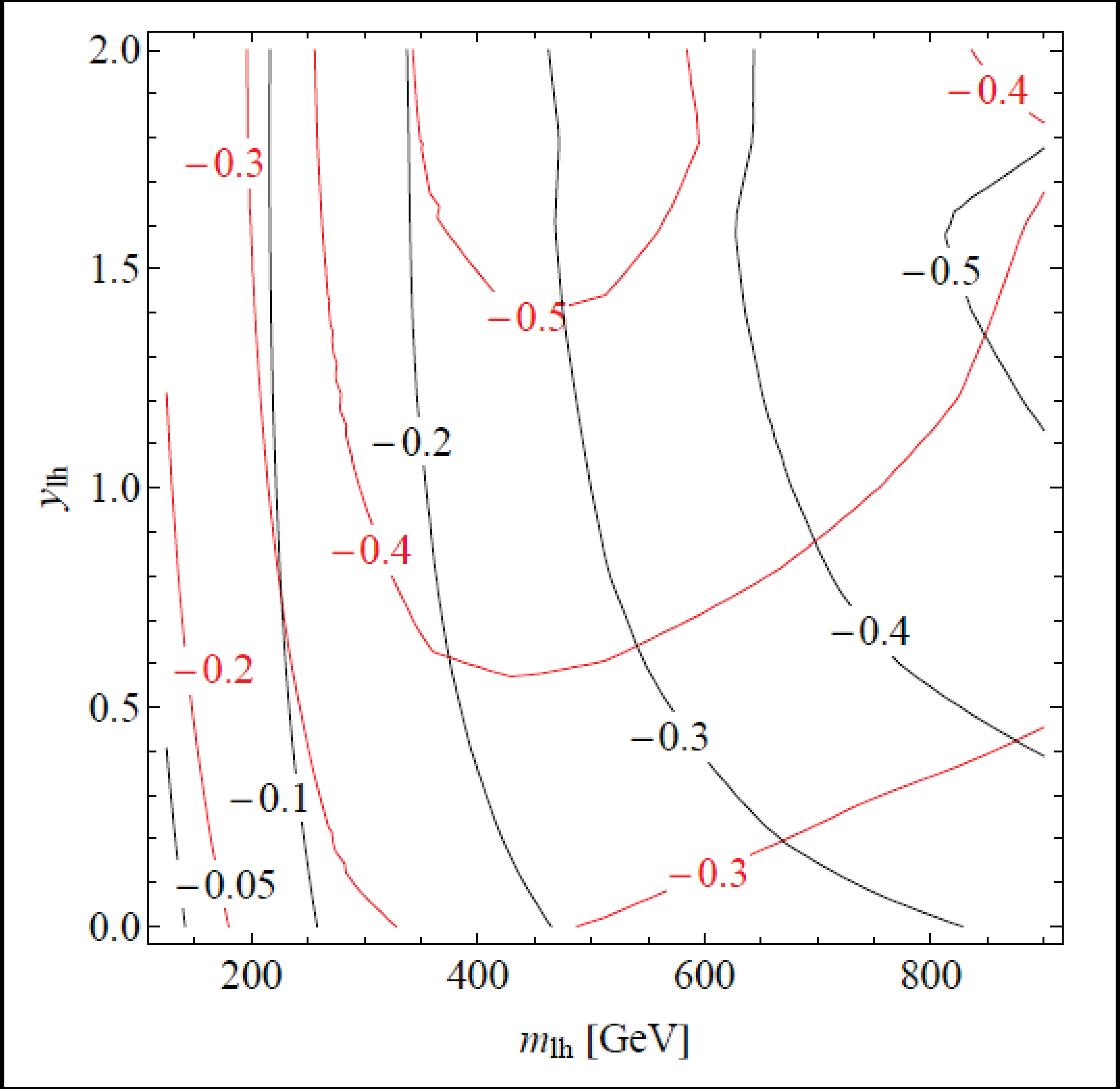
standard trick: use the boost direction, cut on l+H rapidity

$$\tan\gamma = \frac{C_W \hat{s} \beta}{2 A_W}$$

increase asymmetry by cutting hard on the lepton+H invariant mass

asymmetry as function of cuts

LHC@14TeV w/ $A=A_{SM}=1$, $B=B_{SM}=0$ and $C=4/\Lambda^2$



Λ=1TeV
Λ=500GeV

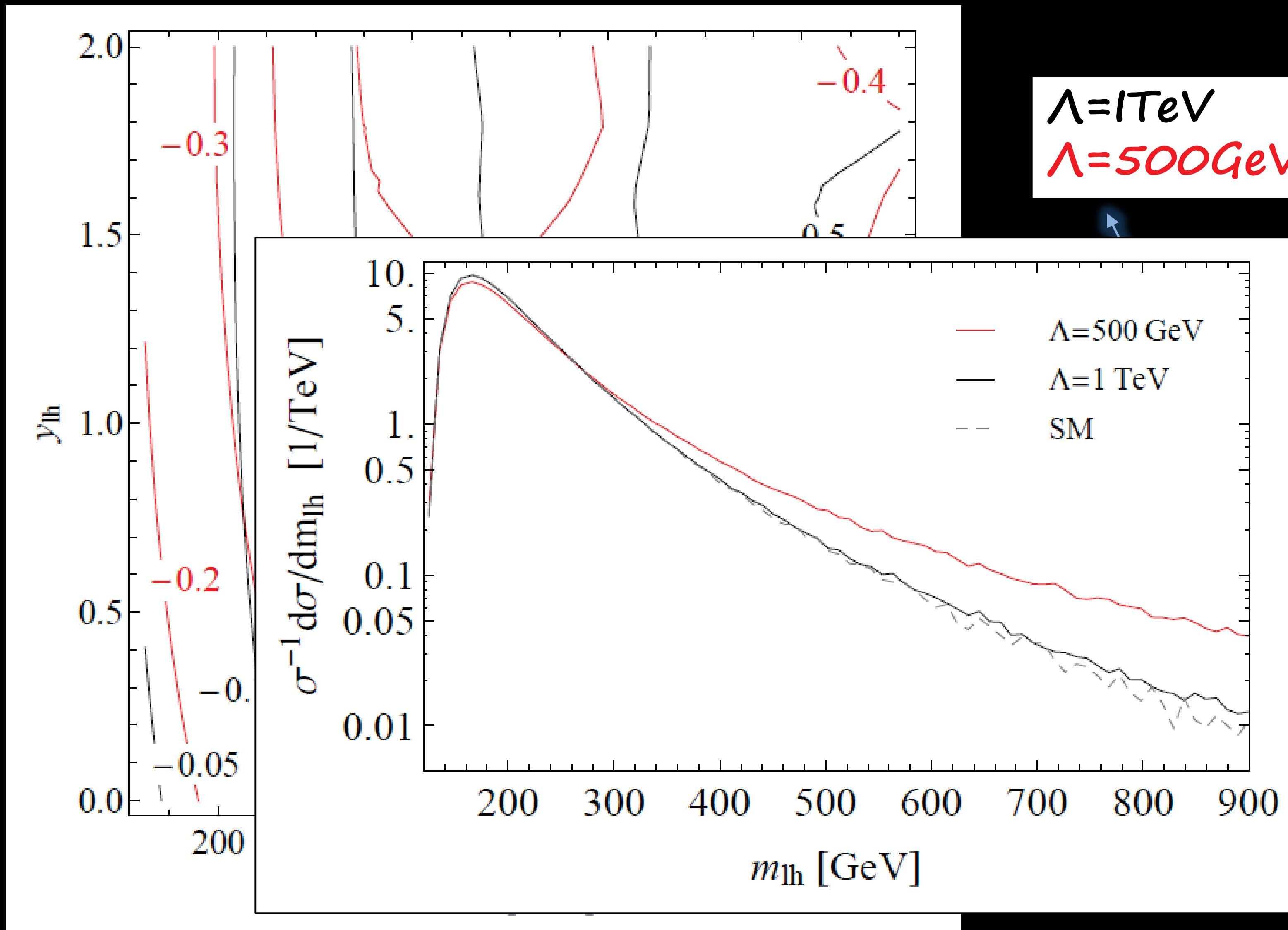
scale of $h^2\widetilde{W}W$

cutoff $\sim \frac{4\pi}{g_2}\Lambda$

asymmetry as function of cuts

LHC@14TeV w/ $A=A_{SM}=1$, $B=B_{SM}=0$ and $C=4/\Lambda^2$

$\Lambda=1$TeV
$\Lambda=500$GeV



Λ~

Λ/g

Summary

- Baryogenesis requires BSM sources of CPV
- Is the newly discovered Higgs sector CP symmetric?
- For heavy new physics, dominant CPV effects from:

$$g_s^2 |H|^2 G^{\mu\nu A} \widetilde{G_{\mu\nu}^A}$$
$$g_1^2 |H|^2 B^{\mu\nu} \widetilde{B_{\mu\nu}}$$
$$g_2^2 |H|^2 W^{\mu\nu a} \widetilde{W_{\mu\nu}^a}$$
$$g_1 g_2 H^\dagger \sigma^a H W^{\mu\nu a} \widetilde{B_{\mu\nu}}$$
$$i \overline{f_L} H f_R |H|^2 + h.c.$$

- Some, e.g. $H^2 W\widetilde{W}$, are weakly constrained
- LHC is the only direct probe of those effects