Examples of sizable Higgs non-Standardness @ the LHC

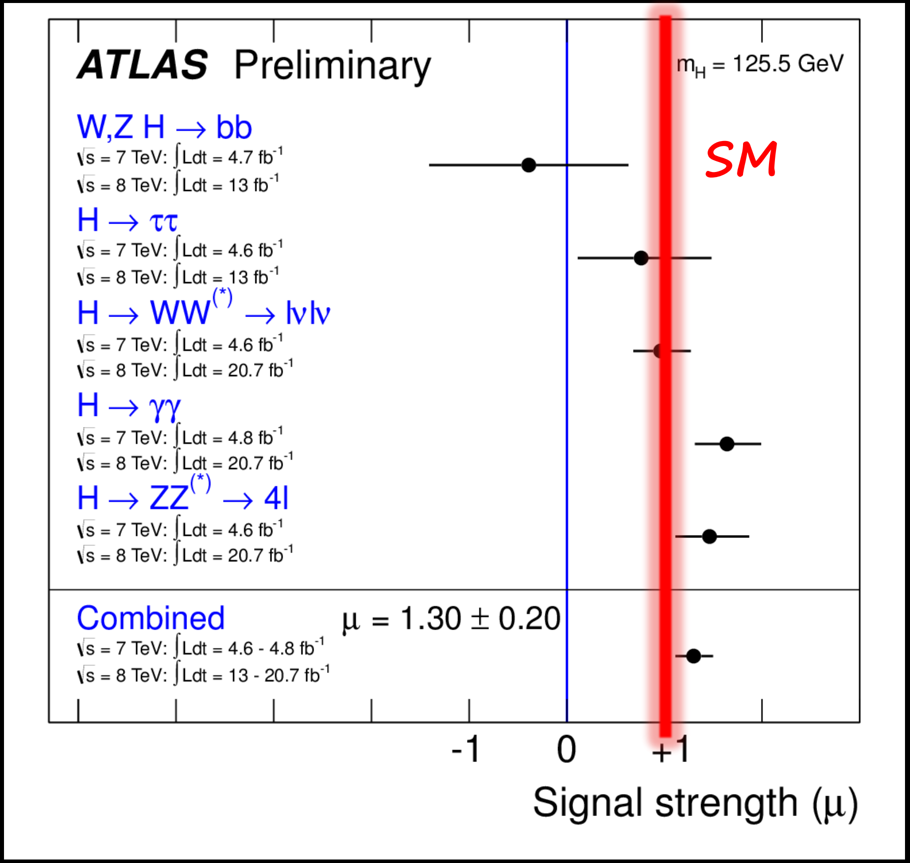
Cédric Delaunay

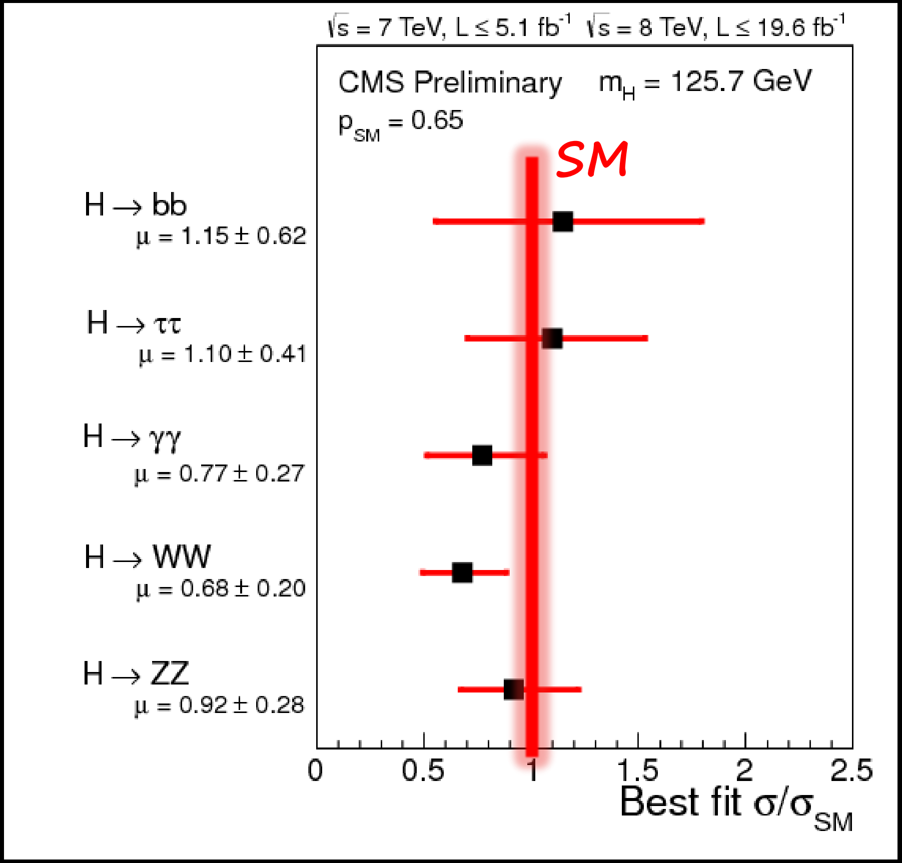
LAPTH – Annecy-le-vieux, France

CD, *G.Perez, H. de Sandes & W. Skiba* [arXiv:1308.4930]

CD, *T. Golling, G. Perez & Y. Soreq* [to appear]

a light Higgs has been found → $W_L W_L \to W_L W_L$ unitary up to $E \gg$ TeV
which so far looks like the SM Higgs



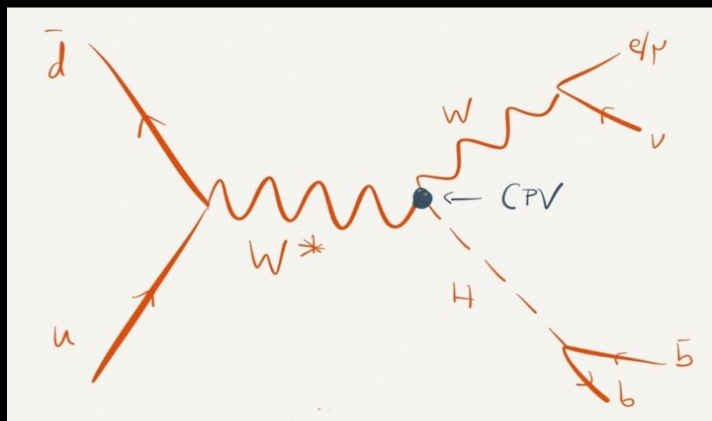


yet, a light SM Higgs has mostly small couplings
so there is *a priori* plenty of room for relatively large BSM effects

this talk = two examples of Higgs non-Standardness at the LHC:

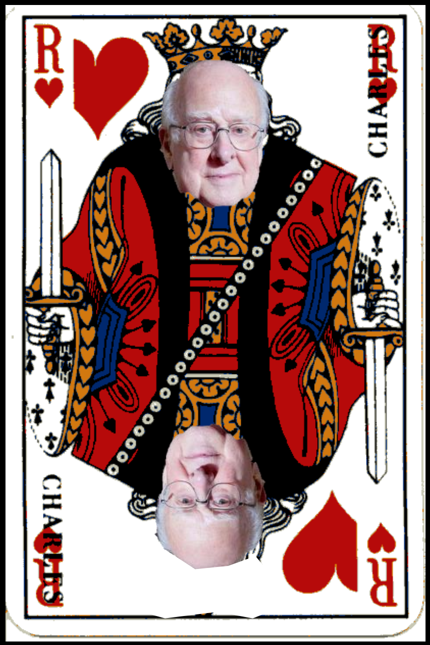
- Higgs CPV in hVV interactions

  → up/down asymmetry in WH



- Charming the Higgs

  → implications of an enhanced H-charm coupling



Higgs CPV in hVV

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

CP-even **CP**-odd

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

- in the SM: - $A_W = A_Z = 1$ (at tree-level)
  - B_V, C_V only loop induced ≈ 0

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

CP-even **CP**-odd

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

- in the SM: - $A_W = A_Z = 1$ (at tree-level)
  - B_V, C_V only loop induced ≈ 0
- going BSM with d=6 operators:

$$\mathcal{O}_{DH} = H^\dagger H |D_\mu H|^2 \,, \; \mathcal{O}_H = |H^\dagger D_\mu H|^2 \,,$$
$$\mathcal{O}_{WW} = \frac{g^2}{2} H^\dagger H \, W^a_{\mu\nu} W^{\mu\nu\, a} \,, \; \mathcal{O}_{BB} = \frac{g'^2}{2} H^\dagger H \, B_{\mu\nu} B^{\mu\nu} \,,$$
$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H \, W^a_{\mu\nu} B^{\mu\nu} \,, \tag{14}$$

$$\widetilde{\mathcal{O}}_{WW} = \frac{g^2}{2} H^\dagger H \, W^a_{\mu\nu} \widetilde{W}^{\mu\nu\, a} \,, \; \widetilde{\mathcal{O}}_{BB} = \frac{g'^2}{2} H^\dagger H \, B_{\mu\nu} \widetilde{B}^{\mu\nu} \,,$$
$$\widetilde{\mathcal{O}}_{WB} = g g' H^\dagger \sigma^a H \, W^a_{\mu\nu} \widetilde{B}^{\mu\nu} \,. \tag{15}$$

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

CP-even **CP**-odd

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

- in the SM: - $A_W=A_Z=1$ (at tree-level)
  - B_V, C_V only loop induced ≈ 0

- going BSM with d=6 operators:

$$\mathcal{O}_{DH} = H^\dagger H |D_\mu H|^2\,,\ \mathcal{O}_H = |H^\dagger D_\mu H|^2\,,$$
$$\mathcal{O}_{WW} = \frac{g^2}{2} H^\dagger H\, W^a_{\mu\nu} W^{\mu\nu\, a}\,,\ \mathcal{O}_{BB} = \frac{g'^2}{2} H^\dagger H\, B_{\mu\nu} B^{\mu\nu}\,,$$
$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H\, W^a_{\mu\nu} B^{\mu\nu}\,, \tag{14}$$

not crucial here, let's ignore them

$$\widetilde{\mathcal{O}}_{WW} = \frac{g^2}{2} H^\dagger H\, W^a_{\mu\nu} \widetilde{W}^{\mu\nu\, a}\,,\ \widetilde{\mathcal{O}}_{BB} = \frac{g'^2}{2} H^\dagger H\, B_{\mu\nu} \widetilde{B}^{\mu\nu}\,,$$
$$\widetilde{\mathcal{O}}_{WB} = g g' H^\dagger \sigma^a H\, W^a_{\mu\nu} \widetilde{B}^{\mu\nu}\,. \tag{15}$$

→ C_W, C_Z, C_γ

$\Lambda > 7$ TeV (e-EDMs)

[McKeen-Pospelov-Ritz PRD '12]

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

CP-even **CP**-odd

Lorentz invariance → $\mathcal{A},\mathcal{B},\mathcal{C}$ = general functions of p^2

CPV requires both $\mathcal{A}_V$ (or $\mathcal{B}_V$) and $\mathcal{C}_V \neq 0$ → $\mathcal{CPV}$ obs. $\propto \mathcal{AC}$

→ interference

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

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. $\propto AC$

→ interference

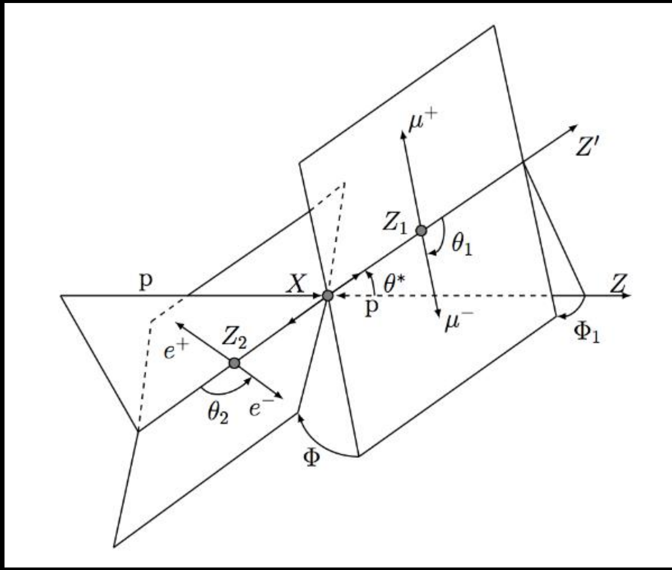
proposed ways to probe $C_V \neq 0$ in the literature:

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

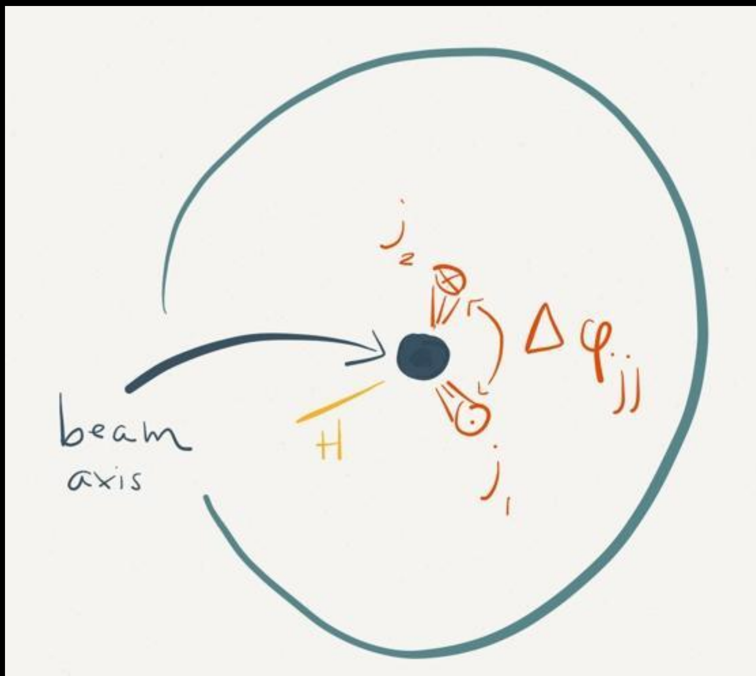
- harder in $WW^* \to 2l2\nu$ due to missing neutrinos

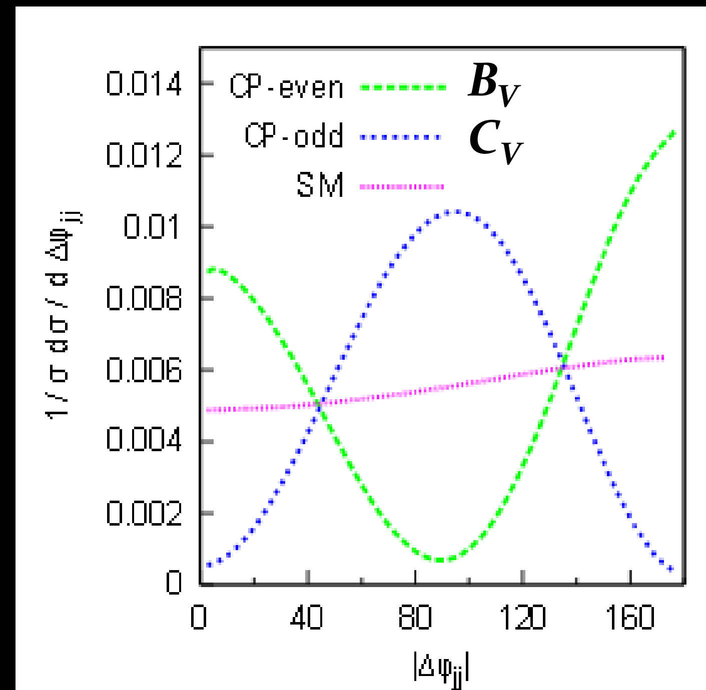
drawbacks:
1) distributions are CP-even, effect $\propto C_V^2$
2) energy is fixed, effect of $O(m_h^4/\Lambda^4)$
3) poor constraint on C_W

- azimuthal difference between 2 forward jets in VBF:

  [Plehn-Rainwater-Zeppenfeld PRL '02]

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





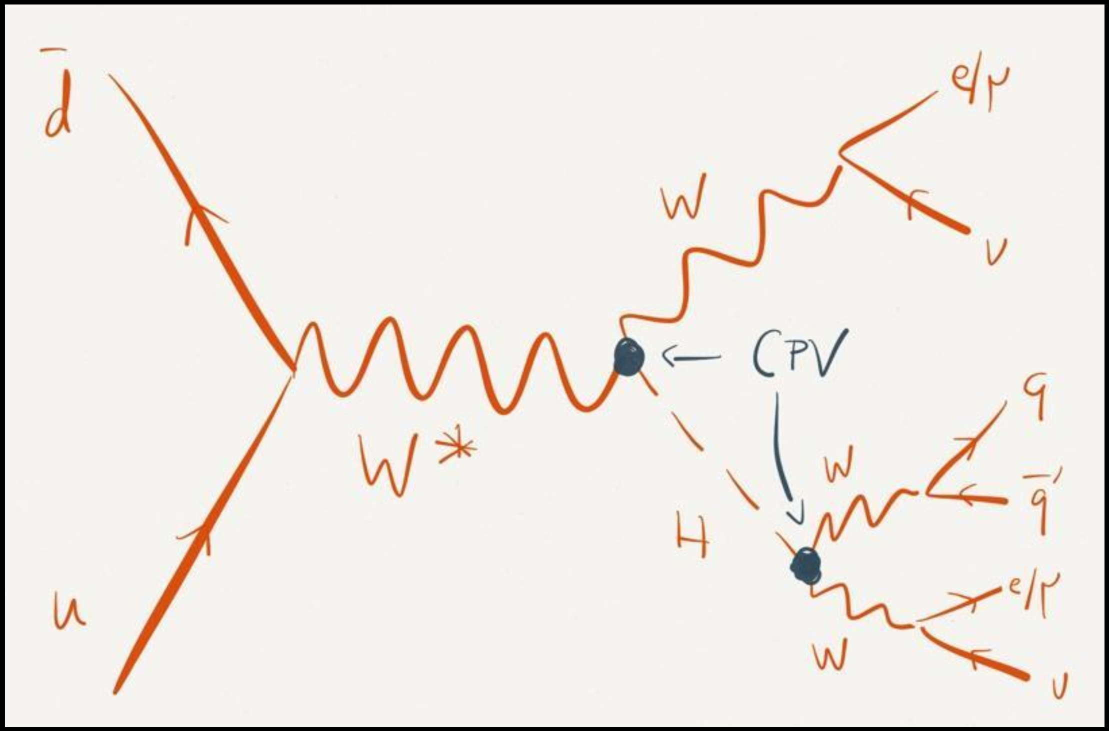
$$\varepsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2p_{T,+}p_{T,-}\sin(\phi_+ - \phi_-) = \boxed{2p_{T,+}p_{T,-}}\sin\Delta\phi_{jj}$$

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 $\Delta\phi = \phi(l_1) - \phi(l_2)$

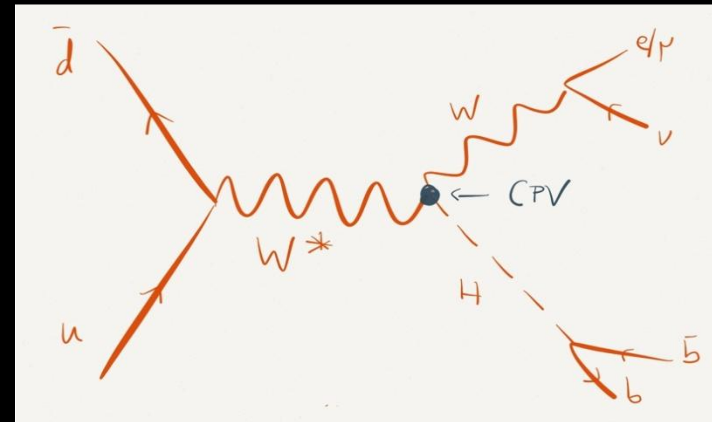
benefits: 1) asymmetries are linear in c_W
2) H boosted, can increase sensitivity to high scales

drawbacks: 1) $H \to WW^*$ only 20% in SM
2) BSM in production and decay

Consider $WH \to l\nu bb$:

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

parton level process →



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

CP-even

CP-odd

induces **P**-odd triple product

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

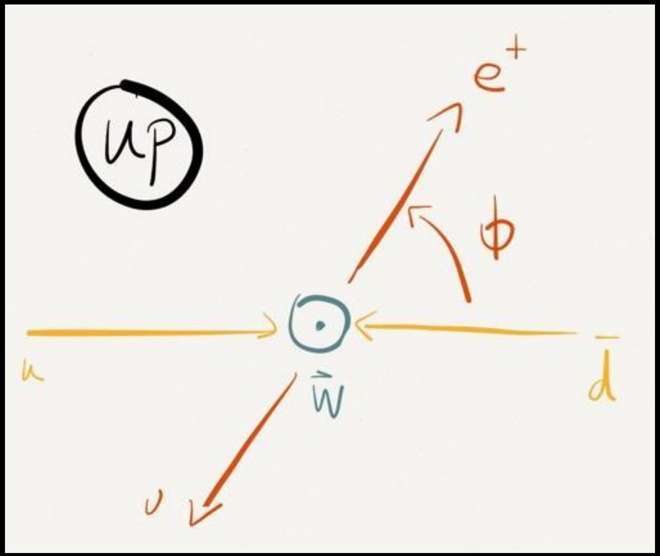
trade W for e/μ momentum*

$$t = \vec{\ell} \cdot (\vec{H} \times \vec{u})$$

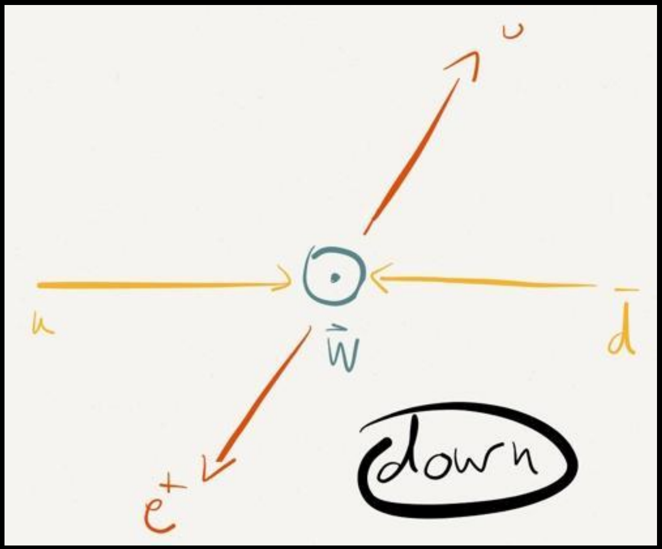
+ **CP**-even couplings → asymmetry in t

*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

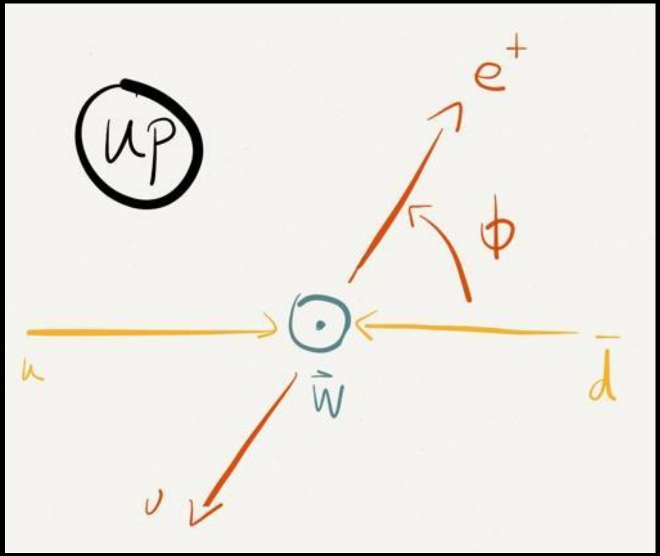
$$\tan\gamma = \frac{C_W\,\hat{s}\,\beta}{2A_W}$$

"weak" phase

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

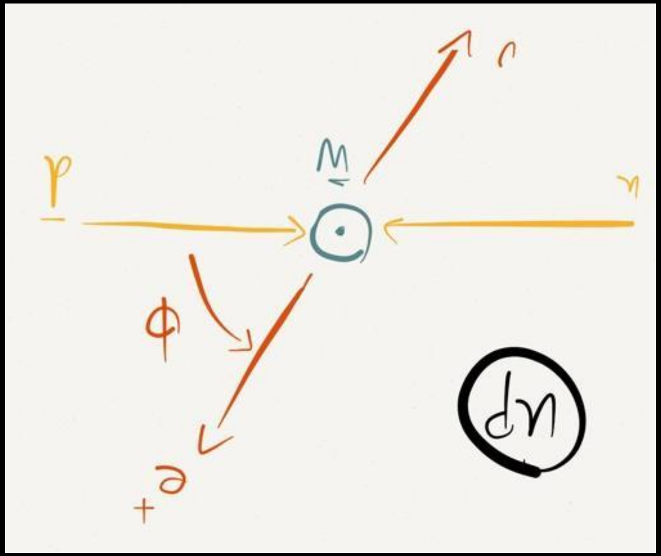
pp@LHC is parity invariant

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



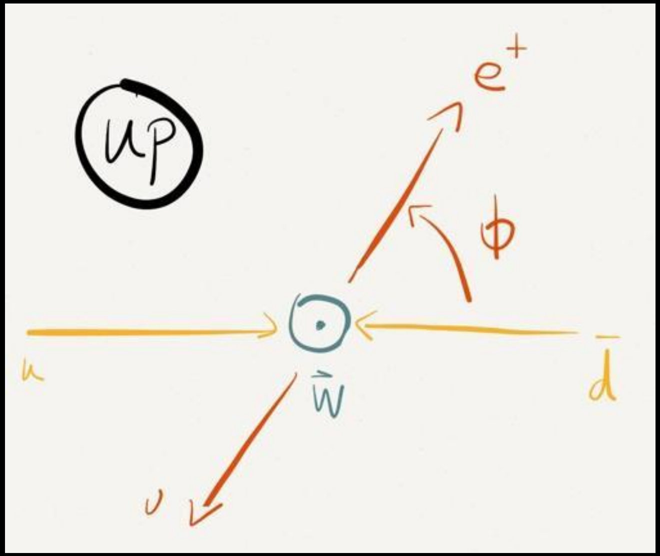
=

A=0!



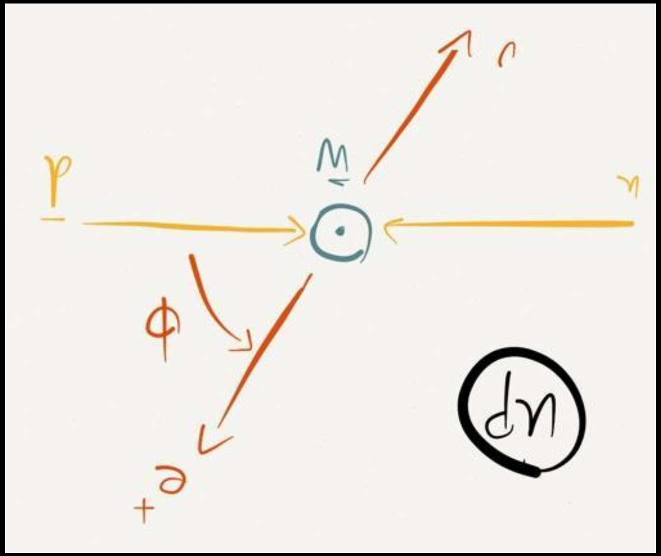
pp@LHC is parity invariant

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



$>$

$A \neq 0$

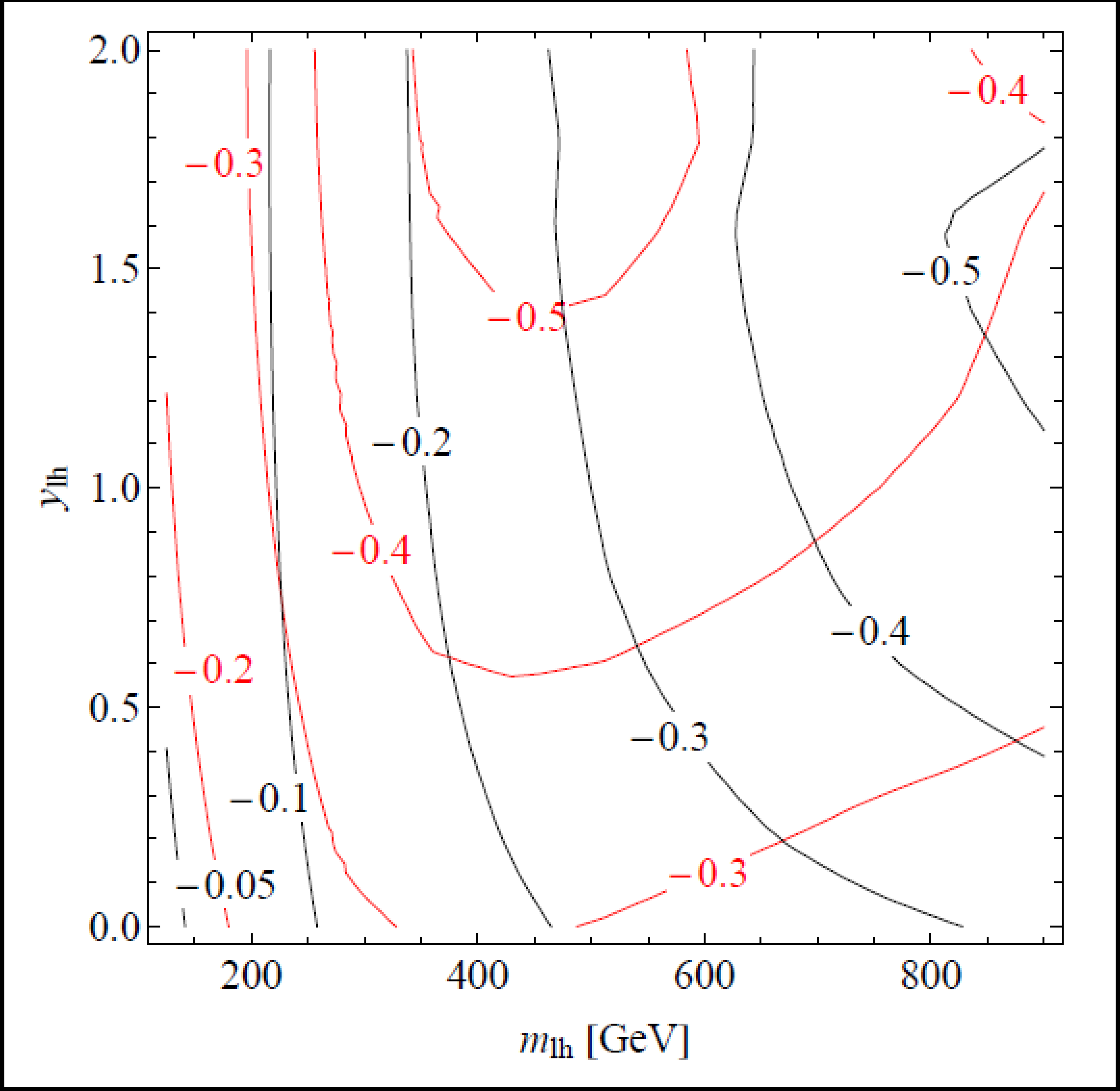


standard trick: use the boost direction, cut on l+H rapidity

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

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 $C=4/\Lambda^2$



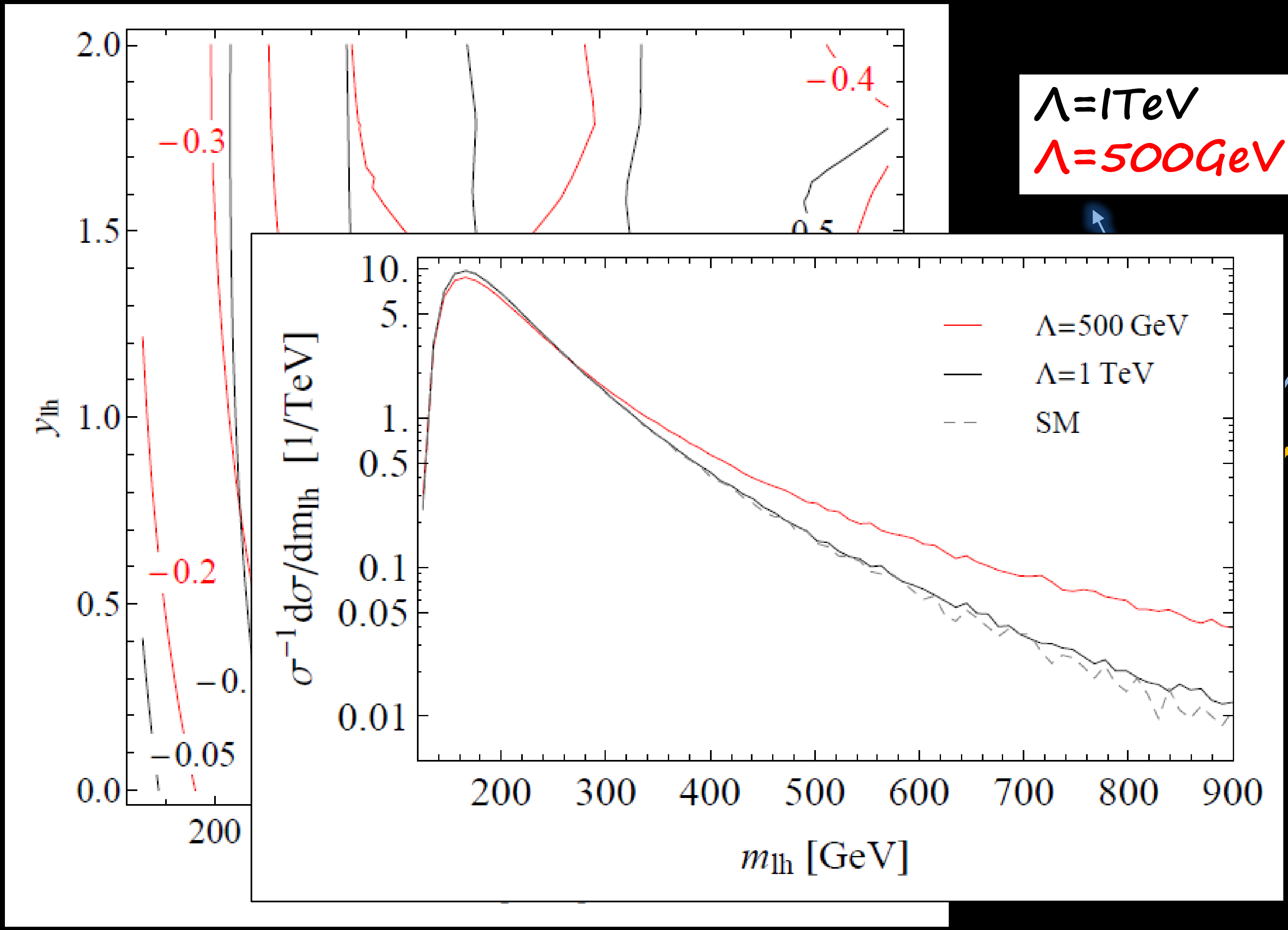
Λ=1TeV
Λ=500GeV

scale of $g^2WW\sim$

cutoff $\sim 4\pi\Lambda/g$

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

$\Lambda\sim$

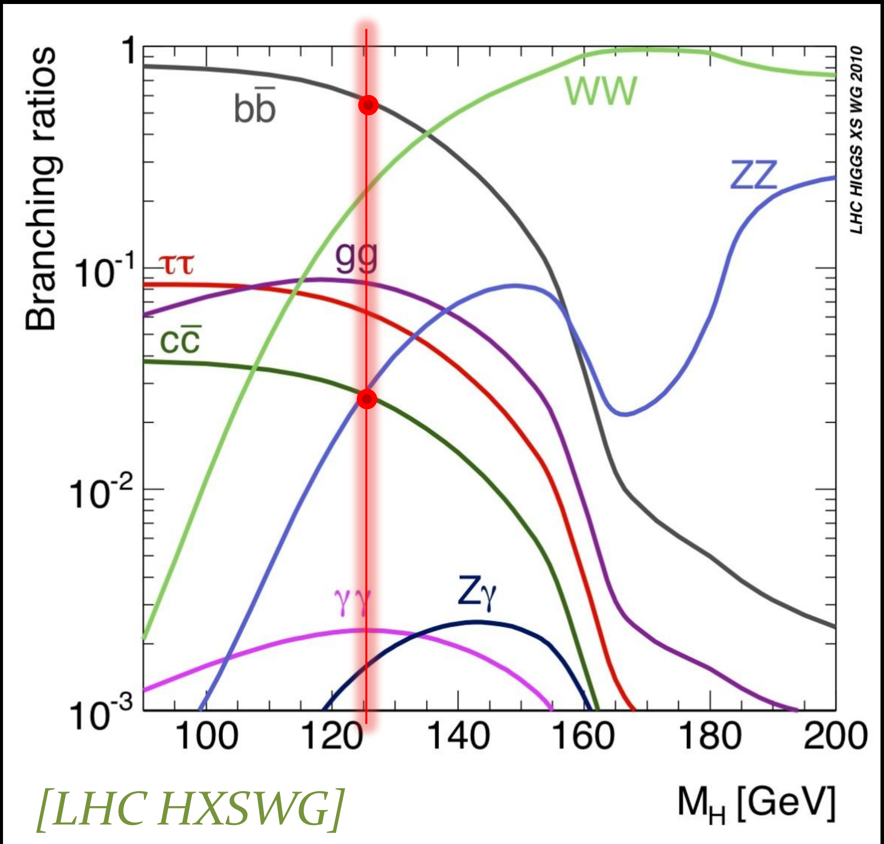
Λ/g

Charming the Higgs

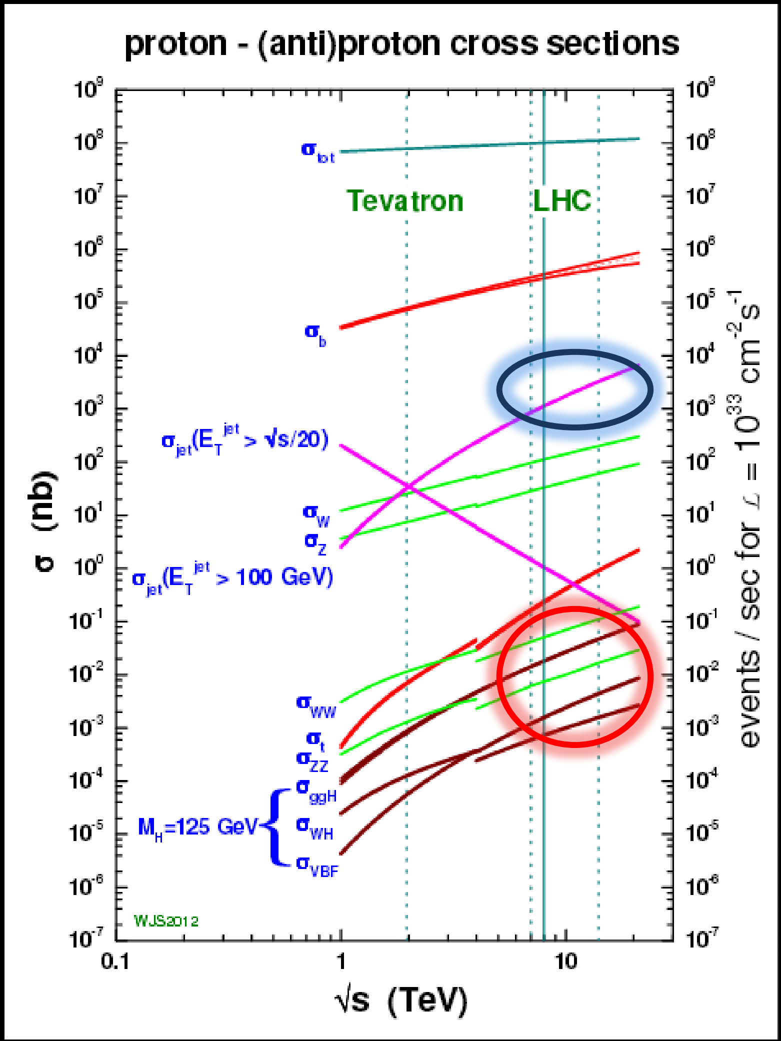
Common lore: *H→cc within the SM* is not visible @LHC:

- $BR(H\to cc) \sim \frac{m_c^2}{m_b^2} BR(H\to bb) \sim 1/16 \times 60\% \sim 4\%$

- hard to resolve charm jets
  → huge QCD dijet bkg



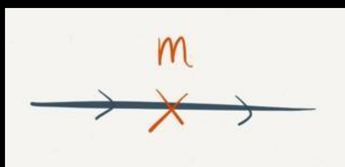
[LHC HXSWG]



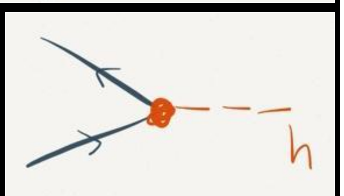
but there is hope as:

- Hcc cpl. could be significantly larger due to BSM physics:

$$\mathcal{L}_{\rm EFT} \supset \lambda^u_{ij}\bar{Q}_i\tilde{H}U_j + \frac{g^u_{ij}}{\Lambda^2}\bar{Q}_i\tilde{H}U_j\left(H^\dagger H\right) + \text{h.c.}$$



$$= \frac{v}{\sqrt{2}}\left(\lambda^u_{ij} + g^u_{ij}\frac{v^2}{2\Lambda^2}\right),$$



$$= \frac{1}{\sqrt{2}}\left(\lambda^u_{ij} + 3g^u_{ij}\frac{v^2}{2\Lambda^2}\right).$$

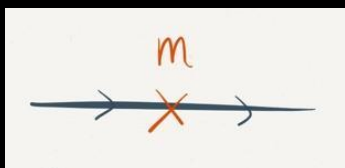
$$\Lambda \simeq \frac{44\,\text{TeV}}{\sqrt{c_c - 1}}.$$

Hcc enhancement

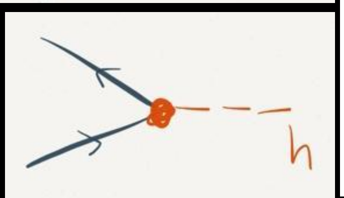
yet, modulo an accidental cancellation of o(1/few) *but there is hope as:*

- *Hcc* cpl. could be significantly larger due to BSM physics:

$$\mathcal{L}_{\rm EFT} \supset \lambda^u_{ij}\bar{Q}_i\tilde{H}U_j + \frac{g^u_{ij}}{\Lambda^2}\bar{Q}_i\tilde{H}U_j\left(H^\dagger H\right) + \text{h.c.}$$



$$= \frac{v}{\sqrt{2}}\left(\lambda^u_{ij} + g^u_{ij}\frac{v^2}{2\Lambda^2}\right),$$



$$= \frac{1}{\sqrt{2}}\left(\lambda^u_{ij} + 3g^u_{ij}\frac{v^2}{2\Lambda^2}\right).$$

$$\Lambda \simeq \frac{44\,\text{TeV}}{\sqrt{c_c - 1}}.$$

Hcc enhancement

yet, modulo an accidental cancellation of o(1/few)

- a method was recently put forward to tag c-jets at the LHC

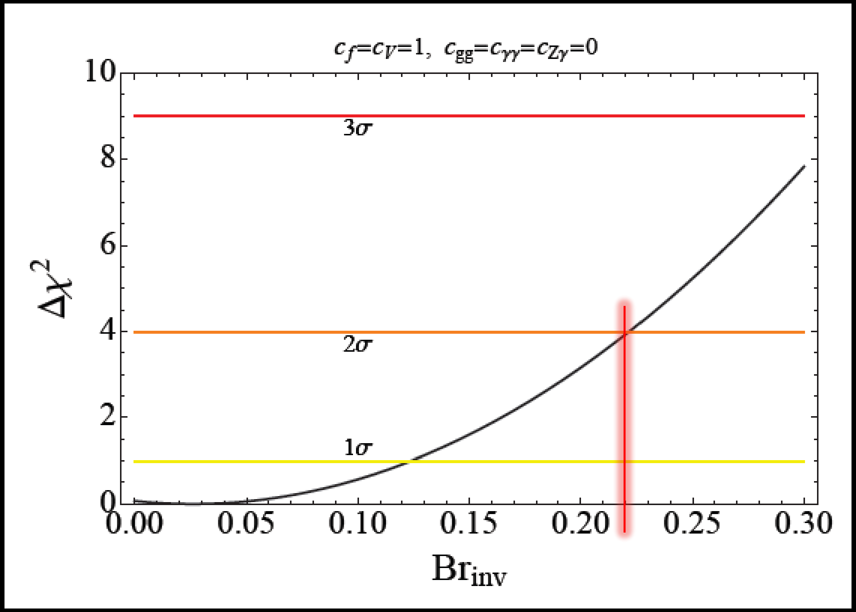
[ATLAS-CONF-2013-068]

medium working point: 20% efficiency w/ 1/5, 1/140, 1/10 rejection for b,QCD,τ-jets

(*loose* point: 95% efficiency w/out significant rejection power for fakes.)

What's the sensitivity to larger charm coupling in Higgs data?

- indirectly constrained through the invisible width:



[Falkowski-Riva-Urbano '13]

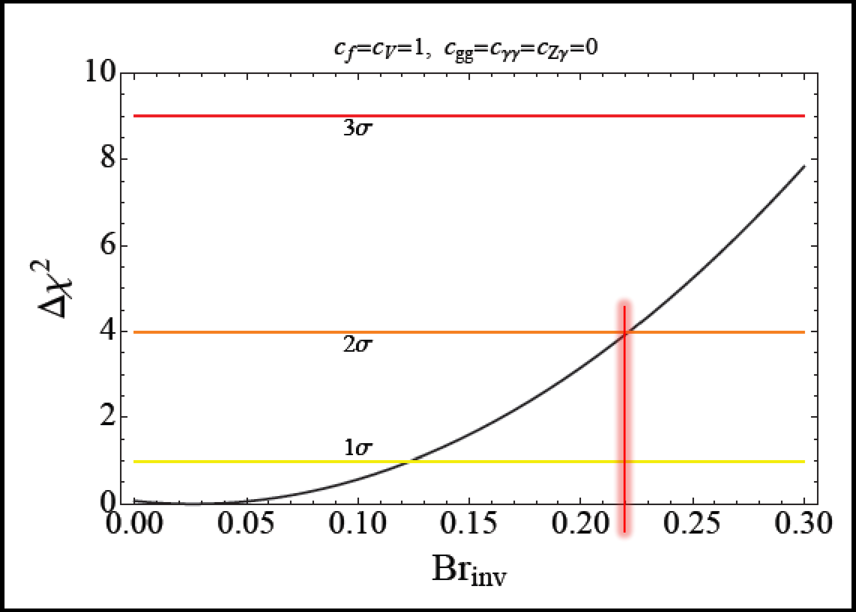
if all other "visible" couplings set to SM values:

Br_{inv} ~< 22% @95%CL

adding a new physics source of ggh: Br_{inv} ~< 50% @95%CL

What's the sensitivity to larger charm coupling in Higgs data?

- indirectly constrained through the invisible width:



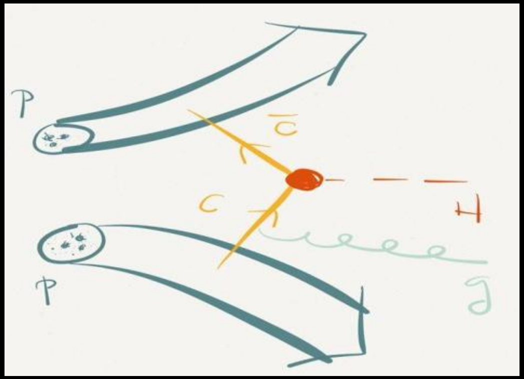
[Falkowski-Riva-Urbano '13]

if all other "visible" couplings set to SM values:

$Br_{inv} \sim< 22\%$ @95%CL

adding a new physics source of ggh: $Br_{inv} \sim< 50\%$ @95%CL

- charm fusion opens up as a significant H prod. mechanism



@NLO: $\sigma_{cc} \approx 0.008\ \sigma_{gg}$ in the SM

$\sim 15\%$ increase in $\sigma_{pp\to h}$ if Hcc $4x$ larger

What's the sensitivity to larger charm coupling in Higgs data?

we perform a global Higgs fit within the EFT framework*:

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + \ldots$$
$$+ m_W^2\, W_\mu^+ W^{-\mu}\left(1 + 2c_W\frac{h}{v} + \ldots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z\frac{h}{v} + \ldots\right)$$
$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \ldots\right) + \ldots$$

$$\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW}W^\dagger_{\mu\nu}W^{\mu\nu} + c_{ZZ}Z_{\mu\nu}Z^{\mu\nu} + 2c_{Z\gamma}A_{\mu\nu}Z^{\mu\nu} + c_{\gamma\gamma}A_{\mu\nu}A^{\mu\nu} - c_{gg}G^a_{\mu\nu}G^{a,\mu\nu}\right],$$

$SU(2)_V$ custodial symmetry, h = custodial singlet, $c_Z=c_W=c_V$

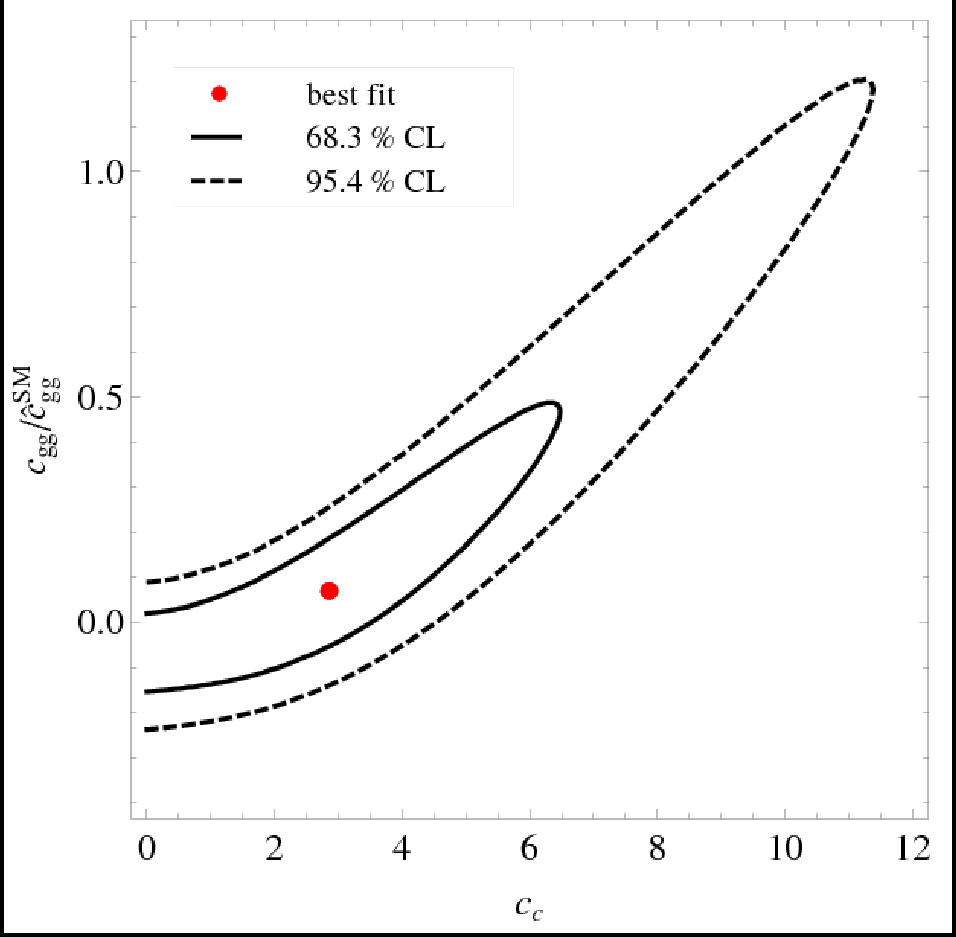
*we follow fit procedure of *[Falkowski-Riva-Urbano '13]*

What's the sensitivity to larger charm coupling in Higgs data?

we perform a global Higgs fit within the EFT framework*:

only allowing c_c to float: $c_c \sim< 4$ @2σ

allowing a new physics source in ggh: $c_c \sim< 8$ @2σ



a fairly large coupling allowed by current Higgs data

*we assume similar efficiencies for cc and gg fusion

This yields significant change (V)H→bb channel:

BR(*H→bb*) is significantly suppressed:

$$\mathrm{BR}_{h\to b\bar{b}} = \frac{\mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}}}{1+(|c_c|^2-1)\mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}} \,. \quad \approx 40\%\ (20\%)$$

with $c_{gg}>0$

but most charm fusion events rejected after VH-enriching cuts:

$\rightarrow\ \mu_{bb} \approx 0.7\ (0.3)$ @8TeV

with $c_{gg}>0$

large part of *bb* signal expected @ATLAS/CMS could be lost!

in the benefit of charm…

now, one can use charm tagging technique to capture $H \to cc$:

build cc-enriched bb signal = "*charming the Higgs*":

$$\mu_{b\bar{b}+c\bar{c}} \equiv \frac{\sigma_{pp\to h}\left(\epsilon_b^2 \mathrm{BR}_{h\to b\bar{b}} + \epsilon_c^2 \mathrm{BR}_{h\to c\bar{c}}\right)}{\sigma_{pp\to h}^{\mathrm{SM}}\left(\epsilon_b^2 \mathrm{BR}_{h\to b\bar{b}}^{\mathrm{SM}} + \epsilon_c^2 \mathrm{BR}_{h\to c\bar{c}}^{\mathrm{SM}}\right)}$$

now, one can use charm tagging technique to capture $H \to cc$:

build cc-enriched bb signal = "*charming the Higgs*":

$$\mu_{b\bar{b}+c\bar{c}} \equiv \frac{\sigma_{pp\to h}\left(\epsilon_b^2 \mathrm{BR}_{h\to b\bar{b}} + \epsilon_c^2 \mathrm{BR}_{h\to c\bar{c}}\right)}{\sigma^{\mathrm{SM}}_{pp\to h}\left(\epsilon_b^2 \mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}} + \epsilon_c^2 \mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}\right)}$$

assume ATLAS' *medium working point* w/ ε_c=20% efficiency, and ε_b=70% for b-tagging efficiency:

$\rightarrow$ $\mu_{bb+cc} \approx 0.75\ (0.4)$ @8TeV

only marginal fraction of lost signal recovered

now, one can use charm tagging technique to capture $H \to cc$:

build cc-enriched bb signal = "*charming the Higgs*":

$$\mu_{b\bar{b}+c\bar{c}} \equiv \frac{\sigma_{pp\to h}\left(\epsilon_b^2 \mathrm{BR}_{h\to b\bar{b}} + \epsilon_c^2 \mathrm{BR}_{h\to c\bar{c}}\right)}{\sigma_{pp\to h}^{\mathrm{SM}}\left(\epsilon_b^2 \mathrm{BR}_{h\to b\bar{b}}^{\mathrm{SM}} + \epsilon_c^2 \mathrm{BR}_{h\to c\bar{c}}^{\mathrm{SM}}\right)}$$

assume ATLAS' *medium working point* w/ $\varepsilon_c = 20\%$ efficiency, and $\varepsilon_b = 70\%$ for b-tagging efficiency:

$\to$ $\mu_{bb+cc} \approx 0.75\ (0.4)$ @8TeV

only marginal fraction of lost signal recovered

assume instead a speculative $\varepsilon_c = 40\%$ c-tagging efficiency:

$\to$ $\mu_{bb+cc} \approx 0.9\ (0.6)$ @8TeV

large fraction recovered, almost back to bb SM rate!

Conclusions

- the observed Higgs boson appeared Standard so far.

- yet, there is still room for significant BSM corrections
  even for new dynamics >~TeV scale