

Large BSM effects in Higgs Physics @ the LHC

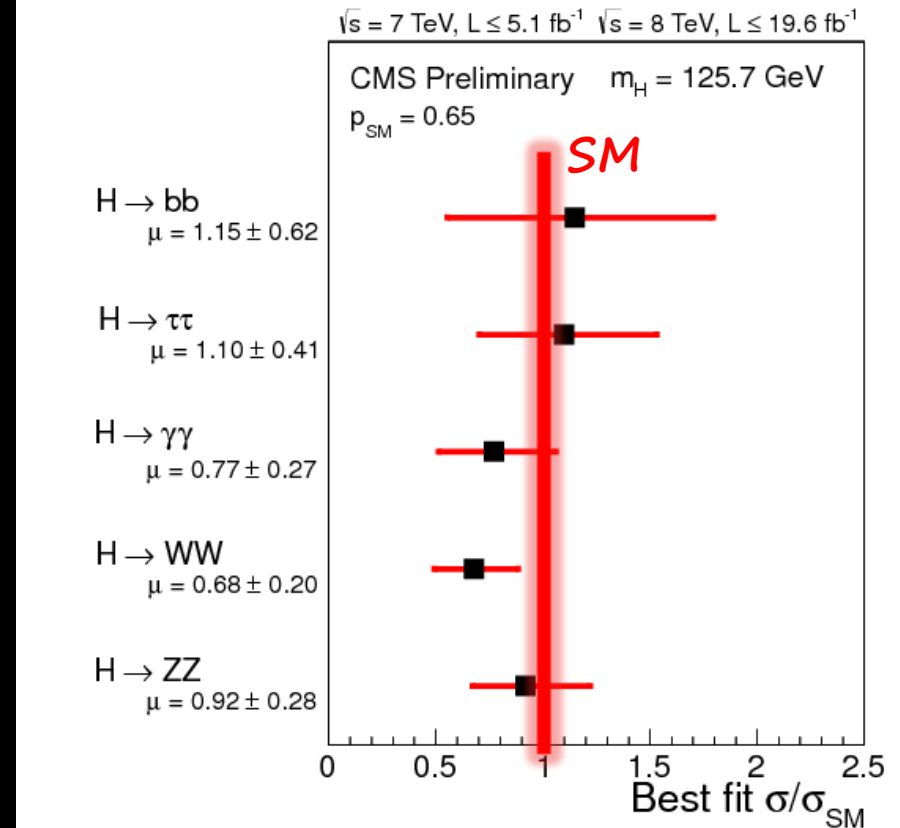
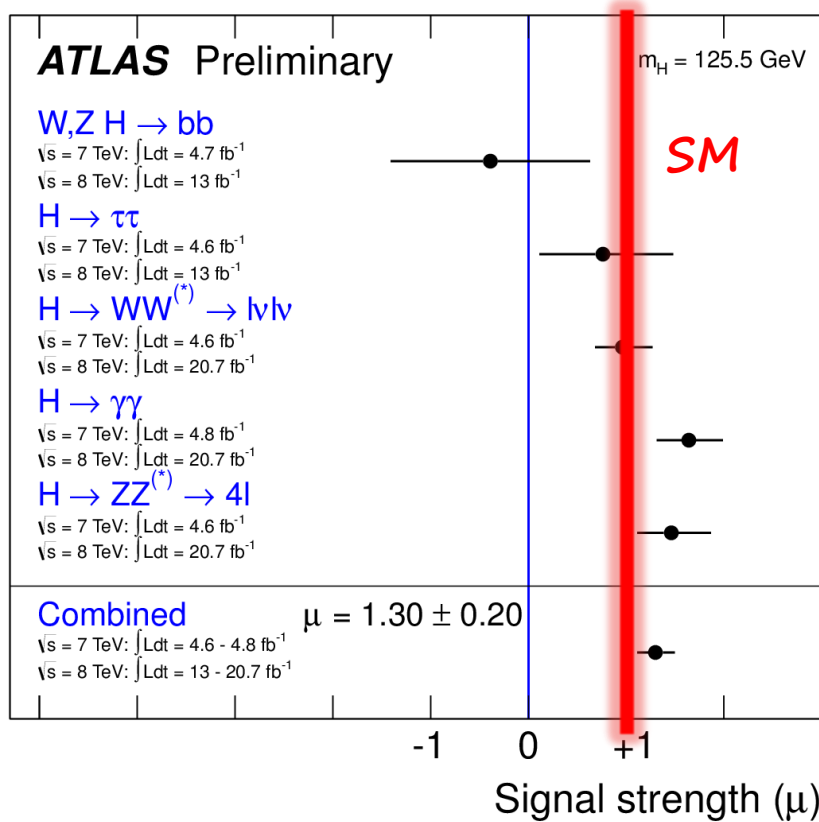
Cédric Delaunay

LAPTh – Annecy-le-vieux, France

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

CD, T. Golling, G. Perez & Y. Soreq [[arXiv:1310.7029](#)]

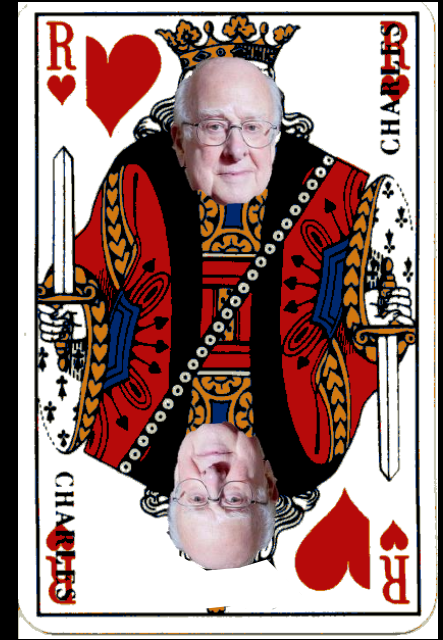
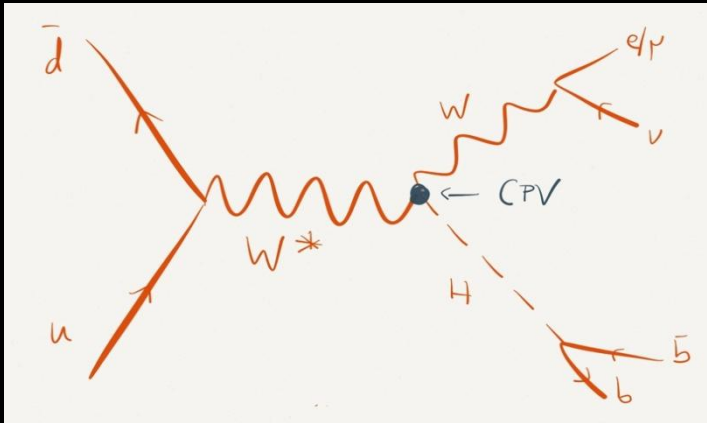
a light Higgs has been found \rightarrow $W_L W_L \rightarrow W_L W_L$ unitary up to $E \gg \text{TeV}$
 which so far looks like the SM Higgs



yet, a light Higgs means small couplings ($y_b^{SM} = 0.02$)
 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

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

CP-even
CP-odd

Lorentz invariance $\rightarrow A, B, C =$ general functions of p^2

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

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- going BSM with d=6 operators:

$$\begin{aligned} \mathcal{O}_{DH} &= H^\dagger H |D_\mu H|^2, \quad \mathcal{O}_H = |H^\dagger D_\mu H|^2, \\ \mathcal{O}_{WW} &= \frac{g^2}{2} H^\dagger H W_{\mu\nu}^a W^{\mu\nu a}, \quad \mathcal{O}_{BB} = \frac{g'^2}{2} H^\dagger H B_{\mu\nu} B^{\mu\nu}, \\ \mathcal{O}_{WB} &= gg' H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}, \end{aligned} \quad (14)$$

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not crucial here,
let's ignore them

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$\rightarrow C_W, C_Z, C_\gamma$

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

[McKeen-Pospelov-Ritz PRD '12]

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

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Lorentz invariance $\rightarrow A, B, C =$ general functions of p^2

CPV requires both A_V (or B_V) and $C_V \neq 0 \rightarrow CPV \text{ obs.} \propto AC$
 \rightarrow interference

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

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Lorentz invariance $\rightarrow A, B, C =$ general functions of p^2

CPV requires both A_V (or B_V) and $C_V \neq 0 \rightarrow$ CPV obs. $\propto AC$
 \rightarrow interference

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

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

- $H \rightarrow VV^* \rightarrow \text{leptons}$:

[Gao et al. PRD '10]

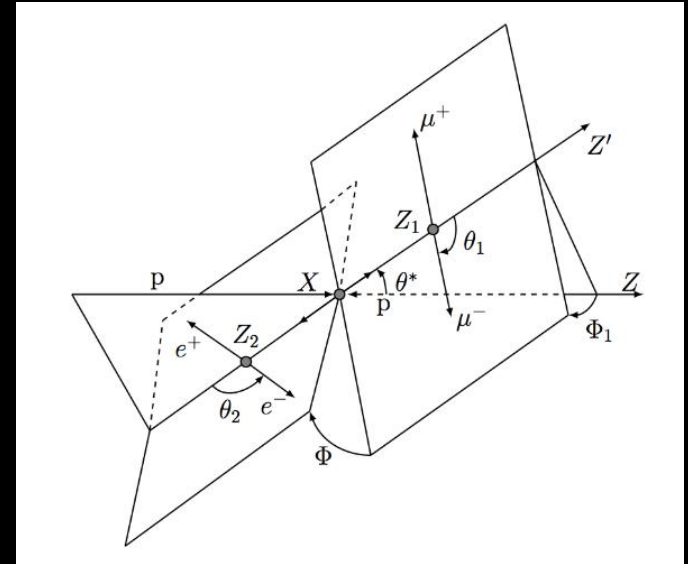
“look at angular distributions to probe $C_V \neq 0$ ”

$H \rightarrow VV^* \rightarrow \text{leptons}$: 5 physical angles

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

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

[CMS-PAS-HIG-13-002]



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

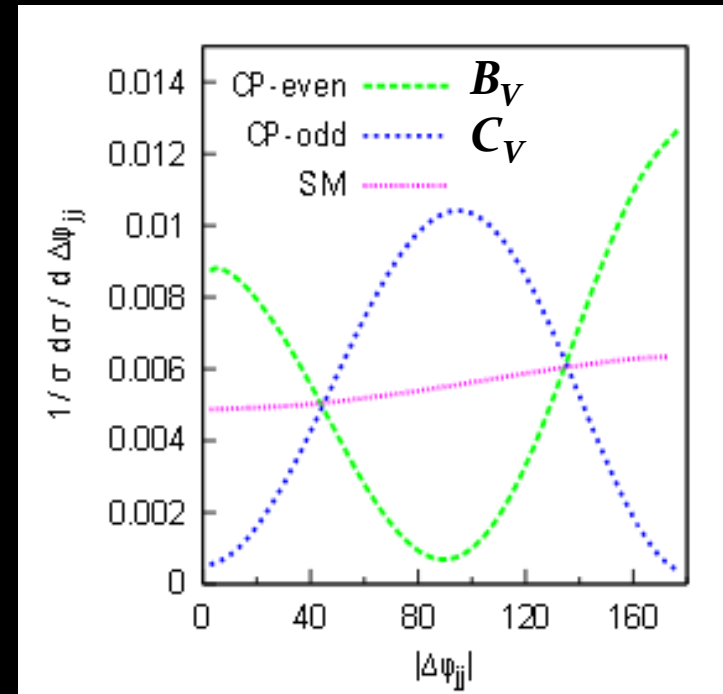
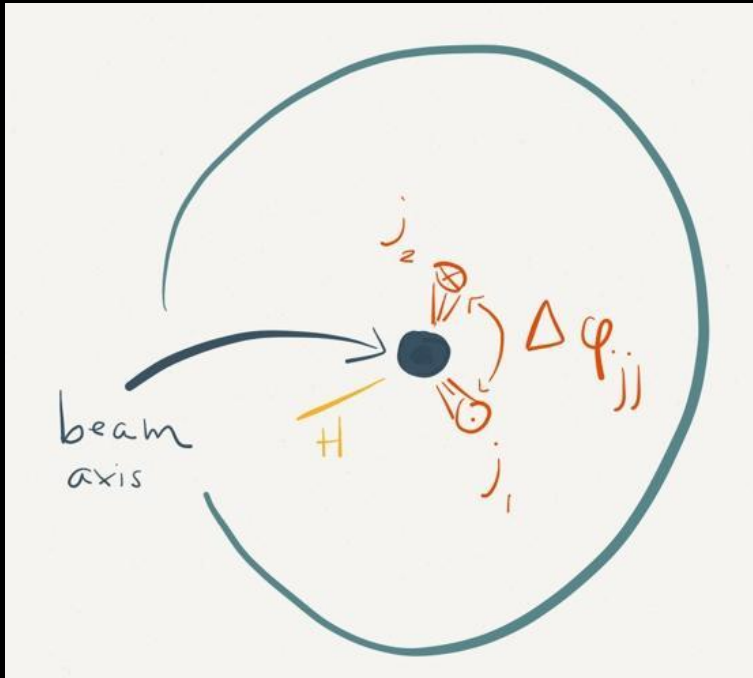
- drawbacks:
- 1) energy is fixed, effect of $O(m_h^2/\Lambda^2)$
 - 2) poor constraint on C_W

- azimuthal difference between 2 forward jets in VBF:

[Plehn-Rainwater-Zeppenfeld PRL '02]

see also: [Hankele PRD '06]

[Englert et al. JHEP '13]

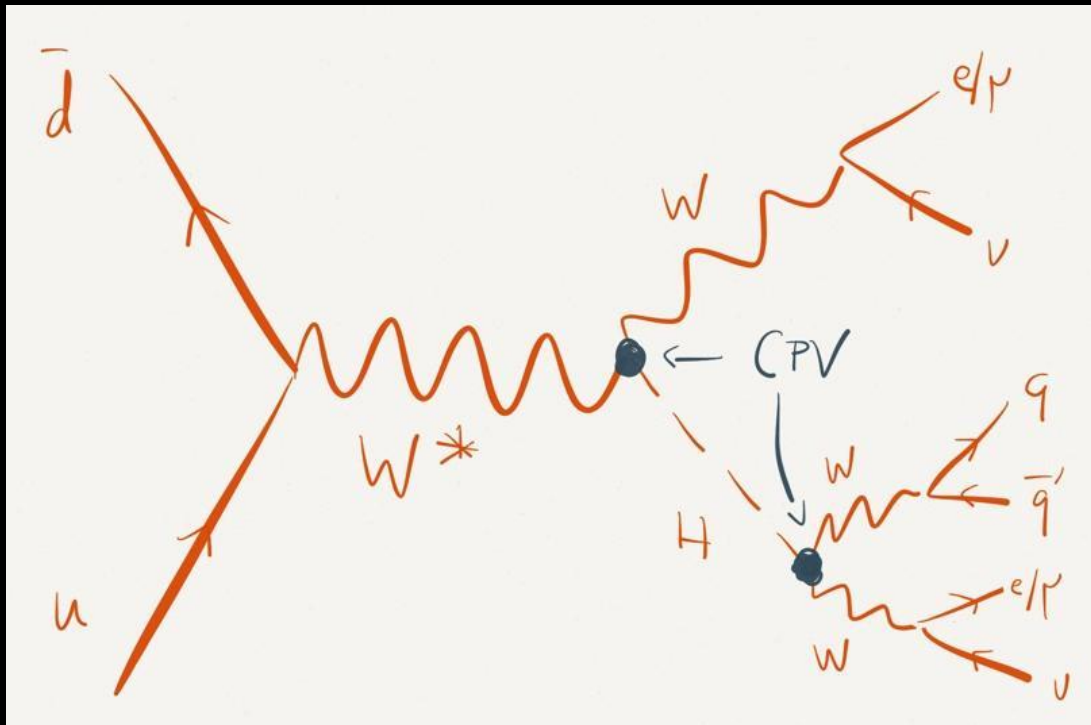


$$\epsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2p_{T,+} p_{T,-} \sin(\phi_+ - \phi_-) = 2p_{T,+} p_{T,-} \sin \Delta\phi_{jj}$$

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

- $WH \rightarrow (l\nu)(WW^* \rightarrow l\nu qq)$

[Desai-Ghosh-Mukhopadhyaya PRD '11]



see also in ZH:

[Christensen-Han-Li PLB '10]

[Englert et al. JHEP '13]

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

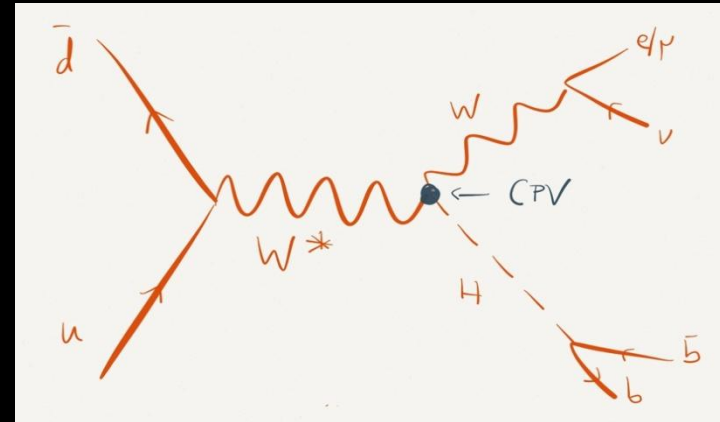
- benefits:
- 1) asymmetries are linear in C_W
 - 2) H boosted, can increase sensitivity to high scales

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

Consider $WH \rightarrow l\nu bb$:

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

parton level process \rightarrow



$H - V_\mu - V_\nu :$

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

CP-even

CP-odd

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

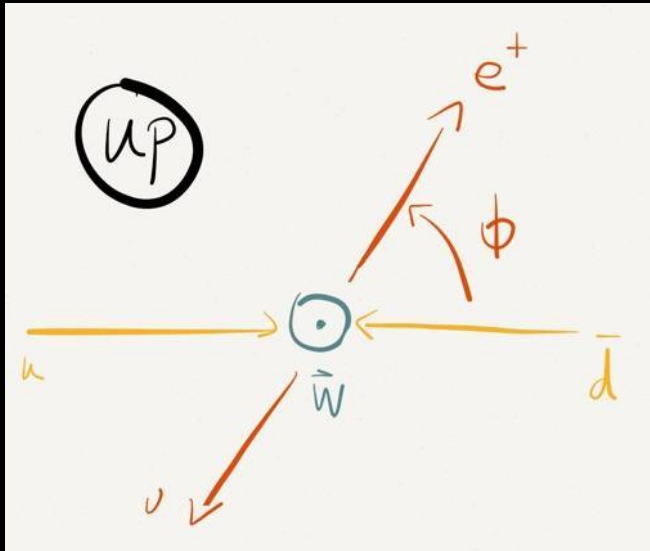
induces **P-odd**
triple product

trade W for
 e/μ momentum*

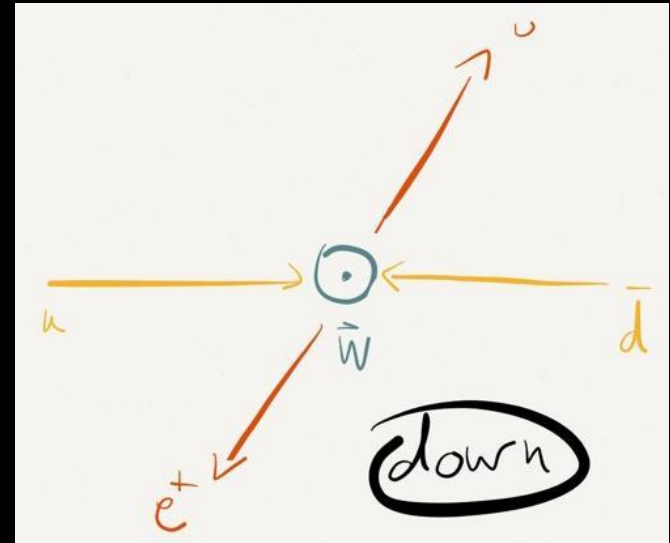
$$t = \vec{\ell} \cdot (\vec{H} \times \vec{u}) + \text{CP-even couplings} \rightarrow \text{asymmetry in } t$$

*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

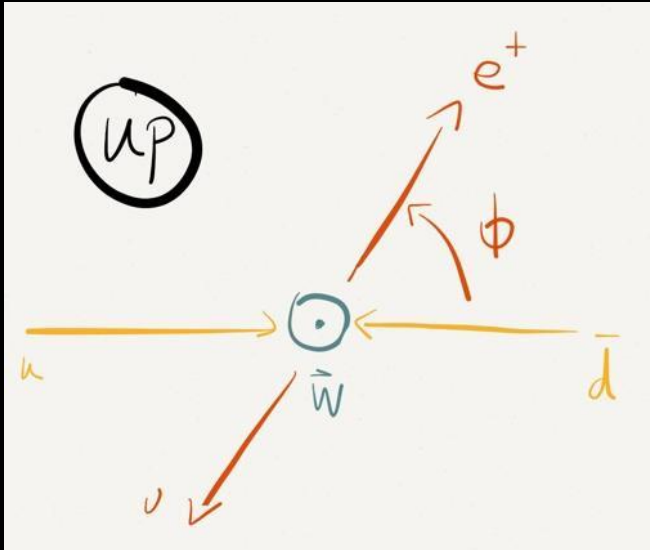
$$\tan \gamma = \frac{C_W \hat{s} \beta}{2A_W}$$

“weak” phase

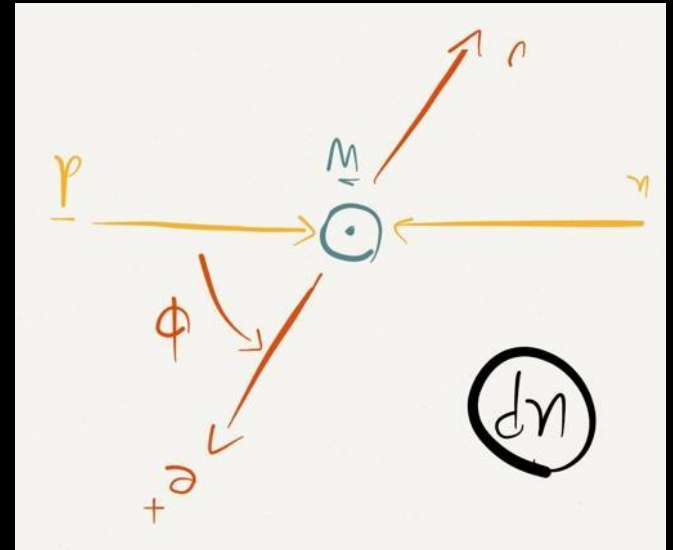
“strong” phase: $M_{W_\lambda \rightarrow l^+ \nu} \propto e^{i\lambda\phi}$

pp@LHC is parity invariant

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

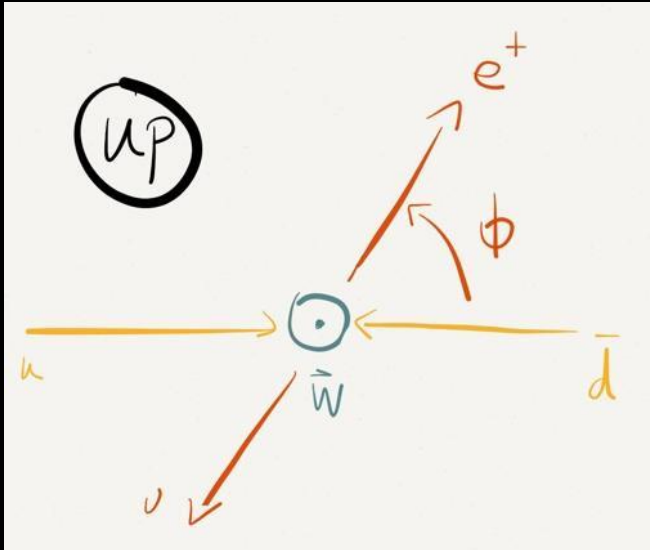


$=$
 \downarrow
 $A=0!$

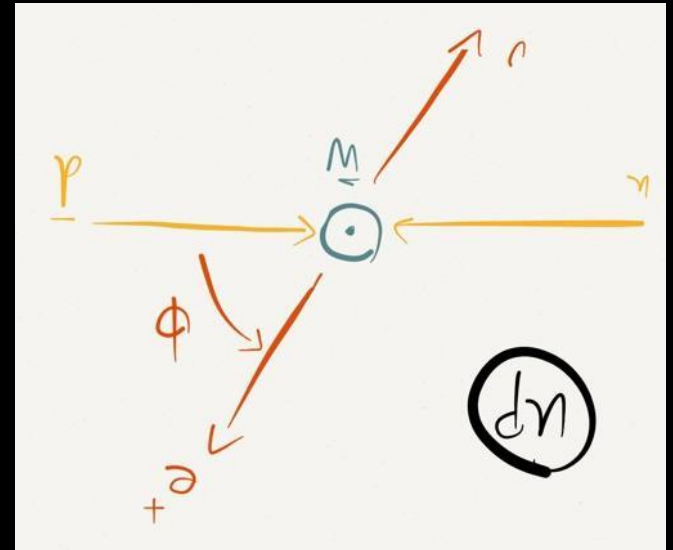


pp@LHC is parity invariant

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



>
↓
 $A \neq 0$



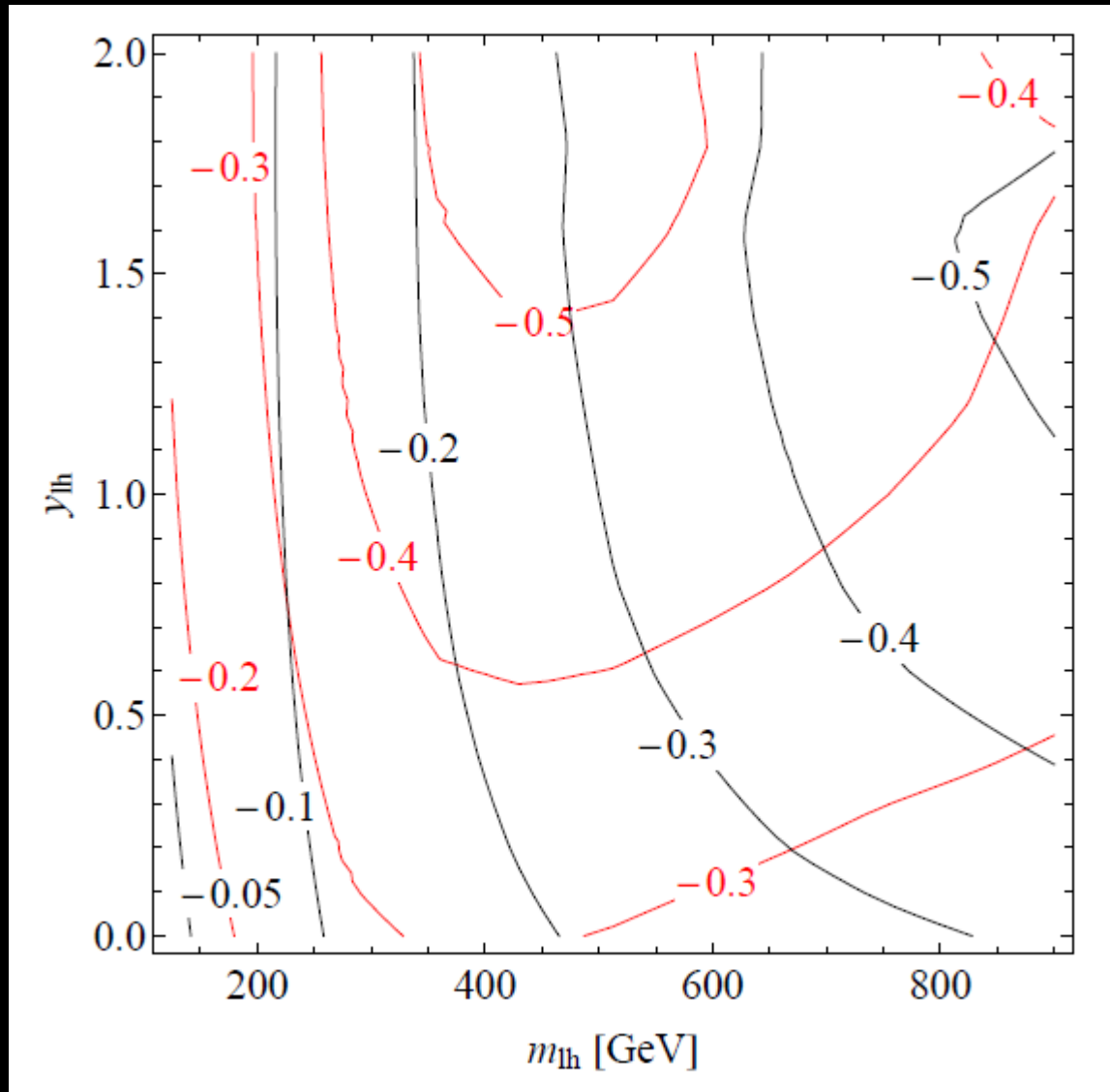
standard trick: use the boost direction, cut on l+H rapidity

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

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 $C=4/\Lambda^2$

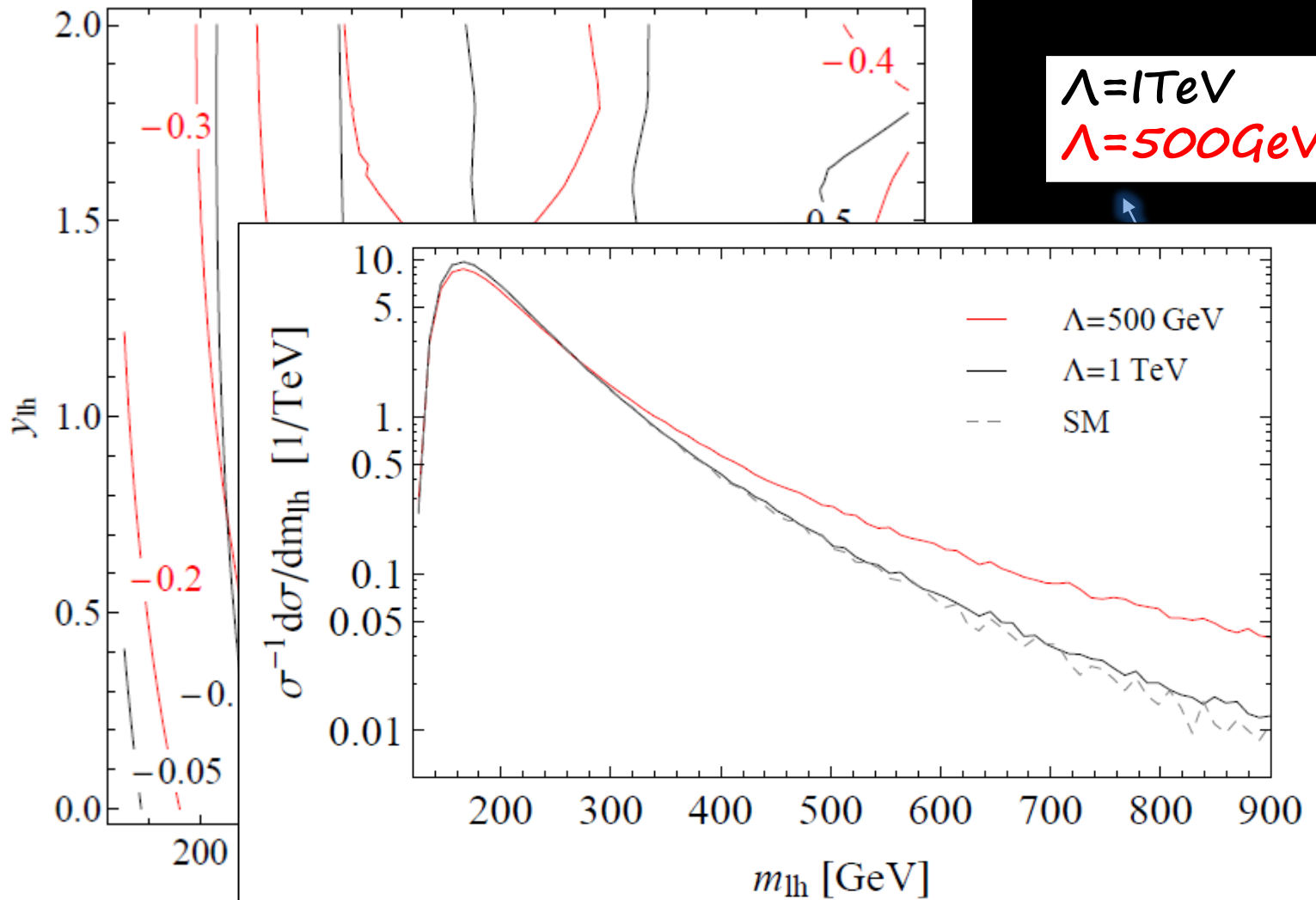


$\Lambda=1\text{TeV}$
 $\Lambda=500\text{GeV}$

scale of $g^2 WW \sim$
cutoff $\sim 4\pi\Lambda/g$

asymmetry as function of cuts

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

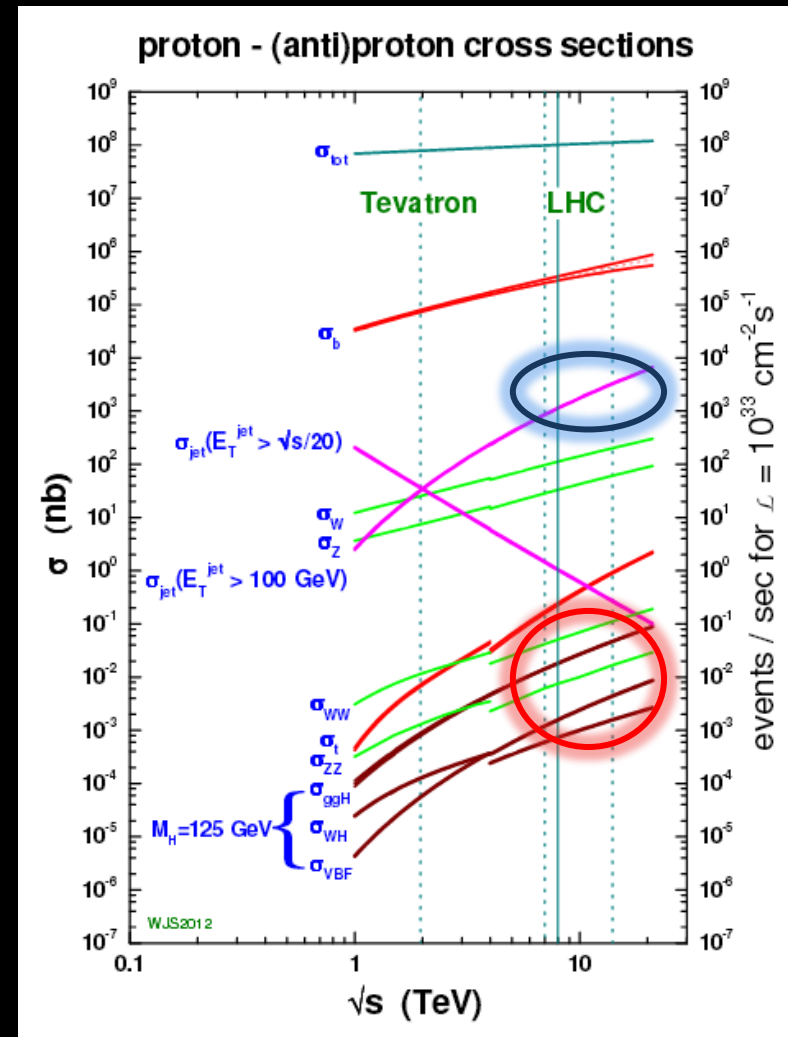
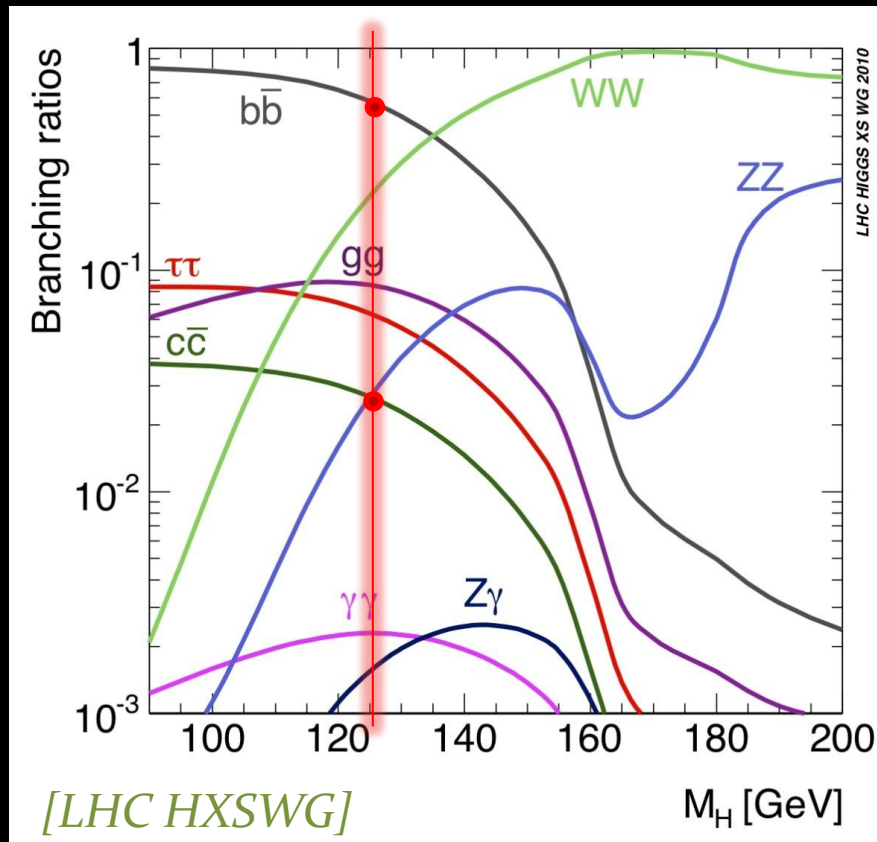




Charming the Higgs

Common lore: $H \rightarrow cc$ within the SM is not visible @LHC:

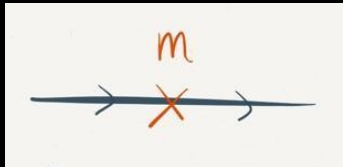
- $\text{BR}(H \rightarrow cc) \sim \frac{m_c^2}{m_b^2}$ $\text{BR}(H \rightarrow bb) \sim 1/16 \times 60\% \sim 4\%$
- hard to resolve charm jets
→ huge QCD dijet bkg



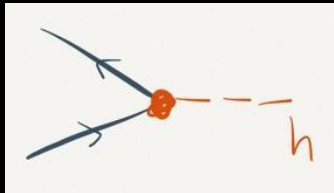
but there is hope as:

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

$$\mathcal{L}_{\text{EFT}} \supset \lambda_{ij}^u \bar{Q}_i \tilde{H} U_j + \frac{g_{ij}^u}{\Lambda^2} \bar{Q}_i \tilde{H} U_j (H^\dagger H) + \text{h.c.}$$



$$= \frac{v}{\sqrt{2}} \left(\lambda_{ij}^u + g_{ij}^u \frac{v^2}{2\Lambda^2} \right),$$



$$= \frac{1}{\sqrt{2}} \left(\lambda_{ij}^u + 3g_{ij}^u \frac{v^2}{2\Lambda^2} \right).$$

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

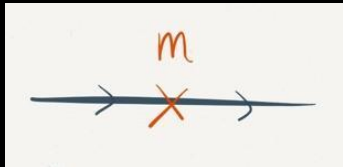
Hcc enhancement

yet, modulo an accidental cancellation of $\mathcal{O}(1/\text{few})$

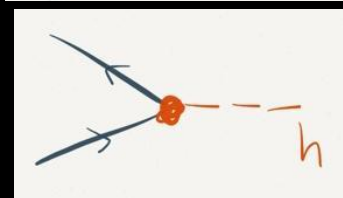
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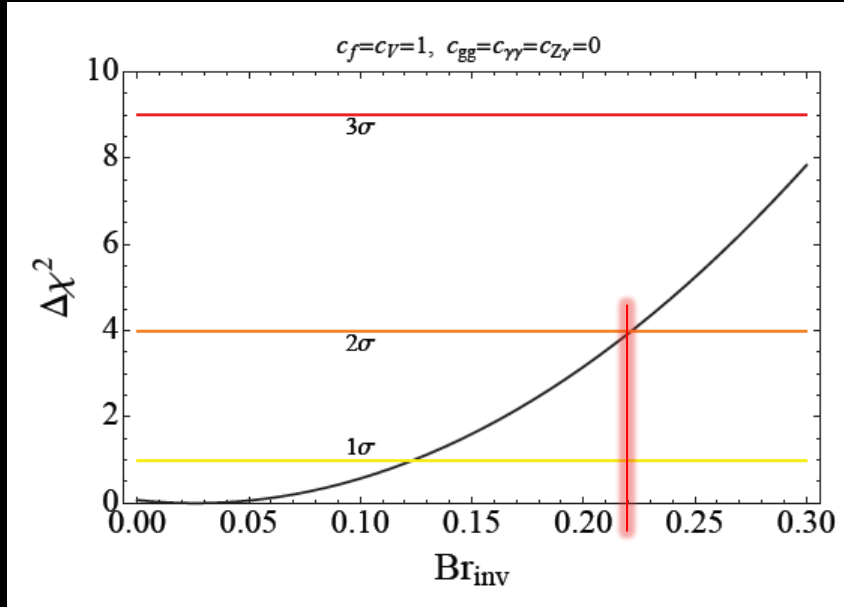
- a method was recently put forward to **tag c-jets at the LHC**
[ATLAS-CONF-2013-068]

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:



if all other “visible” couplings set to SM values:

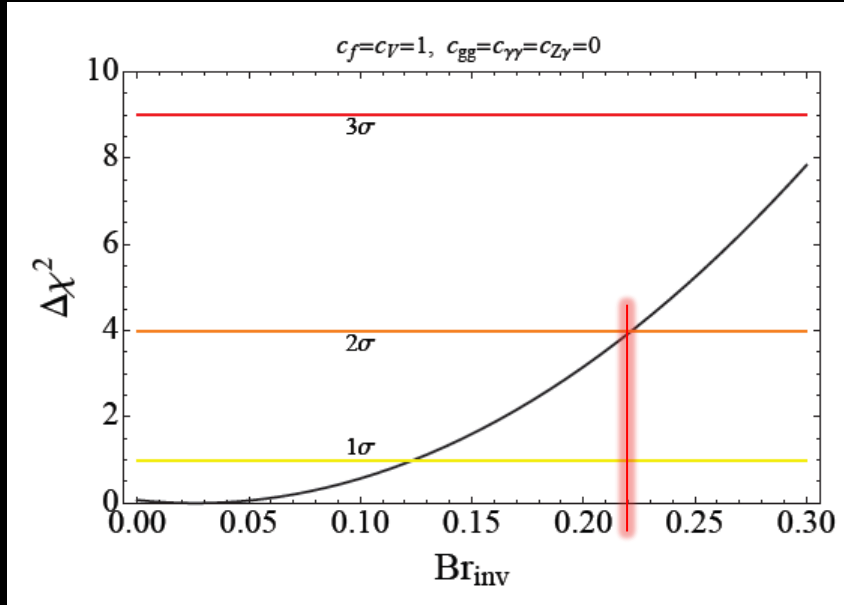
$$Br_{inv} \sim < 22\% \text{ @}95\%CL$$

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

[Falkowski-Riva-Urbano '13]

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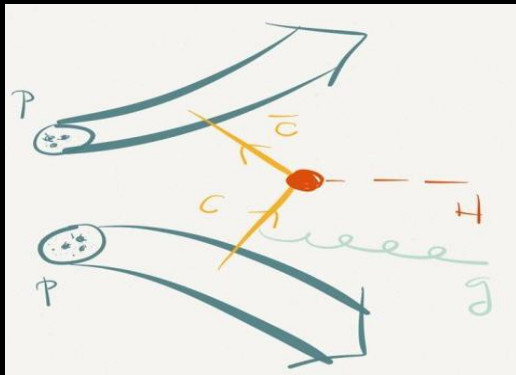
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adding a new physics source of ggh: $Br_{inv} \sim < 50\% \text{ @95\%CL}$

[Falkowski-Riva-Urbano '13]

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



@NLO: $\sigma_{cc} \approx 0.003 \sigma_{gg}$ in the SM

$O(10\%)$ increase in $\sigma_{pp \rightarrow h}$ 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*:

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

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

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

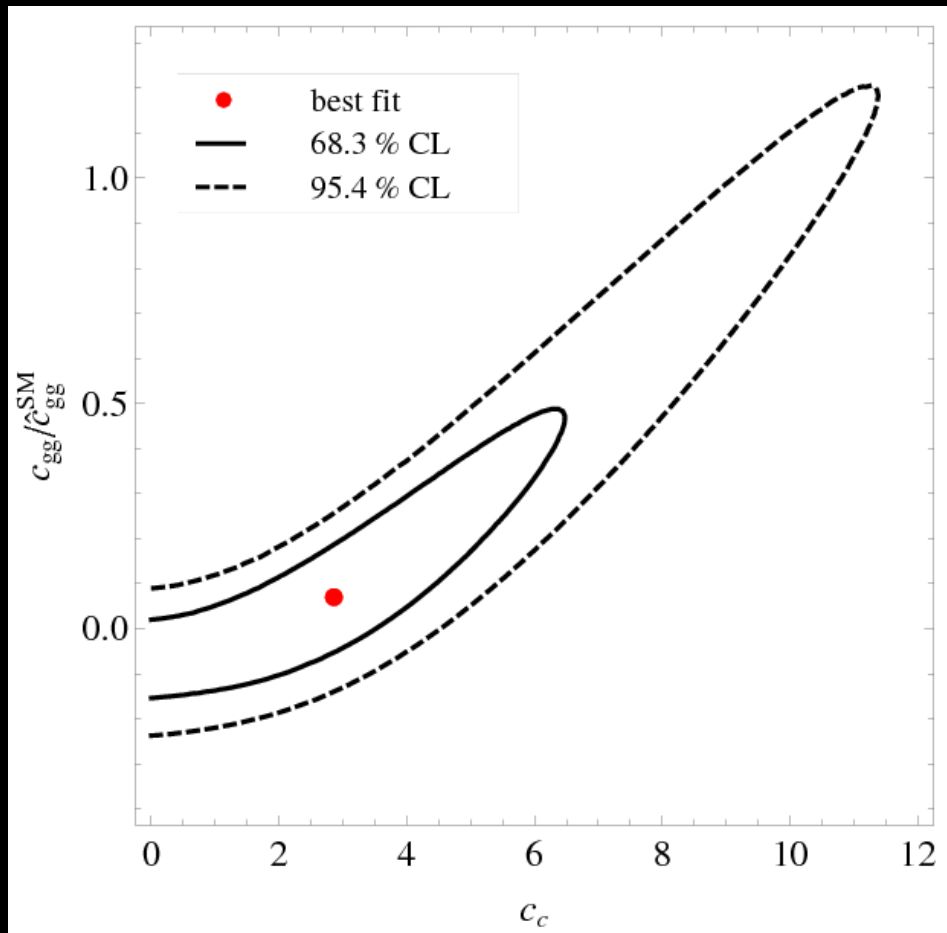
*we follow fit procedure of [Falkowski-Riva-Urbano '13]

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: $c_c \sim < 4 @ 2\sigma$

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



a fairly large coupling allowed by current Higgs data

*we assume similar efficiencies for cc and gg fusion

This yields significant change (\vee) $H \rightarrow b\bar{b}$ channel:

$\text{BR}(H \rightarrow b\bar{b})$ is significantly suppressed:

$$\text{BR}_{h \rightarrow b\bar{b}} = \frac{\text{BR}_{h \rightarrow b\bar{b}}^{\text{SM}}}{1 + (|c_c|^2 - 1) \text{BR}_{h \rightarrow c\bar{c}}^{\text{SM}}} \cdot \approx 40\% (20\%)$$

\swarrow
with $c_{gg} > 0$

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

$$\rightarrow \mu_{b\bar{b}} \approx 0.7 (0.3) @ 8\text{TeV}$$

\swarrow
with $c_{gg} > 0$

large part of $b\bar{b}$ signal expected @ATLAS/CMS could be lost!
in the benefit of charm...

one could use charm tagging techniques to capture $H \rightarrow c\bar{c}$:

build $c\bar{c}$ -enriched $b\bar{b}$ signal = “*charming the Higgs*”:

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

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

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

$$\rightarrow \mu_{b\bar{b}+c\bar{c}} \approx 0.75 \text{ (0.4) @ } 8\text{TeV}$$

only marginal fraction of lost signal recovered

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

build cc -enriched $b\bar{b}$ signal = “charming the Higgs”:

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

$$\rightarrow \mu_{b\bar{b}+c\bar{c}} \approx 0.75 \text{ (0.4) @8TeV}$$

only marginal fraction of lost signal recovered

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

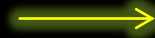
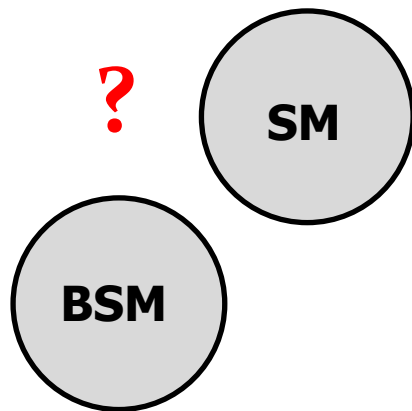
$$\rightarrow \mu_{b\bar{b}+c\bar{c}} \approx 0.9 \text{ (0.6) @8TeV}$$

large fraction recovered, almost back to $b\bar{b}$ SM rate!

Conclusions

- the observed Higgs boson appeared Standard so far.
- yet, there is still room for significant BSM corrections even for new dynamics $> \sim \text{TeV}$ scale

after LHC run 1



more data

