Light-Yukawa Couplings from Off-Shell Higgs Production

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In collaboration with **E. Balzani** and **R. Gröber** [2304.09772]

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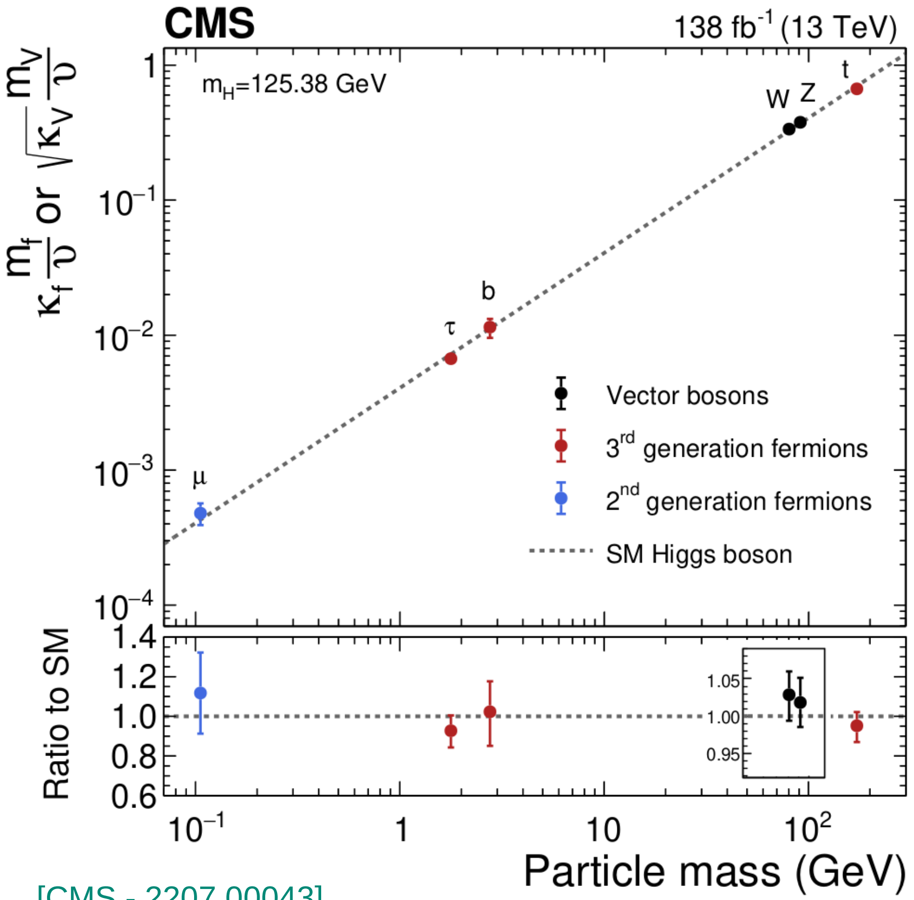
Higgs Couplings

- Couplings to vector bosons and third-generation fermions are well measured and in good agreement with theory expectation
- What can be still done at the LHC?
- First- and second-generation fermions more challenging: few events + large QCD backgrounds
- Let’s consider quark Yukawas



[CMS - 2207.00043]

Light-Quark Yukawa Couplings at the LHC

- Projected bounds on coupling modifiers $\kappa_q = y_q / y_q^{SM}$ at HL-LHC [de Blas et al. - 1905.03764]

$$\kappa_u < 560; \quad \kappa_d < 260; \quad \kappa_s < 13; \quad \kappa_c < 1.2$$

- Alternative: sensitivity from specific processes

  - Higgs decays (mainly charm) [Bodwin et al. - 1306.5770; Kagan et al – 1406.1722; König, Neubert – 1505.03870; Alte et al. - 1609.06310]

  - Higgs+jet $\rightarrow$ diff. distributions [Bishara et al. - 1606.09253; Soreq et al. - 1606.09621; Bonner, Logan - 1608.04376]

  - Other approaches [Aguilar-Saavedra et al. - 2008.12538, Falkowski et al. - 2011.09551; Vignaroli – 2205.09449; Yu - 1609.06592]

  - HH production [Alasfar, Corral Lopez, Gröber – 1909.05279; Alasfar et al. - 2207.04157]

- **This talk:** off-shell Higgs production with $H \rightarrow ZZ \rightarrow 4l$ decay See also [Zhou - 1505.06369]

  Evidence at LHC [CMS – 2202.06923; ATLAS - 2304.01532]

SMEFT Framework

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- Supplement SM Lagrangian with higher-dimensional operators suppressed by NP scale

$$\mathcal{L}^{(D=6)} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i^{(D=6)}$$

Warsaw basis
[Grzadkowski et al. - 1008.4884]

- We are interested in modifications of the Yukawa sector

SM

$$\mathcal{L}_y = -y^u_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R - y^d_{ij}\bar{Q}^i_L\phi d^j_R + \text{ h.c.}$$

$$\Delta\mathcal{L}_y = \frac{\phi^\dagger\phi}{\Lambda^2}\left((C_{u\phi})_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R + (C_{d\phi})_{ij}\bar{Q}^i_L\phi d^j_R + \text{ h.c.}\right)$$

D=6

- After EWSB and rotation to mass basis, Lagrangian for Higgs coupling to quarks is

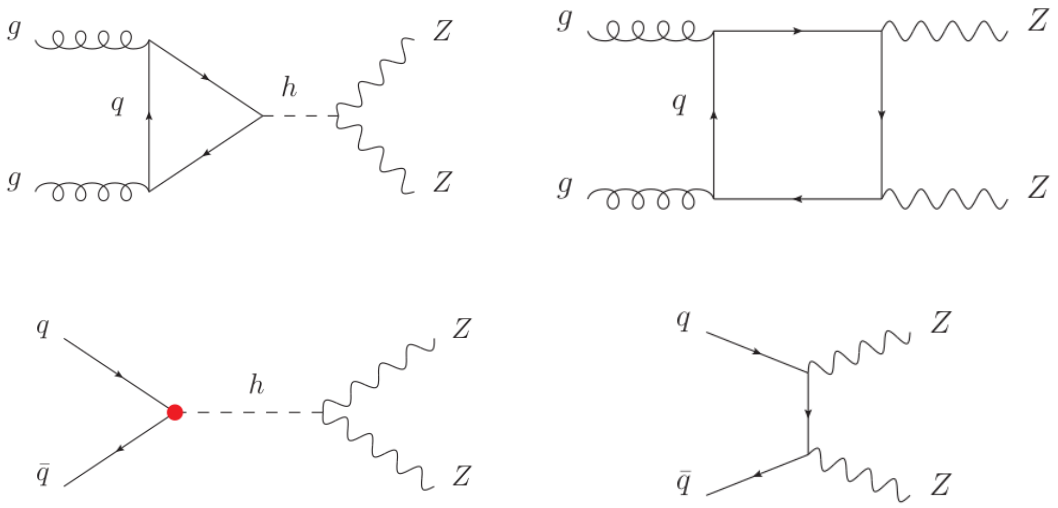
$$\mathcal{L} \supset g_{hq_i\bar{q}_j}\bar{q}_j q_i h + g_{hhq_i\bar{q}_j}\bar{q}_j q_i h^2 + g_{hhhq_i\bar{q}_j}\bar{q}_j q_i h^3$$

$$g_{hq_i\bar{q}_j} = \frac{m_q}{v}\delta_{ij} - \frac{1}{\sqrt{2}}\frac{v^2}{\Lambda^2}(\tilde{C}_{q\phi})_{ij}\,, \quad g_{hhq_i\bar{q}_j} = -\frac{3}{2\sqrt{2}}\frac{v}{\Lambda^2}(\tilde{C}_{q\phi})_{ij}\,, \quad g_{hhhq_i\bar{q}_j} = -\frac{1}{2\sqrt{2}}\frac{1}{\Lambda^2}(\tilde{C}_{q\phi})_{ij}$$

- If we assume flavor-diagonal couplings → $g_{hq\bar{q}} = \kappa_q \frac{m_q}{v}$

Enhancing Light Yukawas in *pp*→*ZZ*

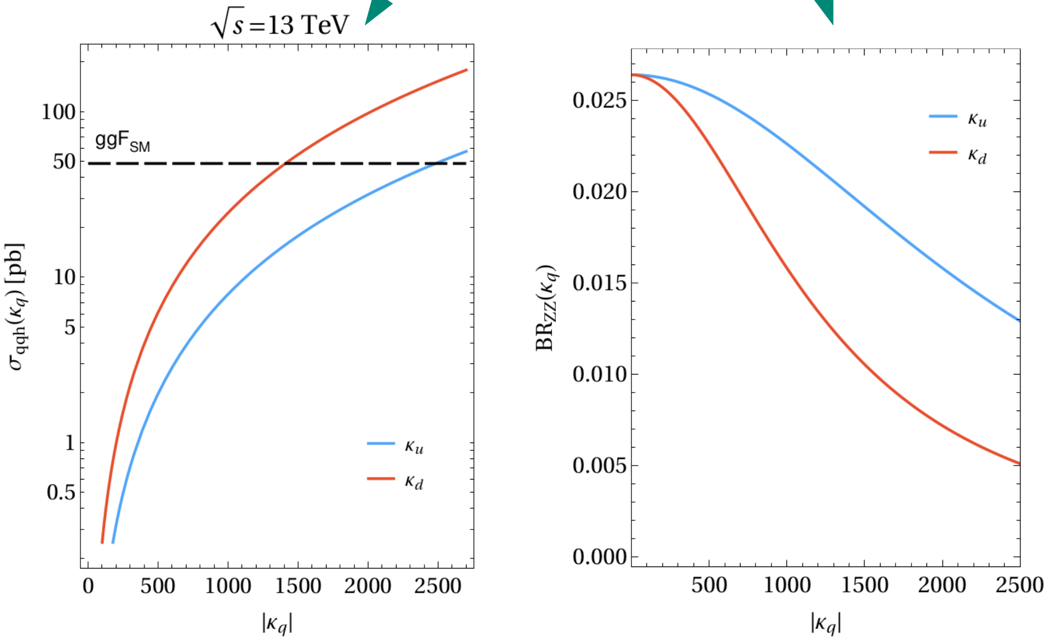
- Negligible effects in ggF
  → treated as SM
- Largest modifications in qq-channel
- NP in coupling with PDFs
  → focus only on first generation



$$g_{hq\bar{q}} = \kappa_q \frac{m_q}{v}$$

On-shell Higgs Production

- Using Narrow Width Approx $\sigma_{\text{on}} = [\sigma(gg \to h)(\kappa_q) + \sigma(q\bar{q} \to h)(\kappa_q)] \times \text{BR}_{ZZ}(\kappa_q)$



- BR decreases due to increased total width

$$\Gamma_h^{\text{BSM}}(\kappa_q) = \Gamma_h^{\text{SM}} + \kappa_q^2\, \Gamma^{\text{SM}}(h \to q\bar{q}) \qquad (q = u, d)$$

Higgs Width Indirect Measurement

- Ratio of on-shell and off-shell signal strengths

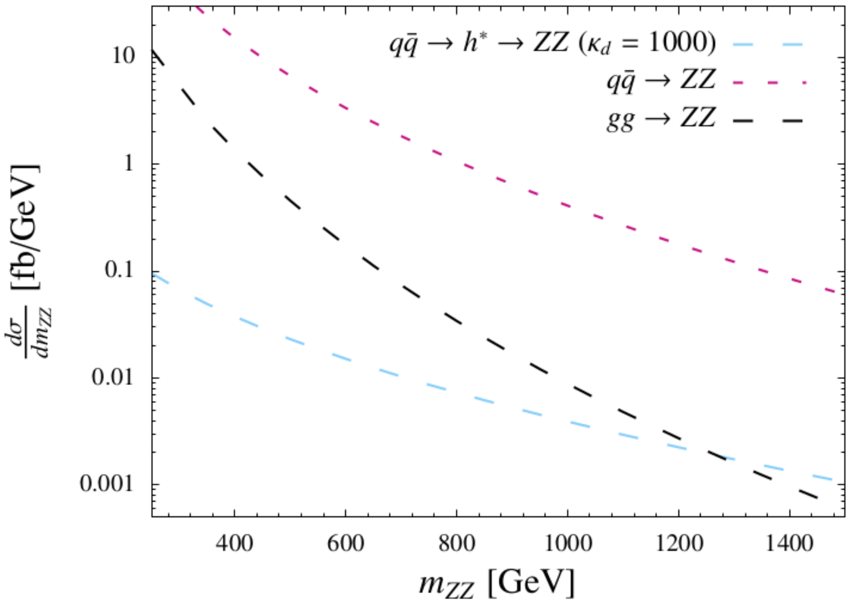
[Kauer, Passarino – 1206.4803]
[Caola, Melnikov – 1307.4935]
[Campbell. Ellis, Williams - 1311.3589]

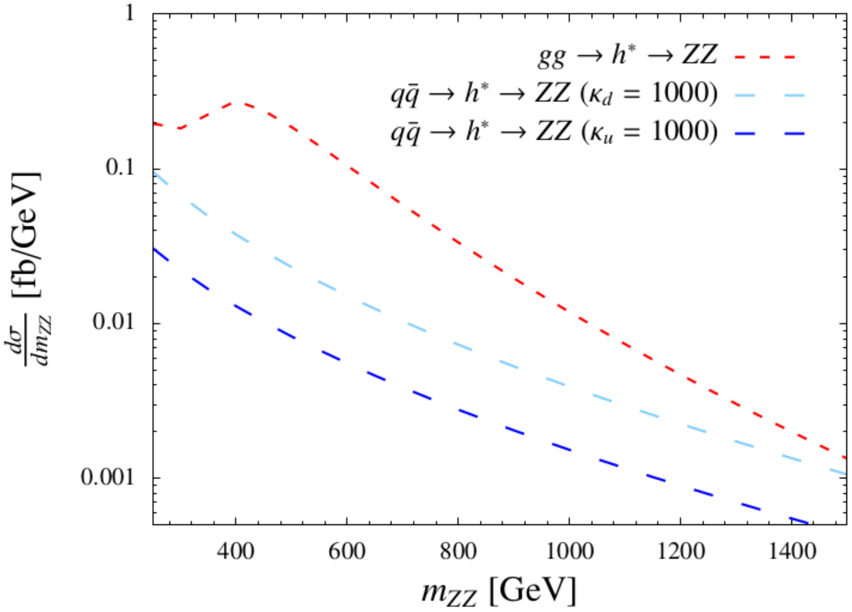
$$\frac{\mu_{\rm on}}{\mu_{\rm off}} \propto \frac{\kappa^2_{ggh}(m_h)\kappa^2_{hZZ}(m_h)}{\Gamma_h/\Gamma_h^{\rm SM}} \frac{1}{\kappa^2_{ggh}(m_{4\ell})\kappa^2_{hZZ}(m_{4\ell})}$$

- The model-independence of the method is spoiled by the additional NP effects in the qq-annihilation channel

- Instead, we can look at the off-shell region only and study effects on the differential distributions

Off-Shell Higgs Production





$\tilde{C}_{d\phi}/(1\ \mathrm{TeV}^2) = 0.45$ $\tilde{C}_{u\phi}/(1\ \mathrm{TeV}^2) = 0.21$

Kinematic discriminants

[Campbell et al. - 1311.3589; CMS – 2202.06923; Haisch, Koole – 2111.12589; etc...]

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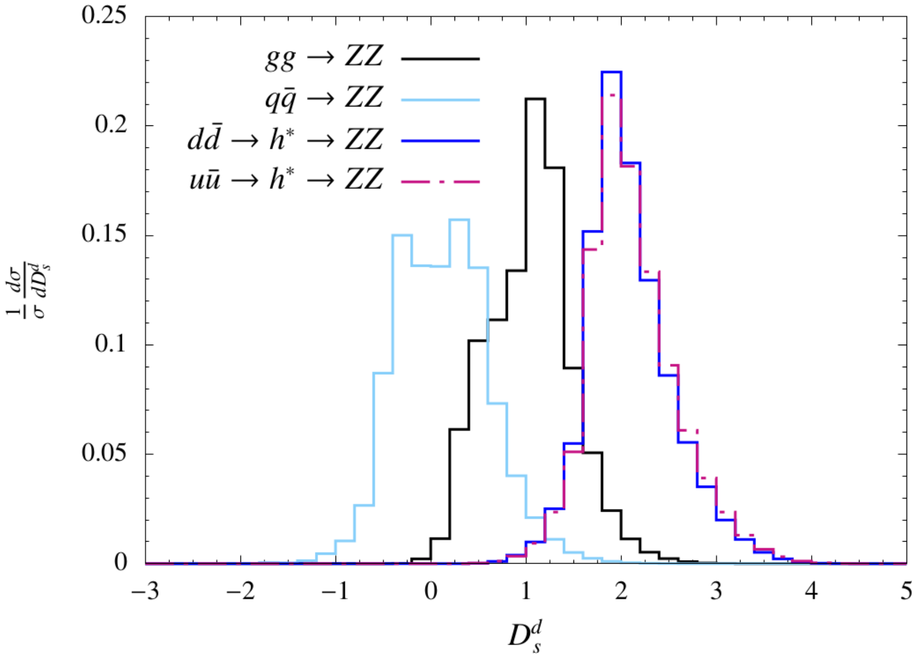
$$D_s^d = \log_{10}\left(\frac{P_{d\bar{d}}^{sig}}{P_{q\bar{q}}^{back} + P_{gg}^{back}}\right)$$

$$P_{ij}(v) = \frac{1}{\sigma_{ij\to 4\ell}} \int dx_1 dx_2 \delta(x_1 x_2 E_{CMS}^2 - m_{4\ell}^2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2, v)$$

- For $D_s^d > 2$ selects basically only events from signal process
- Not possible to distinguish between $d\bar{d} \to h^*$ and $u\bar{u} \to h^*$



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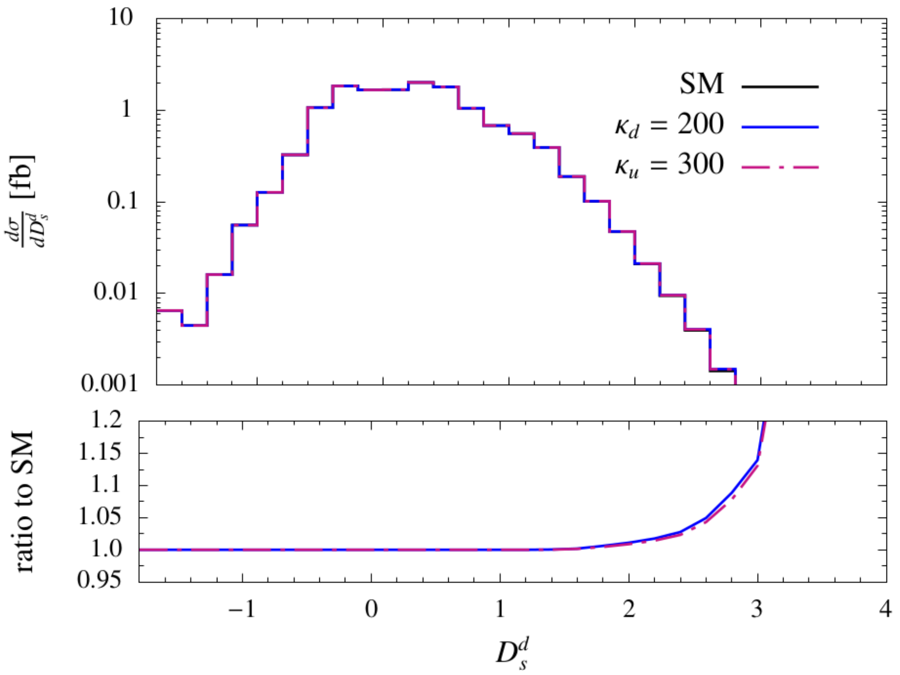

Phenomenological Analysis

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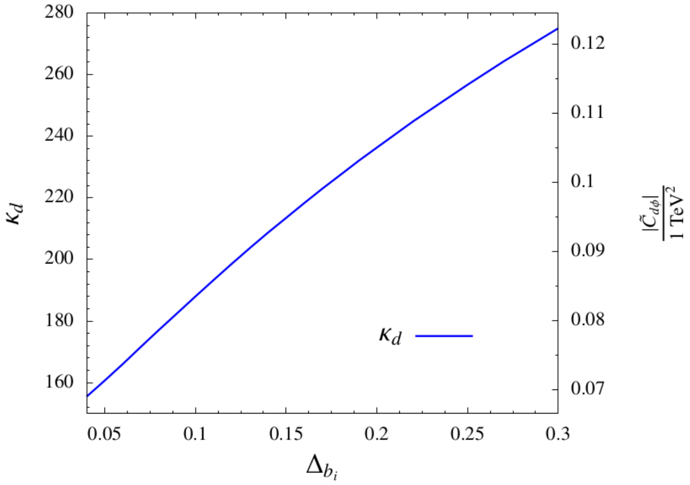
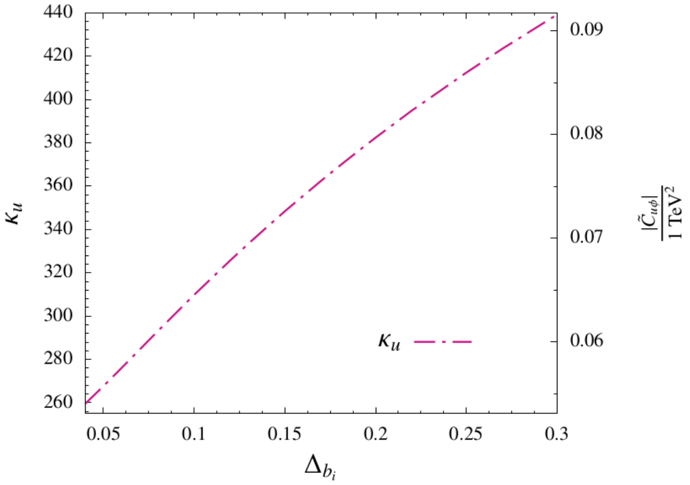
- Shape analysis on D_s^d distributions – off-shell region defined by $m_{ZZ} > 250\,\mathrm{GeV}$
- Consider only the ZZ$\rightarrow$4l final state
- Efficiency factors obtained from MadGraph based on experimental cuts $(p_T > 10\,\mathrm{GeV},\ |\eta| < 2.5)$

For $\Delta_{b_i} = 0.04$
(HL-LHC S2 scenario)

$$Z_i = \sqrt{2\left[(s_i+b_i)\ln\frac{(s_i+b_i)(b_i+\sigma_{b_i}^2)}{b_i^2+(s_i+b_i)\sigma_{b_i}^2} - \frac{b_i^2}{\sigma_{b_i}^2}\ln\left(1+\frac{s_i\sigma_{b_i}^2}{b_i(b_i+\sigma_{b_i}^2)}\right)\right]} \qquad \sigma_{b_i} = \Delta_{b_i} b_i$$

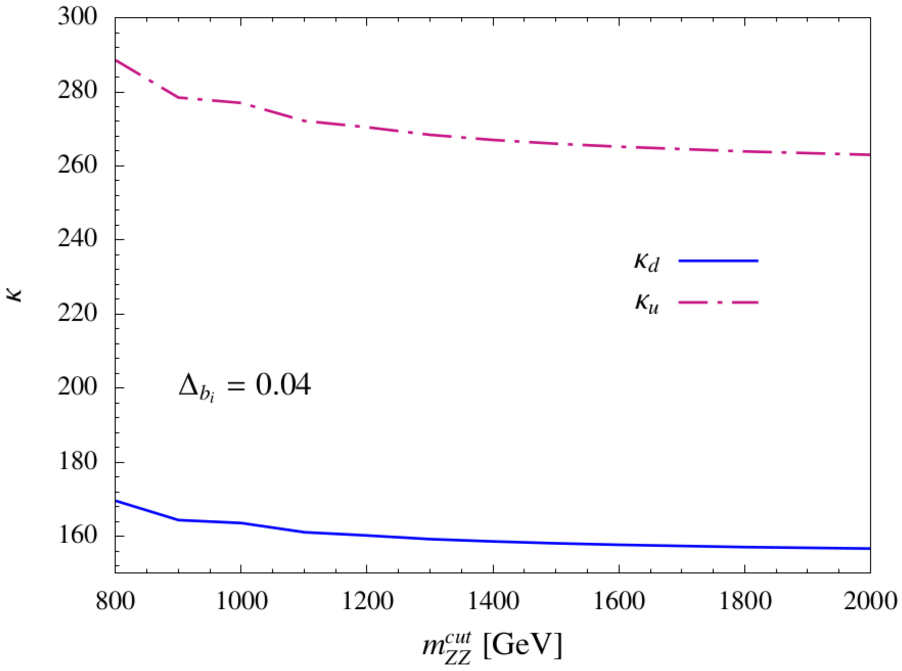
$$|\tilde{C}_{d\phi}|/(1\ \mathrm{TeV})^2 < 0.069/\mathrm{TeV}^2$$
$$|\tilde{C}_{u\phi}|/(1\ \mathrm{TeV})^2 < 0.054/\mathrm{TeV}^2$$
$$\Updownarrow$$
$$(\kappa_d < 156)$$
$$(\kappa_u < 260)$$



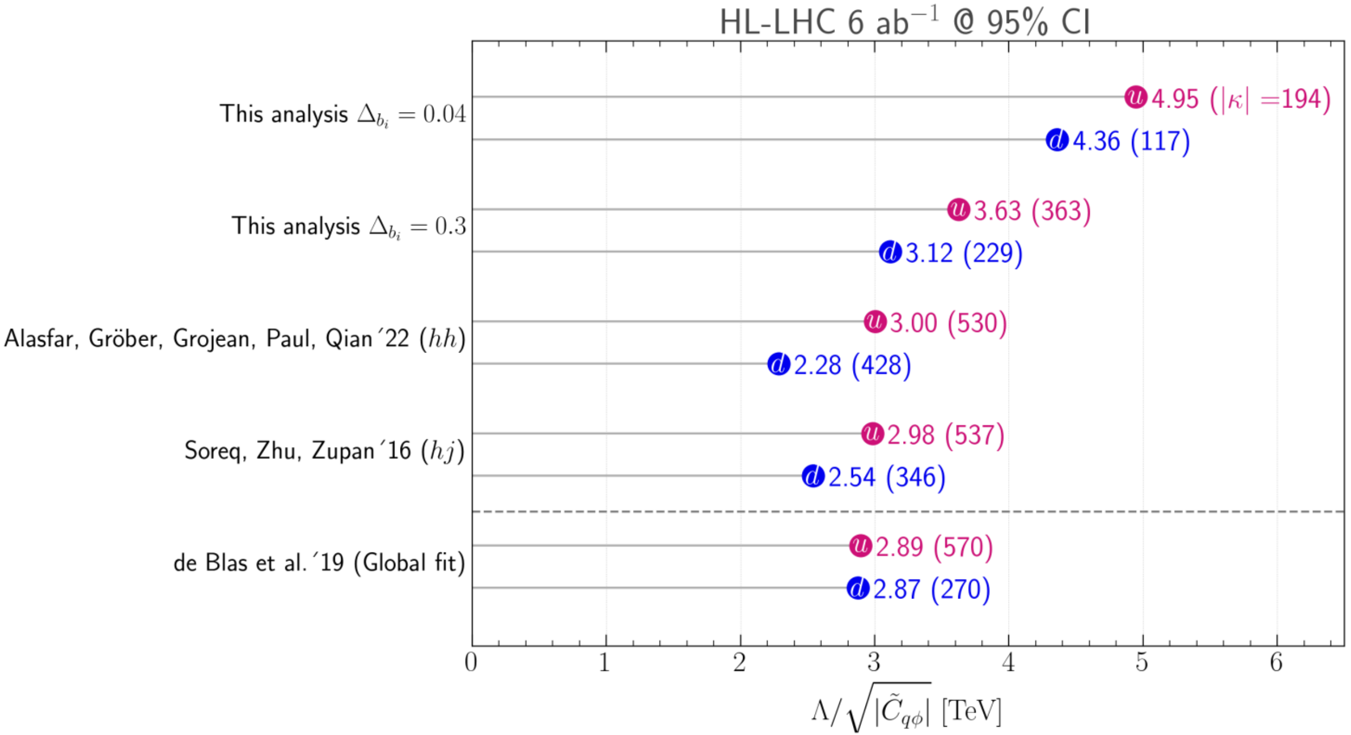


Consistency of EFT Analysis

- Sensitivity is not affected (much) by the choice of invariant mass range



Comparison with previous studies



Conclusions

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- Studied potential of off-shell Higgs production to bound light-Yukawa couplings at HL-LHC
- Used SMEFT framework for more theoretically sound approach
- Kinematic discriminants provide good sensitivity to “signal” process $qq \to h \to ZZ$
- Improvements on current estimated bounds at HL-LHC

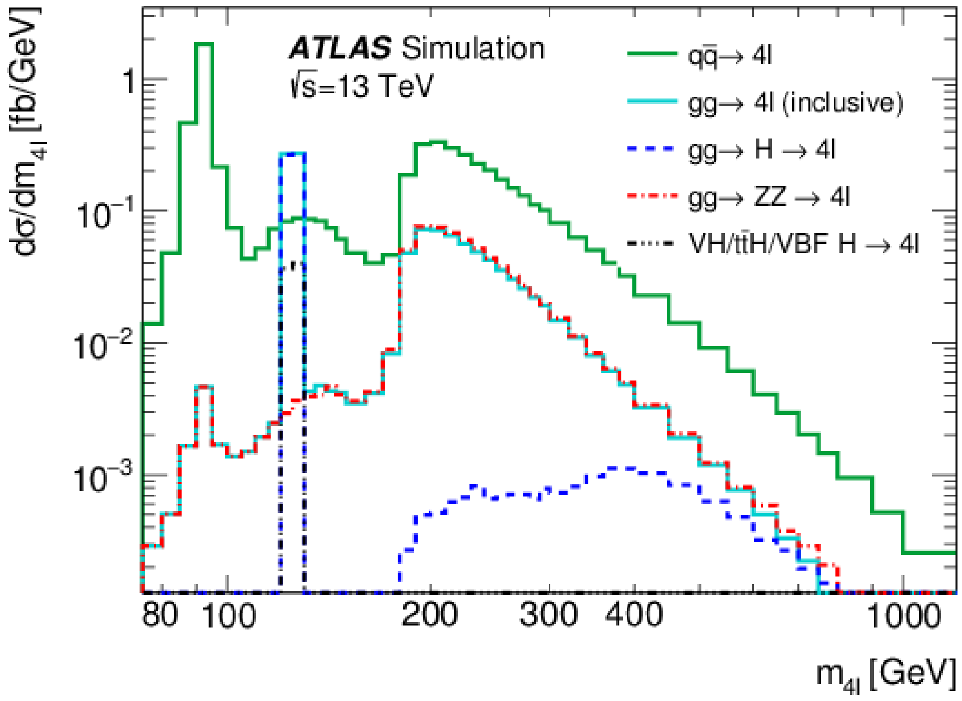
Outlook

- Refine analysis: effects of cuts; include shower and detector effects; NLO effects
- Include results for $2\ell 2\nu$ final states
- Include interplay with other observables/SMEFT operators

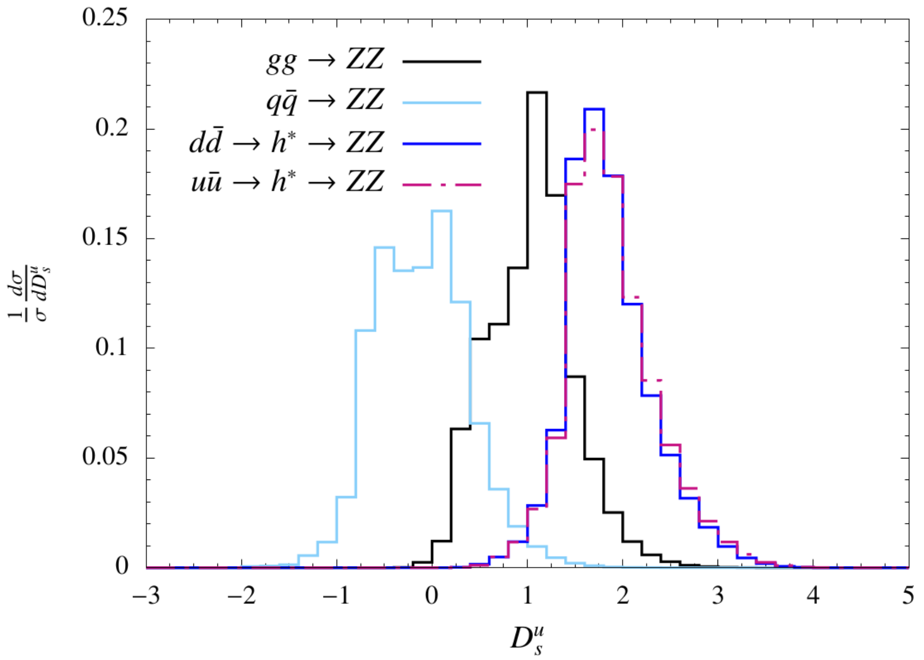
Thank you for your attention

Backup

$pp \rightarrow ZZ$ at the LHC

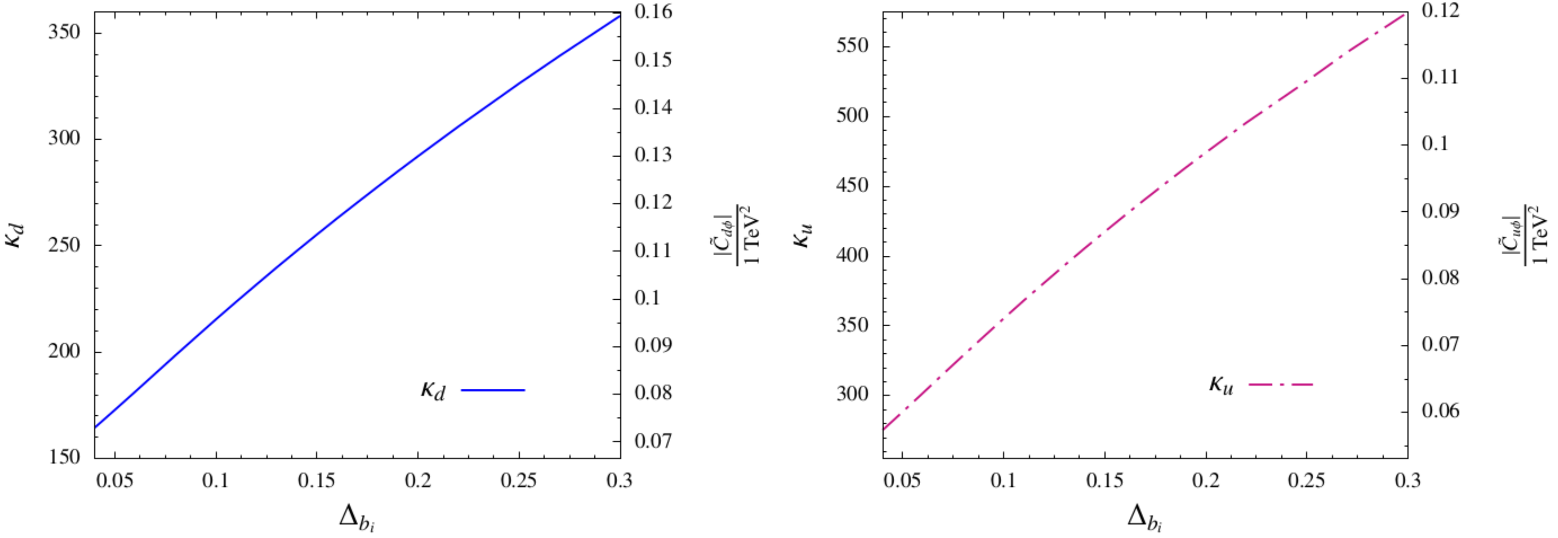


Analysis using Dsu



Analysis using Dsu

$$|\tilde{C}_{d\phi}|/(1\ \text{TeV})^2 < 0.073/\text{TeV}^2 \qquad (\kappa_d < 165),$$
$$|\tilde{C}_{u\phi}|/(1\ \text{TeV})^2 < 0.057/\text{TeV}^2 \qquad (\kappa_u < 275)$$



On-shell Signal Strengths

$\kappa_d \gtrsim 850 \quad \kappa_u \gtrsim 1850$

Excluded at 2σ CL