# Higgs and Flavor: Theory Overview

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

# Motivation

**Is the mechanism responsible for EWSB and fermion mass generation in the SM minimal?**

What we know:

- One complex scalar doublet acquires a vev, breaks EW symmetry and gives W/Z and third generation fermions (most) of their masses

What we don't know:

- Do the first and second generation fermions also get their masses from the same doublet?
- Is this Higgs vev the only source of EWSB?

**The SM itself is not minimal with regards to its matter content.**
**And, 20/26 of its free parameters are associated with the flavor sector.**

# Parametrization

$$\mathcal{L}_{\text{eff,q}} = \overbrace{\underbrace{-\kappa_q \frac{m_q}{v_W}\bar{q}qh}_{\text{CP conserving}} \underbrace{- i\tilde{\kappa}_q \frac{m_q}{v_W}\bar{q}\gamma_5 qh}_{\text{CP violating}}}^{\text{Flavor diagonal}} - \overbrace{\left[\underbrace{\left(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\right)}\bar{q}_L q'_R h + \text{h.c.}\right]}^{\text{Flavor violating}}$$

$\Re\left(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\right)$: CPC

$\Im\left(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\right)$: CPV

In the SM, $\kappa_q = 1$ while $\tilde{\kappa}_q = \kappa_{qq'} = \tilde{\kappa}_{qq'} = 0$

Important def'ns: $\kappa_i = \dfrac{y_i}{y_i^{\text{SM}}}, \qquad \bar{\kappa}_i = \dfrac{y_i}{y_b^{\text{SM}}}$

For lepton Yukawas, see, e.g.:

Dery, Efrati, Nir, Soreq, & Susic [arXiv:1408.1371]; Dery, Efrati, Hiller, Hochberg, & Nir [arXiv:1304.6727]; Dery, Efrati, Hochberg, & Nir [arXiv:1302.3229]

# Flavor violation

- Neutral current FV is generically present in any extension of the SM.

- Arises due to misalignment between the mass and Yukawa matrices – e.g., in D6 extension:

$$M_{u,d} = \frac{v_{\rm W}}{\sqrt{2}} \left( Y_{u,d} + Y'_{u,d} \frac{v_{\rm W}^2}{2\Lambda^2} \right), \qquad y_{u,d} = Y_{u,d} + 3 Y'_{u,d} \frac{v_{\rm W}^2}{2\Lambda^2}$$

- Unless additional assumptions are imposed, FV is "naturally" O(1) → **NP flavor problem**

- In models of flavor discussed earlier, they are typically suppressed by yukawa couplings and CKM matrix elements

# Yukawa modifications in flavor models

[FB, Brod, Uttayarat, Zupan: 1504.04022] – see also CERN YR4 Chap. IV.6 [1610.07922]
+ references therein for the specific models

| Model | $\kappa_t$ | $\kappa_{c(u)}/\kappa_t$ | $\tilde{\kappa}_t/\kappa_t$ | $\tilde{\kappa}_{c(u)}/\kappa_t$ |
|---|---|---|---|---|
| SM | 1 | 1 | 0 | 0 |
| MFV | $1+\frac{\mathrm{Re}(a_u v^2+2b_u m_t^2)}{\Lambda^2}$ | $1-\frac{2\,\mathrm{Re}(b_u)m_t^2}{\Lambda^2}$ | $\frac{\mathrm{Im}(a_u v^2+2b_u m_t^2)}{\Lambda^2}$ | $\frac{\mathrm{Im}(a_u v^2)}{\Lambda^2}$ |
| NFC | $V_{hu}\, v/v_u$ | 1 | 0 | 0 |
| MSSM | $\cos\alpha/\sin\beta$ | 1 | 0 | 0 |
| FN | $1+\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$ | $1+\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$ | $\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$ | $\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$ |
| GL2 | $\cos\alpha/\sin\beta$ | $\simeq 3(7)$ | 0 | 0 |
| RS | $1-\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$ | $1+\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$ | $\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$ | $\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$ |
| pNGB | $1+\mathcal{O}\left(\frac{v^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$ | $1+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$ | $\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$ | $\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$ |

- Generally, modifications $\sim v^2/\Lambda^2 \ll \mathcal{O}(1)$
- Exception: GL2 (modified GL) where

[Giudice, Lebedev: 0804.1753]
[FB, Brod, Uttayarat, Zupan: 1504.04022]
[Carena, Gemmler, Bauer: 1506.01719, 1512.03458]

$$\mathcal{L}_{\text{yuk}} = c_{ij}^f \left(\frac{H_1^\dagger H_1}{M^2}\right)^{n_{ij}^f} \bar{F}_L^i\, f_R^j\, H_{1,2}$$

# Off diagonal Yukawas in flavor models

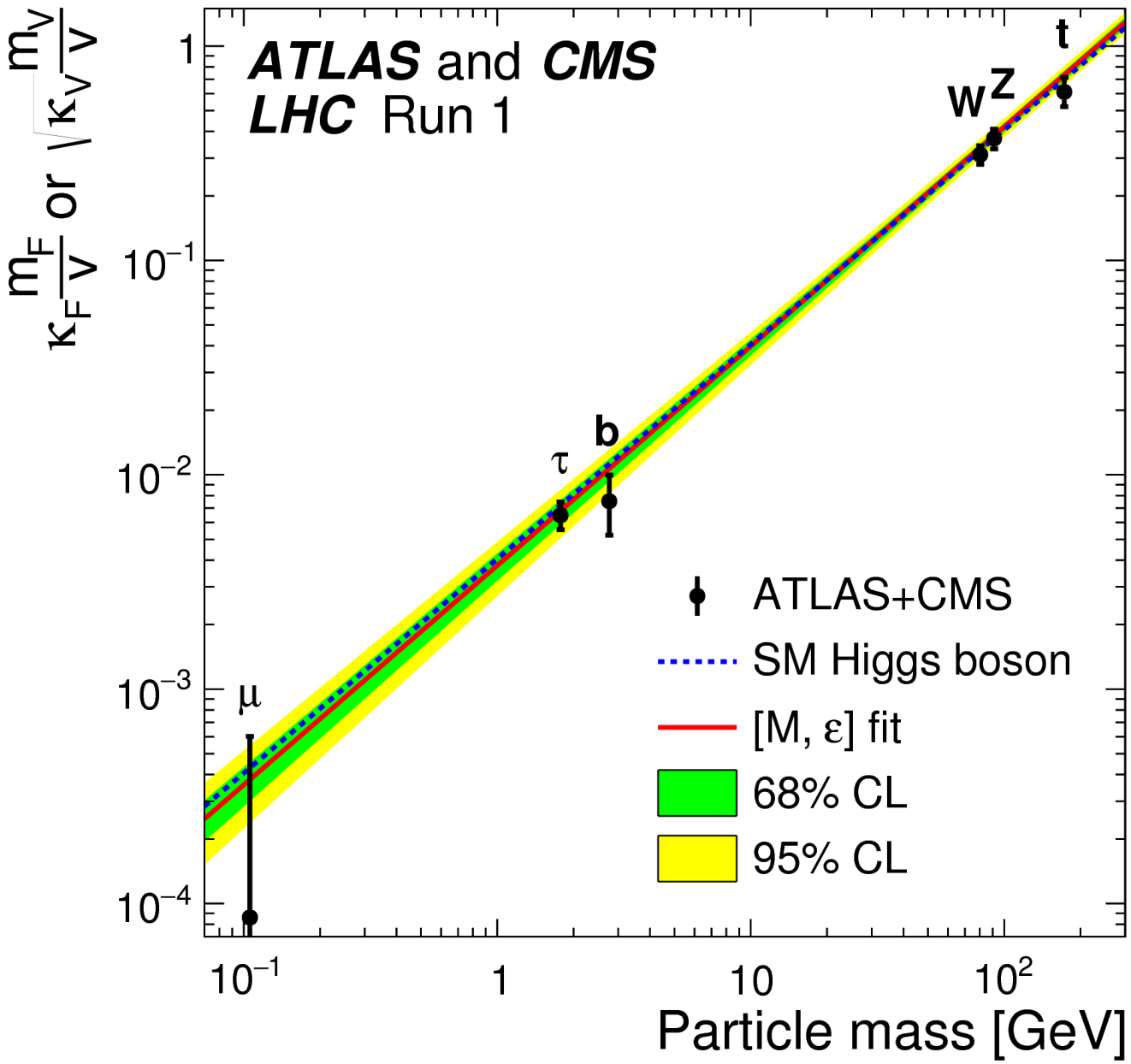
[FB, Brod, Uttayarat, Zupan: 1504.04022] – see also CERN YR4 Chap. IV.6 [1610.07922] + references therein for the specific models; see also Gori, Grojean, Juste, Paul, [1710.03752]

| Model | $\kappa_{ct(tc)}/\kappa_t$ | $\kappa_{ut(tu)}/\kappa_t$ | $\kappa_{uc(cu)}/\kappa_t$ |
|---|---|---|---|
| MFV | $\frac{\mathrm{Re}\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v}$ | $\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v}$ | $\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^{*}\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v}$ |
| FN | $\mathcal{O}\left(\frac{v m_{t(c)}}{\Lambda^2}\lvert V_{cb}\rvert^{\pm 1}\right)$ | $\mathcal{O}\left(\frac{v m_{t(u)}}{\Lambda^2}\lvert V_{ub}\rvert^{\pm 1}\right)$ | $\mathcal{O}\left(\frac{v m_{c(u)}}{\Lambda^2}\lvert V_{us}\rvert^{\pm 1}\right)$ |
| GL2 | $\epsilon(\epsilon^2)$ | $\epsilon(\epsilon^2)$ | $\epsilon^3$ |
| RS | $\sim \lambda^{(-)2}\frac{m_{t(c)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$ | $\sim \lambda^{(-)3}\frac{m_{t(u)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$ | $\sim \lambda^{(-)1}\frac{m_{c(u)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$ |
| pNGB | $\mathcal{O}(y_*^2\frac{m_t}{v}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$ | $\mathcal{O}(y_*^2\frac{m_t}{v}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$ | $\mathcal{O}(y_*^2\frac{m_c}{v}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$ |

| Model | $\kappa_{ct(tc)}$ | Notes/Assumptions | References |
|---|---|---|---|
| SM | $< 4\times 10^{-8}$ | loop-level | [1311.2028] |
| MFV | $\sim 10^{-6(-8)}$ | $\Lambda = 1$ TeV | [0904.2387]<br>[PLB188('87)99], [hep-ph/0207036] |
| FN | $\sim 10^{-3(-2)}$ | $\Lambda = 1$ TeV | [hep-ph/9310320] |
| GL2 | $\sim 10^{-2(-4)}$ | $\epsilon \sim 1/60$ | [0804.1753], [1504.04022] |
| RS | $\sim 10^{-2(-2)}$ | $\bar{Y} = 4$, $m_{KK} = 2.2$ TeV | [09061990], [1505.07018] |
| pNGB | $\sim 10^{-3(-2)}$ | $g_* = 4\pi$, $M_* = 3$ TeV | [1303.5701], [1408.4525] |

# Fermion Yukawas status

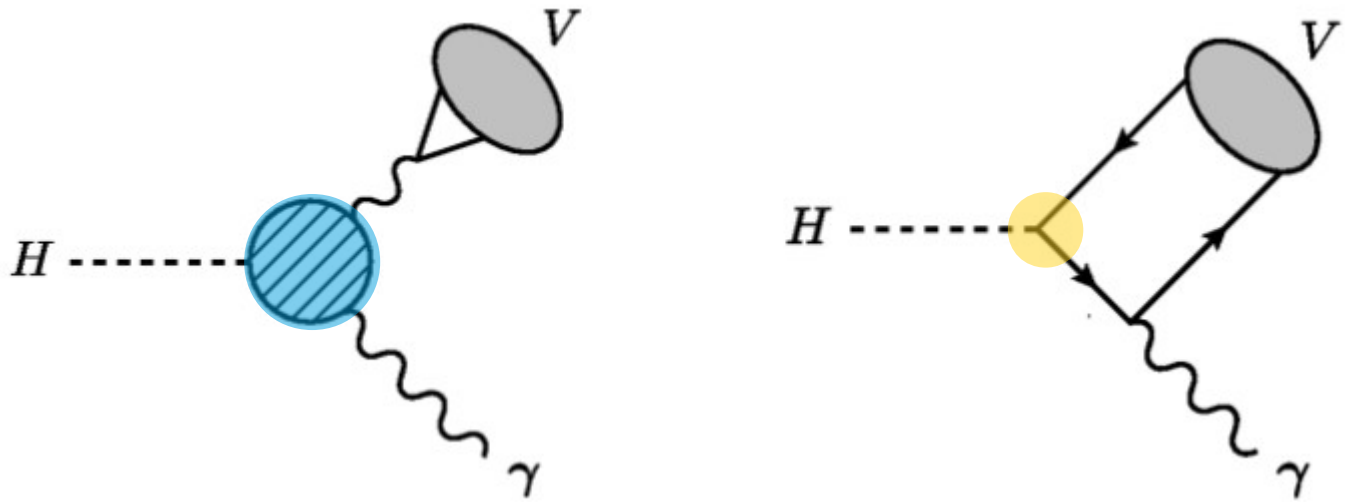
ATLAS+CMS [1606.02266]



# $1^{\text{st}}$ and $2^{\text{nd}}$ generation Yukawas

- Exclusive Higgs decays $h \to MV$ — Bodwin et al.: 1306.5770 & 1407.6695; Kagan et al. 1406:1722 Koenig & Neubert, 1505.03870
- $Vh$ and associated $hQ$ production — Perez et al. 1503.00290 & 1505.06689; Brivio et al. 1505.06689
- Higgs differential distributions — Bishara et al. Soreq et al. 1606.09621
- Charge assymmetry in $W^{\pm}h$ — Yu [1609.06592]

# Exclusive Higgs decays: h $\to J/\psi\gamma$




$$\mathrm{BR}_{h\to J/\psi\gamma} = 2.95\cdot 10^{-6}\,(1.07 - 0.07\kappa_c)$$

Bodwin et al. 13, 14
Koenig, Neubert 15

- ATLAS/CMS search:

$$\mathcal{BR}(h\to J/\psi\gamma) < 1.5\times 10^{-3} \text{ at } 95\%\text{ CL}$$

ATLAS 1501.03276
CMS 1507.03031

$$< 3.5\times 10^{-4} \text{ at } 95\%\text{ CL}$$

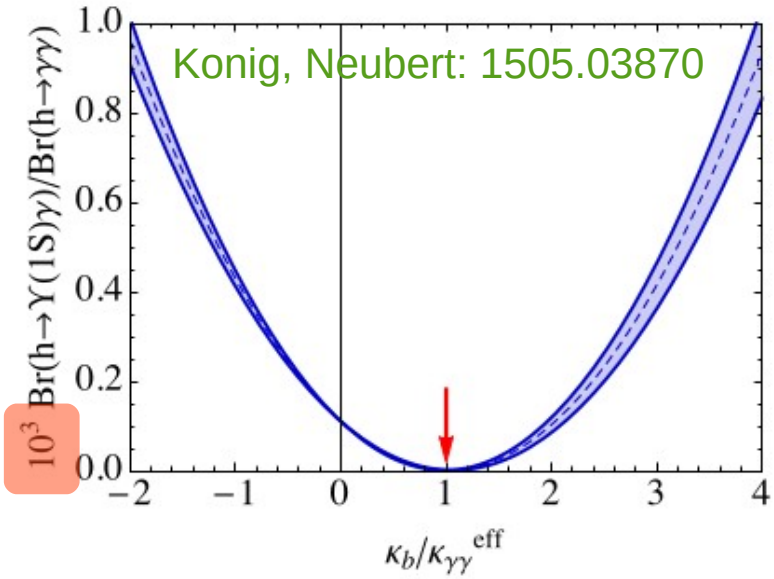
ATLAS 1807.00802

- Can be extended to strange quark (even u & d)

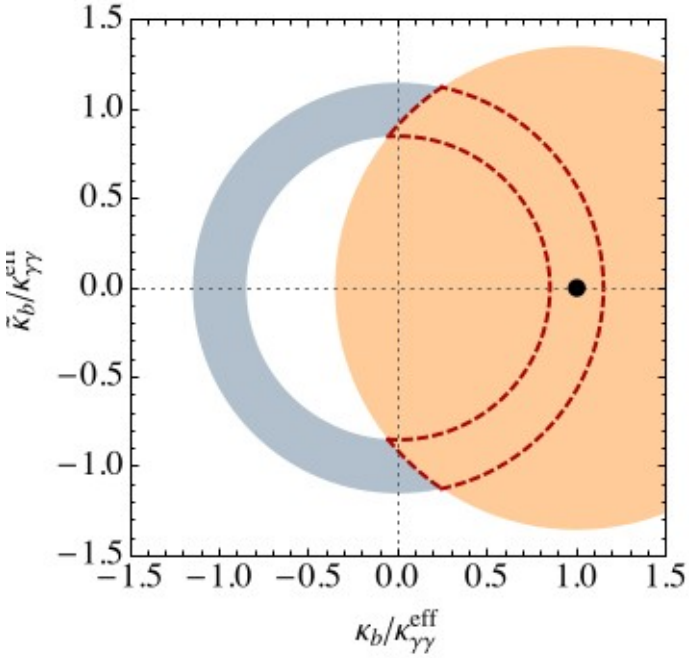
Kagan, Perez, Petriello, Soreq, Stoynev, and Zupan [1406.1722]

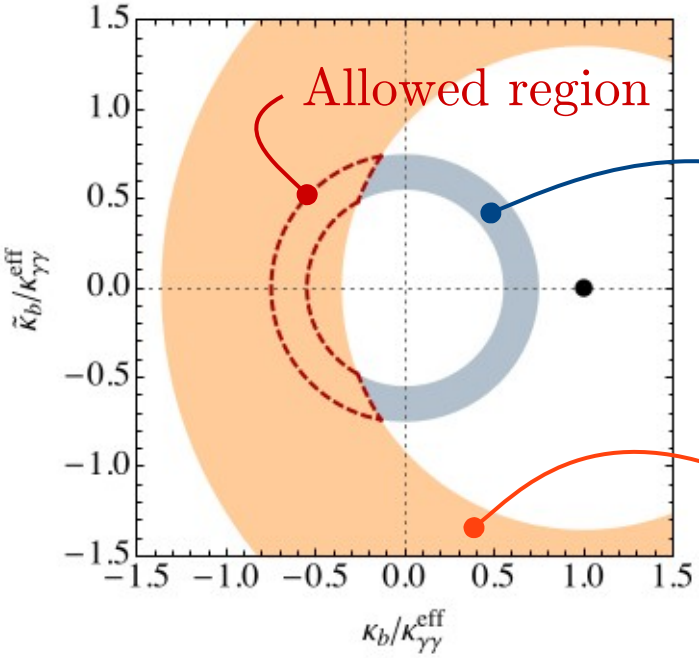
# The interesting case of $\Upsilon+\gamma$

- Interference $\rightarrow$ sensitive to sign of $y_b$
- Strong (accidental) cancellation between the direct and indirect constributions $\rightarrow$ extremely sensitive to deviations from SM




ATLAS [1807.00802]: $BR(h \to \Upsilon(1s)\gamma)/BR(h \to \gamma\gamma) < 0.22$




$$\frac{\mathcal{BR}(h \to b\bar{b})}{\mathcal{BR}(h \to \gamma\gamma)}$$

$$\frac{\mathcal{BR}(h \to \Upsilon(1S)\gamma)}{\mathcal{BR}(h \to \gamma\gamma)}$$

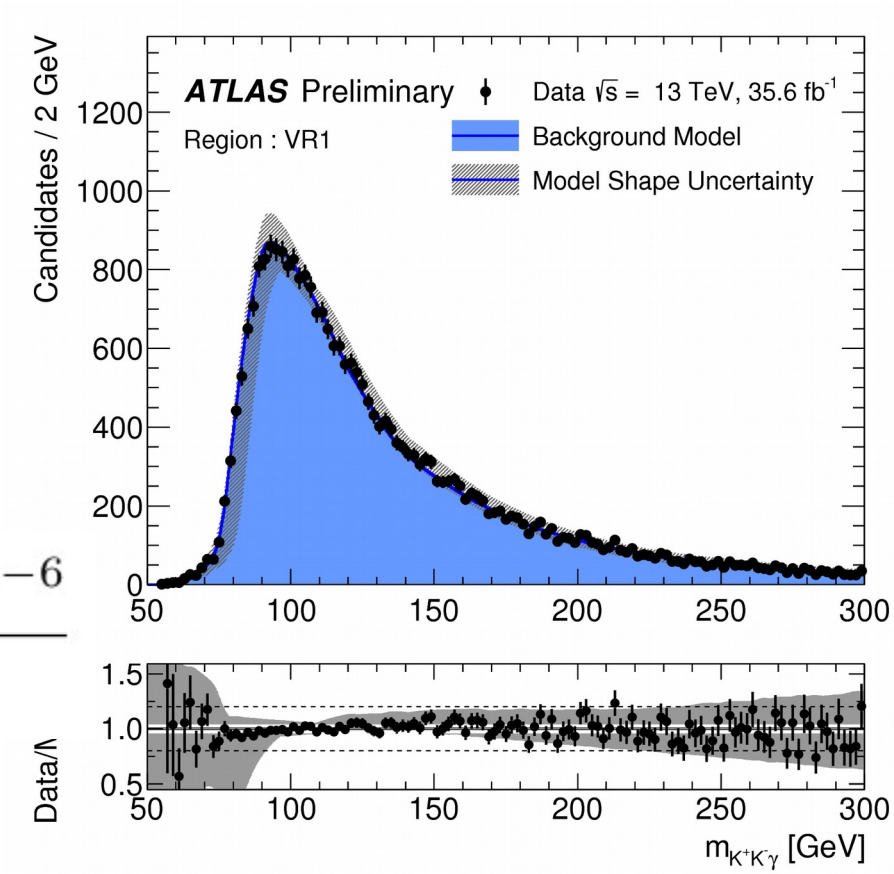
# Fermion Yukawas status

- Same as before, two amplitudes, direct and indirect. Sensitivity from interference
- New bound from ATLAS [ATLAS-CONF-2017-057]

Br($\phi \to K^+K^-$)=48.9% (PDG)

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(2.3\pm 0.1)\kappa_\gamma - 0.43\bar{\kappa}_s]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

Kagan, Perez, Petriello, Soreq, Stoynev, Zupan: [1406.1722]; Konig, Neubert: 1505.03870

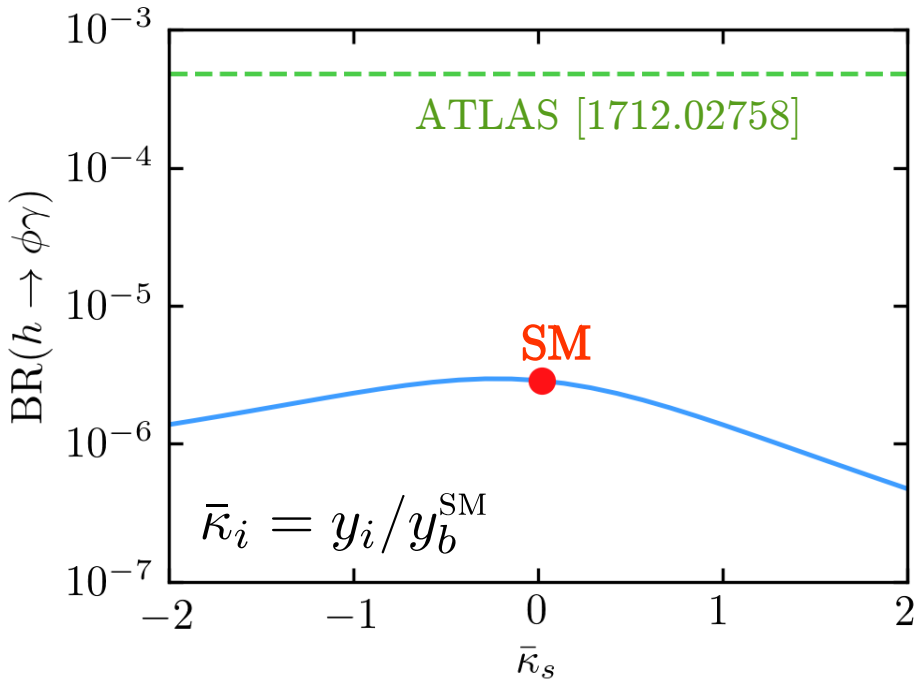



$$Br(h \to \phi(\rho)\gamma < 4.8\times 10^{-4}\ (8.8\times 10^{-4}) \quad \text{at } 95\%\ \text{CL}$$

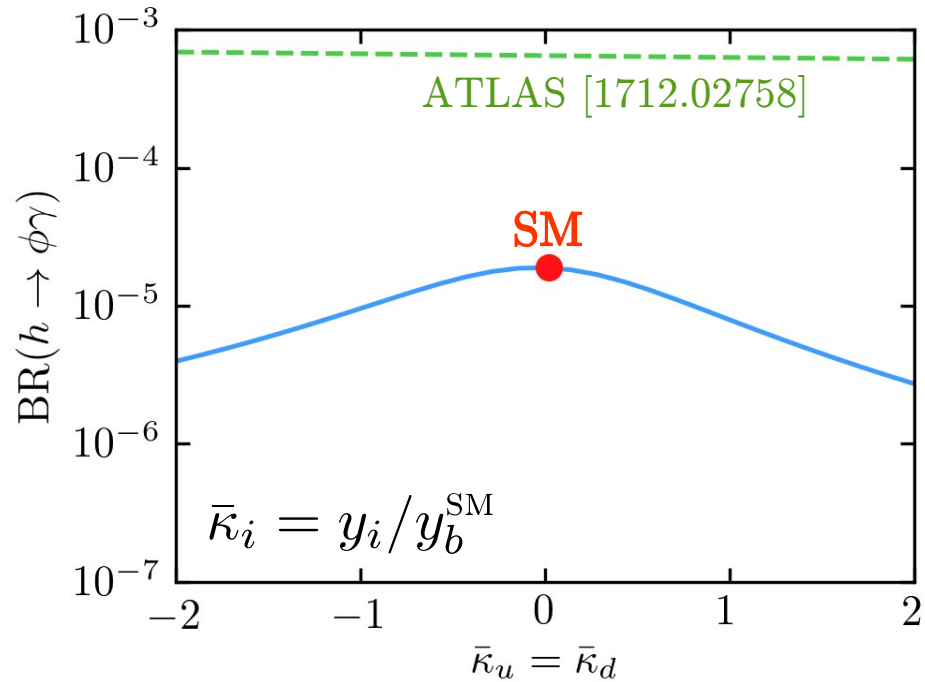
- Order of magnitude improvement on previous ATLAS bound on Br(h→$\phi$+$\gamma$) [1607.03400] and first bound on Br(h→$\rho$+$\gamma$)

# Light quarks: u, d, s

$h \to \phi\gamma$




$h \to \rho\gamma$

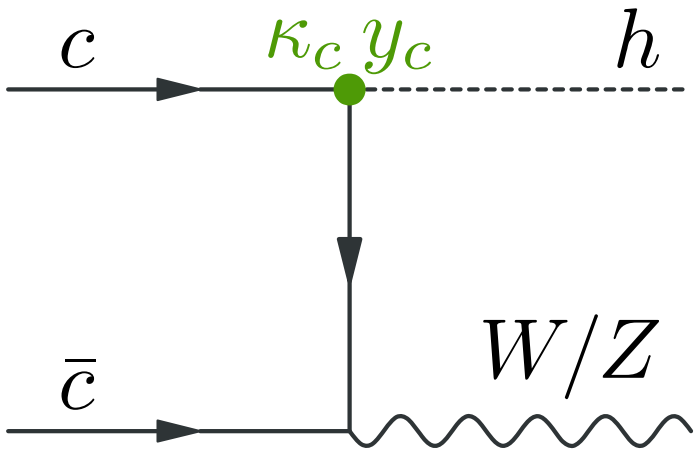


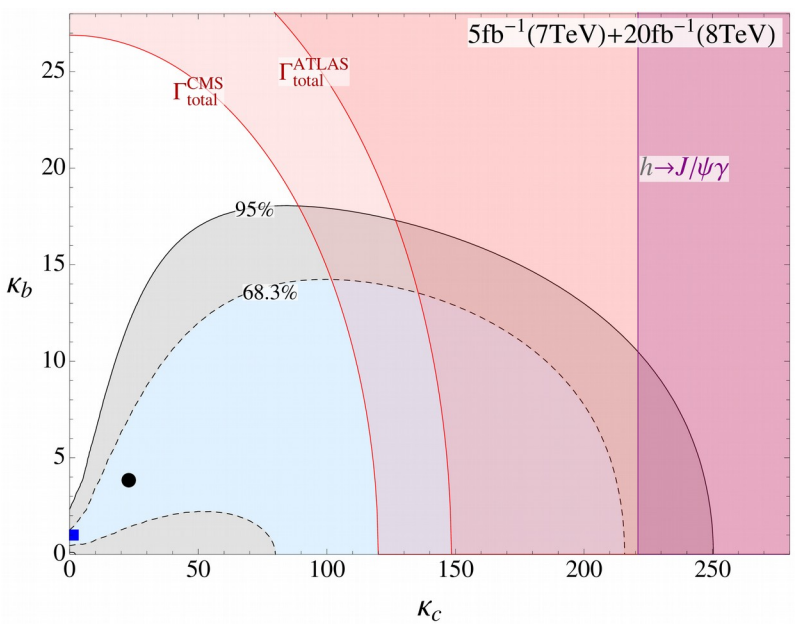

Eby, Petriello, Zupan [unpublished]

$$Br_{h\to\phi\gamma} = \frac{10^{-6}\left[(2.88 \pm 0.12)\kappa_\gamma^2 - (.750 \pm .029)\bar{\kappa}_s\kappa_\gamma + (4.88 \pm .31)10^{-2}\bar{\kappa}_s^2\right]}{\left[1 + \bar{\kappa}_s^2 Br^{\rm SM}_{h\to b\bar{b}} + (\kappa_\gamma^2 - 1)Br^{\rm SM}_{h\to\gamma\gamma}\right]},$$

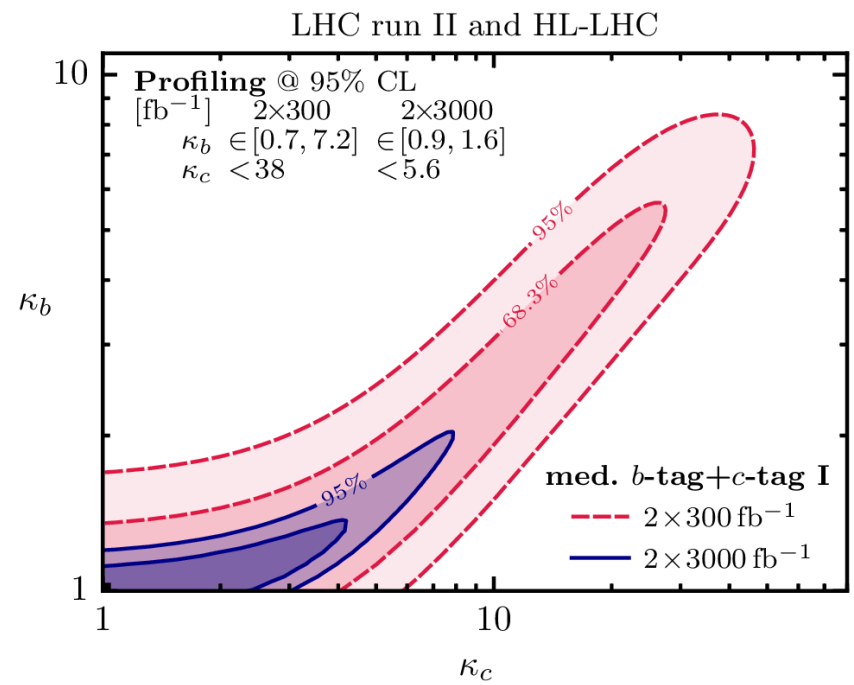
$$Br_{h\to\rho\gamma} = \frac{10^{-5}\left[(1.89 \pm 0.11)\kappa_\gamma^2 - (.228 \pm .017)\bar{\kappa}_u\kappa_\gamma - (.114 \pm 0.008)\bar{\kappa}_d\kappa_\gamma + \ldots\right]}{\left[1 + (\bar{\kappa}_d^2 + \bar{\kappa}_u^2)Br^{\rm SM}_{h\to b\bar{b}} + (\kappa_\gamma^2 - 1)Br^{\rm SM}_{h\to\gamma\gamma}\right]},$$

# VH production + flavour tagging




Perez et al.: 1503.00290




Perez et al.: 1505.06689

$$\left(\mu_b + \frac{\mathrm{BR}^{\rm SM}_{c\bar{c}}}{\mathrm{BR}^{\rm SM}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\mu_c\right) \Big/ \left(1 + \frac{\mathrm{BR}^{\rm SM}_{c\bar{c}}}{\mathrm{BR}^{\rm SM}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)$$

See also: [Brivio, Goertz, Isidori 1507.02916]

They consider $hc$ final state and find ($\mathrm{LHC}_{14}$)

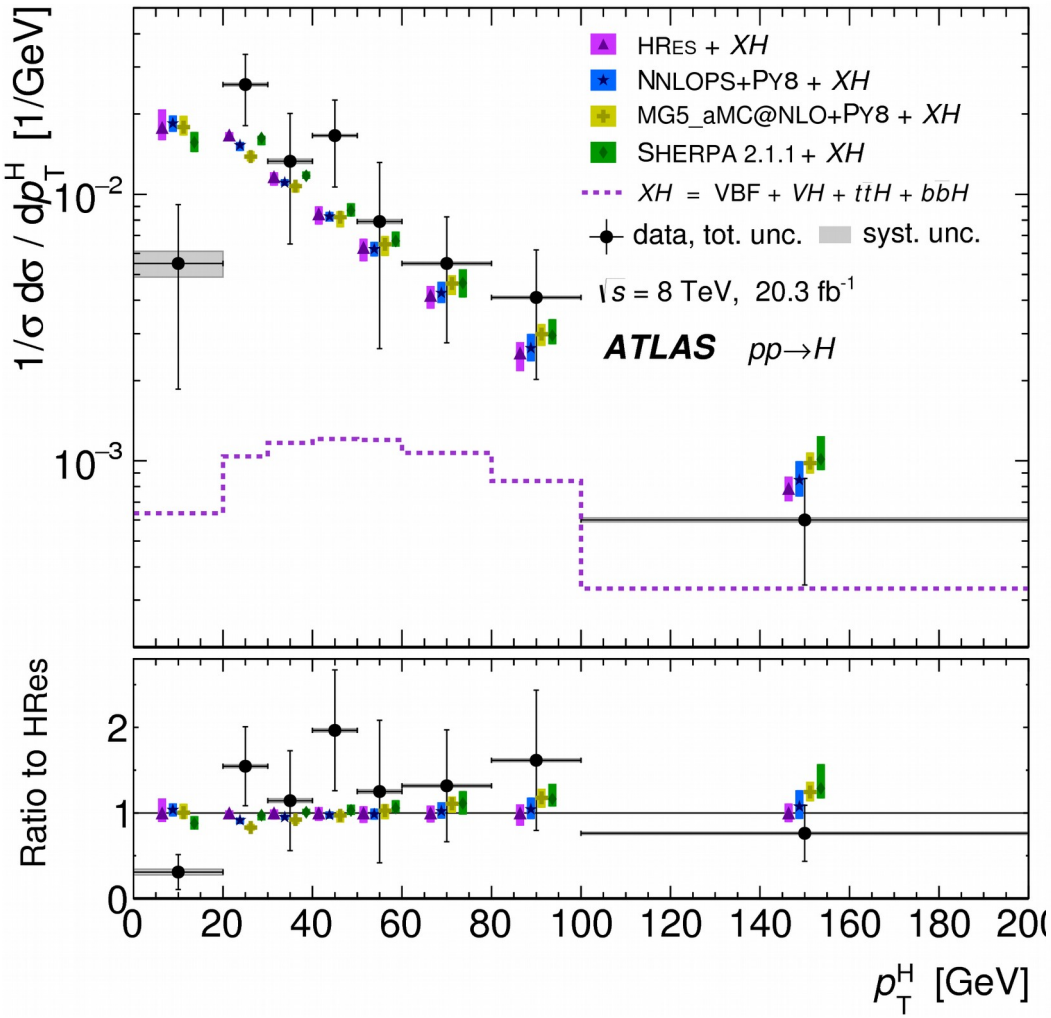
$|\kappa_c| < 3.9$ @ 95% C.L. with 3000 fb$^{-1}$

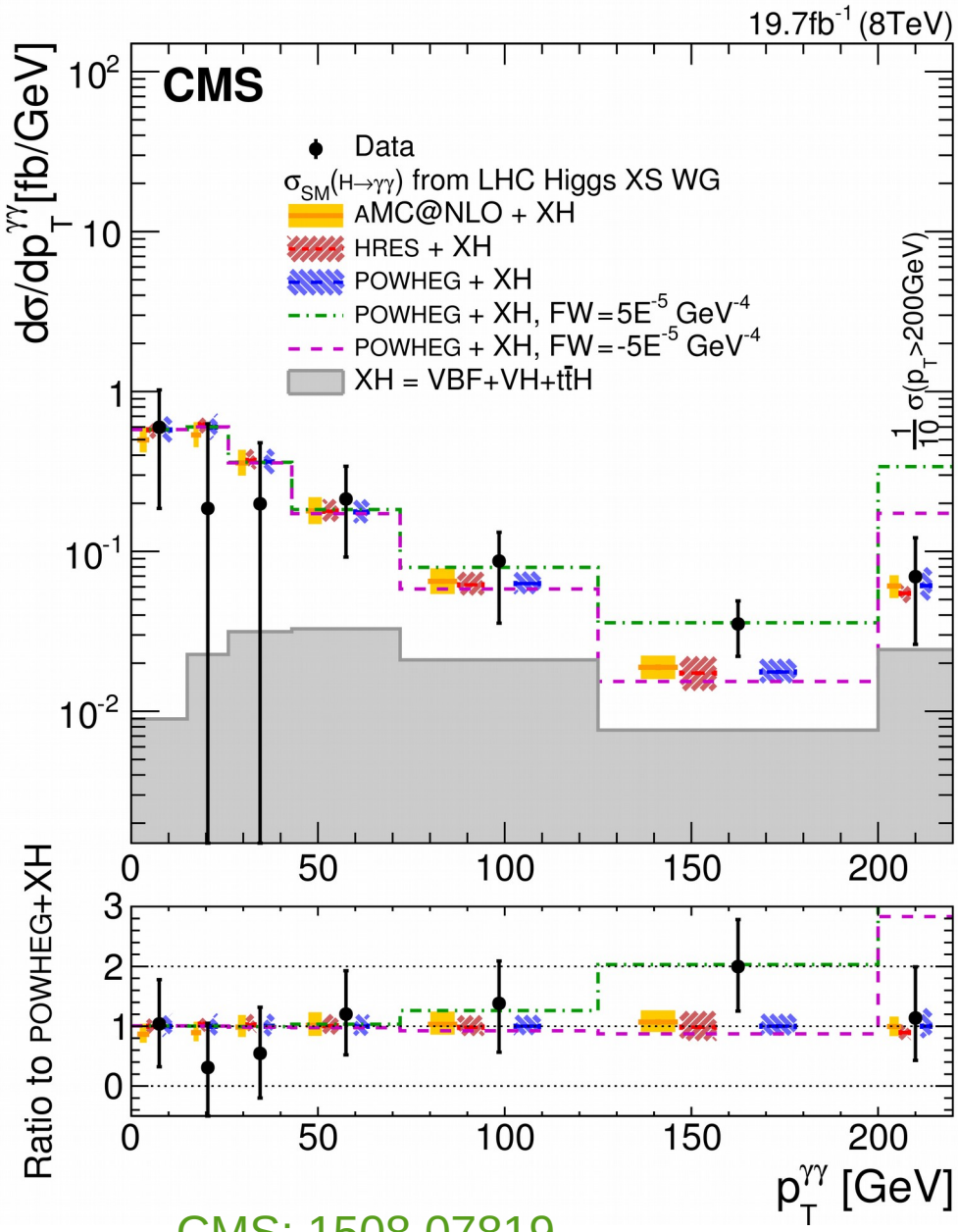
# Higgs transverse momentum

- Additional emissions probe the structure of the loop in $gg \to h + jets$
- The loop has a chirality suppression but ...
- The charm is special $\to$ non-Sudakov double logs dynamically enhance its contribution
- The $p_T$ spectra of the Higgs and the jet have been measured by ATLAS & CMS

See also: [Soreq, Zhu, & Zupan: 1606.09621] for similar work on the u and d yukawas

# Measured distributions




ATLAS: 1504.05833

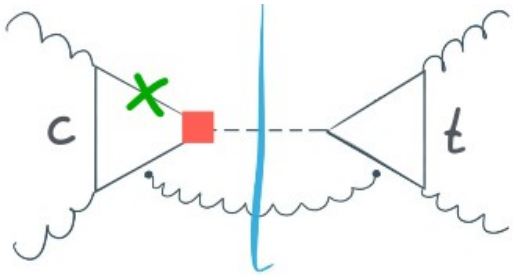
CMS: 1508.07819

# Contributions and their scaling

- Many contributions with different scaling in the $m_Q \lesssim p_T \lesssim m_h$ region
- The quark initiated contribution dominates for $\kappa_Q \gg 1$ [Soreq, Zhu, & Zupan: 1606.09621]
- Normalized distributions in this regime are sensitive to light d.o.f. but heavy new physics can affect the tail

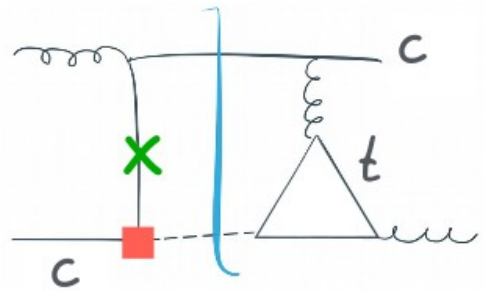
[Banfi, Martin, Sanz: 1606.09621]
[Buschmann, Goncalves, Kuttimalai, Schonherr, Krauss, Plehn: 1410.5806]
[Buschmann, Englert, Goncalves, Plehn, Spannowsky: 1405.7651] + others

# Contributions and their scaling

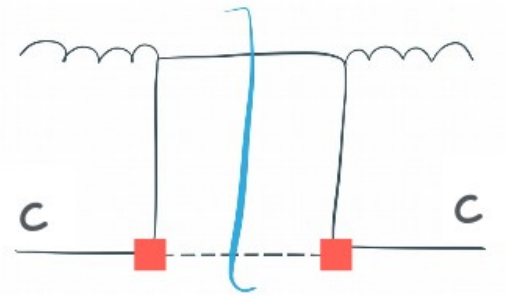



$$\sim \alpha_s^3 \, y_c \, m_c \, \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$

Color coding courtesy of Uli Haisch

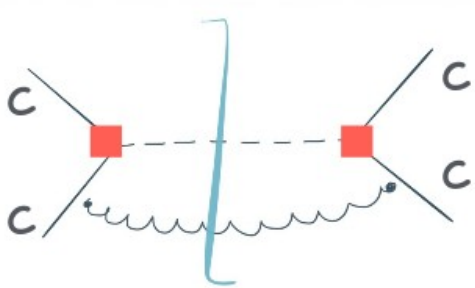



$$\sim \alpha_s \alpha_s^2 \, y_c \, m_c \qquad (= 0 \text{ in 4, 5 flavour scheme})$$




$$\sim \alpha_s \alpha_s \, y_c^2$$

chirality flip



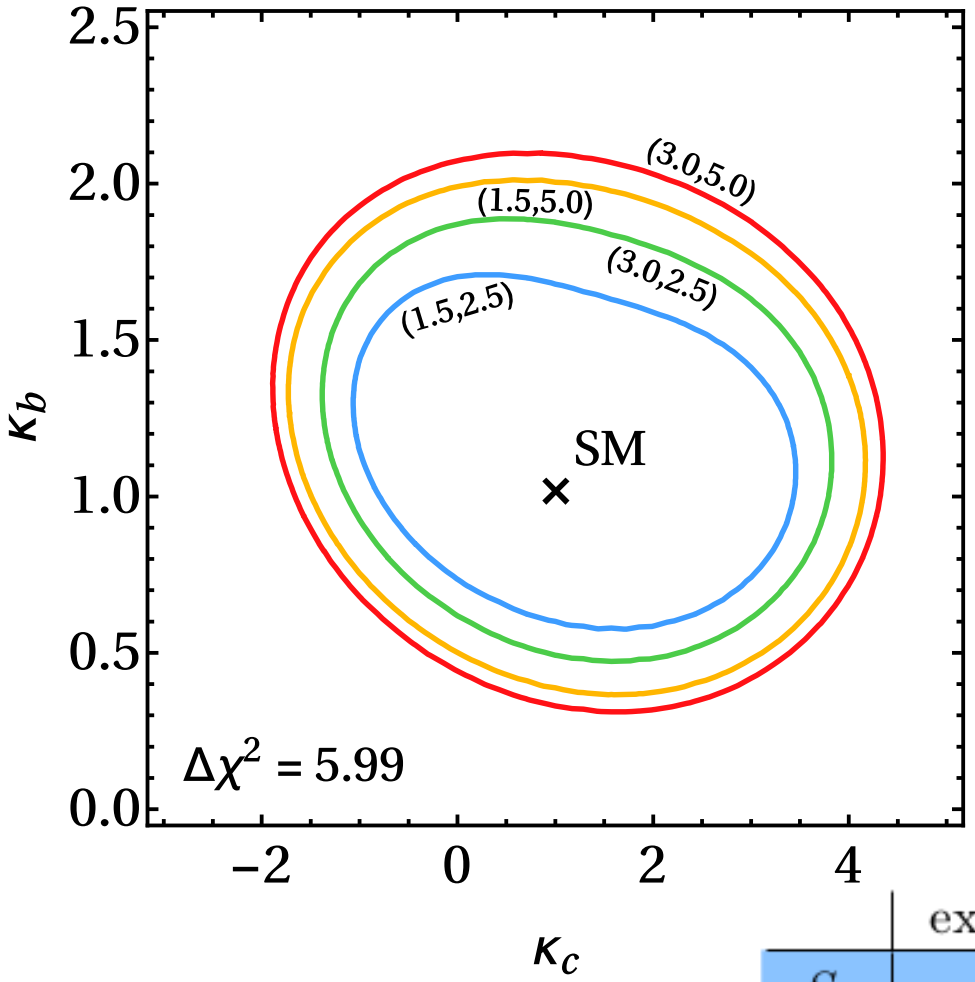

$$\sim \alpha_s^2 \alpha_s \, y_c^2$$

extra powers of $\alpha_s$ from charm PDF

[Sullivan, Nadolsky: hep-ph/0111358]

# Results for $p_{\mathrm{T,h}}$

[FB, Haisch, Monni, Re: 1606.09253 (PRL)]




95% C.I. after profiling over $\kappa_b$

LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

HL-LHC: $[-0.6, 3.0]$

CMS with 35.9 fb$^{-1}$ (13 TeV)

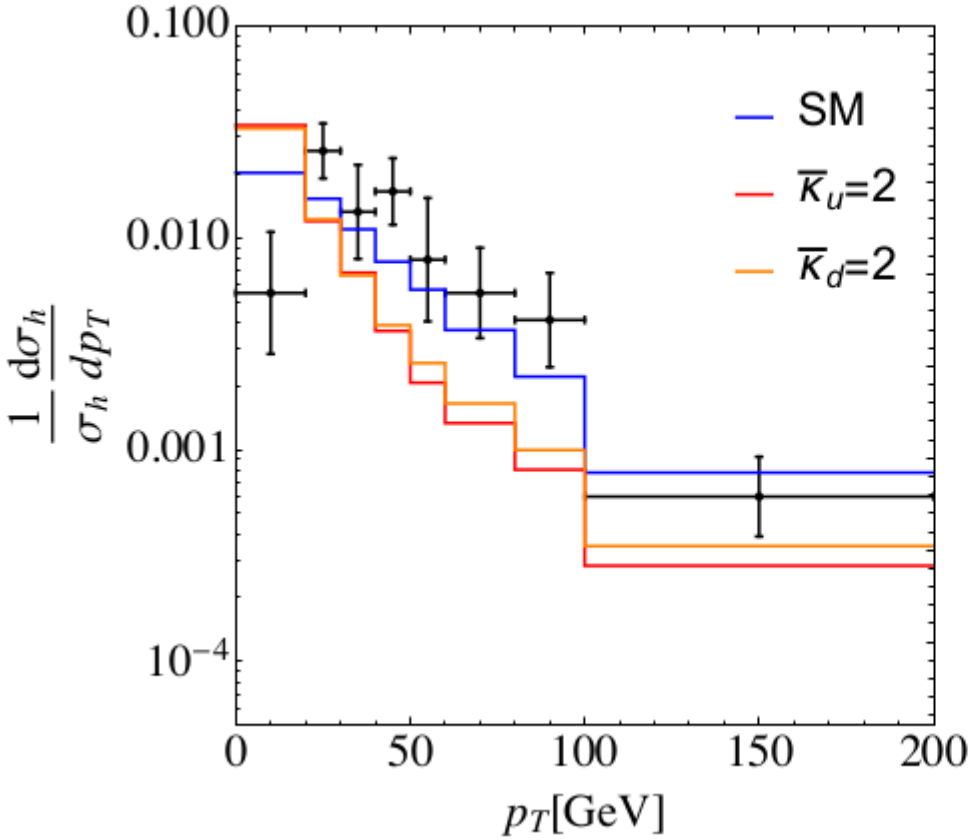
$-8.7 < \kappa_c < 10.6$

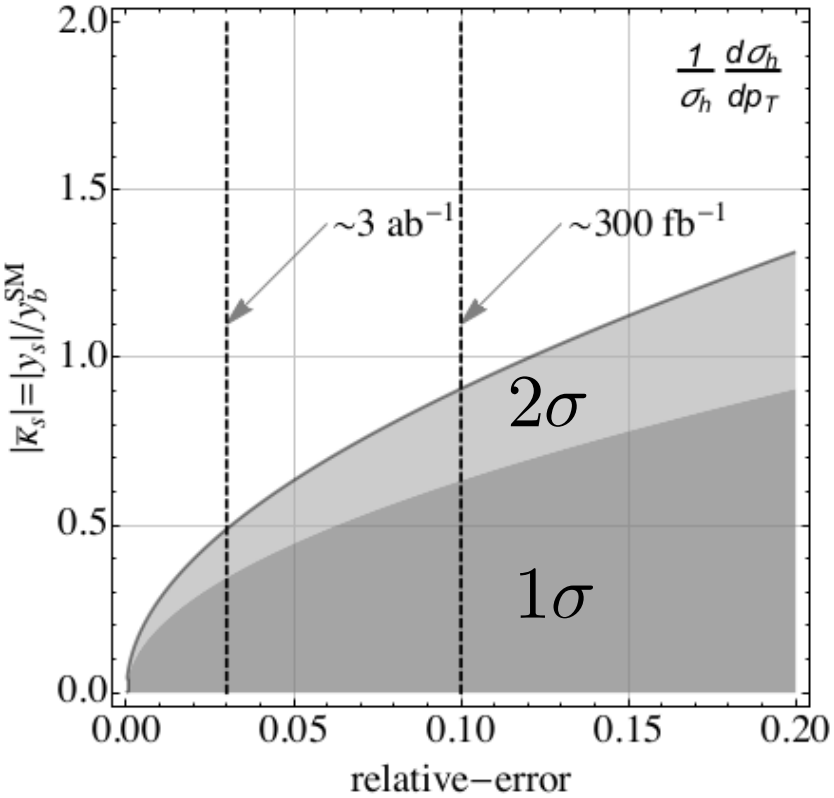
PAS HIG-17-028

| | experimental [%] | theoretical [%] | $\kappa_c \in$ |
|---|---|---|---|
| $S_1$ | 1.5 | 2.5 | [-0.6, 3.0] |
| $S_2$ | 3.0 | 2.5 | [-0.9, 3.3] |
| $S_3$ | 1.5 | 5.0 | [-1.2, 3.6] |
| $S_4$ | 3.0 | 5.0 | [-1.3, 3.7] |

# First generation Yukawas

[Soreq, Zhu, & Zupan: 1606.09621]

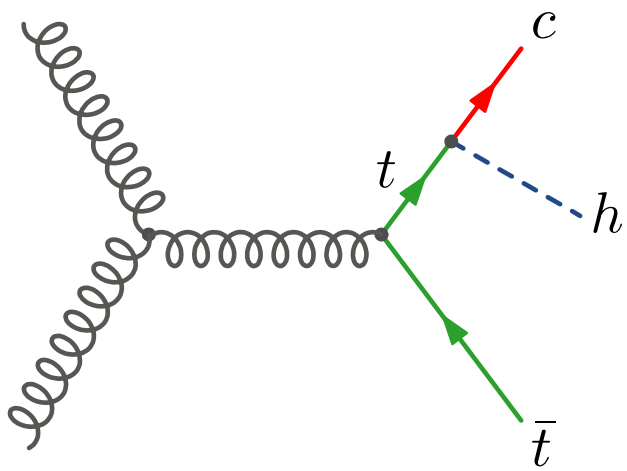


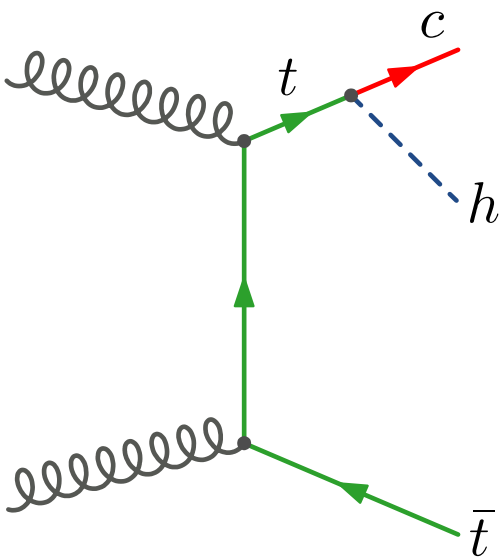



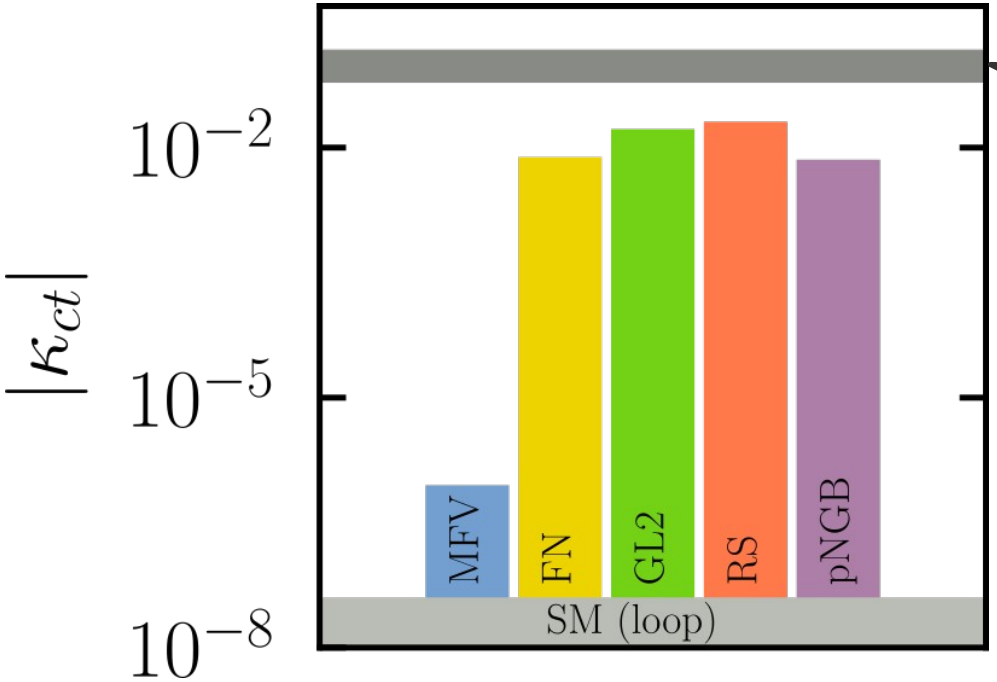

See also Felix Yu [1609.06592] for $W^{\pm}$ Charge asymmetry sensitive to $\mathcal{O}(5)$ deviations in $\bar{\kappa}_{u,d,s}$ at 14 TeV w/3 ab$^{-1}$

$$A = (\sigma(W^+h) - \sigma(W^-h))/(\sigma(W^+h) + \sigma(W^-h))$$

# Top FCNC




ATLAS [1707.01404] – 13 TeV, 36.1 fb$^{-1}$, h→$\gamma\gamma$

ATLAS [1403.6293,1509.06047]
CMS [1610.04857]

# Summary

- Measuring light quark Yukawas crucial to understand mass generation mechanism in SM
- Higgs $p_T$ distribution is sensitive to modified charm Yukawa, constraints at HL-LHC on modification of $y_c$ of O(few) and on $y_s/y_b^{SM} < 0.5$
- LHCb upgrade II projection abs($\kappa_c$)<2.2 and ILC O(10%)
- VH production at LHCb abs($\kappa_c$)< 2–3
- Bounds on BR(t→hc) will cut well into parameter space of flavor models
- Other ideas: strange tagging? Proposal for future $e^+e^-$ using charged Kaon reco. – can something similar be done at LHC?
  Duarte-Campderros, Perez, Schlaffer, Soffer [Perez talk at 1st FCC physics workshop and Schaffer talk at CLIC physics]

Thank you!

# LHCb projections for HL-LHC

## LHCb Upgrade II: constraints on $\kappa_c$

300 fb$^{-1}$ at 14 TeV: $|\kappa_c| \lesssim 7$

↓

30% di-c-tagging efficiency: $|\kappa_c| \lesssim 4$

↓

better electron reconstruction: $|\kappa_c| \lesssim 3$

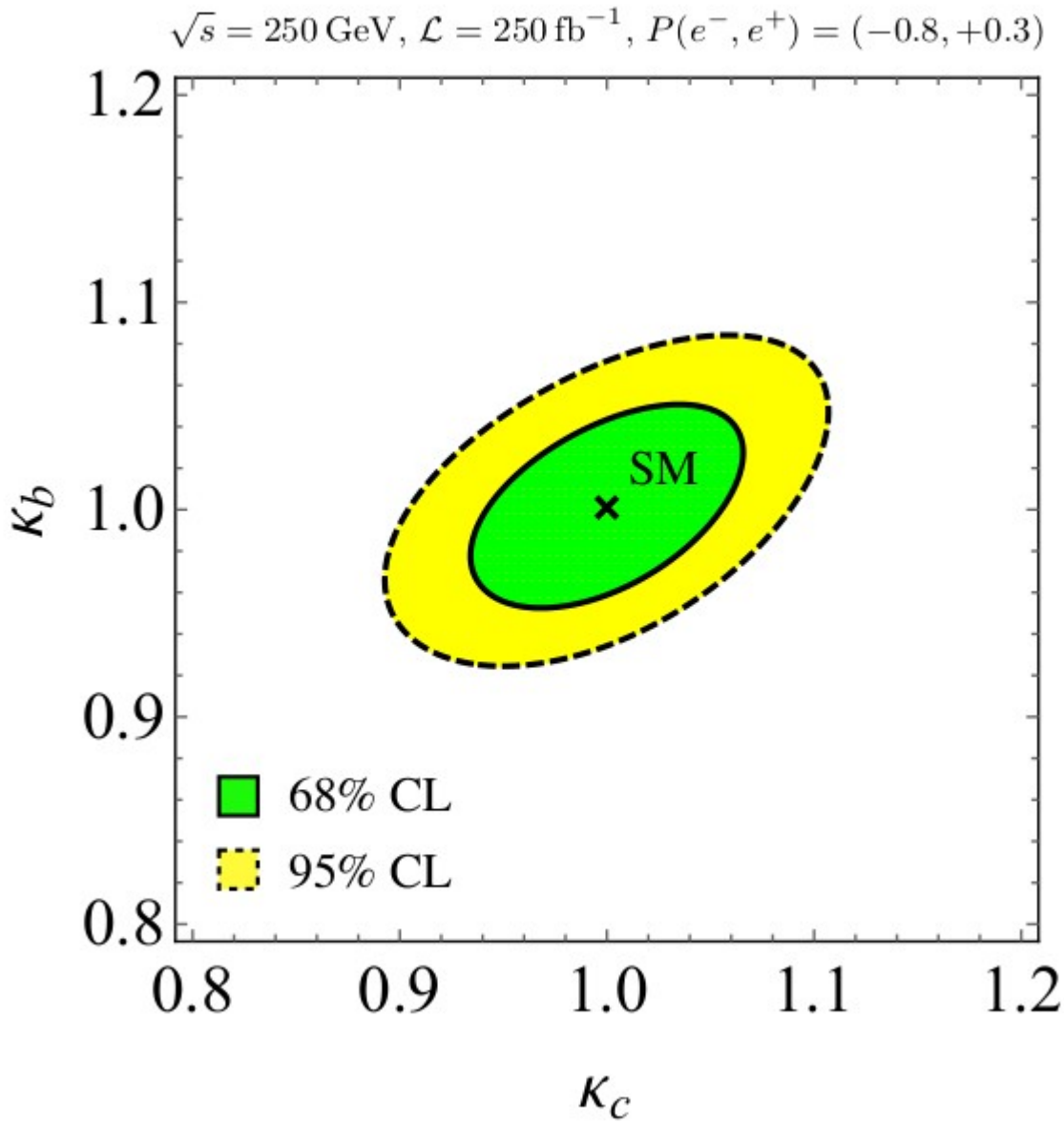
↓

further improvements: $|\kappa_c| \lesssim 2.2$

projections taken from talk by Mike Williams

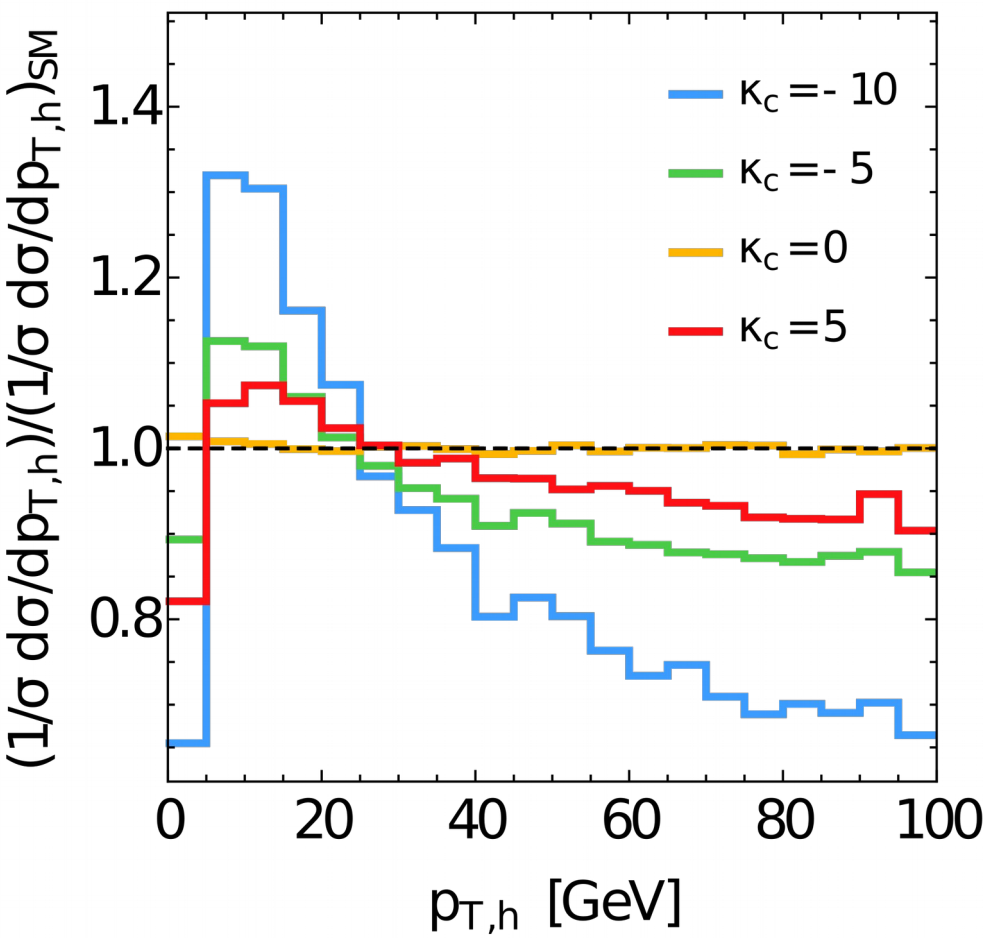
Slide from Uli Haisch talk at Elba 2017
Based on bounds from M. Williams' talk

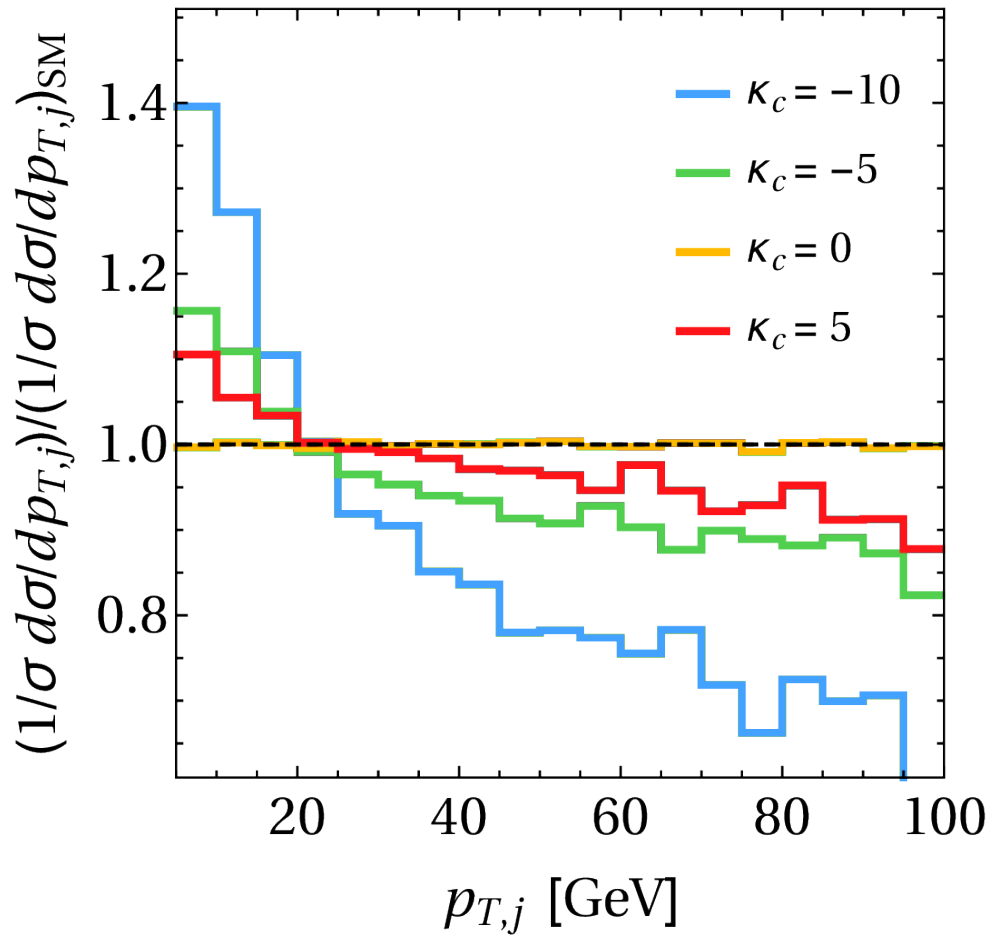
# Projections for the ILC




Uli Haisch based on Ono & Miyamoto [1207.0300]

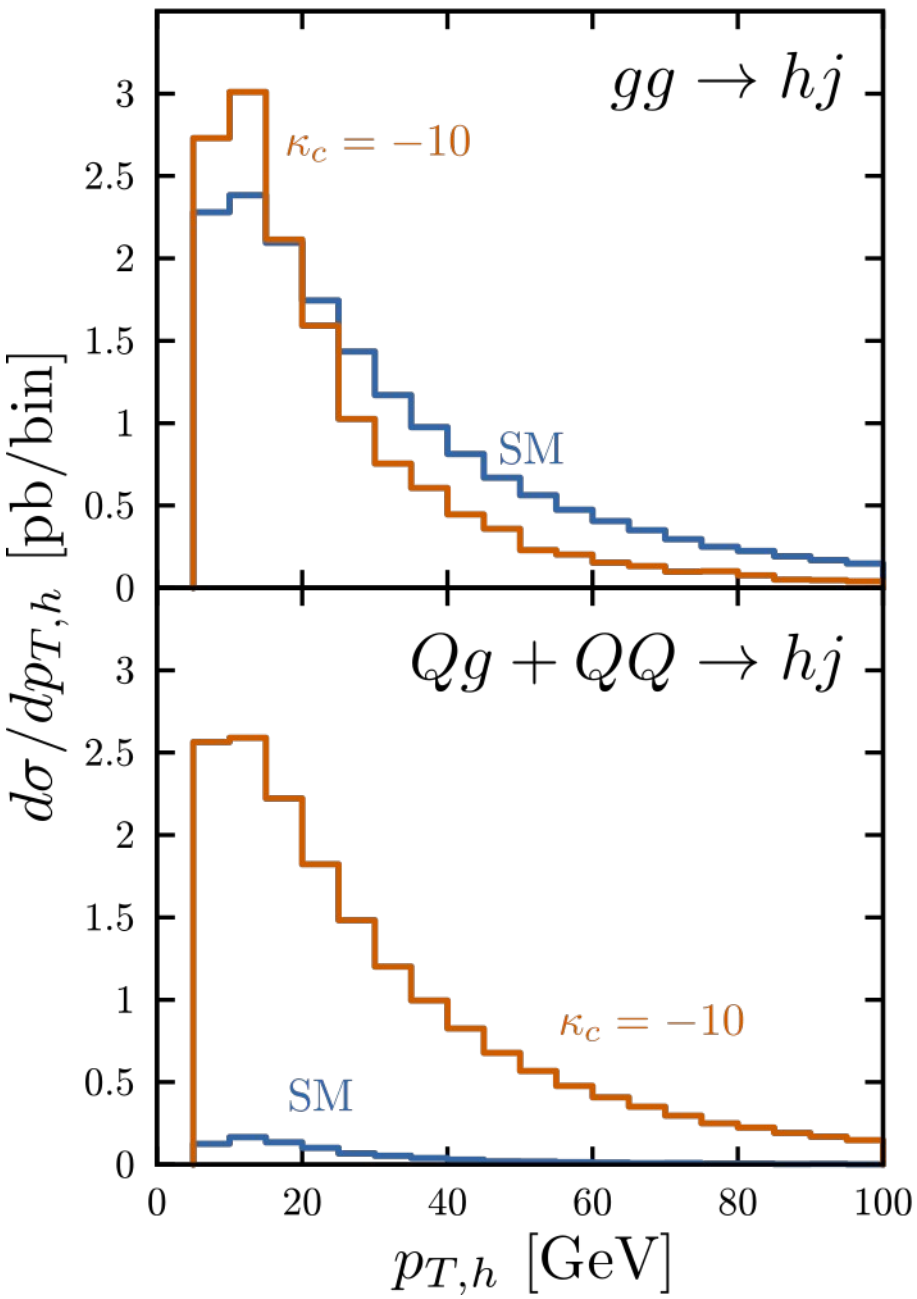
# Normalised distributions @ 8 TeV

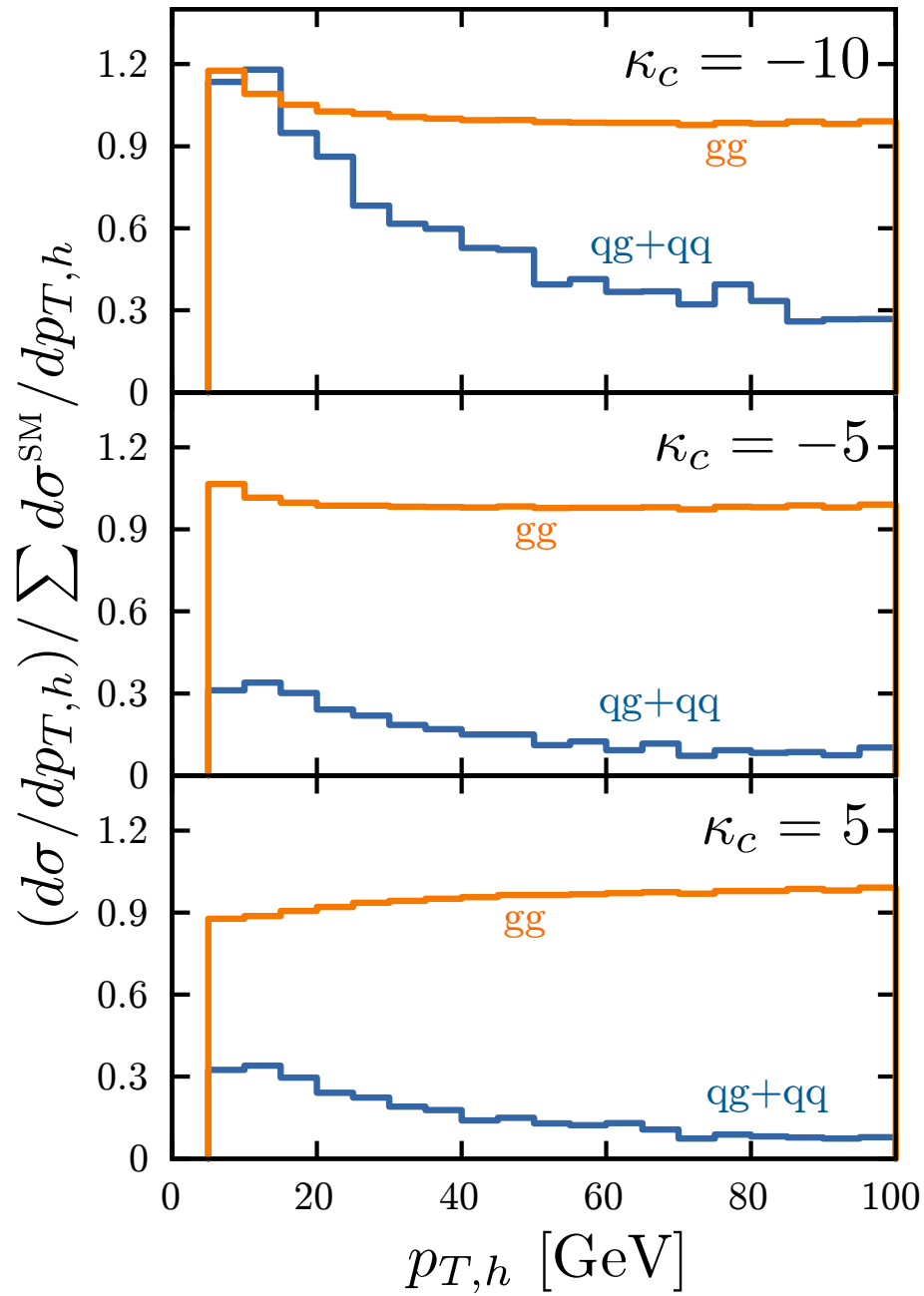



$\mathcal{O}(1)$ deviations in $\kappa_c \rightarrow$ $\sim$ few % effect on the shape

# Contributions to spectrum @ 8 TeV



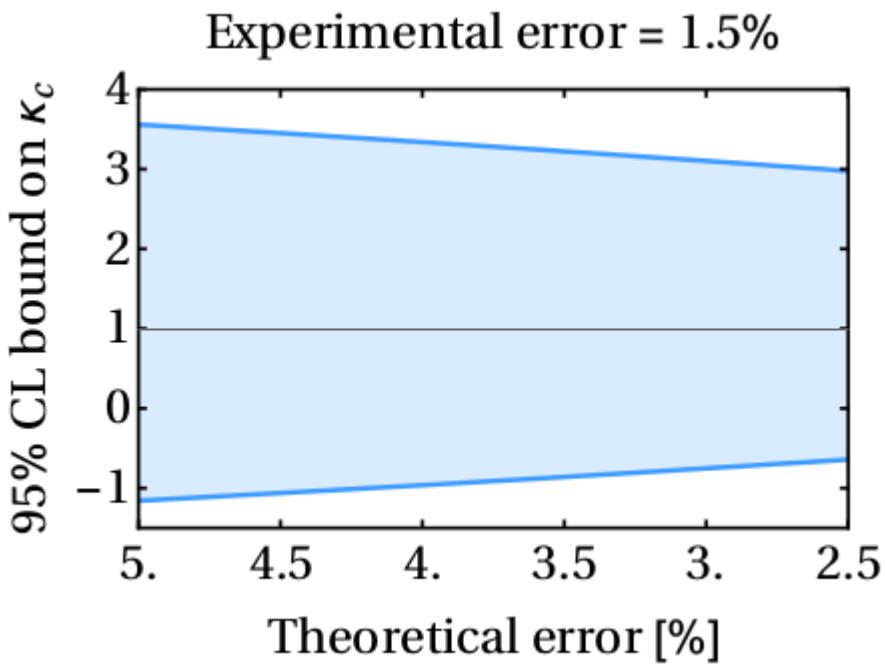
# Quark mass effects

- Exact mass dependence only known at L.O.
  [Ellis, Hinchliffe, Soldate, and van der Bij: Nuc.Phys. B297 (1988)]
  [Baur and Glover: Nuc.Phys. B339 (1990)]
- L.O. differential distributions include non-factorizing terms $\sim \ln^2(p_\perp^2/m_Q^2)$
  [Mantler, Wiesemann [1210.8263], [Banfi, Monni, and Zanderighi: 1
  [Grazzini and Sargsyan 1306.4581]
- These $\ln^2$ terms do not exist for $p_T < m_Q$
- Recent progress in the direction of NLO, NLL

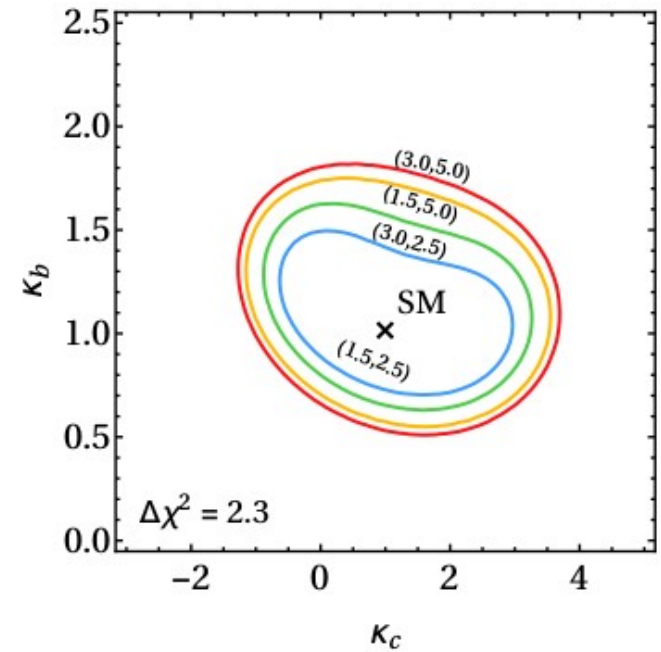
  $\rightarrow$ Soft double Logs resummed in the abelian limit [Melnikov, Penin: 1602.09020]

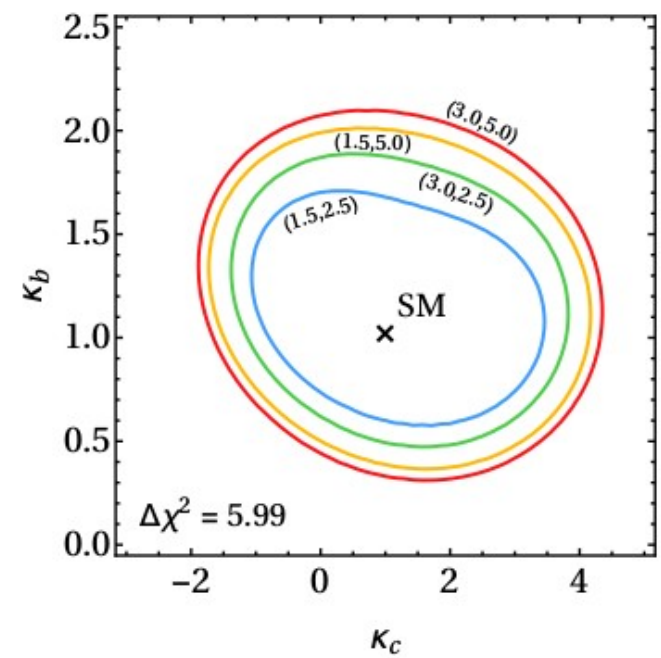
  $\rightarrow$ Two loop virtual corrections in the $m_Q \rightarrow 0$ limit [Melnikov, Tancredi, Wever: 1610.03747 and 1702.0

# Varying the systematic errors...




| | experimental [%] | theoretical [%] | $\kappa_c \in$ |
|---|---|---|---|
| $S_1$ | 1.5 | 2.5 | [-0.6, 3.0] |
| $S_2$ | 3.0 | 2.5 | [-0.9, 3.3] |
| $S_3$ | 1.5 | 5.0 | [-1.2, 3.6] |
| $S_4$ | 3.0 | 5.0 | [-1.3, 3.7] |



# VH production + flavour tagging

$$
\begin{aligned}
\mu_b &= \frac{\sigma\,\mathrm{BR}_{b\bar{b}}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}} \\
&\to \frac{\sigma\,\mathrm{BR}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma\,\mathrm{BR}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma_{\mathrm{SM}}\,\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}} \\
&= \left(\mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\mu_c\right)\Bigg/\left(1 + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)
\end{aligned}
$$

# Fermion mass generation

See Altmannshofer et al. [1610.02398] for a 2HDM model where 1st and 2nd generation fermions couple predominantly to one doublet whereas the 3rd generation fermions and the weak gauge bosons couple to the other doublet