BSM theory prospects in the flavor sector

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Burssels

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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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

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

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

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

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

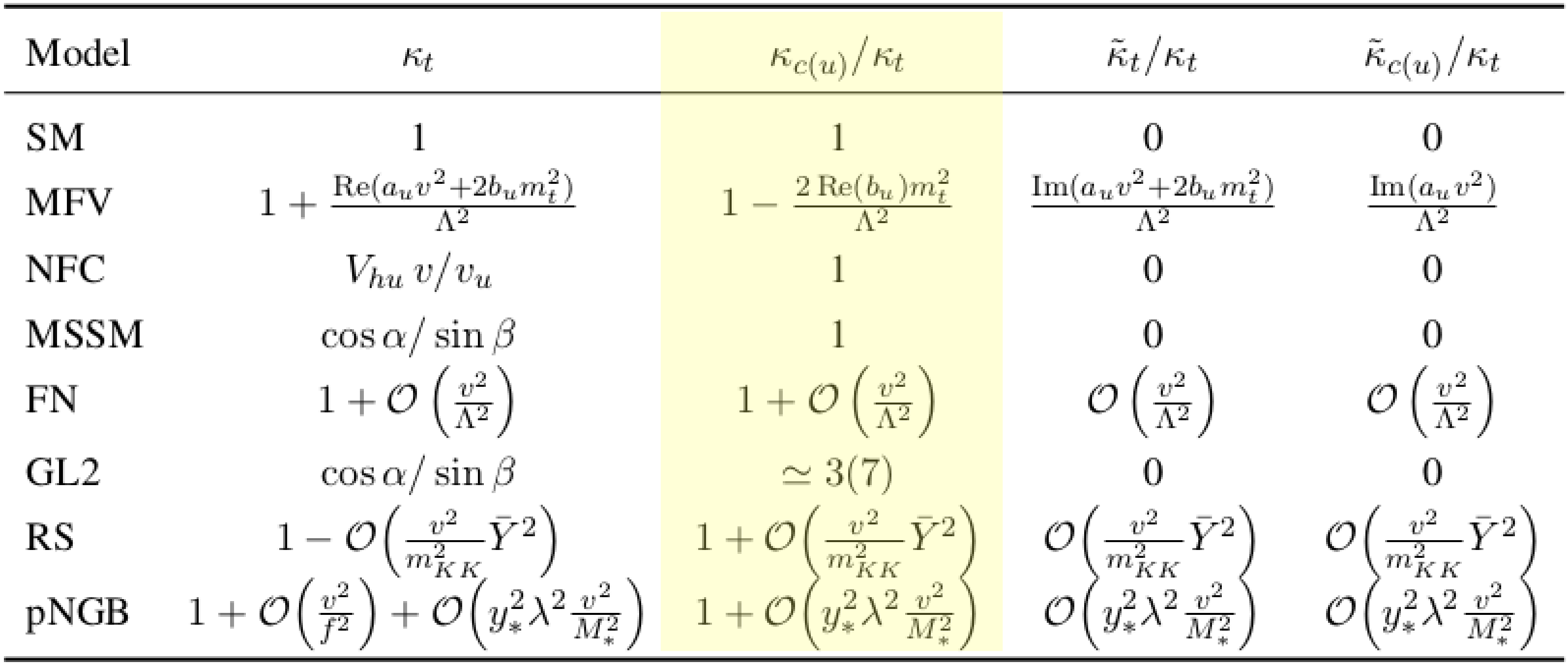
- Neutral current FV is generically present in any extension of the SM.
- Arises due to misalignment between the mass and Yukawa matrices – e.g., in D6 extension:

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

- 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	κ_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	$1+\mathcal{O}\left(\frac{v^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$

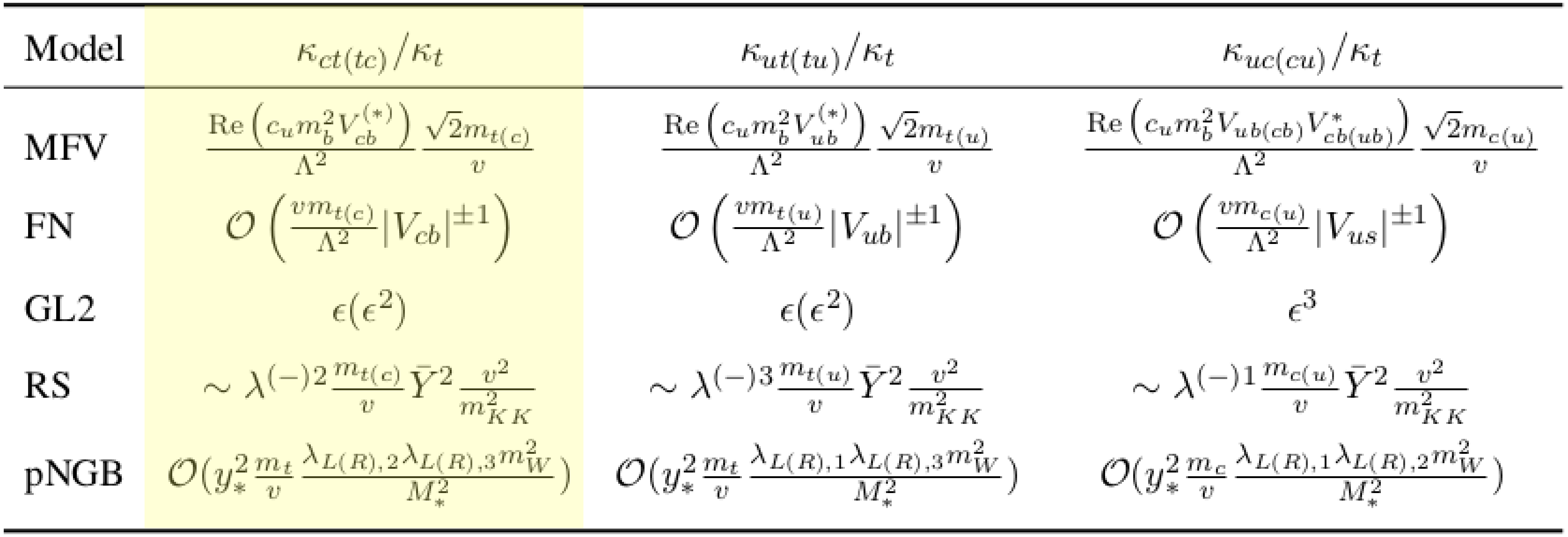
- Generally, modifications $\sim v^2/\Lambda^2 \ll \mathcal{O}(1)$
- Exception: GL2 (modified GL) where

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

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

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]

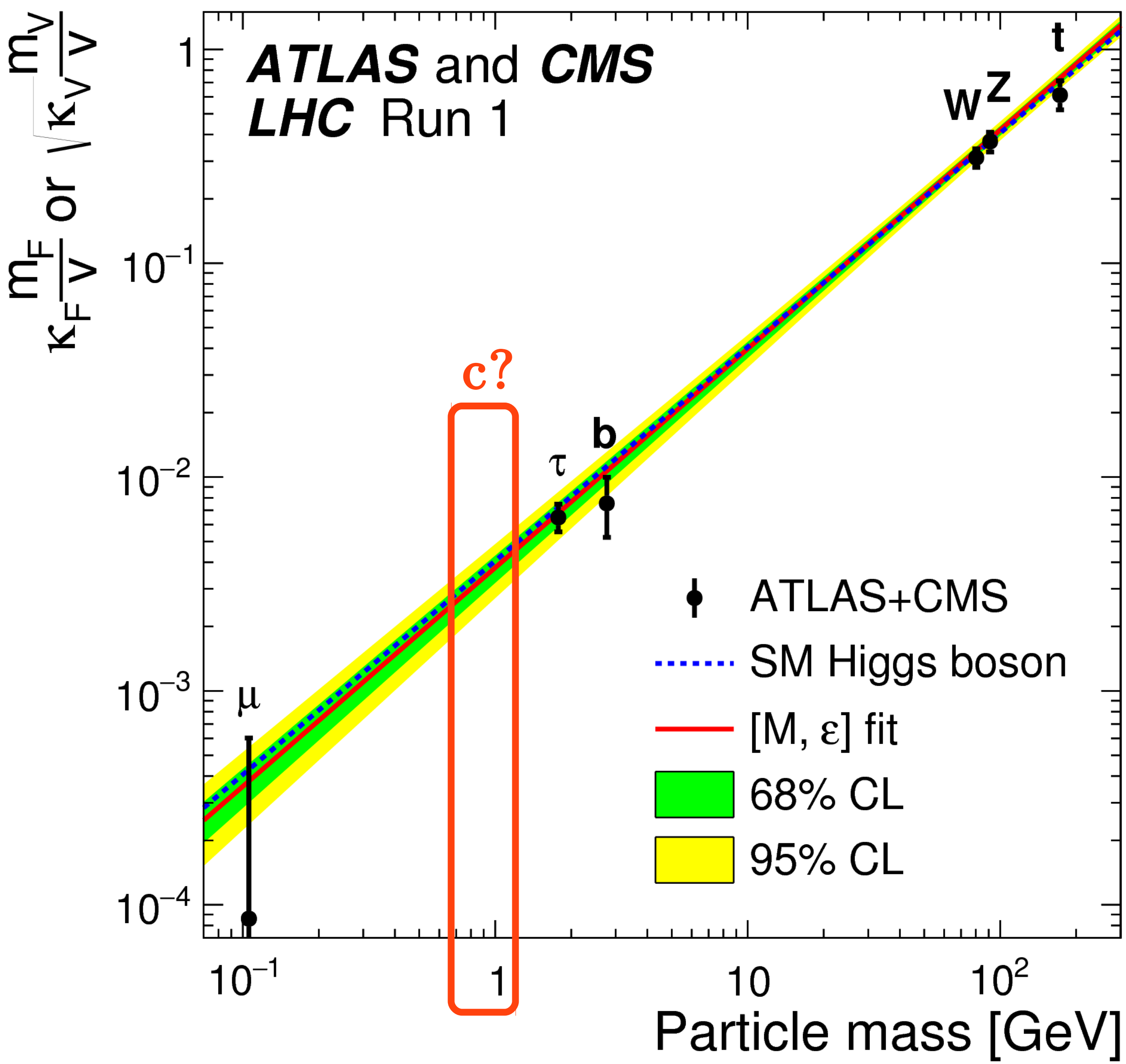


Model	$\kappa_{ct(tc)}/\kappa_t$	$\kappa_{ut(tu)}/\kappa_t$	$\kappa_{uc(cu)}/\kappa_t$
MFV	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^*\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v}$
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	$\epsilon(\epsilon^2)$	$\epsilon(\epsilon^2)$	ϵ^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] [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]



1st and 2nd generation Yukawas

… Ideas for a hadron collider

- 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

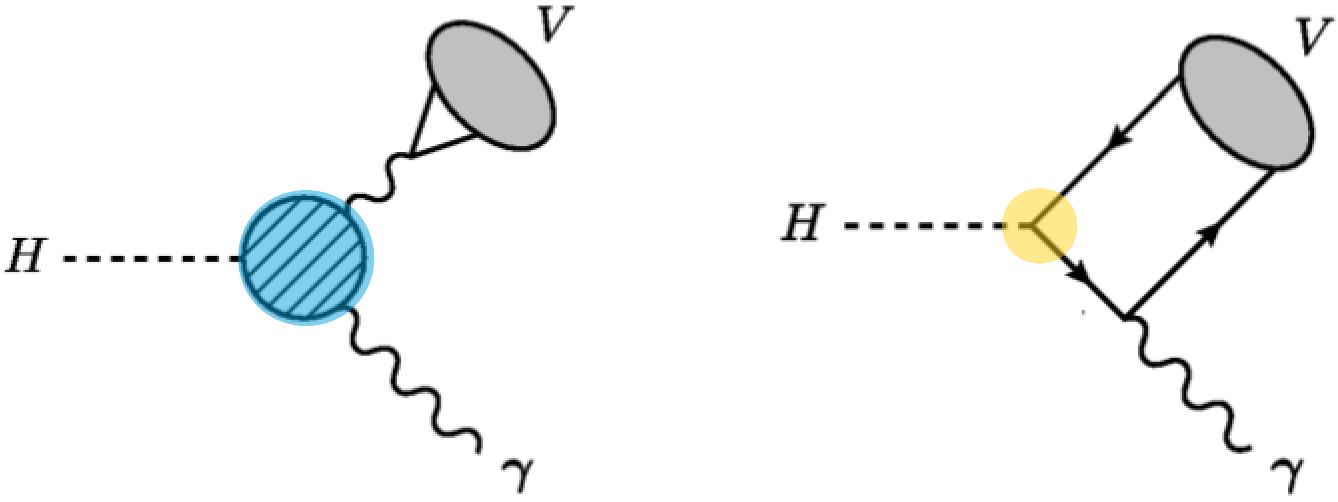
- Higgs differential distributions

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

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

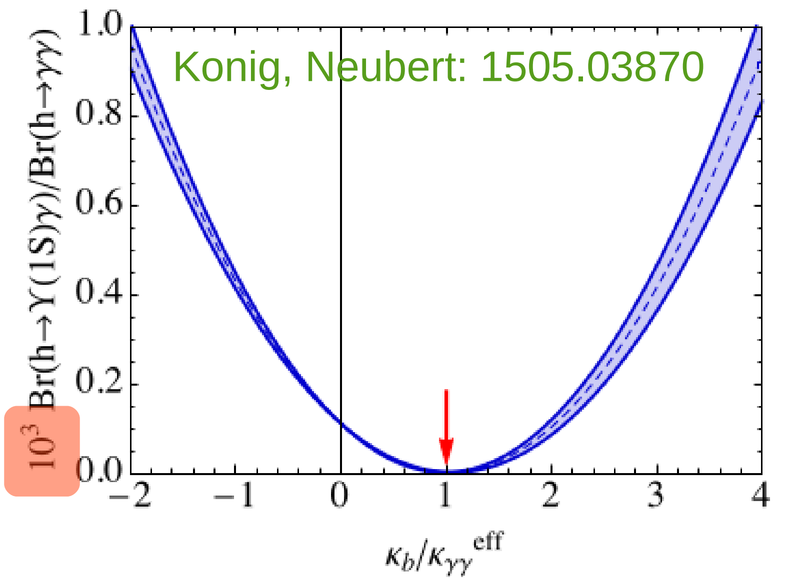
ATLAS 1807.00802

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

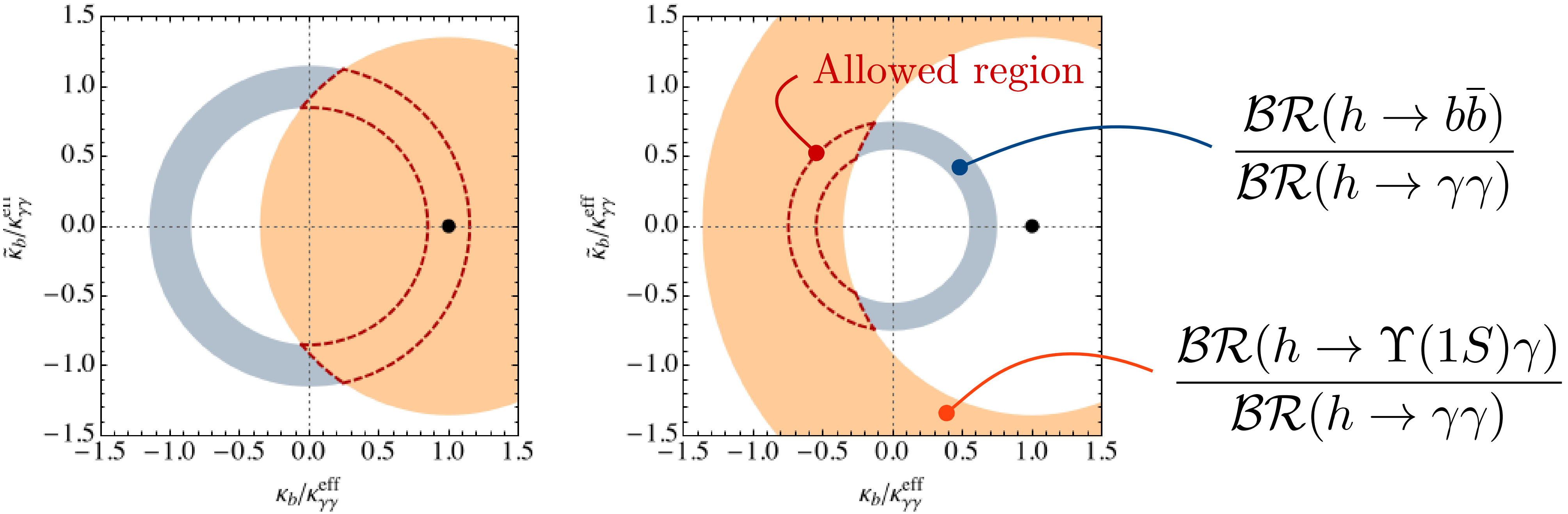
Kagan, Perez, Petriello, Soreq, Stoynev, and Zupan [1406.1722]

The interesting case of $\Upsilon+\gamma$

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



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



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

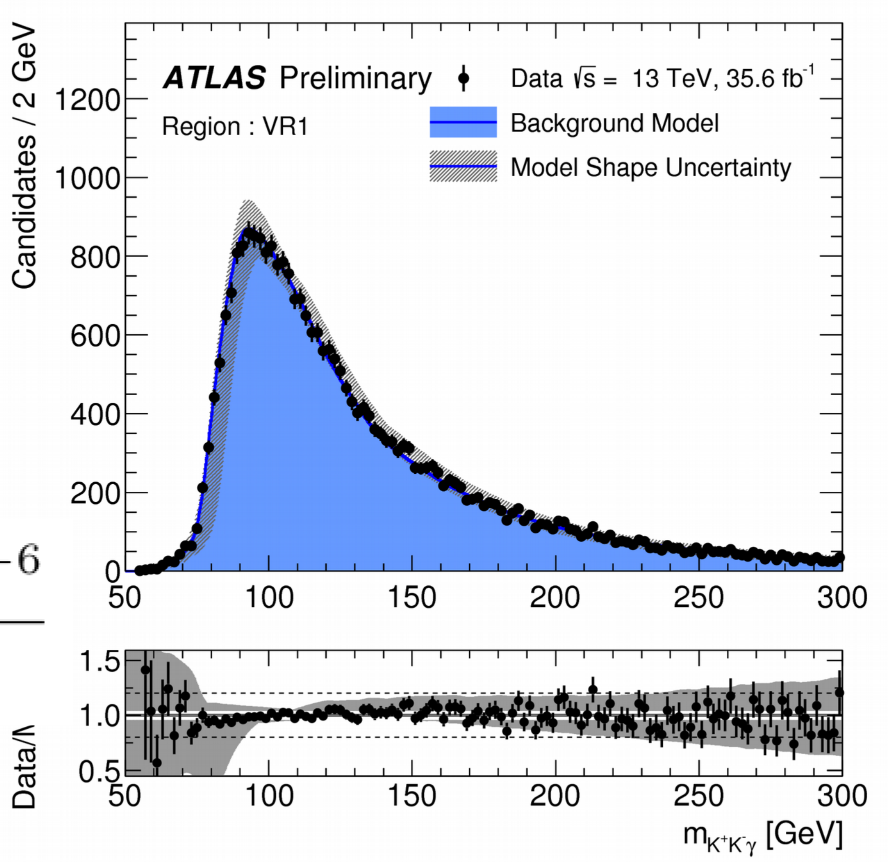
$$\frac{\mathcal{BR}(h\to\Upsilon(1S)\gamma)}{\mathcal{BR}(h\to\gamma\gamma)}$$

Fermion Yukawas status

- Same as before, two amplitudes, direct and indirect. Sensitivity from interference
- New bound from ATLAS [ATLAS-CONF-2017-057]
- Br(ϕK^+K^-)=48.9% (PDG)

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(2.3\pm0.1)\kappa_\gamma - 0.43\bar{\kappa}_s]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

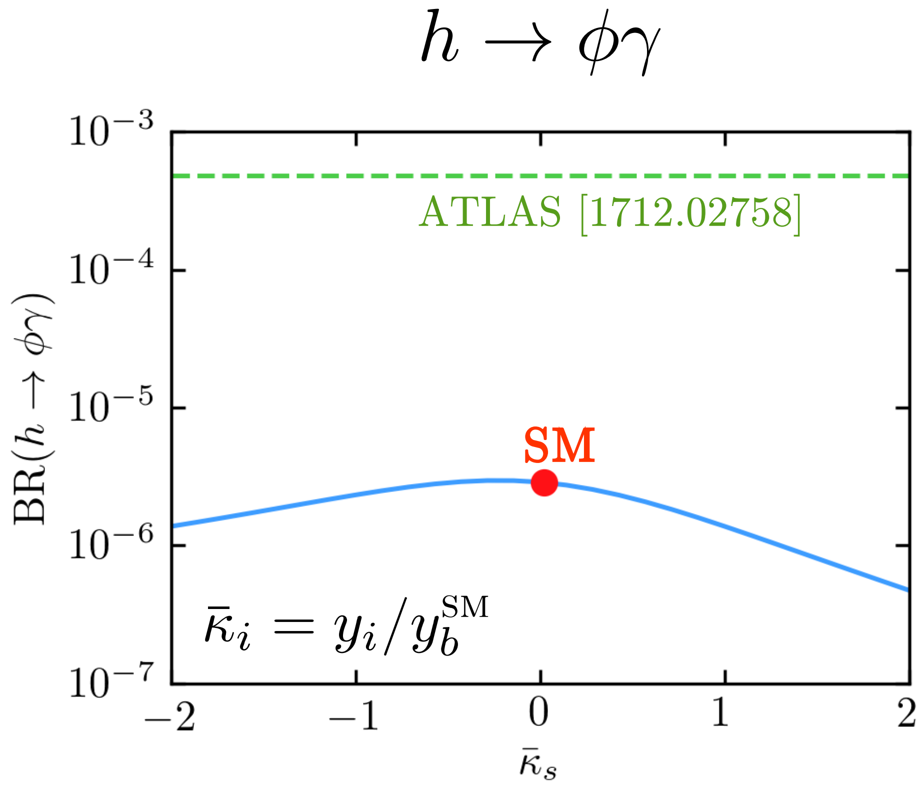
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan: [1406.1722]; Konig, Neubert: 1505.03870

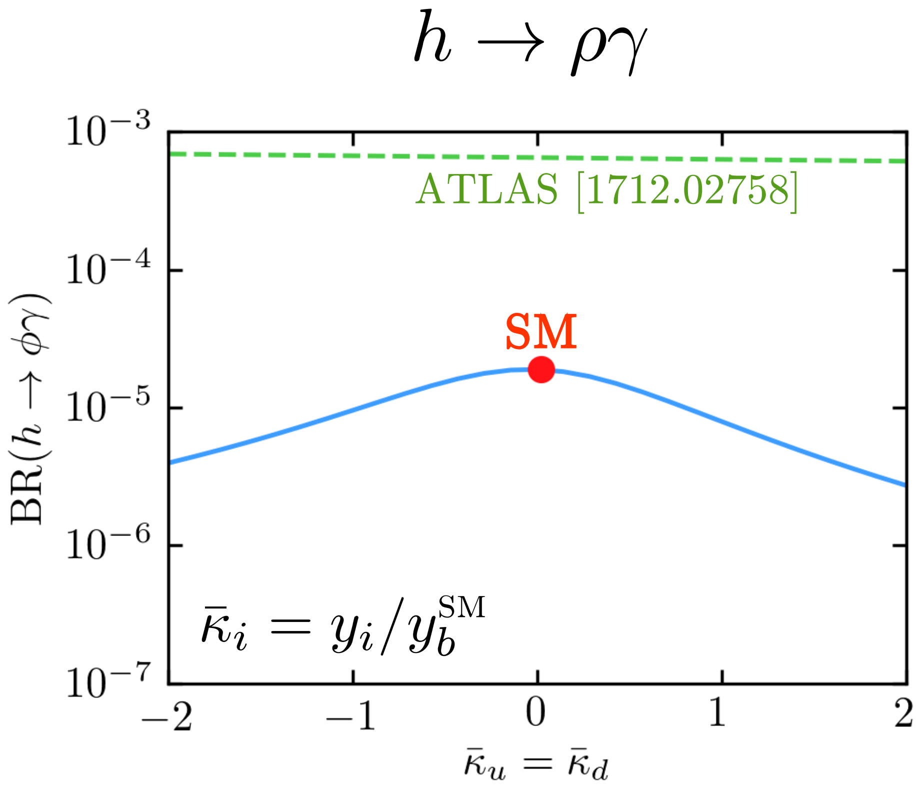


$$Br(h\to\phi(\rho)\gamma < 4.8\times10^{-4}\ (8.8\times10^{-4})\quad \text{at } 95\%\ \text{CL}$$

- Order of magnitude improvement on previous ATLAS bound on Br(ḥϕ+γ) [1607.03400] and first bound on Br(ḥρ+γ)

Light quarks: u, d, s



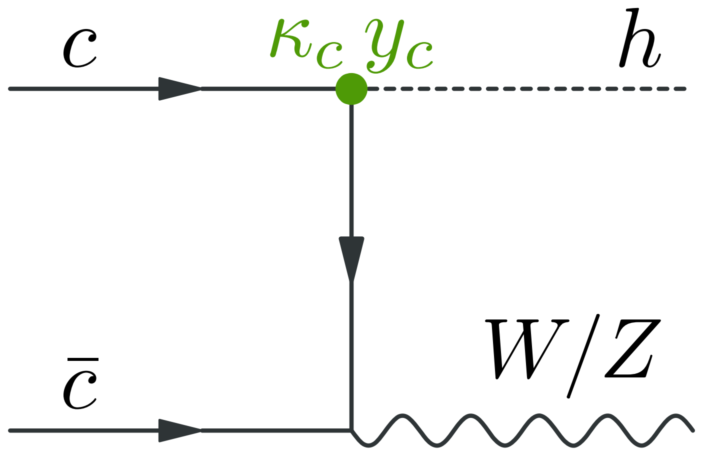


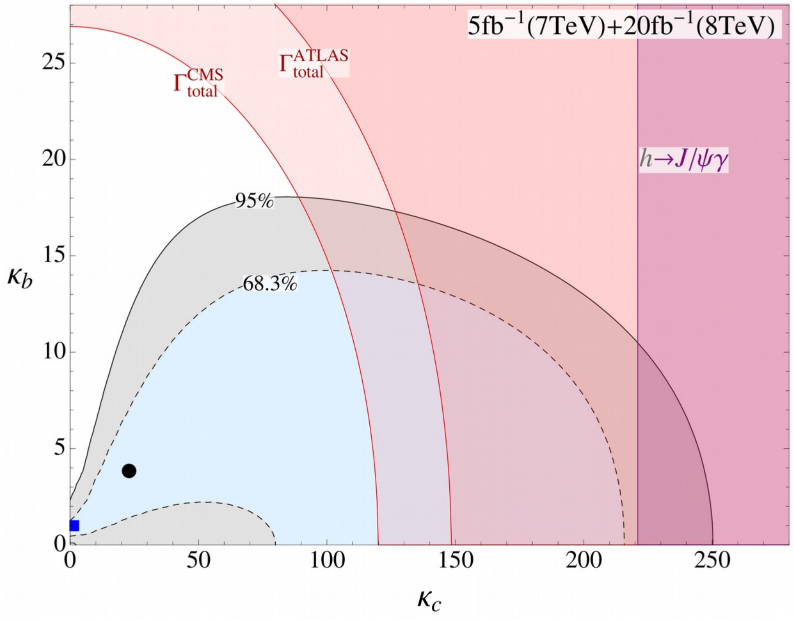
Eby, Petriello, Zupan [unpublished]

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

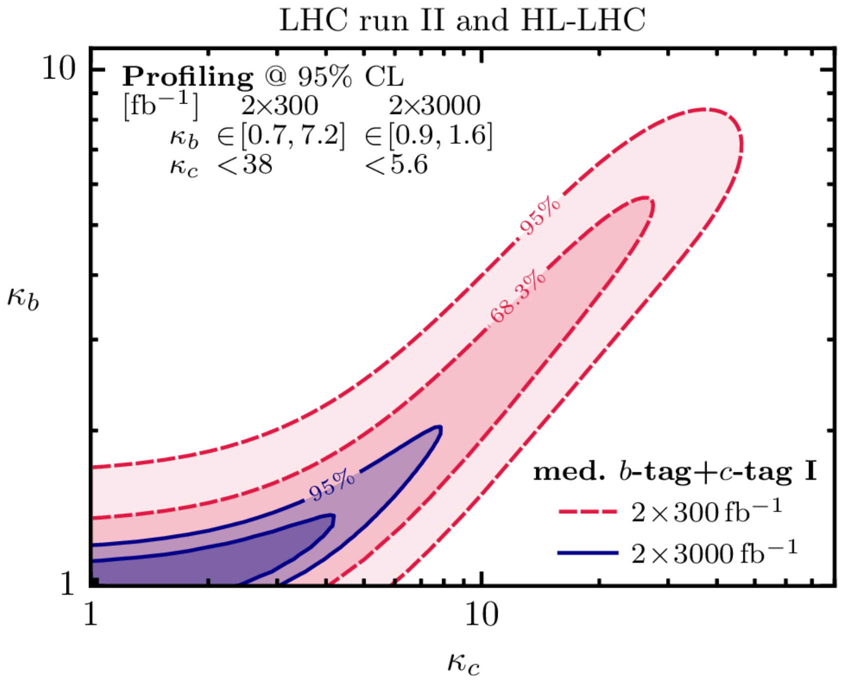
$$Br_{h\to\rho\gamma} = \frac{10^{-5}\left[(1.89 \pm 0.11)\kappa_\gamma^2 - (.228 \pm .017)\bar{\kappa}_u\kappa_\gamma - (.114 \pm 0.008)\bar{\kappa}_d\kappa_\gamma + \ldots\right]}{\left[1 + (\bar{\kappa}_d^2 + \bar{\kappa}_u^2)Br^{\mathrm{SM}}_{h\to b\bar{b}} + (\kappa_\gamma^2 - 1)Br^{\mathrm{SM}}_{h\to\gamma\gamma}\right]},$$

VH production + flavour tagging





Perez et al.: 1503.00290



Perez et al.: 1505.06689

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

See also: [Brivio, Goertz, Isidori 1507.02916]

They consider hc final state and find (LHC_{14})

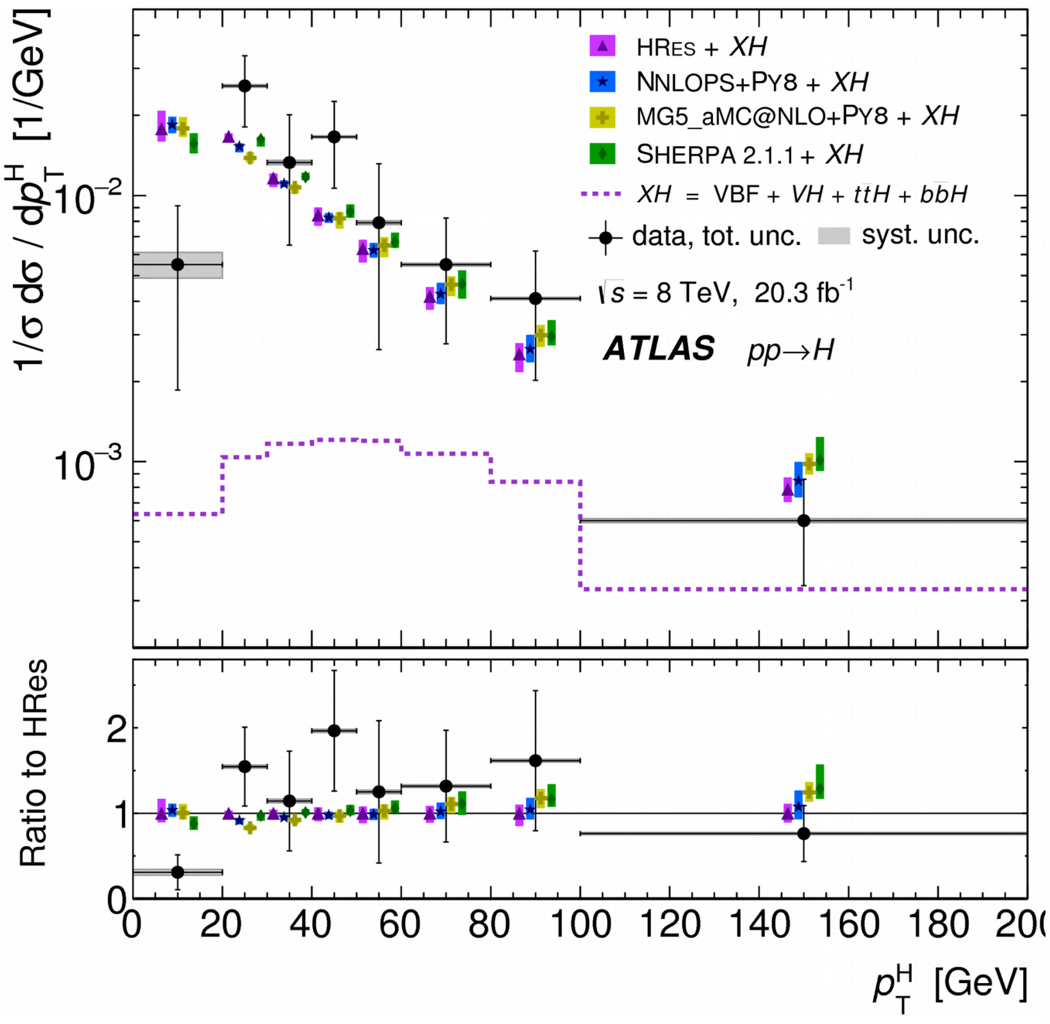
$|\kappa_c| < 3.9$ @ 95% C.L. with 3000 fb^{-1}

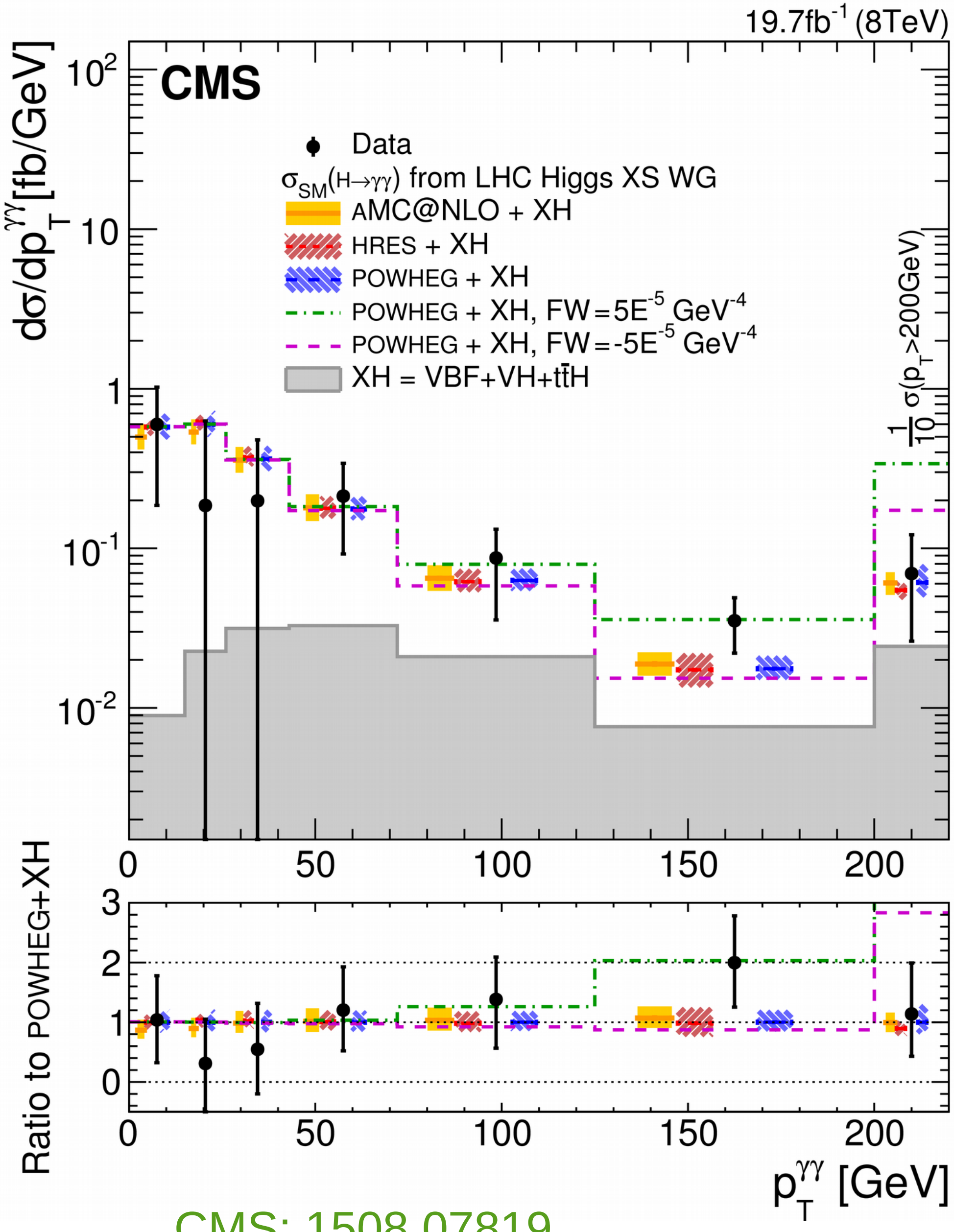
Higgs transverse momentum

- Additional emissions probe the structure of the loop in $gg \to h + jets$
- The loop has a chirality suppression but . . .
- The charm is special → 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

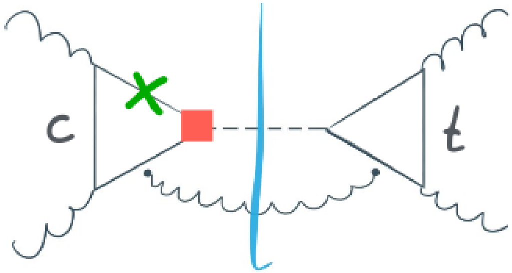
- The quark initiated contribution dominates for $\kappa_Q \gg 1$ [Soreq, Zhu, & Zupan: 1606.09621]

- Normalized distributions in this regime are sensitive to light d.o.f. but heavy new physics can affect the tail

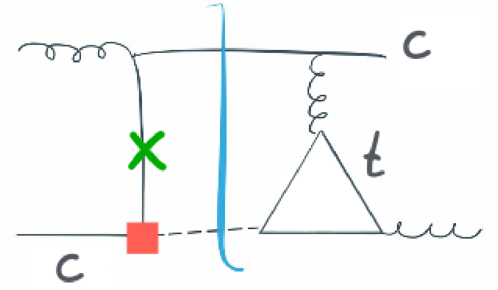
[Banfi, Martin, Sanz: 1606.09621]
[Buschmann, Goncalves, Kuttimalai, Schonherr, Krauss, Plehn: 1410.5806]
[Buschmann, Englert, Goncalves, Plehn, Spannowsky: 1405.7651] + others

Contributions and their scaling

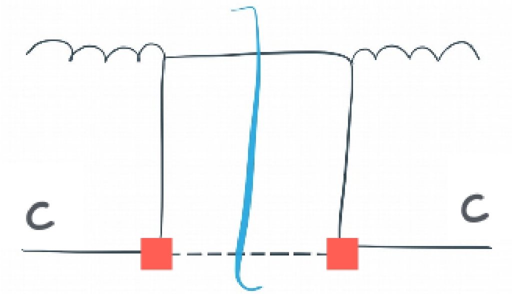
Color coding courtesy
of Uli Haisch



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

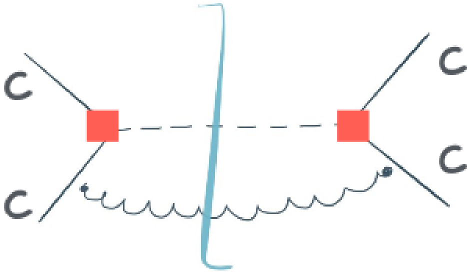


$$\sim \alpha_s \alpha_s^2 \, y_c \, m_c$$ $(=0$ in 4, 5 flavour scheme)



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

🟩 chirality flip



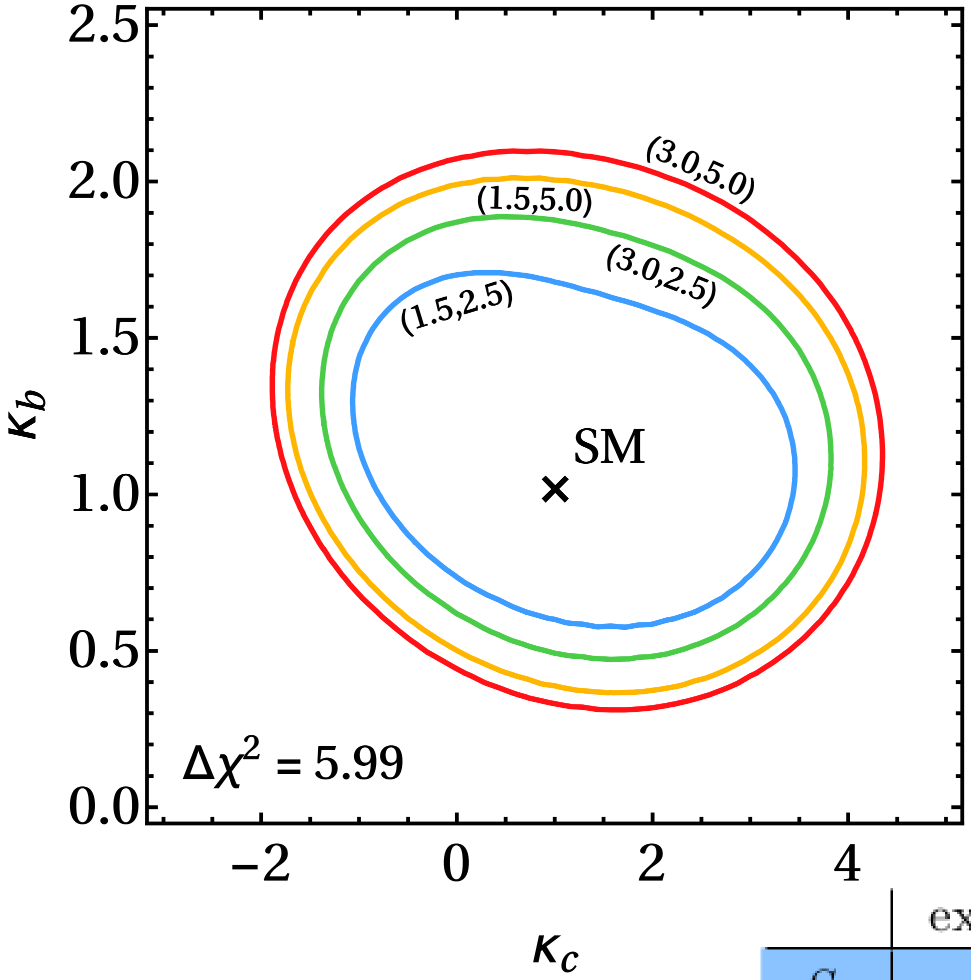
$$\sim \alpha_s^2 \alpha_s \, y_c^2$$

🟦 extra powers of α_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 κ_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)

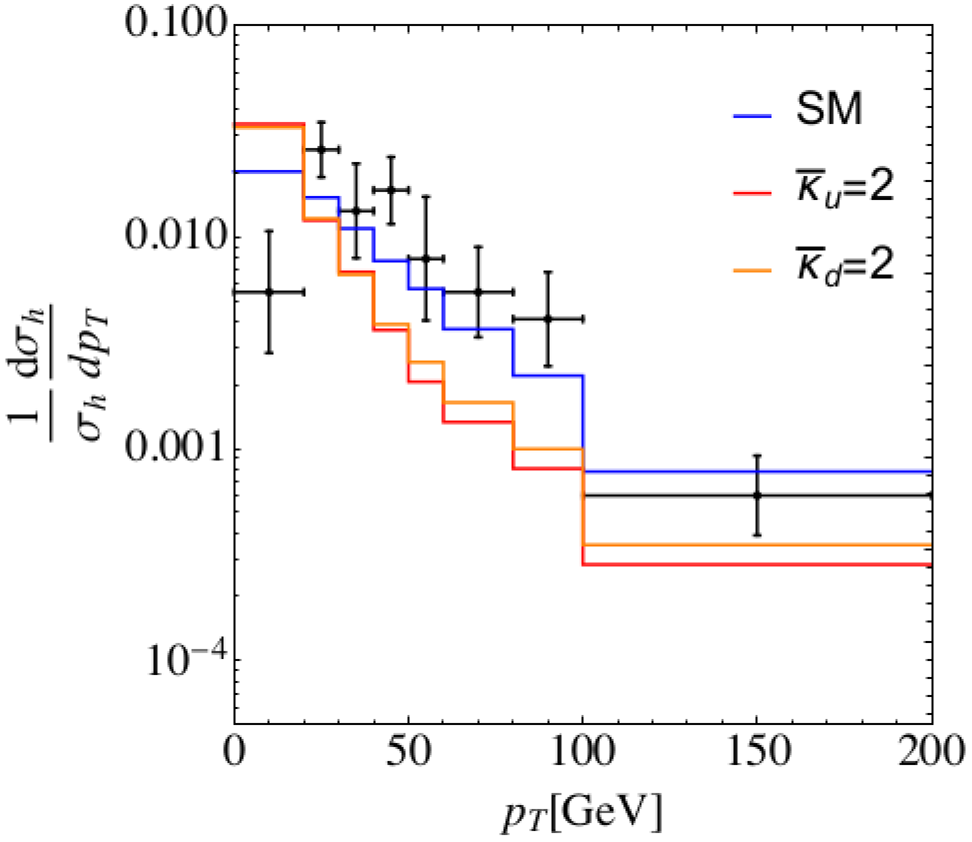
$-8.7 < \kappa_c < 10.6$

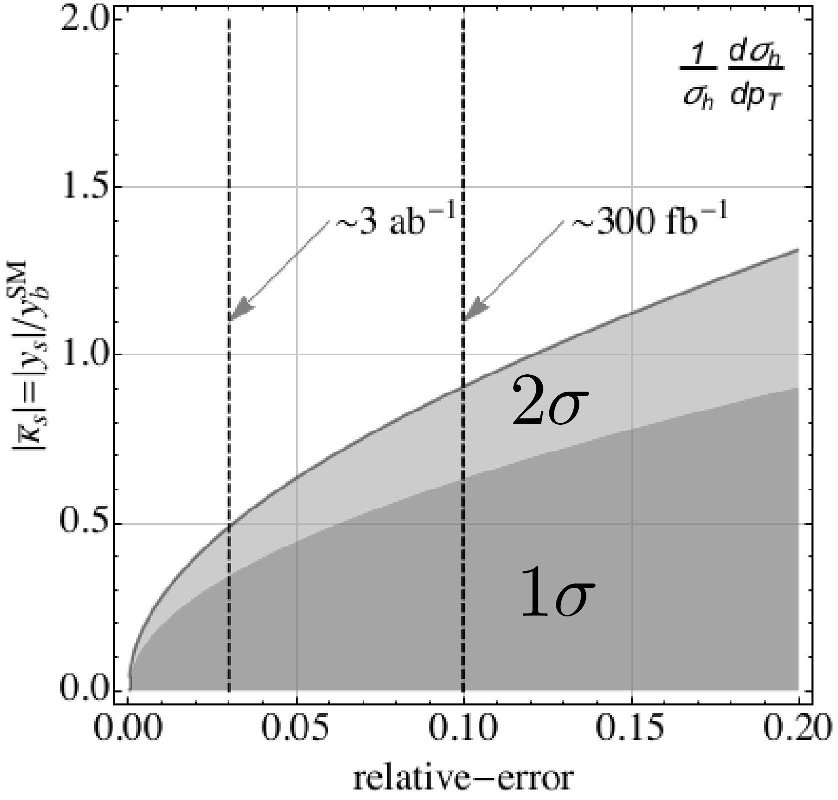
PAS HIG-17-028

	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]

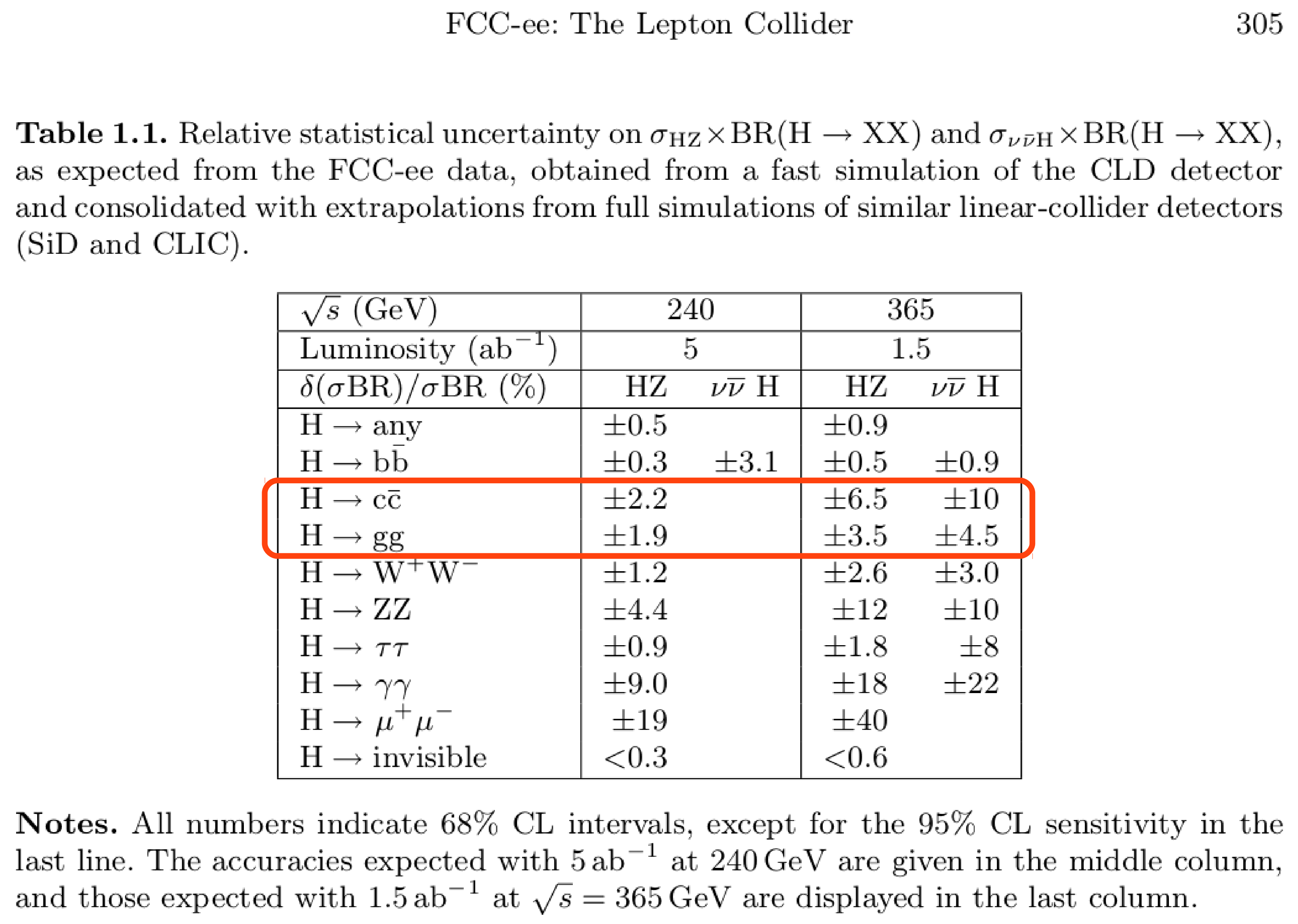




See also Felix Yu [1609.06592] for $W^\pm$ Charge asymmetry sensitive to $\mathcal{O}(5)$ deviations in $\bar{\kappa}_{u,d,s}$ at 14 TeV w/3 ab^{-1}

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

Diagonal Yukawas at FCCee



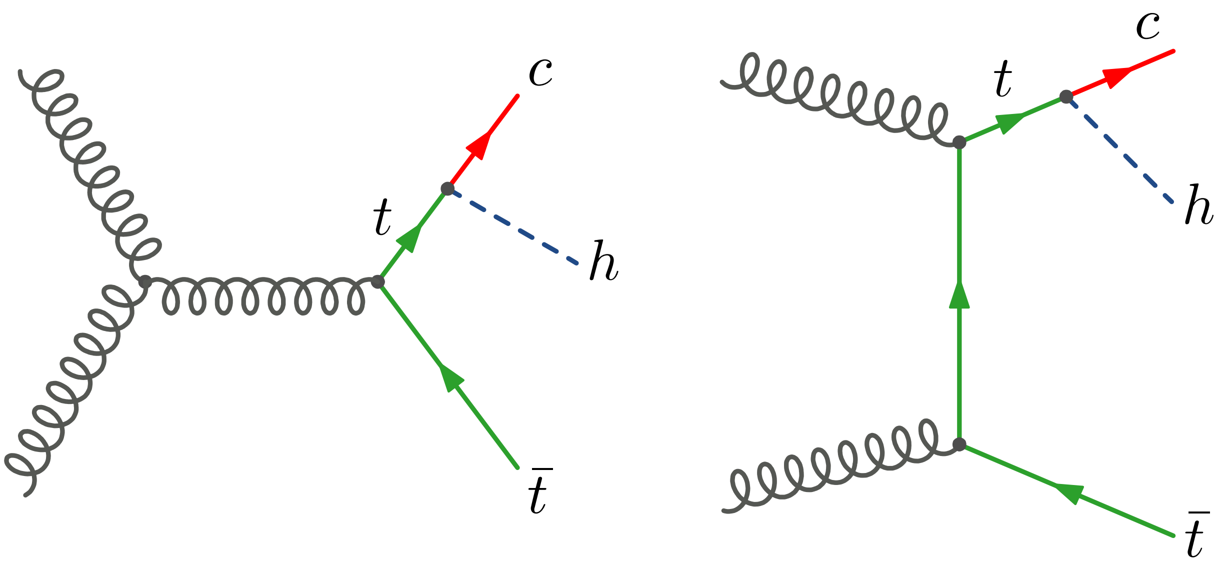
FCC-ee: The Lepton Collider 305

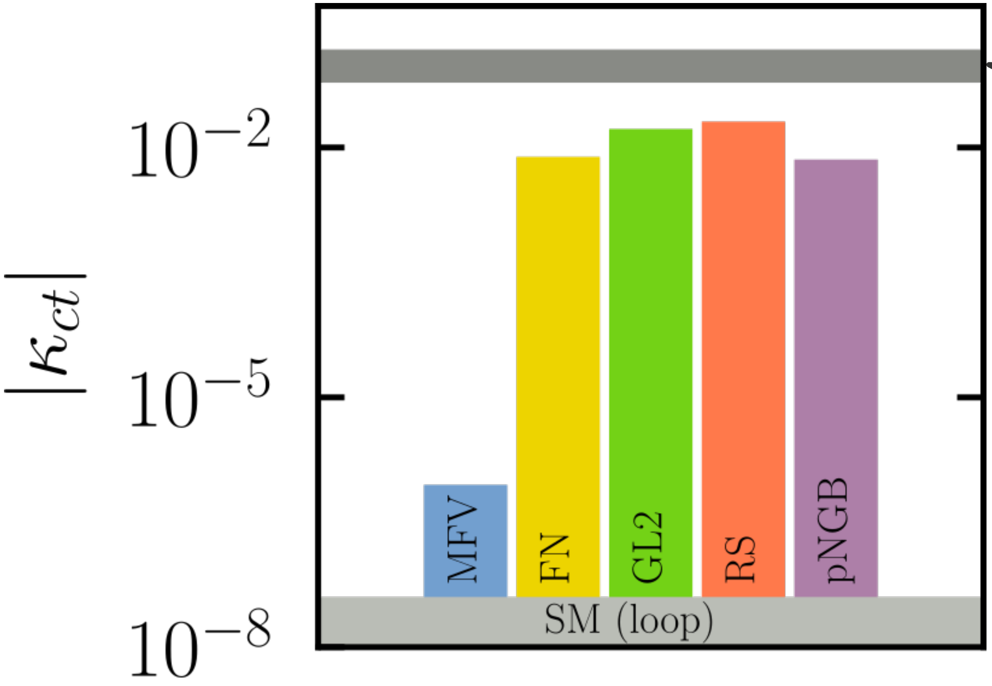
Table 1.1. Relative statistical uncertainty on $\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{XX})$ and $\sigma_{\nu\bar{\nu}\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{XX})$, as expected from the FCC-ee data, obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC).

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$\mathrm{H} \to$ any	±0.5		±0.9	
$\mathrm{H} \to \mathrm{b\bar{b}}$	±0.3	±3.1	±0.5	±0.9
$\mathrm{H} \to \mathrm{c\bar{c}}$	±2.2		±6.5	±10
$\mathrm{H} \to \mathrm{gg}$	±1.9		±3.5	±4.5
$\mathrm{H} \to \mathrm{W^+W^-}$	±1.2		±2.6	±3.0
$\mathrm{H} \to \mathrm{ZZ}$	±4.4		±12	±10
$\mathrm{H} \to \tau\tau$	±0.9		±1.8	±8
$\mathrm{H} \to \gamma\gamma$	±9.0		±18	±22
$\mathrm{H} \to \mu^+\mu^-$	±19		±40	
$\mathrm{H} \to$ invisible	<0.3		<0.6	

Notes. All numbers indicate 68% CL intervals, except for the 95% CL sensitivity in the last line. The accuracies expected with $5\,\mathrm{ab}^{-1}$ at 240 GeV are given in the middle column, and those expected with $1.5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 365$ GeV are displayed in the last column.

Top FCNC





ATLAS [1707.01404] – 13 TeV, $36.1\ \text{fb}^{-1}$, $h\gamma\gamma$
ATLAS [1403.6293,1509.06047]
CMS [1610.04857]

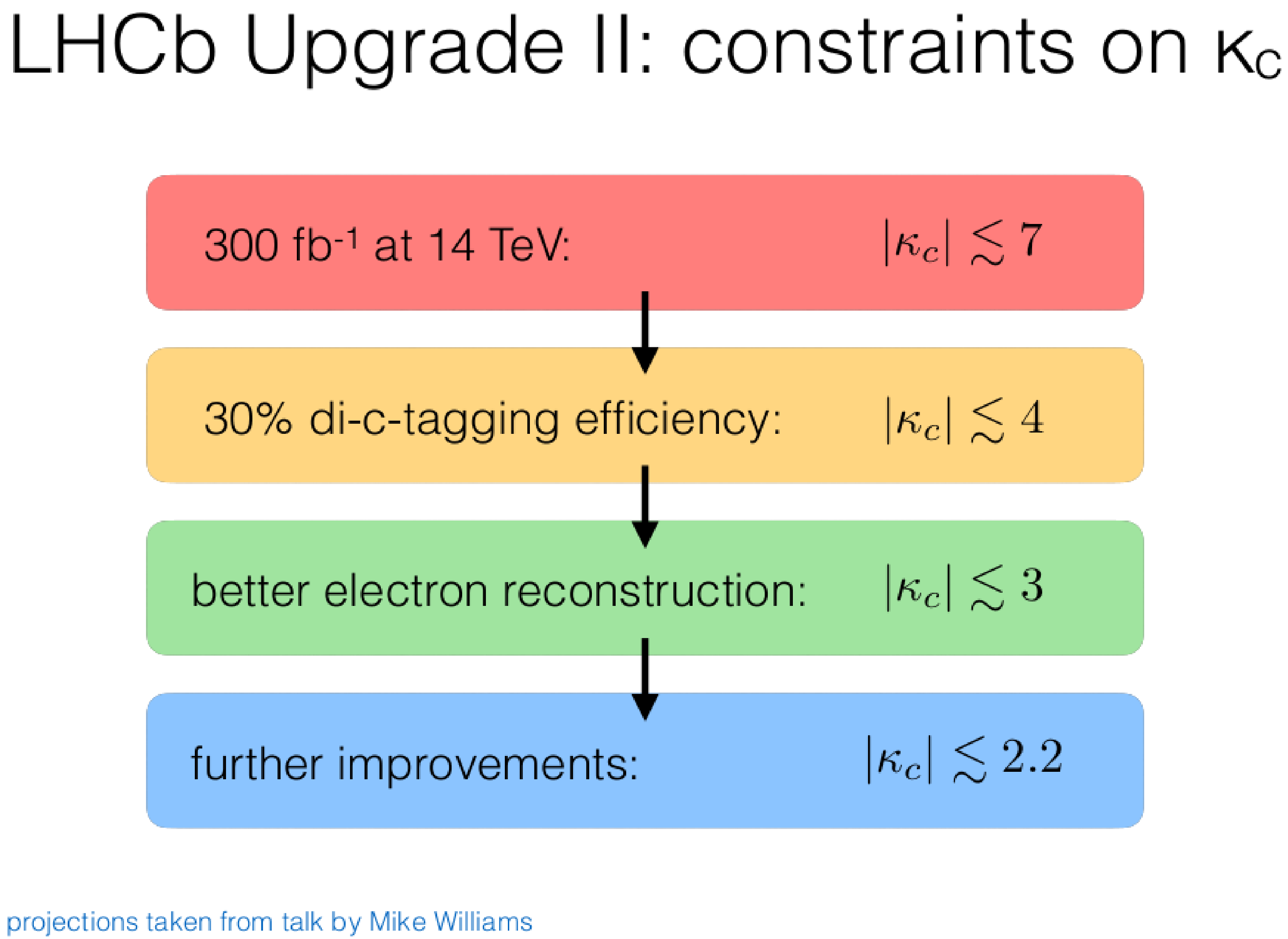
Summary

- 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(κ_c)<2.2 and ILC O(10%)
- VH production at LHCb abs(κ_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 κ_c

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

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

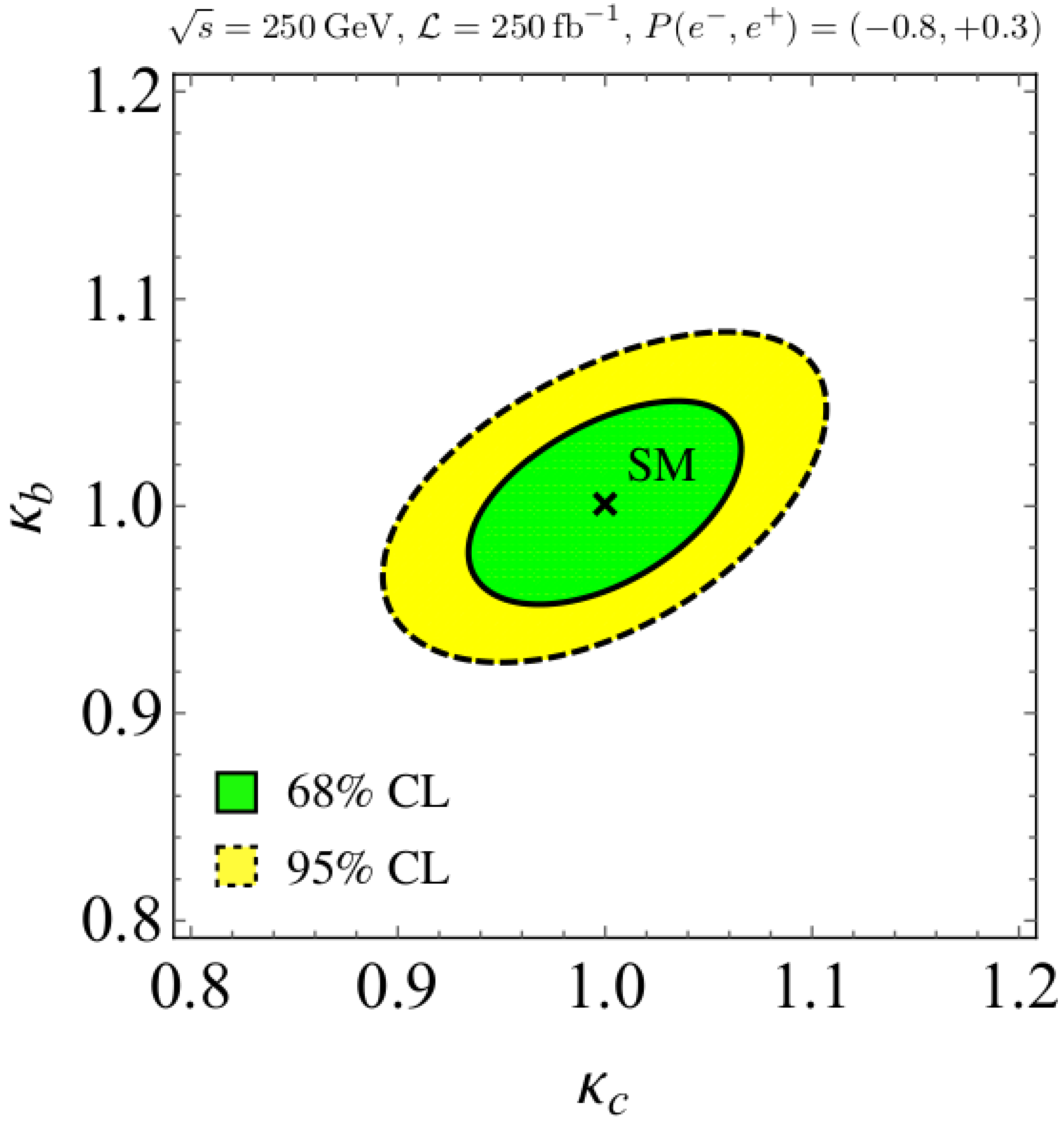
better electron reconstruction: $|\kappa_c| \lesssim 3$

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

projections taken from talk by Mike Williams

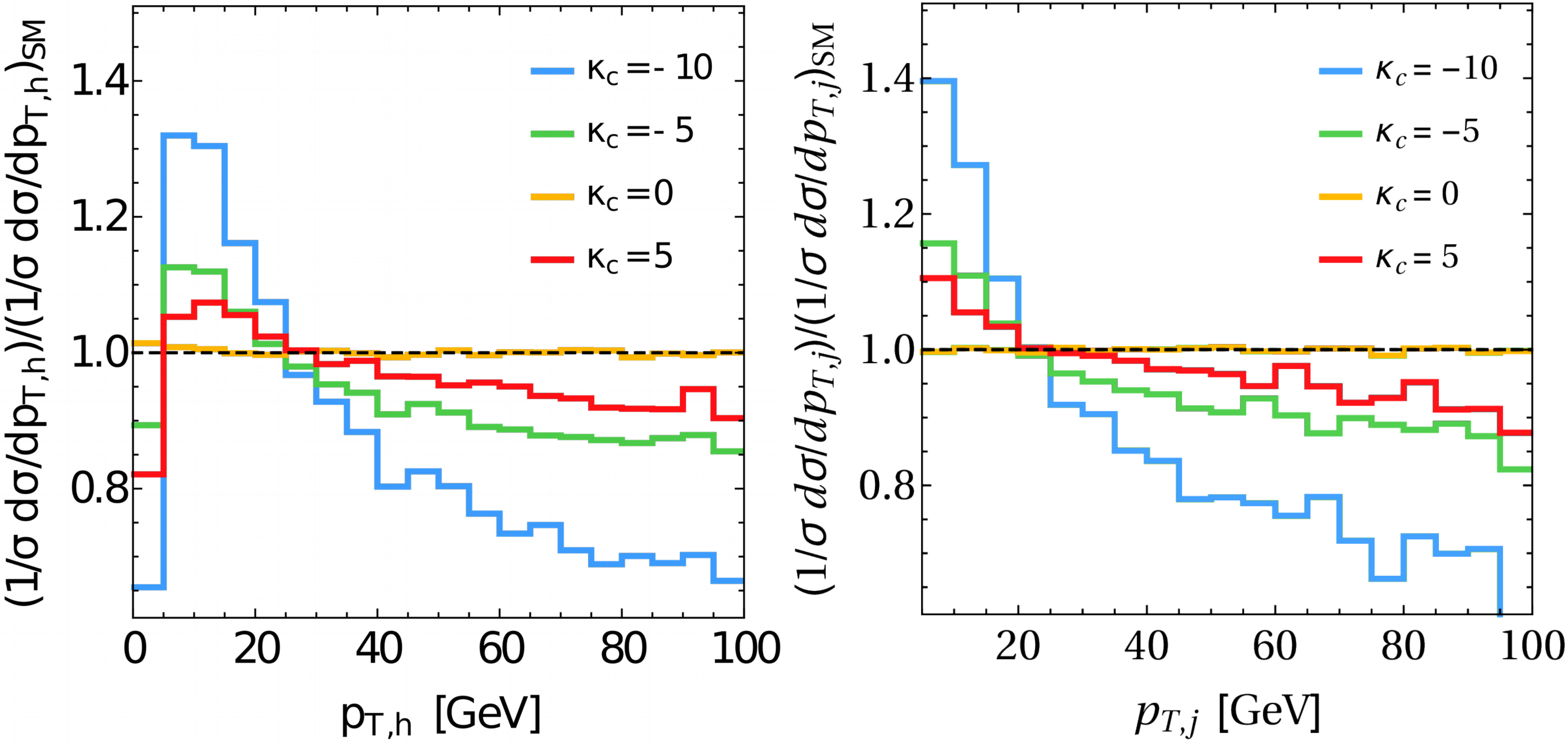
Slide from Uli Haisch talk at Elba 2017
Based on bounds from M. Williams’ talk

Projections for the ILC



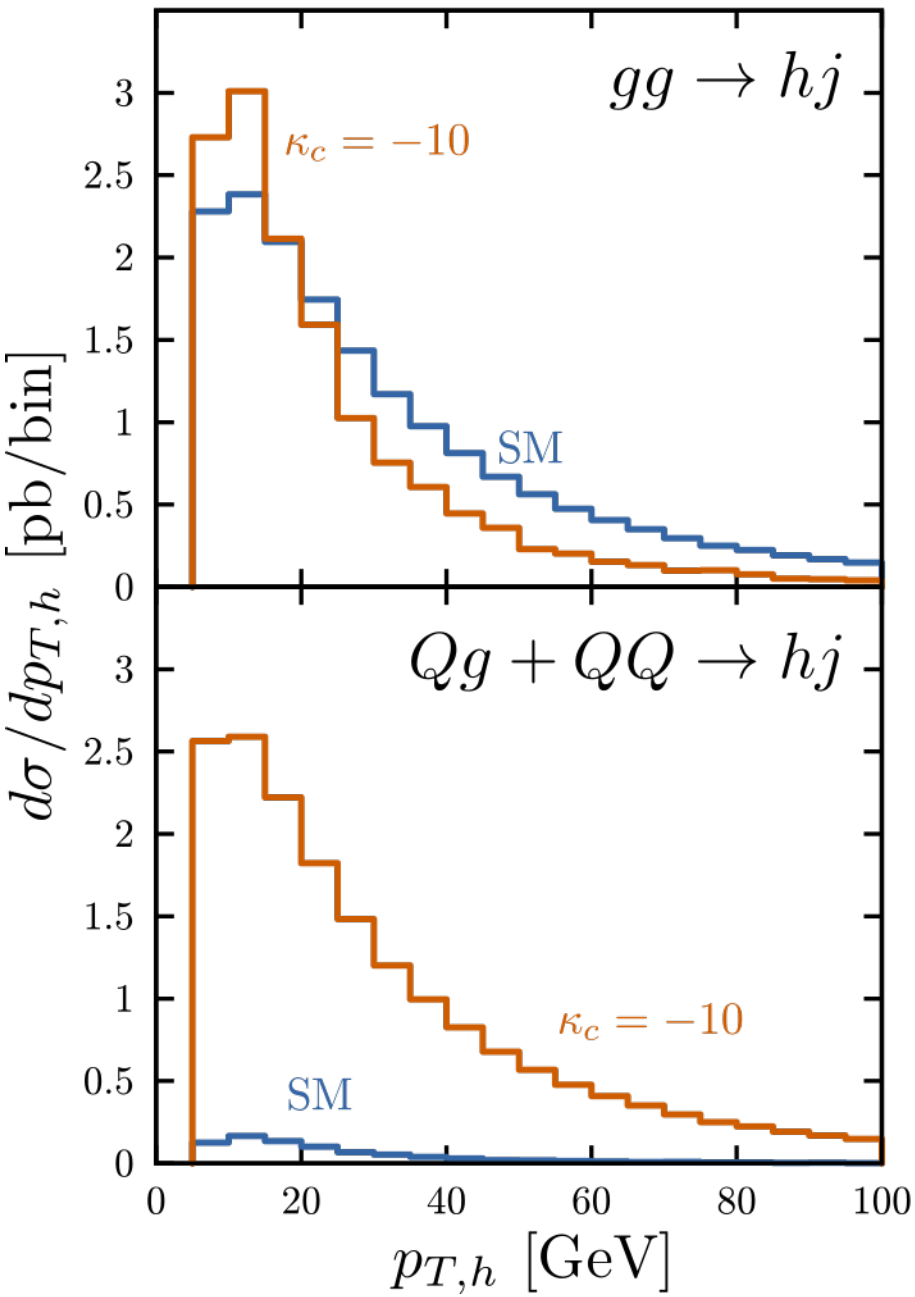
Uli Haisch based on Ono & Miyamoto [1207.0300]

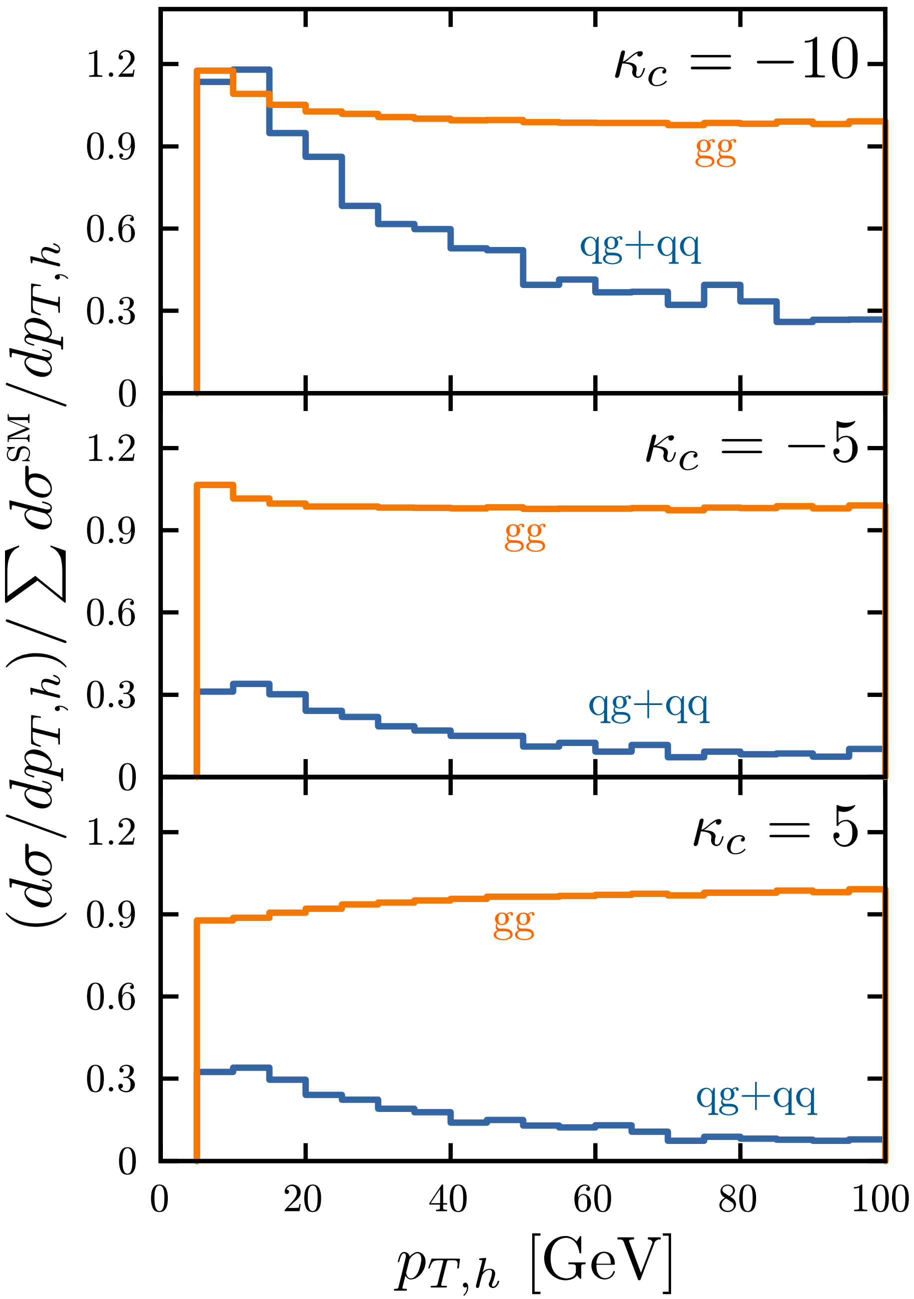
Normalised distributions @ 8 TeV



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

Contributions to spectrum @ 8 TeV





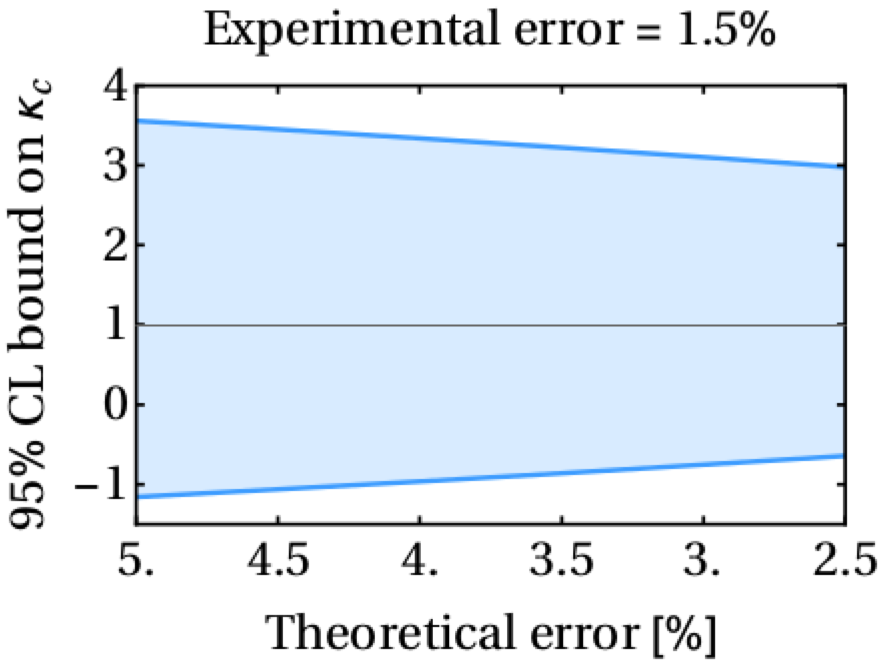
Quark mass effects

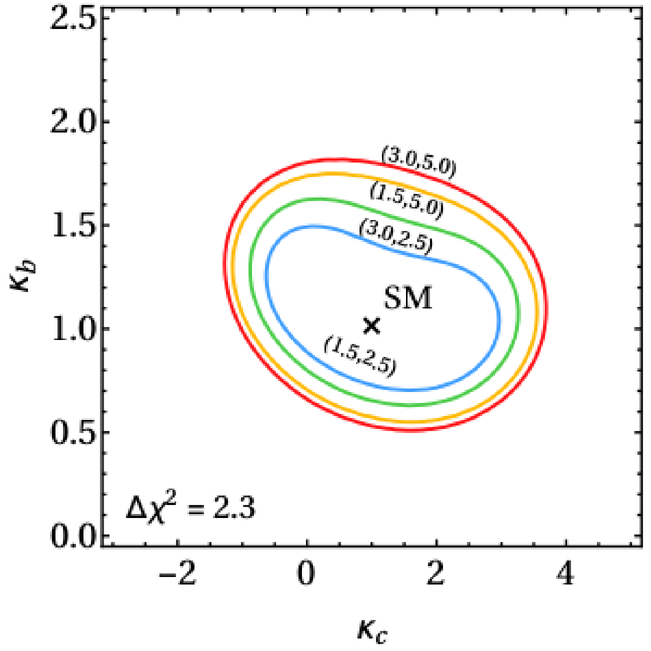
- Exact mass dependence only known at L.O.
  [Ellis, Hinchliffe, Soldate, and van der Bij: Nuc.Phys. B297 (1988)]
  [Baur and Glover: Nuc.Phys. B339 (1990)]
- L.O. differential distributions include non-factorizing terms $\sim \ln^2(p_\perp^2/m_Q^2)$
  [Mantler, Wiesemann [1210.8263], [Banfi, Monni, 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

  → Soft double Logs resummed in the abelian limit [Melnikov, Penin: 1602.09020]

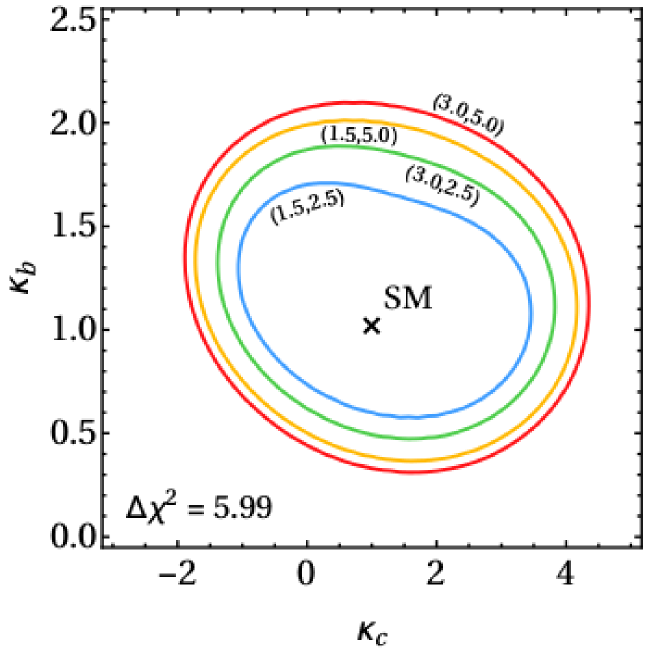
  → Two loop virtual corrections in the $m_Q \to 0$ limit [Melnikov, Tancredi, Wever: 1610.03747 and 1702.0

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