Flavor Opportunities at High pT

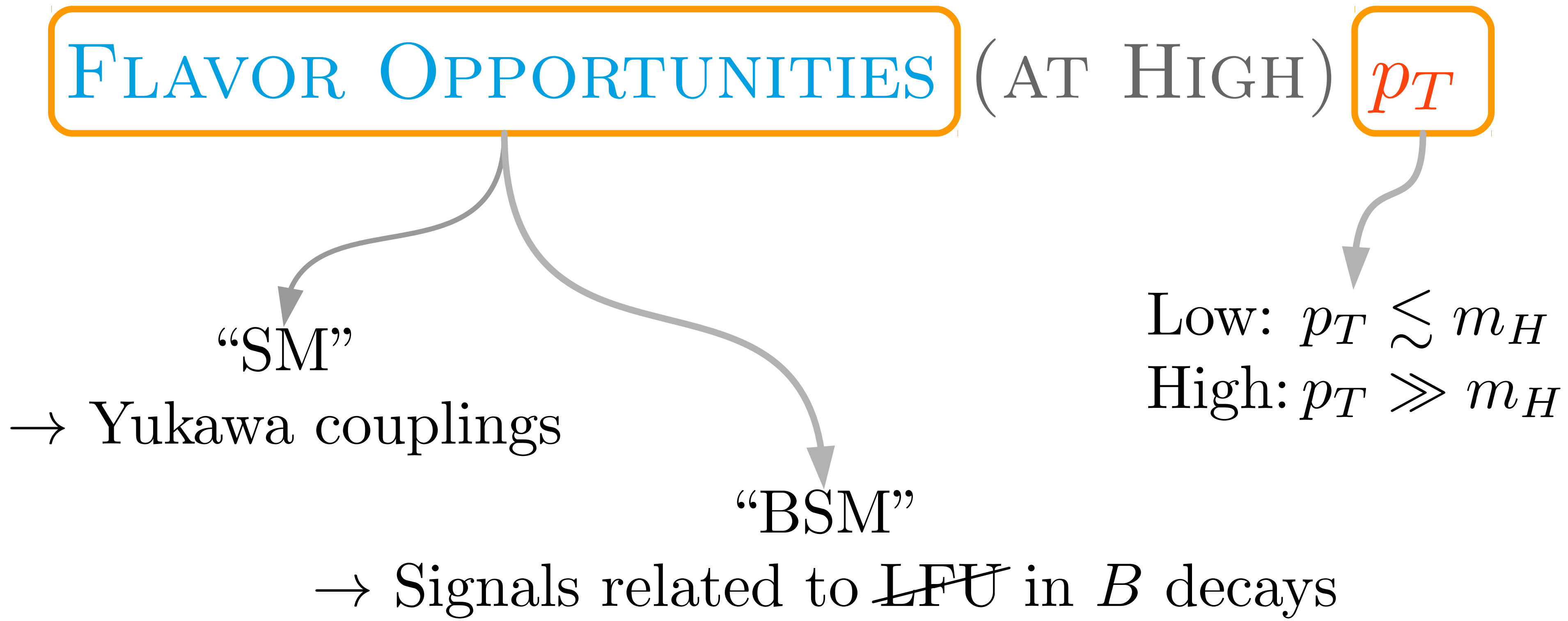
Fady Bishara

SM@LHC 2019
Universität Zürich
25 April

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

European Research Council
Established by the European Commission

DESY.



Flavor Opportunities (at High) p_T

“SM”

→ Yukawa couplings

“BSM”

→ Signals related to ~~LFU~~ in B decays

Low: $p_T \lesssim m_H$

High: $p_T \gg m_H$

---

① Heads: 1st & 2nd gen. Yukawas; (focus on charm Yukawa)

② Tails: EFT operators (~~LFU~~) [See Fuentes-Martin, Takahashi, Reiners talks]

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.

1st and 2nd 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]

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

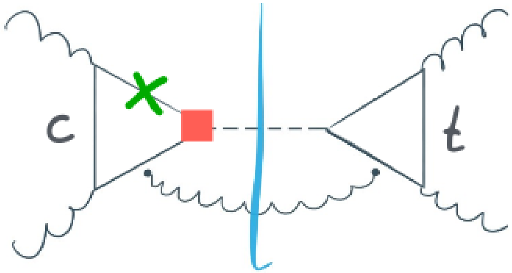
See also: [Soreq, Zhu, & Zupan: 1606.09621] for similar work on the u and d yukawas

Contributions and their scaling

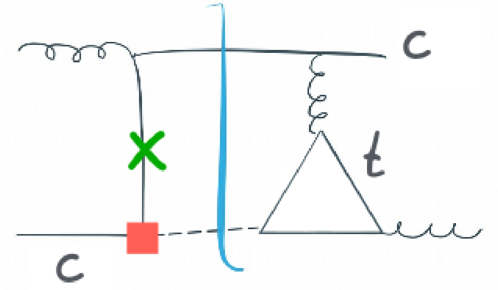
- Many contributions with different scaling in the $m_Q \lesssim p_T \lesssim m_h$ region
- The quark initiated contribution dominates for $\kappa_Q \gg 1$ [Soreq, Zhu, & Zupan: 1606.09621]
- Normalized distributions in this regime are sensitive to light d.o.f. but heavy new physics can affect the tail

[Banfi, Martin, Sanz: 1308.4771]
[Buschmann, Goncalves, Kuttimalai, Schonherr, Krauss, Plehn: 1410.5806]
[Buschmann, Englert, Goncalves, Plehn, Spannowsky: 1405.7651] + others

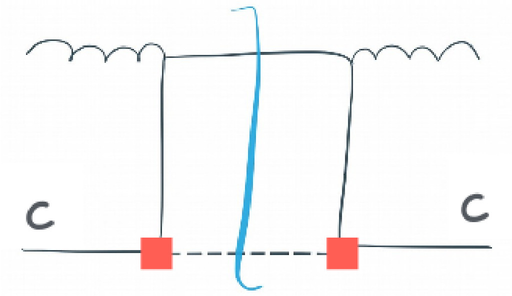
Contributions and their scaling



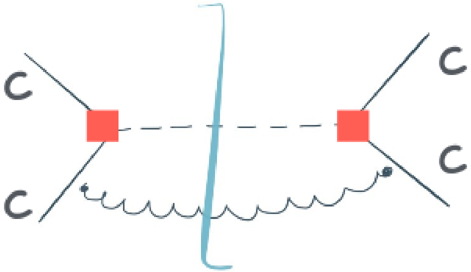
$$\sim \alpha_s^3 y_c m_c \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$



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



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



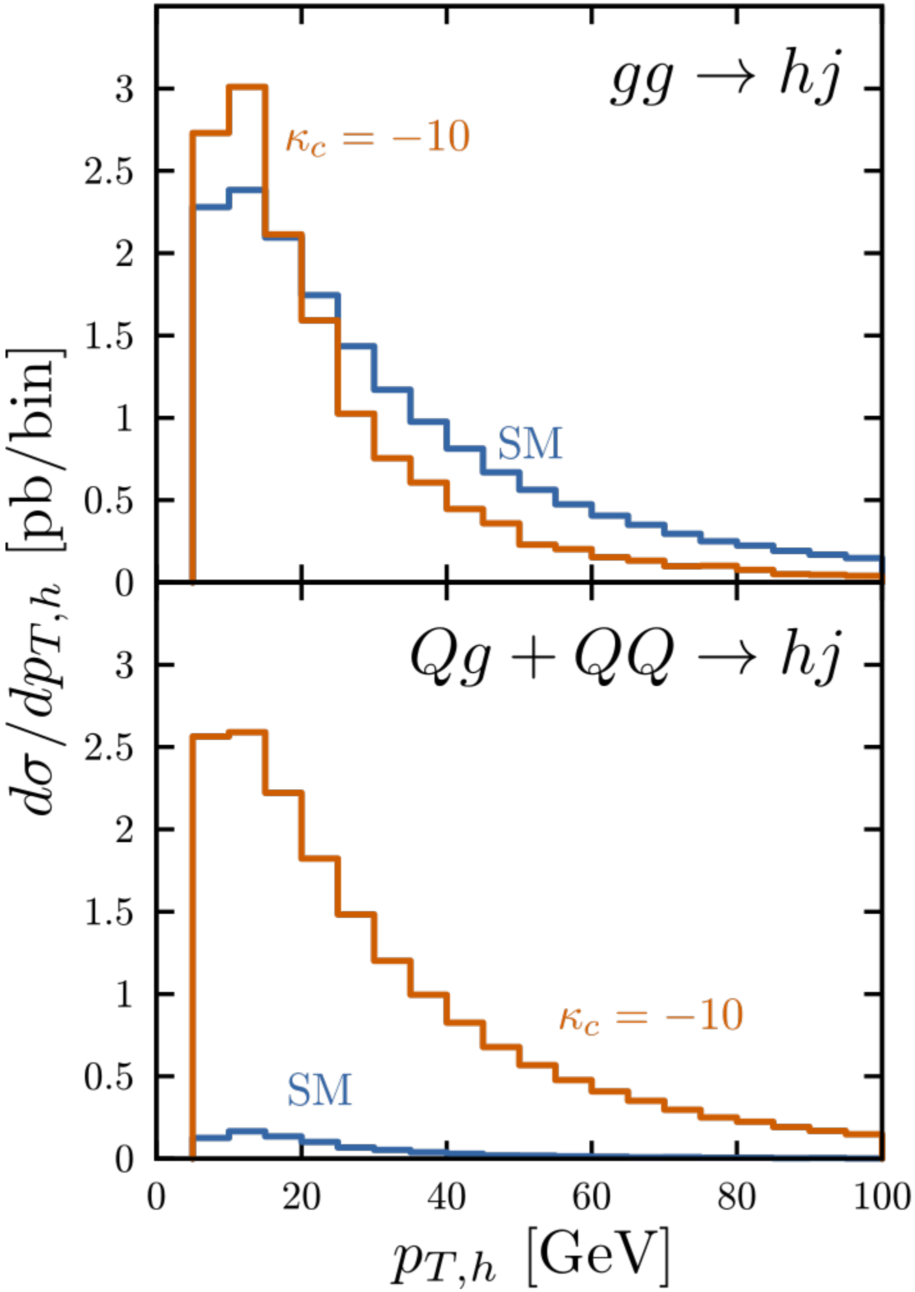
$$\sim \alpha_s^2 \alpha_s y_c^2$$

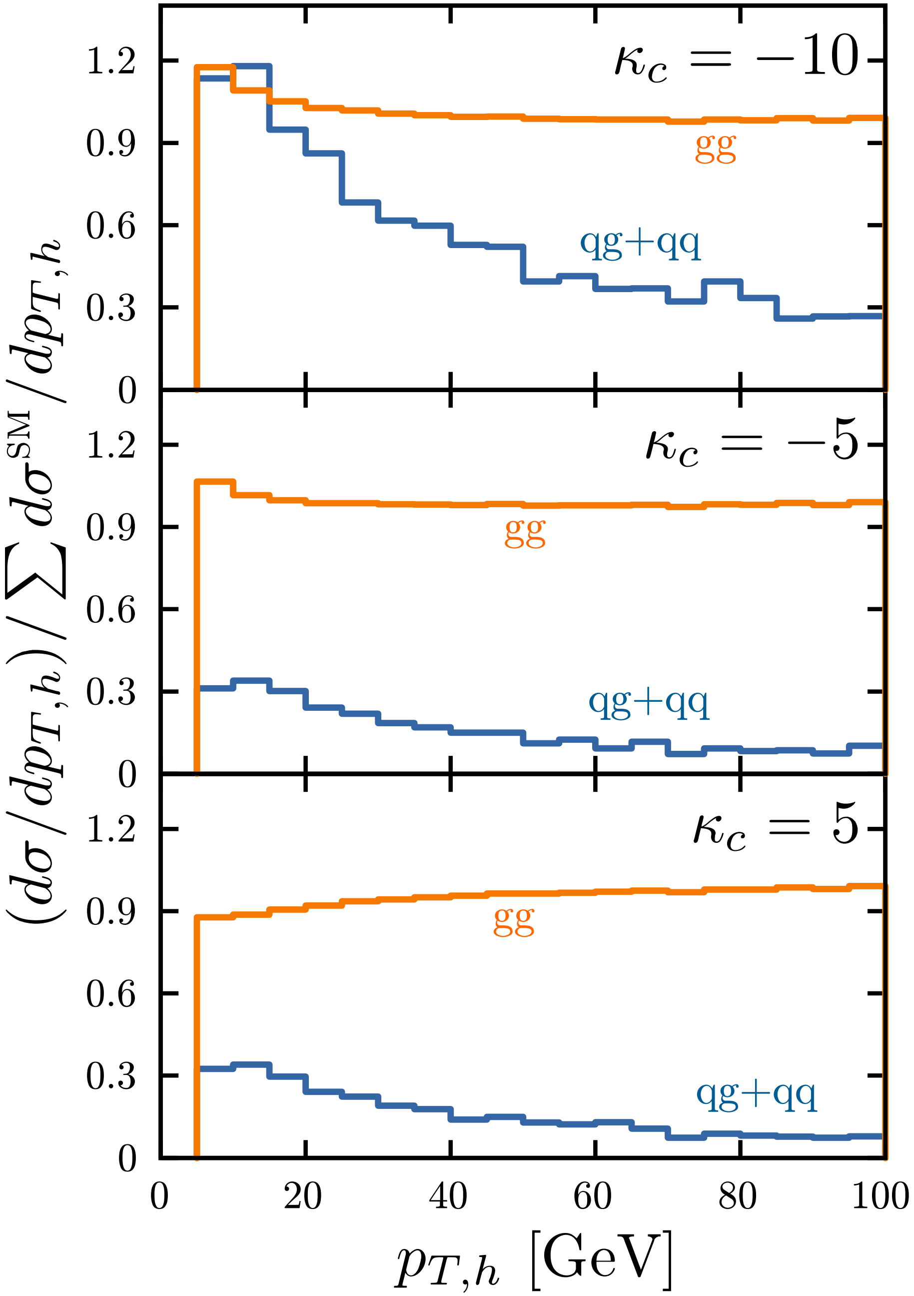
🟩 chirality flip

🟦 extra powers of α_s from charm PDF

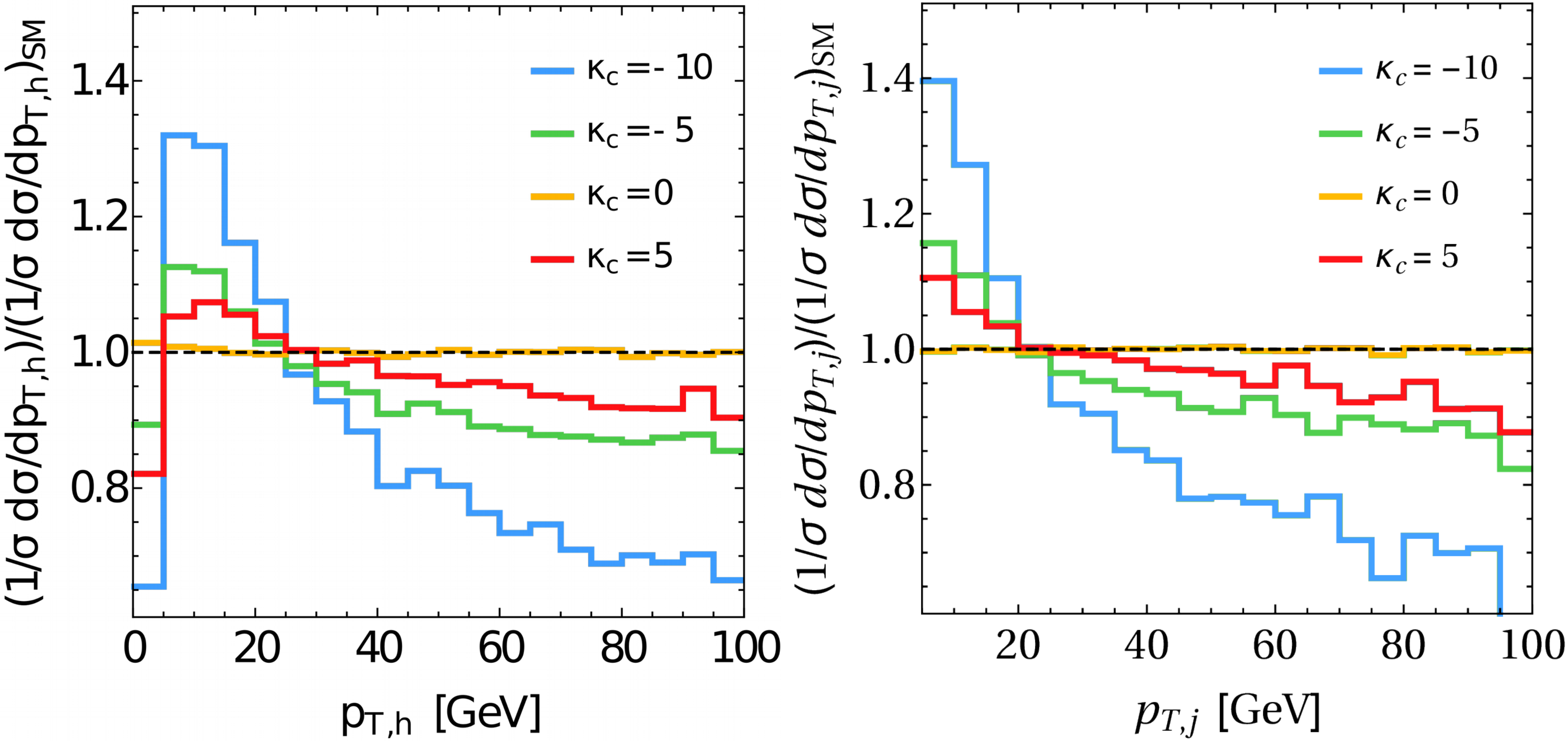
[Sullivan, Nadolsky: hep-ph/0111358]

Contributions to spectrum @ 8 TeV





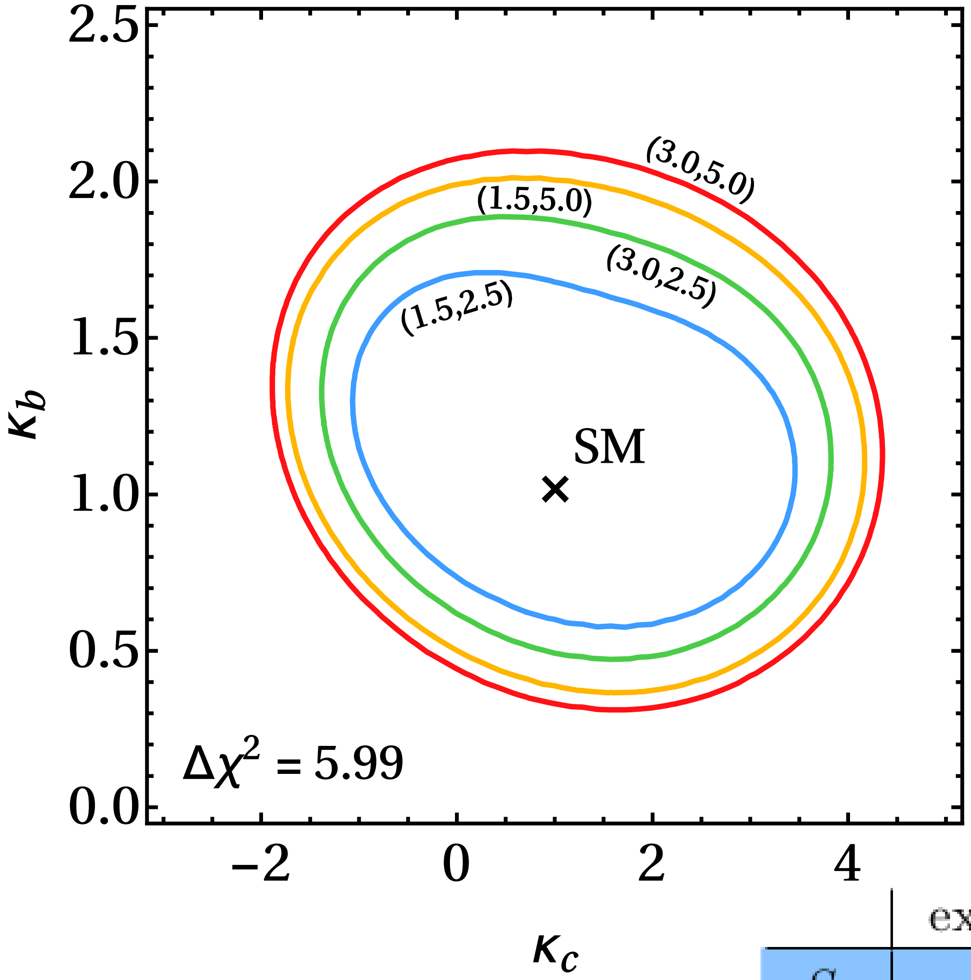
Normalised distributions @ 8 TeV



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

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

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



95% C.I. after profiling over κ_b

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

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

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

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

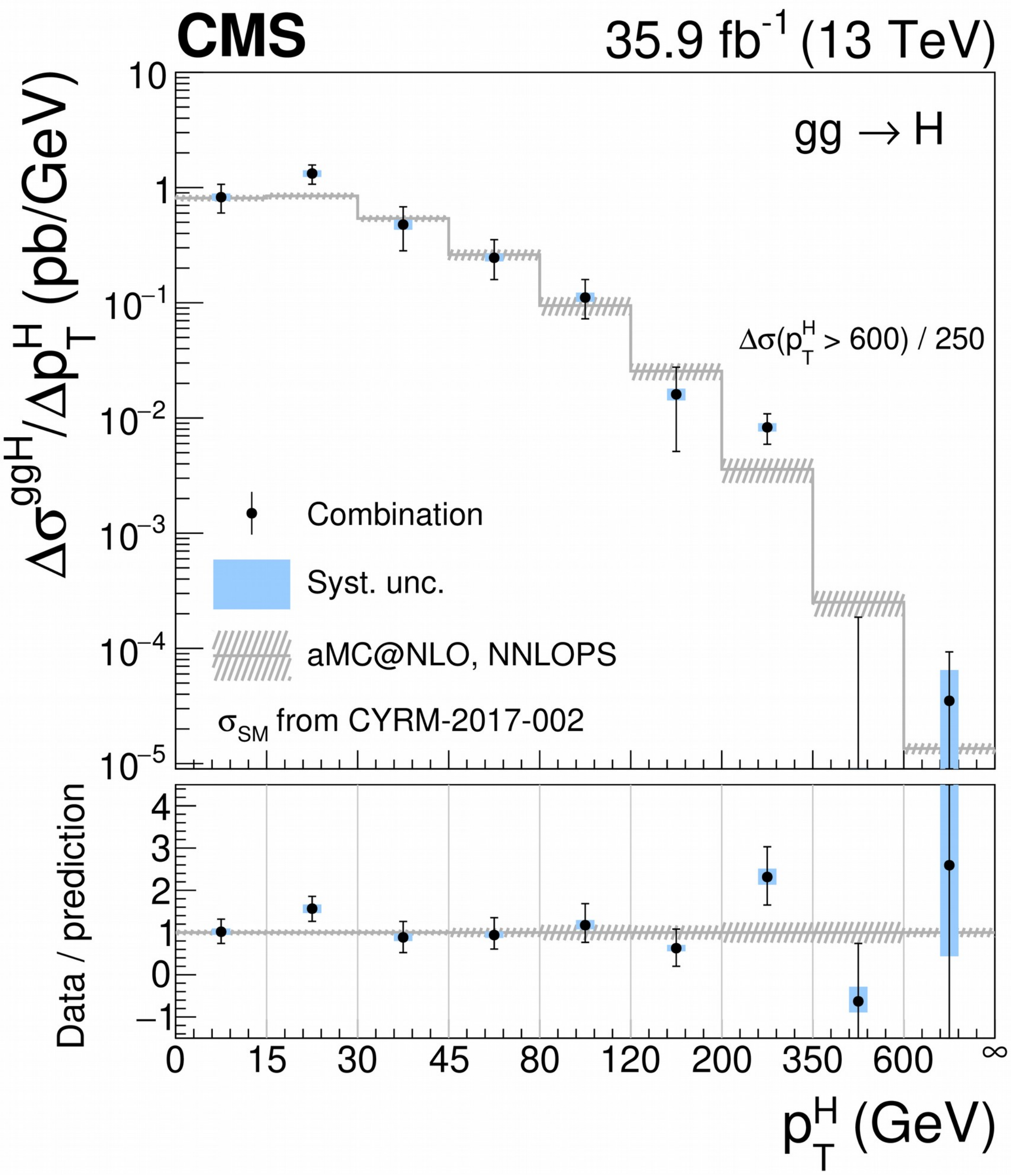
$-13 < \kappa_c < 15$

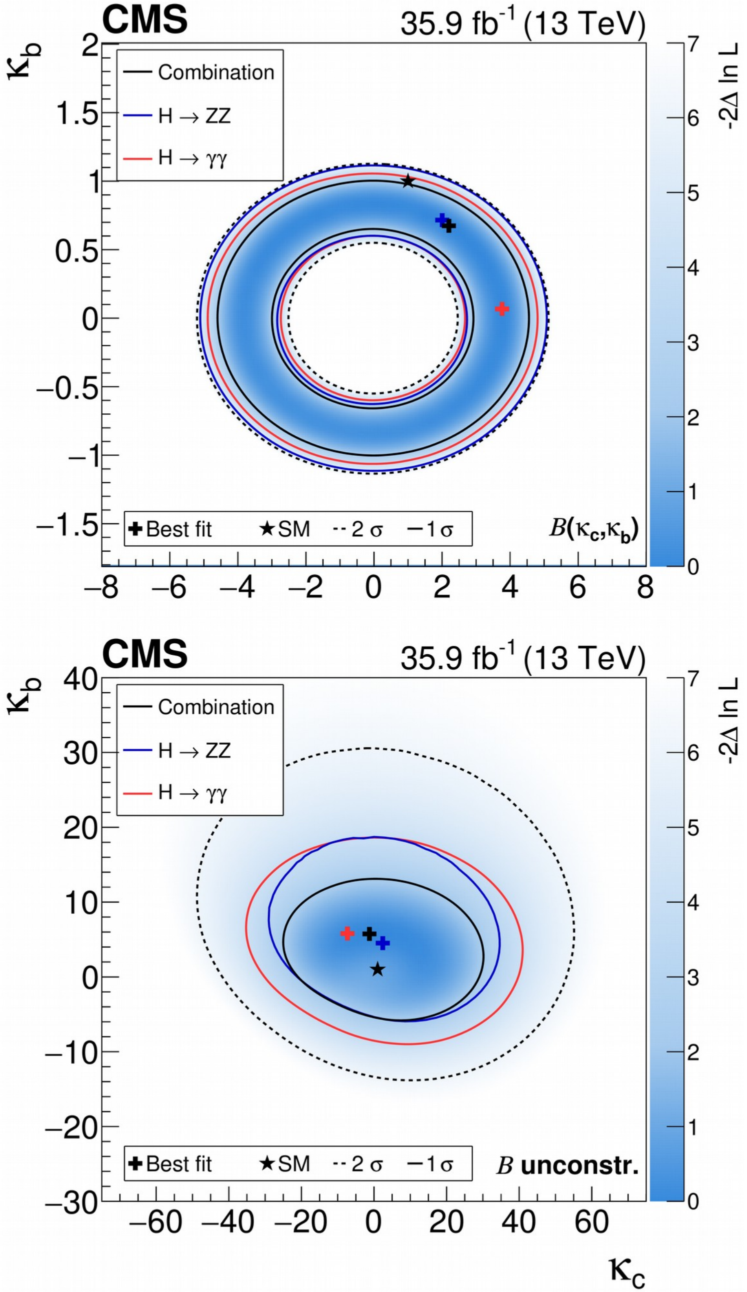
[1812.06504]

	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]

Measured distribution

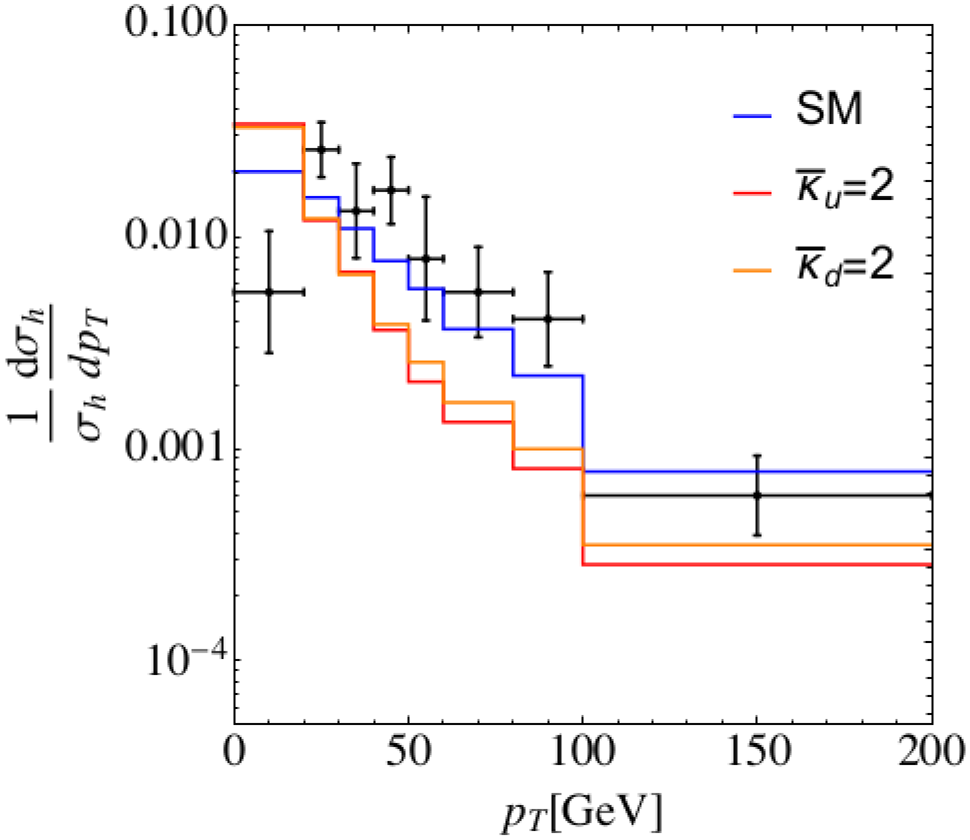
CMS: 1812.06504

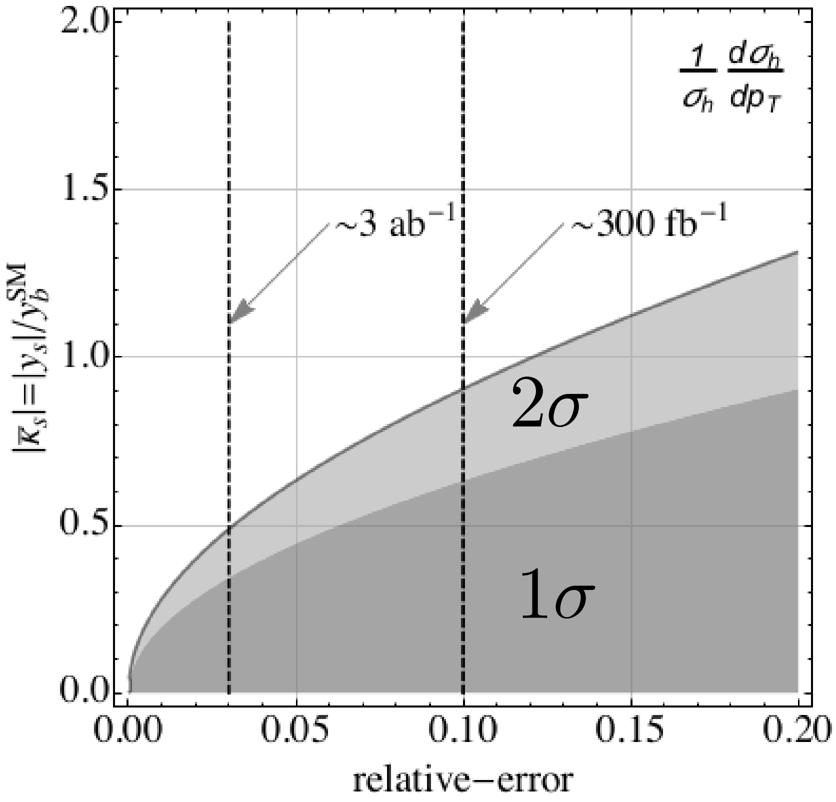




First generation Yukawas

[Soreq, Zhu, & Zupan: 1606.09621]

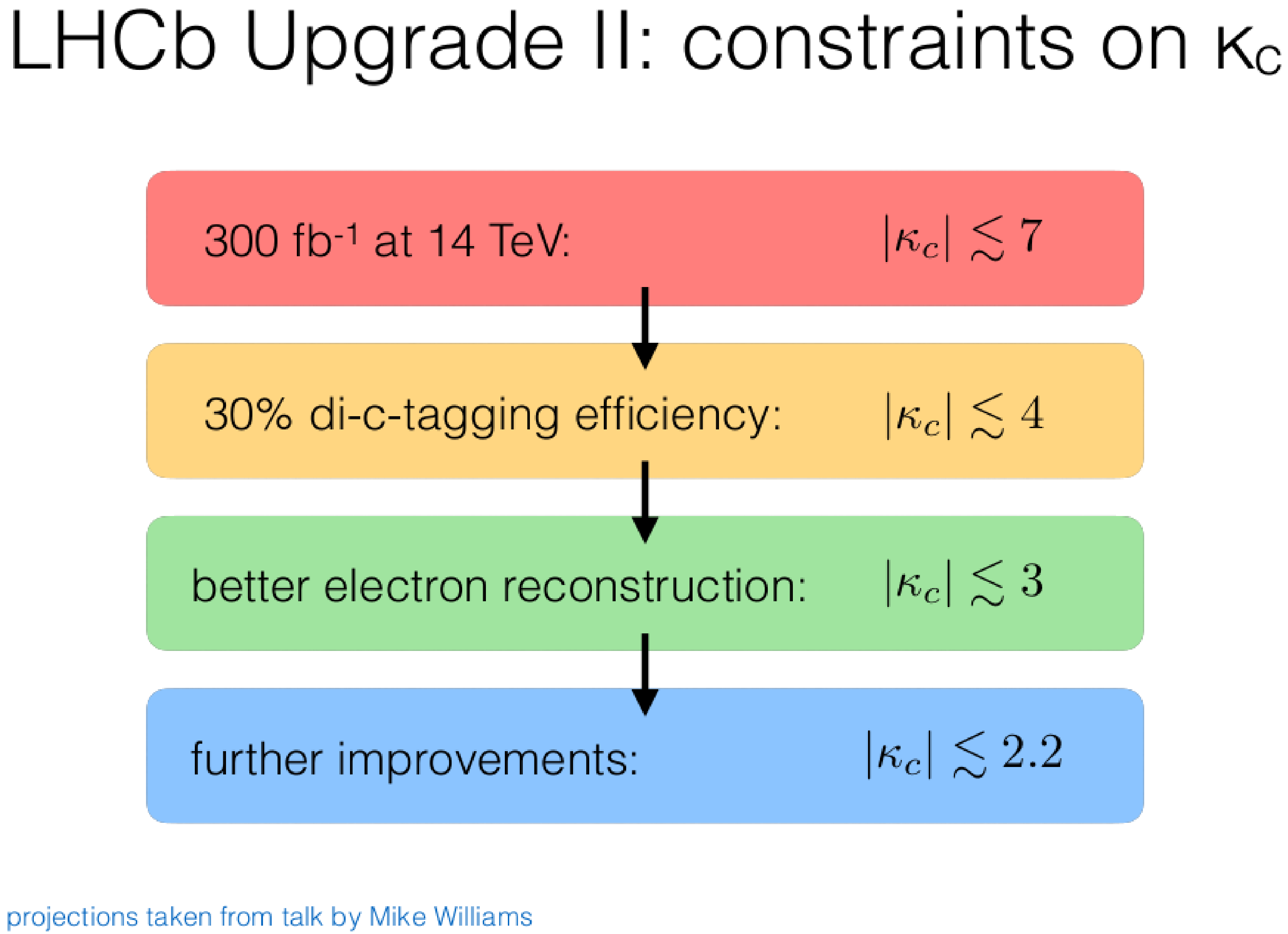




See also Felix Yu [1609.06592] for $W^{\pm}$ charge asymmetry sensitive to $\mathcal{O}(5)$ deviations in $\bar{\kappa}_{u,d,s}$ at 14 TeV w/3 ab^{-1}

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

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

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
- 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!

Parametrization

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

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

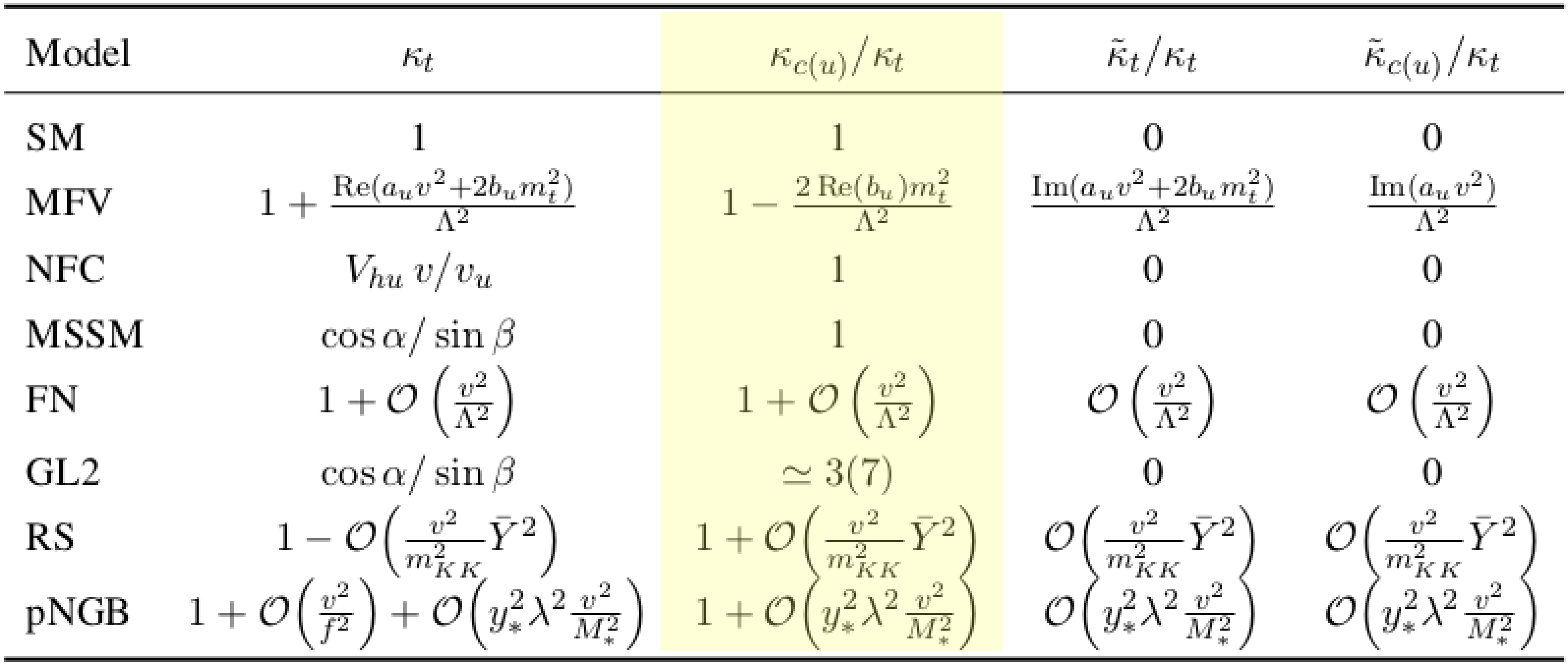
Important def'ns: $\kappa_i = \dfrac{y_i}{y_i^{\text{SM}}}$, $\bar{\kappa}_i = \dfrac{y_i}{y_b^{\text{SM}}}$

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]

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]

$$\mathcal{L}_{\mathrm{yuk}} = c^f_{ij}\left(\frac{H_1^\dagger H_1}{M^2}\right)^{n^f_{ij}} \bar F^i_L\, f^j_R\, H_{1,2}$$

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