Charm Yukawa & New Physics

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18 July 2017
Physics at CLIC

Motivation & plan for the talk

- Direct confirmation of light quark Yukawas (1st and 2nd gen.) is crucial for understanding if EWSB in the SM is minimal.
- New physics extension of SM in general also leads to flavor violation $\rightarrow$ new signatures

1) Focus on the charm Yukawa & associated FV (mainly $t \rightarrow h + c$ and $t \rightarrow \phi/a + c$)

2) What can the LHC do?

3) What can CLIC do?

4) Expected constraints on models of flavor

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: $\boxed{\text{GL2}}$ (modified $\boxed{\text{GL}}$) 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

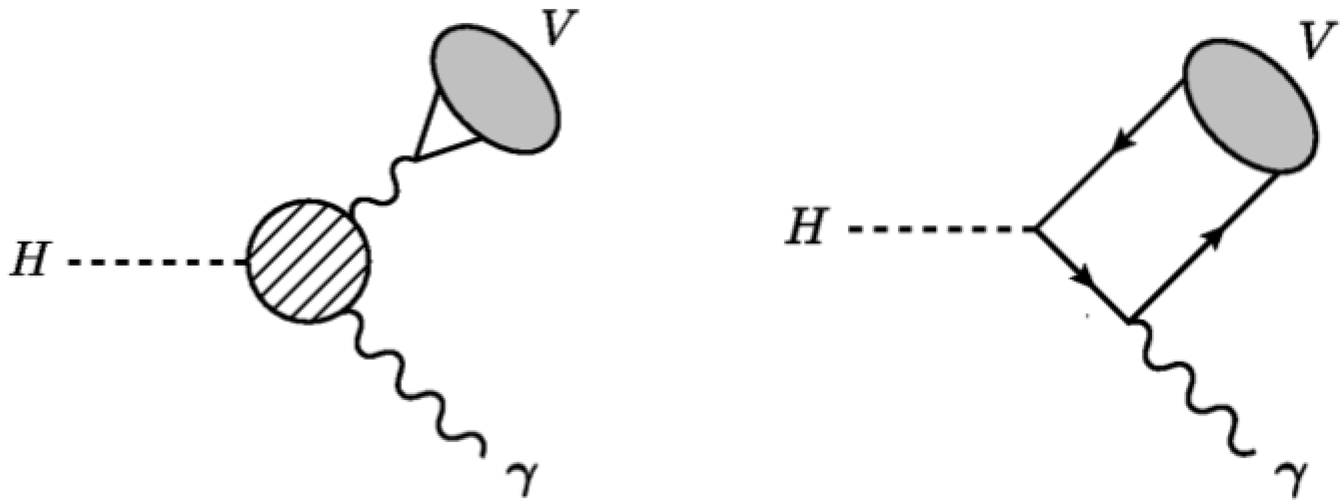
[FB, Brod, Uttayarat, Zupan: 1504.04022] – see also CERN YR4 Chap. IV.6 [1610.07922]
+ references therein for the specific models

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	[PLB188('87)99],[$hep-ph$/0207036] [0904.2387]
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]

1) Charm @ LHC

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



$$\Gamma_{h\to J/\psi\gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10} \ \text{GeV}$$

[Bodwin et al. 13, 14]
[Improved predictions Koenig, Neubert 15]

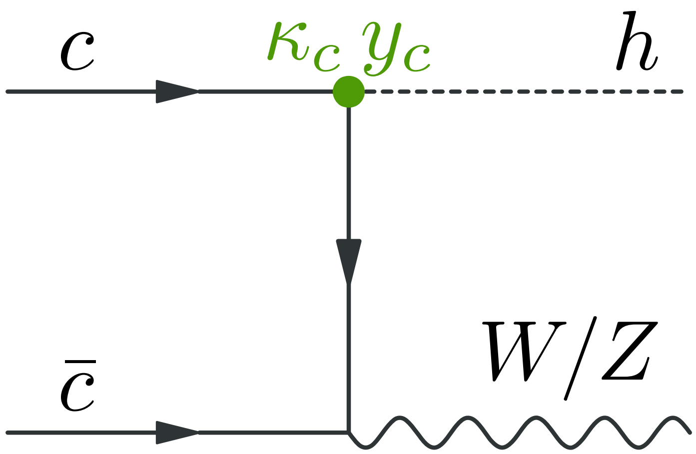
- ATLAS/CMS search: [ATLAS 1501.03276 / CMS 1507.03031]

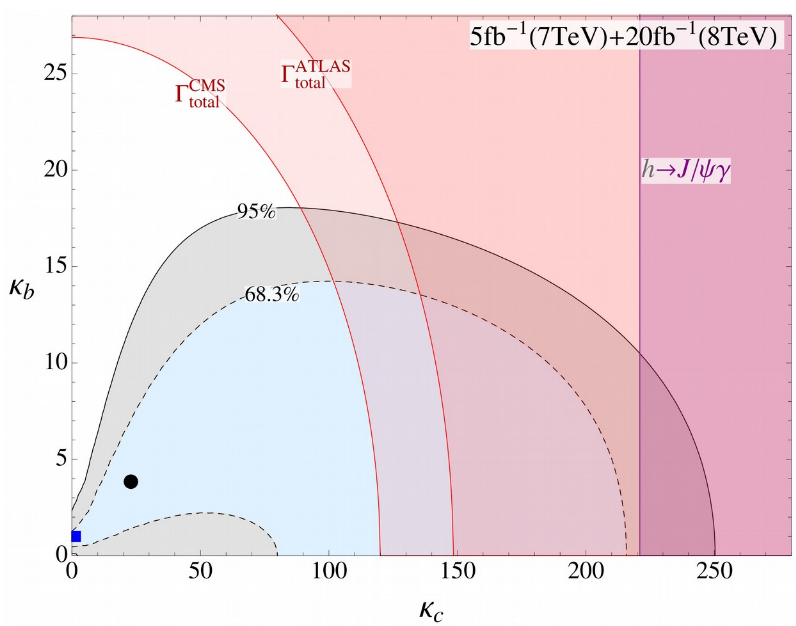
$$\text{BR}(\text{h}\to J/\psi\gamma) < 1.5 \times 10^{-3} \text{ at } 95\% \text{ CL}$$

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

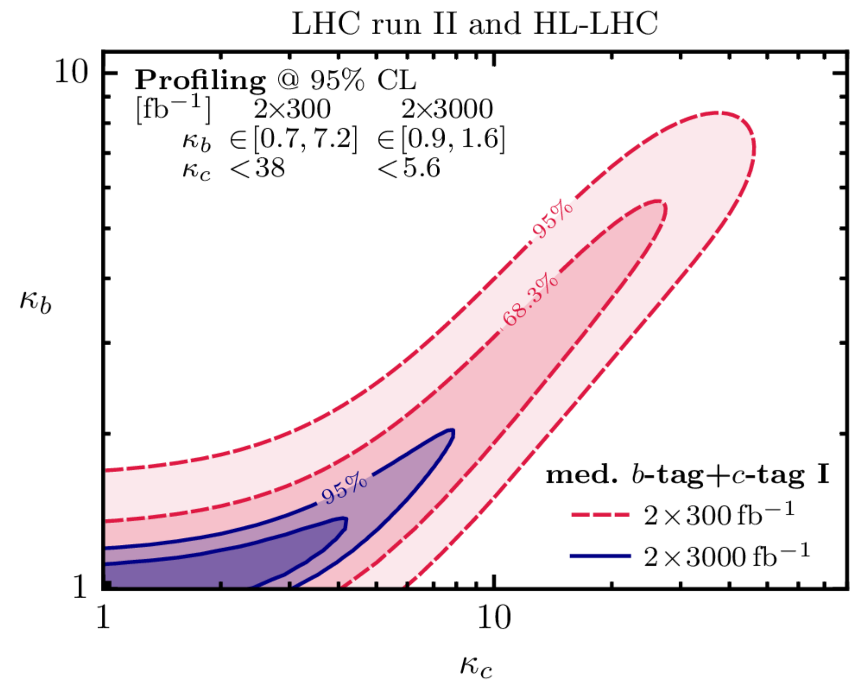
Kagan, Perez, Petriello, Soreq, Stoynev, and Zupan [1406.1722]

VH production + flavour tagging





Perez et al.: 1503.00290



Perez et al.: 1505.06689

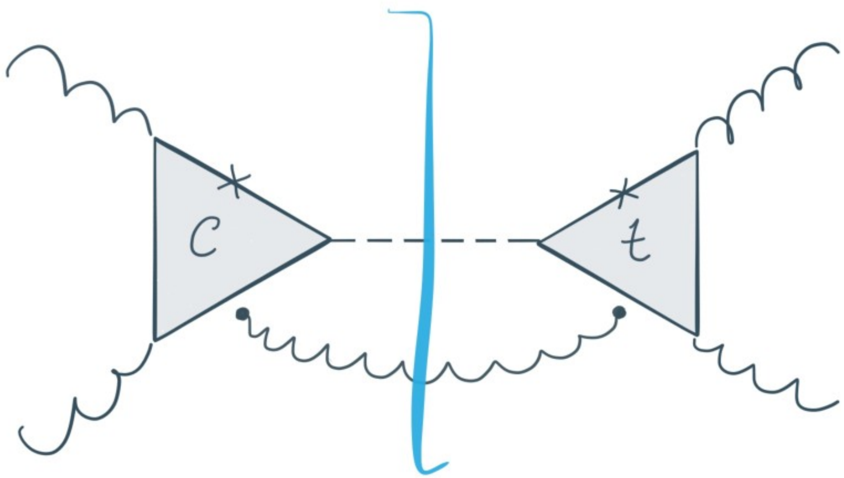
$$\left(\mu_b + \frac{\mathrm{BR}^{\rm SM}_{c\bar{c}}}{\mathrm{BR}^{\rm SM}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\mu_c\right) \Bigg/ \left(1 + \frac{\mathrm{BR}^{\rm SM}_{c\bar{c}}}{\mathrm{BR}^{\rm SM}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)$$

See also: [Brivio, Goertz, Isidori 1507.02916]

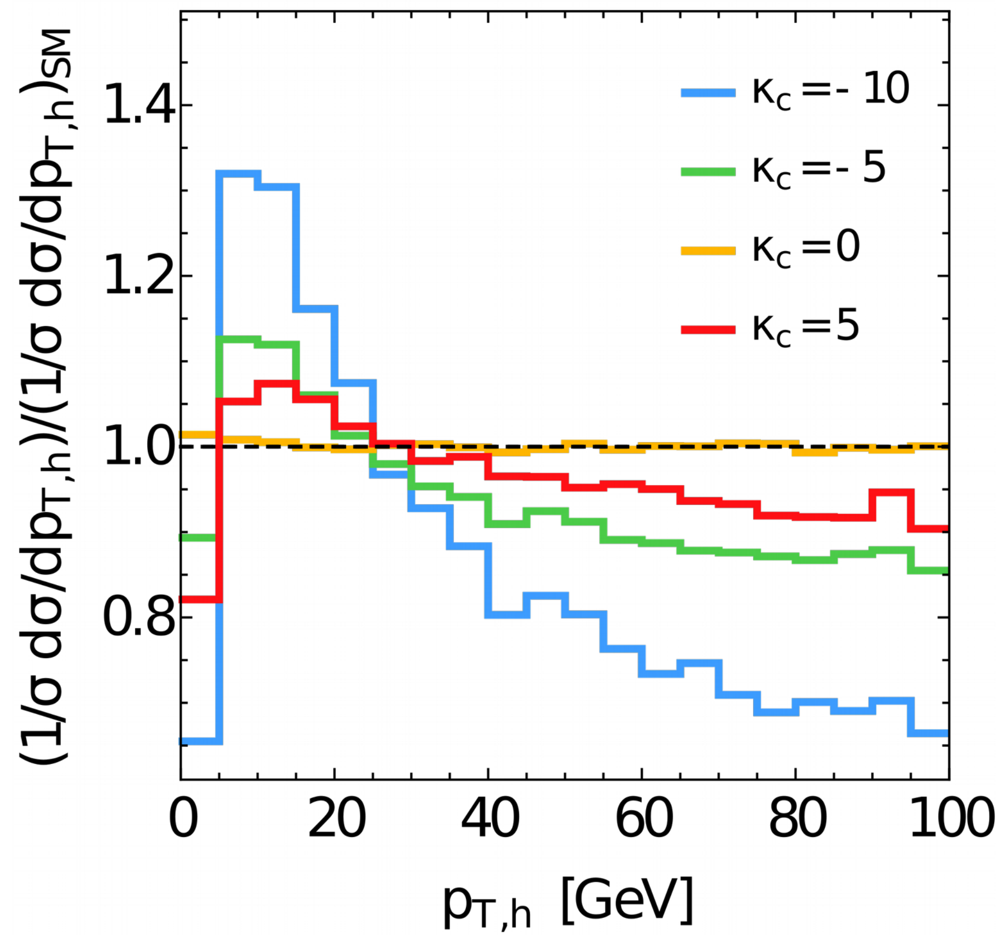
They consider hc final state and find (LHC_{14})

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

Normalized distributions @ 8 TeV



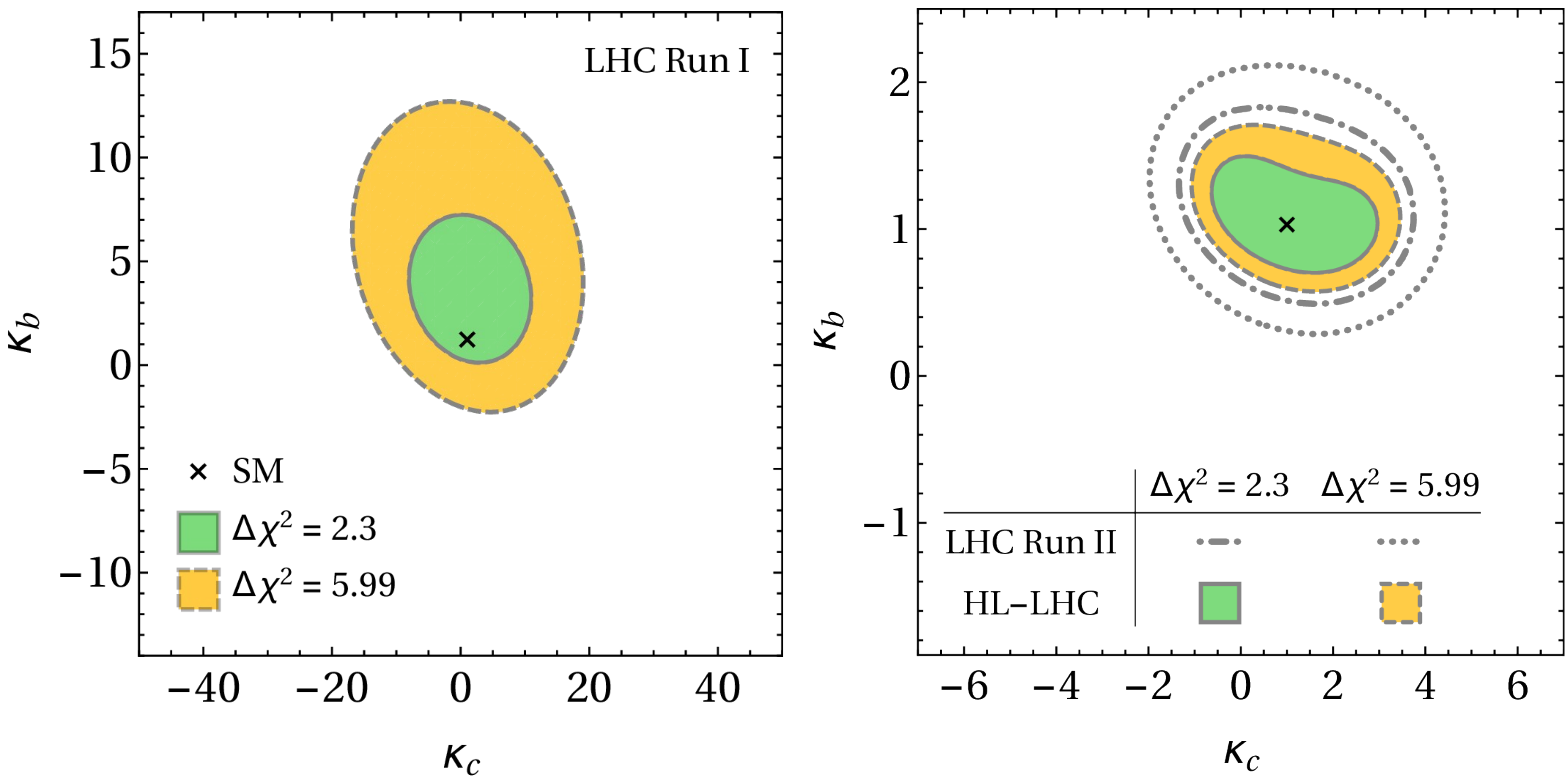
$$\sim \left(\frac{\alpha_s^3}{16\pi^2}\right) \kappa_c \, \frac{m_c^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_c^2}\right)$$



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

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

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



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

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

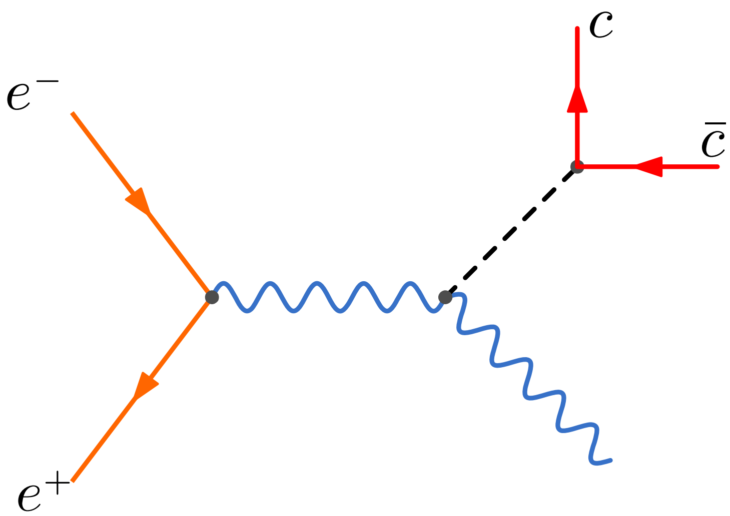
HL-LHC: $[-0.6, 3.0]$

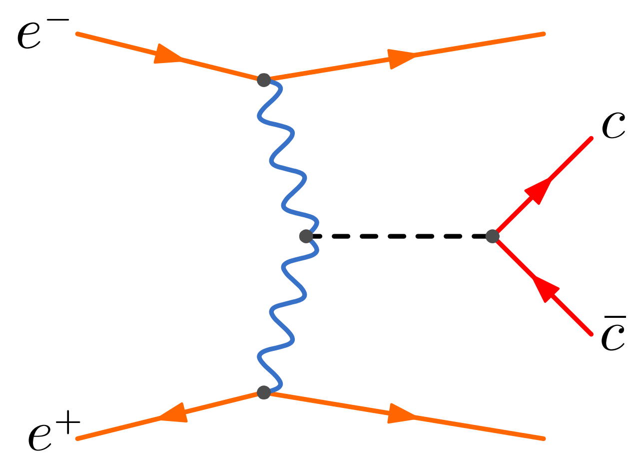
95% C.I. after profiling over κ_b

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

2) Charm @ CLIC

The charm Yukawa at CLIC





Abramowicz et al. [1608.07538]

- Consider two topologies:
  - 4j → minimize χ^2 to find most likely Z and H
  - 2j → clustered jets = H
- Separate BDT classifier for each top.
- Event accepted *iff* one classifier passes threshold

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
κ_{HZZ}	0.6 %	0.4 %	0.3 %
κ_{HWW}	1.1 %	0.2 %	0.1 %
κ_{Hbb}	1.8 %	0.4 %	0.2 %
κ_{Hcc}	5.8 %	2.1 %	1.7 %
$\kappa_{H\tau\tau}$	3.9 %	1.5 %	1.1 %
$\kappa_{H\mu\mu}$	–	14.1 %	7.8 %
κ_{Htt}	–	4.1 %	4.1 %
κ_{Hgg}	3.0 %	1.5 %	1.1 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	3.1 %
$\kappa_{HZ\gamma}$	–	15.6 %	9.1 %
$\Gamma_{H,\mathrm{md,derived}}$	1.4 %	0.4 %	0.3 %

Flavor violation

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

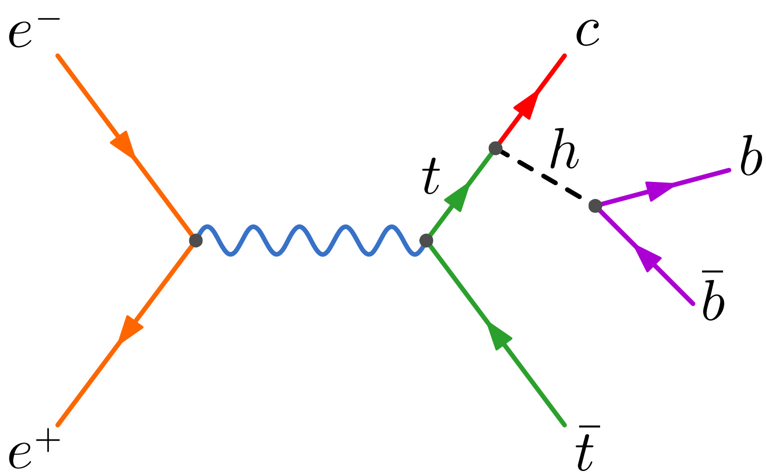
- Arises due to misalignment between the mass and Yukawa matrices – e.g., in D6 extension:

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

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

- In models of flavor discussed earlier, they are typically suppressed by y_q and "CKM"

Rare top decays: t→hc

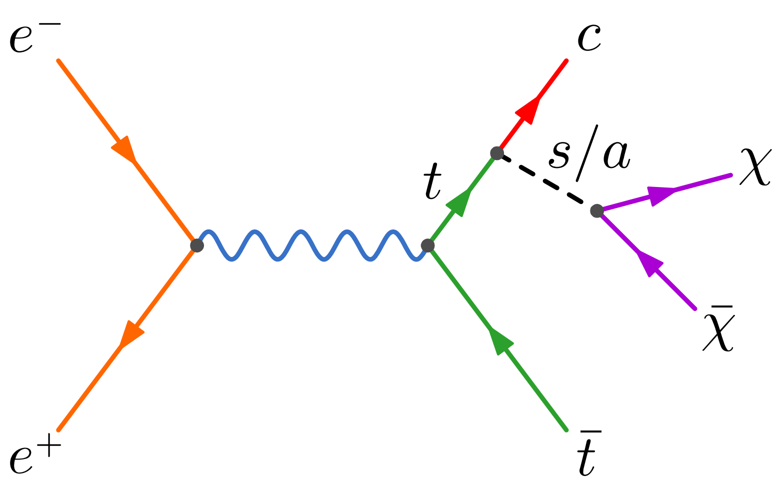


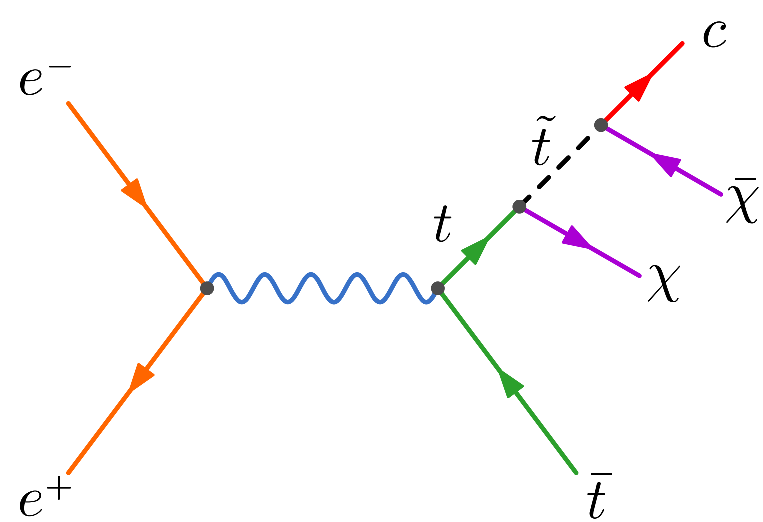
- Rare decay in SM → smoking gun for NP
- CLIC study @ 380 GeV C.M. energy [Zarnecki: 1703.05007]

- Full detector simulation for H→ bb final state
- Limit: $\mathcal{B}(t \to hc) \times \mathcal{B}(h \to b\bar{b}) < 2.6 \cdot 10^{-4}$ with $\sqrt{s} = 380$ GeV, and 500 fb^{-1}
- This translates to $\kappa_{ct,tc} < 10^{-2}$

Improvement on this bound can cut into flavor model parameter space!

Rare top decays: t→c + MET

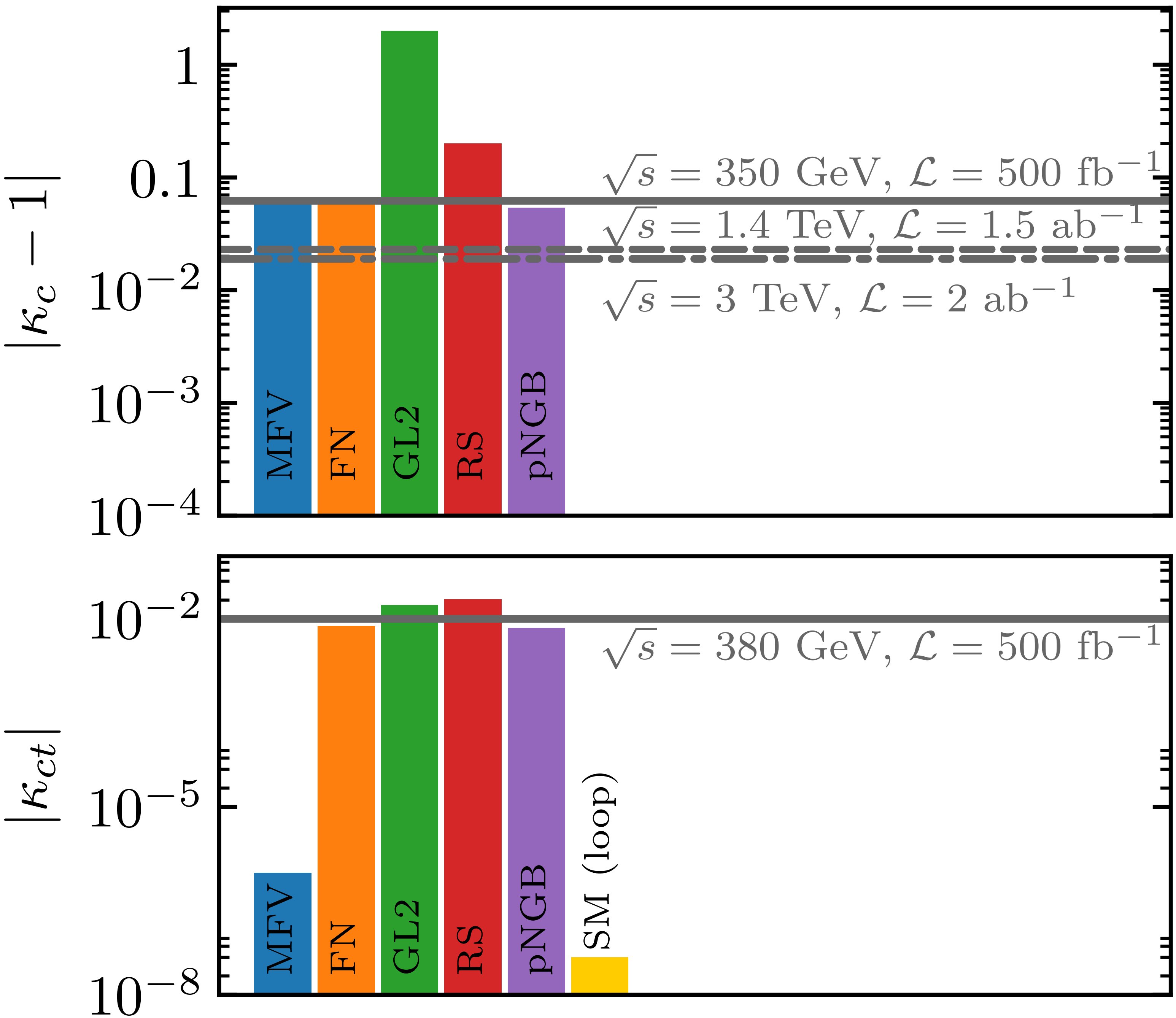




- Arises, e.g., in models of DM with a scalar/pseudoscalar with flavor structure [Isidori, Kamenik: 1103.0016], [Zupan, Kamenik: 1107.0623], [Andrea, Fuks, Maltoni: 1106.6199], [Blanke, Kast: 1702.08457] + many others
- Unique signature with charm + MET reconstructing m_t but presents other challenges (e.g., leptonic W decays?)
- Branching ratios vary by model, e.g.:
  Flavon: $\mathcal{B}(t \to ca) \sim 10^{-3}$ for $m_a = 100$ GeV [Bauer, Schell, Plehn: 1603.06950]

see also [Alvarado, Elahi, Raj: 1706.03081]

CLIC ultimate reach



Summary

- CLIC is crucial for measuring the SM charm Yukawa
- It will also significantly constrain the parameter space of NP models of flavor
- Detailed studies needed for maximizing the reach
- Many more channels to look in – e.g., $t \to Zc$, $t \to \gamma c$, $t \to Vc$, …

Thank you!