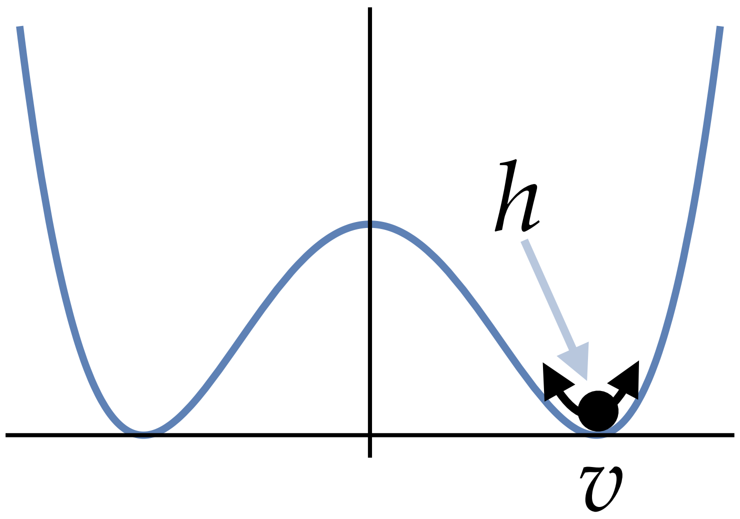
Higgs and flavor

Yotam Soreq

FPCP, 11 June, 2020

the Higgs in the standard model



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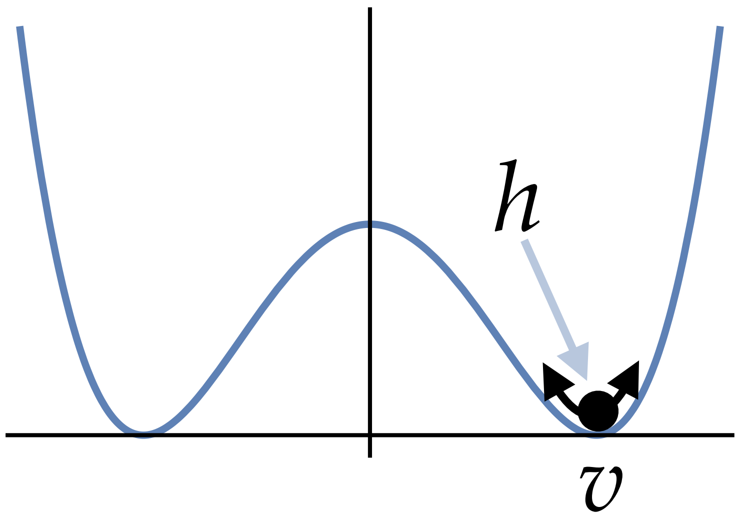

electroweak symmetry breaking

$m_{Z,W} \neq 0\,, \quad V_L V_L \to V_L V_L$

(unitarize)

tests

$h \to WW^*, ZZ^*$ (direct)

EWPM (indirect)

the Higgs is the main source of EWSB

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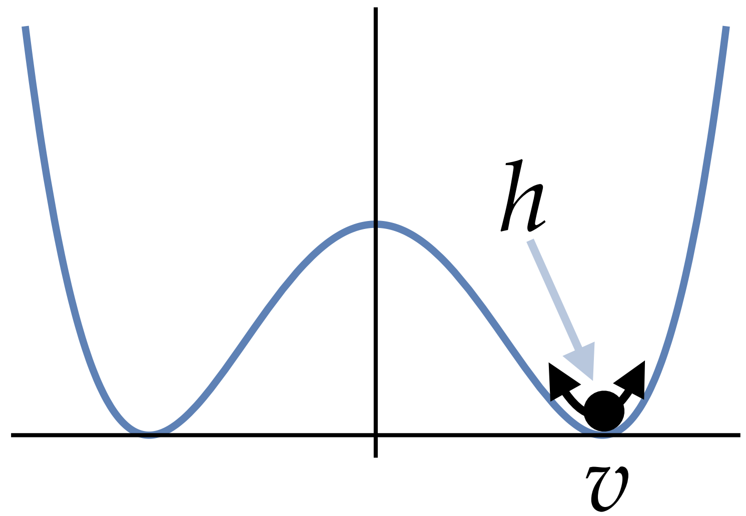

charged fermion masses

$m_{Z,W} \neq 0\,, \quad V_L V_L \to V_L V_L$

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$m_f \neq 0\,, \quad f\bar{f} \to V_L V_L$

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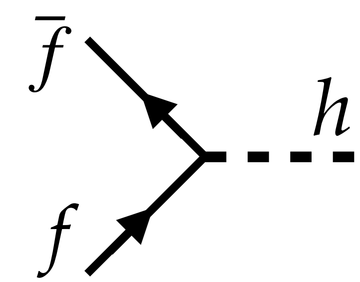

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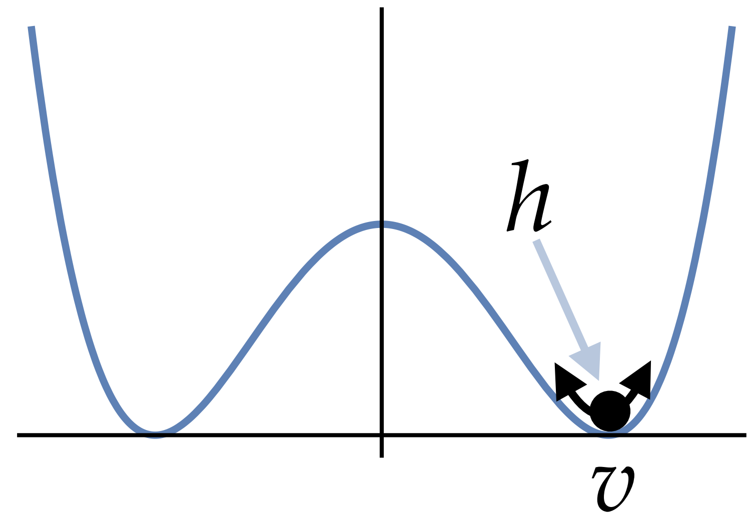

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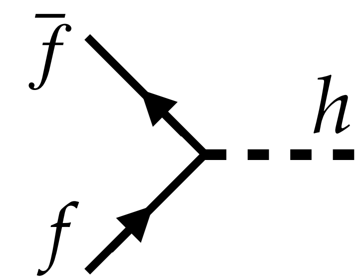

the Higgs is the main source of EWSB

$$y_f = \sqrt{2}\frac{m_f}{v}$$

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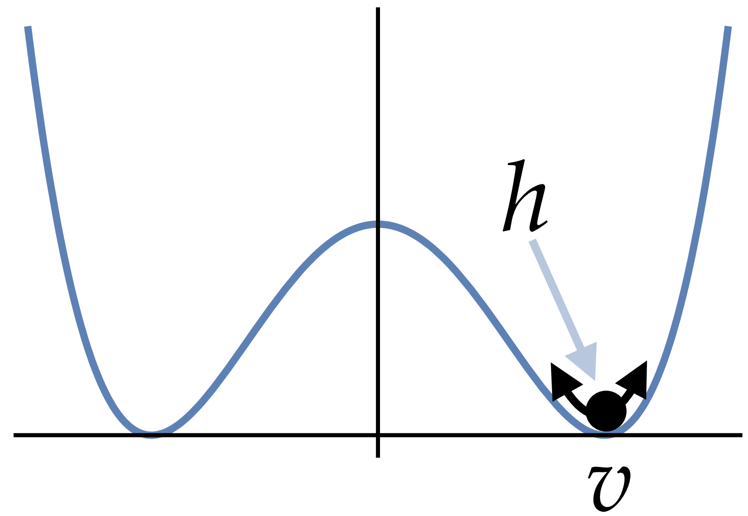

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unitarize)

tes

$h \to WW^*$

h

EWPM (i

testing the SM hypothesis,

what is the source for fermion masses?

implications to new physics

the Higgs is the main source of EWSB

$y_f = \sqrt{2}\frac{m_f}{v}$

the Higgs in the SM and EFT

$$\mathscr{L}_Y^{\rm SM} = Y^u_{ij}\tilde{H}\overline{Q^i_L}U^j_R + Y^d_{ij}H\overline{Q^i_L}D^j_R + Y^\ell_{ij}H\overline{L^i_L}E^j_R$$

the Higgs in the SM and EFT

$$\mathscr{L}_Y^{\rm SM} = Y_{ij}^u \tilde{H}\overline{Q_L^i} U_R^j + Y_{ij}^d H\overline{Q_L^i} D_R^j + Y_{ij}^\ell H\overline{L_L^i} E_R^j$$

$$\Rightarrow \quad y_f^{\rm SM} = \sqrt{2}\frac{m_f}{v}$$

- non universal
- diagonal
- CP conserving

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new physics example: EFT

$$\mathscr{L}_Y^{\rm EFT} = \frac{c_{ij}^u}{\Lambda^2}\tilde{H}\overline{Q_L^i} U_R^j (H^\dagger H) + \frac{c_{ij}^d}{\Lambda^2} H\overline{Q_L^i} D_R^j (H^\dagger H) + \frac{c_{ij}^\ell}{\Lambda^2} H\overline{L_L^i} E_R^j (H^\dagger H)$$

the Higgs in the SM and EFT

$$\mathcal{L}_Y^{\rm SM} = Y_{ij}^u \tilde{H} \overline{Q_L^i} U_R^j + Y_{ij}^d H \overline{Q_L^i} D_R^j + Y_{ij}^\ell H \overline{L_L^i} E_R^j$$

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$$\Rightarrow \quad \kappa_f = 1 + \frac{v^2}{\Lambda^2}\frac{c_f}{y_f^{\rm SM}}$$

$$\Lambda_f \equiv \frac{\Lambda}{\sqrt{c_f}} = 4\,{\rm TeV}\sqrt{\frac{y_c^{\rm SM}/y_f^{\rm SM}}{\left|\kappa_f - 1\right|}}$$

$$\kappa_f \equiv \frac{y_f}{y_f^{\rm SM}}$$

assumes flavour alignment

the Yukawa couplings in different BSM scenarios

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	$1+\frac{\Re(a_u v^2+2b_u m_t^2)}{\Lambda^2}$	$1-\frac{2\Re(b_u)m_t^2}{\Lambda^2}$	$\frac{\Im(a_u v^2+2b_u m_t^2)}{\Lambda^2}$	$\frac{\Im(a_u v^2)}{\Lambda^2}$
NFC	$V_{hu}\,v/v_u$	1	0	0
F2HDM	$\cos\alpha/\sin\beta$	$-\tan\alpha/\tan\beta$	$\mathcal{O}\left(\frac{m_c}{m_t}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_{c(u)}^2}{m_t^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
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	$1+\mathcal{O}\left(\frac{v^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$

Model	κ_b	$\kappa_{s(d)}/\kappa_b$	$\tilde{\kappa}_b/\kappa_b$	$\tilde{\kappa}_{s(d)}/\kappa_b$
SM	1	1	0	0
MFV	$1+\frac{\Re(a_d v^2+2c_d m_t^2)}{\Lambda^2}$	$1-\frac{2\Re(c_d)m_t^2}{\Lambda^2}$	$\frac{\Im(a_d v^2+2c_d m_t^2)}{\Lambda^2}$	$\frac{\Im(a_d v^2+2c_d\lvert V_{ts(td)}\rvert^2 m_t^2)}{\Lambda^2}$
NFC	$V_{hd}\,v/v_d$	1	0	0
F2HDM	$\cos\alpha/\sin\beta$	$-\tan\alpha/\tan\beta$	$\mathcal{O}\left(\frac{m_s}{m_b}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_{s(d)}^2}{m_b^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
MSSM	$-\sin\alpha/\cos\beta$	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	$-\sin\alpha/\cos\beta$	$\simeq 3(5)$	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	$1+\mathcal{O}\left(\frac{v^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$

CERN yellow report, 1902.00134

the Yukawa couplings in different BSM scenarios

Model	κ_τ	$\kappa_{\mu(e)}/\kappa_\tau$	$\tilde{\kappa}_\tau/\kappa_\tau$	$\tilde{\kappa}_{\mu(e)}/\kappa_\tau$
SM	1	1	0	0
MFV	$1+\frac{\Re(a_\ell)v^2}{\Lambda^2}$	$1-\frac{2\Re(b_\ell)m_\tau^2}{\Lambda^2}$	$\frac{\Im(a_\ell)v^2}{\Lambda^2}$	$\frac{\Im(a_\ell)v^2}{\Lambda^2}$
NFC	$V_{h\ell}\, v/v_\ell$	1	0	0
F2HDM	$\cos\alpha/\sin\beta$	$-\tan\alpha/\tan\beta$	$\mathcal{O}\left(\frac{m_\mu}{m_\tau}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m^2_{\mu(e)}}{m^2_\tau}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
MSSM	$-\sin\alpha/\cos\beta$	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	$-\sin\alpha/\cos\beta$	$\simeq 3(5)$	0	0
RS	$1+\mathcal{O}\left(\bar{Y}^2\frac{v^2}{m^2_{KK}}\right)$	$1+\mathcal{O}\left(\bar{Y}^2\frac{v^2}{m^2_{KK}}\right)$	$\mathcal{O}\left(\bar{Y}^2\frac{v^2}{m^2_{KK}}\right)$	$\mathcal{O}\left(\bar{Y}^2\frac{v^2}{m^2_{KK}}\right)$

CERN yellow report, 1902.00134

probing the Higgs Yukawa couplings

lepton sector

$$Y^{\ell} = \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix}$$

lepton sector

$$Y^\ell = \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix}$$

$$pp \to h \to \ell^+ \ell^-$$

$$\mu_{ee} < 3.7 \times 10^5$$
$$\mu_{\mu\mu} = 0.5 \pm 0.7$$
$$\mu_{\tau\tau} = 1.2 \pm 0.3$$

ATLAS, CMS
CERN yellow report, 1812.07638

$$\mu_f \equiv \frac{\sigma_{pp\to h} \mathrm{BR}_{h\to f}}{\sigma^{\mathrm{SM}}_{pp\to h} \mathrm{BR}^{\mathrm{SM}}_{h\to f}}$$

lepton sector

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- non universal coupling: $y_\tau > y_\mu, y_e$
- probe scale of

$$\Lambda_\tau \gtrsim 4\,\mathrm{TeV}\ \Lambda_\mu \gtrsim 18\,\mathrm{TeV}, \Lambda_e \gtrsim 6\,\mathrm{TeV}$$

$$\mu_f \equiv \frac{\sigma_{pp\to h}\,\mathrm{BR}_{h\to f}}{\sigma^{\mathrm{SM}}_{pp\to h}\,\mathrm{BR}^{\mathrm{SM}}_{h\to f}}$$

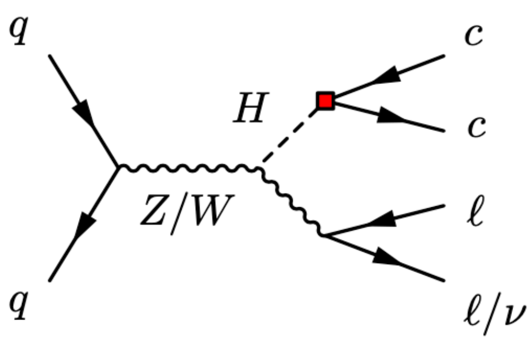
quark sector

direct

indirect

quark sector

inclusive: flavor tagging



ATLAS, CMS, LHCb
Delaunay et al 1310.7029,
Perez et al 1505.06689, 1503.00290
Brivio et al 1507.02916

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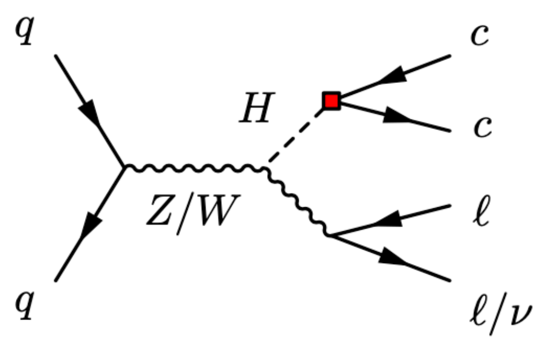

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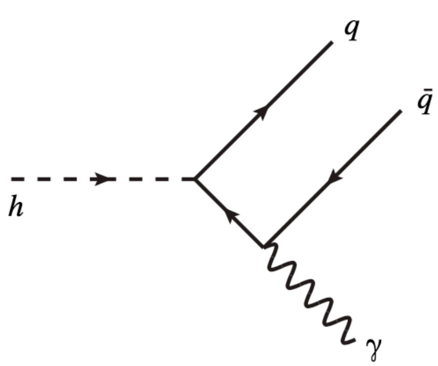
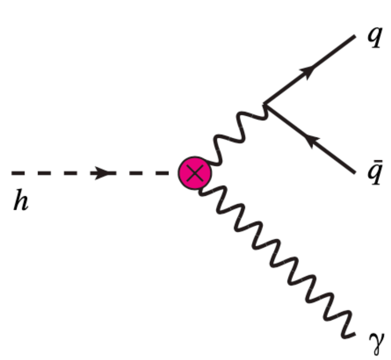
exclusive: $h \to V\gamma$





ATLAS, CMS
Bodwin et al 1306.5770 Kagan et al 1406.1722
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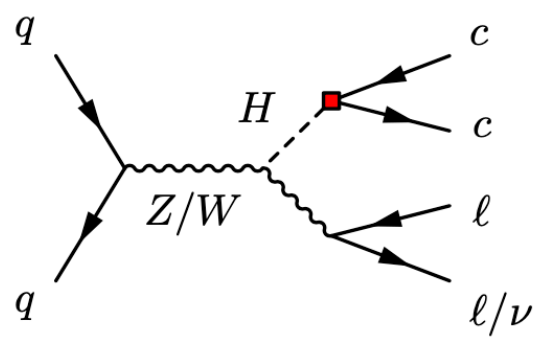

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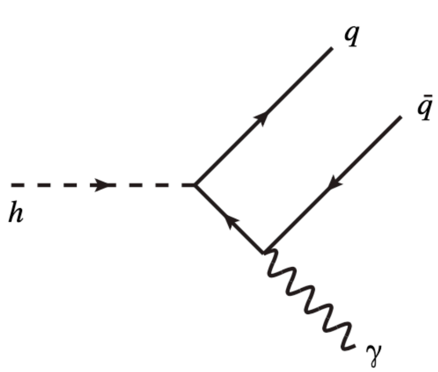

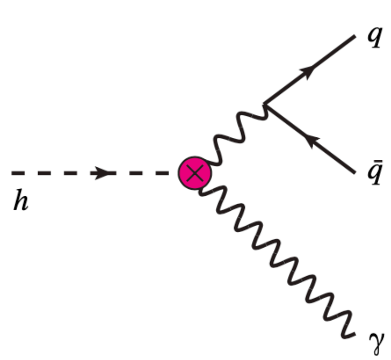

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kinematics

Higgs p_T spectrum

Wh asymmetry

Bishara et al1606.09253, YS et al 1606.09621
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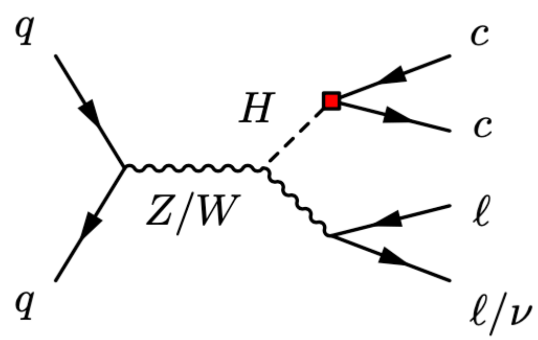

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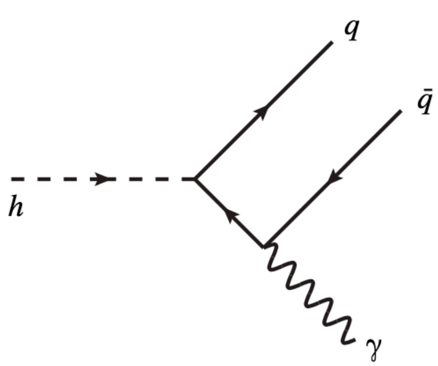

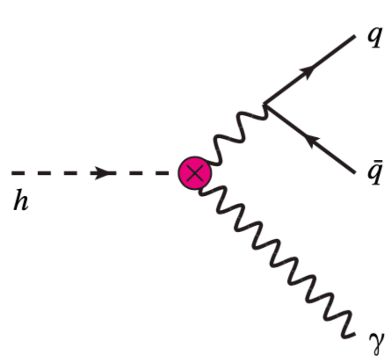

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total width

$\Gamma_{h\to q\bar{q}} < \Gamma_h$

$\gamma\gamma + ZZ$ line-shape

off-shell h

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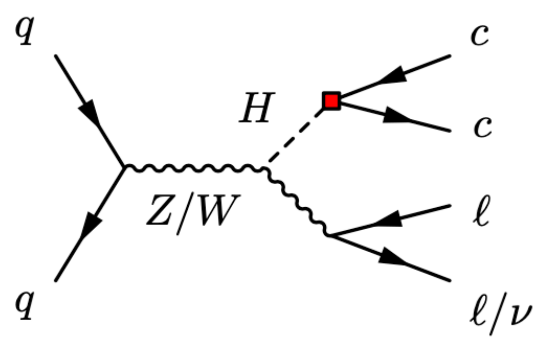
indirect

quark sector

inclusive: flavor tagging



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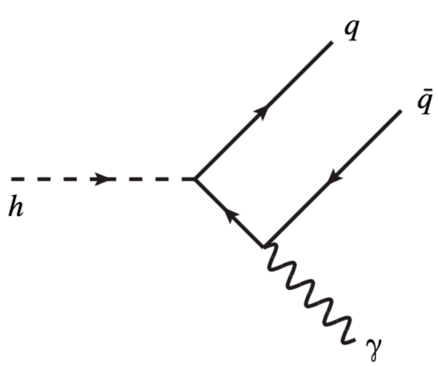

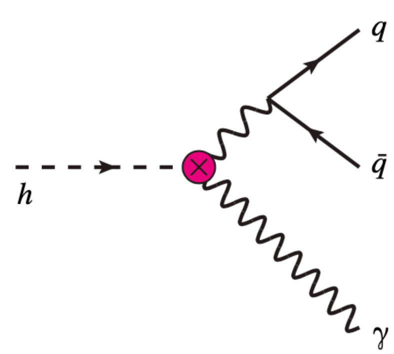

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ATLAS, CMS, Perez et al 1503.00290

global fit

$\kappa_u < 3.4 \times 10^3 \quad \kappa_c < 6.2$

$\kappa_d < 1.7 \times 10^3 \quad \kappa_s < 42$

Delaunay et al 1310.7029,
Perez et al 1503.00290

indirect

quark sector: inclusive rates

$$Y^U = \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \qquad Y^d = \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix}$$

quark sector: inclusive rates

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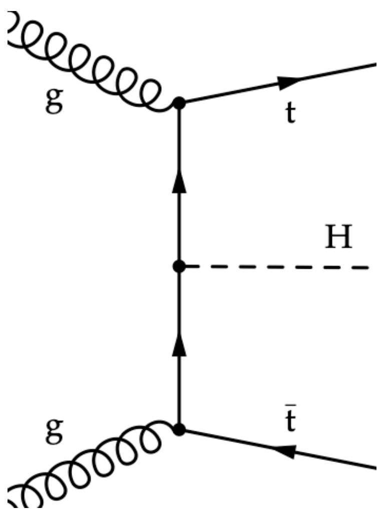
$pp \to t\bar{t}h$



$\mu_{t\bar{t}h} = 1.2 \pm 0.3$ ATLAS, CMS

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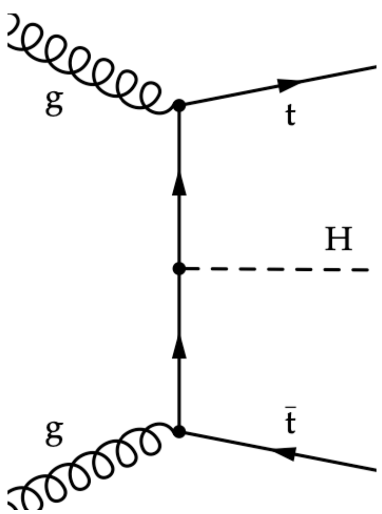

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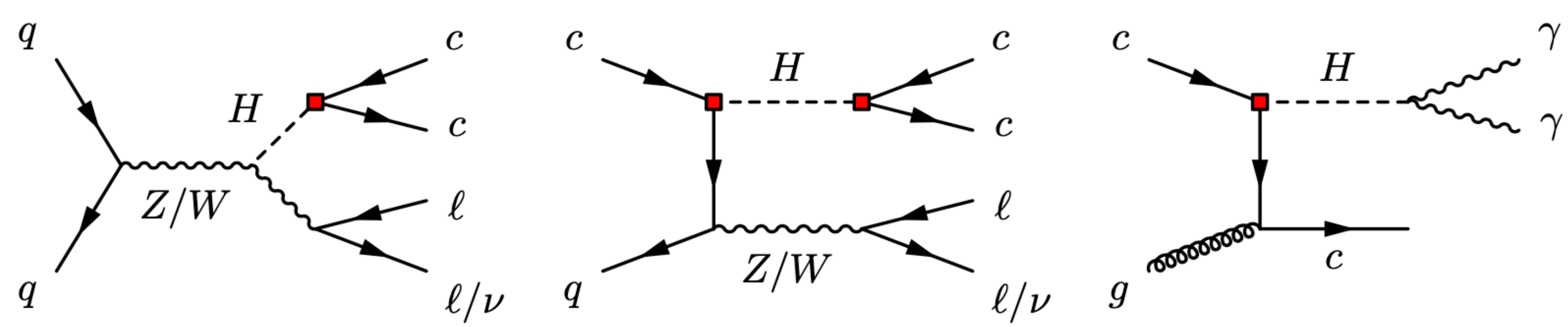
$pp \to Vh, h \to b\bar{b}, c\bar{c}$



$\mu_{b\bar{b}} = 1.1 \pm 0.3$ $\quad \mu_{c\bar{c}} < 70$

ATLAS, CMS, LHCb
Delaunay et al 1310.7029,
Perez et al 1505.06689, 1503.00290
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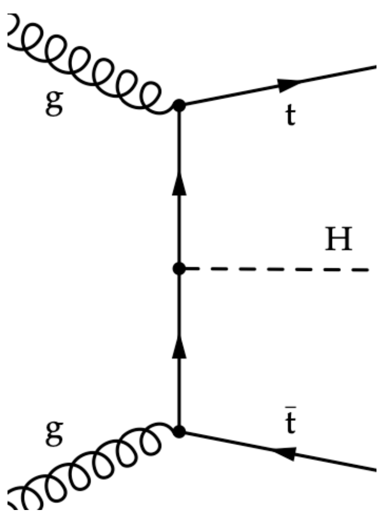
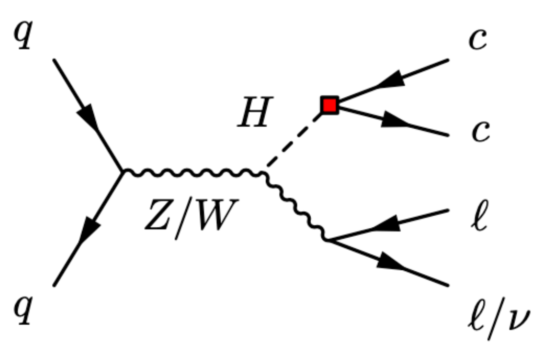
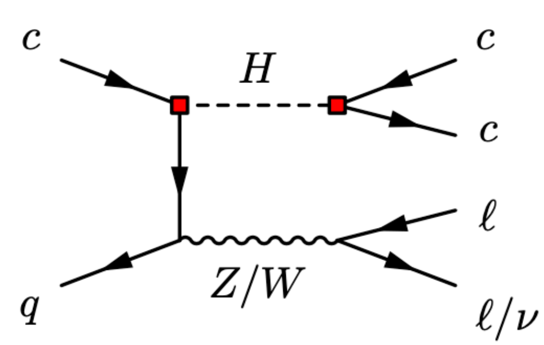
quark sector: inclusive rates

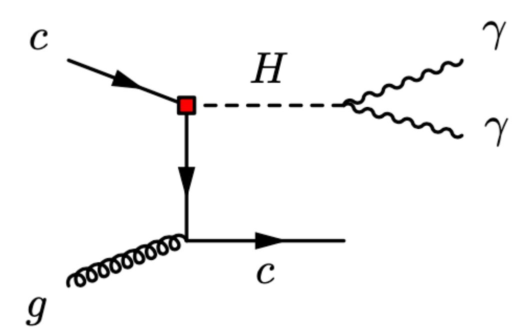
$$Y^U = \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \qquad Y^d = \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix}$$

$pp \to t\bar{t}h$ $\qquad$ $pp \to Vh, h \to b\bar{b}, c\bar{c}$









$\mu_{b\bar{b}} = 1.1 \pm 0.3 \qquad \mu_{c\bar{c}} < 70$

$\mu_{t\bar{t}h} = 1.2 \pm 0.3$ ATLAS, CMS

ATLAS, CMS, LHCb
Delaunay et al 1310.7029,
Perez et al 1505.06689, 1503.00290
Brivio et al 1507.02916

- non universal coupling: $y_t > y_b, y_c$
- probe scale of $\Lambda_t \gtrsim 0.4\,\text{TeV}$, $\Lambda_b \gtrsim 3.6\,\text{TeV}$, $\Lambda_c \gtrsim 1.5\,\text{TeV}$
- s-tagging possible at e^+e^- collider (e.g. Duarte-Campderros et at 1811.09636)

quark sector: exclusive rates

$$Y^U = \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \qquad Y^d = \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix}$$

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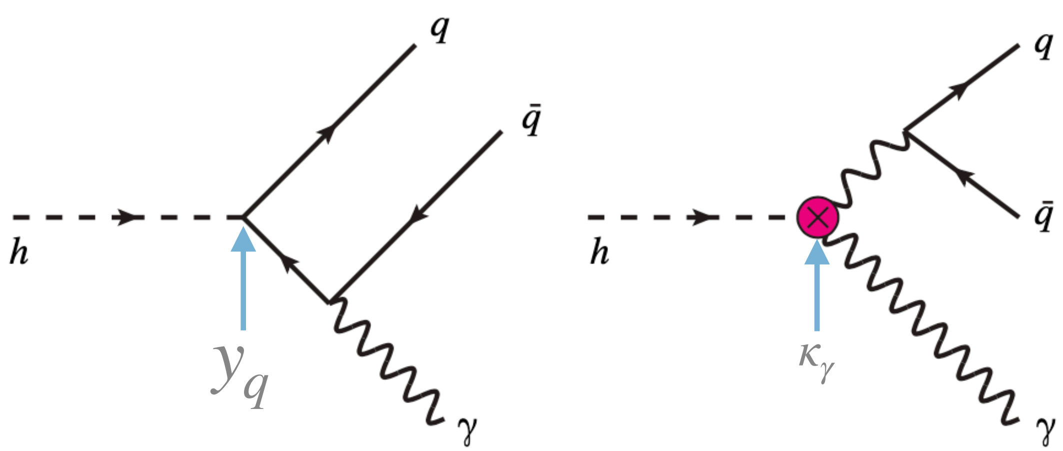
$$h \to V\gamma$$



ATLAS, CMS
Bodwin et al 1306.5770 Kagan et al 1406.1722
Bodwin et al 1407.6695 Perez et al 1503.00290
Koing, Neubert, 1505.03870, Alte et al 1609.06310

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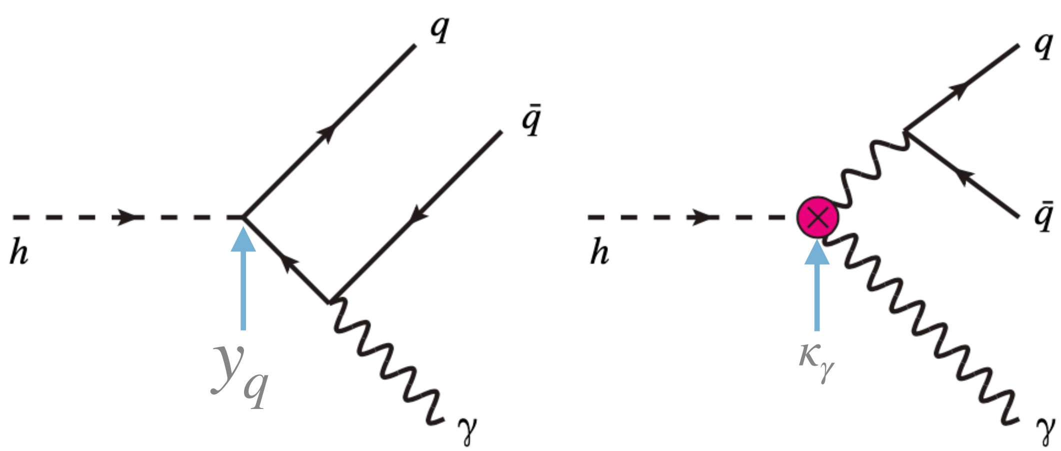

$$\mathscr{R}_{V\gamma,ZZ^*} \equiv \frac{\mu_{V\gamma}}{\mu_{ZZ^*}} \frac{\mathrm{BR}^{\mathrm{SM}}_{h\to V\gamma}}{\mathrm{BR}^{\mathrm{SM}}_{h\to ZZ^*}} \simeq \frac{\Gamma_{h\to V\gamma}}{h \to ZZ^*}$$

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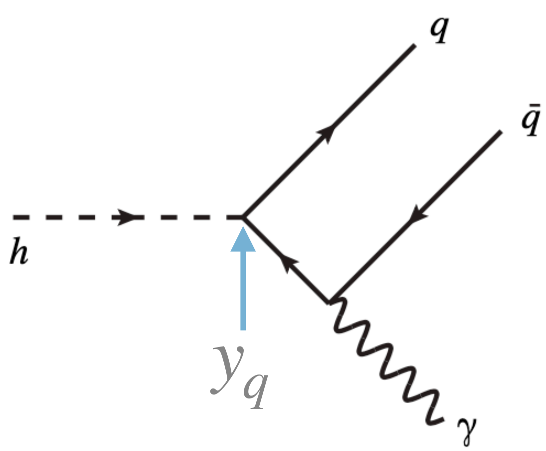

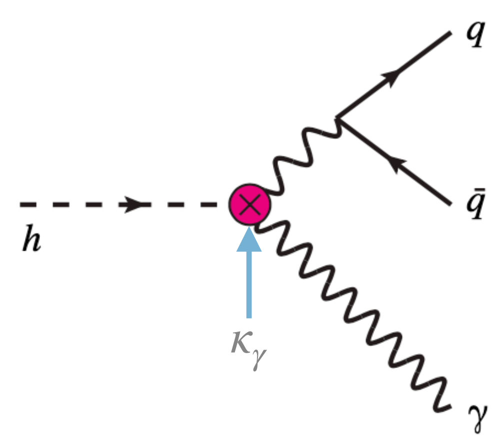

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V	$\mathrm{BR}_{h\to V\gamma} <$	$\mathscr{R}_{V\gamma,ZZ^*} <$	Yukawa range
J/ψ	1.5×10^{-3}	9.3	$\kappa_c < 310$
ϕ	4.8×10^{-4}	3.2	$\bar{\kappa}_s < 150$
ρ	8.8×10^{-4}	5.8	$2\bar{\kappa}_u + \bar{\kappa}_d < 330$

$$\Lambda_q \gtrsim 200\,\mathrm{GeV}$$

$$\bar{\kappa}_q \equiv \frac{y_q}{y_b^{\mathrm{SM}}}$$

CERN yellow report, 1812.07638

ATLAS, CMS
Bodwin et al 1306.5770 Kagan et al 1406.1722
Bodwin et al 1407.6695 Perez et al 1503.00290
Koing, Neubert, 1505.03870, Alte et al 1609.06310

recent CMS results for $h \to \rho Z, \phi Z$

quark sector: from Higgs distributions

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YS et al 1606.09621

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large light quark Yukawa
($y_q \lesssim 0.5 y_b^{\rm SM}$ is allowed)

⇨

$q\bar{q} \to h$ production
(SM is dominated by $gg \to h$)

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YS et al 1606.09621

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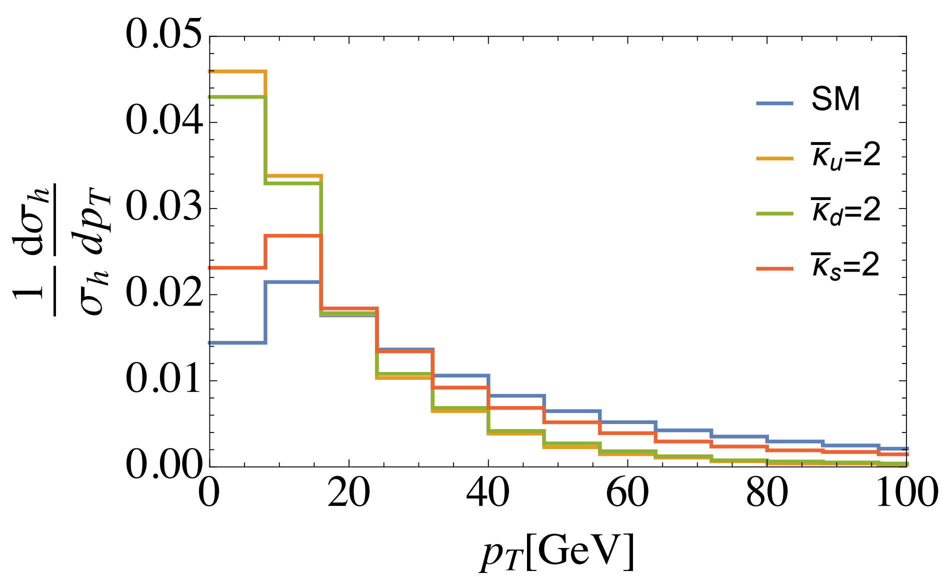

softer p_T spectrum

$$\bar{\kappa}_q \equiv \frac{y_q}{y_b^{\rm SM}}$$

YS et al 1606.09621

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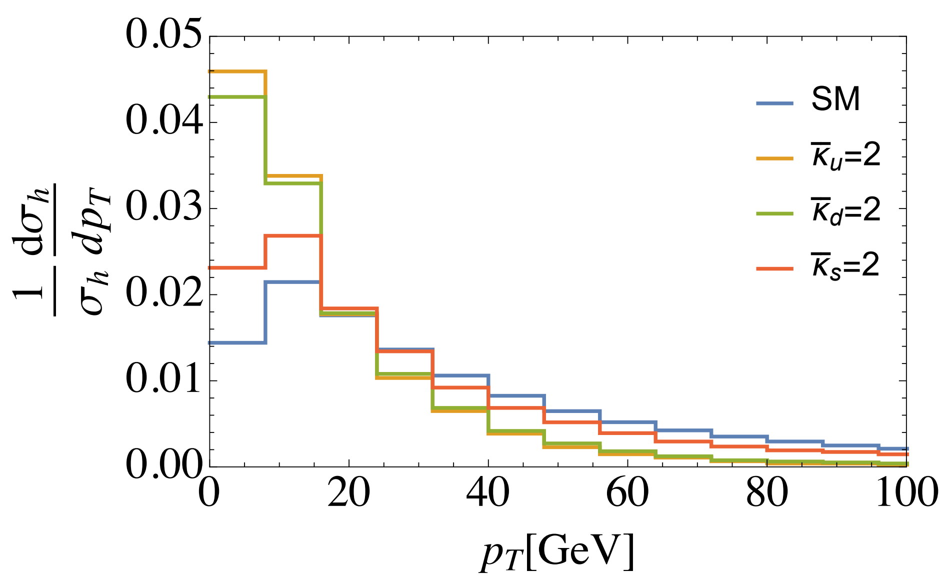

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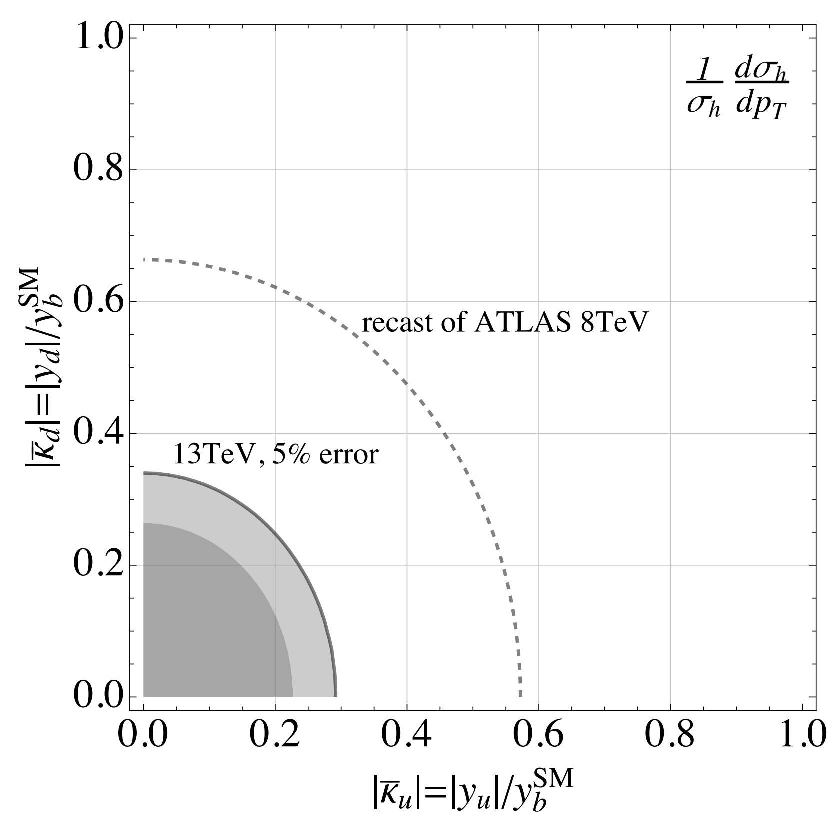

$\bar{\kappa}_u < 0.46$

$\bar{\kappa}_d < 0.54$

recast of ATLAS 8TeV

$\Lambda_q \gtrsim 3\,{\rm TeV}$

$\bar{\kappa}_q \equiv \frac{y_q}{y_b^{\rm SM}}$

YS et al 1606.09621

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Bishara et al1606.09253
Yu 1609.06592

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loop effect in
$gg \to h$

log enhancement: $\kappa_Q \frac{m_Q^2}{m_h^2} \log^2\left(\frac{p_T^2}{m_Q^2}\right)$

Bishara et al1606.09253
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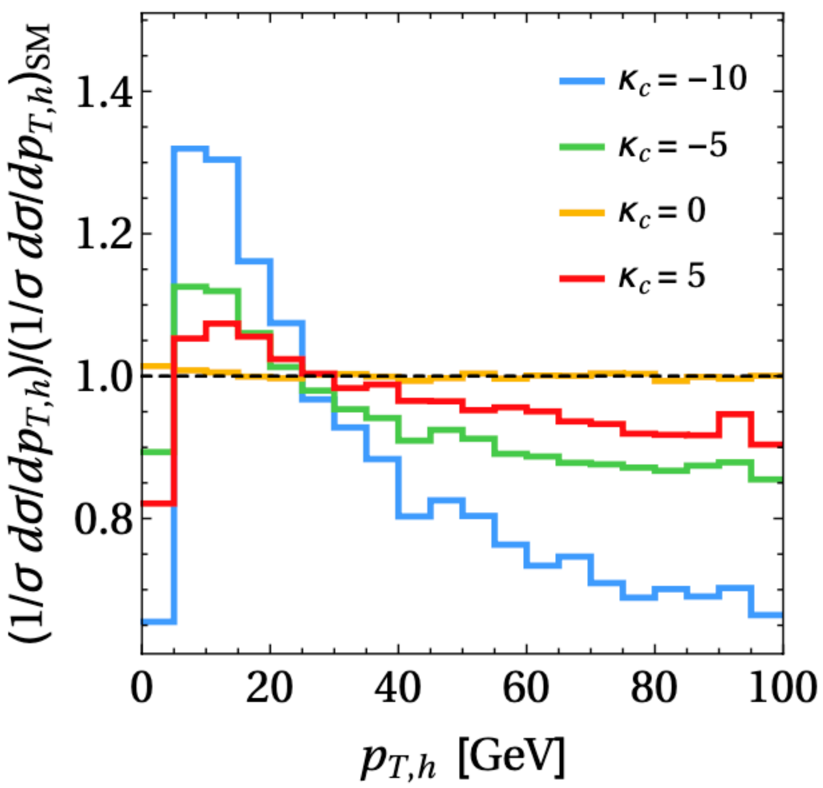

Bishara et al1606.09253
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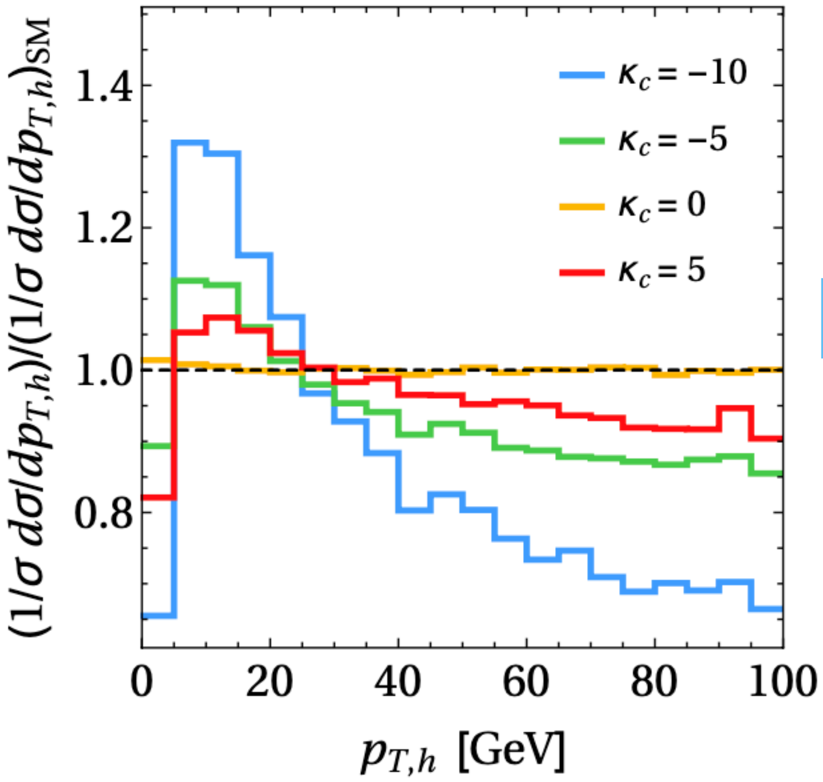

→ $\kappa_c < 38$

$\kappa_b < 18$

CMS, 13TeV, 36 fb^{-1}

Bishara et al1606.09253
Yu 1609.06592

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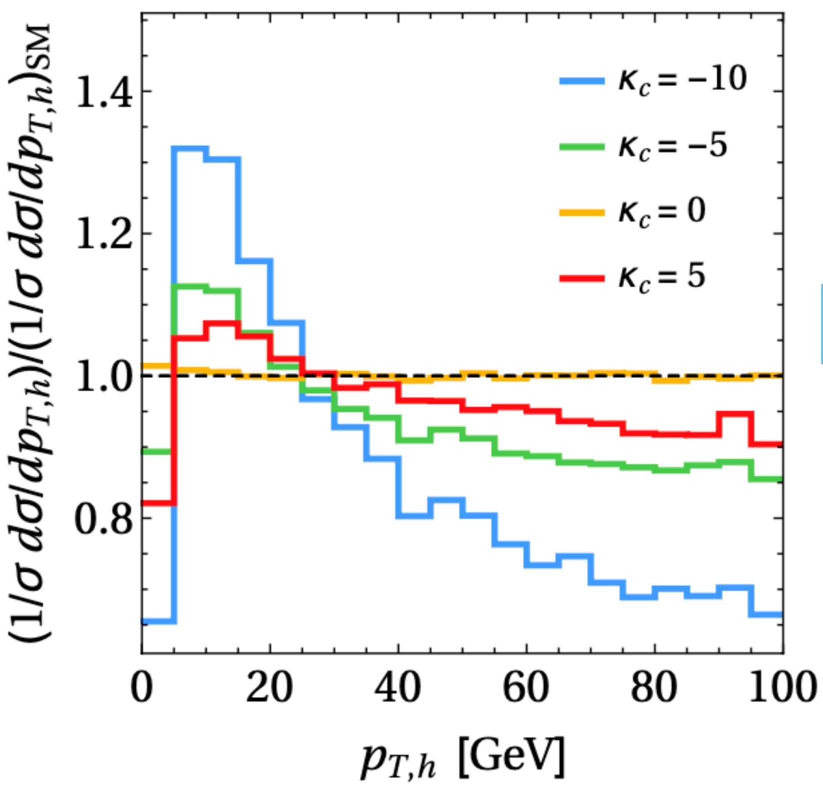
loop effect in $gg \to h$ ⇒ log enhancement: $\kappa_Q \frac{m_Q^2}{m_h^2} \log^2\left(\frac{p_T^2}{m_Q^2}\right)$



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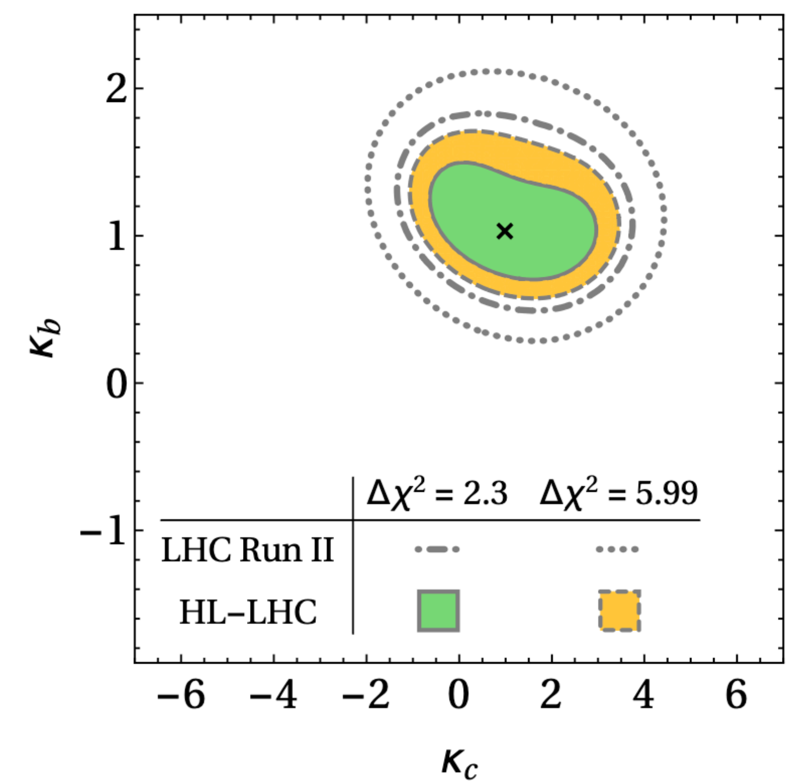

Bishara et al1606.09253
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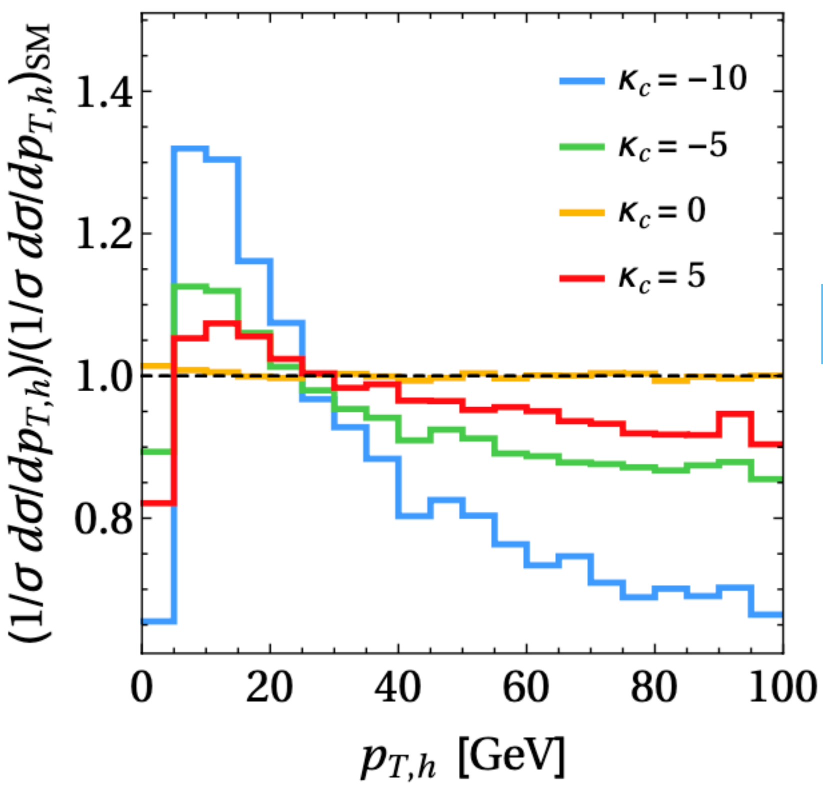

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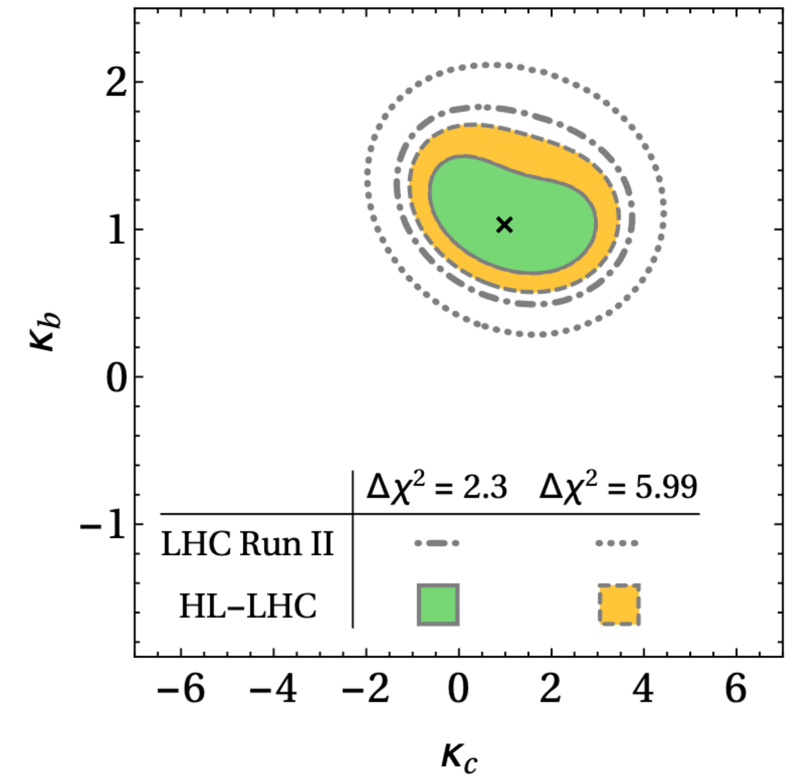


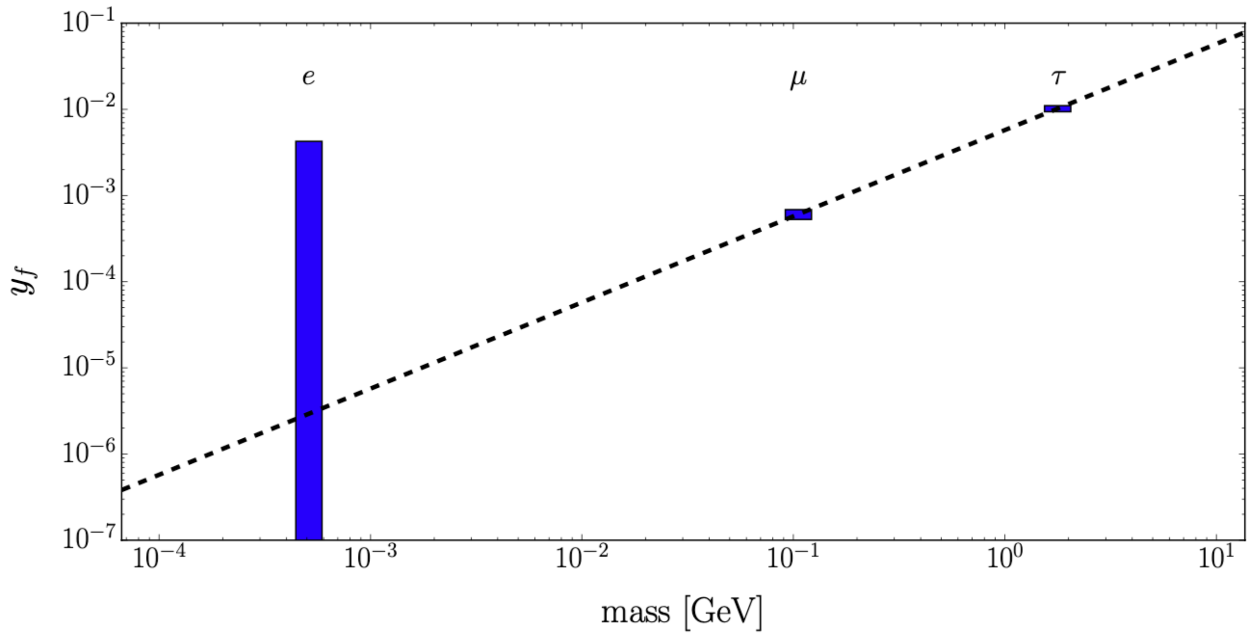
$$A(Wh) = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$ - sensitive to $y_{u,d,s,c}$

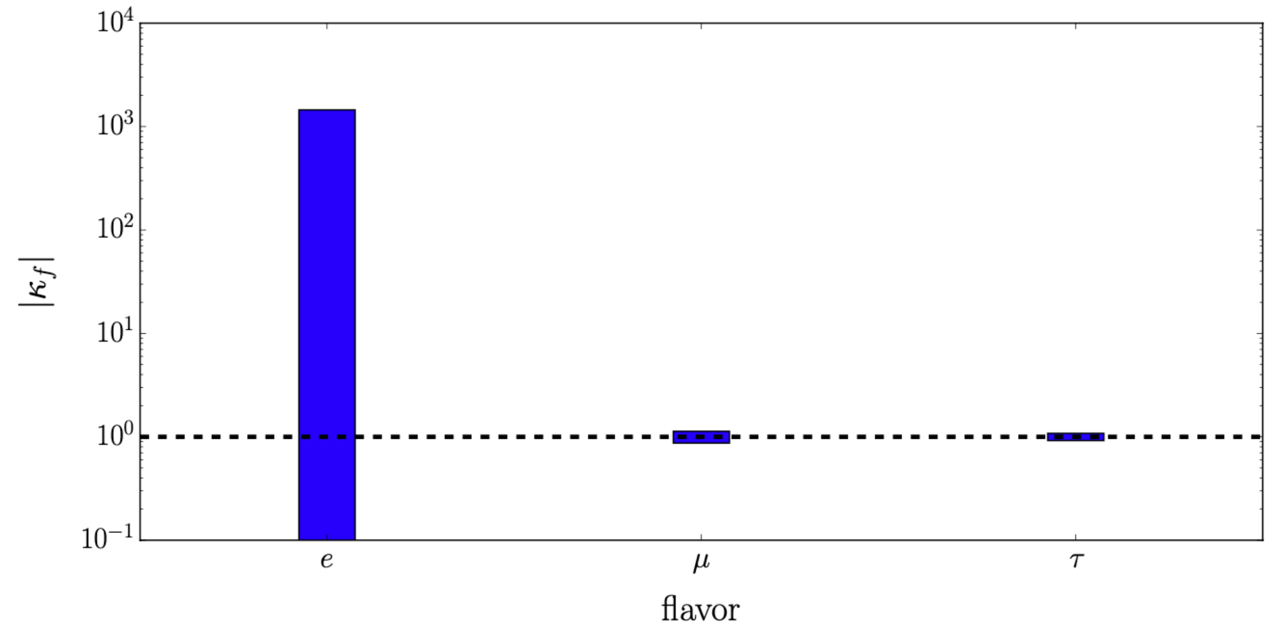
Bishara et al1606.09253
Yu 1609.06592

future projections

future projections

leptons





CERN yellow report, 1812.07638

future projections

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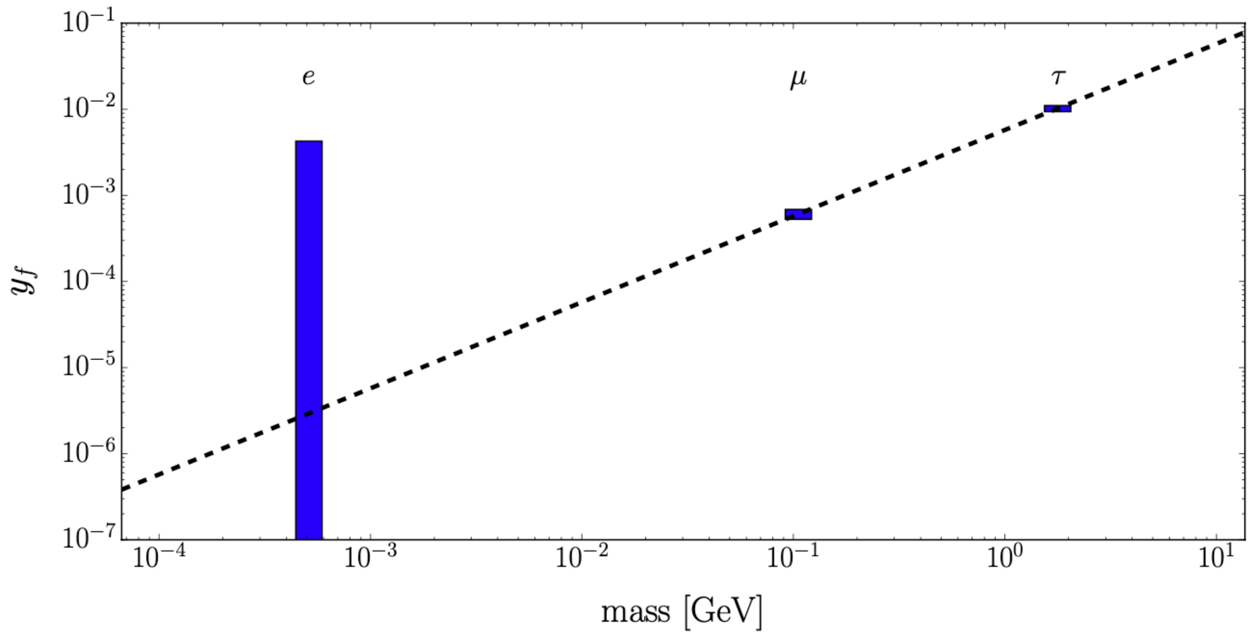
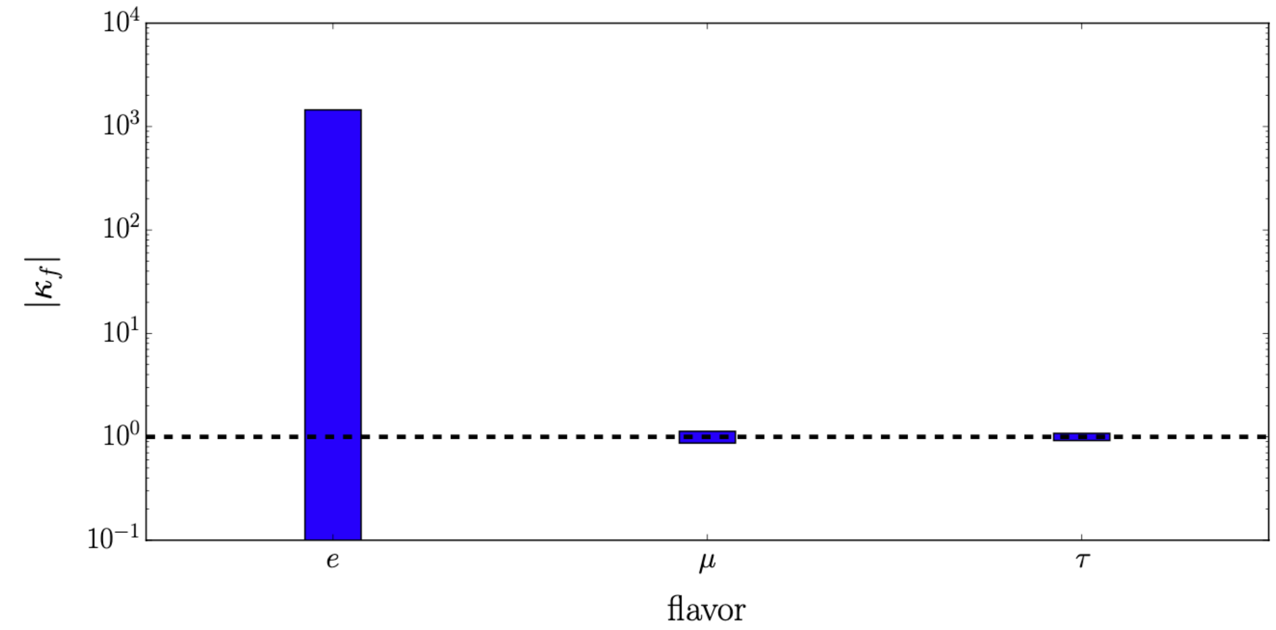
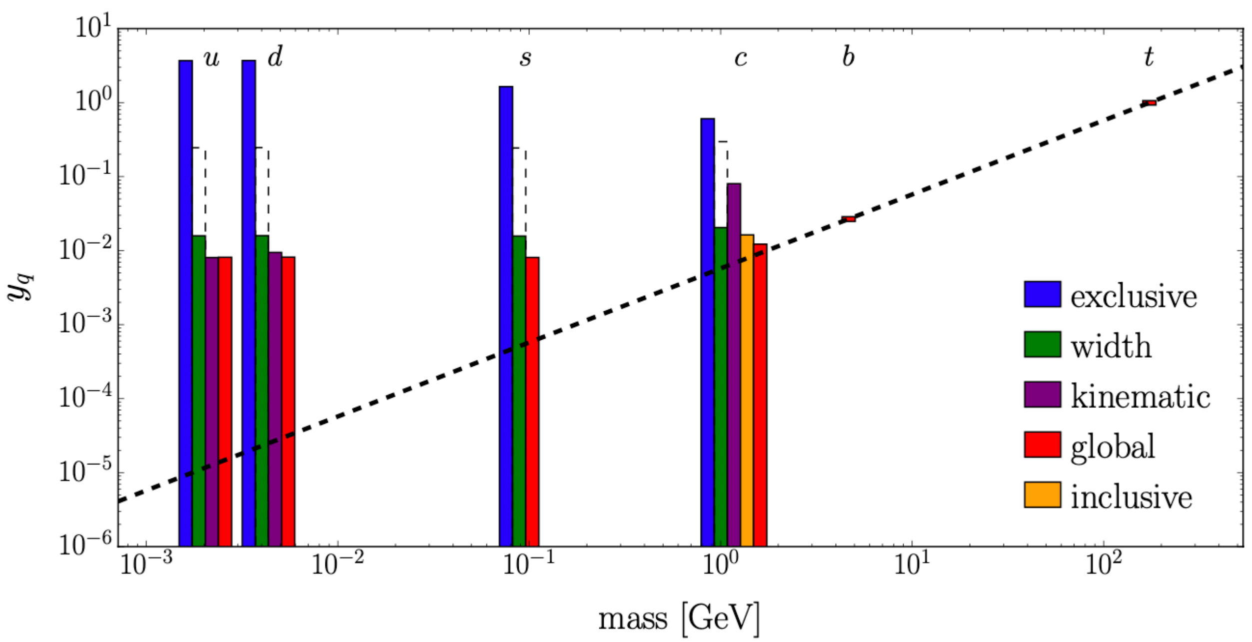
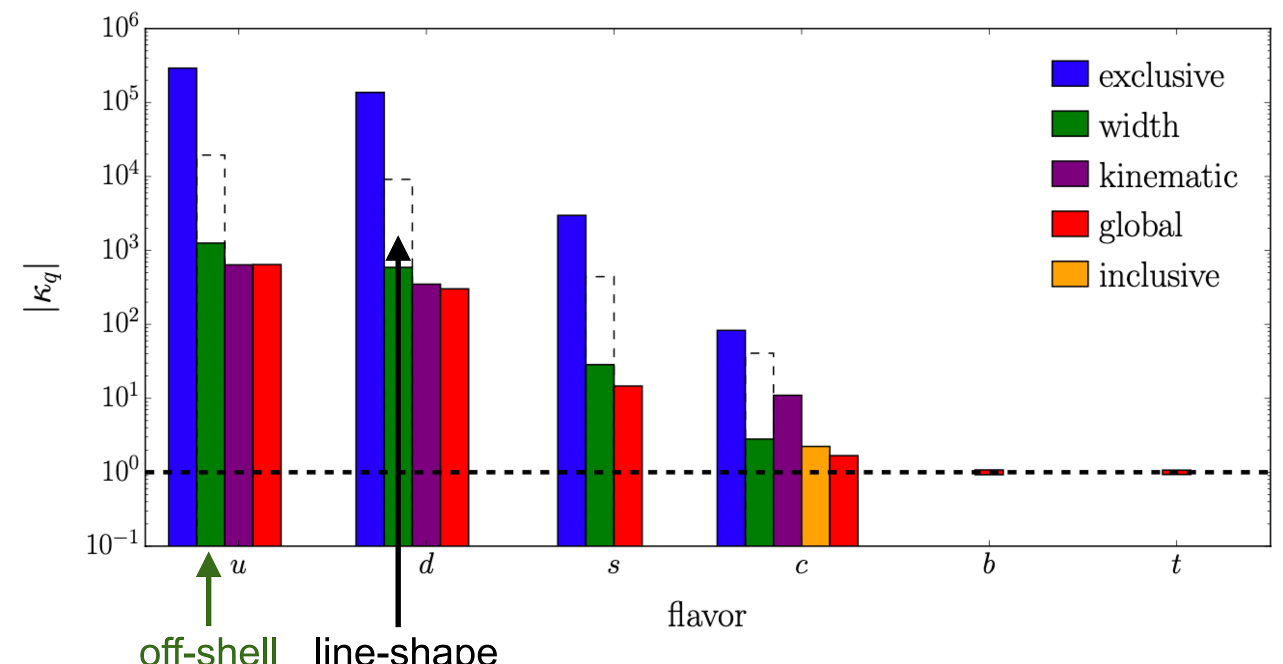




quarks





CERN yellow report, 1812.07638

null tests of the SM

(flavor and CP violation)

Higgs flavor violating decays

$$Y^u_{ij}\tilde{H}\overline{Q^i_L}U^j_R + \frac{c^u_{ij}}{\Lambda^2}\tilde{H}\overline{Q^i_L}U^j_R(H^\dagger H)$$

(similar for down-quarks and leptons)

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(similar for down-quarks and leptons)

$$Y^f_{ij} = \frac{\sqrt{2}m_i}{v}\delta_{ij} + \frac{v^2}{\Lambda^2}c^f_{ij}$$

$$\mathrm{BR}_{h\to\tau\mu} \simeq 0.25\,\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \left(\left|\frac{c^\ell_{\mu\tau}}{0.2}\right|^2 + \left|\frac{c^\ell_{\tau\mu}}{0.2}\right|^2 \right) \quad \mathrm{BR}_{t\to ch} \simeq 0.18\,\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \left(\left|\frac{c^\ell_{tc}}{1.0}\right|^2 + \left|\frac{c^\ell_{ct}}{1.0}\right|^2 \right)$$

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direct

$$h \to \tau\mu, \tau e, \mu e\,,\; t \to hj$$

$$\sqrt{y^2_{\mu\tau} + y^2_{\tau\mu}} < 1.4 \times 10^{-3}$$

$$\sqrt{y^2_{e\tau} + y^2_{\tau e}} < 2.3 \times 10^{-3}$$

$$\sqrt{y^2_{tc} + y^2_{ct}} < 0.06$$

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

ATLAS, CMS,
Bressler et al 1405.4545, Davidson et al 1211.1248

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$$\sqrt{y^2_{tc} + y^2_{ct}} < 0.06$$

ATLAS, CMS,
Bressler et al 1405.4545, Davidson et al 1211.1248

indirect

meson mixing, $\mu \to e\gamma$

$$y_{uc}, y_{uc} < 7 \times 10^{-5}$$

$$y_{ds}, y_{sd} < 3 \times 10^{-5}$$

and more

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

Higgs flavor violating decays

Higgs flavor violating decays

$(c/\Lambda^2)\overline{\psi_R}\sigma_{\mu\nu}\psi_L H F^{\mu\nu}$ - same flavour structure

$$h \to \overline{\psi}^i \psi^j \Longleftrightarrow \psi^i \to \psi^j \gamma$$

$$c \sim \lambda e/16\pi^2$$

$$\mathrm{BR}_{h\to\tau\mu} \sim 26\,\mathrm{BR}_{\tau\to\mu\gamma} \lesssim 10^{-6}$$

Altmannshofer et al 1507.07927
Dorsner et al 1502.07784

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$\tau \to \mu\gamma$ can be avoided by:

- tuning (Aloni et at 1511.00979)
- first two generation receive their masses from additional source of EWSB (Almannshofer et al 1507.07927, Gosh et al 1508.01501)

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- first two generation receive their masses from additional source of EWSB (Almannshofer et al 1507.07927, Gosh et al 1508.01501)

use alignment (holomorphic zeros) to avoid flavor constraints:
approximate horizontal $U(1) \times U(1)$ Froggatt-Nielsen symmetry in SUSY model + non renoramlizable terms

viable model with sizeable $t \to ch$ and $h \to \tau\mu$

Leurer, Nir, Seiberg hep-ph/9310320
Dery et al - 1408.1371

Higgs flavor violating decays

Model	$\kappa_{ct(tc)}/\kappa_t$	$\kappa_{ut(tu)}/\kappa_t$	$\kappa_{uc(cu)}/\kappa_t$
MFV	$\frac{\Re\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v}$	$\frac{\Re\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v}$	$\frac{\Re\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^*\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v}$
F2HDM	$\mathcal{O}\left(\frac{m_c}{m_t}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_u}{m_t}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_c m_u}{m_t^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
FN	$\mathcal{O}\left(\frac{v m_{t(c)}}{\Lambda^2}\lvert V_{cb}\rvert^{\pm1}\right)$	$\mathcal{O}\left(\frac{v m_{t(u)}}{\Lambda^2}\lvert V_{ub}\rvert^{\pm1}\right)$	$\mathcal{O}\left(\frac{v m_{c(u)}}{\Lambda^2}\lvert V_{us}\rvert^{\pm1}\right)$
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	$\kappa_{bs(sb)}/\kappa_b$	$\kappa_{bd(db)}/\kappa_b$	$\kappa_{sd(ds)}/\kappa_b$
MFV	$\frac{\Re\left(c_d m_t^2 V_{ts}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{s(b)}}{v}$	$\frac{\Re\left(c_d m_t^2 V_{td}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{d(b)}}{v}$	$\frac{\Re\left(c_d m_t^2 V_{ts(td)}^* V_{td(ts)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{s(d)}}{v}$
F2HDM	$\mathcal{O}\left(\frac{m_s}{m_b}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_d}{m_b}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_s m_d}{m_b^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
FN	$\mathcal{O}\left(\frac{v m_{b(s)}}{\Lambda^2}\lvert V_{cb}\rvert^{\pm1}\right)$	$\mathcal{O}\left(\frac{v m_{b(d)}}{\Lambda^2}\lvert V_{ub}\rvert^{\pm1}\right)$	$\mathcal{O}\left(\frac{v m_{s(d)}}{\Lambda^2}\lvert V_{us}\rvert^{\pm1}\right)$
GL2	$\epsilon^2(\epsilon)$	ϵ	$\epsilon^2(\epsilon^3)$
RS	$\sim \lambda^{(-)2}\frac{m_{b(s)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim \lambda^{(-)3}\frac{m_{b(d)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim \lambda^{(-)1}\frac{m_{s(d)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$
pNGB	$\mathcal{O}(y_*^2\frac{m_b}{v}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_b}{v}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_s}{v}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$

CERN yellow report, 1902.00134

Higgs flavor violating decays

Model	$\kappa_{\tau\mu(\mu\tau)}/\kappa_\tau$	$\kappa_{\tau e(e\tau)}/\kappa_\tau$	$\kappa_{\mu e(e\mu)}/\kappa_\tau$
F2HDM	$\mathcal{O}\left(\frac{m_\mu}{m_\tau}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_e}{m_\tau}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_\mu m_e}{m_\tau^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
FN	$\mathcal{O}\left(\frac{v m_{\mu(\tau)}}{\Lambda^2}\lvert U_{23}\rvert^{\mp 1}\right)$	$\mathcal{O}\left(\frac{v m_{e(\tau)}}{\Lambda^2}\lvert U_{13}\rvert^{\mp 1}\right)$	$\mathcal{O}\left(\frac{v m_{e(\mu)}}{\Lambda^2}\lvert U_{12}\rvert^{\mp 1}\right)$
GL2	$\epsilon^2(\epsilon)$	ϵ	$\epsilon^2(\epsilon^3)$
RS	$\sim\sqrt{\frac{m_{\mu(\tau)}}{m_{\tau(\mu)}}}\,\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim\sqrt{\frac{m_{e(\tau)}}{m_{\tau(e)}}}\,\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim\sqrt{\frac{m_{e(\mu)}}{m_{\mu(e)}}}\,\bar{Y}^2\frac{v^2}{m_{KK}^2}$

CERN yellow report, 1902.00134

CP violation

$$\mathscr{L}_{\rm eff} = -\frac{m_f}{v}\left(\kappa_f h\bar{f}f + i\tilde{\kappa}_f h\bar{f}\gamma_5 f\right)$$

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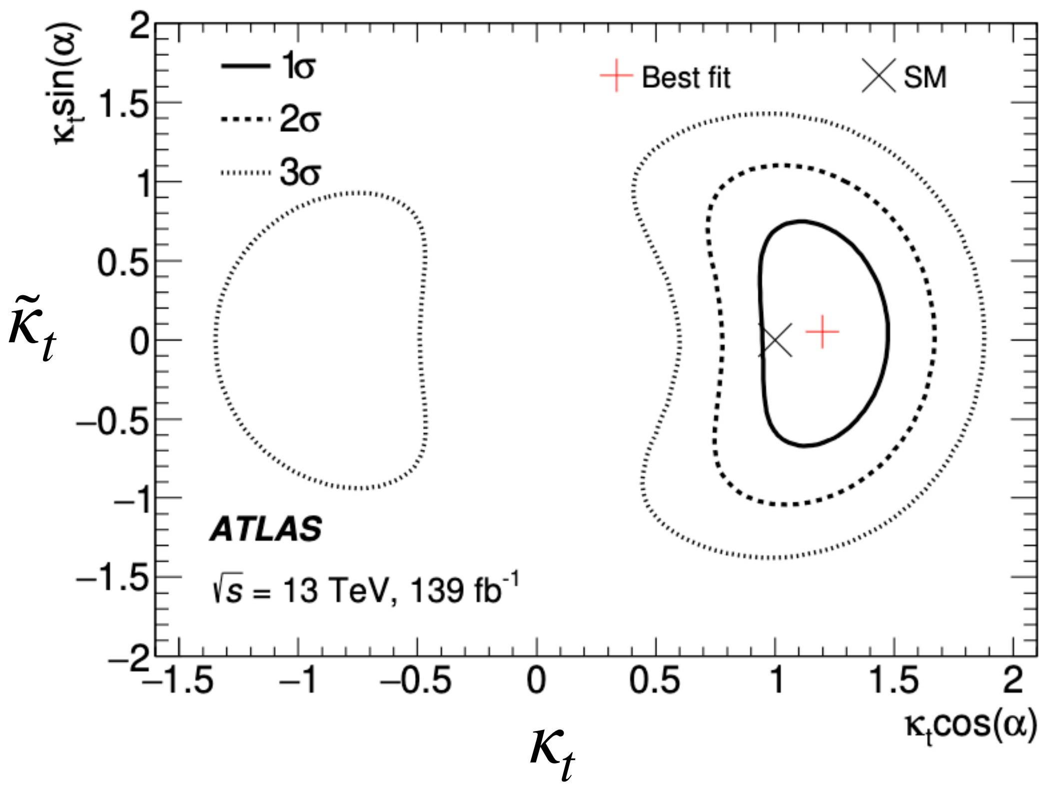
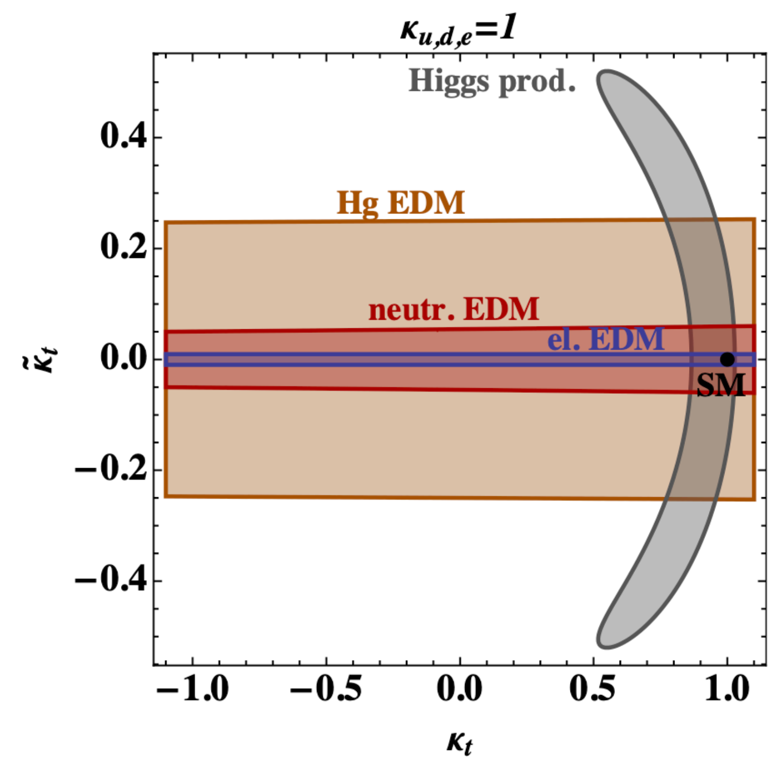
CPV can be directly constrained in $t\bar{t}h$ and $\tau\bar{\tau}h$





$\tilde{\kappa}_\tau$ (the CP phase) can be probed to $11°$at HL-LHC

Harnik et al, 1308.1094
CERN yellow report, 1902.00134

ATLAS, CMS
Brod et al, 1310.1385, Almannshofer et al 1503.04830
Brod et al 1811.05480

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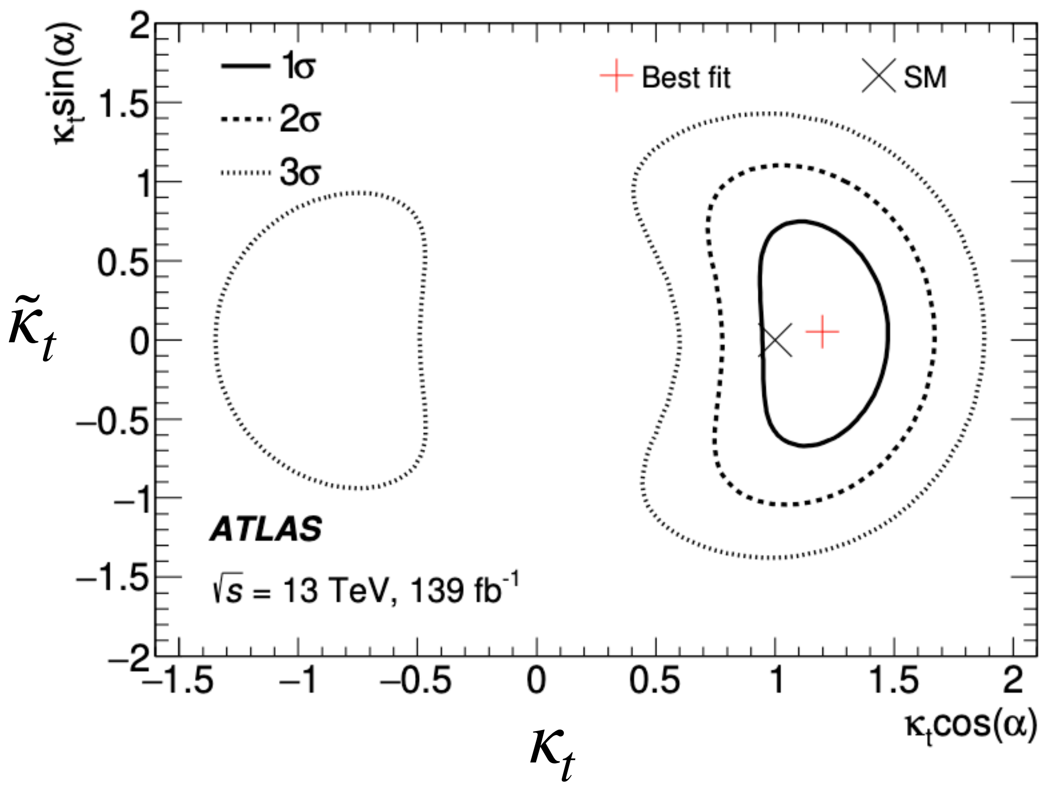

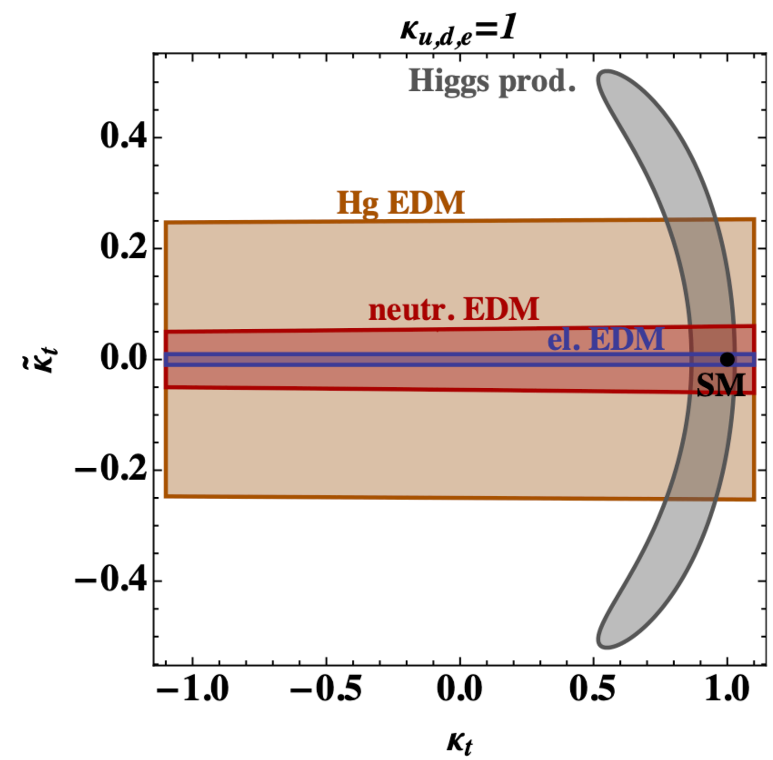

$\tilde{\kappa}_\tau$ (the CP phase) can be probed to $11°$at HL-LHC

Harnik et al, 1308.1094
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eEDM: $\tilde{\kappa}_e < 1.9 \times 10^{-3}$

nEDM: $\tilde{\kappa}_b < 5,\ \tilde{\kappa}_c < 21,\ \tilde{\kappa}_s < 2.2$

HgEDM: $\tilde{\kappa}_u < 0.06,\ \tilde{\kappa}_d < 0.03$

ATLAS, CMS
Brod et al, 1310.1385, Almannshofer et al 1503.04830
Brod et al 1811.05480

few implications

large Yukawa couplings in Higgs portal

large Yukawa coupling for u, d, s have interesting implications for Higgs portal models

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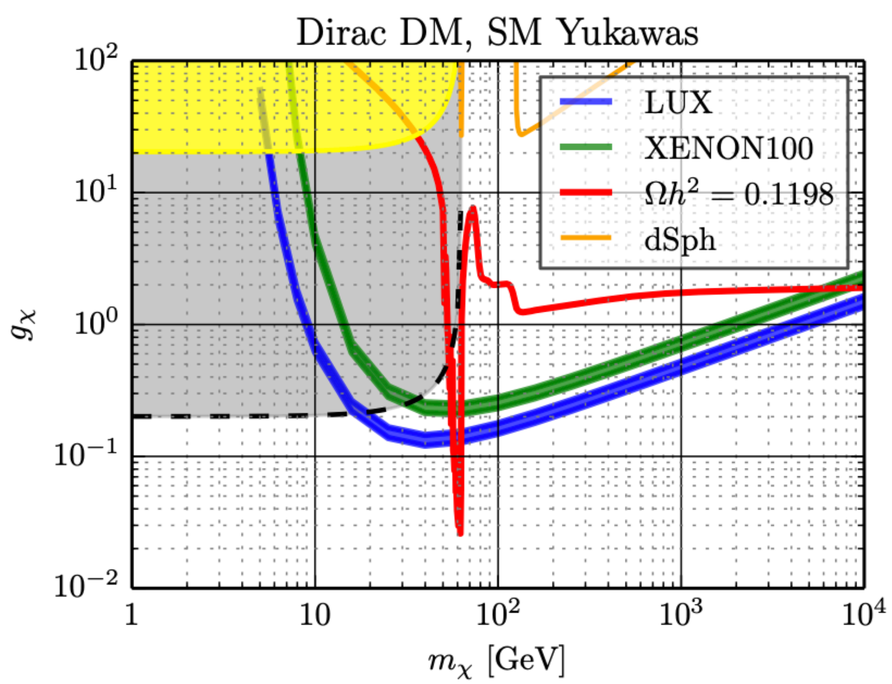
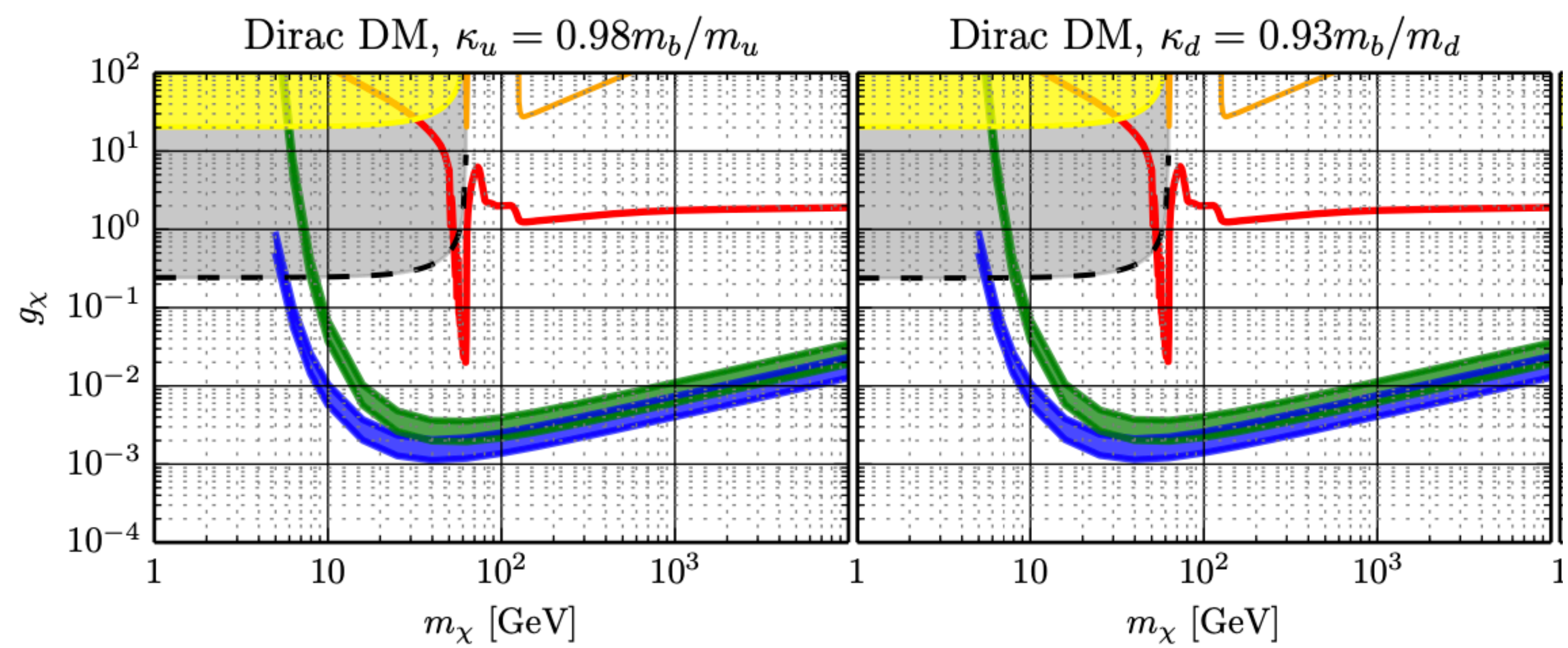
enhanced dark matter direct detection



SM Yukawa



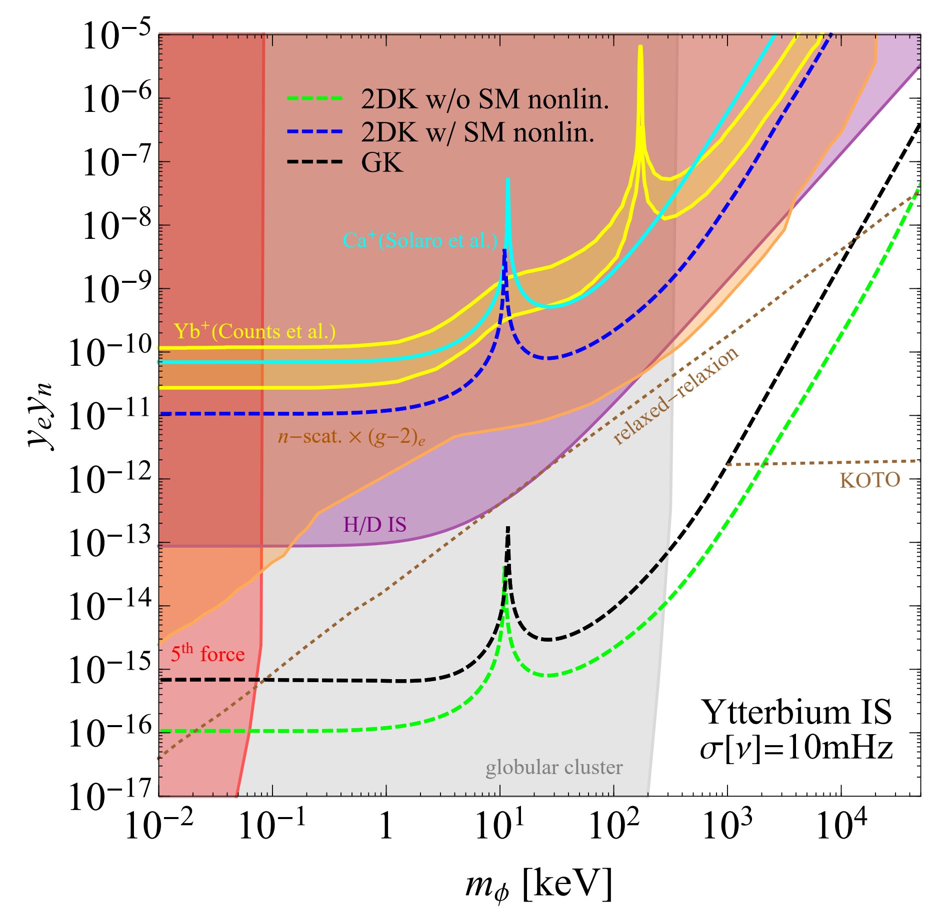
large y_u large y_d

Bishara et al 1504.04022

large Yukawa couplings in Higgs portal

large Yukawa coupling for u, d, s have interesting implications for Higgs portal models

precision measurements of new forces with Higgs mixing



Delaunay et al 1601.05087, Flacke et al 1610.02025, Berengut et al 1704.05068, Banerjee et al 2004.02899, Berengut et al 2005.06144

Higgs CPV and baryogengesis

$\mu_{\mu\mu} < 1.7$
the strongest bound on $\tilde{\kappa}_\mu$

$\mathrm{Im}[y_\mu]$ as dominated source of the baryon asymmetry is excluded (up to 16% of the asymmetry)

de Vries et al1811.11104
Fuchs et al 1911.08495, 2003.00099

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$\mu_{\mu\mu} < 1.7$
the strongest bound on $\tilde{\kappa}_\mu$

→

$\mathrm{Im}[y_\mu]$ as dominated source of the baryon asymmetry is excluded (up to 16% of the asymmetry)

y_τ can account for the baryon asymmetry
y_t and y_b together can account up 12% of the baryon asymmetry (separately up to 2% and 4%)

→

a measurement of $\tilde{\kappa}_\tau$ is a smoking gun of this scenario and is motivated

de Vries et al1811.11104
Fuchs et al 1911.08495, 2003.00099

summary

* the dominant source of t, b and τ masses is the SM-Higgs mechanism
* much less is known about the first two generations, still room for new physics
* interesting effect on Higgs portal models

backups

$$Y^\ell = \begin{pmatrix} y_e & y_{e\mu} & y_{e\tau} \\ y_{\mu e} & y_\mu & y_{\mu\tau} \\ y_{\tau e} & y_{\tau\mu} & y_\tau \end{pmatrix} <$$

	0.54	2.4
0.54		3.2
2.4	3.2	

$\times 10^{-3}$

direct searches

3.6×10^{-6} ($\mu \to e\gamma$)

$(|y_{\tau e}\, y_{\mu\tau}|^2 + |y_{e\tau}\, y_{\tau\mu}|^2)^{1/4} < 3.4\times 10^{-4}$ ($\mu \to e\gamma$)

$$Y^u = \begin{pmatrix} y_u & y_{uc} & y_{ut} \\ y_{cu} & y_c & y_{ct} \\ y_{tu} & y_{tc} & y_t \end{pmatrix} <$$

	7×10^{-5}	0.13
7×10^{-5}		0.13
0.13	0.13	

D^0-$\bar{D}^0$ mixing

$t \to hj$: decay and th production

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

Greljo, Kamenik, Koop 1404.1278

K^0-$\bar{K}^0$ mixing

Re (Im)

$$Y^d = \begin{pmatrix} y_d & y_{ds} & y_{db} \\ y_{sd} & y_s & y_{sb} \\ y_{bd} & y_{bs} & y_b \end{pmatrix} <$$

	$2.4(0.17)\times 10^{-5}$	1.5×10^{-4}
$2.4(0.17)\times 10^{-5}$		1.3×10^{-3}
1.5×10^{-4}	1.3×10^{-3}	

B_d-$\bar{B}_d$ mixing

B_s-$\bar{B}_s$ mixing

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704