

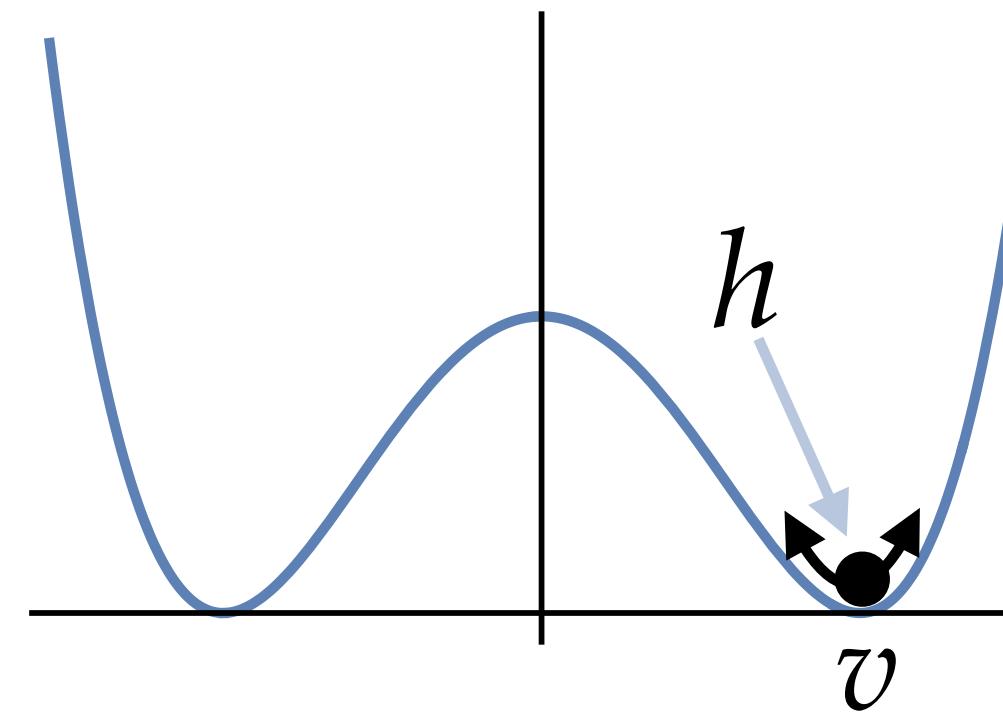


Higgs and Flavor

Yotam Soreq
Technion

FPCP 2023, Lyon, June 1, 2023

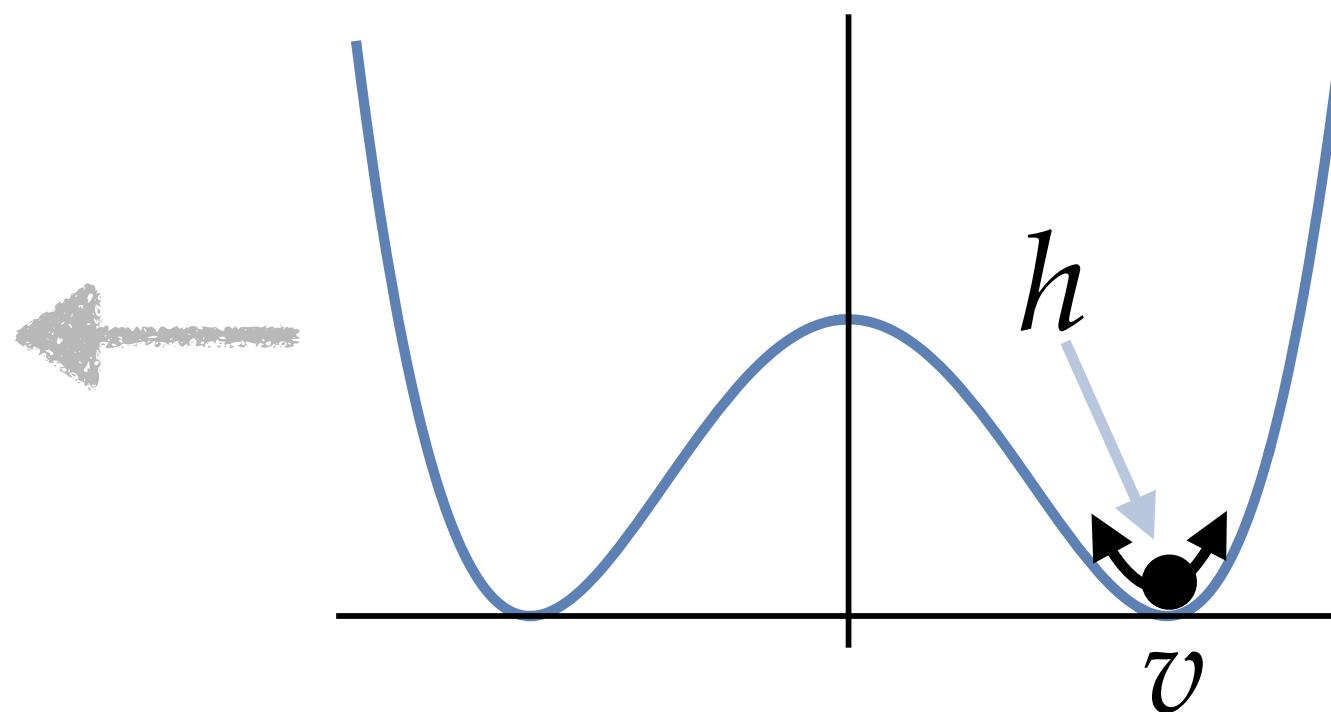
the Higgs in the standard model



the Higgs in the standard model

electroweak symmetry
breaking

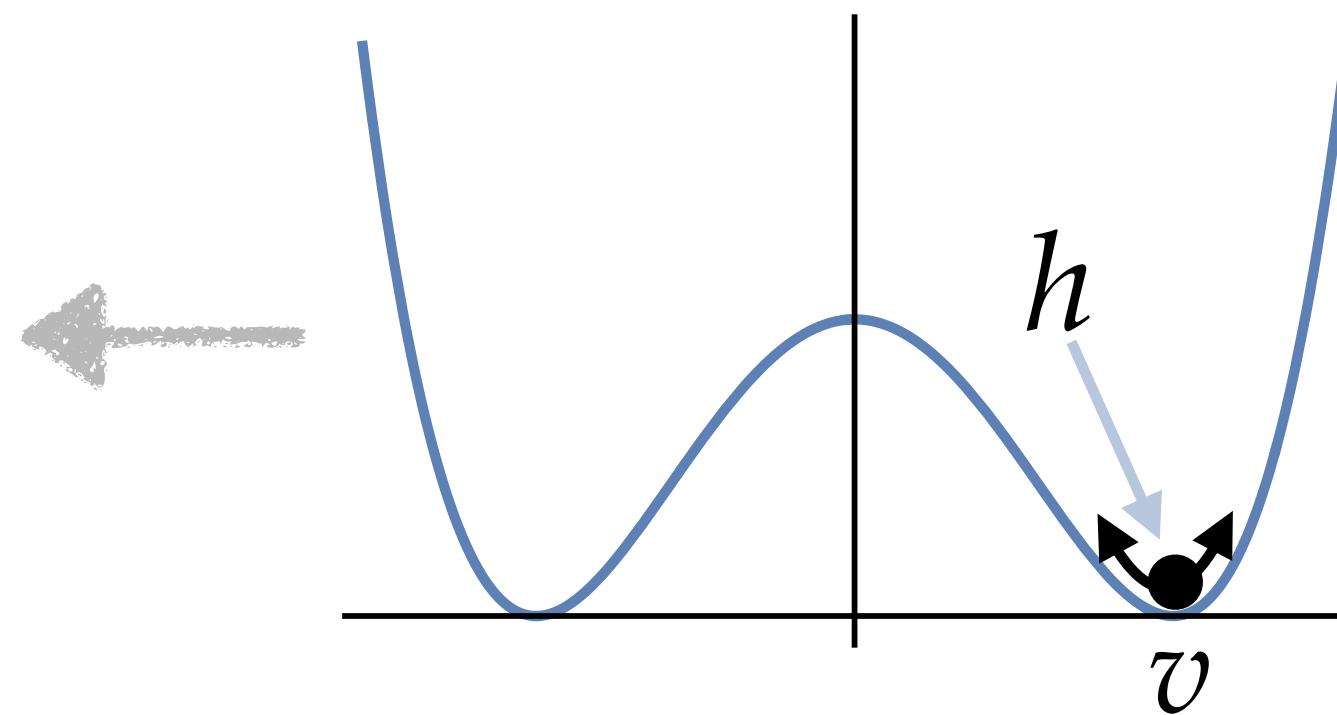
$$m_{Z,W} \neq 0, V_L V_L \rightarrow V_L V_L$$



the Higgs in the standard model

electroweak symmetry
breaking

$m_{Z,W} \neq 0$, $V_L V_L \rightarrow V_L V_L$



tests

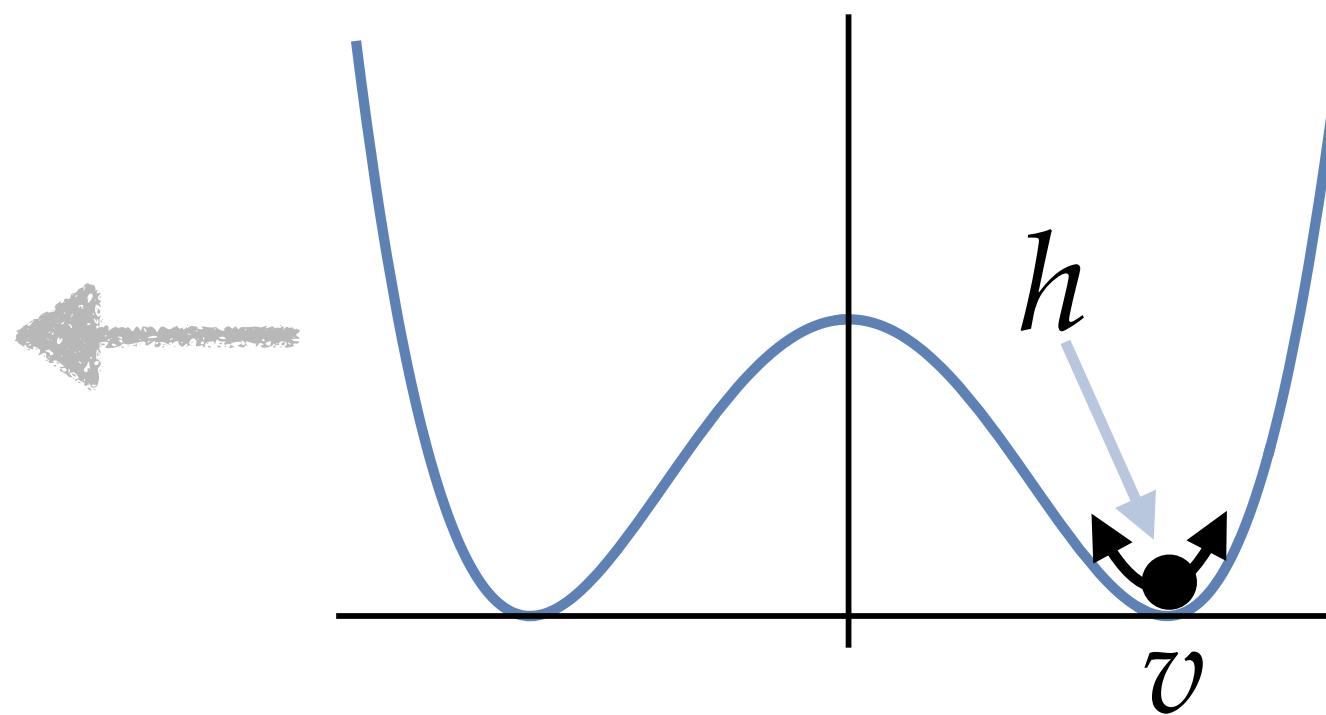
$h \rightarrow WW^*, ZZ^*$

electroweak precision

the Higgs in the standard model

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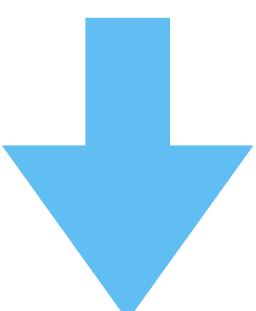
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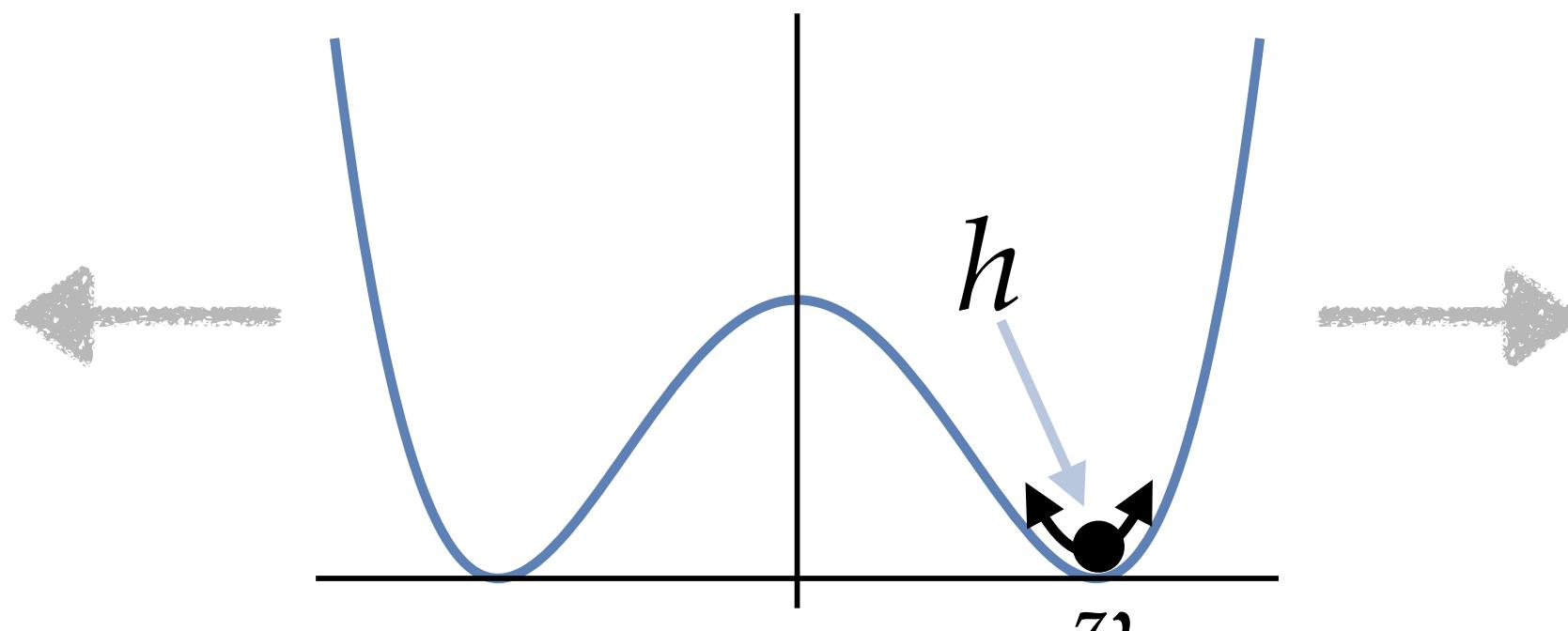


the Higgs is the main
source of EWSB

the Higgs in the standard model

electroweak symmetry
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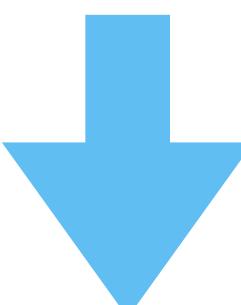
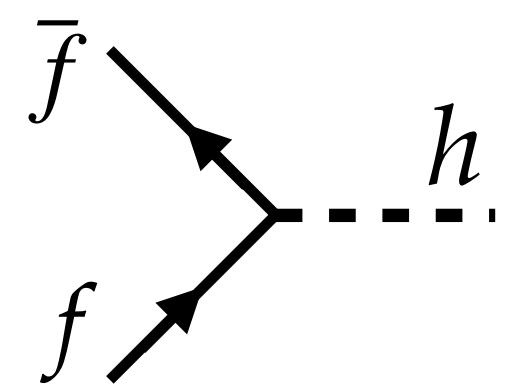
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charged fermion
masses

$$m_f \neq 0, f\bar{f} \rightarrow V_L V_L$$

tests
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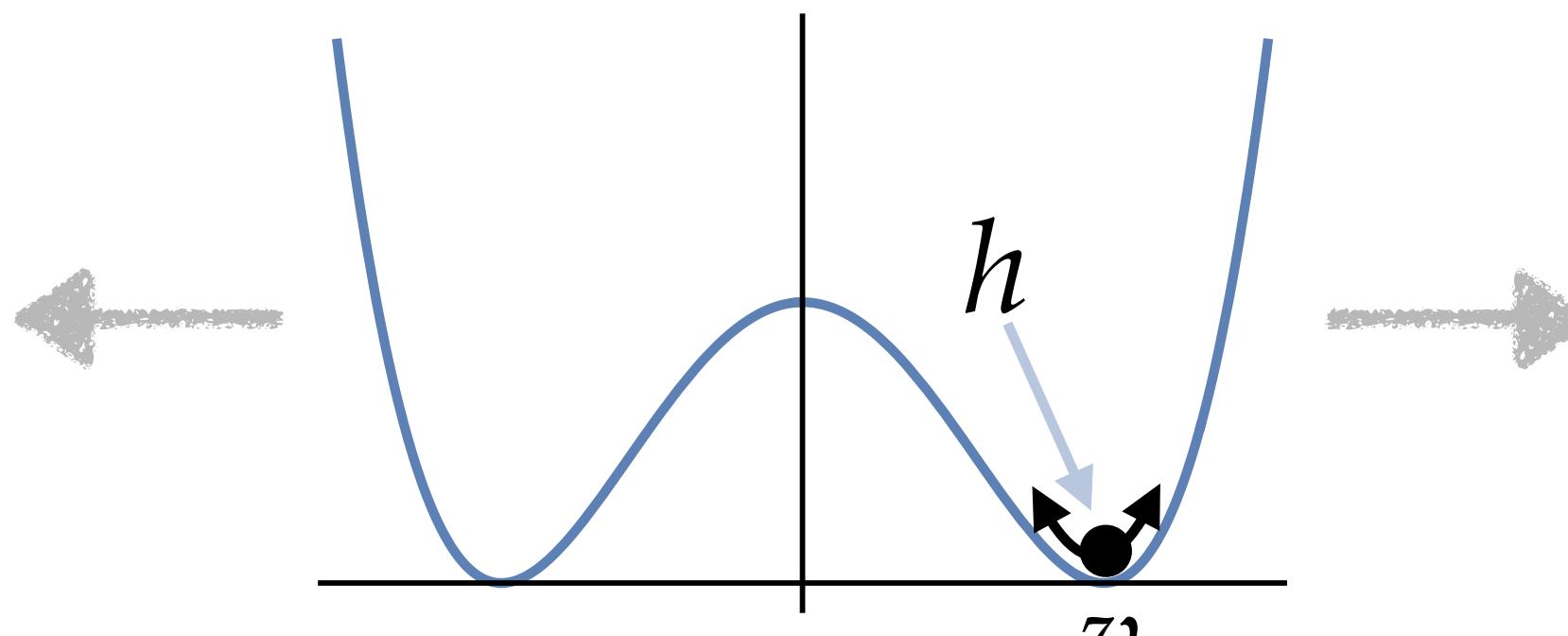


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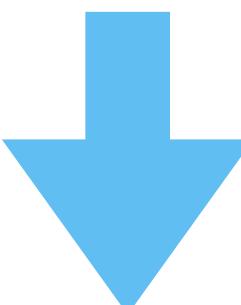
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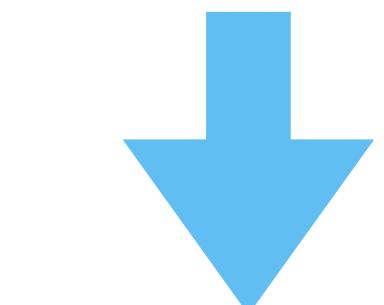
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tests
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electroweak precision



the Higgs is the main
source of EWSB

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



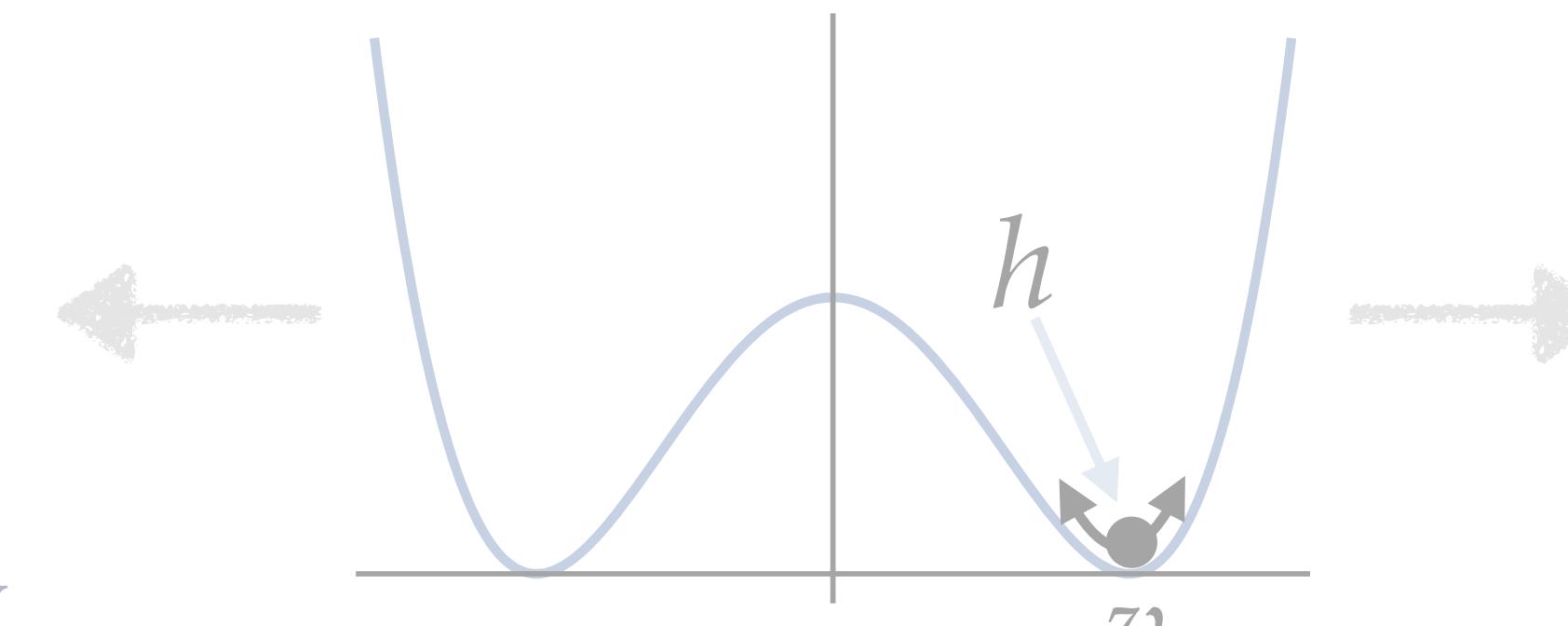
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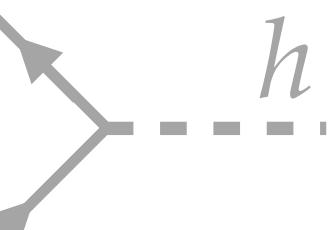
$h \rightarrow WW$

electroweak

testing the SM hypothesis,

what is the source for fermion masses?

implications to new physics



the Higgs is the main
source of EWSB

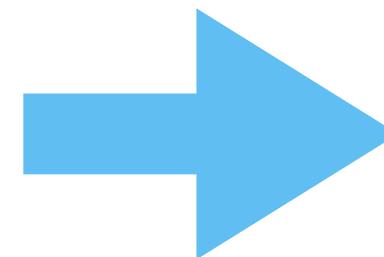
$$y_f = \sqrt{2} \frac{m_f}{v}$$

the Higgs in the SM and EFT

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

the Higgs in the SM and EFT

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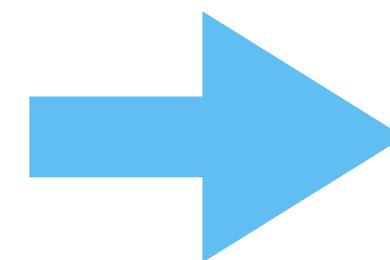


$$y_f^{\text{SM}} = \sqrt{2} \frac{m_f}{v}$$

- non universal
- diagonal
- CP conserving

the Higgs in the SM and EFT

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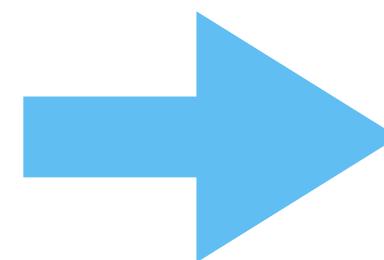
- non universal
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new physics example: EFT

$$\mathcal{L}_Y^{\text{EFT}} = \frac{c_{ij}^u}{\Lambda^2} \tilde{H} \overline{Q}_L^i U_R^j (H^\dagger H) + \frac{c_{ij}^d}{\Lambda^2} H \overline{Q}_L^i D_R^j (H^\dagger H) + \frac{c_{ij}^\ell}{\Lambda^2} H \overline{L}_L^i E_R^j (H^\dagger H)$$

the Higgs in the SM and EFT

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

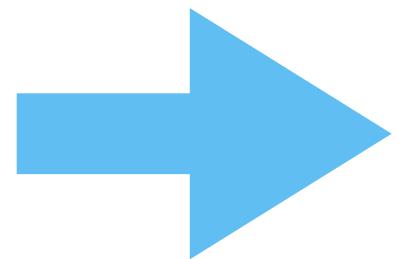


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$$\mathcal{L}_Y^{\text{EFT}} = \frac{c_{ij}^u}{\Lambda^2} \tilde{H} \overline{Q}_L^i U_R^j (H^\dagger H) + \frac{c_{ij}^d}{\Lambda^2} H \overline{Q}_L^i D_R^j (H^\dagger H) + \frac{c_{ij}^\ell}{\Lambda^2} H \overline{L}_L^i E_R^j (H^\dagger H)$$



$$\kappa_f \equiv \frac{y_f}{y_f^{\text{SM}}} = 1 + \frac{v^2}{\Lambda^2} \frac{c_f}{y_f^{\text{SM}}}$$

assumes flavor alignment

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

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	$1 + \frac{\Re(a_d v^2 + 2c_d m_t^2)}{\Lambda^2}$	$1 - \frac{2\Re(c_d)m_t^2}{\Lambda^2}$	$\frac{\Im(a_d v^2 + 2c_d m_t^2)}{\Lambda^2}$	$\frac{\Im(a_d v^2 + 2c_d V_{ts(td)} ^2 m_t^2)}{\Lambda^2}$
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	$1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(y_*^2 \lambda^2 \frac{v^2}{M_*^2}\right)$	$1 + \mathcal{O}\left(y_*^2 \lambda^2 \frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2 \lambda^2 \frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2 \lambda^2 \frac{v^2}{M_*^2}\right)$

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	$\cos\alpha/\sin\beta$	$-\tan\alpha/\tan\beta$	$\mathcal{O}\left(\frac{m_\mu}{m_\tau} \frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_{\mu(e)}^2}{m_\tau^2} \frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
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	$1 + \mathcal{O}\left(\bar{Y}^2 \frac{v^2}{m_{KK}^2}\right)$	$1 + \mathcal{O}\left(\bar{Y}^2 \frac{v^2}{m_{KK}^2}\right)$	$\mathcal{O}\left(\bar{Y}^2 \frac{v^2}{m_{KK}^2}\right)$	$\mathcal{O}\left(\bar{Y}^2 \frac{v^2}{m_{KK}^2}\right)$

probing the Higgs Yukawa couplings

lepton sector

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

lepton sector

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

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

$$\mu_{ee} < 6 \times 10^4$$

$$\mu_{\mu\mu} = 1.2 \pm 0.4$$

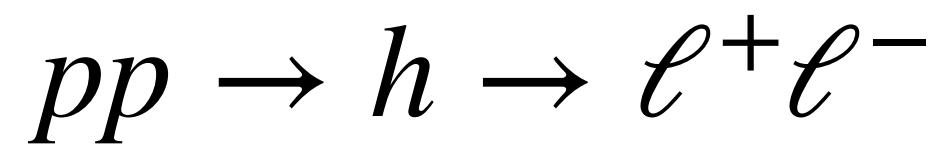
$$\mu_{\tau\tau} = 0.96 \pm 0.12$$

ATLAS, CMS
CERN yellow report, 1812.07638

$$\mu_f \equiv \frac{\sigma_{pp \rightarrow h} \text{BR}_{h \rightarrow f}}{\sigma_{pp \rightarrow h}^{\text{SM}} \text{BR}_{h \rightarrow f}^{\text{SM}}}$$

lepton sector

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



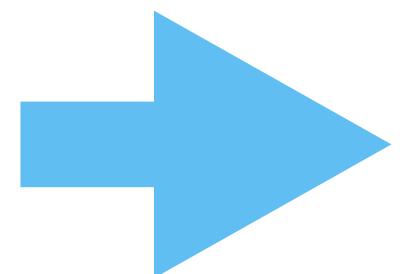
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$$\mu_f \equiv \frac{\sigma_{pp \rightarrow h} \text{BR}_{h \rightarrow f}}{\sigma_{pp \rightarrow h}^{\text{SM}} \text{BR}_{h \rightarrow f}^{\text{SM}}}$$



- non universal coupling: $y_\tau > y_\mu, y_e$
- probe scale of: $\Lambda_e \gtrsim 6 \text{ TeV}$, $\Lambda_\mu \gtrsim 15 \text{ TeV}$, $\Lambda_\tau \gtrsim 7.7 \text{ TeV}$

quark sector

direct

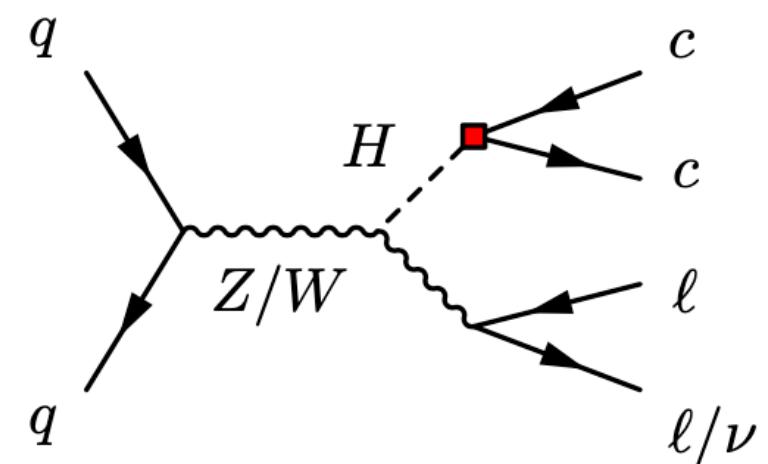
indirect

quark sector

direct

inclusive: flavor tagging

indirect

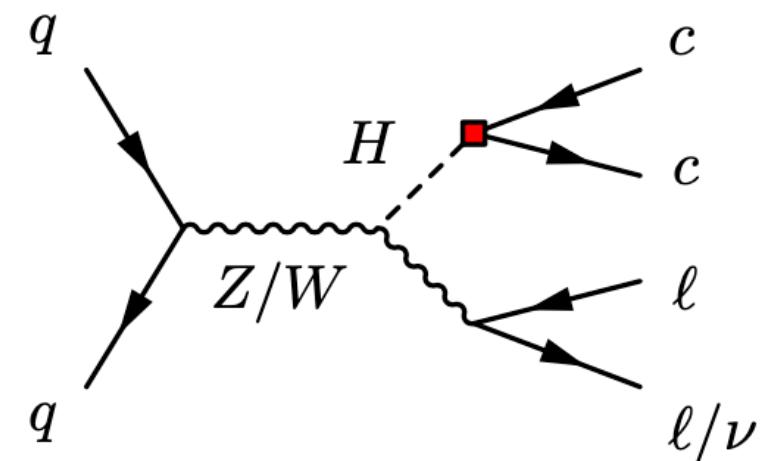


ATLAS, CMS, LHCb
Delaunay et al 1310.7029,
Perez et al 1505.06689, 1503.00290
Brivio et al 1507.02916

quark sector

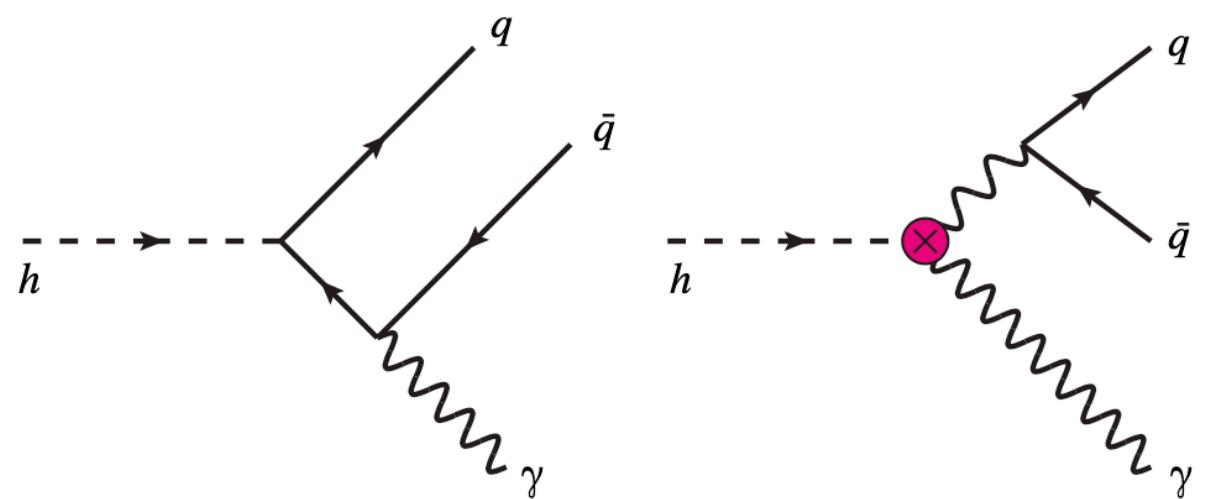
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exclusive: $h \rightarrow V\gamma$



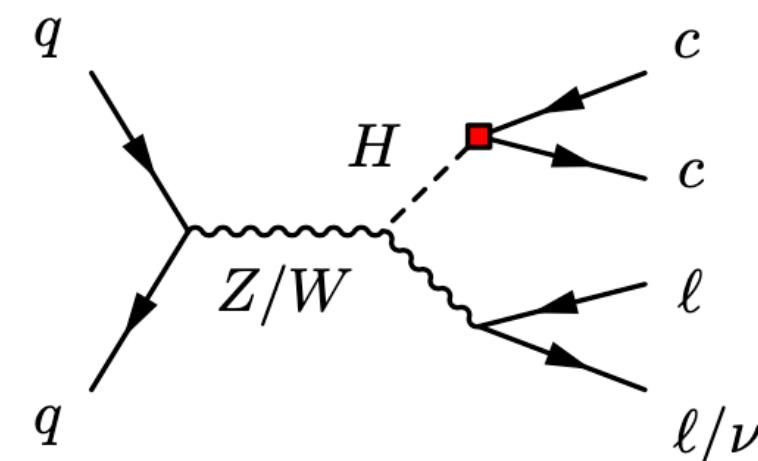
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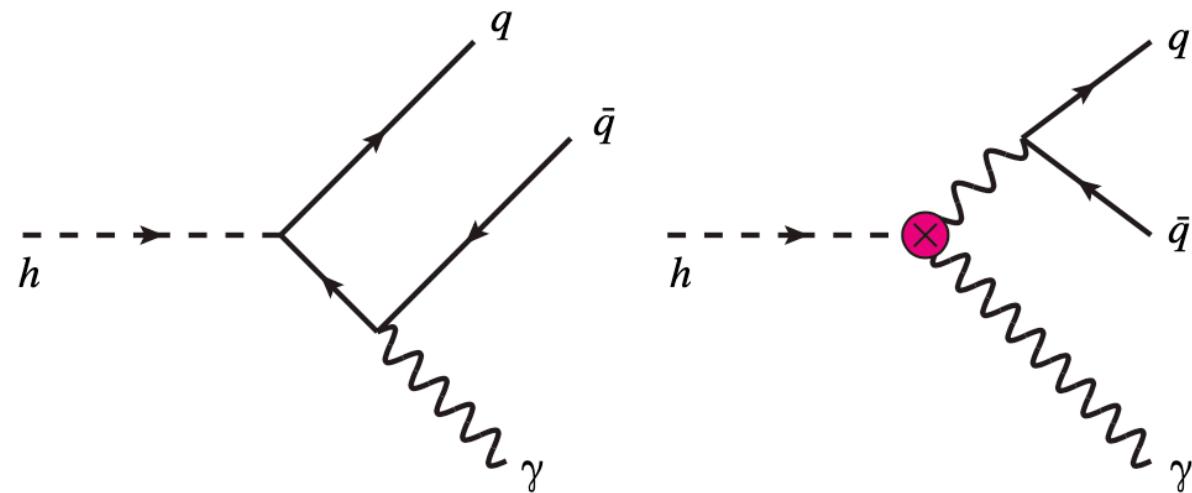
indirect

kinematics

Higgs differential distribution
 Wh asymmetry
triboson final states
off-shell kinematics

Bishara et al 1606.09253,
YS et al 1606.09621
Yu 1609.06592
Falkowski et al 2011.09551
Balzani et al 2304.09772

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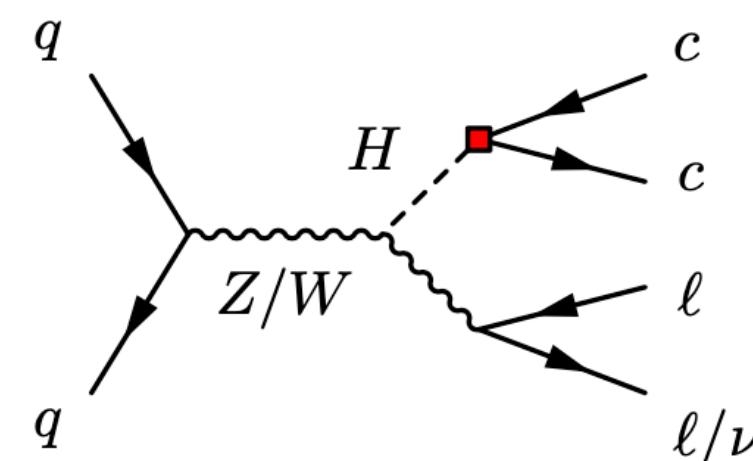


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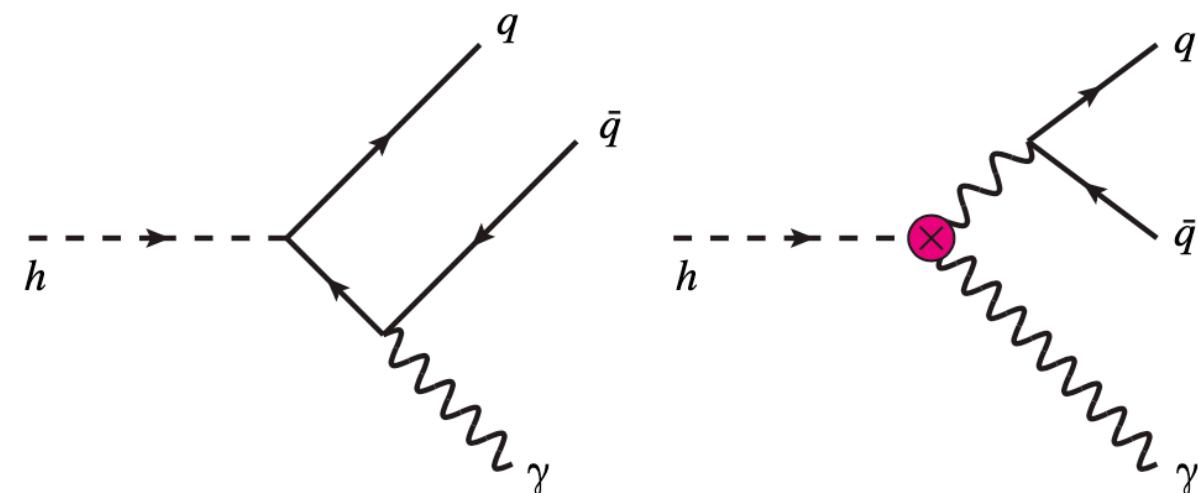
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total width

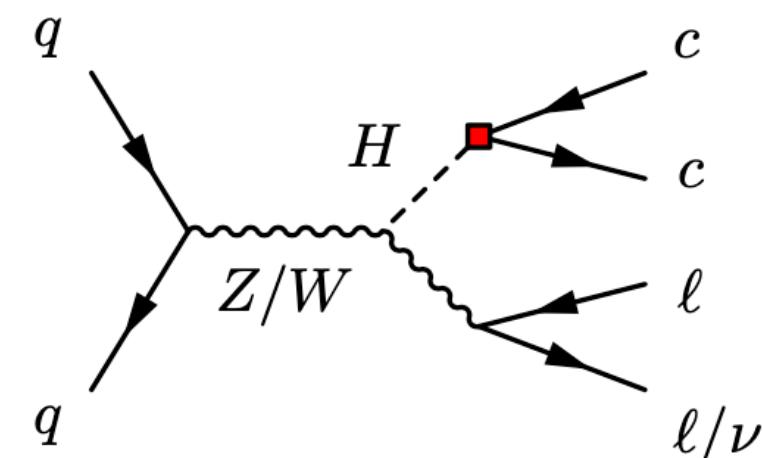
$\Gamma_{h \rightarrow q\bar{q}} < \Gamma_h$
line shape ($\gamma\gamma + ZZ$)
off-shell Higgs

ATLAS, CMS
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quark sector

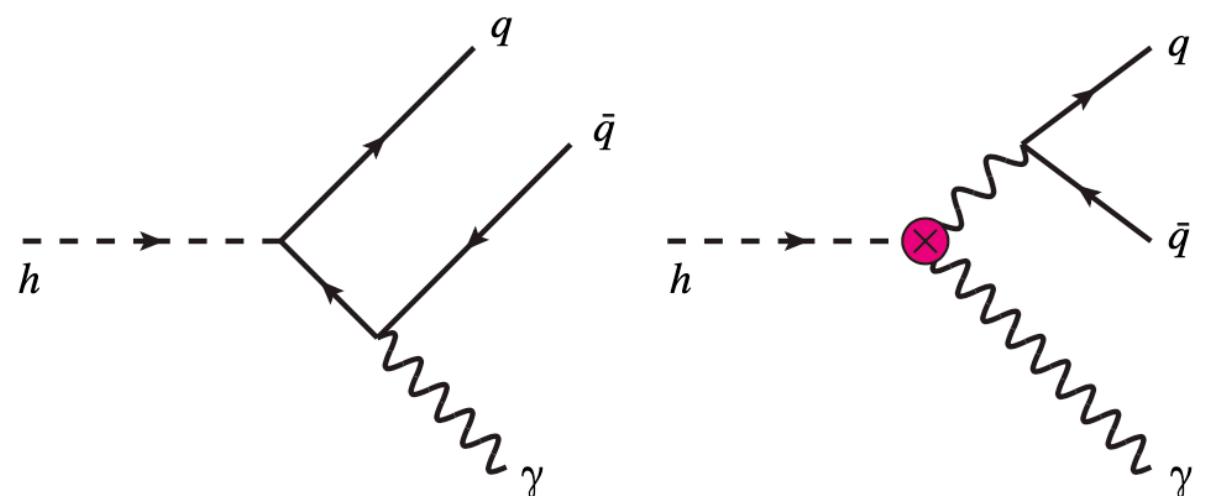
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total width

$\Gamma_{h \rightarrow q\bar{q}} < \Gamma_h$
line shape ($\gamma\gamma + ZZ$)
off-shell Higgs

$\kappa_u < 3.4 \times 10^3$ $\kappa_c < 6.2$
 $\kappa_d < 1.7 \times 10^3$ $\kappa_s < 42$

quark sector: inclusive rates

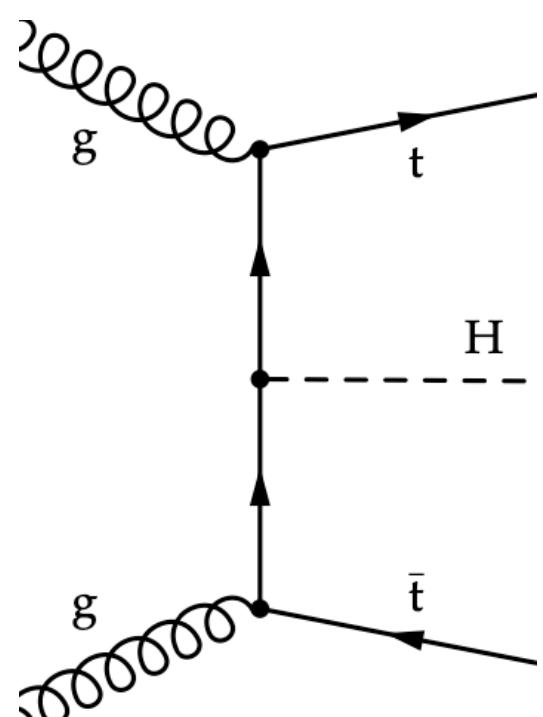
$$Y^U = \begin{pmatrix} y_u \\ & y_c \\ & & y_t \end{pmatrix}$$

$$Y^d = \begin{pmatrix} y_d \\ & y_s \\ & & y_b \end{pmatrix}$$

quark sector: inclusive rates

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

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



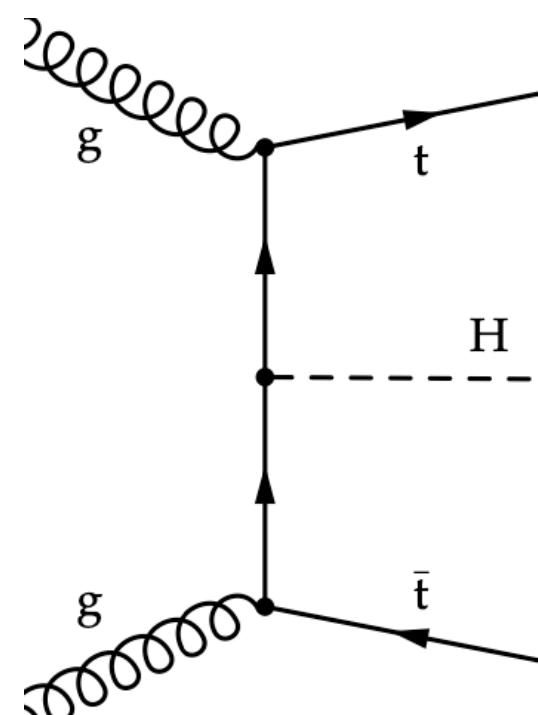
$\mu_{t\bar{t}h} = 1.1 \pm 0.2$ ATLAS, CMS

quark sector: inclusive rates

$$Y^U = \begin{pmatrix} y_u \\ & y_c \\ & & y_t \end{pmatrix}$$

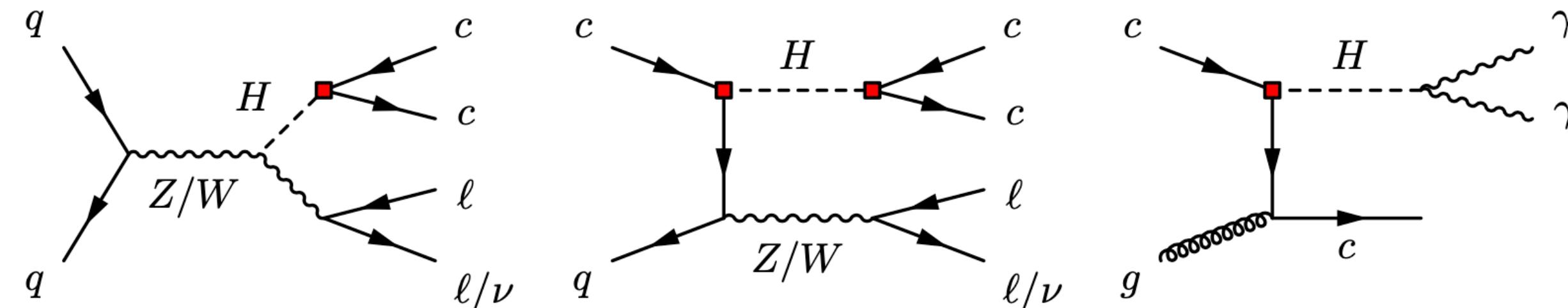
$$Y^d = \begin{pmatrix} y_d \\ & y_s \\ & & y_b \end{pmatrix}$$

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



$$\mu_{t\bar{t}h} = 1.1 \pm 0.2 \quad \text{ATLAS, CMS}$$

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



$$\mu_{b\bar{b}} = 1.0 \pm 0.2 \quad \mu_{c\bar{c}} < 14$$

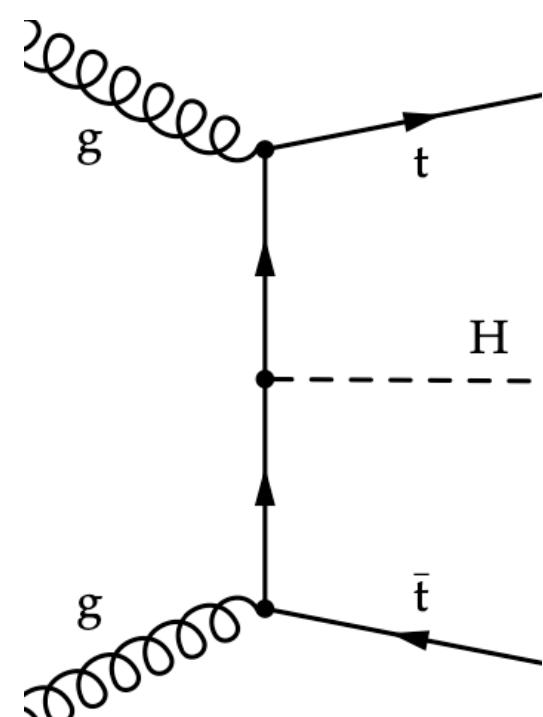
ATLAS, CMS, LHCb
Delaunay et al 1310.7029,
Perez et al 1505.06689, 1503.00290
Brivio et al 1507.02916

quark sector: inclusive rates

$$Y^U = \begin{pmatrix} y_u \\ & y_c \\ & & y_t \end{pmatrix}$$

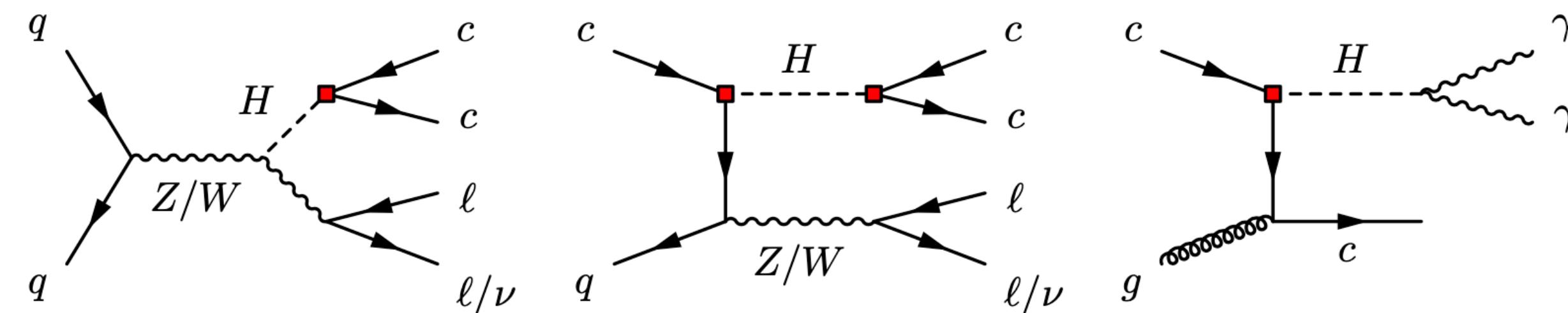
$$Y^d = \begin{pmatrix} y_d \\ & y_s \\ & & y_b \end{pmatrix}$$

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



$$\mu_{t\bar{t}h} = 1.1 \pm 0.2 \quad \text{ATLAS, CMS}$$

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



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

$$\mu_{b\bar{b}} = 1.0 \pm 0.2 \quad \mu_{c\bar{c}} < 14$$

s-tagging possible at e^+e^- collider

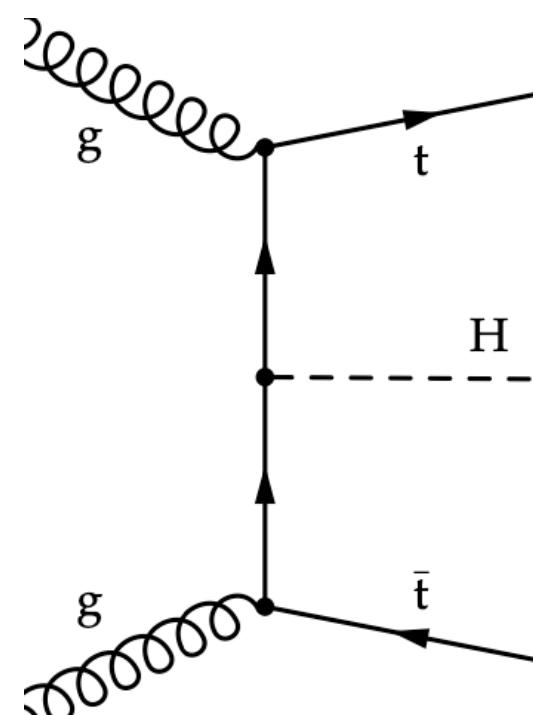
e.g. Duarte-Campderros et al 1811.09636

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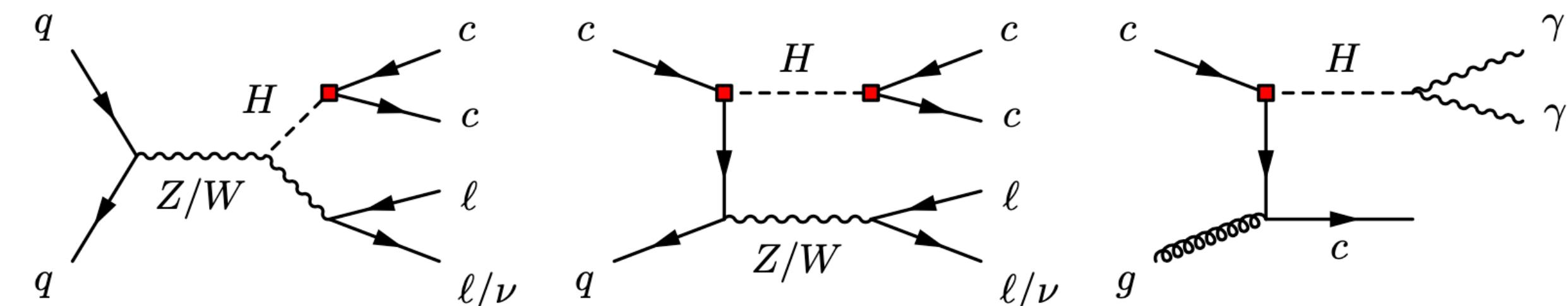
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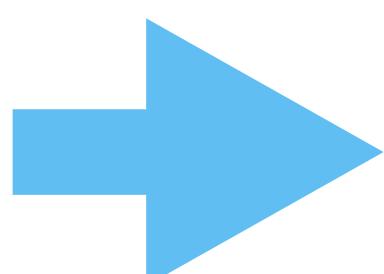
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ATLAS, CMS, LHCb
Delaunay et al 1310.7029,
Perez et al 1505.06689, 1503.00290
Brivio et al 1507.02916



- non universal coupling: $y_t > y_b, y_c$
- probe scale of $\Lambda_t \gtrsim 0.5 \text{ TeV}$, $\Lambda_b \gtrsim 4.5 \text{ TeV}$, $\Lambda_c \gtrsim 2.4 \text{ TeV}$

quark sector: exclusive rates

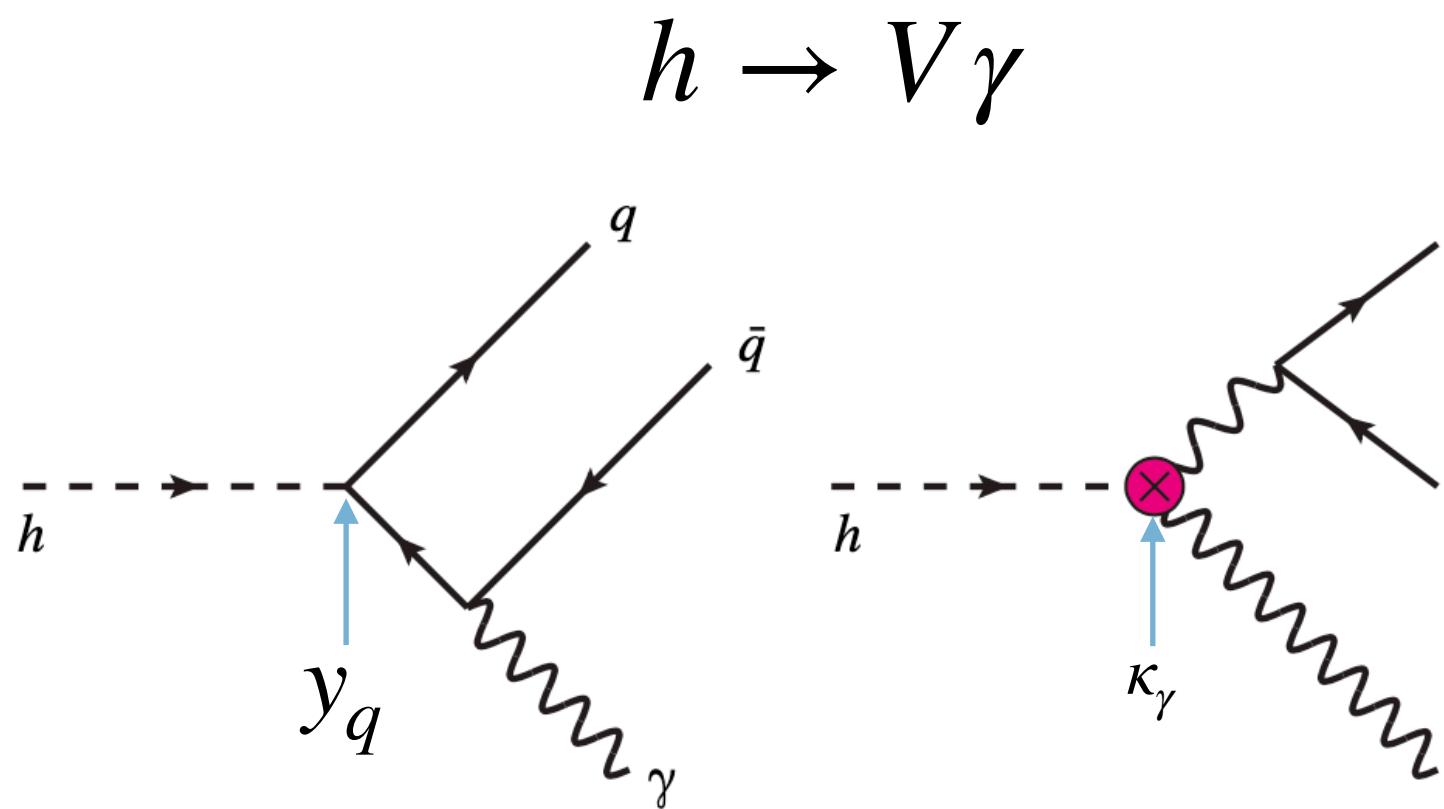
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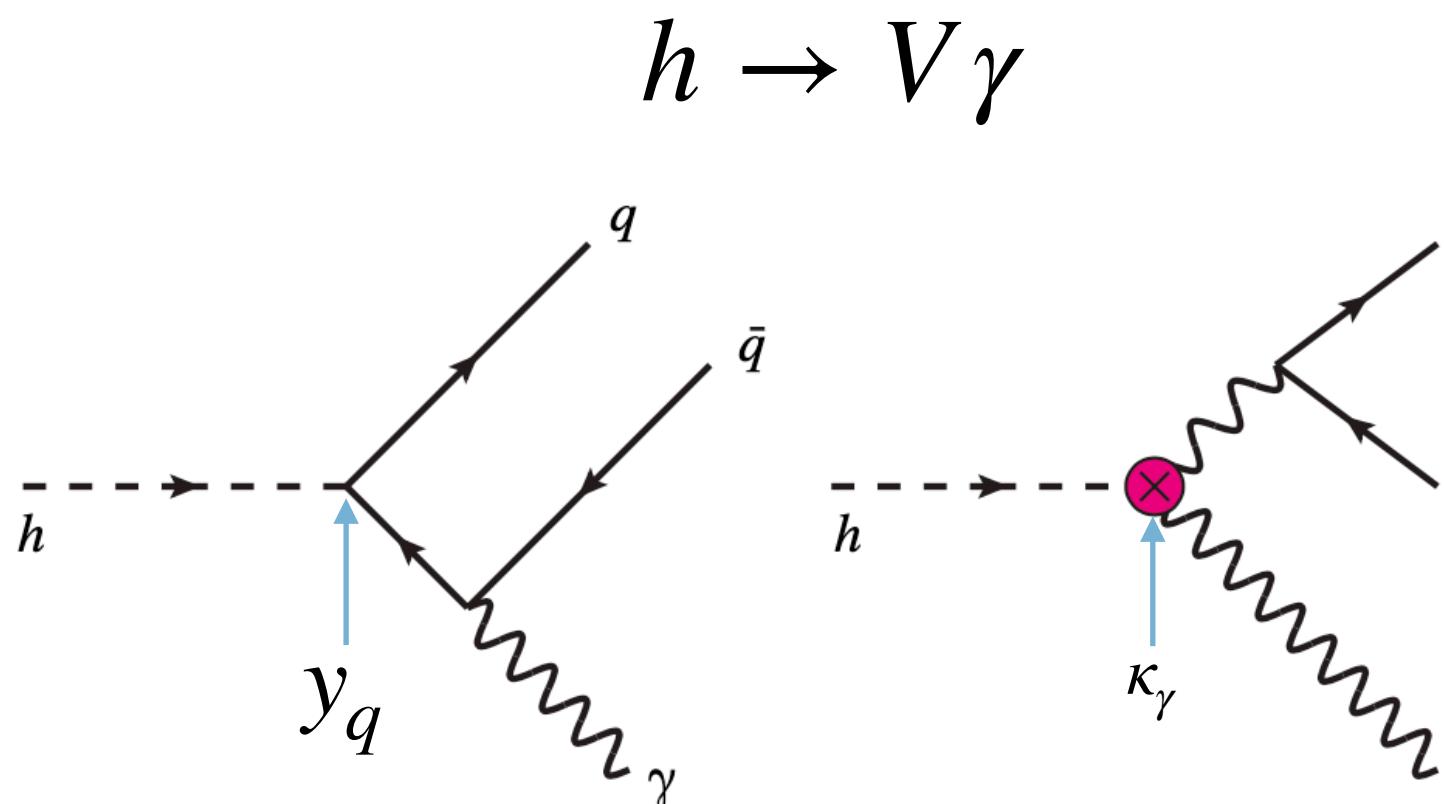


ATLAS, CMS
 Bodwin et al 1306.5770 Kagan et al 1406.1722
 Bodwin et al 1407.6695 Perez et al 1503.00290
 Koing, Neubert, 1505.03870, Alte et al 1609.06310
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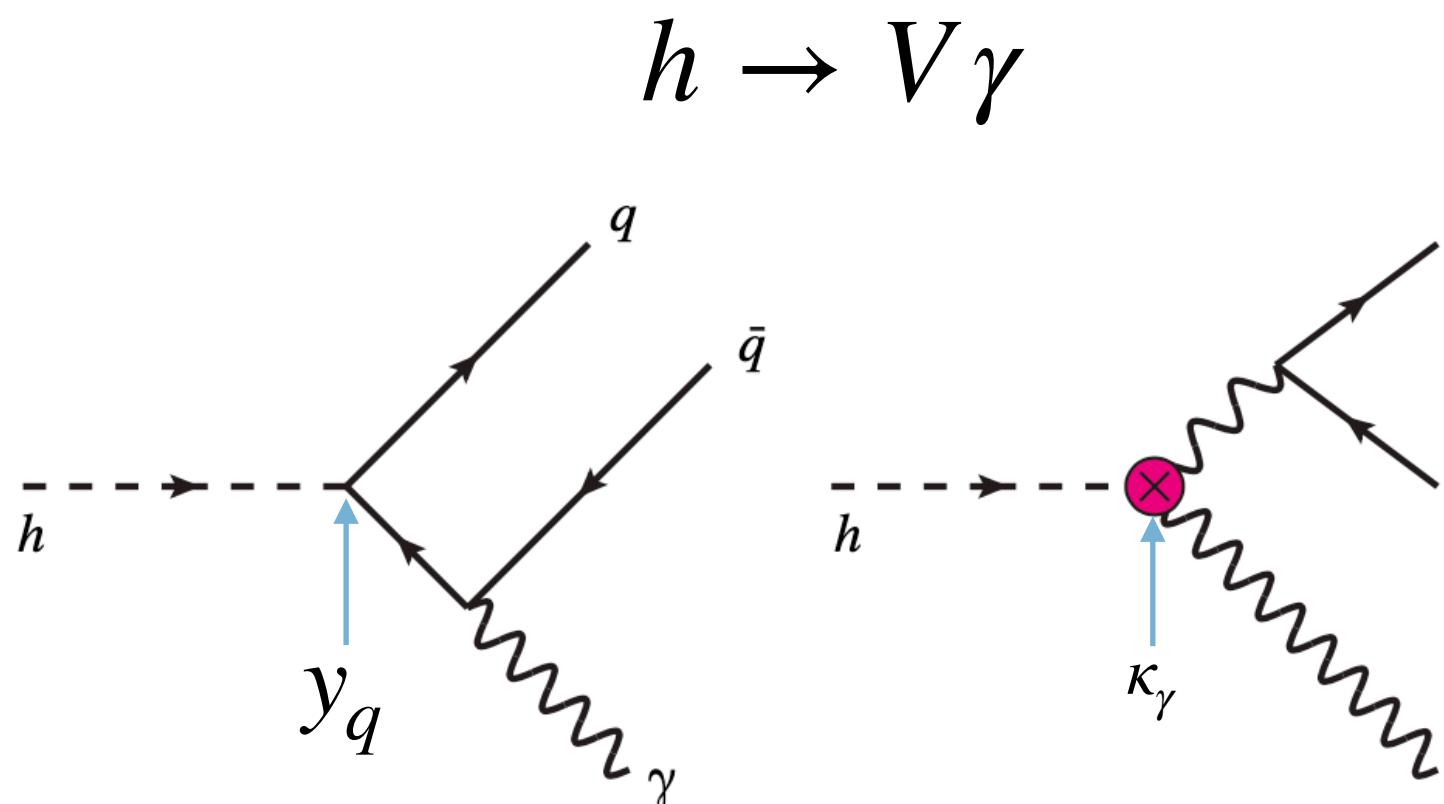
$$\mathcal{R}_{V\gamma, ZZ^*} \equiv \frac{\mu_{V\gamma}}{\mu_{ZZ^*}} \frac{\text{BR}_{h \rightarrow V\gamma}^{\text{SM}}}{\text{BR}_{h \rightarrow ZZ^*}^{\text{SM}}} \simeq \frac{\Gamma_{h \rightarrow V\gamma}}{\Gamma_{h \rightarrow ZZ^*}}$$

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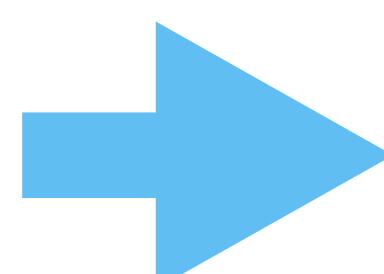
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also $h \rightarrow VZ$



V	$\text{BR}_{h \rightarrow V\gamma} <$	$\mathcal{R}_{V\gamma, ZZ^*} <$	Yukawa range, $\bar{\kappa}_q \equiv y_q/y_b^{\text{SM}}$
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	$2\bar{\kappa}_u + \bar{\kappa}_d < 330$
ω	1.4×10^{-4}	0.9	$2\bar{\kappa}_u - \bar{\kappa}_d < 480$
K^*	8.9×10^{-5}	0.6	

$\Lambda_q \gtrsim 200 \text{ GeV}$

ATLAS, CMS
 Bodwin et al 1306.5770 Kagan et al 1406.1722
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quark sector: from Higgs distributions

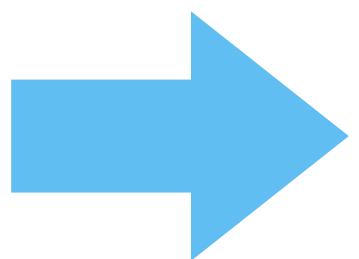
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quark sector: from Higgs distributions

$$Y^U = \begin{pmatrix} y_u \\ & y_c \\ & & y_t \end{pmatrix}$$

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



$$Y^d = \begin{pmatrix} y_d \\ & y_s \\ & & y_b \end{pmatrix}$$

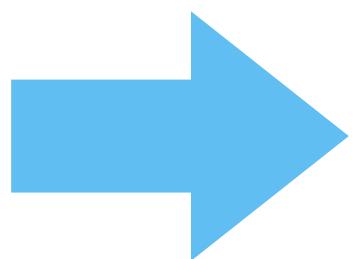
$q\bar{q} \rightarrow h$ production
(SM is dominated by $gg \rightarrow h$)

quark sector: from Higgs distributions

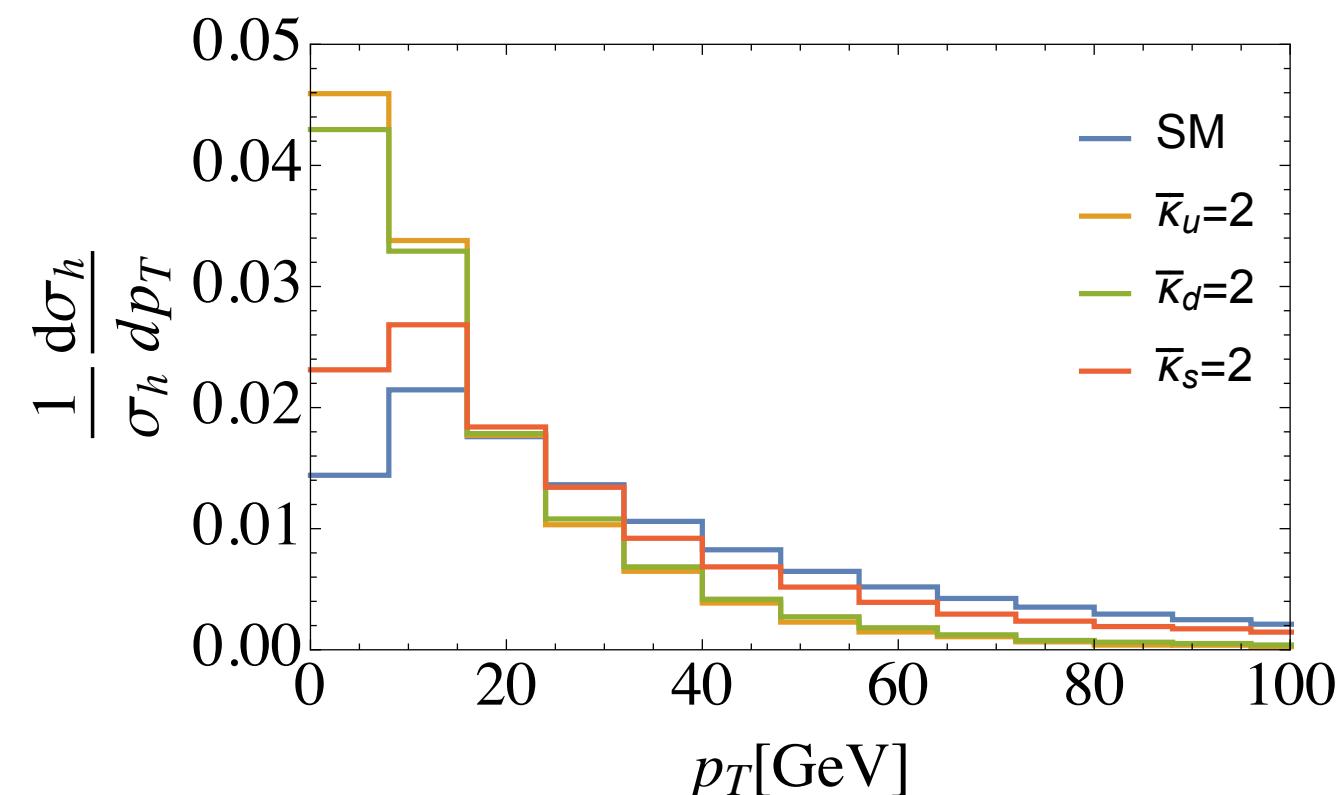
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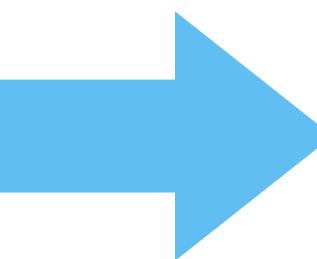
softer p_T spectrum

quark sector: from Higgs distributions

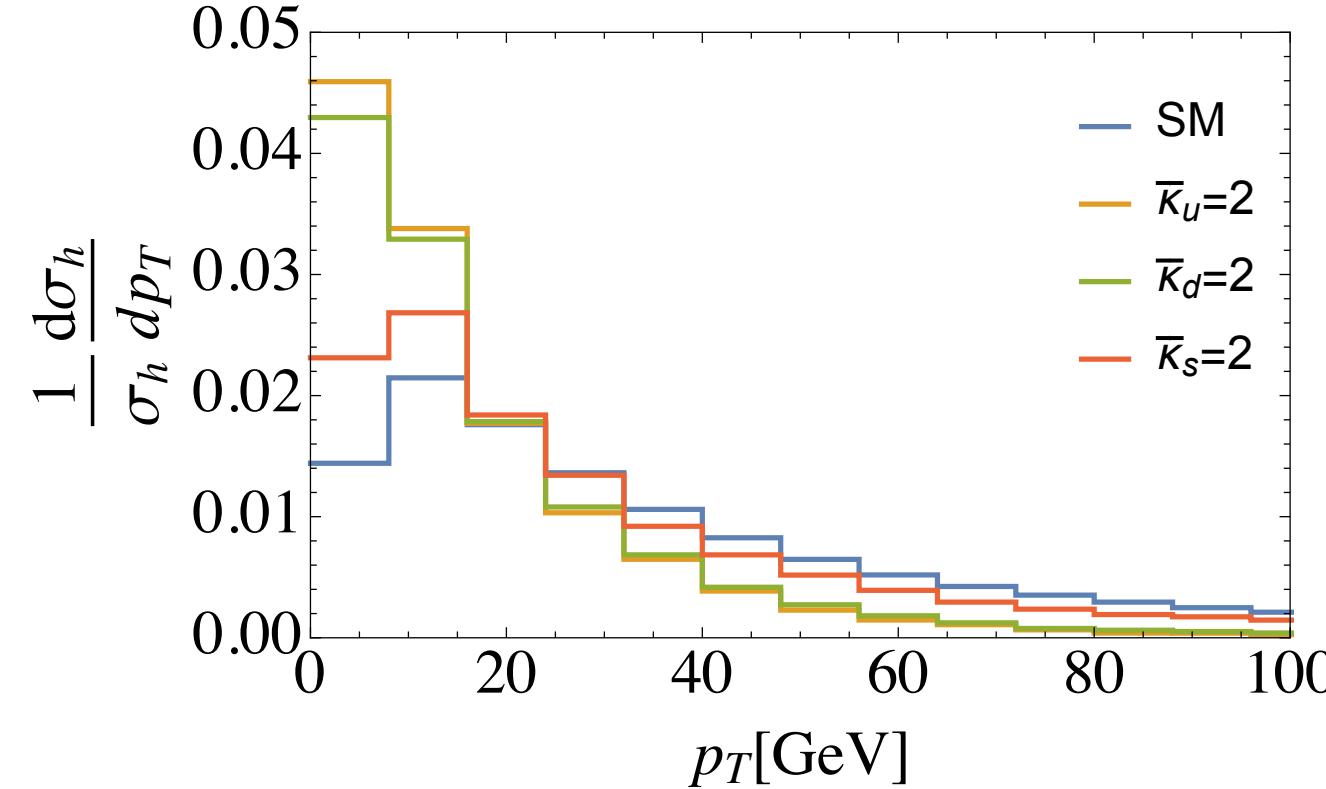
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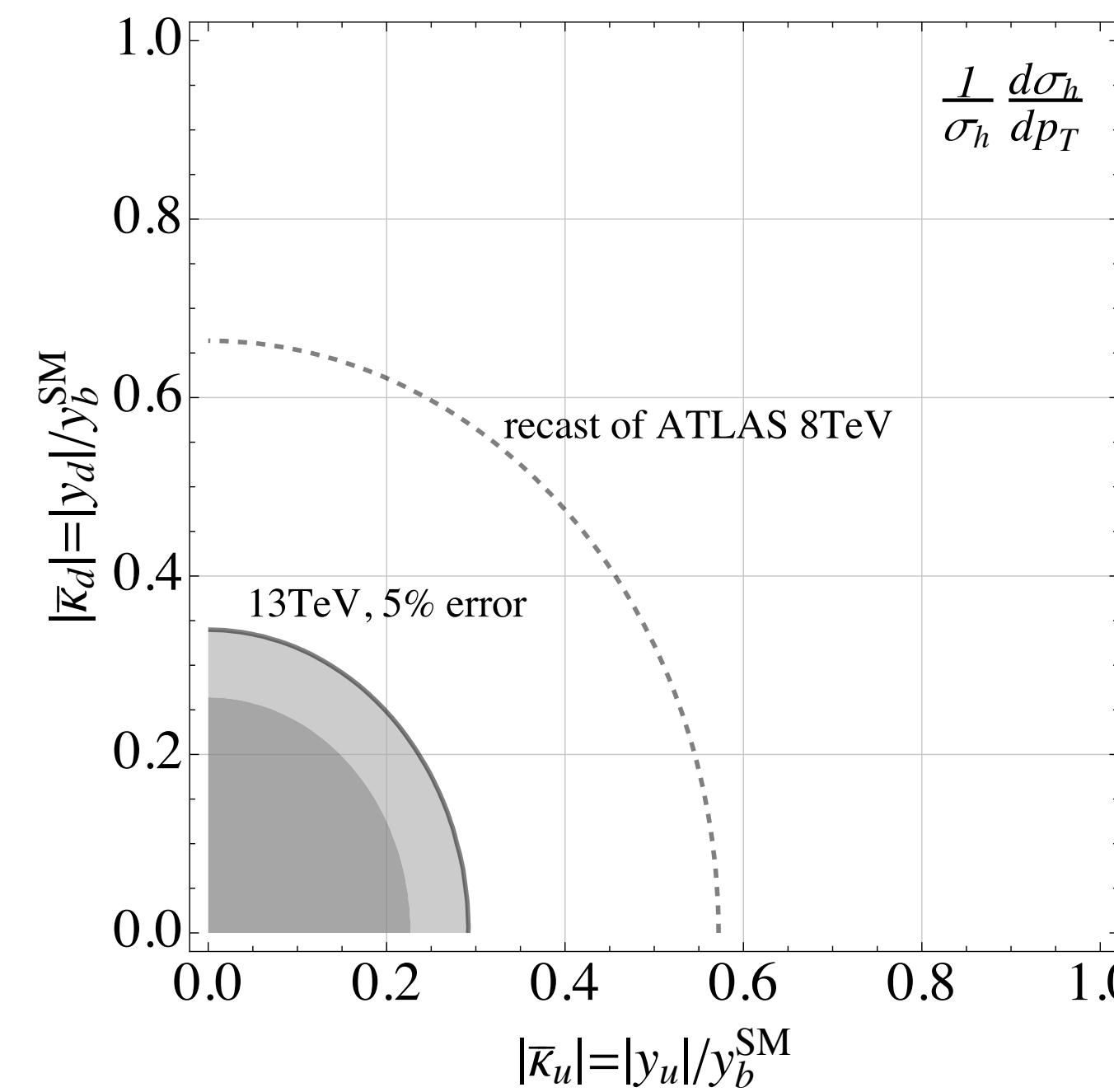
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$q\bar{q} \rightarrow h$ production
(SM is dominated by $gg \rightarrow h$)



softer p_T spectrum



$$\begin{aligned} \bar{\kappa}_u &< 0.46 \\ \bar{\kappa}_d &< 0.54 \end{aligned}$$

recast of
ATLAS 8TeV

$$\Lambda_q \gtrsim 3 \text{ TeV}$$

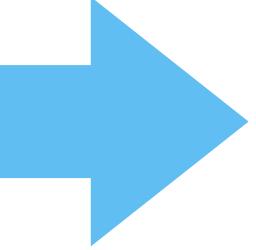
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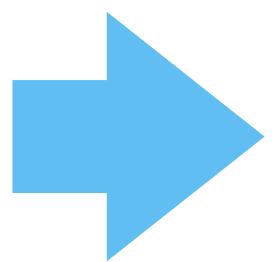
loop effect in $gg \rightarrow h$ 

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

quark sector: from Higgs distributions

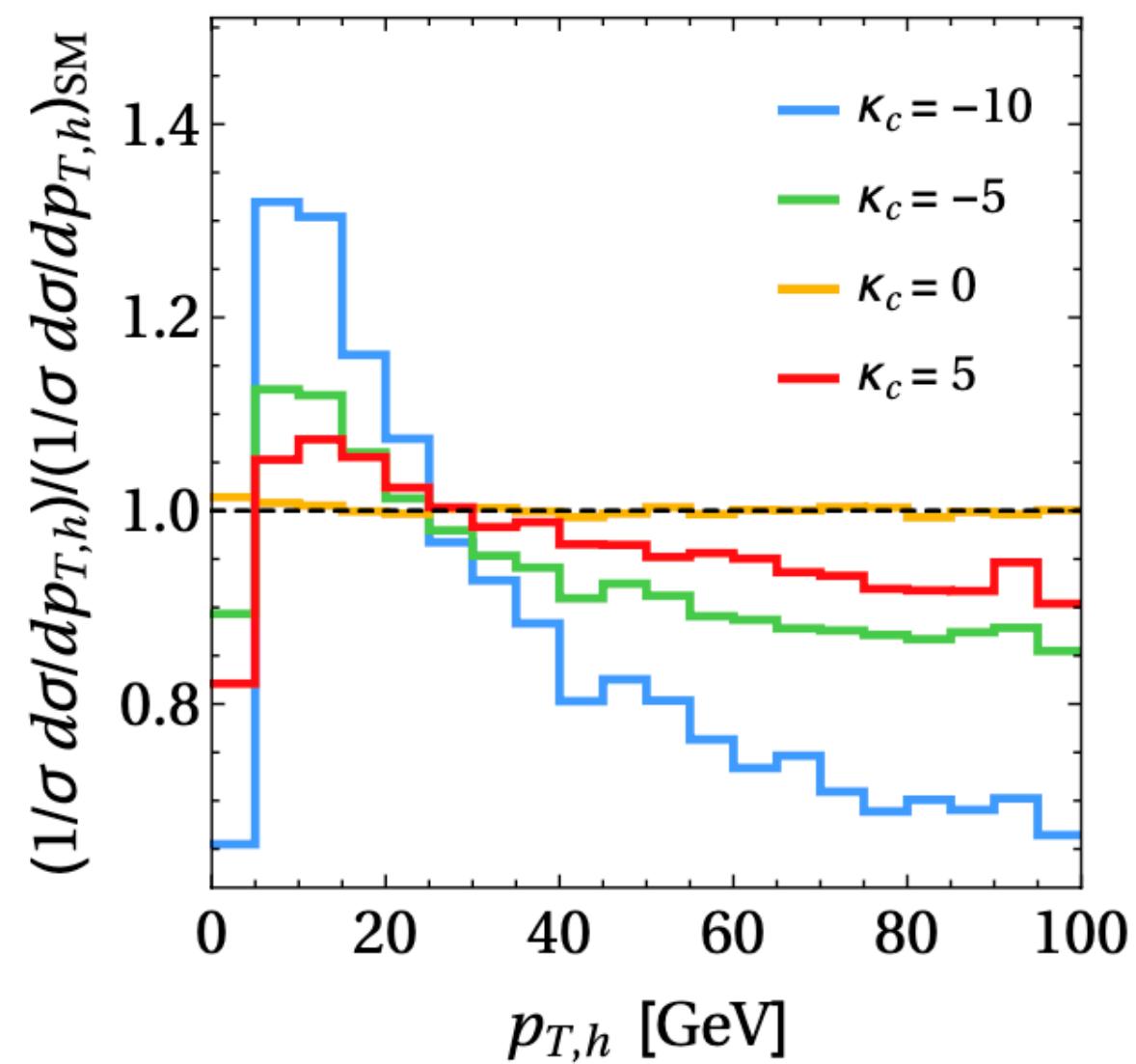
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loop effect in
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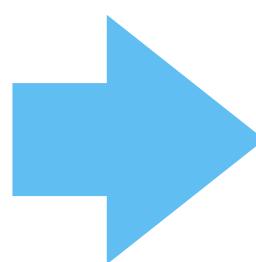


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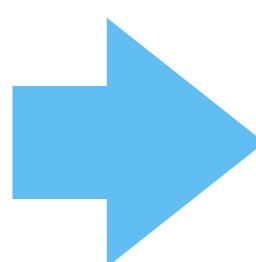
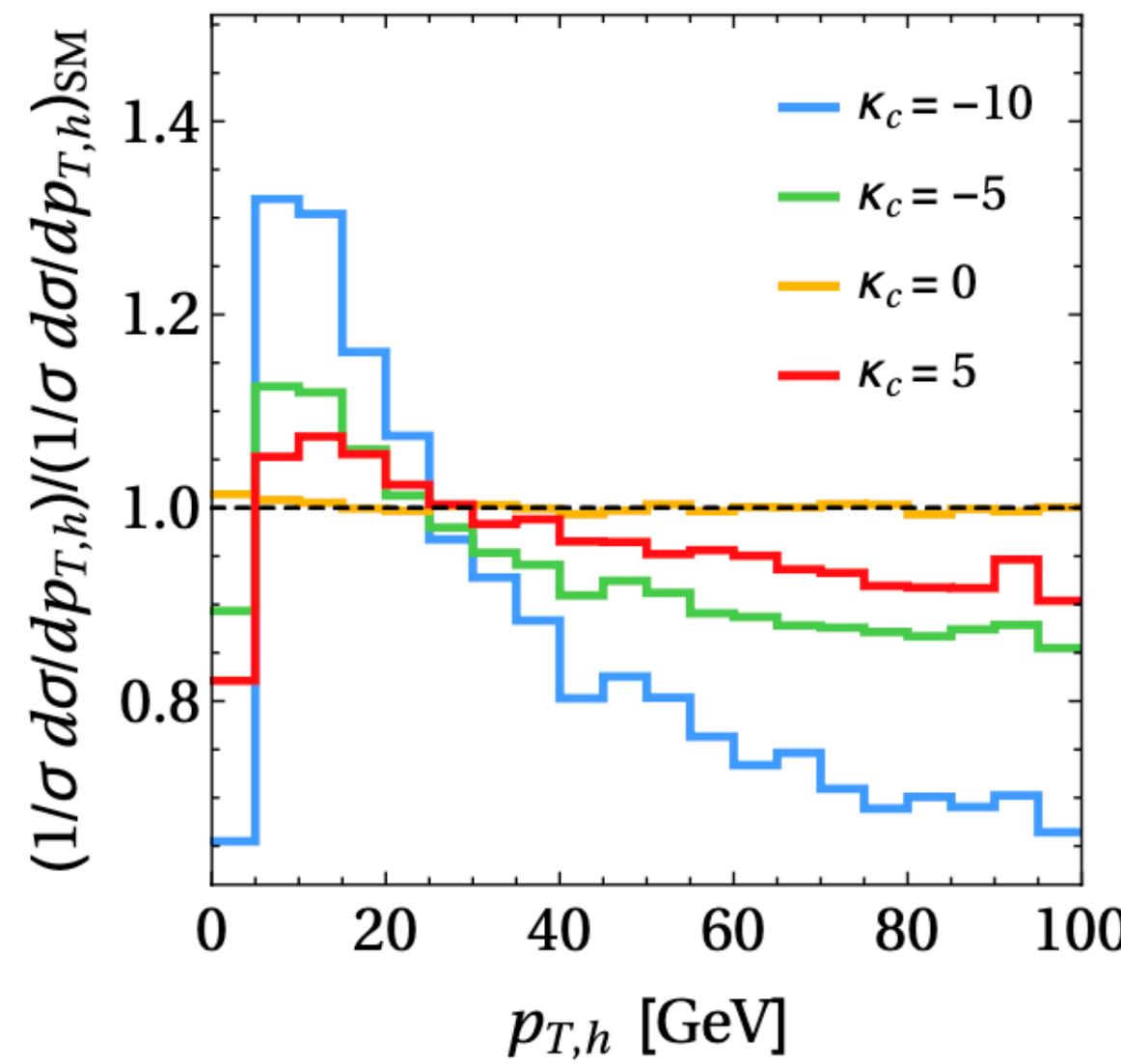
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$$\begin{aligned} \kappa_c &< 38 \\ \kappa_b &< 18 \end{aligned}$$

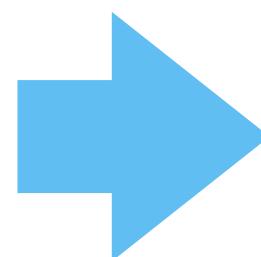
CMS, 13TeV, 36 fb^{-1}

quark sector: from Higgs distributions

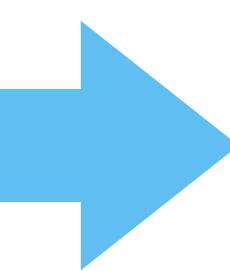
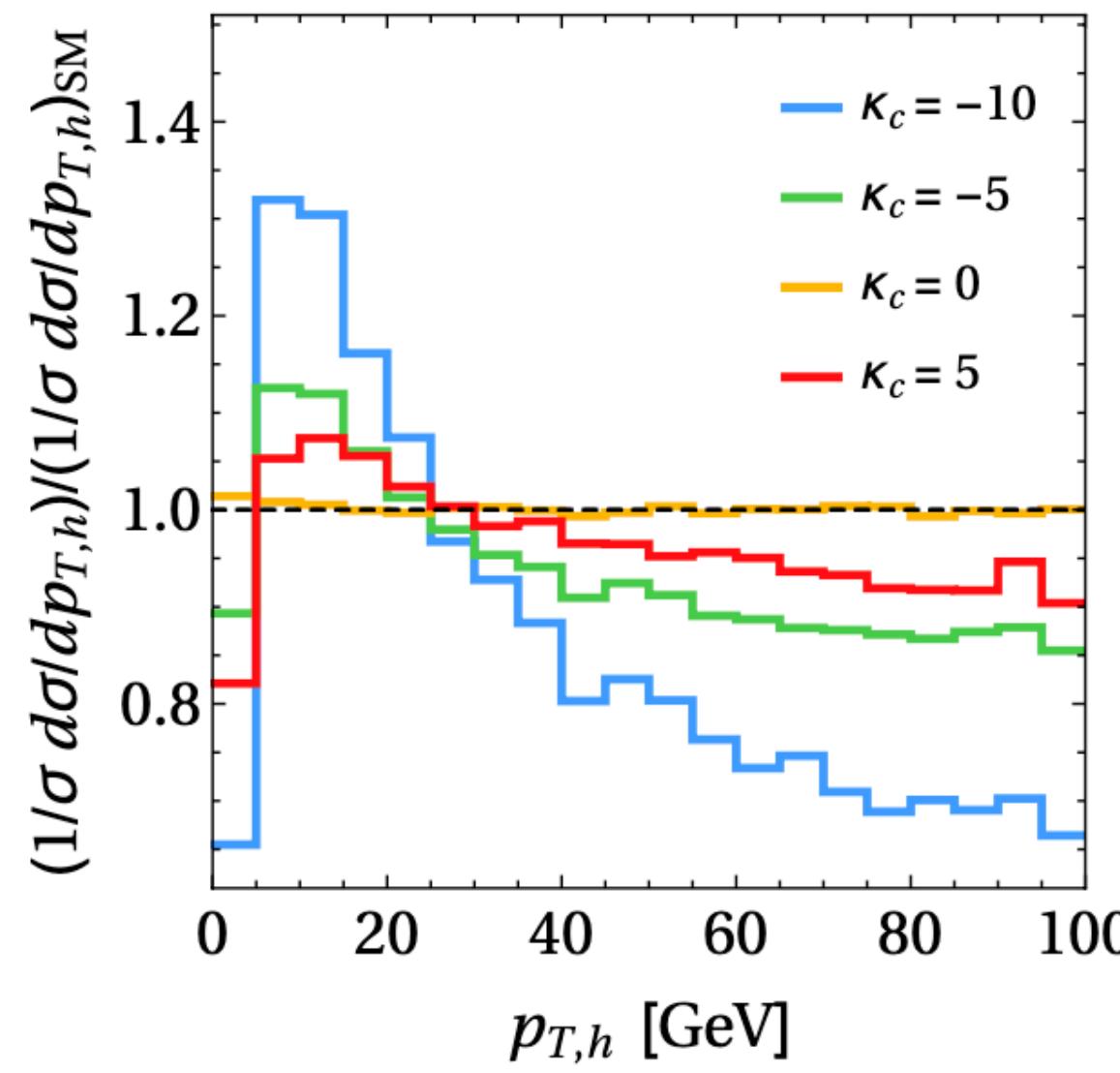
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loop effect in
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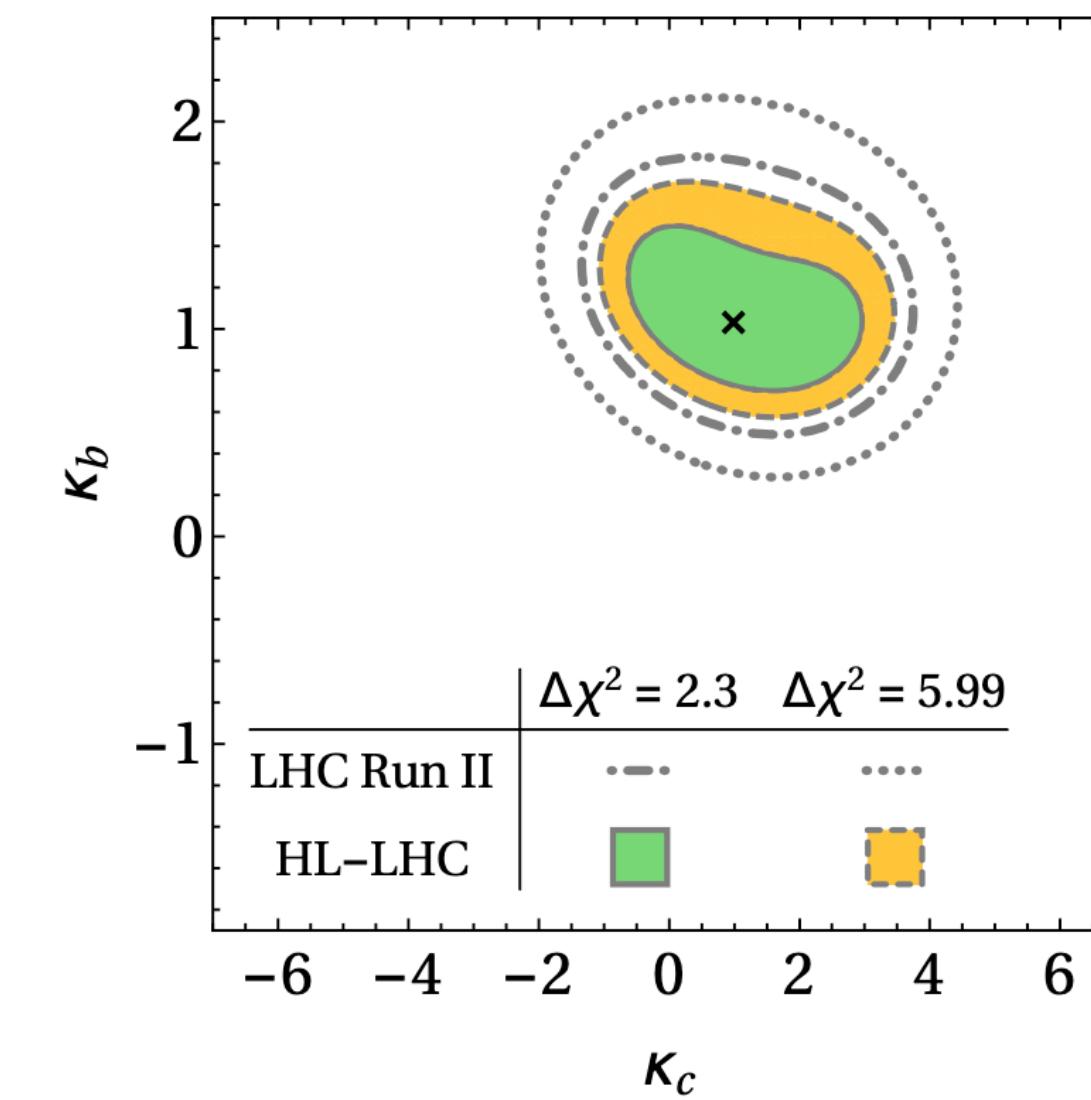
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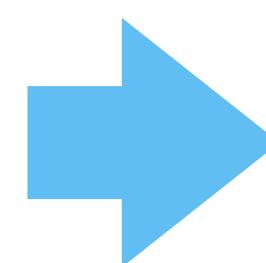


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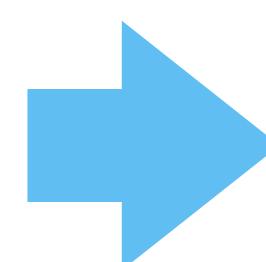
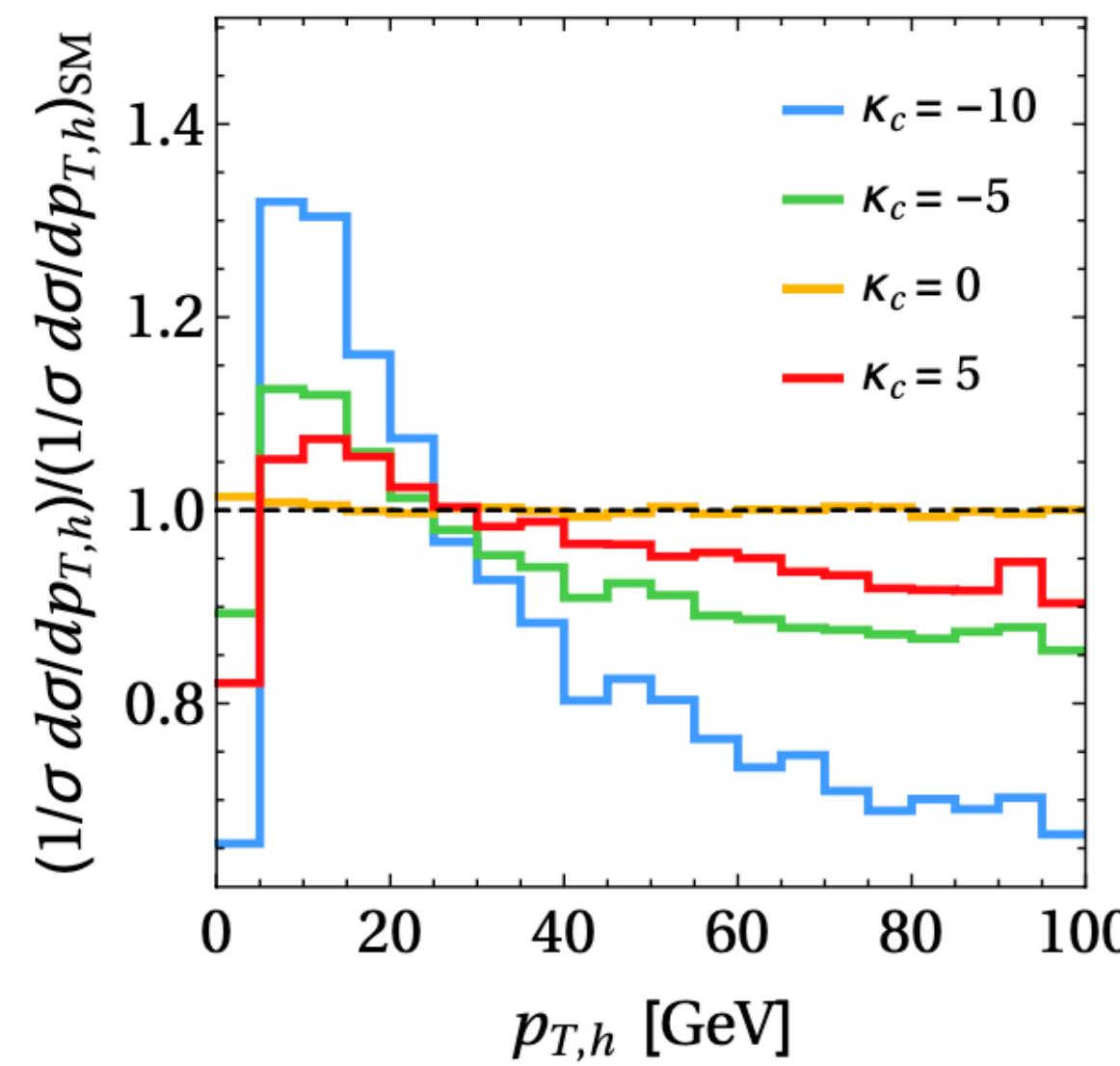
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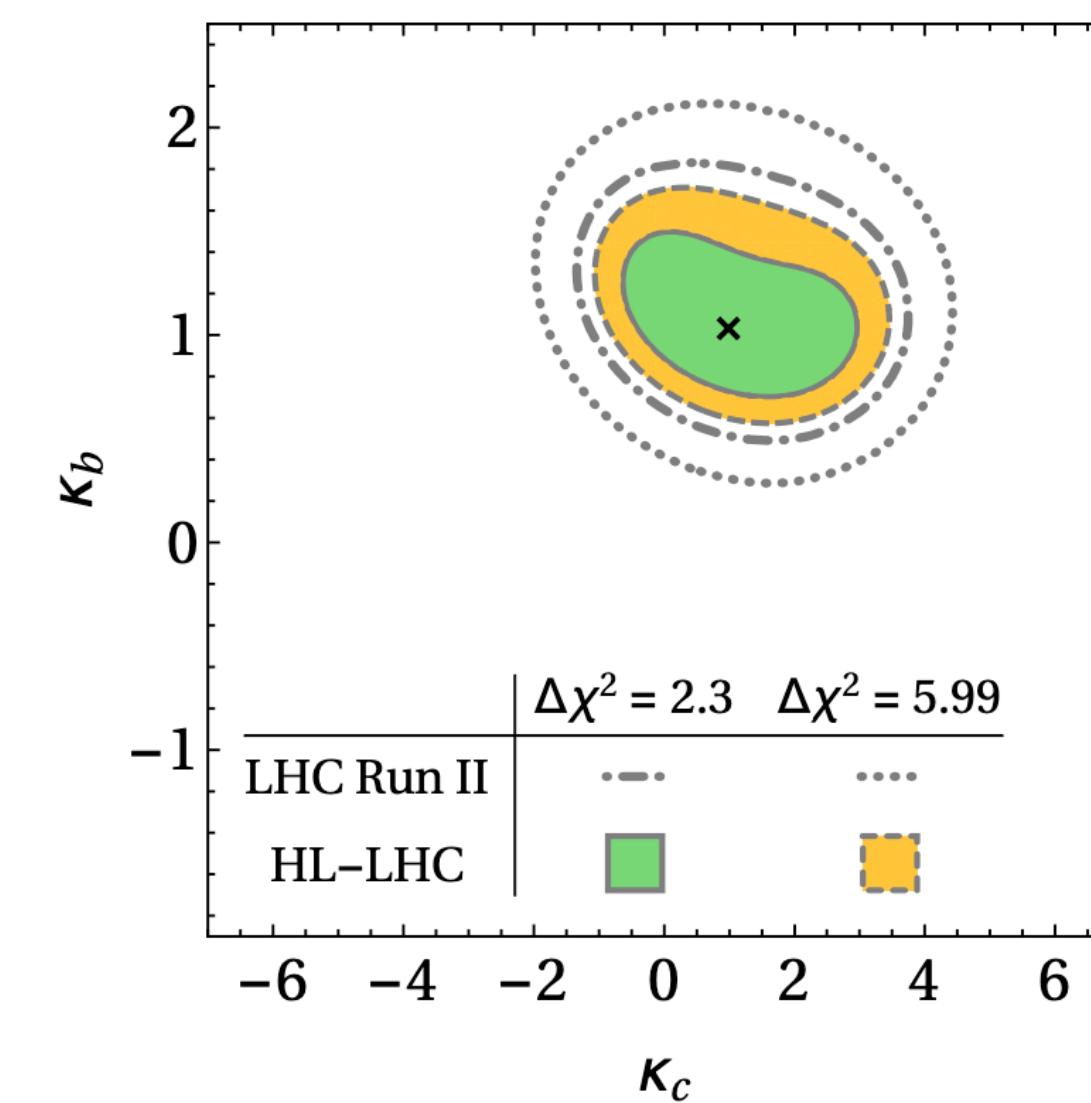
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$$\kappa_c < 38$$

$$\kappa_b < 18$$

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



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

Z (LEP) vs Higgs (LHC)

Z pole observables typically probe

$$\frac{H^\dagger D_\mu H \bar{\psi}_{L,R} \gamma^\mu \psi_{L,R}}{\Lambda^2}$$

$$\Lambda \gtrsim (1 - 10) \text{ TeV}$$

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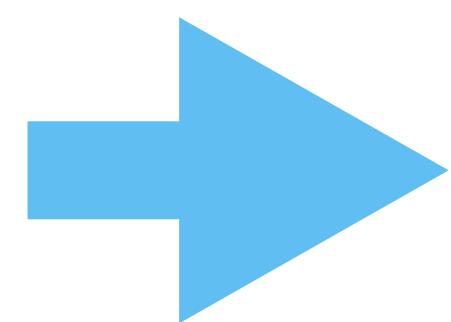
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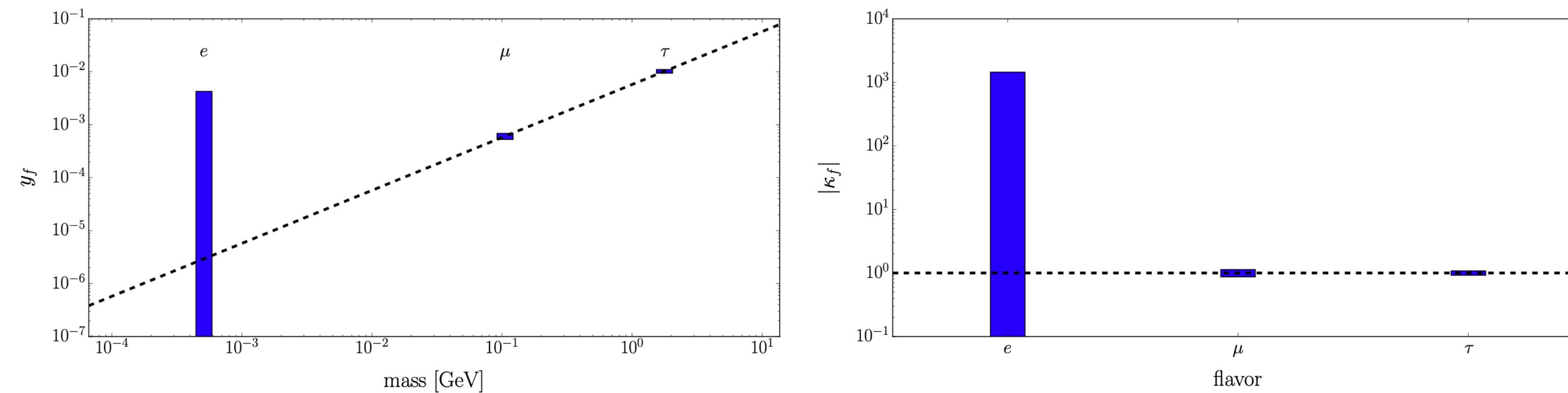


the Higgs program already probe EFT scale as LEP

future projections

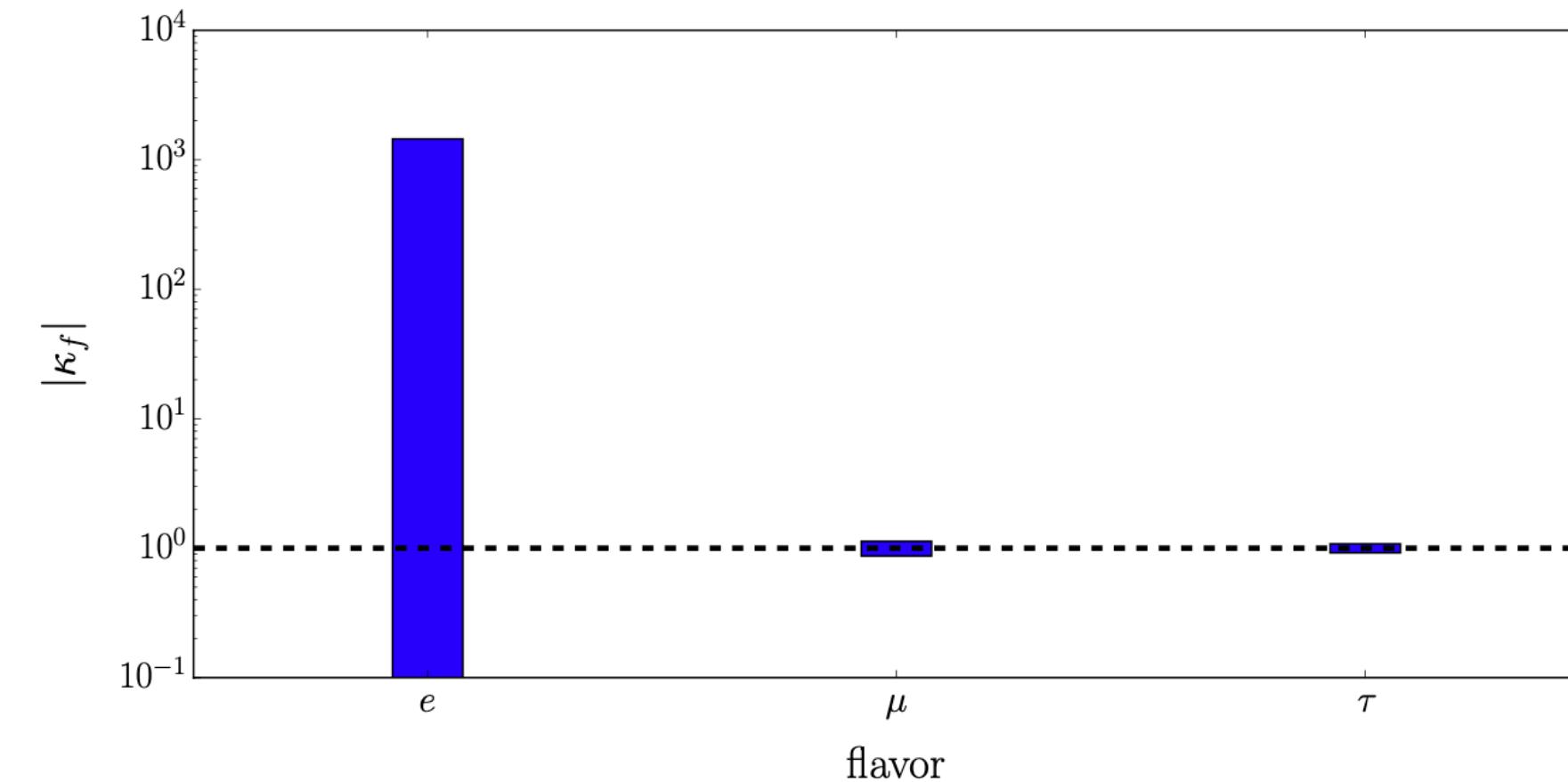
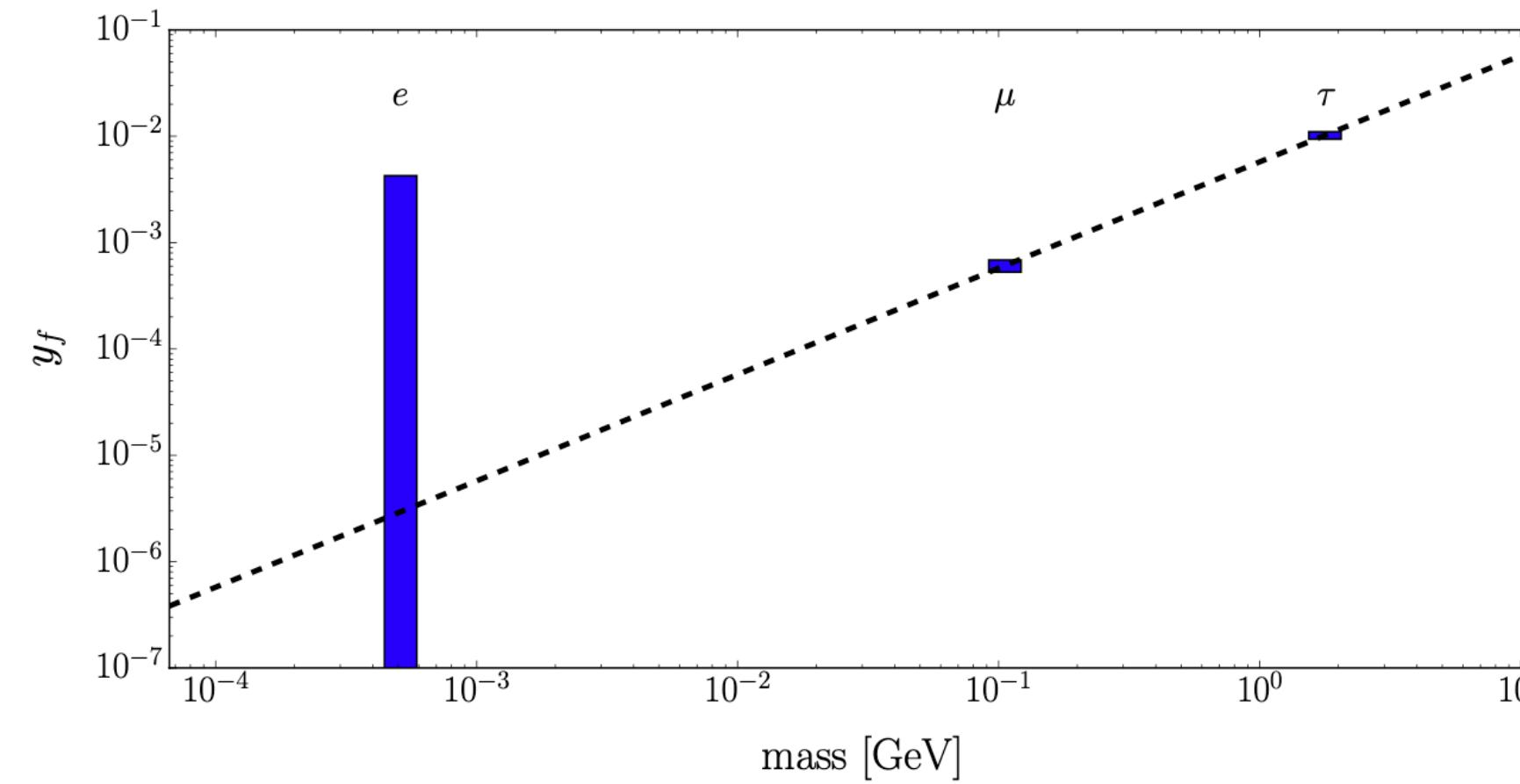
future projections

leptons

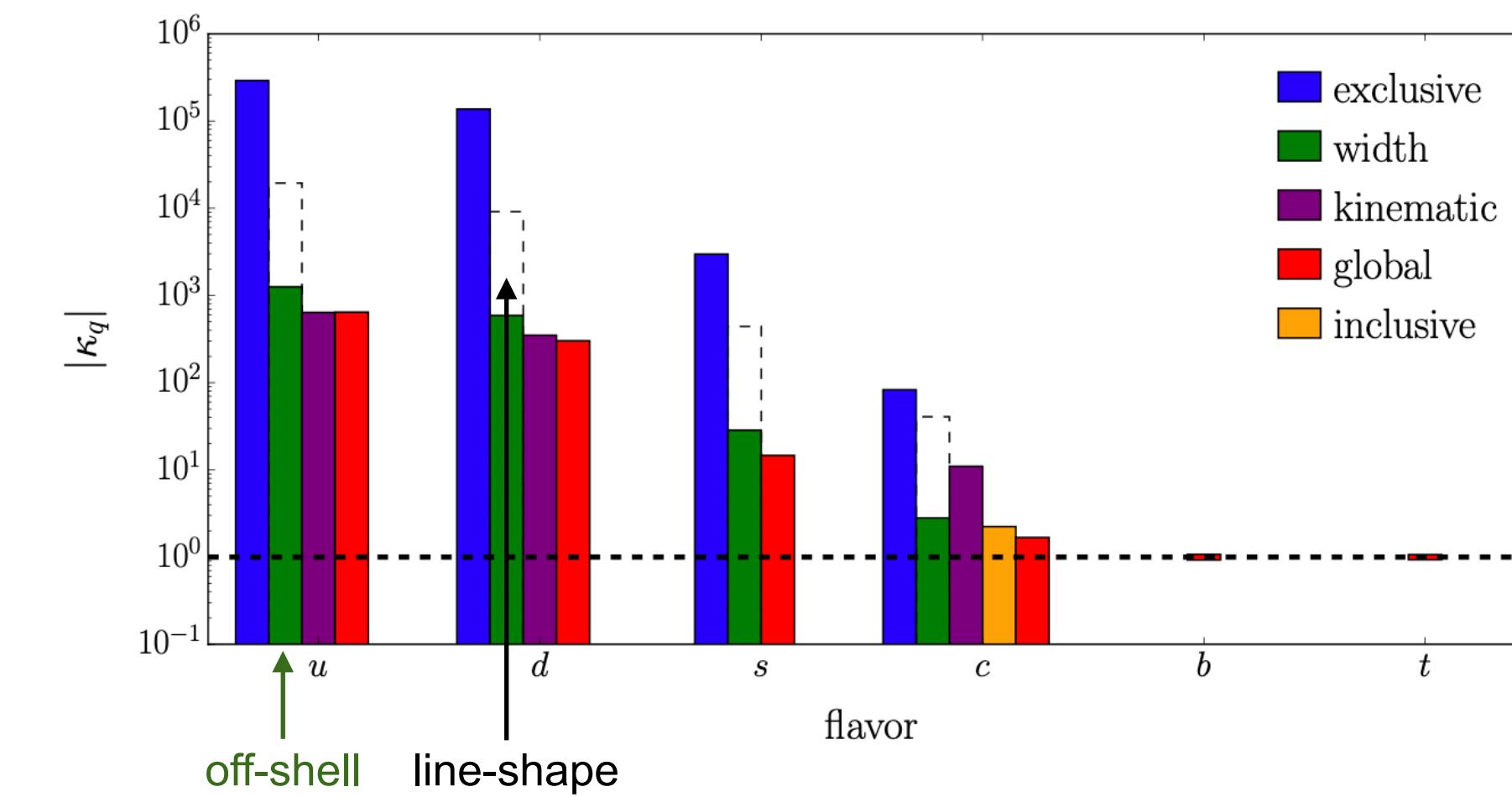
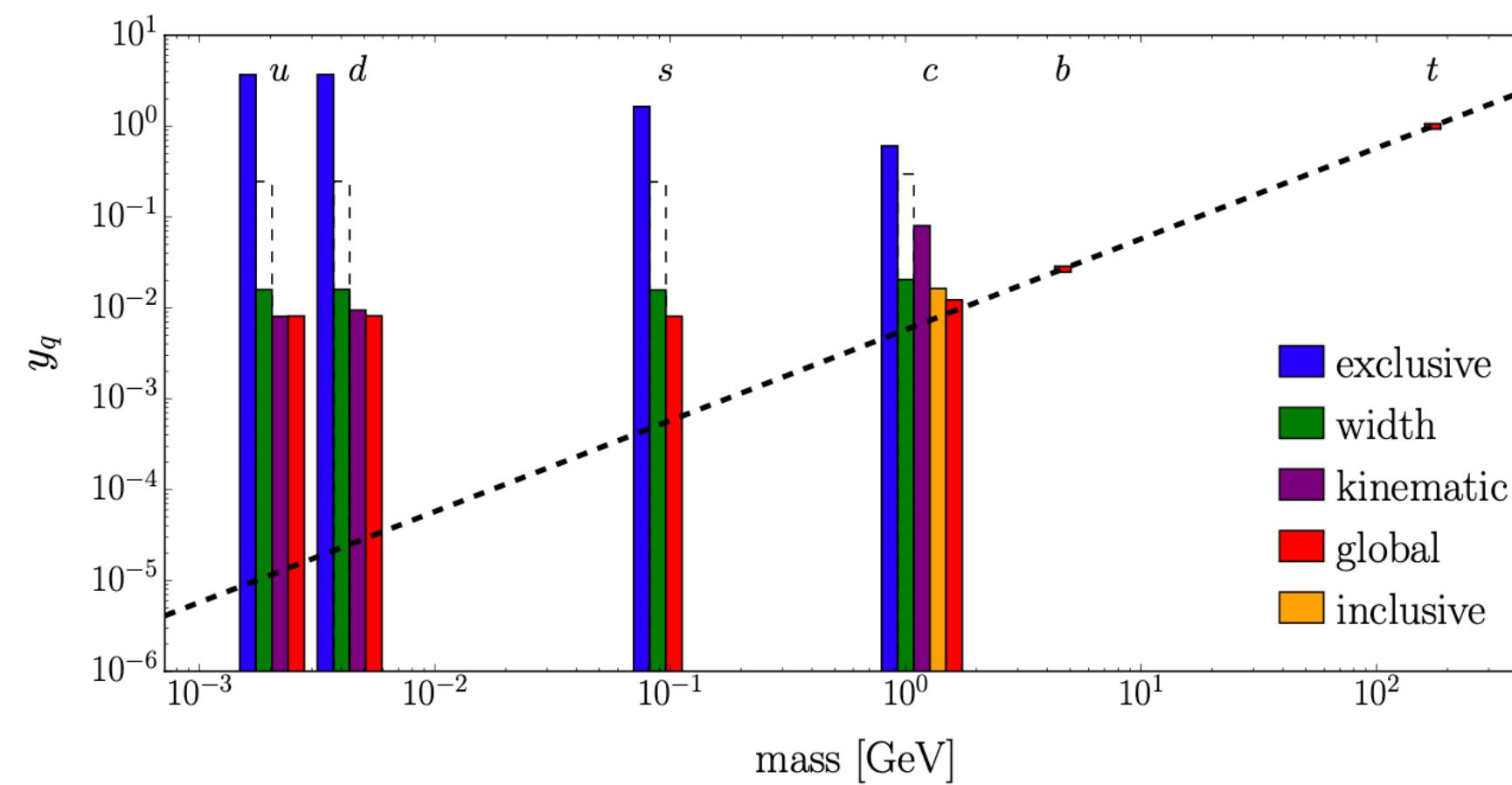


future projections

leptons



quarks



null tests of the SM (flavor and CP violation)

Higgs flavor violating decays

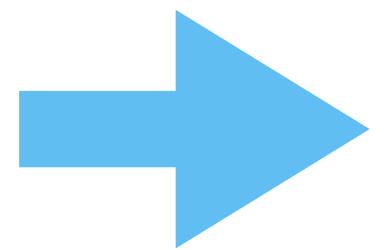
$$Y_{ij}^u \tilde{H} \overline{Q}_L^i U_R^j + \frac{c_{ij}^u}{\Lambda^2} \tilde{H} \overline{Q}_L^i U_R^j (H^\dagger H)$$

(similar for down-quarks and leptons)

Higgs flavor violating decays

$$Y_{ij}^u \tilde{H} \overline{Q}_L^i U_R^j + \frac{c_{ij}^u}{\Lambda^2} \tilde{H} \overline{Q}_L^i U_R^j (H^\dagger H)$$

(similar for down-quarks and leptons)



$$Y_{ij}^f = \frac{\sqrt{2}m_i}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} c_{ij}^f$$

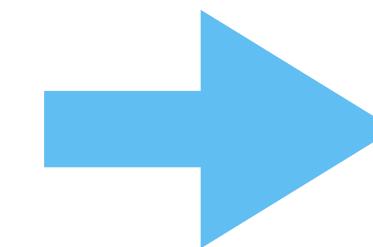
$$\text{BR}_{h \rightarrow \tau\mu} \simeq 0.25 \% \left(\frac{\text{TeV}}{\Lambda} \right)^4 \left(\left| \frac{c_{\mu\tau}^\ell}{0.2} \right|^2 + \left| \frac{c_{\tau\mu}^\ell}{0.2} \right|^2 \right)$$

$$\text{BR}_{t \rightarrow ch} \simeq 0.18 \% \left(\frac{\text{TeV}}{\Lambda} \right)^4 \left(\left| \frac{c_{tc}^\ell}{1.0} \right|^2 + \left| \frac{c_{ct}^\ell}{1.0} \right|^2 \right)$$

Higgs flavor violating decays

$$Y_{ij}^u \tilde{H} \overline{Q}_L^i U_R^j + \frac{c_{ij}^u}{\Lambda^2} \tilde{H} \overline{Q}_L^i U_R^j (H^\dagger H)$$

(similar for down-quarks and leptons)



$$Y_{ij}^f = \frac{\sqrt{2}m_i}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} c_{ij}^f$$

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direct

$$h \rightarrow \tau\mu, \tau e, \mu e, t \rightarrow hj$$

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

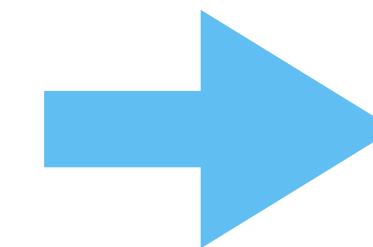
$$\sqrt{y_{e\tau}^2 + y_{\tau e}^2} < 2.3 \times 10^{-3}$$

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

Higgs flavor violating decays

$$Y_{ij}^u \tilde{H} \overline{Q}_L^i U_R^j + \frac{c_{ij}^u}{\Lambda^2} \tilde{H} \overline{Q}_L^i U_R^j (H^\dagger H)$$

(similar for down-quarks and leptons)



$$Y_{ij}^f = \frac{\sqrt{2}m_i}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} c_{ij}^f$$

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direct

$$h \rightarrow \tau\mu, \tau e, \mu e, t \rightarrow h j$$

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

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

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

$$\text{BR}_{t \rightarrow ch} \simeq 0.18 \% \left(\frac{\text{TeV}}{\Lambda} \right)^4 \left(\left| \frac{c_{tc}^\ell}{1.0} \right|^2 + \left| \frac{c_{ct}^\ell}{1.0} \right|^2 \right)$$

indirect

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

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

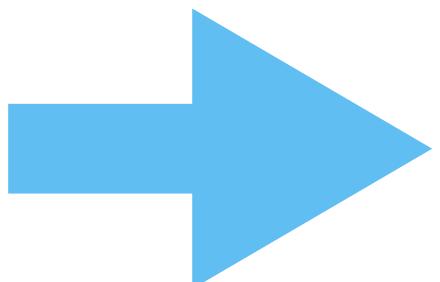
$$y_{ds}, y_{sd} < 3 \times 10^{-5}$$

and more

Higgs flavor violating decays

Higgs flavor violating decays

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



$$h \rightarrow \bar{\psi}^i \psi^j \iff \psi^i \rightarrow \psi^j \gamma$$

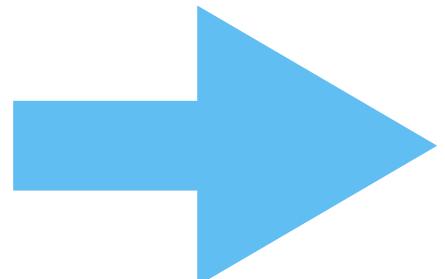
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$$c \sim \lambda e / 16\pi^2$$

Altmannshofer et al 1507.07927
Dorsner et al 1502.07784

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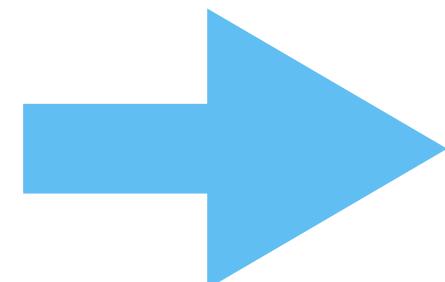
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- first two generation receive their masses from additional source of EWSB,

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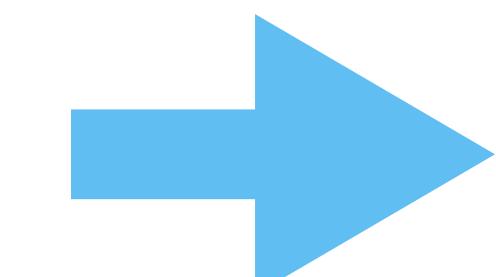
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use alignment (holomorphic zeros) to avoid flavor constraints:

approximate horizontal $U(1) \times U(1)$ Froggatt-Nielsen symmetry in SUSY model + non renormalizable terms



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

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	$\frac{\Re(c_u m_b^2 V_{cb}^{(*)})}{\Lambda^2} \frac{\sqrt{2}m_{t(c)}}{v}$	$\frac{\Re(c_u m_b^2 V_{ub}^{(*)})}{\Lambda^2} \frac{\sqrt{2}m_{t(u)}}{v}$	$\frac{\Re(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^*)}{\Lambda^2} \frac{\sqrt{2}m_{c(u)}}{v}$
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	$\mathcal{O}\left(\frac{v m_{t(c)}}{\Lambda^2} V_{cb} ^{\pm 1}\right)$	$\mathcal{O}\left(\frac{v m_{t(u)}}{\Lambda^2} V_{ub} ^{\pm 1}\right)$	$\mathcal{O}\left(\frac{v m_{c(u)}}{\Lambda^2} V_{us} ^{\pm 1}\right)$
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	$\kappa_{bs(sb)}/\kappa_b$	$\kappa_{bd(db)}/\kappa_b$	$\kappa_{sd(ds)}/\kappa_b$
MFV	$\frac{\Re(c_d m_t^2 V_{ts}^{(*)})}{\Lambda^2} \frac{\sqrt{2}m_{s(b)}}{v}$	$\frac{\Re(c_d m_t^2 V_{td}^{(*)})}{\Lambda^2} \frac{\sqrt{2}m_{d(b)}}{v}$	$\frac{\Re(c_d m_t^2 V_{ts(td)}^* V_{td(ts)})}{\Lambda^2} \frac{\sqrt{2}m_{s(d)}}{v}$
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	$\mathcal{O}\left(\frac{v m_{b(s)}}{\Lambda^2} V_{cb} ^{\pm 1}\right)$	$\mathcal{O}\left(\frac{v m_{b(d)}}{\Lambda^2} V_{ub} ^{\pm 1}\right)$	$\mathcal{O}\left(\frac{v m_{s(d)}}{\Lambda^2} V_{us} ^{\pm 1}\right)$
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	$\mathcal{O}(y_*^2 \frac{m_b}{v} \frac{\lambda_{L(R),2} \lambda_{L(R),3} m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2 \frac{m_b}{v} \frac{\lambda_{L(R),1} \lambda_{L(R),3} m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2 \frac{m_s}{v} \frac{\lambda_{L(R),1} \lambda_{L(R),2} m_W^2}{M_*^2})$

Higgs flavor violating decays

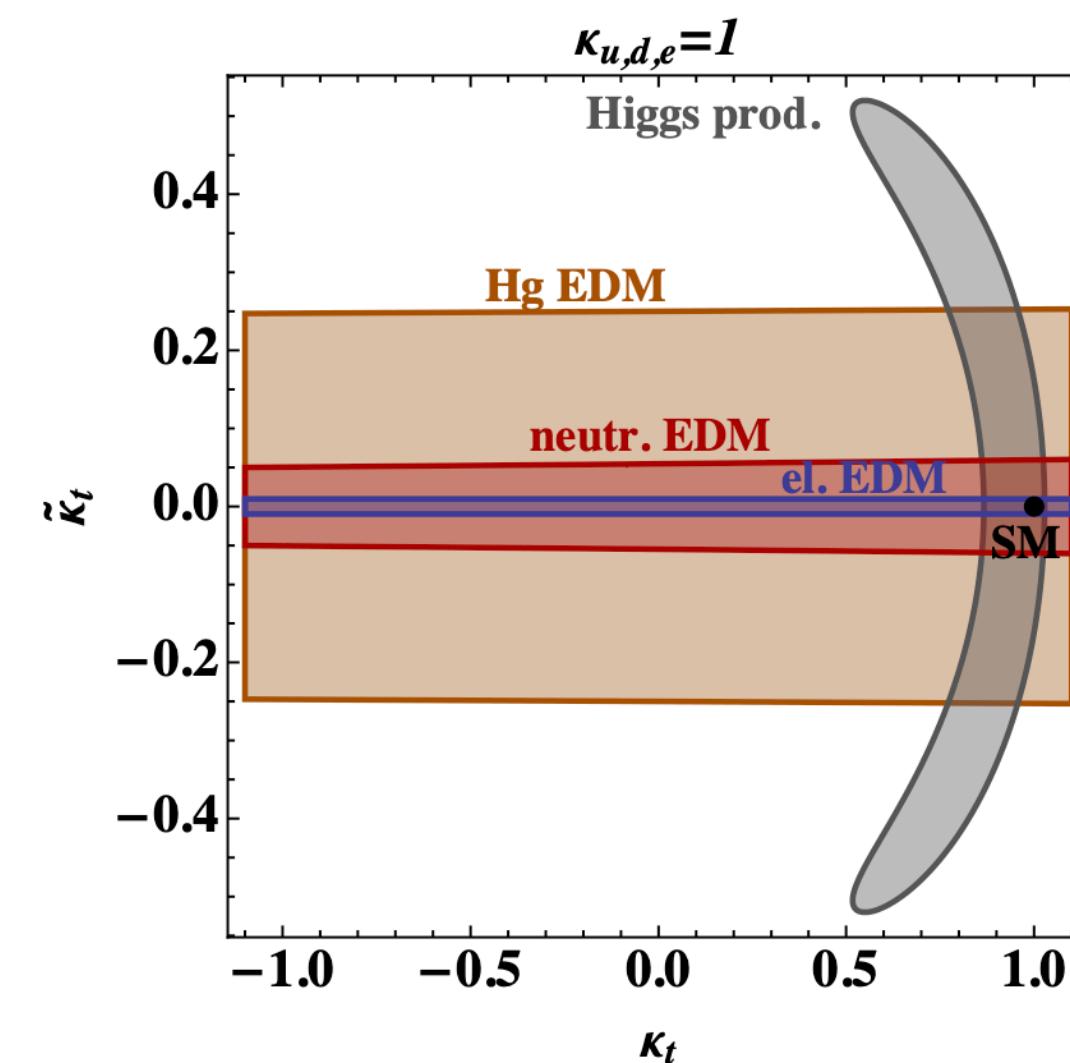
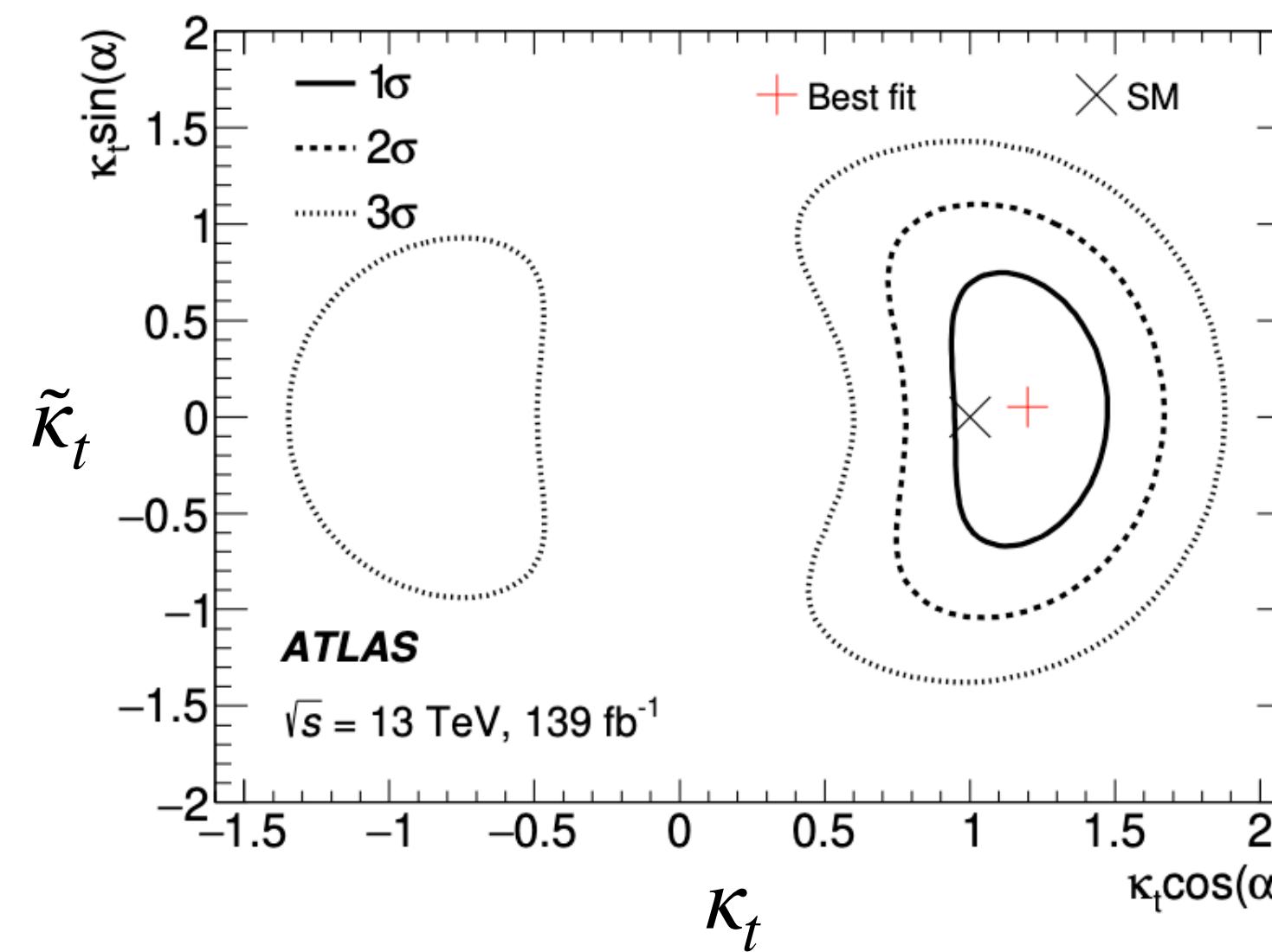
Model	$\kappa_{\tau\mu(\mu\tau)}/\kappa_\tau$	$\kappa_{\tau e(e\tau)}/\kappa_\tau$	$\kappa_{\mu e(e\mu)}/\kappa_\tau$
F2HDM	$\mathcal{O}\left(\frac{m_\mu}{m_\tau} \frac{\cos(\beta-\alpha)}{\cos \alpha \cos \beta}\right)$	$\mathcal{O}\left(\frac{m_e}{m_\tau} \frac{\cos(\beta-\alpha)}{\cos \alpha \cos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

CP violation

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

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

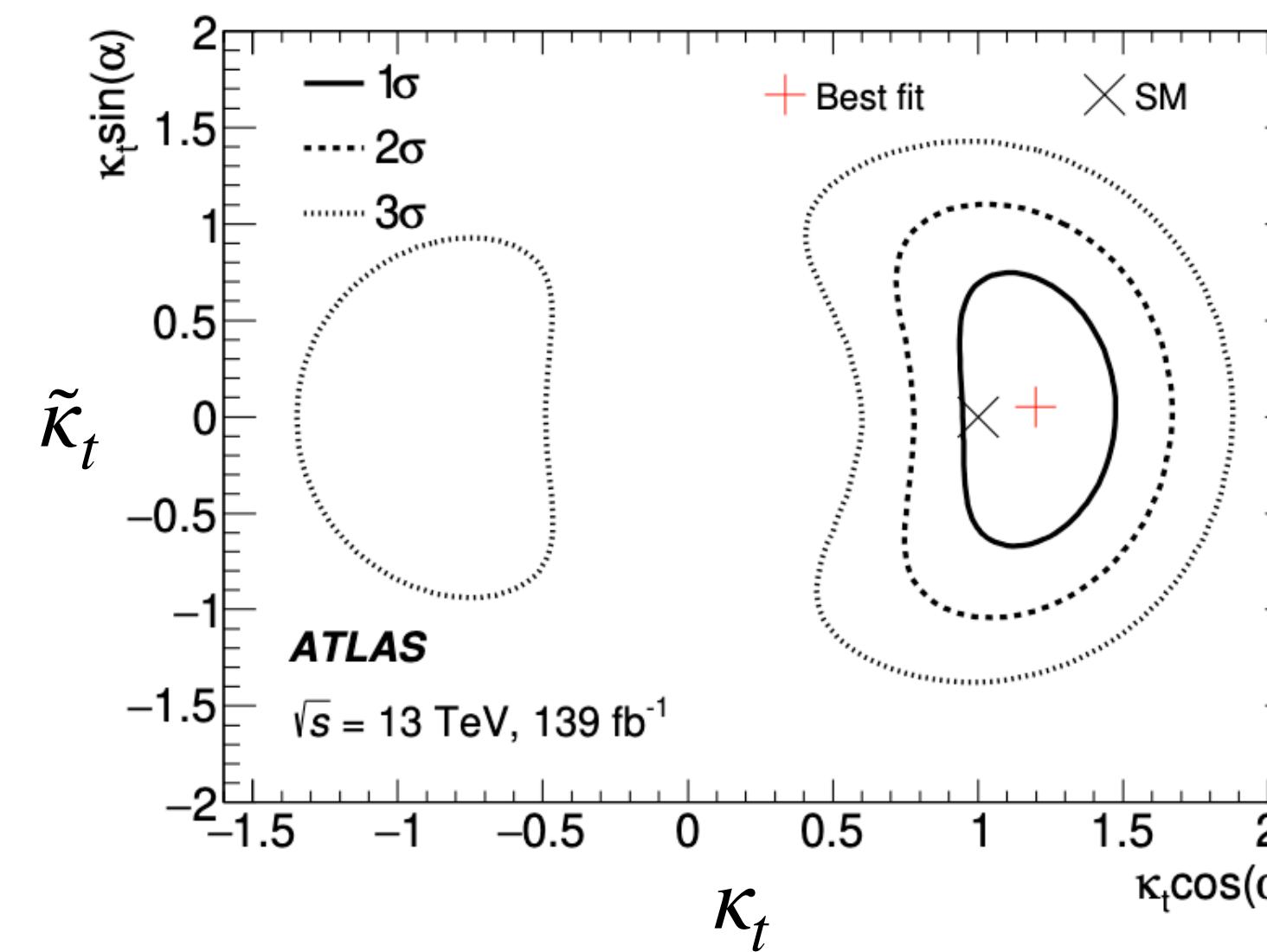
$\tilde{\kappa}_\tau$ (the CP phase) can be probed to 11° at HL-LHC

Harnik et al, 1308.1094
CERN yellow report, 1902.00134

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CP violation

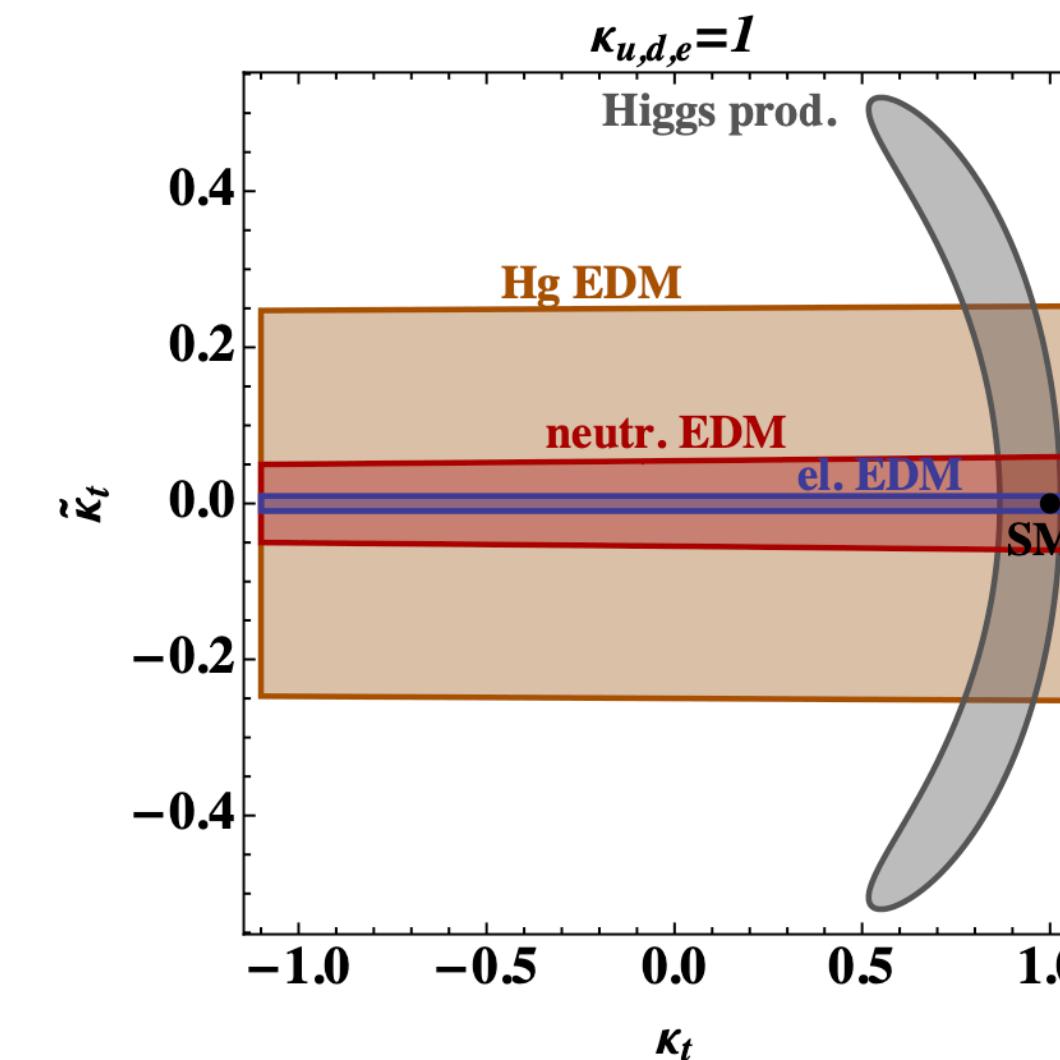
$$\mathcal{L}_{\text{eff}} = - \frac{m_f}{v} \left(\kappa_f h \bar{f} f + i \tilde{\kappa}_f h \bar{f} \gamma_5 f \right)$$



eEDM: $\tilde{\kappa}_e < 1.9 \times 10^{-3}$

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

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



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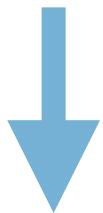
few implications

large Yukawa couplings in Higgs portal

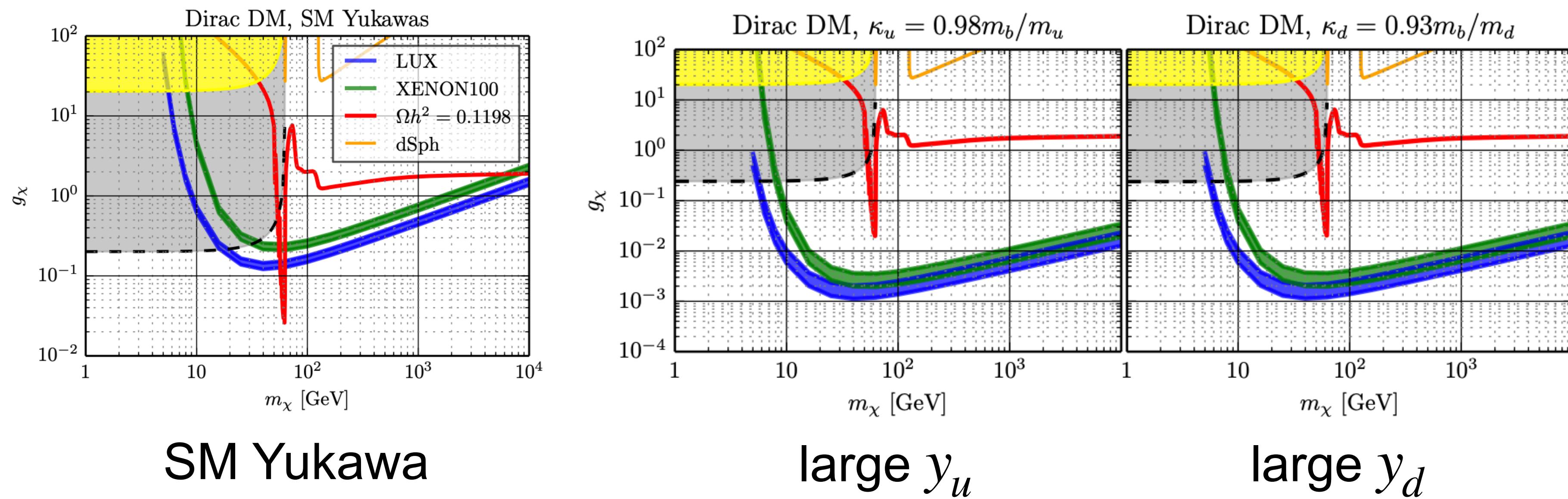
large Yukawa coupling for u, d, s have interesting implications for Higgs portal models

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enhanced dark matter direct detection

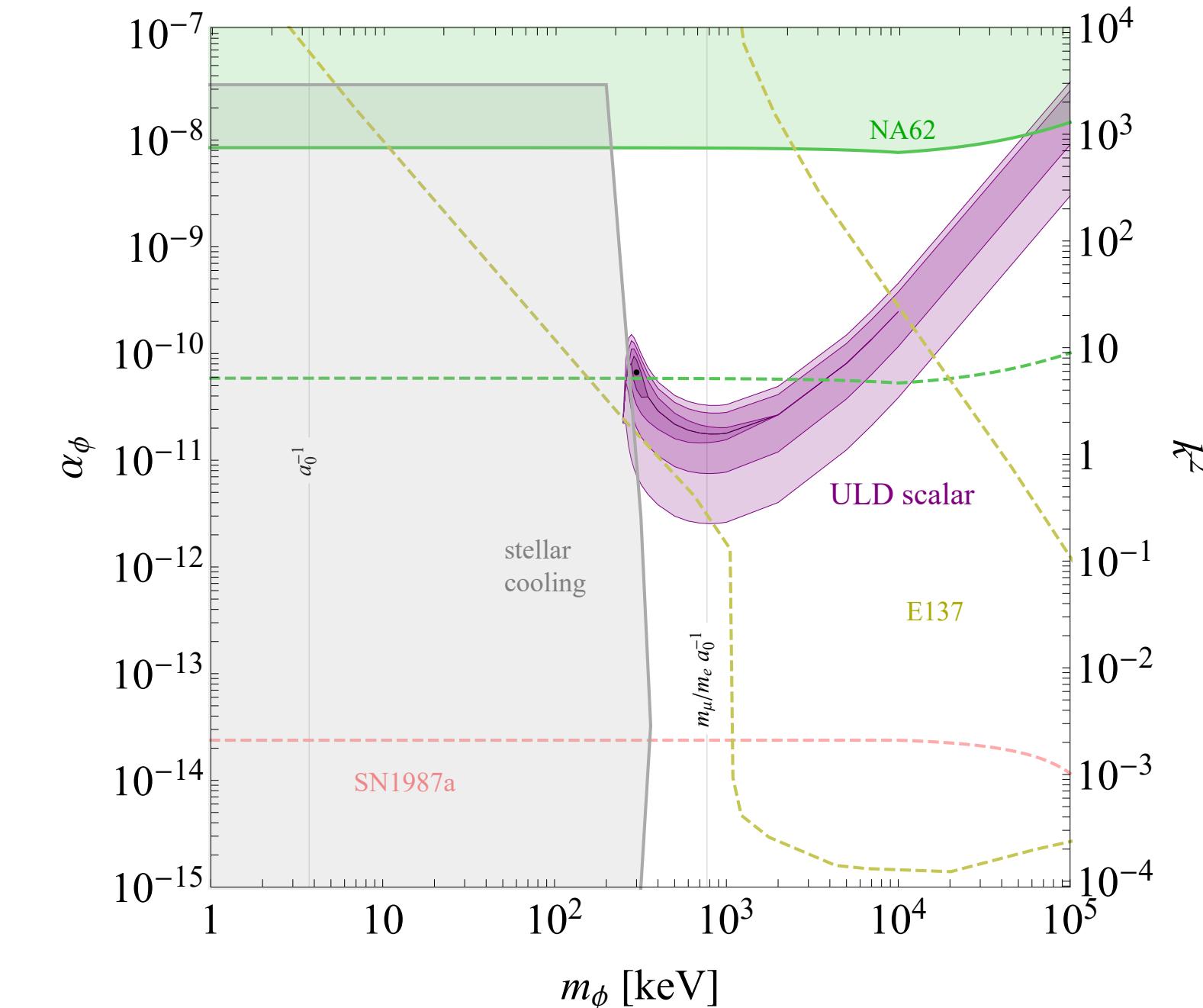
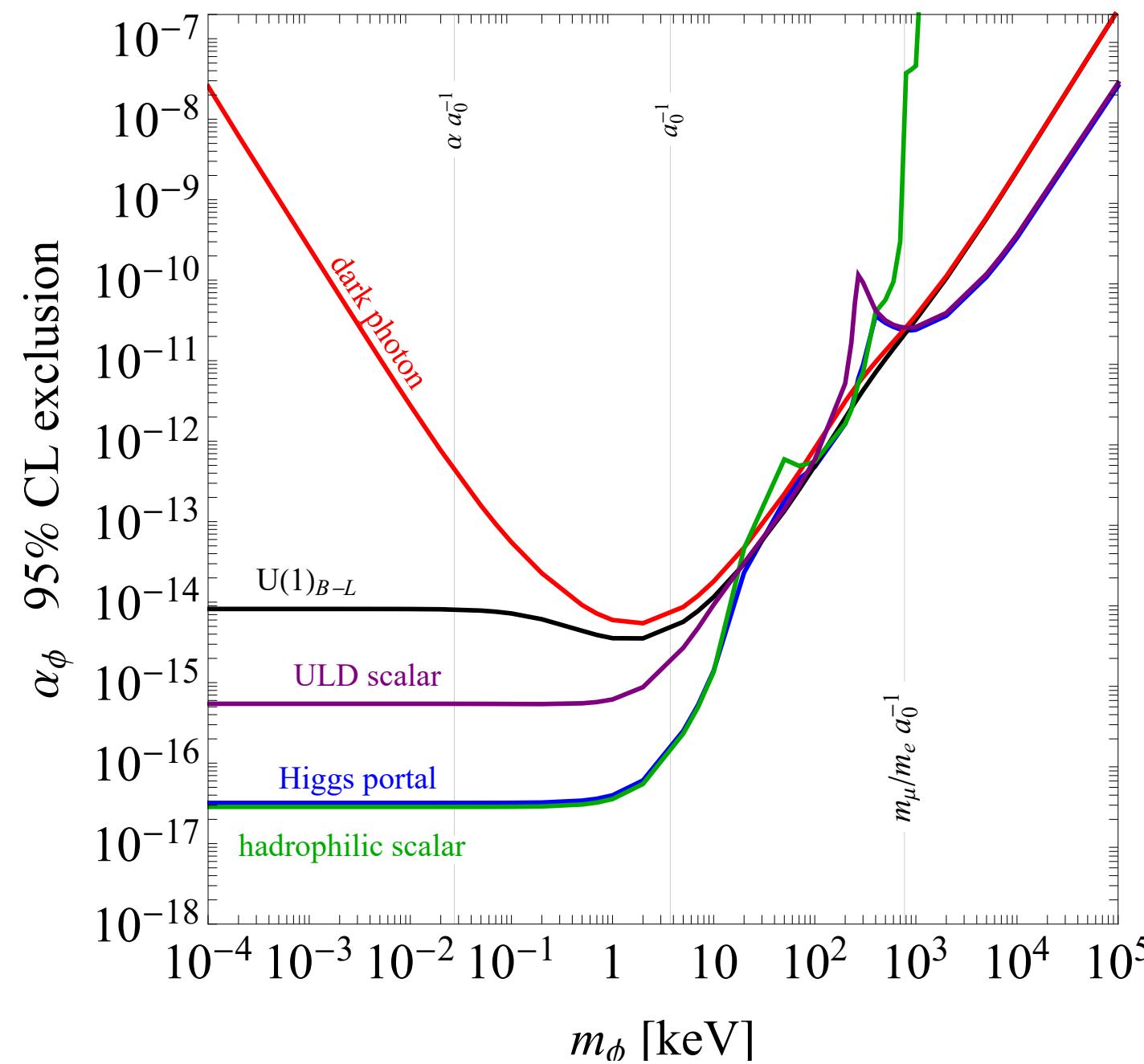


large Yukawa couplings in Higgs portal

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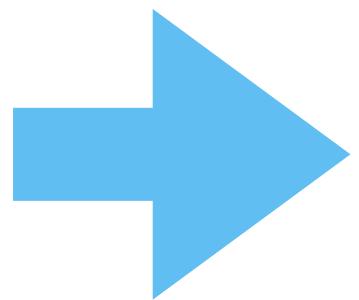


precision measurements of new forces with Higgs mixing



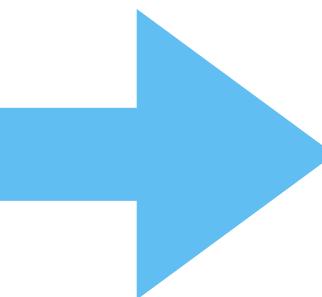
Higgs CPV and baryogengesis

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



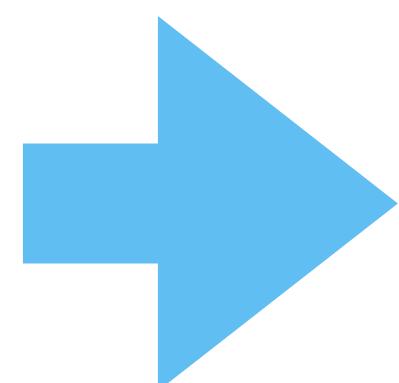
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(up to 16% of the asymmetry)

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

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	

$\times 10^{-3}$

$3.6 \times 10^{-6} (\mu \rightarrow e\gamma)$

direct searches

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

D⁰-D̄⁰ mixing

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

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

t→hj: decay and th production

K⁰-K̄⁰ mixing

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

B_d-B̄_d mixing

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

Re (Im)

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

B_s-B̄_s mixing

backups