Probing light-quark Yukawa couplings & NP in Higgs + jet (b-jet) studies

Jonathan Cohen
Technion, Israel
jcohen@tx.technion.ac.il

Shaouly Bar-Shalom (Technion), Gad Eilam (Technion) & Amarjit Soni (BNL)

arXiv:17……

Outline

- Motivation
- Higgs + jet in the SM
- The Kappa-framework → light-jet, b-jet
- The SMEFT framework → light-jet, b-jet
- Summary

Motivation

- Current experimental bounds on the Yukawa couplings of light-quarks of the 1st and 2nd generations are weak: [G. Perez arXiv:1503.00290, F. Bishara arXiv:1606.09253, Y. Soreq, H.X. Zhu, J. Zupan, arXiv:1606.09621]

$$y_u, y_d \lesssim 0.5 y_b \qquad y_c \lesssim 5 y_b$$

Motivation

- Current experimental bounds on the Yukawa couplings of light-quarks of the 1st and 2nd generations are weak: [G. Perez arXiv:1503.00290, F. Bishara arXiv:1606.09253, Y. Soreq, H.X. Zhu, J. Zupan, arXiv:1606.09621]

$$y_u, y_d \lesssim 0.5 y_b \qquad y_c \lesssim 5 y_b$$

Any sign of these couplings being significantly enhanced w.r.t SM will undermine the SM prediction $y_f \propto m_f/v$

NP signals/searches

- Focus on exclusive $pp \to h + j(j_b)$ followed by $h \to \gamma\gamma$

with the following 2 scenarios in mind:

I. The NP comes in the form of scaled SM couplings (kappa framework)

II. The NP gives rise to new interactions that are absent in the SM and that modify the SM kinetic distributions (SMEFT)

Why exclusive h+j @ the LHC?

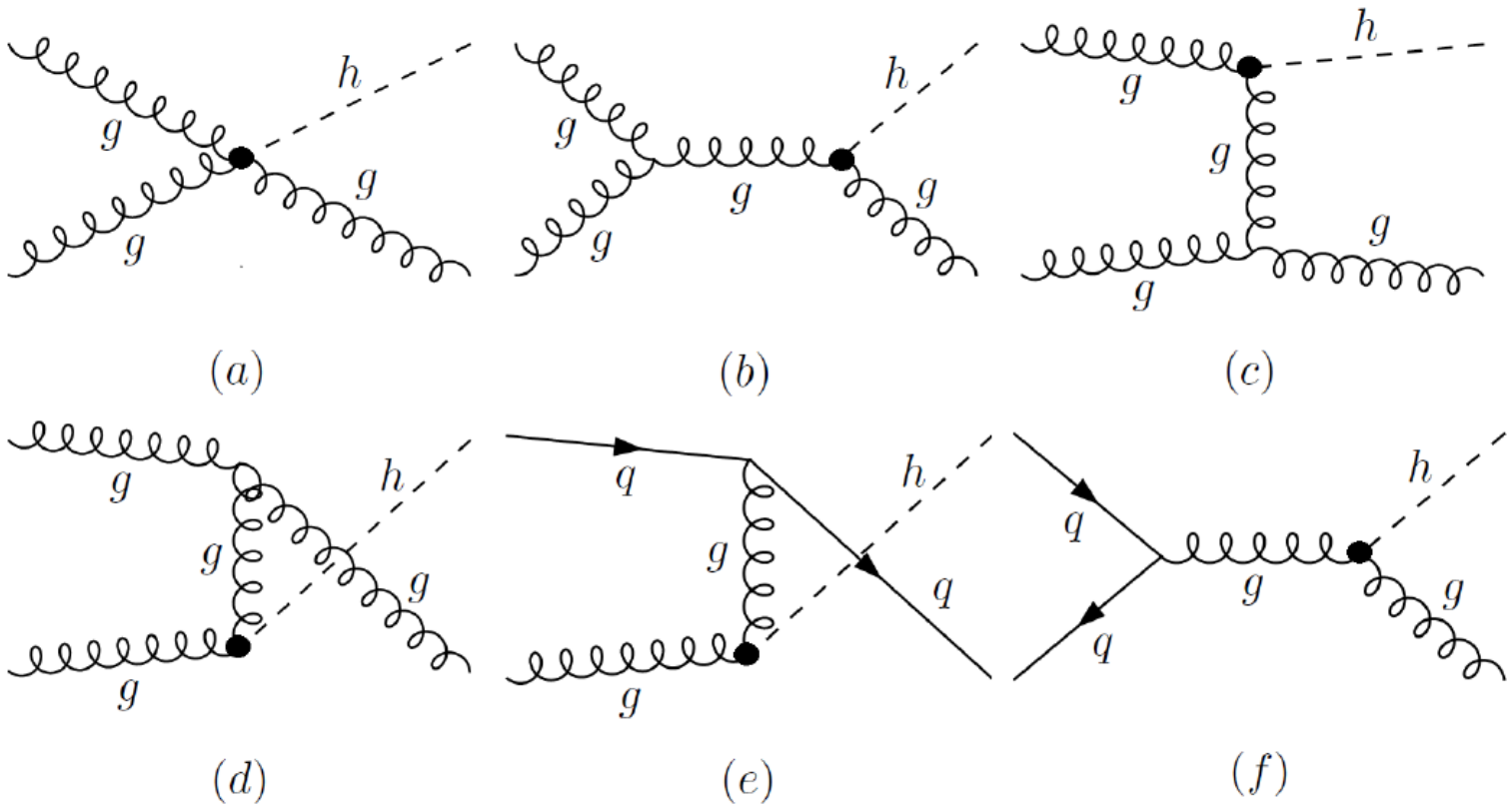
- The high-p_T Higgs distribution may play a key role in distinguishing between NP scenarios:
- Sensitive to a variety of UV completions: SUSY, heavy top-partners…
- And to other model-independent approaches: Kappa framework & SMEFT.

$$pp \to h + j, \quad j = g, u, d, s, c$$

Higgs + light-jet in the SM

(leading term)

$$\mathcal{L}_{eff}^{ggh} = C_g^{SM} h G_{\mu\nu}^a G^{\mu\nu,a} \quad , \; C_g^{SM} \simeq \alpha_s/(12\pi v)$$

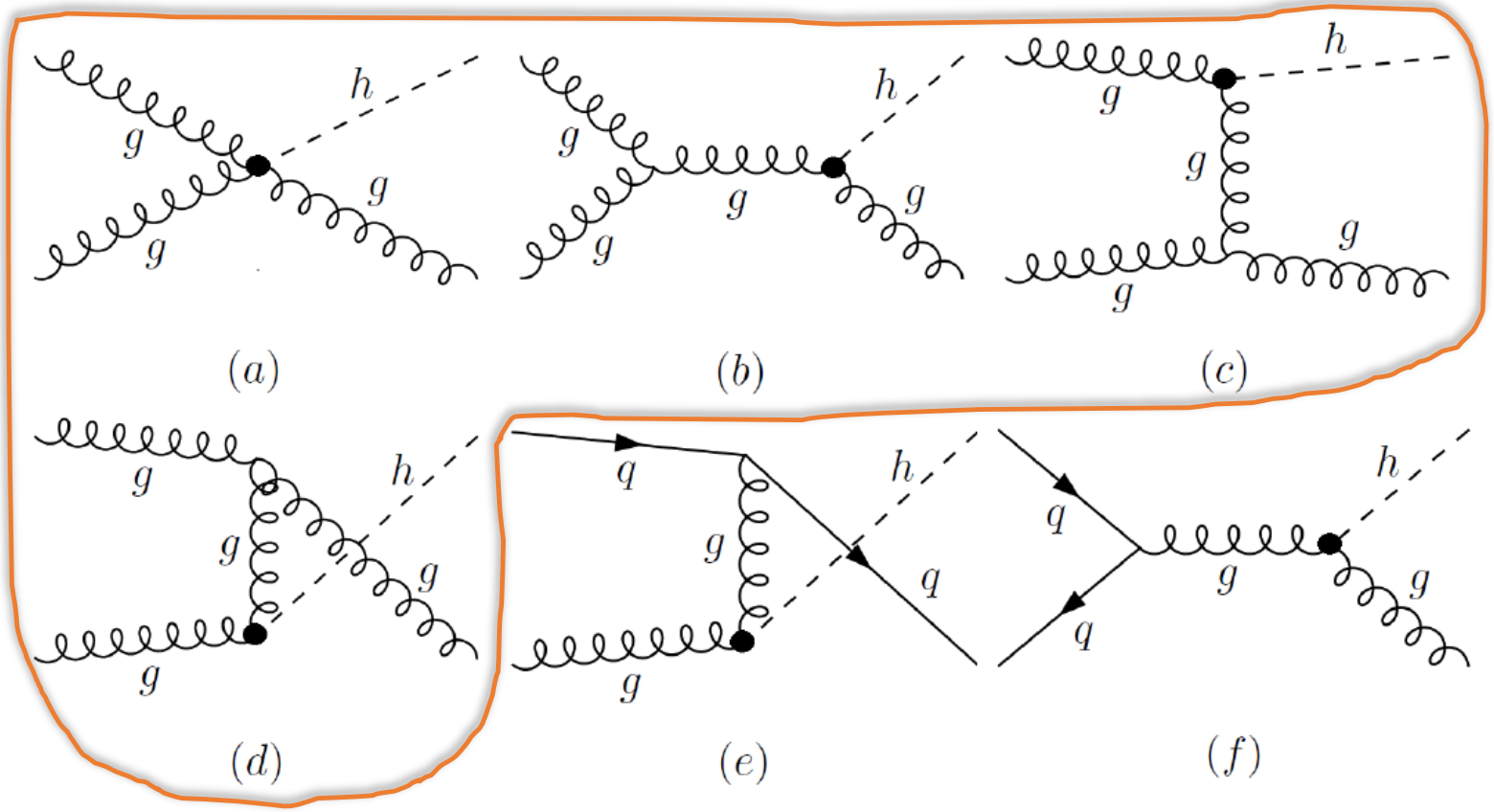


$$pp \to h + j, \quad j = g, u, d, s, c$$

Higgs + light-jet in the SM

(leading term)

$$\mathcal{L}_{eff}^{ggh} = C_g^{SM} h G^a_{\mu\nu} G^{\mu\nu,a} \quad , \quad C_g^{SM} \simeq \alpha_s/(12\pi v)$$



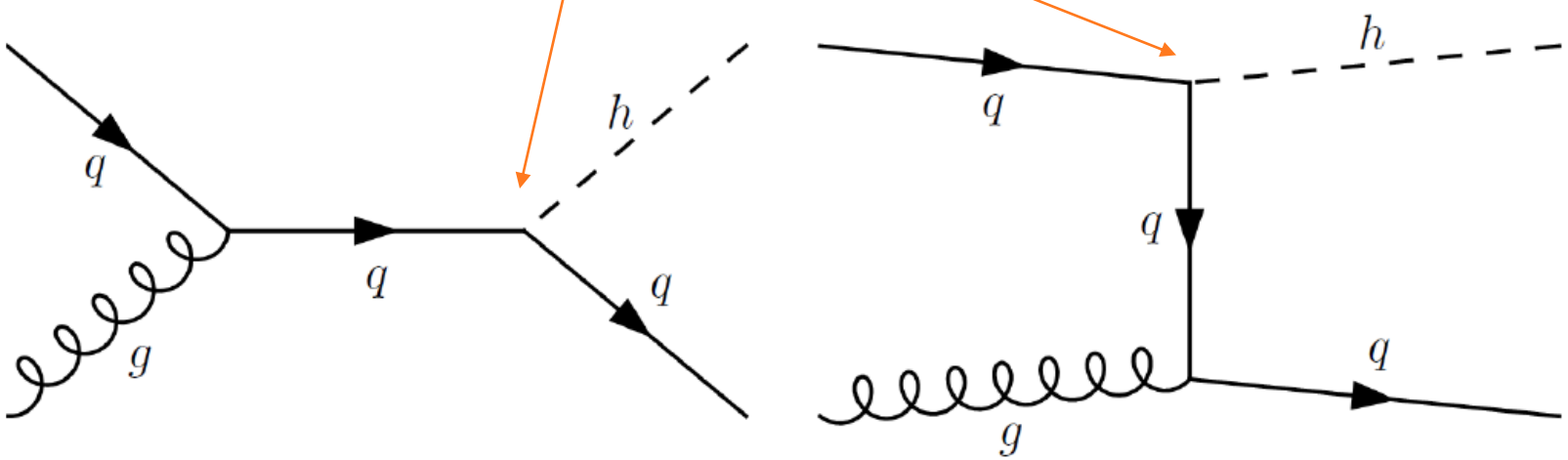
$\to$ $gg \to gh$

dominant in SM

The Kappa Framework

$$\mathcal{L}_{eff}^{h+j} = -\sum_{q=u,d,s,c} \kappa_q \frac{m_b}{v} h\bar{q}q + \kappa_g C_g^{SM} h G_{\mu\nu}^a G^{\mu\nu,a}$$

NP diagrams $\propto \kappa_q$



Only $qg \to hq$ contributes for $q = b$

$$\kappa_q \equiv \frac{y_q}{y_b^{SM}}$$

$$\sigma_{SM}^{hj} = \sigma_{NP}^{hj}(\kappa_g = 1, \kappa_q = 0)$$

Notations & Observables

- Define a signal strength:

$$\mu_{hj}^{f} = \frac{\mathcal{N}(pp \to h + j \to ff + j)}{\mathcal{N}_{SM}(pp \to h + j \to ff + j)}$$

- Event yield:

$$\mathcal{N} = \mathcal{L}\sigma\mathcal{A}\epsilon$$

- Assume $\mathcal{A} \simeq \mathcal{A}_{SM}$ to obtain

$$\mu_{hj}^{f} \simeq \frac{\sigma(pp \to h + j)}{\sigma_{SM}(pp \to h + j)} \cdot \frac{BR(h \to ff)}{BR_{SM}(h \to ff)}$$

Notations & Observables

- Signal Strength for $pp \to h + j(j_b), h \to ff,$
$$f = b,\ \tau,\ \gamma,\ W,\ Z$$

We focus on $h \to \gamma\gamma$

$$\mu^{f}_{hj_{(j_b)}} \simeq \left(\kappa_g^2 + \kappa_q^2 R^{hj(j_b)}_{NP}\right) \cdot \mu^{(j_b)}_{h\to ff}$$

No interference $\kappa_q \kappa_g$ term

- Assume no NP in decay:

$$R^{hj(j_b)}_{NP} \equiv \frac{\sigma^{hj(j_b)}_{qqh}}{\sigma^{hj(j_b)}_{SM}},$$

$$\mu_{h\to ff} = \frac{1}{1 + \left(\kappa_g^2 - 1\right) BR^{gg}_{SM} + \kappa_q^2 BR^{bb}_{SM}}$$

$$\mu^{(j_b)}_{h\to ff} = \frac{1}{1 + \left(\kappa_g^2 - 1\right) BR^{gg}_{SM} + \left(\kappa_b^2 - 1\right) BR^{bb}_{SM}}$$

Notations & Observables

- NP signal:

$$\Delta\mu^f_{hj_{(j_b)}} \equiv | \mu^f_{hj_{(j_b)}} - 1 | \quad , \quad \mu^f_{hj_{(j_b)}}(SM) = 1$$

- Statistical significance of the NP signal:

$$N_{SD} = \frac{\Delta\mu^f_{hj_{(j_b)}}}{\delta\mu^f_{hj_{(j_b)}}}, \quad \delta\mu^f_{hj_{(j_b)}} = 0.05(1\sigma)$$

Notations & Observables

- Cumulative cross-section: (extra handle on NP effects)

$$\sigma(p_T^{cut}) \equiv \sigma\left(p_T(h) > p_T^{cut}\right) = \int_{p_T(h) \geq p_T^{cut}} dp_T \frac{d\sigma}{dp_T}$$

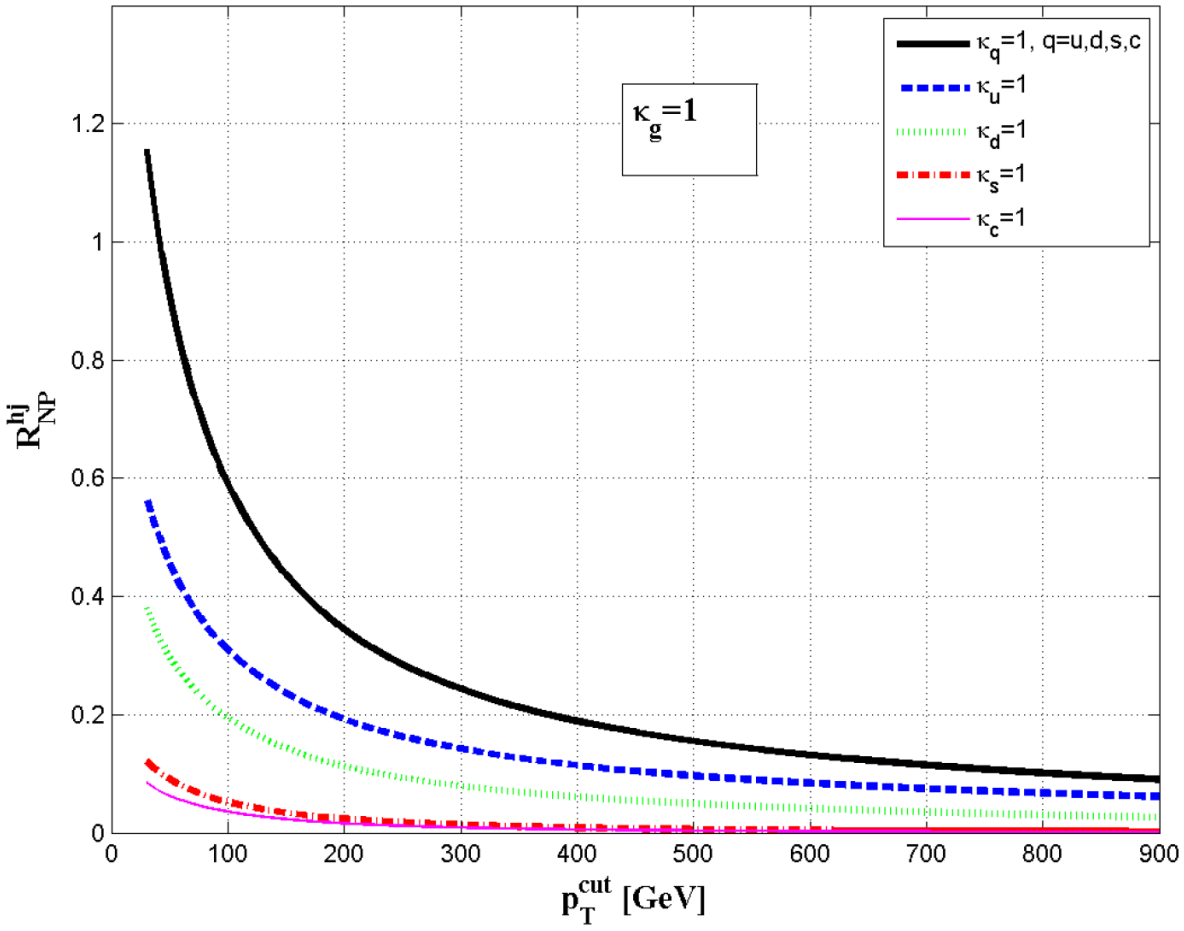
- Minimizes the K-factor at the high PT region [R. Boughezal arXiv:1504.07922, 1505.03893]

Simulation Setup

- Write a dedicated UFO model for the Kappa (SMEFT) framework based on the HEFT model, using FeynRules.
- Use Madgraph5 with LO MSTW 2008 PDF set
- Choose sum of transverse mass as dynamical scale choice
- Impose lower $p_T(h)$ cut.
- Overall invariant mass cut using MadAnalysis5 (SMEFT).
- Assume integrated luminosity of $\mathcal{L} = 300\ \mathrm{fb}^{-1}$ or $3000\,\mathrm{fb}^{-1}$

*Case of $\kappa_g = 1$: no NP in ggh

Results (Light-quarks)



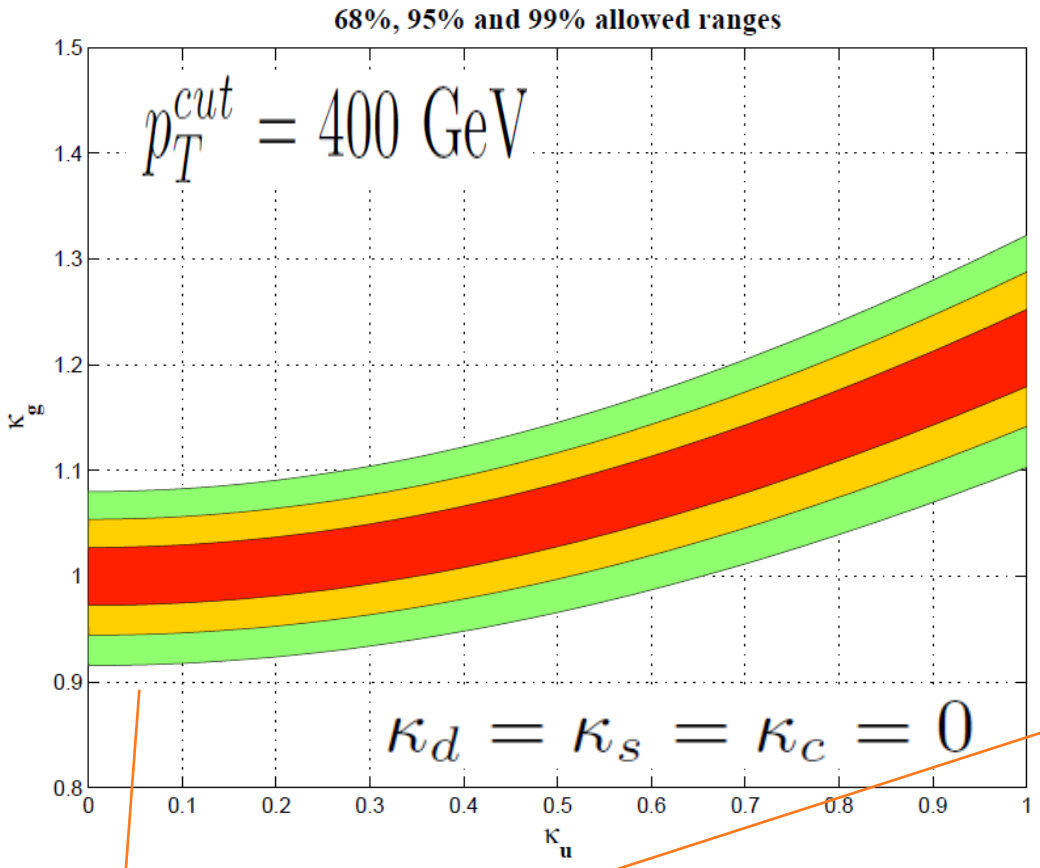
$$R_{NP}^{hj} \equiv \frac{\sigma_{qqh}^{hj}}{\sigma_{SM}^{hj}}$$

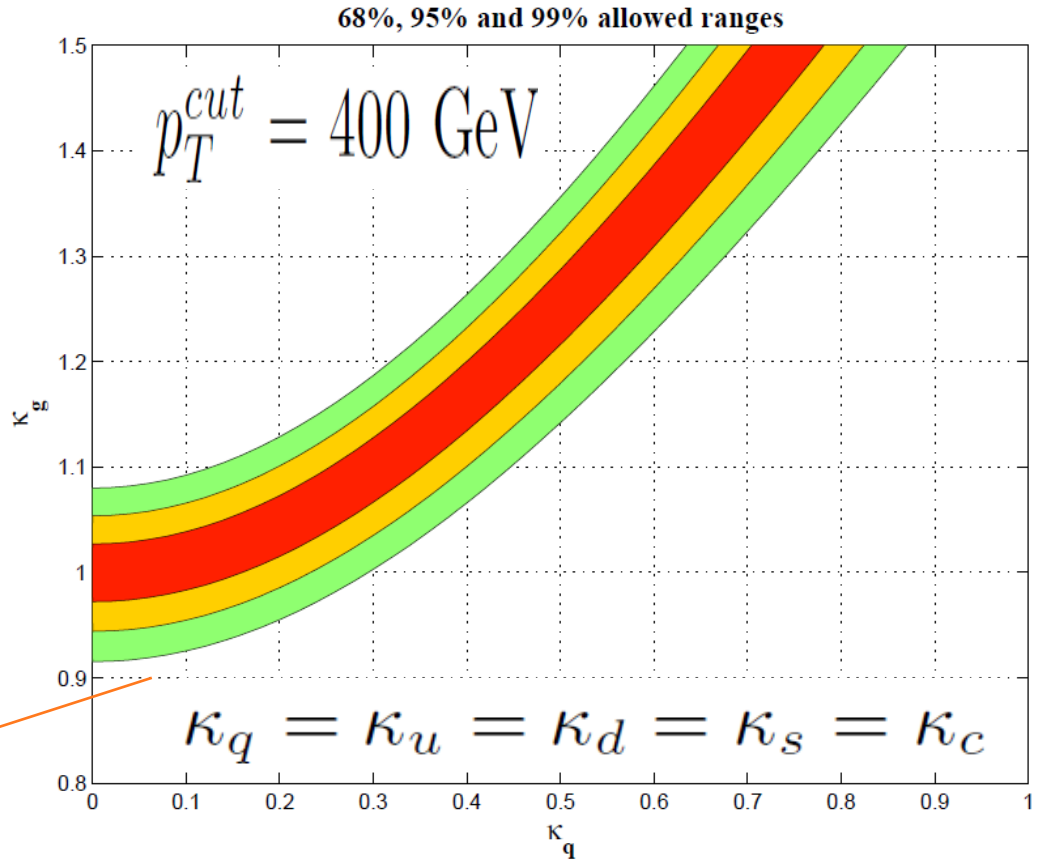
$$\mu_{hj}^{f} = \left(\kappa_g^2 + \kappa_q^2 R_{NP}^{hj}\right) \cdot \mu_{h\to ff}$$

- Low p_T effect of κ_q
- $R_{NP}^{hj} \gtrsim$ 0.2 at $p_T^{cut} \lesssim 200$ GeV for $\kappa_u = 1$

*NP in both hgg (κ_g) and qqh (κ_q) Results (Light-quarks)

$$\Delta\mu^f_{hj} \equiv \left|\mu^f_{hj} - 1\right| \leq 0.05,\ 0.1 \text{ and } 0.15$$





- κ_g dominant at high $p_T(h)$
- e.g. if $0.85 \leq \mu^f_{hj} \leq 1.15$ then κ_g < 0.9 excluded for $p_T^{cut} = 400$ GeV

The Kappa Framework (b-jet case)

- As in the light jet case the κ_b term is important for softer $p_T(h)$ while the κ_g contribution is dominant at the harder $p_T(h)$ regime
- We obtain

$$R_{SM}^{hj_b} \sim 2 \; : \quad p_T^{cut} \sim 35 \text{ GeV}$$

$$\mu_{hj_b}^f(R_{SM}^{hj_b} \ll 1) \simeq \left(\kappa_g^2 + \kappa_b^2 R_{SM}^{hj_b}\right) \cdot \mu_{h\to ff}^b$$

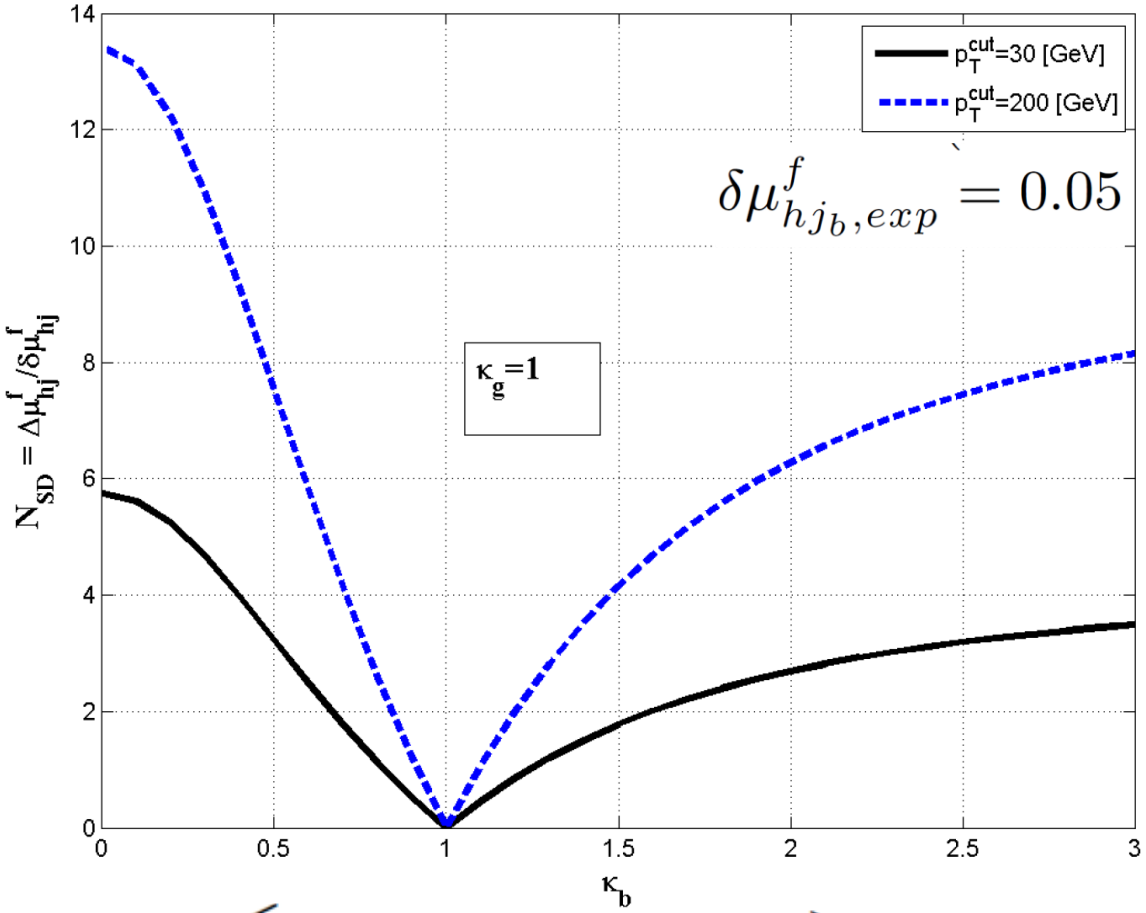
$$R_{SM}^{hj_b} \sim 1 \; : \quad p_T^{cut} \sim 90 \text{ GeV}$$

$$R_{SM}^{hj_b} \sim 0.4 \; : \quad p_T^{cut} \sim 200 \text{ GeV}$$

$$R_{SM}^{hj_b} \sim 0.15 \; : \quad p_T^{cut} \sim 400 \text{ GeV}$$

*Case of $\kappa_g = 1$: no NP in ggh

Results (b-jet)

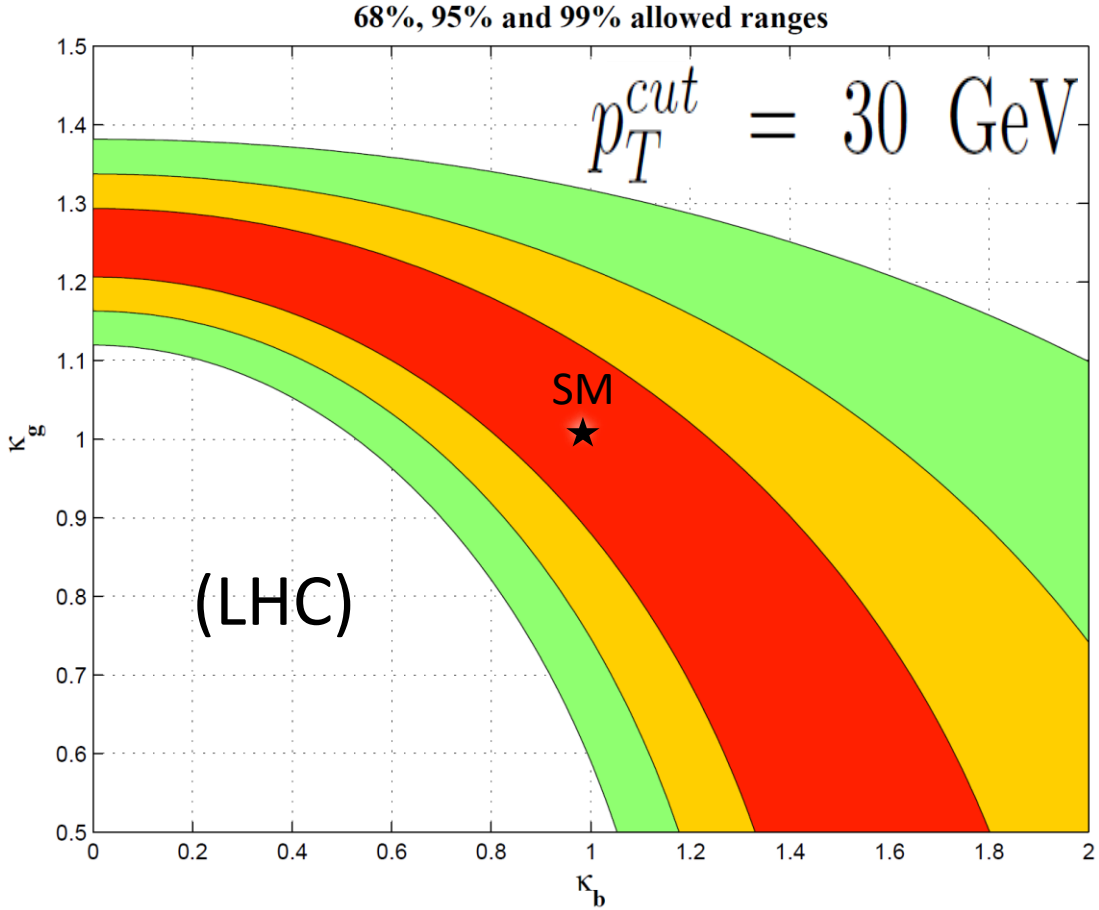


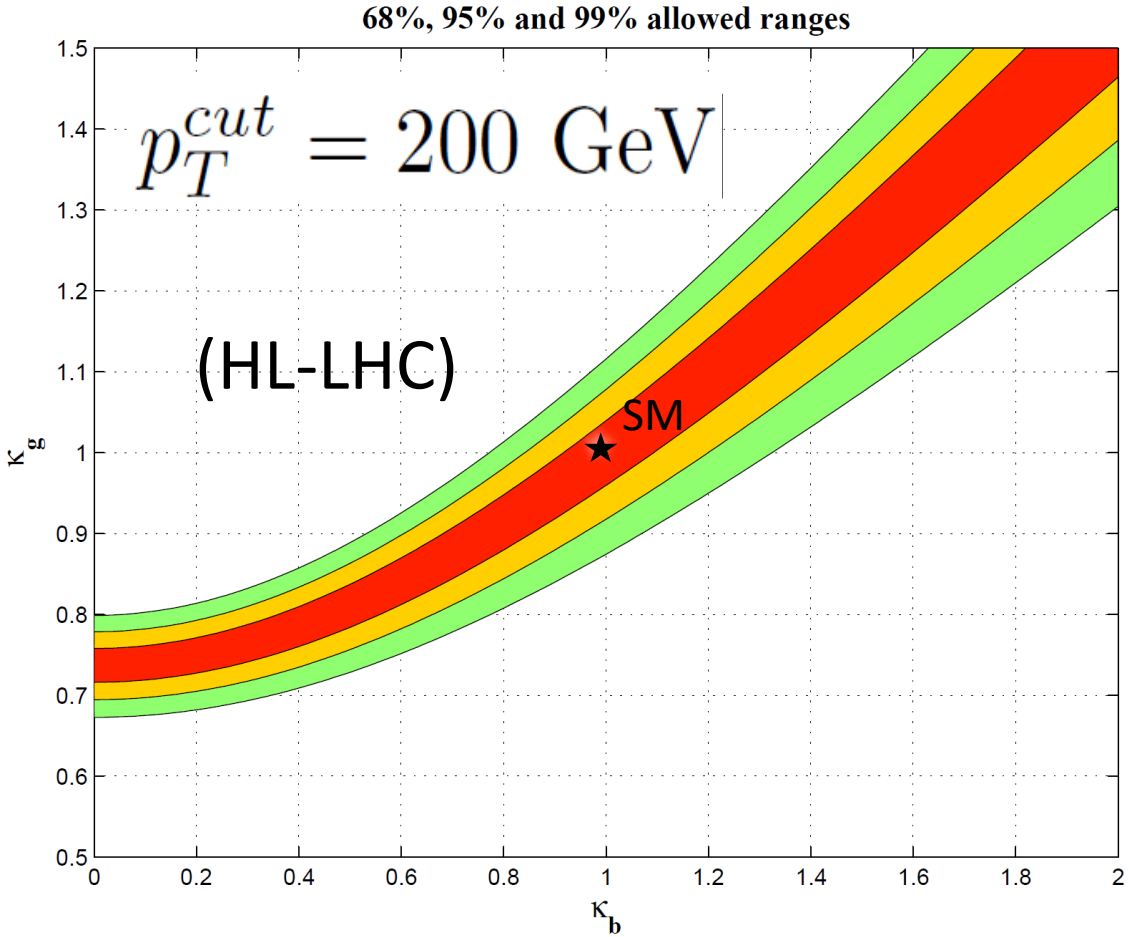
- A 3σ effect if $\kappa_b \lesssim 0.8$ and/or $\kappa_b \gtrsim 1.3$ for $p_T^{cut} = 200$ GeV (HL-LHC)
- Needed larger deviation in κ_b for a 3σ effect in the case of $p_T^{cut} = 30$ GeV

$\kappa_b - \kappa_g$ plane

Results (b-jet)

$$\left|\mu^f_{hj} - 1\right| \leq 0.05,\ 0.1 \text{ and } 0.15$$





- Can probe different regimes in the $\kappa_b - \kappa_g$ plane (complimentary)

The SMEFT Framework [Warsaw Basis arXiv:1008.4884]

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i=u\phi,d\phi,ug,dg,\phi g} \frac{f_i}{\Lambda_i^2}\mathcal{O}_i \ ,$$

$$\begin{aligned}
\mathcal{O}_{u\phi} &= \left(\phi^\dagger\phi\right)\left(\bar{Q}_L\tilde{\phi}u_R\right) + h.c. \ , \\
\mathcal{O}_{d\phi} &= \left(\phi^\dagger\phi\right)\left(\bar{Q}_L\phi d_R\right) + h.c. \ , \\
\mathcal{O}_{ug} &= \left(\bar{Q}_L\sigma^{\mu\nu}T^a u_R\right)\tilde{\phi}G^a_{\mu\nu} + h.c. \ , \\
\mathcal{O}_{dg} &= \left(\bar{Q}_L\sigma^{\mu\nu}T^a d_R\right)\phi G^a_{\mu\nu} + h.c. \ , \\
\mathcal{O}_{\phi g} &= \left(\phi^\dagger\phi\right)G^a_{\mu\nu}G^{a,\mu\nu}
\end{aligned}$$

The SMEFT Framework [Warsaw Basis arXiv:1008.4884]

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i=u\phi,d\phi,ug,dg,\phi g} \frac{f_i}{\Lambda_i^2}\mathcal{O}_i \ ,$$

$$\left.\begin{aligned}
\mathcal{O}_{u\phi} &= \left(\phi^\dagger\phi\right)\left(\bar{Q}_L\tilde{\phi}u_R\right) + h.c. \ , \\
\mathcal{O}_{d\phi} &= \left(\phi^\dagger\phi\right)\left(\bar{Q}_L\phi d_R\right) + h.c. \ , \\
\mathcal{O}_{ug} &= \left(\bar{Q}_L\sigma^{\mu\nu}T^a u_R\right)\tilde{\phi}G^a_{\mu\nu} + h.c. \ , \\
\mathcal{O}_{dg} &= \left(\bar{Q}_L\sigma^{\mu\nu}T^a d_R\right)\phi G^a_{\mu\nu} + h.c. \ ,
\end{aligned}\right\}$$

$$\mathcal{O}_{\phi g} = \left(\phi^\dagger\phi\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

Light-quark operators often neglected in the literature assuming $\propto Y_{u,d}$ e.g. for MFV

The SMEFT Framework [Warsaw Basis arXiv:1008.4884]

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i=u\phi,d\phi,ug,dg,\phi g} \frac{f_i}{\Lambda_i^2}\mathcal{O}_i \ ,$$

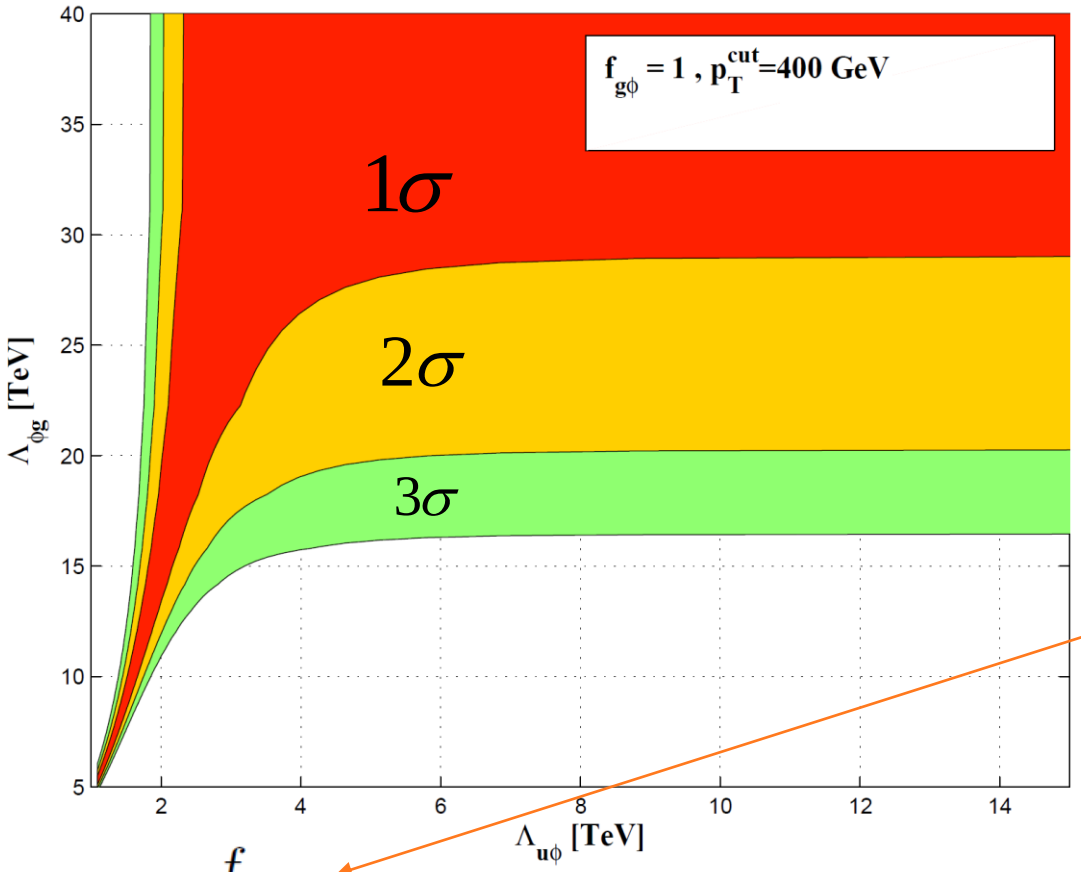
$$\begin{aligned}
\mathcal{O}_{u\phi} &= \left(\phi^\dagger\phi\right)\left(\bar{Q}_L\tilde{\phi}u_R\right) + h.c. \ , \\
\mathcal{O}_{d\phi} &= \left(\phi^\dagger\phi\right)\left(\bar{Q}_L\phi d_R\right) + h.c. \ , \\
\mathcal{O}_{ug} &= \left(\bar{Q}_L\sigma^{\mu\nu}T^a u_R\right)\tilde{\phi}G^a_{\mu\nu} + h.c. \ , \\
\mathcal{O}_{dg} &= \left(\bar{Q}_L\sigma^{\mu\nu}T^a d_R\right)\phi G^a_{\mu\nu} + h.c. \ , \\
\mathcal{O}_{\phi g} &= \left(\phi^\dagger\phi\right)G^a_{\mu\nu}G^{a,\mu\nu}
\end{aligned}$$

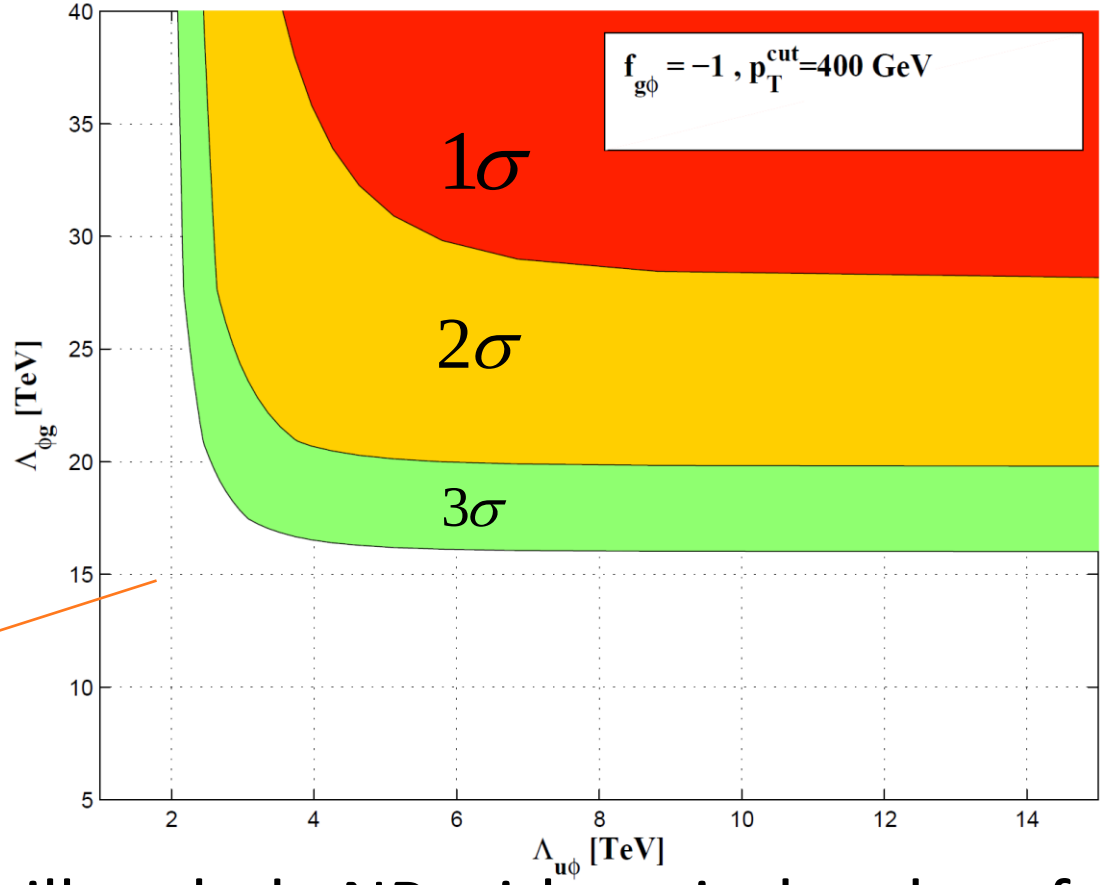
CMDM-like operators

$$\mathcal{O}_{u\phi} = (\phi^\dagger\phi)\left(\bar{Q}_L\tilde{\phi}u_R\right) + h.c. \quad , \quad \mathcal{O}_{\phi g} = (\phi^\dagger\phi)\, G^a_{\mu\nu}G^{a,\mu\nu}$$

Results (light-jet)

$$|f_{u\phi}| = 1, \quad \left|\mu^f_{hj} - 1\right| \leq 0.05,\ 0.1 \text{ and } 0.15$$





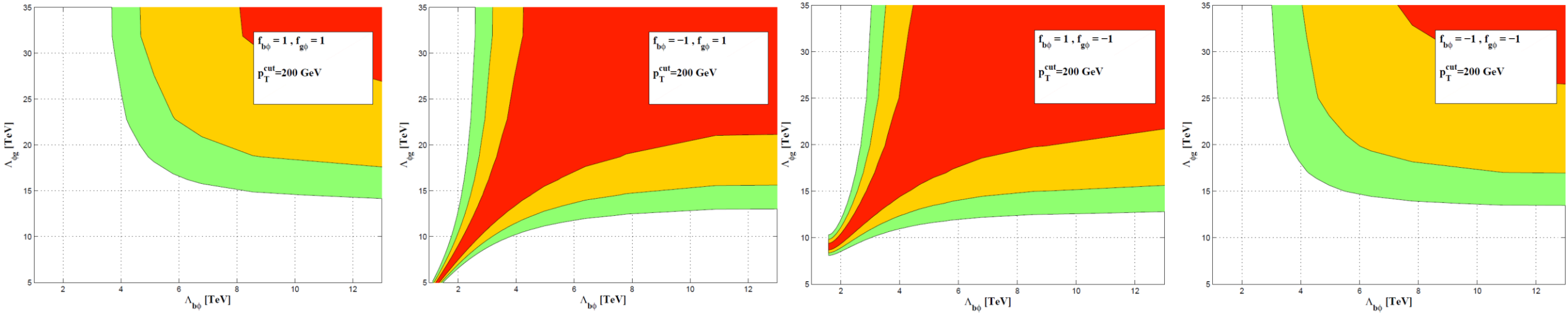
- μ^f_{hj} consistent with SM at 3σ will exclude NP with typical scales of $\Lambda_{\phi g} \lesssim 15$ TeV and $\Lambda_{u\phi} \lesssim 2$ TeV for $f_{\phi g} = -1$

$$\mathcal{O}_{d\phi} = (\phi^\dagger\phi)(\bar{Q}_L\phi d_R) + h.c.\ , \quad \mathcal{O}_{\phi g} = (\phi^\dagger\phi)\, G^a_{\mu\nu} G^{a,\mu\nu}$$

$$p_T^{cut} = 200 \text{ GeV}$$

Results (b-jet)

$$(f_{b\phi}, f_{\phi g}) = (1,1), (1,-1), (-1,1), (-1,-1)$$

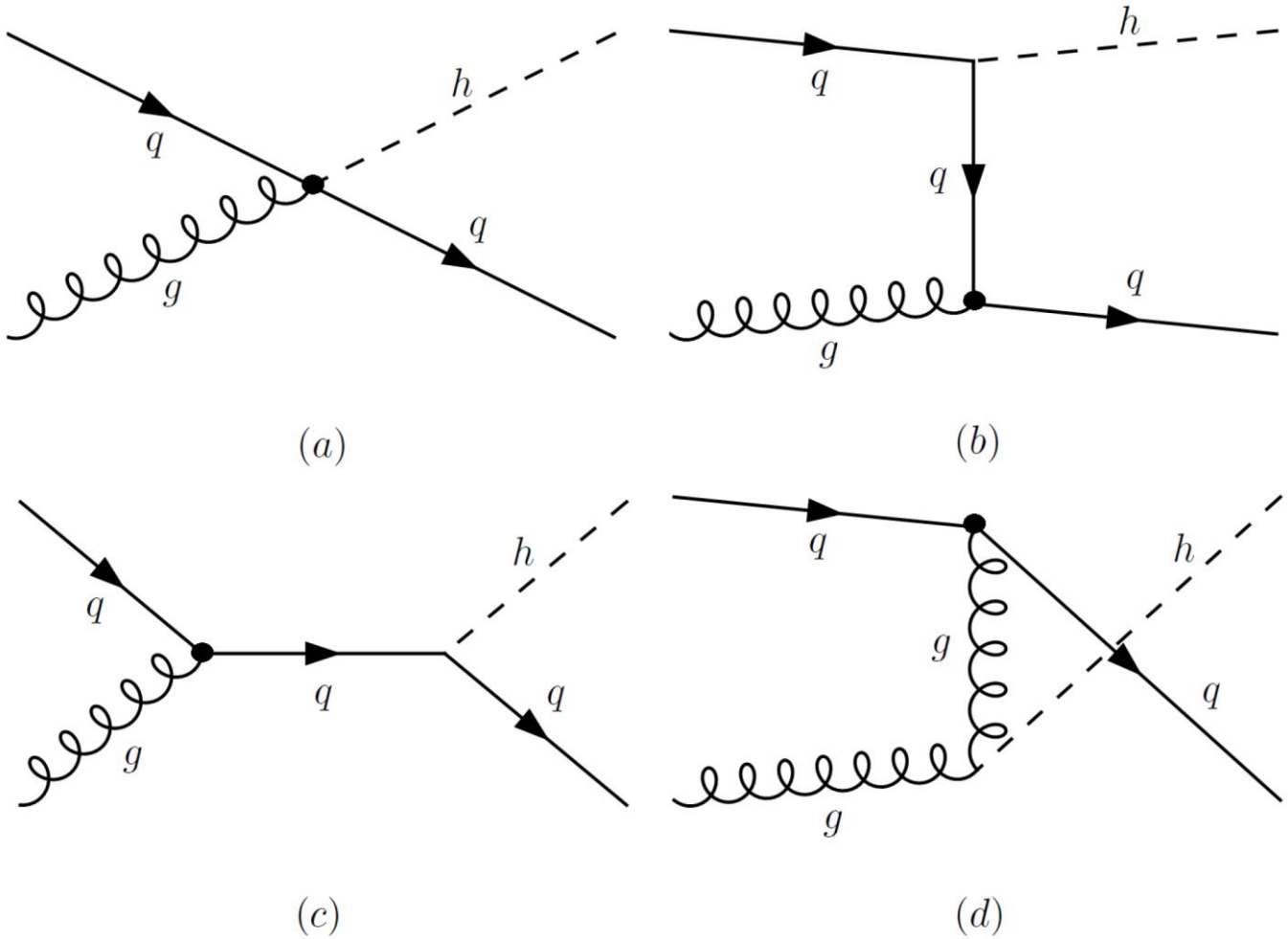


- A slightly better sensitivity than h+j (light-jet case)
- Better sensitivity at high $p_T(h)$

$$\mathcal{O}_{ug} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a u_R\right) \tilde{\phi} G^a_{\mu\nu} + h.c. \,, \quad \mathcal{O}_{dg} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a d_R\right) \phi G^a_{\mu\nu} + h.c.$$

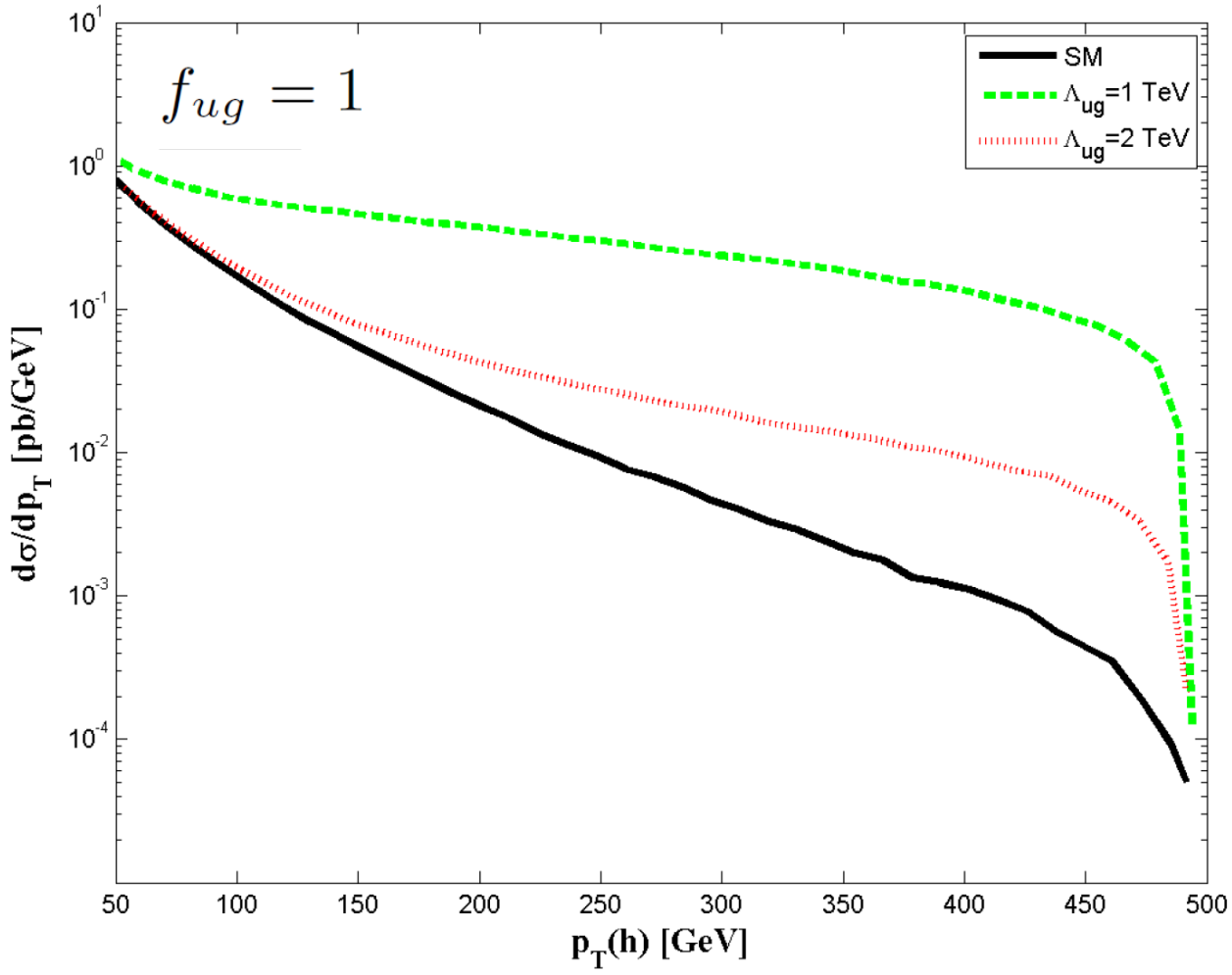
SMEFT: The CMDM-like operators

- Cannot be described in k-framework by scaling SM couplings
- e.g. b-quark CMDM:
- u-quark CMDM: only diagrams (a) & (d) contribute.



$$\mathcal{O}_{ug} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a u_R\right) \tilde{\phi} G^a_{\mu\nu} + h.c.$$

Results u-quark CMDM (light-jet)



$$\sigma^{hj}_{NP} = \sigma^{hj}_{SM} + \left(\frac{f_{ug}}{\Lambda^2_{ug}}\right)^2 \sigma^{hj}_{ug}$$

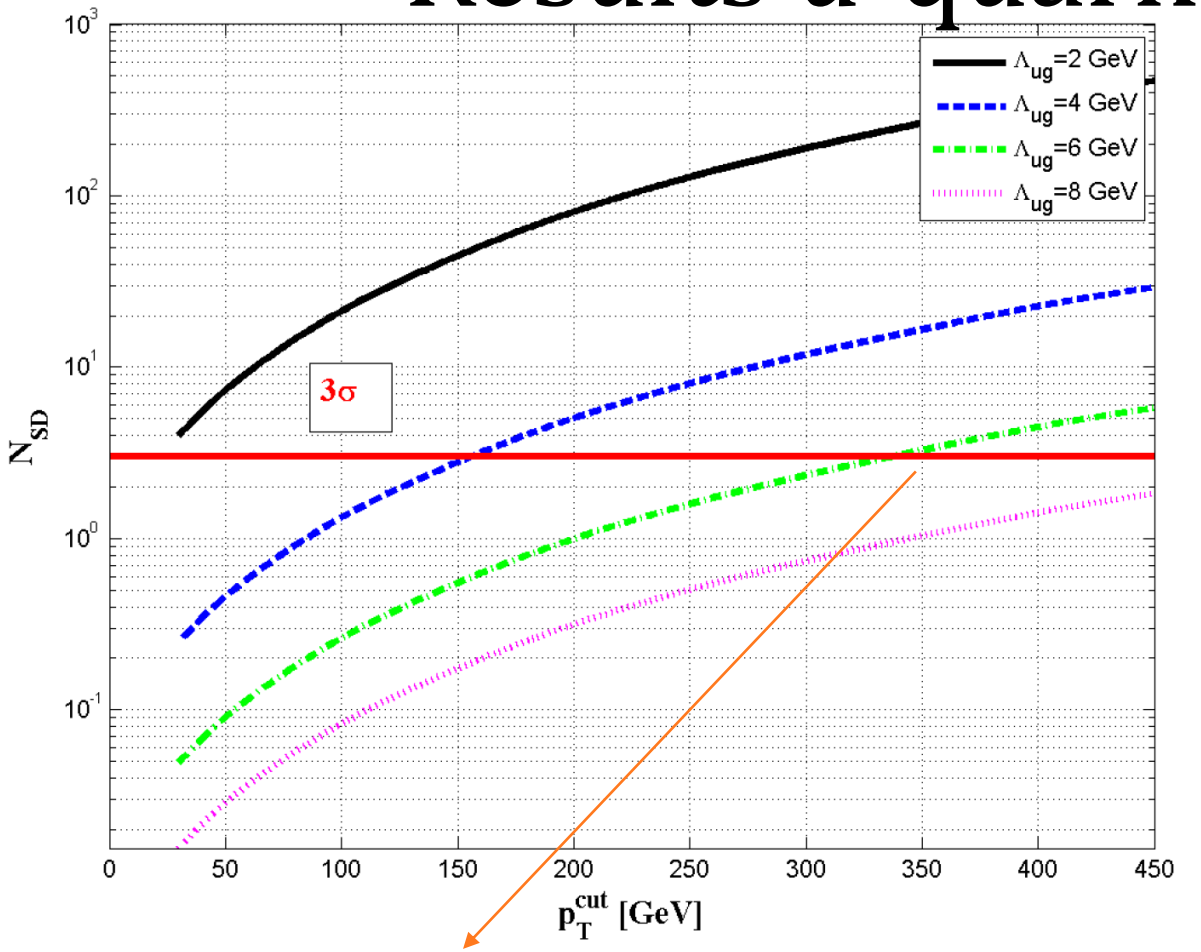
$$m_{h+j} \leq 1 \text{ TeV}$$

(invariant mass cut)

- Much harder $p_T(h)$ spectrum w.r.t SM

$$\mathcal{O}_{ug} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a u_R\right) \tilde{\phi} G^a_{\mu\nu} + h.c.$$

Results u-quark CMDM (light-jet)



$$f_{ug} = 1$$

$$m_{h+j} \leq 2 \text{ TeV}$$

$$\mu^f_{hj}(\mathcal{O}_{ug}) = 1 + \left(\frac{f_{ug}}{\Lambda^2_{ug}}\right)^2 R^{hj}_{ug} \quad , \quad R^{hj}_{ug} \equiv \frac{\sigma^{hj}_{ug}}{\sigma^{hj}_{SM}}$$

$$\Delta\mu^f_{hj}(\mathcal{O}_{ug}) = \mid \mu^f_{hj}(\mathcal{O}_{ug}) - 1 \mid = \left(\frac{f_{ug}}{\Lambda^2_{ug}}\right)^2 R^{hj}_{ug}$$

$$N_{SD} = \mu^f_{hj} / \delta\mu^f_{hj}$$

$$\delta\mu^f_{hj} = 0.05(1\sigma)$$

- If $\Lambda_{ug} = 6$ TeV then $p_T^{cut} \sim 350$ GeV required to obtain 3σ effect

$N(pp \to h+j \to \gamma\gamma+j) \sim \mathcal{O}(10)$ and $\mathcal{O}(100)$ with $\mathcal{L} = 300$ fb^{-1} and $\mathcal{L} = 3000$ fb^{-1}, respectively. $\mathcal{A} = 0.5$

$$\mathcal{O}_{dg} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a d_R\right) \phi G^a_{\mu\nu} + h.c.$$

SMEFT: b-quark CMDM (b-jet case)

- Consider $pp \to h + j_b$
- Now have interference (though small)

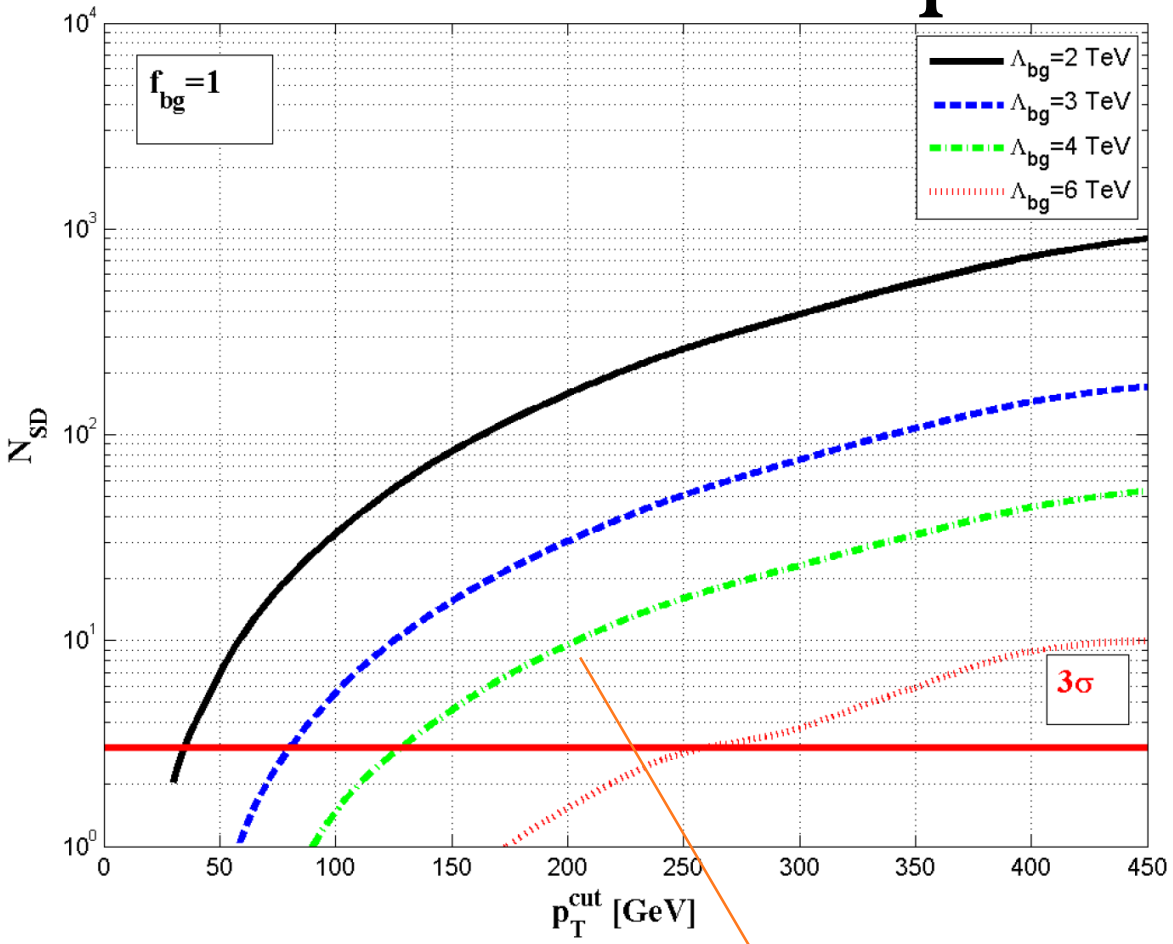
$$\sigma_{NP}^{hj_b} = \sigma_{SM}^{hj_b} + \frac{f_{bg}}{\Lambda_{bg}^2} \sigma_{bg}^{1,hj_b} + \left(\frac{f_{bg}}{\Lambda_{bg}^2}\right)^2 \sigma_{bg}^{2,hj_b} ,$$

$$\sigma_{bg}^{1,hj_b} \sim \mathcal{O}(m_b/v)$$

- Very similar PT spectrum (becomes much harder) as light-jet case!

$$\mathcal{O}_{dg} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a d_R\right) \phi G^a_{\mu\nu} + h.c.$$

Results b-quark CMDM (b-jet case)



$$f_{bg} = 1$$

$$m_{h+j_b} \leq 2 \text{ TeV}$$

$$N_{SD} = \Delta\mu^f_{h(j_b)} / \delta\mu^f_{h(j_b)}$$

$$\Delta\mu^f_{h(j_b)} \equiv | \mu^f_{h(j_b)} - 1 | \ ,$$

$$\delta\mu^f_{h(j_b)} = 0.05(1\sigma)$$

- Results for $f_{bg} = -1$ are similar due to small interference
- b-CMDM with typical scale $\Lambda_{bg} \sim 4$ TeV can be probed at $\mathcal{O}(10\sigma)$ with $p_T^{cut} = 200$ GeV

$$N(pp \to h + j_b \to \gamma\gamma + j_b) \sim 30 \ , \mathcal{A} = 0.5 \, , \epsilon_b = 0.7, \ \mathcal{L} = 3000 \text{ fb}^{-1}$$

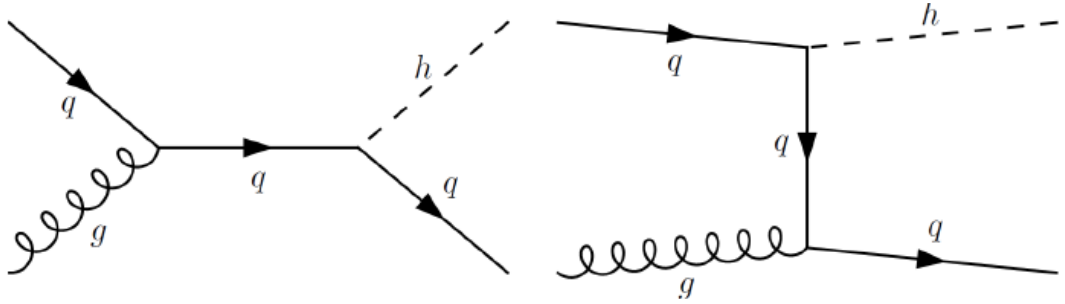
Summary

- We suggest that the exclusive $pp \to h + j(j_b) \to \gamma\gamma + j(j_b)$ production @ the LHC is a rather sensitive probe of the light-quark Yukawa couplings & other forms of NP.
- We study the $p_T(h)$ distribution employing a signal strength formalism.
- NP scenario where qqh and ggh are scaled by κ_q and κ_g (Kappa-framework) retaining the SM kinematics.
- NP in the form of higher dimensional operators (SMEFT).
- We find that this exclusive Higgs+jet channel $pp \to h + j(j_b) \to \gamma\gamma + j(j_b)$ can be sensitive to scales of NP ranging from a few to $\mathcal{O}(10)$ TeV depending on the flavor, chirality and Lorentz structure of the underlying physics.

Thank You

Backup Slides

- Tree-level SM s-t channels



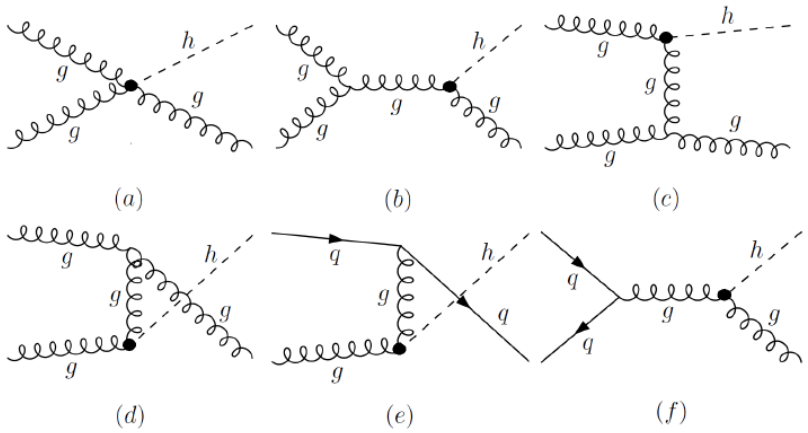
$$\sum \overline{|\mathcal{M}_{SM}|^2}_{q\bar{q}\to gh} = \frac{2g_s^2 y_q^2}{\mathcal{C}_{qq}} \frac{m_h^4 + \hat{s}^2}{\hat{t}\hat{u}} , \quad (1)$$

$$\sum \overline{|\mathcal{M}_{SM}|^2}_{qg\to qh} = -\frac{\mathcal{C}_{qq}}{\mathcal{C}_{qg}} \sum \overline{|\mathcal{M}_{SM}|^2}_{q\bar{q}\to gh} (\hat{s} \leftrightarrow \hat{t}) \quad (2)$$

$$\sum \overline{|\mathcal{M}_{SM}|^2}_{\bar{q}g\to \bar{q}h} = -\frac{\mathcal{C}_{qq}}{\mathcal{C}_{qg}} \sum \overline{|\mathcal{M}_{SM}|^2}_{q\bar{q}\to gh} (\hat{s} \leftrightarrow \hat{u}) \quad (3)$$

Backup Slides

- 1-loop SM amplitudes



$$\sum \overline{|\mathcal{M}_{SM}|^2}_{gg\to gh} = \frac{96 g_s^2 (C_g^{SM})^2}{\mathcal{C}_{gg}} \frac{m_h^8 + \hat{s}^4 + \hat{t}^2 + \hat{u}^2}{\hat{s}\hat{t}\hat{u}} \quad (5)$$

$$\sum \overline{|\mathcal{M}_{SM}|^2}_{q\bar{q}\to gh} = \frac{16 g_s^2 (C_g^{SM})^2}{\mathcal{C}_{qq}} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}} , \quad (6)$$

$$\sum \overline{|\mathcal{M}_{SM}|^2}_{qg\to qh} = -\frac{\mathcal{C}_{qq}}{\mathcal{C}_{qg}} \sum \overline{|\mathcal{M}_{SM}|^2}_{q\bar{q}\to gh} (\hat{s} \leftrightarrow \hat{t}) \quad (7)$$

$$\sum \overline{|\mathcal{M}_{SM}|^2}_{\bar{q}g\to \bar{q}h} = -\frac{\mathcal{C}_{qq}}{\mathcal{C}_{qg}} \sum \overline{|\mathcal{M}_{SM}|^2}_{q\bar{q}\to gh} (\hat{s} \leftrightarrow \hat{u}) \quad (8)$$

The Kappa Framework

- Light-quarks: $pp \rightarrow h + j, \quad j = g, u, d, s, c$

$$\sigma_{SM}^{hj} = \left(C_g^{SM}\right)^2 \left(\sigma_{SM}^{gg} + \sigma_{SM}^{gq} + \sigma_{SM}^{g\bar{q}} + \sigma_{SM}^{q\bar{q}}\right)$$

$$\sigma_{NP}^{hj} = \kappa_g^2 \sigma_{SM}^{hj} + \kappa_q^2 \sigma_{qqh}^{hj}$$

tree-level

- SM recovered for $\sigma_{SM}^{hj} = \sigma_{NP}^{hj}(\kappa_g = 1, \kappa_q = 0)$

Backup Slides – Signal strength

- More on signal strength:

$$\mu_{hj}^{f} = \frac{\mathcal{N}(pp \to h + j \to ff + j)}{\mathcal{N}_{SM}(pp \to h + j \to ff + j)}$$

- Event yield:

$$\mathcal{N} = \mathcal{L}\sigma\mathcal{A}\epsilon$$

- Assume $\mathcal{A} \simeq \mathcal{A}_{SM}$ to obtain

$$\mu_{hj}^{f} \simeq \frac{\sigma(pp \to h + j)}{\sigma_{SM}(pp \to h + j)} \cdot \frac{BR(h \to ff)}{BR_{SM}(h \to ff)}$$

Backup Slides – Signal strength

- Assume μ^f_{hj} will be measured to a given accuracy:

$$\mu^f_{hj,exp} = \hat{\mu}^f_{hj,exp} \pm \delta\mu^f_{hj,exp}(1\sigma)$$

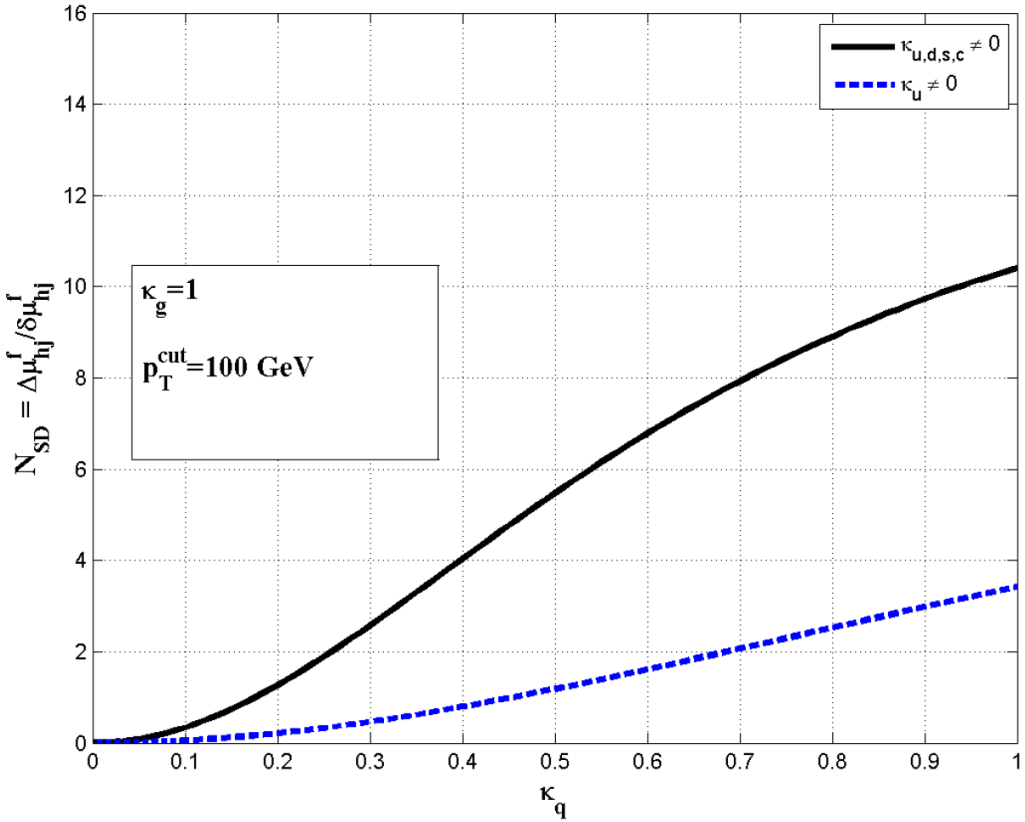
- Taking $\hat{\mu}^f_{hj,exp} = \mu^f_{hj}$ then $N_{SD} = \dfrac{\Delta\mu^f_{hj}}{\delta\mu^f_{hj}}$ where

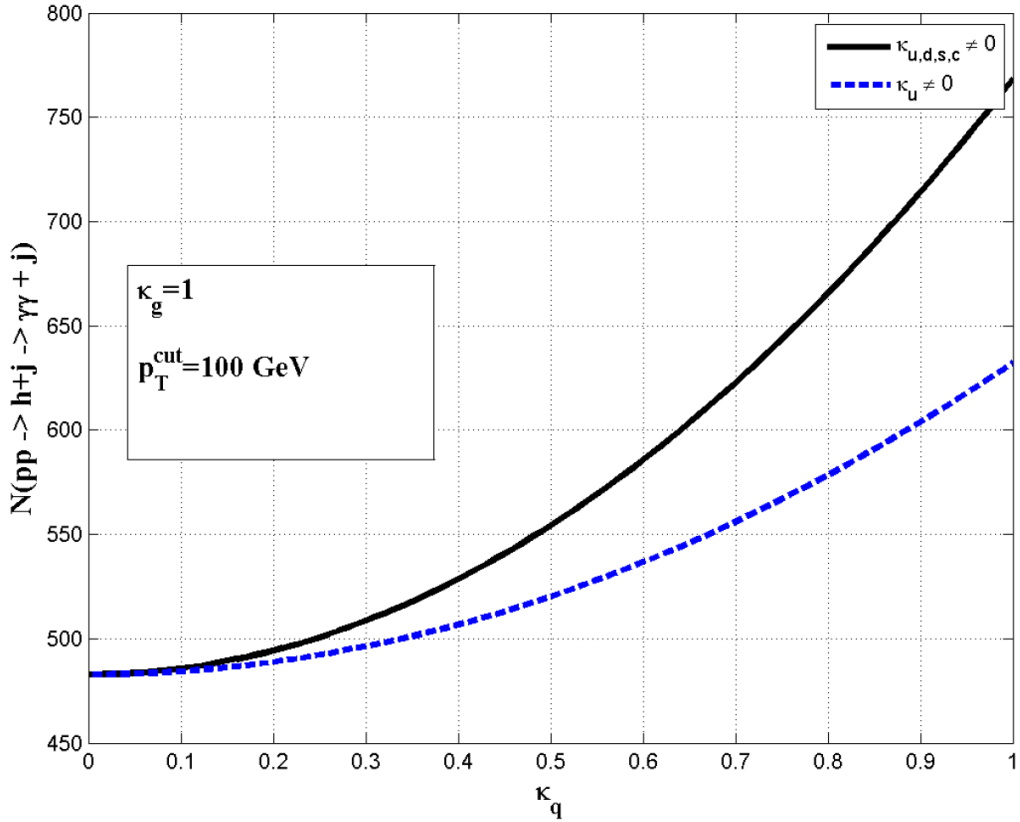
$$\delta\mu^f_{hj} = \sqrt{\left(\delta\mu^f_{hj,theory}\right)^2 + \left(\delta\mu^f_{hj,exp}\right)^2}$$

- Assume $\delta\mu^f_{hj} = 0.05(1\sigma)$ (Ultimate goal of Higgs Program)

Results (Light-quarks) $p_T^{cut} = 100$ GeV

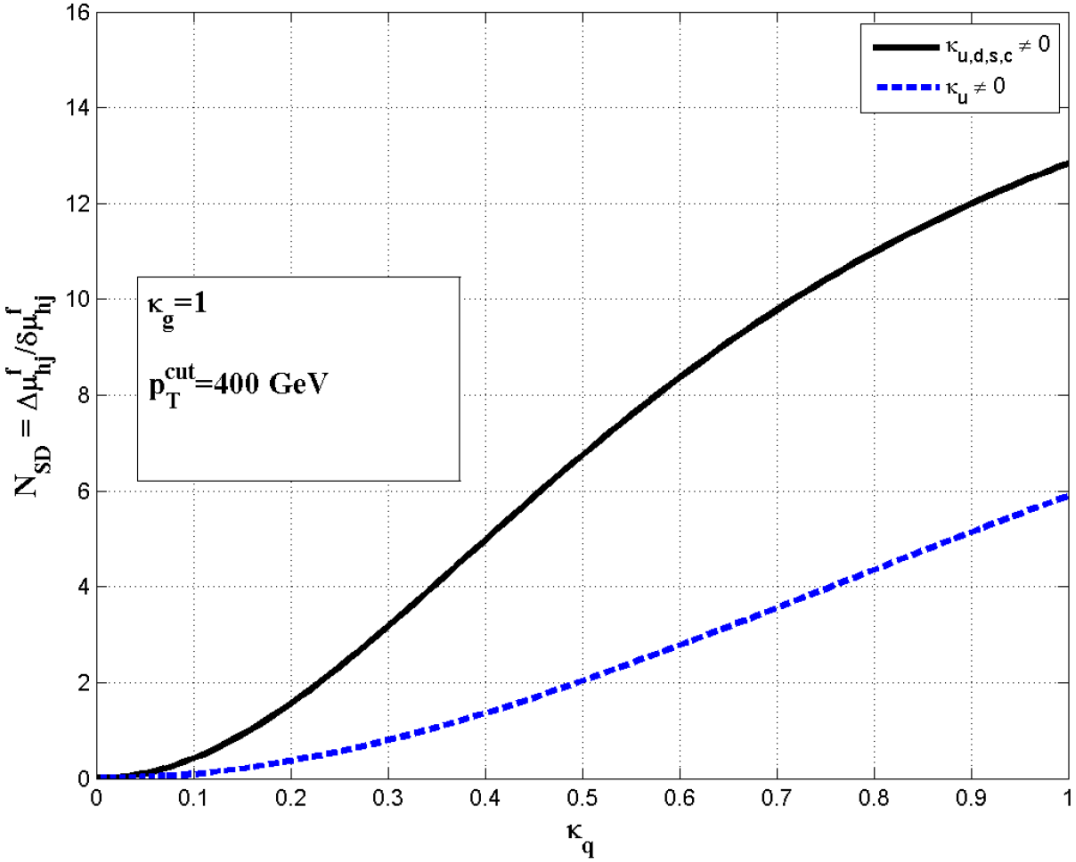
$\mathcal{L} = 300$ fb^{-1} $\mathcal{A} = 0.5$

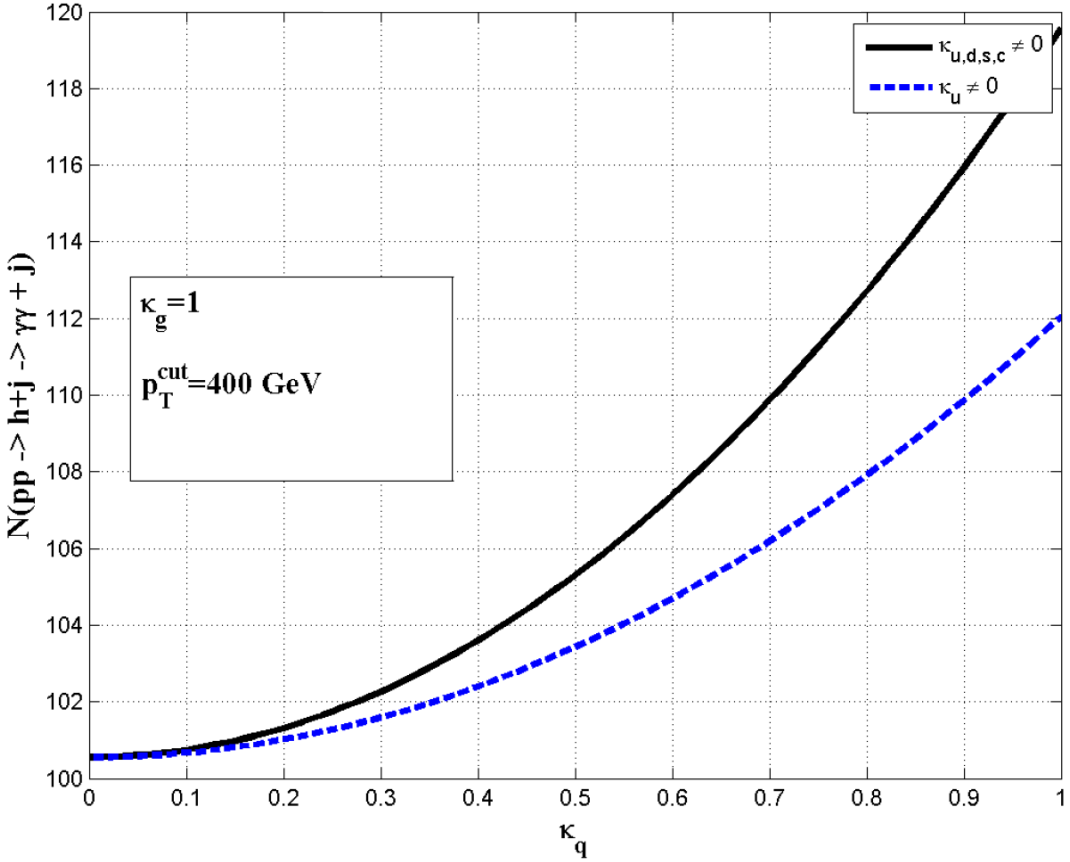




Results Light-quarks $p_T^{cut} = 400$ GeV

$\mathcal{L} = 3000$ fb^{-1} $\mathcal{A} = 0.5$





Results (Light-quarks)

Statistical significance $N_{SD} = \frac{\Delta\mu^f_{hj}}{\delta\mu^f_{hj}}$

$$\delta\mu^f_{hj} = 0.05(1\sigma)$$

$$p_T^{cut} = 400 \text{ GeV}$$

$\kappa_u \neq 0,\ \kappa_d = \kappa_s = \kappa_c = 0$

	$\kappa_u = 0$	$\kappa_u = 0.25$	$\kappa_u = 0.5$
$\kappa_g = 0.8$	6.79	$7.12^{-0.03}_{+0.03}$	$8.0^{-0.11}_{+0.10}$
$\kappa_g = 0.9$	3.53	$3.97^{-0.03}_{+0.03}$	$5.14^{-0.11}_{+0.10}$
$\kappa_g = 1.0$	0	$0.56^{-0.03}_{+0.03}$	$2.03^{-0.11}_{+0.10}$
$\kappa_g = 1.1$	3.78	$3.09^{+0.03}_{-0.03}$	$1.30^{+0.11}_{-0.10}$
$\kappa_g = 1.2$	7.75	$6.95^{+0.03}_{-0.03}$	$4.84^{+0.11}_{-0.10}$

$\kappa_q \neq 0$ for all $q = u, d, s, c$

	$\kappa_q = 0$	$\kappa_q = 0.25$	$\kappa_q = 0.5$
$\kappa_g = 0.8$	6.79	$8.30^{-0.05}_{+0.04}$	$11.13^{-0.13}_{+0.12}$
$\kappa_g = 0.9$	3.53	$5.43^{-0.05}_{+0.04}$	$9.03^{-0.13}_{+0.12}$
$\kappa_g = 1.0$	0	$2.32^{-0.05}_{+0.04}$	$6.74^{-0.13}_{+0.12}$
$\kappa_g = 1.1$	3.78	$1.01^{+0.05}_{-0.04}$	$4.26^{-0.13}_{+0.12}$
$\kappa_g = 1.2$	7.75	$4.55^{+0.04}_{-0.04}$	$1.61^{-0.13}_{+0.11}$

The Kappa Framework (b-jet case)

- Consider $pp \to h + j_b$
- Utilize 5FS
- Only $qg \to hq$ contributes with $q = b$
- Derive similar formulae for cross section, signal strength:

$$\sigma_{NP}^{hj_b} = \kappa_g^2 \sigma_{ggh}^{hj_b} + \kappa_b^2 \sigma_{bbh}^{hj_b}$$

$$\boxed{\text{SM: } \kappa_g = \kappa_b = 1}$$

$$\mu_{hj_b}^{f} = \left(\frac{\kappa_g^2}{1 + R_{SM}^{bg}} + \frac{\kappa_b^2}{1 + \left(R_{SM}^{bg}\right)^{-1}} \right) \cdot \mu_{h \to ff}^{b}$$

$$R_{SM}^{hj_b} \equiv \frac{\sigma_{bbh}^{hj_b}}{\sigma_{ggh}^{hj_b}} \ , \ \mu_{h \to ff}^{b} = \frac{1}{1 + \left(\kappa_g^2 - 1\right) BR_{SM}^{gg} + \left(\kappa_b^2 - 1\right) BR_{SM}^{bb}}$$

Results (b-jet)

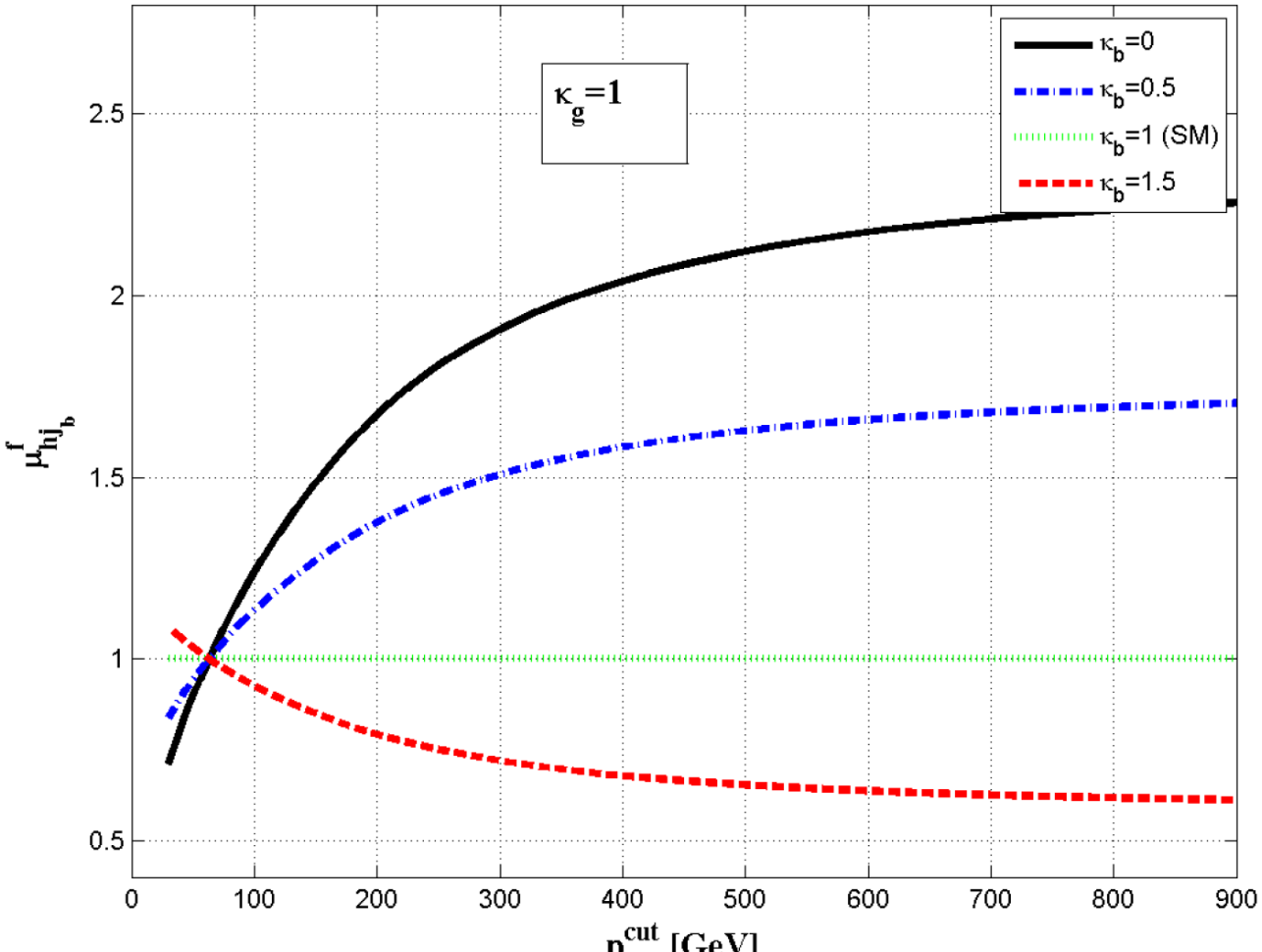
Statistical significance $N_{SD} = \frac{\Delta\mu^f_{hj_b}}{\delta\mu^f_{hj_b}}$

	$\kappa_b = 0.5$	$\kappa_b = 0.75$	$\kappa_b = 1$	$\kappa_b = 1.25$	$\kappa_b = 1.5$
$\kappa_g = 0.8$	$0.4^{+0.6}_{-0.3}$	$2.8^{+0.08}_{-0.08}$	$4.6^{-0.3}_{+0.3}$	$6.0^{-0.6}_{+0.6}$	$6.9^{-0.7}_{+0.7}$
$\kappa_g = 0.9$	$3.5^{-0.8}_{+0.8}$	$0.2^{-0.08}_{+0.3}$	$2.4^{-0.2}_{+0.2}$	$4.3^{-0.4}_{+0.4}$	$5.6^{-0.7}_{+0.7}$
$\kappa_g = 1.0$	$7.5^{-1.0}_{+1.0}$	$3.3^{-0.4}_{+0.5}$	0	$2.4^{-0.3}_{+0.3}$	$4.2^{-0.6}_{+0.6}$
$\kappa_g = 1.1$	$11.8^{-1.3}_{+1.3}$	$6.7^{-0.7}_{+0.7}$	$2.6^{-0.2}_{+0.2}$	$0.4^{-0.2}_{+0.2}$	$2.6^{-0.5}_{+0.5}$
$\kappa_g = 1.2$	$16.1^{-1.5}_{+1.5}$	$10.2^{-0.9}_{+0.9}$	$5.3^{-0.3}_{+0.3}$	$1.7^{-0.07}_{+0.07}$	$0.9^{-0.4}_{+0.4}$

$$\delta\mu^f_{hj_b} = 0.05(1\sigma),\ p_T^{cut} = 200\ \text{GeV}$$

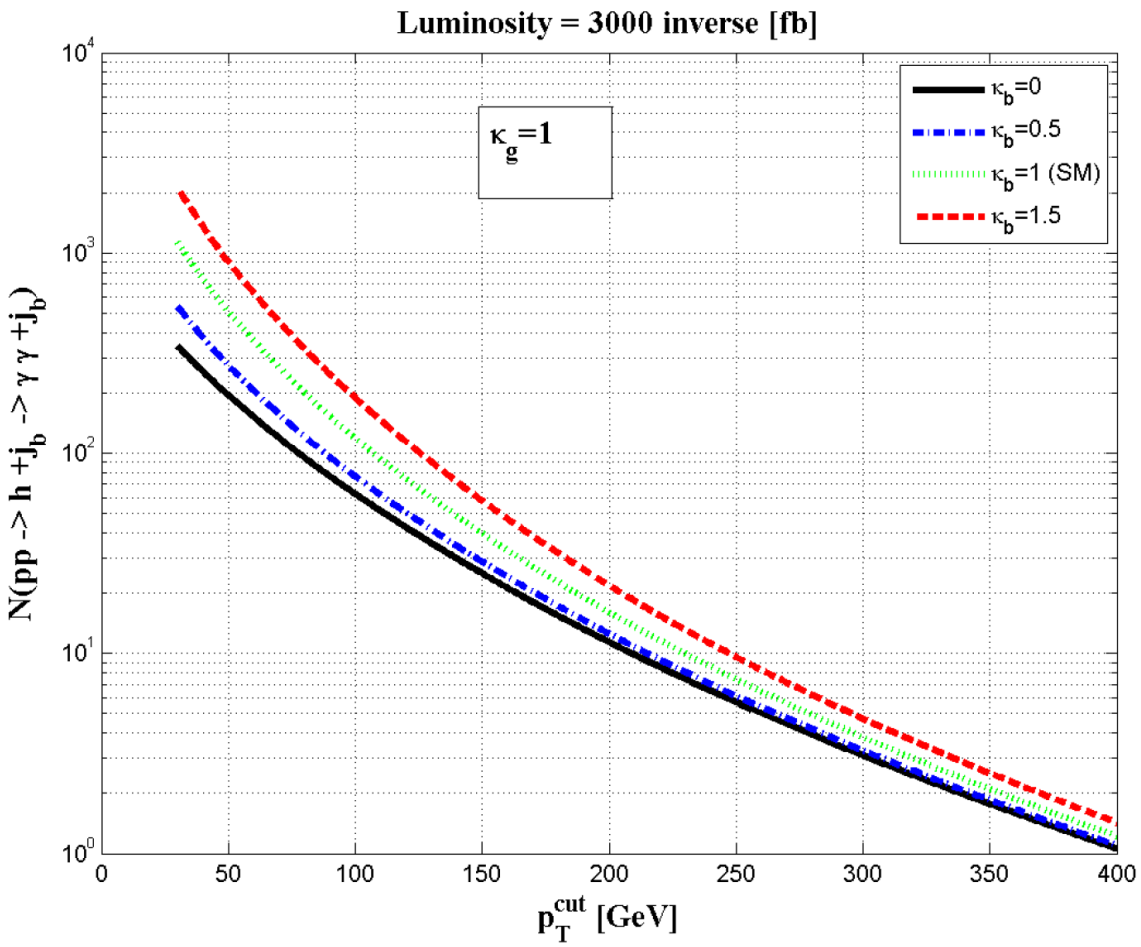
Backup Slides – Results (b-jet)

- K-framework (b-jet): signal strength



Backup Slides – Results # of Events

- K-framework (b-jet): $N(pp \to h + j_b \to \gamma\gamma + j_b) = \mathcal{L} \cdot \sigma(pp \to h + j_b) \cdot \mathcal{A} \cdot \epsilon_b \cdot BR(h \to \gamma\gamma)$



$$\mathcal{L} = 3000 \text{ fb}^{-1}$$
$$\mathcal{A} = 0.5$$
$$\epsilon_b = 0.7$$

The SMEFT Framework

- $\mathcal{O}_{u\phi}$, $\mathcal{O}_{d\phi}$ and $\mathcal{O}_{\phi g}$ can be "mapped" to the kappa-framework:

$$\kappa_q \simeq \frac{y_q^{SM}}{y_b^{SM}} - \frac{f_{q\phi}}{y_b^{SM}} \frac{v^2}{\Lambda_{q\phi}^2} \quad , \quad \kappa_g = 1 + \frac{12\pi f_{\phi g}}{\alpha_s} \frac{v^2}{\Lambda_{\phi g}^2}$$

where $y_q^{SM}/y_b^{SM} \rightarrow 0$ for light-quarks and $y_q^{SM}/y_b^{SM} = 1$ for the b-quark.

- Utilize previous analysis to obtain for $f_{u\phi}$ and $f_{\phi g} \sim \mathcal{O}(1)$

$$|\kappa_u| \lesssim 0.5$$
$$\Lambda_{u\phi} \gtrsim 3 \text{ TeV}$$

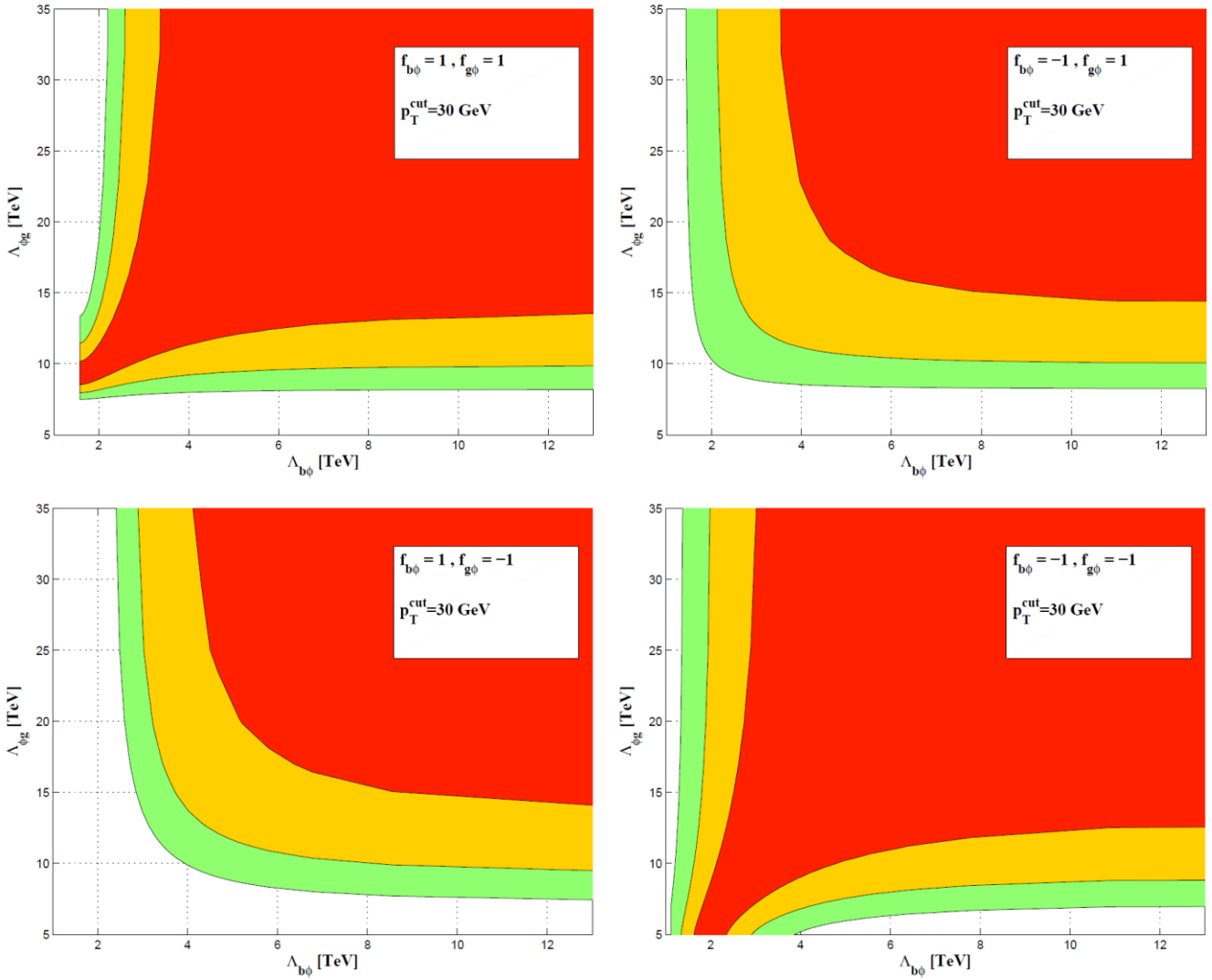
and

$$\Delta\kappa_g = |\kappa_g - 1| \gtrsim 0.1$$
$$\Lambda_{\phi g} \lesssim 15 \text{ TeV}$$

$$\mathcal{O}_{dg} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a d_R\right) \phi G^a_{\mu\nu} + h.c. \ , \quad \mathcal{O}_{\phi g} = \left(\phi^\dagger \phi\right) G^a_{\mu\nu} G^{a,\mu\nu}$$

Results (b-jet)

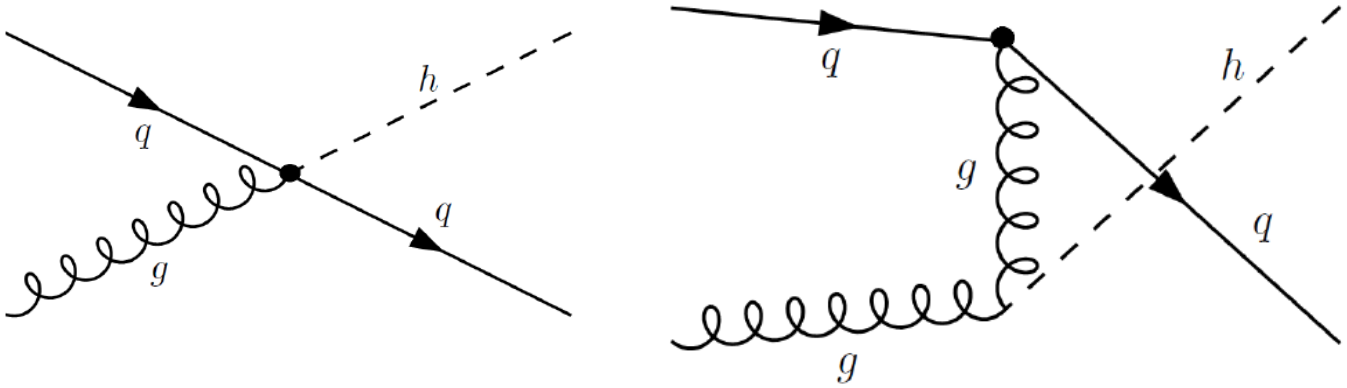
$$(f_{b\phi}, f_{\phi g}) = (1,1), (1,-1), (-1,1), (-1,-1)$$



$$p_T^{cut} = 30\,\text{GeV}$$
$$\mathcal{L} = 300\ \text{fb}^{-1}$$
$$\mathcal{A} = 0.5$$
$$\epsilon_b = 0.7$$

Backup Slides – u-quark CMDM

- u-quark:



$$\sum \overline{|\mathcal{M}_{ug}|^2}_{q\bar{q}\to gh} = \frac{8}{\mathcal{C}_{qq}} \hat{u}\hat{t}\left[1 - 4vC_g^{SM} + 8v^2(C_g^{SM})^2\right], \quad (38)$$

$$\sum \overline{|\mathcal{M}_{ug}|^2}_{qg\to qh} = -\frac{\mathcal{C}_{qq}}{\mathcal{C}_{qg}} \sum \overline{|\mathcal{M}_{ug}|^2}_{q\bar{q}\to gh}(\hat{s} \leftrightarrow \hat{t}) \ , \quad (39)$$

$$\sum \overline{|\mathcal{M}_{ug}|^2}_{\bar{q}g\to \bar{q}h} = -\frac{\mathcal{C}_{qq}}{\mathcal{C}_{qg}} \sum \overline{|\mathcal{M}_{ug}|^2}_{q\bar{q}\to gh}(\hat{s} \leftrightarrow \hat{u}) \ , \quad (40)$$

$$\mathcal{O}_{ug} = \left(\bar{Q}_L \sigma^{\mu\nu} T^a u_R\right) \tilde{\phi} G^a_{\mu\nu} + h.c.$$

SMEFT: u-quark CMDM (light-jet)

- Signal strength:

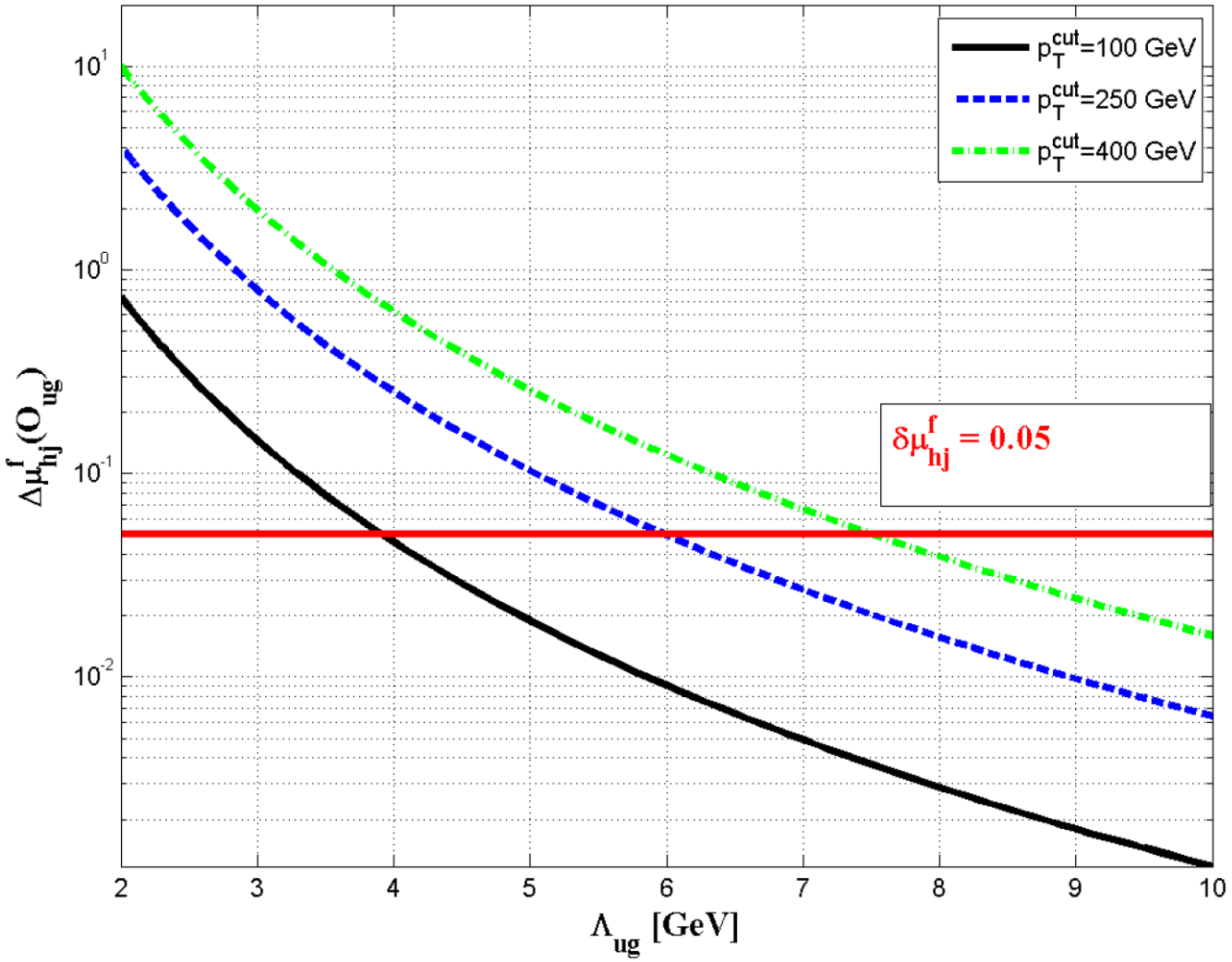
$$\mu^f_{hj}(\mathcal{O}_{ug}) = 1 + \left(\frac{f_{ug}}{\Lambda^2_{ug}}\right)^2 R^{hj}_{ug} \quad , \quad R^{hj}_{ug} \equiv \frac{\sigma^{hj}_{ug}}{\sigma^{hj}_{SM}}$$

- NP signal:

$$\Delta\mu^f_{hj}(\mathcal{O}_{ug}) = \mid \mu^f_{hj}(\mathcal{O}_{ug}) - 1 \mid = \left(\frac{f_{ug}}{\Lambda^2_{ug}}\right)^2 R^{hj}_{ug}$$

- Statistical Significance: $N_{SD} = \mu^f_{hj} / \delta\mu^f_{hj}$

Results u-quark CMDM (light-jet)



$$f_{ug} = 1$$

$$m_{h+j} \leq 2 \text{ TeV}$$

Backup Slides – u-quark CMDM

$$pp \to h + j \to \gamma\gamma + j$$

- # of events:

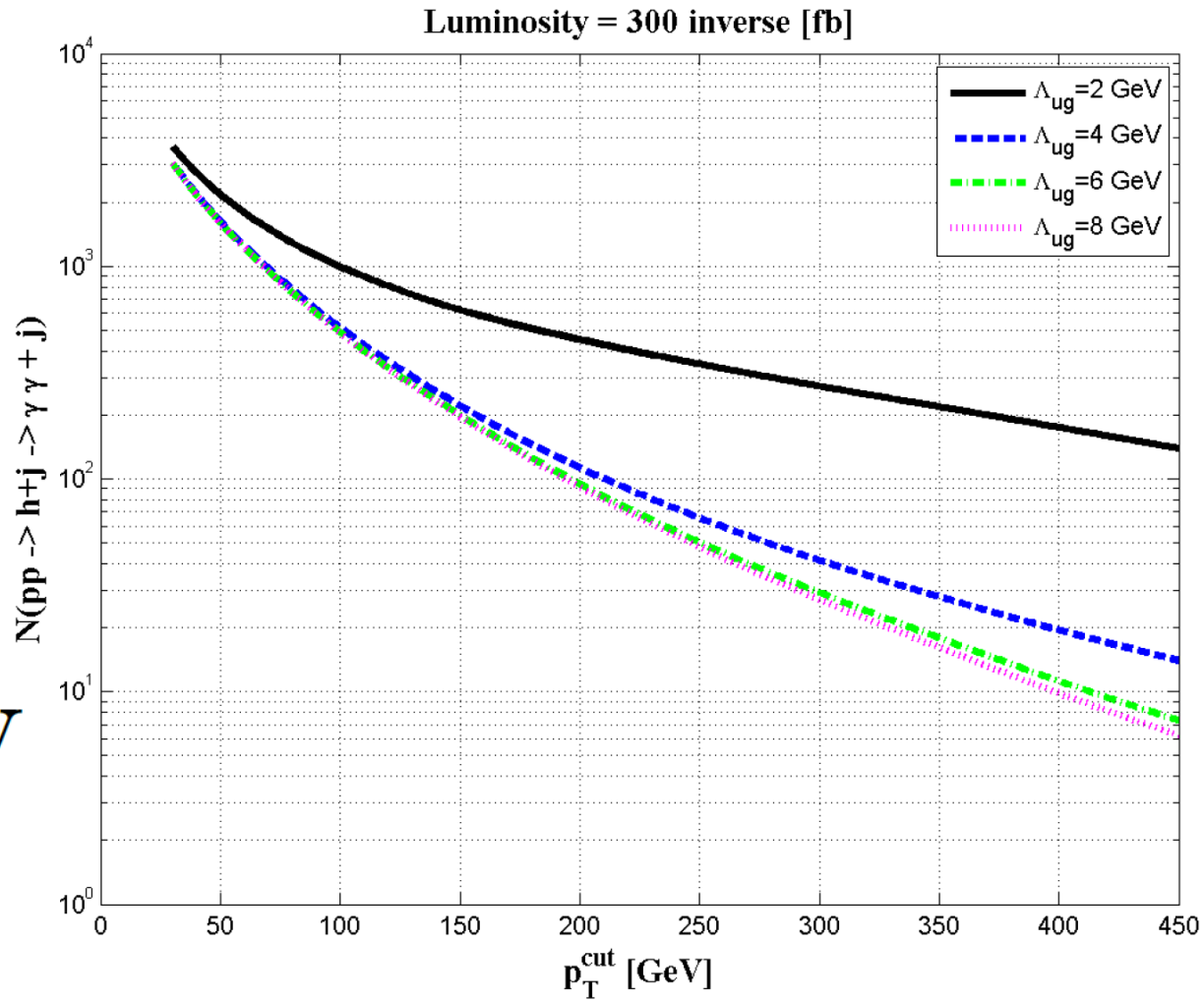
$$\delta\mu^f_{hj} = 0.05(1\sigma)$$

$$\mathcal{A} = 0.5$$

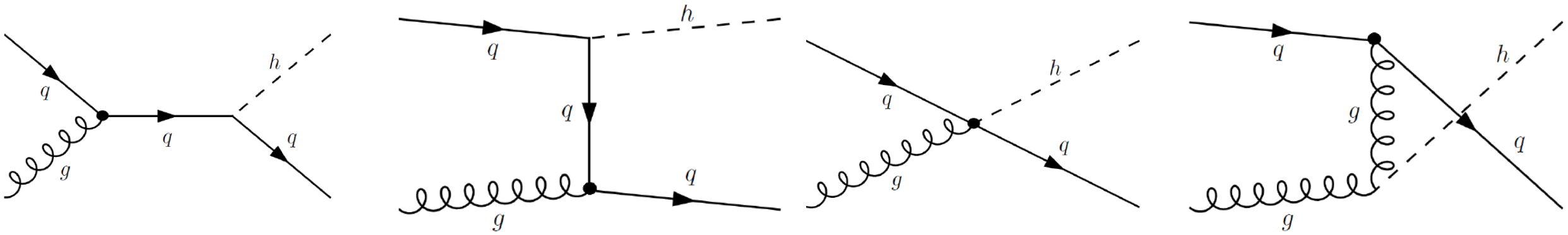
$$\mathcal{L} = 300 \text{ fb}^{-1}$$

$$f_{ug} = 1$$

$$m_{h+j} \leq 2 \text{ TeV}$$



Backup Slides – b-quark CMDM



$$\sum \overline{\left|\mathcal{M}^1_{bg}\right|^2}_{bg\to bh} = \frac{8 g_s y_b}{\mathcal{C}_{qg}} \left(4 v C_g^{SM} \hat{t} - m_h^2\right) \ , \tag{44}$$

$$\sum \overline{\left|\mathcal{M}^2_{bg}\right|^2}_{bg\to bh} = -\frac{8}{\mathcal{C}_{qg}} \left[\hat{s}\hat{u}\left(1 - 4 v C_g^{SM} + 8 v^2 (C_g^{SM})^2\right) + y_b^2 v^2 \hat{t}\right] \ , \tag{45}$$

$$\sum \overline{\left|\mathcal{M}^1_{bg}\right|^2}_{\bar{b}g\to \bar{b}h} = \sum \overline{\left|\mathcal{M}^1_{bg}\right|^2}_{bg\to bh} (\hat{u} \leftrightarrow \hat{t}) \ , \tag{46}$$

$$\sum \overline{\left|\mathcal{M}^2_{bg}\right|^2}_{\bar{b}g\to \bar{b}h} = \sum \overline{\left|\mathcal{M}^2_{bg}\right|^2}_{bg\to bh} (\hat{u} \leftrightarrow \hat{t}) \ , \tag{47}$$

Backup Slides – SMEFT - Flavor

- In general $f_{u\phi},\ f_{d\phi},\ f_{ug}$ and f_{dg} are 3X3 matrices
- One way to avoid flavor violation is to assume MFV:

$$\frac{f}{\Lambda^2}\mathcal{O}_{ug} \to Y_q \cdot \frac{f_{MFV}}{\Lambda^2_{MFV}}\mathcal{O}_{ug}$$

So that for a single flavor q:

$$\frac{\Lambda^2_{MFV}}{\Lambda^2} = y_q \frac{f_{MFV}}{f}$$

- Focus on single flavor (diagonal element) of operators and assume the flavor violation is controlled by underlying theory (not necessarily MFV)