Uli Haisch, MPI Munich, 8th General Meeting of the LHC EFT Working Group, 3.12.24

System of two operators Q_i & Q_j

$$\frac{dC_j(\mu)}{d\ln\mu} = \frac{1}{16\pi^2}\left[\gamma_{ji}(\mu)C_i(\mu) + \gamma_j(\mu)C_j(\mu)\right]$$

mixing $Q_i \to Q_j$

self-mixing $Q_j \to Q_j$

[discussion follows Buras & Jung, 1804.05852]

System of two operators Q_i & Q_j

$$\frac{C_j(\mu)}{C_i(\mu_0)} \simeq -\frac{\gamma_{ji}}{16\pi^2} \ln\left(\frac{\mu_0}{\mu}\right)$$

mixing $Q_i \to Q_j$

leading logarithm (LL)

[discussion follows Buras & Jung, 1804.05852]

A simple example

$$Q^{(1)}_{Hq,33} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_3\gamma^\mu q_3)\,, \qquad Q^{(3)}_{Hq,33} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_3\gamma^\mu \sigma^i q_3)$$

$$\mathcal{L}_{\rm LEFT} \supset -\frac{e}{2 s_w c_w}\left(C^{(1)}_{Hq,33} + C^{(3)}_{Hq,33}\right)\sum_{i,j} V^*_{ti} V_{tj}\, \bar{d}_{L,i}\gamma_\mu d_{L,j} Z^\mu$$

[discussion follows Brod et al., 1408.0792]

A simple example

$$C^{(1)}_{Hq,33}(\Lambda) + C^{(3)}_{Hq,33}(\Lambda) = 0$$

absence of tee-level modifications of $d_j \bar{d}_i Z$ couplings at scale Λ

[discussion follows Brod et al., 1408.0792]

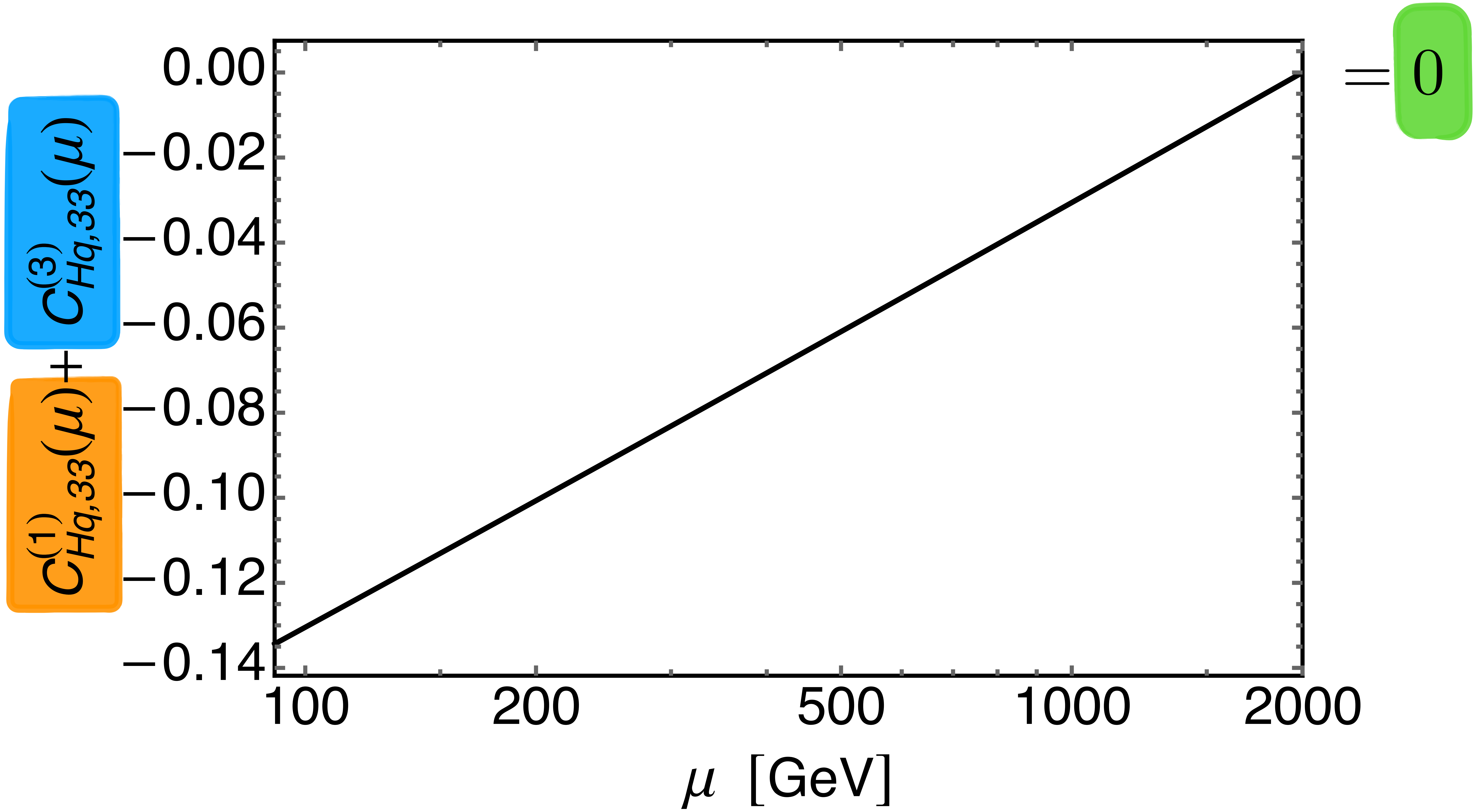
A simple example

$$\frac{dC^{(1)}_{Hq,33}}{d\ln\mu} = \frac{y_t^2}{16\pi^2}\left(10C^{(1)}_{Hq,33} - 9C^{(3)}_{Hq,33}\right) + \ldots$$

$$\frac{dC^{(3)}_{Hq,33}}{d\ln\mu} = \frac{y_t^2}{16\pi^2}\left(-3C^{(1)}_{Hq,33} + 8C^{(3)}_{Hq,33}\right) + \ldots$$

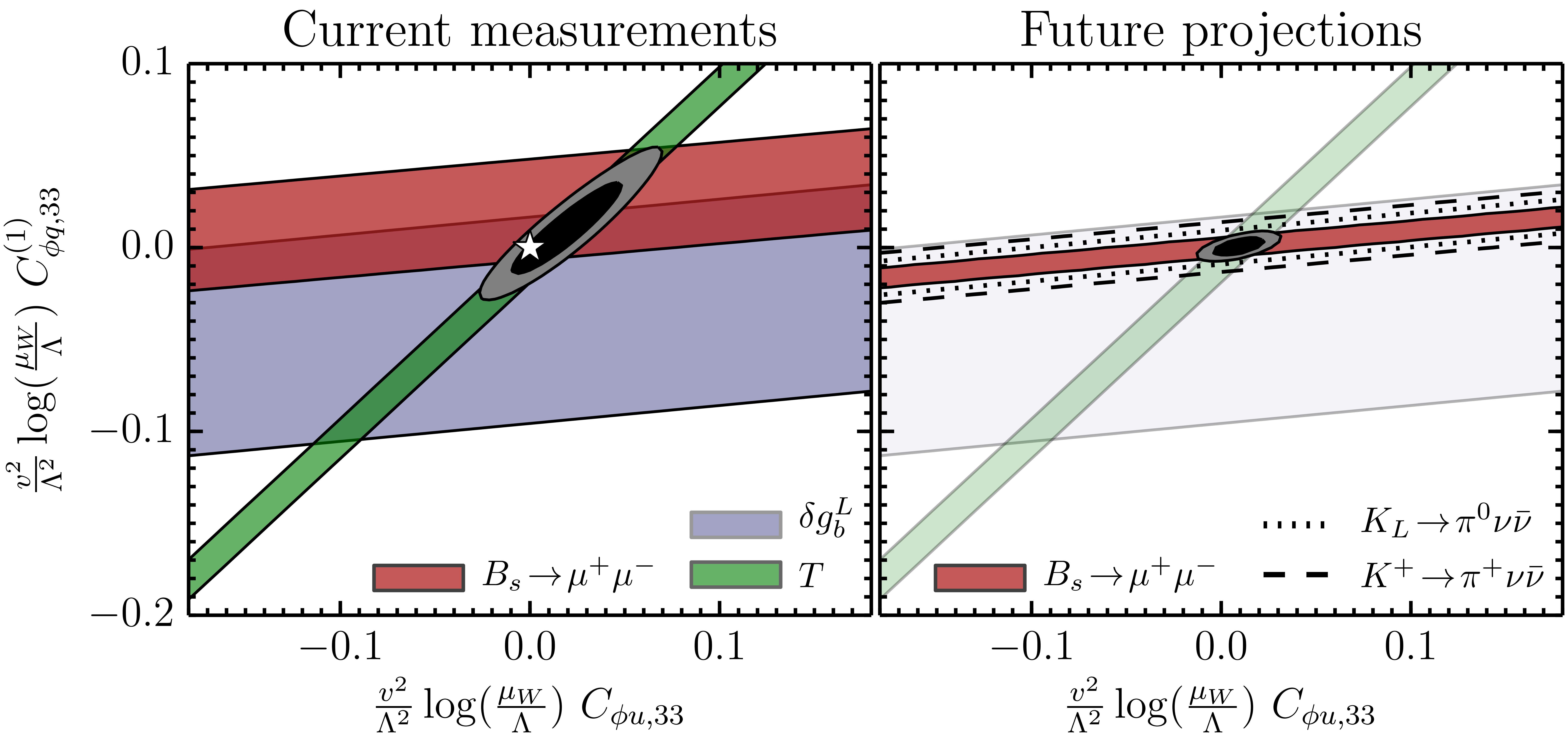
[discussion follows Brod et al., 1408.0792]

A simple example



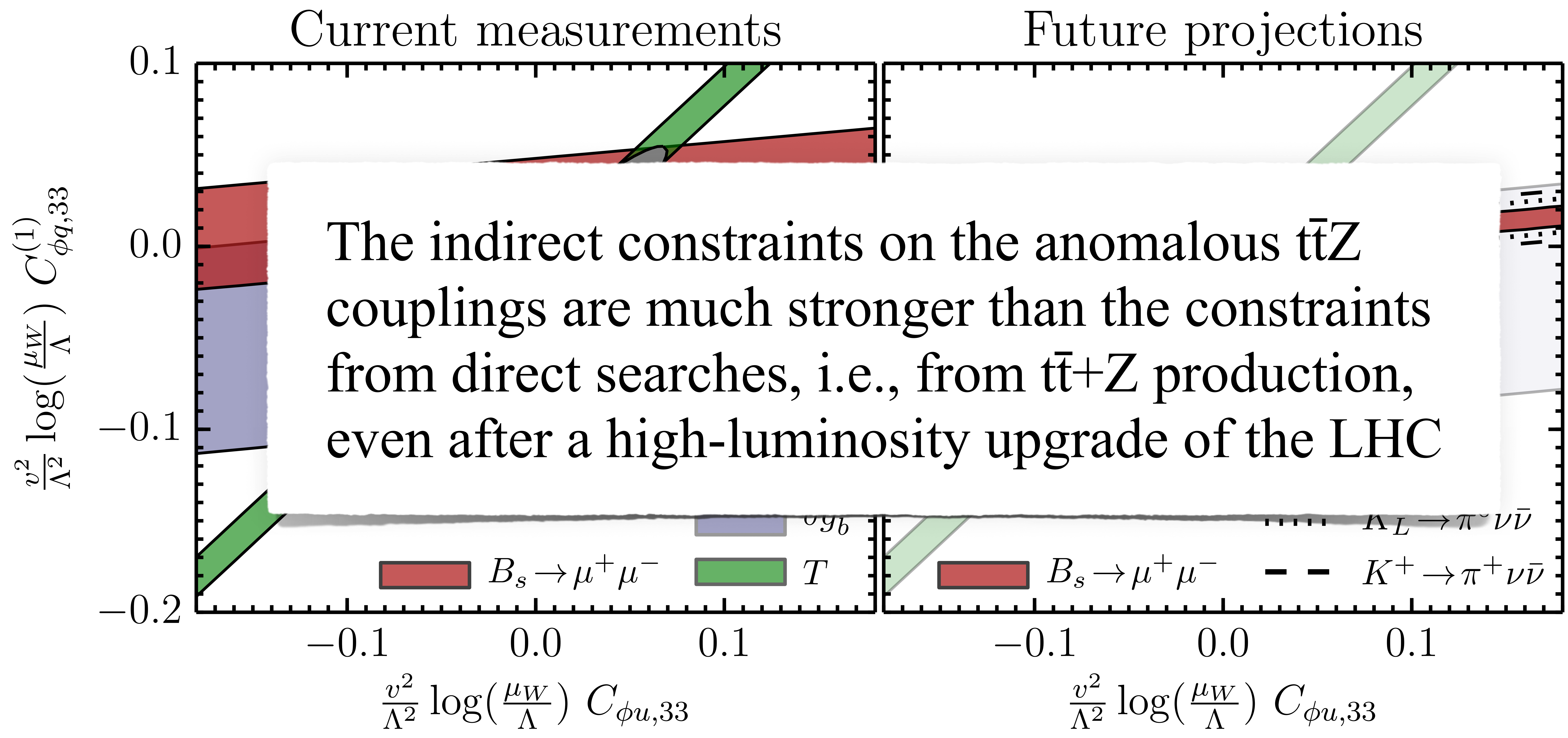
[discussion follows Brod et al., 1408.0792]

A simple example



[Brod et al., 1408.0792]

A simple example



The indirect constraints on the anomalous $t\bar{t}Z$ couplings are much stronger than the constraints from direct searches, i.e., from $t\bar{t}$+Z production, even after a high-luminosity upgrade of the LHC

[Brod et al., 1408.0792]

System of three operators Q_i, Q_m & Q_j

$$\frac{C_j(\mu)}{C_i(\mu_0)} \simeq -\frac{\gamma_{ji}}{16\pi^2} \ln\left(\frac{\mu_0}{\mu}\right) + \frac{\gamma_{jm}\gamma_{mi}}{512\pi^4} \ln^2\left(\frac{\mu_0}{\mu}\right)$$

mixing $Q_i \to Q_j$

mixing $Q_i \to Q_m \to Q_j$

[discussion follows Buras & Jung, 1804.05852; see also talk by Stefanek earlier today]

System of three operators Q_i, Q_m & Q_j

$$\frac{C_j(\mu)}{C_i(\mu_0)} \simeq -\frac{\gamma_{ji}}{16\pi^2} \ln\left(\frac{\mu_0}{\mu}\right) + \frac{\gamma_{jm}\gamma_{mi}}{512\pi^4} \ln^2\left(\frac{\mu_0}{\mu}\right)$$

1-loop LL effect

2-loop LL effect

[discussion follows Buras & Jung, 1804.05852; see also talk by Stefanek earlier today]

System of three operators Q_i, Q_m & Q_j

The 2-loop LL effects can be derived from the known 1-loop anomalous dimensions. The 2-loop anomalous dimensions solely generate next-to-leading logarithms (NLLs)

[discussion follows Buras & Jung, 1804.05852; see also talk by Stefanek earlier today]

Examples of 2-loop LL effects

$$C_{H\Box}(\mu) \propto \frac{y_t^4}{(4\pi)^4} C_{tt}^{(1)}(\mu_0) \ln^2\left(\frac{\mu_0}{\mu}\right),$$

$$C_{HG}(\mu) \propto \frac{g_s^3 y_t^2}{(4\pi)^4} C_G(\mu_0) \ln^2\left(\frac{\mu_0}{\mu}\right),$$

$$C_{HW}(\mu) \propto \frac{g^2 y_b y_t}{(4\pi)^4} C_{qtqb}^{(1)}(\mu_0) \ln^2\left(\frac{\mu_0}{\mu}\right), \ldots$$

[UH, unpublished]

2-loop LL effects in gg→h

$$\delta\kappa_g \simeq \frac{12\pi^2}{\alpha_s}\frac{\gamma_{HG,tG}\,\gamma_{tG,G}}{512\pi^4}\frac{v^2}{\Lambda^2}C_G(\Lambda)\ln^2\left(\frac{\Lambda}{m_h}\right)$$

$$\simeq -\frac{27 g_s y_t^2}{8\pi}\frac{v^2}{\Lambda^2}C_G(\Lambda)\ln^2\left(\frac{\Lambda}{m_h}\right) \simeq -0.09\,C_G$$

[UH, unpublished]

2-loop LL effects in gg→h

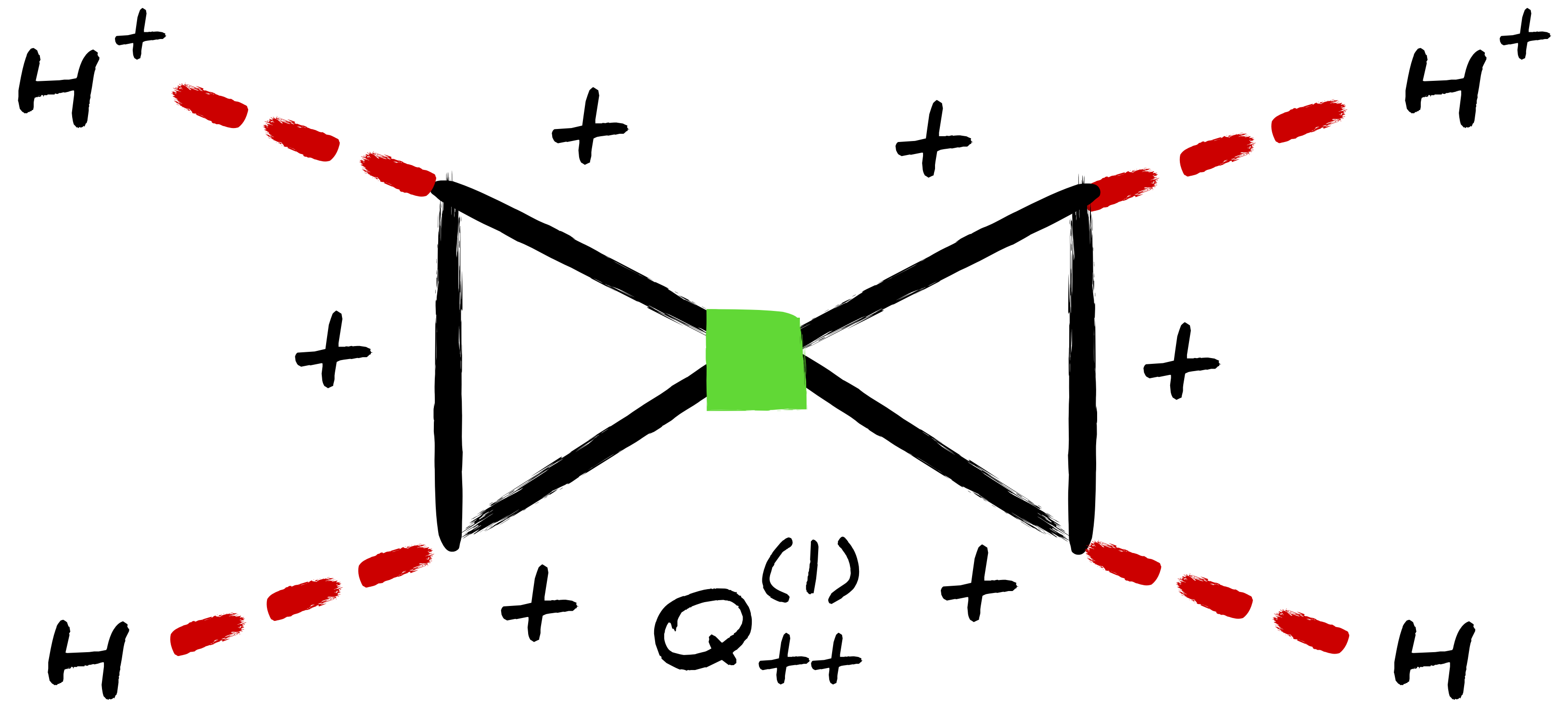
$\delta\kappa_g$

A 10% measurement of the signal strength in gluon-gluon-fusion Higgs production enables setting an indirect bound on the triple gluon operator, which is as good or better than direct limits obtained from di-jet or top-pair production

C_G

[UH, unpublished]

How big are 2-loop NLL effects?

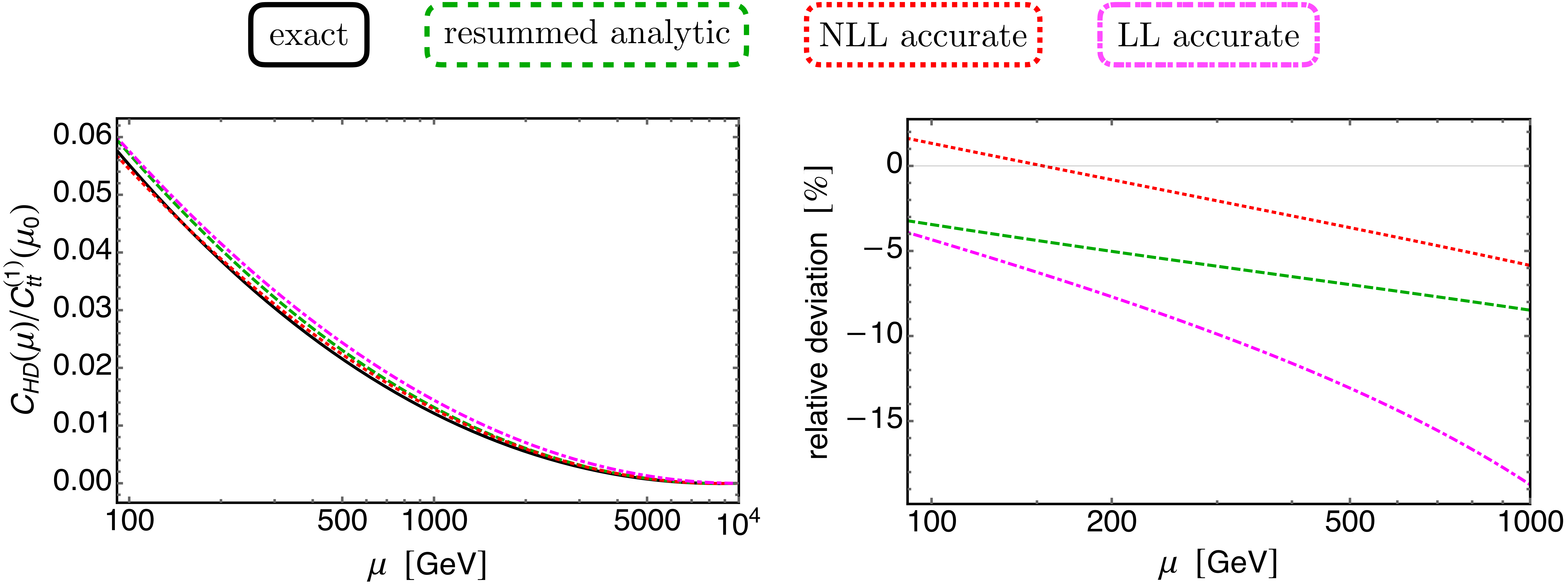


$$\Rightarrow \quad Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$

$$\gamma_{HD,qq}^{(1)}(\mu) = \frac{3y_t^4}{2\pi^2}\,, \quad \gamma_{HD,qq}^{(3)}(\mu) = \frac{9y_t^4}{2\pi^2}\,, \quad \gamma_{HD,tt}^{(1)}(\mu) = \frac{3y_t^4}{\pi^2}$$

[based on UH & Schnell, 2410.13304; unpublished; see also talk by Stefanek earlier today]

How big are 2-loop NLL effects?



[based on UH & Schnell, 2410.13304; unpublished]

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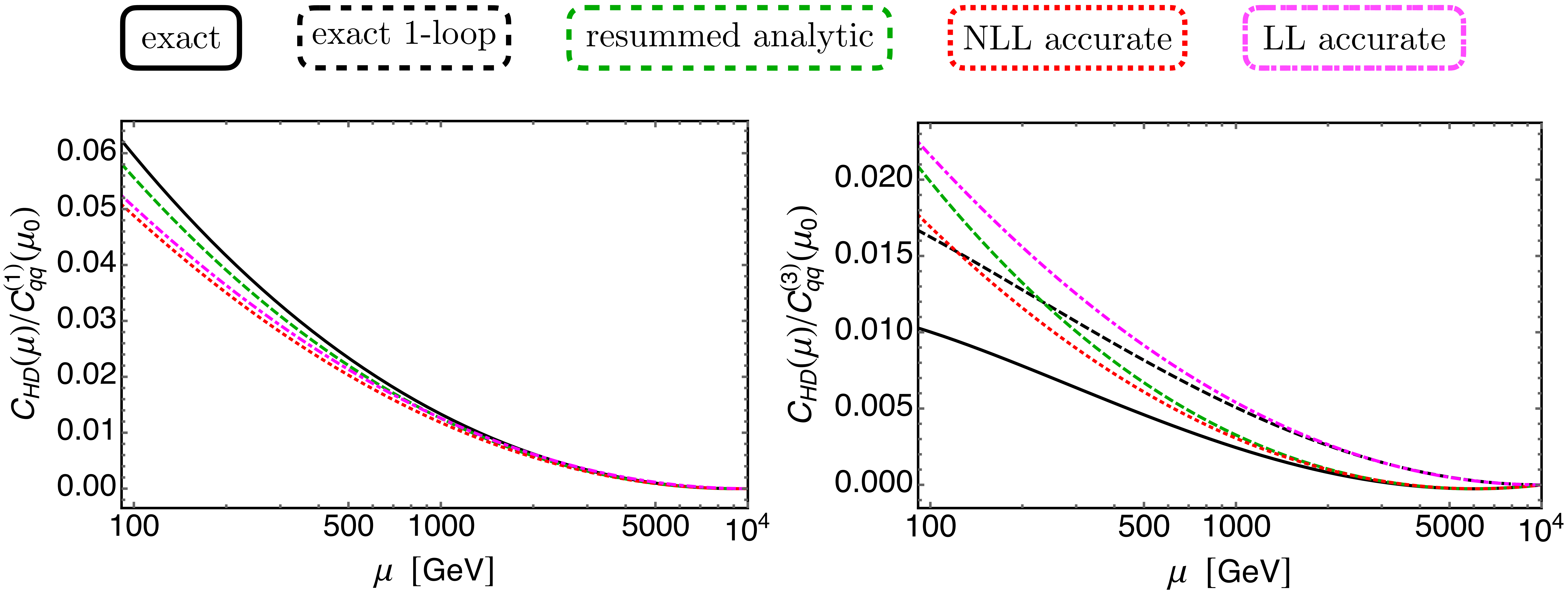
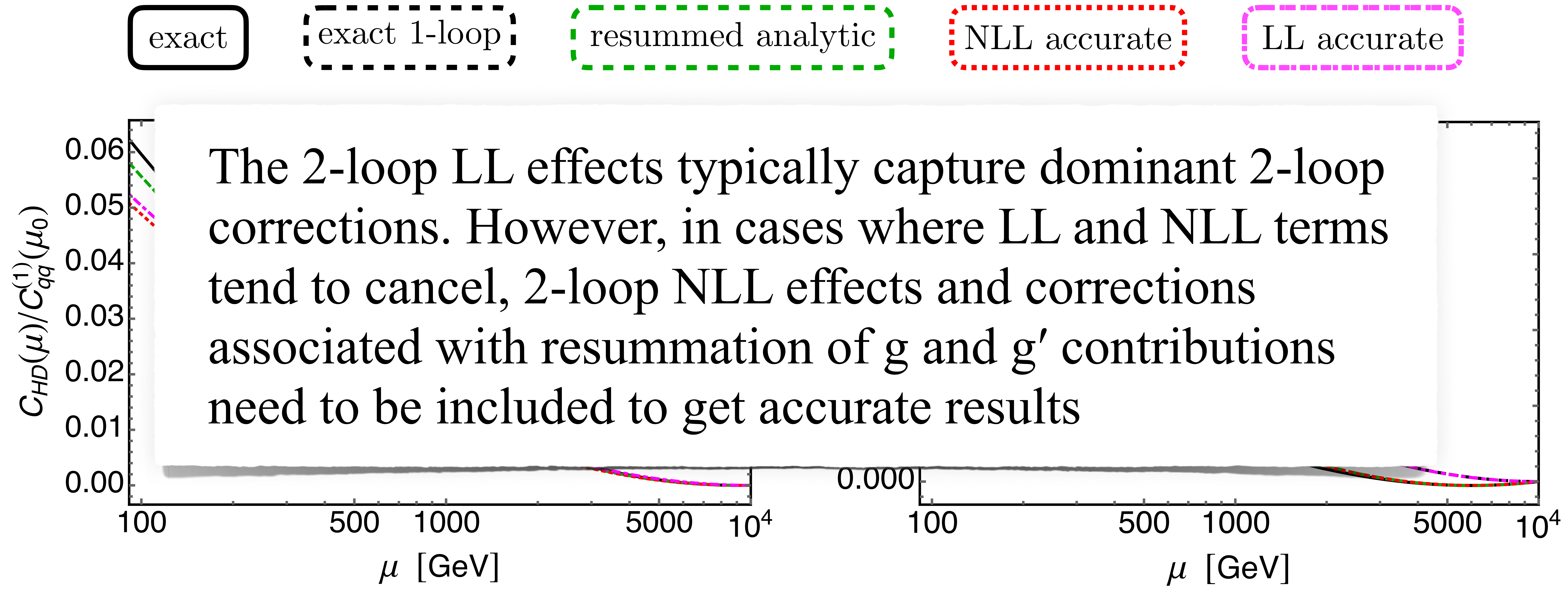


[based on UH & Schnell, 2410.13304; unpublished]

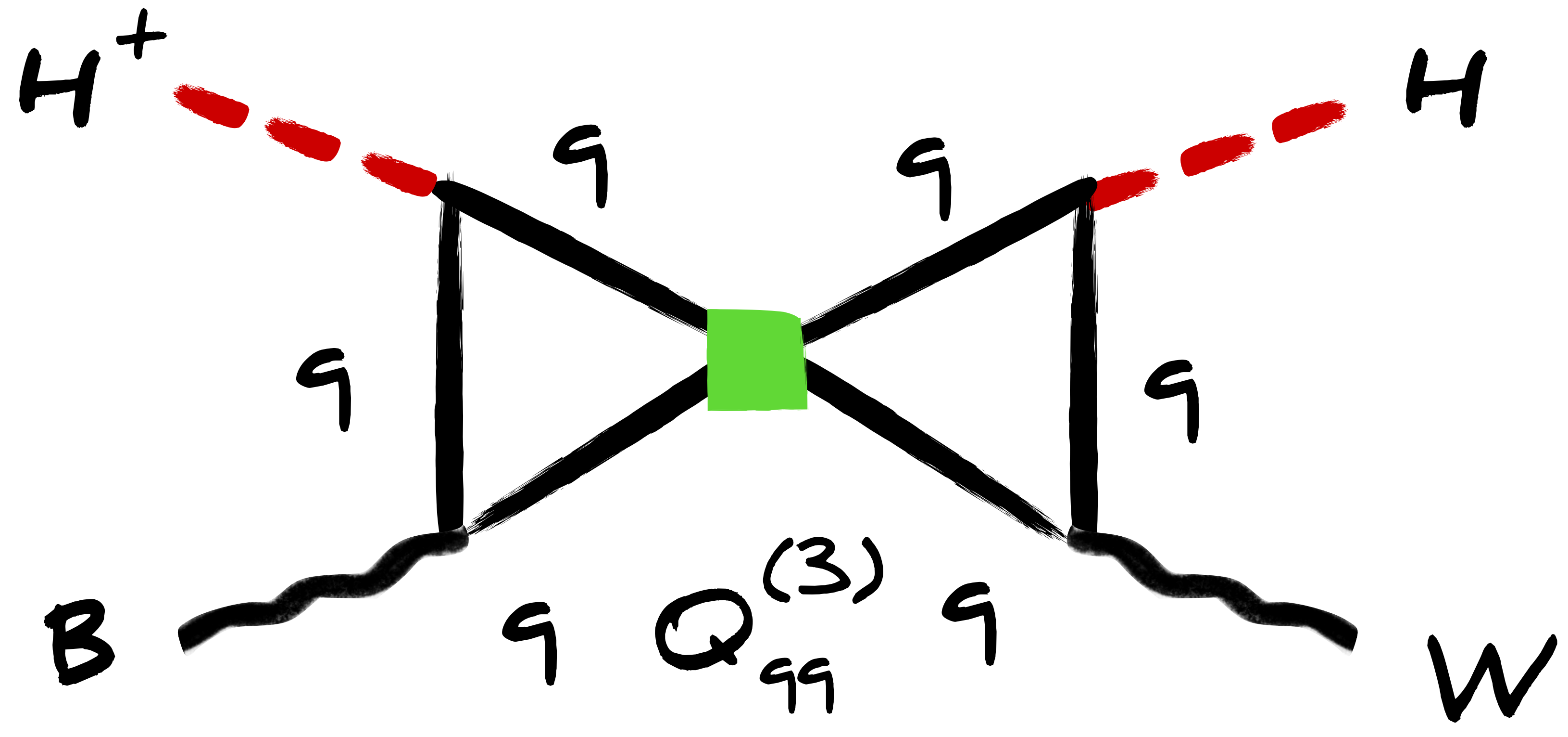
How big are 2-loop NLL effects?



The 2-loop LL effects typically capture dominant 2-loop corrections. However, in cases where LL and NLL terms tend to cancel, 2-loop NLL effects and corrections associated with resummation of g and g′ contributions need to be included to get accurate results

[based on UH & Schnell, 2410.13304; unpublished]

An example with only 2-loop NLLs

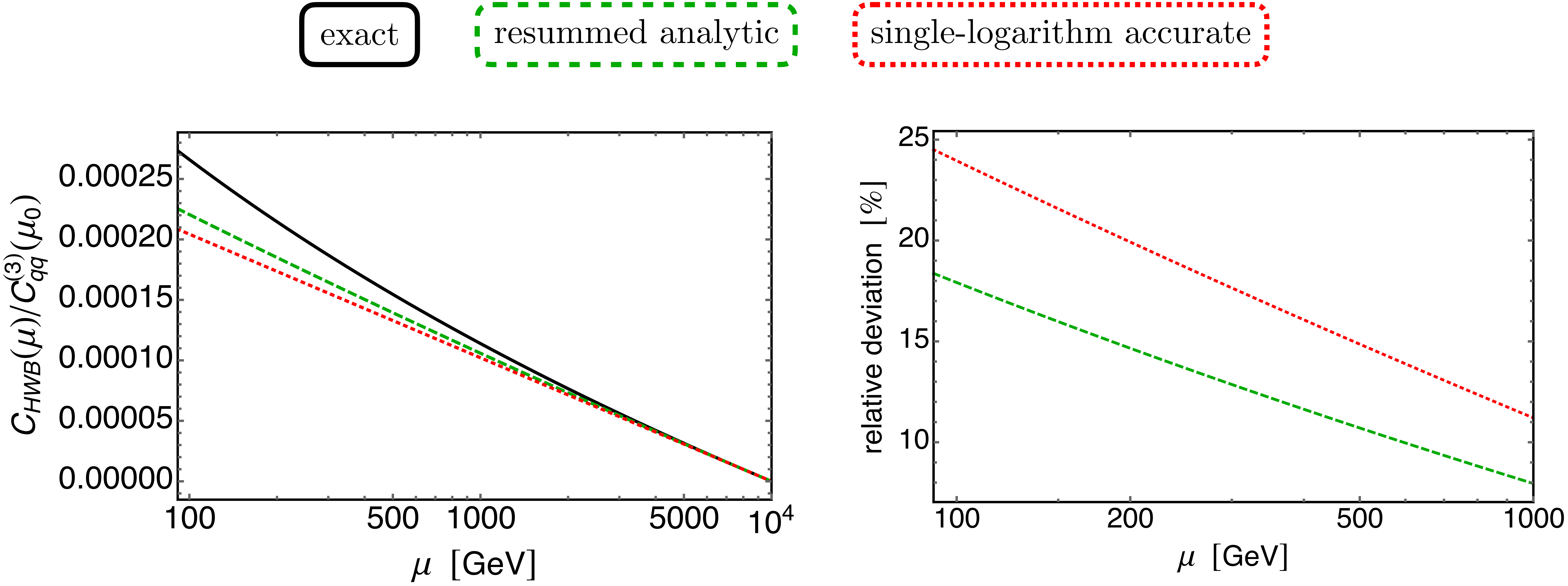


$$\Rightarrow \quad Q_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$

$$\gamma_{HWB,\, {}^{(3)}_{qq}}(\mu) = -\frac{g g' y_t^2}{2\pi^2}$$

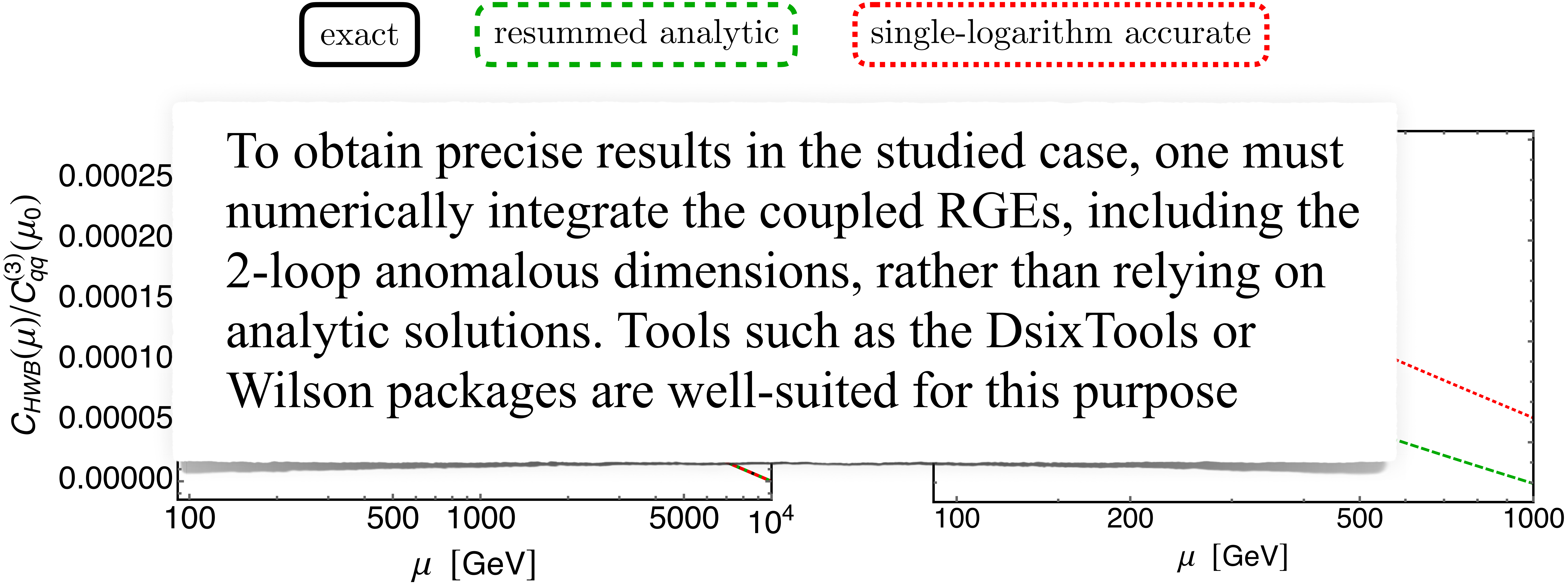
[based on UH & Schnell, 2410.13304; unpublished]

An example with only 2-loop NLLs



[based on UH & Schnell, 2410.13304; unpublished]

An example with only 2-loop NLLs



To obtain precise results in the studied case, one must numerically integrate the coupled RGEs, including the 2-loop anomalous dimensions, rather than relying on analytic solutions. Tools such as the DsixTools or Wilson packages are well-suited for this purpose

[based on UH & Schnell, 2410.13304; unpublished]

New 2-loop anomalous dimensions @ work

$$T \simeq -\frac{3y_t^4}{8\pi^4\alpha}\,\frac{v^2}{\Lambda^2}\,C_{tt}^{(1)}(\Lambda)\left[\ln^2\left(\frac{\Lambda}{M_Z}\right) - \frac{1}{4}\ln\left(\frac{\Lambda}{M_Z}\right)\right]$$

$$T \in [-0.23, 0.25] \quad \Rightarrow \quad \frac{C_{tt}^{(1)}}{\Lambda^2} \in \frac{[-2.04, 1.87]}{\mathrm{TeV}^2}$$

[based on UH & Schnell, 2410.13304; unpublished; see also talk by Stefanek earlier today]

New 2-loop anomalous dimensions @ work

$$S \simeq \frac{y_t^2}{2\pi^3} \frac{v^2}{\Lambda^2} C_{qq}^{(3)}(\Lambda) \ln\left(\frac{\Lambda}{M_Z}\right)$$

$$S \in [-0.24, 0.16] \quad \Rightarrow \quad \frac{C_{qq}^{(3)}}{\Lambda^2} \in \frac{[-63.2, 95.5]}{\mathrm{TeV}^2}$$

[based on UH & Schnell, 2410.13304; unpublished]

New 2-loop anomalous dimensions @ work

Indirect 2-loop constraints on Wilson coefficients from EW precision measurements can match or even surpass the sensitivity of direct tree-level probes (such as 4-top production in the examples shown) only if the indirect probe receives a LL correction at the 2-loop level

[based on UH & Schnell, 2410.13304; unpublished]

Conclusions

- 1-loop RGEs powerful tool to identify 2-loop LL effects. Can be used to compute unknown 2-loop contributions to e.g. $gg \to h$ & $h \to \gamma\gamma$
- If present, 2-loop LL effects often capture dominant 2-loop terms. When numerical resummation of logarithms important use DsixTools or Wilson
- If indirect probe receives 2-loop LLs, constraints from EWPOs can match or even surpass sensitivity of tree-level probes