FLAVOR IN THE SMEFT

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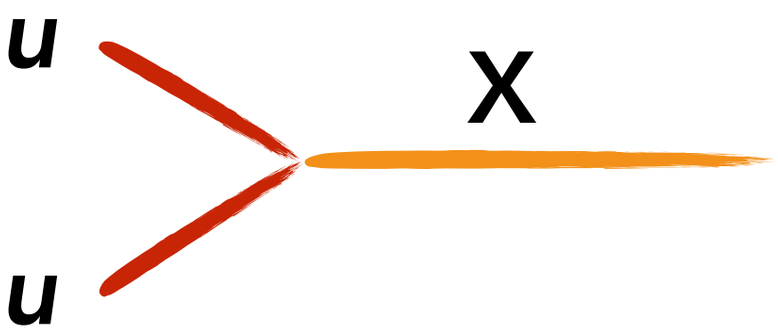
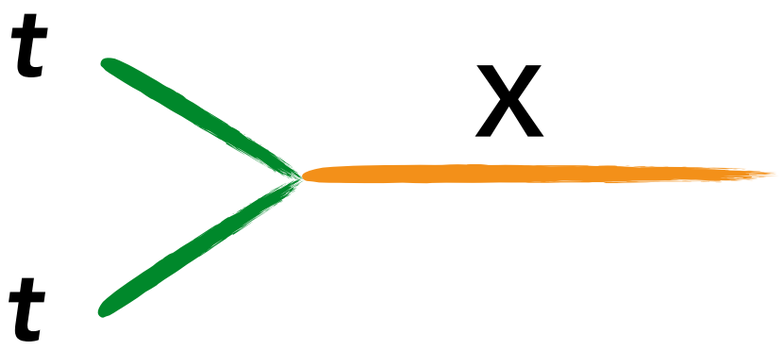
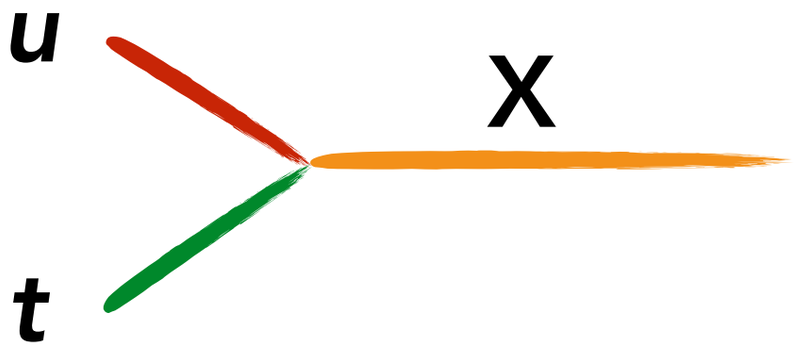
based on work with Sebastian Bruggisser & Danny van Dyk

FlavCC Workshop ∘ Nov 22, 2021 ∘ CRC TRR 257 Online

No theory - no guideline?







Goals for this talk

- **Find a framework for flavor beyond the Standard Model.**
- **Test it on data.**
- **Deduce possible flavor structures.**

The Standard Model of Flavor

$$U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

Gauge: $\mathcal{L} = g\,\overline{Q}_L \not{W}^a \tau^a\, Q_L + \dots$ ✓

Yukawa: $\mathcal{L} = -(\overline{Q} Y_U U)\widetilde{H} - (\overline{Q} Y_D D) H + \dots$ ✗

The Standard Model of Flavor

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Flavor breaking: $Y_U = \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \qquad Y_D = \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix}$

CKM mixing: $Q = \begin{pmatrix} u_L \\ V d_L \end{pmatrix}$

Minimal flavor violation

$$U(3)_Q \times U(3)_U \times U(3)_D$$

- „Restore“ flavor symmetry: $Y_U : (3, \overline{3}, 1), \;\; Y_D : (3, 1, \overline{3})$

Yukawa: $\mathcal{L} = -(\overline{Q} Y_U U)\widetilde{H} - (\overline{Q} Y_D D) H + \ldots$ ✓

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Yukawa: $\mathcal{L} = -(\overline{Q} Y_U U)\widetilde{H} - (\overline{Q} Y_D D) H + \ldots$ ✓

- New interaction: $O = (\overline{Q}_L \gamma_\mu Q_L) X^\mu$

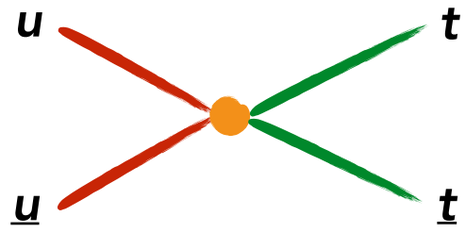
$$C_Q = a\,\mathbf{1} + b\,Y_U^\dagger Y_U + c\,Y_D^\dagger Y_D + \ldots \quad (3 \times \overline{3}, 1, 1)$$

Minimal assumption: no new sources of flavor breaking.

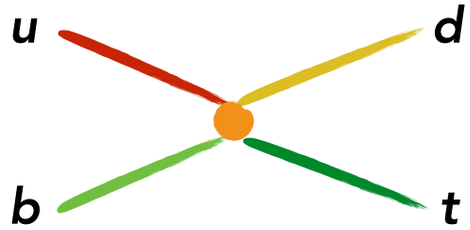
Effective four-quark interactions

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^{\gamma_i}} O_i$$

weak singlet: $O_{qq}^{(1)} = (\overline{Q}\gamma_\mu Q)(\overline{Q}\gamma^\mu Q)$



weak triplet: $O_{qq}^{(3)} = (\overline{Q}\gamma_\mu \tau^a Q)(\overline{Q}\gamma^\mu \tau^a Q)$



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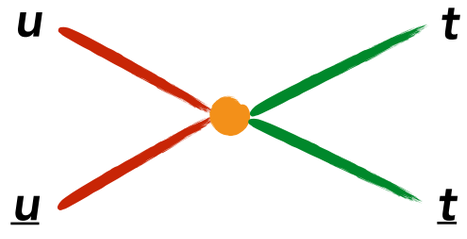

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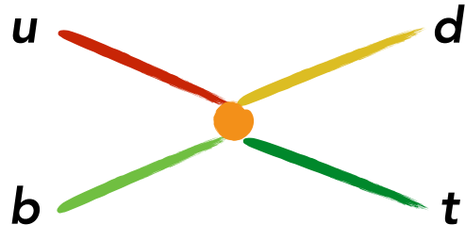
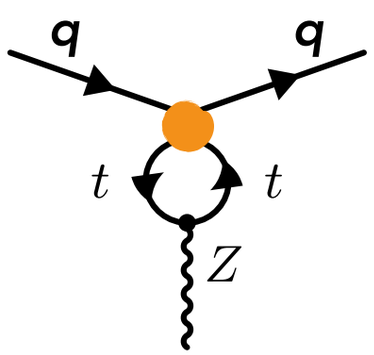


mix into: $O_{\phi q}^{(1)} = (H^\dagger \overleftrightarrow{iD^\mu} H)(\overline{Q}\gamma_\mu Q)$

$O_{\phi q}^{(3)} = (H^\dagger \overleftrightarrow{iD^\mu} \tau^a H)(\overline{Q}\gamma_\mu \tau^a Q)$

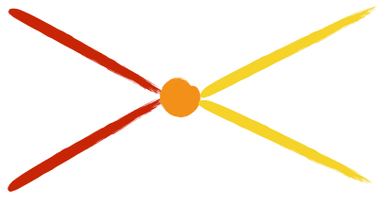


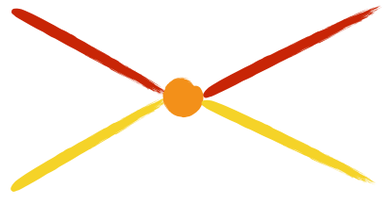
Alonso, Jenkins, Manohar, Trott 2013

Flavor structure

$$\left[(C_Q)_{jk}(C_Q)_{il} + (\widetilde{C}_Q)_{jl}(\widetilde{C}_Q)_{ki}\right](\overline{Q}^j\gamma^\mu Q^k)(\overline{Q}^i\gamma_\mu Q^l)$$

light-light: $(C_{qq})_{jjii} = (aa)$ $(C_{qq})_{jiij} = (\widetilde{aa})$ *





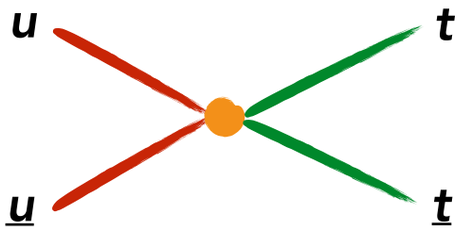
* Wilson coefficients defined in up mass basis.

Flavor structure

$$\left[(C_Q)_{jk}(C_Q)_{il} + (\widetilde{C}_Q)_{jl}(\widetilde{C}_Q)_{ki}\right](\overline{Q}^j \gamma^\mu Q^k)(\overline{Q}^i \gamma_\mu Q^l)$$

light-light: $(C_{qq})_{jjii} = (aa)$ $\qquad (C_{qq})_{jiij} = (\widetilde{aa})$

heavy-light: $(C_{qq})_{33ii} = (aa) + (ba)\, y_t^2$ $\qquad (C_{qq})_{3ii3} = (\widetilde{aa}) + (\widetilde{ba})\, y_t^2$



Flavor structure

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heavy-heavy: $(C_{qq})_{3333} = (aa) + (\widetilde{aa}) + 2\big((ba) + (\widetilde{ba})\big)y_t^2 + \big((bb) + (\widetilde{bb})\big)y_t^4$

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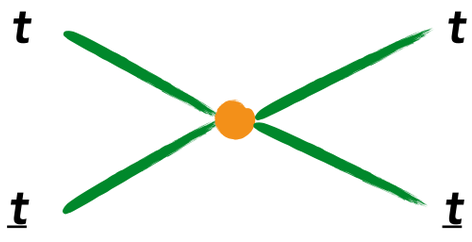
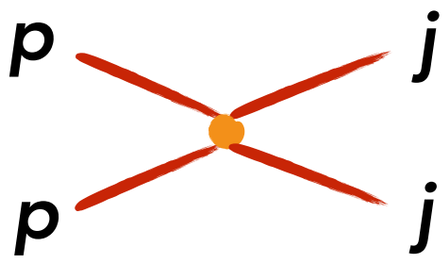
two quarks: $(C_{\phi q})_{kk} = a + b\,y_t^2\,\delta_{k3}$



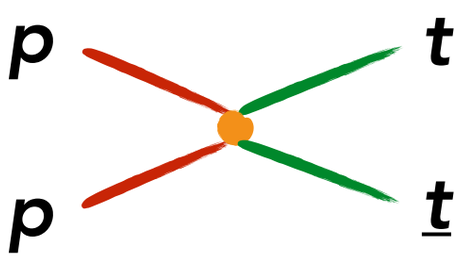
Probing flavor: ATLAS, CMS

light-light	heavy-light	heavy-heavy
(aa), $(\widetilde{aa})$	(ba), $(\widetilde{ba})$	(bb), $(\widetilde{bb})$

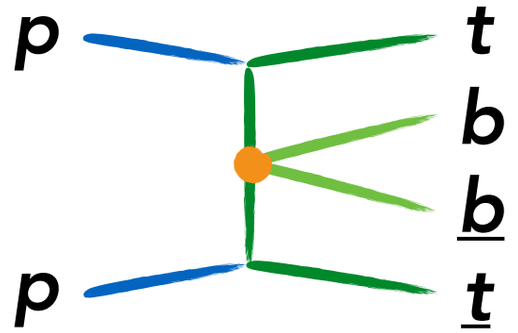
- QCD: dijets



- top-antitop, single-top



- $t\bar{t}b\bar{b}$, $t\bar{t}t\bar{t}$



Probing flavor: Belle II, LHCb

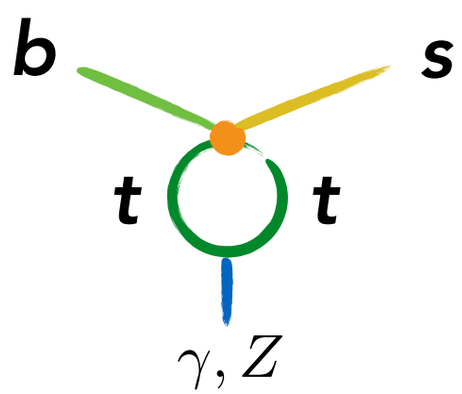
light-light	heavy-light	heavy-heavy
(aa), $(\widetilde{aa})$	(ba), $(\widetilde{ba})$	(bb), $(\widetilde{bb})$

- QCD: dijets

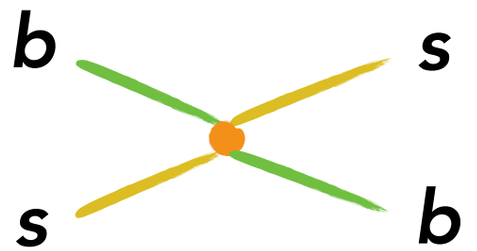
- top-antitop, single-top

- $t\bar{t}b\bar{b}$, $t\bar{t}t\bar{t}$

- rare meson decays

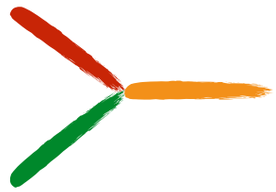


- meson mixing



The flavor collider connection

Λ



$C_i(\Lambda) = F(g_k, m_k)$

flavor-sensitive

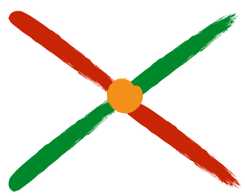
$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \dots$

100 GeV

$\mathcal{C}_a(m_b) = F(C_i(m_t))$

flavor-sensitive

$\mathcal{L}_{\rm WET} = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED} + \sum_a \mathcal{C}_a \mathcal{O}_a + \dots$



1 GeV

Aebischer et al. 2015 & 2017; Dekens et al. 2017 & 2019; Hurth et al. 2019

Resolving the flavor structure

15 fit parameters:

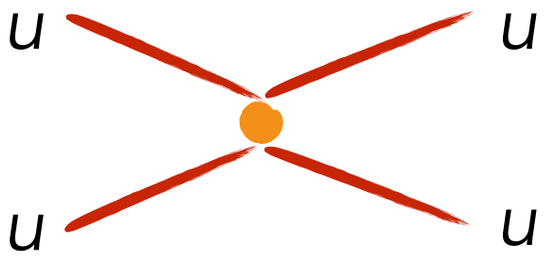
$$\left\{(aa)^{(w)}_{qq}, (\widetilde{aa})^{(w)}_{qq}, (ba)^{(w)}_{qq}, (\widetilde{ba})^{(w)}_{qq}, (bb)^{(w)}_{qq} + (\widetilde{bb})^{(w)}_{qq}, a^{(w)}_{\phi q}, b^{(w)}_{\phi q}\right\} + \nu$$

data:
- dijets: angular correlations — CMS 1803.08030
- top: global fit — Brivio et al. 2019
- $t\bar{t}b\bar{b}$: cross section — CMS 2003.06467
- meson mixing: ΔM_s
- $\mathcal{B}(B_s \to \mu^+\mu^-)$ — Bruggisser et al. 2021

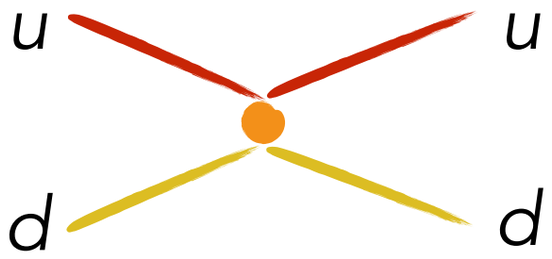
tools: SFitter (fit), wilson (RGE, matching)

ALL FIT RESULTS PRELIMINARY

Light-light: dijets



$$(aa)^{(+)}_{qq} + (\widetilde{aa})^{(+)}_{qq}$$



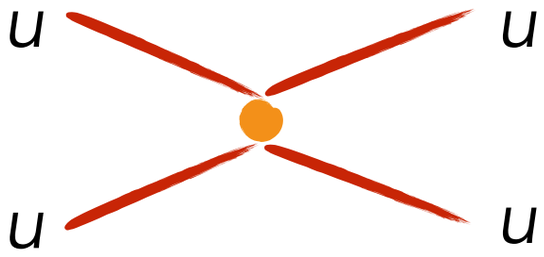
$$(aa)^{(-)}_{qq} + (\widetilde{aa})^{(-)}_{qq}$$

gauge structure

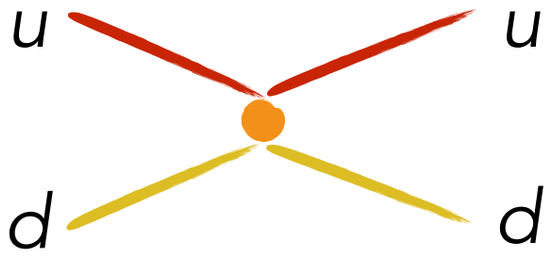
u-u current: $C^{(-)} = C^{(1)} - C^{(3)}$

d-d current: $C^{(+)} = C^{(1)} + C^{(3)}$

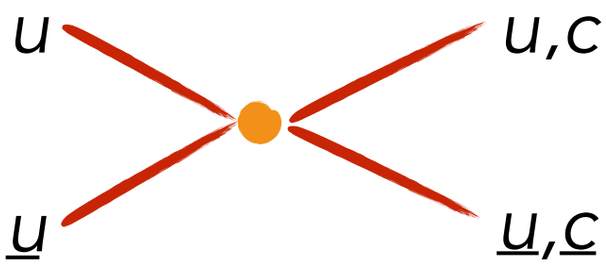
Light-light: dijets



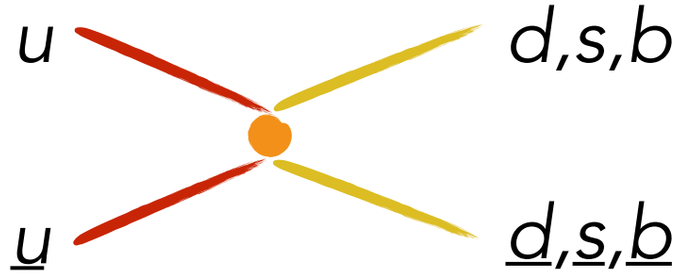
$$(aa)^{(+)}_{qq} + (\widetilde{aa})^{(+)}_{qq}$$



$$(aa)^{(-)}_{qq} + (\widetilde{aa})^{(-)}_{qq}$$



$$2(aa)^{(+)}_{qq} + (\widetilde{aa})^{(+)}_{qq}$$



$$3(aa)^{(-)}_{qq} + (ba)^{(-)}_{qq} + (\widetilde{aa})^{(-)}_{qq}$$

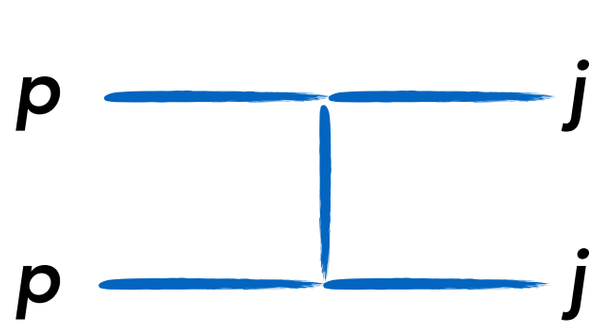
$$(aa)^{(+)}_{qq},\ (\widetilde{aa})^{(+)}_{qq},\ (aa)^{(-)}_{qq},\ (\widetilde{aa})^{(-)}_{qq}$$

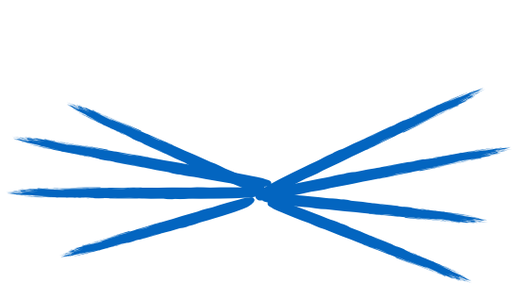
Dijet angular correlations

$$\chi_{jj} = \exp(|y_1 - y_2|)$$

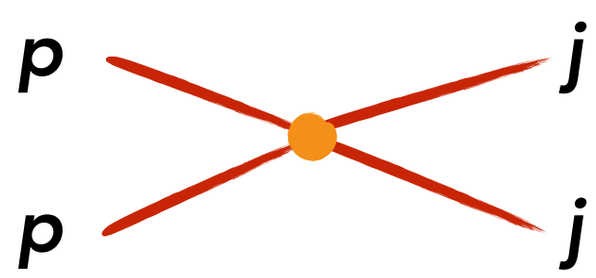
Rutherford scattering: $\dfrac{d\sigma}{d\chi_{jj}} \overset{\chi\to\infty}{\longrightarrow} \text{const.}$

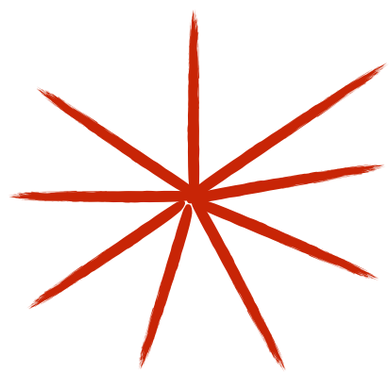
QCD:





4-quark interaction:





Dijet angular correlations

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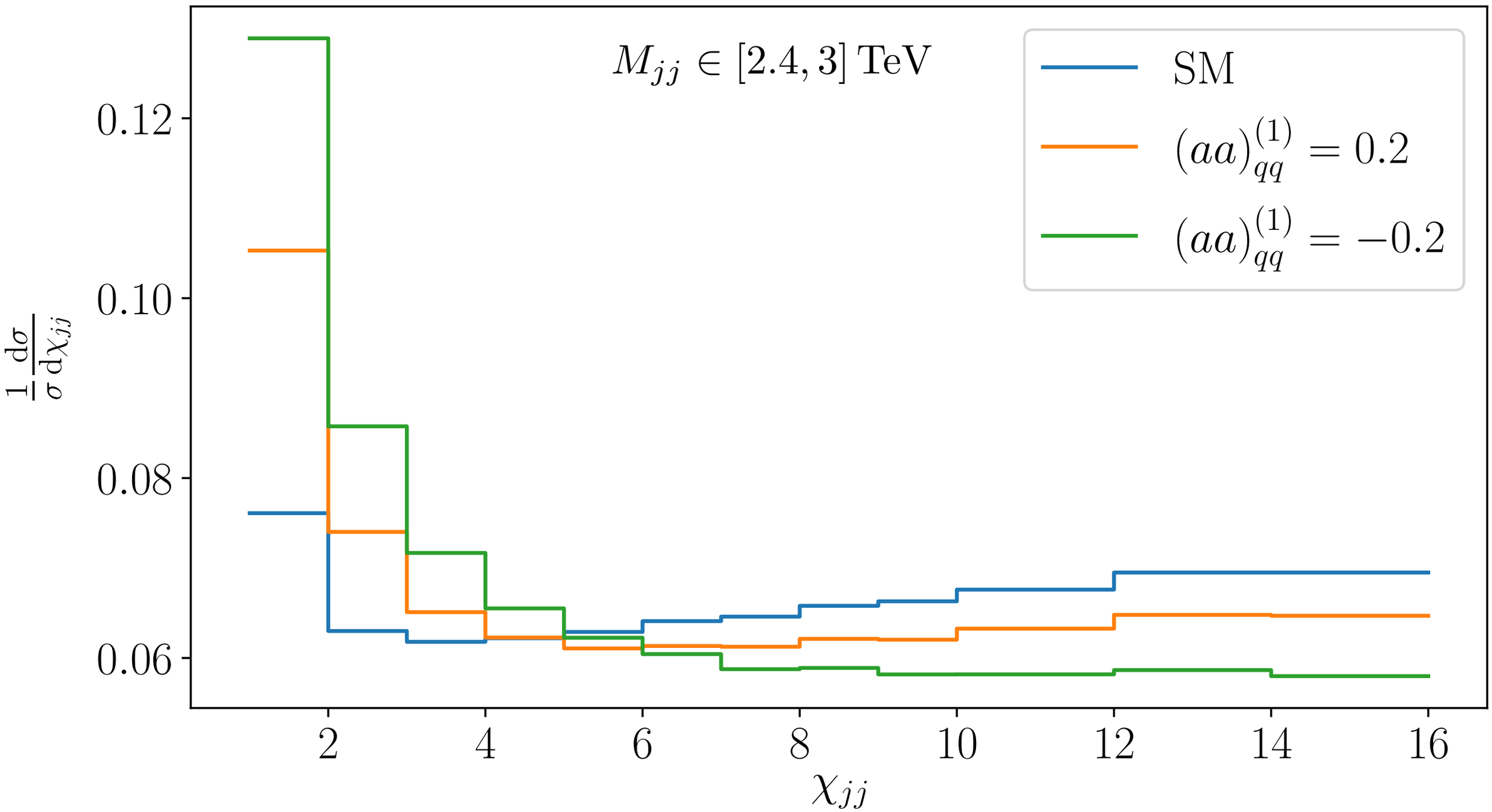
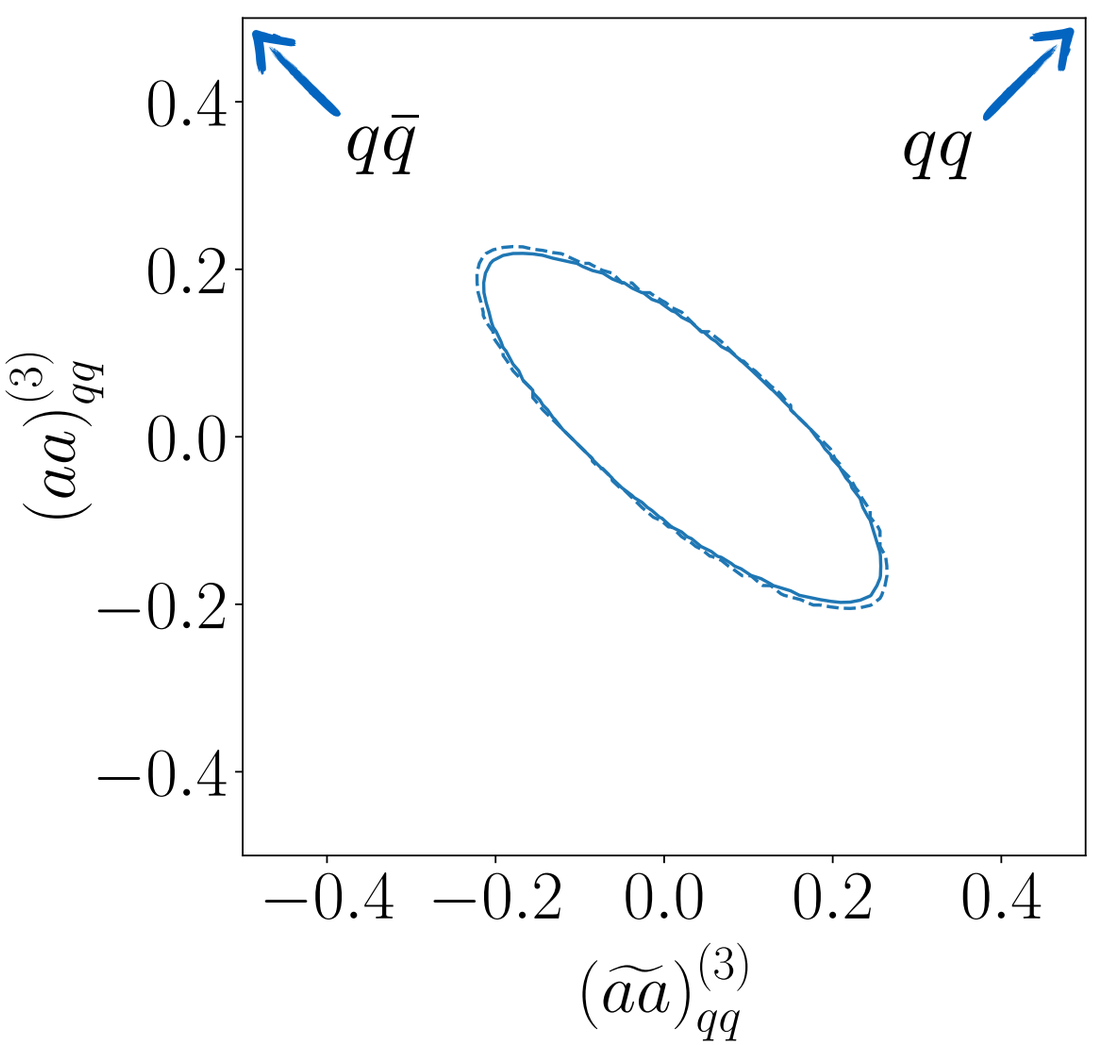
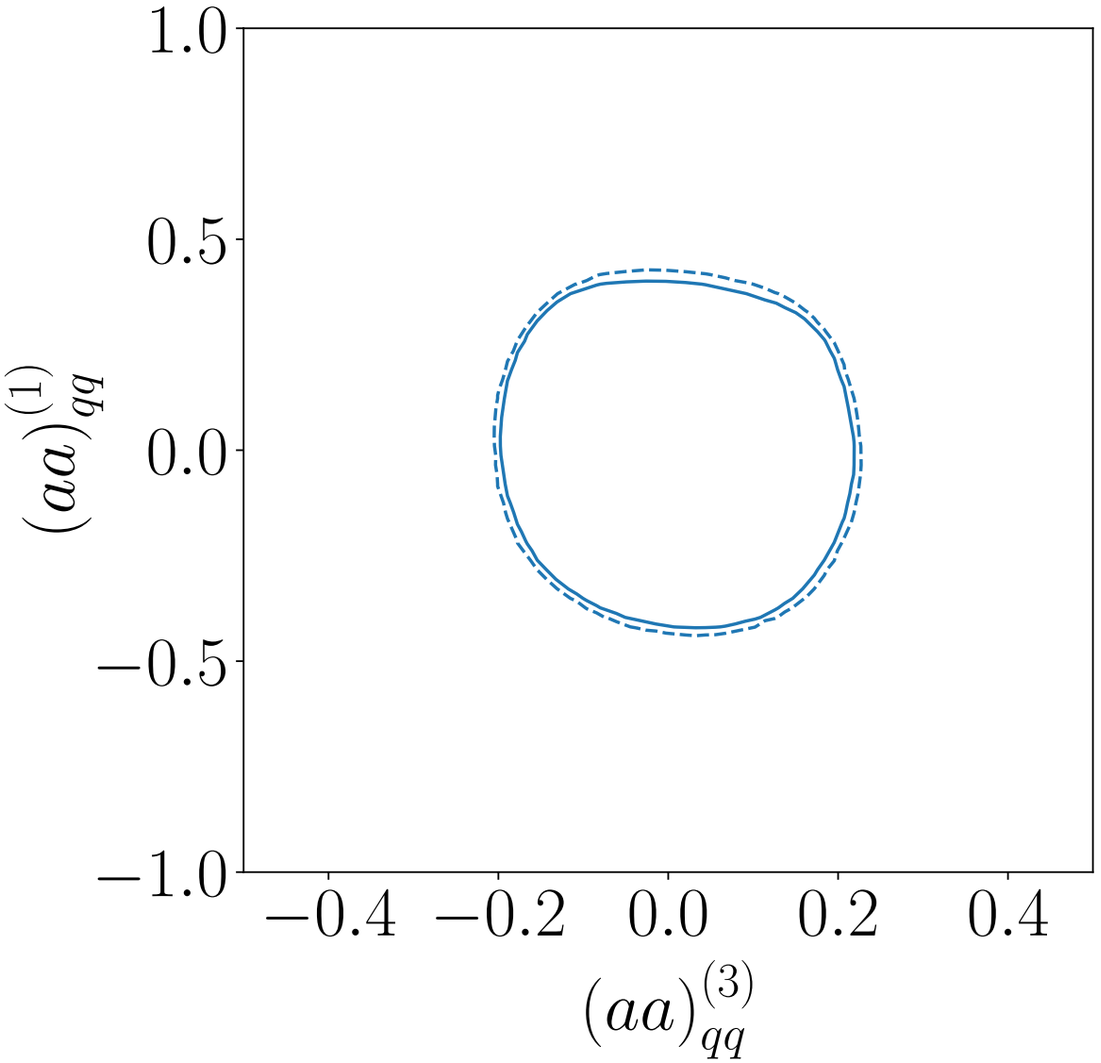


Dijet angular correlations

data: CMS 1803.08030, $M_{jj} \in [2.4, 3]\,\mathrm{TeV}$

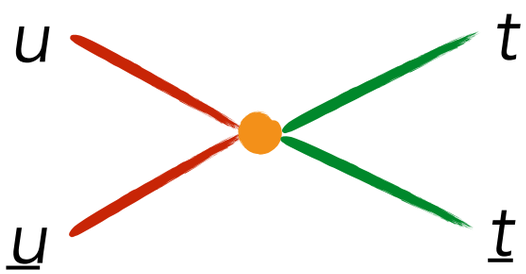




resolve $(aa)^{(+)}_{qq},\ (\widetilde{aa})^{(+)}_{qq},\ (aa)^{(-)}_{qq},\ (\widetilde{aa})^{(-)}_{qq}$

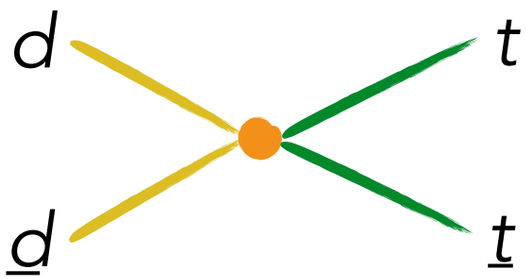
Heavy-light: tops

top-antitop:



$$(aa)^{(+)}_{qq} + (ba)^{(+)}_{qq},\ (\widetilde{aa})^{(+)}_{qq} + (\widetilde{ba})^{(+)}_{qq}$$

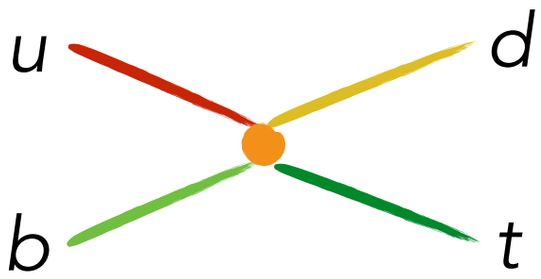
color singlet color octet



$$(aa)^{(-)}_{qq} + (ba)^{(-)}_{qq},\ (\widetilde{aa})^{(-)}_{qq} + (\widetilde{ba})^{(-)}_{qq}$$

color singlet color octet

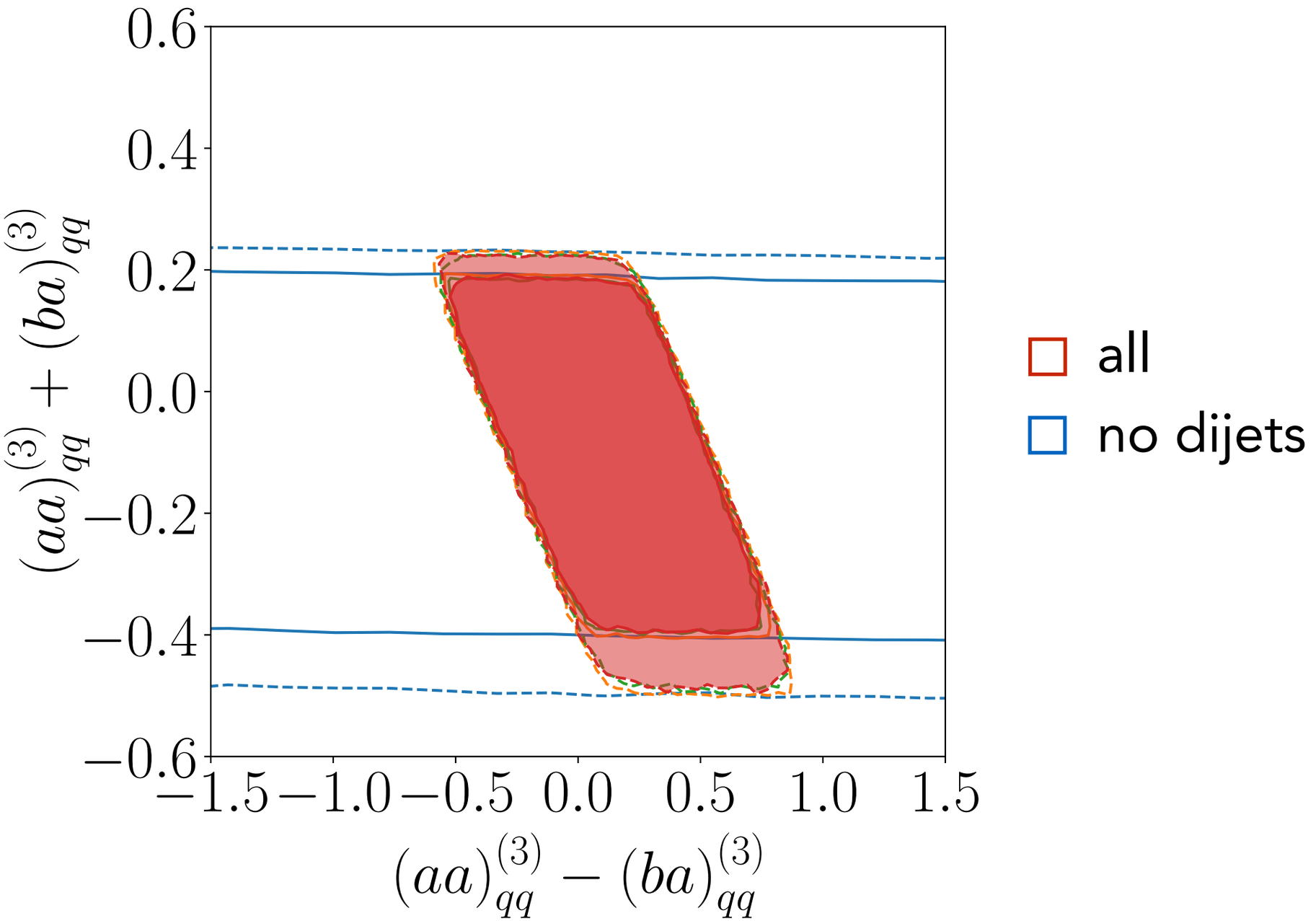
single-top:



$$(aa)^{(3)}_{qq} + (ba)^{(3)}_{qq}$$

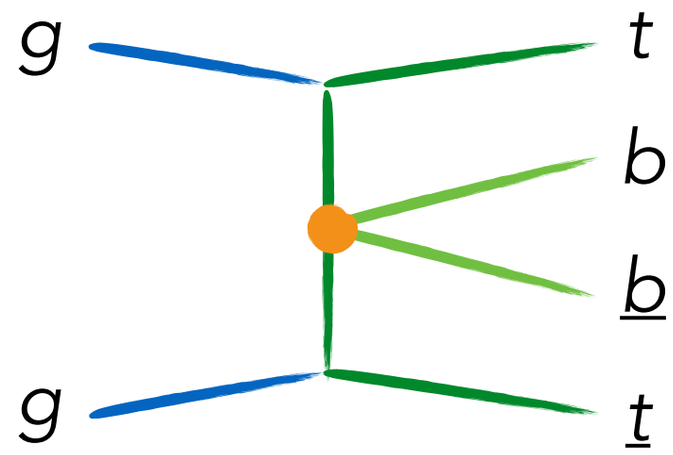
Resolving single flavor breaking

top



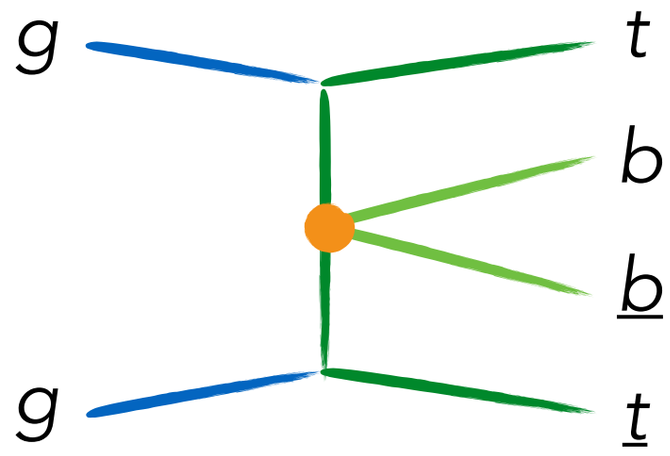
dijets

Heavy-heavy: $t\bar{t}b\bar{b}$



$$(bb)^{(-)}_{qq} + (\widetilde{b\bar{b}})^{(-)}_{qq}$$

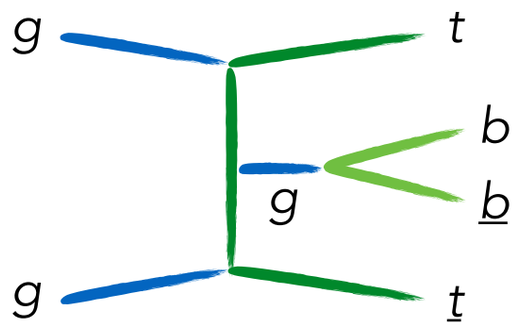
Heavy-heavy: $t\underline{t}b\underline{b}$



$(bb)^{(-)}_{qq} + (\widetilde{b\bar{b}})^{(-)}_{qq}$

- total cross section: $\sigma_{t\bar{t}b\bar{b}} = 2.9 \pm 0.1 \pm 0.5\,\mathrm{pb}$ CMS 2003.06467

- analysis cut: $p_T^j > 30\,\mathrm{GeV}$



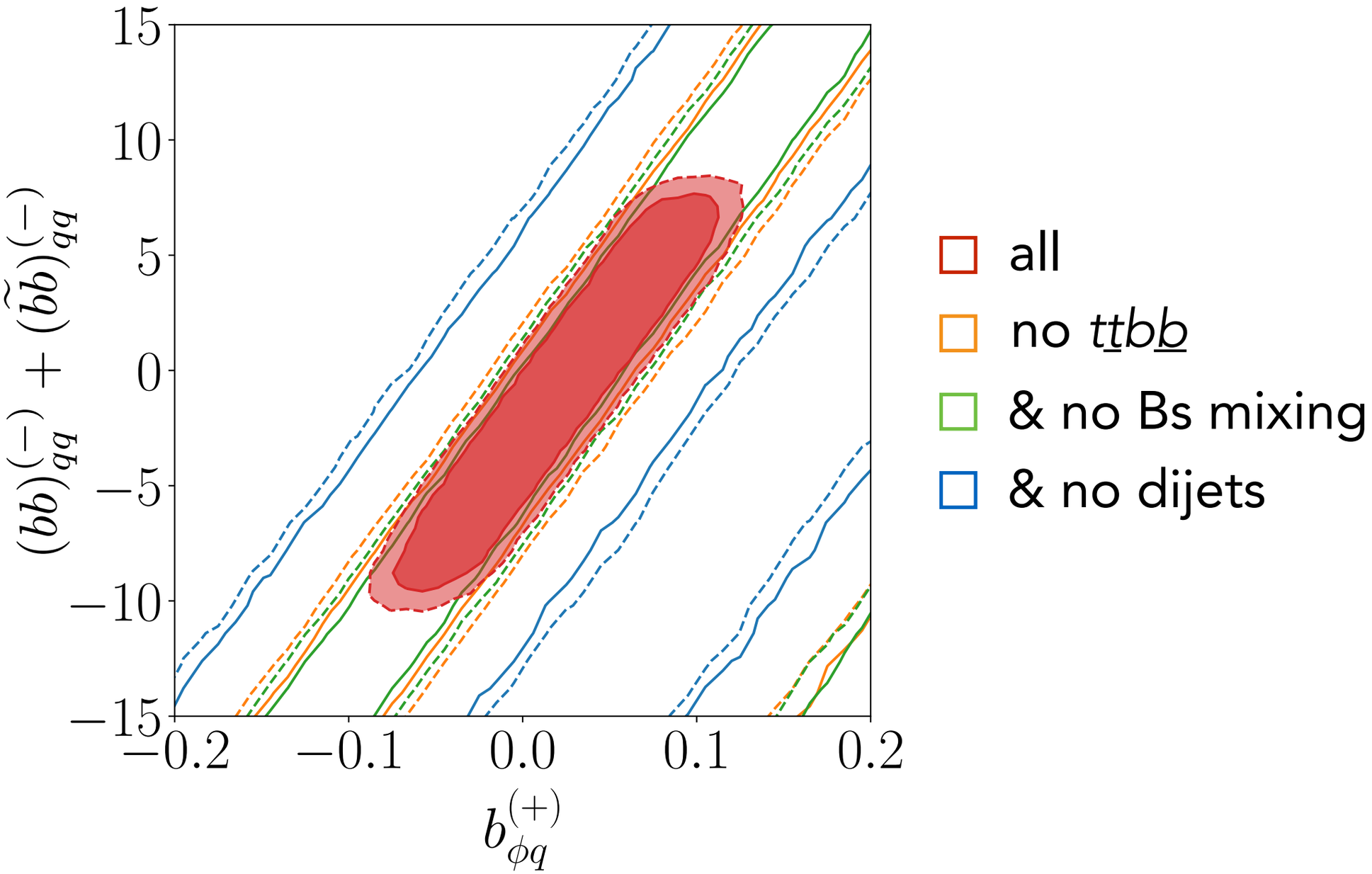
large SM background

→ higher pT?

→ $Z > b\underline{b}$?

Resolving double flavor breaking

$t\bar{t}b\bar{b}$



all

no $t\bar{t}b\bar{b}$

& no Bs mixing

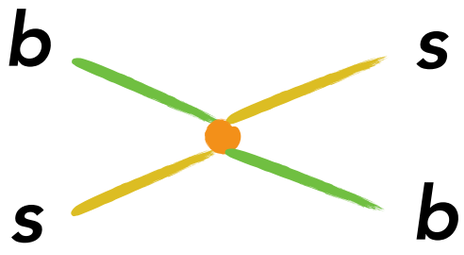
& no dijets

$\mathcal{B}(B_s \to \mu^+\mu^-)$

Meson mixing

$$\mathcal{O}_1^{sbsb} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{s}\gamma^\mu P_L b\right)$$

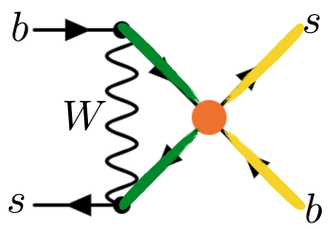
tree level:



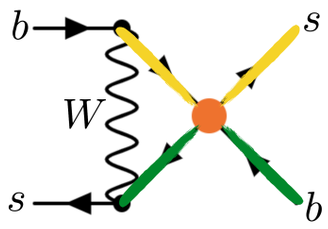
$$(V_{32}^* V_{33})^2\, C_{qq}^{(+)3333}$$

2x flavor breaking

loop level:



$$V_{k2}^* V_{k3} V_{32}^* V_{33}\, C_{qq}^{(-)33kk}$$

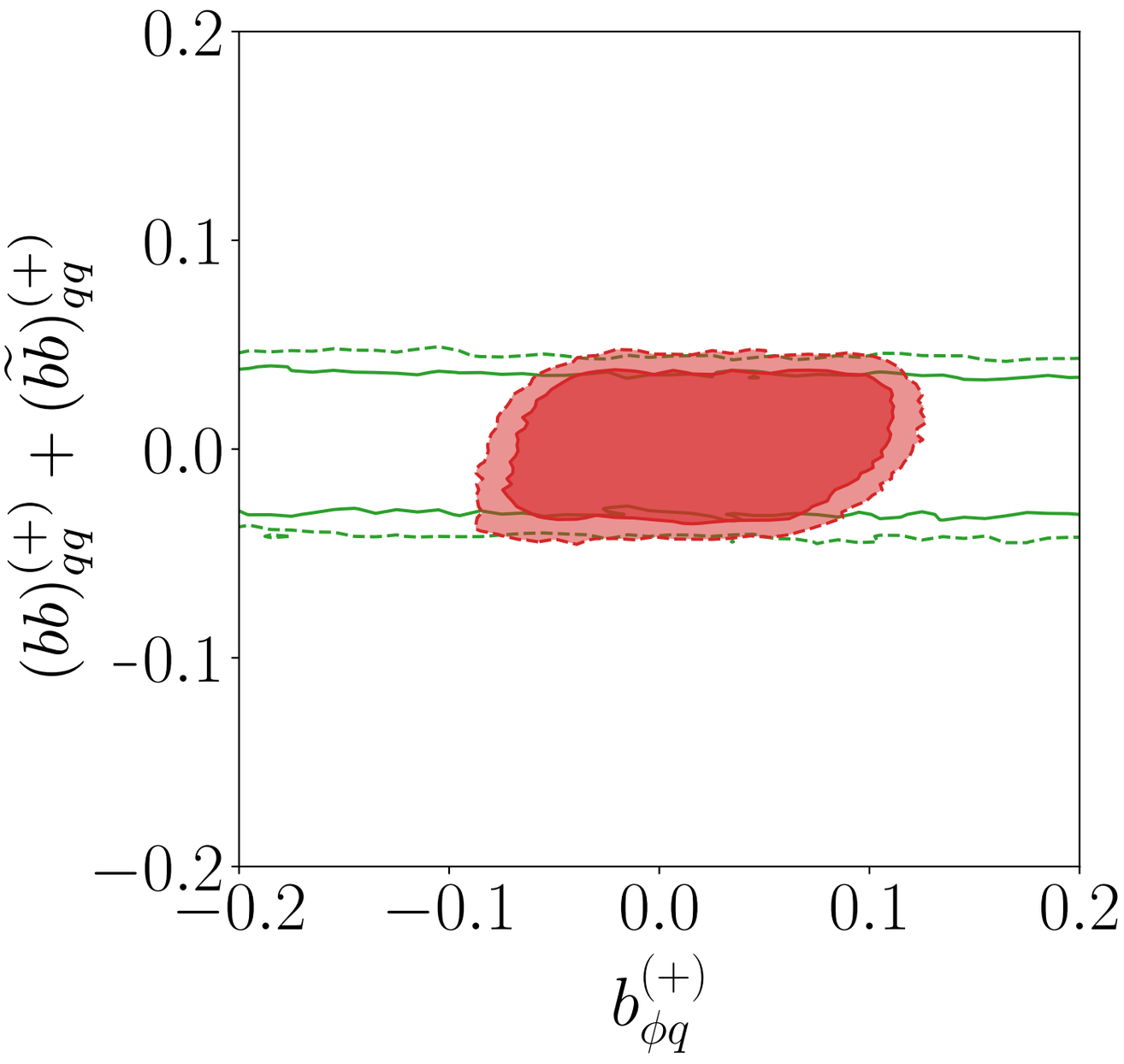


$$V_{k2}^* V_{k3} V_{32}^* V_{33}\, C_{qq}^{(3)3kk3}$$

$$\mathcal{C}_1 \sim (V_{ts}^* V_{tb})^2 \left((bb)_{qq}^{(+)} + (\widetilde{bb})_{qq}^{(+)}\right) y_t^4 + \mathcal{O}\left(\frac{g^2}{16\pi^2}\right)$$

Resolving double flavor breaking

ΔM_s

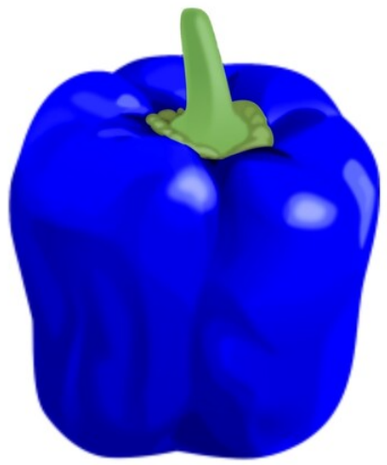


$\mathcal{B}(B_s \to \mu^+\mu^-)$

Summary: Flavor in the SMEFT

- **No theory: form data-driven flavor hypothesis.**
- **LHC + flavor observables: resolve flavor space.**
- **Viable structures: test in full models.**

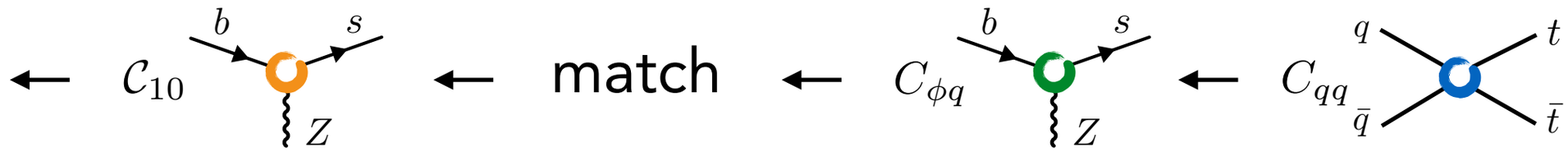
Thank you!

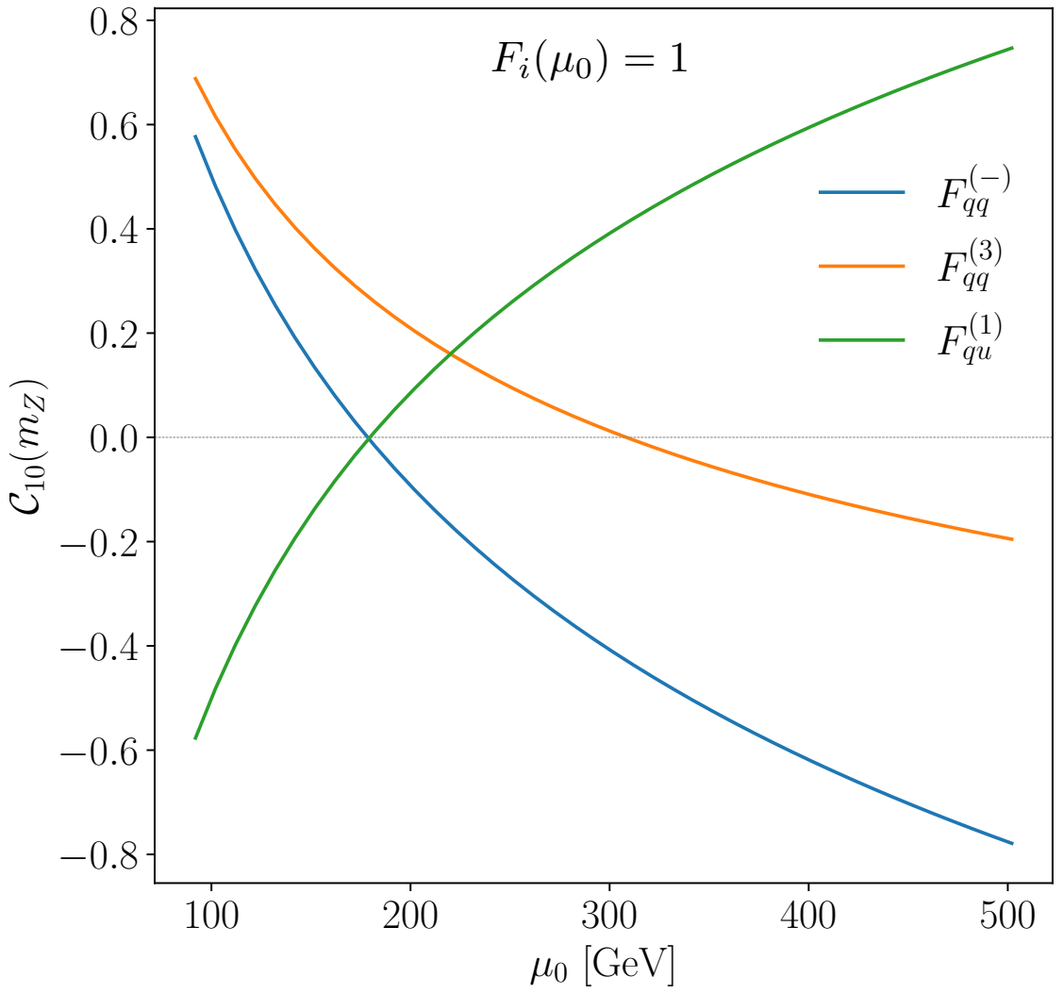


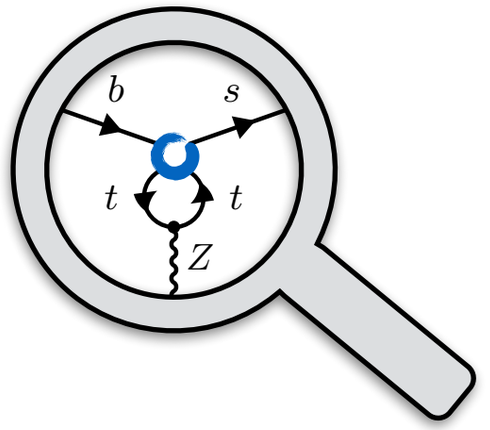
BACKUP

Operator mixing in SMEFT

$$\mathcal{C}_a(m_b) = \left(\mathcal{R}^{\mathrm{WET}}(m_b, m_Z)\right)_{ab} \left(\mathcal{M}(m_Z)\right)_{bc} \left(\mathcal{R}^{\mathrm{SMEFT}}(m_Z, m_t)\right)_{cd} C_d(m_t)$$







High sensitivity to operator mixing:

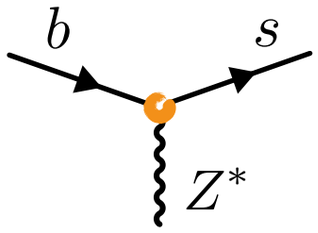
$$\mathcal{C}_{10} = F\left(\frac{4\pi}{\alpha} C_{\phi q}(m_t), C_{qq}(m_t)\right)$$

Bruggisser, Schäfer, van Dyk, Westhoff 2021

Rare B meson decays

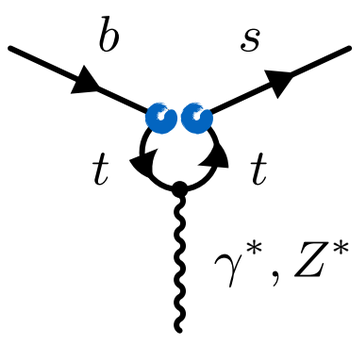
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$$

tree level:

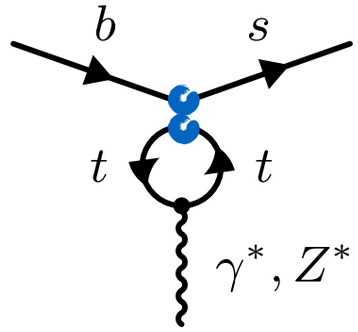


$$\sum (C_{\phi q}^{(1),kk} + C_{\phi q}^{(3),kk})\, V_{k3} V_{k2}^* \sim b_{\phi q}^{(+)}$$

loop level:



$C_{qq}^{(3)}$



$C_{qq}^{(-)}$

$$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b_{\phi q}^{(+)} + 117.8\, (b_{\phi q}^{(+)})^2$$

Bruggisser, Schäfer, van Dyk, Westhoff 2021