

7th Red LHC Workshop

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Organizers:
J.A. Aguilar-Saavedra
D. Alvarez González
C. Escobar Ibáñez
S. Heinemeyer
R. Vázquez Gómez

<https://indico.cern.ch/e/redlhc7>



Institut de Física
d'Altes Energies

A new puzzle in nonleptonic B decays

Based on [arxiv: 2301.10542 \[hep-ph\]](#). In collaboration with Joaquim Matias, Sebastian Descotes-Genon and Gilberto Tetlamatzi-Xolocotzi.

Status of the “famous” flavor anomalies



Non leptonic: Pros and Cons

- FCNC Non leptonic decays : loop suppressed in the SM.
- Increased difficulty in controlling hadronic uncertainties w.r.t semileptonics.
- Theoretical tools available to reduce uncertainties:
Compute hadronic matrix elements.
Relate to other modes using symmetry.
- Ratios constructed out of BR's: reduced sensitivity to endpoint divergences.
- Identify modes with similar sensitivity to same NP: $B \rightarrow K^{(*)} \bar{K}^{(*)}$.
- Use them to construct observables with reduced sensitivities to had. uncertainties:

$$L = \frac{BR_{b \rightarrow s}}{BR_{b \rightarrow d}} \frac{g_{b \rightarrow s}}{g_{b \rightarrow d}} \frac{f_L^{b \rightarrow s}}{f_L^{b \rightarrow d}} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2}$$

- Look for modes where these effects can be clearly disentangled within uncertainties:
 $B \rightarrow K \bar{K}^*, \bar{K}^* K$.

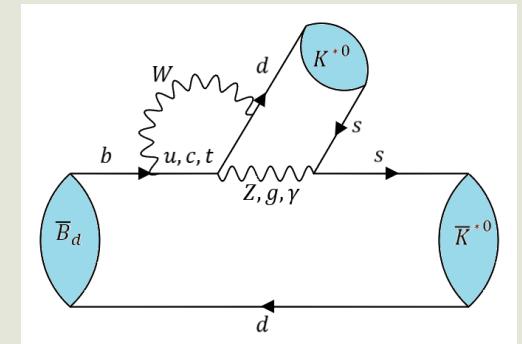
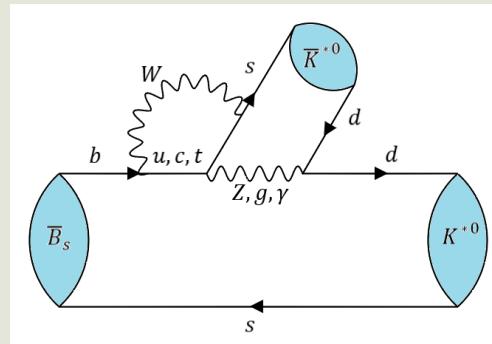
$$B_{d,s} \rightarrow K^* K^*$$

- **Naive factorization:** Hierarchy due to V-A structure. Dominance of longitudinal amplitudes.
- **QCD factorization:** Transverse amps order(s) of $\frac{\Lambda}{m_b}$ suppressed. Plagued by possible $\frac{1}{m_b}$ suppressed LD effects.
- Purely Penguin mediated processes in the SM.

■ Expectations: $f_L = 1 + O(\frac{1}{m_b^2})$ (N.F.)
 $f_L^{B_s} \sim f_L^{B_d} \pm 30\%$ (U-spin)

- Experiment (LHCb 2019): $f_L^{B_s} = 0.240 \pm 0.04$, $f_L^{B_d} = 0.724 \pm 0.053$.
- QCDF predictions: $f_L^{B_s} = 0.72^{+0.16}_{-0.21}$, $f_L^{B_d} = 0.69^{+0.17}_{-0.21}$. (*Nucl.Phys.B* 774 (2007) 64-101, M.Beneke et al).

Something interesting in the B_s case. **NP?!**



Amplitude and “ Δ ”

- $\bar{A}_f = A(\bar{B}_q \rightarrow V_1 V_2) = \lambda_u^{(q)} T_q + \lambda_c^{(q)} P_q = \lambda_u^{(q)} \Delta_q - \lambda_c^{(q)} P_q$ (unitarity).
- Δ_q is free of endpoint divergences. Because:

$$T_q = A_{K^* K^*}^q \left(\alpha_4^u - \frac{1}{2} \alpha_{4,EW}^u + \beta_3^u + 2\beta_4^u - \frac{1}{2} \beta_{3,EW}^u - \beta_{4,EW}^u \right)$$

$$P_q = A_{K^* K^*}^q \left(\alpha_4^c - \frac{1}{2} \alpha_{4,EW}^c + \beta_3^c + 2\beta_4^c - \frac{1}{2} \beta_{3,EW}^c - \beta_{4,EW}^c \right)$$

- Where,
- | Vertex | Hard spectator | Penguin |
|---|----------------|---------|
| $\alpha_i^p(M_1 M_2) \propto [V_i(M_2) + \frac{4\pi^2}{N_c} H_i(M_1 M_2)] + P_i^p(M_2)$ | | |
- $\propto X_H^{M_1} \sim \ln(\frac{m_b}{\Lambda_{QCD}})$
- (soft gluon spectator int, divergent, power suppressed, universal)
- β_i^p : Penguin annihilation, $\beta_{i,EW}^p$: Electroweak penguin annihilation
 - $\propto X_A^{M_1} \sim \text{Endpoint divergence} \sim \ln(\frac{m_b}{\Lambda_{QCD}})$ (universal)
- These divergences are responsible for the model dependence of the analysis.

$L_{K^* K^*}$

- $$L_{K^* K^*} = \kappa \left| \frac{P_S}{P_d} \right|^2 \left[1 + |\alpha_s|^2 \left| \frac{\Delta_S}{P_S} \right|^2 + 2 \text{Re} \left(\frac{\Delta_S}{P_S} \right) \text{Re}(\alpha_s) \right] + \left[1 + |\alpha_d|^2 \left| \frac{\Delta_d}{P_d} \right|^2 + 2 \text{Re} \left(\frac{\Delta_d}{P_d} \right) \text{Re}(\alpha_d) \right]$$

1 ± 0.3 (Naive SU(3))
 $0.91^{+0.20}_{-0.17}$ (Broken SU(3))
 $0.92^{+0.20}_{-0.18}$ (QCD factorization)

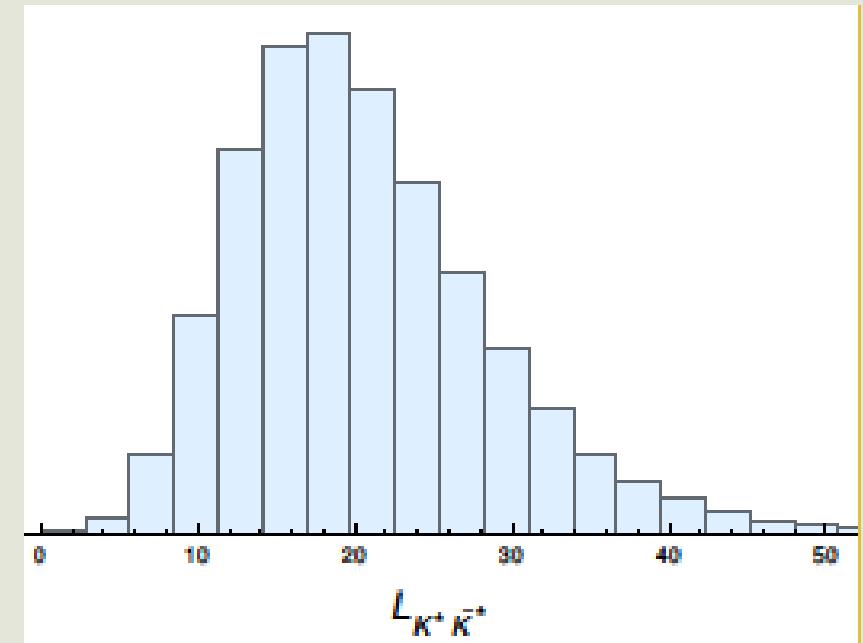
Dominant contribution

Exp: 4.43 ± 0.92

SM: 23^{+16}_{-12} (Naive SU(3))
 $19.2^{+9.3}_{-6.5}$ (Broken SU(3))
 $19.53^{+9.14}_{-6.64}$ (QCD factorization)

Tension: 2.6σ

- Note: Dominant uncertainties from form factors and NOT divergences. (Somewhat) reduced model dependence.



L_{KK}

- Counterpart of the “L” observable for pseudoscalar final states.

- $L_{KK} = \rho(m_{K^0}, m_{\bar{K}^0}) \frac{\text{BR}(\bar{B}_s \rightarrow K^0 \bar{K}^0)}{\text{BR}(\bar{B}_d \rightarrow K^0 \bar{K}^0)} = \frac{|A^s|^2 + |\bar{A}^s|^2}{|A^d|^2 + |\bar{A}^d|^2}$

- No longitudinal polarization here.

- Form factor uncertainties less.

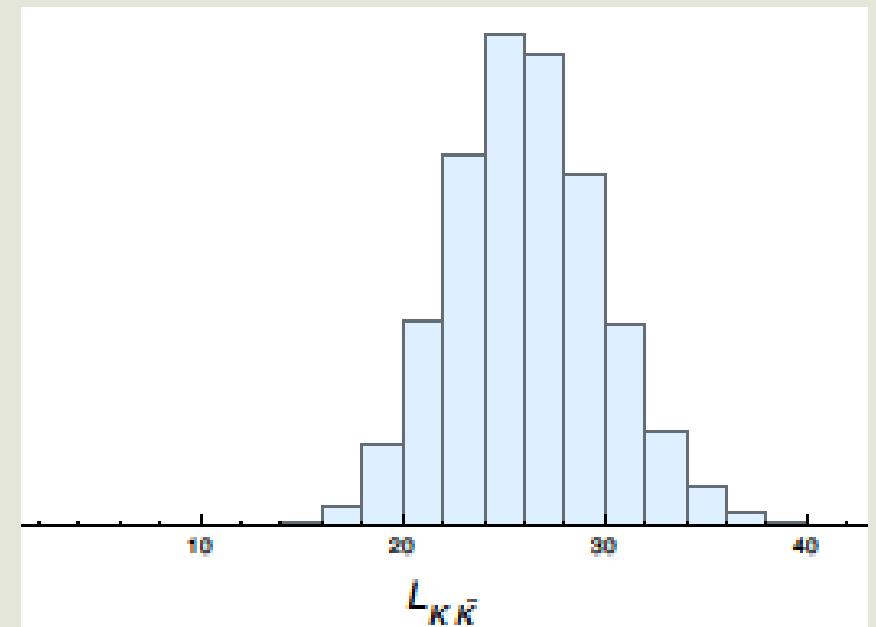
Translates to less uncertainties for L_{KK} .

Less asymmetric w.r.t $L_{K^* \bar{K}^*}$.

- **Exp: 14.58 ± 3.37 SM: $26.00^{+3.88}_{-3.59}$**

- **Tension: 2.4σ**

- Is there a common NP explanation?



NP in $b \rightarrow s$

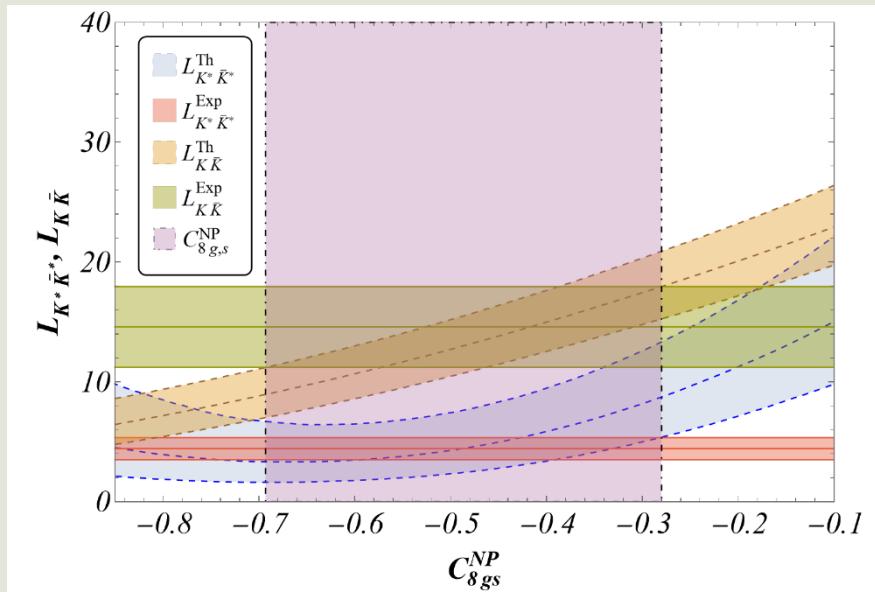
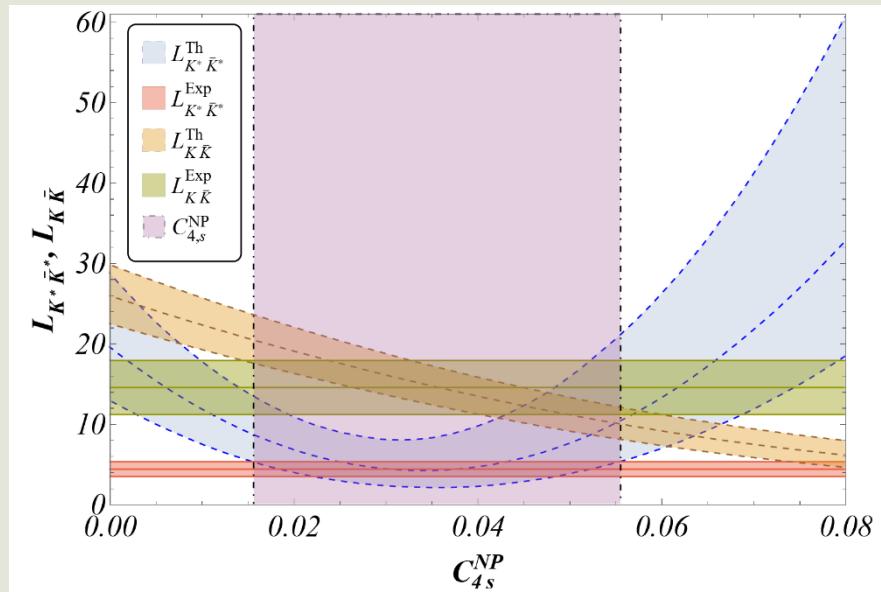
$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{p=c,u} \lambda_p^{(q)} \Big(\mathcal{C}_{1s}^p Q_{1s}^p + \mathcal{C}_{2s}^p Q_{2s}^p + \sum_{i=3\dots 10} \mathcal{C}_{is} Q_{is} + \mathcal{C}_{7\gamma s} Q_{7\gamma s} + \mathcal{C}_{8gs} Q_{8gs} \Big)$$

$$\begin{array}{ll} Q_{1s}^p = (\bar p b)_{V-A}(\bar s p)_{V-A}\,, & Q_{7s} = (\bar s b)_{V-A}\sum_q \frac{3}{2}e_q(\bar q q)_{V+A}\,, \\[1mm] Q_{2s}^p = (\bar p_i b_j)_{V-A}(\bar s_j p_i)_{V-A}\,, & Q_{8s} = (\bar s_i b_j)_{V-A}\sum_q \frac{3}{2}e_q(\bar q_j q_i)_{V+A}\,, \\[1mm] Q_{3s} = (\bar s b)_{V-A}\sum_q (\bar q q)_{V-A}\,, & Q_{9s} = (\bar s b)_{V-A}\sum_q \frac{3}{2}e_q(\bar q q)_{V-A}\,, \\[1mm] Q_{4s} = (\bar s_i b_j)_{V-A}\sum_q (\bar q_j q_i)_{V-A}\,, & Q_{10s} = (\bar s_i b_j)_{V-A}\sum_q \frac{3}{2}e_q(\bar q_j q_i)_{V-A}\,, \\[1mm] Q_{5s} = (\bar s b)_{V-A}\sum_q (\bar q q)_{V+A}\,, & Q_{7\gamma s} = \frac{-e}{8\pi^2}\,m_b\bar s\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu}b\,, \\[1mm] Q_{6s} = (\bar s_i b_j)_{V-A}\sum_q (\bar q_j q_i)_{V+A}\,, & Q_{8gs} = \frac{-g_s}{8\pi^2}\,m_b\,\bar s\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu}b\,, \end{array}$$

NP in $b \rightarrow s$

- C_{1s}^{NP} requires a 60% contribution in order to explain the anomalies. Discarded! (JHEP 07 (2019) 032: A.Lenz, GTX).
- $L_{K^*K^*} = 19.25 - 936.23C_{4s}^{NP} + 14383.60 C_{4s}^{NP^2} + 55.44C_{6s}^{NP} + 50.53C_{8gs}^{NP} + \dots$
 $L_{KK} = 25.90 - 380.76C_{4s}^{NP} + 1646.11 C_{4s}^{NP^2} - 631.58 C_{6s}^{NP} + 4313.58C_{6s}^{NP^2} + 31.92C_{8gs}^{NP} + \dots$
- The potential candidates for simultaneous explanation: C_{4s}^{NP} & C_{8gs}^{NP} .
- C_{6s}^{NP} cannot do the job because dependence is much starker for L_{KK} (12 times almost).
- Origin of this is mainly attributed to the presence of the term $(C_6 + \frac{C_5}{N_c})$ in the pseudoscalar-pseudoscalar case as compared to the vector vector case.

NP in $b \rightarrow s$ but...



HOWEVER

$$\mathcal{B}(\bar{B}_d \rightarrow K^0 \bar{K}^0) [10^{-6}] \quad \mathbf{0.4\sigma}$$

SM (QCDF)

$$1.09^{+0.29}_{-0.20}$$

Experiment

$$1.21 \pm 0.16 \quad [26, 29, 30]$$

$$\mathcal{B}(\bar{B}_s \rightarrow K^0 \bar{K}^0) [10^{-5}] \quad \mathbf{1.6\sigma}$$

SM (QCDF)

$$2.80^{+0.89}_{-0.62}$$

Experiment

$$1.76 \pm 0.33 \quad [26, 31, 32]$$

$$\text{Longitudinal } \mathcal{B}(\bar{B}_d \rightarrow K^{*0} \bar{K}^{*0}) [10^{-7}]$$

$$\mathbf{1.8\sigma}$$

SM (QCDF)

$$2.27^{+0.98}_{-0.74}$$

Experiment

$$6.04^{+1.81}_{-1.78}$$

$$\text{Longitudinal } \mathcal{B}(\bar{B}_s \rightarrow K^{*0} \bar{K}^{*0}) [10^{-6}]$$

$$\mathbf{0.9\sigma}$$

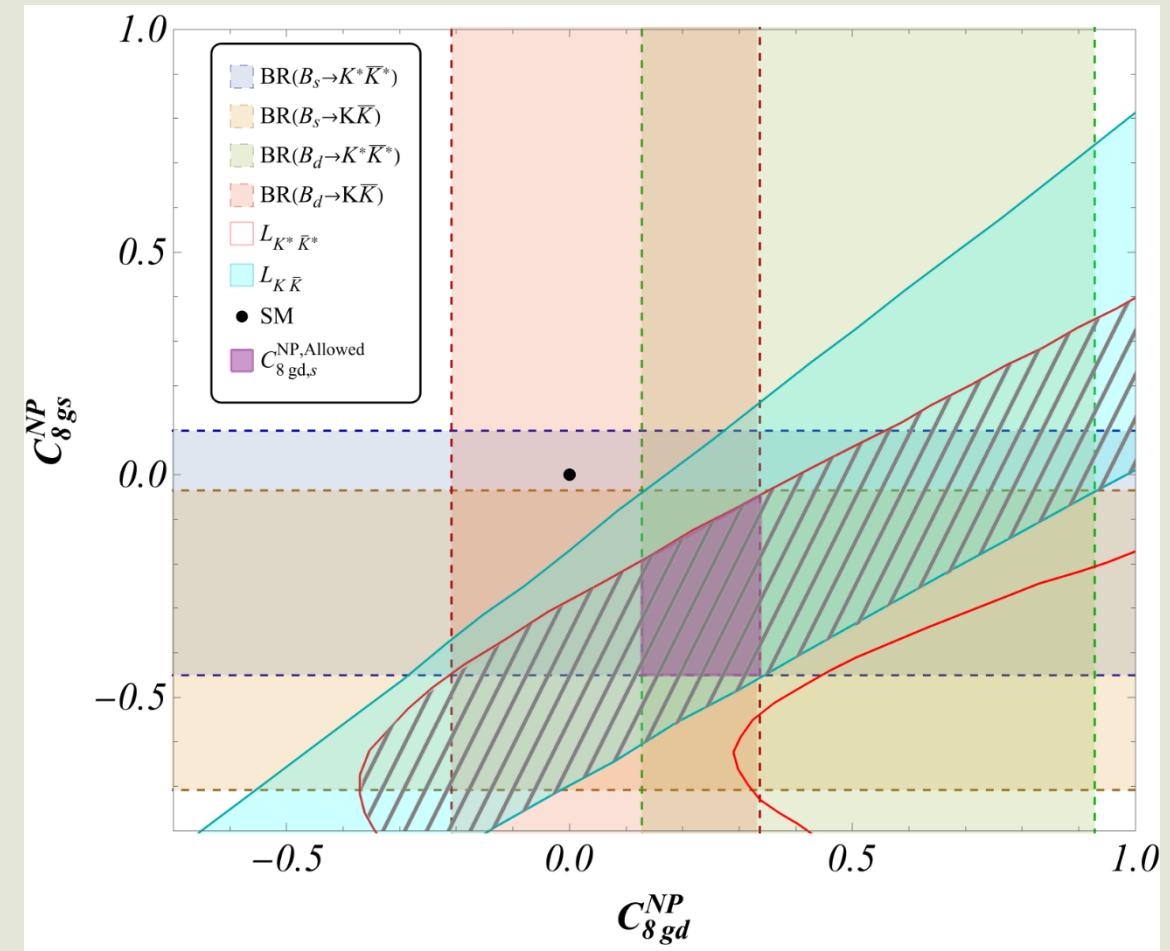
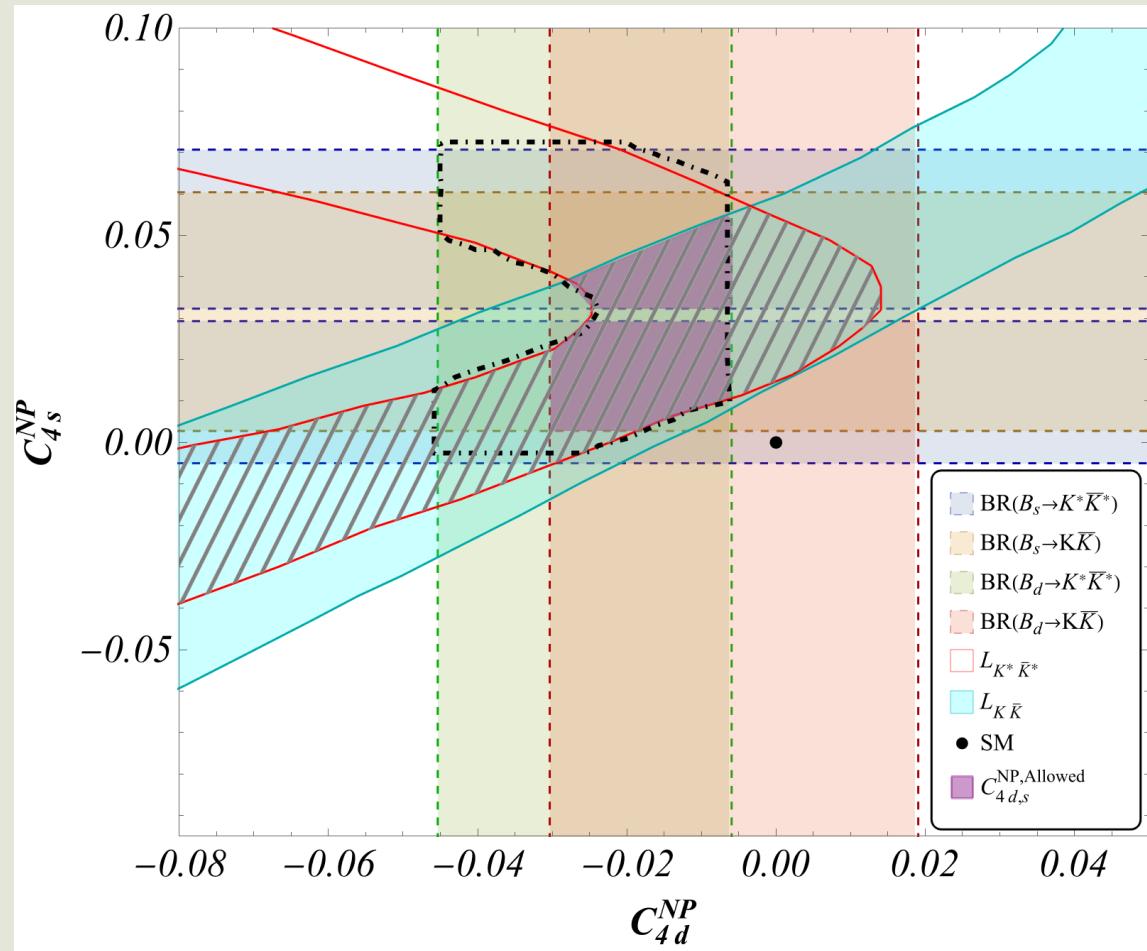
SM (QCDF)

$$4.36^{+2.23}_{-1.65}$$

Experiment

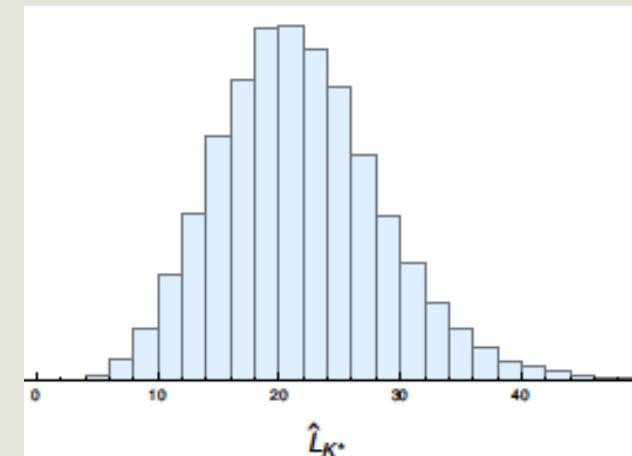
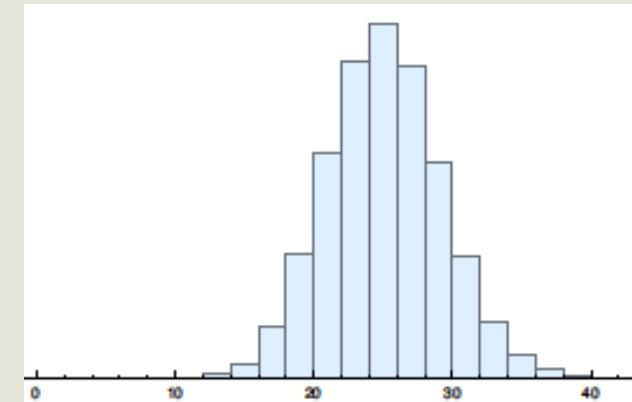
$$2.62^{+0.85}_{-0.75}$$

NP in $b \rightarrow s,d$



Disentangling NP

- Consider mixed modes: $\bar{B}_{d,s} \rightarrow K^{*0} \bar{K}^0, \bar{K}^{*0} K^0$
- For $M_1 = K^0$: $\hat{L}_K = \rho(m_{K^0}, m_{K^{*0}}) \frac{BR(\bar{B}_S \rightarrow K^0 \bar{K}^{*0})}{BR(\bar{B}_d \rightarrow \bar{K}^0 K^{*0})} = \frac{|A^S|^2 + |\bar{A}^S|^2}{|A^d|^2 + |\bar{A}^d|^2}$
SM prediction: $25.01^{+4.21}_{-4.07}$
NP dependence: $25.04 - 1201.22C_{4S}^{NP} + 15994.20C_{4S}^{NP^2} + 149.47C_{6S}^{NP}$
 $+ 66.04C_{8gs}^{NP} + \dots$
- For $M_1 = K^{*0}$: $\hat{L}_{K^*} = \rho(m_{K^0}, m_{K^{*0}}) \frac{BR(\bar{B}_S \rightarrow K^{*0} \bar{K}^0)}{BR(\bar{B}_d \rightarrow \bar{K}^{*0} K^0)} = \frac{|A^S|^2 + |\bar{A}^S|^2}{|A^d|^2 + |\bar{A}^d|^2}$
SM prediction: $21.30^{+7.19}_{-6.30}$
NP dependence: $21.00 + 1040.25C_{4S}^{NP} + 12886.60C_{4S}^{NP^2} - 1504.72C_{6S}^{NP}$
 $+ 27037.90C_{6S}^{NP^2} - 26.72C_{8gs}^{NP} + \dots$



“Easier” observables

- However, tagging B_d modes is challenging and costly.

- $L_K = 2\rho(m_{K^0}, m_{K^{*0}}) \frac{BR(\bar{B}_s \rightarrow K^0 \bar{K}^{*0})}{BR(\bar{B}_d \rightarrow \bar{K}^{*0} K^0) + BR(\bar{B}_d \rightarrow \bar{K}^0 K^{*0})} = \frac{2}{1+R_d} \hat{L}_K$. SM prediction: $29.16^{+5.49}_{-5.25}$.

- $L_{K^*} = 2\rho(m_{K^0}, m_{K^{*0}}) \frac{BR(\bar{B}_s \rightarrow K^{*0} \bar{K}^0)}{BR(\bar{B}_d \rightarrow \bar{K}^{*0} K^0) + BR(\bar{B}_d \rightarrow \bar{K}^0 K^{*0})} = \frac{2R_d}{1+R_d} \hat{L}_{K^*}$. SM prediction: $17.44^{+6.59}_{-5.82}$.

- In the above:

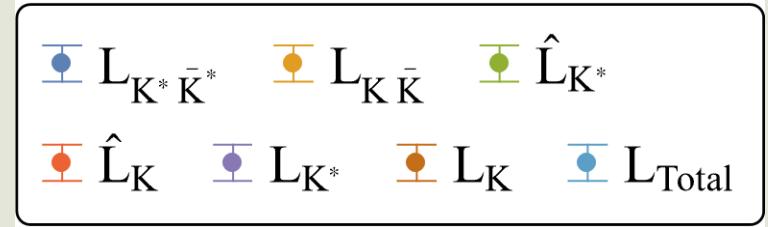
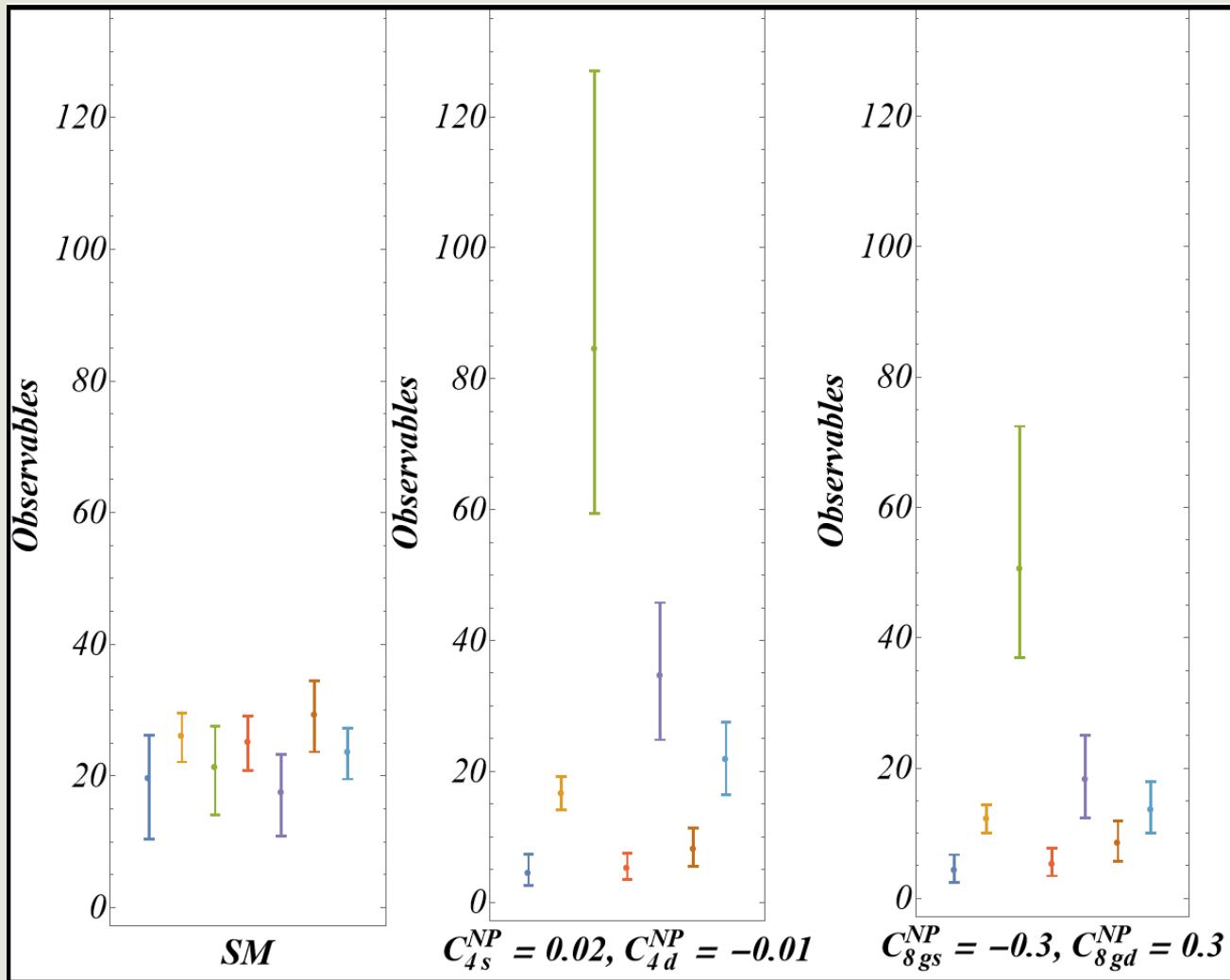
$$R_d = \frac{BR(\bar{B}_d \rightarrow \bar{K}^{*0} K^0)}{BR(\bar{B}_d \rightarrow \bar{K}^0 K^{*0})}. \text{ SM prediction: } 0.70^{+0.30}_{-0.22}.$$

- And finally the easiest, with the most limited NP sensitivity:

$$L_{Total} = \rho(m_{K^0}, m_{K^{*0}}) \frac{BR(\bar{B}_s \rightarrow K^{*0} \bar{K}^0) + BR(\bar{B}_s \rightarrow K^0 \bar{K}^{*0})}{BR(\bar{B}_d \rightarrow \bar{K}^{*0} K^0) + BR(\bar{B}_d \rightarrow \bar{K}^0 K^{*0})} = \frac{L_{K^*} + L_K}{2} = \frac{\hat{L}_K + \hat{L}_{K^*} R_d}{1+R_d}.$$

SM prediction: $23.48^{+3.95}_{-3.82}$.

Pattern



Conclusions

- Two interesting observables in the non leptonic sector: $L_{K^*K^*}$, L_{KK}
- Maybe NP: possible in both $b \rightarrow s$ and $b \rightarrow d$.
- Simultaneous explanations by $C_{4,8g}^{s,d}$.
- Further observables in a futuristic chronological order of measurement to disentangle NP: L_{Total} , L_{K^*} , L_K , \hat{L}_{K^*} , \hat{L}_K

THANK
YOU!



Backup

Input	Relative Error		
	$L_{K^*\bar{K}^*}$	$ P_s ^2$	$ P_d ^2$
f_{K^*}	(−0.1%, +0.1%)	(−6.8%, +7.1%)	(−6.8%, +7%)
$A_0^{B_d}$	(−22%, +32%)	—	(−24%, +28%)
$A_0^{B_s}$	(−28%, +33%)	(−28%, +33%)	—
λ_{B_d}	(−0.6%, +0.2%)	(−4.6%, +2.1%)	(−4.1%, +1.9%)
$\alpha_2^{K^*}$	(−0.1%, +0.1%)	(−3.6%, +3.7%)	(−3.6%, +3.6%)
X_H	(−0.2%, +0.2%)	(−1.8%, +1.8%)	(−1.6%, +1.6%)
X_A	(−4.3%, +4.4%)	(−17%, +19%)	(−13%, +14%)
κ	(−1.4%, +2.2%)	—	—
Others	(−1.3%, +1.1%)	(−2.7%, +2.5%)	(−1.6%, +1.6%)

Table 2. Error budget of $L_{K^*\bar{K}^*}$ and $|P_{d,s}|^2$. The relative error of each theoretical input is obtained by varying them individually. The main sources of uncertainty are the form factors, followed by weak annihilation at a significantly smaller level.

$B_{d,s}$ Distribution Amplitudes (at $\mu = 1$ GeV) [38, 39]									
λ_{B_d} [GeV]		$\lambda_{B_s}/\lambda_{B_d}$		σ_B					
0.383 ± 0.153		1.19 ± 0.14		1.4 ± 0.4					
K^* Distribution Amplitudes (at $\mu = 2$ GeV) [40]									
$\alpha_1^{K^*}$		$\alpha_{1,\perp}^{K^*}$		$\alpha_2^{K^*}$					
0.02 ± 0.02		0.03 ± 0.03		0.08 ± 0.06					
K Distribution Amplitudes (at $\mu = 2$ GeV) [41]									
α_1^K		α_2^K							
0.0525_{-33}^{+31}		0.106_{-16}^{+15}							
Decay Constants for B mesons (at $\mu = 2$ GeV) [42]									
f_{B_d}		f_{B_s}/f_{B_d}							
0.190 ± 0.0013		1.209 ± 0.005							
Decay Constants for Kaons (at $\mu = 2$ GeV) [24, 43, 44]									
f_K		f_{K^*}		$f_{K^*}^\perp/f_{K^*}$					
0.1557 ± 0.0003		0.204 ± 0.007		0.712 ± 0.012					
$B_{d,s} \rightarrow K^*$ form factors [44] and B-meson lifetimes (ps)									
$A_0^{B_s}(q^2 = 0)$		$A_0^{B_d}(q^2 = 0)$		τ_{B_d}					
0.314 ± 0.048		0.356 ± 0.046		1.519 ± 0.004					
τ_{B_s}									
1.515 ± 0.004									
$B_d \rightarrow K$ [45] and $B_s \rightarrow K$ [46] form factors									
$f_0^{B_s}(q^2 = 0)$		$f_0^{B_d}(q^2 = 0)$							
0.336 ± 0.023		0.332 ± 0.012							
Wolfenstein parameters [47]									
A		λ		$\bar{\rho}$					
$0.8235_{-0.0145}^{+0.0056}$		$0.22484_{-0.00006}^{+0.00025}$		$0.1569_{-0.0061}^{+0.0102}$					
$\bar{\eta}$									
$0.3499_{-0.0065}^{+0.0079}$									
QCD scale and masses [GeV]									
$\bar{m}_b(\bar{m}_b)$		m_b/m_c		m_{B_d}					
4.2		4.577 ± 0.008		m_{B_s}					
5.280		5.367		m_{K^*}					
0.892		0.225		Λ_{QCD}					
SM Wilson Coefficients (at $\mu = 4.2$ GeV)									
C_1		C_2		C_3					
1.082		-0.191		C_4					
0.013		-0.036		C_5					
0.009		-0.042							
C_7/α_{em}		C_8/α_{em}		C_9/α_{em}					
C_{10}/α_{em}		C_{10}/α_{em}		$C_{7\gamma}^{\text{eff}}$					
C_{8g}^{eff}		-0.318		-0.151					
-0.011		0.058		-1.254					
0.223		-0.318							

	<i>MLR</i>	<i>CDF</i>
$L_{K^*\bar{K}^*}$	$17.2^{+8.3}_{-5.9}$	$19.5^{+9.1}_{-6.7}$
$L_{K\bar{K}}$	$25.5^{+4.0}_{-3.3}$	$26.0^{+3.9}_{-3.6}$
\hat{L}_{K^*}	$20.5^{+6.8}_{-6.2}$	$21.3^{+7.2}_{-6.3}$
\hat{L}_K	$25.3^{+3.7}_{-4.5}$	$25.0^{+4.2}_{-4.1}$
L_{K^*}	$16.6^{+6.9}_{-6.0}$	$17.4^{+6.6}_{-5.8}$
L_K	$28.8^{+5.2}_{-4.6}$	$29.2^{+5.5}_{-5.3}$
L_{total}	$23.5^{+3.8}_{-4.0}$	$23.5^{+4.0}_{-3.8}$
R_d	$0.67^{+0.23}_{-0.24}$	$0.70^{+0.30}_{-0.22}$
$\mathcal{B}(B_d \rightarrow K^{*0}\bar{K}^{*0}) \times 10^6$	$0.22^{+0.08}_{-0.08}$	$0.23^{+0.10}_{-0.08}$
$\mathcal{B}(B_s \rightarrow K^{*0}\bar{K}^{*0}) \times 10^6$	$3.95^{+1.88}_{-1.54}$	$4.36^{+2.23}_{-1.65}$
$\mathcal{B}(B_d \rightarrow K^0\bar{K}^0) \times 10^6$	$1.01^{+0.24}_{-0.16}$	$1.09^{+0.29}_{-0.20}$
$\mathcal{B}(B_s \rightarrow K^0\bar{K}^0) \times 10^6$	$25.6^{+7.5}_{-5.2}$	$28.0^{+8.9}_{-6.2}$

α_i coefficients $\rightarrow a_i$ [BBNS]

$$a_i^p(M_1 M_2) = \left(C_i + \frac{C_{i\pm 1}}{N_c} \right) N_i(M_2) + \frac{C_{i\pm 1}}{N_c} \frac{C_F \alpha_s}{4\pi} \left[V_i(M_2) + \frac{4\pi^2}{N_c} H_i(M_1 M_2) \right] + P_i^p(M_2),$$

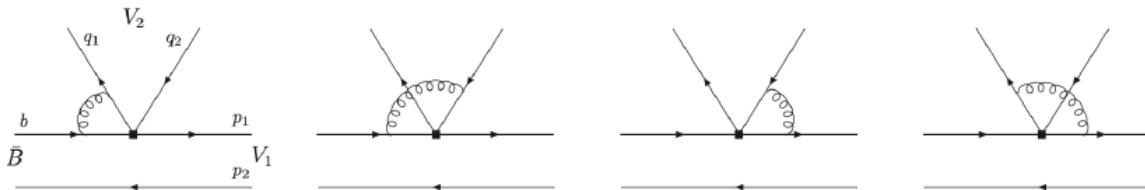


Figure 1: Vertex diagrams.

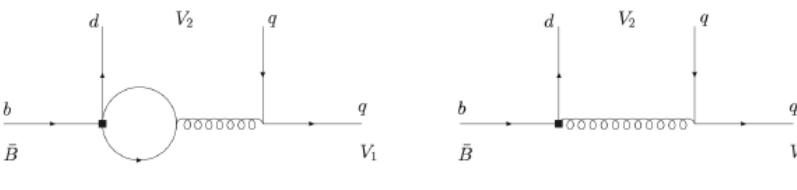


Figure 2: Penguin diagrams.

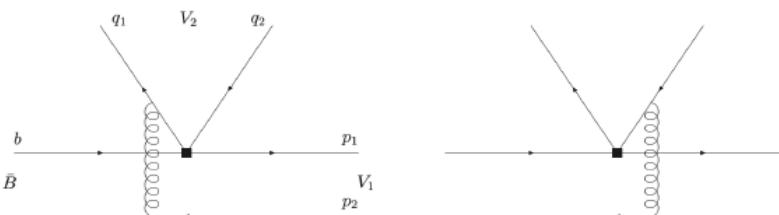


Figure 3: Hard spectator diagrams.

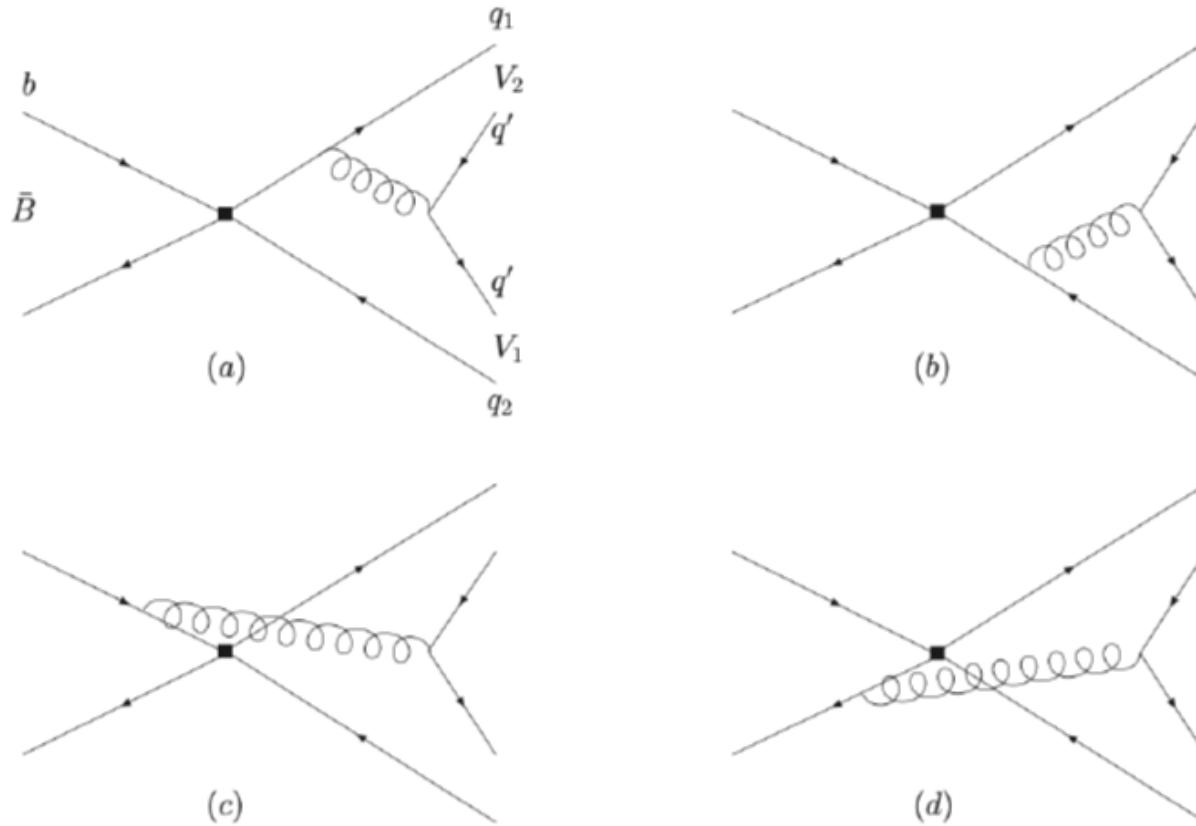


Figure 4: Annihilation diagrams.

Main caveat:

(Existence of some) **Power suppressed** but **IR divergent** spectator scattering and weak annihilation that affects amplitudes:

