Towards a Global Analysis of the $b \to c\bar{u}q$ Puzzle

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based on work with Danny van Dyk and Javier Virto [2411.09458]

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Nonleptonic Decays of Heavy Mesons, 23 March 2025

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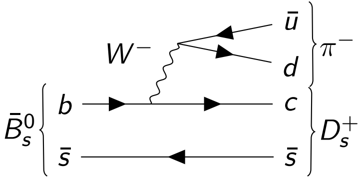
Studienstiftung des deutschen Volkes

Introduction

Motivation

- Consider



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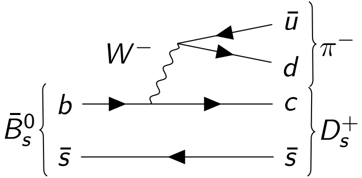

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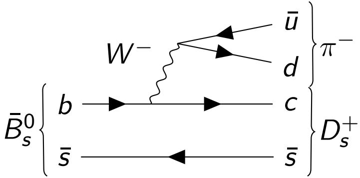

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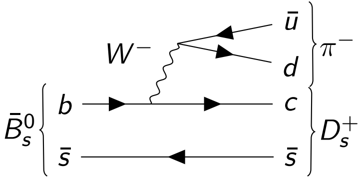

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- Effective theories give systematic framework to do so
- $\bar{B}^0 \to D^{(*)+}K^-$ and $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ especially theoretically clean

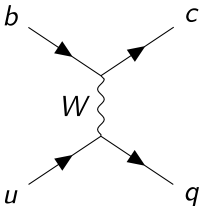
$\lightning$

experimental results

Theoretical Framework

Weak Effective Theory

$\mathcal{L}_{\text{SM}}$



$$\frac{1}{q^2-M_W^2} = -\frac{1}{M_W^2} + \mathcal{O}\left(\frac{q^2}{M_W^4}\right)$$
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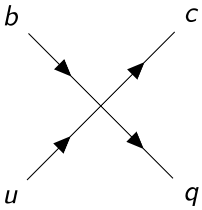

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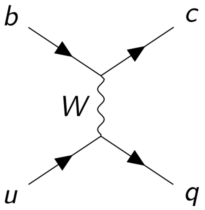

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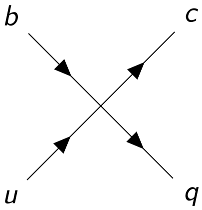

- Typical process energy $\ll M_W$
- Integrate out W-boson

$$\Downarrow$$

$$\mathcal{L}^{qbcu} = -\frac{4G_F}{\sqrt{2}} V_{cb} V_{uq}^* \left(C_1 \mathcal{Q}_1^{VLL} + C_2 \mathcal{Q}_2^{VLL} \right) ,$$

$$\mathcal{Q}_1^{VLL} = \left[\bar{c}^\alpha \gamma_\mu P_L b^\beta \right] \left[\bar{q}^\beta \gamma^\mu P_L u^\alpha \right] , \quad \mathcal{Q}_2^{VLL} = \left[\bar{c}^\alpha \gamma_\mu P_L b^\alpha \right] \left[\bar{q}^\beta \gamma^\mu P_L u^\beta \right] .$$

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- What about scale dependence of amplitude $A \sim \sum_i C_i(\mu) \langle D^+_{(s)} | \bar{c}\Gamma^i_1 b | \bar{B}^0_{(s)} \rangle \langle L^- | \bar{q}\Gamma^i_2 u | 0 \rangle$?

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- Solution: Collinear factorization

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- In the heavy-quark limit, heavy meson decays factorise into form factors, LCDAs and perturbative scattering kernels:

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[Beneke, Buchalla, Neubert, Sachrajda 0006124]

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- Non-factorizable corrections are major source of uncertainties, which can come from e.g. annihilation, penguin and dipole topologies

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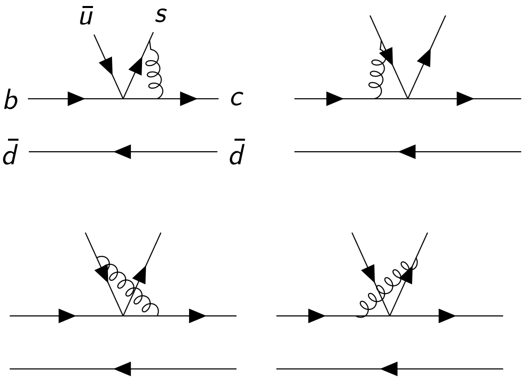
- LCDAs: scalar functions of the momentum fraction u of the light-meson momentum carried by one of the light-like separated constituent quarks that characterizes the light meson:

$$\langle L^-(q)|\,\bar{q}(y)\gamma_\mu\gamma_5 u(x)\,|0\rangle\,|_{(x-y)^2=0} = -if_L q_\mu \int_0^1 du\, e^{i(uq\cdot y+\bar{u}q\cdot x)}\phi(u)$$

Hard-scattering kernel

Hard-scattering kernels $T^{\rm I}_{ij}$ at $\mathcal{O}(\alpha_s)^a$ computed from vertex correction diagrams:



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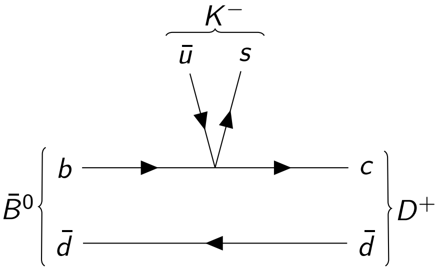
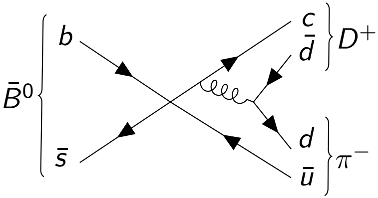
Other diagrams

1. Power-suppressed
2. Included in non-perturbative input
3. Not present due to flavor structure

[a] $\mathcal{O}(\alpha_s^2)$ SM result is known [Huber, Kränkl/Li 1606.02888]

Annihilation free decays





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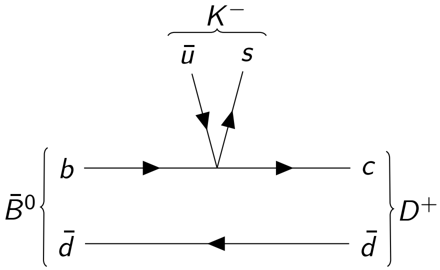

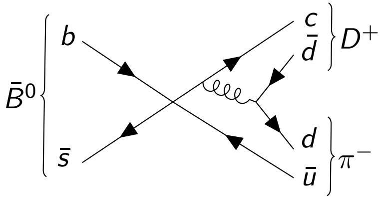

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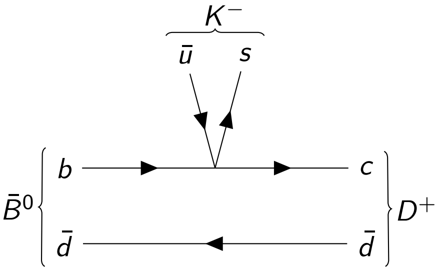

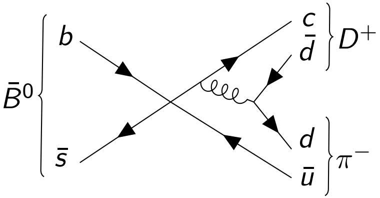

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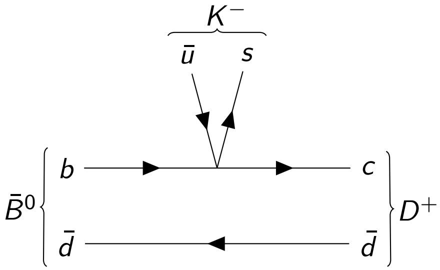

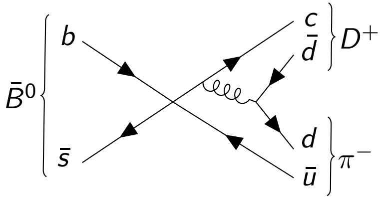

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- LCSR estimate of matrix elements agrees with data, but large uncertainties [Piscopo, Rusov 2307.07594]

The puzzle

The Puzzle in $\bar{B}^0 \to D^+ K^-$ and $\bar{B}_s^0 \to D_s^+ \pi^-$ Decays

QCD factorization prediction within the Standard Model:

$$\mathcal{B}\left(\bar{B}^0 \to D^+ K^-\right) = (0.326 \pm 0.015) \cdot 10^{-3}$$
$$\mathcal{B}\left(\bar{B}_s^0 \to D_s^+ \pi^-\right) = (4.42 \pm 0.21) \cdot 10^{-3}$$

[Bordone, Gubernari, Huber, Jung, van Dyk 2007.10338]

Experimental values:

$$\mathcal{B}\left(\bar{B}^0 \to D^+ K^-\right) = (0.186 \pm 0.020) \cdot 10^{-3}$$
$$\mathcal{B}\left(\bar{B}_s^0 \to D_s^+ \pi^-\right) = (3.00 \pm 0.23) \cdot 10^{-3}$$

[PDG/LHCb/Belle/BaBar/CLEO/ARGUS]

$$\Downarrow$$

Strong tension in $\bar{B}_s^0 \to D_s^+ \pi^-$ and $\bar{B}^0 \to D^+ K^-$

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4. **New physics**: Only possibility left, but is it viable?

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  - Use $B_c^- \to J/\psi(\eta_c)L^-$ BRs [Deng, Cai, Li, Shi, Yang 2503.11279]
- SMEFT analyses: Use constraints from top quark observables [Atkinson, Englert, Kirk, Tetlalmatzi-Xolocotzi 2411.00940]

Interpretation within the Weak Effective Theory: Analytical Calculations

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with

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- Here: WC flavor universal and real

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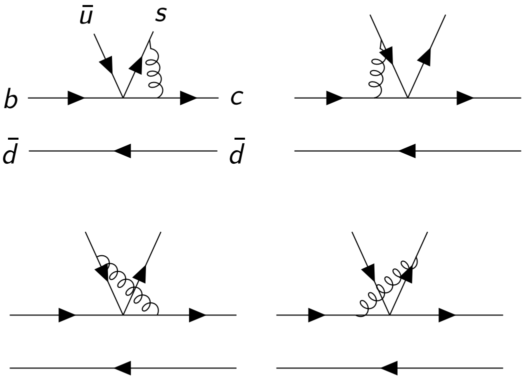

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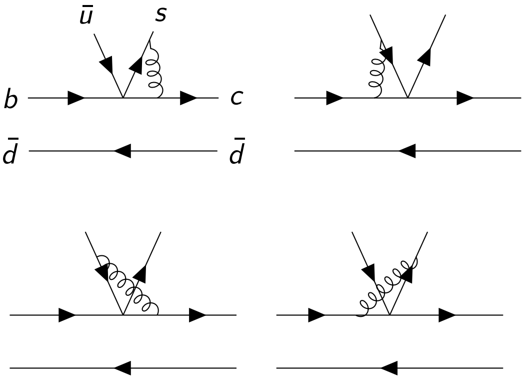

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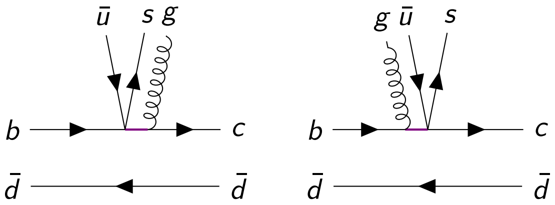
- Checked $m_c \to 0$ limit [Beneke, Neubert 0308039], [Beneke, Buchalla, Neubert, Sachrajda 0104110]

Three-particle states: Next-to-leading power

Contribution from three-particle light meson state :



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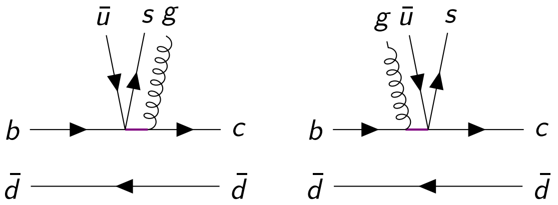

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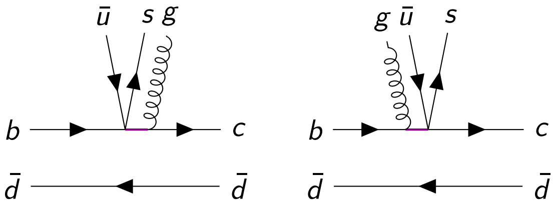

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Interpretation within the Weak Effective Theory: Pheno analysis

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$\vec{\nu} = \left(f_0^{B \to D}(m_K^2),\, f_0^{B_s \to D_s}(m_\pi^2),\, A_0^{B \to D^*}(m_K^2),\, A_0^{B_s \to D_s^*}(m_\pi^2)\right)$

Bayesian framework

- Object of interest is the posterior distribution:

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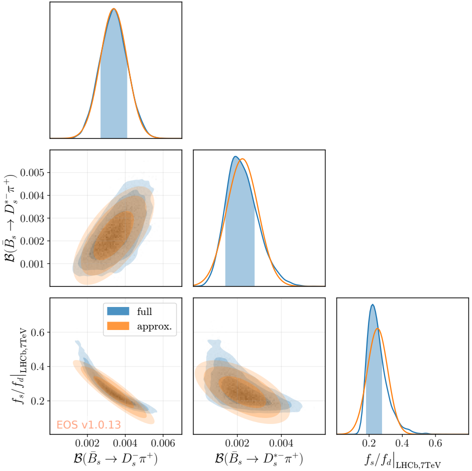
- $1 < K \leq 3$: barely worth mentioning, $3 < K \leq 10$: substantial, $10 < K \leq 100$: strong, $100 < K$: decisive

Likelihood



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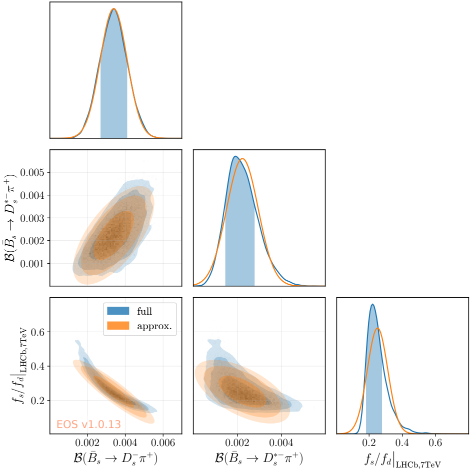

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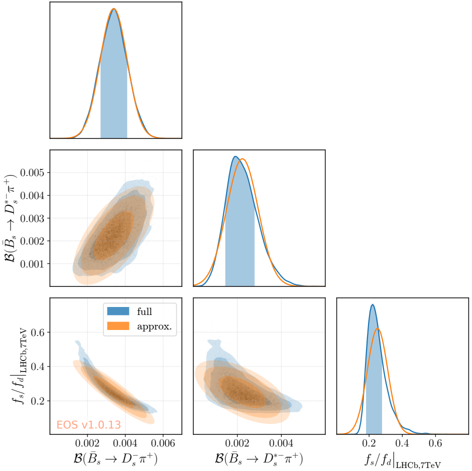

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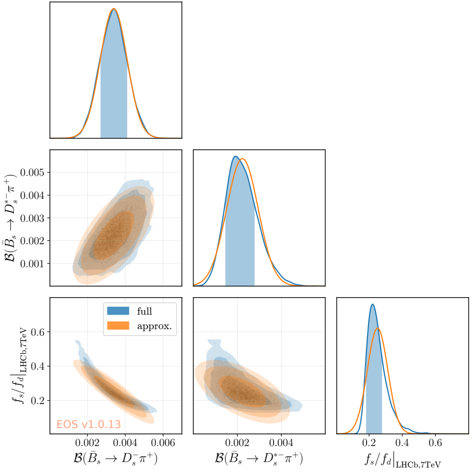

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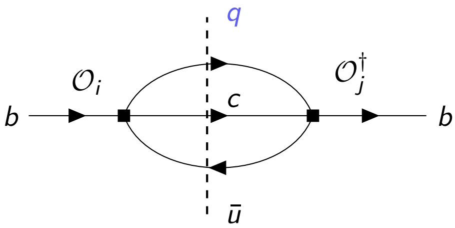
- Impossible to constrain many WCs simultaneously $\Rightarrow$ use global lifetime constraint

Lifetime constraint



- Compute contribution of our *qbcu* operators to the lifetime:

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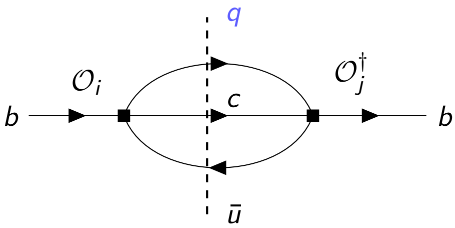

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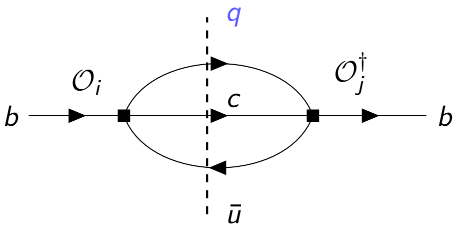

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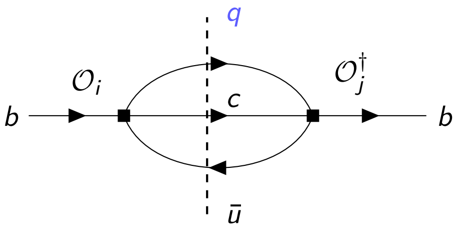

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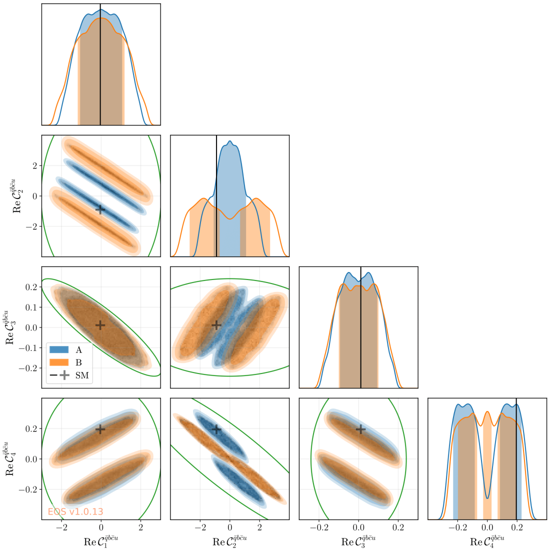
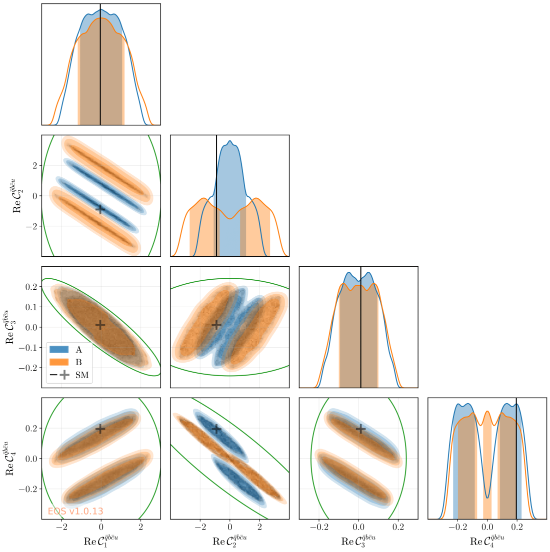
- Scenarios with four WCs preferred, but chiralities are indistinguishable

Bounds on WC



- Bounds on WC in terms of posterior distribution

Bounds on WC



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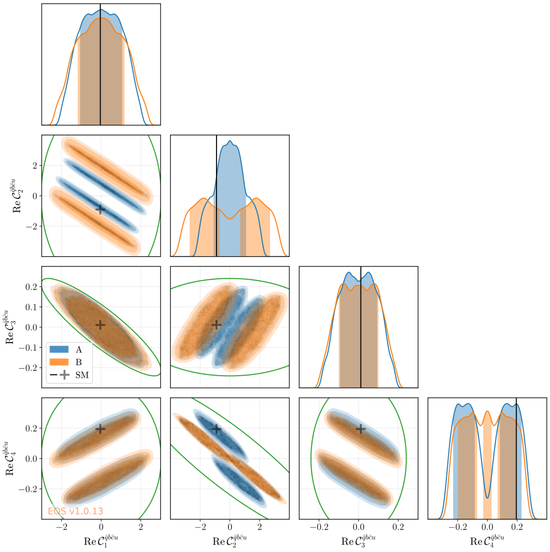

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- SM point seems to be included, but it is not (hollow shell)

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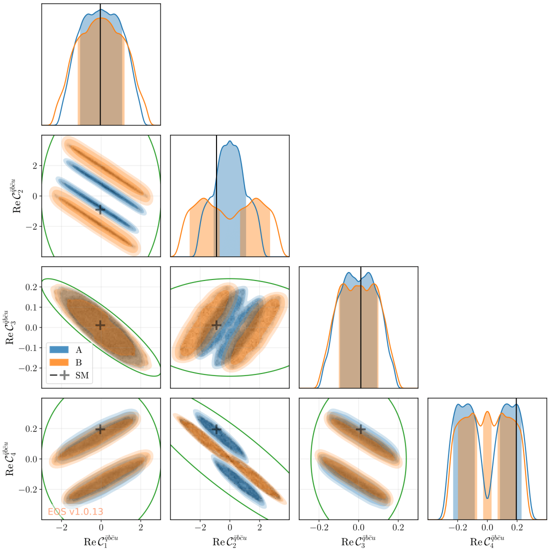

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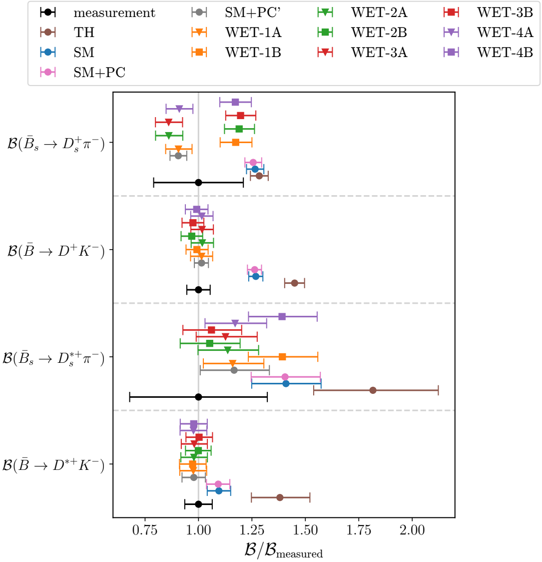
  - mode B farther away from SM
- SM point seems to be included, but it is not (hollow shell)
- Lifetime constraints very important for some combinations of WCs ⇒ directions are poorly constrained by exclusive BRs

Posterior postdictions for the branching ratios



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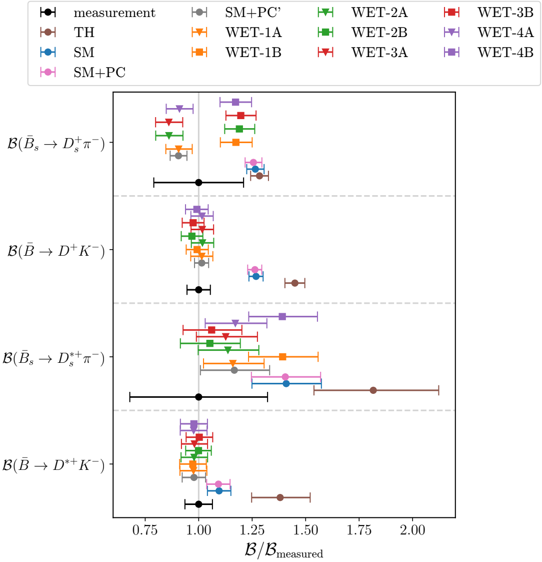

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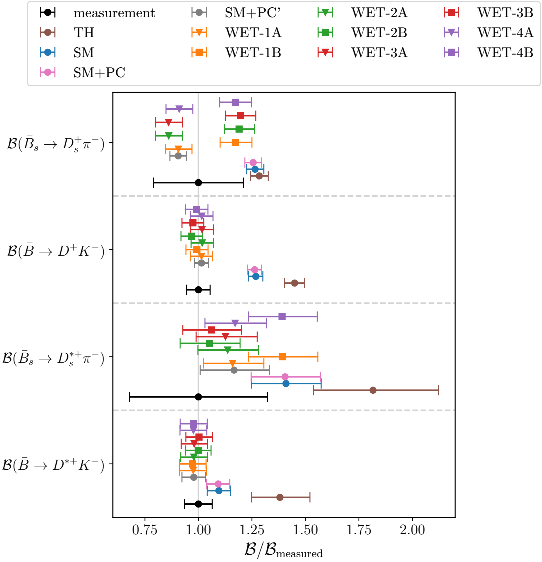

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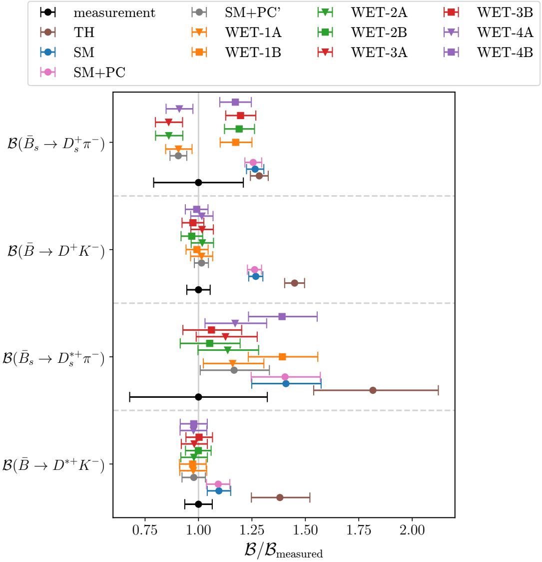

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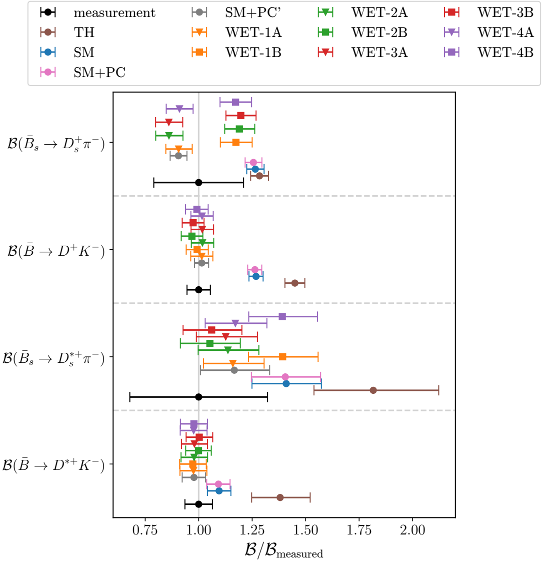

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- We constrain almost all of them!

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- Can we constrain all WC simultaneously by using more constraints (lifetime ratios, top constraints, etc. ...)

Backup Slides

Non-leading Fock state - twist 3 and twist 4 LCDAs

Twist 3:

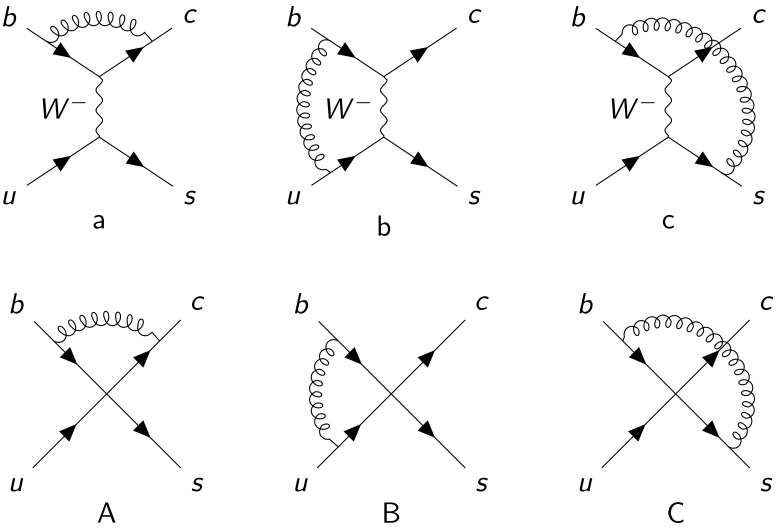
$$\langle L^-(q)|\, \bar{q}(0)\sigma_{\mu\nu}\gamma_5 g_s G_{\alpha\beta}(vx)u(0)\,|0\rangle = if_{3L}[(q_\alpha q_\mu g_{\beta\nu} - q_\beta q_\mu g_{\nu\alpha}) - (\mu \leftrightarrow \nu)] \int \mathcal{D}u e^{ivu_3 q\cdot x}\phi_{3L}(u_i)$$

Twist 4:

$$\begin{aligned}\langle L^-(q)|\, \bar{q}(0)\gamma_\mu\gamma_5 g_s G_{\alpha\beta}(vx)u(0)\,|0\rangle =& f_L \int \mathcal{D}u\ e^{ivu_3 q\cdot x}\Big\{ [q_\beta g_{\alpha\mu} - q_\alpha g_{\beta\mu}]\,\phi_\perp(u_i) \\ &+ \left[\frac{q_\mu q_\alpha x_\beta}{q\cdot x} - \frac{q_\mu q_\beta x_\alpha}{q\cdot x}\right](\phi_\parallel(u_i) + \phi_\perp(u_i)) \Big\}\end{aligned}$$

$$\begin{aligned}\langle L^-(q)|\, \bar{q}(0)\gamma_\mu g_s \tilde{G}_{\alpha\beta}(vx)u(0)\,|0\rangle =& if_L \int \mathcal{D}u\ e^{ivu_3 q\cdot x}\Big\{ [q_\beta g_{\alpha\mu} - q_\alpha g_{\beta\mu}]\,\tilde{\phi}_\perp(u_i) \\ &+ \left[\frac{q_\mu q_\alpha x_\beta}{q\cdot x} - \frac{q_\mu q_\beta x_\alpha}{q\cdot x}\right]\left(\tilde{\phi}_\parallel(u_i) + \tilde{\phi}_\perp(u_i)\right) \Big\}\end{aligned}$$

Matching and renormalization group running



Hard-scattering kernels - calculation

$$\langle D^+_{(s)} L^- | \mathcal{Q}^i_1 | \bar{B}^0_{(s)} \rangle_{\text{1-gluon}}$$
$$= -i g_s^2 \frac{C_F}{N} \int \frac{d^4 k}{(2\pi)^4} \langle D^+_{(s)} | \bar{c} A^i_1(k) b | \bar{B}^0_{(s)} \rangle \frac{1}{k^2} \int_0^1 du \; \text{Tr} \left[M^L(u) A^i_2(l_1, l_2, k) \right] |_{l_1 = uq,\, l_2 = \bar{u} q} \,,$$

with

$$A^i_1(k) = \gamma^\beta \frac{\not{p}_c - \not{k} + m_c}{2 p_c \cdot k - k^2} \Gamma^i_1 - \Gamma^i_1 \frac{\not{p}_b + \not{k} + m_b}{2 p_b \cdot k + k^2} \gamma^\beta \,,$$

$$A^i_2(l_q, l_{\bar{q}}, k) = \Gamma^i_2 \frac{\not{l}_{\bar{q}} + \not{k}}{2 l_{\bar{q}} \cdot k + k^2} \gamma_\beta - \gamma_\beta \frac{\not{l}_q + \not{k}}{2 l_q \cdot k + k^2} \Gamma^i_2 \,,$$

$$M^L = \frac{i f_L}{4} \left\{ \not{q} \gamma_5 \phi_L(u) - \mu_P \gamma_5 \left(\phi_p(u) - i \sigma_{\mu\nu} n^\mu_+ n^\nu_- \frac{\phi'_\sigma(u)}{12} + i \sigma_{\mu\nu} q^\mu \frac{\phi_\sigma(u)}{6} \frac{\partial}{\partial l_{q\perp\nu}} \right) \right\} .$$

ϕ_L : twist-2, vector operators

$\phi_p \,, \phi_\sigma$: twist-3, scalar/tensor operators

Choice of WET bases: BMU basis

$$\mathcal{Q}_1^{VLL} = [\bar{c}_\alpha \gamma_\mu P_L b_\beta]\,[\bar{q}_\beta \gamma^\mu P_L u_\alpha]\,, \qquad \mathcal{Q}_2^{VLL} = [\bar{c}_\alpha \gamma_\mu P_L b_\alpha]\,[\bar{q}_\beta \gamma^\mu P_L u_\beta]\,,$$

$$\mathcal{Q}_1^{SLR} = [\bar{c}_\alpha P_L b_\beta]\,[\bar{q}_\beta P_R u_\alpha]\,, \qquad \mathcal{Q}_2^{SLR} = [\bar{c}_\alpha P_L b_\alpha]\,[\bar{q}_\beta P_R u_\beta]\,,$$

$$\mathcal{Q}_1^{VRL} = [\bar{c}_\alpha \gamma_\mu P_R b_\beta]\,[\bar{q}_\beta \gamma^\mu P_L u_\alpha]\,, \qquad \mathcal{Q}_2^{VRL} = [\bar{c}_\alpha \gamma_\mu P_R b_\alpha]\,[\bar{q}_\beta \gamma^\mu P_L u_\beta]\,,$$

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$$\mathcal{Q}_3^{SRR} = [\bar{c}_\alpha \sigma_{\mu\nu} P_R b_\beta]\,[\bar{q}_\beta \sigma^{\mu\nu} P_R u_\alpha]\,, \qquad \mathcal{Q}_4^{SRR} = [\bar{c}_\alpha \sigma_{\mu\nu} P_R b_\alpha]\,[\bar{q}_\beta \sigma^{\mu\nu} P_R u_\beta]$$

Choice of WET bases: Bern basis

$$\mathcal{O}_1^{qbcu} = [\bar{q} P_R \gamma_\mu b] \, [\bar{c} \gamma^\mu u] \, , \qquad \mathcal{O}_2^{qbcu} = \left[\bar{q} P_R \gamma_\mu T^A b\right] \left[\bar{c} \gamma^\mu T^A u\right] \, ,$$

$$\mathcal{O}_3^{qbcu} = [\bar{q} P_R \gamma_{\mu\nu\rho} b] \, [\bar{c} \gamma^{\mu\nu\rho} u] \, , \qquad \mathcal{O}_4^{qbcu} = \left[\bar{q} P_R \gamma_{\mu\nu\rho} T^A b\right] \left[\bar{c} \gamma^{\mu\nu\rho} T^A u\right] \, ,$$

$$\mathcal{O}_5^{qbcu} = [\bar{q} P_R b] \, [\bar{c} u] \, , \qquad \mathcal{O}_6^{qbcu} = \left[\bar{q} P_R T^A b\right] \left[\bar{c} T^A u\right] \, ,$$

$$\mathcal{O}_7^{qbcu} = [\bar{q} P_R \sigma_{\mu\nu} b] \, [\bar{c} \sigma^{\mu\nu} u] \, , \qquad \mathcal{O}_8^{qbcu} = \left[\bar{q} P_R \sigma_{\mu\nu} T^A b\right] \left[\bar{c} \sigma^{\mu\nu} T^A u\right] \, ,$$

$$\mathcal{O}_9^{qbcu} = [\bar{q} P_R \gamma_{\mu\nu\rho\sigma} b] \, [\bar{c} \gamma^{\mu\nu\rho\sigma} u] \, , \qquad \mathcal{O}_{10}^{qbcu} = \left[\bar{q} P_R \gamma_{\mu\nu\rho\sigma} T^A b\right] \left[\bar{c} \gamma^{\mu\nu\rho\sigma} T^A u\right]$$

Likelihood

Measurement	Central value & Uncertainty	Reference	Notes
B factory analyses			
$\mathcal{B}(B_s^0 \to D_s^- \pi^+)$	$(3.6 \pm 0.5 \pm 0.5) \cdot 10^{-3}$	[43]	
$\frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$	$(6.8 \pm 1.7) \cdot 10^{-2}$	[44]	
$f_{00}\mathcal{B}(B^0 \to D^- \pi^+)\mathcal{B}(D^- \to K^+\pi^-\pi^-)$	$(1.21 \pm 0.05) \cdot 10^{-4}$	[45, 46]	
$\mathcal{B}(B^0 \to D^- \pi^+)\mathcal{B}(D^- \to K^+\pi^-\pi^-)$	$(2.88 \pm 0.29) \cdot 10^{-4}$	[47]	†
$\frac{\mathcal{B}(B_s^0 \to D_s^{*-} \pi^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}$	0.66 ± 0.16	[48]	
$f_{00}\mathcal{B}(B^0 \to D^{*-} \pi^+)$	$(1.40 \pm 0.07) \cdot 10^{-3}$	[45, 49]	
$\frac{\mathcal{B}(B^0 \to D^{*-} \pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$	(0.99 ± 0.14)	[47]	
Tevatron analyses			
$\frac{f_s}{f_d}\Big\rvert_{\text{Tevatron}} \frac{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+)} \frac{\mathcal{B}(D_s^- \to \phi\pi^-)}{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}$	$(6.7 \pm 0.5) \cdot 10^{-2}$	[50]	
LHC analyses			
$\frac{f_s}{f_d}\Big\rvert_{\text{LHCb(7 TeV)}} \frac{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+)} \frac{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}$	$(17.4 \pm 0.7) \cdot 10^{-2}$	[51]	
$\frac{f_s}{f_d}\Big\rvert_{\text{LHCb(7 TeV)}} \frac{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}{\mathcal{B}(B^0 \to D^- K^+)} \frac{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}{\mathcal{B}(D^- \to K^+\pi^-\pi^+)}$	2.08 ± 0.08	[52]	*
$\frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$	$(8.22 \pm 0.28) \cdot 10^{-2}$	[52]	*
PDG averages			
$\mathcal{B}(D_s^- \to \phi\pi^-)\mathcal{B}(\phi \to K^+K^-)$	$(2.27 \pm 0.08) \cdot 10^{-2}$	[53]	
$\mathcal{B}(D_s^- \to K^+K^-\pi^-)$	$(5.45 \pm 0.17) \cdot 10^{-2}$	[53]	
$\mathcal{B}(D^- \to K^+\pi^-\pi^-)$	$(9.38 \pm 0.16) \cdot 10^{-2}$	[53]	
Other			
$\frac{\mathcal{B}(B^0 \to D^{*-} K^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+)}$	$(7.75 \pm 0.30) \cdot 10^{-2}$	[44, 54, 55]	
f_{00}	0.488 ± 0.010	[56–58]	

Form factor prior

Parameter	Value $\pm$ uncertainty	Comments
$f_0^{B_s \to D_s}(m_\pi^2)$	0.669 ± 0.011	Gaussian
$f_0^{B \to D}(m_K^2)$	0.675 ± 0.011	Gaussian
$A_0^{B_s \to D_s^*}(m_\pi^2)$	0.688 ± 0.056	Gaussian
$A_0^{B \to D^*}(m_K^2)$	0.704 ± 0.035	Gaussian

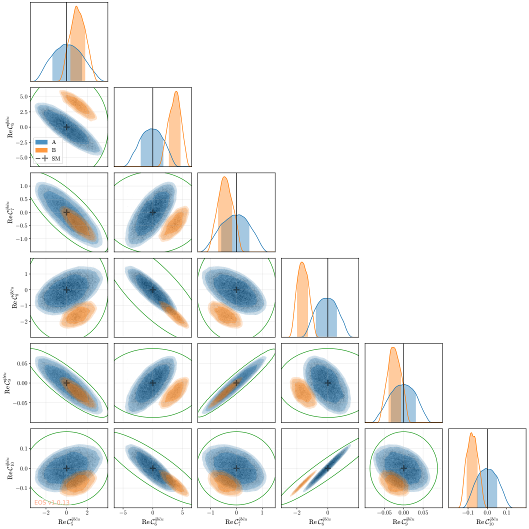
Full FF prior including correlations can be found in EOS under

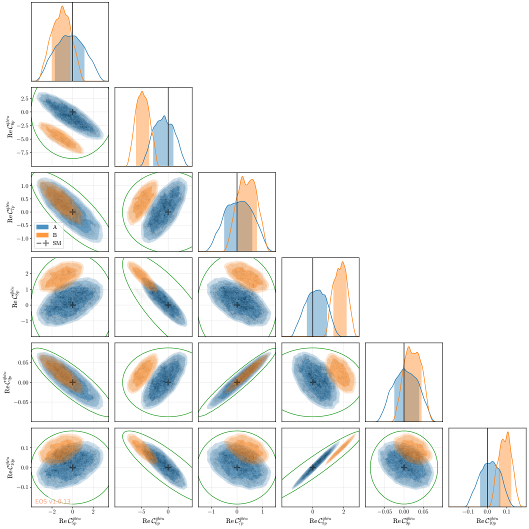
```
B_(s)->D_(s)^(*)::FormFactors[f_0(Mpi2),f_0(MK2),A_0(Mpi2),A_0(MK2)]@BGJvD:2019A
```

Model comparison

Fit model M	Labelled mode	χ^2	$\log P(D, M)$
SM	—	26.69	9.04 ± 0.03
SM+PC	—	25.18	9.71 ± 0.10
SM+PC'	—	1.58	29.12 ± 0.04
WET-1	A	1.61	21.75 ± 0.03
WET-1	B	1.67	21.77 ± 0.03
WET-2	A	1.57	18.40 ± 0.03
WET-2	B	1.34	16.35 ± 0.03
WET-3	A	1.62	21.60 ± 0.03
WET-3	B	1.32	21.50 ± 0.03
WET-4	A	1.54	18.48 ± 0.03
WET-4	B	1.69	16.62 ± 0.03

Corner plots: WET-2 and WET-4





Corner plots: WET-1 and WET-3