Heavy meson decays as precision tools for new physics: A search for beyond Standard Model signals

Nicola Losacco

Dipartimento Interateneo di Fisica "M. Merlin", Università e Politecnico di Bari,
Istituto Nazionale di Fisica Nucleare, Sezione di Bari

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Overview

Research

- The Standard Model as an Effective Field Theory
- Tensions in the flavour sector
- Interplay between flavour physics and hadron spectroscopy
- Chaos and Holography

See Roselli talk

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Motivations to physics beyond the SM

The Standard Model

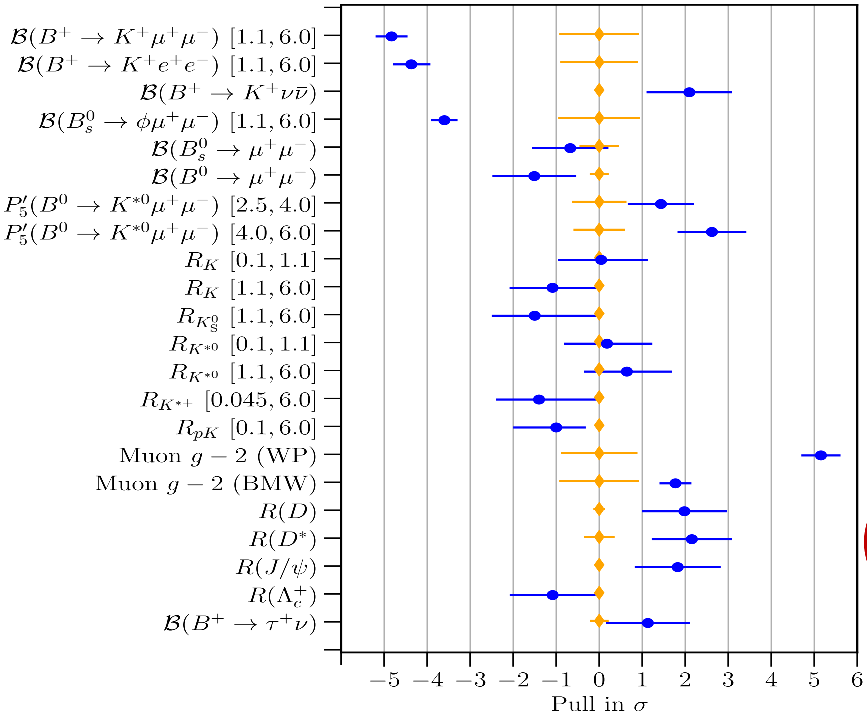
Successes

- All predicted particles have been discovered
- The features of fundamental interactions correctly described

Unsolved issues

- Gravity not included
- No dark matter explanation
- Neutrino masses
- CP asymmetry not sufficient to explain the observed universe
- Instability of the Higgs mass under radiative correction
- Hierarchy among the fermion masses

Flavour anomalies



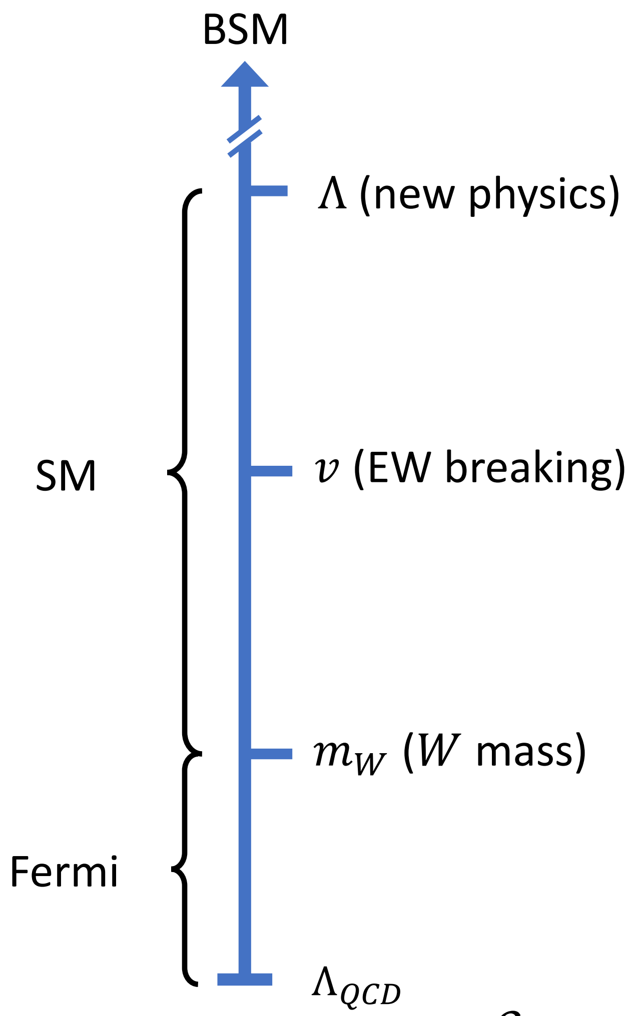
Furthermore, several anomalies in the flavour sector

Two procedures

Bottom-up
From experiments finding hints towards new physics

Top-down
Predictions in a defined NP extension of the SM-check the experimental consequences

Standard Model as an Effective Field Theory



SM as low energy theory of a more fundamental one

Unknown BSM theory

↓

Extention of the SM Lagrangian with higher dimensional operators weighted by Λ^{-n}

Dimensionless Wilson Coefficients

For $\mu \ll \Lambda$

$$\mathcal{L}_{\nu SMEFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Invariant under $\mathcal{G}_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$

d dimension operators only SM fields

A simple extension: $U(1)'$

P. Colangelo, F. De Fazio, F. Loparco, and N. L. Phys. Rev. D 110 (2024), no. 3 035007

$$\mathcal{G}_{BSM} = \mathcal{G}_{SM} \times U(1)'$$ ➡

Z' New gauge field

g_Z Gauge coupling

z_ψ, z_H z-hypercharges of fermions and Higgs

For $\mu \sim \Lambda$

UV Lagrangian involving Z': $$\mathcal{L}^{Z'} = \mathcal{L}^{Z'}_{\text{free}} + \mathcal{L}^{Z'}_{\text{int,fermions}} + \mathcal{L}^{Z'}_{\varphi}$$

Free term $$\mathcal{L}^{Z'}_{\text{free}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu$$ $$Z'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$$

$M_{Z'}$: mass of the Z' after SSB

Fermion interaction

$$\mathcal{L}^{Z'}_{\text{int,fermions}} = \sum_\psi g_Z\, z_\psi\, \bar{\psi}\gamma^\mu\psi\, Z'_\mu = \sum_\psi \left[\left(\Delta^\psi_L\right)^{ij} \bar{\psi}^i_L \gamma^\mu \psi^j_L + \left(\Delta^\psi_R\right)^{ij} \bar{\psi}^i_R \gamma^\mu \psi^j_R \right] Z'_\mu$$

$$\left(\Delta^\psi_{L,R}\right)^{ij} = g_Z\, z_\psi\, \delta^{ij}$$

Higgs interaction

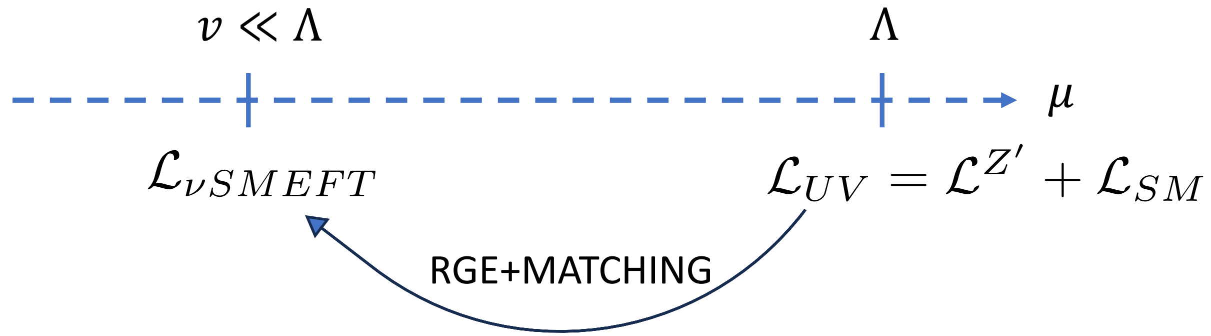
$$\mathcal{L}^{Z'}_\varphi = g_H \left(\varphi^\dagger\, i \overleftrightarrow{D}_\mu\, \varphi \right) Z'^\mu$$

$$g_H = g_Z\, z_H$$

D_μ is the SM covariant derivative

$$\varphi^\dagger\, i \overleftrightarrow{D}_\mu\, \varphi = \varphi^\dagger \left(i D_\mu \varphi\right) - \left(i D_\mu \varphi^\dagger\right) \varphi$$

νSMEFT Lagrangian from $U(1)'$ extension



νSMEFT operators of $d = 6$ dimension after Z' integration

$$
\begin{aligned}
\mathcal{L}_{Z'}^{(6)} = \; & C_{\ell\ell}\,\mathcal{O}_{\ell\ell} + C_{qq}^{(1)}\,\mathcal{O}_{qq}^{(1)} + C_{ee}\,\mathcal{O}_{ee} + C_{uu}\,\mathcal{O}_{uu} + C_{dd}\,\mathcal{O}_{dd} + C_{\nu\nu}^{(6)}\,\mathcal{O}_{\nu\nu}^{(6)} \\
+ \; & C_{\ell q}^{(1)}\,\mathcal{O}_{\ell q}^{(1)} + C_{ud}^{(1)}\,\mathcal{O}_{ud}^{(1)} + C_{eu}\,\mathcal{O}_{eu} + C_{ed}\,\mathcal{O}_{ed} + C_{\ell e}\,\mathcal{O}_{\ell e} + C_{\ell u}\,\mathcal{O}_{\ell u} \\
+ \; & C_{\ell d}\,\mathcal{O}_{\ell d} + C_{qe}\,\mathcal{O}_{qe} + C_{qu}^{(1)}\,\mathcal{O}_{qu}^{(1)} + C_{qd}^{(1)}\,\mathcal{O}_{qd}^{(1)} + C_{\nu e}\,\mathcal{O}_{\nu e} + C_{\nu u}\,\mathcal{O}_{\nu u} \\
+ \; & C_{\nu d}\,\mathcal{O}_{\nu d} + C_{\ell\nu}\,\mathcal{O}_{\ell\nu} + C_{q\nu}\,\mathcal{O}_{q\nu} + C_{\varphi\Box}\,\mathcal{O}_{\varphi\Box} + C_{\varphi D}\,\mathcal{O}_{\varphi D} + C_{e\varphi}\,\mathcal{O}_{e\varphi} \\
+ \; & C_{u\varphi}\,\mathcal{O}_{u\varphi} + C_{d\varphi}\,\mathcal{O}_{d\varphi} + C_{\nu\varphi}\,\mathcal{O}_{\nu\varphi} + C_{\varphi\ell}^{(1)}\,\mathcal{O}_{\varphi\ell}^{(1)} + C_{\varphi e}\,\mathcal{O}_{\varphi e} + C_{\varphi q}^{(1)}\,\mathcal{O}_{\varphi q}^{(1)} \\
+ \; & C_{\varphi u}\,\mathcal{O}_{\varphi u} + C_{\varphi d}\,\mathcal{O}_{\varphi d} + C_{\varphi\nu}\,\mathcal{O}_{\varphi\nu} + \text{h.c.}\,.
\end{aligned}
$$

Wilson coefficients depend on the parameter of the UV theory: g_Z, z_ψ, z_H and Z' mass

Blue terms are 0 for this extension

Relations from the gauge group structure

Few parameters to express all Wilson coefficients ➡ Relations among them

Generation indices

$$\left[C_{\psi_1\psi_2}\right]_{ijkp} = \pm 2\sqrt{\left[C_{\psi_1\psi_1}\right]_{ijij}\left[C_{\psi_2\psi_2}\right]_{kpkp}}$$

$$\left[C_{\psi\psi}\right]_{ijkp} = \frac{\left[C_{\varphi\psi}\right]_{ij}\left[C_{\varphi\psi}\right]_{kp}}{C_{\varphi D}}$$

$$\left[C_{\psi_1\psi_2}\right]_{ijkp} = 2\,\frac{\left[C_{\varphi\psi_1}\right]_{ij}\left[C_{\varphi\psi_2}\right]_{kp}}{C_{\varphi D}}$$

Wilson coefficient $\neq 0$ only if $i = j$ and $\mathrm{k} = p$

Relations from the gauge group structure

Defining $\underline{i} = ii$

Coefficients structure synthetized

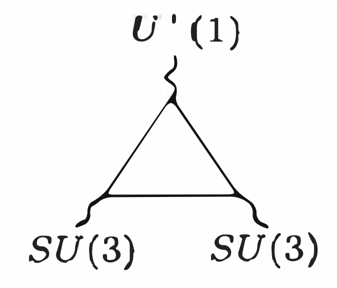
$$C_{\varphi\psi} = \begin{pmatrix} [C_{\varphi\psi}]_{\underline{1}} & [C_{\varphi\psi}]_{\underline{2}} & [C_{\varphi\psi}]_{\underline{3}} \end{pmatrix}$$

$$C_{\psi\psi} = \frac{1}{C_{\varphi D}} \begin{pmatrix} \left([C_{\varphi\psi}]_{\underline{1}}\right)^2 & [C_{\varphi\psi}]_{\underline{1}} [C_{\varphi\psi}]_{\underline{2}} & [C_{\varphi\psi}]_{\underline{1}} [C_{\varphi\psi}]_{\underline{3}} \\ [C_{\varphi\psi}]_{\underline{2}} [C_{\varphi\psi}]_{\underline{1}} & \left([C_{\varphi\psi}]_{\underline{2}}\right)^2 & [C_{\varphi\psi}]_{\underline{2}} [C_{\varphi\psi}]_{\underline{3}} \\ [C_{\varphi\psi}]_{\underline{3}} [C_{\varphi\psi}]_{\underline{1}} & [C_{\varphi\psi}]_{\underline{3}} [C_{\varphi\psi}]_{\underline{2}} & \left([C_{\varphi\psi}]_{\underline{3}}\right)^2 \end{pmatrix}$$

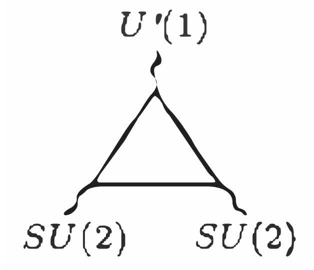
$$C_{\psi_1\psi_2} = \frac{2}{C_{\varphi D}} \begin{pmatrix} [C_{\varphi\psi_1}]_{\underline{1}} [C_{\varphi\psi_2}]_{\underline{1}} & [C_{\varphi\psi_1}]_{\underline{1}} [C_{\varphi\psi_2}]_{\underline{2}} & [C_{\varphi\psi_1}]_{\underline{1}} [C_{\varphi\psi_2}]_{\underline{3}} \\ [C_{\varphi\psi_1}]_{\underline{2}} [C_{\varphi\psi_2}]_{\underline{1}} & [C_{\varphi\psi_1}]_{\underline{2}} [C_{\varphi\psi_2}]_{\underline{2}} & [C_{\varphi\psi_1}]_{\underline{2}} [C_{\varphi\psi_2}]_{\underline{3}} \\ [C_{\varphi\psi_1}]_{\underline{3}} [C_{\varphi\psi_2}]_{\underline{1}} & [C_{\varphi\psi_1}]_{\underline{3}} [C_{\varphi\psi_2}]_{\underline{2}} & [C_{\varphi\psi_1}]_{\underline{3}} [C_{\varphi\psi_2}]_{\underline{3}} \end{pmatrix}$$

Constraints from Anomaly Cancellation Equations (ACE)

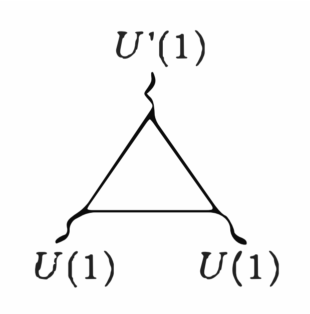
$$z_\psi^{(n)} = \sum_{i=1}^{3} z_{\psi_i}^n$$



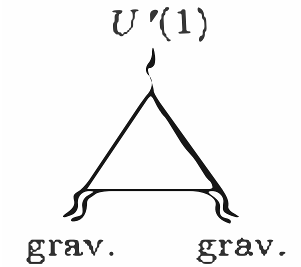
$$A_{33z} = 2\, z_q^{(1)} - z_u^{(1)} - z_d^{(1)} = 0$$



$$A_{22z} = 3\, z_q^{(1)} + z_\ell^{(1)} = 0$$

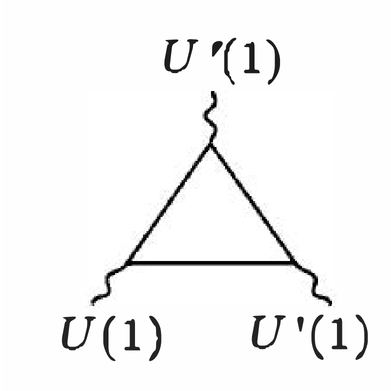


$$A_{11z} = \frac{1}{6}\, z_q^{(1)} - \frac{4}{3}\, z_u^{(1)} - \frac{1}{3}\, z_d^{(1)} + \frac{1}{2}\, z_\ell^{(1)} - z_e^{(1)} = 0$$

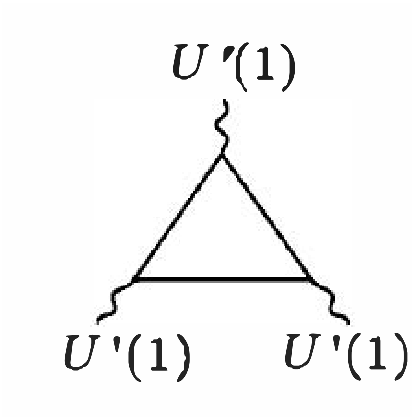


$$A_{GGz} = 2\, z_\ell^{(1)} - z_e^{(1)} - z_\nu^{(1)} = 0$$

Constraints from Anomaly Cancellation



$$A_{1zz} = [z_q^{(2)} - 2\, z_u^{(2)} + z_d^{(2)}] - [z_\ell^{(2)} - z_e^{(2)}] = 0$$



$$A_{zzz} = 3\,[2\, z_q^{(3)} - z_u^{(3)} - z_d^{(3)}] + [2\, z_\ell^{(3)} - z_\nu^{(3)} - z_e^{(3)}] = 0$$

Relations among coefficients

$$\tilde{C}^{(n)}_{\varphi\psi} = \sum_{\underline{i}=\underline{1}}^{3} \left(\left[C_{\varphi\psi} \right]_{\underline{i}} \right)^{n} \qquad \underline{i} = ii$$

z-hypercharge dependence

$$z_{\psi_i} = -\frac{M^2_{Z'}}{g_Z} \frac{1}{g_H} \left[C_{\varphi\psi} \right]_{\underline{i}} \quad \Rightarrow \quad z^{(n)}_{\psi} = \left(-\frac{M^2_{Z'}}{g_Z} \frac{1}{g_H} \right)^{n} \tilde{C}^{(n)}_{\varphi\psi}$$

$$\Downarrow$$

$$A_{33z} \rightarrow 2\,\tilde{C}_{\varphi q} - \tilde{C}_{\varphi u} - \tilde{C}_{\varphi d} = 0$$

$$A_{22z} \rightarrow 3\,\tilde{C}_{\varphi q} + \tilde{C}_{\varphi \ell} = 0$$

$$A_{11z} \rightarrow \tilde{C}_{\varphi q} - 8\,\tilde{C}_{\varphi u} - 2\,\tilde{C}_{\varphi d} + 3\,\tilde{C}_{\varphi \ell} - 6\,\tilde{C}_{\varphi e} = 0$$

$$A_{GGz} \rightarrow 2\,\tilde{C}_{\varphi \ell} - \tilde{C}_{\varphi e} - \tilde{C}_{\varphi \nu} = 0$$

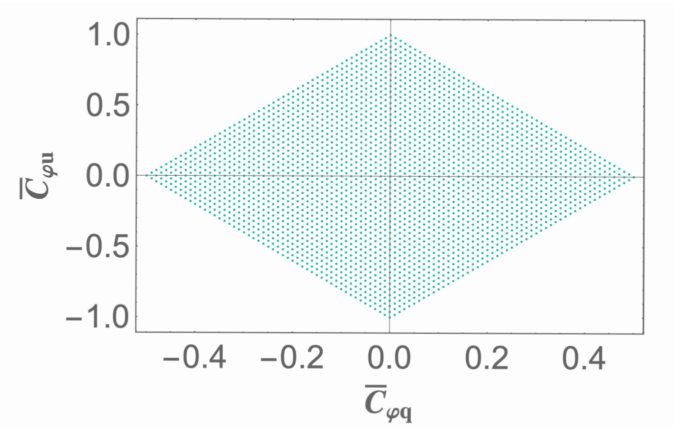
$$\left\} \begin{aligned} \tilde{C}_{\varphi q} &= \frac{\tilde{C}_{\varphi u} + \tilde{C}_{\varphi d}}{2} \\ \tilde{C}_{\varphi \ell} &= -3\,\tilde{C}_{\varphi q} = -3\,\frac{\tilde{C}_{\varphi u} + \tilde{C}_{\varphi d}}{2} \\ \tilde{C}_{\varphi e} &= -2\,\tilde{C}_{\varphi u} - \tilde{C}_{\varphi d} \\ \tilde{C}_{\varphi \nu} &= -\tilde{C}_{\varphi u} - 2\,\tilde{C}_{\varphi d} \end{aligned} \right.$$

$$A_{1zz} \rightarrow \tilde{C}^{(2)}_{\varphi q} - 2\,\tilde{C}^{(2)}_{\varphi u} + \tilde{C}^{(2)}_{\varphi d} - \tilde{C}^{(2)}_{\varphi \ell} + \tilde{C}^{(2)}_{\varphi e} = 0$$

$$A_{zzz} \rightarrow 3\,[2\,\tilde{C}^{(3)}_{\varphi q} - \tilde{C}^{(3)}_{\varphi u} - \tilde{C}^{(3)}_{\varphi d}] + [2\,\tilde{C}^{(3)}_{\varphi \ell} - \tilde{C}^{(3)}_{\varphi \nu} - \tilde{C}^{(3)}_{\varphi e}] = 0$$

Example I:

Z' universal and only coupled to the third generation



Universal coupling

$$z_{\psi_1} = z_{\psi_2} = z_{\psi_3} = z_\psi$$

$$\left[C_{\varphi\psi}\right]_{\underline{1}} = \left[C_{\varphi\psi}\right]_{\underline{2}} = $$
$$= \left[C_{\varphi\psi}\right]_{\underline{3}} = \bar{C}_{\varphi\psi}$$

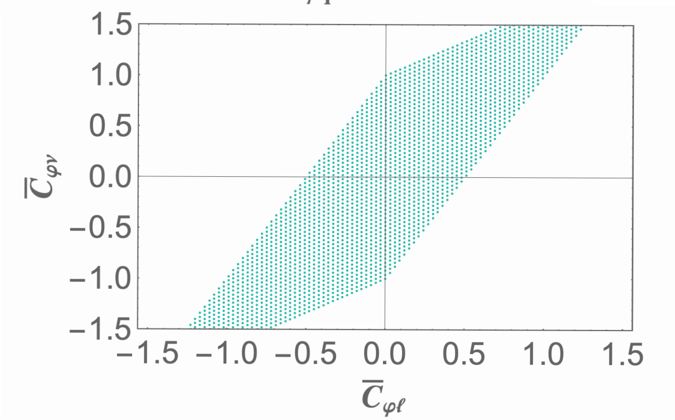
$$\tilde{C}^{(n)}_{\varphi\psi} = 3\left(\bar{C}_{\varphi\psi}\right)^n$$

Only third generation coupling:

$$z_{\psi_3} = z_\psi$$
$$z_{\psi_1} = z_{\psi_2} = 0$$

$$\left[C_{\varphi\psi}\right]_{\underline{1}} = \left[C_{\varphi\psi}\right]_{\underline{2}} = 0$$
$$\left[C_{\varphi\psi}\right]_{\underline{3}} = \bar{C}_{\varphi\psi}$$

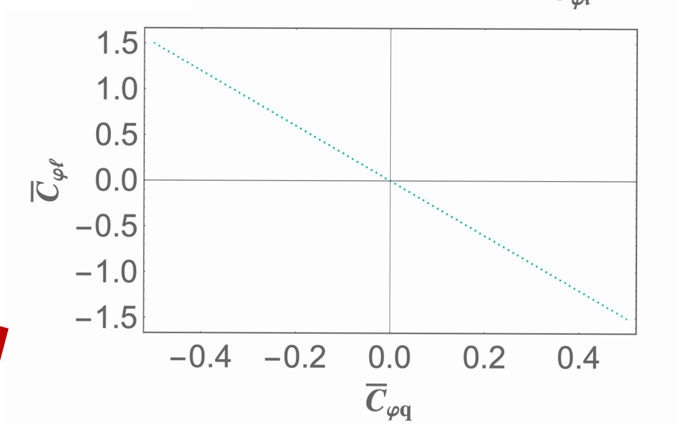
$$\tilde{C}^{(n)}_{\varphi\psi} = \left(\bar{C}_{\varphi\psi}\right)^n$$



Same constraints
from the linear ACE

6 coefficients and 4 linear relations

Correlation plots varying
$\bar{C}_{\varphi d}, \bar{C}_{\varphi e} \in [-1, 1]$



Example II:

Z' only coupled to left-handed fermions

Only left-handed coupling

$z_{\ell_i} \neq 0 \qquad z_{q_i} \neq 0$ → 6 parameters

↓

2 constraints from linear ACE → $\tilde{C}_{\varphi q} = \tilde{C}_{\varphi \ell} = 0$

↓

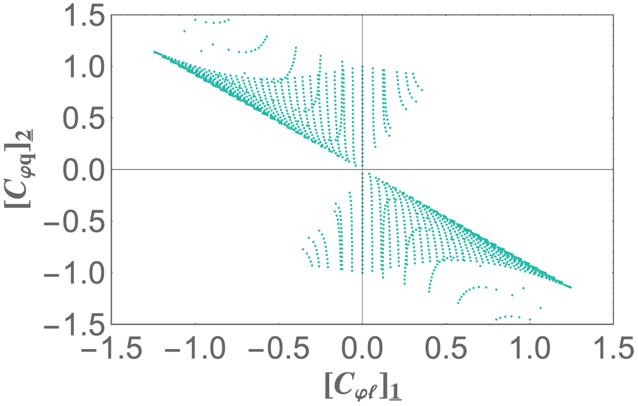
2 constraints from quadratic and cubic ACE

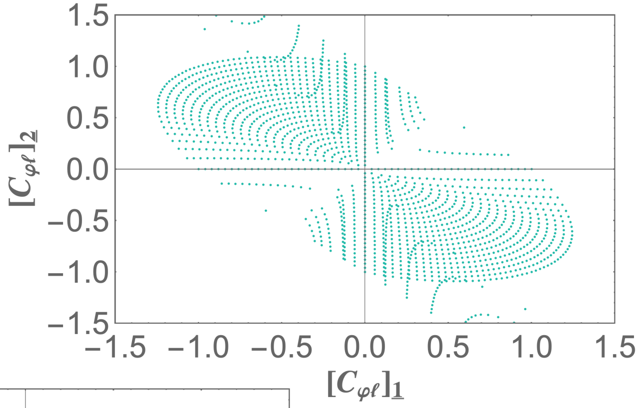
↓

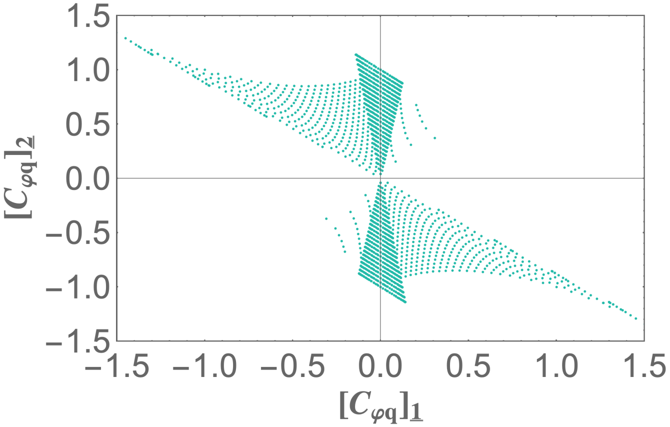
6 coefficients and 4 constraints

Correlation plots varying

$$[C_{\varphi q}]_{\underline{3}}\,, [C_{\varphi \ell}]_{\underline{3}} \in [-1, 1]$$







Correlations among coefficients produce correlations among observables

Conclusions and perspectives

SM might not be the ultimate theory

LO of an EFT ➡ SMEFT/νSMEFT

Effects of new physics
in its parameters

⬇

Constrained by experiments or
theoretical assumptions

Explored U(1)′ with νSMEFT :

- Gauge structure ➡ relations between coefficients
- Gauge anomaly cancellations significantly narrow down coefficients space

Results guide experimental searches and global fits

Future Work: Include experimental data to refine constraints.

THANKS

FOR YOUR

ATTENTION

BACK UP

Overview

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- The Standard Model as an Effective Field Theory
- Tensions in the flavour sector
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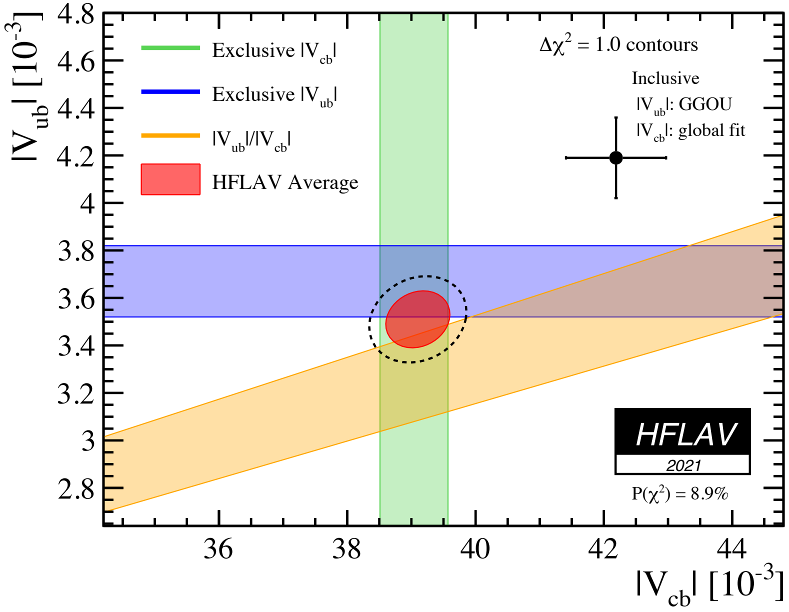
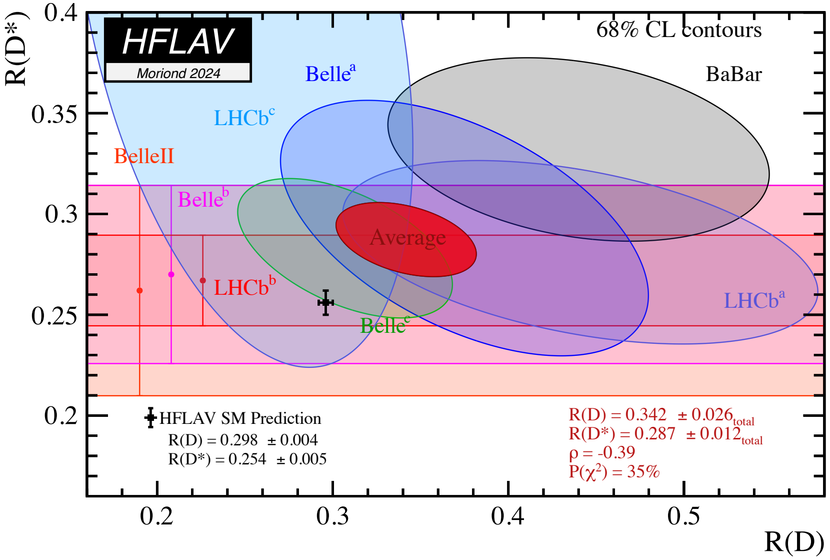
Anomalies in $b \to c\, \ell\, \nu$ transitions

Determinations of $|V_{cb}|$ and $|V_{ub}|$ from inclusive and exclusive B decays





Lepton Flavour Universality (LFU)

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\bar{B} \to D^{(*)}\, \tau^- \bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^{(*)}\, \ell^- \bar{\nu}_\ell\right)}$$

Possibility to investigate NP that can explain both anomalies

$\bar{B} \to D^*(D\,\pi)\,\ell\,\bar{\nu}_\ell$ process

Generalized effective Hamiltonian

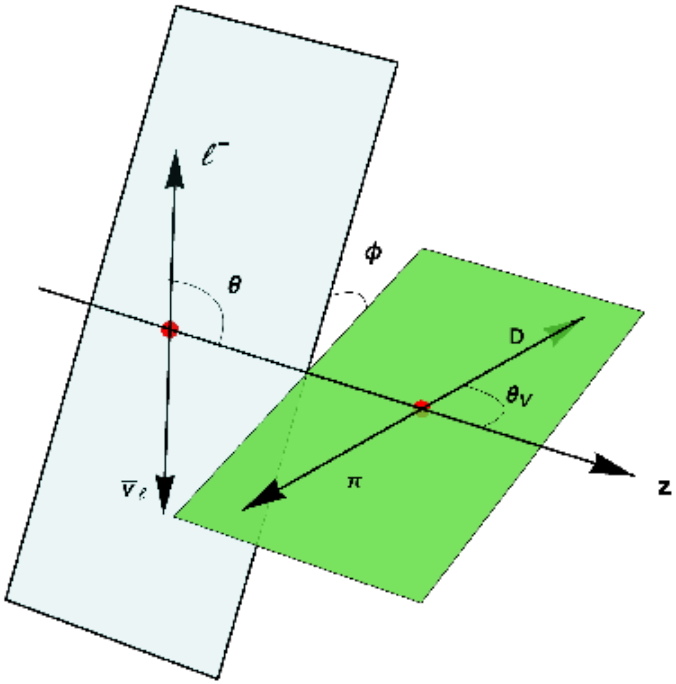
$$H_{eff}^{b\to U\ell\nu} = \frac{G_F}{\sqrt{2}} V_{Ub} \times \Big\{ (1+\epsilon_V^\ell)\left(\bar{U}\gamma_\mu(1-\gamma_5)b\right)\left(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right) + \epsilon_R^\ell\left(\bar{U}\gamma_\mu(1+\gamma_5)b\right)\left(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right)$$

$$+ \epsilon_S^\ell\left(\bar{U}b\right)\left(\bar{\ell}(1-\gamma_5)\nu_\ell\right) + \epsilon_P^\ell\left(\bar{U}\gamma_5 b\right)\left(\bar{\ell}(1-\gamma_5)\nu_\ell\right) + \epsilon_T^\ell\left(\bar{U}\sigma_{\mu\nu}(1-\gamma_5)b\right)\left(\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell\right) \Big\} + h.c.$$

For $V = D^*$

$\epsilon_i^\ell \neq 0$ new physics lepton flavour dependent couplings

Angular decomposition



$$\mathcal{N} = \frac{3G_F^2|V_{Ub}|^2\mathcal{B}(V \to P_1P_2)}{128(2\pi)^4 m_B^2}$$

$\vec{p}_V$ three momentum of the V meson in B rest frame

$$\frac{d^4\Gamma(\bar{B} \to V(P_1P_2)\ell^-\bar{\nu}_\ell)}{dq^2\, d\cos\theta\, d\phi\, d\cos\theta_V} = \mathcal{N}|\vec{p}_V|\left(1-\frac{m_\ell^2}{q^2}\right)^2$$

$$\times\Big\{ I_{1s}\sin^2\theta_V + I_{1c}\cos^2\theta_V$$

$$+\left(I_{2s}\sin^2\theta_V + I_{2c}\cos^2\theta_V\right)\cos 2\theta$$

$$+I_3\sin^2\theta_V\sin^2\theta\cos 2\phi + I_4\sin 2\theta_V\sin 2\theta\cos\phi$$

$$+I_5\sin 2\theta_V\sin\theta\cos\phi$$

$$+\left(I_{6s}\sin^2\theta_V + I_{6c}\cos^2\theta_V\right)\cos\theta$$

$$+I_7\sin 2\theta_V\sin\theta\sin\phi + I_8\sin 2\theta_V\sin 2\theta\sin\phi$$

$$+I_9\sin^2\theta_V\sin^2\theta\sin 2\phi\Big\}$$

Only in presence of NP

Experiment

Full set of angular coefficient functions measured by Belle Collaboration

M. T. Prim et al. (Belle), Phys. Rev. Lett. 133 (2024)

Experimental results presented in terms of

$$\hat{J}_i(w) = \frac{kFI_i(w)}{N} = J_i(w)/N$$

$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2\, m_B\, m_{D^*}} \qquad k = \begin{cases} -1 & \text{for } i = 4, 6s, 6c, 8 \\ 1 & \text{all the others} \end{cases} \qquad F = \frac{3|\vec{p}_{D^*}|}{2^{10}\, m_B^5}$$

Integrated width modulo a constant

$$N = \frac{8}{9}\pi \sum_{a=1}^{4} (3\,\bar{J}_{1c}^a + 6\,\bar{J}_{1s}^a - \bar{J}_{2c}^a - 2\,\bar{J}_{2s}^a)$$

4 bins $\Delta w^{(a)}$ of w

$$\Delta w^{(1)} = [1, 1.15] \qquad \Delta w^{(3)} = [1.25, 1.35]$$
$$\Delta w^{(2)} = [1.15, 1.25] \qquad \Delta w^{(4)} = [1.35, 1.5]$$

2 possible uses

NP contribution considered → Constraints on NP parameters ϵ_i^ℓ

P. Colangelo, F. De Fazio, F. Loparco, N.L., Phys. Rev. D 109 (2024)

NP contribution NOT considered → Evaluation of the hadronic form factors and improvement on $|V_{cb}|$

Results

w dependence of the form factors needed → Caprini-Lellouch-Neubert parametrization
P. Colangelo, F. De Fazio, JHEP 06, 082 (2018)

From the theoretical expression of I_i fixing N from the measured BR

$$\left(\hat{J}_i^a\right)_{int}^{th} = \int_{\Delta w(a)} \hat{J}_i^{th}\,(\mathrm{w})\mathrm{dw}$$

From the experimental value of $\hat{J}_i$

$$\left(\hat{J}_i^a\right)_{int}^{exp} = \hat{J}_i \cdot (\Delta w)^a$$

1° constraint

$$\left(\hat{J}_i^a\right)_{int}^{th} \in \left[\left(\hat{J}_i^a\right)_{int}^{exp} - k\,\sigma_i^a, \left(\hat{J}_i^a\right)_{int}^{exp} + k\,\sigma_i^a\right]$$

σ_i^a: $\sigma_i \cdot (\Delta w)^a$

k: Found to be 2.5

↓

Set 1 $\epsilon_V^\mu, \epsilon_R^\mu, \epsilon_p^\mu, \epsilon_T^\mu$

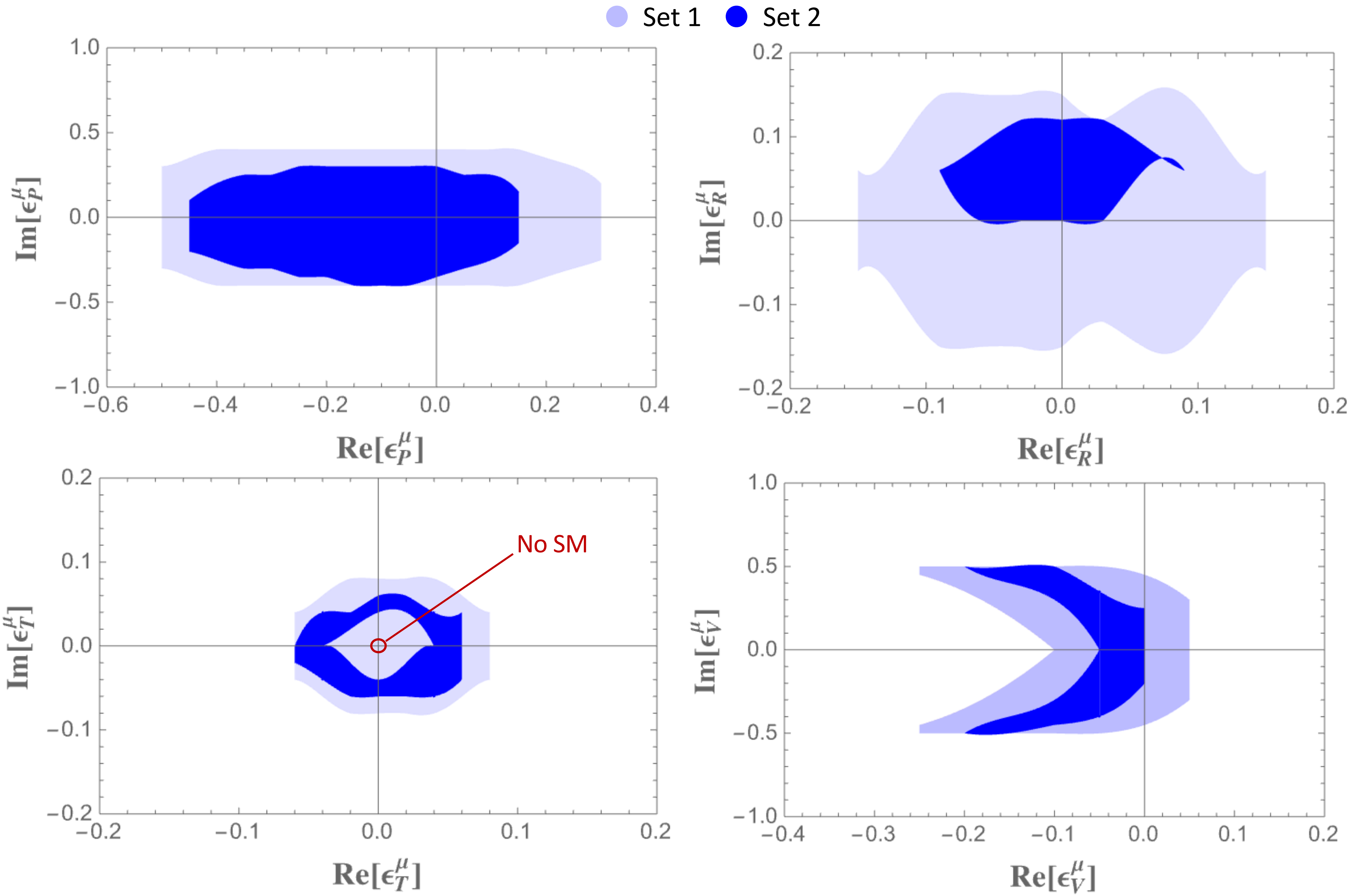
↓

2° constraint

$$\chi^2_{red} = \frac{1}{\nu}\sum_{i,a}\left(\left(\hat{J}_i^a\right)_{int}^{th} - \left(\hat{J}_i^a\right)_{int}^{exp}\right)^2 / (\sigma_i^a)^2 \leq 1.875$$

↓

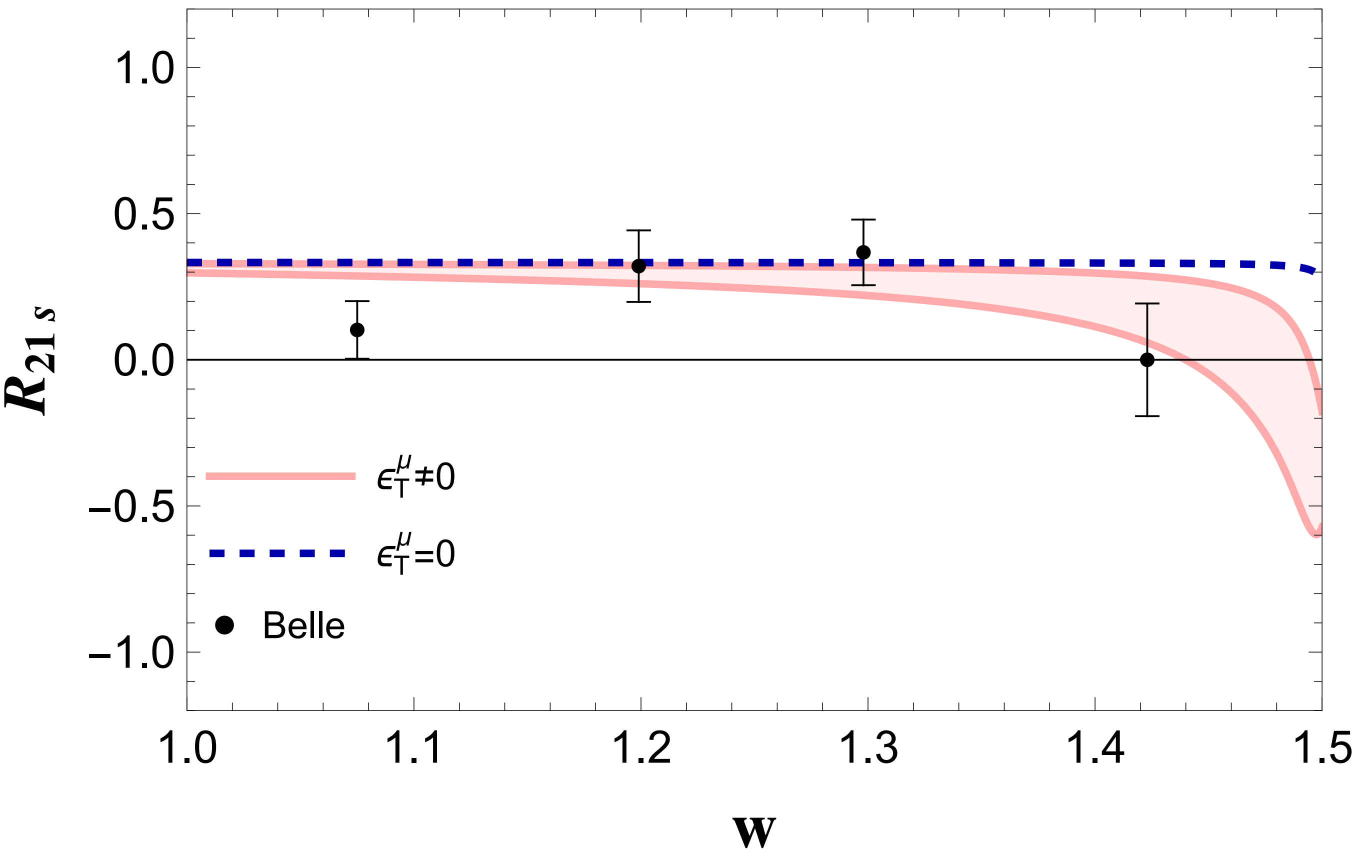
Set 2 $\epsilon_V^\mu, \epsilon_R^\mu, \epsilon_p^\mu, \epsilon_T^\mu$


Set 1
Set 2
1.0
0.5
0.0
−0.5
−1.0
−0.6
−0.4
−0.2
0.0
0.2
0.4
$Im[\epsilon_P^\mu]$
$Re[\epsilon_P^\mu]$
0.2
0.1
0.0
−0.1
−0.2
−0.2
−0.1
0.0
0.1
0.2
$Im[\epsilon_R^\mu]$
$Re[\epsilon_R^\mu]$
No SM
0.2
0.1
0.0
−0.1
−0.2
−0.2
−0.1
0.0
0.1
0.2
$Im[\epsilon_T^\mu]$
$Re[\epsilon_T^\mu]$
1.0
0.5
0.0
−0.5
−1.0
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
$Im[\epsilon_V^\mu]$
$Re[\epsilon_V^\mu]$

Observables

$$R_{21s}(w) = \frac{\hat{J}_{2s}(w)}{\hat{J}_{1s}(w)}$$

Do NOT depend on ϵ_P



$\epsilon_T = 0$ → Insensitive to ϵ_V and ϵ_R

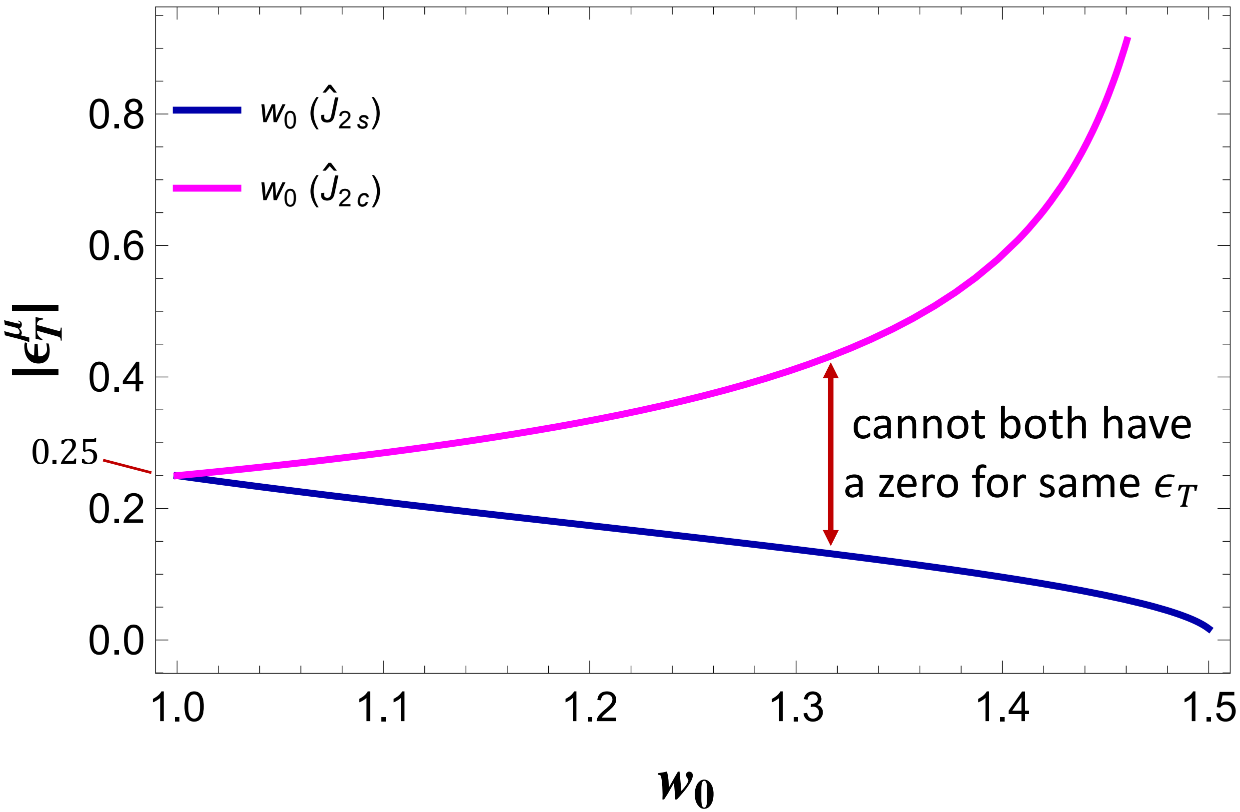
↓

Different behaviours imply presence of tensor operator

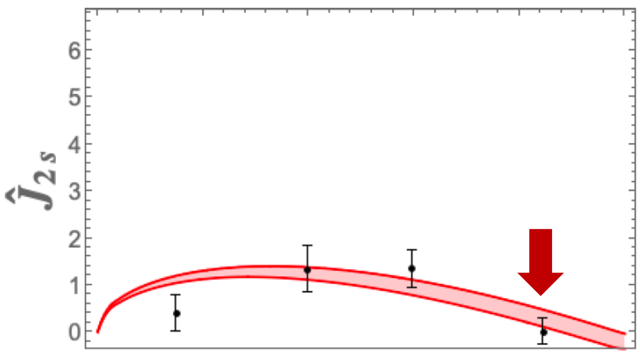
Observables

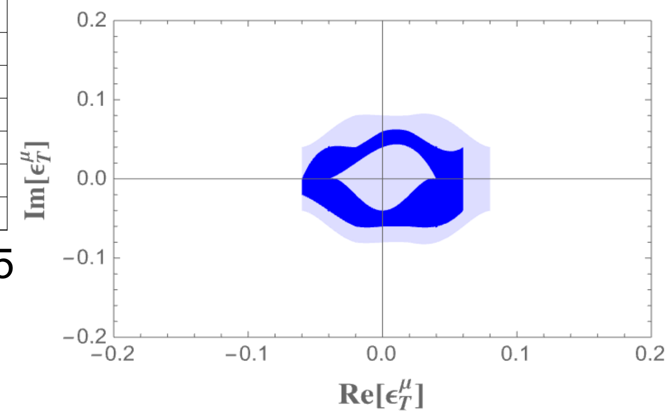
$w_0\ (\hat{J}_i)$ = Zero of the J_i angular coefficient function

$\epsilon_V = \epsilon_R = 0$



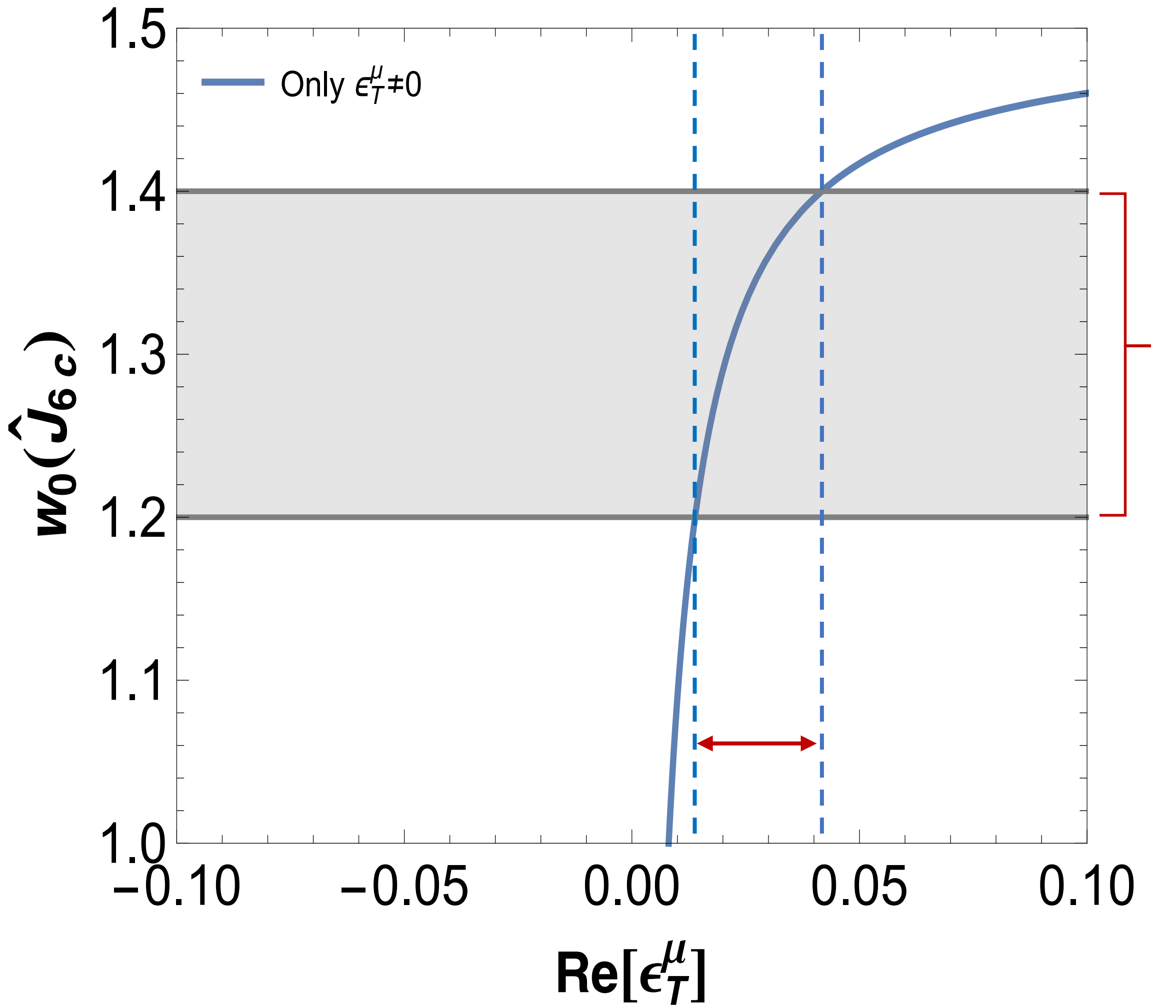
Belle results compatible with the presence of a zero in $\hat{J}_{2s}$





Observables

$\epsilon_V = \epsilon_R = \epsilon_P = 0$ ➡ J_{6c}: $\sqrt{q^2} H_L^{\rm NP}(q^2) {\rm Re}[\epsilon_T] - 4 m_\ell H_0(q^2) = 0$



Range compatible with Belle results

⬇

Small values of $Re[\epsilon_T]$

⬇

Compatible with $\hat{J}_{2s}$ zeros

B_c meson

$c\bar{b}$ system

↓

Heavy quarkonium
with open flavour

↓

NO annihilation into gluons

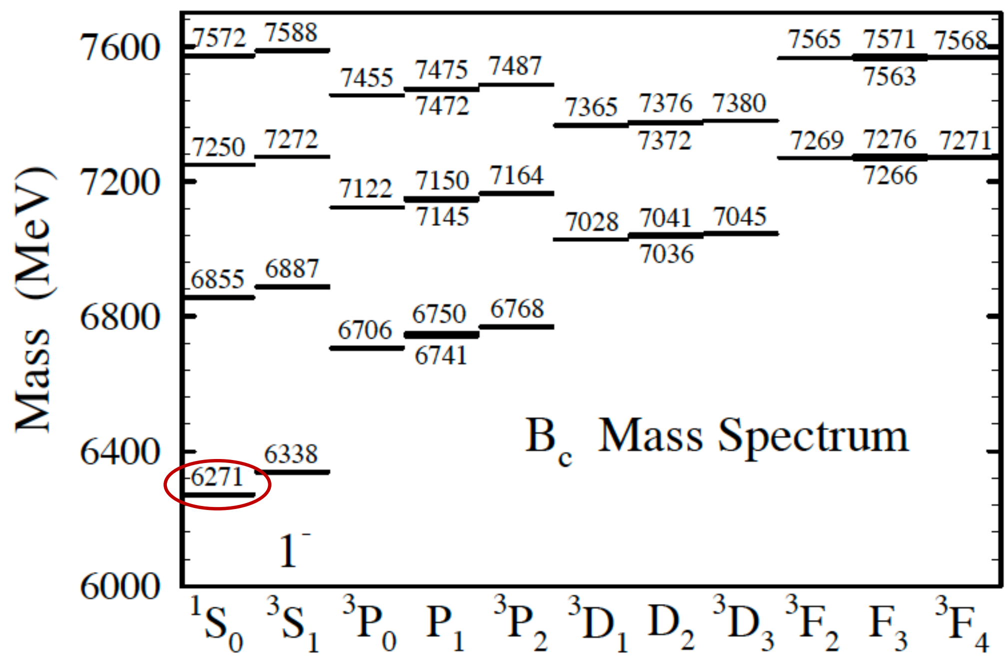
↓

Stable with widths less
than a hundred keV

↓

Only decays weakly

Relativistic quark model predictions



Semileptonic B_c meson decays

Effective Hamiltonian for the process $b \to c\, \ell\, \bar{\nu}_\ell$ (same as in previous study)

$$H_{eff}^{b\to c\,\ell\,\bar{\nu}_\ell} = \frac{G_F}{\sqrt{2}} V_{cb}[(1+\epsilon_V^\ell)(\bar{c}\gamma_\mu(1-\gamma_5)b)(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell) \quad \text{— SM}$$

$$+\epsilon_R^\ell\left(\bar{c}\gamma_\mu(1+\gamma_5)b\right)\left(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right) + \epsilon_S^\ell(\bar{c}b)\left(\bar{\ell}(1-\gamma_5)\nu_\ell\right)$$

$$+\epsilon_P^\ell(\bar{c}\gamma_5 b)(\bar{\ell}(1-\gamma_5)\nu_\ell) + \epsilon_T^\ell(\bar{c}\sigma_{\mu\nu}(1-\gamma_5)b)(\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell)] \quad \text{BSM}$$

The matrix elements of these operators parametrized through hadronic form factors

Example I:

$$\langle V(p',\epsilon)|\bar{Q}'\gamma_\mu Q|B_c(p)\rangle = -\frac{2V^{B_c\to V}(q^2)}{m_{B_c}+m_V}\, i\,\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p^\alpha p'^\beta$$

Example II:

$$\langle V(p',\epsilon)|\bar{Q}'\sigma_{\mu\nu}Q|B_c(p)\rangle = T_0^{B_c\to V}(q^2)\frac{\epsilon^*\cdot q}{(m_{B_c}+m_V)^2}\,\epsilon_{\mu\nu\alpha\beta}p^\alpha p'^\beta$$

$$+T_1^{B_c\to V}(q^2)\,\epsilon_{\mu\nu\alpha\beta}p^\alpha\epsilon^{*\beta} + T_2^{B_c\to V}(q^2)\,\epsilon_{\mu\nu\alpha\beta}p'^\alpha\epsilon^{*\beta}$$

Semileptonic B_c decays

Two energy scales: m_b and m_c → Expansion of the heavy quark field in $1/m_Q$

A.F. Falk and M. Neubert, Phys. Rev. D 47 (1993) 2965

Heavy quark expansion

Positive energy component of the field

$$Q(x) = e^{-im_Q v\cdot x}\left(1 + \sum_{n=0}^{\infty}\left(-\frac{iv\cdot D}{2m_Q}\right)^n i\not{D}_\perp\right)\psi_+(x)$$

v 4-velocity of the meson containing the heavy quark

$$p = m_{B_c} v \qquad p' = m_{J/\psi(\eta_c)} v'$$

NRQCD suitable for the description of the dynamic of mesons with two heavy quaks → Power counting using $\tilde{v}$, relative velocity of the heavy quarks → $D \sim \tilde{v}^2$, $D_\perp \sim \tilde{v}$

G.P. Lepage, L. Magnea, C. Nakhleh, U. Magnea and K. Hornbostel, Phys. Rev. D 46 (1992) 4052

Semileptonic B_c decays

Spin interaction terms suppressed by powers of in $1/m_Q$ → Heavy quark spin symmetry manifests

The heavy quark spin symmetry allows us to parametrize the current matrix elements using universal functions near the zero recoil point $w = 1$

$$\langle M'(v')| J_0 |M(v)\rangle = -\Delta(w)\mathrm{Tr}\left[\bar{H}'(v')\Gamma H(v)\right]$$

Leading order term of the current expansion

$$w = v \cdot v' = \frac{m_M^2 + m_{M'}^2 - q^2}{2m_M m_{M'}}$$

$H'(v')$ and $H(v)$ 4×4 matrix describing the mesons that differ only by the quark spins orientation

$$(B_c, B_c^*) \qquad H(v) = \frac{1+\not{v}}{2}\left[B_c^{*\mu}\gamma_\mu - B_c\gamma_5\right]\frac{1-\not{v}}{2}$$

$$(\eta_c, J/\psi) \qquad H'(v') = \frac{1+\not{v}'}{2}\left[\Psi_c^{*\mu}\gamma_\mu - \eta_c\gamma_5\right]\frac{1-\not{v}'}{2}$$

$B_c \to J/\psi(\eta_c)\ell\,\bar{\nu}$

- Relations between form factors

P. Colangelo, F. De Fazio, F. Loparco, M. Novoa-Brunet, N. L, JHEP 09 (2022) 028

- Universal functions

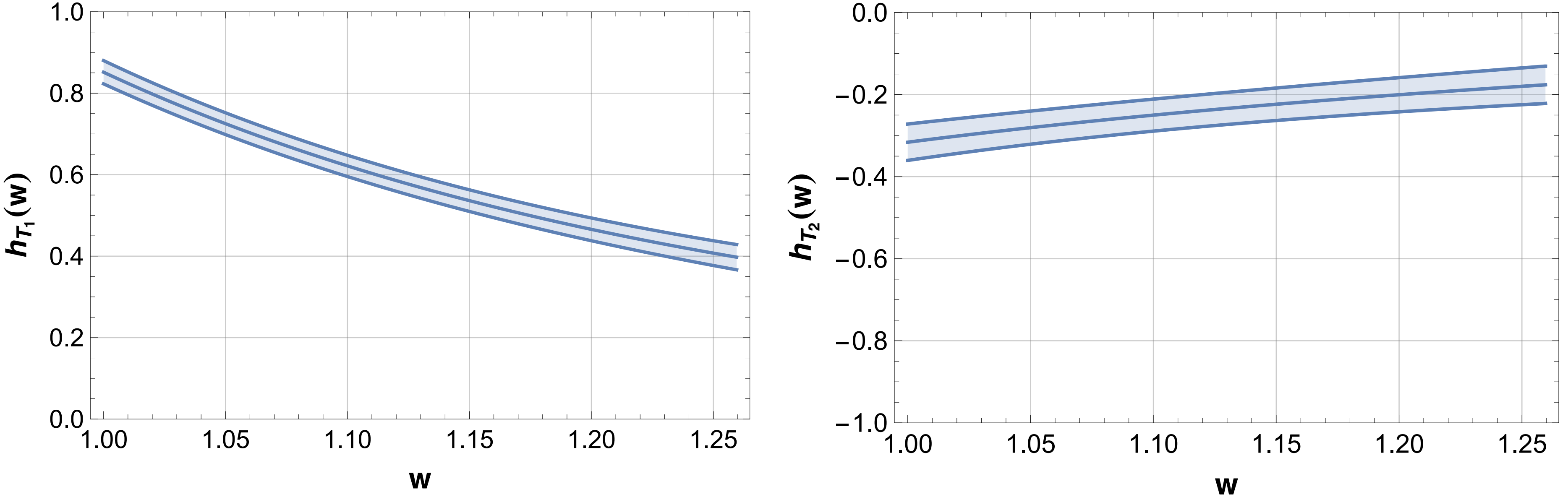
Form factors validity test

Form factors evaluation from known ones, e.g. from lattice QCD

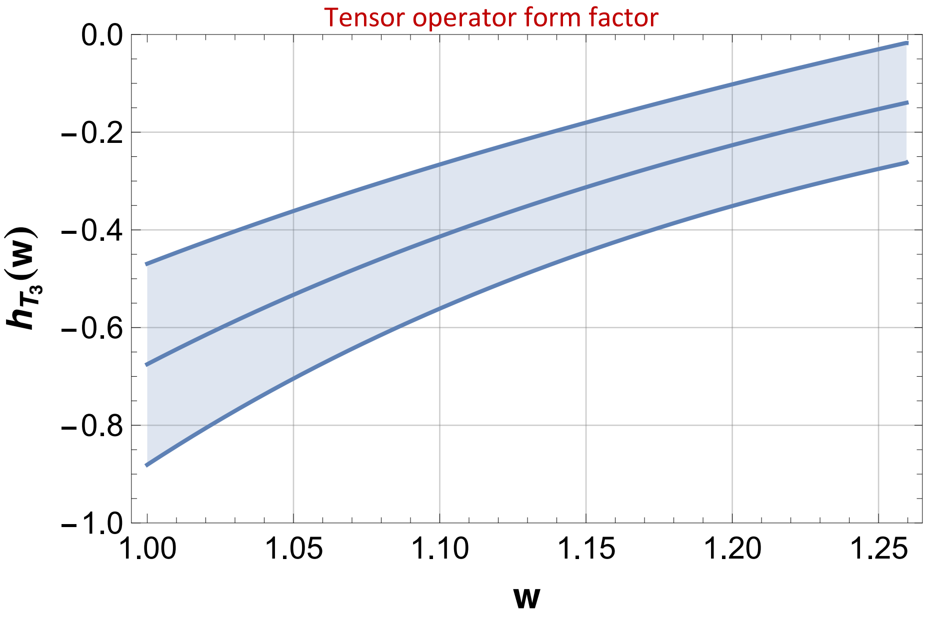
HPQCD collaboration, Phys. Rev. D 102 (2020) 094518

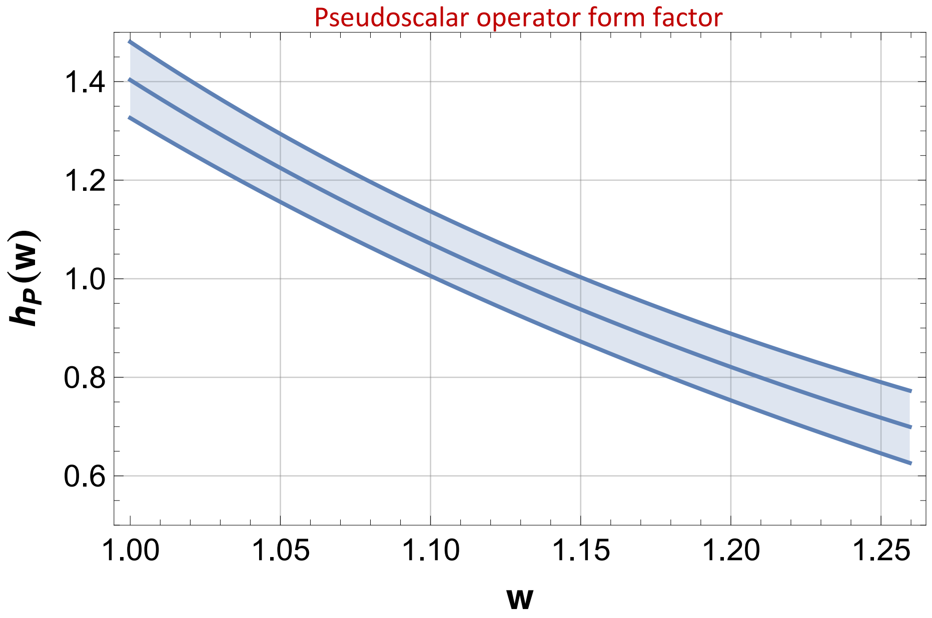
- $B_c \to J/\psi$

Tensor operator form factor

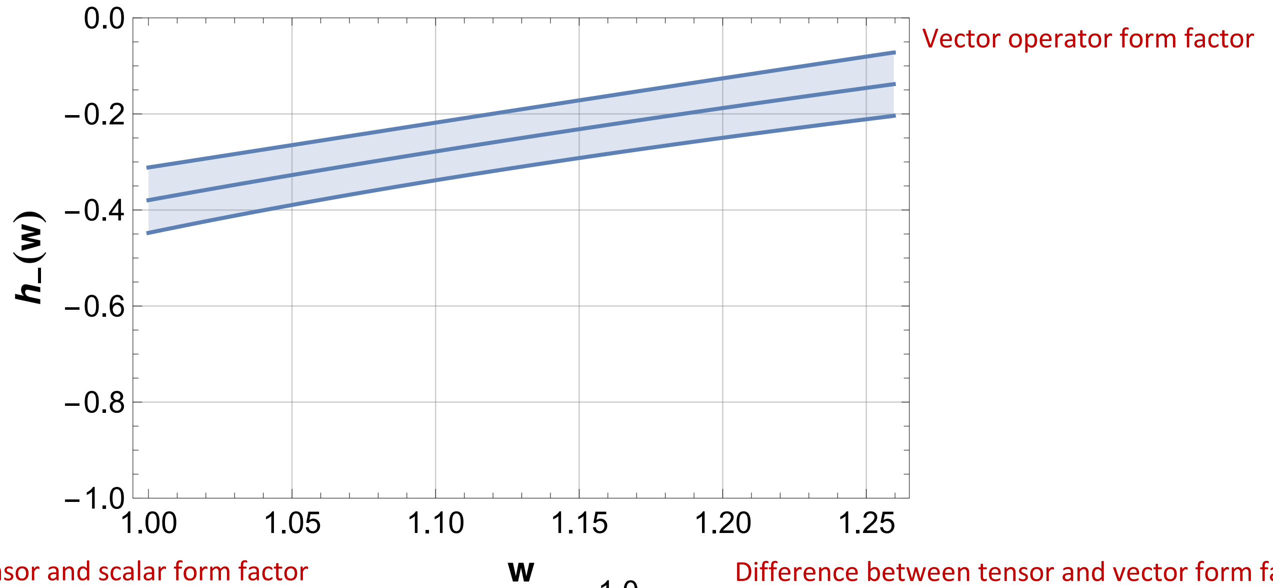


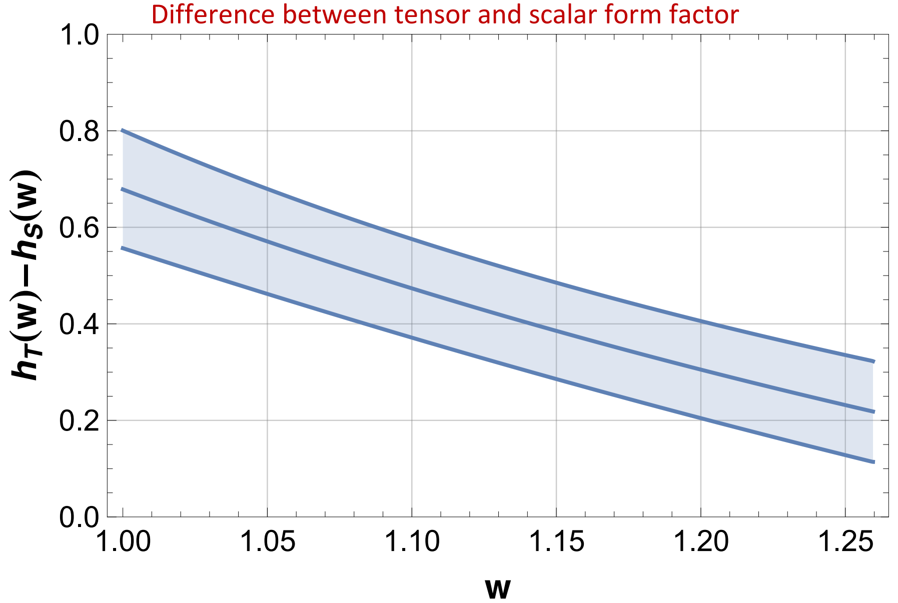
$B_c \to J/\psi(\eta_c)\ell\,\bar{\nu}$

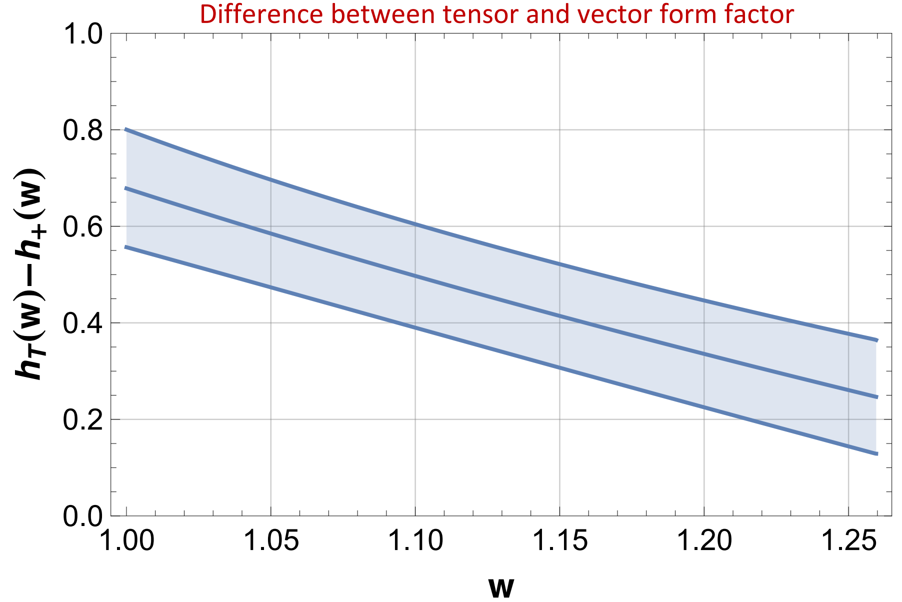




- $B_c \to \eta_c$


Vector operator form factor
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
h_(w)
1.00
1.05
1.10
1.15
1.20
1.25
w


Difference between tensor and scalar form factor
1.0
0.8
0.6
0.4
0.2
0.0
hT(w)−hS(w)
1.00
1.05
1.10
1.15
1.20
1.25
w


Difference between tensor and vector form factor
1.0
0.8
0.6
0.4
0.2
0.0
hT(w)−h+(w)
1.00
1.05
1.10
1.15
1.20
1.25
w

$B_c \to \chi_{cJ}(h_c)\ell\,\bar{\nu}$

The formalism can be applied to the transition

P. Colangelo, F. De Fazio, F. Loparco, M. Novoa-Brunet, N.L., Phys. Rev. D 106 (2022), no. 9 094005

$$B_c \to \chi_{cJ}(h_c)\ell\bar{\nu}$$

Positive parity orbitally excited charmonium system

P-wave charmonium $(\chi_{c0}, \chi_{c1}, \chi_{c2}, h_c)$ fields

$$\mathcal{M}^\mu(v') = \frac{1+\not{v}'}{2}\left[\chi_{c2}^{\mu\nu}\gamma_\nu + \frac{1}{\sqrt{2}}\chi_{c1,\gamma}\epsilon^{\mu\alpha\beta\gamma}v'_\alpha\gamma_\beta + \frac{1}{\sqrt{3}}\chi_{c0}(\gamma^\mu - v'^\mu) + h_c^\mu\gamma_5\right]\frac{1-\not{v}'}{2}$$

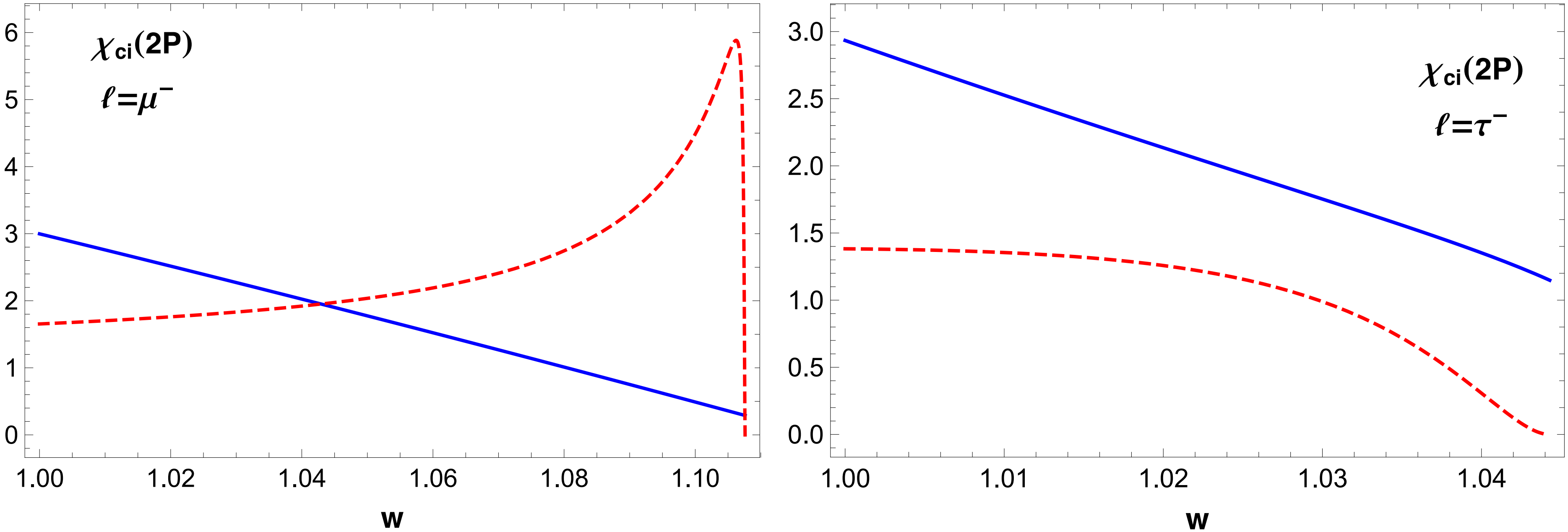
R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, and G. Nardulli, Phys. Lett. B 309, 163 (1993)

The obtained relations can be applied to the radial excitations → Useful to obtain information on the structure of $\chi_{c1}(3872)$ $J^{PC} = 1^{++}$

- $X(3872)$: tetraquark, molecular state
- $\chi_{c1}(2P)$: radial excitation of the P-wave charmonium

$B_c \to \chi_{cJ}(h_c)\ell\,\bar{\nu}$

Ratios $\frac{d\Gamma(B_c\to\chi_{c1}\ell\bar{\nu})/dw}{d\Gamma(B_c\to\chi_{c0}\ell\bar{\nu})/dw}$ and $\frac{d\Gamma(B_c\to\chi_{c2}\ell\bar{\nu})/dw}{d\Gamma(B_c\to\chi_{c1}\ell\bar{\nu})/dw}$ in the hypothesis that $\chi_{c1}(3872)$ is the $2P$ state

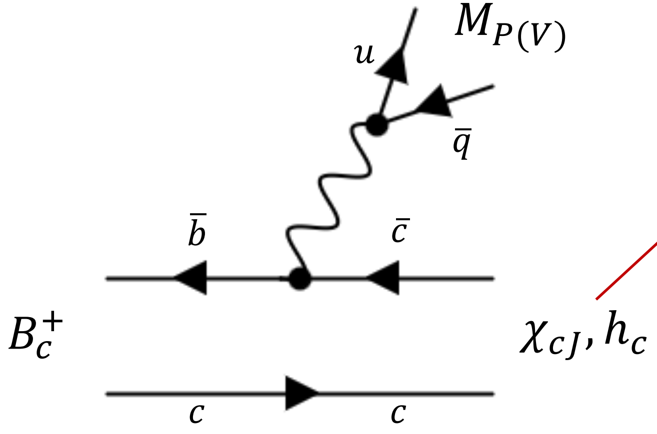


Deviations → Exotic structure of the $\chi_{c1}(3872)$ state?

HQ symmetry inaccurate? → Check the other predictions

Nonleptonic B_c decays to P-wave charmonia

Focus on $B_c^+ \to \chi_{cJ}(h_c)\, M_{P(V)}$ → further probe of the structure of $\chi_{c1}(3872)$



Positive parity charmonium states

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{uq} \left(C_1(\mu) Q_1(\mu) + C_2(\mu) Q_2(\mu) \right) + \text{h.c.}$$

$$Q_1 = \bar{u}_\alpha \gamma^\mu (1-\gamma_5) q_\alpha \bar{b}_\beta \gamma_\mu (1-\gamma_5) c_\beta \qquad Q_2 = \bar{u}_\alpha \gamma^\mu (1-\gamma_5) q_\beta \bar{b}_\beta \gamma_\mu (1-\gamma_5) c_\alpha$$

After Fierz transformation and discarding color-octect operator

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{uq} a_1(\mu) Q_1(\mu)$$

Nonleptonic B_c decays to P-wave charmonia

$$\mathcal{A}(B_c^+ \to M_{c\bar{c}}(P)\, M_{P(V)}) = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{uq} a_1(\mu) \langle M_{c\bar{c}}(P)| \bar{b}\gamma_\mu(1-\gamma_5)c\, |B_c^+\rangle \langle M_{P(V)}| \bar{u}\gamma^\mu(1-\gamma_5)q\, |0\rangle$$

Application of QCD factorization to nonleptonic decays → Decay amplitude depends on form factors and decay constants

$B_c \to \chi_{cJ}(h_c)\, M$

M light pseudoscalar or vector meson

Pseudoscalar case (π^+, K^+):

$$f_0^{\chi_{c0}}(q^2) = -\frac{((m_{B_c}-m_{\chi_{c0}})^2-q^2)((m_{B_c}+m_{\chi_{c0}})^2-q^2)}{4\sqrt{3}(m_{B_c}-m_{\chi_{c0}})(m_{B_c}m_{\chi_{c0}})^{3/2}}\Xi(q^2),$$

$$A_0^{\chi_{c1}}(q^2) = 0,$$

$$A_0^{h_c}(q^2) = -i\frac{(m_{B_c}-m_{h_c})((m_{B_c}+m_{h_c})^2)-q^2)}{4(m_{B_c}m_{h_c})^{3/2}}\Xi(q^2),$$

$$A_0^{\chi_{c2}}(q^2) = i\frac{m_{B_c}+m_{\chi_{c2}}}{2\sqrt{m_{B_c}m_{\chi_{c2}}}}\Xi(q^2),$$

Vector case (ρ^+, K^{*+}):

$$f_+^{\chi_{c0}}(q^2) = -\frac{((m_{B_c}+m_{\chi_{c0}})^2-q^2)(m_{B_c}-m_{\chi_{c0}})}{4\sqrt{3}(m_{B_c}m_{\chi_{c0}})^{3/2}}\Xi(q^2),$$

$$V^{\chi_{c1}}(q^2) = -\frac{((m_{B_c}+m_{\chi_{c1}})^2-q^2)(m_{B_c}+m_{\chi_{c1}})}{4\sqrt{2}(m_{B_c}m_{\chi_{c1}})^{3/2}}\Xi(q^2),$$

$$A_1^{\chi_{c1}}(q^2) = -\frac{m_{B_c}^4+(m_{\chi_{c1}}-q^2)^2-2m_{B_c}^2(m_{\chi_{c1}}^2+q^2)}{4\sqrt{2}(m_{B_c}m_{\chi_{c1}})^{3/2}(m_{B_c}+m_{\chi_{c1}})}\Xi(q^2),$$

$$A_2^{\chi_{c1}}(q^2) = \frac{(m_{B_c}^2-m_{\chi_{c1}}^2-q^2)(m_{B_c}+m_{\chi_{c1}})}{4\sqrt{2}(m_{B_c}m_{\chi_{c1}})^{3/2}}\Xi(q^2),$$

$$V^{\chi_{c2}}(q^2) = \frac{m_{B_c}+m_{\chi_{c2}}}{2\sqrt{m_{B_c}m_{\chi_{c2}}}}\Xi(q^2), \quad A_1^{\chi_{c2}}(q^2) = i\frac{((m_{B_c}+m_{\chi_{c2}})^2-q^2)}{2\sqrt{m_{B_c}m_{\chi_{c2}}}(m_{B_c}+m_{\chi_{c2}})}\Xi(q^2),$$

$$A_2^{\chi_{c2}}(q^2) = i\frac{m_{B_c}+m_{\chi_{c2}}}{2\sqrt{m_{B_c}m_{\chi_{c2}}}}\Xi(q^2),$$

$$V^{h_c}(q^2) = 0,$$

$$A_1^{h_c}(q^2) = 0,$$

$$A_2^{h_c}(q^2) = i\frac{m_{h_c}(m_{B_c}+m_{h_c})^2}{2(m_{B_c}m_{h_c})^{3/2}}\Xi(q^2).$$

Nonleptonic B_c decays to P-wave charmonia

Predictions on ratios of branching fractions

N. L., Mod. Phys. Lett. A 38 (2023), no. 04 2350027

	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}\,\pi^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,\pi^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,\pi^+)}{\mathcal{B}(B_c^+\to\chi_{c0}\,\pi^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,\pi^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,\pi^+)}$
$1P$	0.658	2.429	1.597
$2P$	0.583	2.746	1.601

	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,K^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c0}\,K^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,K^+)}$
$1P$	0.663	2.482	1.645
$2P$	0.586	2.845	1.668

	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}\rho^+)}{\mathcal{B}(B_c^+\to\chi_{c0}\rho^+)}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}\rho^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\rho^+)}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}\rho^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\rho^+)}$
$1P$	0.206	0.122	0.590
$2P$	0.315	0.159	0.503
	$\frac{\mathcal{B}(B_c^+\to h_c\rho^+)}{\mathcal{B}(B_c^+\to\chi_{c0}\rho^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\rho^+)}{\mathcal{B}(B_c^+\to\chi_{c1}\rho^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\rho^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\rho^+)}$
$1P$	2.226	10.790	1.312
$2P$	2.449	7.770	1.232

	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$
$1P$	0.276	0.157	0.570
$2P$	0.422	0.203	0.481
	$\frac{\mathcal{B}(B_c^+\to h_cK^{*+})}{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to h_cK^{*+})}{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to h_cK^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$
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N. L., Mod. Phys. Lett. A 38 (2023), no. 04 2350027

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$1P$	0.658	2.429	1.597
$2P$	0.583	2.746	1.601

	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,K^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c0}\,K^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,K^+)}$
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	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$
$1P$	0.276	0.157	0.570
$2P$	0.422	0.203	0.481
	$\frac{\mathcal{B}(B_c^+\to h_cK^{*+})}{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to h_cK^{*+})}{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to h_cK^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$
$1P$	2.159	7.834	1.231
$2P$	2.350	5.568	1.131

χ_{c1} state suppressed → If $\chi_{c1}(3872)$ is NOT a pure charmonium state different hierarchy

Rare charm decays induced by $c \to u\,\gamma$ transition

Electromagnetic dipole operator

$$\mathcal{H}_{eff}^{c\to u\,\gamma} = 4\frac{G_F}{\sqrt{2}}\left(V_{cb}^{*}V_{ub}\left(C_1\mathcal{O}_1 + C_2\mathcal{O}_2\right) + C_7\mathcal{O}_7 + C_7'\mathcal{O}_7'\right)$$

$$\mathcal{O}_1 = \bar{u}_{L\alpha}\gamma^{\mu}b_{L\alpha}\bar{b}_{L\beta}\gamma_{\mu}c_{L\beta} \qquad \mathcal{O}_2 = \bar{u}_{L\alpha}\gamma^{\mu}b_{L\beta}\bar{b}_{L\beta}\gamma_{\mu}c_{L\alpha}$$

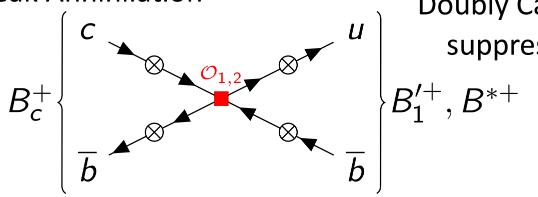
$$\mathcal{O}_7 = \frac{e}{16\,\pi^2}\,m_c\,\bar{u}_L\sigma^{\mu\nu}c_R F_{\mu\nu} \qquad \mathcal{O}_7' = \frac{e}{16\,\pi^2}\,m_c\,\bar{u}_R\sigma^{\mu\nu}c_L F_{\mu\nu}$$

Process analysed:

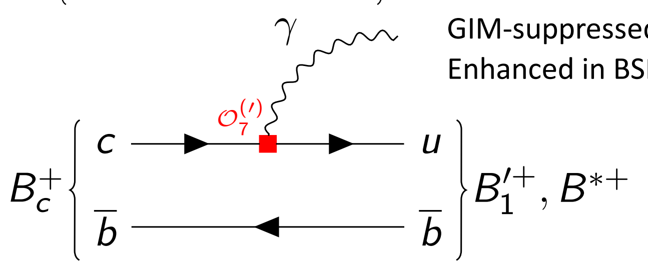
$B_c \to B'_1\gamma$ and $B_c \to B^*\gamma$

Short Distance Contributions

Weak Annihilation



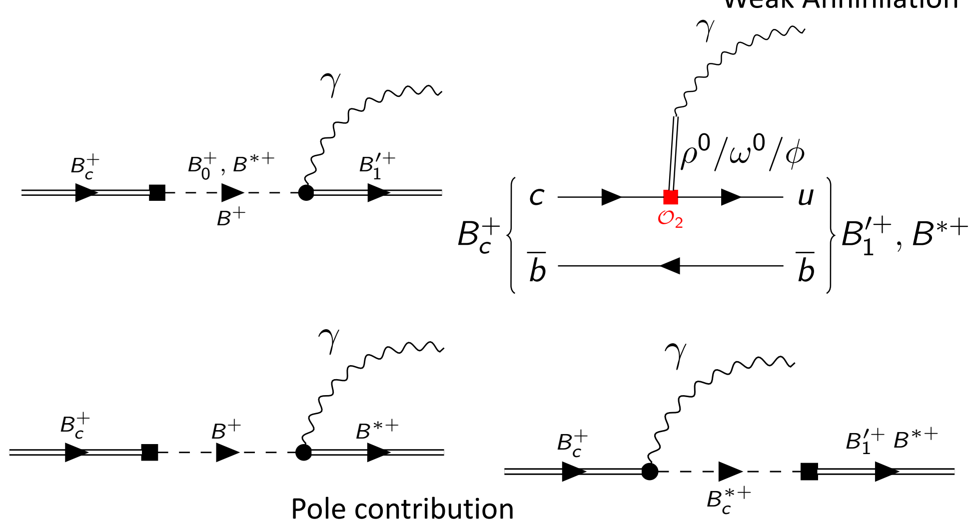
Doubly Cabibbo suppressed



GIM-suppressed in the SM
Enhanced in BSM

Long Distance Contributions

Weak Annihilation



Pole contribution

Rare charm decays induced by $c \to u\,\gamma$ transition

Amplitude for the transition $B_c(p) \to A(p', \epsilon)\,\gamma(q, \lambda)$

$$\mathcal{A}(B_c(p) \to B_1'(p', \epsilon)\gamma(q, \lambda)) = \left\{A_{PC}\left[p\cdot q g^{\alpha\beta} - q^\alpha p^\beta\right] + i A_{PV}\varepsilon^{\alpha\beta\mu\nu}p_\mu q_\nu\right\}\epsilon^*_\alpha \lambda^*_\beta$$

SD contribution:

$$A^{SD}_{PC} = i\frac{G_F}{(2\pi)^{3/2}}m_c\alpha^{1/2}(C_7^{eff} + C_7')(T_1'(0) + T_2'(0))$$

$$A^{SD}_{PV} = -i\frac{G_F}{(2\pi)^{3/2}}m_c\alpha^{1/2}(C_7^{eff} - C_7')(T_1'(0) + T_2'(0))$$

P. Colangelo, F. De Fazio, F. Loparco, PRD103 (2021) 075019

Heavy quark spin symmetry relates new physics form factors to SM ones through universal functions

Y.-J. Shi, W. Wang, and Z.-X. Zhao, Eur. Phys. J. C 76 (2016), no. 10 555

$$T_0'(q^2) = 2i\frac{(m_{B_c}+m_{B_1'})^2\sqrt{m_{B_1'}}}{m_{B_c}^{3/2}}a_0\,\Omega_2'$$

Hadronic suppression ➡

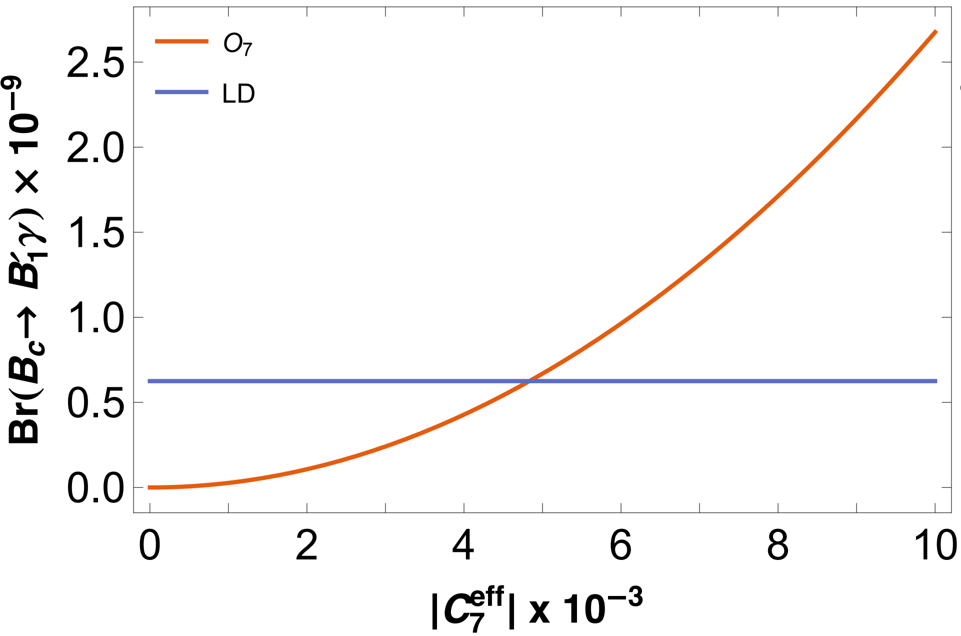
$$T_1'(q^2) = -\frac{m_{B_1'}}{m_{B_c}}T_2'(q^2)$$

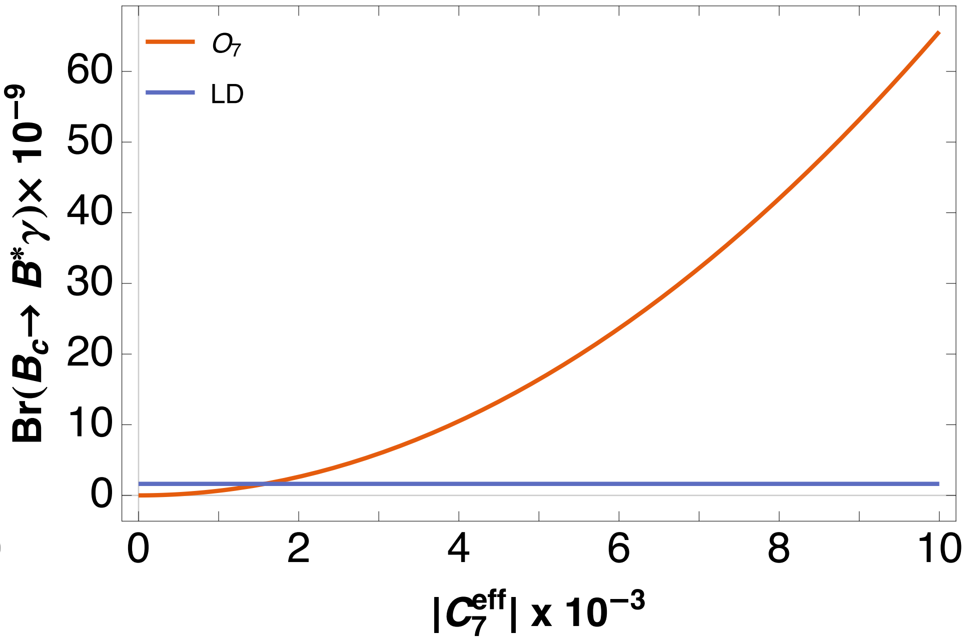
$$T_2'(q^2) = -i\sqrt{\frac{m_{B_c}}{m_{B_1'}}}\Omega_1'$$

Universal functions

Rare charm decays induced by $c \to u\, \gamma$ transition

LD vs SD contributions to branching ratios



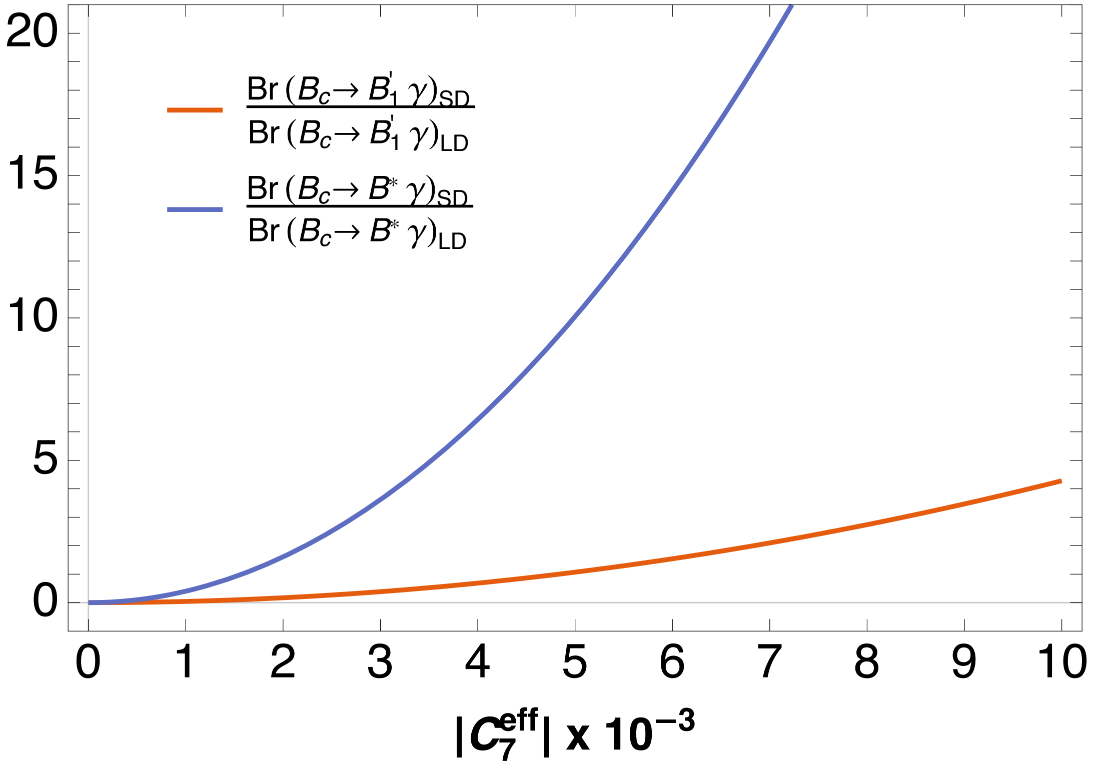


LD overwhelms SD for small $|C_7^{eff}|$

LD same order as SD for small $|C_7^{eff}|$

Rare charm decays induced by $c \to u\,\gamma$ transition

Ratio of branching fraction: LD vs SD contributions



NP better accessible in $B_c \to B^* \gamma$ channel

Overview

Research

- The Standard Model as an Effective Field Theory
- Tensions in the flavour sector
- Interplay between flavour physics and hadron spectroscopy
- Chaos and Holography

Dalitz decays of positive parity charmed mesons

Use Dalitz decays $D_{sJ}^{(*)} \to D_s^{(*)} \ell^+ \ell^-$ to probe the nature of D_{s0}^* and D_{s1}' ➡ complement the information from the electric dipole radiative decays $D_{s0}^* \to D_s^* \gamma,\, D_{s1}' \to D_s^{(*)} \gamma$

$c\bar{s}$ system composed of heavy-light quarks

Heavy degrees of freedom decouple ➡ Heavy quark spin $\vec{s}_Q$ and total angular momentum of the light degrees of freedom $\vec{s}_\ell$ separately conserved

heavy quark spin symmetry ➡ States classified in doublets

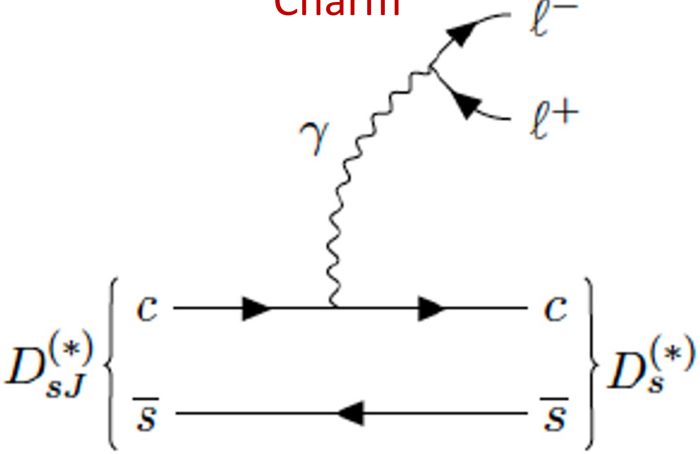
$$H_a = \frac{1+\slashed{v}}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5] \qquad (s_\ell^P = \frac{1}{2}^-) \qquad D_s, D_s^*$$

$$S_a = \frac{1+\slashed{v}}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right] \qquad (s_\ell^P = \frac{1}{2}^+) \qquad D_{s0}^*, D_{s1}'$$

$$T_a^\mu = \frac{1+\slashed{v}}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} \qquad (s_\ell^P = \frac{3}{2}^+) \qquad D_{s1}, D_{s2}^*$$

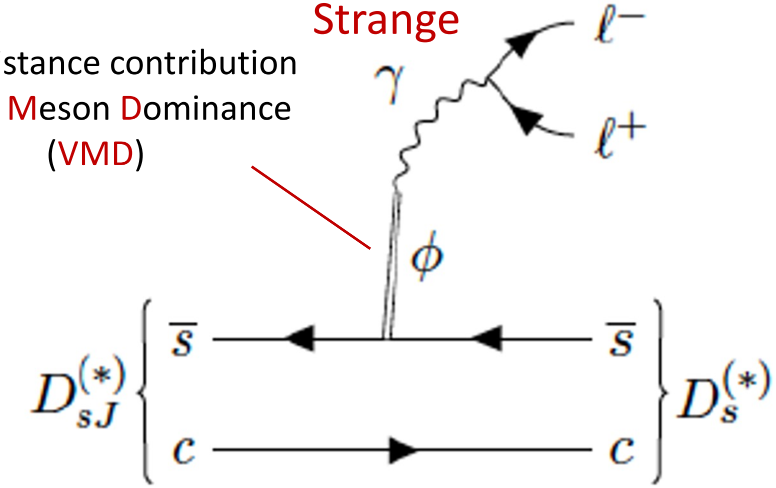
Dalitz decays of positive parity charmed mesons

Charm



Strange

Long distance contribution
Vector Meson Dominance
(VMD)



$$\mathcal{A}(D_{sJ}^{(*)}(p') \to D_s^{(*)}(p)\ell^-(p_1)\ell^+(p_2)) = \langle D_s^{(*)}(p,\epsilon)|iJ_\mu^{\rm em}|D_{sJ}^{(*)}(p',\epsilon')\rangle \frac{-ig^{\mu\nu}}{q^2}(-ie)\bar{u}(p_1)\gamma_\nu v(p_2)$$

$$J_\mu^{\rm em} = e\,(e_c\,\bar{c}\gamma_\mu c + e_s\,\bar{s}\gamma_\mu s)$$

Computed using heavy quark spin symmetry

$\tau_{1/2}$, $\tau_{3/2}$ universal functions

Effective Lagrangian constructed using

HQS + CS + HGI

Heavy Quark Symmetry

Chiral Symmetry

Hidden Gauge Invariance

g_1^S, g_2^S, h^T strong couplings

Dalitz decays of positive parity charmed mesons

Uncertainties from $\tau_{1/2}$, $\tau_{3/2}$ and g_1^S, g_2^S, h^T

g_1^S: from the semileptonic $D \to K^*$ form factor
Phys. Rept. 281 (1997) 145{238}

g_2^S: from light-cone QCD sum rule computation of the decay amplitude of the positive parity charmed mesons to real photons
Phys. Rev. D 72 (2005) 074004

h^T: from strong decay width of excited charmed mesons
Phys. Rev. D 98 (2018) 114028

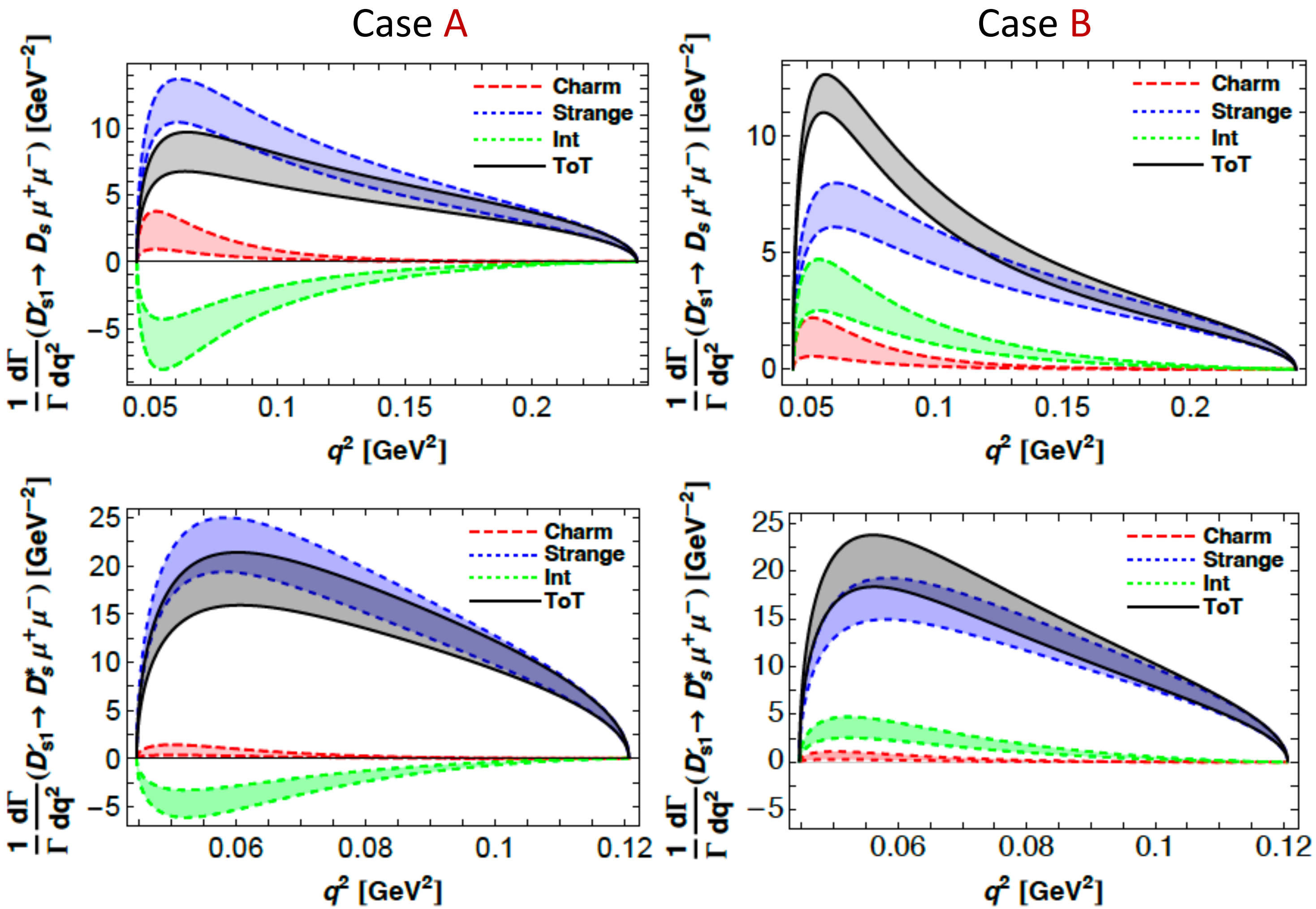
$\tau_{1/2}$, $\tau_{3/2}$: from semileptonic B decays to positive parity charmed mesons
Phys. Rev. D 58 (1998) 116005

Sign of interference not known ➡ Two extreme cases depending on the product between $\tau_{1/2}$, $\tau_{3/2}$ and g_1^S, g_2^S, h^T

Case A	Case B
POSITIVE	NEGATIVE

Dalitz decays of positive parity charmed mesons

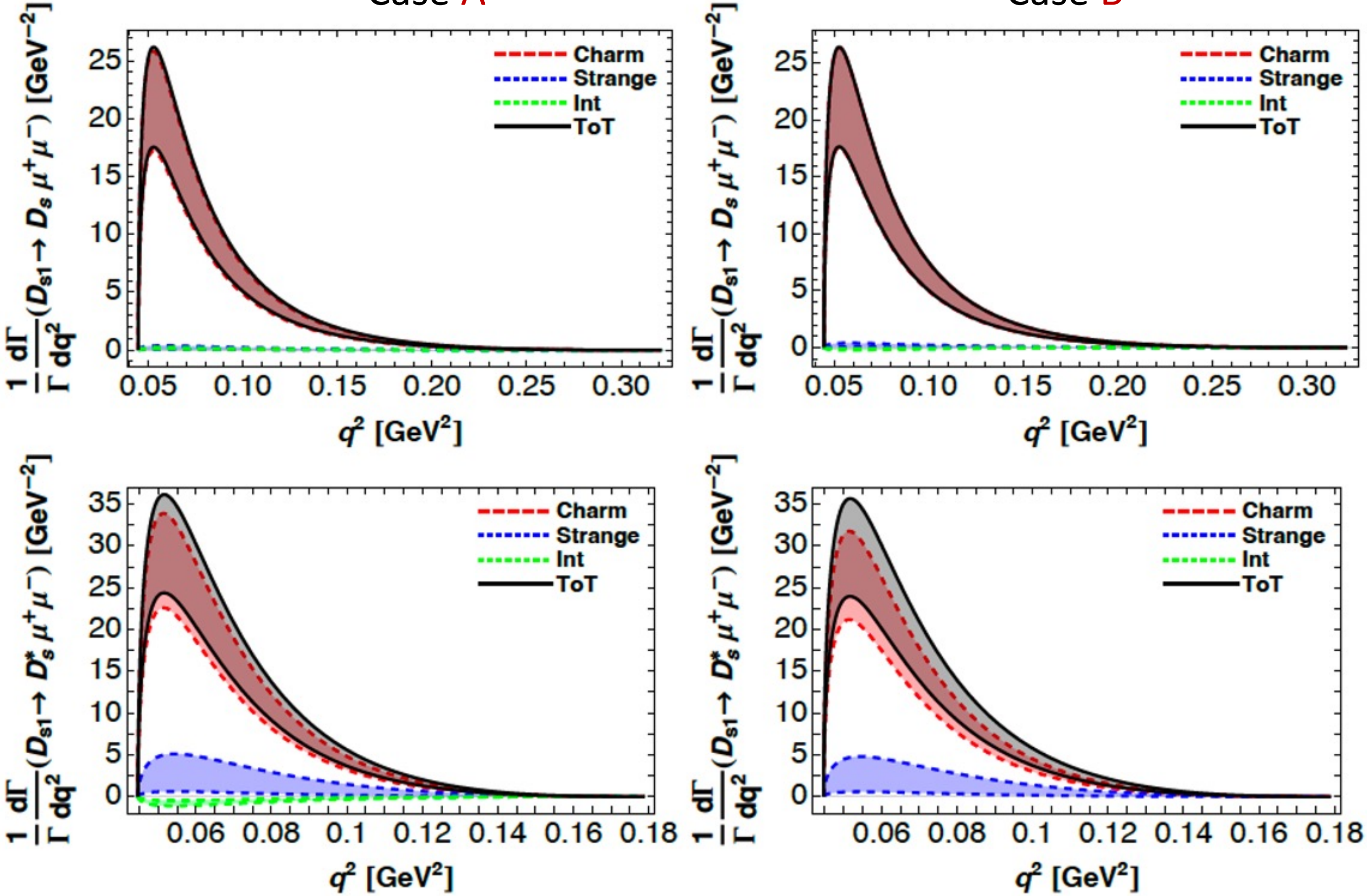
- $D'_{s1} \to D_s^{(*)} \mu^+ \mu^-$ P. Colangelo, F. De Fazio, F. Loparco, and N. L., Phys. Rev. D 108 (2023), no. 7 074027



Dalitz decays of positive parity charmed mesons

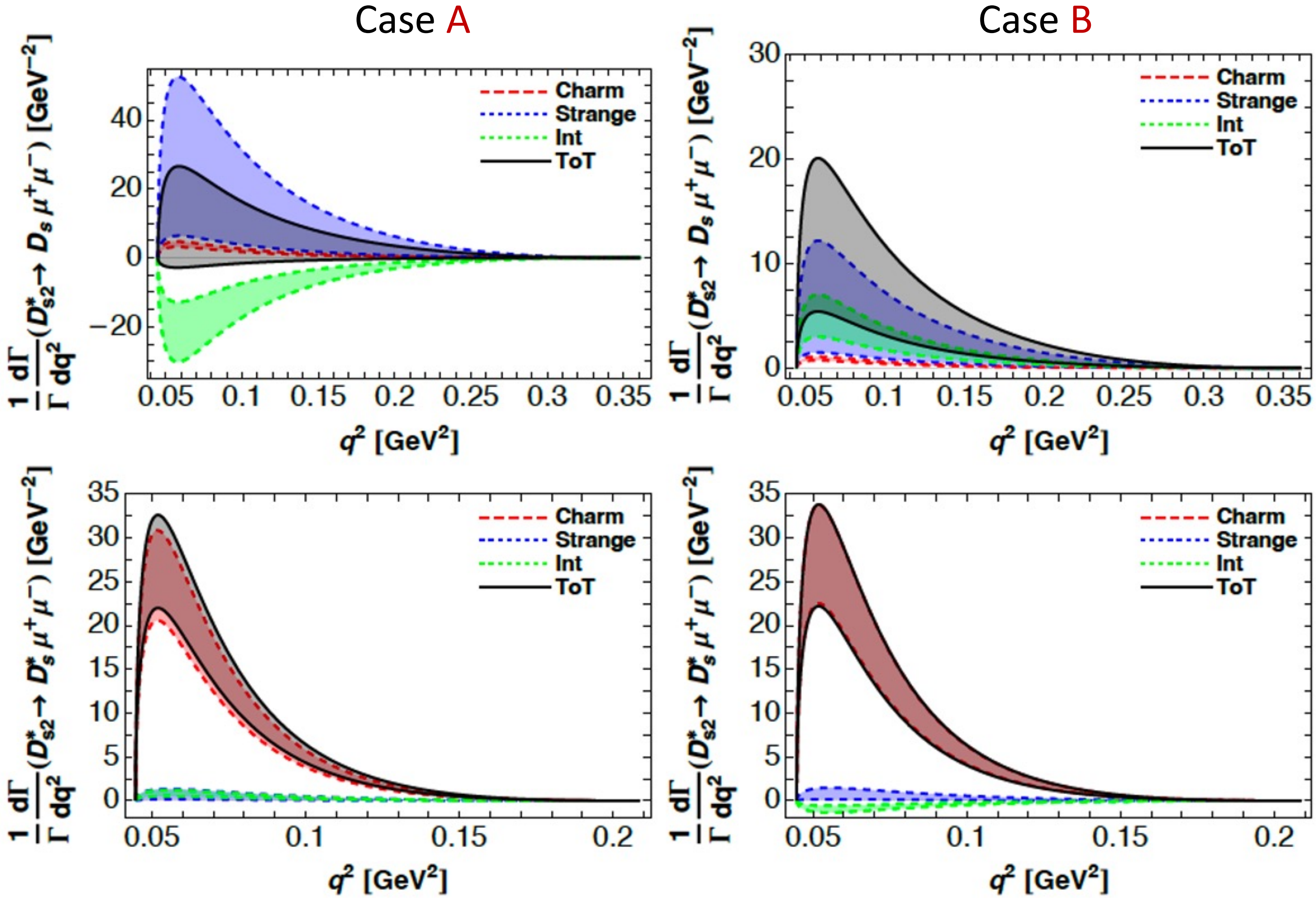
- $D_{s1} \to D_s^{(*)} \mu^+ \mu^-$

Case A | Case B



Dalitz decays of positive parity charmed mesons

- $D^*_{s2} \to D_s^{(*)}\, \mu^+\, \mu^-$



Dalitz decays of positive parity charmed mesons

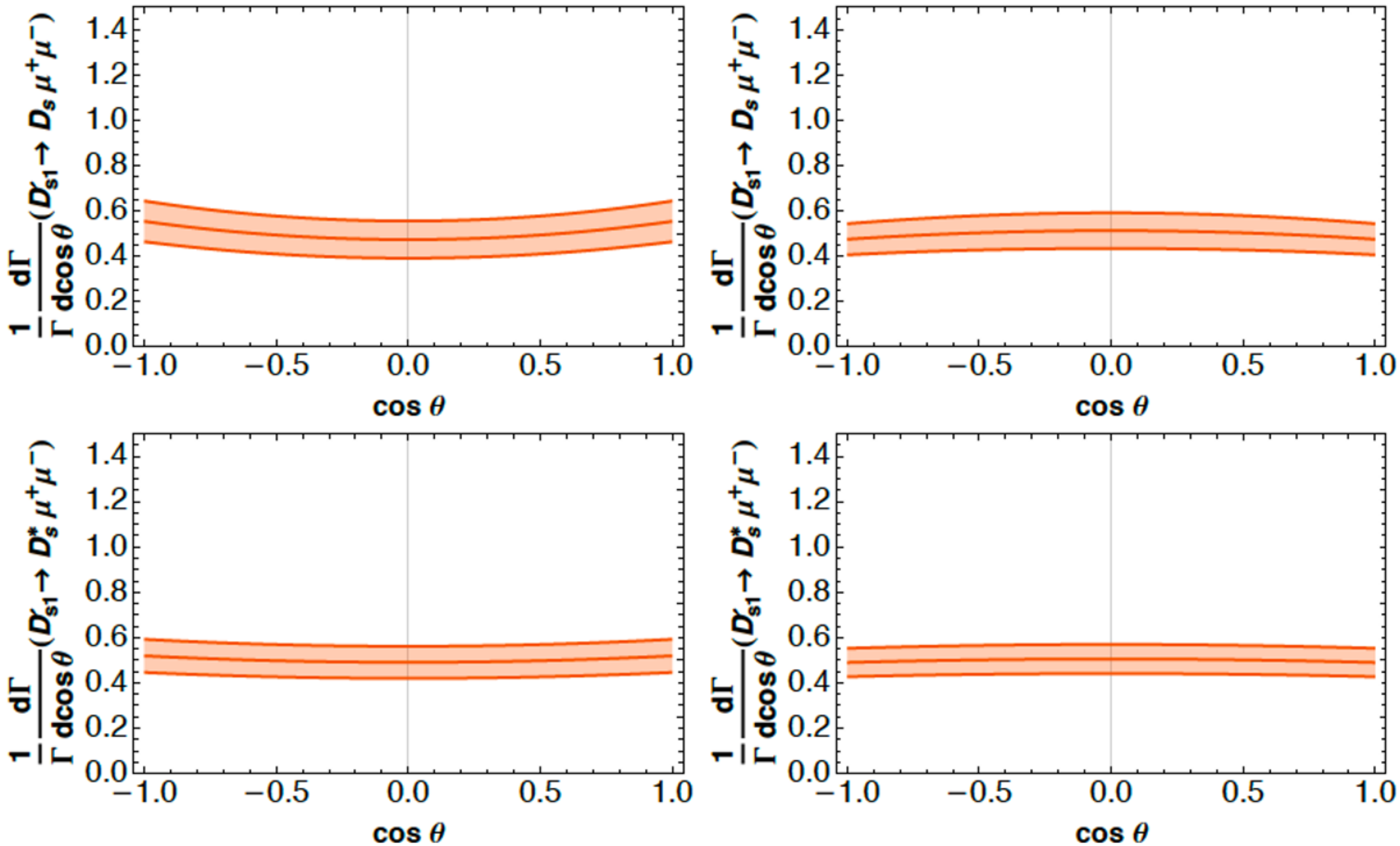
- $D'_{s1} \to D_s^{(*)} \mu^+ \mu^-$ **Angular Distribution**

$$\cos\theta = \frac{\vec{p}_1 \cdot \vec{p}}{|\vec{p}_1||\vec{p}|}$$

$\vec{p}_1$ = lepton momentum
$\vec{p}$ = $D_s^{(*)}$ momentum

Case A

Case B

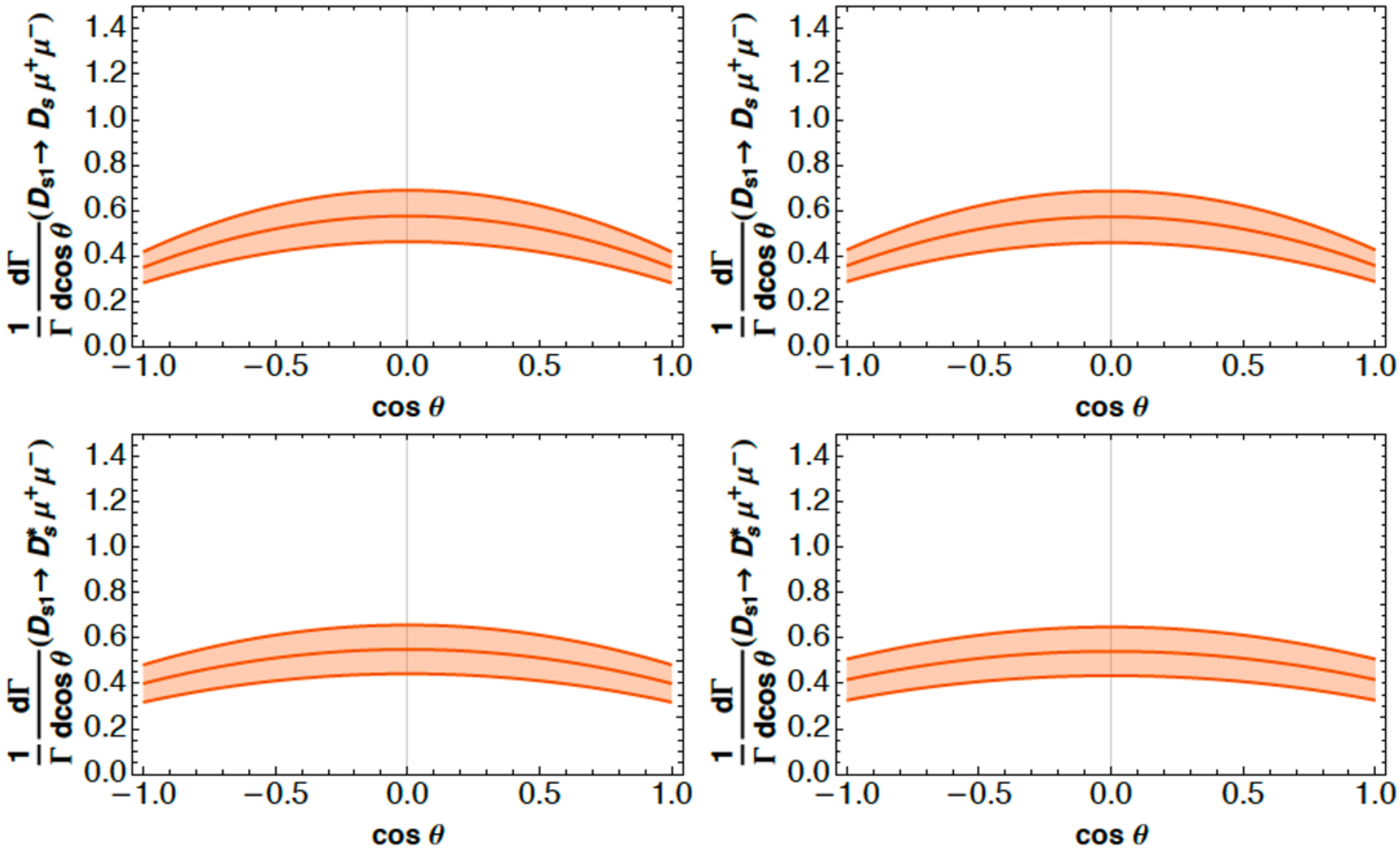


Dalitz decays of positive parity charmed mesons

- $D_{s1} \to D_s^{(*)} \mu^+ \mu^-$ **Angular Distribution**

Case A

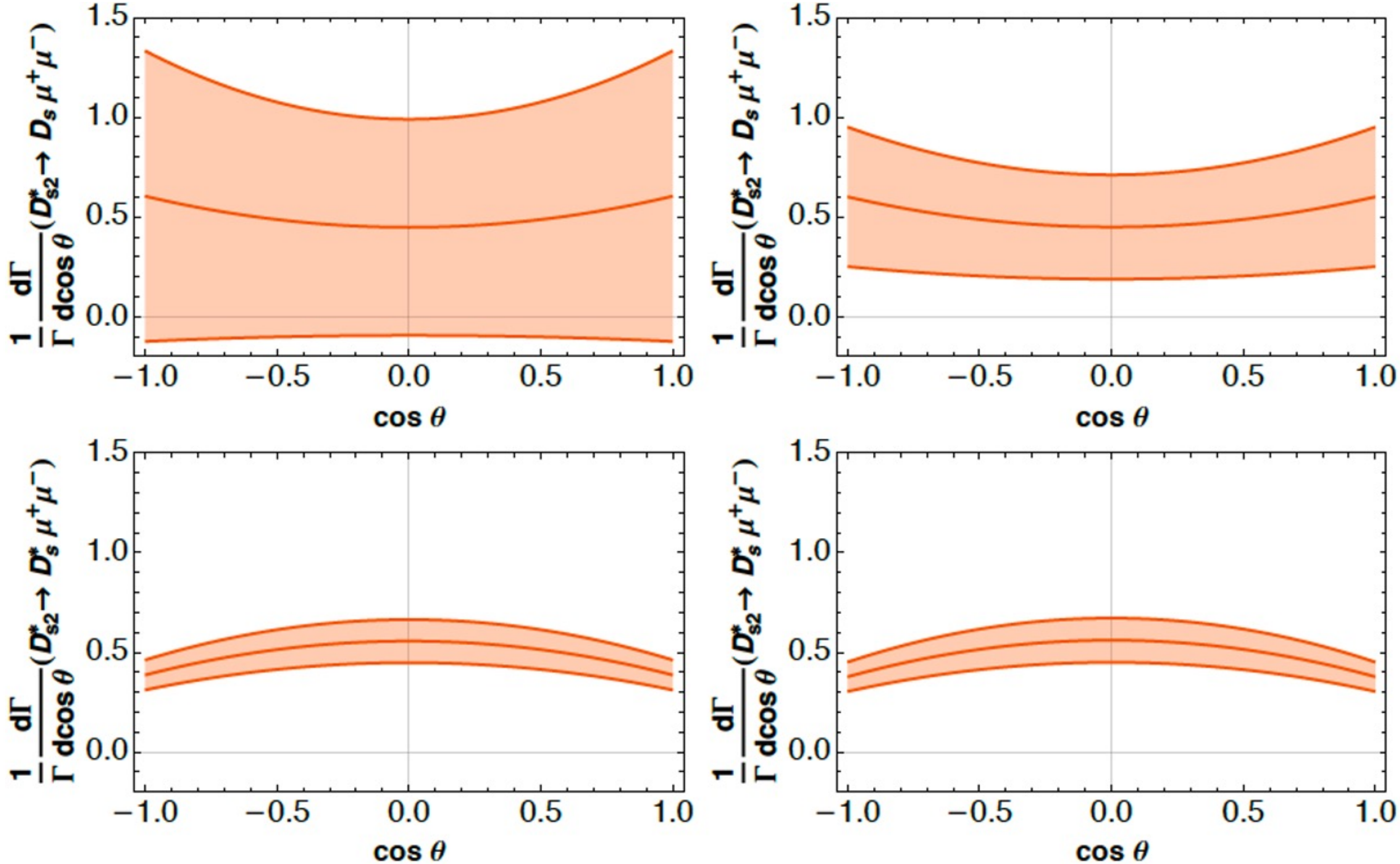
Case B



Dalitz decays of positive parity charmed mesons

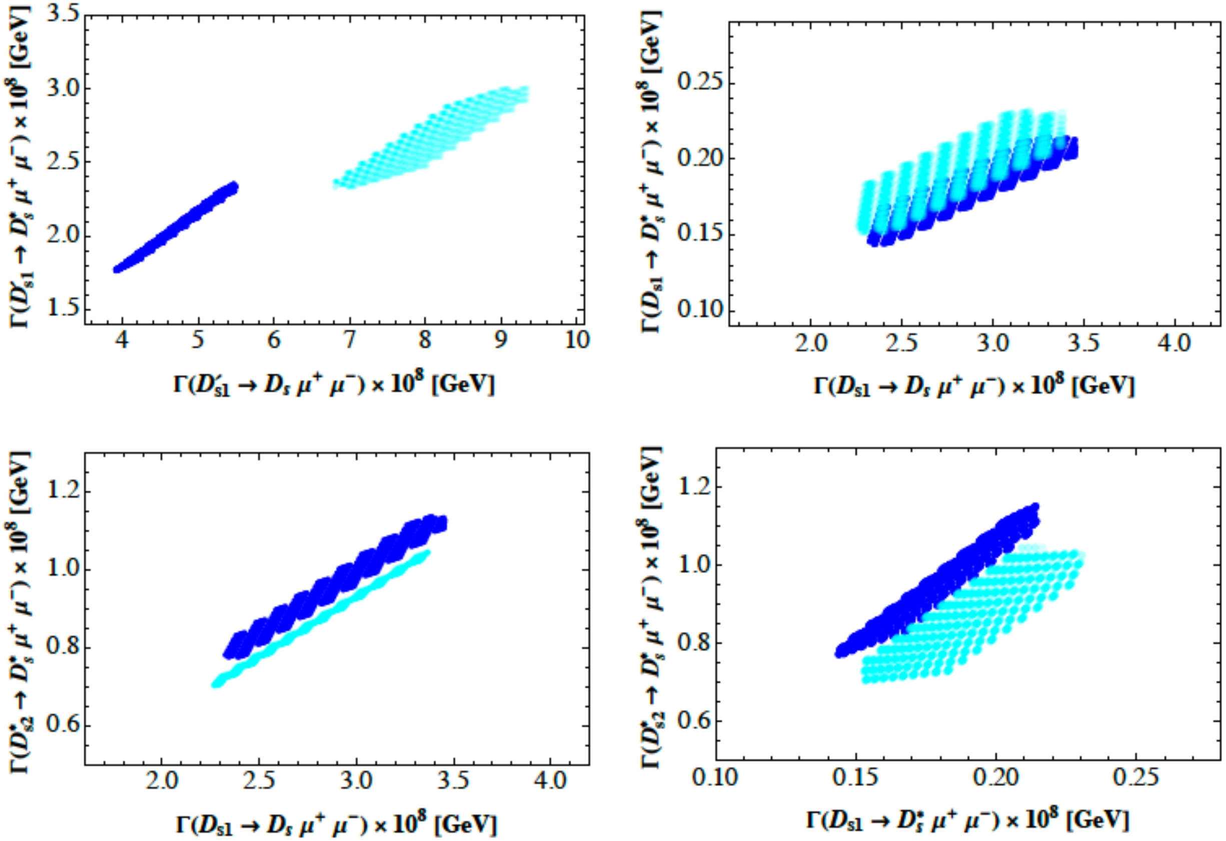
- $D_{s2}^{*} \to D_s^{(*)}\, \mu^+\, \mu^-$ **Angular Distribution**

Case A | Case B



Dalitz decays of positive parity charmed mesons

amplitudes of different modes related through the hadronic parameters → Correlations between decay widths



- BR of $\frac{3}{2}^+$ and width of $\frac{1}{2}^+$ small
- Processes currently under investigation by the LHCb collaboration

Overview

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- Interplay between flavour physics and hadron spectroscopy
- Chaos and Holography

Bound on Chaos

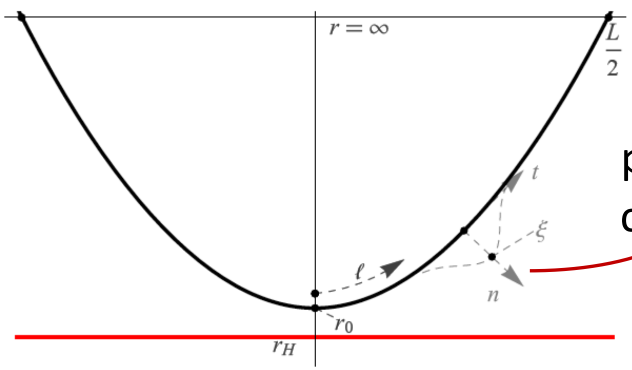
Maldacena, Shenker and Stanford conjecture
J. Maldacena, S. H. Shenker, and D. Stanford, A bound on chaos, JHEP 08 (2016) 106

Thermodynamic quantum system at temperature T ➡ Bound on chaos: $\lambda \leq 2\pi T$

λ: Largest Lyapunov exponent

Using holographic methods to test the MSS bound on chaos

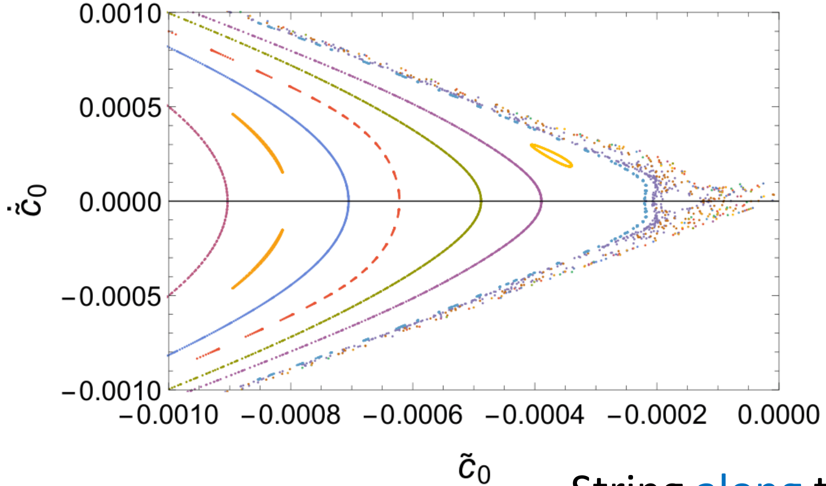
Strongly coupled $Q\bar{Q}$ pair in a finite temperature and density/constant and uniform magnetic field B ➡ Open string in a 5-dimensional metric with suitable boundary conditions

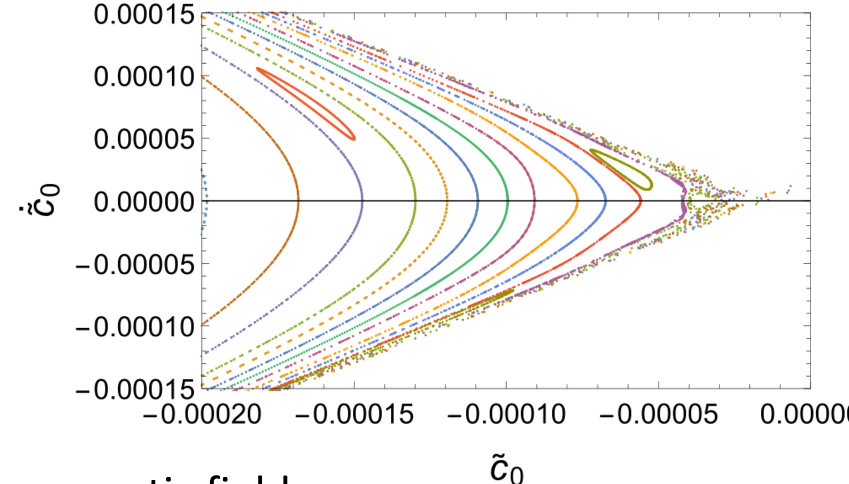


Perturbation parametrized by coefficient c_0, c_1 ➡ Observing chaos studying the dynamics of the perturbation

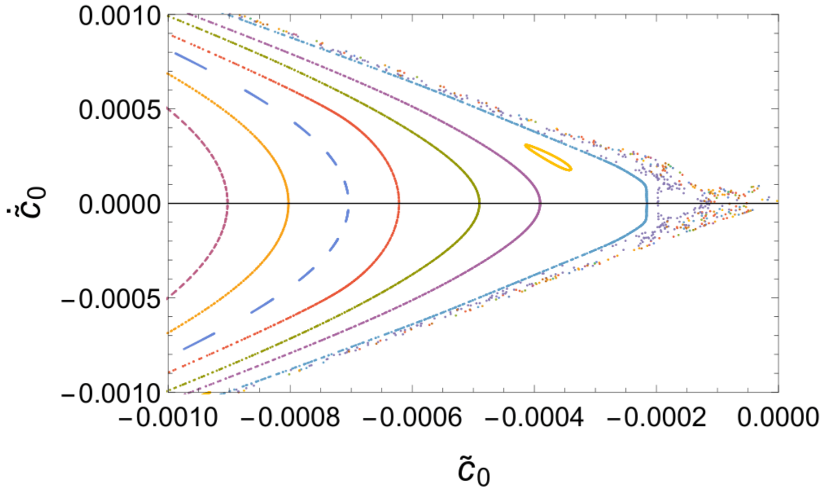
Exemple: external magnetic field

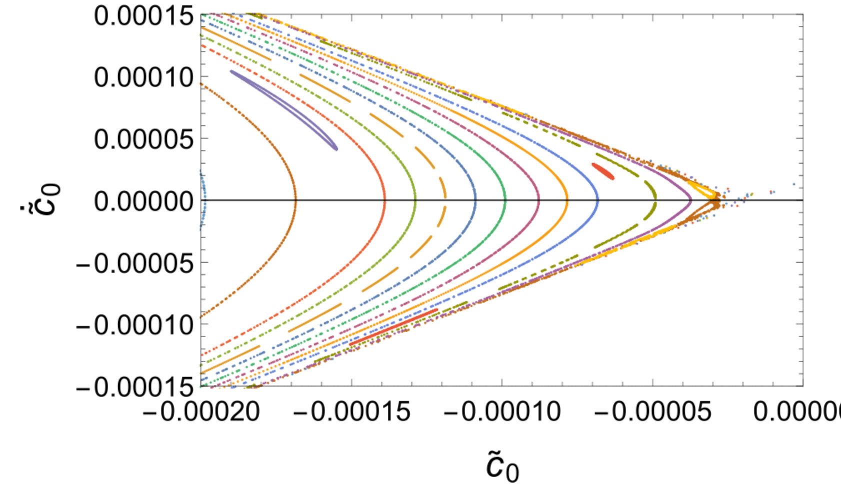
$B = 0.3$ String orthogonal to the magnetic field $B = 1$





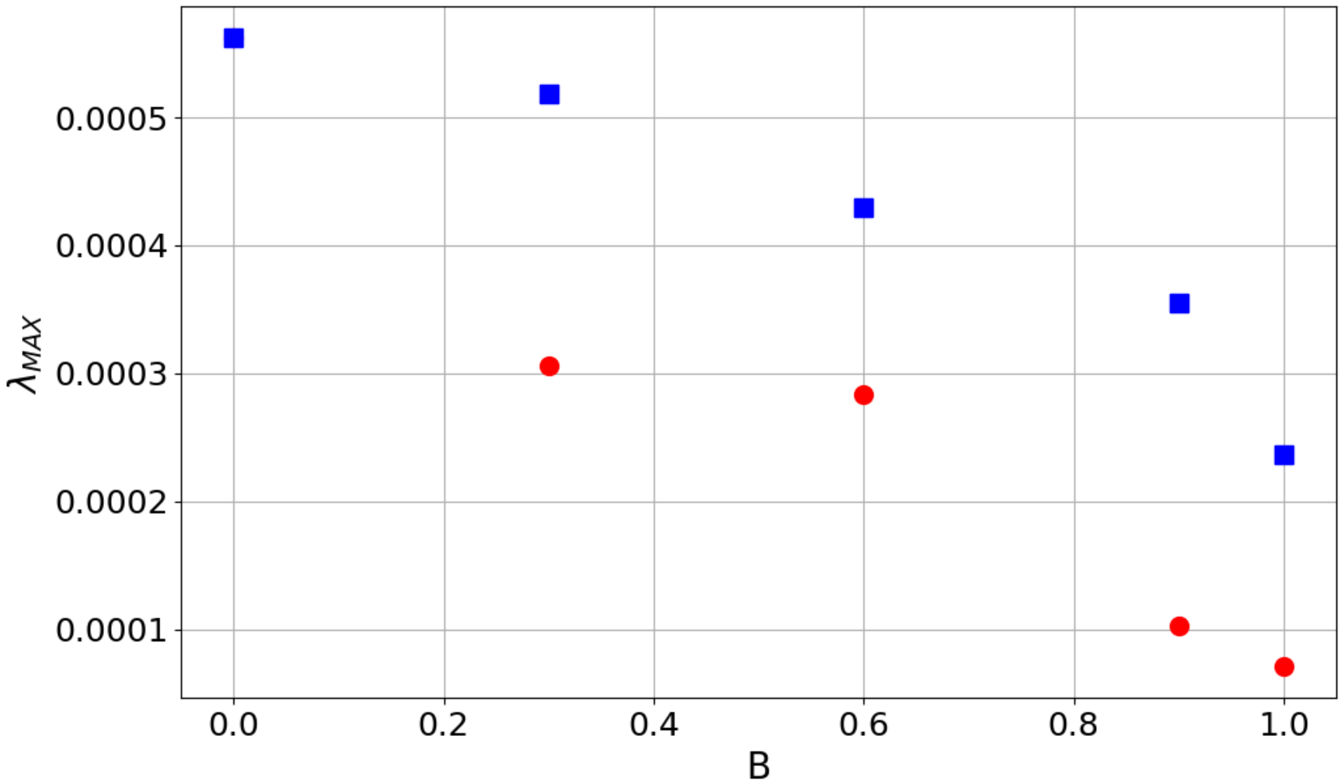
String along the magnetic field





Bound on Chaos

Largest Lyapunov exponent for different values of magnetic field



Configuration orthogonal the magnetic field

Configuration along to the magnetic field

$0.56 \leq \lambda_{MSS} \leq 2$

Due to the B dependence of the Hawking temperature

Conclusions and perspectives

SM might not be the ultimate theory

LO of an EFT → SMEFT/νSMEFT

Effects of new physics in its parameters

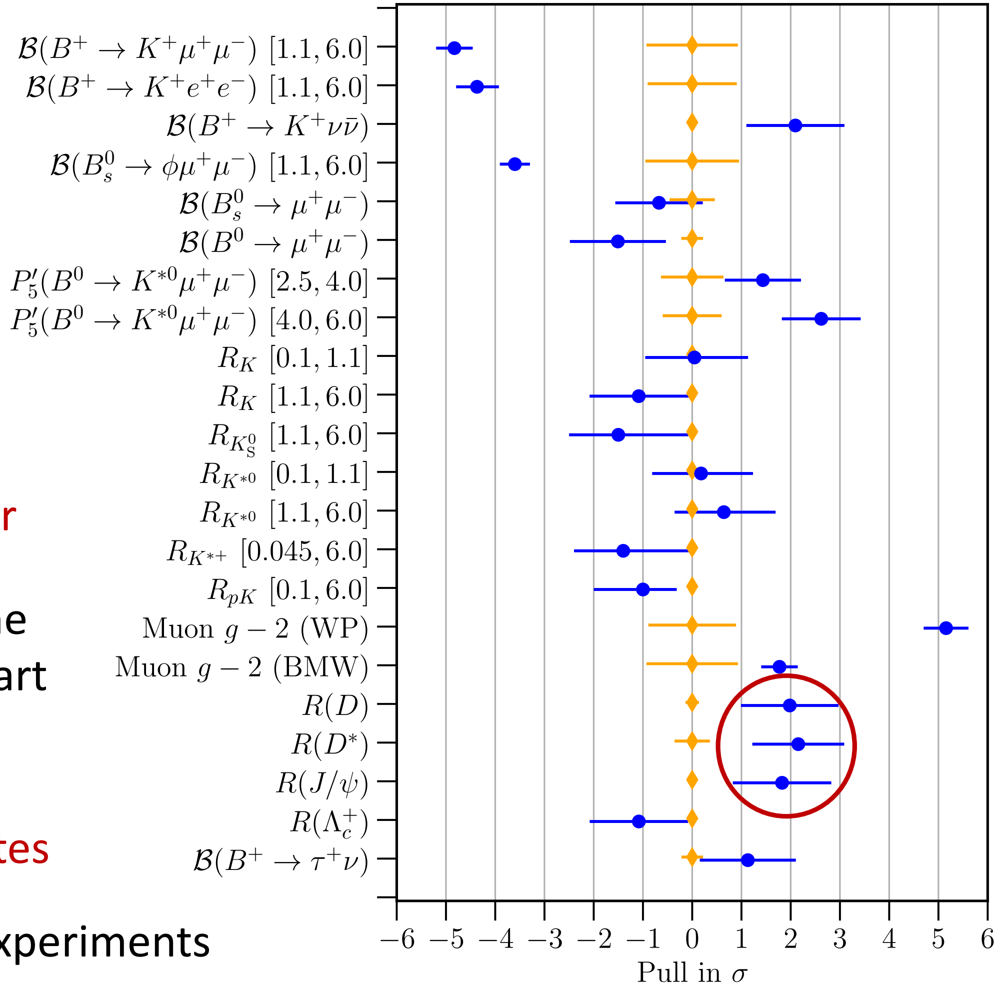
↓

Constrained by experiments or theoretical assumptions

Many anomalies in the heavy flavour sector

Reduce Theoretical uncertainties to confirm/disprove them → Use of HQET for the non-perturbative part

HQET analysis and HQ symmetry → Tools to identify debated hadron states



Results to be tested in current and future experiments

Necessity to continue the investigation for a deeper understanding of nature

THANKS

FOR YOUR

ATTENTION