Theoretical status and perspectives for semileptonic decays

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Motivations to physics beyond the SM

The Standard Model

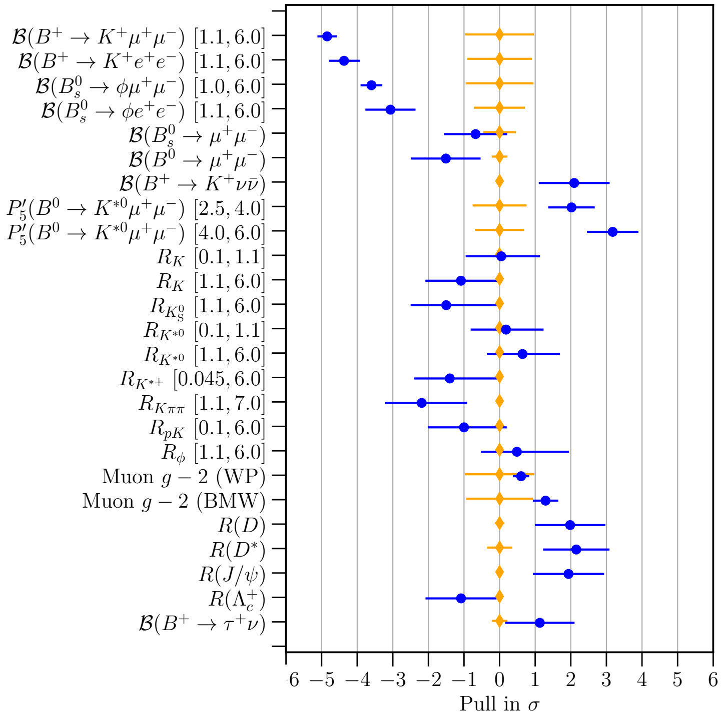
Successes

- 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

Semileptonic Decays: A Window into Flavor Physics

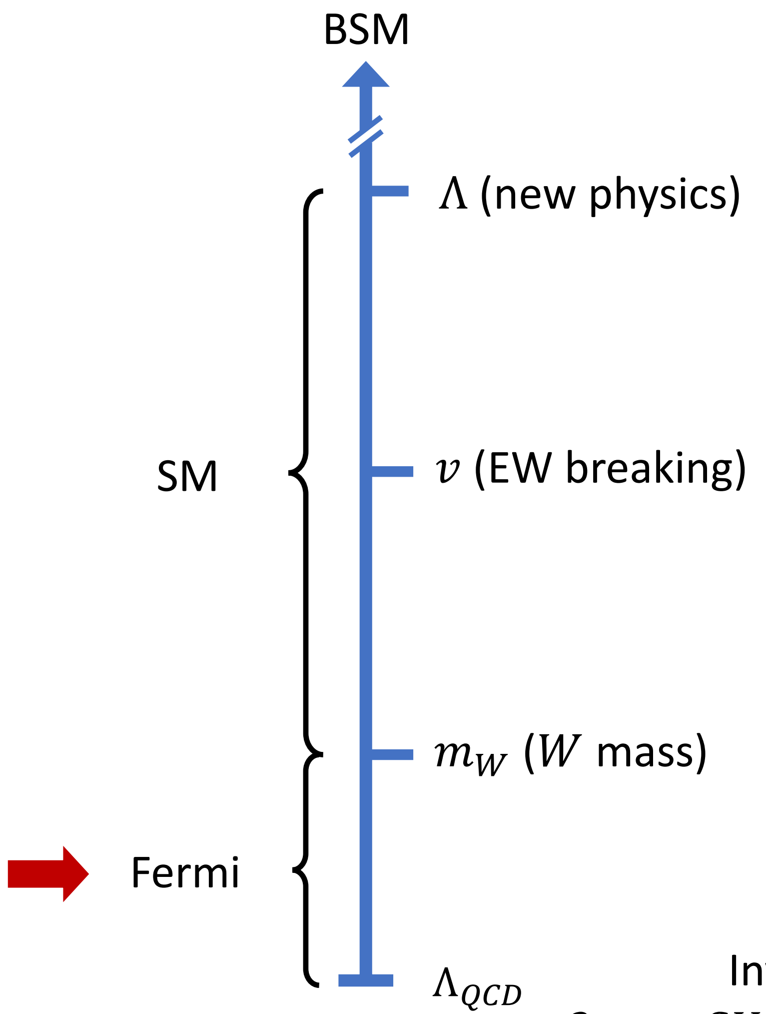
Involve both hadronic and leptonic currents ➡ clean probe of weak interactions and hadron dynamics

Examples: $B \to D^* \ell \nu,\ B_c \to J/\psi(\eta_c)\ell\nu,\ D_{sJ}^{(*)} \to D_s^{(*)} \ell^+ \ell^-$

Why they matter:

- direct access to CKM matrix elements
- Combine perturbative electroweak physics and non-perturbative QCD effects
- Test the Standard Model and search for New Physics in flavor anomalies.

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

Overview

Tensions in the flavour sector

- Angular distribution function in $\bar{B} \to D^*(D\,\pi)\,\ell\,\bar{\nu}_\ell$ process
- Semileptonic B_c meson decay to charmonium states

Interplay between flavour physics and hadron spectroscopy

- Dalitz decays of positive parity charmed mesons

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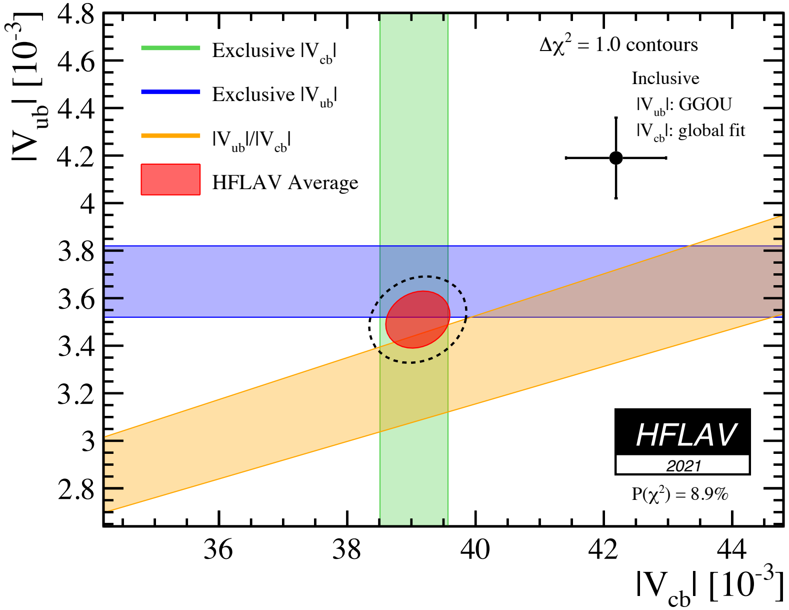
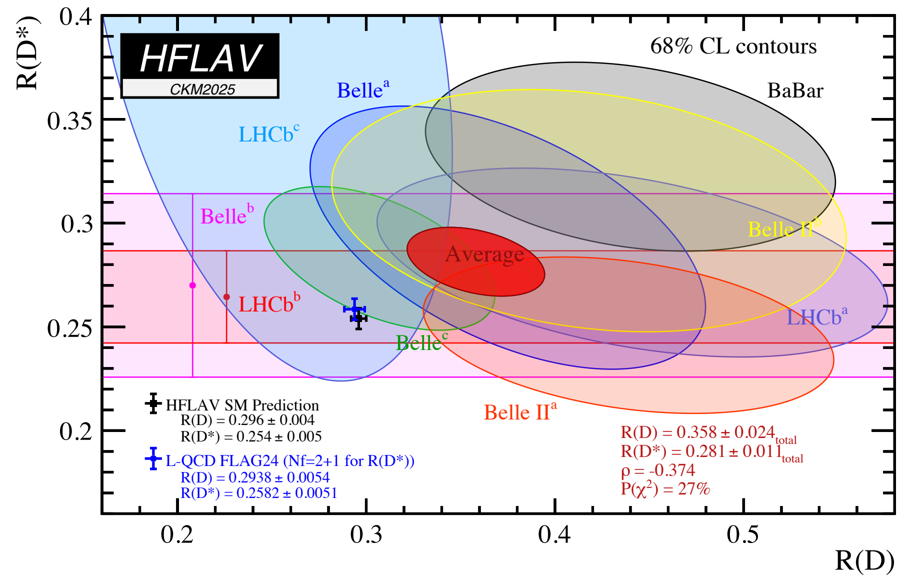
Anomalies in $b \to c\, \ell\, \nu$ transitions

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

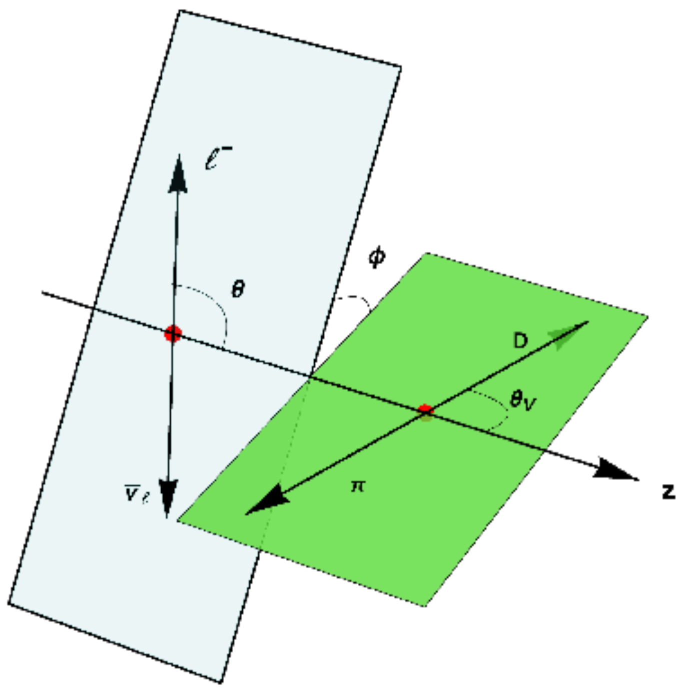
Generalized effective Hamiltonian

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

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

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

$\sigma_i \cdot (\Delta w)^a$

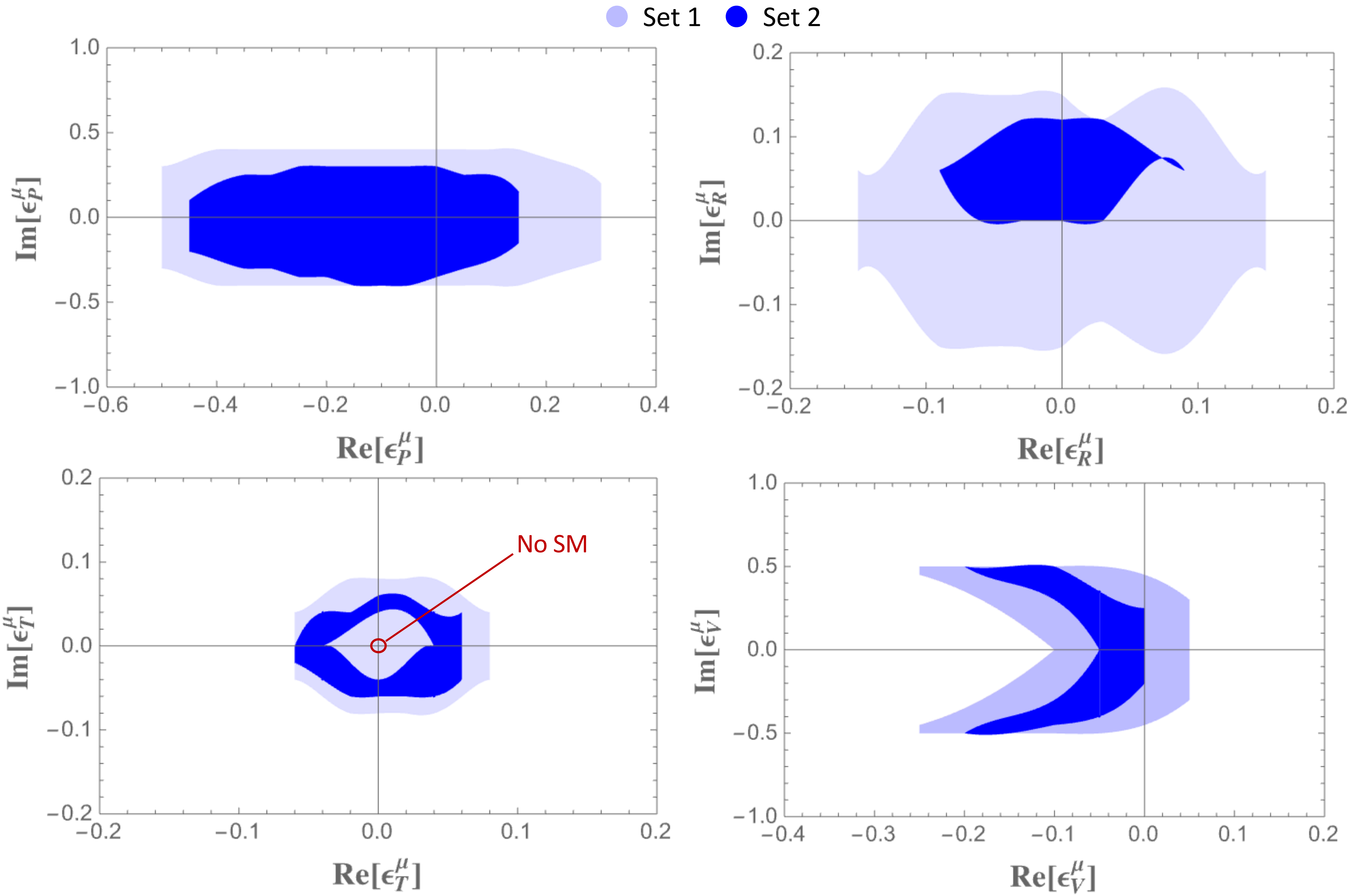
Found to be 2.5

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

2° constraint

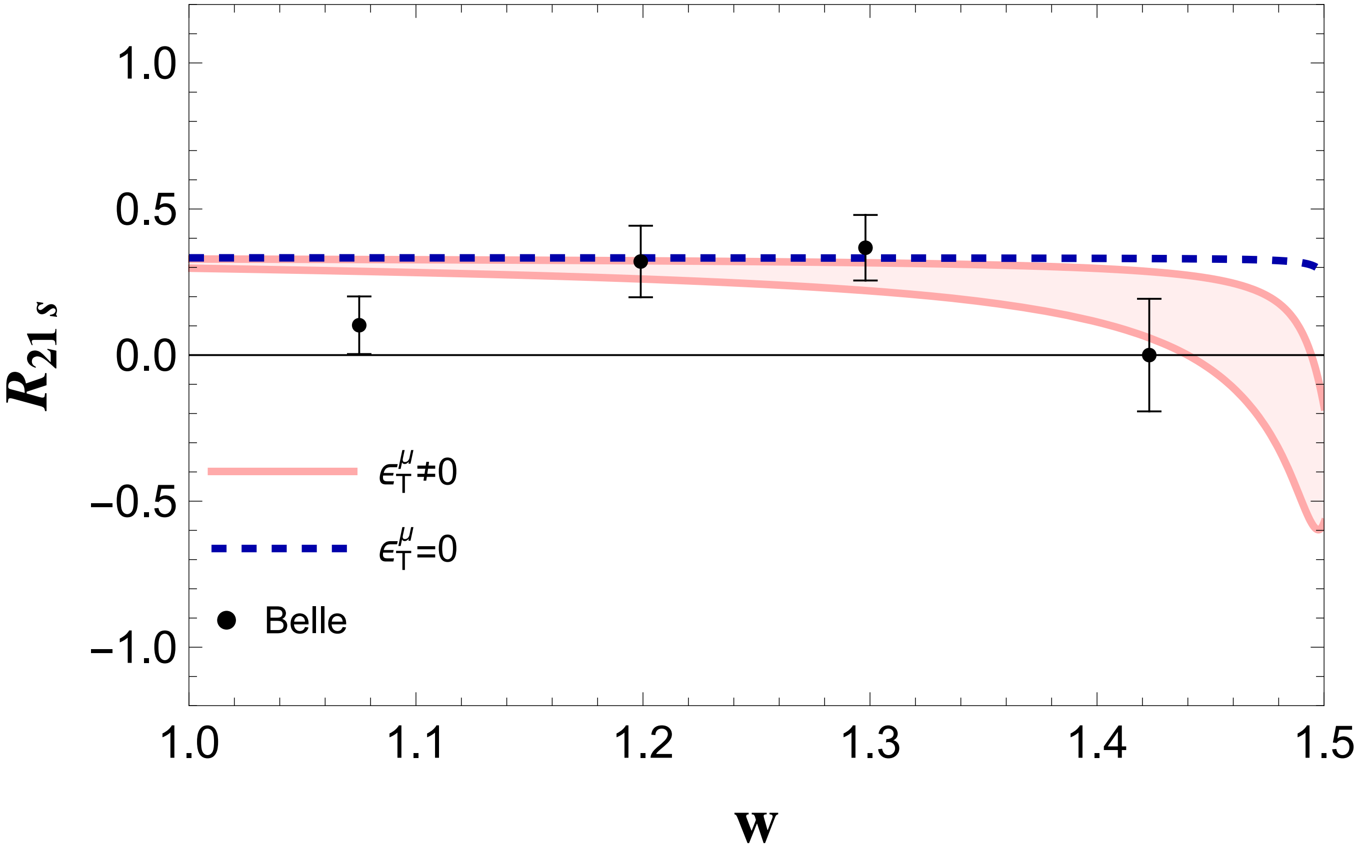
$$\chi^2_{red} = \frac{1}{\nu}\sum_{i,a}\left(\left(\hat{J}_i^a\right)_{int}^{th} - \left(\hat{J}_i^a\right)_{int}^{exp}\right)^2 / (\sigma_i^a)^2 \leq 1.875$$

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


Set 1
Set 2
$\mathrm{Im}[\epsilon_P^\mu]$
$\mathrm{Re}[\epsilon_P^\mu]$
$\mathrm{Im}[\epsilon_R^\mu]$
$\mathrm{Re}[\epsilon_R^\mu]$
No SM
$\mathrm{Im}[\epsilon_T^\mu]$
$\mathrm{Re}[\epsilon_T^\mu]$
$\mathrm{Im}[\epsilon_V^\mu]$
$\mathrm{Re}[\epsilon_V^\mu]$

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

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B_c meson

$c\bar{b}$ system

↓

Heavy quarkonium
with open flavour

↓

NO annihilation into gluons

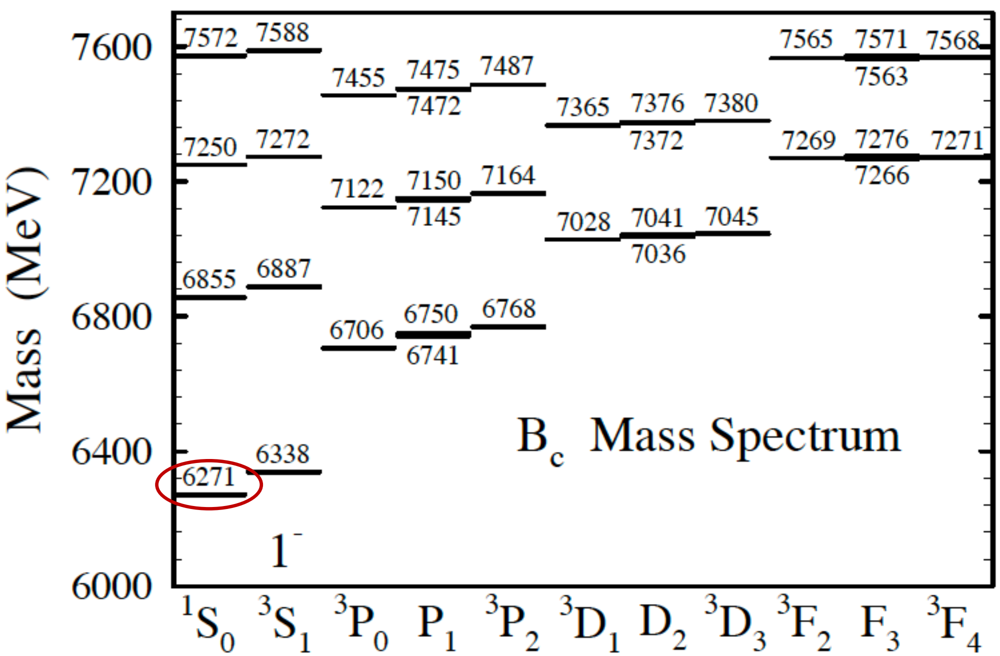
↓

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

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

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 $1/m_Q$ ➡ 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

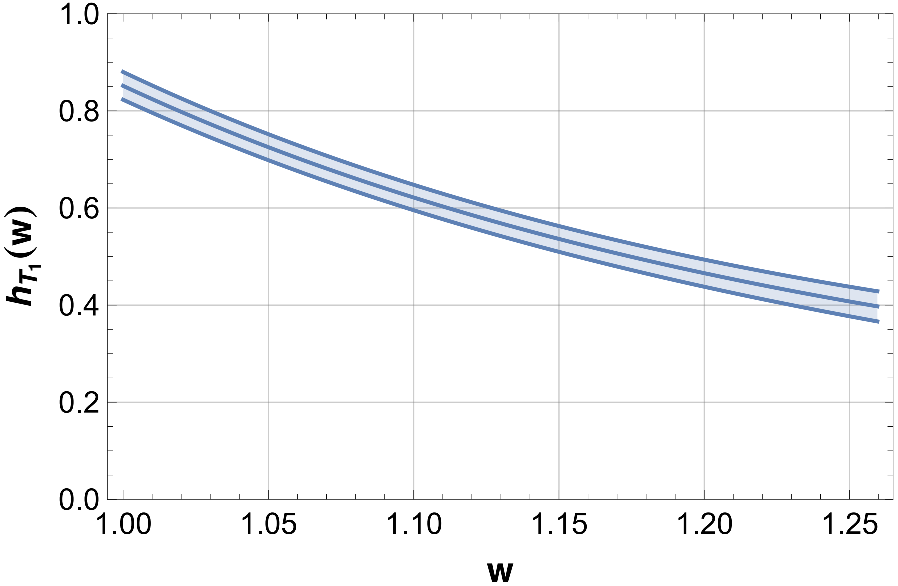
Form factors validity test

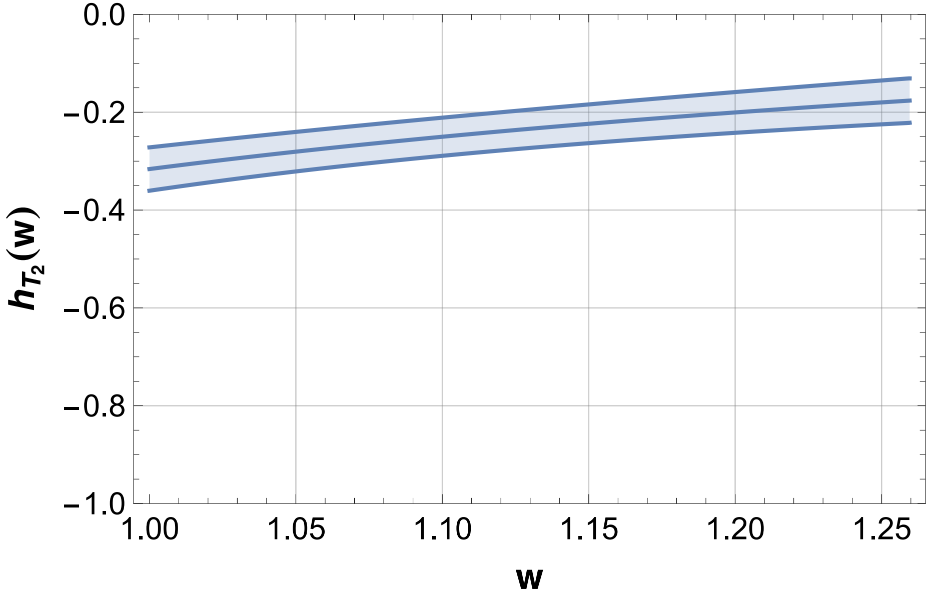
Form factors evaluation from known ones, e.g. from lattice QCD

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

- $B_c \to J/\psi$

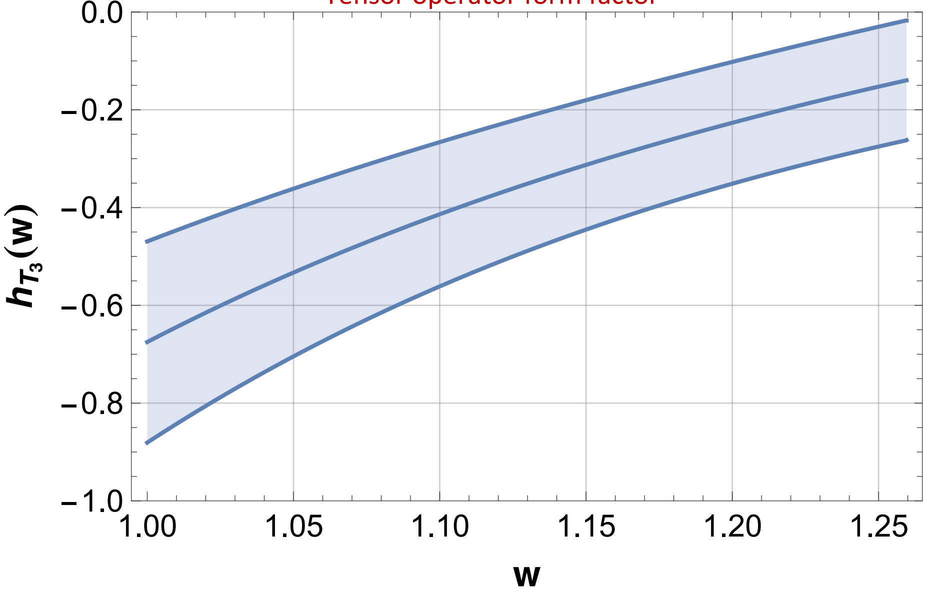
Tensor operator form factor



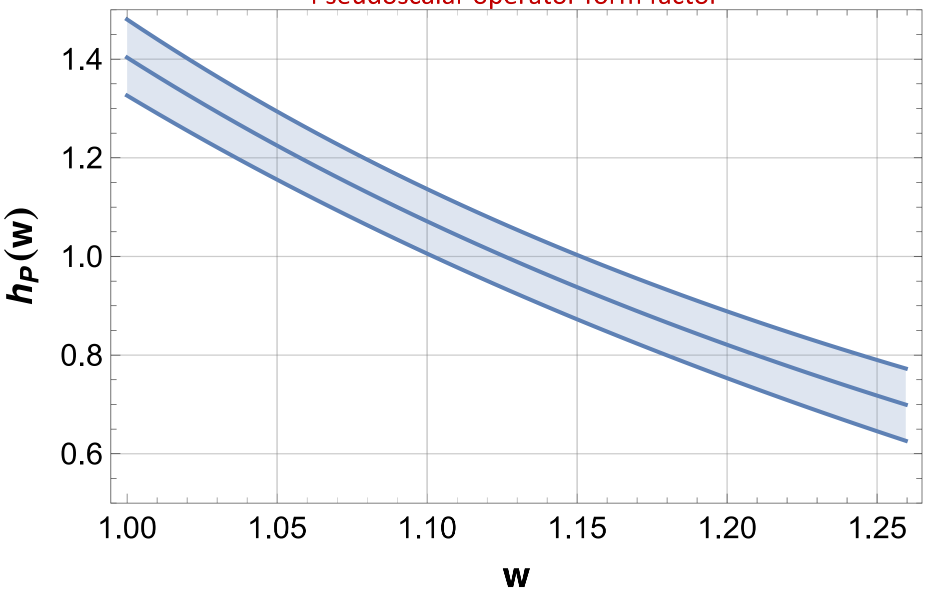


$B_c \to J/\psi(\eta_c)\ell\,\bar{\nu}$

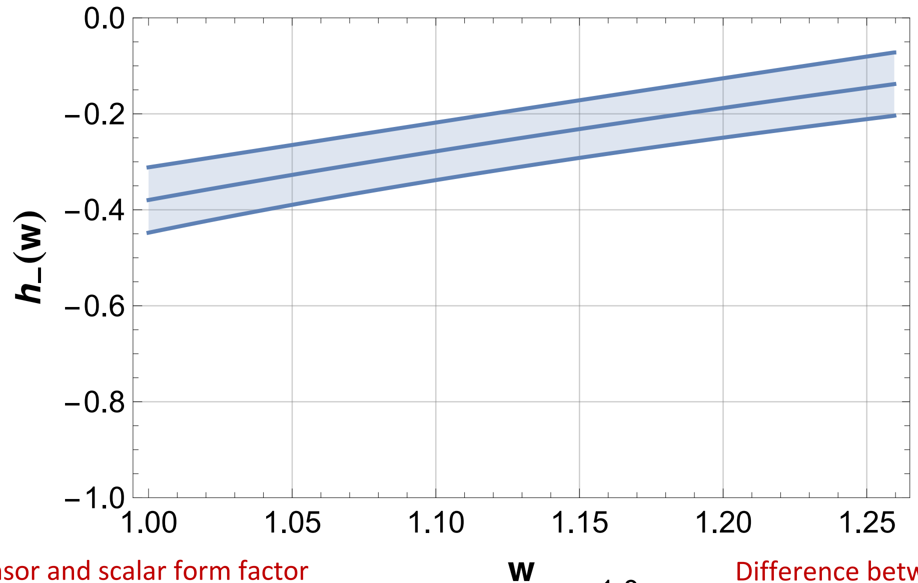
Tensor operator form factor



Pseudoscalar operator form factor

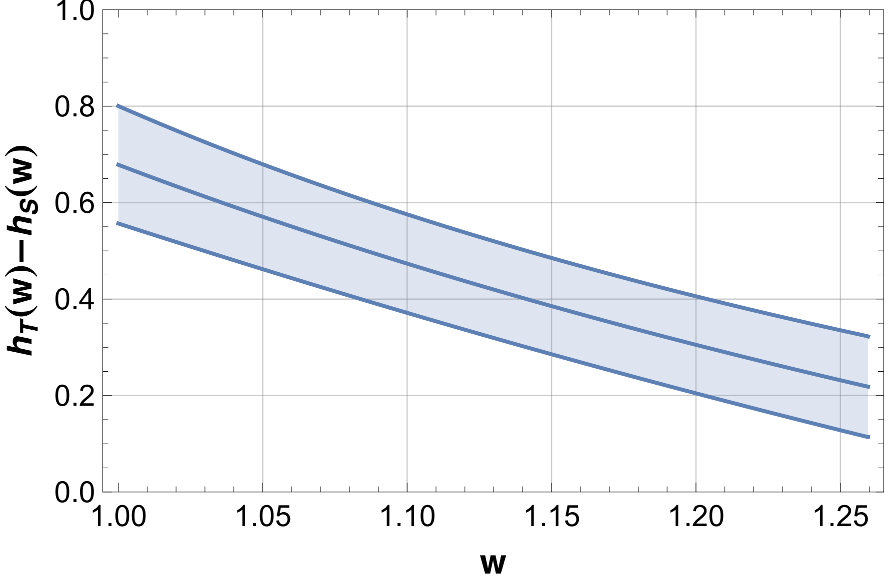


- $B_c \to \eta_c$

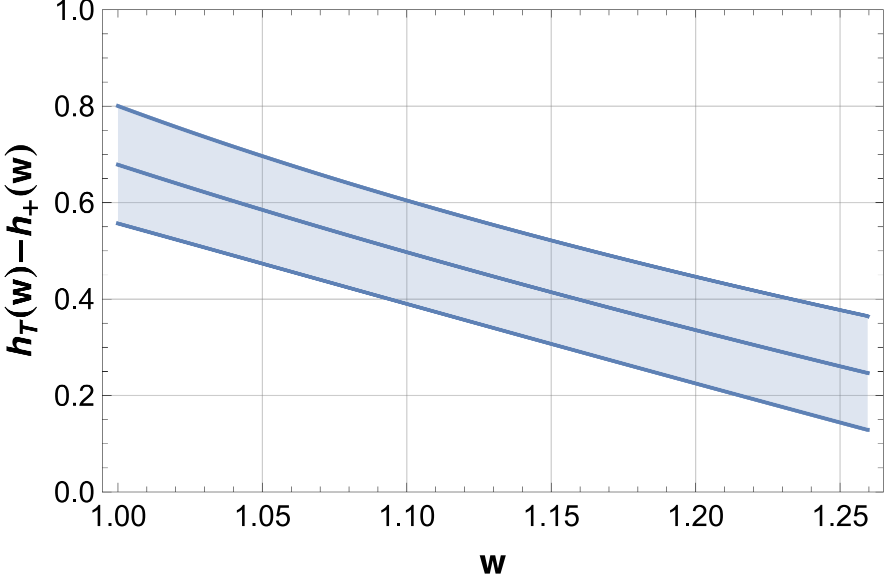


Vector operator form factor

Difference between tensor and scalar form factor



Difference between tensor and vector form factor



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

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 $\chi_{c1}(3872)\ J^{PC} = 1^{++}$

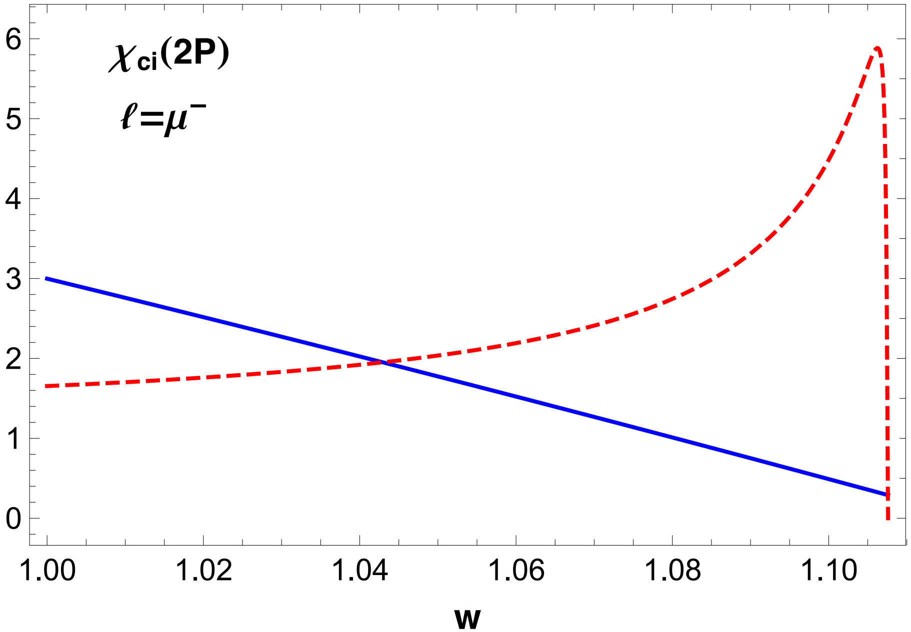
The charming case of X(3872) and $\chi_{c1}(2P)$
Giuseppe Roselli

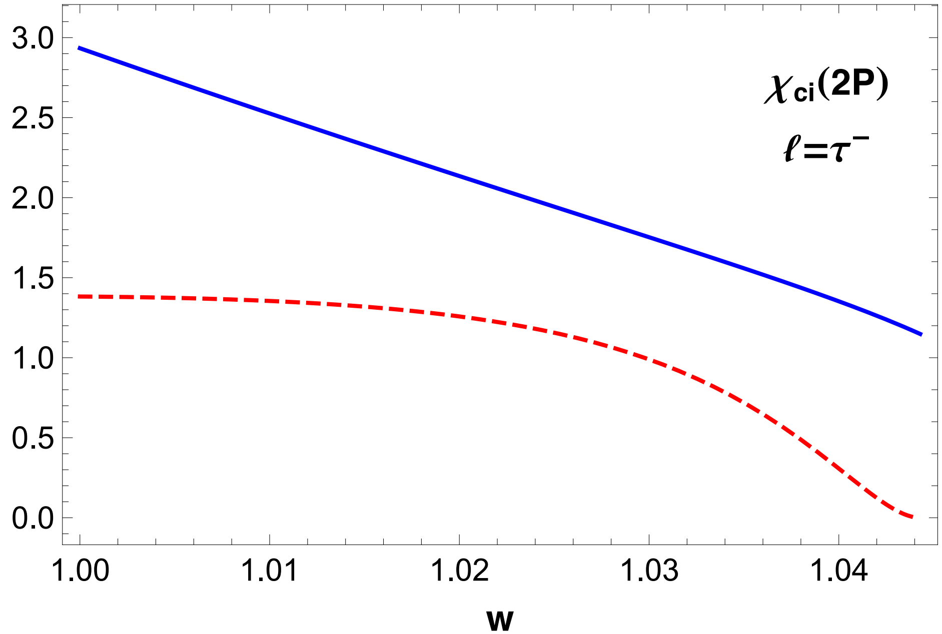
$X(3872)$: tetraquark, molecular state

$\chi_{c1}(2P)$: 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

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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

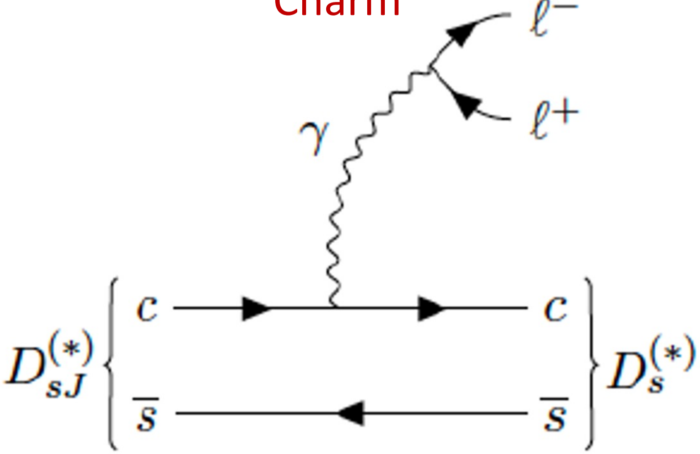
$$H_a = \frac{1+\not{v}}{2}[P_{a\mu}^{*}\gamma^\mu - P_a\gamma_5] \qquad (s_\ell^P = \frac{1}{2}^-) \qquad D_s, D_s^*$$

$$S_a = \frac{1+\not{v}}{2}\left[P_{1a}^{\prime\mu}\gamma_\mu\gamma_5 - P_{0a}^{*}\right] \qquad (s_\ell^P = \frac{1}{2}^+) \qquad D_{s0}^*, D_{s1}'$$

$$T_a^\mu = \frac{1+\not{v}}{2}\left\{P_{2a}^{\mu\nu}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} \qquad (s_\ell^P = \frac{3}{2}^+) \qquad D_{s1}, D_{s2}^*$$

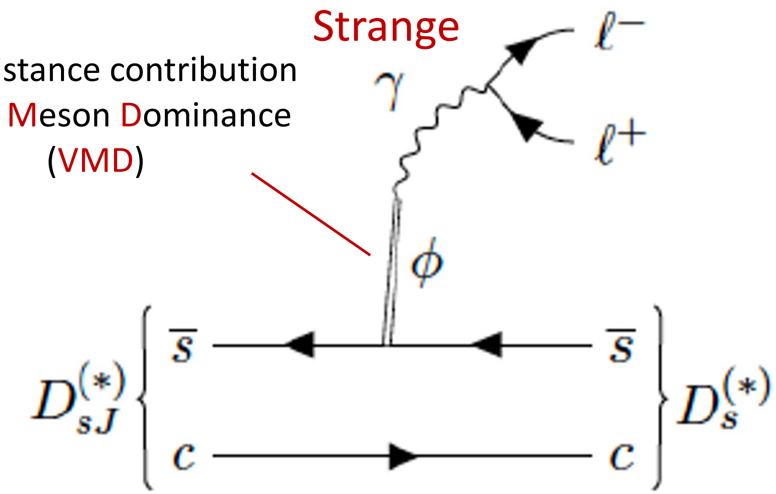
Dalitz decays of positive parity charmed mesons

Charm



Strange

Long distance contribution
Vector Meson Dominance
(VMD)



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

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

Computed using heavy quark spin symmetry

Effective Lagrangian constructed using
HQS + CS + HGI

Heavy Quark Symmetry
Chiral Symmetry
Hidden Gauge Invariance

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

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

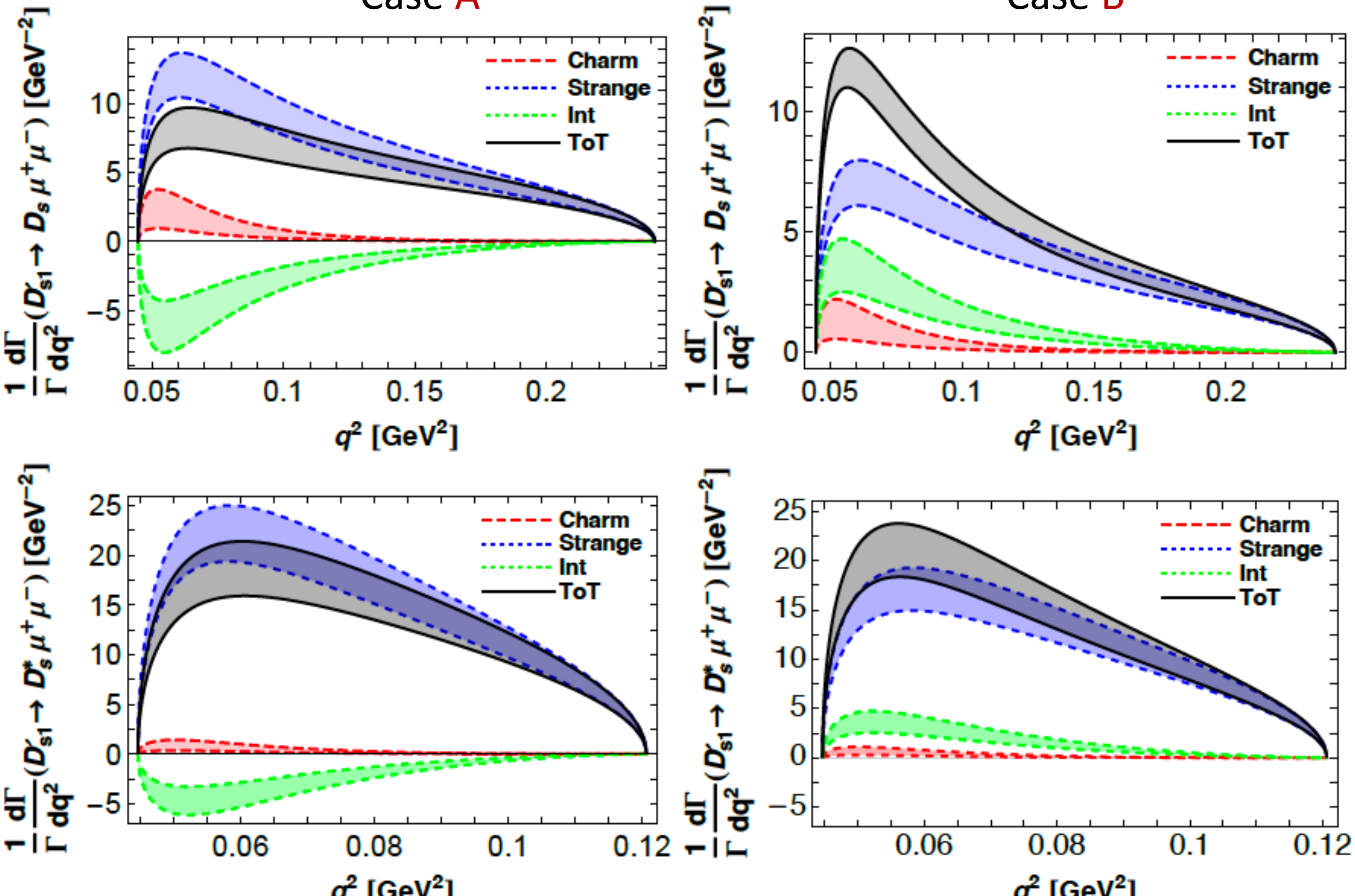
Case A
POSITIVE

Case B
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

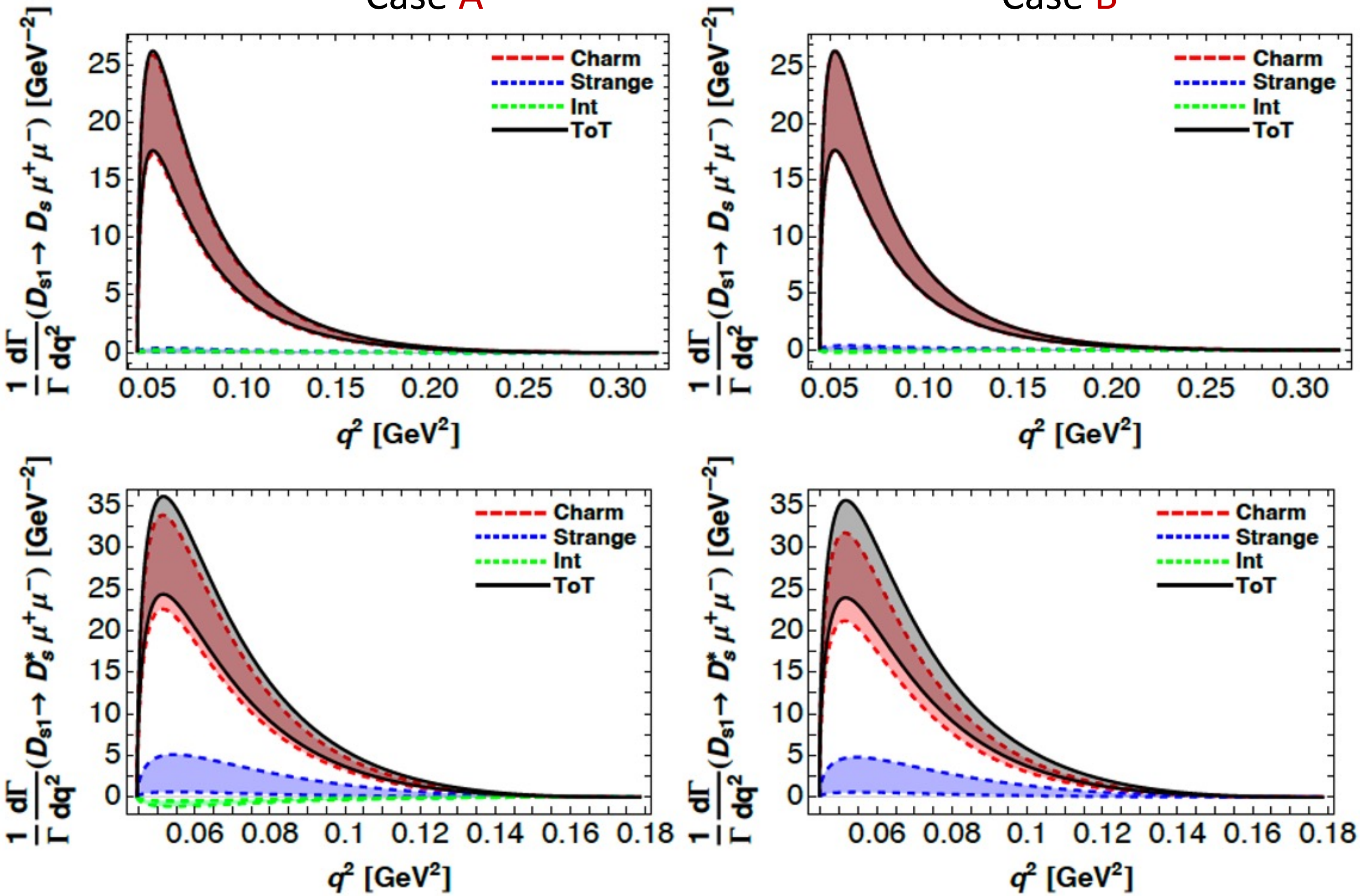
Case A Case B



Dalitz decays of positive parity charmed mesons

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

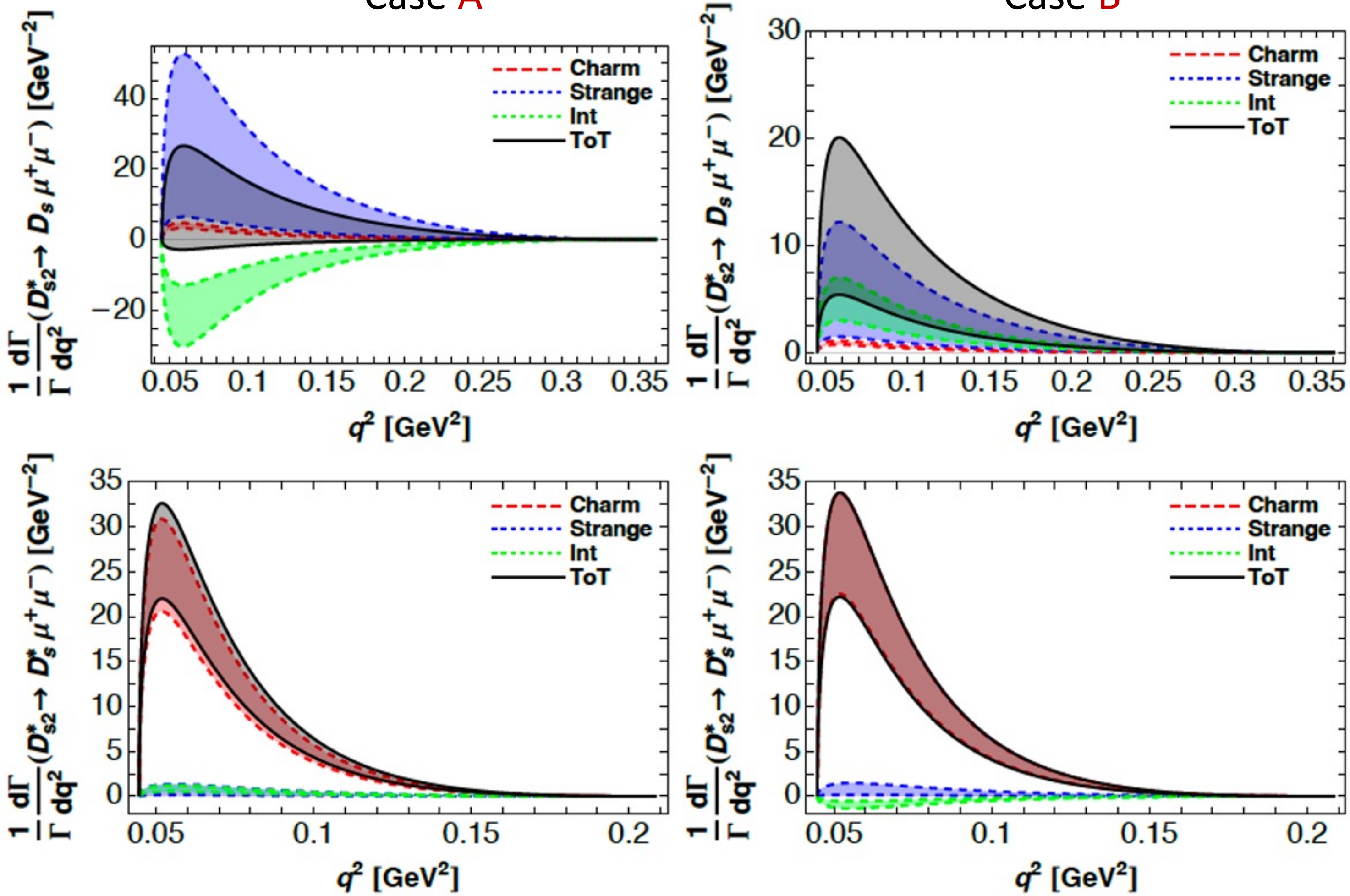
Case A Case B



Dalitz decays of positive parity charmed mesons

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

Case A Case B



Dalitz decays of positive parity charmed mesons

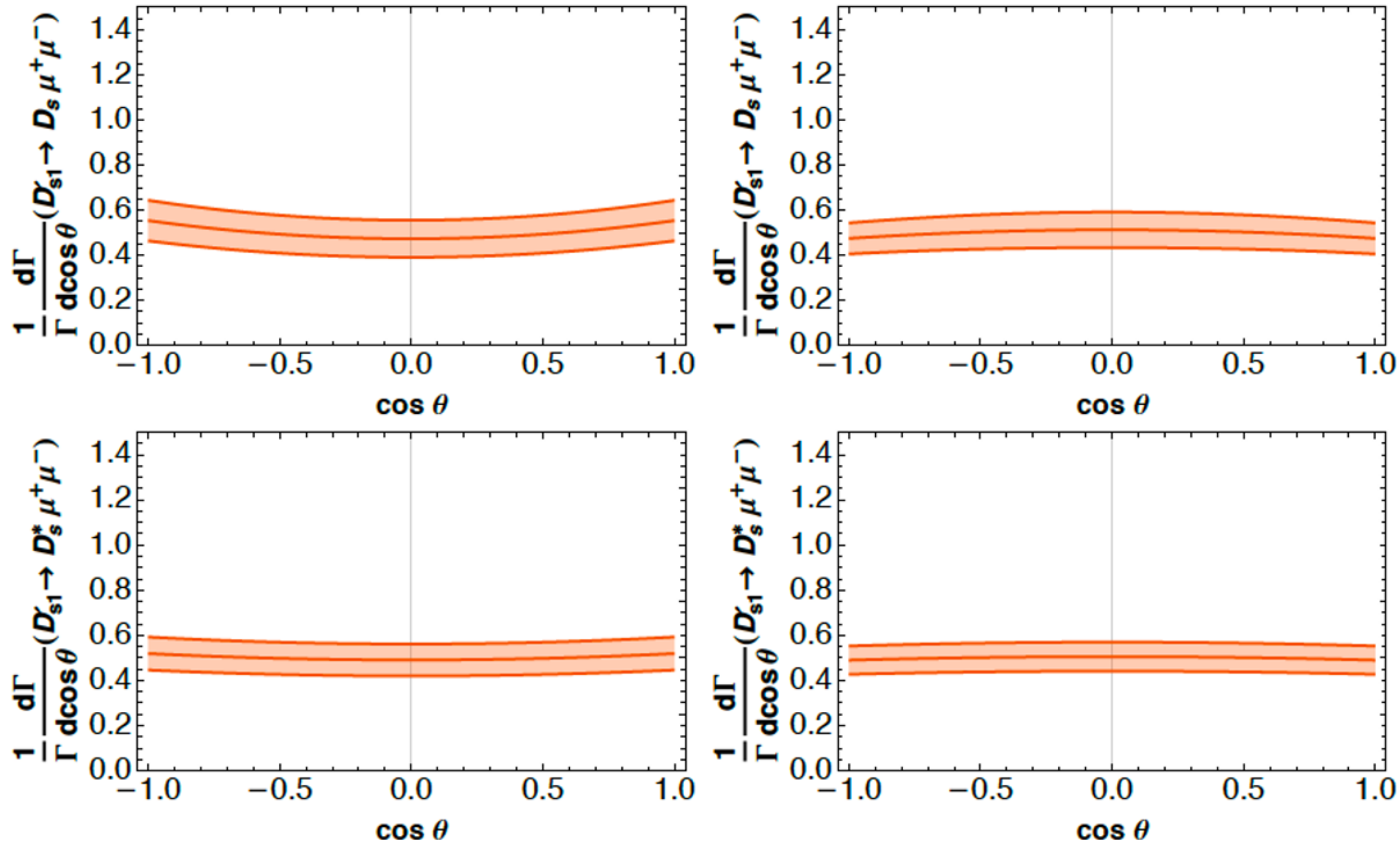
- **$D'_{s1} \to D_s^{(*)} \mu^+ \mu^-$ Angular Distribution**

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

$\vec{p}_1$ = lepton momentum

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

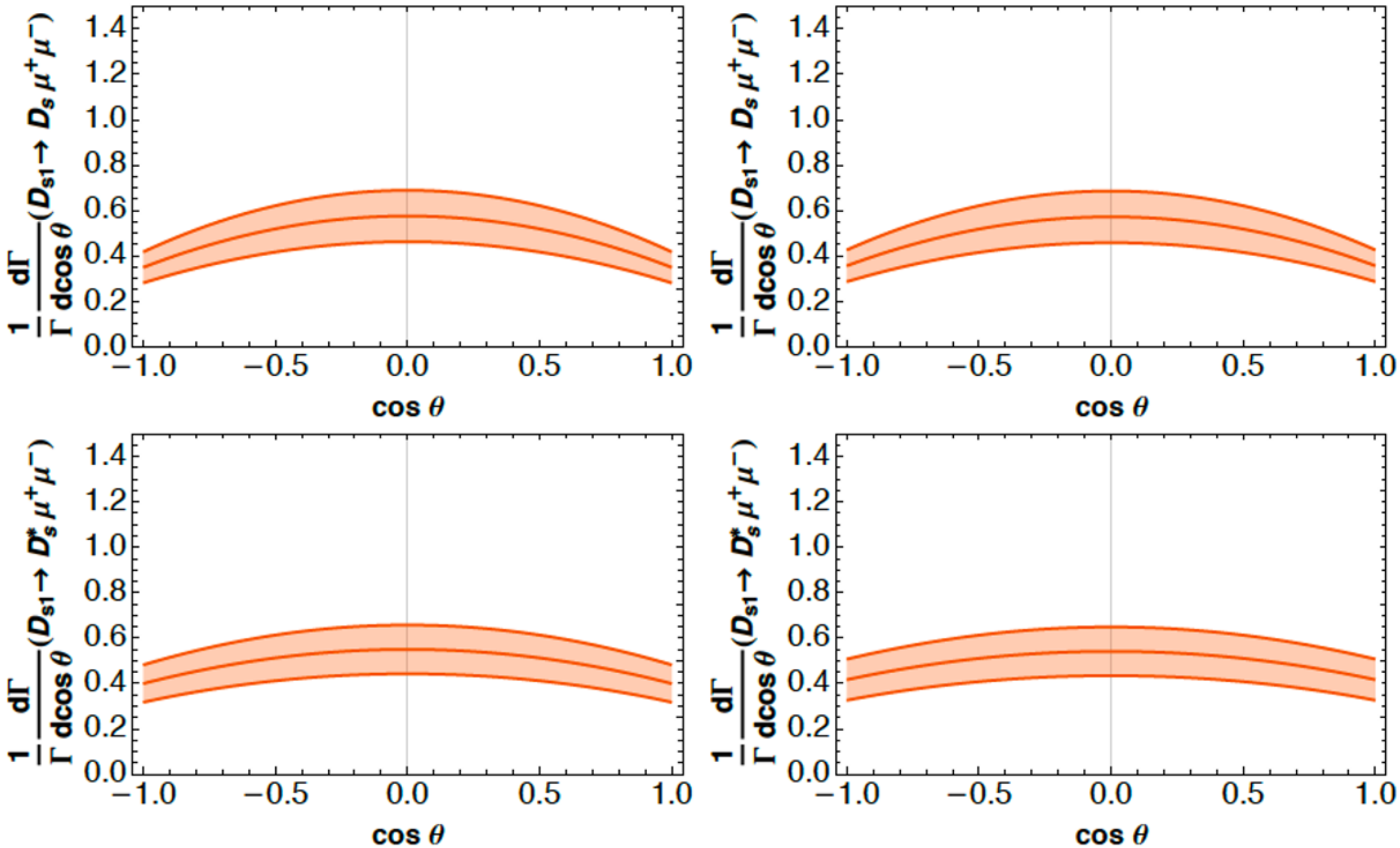
Case A Case B



Dalitz decays of positive parity charmed mesons

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

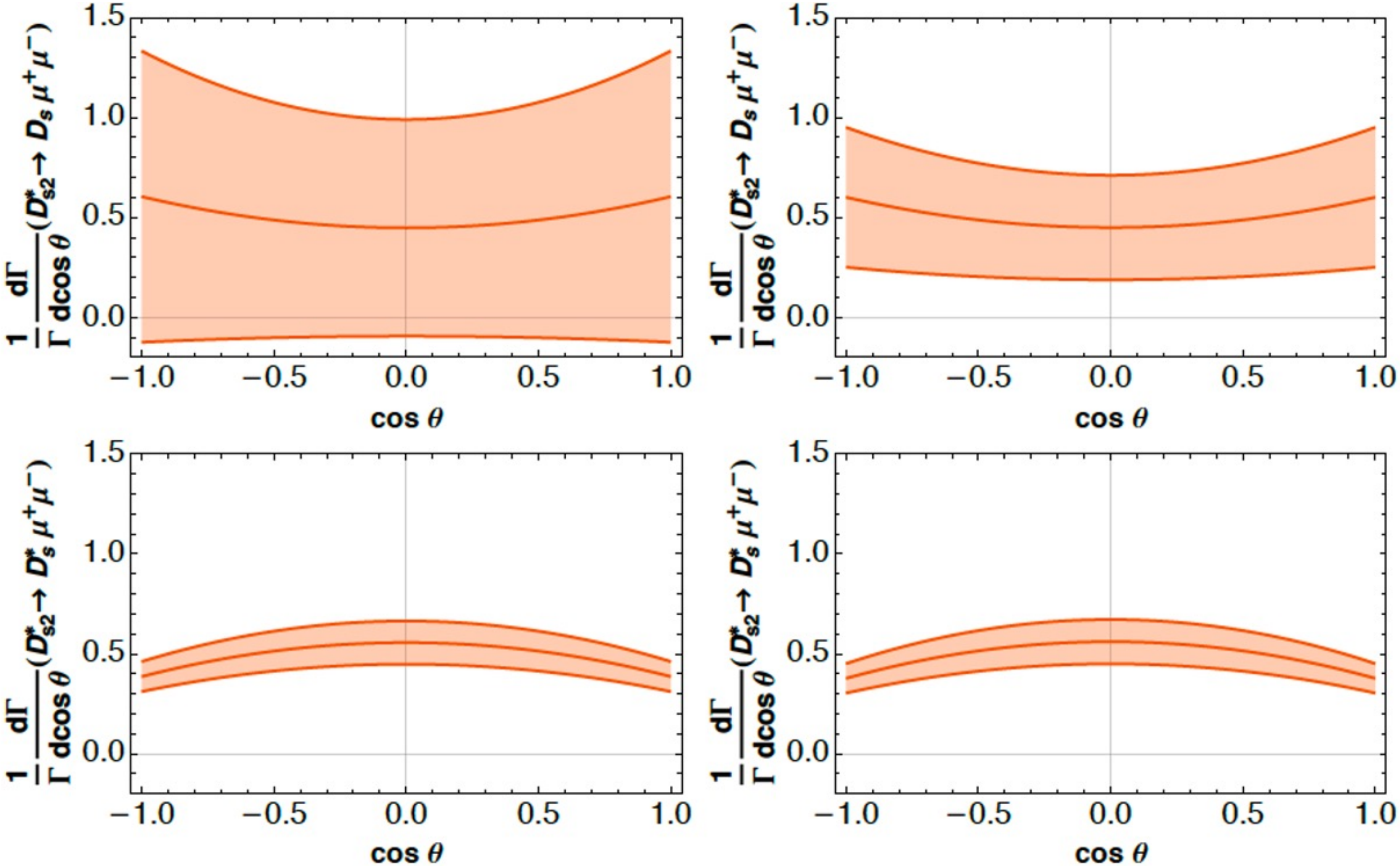
Case A Case B



Dalitz decays of positive parity charmed mesons

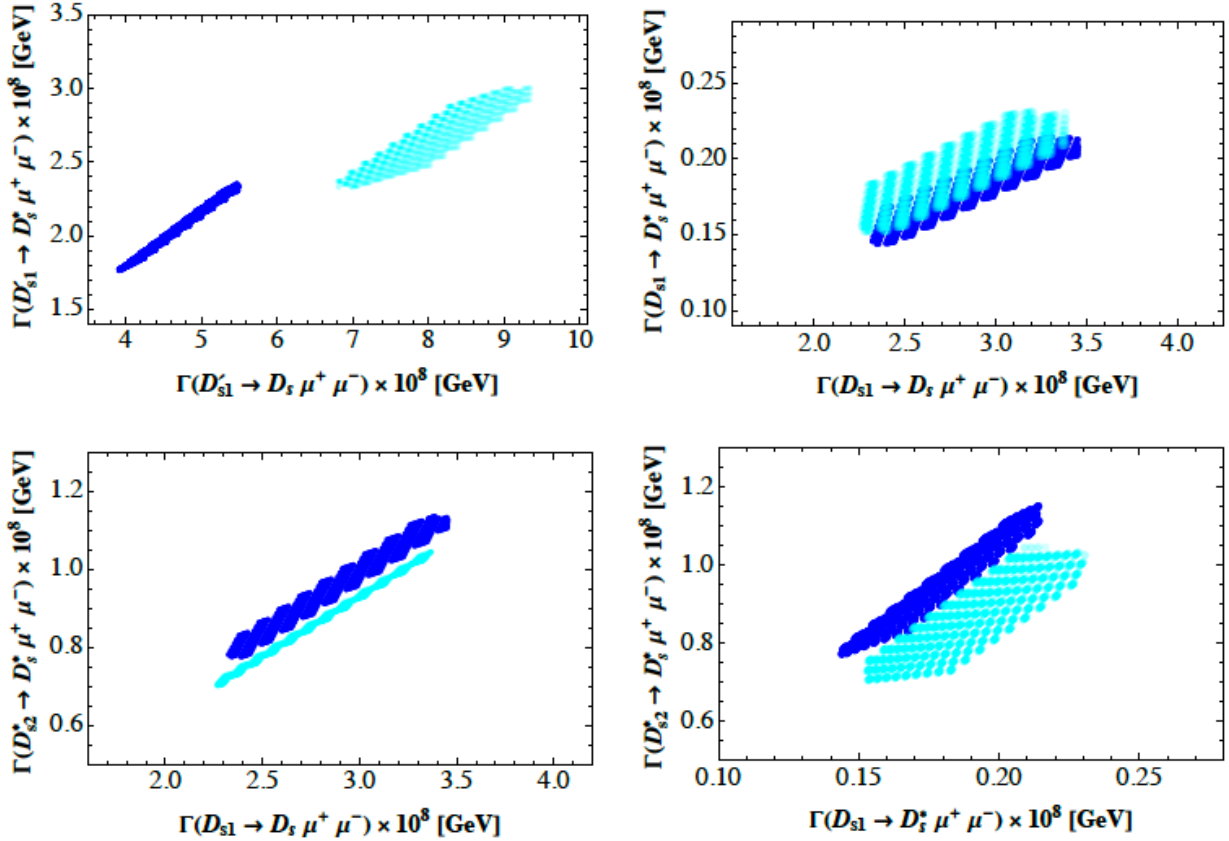
- $D_{s2}^* \to D_s^{(*)} \mu^+ \mu^-$ **Angular Distribution**

Case A Case B



Dalitz decays of positive parity charmed mesons

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



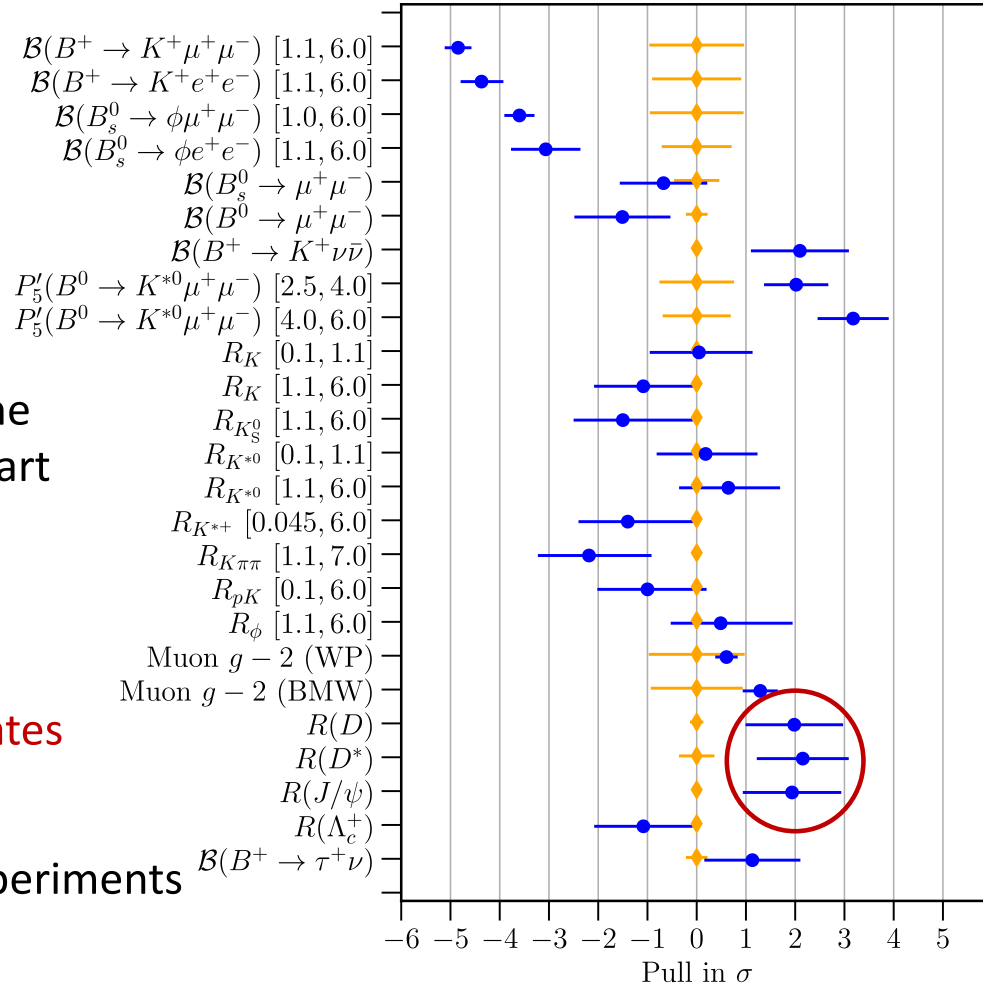
- BR of $\frac{3}{2}^+$ and width of $\frac{1}{2}^+$ small
- Processes investigated by the LHCb collaboration

Conclusions and perspectives

Many anomalies in the heavy flavour sector → Use of semileptonic decay to test them

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

BACKUP

Relations from the gauge group structure

Few parameters to express all Wilson coefficients $\Rightarrow$ Relations among them

Generation indices

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

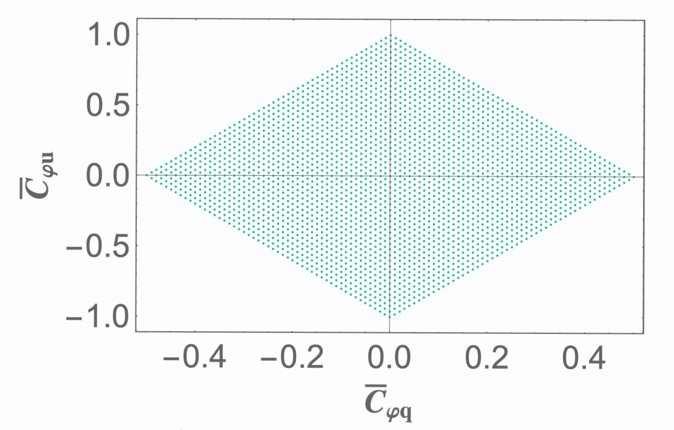
$$\left[C_{\psi\psi}\right]_{ijkp} = \frac{\left[C_{\varphi\psi}\right]_{ij}\left[C_{\varphi\psi}\right]_{kp}}{C_{\varphi D}}$$

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

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

Example:

Z' universal and only coupled to the third generation



Universal coupling

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

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

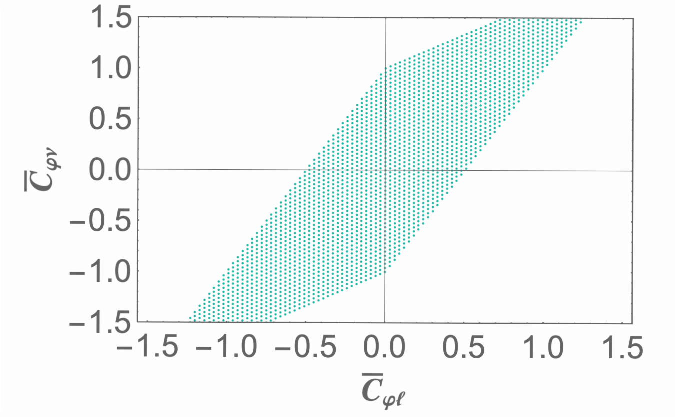
$$\tilde{C}^{(n)}_{\varphi\psi} = 3\left(\bar{C}_{\varphi\psi}\right)^n$$

Only third generation coupling:

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

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

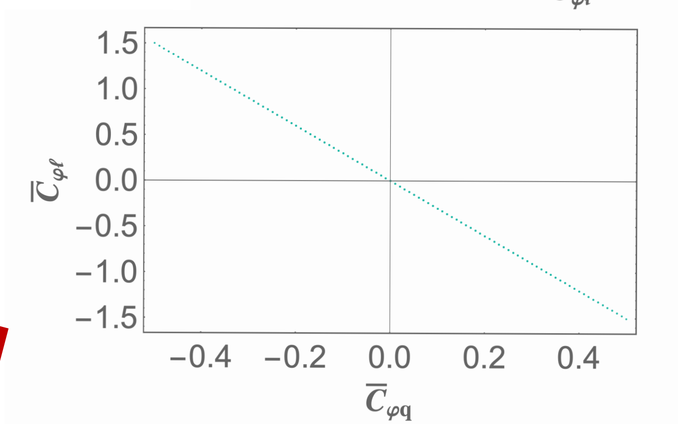
$$\tilde{C}^{(n)}_{\varphi\psi} = \left(\bar{C}_{\varphi\psi}\right)^n$$



Same constraints from the linear ACE

6 coefficients and 4 linear relations

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



Angular Coefficient Functions

$$I_i = |1+\epsilon_V|^2 I_i^{SM} + |\epsilon_R|^2 I_i^{NP,R} + |\epsilon_P|^2 I_i^{NP,P} + |\epsilon_T|^2 I_i^{NP,T} + 2\,\mathrm{Re}\left[\epsilon_R(1+\epsilon_V^*)\right] I_i^{INT,R} + 2\,\mathrm{Re}\left[\epsilon_P(1+\epsilon_V^*)\right] I_i^{INT,P} + 2\,\mathrm{Re}\left[\epsilon_T(1+\epsilon_V^*)\right] I_i^{INT,T} + 2\,\mathrm{Re}\left[\epsilon_R\epsilon_T^*\right] I_i^{INT,RT} + 2\,\mathrm{Re}\left[\epsilon_P\epsilon_T^*\right] I_i^{INT,PT} + 2\,\mathrm{Re}\left[\epsilon_P\epsilon_R^*\right] I_i^{INT,PR}$$

$i = 1, \dots, 6$

I_i functions properties:

- depend only on q^2
- expressed in terms of SM and NP contributions

$$I_i = 2\,\mathrm{Im}\left[\epsilon_R(1+\epsilon_V^*)\right] I_i^{INT,R}$$

$i = 8, 9$

$$I_7 = 2\,\mathrm{Im}\left[\epsilon_R(1+\epsilon_V^*)\right] I_7^{INT,R} + 2\,\mathrm{Im}\left[\epsilon_P(1+\epsilon_V^*)\right] I_7^{INT,P} + 2\,\mathrm{Im}\left[\epsilon_T(1+\epsilon_V^*)\right] I_7^{INT,T} + 2\,\mathrm{Im}\left[\epsilon_R\epsilon_T^*\right] I_7^{INT,RT} + 2\,\mathrm{Im}\left[\epsilon_P\epsilon_T^*\right] I_7^{INT,PT} + 2\,\mathrm{Im}\left[\epsilon_P\epsilon_R^*\right] I_7^{INT,PR}$$

Angular Coefficient Functions

Tensor current

$$H_\pm^{NP} = \frac{1}{\sqrt{q^2}}\Big\{q^2(T_1(q^2) - T_2(q^2))$$

$$+\left(m_B^2 - m_V^2 \pm \sqrt{\lambda(m_B^2, m_V^2, q^2)}\right)(T_1(q^2) + T_2(q^2))\Big\}$$

$$H_L^{NP} = 4\Big\{\frac{\lambda(m_B^2, m_V^2, q^2)}{m_V(m_B + m_V)^2} T_0(q^2)$$

$$+2\frac{m_B^2 + m_V^2 - q^2}{m_V} T_1(q^2) + 4m_V T_2(q^2)\Big\}$$

V-A current

$$H_0 = \frac{1}{2m_V(m_B + m_V)\sqrt{q^2}}$$

$$\Big((m_B + m_V)^2(m_B^2 - m_V^2 - q^2)A_1(q^2)$$

$$-\lambda(m_B^2, m_V^2, q^2)A_2(q^2)\Big)$$

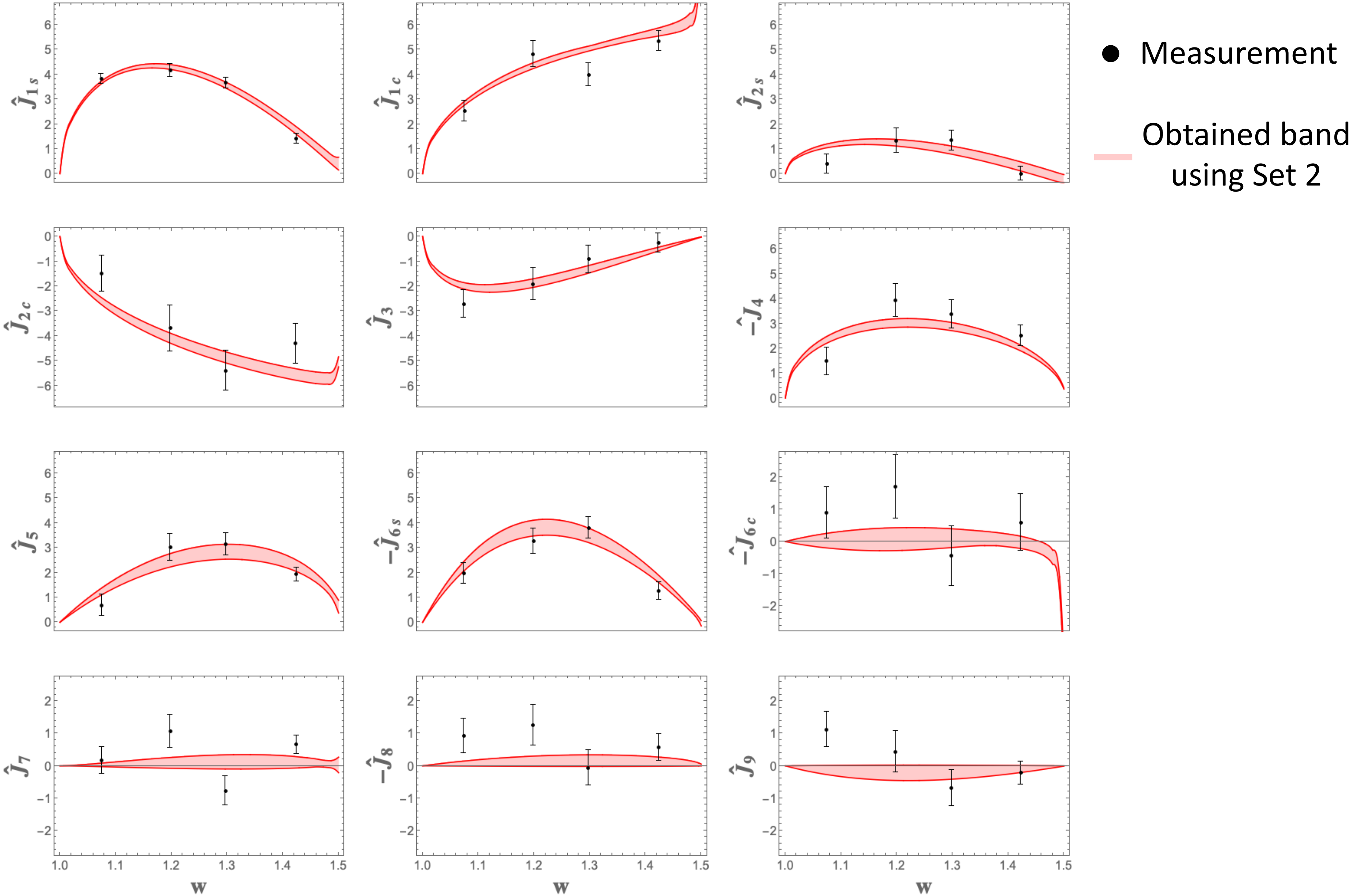
$$H_\pm = \frac{(m_B + m_V)^2 A_1(q^2) \mp \sqrt{\lambda(m_B^2, m_V^2, q^2)}V(q^2)}{m_B + m_V}$$

$$H_t = -\frac{\sqrt{\lambda(m_B^2, m_V^2, q^2)}}{\sqrt{q^2}} A_0(q^2)$$

q^2 dependence through Helicity Amplitudes parametrizing the matrix elements of different operators

$A_{0,1,2}$, V and $T_{0,1,2}$ parametrize respectively:

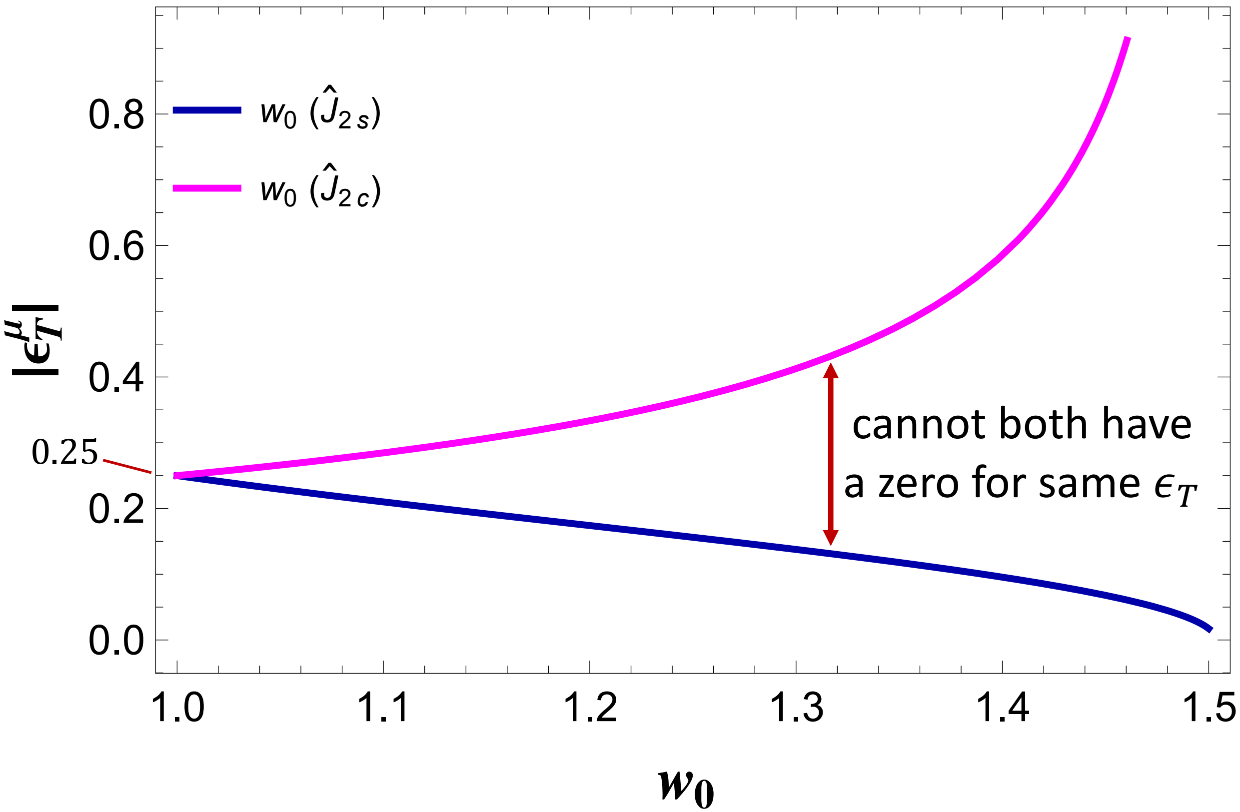
- $\langle V(p',\epsilon)|\bar{U}\gamma_\mu(1-\gamma_5)b|B(p)\rangle$
- $\langle V(p',\epsilon)|\bar{U}\sigma_{\mu\nu}b|B(p)\rangle$


Measurement
Obtained band using Set 2
w
w
w

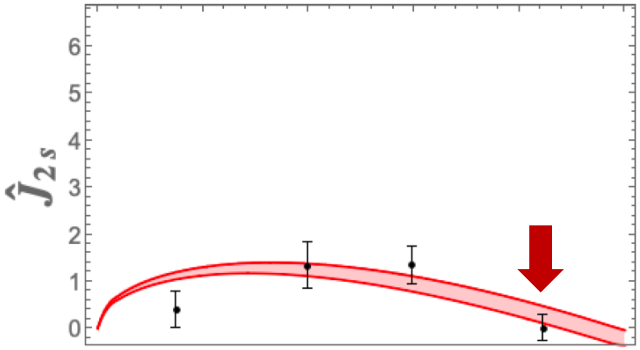
Observables

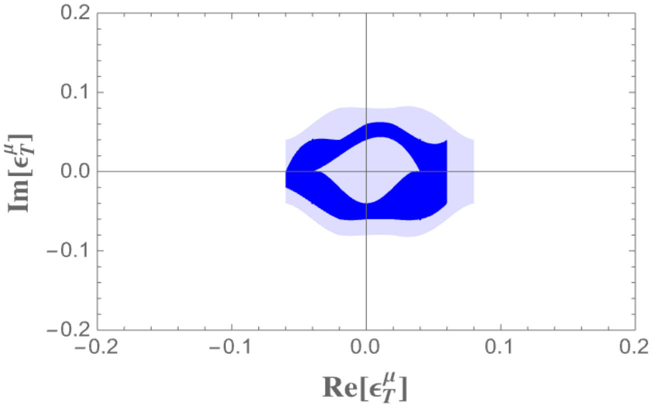
$w_0\ (\hat{J}_i)$ = Zero of the J_i angular coefficient function

$\epsilon_V = \epsilon_R = 0$



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

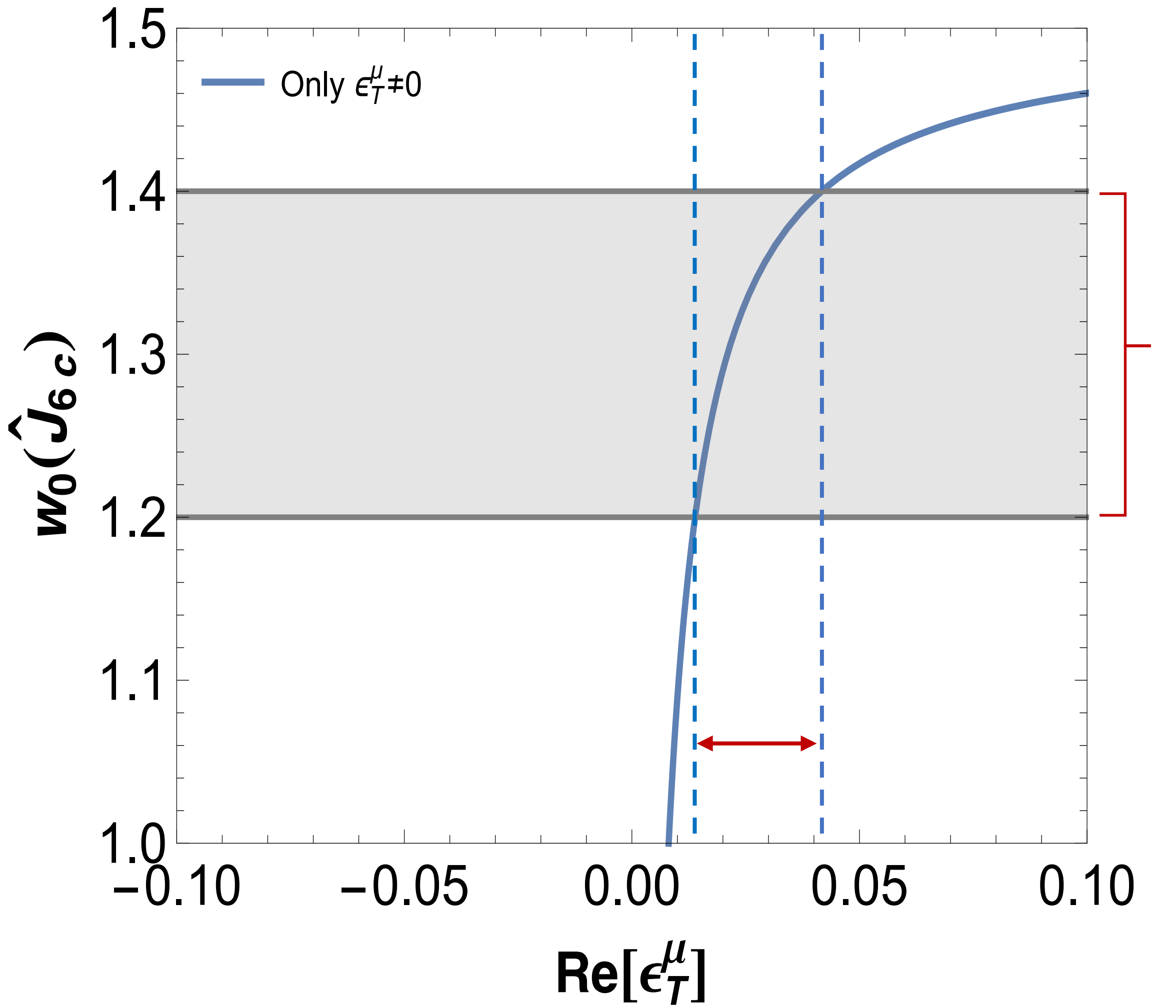




Observables

J_{6c}

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



Range compatible with Belle results

Small values of $Re[\epsilon_T]$

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

Semileptonic B_c decays

Expansion for the current up to $\mathcal{O}(\tilde{v}^3)$ and $\mathcal{O}(1/m_Q^2)$

$$\bar{Q}'(x)\Gamma Q(x) = J_0 + \left(\frac{J_{1,0}}{2m_Q} + \frac{J_{0,1}}{2m_{Q'}}\right) + \left(-\frac{J_{2,0}}{4m_Q^2} - \frac{J_{0,2}}{4m_{Q'}^2} + \frac{J_{1,1}}{4m_Q m_{Q'}}\right)$$

$$J_0 = \bar{\psi}'_+ \Gamma \psi_+$$

$$J_{1,0} = \bar{\psi}'_+ \Gamma\, i\, \overrightarrow{\not{D}}_\perp \psi_+$$

$$J_{0,1} = \bar{\psi}'_+ \left(-i\, \overleftarrow{\not{D}}'_\perp\right) \Gamma\, \psi_+$$

$$J_{2,0} = \bar{\psi}'_+ \Gamma \left(iv \cdot \overrightarrow{D}\right) i\, \overrightarrow{\not{D}}_\perp \psi_+$$

$$J_{0,2} = \bar{\psi}'_+\, i\, \overleftarrow{\not{D}}'_\perp \left(i\, v' \cdot \overleftarrow{D}\right) \Gamma\, \psi_+$$

$$J_{1,1} = \bar{\psi}'_+ \left(-i\, \overleftarrow{\not{D}}'_\perp\right) \Gamma \left(i\, \overrightarrow{\not{D}}_\perp\right) \psi_+$$

Overview

Tensions in the flavour sector

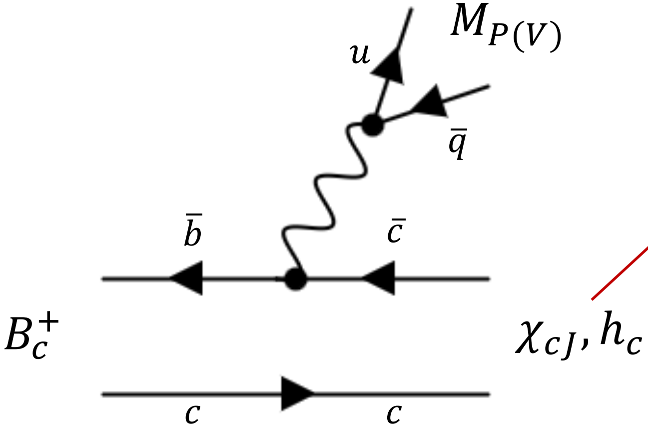
- Angular distribution function in $\bar{B} \to D^*(D\,\pi)\,\ell\,\bar{\nu}_\ell$ process
- Semileptonic B_c meson decay to charmonium states
- Nonleptonic B_c meson decay to orbitally excited charmonium states

Interplay between flavour physics and hadron spectroscopy

- Dalitz decays of positive parity charmed mesons

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

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

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

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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	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,K^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c0}\,K^+)}$	$\frac{\mathcal{B}(B_c^+\to h_c\,K^+)}{\mathcal{B}(B_c^+\to\chi_{c2}\,K^+)}$
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	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c1}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$	$\frac{\mathcal{B}(B_c^+\to\chi_{c0}K^{*+})}{\mathcal{B}(B_c^+\to\chi_{c2}K^{*+})}$
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$1P$	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

Search for the $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay LHCb Collaboration Roel Aaij (Nikhef, Amsterdam) et al.: 2503.20039 [hep-ex]