Constraints on New Physics couplings from $\bar{B} \to D^*(D\,\pi)\,\ell\,\bar{\nu}_\ell$ analysis

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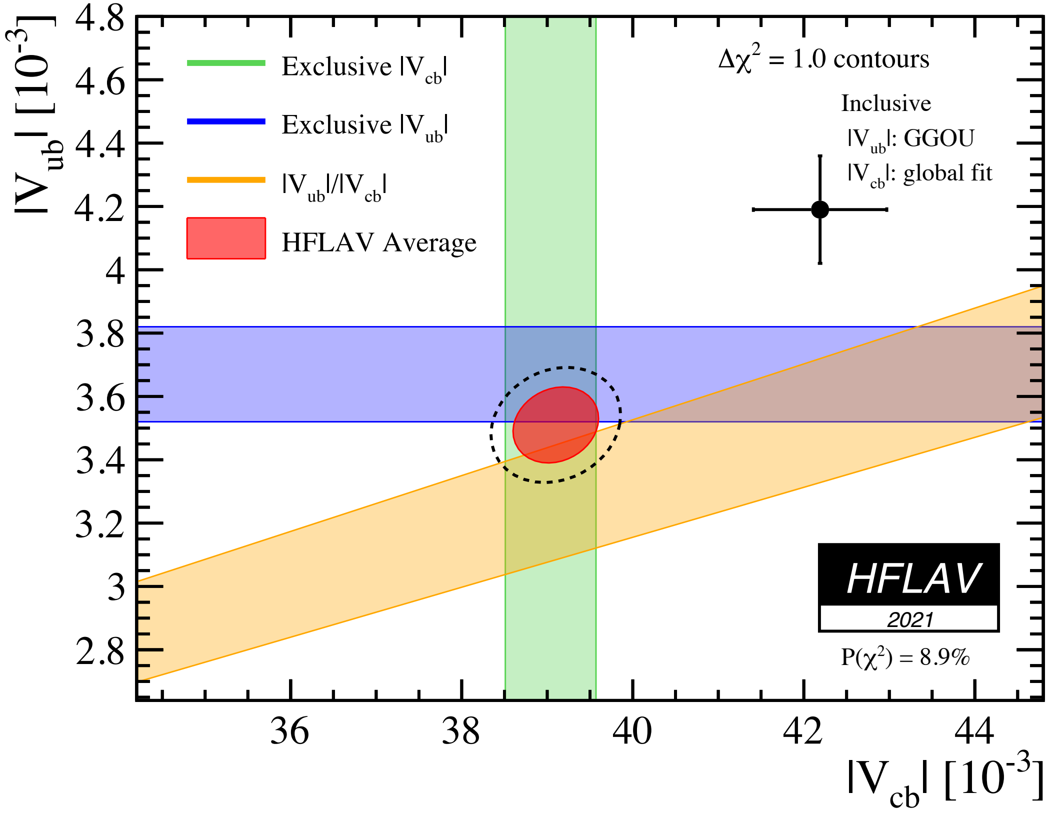
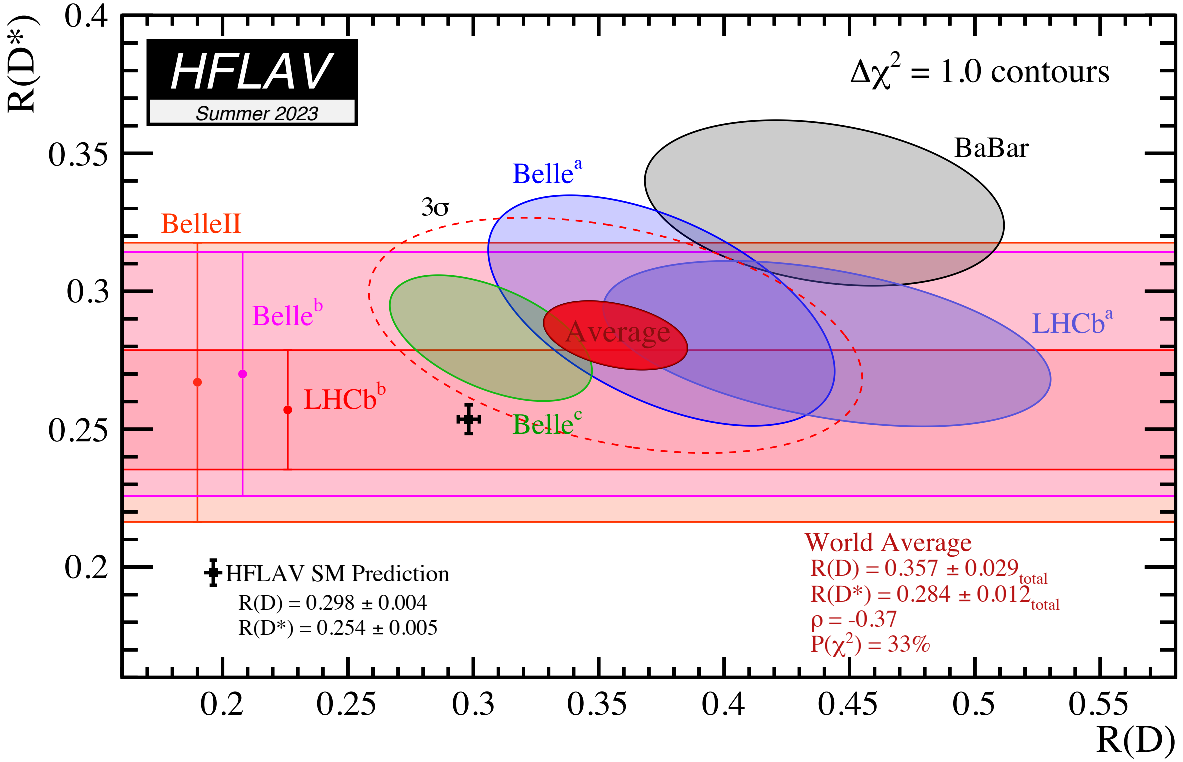
Based on: New Physics couplings from angular coefficient functions of $\bar{B} \to D^*(D\,\pi)\,\ell\,\bar{\nu}_\ell$, Phys. Rev. D, 109 (2024) no.7, 075047 [arXiv:2401.12304 [hep-ph]], **P. Colangelo, F. De Fazio, F. Loparco**, **N.L.**

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

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





Lepton Flavour Universality Violation (LFUV)

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

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

Possibility to investigate NP that can explain both anomalies

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 $V = D^*$

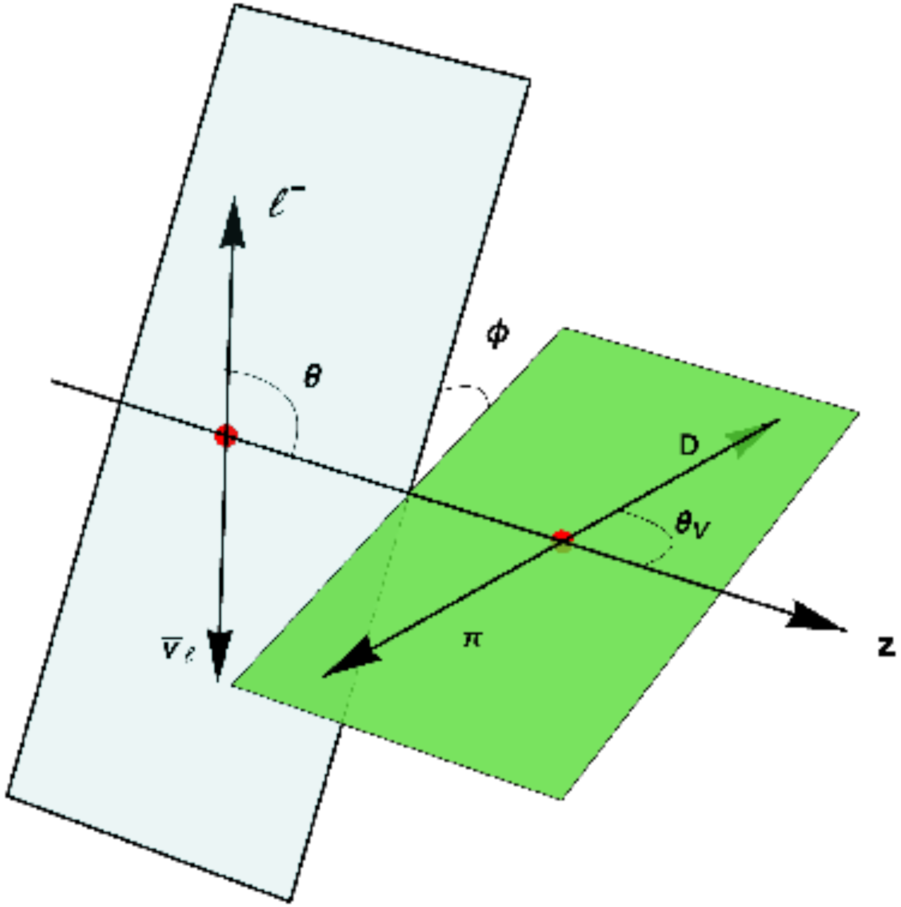
$\epsilon_i^\ell \neq 0$ new physics contributions lepton flavour dependent

possibility to extract V_{Ub} CKM matrix element

Angular decomposition

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

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



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

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

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

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

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

Only for $m_\ell \neq 0$ in SM

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

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

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

Only in presence of NP

Angular Coefficient Functions

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

$i = 1s, \dots, 6c$

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

V-A current

$$H_0 = \frac{1}{2m_V(m_B+m_V)\sqrt{q^2}} \left((m_B+m_V)^2(m_B^2-m_V^2-q^2)A_1(q^2) - \lambda(m_B^2, m_V^2, q^2)A_2(q^2)\right)$$

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

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

Tensor current

$$H_\pm^{NP} = \frac{1}{\sqrt{q^2}}\left\{q^2(T_1(q^2) - T_2(q^2)) + \left(m_B^2 - m_V^2 \pm \sqrt{\lambda(m_B^2, m_V^2, q^2)}\right)(T_1(q^2) + T_2(q^2))\right\}$$

$$H_L^{NP} = 4\left\{\frac{\lambda(m_B^2, m_V^2, q^2)}{m_V(m_B+m_V)^2} T_0(q^2) + 2\frac{m_B^2 + m_V^2 - q^2}{m_V} T_1(q^2) + 4m_V T_2(q^2)\right\}$$

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:

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

Experimental results

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

Full set of angular coefficient functions from Belle Collaboration

M. T. Prim et al. (Belle), (2023), arXiv:2310.20286[hep-ex]

Experimental results taken from plots presented in term of

$$F = \frac{3|\vec{p}_{D^*}|}{2^{10}\, m_B^5}$$

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

Integrated width modulo a constant

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

$$\bar{J}_i^a = \int_{\Delta w^{(a)}} J_i\,(\mathrm{w})\mathrm{dw}$$

In 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

Boyd, Grinstein, and Lebed

Caprini, Lellouch, and Neubert

BGL and CLN

Evaluation of the hadronic form factors and improvement on $|V_{cb}|$

Results

w dependence of the form factors needed → Use of CLN parametrization
P. Colangelo, F. De Fazio, JHEP 06, 082 (2018)

From the theoretical expression of I_i and fixing N from the known BR we get

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

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

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

Found to be 2.5

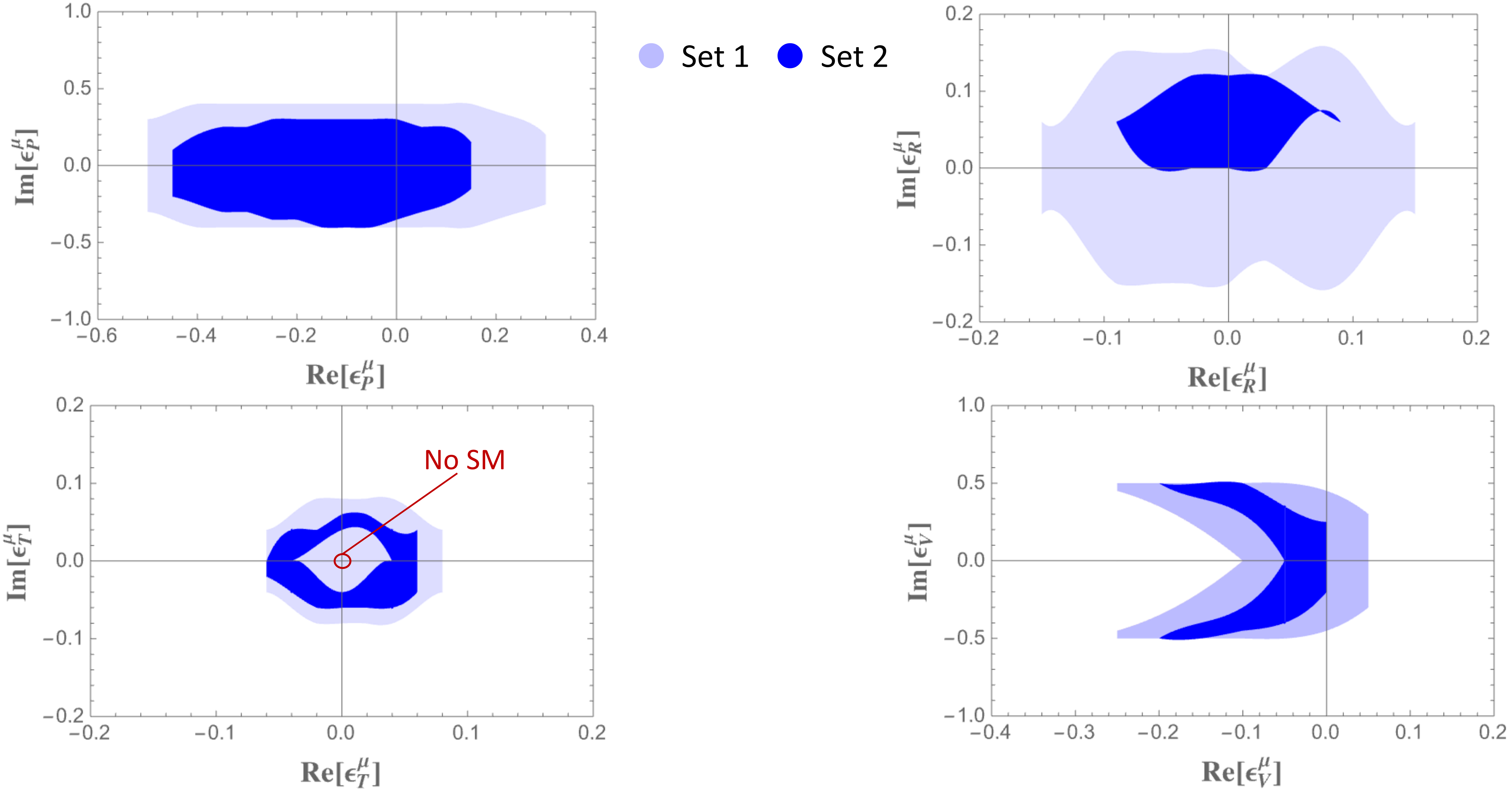
$\sigma_i \cdot (\Delta w)^a$

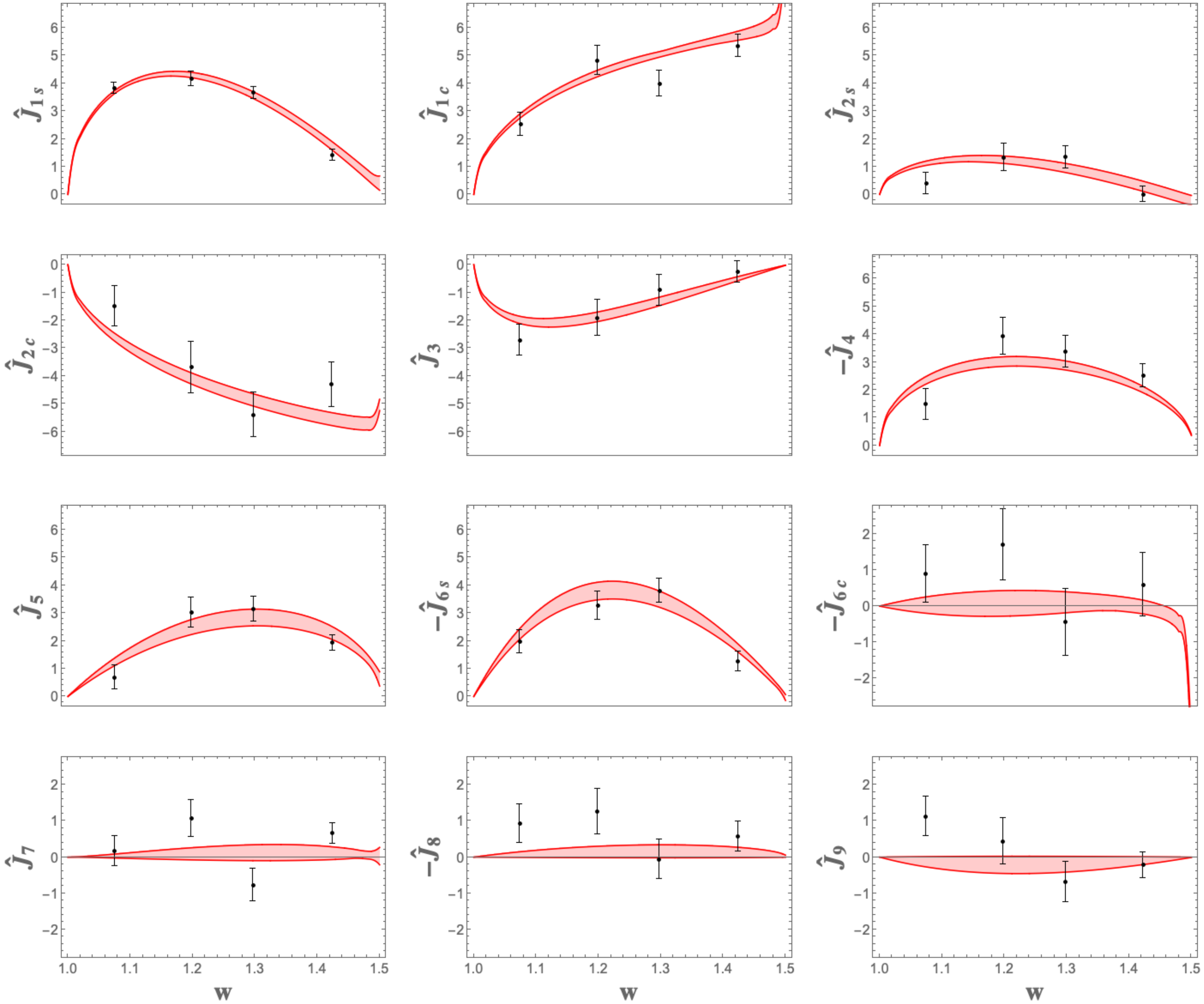
Set 1 $\epsilon_V^\mu, \epsilon_R^\mu, \epsilon_p^\mu, \epsilon_T^\mu$

2° constraint

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

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


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



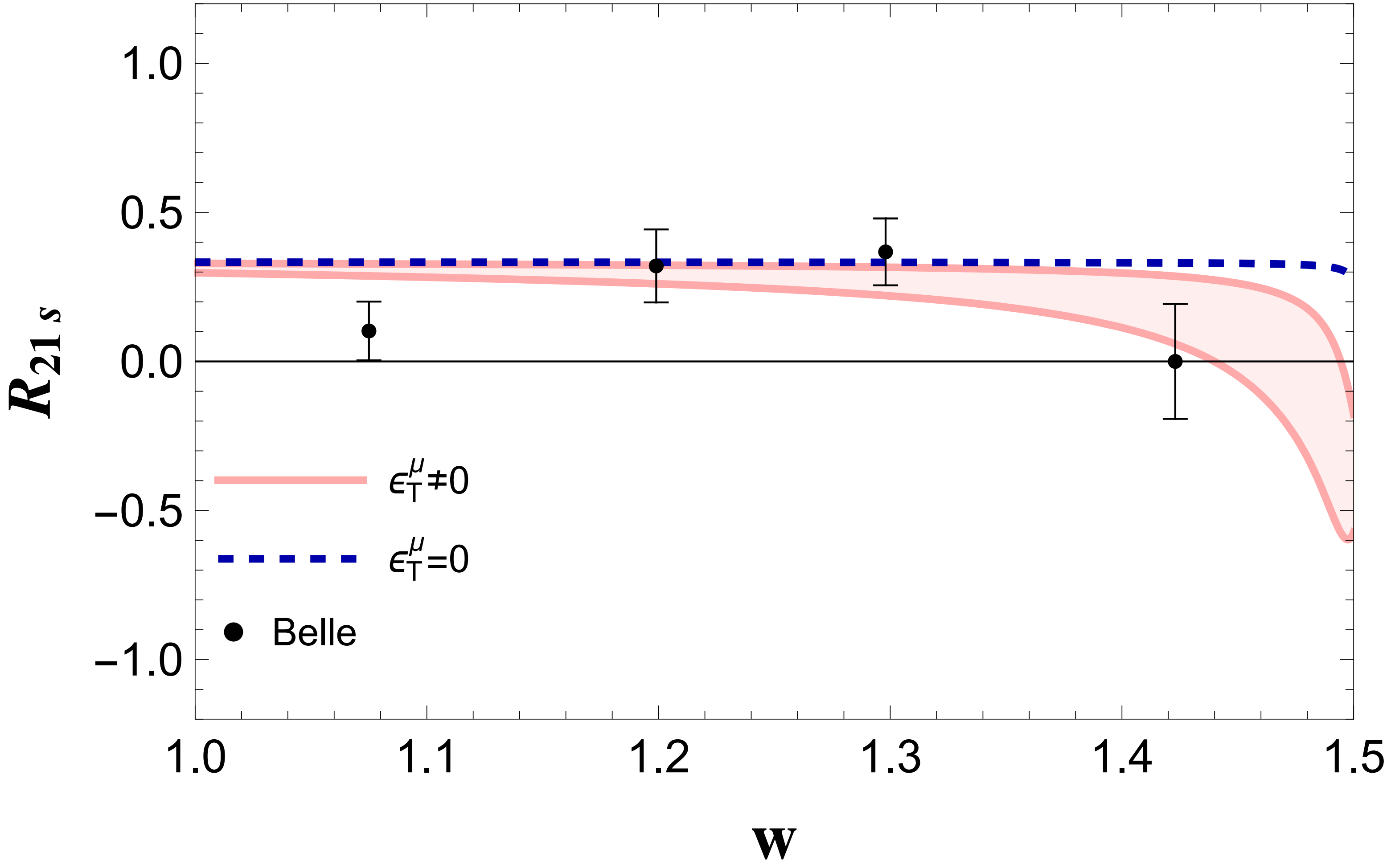
● Measurement

Obtained band using Set 2

Observables

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

Do NOT depend on ϵ_P



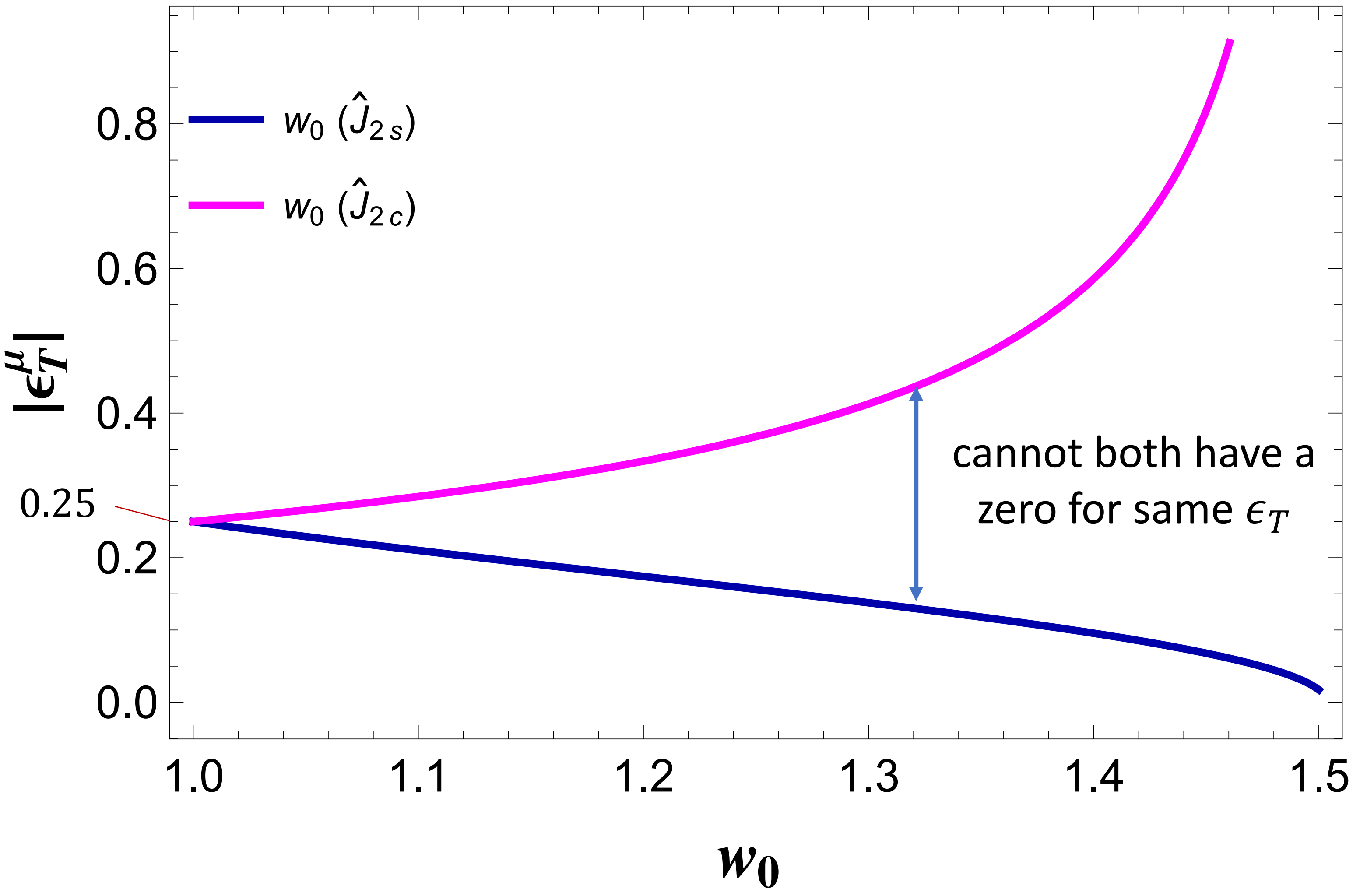
$\epsilon_T = 0$ ➡ Insensitive to ϵ_V and ϵ_R

⬇

Different behaviours imply presence of tensor operator

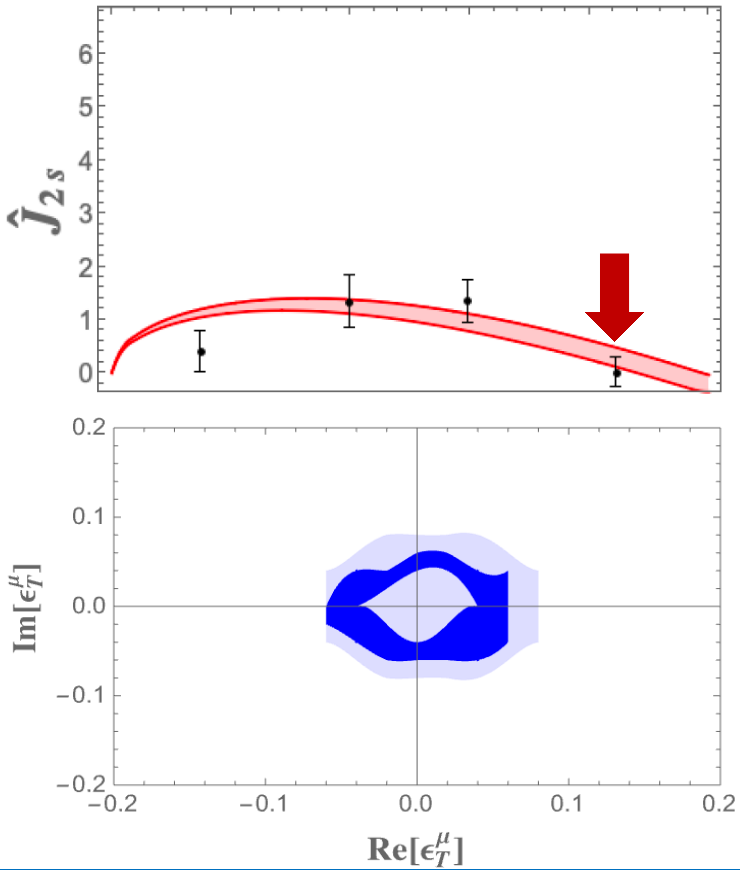
Observables

$\epsilon_V = \epsilon_R = 0$



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

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

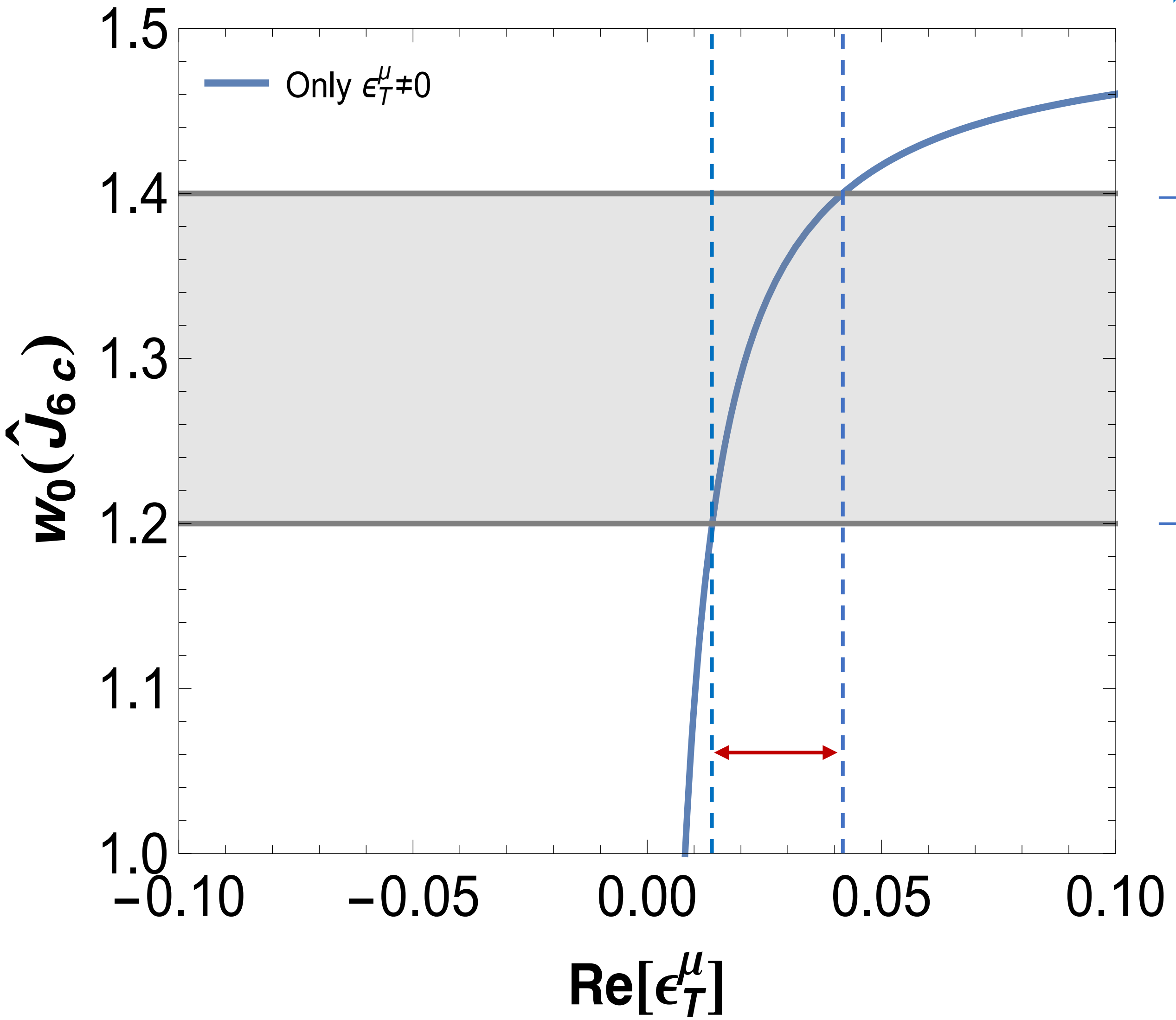


Observables

$\epsilon_V = \epsilon_R = \epsilon_P = 0$

J_{6c}

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



Range compatible with Belle results

Small values of $Re[\epsilon_T]$

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

Conclusions

Belle measurements allow us to constrain NP couplings

We have shown:

- the allowed NP parameter space
- the angular coefficient functions fitting the data
- NP sensitive observables
  - $R_{21s}(w)$ sensitive to ϵ_T
  - NP parameters dependence of the zeros of some angular coefficient functions $\hat{J}_{2s}, \hat{J}_{2c}, \hat{J}_{6c}$

Analysis compatible with the possibility of NP tensor operator

THANKS
FOR YOUR
ATTENTION

Backup Slides

Angular Coefficient Functions Expression

SM		Right		Right-SM
i	I_i^{SM}	i	$I_i^{\mathrm{NP},R}$	$I_i^{\mathrm{INT},R}$
I_{1s}	$\frac{1}{2}(H_+^2+H_-^2)(m_\ell^2+3q^2)$	I_{1s}	$\frac{1}{2}(H_+^2+H_-^2)(m_\ell^2+3q^2)$	$-H_-H_+(m_\ell^2+3q^2)$
I_{1c}	$4m_\ell^2H_t^2+2H_0^2(m_\ell^2+q^2)$	I_{1c}	$4m_\ell^2H_t^2+2H_0^2(m_\ell^2+q^2)$	$-2(2H_t^2m_\ell^2+H_0^2(m_\ell^2+q^2))$
I_{2s}	$-\frac{1}{2}(H_+^2+H_-^2)(m_\ell^2-q^2)$	I_{2s}	$-\frac{1}{2}(H_+^2+H_-^2)(m_\ell^2-q^2)$	$H_-H_+(m_\ell^2-q^2)$
I_{2c}	$2H_0^2(m_\ell^2-q^2)$	I_{2c}	$2H_0^2(m_\ell^2-q^2)$	$-2H_0^2(m_\ell^2-q^2)$
I_3	$2H_+H_-(m_\ell^2-q^2)$	I_3	$2H_+H_-(m_\ell^2-q^2)$	$-(H_+^2+H_-^2)(m_\ell^2-q^2)$
I_4	$H_0(H_++H_-)(m_\ell^2-q^2)$	I_4	$H_0(H_++H_-)(m_\ell^2-q^2)$	$-H_0(H_++H_-)(m_\ell^2-q^2)$
I_5	$-2H_t(H_++H_-)m_\ell^2-2H_0(H_+-H_-)q^2$	I_5	$-2H_t(H_++H_-)m_\ell^2+2H_0(H_+-H_-)q^2$	$2H_t(H_++H_-)m_\ell^2$
I_{6s}	$2(H_+^2-H_-^2)q^2$	I_{6s}	$-2(H_+^2-H_-^2)q^2$	0
I_{6c}	$-8H_tH_0m_\ell^2$	I_{6c}	$-8H_tH_0m_\ell^2$	$8H_0H_tm_\ell^2$
I_7	0	I_7	0	$2(H_+-H_-)H_tm_\ell^2$
I_8	0	I_8	0	$-H_0(H_+-H_-)(m_\ell^2-q^2)$
I_9	0	I_9	0	$-(H_+^2-H_-^2)(m_\ell^2-q^2)$

Angular Coefficient Functions Expression

	Pseudoscalar	Pseudo-SM
i	$I_i^{\mathrm{NP},P}$	$I_i^{\mathrm{INT},P}$
I_{1s}	0	0
I_{1c}	$4H_t^2\frac{q^4}{(m_b+m_U)^2}$	$4H_t^2\frac{m_\ell q^2}{m_b+m_U}$
I_{2s}	0	0
I_{2c}	0	0
I_3	0	0
I_4	0	0
I_5	0	$-H_t(H_+ + H_-)\frac{m_\ell q^2}{m_b+m_U}$
I_{6s}	0	0
I_{6c}	0	$-4H_tH_0\frac{m_\ell q^2}{m_b+m_U}$
I_7	0	$-H_t(H_+ - H_-)\frac{m_\ell q^2}{m_b+m_U}$
I_8	0	0
I_9	0	0

	Tensor	Tensor-SM
i	$I_i^{\mathrm{NP},T}$	$I_i^{\mathrm{INT},T}$
I_{1s}	$2[(H_+^{\mathrm{NP}})^2+(H_-^{\mathrm{NP}})^2](3m_\ell^2+q^2)$	$-4(H_+^{\mathrm{NP}}H_+ + H_-^{\mathrm{NP}}H_-)m_\ell\sqrt{q^2}$
I_{1c}	$\frac{1}{8}(H_L^{\mathrm{NP}})^2(m_\ell^2+q^2)$	$-H_L^{\mathrm{NP}}H_0 m_\ell\sqrt{q^2}$
I_{2s}	$2[(H_+^{\mathrm{NP}})^2+(H_-^{\mathrm{NP}})^2](m_\ell^2-q^2)$	0
I_{2c}	$\frac{1}{8}(H_L^{\mathrm{NP}})^2(q^2-m_\ell^2)$	0
I_3	$8H_+^{\mathrm{NP}}H_-^{\mathrm{NP}}(q^2-m_\ell^2)$	0
I_4	$\frac{1}{2}H_L^{\mathrm{NP}}(H_+^{\mathrm{NP}}+H_-^{\mathrm{NP}})(q^2-m_\ell^2)$	0
I_5	$-H_L^{\mathrm{NP}}(H_+^{\mathrm{NP}}-H_-^{\mathrm{NP}})m_\ell^2$	$\frac{1}{4}[H_L^{\mathrm{NP}}(H_+ - H_-)+8H_+^{\mathrm{NP}}(H_t+H_0)+8H_-^{\mathrm{NP}}(H_t-H_0)]m_\ell\sqrt{q^2}$
I_{6s}	$8[(H_+^{\mathrm{NP}})^2-(H_-^{\mathrm{NP}})^2]m_\ell^2$	$-4(H_+^{\mathrm{NP}}H_+ - H_-^{\mathrm{NP}}H_-)m_\ell\sqrt{q^2}$
I_{6c}	0	$H_L^{\mathrm{NP}}H_t m_\ell\sqrt{q^2}$
I_7	0	$\frac{1}{4}[H_L^{\mathrm{NP}}(H_+ + H_-)-8H_+^{\mathrm{NP}}(H_t+H_0)+8H_-^{\mathrm{NP}}(H_t-H_0)]m_\ell\sqrt{q^2}$
I_8	0	0
I_9	0	0

Angular Coefficient Functions Expression

i	Pseudo-Right $I_i^{\text{INT},PR}$	Right-Tensor $I_i^{\text{INT},RT}$	Pseudo-Tensor $I_i^{\text{INT},PT}$
I_{1s}	0	$4(H_-^{\text{NP}}H_+ + H_-H_+^{\text{NP}})m_\ell\sqrt{q^2}$	0
I_{1c}	$-4H_t^2 m_\ell \frac{q^2}{m_b+m_U}$	$H_0\, H_L^{\text{NP}} m_\ell\sqrt{q^2}$	0
I_{2s}	0	0	0
I_{2c}	0	0	0
I_3	0	0	0
I_4	0	0	0
I_5	$(H_+ + H_-)H_t m_\ell \frac{q^2}{m_b+m_U}$	$\frac{1}{4}[H_L^{\text{NP}}(H_+ - H_-) - 8H_+^{\text{NP}}(H_t + H_0) - 8H_-^{\text{NP}}(H_t - H_0)]m_\ell\sqrt{q^2}$	$2H_t(H_+^{\text{NP}} + H_-^{\text{NP}})\frac{(q^2)^{3/2}}{m_b+m_U}$
I_{6s}	0	$4(-H_-^{\text{NP}}H_+ + H_-H_+^{\text{NP}})m_\ell\sqrt{q^2}$	0
I_{6c}	$4H_0H_t m_\ell \frac{q^2}{m_b+m_U}$	$-H_t\, H_L^{\text{NP}} m_\ell\sqrt{q^2}$	$H_t\, H_L^{\text{NP}}\frac{(q^2)^{3/2}}{m_b+m_U}$
I_7	$-H_t(H_+ - H_-)m_\ell \frac{q^2}{m_b+m_U}$	$\frac{1}{4}[H_L^{\text{NP}}(H_+ + H_-) - 8H_+^{\text{NP}}(H_t + H_0) + 8H_-^{\text{NP}}(H_t - H_0)]m_\ell\sqrt{q^2}$	$2H_t(H_+^{\text{NP}} - H_-^{\text{NP}})\frac{(q^2)^{3/2}}{m_b+m_U}$
I_8	0	0	0
I_9	0	0	0