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

Nicola Losacco

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

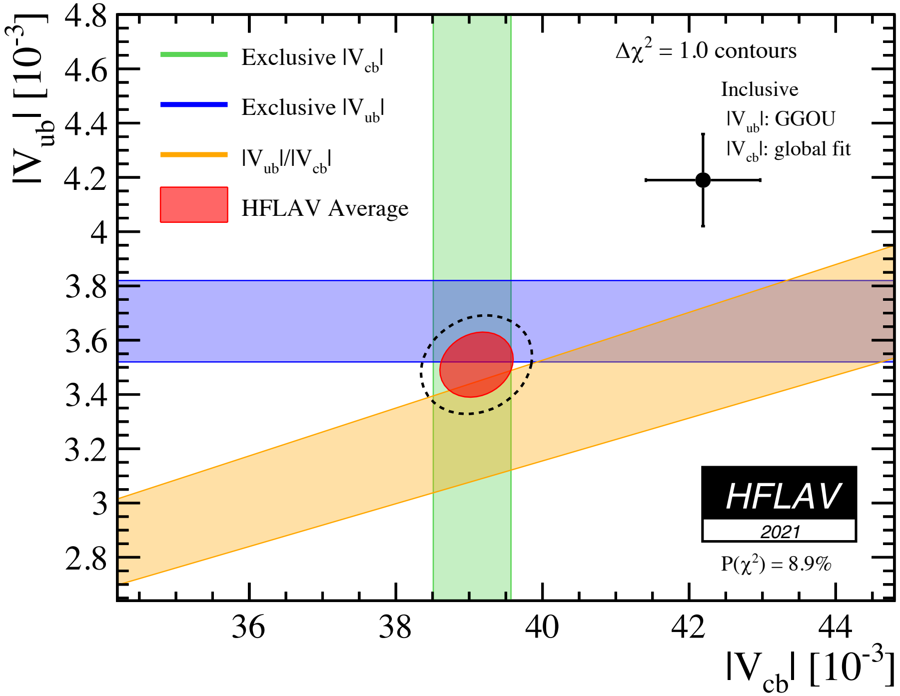
3-9 March 2024

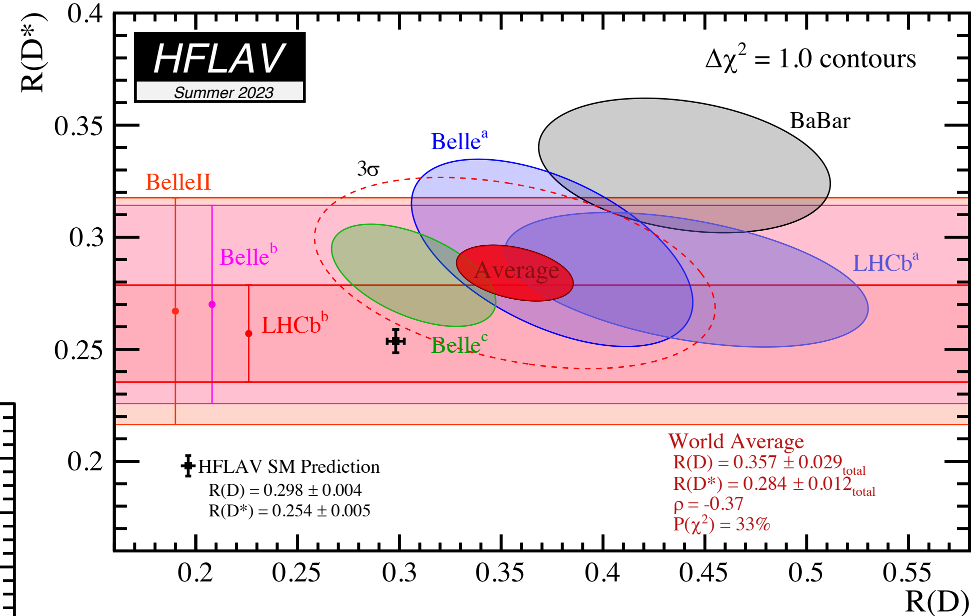
LA THUILE 2024 - Les Rencontres de Physique de la Vallée d'Aoste

Based on: New Physics couplings from angular coefficient functions of $\bar{B} \to D^*(D\,\pi)\,\ell\,\bar{\nu}_\ell$, [arXiv: 2401.12304 [hep-ph]], **P. Colangelo, F. De Fazio, F. Loparco**, **N.L.**

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

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





Lepton Flavour Universality Violation (LFUV)

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

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

Possibility to investigate NP that can explain both anomalies

Generalized effective Hamiltonian

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

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

For $V = D^*$

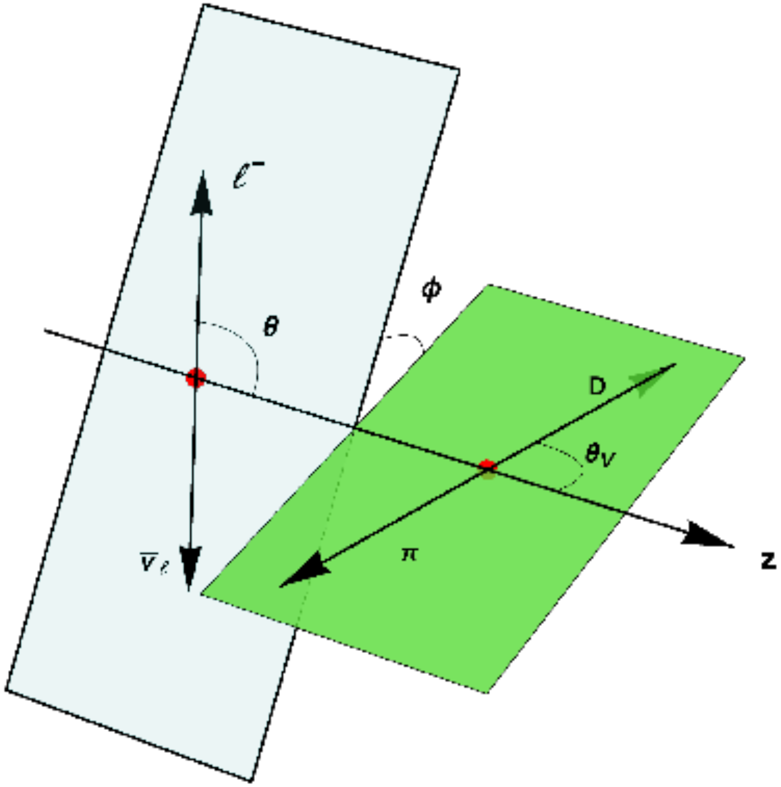
$\epsilon_i^\ell \neq 0$ new physics contributions lepton flavour dependent

possibility to extract V_{Ub} CKM matrix element

Angular decomposition

$$\mathcal{N} = \frac{3G_F^2 |V_{Ub}|^2 \mathcal{B}(V \to P_1 P_2)}{128(2\pi)^4 m_B^2}$$

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



$$\frac{d^4\Gamma(\bar{B} \to V(P_1 P_2)\ell^- \bar{\nu}_\ell)}{dq^2\, d\cos\theta\, d\phi\, d\cos\theta_V} = \mathcal{N} |\vec{p}_V| \left(1 - \frac{m_\ell^2}{q^2}\right)^2$$

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

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

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

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

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

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

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

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

Only in presence of NP

Angular Coefficient Functions

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

$i = 1, \dots, 6$

I_i functions properties:

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

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

$i = 8, 9$

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

Angular Coefficient Functions

Tensor current

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

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

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

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

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:

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

Experimental results

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

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

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

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

Integrated width modulo a constant

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

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

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

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

2 possible uses

NP contribution considered → Constraints on NP parameters ϵ_i^ℓ

P. Colangelo, F. De Fazio, F. Loparco, N.L., [arXiv: 2401.12304 [hep-ph]]

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

Boyd, Grinstein, and Lebed — Caprini, Lellouch, and Neubert → BGL and CLN

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

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

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

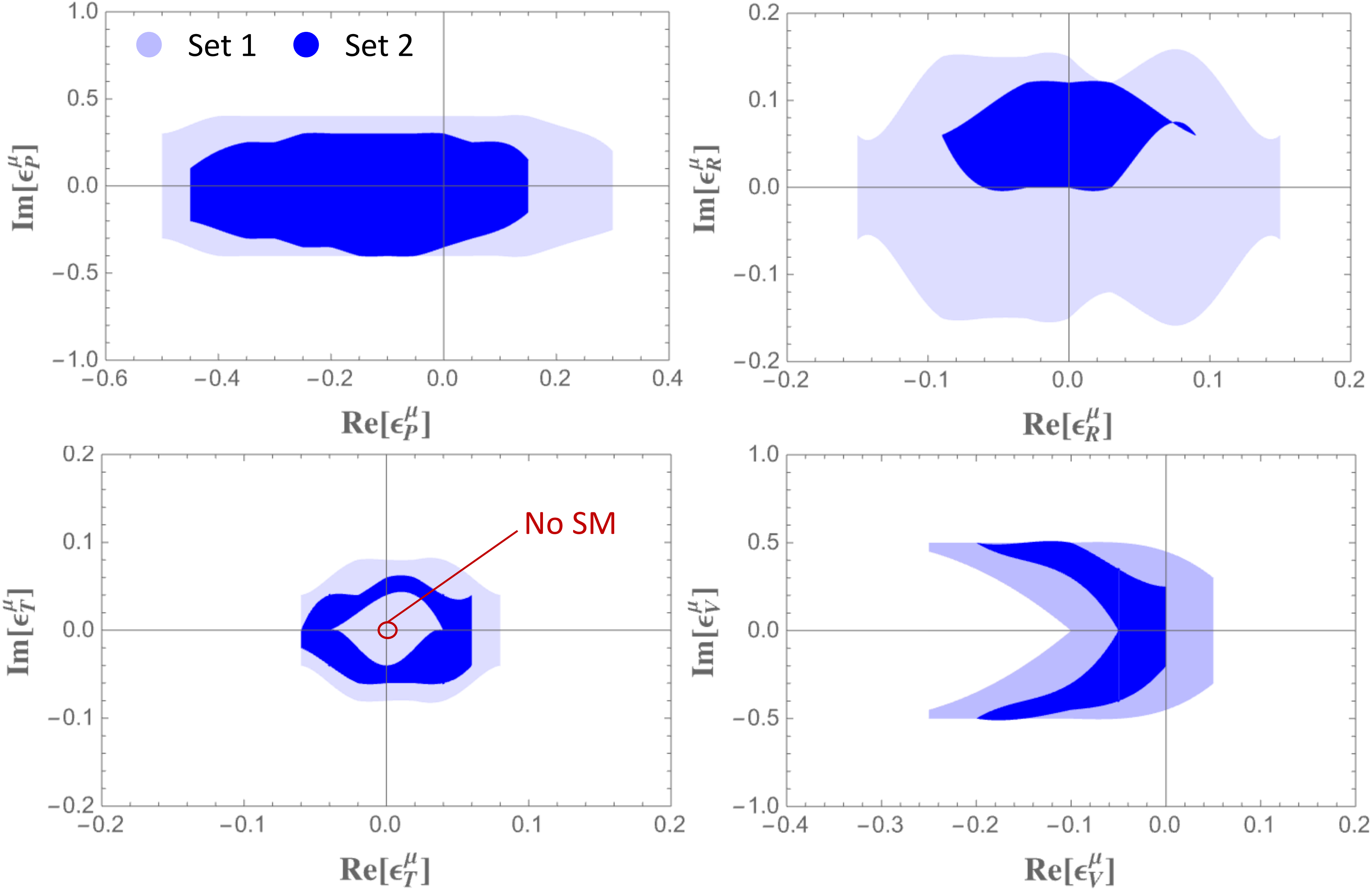
Found to be 2.5

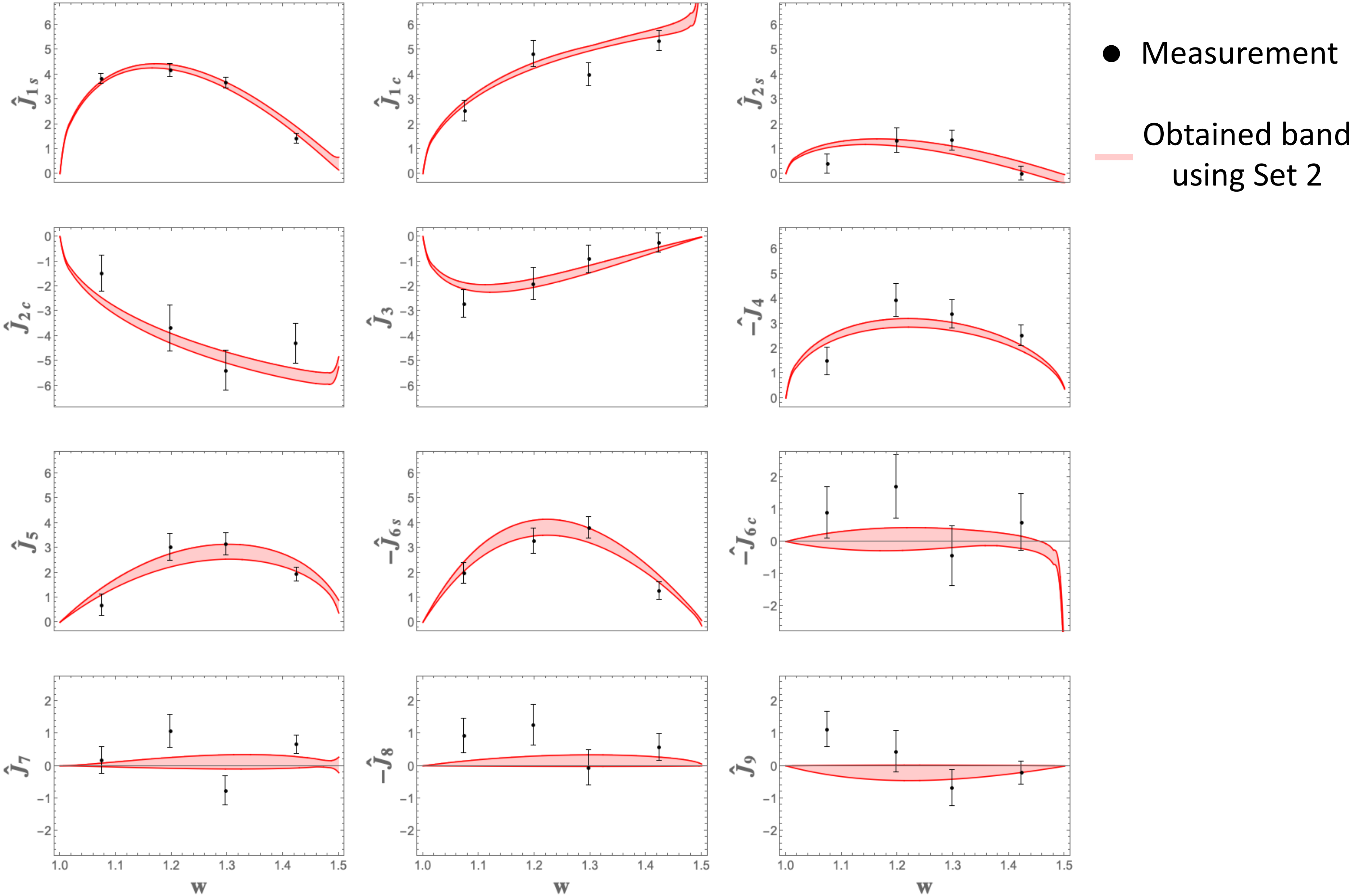
Set 1 $\epsilon_V^\mu, \epsilon_R^\mu, \epsilon_p^\mu, \epsilon_T^\mu$

2° constraint

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

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


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

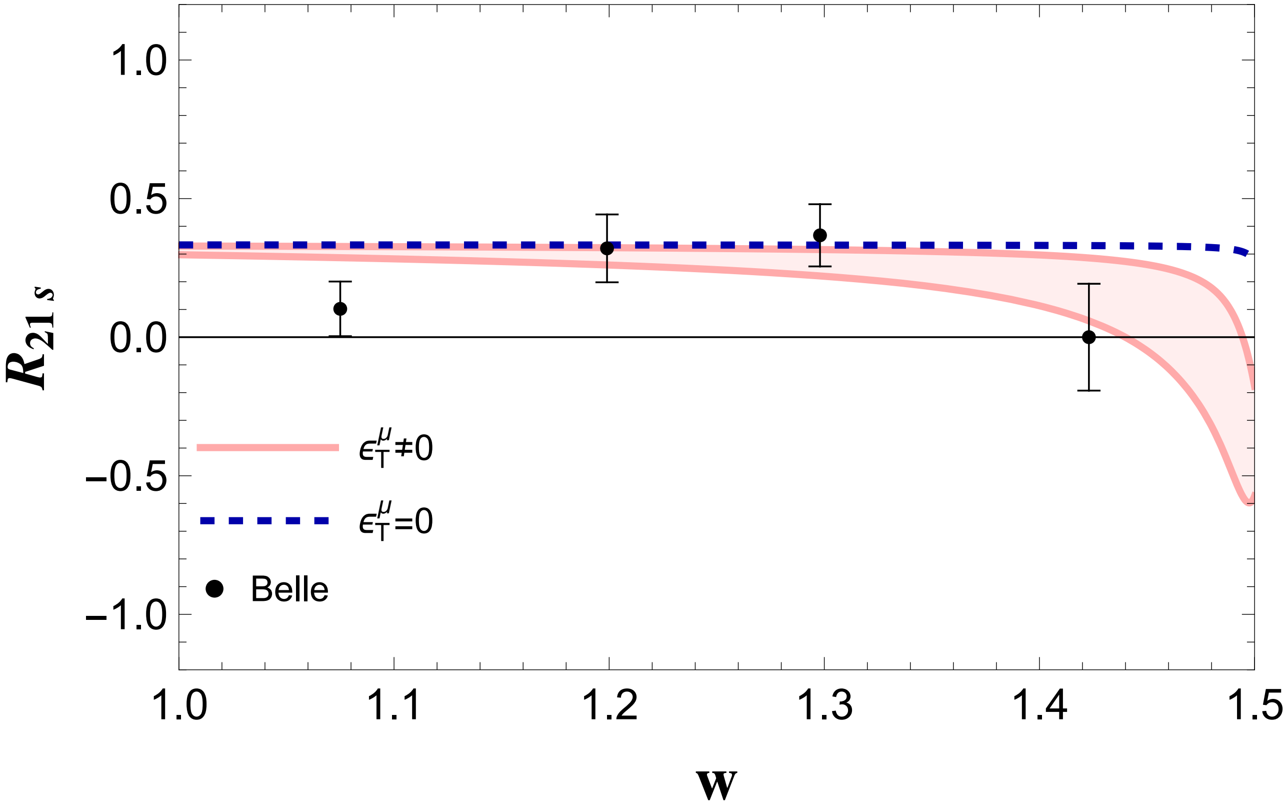


Measurement
Obtained band using Set 2
$\hat{J}_{1s}$
$\hat{J}_{1c}$
$\hat{J}_{2s}$
$\hat{J}_{2c}$
$\hat{J}_3$
$-\hat{J}_4$
$\hat{J}_5$
$-\hat{J}_{6s}$
$-\hat{J}_{6c}$
$\hat{J}_7$
$-\hat{J}_8$
$\hat{J}_9$
w

Observables

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

Do NOT depend on ϵ_P



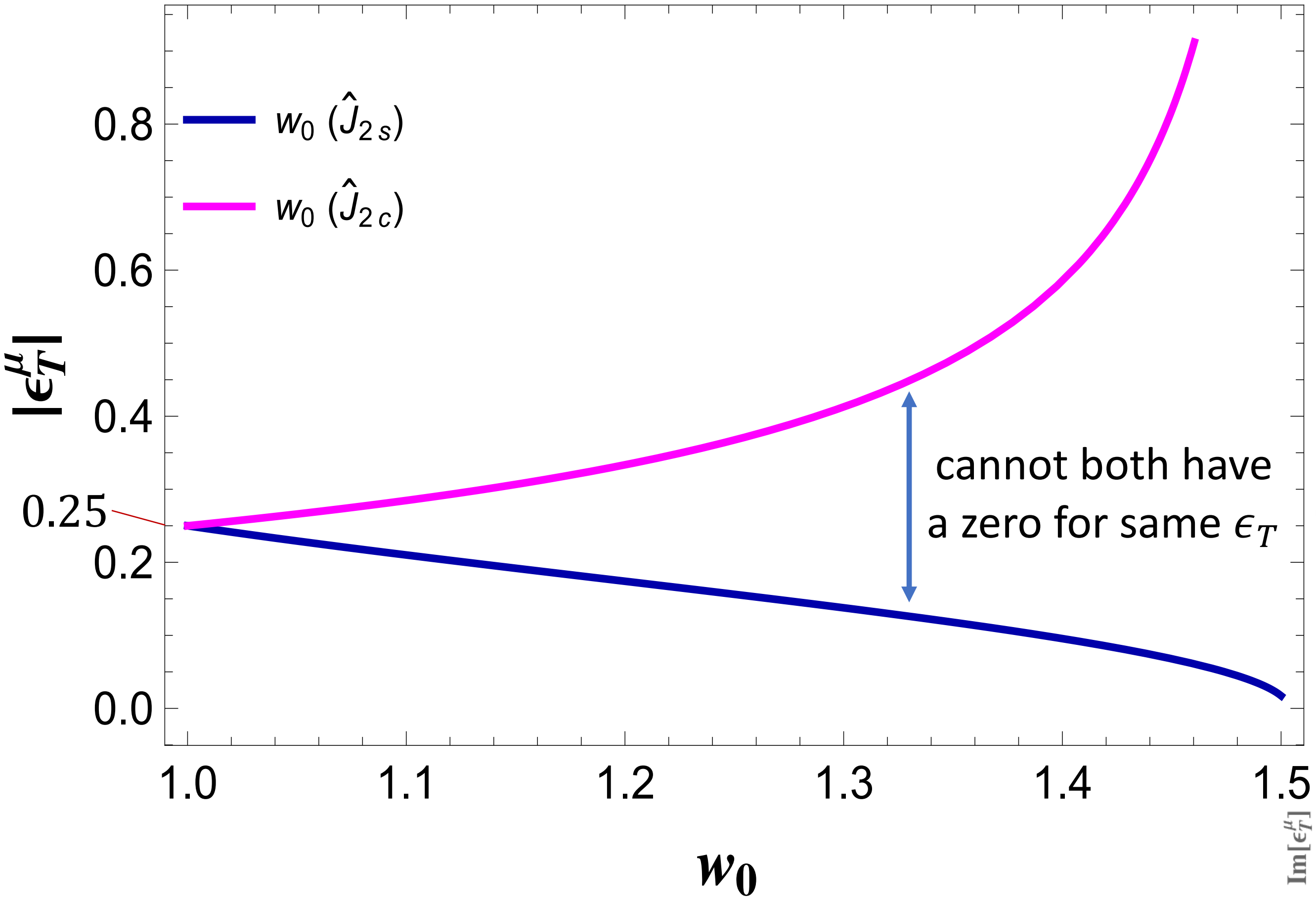
$\epsilon_T = 0$ → Insensitive to ϵ_V and ϵ_R

↓

Different behaviours imply presence of tensor operator

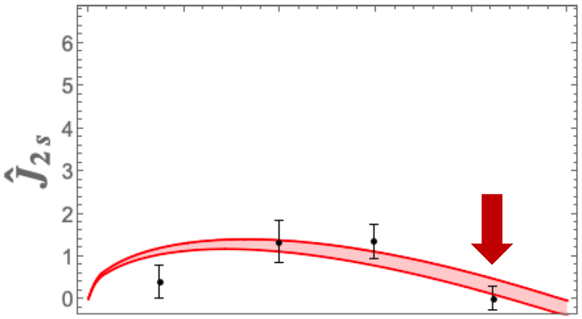
Observables

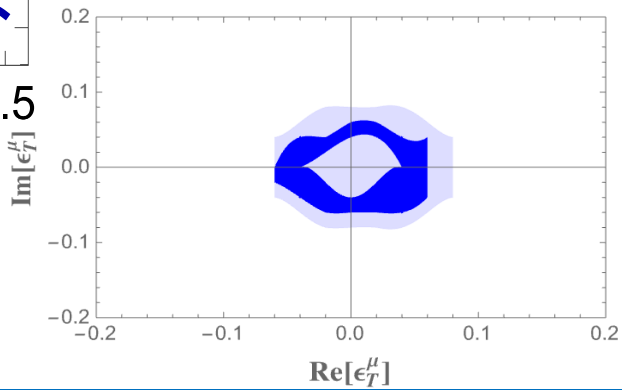
$\epsilon_V = \epsilon_R = 0$



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

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

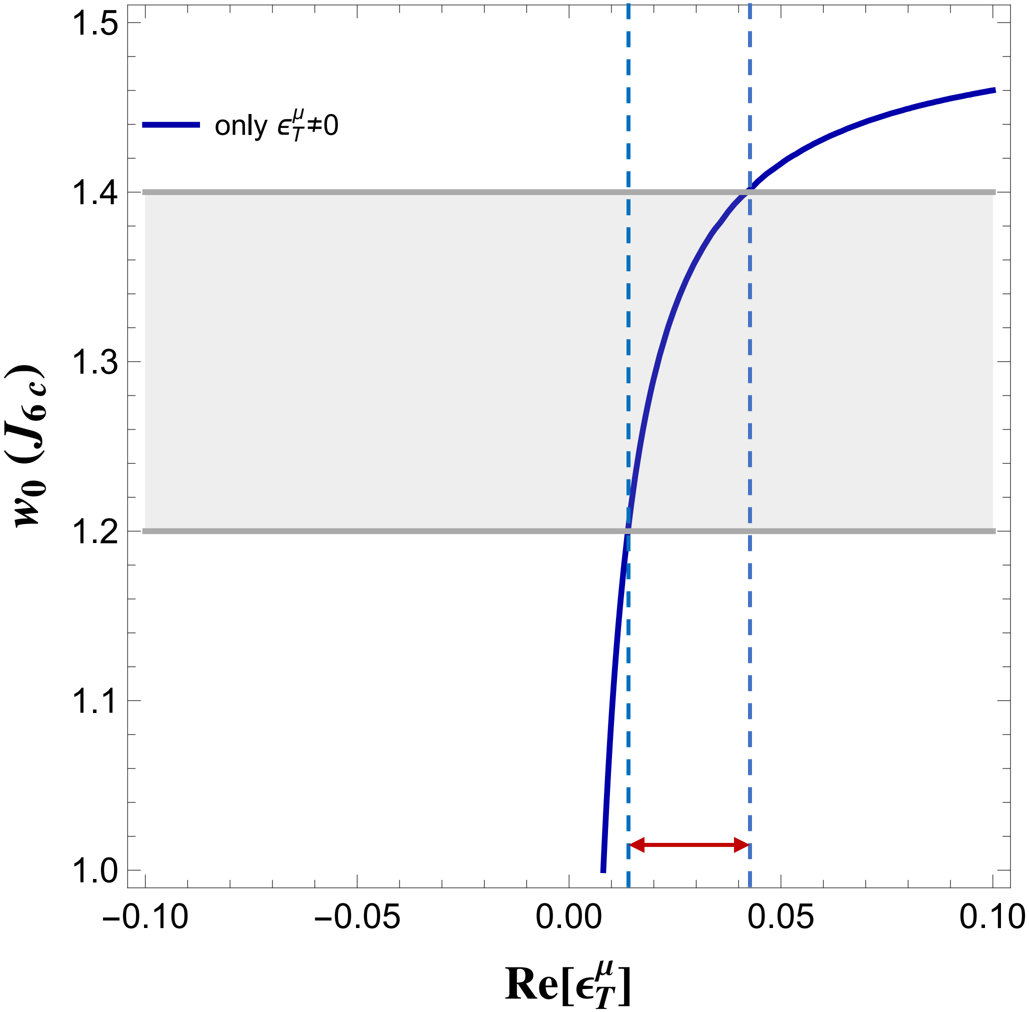




Observables

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

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

The public table of measurements and the covariance error matrix are waited to improve this analysis

THANKS
FOR YOUR
ATTENTION

Backup Slides

Angular Coefficient Functions Expression

	SM		Right	Right-SM
i	I_i^{SM}	i	$I_i^{\text{NP},R}$	$I_i^{\text{INT},R}$
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}	$\frac{1}{8}(H_L^{\mathrm{NP}})^2(m_\ell^2+q^2)$	$-H_L^{\mathrm{NP}}H_0m_\ell\sqrt{q^2}$
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	$H_L^{\mathrm{NP}}H_tm_\ell\sqrt{q^2}$
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}	$4H_0 H_t m_\ell \frac{q^2}{m_b+m_U}$	$-H_t\, H_L^{\text{NP}} m_\ell \sqrt{q^2}$	$H_t\, H_L^{\text{NP}} \frac{(q^2)^{3/2}}{m_b+m_U}$
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