

Polarisation in heavy meson decays

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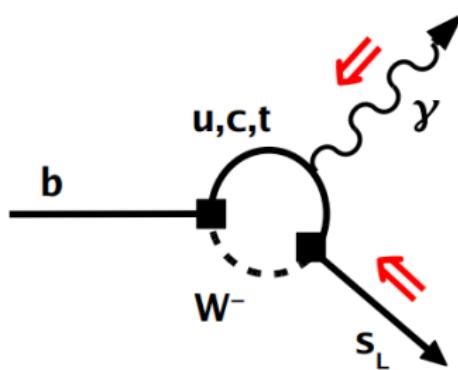
16 December 2020



Introduction

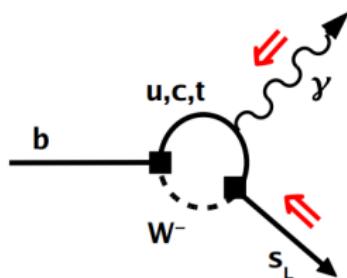
- I will review the measurements of polarisation of decay products in B meson decays (and some of b baryons).
- Polarisation of decay products carries information about the spin structure of the internal dynamics of the decay.
 - Good probe of New Physics.
- Limit myself to the two groups of measurements:
 - Photon polarisation in radiative transitions
 - Polarisation observables in semileptonic decays

Radiative decays



Photon polarisation in $b \rightarrow s\gamma$ transition

$$\mathcal{H} \propto V_{ts}^* V_{tb} \bar{s} i\sigma_{\mu\nu} q^\nu \left(m_b \frac{1 + \gamma_5}{2} + m_s \frac{1 - \gamma_5}{2} \right) b$$



W couples to left-handed quarks (and right-handed antiquarks)

\Rightarrow photon mostly left-handed (RH admixture $\sim m_s/m_b$)

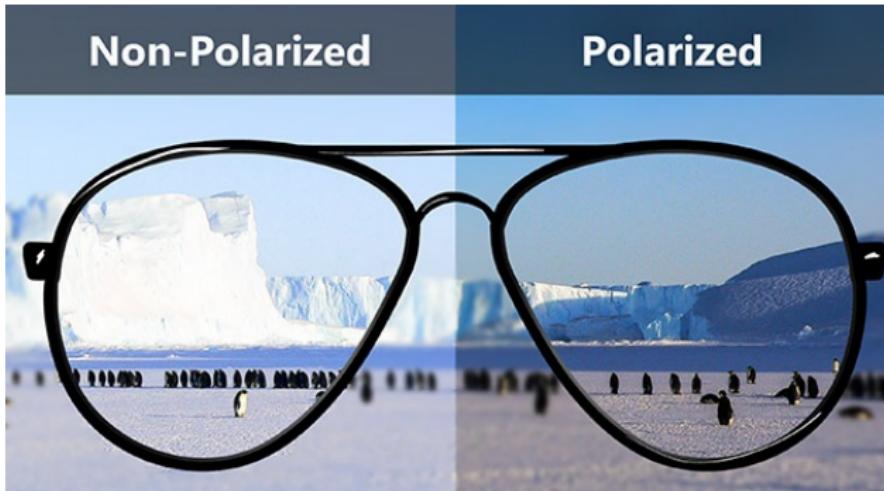
Effective field theory:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed}}$$

\mathcal{C}_i – left handed, \mathcal{C}'_i – right-handed

Photon polarisation is sensitive to *right-handed BSM currents*, e.g. models with right-handed neutrino.

Photon polarisation in $b \rightarrow s\gamma$ transition



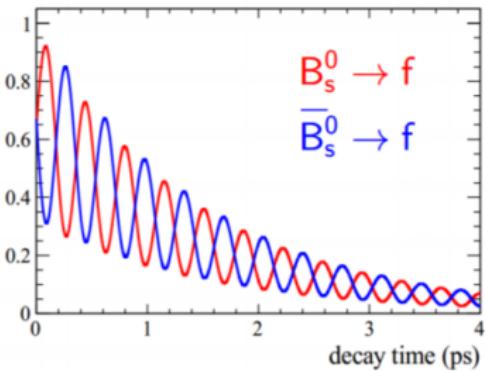
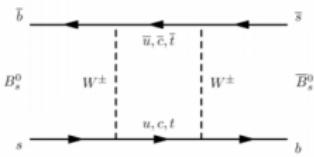
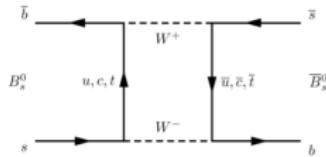
Methods to measure γ polarisation

- Mixing-induced CP asymmetry in $B \rightarrow V\gamma$ decays
- Triple product observables in $B \rightarrow 3h\gamma$ decays
- Baryon polarisation in $\Lambda_b^0 \rightarrow \Lambda\gamma$
- Angular observables in $B \rightarrow K^*\gamma^*(\rightarrow e^+e^-)$

Time-dependent CP asymmetry in $B_s^0 \rightarrow \phi\gamma$

[D. Atwood, M. Gronau, A. Soni, PRL 79:185 (1997)]

- If $B_s^0 \rightarrow \phi\gamma_L$ and $\bar{B}_s^0 \rightarrow \phi\gamma_R$: no interference between two decays
- However, if γ is a mixture of γ_L and γ_R , interference between $B \rightarrow \phi\gamma$ decays with and without mixing.



Time-dependent CP asymmetry in $B_s^0 \rightarrow \phi\gamma$

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- However, if γ is a mixture of γ_L and γ_R , interference between $B \rightarrow \phi\gamma$ decays with and without mixing.
 - Flavour-tagged decay time distributions are modified
 - Sensitive to parameters of the γ_L/γ_R admixture

$$P(t) \propto e^{-\Gamma_s t} \left\{ \cosh(\Delta\Gamma_s t/2) - \mathcal{A}^\Delta \sinh(\Delta\Gamma_s t/2) + \zeta C \cos(\Delta m_s t) - \zeta S \sin(\Delta m_s t) \right\}$$

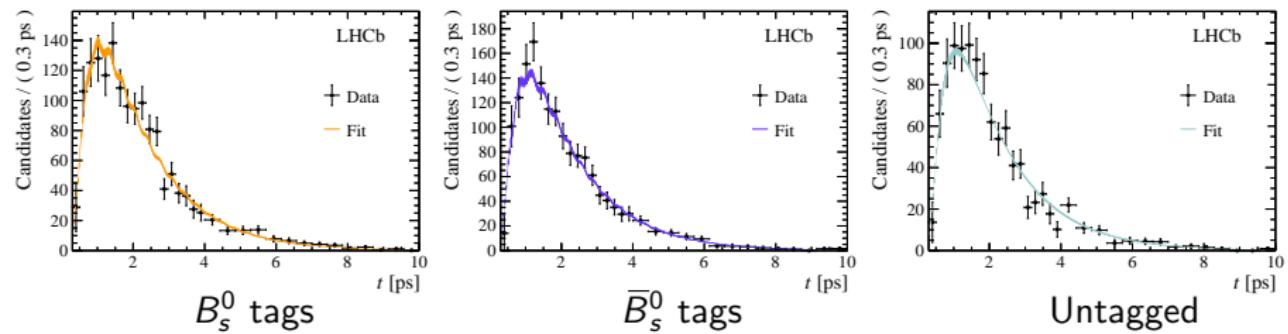
$\zeta = +1$ for B_s^0 , $\zeta = -1$ for \bar{B}_s^0 (need *flavour tagging*)

C — CP violation in decay (*direct*)

S, \mathcal{A}^Δ terms appear for nonzero interference

Time-dependent CP asymmetry in $B_s^0 \rightarrow \phi\gamma$

[LHCb, PRL 123 (2019) 081802]



$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$

$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$

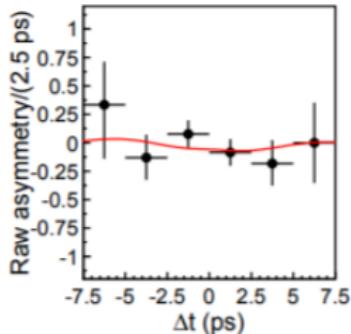
$$\mathcal{A}_{\phi\gamma}^{\Delta} = 0.67^{+0.37}_{-0.41} \pm 0.17$$

$B \rightarrow K_s \pi^0 \gamma$ at B factories

Similar technique is available at $e^+ e^-$ B factories.

- B_0 decays: $B \rightarrow K^* \gamma$ transition.
- Need K^* in CP eigenstate for maximum interference: $K^* \rightarrow K_S \pi^0$
- Hard since no good vertex, but possible at B factories.

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[\mathcal{S} \sin(\Delta m_d \Delta t) + \mathcal{A} \cos(\Delta m_d \Delta t) \right] \right\}.$$



[Belle, PRD 74 (2006) 111104]

$$\begin{aligned} S_{K_S^0 \pi^0 \gamma} &= -0.10 \pm 0.31(\text{stat}) \pm 0.07(\text{syst}), \\ \mathcal{A}_{K_S^0 \pi^0 \gamma} &= -0.20 \pm 0.20(\text{stat}) \pm 0.06(\text{syst}), \end{aligned}$$

[BaBar, PRD 78:071102(2008)]

$$\begin{aligned} S_{K^* \gamma} &= -0.03 \pm 0.29 \text{ (stat)} \pm 0.03 \text{ (syst)}, \\ C_{K^* \gamma} &= -0.14 \pm 0.16 \text{ (stat)} \pm 0.03 \text{ (syst)}, \end{aligned}$$

Triple products in $B \rightarrow K\pi^+\pi^-\gamma$

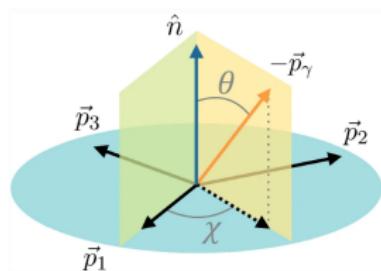
[M. Gronau, D. Pirjol, PRD 66(2002)054008]

$$\lambda_\gamma = \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2} = \frac{|C_7^{\text{eff}}|^2 - |C_7'|^2}{|C_7^{\text{eff}}|^2 + |C_7'|^2}$$

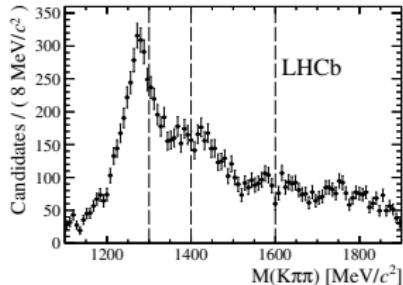
- Decays like $B \rightarrow K^*(K\pi)\gamma$ are insensitive to γ polarisation.
- Need a four-body decay, e.g. $B^+ \rightarrow K^+\pi^+\pi^-\gamma$
- Up-down asymmetry:

$$A_{UD}^\pm = \pm \frac{\int_0^1 d \cos \theta \frac{d\Gamma}{d \cos \theta} - \int_{-1}^0 d \cos \theta \frac{d\Gamma}{d \cos \theta}}{\int_{-1}^1 d \cos \theta \frac{d\Gamma}{d \cos \theta}}$$

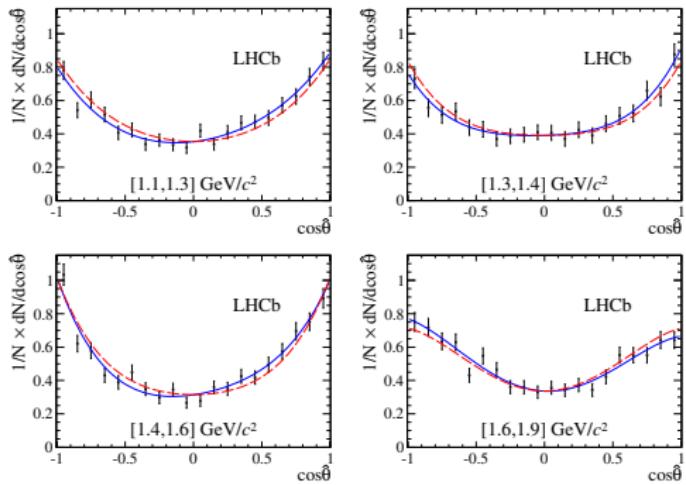
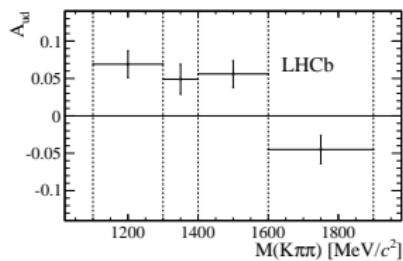
is proportional to λ_γ



Triple products in $B \rightarrow K\pi^+\pi^-\gamma$



[LHCb, PRL 112, 161801 (2014)]



- Perform angular fit of $\cos\theta$ distribution to determine A_{ud} in 4 bins of $M(K\pi\pi)$
- First observation of non-zero photon polarisation at 5.2σ in combination
- To determine precise value for λ_γ , resonance structure of final state needs to be resolved

Amplitude analysis of $B \rightarrow K\pi\pi\gamma$

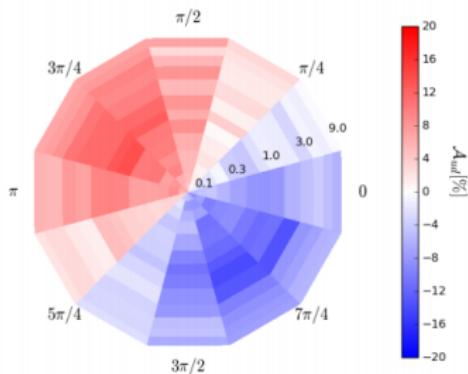
[E. Kou et al., PRD 83:094007(2011)]

Photon polarisation is “duplicated” in the polarisation of K_1 axial vector:

$$\Gamma(B \rightarrow K_1\gamma) = \Gamma(B \rightarrow K_{1L}\gamma_L) + \Gamma(B \rightarrow K_{1R}\gamma_R)$$

To measure γ polarisaion though amplitude analysis, need at least 2 amplitudes with varying phase difference.

- K_1 decay though different channels (e.g. $K\rho$, $K^*\pi$)
- Overlapping K_1 states ($K_1(1270)$, $K_1(1400)$)



[V. Bellee et al., EPJC 79 (2019) 622]

Proof of concept using realistic models:

- $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ (LHCb, 9 fb^{-1}):
 $\sigma(\lambda_\gamma) \simeq 0.009$
- $B^0 \rightarrow K^+\pi^-\pi^0\gamma$ (Belle II, 5 ab^{-1}):
 $\sigma(\lambda_\gamma) \simeq 0.018$

Baryon polarisation in $\Lambda_b^0 \rightarrow \Lambda\gamma$

[T. Mannel, S. Recksiegel, APP B28:2489(1997)]

Baryons carry spin, so photon polarisation is reflected in their angular distributions

Decay $\Lambda_b^0 \rightarrow \Lambda\gamma$:

- Λ_b^0 can be polarised, sensitivity through initial state polarisation ($\cos \theta_{\Lambda_b^0}$)
- $\Lambda \rightarrow p\pi^-$ weak decay, preserves information of Λ polarisation through proton helicity ($\cos \theta_p$)

Full distribution:

[L.M. Garcia Martin et al., EPJC 79, 634(2019)]

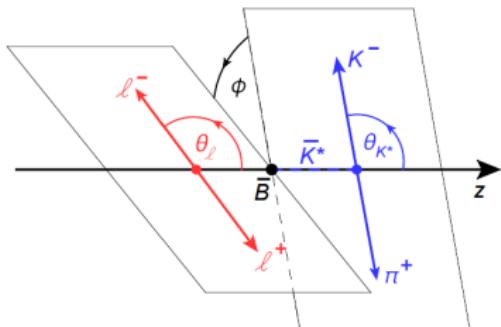
$$\frac{d\Gamma}{d \cos \theta_p} \propto 1 - \alpha_\Lambda P_{\Lambda_b^0} \cos \theta_p \cos \theta_\Lambda - \alpha_\gamma (\alpha_\Lambda \cos \theta_p - P_{\Lambda_b^0} \cos \theta_\Lambda)$$

Λ_b^0 polarisation in pp collisions is small (see talks by Misha and Elisabeth), thus

$$\frac{d\Gamma}{d \cos \theta_p} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos \theta_p$$

$\alpha_\Lambda = 0.642 \pm 0.013$ — asymmetry parameter of $\Lambda \rightarrow p\pi^-$ decay

Angular distribution of $B \rightarrow K^* e^+ e^-$



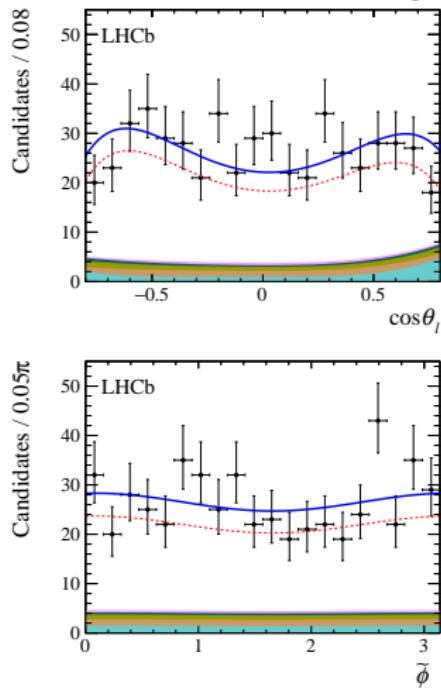
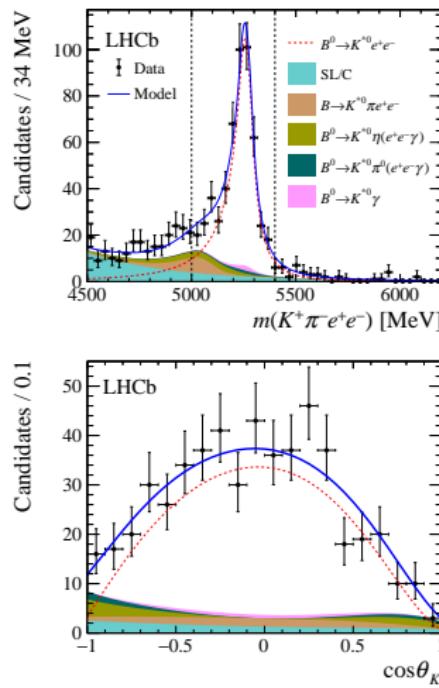
[Yu. Grossman, D. Pirjol, JHEP 0006 (2000) 029]

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\cos \theta_\ell d\cos \theta_K d\tilde{\phi}} = \frac{9}{16\pi} \left[\begin{aligned} & \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\ & + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \\ & + (1 - F_L) A_T^{\text{Re}} \sin^2 \theta_K \cos \theta_\ell \\ & + \frac{1}{2}(1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\tilde{\phi} \\ & + \frac{1}{2}(1 - F_L) A_T^{\text{Im}} \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\tilde{\phi} \end{aligned} \right]. \quad \text{.}$$

$A_T^{(2)}$ and A_T^{Im} are related to photon polarisation at $q^2 \rightarrow 0$ \Rightarrow constrain C_7'/C_7

Angular distribution of $B \rightarrow K^* e^+ e^-$

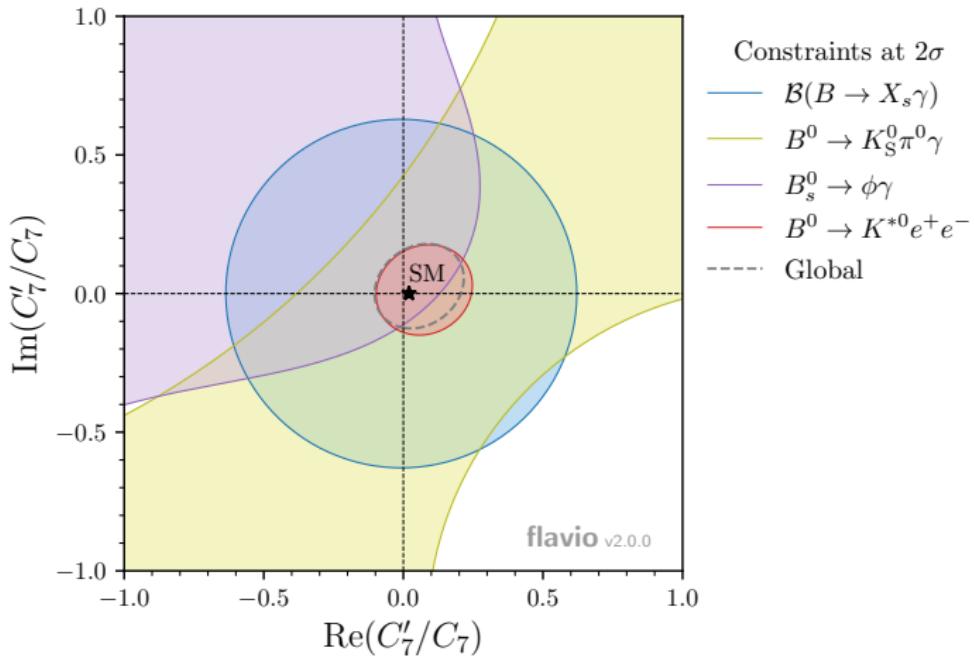
[LHCb, arXiv:2010:06011]



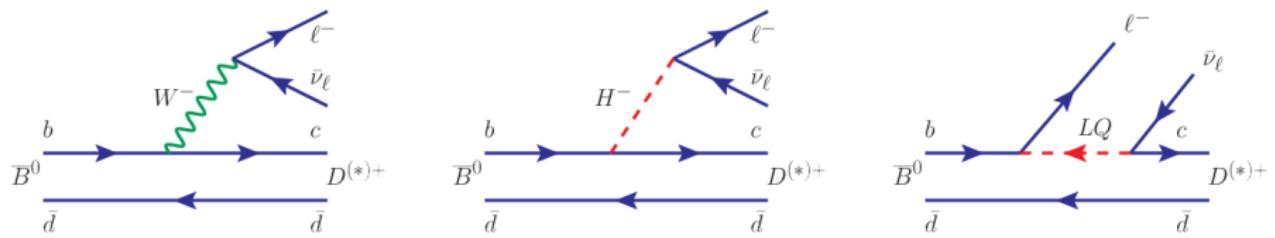
$$\begin{aligned}
 F_L &= 0.044 \pm 0.026 \pm 0.014, \\
 A_T^{\text{Re}} &= -0.06 \pm 0.08 \pm 0.02, \\
 A_T^{(2)} &= +0.11 \pm 0.10 \pm 0.02, \\
 A_T^{\text{Im}} &= +0.02 \pm 0.10 \pm 0.01,
 \end{aligned}$$

Constraints on C'_7

[LHCb, arXiv:2010:06011]

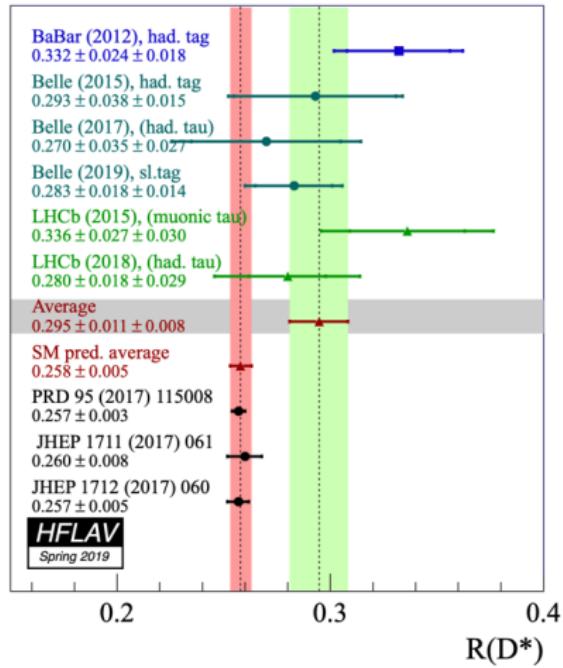


Semileptonic decays



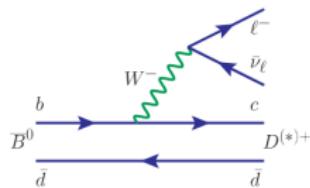
Charged current anomaly

$$R(D^*) = \frac{BR(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{BR(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

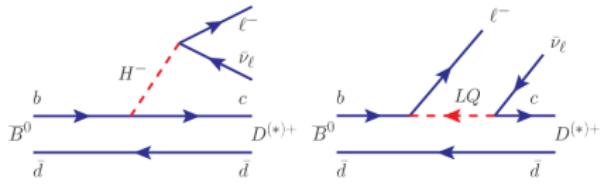


All $R(D)$, $R(D^*)$, $R(J/\psi)$ measurements consistently higher than SM expectations.

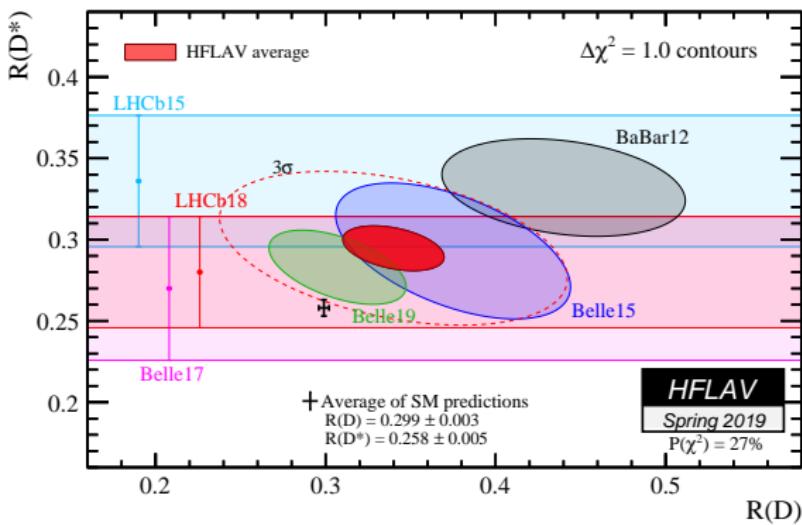
SM process: $b \rightarrow c$ tree



Possible NP contributions:



Charged current anomaly



- $R(D^*)$ alone: 2.5σ from SM
- $R(D^*)$ and $R(D)$ combined: 3.1σ from SM

Interesting hints, need more observables sensitive to various NP models:

- Polarisation, angular, CP asymmetries, ...

$b \rightarrow c\ell\nu$ transitions

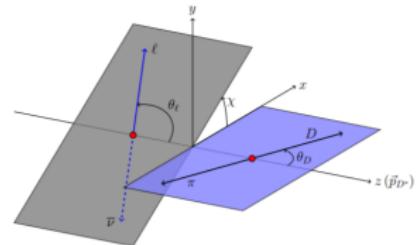
The most general effective hamiltonian for $b \rightarrow c\ell\nu$ transitions:

(see, e.g., [D. Becirevic et al., arXiv:1907.02257])

$$\begin{aligned}\mathcal{H}_{\text{eff}} = \sqrt{2}G_F V_{cb} & \left[(1 + g_V)(\bar{c}\gamma_\mu b)(\bar{\ell}_L \gamma^\mu \nu_L) + (-1 + g_A)(\bar{c}\gamma_\mu \gamma_5 b)(\bar{\ell}_L \gamma^\mu \nu_L) \right. \\ & + g_S(\bar{c}b)(\bar{\ell}_R \nu_L) + g_P(\bar{c}\gamma_5 b)(\bar{\ell}_R \nu_L) \\ & \left. + g_T(\bar{c}\sigma_{\mu\nu} b)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) + g_{T5}(\bar{c}\sigma_{\mu\nu} \gamma_5 b)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}\end{aligned}$$

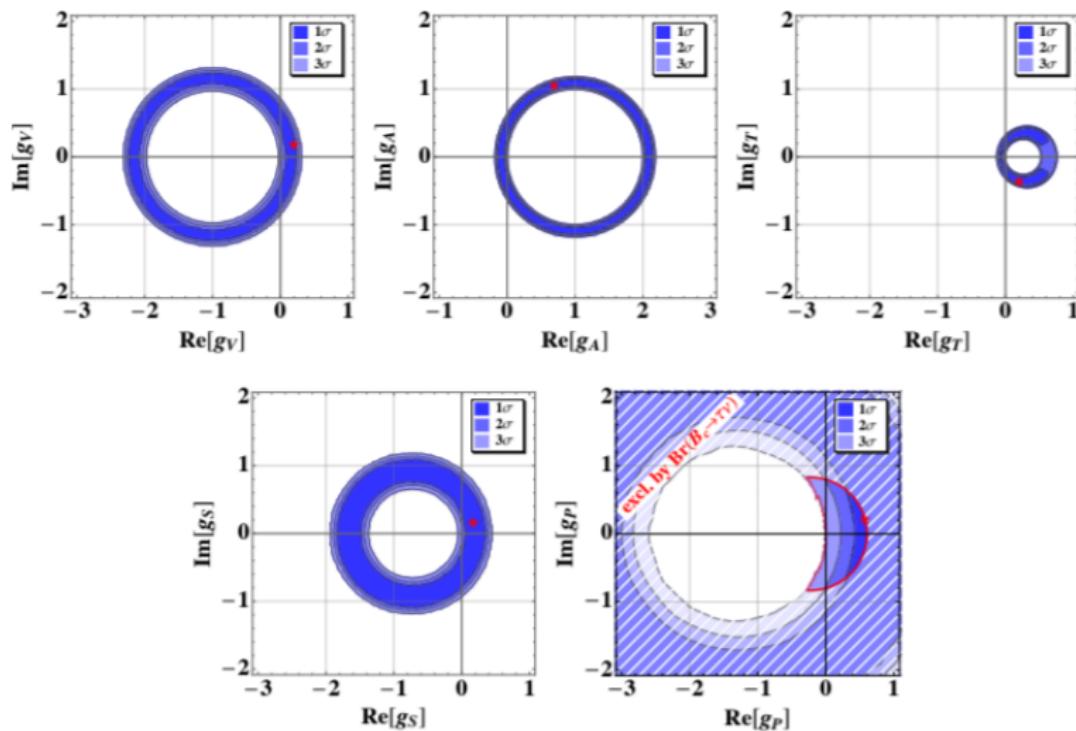
$B \rightarrow D^*\ell\nu$ decays. full angular distribution:

$$\begin{aligned}\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{9}{32\pi} & \left\{ I_{1c} \cos^2\theta_D + I_{1s} \sin^2\theta_D \right. \\ & + [I_{2c} \cos^2\theta_D + I_{2s} \sin^2\theta_D] \cos 2\theta_\ell \\ & + [I_{6c} \cos^2\theta_D + I_{6s} \sin^2\theta_D] \cos\theta_\ell \\ & + [I_3 \cos 2\chi + I_9 \sin 2\chi] \sin^2\theta_\ell \sin^2\theta_D \\ & + [I_4 \cos\chi + I_8 \sin\chi] \sin 2\theta_\ell \sin 2\theta_D \\ & \left. + [I_5 \cos\chi + I_7 \sin\chi] \sin\theta_\ell \sin 2\theta_D \right\},\end{aligned}$$



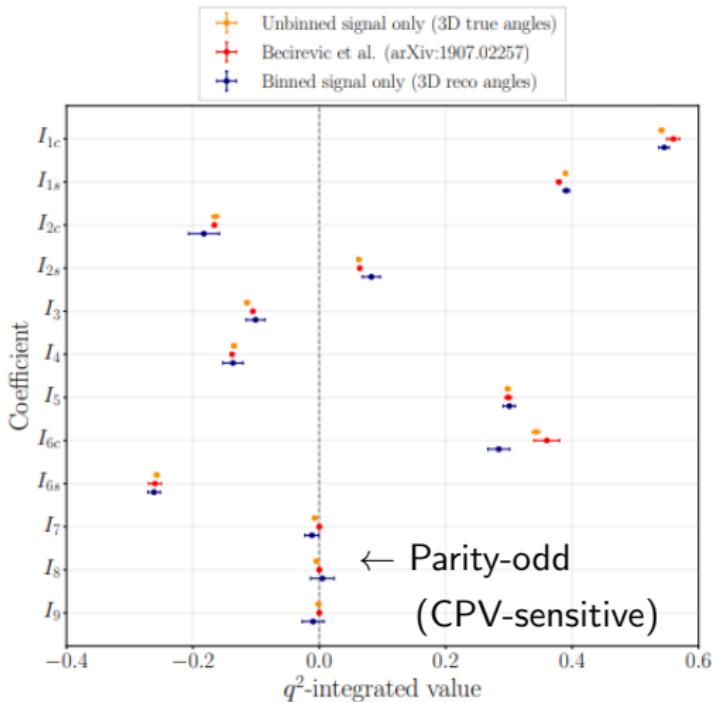
Constraints on NP couplings

Allowed regions for NP couplings from $R_{D^{(*)}}$ measurements



$B \rightarrow D^* \ell \nu$ angular terms

[D. Hill et al., JHEP11(2019)133]



Polarisation observables in $B \rightarrow D^* \tau \nu$ decays

Some derived observables from this angular distribution:

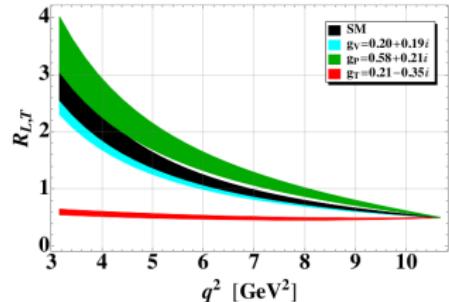
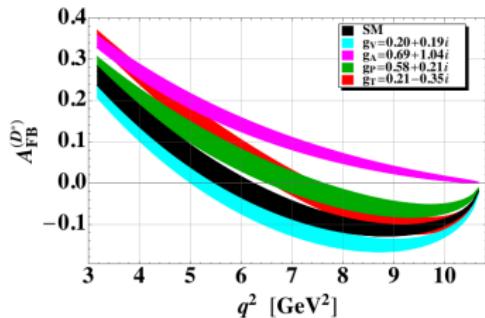
- Forward-backward asymmetry A_{FB} :

$$\frac{d\Gamma}{dq^2 d \cos \theta_I} \propto \dots + A_{FB} \cos \theta_I + \dots$$

- D^* longitudinal polarisation fraction F_L

$$\frac{d\Gamma}{dq^2 d \cos \theta_D} \propto 2F_L \cos^2 \theta_D + (1 - F_L) \sin^2 \theta_D$$

- CP-odd terms $\propto \sin \chi$
- Plenty of others ($R_{A,B}$, asymmetries A_n ($n = 3 \dots 9$))
(see [D. Becirevic et al., arXiv:1907.02257])



τ polarisation in $B \rightarrow D\tau\nu$ decays

Angular distribution above was summed over ℓ polarisations.

With hadronic decays like $\tau \rightarrow \pi\nu$, one has access to lepton polarisation

$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

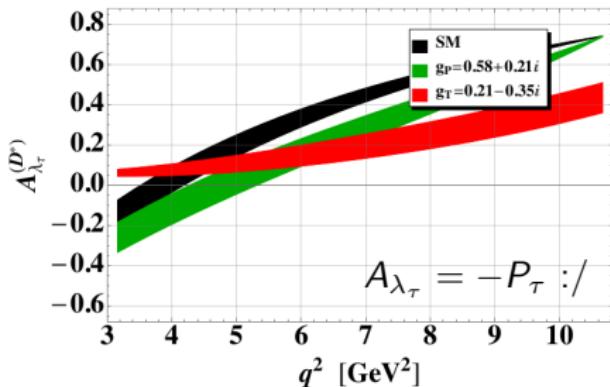
Distribution of $\tau \rightarrow h\nu$ helicity angle θ_{hel} :

$$\frac{d\Gamma}{d \cos \theta_{hel}} \propto 1 + \alpha P_\tau \cos \theta_{hel}$$

Asymmetry parameter

$$\alpha = 1 \text{ for } \tau \rightarrow \pi\nu$$

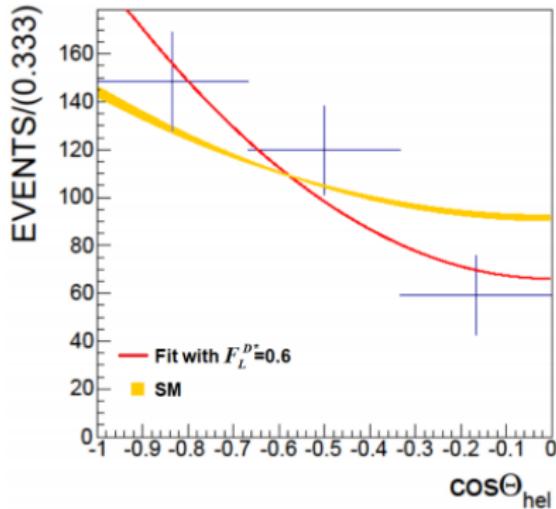
$$\alpha \simeq 0.45 \text{ for } \tau \rightarrow \rho\nu$$



Polarisation measurements at Belle

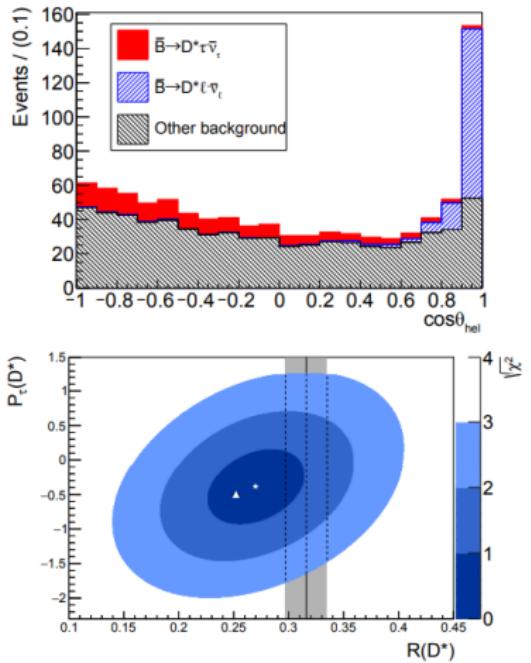
[Belle, PRD 97, 012004 (2018)]

[Belle, arXiv:1903.03102]



$$F_L = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$$

SM expectation: 0.441 ± 0.006



$$P_\tau = -0.38 \pm 0.51^{+0.21}_{-0.16} (\text{syst})$$

SM expectation: -0.497 ± 0.013

Conclusion

- Measurements of polarisation of decay products of beauty mesons provide strong constraints on spin structure of underlying dynamics
- Sensitive probe of New Physics models
- Two examples:
 - Radiative $b \rightarrow s$ transitions: photon polarisation
 - Tree-level $b \rightarrow c$ transitions: angular and lepton polarisation observables
- Many prospects for Belle II and LHCb to perform interesting measurements
 - A lot can still be explored with the current Run I+II data at LHCb
 - Looking forward to Belle II and LHCb upgrade