# Angular analyses of semitauonic $B$ decays

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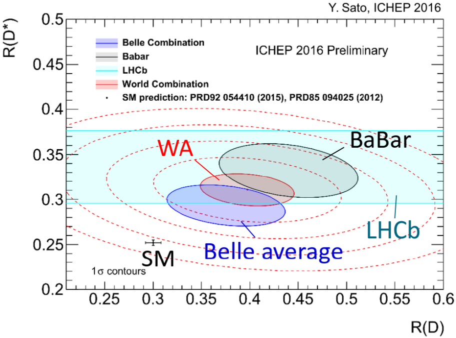
# Outline

1. Intro
2. *Naïve* angular analysis
3. Angular analyses of the *observable* decay products
   - $B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$
   - $B \to D^{(*)}\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$

# $R_{D^{(*)}}$ anomalies

- **Lepton-universality ratios**

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu})}, \qquad \ell = e, \mu$$




- ***Excesses*** reported consitently by different experiments in two channels at $\sim 4\sigma$

$$\Lambda_{\rm NP} \sim \; 1 \text{ TeV}$$

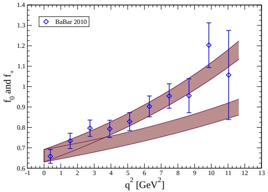
# Hadronic uncertainties (Form factors)

- Form factors are fitted to **experimental** $B \to D^{(*)}\ell\nu$ spectrum and **LQCD!**

Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98

- **Example:** $B \to D$

$$\langle D(k)|\bar{c}\gamma^{\mu} b|\bar{B}(p)\rangle = (p+k)^{\mu} f_{+}(q^2) + q^{\mu}\frac{m_B^2 - m_D^2}{q^2}\left(f_{+}(q^2) - f_0(q^2)\right)$$




  - Scalar $f_0(q^2)$ enters rate $\propto m_\ell^2$
  - **CVC** implies $f_0(0) = f_+(0)$

Na *et al.* PRD92(2015)no.5,054510 (see also Bailey *et al.* PRD92,034506)

- In $B \to D^*$ (pseudo)scalar form factor $A_0(q^2)$ much less important

| | $R_D$ | $R_{D^*}$ HFAG (CLN) |
|---|---|---|
| SM | 0.300(8) | 0.252(4) |
| Expt. | 0.391(41)(28) | 0.322(18)(12) |

SM predictions of $R_{D^{(*)}}$ well under control!

# New physics in $\tau$ decays?

- New physics..
  - could **look different** in different $\tau \to X\nu$ decay channels
  - should **appear universally** in all $Y \to Z\tau(\to X\nu)$ decays
- Leptonic $\tau$ decays: **Michel parameters**

A. Pich PPNP75(2014)41

Bounds on the $g^V_{\epsilon\omega}$ couplings, assuming that (non-standard) $W$-exchange is the only relevant interaction. The $\tau$-decay ($\mu$-decay) limits are at 95% CL (90% CL). Numbers within parentheses use $\mu$-decay data through cross-channel identities.

| | $\lvert g^V_{RR}\rvert$ | $\lvert g^V_{LR}\rvert$ | $\lvert g^V_{RL}\rvert$ | $\lvert g^V_{LL}\rvert$ |
|---|---|---|---|---|
| $\mu \to e$ | <0.0004 | <0.023 | <0.017 | >0.999 |
| $\tau \to \mu$ | <0.017 (0.003) | <0.12 | <0.14 (0.023) | >0.983 |
| $\tau \to e$ | <0.017 (0.002) | <0.13 | <0.13 (0.017) | >0.983 |

  - 4-lepton **(pseudo)scalar** interactions less constrained
- Hadronic $\tau$ decays: **Lepton universality ratios**

$$R_{\tau/P} \equiv \frac{\Gamma(\tau^- \to \nu_\tau P^-)}{\Gamma(P^- \to \mu^- \bar{\nu}_\mu)} = \left|\frac{g_\tau}{g_\mu}\right|^2 \frac{m_\tau^3}{2m_P m_\mu^2} \frac{(1-m_P^2/m_\tau^2)^2}{(1-m_\mu^2/m_P^2)^2} \left(1+\delta R_{\tau/P}\right)$$

$$R_{\tau/\pi} = (0.16 \pm 0.14)$$

  - New physics constrained at **subpercent level** in hadronic modes

# New physics in $b \to c\tau\nu$: EFT

- Low-energy effective Lagrangian (no RH $\nu$)

$$\mathcal{L}_{\rm eff}^{\ell} = -\frac{G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{c}\gamma^\mu(1-\gamma_5)b + \epsilon_R^{\ell}\,\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\;\bar{c}\gamma^\mu(1+\gamma_5)b$$
$$+\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{c}[\epsilon_S^{\ell}-\epsilon_P^{\ell}\gamma_5]b + \epsilon_T^{\ell}\,\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b] + \text{h.c.},$$

**Wilson coefficients:** $\epsilon_\Gamma$ decouple as $\sim v^2/\Lambda_{\rm NP}^2$

- Matching to high-energy Lagrangian – SMEFT Buchmuller& Wyler'86, Grzadkowski *et al.*'10
  - Symmetry relations for $\epsilon_\Gamma$
    - ★ Specially powerful in rare $D \to D'\ell\ell$: No $C_T$ and less $C_S$ Alonso, Grinstein, JMC, PRL113(2014)241802
    - ★ In charged-currents $\epsilon_R^{\ell}$: Bernard, Oertel, Passemar & Stern PLB638(2006)480

$$\mathcal{O}_{Hud} = \frac{i}{\Lambda_{\rm NP}^2}\left(\tilde{H}^\dagger D_\mu H\right)\left(\bar{u}_R\gamma^\mu d_R\right)$$

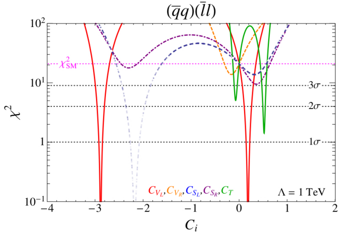
☛ **RHC is lepton universal:** $\epsilon_R^{\ell} \equiv \epsilon_R + \mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4})$

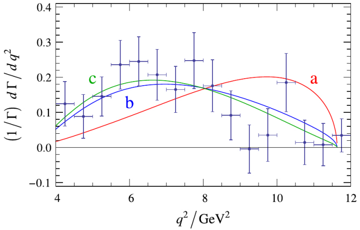
**RHC** cannot explain **LUR** $R_{D^{(*)}}$!

  - High-energy $\Longleftrightarrow$ low-energy dictionary
    - ★ Streamline tests of your favorite UV completion! Faroughy *et al.* arXiv:1609.07138

# Fits to new physics

- The $R_{D(*)}$ and **spectrum** do not provide enough discriminating power



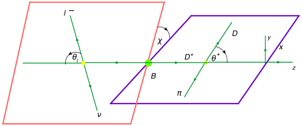

Freytsis *et al.*, PRD92(2015)no.5,054018; also Sasaki *et al.* PRD91(2015)no.11, 114028, . . .

- Looking for LUR in **new decay modes**
  - $\Lambda_b \to \Lambda_c^{(*)} \ell\nu$ S. Meinel @ HC2NP–Tenerife
  - Semileptonic $B_c$ decays Lytle *et al.* @ BEAUTY2016 (arXiv: 1605.05645)
  - $B_s \to D_s^{(*)} \ell\nu$ A. Bhol, EPL106(2014)31001
- Measure new observables

**Look at the full kinematic (angular) distributions!**

# A first approach: Full angular analysis of the $B \to D^{(*)}\tau\nu$

- Many angular observables as functions of helicity amplitudes (like $B \to K^{(*)}\mu\mu$!)




$$\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_{D^*} d\chi} = \frac{9}{32\pi} NF\{\cos^2\theta_{D^*}(V_1^0 + V_2^0\cos 2\theta_l + V_3^0\cos\theta_l) + \sin^2\theta_{D^*}(V_1^T + V_2^T\cos 2\theta_l + V_3^T\cos\theta_l)$$
$$+ V_4^T\sin^2\theta_{D^*}\sin^2\theta_l\cos 2\chi + V_1^{0T}\sin 2\theta_{D^*}\sin 2\theta_l\cos\chi + V_2^{0T}\sin 2\theta_{D^*}\sin\theta_l\cos\chi$$
$$+ V_5^T\sin^2\theta_{D^*}\sin^2\theta_l\sin 2\chi + V_3^{0T}\sin 2\theta_{D^*}\sin\theta_l\sin\chi + V_4^{0T}\sin 2\theta_{D^*}\sin 2\theta_l\sin\chi\},$$

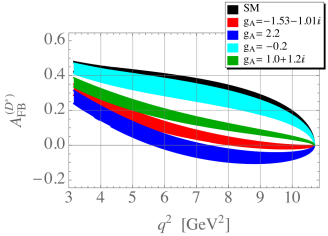
$$V_1^0 = 2\left[\left(1+\frac{m_l^2}{q^2}\right)(|\mathcal{A}_0|^2 + 16|\mathcal{A}_{0T}|^2) + \frac{2m_l^2}{q^2}|\mathcal{A}_{tP}|^2 - \frac{16m_l}{\sqrt{q^2}}\mathrm{Re}[\mathcal{A}_{0T}\mathcal{A}_0^*]\right],$$

$$V_2^0 = 2\left(1-\frac{m_l^2}{q^2}\right)[-|\mathcal{A}_0|^2 + 16|\mathcal{A}_{0T}|^2],$$
$$V_3^0 = -8\mathrm{Re}\left[\frac{m_l^2}{q^2}\mathcal{A}_{tP}\mathcal{A}_0^* - \frac{4m_l}{\sqrt{q^2}}\mathcal{A}_{tP}\mathcal{A}_{0T}^*\right]$$

...

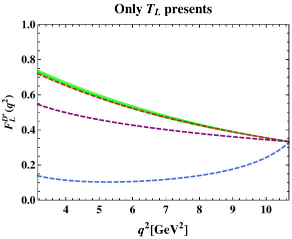
Duraisamy *et al.*, PRD90, 074013 (2014)

- Leptonic forward-backward asymmetry




Becirevic *et al.*, arXiv:1602.03030.

- Longitudinal polarization of the $D^*$




Duraisamy *et al.*, PRD90, 074013 (2014)

- **However** the $\tau$'s lifetime is $\sim 10^{-13}$ $s$
  It is not *observed* but *reconstructed* from decay products with **missing neutrinos**!

**QUESTION TO EXPT's**

How **realistic** it is to fully reconstruct the kinematics of the $\tau$?
With which precision?

- **Alternatively**, study the kinematic distributions of the **observable** $\tau$ decay products!
  - Maximize the coverage of the $\tau$'s lifetime

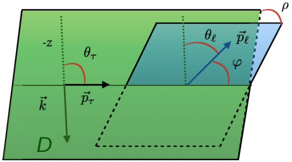
| Channel | $\tau \to \mu\nu\nu$ | $\tau \to e\nu\nu$ | $\tau \to \pi\nu$ | $\tau \to \rho\nu$ | $\tau \to 3\pi\nu$ | TOTAL |
|---|---|---|---|---|---|---|
| $\mathcal{B}$ | 17.4% | 17.8% | 10.82% | 25% | 9% | $\sim$ 80% |

  - **Two different strategies in the literature:**
    - ★ **Analytical:** Nierste *et al.* PRD78,015006 '08 ($BD$-$\pi\nu$), **Alonso, Kobach & JMC, arXiv:1602.07671** ($BD^{(*)}$-$\ell\nu\nu$), **Alonso, JMC & Westhoff, in preparation** ($BD^{(*)}$-$\pi\nu$ or $\rho\nu$) **This talk**
    - ★ **Montecarlo:** Hagiwara *et al.* PRD89, 094009 (2014) ($BD$-$3\pi\nu$), Bordone *et al.* EPJC76 (2016) no.7, 360 ($BD$-$\ell\nu\nu$), Ligeti *et al.* arXiv:1610.02045 ($BD^*(\to D\pi)$-$\ell\nu\nu, \ldots$) **Marzia's (next) talk**

Test new physics and understand better what we are measuring!

# $B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$

Alonso, Kobach, JMC, arXiv: 1602.07671




- The amplitude factorizes

$$\mathcal{M}=\frac{4G_F^2 V_{cb}\eta_{\rm ew}}{p_\tau^2-m_\tau^2+i\,m_\tau\Gamma_\tau}\sum_{\lambda_\tau=\pm1/2}\langle\ell^-\bar{\nu}_\ell|\bar{\ell}\gamma^\rho P_L\nu_\ell|0\rangle\langle\nu_\tau|\bar{\nu}_\tau\gamma_\rho P_L\tau|\tau^-(\lambda_\tau)\rangle\times$$

$$\times\left\{H_V^\mu\langle\tau^-(\lambda_\tau)\bar{\nu}_\tau|\bar{\tau}\gamma_\mu P_L\nu_\tau|0\rangle+H_S\langle\tau^-(\lambda_\tau)\bar{\nu}_\tau|\bar{\tau}P_L\nu_\tau|0\rangle+H_T^{\mu\nu}\langle\tau^-(\lambda_\tau)\bar{\nu}_\tau|\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau|0\rangle\right\}$$

  - $H_\Gamma$: $b\to c$ matrix elements ($\epsilon_\Gamma$)

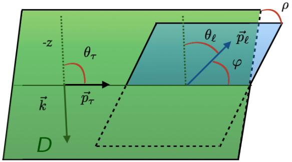
- **Total rate:** $d\Gamma=\tau_\tau\sum_{\lambda_\tau}d\Gamma_{B,\lambda_\tau}\times d\Gamma_{\tau,\lambda_\tau}+\tau_\tau\left(\cos\rho\, d\Gamma_B^\perp-\sin\rho\, d\Gamma_B^T\right)d|\mathcal{I}_\tau|$
  - **Interference terms:**

$$d\Gamma_B^\perp=\frac{(2\pi)^4\,d\Phi_3}{2m_B}2{\rm Re}\left[\mathcal{M}_{B+}\mathcal{M}_{B-}^\dagger\right],\qquad d\Gamma_B^T=\frac{(2\pi)^4\,d\Phi_3}{2m_B}2{\rm Im}\left[\mathcal{M}_{B+}\mathcal{M}_{B-}^\dagger\right]$$

    - ★ Interference terms vanish upon integration of the angular variables
    - ★ In principle sensitive to $T-$odd contribution $d\Gamma_B^T$ (not really in the end)

# $B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$

Alonso, Kobach, JMC, arXiv: 1602.07671




- **Integrate analytically $\tau$ angular phase-space:** (nontrivial)

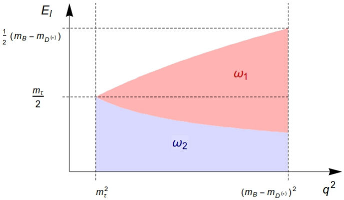
$$\frac{d^3\Gamma_5}{dq^2 dE_\ell d(\cos\theta_\ell)} = \mathcal{B}[\tau_\ell]\,\frac{G_F^2|V_{cb}|^2\eta_{\rm EW}^2}{32\pi^3}\,\frac{|\vec{k}|}{m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\frac{E_\ell^2}{m_\tau^3}\times\left[I_0(q^2,E_\ell)+I_1(q^2,E_\ell)\cos\theta_\ell+I_2(q^2,E_\ell)\cos\theta_\ell^2\right]$$

  - $\cos\theta_\ell$ defined as for the normalization mode (w.r.t recoiling $D^{(*)}$ in the $q$ rest frame)
  - $I_{0,2}(q^2, E_\ell)$ accessed in $R_{D^{(*)}}$
  - $I_1(q^2, E_\ell)$ accessible only with a FB leptonic asymmetry!

$$\frac{d^2A_{FB}(q^2,E_\ell)}{dq^2 dE_\ell} = \left(\int_0^1 d(\cos\theta_\ell) - \int_{-1}^0 d(\cos\theta_\ell)\right)\frac{d^3\Gamma_5}{dq^2 dE_\ell d(\cos\theta_\ell)}$$

$$R_{FB}^{(*)} = \frac{1}{\mathcal{B}[\tau_\ell]}\frac{1}{\Gamma_{\rm norm.}}A_{FB},$$

Alonso, Kobach, JMC, arXiv: 1602.07671




$$x^2 = \frac{q^2}{m_\tau^2}\,, \qquad\qquad y = \frac{E_\ell}{m_\tau}$$

- Over the region $\omega_2$:

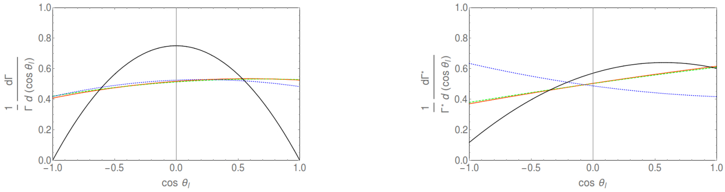
$$I_0 = -\frac{2\left(2x^2+1\right)\left(4xy-3\right)}{3x}\Gamma_-^{(0)} + \frac{2\left(x^2+2\right)\left(3x-4y\right)}{3x^2}\Gamma_+^{(0)} + \frac{2}{15}\left(-12x^2y+10x+\frac{5}{x}-8y\right)\Gamma_-^{(2)} + \frac{\left(10x\left(x^2+2\right)-8\left(2x^2+3\right)y\right)}{15x^2}\Gamma_+^{(2)} - \frac{4\left(x^2-1\right)y}{15x}\mathcal{I}^{(1)}\,,$$

$$I_1 = \frac{\left(8x^3y-4x^2+2\right)}{3x}\Gamma_-^{(1)} - \frac{2\left(x^3-2x+4y\right)}{3x^2}\Gamma_+^{(1)} + \frac{4}{3}\left(-2xy-\frac{2y}{x}+1\right)\mathcal{I}^{(0)}\,,$$

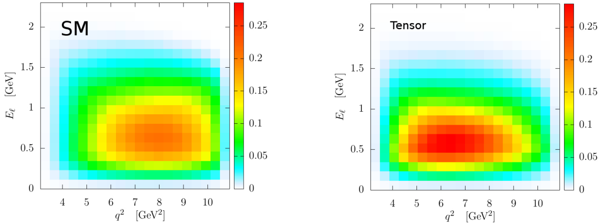
$$I_2 = \frac{8\left(x^2-1\right)y}{15x^2}\Gamma_+^{(2)} - \frac{8}{15}\left(x^2-1\right)y\Gamma_-^{(2)} + \frac{4\left(x^2-1\right)y}{5x}\mathcal{I}^{(1)}\,.$$

- $\Gamma_\lambda^{(i)}$ ($\mathcal{I}^{(i)}$): **diagonal** (**interference**) angular coefficients of $B \to D^{(*)}\tau\nu$
- Similar results for $\omega_1$

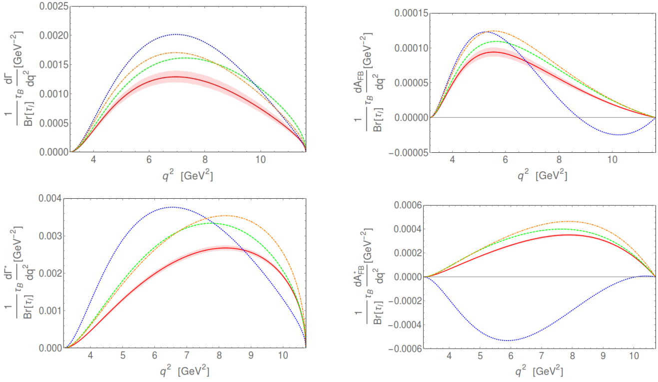
- Angular distributions can help to discriminate signal *vs.* normalization




- $E_\ell$ and double $(E_\ell,\ q^2)$ spectra can also be studied




Ligeti *et al.* arXiv:1610.02045

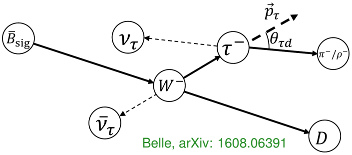



- FB-asymmetry can be useful to discriminate and confirm NP!

| | $R_D$ | $R_{FB}$ | $R_{D^*}$ | $R^*_{FB}$ |
|---|---|---|---|---|
| SM | 0.310(19) | 0.0183(9) | 0.252(4) | 0.0310(7) |
| Current | 0.410 | 0.0242 | 0.333 | 0.0410 |
| Scalar | 0.400 | 0.0218 | 0.315 | 0.0363 |
| Tensor | 0.467 | 0.0151 | 0.346 | −0.0377 |
| Expt. | 0.391(41)(28) | – | 0.322(18)(12) | – |

# $B \to D\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$

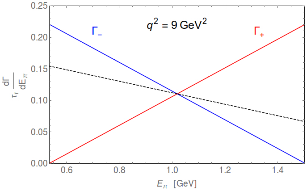
Alonso, JMC & Westhoff, to appear (all preliminary)




Belle, arXiv: 1608.06391

- Only two neutrinos in f.s. $\Rightarrow$ **Less kinematic information loss**
  - $E_\pi$ in the $q$ rest frame gives $\theta_{\tau d}$!!

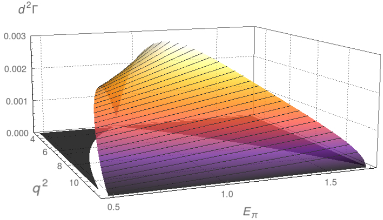
$$\cos\theta_{\tau d} = \frac{2E_\pi E_\tau - m_\pi^2 - m_\tau^2}{2|\vec{p}_\pi||\vec{p}_\tau|}$$




  - $\tau \to \pi\nu$ is an obvious $\tau$ polarimeter!
- Fully-observable differential rate

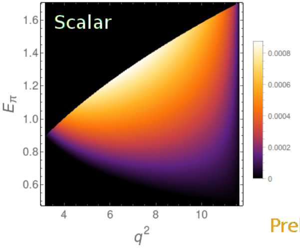
$$\frac{d^3\Gamma_4}{dq^2\, dE_\pi\, d(\cos\theta_\pi)} = \frac{G_F^2|V_{cb}|^2\eta_{\rm ew}^2}{256\pi^3}\frac{|\vec{k}|}{m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\frac{\mathcal{B}[\tau\pi]\,m_\tau^3}{(m_\tau^2-m_\pi^2)^2}\times\left[I_0(q^2,E_\pi)+I_1(q^2,E_\pi)\cos\theta_\pi+I_2(q^2,E_\pi)\cos^2\theta_\pi\right]$$

- Two-fold ($q^2$, $E_\pi$) differential decay rates

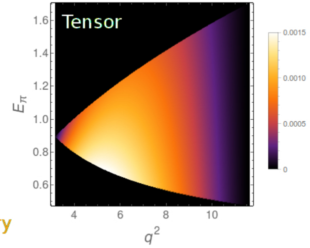



$$\frac{d^2\Gamma_4}{dq^2\,dE_\pi} = \frac{G_F^2\,|V_{cb}|^2\,\eta_{\rm ew}^2}{128\pi^3}\,\frac{|\vec{k}|}{m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \times \frac{\mathcal{B}[\tau_\pi]\,m_\tau^3}{(m_\tau^2-m_\pi^2)^2}\times\left[I_0(q^2,E_\pi)+\frac{1}{3}I_2(q^2,E_\pi)\right]$$

- **Scalar** and **Tensor** modify $d^2\Gamma_4$ up to 50% in some regions of phase-space




Preliminary




Alonso, JMC & Westhoff, to appear

# $\tau^- \to \pi^- \nu_\tau$ as a $\tau$ polarimeter

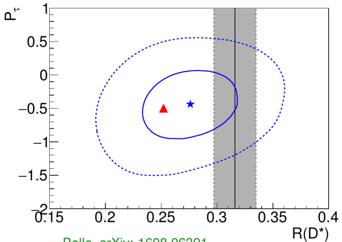
$$\frac{d^2\Gamma_4}{dq^2 dE_\pi} = \frac{\mathcal{B}[\tau_\pi]\, m_\tau^2}{|\vec{p}_\tau|(m_\tau^2 - m_\pi^2)} \frac{d\Gamma_B}{dq^2} \left[1 + \xi(E_\pi,\, q^2) \frac{dP_L}{dq^2}\right], \quad \xi(E_\pi, q^2) = \frac{1}{\beta_\tau}\left(2\frac{E_\pi}{E_\tau} - 1\right)$$

Tanaka&Watanabe, PRD82, 034027 (2010)

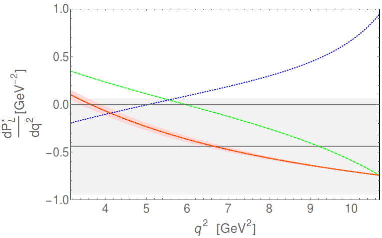
**Slope** in $E_\pi$ of $d\Gamma_4 \Rightarrow$ **Longitudinal Polarization**

$$\frac{dP_L}{dq^2} = \frac{d\Gamma_{B,+}/dq^2 - d\Gamma_{B,-}/dq^2}{d\Gamma_B/dq^2}$$

- Applied to the $BD^*$ channel by *Belle*



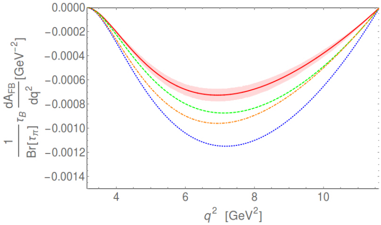

Belle, arXiv: 1608.06391

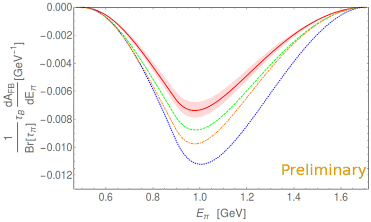


# Angular analysis in $B \to D\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$

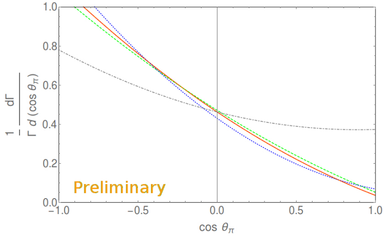
- The pionic forward-backward asymmetry

$$\frac{d^2 A_{FB}}{dq^2 dE_\pi} = \left( \int_0^1 d(\cos\theta_\pi) - \int_{-1}^0 d(\cos\theta_\pi) \right) \frac{d^3\Gamma_4}{dq^2 dE_\pi d(\cos\theta_\pi)}$$




- Angular distribution (w and w/o interference)



# Conclusions

- $R_{D^{(*)}}$ anomalies may imply new physics
  - Very clean from the point of view of hadronic uncertainties: **Data+LQCD**
  - Different experiments consistently agreeing on the enhancent
- **However,** tricky measurements: $\tau$ decaying with missing neutrinos

- We developed a **general** method to obtain the observable kinematic distributions of the 4- and 5-body decays
  - **Analytic**
  - **Modular:** Factorizes rates of primary $B$ decay from secondary $\tau$ decay
  - **Flexible:** Can easily adapted to any **primary** decay modes

Two questions:

1. **Analytic** vs **Montecarlo** methods
   - Are analytic derivations of the distributions too far from what expt's can provide?
   - **Future:** $(q^2, E)$ distributions of the angular coefficients? (like in $B \to K^* \mu\mu$)
2. **LHCb:** Which channels or distributions should be prioritized?
   - Hadronic modes beyond 3-prong decays?
   - Improvements in the reconstruction of the $B$-meson rest frame?