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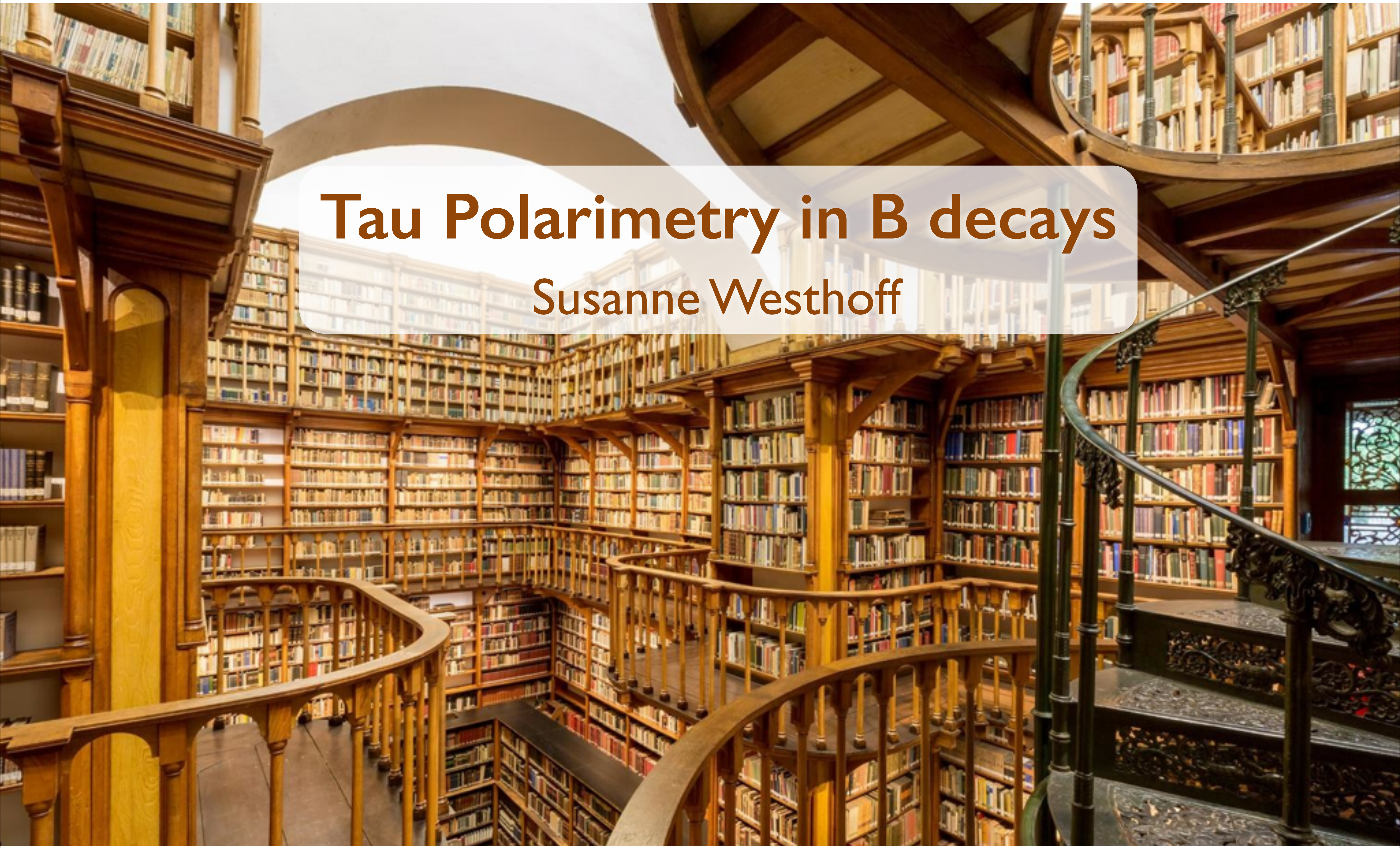
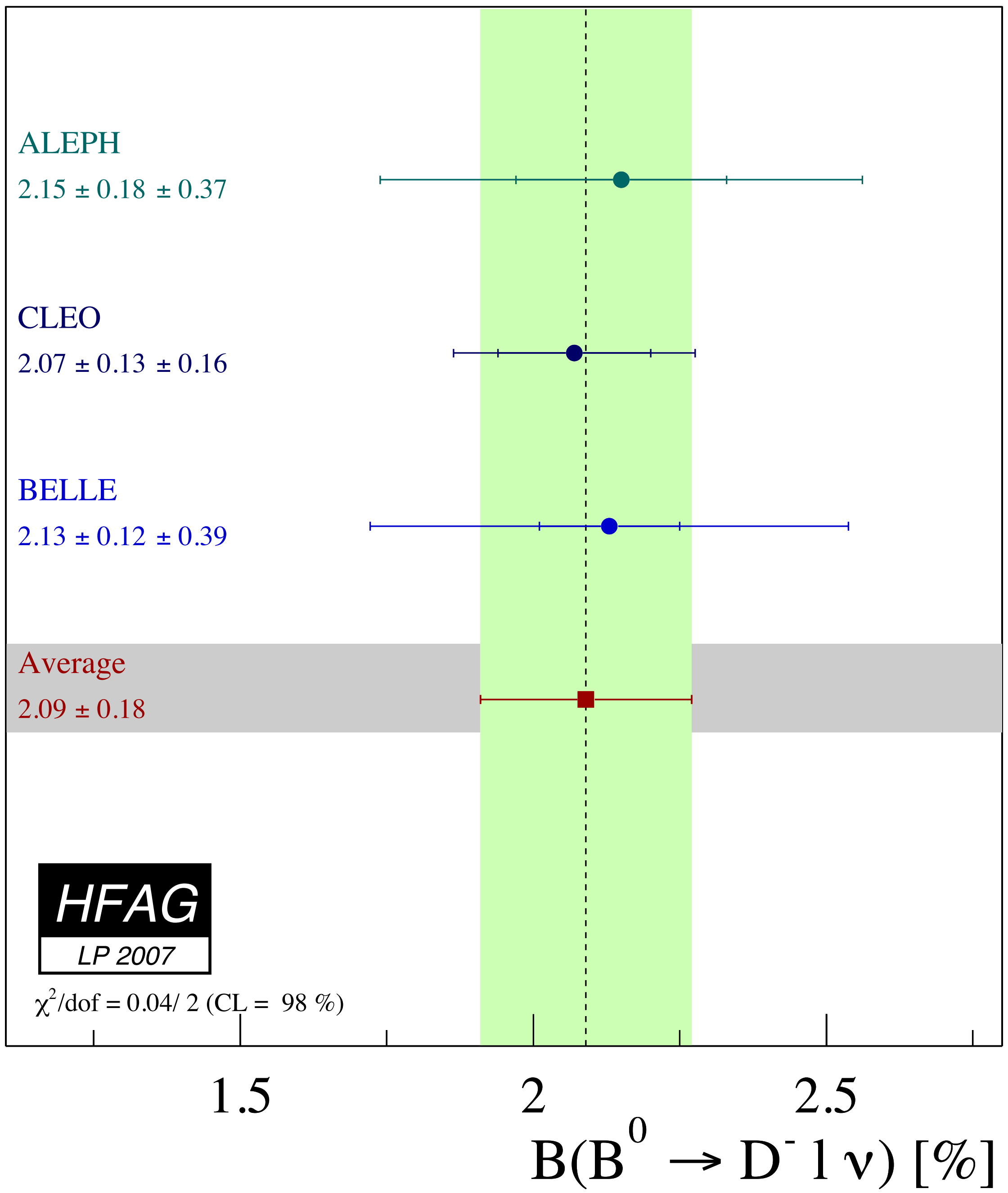


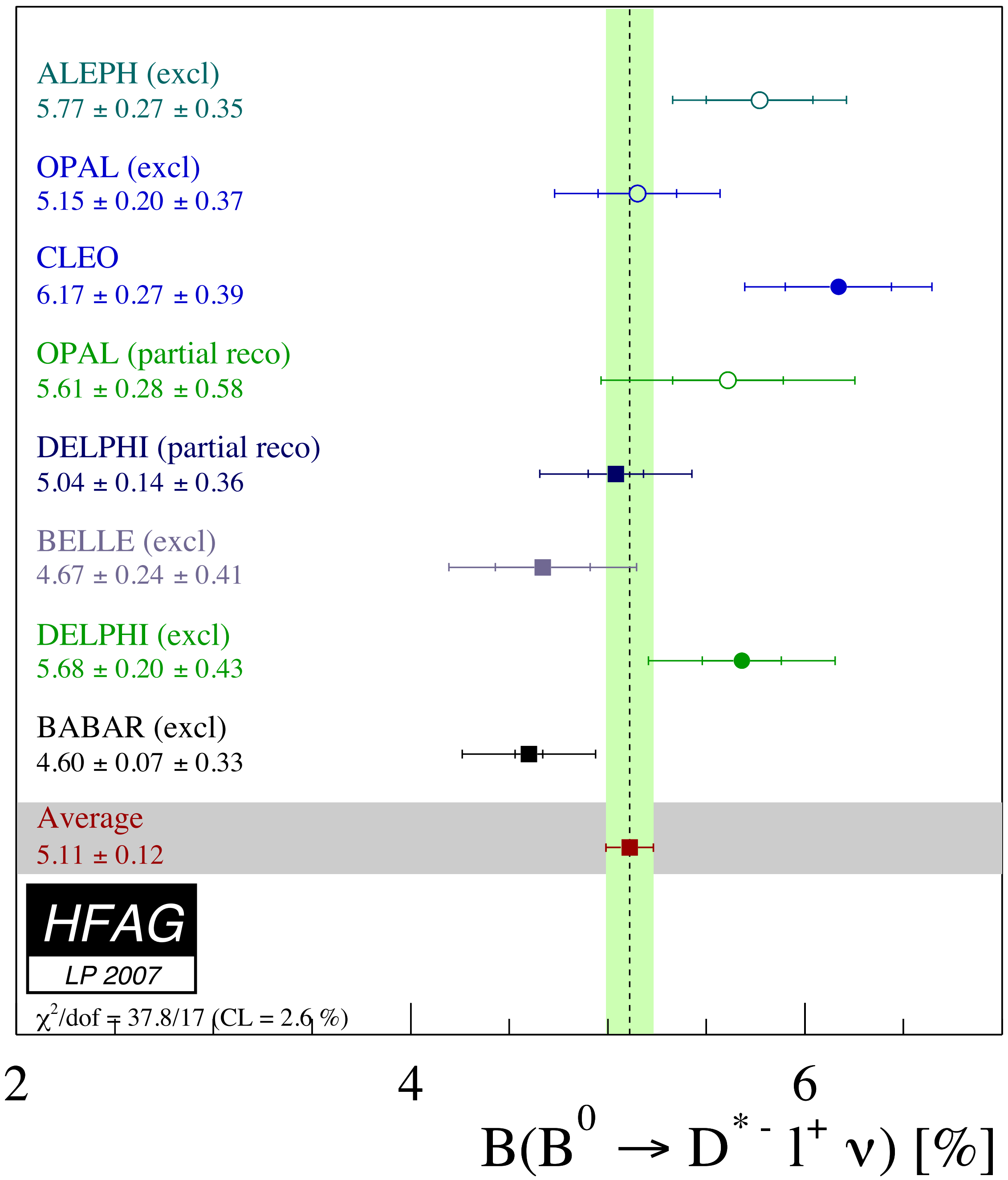
Tau Polarimetry in B decays

Susanne Westhoff

Heavy Quarks through the Looking Glass — Oct 4-5, 2018 — University of Siegen

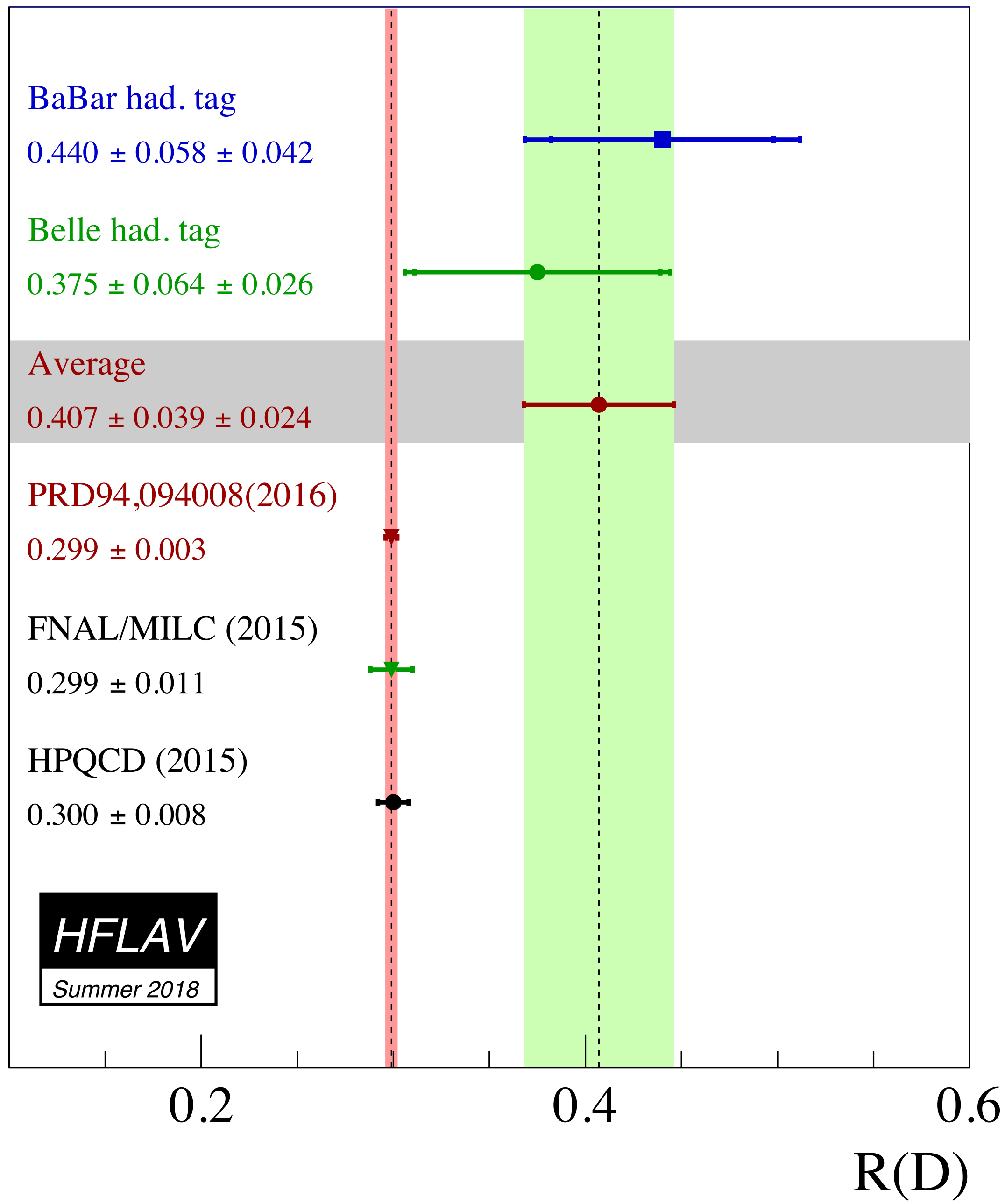
SEMILEPTONIC B DECAYS IN 2007

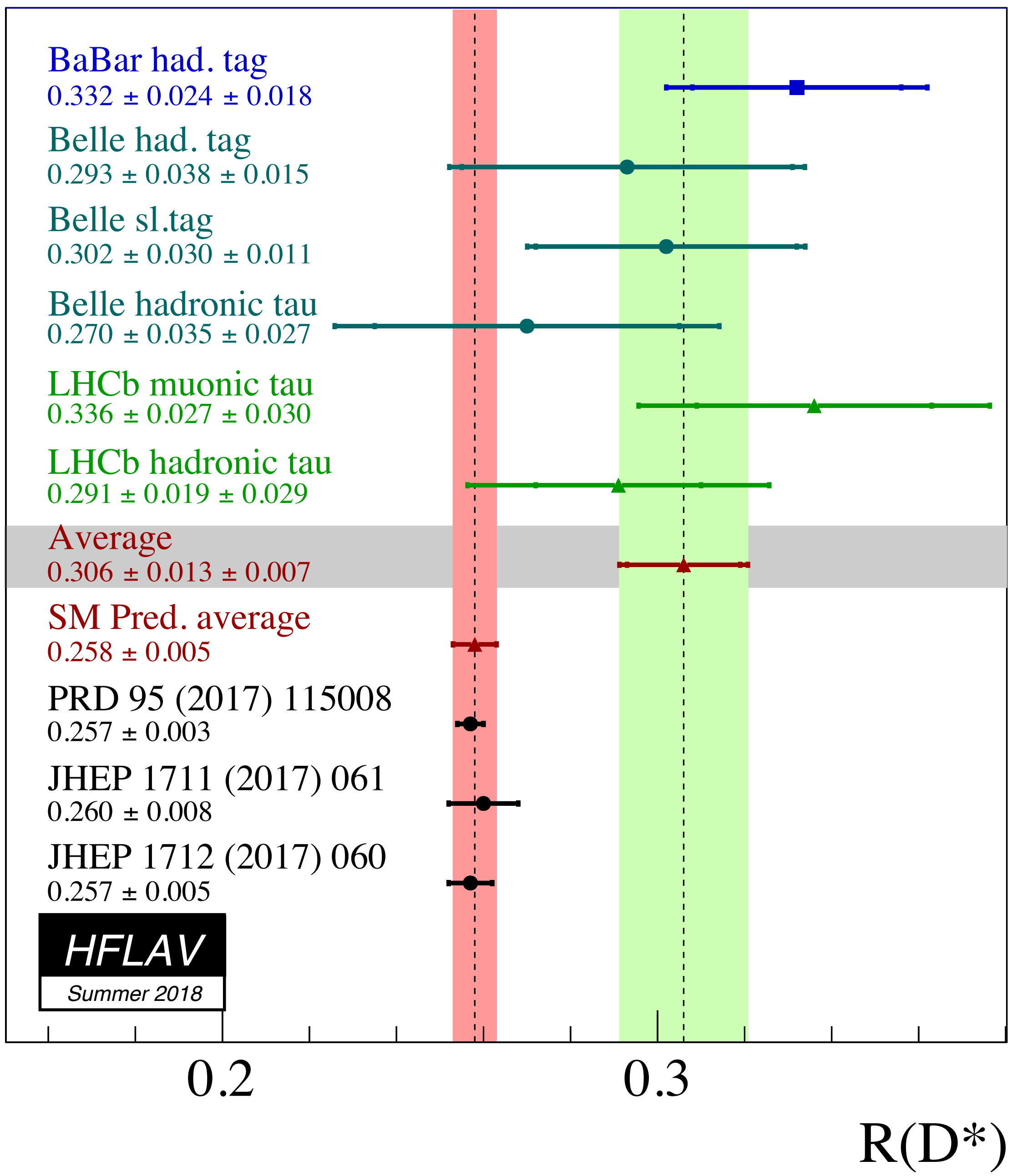




Decays to taus are starting to be explored: $B \to \tau\nu$.

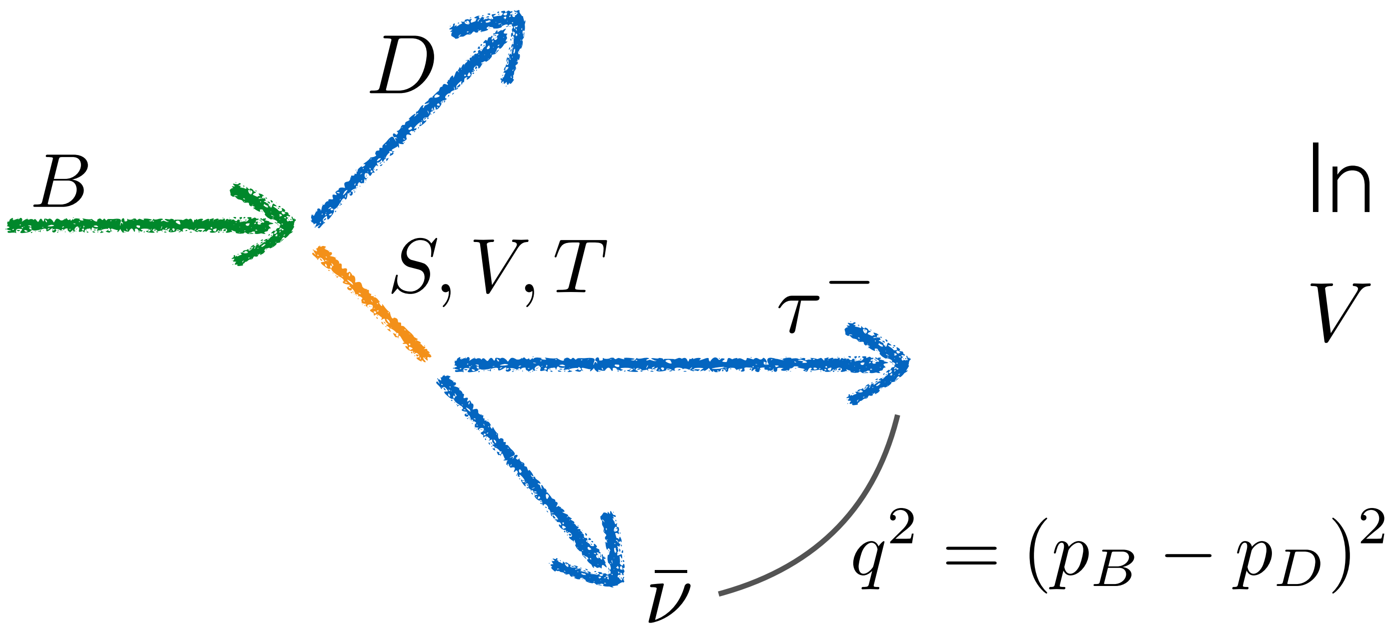
REACHING PRECISION IN B DECAYS TO TAUS





$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$ known up to a few % (th) / 10% (exp).

SEMI-LEPTONIC B DECAYS BEYOND TOTAL RATES



In the standard model:
$V \sim \langle D|\overline{c_L}\gamma_\mu b_L|\bar{B}\rangle$ only.

The tau lepton's mass probes the scalar form factor:

$$\frac{d\Gamma(B \to D\tau\nu)}{dq^2} = \frac{d\Gamma_\ell}{dq^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[1 + \frac{m_\tau^2}{2q^2} + \frac{m_\tau^2}{q^2} f(q^2) \frac{f_0^2(q^2)}{f_+^2(q^2)}\right]$$

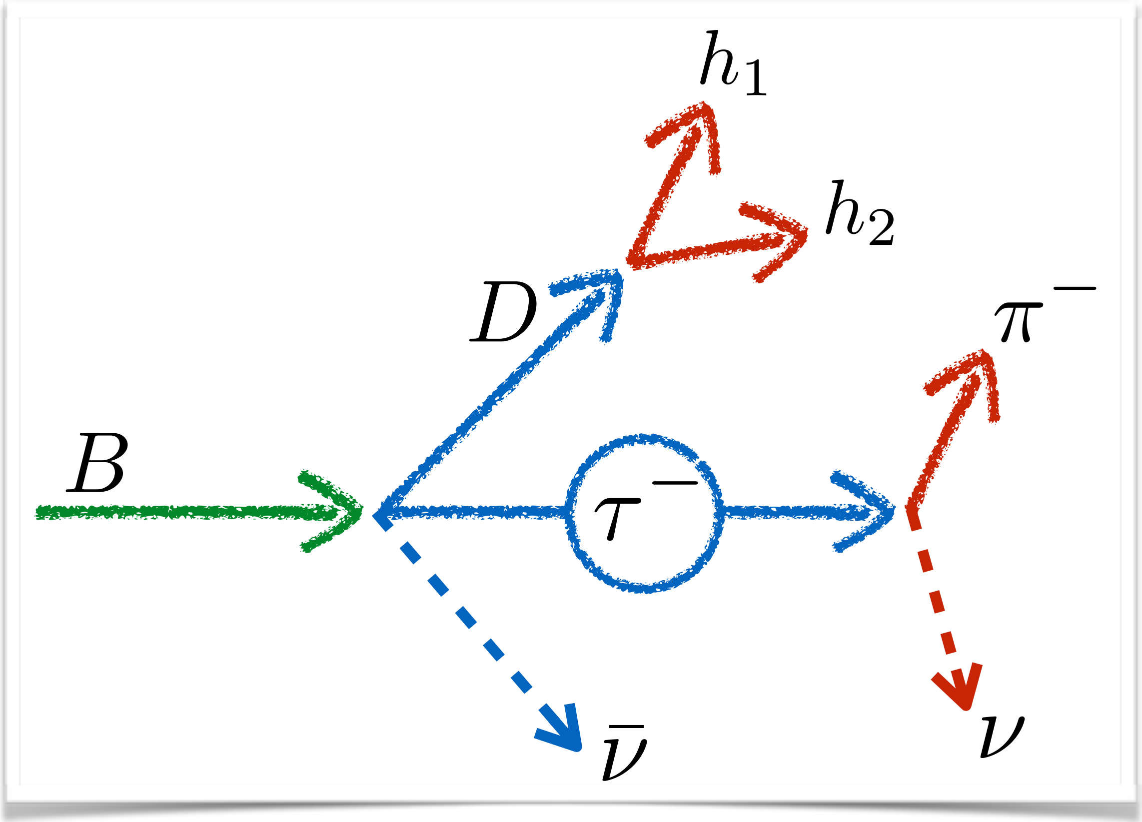
Precise form factor predictions allow us to study the tau's properties in kinematic distributions.

[HQET: Gambino, Mannel, Uraltsev, 2010+]

[recent progress on the lattice: HPQCD, FNAL/MILC, 2017&2018]

THE FULL DECAY CHAIN

Alas, the tau's momentum
cannot (?) be fully reconstructed experimentally:



Idea: Obtain information on tau production ***directly*** from kinematics of ***visible*** particles in final state.

[Kiers, Soni, 1997] [Nierste, Trine, SW, 2008]

RECENT FINAL-STATE ANALYSES

Numerical approach

CP violation: [Hagiwara, Nojiri, Sakaki, 2014]

$B \to D\nu[\tau \to 3\pi\nu]$

Background for $B \to (D, \pi)\mu\nu$:

$B \to (D, \pi)\nu[\tau \to \mu\nu\nu]$

[Bordone, Isidori, van Dyk, 2016]

Analytical approach

Tau pol. and asymmetry:

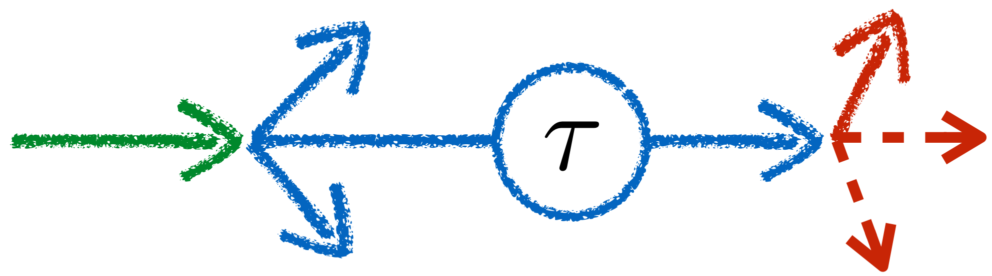
$B \to D^{(*)}\nu[\tau \to (\ell\nu, \pi, \rho)\nu]$

[Tanaka, Watanabe, 2010]

[Sakaki, Tanaka, 2013]

[Alonso, Martin Camalich, SW, 2017]

[Ivanov, Koerner, Tran, 2017+]



Search for new physics: $B \to [D^{(*)} \to D(\pi, \gamma)]\nu[\tau \to (\ell\nu, \pi)\nu]$

[Ligeti, Papucci, Robinson, 2016+]

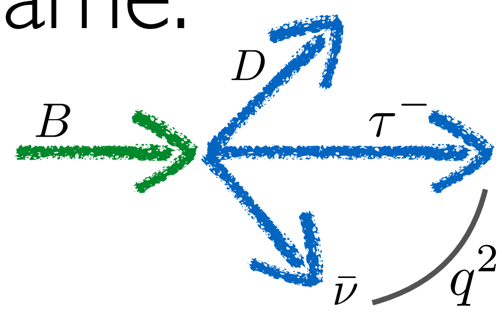
[Alonso, Kobach, Martin Camalich, 2016]

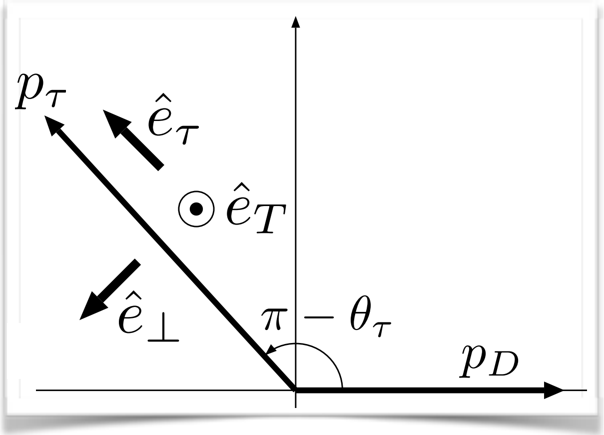
[Bhattacharya et al., 2018]

[Colangelo, De Fazio, 2018]

TAU PRODUCTION PROPERTIES

In q rest frame:

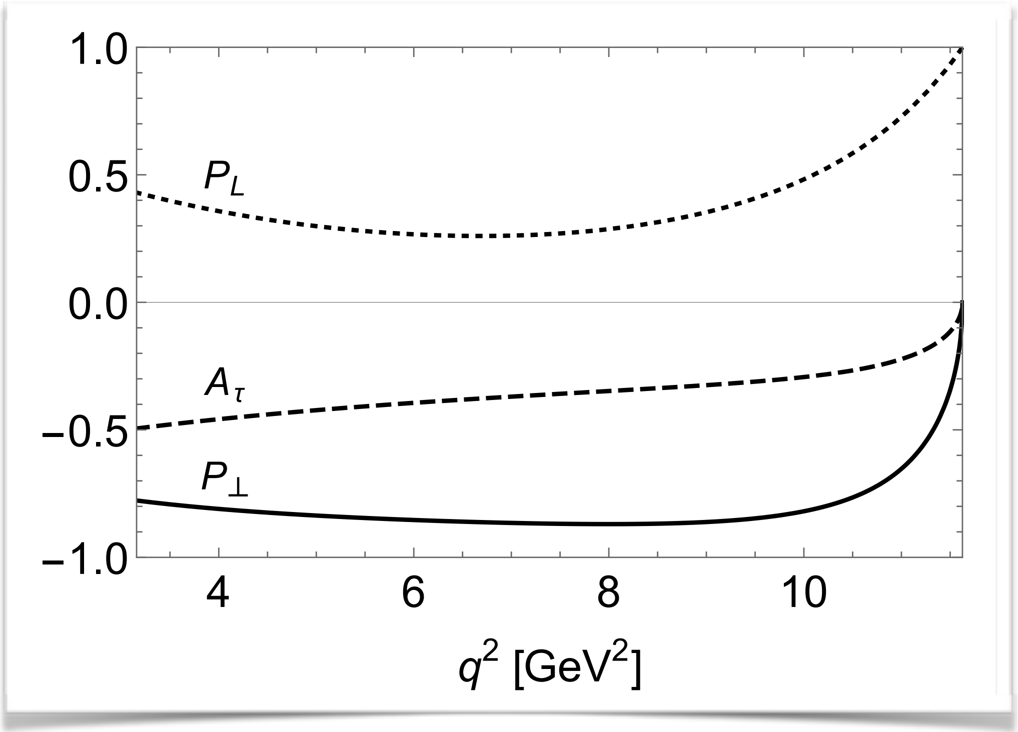




[Tanaka, 1994]

Tau polarizations $dP_i = \dfrac{d\Gamma_i}{d\Gamma}$ from

$$d\Gamma(\hat{s}) = \frac{1}{2}\left[d\Gamma + (d\Gamma_L \hat{e}_\tau + d\Gamma_\perp \hat{e}_\perp + d\Gamma_T \hat{e}_T) \cdot \hat{s}\right]$$



Tau forward-backward asymmetry

$$\Gamma A_\tau = \int_0^1 d\cos\theta_\tau \frac{d\Gamma}{d\cos\theta_\tau} - \int_{-1}^0 d\cos\theta_\tau \frac{d\Gamma}{d\cos\theta_\tau}$$

Standard-model predictions:

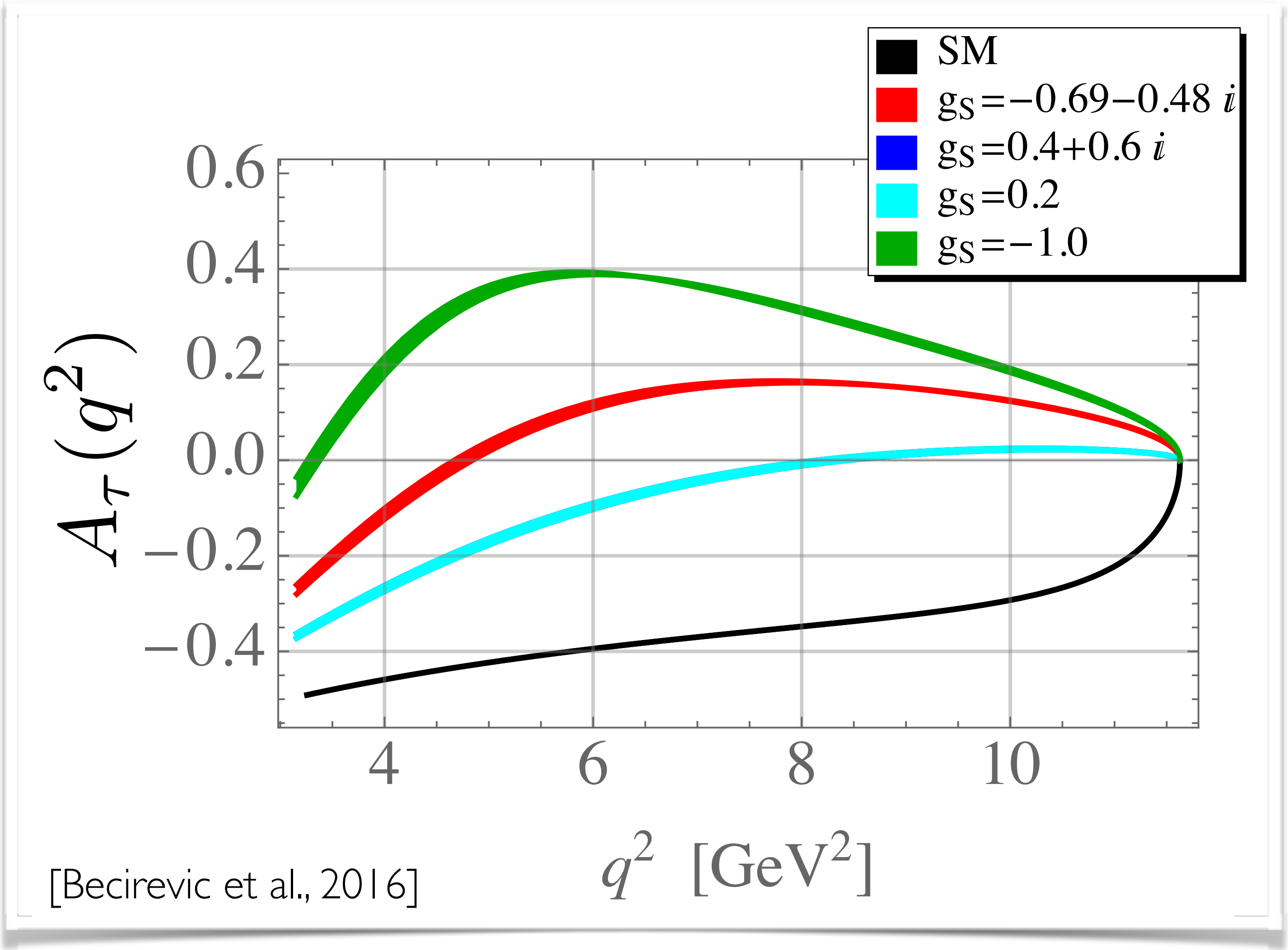
$$P_L = 0.34(3), \quad P_\perp = -0.839(7), \quad A_\tau = -0.359(3)$$ [Alonso, Martin Camalich, SW, 2017]

$$m_\tau = 0: \to 1 \qquad \to 0 \qquad \to 0$$

TAU ASYMMETRY AND NEW PHYSICS

Tau asymmetry has high sensitivity to new scalar contribution:

$$A_\tau(q^2) \sim -\frac{m_\tau^2}{q^2}\left[1 + \mathrm{Re}[g_S] f(q^2) \frac{f_0(q^2)}{f_+(q^2)} + \dots\right]$$



[Martin Jung's talk]

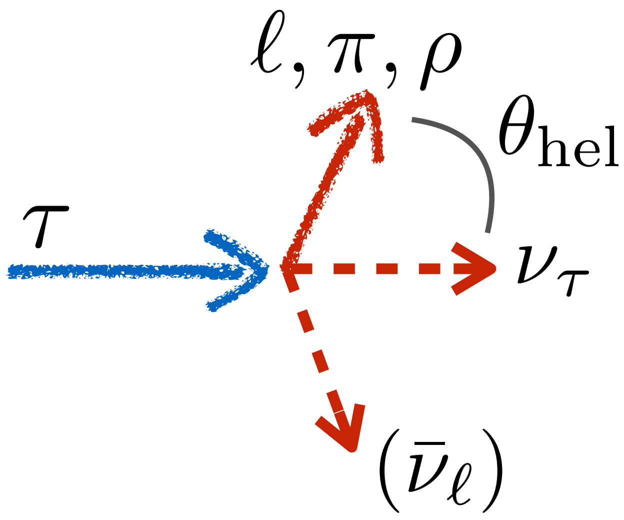
TAU DECAYS

Tau decay branching ratios:

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%

Hadronic tau decays have highest analyzing power:

$$\frac{1}{\Gamma_\tau}\frac{d\Gamma_\tau}{d\cos\theta_{\rm hel}} = \frac{1}{2}(1+\alpha P_L \cos\theta_{\rm hel})$$



Scalar pion: $\alpha = 1$

Vector meson rho: $\alpha = \dfrac{m_\tau^2 - 2m_\rho^2}{m_\tau^2 + 2m_\rho^2} \approx 0.45$

Strong experimental bounds on new physics in tau decays.

[Cirigliano et al., 2018]

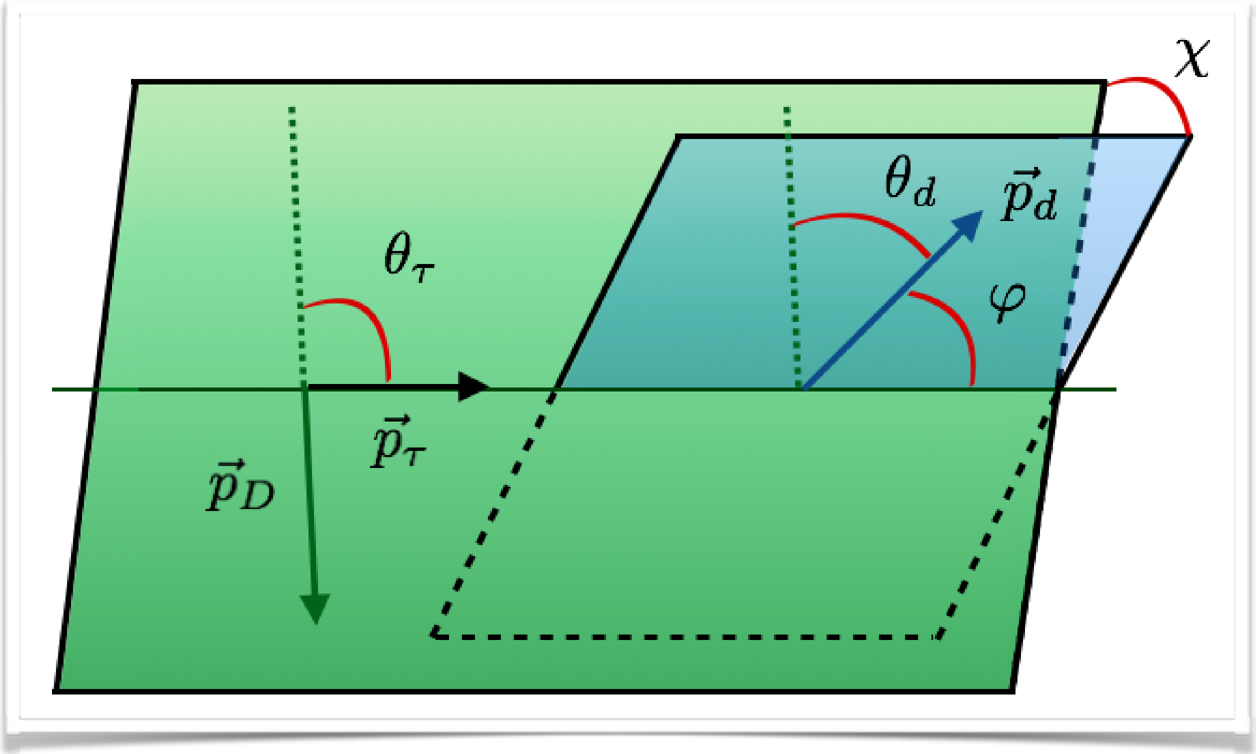
DIFFERENTIAL DECAY DISTRIBUTIONS

Full decay chain $B \to D\nu[\tau \to d\nu(\nu)]$:

Integration over phase-space of invisible neutrinos yields

$$\frac{d^3\Gamma_d}{dq^2\, ds_d\, d\cos\theta_d} \sim I_0(q^2, s_d) + I_1(q^2, s_d)\cos\theta_d + I_2(q^2, s_d)\cos^2\theta_d$$

→ visible final state described by $q^2,\ s_d = E_d/\sqrt{q^2},\ \cos\theta_d$



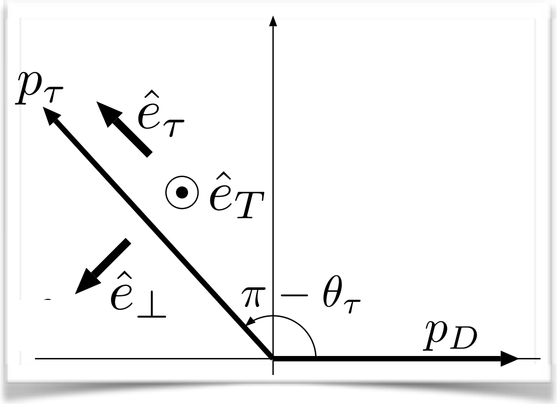
[Alonso, Martin Camalich, SW, 2017]

[Alonso, Kobach, Martin Camalich, 2016]

OBSERVABLES OF TAU PROPERTIES

P_L : from **energy distribution** of visible tau decay particle *d*

$$\frac{d^2\Gamma_d}{dq^2 ds_d} = \mathcal{B}_d \frac{d\Gamma}{dq^2}\left[f_0^d + f_L^d(s_d) P_L(q^2)\right]$$



$P_\perp$: from **angular asymmetry of *d*** in *D* direction

$$\frac{dA_d}{ds_d} = \left(\mathcal{B}_d \frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^1 d\cos\theta_d\, d^3\Gamma_d - \int_{-1}^0 d\cos\theta_d\, d^3\Gamma_d\right]$$
$$= f_A^d(s_d) A_\tau(q^2) + f_\perp^d(s_d) P_\perp(q^2)$$

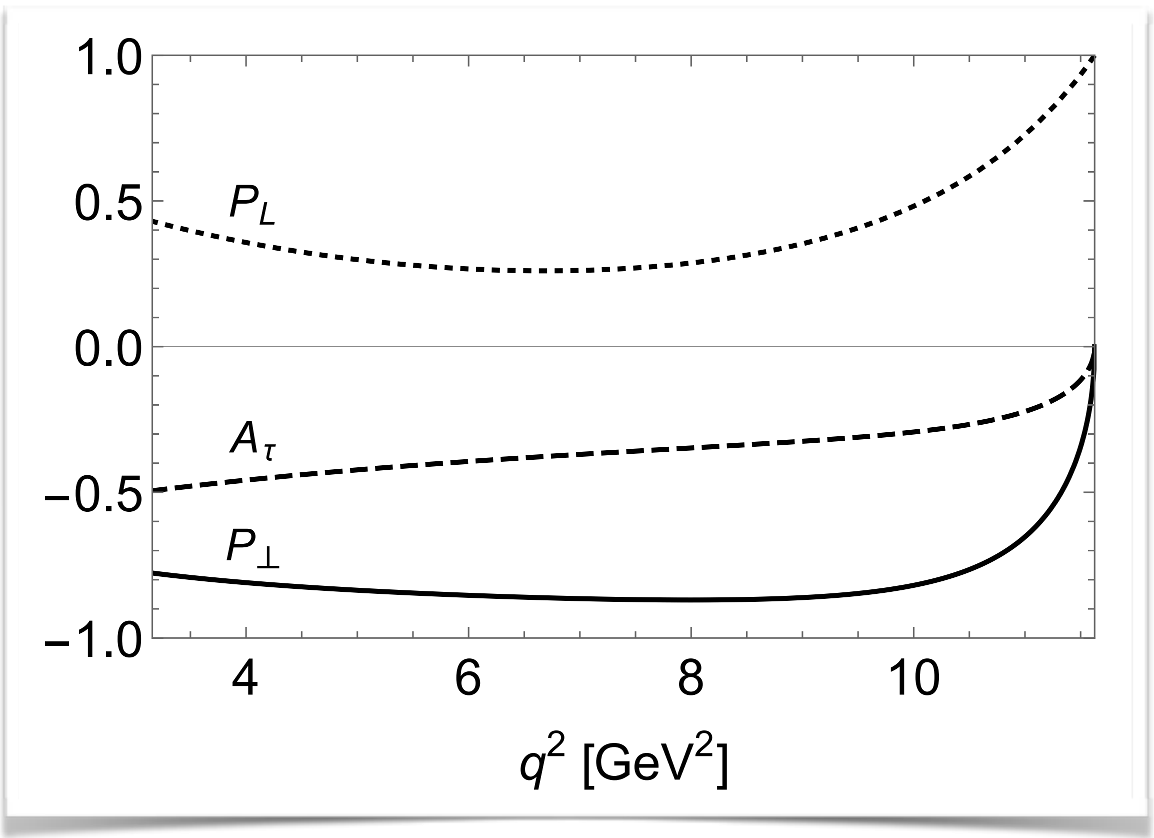
complementary to tau forward-backward asymmetry!

P_T : requires additional information perpendicular to *d*-*D* plane (tau tracks? three-prong decay?) [see Guy Wormser's talk at Moriond EW, 2017]

EXTRACTING TAU PROPERTIES

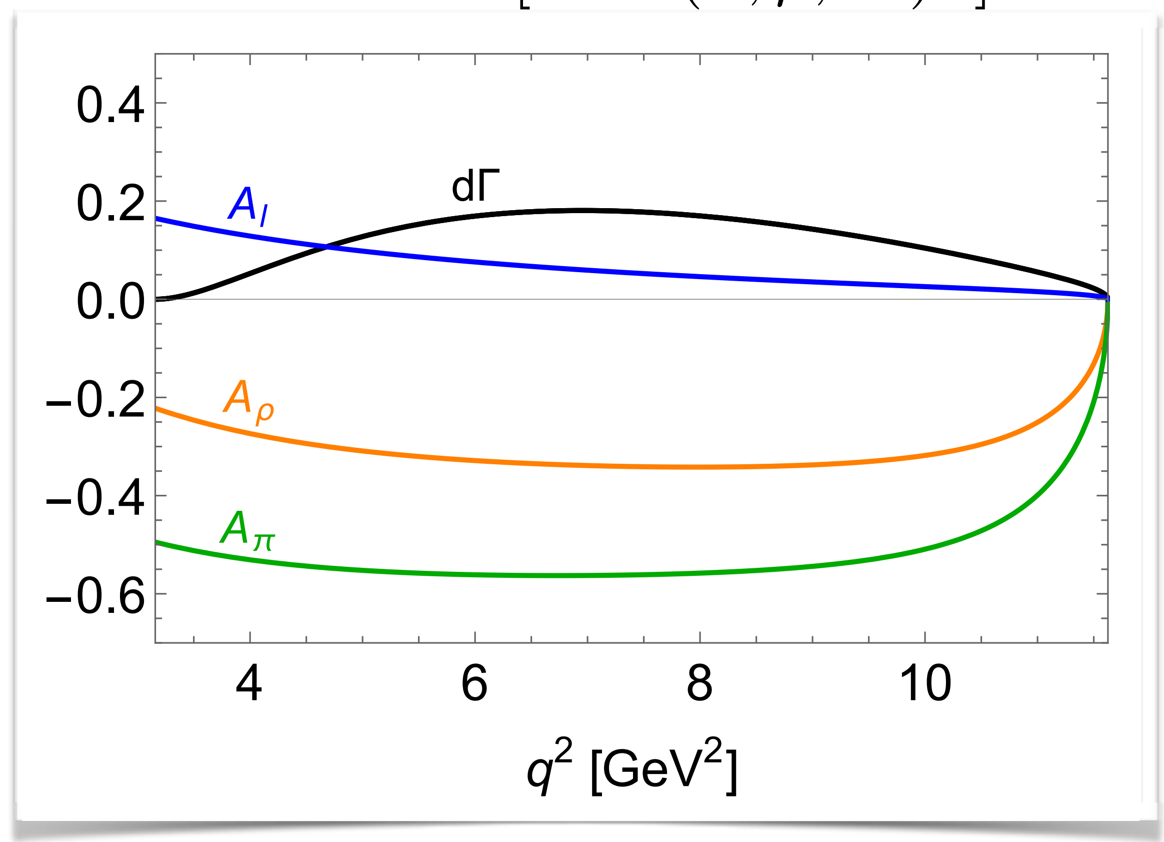
Production:

$B \to D\tau\nu$

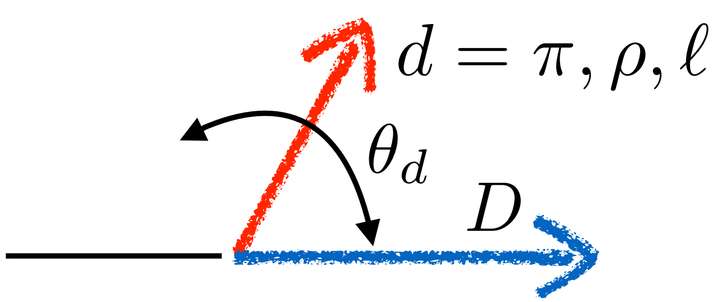


Observable:

$B \to D\nu[\tau \to (\pi, \rho, \ell\nu)\nu]$



Forward-backward asymmetry of decay particle *d*:



Integrated over q^2:

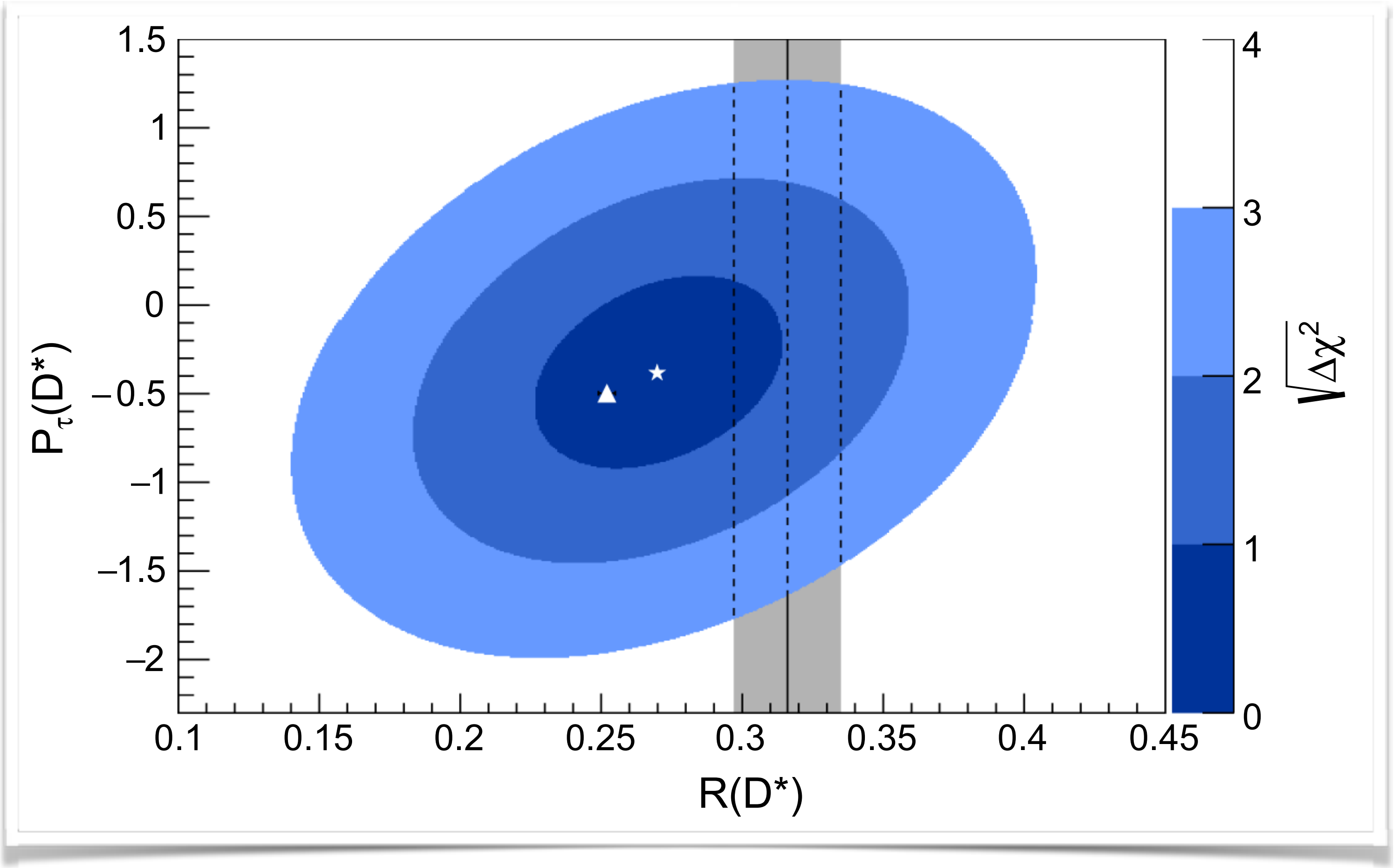
$$A_\pi = -0.54, \quad A_\rho = -0.32, \quad A_\ell = +0.06$$

[Alonso, Martin Camalich, SW, 2017]

TAU POLARIZATION MEASUREMENT

Based on hadronic decay modes $\tau \to \pi\nu,\ \tau \to \rho\nu$: [BELLE coll., 2017]

$$P_\tau(D^*) = P_L(D^*) = -0.38 \pm 0.51\,(\mathrm{stat})\,{}^{+0.21}_{-0.16}\,(\mathrm{syst})$$



Also: D* longitudinal polarization [BELLE collaboration, 2018]

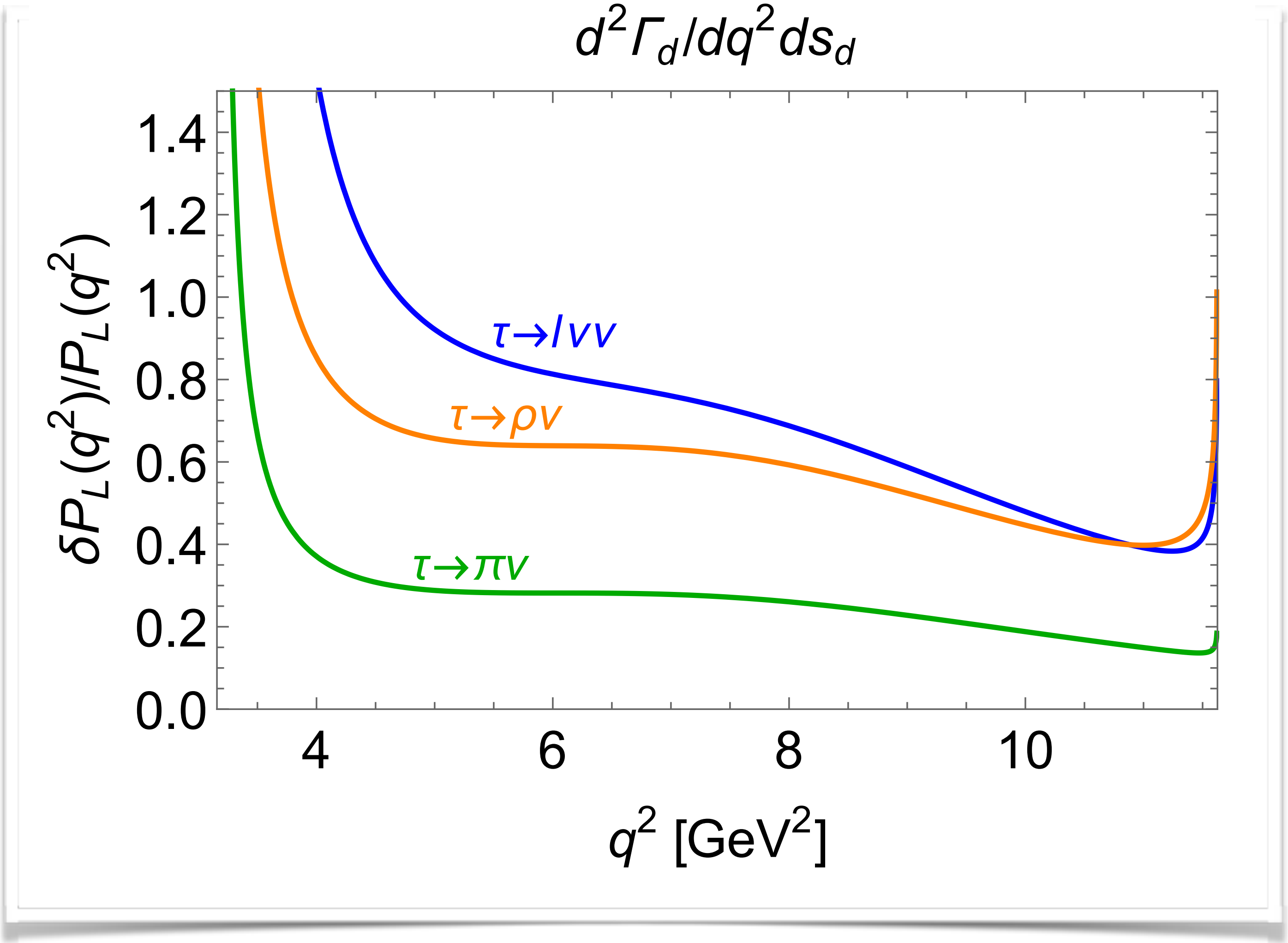
$$F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)} = 0.60 \pm 0.08\,(\mathrm{stat}) \pm 0.035\,(\mathrm{syst})$$

[Karol Adamczyk's talk at CKM 2018]

LONGITUDINAL POLARIZATION AT BELLE II

Statistical uncertainty with $N(q^2)$ events per q^2(bin):

$$\delta P_L(q^2) = \frac{1}{\sqrt{N(q^2)}S_L(q^2)} \quad \text{with} \quad S_L^2(q^2) = \int ds_d \frac{f_L^d(s_d)^2}{f_0^d + f_L^d(s_d)P_L(q^2)}$$



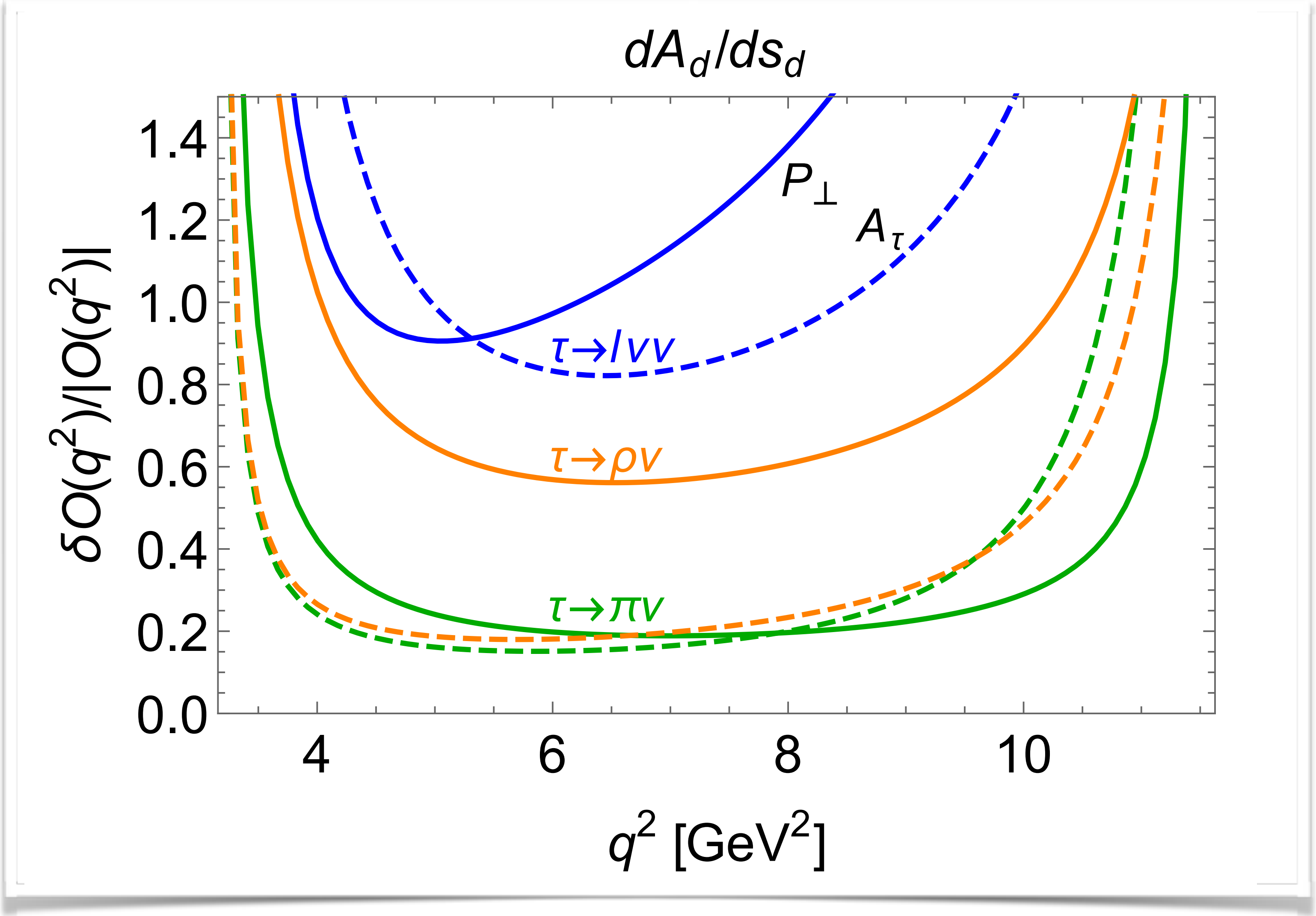
[Alonso, Martin Camalich, SW, 2017]

At BELLE II with luminosity $\mathcal{L} = 50\,\mathrm{ab}^{-1}$: $N_{\mathrm{tot}} \approx 3000$.

PERPENDICULAR POLARIZATION AT BELLE II

Maximum-likelihood fit to energy distribution of *d* asymmetry

$$\frac{dA_d}{ds_d} = f_A^d(s_d)A_\tau(q^2) + f_\perp^d(s_d)P_\perp(q^2)$$



[Alonso, Martin Camalich, SW, 2017]

STATISTICAL SENSITIVITY AT BELLE II

Expected statistical precision for $\tau \to \{\pi\nu, \rho\nu, \ell\nu\nu|\mathrm{comb.}\}$:

	Belle [total]	Belle II [1 year]	Belle II [total]
$\mathcal{L}$ [ab^{-1}]/N [events]	1/60	5/300	50/3000
$\delta P_L/P_L$	$\{0.21, 0.49, 0.62 \,\|\, 0.19\}$	$\{0.10, 0.22, 0.28 \,\|\, 0.08\}$	$\{0.03, 0.07, 0.09 \,\|\, 0.03\}$
$\delta P_\perp/\|P_\perp\|$	$\{0.62, 1.8, 4.0 \,\|\, 0.58\}$	$\{0.28, 0.81, 1.8 \,\|\, 0.26\}$	$\{0.09, 0.25, 0.57 \,\|\, 0.08\}$
$\delta A_\tau/\|A_\tau\|$	$\{0.74, 0.69, 2.8 \,\|\, 0.50\}$	$\{0.33, 0.31, 1.3 \,\|\, 0.22\}$	$\{0.11, 0.10, 0.40 \,\|\, 0.07\}$

Theory prediction:

Best sensitivity to tau properties from **hadronic** decays.

BEYOND THE STANDARD POLARIZATION

Disentangle new effective b-c-tau-nu interactions:

[Belle II Physics Book, 2018]

scalar

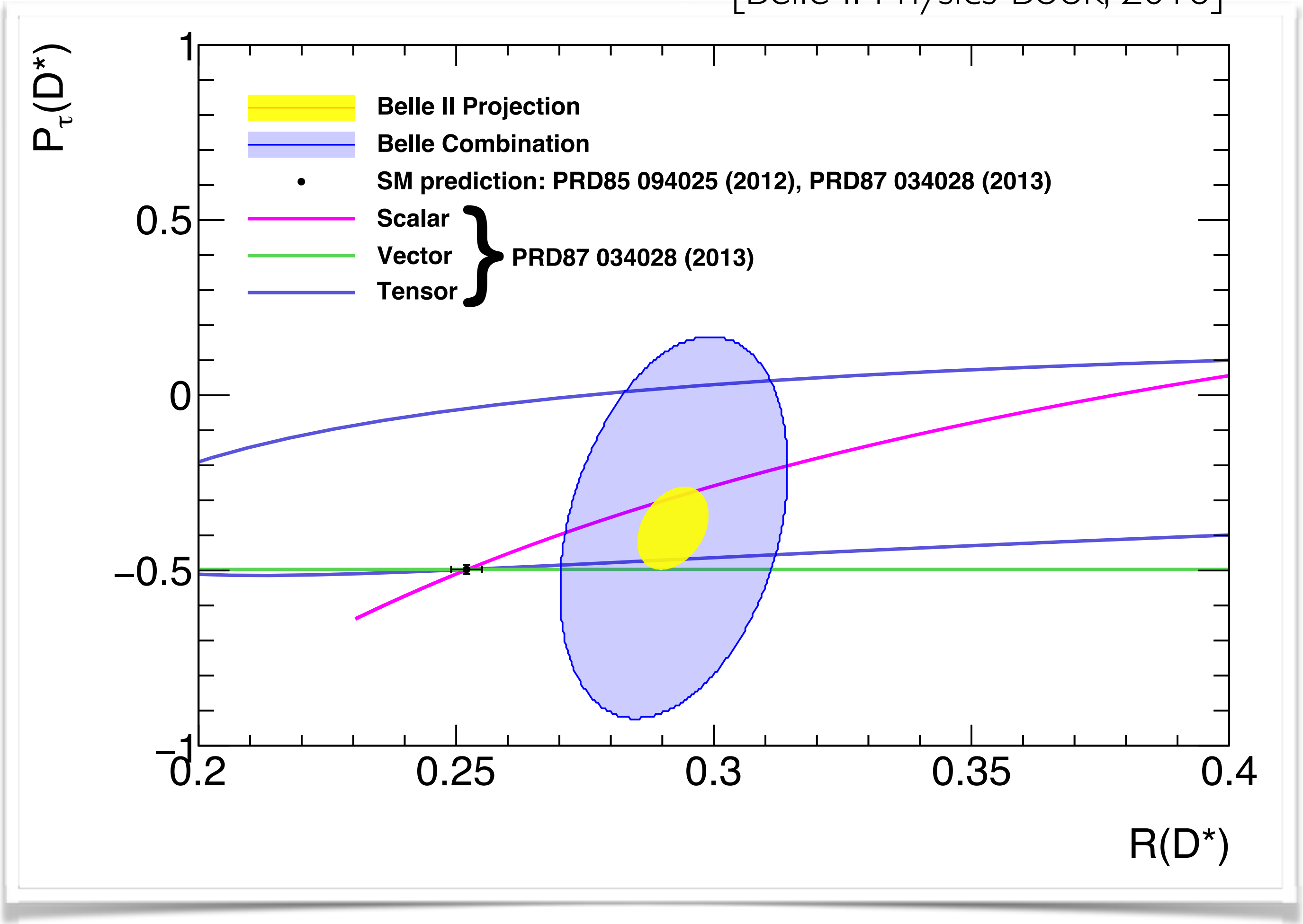
$$\mathcal{O}_{S_1} = \bar{c}_L b_R \, \bar{\tau}_R \nu_L$$

vector

$$\mathcal{O}_{V_1} = \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L$$

tensor

$$\mathcal{O}_T = \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\tau}_R \sigma_{\mu\nu} \nu_L$$



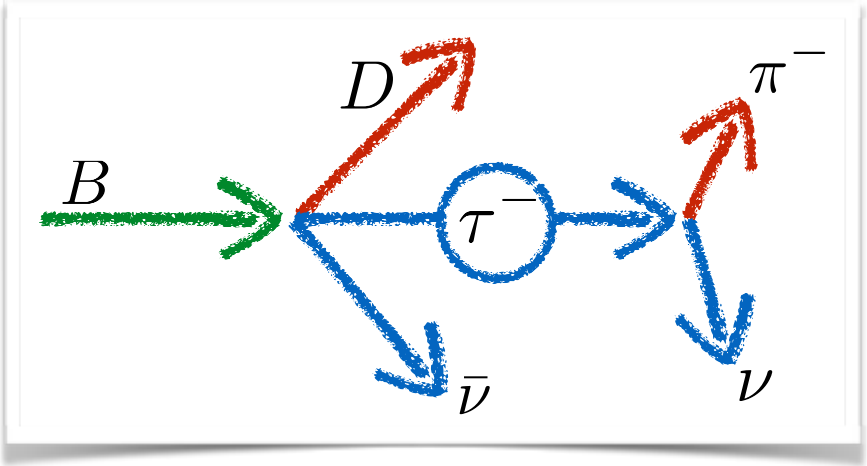
Tension with inclusive B to tau decays [Ligeti, Tackmann, 2014] [Mannel, Rusov, Shahriaran, 2017]

Leptonic tau decays in b-c-tau-nu [Alonso, Kobach, Martin Camalich, 2016]

[global interpretation: Svjetlana Fajfer's talk]

TAKE HOME

- Tau properties in semi-leptonic *B* decays from final states:
  - longitudinal polarization $P_L \leftrightarrow d\Gamma_d(E_d)$
  - perpendicular pol. and asymmetry $P_\perp, A_\tau \leftrightarrow A_d(E_d)$



(similar strategy for D^*)

- **Hadronic** tau decays have **high sensitivity** to tau properties.
- Good prospects for **measurements** at BELLE II (and LHCb?).
- Opportunity to probe **new physics** with tau interactions.


Herbstschule für Teilchenphysik
Maria Laach 2007
HAPPY BIRTHDAY THOMAS!