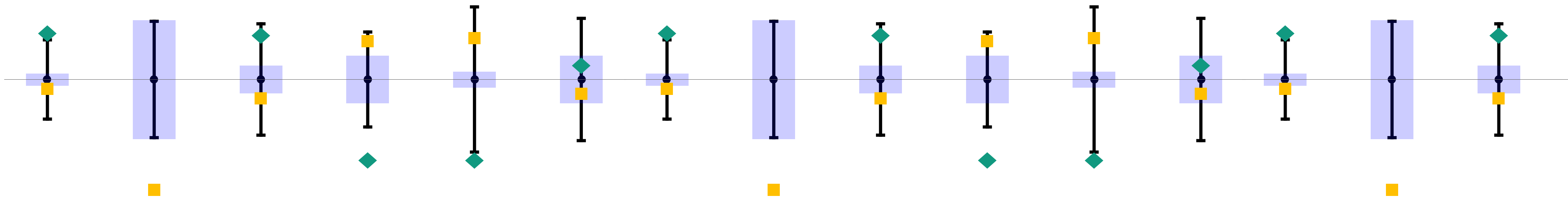
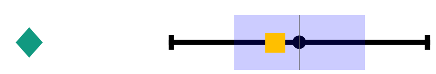
CRC-TRR-257

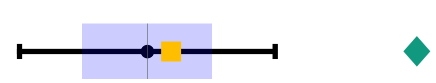


THEORY OF RD(*) AND TAU POLARIZATION



Susanne Westhoff

Heidelberg University



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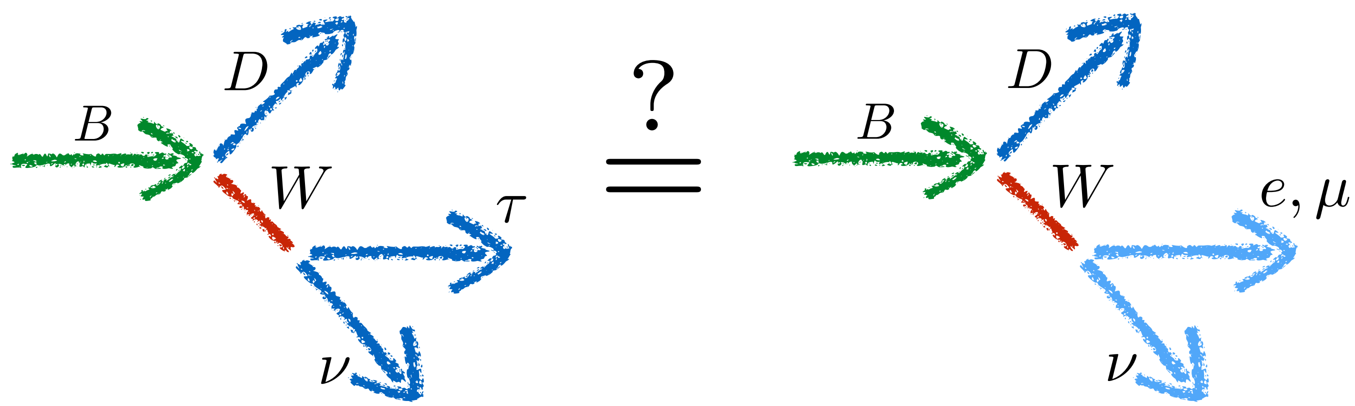
Why do we care?

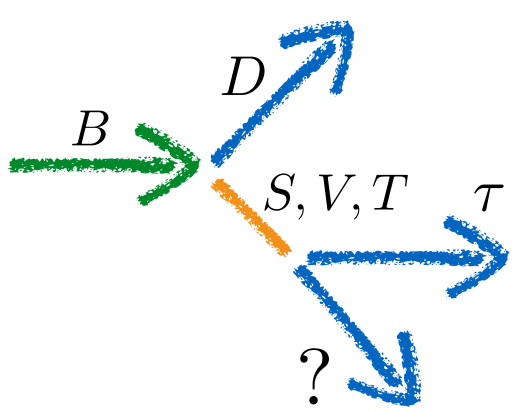
In the standard model:

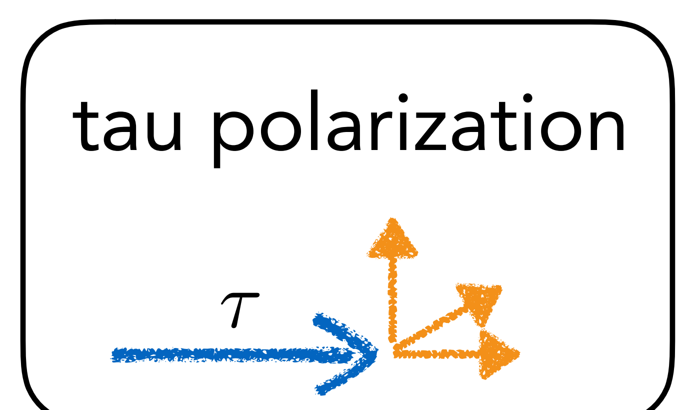
- Are the weak interactions flavor-universal? CP violation?
- Are they mediated by a massive vector boson?



Beyond:

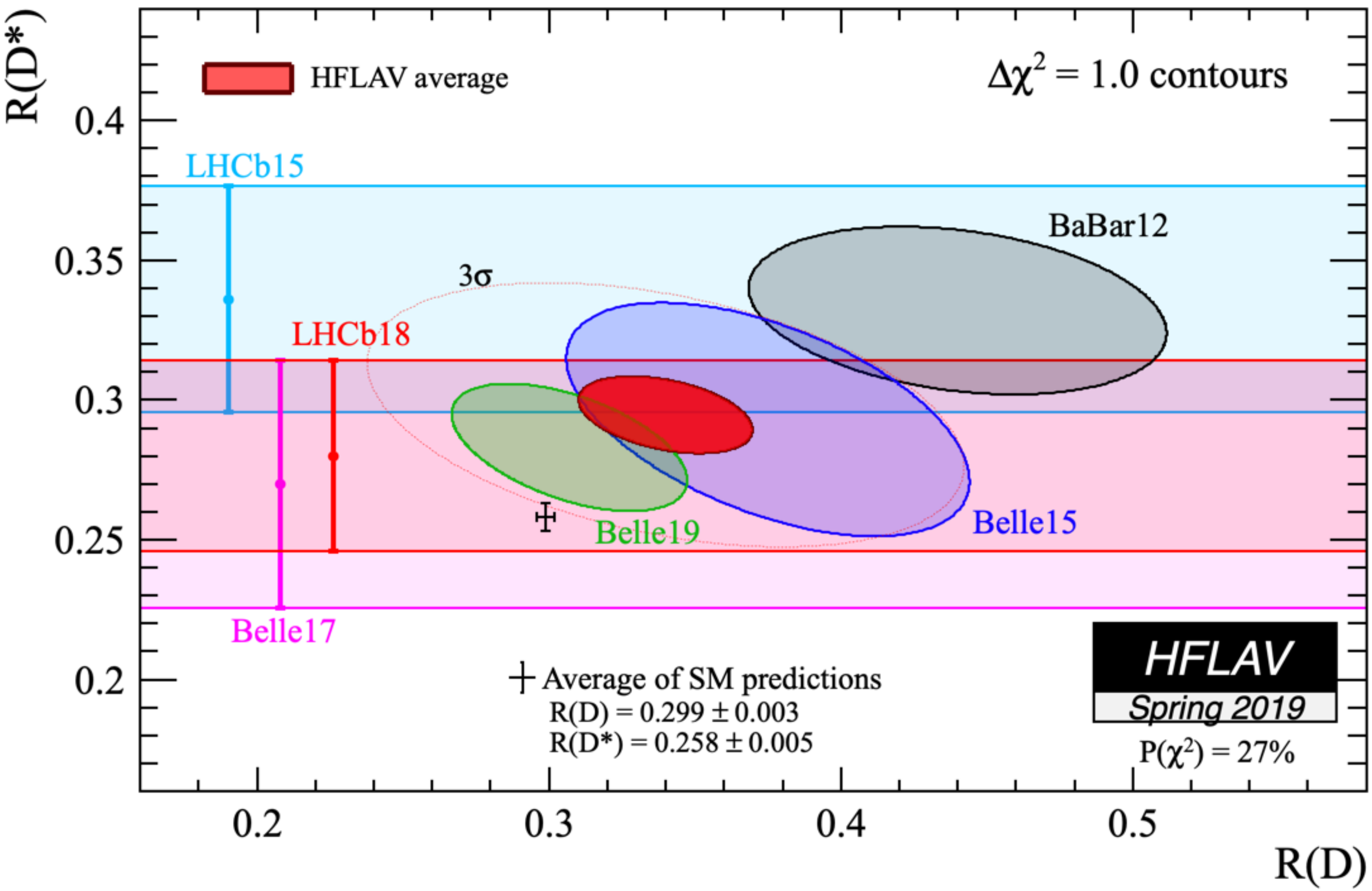
- Is there a new force mediating b-c-tau-nu interactions?
- Is the emitted missing energy a neutrino?





Ratios of branching ratios

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

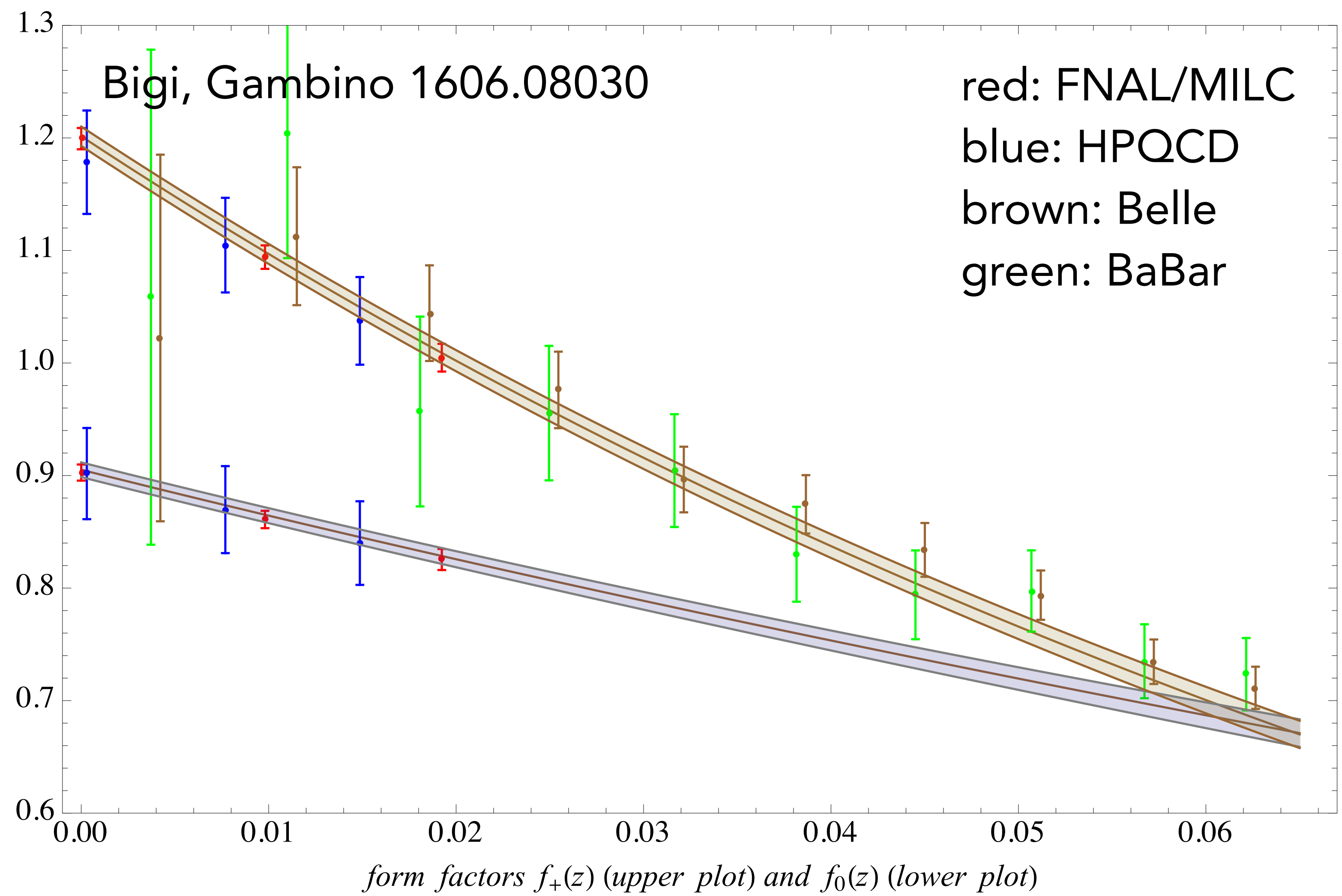


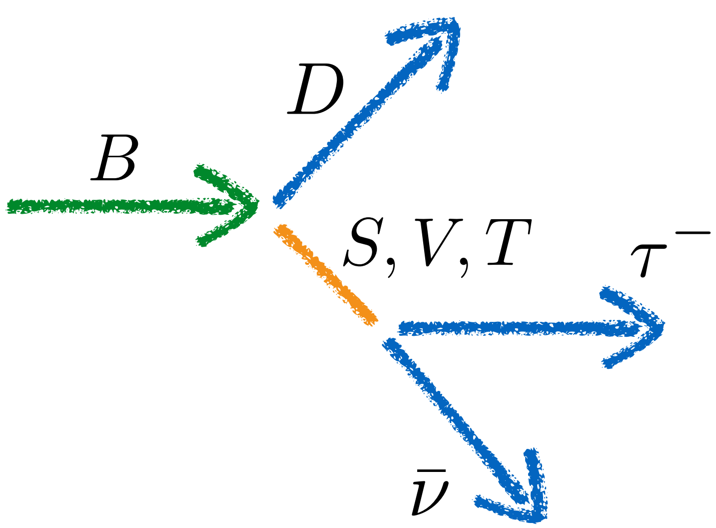
Beyond rates

Tau mass probes scalar form factor:

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

Form factors determined with input from lattice and data:



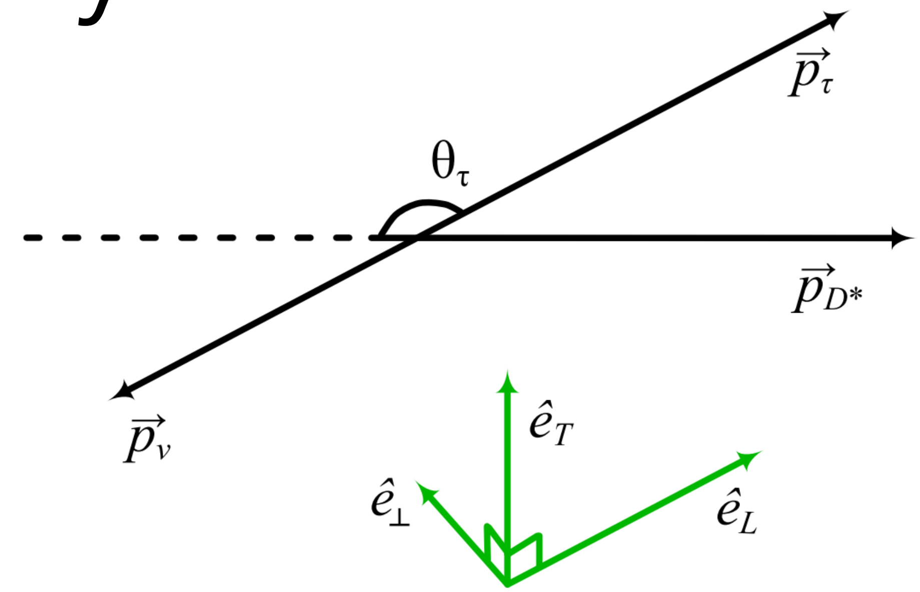


$$q^2 = (p_B - p_D)^2$$

B > D*: Bigi, Gambino, Schacht 1707.09509

Tau polarimetry

Tau helicity amplitudes in $B \to D^{(*)}\tau\nu$:



$\cos\theta_\tau,\ \lambda_\tau = \pm$ (q^2 frame)

Expand differential rates in spherical harmonics.

Koerner, Schuler 1990

$$\frac{d^2\Gamma_B^{\lambda_\tau}}{dq^2 d\cos\theta_\tau} = \frac{d\Gamma_B}{dq^2}\sum_{\ell=0}^{2} B_\ell^{\lambda_\tau}(q^2) P_\ell^0(\cos\theta_\tau)$$

$$\frac{d^2\mathcal{P}_B^{\perp}}{dq^2 d\cos\theta_\tau} = \frac{d\Gamma_B}{dq^2}\sum_{\ell=1}^{2} \mathrm{Re}[C_\ell(q^2)] P_\ell^1(\cos\theta_\tau)$$

$$\frac{d^2\mathcal{P}_B^{T}}{dq^2 d\cos\theta_\tau} = \frac{d\Gamma_B}{dq^2}\sum_{\ell=1}^{2} \mathrm{Im}[C_\ell(q^2)] P_\ell^1(\cos\theta_\tau)$$

Rate:

$$d\Gamma_B = d\Gamma_B^{+,L} + d\Gamma_B^{-,L}$$

Spin asymmetries:

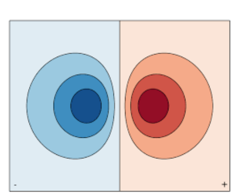
$$d\mathcal{P}_B^a = d\Gamma_B^{+,a} - d\Gamma_B^{-,a}$$

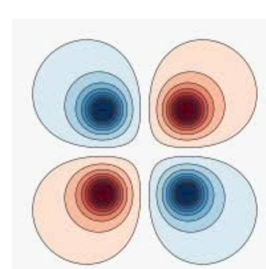
10 independent helicity amplitudes to fully describe tau production.

picture: Anna Hallin

Tau asymmetries

	1	dipole	quadrupole
1	Γ	A_{FB}	A_Q
L	P_L	Z_L	Z_Q
$\perp$	$P_\perp$	$Z_\perp$	
T	P_T	Z_T	





Polarization:

$$P_a(q^2) \sim \int \frac{d\mathcal{P}_a}{dq^2 d\cos\theta_\tau} d\cos\theta_\tau$$

Angular asymmetry:

$$A_\ell(q^2) \sim \int \frac{d\Gamma}{dq^2 dc\theta_\tau} P_\ell^0(c\theta_\tau)\, dc\theta_\tau$$

Zweifach (double):

$$Z_{a,\ell}(q^2) \sim \int \frac{d\mathcal{P}_a}{dq^2 dc\theta_\tau} P_\ell^0(c\theta_\tau)\, dc\theta_\tau$$

Total: 10 observables

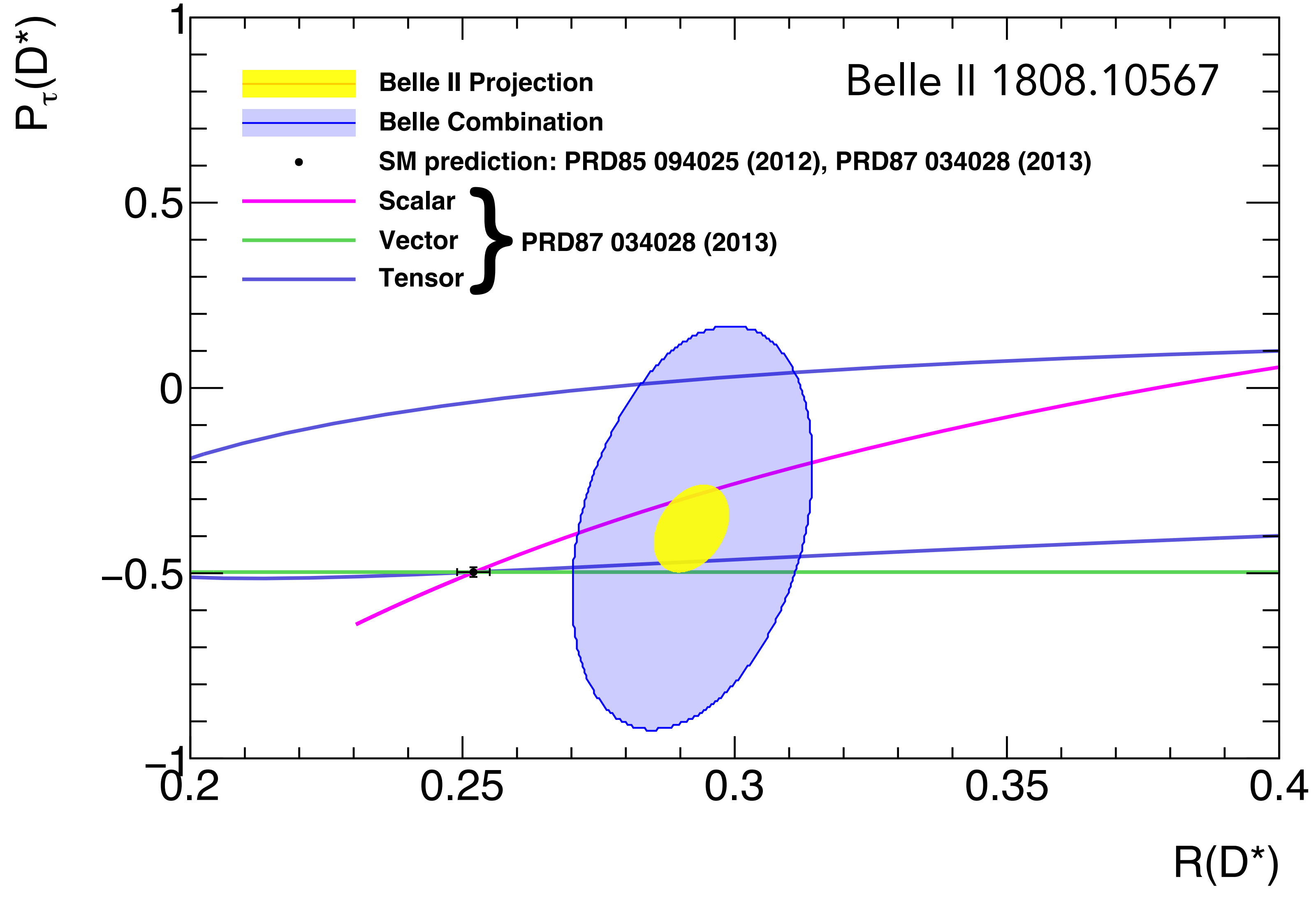
Asadi, Hallin, Martin Camalich, Shih, Westhoff 2006.16416

Currently: tau polarization

Measured in hadronic tau decays $\tau \to \pi\nu,\ \tau \to \rho\nu$: Belle 1709.00129

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

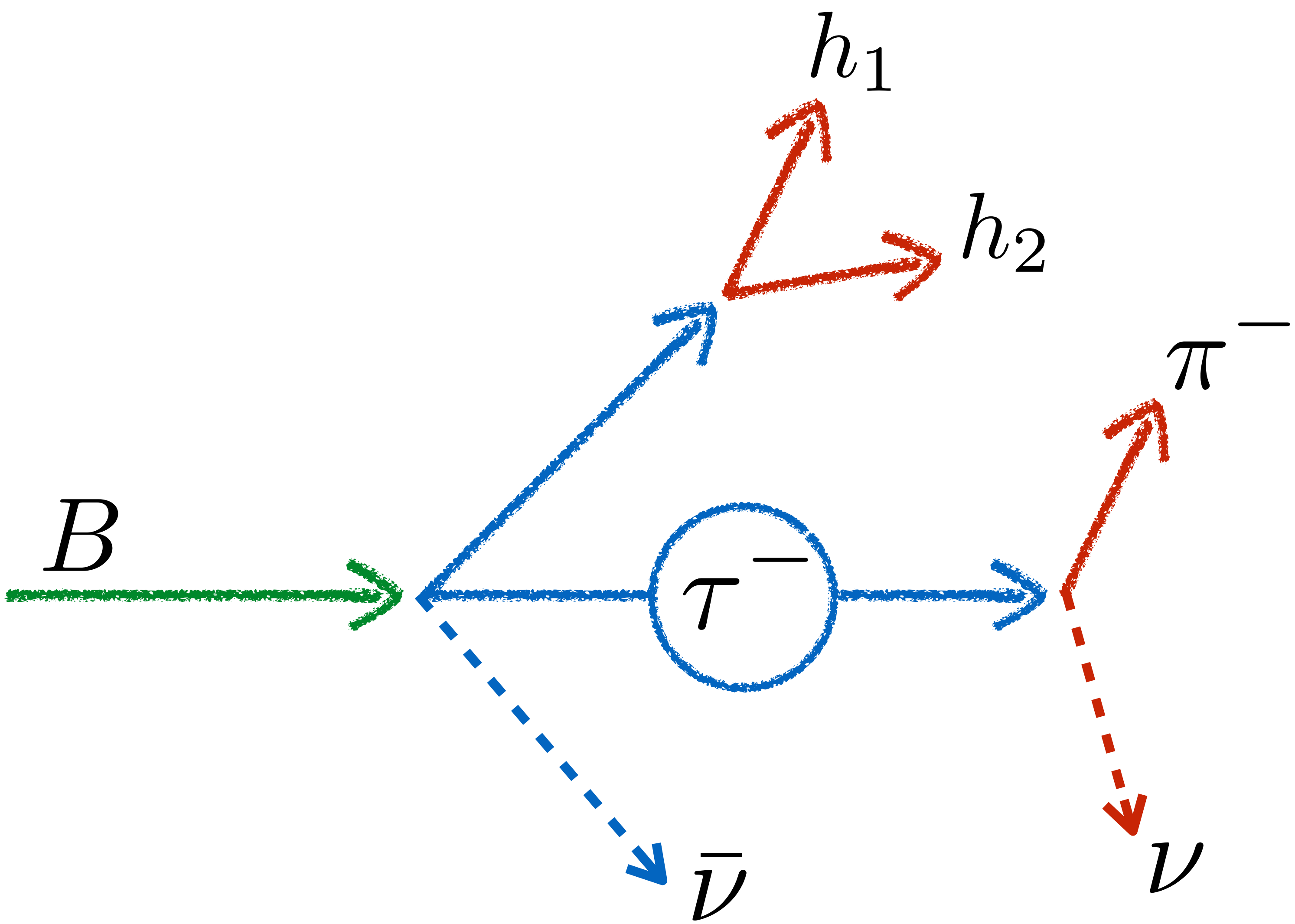
Prospects for Belle II:



What we observe

Idea: reconstruct tau production from **visible** final-state kinematics.

Bullock, Hagiwara, Martin 1993; Kiers, Soni 1997; Nierste, Trine, SW 2008



Hadronic decays $\tau \to \pi\nu, \ \tau \to \rho\nu$ preserve most information.

Tau production properties from the final state

Tau polarisations and FB 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+
Asadi, Buckley, Shih 2018
Asadi, Hallin, Martin Camalich, Shih, SW 2020

CP violation:

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

Hagiwara, Nojiri, Sakaki 2014

$$B \to [D^* \to D\pi][\tau \to \pi\nu]\nu$$

Bhattacharya, Datta, Kamali, London 2020

Search for new physics:

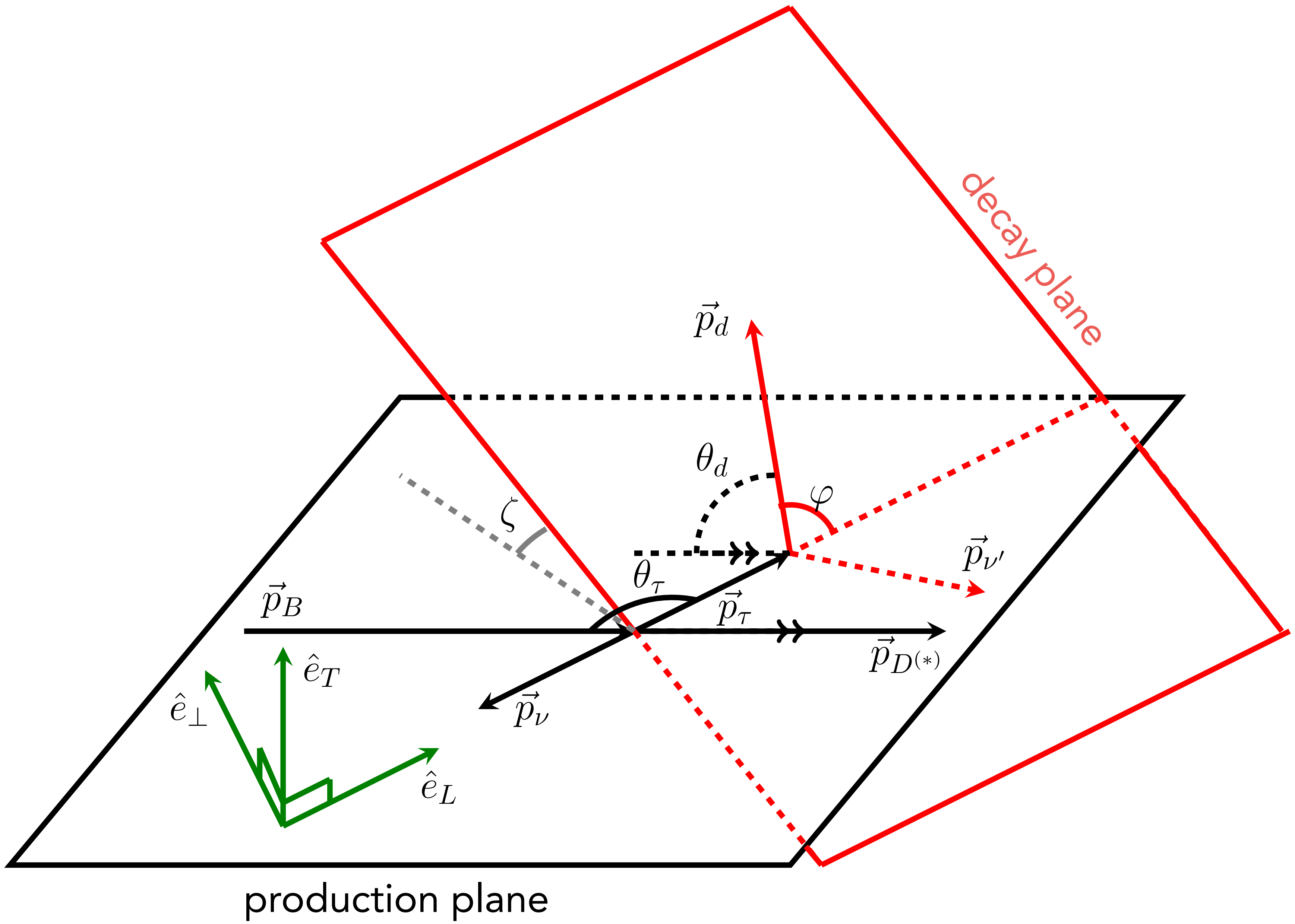
$$B \to [D^{(*)} \to D(\pi, \gamma)]\nu[\tau \to (\ell\nu, \pi)\nu]$$

Ligeti, Papucci, Robinson 2016+
Alonso, Kobach, Martin Camalich 2016
Bhattacharya et al. 2018
Colangelo, De Fazio 2018
Asadi, Buckley, Shih 2018

Reweighing simulations for NP:

HAMMER software: Bernlochner et al. 2020

Final-state kinematics



Measurable: $q^2, \ \cos\theta_d, \ s_d = \dfrac{E_d}{\sqrt{q^2}}$ (meson fully resonstructed)

Here: $\tau \to \pi\nu, \ \tau \to \rho\nu$ (most information on tau production)

Tau asymmetries from final-state kinematics

Differential rate factorizes into tau production and decay

$$\frac{d^4\Gamma_d}{dq^2 d\cos\theta_\tau ds_d\, d\zeta} = \frac{E_\tau}{\Gamma_\tau m_\tau}\left(\frac{d^2\Gamma_B^{\lambda_\tau}}{dq^2 d\cos\theta_\tau}\frac{d^2\Gamma_\tau^{\lambda_\tau}}{ds_d\, d\zeta} + \frac{1}{2}\left[\frac{d^2\mathcal{P}_B^{\perp}}{dq^2 d\cos\theta_\tau}\frac{d^2\mathcal{P}_\tau^{\perp}}{ds_d\, d\zeta} - \frac{d^2\mathcal{P}_B^{T}}{dq^2 d\cos\theta_\tau}\frac{d^2\mathcal{P}_\tau^{T}}{ds_d\, d\zeta}\right]\right)$$

What we (strive to) measure:

$$\frac{d^3\Gamma_d}{dq^2 d\cos\theta_d ds_d} = \mathrm{BR}(\tau\to d\nu)\frac{d\Gamma_B}{dq^2}\sum_{\ell=0}^{2} P_\ell(\cos\theta_d) I_\ell(q^2, s_d)$$

$$I_0 = \frac{1}{2}\left(f_0^d(q^2) + f_L^d(q^2, s_d)P_L(q^2)\right)$$

$$I_1 = f_{A_{FB}}^d(q^2, s_d)A_{FB}(q^2) + f_\perp^d(q^2, s_d)P_\perp(q^2) + f_{Z_L}^d(q^2, s_d)Z_L(q^2)$$

$$I_2 = f_{Z_\perp}^d(q^2, s_d)Z_\perp(q^2) + f_{Z_Q}^d(q^2, s_d)Z_Q(q^2) + f_{A_Q}^d(q^2, s_d)A_Q(q^2).$$

$P_T,\, Z_T$: need second plane (meson decay, 3-prong tau decay)

Extract tau asymmetries from a fully differential fit to data.

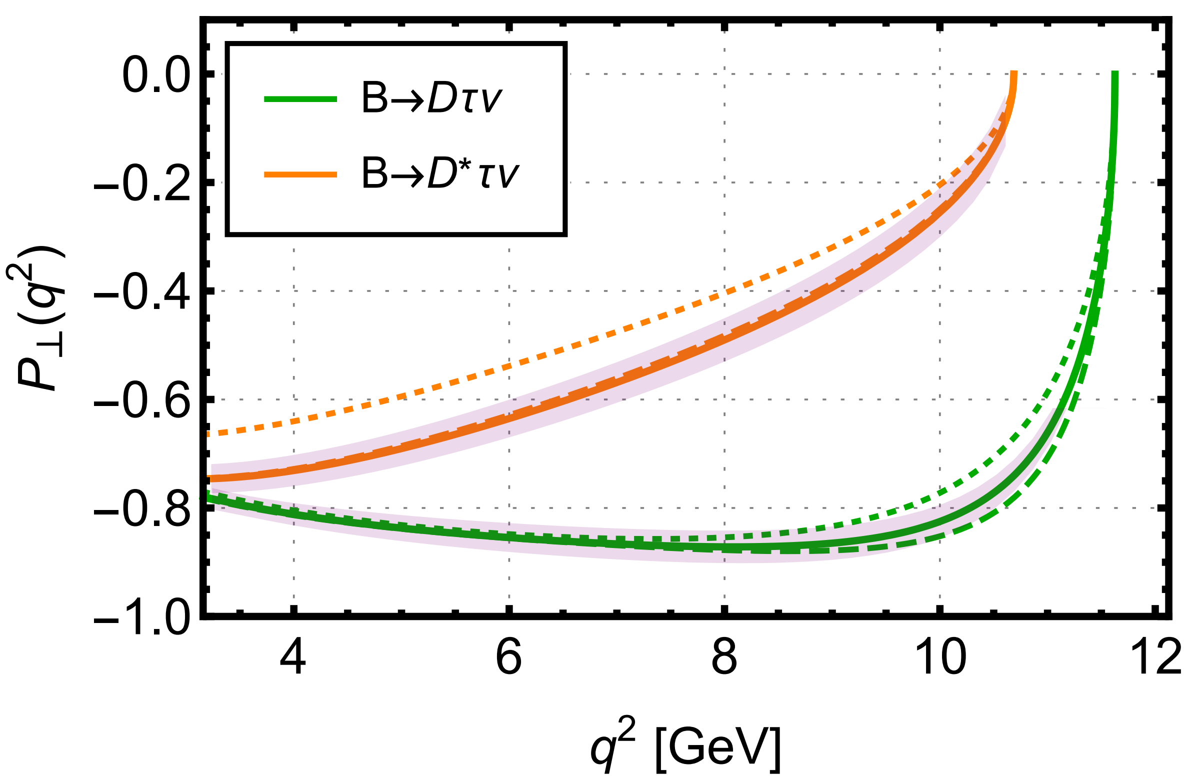
Asadi, Hallin, Martin Camalich, Shih, Westhoff 2006.16416

Belle II prospects: distributions

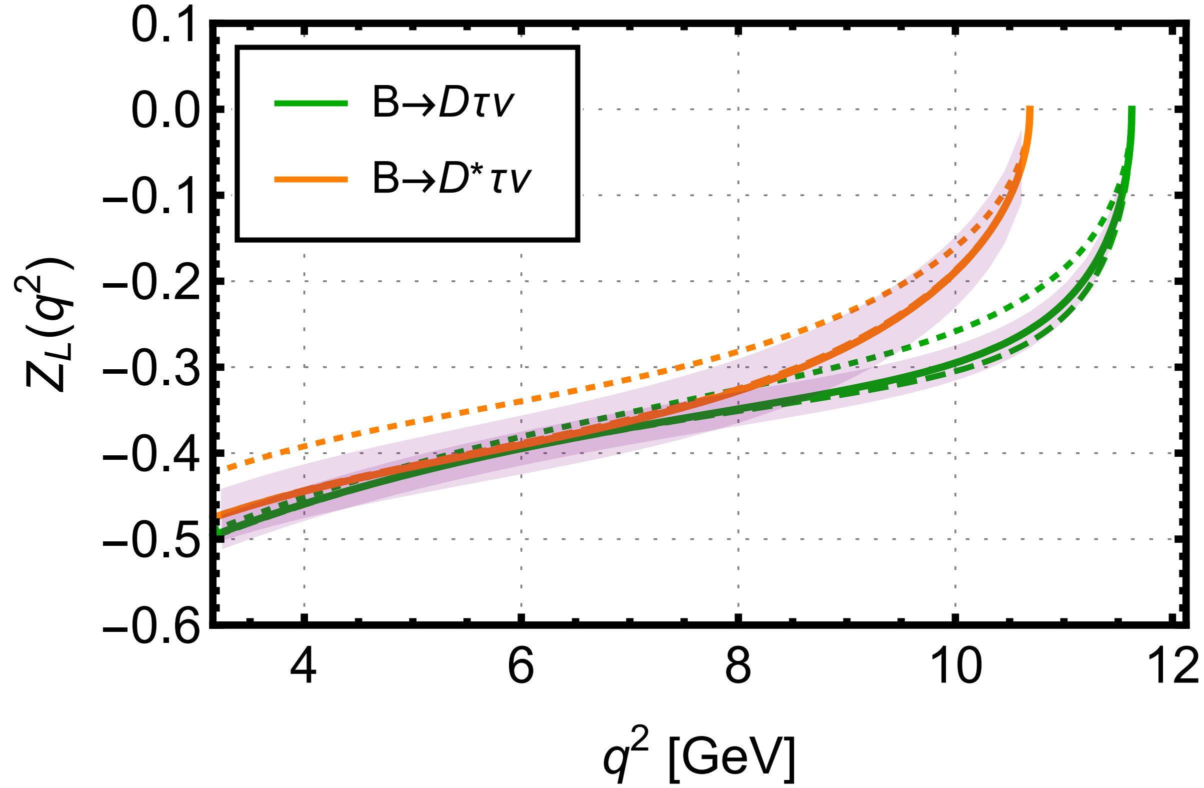
Expect 3000 events/channel (~in 50/ab).

Here: $\tau \to \pi\nu$. Unbinned maximum likelihood fit in $\cos\theta_d,\ s_d$.

transverse polarization



double asymmetry



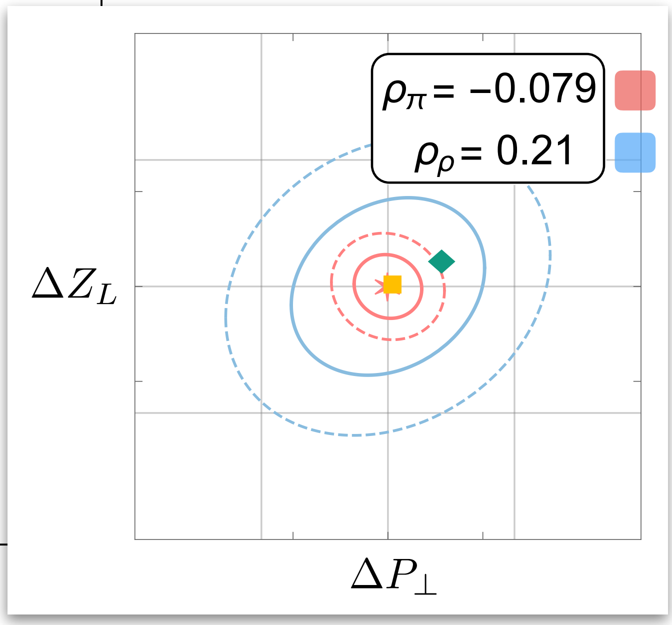
Distributions can be measured with good statistical precision.

Asadi, Hallin, Martin Camalich, Shih, Westhoff 2006.16416

Belle II: integrated asymmetries

		SM	$\sigma_{\rm th}$	σ_π	σ_ρ	measured	
$B \to D\tau\nu$	$A_{\rm FB}$	-0.359	0.003	0.020	0.024	$= Z_L$	–
	P_L	0.34	0.03	0.029	0.069		–
	$P_\perp$	-0.839	0.007	0.028	0.094		–
	$Z_\perp$	0.224	0.012	0.024	0.091		–
	Z_Q	0.243	0.012	0.037	0.118		–
	A_Q	-0.088	0.004	0.031	0.042		–
$B \to D^*\tau\nu$	$A_{\rm FB}$	0.07	0.02	0.031	0.037		–
	P_L	-0.50	0.02	0.029	0.070	$-0.38(54)$	[Belle]
	$P_\perp$	-0.49	0.02	0.039	0.113		–
	Z_L	-0.323	0.007	0.037	0.104		–
	$Z_\perp$	0.054	0.002	0.041	0.101		–
	Z_Q	0.058	0.002	0.055	0.046		–
	A_Q	-0.0189	0.0005	0.146	0.050		–

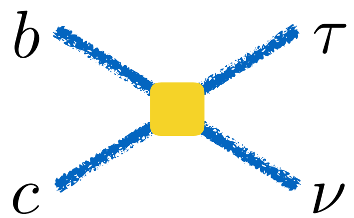
stat. correlation



Asadi, Hallin, Martin Camalich, Shih, Westhoff 2006.16416

New physics in tau production

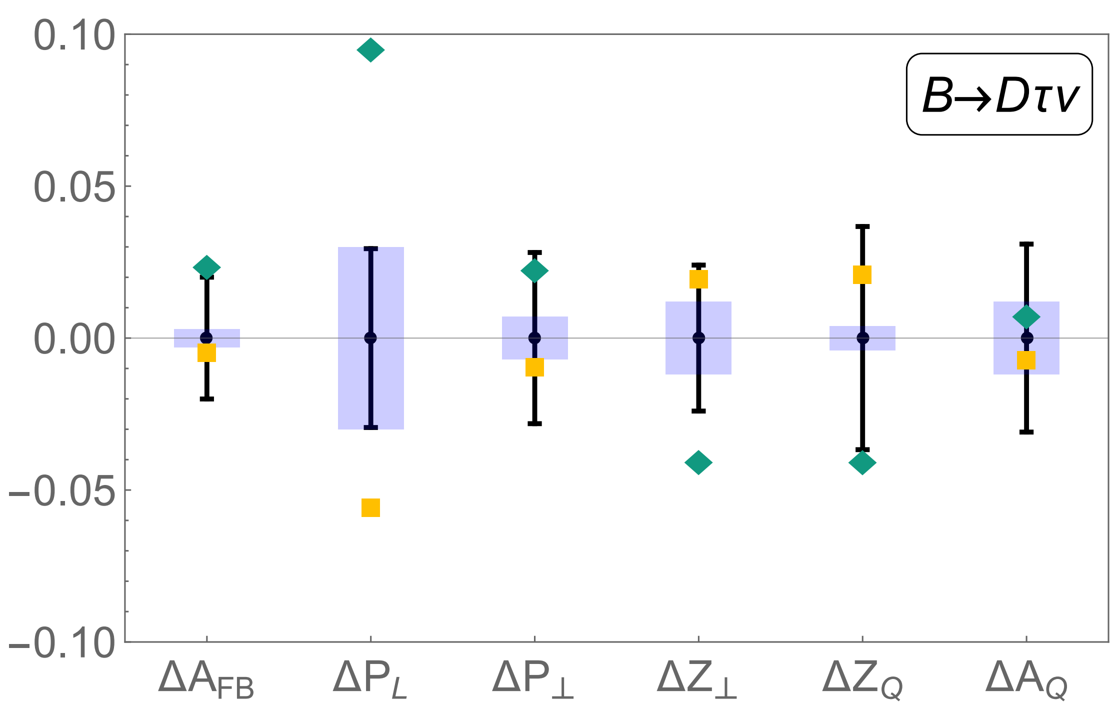
Effective four-fermion interactions change tau kinematics:

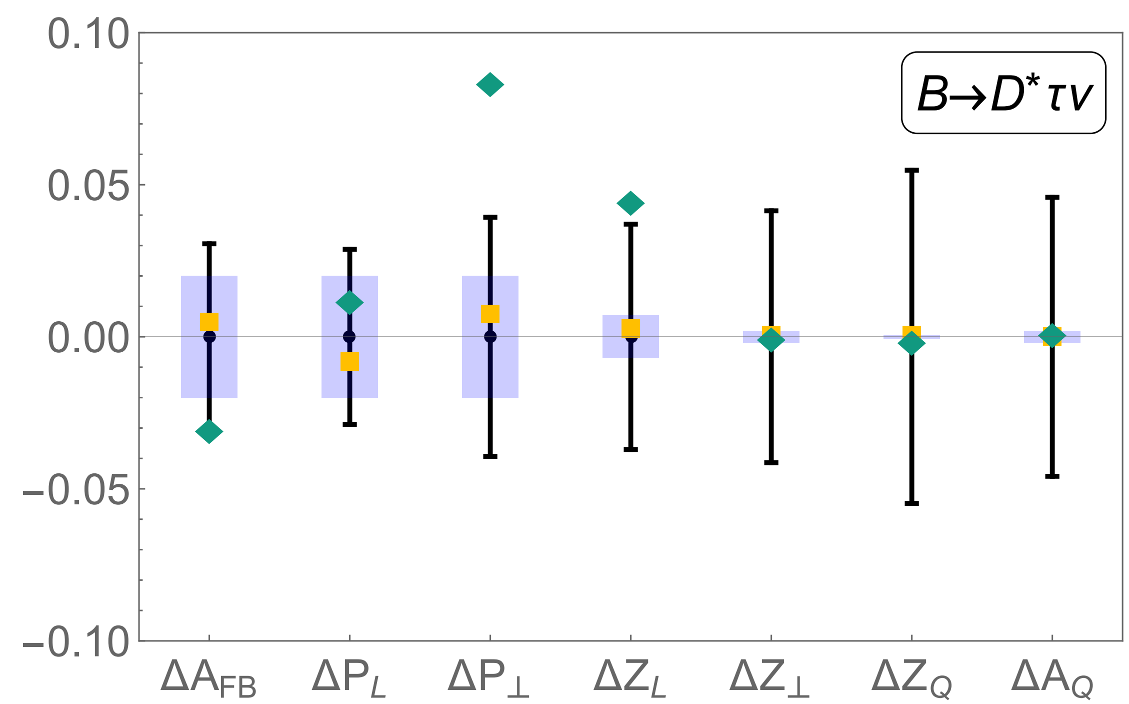


$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left(O^V_{LL} + \sum_{X,Y=L,R} (C^S_{XY} O^S_{XY} + C^V_{XY} O^V_{XY}) + \sum_{X=L,R} C^T_{XX} O^T_{XX} \right)$$

Motivated by b-c-tau-nu data: Shi et al. 1905.08498, see also Blanke et al. 1811.09603

- "U_1 vector leptoquark" : $C^V_{LL} = 0.08, \quad C^S_{RL} = -0.05$
- "$S_1 - R_2$ scalar leptoquarks" : $C^S_{LL} = 0.07, \quad C^T_{LL} = -0.03$





Tau asymmetries are sensitive to new scalar/tensor currents.

Summary: tau polarimetry in B to D(*) tau nu

- **new** full analytic description by 9 tau asymmetries
- **measure** them in differential distributions at Belle II
- **probe CP violation** with meson decays and 3-prong tau decays
- **probe new physics** with new asymmetry observables

Questions? westhoff@thphys.uni-heidelberg.de

Thank you!

Backup

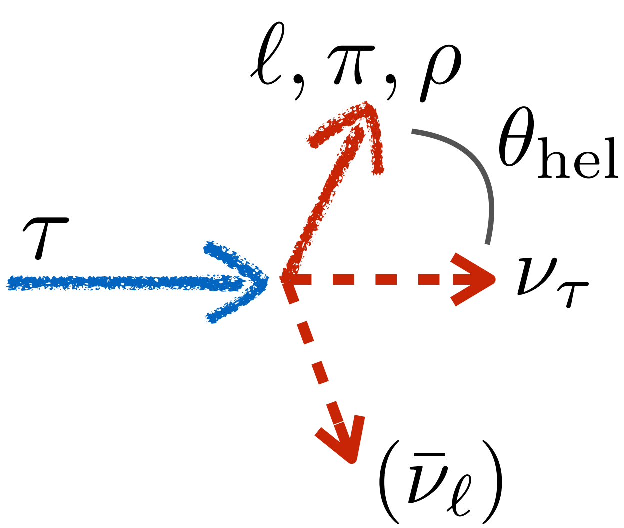
TAU DECAYS

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.