$B \to X\tau\nu$ polarisation measurements

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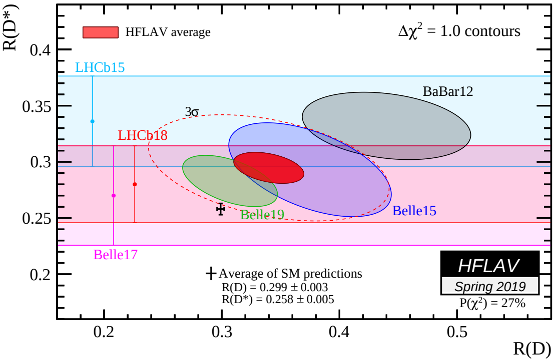
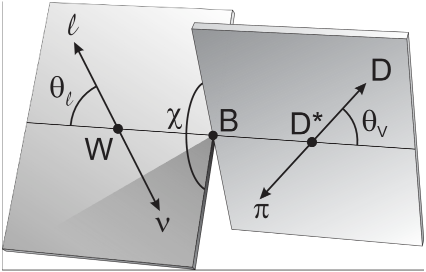
Introduction



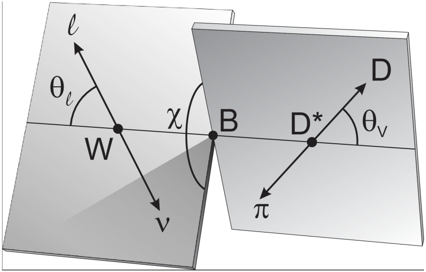
- $\mathcal{R}(D^{(*)})$still hints at possible new physics, updates long overdue...
- If a tension were to be established, question would then be to constrain the spin structure of the enhancement
  - Differential measurements - $B \rightarrow D^{(*)}\ell\nu$ angular distributions and τ polarisation

Full kinematic basis for $B \to D^*\tau\nu$



- Full basis for $B \to D^*\ell\nu$: q^2 and three angles
  - q^2 and E^*_μ (lepton energy in B rest frame) is a complete basis for $B \to D^0\ell\nu$
- ...until the τ decays!
  - The θ_ℓ or E^*_μ from the final state decay products is no longer truly θ_ℓ or E^*_μ
  - Bias in part depends on the τ polarisation, m^2_{miss} now carries some information about τ decay
  - Explaining this is a job for a theorist!

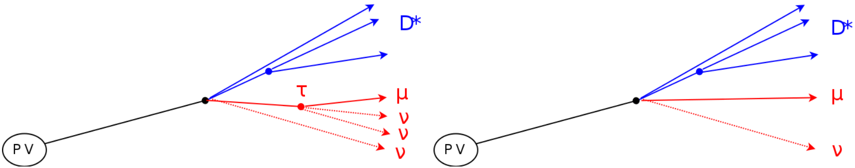
Full kinematic basis for $B \to D^{*}\tau\nu$



- Full basis for $B \to D^{*}\ell\nu$: q^2 and three angles
    - q^2 and E^{*}_{μ} (lepton energy in B rest frame) is a complete basis for $B \to D^{0}\ell\nu$
- ...until the τ decays!
    - Simpler picture: for a two body (hadronic) decay, hadron helicity angle carries τ spin information
    - Maximum sensitivity for $\tau \to \pi\nu$, greater hadron masses reduce sensitivity: ~ 0.45 for $\tau \to \rho\nu$, ~ 0.1 for $\tau \to \pi\pi\pi\nu$
    - Leptonic decay modes also have lower sensitivity, ~ 0.25

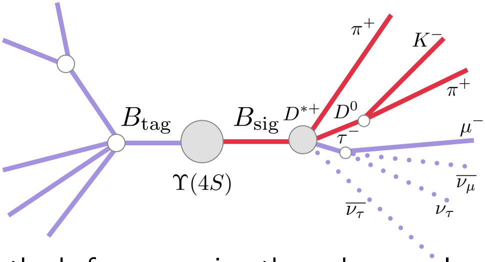
Experimental challenge

$B \to D^* \tau \nu$ $B \to D^* \mu \nu$



- Difficulty: neutrinos - 2 for $(\tau \to \pi\pi\pi\nu)\nu$, 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^* \mu\nu$, $B \to D^{**} \mu\nu$, $B \to D^* D(\to \mu X) X$ ...
  - $B \to D^* \pi\pi\pi X$, $B \to D^* D(\to \pi\pi\pi X) X$ ...
- Also combinatorial, misidentified background

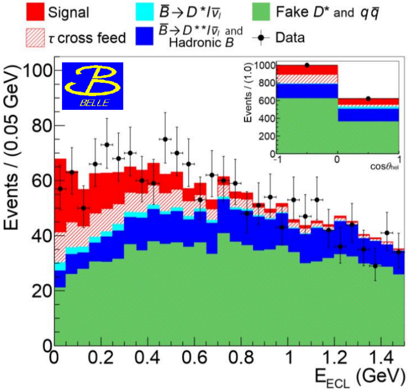
B Factory method

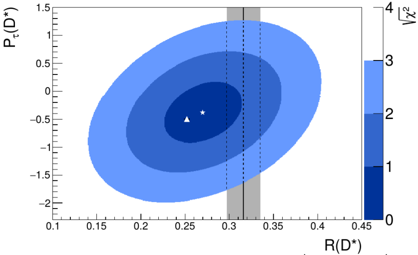


- Traditional methods for measuring these decays rely on $e^+e^- \to B\overline{B}$ event properties
  - Centre of mass fixed
  - Nothing else produced in event
- "Tag reconstruction"
  - Fully reconstruct other B $\to$ measurement of signal B kinematics
  - Signal B + other B should be entire event $\to$ strong rejection against other missing reconstructable particles
- Penalty: sub percent efficiency

Phys. Rev. Lett. 118, 211801 (2017)
Phys. Rev. D 97, 012004 (2018)

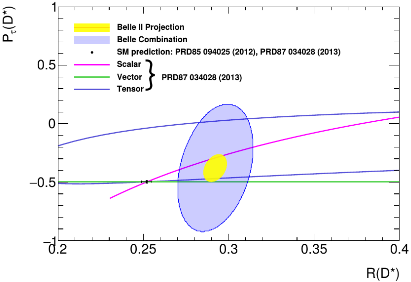
Belle $\tau^+ \to \pi^+(\pi^0)\nu$





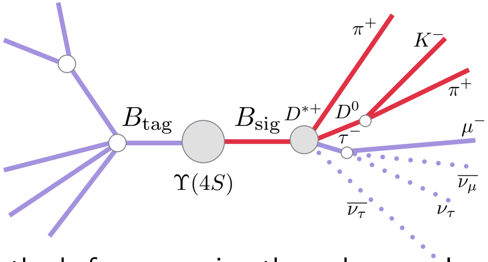
- Belle made the first measurement of τ polarisation with $\tau^+ \to \pi^+\nu$ and $\tau^+ \to \rho^+\nu$
- Fit variable: energy left over in Calorimeters after tag+signal reconstruction ($\mathrm{E_{ECL}}$)
  - Independent of the signal dynamics, no model dependence
- Split fit in halves of π or ρ helicity angle, reconstruct polarisation

Belle II $\tau^+ \to \pi^+(\pi^0)\nu$



- This will be a powerful measurement at Belle-II - 7% uncertainty on $P_\tau(D^*)$ with 50 ab^{-1} (55% now)

Can you do this at a hadron collider?

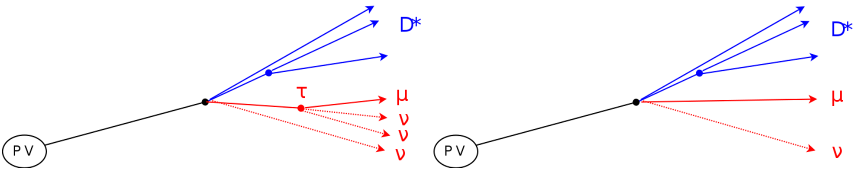


- Traditional methods for measuring these decays rely on $e^+e^- \to B\overline{B}$ event properties
  - Centre of mass fixed
  - Nothing else produced in event
- In a hadron collider the $B\overline{B}$ centre of mass isn't fixed $\to$ rest of event provides little constraint on the signal B kinematics
  - Event also contains a lot of junk from the proton-proton interaction $\to$ reconstructing the whole event is meaningless
- Needed completely different methods

Fit strategy

Phys. Rev. Lett. 115 (2015) 111803

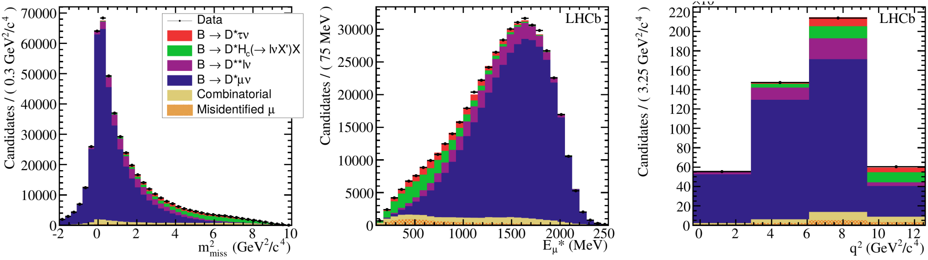
$B \rightarrow D^* \tau \nu$ $B \rightarrow D^* \mu \nu$



- Can use B flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component $\rightarrow$ use approximation to access rest frame kinematics
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$20% resolution on B momentum, long tail on high side
- Can then calculate rest frame quantities - $m^2_{missing}$, E_μ, q^2

Fit strategy

Phys. Rev. Lett. 115 (2015) 111803

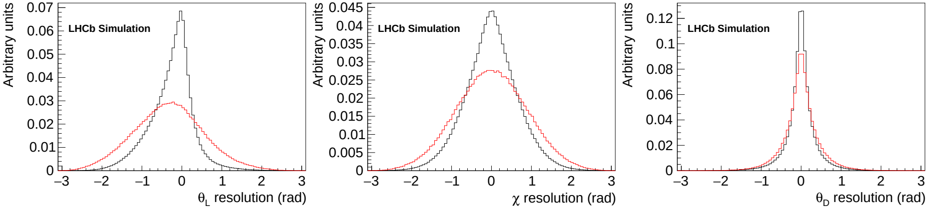


- Three dimesional template fit in E_μ (left), $m^2_{missing}$ (middle), and q^2
  - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
  - For our systematics, we already have form-factors floating in the fit (with constraints for the helicity suppressed terms)

Angular analysis

- Can we extend this fit to a full basis, and measure angular observables/wilson coefficients? Yes - full angular analysis planned
  - Big complication - signal yield depends on kinematic distributions
  - τ polarisation changes $\rightarrow$ final state kinematics change $\rightarrow$ signal yield changes
  - Most consistent way to make a measurement - everything together
  - Full angular analysis implies measuring both

Angular resolutions for $B \to D^*\tau\nu$



- Angular resolution for $B \to D^*\mu\nu$, $B \to D^*\tau\nu$ $(\tau \to \mu\nu\nu)$
- Tau decay results in loss of information
  - θ_ℓ and χ degraded
  - θ_D about the same $\to$ $D^{*+}(\Lambda_c)$ polarisation related observables maybe a good first target
- These resolutions are challenging, but not impossible

Hammer

HAMMER website
arxiv:2002.00020

MC

Helicity Amplitude Module
for Matrix Element Reweighting

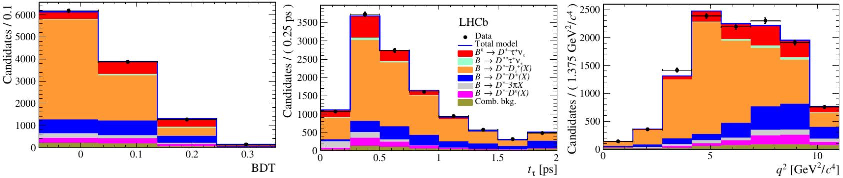
Process	Form factor parametrizations
$B \to D^{(*)}\ell\nu$	ISGW2* [34, 35], BGL* [36–38], CLN*‡ [39], BLPR‡ [16]
$B \to (D^* \to D\pi)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$B \to (D^* \to D\gamma)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$\tau \to \pi\nu$	—
$\tau \to \ell\nu\nu$	—
$\tau \to 3\pi\nu$	RCT* [40–42]
$B \to D_0^*\ell\nu$	ISGW2*, LLSW* [43, 44], BLR‡ [45, 46]
$B \to D_1^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_1\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_2^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$\Lambda_b \to \Lambda_c\ell\nu$	PCR* [47], BLRS‡ [48, 49]
Planned for next release	
$B_{(c)} \to \ell\nu$	MSbar
$B \to (\rho \to \pi\pi)\ell\nu$	BCL*, BSZ
$B \to (\omega \to \pi\pi\pi)\ell\nu$	BCL*, BSZ
$B_c \to (J/\psi \to \ell\ell)\ell\nu$	
$\Lambda_b \to \Lambda_c^*\ell\nu$	PCR*, BLRS
$\tau \to 4\pi\nu$	RCT*
$\tau \to (\rho \to \pi\pi)\nu$	—

Table 3 Presently implemented amplitudes in the Hammer library, and corresponding form factor parametrizations. SM-only

- HAMMER package allows us to reweight our MC using a histogram expansion, fast enough for us to use in our fits
- Implements physics models for various $B \to X\ell\nu$ processes, including tau polarisation effects

$\tau \to \pi\pi\pi$ at LHCb

LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- 3D template fit in BDT,q^2, tau lifetime to determine signal yield
  - BDT contains 3π dalitz information, partially reconstructed kinematics, neutral isolation...
- For the full angular analysis, similar situation to muonic case
  - Slightly better resolution, 10-15% resolution on tau momentum
- Less sensitivity to τ polarisation from combined 3π kinematics
  - However, looking at the 3π substructure can buy much of this sensitivity back
  - Phys.Lett. B306 (1993) 411-417, L. Duflot Thesis

Conclusion

- Updates on $\mathcal{R}(D^{(*)})$are long overdue
- Next step from LHCb is differential measurements
  - Both τ polarisation and $B \to D^{(*)}\ell\nu$ angular information
  - These are an extension of what we are already doing
  - Still complicated measurements, will no doubt also be overdue
- Belle have already demonstrated a polarisation measurement
  - Looking forward to seeing this with Belle-II statistics