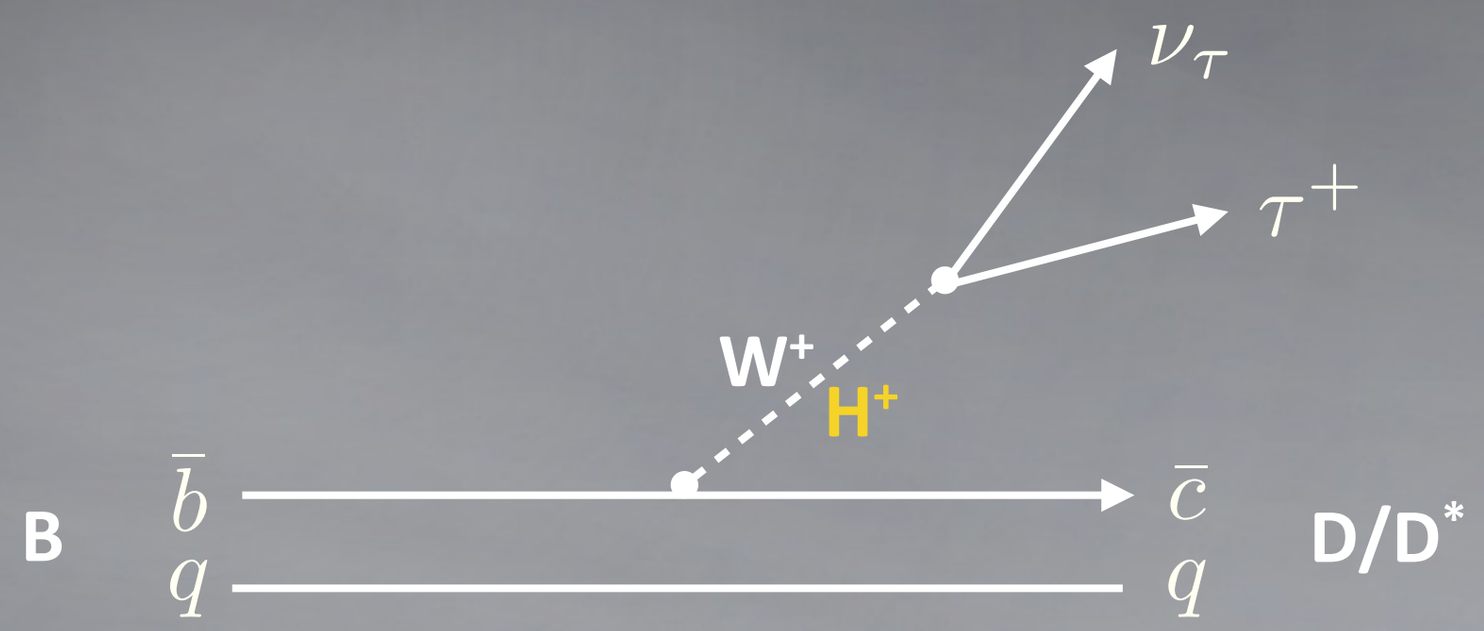
New Physics searches in $B \to D^{(*)} \tau \nu_\tau$ decays



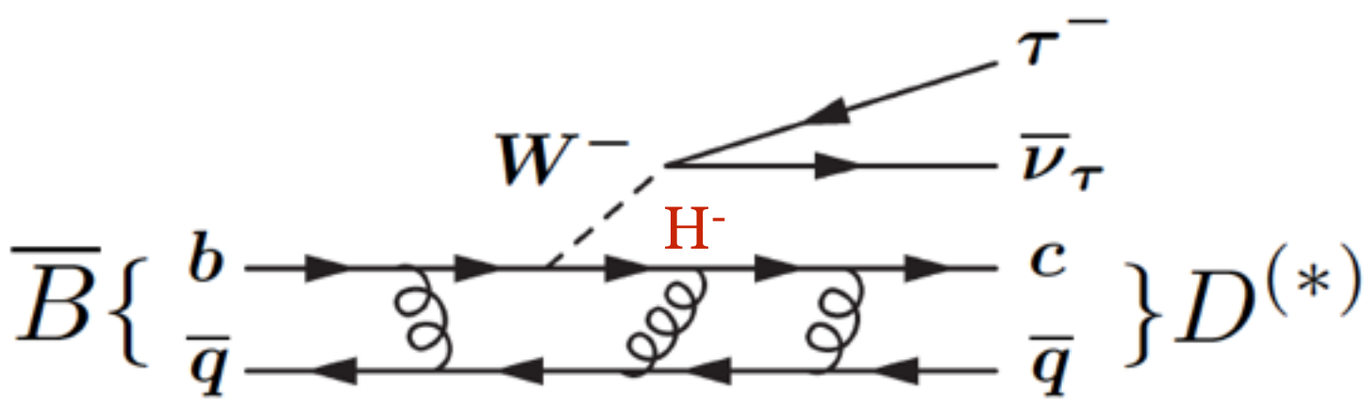
VIKAS BANSAL
Pacific Northwest National Laboratory, Richland, United States

CKM Workshop in Vienna, September 2014

Motivation

- Search for new physics via b→c τν transitions. Particularly interesting as both initial state and final state have third-generation fermions.

- Leptoquarks via tensor operators or charged Higgs boson in Minimal Supersymmetric Standard Model (MSSM) could show up in these transitions. (Tanaka et al., PRD 87:034028, 2013)



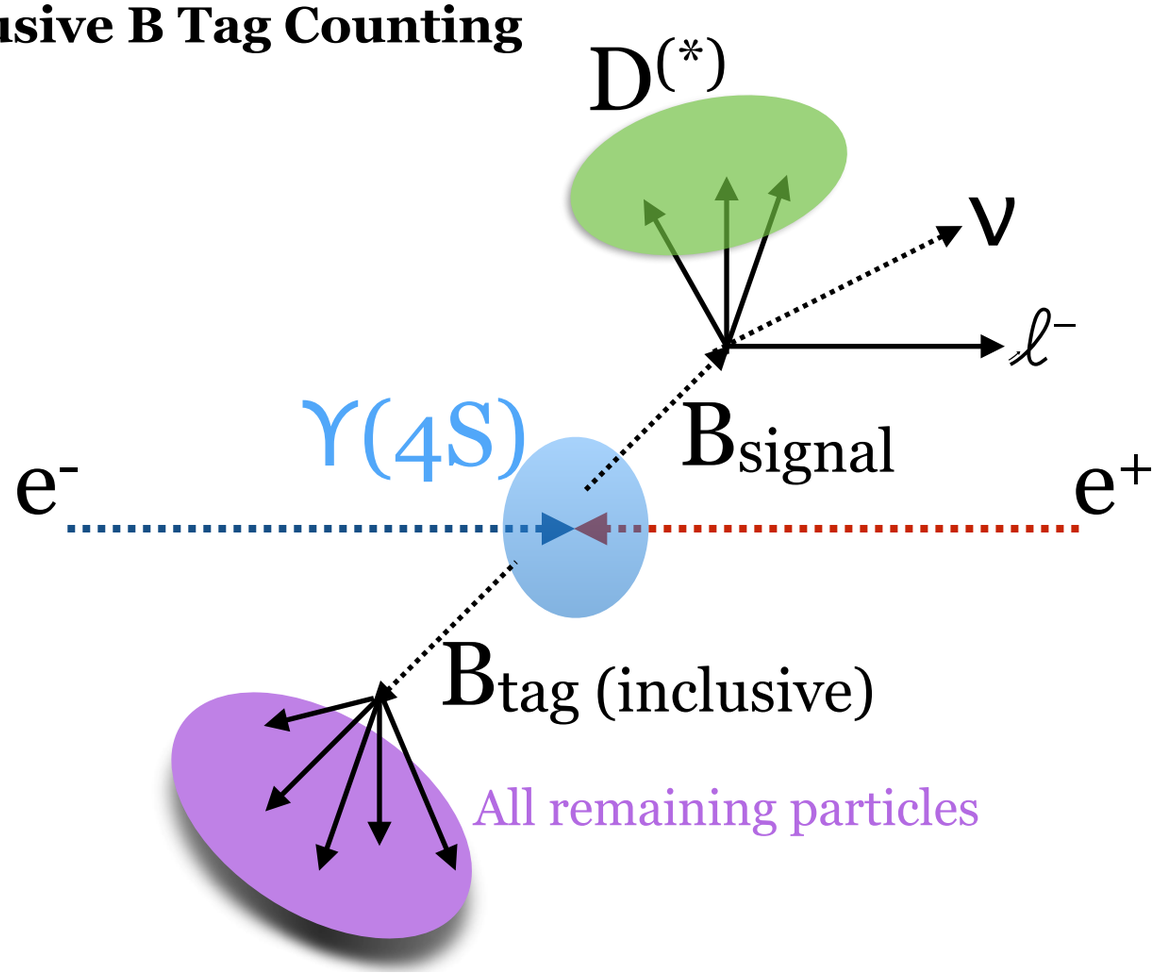
- Higgs, being a scalar, couples to select helicity states - this affects semileptonic decays into D and D* differently.

- In addition, study of τ polarizations in its hadronic decay modes can also be sensitive to New Physics (NP). (Fajfer et al., PRD 85:094025, 2012)

Experimental Technique: B Tagging

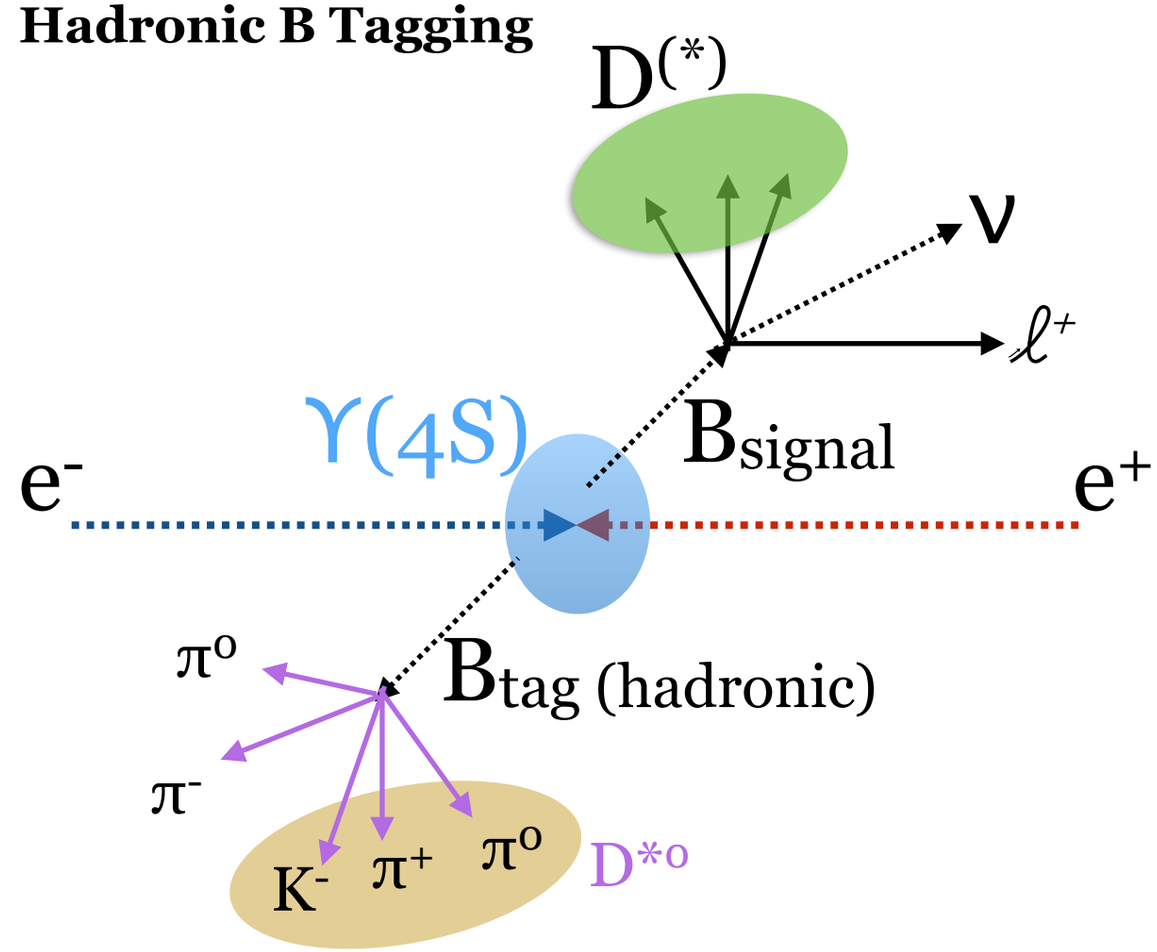
- Depending upon the τ decay mode, final state has 2 or 3 undetected neutrinos.
- At electron-positron B-factories, we have the advantage to exclusively produce $B\bar{B}$.
- Missing mass reconstruction is possible using B tagging methods.
- This method cannot be applied by LHCb where missing mass is not accessible.

Inclusive B Tag Counting



More Efficient; More Background

Hadronic B Tagging



Less Efficient; Less Background

Experimental Technique: Feasible Tagging Methods

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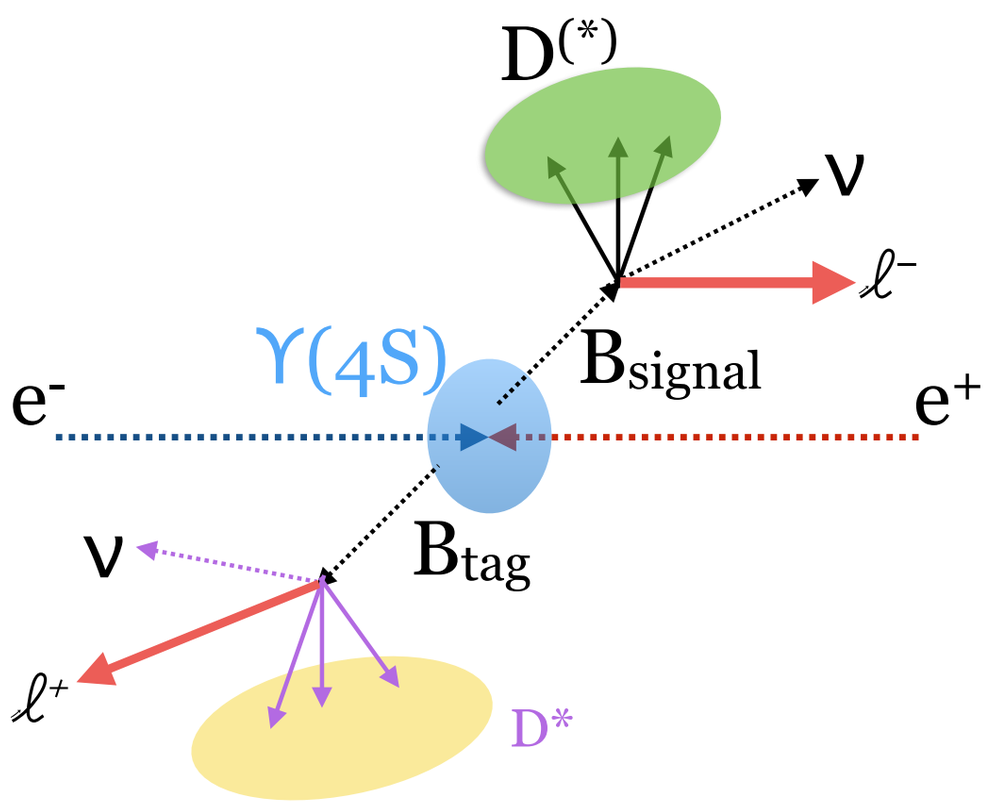
Approximate branching fractions of B meson

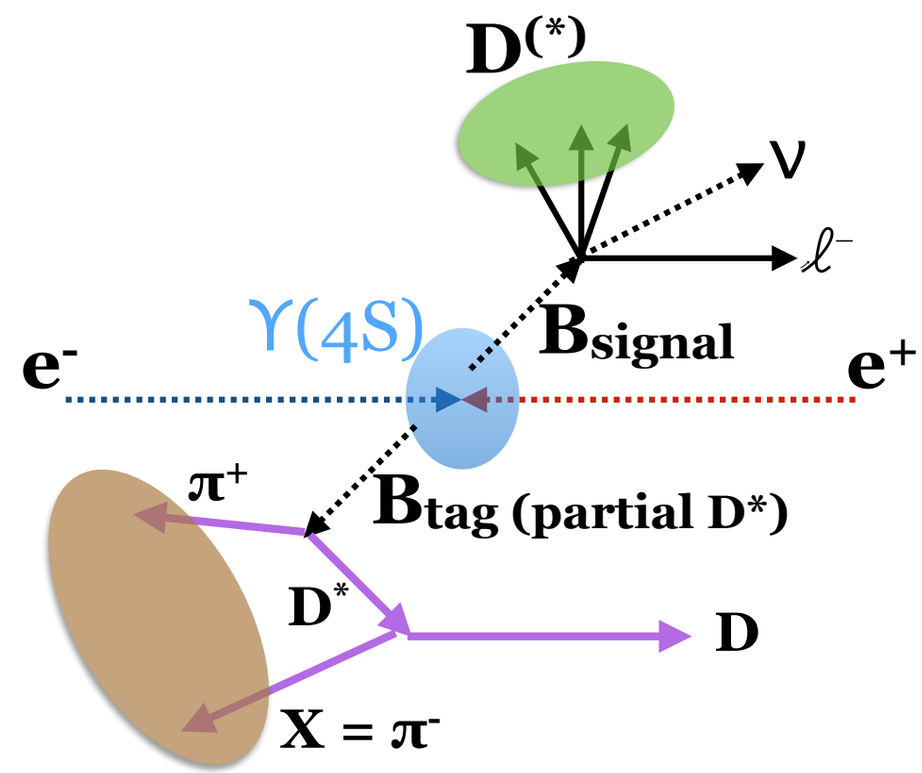
Xeν + Xμν	Xτν	DX	D*X	D**X
~20%	~3%	~13%	~30%	~7%

Double Semileptonic Tagging



Complementary to hadronic tagging

Partial D* Tagging



100% D reconstruction efficiency using kinematic constraints

Signal Extraction in Inclusive and Exclusive B Tagging

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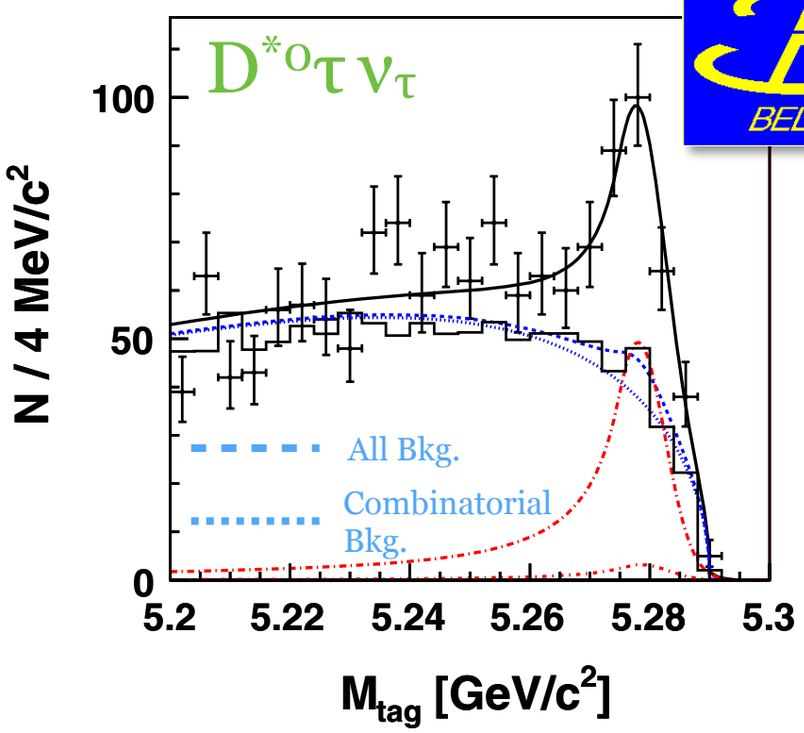
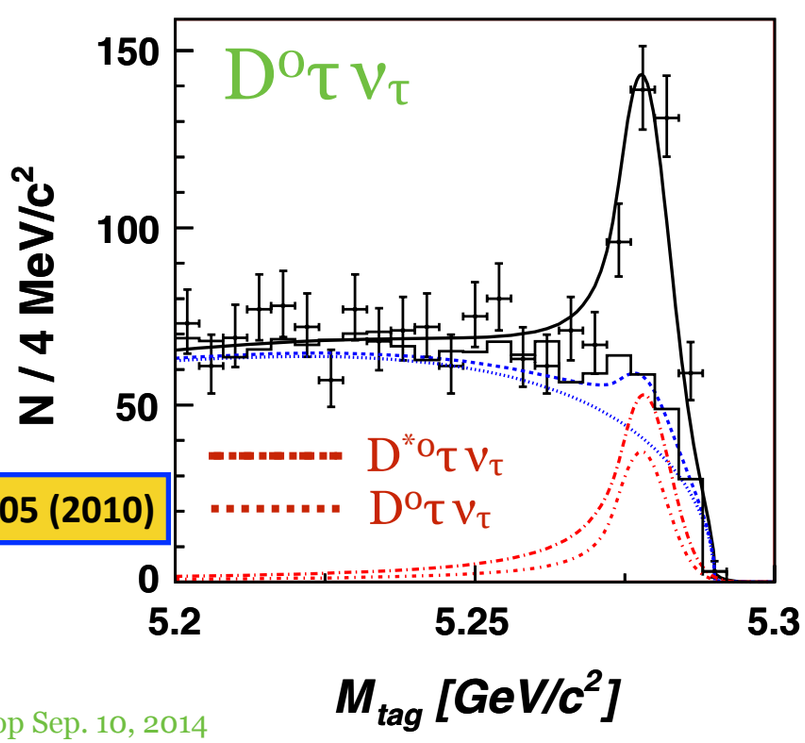
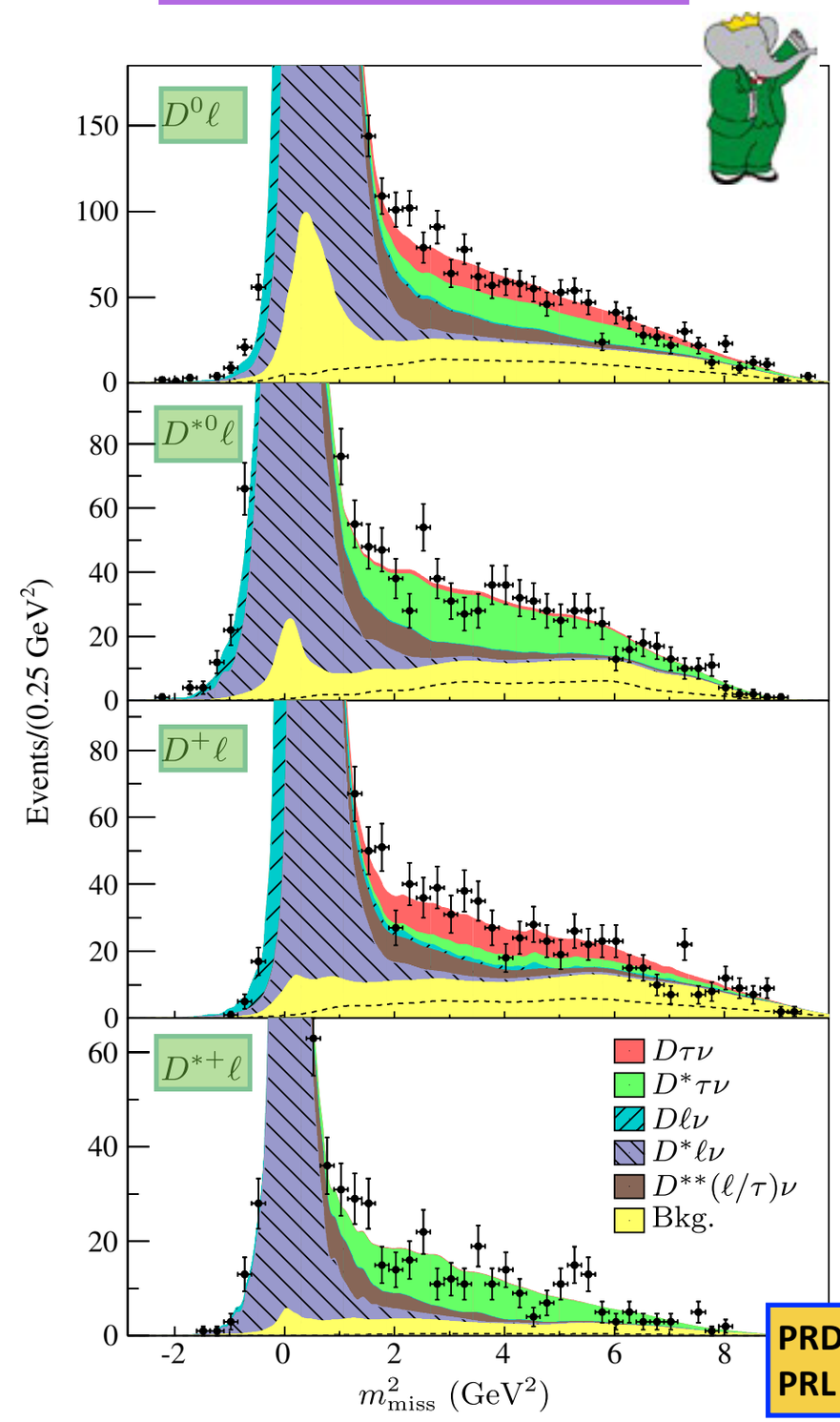
Inclusive B Tag Counting





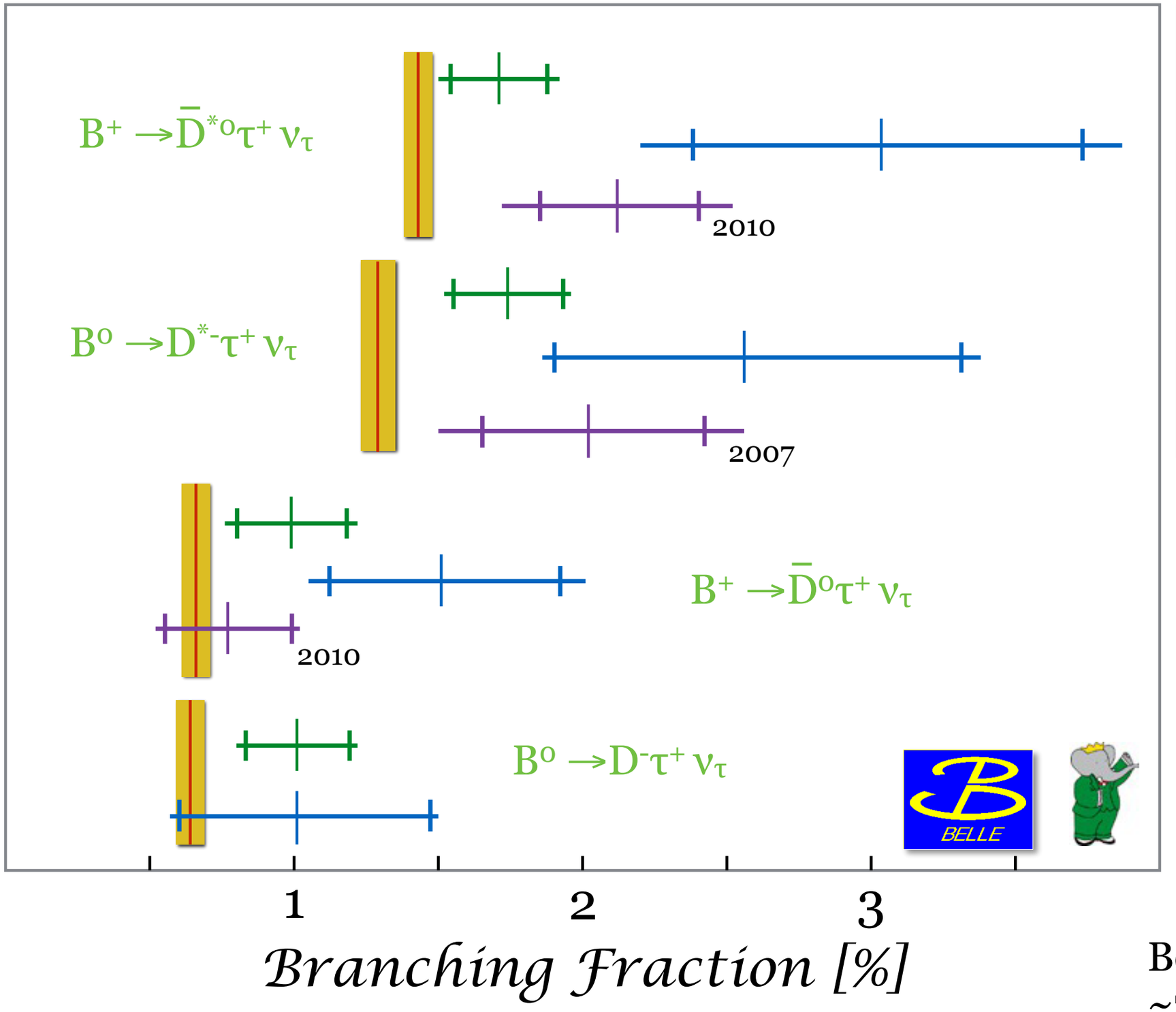
PRD 82 072005 (2010)

Hadronic B Tagging



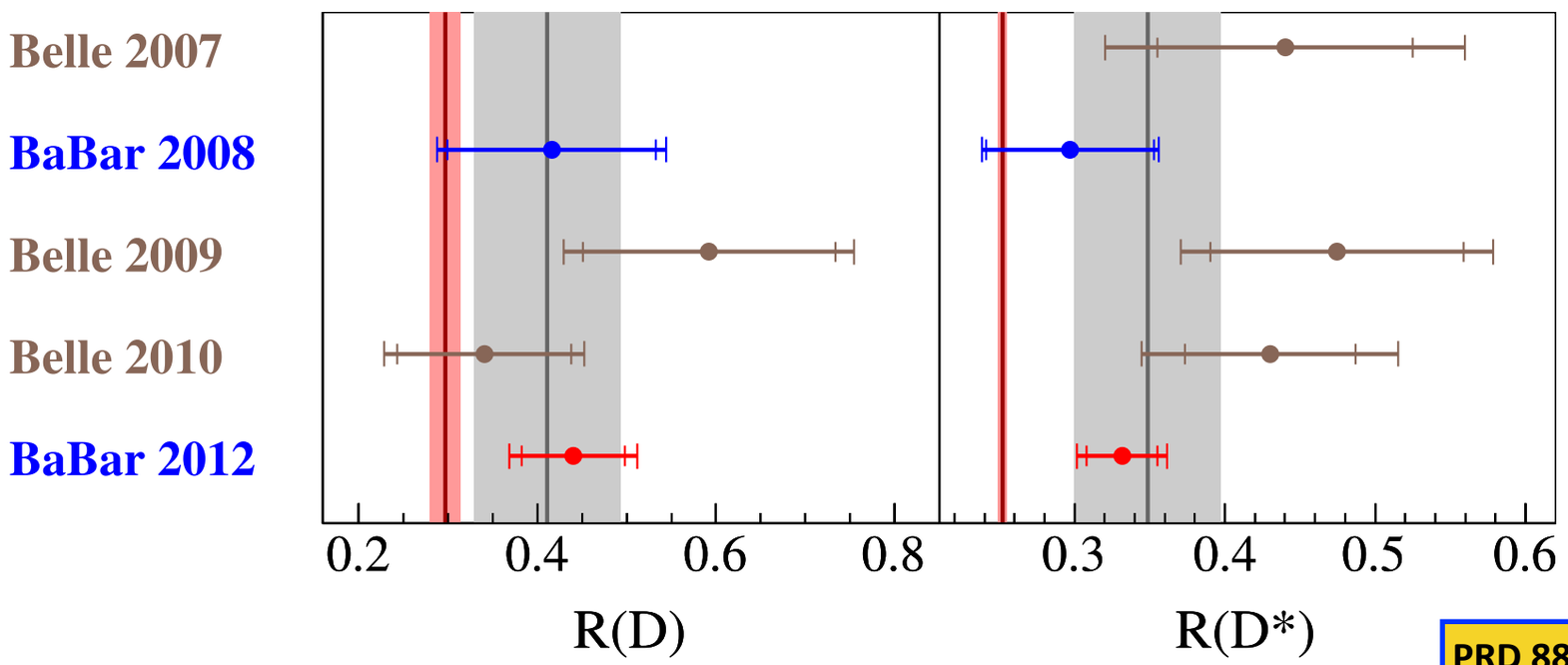
PRD 88 072012 (2013)
PRL 109 101802 (2012)

$B \to D^{(*)} \tau \nu_\tau$ Branching Fraction Measurements



Belle measurement with ~770 x 10^6 $B\bar{B}$ pairs is underway.

Current Status of $B \to D^{(*)} \tau \nu_\tau$ measurements



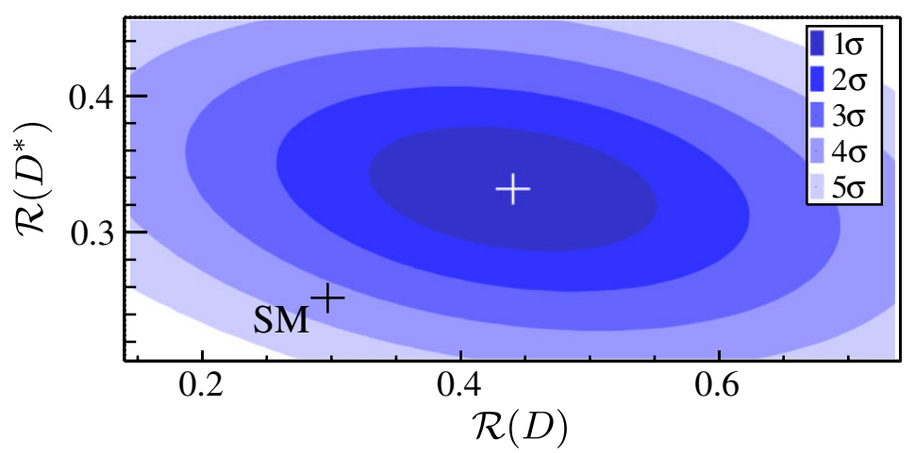
$$\mathcal{R}(D) \equiv \frac{\mathcal{B}(B \to D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to Dl^- \bar{\nu}_l)}$$

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B \to D^*\tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D^*l^- \bar{\nu}_l)}$$

$$\mathcal{R}(D^0) = \mathcal{R}(D^+) = \mathcal{R}(D)$$

$$\mathcal{R}(D^{*0}) = \mathcal{R}(D^{*+}) = \mathcal{R}(D^*)$$

PRD 88 072012 (2013)



Lattice QCD has R(D) = 0.316 ± 0.012 ± 0.007

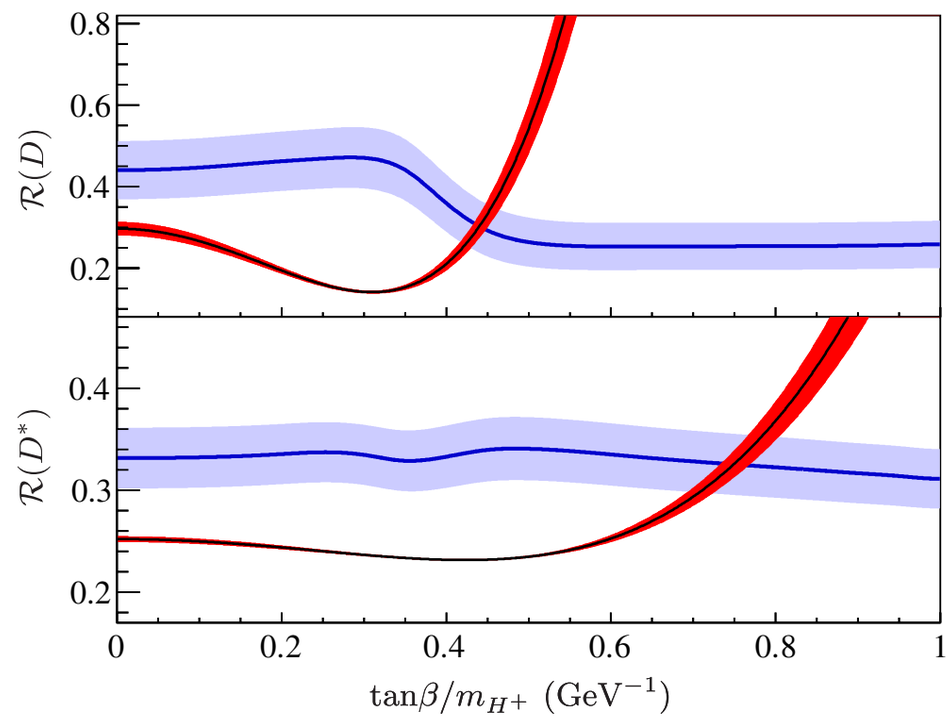
Bailey et al. PRL 109 071802 (2012)

$$\mathcal{R}(D)^{SM(HQET)} = 0.305 \pm 0.012, \quad \mathcal{R}(D^*)^{SM(HQET)} = 0.252 \pm 0.004$$

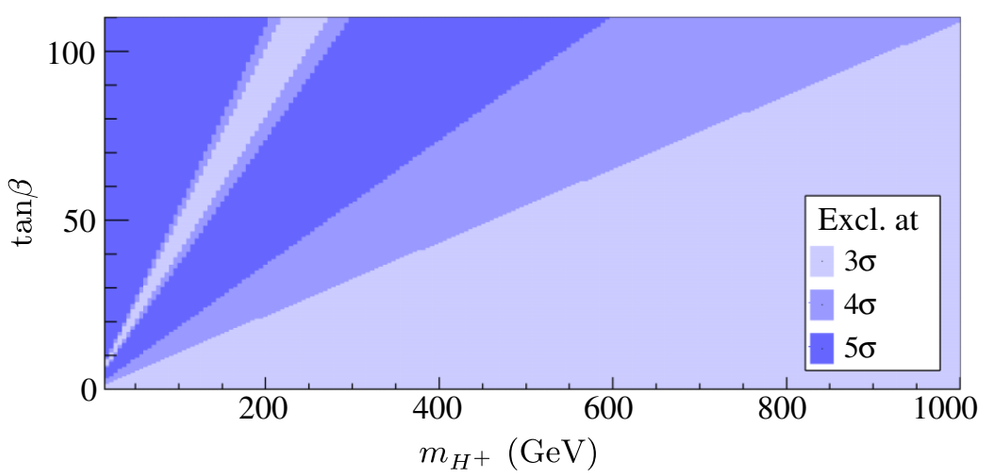
PRD 87 034028 (2013)

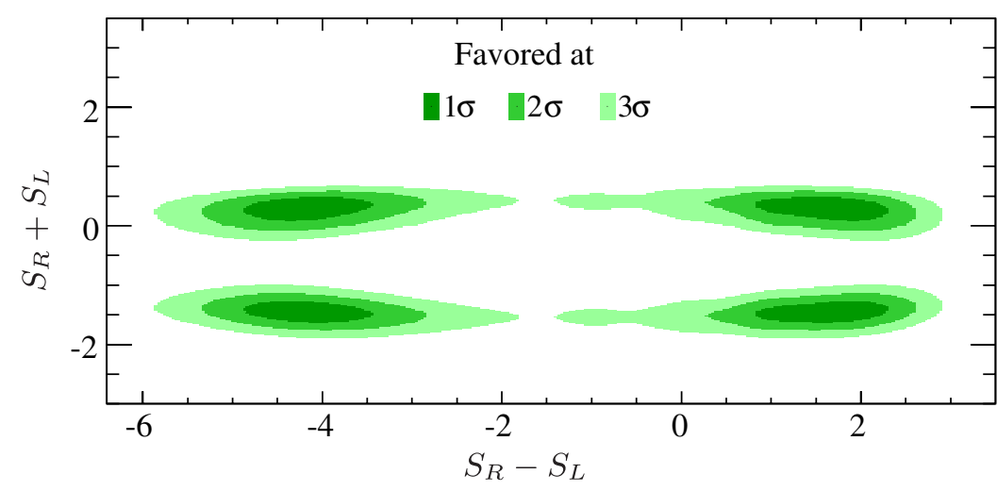
Comparison with Two Higgs Doublet Model (2HDM)

PRD 88 072012 (2013)



- $\mathcal{R}(D^{(*)})$ in $B \to D^* \tau \nu_\tau$ and $B \to D \tau \nu_\tau$ suggests different values for $\tan\beta / m_{H^\pm}$.
  - $\mathcal{R}(D) \to 0.4 - 0.5$ GeV^{-1}
  - $\mathcal{R}(D^*) \to 0.7 - 0.9$ GeV^{-1}
- BaBar's latest result excludes 2HDM Type II charged Higgs at 99.8% confidence level for charged Higgs mass > 15 GeV.
- The result also has favored region for S_R and S_L parameters of 2HDM Type III.





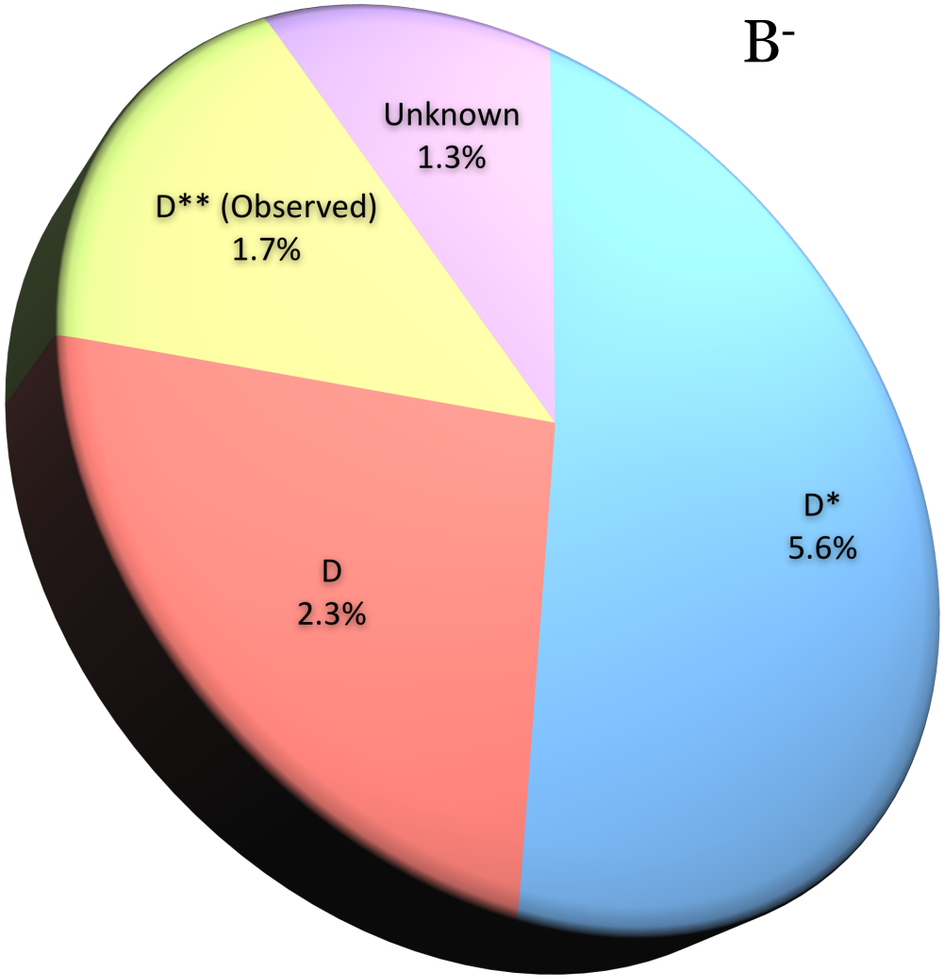
$m_{H^+} \leq 15$ GeV is already excluded by $B \to X_s \gamma$

Misiak et al., PRL 98 022002 (2007)

D** Background in b→c τν studies

- Exclusive branching fractions do not sum up to the inclusive branching fraction.
  - Inclusive $\mathcal{B}$ (B→X_c lν) = (10.9 ± 0.2) %
  - $\mathcal{B}$ (B→D lν) = (2.3 ± 0.1) %
  - $\mathcal{B}$ (B→D* lν) = (5.6 ± 0.2) %
  - $\mathcal{B}$ (B→$D^{**}_{observed}$ lν) = (1.7 ± 0.1) %
  - Missing fraction from inclusive → (1.3 ± 0.3) %

PDG 2010; HFAG



- The study of b→c τν is sensitive to D** background modeling.
- Both Belle and BaBar measurements make an effort to account for it.
  - BaBar explicitly considers four 1P excited states of charm mesons to model D**.
  - Should 2S excited states BaBar: PRD 82 111101 (2010) or multi-pion transitions of D** be modeled?
  - Can "1/2 vs 3/2 Puzzle" in D** play some role? Bigi et al., Eur. Phys. J C52, 975 (2007)
  - B →D** τν is estimated using available phase-space with the largest ratio (with B →D** ℓν) PRD 88 072012 (2013) from the four 1P excited charm states. Will matrix element based modeling help?

Virtual Boson Mass: q^2 distributions

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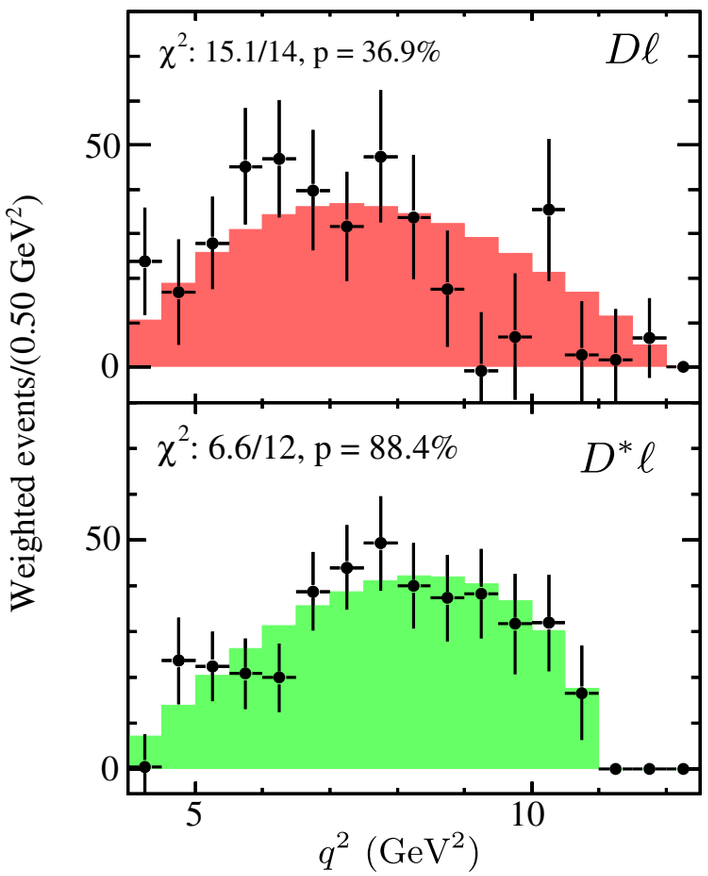
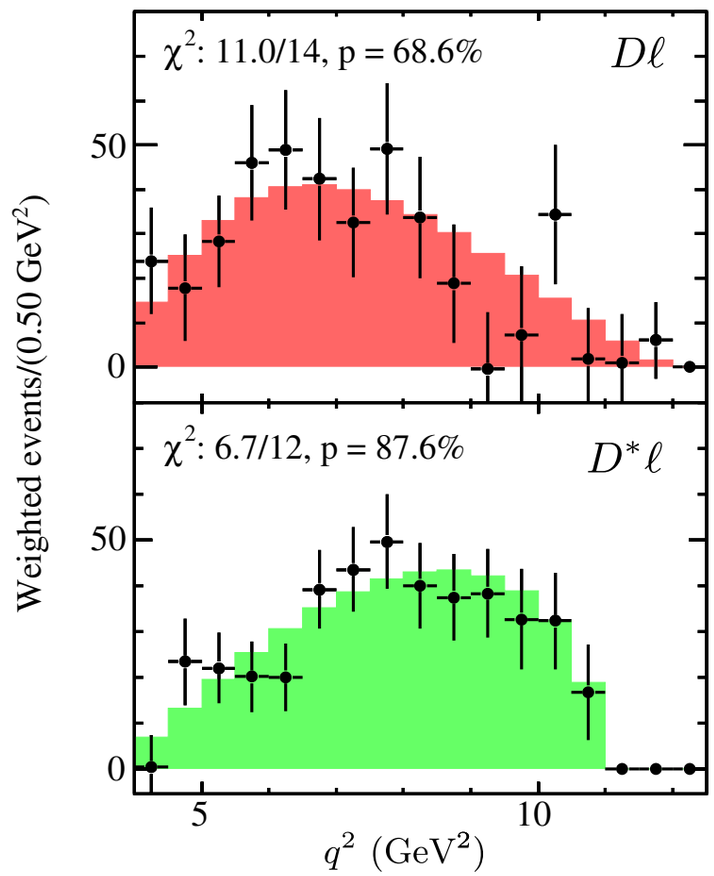
SM



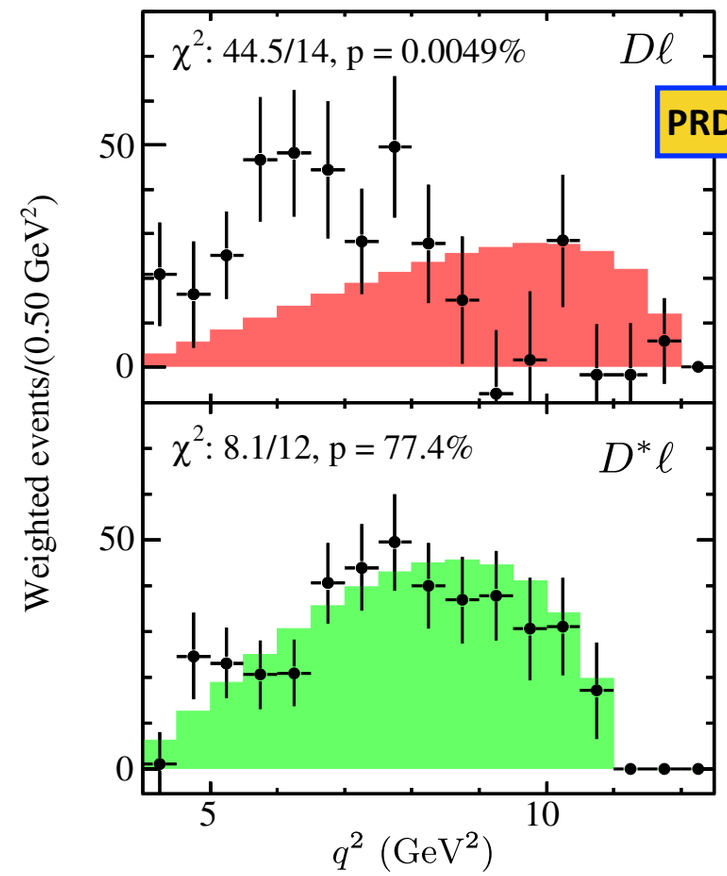
D: P_{max} = 83.1%
D*: P_{max} = 98.8%

$\tan\beta$ / $m_{H^\pm}$ = 0.3 GeV^{-1}



D: P_{max} = 95.7%
D*: P_{max} = 98.9%

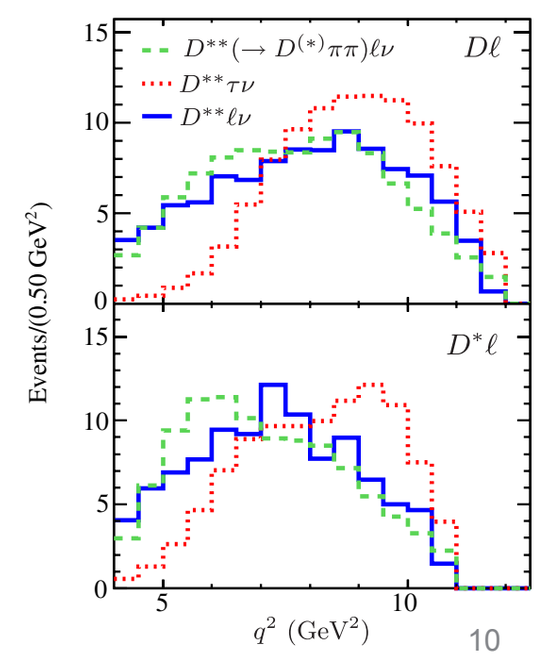
$\tan\beta$ / $m_{H^\pm}$ = 0.45 GeV^{-1}



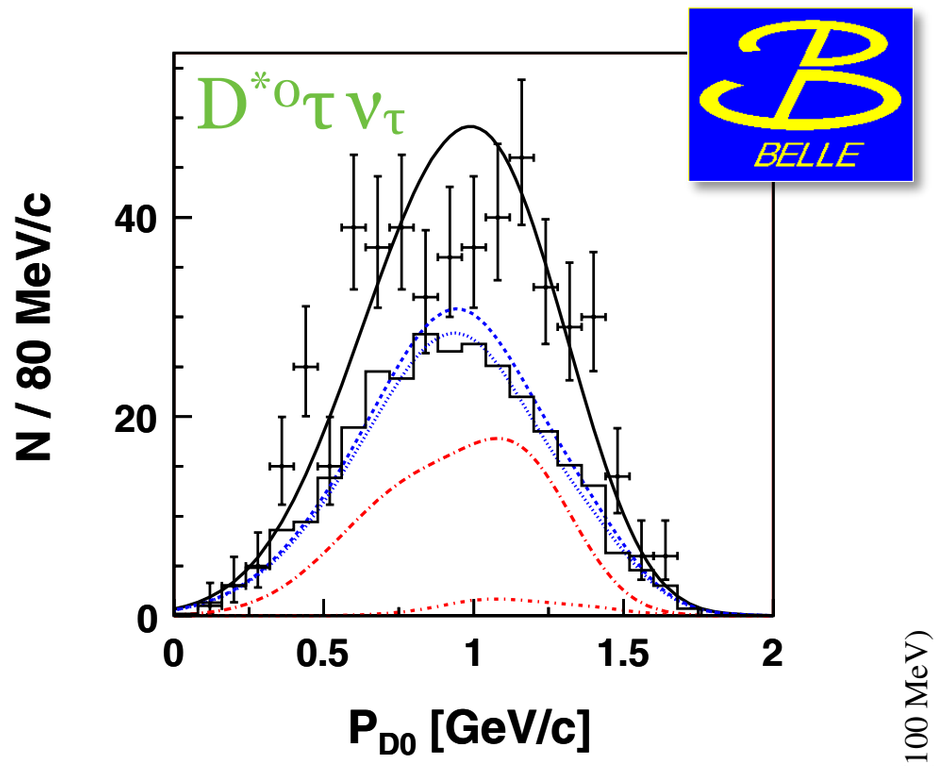
D: P_{max} = 0.4%
D*: P_{max} = 97.9%

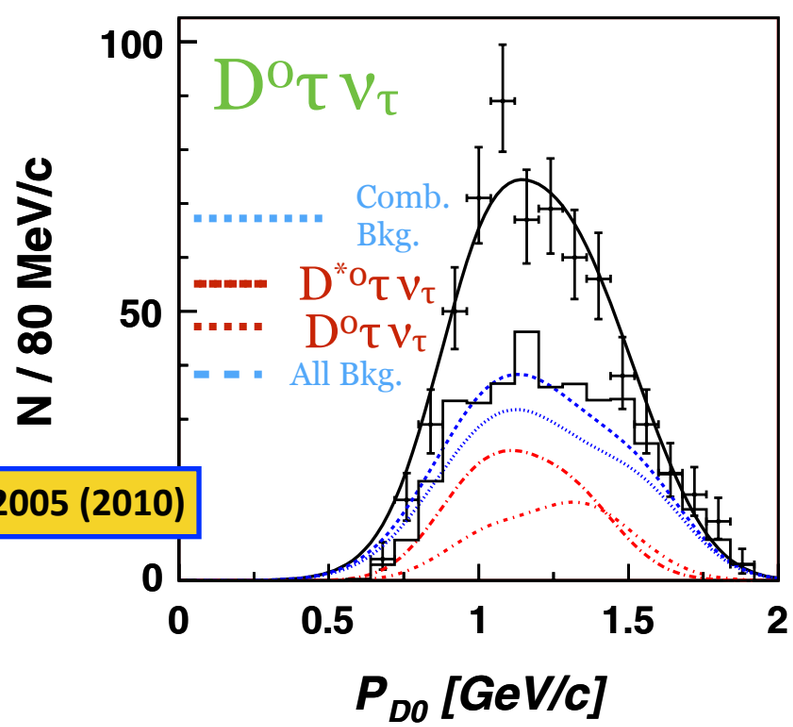
PRD 88 072012 (2013)

Additional D** modeling and q^2 distribution →

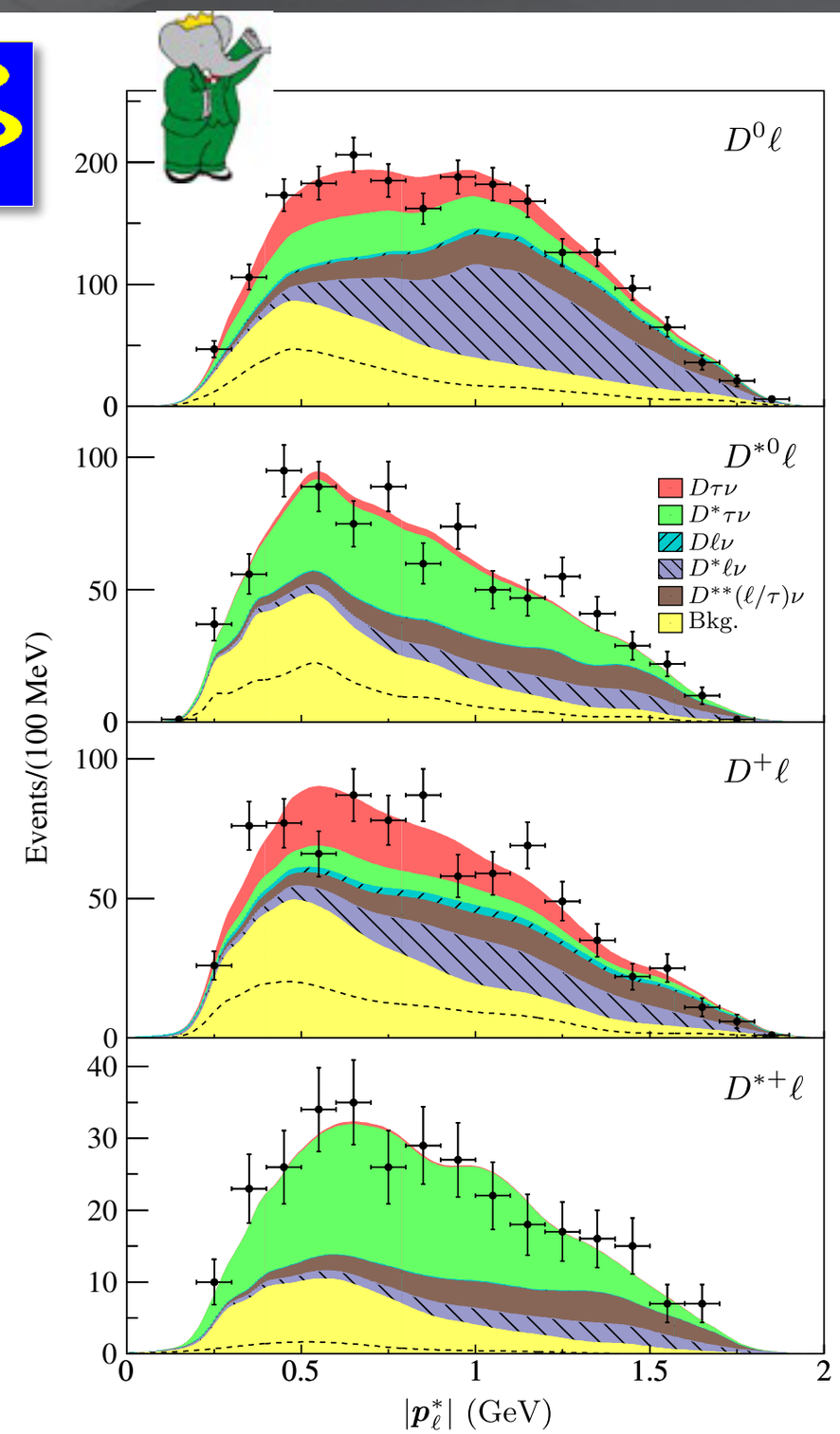


Lepton and D meson momentum spectra





PRD 82 072005 (2010)



Large P_ℓ^* reweighting

Both variables also used in signal extraction

PRD 88 072012 (2013)
PRL 109 101802 (2012)

Form Factors sensitivity in b→c τν measurements

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- Measurement of ratio of b→c τν / b→c lν has the advantage of canceling uncertainty due to V_{cb} matrix element of CKM matrix and also due to Fermi coupling constant.
- The ratio also helps in reducing hadronic uncertainties associated with the respective form factors.
- Theoretical uncertainty on the ratio is 6% for $\mathcal{R}(D)$ and 2% for $\mathcal{R}(D^*)$.
- BaBar's latest analysis has signal Monte Carlo simulations reweighted event-by-event to incorporate HQET evaluated Form Factors (FF).
- Some FF are theory driven - $R_0(1)$. **PRD 85 094025 (2012)**
- Measurement of various differential distributions is potentially dependent on the FF.
- This can be a cumbersome iterative process due to feedback from theory + experiment derived FF.
- Should irreducible background of D** in these measurements be also reweighted with latest FF?

New Physics Models in b→c τν

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Model-independent approach

Effective Lagrangian for $b \to c\tau\bar{\nu}$

all possible 4-fermi operators with LH neutrinos

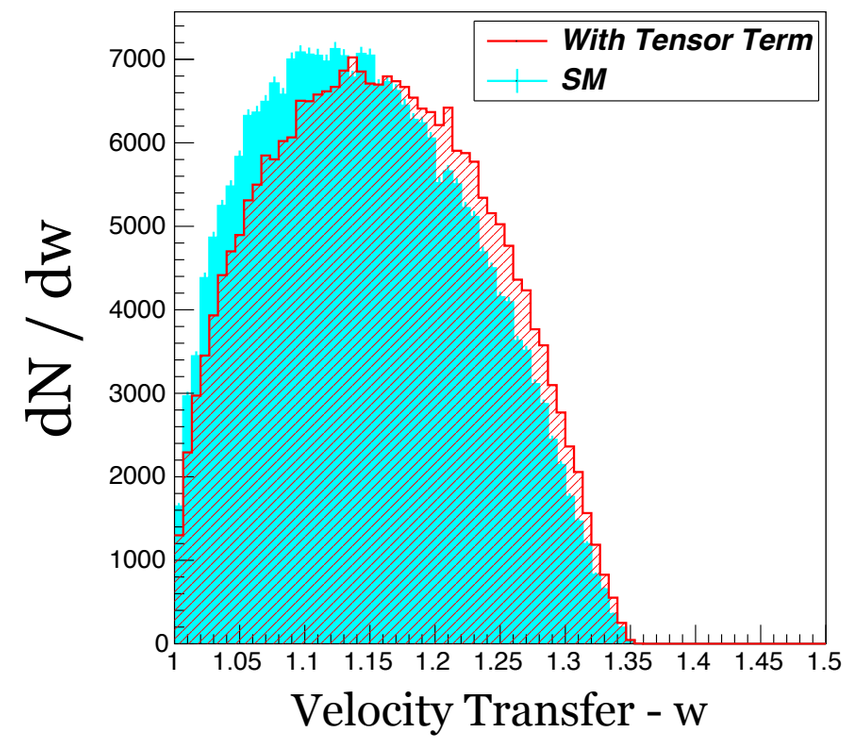
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb} \sum_{l=e,\mu,\tau} [(\delta_{l\tau} + C^l_{V_1})\mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T]$$

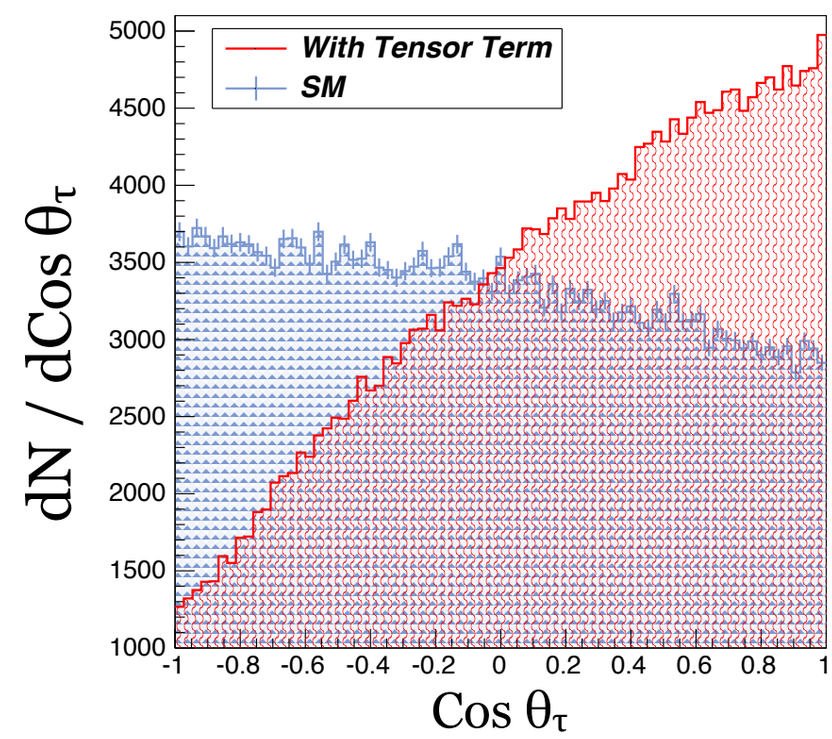
SM

$\mathcal{O}^l_{V_1} = \bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,,$	V−A	SM-like
$\mathcal{O}^l_{V_2} = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,,$	V+A	RH current
$\mathcal{O}^l_{S_1} = \bar{c}_L b_R\,\bar{\tau}_R\nu_{Ll}\,,$	S+P	charged Higgs (ll)
$\mathcal{O}^l_{S_2} = \bar{c}_R b_L\,\bar{\tau}_R\nu_{Ll}\,,$	S−P	charged Higgs
$\mathcal{O}^l_T = \bar{c}_R\sigma^{\mu\nu}b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_{Ll}$	Tensor	GUT?

Tanaka and Watanabe, PRD 87 034028 (2013)

For $B \to D^* \tau \nu_\tau$





- New Physics model with model-independent approach is available.
- τ angle is sensitive in distinguishing model parameters from the SM.
- Which few NP points to preferentially simulate to potentially scan all the parameter space by interpolation?

Summary

- $b \to c\,\tau\nu$ is sensitive to New Physics.
- $\mathcal{R}(D^*)$ and $b \to c\,\tau\nu$ branching fractions measurements show discrepancies from the Standard Model (especially for $B \to D^* \tau \nu_\tau$).
- Current measurements inconsistent with 2HDM Type II charged Higgs. Other alternatives?
- Kinematic distributions - q^2, differential distributions of lepton and D meson are accessible.
- $b \to c\,\tau\nu$ measurements are sensitive to D^{**} modeling.
- Should hadronic form factors account for some discrepancy in the $\mathcal{R}(D^*)$ measurement from the SM?

Backup