Recent Results of B Decays from Belle

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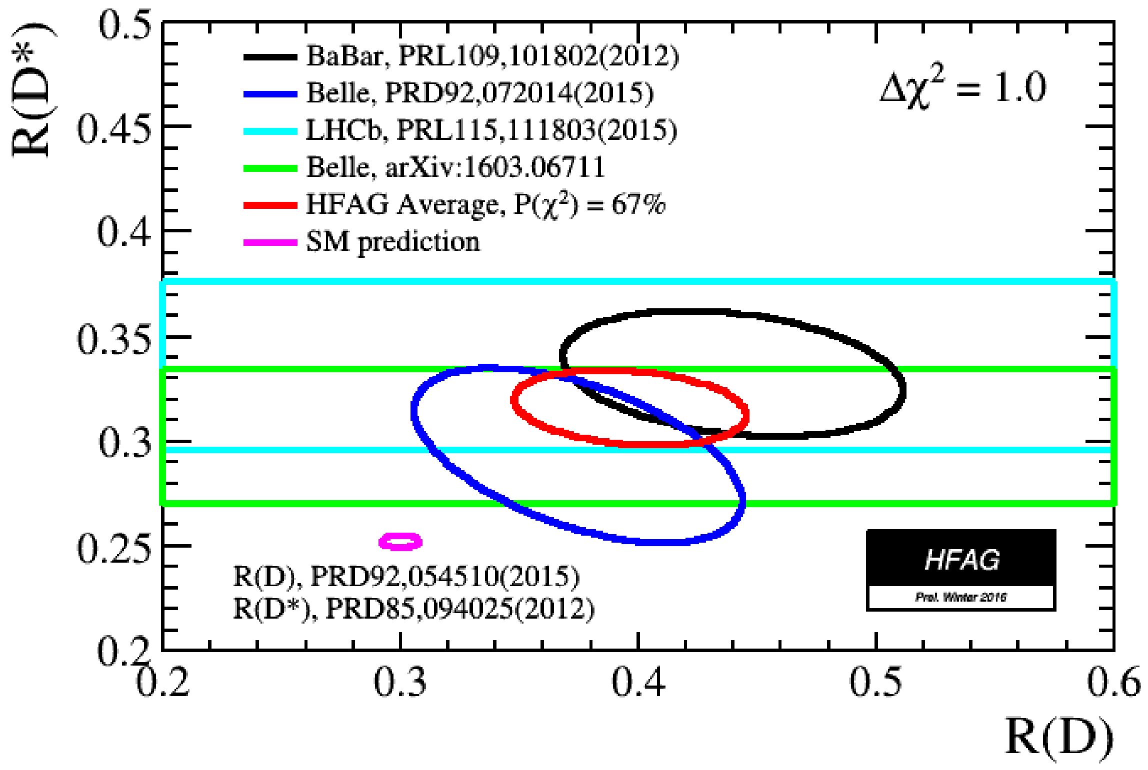
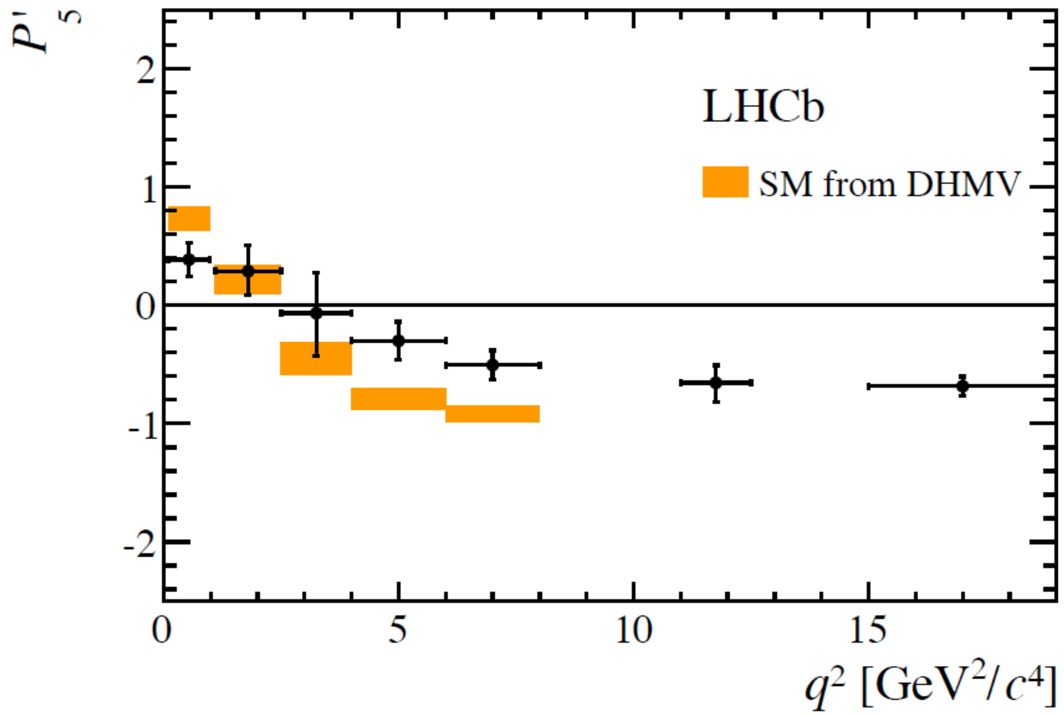
Introduction

- Successful SM has been confirmed experimentally but,
  - Dark energy & Dark matter
  - Neutrino masses
  - Hierarchy problem, Gravity …
- Mission for HEP $\Rightarrow$ Find New Physics
- Possible new physics hints:
  - muon g-2
  - R(D*) – R(D), P_5' in $B \to K^* \ell^+ \ell^-$

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\,(B \to D^{(*)}\tau\nu)}{\mathcal{B}\,(B \to D^{(*)}\ell\nu, \ell = e, \mu)}$$

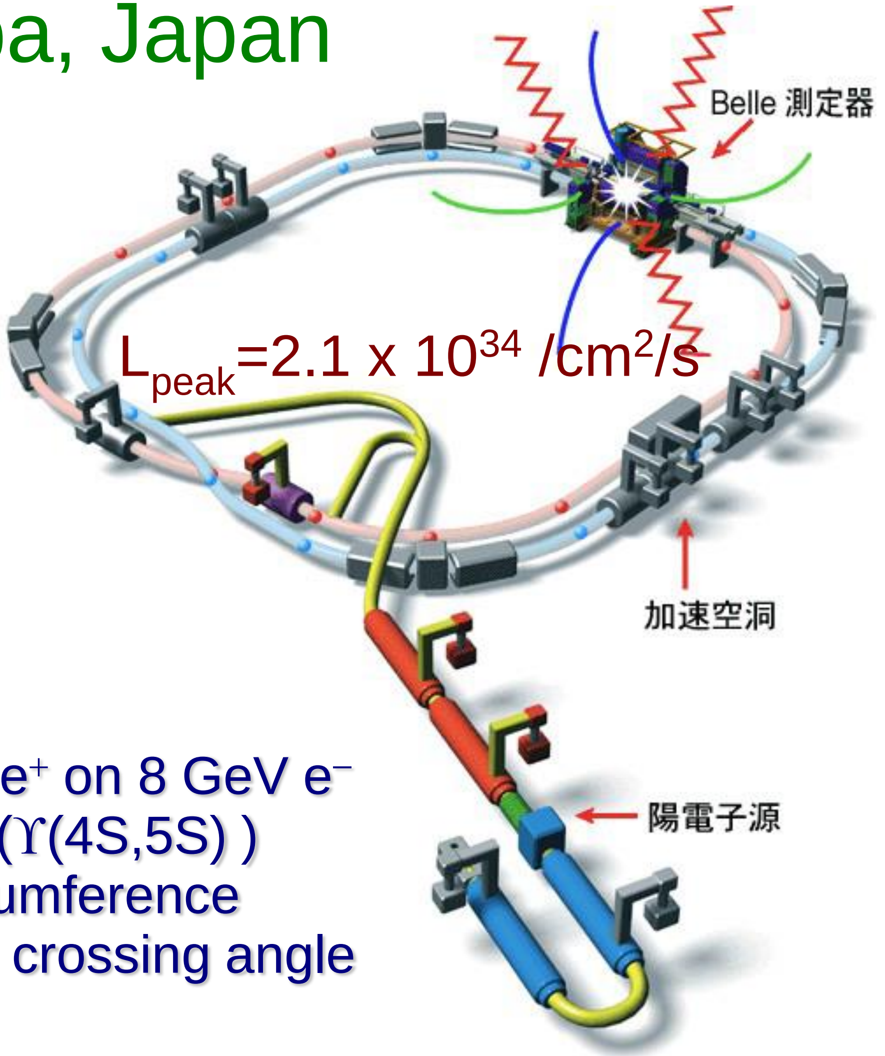




Topics covered today: $R(D^*)$ and P_5' measurements.

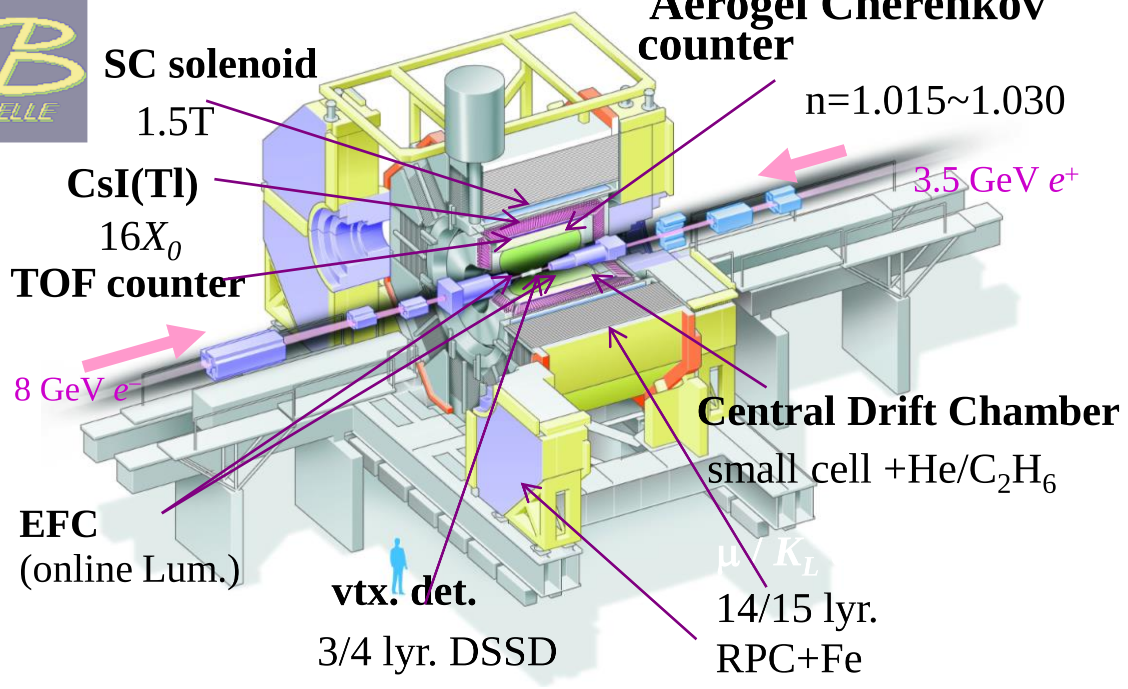
KEKB and Belle Detector

Tsukuba, Japan

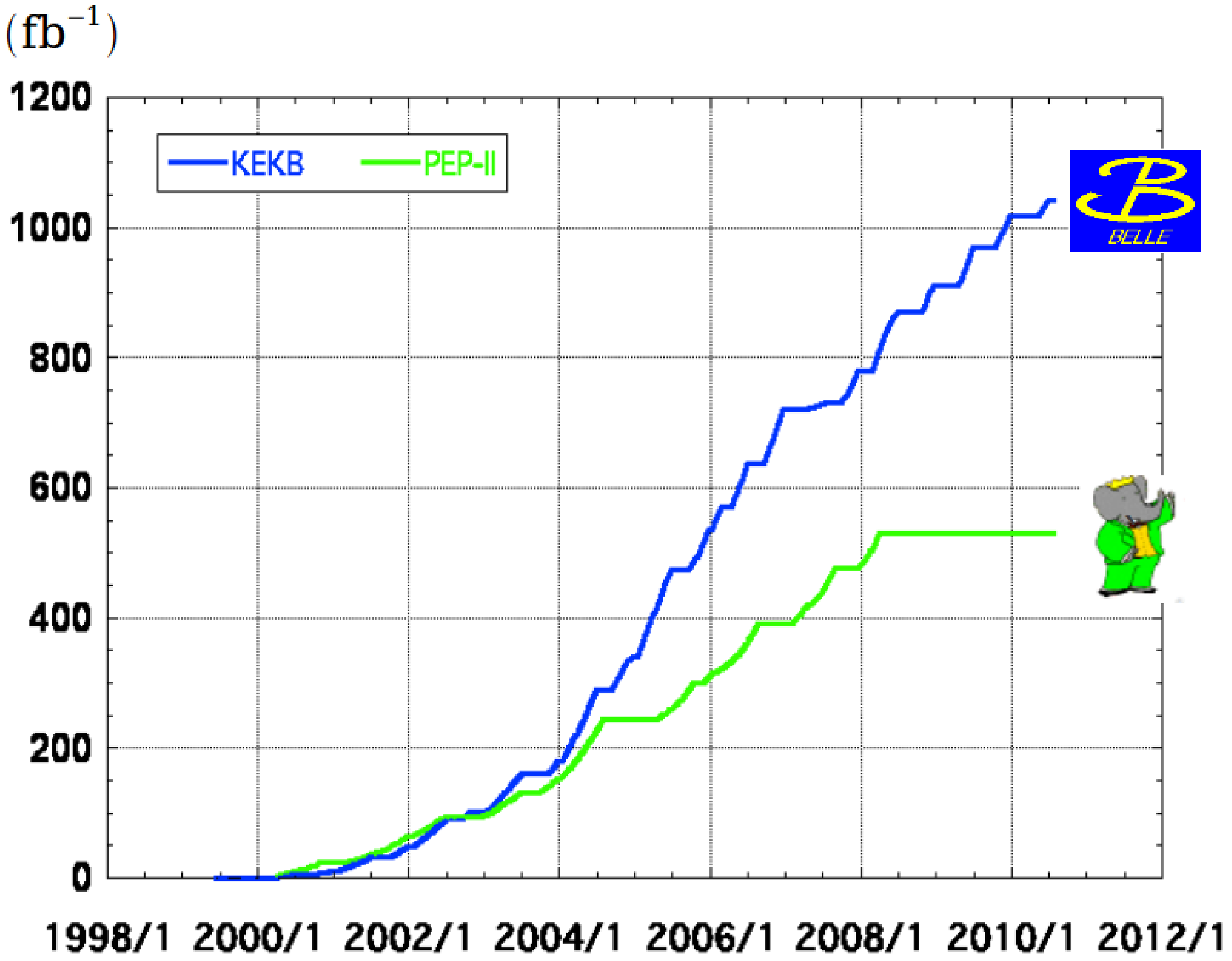


L_{peak}=2.1 x 10^{34} /cm^2/s

3.5 GeV e^+ on 8 GeV e^-
W_{CM} = M(ϒ(4S,5S))
3km circumference
~11mrad crossing angle



Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

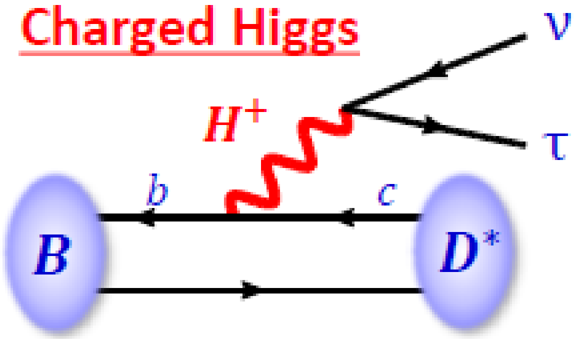
Off resonance:

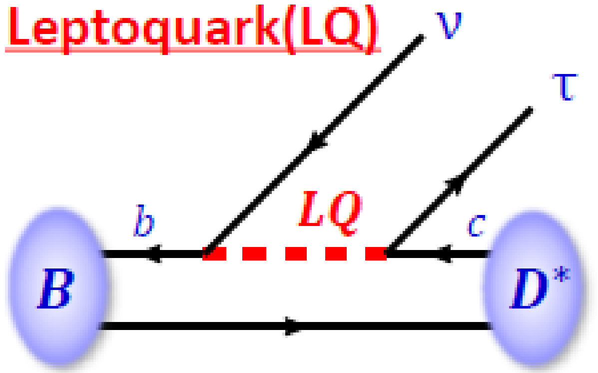
~ 54 fb^{-1}

Belle $B \to D^*\tau\nu$ analysis

- Lepton Universality $R(D^*)$
  - **Belle Hadronic tag, $\tau^+ \to \ell^+\nu_\ell\,\bar{\nu}_\tau$**
    $R(D^*) = 0.293 \pm 0.083 \pm 0.015$
  - Belle semileptonic tag, $\tau^+ \to \ell^+\nu_\ell\,\bar{\nu}_\tau$
    $R(D^*) = 0.302 \pm 0.030 \pm 0.011$
  - $R(D^*)_{SM} = 0.252 \pm 0.003$ S. Fajfer et al. PRD 85, 094025
- Polarization P_τ
  - $P_\tau^{SM} = -0.497 \pm 0.014$ M. Tanaka, R. Watanabe PRD 87, 034028
  - No measurements!
    $\Rightarrow$ Try two-body τ decays

Possible New physics



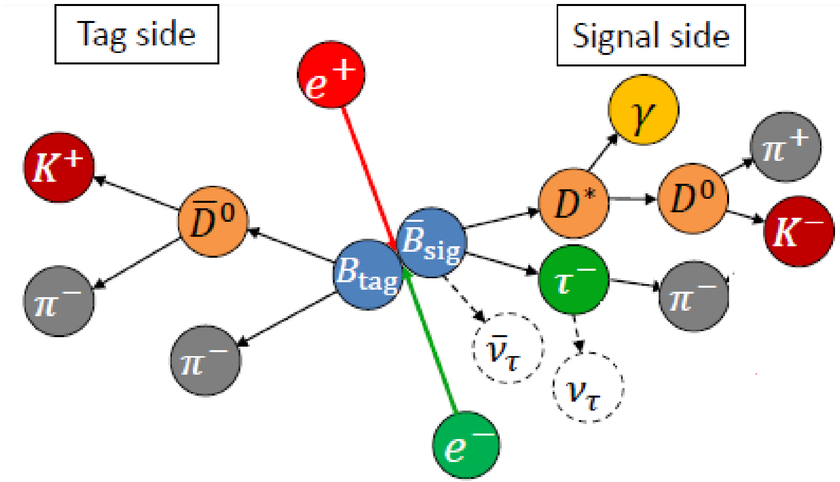


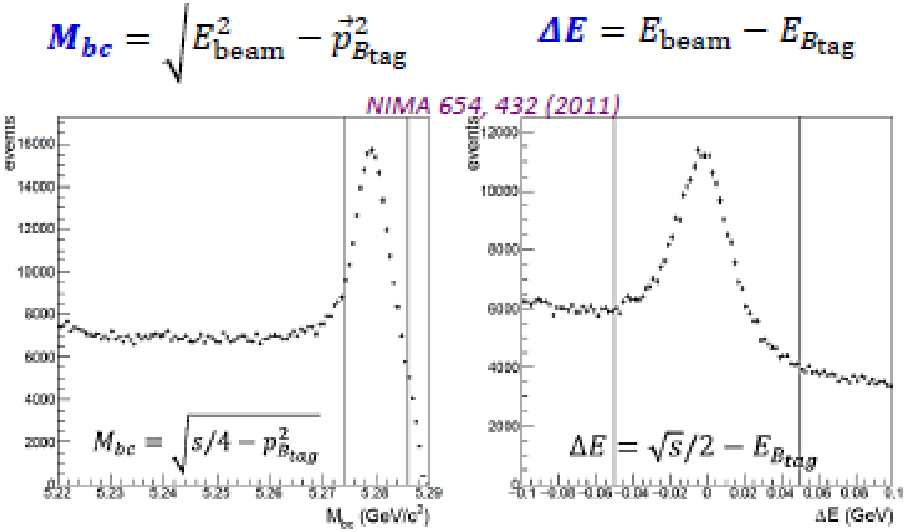
Analysis Strategy

- Fully reconstruct tagged B mesons and search for a π^+/ρ^+ and D^*.
  - Identify Tagged B's in 1149 exclusive modes.
  - $M_{bc} > 5.272$ GeV/c², $-150 < \Delta E < 100$ MeV
  - >100 variables in NeuroBayes $\Rightarrow O_{\text{NB}}$

    Cut on $O_{\text{NB}} \Rightarrow$ 90% true tags, 30% bkg.

    Choose best candidate based on O_{NB}.





- Signal B reconstruction (both B^0 and B^+)
  - $D^{*0} \to D^0\gamma,\ D^0\pi^0;\ D^{*+} \to D^0\pi^+, D^+\pi^0$

    $8\ D^0$ decay modes and 7 D^+ modes
  - Identify $\tau^+ \to \pi^+\bar{\nu}_\tau,\ \rho^+\bar{\nu}_\tau$

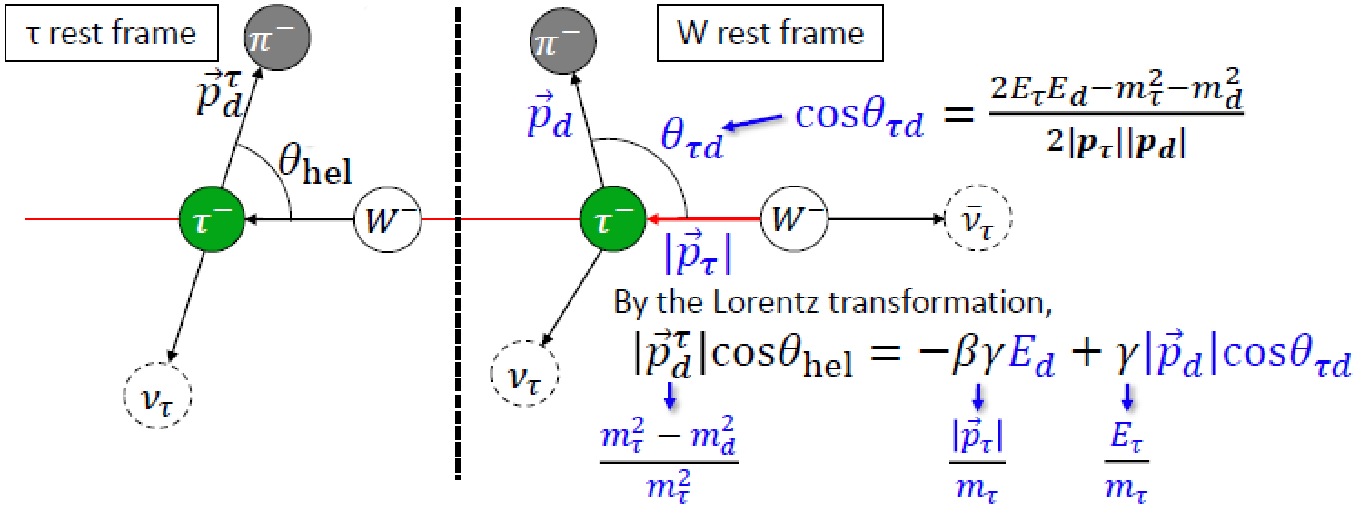
Signal reconstruction and τ helicity angle

- Mode dependent selections on $\Delta M \equiv M_{D^*} - M_D$
- Proton veto for the π^+ mode to reduce $\overline{B} \to D^* \overline{p} n$ background
- No extra charged tracks and π^0s
- Require $q^2 = (p_{e^+e^-} - p_{tag} - p_{D^*})^2 > 4$ GeV²/c⁴ for the signal mode.
- τ helicity angle and $P_\tau(D^*)$

$d = \pi$ or ρ

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1}{2}\left[1 + \alpha\, P_\tau(D^*)\cos\theta_{hel}\right]$$

$$\alpha = 1, \quad \tau^- \to \pi^- \nu_\tau$$
$$= 0.45, \quad \tau^- \to \rho^- \nu_\tau$$



For the $\tau \to \pi\nu$ mode, $\cos\theta_{hel} < 0.8$ to reduce $D^*\ell\nu_\ell$ background.

Signal and Background PDFs

- Normalization mode $B \to D^*\ell\bar{\nu}_\ell \Rightarrow$ replace $\pi^+(\rho^+)$ with ℓ^+. $\Rightarrow$ Clean M^2_{miss} is used to identify signals of the normalized mode.
- Fit on $E_{\rm ECL}$ to extract signals.
  - Signal PDF is modelled as histograms from the normalized mode.
  - Backgrounds:
    1. fake D^* $\Rightarrow \Delta M$ sidebands. Yield is fixed in the fit.
    2. $D^{**}\ell\nu_\ell$ and hadronic decays $\Rightarrow$ Vary $E_{\rm ECL}$ shape from MC
       (i) Vary B decay compositions in MC for modes with measurements.
       (ii) For unmeasured decays, use calibration samples: 7B decay modes $(D^*\pi n\pi)$
    3. $D^*\ell^+\nu_\ell$: fixed based on the yield of normalization mode. 4. $q\bar{q}$ background.

Signal Extraction

- For signals, consider
  - (a) $\pi^+ \leftrightarrow \rho^+$ cross feed.
  - (b) other τ^+ cross feed.
- $R(D^*) = (\epsilon_{\text{norm}} \text{N}_{\text{sig}})/(B_\tau \epsilon_{\text{sig}}\, N_{\text{norm}})$

  B_τ is the branching fraction of $\tau \to \pi(\rho)\nu$

- $P_\tau(D^*)$ can be determined using the number of events in the forward and backward regions.

  $\Rightarrow$ Correct for the acceptance and efficiency based on MC.

$\Rightarrow$ Fix relative contributions based on MC.

- 8 independent samples

  $(B^+, B^0) \otimes$ (Forward, backward) $\otimes(\pi^+\nu, \rho^+\nu)$
- Fit normalization sample first.

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^{+(-)}$ for right-(left-)handed τ

$P_\tau(D^*)_{\text{SM}} = -0.497 \pm 0.013$

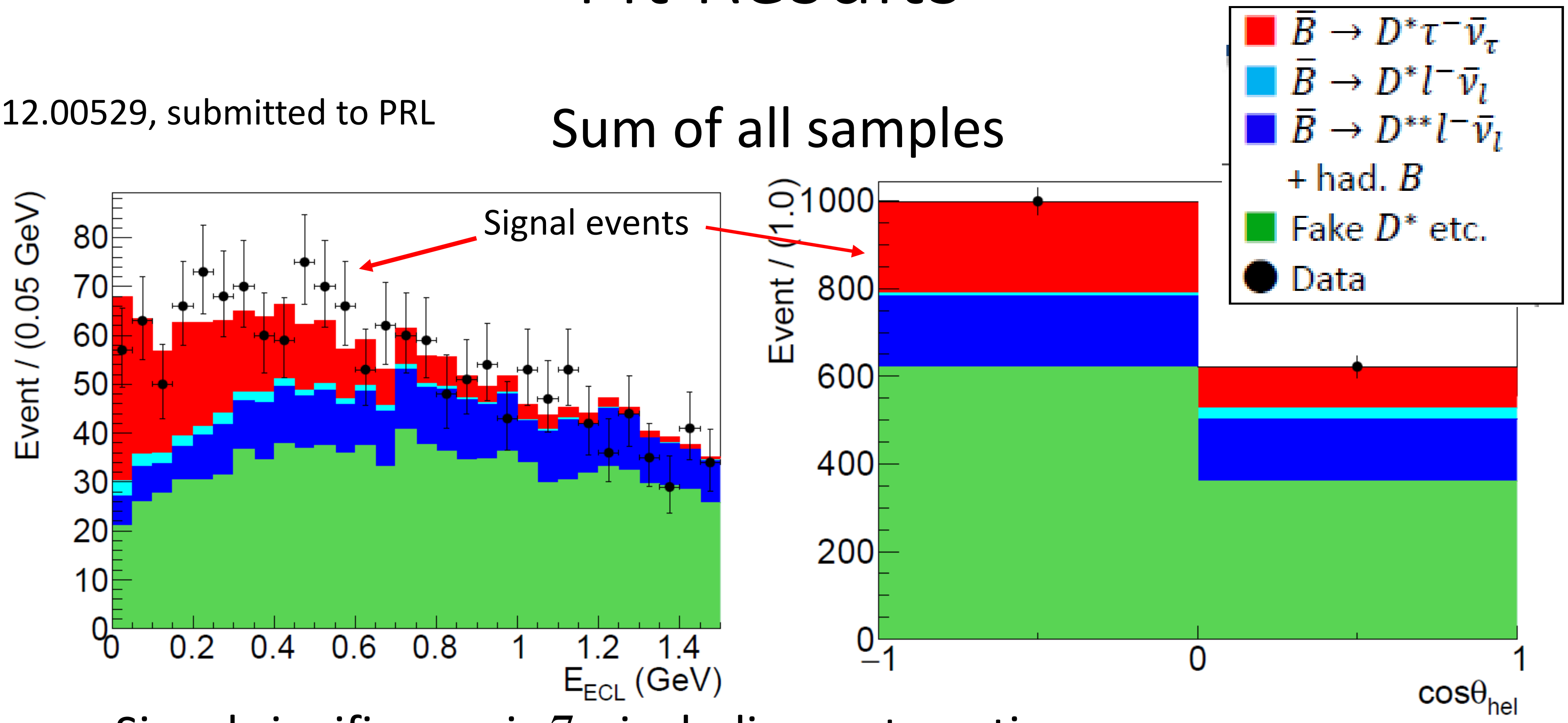
M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)

$$P_\tau(D^*) = \frac{[2(N^F - N^B)]}{[\alpha(N^F + N^B)]}$$

Fit Results

arXiv: 1612.00529, submitted to PRL

Sum of all samples

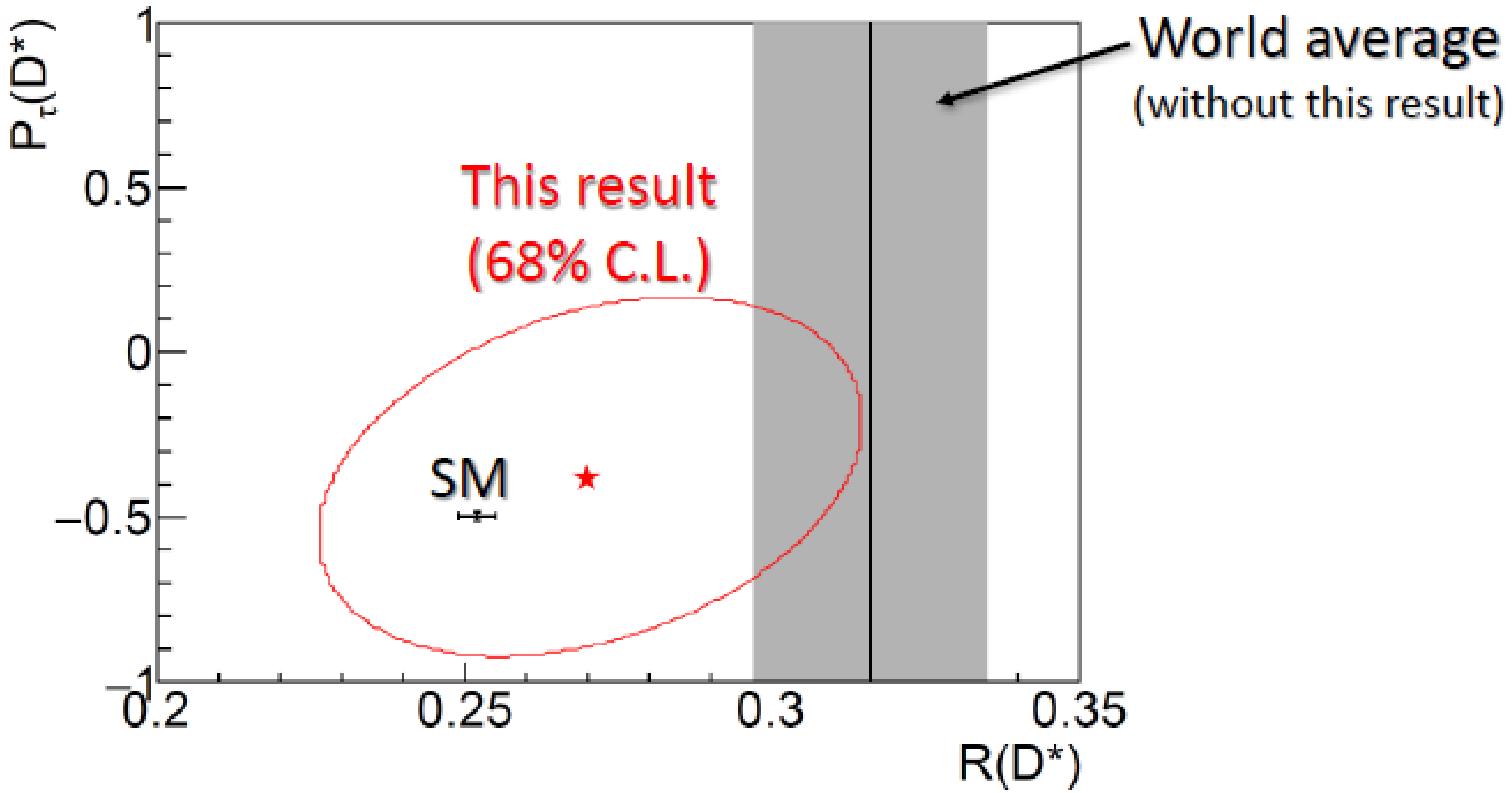


- Signal significance is 7σ including systematics.

$$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,^{+0.028}_{-0.025}(\text{syst.})$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,^{+0.21}_{-0.16}(\text{syst.})$$

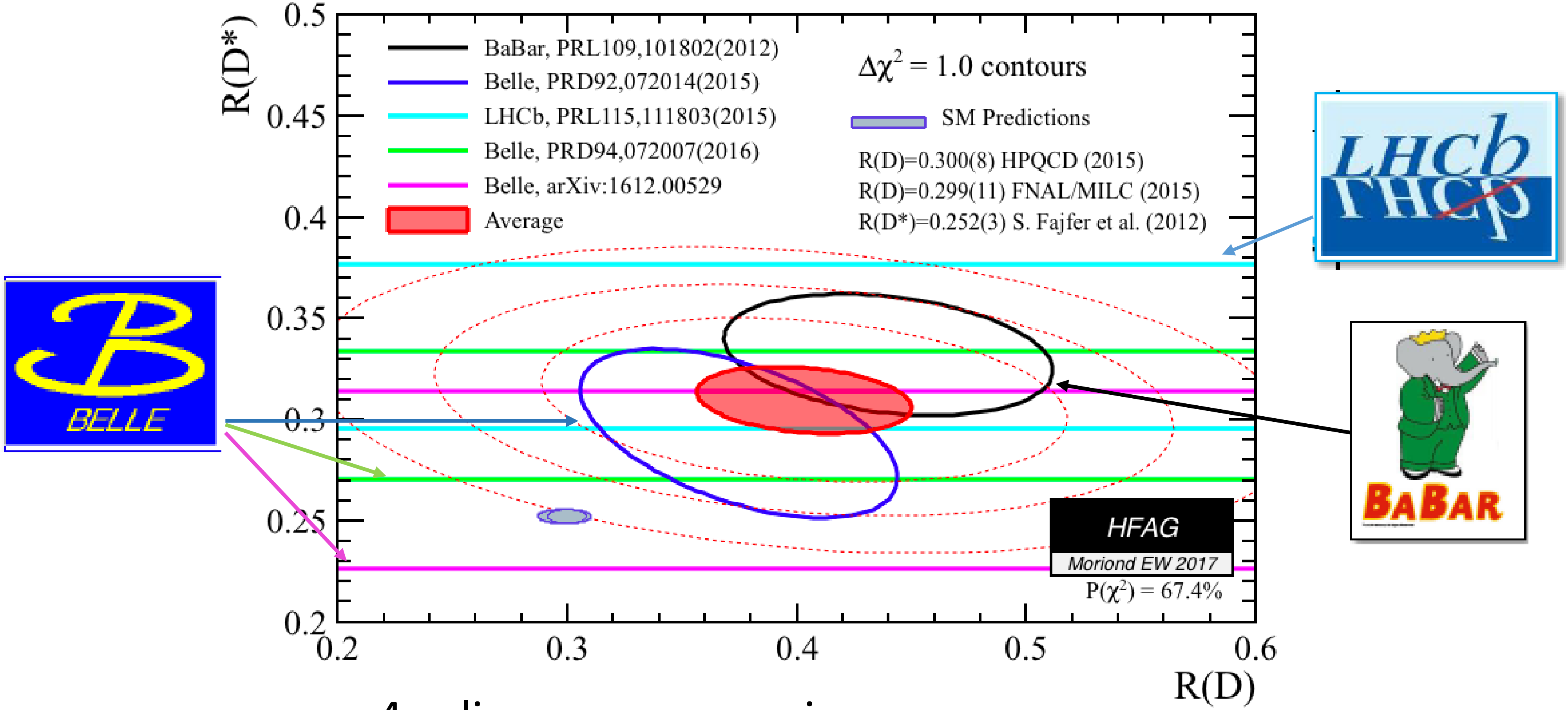
$\Rightarrow$ First measurement

Compared with the SM



- Results consistent with the SM within 0.4σ
- Exclude $P_\tau(D^*) > +0.5$ @90% C. L.
- First $R(D^*)$ measurement with hadronic τ

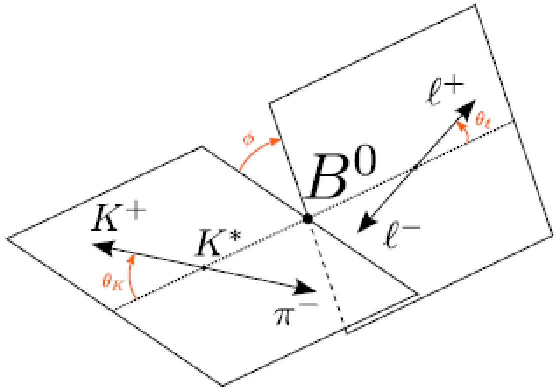
$R\left(D^{(*)}\right)$ by HFAG



- ~4σ discrepancy remains
- More precise measurements will be from Belle II & LHCb

Angular analysis for $B \to K^*\ell^+\ell^-$

- Advantages of B factory: Clean environment, Good acceptance, Understandings the detectors
- Angular variables



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$\left. + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\right],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

$P'_i \Rightarrow$ Largely free from form-factor uncertainties. JHEP 05, 137 (2013)

Signal Reconstructions

- Consider both $K^*e^+e^-$ and $K^*\mu^+\mu^-$
- $K^{*0} \to K^+\pi^-$; $K^{*+} \to K_S^0\pi^+, K^+\pi^0$

  $\Rightarrow$ 0.6 GeV/c² $< M_{K\pi} <$ 1.4 GeV/c²
- Signal identification:

$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{P}_B|^2}$$

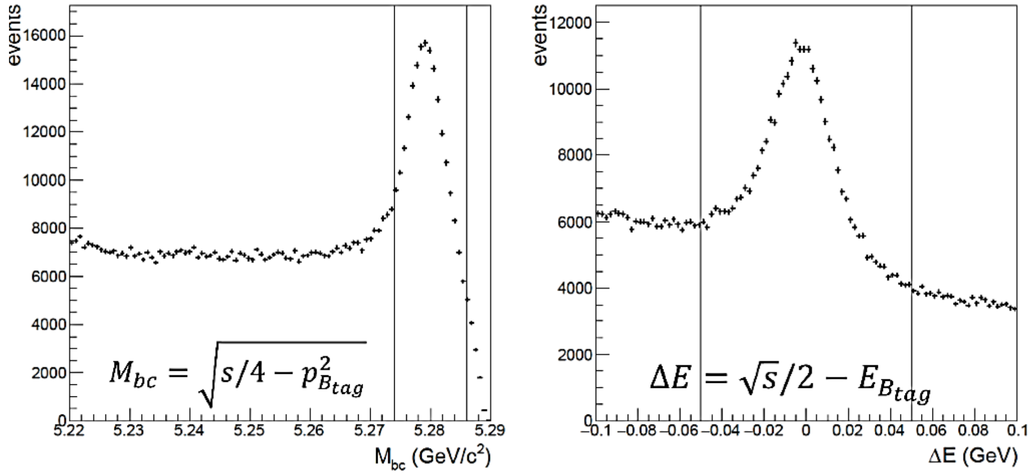
$$\Delta E = E_B - E_{beam}$$

- Veto J/ψ and ψ'

$$-0.25(-0.15) < \Delta m_1 < 0.08 \text{ GeV/c}^2$$

$$-0.20(-0.10) < \Delta m_2 < 0.08 \text{ GeV/c}^2$$

$$\Delta m_{1(2)} = m_{\ell\ell} - m_{J/\psi(\psi')}$$

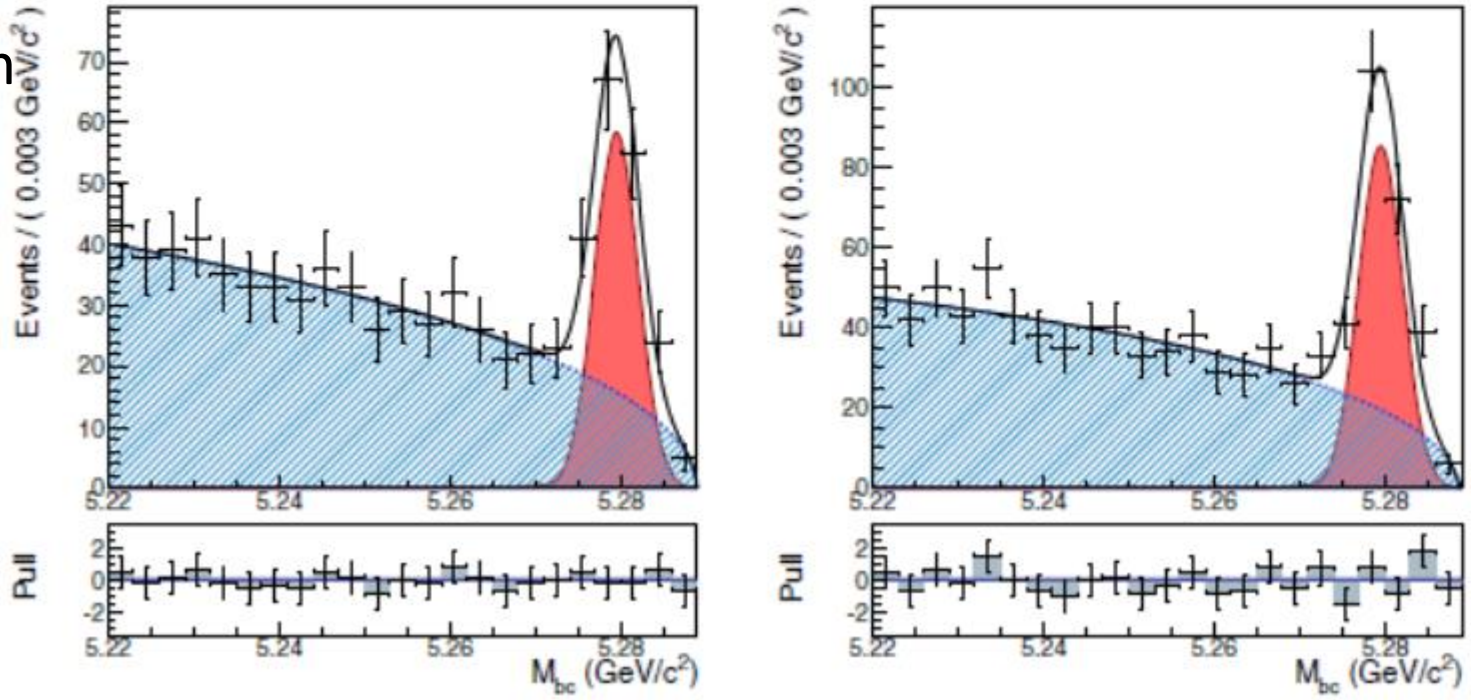


- Event selections:
  - Neural network output for all particles
  - K^* kinematics and vertex fit
  - shape variables
  - ΔE and $\Delta Z_{\ell\ell}$

  $\Rightarrow$ Cut on $O_{\rm NB}$ based on $N_{sig}/\sqrt{N_{sig}+N_{bkg}}$

Extracting $B \to K^{*}\ell^{+}\ell^{-}$ signals

- Unbinned extended maximum likelihood fit to M_{bc}
- Signal PDF
  $\Rightarrow$ Crystal Ball function
  function parameters from $B \to J/\psi\, K^{*}$ in veto regions
- Background PDF
  $\Rightarrow$ Argus function with parameters floated in the fit.
- Obtain signal fraction as a function of M_{bc} for the angular analysis.



$B \to K^{*}e^{+}e^{-}$
127 ± 15 signals

$B \to K^{*}\mu^{+}\mu^{-}$
185 ± 17 signals

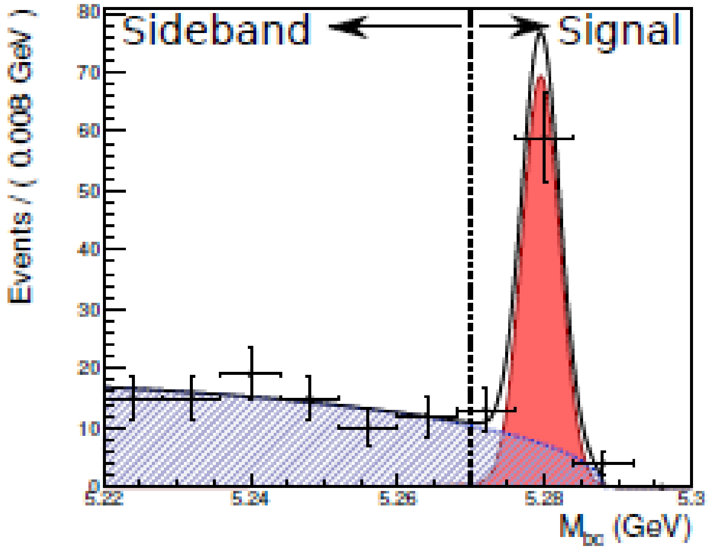
Procedure for Angular Fits

- Apply transformation to specific region of angular space.
- The transformed differential rates are sensitive to P_4' and P_5'

$$P_4', S_4: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

$$P_5', S_5: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

- Divide data into 5 q^2 bins.
- For each q^2, obtain signal fraction as a function of M_{bc}
- Background PDFs: Kernel density templates from sideband events
- Signal: Transformed differential decay rate
- Consider acceptance and efficiency as event weights.

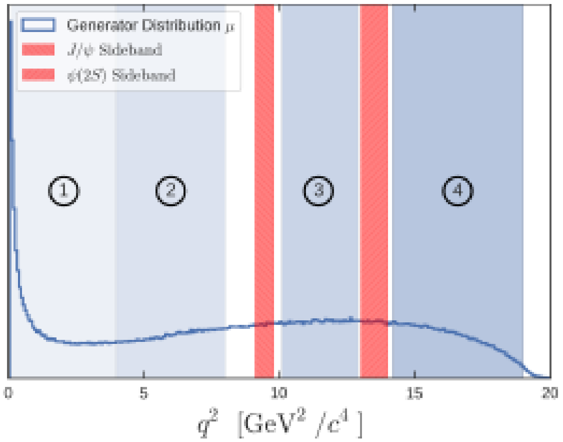


Summary Table of Fit Results

TABLE I. Fit results for P'_4 and P'_5 for all decay channels and separately, for the electron and muon modes. The first uncertainties are statistical and the second systematic.

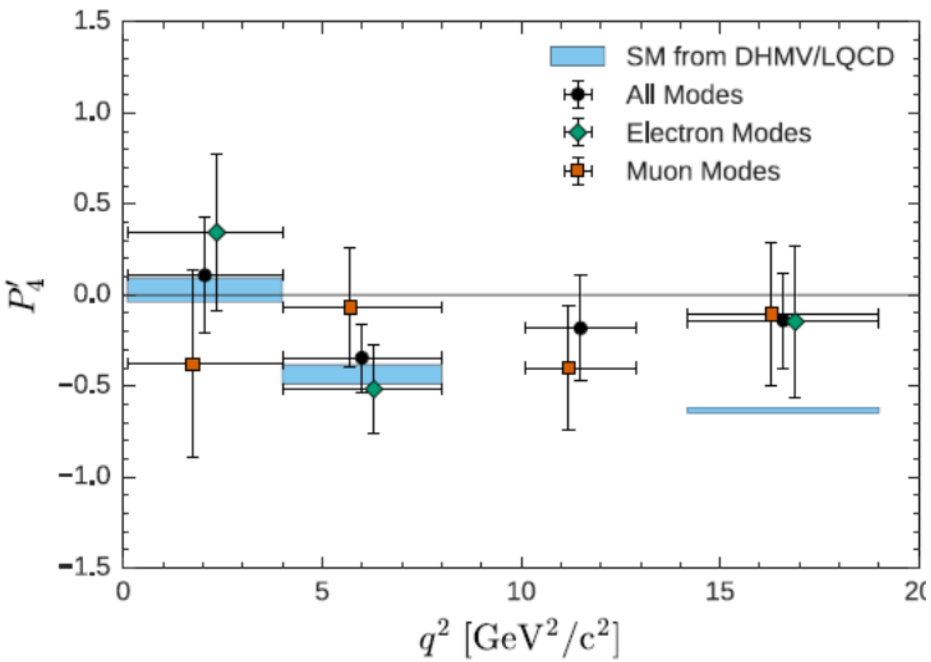
q^2 in GeV$^2/c^2$	P'_4	$P^{e\prime}_4$	$P^{\mu\prime}_4$	P'_5	$P^{e\prime}_5$	$P^{\mu\prime}_5$
[1.00, 6.00]	$-0.45^{+0.23}_{-0.22} \pm 0.09$	$-0.72^{+0.40}_{-0.39} \pm 0.06$	$-0.22^{+0.35}_{-0.34} \pm 0.15$	$0.23^{+0.21}_{-0.22} \pm 0.07$	$-0.22^{+0.39}_{-0.41} \pm 0.03$	$0.43^{+0.26}_{-0.28} \pm 0.10$
[0.10, 4.00]	$0.11^{+0.32}_{-0.31} \pm 0.05$	$0.34^{+0.41}_{-0.45} \pm 0.11$	$-0.38^{+0.50}_{-0.48} \pm 0.12$	$0.47^{+0.27}_{-0.28} \pm 0.05$	$0.51^{+0.39}_{-0.46} \pm 0.09$	$0.42^{+0.39}_{-0.39} \pm 0.14$
[4.00, 8.00]	$-0.34^{+0.18}_{-0.17} \pm 0.05$	$-0.52^{+0.24}_{-0.22} \pm 0.03$	$-0.07^{+0.32}_{-0.31} \pm 0.07$	$-0.30^{+0.19}_{-0.19} \pm 0.09$	$-0.52^{+0.28}_{-0.26} \pm 0.03$	$-0.03^{+0.31}_{-0.30} \pm 0.09$
[10.09, 12.90]	$-0.18^{+0.28}_{-0.27} \pm 0.06$	...	$-0.40^{+0.33}_{-0.29} \pm 0.09$	$-0.17^{+0.25}_{-0.25} \pm 0.01$	...	$0.09^{+0.29}_{-0.29} \pm 0.02$
[14.18, 19.00]	$-0.14^{+0.26}_{-0.26} \pm 0.05$	$-0.15^{+0.41}_{-0.40} \pm 0.04$	$-0.10^{+0.39}_{-0.39} \pm 0.07$	$-0.51^{+0.24}_{-0.22} \pm 0.01$	$-0.91^{+0.36}_{-0.30} \pm 0.03$	$-0.13^{+0.39}_{-0.35} \pm 0.06$

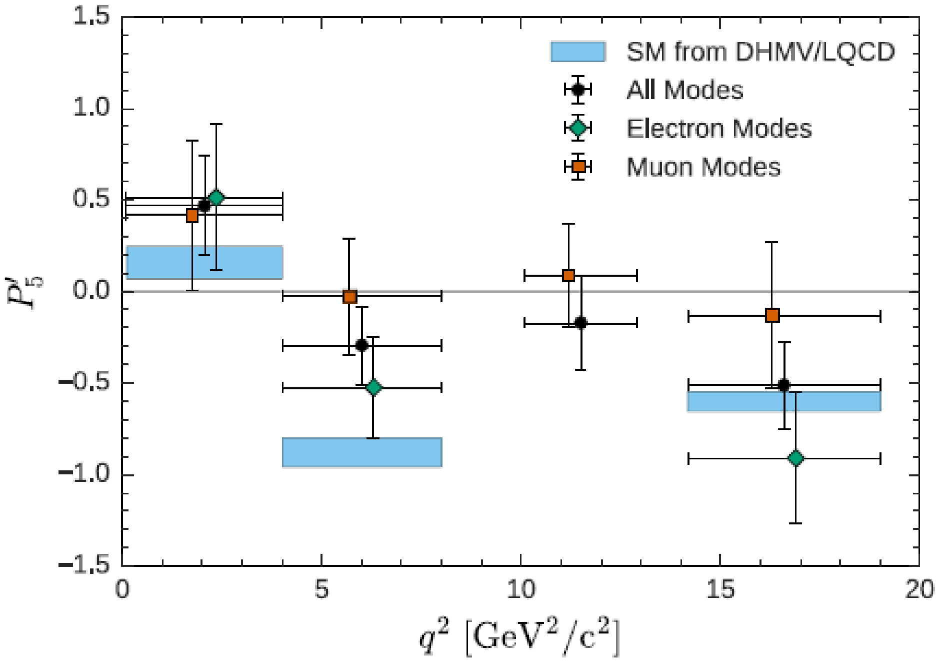
- No sufficient statistics in $10.09 < q^2 < 12.90$ GeV/c² for the electron mode due to the ψ' veto.
- Range $1.00 < q^2 < 6.00$ is preferred by theorists.



P_4', P_5' Fit Results

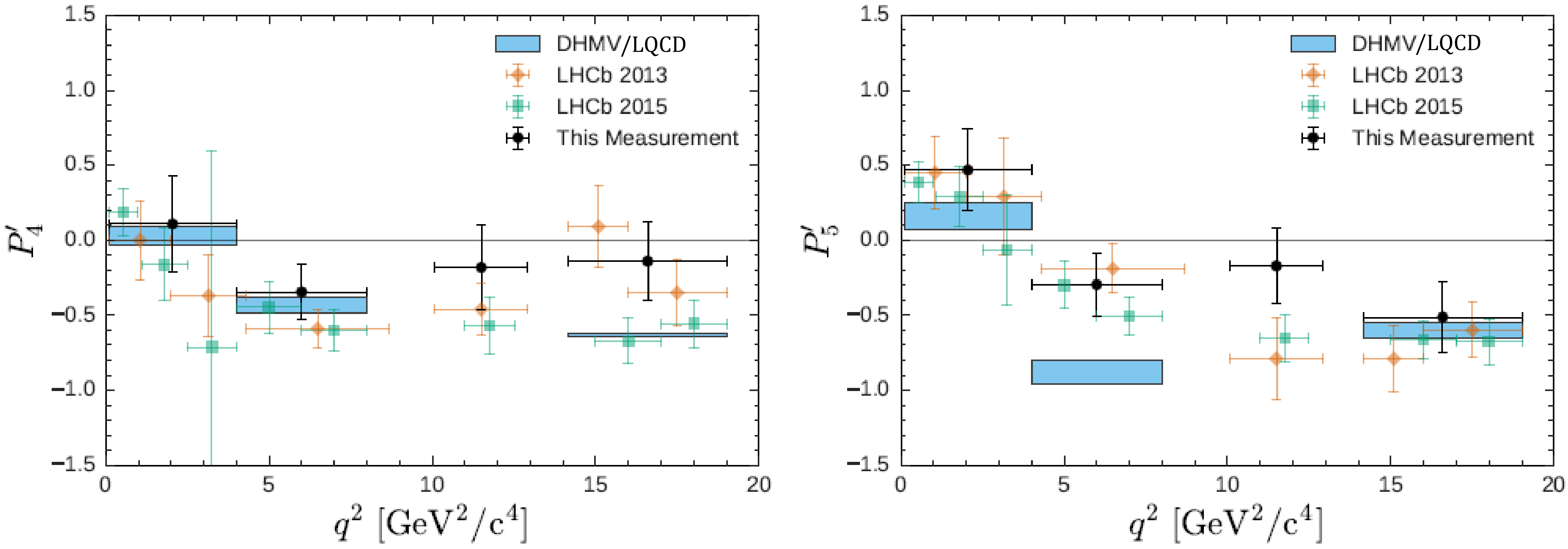
PRL 118, 111801 (2017)





- P_4' measurements are consitent with the SM predictions
- The largest deviation is 2.6σ for the 2nd q^2 bin in the muon mode. It is 1.3σ for the electron mode.

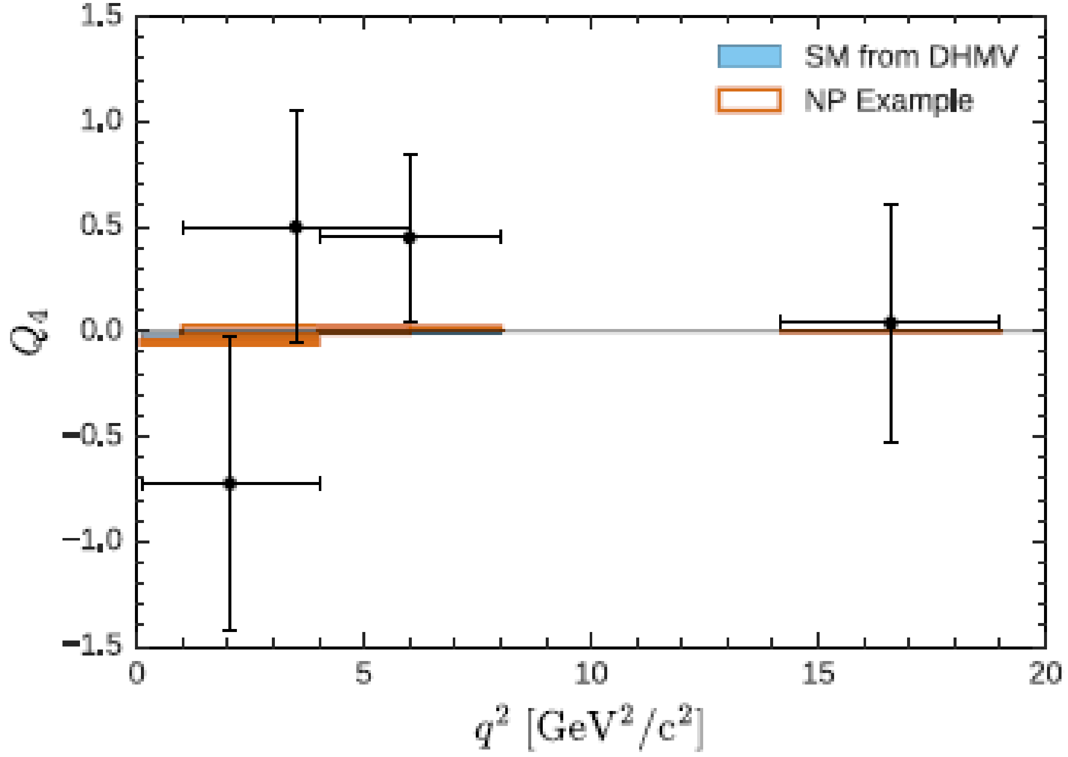
P_4', P_5' with Combined data

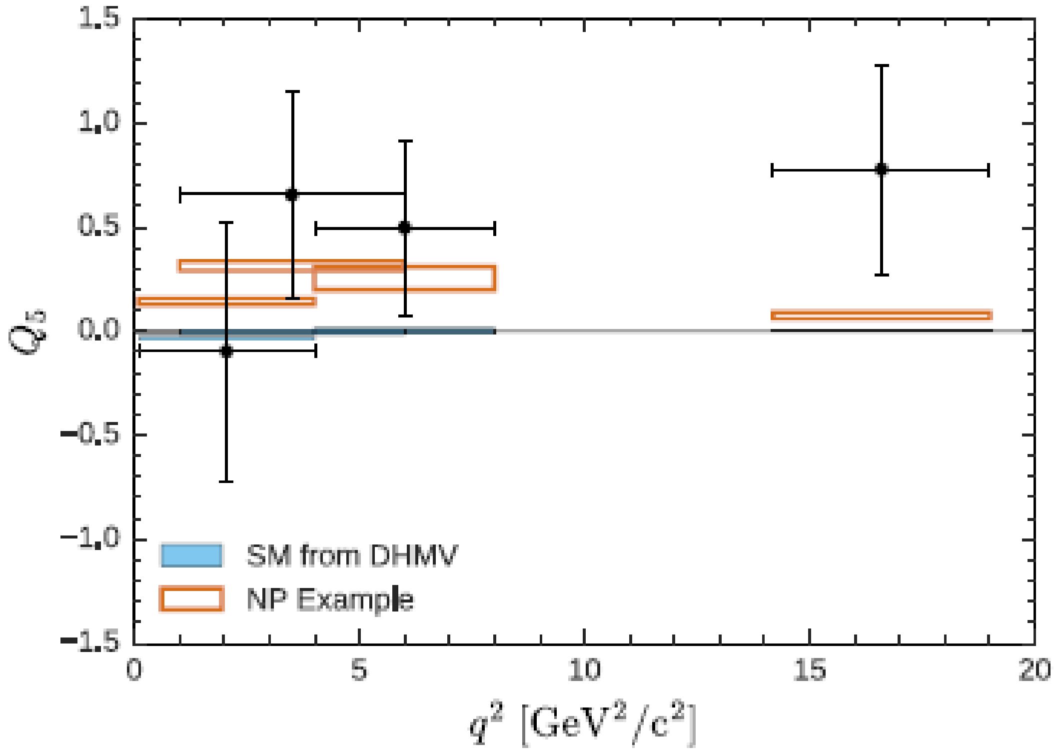


- Results are consistent with SM and LHCb measurements.
- Similar central value of P_5' with 2.5σ tension.
- SM predictions displayed are for the muon modes.

Check Lepton Universality

- $Q_i = P_i^{\mu} - P_i^{e}$
- Deviations from zero are sensitive to new physics.
- First presentation of Q_4 and Q_5





Summary

- $B \to D^* \tau \nu$ and $B \to K^* \ell\ell$ are two decay modes that show discrepancy or tension from the SM predictions.
- Recent Belle measurements presented in this talk:
  - First measurement of $R(D^*)$ in $\tau^+ \to \pi^+ \nu_\tau$ and $\tau^+ \to \rho^+ \nu_\tau$.

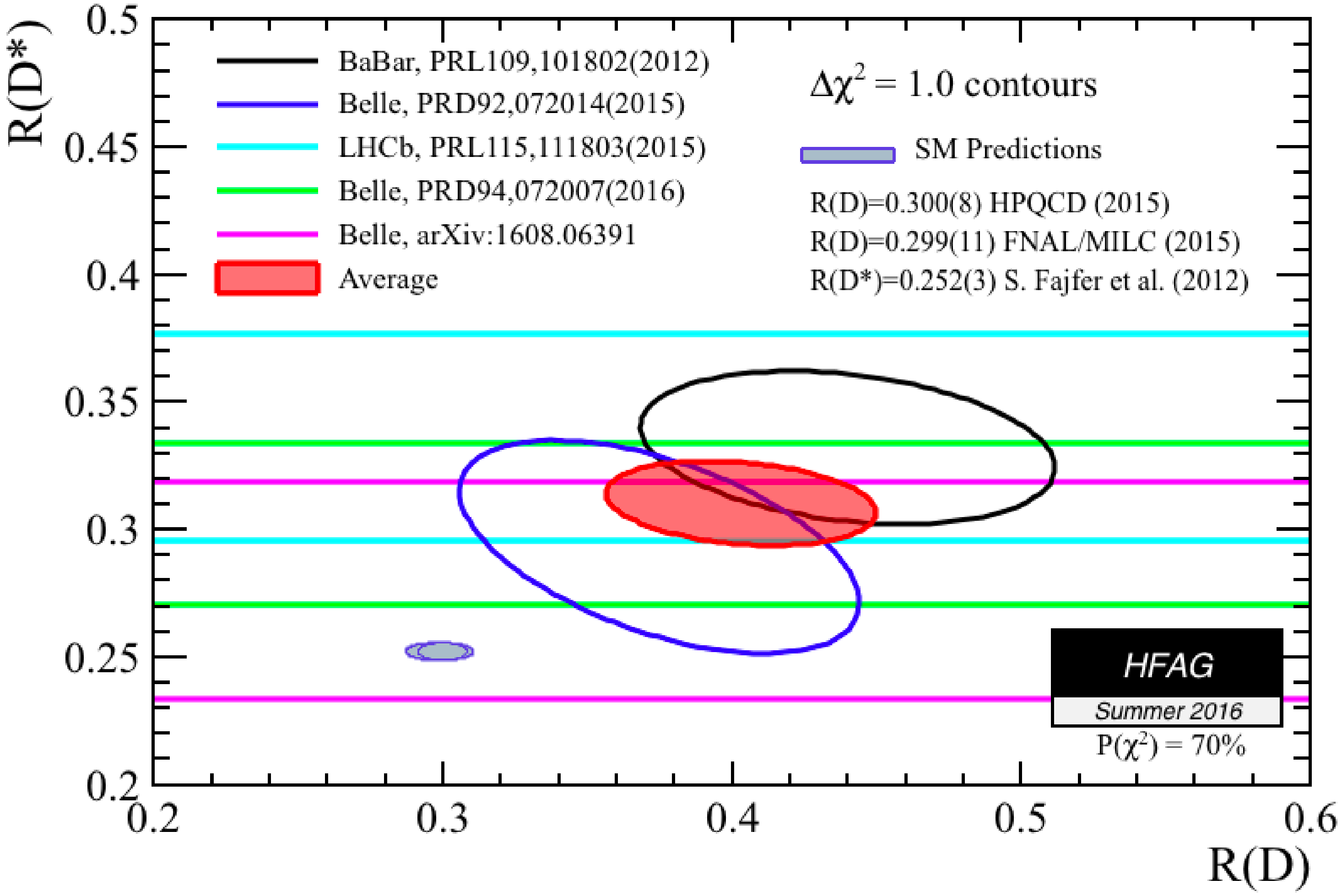
    $R(D^*)$ and $P_\tau(D^*)$ results consistent with SM, but the world average of $(R(D), R(D^*))$ still has ~4σ deviation from the SM.
  - First lepton flavor-dependent angular analysis for $B \to K^* \ell\ell$.

    Observe 2.6σ deviation in P_5' for the muon mode.⇒ Same place for LHCb

    The deviation of the same bin for the electron mode is 1.3σ
- Need high statistics from LHCb and Belle II to verify the deviations.

Back up

Summer 2016 with Belle preliminary results



$B \to D^{*}\tau\nu$, PRL paper figures