Test of lepton flavor universality in the semileptonic B decays at LHCb

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Outline

1. Introduction.

2. $\mathcal{R}(D^*)$ with $\dfrac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$, $\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu$

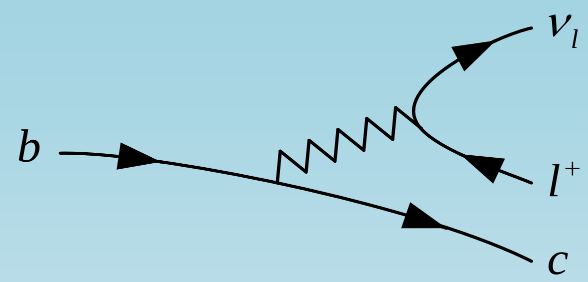
3. $\mathcal{R}(J/\psi)$ with $\dfrac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$, $\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu$

4. $\mathcal{R}(D^*)$ with $\dfrac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$, $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

5. Prospect, Conclusion.

arXiv:1703.01766v3

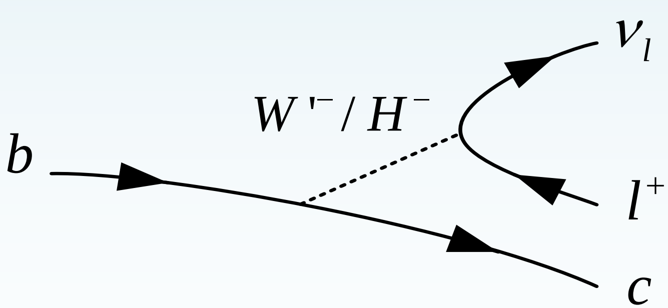
Lepton flavor universality

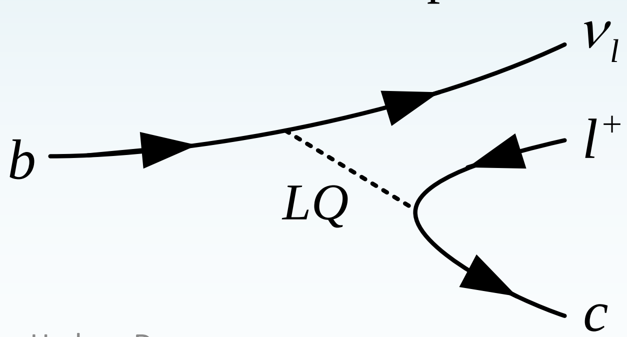


- In SM, electroweak couplings to gauge bosons are trivially equal for leptons.
  - Amplitudes involving leptons differs from their masses and helicities.

$$\mathcal{H}_{eff} = \frac{4}{\sqrt{2}} V_{cb} \bar{c} \gamma_\mu P_L b \times G_F \sum_{l=e,\mu,\tau} (\bar{l} \gamma^\mu P_L \nu_l) + \text{h.c.}$$

- New physics may have increased coupling to heavier fermions.
  - Semileptonic decays $b \to c\tau\nu$ are sensitive to exotic particles.





LFU test on other systems

- Searches on lepton universality on different systems for years.
  - $J/\psi \to ll, \tau \to l\nu\bar{\nu}, \pi \to l\nu, K \to \pi l\nu, ...$
- More tests involve the 1st and 2nd quark and lepton generations.
  - $m > m(\tau)$ to allow taunic decay: $Z^0, W^\pm, H^0, b.$

In order to test lepton universality in Z decays quantitatively, the ratios of the leptonic partial widths or equivalently the ratios of the leptonic branching fractions are calculated. The results are:

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028, \quad (7.4)$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032 \quad (7.5)$$

with a correlation of +0.63. In both cases, good agreement with lepton universality is observed. Assuming lepton universality, τ mass effects are expected to decrease $\Gamma_{\tau\tau}$ and $B(Z \to \tau^+\tau^-)$ as quoted here by 0.23% relative to the light lepton species e and μ.

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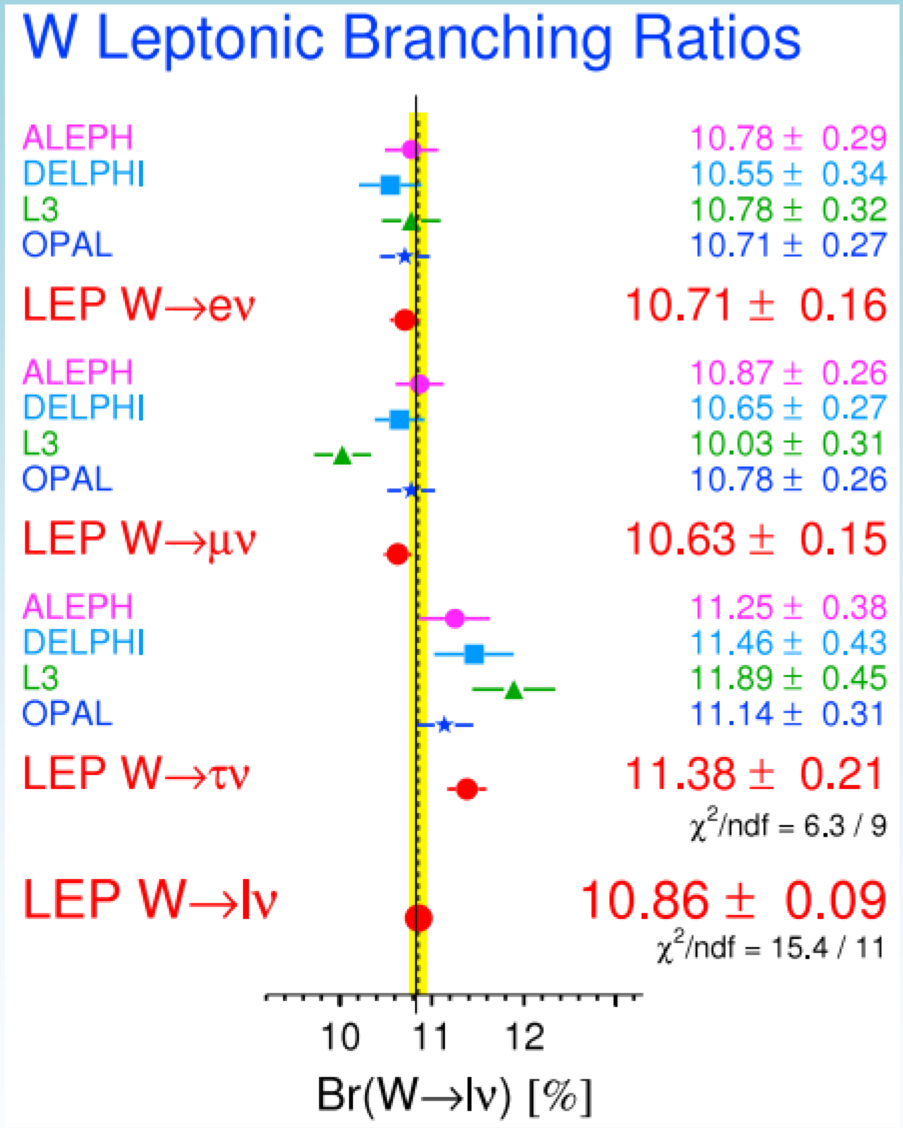
LFU test on W bosons

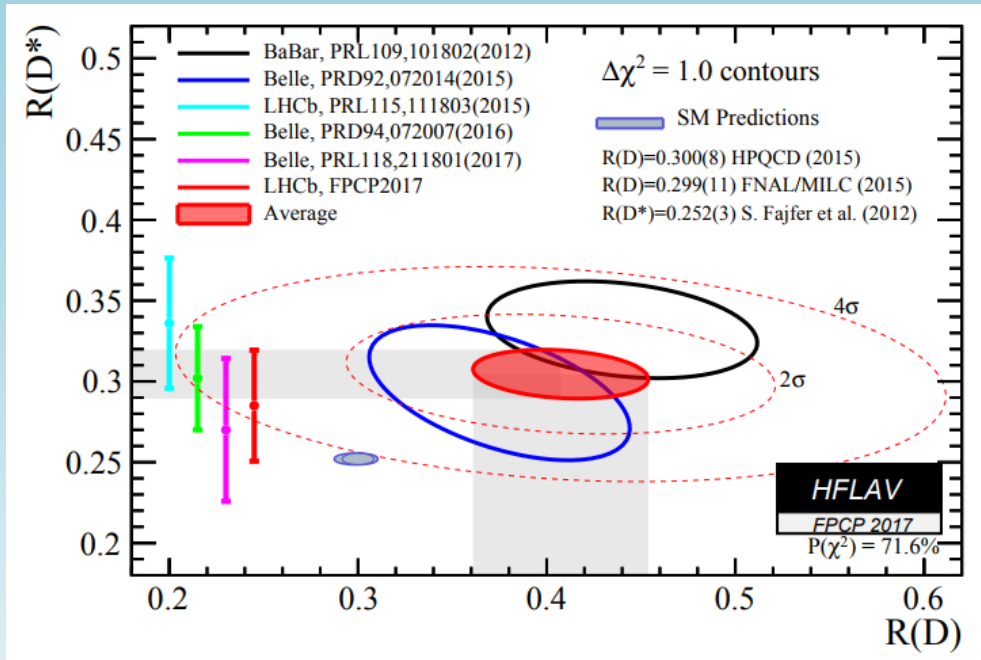


LFU test on on-shell W bosons:

$$\frac{\mathcal{B}(W\to\mu\bar{\nu}_\mu)}{\mathcal{B}(W\to e\bar{\nu}_e)}=0.993\pm0.019$$

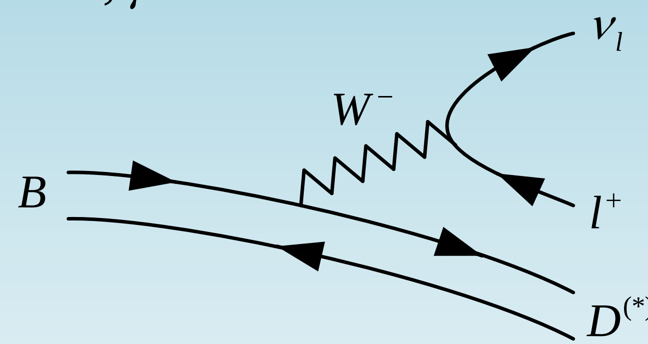
$$\left.\begin{aligned}\frac{\mathcal{B}(W\to\tau\bar{\nu}_\tau)}{\mathcal{B}(W\to e\bar{\nu}_e)}&=1.063\pm0.027\\ \frac{\mathcal{B}(W\to\tau\bar{\nu}_\tau)}{\mathcal{B}(W\to\mu\bar{\nu}_\mu)}&=1.070\pm0.026\end{aligned}\right\}2\sigma$$

LFU test on B mesons



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

$l = e, \mu$



Exp.	Channel	τ reconstruction	Deviation from SM
BaBar 2012	$\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu}_l)$	$\tau \to l\nu\bar{\nu}$	$+3.4\sigma$
Belle 2015	$\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu}_l)$	$\tau \to l\nu\bar{\nu}$	$+1.8\sigma$
LHCb 2015	$\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$	$\tau \to \mu\nu\bar{\nu}$	$+2.1\sigma$
Belle 2016	$\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)$	$\tau \to l\nu\bar{\nu}$	$+1.6\sigma$
Belle 2017.5	$\mathcal{B}(\bar{B} \to D^{*}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{*}l^-\bar{\nu}_l)$	$\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau$	$<1\sigma$
LHCb 2017.8	$\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$	$\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$	$+1.0\sigma$

Semileptonic B decay in LHCb: Difficulties

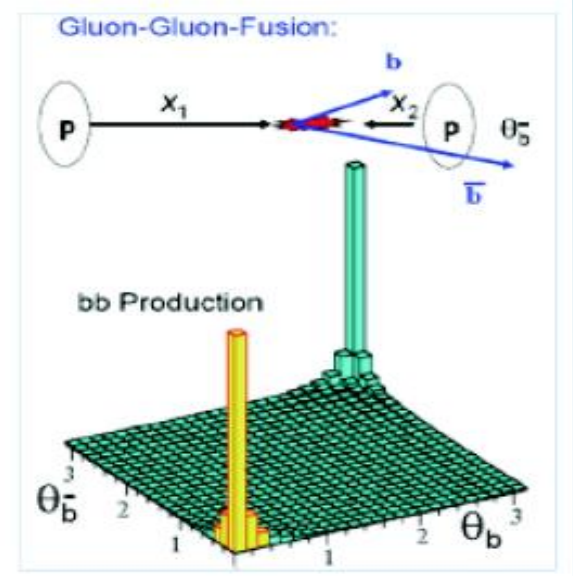
LHCb2015 Muonic decay: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau, \tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$

LHCb2017 Muonic decay: $B_c^+ \to J/\psi\tau^+\bar{\nu}_\tau, \tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu$

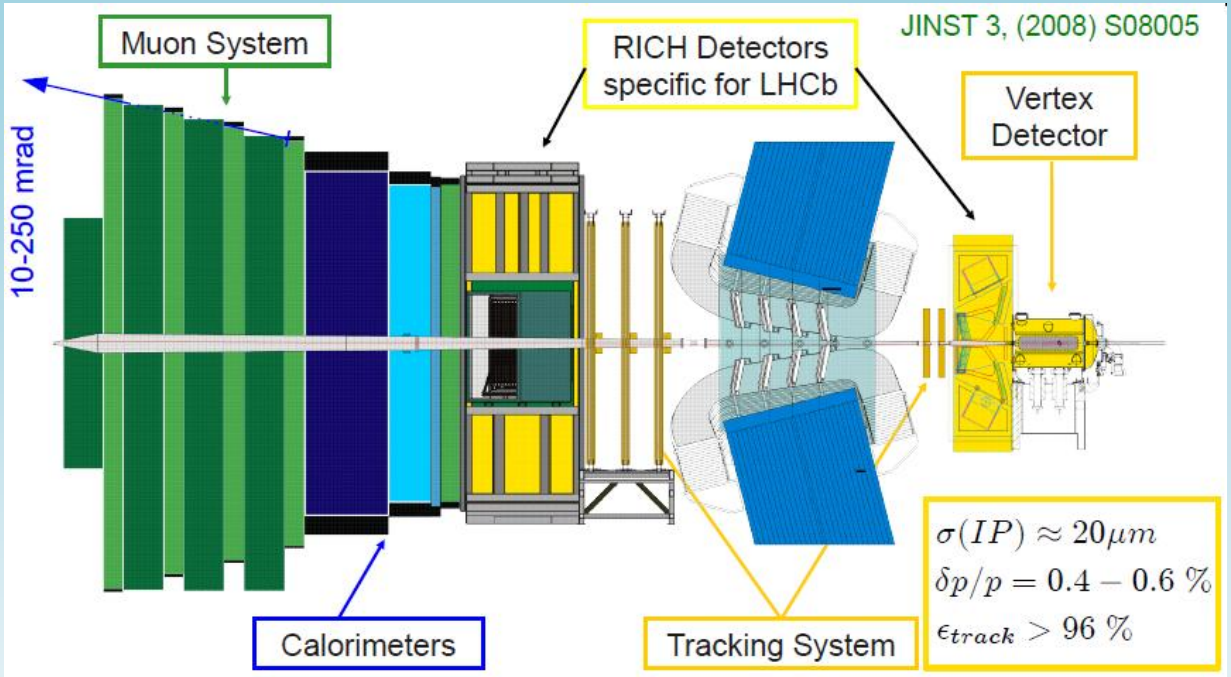
LHCb2017 Hadronic decay: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau, \tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

Difficulties:

- No center mass constrain, no tag side, neutrinos.
  - Partial rec. mass peak washed out.
- Main background: partial reconstructed B decays.
  - $B \to D^{**}l\nu$ as D^*side background.
  - $B \to D^* D_{(s)}^{(\pm 0*)}$ as τ side background.

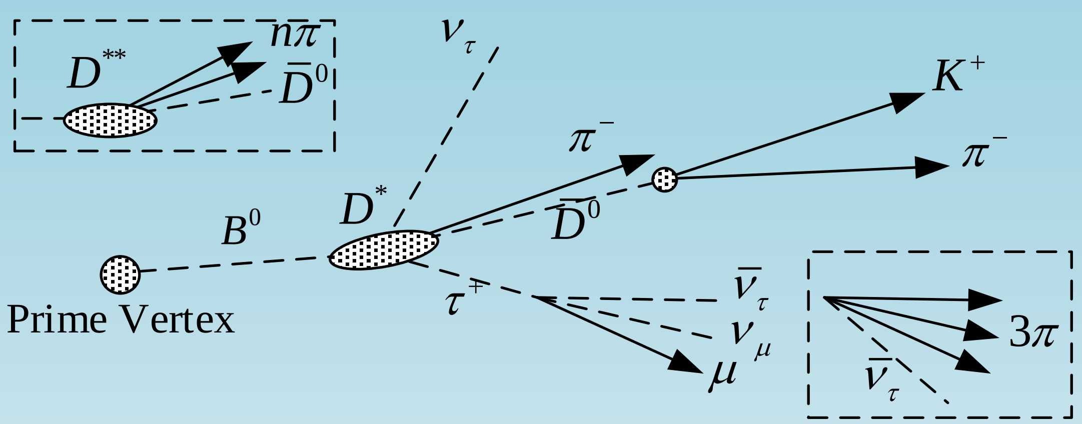


Keys: LHCb detector



- Exellent vertexing and tracking
  - Prime vertex & secondary vertex separation
  - decay time, length, angle…
- High efficiency for muon, D trigger.

Analysis methods for LFU test



Solution:

- Precise secondary vertex reconstruction and correction.
  - Soft π for D*, $\pi^-\pi^+\pi^-$ for τ decay vertex.
- B flight direction → approximation to rest frame kinematics.

$$\frac{(p_B)_z}{m_B} \simeq \frac{(p_{visible})_z}{m_{visible}} \rightarrow |p_B| = (p_B)_z\sqrt{1+\tan^2\alpha}$$

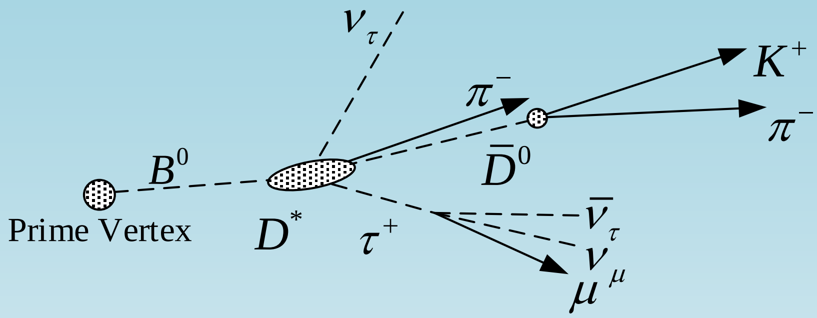
- Isolation method for reconstructed candidates.
  - Signal hadrons are isolated, BGs' are not.

$R(D^*)$ with tau leptonic decay

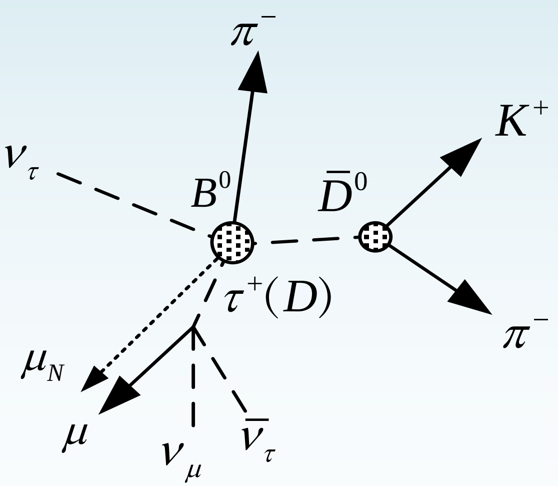
Phys. Rev. Lett. 115, 111803 (2015)

$R(D^*)$ with tau leptonic decay

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}, \begin{cases} \tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu \\ D^{*+} \to D^0\pi^+ \\ D^0 \to K^-\pi^+ \end{cases}$$



- Theoretically clean due to cancellation of form factor uncertainties.
- Large, well measured BF
  - $\mathcal{B}(\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu) = (17.41 \pm 0.04)\%$
- Three dimensional template fit: in B rest frame
  - Muon energy. E_μ^*
  - Missing mass square. $m_{miss}^2 = (p_B^\mu - p_{D*}^\mu - p_l^\mu)^2$
  - Transferred 4-momentum square. $q^2 = (p_B^\mu - p_{D*}^\mu)^2$



signal & D^*D

soft E_μ^*

larger $q^2 \to m_{miss} > 0$

Normalization CH

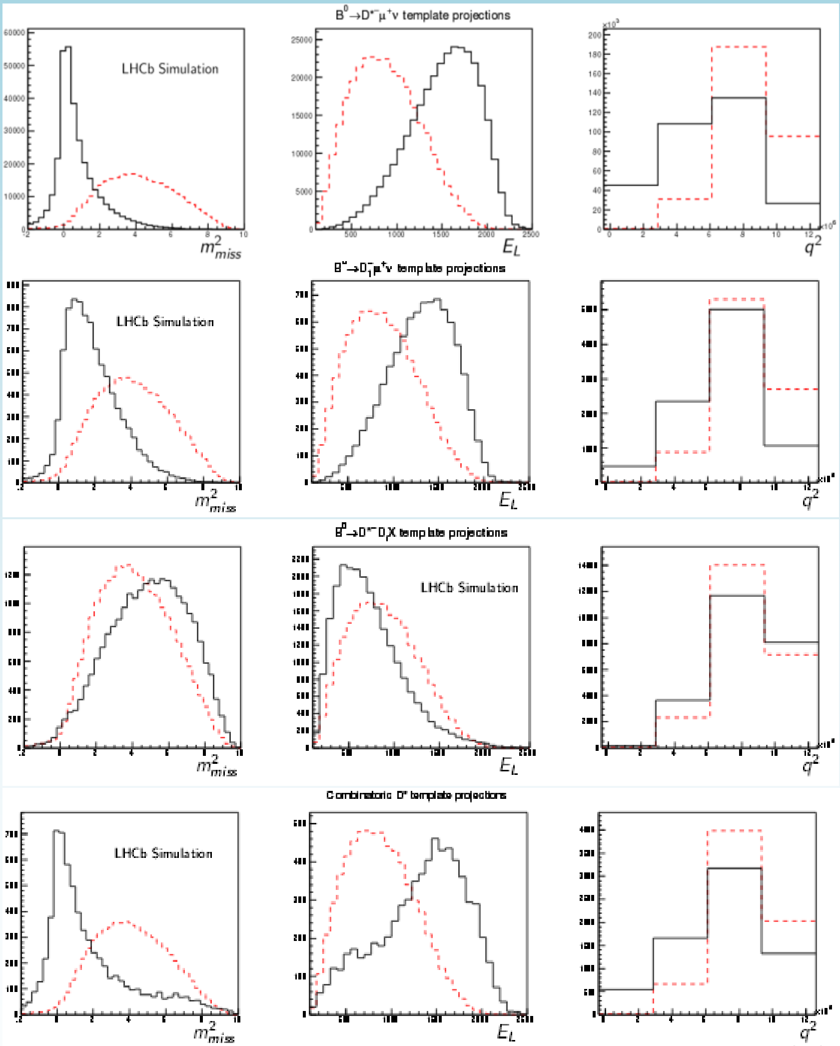
hard E_μ^*

Average $q^2 \to m_{miss} \approx 0$

Phys. Rev. Lett. 115, 111803 (2015)

$R(D^*)$ with tau leptonic decay

m^2_{miss} E^*_μ q^2



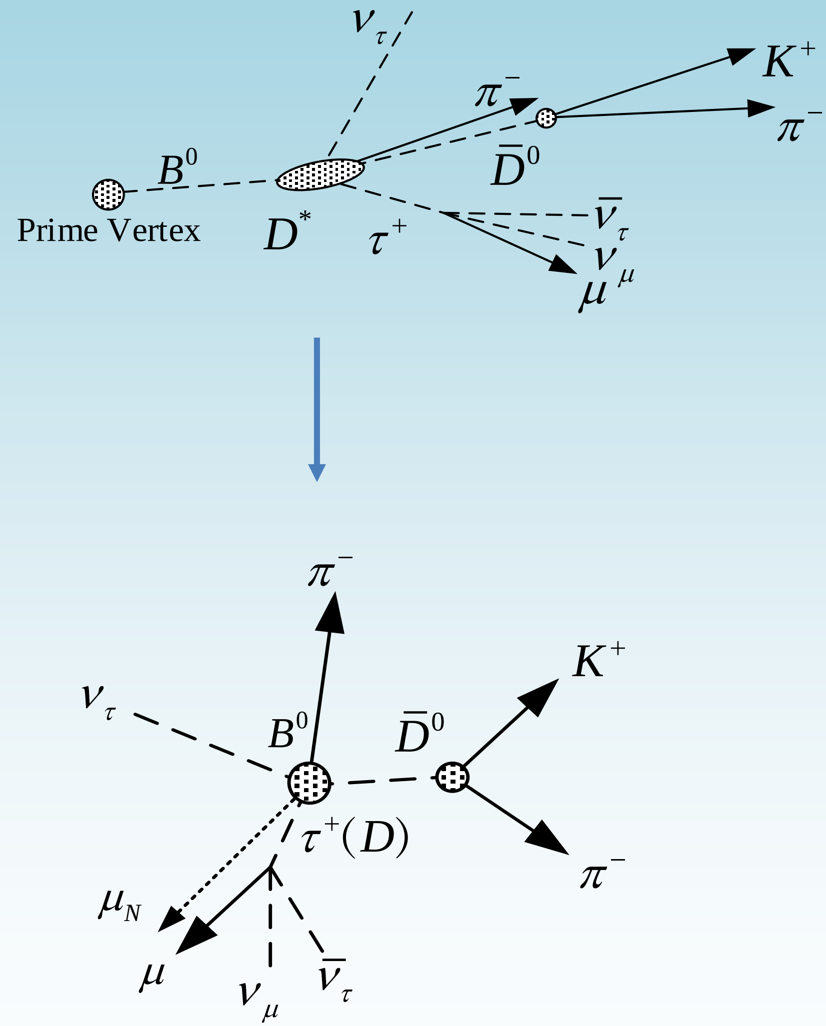
Normalize

Signal

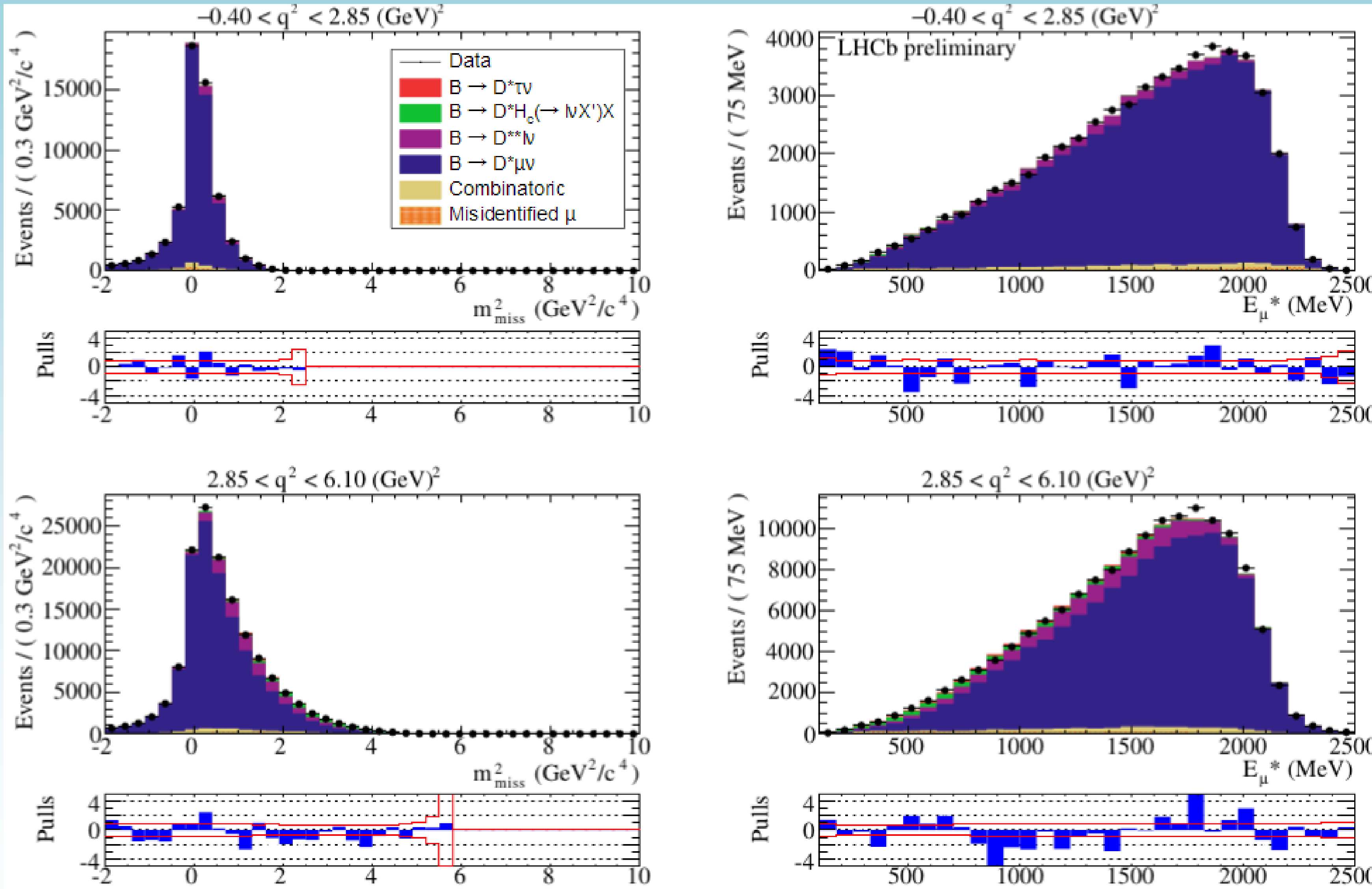
D**lv

D*D

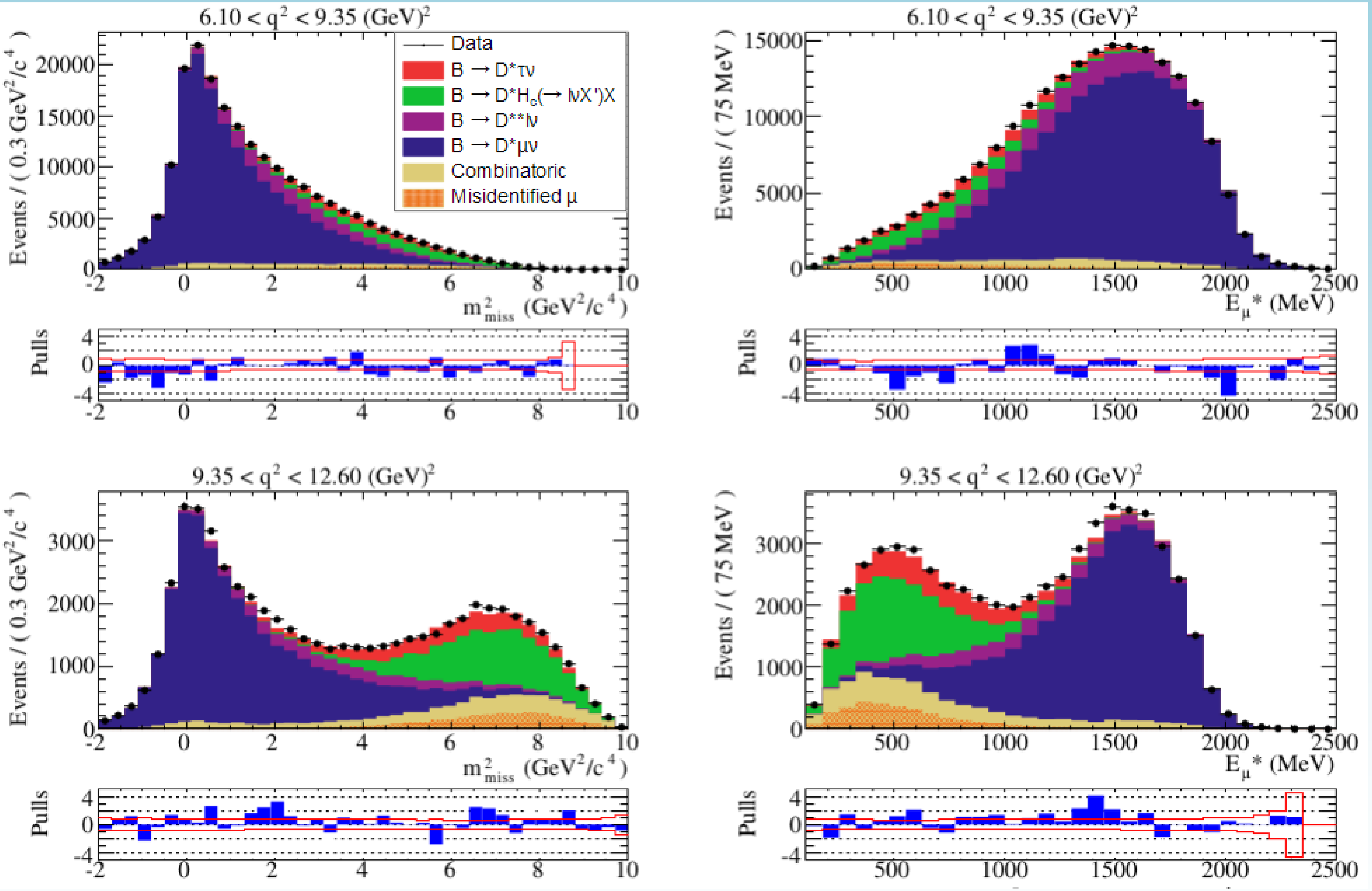
Comb.



Leptonic $R(D^*)$ 3D fit result: small q^2

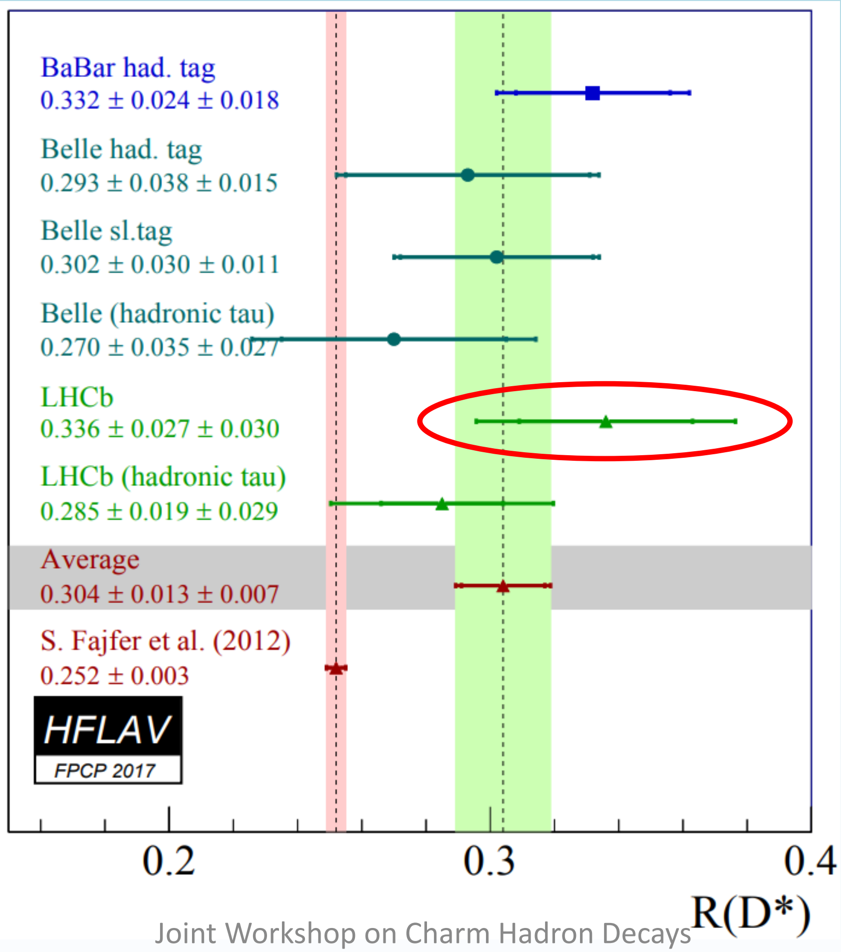


Leptonic $R(D^*)$ 3D fit result: large q^2



$R(D^*)$ - leptonic tau result

- Using LHC 3.0fb^{-1} data in 2011 & 2012 @ 7TeV & 8TeV
- $\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$, 2.1σ larger than prediction.

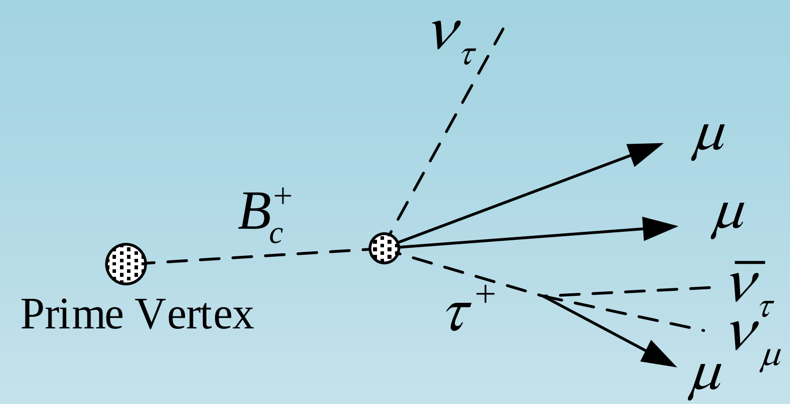


$R(J/\psi)$ with tau leptonic decay

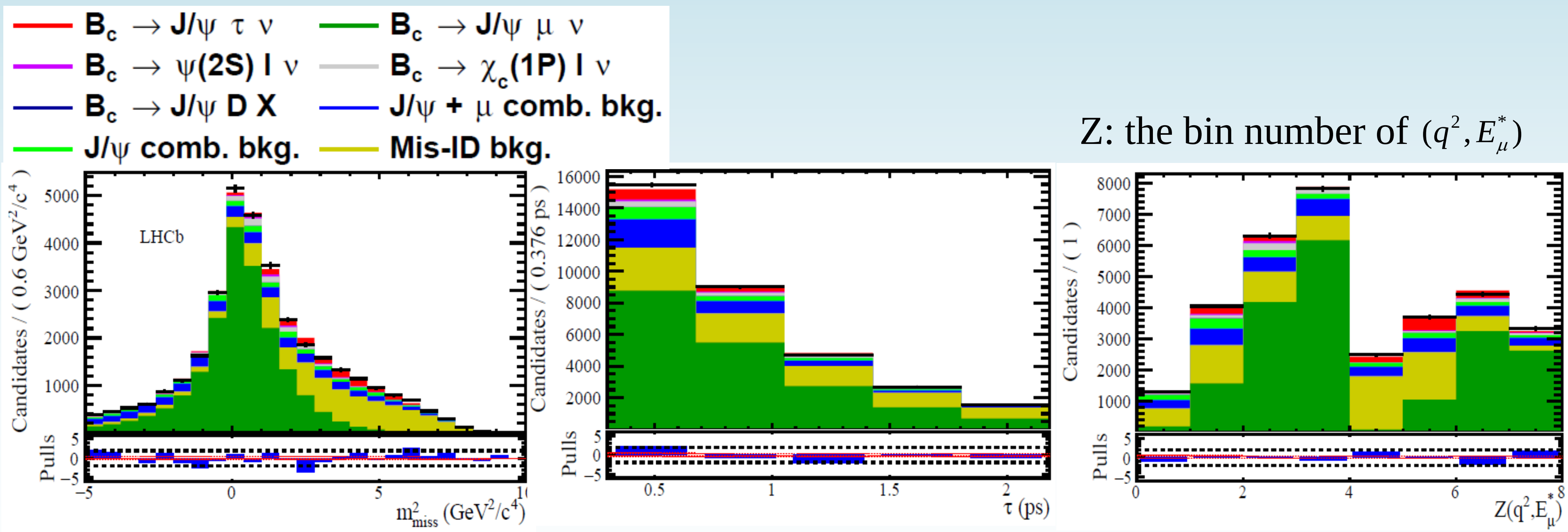
$R(J/\psi)$ with tau leptonic decay

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}, \begin{cases} \tau^+ \to \mu^+ \bar{\nu}_\tau \nu_\mu \\ J/\psi \to \mu\mu \end{cases}$$

- Same methods as $R(D^*)$
- Bc decay time $\tau(B_c) < \tau(B_{u,d,s})$

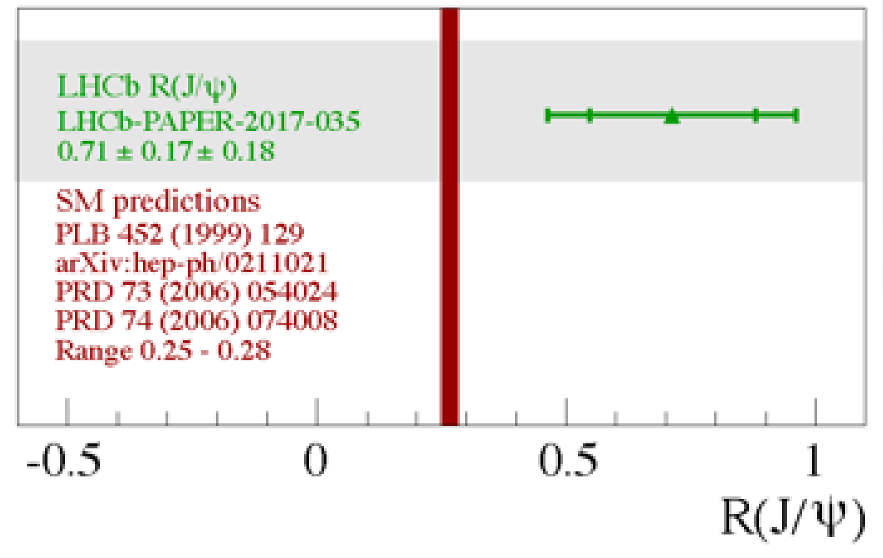


Z: the bin number of (q^2, E_μ^*)



$R(J/\psi)$ with tau leptonic decay

- Using LHC 3.0fb^{-1} data in 2011 & 2012 @ 7TeV & 8TeV.
- Evidence for $B_c^+ \to J/\psi \tau^+ \nu_\tau$ at a significance of 3σ.
- $\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$,
  2σ higher than prediction under SM framework: 0.25~0.28.



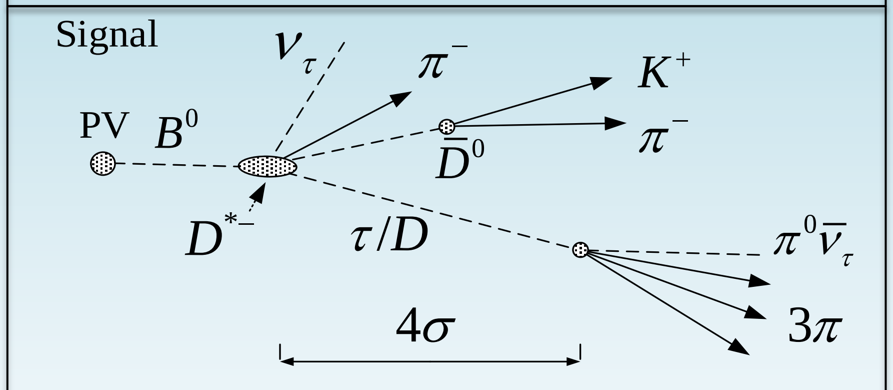
$R(D^*)$ with tau hadronic decay

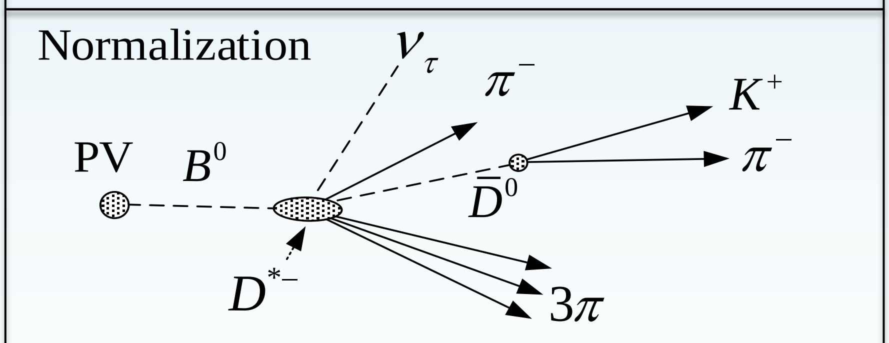
arXiv:1708.08856v1, submitted to PRL

$R(D^*)$ with tau hadronic decay

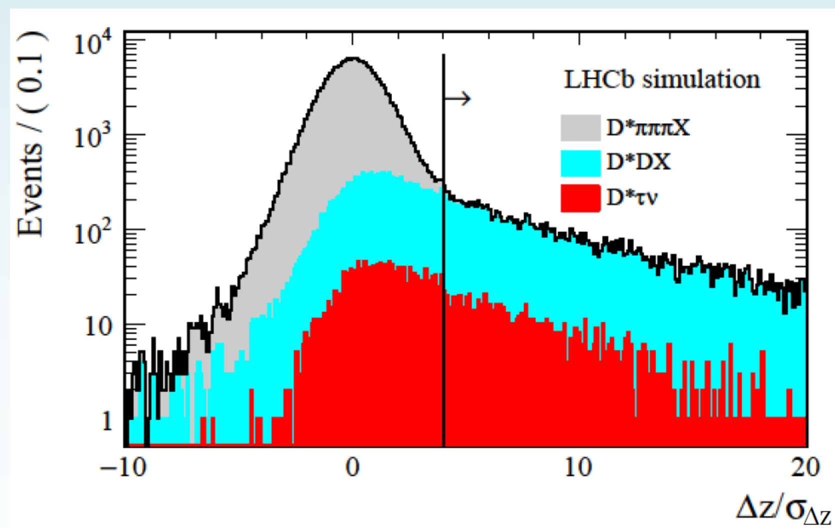
$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \qquad \begin{cases} \tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau \\ D^{*+} \to D^0\pi^+ \\ D^0 \to K^-\pi^+ \end{cases}$$

$$= \frac{\overbrace{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}^{\text{Signal}}}{\underbrace{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}_{\text{Normalization}}} \times \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$





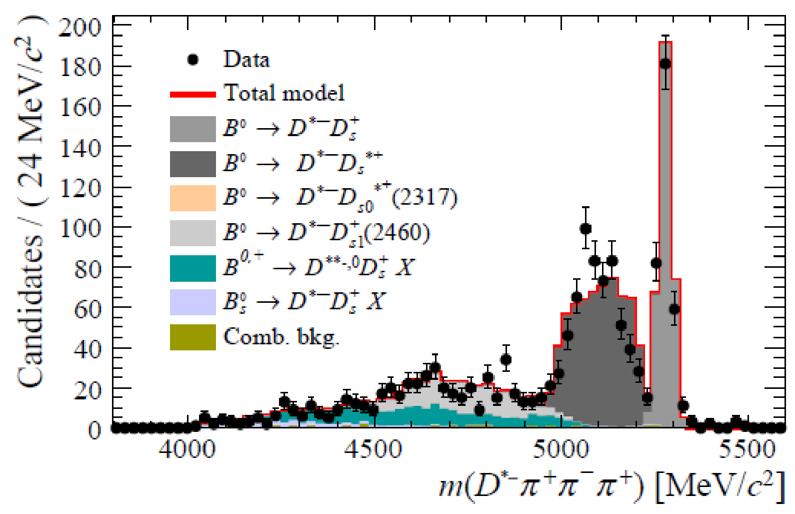
- $B \to D^*3\pi$ as normalization channel, rest with high precision.
- With a detached 3π vertex cut,
  - $D3\pi$ restrained(10^3 suppression),
  - 35% signal efficiency,
  - double charm remaining.

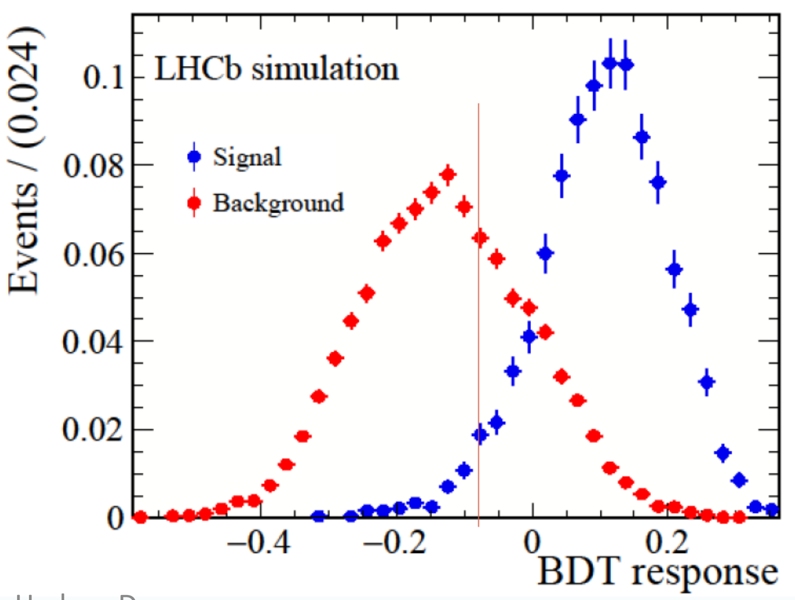


$R(D^*)$ with tau hadronic decay double charm rejection

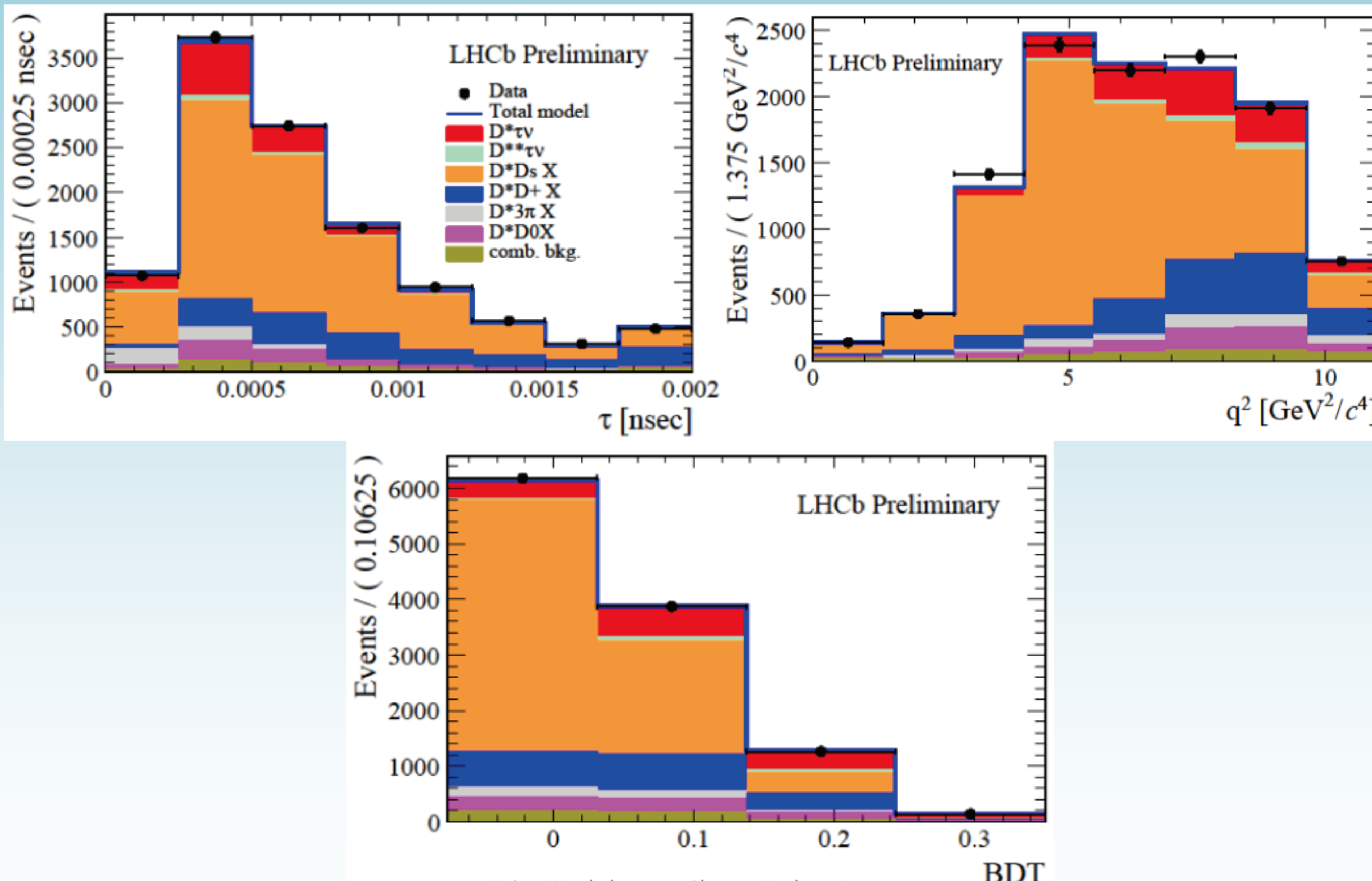
$$X_b \to D^{*-} D^0 X : 0.2 \times \text{signal}$$
$$X_b \to D^{*-} D^+ X : 1 \times \text{signal}$$
$$X_b \to D^{*-} D_s^+ X : 10 \times \text{signal}$$

- The BG leads to nice mass peak and not the signal
- Train a BDT with variables sensitive to
  - Additional neutral energy
  - Different resonant structure of 3π system.

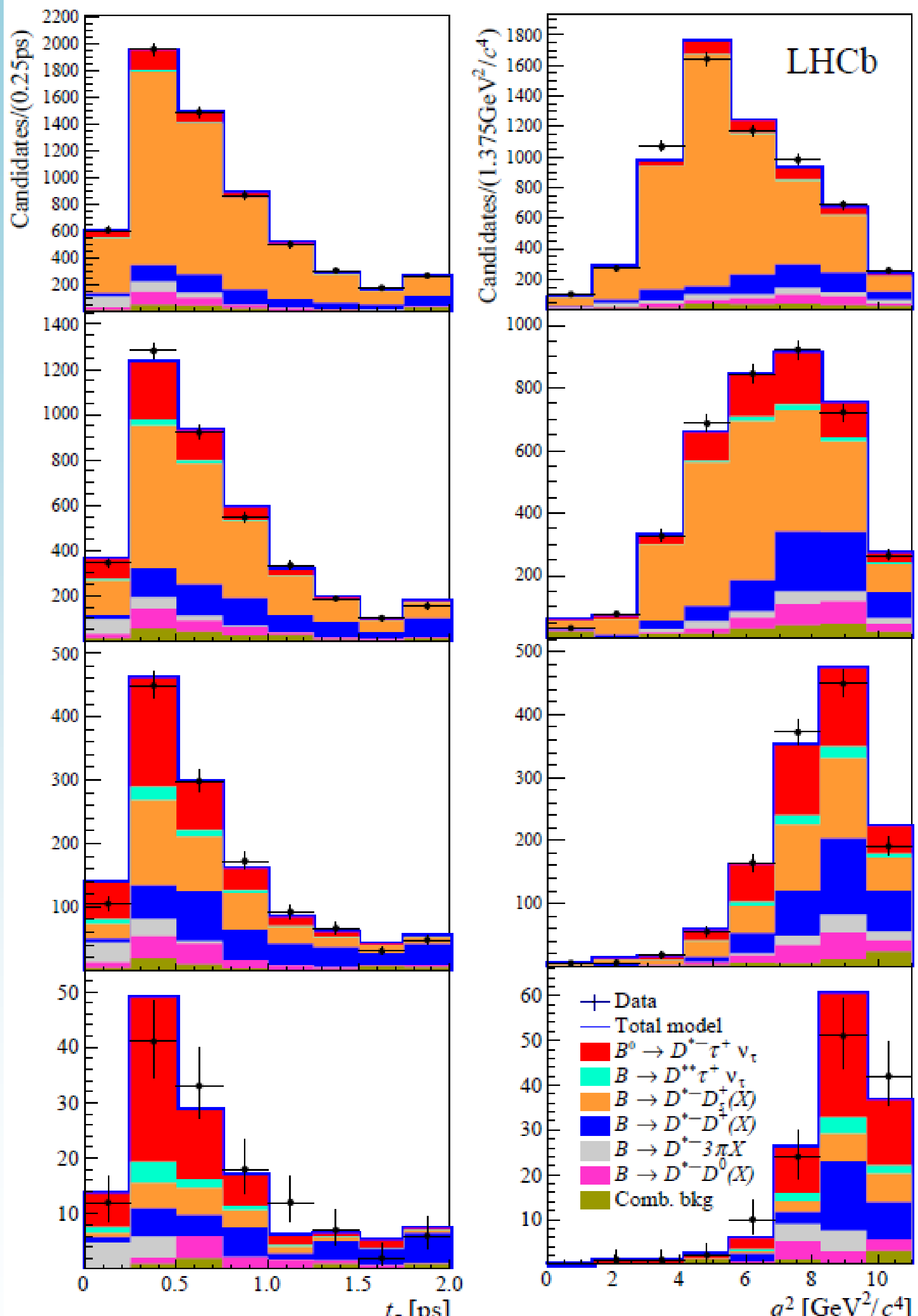




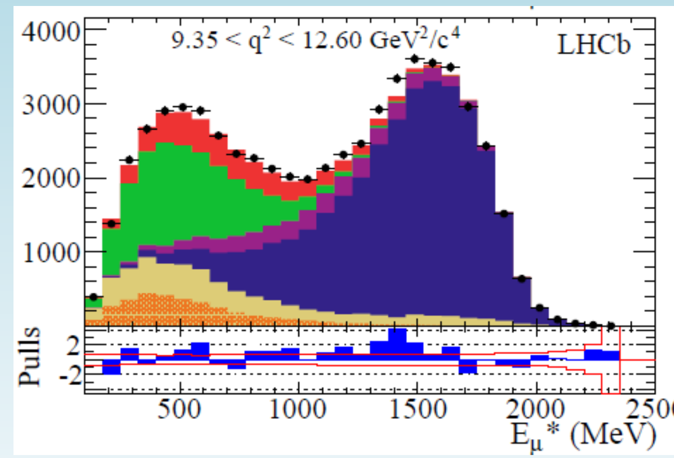
Hadronic $R(D^*)$ 3D fit result

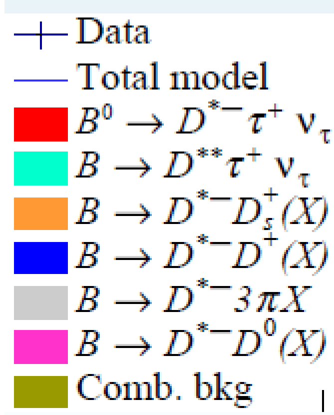


Hadronic $R(D^*)$
Fit result divided by BDT bins



Hadronic rec. method can lead to high purity samples, comparing to muonic one.





$R(D^*)$ hadronic tau result

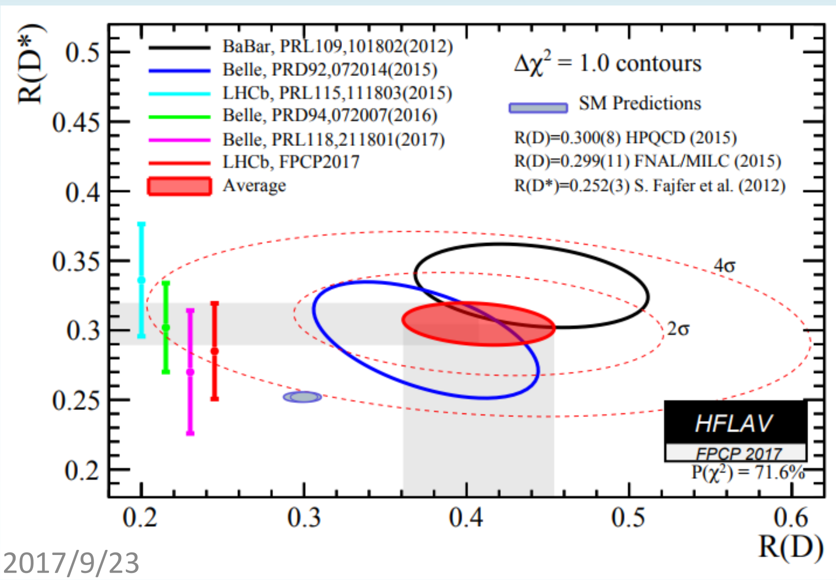
Using LHC 3.0fb^{-1} data in 2011 & 2012 @ 7TeV & 8TeV.

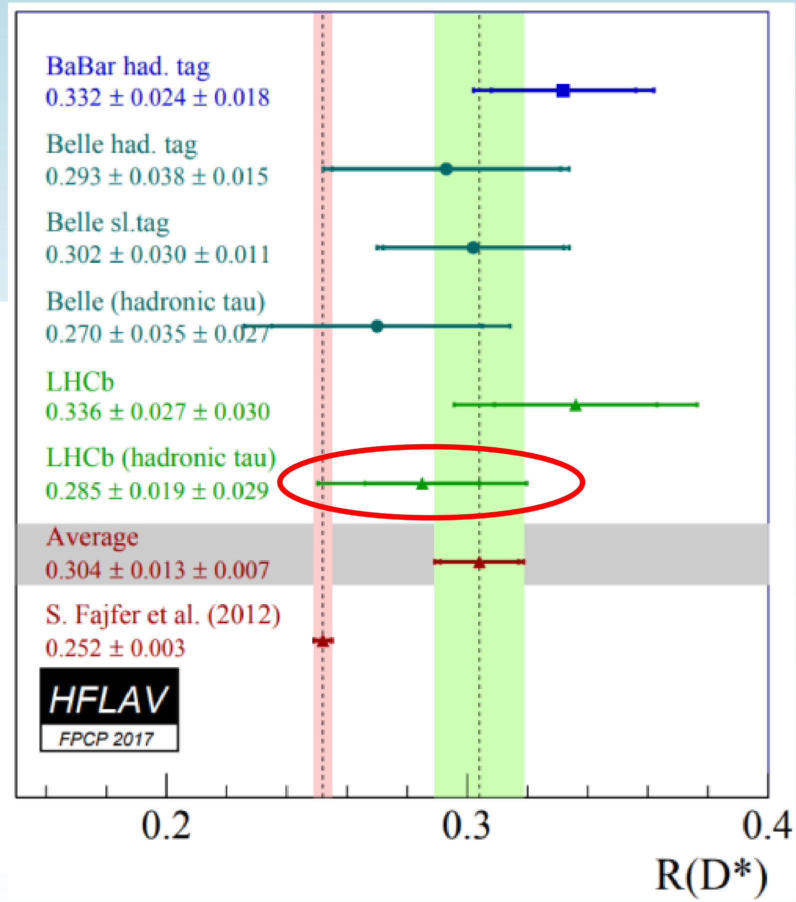
$$\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)} = 1.93 \pm 0.13_{stat} \pm 0.17_{syst}$$

$R(D^{*-}) = 0.285 \pm 0.019_{stat} \pm 0.025_{syst} \pm 0.13_{ext}$, 1.0σ higher than prediction.

World average $R(D^*)$=0.304 ± 0.015, 3.4σ above prediction.

$R(D)$ *and* $R(D^*)$ give 4.1σ above prediction.

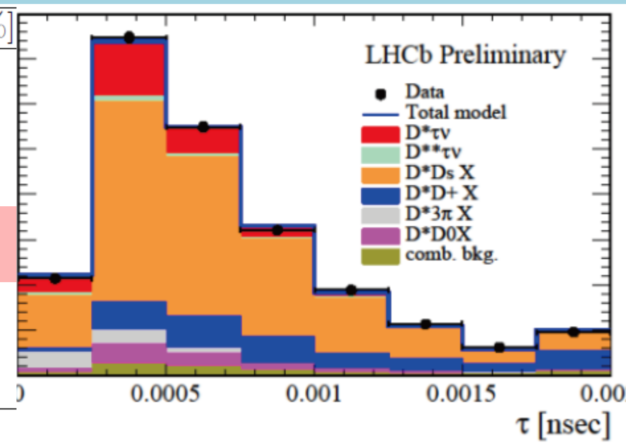




Prospect & cooperation

More precise branch ratio

Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

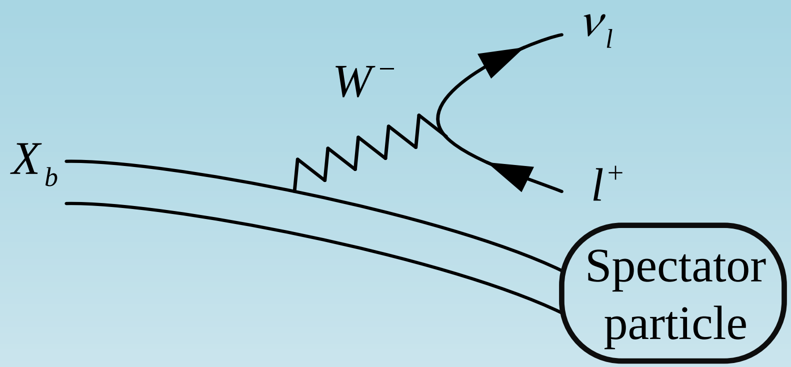


- $D_s \to 3\pi X$ has large BR(~25%)
  - $D_s \to (\eta/\eta'/\phi/\omega)(\pi/\rho)X$
    $(K^0\eta\eta'\omega...)3\pi$
  - We do not have precise BR for all of these.

Need Your Help!

- $D^+ \to K3\pi\pi^0$ is poorly known, the inclusive BR not measured.
- For all these D decays, contacts have been established with BESIII collaboration to measure these numbers.

Other LFU SL researches in LHCb



Muonic channel:

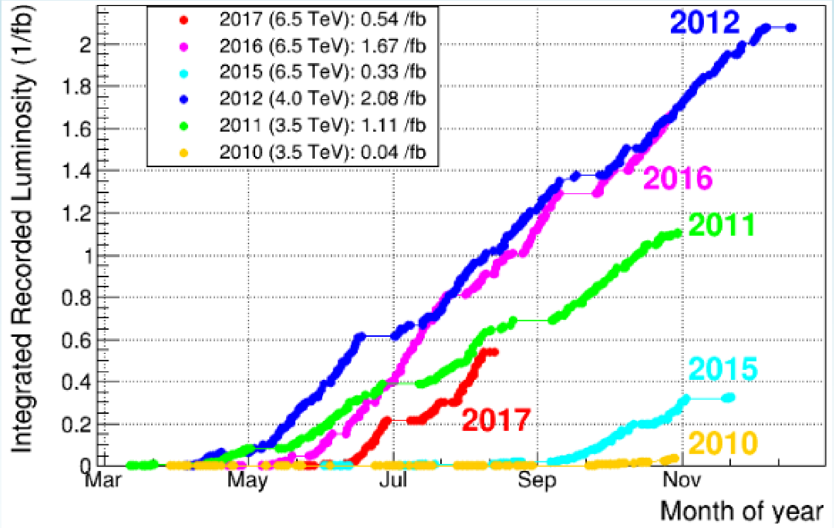
$R(D), R(D_s), R(\Lambda_c^*)$

Hadronic channel:

$R(D), R(J/\psi), R(\Lambda_c), R(D_s)$

Light lepton:

$$R_{unnamed} = \frac{B \to D^{(*)} e\nu \,/\, B \to D^{(*)} \mu\nu}{D^0 \to K e\nu \,/\, D^0 \to K \mu\nu}$$



Conclusion

- Semileptonic B decays are good probe to new physics:
  - High SM precision, high rate and high sensitivity
- Due to LHCb excellent vertex reconstruction capabilities, LFU test on $\mathcal{R}(D^*), \mathcal{R}(J/\psi)$, with τ leptonic and hadronic decay.
- World average exceed prediction by 3.4σ and 2σ deviation in $\mathcal{R}(D^*)$ and $\mathcal{R}(J/\psi)$.
- We need more knowledge on Ds, D^0, D^+ to $3\pi X$ decays, and LHCb run II data, to have more preciously measurement.

中国科学院大学
University of Chinese Academy of Sciences

LHCb

Thank you !