Status and prospects for lepton universality tests in $b \to c\ell\nu$ decays

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on behalf of the LHCb collaboration

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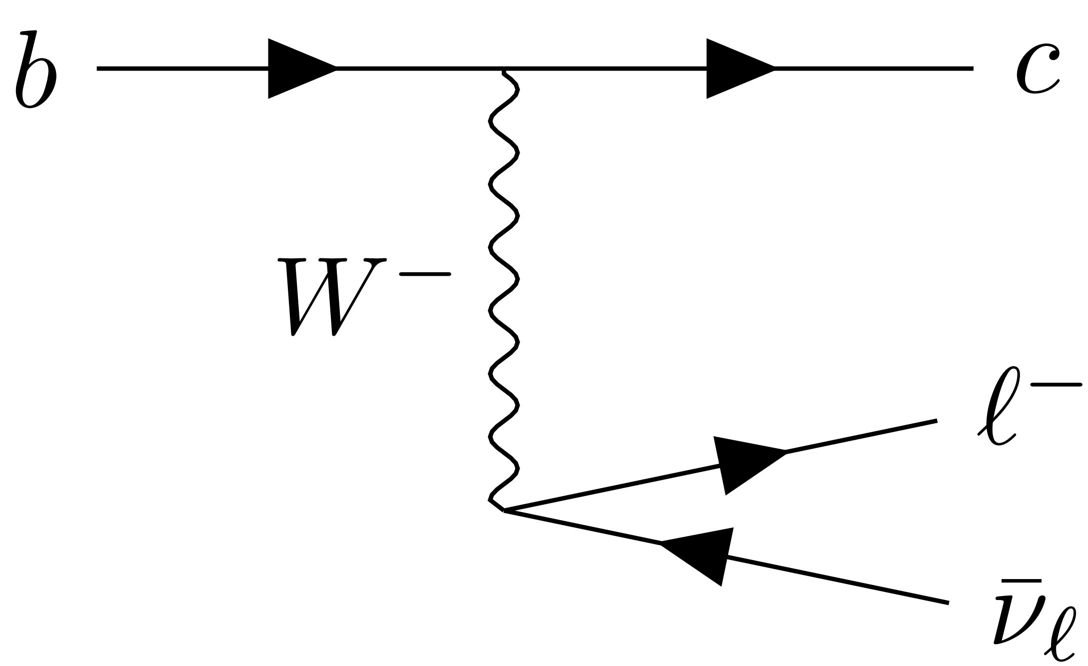
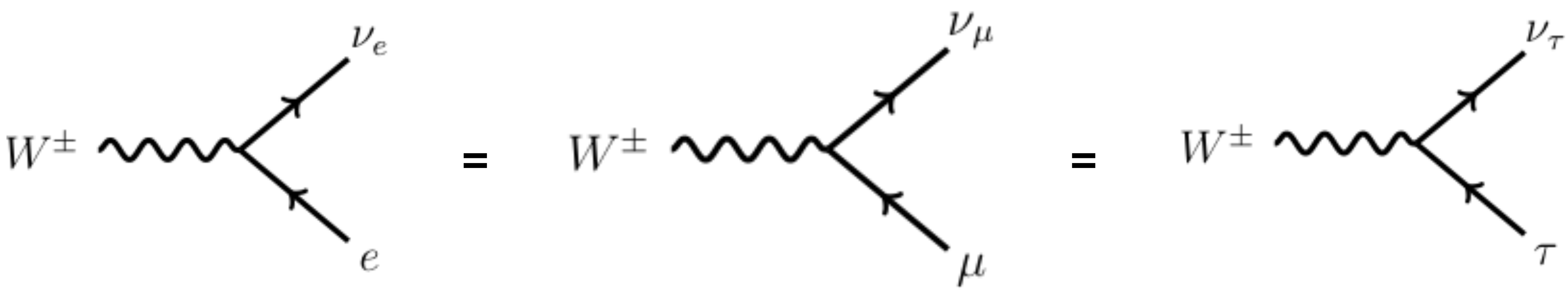
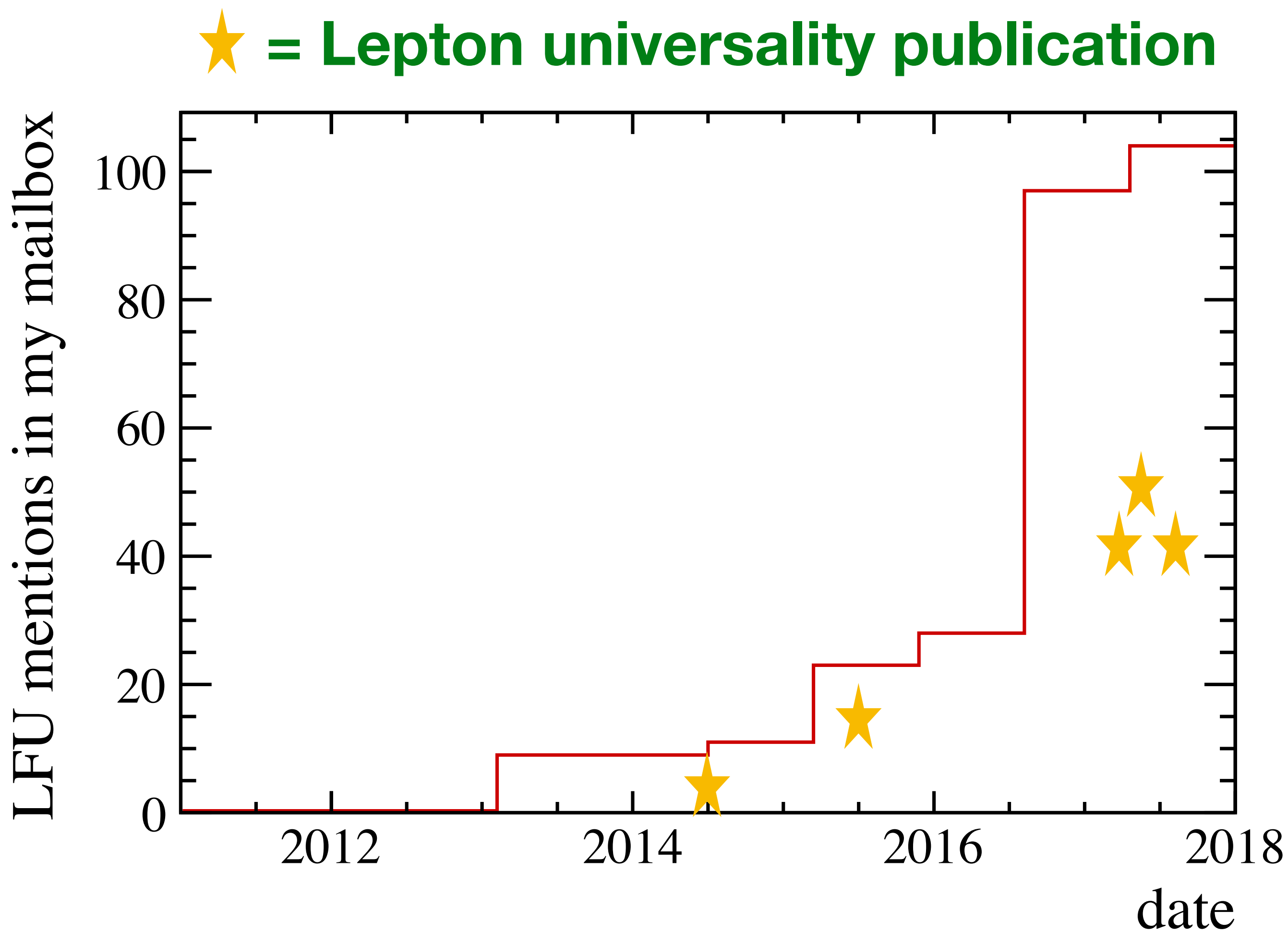
The most common B decay



$\ell^+ \nu_\ell$ anything	[1]	$(10.33 \pm 0.28)\%$
$e^+ \nu_e X_c$		$(10.1 \pm 0.4)\%$
$D \ell^+ \nu_\ell$ anything		$(9.2 \pm 0.8)\%$
$D^- \ell^+ \nu_\ell$	[1]	$(2.19 \pm 0.12)\%$
$D^- \tau^+ \nu_\tau$		$(1.03 \pm 0.22)\%$
$D^*(2010)^- \ell^+ \nu_\ell$	[1]	$(4.93 \pm 0.11)\%$
$D^*(2010)^- \tau^+ \nu_\tau$		$(1.67 \pm 0.13)\%$
$\overline{D}^0 \pi^- \ell^+ \nu_\ell$		$(4.3 \pm 0.6) \times 10^{-3}$
$D_0^*(2400)^- \ell^+ \nu_\ell , D_0^{*-} \to \overline{D}^0 \pi^-$		$(3.0 \pm 1.2) \times 10^{-3}$
$D_2^*(2460)^- \ell^+ \nu_\ell , D_2^{*-} \to \overline{D}^0 \pi^-$		$(1.21 \pm 0.33) \times 10^{-3}$
$\overline{D}^{(*)} n \pi \ell^+ \nu_\ell$ ($n \geq 1$)		$(2.3 \pm 0.5)\%$

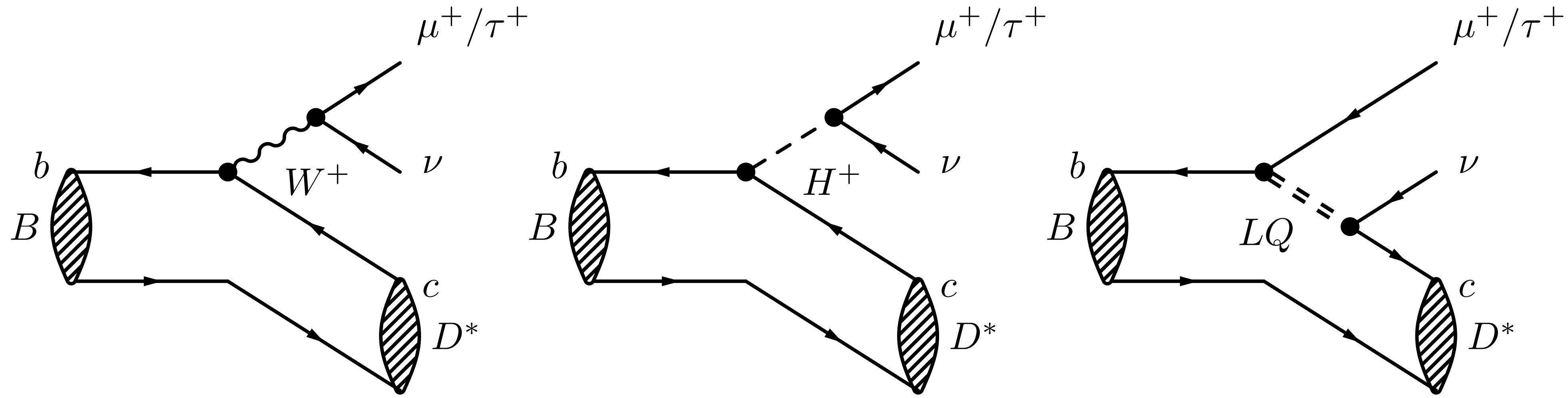
Lepton universality





$b \to c\ell\nu$ decays and R(D*)

- $b \to c\ell\nu$ decays can be factorised, greatly simplifying theoretical calculations.



- Lepton universality ratios further cancel theoretical uncertainties.

- The lepton universality ratio, R(D*), is sensitive to any NP model coupling preferentially to third generation leptons.

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

Who has made measurements

- Three experiments have made measurements

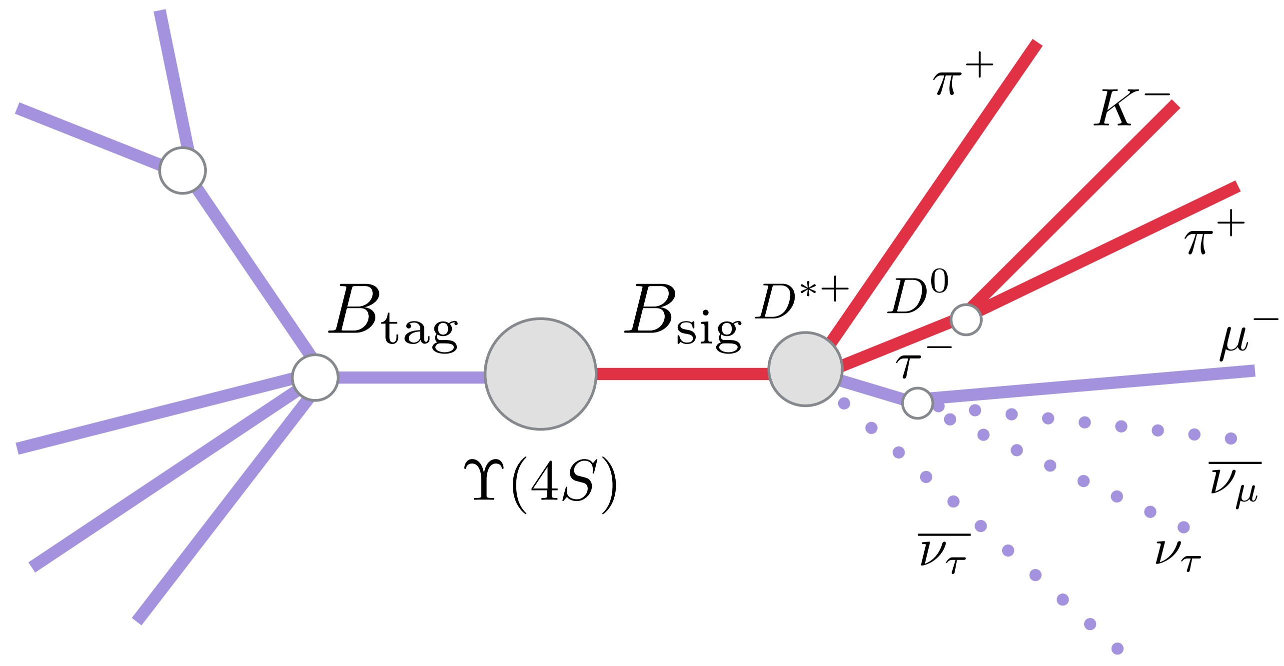
	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \to B\bar{B}$	$\Upsilon(4S) \to B\bar{B}$	$pp \to gg \to b\bar{b}$
Publications	Phys.Rev.Lett 109, 101802 Phys. Rev. D 88, 072012	Phys.Rev.D 92, 072014 Phys. Rev. D 94, 072007 Phys. Rev. Lett. 118, 211801	Phys.Rev.Lett.115, 111803 Phys. Rev. Lett. 120, 171802 Phys. Rev. D 97, 072013

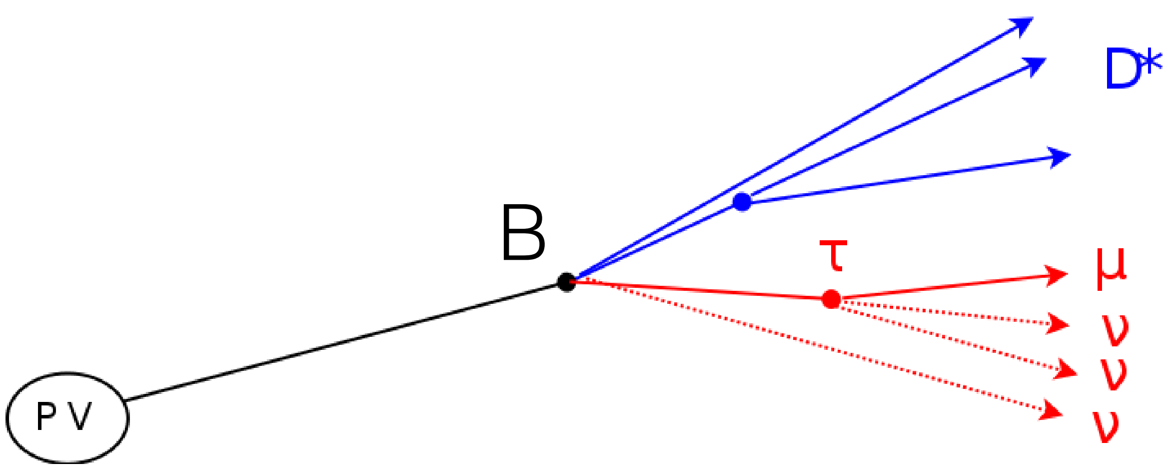
* during run 1 of the LHC

Experimental challenges

- At least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$).
    - No sharp peak to fit in any distribution.

- At B-factories, can control this using ‘tagging’ technique.





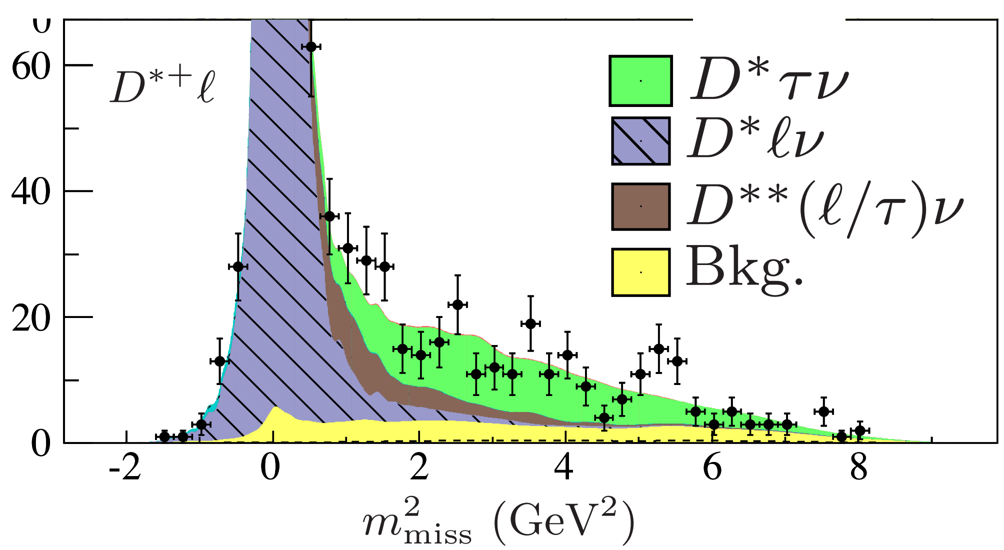
- More difficult at LHCb, compensate using large boost (flight information) and huge B production.

Signal fits

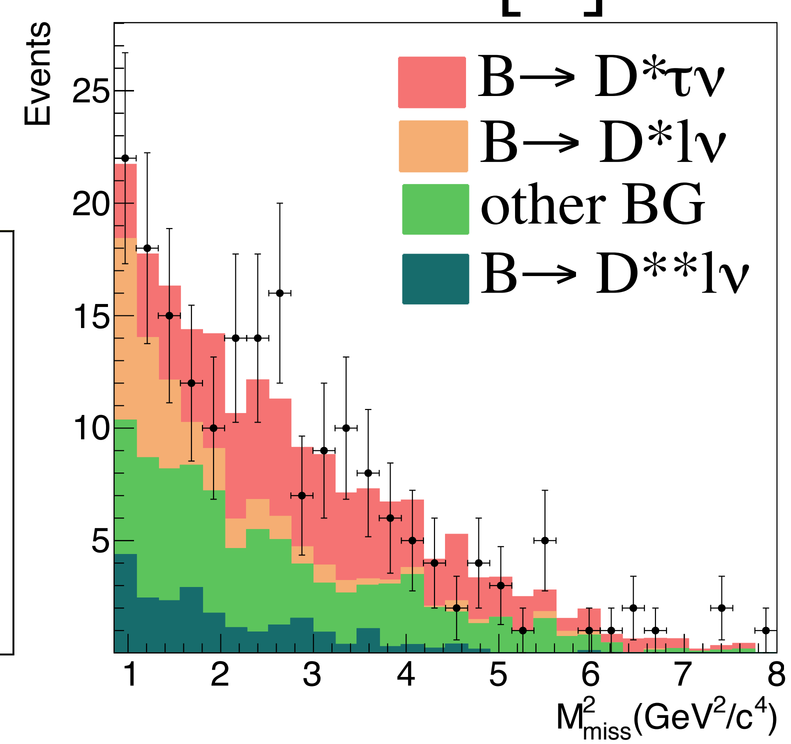
- Three main backgrounds:

$$B \to D^* \ell \nu$$
$$B \to D^{**} \ell \nu$$
$$B \to D^* D X$$

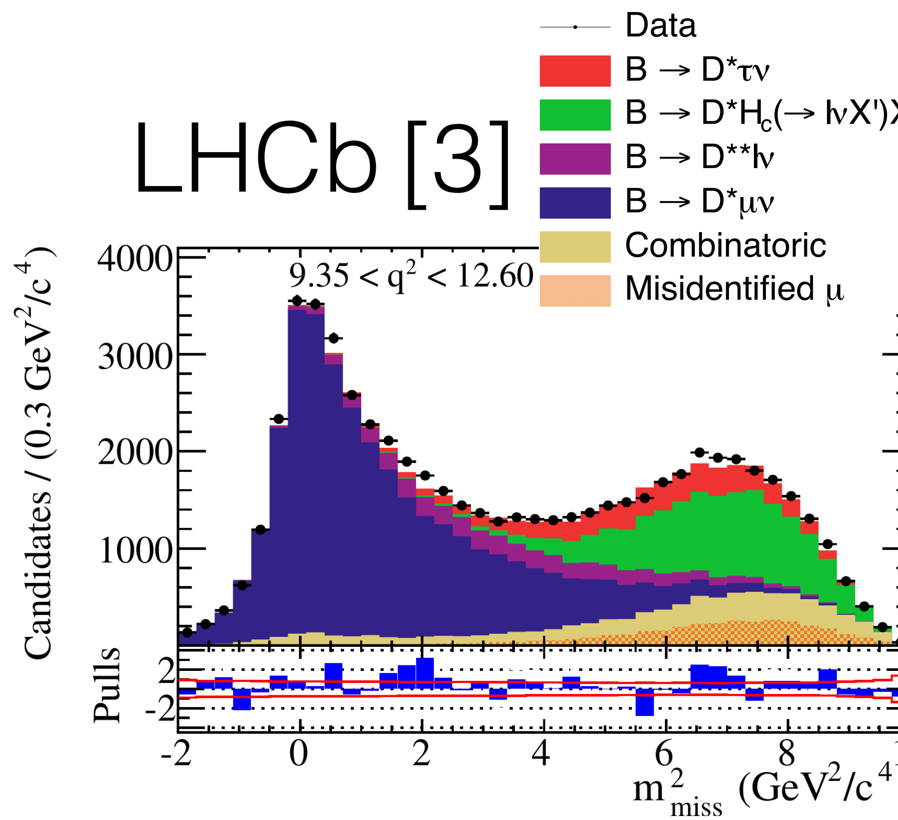
BaBar [1]



Belle [2]



LHCb [3]



- Fit variables which discriminate between muon and tauonic mode.

[1] Phys. Rev. D 88, 072012 (2013)

[2] Phys.Rev.D 92, 072014 (2015)

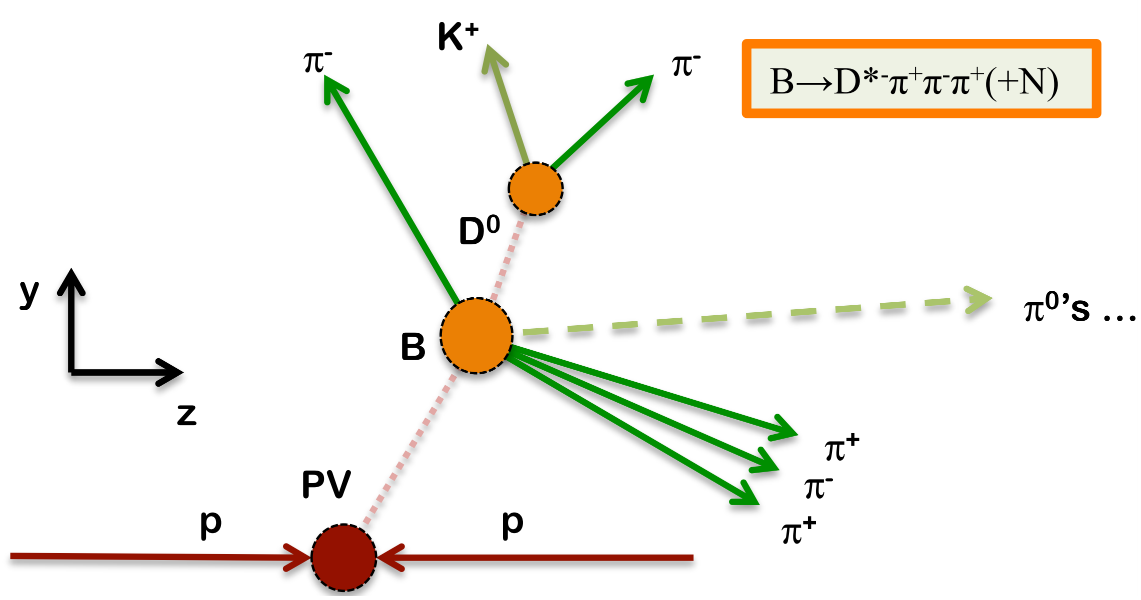
[3] Phys.Rev.Lett.115, 111803 (2015)

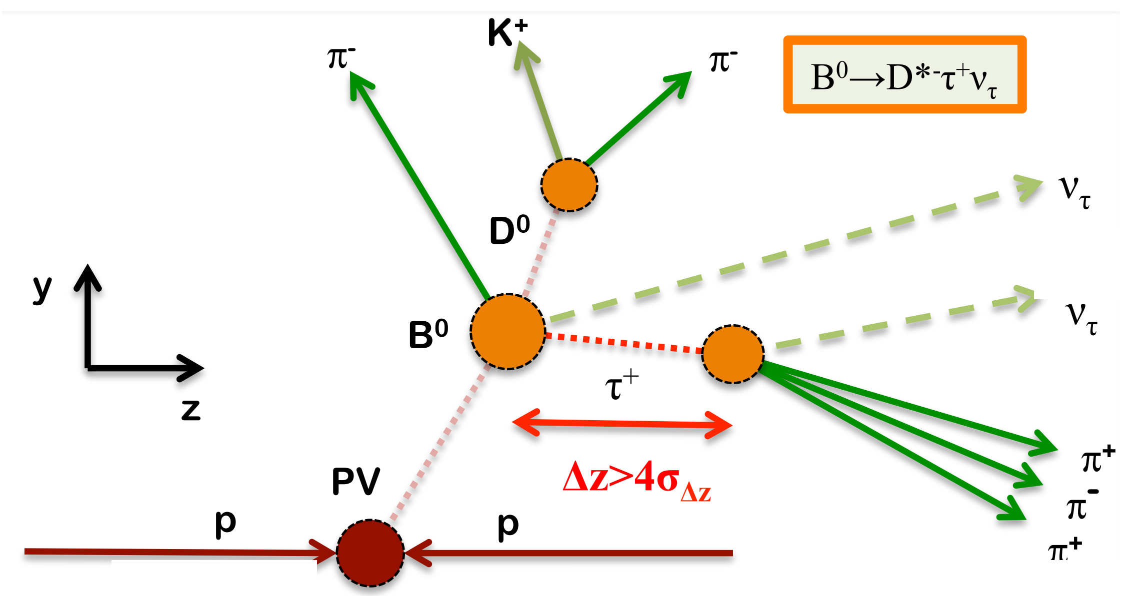
Latest LHCb measurement

Phys. Rev. Lett. 120, 171802 + Phys. Rev. D 97, 072013

- First measurement with $\tau^+ \to \pi^+\pi^-\pi^+ X$ decays.
  - No background from $B \to D^{*(*)}\ell\nu$.
- Normalise signal yield to decay $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

$$\boxed{K_{had}(D^*) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}} = \frac{N(B^0 \to D^{*-}\tau^+\nu_\tau)}{N(B^0 \to D^{*+}\pi^-\pi^+\pi^-)} \times \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau)} \times \frac{\varepsilon(B^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\varepsilon(B^0 \to D^{*-}\tau^+\nu_\tau)}$$

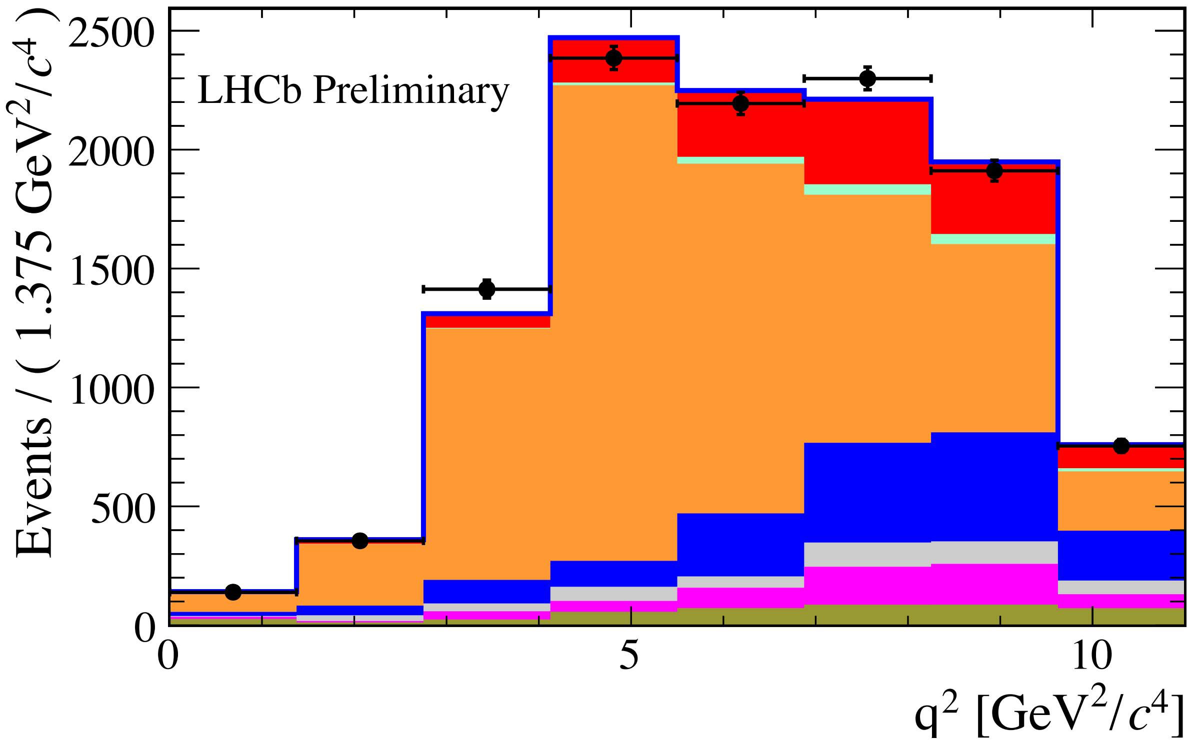


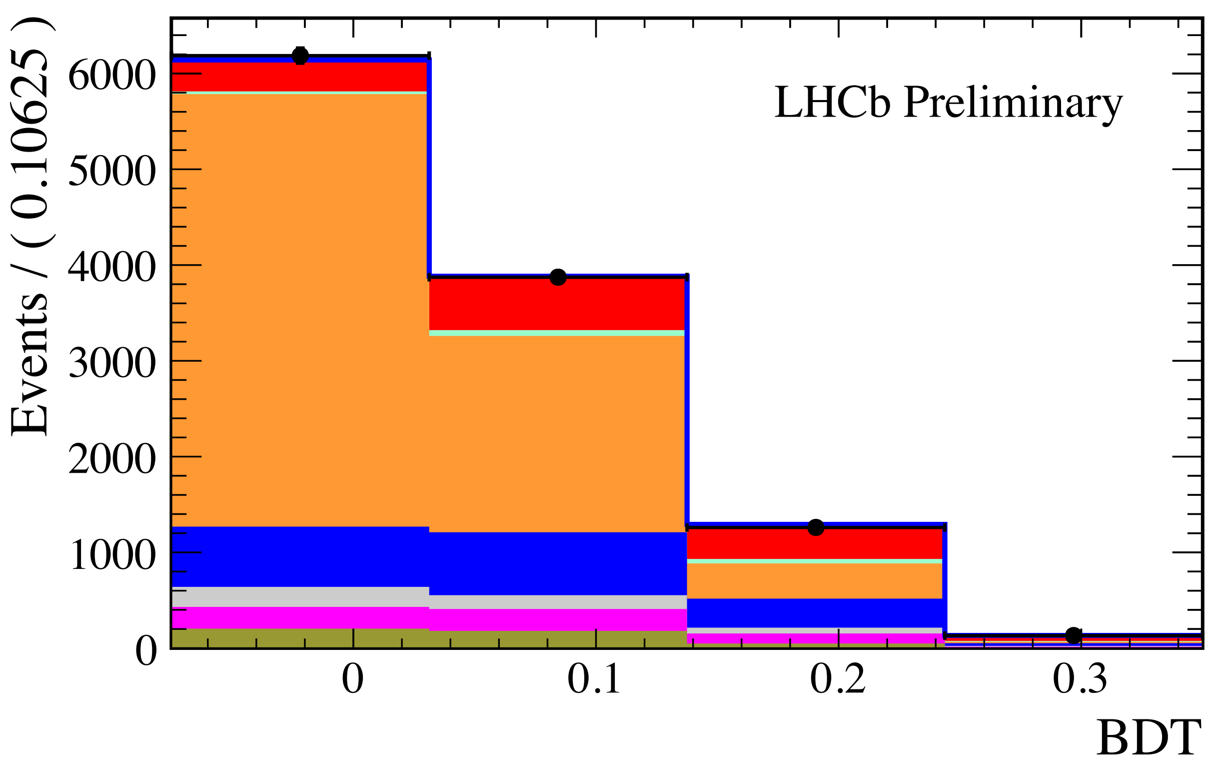


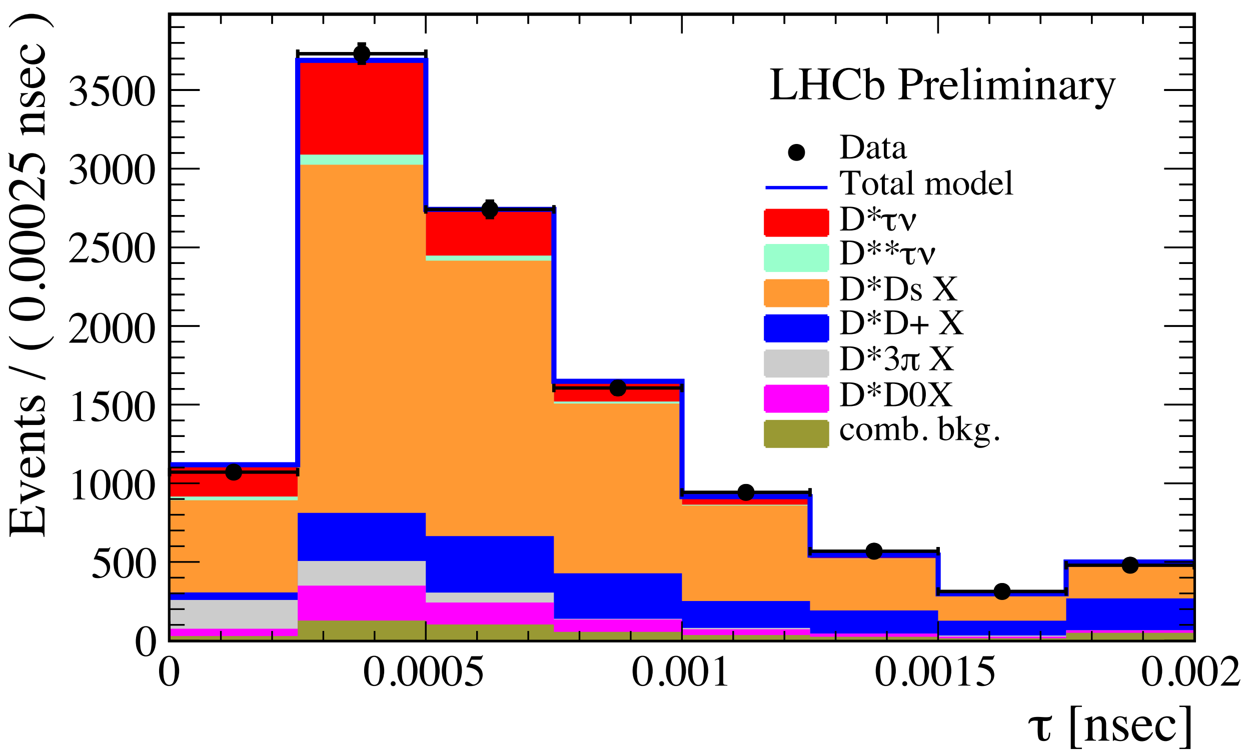
Signal fit

Phys. Rev. Lett. 120, 171802 + Phys. Rev. D 97, 072013

- Combine isolation and kinematic information into a multivariate classifier (BDT).
- Perform 3D template fit (BDT response, τ decay time, q^2).



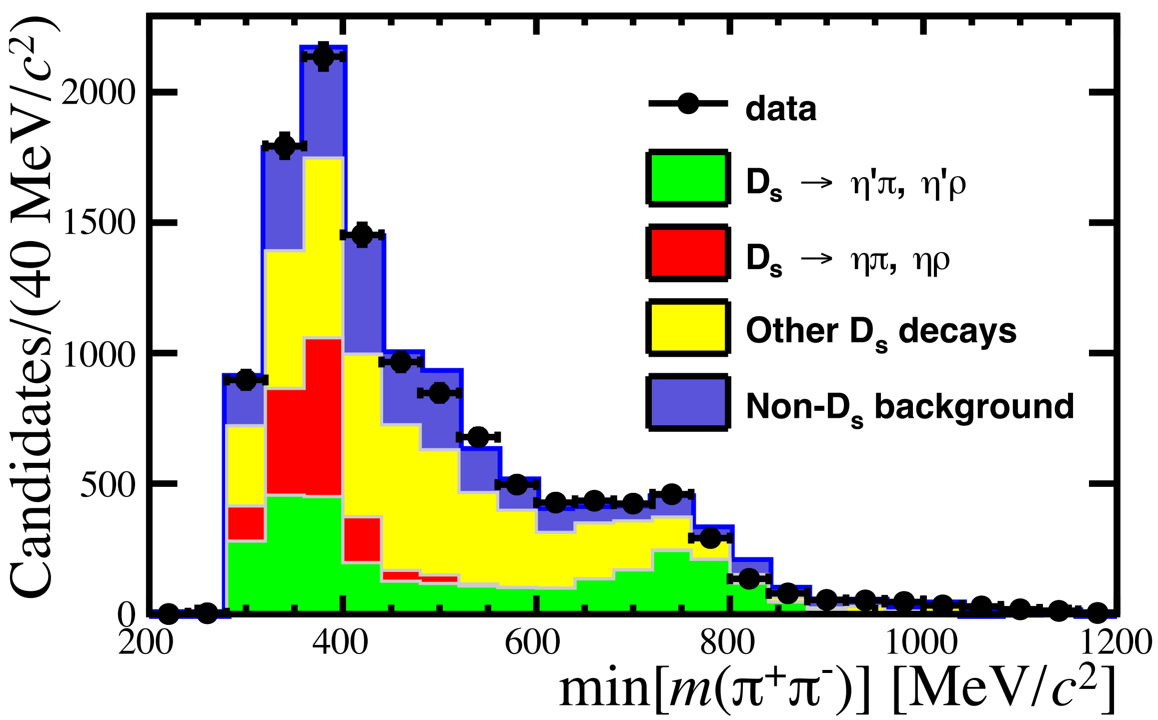


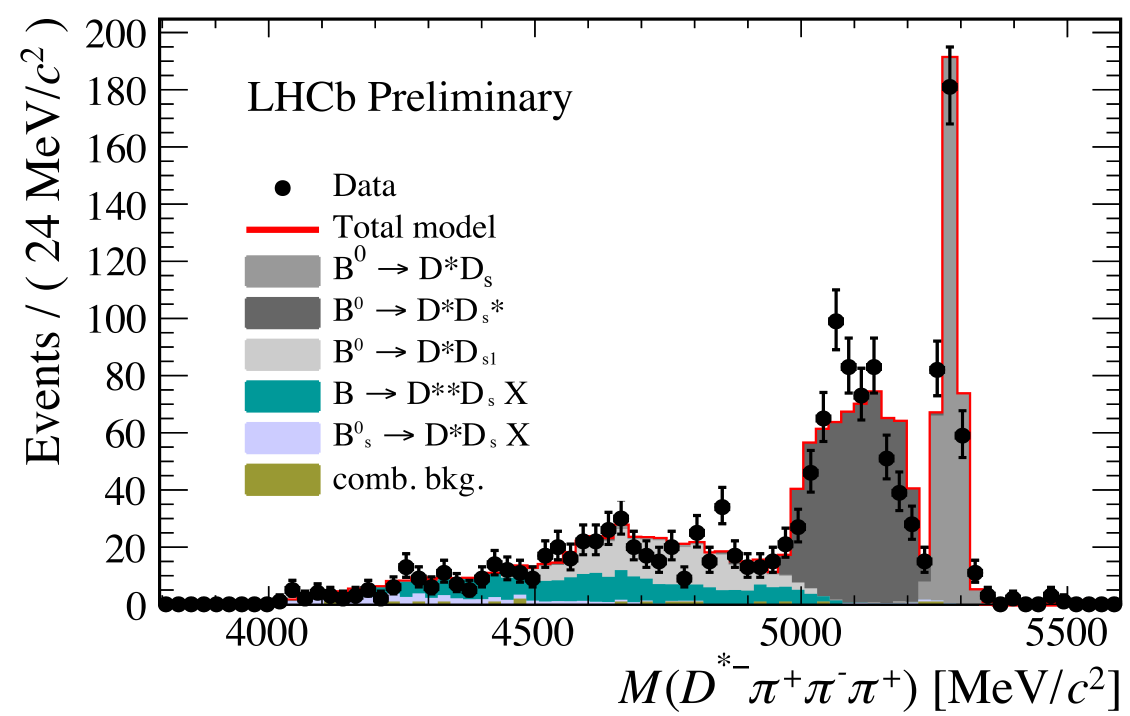


Backgrounds

Phys. Rev. Lett. 120, 171802 + Phys. Rev. D 97, 072013

- Largest background from $B \to D^{*-} D_s^+ X$.

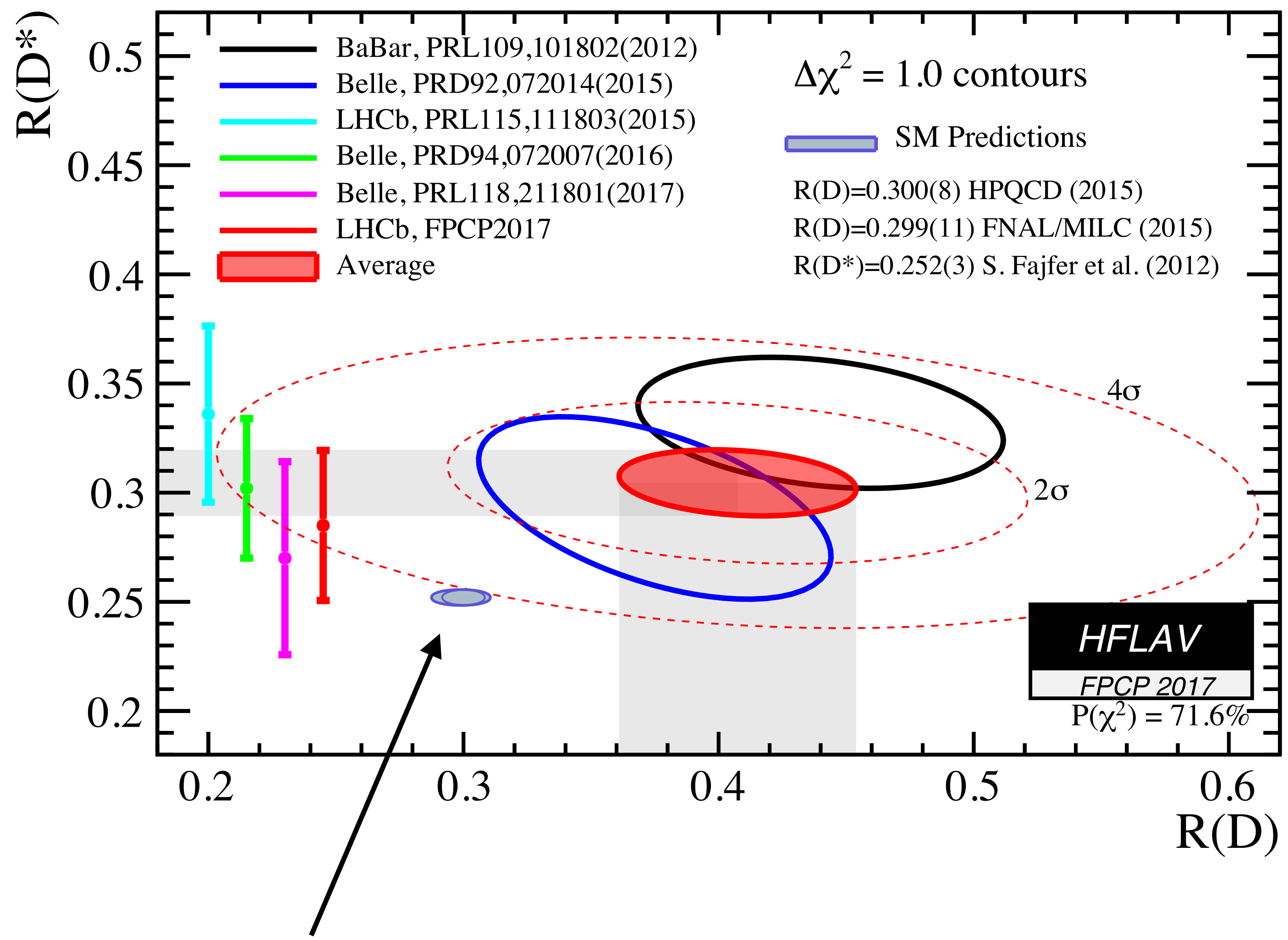




- Controlled using data.   .

Combination

- All experiments see an excess of signal w.r.t. SM prediction.



Horizontal bands refer to R(D*), ellipses refer to both R(D*,D)

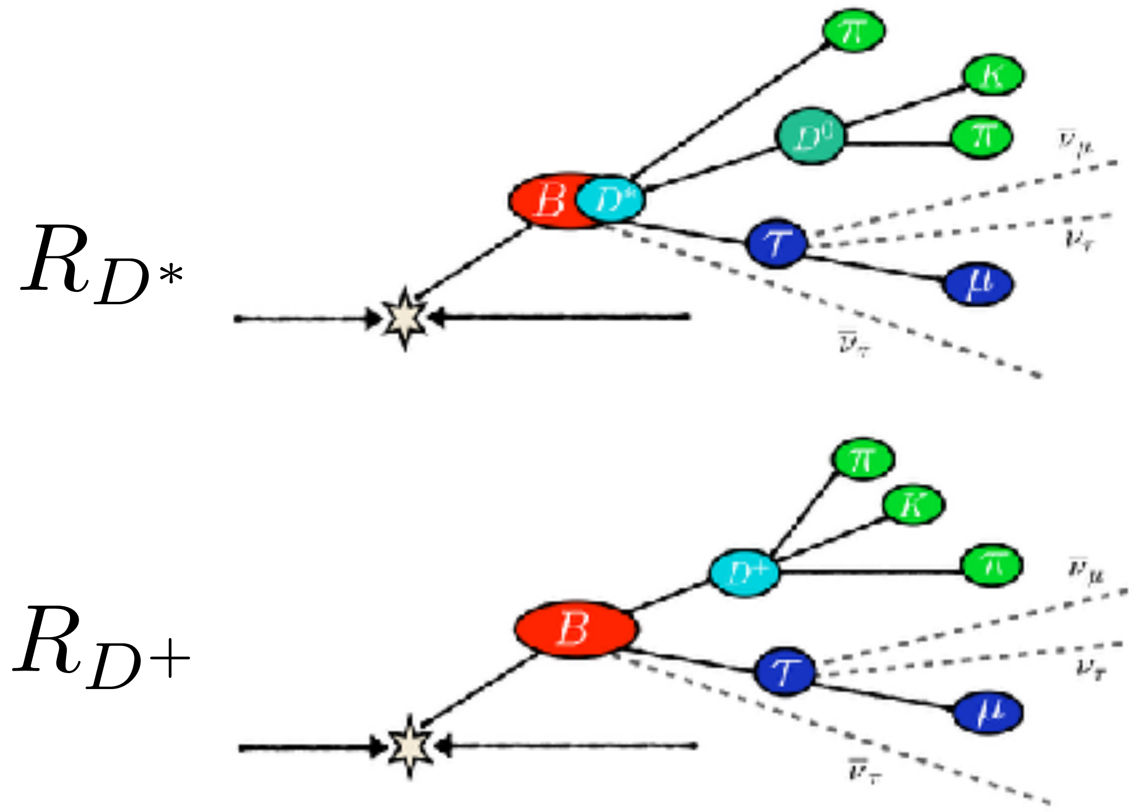
QCD uncertainties very small, but perhaps underestimated [Bigi, Gambino, Schacht]

Latest HFLAV average quotes ~4**σ** from SM prediction

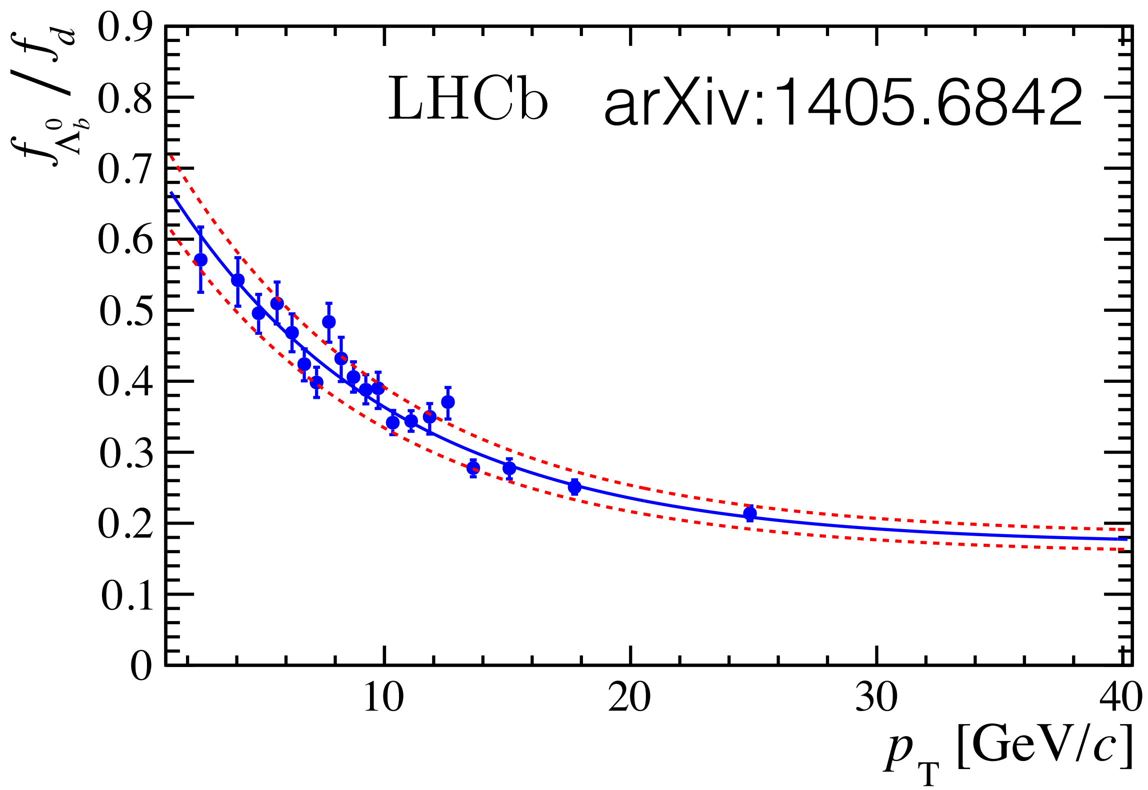
What now?

- Main priority is to clarify the existence of any NP signal.

Improve the precision of R_{D^*} ratios.



Explore other b-hadron systems.

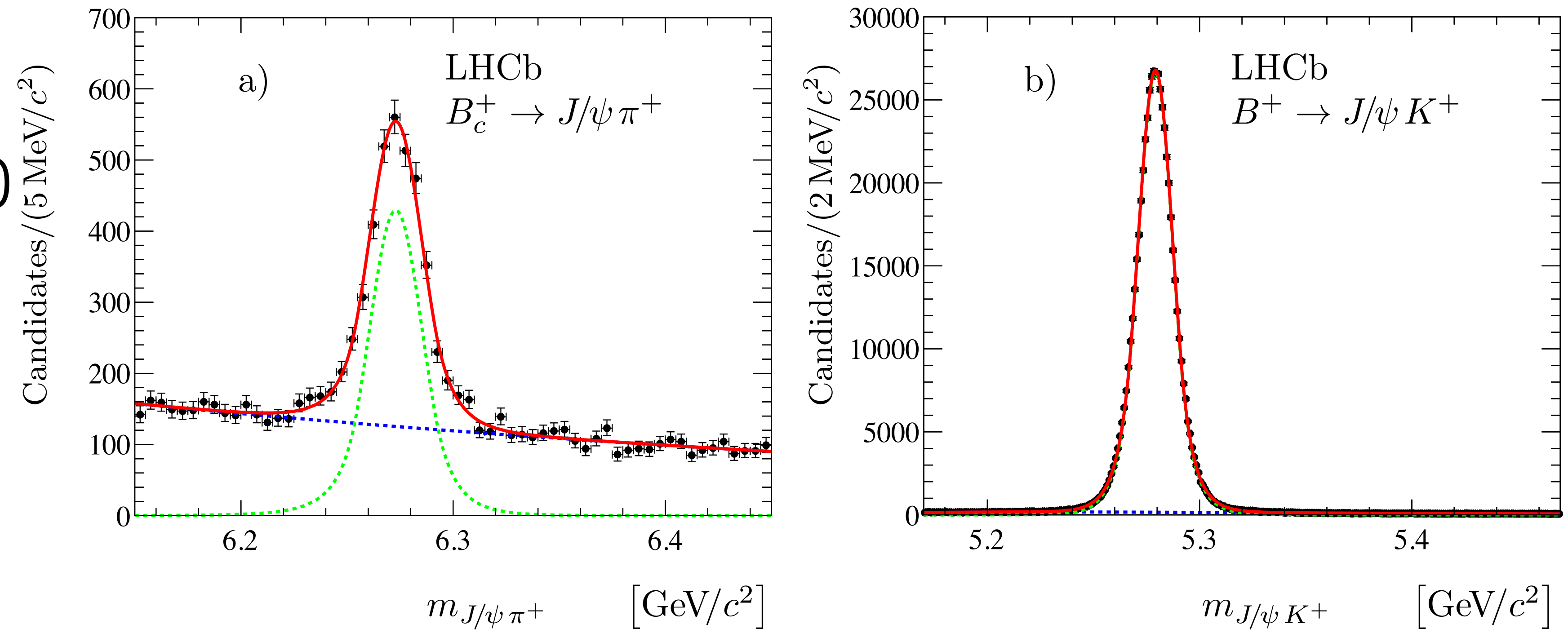


- We are already doing this with the current data in hand.

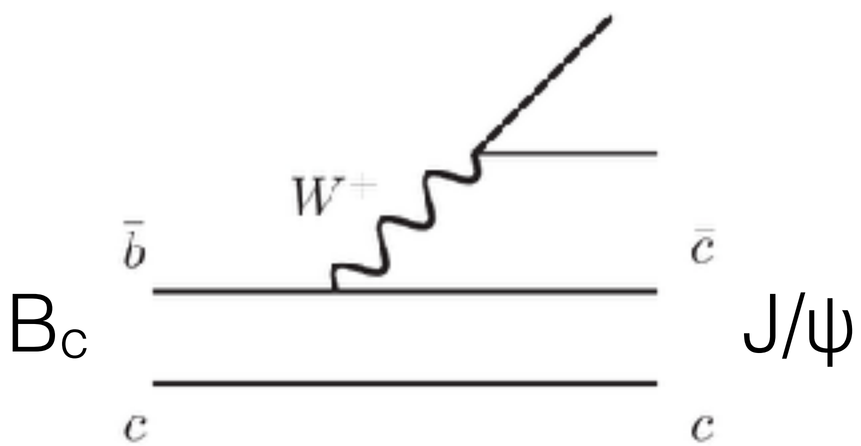
Testing LFU with other hadrons

- Unlike at the B-factories, b-quarks at the LHC are free to hadronise into all sorts of different flavoured particles.

PHYSICS LETTERS B 742 (2015) 29-37



- An example is the B_c meson, produced ~ 200 times less often than regular b-hadrons.



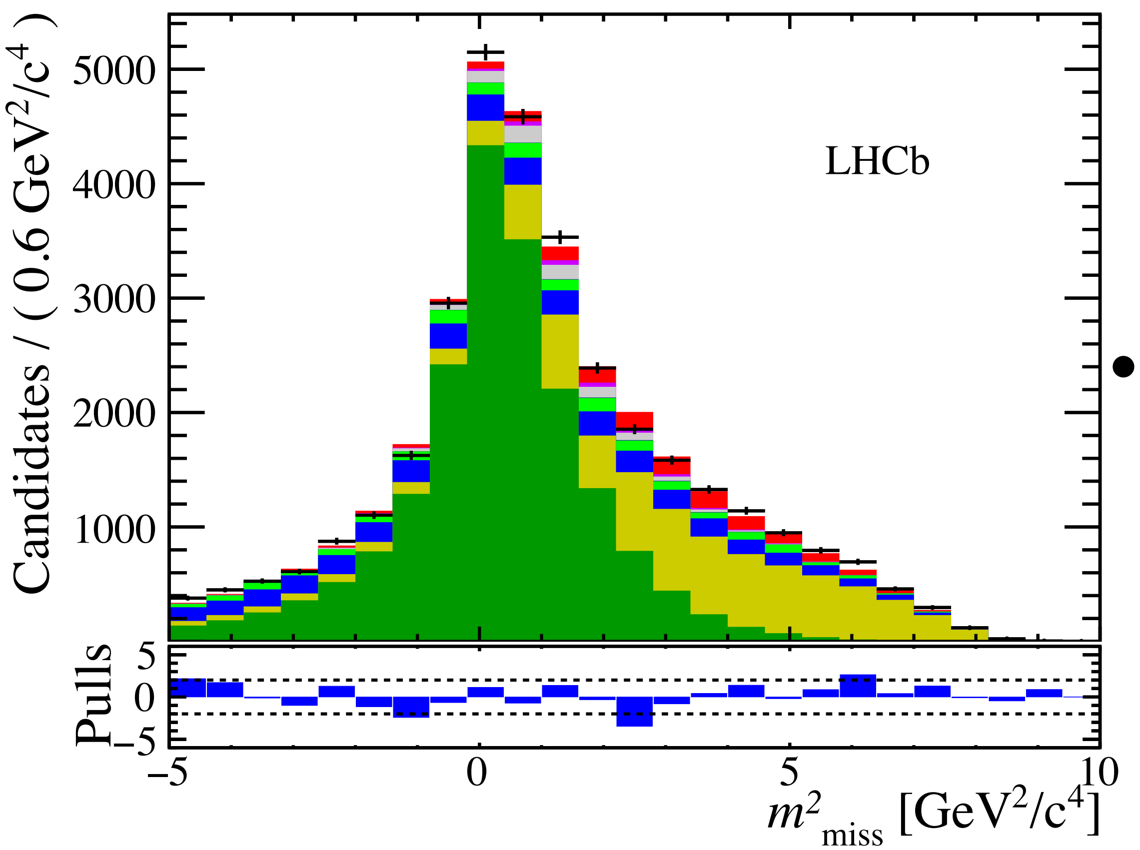
- Testing lepton universality here involves measuring the ratio R(J/ψ).

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}\left(B_c^+ \to J/\psi\tau^+\nu_\tau\right)}{\mathcal{B}\left(B_c^+ \to J/\psi\mu^+\nu_\mu\right)}$$

R(J/ψ) measurement

Phys. Rev. Lett. 120, 121801

- Similar approach to R(D*) measurement.
- Main difference due to large presence of fake muon background (due to low B_c production rate).



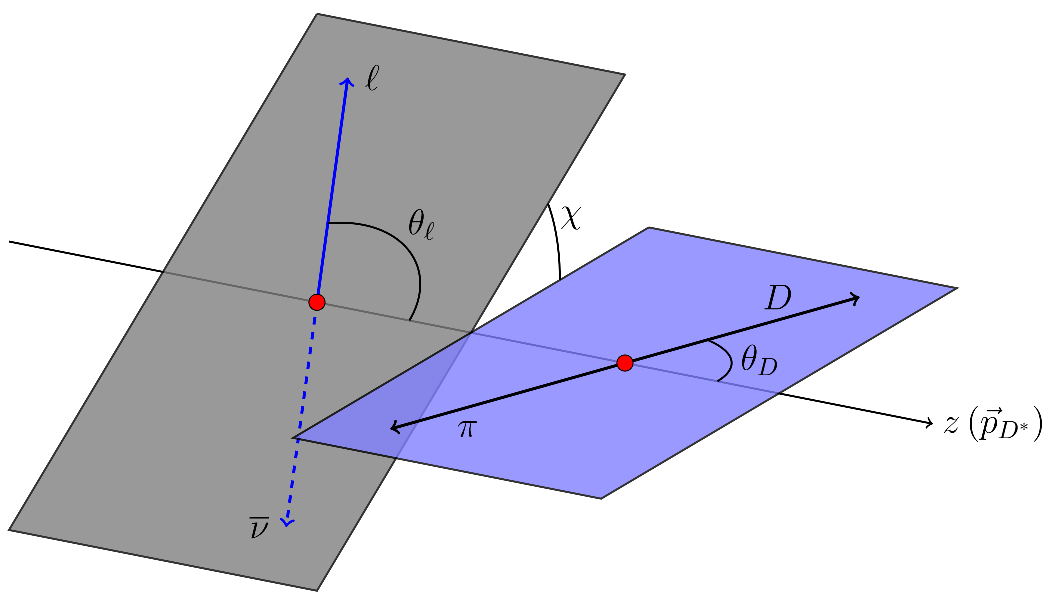
$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

- Within two sigma of SM and NP models

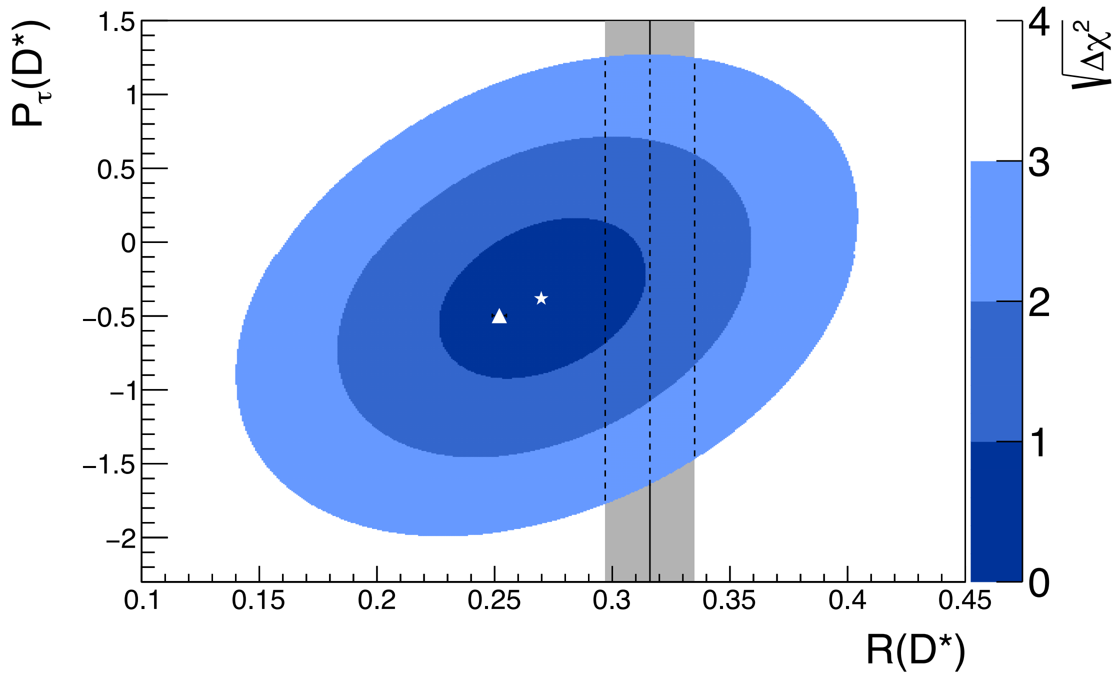
What next?

- NP can also alter angular distribution of decay products.
  - e.g. charged Higgs boson would mean isotropic distribution of the lepton pairs.

Becirevic, Fajfer, Nisandzic, and Tayduganov



Phys. Rev. Lett. 118, 211801 (2017)

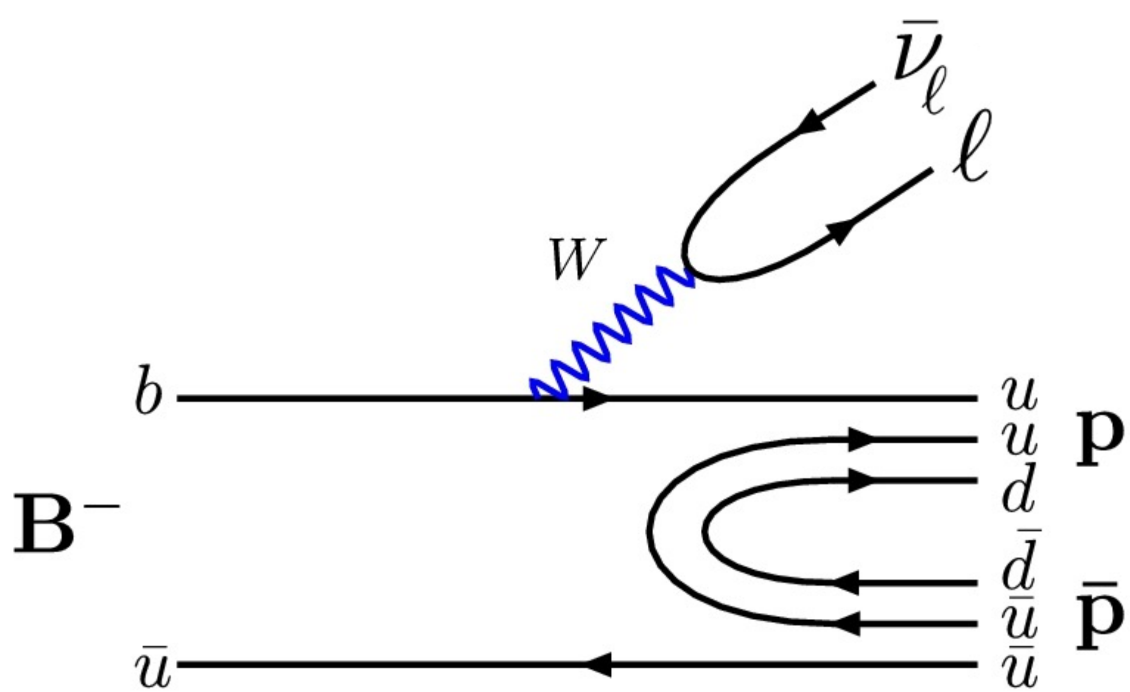


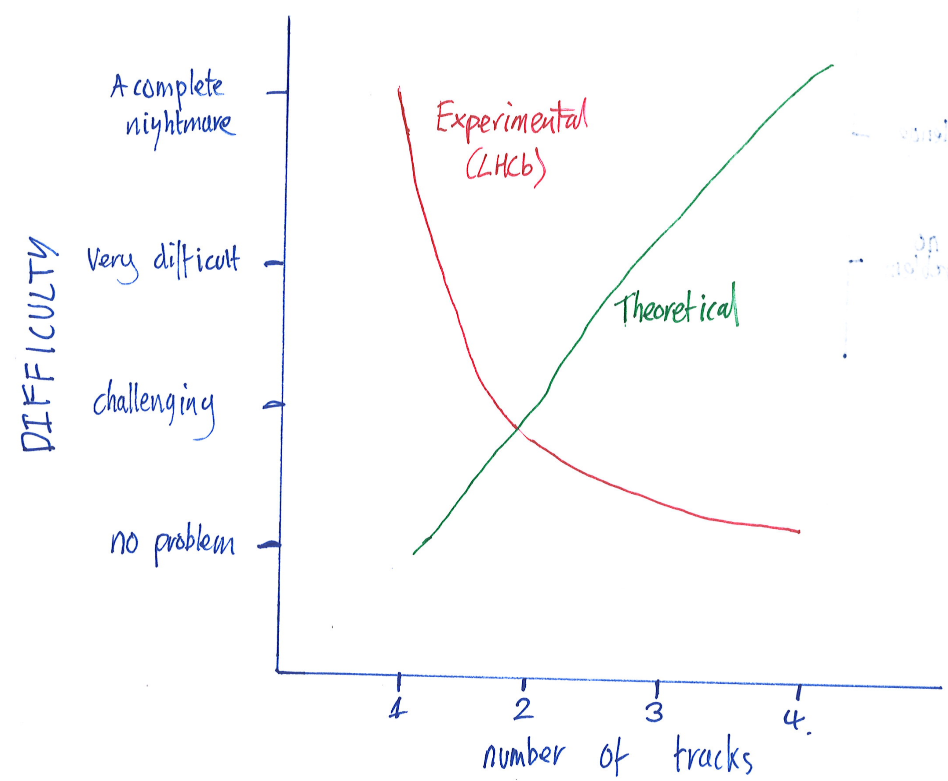
- With the upgrade 2 of LHCb, we will have 10M $B \to D^*\tau\nu$ signal(!), should be able to make precise measurements.

More ambitious

- Also want to test the flavour structure of NP, does it also have $|V_{ub}/V_{cb}|$ suppression?
- Plenty of signal - expect 500,000 $\Lambda_b^0 \to p\tau\nu$ candidates with 300fb^{-1}
- Open yourself up to many, many more backgrounds.

Need to balance experimental and theoretical feasibility.





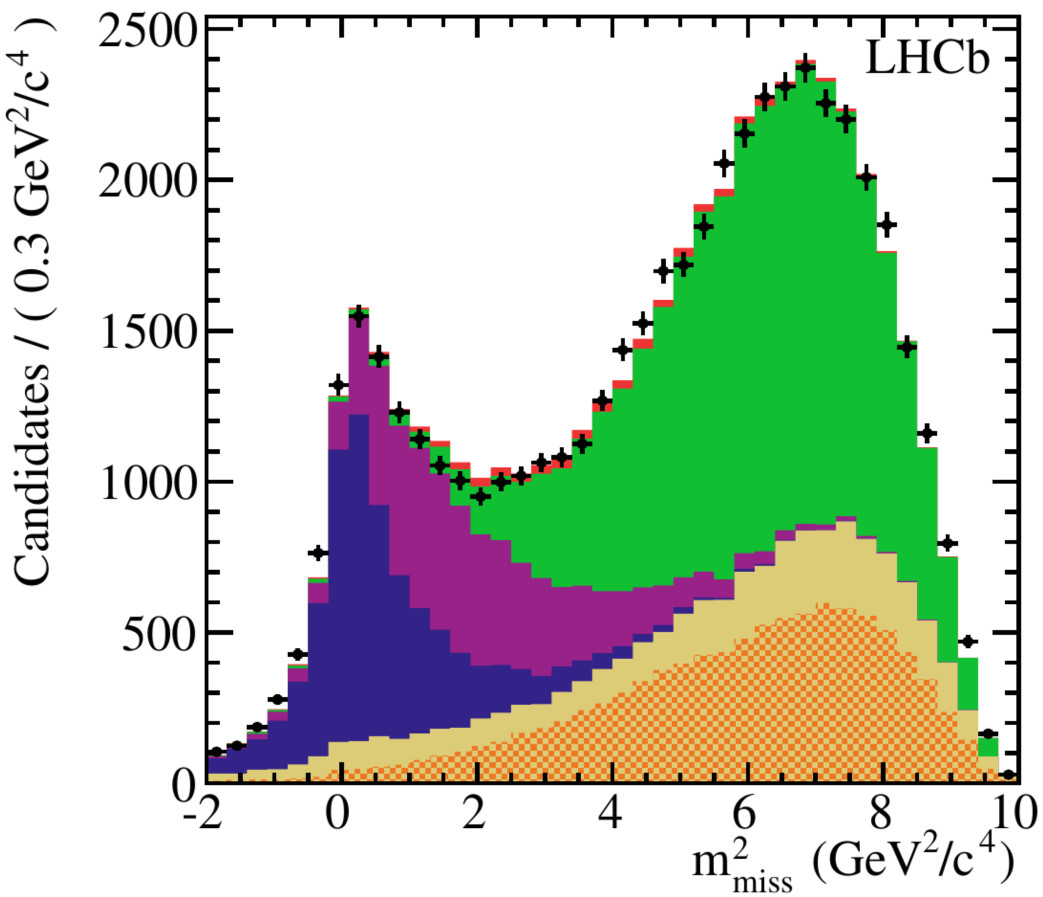
Summary

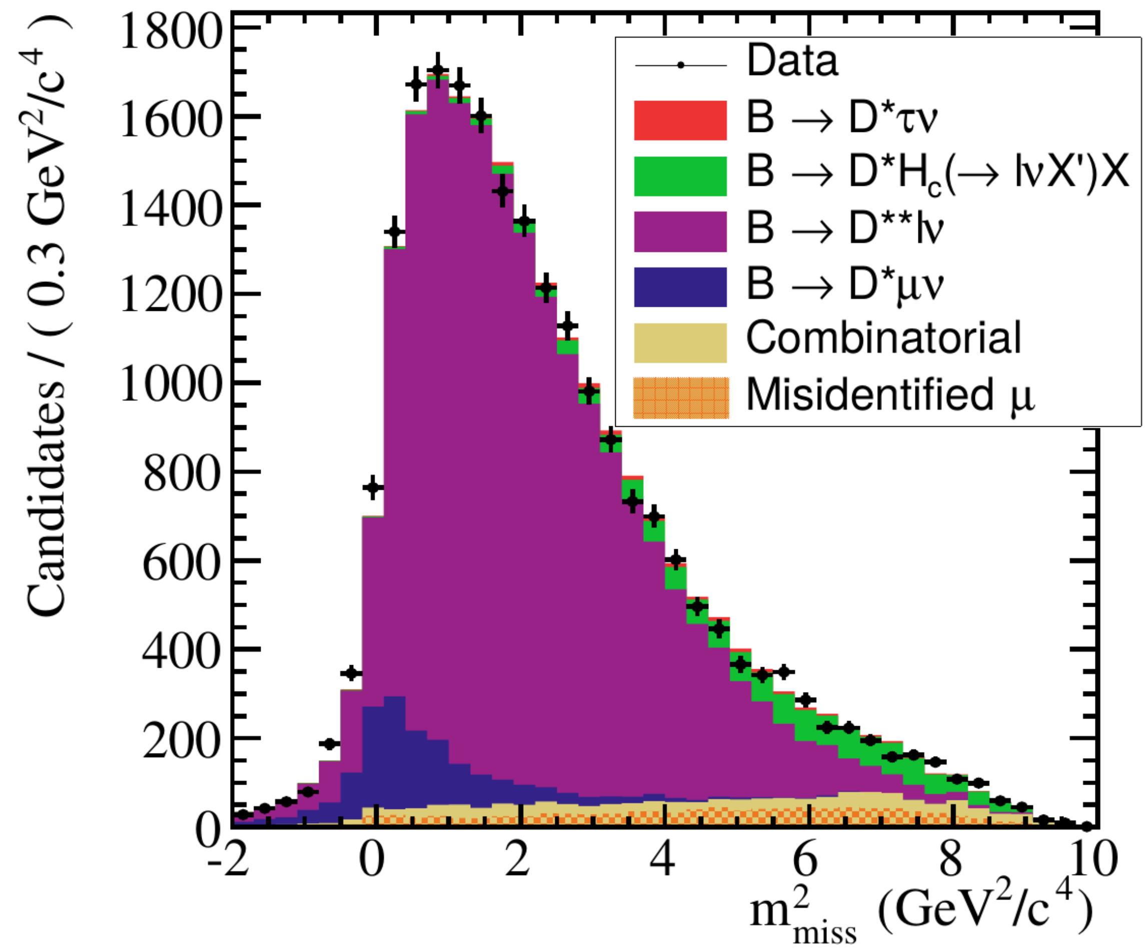
- There is evidence for an enhancement in the decay rate of $b \to c\tau\nu$ decays.
- LHCb should clarify this with the existing dataset.
- Regardless of the signal, this opens up a field of measurements which are sensitive to sensible NP models.
- Looking forward to measurements from Belle-II.

Back-ups

R(D*) control samples

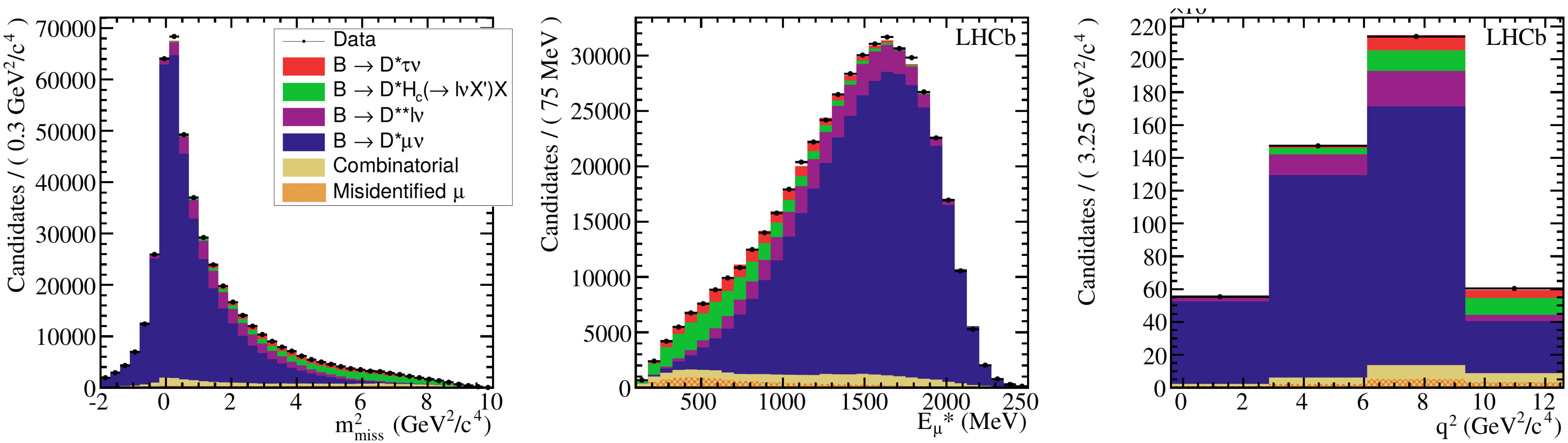
Anti-isolate signal to enrich particular backgrounds.





R(D*) 3D fit

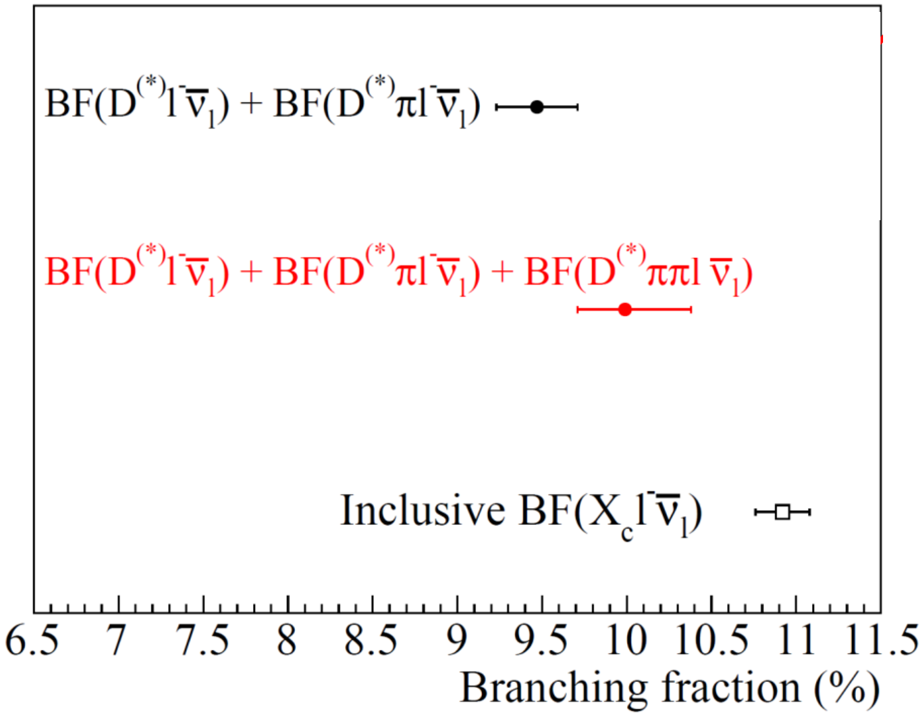
3D fit used to discriminate signal from backgrounds



Good agreement seen everywhere

Remarks

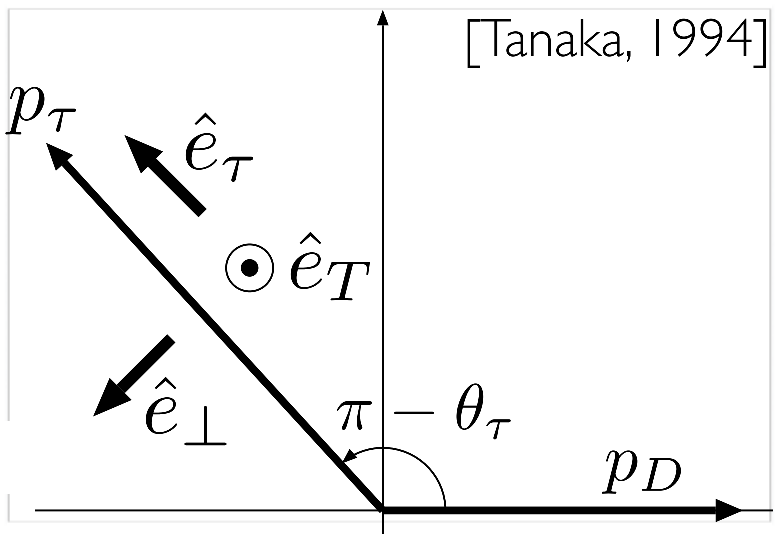
- Because this measurement is so difficult, it has received a fairly healthy level of scepticism by the theory community.
- People are worried about backgrounds from $B \to D^{**}\ell\nu$ decays where the charm spectrum is not so well measured.
  - This is why the hadronic modes are crucial.
- This is unlikely to be the issue:
  - Rely on data for control of background.
  - B-factories/LHCb have very different background levels.

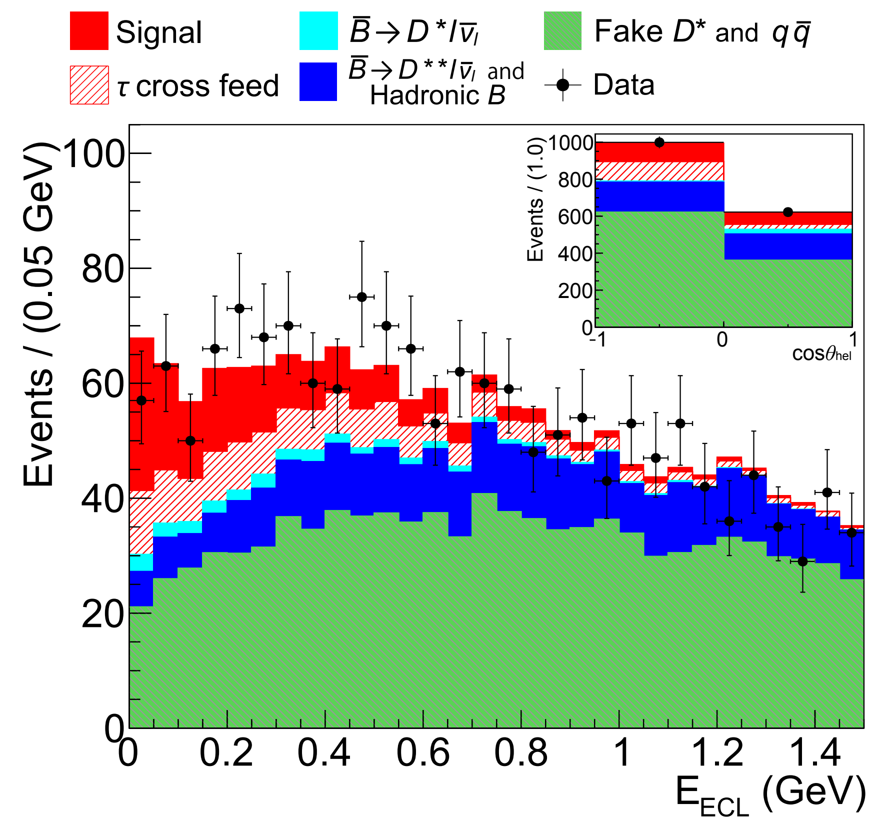


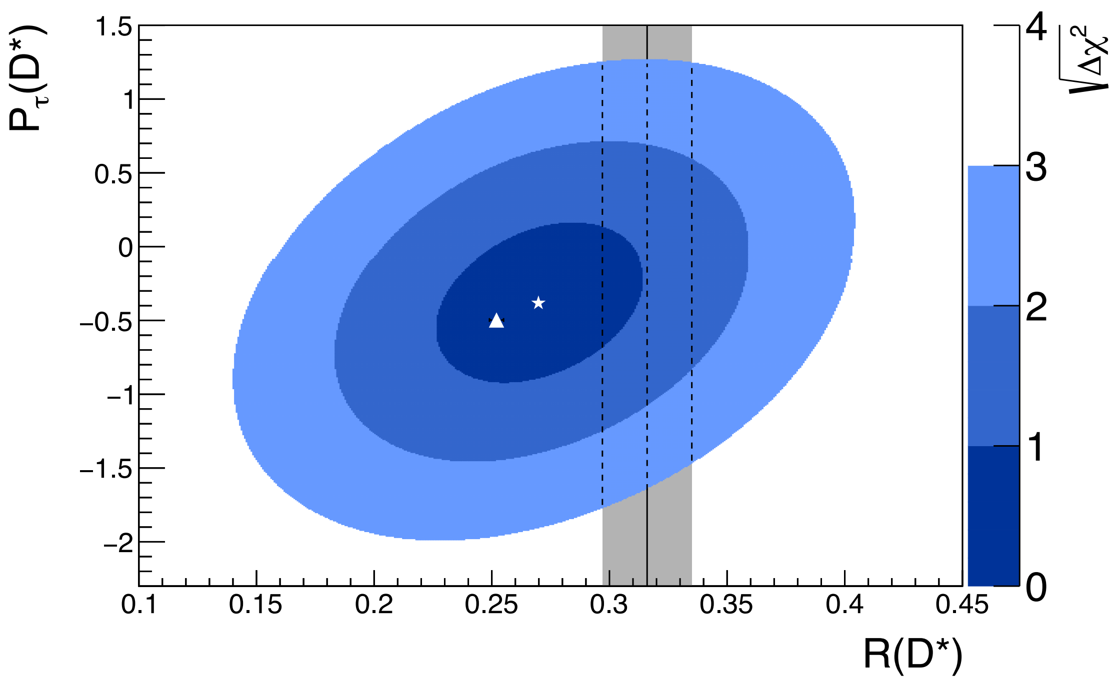
Latest result from Belle

arXiv:1612.00529, submitted to PRL

- First result to use hadronic $\tau \to \pi\nu$ decays.



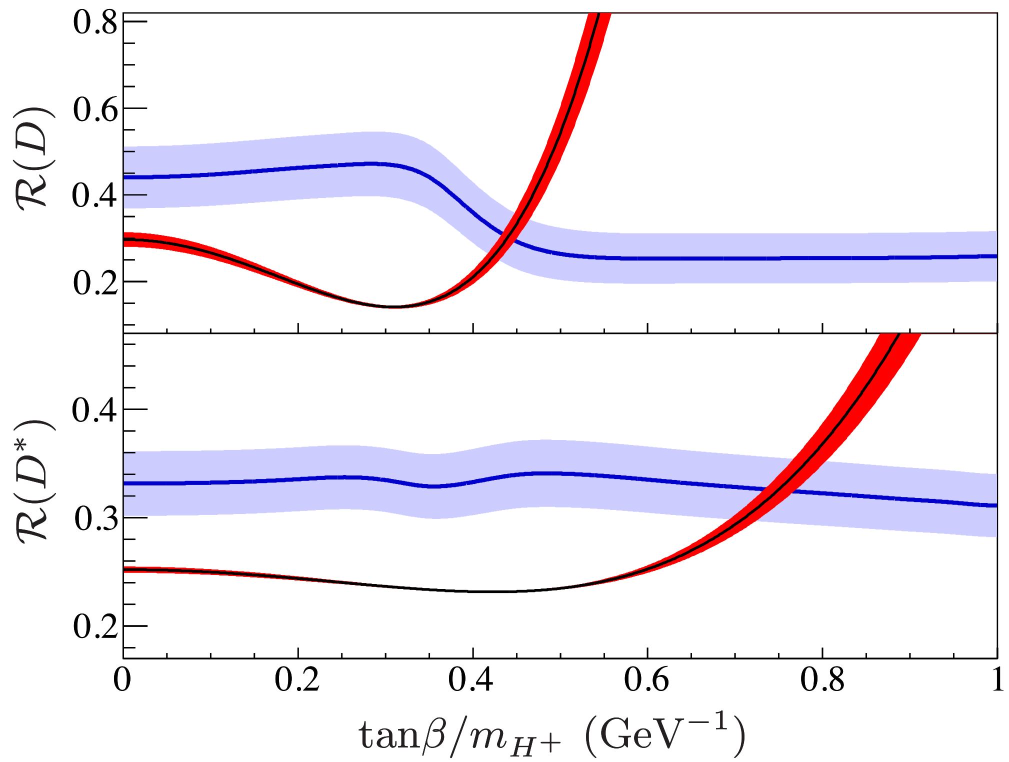




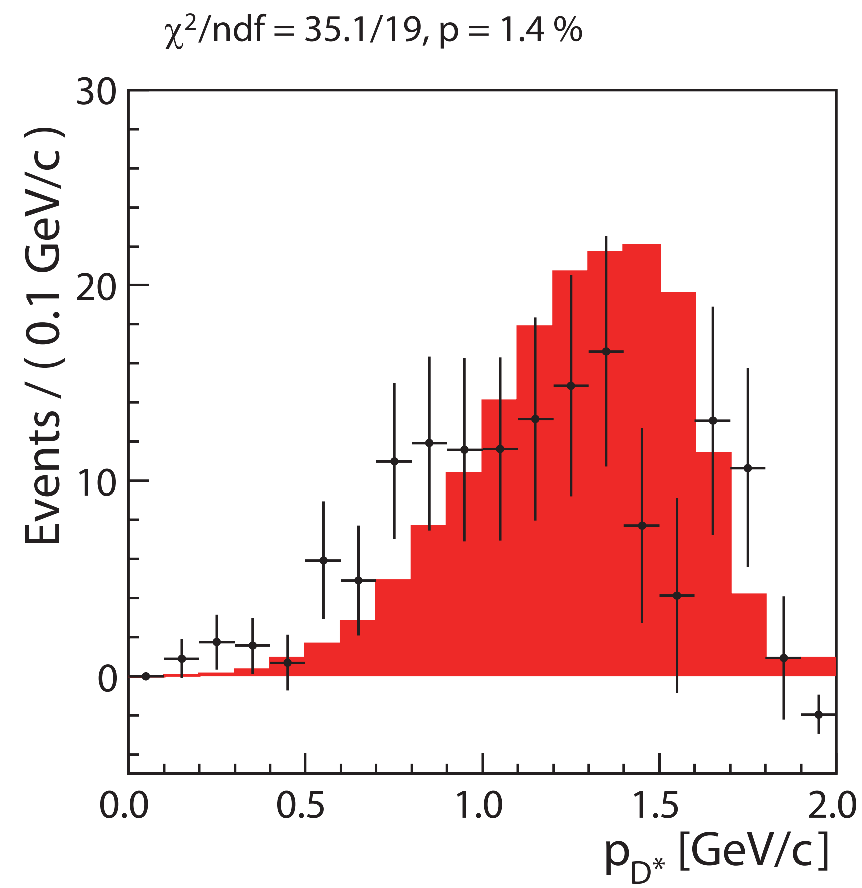
- Also first measurement to measure τ polarisation.

Constraining models

Phys. Rev. D 88, 072012 (2013)



- The central values of R(D*) and R(D) cannot be explained by 2HDM type II.



(c) R_2 type leptoquark model with $C_T = +0.36$.

Phys.Rev.D 92, 072014 (2015)

- Can also compare kinematic distributions to narrow down model possibilities.

Difficult in general to explain with a scalar particle, constraints from B_c disfavour this (arXiv:1611.06676).