Recent R(D) and R(D*) measurements

Beyond the flavour anomalies IV

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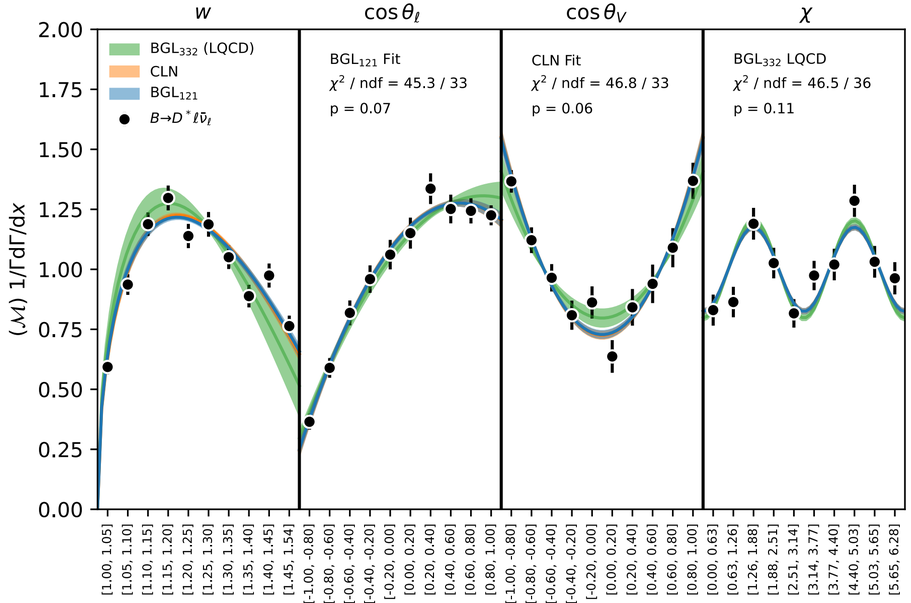
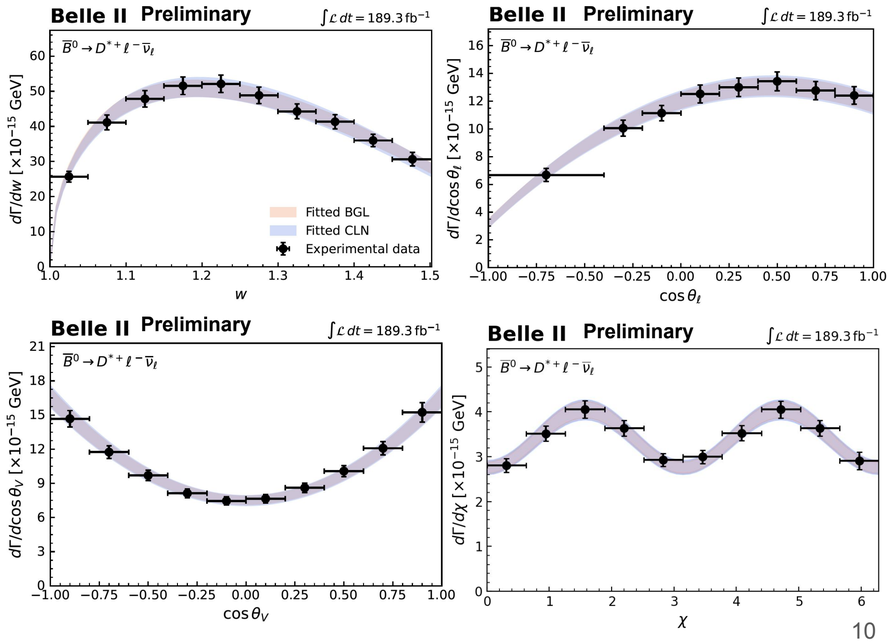
Content

- The decay $b \to c\ell\nu$ used for $|V_{cb}|$ - huge topic with its own puzzles.
  - Not the main focus today, but wanted to flash a couple of recent measurements.

Belle, https://arxiv.org/abs/2301.07529



Belle II, ALPS 2023



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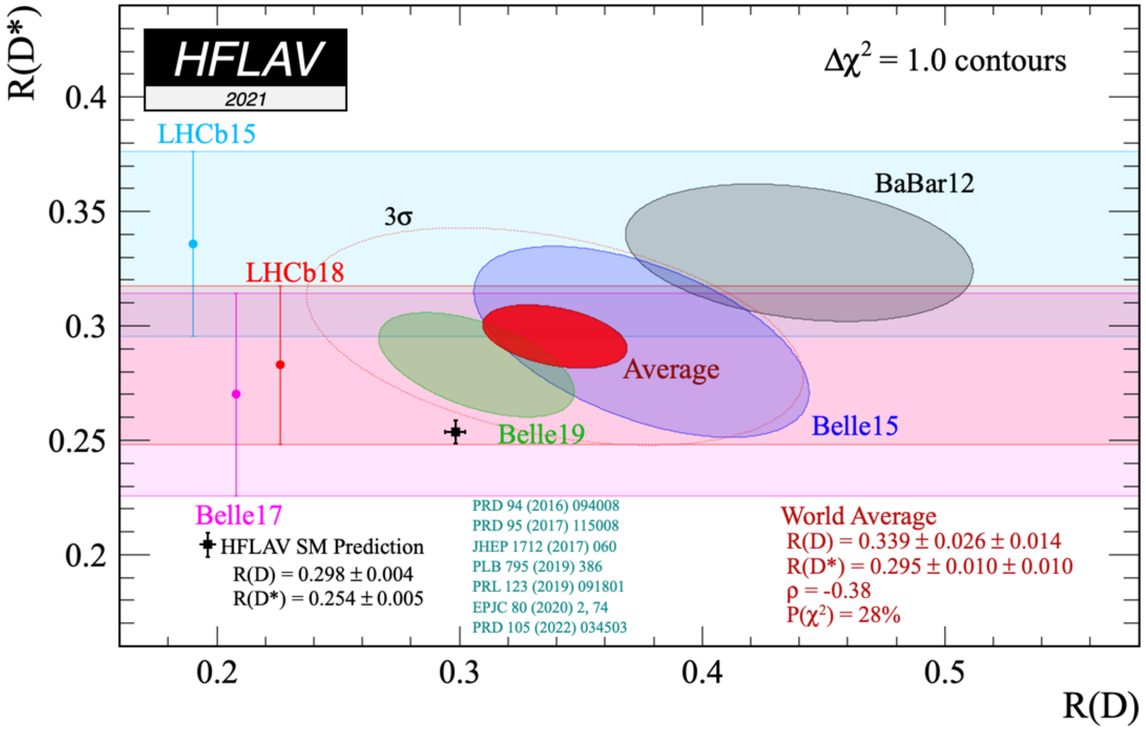
- Great interest in seeing how these measurements compare to lattice when/if data is released.
- I will instead talk about the semitauonic measurements, focussing on recent updates.

Semitauonic status as of 2021



Note I: Ellipses cover at 39% so measurements less compatible than they actually are.
(No, it would not make sense to enlarge them to 68% due to comparison with 1D measurements).

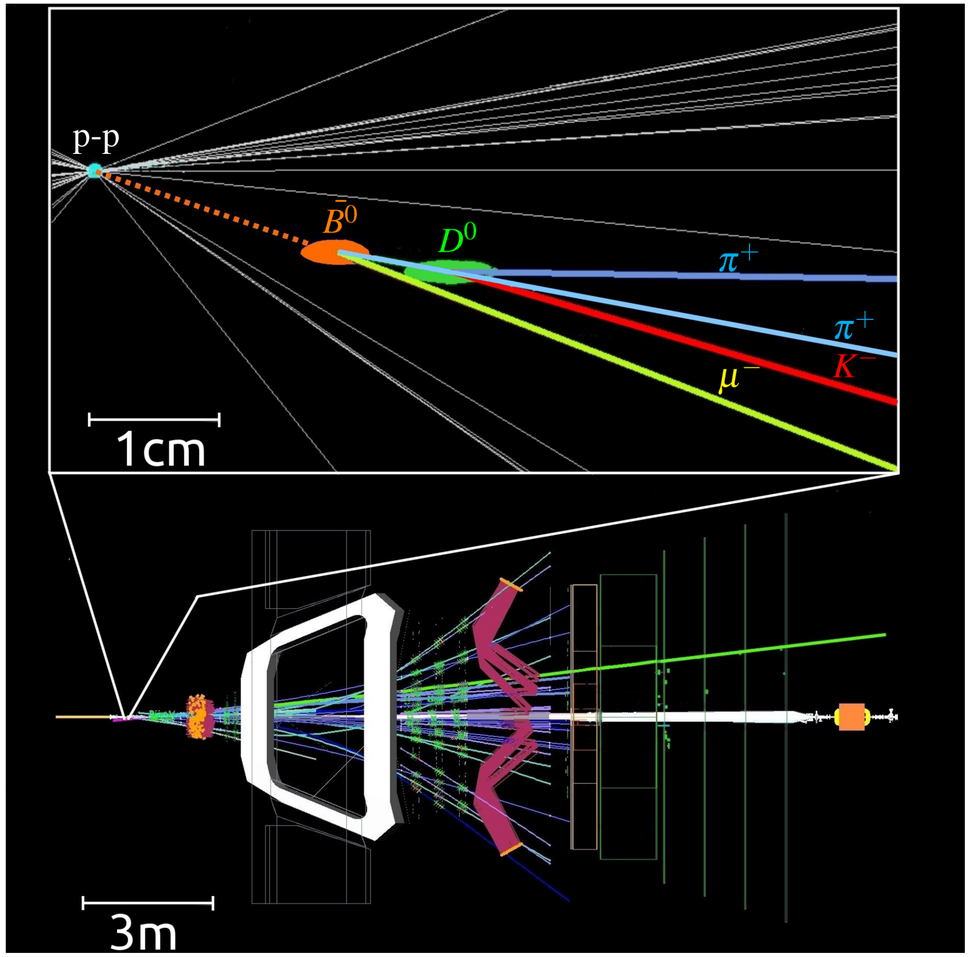
Note II: WA significantly more precise than most precise single measurement: Global significance has large inertia to new measurements (don't expect the 3σ tension to move much).

- I will cover two recent updates on two τ decay channels from LHCb:
  - LHCb-PAPER-2022-039, measurement of R(D) and R(D*) with $\tau \to \mu\nu\nu$ [3 fb^{-1}].
  - LHCb-PAPER-2022-052, measurement of R(D*) with $\tau \to 3\pi(X)\nu$ [4.5 fb^{-1}].

A word on neutrinos at a hadron collider

- For semitauonics, at least two neutrinos in the final state.
  - Signal and backgrounds have broad overlapping shapes.
- Difficult to reconstruct B rest frame.
  - Gain some information using the direction of the primary and secondary vertices.
  - This with rest frame approximations allows to reconstruct kinematic observables.

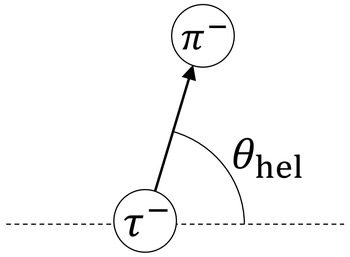
Nature volume 546, pages 227–233



Semitauonic analyses in a nutshell

1. Simulate signal and backgrounds, e.g:
   $B \to D^* \ell \nu$
   $B \to D^{**} \ell \nu$
   $B \to D^* D X$
3. Correct simulation for data/MC differences (e.g. PID).
4. Design selection to select signal.
5. Use control regions to further correct details of backgrounds (decay model).
6. Perform multi-dimensional template fit to extract signal.
7. Determine efficiency using corrected simulation.
8. For three-prong decays: use external normalisation to convert to LFU ratio.

Tau decays

$\tau \to \mu\nu\nu$	$\tau \to 3\pi\nu$	$\tau \to \pi\nu$
Large statistics	More kinematic information	Good polarimeter
Efficiency largely cancels with muonic mode $B \to D^*(\tau \to \mu\nu\nu)\nu$ vs $B \to D^*\mu\nu$	Precise tau flight information	
Tau decay well understood	No background from muonic modes	Tau decay well understood

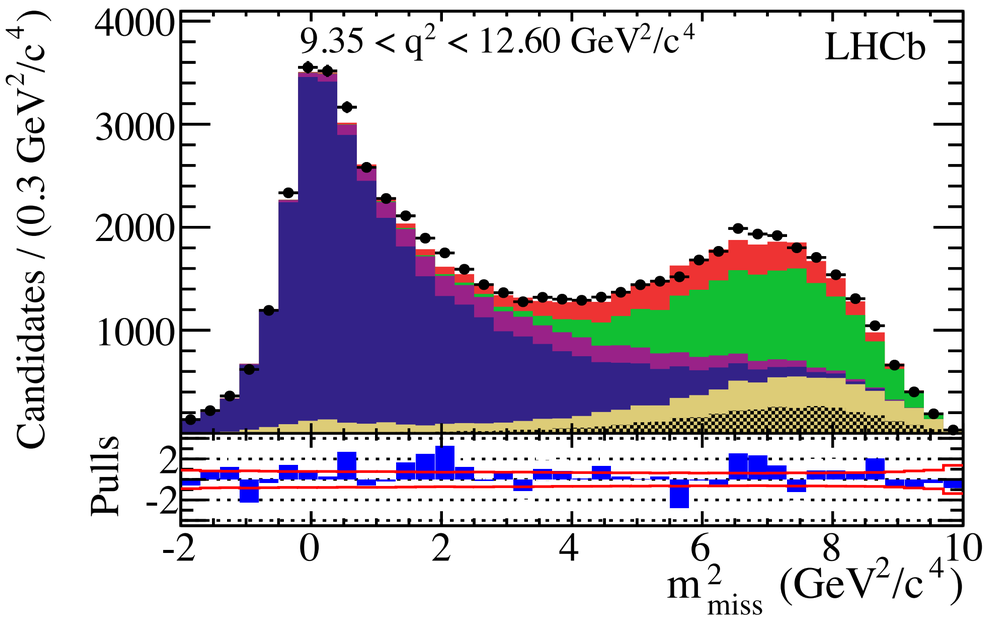
We start with the measurements using $\tau \to \mu\nu\nu$

Main differences in new muonic result

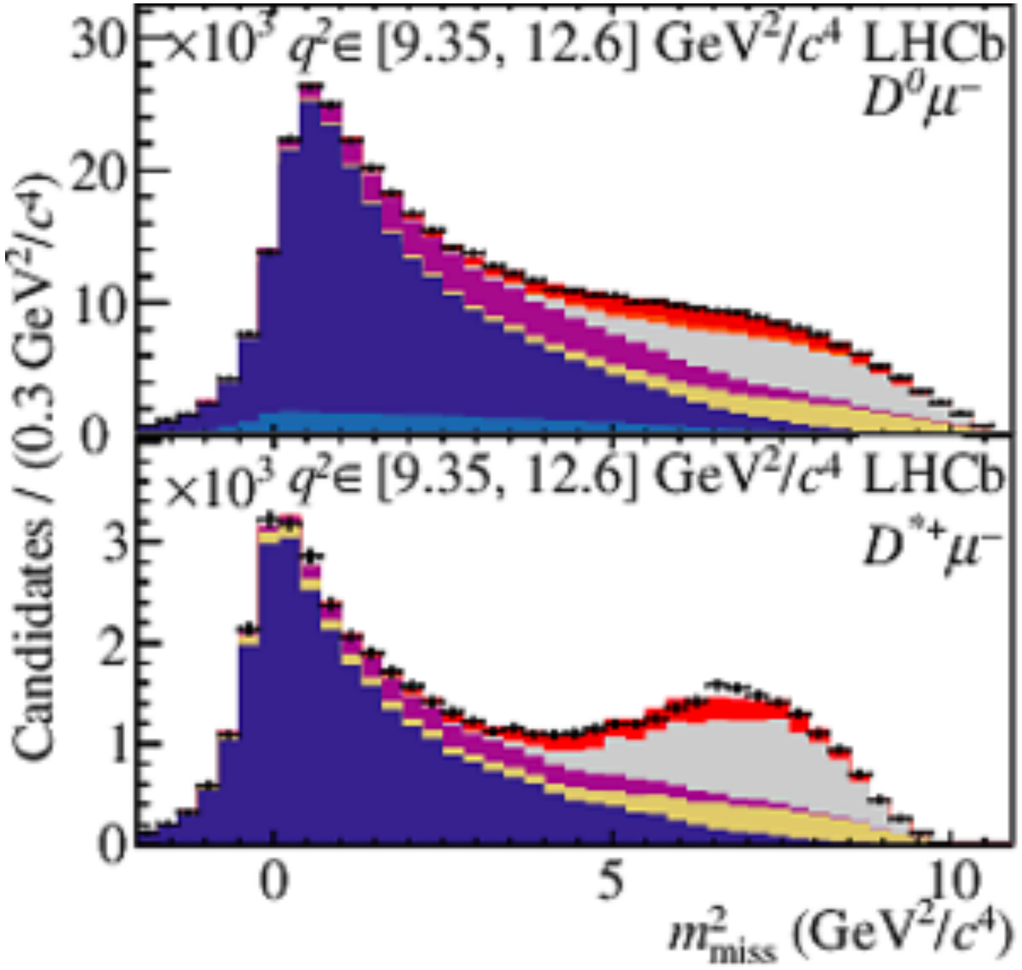
	LHCb-PAPER-2015-025	LHCb-PAPER-2022-052
Signature	400k $D^{*+}\mu^{-}X$ candidates	2M $D^{*+}\mu^{-}X + D^{0}\mu^{-}X$ candidates
Mis-ID treatment	Standard PID selection	Custom PID with updated unfolding methods.
Simulation	Full	Fast
Form factors	CLN ($D^{(*)}$) and LLSW (D**)	BGL ($D^{(*)}$) and BLR (D**)
Data/MC agreement	Very good	Almost perfect

Signal increase

400k $D^{*+}\mu^- X$ candidates

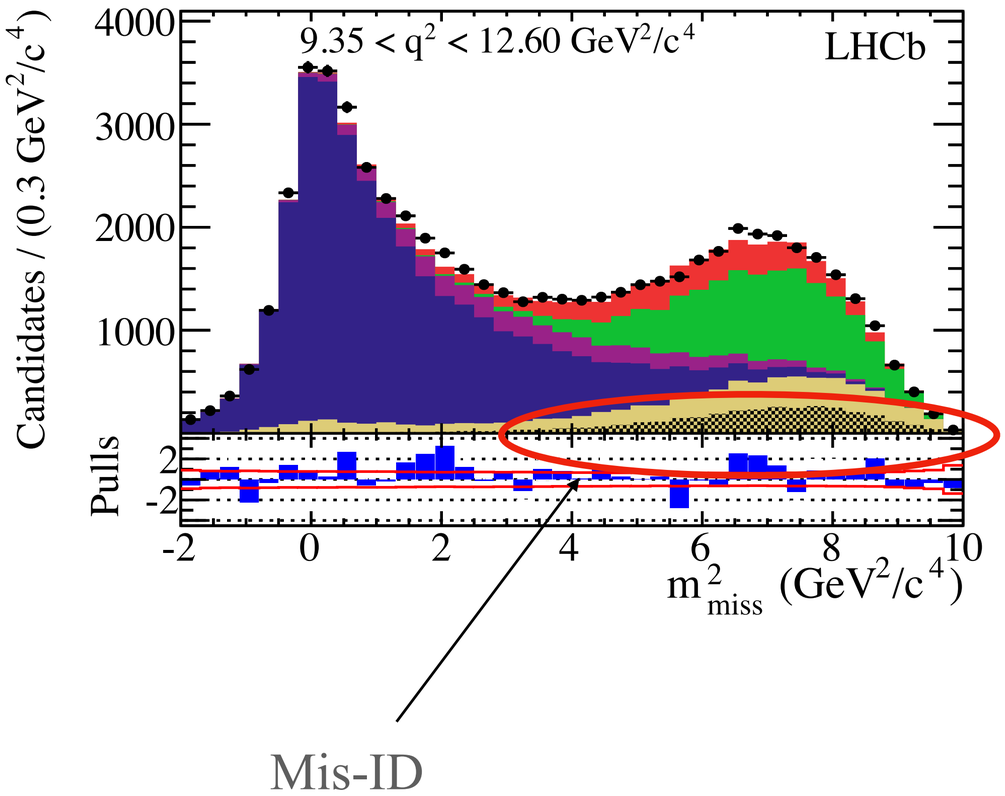


2M $D^{*+}\mu^- X + D^0\mu^- X$ candidates

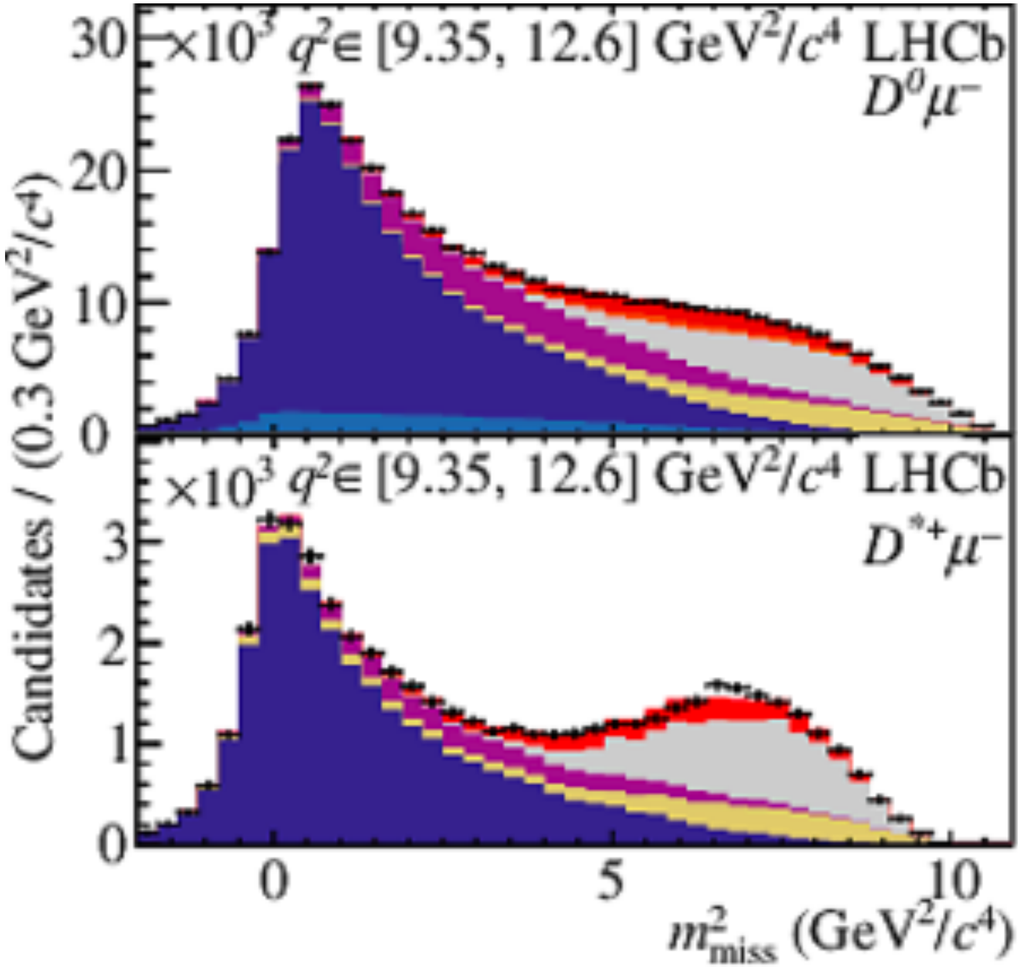


Signal increase

400k $D^{*+}\mu^{-}X$ candidates

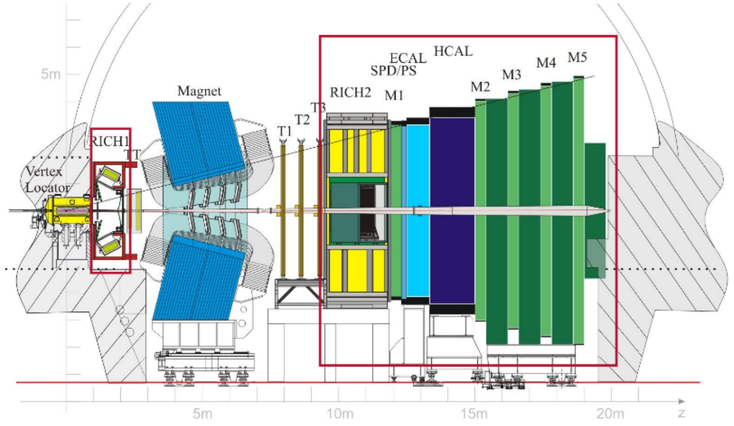
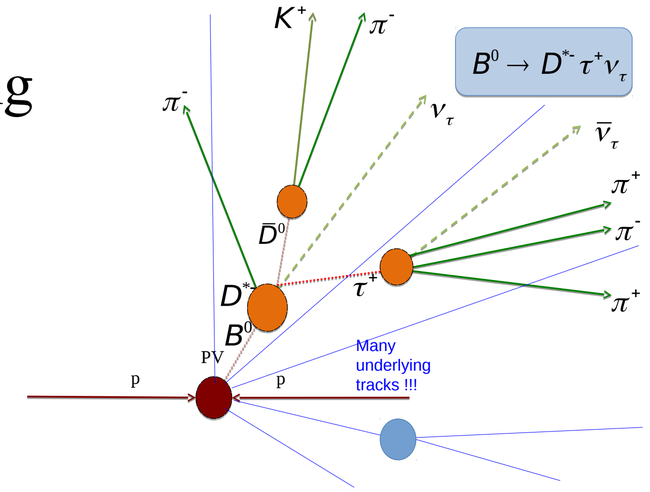


2M $D^{*+}\mu^{-}X + D^{0}\mu^{-}X$ candidates



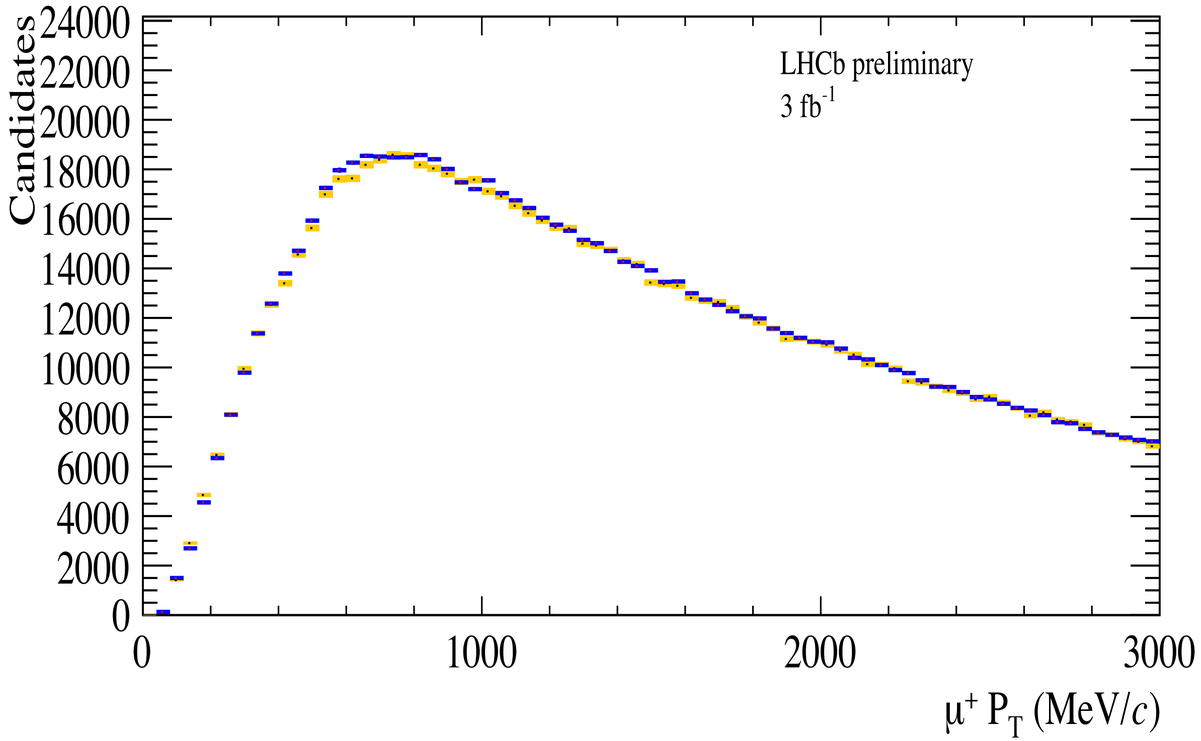
Simulation

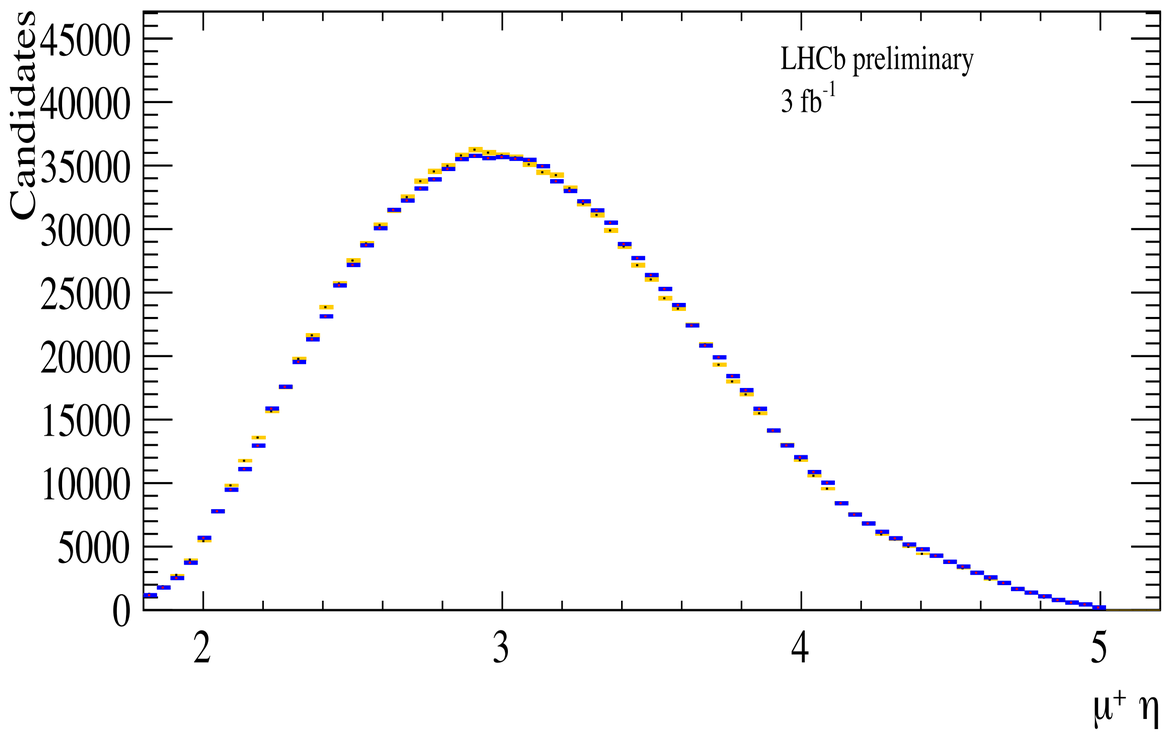
- LHC takes 25ns to produce an event, full simulation takes O(10s).
- Roughly 1 in 200 bunch crossings have bb pair.
- Visible branching fractions are O(10^{-3}) level.
- Leaves 4 orders of magnitude difference in the production rate between simulation and data.
- Producing enough simulation is **difficult**, and usually requires lots of tricks. Two main methods:

	Simulate less of detector (e.g. tracker-only)	Reuse rest of the event for many candidates
Muonic		Three-prong 

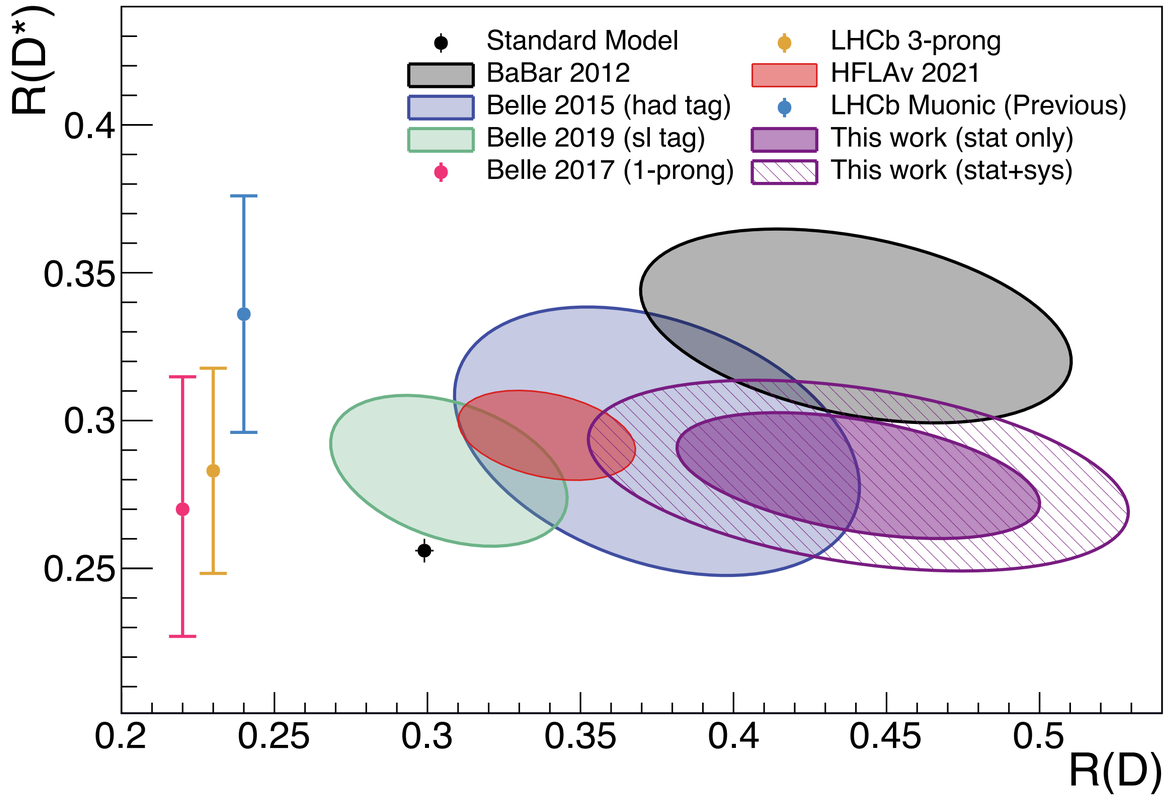
Data/MC agreement

- Agreement is excellent, particularly in the variables which differ between muonic and tauonic modes.





Results



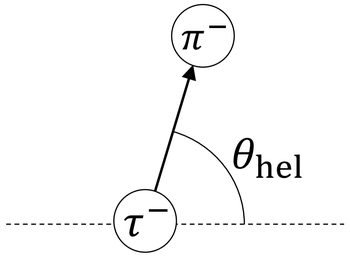
$\mathcal{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$

$\mathcal{R}(D) = 0.441 \pm 0.060 \pm 0.066$

$\rho = -0.43$

1.9σ agreement with SM

Tau decays

$\tau \to \mu\nu\nu$	$\tau \to 3\pi\nu$	$\tau \to \pi\nu$
Large statistics	More kinematic information	Good polarimeter
Efficiency largely cancels with muonic mode $B \to D^*(\tau \to \mu\nu\nu)\nu$ vs $B \to D^*\mu\nu$	Precise tau flight information	
Tau decay well understood	No background from muonic modes	Tau decay well understood

Three-prong measurement

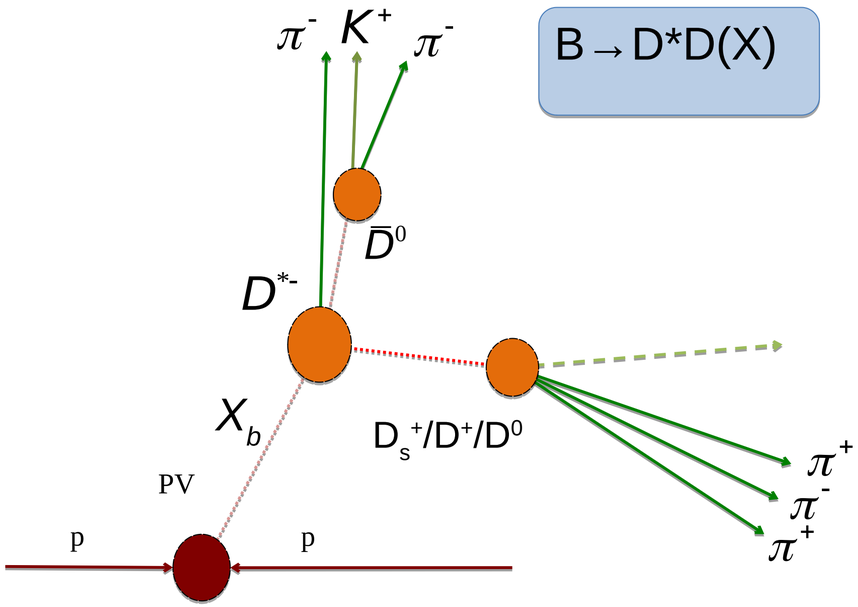
- Update of R(D*) with $\tau \to 3\pi\nu(X)$ with 4.5 fb^{-1}.
- Normalise to hadronic mode $B^0 \to D^{*-}3\pi^{\pm}$.
  - Why not normalise directly to muonic mode? In that case we would suffer systematic uncertainties on the efficiency

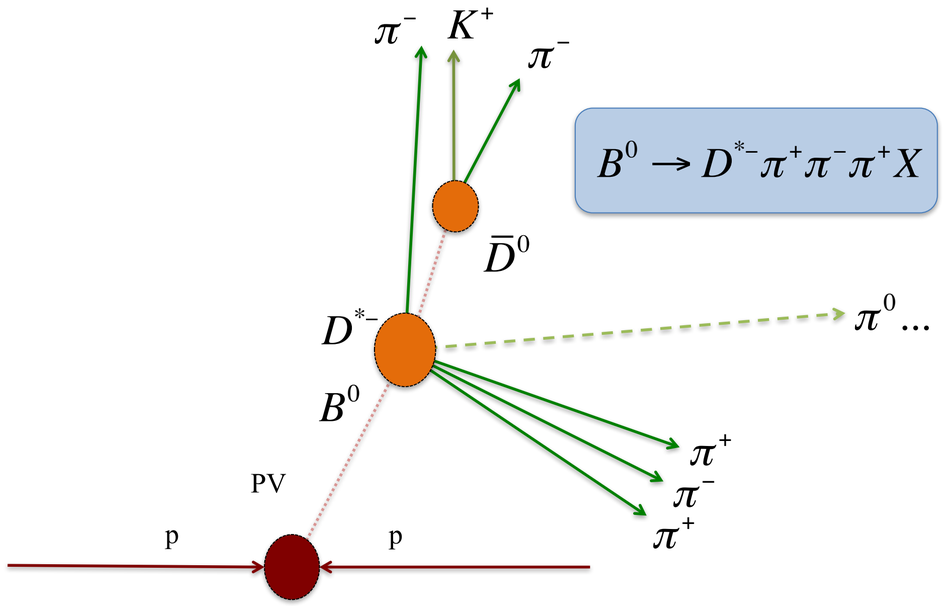
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^{\pm})}$$

$$R(D^*) = \mathcal{K}(D^*)\left\{\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^{\pm})}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right\}$$

Key selection of analysis

- Reminder that key selection is to reject the huge $B^0 \to D^{*-}3\pi^{\pm}X$ background.

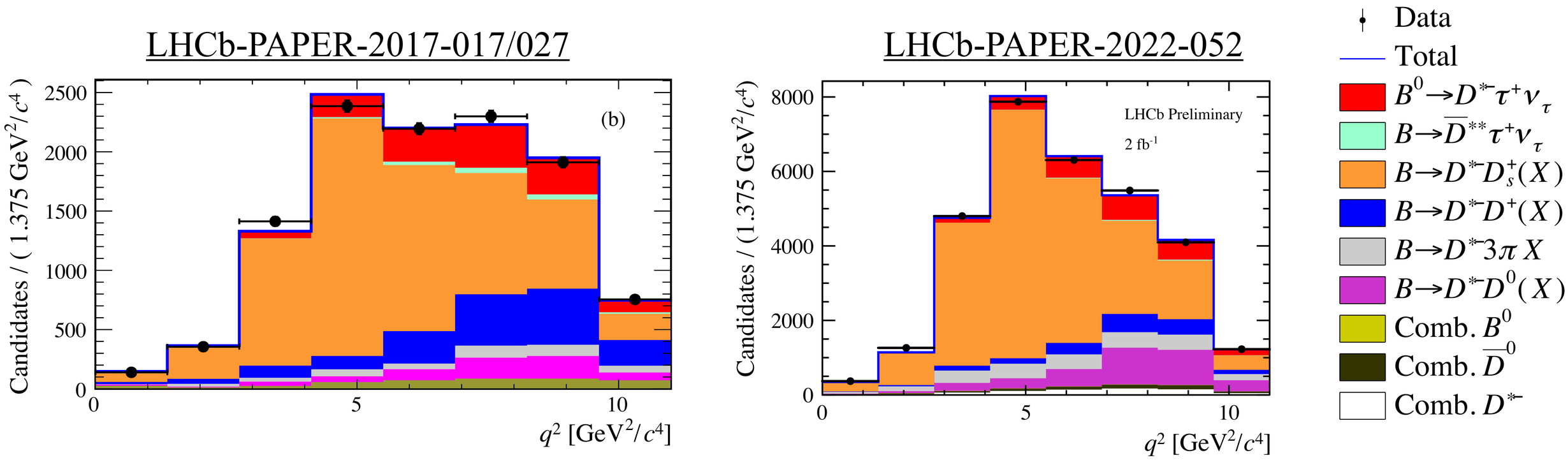




- Compared to last time,

Signal fits

- Run I dataset not reanalysed and instead averaged with run II, taking into account systematic correlations.

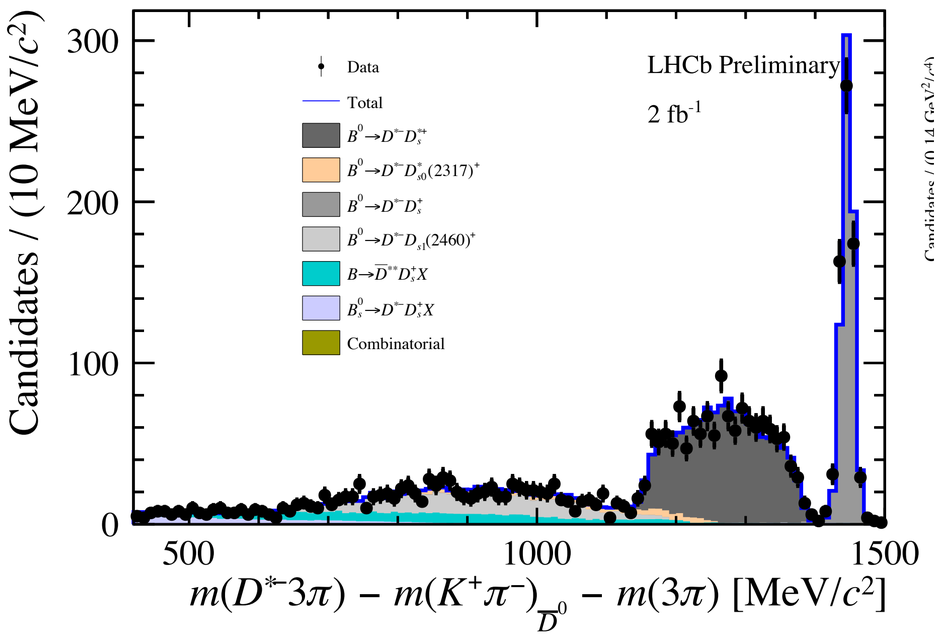


- Different background composition between run periods due to the improved selection (compare the Y-axis scales).

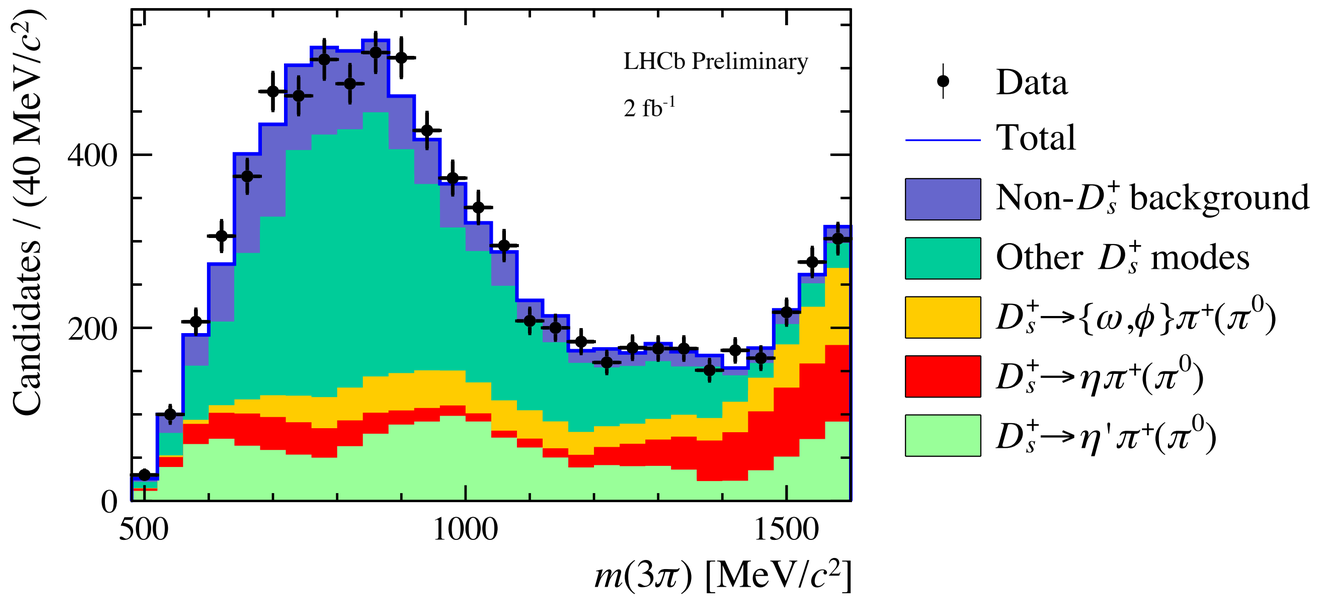
Main control channel

- Controlling the orange B—>DD$_s$ means inverting the BDT selection.

B—>DD$_s^{(*)}$ decay



D$_s$—>3pi(X)



- Both aspects of the decay controlled in data and look good.

Results

LHCb-PAPER-2022-052

- Run I dataset not reanalysed and instead averaged with run II, taking into account systematic correlations.

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

- Using external measurements of normalisation and muonic mode:

$$\boldsymbol{R(D^*) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})}$$

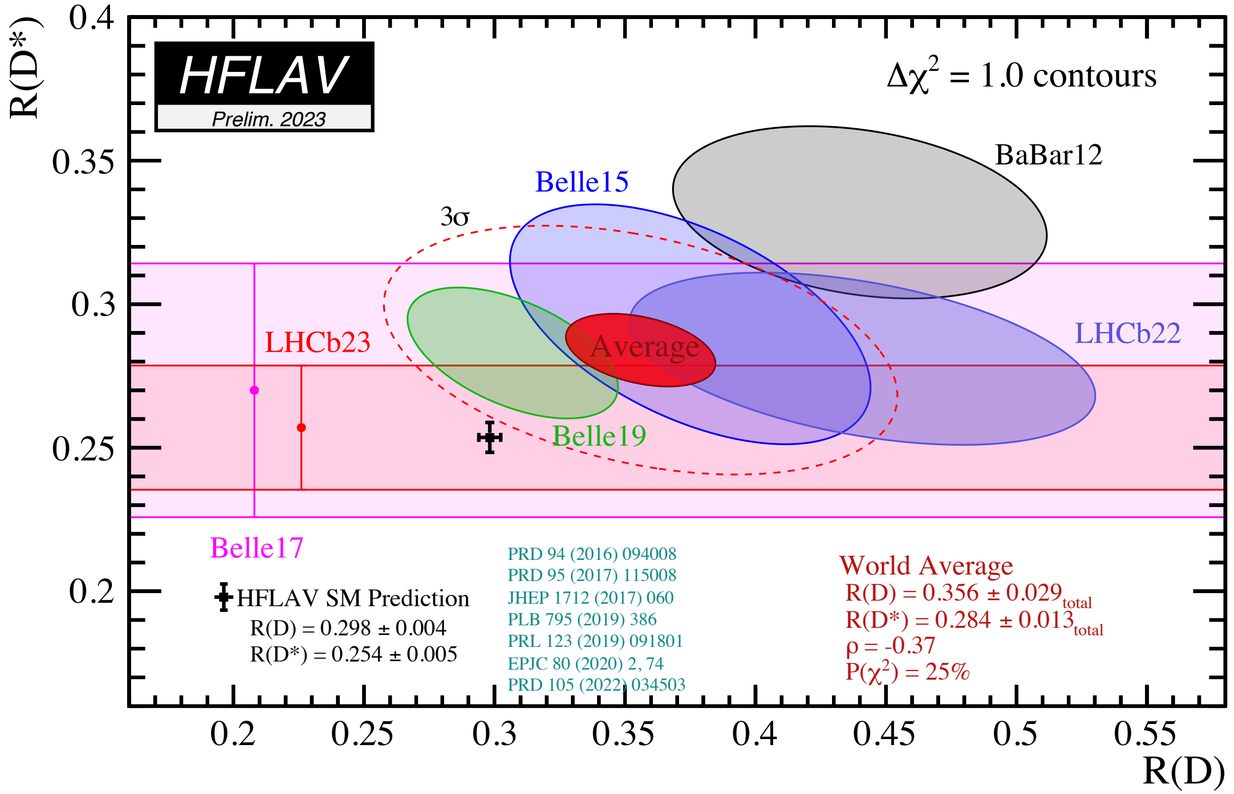
- Doing the average with the run 1 result:

$$\boldsymbol{R(D^*)_{2011-2016} = 0.257 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.012\,(\text{ext})}$$

- Very consistent with SM prediction.

$$R(D^*)_{\text{SM}} = 0.254 \pm 0.005$$ [HFLAV]

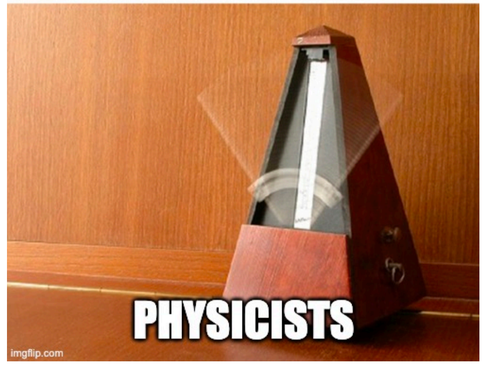
Latest combination



- Three-prong measurement strong consistency with SM has led to some fairly hyperbolic proclamations that the anomaly is going away.
  - However, latest significance remains at 3.2σ, very similar to pre-2022.

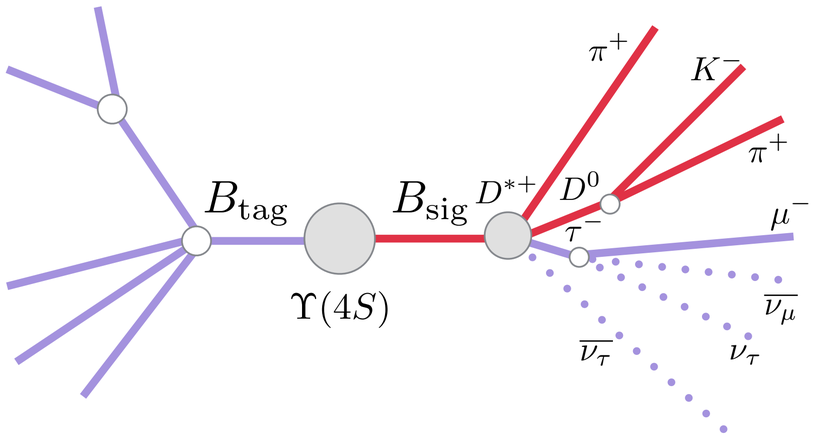
What Is an Overreaction?

An overreaction is an extreme emotional response to new information. In finance and investing, it is an emotional response to a security such as a stock or other investment, which is led either by greed or fear. Investors overreacting to news cause the security to become either overbought or oversold until it returns to its intrinsic value.

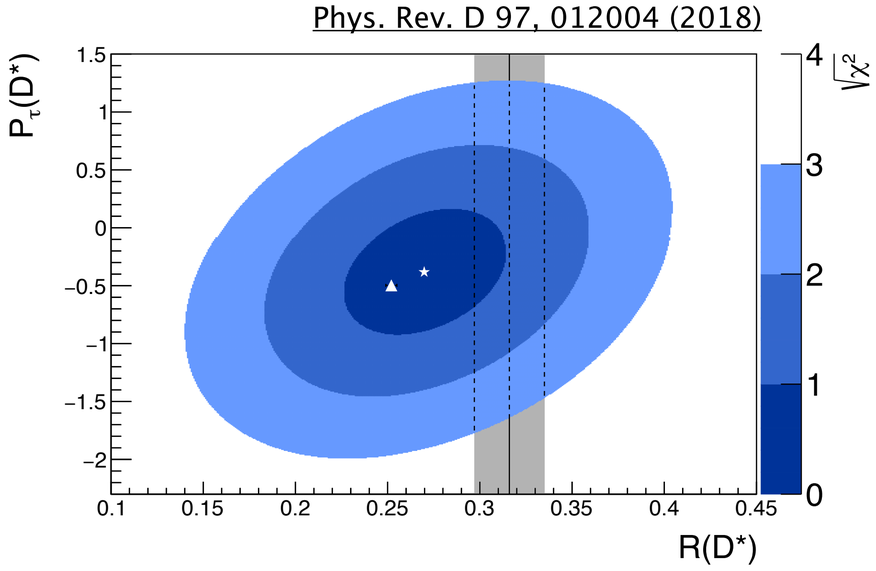


Measurements at the B-factories

- Doubly biased towards LHCb in this talk due recency and my own wheelhouse.
- B-factory measurements have big advantages with respect to LHCb on the purity and resolution.
- Kinematic tagging helps hugely to clean up signal, improved by factor ~2 for Belle II [arXiv:1807.08680]



- For example measuring the polarisation of the tau using $\tau \to \pi\nu$.



- Eagerly awaiting Belle-II measurements

Summary

- Semileptonic analyses are complicated, take time to complete.
  - Since last BFA progress made in R(D(*)) for two different τ decay modes at LHCb.
- Significance doesn't move much as its combination of many measurements of equal precision.
  - It will take a long time to clarify the situation.
- There's plenty more b->clu measurements that I didn't cover here today. Take a look at last week's semileptonic workshop for a nice overview: https://agenda.infn.it/event/34419/timetable/