Experimental mini-review on SL decays

Excluding results on $|V_{xb}|$ and $R(D^{(*)})$

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on behalf of the LHCb, Belle and BaBar collaborations

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Why other decays?

- The decays $B \to D^{(*)}\ell\nu$ allow measurements of $|V_{cb}|$ and $R(D^{(*)})$.
- Motivations for looking elsewhere:
  - Complimentary sensitivity/systematics from other b-hadron species.
  - Study charm hadron spectroscopy - tests of non-perturbative QCD.
  - Feed-down from more exotic hadrons can be important backgrounds.

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

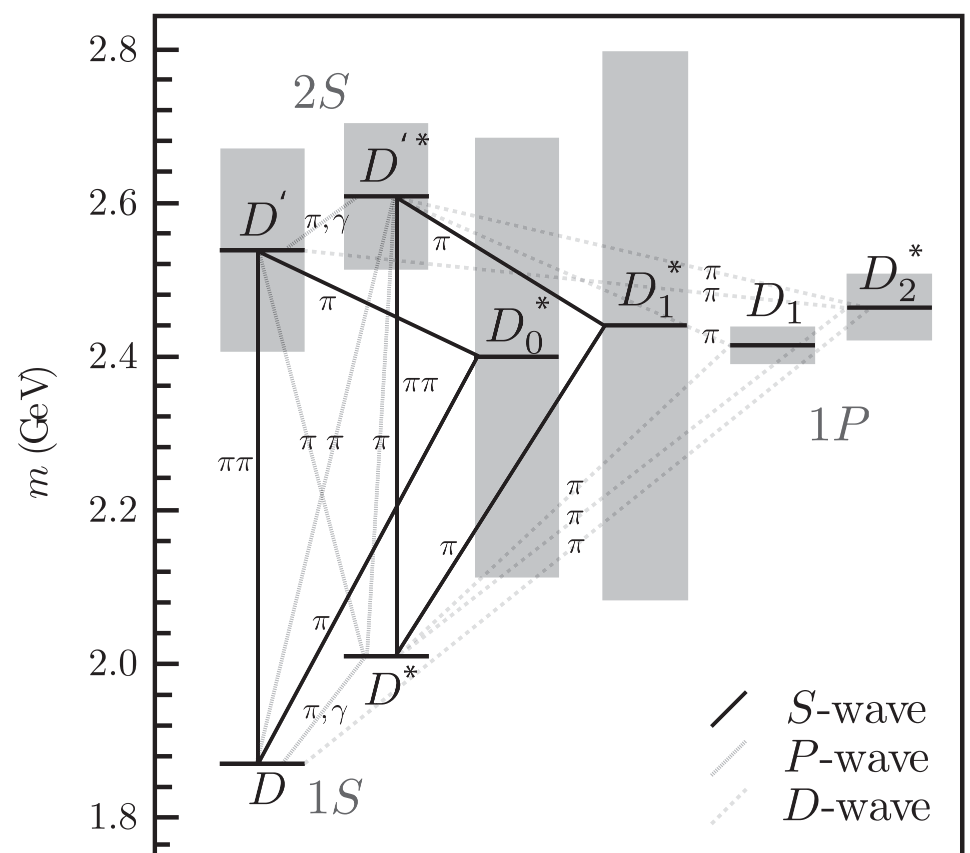
- The decays $B \to D^{(*)}\ell\nu$ make up about 70% of the inclusive semileptonic rate.

$$\left.\begin{array}{r}\mathcal{B}(B \to D^{*}\ell\nu) = (4.95 \pm 0.11)\% \\ \mathcal{B}(B \to D\ell\nu) = (2.42 \pm 0.12)\%\end{array}\right\rangle (7.37 \pm 0.15)\%$$

$$\mathcal{B}(B \to X_c\ell\nu) = (10.65 \pm 0.15)\%$$

- The rest, which should have a BF of about 3%, is referred to as $B \to D^{**}\ell\nu$

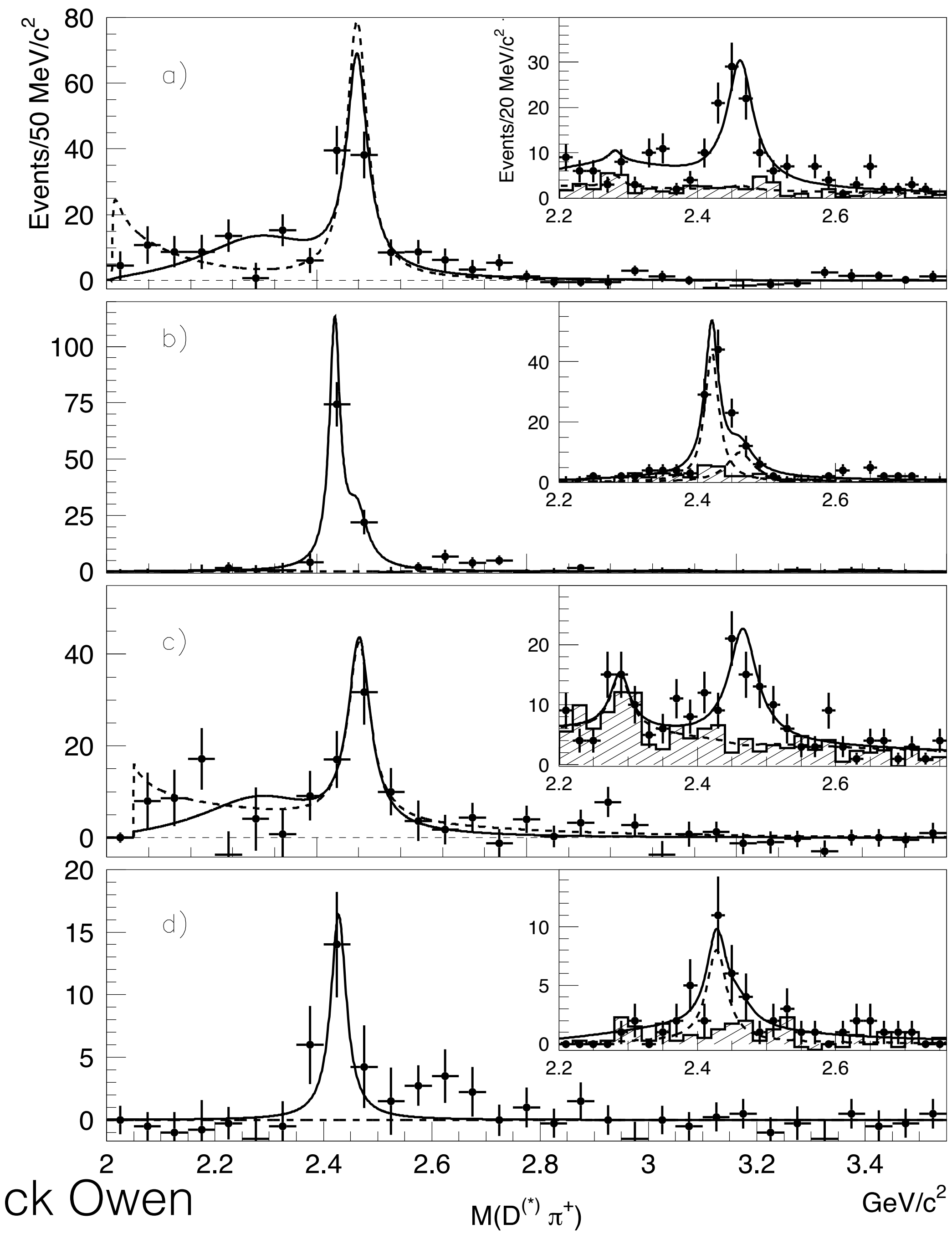
meson	L	j_l	J^P	mass $[GeV/c^2]$	width $[GeV/c^2]$	decay modes
D	0	1/2	0^-	1.867	-	various
D^*	0	1/2	1^-	2.009	-	$D\pi$, $D^0\gamma$
D_0^*	1	1/2	0^+	2.360	0.275	$D\pi^-$
D_1'	1	1/2	1^+	2.427	0.384	$D^*\pi^-$
D_1	1	3/2	1^+	2.422	0.026	$D^*\pi^-$, $D\pi^+\pi^-$
D_2^*	1	3/2	2^+	2.464	0.043	$D^*\pi^-$, $D\pi^-$



The four lightest states

- Measurements of the four lightest states performed by the BaBar and Belle.

PRD77,091503 (2008)



Charm state X_c	$\mathcal{B}(B^+ \to X_c\, \ell^+\, \nu)$
D	$(2.31 \pm 0.09)\,\%$
D^*	$(5.63 \pm 0.18)\,\%$
$\sum D^{(*)}$	$\mathbf{(7.94 \pm 0.20)\,\%}$
$D_0^* \to D\,\pi$	$(0.41 \pm 0.08)\,\%$
$D_1^* \to D^*\,\pi$	$(0.45 \pm 0.09)\,\%$
$D_1 \to D^*\,\pi$	$(0.43 \pm 0.03)\,\%$
$D_2^* \to D^{(*)}\,\pi$	$(0.41 \pm 0.03)\,\%$
$\sum D^{**} \to D^*\pi$	$\mathbf{(1.70 \pm 0.12)\,\%}$
$D\,\pi$	$(0.66 \pm 0.08)\,\%$
$D^*\,\pi$	$(0.87 \pm 0.10)\,\%$
$\sum D^*\pi$	$\mathbf{(1.53 \pm 0.13)\,\%}$
$\sum D^{(*)} + \sum D^*\pi$	$\mathbf{(9.47 \pm 0.24)\,\%}$
$\sum D^{(*)} + \sum D^{**} \to D^{(*)}\pi$	$\mathbf{(9.64 \pm 0.23)\,\%}$
Inclusive X_c	$\mathbf{(10.92 \pm 0.16)\,\%}$

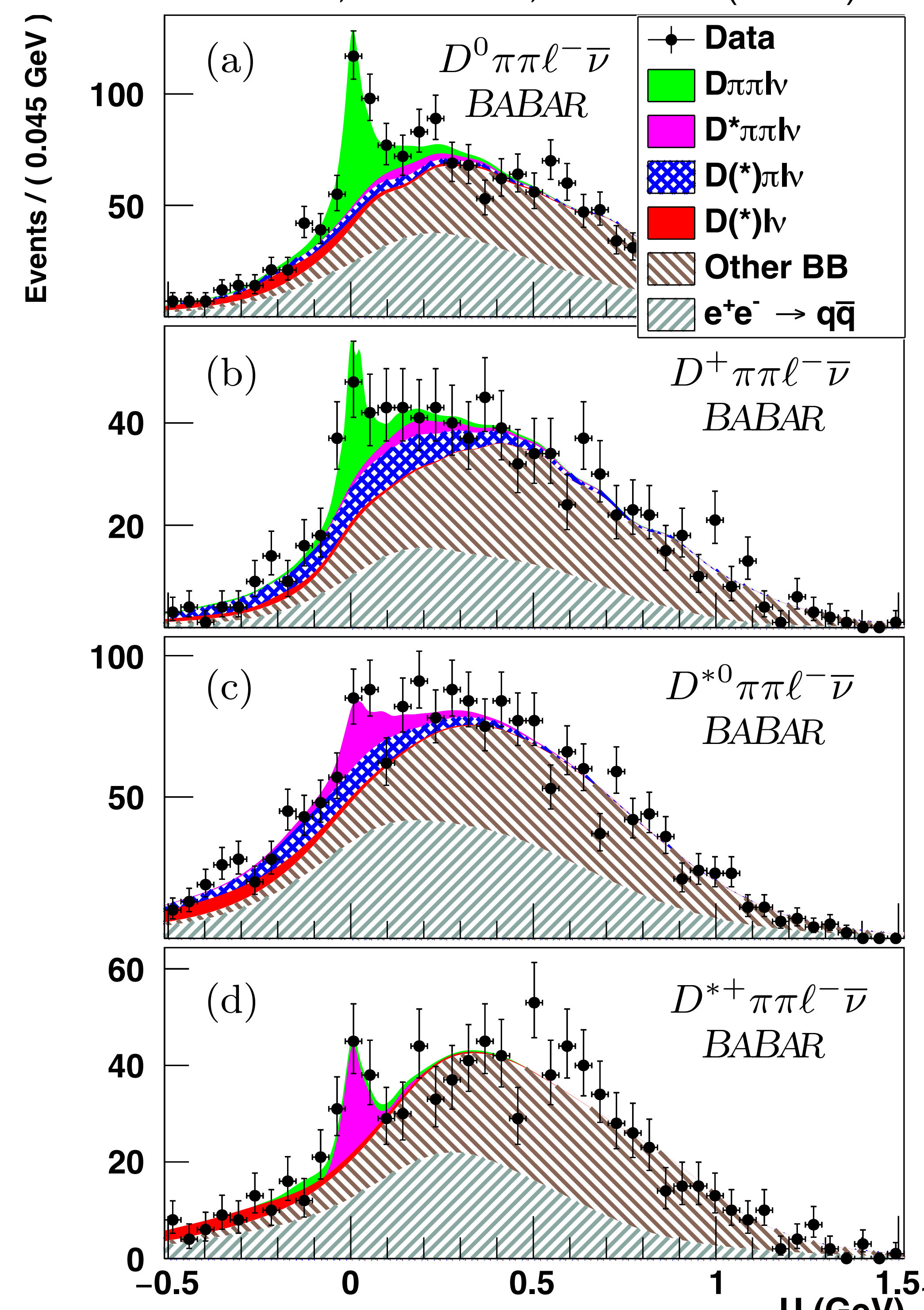
S. Turczyk, CKM 2012

With just $D^{(*)}\pi$ combinations, get significant gap between sum of exclusives/inclusive measurements.

Measurement of $B \to D^{(*)}\pi^+\pi^-\ell\nu$

- More recently, BaBar extended the search to $D^{(*)}\pi^+\pi^-$

BaBar, PRL116, 041801 (2016)



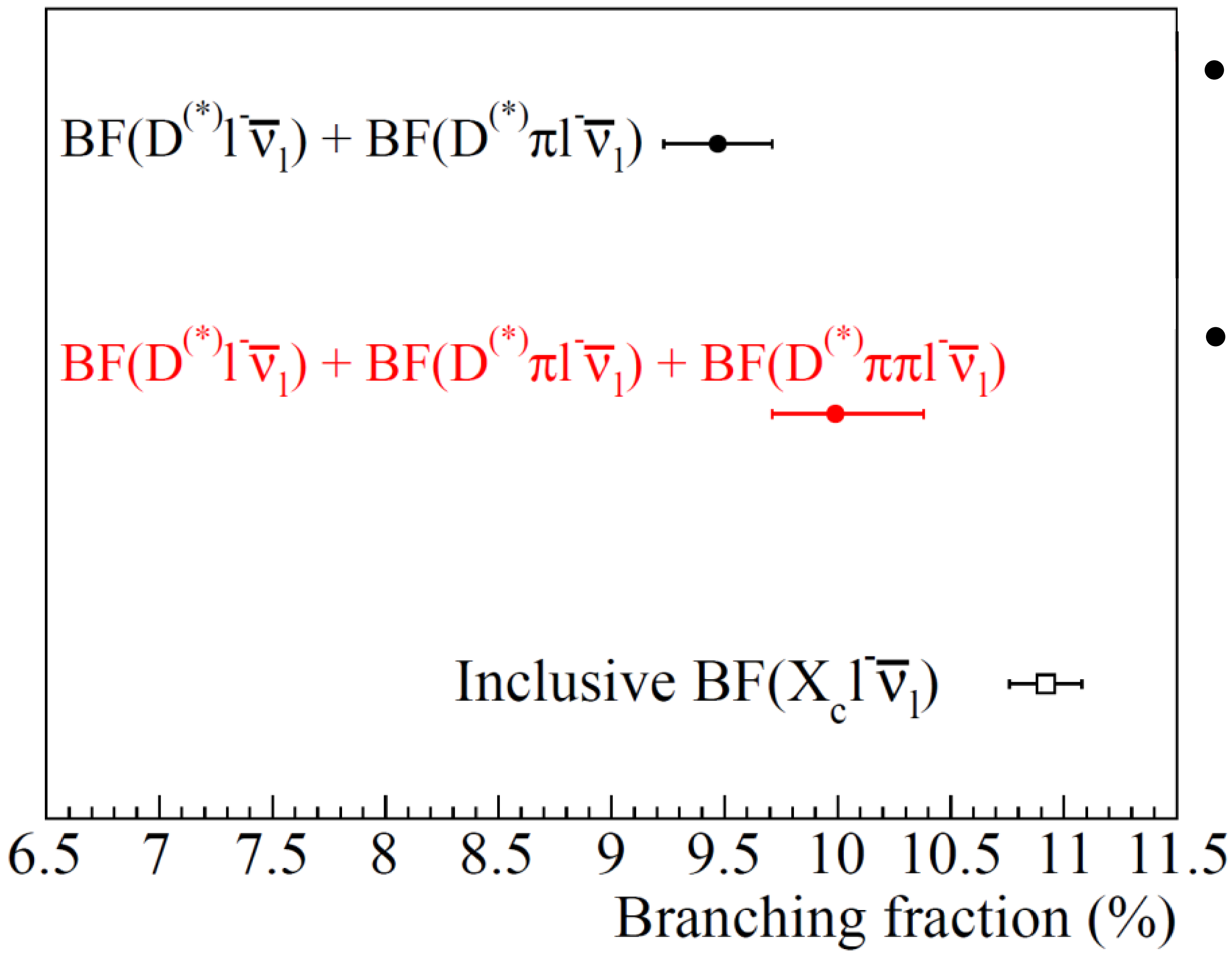
- Use hadronic tagging to improve kinematic discrimination.
- Fit variable $U \equiv E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|c$
- Largest systematic uncertainty arises from the knowledge of the contributions to the signal.

Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\overline{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\overline{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\overline{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

- Belle/LHCb should be able to do a competitive measurement.

Update to the inclusive/exclusive gap

- Add neutral pion modes using isospin symmetry to get $BF(\bar{B} \rightarrow D\pi\pi l^{-}\bar{\nu_l}) + BF(\bar{B} \rightarrow D^{*}\pi\pi l^{-}\bar{\nu_l}) = (0.52^{+0.14+0.27}_{-0.07-0.13})\%$



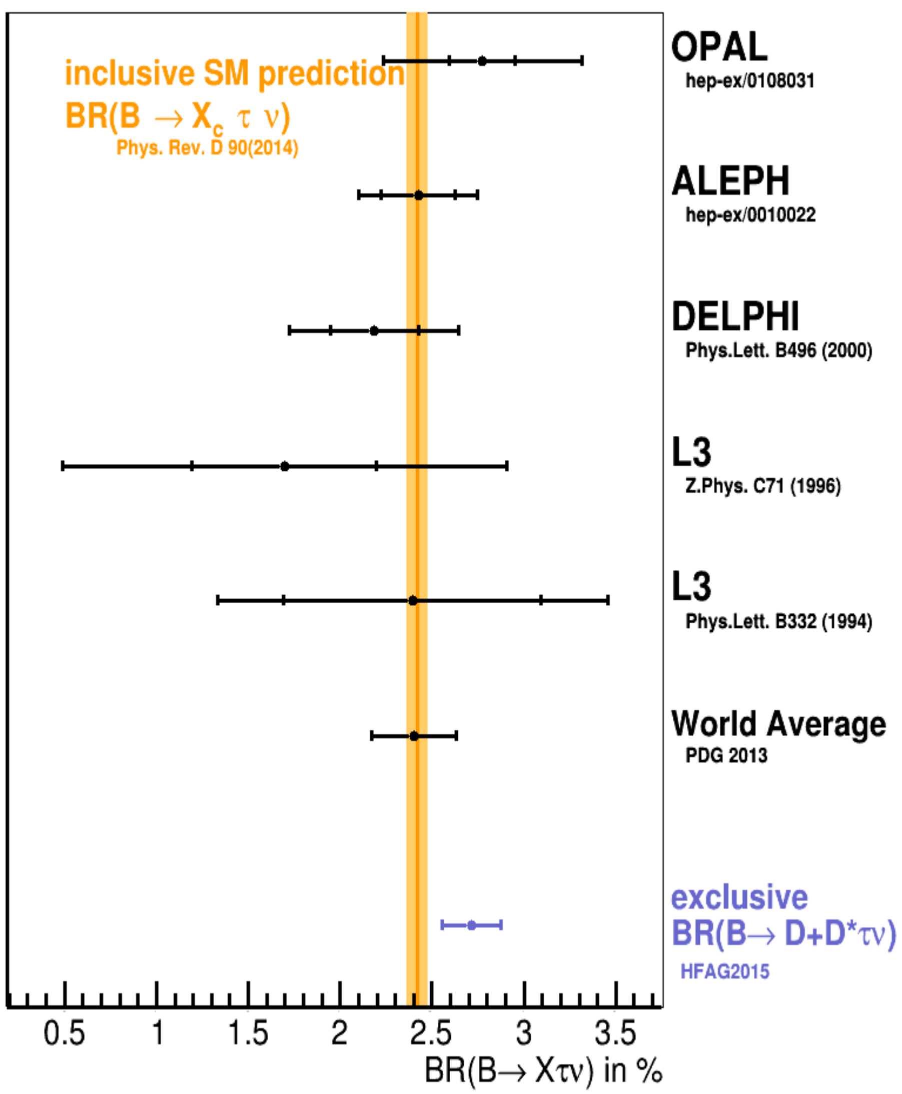
From S. Hirose @ FPCP 2016

- Gap between sum of exclusives and inclusive now down to 2/3 σ.
- What else is missing?
  - $B \rightarrow D^{(*)}\eta\ell\nu$?
  - Non-resonant?
  - More excited states?

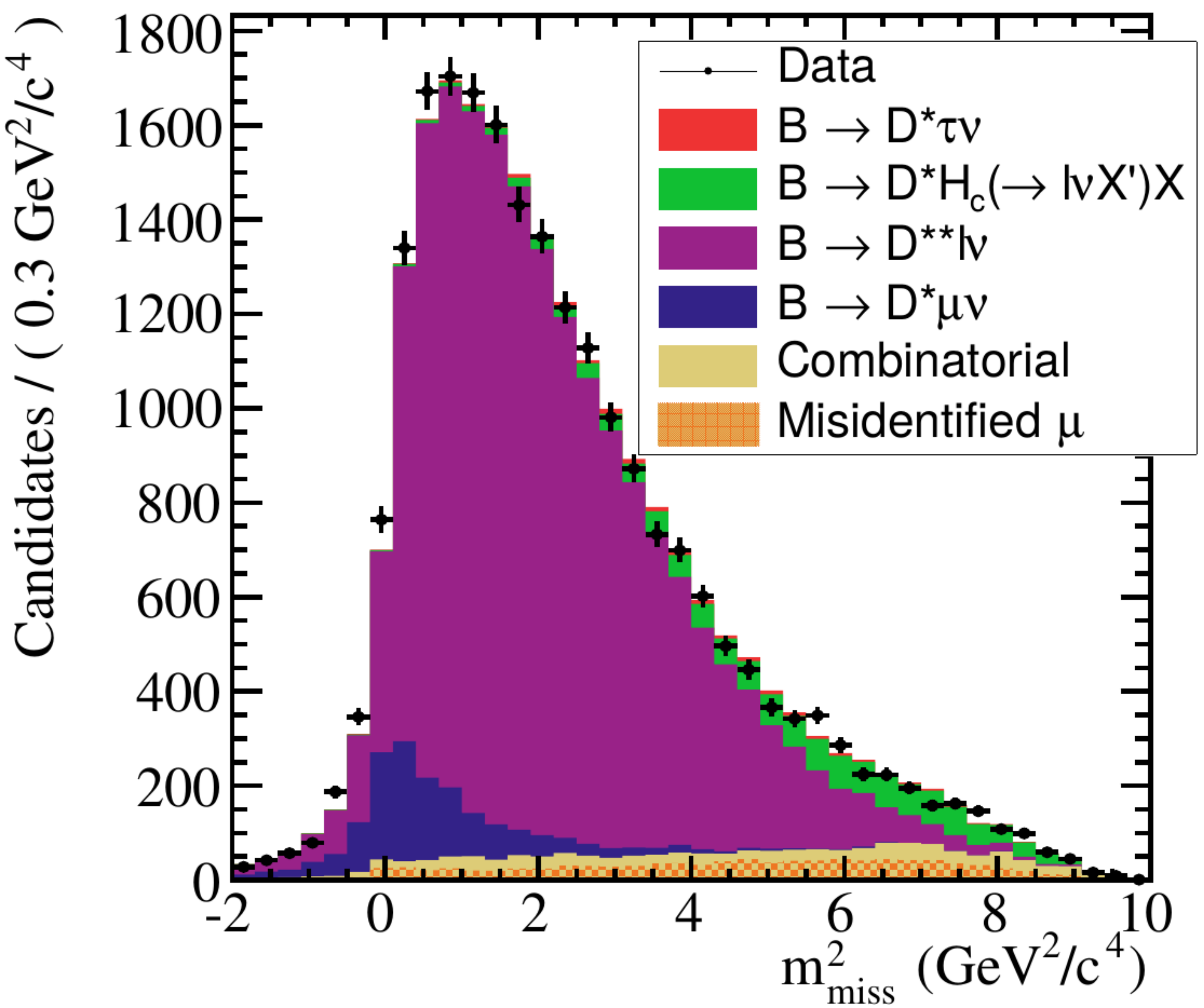
- Constraints on composition found from moment analysis [F. Bernlochner et al, arXiv:1402.2849]. No signal resonance can fill the gap.

Have opposite problem in τ channels

- The decays $B \to D\tau\nu$ and $B \to D^*\tau\nu$ saturate inclusive rate
- Should also study $B \to D^{**}\tau\nu$



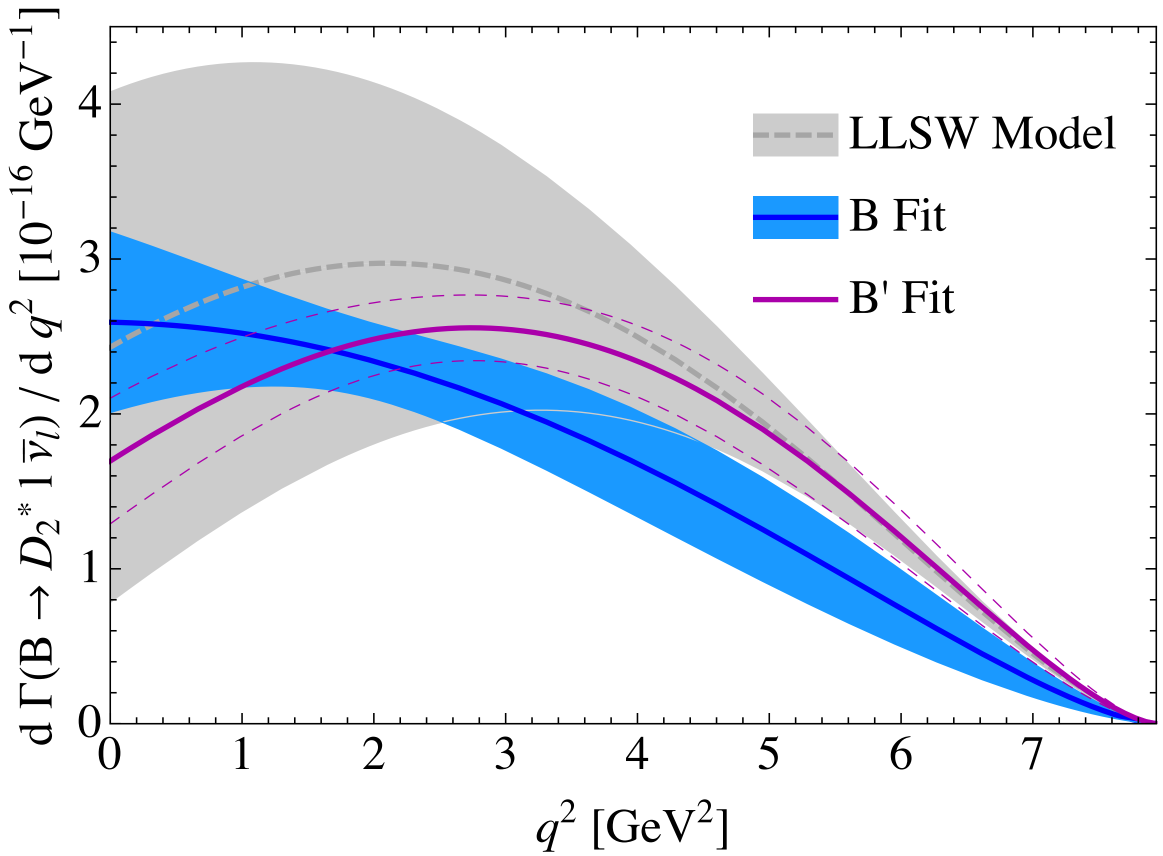
LHCb, PRL115,111803(2015)

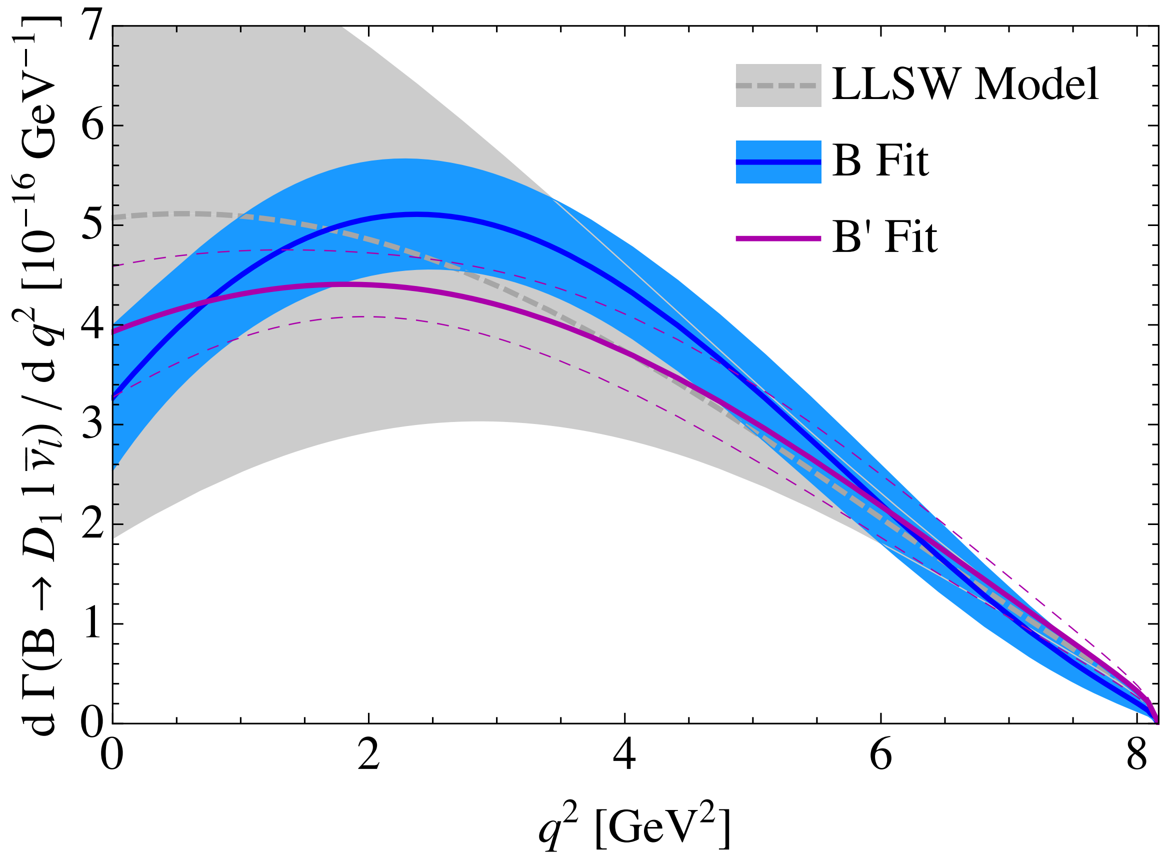


- Should have enough signal in LHCb/Belle 2 datasets.

What about R(D**)?

- With experimental information, possible to control uncertainty on R(D**)?





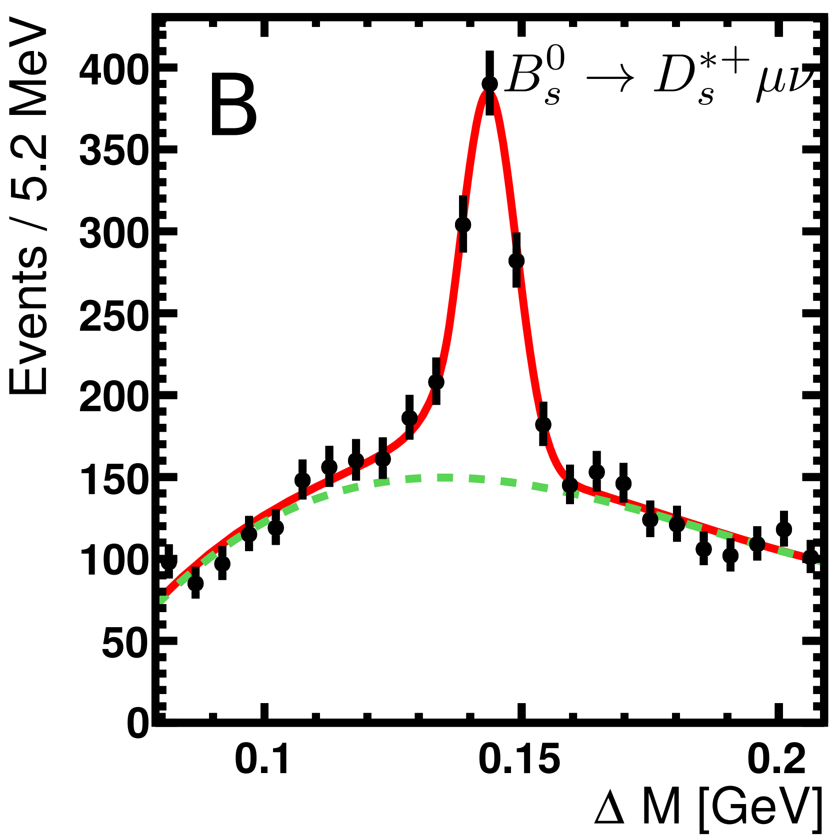
F. Bernlochner and Z. Ligeti: arXiv:1606.09300

- By fitting data, can get ~10% on R(D**), with different uncertainties depending on hadron species.

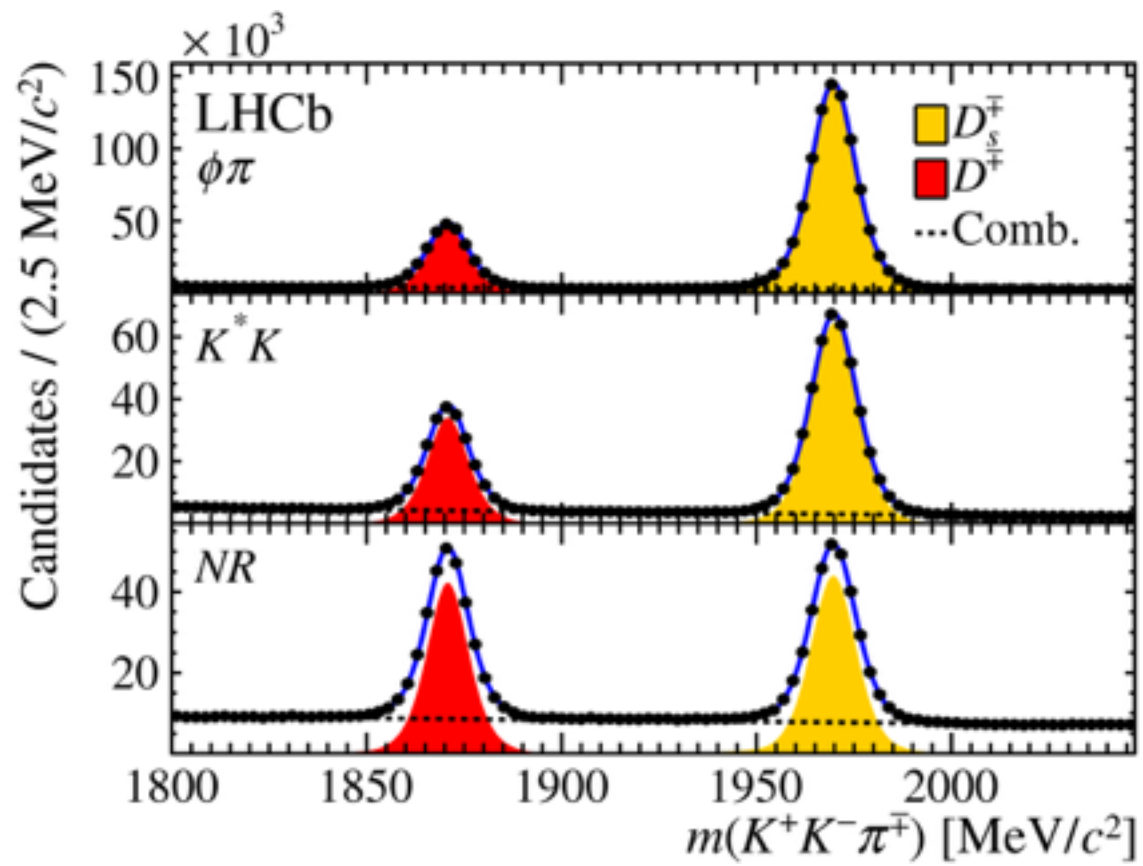
- Uses information on fully hadronic decays for the form factor at q^2=0.

Other b-hadron species

- We can learn more from other b-hadron species.
- For the excited cs system, the 1/2 states are narrow - could shed light on the 1/2 vs 3/2 puzzle?
- Not so well studied, most precise measurement from Belle.



Belle, Phys. Rev. D 92, 072013 (2015)

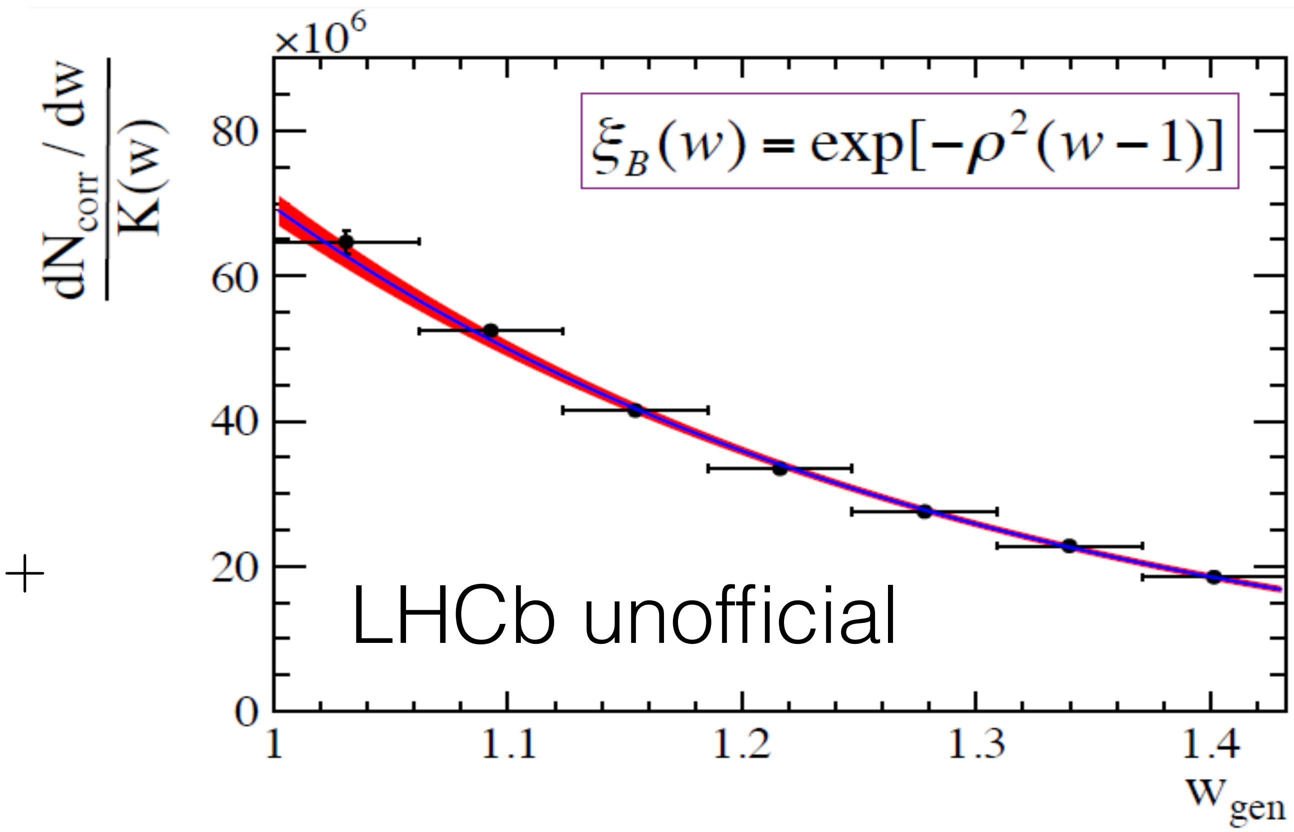


Phys. Rev. Lett. 117, 061803 (2016)

- Only two helicity states for D_s^{*+}, form factor measurement would be interesting.

b-bayrons

- Even less studied - semileptonic b-baryon decays.
- Here LHCb should be able to make precise studies - 20% of b-hadrons are b-baryons.
- Form-factor measurement of the ground state ongoing.
- Should be able to measure also the first two excited states, $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$.



- Should constrain on R(Λ_c^{*+}), which should also be possible in the near future.

Summary

- There are a couple of puzzles outside the usual $|V_{xb}|$ and $R(D^{(*)})$ ones.
  - Inclusive vs exclusive gap.
  - 1/2 vs 3/2 puzzle still exists.
- It is important to understand these D** states if we want to convince everyone of the $R(D^*)$ results.
- BaBar has helped with their $B \to D^{(*)}\pi^+\pi^-\ell\nu$ measurement.
  - More measurements needed for Belle and LHCb!
- Other b-hadron species provide complimentary information - looking forward to B_s^0 and Λ_b measurements.