Differential branching fraction and angular analyses in rare b decays at LHCb

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On behalf of the LHCb collaboration

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The first penguins

- CLEO found evidence of B→K*γ with BF~5 x 10^{-5} in 1993

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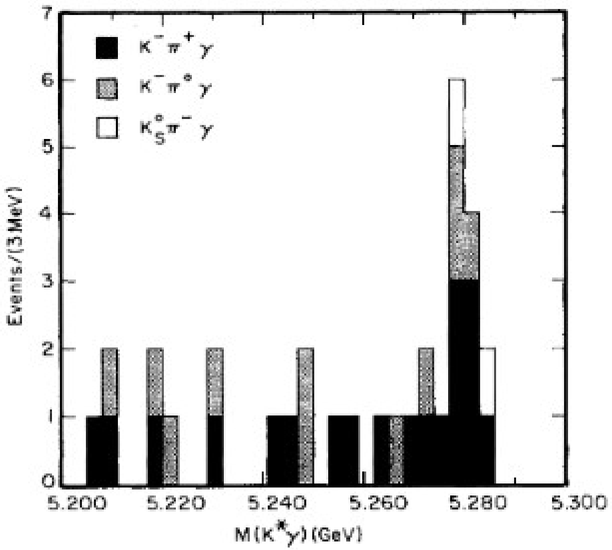
Evidence for Penguin-Diagram Decays: First Observation of $B \to K^*(892)\gamma$



Many penguins have followed

- We are now looking at many penguins and in many different ways
- What do we want from the studies
  - Cross check current results from experimental and theoretical view
  - Look for “forbidden” decays
  - Clarify if current anomalies are due to New Physics
  - Improve our understanding of QCD in non-pertubative regime

Penguin studies on Macquarie island, 1968

$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$

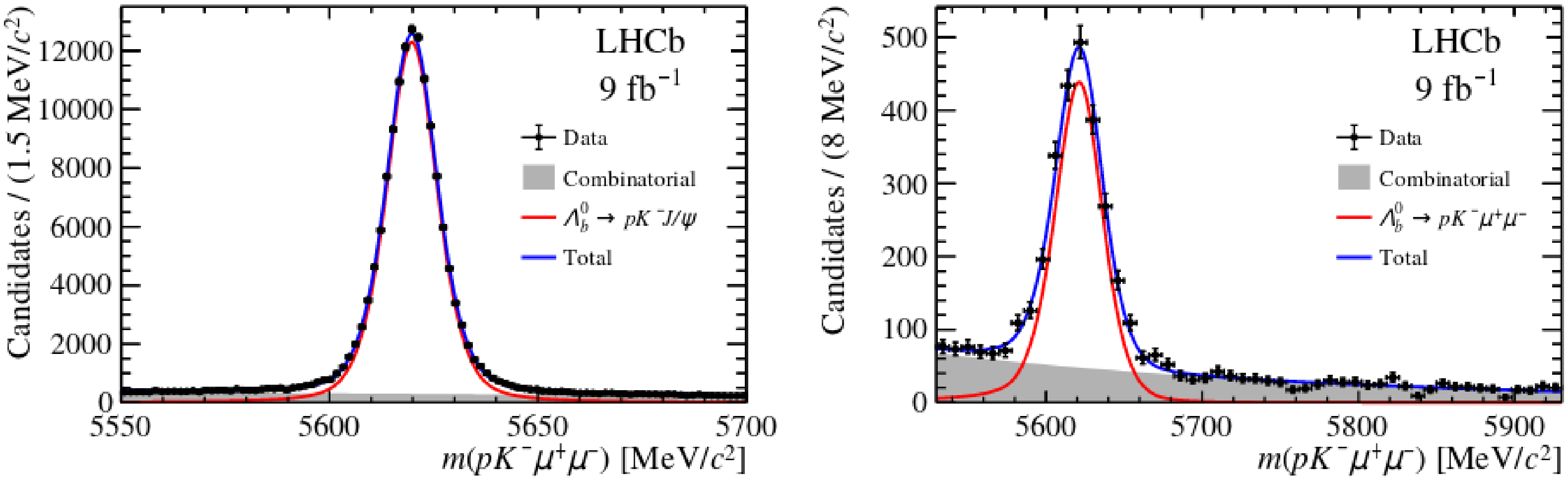
- In contrast to Belle II, LHCb has a very large sample of b baryons
  - This means that we get different angular structures in decay
  - Previous measurements with Λ where $J^P=(1/2)^-$, now with Λ(1520) where $J^P=(3/2)^-$
- First question to answer is if we can isolate the Λ(1520) sufficiently well in the *pK* mass spectra

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	

$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$

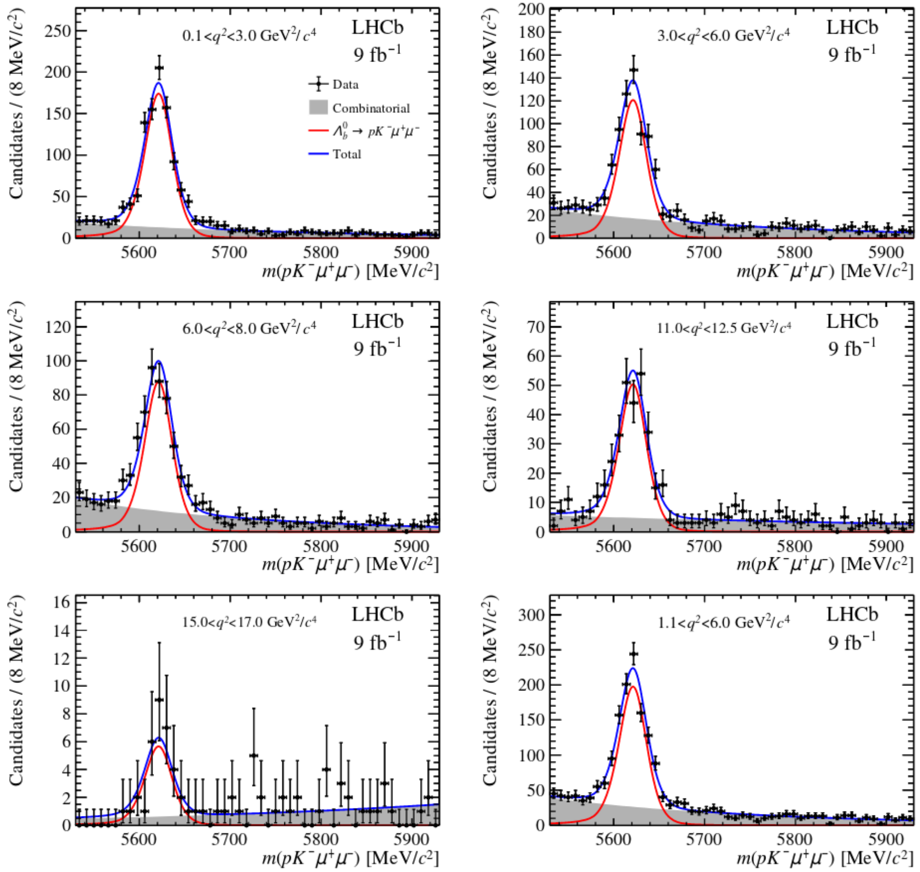
- As all other electroweak penguin analyses, the normalisation of the branching fraction is done through the corresponding J/ψ decay mode

$$\left[\frac{d\mathcal{B}(\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-)}{dq^2}\right]_{q^2_{\rm min}}^{q^2_{\rm max}} = \frac{1}{(q^2_{\rm max} - q^2_{\rm min})}\frac{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi)\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\Lambda(1520) \to pK^-)} \times \frac{N_{\Lambda(1520)\mu^+\mu^-}}{N_{pK^- J/\psi}}\frac{\varepsilon_{pK^- J/\psi}}{\varepsilon_{\Lambda(1520)\mu^+\mu^-}},$$



$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

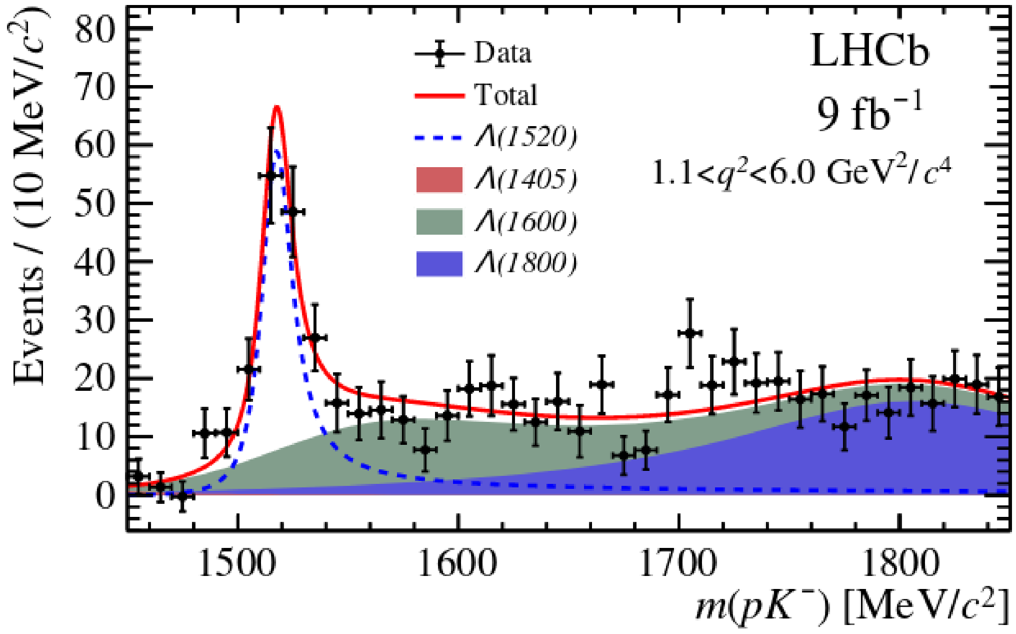
- Fits of *pK*μμ mass distribution made in regions of q^2 outside the J/ψ and ψ(2S) resonances
- Very clear signal in all regions
- sWeights are then derived from this distribution to get the *signal only pK* mass distribution



arXiv:2302.08262

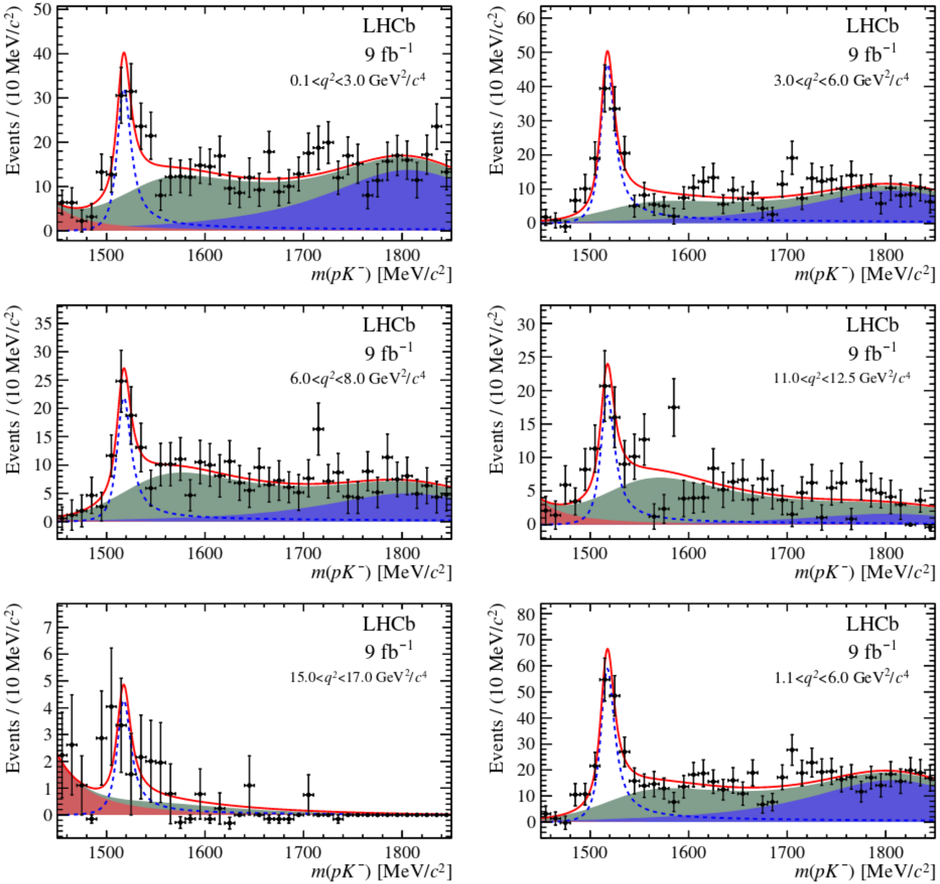
$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

- The Λ(1520), Λ(1405), Λ(1600), and Λ(1800) resonances all included in fit
- Relativistic Breit-Wigner lineshapes used
- Mass resolution so good that it only matters for Λ(1520)
- Uncertainty in resonance parameters and interference treated as systematics



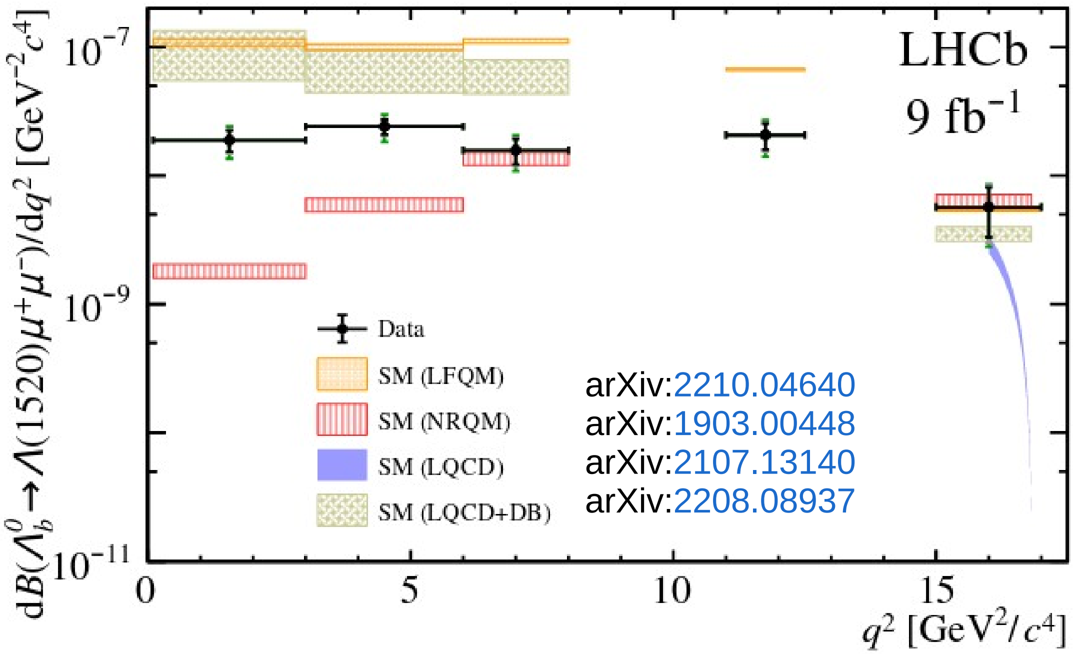
$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

- Fits in all regions show:
  - Clear Λ(1520) peak
  - Not as isolated as the K* in $B^0 \to K^{*0}\mu^+\mu^-$
  - Still promising for angular analysis



$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$

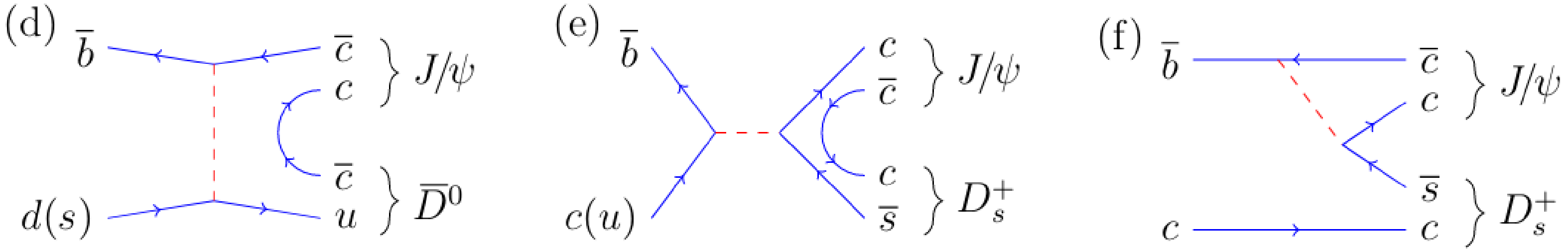
- Branching fraction measurement at the end is dominated by statistical uncertainty
- Comparison to theoretical predictions are all over the place
- Some consolidation required on theory side to be conclusive



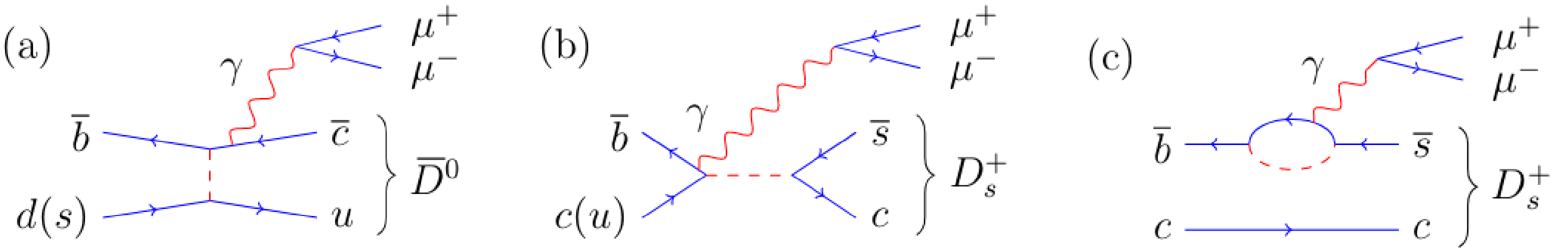
arXiv:2210.04640
arXiv:1903.00448
arXiv:2107.13140
arXiv:2208.08937

Search for $B \to D\mu^+\mu^-$

- Decays can proceed through either charmonium resonances



- … through ISR/FSR photons … or penguins

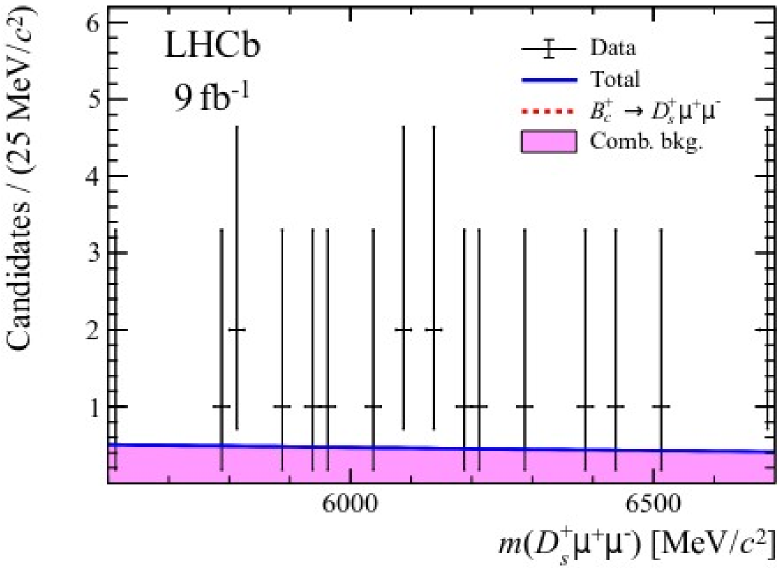


- For B^+, B^0 and B^0_s decays there will also be tree level decays with light resonances

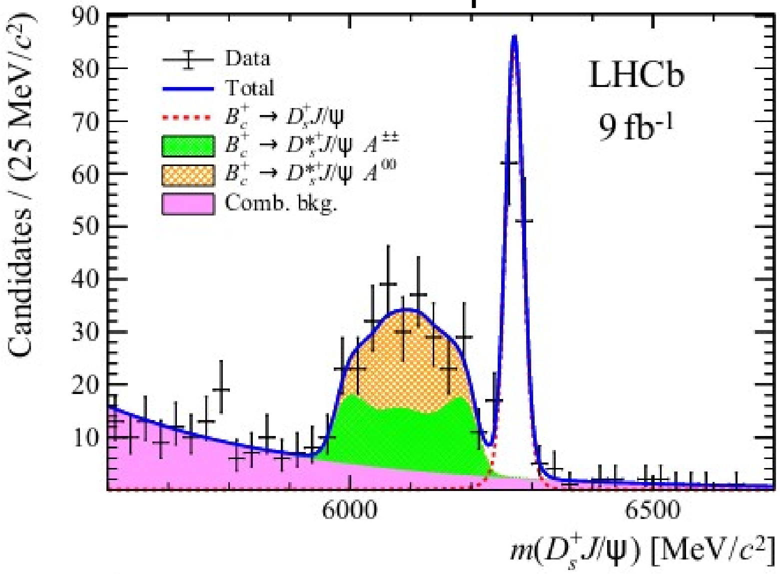
$B_c \to D_s \mu^+ \mu^-$

- Non-resonant selected as $q^2 < 8.0$ GeV^2 to avoid all charmonium
- Charmonium region selected narrowly around J/ψ

Non-resonant



J/ψ



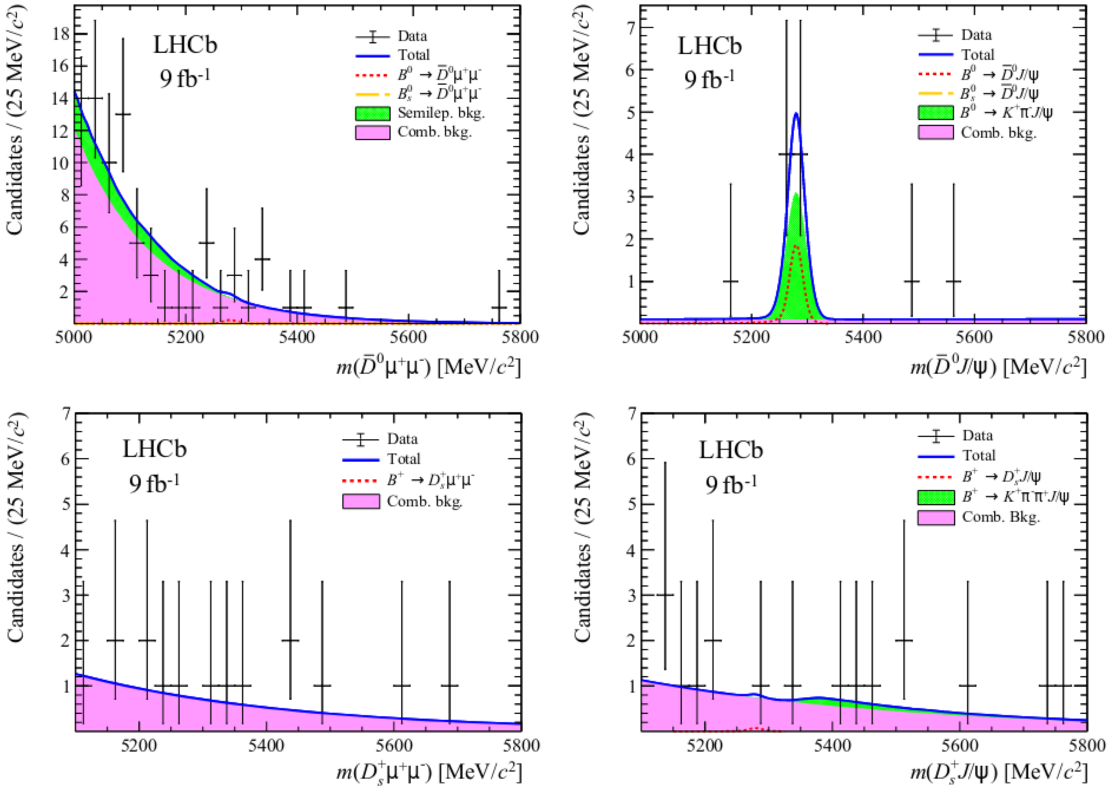
$$\frac{f_c}{f_u} \cdot \mathcal{B}\left(B_c^+ \to D_s^+ J/\psi\right) = (1.63 \pm 0.15 \pm 0.13) \times 10^{-5}$$

Limits on $B \to D\mu^+\mu^-$

- For all other decays we set upper limits on the branching fractions

Branching fraction	Upper limits 90 % CL	Upper limits 95 % CL
$\mathcal{B}(B^0 \to \overline{D}^0\mu^+\mu^-)$	4.0×10^{-8}	5.1×10^{-8}
$\mathcal{B}(B^+ \to D_s^+\mu^+\mu^-)$	2.4×10^{-8}	3.2×10^{-8}
$\mathcal{B}(B_s^0 \to \overline{D}^0\mu^+\mu^-)$	1.2×10^{-7}	1.6×10^{-7}
$f_c/f_u \cdot \mathcal{B}(B_c^+ \to D_s^+\mu^+\mu^-)$	7.5×10^{-8}	9.6×10^{-8}
$\mathcal{B}(B^0 \to \overline{D}^0 J/\psi)$	9.6×10^{-7}	1.1×10^{-6}
$\mathcal{B}(B^+ \to D_s^+ J/\psi)$	2.8×10^{-7}	3.5×10^{-7}
$\mathcal{B}(B_s^0 \to \overline{D}^0 J/\psi)$	1.0×10^{-6}	1.5×10^{-6}

- First measurements or improvements by 3+ orders of magnitude!

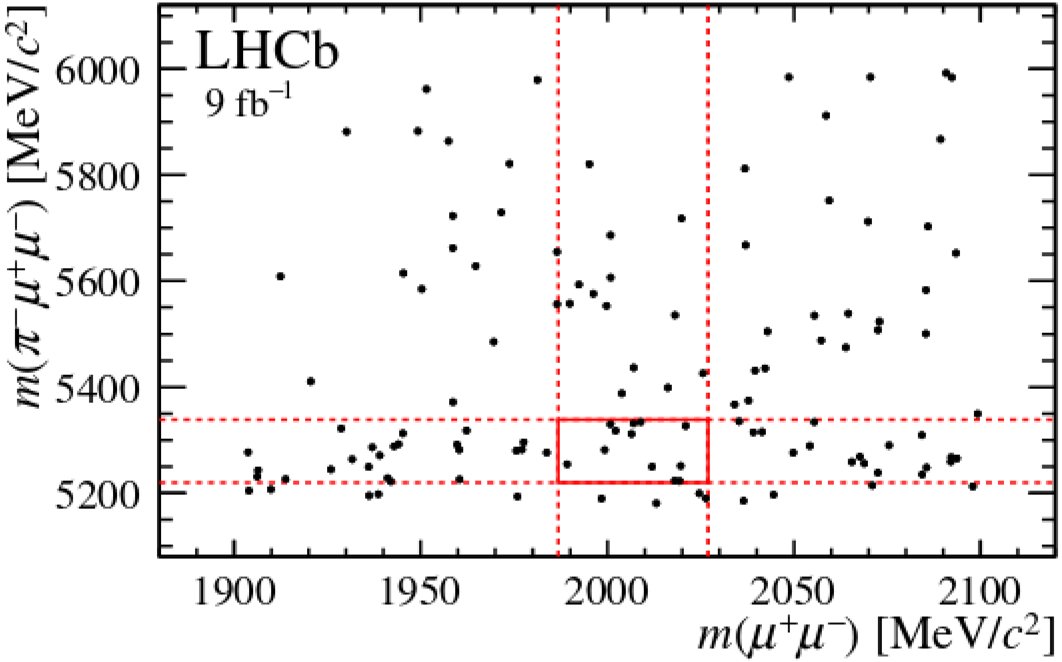


Search for $D^{*0}\to\mu^+\mu^-$

- The decay $D^{*0}\to\mu^+\mu^-$ can't proceed via EM or QCD
  - Partial width of weak decay is GIM suppressed but not helicity suppressed
  - Has to be compared to "large" width from strong and EM decay
  - Expectation is $BF=O(10^{-19})$
- Such a "forbidden" decay is a place to search for New Physics
  - No helicity suppression when comparing to $D^0\to\mu^+\mu^-$ searches
- Strong decay of D^{*0} means that prompt search would look for muons from primary vertex at LHC – not viable as pion mis-ID would drown it
  - Search instead for $B^-\to D^{*0}\pi^-$, $D^{*0}\to\mu^+\mu^-$, which is just a narrow peak in the $B^-\to\pi^-\mu^+\mu^-$ decay

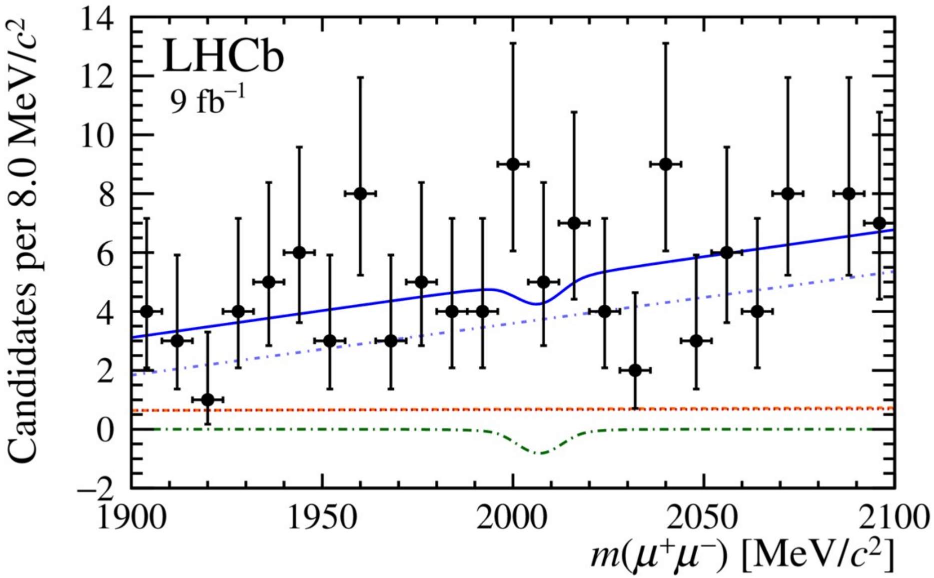
Search for $D^{*0} \to \mu^+\mu^-$

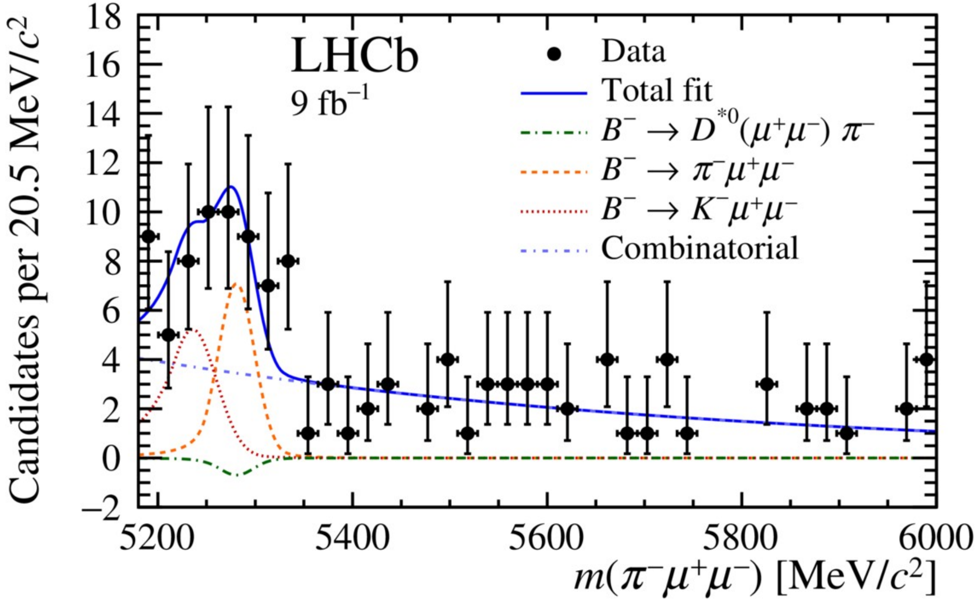
- Perform a 2D fit in the πμμ and μμ with 4 components
  - Signal peaking in both dimensions at B^- and D^{*0} mass
  - Non-resonant $B^- \to \pi^-\mu^+\mu^-$ decays (b→d penguin is a background!)
  - Non-resonant $B^- \to K^-\mu^+\mu^-$ decays with K→π mis-identification
  - Combinatorial background



Search for $D^{*0} \rightarrow \mu^+\mu^-$

- Projections of 2D fit shows that there is clearly no signal to be seen





Search for $D^{*0} \to \mu^+\mu^-$

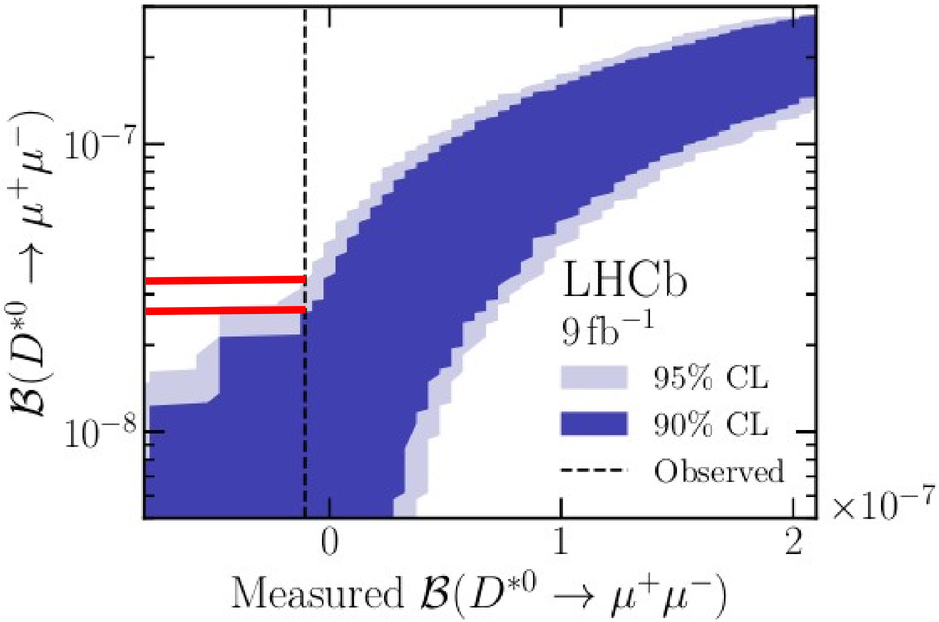
- Perform a 2D fit in the πμμ and μμ with 4 components
- In terms of yields we see -2 ± 3 $D^{*0} \to \mu^+\mu^-$ events, translating into

$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = (-1.06 \pm 1.85) \times 10^{-8}$$

- Using a Feldman-Cousins based method with pseudo experiments, set an upper limit

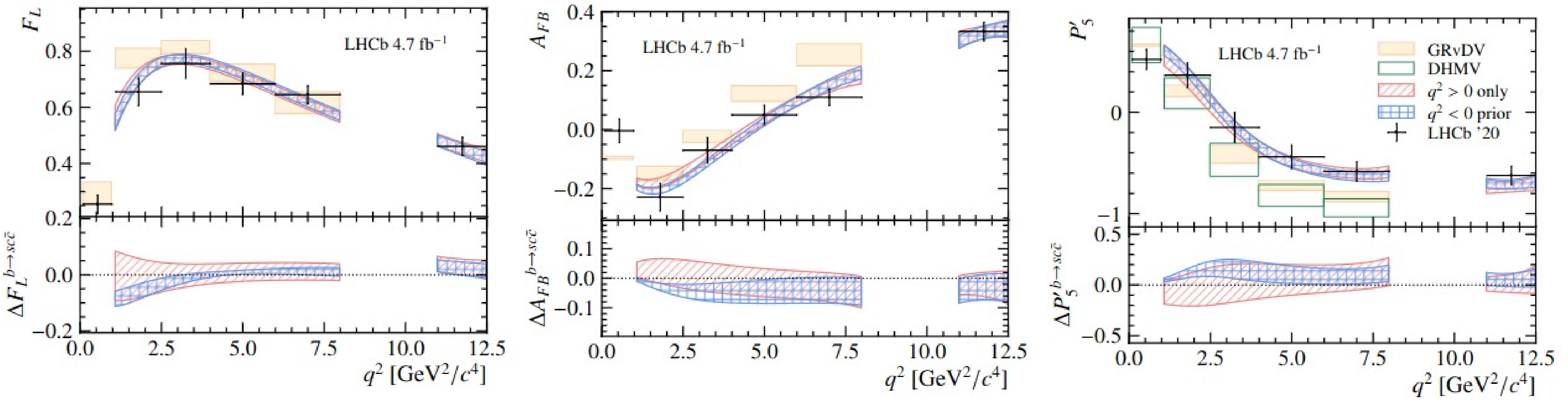
$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8}$$

at 90 (95)% CL



Current anomalies due to New Physics?

- Earlier presentation directly address the issue of the interplay between NP contributions and unaccounted QCD effects



- Analysis shows no weaknesses in the theoretical assumptions made for the previous binned analyses of the observables

Look for matter-antimatter differences

- QCD treat matter and antimatter identically – no CP violation
  - An observation of CP violation would indicate new physics amplitudes
  - To observe it requires interference with SM amplitudes of different phase
  - Unfortunately existing measurement exactly avoids regions where we will have phase difference

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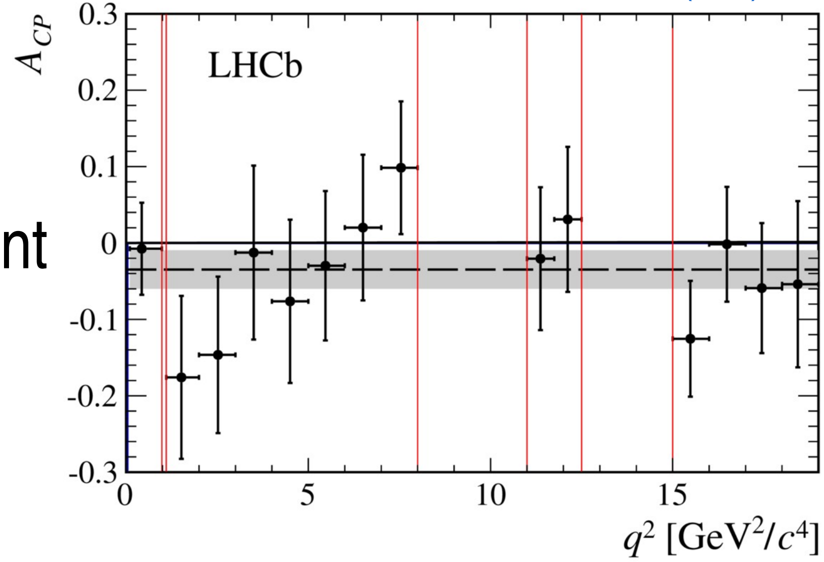

Look for matter-antimatter differences

- QCD treat matter and antimatter identically – no CP violation
  - An observation of CP violation would indicate new physics amplitudes
  - To observe it requires interference with SM amplitudes of different phase
  - Combining unbinned fit with CP violation analysis will allow for this

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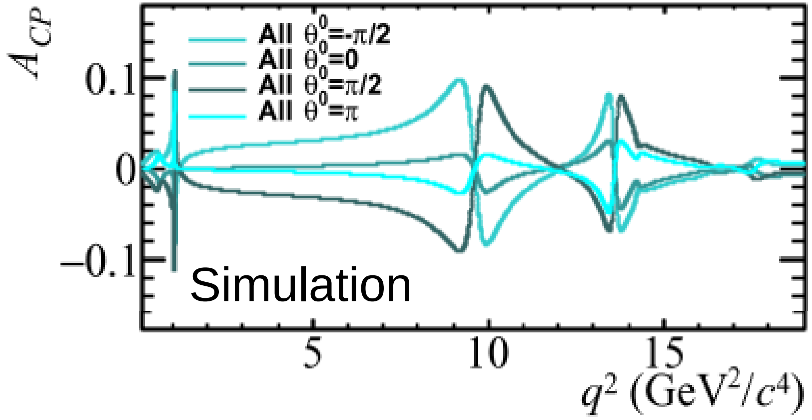

Conclusion

With enough data, we **WILL** be able to distinguish New Physics from QCD

LHCb upgrade I and Upgrade II will form big part of this