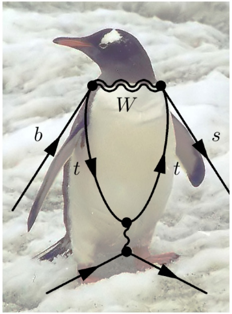
The potent power of the penguin

QMUL seminar

LHCb-PAPER-2025-041 (in preparation)

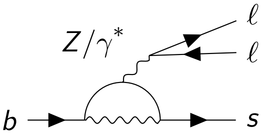


Mark Smith

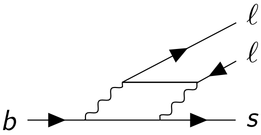
1 October 2025

Flavour changing neutral currents

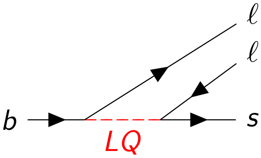
SM penguin:



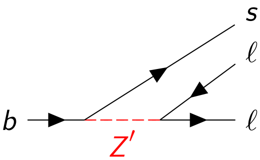
SM box:



NP leptoquark:



NP Z':



Flavour changing neutral currents

Small SM amplitude → excellent place to search for NP!

(Differential) BFs	Angular analyses	CP-violation
$\frac{d\Gamma(H_b \to F\ell\ell)}{d\,q^2}$	P_5', A_{FB} etc	$\frac{\bar{\Gamma}-\Gamma}{\Gamma+\bar{\Gamma}}$, $\frac{\bar{J}_i - J_i}{\Gamma+\bar{\Gamma}}$

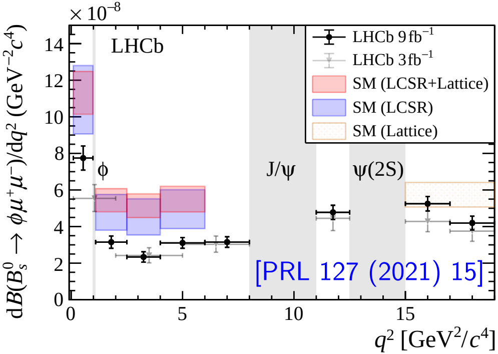
Many possibilities

Initial hadron	Final state hadrons	leptons
B^+, B^0, B_s^0, Λ_b	K^+, K^0, K^{*+}, K^{*0}, $K^+\pi^+\pi^-$ ϕ, $f_2'(1525)$, pK^-, none	e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$

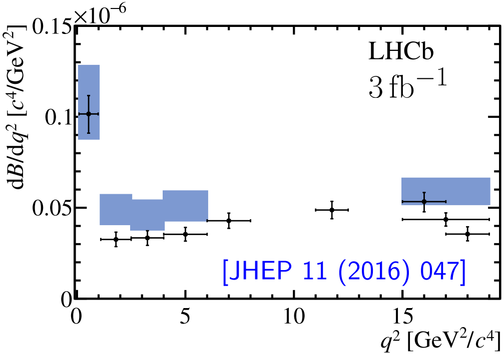
Branching fraction discrepancies

$q^2 = m(\ell^+\ell^-)^2$

$B^0_s \to \phi\mu^+\mu^-$



$B^0 \to K^{*0}\mu^+\mu^-$



Similarly for $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_S\mu^+\mu^-$ [JHEP 06 (2014) 133]

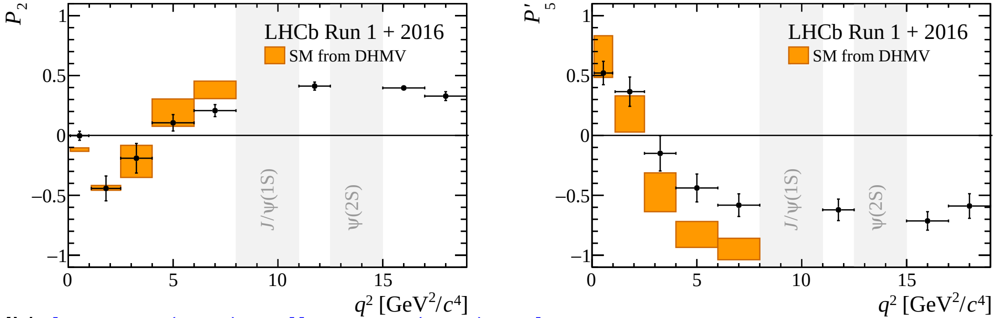
Angular discrepancies

[PRL 125 (2020) 011802]

"Optimised" angular observables cancel theory uncertainties:
[JHEP 05 (2013) 137][JHEP 01 (2013) 048]

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \sum_i S_i(q^2) f_i(\vec{\Omega}) \qquad P_{1,2,3} \sim \frac{S_{3,6s,9}}{S_2^s} \qquad P'_{4,5,6,8} \sim \frac{S_{4,5,7,8}}{\sqrt{-S_2^s S_2^c}}$$

LHCb has measured complete basis of optimised angular observables. E.g.:

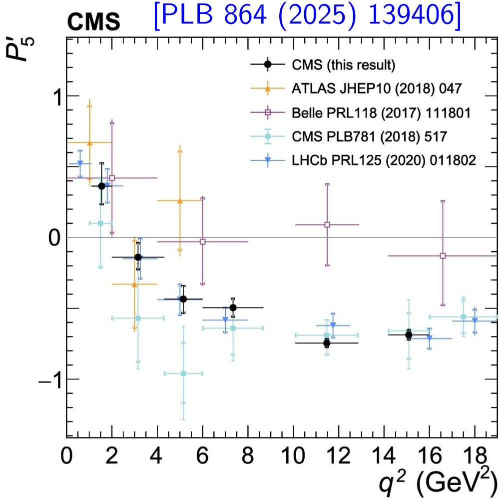


DHMV: [JHEP 12 (2014) 125][JHEP 09 (2010) 089]

$B^0 \to K^{*0}\mu^+\mu^-$ - other experiments

- Measurements from other experiments agree well with LHCb
- E.g. CMS angular analysis
  - $140\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
  - The complete basis of optimised $P_i^{(\prime)}$ optimised observables in bins of q^2
  - Agreement with LHCb Run 1 + 2016 results

[PLB 864 (2025) 139406]



New physics?

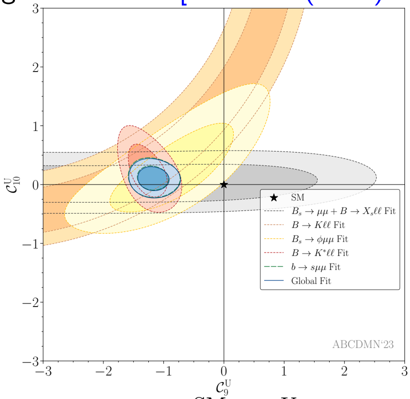
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

$\mathcal{O}_i$: effective operator
$\mathcal{C}_i$: Wilson coefficient $\rightarrow$ parameterise short-distance physics
$\mathcal{C}_9$: vector ; C_{10}: axial-vector

Several fitting groups:

- ABCDMN: [EPJC 83 (2023) 648]
- AS/GSSS: [JHEP 05 (2023) 087]
- CFFPSV: [PRD 107 (2023) 055036]
- HMMN: [PLB 824 (2022) 136838]
- GRvDV: [JHEP 09 (2022) 133]

E.g. ABCDMN: [EPJC 83 (2023) 648]



$$\mathcal{C}_i = \mathcal{C}_i^{\text{SM}} + \mathcal{C}_i^{\text{U}}$$

5.5 σ overall tension

Beware: not all WCs [PLB 822 (2021) 136644]

New physics?

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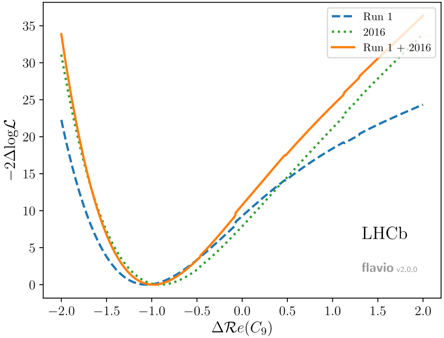
LHCb [PRL 125 (2020) 011802]



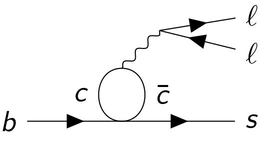
$3.3\,\sigma$ with just $B^0 \rightarrow K^{*0}\mu^+\mu^-$
[arXiv:1810.08132]

New physics?

Is this all NP?

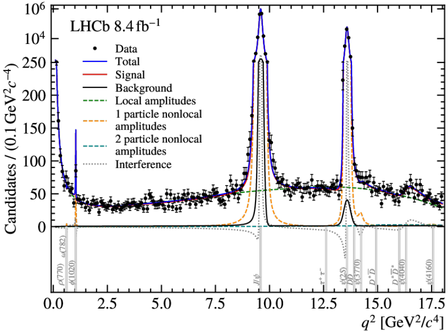
[PRD 109 (2024) 052009] [PRL 132 (2024) 131801] [JHEP 09 (2024) 026]

- Is effect from long-distance charm loop fully accounted for?



$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9^{SM} + \mathcal{C}_9^{c\bar{c}} + \mathcal{C}_9^{NP}$$

- Fit long-distance physics in the data?
- Unaccounted for long-distance effects under debate [arXiv:2507.17824]



Fitted long-distance effects do not cover shift in $\mathcal{C}_9$

This new measurement

$B^0 \to K^{*0}\mu^+\mu^-$ angular observables in bins of q^2

For the first time:

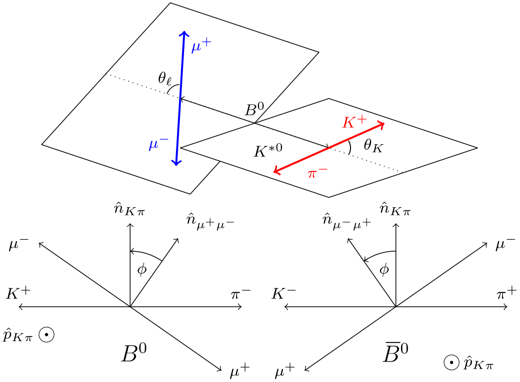
- Extract differential BF with angular observables
  - Assessed correlation vital for Wilson coefficient fits
- Consider effect of lepton masses on the angular distribution
  - Effect not confined to very low q^2!
- Determine the full basis of *CP*-asymmetries with the *CP*-averaged observables
  - Assess the correlation between them all
- Full suite of S-wave and P-/S-wave interference observables
- Finer binning scheme
  - Shape information important to probe long-distance effects

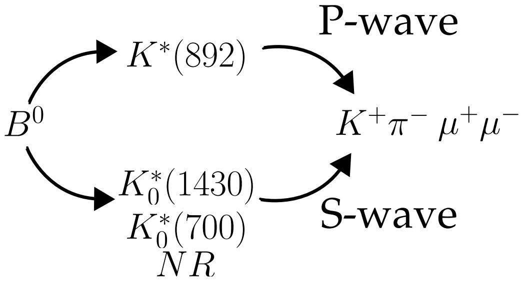
Furthermore:

- Double the data set $\to$ more precision

The $B^0 \to K^{*0}\mu^+\mu^-$ decay

$P \to V\ell^+\ell^-$ - 3 decay angles $\vec{\Omega} = [\cos\theta_\ell, \cos\theta_K, \phi]$, $q^2 = m(\ell^+\ell^-)^2$, $m(K^+\pi^-)$
$P = B^0$, $V = K^{*0}(892)$, $K^{*0} \to K^+\pi^-$





Differential rate: $B^0 \to K^+\pi^-\mu^+\mu^-$

$$\frac{\mathrm{d}^5\Gamma}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}}\frac{1}{\Gamma+\bar{\Gamma}} = (1-\hat{\Gamma}_{\mathrm{S}})\frac{9}{64\pi}\sum_i (S_i - A_i) f_i(\vec{\Omega})|\mathcal{BW}_{\mathrm{P}}(m_{K\pi})|^2 + \frac{1}{8\pi}\sum_{1ac,2ac}(\tilde{S}_i - \tilde{A}_i) f_i(\vec{\Omega})|\mathcal{BW}_{\mathrm{S}}(m_{K\pi})|^2 + \frac{1}{8\pi}\sum_{1bc,\mathrm{S1-S5}}\mathcal{R}e/\mathcal{I}m\left[(\tilde{S}_i - \tilde{A}_i) f_i(\vec{\Omega})\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}_{\mathrm{P}}(m_{K\pi})^*\right]$$

$$\hat{\Gamma}_{\mathrm{S}} = 2\tilde{S}^c_{1a} - \tfrac{2}{3}\tilde{S}^c_{2a}$$

- Fit differential rate to data, extract S_i (or optimised $P_i^{(\prime)}$), $\tilde{S}_i$, A_i, $\tilde{A}_i$
  - S_i, $\tilde{S}_i$ $\to$ CP-average, A_i, $\tilde{A}_i$ $\to$ CP-asymmetry, $\tilde{S}_i$, $\tilde{A}_i$ $\to$ S-wave/interference
  - Model-independent *observables*
- **NEW:** $m(K^+\pi^-)$ explicitly included in the angular rate
  - Interference observables $\to$ real and imaginary parts [JHEP 12 (2021) 085]
- **NEW:** Full set of angular CP asymmetries, A_i to describe the angular rate
  - Require an extended term for difference in rates between B^0 and $\overline{B}^0$
    $\to$ **measure the CP-average BF at the same time**

Lepton mass

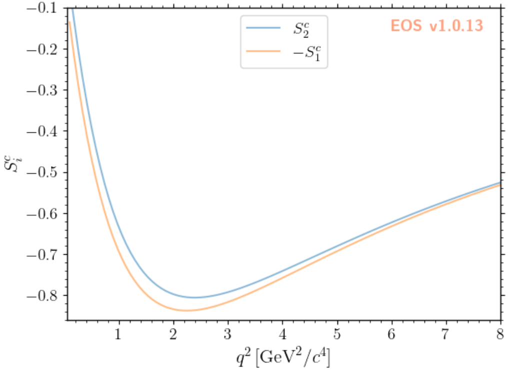
If $m_\ell \to 0$ or $q^2 >> m_\ell^2$, and no scalar or tensor amplitudes:

- Observables are related, e.g.

$$S_1^c = -S_2^c \qquad S_1^s = 3S_2^s$$

- Relation broken, even for $q^2 \sim 3\,\mathrm{GeV}^2$
- **NEW:** Account for effects of lepton mass
- $q^2 < 1\,\mathrm{GeV}^2$: always massive muons
- $q^2 > 1\,\mathrm{GeV}^2$:
  - Nominal: Fit S_1^c and S_2^c, fix $S_1^s = 3S_2^s$
  - Alternative: Massive muons for P-wave observables in all q^2
    - Most model-independent - scalar or tensor amplitudes

[EPJC 82 (2022) 569]



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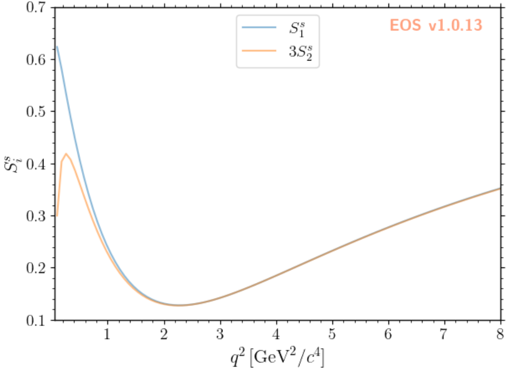
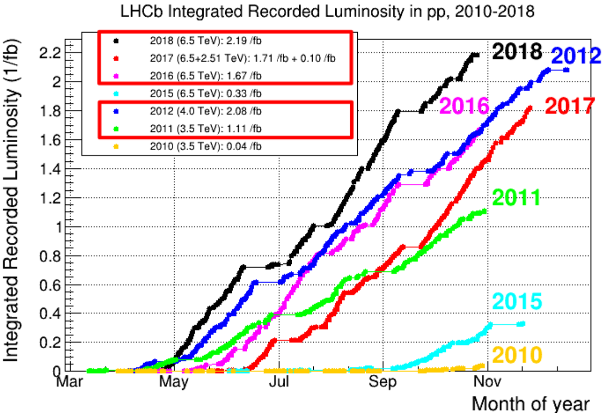


Data sample



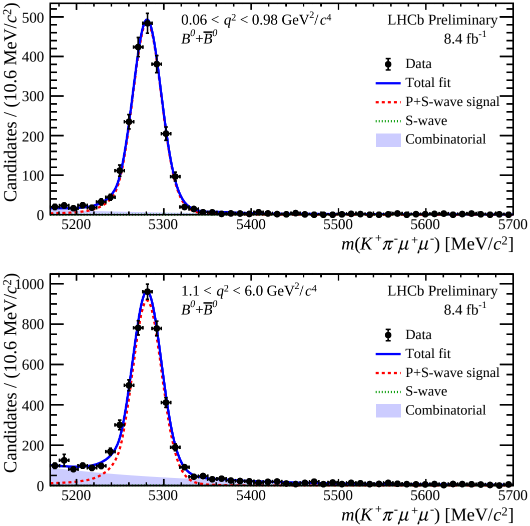
- 2011 + 2012: $3\,\text{fb}^{-1}$, 7-8 TeV
- 2016: $1.6\,\text{fb}^{-1}$, 13 TeV
- **2017+2018: $3.8\,\text{fb}^{-1}$, 13 TeV**

Note: A complete re-analysis

- New analysis strategy
- Re-optimised selections

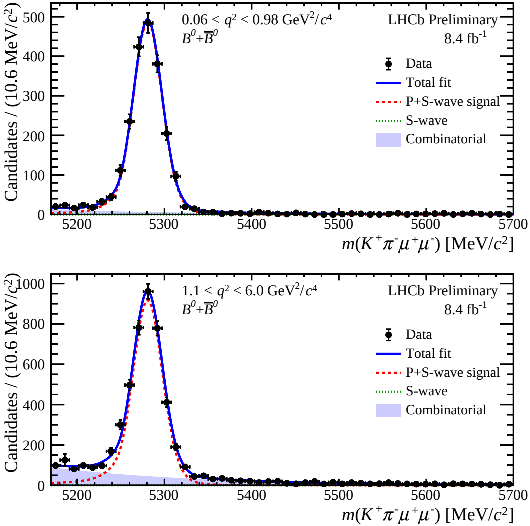
Backgrounds

- Combinatorial - random combinations of tracks
  - Reduced with BDT
  - Residual background modelled in fit



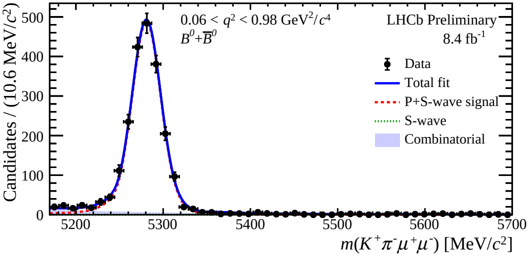
Backgrounds

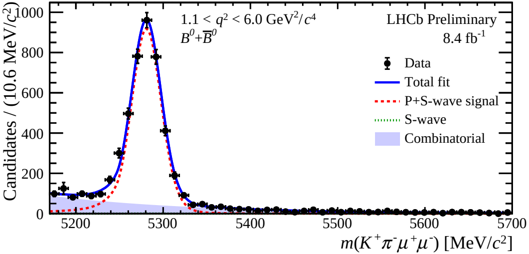
- Combinatorial - random combinations of tracks
- Particle mis-identification - reduced to negligible
  - i.e. $B_s^0 \to (\phi \to K^+K^-)\mu^+\mu^-$ $K^- \to \pi^-$
  - PID requirements and dedicated vetoes on alternative mass hypotheses



Backgrounds

- Combinatorial - random combinations of tracks
- Particle mis-identification - reduced to negligible
- Quasi-combinatorial - reconstruct part of a decay and add a random particle
  - $B^+ \to K^+\mu^+\mu^- + \pi^-$
    - Removed with a mass veto
    - Sculpting of combinatorial shape modelled in the fit
  - $B^+ \to K^+(J/\psi \to \mu^+\mu^-) + \pi^-$
    - Long tail of the J/ψ escapes the $B^+ \to K^+\mu^+\mu^-$ veto
    - Removed with a dedicated BDT





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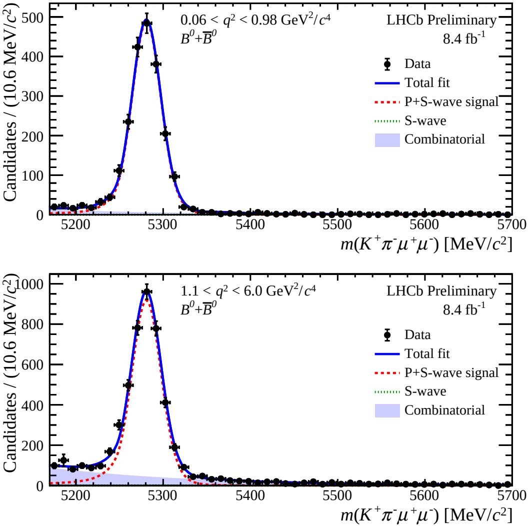
  - $B^+ \to K^+\mu^+\mu^- + \pi^-$
  - $B^+ \to K^+(J/\psi \to \mu^+\mu^-) + \pi^-$
  - $B \to \bar{D}\mu^+\nu_\mu X$, $\bar{D} \to K^+\mu^-\bar{\nu}_\mu X + \pi^-$
    - Characteristic shape in $\cos\theta_\ell$ from μ^+–μ^- momentum asymmetry
    - Gathers in $1 < q^2 < 8\,\mathrm{GeV}^2$
    - Dedicated BDT reduces to a negligible level

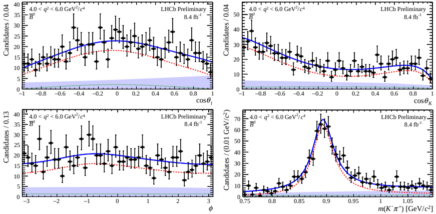


The fit

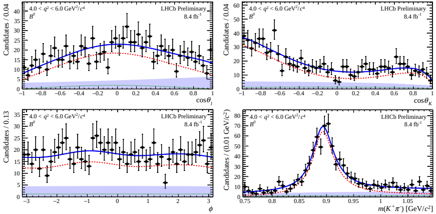
5D unbinned, maximum likelihood fit in bins of q^2:

- $m(K^+\pi^-\mu^+\mu^-)$ discriminates signal and background
- 3 decay angles and $m(K^+\pi^-)$ - angular observables
  - Up to 25 CP-average
  - Up to 25 CP-asymmetry $\rightarrow$ 50 total
- Data split into B^0 and $\overline{B}^0$ and fit simultaneously
- Extended terms $\rightarrow$ q^2-integrated CP-average BF relative to normalisation mode
  - Integrate angular decay-rate $\times$ angular efficiency for *model independence*
- Background shape determined in fit

$\overline{B}^0$:



B^0:

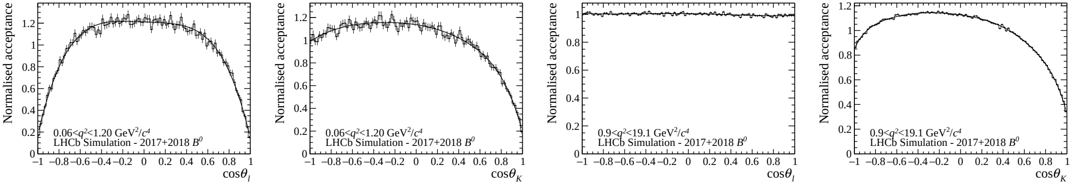


Acceptance function

Model detector acceptance and selection effects with an acceptance function:

- Derived from large samples of calibrated simulation
- Use Legendre polynomials for an analytic function
  - Polynomial orders determined with a 5D, unbinned, BDT GoF test [arXiv:1612.07186]

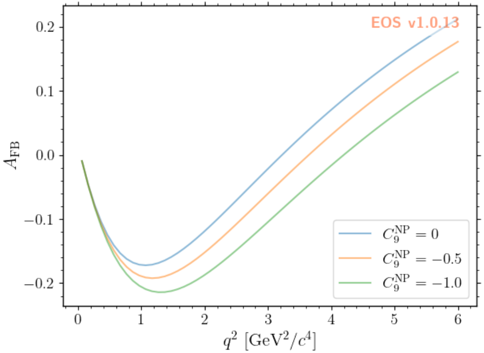
$$\epsilon(\vec{\Omega}, m_{K\pi}, q^2) = \sum_{ijklm} c_{ijklm} \mathcal{L}_i(q^2) \mathcal{L}_j(\cos\theta_\ell) \mathcal{L}_k(\cos\theta_K) \mathcal{L}_l(\phi) \mathcal{L}_m(m_{K\pi})$$



q^2 and $m_{K\pi}$ regions

- q^2 binning as in previous analysis iterations
  - Exclude $\phi(1020)$, J/ψ, $\psi(2S)$
  - 8 bins $\approx 1.5 - 2\,\mathrm{GeV}^2/c^4$
  - 2 wide bins
  - Low q^2 edge extended to $0.06\,\mathrm{GeV}^2/c^4$
- **NEW: 16 half-sized q^2 bins**
  - Better resolution of q^2 dependence of observables
- Select $745.9 < m_{K\pi} < 1095.9\,\mathrm{MeV}/c^2$
  - Larger than in previous analysis iterations
  - Better precision on S-wave and interference observables

[EPJC 82 (2022) 569]



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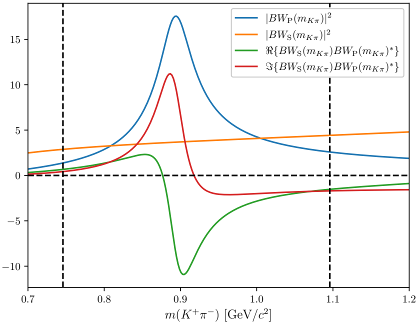
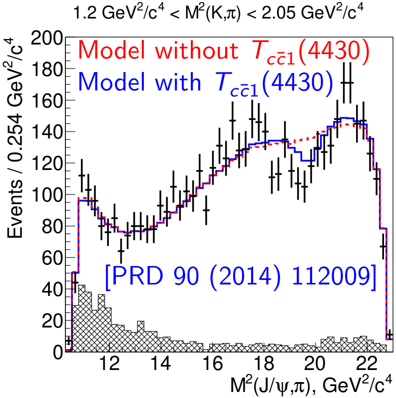


Normalisation mode

BF normalisation: $B^0 \to K^+\pi^- J/\psi$

- Exotic resonances in the $J/\psi\,\pi^-$ spectrum
- Disentangling pure $B^0 \to K^{*0} J/\psi$ requires a dedicated amplitude analysis



We provide an estimate of the normalisation BF for use in further analysis:

- Take the Belle $B^0 \to K^+\pi^- J/\psi$ amplitudes [PRD 90 (2014) 112009]
- Estimate fraction of decay in $745.9 < m_{K\pi} < 1095.9\,\mathrm{MeV}/c^2$

$$\mathcal{B}(B^0 \to K^+\pi^-(J/\psi \to \mu^+\mu^-)|745.9 < m_{K\pi} < 1095.9\,\mathrm{MeV}/c^2) = (4.88 \pm 0.22) \times 10^{-5}$$

Systematic uncertainties and checks

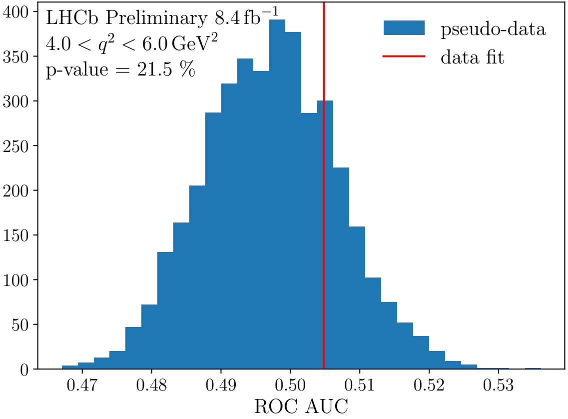
NEW: Assessed coherently across all q^2 bins

- A single correlation matrix for all observables in all bins
  - E.g. simulation corrections are common to all q^2 bins
- **P-wave observables dominated by σ_{stat}**
  - Largest σ_{syst} sources vary by observable and q^2 bin
- S-wave and interference observables have larger systematic uncertainties
  - Dominant contribution due to form of $\mathcal{BW}_{\mathrm{S}}(m_{K\pi})$ in the fit
- Some observables show biases or poor uncertainty estimation ($\sim 10-20\%$ of σ_{stat})
  - Arise from boundaries for PDF to be positive and correlations between fit parameters
  - Assessed with pseudo-experiments
  - Corrections obtained with a Neyman construction

Cross-checks:

- Check of $\mathcal{B}(B^0 \to \psi(2S)K^{*0})$ against PDG [PRD 110 (2024) 030001]
- No dependence on data-taking period or magnet polarity

Goodness-of-fit



We are confident the 5D fit is a good description of the data in each q^2 bin

- 5D unbinned goodness-of-fit using BDTs [arXiv:1612.07186] and point-to-point disimilarity [JINST 5 (2010) P09004]
  - Compare pseudodata from the fit model with the real data
- Same approach as for the acceptance functions

Observable check

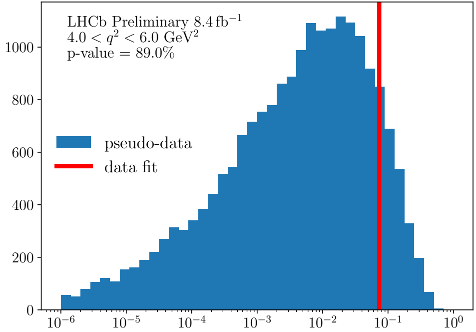
[JHEP 12 (2021) 085]

E.g. relation III:

$$0 = +\frac{27}{16}\beta^2 F_S(16J_{2s}^2 - 4J_3^2 - \beta^2 J_{6s}^2 - 4J_9^2) - 2\Gamma'[-2(\beta^2 J_{6s} S_{S2}^i S_{S3}^i - \beta^2 J_9 S_{S3}^i S_{S4}^r$$
$$+4J_9 S_{S2}^i S_{S5}^r + \beta^2 J_{6s} S_{S4}^r S_{S5}^r) + 4S_{S2}^{i\,2}(J_3 + 2J_{2s}) + \beta^2 S_{S3}^{i\,2}(2J_{2s} - J_3)$$
$$+\beta^2 S_{S4}^{r\,2}(J_3 + 2J_{2s}) + 4S_{S5}^{r\,2}(2J_{2s} - J_3)].$$

$$\beta^2 = 1 - \frac{4m_\ell^2}{q^2}$$

- 6 relations between observables check analysis procedure
  - Take product of 6 to form a figure of merit
- Exact at any point in q^2- approximate when integrated
- Constructed from amplitudes $\rightarrow$ NP agnostic (ignoring scalar or tensors)



Fit configurations

Panoply of insights possible - several fit configurations to extract maximum information with best sensitivity

1. Partially-massive non-optimised observables, *CP*-average only
2. Partially-massive optimised observables, *CP*-average only
3. Massless, non-optimised observables, with *CP*-asymmetries
4. Massive P-wave, non-optimised observables, *CP*-average only
5. Partially-massive non-optimised observables, *CP*-average only, 16 half-sized q^2 bins
6. Massless, optimised observables, *CP*-average only

- Massive leptons for $q^2 < 1\,\mathrm{GeV}^2$
  S_1^c, S_2^s, S_2^c, S_{3-9}, S_6^c
  S_1^c, S_2^s, S_2^c, $P_{1-8}^{(\prime)}$, P_6^c
- Fit S_1^c for $q^2 > 1\,\mathrm{GeV}^2$
  S_1^c, S_2^c, S_{3-9}
  S_1^c, S_2^c, $P_{1-8}^{(\prime)}$
- **Best precision on individual *CP*-average observables**

Fit configurations

Panoply of insights possible - several fit configurations to extract maximum information with best sensitivity

1. Partially-massive non-optimised observables, *CP*-average only
2. Partially-massive optimised observables, *CP*-average only
3. Massless, non-optimised observables, with *CP*-asymmetries
4. Massive P-wave, non-optimised observables, *CP*-average only
5. Partially-massive non-optimised observables, *CP*-average only, 16 half-sized q^2 bins
6. Massless, optimised observables, *CP*-average only

- Massive leptons for $q^2 < 1\,\mathrm{GeV}^2$
  S_1^c, S_2^s, S_2^c, S_{3-9}, S_6^c
  A_{CP}, A_1^c, A_2^c, A_2^s, $A_3 - A_9$, A_{FB}^{CP}
- Massless leptons for $q^2 > 1\,\mathrm{GeV}^2$
  S_2^c, S_{3-9}
  A_{CP}, A_2^c, $A_3 - A_9$
- **Sensitivity to *CP*-asymmetries**

Fit configurations

Panoply of insights possible - several fit configurations to extract maximum information with best sensitivity

1. Partially-massive non-optimised observables, *CP*-average only
2. Partially-massive optimised observables, *CP*-average only
3. Massless, non-optimised observables, with *CP*-asymmetries
4. Massive P-wave, non-optimised observables, *CP*-average only
5. Partially-massive non-optimised observables, *CP*-average only, 16 half-sized q^2 bins
6. Massless, optimised observables, *CP*-average only

- Massive leptons for P- and S-wave for $q^2 < 1\,\mathrm{GeV}^2$
- Massive leptons for P-wave only for $q^2 > 1\,\mathrm{GeV}^2$
  S_1^c, S_2^s, S_6^c, S_2^c, S_{3-9}
- **Sensitivity to scalar or tensor amplitudes**

Fit configurations

Panoply of insights possible - several fit configurations to extract maximum information with best sensitivity

1. Partially-massive non-optimised observables, CP-average only
2. Partially-massive optimised observables, CP-average only
3. Massless, non-optimised observables, with CP-asymmetries
4. Massive P-wave, non-optimised observables, CP-average only
5. Partially-massive non-optimised observables, CP-average only, 16 half-sized q^2 bins
6. Massless, optimised observables, CP-average only

- Massive leptons for $q^2 < 1\,\mathrm{GeV}^2$
  S_1^c, S_2^s, S_2^c, S_{3-9}, S_6^c
- Fit S_1^c for $q^2 > 1\,\mathrm{GeV}^2$
  S_1^c, S_2^c, S_{3-9}
- **Best resolution of q^2 dependence of observables**

Fit configurations

Panoply of insights possible - several fit configurations to extract maximum information with best sensitivity

1. Partially-massive non-optimised observables, *CP*-average only
2. Partially-massive optimised observables, *CP*-average only
3. Massless, non-optimised observables, with *CP*-asymmetries
4. Massive P-wave, non-optimised observables, *CP*-average only
5. Partially-massive non-optimised observables, *CP*-average only, 16 half-sized q^2 bins
6. Massless, optimised observables, *CP*-average only

- An imitation of [PRL 125 (2020) 011802]
- Optimised observables, massless leptons in all q^2 S_2^c, $P_{1-8}^{(\prime)}$
- **Direct comparison with previous analysis**

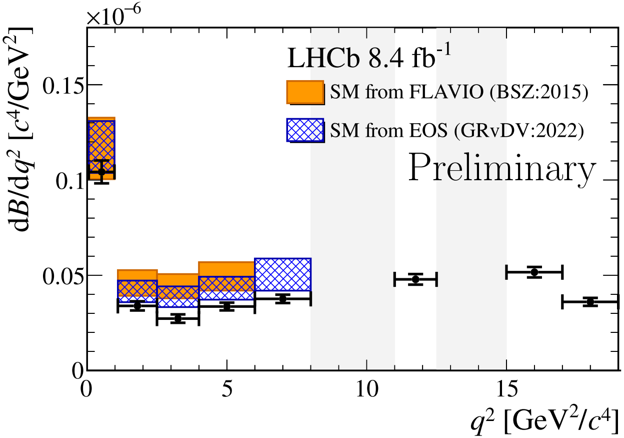
Results highlights

Prediction	Experiment
The Ashes 2010: I'm sticking with a 5-0 Aussie win, says Glenn McGrath	**The Ashes 2010-11: England wrap up series win over Australia in style**
Guardian, 17 November 2010	Guardian, 7 January 2011

HEPData

[https://www.hepdata.net/]

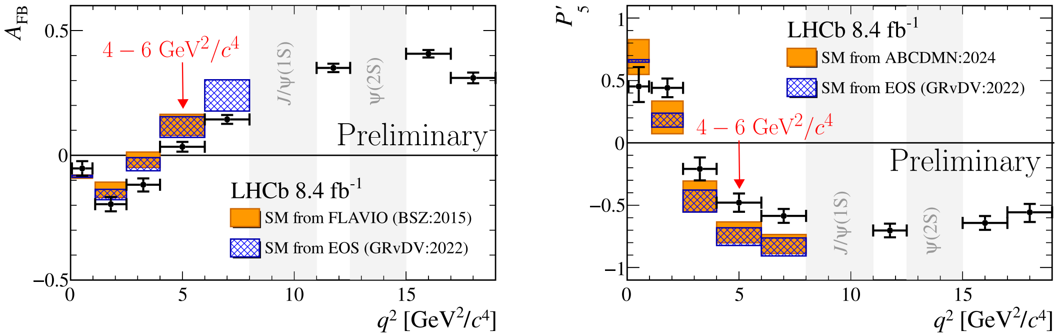
Branching fraction



BSZ:
[arXiv:1810.08132]
[JHEP 08 (2016) 098]
GRvDV:
[EPJC 82 (2022) 569]
[JHEP 09 (2022) 133]
ABCDMN:
[EPJC 83 (2023) 648]

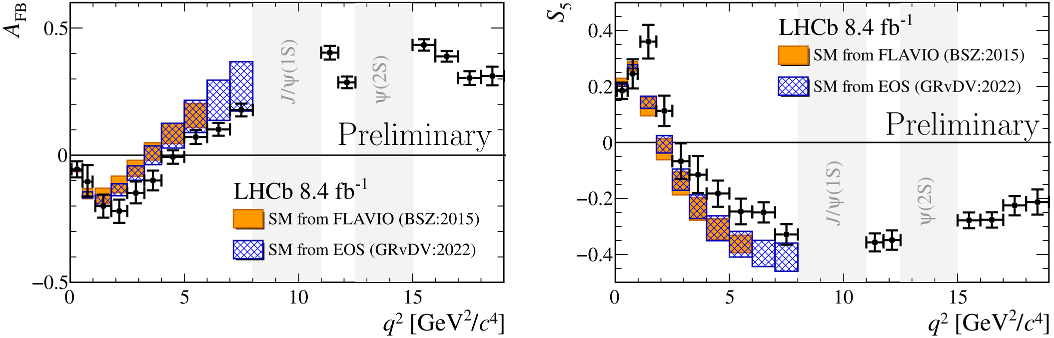
- $\frac{d\mathcal{B}}{dq^2}$ remains consistently below theory prediction
- Experimental results dominated by normalisation BF uncertainty
- Theory uncertainties significant

CP-average observables



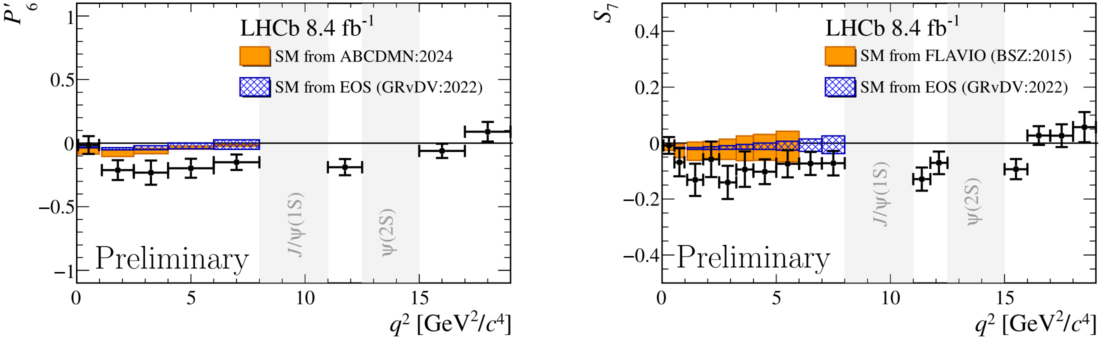
- **Discrepancy between experiment and theory in A_{FB} and P_5' increases**
- P_5' tension in $4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ now $2.7\,\sigma$
- A_{FB} tension in $4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ now $1.9\,\sigma$

CP-average observables - half-sized q^2 bins



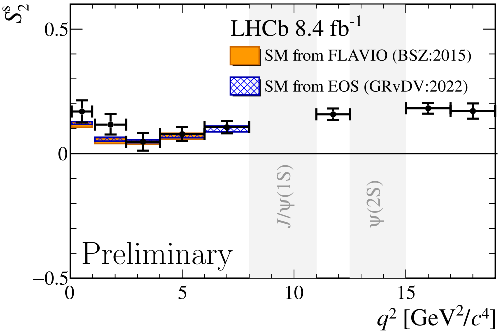
- **Consistent results with the nominal sized bins**
- $\frac{d\mathcal{B}}{dq^2}$, $A_{\rm FB}$, S_7 below predictions, S_5 above

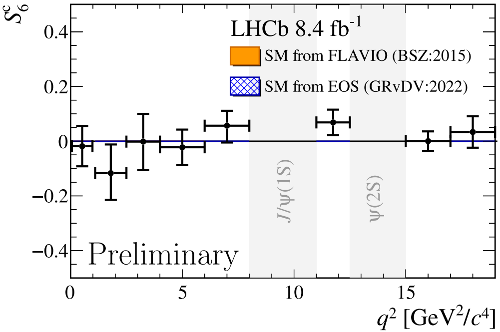
CP-average observables



- P'_6 (S_7) consistently below predictions
  - Sensitive to relative phases of the amplitudes
- No single bin has a significant discrepancy

CP-average observables - massive



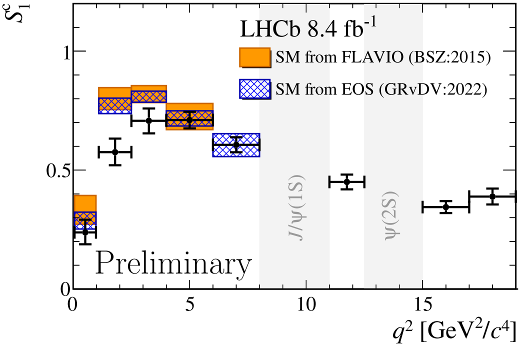


- First extraction of S_2^s and S_6^c across all q^2.
- S_6^c consistent with 0 in all bins $\rightarrow$ no sign of NP tensor or scalar amplitudes

CP-average observables - massive

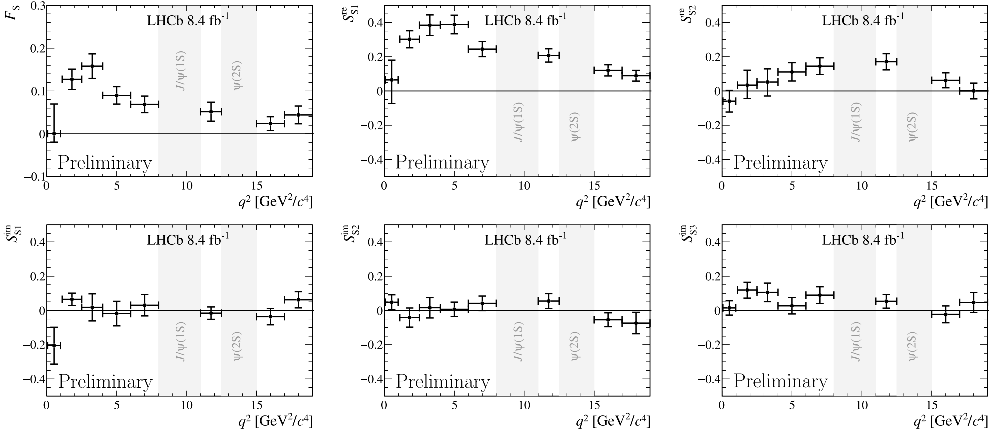
From the ‘fully massive’ fit:

- First measurement of S_1^c - here with no assumptions on the P-wave observables
- In $1.1 < q^2 < 2.5\,\mathrm{GeV}^2/c^4$ our results find $S_1^c = -S_2^c$ differ $\sim 1.7\,\sigma$



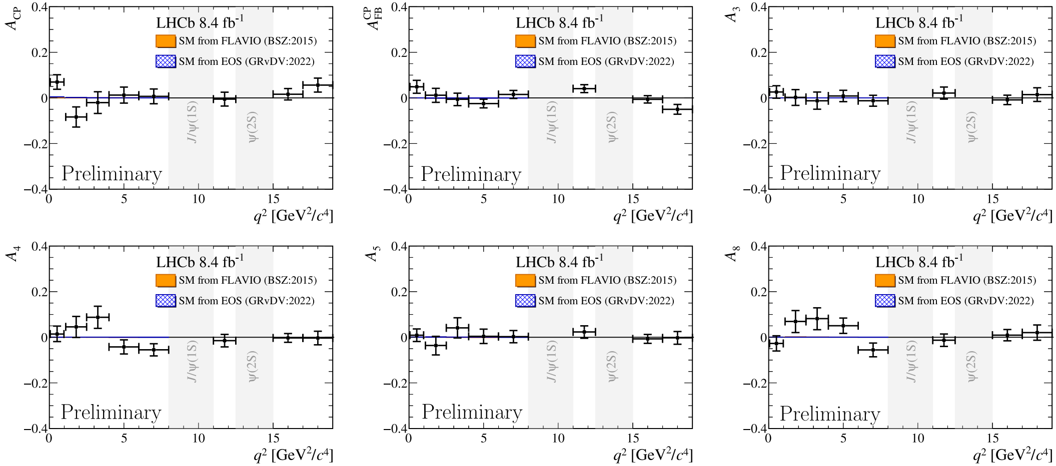
The remaining CP-average P-wave observables (S_2^c, S_3, S_4, S_8, S_9) consistent with SM expectations in all fit configurations

CP-average observables - S-wave



- New determination of F_S as a function of q^2, $745.9 < m(K^+\pi^-) < 1095.9\,\mathrm{MeV}/c^2$
- First publication of interference observables, split into real and imaginary parts

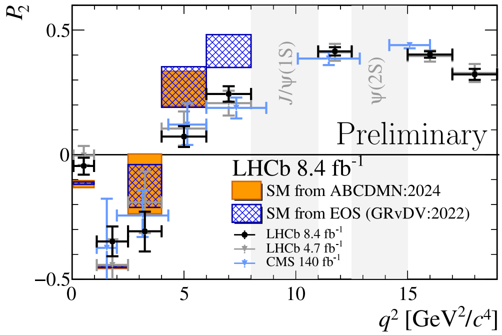
CP-asymmetry observables

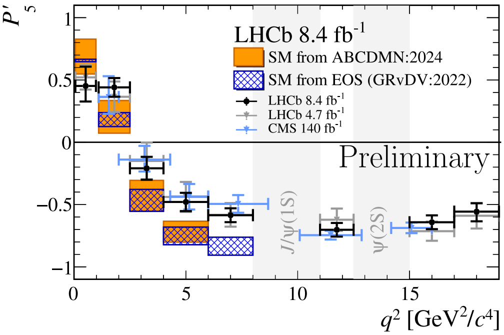


No significant CP-asymmetry

Comparison with previous result

Compare new nominal (including extra parameters) with old:





- This is a re-analysis - the 8.4 fb^{-1} results supersede the previous
- New results consistent with previous LHCb measurement (4.7 fb^{-1}) and with most recent CMS measurement (140 fb^{-1})

Wilson coefficients

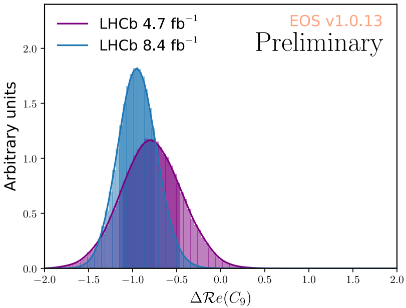
[EPJC 82 (2022) 569]
[arXiv:1810.08132]

LHCb $B^0 \to K^{*0}\mu^+\mu^-$ only fit for $\mathcal{C}_9$ with `EOS` and `flavio`

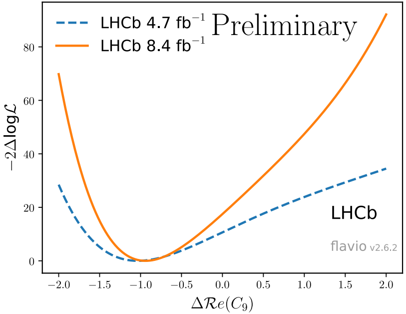
- Precise numbers depend on how the fit is set up
  - Treatment of non-local effects → significant debate in the community
- **These are illustrative!**

Angular observables and $\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}$:

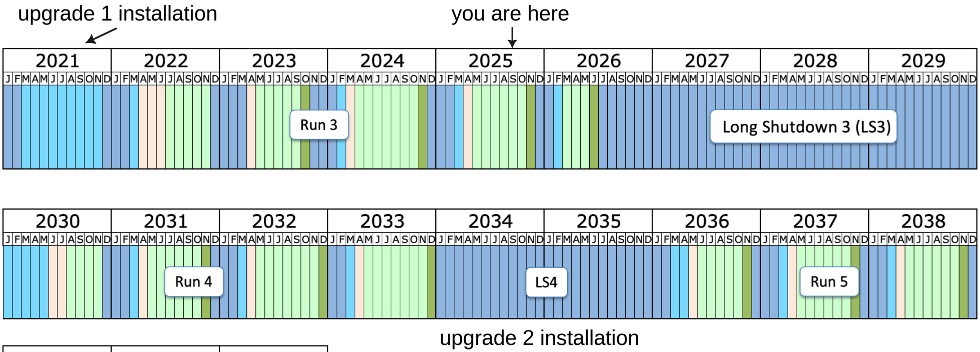
Significance: $4.0\,\sigma$

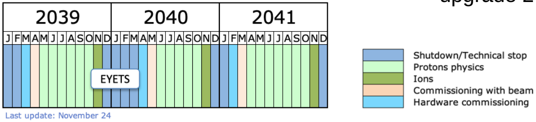


Significance: $4.1\,\sigma$



The future

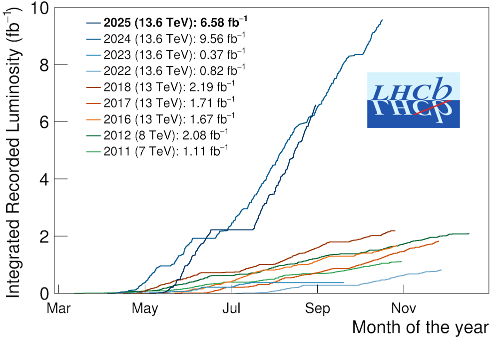


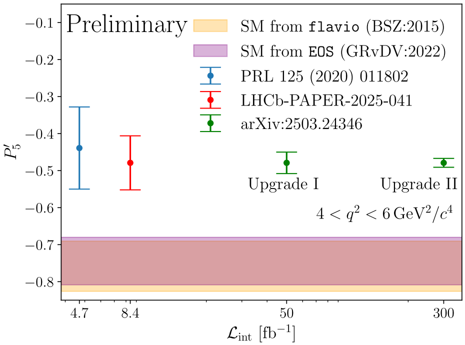


LHCb v1:

- 2010-2012 - Run 1, 7/8 TeV
- 2015-2018 - Run 2, 13 TeV

The future





- The upgraded detector is performing excellently
- Initial studies of new data show excellent mass resolution and background suppression

Conclusion

LHCb-PAPER-2025-041 (in preparation)

- New study of the FCNC decay $B^0 \to K^{*0}\mu^+\mu^-$ with the LHCb Run 1 and Run 2 data sets
- **Several innovations and new approaches in this analysis**
  - $\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}$ extracted with the angular observables
  - Full set of *CP*-asymmetries
  - First consideration of the effect of the muon mass on the angular distribution
  - New binning scheme for finer q^2 determination of the observables
  - Full set of P- and S-wave interference observables presented for the first time
- **Unprecedented precision**
- **The discrepancies with theory predictions remain and the significances have increased**

BONUS ROUND

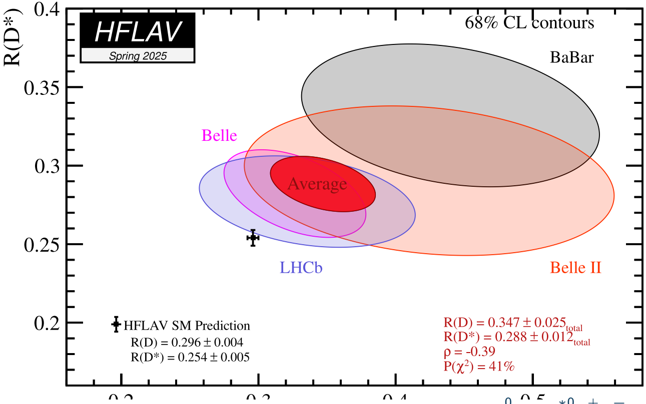
$b \to s\tau^+\tau^-$

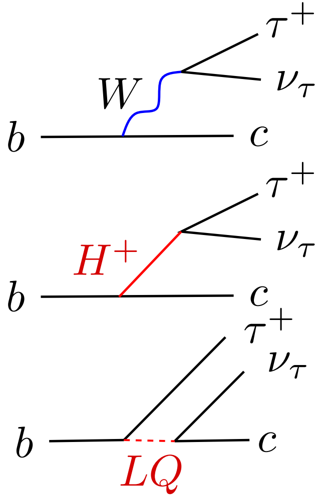
LHCb-PAPER-2025-048 (in preparation)

$R(D) - R(D^*)$

[HFLAV]

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}$$





τ-rrific penguins

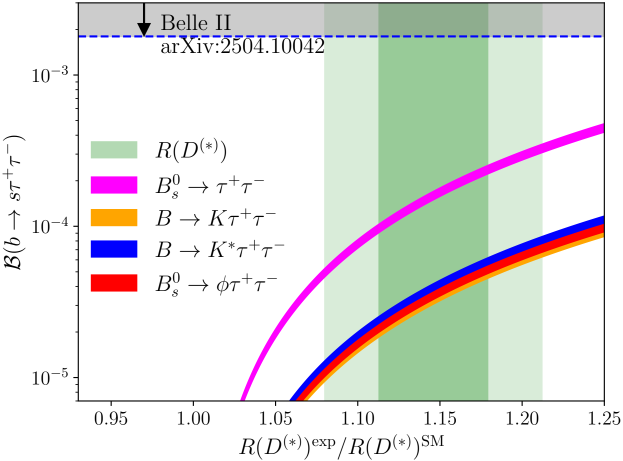
[EPJC 83 (2023) 153]
[PRL 120 (2018) 181802]

What if the NP for $R(D^{(*)})$ is in the EW penguins? It couples to τ leptons:

$$C_9^{\tau\tau} = C_9^{\mathrm{SM}} - \Delta$$
$$C_{10}^{\tau\tau} = C_{10}^{\mathrm{SM}} + \Delta$$

$\Delta \sim 100$ shift in WC from NP that explains $R(D^{(*)})$

Massive rate enhancement for $b \to s\tau^+\tau^-$! Unambiguous NP!



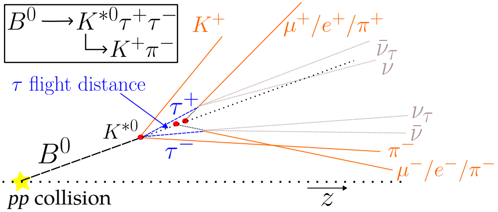
$\mathcal{B}(b \to s\tau^+\tau^-)^{\mathrm{SM}} \sim 10^{-7}$

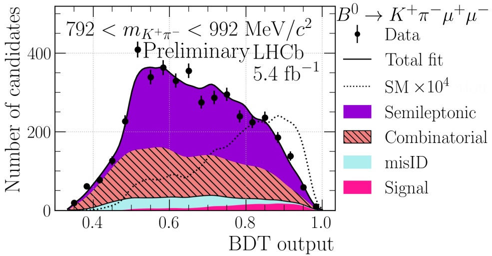
τ-rrific penguins

LHCb-PAPER-2025-048

LHCb search for $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B_s^0 \to K^+K^-\tau^+\tau^-$:

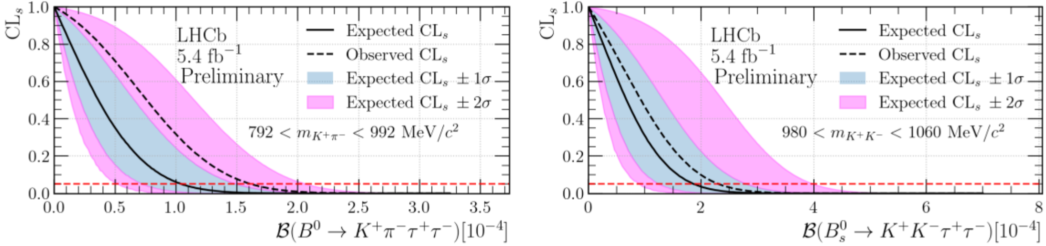
- $5.4\,\text{fb}^{-1}$ Run 2 data set
- Reconstruct both τ via $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$
- Train a multiclass BDT to separate signal and principal backgrounds
- Fit BDT classifier output to search for signal
- Bin in dihadron mass
    - Split into resonance and NR regions





τ-rrific penguins

No signal seen in either mode, in any $m(h_1 h_2)$ region, $\rightarrow$ set limits:



$$\mathcal{B}(B^0 \rightarrow K^{*0}\tau^+\tau^-) < 2.8(2.5) \times 10^{-4} @ 95(90)\% \mathrm{CL_s}$$

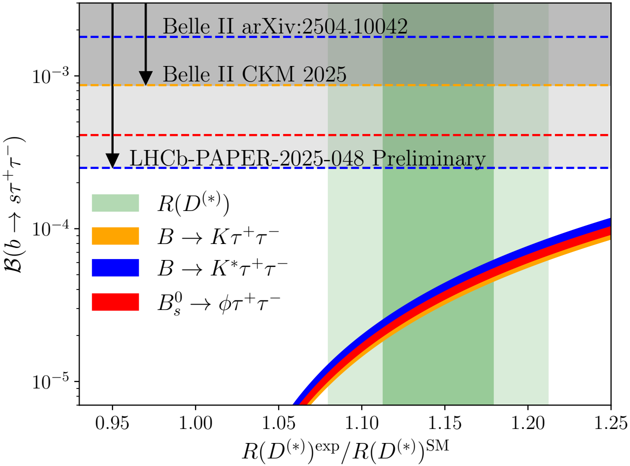
$$\mathcal{B}(B_s^0 \rightarrow \phi\tau^+\tau^-) < 4.7(4.1) \times 10^{-4} @ 95(90)\% \mathrm{CL_s}$$

Limits also recast to Δ, $\mathcal{B}(B_s^0 \rightarrow K^-\pi^+\tau^+\tau^-)$

τ-rrific penguins

LHCb-PAPER-2025-048

- Limit on $B^0 \to K^{*0}\tau^+\tau^-$ order of magnitude better than recent Belle II [arXiv:2504.10042]
  - A type of decay LHCb not expected to be competitive in!
  - Only Run 2, only single *tau* decay mode
- Recent Belle II $\mathcal{B}(B \to K\tau^+\tau^-) < 8.7 \times 10^{-4}$ also encouraging [N. Rout @ CKM]



Much more to come from Belle II and LHCb

Conclusions

LHCb-PAPER-2025-041 (in preparation)
LHCb-PAPER-2025-048 (in preparation)

- Two new searches for NP with electroweak penguin decays
- For $B^0 \to K^{*0}\mu^+\mu^-$ alone the tension with the SM is $\sim 4\,\sigma$
  - New limits on NP weak phase, tensor, scalar amplitudes
  - Better q^2 determination of the observables
  - Unprecedented precision
- First LHCb searches for $b \to s\tau^+\tau^-$ decays
  - World's best limit for $B^0 \to K^{*0}\tau^+\tau^-$
  - First limits for $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B_s^0 \to K^+K^-\tau^+\tau^-$ across all $m(h_1 h_2)$

Much more to come from precision studies of electroweak penguin decays

The End

Extended term

Each subsample has an extended term in the LH

$$N = N_{\mathrm{bkg}} + N_{J/\psi} \frac{\mathcal{B}_{\mathrm{sig}}}{\mathcal{B}_{J/\psi}} \times \frac{\int PDF_{\mathrm{sig}}(\vec{\Omega}, m_{K\pi})\epsilon(\vec{\Omega}, m_{K\pi}|q^2)\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}}{\int PDF_{J/\psi}(\vec{\Omega}, m_{K\pi})\epsilon(\vec{\Omega}, m_{K\pi}|q^2 = 3.096^2)\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}}$$

- Fit parameter is the *relative* CP-averaged BF, $\frac{\mathcal{B}_{\mathrm{sig}}}{\mathcal{B}_{J/\psi}}$, with $\mathcal{B}_{\mathrm{sig}}$ integrated over the bin width
- By separately normalising the B^0 and $\overline{B}^0$ samples the q^2-independent detection and production asymmetries are are taken care of
  - q^2-dependent effects are assigned as systematic uncertainties

Differential rate: P-wave $B^0 \to K^{*0}\mu^+\mu^-$

$$\frac{\mathrm{d}^4\Gamma_P}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}} = \frac{9}{64\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K$$
$$+(J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell$$
$$+J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+J_5\sin 2\theta_K\sin\theta_\ell\cos\phi + J_{6s}\sin^2\theta_K\cos\theta_\ell$$
$$+J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]|\mathcal{BW}_P(m_{K\pi})|^2$$

$$J_2^c = \left(1 - \frac{4m_\ell^2}{q^2}\right)\left[|A_0^L|^2 + |A_0^R|^2 - 8(|A_{0t}|^2 + |A_{\parallel\perp}|^2)\right]$$

$$A_0 \sim f(C_{7^{(\prime)}},\ C_{9^{(\prime)}},\ C_{10^{(\prime)}},\ \text{local FFs, non-local FFs})$$

Differential rate: P-wave $B^0 \to K^{*0}\mu^+\mu^-$

Integrate over $\vec{\Omega}$, $\frac{\mathrm{d}\Gamma_P}{\mathrm{d}q^2} \to \Gamma_P$:

$$1 = \frac{3}{4}(S_1^c + 2S_1^s) - \frac{1}{4}(S_2^c + 2S_2^s) \qquad S_i = \frac{J_i + \bar{J}_i}{\Gamma_P + \bar{\Gamma}_P}$$

$$A_{CP} = \frac{\Gamma_P - \bar{\Gamma}_P}{\Gamma_P + \bar{\Gamma}_P} = \frac{3}{4}(A_1^c + 2A_1^s) - \frac{1}{4}(A_2^c + 2A_2^s) \qquad A_i = \frac{J_i - \bar{J}_i}{\Gamma_P + \bar{\Gamma}_P}$$

To measure the complete basis of angular asymmetries you need to measure A_{CP} $\to$ extended term

Construct theory-optimised observables:

$$P_{1,2,3} = N_i \frac{S_{3,6s,9}}{S_2^s} \qquad P'_{4,5,6,8} = N_i \frac{S_{4,5,7,8}}{\sqrt{-S_2^s S_2^c}}$$

Differential rate: S-wave $B^0 \to K^{*0}\mu^+\mu^-$

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}} = \left(1-\hat{\Gamma}_S\right)\frac{\mathrm{d}^4\Gamma_P}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}\mathrm{d}m_{K\pi}}$$
$$+\frac{1}{8\pi}\left[(\tilde{S}^c_{1a}+\tilde{S}^c_{2a}\cos\theta_\ell)|\mathcal{BW}_\mathrm{S}(m_{K\pi})|^2\right.$$
$$+\frac{1}{8\pi}\mathcal{R}e\left(\left[\tilde{S}^c_{1b}\cos\theta_K+\tilde{S}^c_{\mathrm{S1}}\cos\theta_K\cos 2\theta_\ell\right]\mathcal{BW}_\mathrm{S}(m_{K\pi})\mathcal{BW}^*_\mathrm{P}(m_{K\pi})\right)$$
$$+\frac{1}{8\pi}\mathcal{R}e\left(\left[\tilde{S}_{\mathrm{S2}}\sin\theta_K\sin 2\theta_\ell\cos\phi+\tilde{S}_{\mathrm{S3}}\sin\theta_K\sin\theta_\ell\cos\phi\right]\mathcal{BW}_\mathrm{S}(m_{K\pi})\mathcal{BW}^*_\mathrm{P}(m_{K\pi}\right.$$
$$+\frac{1}{8\pi}\mathcal{I}m\left(\left[\tilde{S}_{\mathrm{S4}}\sin\theta_K\sin\theta_\ell\sin\phi+\tilde{S}_{\mathrm{S5}}\sin\theta_K\sin 2\theta_\ell\sin\phi\right]\mathcal{BW}_\mathrm{S}(m_{K\pi})\mathcal{BW}^*_\mathrm{P}(m_{K\pi})\right.$$

$$\tilde{S}_i=\frac{J_i+\bar{J}_i}{\Gamma_P+\bar{\Gamma}_P+\Gamma_S+\bar{\Gamma}_S}\qquad \tilde{A}_i=\frac{\bar{J}_i-J_i}{\Gamma_P+\bar{\Gamma}_P+\Gamma_S+\bar{\Gamma}_S}\qquad \hat{\Gamma}_S=2\tilde{S}^c_{1a}-\frac{2}{3}\tilde{S}^c_{2a}$$

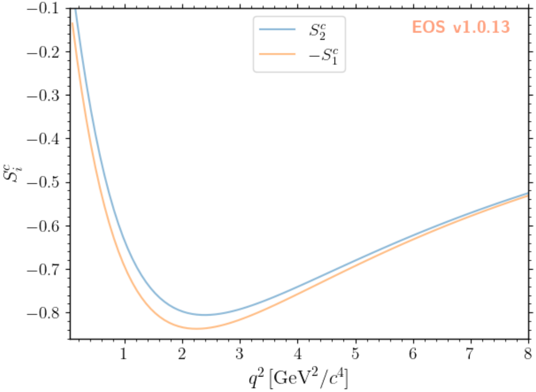
S-wave and interference

$$\mathcal{R}e\left(\tilde{S}^{c}_{\mathrm{S1}}\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^{*}_{\mathrm{P}}(m_{K\pi})\right)$$
$$\rightarrow \tilde{S}^{c,\mathrm{re}}_{\mathrm{S1}}\mathcal{R}e(\mathcal{BW}_{\mathrm{S}}\mathcal{BW}^{*}_{\mathrm{P}}(m_{K\pi})) - \tilde{S}^{c,\mathrm{im}}_{\mathrm{S1}}\mathcal{I}m(\mathcal{BW}_{\mathrm{S}}\mathcal{BW}^{*}_{\mathrm{P}}(m_{K\pi}))$$

- The interference observables have real and imaginary parts - extra observables
  - These can be measured
- Value of S-wave and interference observables depends on the analysed range of $m_{K\pi}$
  - $745.9 < m_{K\pi} < 10959.9\,\mathrm{MeV}/c^2$
- $\mathcal{BW}_P(m_{K\pi})$ is a relativistic Breit-Wigner
- $\mathcal{BW}_S(m_{K\pi})$ is a LASS amplitude [NPB 296 (1988) 3]
- Both lineshapes normalised in the analysed region $\int_{\mathrm{min}}^{\mathrm{max}} |\mathcal{BW}(m_{K\pi})|^2 \mathrm{d}m_{K\pi} = 1$

Lepton mass

$$S_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*})\right]$$
$$+ \beta_\ell^2|A_S|^2 + 8(2-\beta_\ell^2)|A_{t0}|^2 + 8\beta_\ell^2|A_{\parallel\perp}|^2$$
$$+ \frac{16m_\ell}{\sqrt{q^2}}\Re\left[(A_0^L + A_0^R)A_{t0}^*\right]$$
$$S_2^c = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2 - 8(|A_{t0}|^2 + |A_{\parallel\perp}|^2)\right]$$
$$\beta_\ell^2 = 1 - \frac{4m_\ell^2}{q^2}$$



If $m_\ell \to 0$ or $q^2 >> m_\ell^2$, and no scalar or tensor amplitudes:

$$\beta_\ell^2 = 1 \qquad S_1^c = -S_2^c \qquad S_1^s = 3S_2^s \qquad A_1^c = -A_2^c \qquad A_1^s = 3A_2^s$$
$$S_{1a}^c = -S_{2a}^c \qquad S_{1b}^{c,\mathrm{re/im}} = -S_{\mathrm{S1}}^{\mathrm{re/im}}$$

Fit configurations

Panoply of insights possible - several fit configurations to extract maximum information with best sensitivity

1. Partially-massive non-optimised observables, *CP*-average only
2. Partially-massive optimised observables, *CP*-average only
3. Massless, non-optimised observables, with *CP*-asymmetries
4. Massive P-wave, non-optimised observables, *CP*-average only
5. Partially-massive non-optimised observables, *CP*-average only, 16 half-sized q^2 bins
6. Massless, optimised observables, *CP*-average only

- Fit S_1^c for $q^2 > 1\,\mathrm{GeV}^2$
- Massive leptons for $q^2 < 1\,\mathrm{GeV}^2$
- **Best precision on individual *CP*-average observables**

S_1^c, S_2^c, S_{3-5}, A_{FB}, S_{7-9}

S_1^c, S_2^c, $P_{1-8}^{(\prime)}$

F_{S}, $S_{\mathrm{S1-5}}^{\mathrm{re/im}}$

$q^2 < 1\,\mathrm{GeV}^2$:

S_2^s, S_6^c, $\tilde{S}_{1a}^c$, $\tilde{S}_{1b}^{c,\,\mathrm{re/im}}$

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- Massive leptons for $q^2 < 1\,\mathrm{GeV}^2$
- Massless leptons for $q^2 > 1\,\mathrm{GeV}^2$
- **Sensitivity to *CP* asymmetries**

S_2^c, S_{3-9}, A_{CP}, A_2^c, $A_3 - A_9$

F_S, $S_{\mathrm{S}1-5}^{\mathrm{re/im}}$, AF_S, $AS_{\mathrm{S}1-5}^{\mathrm{re/im}}$

$q^2 < 1\,\mathrm{GeV}^2$:

S_2^s, S_6^c, $\tilde{S}_{1a}^c$, $\tilde{S}_{1b}^{c,\,\mathrm{re/im}}$

A_2^s, A_FB^{CP}, $\tilde{A}_{1a}^c$, $\tilde{A}_{1b}^{c,\,\mathrm{re/im}}$

Fit configurations

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- Massive leptons for P- and S-wave for $q^2 < 1\,\mathrm{GeV}^2$
- Massive leptons for $q^2 > 1\,\mathrm{GeV}^2$
- **Sensitivity to scalar or tensor amplitudes**

S_1^c, S_2^s, S_6^c, S_2^c, S_{3-9}, F_S, $S_{\mathrm{S1-5}}^{\mathrm{re/im}}$

$q^2 < 1\,\mathrm{GeV}^2$:

S_2^s, S_6^c, $\tilde{S}_{1a}^c$, $\tilde{S}_{1b}^{c,\,\mathrm{re/im}}$

Fit configurations

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- Fit S_1^c for $q^2 > 1\,\mathrm{GeV}^2$
- Massive leptons for $q^2 < 1\,\mathrm{GeV}^2$
- **Best resolution of q^2 dependence of observables**

S_1^c, S_2^c, S_{3-9}, F_S, $S_{\mathrm{S1-5}}^{\mathrm{re/im}}$

$q^2 < 1\,\mathrm{GeV}^2$:

S_2^s, S_6^c, $\tilde{S}_{1a}^c$, $\tilde{S}_{1b}^{c,\,\mathrm{re/im}}$

Fit configurations

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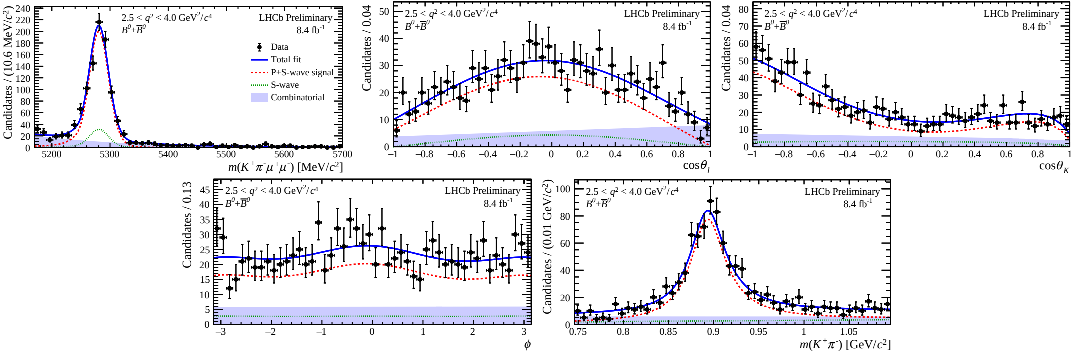
- A palimpsest from [PRL 125 (2020) 011802]
- **Direct comparison with previous analysis**

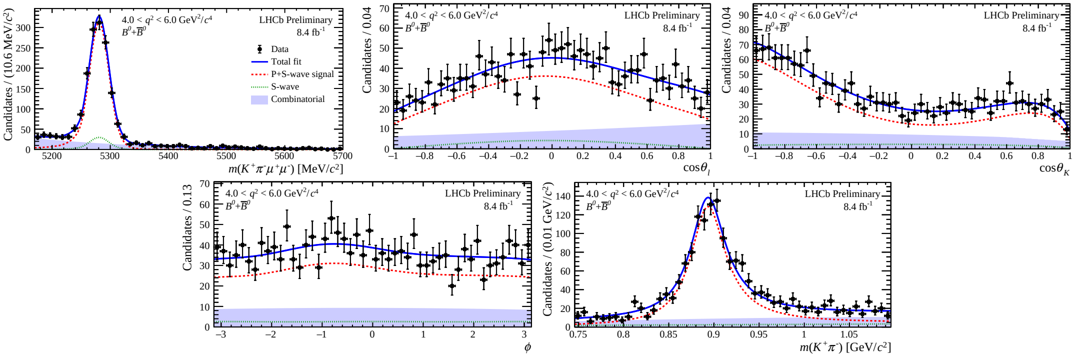
S_2^c, $P_{1-8}^{(\prime)}$

F_{S}, $S_{\mathrm{S1-5}}^{\mathrm{re/im}}$

Fit projections



Fit projections



HEPData page

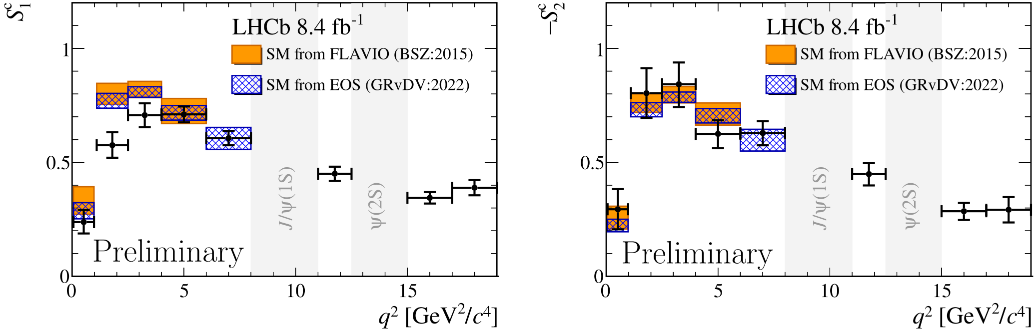
[https://www.hepdata.net/]

`Machine readable format - all fit configurations`

- Central values and statistical uncertainties from the fit of the data
  - Correlation matrix of the statistical uncertainties
- Corrected central values and statistical uncertainties
  - Uncertainties of the statistical corrections
- Total systematic uncertainties
  - Correlation matrix of the systematic uncertainties
- README for the various labels of the information

S_1^s and S_2^c

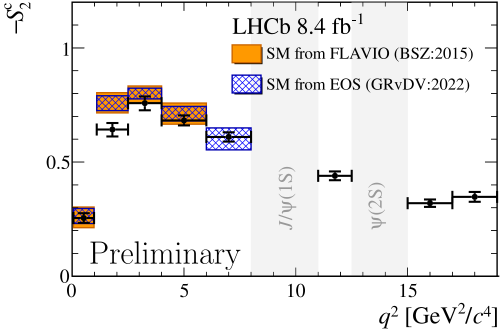
From the fully massive P-wave fit configuration:

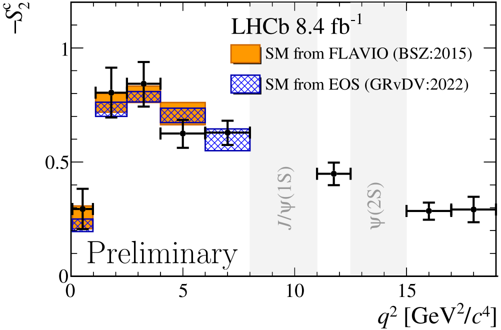


- In the q^2 region $1.1 < q^2 < 4.0\,\mathrm{GeV}^2/c^4$ $S_1^c \neq S_2^c$
- This is also true in the fit with only S_1^c fitted in addition to S_2^c

S_1^s and S_2^c

Compare S_2^c (left) fully massive P-wave fit and (right) fully massless fit:





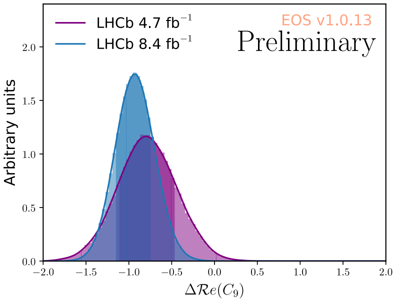
Wilson coefficients

[EPJC 82 (2022) 569]
[arXiv:1810.08132]

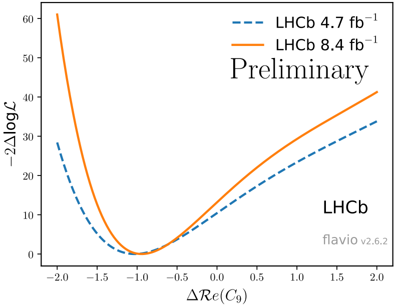
- LHCb $B^0 \to K^{*0}\mu^+\mu^-$ only fit for $\mathcal{C}_9$ with `EOS` and `flavio`
- Precise numbers depend on how the fit is set up
  - Treatment of non-local effects $\to$ significant debate in the community
- These are illustrative!

Angular observables only:

Significance: $3.8\,\sigma$



Significance: $3.6\,\sigma$



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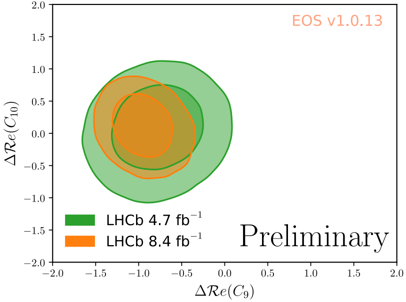

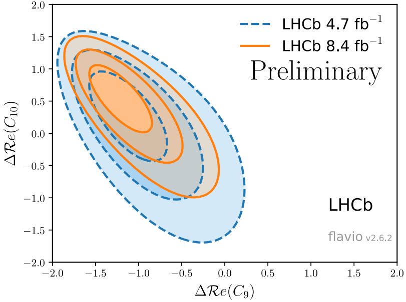

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