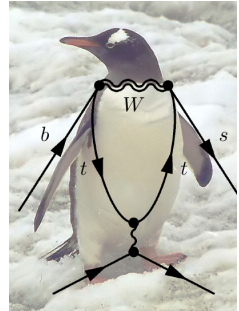


The potent power of the penguin

Imperial College seminar
LHCb-PAPER-2025-041 (in preparation)

Mark Smith

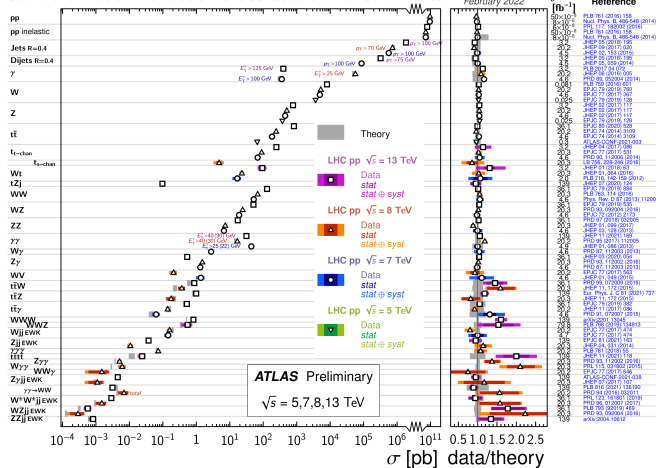
17 October 2025



The Standard Model problem

[ATLAS-PHYS-PUB-2022-009]

Standard Model Production Cross Section Measurements

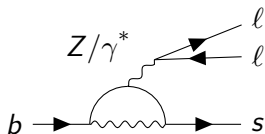


- The SM has issues
 - Hierarchy problem, dark matter ...
- No (direct) sign of new physics at the LHC
 - No new particles in direct searches
 - Measured processes agree with SM predictions

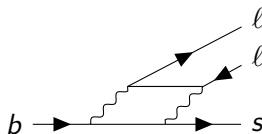
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

Flavour changing neutral currents

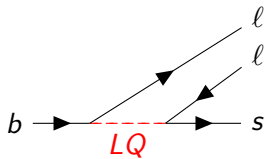
SM penguin:



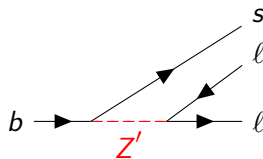
SM box:



NP leptoquark:



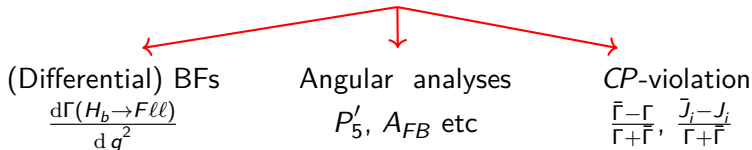
NP Z' :



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

Flavour changing neutral currents

Small SM amplitude $\rightarrow$ excellent place to search for NP!



Many possibilities

Initial hadron

$B^+, B^0, B_s^0, \Lambda_b$

Final state hadrons

$K^+, K^0, K^{*+}, K^{*0}, K^+\pi^+\pi^-$
 $\phi, f'_2(1525), pK^-,$
 none

leptons

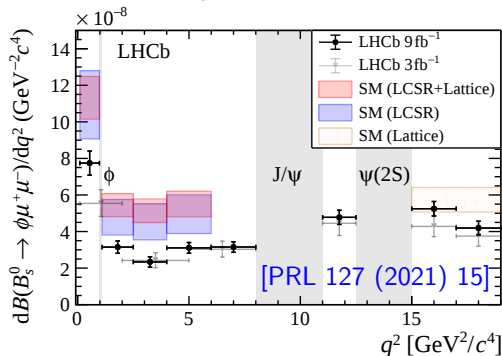
$e^+e^-, \mu^+\mu^-,$
 $\tau^+\tau^-$

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

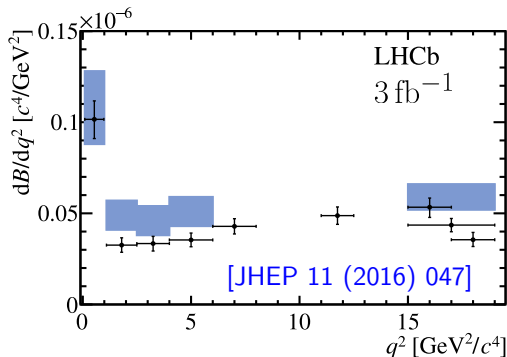
Branching fraction discrepancies

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

$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$



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



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

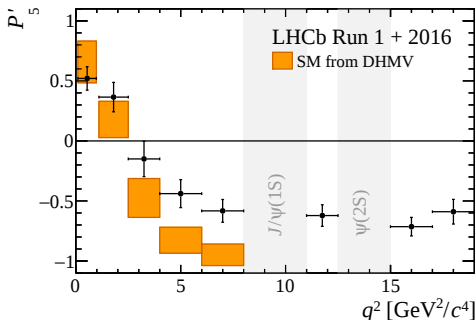
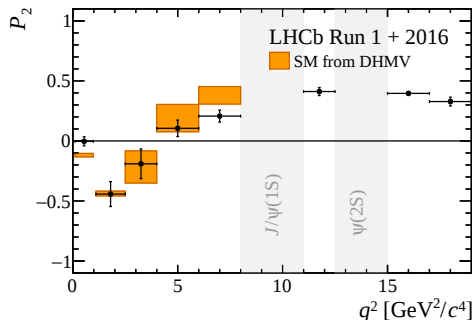
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

Angular discrepancies - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

“Optimised” angular observables cancel theory uncertainties: [\[PRL 125 \(2020\) 011802\]](#)
[\[JHEP 05 \(2013\) 137\]](#)[\[JHEP 01 \(2013\) 048\]](#)

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

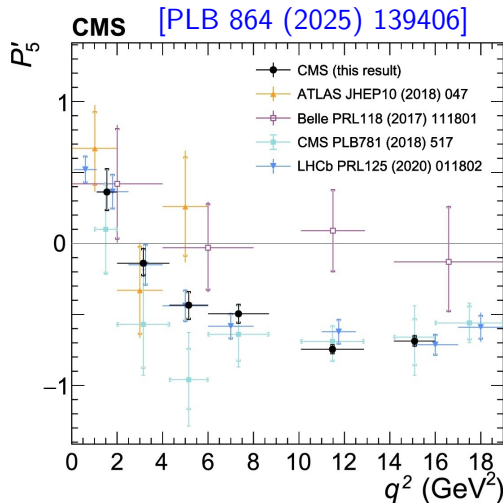
LHCb has measured complete basis of optimised angular observables. E.g.:



DH MV: [\[JHEP 12 \(2014\) 125\]](#)[\[JHEP 09 \(2010\) 089\]](#)
 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

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

- Measurements from other experiments agree well with LHCb
- E.g. CMS angular analysis
 - 140 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



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

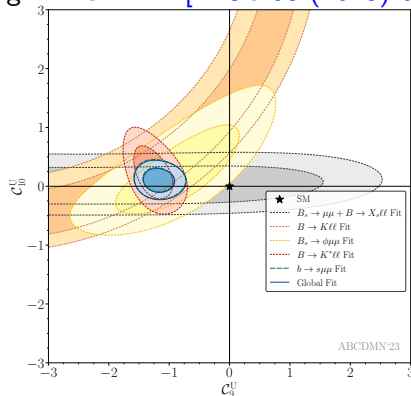
$\mathcal{C}_i$: Wilson coefficient $\rightarrow$ parameterise short-distance physics

$\mathcal{C}_9$: vector ; $\mathcal{C}_{10}$: 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]

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

New physics?

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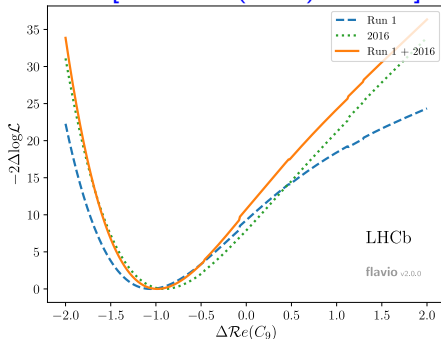
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- HMMN: [PLB 824 (2022) 136838]
- GRvDV: [JHEP 09 (2022) 133]

LHCb [PRL 125 (2020) 011802]



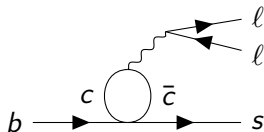
3.3σ with just $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
[arXiv:1810.08132]

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

New physics?

Is this all NP?

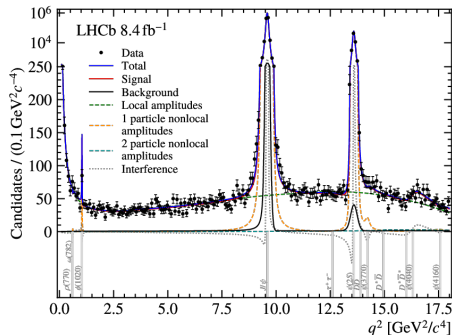
- Is effect from long-distance charm loop fully accounted for?



$$C_9^{\text{eff}} = C_9^{\text{SM}} + C_9^{c\bar{c}} + C_9^{\text{NP}}$$

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

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



Fitted long-distance effects do not cover shift in C_9

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

This new measurement

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

For the first time:

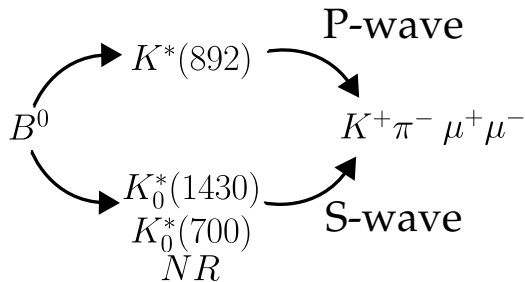
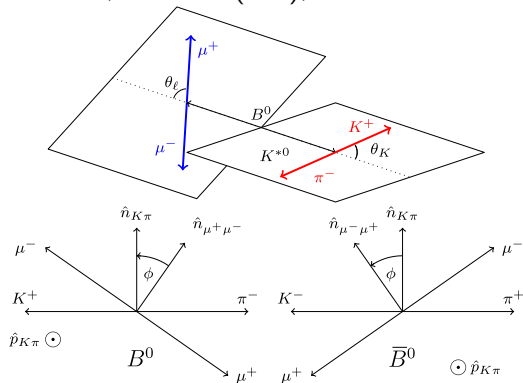
- Extract differential BF with angular observables
 - Assessed correlation vital for Wilson coefficient fits
- Consider effect of lepton masses on the angular distribution
 - Effect not confined to very low q^2 !
- Determine the full basis of CP -asymmetries with the CP -averaged observables
 - Assess 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 $\rightarrow$ more precision

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

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



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

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

$$\frac{d^5\Gamma}{dq^2 d\vec{\Omega} dm_{K\pi}} \frac{1}{\Gamma + \bar{\Gamma}} = (1 - \hat{\Gamma}_S) \frac{9}{64\pi} \sum_i (S_i - A_i) f_i(\vec{\Omega}) |\mathcal{BW}_P(m_{K\pi})|^2$$

$$+ \frac{1}{8\pi} \sum_{1ac, 2ac} (\tilde{S}_i - \tilde{A}_i) f_i(\vec{\Omega}) |\mathcal{BW}_S(m_{K\pi})|^2$$

$$+ \frac{1}{8\pi} \sum_{1bc, S1-S5} \mathcal{Re}/\mathcal{Im} \left[(\tilde{S}_i - \tilde{A}_i) f_i(\vec{\Omega}) \mathcal{BW}_S(m_{K\pi}) \mathcal{BW}_P(m_{K\pi})^* \right]$$

$$\hat{\Gamma}_S = 2\tilde{S}_{1a}^c - \frac{2}{3}\tilde{S}_{2a}^c$$

- Fit differential rate to data, extract S_i (or optimised $P_i^{(r)}$), $\tilde{S}_i$, A_i , $\tilde{A}_i$
 - $S_i, \tilde{S}_i \rightarrow CP$ -average, $A_i, \tilde{A}_i \rightarrow CP$ -asymmetry, $\tilde{S}_i, \tilde{A}_i \rightarrow S$ -wave/interference
 - **Model-independent observables**
- **NEW:** $m(K^+ \pi^-)$ explicitly included in the angular rate
 - Interference observables $\rightarrow$ **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 $\bar{B}^0$
 - $\rightarrow$ **measure the CP -average BF at the same time**

Lepton mass

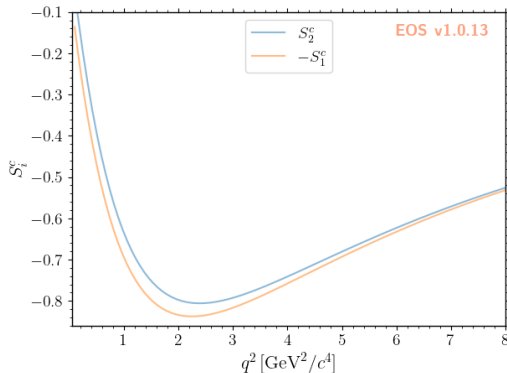
If $m_\ell \rightarrow 0$ or $q^2 \gg m_\ell^2$, and no scalar or tensor amplitudes:

- Observables are related, e.g.

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

- **Relation broken, even for $q^2 \sim 3 \text{ GeV}^2$**
- **NEW:** Account for effects of lepton mass
- $q^2 < 1 \text{ GeV}^2$: always massive muons
- $q^2 > 1 \text{ GeV}^2$:
 - 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]



Lepton mass

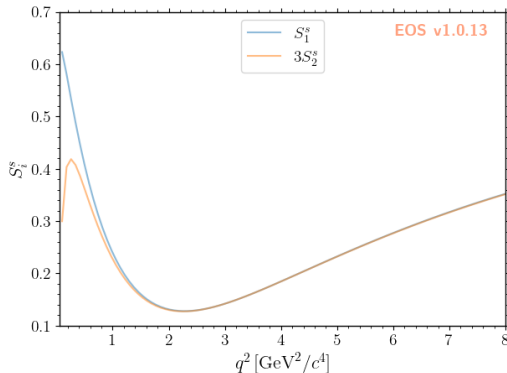
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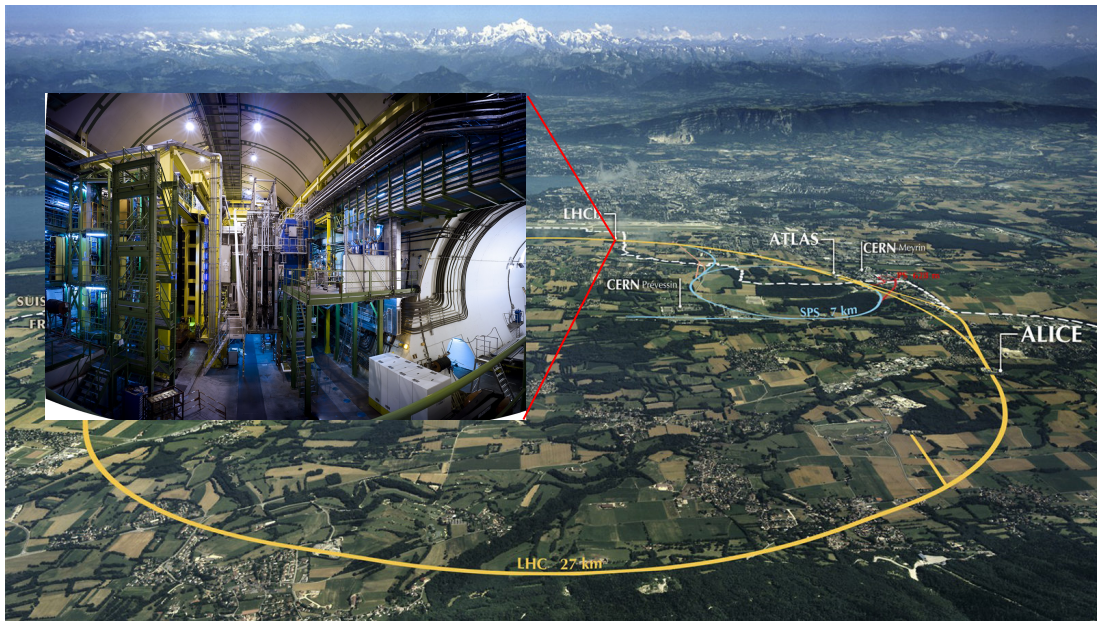
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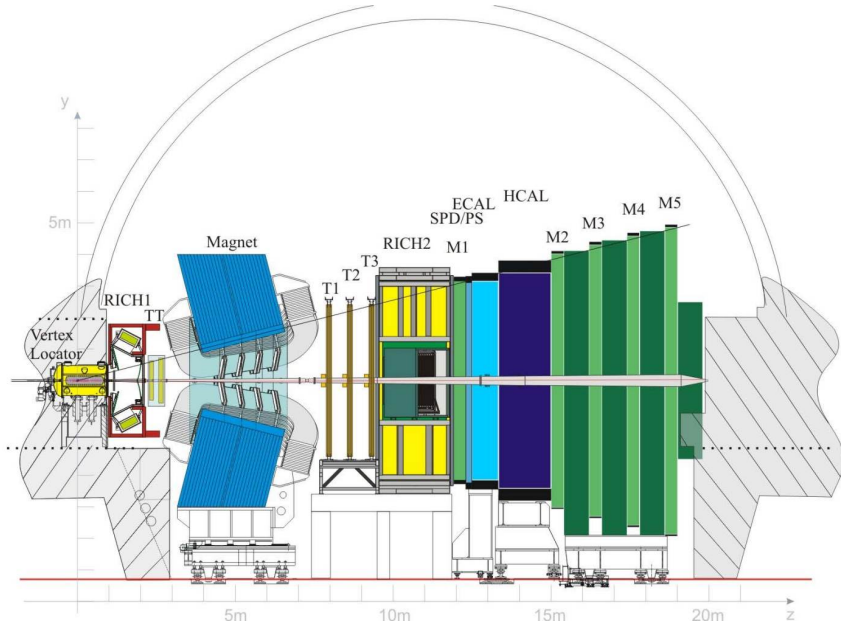
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[EPJC 82 (2022) 569]

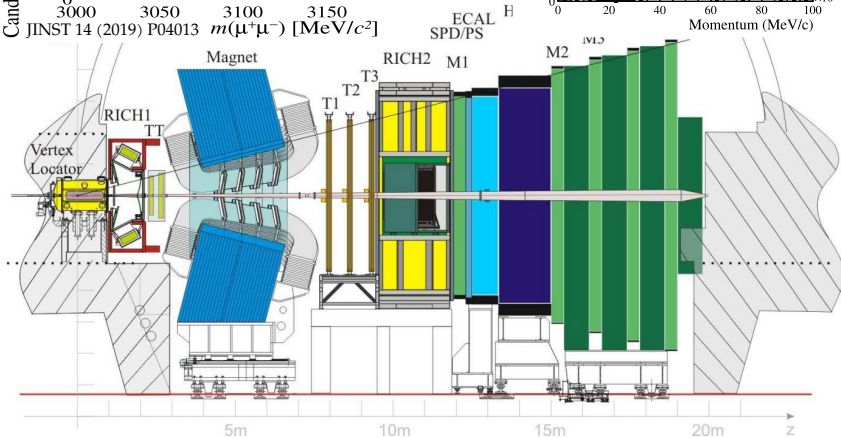
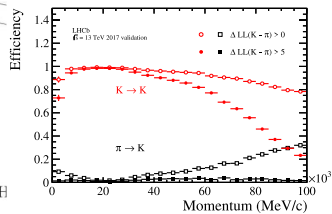
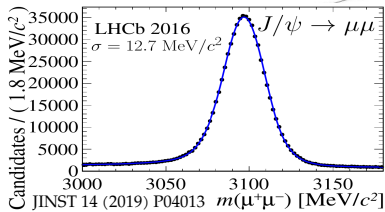




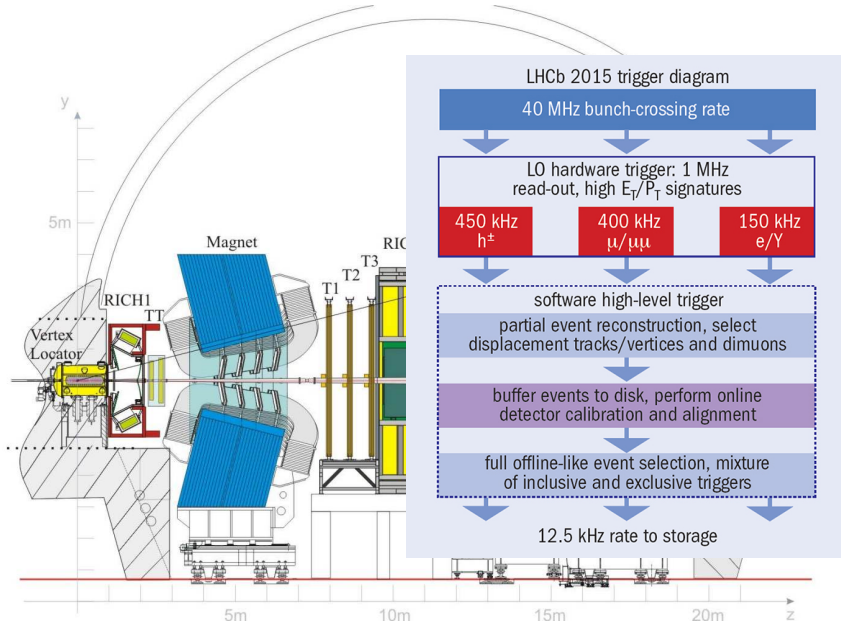
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$



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

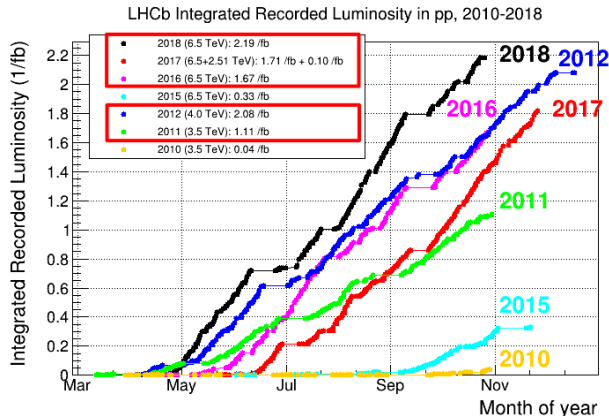


$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$



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

Data sample



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

Note: A complete re-analysis

- New analysis strategy
- Re-optimised selections

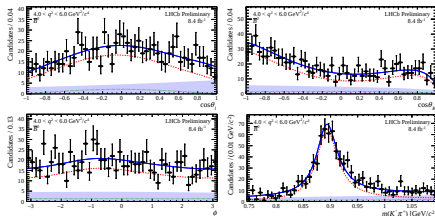
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

The fit

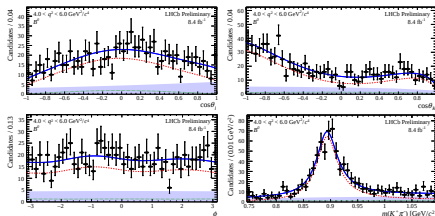
5D unbinned, maximum likelihood fit in bins of q^2 :

- $m(K^+\pi^-\mu^+\mu^-)$ 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 $\bar{B}^0$ 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

$\bar{B}^0$:



B^0 :



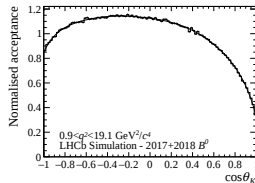
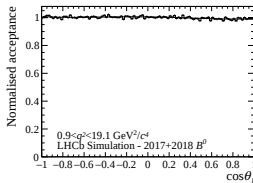
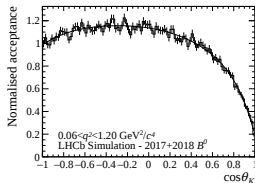
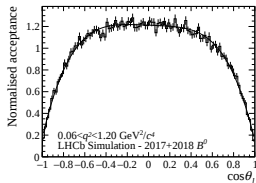
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

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 [\[arXiv:1612.07186\]](#)

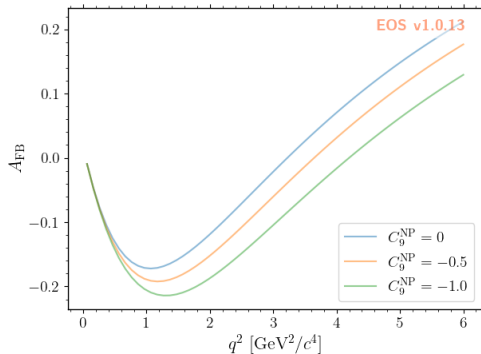
$$\epsilon(\vec{\Omega}, m_{K\pi}, q^2) = \sum_{ijklm} c_{ijklm} \mathcal{L}_i(q^2) \mathcal{L}_j(\cos \theta_\ell) \mathcal{L}_k(\cos \theta_K) \mathcal{L}_l(\phi) \mathcal{L}_m(m_{K\pi})$$



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

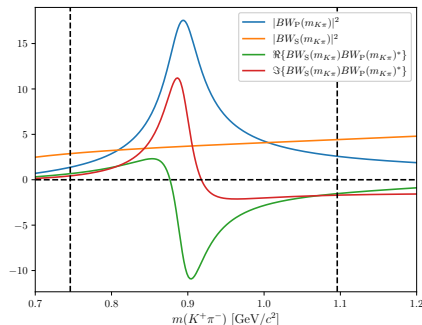
- q^2 binning as in previous analysis iterations
 - Exclude $\phi(1020)$, J/ψ , $\psi(2S)$
 - 8 bins $\approx 1.5 - 2 \text{ GeV}^2/c^4$
 - 2 wide bins
 - Low q^2 edge extended to $0.06 \text{ GeV}^2/c^4$
- **NEW: 16 half-sized q^2 bins**
 - Better resolution of q^2 dependence of observables
- Select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

[EPJC 82 (2022) 569]



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

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Normalisation mode

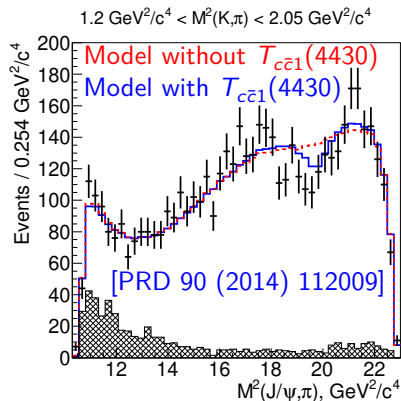
BF normalisation: $B^0 \rightarrow K^+ \pi^- J/\psi$

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

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

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

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



Systematic uncertainties and checks

NEW: Assessed coherently across all q^2 bins

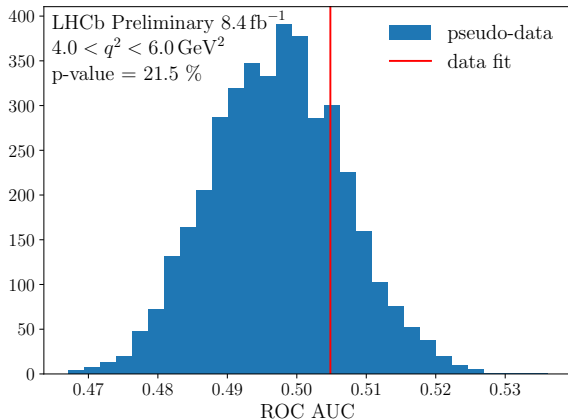
- A single correlation matrix for all observables in all bins
 - E.g. simulation corrections are common to all q^2 bins
- **P-wave observables dominated by σ_{stat}**
 - Largest σ_{syst} sources vary by observable and q^2 bin
- S-wave and interference observables have larger systematic uncertainties
 - Dominant contribution due to form of $\mathcal{BW}_S(m_{K\pi})$ 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 $\mathcal{B}(B^0 \rightarrow \psi(2S)K^{*0})$ against PDG [PRD 110 (2024) 030001]
- No dependence on data-taking period or magnet polarity

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

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 dissimilarity [[JINST 5 \(2010\) P09004](#)]
 - Compare pseudodata from the fit model with the real data
- Same approach as for the acceptance functions

Observable check

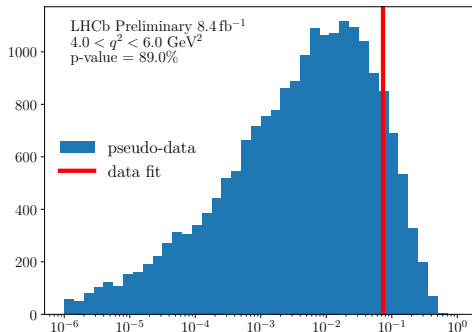
[JHEP 12 (2021) 085]

E.g. relation III:

$$0 = +\frac{27}{16}\beta^2 F_S(16J_{2s}^2 - 4J_3^2 - \beta^2 J_{6s}^2 - 4J_9^2) - 2\Gamma'[-2(\beta^2 J_{6s} S_{S2}^i S_{S3}^i - \beta^2 J_9 S_{S3}^i S_{S4}^r + 4J_9 S_{S2}^i S_{S5}^r + \beta^2 J_{6s} S_{S4}^r S_{S5}^r) + 4S_{S2}^{i2}(J_3 + 2J_{2s}) + \beta^2 S_{S3}^{i2}(2J_{2s} - J_3) + \beta^2 S_{S4}^{r2}(J_3 + 2J_{2s}) + 4S_{S5}^{r2}(2J_{2s} - J_3)].$$

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

- 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)



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

17 October 2025

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Results highlights

Prediction

The Ashes 2010: I'm sticking with a 5-0 Aussie win, says Glenn McGrath

Guardian, 17 November 2010

Experiment

The Ashes 2010-11: England wrap up series win over Australia in style

Guardian, 7 January 2011

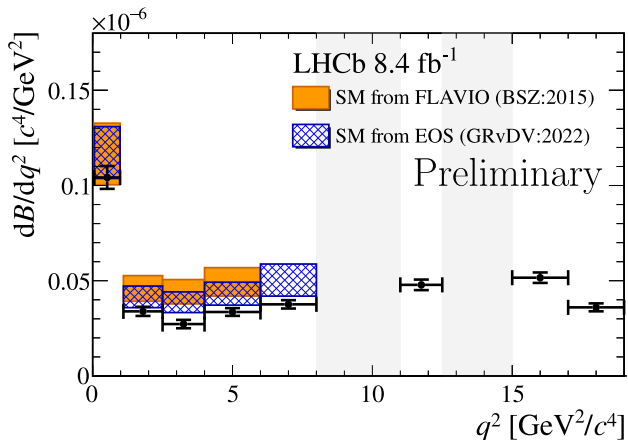


HEPData

[\[https://www.hepdata.net/\]](https://www.hepdata.net/)

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

Branching fraction



BSZ:

[arXiv:1810.08132]

[JHEP 08 (2016) 098]

GRvDV:

[EPJC 82 (2022) 569]

[JHEP 09 (2022) 133]

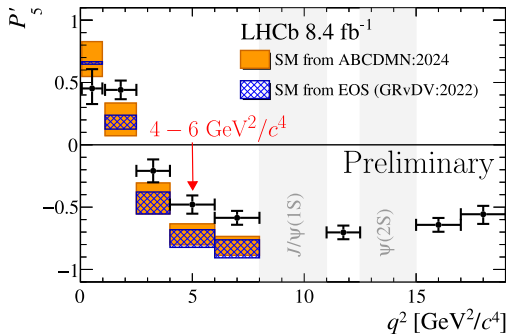
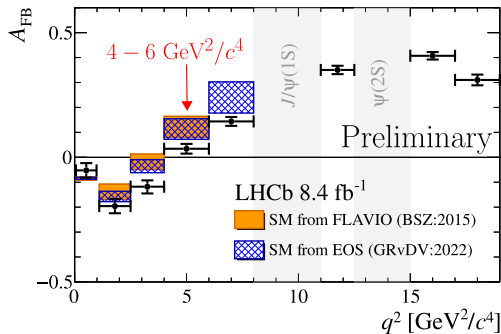
ABCDMN:

[EPJC 83 (2023) 648]

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

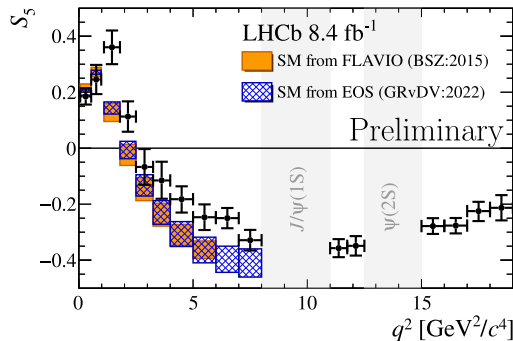
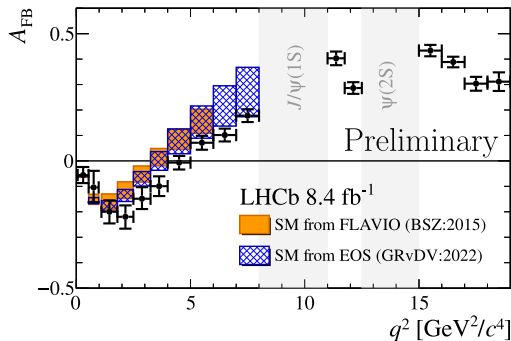
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

CP-average observables



- Discrepancy between experiment and theory in A_{FB} and P'_5 increases
- P'_5 tension in $4.0 < q^2 < 6.0 \text{ GeV}^2/c^4$ now 2.7σ
- A_{FB} tension in $4.0 < q^2 < 6.0 \text{ GeV}^2/c^4$ now 1.9σ

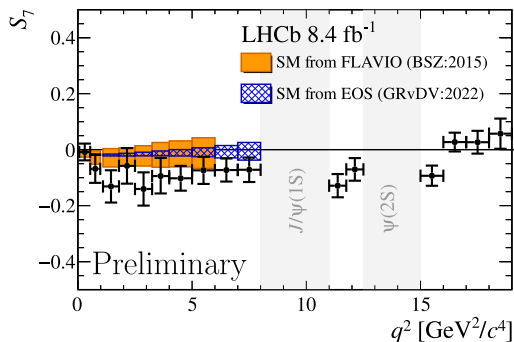
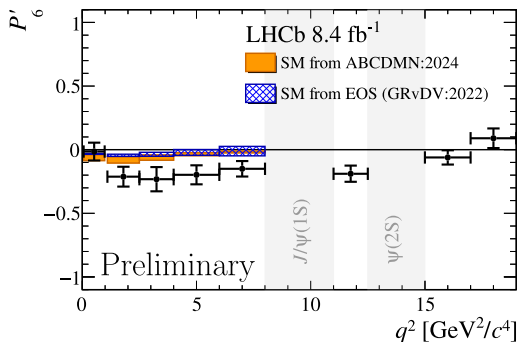
CP-average observables - half-sized q^2 bins



- Consistent results with the nominal sized bins

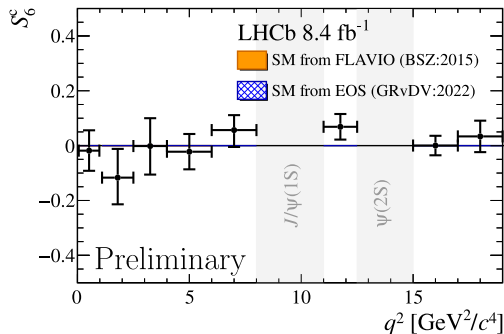
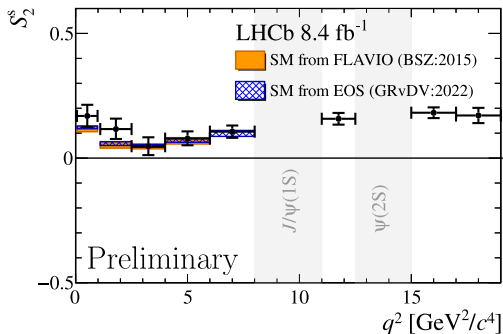
- $\frac{d\mathcal{B}}{dq^2}$, A_{FB} , S_7 below predictions, S_5 above

CP-average observables



- P'_6 (S_7) consistently below predictions
 - $S_7 \sim \text{Im} \left[A_0^L A_{||}^{L*} - A_0^R A_{||}^{R*} \right]$
- No single bin has a significant discrepancy

CP-average observables - massive

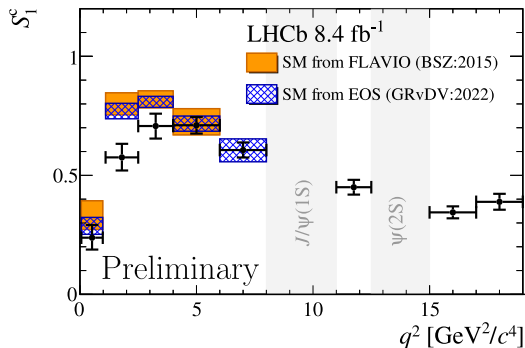


- First extraction of S_2^s and S_6^c across all q^2 .
- S_6^c consistent with 0 in all bins $\rightarrow$ no sign of NP tensor or scalar amplitudes

CP -average observables - massive

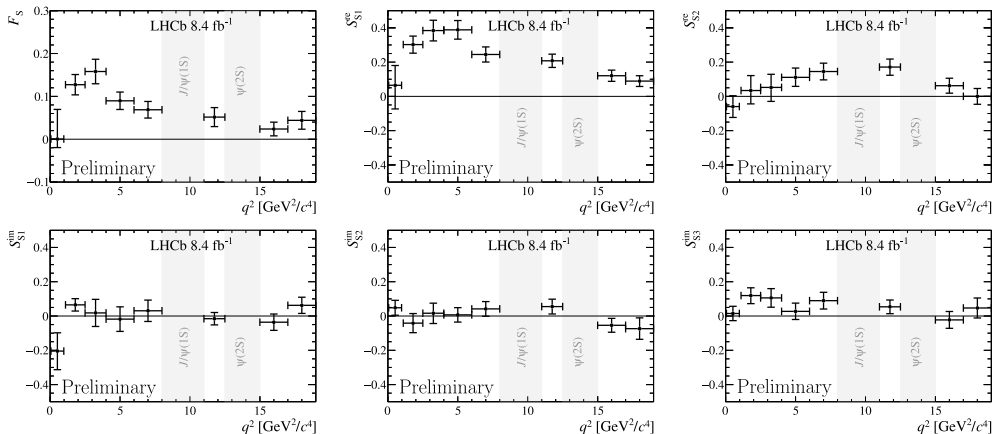
From the 'fully massive' fit:

- First measurement of S_1^c - here with no assumptions on the P-wave observables
- In $1.1 < q^2 < 2.5 \text{ GeV}^2/c^4$ 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

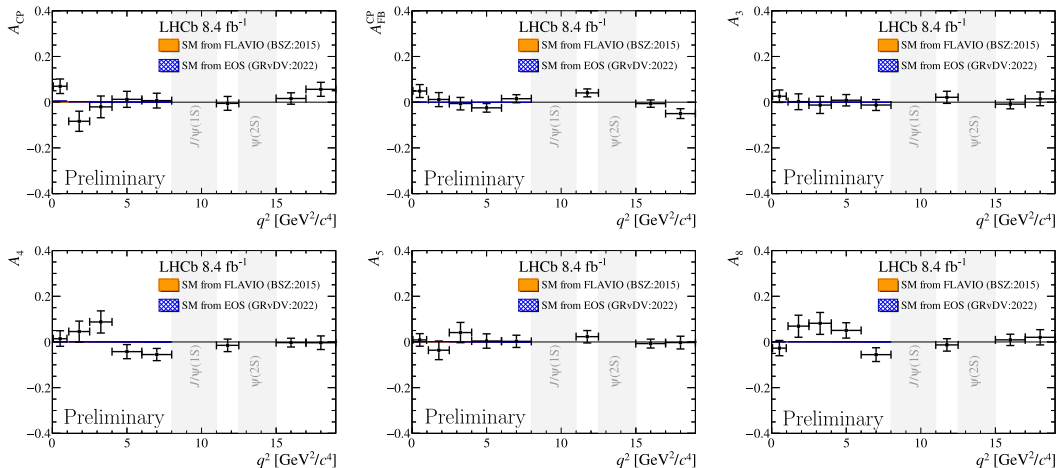
CP-average observables - S-wave



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

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

CP-asymmetry observables

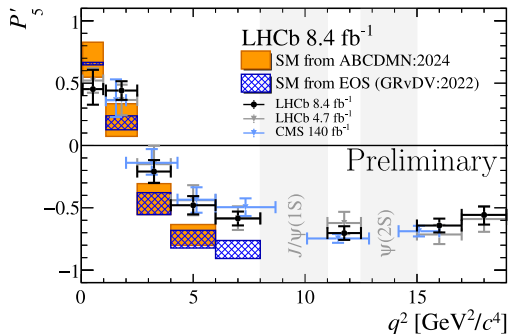
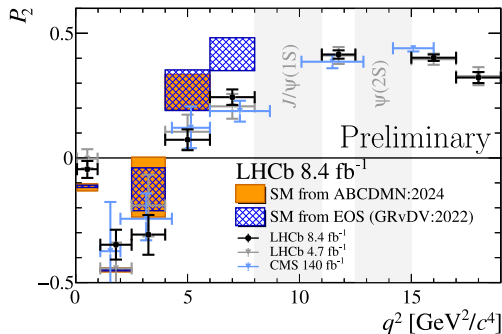


No significant *CP*-asymmetry

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

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

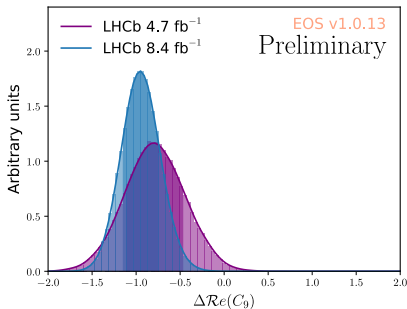
[EPJC 82 (2022) 569]
[arXiv:1810.08132]

LHCb $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ only fit for C_9 with EOS and flavio

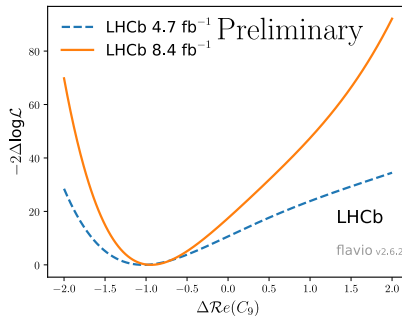
- Precise numbers depend on how the fit is set up
 - Treatment of non-local effects $\rightarrow$ significant debate in the community
- **These are illustrative!**

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

Significance: 4.0σ

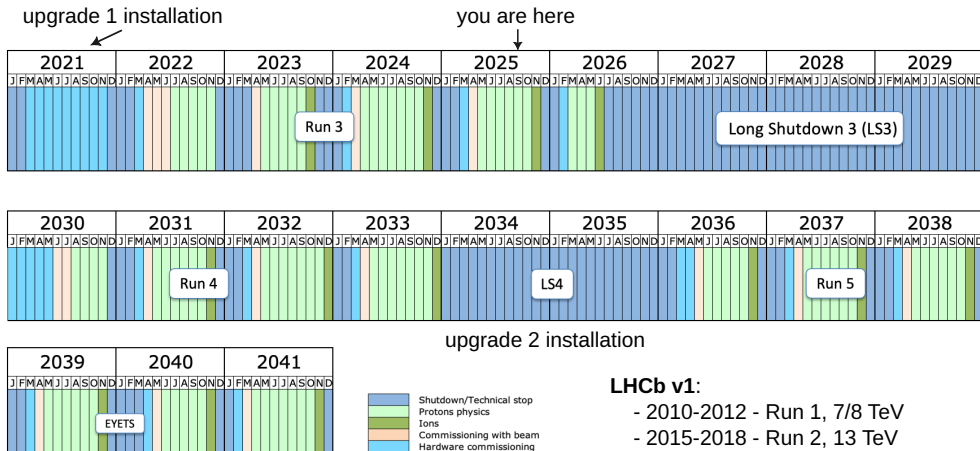


Significance: 4.1σ



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

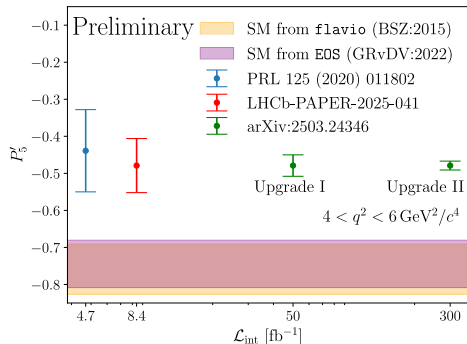
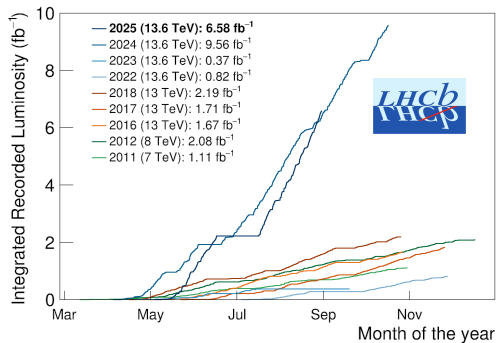
The future



Last update: November 24

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

The future



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

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

Conclusion

LHCb-PAPER-2025-041 (in preparation)

- New study of the FCNC decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ with the LHCb Run 1 and Run 2 data sets
- **Several innovations and new approaches in this analysis**
 - $\frac{d\mathcal{B}}{dq^2}$ 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**

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

BONUS ROUND

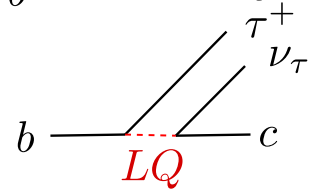
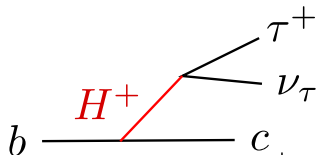
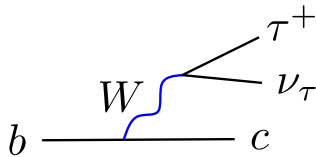
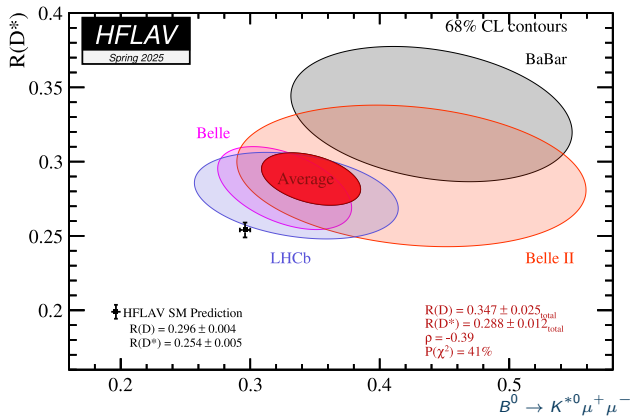
$$b \rightarrow s \tau^+ \tau^-$$

[arXiv:2510.13716]

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

[HFLAV]

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



τ -rrific penguins

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

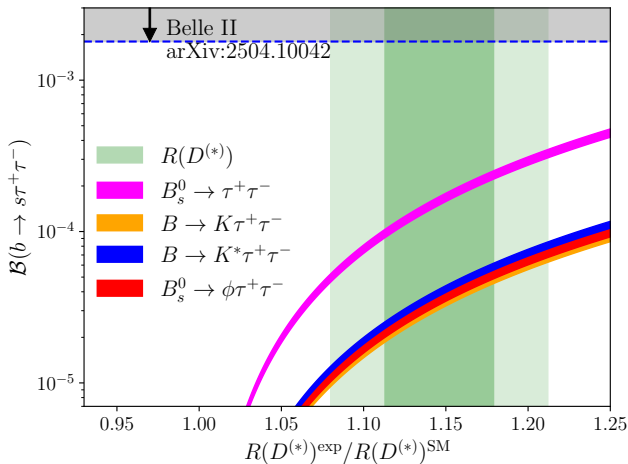
What if the NP for $R(D^{(*)})$ is in the EW penguins? It couples to τ leptons:

$$C_9^{\tau\tau} = C_9^{\text{SM}} - \Delta$$

$$C_{10}^{\tau\tau} = C_{10}^{\text{SM}} + \Delta$$

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

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



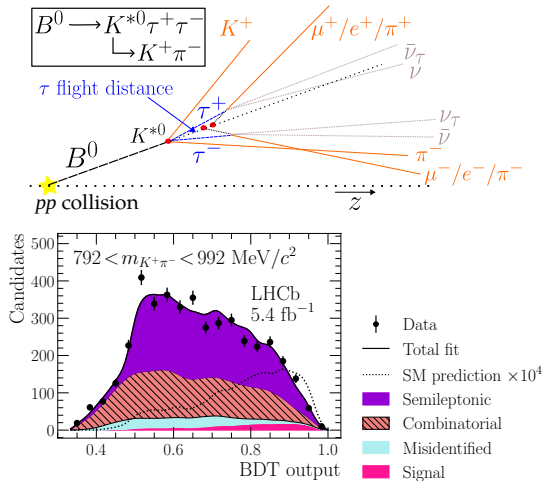
$$\mathcal{B}(b \rightarrow s\tau^+\tau^-)^{\text{SM}} \sim 10^{-7}$$

τ -rrific penguins

[arXiv:2510.13716]

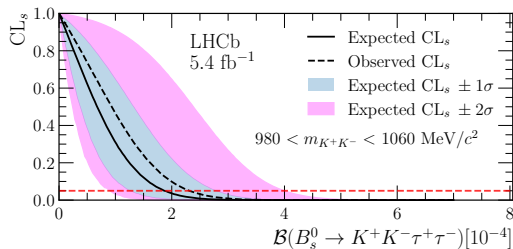
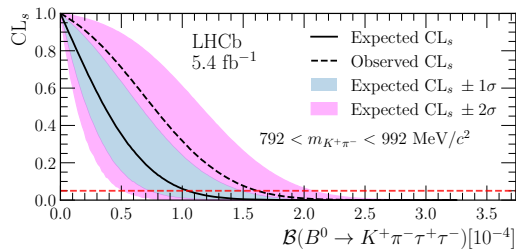
LHCb search for $B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-$ and $B_s^0 \rightarrow K^+ K^- \tau^+ \tau^-$:

- 5.4 fb⁻¹ Run 2 data set
- Reconstruct both τ via $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
- 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



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

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



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

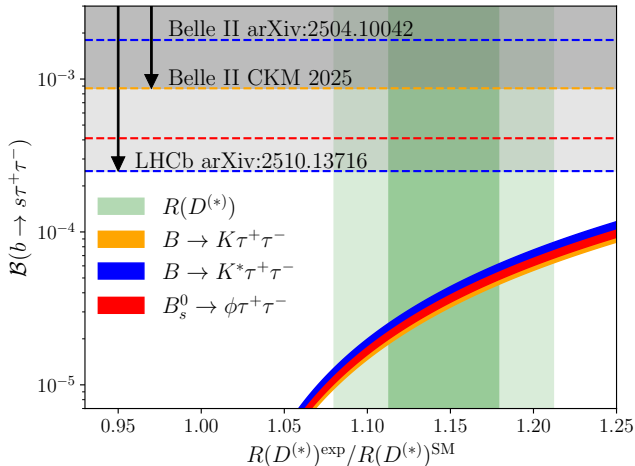
$$\mathcal{B}(B_s^0 \rightarrow \phi \tau^+ \tau^-) < 4.7(4.1) \times 10^{-4} @ 95(90)\% CL_s$$

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

τ -rrific penguins

[arXiv:2510.13716]

- Limit on $B^0 \rightarrow K^{*0} \tau^+ \tau^-$ 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 $\mathcal{B}(B \rightarrow K \tau^+ \tau^-) < 8.7 \times 10^{-4}$ also encouraging
[N. Rout @ CKM]



Much more to come from Belle II and LHCb

Conclusions

LHCb-PAPER-2025-041 (in preparation)

[\[arXiv:2510.13716\]](#)

- Two new searches for NP with electroweak penguin decays
- For $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ 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 $b \rightarrow s \tau^+ \tau^-$ decays
 - World's best limit for $B^0 \rightarrow K^{*0} \tau^+ \tau^-$
 - First limits for $B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-$ and $B_s^0 \rightarrow K^+ K^- \tau^+ \tau^-$ across all $m(h_1 h_2)$

Much more to come from precision studies of electroweak penguin decays

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

The End

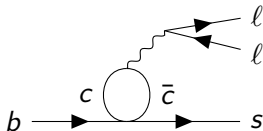


$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

New physics?

Is this all NP?

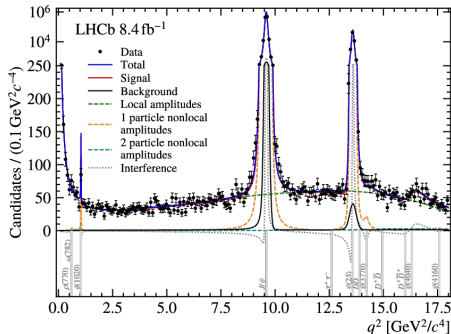
- Is effect from long-distance charm loop fully accounted for?



$$C_9^{\text{eff}} = C_9^{\text{SM}} + C_9^{c\bar{c}} + C_9^{\text{NP}}$$

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

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



Fitted long-distance effects do not cover shift in C_9

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

Extended term

Each subsample has an extended term in the LH

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

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

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

$$\begin{aligned} \frac{d^4 \Gamma_P}{dq^2 d\vec{\Omega} dm_{K\pi}} = & \frac{9}{64\pi} \left[J_{1s} \sin^2 \theta_K + J_{1c} \cos^2 \theta_K \right. \\ & + (J_{2s} \sin^2 \theta_K + J_{2c} \cos^2 \theta_K) \cos 2\theta_\ell \\ & + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\ & + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_{6s} \sin^2 \theta_K \cos \theta_\ell \\ & + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi \\ & \left. + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] |\mathcal{BW}_P(m_{K\pi})|^2 \end{aligned}$$

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

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

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

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

Integrate over $\vec{\Omega}$, $\frac{d\Gamma_P}{dq^2} \rightarrow \Gamma_P$:

$$1 = \frac{3}{4}(S_1^c + 2S_1^s) - \frac{1}{4}(S_2^c + 2S_2^s) \quad S_i = \frac{J_i + \bar{J}_i}{\Gamma_P + \bar{\Gamma}_P}$$
$$A_{CP} = \frac{\Gamma_P - \bar{\Gamma}_P}{\Gamma_P + \bar{\Gamma}_P} = \frac{3}{4}(A_1^c + 2A_1^s) - \frac{1}{4}(A_2^c + 2A_2^s) \quad A_i = \frac{J_i - \bar{J}_i}{\Gamma_P + \bar{\Gamma}_P}$$

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

Construct theory-optimised observables:

$$P_{1,2,3} = N_i \frac{S_{3,6s,9}}{S_2^s}$$

$$P'_{4,5,6,8} = N_i \frac{S_{4,5,7,8}}{\sqrt{-S_2^s S_2^c}}$$

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

$$\begin{aligned} \frac{d^4\Gamma}{dq^2 d\vec{\Omega} dm_{K\pi}} &= (1 - \hat{\Gamma}_S) \frac{d^4\Gamma_P}{dq^2 d\vec{\Omega} dm_{K\pi}} \\ &+ \frac{1}{8\pi} [(\tilde{S}_{1a}^c + \tilde{S}_{2a}^c \cos \theta_\ell) |\mathcal{BW}_S(m_{K\pi})|^2 \\ &+ \frac{1}{8\pi} \text{Re} \left(\left[\tilde{S}_{1b}^c \cos \theta_K + \tilde{S}_{S1}^c \cos \theta_K \cos 2\theta_\ell \right] \mathcal{BW}_S(m_{K\pi}) \mathcal{BW}_P^*(m_{K\pi}) \right) \\ &+ \frac{1}{8\pi} \text{Re} \left(\left[\tilde{S}_{S2} \sin \theta_K \sin 2\theta_\ell \cos \phi + \tilde{S}_{S3} \sin \theta_K \sin \theta_\ell \cos \phi \right] \mathcal{BW}_S(m_{K\pi}) \mathcal{BW}_P^*(m_{K\pi}) \right) \\ &+ \frac{1}{8\pi} \text{Im} \left(\left[\tilde{S}_{S4} \sin \theta_K \sin \theta_\ell \sin \phi + \tilde{S}_{S5} \sin \theta_K \sin 2\theta_\ell \sin \phi \right] \mathcal{BW}_S(m_{K\pi}) \mathcal{BW}_P^*(m_{K\pi}) \right) \end{aligned}$$

$$\tilde{S}_i = \frac{J_i + \bar{J}_i}{\Gamma_P + \bar{\Gamma}_P + \Gamma_S + \bar{\Gamma}_S}$$

$$\tilde{A}_i = \frac{\bar{J}_i - J_i}{\Gamma_P + \bar{\Gamma}_P + \Gamma_S + \bar{\Gamma}_S}$$

$$\hat{\Gamma}_S = 2\tilde{S}_{1a}^c - \frac{2}{3}\tilde{S}_{2a}^c$$

S-wave and interference

$$\begin{aligned} & \mathcal{R}e \left(\tilde{S}_{S1}^c \mathcal{B}\mathcal{W}_S(m_{K\pi}) \mathcal{B}\mathcal{W}_P^*(m_{K\pi}) \right) \\ & \rightarrow \tilde{S}_{S1}^{c,\text{re}} \mathcal{R}e(\mathcal{B}\mathcal{W}_S \mathcal{B}\mathcal{W}_P^*(m_{K\pi})) - \tilde{S}_{S1}^{c,\text{im}} \mathcal{I}m(\mathcal{B}\mathcal{W}_S \mathcal{B}\mathcal{W}_P^*(m_{K\pi})) \end{aligned}$$

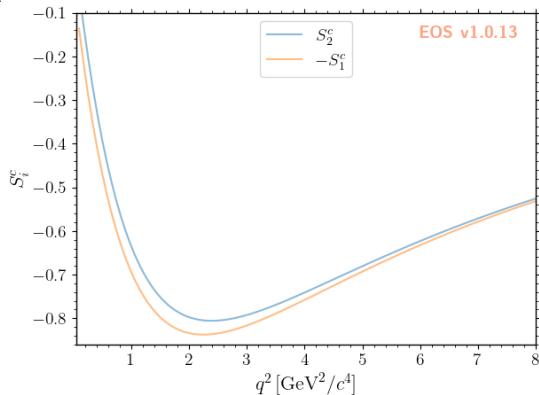
- The interference observables have real and imaginary parts - extra observables
 - These can be measured
- Value of S-wave and interference observables depends on the analysed range of $m_{K\pi}$
 - $745.9 < m_{K\pi} < 10959.9 \text{ MeV}/c^2$
- $\mathcal{B}\mathcal{W}_P(m_{K\pi})$ is a relativistic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

Lepton mass

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

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

$$\begin{array}{ccccc}
 \beta_\ell^2 = 1 & S_1^c = -S_2^c & S_1^s = 3S_2^s & A_1^c = -A_2^c & A_1^s = 3A_2^s \\
 S_{1a}^c = -S_{2a}^c & & & S_{1b}^{c,\text{re/im}} = -S_{S1}^{\text{re/im}} &
 \end{array}$$



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 $q^2 > 1 \text{ GeV}^2$
- Massive leptons for $q^2 < 1 \text{ GeV}^2$
- **Best precision on individual CP -average observables**

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

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

$F_S, S_{S1-5}^{\text{re/im}}$

$q^2 < 1 \text{ GeV}^2$:

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

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

$$S_2^c, S_{3-9}, A_{CP}, A_2^c, A_3 - A_9$$
$$F_S, S_{S1-5}^{\text{re/im}}, AF_S, AS_{S1-5}^{\text{re/im}}$$
$$q^2 < 1 \text{ GeV}^2:$$
$$S_2^s, S_6^c, \tilde{S}_{1a}^c, \tilde{S}_{1b}^{c, \text{re/im}}$$
$$A_2^s, A_{\text{FB}}^{CP}, \tilde{A}_{1a}^c, \tilde{A}_{1b}^{c, \text{re/im}}$$

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

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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 $q^2 < 1 \text{ GeV}^2$
- Massive leptons for $q^2 > 1 \text{ GeV}^2$
- **Sensitivity to scalar or tensor amplitudes**

$$S_1^c, S_2^s, S_6^c, S_2^c, S_{3-9}, F_S, S_{S1-5}^{\text{re/im}}, \\ q^2 < 1 \text{ GeV}^2: \\ S_2^s, S_6^c, \tilde{S}_{1a}^c, \tilde{S}_{1b}^{c,\text{re/im}}$$

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

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 $q^2 > 1 \text{ GeV}^2$
- Massive leptons for $q^2 < 1 \text{ GeV}^2$
- **Best resolution of q^2 dependence of observables**

$$S_1^c, S_2^c, S_{3-9}, F_S, S_{S1-5}^{\text{re/im}}, \\ q^2 < 1 \text{ GeV}^2: \\ S_2^s, S_6^c, \tilde{S}_{1a}^c, \tilde{S}_{1b}^{c, \text{re/im}}$$

Fit configurations

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

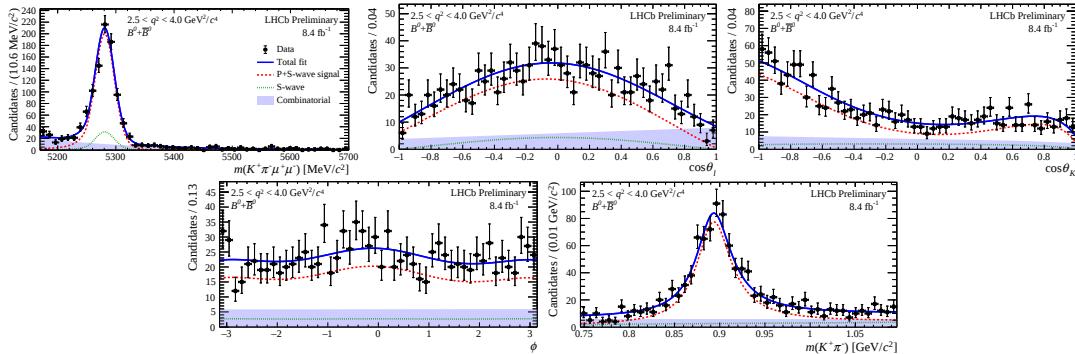
1. Partially-massive non-optimised observables, CP -average only
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6. Massless, optimised observables, CP -average only

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

$$S_2^c, P_{1-8}^{(\prime)}$$
$$F_S, S_{S1-5}^{\text{re/im}}$$

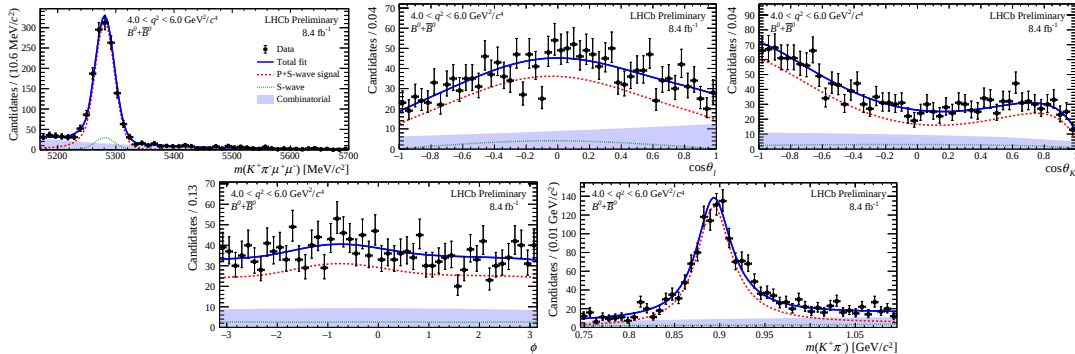
$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

Fit projections



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

Fit projections



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

HEPData page

[\[https://www.hepdata.net/\]](https://www.hepdata.net/)

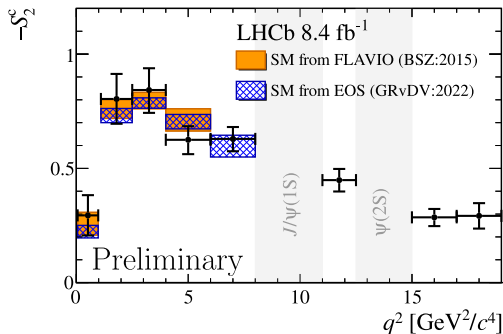
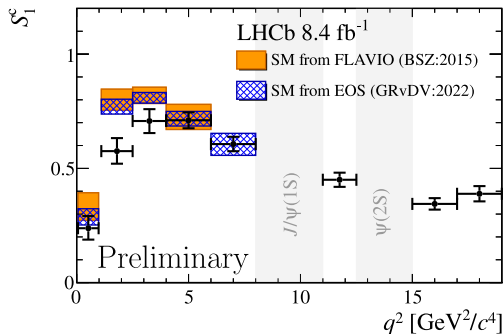
Machine readable format - all fit configurations

- 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

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

S_1^s and S_2^c

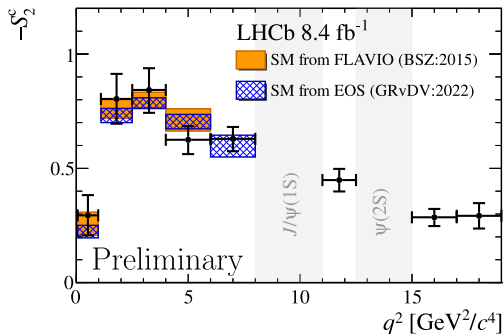
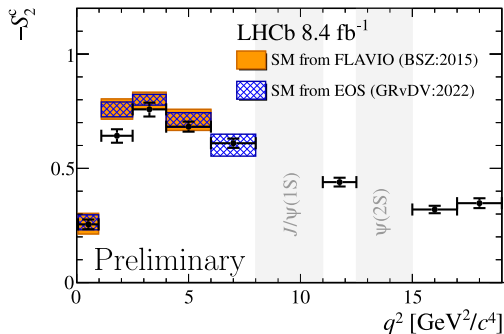
From the fully massive P-wave fit configuration:



- In the q^2 region $1.1 < q^2 < 4.0 \text{ GeV}^2/c^4$ $S_1^c \neq S_2^c$
- 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:



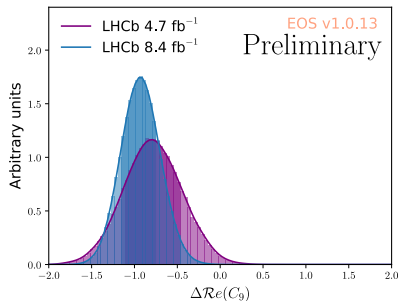
Wilson coefficients

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

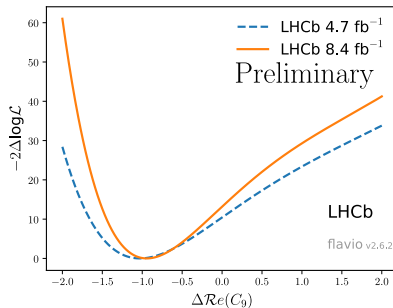
- LHCb $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ only fit for C_9 with EOS and flavio
- Precise numbers depend on how the fit is set up
 - Treatment of non-local effects $\rightarrow$ significant debate in the community
- These are illustrative!

Angular observables only:

Significance: 3.8σ



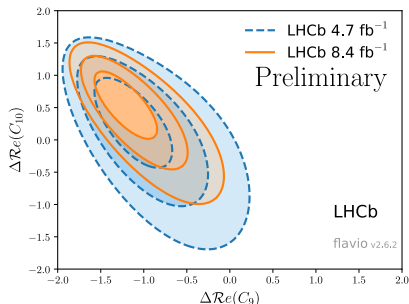
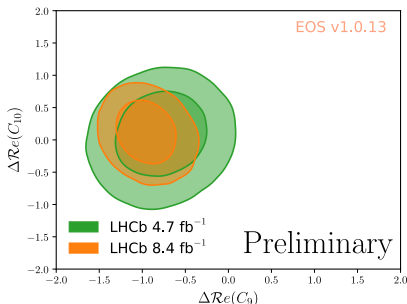
Significance: 3.6σ



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

- LHCb $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ only fit for $C_9 - C_{10}$ with EOS and flavio
- Precise numbers depend on how the fit is set up
 - Treatment of non-local effects $\rightarrow$ significant debate in the community
- These are illustrative!

Angular observables only:

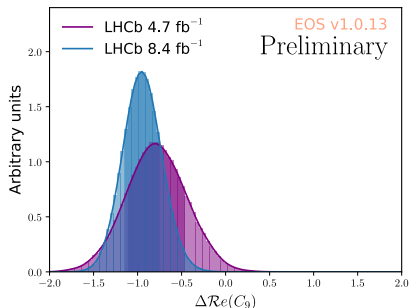
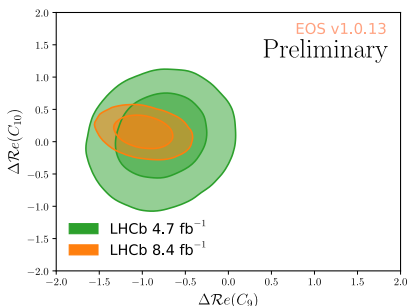


Wilson coefficients

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

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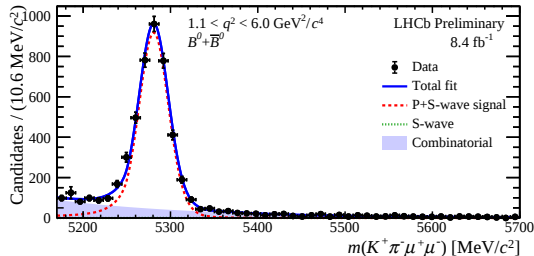
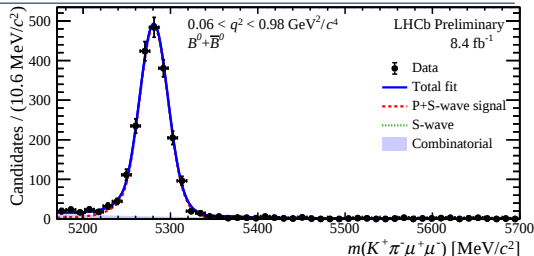
Angular observables only:



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

Backgrounds

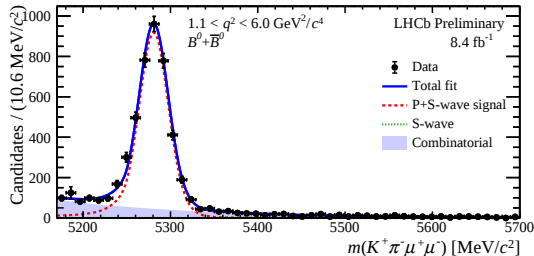
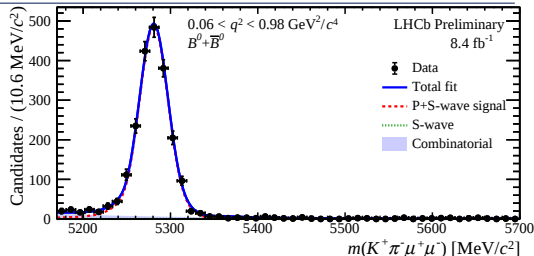
- Combinatorial - random combinations of tracks
 - Reduced with BDT
 - Residual background modelled in fit



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

Backgrounds

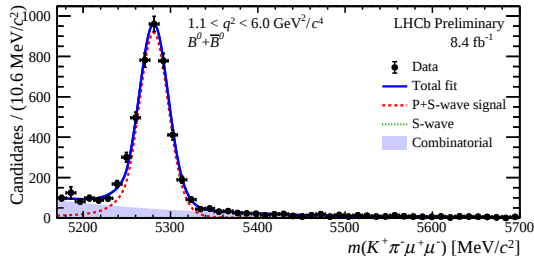
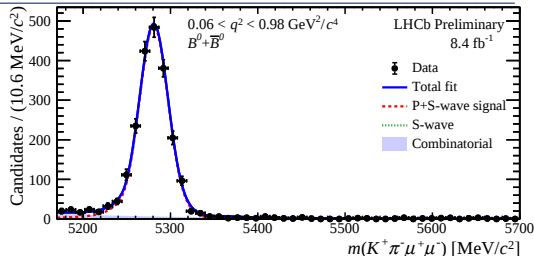
- Combinatorial - random combinations of tracks
- Particle mis-identification - reduced to negligible
 - i.e. $B_s^0 \rightarrow (\phi \rightarrow K^+ K^-) \mu^+ \mu^-$
 $K^- \rightarrow \pi^-$
- PID requirements and dedicated vetoes on alternative mass hypotheses



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

Backgrounds

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

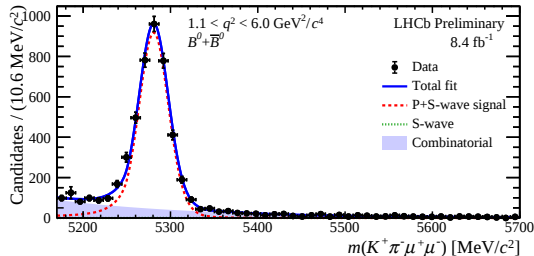
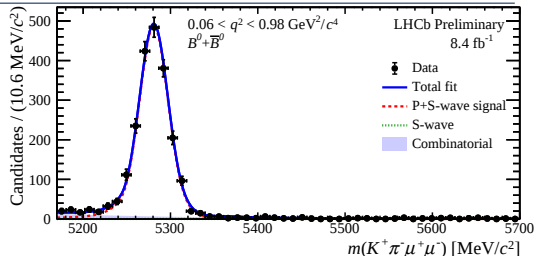


$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

Backgrounds

- Combinatorial - random combinations of tracks
- Particle mis-identification - reduced to negligible
- Quasi-combinatorial - reconstruct part of a decay and add a random particle

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



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