

Search for new physics in $b \rightarrow s\ell^+\ell^-$ transitions at CMS

Alessio Boletti
on behalf of CMS collaboration

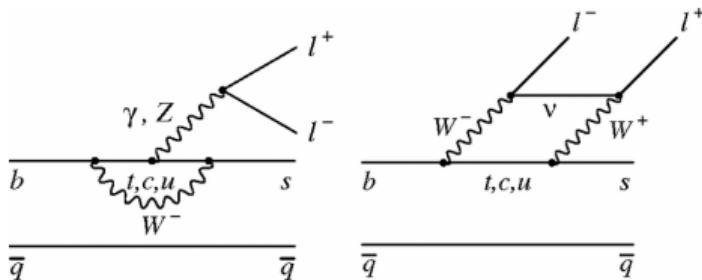
LIP - Laboratório de Instrumentação e Física Experimental de Partículas

ICHEP 2020
30th July 2020



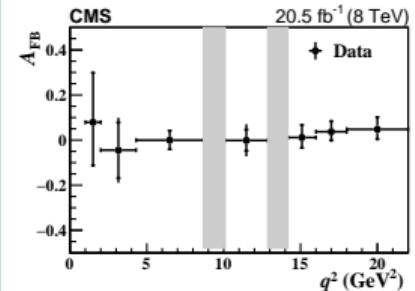
Introduction

- Flavour-changing neutral current decays
 $b \rightarrow s\ell^+\ell^-$ are doubly suppressed in the Standard Model
- Good laboratory to probe new-physics effects, through angular analysis and branching fraction measurement
- The pseudoscalar $B^+ \rightarrow K^+ \mu\mu$ decay
 - muon direction defines one angular variable
 - allows measuring the muon forward-backward asymmetry
- The vector-state $B \rightarrow K^* \mu\mu$ decays
 - muon direction and K^* polarisation define three angles
 - allows measuring a large set of angular parameters, sensitive to Wilson coefficients $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}, \mathcal{C}_{S,P}^{(\prime)}$
- Channels are experimentally accessible, thanks to the fully-charged final states and easy-to-identify muon pair

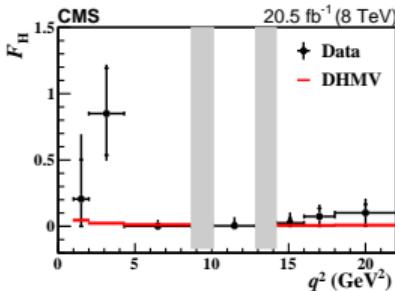


Angular analyses in CMS with Run 1 data

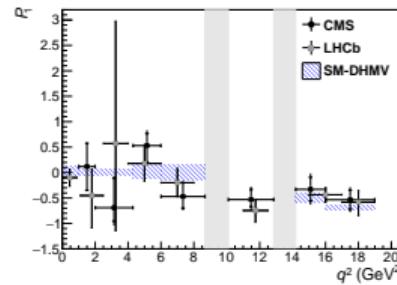
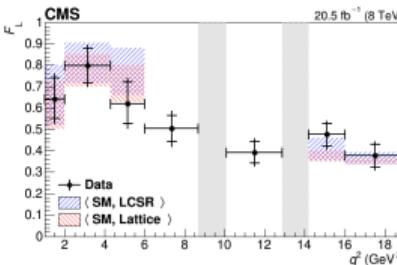
$$B^+ \rightarrow K^+ \mu\mu$$



$$[\text{Phys Rev D} 98 (2018) 112011]$$



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



New!

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

[CMS-PAS-BPH-15-009]

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

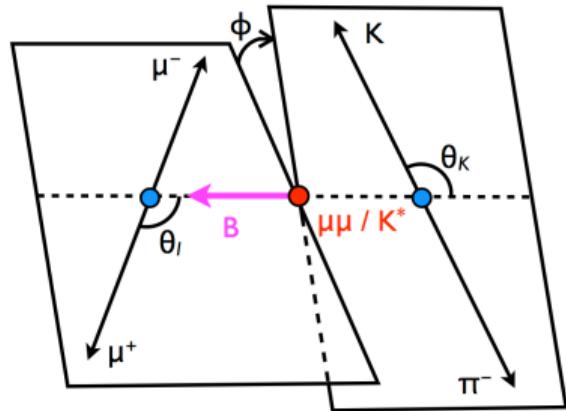
CMS-PAS-BPH-15-009

- Fully described by three angles: $\theta_\ell, \theta_K, \phi$ and $q^2 = M_{\mu\mu}^2$
- Angle ϕ is integrated out, leaving the decay rate:

$$\frac{1}{d\Gamma/dq^2} \frac{d^3\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K} = \frac{9}{16} \left[\frac{1}{2} (1 - F_L) (1 - \cos^2\theta_K) (1 + \cos^2\theta_\ell) \right. \\ \left. + 2F_L \cos^2\theta_K (1 - \cos^2\theta_\ell) + \frac{4}{3} A_{FB} (1 - \cos^2\theta_K) \cos\theta_\ell \right]$$

- Measured the fraction of longitudinally polarised K^{*+} , F_L , and the forward-backward asymmetry, A_{FB}
- The q^2 range has been divided in 5 bins

- 3 signal bins, in each of them the angular analysis is performed independently
- 2 control-region bins, covering the two resonant decays $B^+ \rightarrow J/\psi K^{*+}$ and $B^+ \rightarrow \psi(2S)K^{*+}$
- the analysis is also performed on the whole signal q^2 spectrum



q^2 bins [GeV 2]
1.00 – 8.68
10.09 – 12.89
14.18 – 19.00

Selection criteria

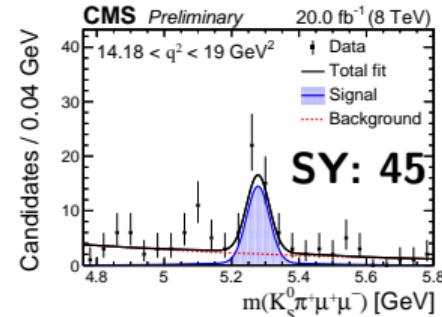
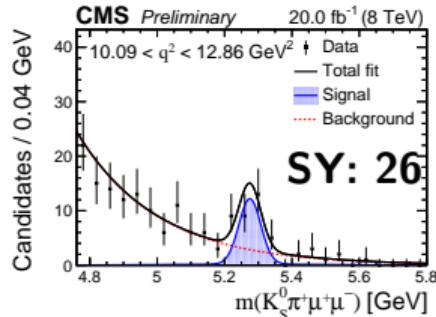
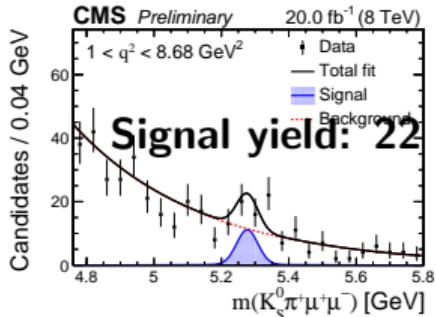
Dedicated HLT trigger path: low pt dimuon, forming displaced vertex, low invariant mass

K^{*+} reconstructed using its decay in $K_s \pi^+$

- K_s decay in $\pi^+ \pi^-$ is forming a two-track vertex displaced from the B-decay vertex
- mass and vertex quality requirements applied to K_s and K^{*+} candidates
- veto applied to exclude $\Lambda \rightarrow p\pi$ decays

Selections on momenta and B-vertex quality and displacement have been optimised to maximise signal significance

Contamination from resonant J/ψ and $\psi(2S)$ decays removed by combined cuts on q^2 and $m(B^+)$



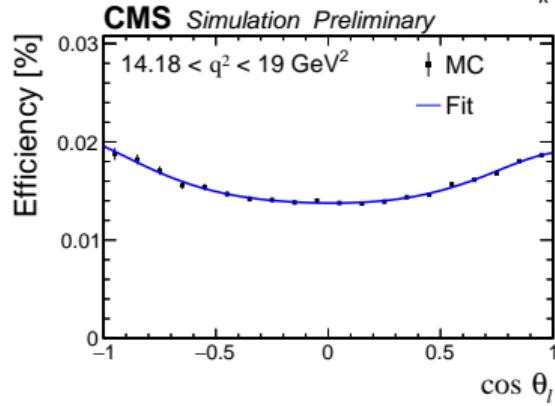
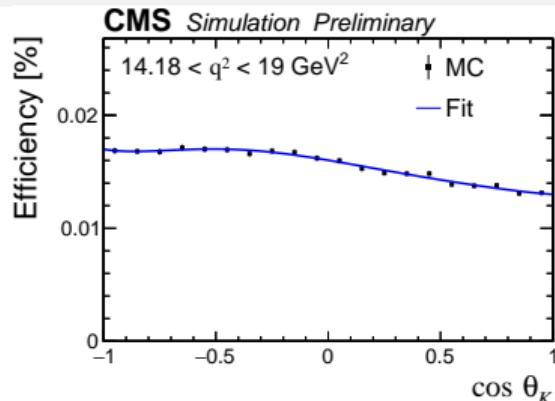
Efficiency parametrisation

Efficiency described by 2D function using simulated sample.

Two steps:

- For each angle, 1D polynomial or combination of Gaussian functions
- Correlation term with product of Legendre and ordinary polynomials

$$\varepsilon(\cos \theta_K, \cos \theta_l) = \varepsilon_{1D}(\cos \theta_K) \cdot \varepsilon_{1D}(\cos \theta_l) \cdot [1 + C(\cos \theta_K, \cos \theta_l)]$$

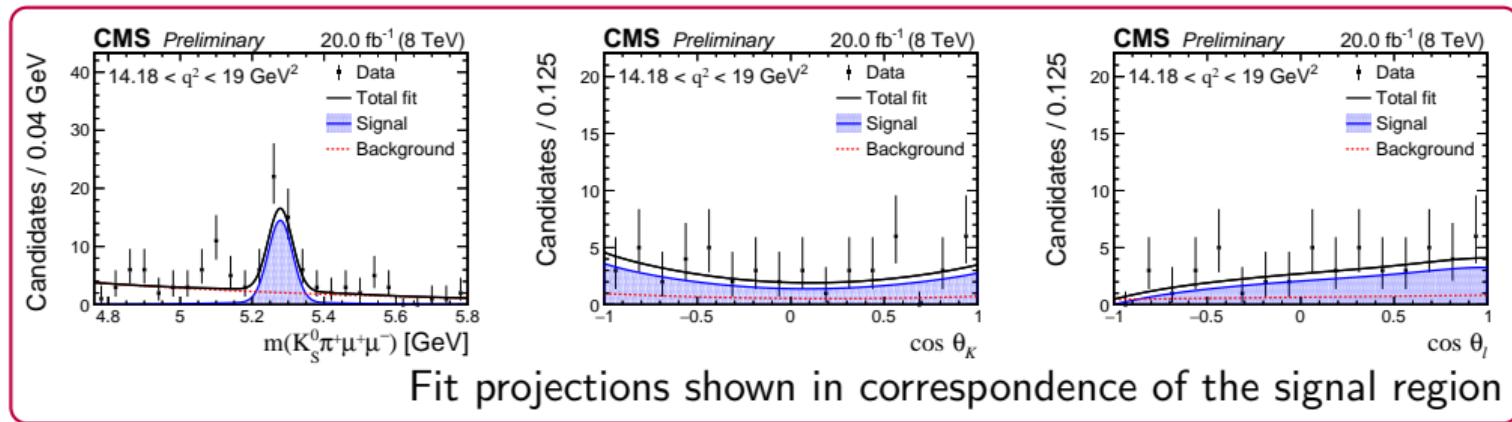


Fit algorithm

$$\begin{aligned} \text{p.d.f.}(m, \cos \theta_K, \cos \theta_I) = & Y_S \cdot S^m(m) \cdot S^a(\cos \theta_K, \cos \theta_I) \cdot \epsilon(\cos \theta_K, \cos \theta_I) \\ & + Y_B \cdot B^m(m) \cdot B^{\theta_I}(\cos \theta_I) \cdot B^{\theta_K}(\cos \theta_K) \end{aligned}$$

- Signal pdf component
 - double Gaussian mass shape with parameters determined on MC
 - decay rate and efficiency functions as in previous slides
- Background pdf component
 - exponential mass shape
 - polynomial or Gaussian or exponential shapes combined for the angular shape
- Two-step fit performed:
 - fit m side bands to determine the background angular shape (fixed in second step)
 - fit whole mass spectrum with 5 floating parameters (2 yields + 2 angular param + bkg slope)
- Unbinned extended maximum likelihood estimator used
- Statistical uncertainty using profiled Feldman-Cousins method

Fit projections and systematic uncertainties

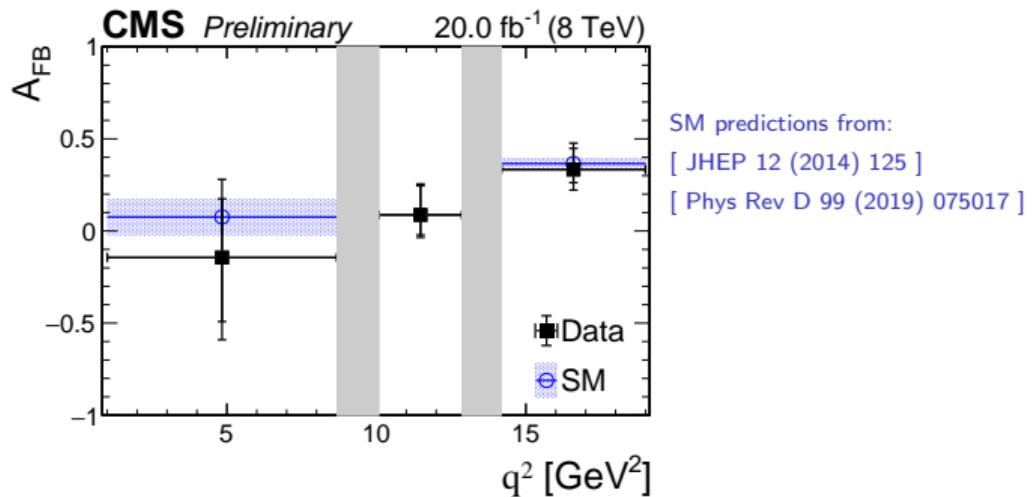
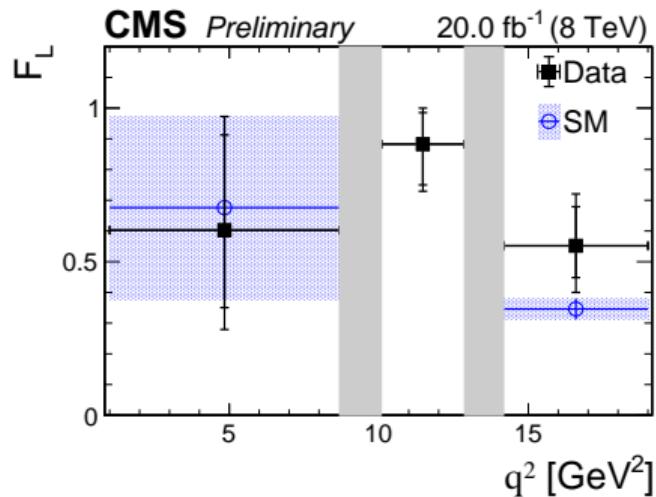


Source	A_{FB} (10^{-3})	F_L (10^{-3})
MC statistical uncertainty	12 – 29	18 – 38
Efficiency model	3 – 25	4 – 12
Background shape	34 – 170	46 – 121
S-wave contamination	4 – 22	5 – 12
Total systematic uncertainty	42 – 174	55 – 127

Dominant systematic uncertainty from background angular description taking into account:

- Function choice
- Extension of the sideband in mass spectrum
- Propagation of sidebands' statistical uncertainty

Results

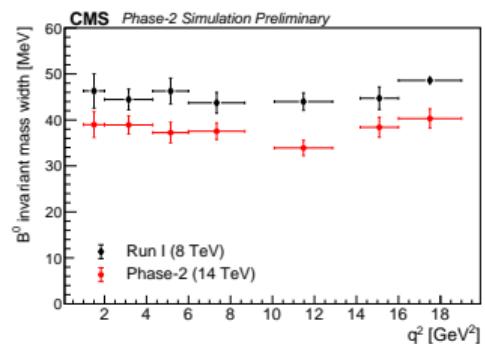
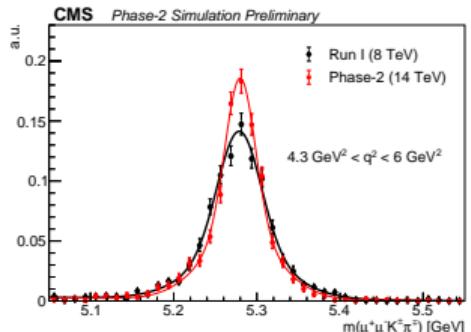


- Inner error bar is statistical uncertainty
- Full bar is total uncertainty
- Results compatible with SM predictions within uncertainties

Prospects for $B^0 \rightarrow K^{*0} \mu\mu$ analysis at HL-LHC

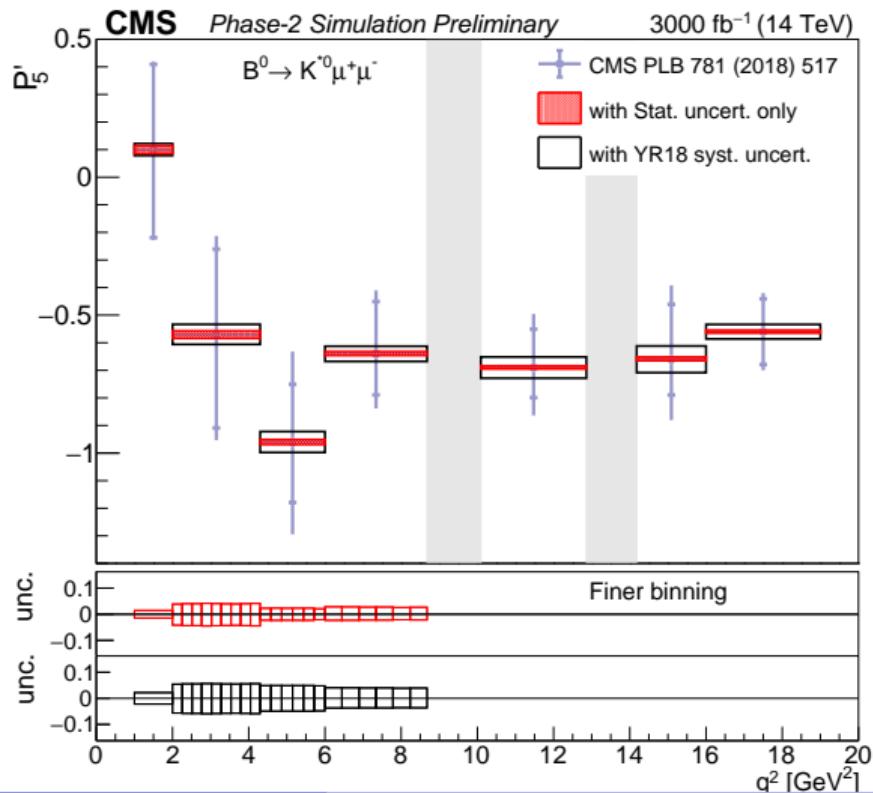
Report: CMS-PAS-FTR-18-033

- **Uncertainty on P'_5** measurement in $B^0 \rightarrow K^{*0} \mu\mu$ angular distribution is extrapolated to **HL-LHC** scenario at 3000 fb^{-1}
- Run 1 results used as baseline
- Upgraded CMS tracker detector provides **improved mass resolution**
- No changes in trigger performances and analysis strategy have been considered
- Signal yield has been obtained from MC simulations with Phase-2 detector upgrade and pileup of 200
 - Scaled to 3000 fb^{-1} : $\sim 700\text{k}$ events in the full q^2 range



Projections on P'_5 uncertainty (HL-LHC)

- Run 1 statistical uncertainty scaled according to the expected yield
- Systematic uncertainties based on data control channel scaled according to statistics
- Other systematic uncertainties scaled by factor of 2
- Total uncertainty is expected to improve by 15 times wrt Run 1 result
- Large signal yield allows to split q^2 range in finer bins



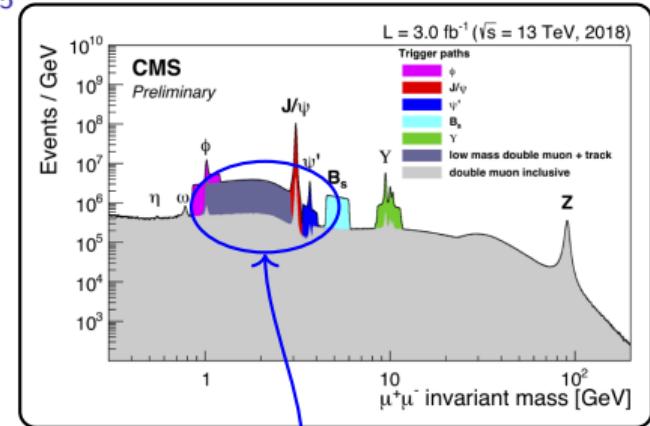
Summary

FCNC rare decays have been extensively studied in Run 1 CMS data

- $B^0 \rightarrow K^{*0} \mu\mu$ angular analysis to measure F_L , A_{FB} , P_1 and P'_5
- $B^+ \rightarrow K^+ \mu\mu$ angular analysis to measure A_{FB} and F_H
- New results shown here on $B^+ \rightarrow K^{*+} \mu\mu$ angular analysis to measure F_L and A_{FB}
- Prospects of $B^0 \rightarrow K^{*0} \mu\mu$ angular analysis in HL-LHC

Currently working on Run 2 data

- dedicated trigger requiring two muons + 1 track with common vertex
- more decay channels to be explored
- Stay tuned



Backup slides

Selection criteria

Trigger requirements:

- two muons with $p_T > 3.5$ GeV and $|\eta| < 2.2$
- common vertex with χ^2 probability $> 10\%$
- vertex 3σ displaced from beamspot
- dimuon system with $p_T > 6.9$ GeV
- $1 \text{ GeV} < m(\mu\mu) < 4.8 \text{ GeV}$
- $\cos \alpha > 0.9$ of angle between dimuon momentum and beamspot-to-vertex segment

(reapplied to offline muons, which are matched to trigger muons)

Selections optimised for expected signal significance:

- $p_T(K_s^0) > 1$ GeV
- $p_T(\pi_{K^*}) > 0.4$ GeV
- $d_{xy}(\pi_{K^*}, \text{beamspot}) > 0.4\sigma$
- B^+ vtx χ^2 prob $> 10\%$
- B^+ vtx 12σ displaced from beamspot
- $\cos \alpha > 0.9994$ of angle between B^+ momentum and beamspot-to-vertex segment

Multiple candidates per event: best vtx χ^2 is kept

K_s^0 reconstruction:

- π tracks with at least 6 hits in tracker detector
- π track fit with $\chi^2/\text{dof} < 5$
- π transverse distance from beamspot $> 2\sigma$
- $\pi - \pi$ closest approach < 1 cm
- $\pi - \pi$ vertex has $\chi^2/\text{dof} < 7$
- $\pi - \pi$ vertex 15σ displaced from beamspot
- $|m(\pi\pi) - m_{\text{PDG}}(K_s^0)| < 17.3$ MeV
- [1.11, 1.125] GeV mass range vetoed, with proton+pion mass hypothesis

$$|m(K_s^0 \pi) - m_{\text{PDG}}(K^{*+})| < 100 \text{ MeV}$$

$$4.76 \text{ GeV} < m(K_s^0 \pi \mu\mu) < 5.8 \text{ GeV}$$

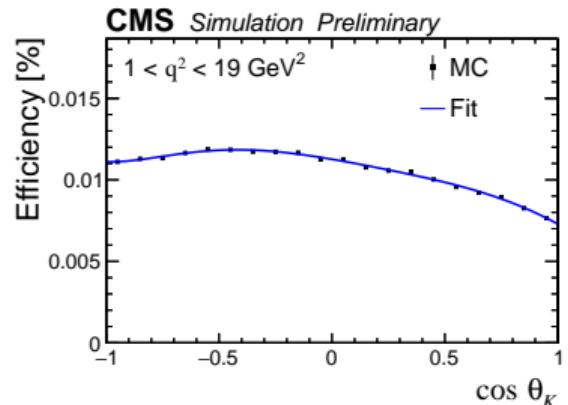
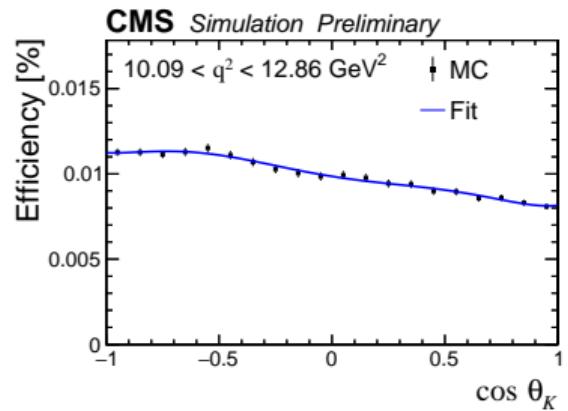
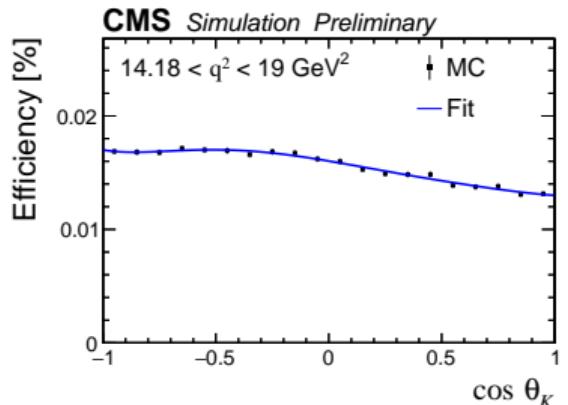
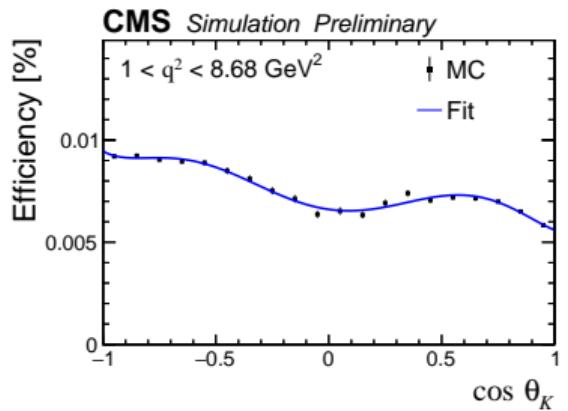
Removed events with dimuon invariant mass in

- $m_{J/\psi} - 5\sigma_q < q < m_{J/\psi} + 3\sigma_q$
- $m_{\psi(2S)} - 3\sigma_q < q < m_{\psi(2S)} + 3\sigma_q$

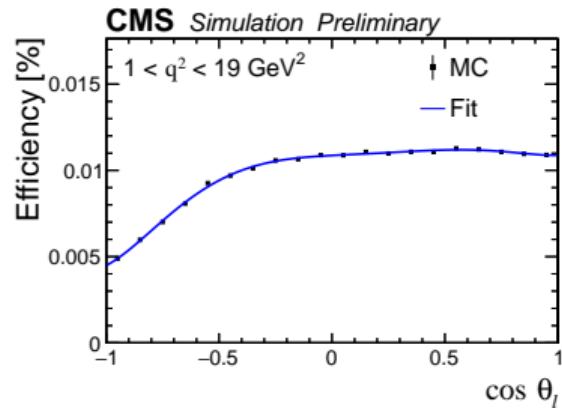
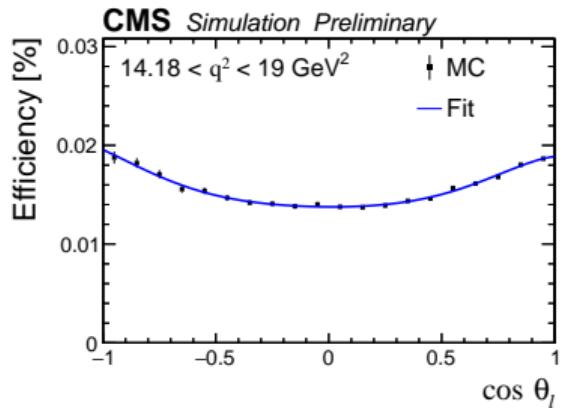
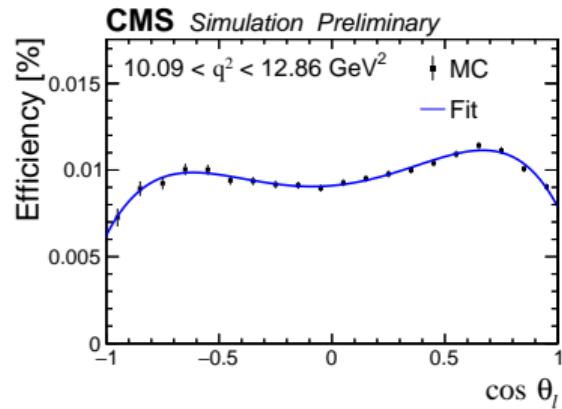
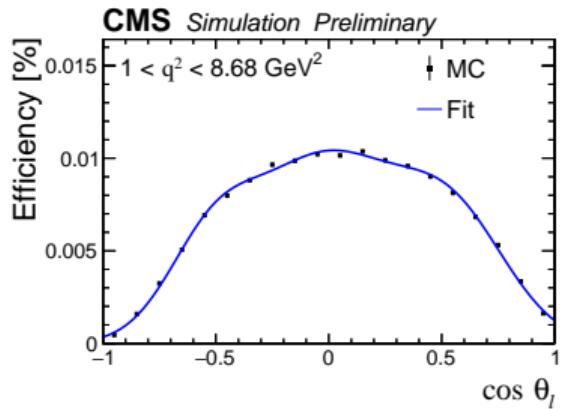
Anti radiation diagonal cut:

- $|(m(K_s^0 \pi \mu\mu) - m_{\text{PDG}}(B^+)) - (q - m_{J/\psi})| > 0.09 \text{ GeV}$
- $|(m(K_s^0 \pi \mu\mu) - m_{\text{PDG}}(B^+)) - (q - m_{\psi(2S)})| > 0.03 \text{ GeV}$

Efficiency projections on $\cos \theta_K$

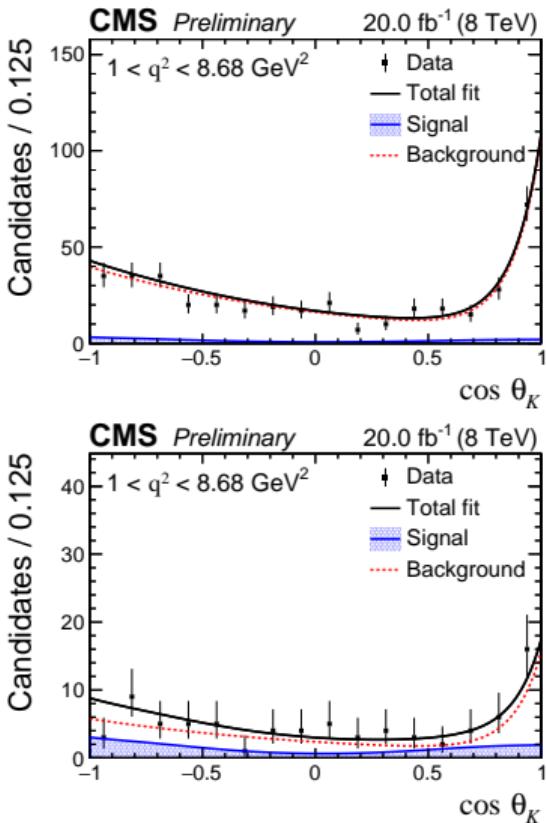
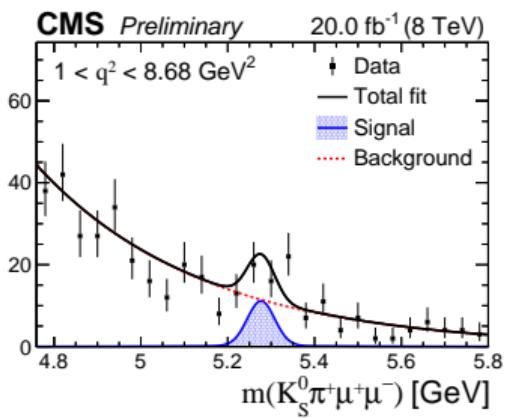


Efficiency projections on $\cos \theta_l$

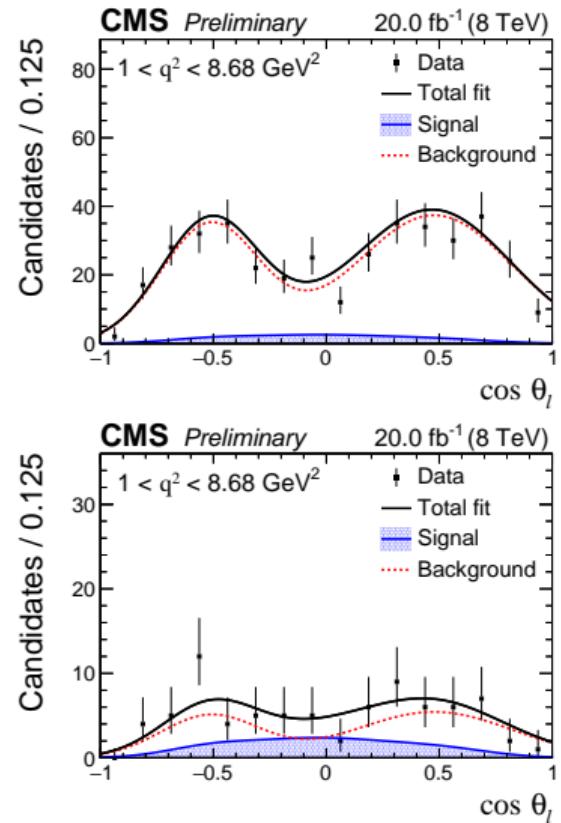


Fit projections - q^2 bin 1

Signal region + sidebands →

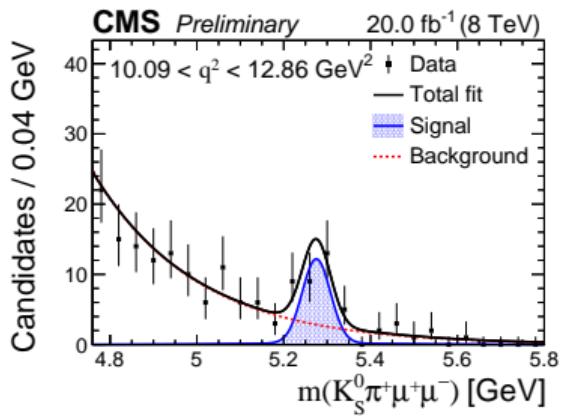


Signal region only →

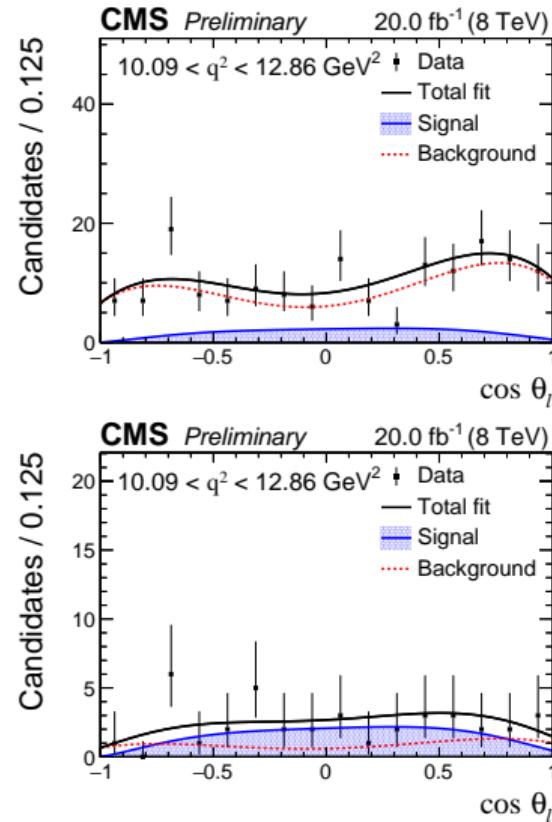
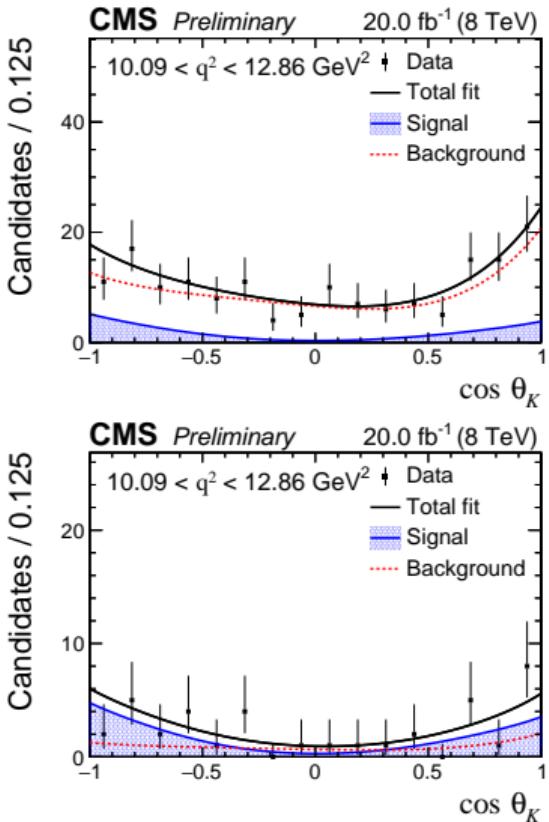
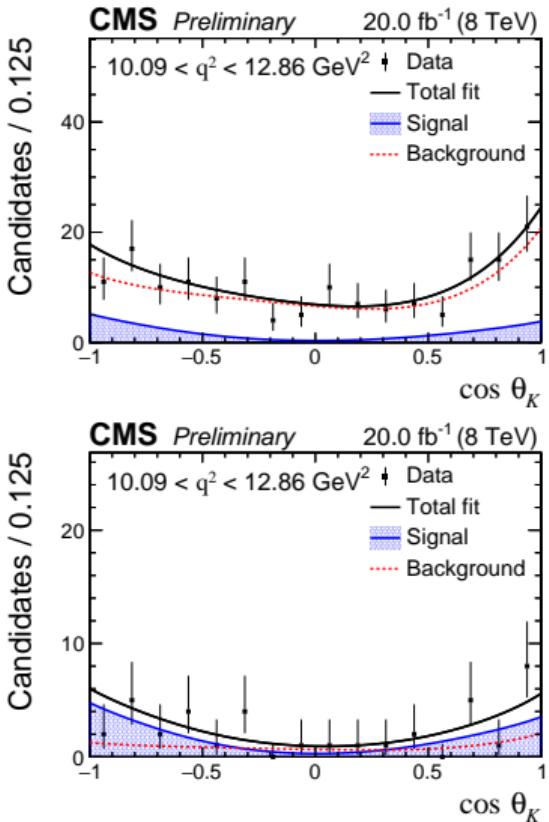


Fit projections - q^2 bin 3

Signal region + sidebands →

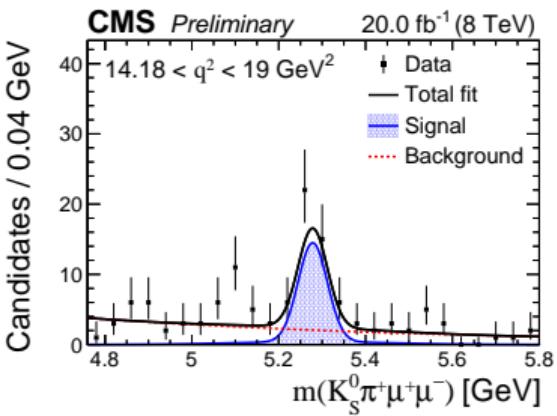


Signal region only →

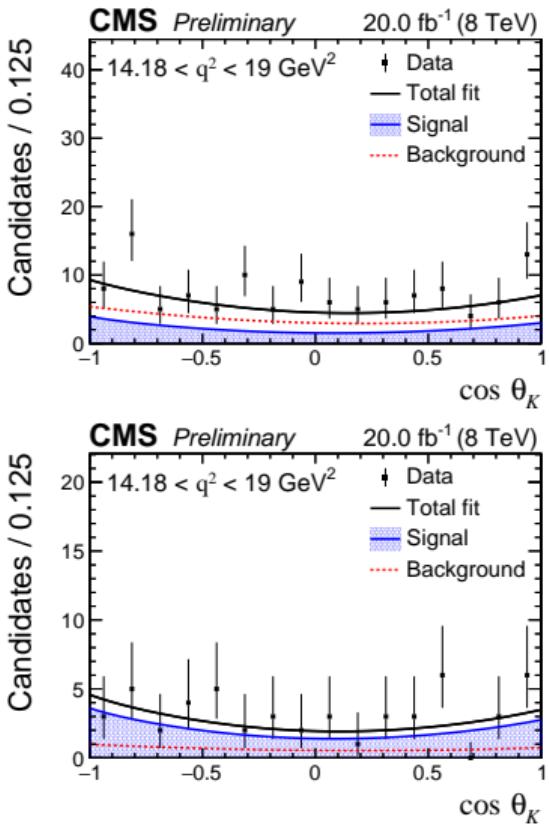


Fit projections - q^2 bin 5

Signal region + sidebands →

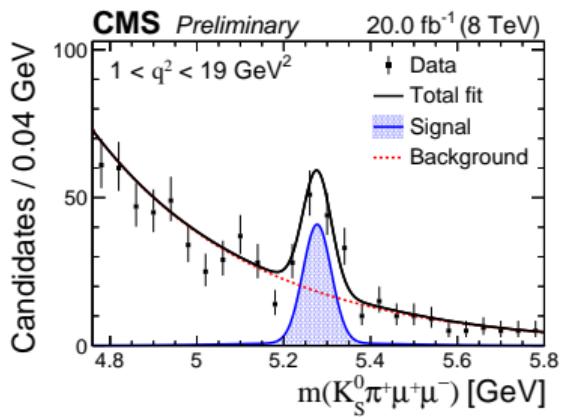


Signal region only →



Fit projections - Full q^2 spectrum

Signal region + sidebands →



Signal region only →

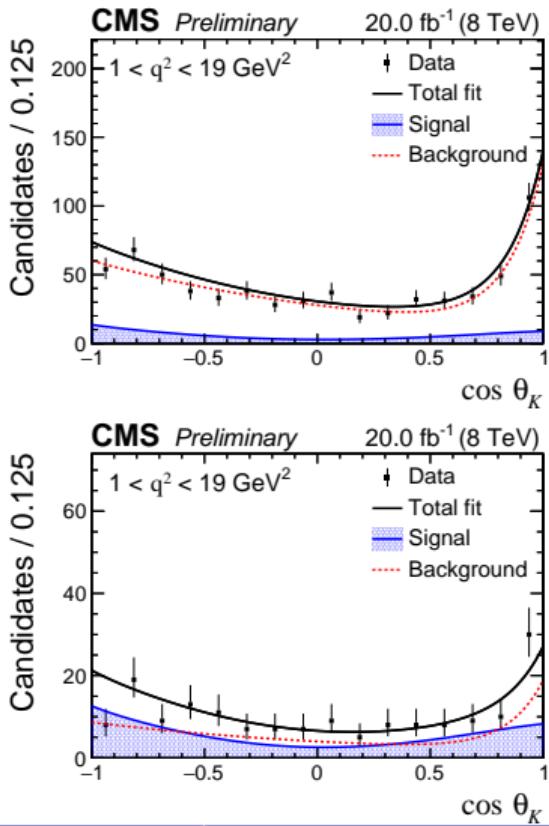


Table of results

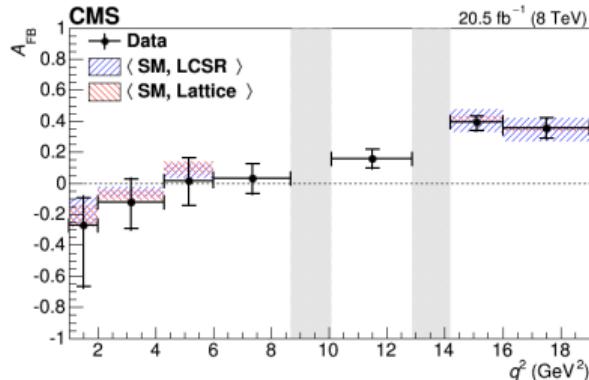
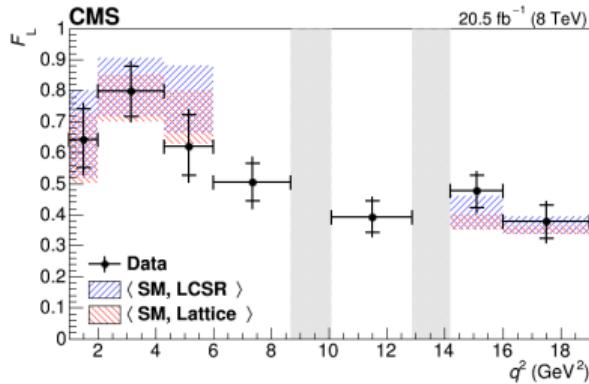
Table 2: The signal yield with statistical uncertainty and the fitted A_{FB} and F_L values with statistical and systematic uncertainties, for each q^2 range.

q^2 (GeV 2)	Signal yield	A_{FB}	F_L
1.00 – 8.68	22.1 ± 8.1	$-0.14^{+0.32}_{-0.35} \pm 0.17$	$0.60^{+0.31}_{-0.25} \pm 0.13$
10.09 – 12.86	25.9 ± 6.3	$0.09^{+0.16}_{-0.11} \pm 0.04$	$0.88^{+0.10}_{-0.13} \pm 0.05$
14.18 – 19.00	45.1 ± 8.0	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$
1.00 – 19.00	90.0 ± 13.5	$0.17^{+0.10}_{-0.06} \pm 0.08$	$0.71^{+0.11}_{-0.09} \pm 0.06$

$B^0 \rightarrow K^{*0} \mu\mu$ with integration over ϕ

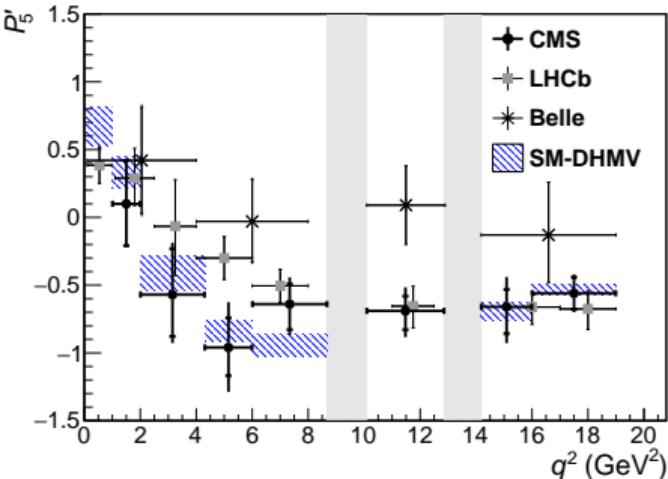
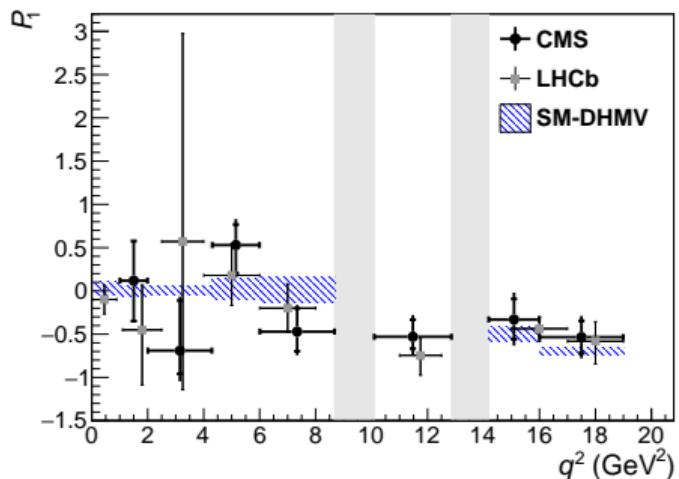
2011 data: Phys. Lett. B 727 (2013) 77
2012 data: Phys. Lett. B 753 (2016) 424

- Two analyses performed and published by CMS with 2011 and 2012 data
- The parameter space was reduced by integrating over the ϕ angular variable
- A_{FB} and F_L parameters and differential branching fraction were measured
- No deviations from SM prediction

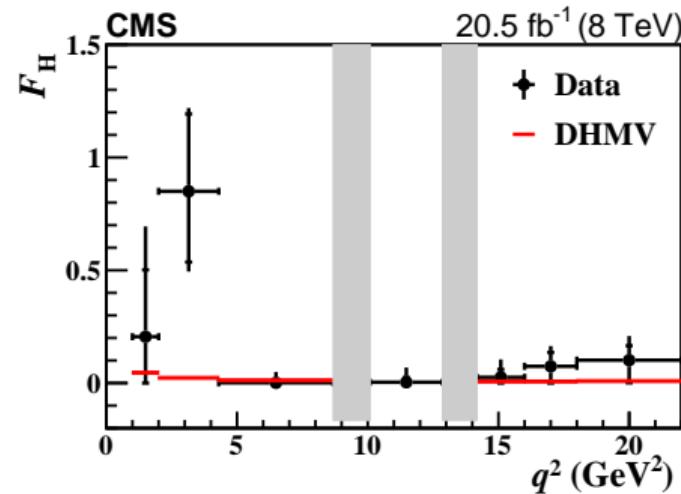
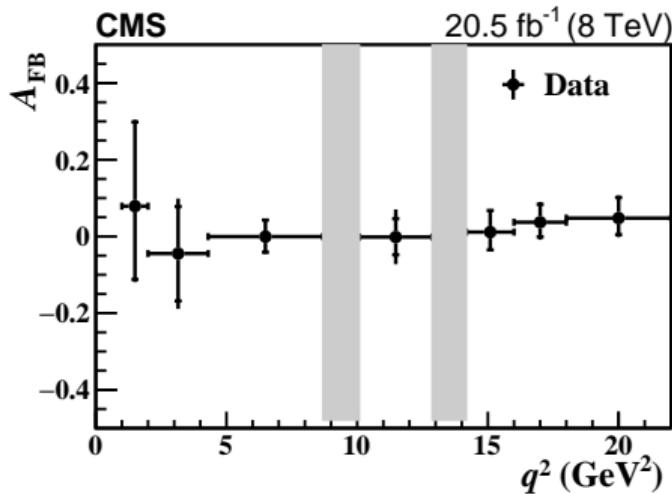


$B^0 \rightarrow K^{*0}(892)\mu^+\mu^-$ with variables' folding

Phys. Lett. B 781 (2018) 517-541
arXiv:1710.02846



- SM-DHMV prediction computed using
 - soft form factors + parametrised power corrections
 - hadronic charm-loop contribution derived from calculations
- Results compatible with SM predictions within uncertainties
- No significant deviations from other experimental results

$B^+ \rightarrow K^+ \mu^+ \mu^-$ angular analysisPhys. Rev. D 98 (2018) 112011
arXiv:1806.00636

- Inner error bar is statistical uncertainty
- Full bar is total uncertainty
- Results compatible with SM predictions within uncertainties