# Search for new physics in *b⟶sll* transitions at CMS

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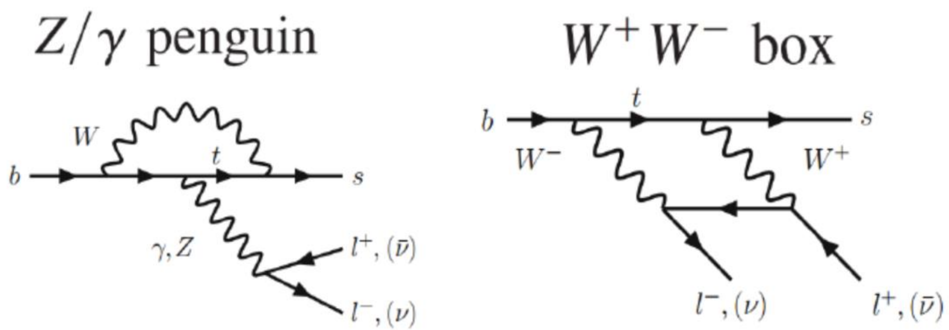
# Motivation



- New physics can be discovered by two ways: (1) by producing new particles, or (2) by searching discrepancies between measured observables and SM predictions in rare decays.
- In SM, $b \rightarrow sll$ is a flavor-changing neutral current (FCNC) process which is forbidden at tree level.




- The amplitudes may interfere with non-SM particle contributions.
- The transition can probe NEW particles and processes.

- New physics can contribute to the loop diagrams and make pronounced modifications.

# Analyses of $b\rightarrow sll$ in CMS experiments

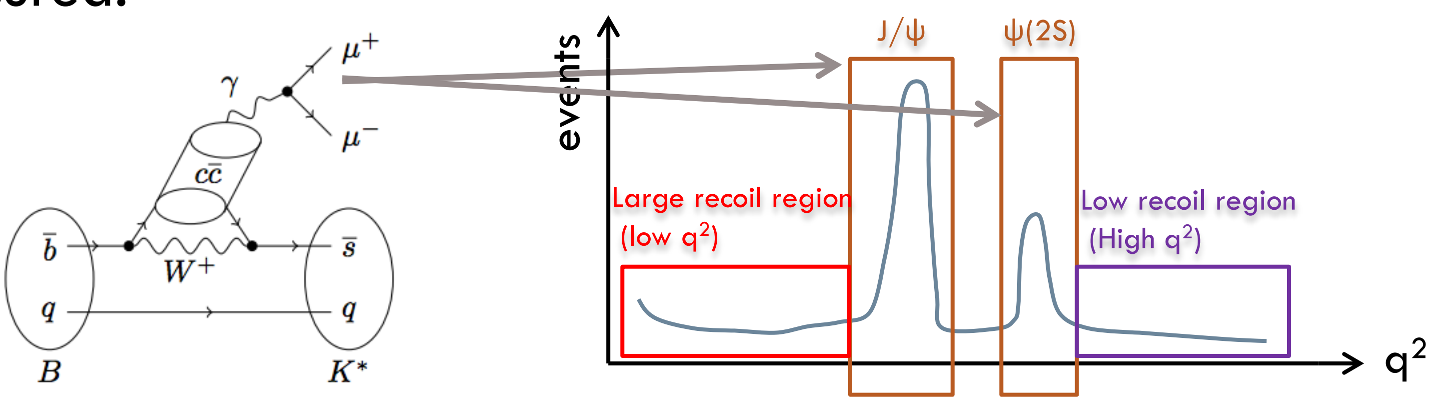


- Many B meson rare decays have been investigated(ing) in CMS experiments, such as $B^0\rightarrow K^{*0}\mu^+\mu^-$ , $B^+\rightarrow K^+\mu^+\mu^-$ , $B^+\rightarrow K^{*+}\mu^+\mu^-$ …
- Run1 analyses based on 20fb$^{-1}$ 8TeV data have been completed, while Run2 analyses are ongoing.
- Publications (following measurements are all based on 2012 20 fb$^{-1}$ of 8 TeV CMS data):
  - Angular analysis of $B^+\rightarrow K^+\mu^+\mu^-$ : Phys.Rev. D98 (2018) no.11, 112011
  - Angular analysis of $B^0\rightarrow K^{*0}\mu^+\mu^-$ : Phys.Lett. B781 (2018) 517-541
  - Angular analysis of $B^+\rightarrow K^{*+}\mu^+\mu^-$ : CMS-PAS-BPH-15-009 (New!) arXiv: 2010.13968

# $q^2$ spectrum



- $q^2$ represents the invariant mass of the muon pair in the final state particles.
- The parameters of interest are always measured as functions of $q^2$.
- Because of the large number of background events from the narrow charmonium resonances, the $J/\psi$, $\psi(2S)$ $q^2$ bins are not measured.



# Angular analysis of $B^+ \to K^+\mu^+\mu^-$

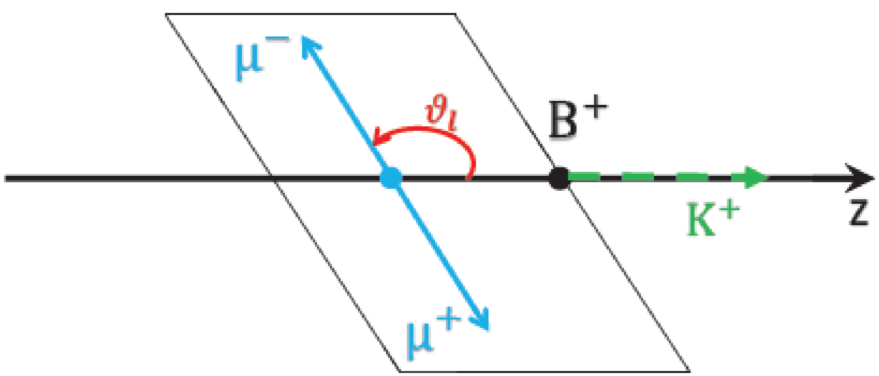


- Using 20.5 $fb^{-1}$ of 8 TeV pp data taken in 2012
- The decay for the process $B^+ \to K^+\mu^+\mu^-$ can be described by $\cos\theta_\ell$ and $q^2$
- Differential decay rate formula:

$$\frac{1}{\Gamma}\frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{d\cos\theta_l} = \frac{3}{4}(1 - F_H)(1 - \cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$

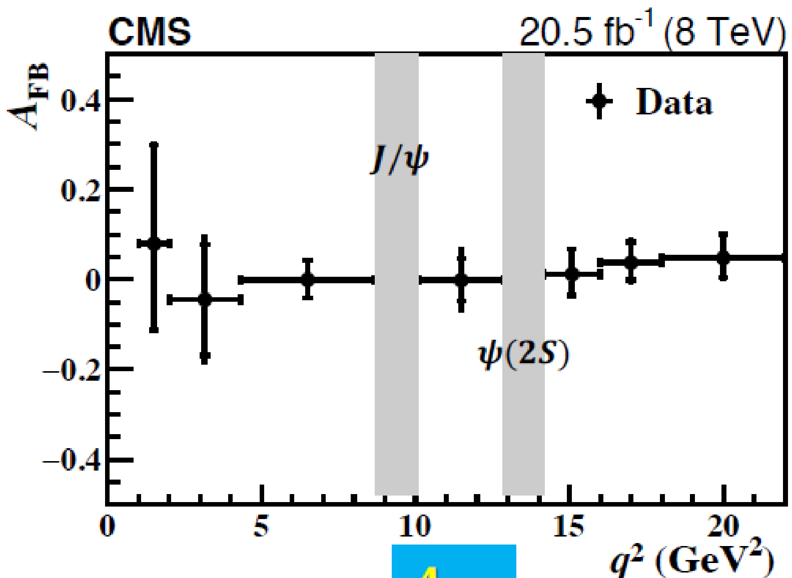
$$0 \le F_H \le 3, A_{FB} \le \min(1, F_H/2)$$

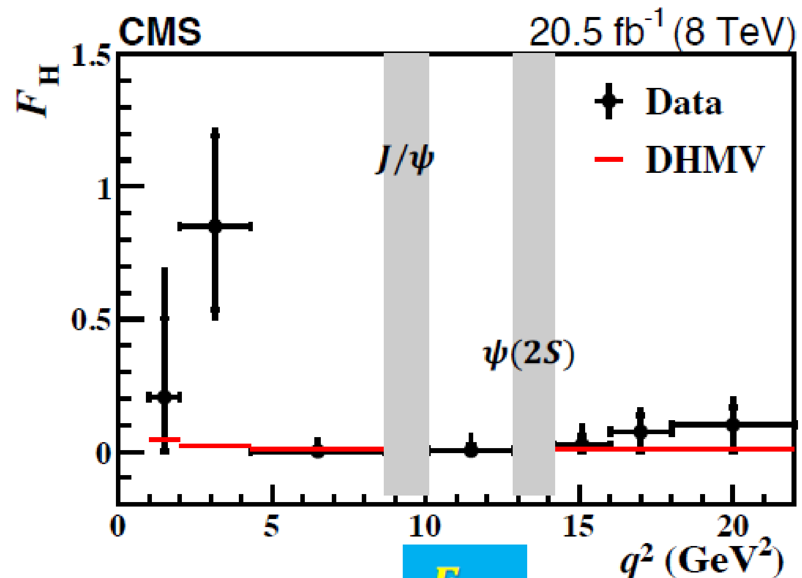
$\theta_l$: $l = \mu$, the angle between the $\mu^+$ ($\mu^-$) and the $K^-$($K^+$) in the rest frame of the dimuon system.
$A_{FB}$: $\mu^+ \mu^-$ forward-backward asymmetry.
$F_H$: is a measure of the contribution from pseudoscalar, scalar and tensor amplitudes to the decay width Γ.



# Result of Angular analysis of $B^+ \to K^+\mu^+\mu^-$





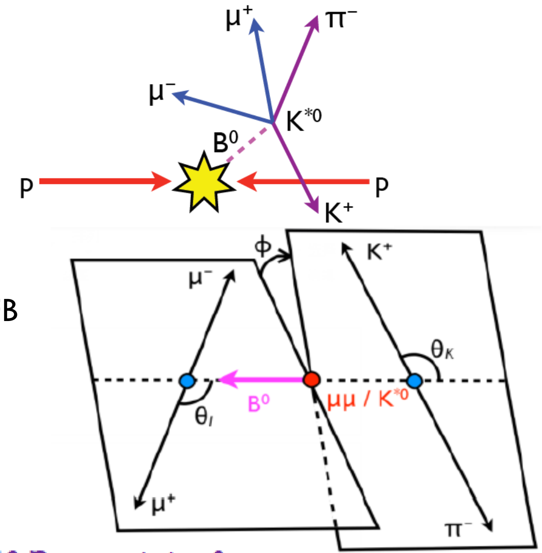

$A_{FB}$ $F_H$

- The events are fit in seven $q^2$ bins from 1 to 22 GeV$^2$, yielding 2286 signal events in total.
- The measured $A_{FB}$ and $F_H$ show good agreement with the SM predictions within the uncertainties. No clear indication of new physics beyond the SM could be drawn from present results.

# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



- Using 20.5 $fb^{-1}$ of 8 TeV pp collision data taken in 2012
- Fully described by the three angles ($\theta_\ell$, $\theta_K$, $\phi$) and the dimuon invariant mass squared $q^2$.
- Robust SM predictions of several angular parameters, $A_{FB}$, $F_L$, $P_1$ and $P_5'$, are available.
- $P_1$ and $P_5'$ are measured in $q^2$ bins from 1 to 19 $GeV^2$.
- Differential decay rate:




S-wave and S&P-wave interference

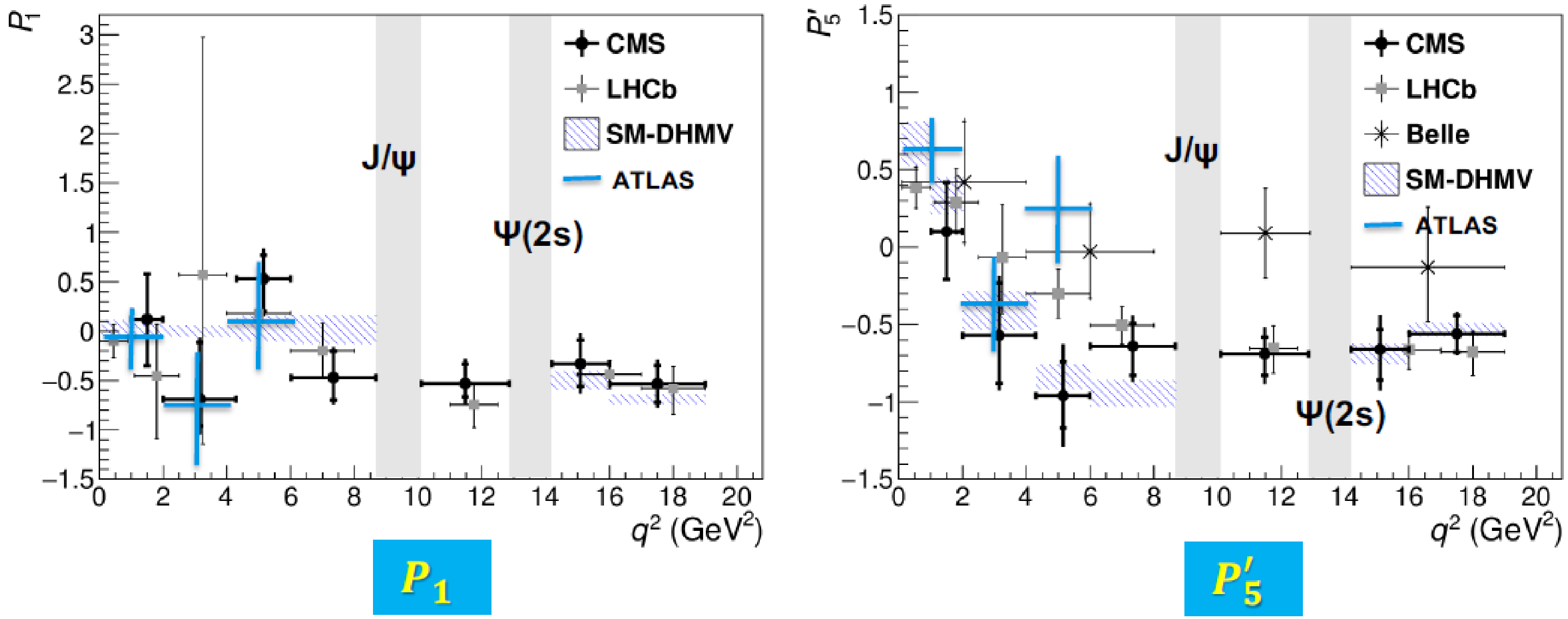
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{8\pi}\Big\{\frac{2}{3}\Big[(\boxed{F_S} + \boxed{A_S}\cos\theta_K)(1-\cos^2\theta_l) + \boxed{A_S^5}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big] + (1-\boxed{F_S})\Big[2\boxed{F_L}\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-\boxed{F_L})(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{1}{2}\boxed{P_1}(1-\boxed{F_L})(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi + 2\boxed{P_5'}\cos\theta_K\sqrt{\boxed{F_L}(1-\boxed{F_L})}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big]\Big\}$$

P-wave

$A_S^5$: nuisance parameter
$P_1$, $P_5'$: measured parameters
$F_L$, $F_S$, $A_S$: fixed from previous CMS measurement

# Result of Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$





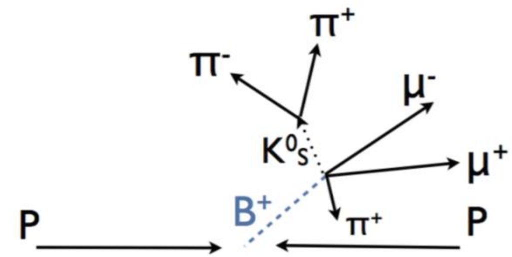

The events are fit in seven $q^2$ bins from 1 to 19 GeV$^2$, yielding 1397 signal events in total.

The measured $P_1$ and $P'_5$ are consistent with the SM predictions and previous measurements within the uncertainties.

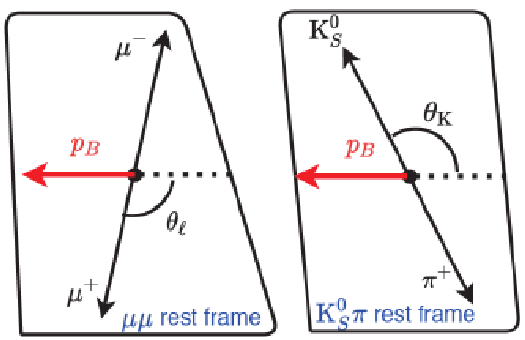
# Angular analysis of $B^+ \rightarrow K^{*+}\mu^+\mu^-$



- Using 20 $fb^{-1}$ of 8 TeV pp collision data




- The decay can be fully described by the three angles ($\theta_\ell$, $\theta_K$, $\phi$) and $q^2$




- Differential decay rate (integrate out $\phi$):

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

- Two observables, the forward-backward asymmetry of the muon ($A_{FB}$) and the longitudinal polarization fraction of the $K^{*+}$ ($F_L$), are measured as a function of $q^2$

# $q^2$ binning



| Bin index | $m_{\mu\mu}^2$ [$GeV^2$] |
|---|---|
| 1 | 1 - 8.68 |
| 2 | 8.68 - 10.09 ($J/\psi$) |
| 3 | 10.09 - 12.86 |
| 4 | 12.86 - 14.18 ($\psi'$) |
| 5 | 14.18 - 19 |
| 0 | Bin1 + Bin3 + Bin5 |

# Events selection



- HLT:
  - $\mu$: [ $p_T$ > 3.5GeV, |$\eta$|< 2.2 ],
  - $\mu\mu$: [ vertex CL > 0.1, $p_T$ > 6.9GeV, 1<M<4.8GeV, cos(∠$p_T$ , vertex to beamspot vector〉) > 0.9]
- Final state particles:
  - *good common vertices,*
  - *invariant masses consistent with mother particles,*
  - *Significant displaced from beamline*
  - *$P_T$ vector is roughly parallel to the vector from beamspot to B vertex*
- Kinematic cuts (optimized to maximize signal significance):
  - $p_T(K_s^0)>1GeV$,
  - $p_T(K^{*+})>0.4GeV$,
  - $L_{xy}(K^{*+}$ *to beamline*$)/\sigma>0.4$

# Fitting strategy



- The measurement of $A_{FB}$ and $F_L$ is performed in three $q^2$ regions: 1 < q2 < 8.68 $GeV^2$, 10.09 < q2 < 12.86 $GeV^2$, and 14.18 < q2 < 19 $GeV^2$.
- For each $q^2$ bin, the observables $A_{FB}$ and $F_L$ are extracted by performing an unbinned extended maximum-likelihood fit on three variables: m, $\cos\theta_K$, and $\cos\theta_\ell$.
- The unnormalized PDF used to fit the data is:

$$\mathrm{pdf}(m, \cos\theta_{\mathrm{K}}, \cos\theta_\ell) = Y_S\, S^m(m)\, S^a(\cos\theta_{\mathrm{K}}, \cos\theta_\ell)\, \epsilon(\cos\theta_{\mathrm{K}}, \cos\theta_\ell) + Y_B\, B^m(m)\, B^{\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}})\, B^{\theta_\ell}(\cos\theta_\ell).$$

| | What p.d.f? | Determined from? | Fixed in final extended ML fit? |
|---|---|---|---|
| $S^M$ | Double Gaussian | Official MC | Fixed from unbinned ML fit |
| $S^A$ | From theory | - | Float |
| ε | (Next page) | Official/Private MC | Fixed from binned $\chi^2$ fit |
| $B^M$ | Exponential | Data | Float |
| $B^{K/l}$ | Analytic models | Data sidebands | Fixed from unbinned ML fit |

# Efficiency description



- The signal efficiency function is obtained from the simulated samples in a two step:

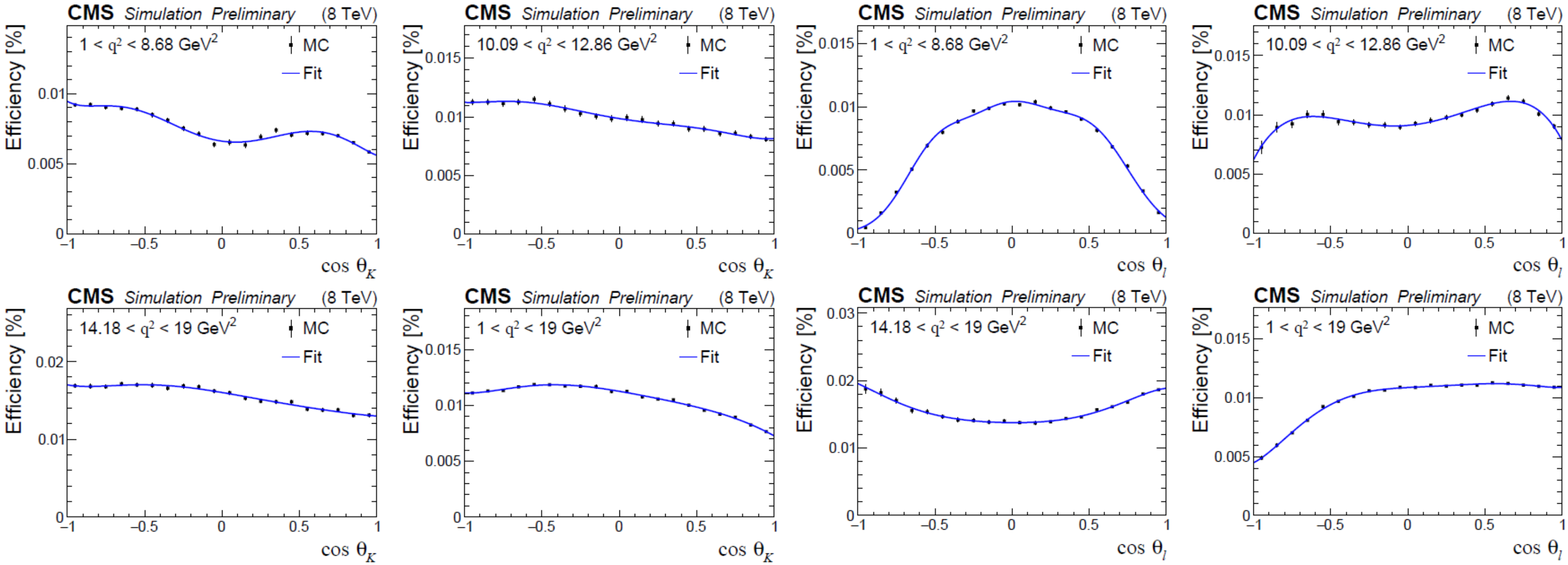
1. Fit to MC by a product of two one-dimensional functions, one for each angular variable
2. The results from the first step are fixed and an additional cross-term function is added to account for correlations and refit to MC

$$\varepsilon(\cos\theta_K, \cos\theta_l) = \underbrace{\boxed{\varepsilon_{1D}(\cos\theta_K)\cdot\varepsilon_{1D}(\cos\theta_l)}}_{\text{get in step 1}}\cdot[1 + \underbrace{\boxed{\mathcal{C}(\cos\theta_K, \cos\theta_l)}}_{\text{get in step 2}}]$$

# Efficiency projections



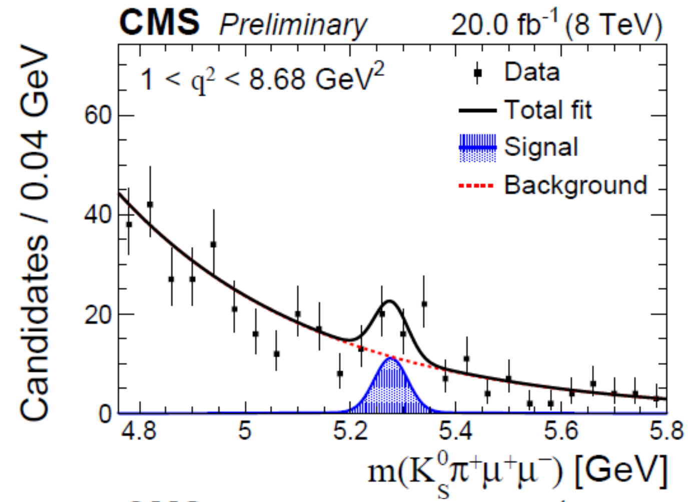
| Bin index | cosθK | cosθl | X-term |
|---|---|---|---|
| 1 | pol6 | 3 gaus | 3rd Legendre(K)*pol4(l) |
| 3, 5, 0 | pol6 | pol6 | 3rd Legendre(K)*pol4(l) |

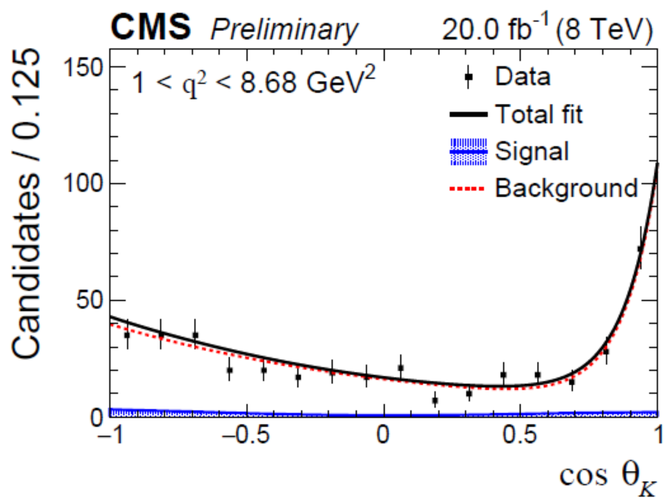


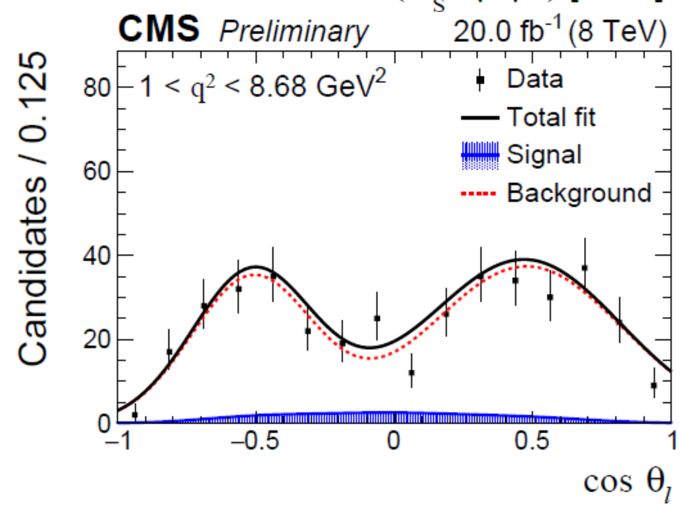
# Fitting results projections (bin0)



*The results of the unbinned maximum likelihood fit are overlaid on the data in projections on the $B^+$ invariant mass, $\cos\theta_K$, and $\cos\theta_\ell$ for each $q^2$ region.*



# Systematic uncertainties



| Source | $A_{\mathrm{FB}}$ $(10^{-3})$ | $F_{\mathrm{L}}$ $(10^{-3})$ |
|---|---|---|
| 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 is from background description:***

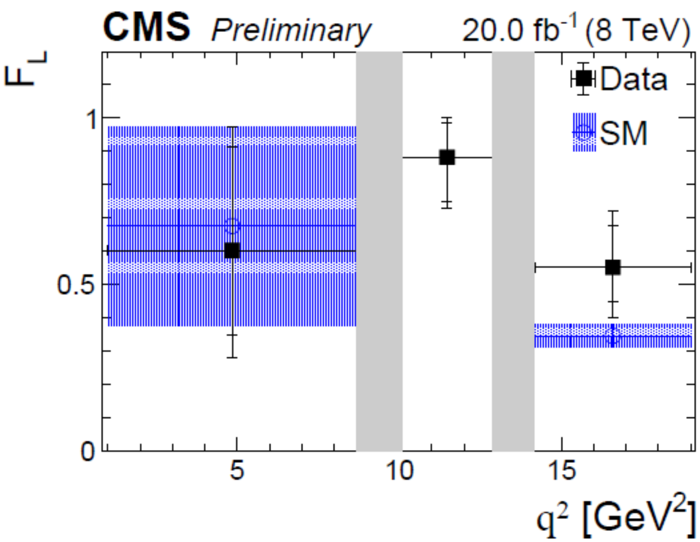
(1) Background functional form

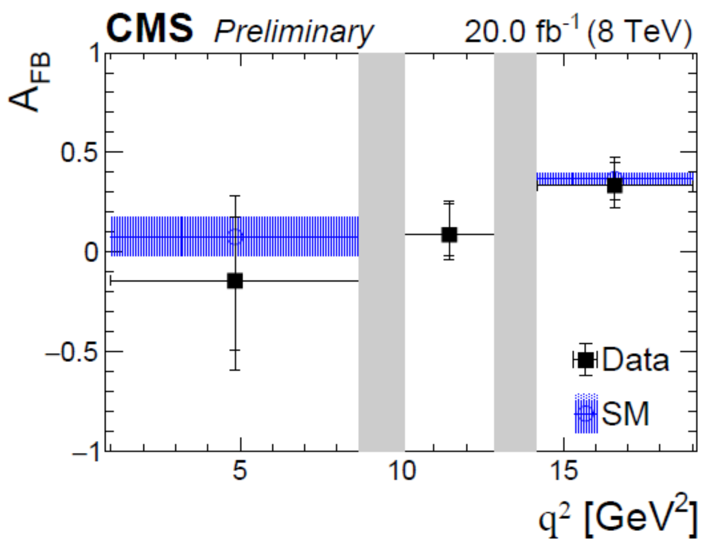
(2) Effect of alternate sideband definition

(3) Sideband statistics uncertainty

# Result of Angular analysis of $B^+ \rightarrow K^{*+}\mu^+\mu^-$






SM predictions from:
[ JHEP 12 (2014) 125 ]
[ Phys Rev D 99 (2019) 075017 ]

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

# Summary



- The angular analyses of FCNC B rare decays are important ways to search BSM phenomena.

- The three measurements, $\boldsymbol{B^+ \rightarrow K^+ \mu^+ \mu^-}$ , $\boldsymbol{B^0 \rightarrow K^{*0} \mu^+ \mu^-}$ , and $\boldsymbol{B^+ \rightarrow K^{*+} \mu^+ \mu^-}$ , all obtained results consistent with standard model within the uncertainties.

- Currently more analyses are proceeding in CMS, with new data(Run2 data) and new decays(e.g. $B_s \rightarrow \phi \mu^+ \mu^-$ ).

# END

*Thank you!*

# Backup

# Definition of observables $P_i^{(\prime)}$



$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega}) \quad \text{and}$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}),$$

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right) \quad \text{and}$$

$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right).$$

$$P_1 = \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)},$$

$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})},$$

$$P_3 = \frac{-S_9}{(1-F_{\rm L})},$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}},$$

$$P'_6 = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}.$$

$S_i$ : CP averages; $A_i$ : CP asymmetries;

$P_i^{(\prime)}$ : constructed observables for $B^0 \to K^{*0}$ leading form-factor uncertainty cancel

# Fitting results projections of all bins