# Angular analyses at CMS

**Peking University**

**Geng CHEN**

On behalf of CMS Collaboration

Jul 5th, 2018 ICHEP 2018 @Seoul

# Outline

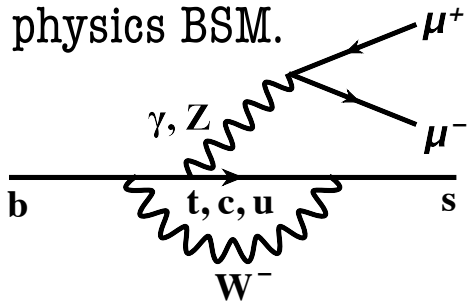
- ❖FCNC process $b \to s\,\mu^+\,\mu^-$
- ❖Rare B-decay anomalies and logical possible BSM models
- ❖CMS rare B-decay angular analyses
  - ➢ Angular analysis of the decay: $B^0 \to K^{*0}\mu^+\mu^-$

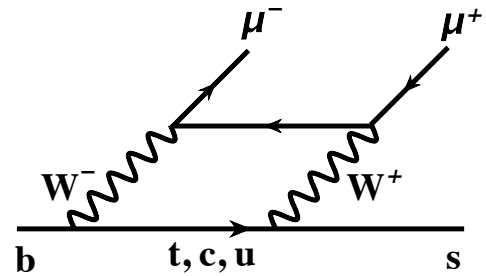
    **arXiv: 1710.02846, Phys. Lett. B 781 (2018) 571**
  - ➢ Angular analysis of the decay: $B^+ \to K^+\mu^+\mu^-$

    **arXiv: 1806.00636, submitted to Phys. Rev. D**
- ❖Summary

# FCNC processes $b \to s\,\mu^+\mu^-$

- The rare decays $B^{0(+)} \to K^{*0(+)}\mu^+\mu^-$ are $b \to s\,\mu^+\,\mu^-$ flavor-changing neutral current (FCNC) processes mediated by electroweak loop and box diagrams, and sensitive to physics BSM.




- Clean experimental signature; robust theory calculation; high sensitivity.

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm tq}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\rm NP}^2} \mathcal{O}_{\rm NP}$$

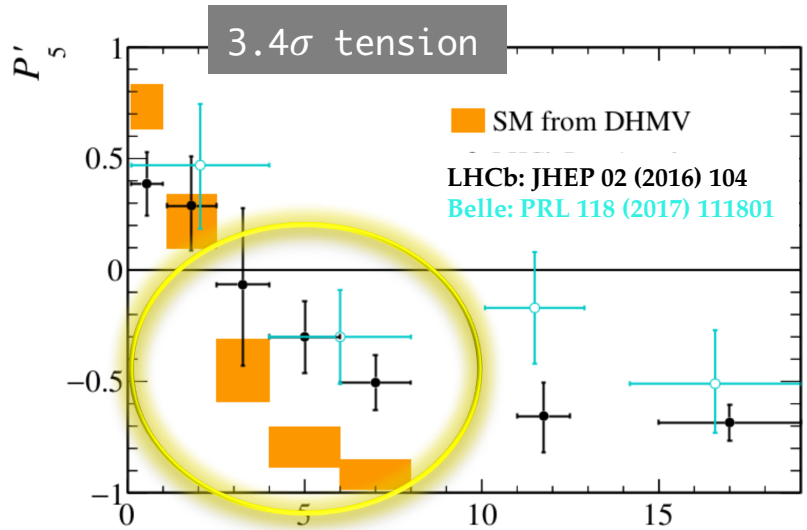
| | |
|---|---|
| $i = 1, 2$ | Tree |
| $i = 3 - 6, 8$ | Gluon penguin |
| $i = 7$ | Photon penguin |
| $i = 9, 10$ | EW penguin |
| $i = S, P$ | (Pseudo)scalar penguin |

- Effective theory: different processes are sensitive to different operators

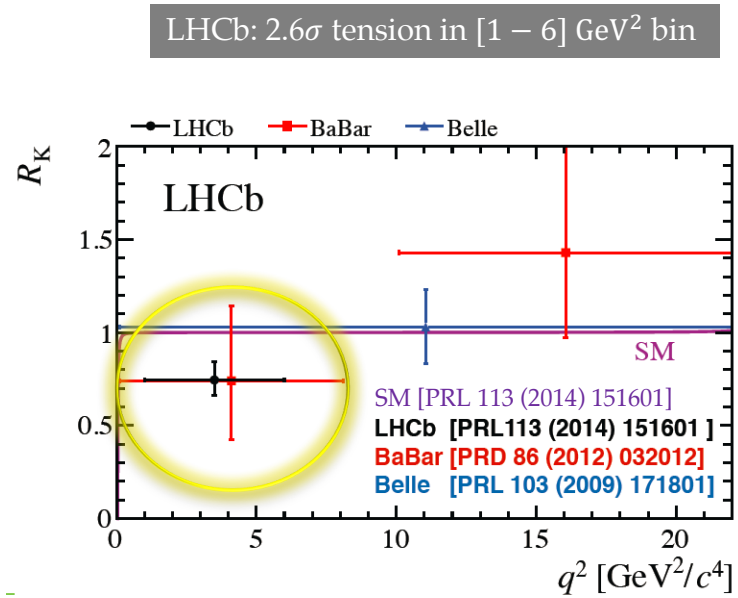
| Operator $\mathcal{O}_i$ | $B_{s,d} \to X_{s,d}\mu^+\mu^-$ | $B_{s,d} \to \mu^+\mu^-$ | $B_{s,d} \to X_{s,d}\gamma$ |
|---|---|---|---|
| $\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$ | ✓ | | ✓ |
| $\mathcal{O}_9 \sim (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell)$ | ✓ | | |
| $\mathcal{O}_{10} \sim (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu\ell)$ | ✓ | ✓ | |
| $\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$ | (✓) | ✓ | |

# B-decay anomalies and BSM models

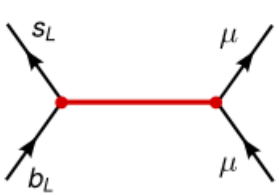
➢ The rare B-decay anomalies in recent experimental results.



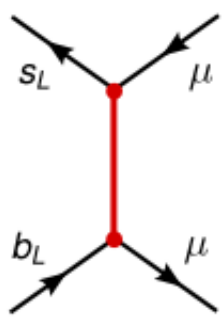

With the vector coupling $\Delta C_9 = -1.04 \pm 0.25$



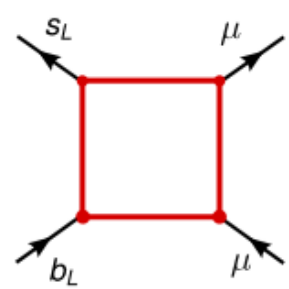

➢ Possible BSM models




- Heavy $Z'$ model
- $SU(2)_L$ singlet or triplet
- arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...



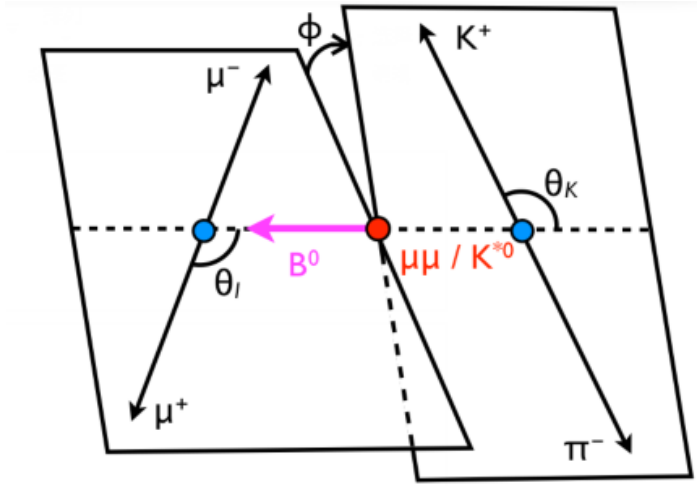

- Leptoquark model
- Spin 0 or 1
- arXiv:01511.01900, 1503.01084, 1704.05835, 1512.01560, 1511.06024, 1408.1627, ...



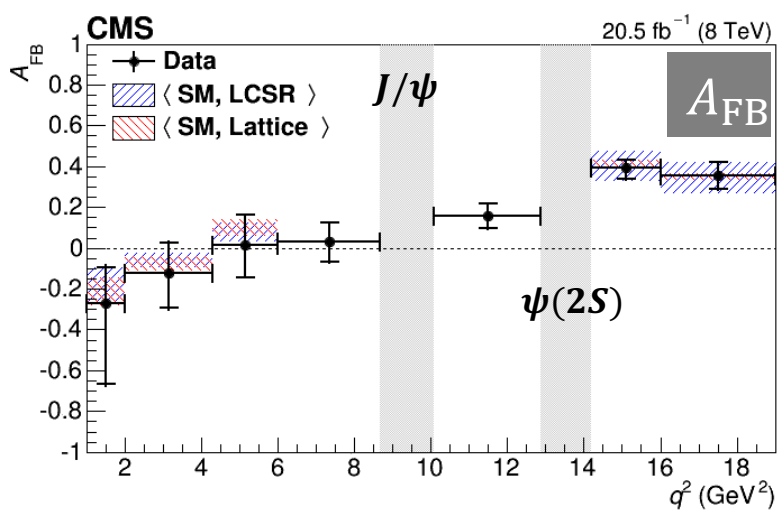

- Other new heavy scalars/vectors also leptoquark possible
- arXiv:01509.05020, 1608.07832, 1704.05438, 1607.01659, 1704.07845, hep-ph/0610037, ...

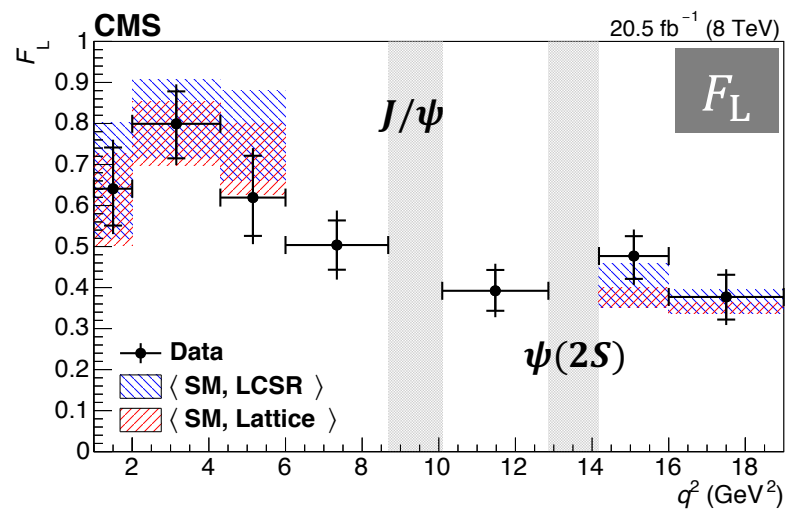
# Angular analysis: $B^0 \to K^{*0}\mu^+\mu^-$

- The process can be fully described by the three angles ($\theta_\ell$, $\theta_K$, $\phi$) and the dimuon invariant mass squared $q^2$.
- Robust SM calculation of several angular parameters, $A_{FB}$, $F_L$, $P_1$ and $P_5'$, are available for much of the phase space.
- Discrepancy of the angular parameters vs $q^2$ with respect to SM might be hint of NP.




Phys. Lett. B 753 (2016) 424



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

- Using 20.5 fb$^{-1}$ of 8 TeV pp data taken in 2012
  - Control channels: $B^0 \to K^{*0}J/\psi(\mu^+\mu^-)$, $B^0 \to K^{*0}\psi'(\mu^+\mu^-)$
- Two channels can contribute to the final state $K^+\pi^-\mu^+\mu^-$:

  P-wave resonant channel, $K^+\pi^-$ from the meson vector resonance $K^{*0}$ decay;

  S-wave non-resonant channel, $K^+\pi^-$ don't come from any resonance.
- Folding the p.d.f. around $\phi = 0$ and $\theta_\ell = \pi/2$.

S-wave and S&P-wave interference

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

P-wave

- ✓ $F_L, F_S, A_s$: fixed from previous CMS measurement (Phys.Lett.B 753 (2016) 424)
- ✓ $P_1, P_5'$: recently measured parameters
- ✓ $A_s^5$: nuisance parameter

# The pdf and efficiency



## ➢The probability density function and efficiency

$$\text{p.d.f.}(m,\theta_K,\theta_l,\Phi) = Y_S^C \Big[ S^C(m)\, S^a(\theta_K,\theta_l,\phi)\, \epsilon^C(\theta_K,\theta_l,\phi) \quad \text{Correctly tagged events}$$

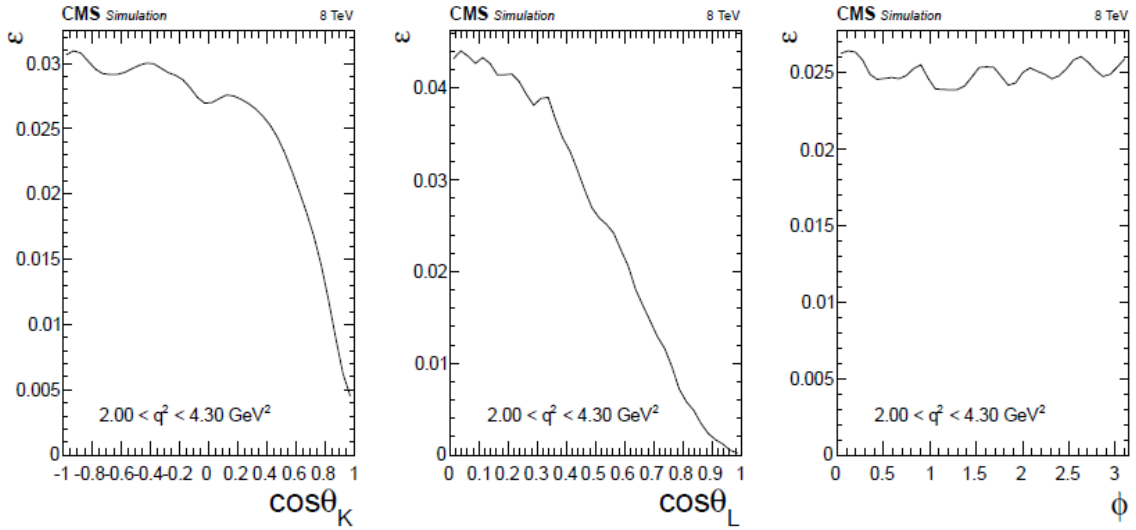
Mistag fraction

$$+ \frac{f^M}{1-f^M} S^M(m)\, S^a(-\theta_K,-\theta_l,\phi)\, \epsilon^M(\theta_K,\theta_l,\phi) \Big] \quad \text{Mistagged events}$$

$$+ Y_B\, B^m(m)\, B^{\theta_K}(\theta_K)\, B^{\theta_l}(\theta_l)\, B^{\phi}(\phi), \quad \text{Background}$$

- ✓ Signal contribution: mass shape (double Gaussian), decay rate, and 3D efficiency function.
- ✓ Background contribution: mass shape (exponential) and different degrees polynomial functions for each angular variable.

$q^2$ bin: $2 < q^2 < 4.3\ \text{GeV}^2$
Correctly tagged events



# Fitting and validation

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

## ➢ Fitting strategy:

- ✓ Parameters are extracted from un-binned extended maximum likelihood fit in each bin:

  $m(K^+\pi^-\mu^+\mu^-)$, $\cos\theta_\ell$, $\cos\theta_K$, $\phi$.

- ✓ Fit performed in two steps:

  1) Fit sidebands to determine angular background shape, fixed in the next step;

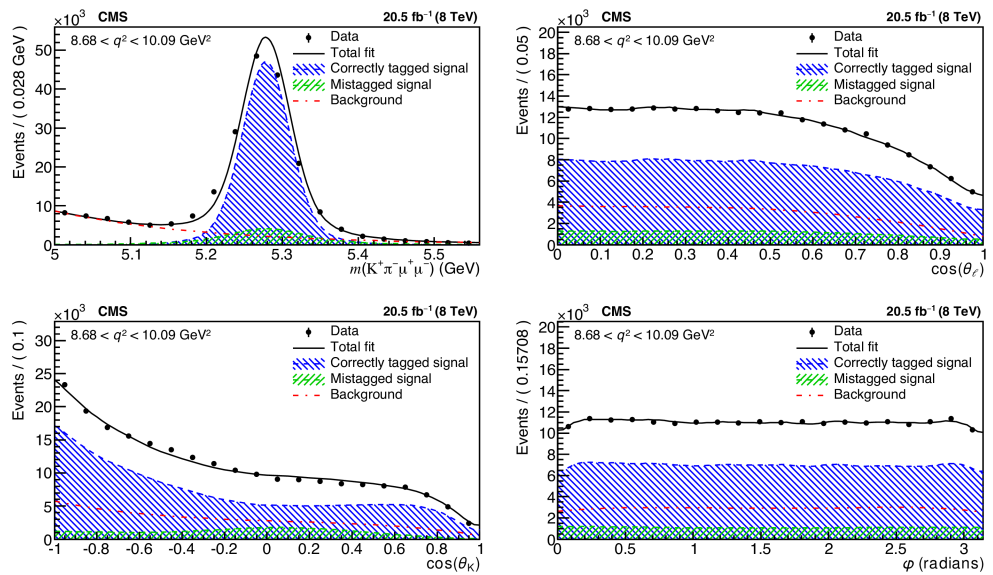
  2) Fit whole mass spectrum, 5 free parameters, $A_S^5$, $P_1$, $P_5'$, yields .

- ✓ Feldman-Cousins method with nuisance parameters.

## ➢ Validation with data control channels:

- ✓ Fit performed with $F_L$ free to float;
- ✓ $F_L$ measured agrees with PDG value.

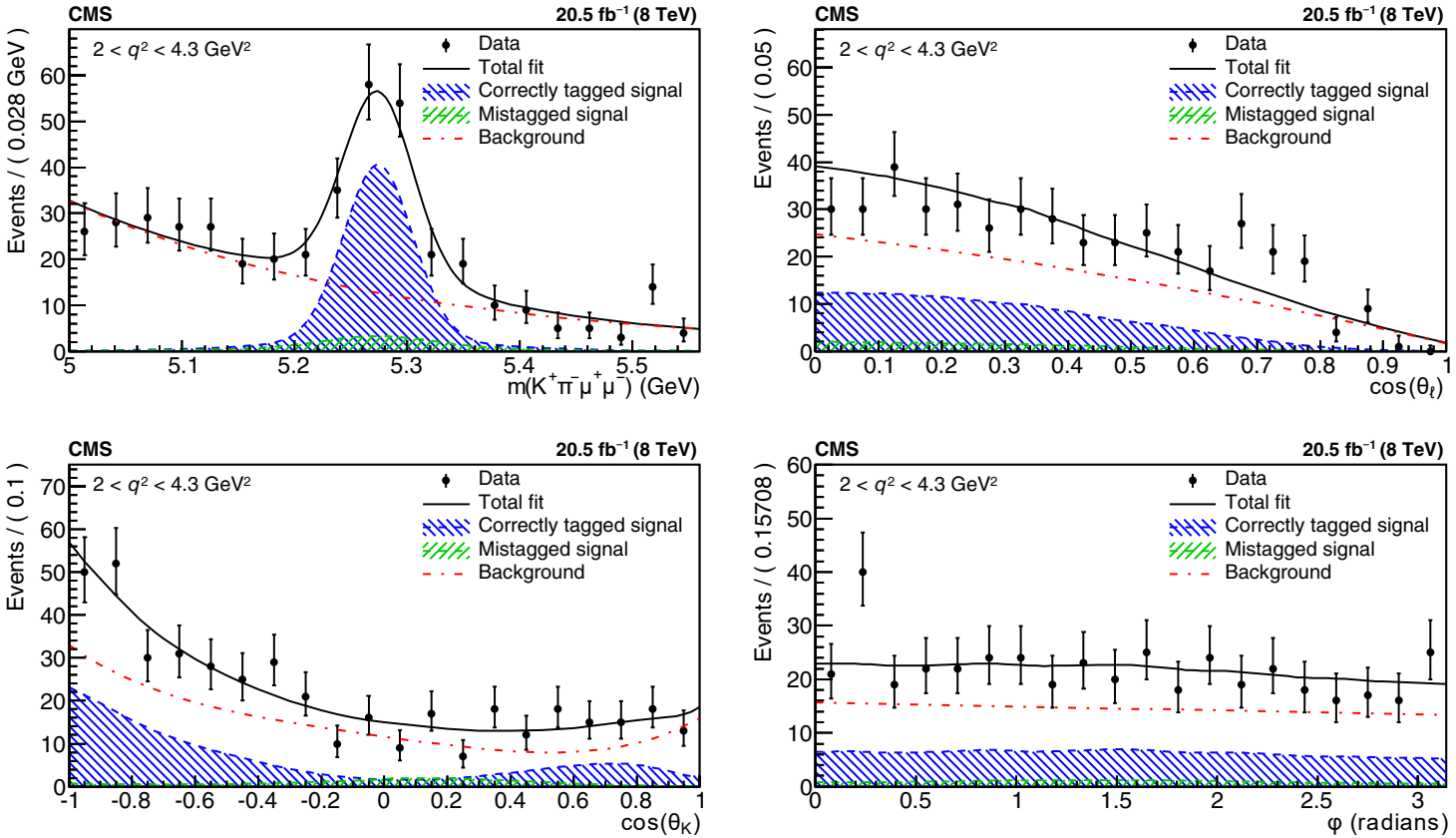
$B^0 \to K^{*0}J/\psi(\mu^+\mu^-)$



# Fitting result projections

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

➢ $q^2$ bin: $2 < q^2 < 4.3\ \mathrm{GeV}^2$




Total fit

Signal ( correctly tagged)

Signal (wrongly tagged)

Background

# Systematic uncertainty



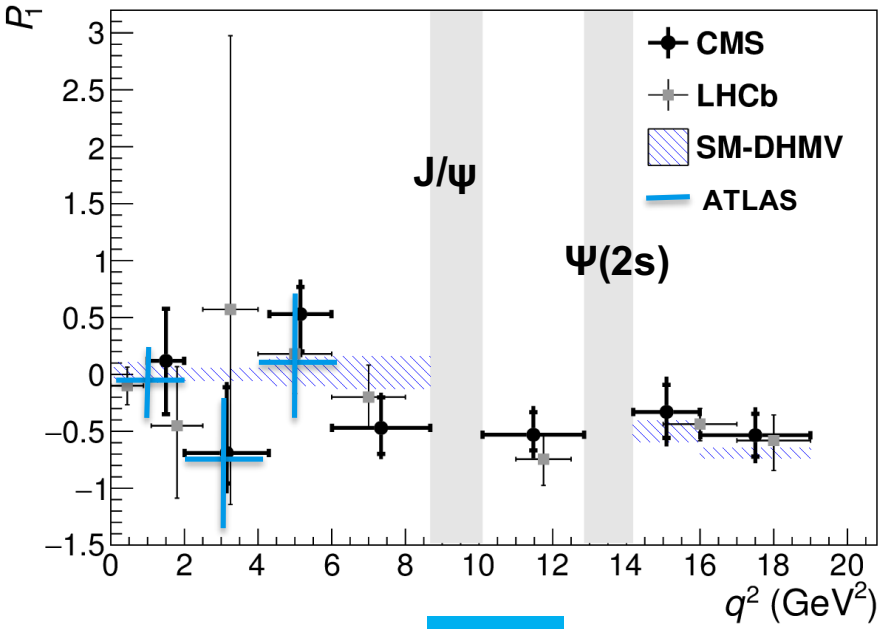
| Systematic uncertainty | $P_1(10^{-3})$ | $P_5'(10^{-3})$ |
|---|---|---|
| Simulation mismodeling | $1-33$ | $10-23$ |
| Fit bias | $5-78$ | $10-119$ |
| MC statistical uncertainty | $29-73$ | $31-112$ |
| Efficiency | $17-100$ | $5-65$ |
| Kπ mistagging | $8-110$ | $6-66$ |
| Background distribution | $12-70$ | $10-51$ |
| Mass distribution | 12 | 19 |
| Feed-through background | $4-12$ | $3-24$ |
| $F_L$, $F_S$, $A_s$ uncertainty propagation | $0-126$ | $0-200$ |
| Angular resolution | $2-68$ | $0.1-12$ |
| Total | $60-220$ | $70-230$ |

$F_L$, $F_S$, $A_s$ uncertainty propagation:

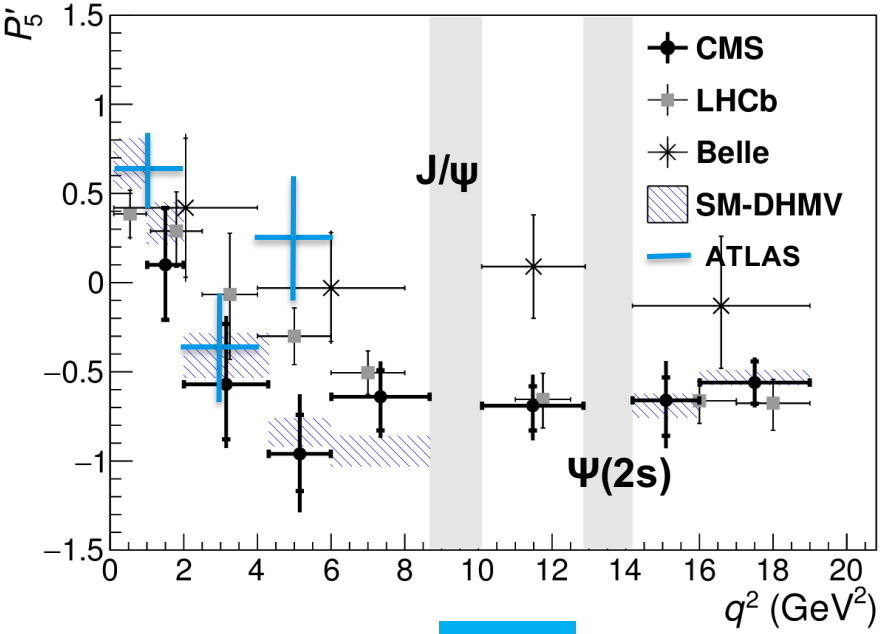
- Generate a large data, $\mathcal{O}(100\times\text{data})$, pseudo experiments (one per $q^2$);
- Fit with all 6 angular parameters free to float;
- Fit with $F_L$, $F_S$, $A_s$ fixed;
- Ratio of uncertainties between free and partially-fixed fit is used to compute the systematic uncertainty.

# $P_1$ and $P'_5$ distributions

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




$P_1$




$P'_5$

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.

CMS-BPH-15-008
arXiv: 1710.02846
Phys. Lett. B 781 (2018) 517

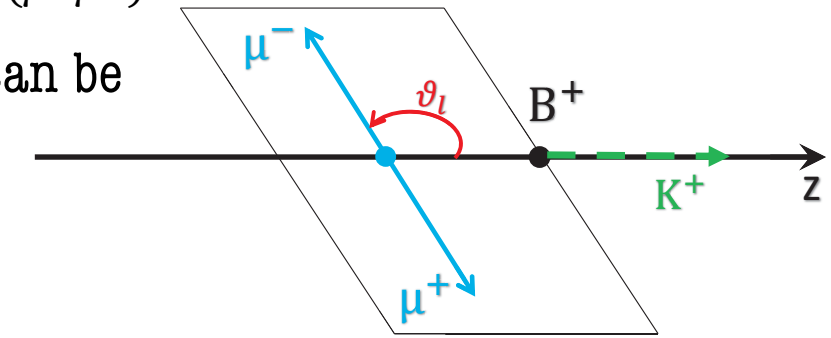
Belle: Phys. Rev. Lett. 118 (2017) 111801
LHCb: JHEP 02 (2016) 104
ATALS: arXiv:1805.04000
SM-DHMV: JHEP 01 (2013) 048, JHEP 05 (2013) 137

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

- Using 20.5 fb$^{-1}$ of 8 TeV pp data taken in 2012

  Control channels: $B^+ \to K^+ J/\psi(\mu^+\mu^-)$, $B^+ \to K^+\psi'(\mu^+\mu^-)$

- The decay for the process $B^+ \to K^+\mu^+\mu^-$ can be described by $\cos\theta_\ell$ and $q^2 = m^2_{\mu^+\mu^-}$




- The differential decay:

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

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

$\theta_\ell$ : $\ell = \mu$, 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 $\Gamma$.

# The pdf and efficiency

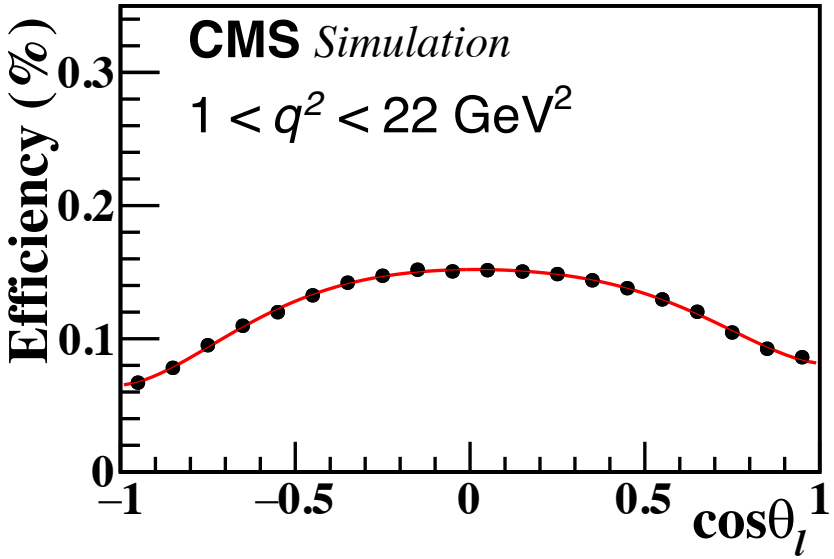


- The probability density function:

$$\mathrm{pdf}(m, \cos\theta_\ell) = Y_S \cdot \boxed{S(m)} \cdot \boxed{S(\cos\theta_\ell)} \cdot \boxed{\varepsilon(\cos\theta_\ell)} + Y_B \cdot B(m) \cdot B(\cos\theta_\ell)$$

  - ✓ Signal contribution: mass shape (double Gaussian), decay rate, and efficiency function.
  - ✓ Background contribution: mass shape (exponential) and angular variable (3rd or 4th degrees polynomial + a Gaussian function).

- Efficiency:
  - ✓ Factorized into an acceptance and a reco-efficiency, for each $q^2$ bin.
  - ✓ The signal efficiency $\varepsilon(\cos\theta_\ell)$ is parametrized with a sixth-order polynomial.



# Fitting and validation

$B^+ \to K^+\mu^+\mu^-$

## ➢ Fitting strategy:

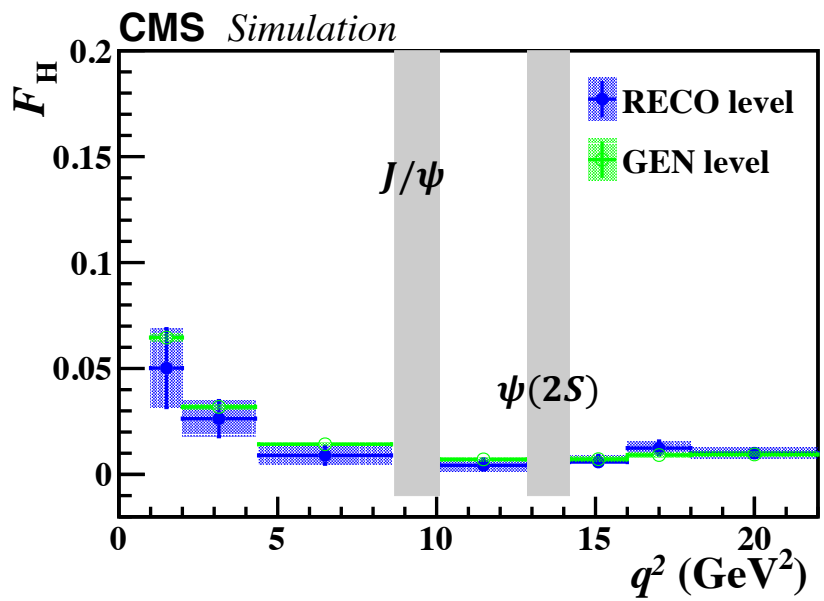
- ✓ Parameters are extracted from un-binned extended maximum likelihood fit in each bin: $m(K^+\mu^+\mu^-)$, $\cos\theta_\ell$
- ✓ Fit performed in two steps:

  1) Fit sidebands to determine background angular shape, fixed in the next step;

  2) Fit whole mass spectrum, 5 free parameters, $A_{FB}$, $F_H$, yields and background mass shape parameters.
- ✓ Feldman-Cousins method with nuisance parameters

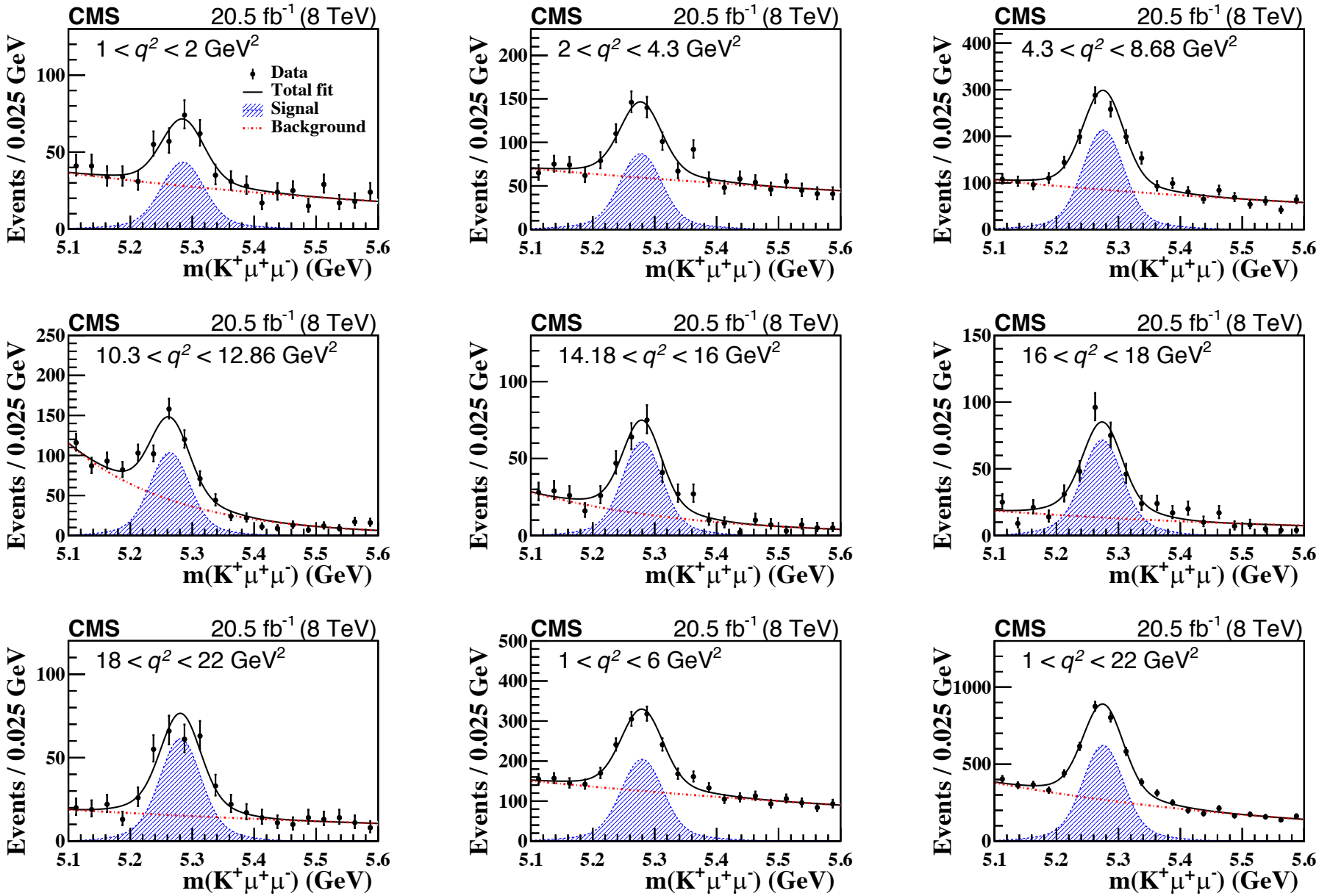
## ➢ Validations:

- ✓ with resonant control regions
- ✓ with data-like signal MC sample
- ✓ with large size of signal MC sample



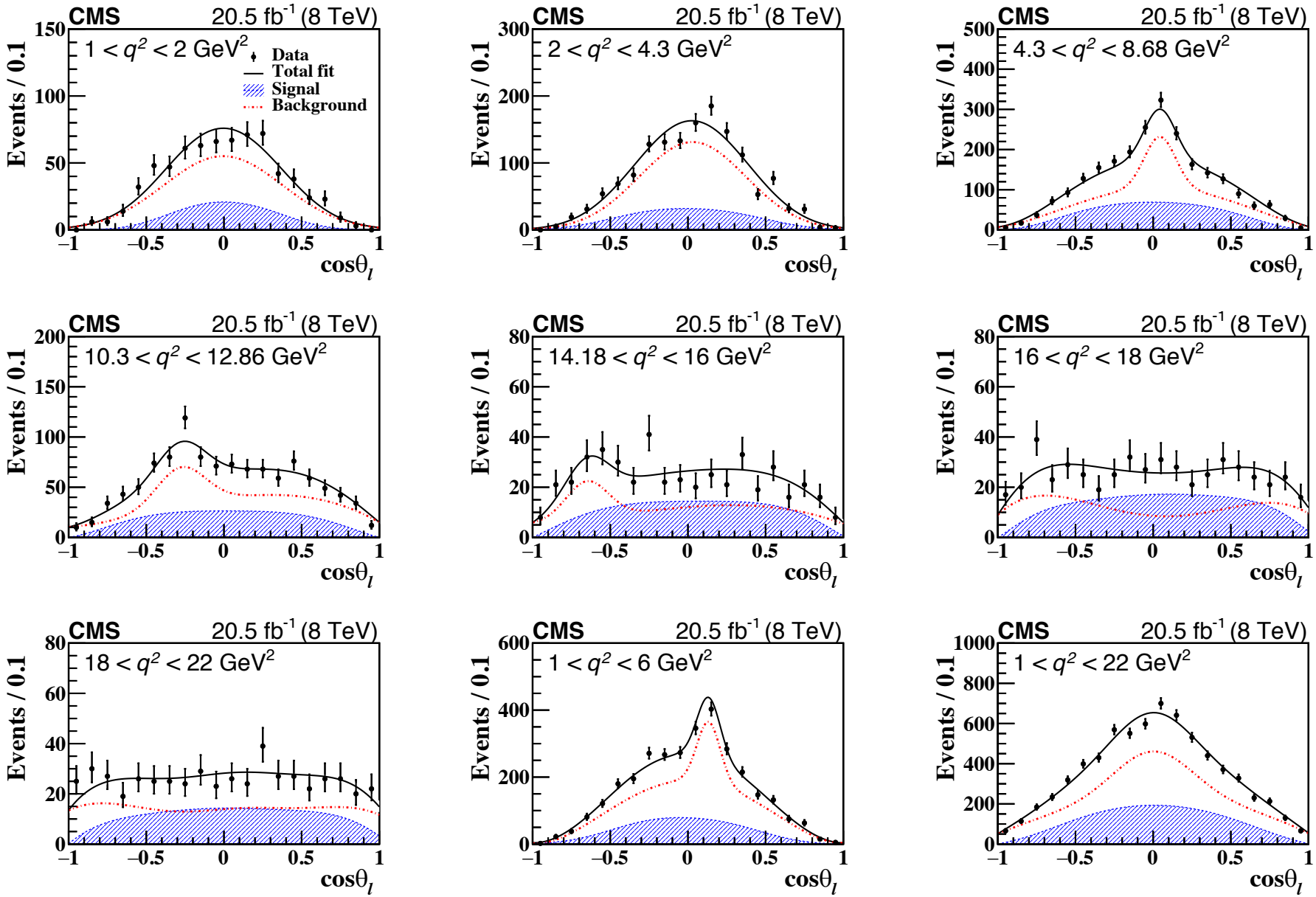
# Projections of $B^+$ invariant mass

$B^+ \to K^+\mu^+\mu^-$



# Projections of $\cos\theta_\ell$

$B^+ \to K^+\mu^+\mu^-$



# Systematic uncertainty

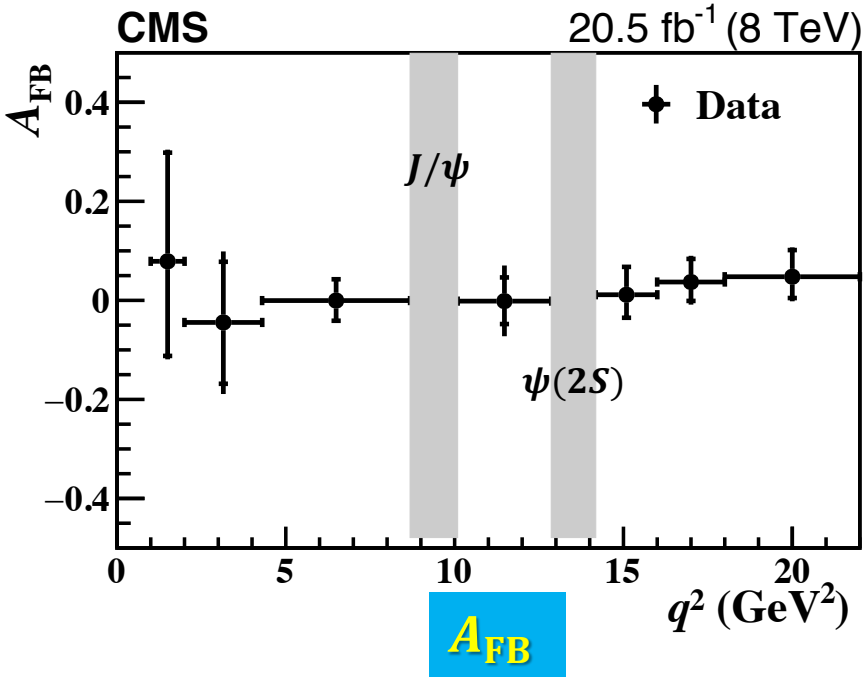
$B^+ \to K^+\mu^+\mu^-$

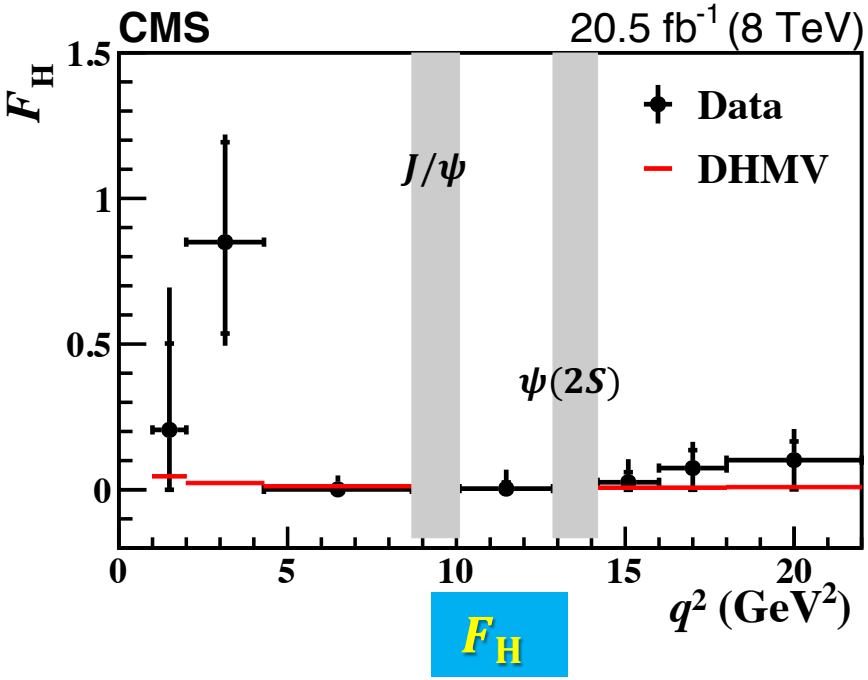
- **Finite size of MC samples:**
  - ✓ Generating 200 sets of efficiency with parameters varied in multi-Gaussian phase space.
- **Efficiency description:**
- **Simulation mismodeling:**
- **Background parametrization model:**
- **Angular resolution:**
  - ✓ Propagation of efficiency difference from reco'd or gen'd value($\cos\theta_\ell$) with signal MC.
- **Dimuon mass resolution:**
  - ✓ Propagation of efficiency difference from reco'd or gen'd dimuon mass with signal MC.
- **Fitting procedure:**
  - ✓ Fluctuations (RMS) from signal MC sub-samples fitting results.
  - ✓ Generate pseudo-experiments with signal from MC and background from data, fit with data fitting procedure.
- **Background distribution:**
  - ✓ Use the pseudo-experiments above, change the background angular p.d.f. to one of the two data side bands, chose the larger deviation as systematic uncertainty.
- **Total systematic uncertainty:**
  - ✓ All added in quadrature.

| Systematic uncertainty | $A_{FB}$ ($\times 10^{-2}$) | $F_H$ ($\times 10^{-2}$) |
|---|---|---|
| Finite size of MC samples | 0.4–1.8 | 0.9–5.0 |
| Efficiency description | 0.1–1.5 | 0.1–7.8 |
| Simulation mismodeling | 0.1–2.8 | 0.1–1.4 |
| Background parametrization model | 0.1–1.0 | 0.1–5.1 |
| Angular resolution | 0.1–1.7 | 0.1–3.3 |
| Dimuon mass resolution | 0.1–1.0 | 0.1–1.5 |
| Fitting procedure | 0.1–3.2 | 0.4–25 |
| Background distribution | 0.1–7.2 | 0.1–29 |
| Total systematic uncertainty | 1.6–7.5 | 4.4–39 |

# $A_{FB}$ and $F_H$ distributions

$B^+ \to K^+\mu^+\mu^-$




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.

CMS-BPH-15-001
arXiv: 1806.00636
Submitted to Phys. Rev. D

DHMV: JHEP 12 (2014) 125; JHEP 06 (2016) 092

# Summary

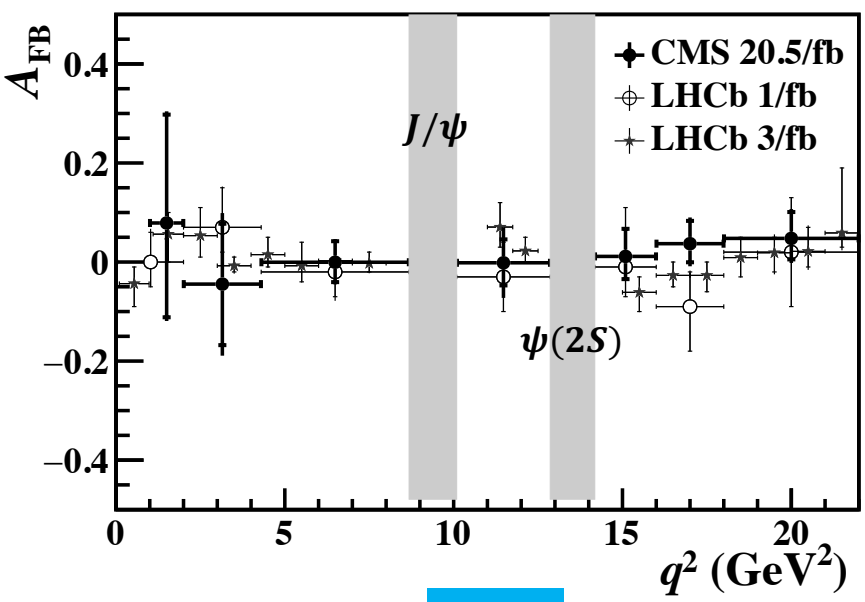
- Rare FCNC transitions $\mathrm{b} \to \mathrm{s}\,\mu^+\mu^-$ are good probes of physics beyond standard model.
- CMS has carried out the angular analyses of the decays $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ and $\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-$. The measurements of $P_1$, $P_5'$, $A_{\mathrm{FB}}$, and $F_{\mathrm{H}}$ show no significant deviations from SM.
- CMS is an ideal environment to study rare B-decays, more measurements are being prepared.
- More data and future theoretical developments will clarify these anomalies.

# Thank you !

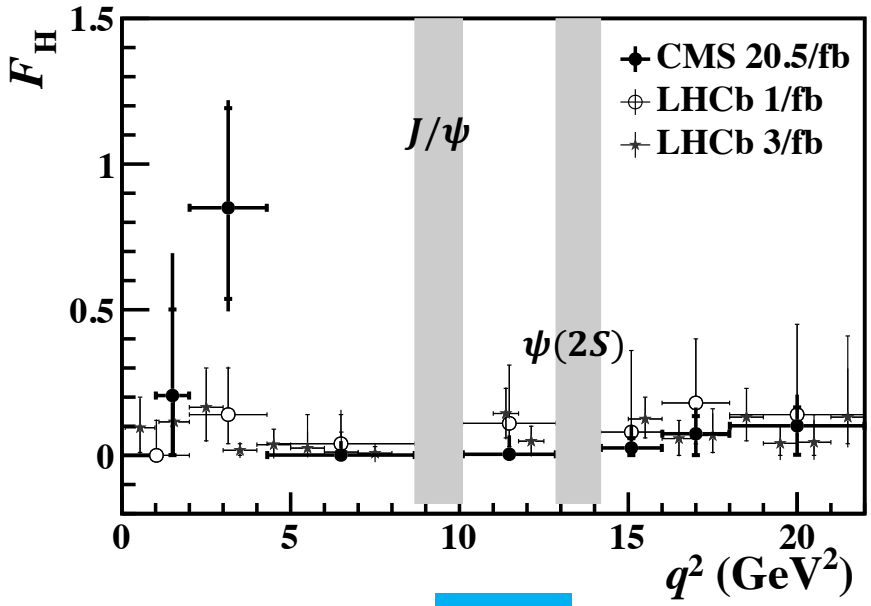
## Additional materials

# A comparison with LHCb measurements

$B^+ \to K^+\mu^+\mu^-$




$A_{FB}$




$F_H$

The CMS measurements have a better uncertainty estimation for the range of $q^2 > 14$ GeV$^2$.

Over all, the CMS measurements of $A_{FB}$ and $F_H$ from this angular analysis show good agreement with LHCb measurements within the uncertainty.

CMS-BPH-15-001
arXiv: 1806.00636
Submitted to Phys. Rev. D

**Public results:**
http://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-15-001/