b→sll angular analyses on CMS

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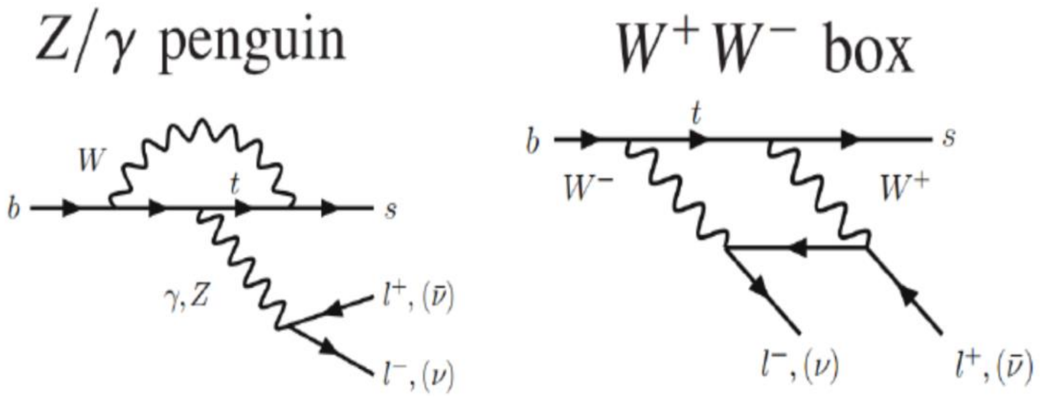
on behalf of CMS collaboration

Outline

- Introduction
- b→sll angular analyses on CMS Run1
  - ***$B^+ \to K^+\mu^+\mu^-$***
  - ***$B^0 \to K^{*0}\mu^+\mu^-$***
  - ***$B^+ \to K^{*+}\mu^+\mu^-$***
- b→sll angular analyses on CMS Run2
  - ***$B^+ \to K^+\mu^+\mu^-$***
  - ***$B^0 \to K^{*0}\mu^+\mu^-$***
  - ***$B_s \to \Phi\, \mu^+\mu^-$***
- Prospect of HL-LHC
- Summary

Introduction: theoretical motivation

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



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

Introduction: effective hamiltonian

- $b \to sll$ porcess can be described using effective theory[1]， the effective Hamiltonian is：

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu)$$

Where $O_i(\mu)$ indicate operator, $C_i(\mu)$ is Wilson coefficients, μ is the scale

- For SM, $i = 1, \ldots, 10$. Terms 7, 9, 10 dominate in $b \to sl\bar{l}$

$$\mathcal{O}_7 = \frac{e}{(4\pi)^2} \overline{m}_b [\bar{s}\sigma^{\mu\nu} P_R b] F_{\mu\nu},\ \mathcal{O}_9 = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma_\mu P_L b][\bar{l}\gamma^\mu l],\ \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma_\mu P_L b][\bar{l}\gamma^\mu \gamma_5 l],$$

- To describe new physics in $b \to sll$. Following terms are taken into consideration.

$$\mathcal{O}_S^l = \frac{e^2}{(4\pi)^2} [\bar{s}P_R b][\bar{l}l], \qquad \mathcal{O}_S^{l\prime} = \frac{e^2}{(4\pi)^2} [\bar{s}P_L b][\bar{l}l],$$

$$\mathcal{O}_P^l = \frac{e^2}{(4\pi)^2} [\bar{s}P_R b][\bar{l}\gamma_5 l], \qquad \mathcal{O}_P^{l\prime} = \frac{e^2}{(4\pi)^2} [\bar{s}P_L b][\bar{l}\gamma_5 l],$$

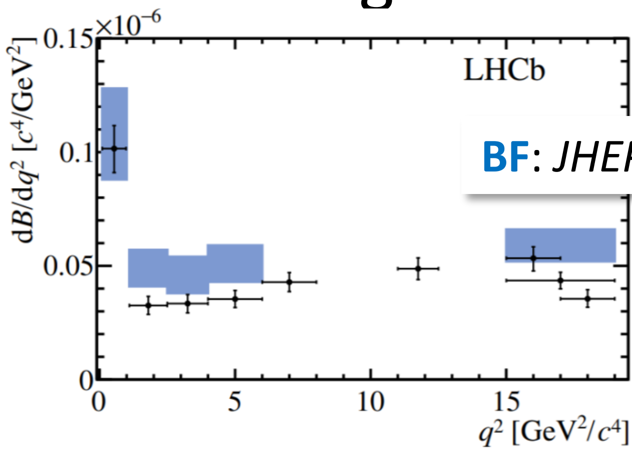
$$\mathcal{O}_T^l = \frac{e^2}{(4\pi)^2} [\bar{s}\sigma_{\mu\nu} b][\bar{l}\sigma^{\mu\nu} l], \qquad \mathcal{O}_{T5}^l = \frac{e^2}{(4\pi)^2} [\bar{s}\sigma_{\mu\nu} b][\bar{l}\sigma^{\mu\nu}\gamma_5 l],$$

Definitions of $O_i(\mu)$ are in [1][2]

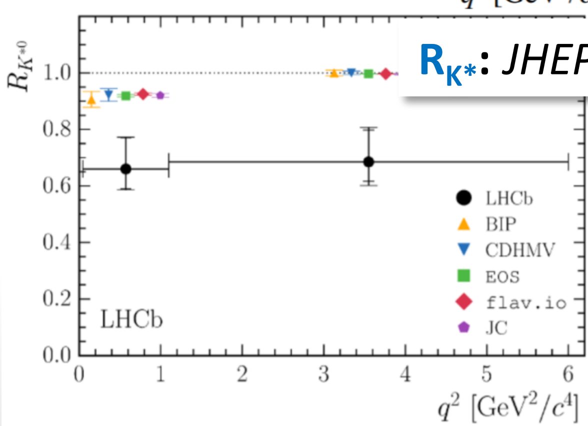
[1] C. Bobeth, G. Hiller and G. Piranishvili, JHEP, 2007, 12: 040.
[2] K.G. Chetyrkin, M. Misiak and M. Munz, Phys. Lett. B 400 (1997) 206.

Introduction: ***b→sll*** anomaly

- Some observables of ***b→sll*** process are found deviating from SM predictions by 2-3σ, e.g. branching fraction, R_{K^*}, P_5'…

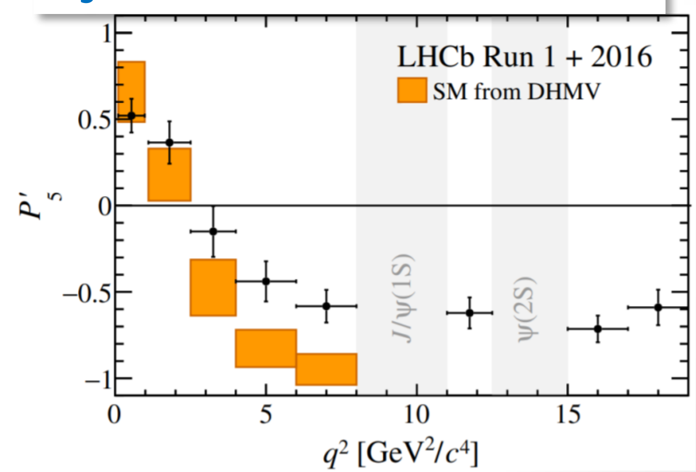


BF: *JHEP* 04 (2017) 142



R_{K^*}: *JHEP* 04 (2017) 142

P_5': *PRL* 125 (2020) 1, 011802

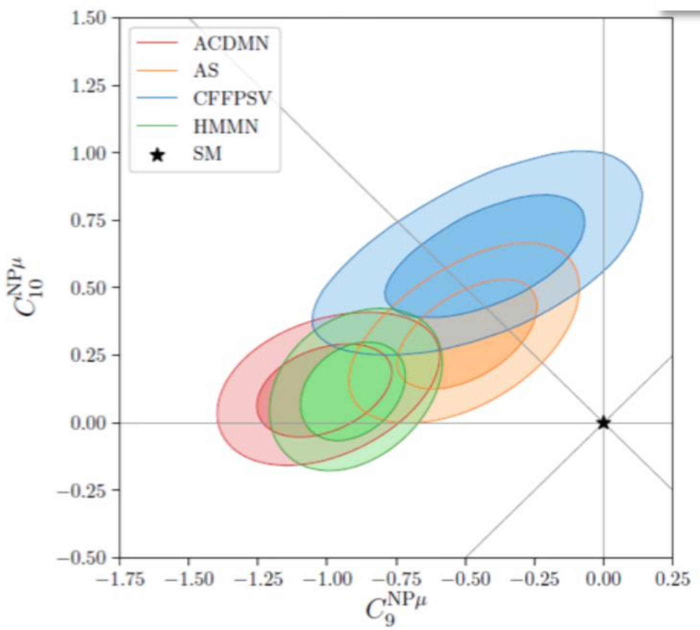


Introduction: *b→sll* anomaly

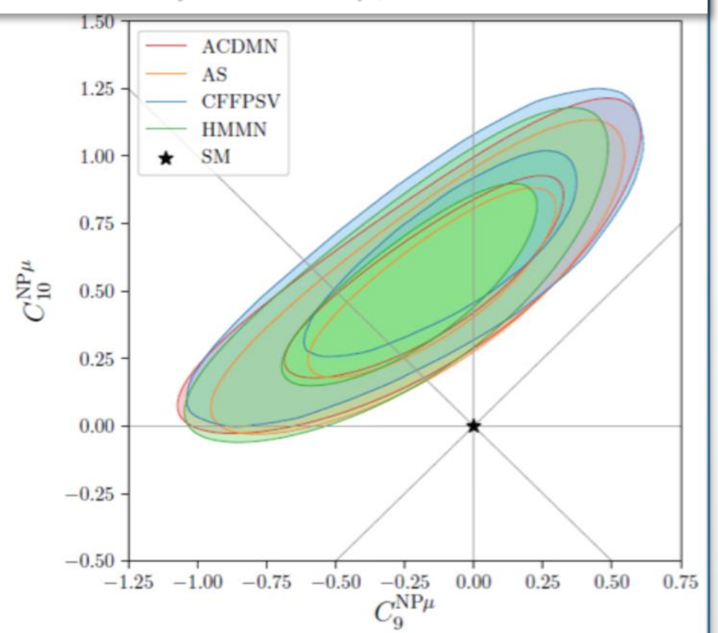
- Global fit of many observables from various measurements presents a result in tension with SM prediction by >4σ.

2-dimensional fits

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl @ Flavour Anomaly Workshop, 20 Oct. 2021



global fit

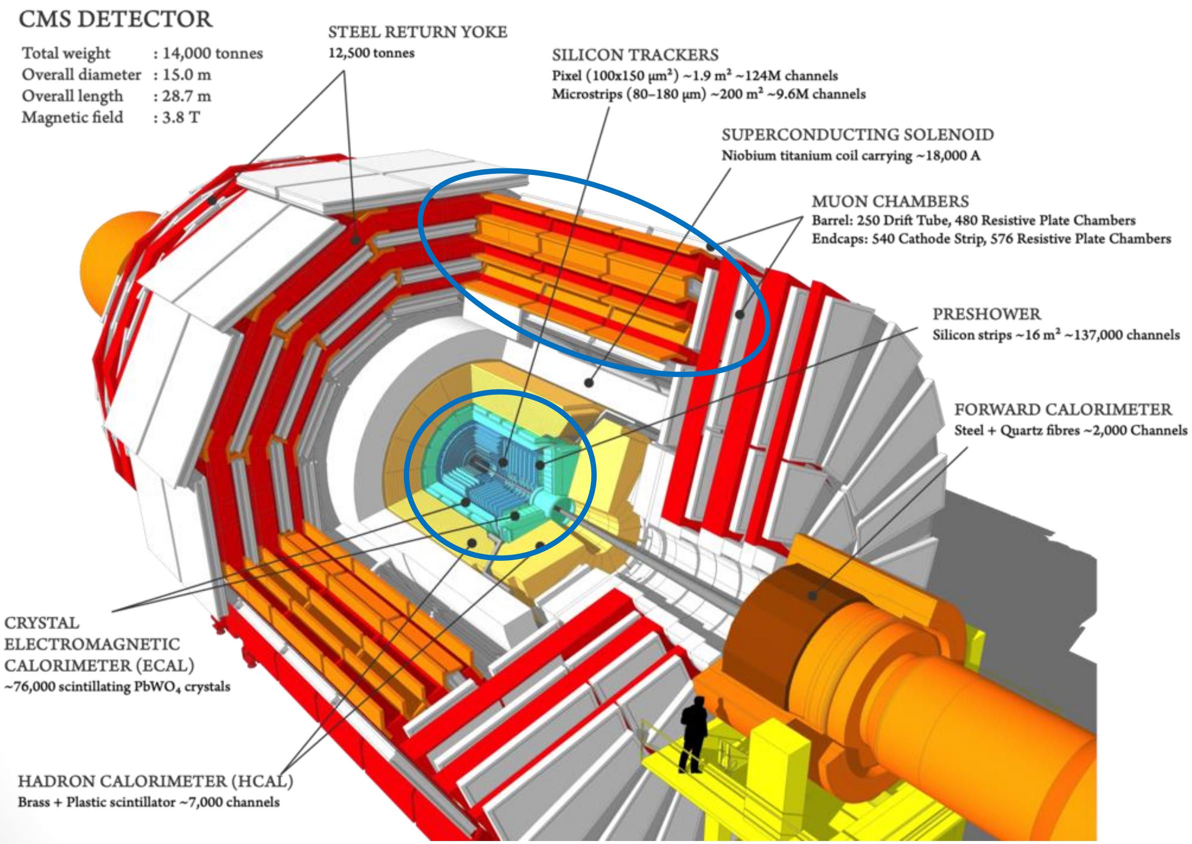


fit to LFU observables + $B_s \to \mu\mu$

Introduction: angular analyses

- Investigate the angular distribution of the final state particles.
- ***Pros:***
  - More utilizable observables than branching fraction measurement. More information.
  - Some observables can be constructed to reduce the hadronic uncertainty.
- ***Cons:***
  - Low statistics. More dimensions to be investigate than branching fraction measurement
  - Difficult to determine the angular distribution of background

Introduction: CMS



- COM energy 13 TeV
- Lumi ~ 10^{34} $cm^{-2}s^{-1}$
- $\Delta p_T/p_T$ ~ 1% when $p_T < 100$ GeV
- transverse impact parameter resolution O(10 — 100μm)
- Vertex resolution O(20 — 100μm)
- Covering most of the 4π solid angle

11/13/2021 @ HFCPV2021

b→sll angular analyses on CMS Run1

- Several *b→sll* angular analyses have been studied on CMS, such as $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$

- Run1 analyses based on 20fb^{-1} 8TeV data have been completed.

- Publications:
  - Angular analysis of $B^+ \to K^+\mu^+\mu^-$: Physical Review D, 98(2018), 112011
  - Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (A_{FB}) : Physics Letters B, 753(2016), 424-448
  - Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (P_5') : Physics Letters B, 781(2018), 517-541
  - Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$: Journal of High Energy Physics, 04(2021), 124

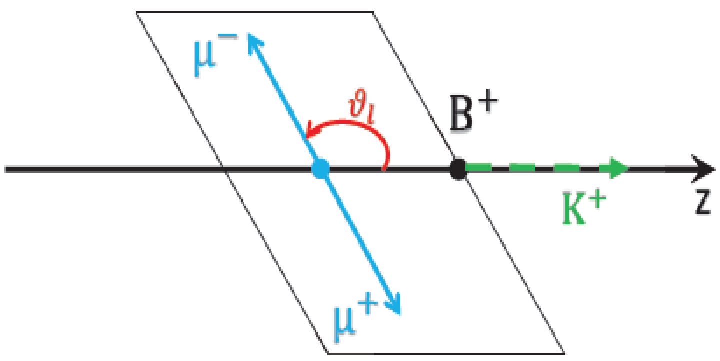
Run1 angular analysis: $B^+ \rightarrow K^+ \mu^+ \mu^-$

- The decay for the process $B^+ \rightarrow K^+ \mu^+ \mu^-$ can be described by $\cos\vartheta_\ell$ and q^2
- Differential decay rate formula:

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

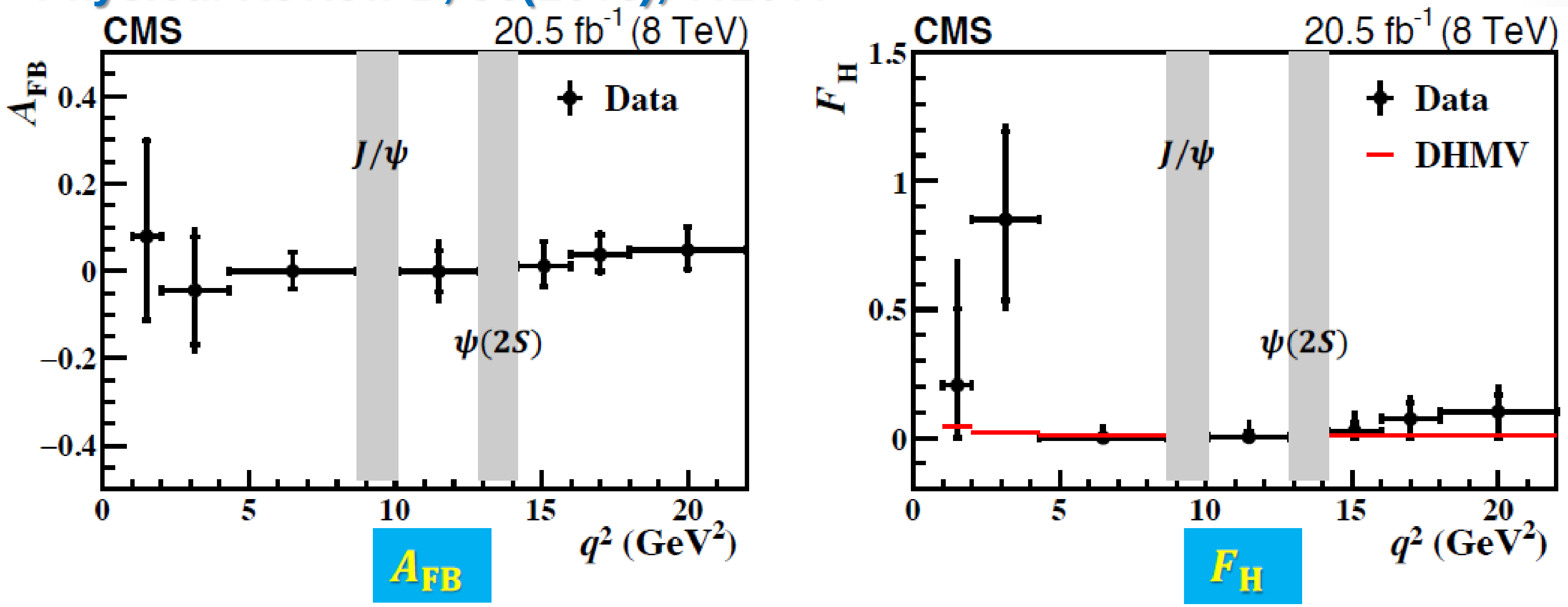
$$0 \leq F_H \leq 3, A_{FB} \leq \min(1, F_H/2)$$

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



Run1 result: $B^+ \to K^+\mu^+\mu^-$

Physical Review D, 98(2018), 112011

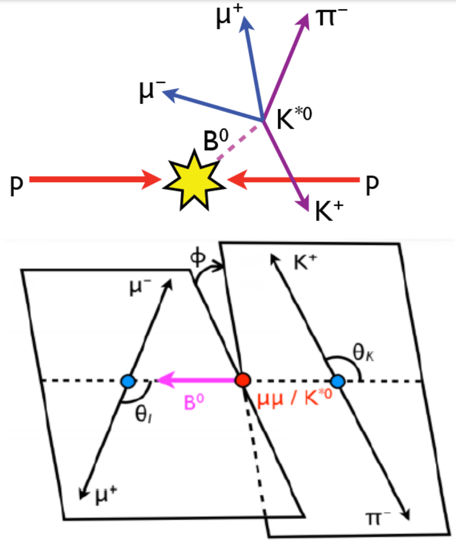


The events are measured in seven q^2 bins ranging from 1 to 22 GeV^2, 2286 signal events in total.

The measured A_{FB} and F_H are in agreement with the SM predictions within the uncertainties.

Run1 angular analysis: $B^0 \to K^{*0}\mu^+\mu^-$

- Final state: $K^+\pi^-\mu^+\mu^-$
- Fully described by the three angles (ϑ_ℓ, ϑ_K, ϕ) and q^2.
- Robust SM predictions of several angular parameters, A_{FB} , F_L , P_1 and P_5', are available.
- Angular observables are measured in q^2 bins from 1 to 19 GeV^2.



❖ ***Differential decay rate :***

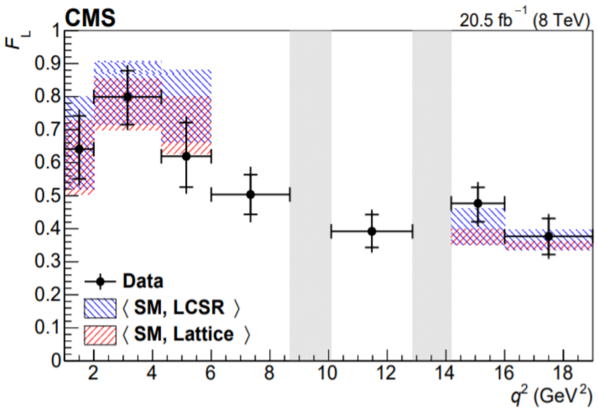
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{8\pi}\Big\{\frac{2}{3}\Big[(F_S + A_S\cos\theta_K)(1-\cos^2\theta_l) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big] + (1-F_S)\Big[2F_L\cos^2\theta_K(1-\cos^2\theta_l)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

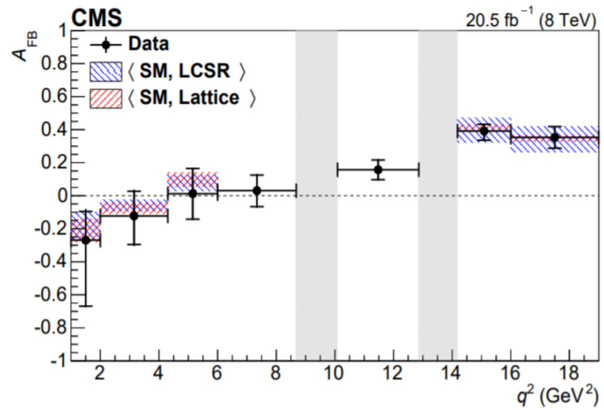
P-wave

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

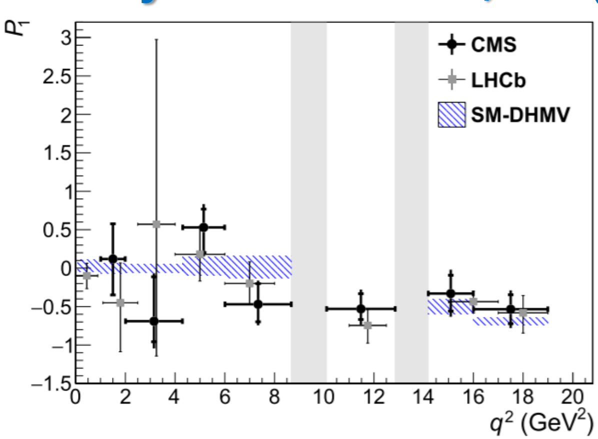
Run1 result: $B^0 \rightarrow K^{*0}\mu^+\mu^-$

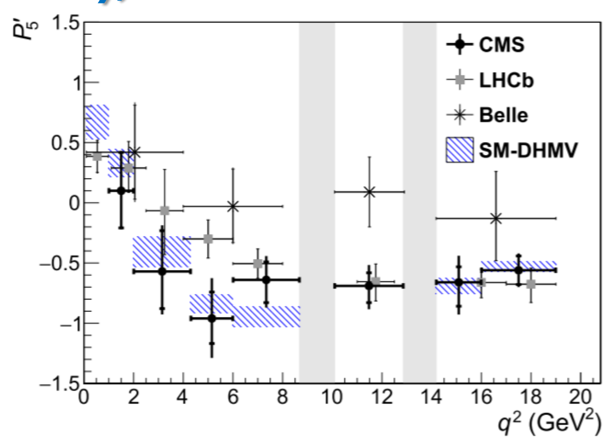
Physics Letters B, 753(2016), 424-448





Physics Letters B, 781(2018), 517-541



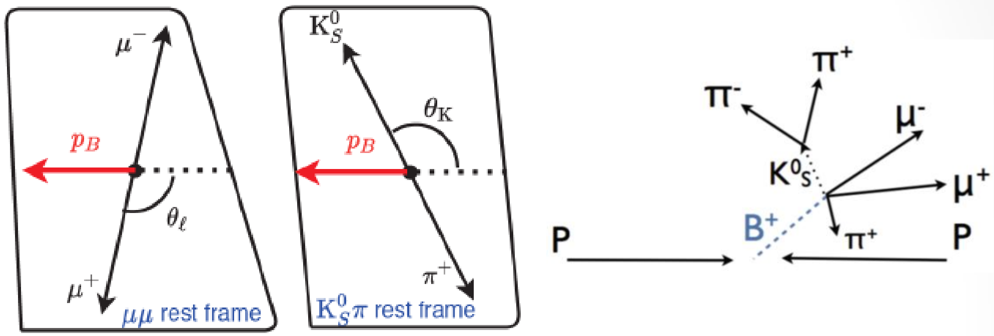


The events are fit in seven q^2 bins ranging from 1 to 19 GeV^2

The measured (A_{FB}, F_H) and (P_1, P_5’) are in agreement with the SM predictions within the uncertainties.

Run1 angular analysis: $B^+ \to K^{*+}\mu^+\mu^-$

- Final state: $\pi^+\pi^+\pi^-\mu^+\mu^-$
- The decay can be fully described by the three angles (ϑ_ℓ, ϑ_K, ϕ) and q^2



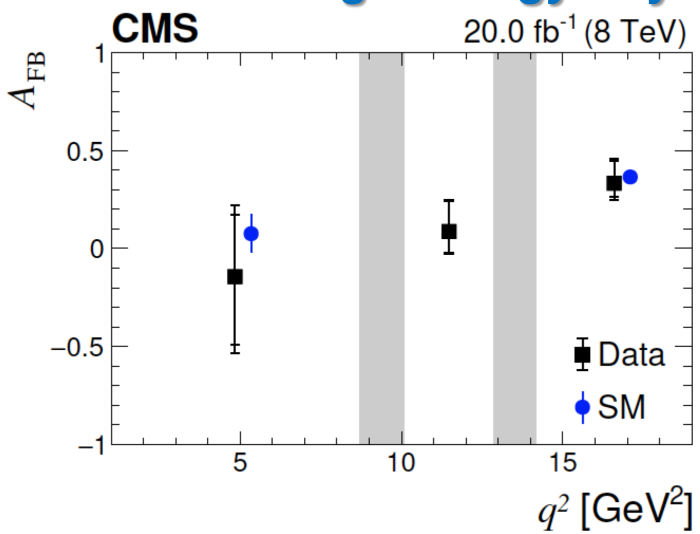
- Differential decay rate (integrate out ϕ):

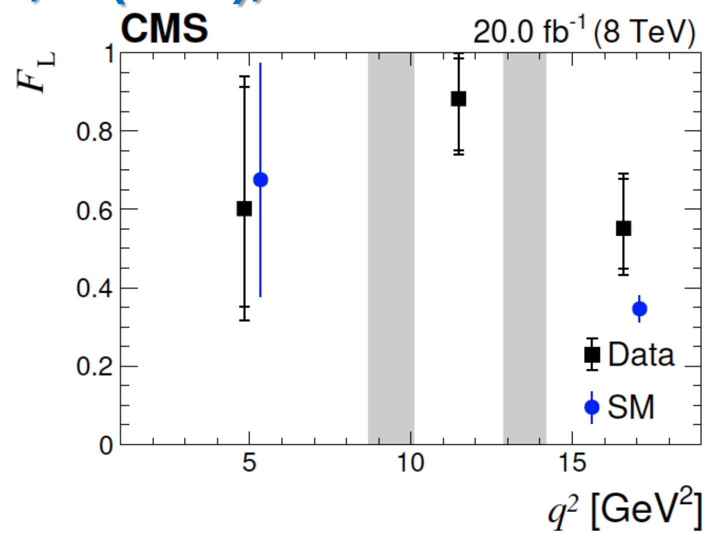
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K} = \frac{9}{16}\left[\frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right) + 2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_l\right]$$

- 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

Run1 result: $B^+ \to K^{*+} \mu^+ \mu^-$

Journal of High Energy Physics, 04(2021), 124





q^2 (GeV^2)	Y_S	A_{FB}	F_L
1–8.68	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	45.1 ± 8.0	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$

A_{FB} and F_L in bins of q^2 are found to be consistent with a standard model prediction.

$b \to sll$ angular analyses on CMS Run2

- Based on 137fb^{-1} 13TeV data collected in CMS Run2, new $b \to sll$ angular analyses are being studied.

- The new angular analyses are: $\boldsymbol{B^0 \to K^{*0}\mu^+\mu^-}$ **,** $\boldsymbol{B^+ \to K^+\mu^+\mu^-}$ **,** $\boldsymbol{B_s \to \Phi\, \mu^+\mu^-}$ based on Run2 data.

- The three analyses are ongoing.

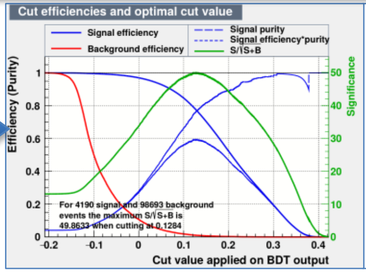
Updates of Run2 angular analyses

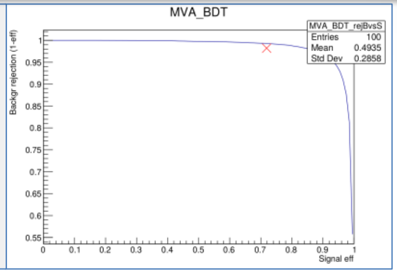
- **Luminosity**
  - From 20 fb^{-1} to 137 fb^{-1}, 7 times improvement
- **Selection**
  - Using new offline selection, improving the signal efficiency and the background rejection
- **Fitting**
  - Using new fitting PDF, stability improved
- **Statistic error**
  - Using new statistic error evaluation method

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

Selection

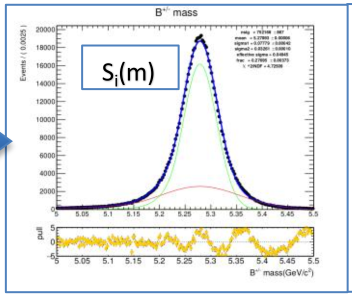
Pre-selection;
Offline-selection (using AdaBoost BDT);

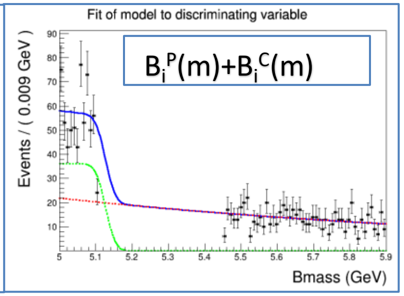




PDF components detemination

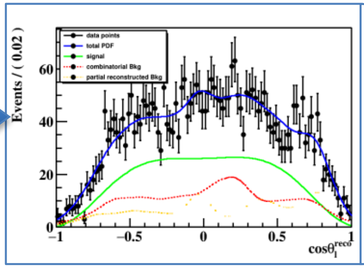
Signal mass shape (using signal MC);	Bkg mass shape (using data sideband);	Bkg angular shape (using data sideband);

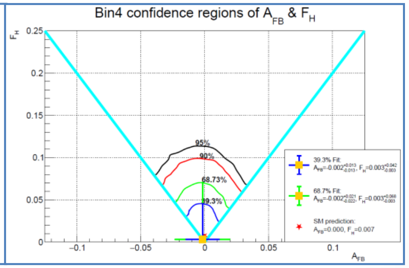




Fitting

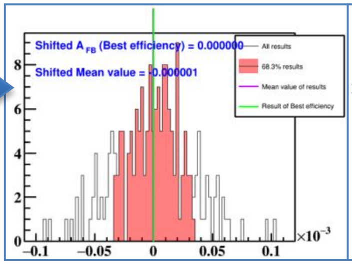
2 dimensional fitting;
Statistic uncertainty (using 2D F-C method);

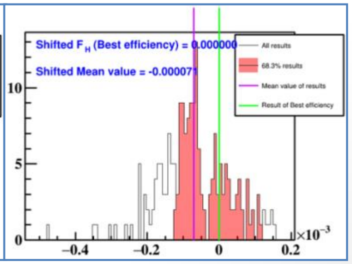




Systematic uncertainty

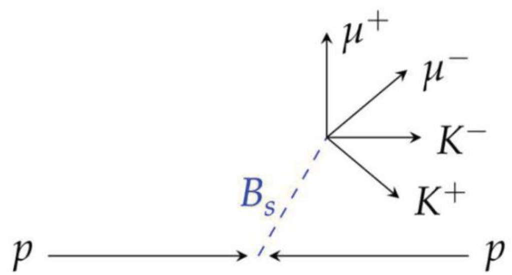
Fitting bias;
MC mismodelling;
PDF function forms ...

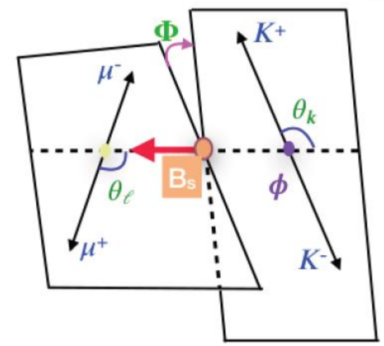




Run2 angular analysis: $B_s \to \Phi\, \mu^+\mu^-$

- Final state: $K^+K^-\mu^+\mu^-$
- The decay can be described by the three angles (ϑ_ℓ, ϑ_K, ϕ) and q^2





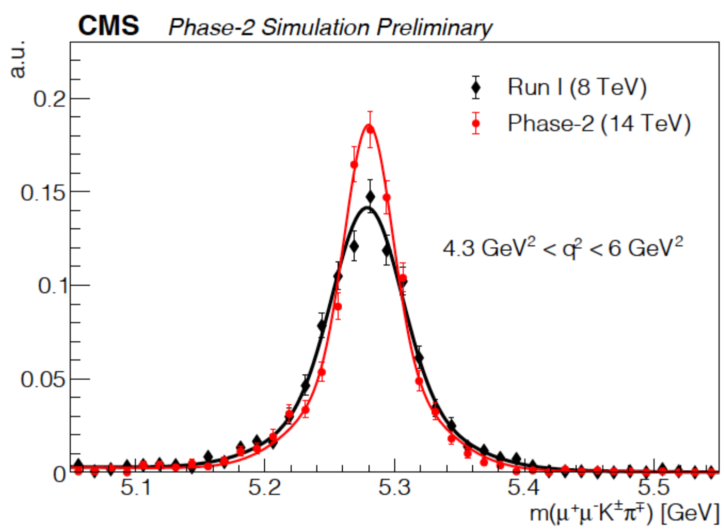
- Differential decay rate (integrate out ϕ):

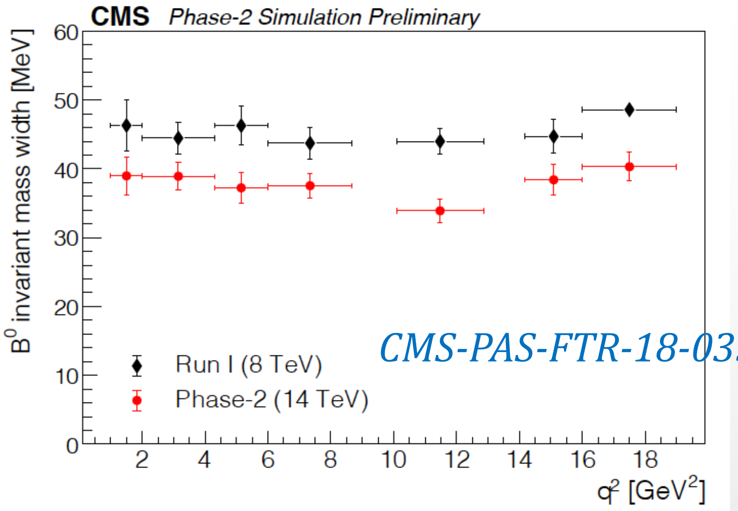
$$\frac{1}{d\Gamma/dq^2}\frac{d^2\Gamma}{d\cos\theta_k d\cos\theta_l} = \frac{9}{16}\Big(\frac{1}{2}(1-F_L)\cdot(1-\cos^2\theta_K)\cdot(1+\cos^2\theta_l) + 2F_L\cdot\cos^2\theta_K\cdot(1-\cos^2\theta_l) + A_6\cdot(1-\cos^2\theta_K)\cdot\cos\theta_l\Big)$$

- Two observables, the muon CP asymmetry (A_6) and the longitudinal polarization fraction (F_L), are measured as a function of q^2

Prospect of HL-LHC

- Motivation: P_5' discrepancy between experimental measurement and SM
- Run 1 results used as base line, the expected sensitivity of P_5' with HL-LHC statistics at 3000 fb^{-1} was studied
  - Improved mass resolution with upgraded tracker detector
  - No changes in trigger performances and analysis strategy have been considered
  - Expected signal yield: ~700k in full q^2 bin in 200 pileup scenario

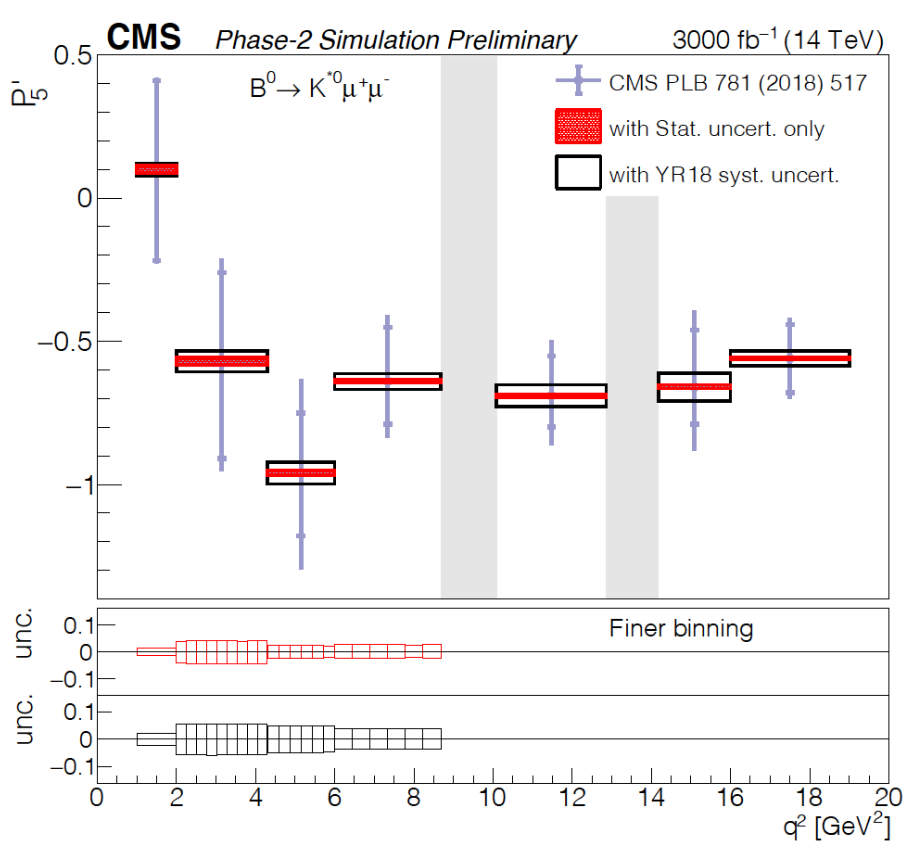




CMS-PAS-FTR-18-033

Prospective uncertainties on P_5'

- Statistical uncertainty: scaled according to simulation yield
- Systematic uncertainty
  - Based on data control channel: scaled according to statistics
  - Others: scaled by factor of 2
- Total uncertainty: improve by up to a factor of 15 compared with Run 1 results
- Allow to split q^2 range in finer bins



Summary

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

- The three measurements done on CMS, $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$, and $B^+ \to K^{*+}\mu^+\mu^-$, presented results consistent with standard model predictions.

- New angular analyses are ongoing, with larger amount of CMS datasets and updated procedure.

- More sensitive results can be expected on HL-LHC

END

Thank you!

Backup

Definition of observables $P_i^{(')}$

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

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

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

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

$$P_1 = \frac{2\,S_3}{(1-F_L)} = A_T^{(2)},$$

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

$$P_3 = \frac{-S_9}{(1-F_L)},$$

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

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

***S_i*:** CP averages; ***A_i*:** CP asymmetries;
$P_i^{(')}$*:** constructed observables for ***$B^0 \to K^{*0}$ leading form-factor uncertainty cancel