Angular analyses of B meson decays at CMS

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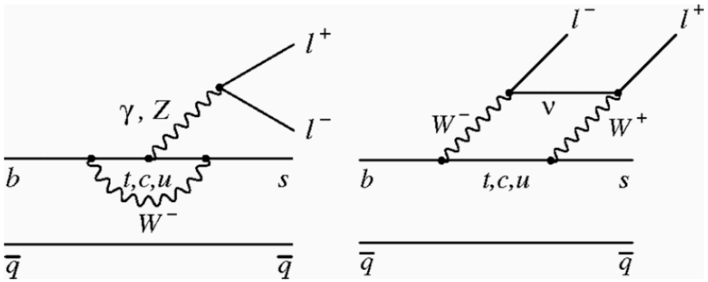
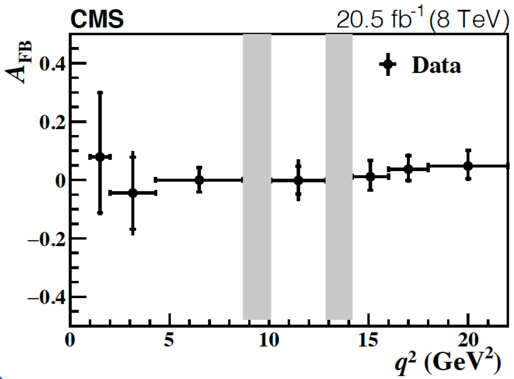
Introduction

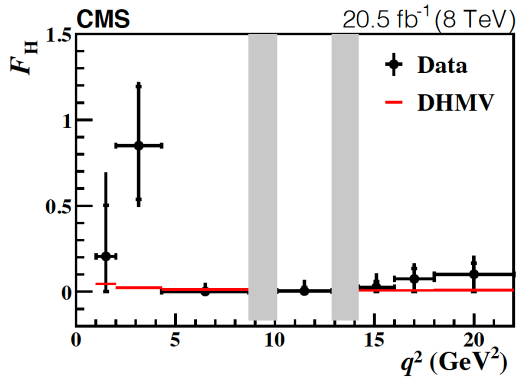
- $b \to sll$ transitions
  - Flavor-changing neutral current decays
  - Forbidden at tree level, but allowed via loop diagrams in SM
  - High sensitivity to NP through BSM particles in the loop
  - Experimentally attractive channels
    - ✓ Fully charged final states
    - ✓ Easy to trigger and reconstruct muon pair



- Angular analysis
  - Measure the rate of the decay as a function of the angles of the final decay products
  - Access to a large set of observables with reduced theory uncertainties
  - Sensitive probe to New Physics

Analyses with RUN 1 data





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

PRD 98 (2018) 112011

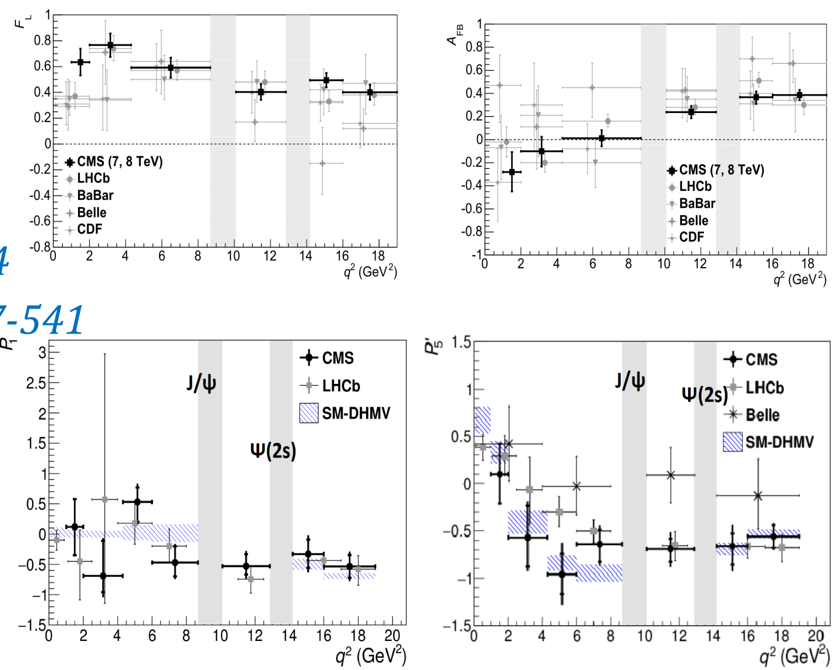
CMS-PAS-15-001

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

PLB 753 (2016) 424

PLB 781 (2018) 517-541

CMS-PAS-15-008



Latest result!

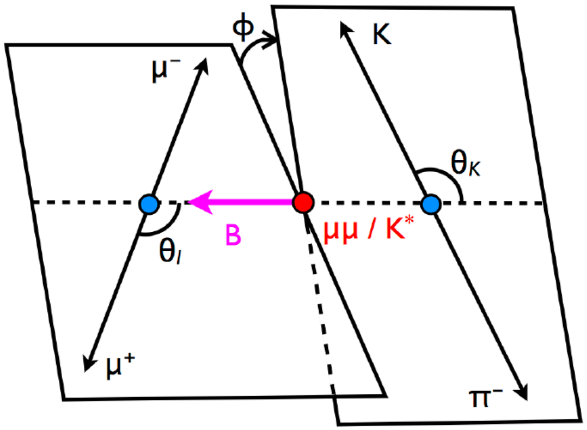
$B^+ \to K^{*+}\mu\mu$

JHEP 04 (2021) 124

CMS-PAS-15-009

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

- Described by **the three angles (θ_l, θ_k, ϕ)** and **the dimuon invariant mass squared q^2**
- About 20 fb^{-1} of CMS data at 8 TeV
- The decay rate after ϕ is integrated out



$$
\begin{aligned}
\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_{\mathrm{K}}\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}q^2} = \frac{9}{16}\Bigg\{ & \frac{2}{3}\left[F_S + 2A_S\cos\theta_{\mathrm{K}}\right]\left(1-\cos^2\theta_\ell\right) \\
& + (1-F_S)\left[2F_{\mathrm{L}}\cos^2\theta_{\mathrm{K}}\left(1-\cos^2\theta_\ell\right)\right. \\
& + \frac{1}{2}(1-F_{\mathrm{L}})\left(1-\cos^2\theta_{\mathrm{K}}\right)\left(1+\cos^2\theta_\ell\right) \\
& \left. + \frac{4}{3}A_{\mathrm{FB}}\left(1-\cos^2\theta_{\mathrm{K}}\right)\cos\theta_\ell\right]\Bigg\}.
\end{aligned}
$$

- F_L: fraction of longitudinally polarized K^{*+}
- A_{FB}: forward-backward asymmetry of dimuon
- F_S: fraction of S wave
- A_S: interference between S and P wave

Bin index	$q^2(\mathrm{GeV}^2)$
1	1– 8.68
2	8.68 – 10.09 (J/ψ)
3	10.09 – 12.86
4	12.86 – 14.18 (ψ(2S))
5	14.18 - 19
0	Bin1 + Bin3 + Bin5

Event Selection

HLT: especially designed trigger to reduce trigger rate

- Single muon $p_T > 3.5$ GeV
- Dimuon $p_T > 6.9$ GeV
- $1 < m(\mu\mu) < 4.8$ GeV
- $Lxy/\sigma > 3$ wrt beamspot
- Vtx CL > 10%

Offline reconstruction: two oppositely charged muons and a K^{*+} meson

- K^{*+}: $K_S^0\pi^+$ mode
- K_S^0: $\pi^+\pi^-$ mode
- Mass and vertex quality constraints on K_S^0 and K^{*+}

Background rejections and suppressions

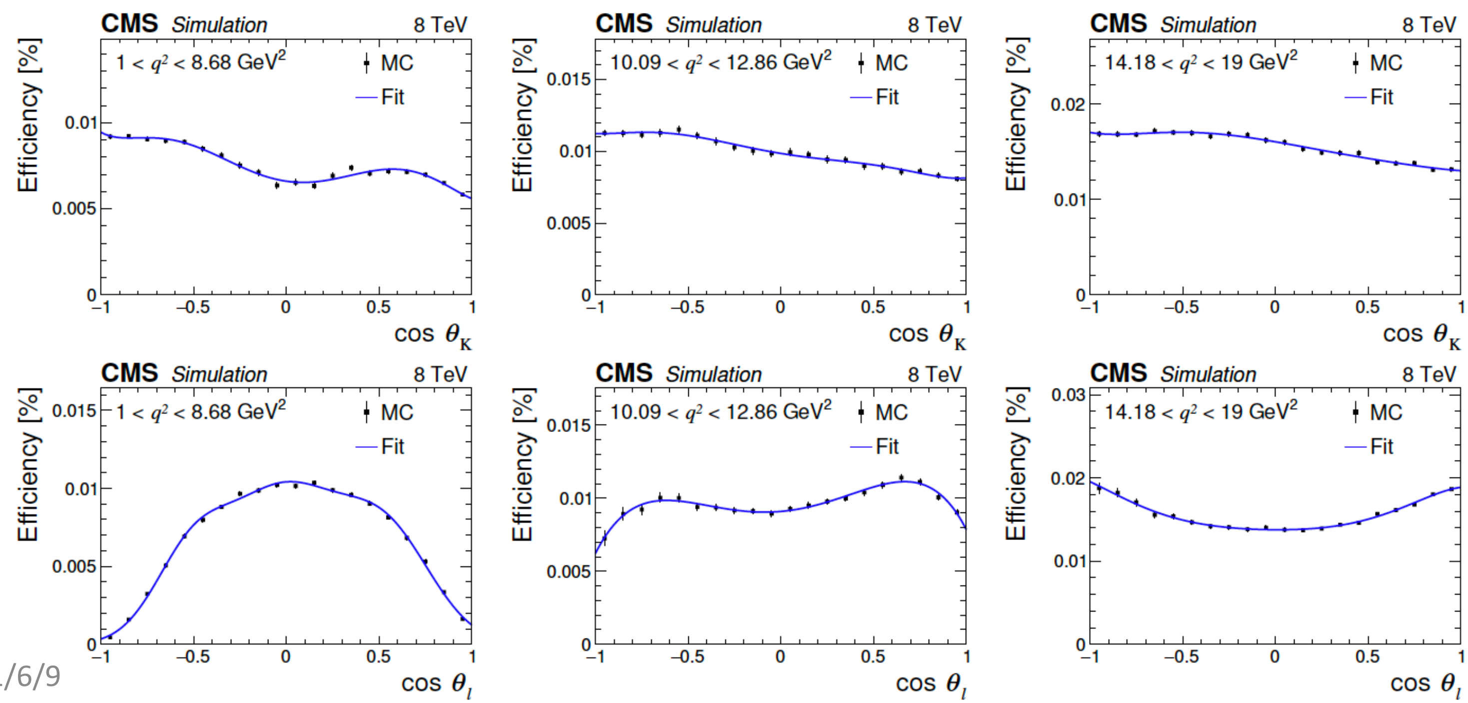
- Suppress resonant backgrounds $B^+ \to K^{*+}J/\psi$ and $B^+ \to K^{*+}\psi(2S)$ through dimuon invariant mass and anti-radiation cuts
- Optimize selection criteria based on the maximization of $S/\sqrt{S+B}$
- Remove $\Lambda \to p\pi$ decays based on $p\pi$ invariant mass hypothesis

Efficiency description

2D Efficiency is obtained from simulated samples using a two-step fit process

- For each angular variable: polynomial/sum of three Gaussians
- An additional correlation term: product of Legendre and ordinary polynomials

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



3D likelihood fit

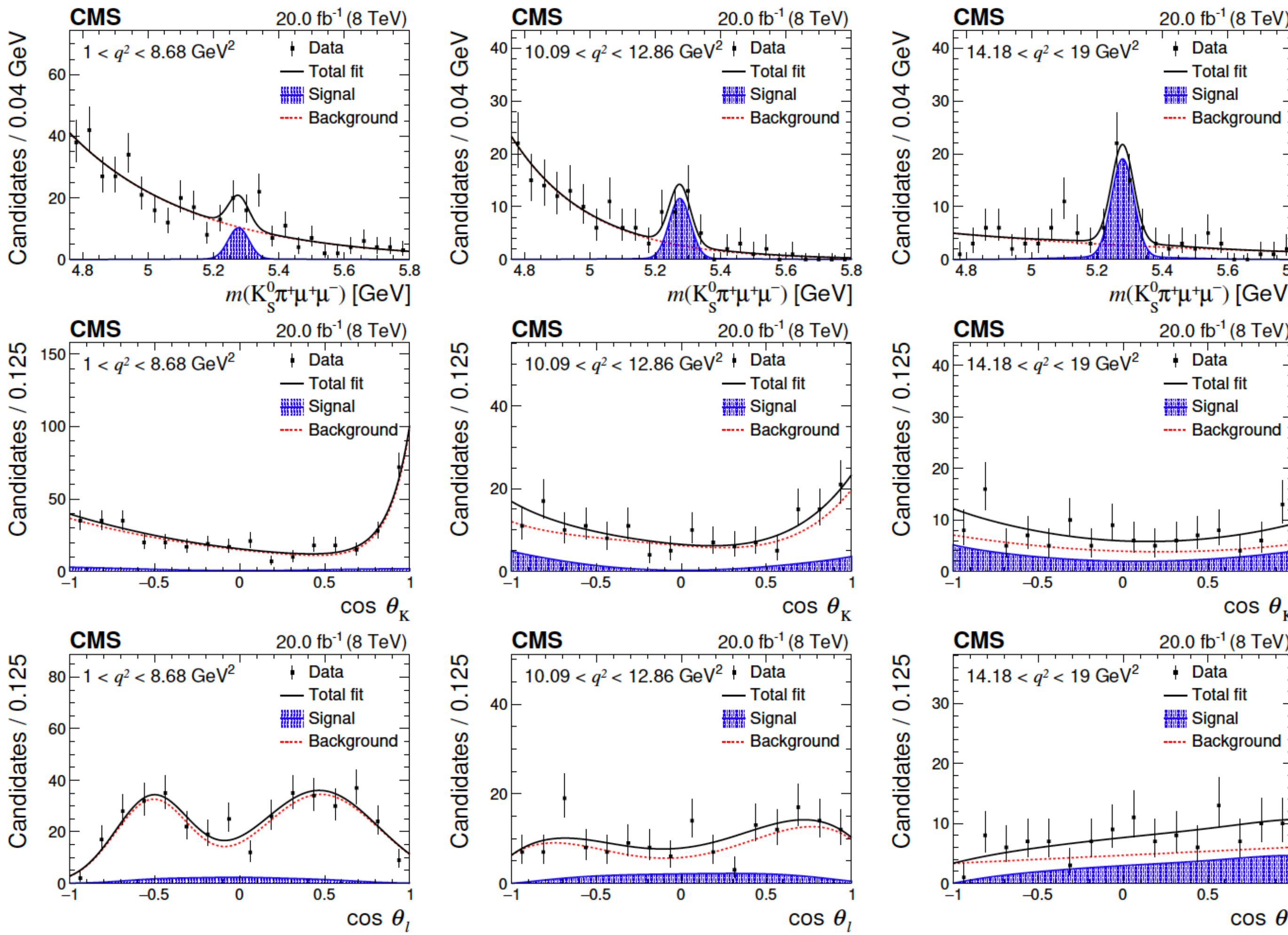
For each q2 Bin: 3D($m, cos\theta_K, cos\theta_l$) pdf :

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

- Unbinned extended maximum likelihood estimator used
- Y_S, Y_B: signal and background yields
- Signal component
  - $S^m(m)$: double Gaussian with parameters obtained from MC
  - $S^a(cos\theta_K, cos\theta_l)$: decay rate
  - $\epsilon(cos\theta_K, cos\theta_l)$: last slide
- Background component
  - $B^m(m)$: exponential
  - $B^{\theta_K}(cos\theta_K), B^{\theta_l}(cos\theta_l)$: analytical models from data sidebands
- Float parameters: 2 yields + angular parameters + bkg slope

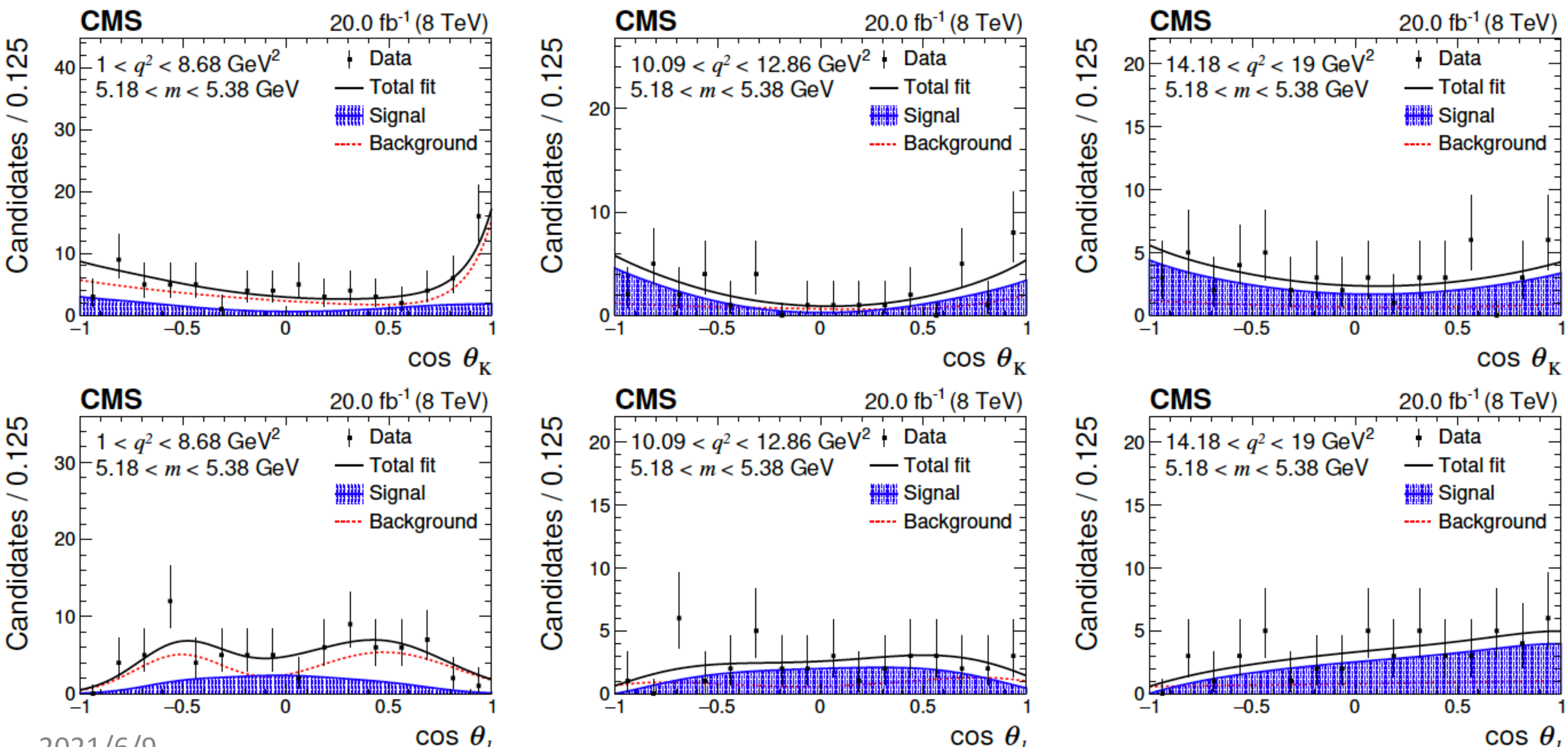
Fit projections to data

- Projections of each variables from 3D fit
- Bmass(m) fit range: [4.76, 5.8] GeV
- $cos\theta_K$, $cos\theta_l$ fit range: [-1,1]



Post-fit check

- Validation of angular PDFs ($cos\theta_K$, $cos\theta_l$) from final fit with signal region events → Bmass(m): 5.18-5.38 GeV
- Angular distributions for the events in the above Bmass region overlaid with final fit PDF
- Good consistency between data events and pdfs in the signal region



Systematic uncertainties

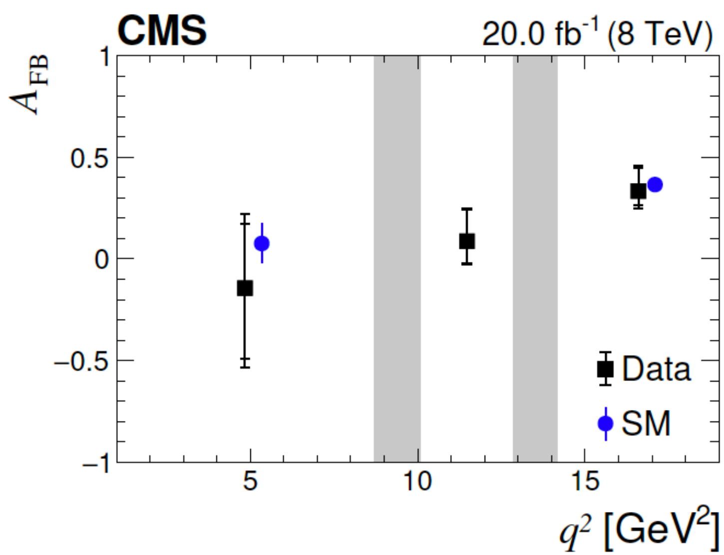
Source	A_{FB} (10^{-3})	F_{L} (10^{-3})
MC statistical uncertainty	12–29	18–38
Efficiency model	3–25	4–12
Background shape functional form	0–9	0–33
Background shape statistical uncertainty	16–73	20–87
Background shape sideband region	28–153	38–78
S-wave contamination	4–22	5–12
Total systematic uncertainty	42–174	55–127

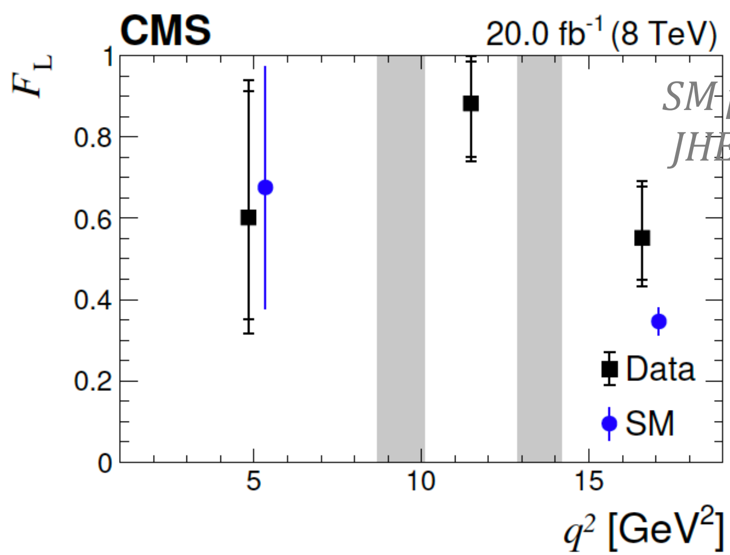
Dominate systematic uncertainty from background description and effect:

- Shape functional form
- Effect of alternate sideband region
- Sideband statistical uncertainty

Results

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	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$



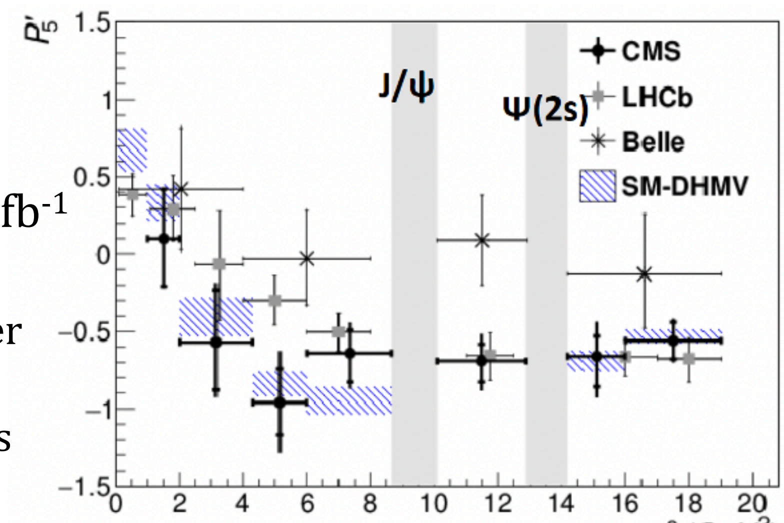


SM predictions from: JHEP 12(2014) 125

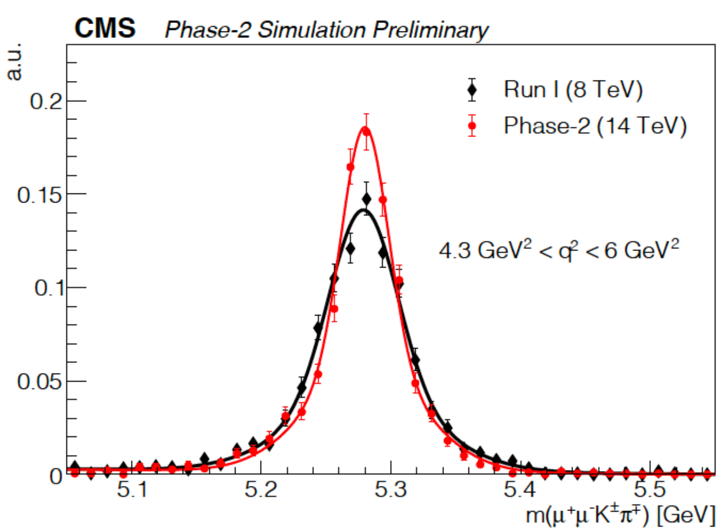
- Inner error bar: statistical uncertainty
- Total error bar: total uncertainty
- Consistent with SM predictions within uncertainties

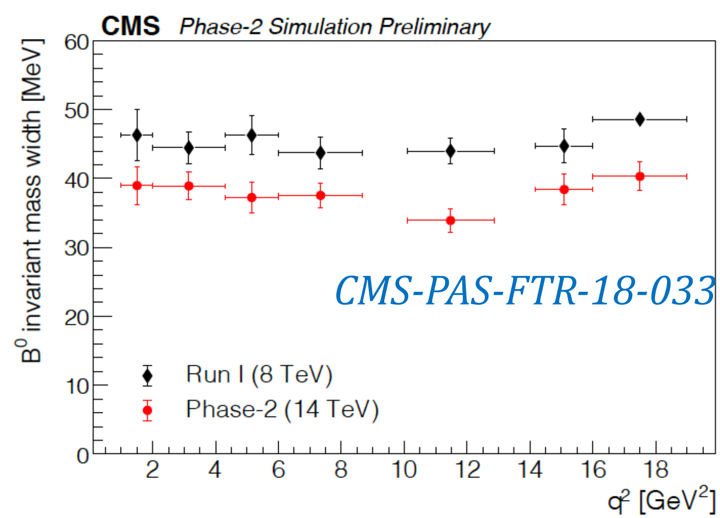
Prospect of $B^0 \to K^{*0}\mu\mu$ at HL-LHC

- Motivation: discrepancies in P_5' between experimental measurements with 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



PLB 781 (2018) 517-541

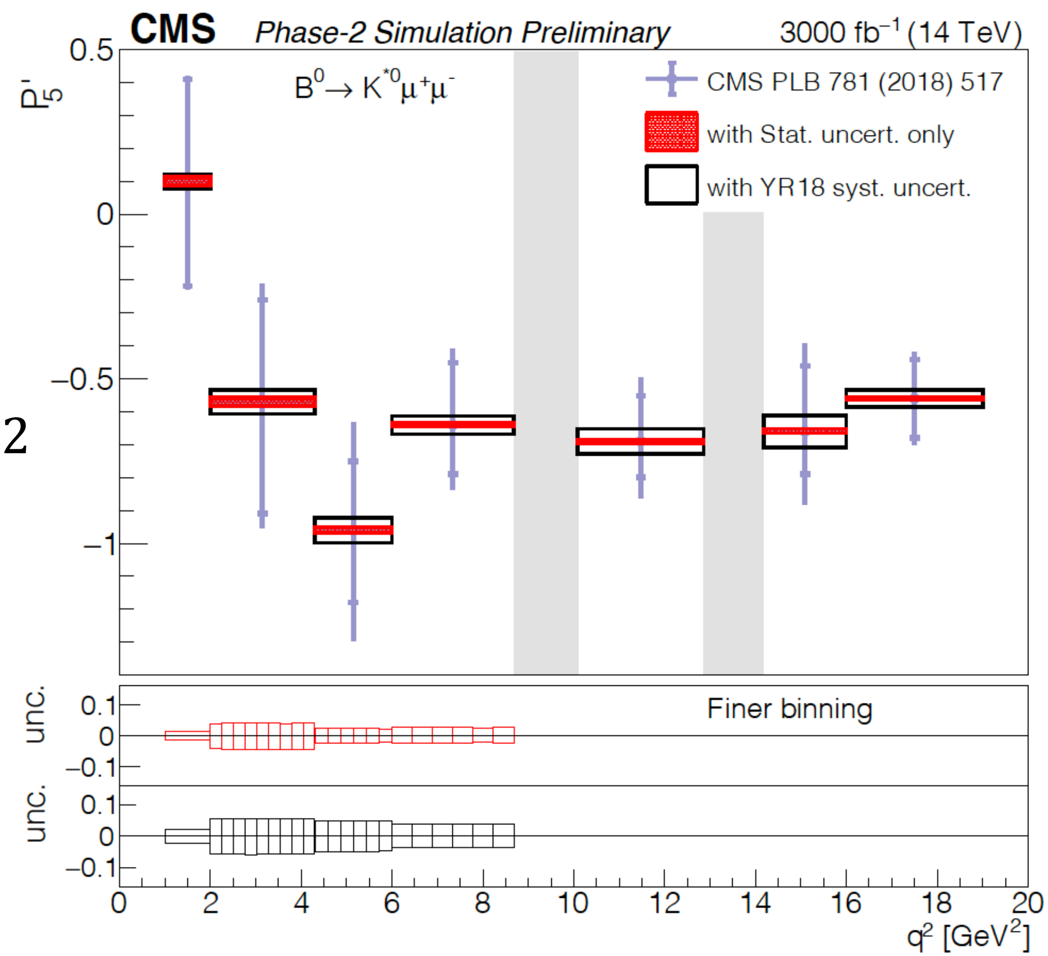




CMS-PAS-FTR-18-033

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

- FCNC B rare decays play an important role in search for New Physics

- Several angular analyses based on CMS Run 1 data
  - ✓ Results are compatible with Standard Model
  - ✓ Latest results on $B^+ \to K^{*+}\mu\mu$ angular analysis *JHEP 04 (2021) 124*

- Analyses based on CMS Run 2 data are underway: $B \to K^*\mu\mu$, $B^+ \to K^+\mu\mu$, $B_s \to \phi\mu\mu$ etc

- More sensitive results can be expected on HL-LHC

Thank you!