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New Physics Search With $b \to s l^{+} l^{-}$ Decays @CMS

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(on behalf of the CMS collaboration)

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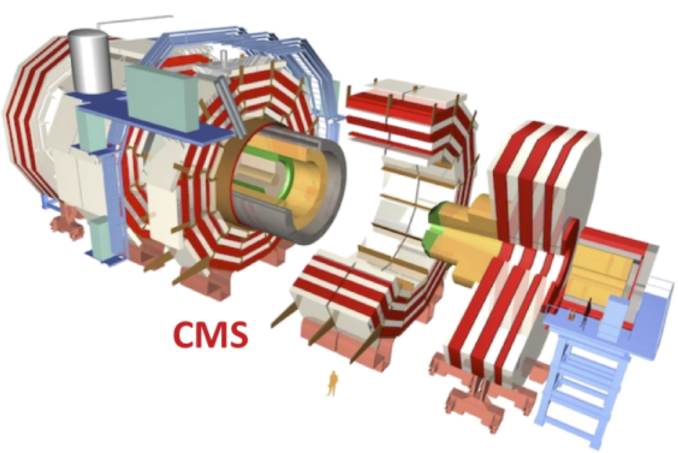
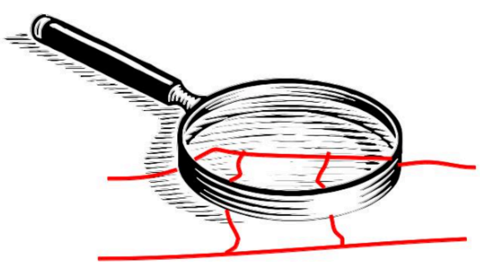
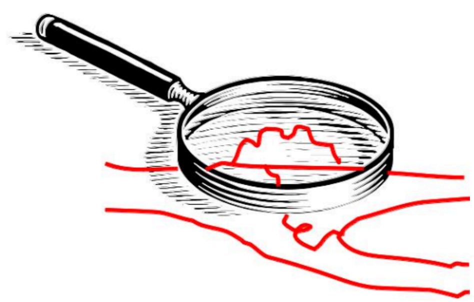


Introduction

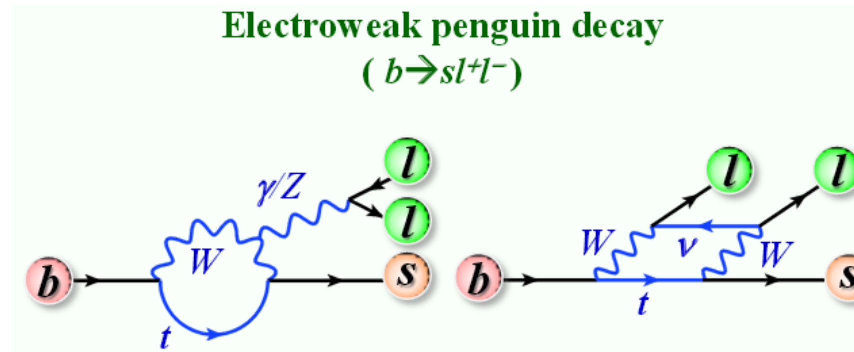
- One way to search for New Physics (NP) at the LHC is to directly produce heavier beyond Standard Model (BSM) particles.
- However, the complementary way to search for NP is through SM rare processes.
- This offers a way to search for NP by probing indirect effects of new interactions in higher order processes. Specifically, the loop induced couplings can test the detailed SM structure at the level of radiative corrections.
- Semi-leptonic decays of B-meson ($b \to s l^{+} l^{-}$) are a good place to determine decay constant, angular observables and search for NP effects.



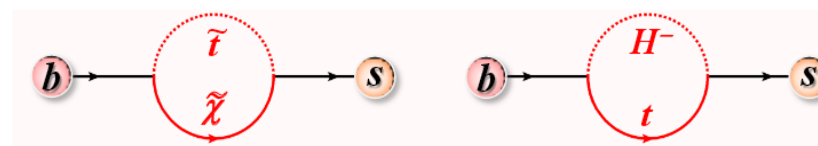


NP search in the decays of $B \rightarrow X_s \ell^+\ell^-$

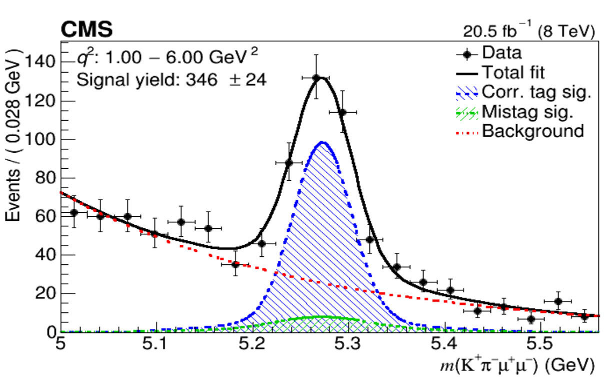
- Use decay modes such as, $B^0 \to K^{*0}\mu^+\mu^-$ $B^+ \to K^{(*)+}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and many more
- Forbidden at the tree level, but allowed via loop diagrams in SM
- Sensitive to NP through BSM particles in the loop

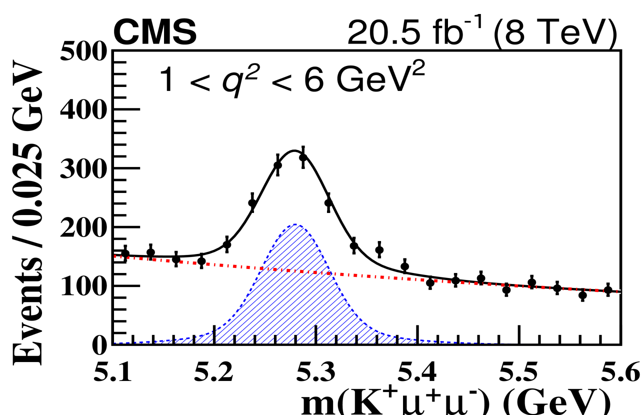


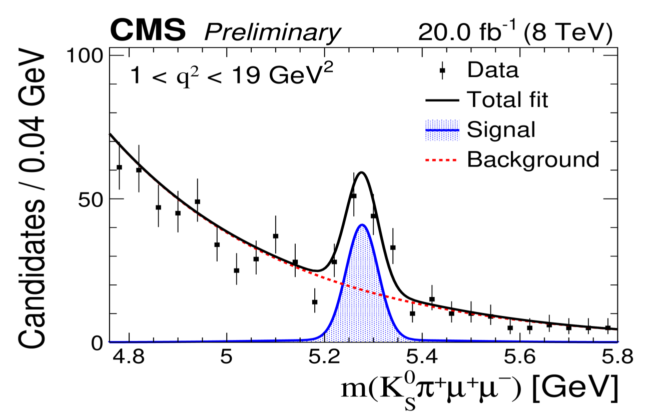
- Small branching fraction
- List of observables to compare with SM predictions (as function of square of dimuon mass): Branching fractions, differential BFs, ratio of BFs between different flavors, CP asymmetry, Isospin asymmetry, Forward-backward asymmetry of muons etc



- Signals from these kind of decays (below) already used to measure such observables





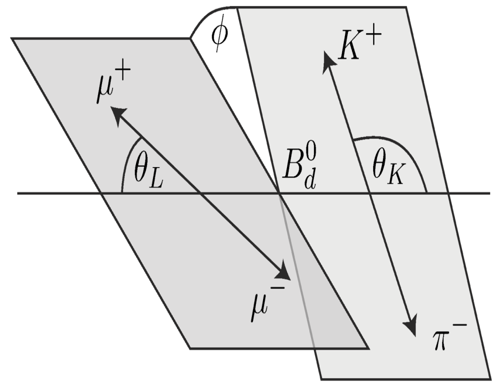


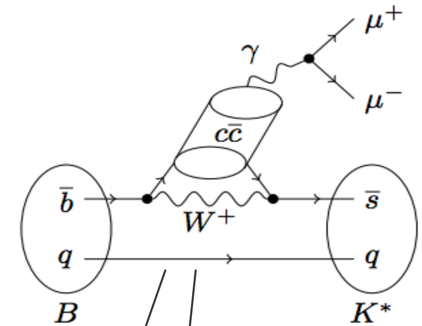
Decay rate for $B \to X_s \ell^+ \ell^-$ as function of angles

- The decay can be fully describe by angular variables (θ_K, θ_l and ϕ):

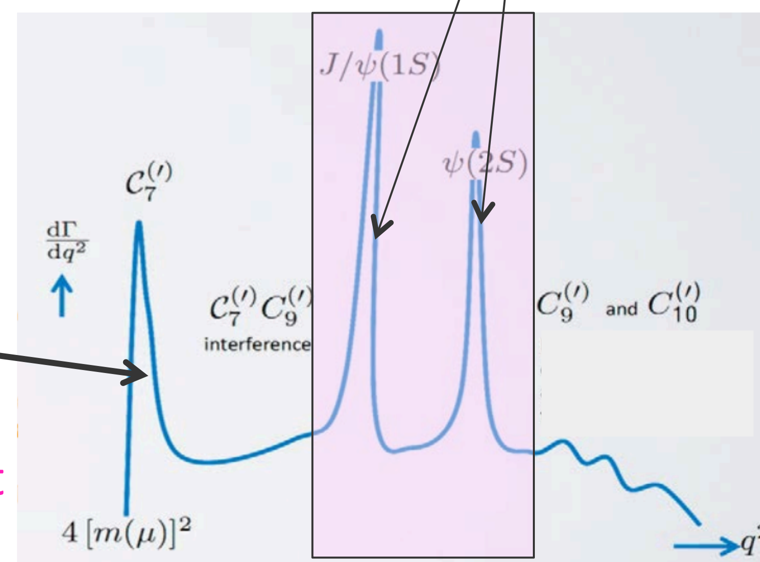
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}} =$$

$$\frac{9}{16\pi}\Big[F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) -$$
$$F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) +$$
$$\frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) +$$
$$S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} +$$
$$\frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell +$$
$$A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big] .$$



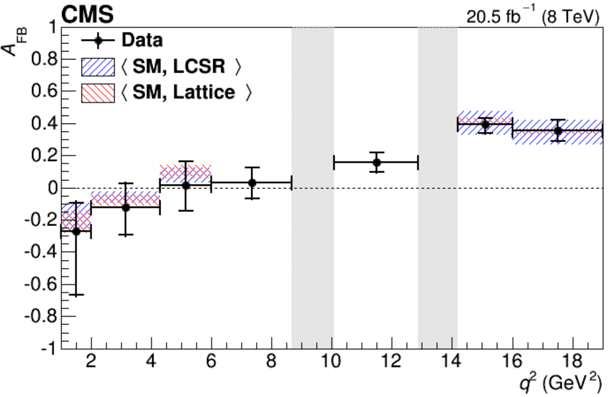


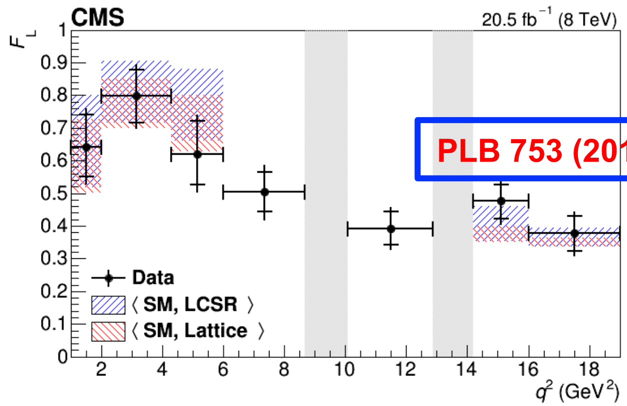
- Large-recoil region (low q^2):
  Dominant effect of Photon Pole
- Charmonium region:
  Dominated by long distance (hadronic) effect
- Low-recoil region (high q^2):
  Dominated by semi-leptonic operators



Results from B → $K^{(*0/+)}\mu^+\mu^-$ angular analysis

- $B^0 \to K^{*0}$ $(K\pi)\mu^+\mu^-$ fully described by three angles (θ_ℓ, θ_K and ϕ):





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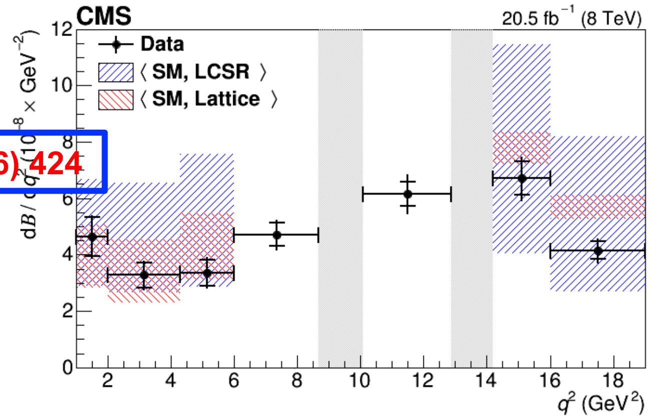
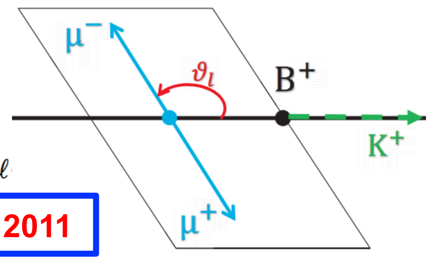


- $B^+ \to K^+\mu^+\mu^-$ described by:



$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell$$

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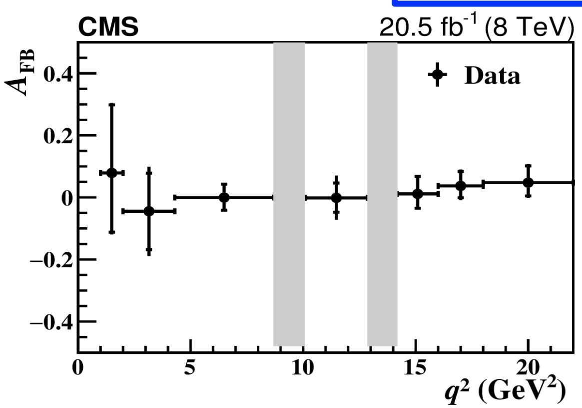

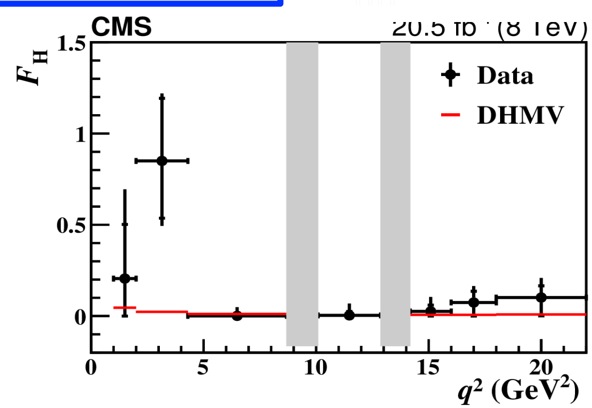

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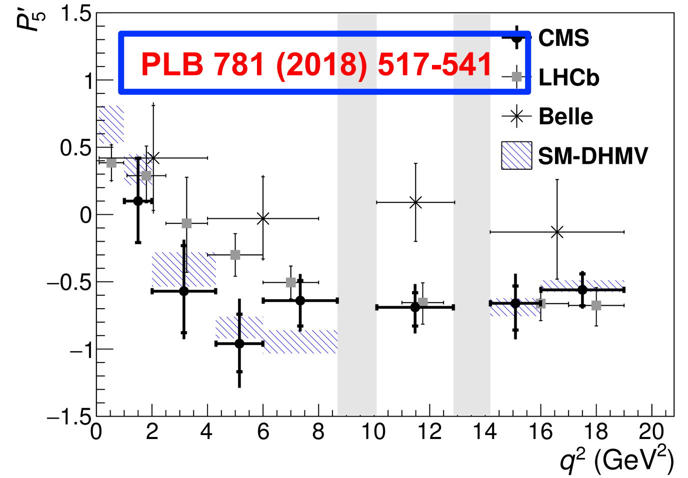
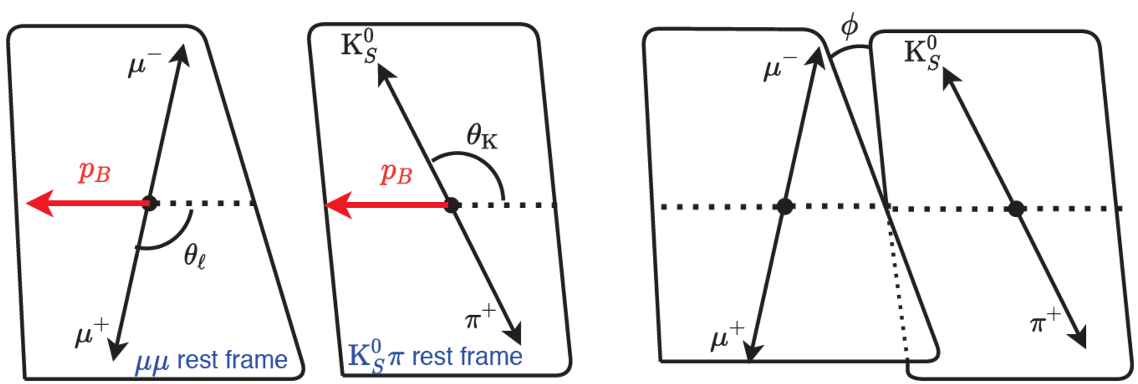


Angular analysis for decay: $B^+ \rightarrow K^{*+}\mu^+\mu^-$ (new)

- The final state decay products: $B^+ \to K^{*+}\mu^+\mu^-$ where $K^{*+} \to K^0_s\,\pi^+$
- Uses data collected with CMS detector at pp collision energy of 8TeV
- Integrated luminosity of about 20 fb^{-1}
- The decay is fully described by three angle: θ_K, θ_l and ϕ
- Integrating out ϕ, the decay rate is given by:

CMS-PAS-BPH-15-009

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



- The aim is to measure the longitudinal polarization of K^{*+} (F_L) meson and the forward-backward asymmetry of muons (A_{FB})
- To be measured for different ranges of square of dimuon mass ($q^2 = m_{\mu\mu}^2$)

PDF used in the 3-dimensional angular fit

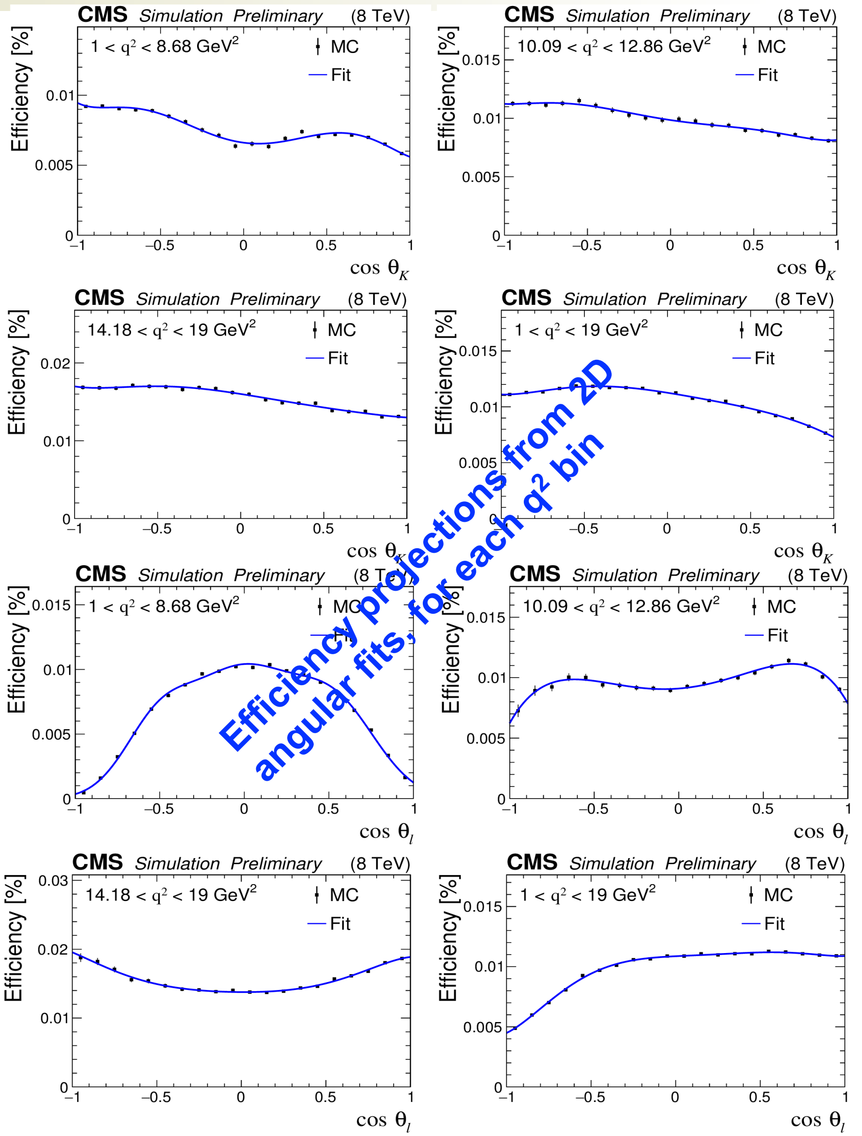
- The observables (A_{FB} and F_L) are obtained by the fit to the data in three dimensions [$K^{*+}\mu^+\mu^-$ invariant mass(m), $\cos\theta_K$, $\cos\theta_l$]
- The total PDF is of the form

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

- Y_S, Y_B => signal and background yields
- S^m => signal mass shape
- S^a => signal shape in ($\cos\theta_K$, $\cos\theta_l$)
- ε => efficiency in two angular space

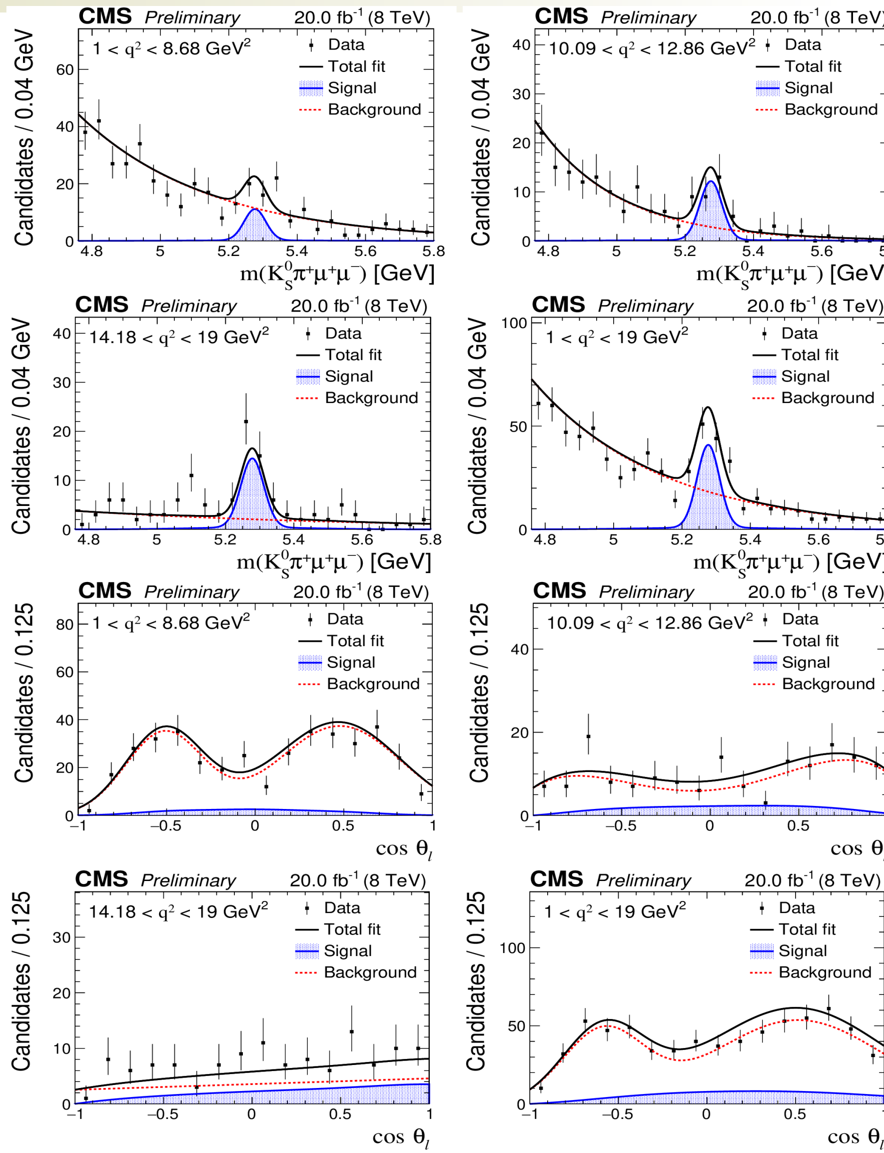
$$\varepsilon_{1D}(\cos\theta_K)\cdot\varepsilon_{1D}(\cos\theta_l)\cdot[1 + \mathcal{C}(\cos\theta_K, \cos\theta_l)]$$

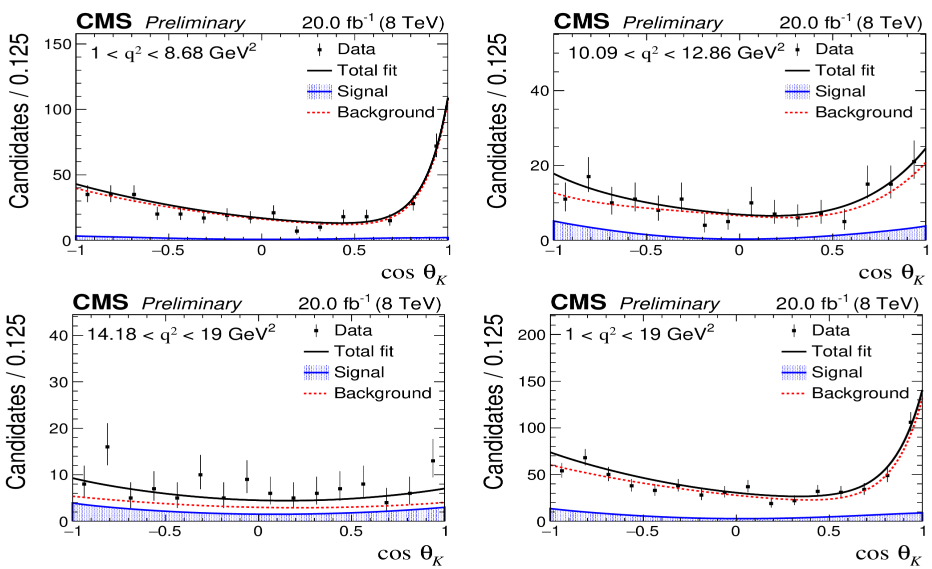
- B^m => background mass shape (exponential function)
- B ($\cos\theta_K$), B($\cos\theta_l$) => background shapes in corresponding angular spaces (analytic functions from sideband data)



Fit projections from the angular fit to the data

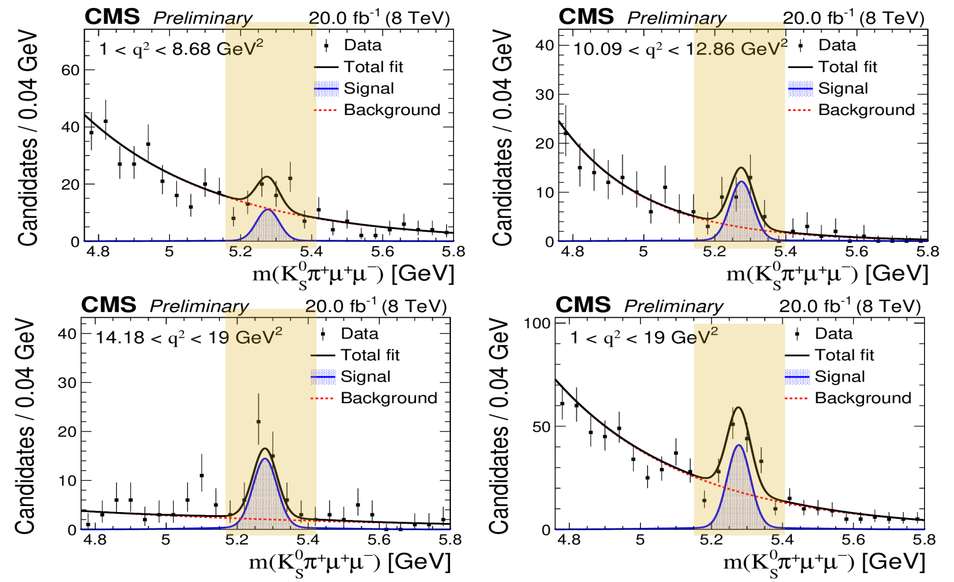
- Projections of each variables from three dimensional un-binned maximum likelihood fit
- Done in four q2 ranges: 1 - 8.68 GeV^2, 10.09 - 12.86 GeV^2, 14.18 - 19 GeV^2 and the combined three q^2 ranges.
- Bmass (m) fit range:[4.76, 5.8]GeV
- $\cos\theta_K$, $\cos\theta_l$: [-1.0, +1.0]

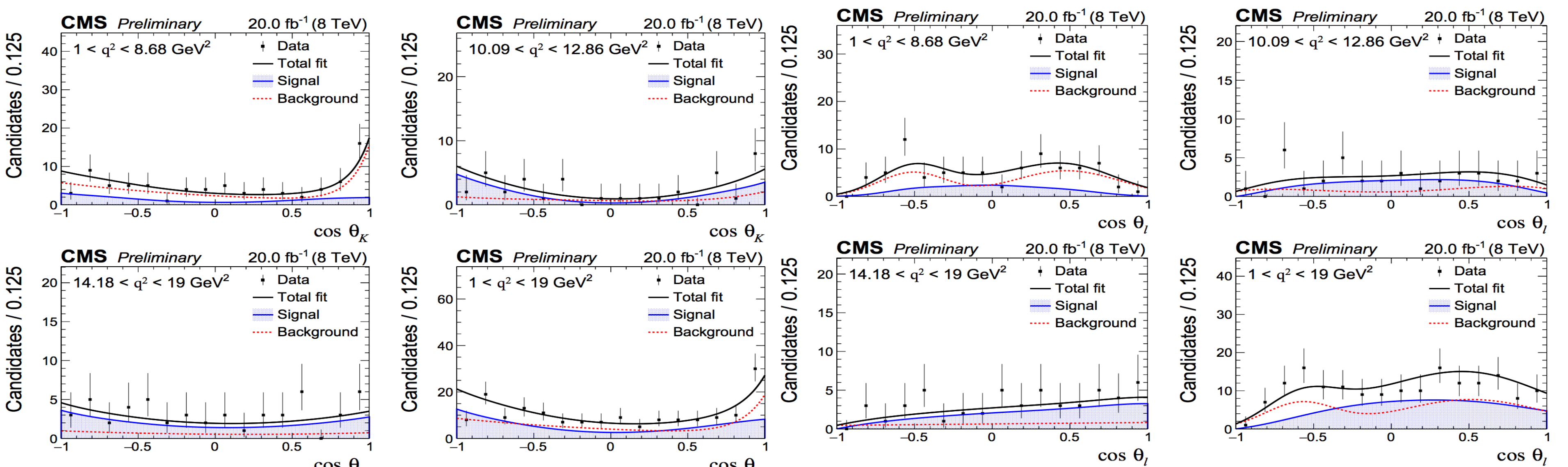




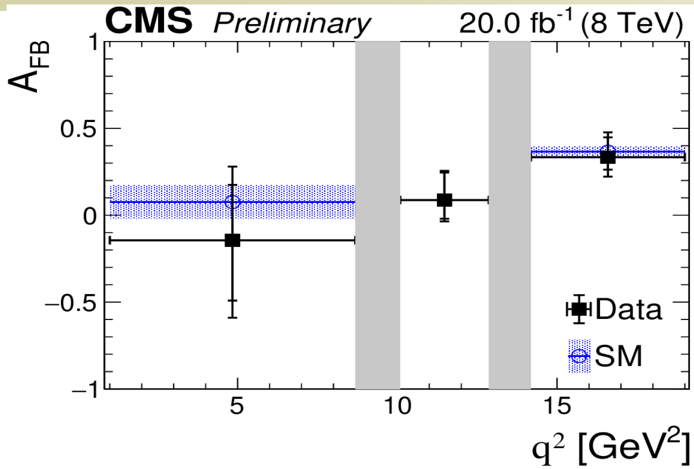
Fit validation in the signal region

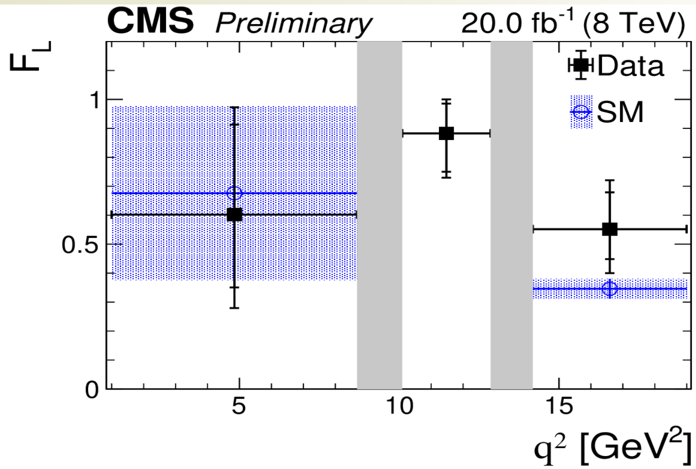
- Validation of angular PDFs ($\cos\theta_K$, $\cos\theta_l$) from final fit with signal region events.
  => Bmass (m) : 5.18-5.38GeV
- The angular distributions for the events in the above Bmass range are overlaid with our final fit PDF.
- Good description of the signal and background angular PDFs in signal region





Final results and systematic uncertainty





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 syst. uncertainty is from background description and effect:
(1) Background functional form
(2) Effect of alternate sideband definition
(3) Sideband statistics uncertainty

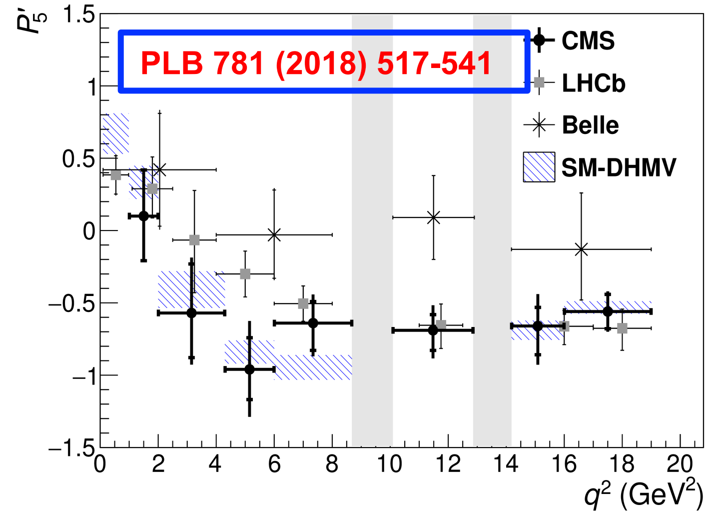
q^2 (GeV^2)	Signal yield	A_{FB}	F_L
1.00 – 8.68	22.1 ± 8.1	$-0.14^{+0.32}_{-0.35} \pm 0.17$	$0.60^{+0.31}_{-0.25} \pm 0.13$
10.09 – 12.86	25.9 ± 6.3	$0.09^{+0.16}_{-0.11} \pm 0.04$	$0.88^{+0.10}_{-0.13} \pm 0.05$
14.18 – 19.00	45.1 ± 8.0	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$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

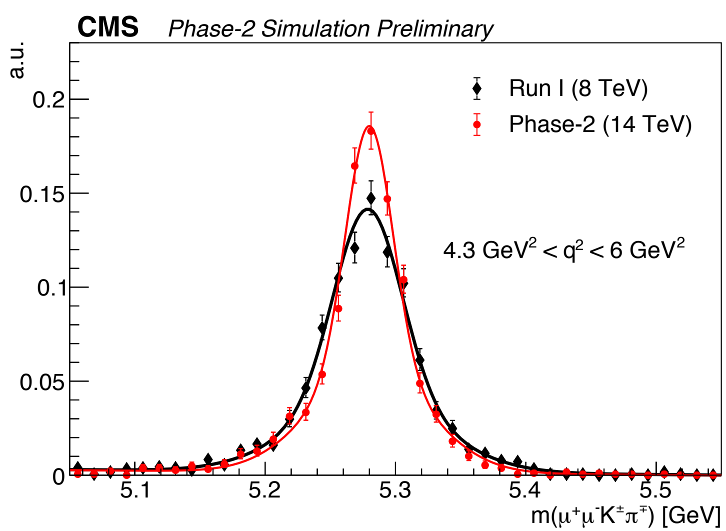
SM prediction uses the method described in: JHEP 12(2014) 125

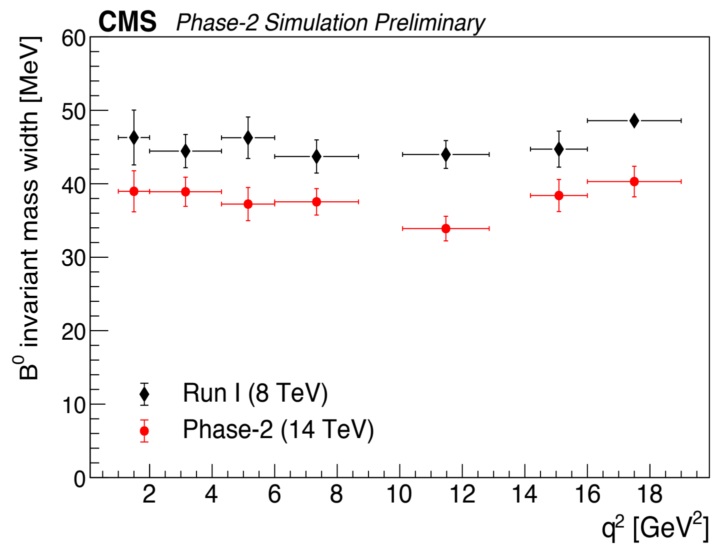
CMS results consistent with SM.

Feasibility study of $B \rightarrow K^{*0}\mu^+\mu^-$ with HL-LHC

- Recap: There were discrepancies in P_5' between SM prediction and the experimental measurements.
- CMS performed the feasibility study of this parameter with HL-LHC statistics, ~3000 fb^{-1}
- Run-1 (collected with 8TeV) was used as baseline
- Improved mass resolution with upgrade detector
- 200 Pileup scenario was considered.
- No change in trigger threshold or efficiency
- Expected signal ~ 700k in full q^2 bin







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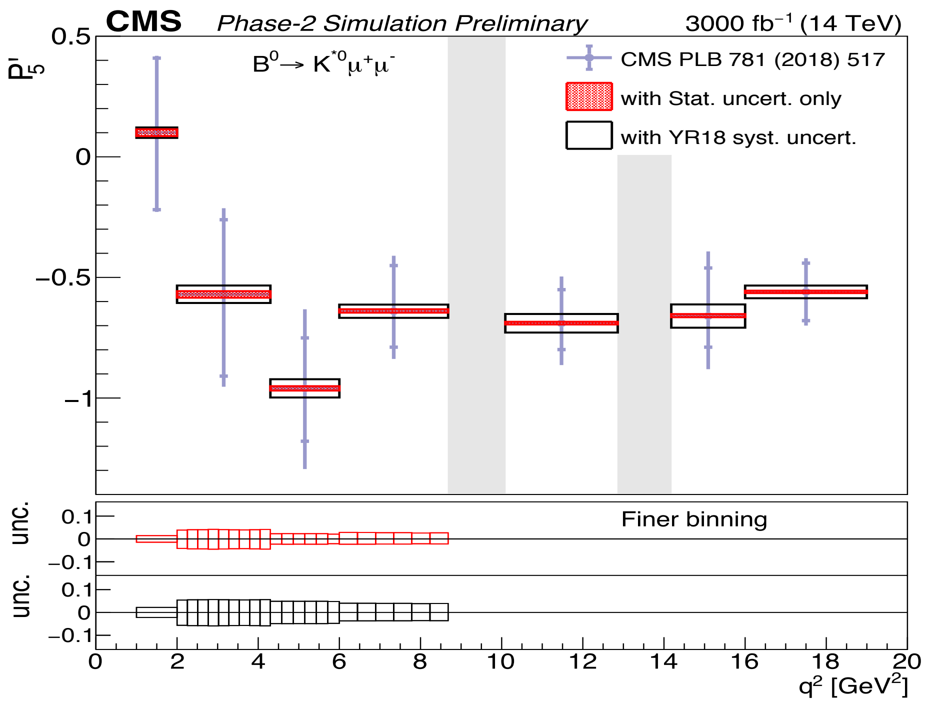
Extrapolated result for $B \rightarrow K^{*0}\mu^+\mu^-$



q^2 bin (GeV^2)	Run I	Phase-2
$1.00 < q^2 < 2.00$	$\sigma_{stat} = ^{+0.32}_{-0.31}$ $\sigma_{syst} = \pm 0.07$	$\sigma_{stat} = \pm 0.014$ $\sigma_{syst} = \pm 0.017$
$2.00 < q^2 < 4.30$	$\sigma_{stat} = ^{+0.34}_{-0.31}$ $\sigma_{syst} = \pm 0.18$	$\sigma_{stat} = ^{+0.014}_{-0.013}$ $\sigma_{syst} = \pm 0.034$
$4.30 < q^2 < 6.00$	$\sigma_{stat} = ^{+0.22}_{-0.21}$ $\sigma_{syst} = \pm 0.25$	$\sigma_{stat} = \pm 0.009$ $\sigma_{syst} = \pm 0.037$
$6.00 < q^2 < 8.68$	$\sigma_{stat} = ^{+0.15}_{-0.19}$ $\sigma_{syst} = \pm 0.13$	$\sigma_{stat} = ^{+0.006}_{-0.008}$ $\sigma_{syst} = \pm 0.026$
$10.09 < q^2 < 12.86$	$\sigma_{stat} = ^{+0.11}_{-0.14}$ $\sigma_{syst} = \pm 0.13$	$\sigma_{stat} = ^{+0.005}_{-0.006}$ $\sigma_{syst} = \pm 0.038$
$14.18 < q^2 < 16.00$	$\sigma_{stat} = ^{+0.13}_{-0.20}$ $\sigma_{syst} = \pm 0.18$	$\sigma_{stat} = ^{+0.005}_{-0.008}$ $\sigma_{syst} = \pm 0.048$
$16.00 < q^2 < 19.00$	$\sigma_{stat} = \pm 0.12$ $\sigma_{syst} = \pm 0.07$	$\sigma_{stat} = \pm 0.005$ $\sigma_{syst} = \pm 0.026$

- Statistical uncertainty scaled as per increase in yield with HL-LHC condition.
- Syst. errors decreased by factor of 2 (except the one depend on control sample)
- Total error will be reduced by factor of 15

Summary

- Semi-leptonic rare quark decays play an important role in search for New Physics.
- So far there is no conclusive hint for New Physics. However few observables, such as P_5' , lepton universality, showed some deviation from SM.
- Need more work from theory as well as experimental side.
- Many more new results using full Run-II data from CMS to come out soon:

  -> $B \to K^{(*)}\mu^+\mu^-$, $\phi\mu^+\mu^-$ etc.
- Lets hope we see some hints new physics in near future.