CP violation and P_5' and Kmumu angular analysis

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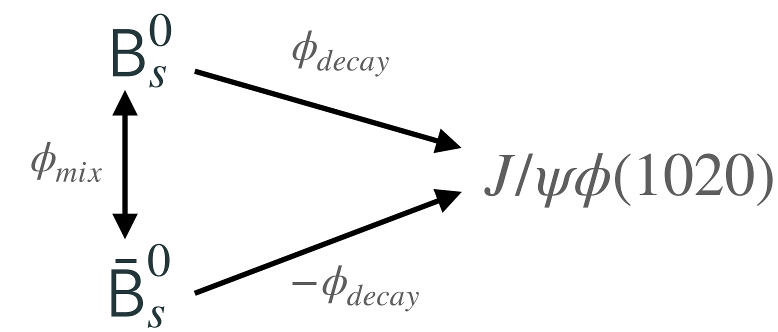
NISER

CMS

CP violation in B_s^0 decays

- CP-violating phase ϕ_s arises from the **interference** between direct B_s^0 decays to a CP final state and decays through B_s^0-$\bar{B}_s^0$ mixing



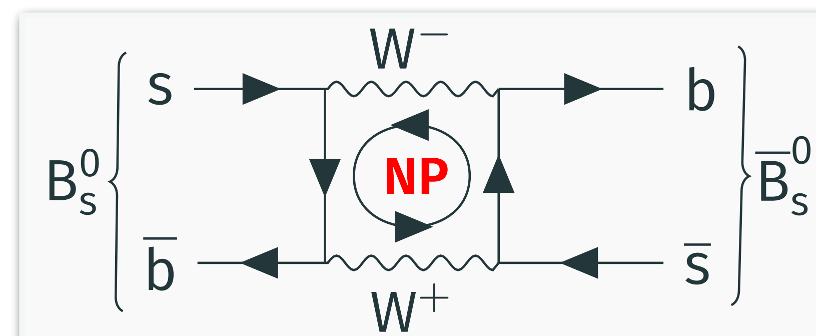
$$\phi_s = \phi_{mix} - 2\phi_{decay}$$

SM prediction:

$$\phi_s \simeq -2\beta_s = -2arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.96^{+0.72}_{-0.84} \text{ mrad}$$

NP prediction:

New elusive particle contributing to the mixing can modify the phase by ~100%. (DOI)



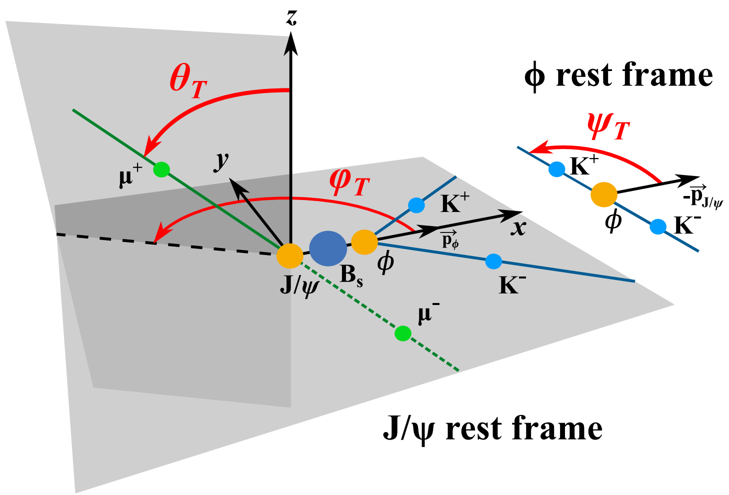
- $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ is a golden channel to measure the phase.

Experimental results

- ϕ_s was first measured by the Tevatron experiments D0 [PRD 85(2012) 032006] and CDF [PRL 109 (2012) 171802]
- Previous result at 8 TeV by CMS [PLB 757 (2016), 424] and ATLAS [JHEP 08 (2016) 147]
- LHCb also measured ϕ_s in other final states: $J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$, $\psi(2S)\phi(1020)$, $D_s^+D_s^-$ [PLB 762 (2016) 253, PRL 113 (2014) 211801]
- Precise measurement of the CP-violating phase ϕ_s by LHCb experiment (CERN seminar) (NEW)

Analysis strategy

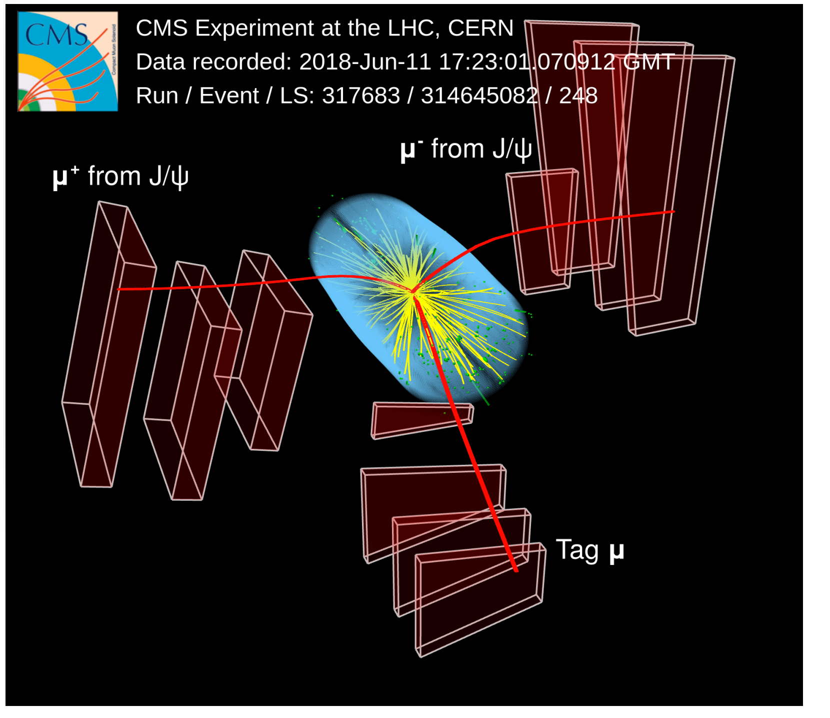
- Decay of B_s^0 meson into a final state $J/\psi\phi(1020)$, which is a mixture of two CP eigenstates (odd/even).
  - Need to disentangle the two states using an angular analysis
  - Time dependent analysis, the proper decay time of B_s^0 is reconstructed
- An unbinned maximum-likelihood fit is performed on the combined data samples extracting parameters of interest:
  - Amplitudes and strong phases: A_0, $A_\perp$, $A_{||}$, A_s, δ_0, $\delta_\perp$, $\delta_{||}$, δ_s, $\delta_{S\perp} = \delta_S - \delta_\perp$
  - CPV parameters: ϕ_s, $|\lambda|$
  - Mixing parameters: $\Delta\Gamma_s$, Δm_s
  - B_s^0 properties: Γ_s, $\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}$



- Observables used in the fit are,
  - m, ct (B_s^0 proper decay time), angular observable ($\psi_T, \varphi_T, \theta_T$)
  - Per-candidate quantities: resolutions**, flavor tagging** probability

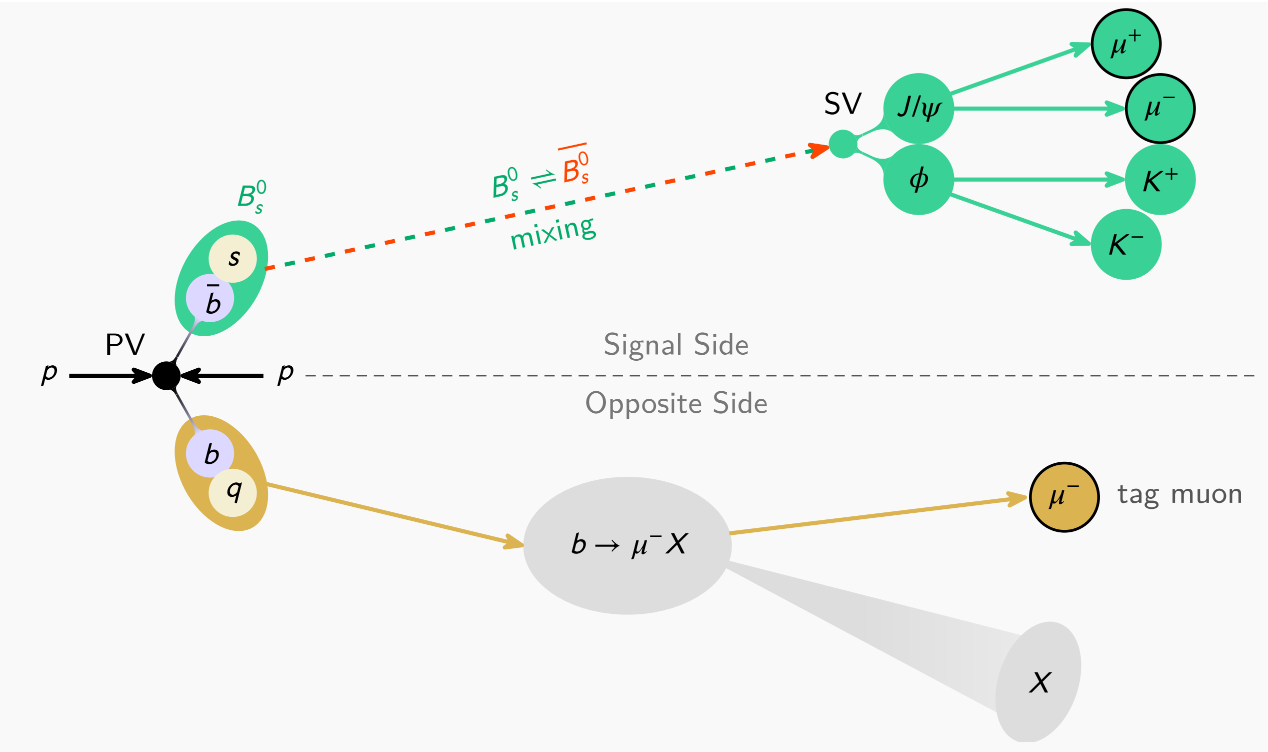
Event selection

- $B_s^0 \to J/\psi\phi(1020)$ is a good channel to measure the ϕ_s phase
  - easy to reconstruct with high S/B ratio
  - easy to trigger
  - SM predicts no direct CPV
- Trigger: non-displaced $J/\psi \to \mu^+\mu^-$ candidate plus additional muon used to tag the B_s^0 flavour
  - allows for improved tagging efficiency at the cost of reduced number of signal events
- Offline selections
  - J/ψ reconstructed from $\mu^+\mu^-$ with $p_T > 3.5$ GeV and $\eta < 2.4$, good common vertex.
  - ϕ formed from pairs of OS tracks with invariant mass compatible with $\phi(1020)$ meson mass (kaon mass assumed for both tracks)
  - B_s^0 from combination of $\boldsymbol{J/\psi}$ and $\phi(1020)$ candidates with refitted 2μ + 2tracks common vertex
    - $p_T(B_s^0)$: > 11 GeV
    - $ct(B_s^0)$: ≥ 70 μm
    - $m(\mu^+\mu^-K^+K^-) \in [5.24, 5.49]$ GeV



Flavour tagging

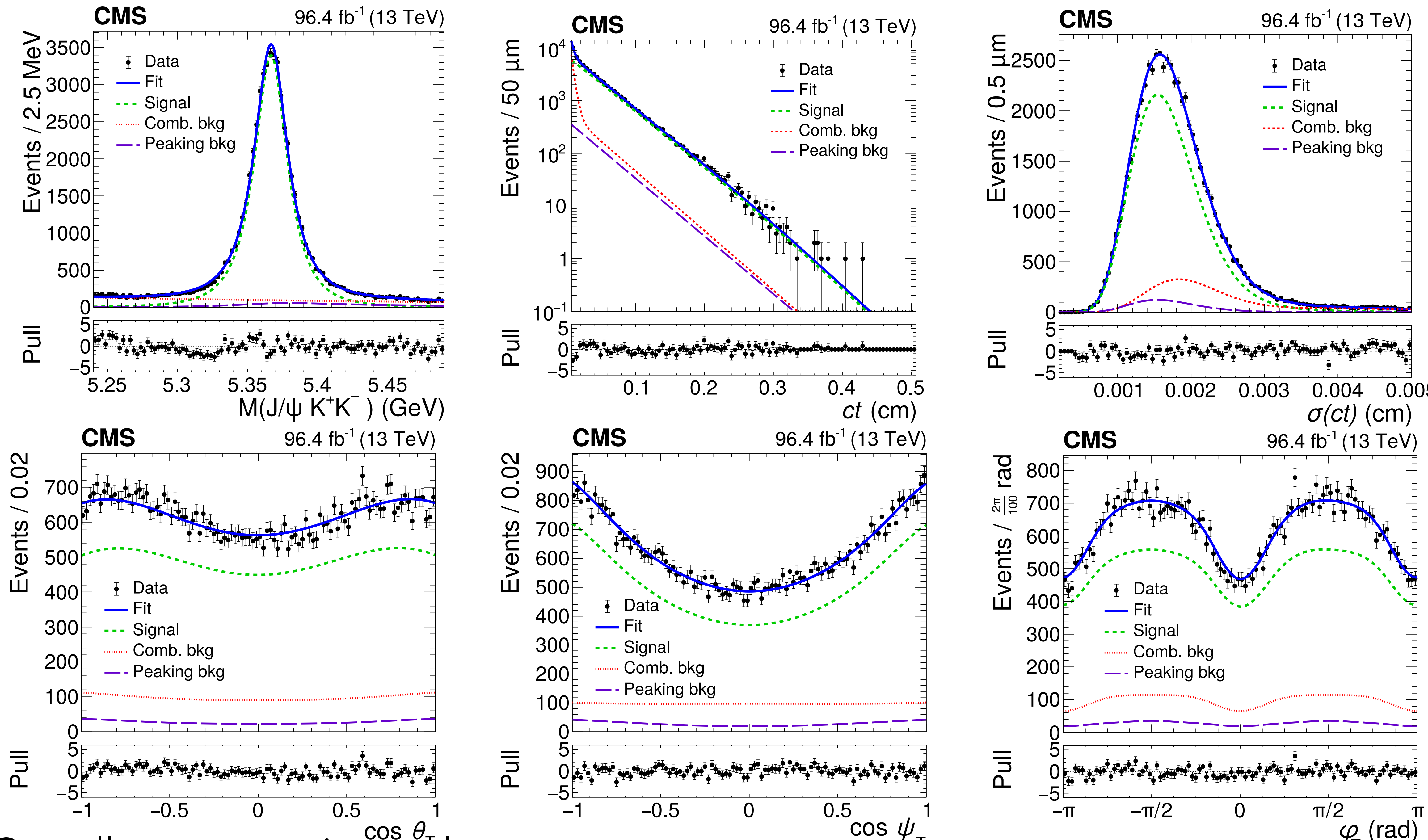
- Tagger: Opposite-side (OS) muon → To identify the flavour of B_s^0 and $\bar{B}_s^0$
  - Exploits the semileptonic b → $\mu + X$, tagger feature: μ charge
  - Sources of dilution: cascade decays, pile-up, gluon splitting, mixing
  - DNN is trained on $B_s^0 \rightarrow J/\psi\phi$ MC
    - Mis-tag probability and tagging power are evaluated on per-event basis
    - Calibrated in data using $B^+ \rightarrow J/\psi K^+$
- Tagging efficiency ≈ 50% both in 2017 and 2018 data



Data sample	ε_{tag} (%)	ω_{tag} (%)	P_{tag} (%)
2017	45.7 ± 0.1	27.1 ± 0.1	9.6 ± 0.1
2018	50.9 ± 0.1	27.3 ± 0.1	10.5 ± 0.1

Fit projections

- Unbinned maximum likelihood fit is performed to extract the parameter of interests.
- Likelihood function: components describing the sig. and bkg contributions (combinatorial and peaking bkg, dominated by $B^0 \to J/\psi K^{*0}(982)$)



- Overall agreement is good.

$B_s^0 \to J/\psi\phi$: Results

- Simultaneous fit on 2017 and 2018 datasets
- ϕ_s and $\Delta\Gamma_s$ are in agreement with the SM expectations
- |λ| compatible with no direct CPV

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0045
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

- Dominant systematic uncertainties on the ϕ_s and $\Delta\Gamma_s$
  - Fit bias
  - Proper decay length resolution
  - Angular efficiency
  - Sig./bkg. ω_{tag} difference

$B_s^0 \to J/\psi\phi$: Results

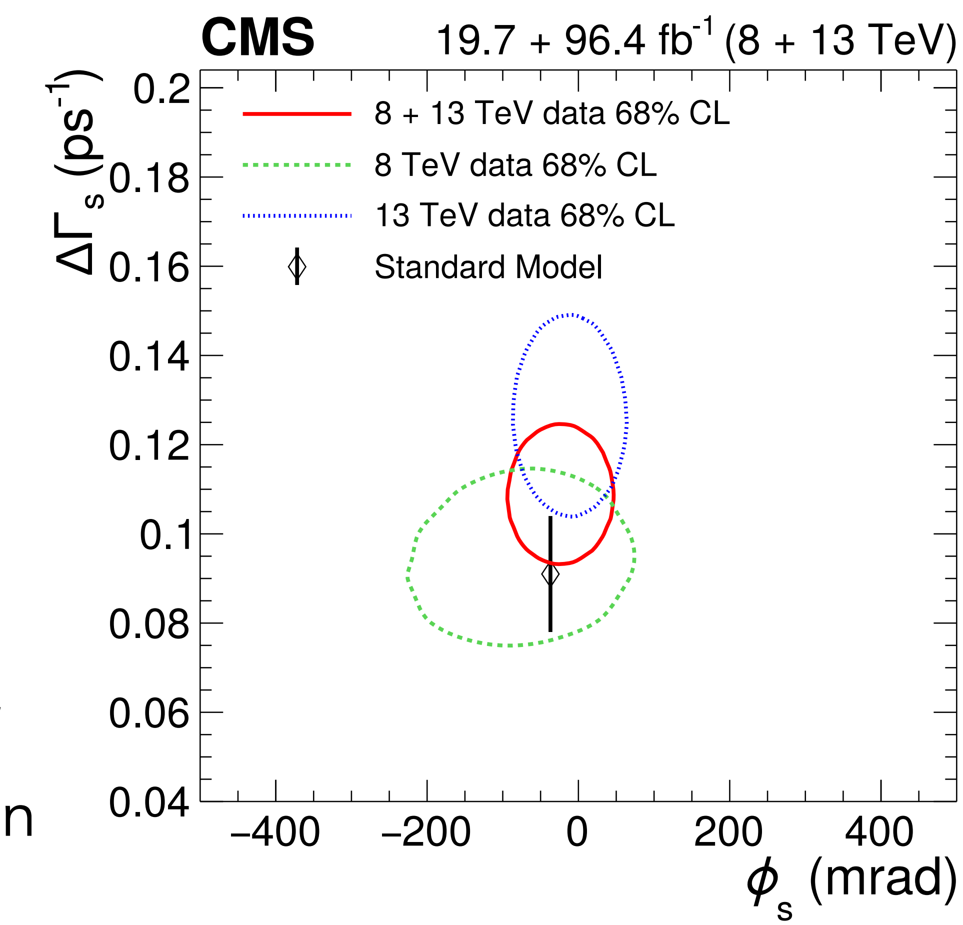
8 TeV+13 TeV combination

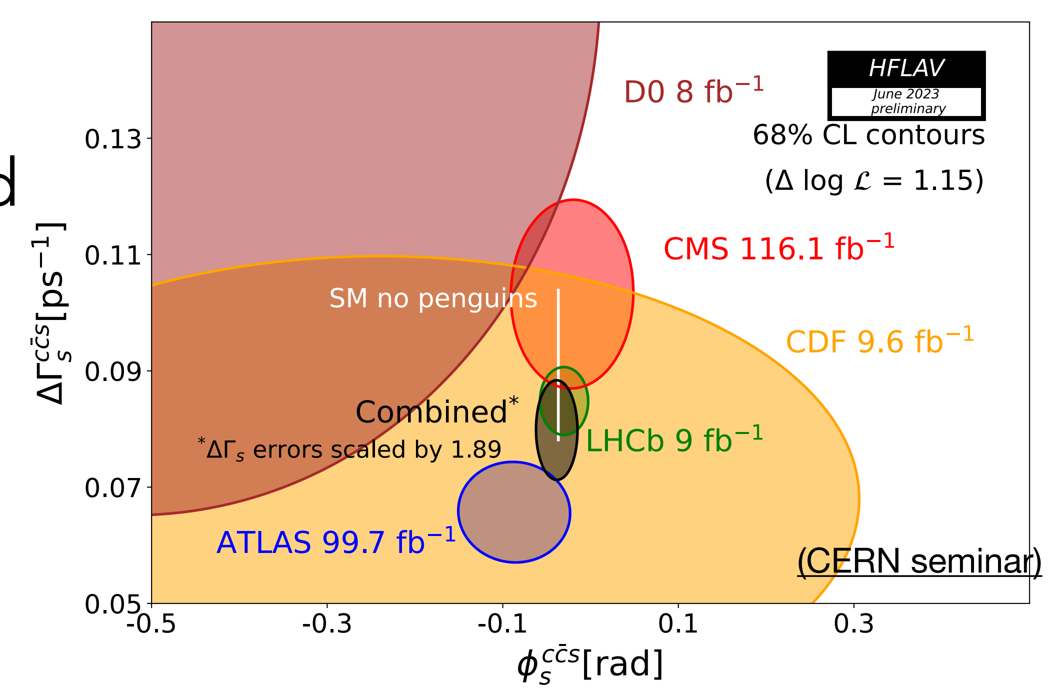
- Uses Run 1(19.7 fb^{-1})+ partial Run 2(96.4 fb^{-1}) data

$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad},$$
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\,\text{ps}^{-1},$$

- Significantly more precise than CMS Run 1 results using 8 TeV data [PLB 757 (2016) 97] because of more statistics and better tagging strategy in Run 2 data analysis.

- Results are consistent with SM predictions and no CPV in the interference between mixing and decay.

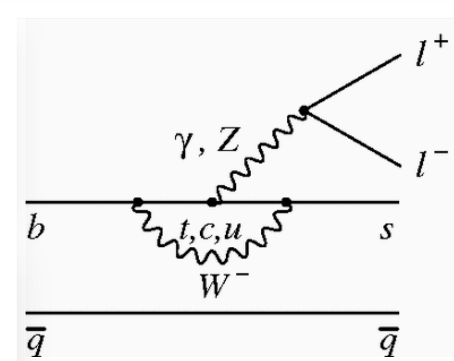


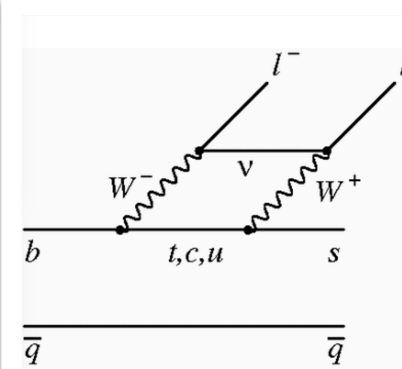


$P_5^{'}$ and Kmumu angular analysis

- In this talk, following analysis will be covered.
  - Measurement of angular parameters from the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ in proton–proton collisions at $\sqrt{s} = 8$ TeV. [Phys Lett B 781 (2018) 517-541]
  - Angular analysis of the decay $B^+ \rightarrow K^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV. [Phys Rev D 98 (2018) 112011]
  - Angular analysis of the decay $B^+ \rightarrow K^{*+}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV. [JHEP 04 (2021) 124]

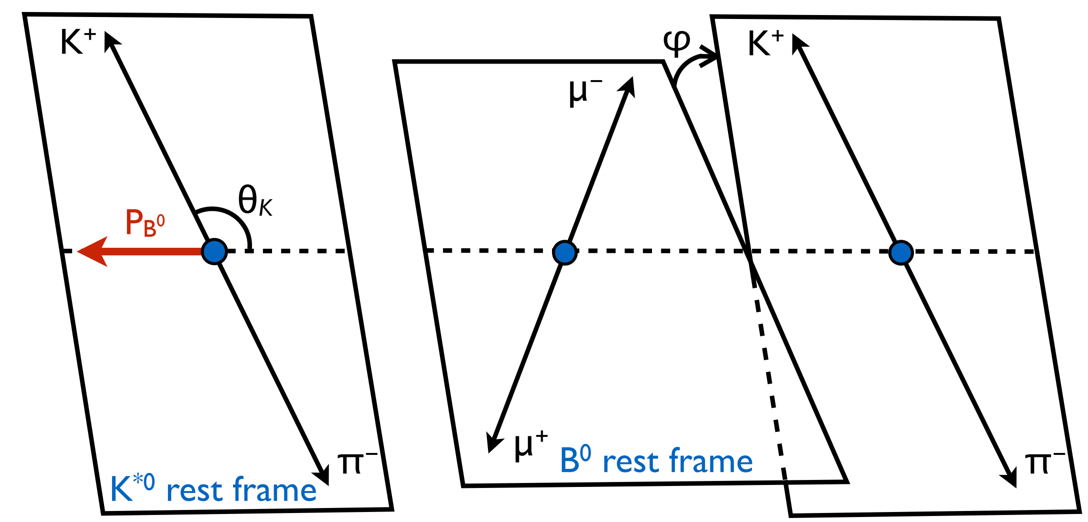
  - $b \rightarrow sll$ decays are Flavour changing neutral current process
    - Forbidden in Standard Model at tree level
    - Proceed through higher order diagrams (penguin, box)
      - Sensitive to New Physics effect



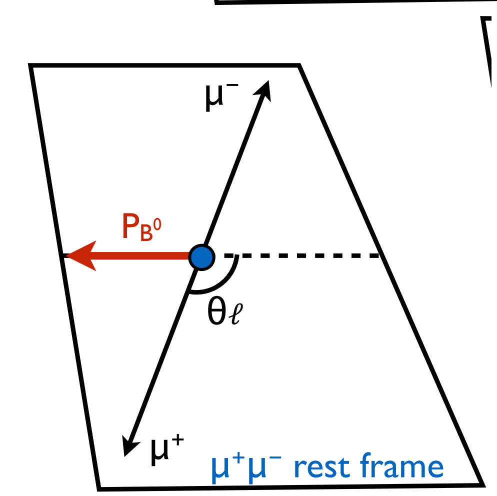


$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- Differential decay rate fully described by three angles ($\theta_l, \theta_K, \varphi$) and q^2($=m^2_{\mu\mu}$)
- In total 14 parameters, fold around $\varphi = 0$ and $\theta_l = \pi/2$ to reduce them to six



$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\mathrm{K}\,\mathrm{d}\varphi} = \frac{9}{8\pi}\Bigg\{ \frac{2}{3}\Big[& (F_\mathrm{S} + A_\mathrm{S}\cos\theta_\mathrm{K})\left(1-\cos^2\theta_\ell\right) \\
& + A_\mathrm{S}^5\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_\ell}\cos\varphi \Big] \\
+ (1-F_\mathrm{S})\Big[& 2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_\ell\right) \\
& + \frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_\ell\right) \\
& + \frac{1}{2}P_1(1-F_\mathrm{L})(1-\cos^2\theta_\mathrm{K})(1-\cos^2\theta_\ell)\cos 2\varphi \\
& + 2P_5'\cos\theta_\mathrm{K}\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_\ell}\cos\varphi \Big]\Bigg\}
\end{aligned}
$$



- Since the expected signal events are small, floating all parameters will lead to non convergence of fit.
- F_L, F_S, and A_S are fixed from previous CMS measurement.
- P_1 and P_5' are measured, A_S^5 used as nuisance parameter.
- q^2 separated in 9 bins
  - 7 signal bins, angular fit performed independently
  - 2 resonant bins ($B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$)

Fit pdf description

- PDF to describe the data distribution

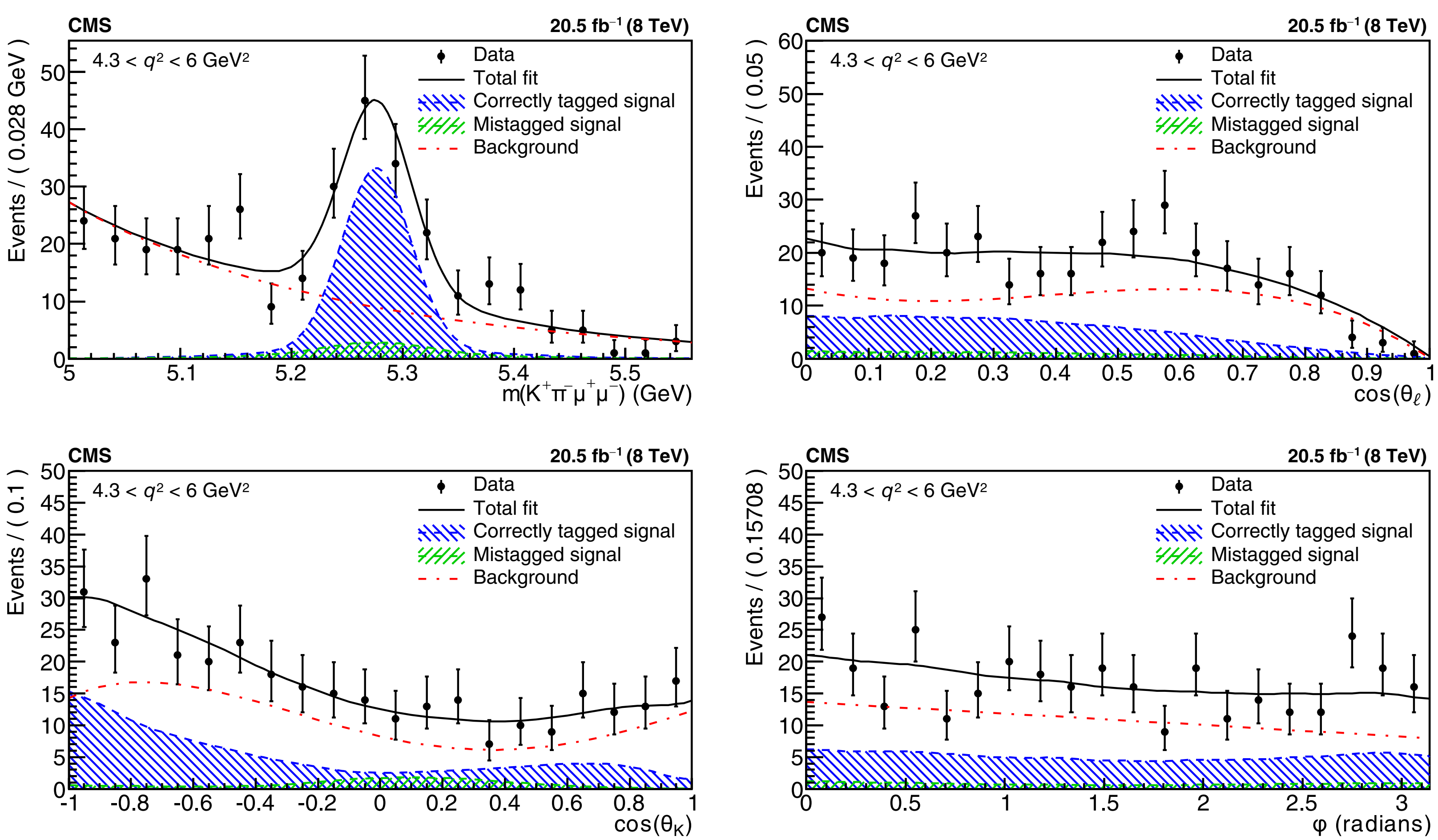
$$\mathrm{pdf}(m,\theta_K,\theta_\ell,\varphi) = Y_S^C \Big[S^C(m)\, S^a(\theta_K,\theta_\ell,\varphi)\, \epsilon^C(\theta_K,\theta_\ell,\varphi) + \frac{f^M}{1-f^M} S^M(m)\, S^a(-\theta_K,-\theta_\ell,\varphi)\, \epsilon^M(\theta_K,\theta_\ell,\varphi) \Big] + Y_B\, B^m(m)\, B^{\theta_K}(\theta_K)\, B^{\theta_\ell}(\theta_\ell)\, B^{\varphi}(\varphi),$$

Signal distribution ($K^+\pi^-\mu^+\mu^-$)

Efficieny from dedicated MC

Mistagged signal distribution

Background distribution



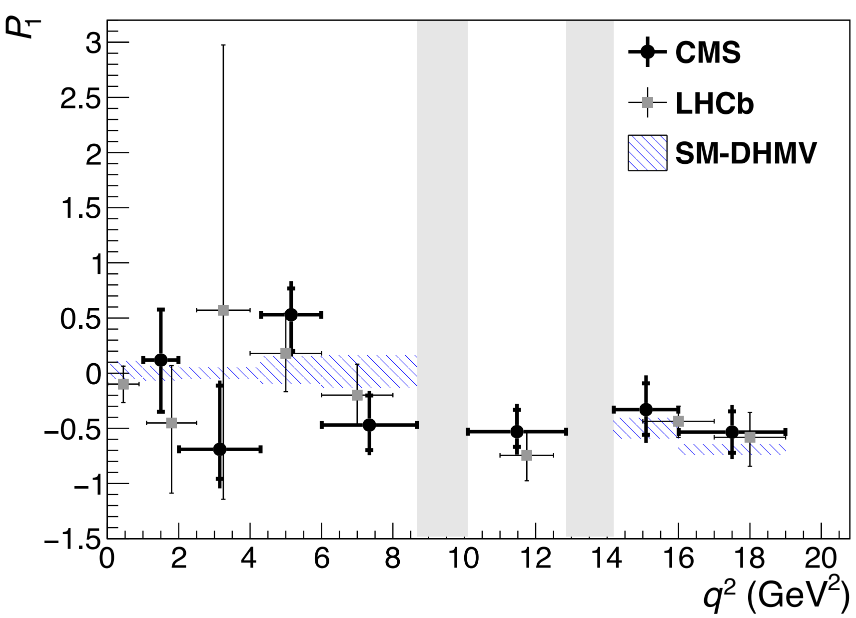
Mistagged signal distribution

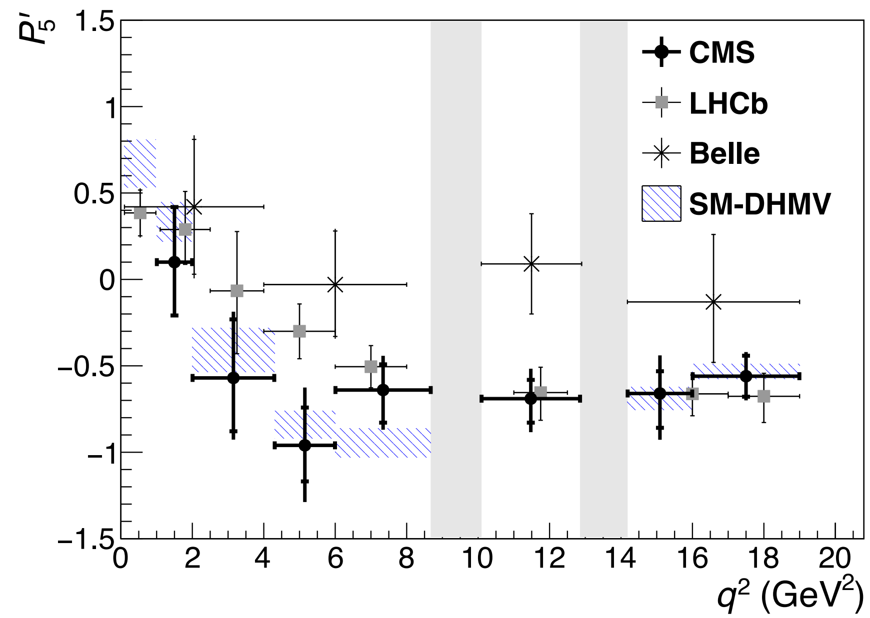
- Flavour state assignment based on M(Kπ) value
  - mis-tagged event fraction 12-14% based on q^2, measured on MC

- Two step fit performed for 7 q^2 bin
  - fit mass side bands to determine the background shape
  - fit whole mass spectrum with 5 floating parameters
    - (2 yields, P_5', P_1 and A_S^5)

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

- Results compared with Run 1 LHCb result and SM prediction.
- CMS result are compatible with SM predictions within uncertainties.
- No significant deviations from other experimental results.

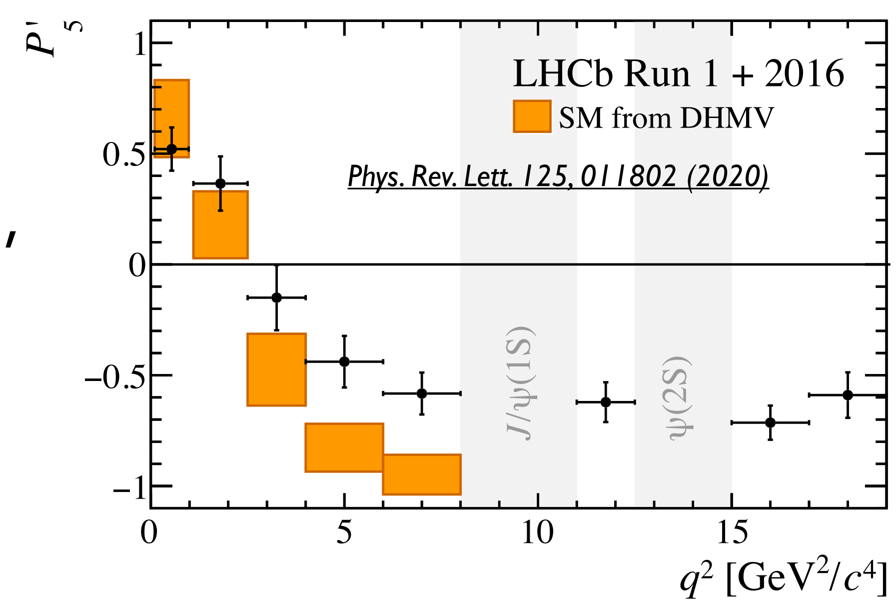




Systematics

Source	$P_1(\times10^{-3})$	$P'_5(\times10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
Efficiency	17–100	5–65
$K\pi$ 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	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

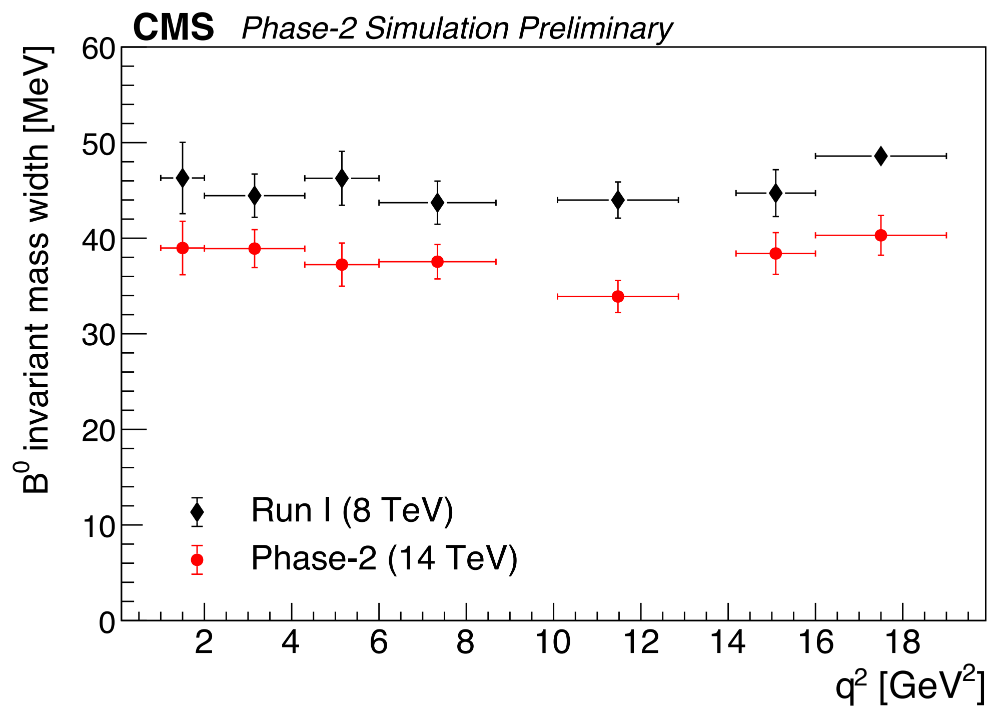
- Latest LHCb result with Run 1+2016 data shows some mismatch wrt SM in q^2 bin [4.0, 6.0] GeV^2 and [6.0, 8.0] GeV^2.



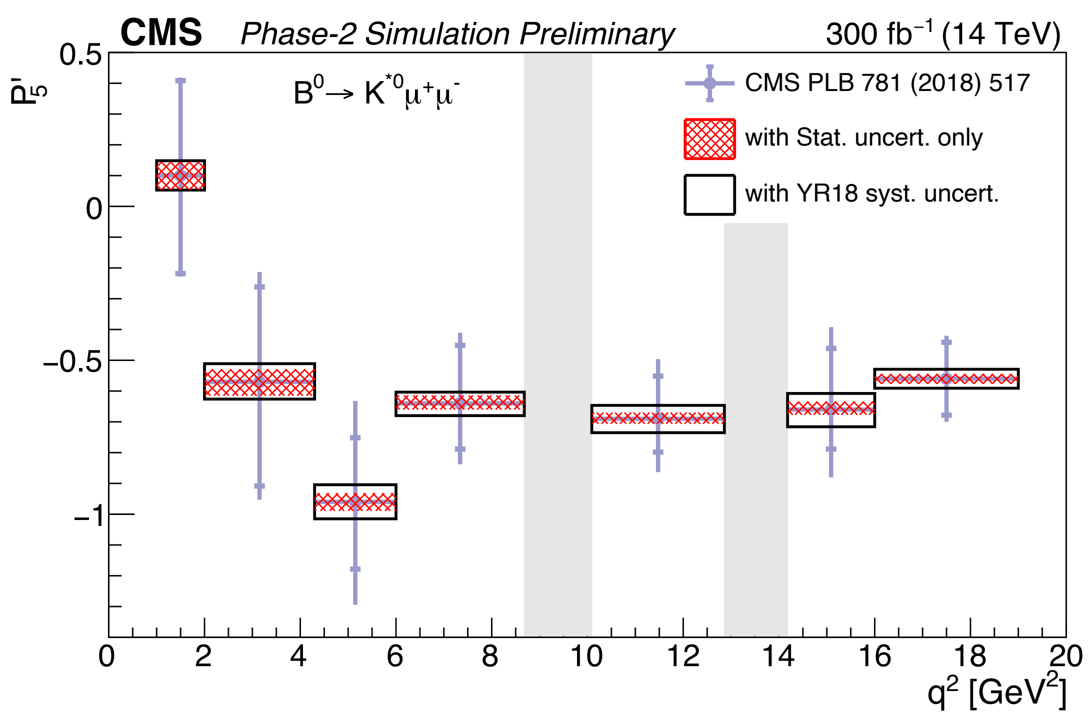
$B^0 \to K^{*0}\mu^+\mu^-$: HL-LHC

[CMS-PAS-FTR-18-033]

- CMS performed the feasibility study of this parameter with HL-LHC statistics, ~3000 fb^{-1}, (200 pileup scenario)
- Using Run-1 analysis as baseline to project the result
  - No change in trigger threshold or efficiency
  - Improved mass resolution with upgrade
  - Expected signal ~700k in full q^2 bin



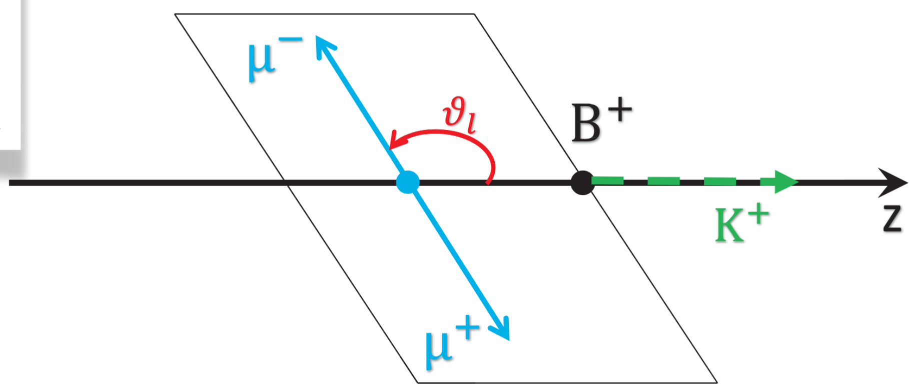
- Statistical uncertainty scaled according to the expected yield
- Systematic uncertainties based on data control channel scaled according to statistics
- Other systematic uncertainties are scaled by a factor of 2
- Total uncertainty is expected to improve by 15 times wrt Run 1 result.



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

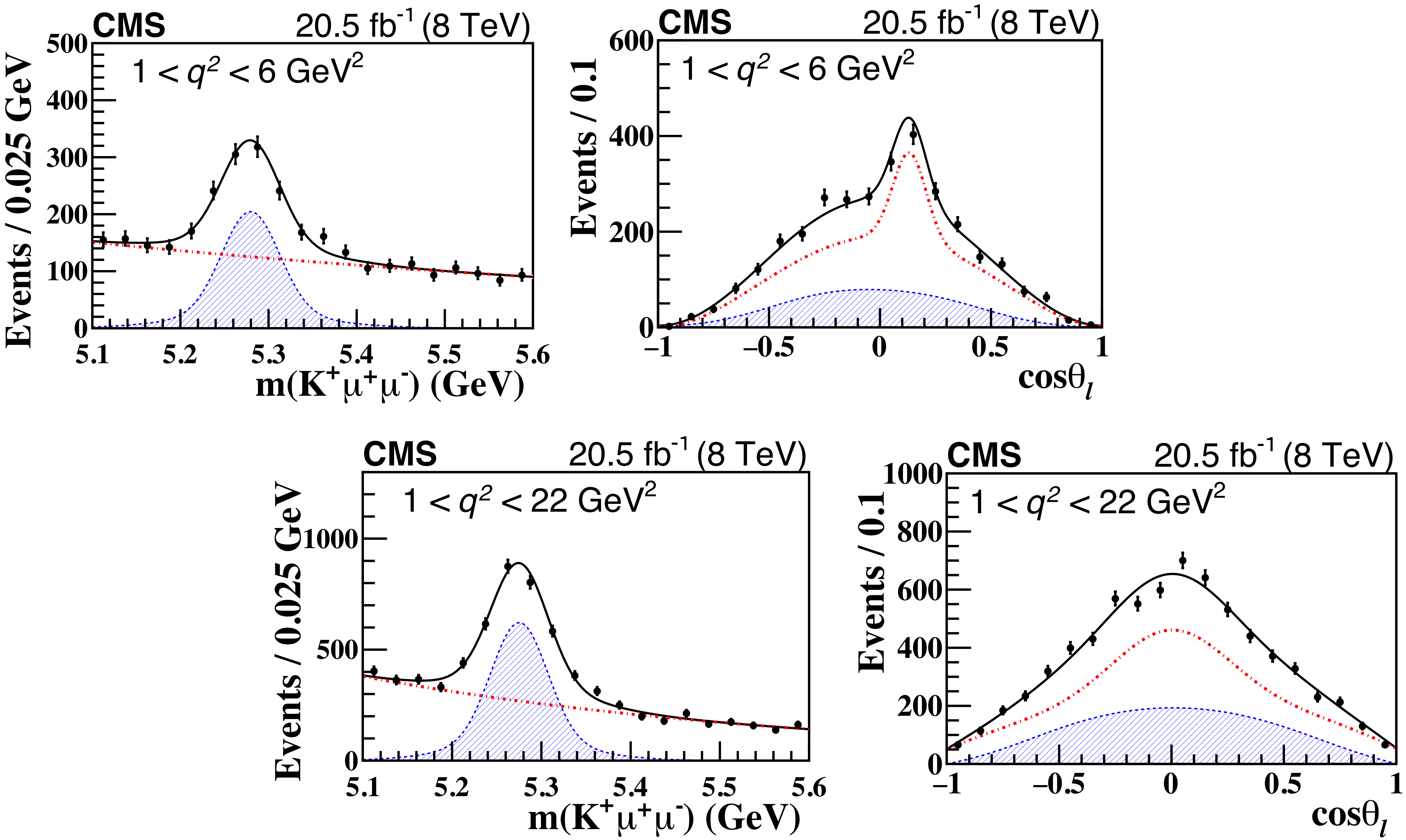
- Three body final state, one angle (θ_l) and q^2 are sufficient to describe the decay rate.

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l} = \frac{3}{4}(1-F_{\mathrm{H}})\left(1-\cos^2\theta_\ell\right)+\frac{1}{2}F_{\mathrm{H}}+\mathcal{A}_{\mathrm{FB}}\cos\theta_\ell$$

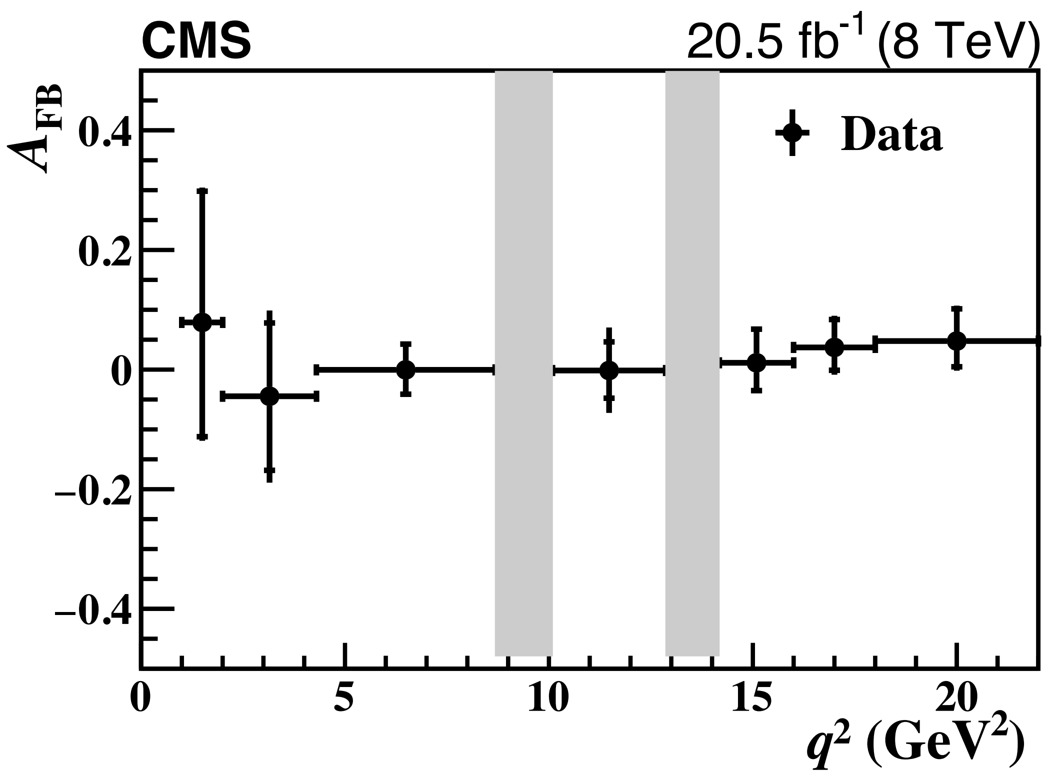


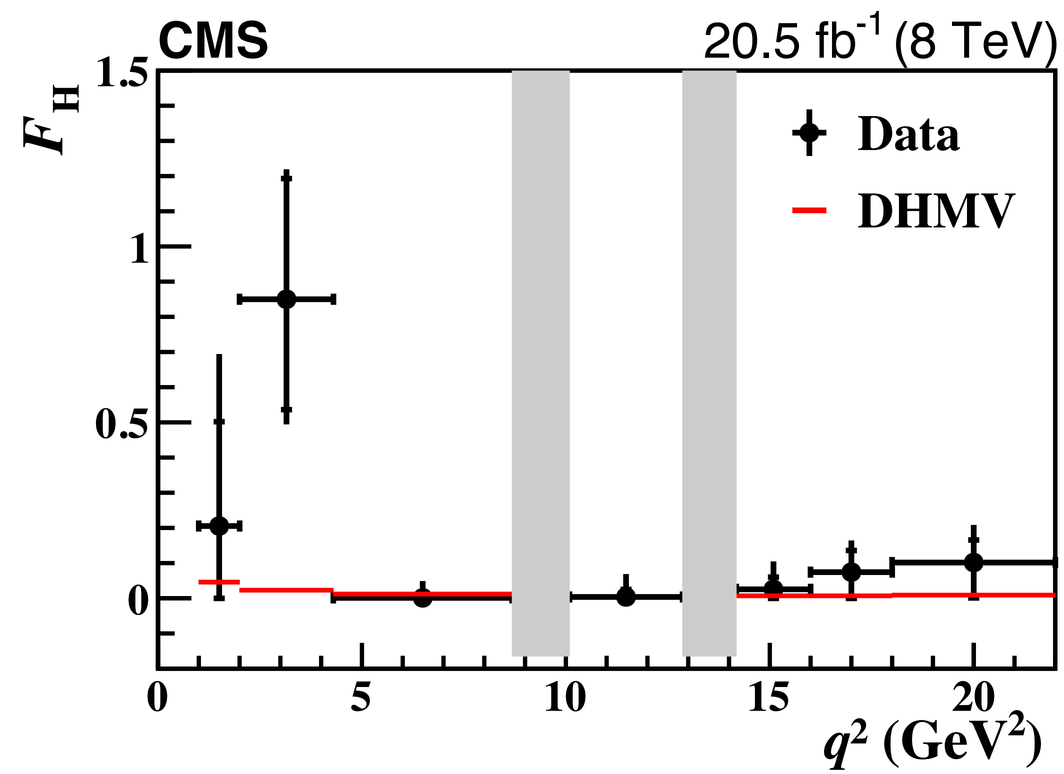
- Parameters of interest: forward backward asymmetry of muons (A_{FB}), angular parameter (F_{H})
- Full q^2 bin is splitted in 9 bins
  - 7 signal q^2 bin, 2 control channel bins ($B^+ \to J/\psi K^+$, $B^+ \to \psi(2S)K^+$)
  - 2 more special bins: [1-6] GeV^2 and [1-22] GeV^2
- An unbinned maximum likelihood fit is performed in signal q^2 bin.
  - Validations are performed on signal MC sample (both high and data-like statistics)

Fit projections



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





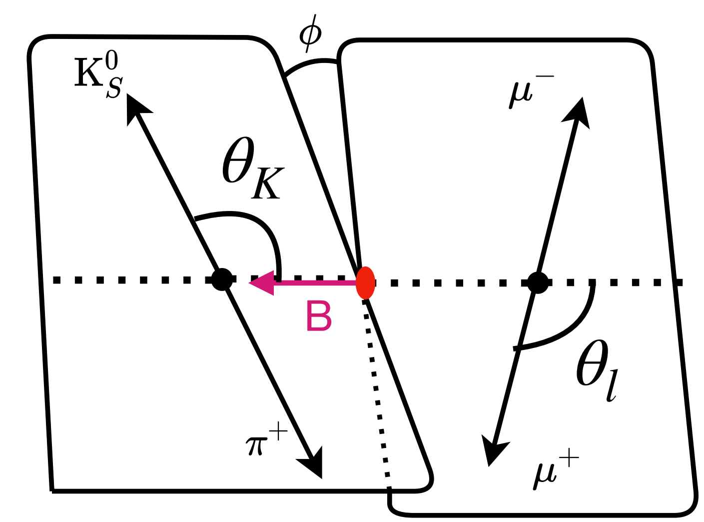
- Two error bar on the data point: Inner error bar is statistical uncertainty, full bar is total uncertainty.
- Dominant systematic uncertainty is from the background shape modelling.
- Observed results are compatible with SM predictions within uncertainties.

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

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

- K^{*+} is reconstructed using $K_s^0(\pi^+\pi^-)\pi^+$
- Differential decay rate as a function of θ_l, θ_K, and $q^2(= m_{\mu\mu}^2)$

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

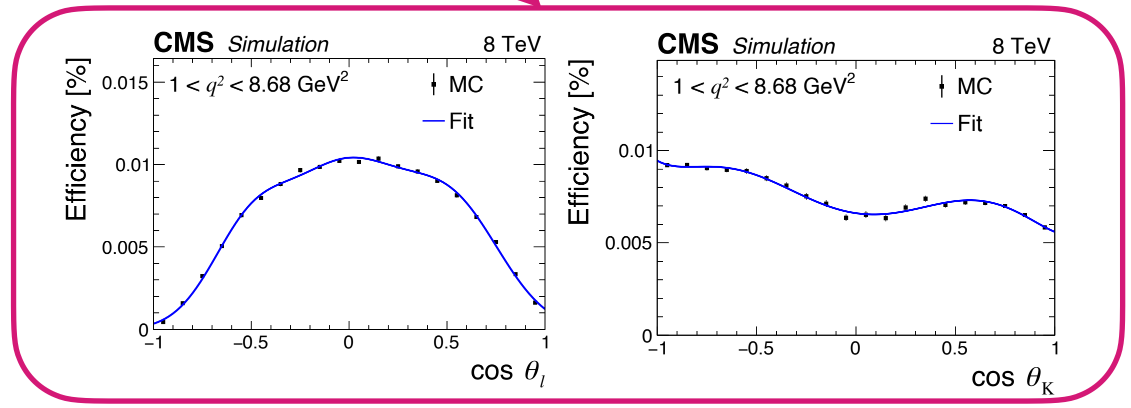


- Parameter of interests: longitudinal polarization of K^{*+}(F_L) and forward-backward asymmetry of muons (A_{FB})
- Measurement performed on three q^2 bins.
- Two additional q^2 control regions to include $B^+ \to J/\psi K^{*+}$ and $B^+ \to \psi(2S)K^{*+}$ resonant decays.

Fit algorithm

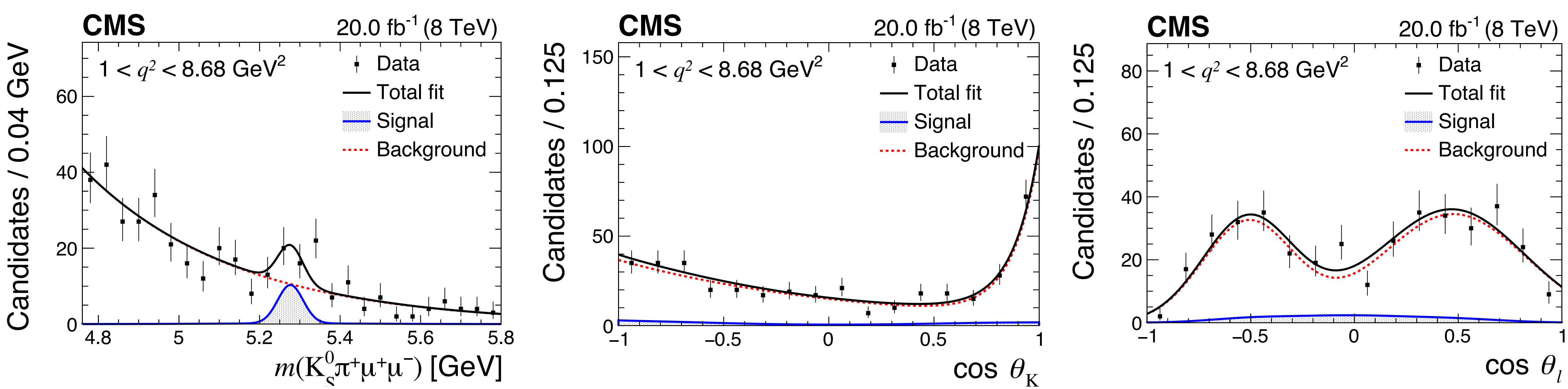
- F_L and A_{FB} extracted for each q^2 bin by unbinned extended maximum-likelihood fit on θ_l, θ_K and m

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



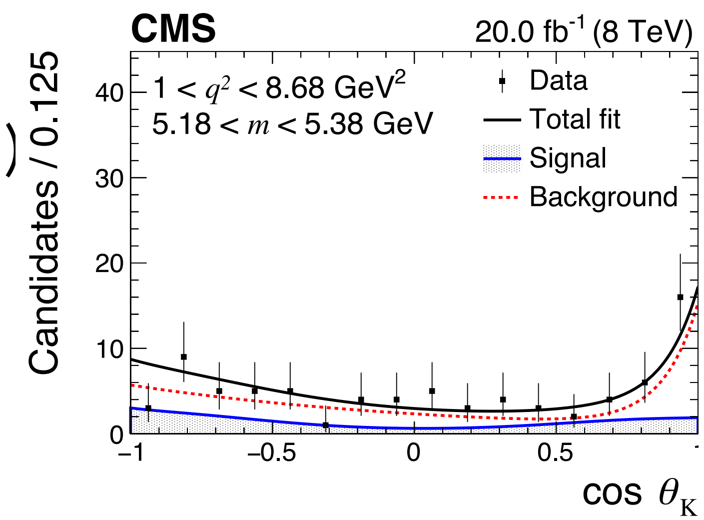
- Υ_S and Υ_B are the signal and background yields (free parameters).
- $S^m(m)$ and $B^m(m)$ are double Gaussian shape with parameters determined on MC and exponential function (slope free)
- $B^{\theta_K}(cos\theta_K)$ and $B^{\theta_l}(cos\theta_l)$ are polynomial or exponential functions depending on the q^2.

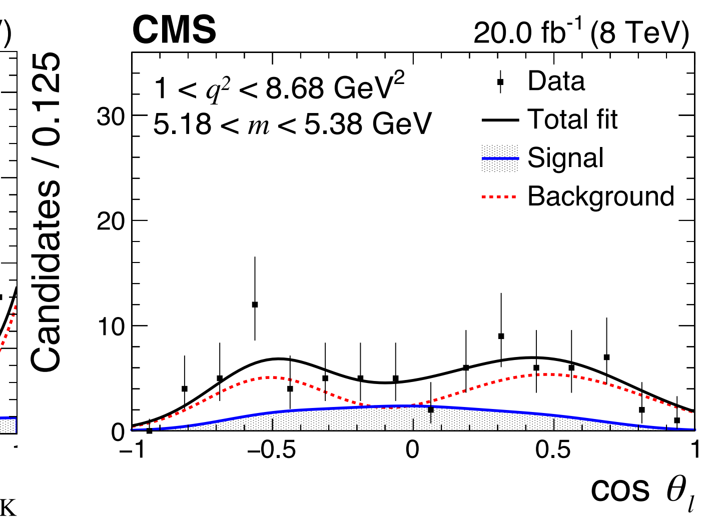
Examples of fit projections in $1 < q^2 < 8.68$ GeV^2



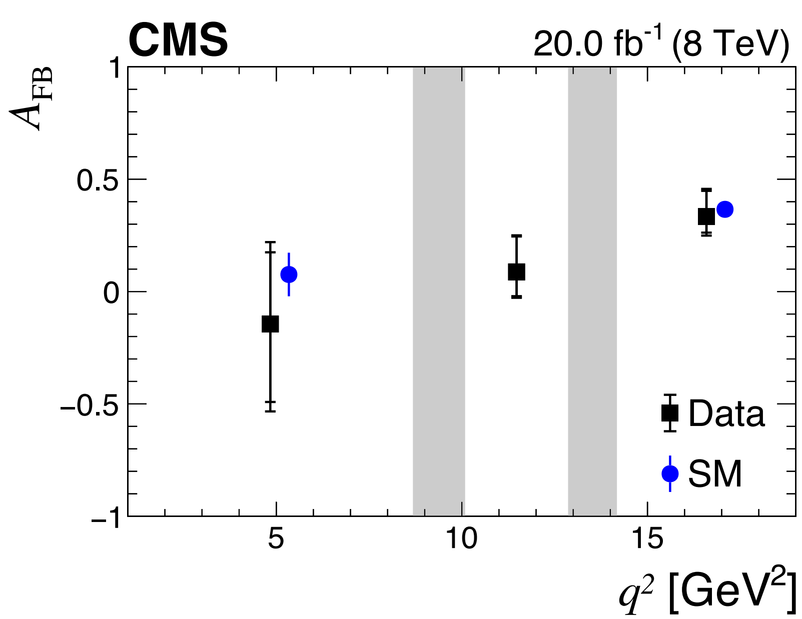
$B^+ \to K^{*+}\mu^+\mu^-$: Results

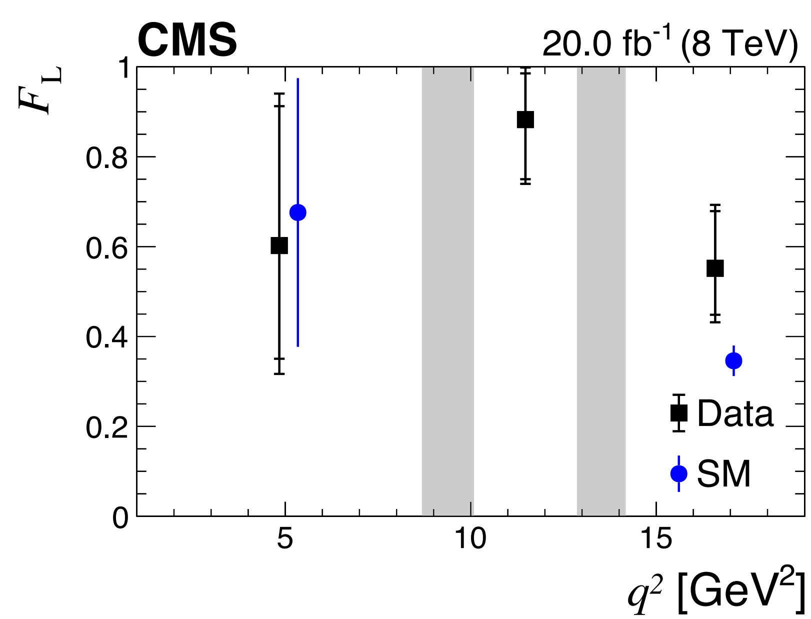
- Validation of angular PDFs ($cos\theta_l, cos\theta_K$) from final fit with signal region events
  - $M_{B_s^0}$: 5.18-5.38 GeV





- Good description of the signal and background angular PDFs in signal region





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 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

- Inner error bar indicates the statistical uncertainty, full bar is total uncertainty
- Results compatible with Standard Model predictions within uncertainties

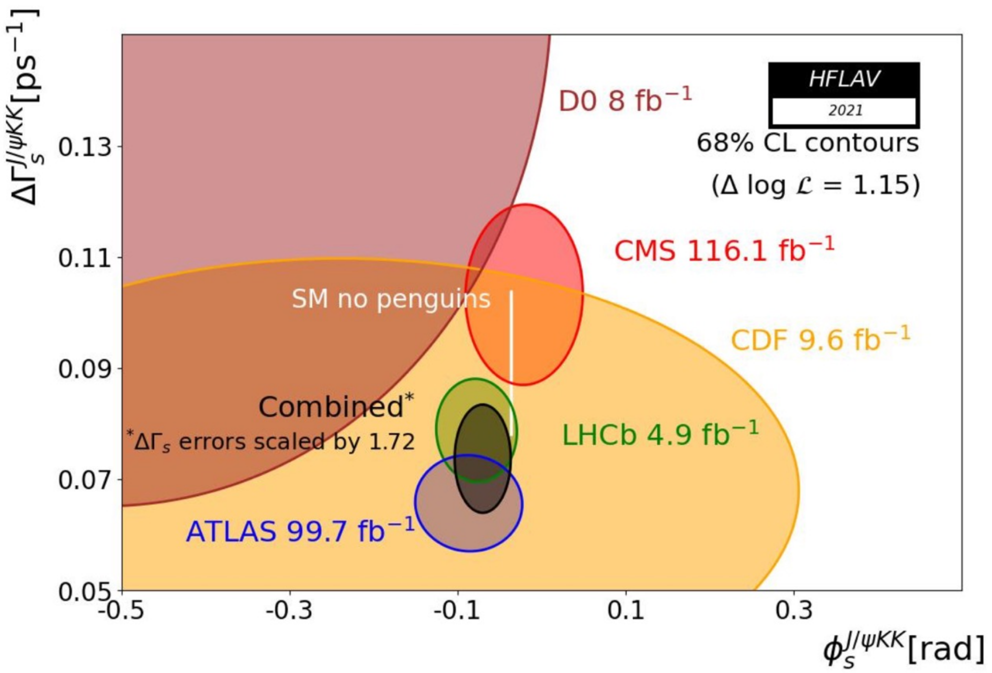
Summary

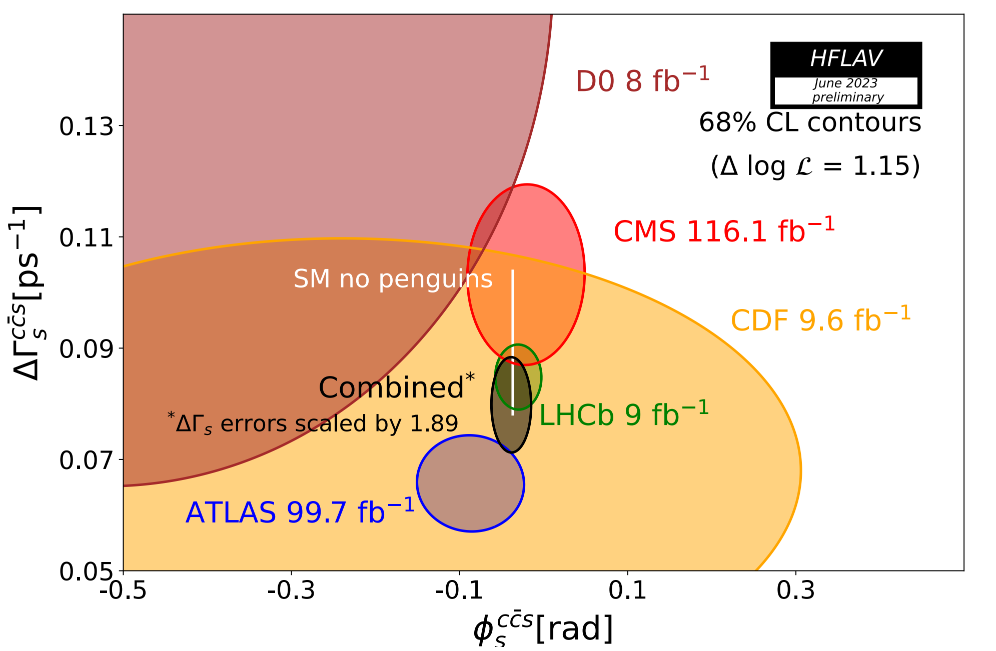
- **CP violation in B_s^0 decays**
  - CPV phase ϕ_s and decay width difference $\Delta\Gamma_s$ is measured in $B_s^0 \to J/\psi\phi$ channel.
    - Consistent with the SM prediction
- **FCNC rare decays are being extensively studied in CMS using Run 1 data**
  - $B^0 \to K^{*0}\mu^+\mu^-$ has been extended to measure P_1 and $P_5^{'}$.
    - $P_5^{'}$ showed some deviation from SM (by different experiments)
  - $B^+ \to K^+\mu^+\mu^-$ angular analysis performed for the first time in CMS, to measure A_{FB} and F_H
  - $B^+ \to K^{*+}\mu^+\mu^-$ angular analysis performed to extract A_{FB} and F_L.
    - Results are in agreement with SM
- Run 2 analyses are underway and new results are expected to be out soon.

Backup

$B_s^0 \to J/\psi\phi$: Results

- Results are consistent with SM predictions and no CPV in the interference between mixing and decay.





Systematic uncertainties

Source	$P_1 (\times 10^{-3})$	$P_5' (\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
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	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

Fit bias with cocktail signal MC + toy background from data side-bands

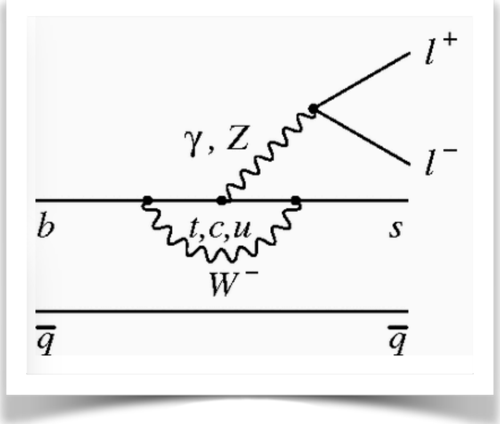
MC stat due to limited statistics in efficiency shape evaluation

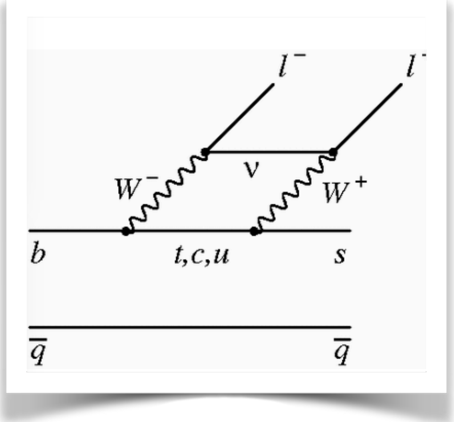
Kπ **mistag** evaluated in J/ψ control region and propagated to all bins

F_L, F_S, A_S **uncertainty propagation** studied with pseudo experiment, take ratio of stat. uncert. on P_1 and P_5' with free and fixed fit to estimate systematic uncertainties.

New physics in $b \to s l^+ l^-$ transitions

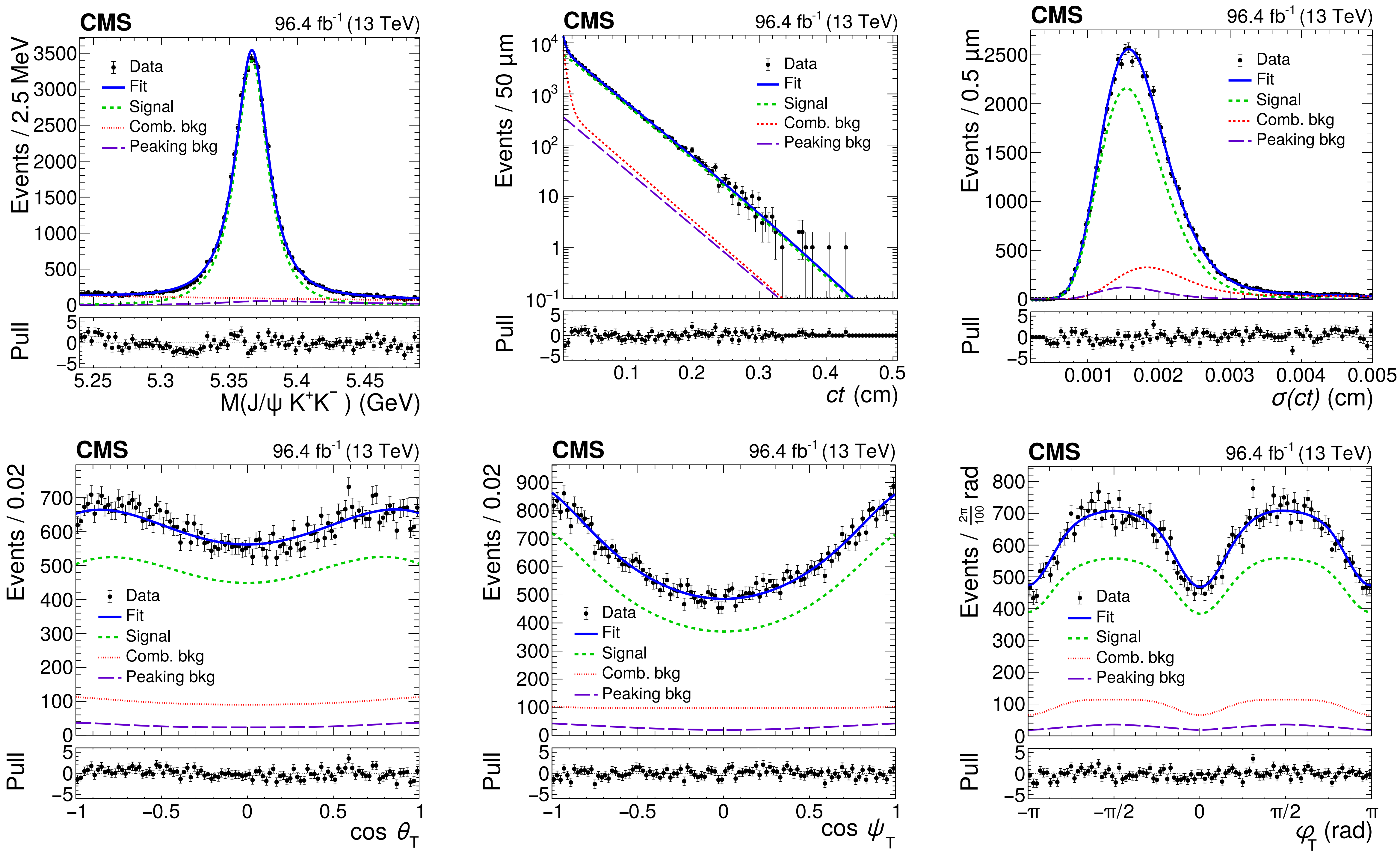
- $b \to sll$ decays are Flavour changing neutral current process
  - Forbidden in Standard Model at tree level
  - Proceed through higher order diagrams (penguin, box)
    - Sensitive to New Physics effect
- Suitable decay modes are: $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ etc
- List of observables to compare with SM predictions (as function of square of dimuon mass): Branching fractions, differential BFs, CP asymmetry, Isospin asymmetry, Forward-backward asymmetry of muons etc





- In this talk, following analysis will be covered.
  - Measurement of angular parameters from the decay $B^0 \to K^{*0}\mu^+\mu^-$ in proton–proton collisions at $\sqrt{s} = 8$ TeV. [Phys Lett B 781 (2018) 517-541]
  - Angular analysis of the decay $B^+ \to K^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV. [Phys Rev D 98 (2018) 112011]
  - Angular analysis of the decay $B^+ \to K^{*+}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV. [JHEP 04 (2021) 124]

Fit projections



- Overall agreement is good.
- Systematic uncertainty on the model assumptions are considered.