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Rare Decays at CMS and ATLAS

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On behalf of the CMS and ATLAS Collaboration

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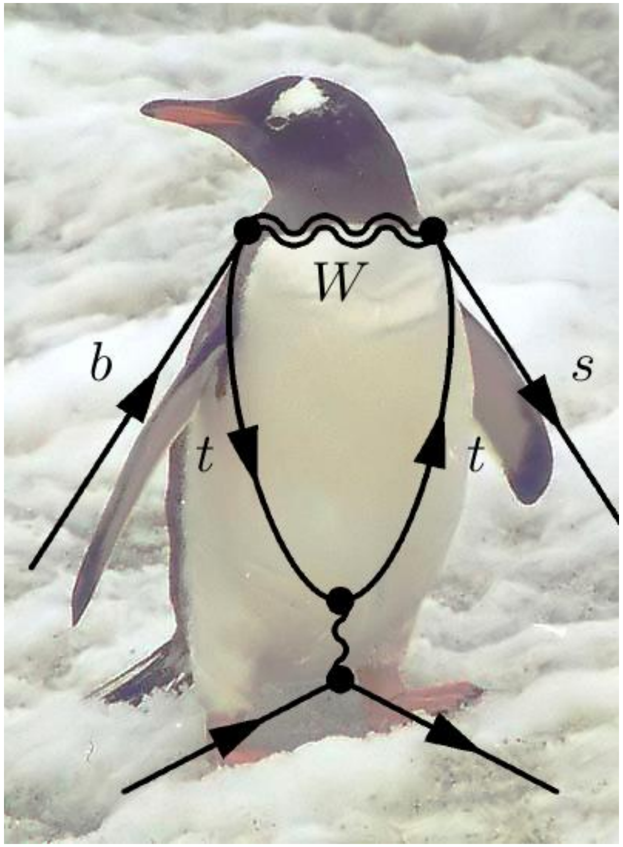
Outline

- Introduction
- $B^0 \to K^* \mu\mu$ angular analysis at CMS
  - Analysis Strategy
  - Selections and Fitting Procedure
  - Results
- $B_s \to \mu\mu$ lifetime measurement at ATLAS
- Summary

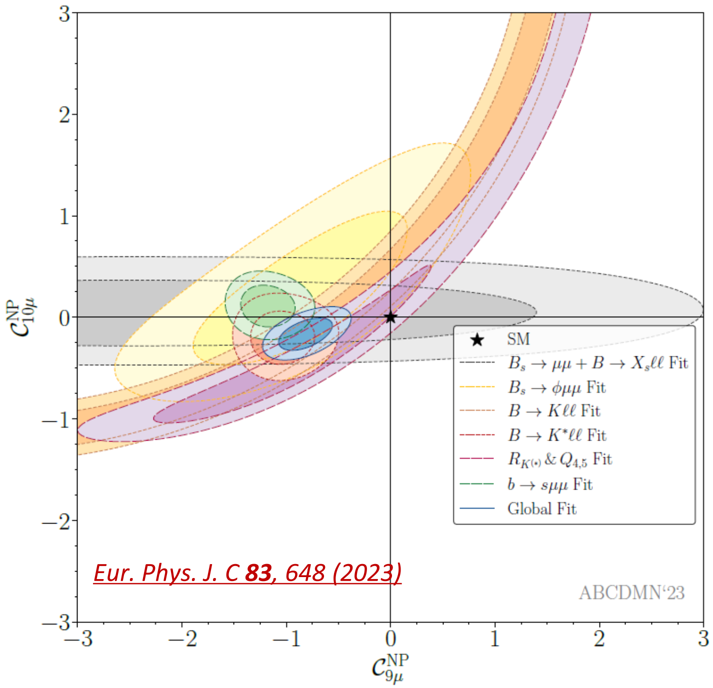
Detailed talk this afternoon

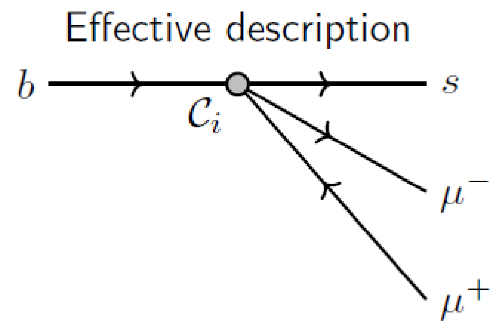
Motivation of B Rare Decays

- The B rare decay is the promising way for indirect new physics searches
  - Flavor Changing Neutral Current (FCNC) decays are suppressed in the SM, typical BR < 10^{-6}
  - New physics might enter at this level
  - A sensitive probe to new physics
    - Branching fraction
    - Angular distribution
    - Lifetime
- Unique rare b→sℓℓ process
  - B→K(*)ℓℓ where multiple discrepancies from the SM are observed
    - First full angular result by CMS
  - $B_s \to \mu\mu$
    - Lifetime measurement by ATLAS



Rare B Decay Anomalies





$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Effective coupling
"Wilson coefficient"
short distance physics

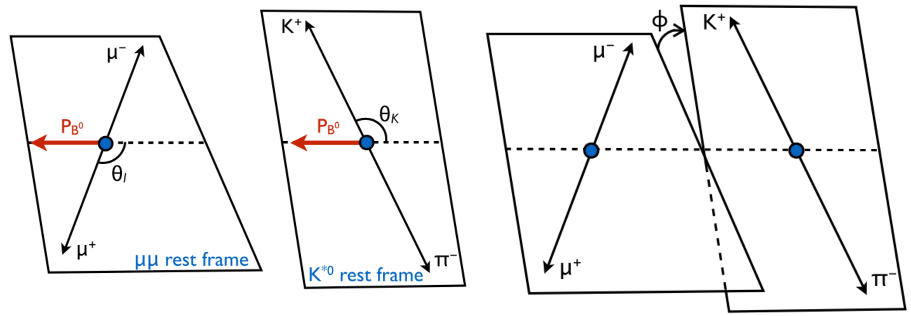
Local operator
long distance physics

- Global fits with the Wilson coefficients C_9 and C_{10} of the vector and pseudo-vector operators O_9 and O_{10} in the effective 4-fermion interaction
- Multiple discrepancies are observed in rare B decays
  - 2-3σ anomalies in branching ratios and angular observables
- Recent B(s)→μμ measurements indicate that the abnormally comes from vector leptonic coupling (Only O_{10} contributes to B(s)→μμ).
  - the C9 Wilson coefficient are consistent throughout the different b → sμμ modes

$B^0 \to K^* \mu\mu$ angular analysis at CMS

B→K*ℓℓ Angular Rare Decay

- $B^0 \to K^*(K^* \to K\pi)\,\mu\mu$
- Three observables: θ_l, θ_k, ϕ
  - Two planes for $K\pi$ and $\mu\mu$
  - θ_l, θ_k in rest frame



- Expressed by a set of clean observables related to the Wilson coefficients

JHEP 01 (2013) 048

P-wave

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\left(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right)\cos 2\theta_l$$
$$+\frac{1}{2}P_1(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\sqrt{(1-F_L)F_L}\left(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{(1-F_L)F_L}\left(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$
$$+2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

F_L is the fraction of longitudinal polarization of the K^* meson

$P_i^{(\prime)}$ is the base of optimized clean observables

q^2 : invariant mass squared of dimuon

- The Kπ system could also be in S-wave configuration, which is added as another signal component.

Current Experimental Results

CMS, Run1 data (20 fb-1) ~1400 signal events
Measure partial angular observables, including P5’.

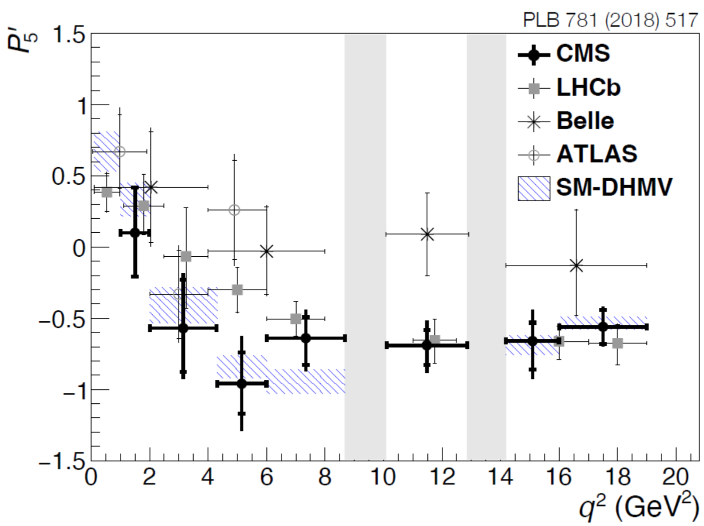
PLB 753 (2016) 424
PLB 781 (2018) 517

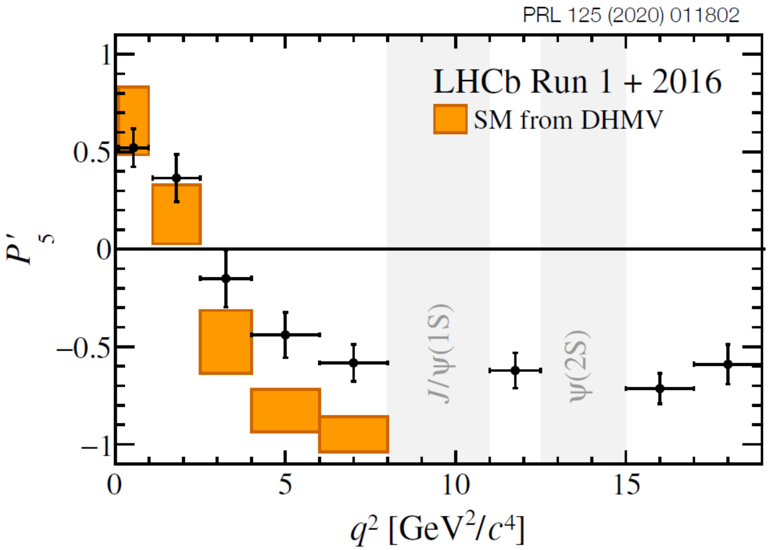
ATLAS, Run1 data (20 fb-1)
in turn, different foldings used to measure the various parameters

JHEP 10 (2018) 047

LHCb, Run1 data + 2016 (3 + 1.7 fb-1)
Full angular analysis, discrepancy in both Run 1 and 2016 data measurement

PRL 125 (2020) 011802

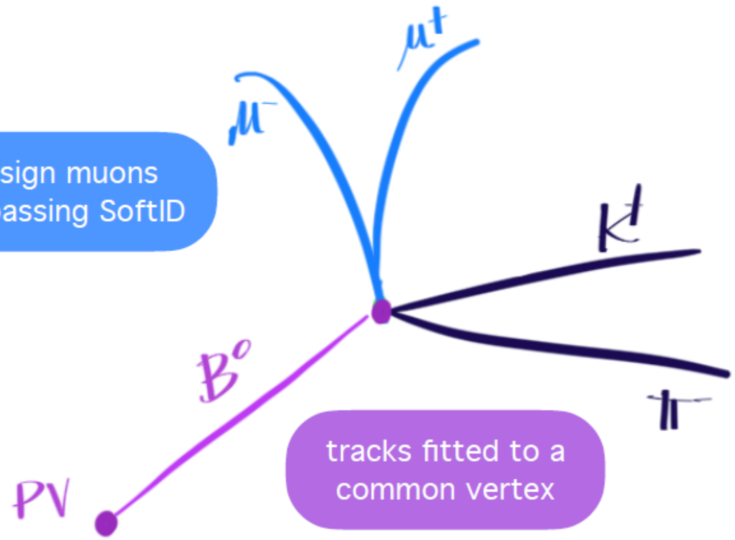




Discrepancies between LHCb results and the prediction, not seen in CMS Run 1 result.

Selections

2 opposite-sign muons
p_T > 4 GeV, passing SoftID

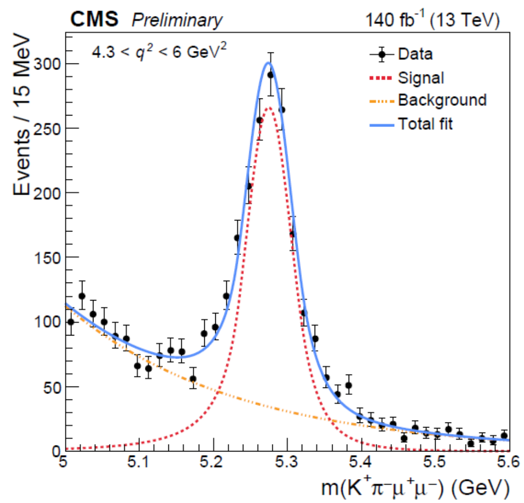


2 opposite-sign high-purity tracks
p_T > 0.8 (1.2) GeV
DCA/σ > 0.8 (2) in 2016 (2017,2018)
muon veto applied
fitted to a common vertex

tracks fitted to a common vertex

K/π mass hypothesis assigned according to the combination with inv. mass closer to $m^{PDG}(K^*)$ (mistag rate 13%)

- CMS Run 2 data 2016—2018
- Final states reconstructed with 2 muons + 2 hadrons
- BDT used to further suppress the background
  - input features: decay-vertex quality and displacement, isolation, mass of Kπ system
- Veto based on mass is applied
  - exclude $B^+ \to K^+\mu\mu$, $B_s \to \phi\mu\mu$ processes



Angular Analysis

- In each q^2 bin, a 4D unbinned maximum likelihood fit to is performed

$$\text{pdf}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S \Big[S^C(m) S^a(\cos\theta_K, \cos\theta_l, \phi) \epsilon^C(\cos\theta_K, \cos\theta_l, \phi) + R \cdot S^M(m) S^a(-\cos\theta_K, -\cos\theta_l, -\phi) \epsilon^M(\cos\theta_K, \cos\theta_l, \phi) \Big] + Y_B B^m(m) B^a(\cos\theta_K, \cos\theta_l, \phi)$$

signal component

signal yield

mistagged signal ~13%

R = ratio of average mistag fraction on data and on MC

background component

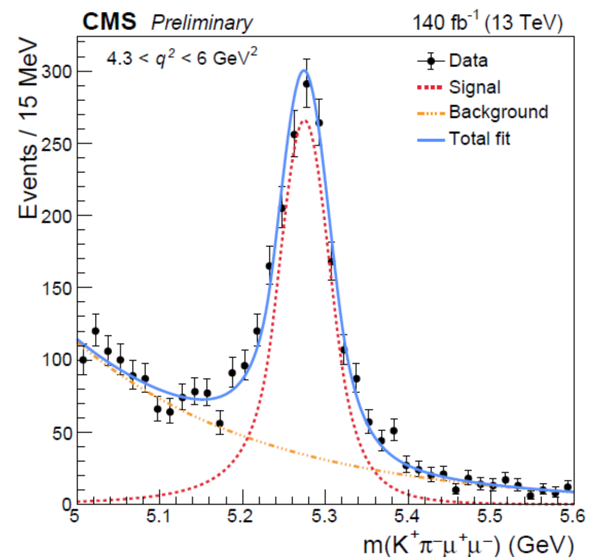
bkg yield

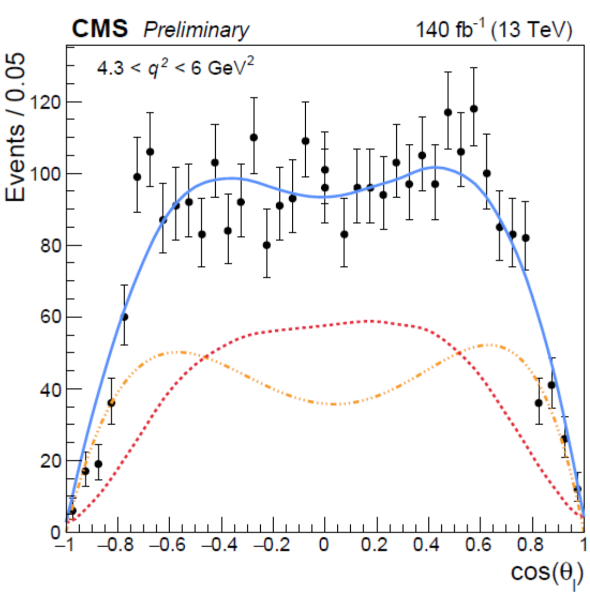
S^a is the decay rate formula

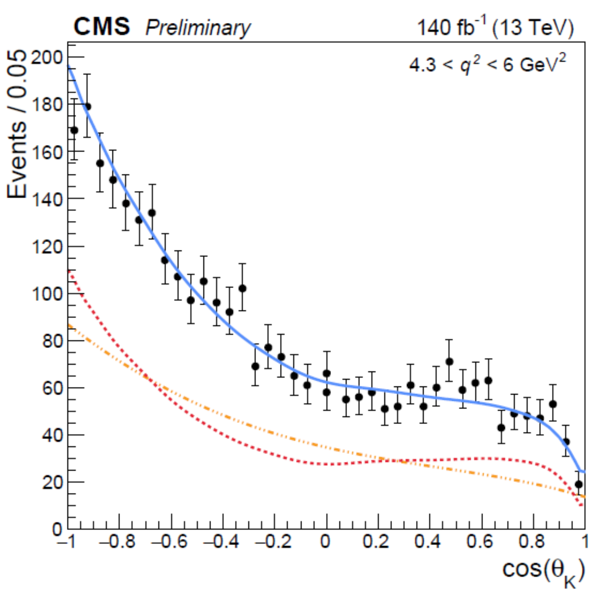
- Fitting set up
  - Mass shapes (signal and background) $S^c(m), S^M(m), B^m(m)$
  - Signal efficiency ϵ^C, ϵ^M from simulation.
  - Angular distribution of the background $B^a(cos\theta_K, cos\theta_l, \phi)$, determined using sidebands
  - Simultaneous fit on each year of collected data.

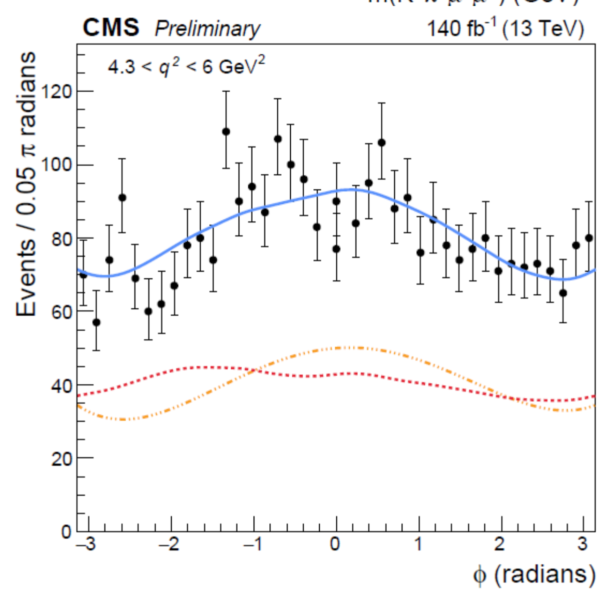
Fit Projections

- Angular fit validated in simulation and control regions
- Projections on invariant mass and 3 angle observables
- Good agreement between data and pdf projections
  - Example $4.3 < q^2 < 6\ GeV^2$
  - Others in back up

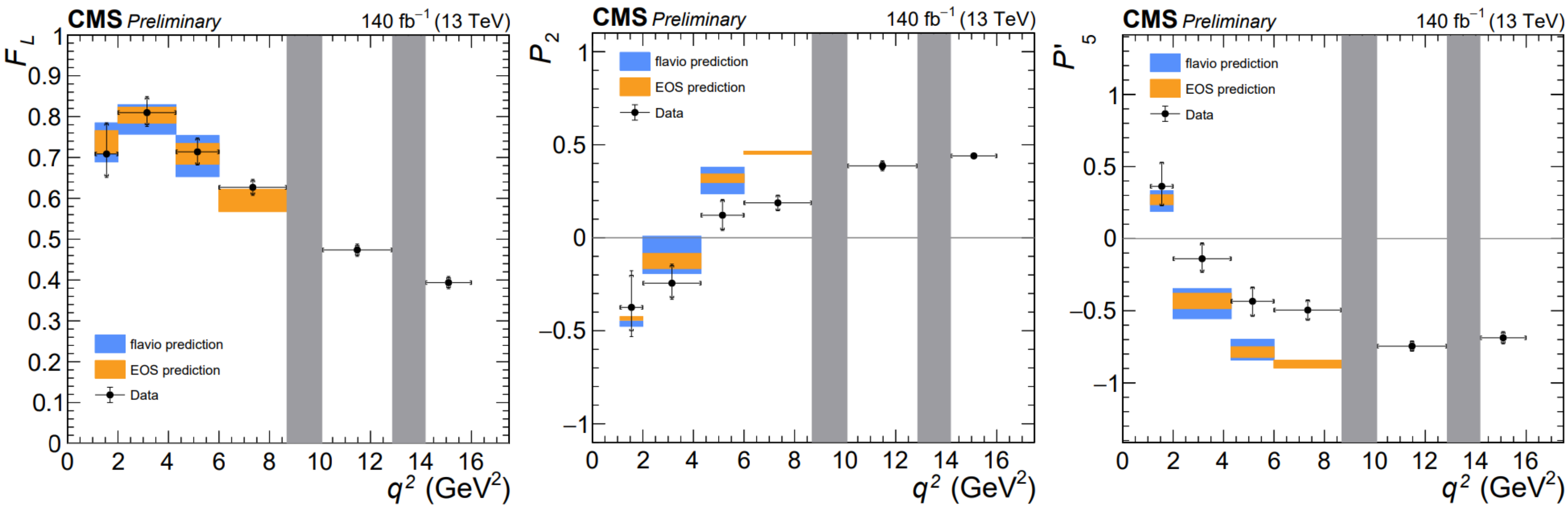








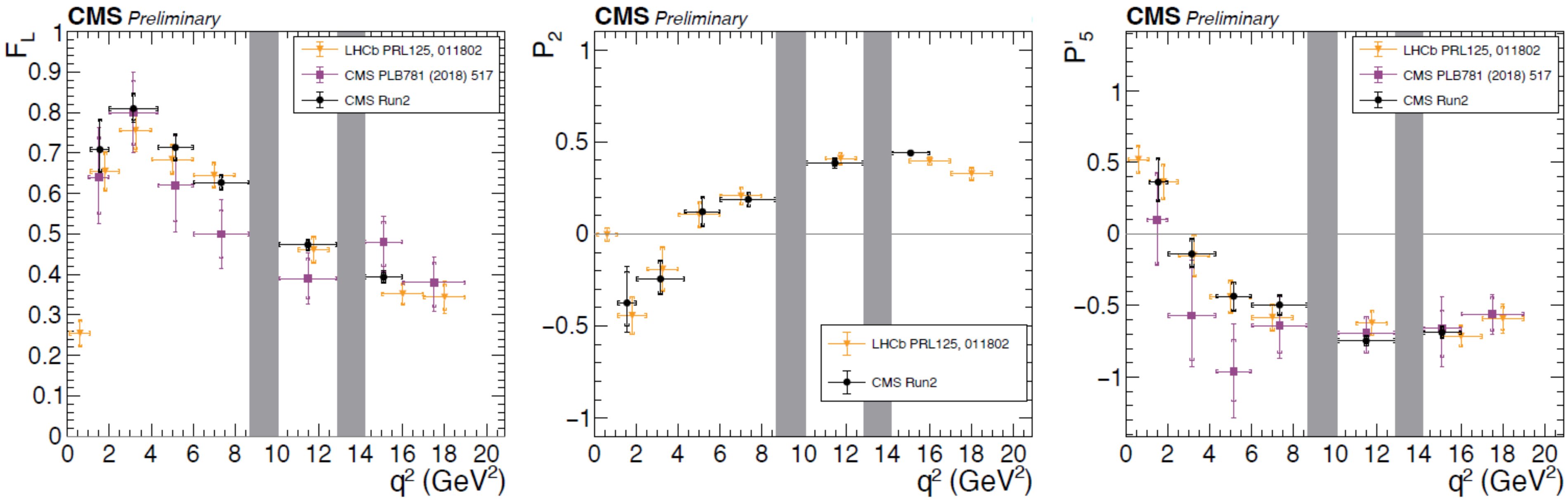
Results



- Two sets of predictions are shown: FLAVIO and EOS
  - FLAVIO: local form-factors (LQCD and Light-Cone Sum Rule) + non-local form-factors (QCDF)
  - EOS: local form-factors (LQCD and LCSR), novel parametrization of non-local form-factors
- Clear tensions in the q^2 region below the J/ψ for the P5′ and P2 parameters
- The other observables are in agreement with the prediction (in back up).

Public result link (CMS-PAS-BPH-21-002)

Comparison to Experimental Results



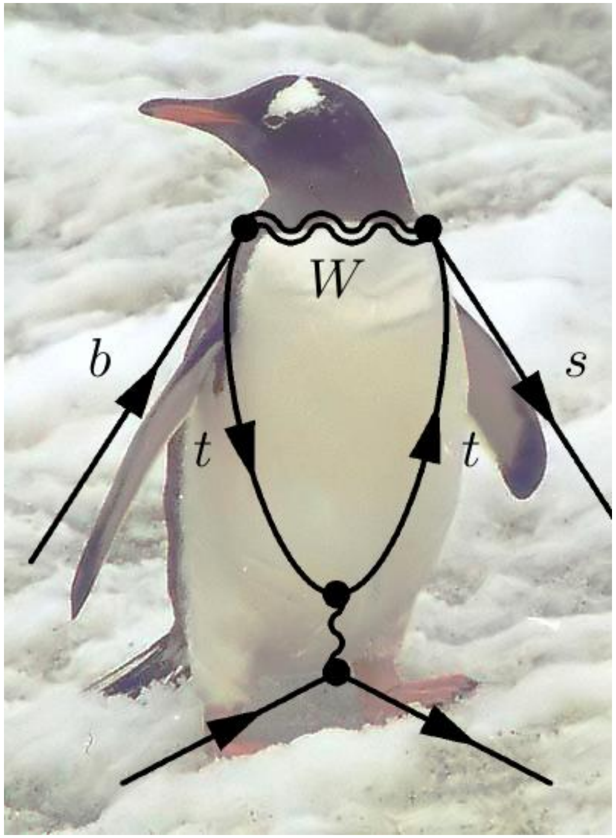
- The results are among the most precise experimental measurements of the angular observables of this decay.
- Good agreement with LHCb result. Same tension from the predictions observed in P_2 and P_5'.
- The combined tension from the prediction will increase.

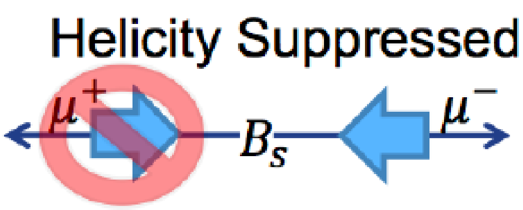
$B_s \to \mu\mu$ lifetime measurement at ATLAS

Detailed talk this afternoon

Why $B_s \to \mu\mu$ lifetime ?

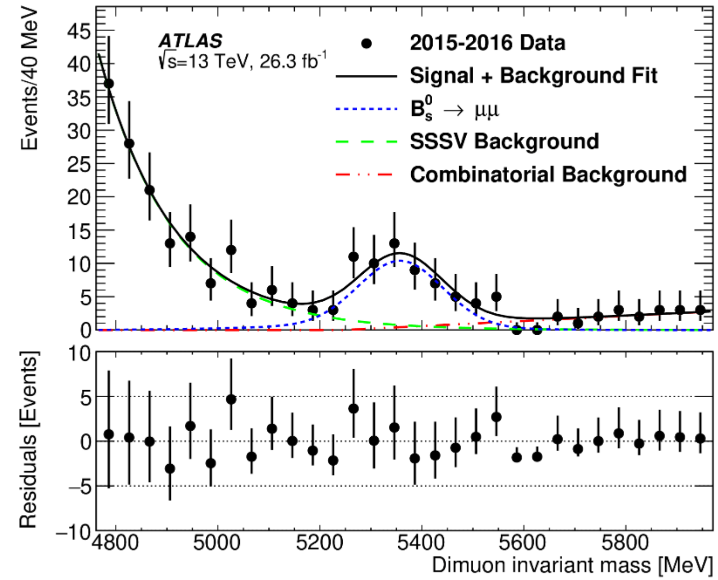
- $B_s \to \mu\mu$ is a extremely rare decay in standard model
  - b->u flavor changing neutral current
  - Helicity suppressed
  - Branching fraction $(3.66 \pm 0.14) \times 10^{-9}$
- Why lifetime is important?
  - only the CP-odd heavy mass eigenstate of B_s meson decays into a dimuon final state
  - Light state lifetime: $1.427\ ps$
  - Heavy state lifetime: $1.616\ ps$
- Different composition of states may be allowed by New Physics.

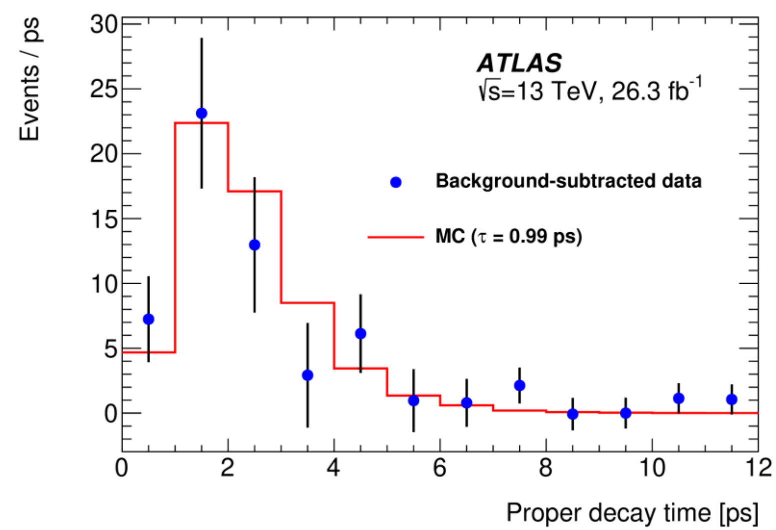




Lifetime Measurement Strategy

- Using ATLAS 2015-2016 data (26.3 fb^-1)
- Dimuon final states
  - Invariant mass [4.766, 5.966] GeV
- Normalization channel
  - $B \to J/\psi K$
- Proper decay time calculated from decay length
  - $t_{\mu\mu} = \frac{L_{xy} m_{B_s}}{p_T^{B_s}}$ (L_{xy} decay length)
- Conducted fit on mass distribution
- Extract background-subtracted data in proper decay time using sPlot.
- Fit with different lifetime signals to extract the $B_s \to \mu\mu$ lifetime





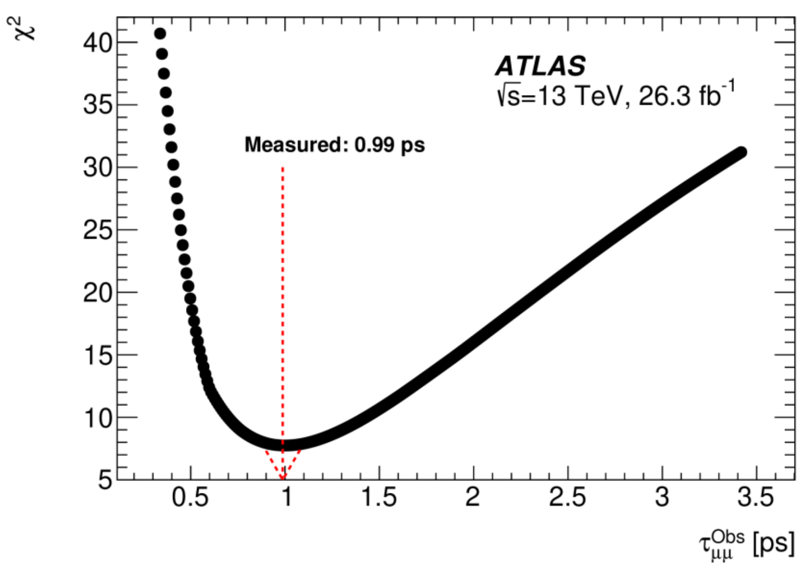
Measured Lifetime

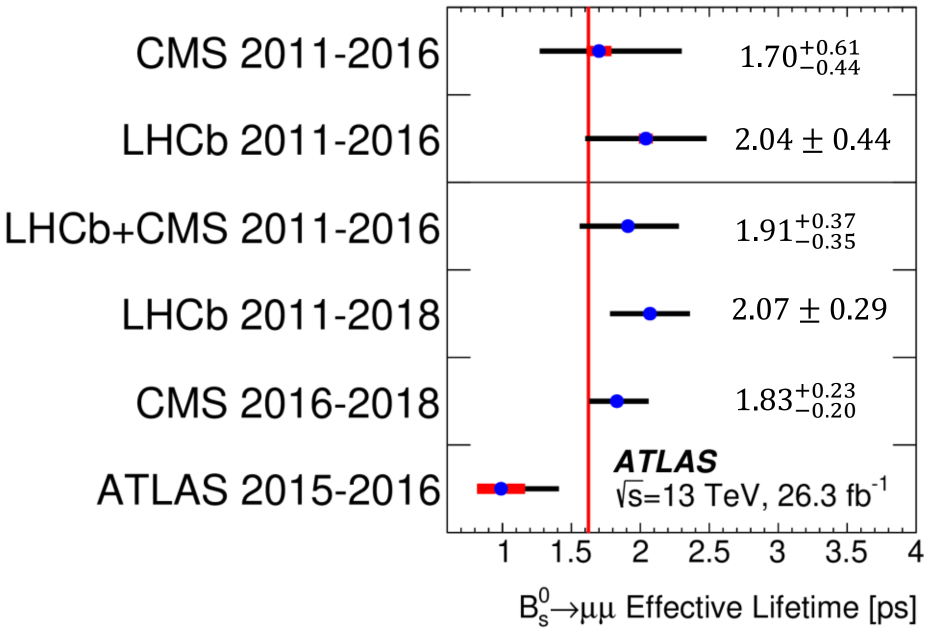
- Measured Value

$$\tau_{\mu\mu}^{\mathrm{Obs}} = 0.99^{+0.42}_{-0.07}\ (\mathrm{stat.}) \pm 0.17\ (\mathrm{syst.})\ \mathrm{ps}$$

$$\tau(B_{s,L}) = 1.427\ ps$$
$$\tau(B_{s,H}) = 1.616\ ps$$

- The result is consistent with the SM prediction.
- Value smaller than the other measurements, which will lower the world average.





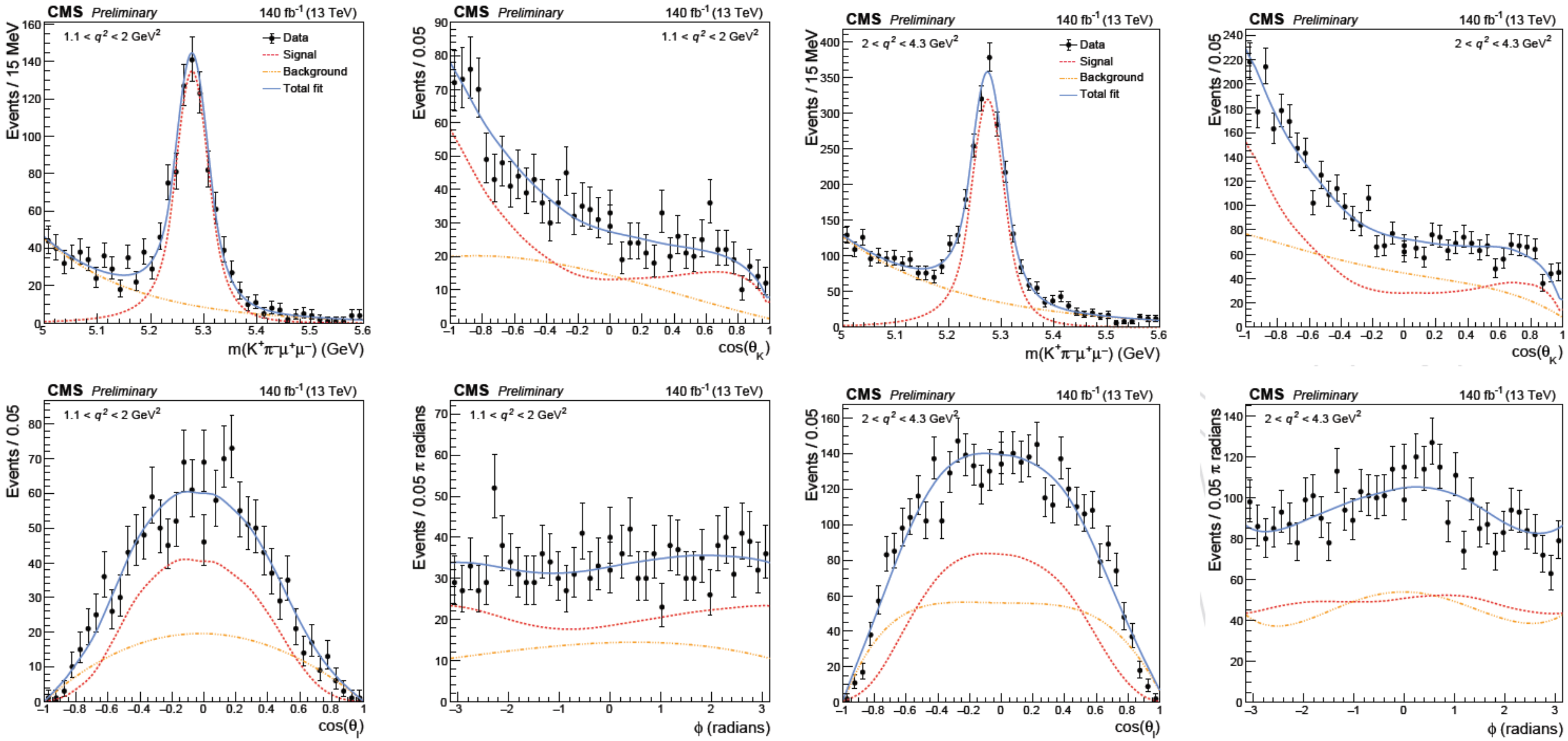
Conclusion

- B rare decay is a sensitive probe to new physics
- Several B anomalies observed in the previous measurements
- $B^0 \rightarrow K^* \mu\mu$ angular measurement by CMS reported
  - Among the most precise measurements of the angular observables
  - Similar effect as LHCb observed in P2 and P5' parameter
- $B_s \rightarrow \mu\mu$ lifetime measurement by ATLAS reported
  - The world average will be more consistent with SM prediction
- More interesting results regarding the rare decays are on the way. Stay tuned ....

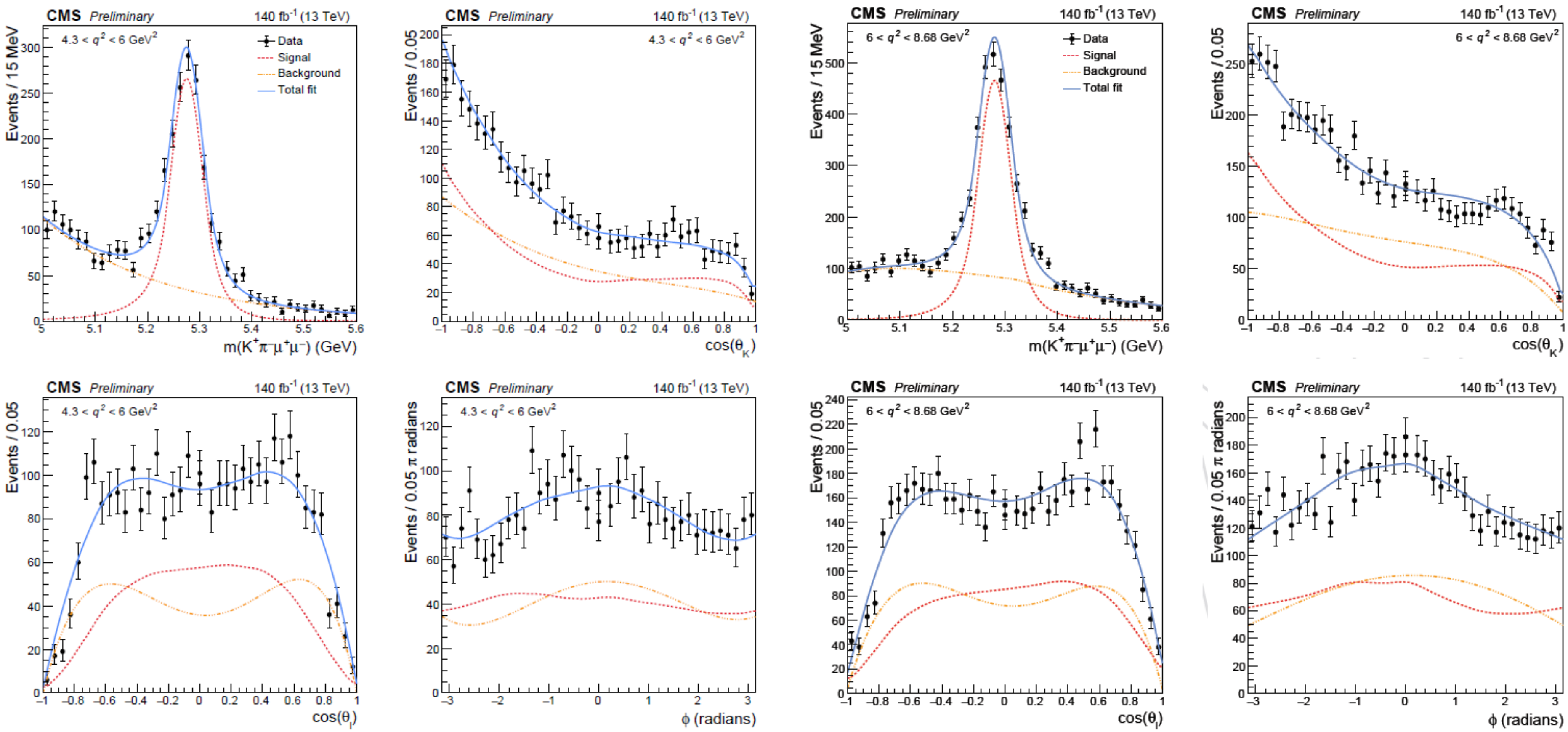
Thank you

Back up

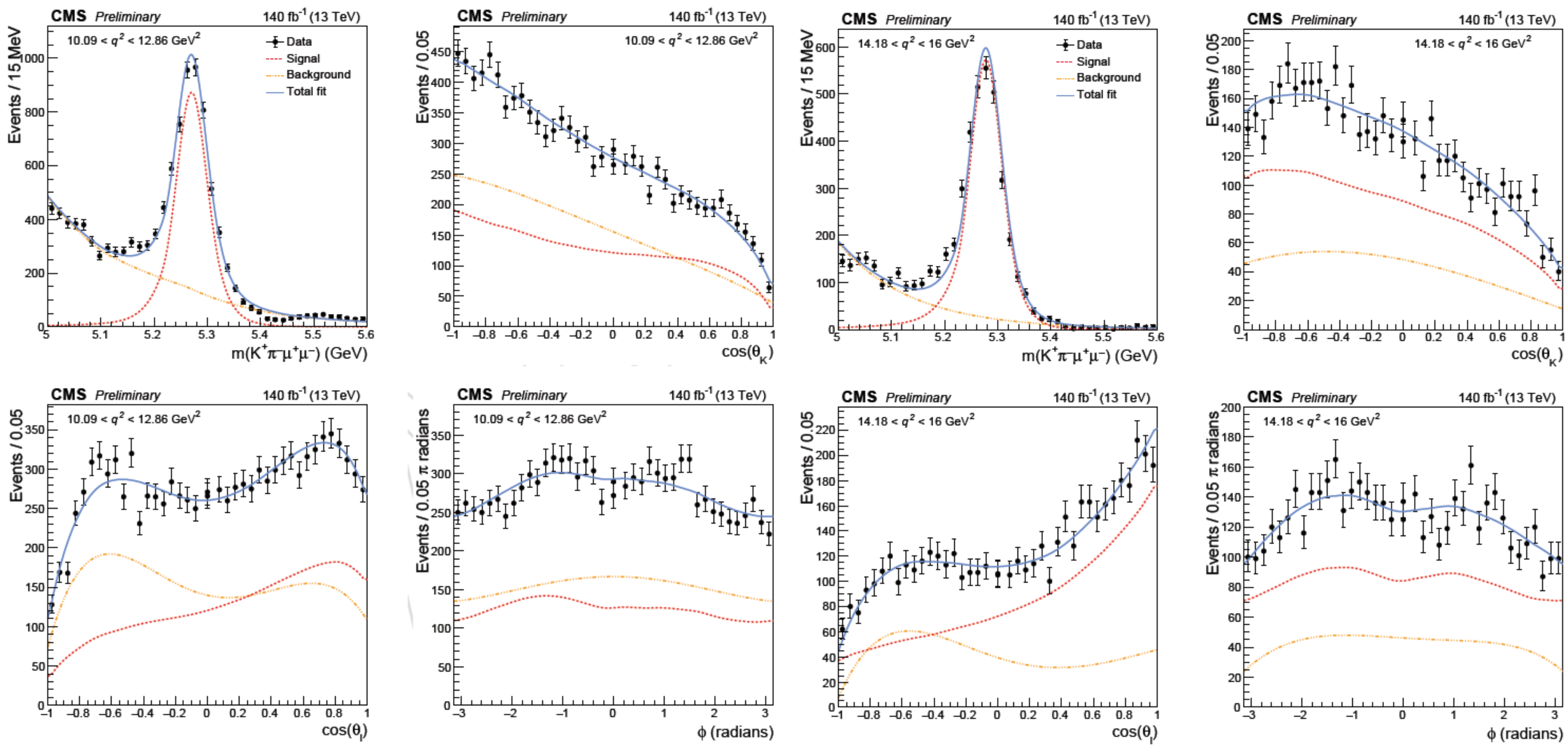
Projections (1)



Projections (2)



Projections (3)



Fit Setup

	Parameter	Range 2016	Range 2017	Range 2018
Signal angular pdf	F_L	$[0, 1]$		
	P_1	$[-1, 1]$		
	P_2	$[-0.5, 0.5]$		
	P_3	$[-0.5, 0.5]$		
	P'_4	$[-\sqrt{2}, \sqrt{2}]$		
	P'_5	$[-\sqrt{2}, \sqrt{2}]$		
	P'_6	$[-\sqrt{2}, \sqrt{2}]$		
	P'_8	$[-\sqrt{2}, \sqrt{2}]$		
	F_S	$[0, 1]$		
	a^i_S	$[-1, 1]$		
Signal mass pdf RT	$\sigma_{RT1}, \sigma_{RT2}, \alpha_{RT1}, \alpha_{RT2}, n_{RT1}, n_{RT2}, f^{RT}$	constr. to MC	constr. to MC	constr. to MC
	m_{RT}	free	free	free
Signal mass pdf WT	$(m_{WT} - m_{RT}), \sigma_{WT}, \alpha_{WT1}, \alpha_{WT2}, n_{WT1}, n_{WT2}, f^{WT}$	constr. to MC	constr. to MC	constr. to MC
Mistag corr. factor	R	constr. to MC	constr. to MC	constr. to MC
Bkg mass shape	slope	free	free	free
Bkg angular shape	various c_i	fixed from sb	fixed from sb	fixed from sb
Yields	Y_S, Y_B	free	free	free

Parameters of interest

Nuisance pars

Systematic Uncertainties

Can be grouped into 3 categories:

dependent on the data or MC statistics:

evaluated by propagating the related statistical uncertainty to the final result

due to possible bias given assumptions/choices in the fit model:

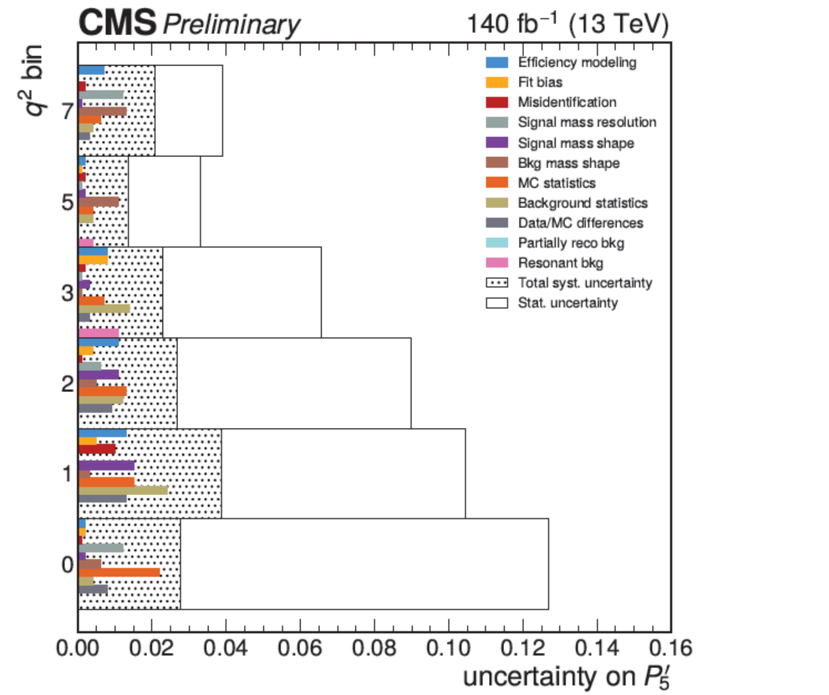
evaluated using alternative assumption(s) in the fit model and taking the difference wrt the nominal result as uncertainty

fit bias: bias introduced by the fit procedure applied in realistic conditions:

evaluated as the difference between the average of the results to signal+bkg sub-samples with data-like stat and the results of the angular fit to the MC sample

Systematic Uncertainties Summary

- Amount of the various contributions varies depending on the q^2 and the parameter under consideration
- Sideband and MC statistics are the dominant systematics on P_5' at low q^2
- Measurement is still statistically limited



Source	F_L ($\times10^{-3}$)	P_1 ($\times10^{-3}$)	P_2 ($\times10^{-3}$)	P_3 ($\times10^{-3}$)	P_4' ($\times10^{-3}$)	P_5' ($\times10^{-3}$)	P_6' ($\times10^{-3}$)	P_8' ($\times10^{-3}$)
Efficiency modeling	1-9	7-44	3-11	0-46	3-87	2-13	5-16	6-28
Fit bias	1-2	0-6	2-62	1-12	9-54	0-8	0-3	0-24
Mistag fraction	0-2	1-4	1-3	0-14	1-5	1-10	0-4	0-12
Signal mass resolution	1-10	1-12	2-11	1-21	4-23	0-12	0-5	0-16
Signal mass shape	0-9	1-22	0-10	3-70	2-16	1-15	0-7	0-91
Background mass shape	0-5	1-16	1-13	0-8	6-30	1-13	0-7	1-10
MC statistics	1-10	5-31	1-64	4-45	5-47	4-22	4-13	10-59
Background statistics	2-6	4-20	1-21	2-16	6-37	4-24	3-9	5-23
Data/MC differences	8-8	0-23	0-16	0-13	0-11	0-13	0-3	0-30
Partially reco bkg	1-1	1-1	0-0	1-1	25-25	0-0	0-0	2-2
Resonant bkg	0-1	0-6	0-5	0-2	0-30	0-11	0-5	0-12

Results of Parameters