Prospects for rare decays at ATLAS and CMS

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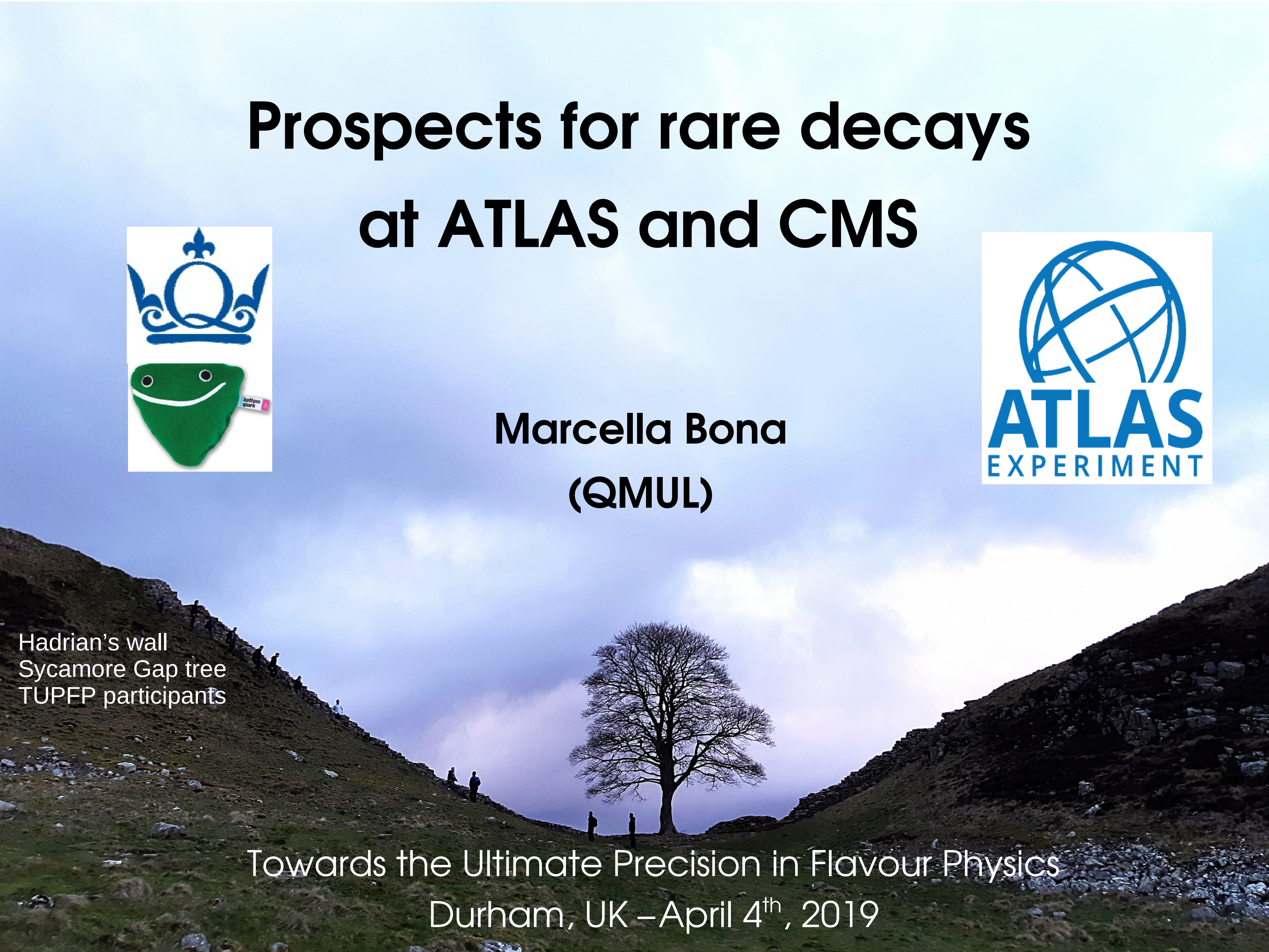
(QMUL)



Hadrian's wall
Sycamore Gap tree
TUPFP participants

Towards the Ultimate Precision in Flavour Physics
Durham, UK – April 4th, 2019

B physics in ATLAS & CMS

- **CMS**
  - *“Measurement of the B0s μ+μ− Branching Fraction and Search for B^0→ μ+μ− with the CMS experiment”*, Nature 522 (2015) 68
  - *“Angular analysis of the decay $B^+ \to K^+\mu^+\mu^-$ in proton-proton collisions at √s= 8 TeV”*, A_{FB}, F_H: PRD 98 (2018) 112011
  - *“Measurement of angular parameters from the decay $B^0 \to K^{0*} \mu^+\mu^-$ in proton-proton collisions at √s= 8 TeV”*, P_1,P_5’: Phys. Lett. B 781 (2018) 517, A_{FB}, F_L and BF: Phys. Lett. B 753, 424 (2016)
- **ATLAS**
  - “Angular analysis of the decay $B^0 \to K^*\mu^+\mu^-$”, JHEP10 (2018) 047
  - “Study of the rare decays of B^0_s and B^0 into muon pairs from data collected during the LHC Run 1 with the ATLAS detector”, EPJC 76 (2016) 513
  - “Study of the rare decays of B^0_s and B^0 into muon pairs from data collected during 2015 and 2016 with the ATLAS detector”, arXiv: 1812.03017, accepted by JHEP

B physics in ATLAS and CMS

- Prospects:
  "Opportunities in Flavour Physics at the HL-LHC and HE-LHC" arXiv:1812.07638
  - **CMS**: *"Study of the expected sensitivity to the P_5' parameter in the $B^0 \to K^{0*}\mu^+\mu^-$ decay at the HL-LHC"*, CMS-PAS-FTR-18-033, 2018. http://cds.cern.ch/record/2651298.
  - **CMS**: *"Measurement of rare $B \to \mu^+\mu^-$ decays with the Phase-2 upgraded CMS detector at the HL-LHC"*, CMS-PAS-FTR-18-013, 2018, http://cdsweb.cern.ch/record/2650545.
  - **ATLAS**: *"$B_d^0 \to K^{0*}\mu\mu$ angular analysis prospects with the upgraded ATLAS detector at the HL-LHC"*, ATL-PHYS-PUB-2019-003, 2019, https://cds.cern.ch/record/2654519.
  - **ATLAS**: *"Prospects for the $B(B_{(s)} \to \mu^+\mu^-)$ measurements with the ATLAS detector in the Run 2 and HL-LHC data campaigns"*, ATL-PHYS-PUB-2018-005, 2018. https://cds.cern.ch/record/2317211.

rare B decays $B_{(s)} \to \mu^+\mu^-$

ATLAS:

EPJ C76 (2016) 513, arXiv:1604.04263

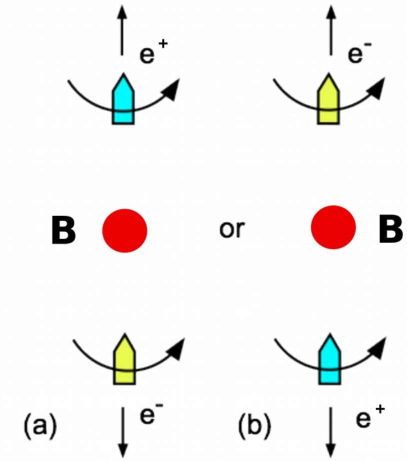
arXiv:1812.03017, accepted by JHEP

CMS

Nature (2015) 14474, arXiv:1411.4413

Motivations and predictions

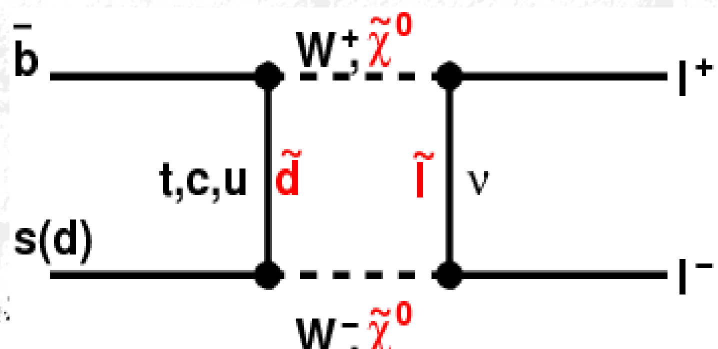
- Decays of B^0 and B^0_S into two leptons have to proceed through Flavour Changing Neutral Currents (FCNC)
  → forbidden at tree level in the SM
- In addition, they are CKM and helicity suppressed.
- Within the SM, they can be calculated with small theoretical uncertainties of order 6-8%

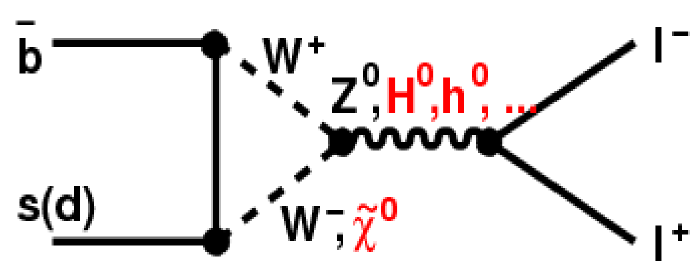


meson	Lepton type		
type	e	μ	τ
B^0	$(2.48 \pm 0.21)10^{-15}$	$(1.06 \pm 0.09)10^{-10}$	$(2.22 \pm 0.19)10^{-8}$
B^0_s	$(8.54 \pm 0.55)10^{-14}$	$(3.65 \pm 0.23)10^{-9}$	$(7.73 \pm 0.49)10^{-7}$

Bobeth et al., PRL 112 (2104) 101801 [includes NLO EM and NNLO QCD corrections]

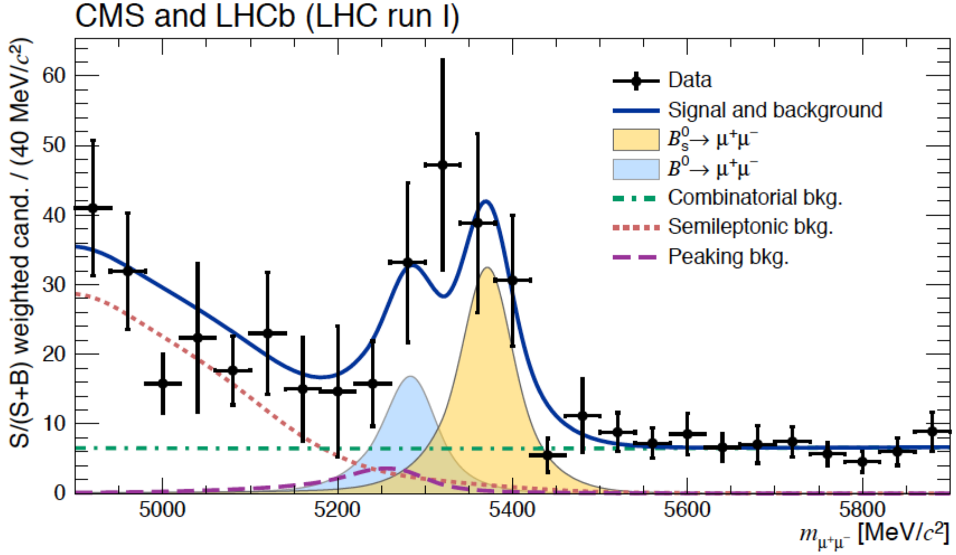
- Perfect ground for indirect new physics searches:
  - virtual new particles can contribute to the loop
  - both enhancement and suppression effects are possible





CMS analysis on full Run 1 data (with LHCb)

Simultaneous
20 bin
CMS+LHCb fit



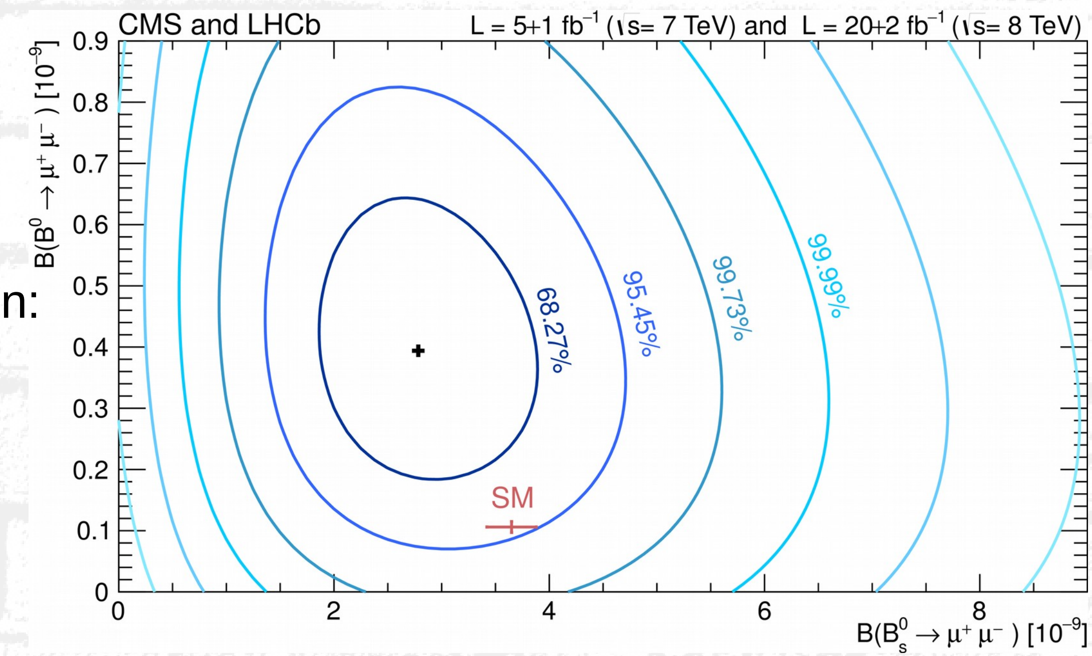
CMS and LHCb,
Nature (2015) 14474
arXiv:1411.4413

6.2σ (7.4σ exp.)

$B(B^0_s \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$

$B(B^0_s \to \mu^+\mu^-) = 3.0^{+1.0}_{-0.9} \times 10^{-9}$

3.2σ (0.8σ exp.)



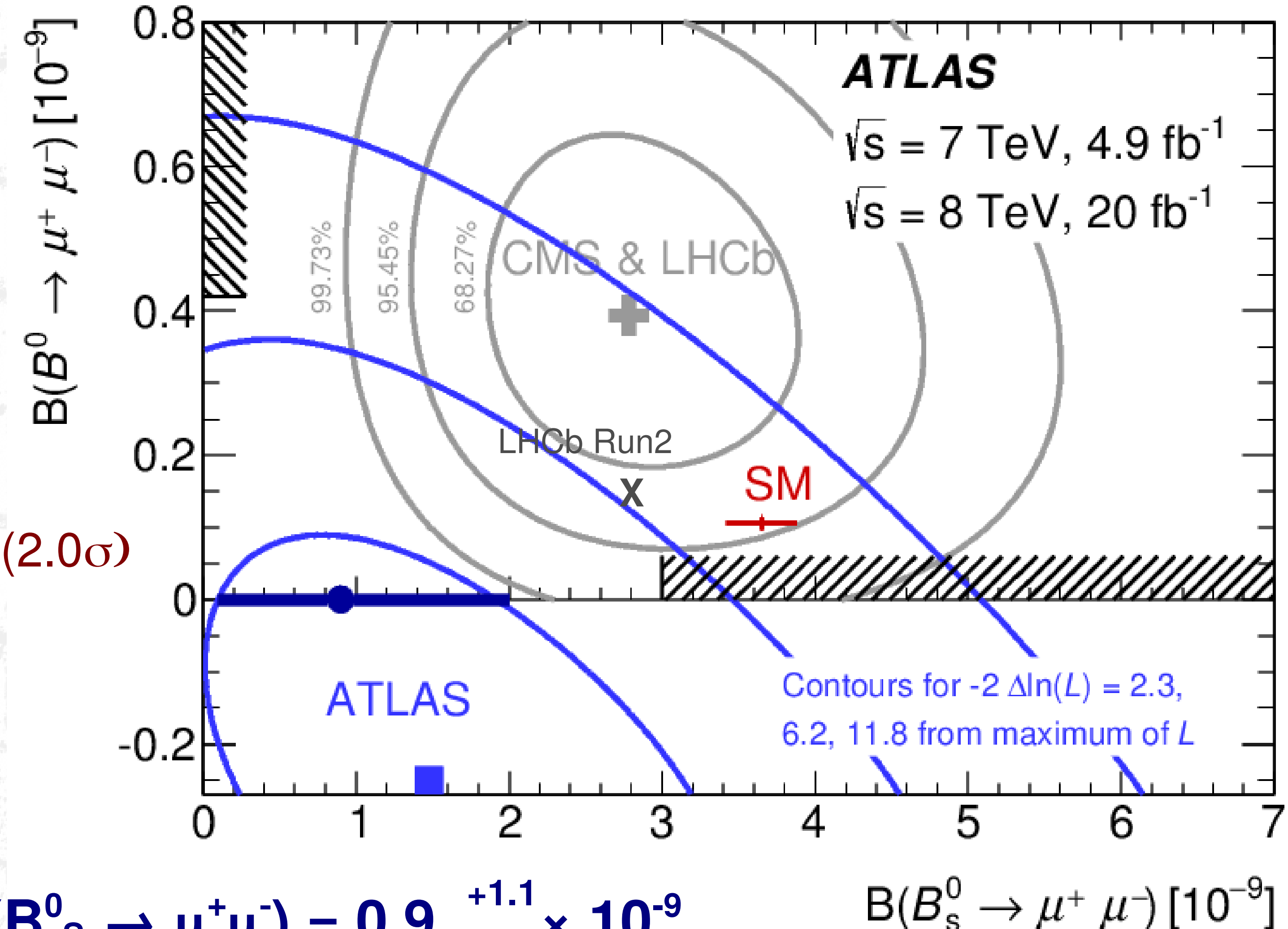
2016+2017 CMS analysis in preparation:

- Dedicated triggers
- New pixel detector -> better tracking
- Improved MVA-based muon-ID
- Combined BF and lifetime analysis
- Expect.: 433 B_s / 54 B_d cand. @ end Run 2 (assuming 300 fb -1)

ATLAS analysis on full Run 1 data

ATLAS, EPJ C76 (2016) 513, arXiv:1604.04263

$B(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL



compatibility of the simultaneous fit with the SM:
p-value = 0.048 (2.0σ)

reduced tension in B^0 with the SM with the Run2 LHCb result
arXiv:1703.05747

$B(B^0_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$

ATLAS analysis on 2015-2016 Run 2 data

ATLAS arXiv:1812.03017

- 36.2/fb dataset of 2015-2016 data taking:
  - effectively 26.3/fb for B → μ μ
  - 15.1/fb for B → J/ψΦ and B → J/ψK
- Trigger: higher thresholds [4-6 GeV] than in Run1,
  - Lxy > 0 request at trigger level

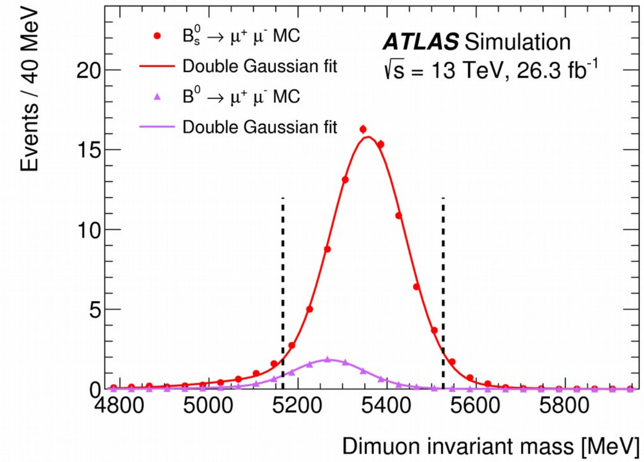
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}} \times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

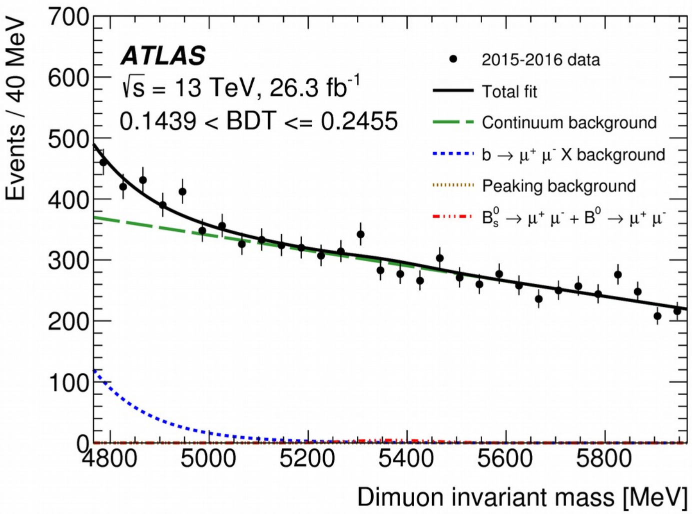
- correction for the different hadronisation probabilities for B^0_S and B^0 vs $B^\pm$
- include the $B^\pm$ and J/ψ branching fractions
- correction for the efficiencies of the two channels
- normalisation yield and efficiency ratio define the factor:

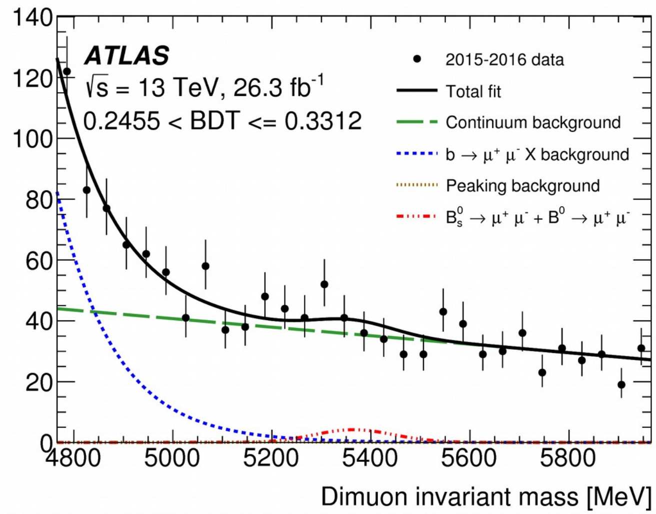
$$\mathcal{D}_{\text{norm}} = N_{J/\psi K^+} \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}} \right)$$

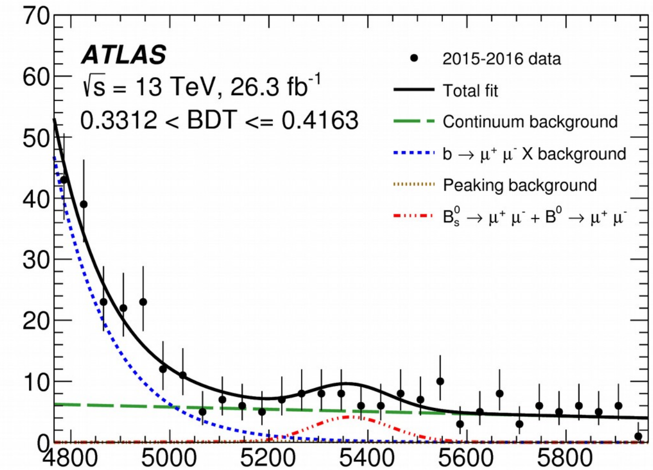
Signal yield extraction

- yields unconstrained:
  - $N_S = 80 \pm 22$ and $N_d = -12 \pm 20$
- expected from the SM:
  - $N_S = 91 \pm$ and $N_d = 10$





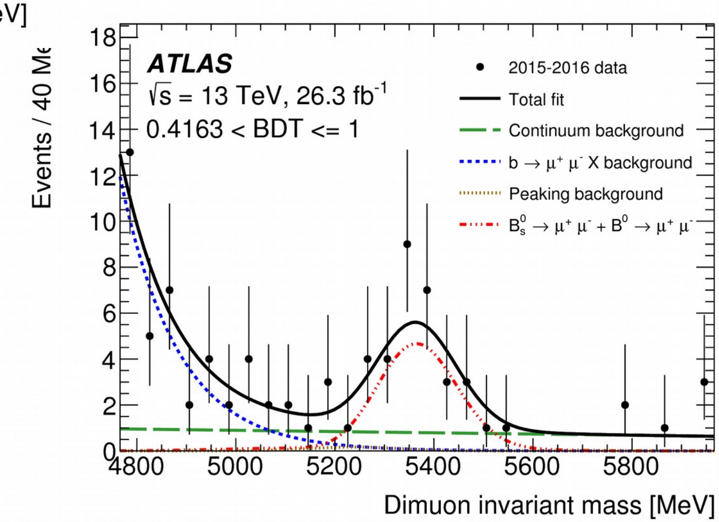




- consistent with Standard Model predictions
- likelihood maximum:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.90+0.48}_{-0.83-0.31}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(-1.3^{+2.2+0.7}_{-1.9-0.8}\right) \times 10^{-10}$$

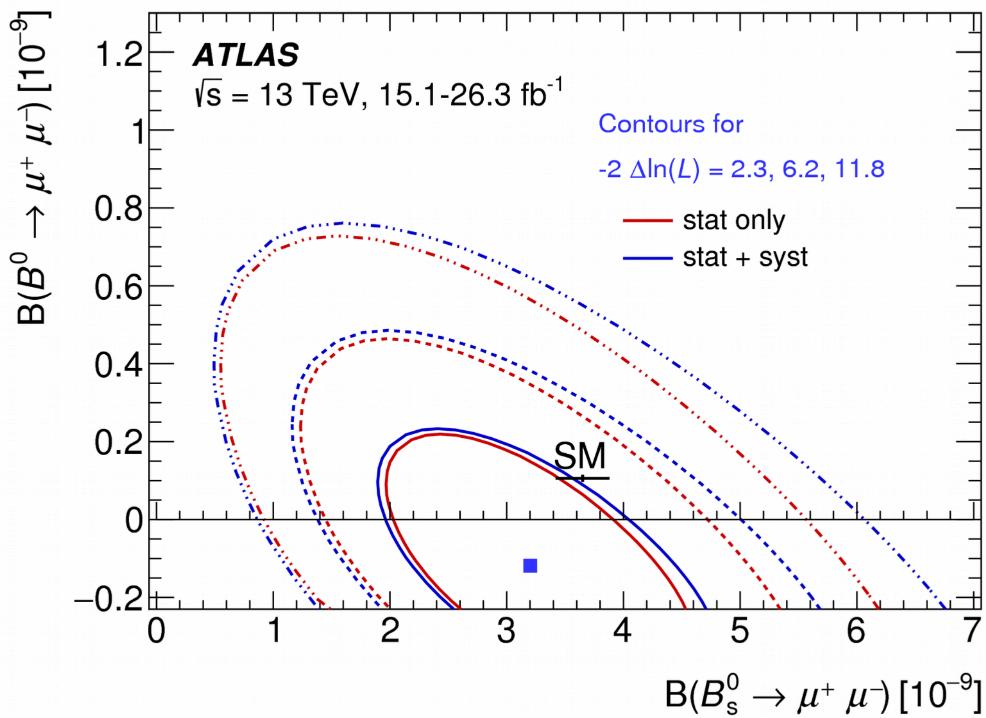


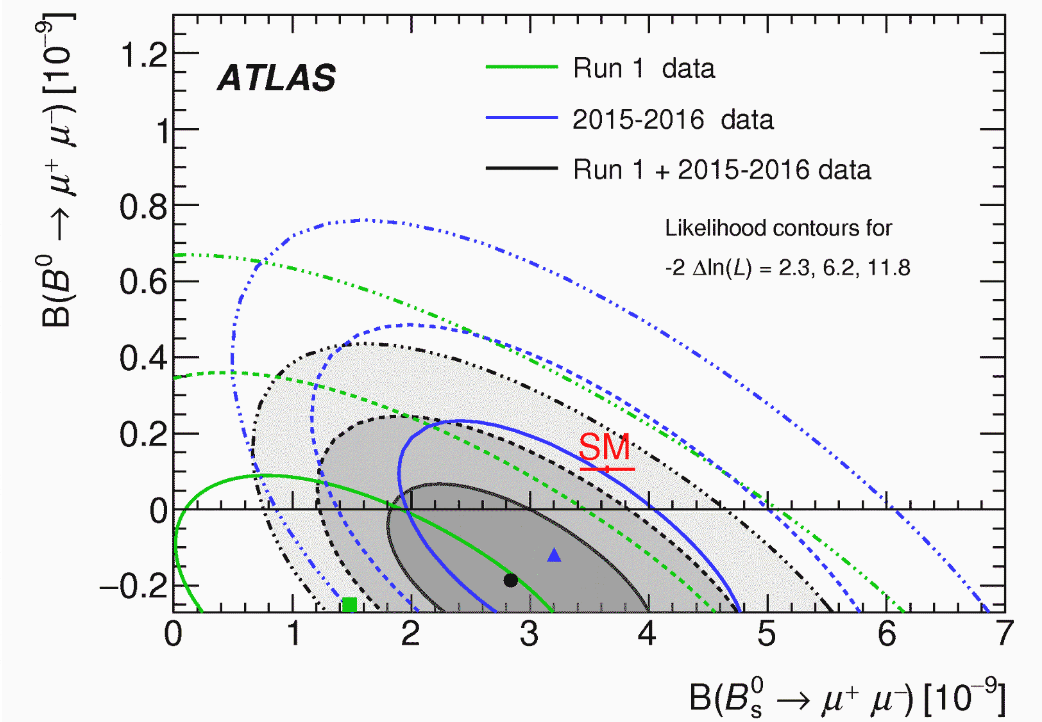
Combination of Run 1 and Run 2 results at ATLAS

Neyman Contours yield for Run 2:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9} = \left(3.2^{+1.1}_{-1.0}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$$ @ 95% CL





Run 1 + Run 2 (2015+2016) combination:
Compatible with SM at 2.4σ

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

Angular analysis on $B \to K^{*}\mu\mu$

ATLAS

JHEP 10 (2018) 047, arXiv:1805.04000

CMS

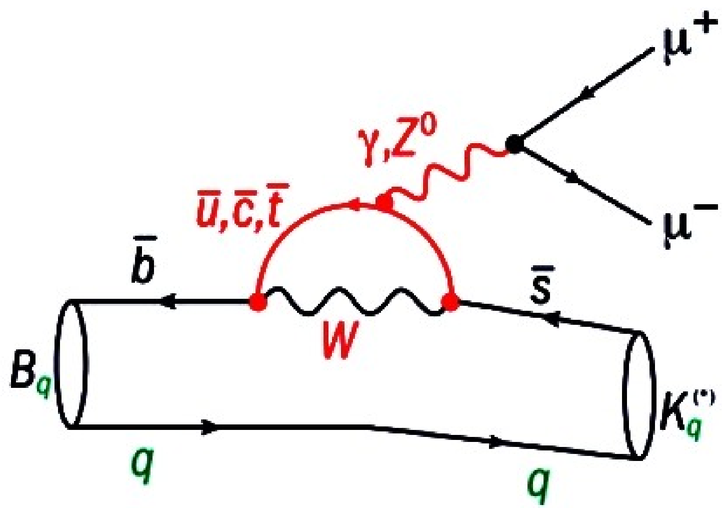
2011 data: Phys. Lett. B 727 (2013) 77

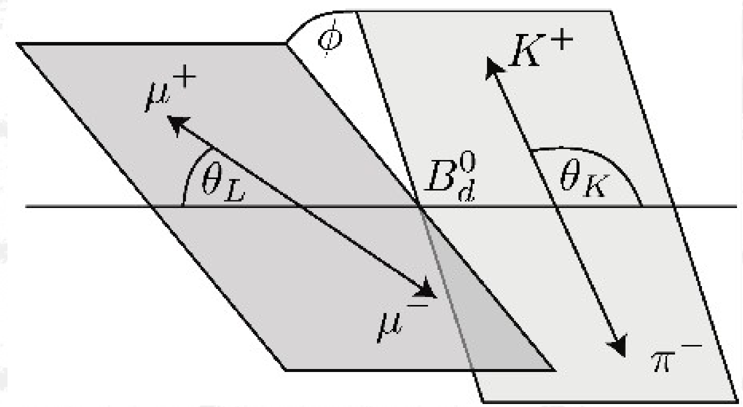
2012 data: Phys. Lett. B 753 (2016) 424

PLB 781 (2018) 517, arXiv:1710.02846

Angular analysis on $B \to K^*\mu\mu$

- another way to look at FCNC: $b \to s$ transition with a BR ~ $1.1\ 10^{-6}$
- angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams
  - allows measuring a large set of angular parameters sensitive to Wilson coefficients $C^{(\prime)}_7$, $C^{(\prime)}_9$, $C^{(\prime)}_{10}$, $C^{(\prime)}_{S,P}$





- decay described by three angles (θ_L, θ_K, ϕ) and the di-muon mass squared q^2 → the angular distribution is analysed in finite bins of q^2 as a function of θ_L, θ_K and ϕ.
- LHCb reports a 3.4σ deviation from the SM.

JHEP 02 (2016) 104
arXiv:1512.04442

Angular analysis on $B \to K^*\mu\mu$

- B^0 flavour eigenstate can be identified through the $K^* \to K^- \pi^+$ decay
- angular distribution given by:

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big].$$

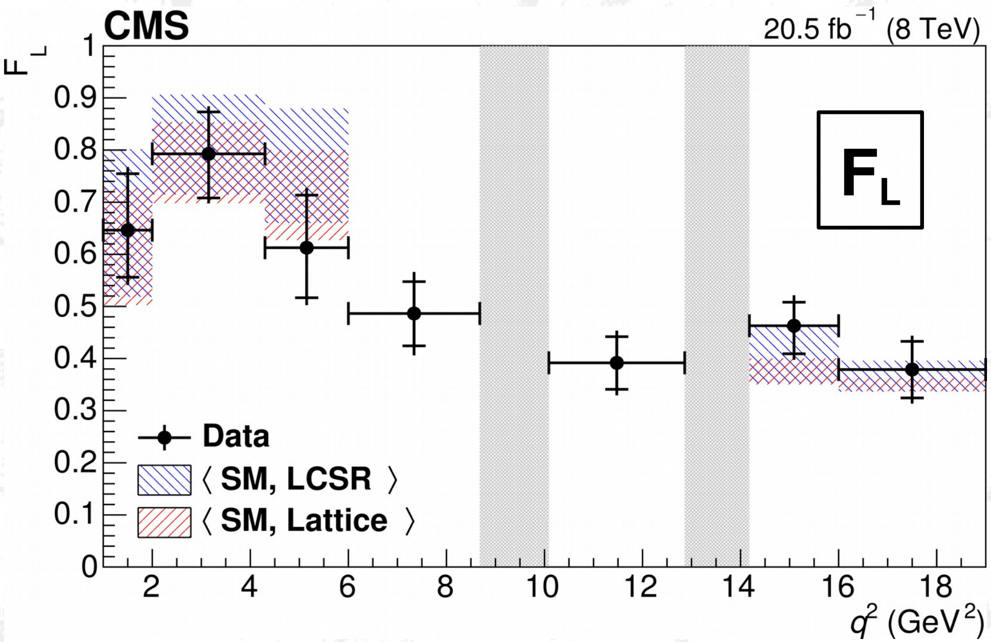
- the S parameters are translated into the $P^{(\prime)}$ parameters via

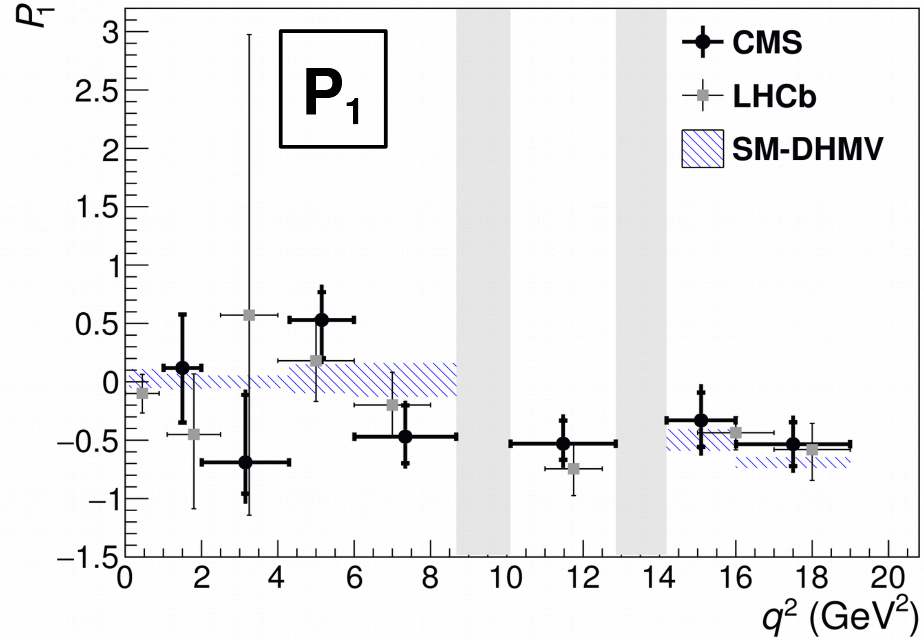
$$P_1 = \frac{2S_3}{1-F_L} \qquad P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

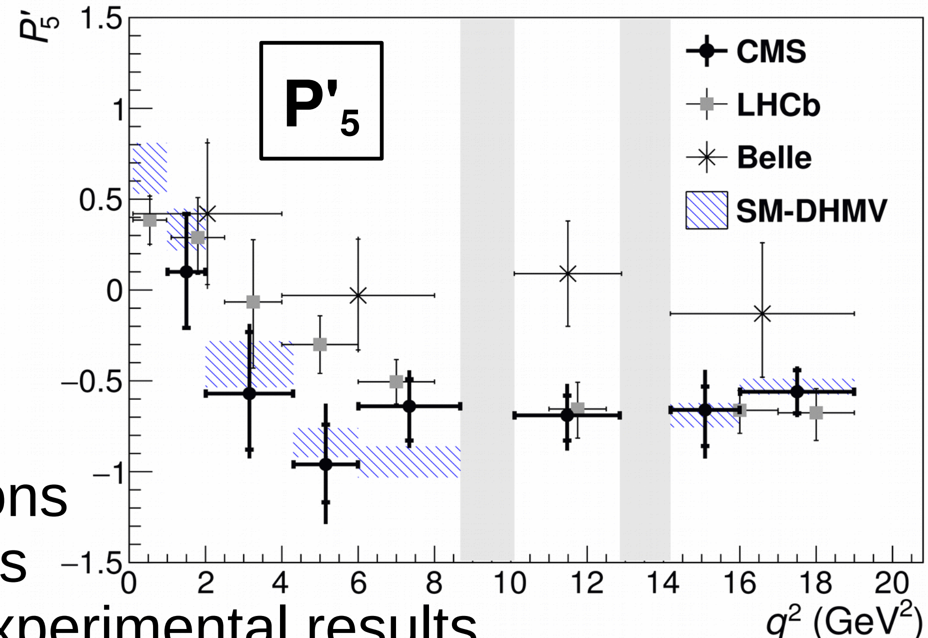
- the $P^{(\prime)}$ parameters are expected to have a reduced dependence on the hadronic form factors.
- ATLAS and CMS need to fold the angular distribution via trigonometric relations to reduce the number of free parameters

Angular analysis results at CMS

- No deviations from SM prediction



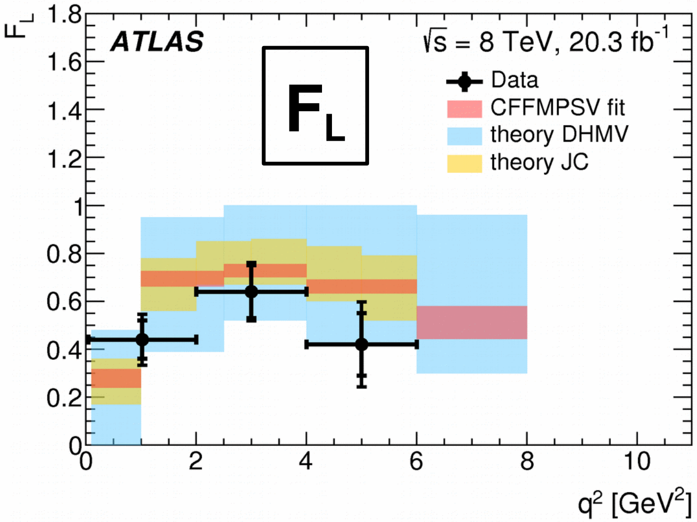


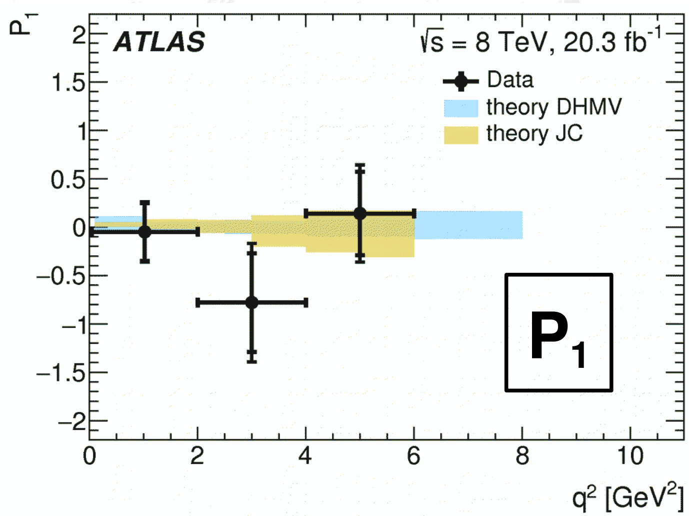


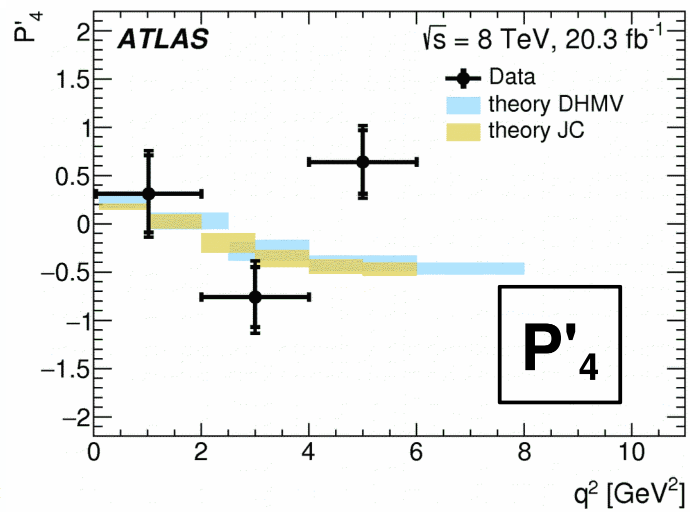
- Two steps: A_{FB} and F_L / P_1 and P_5'
- SM-DHMV prediction computed
  - using soft form factors + parametrised power corrections
  - hadronic charm-loop from calculations
- results compatible with SM predictions
- no significant deviations from other experimental results

Angular analysis results at ATLAS

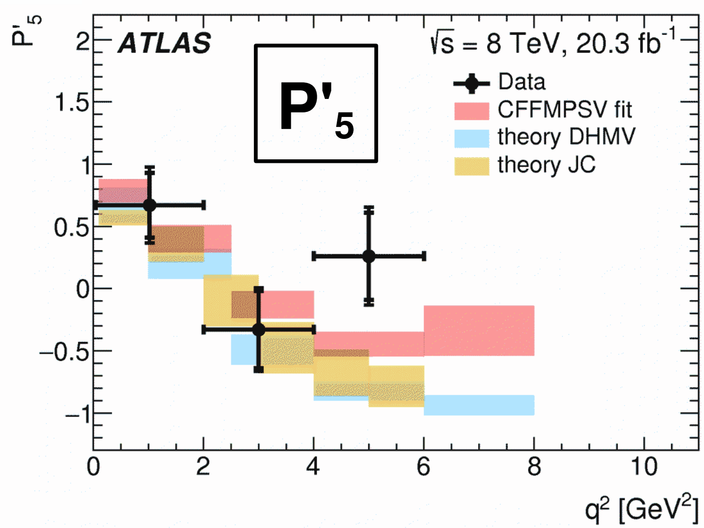
- Two steps: mass fit / angular fits for F_L, S_3, and S_j (j=4,5,7,8)
- Results are compatible with theoretical calculations & fits:







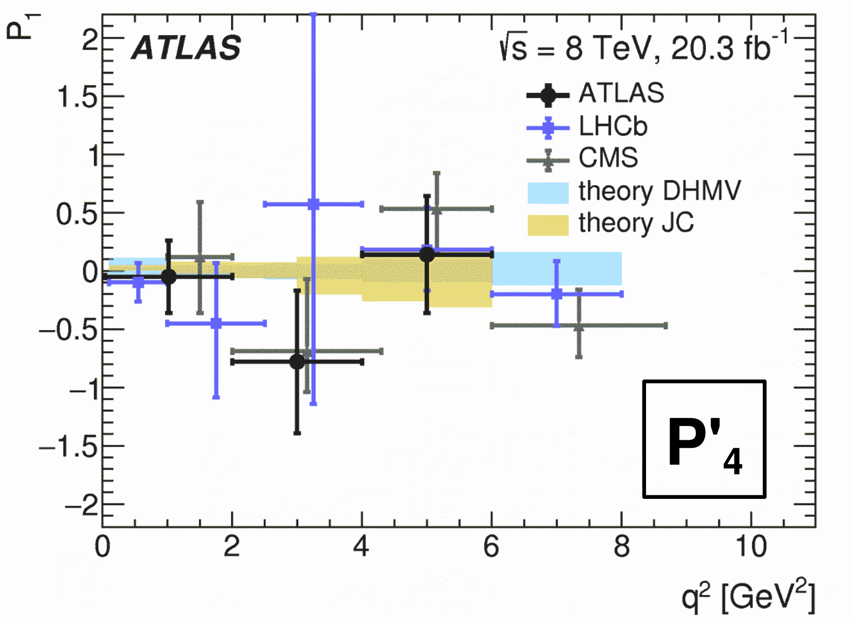
q^2 [GeV^2]	P_1	P'_4	P'_5
[0.04, 2.0]	$-0.05 \pm 0.30 \pm 0.08$	$0.31 \pm 0.40 \pm 0.20$	$0.67 \pm 0.26 \pm 0.16$
[2.0, 4.0]	$-0.78 \pm 0.51 \pm 0.34$	$-0.76 \pm 0.31 \pm 0.21$	$-0.33 \pm 0.31 \pm 0.13$
[4.0, 6.0]	$0.14 \pm 0.43 \pm 0.26$	$0.64 \pm 0.33 \pm 0.18$	$0.26 \pm 0.35 \pm 0.18$
[0.04, 4.0]	$-0.22 \pm 0.26 \pm 0.16$	$-0.30 \pm 0.24 \pm 0.17$	$0.32 \pm 0.21 \pm 0.11$
[1.1, 6.0]	$-0.17 \pm 0.31 \pm 0.13$	$0.05 \pm 0.22 \pm 0.14$	$0.01 \pm 0.21 \pm 0.08$
[0.04, 6.0]	$-0.15 \pm 0.23 \pm 0.10$	$0.05 \pm 0.20 \pm 0.14$	$0.27 \pm 0.19 \pm 0.06$

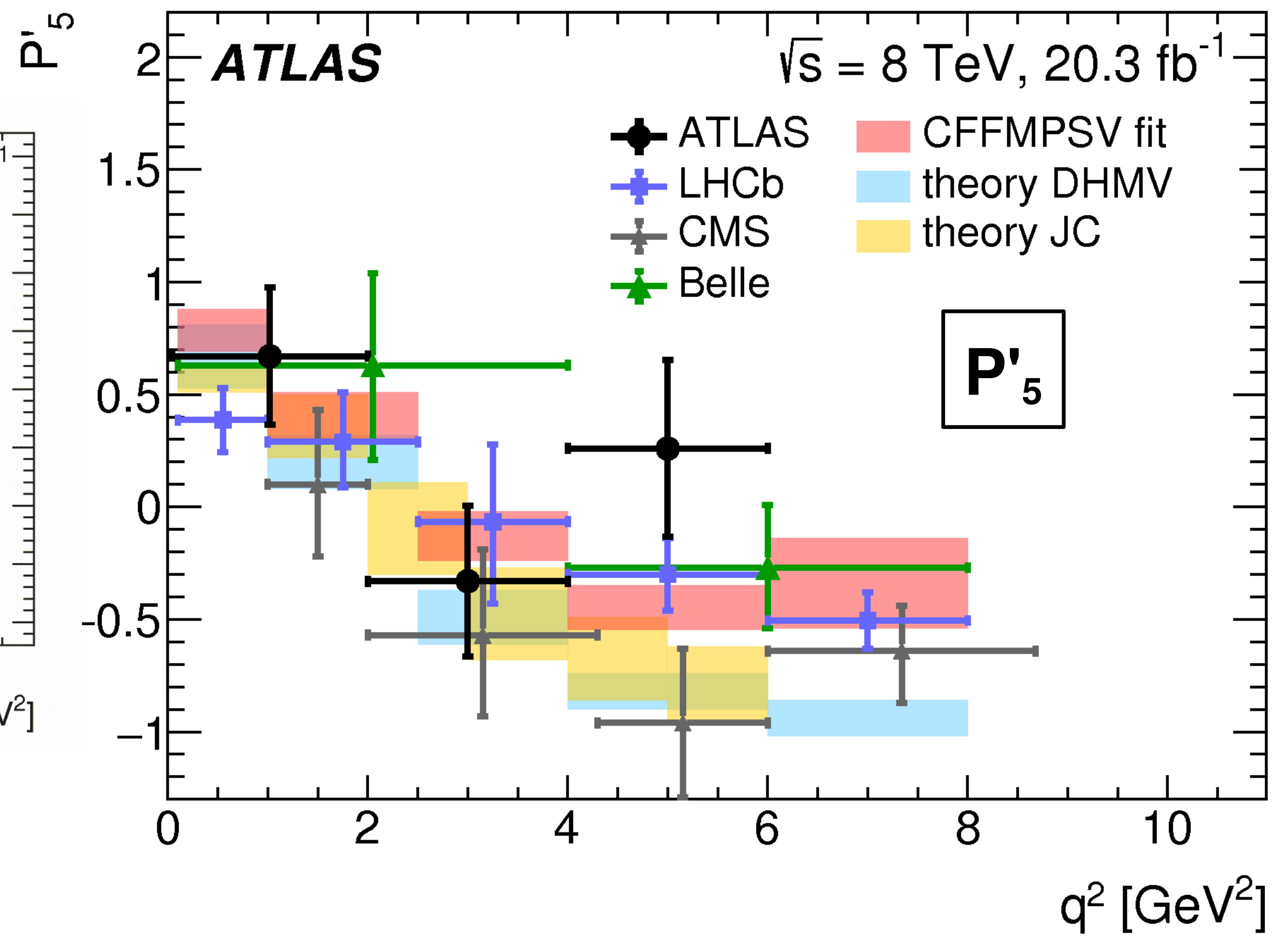


OPE and LHCb data fit: CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
QCD factorisation: DMVH: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.

Angular analysis results at ATLAS and CMS

- ATLAS gets deviations of about 2.5σ (2.7σ) from DHMV in $P'_4(P'_5)$ in [4,6] GeV^2





CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
DHMV: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.

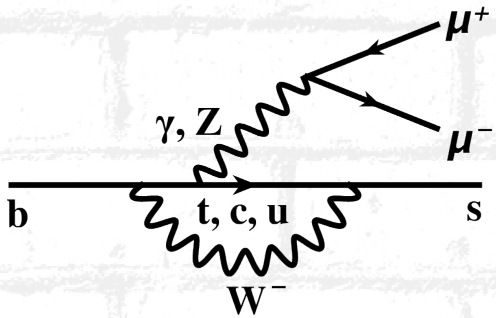
Angular analysis on $B \rightarrow K^{+}\mu\mu$

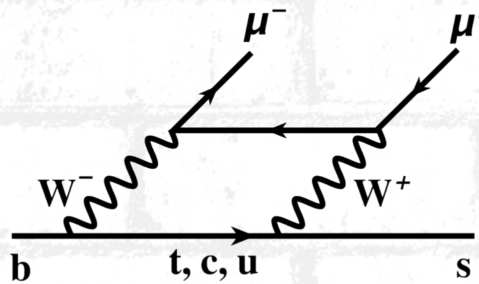
CMS

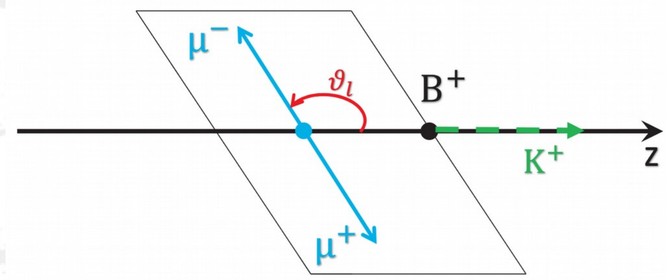
arXiv:1806.00636, PRD 98 (2018) 112011

Angular analysis on B → K⁺μμ at CMS

- another FCNC: b → s transition with a BR ~ 4.5 10^{-7}



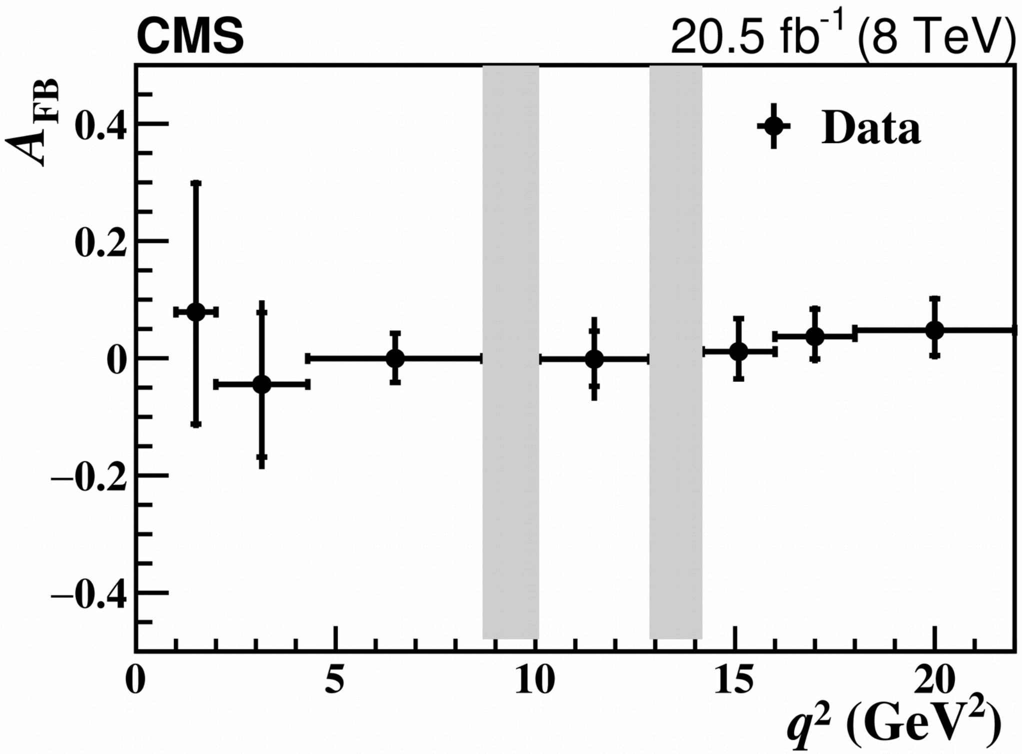


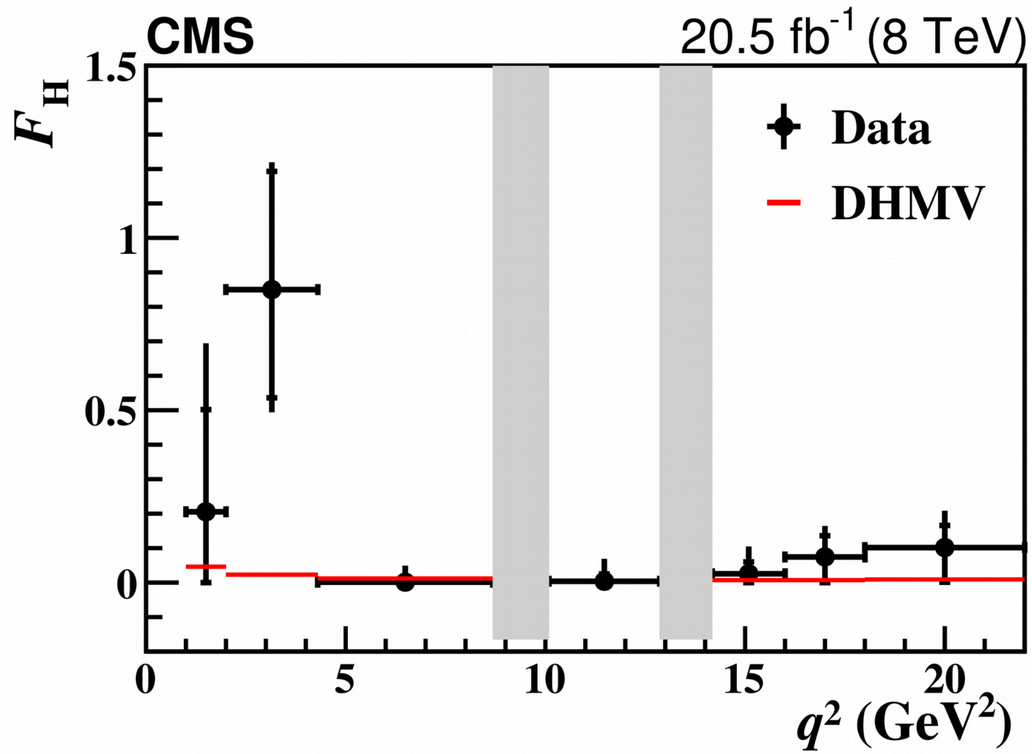


- Fully described by the angle θ_ℓ and $q^2 = M_{\mu\mu}$
- Angular decay rate: $$\frac{1}{d\Gamma/dq^2}\frac{d^2\Gamma}{dq^2 d\cos\theta_l} = \frac{3}{4}(1-F_H)\left(1-\cos^2\theta_\ell\right) + \frac{1}{2}F_H + \mathcal{A}_{FB}\cos\theta_\ell$$
- The forward-backward asymmetry of the muons, A_{FB}, and the angular parameter F_H extracted via angular analysis
- Range [1, 22] GeV^2 of q^2 divided in 9 bins
  - analysis performed in 7 signal bins
  - 2 bins with $B^+ \to J/\psi K^+$ and $B^+ \to \psi' K^+$ are control channels
  - 2 additional special bins: [1-6] GeV^2 (clean predictions) and [1-22] GeV^2 (full signal)

Angular analysis on B → K⁺μμ at CMS

- Inner error bar is statistical uncertainty
- Full bar is total uncertainty
- Results compatible with SM predictions within uncertainties





Prospects for ATLAS & CMS

HL-LHC: arXiv:1812.07638

ATLAS: ATL-PHYS-PUB-2018-005
ATL-PHYS-PUB-2019-003

CMS: CMS-PAS-FTR-18-013
CMS-PAS-FTR-18-033

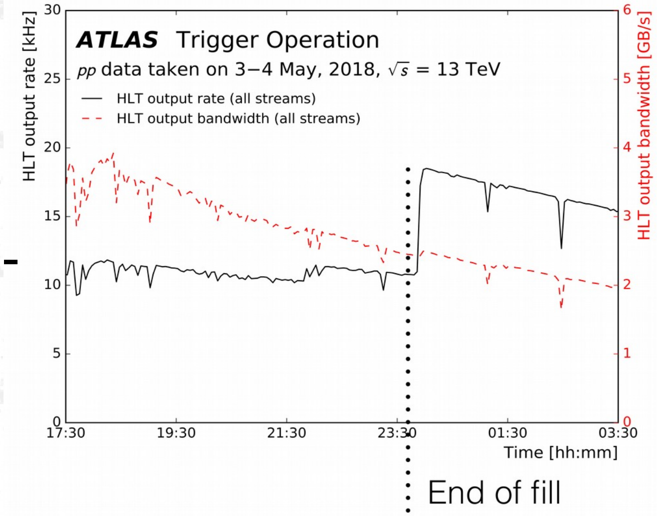
Future Prospects for ATLAS and CMS

- ATLAS&CMS can be competitive on favourable final states
- Di-muon is the quintessence of low-p_T clean signature @LHC
- More statistics will allow to improve these results
- New triggers (e.g., tracking @L1) will allow to deal with 200 PU
- Detector limitation: experiments designed to do something else, namely cover 10-1000 GeV range
  - going below 10 GeV (e.g., with electrons and muons) requires effort
- Limited trigger bandwidth (general purpose vs. dedicated experiments)
- Needed customisation (reconstruction, trigger, etc.) vs working force (<50 people)
- Muons are the essential handle for flavour physics in ATLAS & CMS
- Electron reconstruction at ATLAS & CMS is about matching a track to >= 1 calorimeter deposit
  - At low pT, the track might not even make it to the calorimeter and, in any case, deposits are very low energetic: difficult to disentangle them from noise, pileup, etc
- Growing interest in flavour (thanks to LHCb anomalies) is helping
- Still, there is much to do in view of HL-LHC

Data taking in 2018 for ATLAS and CMS

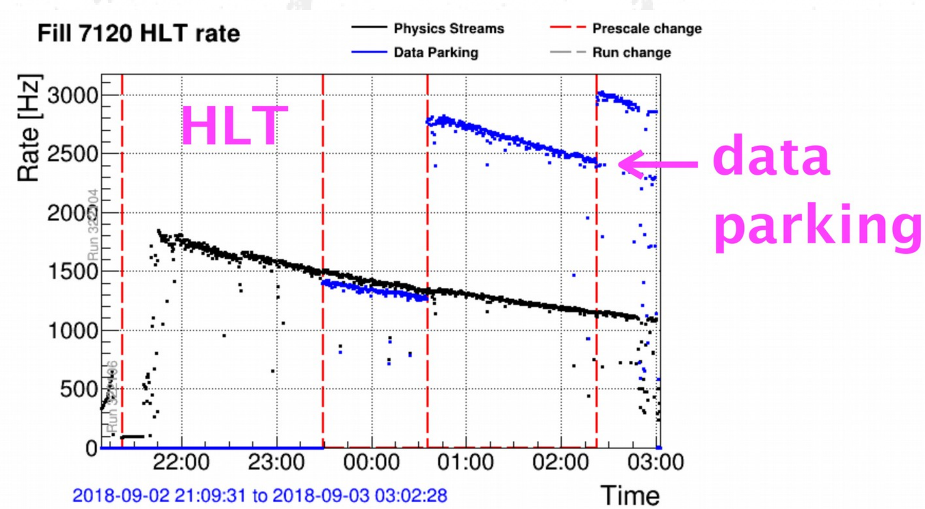
ATLAS data taking in 2018

- After few hours of collisions, L1 rate and HLT processing slots free up thanks to luminosity exponential decay
- High-rate and CPU-intensive triggers can be enabled within the data storage output limitation
- Strategy is used for the Trigger-level Analysis (ATL-DAQ-PUB-2017-003) → total HLT output is only marginally increased by these additional events
- End-of-fill strategy used for triggers for B-physics signals



CMS data taking in 2018

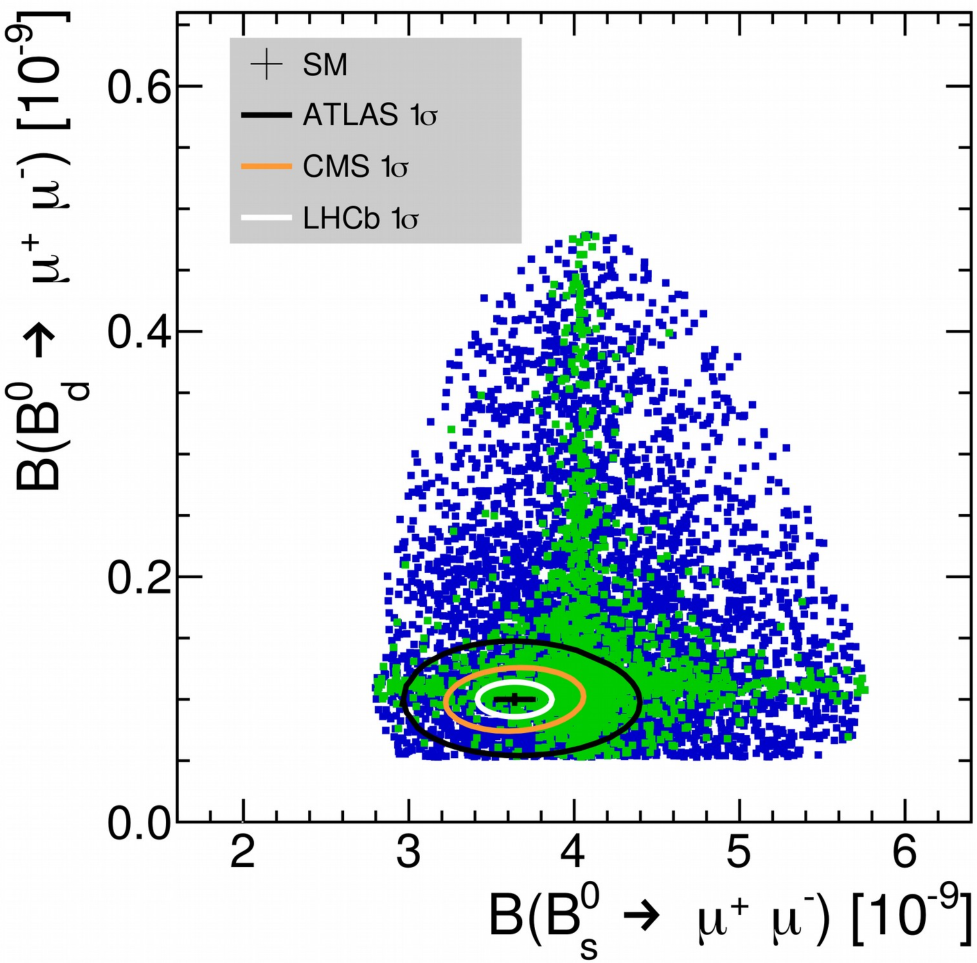
- Smooth running since May: only minor updates to the trigger implemented
- L1 trigger rate → 95 kHz at 2×10^{34} cm^{-2}s^{-1}
  - able to lower L1 thresholds for single Egamma, MET, di-tau to improve HLT turn-on curves
- HLT rate → 1.8 kHz at 2×10^{34} cm^{-2}s^{-1}
  - averages 1.1 kHz over 12h fill
- "parking" an unbiased sample of B mesons
  - so far recorded over 9B events



Prospects on $B_{(s)} \rightarrow \mu^+\mu^-$ at HL-LHC

arXiv:1812.07638

- Theory prediction limited by $|V_{cb}|$
- Experimental uncertainty on B_s dominated by f_s/f_d
- Mass resolution improvements will help reduce the B_s-B_d mass correlation
- Additional information from measurements of the effective lifetime and time-dependent CP asymmetry
  - Sensitive to NP from scalar and pseudo-scalar sectors
  - Complementary to BR
- Inclusion of $B_s \rightarrow \mu\mu\gamma$ studies
  - Sensitive to extra effective operators (O_7, O_9, O_{10})
  - No helicity suppressed (one order of magnitude gained)

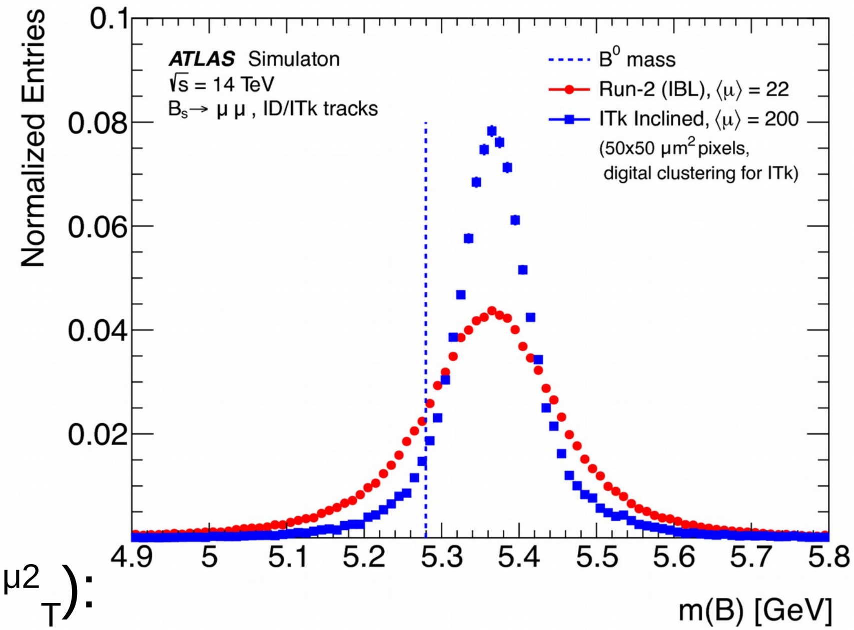


Prospects on $B_{(s)} \to \mu^+\mu^-$ at HL-LHC at ATLAS

ATL-PHYS-PUB-2018-005

Study based on the Run-1 analysis.

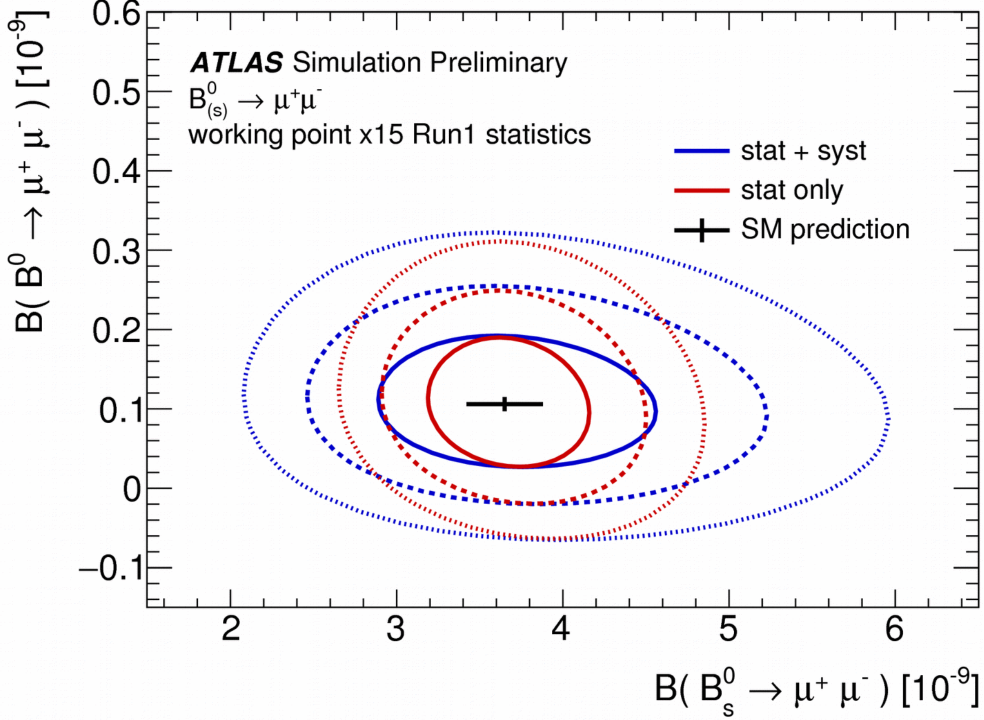
- Yield extrapolated for the total expected Run 2 yield, and then for 3/ab
- Central value from the the SM expectation.
- Same selection and reconstruction eff / same signal/background ratio
- The tracker upgrade improves vertex and mass determination, partly enhanced by the increased muon trigger momentum thresholds.
- The signal mass resolution included



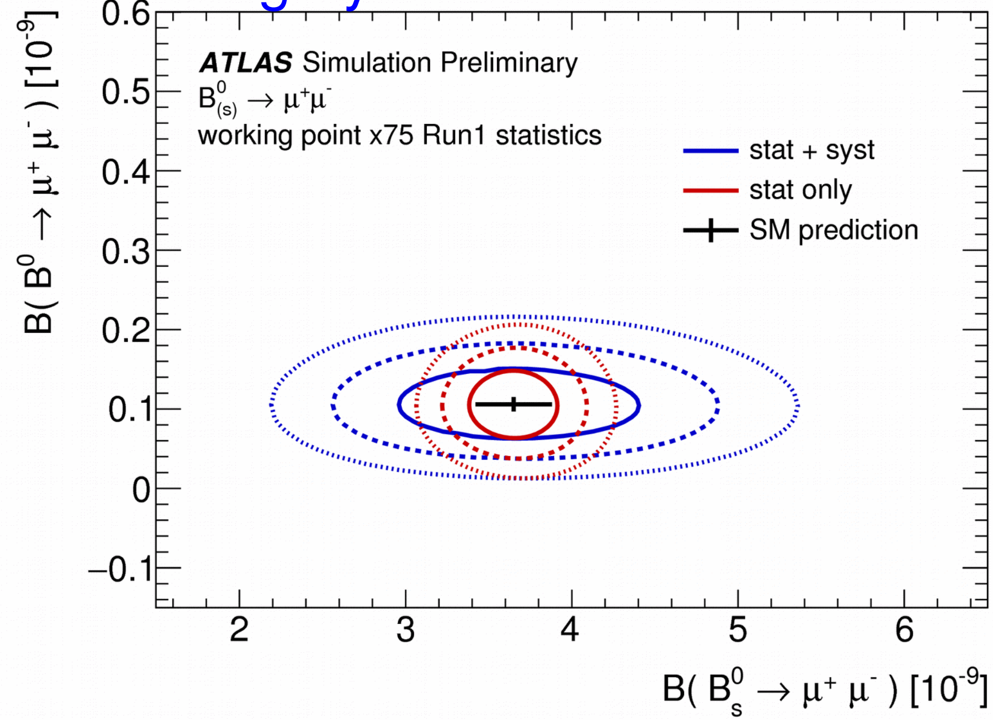
- Full Run 2: assuming 130/fb
  - σ(bb): 8 TeV → 13/14 TeV → x1.7
  - 2MU6||MU6_MU4 topological triggers (6 GeV p_T thresholds)
  - Estimate N(Run 2) ~7 x N(Run 1)
- HL-LHC → 3 trigger scenarios: dimuon transverse momentum thresholds ($p^{\mu 1}_T$, $p^{\mu 2}_T$):
  - Conservative: (10 GeV, 10 GeV) → ×15 Run 1 statistics;
  - Intermediate: (6 GeV, 10 GeV) → ×60 Run 1 statistics;
  - High-yield: (6 GeV, 6 GeV) → ×75 Run 1 statistics.

Prospect on rare B decays $B_{(s)} \to \mu^+\mu^-$ at ATLAS

Conservative



High-yield



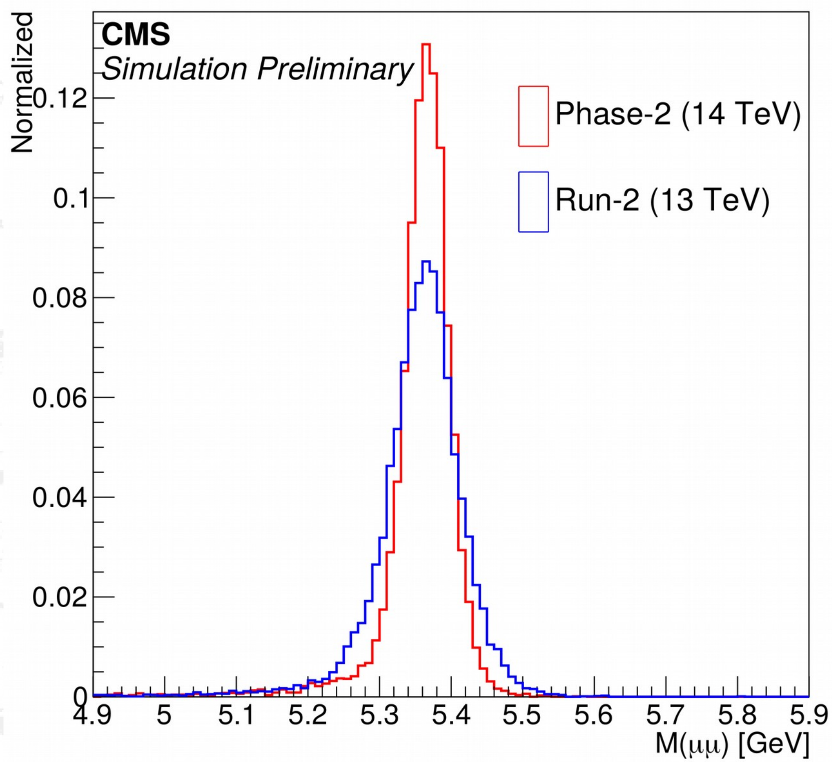
	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
	stat $[10^{-10}]$	stat + syst $[10^{-10}]$	stat $[10^{-10}]$	stat + syst $[10^{-10}]$
Run 2	7.0	8.3	1.42	1.43
HL-LHC: Conservative	3.2	5.5	0.53	0.54
HL-LHC: Intermediate	1.9	4.7	0.30	0.31
HL-LHC: High-yield	1.8	4.6	0.27	0.28

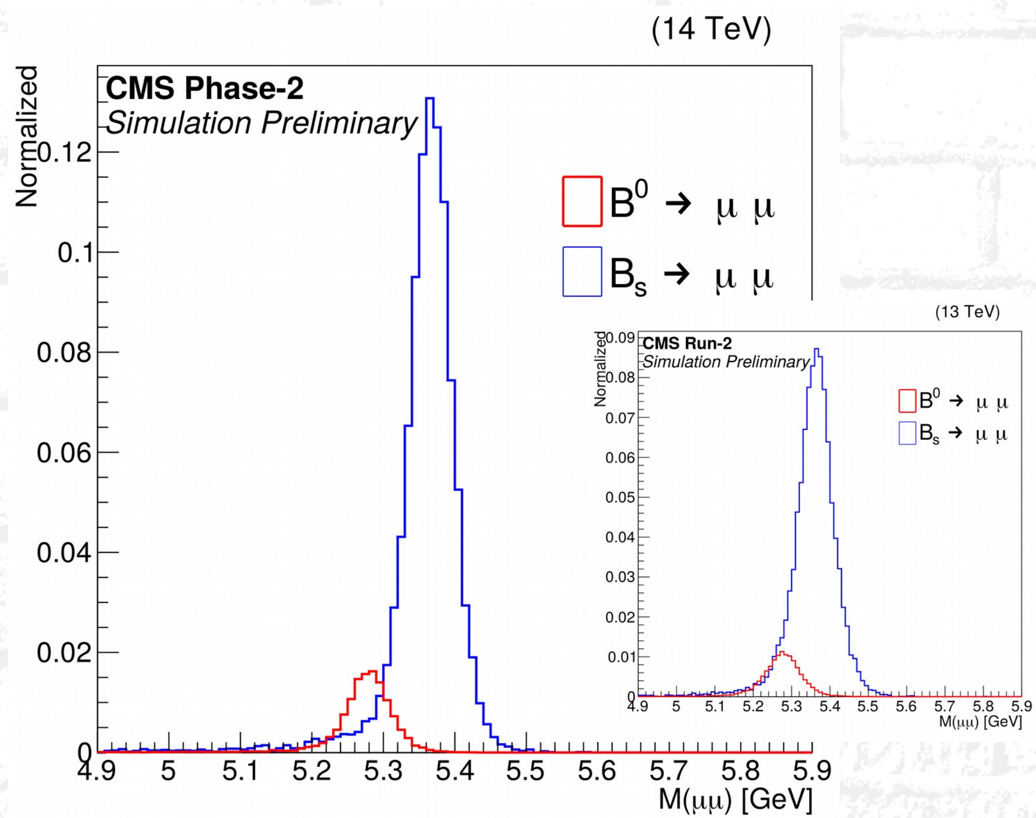
Prospect on rare B decays $B_{(s)} \rightarrow \mu^+\mu^-$ at CMS

CMS-PAS-FTR-18-013

Phase 2 with improved tracker:

- Study using Run-2 analysis strategy and same Run-2 trigger
- BDT from Run-1 analysis
- Improvement in the momentum resolution leads to about 40-50% gain in mass resolution for |η| < 1.4 (w.r.t. a Run-2 scenario)
- about 25 % improvement in mass peak separation



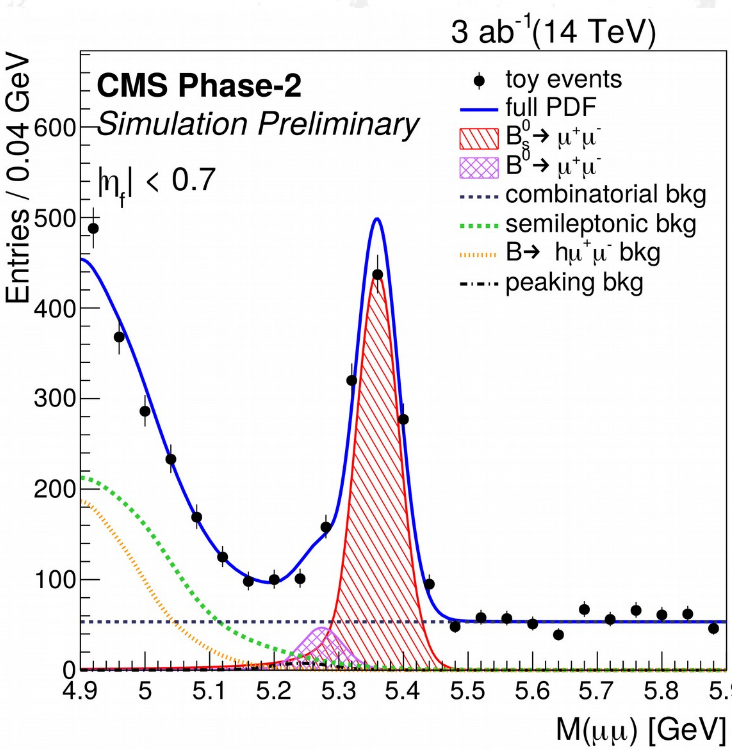


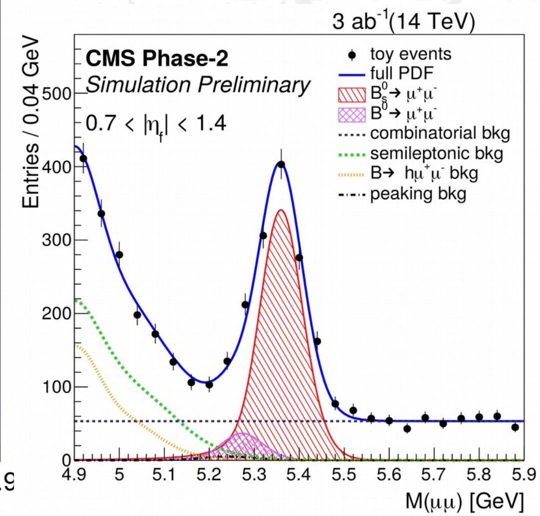
Prospect on rare B decays $B_{(s)} \to \mu^+\mu^-$ at CMS

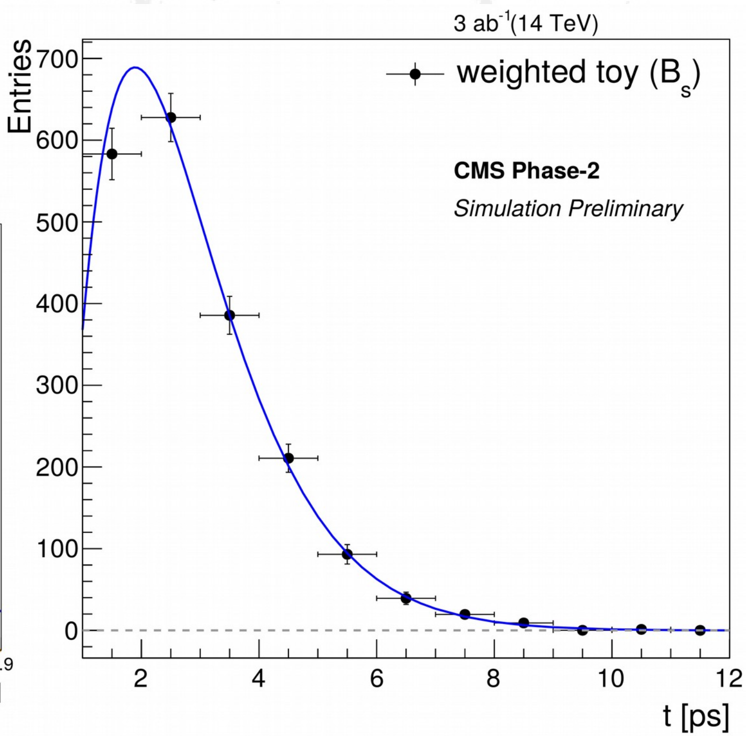
Yield extraction and lifetime measurement:

- Two pseudorapidity regions: $|\eta| < 0.7$ and $0.7 < |\eta| < 1.4$
- Unbinned maximum likelihood fit to the dimuon invariant mass distribution is performed in bins of the BDT discriminant variable.
- For the lifetime, binned fit to sPlot produced with mass fit likelihood.

$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps





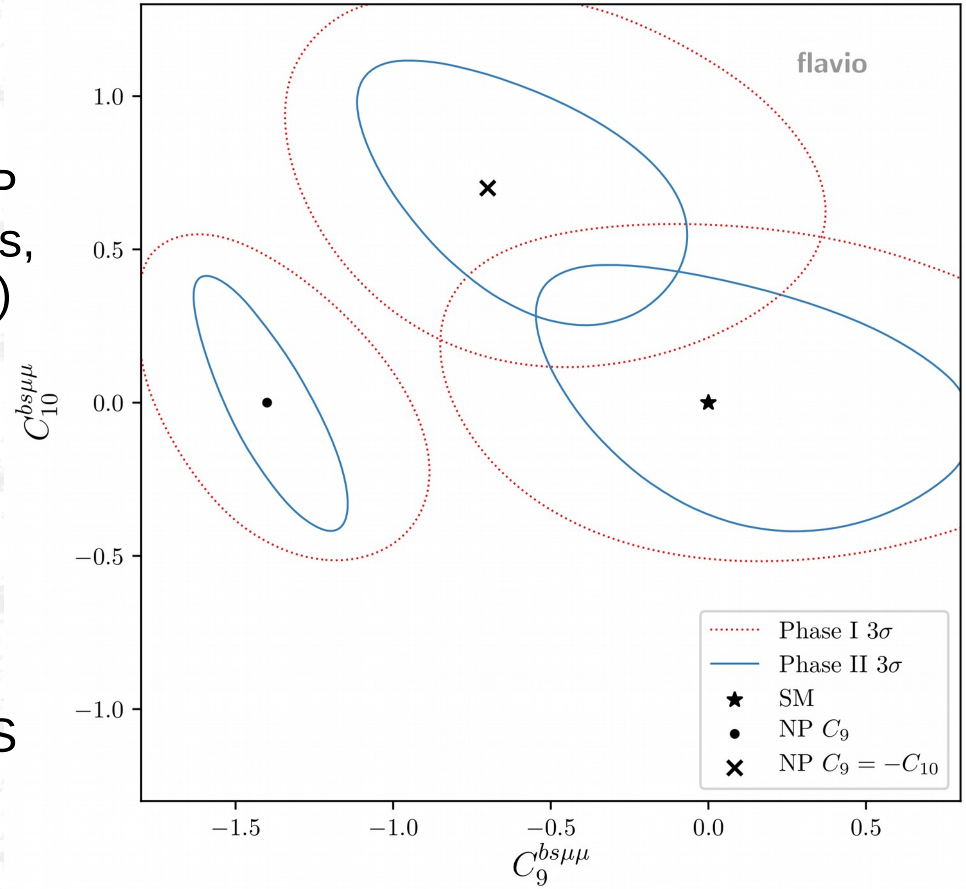


Prospects on $B \to K^* \mu^+ \mu^-$ at HL-LHC

arXiv:1812.07638

- Large data set allows for precise determination of the angular observables in narrow bins of q^2 or using a q^2-unbinned approach
- ~440k signal events in LHCb / ~700k events in CMS
- Most systematic uncertainties expected to reduce significantly with luminosity due to larger control samples → not systematically limited

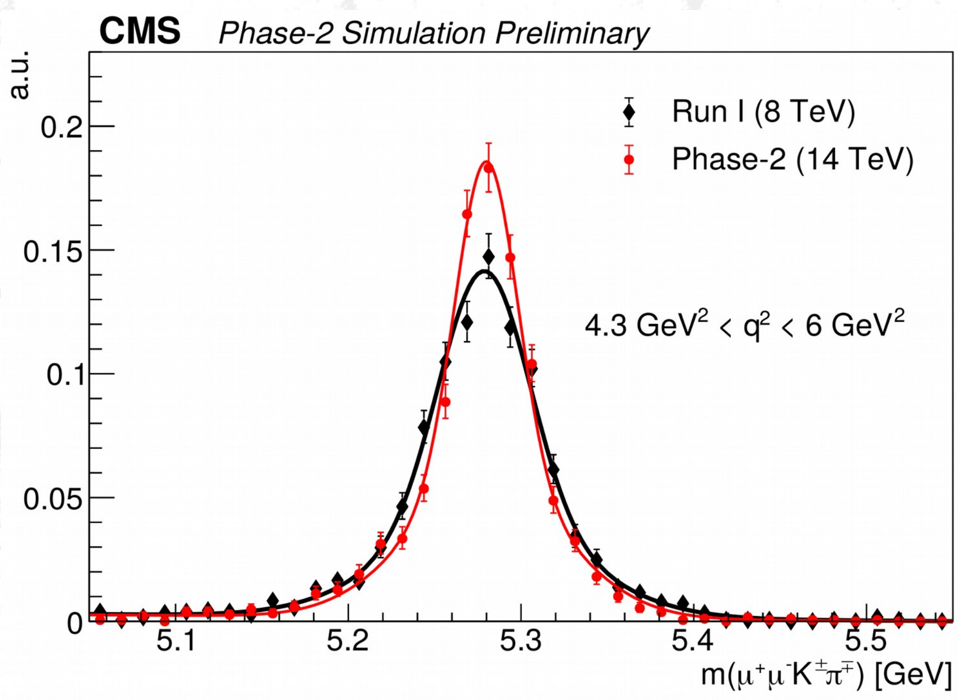
- Combining many observables help discriminate NP scenarios.
- Potential sensitivity to the SM and to NP scenarios motivated by LHCb anomalies,
- Scenarios are $C_9 = -1.4$ (vector current) and $C_9 = -C_{10} = -0.7$ (pure left-handed current).
- Included are the branching fraction of $B_s \to \mu^+\mu^-$ and the angular observables of $B^0 \to K^{0*}\mu^+\mu^-$ in the low-q^2 region (e.g., P_5^0).
- ATLAS and CMS combined after the HL-LHC phase. Expectations for ATLAS and CMS in Phase I from the CMS projection scaled by 1/√2

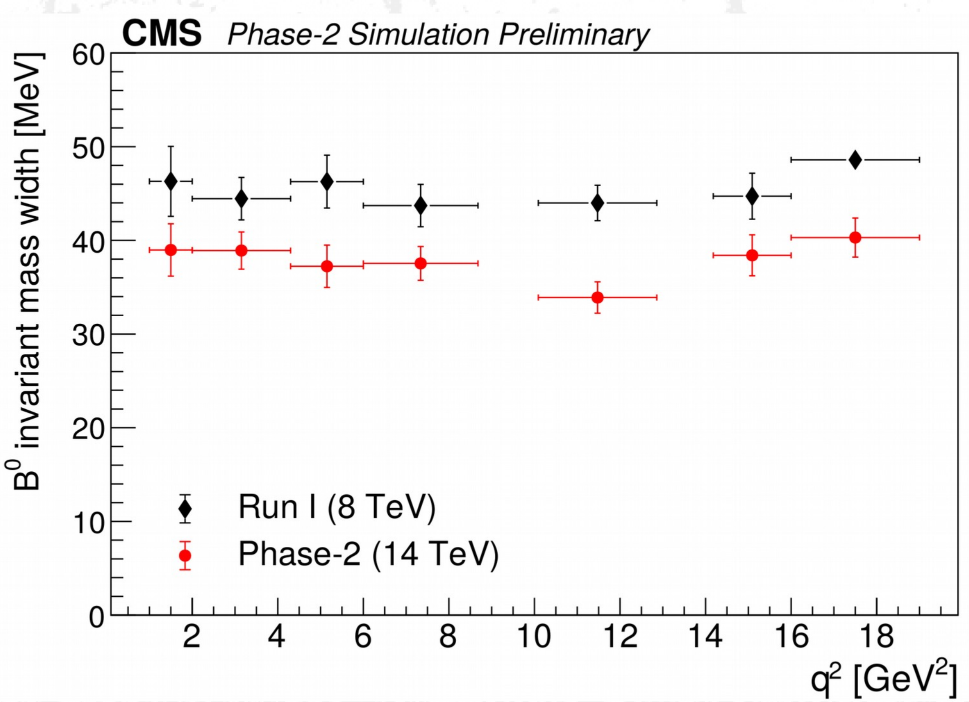


Prospects on $B \to K^{*}\mu^{+}\mu^{-}$ at HL-LHC at CMS

CMS-PAS-FTR-18-033

- Extrapolation from Run-1 results
- No improvements in the analysis strategy (e.g., selection or fits)
- Same trigger thresholds and efficiency → conservative
- Same signal-to-background, but mass resolution improvement included
- For each q^2 bin, expected yields obtained from simulated events generated for Phase-2, including an average of 200 pileup, and scaled to the luminosity of 3000/fb.

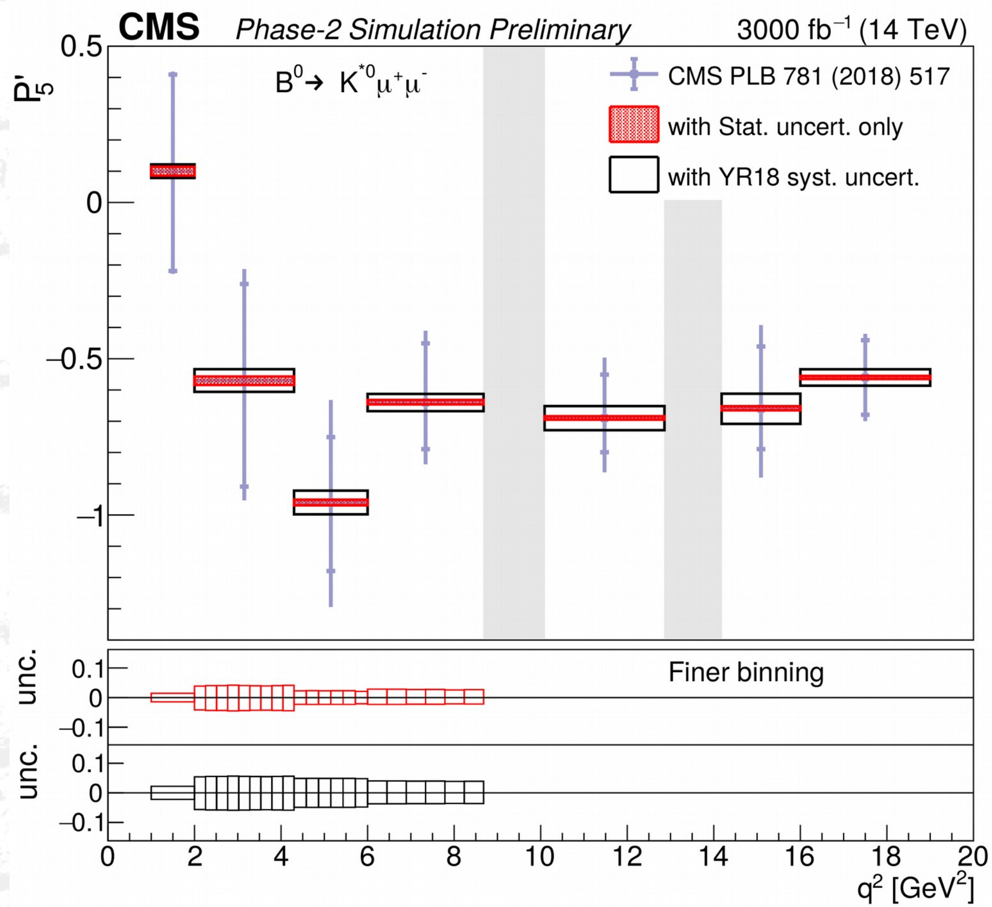




Prospects on $B \to K^* \mu^+ \mu^-$ at HL-LHC at CMS

CMS-PAS-FTR-18-033

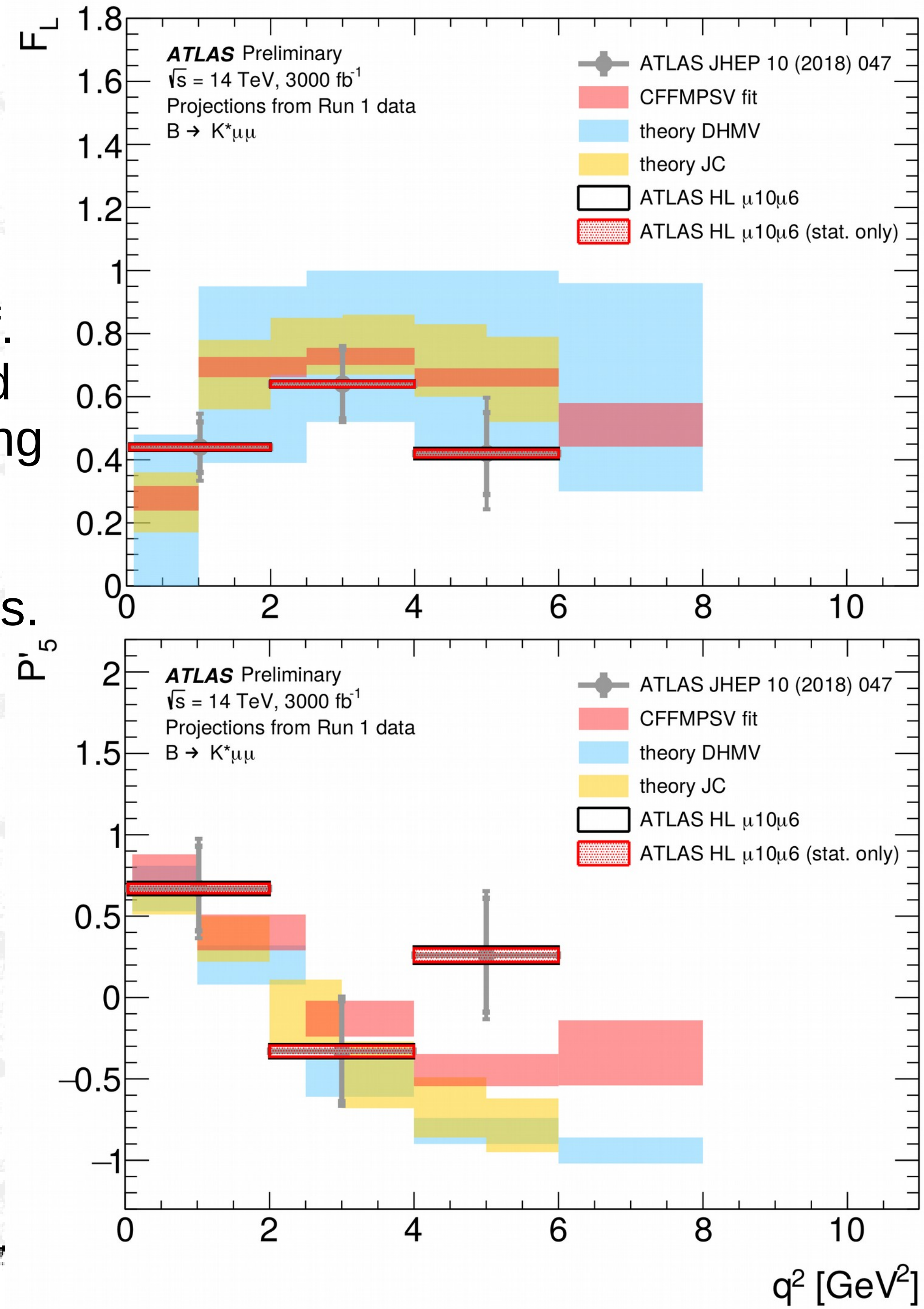
- Statistical uncertainty on P_5^0 at 3000/fb obtained by scaling Run 1 by the √ of the ratio of Run-1 yields over Phase-2 simulation.
- Most systematic uncertainties extrapolated from the Run-1 analysis with factor of 2 reduction (contamination from resonant decays, signal mass shape, CP mistagging rate, efficiency, angular resolution…)
- Other systematics scale with statistic of control samples



Prospects on $B \rightarrow K^{*}\mu^{+}\mu^{-}$ at HL-LHC at ATLAS

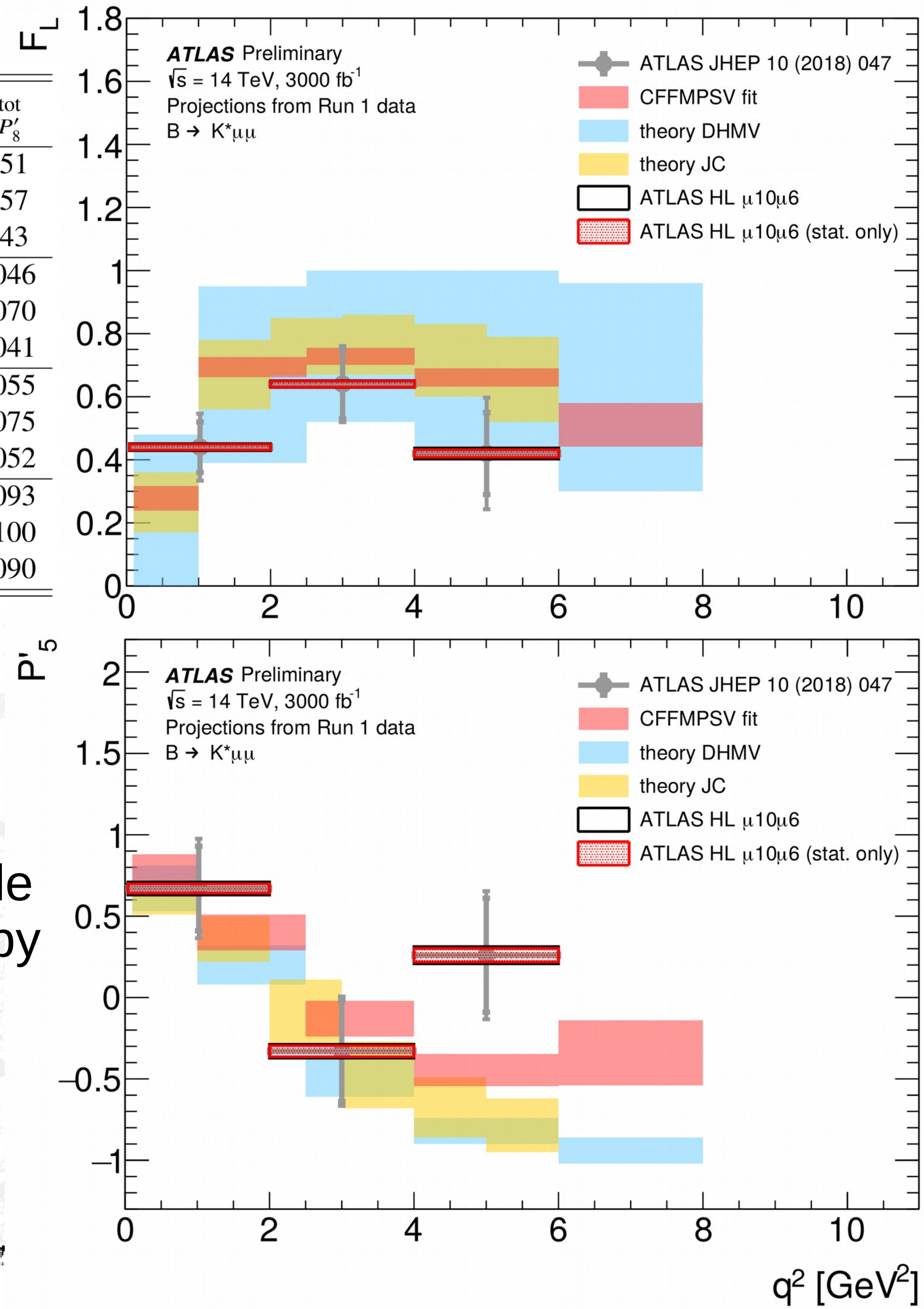
- Based on the Run 1 analysis
- Scaled to 3000/fb of luminosity and ×1.7 b production cross-section.
- Same selection and reconstruction eff.
- Simulations include the 30% improved mass resolution from upgraded tracking
- Three di-muon trigger threshold scenarios: two 6 GeV muons, one 6 and one 10 GeV or two 10 GeV muons.

- Inclusion of S-wave contributions in the fit improves the systematic by x5
- Detector alignment and B-field systematic uncertainties improved by ~x4 with larger control samples and new techniques



Prospects on $B \rightarrow K^* \mu^+ \mu^-$ at HL-LHC at ATLAS

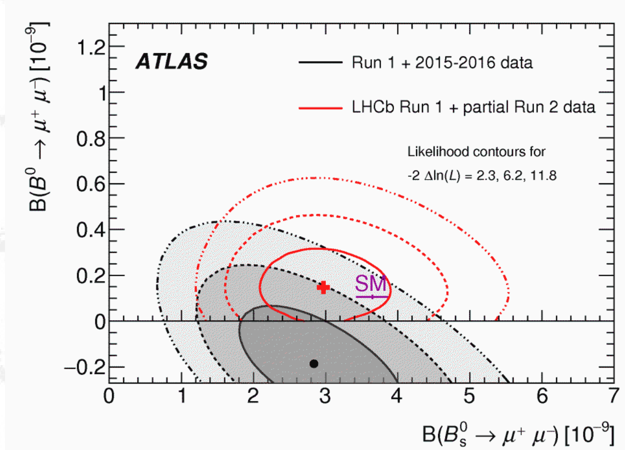
LHC phase	q^2 [GeV^2]	$\delta^{tot}_{F_L}$	$\delta^{tot}_{P_1}$	$\delta^{tot}_{P'_4}$	$\delta^{tot}_{P'_5}$	$\delta^{tot}_{P'_6}$	$\delta^{tot}_{P'_8}$
Run 1	[0.04, 2.0]	0.11	0.31	0.45	0.31	0.21	0.51
	[2.0, 4.0]	0.12	0.61	0.37	0.34	0.34	0.57
	[4.0, 6.0]	0.18	0.50	0.38	0.39	0.30	0.43
HL-LHC μ6μ6	[0.04, 2.0]	0.010	0.027	0.037	0.037	0.019	0.046
	[2.0, 4.0]	0.008	0.093	0.040	0.038	0.040	0.070
	[4.0, 6.0]	0.016	0.083	0.032	0.047	0.033	0.041
HL-LHC μ10μ6	[0.04, 2.0]	0.011	0.037	0.046	0.040	0.023	0.055
	[2.0, 4.0]	0.011	0.103	0.047	0.042	0.044	0.075
	[4.0, 6.0]	0.018	0.100	0.040	0.053	0.038	0.052
HL-LHC μ10μ10	[0.04, 2.0]	0.018	0.065	0.076	0.059	0.041	0.093
	[2.0, 4.0]	0.017	0.15	0.074	0.068	0.059	0.100
	[4.0, 6.0]	0.026	0.17	0.074	0.082	0.063	0.090

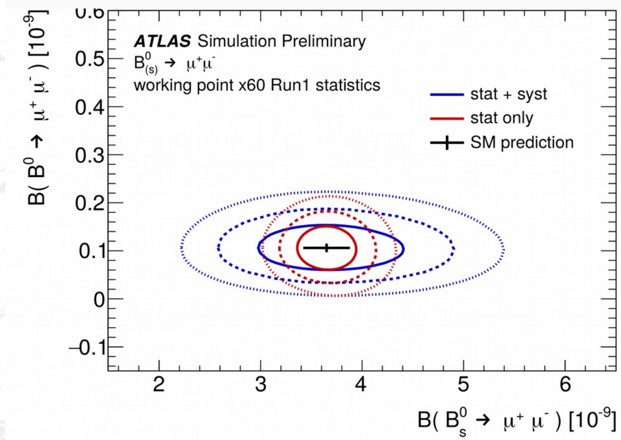


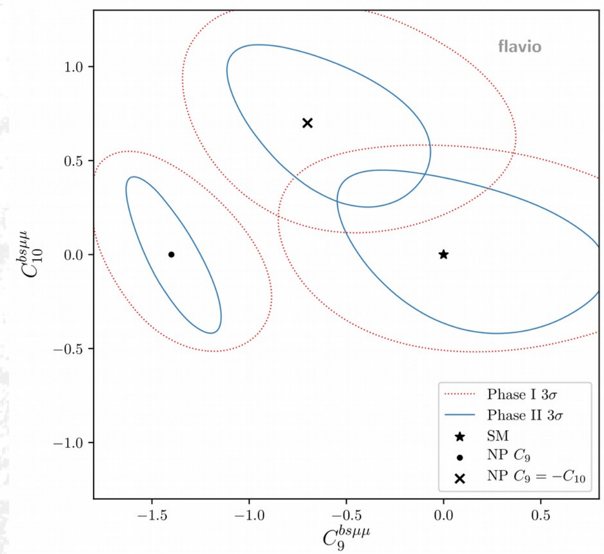
- Analysis not systematic dominated
- Few exceptions where at most the systematics is ~ x1.6 larger than statistical precision.
- The precision in measuring for example P_5' parameter is expected to improve by factors of ~ x9, ~ x8, ~ x5 (correspondingly in the three trigger scenarios) relative to the Run 1 measurement.

Conclusions

- B physics in ATLAS and CMS is more challenging but still much alive and with promising perspectives
- The B anomalies are boosting a wider interest in flavour physics
- Ongoing studies on final states with electrons
- Various ways to counteract the low trigger efficiency
- Still quite limited (wo)manpower in general





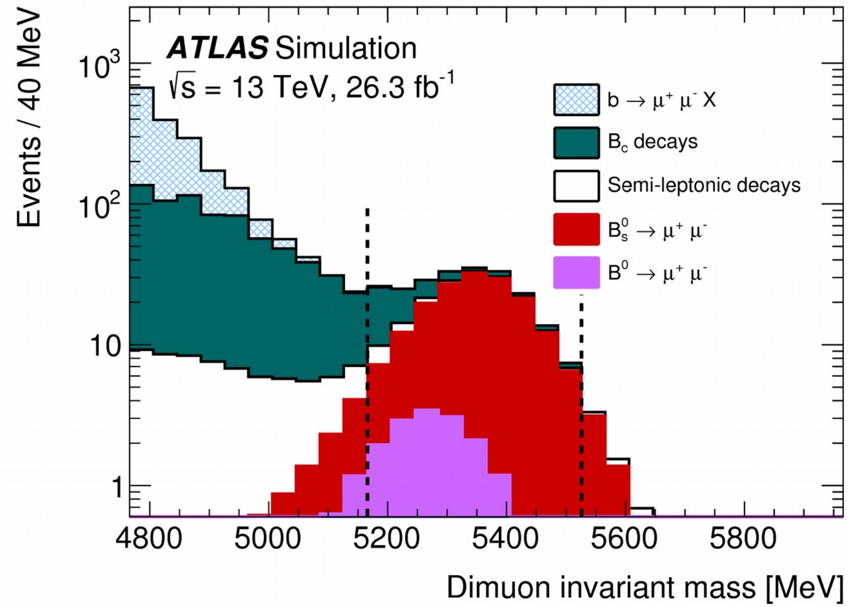


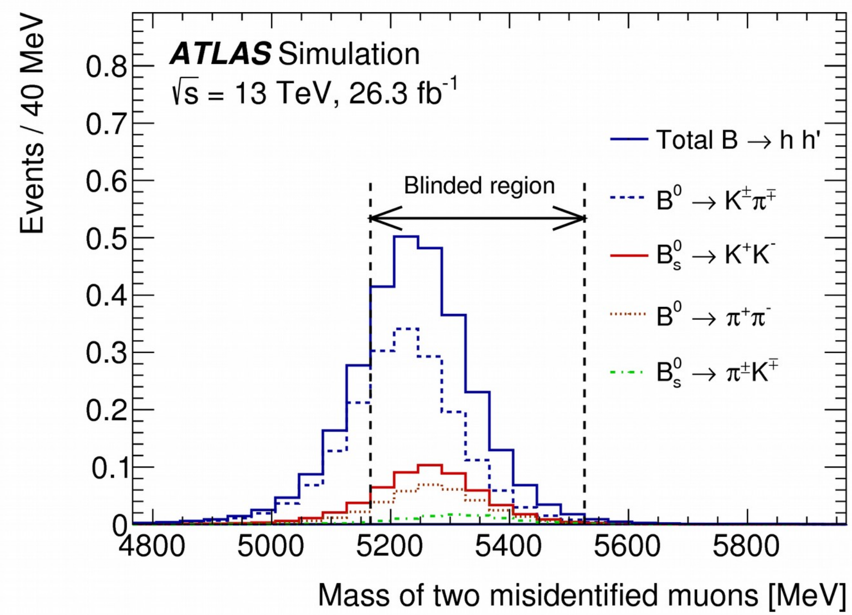
back-up slides

Background contributions

In order of relative magnitude:

- combinatorial background:
  - two real muons from different b quarks
- partially reconstructed B decays:
  - two real muons
  - Same Vertex (SV): $B \rightarrow \mu\mu X$ decays
  - Same Side (SS): semileptonic decay cascac
    ($b \rightarrow c\mu\nu \rightarrow s(d)\mu\mu\nu\nu$)
  - B_c decays: like $B_c \rightarrow J/\psi\ \mu\nu$
  - all these accumulate at low values of the dimuon invariant mass
- semileptonic B and B_S decays:
  - one real muon and a charged hadron.
- peaking background from charmless hadronic $B_{(S)}$ decays:
  - B decays into two hadrons h (kaons and pions): $B^0_{(S)} \rightarrow hh'$
  - smaller component, but overlays with the signal in dimuon invariant mass

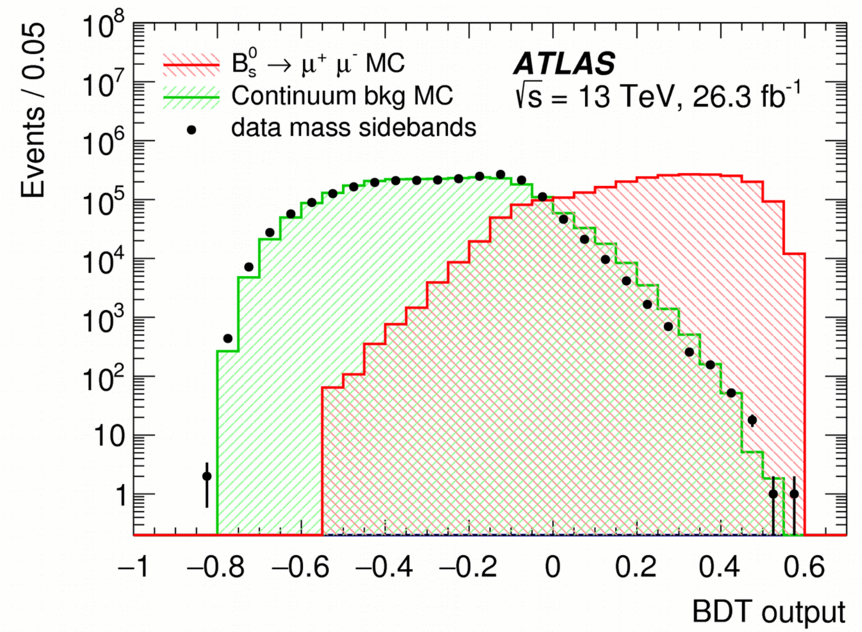




Tight muon-ID against hadron misidentification

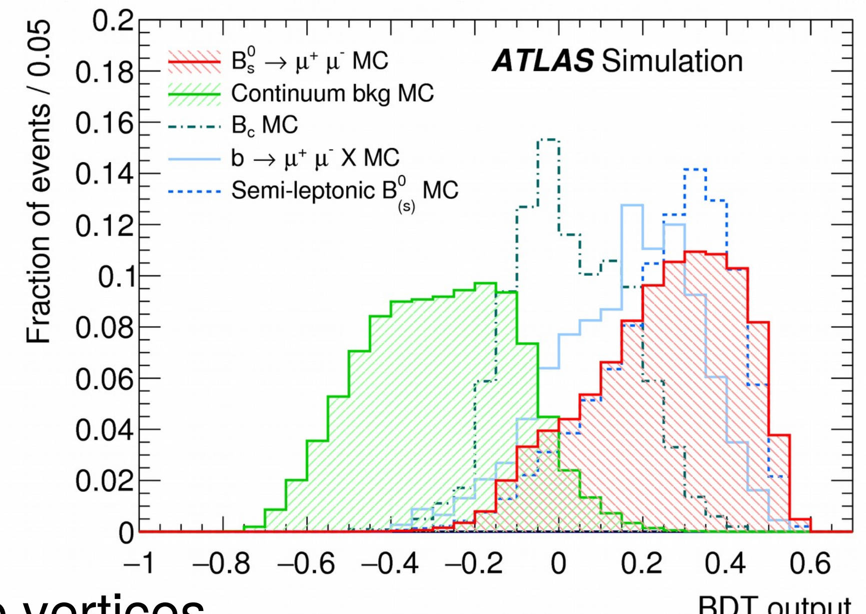
- mis-identification reduced by 0.39^2 using standard 'tight' ATLAS selections
- studied on simulated samples
- validated on control regions
- negligible misidentification of protons (< 0.01%
- misidentification is 0.08%(0.10%) for K(π).

peaking-background events: 2.7±1.3



BDT against combinatorial bkg

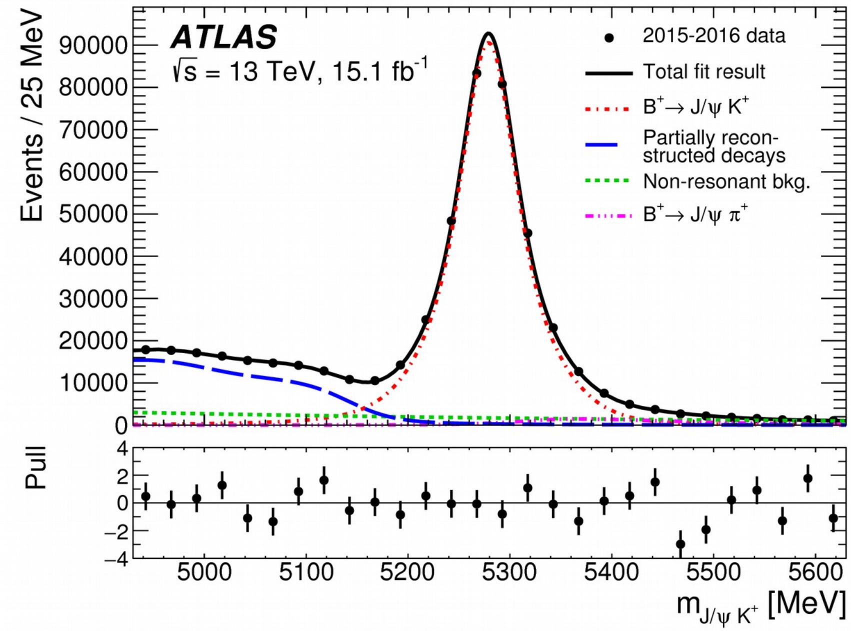
- MVA classifier to discriminate from signal
- trained and tested on mass sidebands
  - divided in 3 subsets
    - 3 independent BDTs
    - compatible performance
- 15 variables related to properties of B candidates, muons from the B decay, other tracks from the same collision and to pile-up vertices.



Normalisation B yield extraction

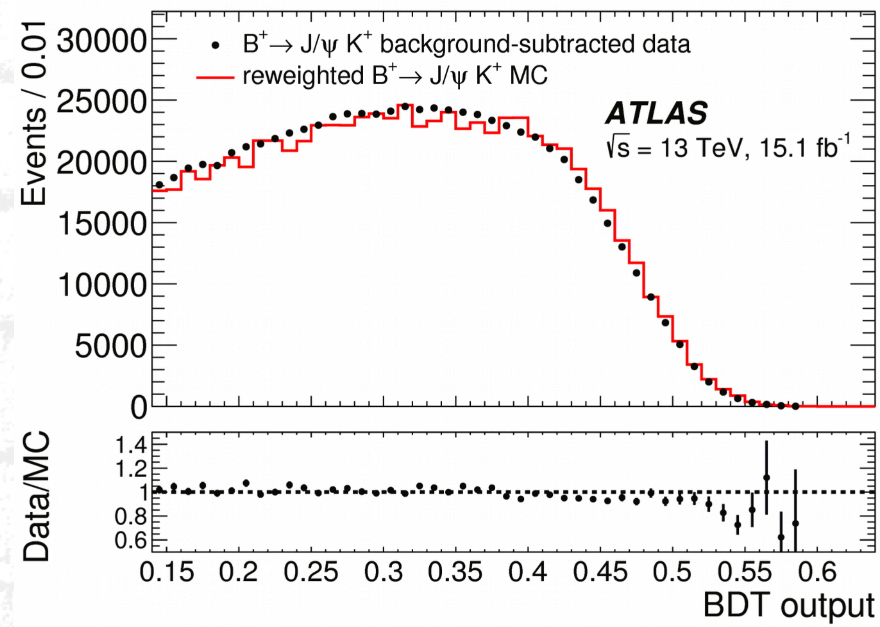
- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \rightarrow m_{\mu\mu K}$
- cross-checked with raw relative yield of $J/\psi\pi$ over $J/\psi K$ ratio
  $\rho_{\pi/K} = (3.71 \pm 0.09)\%$

$$\mathcal{D}_{\text{norm}} = N_{J/\psi K^+} \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}} \right)$$



Efficiency ratio $\varepsilon_{\mu\mu}/\varepsilon_{J/\psi K}$

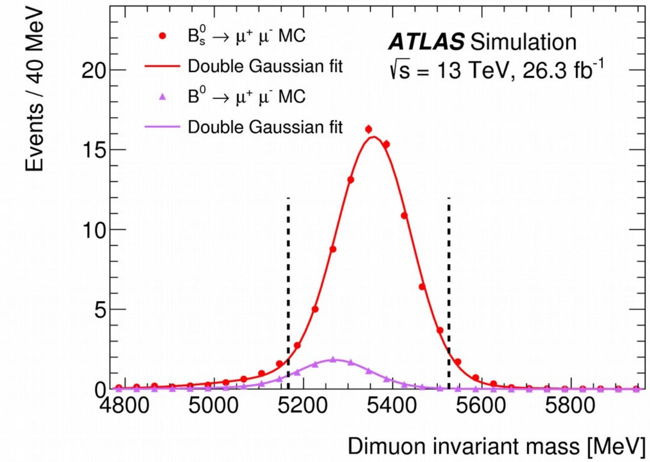
- efficiency ratio from MC
- systematic from data-MC discrepancies
- For B^0_S: 2.7% correction for lifetime difference of the B^0_S mass eigenstates

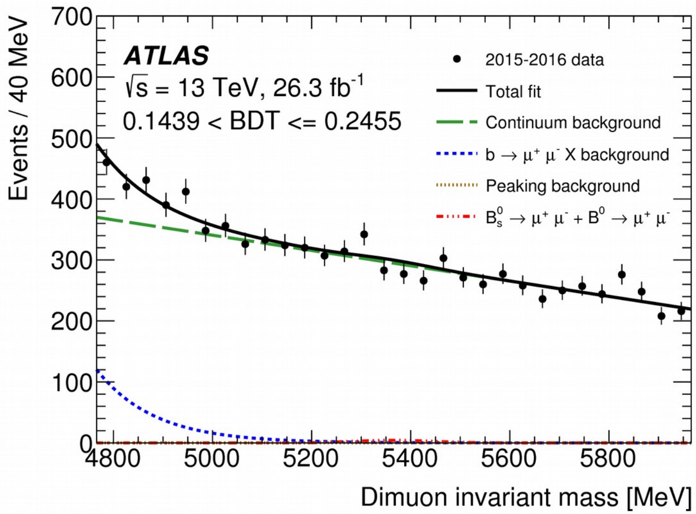


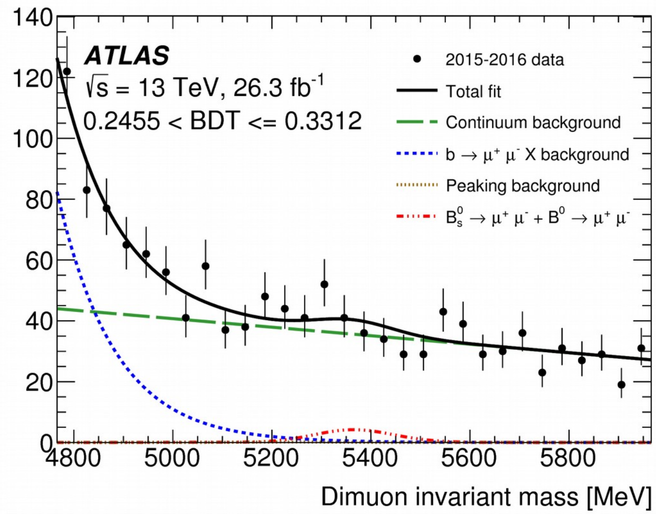
Source	Contribution (%)
Statistical	0.8
BDT Input Variables	3.2
Kaon Tracking Efficiency	1.5
Muon trigger and reconstruction	1.0
Kinematic Reweighting (DDW)	0.8
Pile-up Reweighting	0.6

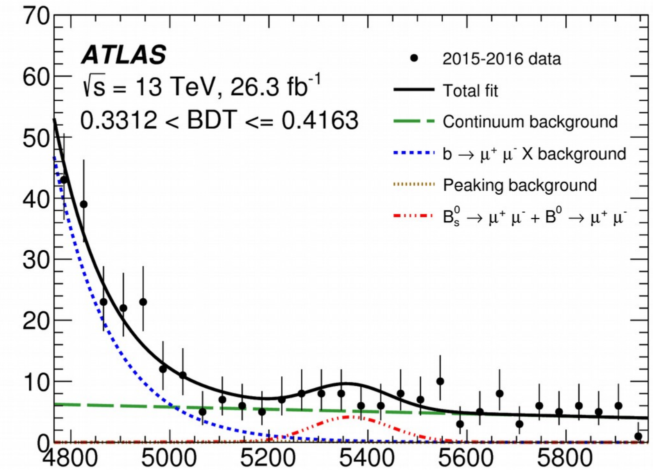
Signal yield extraction

- signal yields extracted with a unbinned maximum likelihood fit to the dimuon mass
- fit performed simultaneously in four BDT bins
  - 18% signal efficiency

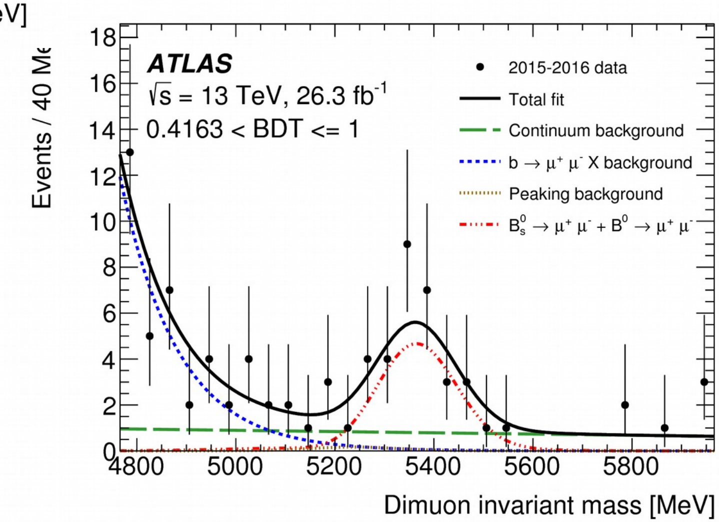








- signals, B to hh: 3 double Gaussians
- continuum: first order polynomial
- partially reconstructed B: exponential
- semi-leptonic: exponential



Analysis strategy for $B \to K^*\mu\mu$ at CMS

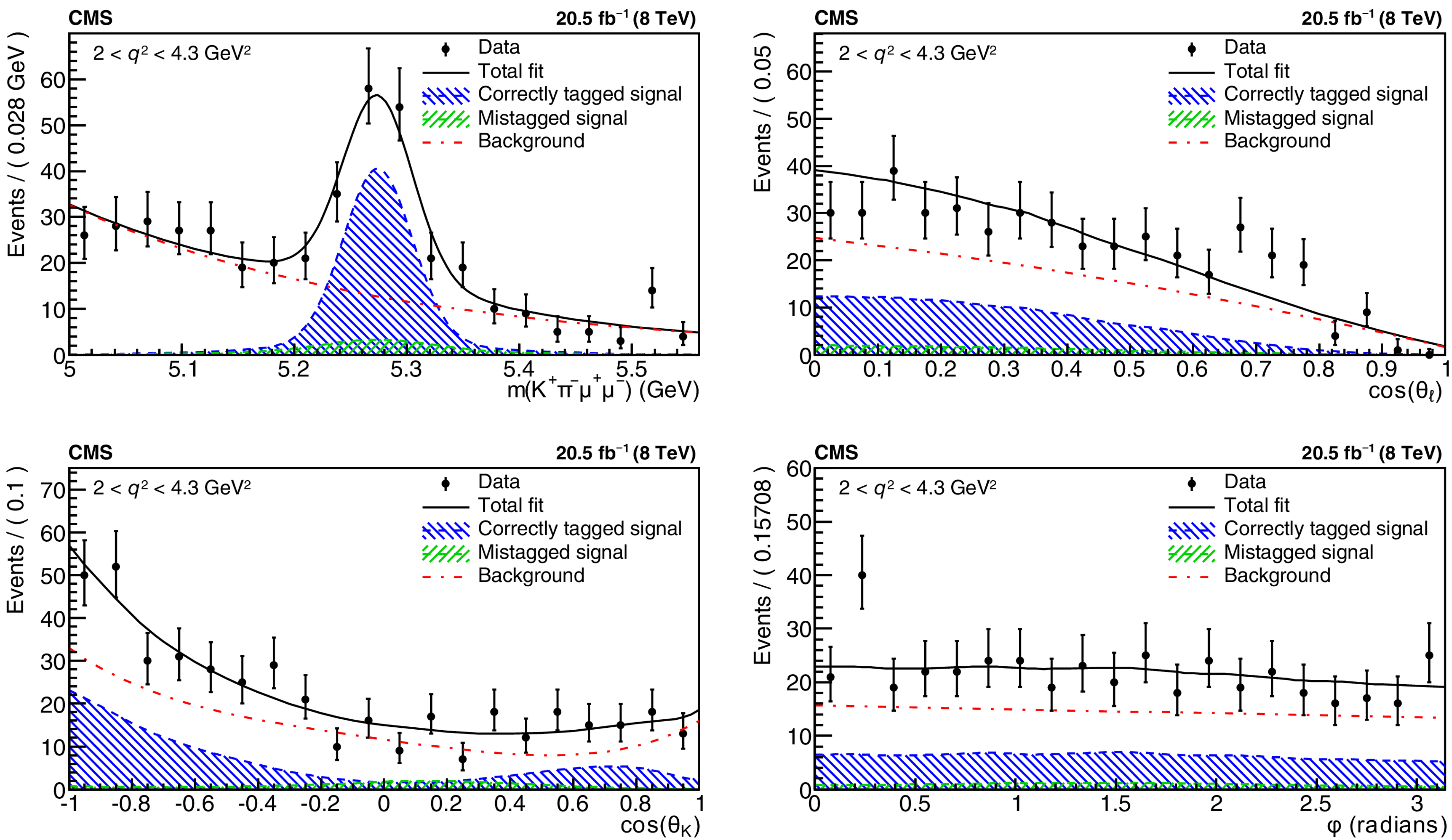
- Phys. Lett. B 727 (2013) 77 and Phys. Lett. B 753 (2016) 424
  - A_{FB} and F_L parameters and differential branching fraction measured
  - no deviations from SM prediction
- PLB 781 (2018) 517
  - fold around $\phi = 0$ and $\theta_\ell = \pi/2 \to$ 6 parameters $\to$ still too many
  - F_L, F_S , and A_S fixed from previous CMS measurement
  - P_1 and P'_5 measured, A^5_S nuisance parameter
  - q^2 range divided in 9 bins:
    - 7 signal bins, in each the angular analysis performed independently
    - 2 control-region bins, for resonant decays $B^0 \to J/\psi K^*$ / $B^0 \to \psi' K^*$
  - flavour assignment: mis-tagged event fraction 14%, measured on MC
  - two-step fit performed for 7 (+2 control regions) q^2 bins:
    - fit mass sidebands to determine the background shape
    - fit whole mass spectrum to extract 5 parameters: 2 yields, P_1, P'_5, A^5_S

Analysis strategy for $B \to K^*\mu\mu$ at ATLAS

- Data collected in 2012 at 8 TeV with 20.3 fb^{-1} Run 1 data
- Measured in 6 (overlapping) bins of q^2 in the range [0.04, 6] GeV^2
- 4 sets of fits for three parameters (F_L , S_3 and S_j with j=4,5,7,8)
- Selection of triggers with muon p_T thresholds starting at 4 GeV
- K* tagged by the kaon sign:
  - dilution from mistag probability included in (1-2⟨w⟩):
    - ⟨w⟩ ~ 10.9(1)% with small dependence on q^2
- 787 events selected with $q^2 < 6$ GeV^2
- Extended unbinned maximum likelihood fits in each of the fit variants in each q^2 bin:
  - two step fit procedure: first fit the invariant mass distribution
  - then add to the fit the angular distributions
    to extract the F_L and S(P) parameters
- Signal shape studies from control samples K^*J/ψ and $K^*\psi(2S)$

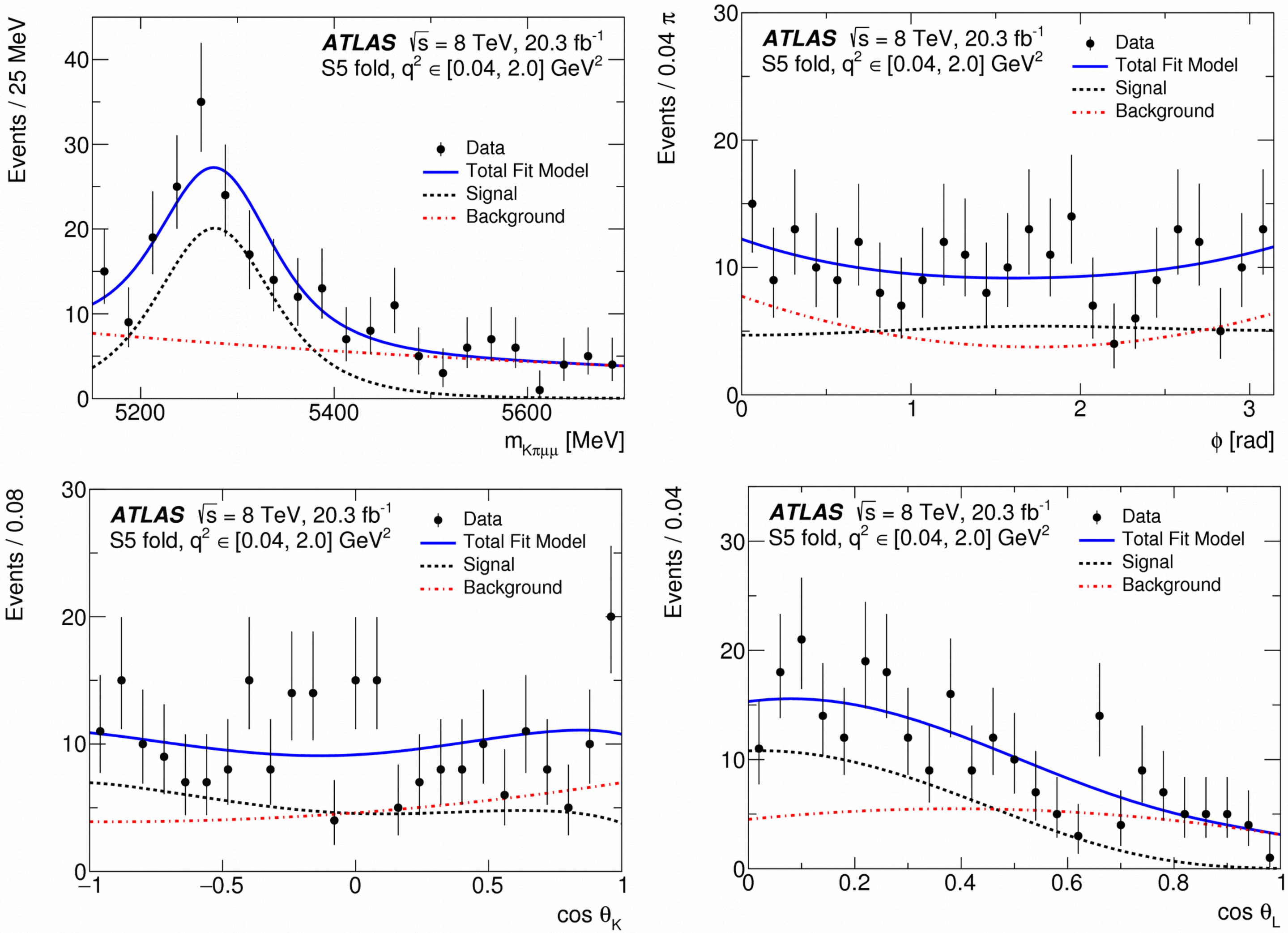
Fit projections for CMS

- fit projection for second bin: $2.0 < q^2 < 4.3\ \text{GeV}^2$.



Fit projections for ATLAS

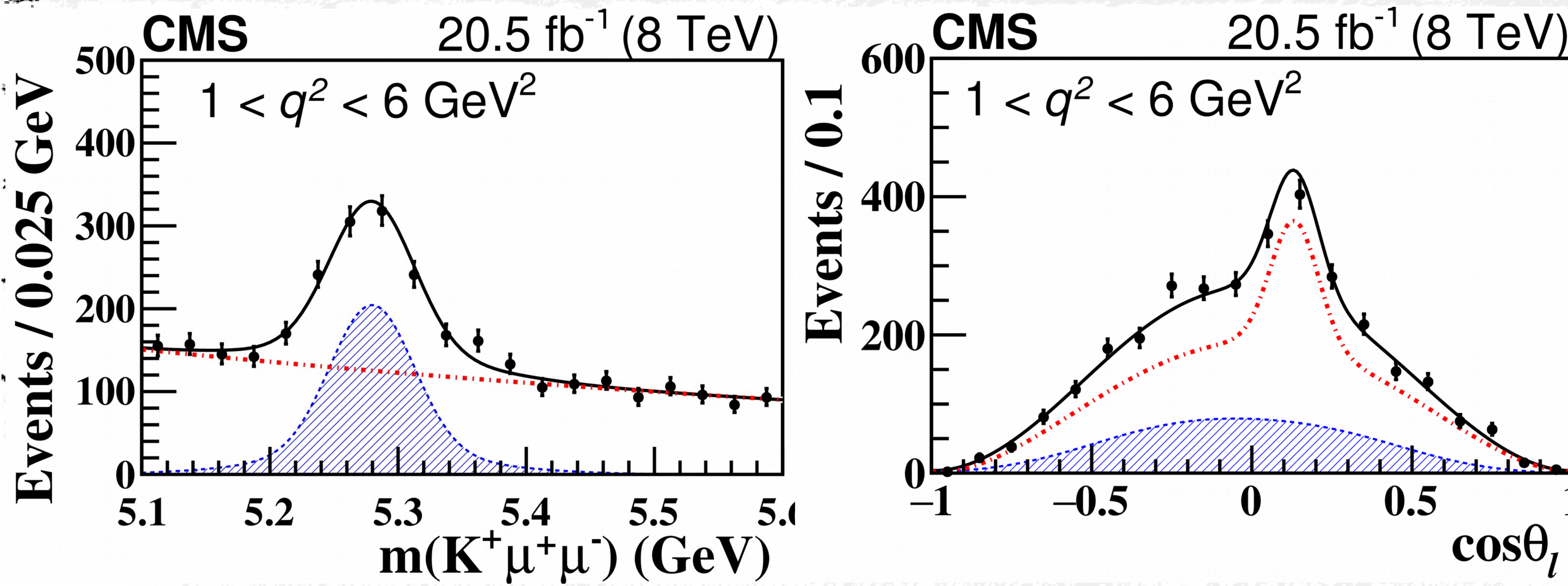
- fit m(K*μμ), $\cos\theta_L$, $\cos\theta_K$ and ϕ to isolate signal and extract parameters of interest.



- Data shown for [0.04,2.0] GeV^2
- projections for the S_5 fit.
- Approx 106-128 signal events in 2 GeV^2 q^2 bin.
- Similar results for the other q^2 bins and other fit variants.

Angular analysis on $B \to K^+\mu\mu$ at CMS

- Two-step unbinned extended maximum likelihood fit performed:
  - fit mass sidebands to determine the background shape
    - fixed in second step
  - fit whole mass spectrum with 4 floating parameters
    - 2 yields + 2 angular param



fit projections for special bin $1 < q^2 < 6$ GeV^2

Strategies for data collection

Scouting

- Since 2010, CMS is taking special “scouting” streams:
  - Run reconstruction in trigger farm (muons, jets, ...)
  - Write object features (e.g., four momenta) rather than the full event
  - Few KB traded for 1 MB: can write thousands more
  - Same now by ATLAS (TLA) and ALICE

Parking

- Limitation to write 1000 evt/sec is not the trigger itself
- The problem is computing resources downstream → disk & CPU power
- In 2012, both ATLAS&CMS took more data, counting on shutdown computing pledges & opportunistic computing resources to process them
- Extra 300-350 Hz of “parked” data are collected to extend the physics program: standard model measurements and searches for new physics
- The triggers defining the parked datasets are either a looser version of the core physics triggers (for instance with reduced pT thresholds on the reconstructed objects) or brand new triggers with small overlap with the rest