Rare decays in ATLAS and CMS

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On behalf of the ATLAS & CMS Collaborations
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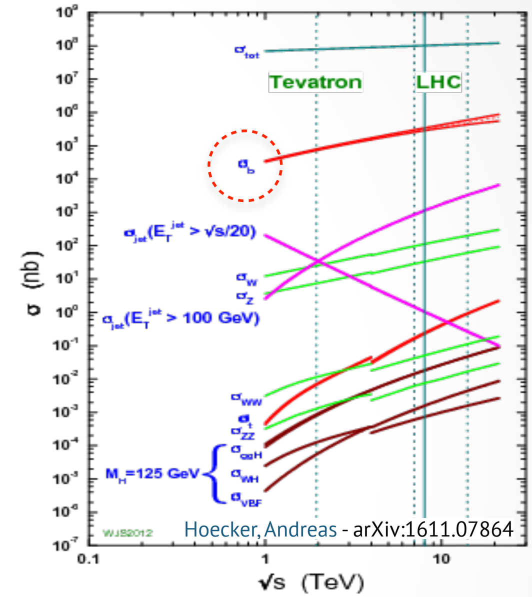
Outline

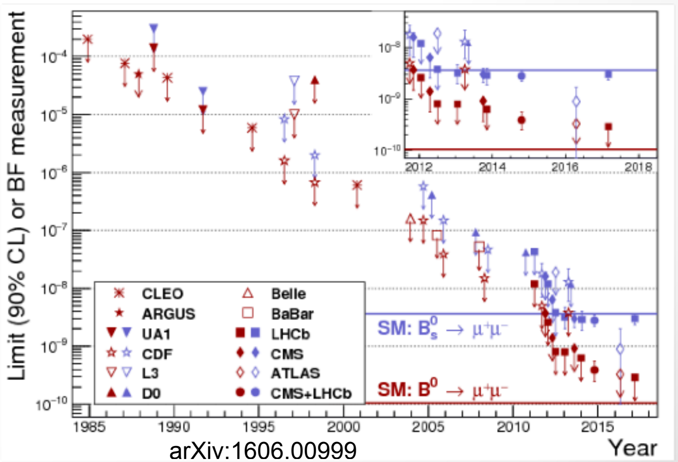
- Introduction.
- ATLAS & CMS **heavy flavor** trigger.
- $B^{(0)}_s \to \mu^+\mu^-$ status and future.
- $B^0 \to K^*\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$ Run-1 results.
- Search for $\tau \to 3\mu$ [CMS-PAS-17-004].
- Summary.

See also experimental and theoretical reviews by N. Leonardo & A. Pitch (last Monday)

Introduction

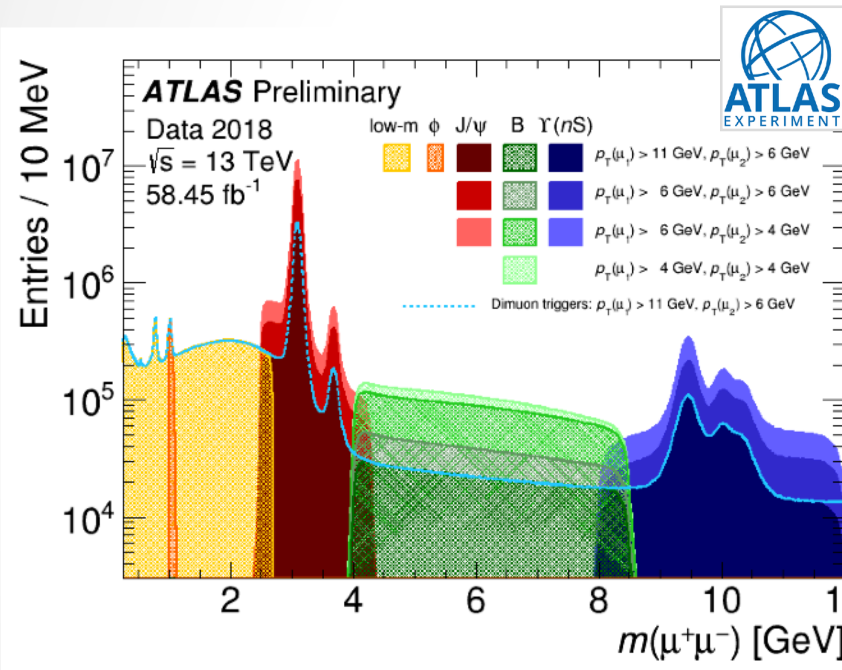
- LHC: pp collisions @ 7-8 (Run I) & 13 TeV (Run II) ⇒ large *b* and *c* hadron (and τ) production.
- Rare **heavy-flavor** decays could **indirectly** reveal the existence of new particles in loops or constrain BSM theories, testing energy scales beyond 14 TeV (up to 100 TeV).
- ATLAS and CMS rare decay searches are competitive or complementary to the searches by other experiments, such as LHCb or Belle (II).

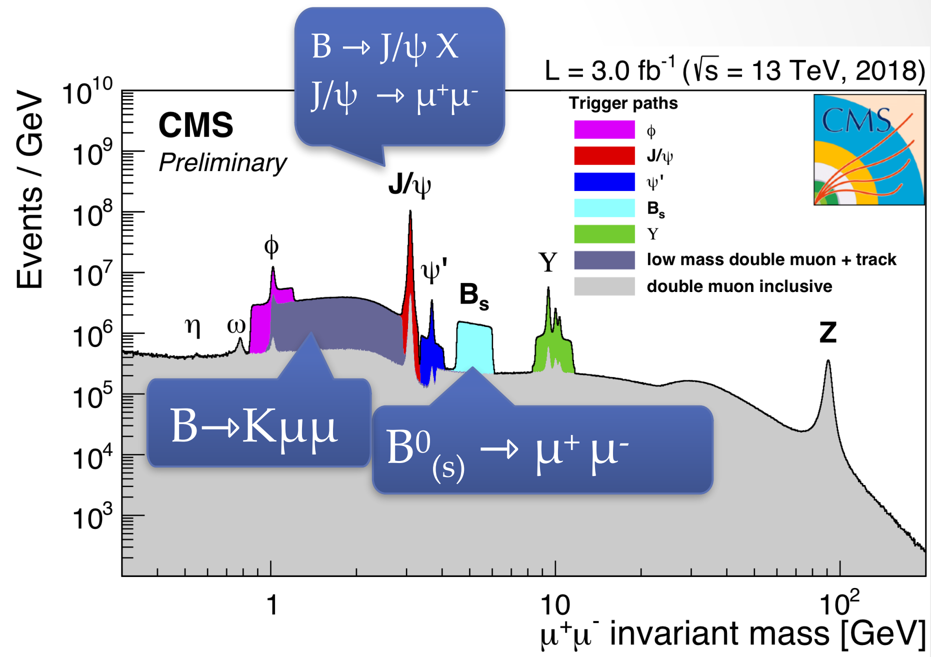




HF trigger

ATLAS and CMS High Level Triggers: oppositely charged muon pairs, fit to common vertex, in different invariant mass regions:





CMS (≥ 2016):

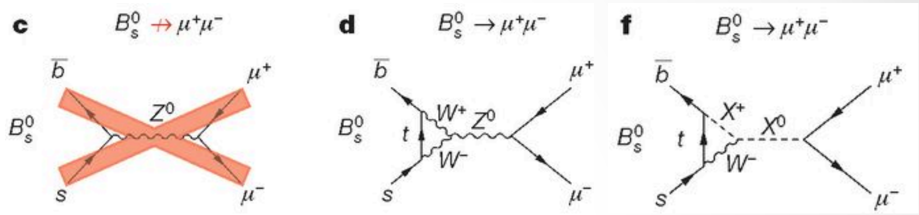
- *L1_TripleMu0,*
- *L1_DoubleMu_10_0_dEta_Max1p8,*
- *L1_DoubleMu0er1p6_dEta_Max1p8_OS.*

⇨ *HLT_DoubleMu3_Trk_Tau3mu*

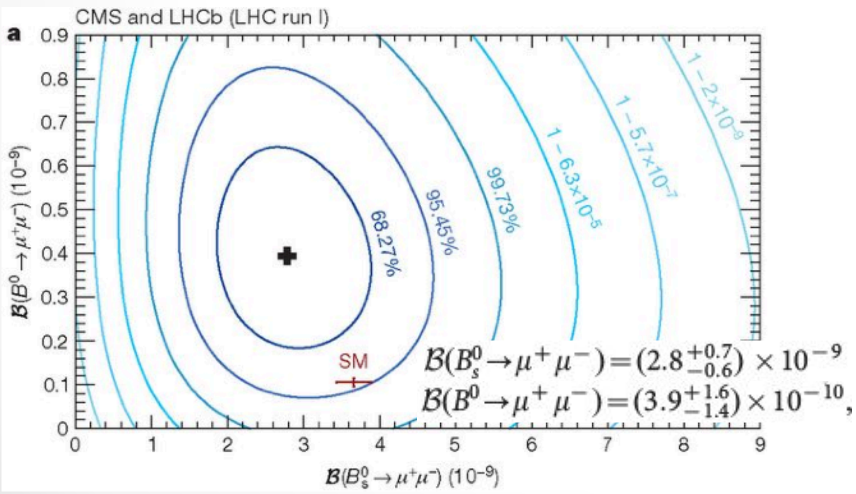
2μ+*t* displaced vtx., $M = 1.6 - 2.02$ GeV

Search for $B^{(0)}_s \rightarrow \mu^+\mu^-$

- FCNC process. New physics in loops could modify Wilson coefficients of S/PS [V/A-V in $B \rightarrow K\mu\mu$] operators.
- SM predictions are reliable.



CMS & LHCb: Nature 522, 68–72 (2015)



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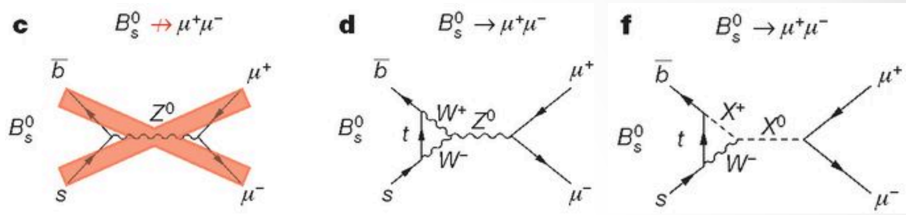

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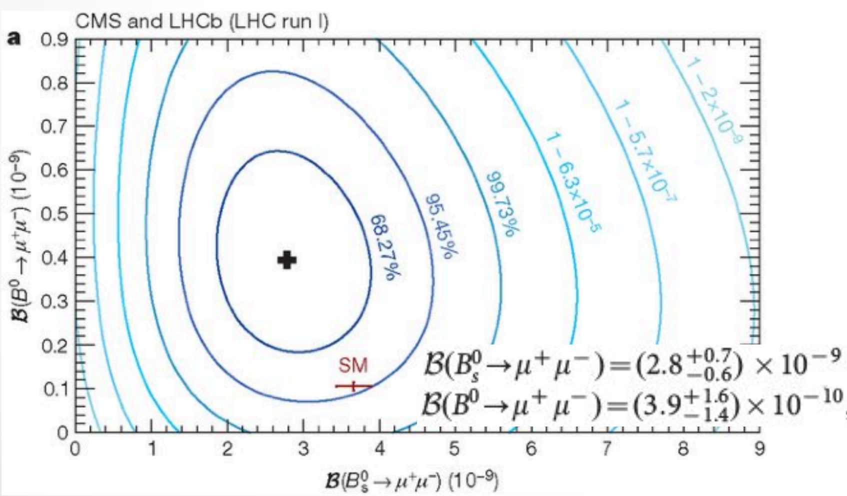

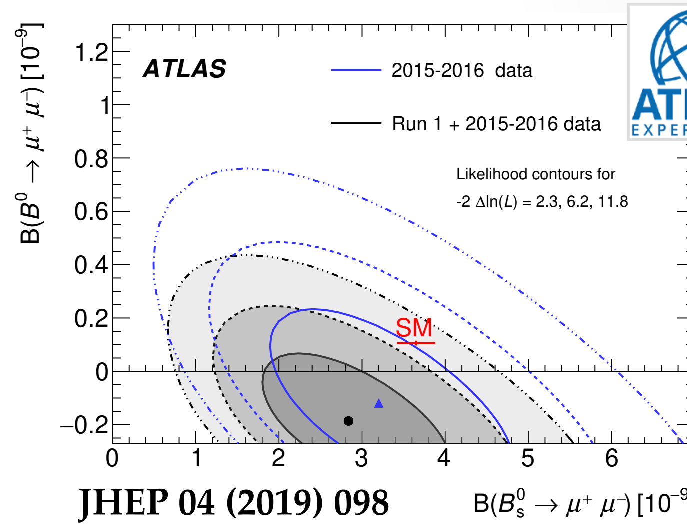

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$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

ATLAS Run 1 + 2015-16 combined sensitivity is similar to the CMS+LHCb (2015) or the LHCb (2017) analyses.

$B^{(0)}_s \rightarrow \mu^+\mu^-$: future

- The LHC and the ATLAS & CMS experiments are being upgraded to reach 14 TeV and to increase detection capabilities. Run III will start in 2021. The HL-LHC after 2025 could provide ~3 ab^{-1}.

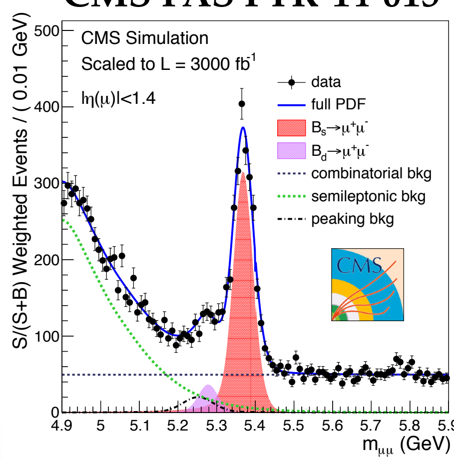
Estimate of analysis sensitivity **CMS PAS FTR-14-015**

$\mathcal{L}$ (fb^{-1})	$N(B^0_s)$	$N(B^0)$	$\delta\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$
20	18.2	2.2	35%	$>100\%$	$0.0-1.5\,\sigma$	$>100\%$
100	159	19	14%	63%	$0.6-2.5\,\sigma$	66%
300	478	57	12%	41%	$1.5-3.5\,\sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2-3.3\,\sigma$	50%
3000 (barrel)	2250	271	11%	18%	$5.6-8.0\,\sigma$	21%

arXiv:1812.07638

Experiment	Scenario	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ stat + syst %	$\mathcal{B}(B^0 \to \mu^+\mu^-)$ stat + syst %
LHCb	23 fb^{-1}	8.2	33
LHCb	300 fb^{-1}	4.4	9.4
CMS	300 fb^{-1}	12	46
CMS	3 ab^{-1}	7	16
ATLAS	Run 2	22.7	135
ATLAS	3 ab^{-1} Conservative	15.1	51
ATLAS	3 ab^{-1} Intermediate	12.9	29
ATLAS	3 ab^{-1} High-yield	12.6	26

CMS PAS FTR-14-015



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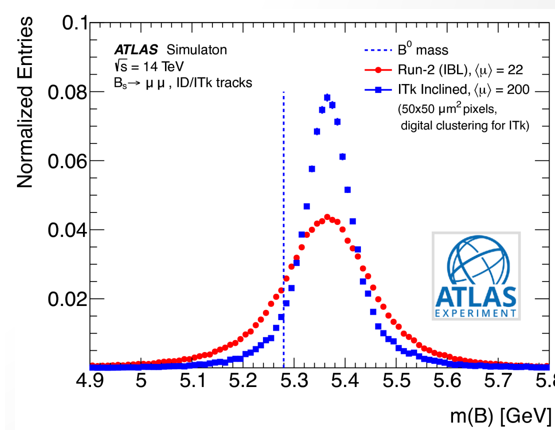
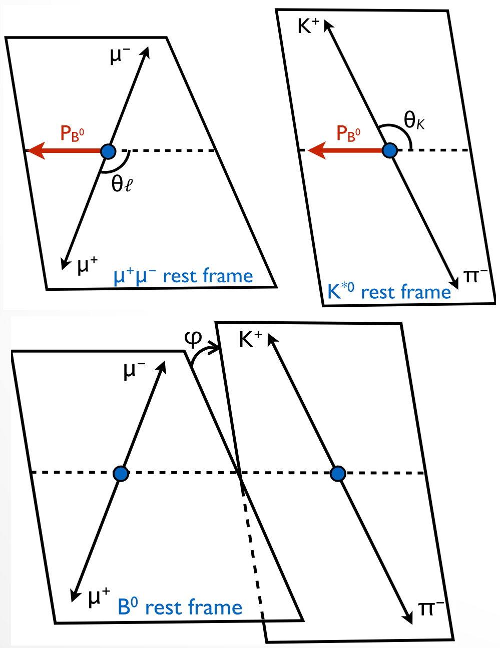


$B^0 \to K^*\mu^+\mu^-$ angular analysis

- Anomalies (≳3σ) have been reported by LHCb (and Belle) for the "optimized" observables ***Pj(')***, that minimize uncertainties from hadronic form factors:

$$g(\cos\theta_K,\cos\theta_L,\phi) = \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\mathrm{d}\cos\theta_K\mathrm{d}\phi\mathrm{d}q^2} = \frac{9}{32\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K+F_L\cos^2\theta_K+\frac{1-F_L}{4}\sin^2\theta_K\cos2\theta_L$$
$$-F_L\cos^2\theta_K\cos2\theta_L+S_3\sin^2\theta_K\sin^2\theta_L\cos2\phi$$
$$+S_4\sin2\theta_K\sin2\theta_L\cos\phi+S_5\sin2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L+S_7\sin2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin2\theta_K\sin2\theta_L\sin\phi+S_9\sin^2\theta_K\sin^2\theta_L\sin2\phi\Bigg]. \qquad (2.1)$$



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

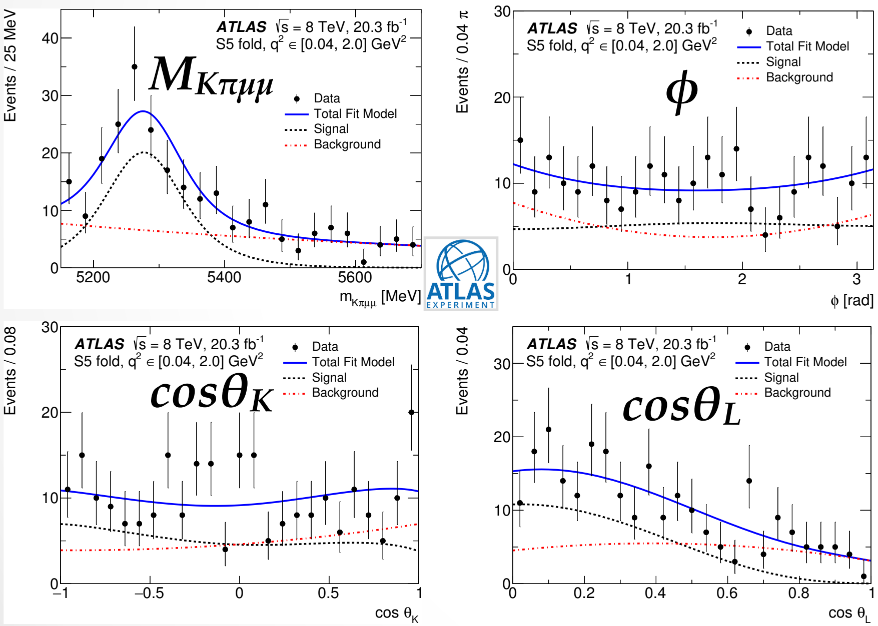
$$P_2 = \frac{2}{3}\frac{A_{\mathrm{FB}}(=S_6)}{1-F_L}$$

$$P_3 = -\frac{S_9}{1-F_L}$$

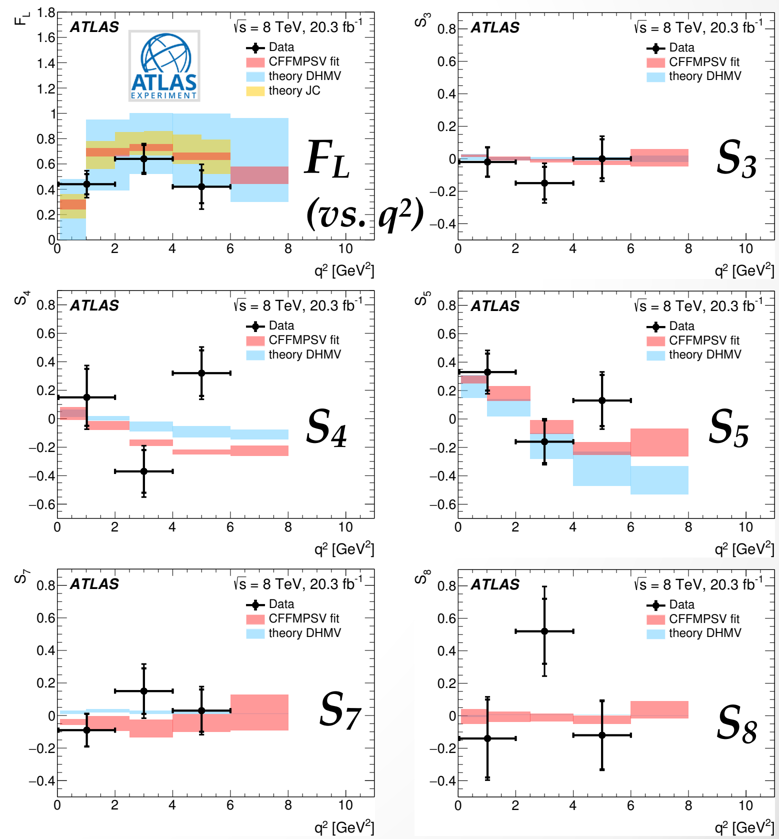
Angular foldings allow fitting F_L, S_3 and one of the S_i parameters at a time.

$B^0 \to K^*\mu^+\mu^-$: ATLAS

- Minimize $\mathcal{L} = \frac{e^{-n}}{N!}\prod_{k=1}^{N}\sum_{l} n_l P_{kl}(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; \hat{p}, \hat{\theta})$ **for each $q^2 = m^2_{\mu\mu}$ bin**, where $P_{kl} = \varepsilon(\cos\theta_K)\varepsilon(\cos\theta_L)\varepsilon(\phi)g(\cos\theta_K, \cos\theta_L, \phi) \cdot G(m_{K\pi\mu\mu})$ and $\boldsymbol{\varepsilon}$ are angular efficiencies.



for $q^2 = 0.04$ - 2.0, and similar plots for other five q^2 regions.



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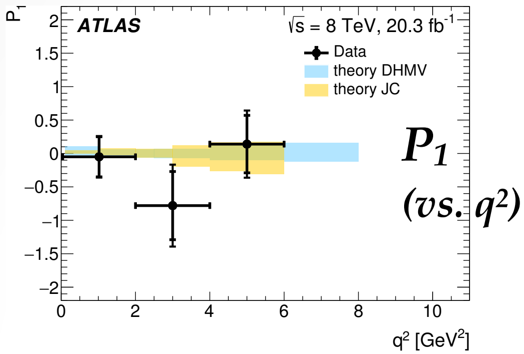
$B^0 \to K^*\mu^+\mu^-$: ATLAS (II)



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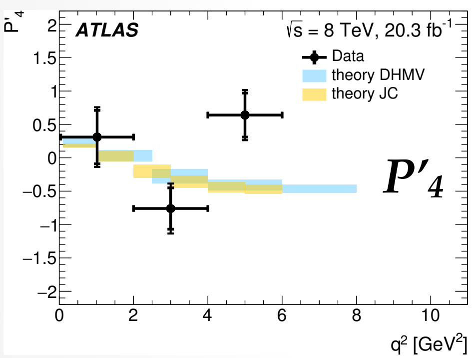
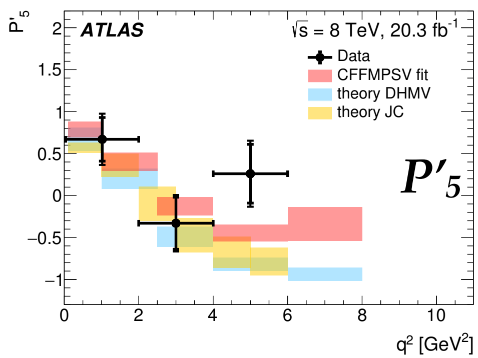
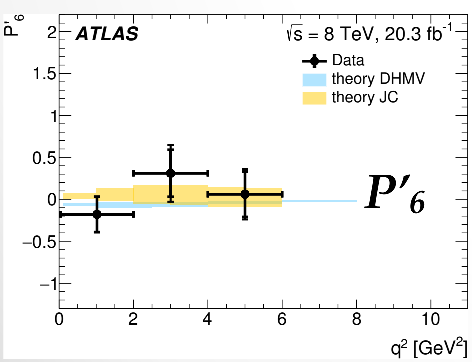
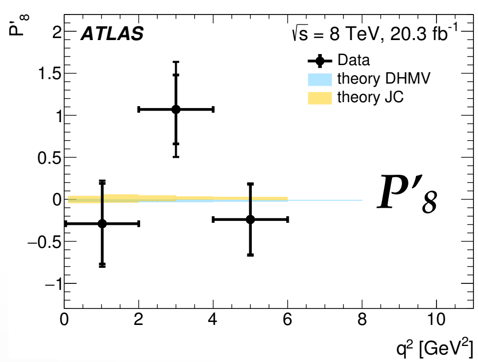




Data points include systematic uncertainties (mainly from the background angular model).



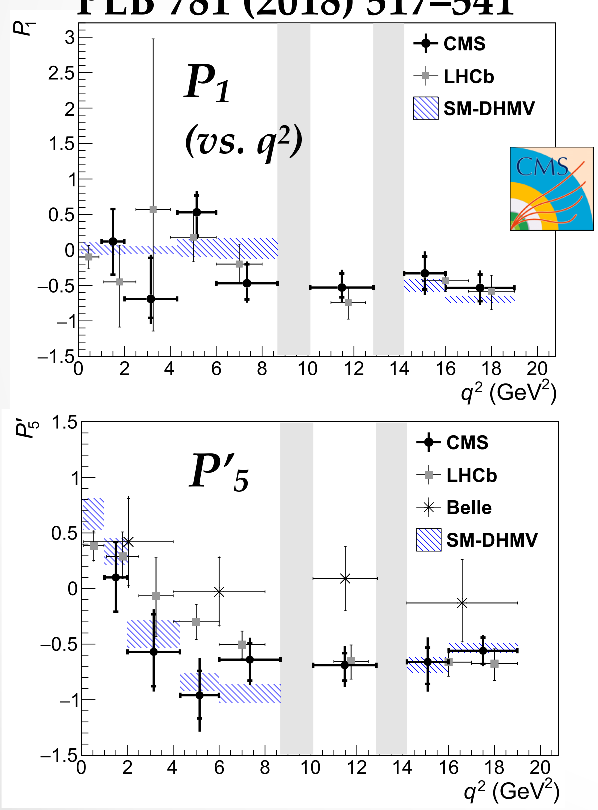


All measurements are within 3σ of the range covered by the different SM predictions, and compatible with LHCb, CMS (see next slide) and Belle results.

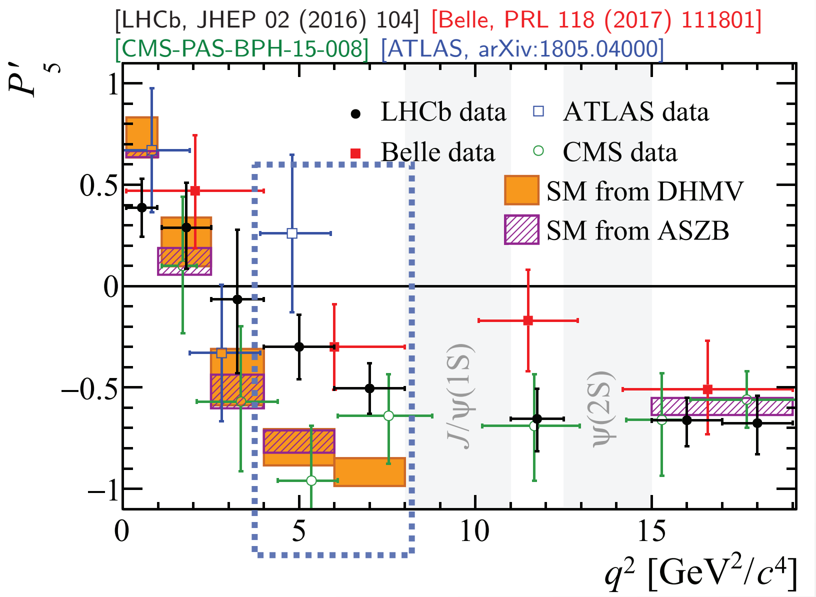
$B^0 \to K^*\mu^+\mu^-$: CMS

- Similar approach in CMS to obtain P_1 and P_5' (F_L is fixed to previous CMS measurements where ϕ was integrated out):

PLB 781 (2018) 517–541



SM agrees with CMS measurements. CMS also agrees with Belle, LHCb & ATLAS, though these lie systematically above in P_5' in the $q^2 = 4$ - $8\ GeV^2$ region.

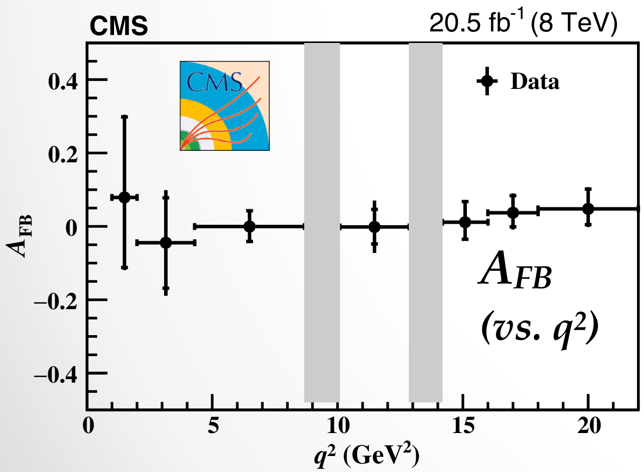


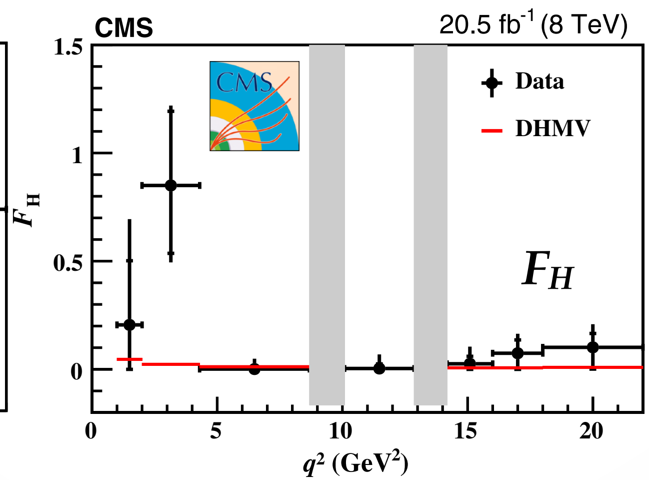
$B^+ \to K^+\mu^+\mu^-$: CMS

- Decay rate is described by $A_{FB}(\mu\mu)$ and the contribution, F_H, of the S, PS and T amplitudes to the decay width, both expected to be negligibly small (~null test):

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

θ_l angle btw μ^- and K^+ in the $\mu\mu$ rest frame.



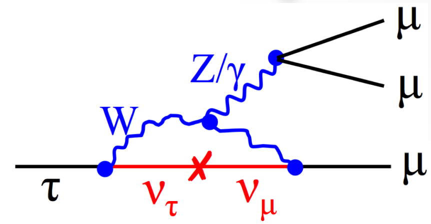


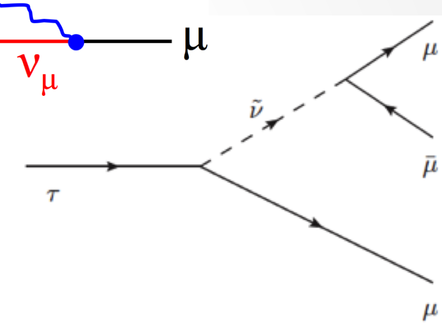
PRD 98, 112011 (2018)

CMS results are consistent with previous measurements (BaBar/Belle/LHCb) and compatible with the SM predictions (including $A_{FB}^{(SM)} \approx 0$).

Search for $\tau \to 3\mu$

- CFLV decays, e.g. $\ell \to 3\ell'$, possible due to ν oscillations, but very rare.
- NP models can enhance CFLV decays to the current experimental sensitivity.
- Best Br($\tau \to 3\mu$) UL set by B-factories.
- **Large τ production in the LHC**, $\sigma(pp \to \tau + X) \sim 2 \times 10^{11}$ fb, allows for $\tau \to 3\mu$ search. Best LHC UL by LHCb [4].
- **ATLAS** Run 1 search used $W \to \tau\nu$ [5].
- Similarly to [4], we present a search in **CMS** for $\tau \to 3\mu$ coming from B & D decays (main source of τ's at the LHC), using **33 fb^{-1} @13 TeV** (2016).





Theory / Experiment	Br($\tau \to 3\mu$) / UL @ 90% CL	Source
SM [1]	$\sim 10^{-55}$	ν osc.
BSM	$\lesssim 10^{-9}$	Many
Belle [2]	$< 2.1 \times 10^{-8}$	$e^+e^- \to \tau^+\tau^-$
BaBar [3]	$< 3.3 \times 10^{-8}$	$e^+e^- \to \tau^+\tau^-$
LHCb [4]	$< 4.6 \times 10^{-8}$	B & D dec.
ATLAS [5]	$< 3.8 \times 10^{-7}$	$W \to \tau\nu$

[1] Hernández-Tomé et al. EPJC (2019) 79:84. [2] Belle, PLB **687** (2010) 139. [3] BaBar, PRD 81 (2010) 111101. [4] LHCb, JHEP 02 (2015) 121. [5] ATLAS, EPJC (2016) 76:232.

Selection, MC and resolution

- **3μ selection:** L1+HLT (slide 4), $p_{T\mu} > 2$ GeV, $|\eta_\mu| < 2.4$, $\Delta R_{\mu\mu} < 0.8$, $|\Delta z_\mu| < 0.5$ cm, $\Sigma_\mu q_\mu = \pm 1$, $m_{3\mu} = 1.75$-1.8 GeV, $\phi(1020)$ veto.
- **MC samples:** $\tau \to 3\mu$ either from $D_s^{+¶}$ or B^+/B^0 (cover ~94%) using PYTHIA+EvtGen; and $D_s \to \phi(\mu\mu)\pi^{¶}$.

Process (PYTHIA 13 TeV)	Number of τ leptons (33 fb^{-1})
$pp \to c\bar{c} + ...$	
$D \to \tau\nu$	4.0×10^{12} (95% D_s, 5% $D^\pm$)
$pp \to b\bar{b} + ...$	
$B \to \tau\nu + ...$	1.5×10^{12} (44% $B^\pm$, 45% B^0, 11% B_s^0, 0% $B_c^\pm$)
$B \to D(\tau\nu) + ...$	6.3×10^{11} (98% D_s, 2% $D^\pm$)
W & Z decays	8×10^8 (τ isolated and large MET)

Low p_τ

assuming $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$	Signal $D_s \to \tau\nu$	Signal $B^\pm/B^0 \to \tau...$	Data
Produced in pp collisions	4.4×10^5	1.5×10^5	
(with three muons in fiducial volume)	(6.6×10^3)	(2.3×10^3)	
L1/HLT trigger	214	114	
At least 3 global muons ($p_T > 2$ GeV)	88	47	1.0×10^7
Trimuon candidate selection	64	29	1.0×10^5

$\mathcal{A} \times \varepsilon \sim \mathcal{O}(0.01\%)$

¶ from $c\bar{c}$ and $b\bar{b}$ inclusive production.

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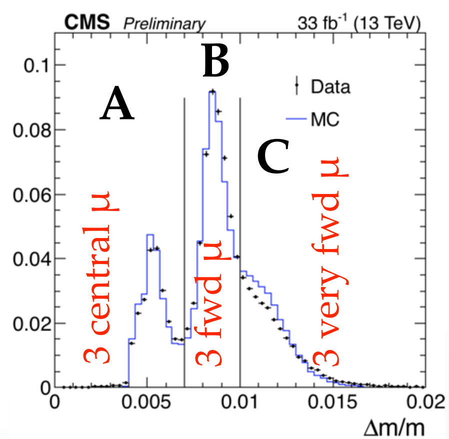
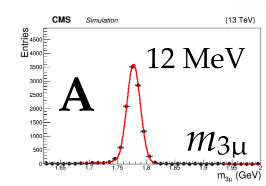
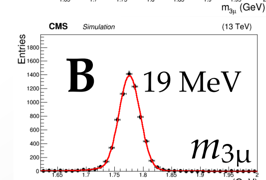
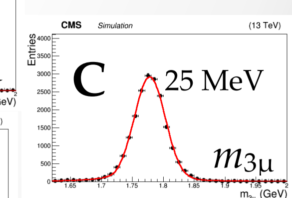
$\mathcal{A} \times \varepsilon \sim \mathcal{O}(0.01\%)$

- $\Delta m_{3\mu}$ varies with $|\eta_\mu|$:
  - **3 categories (A, B, C).**
  - $m_{3\mu}$ fitted with Gaussian + Crystal Ball function.









¶ from $c\bar{c}$ and $b\bar{b}$ inclusive production.

Normalization and trigger corrections

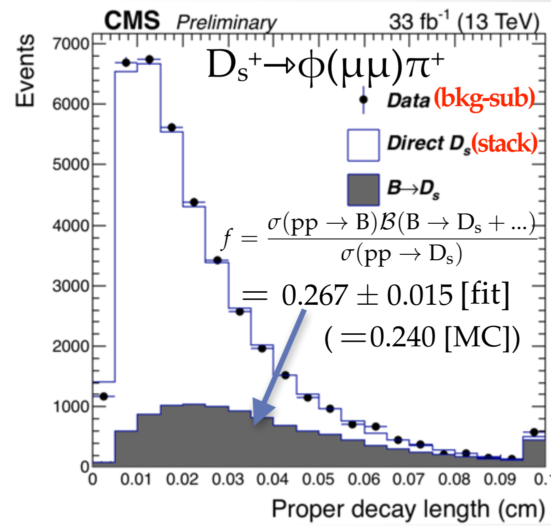
- ~75% of MC events fires **2μ-L1 trigger**; then:
  - $D_s^+ \to \tau^+(3\mu)\nu$ [$\mathbf{N_{sig(D)}}$] normalized to $D_s^+ \to \varphi(\mu\mu)\pi^+$ [**N**]:

$$N_{\mathrm{sig(D)}} = N \frac{\mathcal{B}(\mathrm{D_s} \to \tau\nu)}{\mathcal{B}(\mathrm{D_s} \to \phi\pi \to \mu\mu\pi)} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{2\mu\pi}} \frac{\epsilon^{3\mu}_{\mathrm{reco}}}{\epsilon^{2\mu\pi}_{\mathrm{reco}}} \frac{\epsilon^{2\mu}_{\mathrm{trig,sig}}}{\epsilon^{2\mu}_{\mathrm{trig}(\mu\mu\pi)}} \mathcal{B}(\tau \to 3\mu)$$

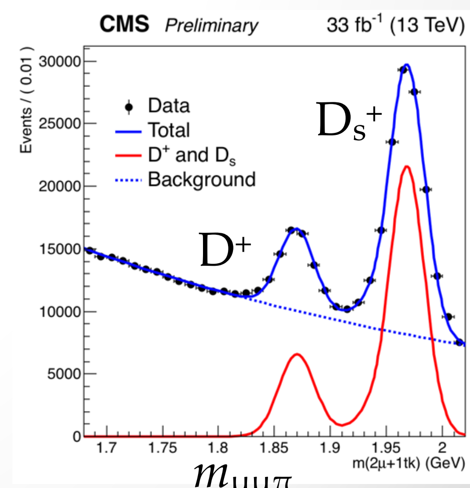
  - $B \to \tau(3\mu)+X$ yield [$\mathbf{N_{sig(B)}}$] normalized to **N**, using the D_s^+ B-*like* fraction ***f*** (MC ≈ data):

$$N_{\mathrm{sig(B)}} = N f \frac{\mathcal{B}(\mathrm{B} \to \tau + ...)}{\mathcal{B}(\mathrm{D_s} \to \phi\pi \to \mu\mu\pi)\mathcal{B}(\mathrm{B} \to \mathrm{D_s} + ...)} \frac{\mathcal{A}_{3\mu(B)}}{\mathcal{A}_{2\mu\pi}} \frac{\epsilon^{3\mu}_{\mathrm{reco}}}{\epsilon^{2\mu\pi}_{\mathrm{reco}}} \frac{\epsilon^{2\mu}_{\mathrm{trig,sig}}}{\epsilon^{2\mu}_{\mathrm{trig}(\mu\mu\pi)}} \mathcal{B}(\tau \to 3\mu)$$

  - $D_s^+ \to \varphi\pi^+$ yield data/MC comparison ⇒ **MC correction** due to 2μ-trigger performance.
- ~25% of signal **exclusively** selected by **3μ-L1**:
  - $N_{\mathbf{3\mu\text{-}L1}}/N_{2\mu\text{-}L1}$ from $m_{3\mu}$ sidebands $\overset{!}{=}$ $N_{\mathbf{3\mu\text{-}L1}}/N_{2\mu\text{-}L1}$ in MC ⇒ **MC correction** due to 3μ-trigger.

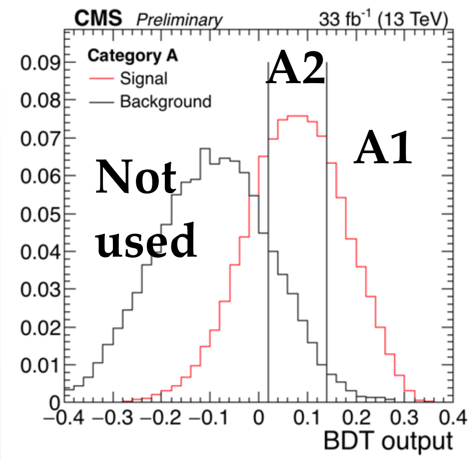


$ct = L_{\mu\mu\pi\text{-IP}}\, m_{\mu\mu\pi} / p_{\mu\mu\pi}$



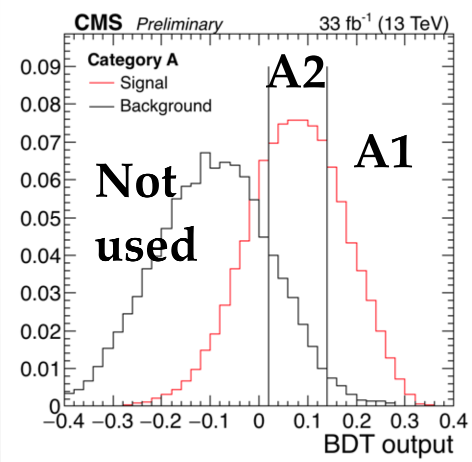
Background suppression

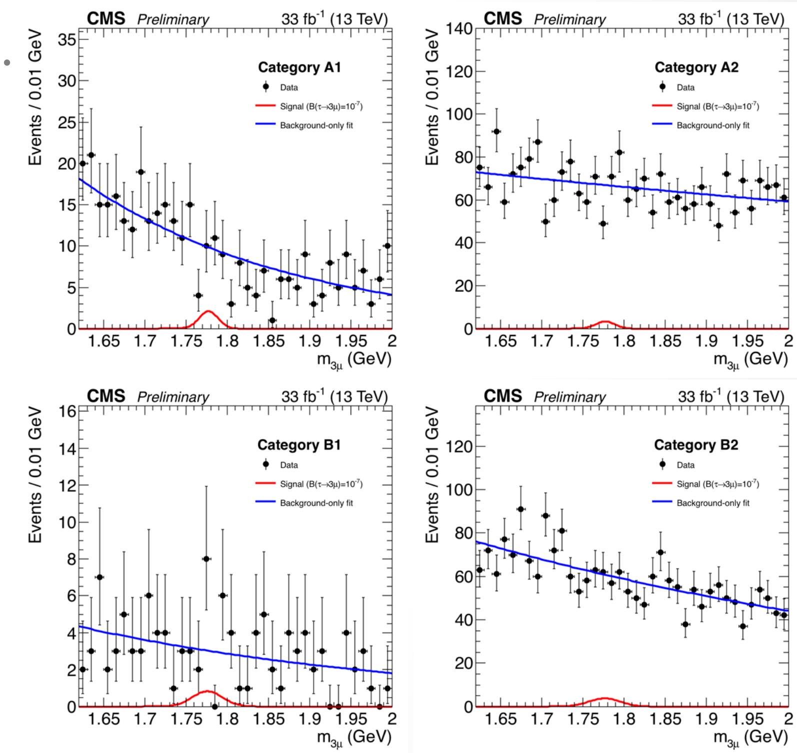
- Remaining bkg ~ [$B(\bar{B}) \rightarrow \ldots \rightarrow \mu\mu X$] + [$K/\pi$ misID as μ *or* $K/\pi \rightarrow \mu$].
- Further suppression with a BDT:
  - *signal*: MC samples properly mixed.
  - *bkg*: data $m_{3\mu}$ sidebands.
  - Variables: 4 ($\chi^2_{3\mu}$, $L_{3\mu\text{-IP}}/\sigma_{L_{3\mu\text{-IP}}}$, $\alpha_{3\mu\text{-IP}}$, $DCA_{3\mu\text{-}t}$) + 6 (muon track quality).
  - **2 subcategories (1, 2)** based on purity.



Background suppression

- Remaining bkg ~ $[B(\bar{B}) \rightarrow \ldots \rightarrow \mu\mu X]$ + [K/π misID as μ or $K/\pi \rightarrow \mu$].
- Further suppression with a BDT:
  - *signal*: MC samples properly mixed.
  - *bkg*: data $m_{3\mu}$ sidebands.
  - Variables: 4 ($\chi^2_{3\mu}$, $L_{3\mu\text{-IP}}/\sigma_{L_{3\mu\text{-IP}}}$, $\alpha_{3\mu\text{-IP}}$, $DCA_{3\mu\text{-}t}$) + 6 (muon track quality).
  - **2 subcategories (1, 2)** based on purity.

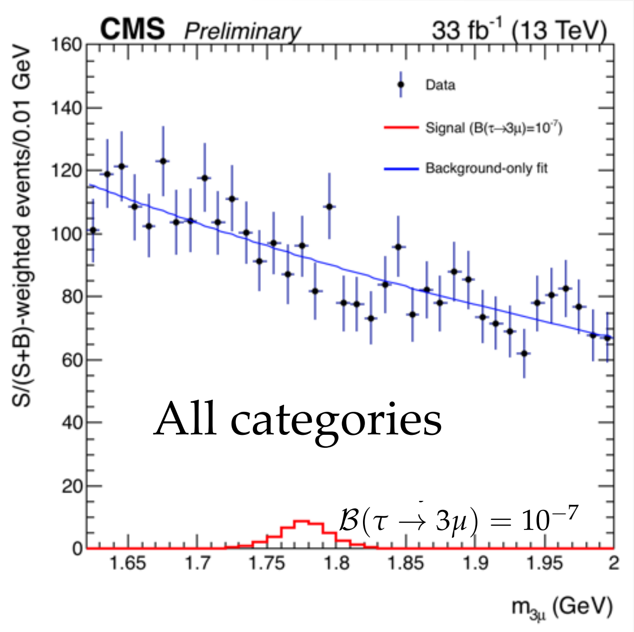




Fitted with an exponential function

Results

Source of uncertainty	Yield	Shape
Uncertainty on D_s normalization [10%]	10%	
Relative uncertainty in $\mathcal{B}(D_s \to \tau\nu)$ [4%]	3%	
Relative uncertainty in $\mathcal{B}(D_s \to \phi\pi \to \mu\mu\pi)$ [8%]	8%	
Relative uncertainty in $\mathcal{B}(B \to D_s + ...)$ [16%]	5%	
Relative uncertainty in $\mathcal{B}(B \to \tau + ...)$ [11%]	3%	
Uncertainty in f (B/D ratio) [11%]	3%	
Uncertainty on D^+ as a source of τ [100%]	3%	
Uncertainty on B_s as a source of τ [100%]	4%	
Uncertainty in number of events triggered by trimuon trigger [8%]	2%	
Uncertainty in the ratio of acceptances $\mathcal{A}_{sig}/\mathcal{A}_{2\mu\pi}$ [1%]	1%	
Muon reconstruction efficiency [1.5%]	1.5%	
Charged pion reconstruction efficiency [2.3%]	2.3%	
BDT cut efficiency [5%]	5%	
Mass scale uncertainty [0.07%]	–	yes
Mass resolution uncertainty [2.5%]	–	yes



Observed combined upper limit (CLs):

$\mathrm{Br}(\tau \to 3\mu) < 8.8 \times 10^{-8}$ @ 90% CL
(expected: 9.9×10^{-8})

CMS PAS BPH-17-004

A CMS analysis using $W \to \tau\nu$ is in preparation.

Summary

- Study and search for rare decays are important probes to look for new physics.
- So far, results are consistent with the SM (but interesting single experiment deviations remain; NP preferred when combining all flavor anomalies, including "non-LU").
- Some of the analyses presented here will be updated using the complete Run II data sample. New studies (LU, Br($\tau \to 3\mu$) using $W \to \tau\nu$, etc.) are also in the pipeline.
- ATLAS and CMS will continue exploring rare decays in the future with upgraded LHC and detectors.

THANKS for listening!

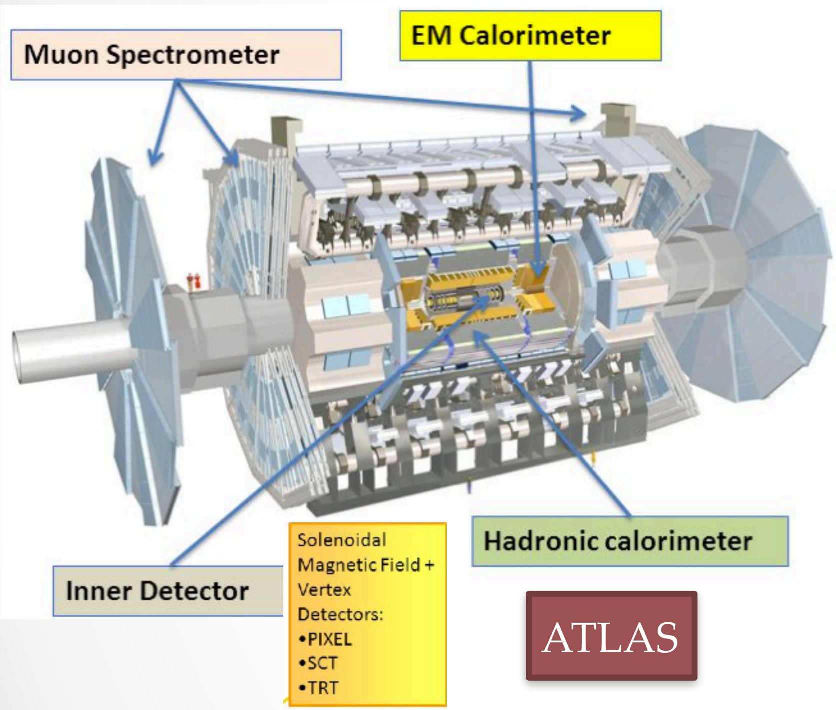
Backup

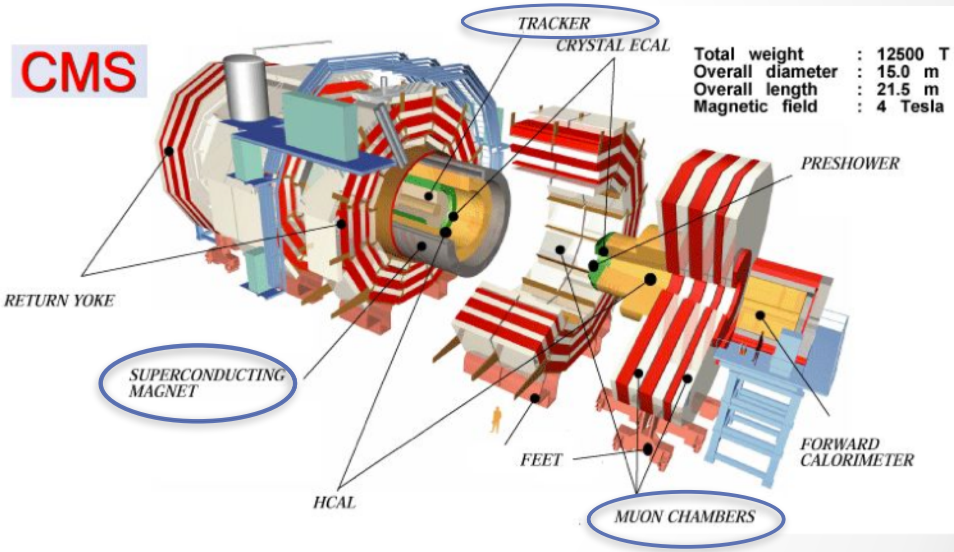
History of indirect vs. direct searches

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \rightarrow e\nu$	UA1, UA2	1983
c	$K^0 \rightarrow \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \rightarrow \pi\pi$	CKM, 3rd gen	1964/	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \rightarrow e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \rightarrow Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \rightarrow 4\mu/\gamma\gamma$	CMS, ATLAS	2012

R. Forty, Corfu Summer School (2018)

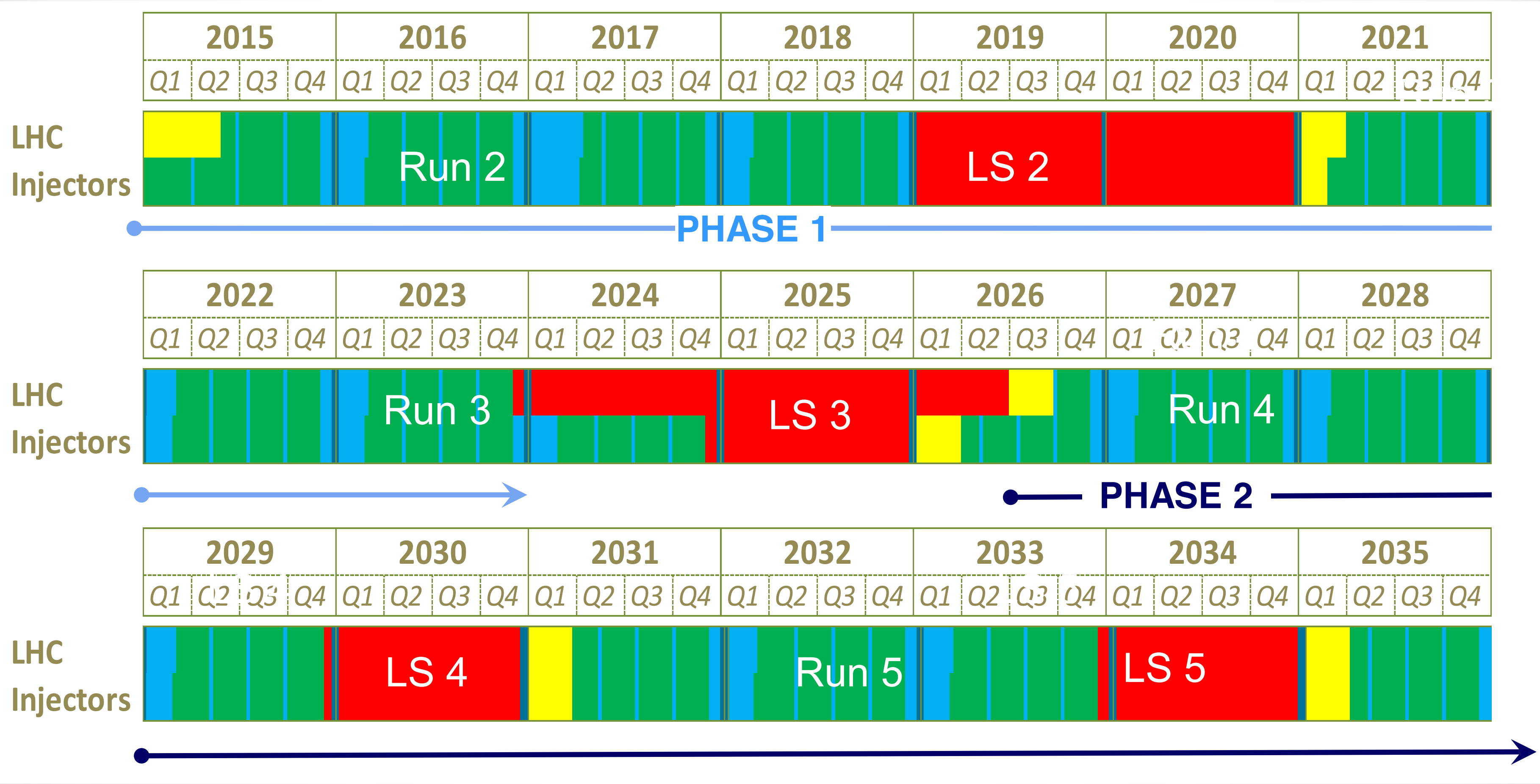
ATLAS & CMS detectors





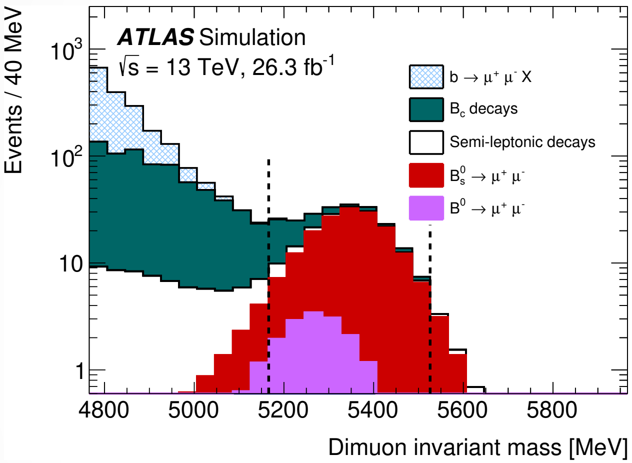
ATLAS and CMS heavy flavors programs
$\leftrightarrow$ Excellent μ ID + Track and vertex reconstruction

LHC roadmap

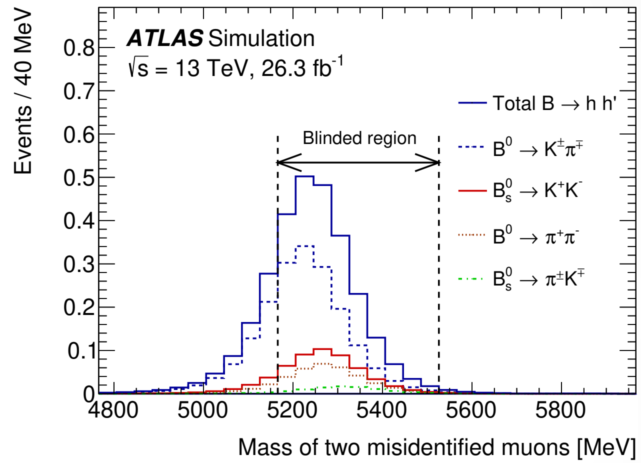


2015
2016
2017
2018
2019
2020
2021
Q1 Q2 Q3 Q4
LHC
Injectors
Run 2
LS 2
PHASE 1
2022
2023
2024
2025
2026
2027
2028
Run 3
LS 3
Run 4
PHASE 2
2029
2030
2031
2032
2033
2034
2035
LS 4
Run 5
LS 5

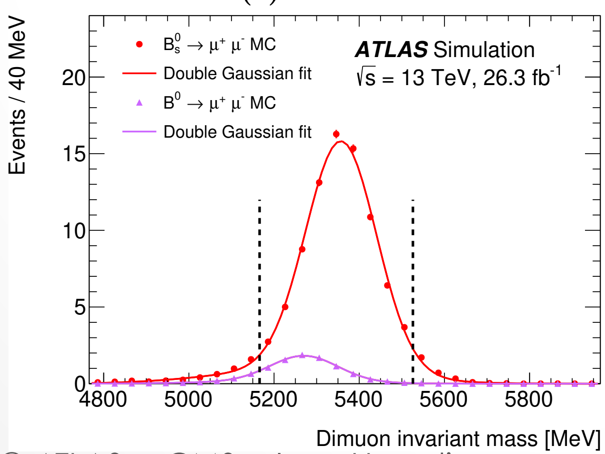
ATLAS $B^{(0)}_s \to \mu^+\mu^-$ modeling and analysis

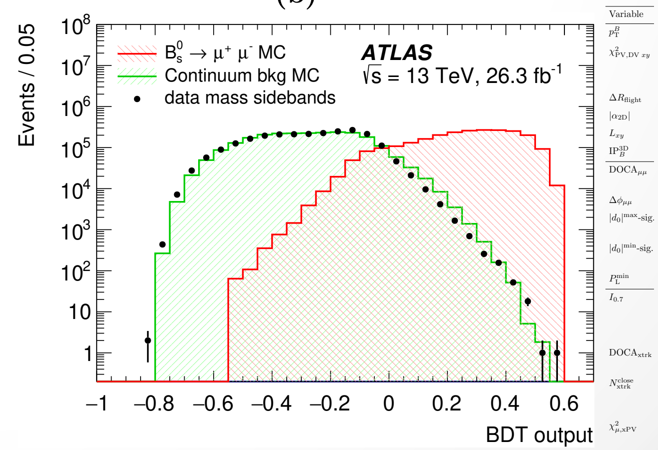


(a)

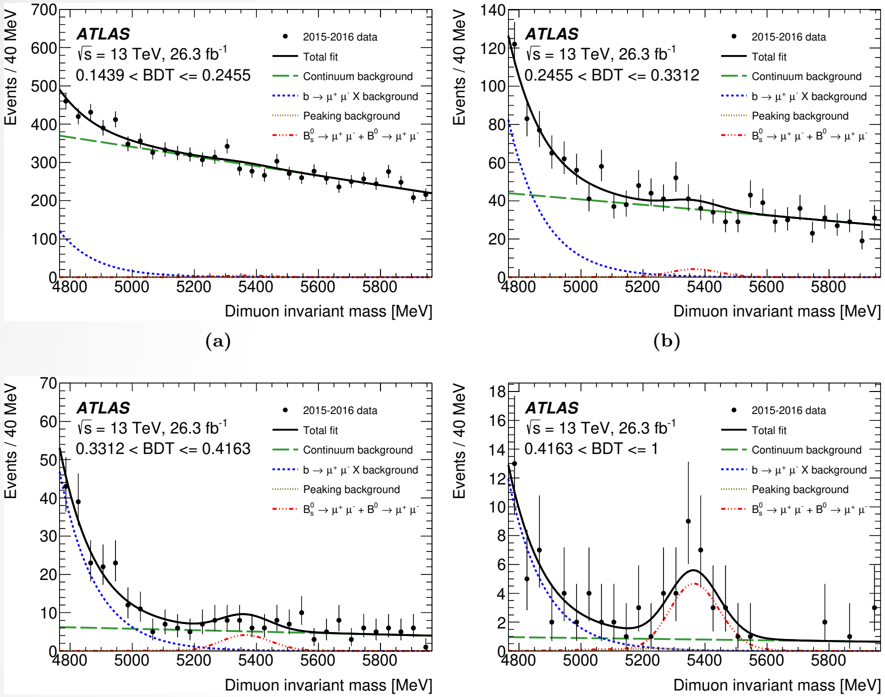


(b)





ATLAS $B^{(0)}_s \to \mu^+\mu^-$ fit results



(a) (b) (c) (d)

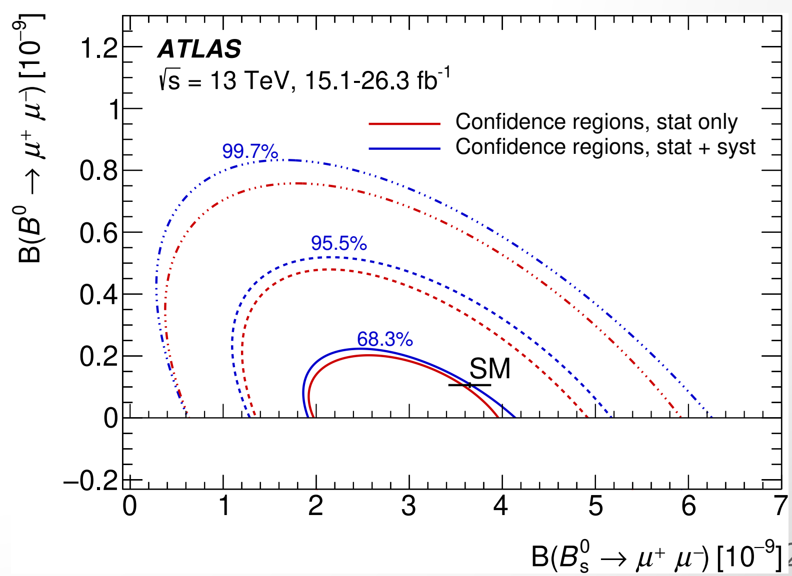
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \frac{\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{D}_{\text{ref}}} \times \frac{f_u}{f_{d(s)}}$$

$$\mathcal{D}_{\text{ref}} = N_{J/\psi K^+}/R_\varepsilon$$

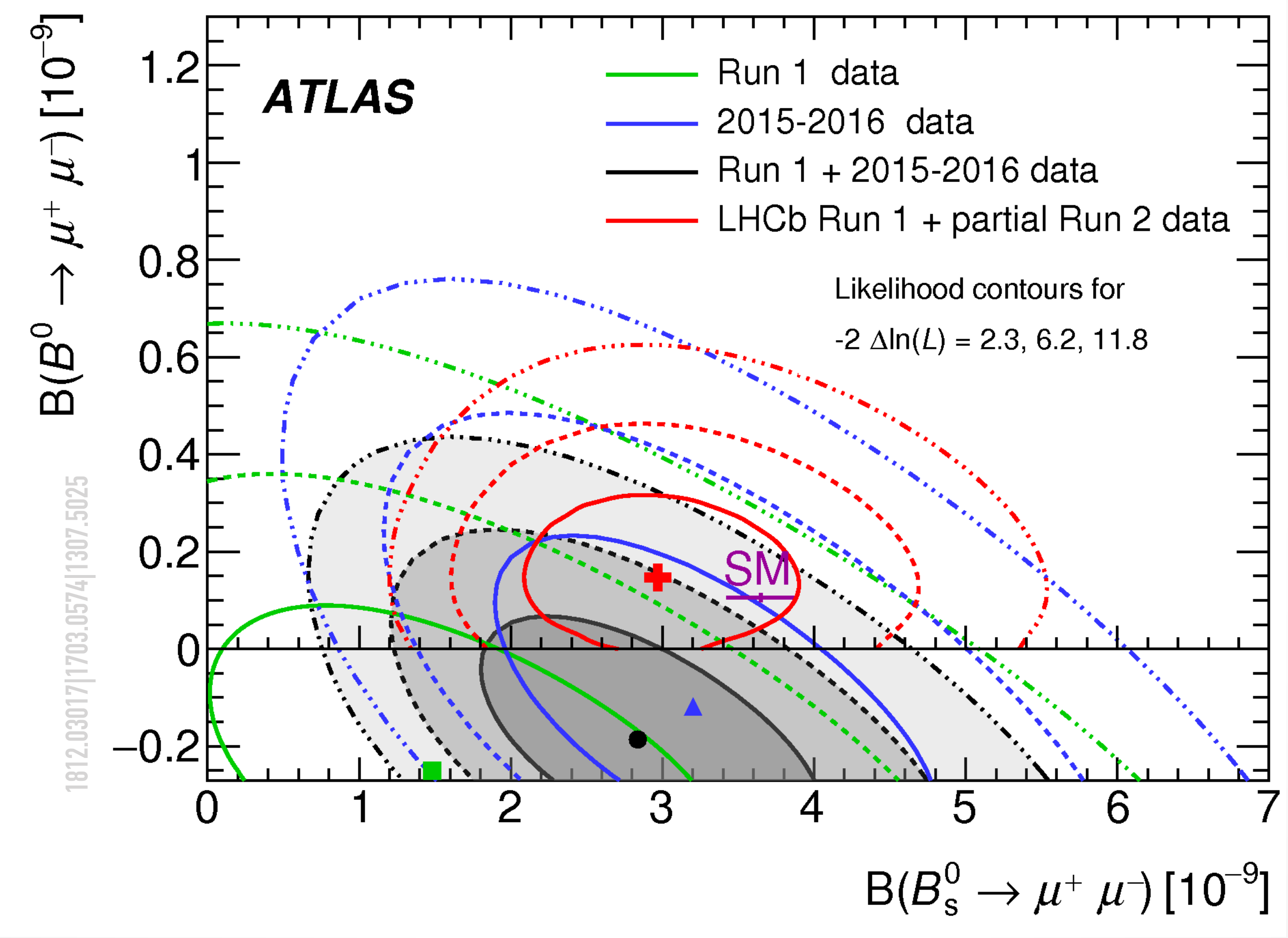
$$R_\varepsilon = \varepsilon(B^+ \to J/\psi\, K^+)/\varepsilon(B^0_{(s)} \to \mu^+\mu^-)$$

Source	Contribution [%]
Statistical	0.8
Kinematic reweighting (DDW)	0.8
Muon trigger and reconstruction	1.0
BDT input variables	3.2
Kaon tracking efficiency	1.5
Pile-up reweighting	0.6

Source	B^0_s [%]	B^0 [%]
f_s/f_d	5.1	—
B^+ yield	4.8	4.8
R_ε	4.1	4.1
$\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$	2.9	2.9
Fit systematic uncertainties	8.7	65
Stat. uncertainty (from likelihood est.)	27	150



$B^{(0)}_s \to \mu^+\mu^-$:ATLAS vs LHCb



Angular folding to the $B^0 \to K^*\mu^+\mu^-$ angular function

To avoid difficulties in the fit due to the small data sample, **ATLAS** apply trigonometric transformations to obtain the following observables :

The angular domain is reduced to:

$$F_L, S_3, S_4, P_4^{'} : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

$$\cos\theta_L \in [0,1], \quad \cos\theta_K \in [-1,1] \quad \text{and} \quad \phi \in [0,\pi]$$

$$F_L, S_3, S_5, P_5^{'} : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

$$\cos\theta_L \in [0,1], \quad \cos\theta_K \in [-1,1] \quad \text{and} \quad \phi \in [0,\pi].$$

This one is used by CMS.

$$F_L, S_3, S_7, P_6^{'} : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

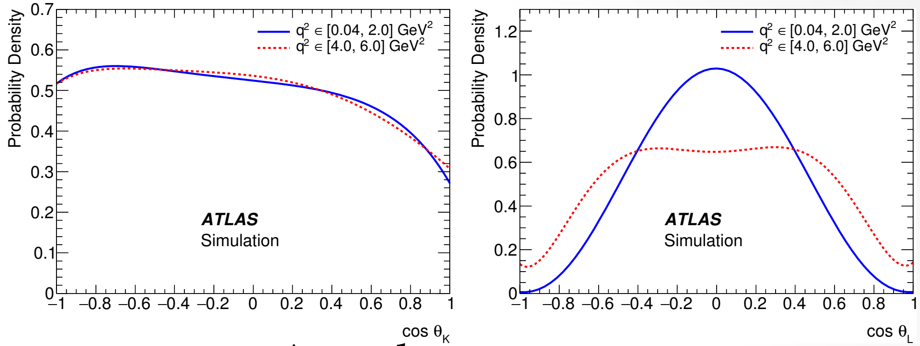
$$\cos\theta_L \in [0,1], \quad \cos\theta_K \in [-1,1] \quad \text{and} \quad \phi \in [-\pi/2,\pi/2]$$

$$F_L, S_3, S_8, P_8^{'} : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_K \to \pi - \theta_K & \text{for } \theta_L > \frac{\pi}{2}. \end{cases}$$

$$\cos\theta_L \in [0,1], \quad \cos\theta_K \in [-1,1] \quad \text{and} \quad \phi \in [-\pi/2,\pi/2]$$

$B^0 \to K^*\mu^+\mu^-$: ATLAS fit results & syst.

q^2 [GeV^2]	n_{signal}	$n_{\text{background}}$
[0.04, 2.0]	128 ± 22	122 ± 22
[2.0, 4.0]	106 ± 23	113 ± 23
[4.0, 6.0]	114 ± 24	204 ± 26
[0.04, 4.0]	236 ± 31	233 ± 32
[1.1, 6.0]	275 ± 35	363 ± 36
[0.04, 6.0]	342 ± 39	445 ± 40



Angular acceptances

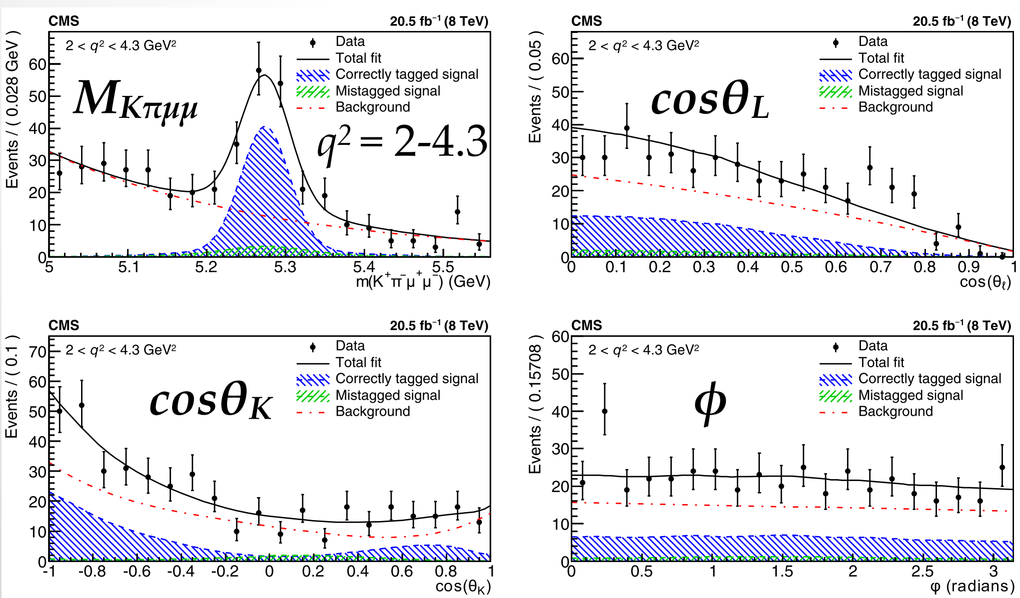
q^2 [GeV^2]	F_L	S_3	S_4	S_5	S_7	S_8
[0.04, 2.0]	$0.44\pm0.08\pm0.07$	$-0.02\pm0.09\pm0.02$	$0.15\pm0.20\pm0.10$	$0.33\pm0.13\pm0.08$	$-0.09\pm0.10\pm0.02$	$-0.14\pm0.24\pm0.09$
[2.0, 4.0]	$0.64\pm0.11\pm0.05$	$-0.15\pm0.10\pm0.07$	$-0.37\pm0.15\pm0.10$	$-0.16\pm0.15\pm0.06$	$0.15\pm0.14\pm0.09$	$0.52\pm0.20\pm0.19$
[4.0, 6.0]	$0.42\pm0.13\pm0.12$	$0.00\pm0.12\pm0.07$	$0.32\pm0.16\pm0.09$	$0.13\pm0.18\pm0.09$	$0.03\pm0.13\pm0.07$	$-0.12\pm0.21\pm0.05$
[0.04, 4.0]	$0.52\pm0.07\pm0.06$	$-0.05\pm0.06\pm0.04$	$-0.15\pm0.12\pm0.09$	$0.16\pm0.10\pm0.05$	$0.01\pm0.08\pm0.05$	$0.19\pm0.16\pm0.12$
[1.1, 6.0]	$0.56\pm0.07\pm0.06$	$-0.04\pm0.07\pm0.03$	$0.03\pm0.11\pm0.07$	$0.00\pm0.10\pm0.04$	$0.02\pm0.08\pm0.06$	$0.11\pm0.14\pm0.10$
[0.04, 6.0]	$0.50\pm0.06\pm0.04$	$-0.04\pm0.06\pm0.03$	$0.03\pm0.10\pm0.07$	$0.14\pm0.09\pm0.03$	$0.02\pm0.07\pm0.05$	$0.07\pm0.13\pm0.09$

q^2 [GeV^2]	P_1	P'_4	P'_5	P'_6	P'_8
[0.04, 2.0]	$-0.05\pm0.30\pm0.08$	$0.31\pm0.40\pm0.20$	$0.67\pm0.26\pm0.16$	$-0.18\pm0.21\pm0.04$	$-0.29\pm0.48\pm0.18$
[2.0, 4.0]	$-0.78\pm0.51\pm0.34$	$-0.76\pm0.31\pm0.21$	$-0.33\pm0.31\pm0.13$	$0.31\pm0.28\pm0.19$	$1.07\pm0.41\pm0.39$
[4.0, 6.0]	$0.14\pm0.43\pm0.26$	$0.64\pm0.33\pm0.18$	$0.26\pm0.35\pm0.18$	$0.06\pm0.27\pm0.13$	$-0.24\pm0.42\pm0.09$
[0.04, 4.0]	$-0.22\pm0.26\pm0.16$	$-0.30\pm0.24\pm0.17$	$0.32\pm0.21\pm0.11$	$0.01\pm0.17\pm0.10$	$0.38\pm0.33\pm0.24$
[1.1, 6.0]	$-0.17\pm0.31\pm0.13$	$0.05\pm0.22\pm0.14$	$0.01\pm0.21\pm0.08$	$0.03\pm0.17\pm0.12$	$0.23\pm0.28\pm0.20$
[0.04, 6.0]	$-0.15\pm0.23\pm0.10$	$0.05\pm0.20\pm0.14$	$0.27\pm0.19\pm0.06$	$0.03\pm0.15\pm0.10$	$0.14\pm0.27\pm0.17$

$B^0 \to K^*\mu^+\mu^-$: CMS fit results & syst.

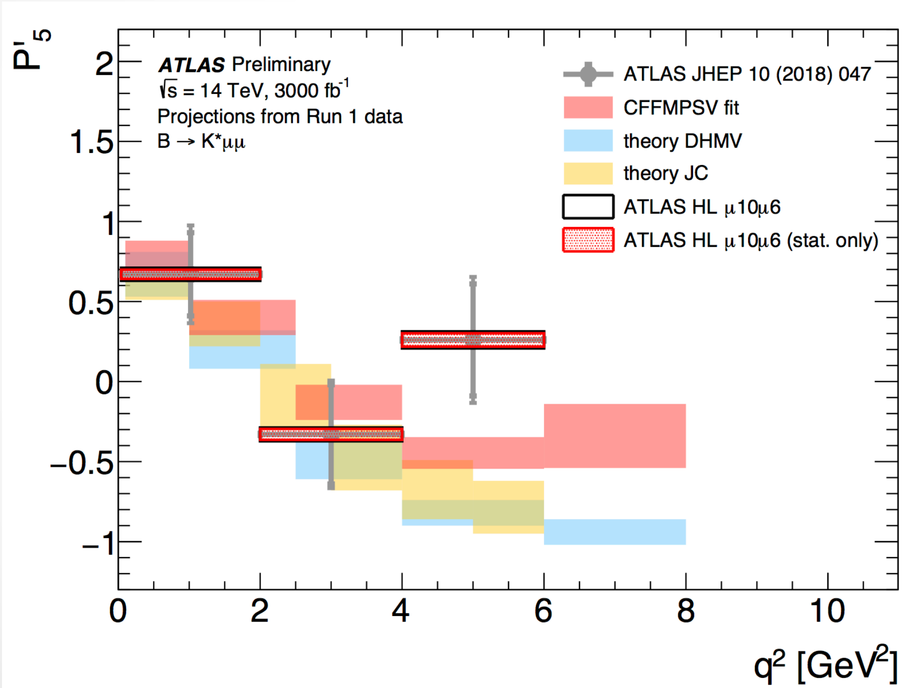
The measured signal yields, which include both correctly tagged and mistagged events, the P_1 and P_5' values, and the correlation coefficients, in bins of q^2, for $B^0 \to K^{*0}\mu^+\mu^-$ decays. The first uncertainty is statistical and the second is systematic. The bin ranges are selected to allow comparison with previous measurements.

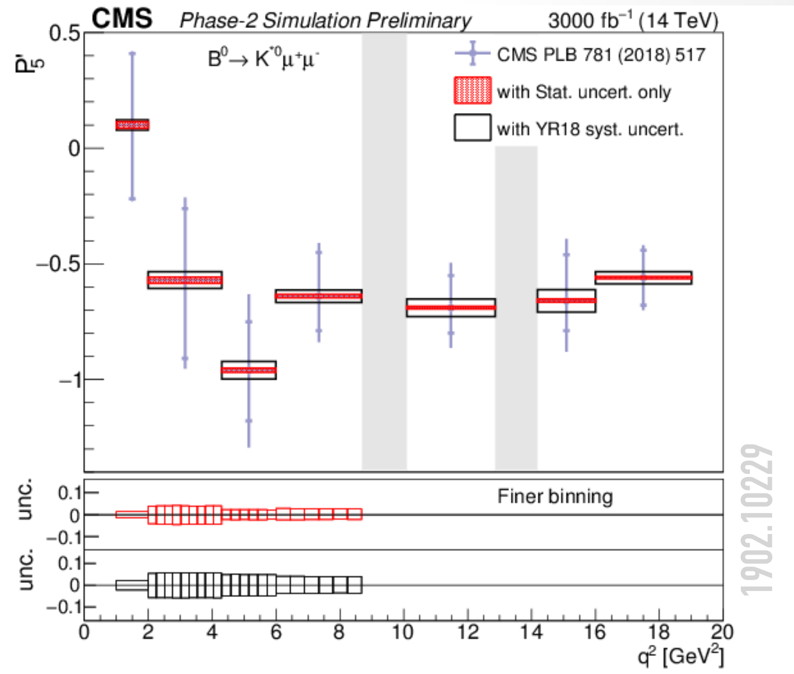
q^2 (GeV^2)	Signal yield	P_1	P_5'	Correlations
1.00–2.00	80 ± 12	$+0.12\ ^{+0.46}_{-0.47} \pm 0.10$	$+0.10\ ^{+0.32}_{-0.31} \pm 0.07$	-0.0526
2.00–4.30	145 ± 16	$-0.69\ ^{+0.58}_{-0.27} \pm 0.23$	$-0.57\ ^{+0.34}_{-0.31} \pm 0.18$	-0.0452
4.30–6.00	119 ± 14	$+0.53\ ^{+0.24}_{-0.33} \pm 0.19$	$-0.96\ ^{+0.22}_{-0.21} \pm 0.25$	$+0.4715$
6.00–8.68	247 ± 21	$-0.47\ ^{+0.27}_{-0.23} \pm 0.15$	$-0.64\ ^{+0.15}_{-0.19} \pm 0.13$	$+0.0761$
10.09–12.86	354 ± 23	$-0.53\ ^{+0.20}_{-0.14} \pm 0.15$	$-0.69\ ^{+0.11}_{-0.14} \pm 0.13$	$+0.6077$
14.18–16.00	213 ± 17	$-0.33\ ^{+0.24}_{-0.23} \pm 0.20$	$-0.66\ ^{+0.13}_{-0.20} \pm 0.18$	$+0.4188$
16.00–19.00	239 ± 19	$-0.53 \pm 0.19 \pm 0.16$	$-0.56 \pm 0.12 \pm 0.07$	$+0.4621$



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
$K\pi$ 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

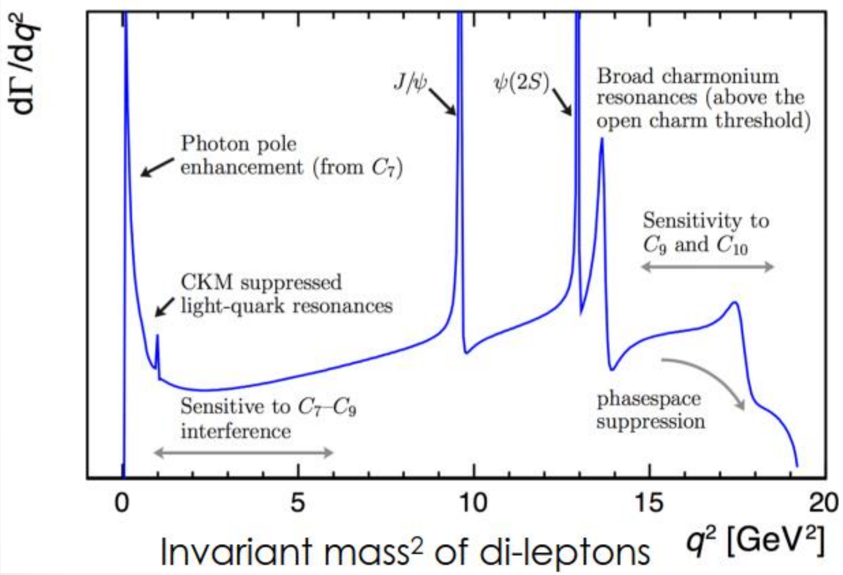
$B^0 \to K^*\mu^+\mu^-$: future

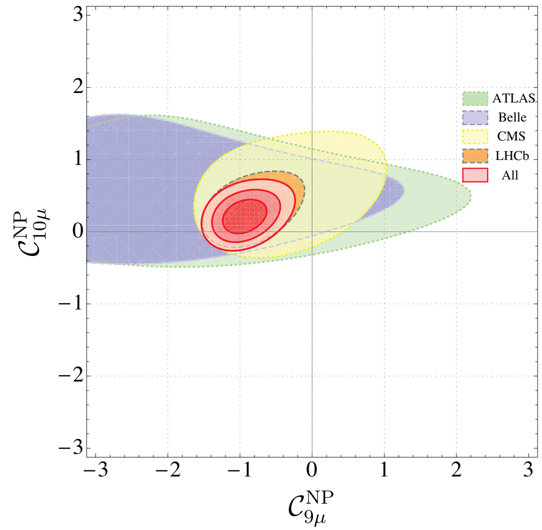




Wilson coefficients

Plot from Prog. Part. Nucl. Phys 92 (2017) 50



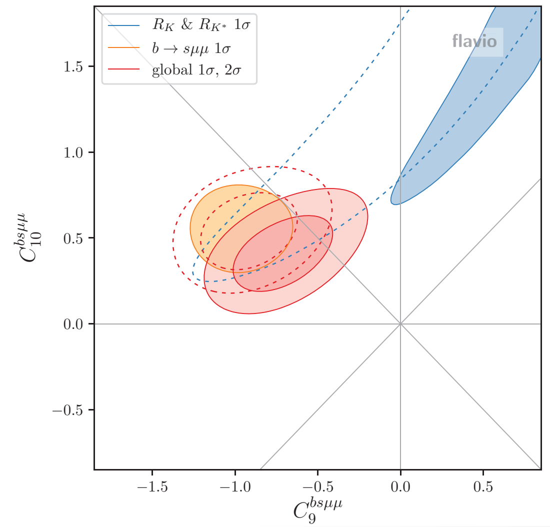


Algueró et al
1903.09578

$C_{9,\mu}^{\rm NP} \sim -0.95$

$C_{10,\mu}^{\rm NP} \sim 0.20$

(5.7 σ pull)



Aebischer et al
1903.10434

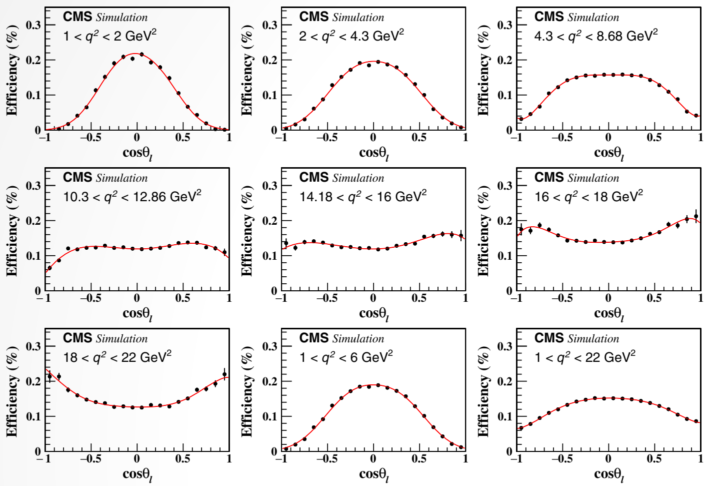
$C_{9,\mu}^{\rm NP} \sim -0.72$

$C_{10,\mu}^{\rm NP} \sim 0.40$

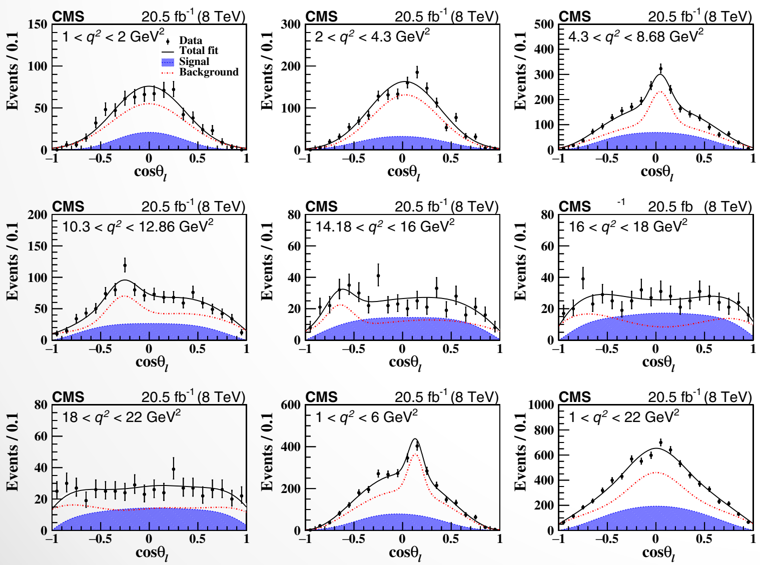
(6.2 σ pull)

$B^+ \to K^+\mu^+\mu^-$: CMS fits and syst.

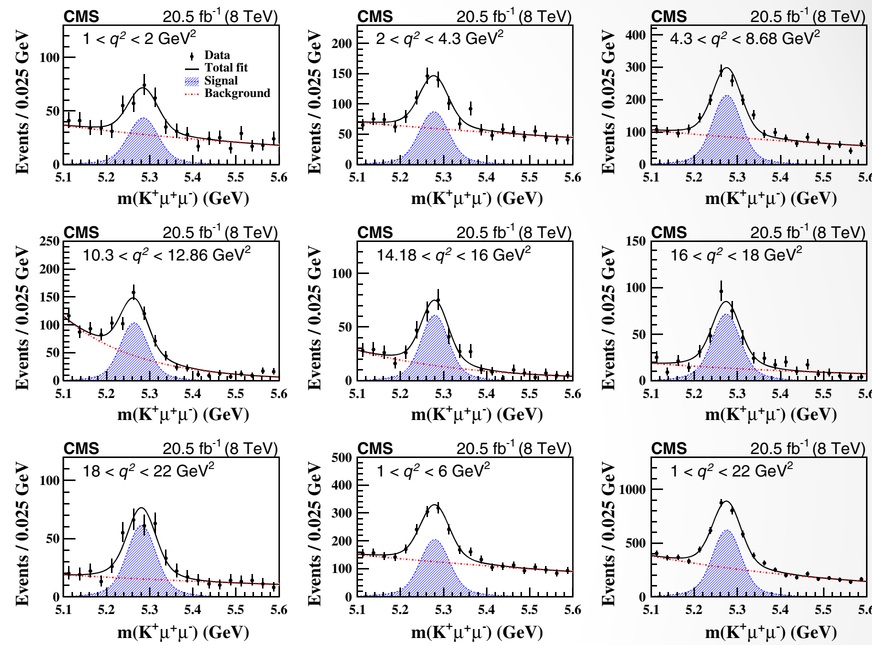
Angular efficiencies



Angular projections



Mass fits



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

$B^+ \to K^+\mu^+\mu^-$: CMS fits and syst. (II)

q^2 (GeV^2)	Y_S	A_{FB}	F_H	F_H (EOS)	F_H (DHMV)	F_H (FLAVIO)
1.00–2.00	169 ± 22	$0.08\,^{+0.22}_{-0.19} \pm 0.05$	$0.21\,^{+0.29}_{-0.21} \pm 0.39$	0.047	0.046	0.045
2.00–4.30	331 ± 32	$-0.04\,^{+0.12}_{-0.12} \pm 0.07$	$0.85\,^{+0.34}_{-0.31} \pm 0.14$	0.024	0.023	0.022
4.30–8.68	785 ± 42	$0.00\,^{+0.04}_{-0.04} \pm 0.02$	$0.01\,^{+0.02}_{-0.01} \pm 0.04$	...	0.012	0.011
10.09–12.86	365 ± 29	$0.00\,^{+0.05}_{-0.05} \pm 0.05$	$0.01\,^{+0.02}_{-0.01} \pm 0.06$	...	...	...
14.18–16.00	215 ± 19	$0.01\,^{+0.06}_{-0.05} \pm 0.02$	$0.03\,^{+0.03}_{-0.03} \pm 0.07$	0.007	0.007	0.006
16.00–18.00	262 ± 21	$0.04\,^{+0.05}_{-0.04} \pm 0.03$	$0.07\,^{+0.06}_{-0.07} \pm 0.07$	0.007	0.007	0.006
18.00–22.00	226 ± 20	$0.05\,^{+0.05}_{-0.04} \pm 0.02$	$0.10\,^{+0.06}_{-0.10} \pm 0.09$	0.008	0.009	0.008
1.00–6.00	778 ± 47	$-0.14\,^{+0.07}_{-0.06} \pm 0.03$	$0.38\,^{+0.17}_{-0.21} \pm 0.09$	0.025	0.025	0.020
1.00–22.00	2286 ± 73	$0.00\,^{+0.02}_{-0.02} \pm 0.03$	$0.01\,^{+0.01}_{-0.01} \pm 0.06$	...	...	...

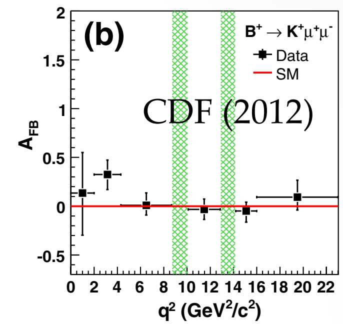
B+ → K+μ+μ- measurements

B+ & B0 BaBar (2006)

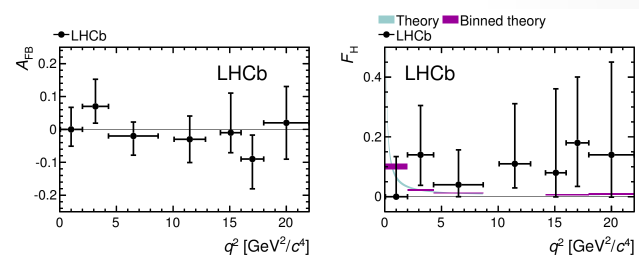
q^2 (GeV^2/c^4)	$\mathcal{B}$ (10^{-6})	F_S	A_{FB}
0.1 − 8.41	$0.10^{+0.04}_{-0.04} \pm 0.01$	0	$-0.49^{+0.51}_{-0.99} \pm 0.18$
>10.24	$0.22^{+0.05}_{-0.05} \pm 0.02$	0	$0.26^{+0.23}_{-0.24} \pm 0.03$
>0.1	$0.34^{+0.07}_{-0.07} \pm 0.02$	$0.81^{+0.58}_{-0.61} \pm 0.46$	$0.15^{+0.21}_{-0.23} \pm 0.08$

Belle (2009)

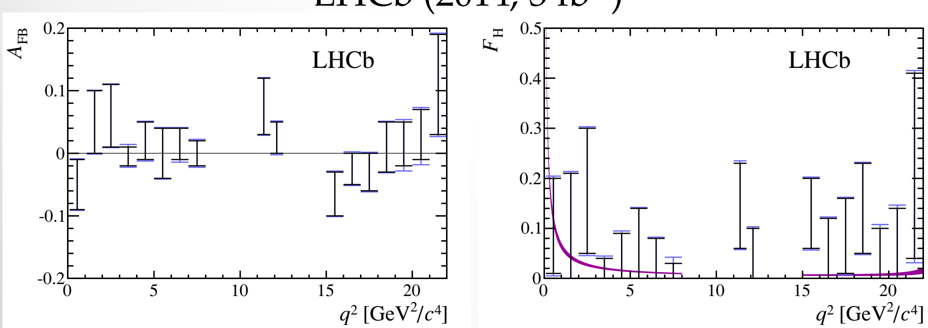
q^2 (GeV^2/c^2)	N_s	$\mathcal{B}(10^{-7})$	F_L	A_{FB}
0.00–2.00	$27.0^{+6.0}_{-5.4}$	$0.81^{+0.18}_{-0.16} \pm 0.05$	⋯	$0.06^{+0.32}_{-0.35} \pm 0.02$
2.00–4.30	$17.6^{+5.5}_{-4.8}$	$0.46^{+0.14}_{-0.12} \pm 0.03$	⋯	$-0.43^{+0.38}_{-0.40} \pm 0.09$
4.30–8.68	$39.1^{+7.5}_{-6.9}$	$1.00^{+0.19}_{-0.18} \pm 0.06$	⋯	$-0.20^{+0.12}_{-0.14} \pm 0.03$
10.09–12.86	$22.0^{+6.2}_{-5.5}$	$0.55^{+0.16}_{-0.14} \pm 0.03$	⋯	$-0.21^{+0.17}_{-0.15} \pm 0.06$
14.18–16.00	$15.6^{+4.9}_{-4.3}$	$0.38^{+0.19}_{-0.12} \pm 0.02$	⋯	$0.04^{+0.32}_{-0.26} \pm 0.05$
>16.00	$40.3^{+8.2}_{-7.5}$	$0.98^{+0.20}_{-0.18} \pm 0.06$	⋯	$0.02^{+0.11}_{-0.08} \pm 0.02$
1.00–6.00	$52.0^{+8.7}_{-8.0}$	$1.36^{+0.23}_{-0.21} \pm 0.08$	⋯	$-0.04^{+0.13}_{-0.16} \pm 0.05$

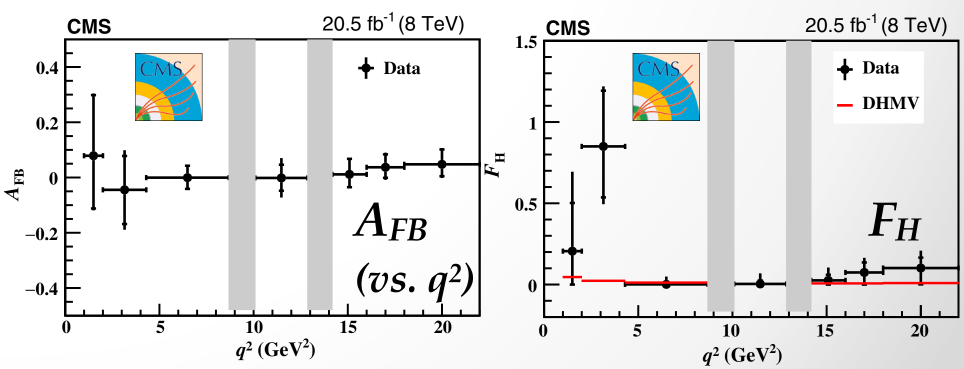


LHCb (2013, 1 fb-1)



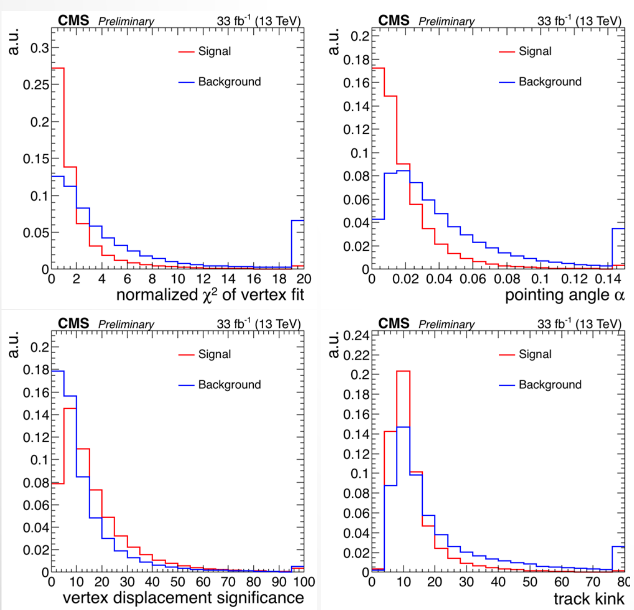
LHCb (2014, 3 fb-1)

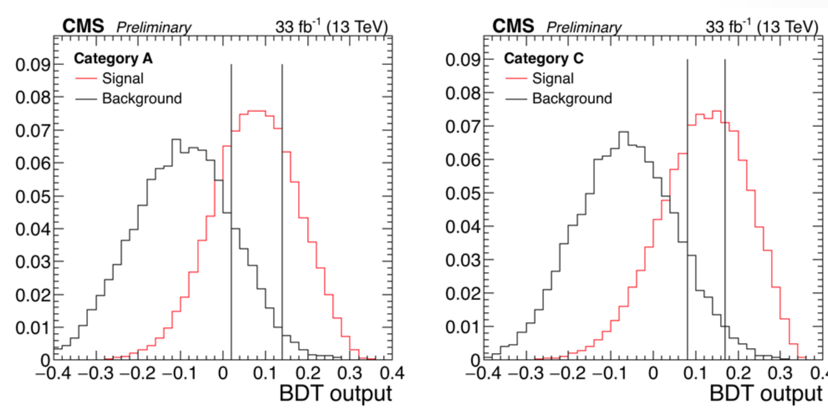




Known BRs for Br($\tau \to 3\mu$) UL measurement — BDT — yields

Process	Branching ratio	Reference
$D_s \to \tau\nu$	$5.48 \pm 0.23\%$	PDG [13]
$B^+ \to \tau + \nu + D^{0(*)}$	$2.7 \pm 0.3\%$	PDG [13]
Other $B^+ \to \tau + X$ decays	0.7%	PYTHIA [5]
$B^0 \to \tau + \nu + D^{+(*)}$	$2.7 \pm 0.3\%$	PDG [13]
Other $B^0 \to \tau + X$ decays	0.7%	PYTHIA [5]
$B^+ \to D_s + X$	$9.0 \pm 1.5\%$	PDG [13]
$B^0 \to D_s + X$	$10.3 \pm 2.1\%$	PDG [13]
$D_s \to \phi(\mu\mu)\pi$	$1.3(\pm 0.1) \times 10^{-5}$	PDG [13]





	Signal		Data	
	sub-category 1	sub-category 2	sub-category 1	sub-category 2
Category A	6.3	10.3	360(44)	2502(319)
Category B	3.9	18.5	110(27)	2229(449)
Category C	9.4	9.6	389(107)	1549(400)

Br($\tau \to 3\mu$) UL: LHC