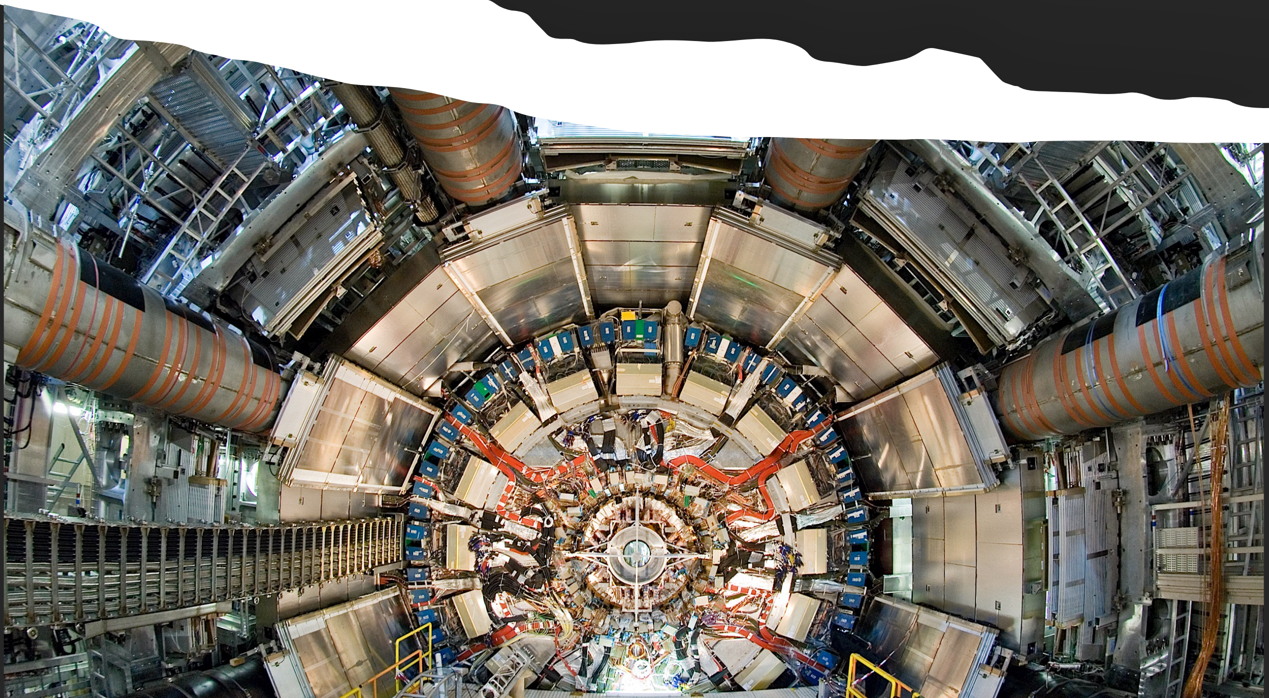
Status and perspectives of physics at high intensity

Frascati - November 9th, 2022

Rare decays at ATLAS and CMS



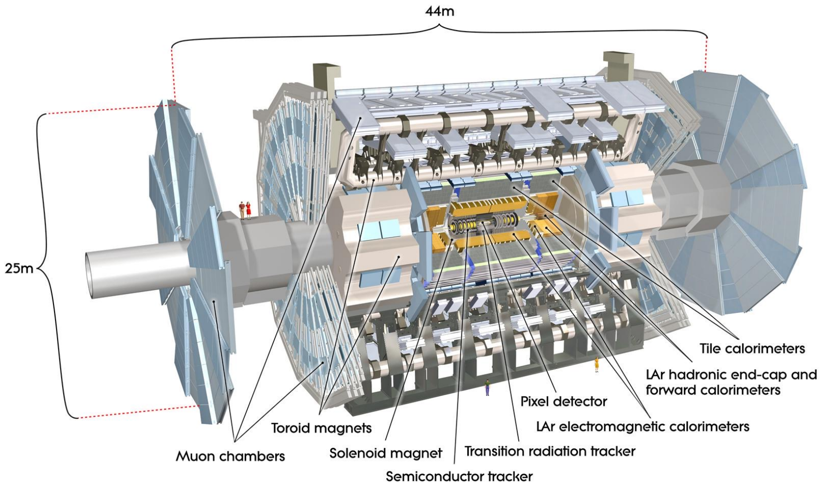
Luca Guzzi – INFN Milano-Bicocca

OVERVIEW

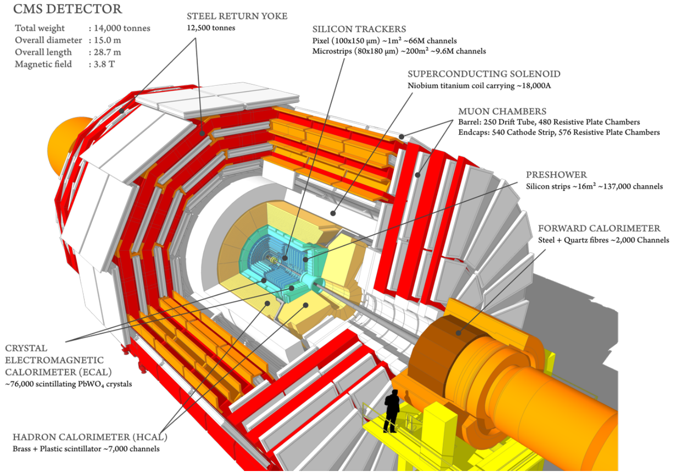
results from rare decays searches in B-physics at ATLAS and CMS

- search for $\mathrm{B}^0_{(s)}\to\mu^+\mu^-$ events at CMS and B^0_s life-time measurement on Run2 data
- search for $\mathrm{B}^0_{(s)}\to\mu^+\mu^-$ events at ATLAS on (partial) Run2 data
- angular analysis $B^0 \to K^{0*} \mu^+\mu^-$ at CMS on Run1 data
- angular analysis $B^0 \to K^{0*} \mu^+\mu^-$ at ATLAS on Run1 data
- search for the LFV decay $\tau^+\to\mu^+\mu^+\mu^-$ at CMS in (partial) Run2 data
- search for the LFV decay $\tau^+\to\mu^+\mu^+\mu^-$ at ATLAS on Run1 data

The ATLAS and CMS detectors



- cylindric detector (25m x 44m)
- high granularity pixel+strip detector + transition detector for electron identification
- 2T solenoid for pT measurement
- liquid Ar+metal ECAL and steel+plastic HCAL for jet+EG shower measurement
- and 3 toroidal 3.5T magnets for muon momentum measurement
- external muon chambers for muon detection and momentum measurement
- Two level trigger system (hardware + software)



- cylindric compact (15m x 21m) detector
- high granularity pixel + strip silicon tracker for excellent track, PV and SV measurements
- $PbWO_4$ crystal ECAL and brass+plastic HCAL to achieve hermeticity and for jet+EG shower measurement
- 3.8T solenoid for pT measurement
- external muon chambers outside steel return yoke for a clean muon detection and pT measurement
- Two level trigger system (hardware + software)

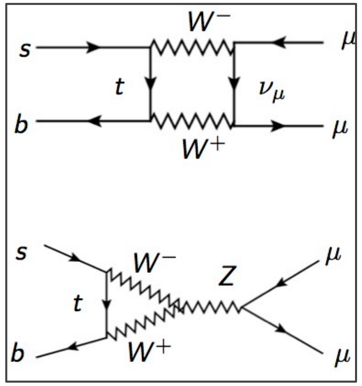
$B^0_{(s)} \to \mu^+\mu^-$

$B^0_{(s)}\to\mu^+\mu^-$

THE PHYSICS CASE

motivations

- $B^0_{(s)}\to\mu^+\mu^-$ strongly suppressed in the SM (FCNC and helicity)
- connected to $b\to sl^+l^-$ transitions via the EFT operator O_{10} can help understand $b\to s$ anomalies doi.org/10.1140/epjc/s10052-021-09725-1
- probe SM through lifetime measurements
- clear final state experimental signature for both ATLAS and CMS



CMS

- pp @ 13 TeV Run2 data (2016-2018) 140 /fb
  - updates the published result on 2016 data (30 /fb)
- 12.5 sigma observation of the $B^0_s\to\mu^+\mu^-$, upper limit on the $\mathcal{B}(B^0\to\mu^+\mu^-)$ and the life time measurement of $B^0_s\to\mu^+\mu^-$

ATLAS

- pp @ 13 TeV Run2 data (2015 and 2016) 26.3 /fb and combination with Run1 (25 /fb) @ 7 and 8 TeV
- 4.6 sigma observation of the $B^0_s\to\mu^+\mu^-$ and upper limit on $\mathcal{B}(B^0\to\mu^+\mu^-)$

cds.cern.ch/record/2815334

CMS: $B^0_{(s)}\rightarrow\mu^+\mu^-$

EVENT SELECTION

Data collection

- trigger selection: di-muon triggers with tight quality tracks and a valid secondary vertex (SV)
- similar selection for the control channels $B\rightarrow J/\Psi K^+$ and $B\rightarrow J/\Psi\phi$

signal selection

- two opposite-sign muons with $p_T > 4$ GeV and $|\eta| < 1.4$
- decay vertex of B meson→ kinematic re-fit of the muon tracks with additional SV constraint
- 16 categories: 4 years x 2 BDT bins x 2 detector $|\eta|$ regions

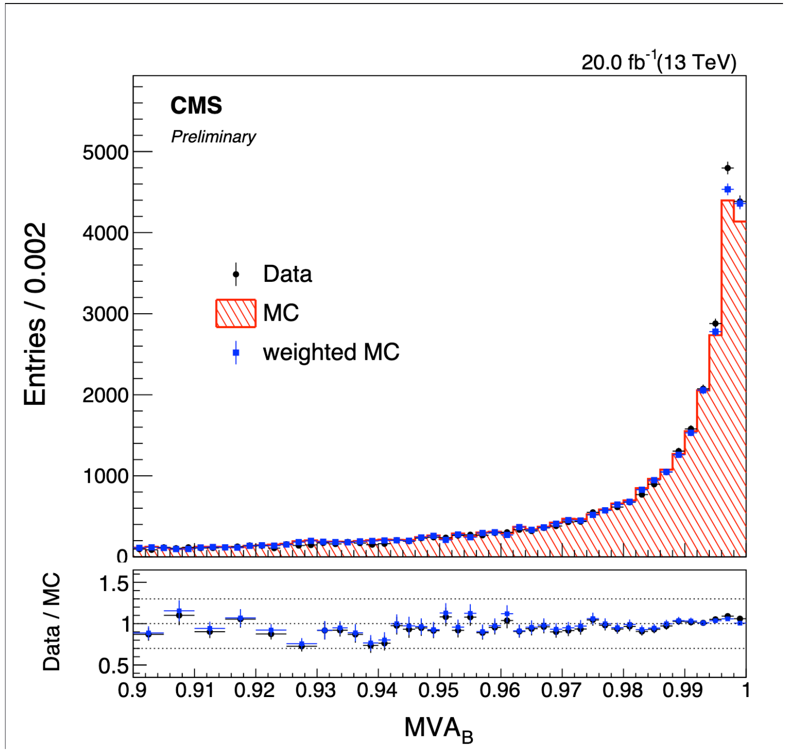
Background contamination

- combinatorial from $b\bar{b}$ events → MVA reduction
- partially reconstructed semi-leptonic $b\rightarrow h\mu\nu$ and $b\rightarrow hhX$ decays → MVA reduction
- charmless hadronic two-body decays $B\rightarrow hh$ → negligible after tight muon track selection

CMS: $B^0_{(s)} \to \mu^+\mu^-$

MVA ANALYSIS

- exploit several weak discrimination variables with a BDT (XGBoost)
  - features: pointing angles (2D and 3D) → effective vs. all non-two-body backgrounds
  - features: SV (quality and displacement) → effective vs. combinatorial
  - features: isolation (sum of pT surrounding the signal) → effective vs. semi-leptonic decays
- trained on data from the signal mass sidebands and MC signal samples
  - validate on $B^+ \to J/\Psi\, K^+$ events



MVA score distribution for data (black dots), MC (bars) and re-weighted MC (blue dots) for 2016a $B^+ \to J/\Psi K^+$ events

CMS: $B^0_{(s)} \rightarrow \mu^+\mu^-$

SIGNAL FIT

- 2D UML fit to the μμ mass x mass-resolution to extract the B→μμ signal yields. Two strategies for B^0_s normalization:
  - ○ $B^+ \rightarrow J/\Psi(\rightarrow \mu^+\mu^-) K^+$ normalization → rely on the knowledge of fs / fu
  - ○ $B^0_s \rightarrow J/\Psi(\rightarrow \mu^+\mu^-)\, \phi(\rightarrow K^+K^-)$ normalization → higher systematic (additional kaon)

$$\mathscr{B}(B^0_s \to \mu\mu) = \mathscr{B}(B^+ \to J/\Psi K^+) \cdot \frac{N_{B^0_s\to\mu\mu}}{N_{B^+\to J/\Psi K^+}} \cdot \frac{\epsilon_{B^+\to J/\Psi K^+}}{\epsilon_{B^0_s\to\mu\mu}} \cdot \boxed{\frac{f_u}{f_s}}$$

derived from LHCb measurement: 0.231 ± 0.008

doi.org/10.1103/PhysRevD.104.032005

$$\mathscr{B}(B^0_s \to \mu\mu) = \mathscr{B}(B^0_s \to J/\Psi\Phi) \cdot \frac{N_{B^0_s\to\mu\mu}}{N_{B^0_s\to J/\Psi\Phi}} \cdot \frac{\epsilon_{B^0_s\to J/\Psi\Phi}}{\epsilon_{B^0_s\to\mu\mu}}$$

$$\mathscr{B}(B^0 \to \mu\mu) = \mathscr{B}(B^+ \to J/\Psi K^+) \cdot \frac{N_{B^0\to\mu\mu}}{N_{B^+\to J/\Psi K^+}} \cdot \frac{\epsilon_{B^+\to J/\Psi K^+}}{\epsilon_{B^0_s\to\mu\mu}} \cdot \frac{f_u}{f_d}$$

- UML fit to the decay time to extract τ (3D fit: decay time, its uncertainty and μμ mass)

CMS: $B^0_{(s)} \to \mu^+\mu^-$

RESULTS

$\mathcal{B}(\mathbf{B_s^0}\to\mu^+\mu^-) = 3.83^{+0.38}_{-0.36}(stat)^{+0.14}_{-0.13}(syst)\;^{+0.14}_{-0.13}(fs/fu)$

x 10^{-9} (from J/Ψ K$^+$)

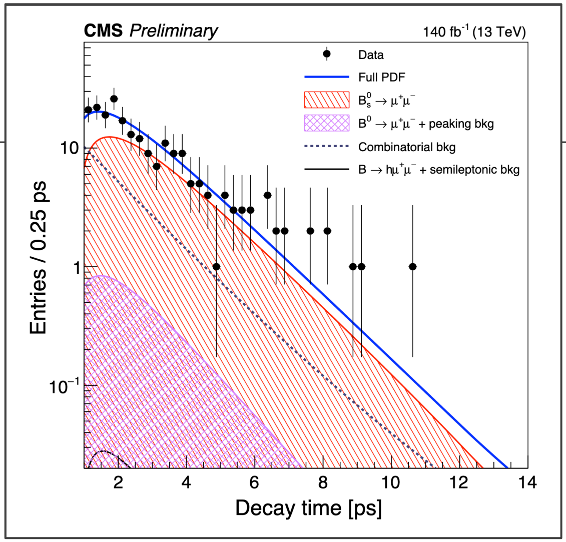
$\mathcal{B}(\mathbf{B_s^0}\to\mu^+\mu^-) = 3.95^{+0.39}_{-0.37}(stat)^{+0.27}_{-0.22}(syst)\;^{+0.21}_{-0.19}(BF)$

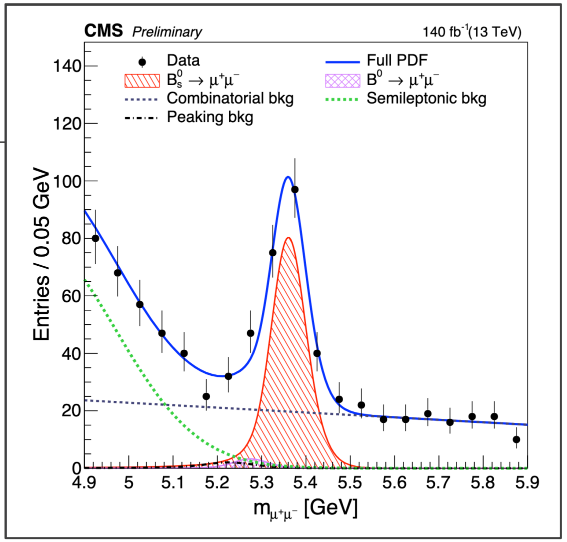
x 10^{-9} (from J/Ψϕ)

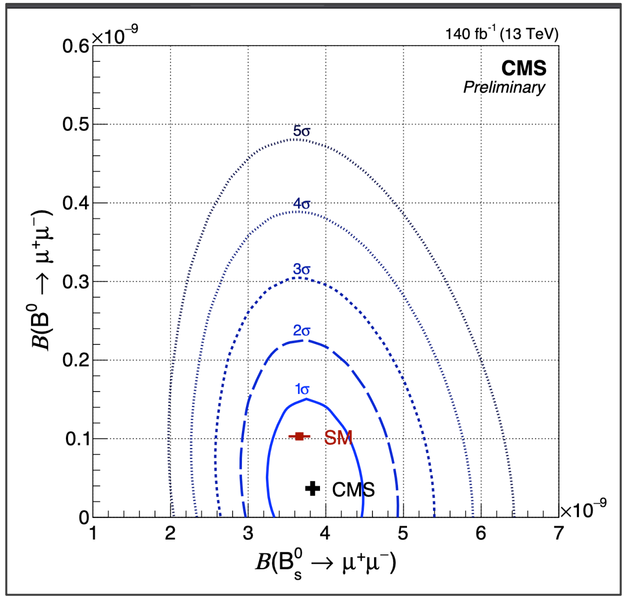
$\mathcal{B}(B^0\to\mu^+\mu^-) < 1.5 \times 10^{-10}$ @ 90% CL

$\mathcal{B}(B^0\to\mu^+\mu^-) < 1.9 \times 10^{-10}$ @ 95% CL

$\tau(\mathbf{B_s^0}) = 1.83^{+0.23}_{-0.20}(stat)^{+0.04}_{-0.04}\;(syst)$ ps







- All UML fit results are compatible with the SM prediction within 1 sigma
- most precise measurement of $B_s^0\to\mu^+\mu^-$ branching fraction and lifetime to date

cds.cern.ch/record/2650545

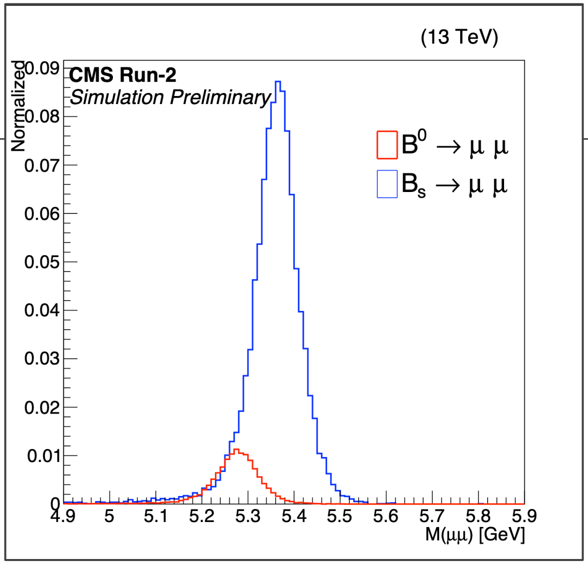
CMS: $B^0_{(s)} \to \mu^+\mu^-$

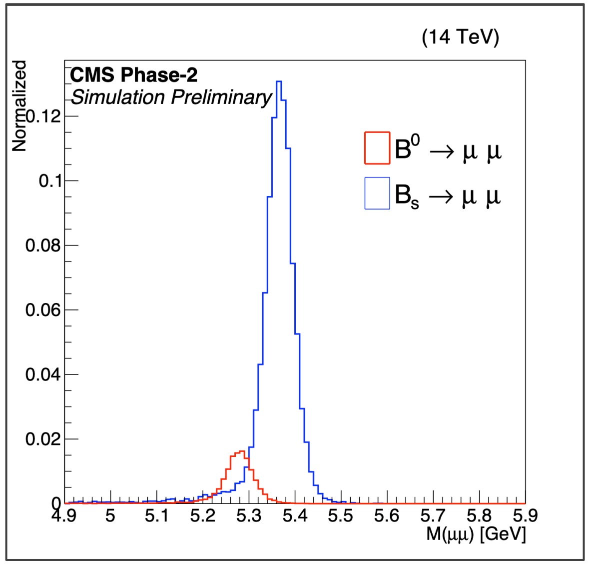
PERSPECTIVES

- CMS prediction for HL-LHC (Phase 2) starting in 2029
  - 14 TeV pp collision → ~ same b production
  - x5 collision rate (200 PU) → no large impact from 200PU is expected
  - 3 /ab of luminosity → x20 Run-2
- extrapolation via MC simulation (full Phase2 detector) + toys from Run-1 results
  - reasonable projection of most of the systematic uncertainties (x0.5)
- much better mass resolution following tracker upgrade
  - less contamination from semi-leptonic fakes
  - better B^0_s - B^0 hypothesis separation

➢ Time resolution on lifetime: 0.05 ps

➢ observation of $B^0 \to \mu\mu$ at more than 5 sigmas





doi.org/10.1007/JHEP04(2019)098

ATLAS: $B^0_{(s)} \rightarrow \mu^+\mu^-$

ANALYSIS OVERVIEW

event selection

- tight quality di-muon candidate selection with pT > 4 & 6 GeV, |η| < 2.5 with information from ID and MS
- good quality B vertex (SV)
- loose collinearity requirement in the transverse plane

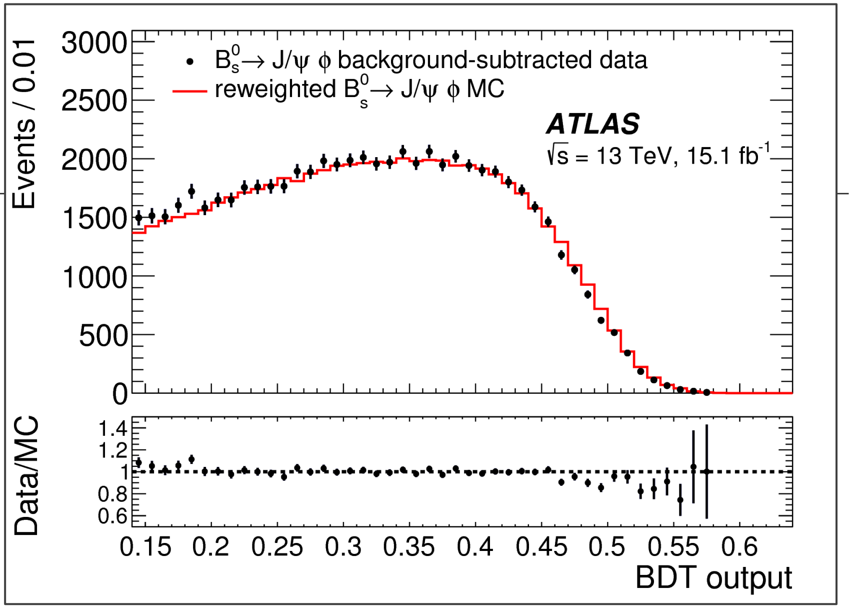
background contamination

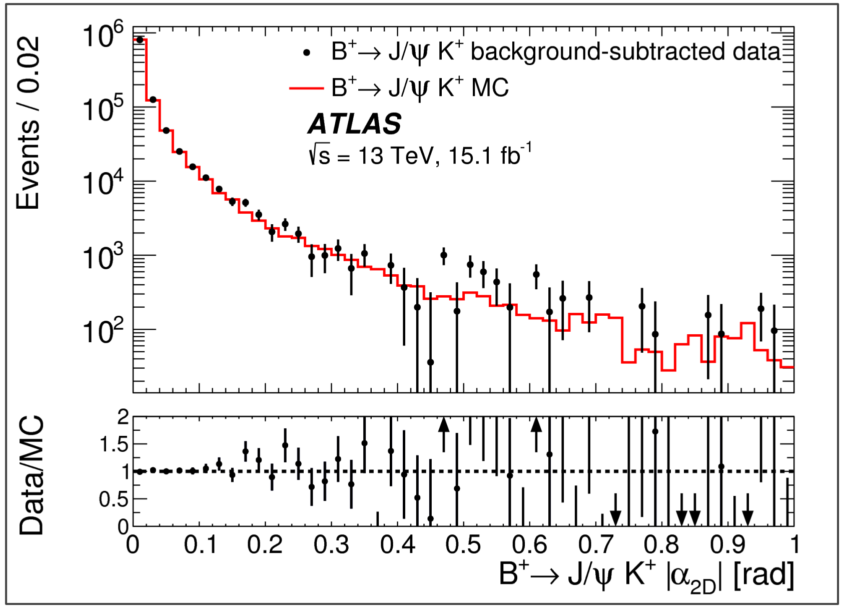
- combinatorial (different h-quarks - dominant) → well described by inclusive MC and reduced by MVA
- partially reconstructed semi-leptonic B decays → reduced by MVA and tight muon quality requirement
- charmless hadronic two-body decays of B mesons → reduced by tight muon quality selection to 2.7±1.3 events

ATLAS: $B^0_{(s)} \rightarrow \mu^+\mu^-$

MVA ANALYSIS

- MVA analysis to maximize the background rejection (TMVA)
  - B meson and SV variables
  - muon variables
  - event variables (e.g. isolation)
- model signal from MC, background from data mass side-bands
- control channels used for BDT validation and systematic estimation





ATLAS: $B^0_{(s)} \to \mu^+\mu^-$

RESULTS

- UML fit to the μμ invariant mass distribution
  - normalize signal to $B^+ \to J/\Psi\, K^+$ rate
  - sim. fit to four bins of BDT score of increasing signal purity
- results are compatible with the SM

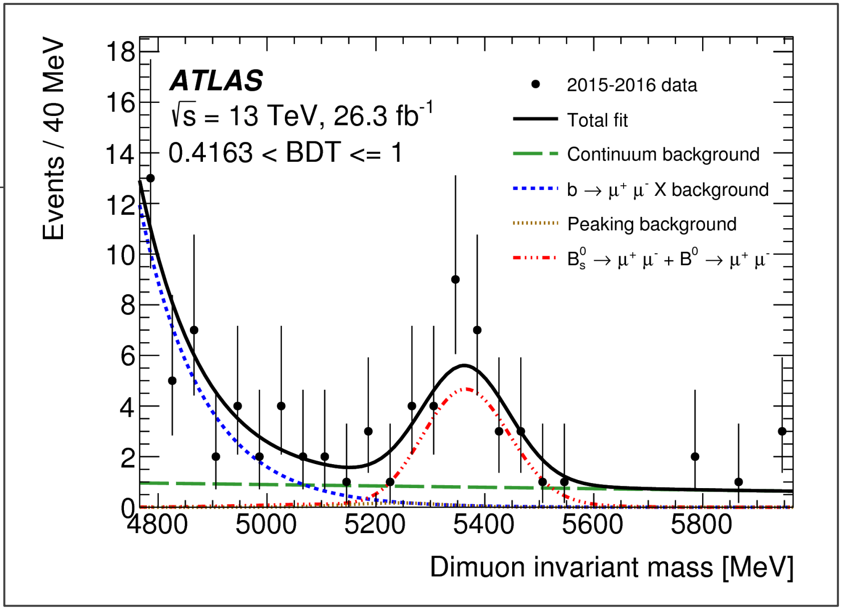
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.21^{+0.96}_{-0.91}(\text{stat})^{+0.49}_{-0.30}\ (syst) \times 10^{-9}$$

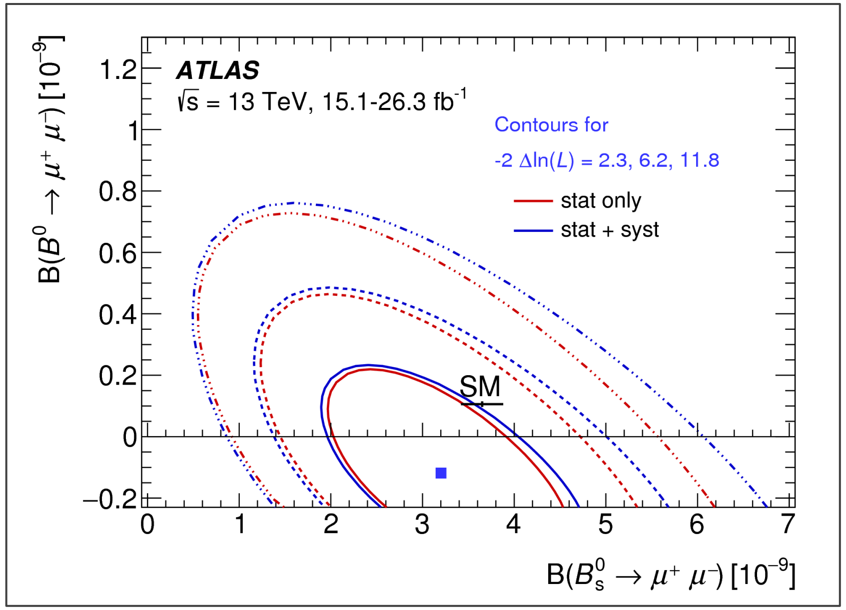
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10} \text{ @ 95\% CL}$$

- Combination with Run1 results (25 /fb pp @ 7 and 8 TeV)

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

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{ @ 95\% CL}$$





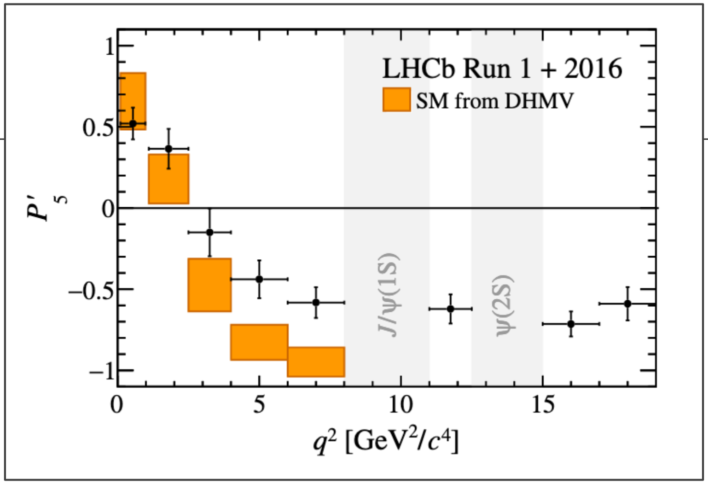
$B^0 \longrightarrow K^{0*}\mu^+\mu^-$

doi.org/10.1016/j.physletb.2018.04.030

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

THE PHYSICS CASE

- FCNC strongly suppressed in the SM
- angular analysis
- study the deviation from the SM of the angular parameters describing the decay
    - P5' most interesting following 2–3 sigmas deviation from SM observed by LHCb in the $4<q^2<6$ and $6<q^2<8$ GeV^2 bins in Run1



CMS

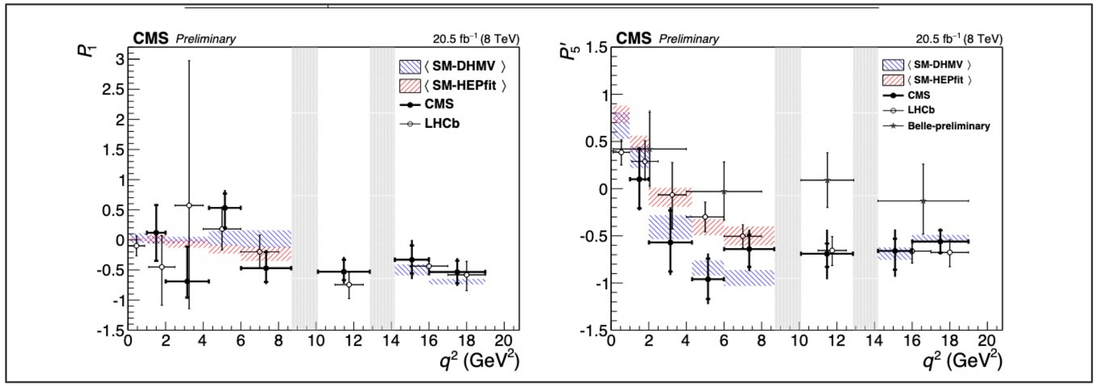
- pp @ 8 TeV Run1 data 20.5 /fb
- P5' distributions compatible with the SM

ATLAS

- pp @ 8 TeV Run1 data 20.3 /fb
- P5' distributions compatible with the SM within 2.7 sigmas

CMS: $B^0 \rightarrow K^{0*}\mu^+\mu^-$

- q^2 binned
- trigger di-muon events with displaced vertex
- build signal candidates by requiring two muons and two tracks (K* candidate) from the same vertex
    - resolve PID ambiguity by selecting the Kπ hypothesis closest to the K* mass (misid: 12-14%)
- background mainly from combinatorial
    - negligible contamination from peaking B and Λ_b decays and b→cX decays
- UML fit to the B0 mass x angular distributions to extract the POIs (P_1 and P_5’)
    - B→JPsi/Ψ’ K* for fit validation and systematic assesment

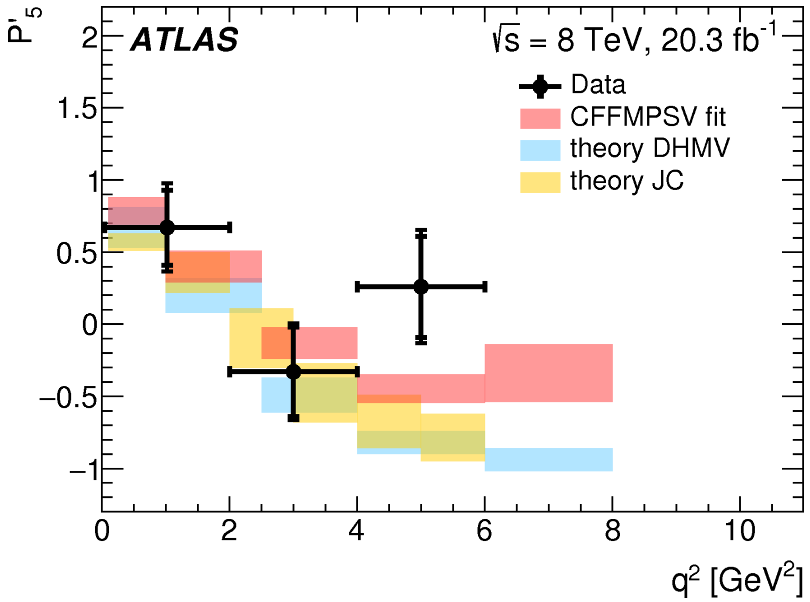


- both the angular parameters are compatible with the SM

doi.org/10.1007/JHEP10(2018)047

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

- q^2 binned analysis below q^2=6 GeV^2
- select events by di-muon triggers
- build signal candidates by requiring two muons and two tracks (K* candidate) from the same vertex
    - resolve PID ambiguity by selecting the Kπ hypothesis closest to the K* mass (misid: 11%)
- background dominated by combinatorial below 6 GeV^2
    - address non-smooth structures and S-wave contributions as systematic uncertainties
- UML fit to the B^0 mass x angular distributions to extract the POIs

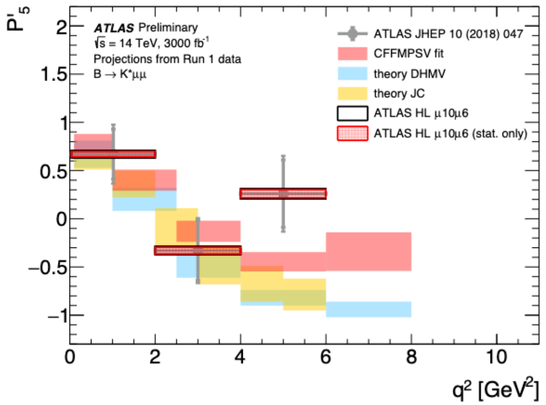


- all angular parameters are compatible with SM
- P5' deviates 2.7 sigmas from the SM in the 4<q^2<6 GeV^2 bin for the DHMV model

PRECISION OF THE P$_5$' MEASUREMENT AT THE HL-LHC

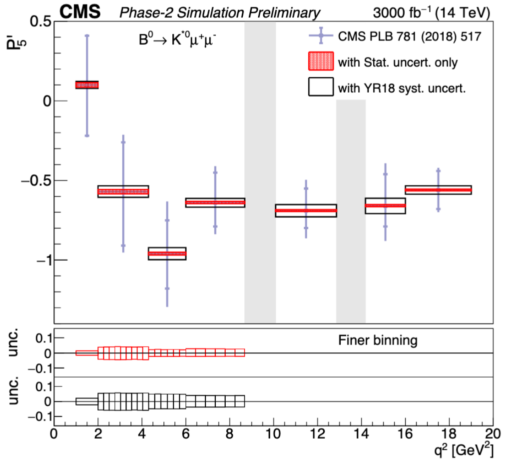
ATLAS cds.cern.ch/record/2654519

- MC study to address the precision reached by ATLAS at the HL-LHC (3 /ab)
- analysis strategy same as Run1
  - reduce signal and background model systematics by 1/sqrt(L)
  - neglect mis-tag systematic uncertainty (MC-driven)
  - scale S-wave uncertainty by a factor 5
  - reduce calibration systematics by a factor 4
- precision increase x9, x8, x5 (depending on the trigger scenario)



CMS cds.cern.ch/record/2651298

- MC study to address the precision reached by ATLAS at the HL-LHC (3 /ab)
- analysis strategy same as Run1
  - reduce fit-related systematics by 1/sqrt(L)
  - reduce most of uncertainties (signal shape, efficiency shape, mis-tag, detector-related) by a factor 2
- precision increase up to x15 better → also explore possibilities of finer binning



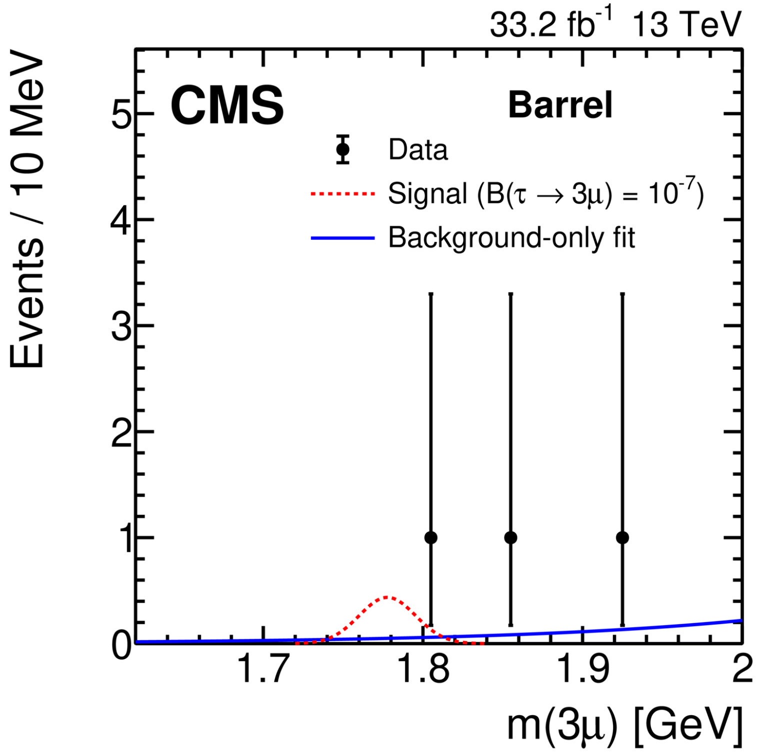
$\tau^+ \rightarrow \mu^+\mu^+\mu^-$

doi.org/10.1007/JHEP01%282021%29163

CMS: $\tau^+ \to \mu^+\mu^+\mu^-$

- $\tau \to 3\mu$ excellent candidate for new physics searches
  - LFV process, strongly suppressed in the SM ($\sim 10^{-55}$), but predicted at the level of $10^{-8} - 10^{-10}$ by some BSM models Bordone et al., 10.1007/JHEP10(2018)148
  - clear final state signature
  - fairly abundant in pp collisions (per /fb)

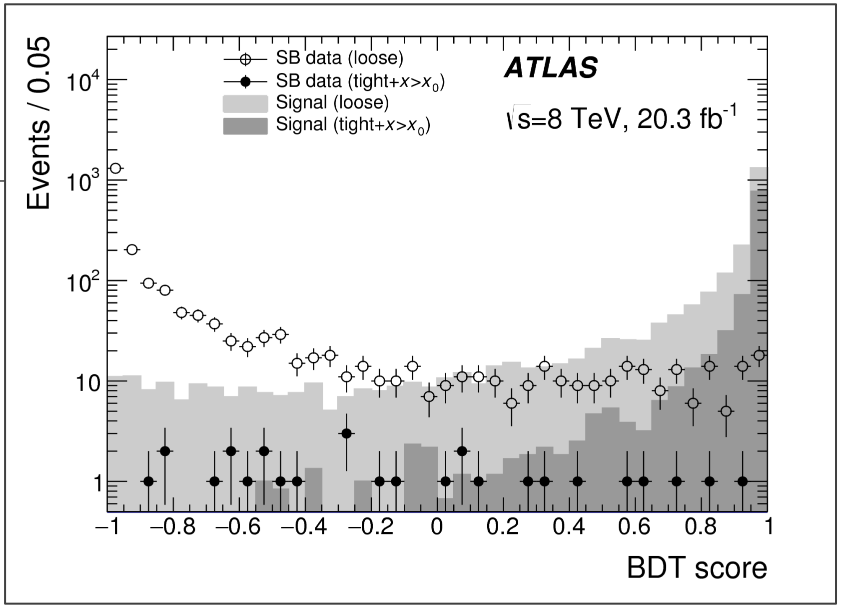
- CMS targets τ leptons produced via D/B mesons and via W bosons
- analysis on 2016 pp data @ 13 TeV (30 /fb)
- select three-muon events and reduce the background contamination via BDT
- observed (expected) UL from three-muon invariant mass distribution
  - $B^{HF}(\tau \to 3\mu) < 9.2\ (10.0) \times 10^{-8}$ @ 90% CL
  - $B^{W}(\tau \to 3\mu) < 20.0\ (13.0) \times 10^{-8}$ @ 90% CL
  - **$B(\tau \to 3\mu) < 8.0\ (6.9) \times 10^{-8}$ @ 90% CL**

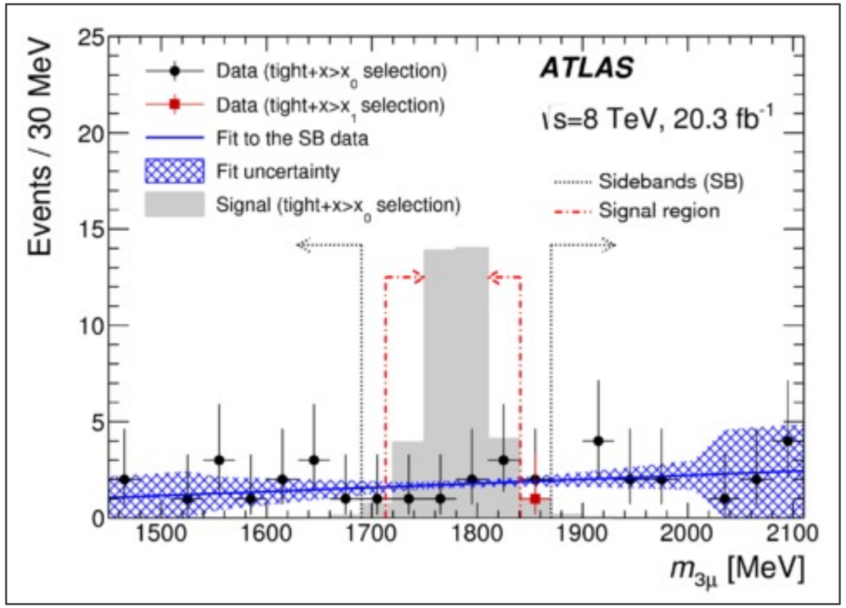


doi.org/10.1140/epjc/s10052-016-4041-9

ATLAS: $\tau^+\rightarrow\mu^+\mu^+\mu^-$

- 2012 pp collisions @ 8 TeV (20.3 /fb)
- target τ leptons produced via W boson
- select three-muon events and reduce background contamination via BDT
- look for excess of events in the signal region → no events found
- observed (expected) upper limit to the τ→3μ branching fraction
  - ○ **$B(\tau\rightarrow3\mu) < 3.76\ (3.94) \times 10^{-7}$ @ 90% CL**





$\tau \rightarrow 3\mu$ AT THE HL-LHC

ATLAS cds.cern.ch/record/2647956

- target detector, luminosity and cross section improvements foreseen at HL-LHC
- consider three W scenarios
  - ○ conservative → scale by luminosity → 13.5 x 10^{-9} @ 90% CL
  - ○ intermediate → consider also trigger improvement (x2.2) → 6.2 x 10^{-9} @ 90% CL
  - ○ best → consider also mass resolution improvement (x1.25) → 5.4 x 10^{-9} @ 90% CL
- add HF channel with three different background scenarios
  - ○ x10 W background → 6.4 x 10^{-9} @ 90% CL
  - ○ x3 W background → 2.3 x 10^{-9} @ 90% CL
  - ○ same as W → 1.0 x 10^{-9} @ 90% CL

CMS arXiv:1812.07638

- luminosity-scaled projections based on the HF results place CMS sensitivity at 3.7 x 10^{-9} @ 90% CL

SUMMARY

SUMMARY OF THE TALK

ATLAS

- $B^0_{(s)} \to \mu^+\mu^-$ at ATLAS on pp collisions @ 13 TeV (26.3 /fb)
    - $B(B^0_s \to \mu^+\mu^-) = 2.8^{+0.8}_{-0.7} \times 10^{-9}$
    - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @ 95% CL
- $B^0 \to K^{0*} \mu^+\mu^-$ at ATLAS on pp collisions @ 8 TeV (20.3 /fb)
    - angular analysis: all angular parameters compatible with SM, 2.7 sigma deviation observed in the P5' parameter
- $\tau^+ \to \mu^+\mu^+\mu^-$ (W channel) at CMS on pp collisions @ 8 TeV (20 /fb)
    - $B(\tau \to 3\mu) < 3.47 \times 10^{-7}$ @ 90% CL

(*) most precise up to date

CMS

- $B^0_{(s)} \to \mu^+\mu^-$ at CMS on pp collisions @ 13 TeV (140 /fb)
    - $B(B^0_s \to \mu^+\mu^-) = 3.83^{+0.38}_{-0.36}(\text{stat})^{+0.14}_{-0.13}(\text{syst})\,^{+0.14}_{-0.13}(\text{fs/fu}) \times 10^{-9}$ (*)
    - $B(B^0 \to \mu^+\mu^-) < 1.5\ (1.9) \times 10^{-10}$ @ 90% (95%) CL
    - $\tau(B^0_s) = 1.83^{+0.23}_{-0.20}(\text{stat})^{+0.04}_{-0.04}(\text{syst})$ ps (*)
- $B^0 \to K^{0*} \mu^+\mu^-$ at CMS on pp collisions @ 8 TeV (20.5 /fb)
    - angular analysis: all angular parameters compatible with SM, no deviation observed in the P5' parameter
- $\tau^+ \to \mu^+\mu^+\mu^-$ (W and D/B channels) at CMS on pp collisions @ 13 TeV (30 /fb)
    - $B(\tau \to 3\mu) < 8.0 \times 10^{-8}$ @ 90% CL

Backup

CMS: $B^0_{(s)}\to\mu^+\mu^-$

SYSTEMATIC UNCERTAINTIES

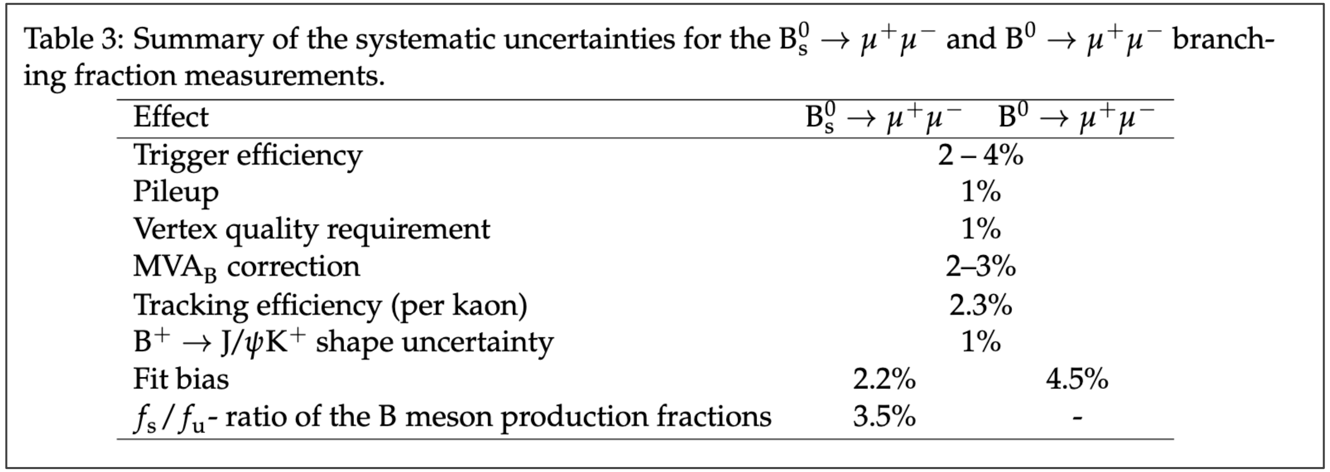


Table 3: Summary of the systematic uncertainties for the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fraction measurements.

Effect	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
Trigger efficiency	2 – 4%	
Pileup	1%	
Vertex quality requirement	1%	
MVA_B correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
Fit bias	2.2%	4.5%
f_s/f_u- ratio of the B meson production fractions	3.5%	-

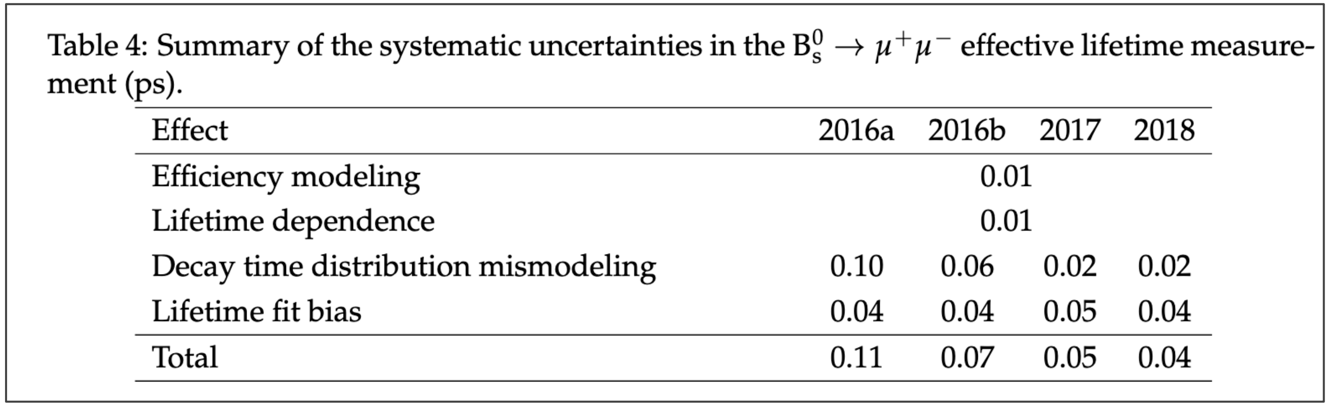


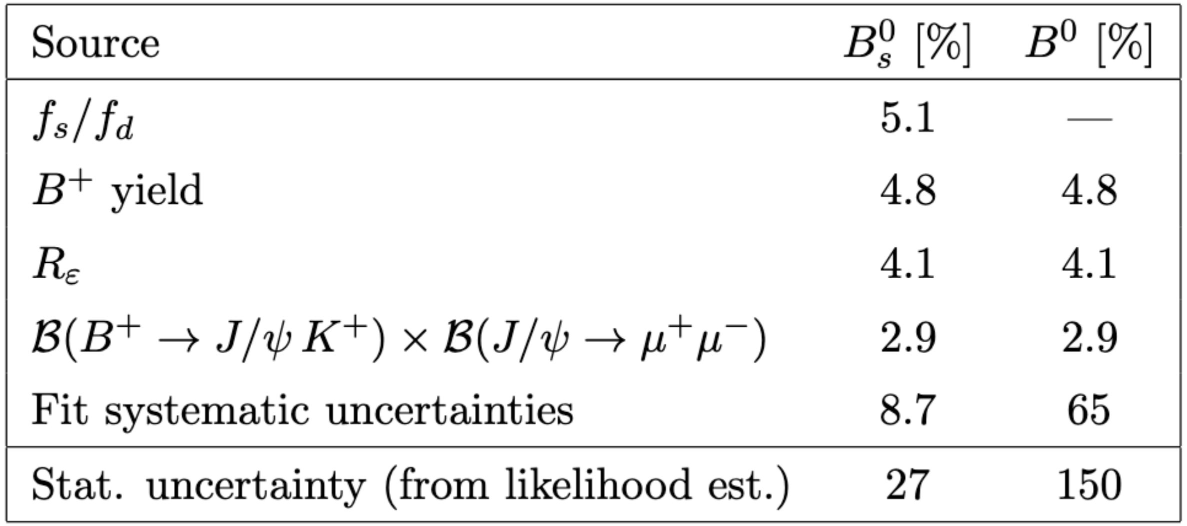
Table 4: Summary of the systematic uncertainties in the $B^0_s \to \mu^+\mu^-$ effective lifetime measurement (ps).

Effect	2016a	2016b	2017	2018
Efficiency modeling	0.01			
Lifetime dependence	0.01			
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Lifetime fit bias	0.04	0.04	0.05	0.04
Total	0.11	0.07	0.05	0.04

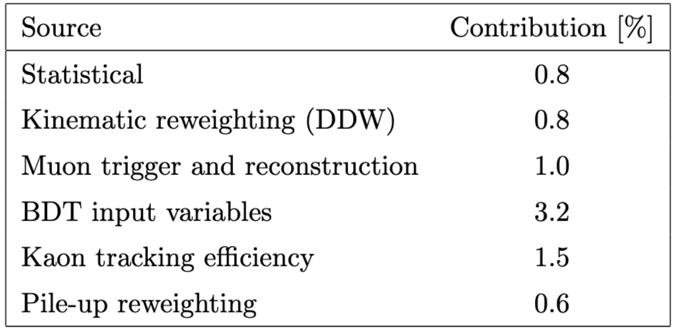
- **trigger:** data-MC comparison of control channels
- **pileup:** by means of reweighing
- **vertex:** the control channel triggers require a tighter selection. Evaluated the difference of the two selections.
- **MVA:** difference between data and MC efficiencies evaluated after an MVA reweight of the control channel
- **tracking:** comparing D^0→Kπ and D^0→ Kπππ ratio with world average
- **B→J/ΨK shape:** evaluating different shapes
- **fit bias:** with pseudo-experiments
- **fs/fu:** from external measurement
- **lifetime fit bias:** correlation of the BDT to the life-time. Measured by comparing the B→J/ΨK fit to the SM prediction after the BDT cut
- **decay time distribution mismodeling:** the lifetime distribution of simulated signal events is corrected using scale factors from B→J/ΨK events taken after BDT>.9 over BDT>.99. The fit difference introduced by data- or MC-derived corrections is taken as uncertainty.
- **efficiency modelling:** evaluated using different efficiency functions
- **lifetime fit bias:** measured with pseudo-experiments with different lifetimes

ATLAS: $B^0_{(s)}\to\mu^+\mu^-$

SYSTEMATIC UNCERTAINTIES



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



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

Table 2. Summary of the uncertainties in R_ε.

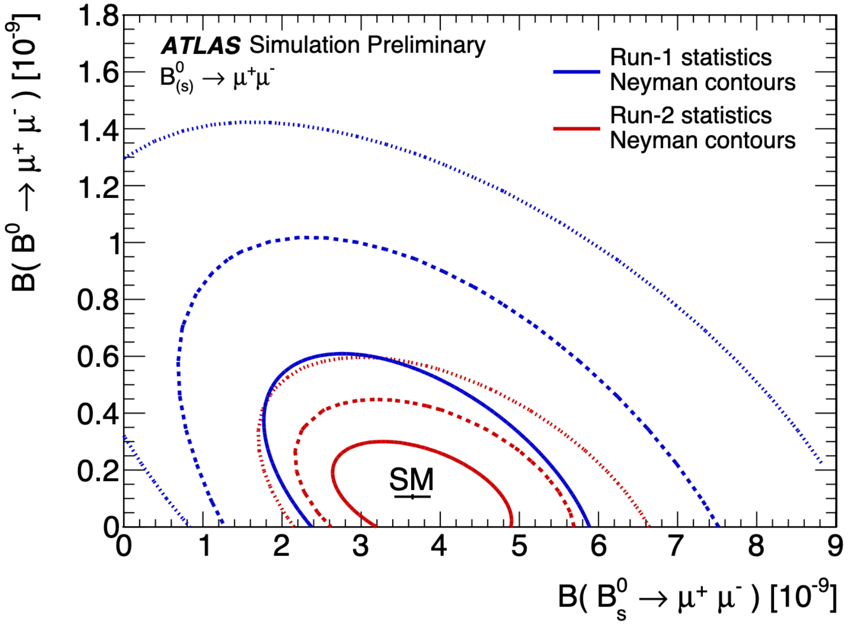
- **fs/fd:** external measurement
- **B^+ yield:** the control channel triggers require a tighter selection. Evaluated the difference of the two selections.
- **R_ε:** ratio of the control channel and signal efficiencies.
- **branching fractions:** comparing $D^0\to K\pi$ and $D^0\to K\pi\pi\pi$ ratio with world average. This number is taken from MC simulations and includes different contributions:
  - **kinematic reweighting:** pT and |η| gen. level correction (comparing to the efficiency with larger b-quark gen. cuts) + data/MC corrections from the B→ J/ΨK control channel
  - **muon trigger and reconstruction:** from data-driven studies with tag-and-probe oon J/Ψ→μμ events
  - **BDT features:** from differences introduced by data/MC weights from the B→ J/ΨK control channel
  - **kaon tracking:** estimated varying the detector simulation (passive material)
  - **pileup:** by means of reweighting
- **fit systematic uncertainty:** evaluating different shapes

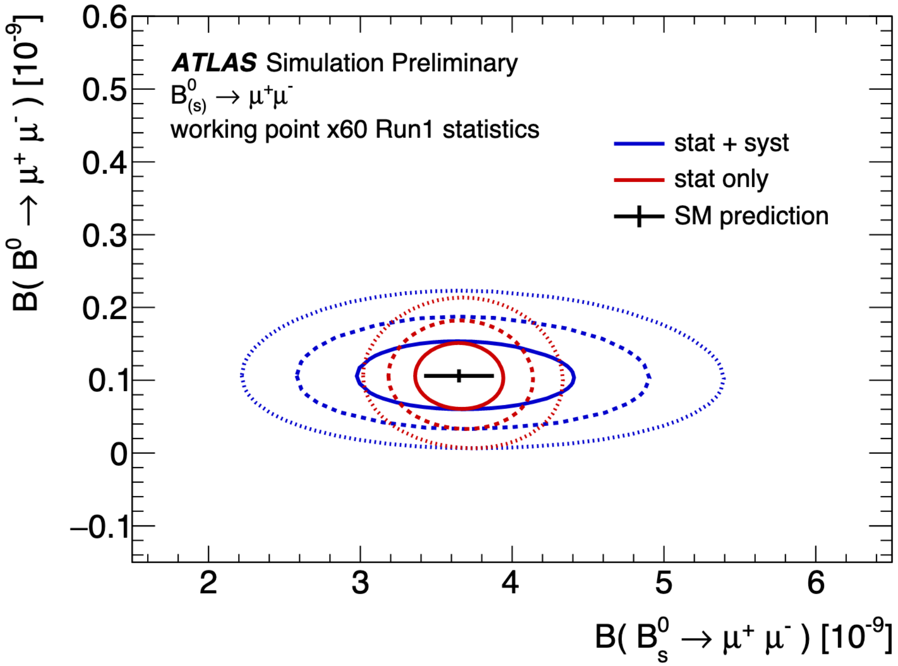
http://cds.cern.ch/record/2317211

ATLAS: $B^0_{(s)} \to \mu^+\mu^-$

PROJECTION TO PHASE 2

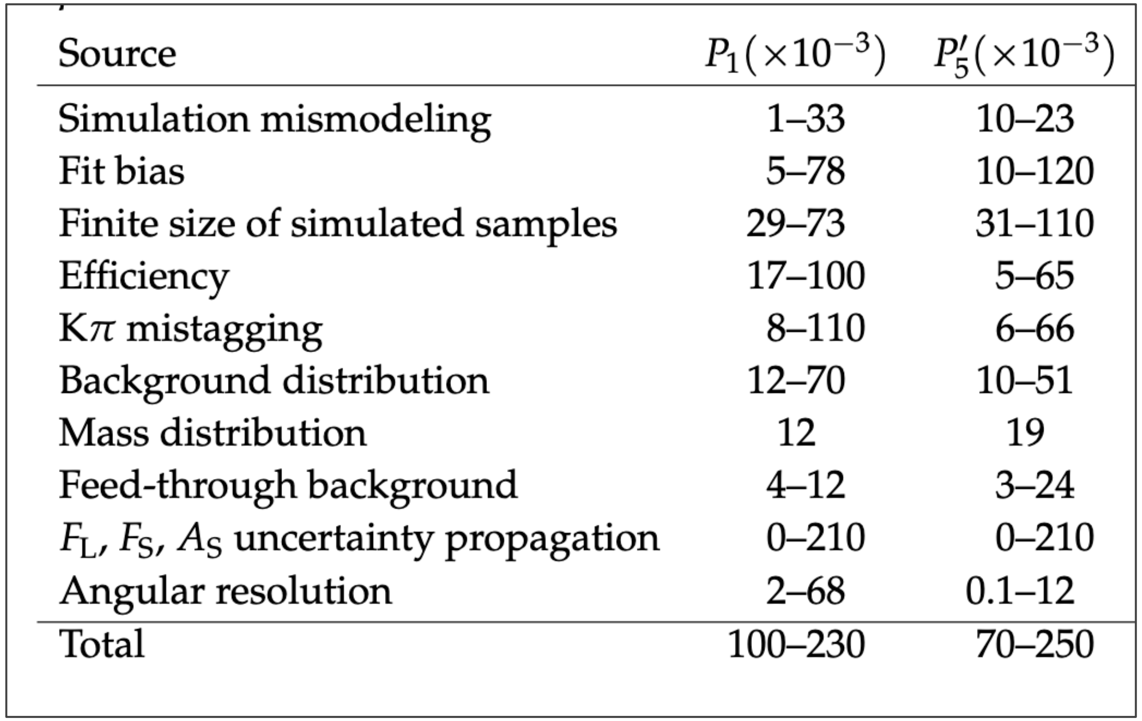
- extrapolate b production cross section to 14 TeV (x1.7)
- extrapolate collected statistics
- consider gain from trigger upgrade





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

SYSTEMATIC UNCERTAINTIES



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
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

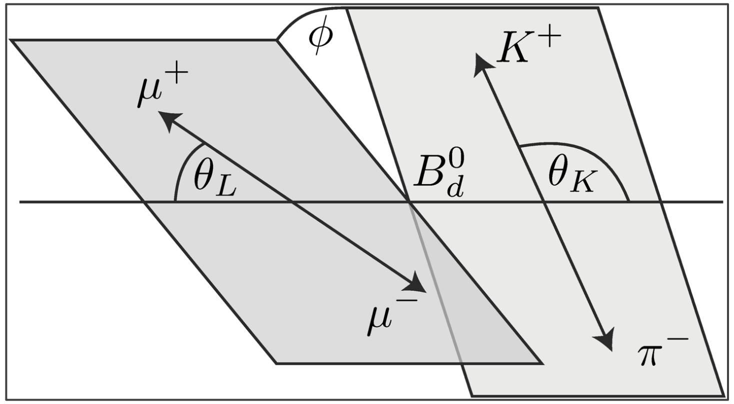
- **simulation mismodeling:** fit a simulated signal sample with 400x data and see the fit difference wrt to the input
- **fit bias:** use 200 simulated signal samples + simulated data (~data size) to estimate the fit bias
- **finite size of simulated samples:** due to the finite size of the MC used to derive the efficiency shape. Generate 100 numerator and denominator shapes from the original ones and refit them to estimate the difference due to the statistical uncertainty.
- **efficiency:** fit the control channels to extrapolate fixed parameters (FL) and cross check with PDG
- **Kπ mistagging:** fit the mistag rate on the control channel B→J/ΨK* and take the diffference wrt the simulation as systematics
- **background shape:** fit the data 200 times varying the shape of the background distributions within their error (fixed in these test fits) and evaluating the POIs distribution RMS
- **signal mass shape:** fit the control channels letting their width vary alternately and see the effect on the POIs
- **background feed-through:** see the difference in the POIs after counting for an additional systematic uncertainty describing the feed-through from B→J/Ψ / Ψ' K* events
- **F_L, F_S, A_S uncertainties propagation:** fit pseudo-experiments allowing these parameters to change and compare the POIs values with the nominal procedure
- **angular resolution:** fit a siulated sample using generated or reconstructed values of the angular parameters and see the difference

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

FIT STRATEGY

- simplify the angular pdf by considering symmetries in the $\phi=0$ and $\theta_l=\pi/2$ angles
    - reduce the POIs that can be extracted to P_1 and P_5'
- UML fit to the mass and angular distributions
    - signal mass shape: double-gaussian different for correct- and wrong-tagged events, with paramters obtained from simulated samples
    - angular pdf for background: polynomials (factorizing)
    - mass pdf for background: exponential
    - angular efficiencies: obtained from kernel-density estimators, different for correct- and wrong-tagged events
- Fit run in two steps:
    1. fit the sidebands and fix the background shapes
    2. fit the full distribution and obtain the POIs

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



CMS: $B^0 \rightarrow K^{0*}\mu^+\mu^-$

RESULTS

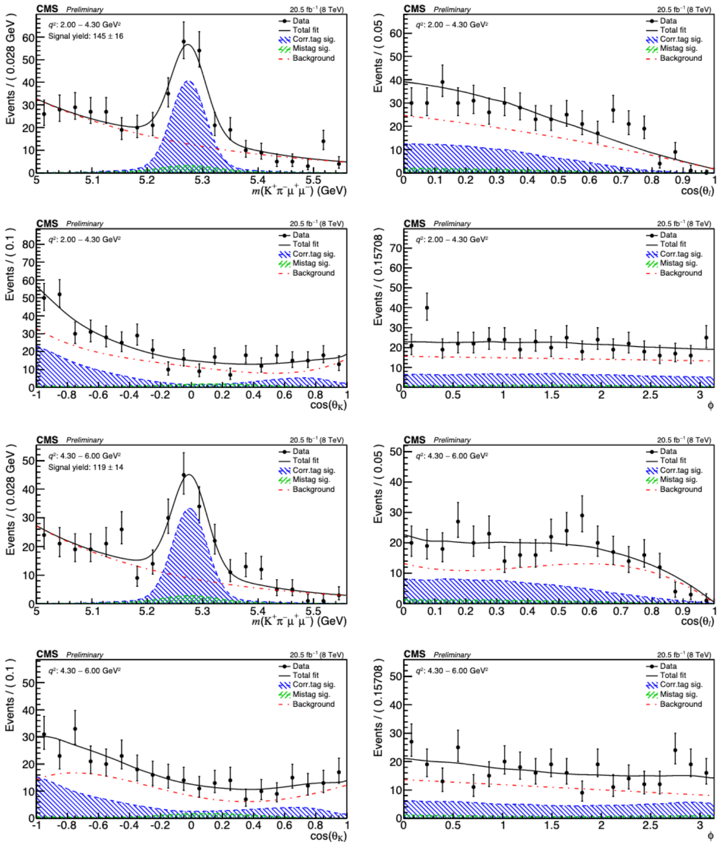
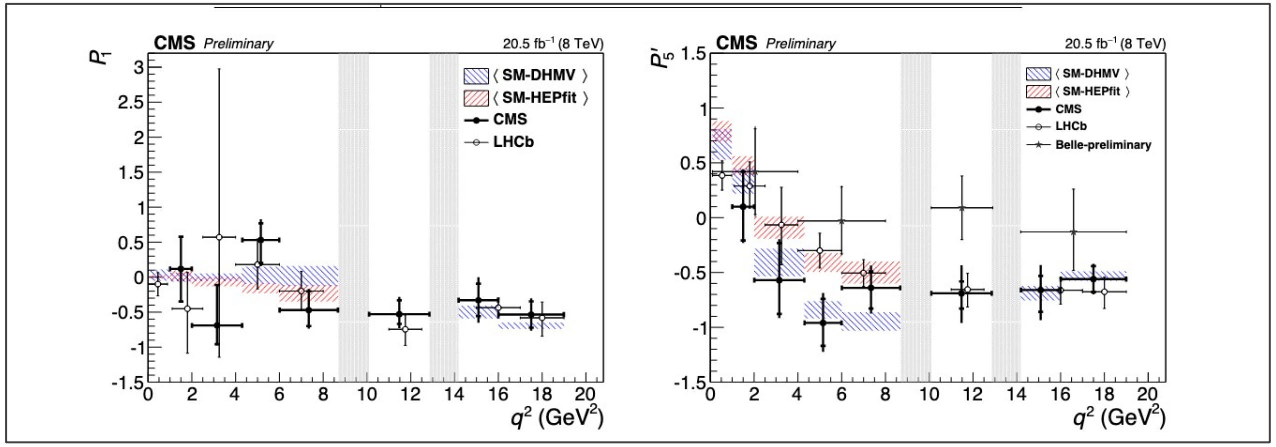


Figure 2: $K^+\pi^-\mu^+\mu^-$ invariant mass and angular distributions for the second and third q^2 bin (top four plots) $2.00 < q^2 < 4.30$ GeV^2, and (bottom four plots) $4.30 < q^2 < 6.00$ GeV^2. Overlaid on each plot is the projection of the results for the total fit, as well as for the three components: correctly tagged signal, mistagged signal, and background. The vertical bars indicate the statistical uncertainties.

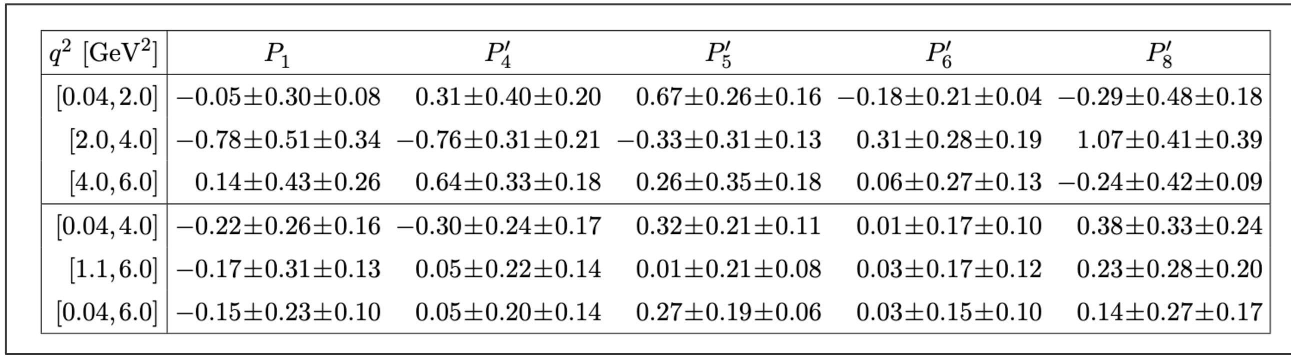


ATLAS: $B^0 \to K^{0*}\mu^+\mu^-$

SYSTEMATIC UNCERTAINTIES

- **fake K* background:** peaking structure observed at $\cos(\theta_K)=1$ (possible D* mis-reconstructed decays), evaluated fitting the $\cos(\theta_K)$ range excluding the region around 1
- **partially reconstructed B→D decays:** manifesting around $\cos(\theta_K)=0.7$, evaluated removing these events from the fit
- **combinatorial background pdf shape:** evaluated fitting with Chebychev polynomials
- **factorization of the acceptance function ($\cos(\theta_K)$, $\cos(\theta_L)$, Φ):** evaluated fitting simulated samples with the shape used for the same sample
- **angular pdf model:** compare the nominal pdf with the one obtained fitting events in a reduced fit range 5.2-5.7 GeV (to exclude partially reconstructed B decays)
- **ID alignment and mag. field knowledge:** from tracks pT and η uncertainties
- **fit bias:** evaluated on simulated toy fits
- **B^0 pT spectrum:** reweight the MC with data-driven scale factors and state the change in the fitted POIs a a systematic uncertainty
- **S-wave:** non resontant Kπ contribution evaluated from simulated toys (5% magnitude from LHCb studies)
- **nuisances:** m, ε, sig. and bkg yields, combinatorial shape, signal acceptance are fixed in the second stage of the fit. The impact of this strategy is investigated varying them alternatively within their uncertainty.

- **fake K* background:** count for peaking Kπμμ events by putting them into combinatorial-only simulated toys. Included MC samples are:
    - $\Lambda_b \to \Lambda\mu\mu$, $\Lambda_b \to pK\mu\mu$, $B^+ \to K^{(*)+}\mu\mu$, $B^0_s \to \phi\mu\mu$
- **mistag:** uncertainty on the mistag comes from the statistical uncertainty of the simulated sample used to compute it. Data-MC differences are negligible.

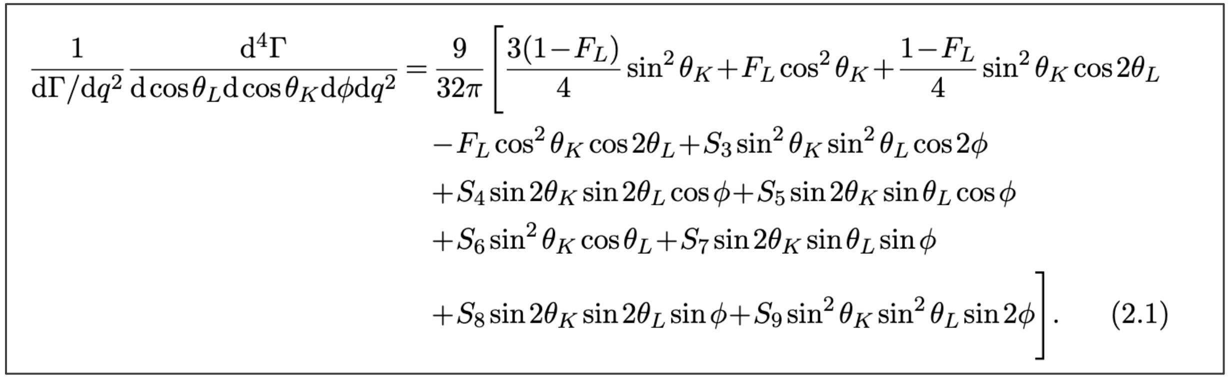


q^2 [GeV^2]	P_1	P'_4	P'_5	P'_6	P'_8
[0.04, 2.0]	−0.05±0.30±0.08	0.31±0.40±0.20	0.67±0.26±0.16	−0.18±0.21±0.04	−0.29±0.48±0.18
[2.0, 4.0]	−0.78±0.51±0.34	−0.76±0.31±0.21	−0.33±0.31±0.13	0.31±0.28±0.19	1.07±0.41±0.39
[4.0, 6.0]	0.14±0.43±0.26	0.64±0.33±0.18	0.26±0.35±0.18	0.06±0.27±0.13	−0.24±0.42±0.09
[0.04, 4.0]	−0.22±0.26±0.16	−0.30±0.24±0.17	0.32±0.21±0.11	0.01±0.17±0.10	0.38±0.33±0.24
[1.1, 6.0]	−0.17±0.31±0.13	0.05±0.22±0.14	0.01±0.21±0.08	0.03±0.17±0.12	0.23±0.28±0.20
[0.04, 6.0]	−0.15±0.23±0.10	0.05±0.20±0.14	0.27±0.19±0.06	0.03±0.15±0.10	0.14±0.27±0.17

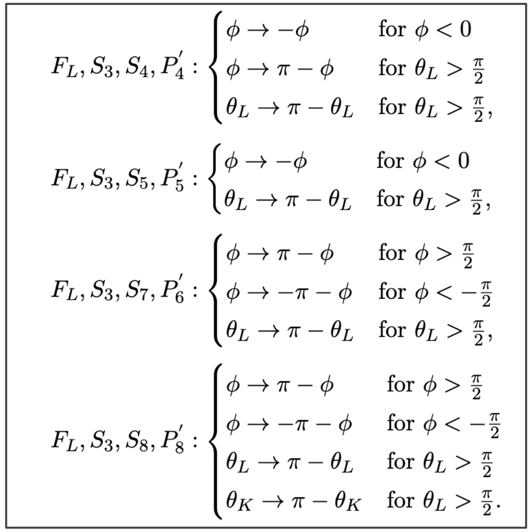
ATLAS: $B^0 \to K^{0*}\mu^+\mu^-$

FIT STRATEGY

- simplify the angular pdf by considering symmetries in the φ=0 and θl=π/2 angles
  - reduce the POIs that can be extracted depending on the adopted folding
- UML fit to the mass and angular distributions
  - signal mass shape: gaussian with width set to the per-event mass resolution
  - mass pdf for background: exponential
  - angular pdf for background: polynomials (factorizing)
  - angular efficiencies: polynomials obtained from simulated events
- Fit run in two steps:
  1. fit the mass distribution and fix the mass signaland background shapes
  2. fit the full distribution and obtain the POIs



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



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

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

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

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

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

RESULTS

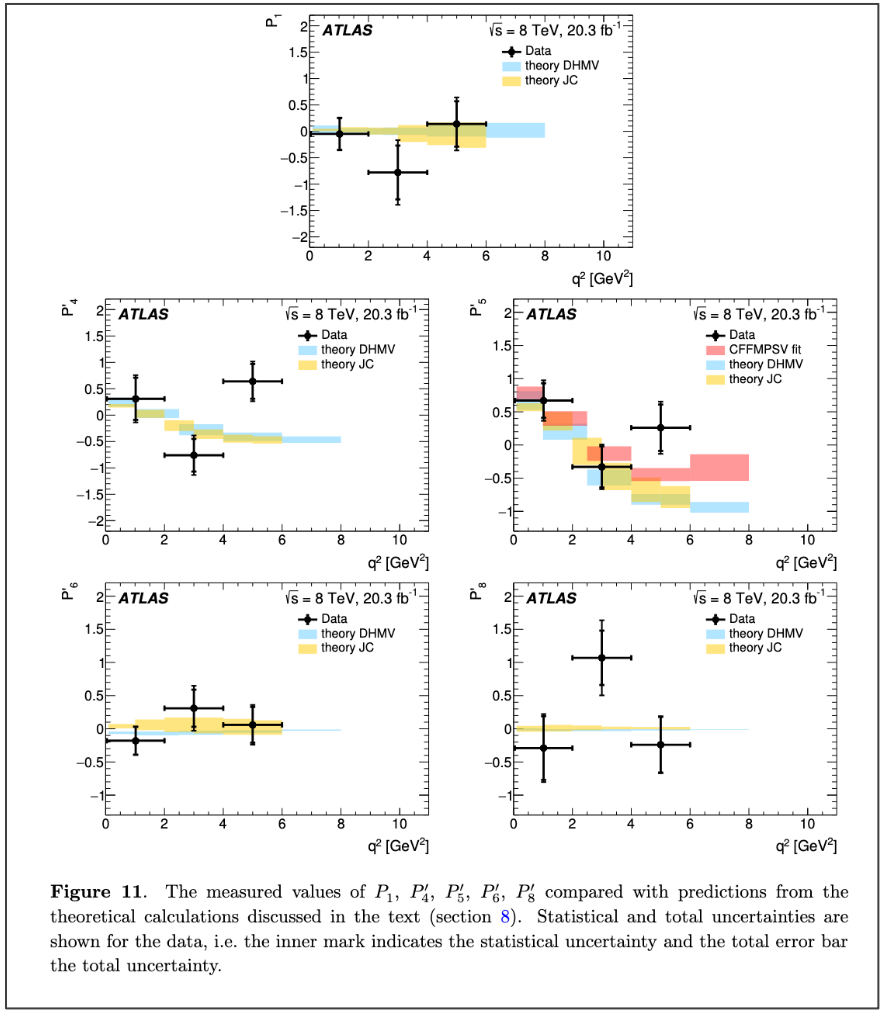
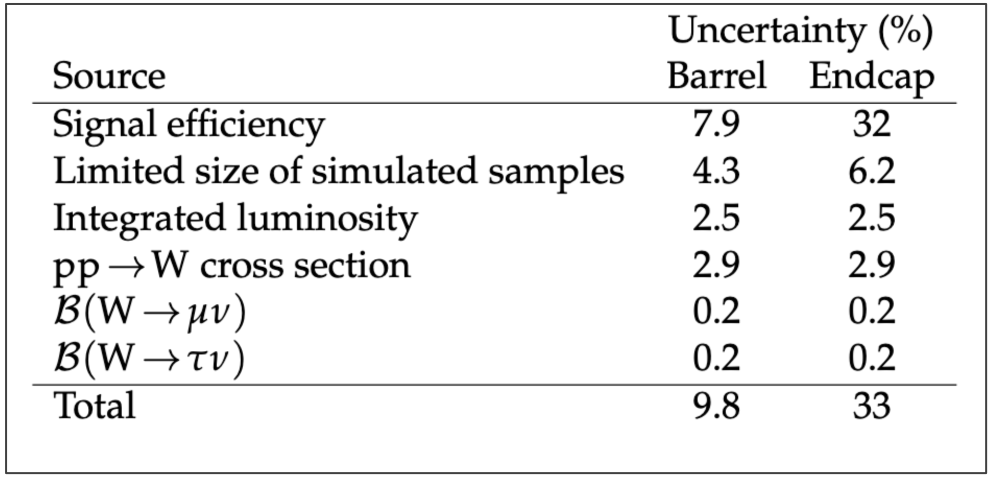


Figure 11. The measured values of P_1, P_4', P_5', P_6', P_8' compared with predictions from the theoretical calculations discussed in the text (section 8). Statistical and total uncertainties are shown for the data, i.e. the inner mark indicates the statistical uncertainty and the total error bar the total uncertainty.

CMS: $\tau^+ \to \mu^+\mu^+\mu^-$

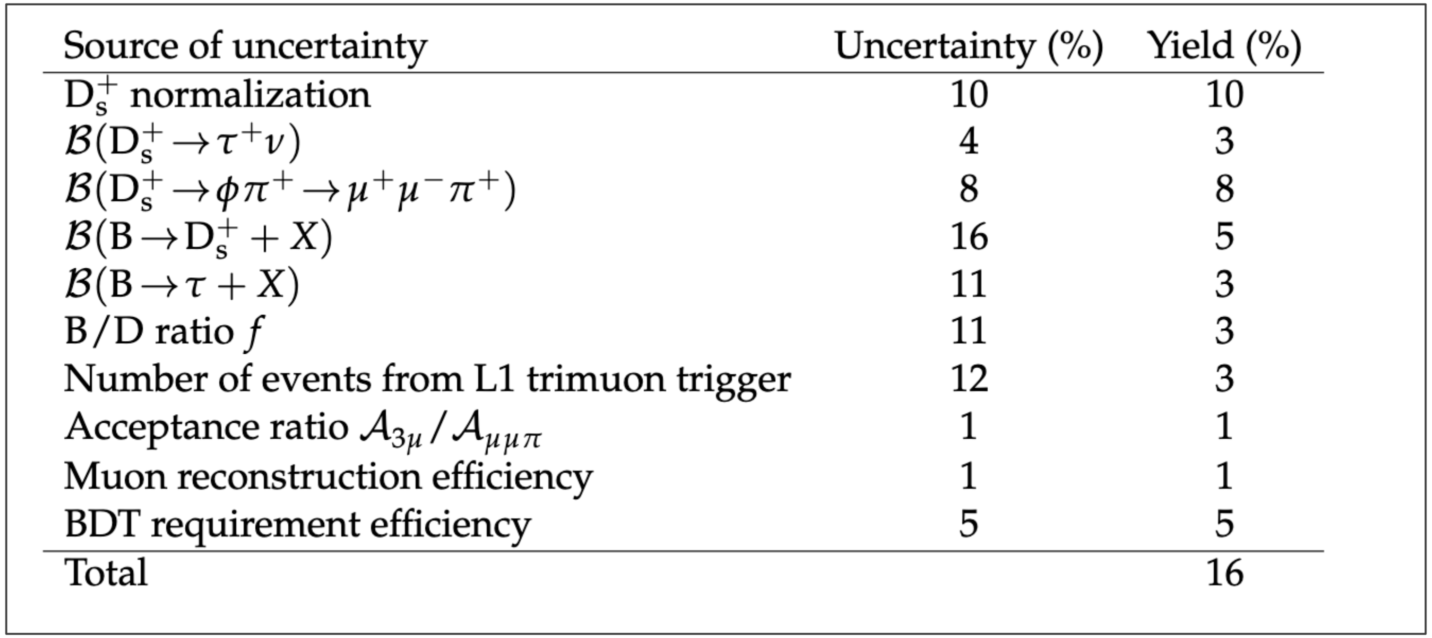
SYSTEMATIC UNCERTAINTIES

W channel



Source	Uncertainty (%) Barrel	Uncertainty (%) Endcap
Signal efficiency	7.9	32
Limited size of simulated samples	4.3	6.2
Integrated luminosity	2.5	2.5
$pp \to W$ cross section	2.9	2.9
$\mathcal{B}(W \to \mu\nu)$	0.2	0.2
$\mathcal{B}(W \to \tau\nu)$	0.2	0.2
Total	9.8	33

HF channel



Source of uncertainty	Uncertainty (%)	Yield (%)
D_s^+ normalization	10	10
$\mathcal{B}(D_s^+ \to \tau^+\nu)$	4	3
$\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)$	8	8
$\mathcal{B}(B \to D_s^+ + X)$	16	5
$\mathcal{B}(B \to \tau + X)$	11	3
B/D ratio f	11	3
Number of events from L1 trimuon trigger	12	3
Acceptance ratio $\mathcal{A}_{3\mu}/\mathcal{A}_{\mu\mu\pi}$	1	1
Muon reconstruction efficiency	1	1
BDT requirement efficiency	5	5
Total		16

ATLAS: $\tau^+ \to \mu^+\mu^+\mu^-$

SYSTEMATIC UNCERTAINTIES

- uncertainty on the number of background events 19%
- signal efficiency: 13.1%
- trigger efficiency: 11%
- MC modelling: 4%
- jet and MET calibration: 2.1%
- signal normalization: 3.9%