Flavor Anomalies and ATLAS B Physics

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Flavour Anomalies Workshop, 20 Oct 2021

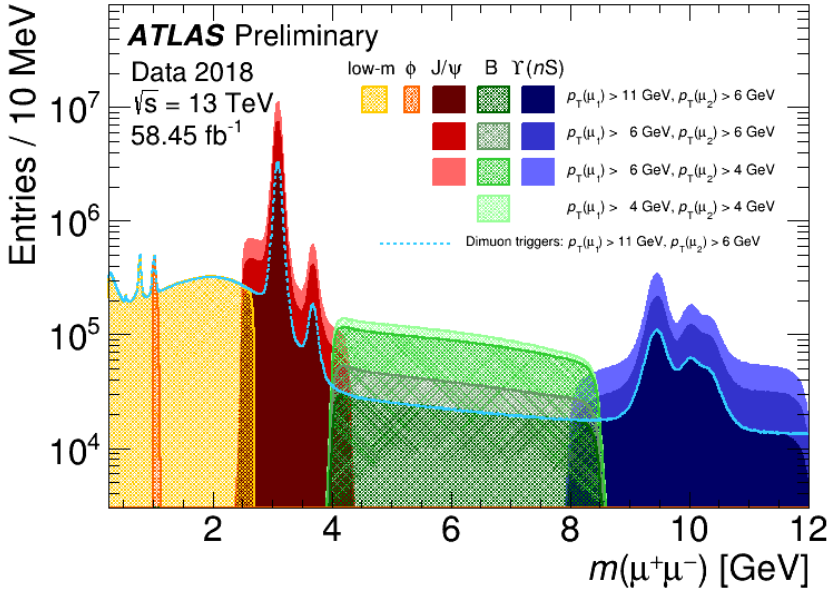
Introduction

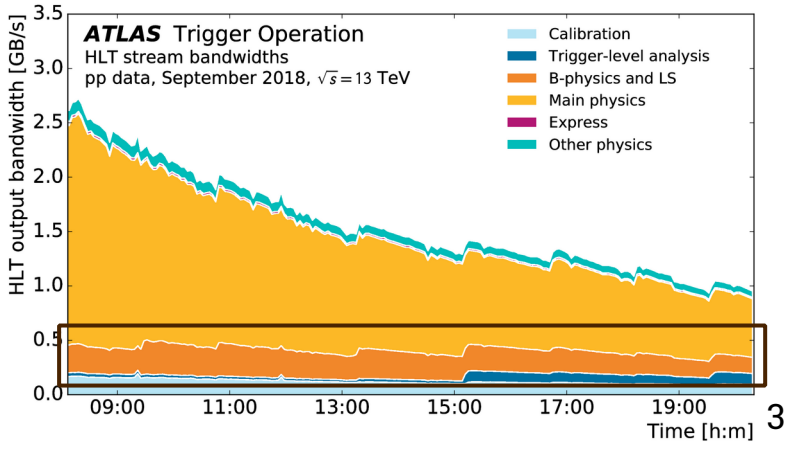
- Possible deviations from the SM in B decays have captured the interest of the HEP community
  - Anomalies appear to be related to $b \to s\mu\mu$ and $b \to c\tau\nu$ transitions
- As the final states can be fully reconstructed, ATLAS has paid more attention to the $bs\mu\mu$ vertex
  - $B \to K^*\mu\mu$ angular distributions
  - B_s, $B \to \mu\mu$
- ATLAS is adding capabilities to make future measurements
  - R(K*), R(K), ...

B Physics Trigger Strategies: Muons

Events must be triggered!

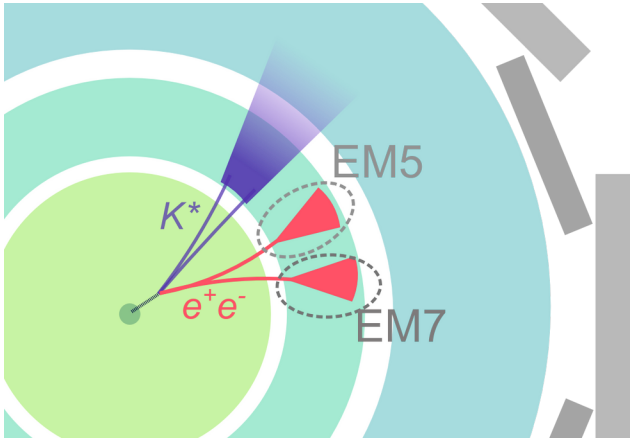
- Typically the limitation is the hardware Level 1 trigger maximum accept rate (~ 100 kHz)
- Standard strategy: multiple low-p_T muons or a high-p_T muon
  - in B decays this often means relying on J/ψ or other dimuon modes
  - muon p_T thresholds of 4 GeV or higher
  - mass cuts can be applied to increase signal for a given trigger rate (crude cuts with L1 topological trigger system, precision at high level software trigger)
  - Run 1 data with lower thresholds + prescales is valuable
- Set of enabled triggers & prescales evolves during LHC fills as luminosity changes

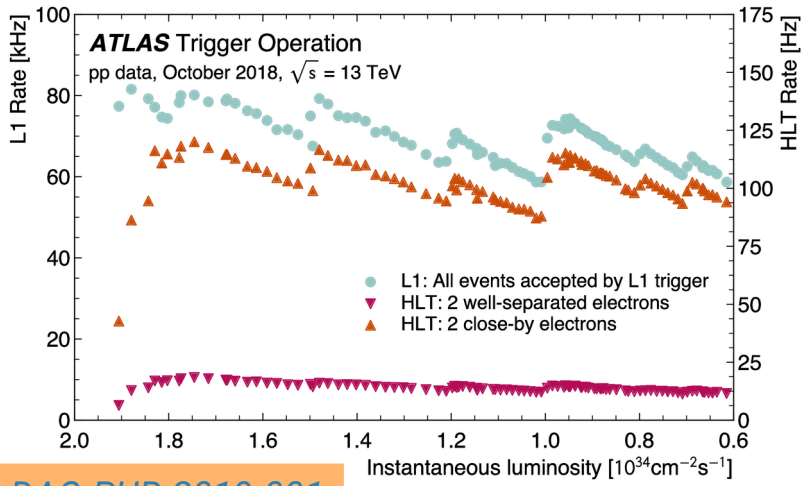




B Physics Trigger Strategies: Electrons

- Target $B \rightarrow K^{(*)}ee$
- L1 triggers: new topological triggers which look for a pair of soft electrons with low mass, or a soft "jet" near an electron (the jet assumed to combine two electrons)
  - to reduce rates also require additional muons from other B hadrons in event
- Software HLT dielectron low-mass triggers:
  - some seeded by the L1 topological triggers
  - also triggers that look at **all** events accepted by the L1 – very powerful
- Deployed mid-2018, ran for ~ 40 fb^{-1}





ATL-DAQ-PUB-2019-001

Analysis Strategies

- Other than muons/electrons, particle identification capabilities are extremely limited
  - intermediate narrow resonances in decay chains (e.g. J/ψ, ϕ) are very helpful to resolve hypothesis ambiguities
- Strongly prefer all-charged final states
  - K^0_S and photons are possible but have complications
- Sensitive to low-p_T lepton identification and tracking in "unusual" ways for ATLAS – additional work often needed to improve sensitivity & control systematics
  - muon identification under control down to $p_T \sim 3$ GeV
- Increasing use of machine learning to improve signal classification

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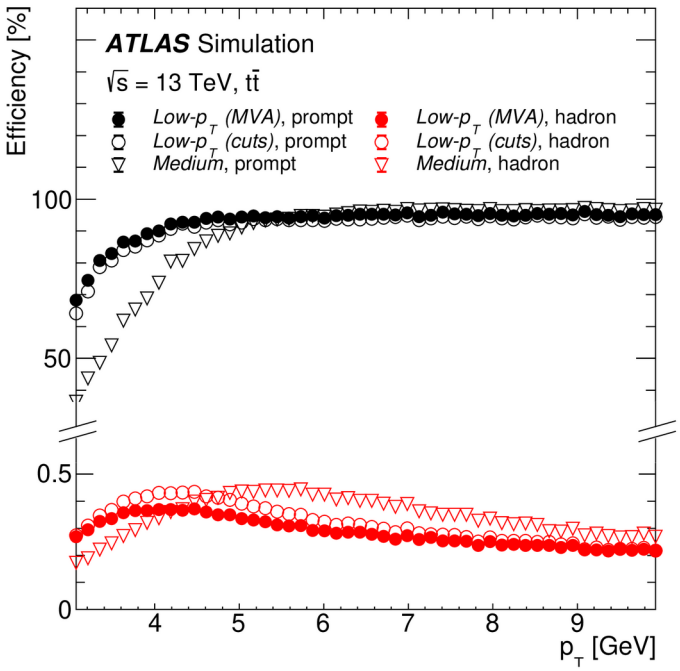
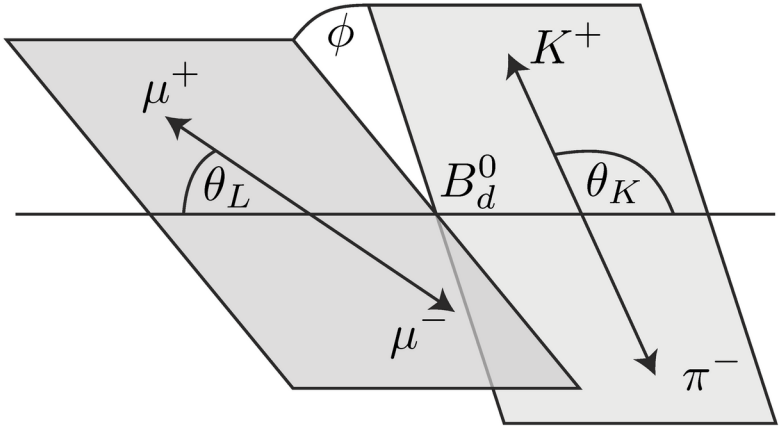


$B^0 \rightarrow K^*\mu\mu$ Angular Distributions

- New physics in $b \rightarrow s\mu\mu$ can alter the angular distributions of the decay products in $B^0 \rightarrow K^*\mu\mu \rightarrow K^+\pi^-\mu\mu$
- Particular interest in "P'_5" coefficient which shows a potential deviation from SM in previous results
  - look in different bins of $q^2(\mu\mu)$, avoiding J/ψ, ψ(2S), ϕ resonances
- Well-suited to ATLAS's capabilities
- Result from Run 1, 20 fb^{-1}



$$\frac{9}{32\pi}\left[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L\right.$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$\left.+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\right]$$

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

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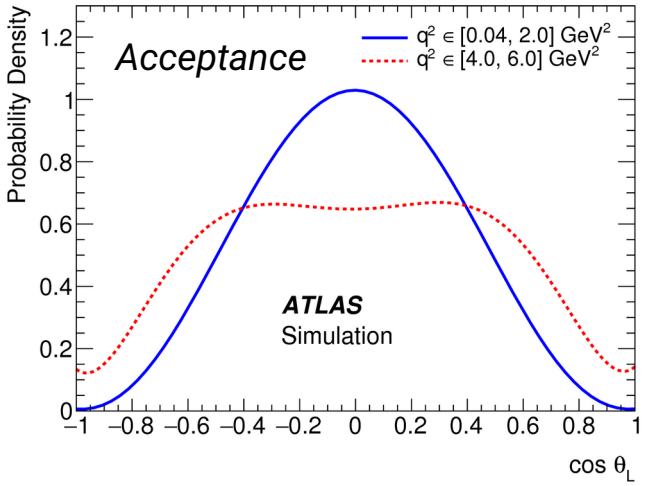
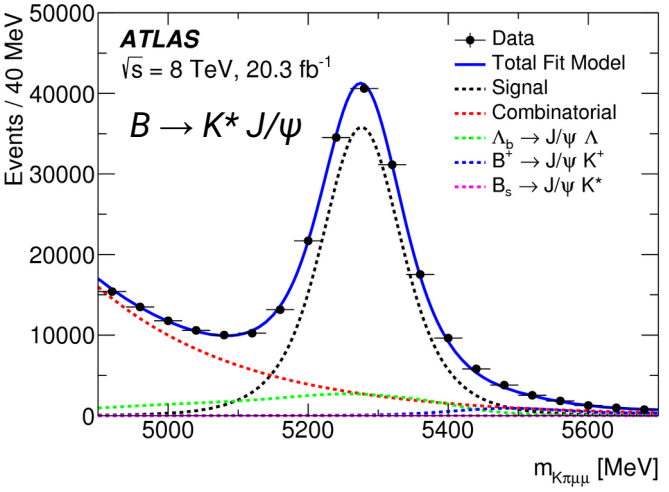
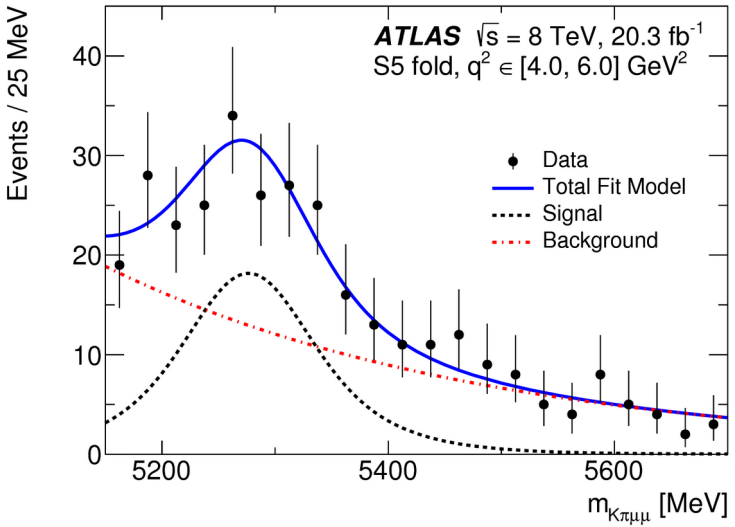
$B^0 \rightarrow K^*\mu\mu$ Angular Distributions

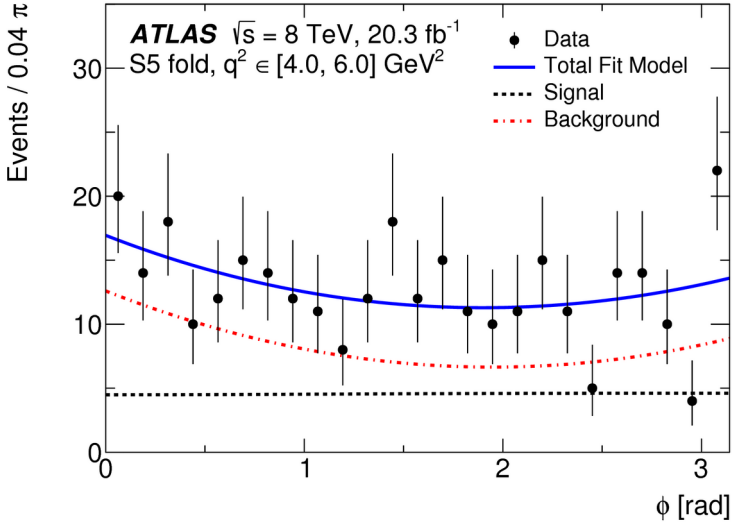
- Acceptance functions for the angular variables determined from MC
- Signal mass resolution calibrated from $B \rightarrow K^*$ J/ψ and K^* ψ(2S) samples
- Simultaneous fit to B candidate mass and angular distributions
  - background angular distributions described by polynomials, determined in fits
  - folding in angular variables permits fitting only a subset of coefficients (e.g. cancel variations ∝ sin φ)





$B^0 \rightarrow K^*\mu\mu$ Angular Distributions





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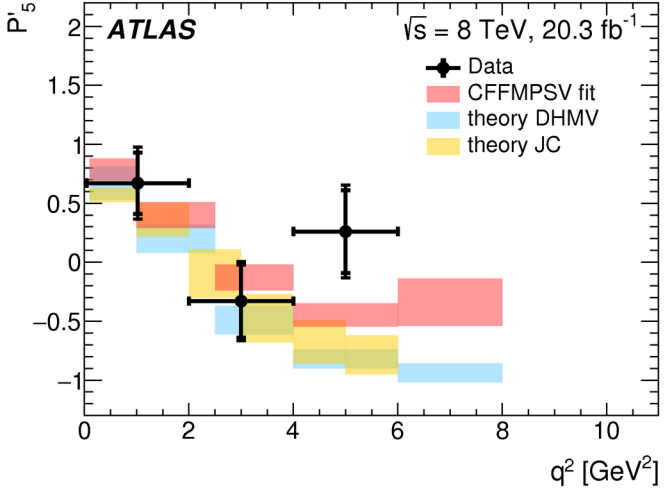
- "Most interesting bin" is P'_5, $q^2 \in [4\ \text{GeV}, 6\ \text{GeV}]$
- Can see e.g. lack of expected cos φ modulation in signal fit: $P'_5 \approx 0$ in our fit for this bin
  - of course, simultaneous fit to θ_K and θ_L as well
  - not a significant difference from predictions but deviation in the same direction as other results
- Results available for other coefficients



$B_{(s)} \to \mu\mu$

- Use 2015+2016 data, 26.3 fb^{-1} after prescales
- Rare decays sensitive to bsμμ and bdμμ couplings (incl. O_{10})
- ATLAS dimuon mass resolution not good enough to separate B_s and B peaks
  - fit simultaneously, but expect strong correlation of branching fractions
- Normalize number of observed decays to the number of $B^+ \to J/\psi\, K^+$:

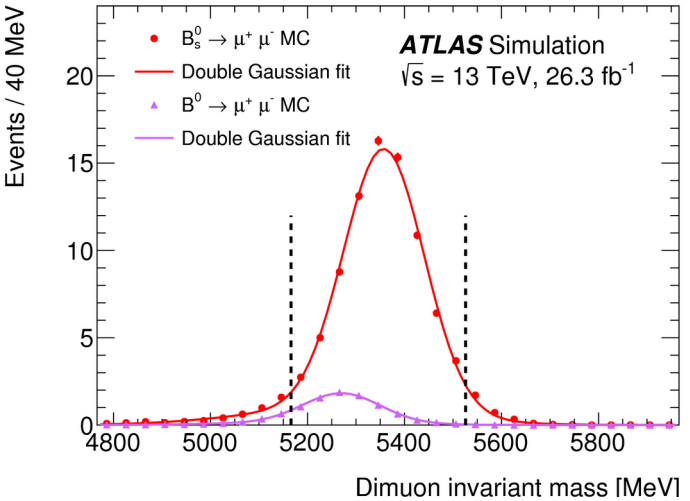
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \left[\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

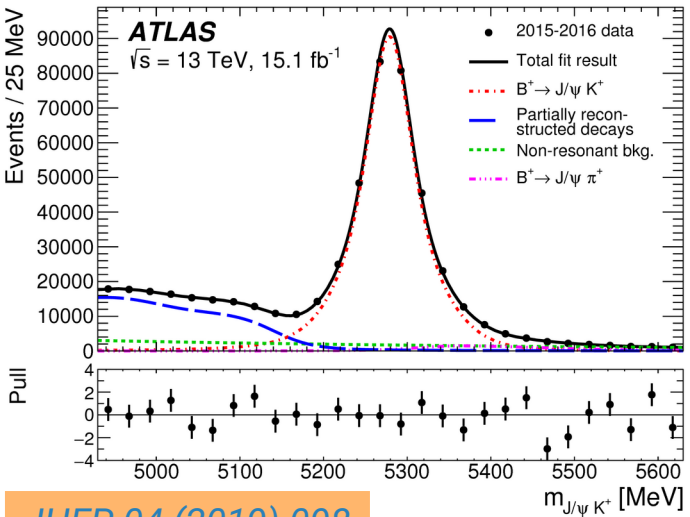
Reference branching fraction

Ratio of B meson species production

Efficiency-corrected $B_{(s)} \to \mu\mu$ yield

Efficiency-corrected $B \to J/\psi\, K$ yield





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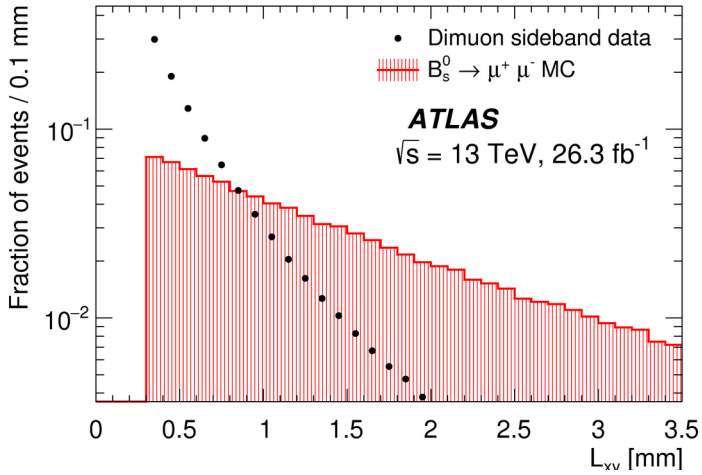
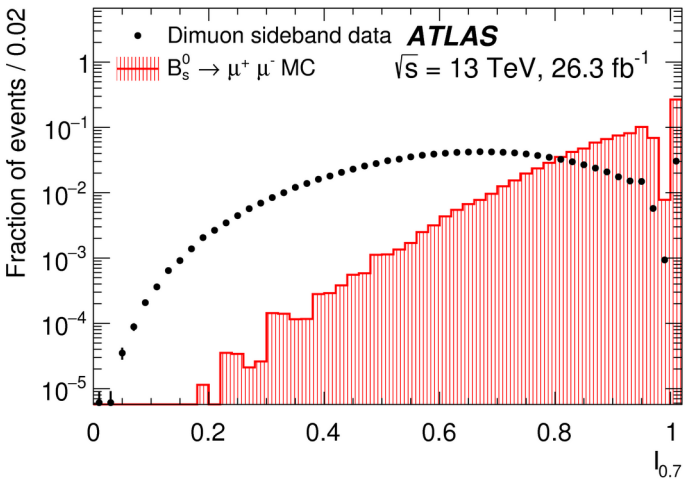
$B_{(s)} \rightarrow \mu\mu$ Background

- Backgrounds:
  - Major background under peak: “continuum” (muons from different b hadrons)
  - Major background with shape: b hadrons → μμX or μhX where hadron h is misidentified as a muon
  - Peaking background of B → hh’ with both hadrons being identified as muons
- Boosted Decision Tree used to suppress continuum backgrounds using
  - B kinematics/vertex position
  - muon kinematics
  - information on additional tracks from primary vertex
- BDT performance validated with muons in $B^+ \rightarrow J/\psi\, K^+$ and $B_s \rightarrow J/\psi\, \phi$





$B_{(s)} \rightarrow \mu\mu$ Results

- Combine Run 1 and early 13 TeV data
  - results compatible
  - sensitive to lower BRs for $B \rightarrow \mu\mu$ vs $B_s \rightarrow \mu\mu$ because $f_d >> f_s$
  - anticorrelation of B and B_s BR

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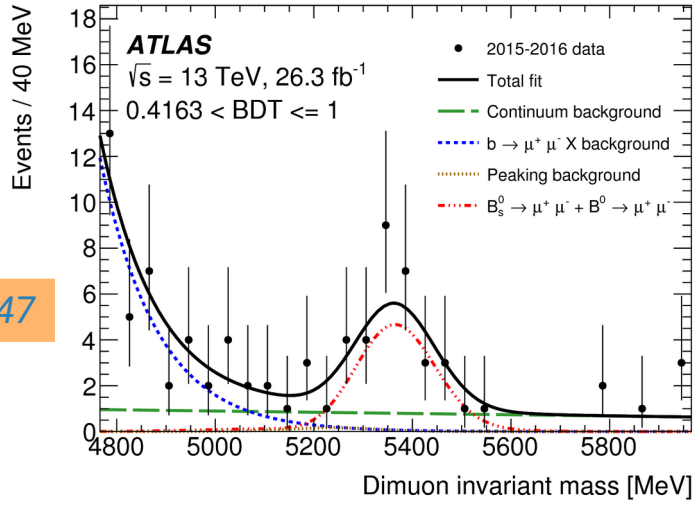
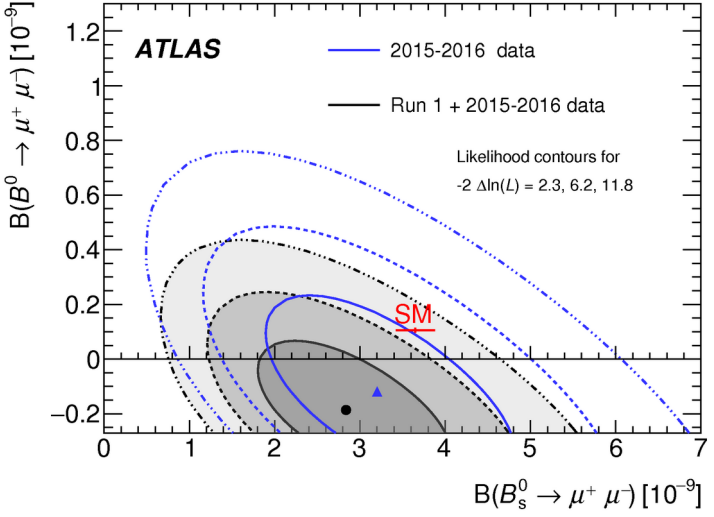


Combined Run 1 + 2015/6

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9},$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (-1.9 \pm 1.6) \times 10^{-10}.$$

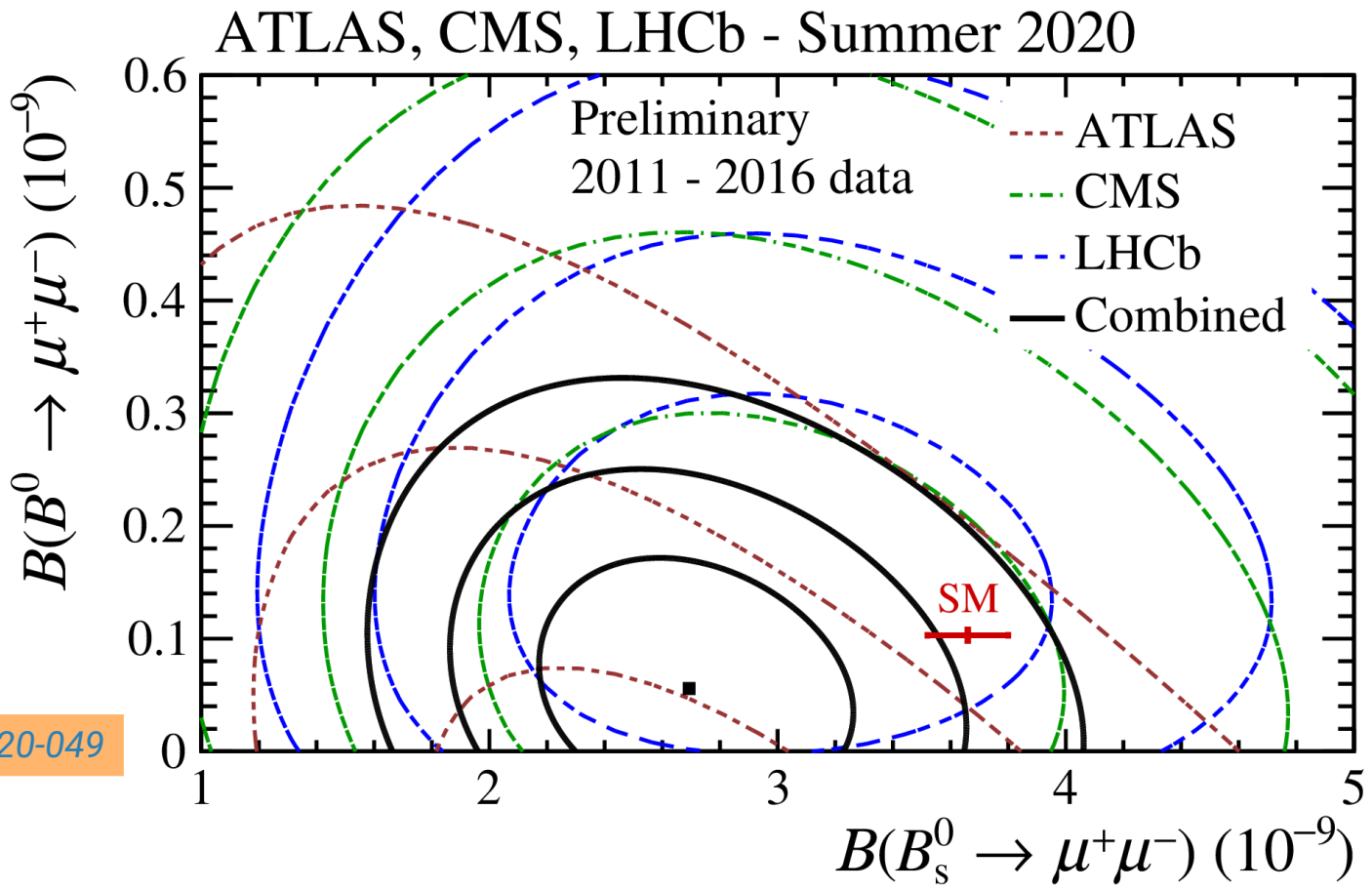


2015/6 result uncertainties

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

$B_{(s)} \rightarrow \mu\mu$ Combination

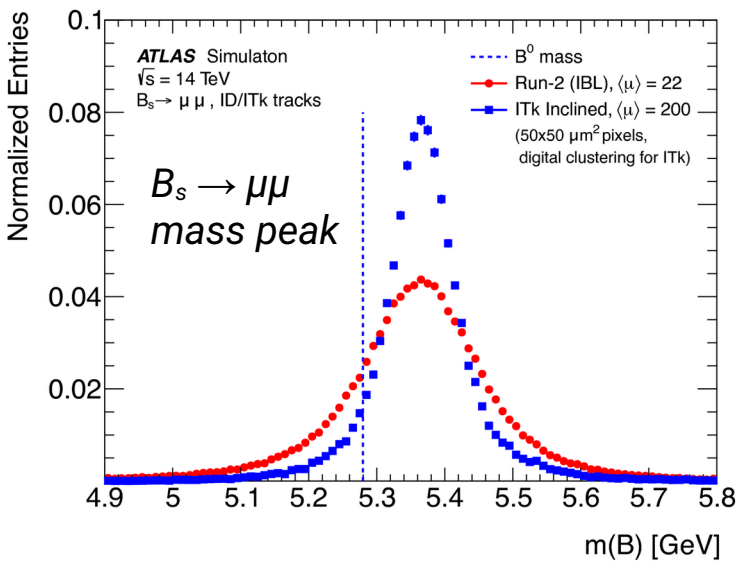
ATLAS results are an important component of the global LHC combination

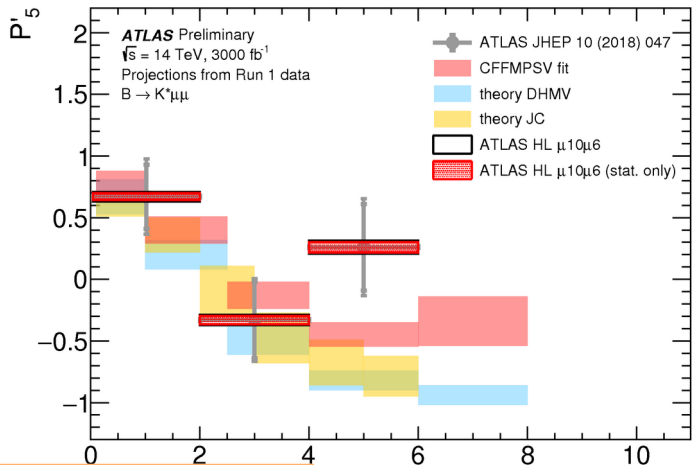


ATLAS-CONF-2020-049

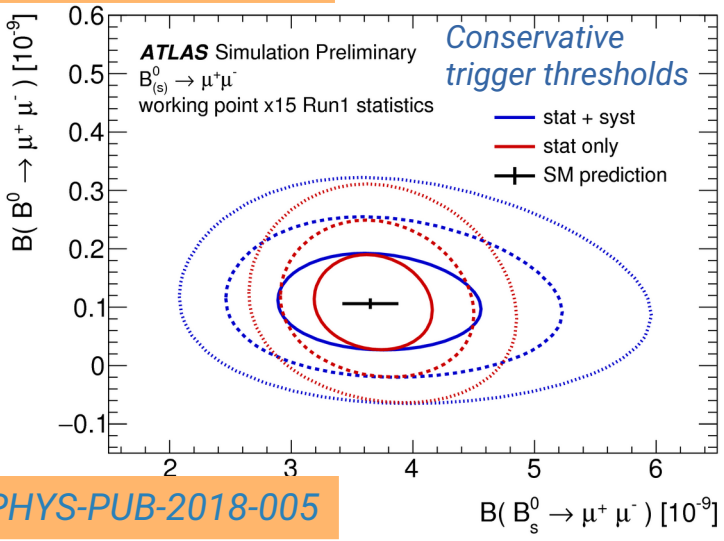
Projections

- Main impacts of HL-LHC:
  - larger dataset, ~ 20x Run 2
  - new inner tracker (ITk) with less material and better mass resolution
  - higher pileup → most likely higher trigger thresholds





ATL-PHYS-PUB-2019-003



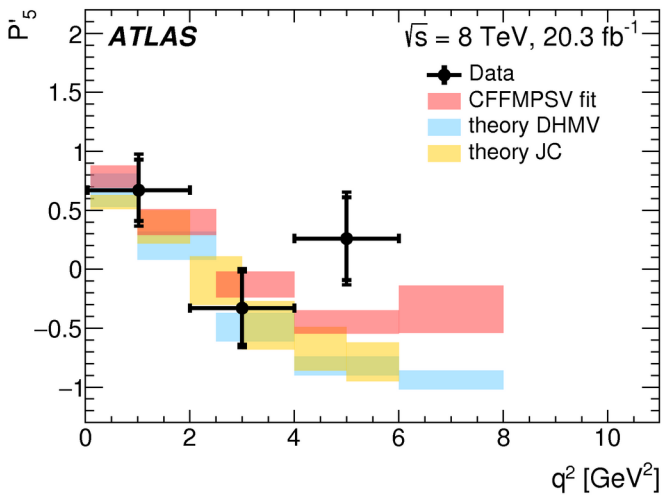
ATL-PHYS-PUB-2018-005

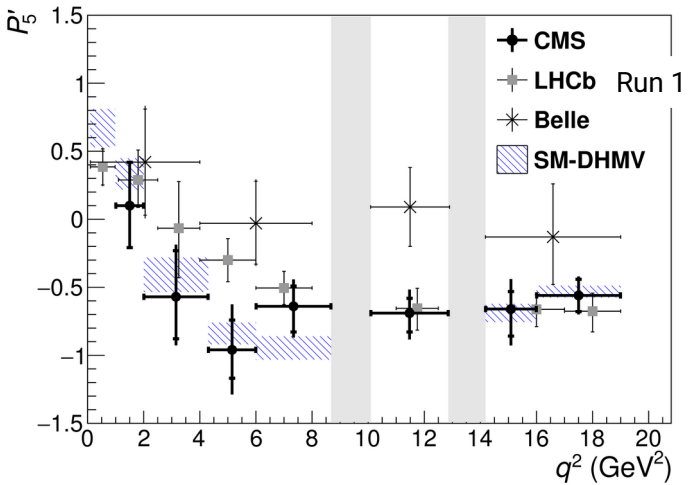
Summary & Prospects

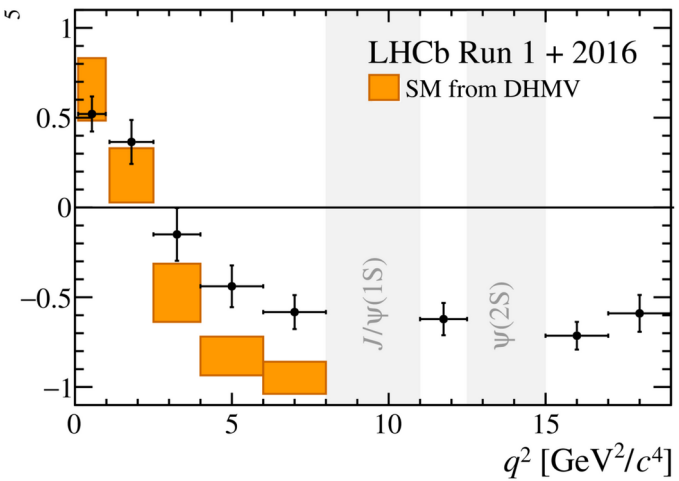
- ATLAS has results on $b \to s\mu\mu$ transitions
- Much more data now available from full Run 2 for $B_{(s)} \to \mu\mu$ and $B^0 \to K^*\mu\mu$ angular distributions
  - statistical uncertainties are dominant in published results
- Collected data in 2018 for initial $B^0 \to K^*ee$ studies
  - necessary triggers are prepared and planned for Run 3
- ATLAS has potential to investigate other channels that work with our trigger/analysis constraints + expects to maintain capacity into the HL-LHC era

Extra

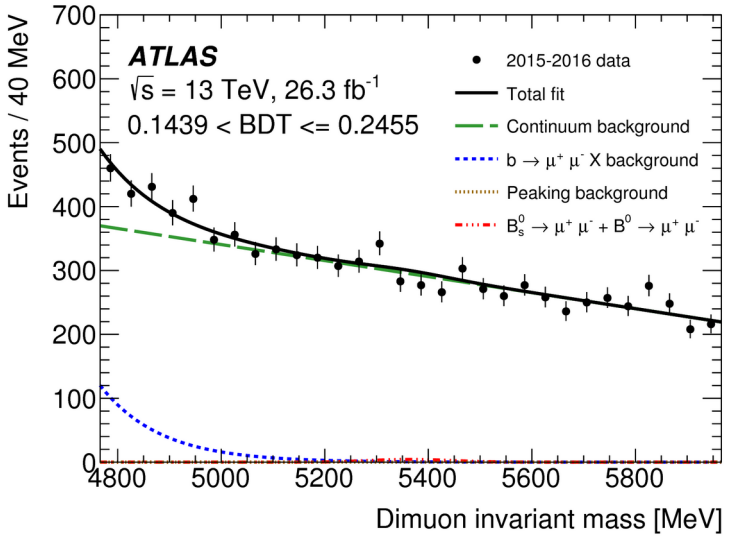
K^{*0} μμ P'_5

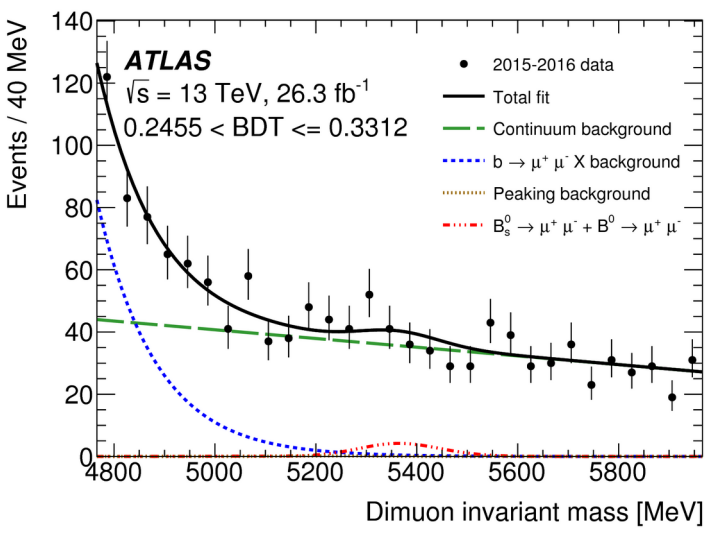

ATLAS
√s = 8 TeV, 20.3 fb-1
Data
CFFMPSV fit
theory DHMV
theory JC
P'5
q2 [GeV2]

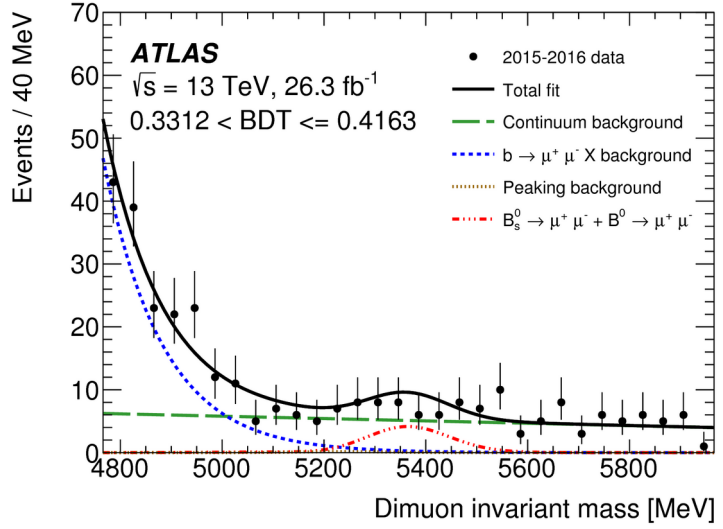

CMS
LHCb Run 1
Belle
SM-DHMV
P'5
q2 (GeV2)

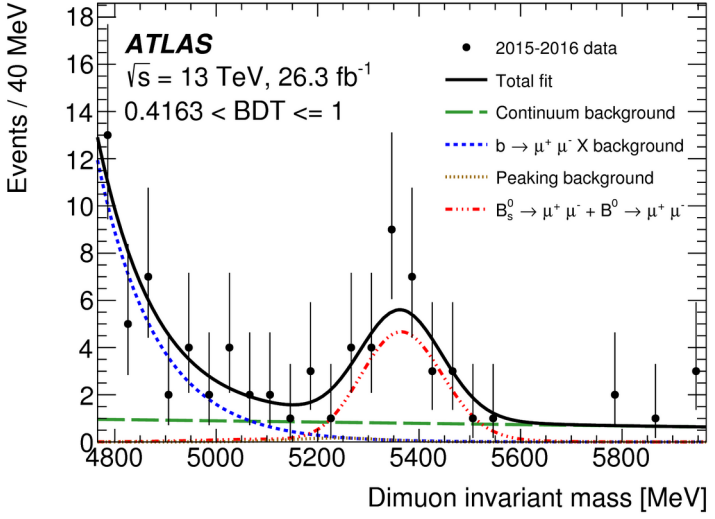

LHCb Run 1 + 2016
SM from DHMV
J/ψ(1S)
ψ(2S)
P'5
q2 [GeV2/c4]

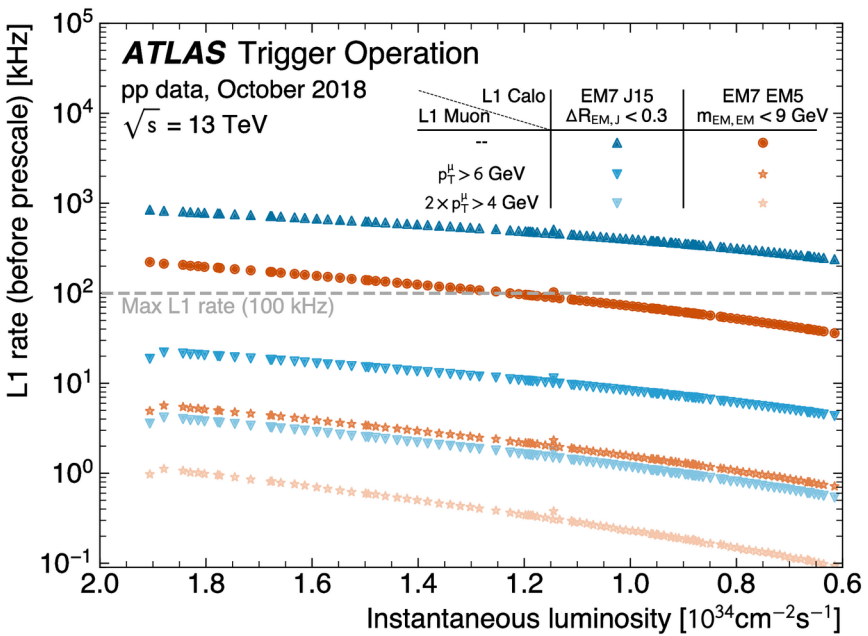
$B_{(s)} \rightarrow \mu\mu$: all BDT bins

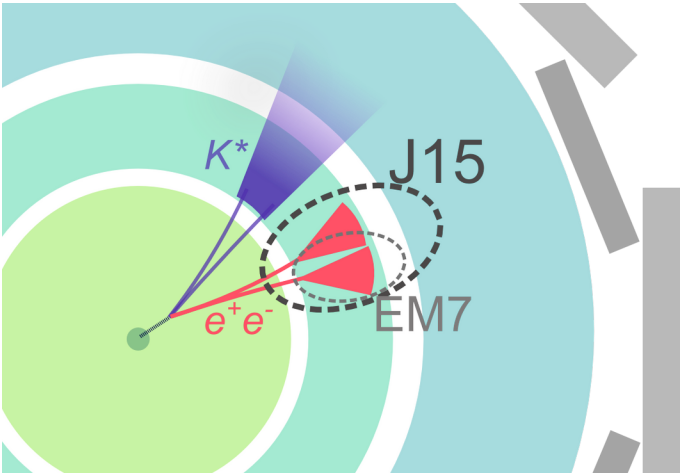


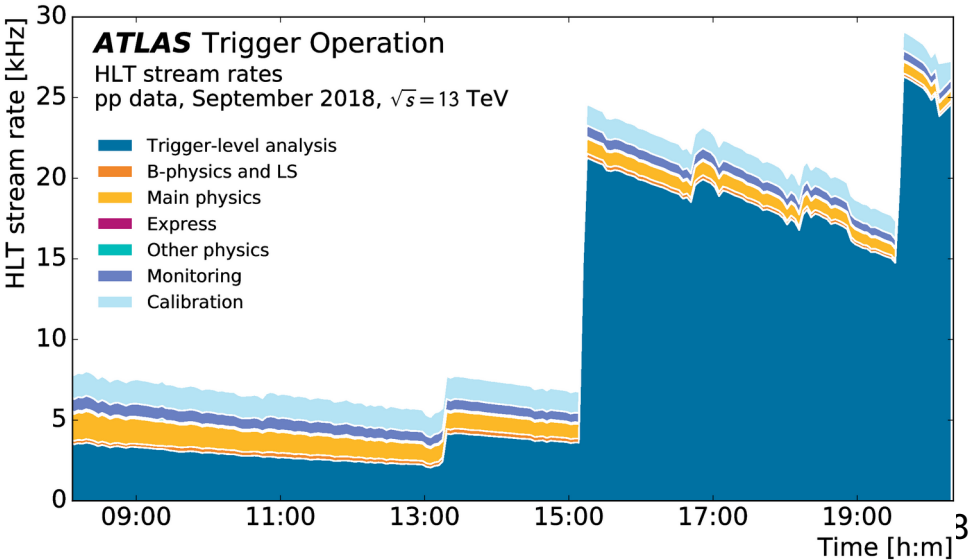







ATLAS Trigger Operation
pp data, October 2018
√s = 13 TeV
L1 Calo
L1 Muon
EM7 J15 ΔR_EM,J < 0.3
EM7 EM5 m_EM,EM < 9 GeV
--
p_T^μ > 6 GeV
2 × p_T^μ > 4 GeV
Max L1 rate (100 kHz)
L1 rate (before prescale) [kHz]
Instantaneous luminosity [10^34 cm^-2 s^-1]


K*
J15
e+e-
EM7


ATLAS Trigger Operation
HLT stream rates
pp data, September 2018, √s = 13 TeV
Trigger-level analysis
B-physics and LS
Main physics
Express
Other physics
Monitoring
Calibration
HLT stream rate [kHz]
Time [h:m]