Status and prospects of rare decay searches at ATLAS and CMS

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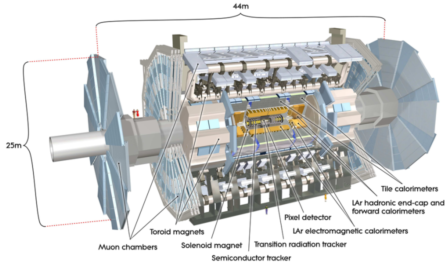
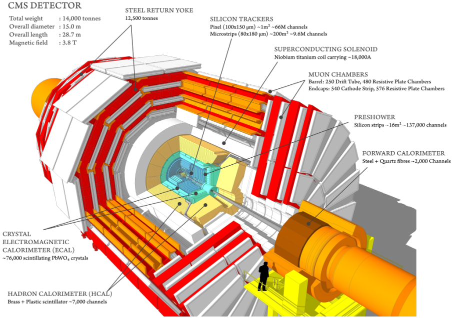
Workshop Italiano sulla Fisica ad Alta Intensità
Bologna, Italy
12–15 November 2024

ATLAS and CMS detectors

- Compared to B-factory experiments
  - Abundant production of B_s^0, B_c^+, b baryons, including excited states
  - Challenging reconstruction and triggering in pp environment
- Compared to LHCb
  - Central acceptance for tracks and muons ($|\eta| \lesssim 2.5$) – complementary production measurements
  - Higher integrated luminosity ($140\,\text{fb}^{-1}$ vs $6\,\text{fb}^{-1}$ in Run-2) and pile-up – beneficial in certain studies but higher background
  - Practically no particle identification
  - Lower acceptance in p_T due to trigger limitations
- Most of the B-physics program is based on (multi-)muon triggers





Outline

Suppressed electroweak loop processes

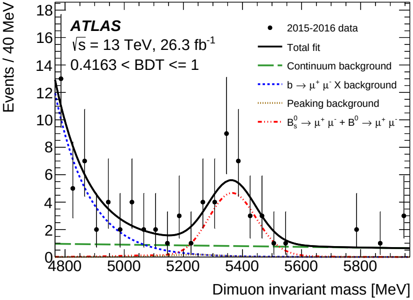
- $B^0_{(s)} \to \mu^+\mu^-$ studies
  - CMS with full Run-2 (PLB 842 (2023) 137955) and ATLAS with partial Run-2 (JHEP 04 (2019) 098, JHEP 09 (2023) 199)
- $D^0 \to \mu^+\mu^-$ (CMS-PAS-BPH-23-008)
- Semileptonic decays
  - $B^+ \to K^+\mu^+\mu^-$ differential $\mathcal{B}$ measurement in CMS (Rept.Prog.Phys. 87 (2024) 077802)
  - Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ in CMS (CMS-PAS-BPH-21-002)

"Rare" in practical sense

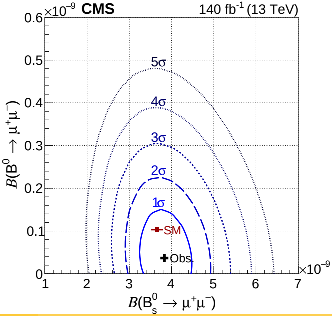
- First observation of $J/\psi \to 4\mu$ (PRD 109 (2024) L111101)
- First observation of $\Lambda^0_b \to J/\psi\Xi^-K^+$ (EPJC 84 (2024) 1062)

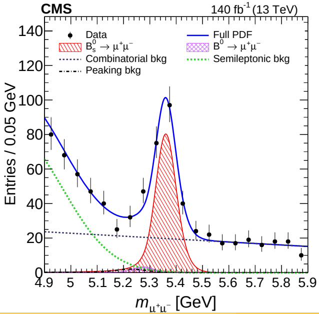
- Rare but clean signature, highly suppressed in SM (FCNC, V_{ts} or V_{td}, helicity)
- Similar analysis techniques in both experiments
- $\mathcal{B}$ measured with $B^+ \to J/\psi K^+$ reference channel:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0_s \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0_s \to \mu^+\mu^-}}$$

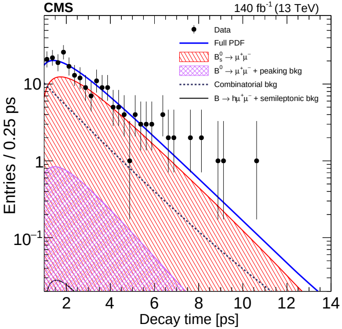


- Main backgrounds: dimuon continuum, semileptonic decays, peaking $B^0_{(s)} \to h^+h^-$ decays
- MVA-based event selection
  - trained on data sidebands (CMS) or $b\bar{b} \to \mu^+\mu^- X$ MC (ATLAS)

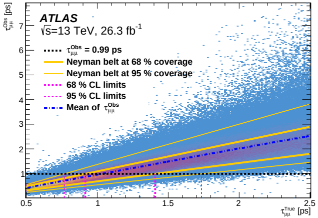


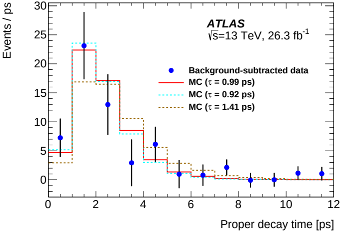


- In SM, only CP-odd $B^0_{s,H}$ contributes to $B_s^0 \to \mu^+\mu^-$
  - In BSM CP-even $B^0_{s,L}$ contribution possible
  - $\to$ sensitivity due to large $\tau_{B^0_{s,H}} - \tau_{B^0_{s,L}} = 1.624 - 1.431 = 0.193\,ps$
- Complementary observable to $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ – different set of effective operators



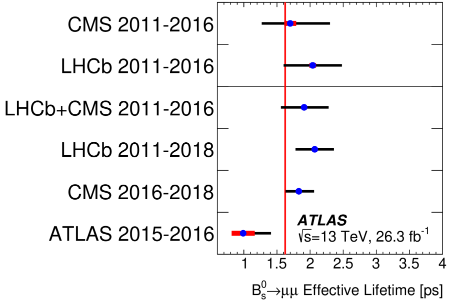
- CMS: unbinned ML fit to mass and lifetime (+error)
- ATLAS: sPlot to extract signal $\tau_{\mu^+\mu^-}$ distribution
  - fit with MC templates
  - Stat. uncertainty with toys

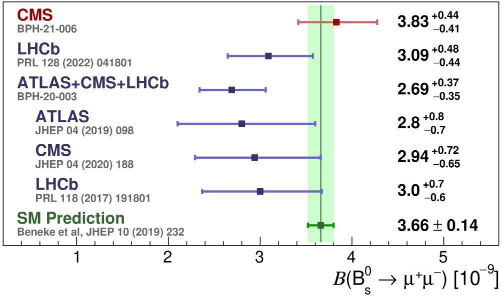


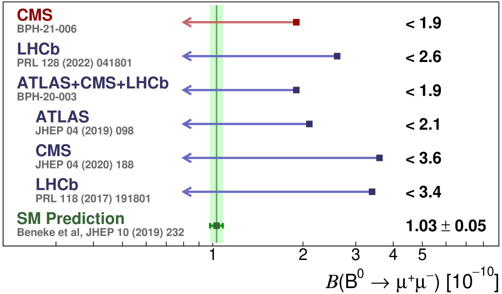


$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$: results

- Overall, no deviations from SM
- Similar precision for CMS and LHCb with full Run-2
  - ATLAS full Run-2 underway
  - $\to$ then LHC combination
- No sensitivity to $B^0 \to \mu^+\mu^-$ yet
  - $\to$ Run-3 should improve







Motivation

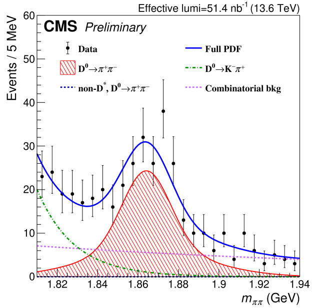
- $c \to u$ transition less studied vs $b \to s$
  - involve loops with lighter quarks → challenging long-distance contributions; $\mathcal{B} = \mathcal{O}(3 \times 10^{-13})$ in SM

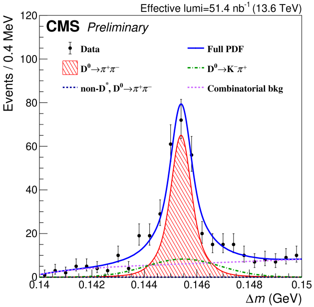
Analysis strategy

- Look for signal in $D^{*+} \to D^0\pi^+$ cascades
  - orders of magnitude reduction of combinatorial background
- Normalization channel $D^0 \to \pi^+\pi^-$, using *zero-bias triggers*

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-)\frac{N_{\mathrm{D}^0\to\mu^+\mu^-}}{N_{\mathrm{D}^0\to\pi^+\pi^-}}\frac{\varepsilon_{\mathrm{D}^0\to\pi^+\pi^-}}{\varepsilon_{\mathrm{D}^0\to\mu^+\mu^-}}$$

  - optimized considering both prompt and $b \to D^{*+}$ production
- Preselection + MVA-based selection of D^{*+} candidates
  - Same for signal and normalization channels
  - Trained with right side-band of Δm as background
- For signal fit, consider also $D^0 \to \pi^-\mu^+\nu_\mu$ and $D^0 \to \pi^+\pi^- \to \mu^+\mu^-$ (double-fake) backgrounds



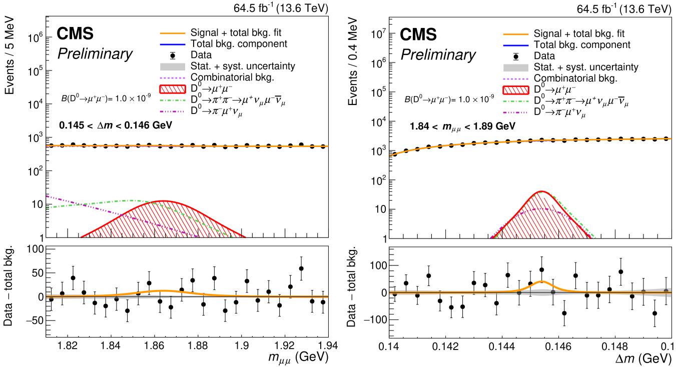


Search for $D^0 \to \mu^+\mu^-$ (2)

- $\mathcal{B}(D^0 \to \mu^+\mu^-)$ extracted from 2D UML fit to $m_{\mu\mu}$ and Δm
  - all shapes constrained with simulation (except combinatorial bkg)
  - yields of $D^0 \to \pi^-\mu^+\nu_\mu$ and $D^0 \to \pi^+\pi^- \to \mu^+\mu^-$ constrained with normalization channel and MC efficiencies
- No significant excess in data

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = (1.0 \pm 0.9) \times 10^{-9}$$

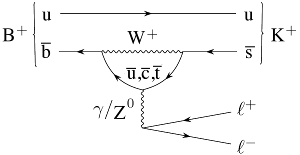
Analysis uses 2022+2023 data

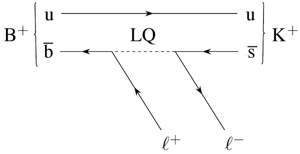


- Most stringent limit do date
- Benefits from CMS low-mass *di-muon parking triggers in Run-3* (arXiv:2403.16134)

Differential $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ measurement

- $\bar{b} \to \bar{s}\ell^+\ell^-$ forbidden at tree level
- BSM physics could modify the $\mathcal{B}$
  - also differently for lepton species – LFUV
- CMS measures $R(K)$ ratio
  - in *low-q^2 region* 1.1–6.0 GeV^2
  - *more in LFV section
- $d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/dq^2$
  - in wider range and finer binning





$$R(\mathrm{K})(q^2)[q^2_{\min}, q^2_{\max}] = \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)[q^2_{\min}, q^2_{\max}]}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+)} \Big/ \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-)[q^2_{\min}, q^2_{\max}]}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mathrm{e}^+\mathrm{e}^-)\mathrm{K}^+)}$$

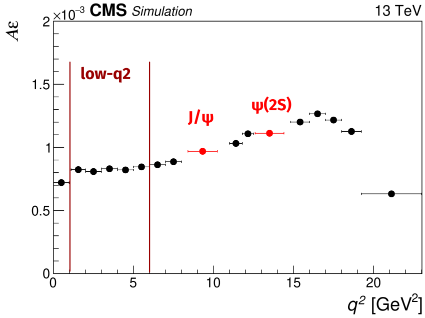
- "B parking" trigger strategy $\to \sim 10^{10}$ events
  - Single displaced muon trigger $\to$ *muon channel*
  - *electron channel* events – from unbiased opposite-side B

$\mathcal{L}$ $[10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	L1 p_T^μ thr. [GeV]	HLT p_T^μ thr. [GeV]	HLT μ IP$_{sig}$ thr.	Purity [%]	Peak HLT rate [kHz]	$\int\mathcal{L}dt$ [fb^{-1}]
1.7	12	12	6	92	1.5	34.7
1.5	10	9	6	87	2.8	6.9 + 26.7
1.3	9	9	5	86	3.0	20.9
1.1	8	8	5	83	3.7	8.3
0.9	7	7	4	59	5.4	6.9

Integrated $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$

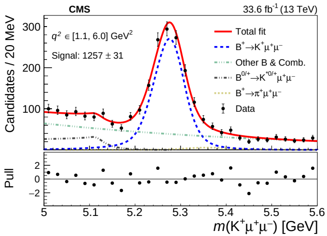
Normalize to the resonant channel

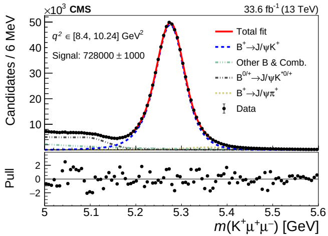
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)[q^2_{\min}, q^2_{\max}] = \frac{N_{B^+\to K^+\mu^+\mu^-}[q^2_{\min}, q^2_{\max}]}{N_{B^+\to J/\psi(\mu^+\mu^-)K^+}[8.41, 10.24]\ \mathrm{GeV}^2} \times \frac{(\mathcal{A}\epsilon\epsilon_{\mathrm{trig}})_{B^+\to J/\psi(\mu^+\mu^-)K^+}[8.41, 10.24]\ \mathrm{GeV}^2}{(\mathcal{A}\epsilon\epsilon_{\mathrm{trig}})_{B^+\to K^+\mu^+\mu^-}[q^2_{\min}, q^2_{\max}]} \mathcal{B}(B^+ \to J/\psi K^+)\mathcal{B}(J/\psi \to \mu^+\mu^-)$$



Integrated $\mathcal{B}$ uses the low-q^2 bin to minimize dependence on theory:

Source	$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)[1.1, 6.0]\ \mathrm{GeV}^2$ $[10^{-8}]$
Measurement	12.42 ± 0.68
EOS	18.9 ± 1.3
FLAVIO	17.1 ± 2.7
SUPERISO	16.5 ± 3.4
HEPFIT	19.8 ± 7.3

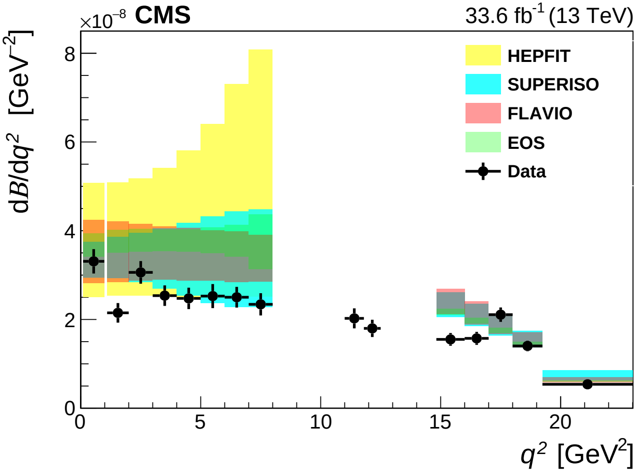




- Extrapolate to q^2-integrated $\mathcal{B}$ using two theory models
  - $(43.5 \pm 2.4) \times 10^{-8}$ (FLAVIO)
  - $(43.9 \pm 2.4) \times 10^{-8}$ (SUPERISO)
- Agrees with PDG and LHCb

Differential $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$

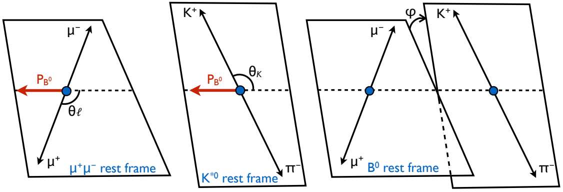
- Measured in 18 q^2 bins
- Uncertainty small compared to theory, statistically dominated
  - only 33/fb from 2018
- Data generally at the lower edge or below predictions for $q^2 < 17\,\text{GeV}^2$
  - agrees and competitive with earlier LHCb result
  - Is it an anomaly? Still no consensus on theory side...

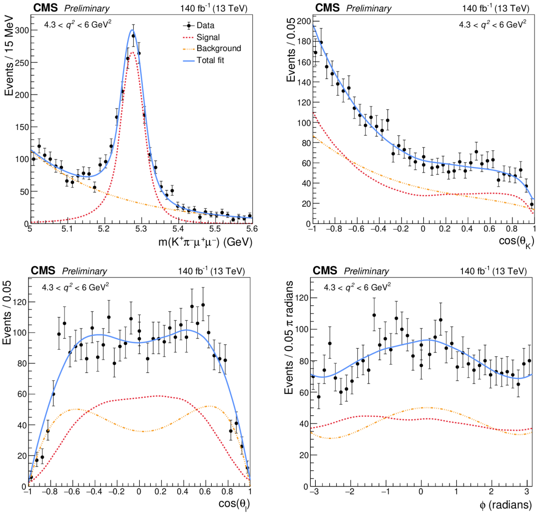


no calculations for the range between J/ψ and $\psi(2S)$
HEPFIT only available for $q^2 < 8\,\text{GeV}^2$

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

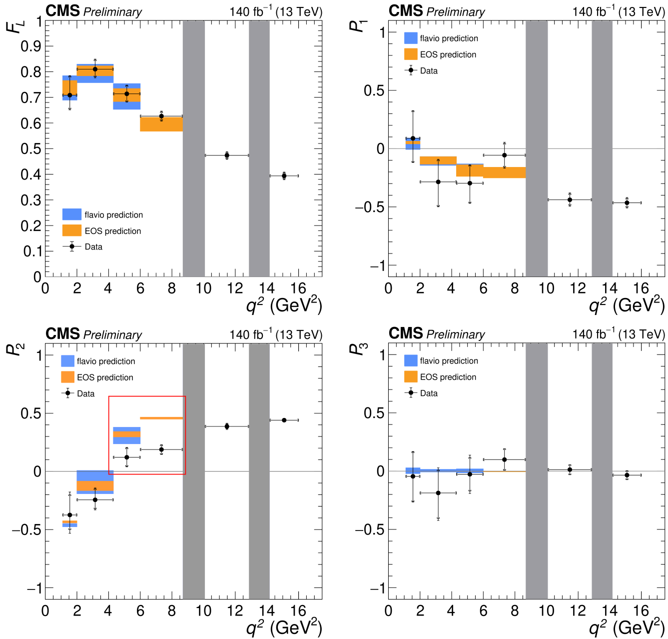
- Long-term tension between data and theory in angular observables
- CMS uses full Run-2 dataset with dimuon+track triggers
- Final state described by q^2 and θ_K, θ_ℓ, ϕ
  - decay rate expressed via F_L and *optimized observables* $P_{1,2,3}$, $P'_{4,5,6,8}$
    - and F_S, A_S for S-wave component
- UML fit to the mass and 3 angles in 6 bins of q^2





Angular analysis of $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$ (2)

- Extract all 8 observables
- Two sets of predictions compatible to data, **except:**
  - P_2 and P_5' at q^2 below J/ψ
- The P_5' discrepancy consistent with Belle, LHCb, ATLAS
- One of the most precise measurements to date
  - Still limited statistically



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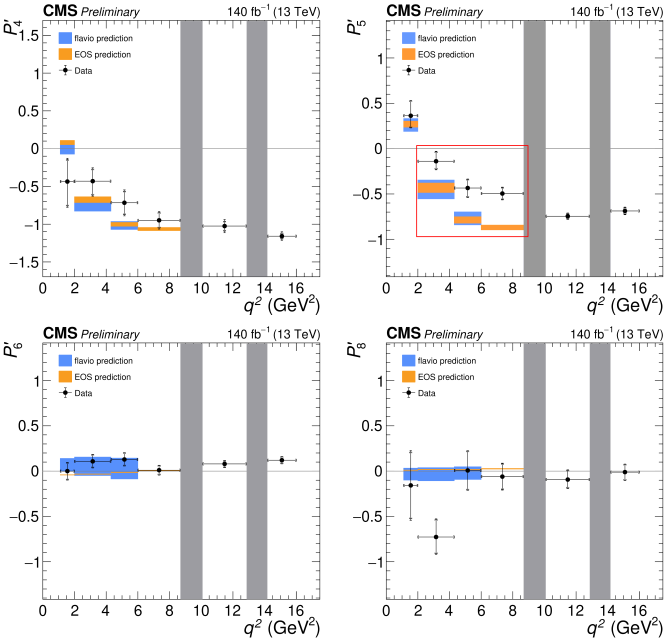
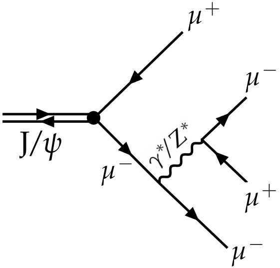


First observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay in CMS PRD 109 (2024) L111101

- In SM proceeds via $\gamma^*/Z*$, $\mathcal{B}(J/\psi \to 4\mu) = (9.74 \pm 0.05) \times 10^{-7}$
  - probe for various BSM scenarios
  - novel testing ground for QED calculations
  - only upper limit from BESIII so far: $\mathcal{B} < 1.6 \times 10^{-6}$
- CMS uses the B-parked 2018 dataset with single-muon triggers

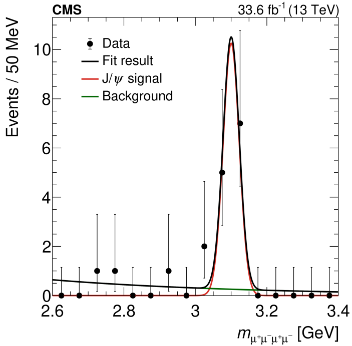


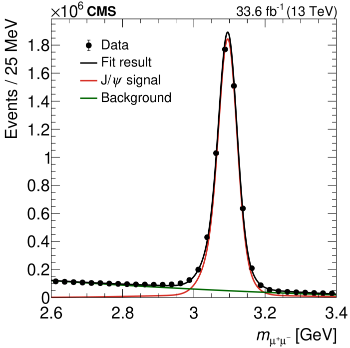
Normalization to $\mathcal{B}(J/\psi \to \mu^+\mu^-)$:

- $\frac{\mathcal{B}(J/\psi \to 4\mu)}{\mathcal{B}(J/\psi \to 2\mu)} = \frac{N_{4\mu}}{N_{2\mu}} \times \frac{\epsilon_{2\mu}}{\epsilon_{4\mu}}$
- Observe $11.6^{+3.8}_{-3.1}$ signal events
- Significance above 7σ

$\mathcal{B}(J/\psi \to 4\mu) = (10.1^{+3.3}_{-2.7}(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-7}$

- agrees with SM



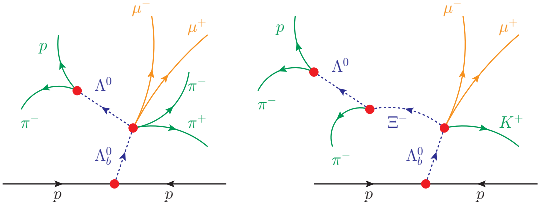


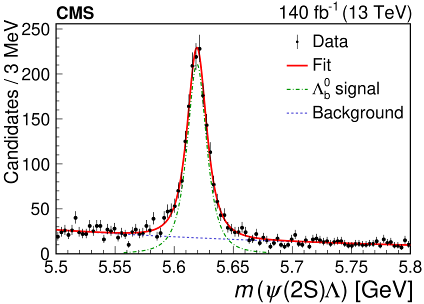
First observation of $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay in CMS

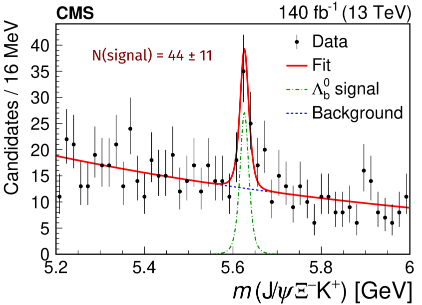
EPJC 84 (2024) 1062

- Study motivated by recent discoveries of pentaquark structures in $J/\psi p$ and $J/\psi\Lambda^0$ systems
  - Studying $J/\psi\Xi$ and $J/\psi\Omega^-$ can lead to doubly-/triply-strange pentaquarks
- Challenging reconstruction of 3-vertex cascade decay
- Observation significance above 5σ
- Measure $\mathcal{B}$ w.r.t. reference $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay
  - different cascade, still high systematics cancellation

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = [3.38 \pm 1.02\,(\text{stat}) \pm 0.61\,(\text{syst}) \pm 0.03\,(\mathcal{B})]\%$$







Summary

- Great progress with clear di-muon signatures
  - $\sim$11% precision achieved for $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with a single CMS measurement
  - Effective lifetime as another sensitive observable
    - Combination with ATLAS full Run-2 will further improve precision soon
  - Large potential for charm meson rare decays
    - New CMS data parking strategy in Run-3
- Rare semileptonic decays challenging both for theory and experiment
  - $d\mathcal{B}/dq^2$ predictions suffer from large uncertainties
  - Still no consensus on long-standing discrepancies
  - Room for more synergy between the experiments and with theory community
    - Promising start of the discussion at LHC HF WG meeting on $b \to s\ell\ell$
    - e.g. define *common q^2 binning options...*
- Looking to the future
  - Phase-2 upgrade of the trackers will bring mass resolution improvement – *factor $\sim$1.5 in both ATLAS and CMS*

Backup slides

PRL 131 (2023) 091903

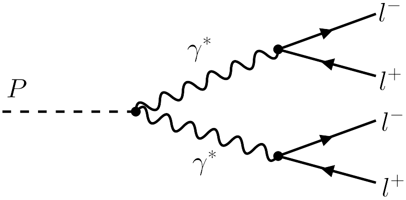
- Double-Dalitz decay serving a precision SM test, sensitive to certain new physics scenarios
  - light-by-light hadronic component of the muon anomalous magnetic moment
- Data collected by dedicated high-rate low-p_T dimuon triggers saving only HLT information
- Measure the $\mathcal{B}$ w.r.t. $\eta \to \mu^+\mu^-$ decay

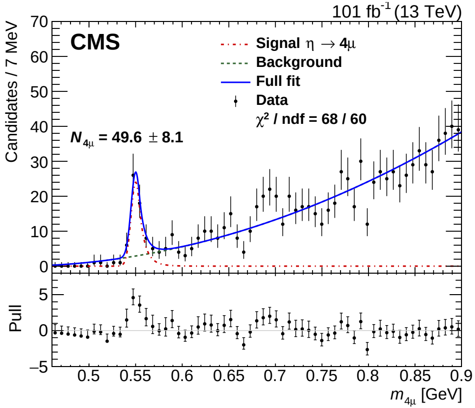
$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.86 \pm 0.14\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-3}$$

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$

  - agrees with the prediction of $(3.95 \pm 0.15) \times 10^{-9}$

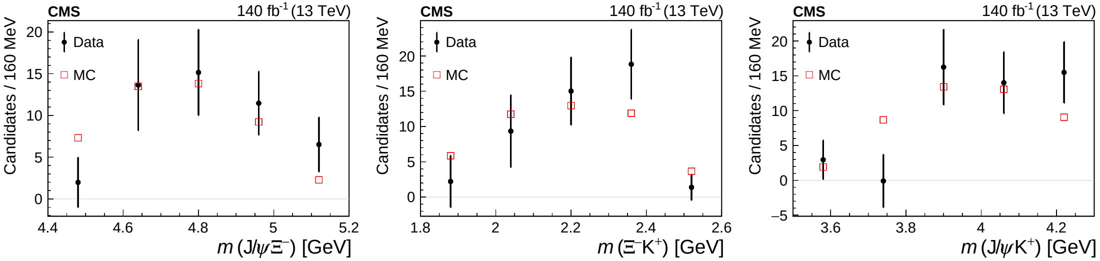
A unique measurement made possible by special trigger strategy





$\Lambda_b^0 \to J/\psi \Xi^- K^+$ – intermediate system masses

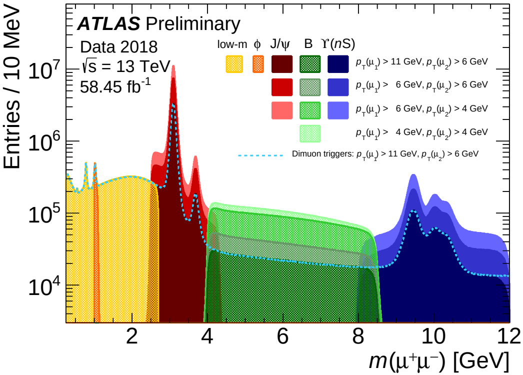
- First observation of a multi-body decay with $J/\psi\Xi^-$ system
  - Nice demonstration of the potential in studying complicated multi-body final states
- Limited statistics does not yet allow to study intermediate resonances

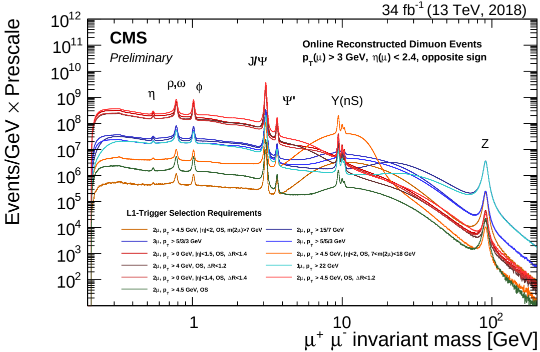


Di-muon triggers

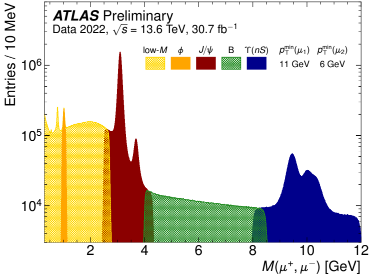
Dedicated trigger options to overcome the rate limitations for low-p_T dimuons

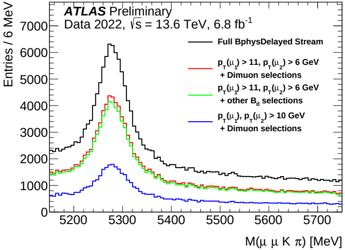
- ATLAS uses *topological selection* using muon trigger hardware information (cuts on $m(\mu^+\mu^-)$, $\Delta R(\mu^+\mu^-)$), software selection based on *full reconstruction of certain decays* with precision tracking (e.g. $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$)
- *Data scouting* in CMS – doing certain analyses using only trigger-level information to save bandwidth throwing away raw data

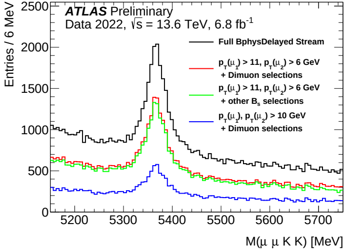


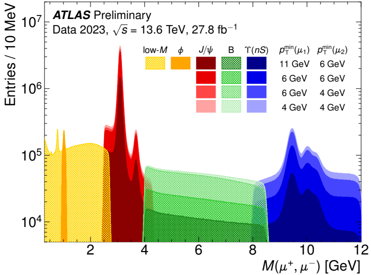


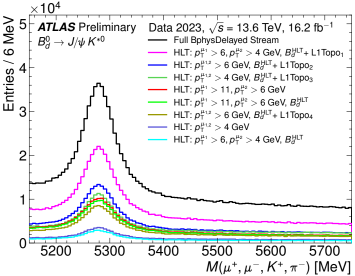
ATLAS B-physics trigger in Run-3

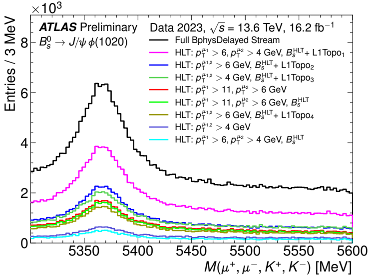




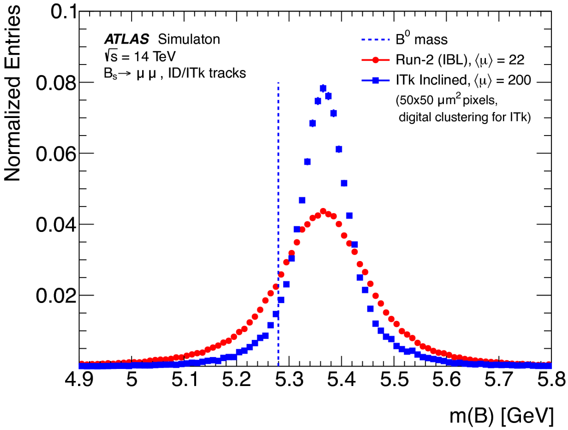








Phase-2 upgrade di-muon mass resolution



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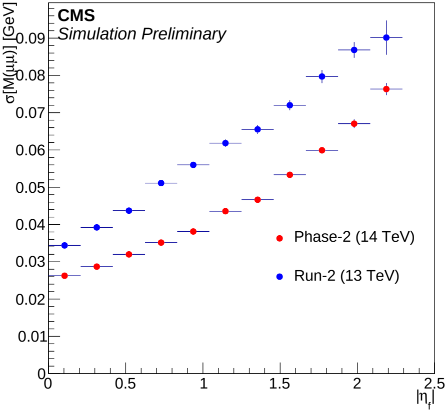

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