Summary of flavor results by ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

La Thuile 2024, La Thuile
March 5, 2024

ATLAS EXPERIMENT
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Outline

This talk will cover the following analyses:

- Search for the lepton flavor violating $\tau \to 3\mu$ decay in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ CMS-BPH-21-005
- Test of lepton flavor universality violation in semileptonic B_c^+ meson decays CMS-PAS-BPH-22-012
- Test of lepton flavor universality in $B^\pm \to K^\pm l^+ l^-$ decays CMS-BPH-22-005
- Measurement of the $B_s^0 \to \mu\mu$ effective lifetime with the ATLAS Detector ATLAS-BPHY-2020-07
- Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ ATLAS-BPHY-2019-08
- Observation of an excess of di-charmonium events in the four-muon final state ATLAS-BPHY-2022-01
- Observation of the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay CMS-BPH-22-002

Lepton flavor violating in $\tau \to 3\mu$ decay (1/3)

CMS-BPH-21-005

- The branching fraction of the $\tau \to 3\mu$ decay in SM is vanishingly small (10^{-55})
- Some extensions of the SM predict branching fractions as high as $10^{-10} - 10^{-8}$
- Most stringent upper limit set by Belle experiment is $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at 90% CL

- CMS experiment performed search for the $\tau \to 3\mu$ decay, using data collected in 2017 and 2018 which corresponds to integrated luminosities $38.0\,\text{fb}^{-1}$ and $59.7\,\text{fb}^{-1}$, respectively
- $\tau \to 3\mu$ can be studied in heavy-flavor hadron events as well as in the events associated with W boson

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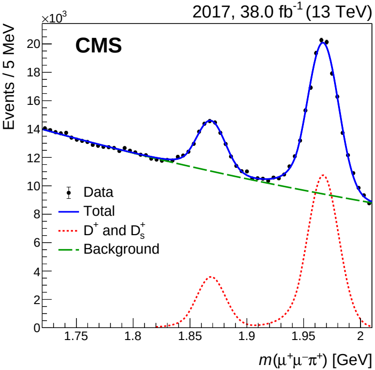
HF channel

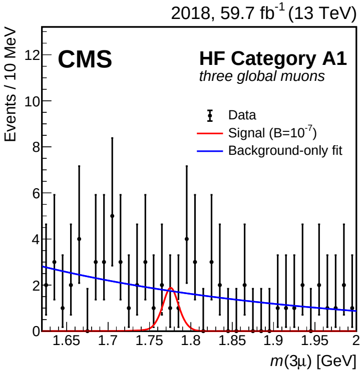
- Events are collected by low-p_T dimuon and trimuon triggers
- The normalization channel $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ is used
- Events categorized based on σ_m/m and labeled as A, B and C



Lepton flavor violating in $\tau \to 3\mu$ decay (2/3)

CMS-BPH-21-005

- The candidate extraction is based on BDT:
  - signal mixture of D and B meson decays MC simulations
  - background data mass-sideband regions
- The lowest score is discarded
- Figure with background only fit (blue) and projected signal at $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$(red)



W channel

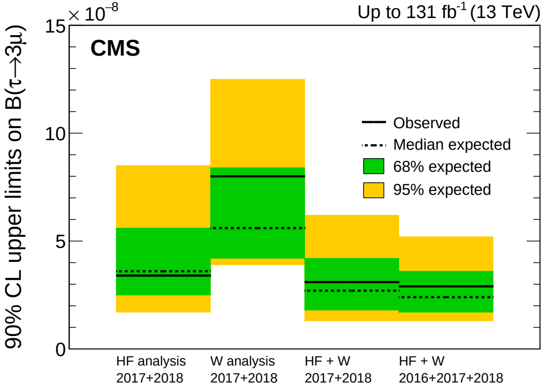
- $W^+ \to \tau^+\nu_\tau \to \mu^+\mu^-\mu^+\nu_\tau$ topology
- Muon p_T are relatively high and the trigger decisions are based on single muon triggers
- The candidate selections were optimized using the BDT trained on simulated events
- Event categorization is done in the same way as in the HF case

Lepton flavor violating in $\tau \to 3\mu$ decay (3/3)

CMS-BPH-21-005

- Upper limits on $\mathcal{B}(\tau \to 3\mu)$ are determined using a frequentist method based on a modified profile likelihood test statistic and the $\mathrm{CL_s}$ criterion

- Results observed (expected) at 90% CL:
  - HF: $\mathcal{B}(\tau \to 3\mu) < 3.4(3.6) \times 10^{-8}$
  - W: $\mathcal{B}(\tau \to 3\mu) < 8.0(5.6) \times 10^{-8}$
  - HF+W: $\mathcal{B}(\tau \to 3\mu) < 3.1(2.7) \times 10^{-8}$
- Combination with result from 2016 data:
  - HF+W : $\mathcal{B}(\tau \to 3\mu) < 2.9(2.4) \times 10^{-8}$
- **The most stringent limit from a hadron collider experiment**



LFU violation in semileptonic B_c^+ meson decays (1/2)

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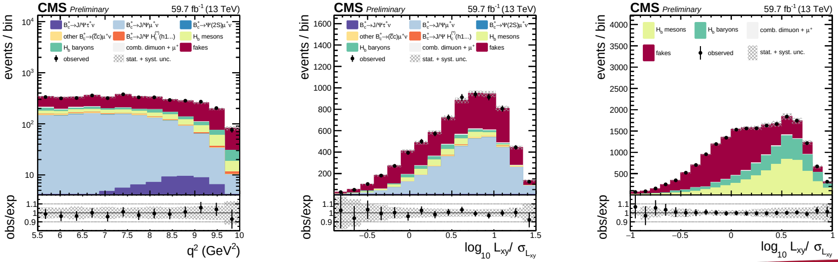
CMS-PAS-BPH-22-012

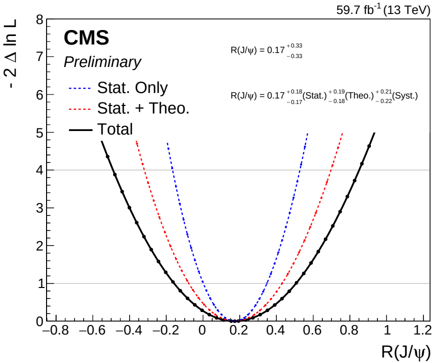
- Lepton flavor universality (LFU) can be violated in several beyond-the-SM (BSM) models
- In recent years, the $b \to c\tau\nu_\tau$ quark transition has been studied by looking at the $R(D^*) = \frac{B^0 \to D^{*-}\tau^+\nu_\tau}{B^0 \to D^{*-}\mu^+\nu_\mu}$
- LFU violation in semileptonic B_c^+ meson decays is studied through the ratio $R(J/\psi) = \frac{B_c^+ \to J/\psi\tau^+\nu_\tau}{B_c^+ \to J/\psi\mu^+\nu_\mu}$
- The measurement uses data from pp collisions collected by the CMS experiment at 13 TeV with integrated luminosity of 59.7 fb^{-1}
- The τ is reconstructed in $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ decays which result in identical visible final states for both channels
- A binned maximum likelihood fit is performed to the q^2 and the $L_{xy}/\sigma_{L_{xy}}$ distributions



LFU violation in semileptonic B_c^+ meson decays (2/2)

CMS-PAS-BPH-22-012

- The measured branching fraction ratio is $R(J/\psi) = 0.17^{+0.18}_{-0.17}(\text{stat.})^{+0.21}_{-0.22}(\text{syst.})^{+0.19}_{-0.18}(\text{theo.})$, where the statistical, experimental systematic and form-factor uncertainties, labeled as theoretical, are reported separately
- This result agrees within 0.3 standard deviations with the value 0.2582(38) predicted by the SM
- Also in agreement within 1.3 standard deviations with the previous measurement performed at LHCb[1]

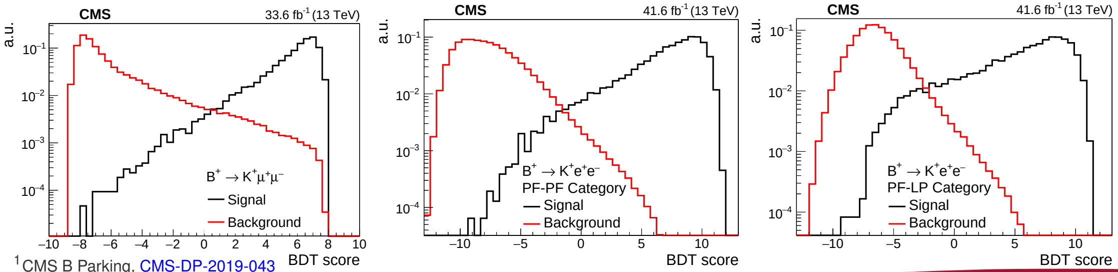


[1] LHCb $R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$, arXiv:1711.05623

LFU in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ decays (1/3)

CMS-BPH-22-005

- Measurements in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ tests LVU in the $\bar{b} \to \bar{s} l^{+} l^{-}$ transition
- The branching ratio $R(K) = \frac{\mathcal{B}(B^{+} \to K^{+} \mu^{+} \mu^{-})}{\mathcal{B}(B^{+} \to K^{+} e^{+} e^{-})}$ is expected to be equal to unity in the SM
- CMS measured this ratio with data collected in 2018 with a new trigger strategy, "B parking"[1], which enables collection of order 10^{10} unbiased b hadron decays
- R(K) is measured as a double ratio normalized to the corresponding $B^{+} \to J/\psi K^{+}$ decay
- For electron reconstruction a combination of the **particle-flow (PF)** and **low-p_{T} (LP)** algorithms are used
- The final selection is based on a BDT, which combines several variables into a classifier built using the XGBOOST package



[1] CMS B Parking, CMS-DP-2019-043

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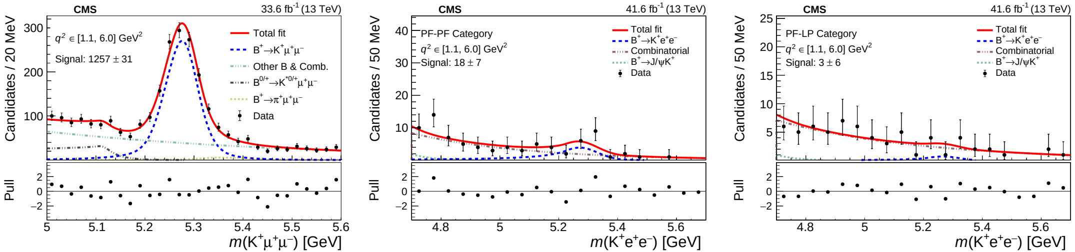
LFU in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ decays (2/3)

CMS-BPH-22-005

- The R (K) ratio is measured in the low-q^2 region from 1.1 to 6.0 GeV^2
- Analysis uses also two control regions (CR):
  - J/ψ CR: $8.41 < q^2 < 10.24$ GeV
  - $\psi(2S)$ CR: $12.6 < q^2 < 14.44$ GeV (which is the secondary normalization channel) and also for additional cross-checks with $R_{\psi(2S)}$ ratio defined as:

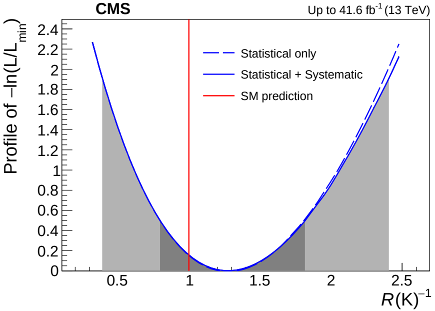
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\mu^+\mu^-)K^+)} \frac{\mathcal{B}(B^+ \to \psi(2S)(e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(e^+e^-)K^+)}$$

- In each channel, the $B^+ \to K^+ l^+ l^-$ signal yield is extracted from an unbinned maximum likelihood fit to the invariant mass spectrum.

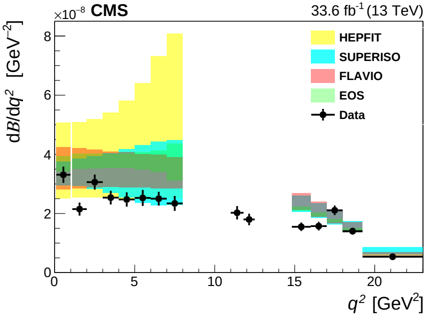


LFU in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ decays (3/3)

CMS-BPH-22-005



- The measured $R(K)$ ratio in the low-q^2 region is: $R(K) = 0.78^{+0.46}_{-0.23}(\text{stat.})^{+0.09}_{-0.05}(\text{syst.}) = 0.78^{+0.47}_{-0.23}$
- A profile likelihood is used to obtain the confidence interval of the parameter of interest, $R(K)^{-1}$



- The differential $B^+ \to K^+\mu^+\mu^-$ branching fraction was compared to the theoretical predictions using HEPFIT, SUPERISO, FLAVIO, and EOS packages
- Integrated $B^+ \to K^+\mu^+\mu^-$ over specified q^2 region is measured to be: $B^+ \to K^+\mu^+\mu^-[1.1, 6.0]\text{GeV} = (12.42 \pm 0.54(\text{stat.}) \pm 0.40(\text{syst.})) \times 10^{-8} = (12.42 \pm 0.68) \times 10^{-8}$
- This result is consistent with world average value

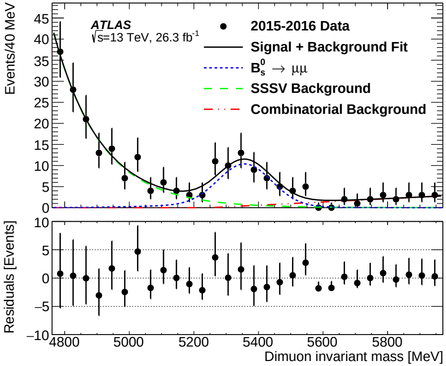
Measurement of the $B_s^0 \to \mu\mu$ Effective Lifetime (1/2)

ATLAS-BPHY-2020-07

- SM predicts only CP-odd heavy-mass eigenstate in $B_s^0 - \bar{B}_s^0$ pair decay
- Some BSM models can potentially perturb the effective lifetime in $B_s^0 \to \mu\mu$ decays
- The effective lifetime in $B_s^0 \to \mu\mu$ is defined as:

$$\tau_{\mu\mu} = \frac{\int_0^\infty t\Gamma(B_s^0(t) \to \mu\mu)dt}{\int_0^\infty \Gamma(B_s^0(t) \to \mu\mu)dt}$$

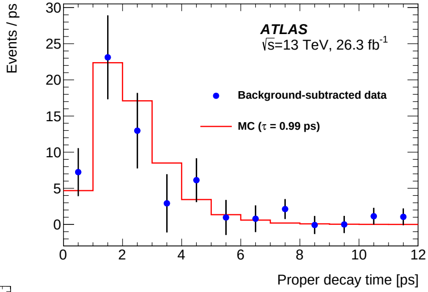
- Experimental average of the $B_s^0 \bar{B}_s^0$ lifetimes and their difference yields prediction $\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)$ ps
- ATLAS used data recorded in 2015 and 2016 at LHC
- The final event selection is simplified from multiple BDT output categories to a single one
- Invariant mass distribution was fitted by the unbinned maximum likelihood fit where the background model includes same-side same-vertex (SSSV) component
- Fit yields $58 \pm 13(\mathrm{stat.})$ $B_s^0 \to \mu\mu$ signal events

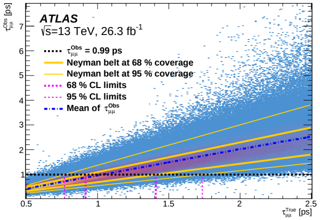


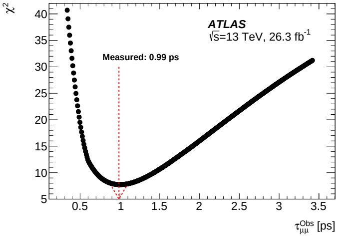
Measurement of the $B_s^0 \to \mu\mu$ Effective Lifetime (2/2)

ATLAS-BPHY-2020-07

- The proper decay time of the signal candidates was extracted by the *sPlot* technique, where the signal and background yields are extracted from the invariant mass fit
- The lifetime is obtained by minimizing the binned χ^2 between data histogram and lifetime dependent pure signal MC template
- The statistical uncertainty is derived from Neyman CL band construction that results in $\tau_{\mu\mu}^{\mathrm{OBS}} = 0.99^{+0.42}_{-0.07}(\mathrm{stat\ only.})$ ps





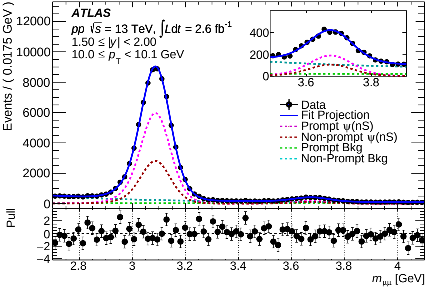


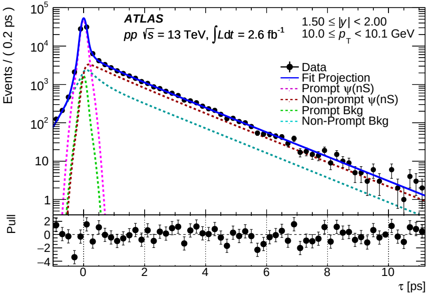
- After accounting for all systematic effects, the effective lifetime was observed to be: $\tau_{\mu\mu}^{\mathrm{OBS}} = 0.99^{+0.42}_{-0.07}(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})$ ps

Production cross-section of J/ψ and $\psi(2S)$ mesons (1/3)

ATLAS-BPHY-2019-08

- Heavy quarkonia provide a unique insight into the nature of quantum chromodynamics (QCD)
- In high-energy hadronic collisions, charmonium states can be produced either from short-lived QCD sources ('prompt' production) or from long-lived sources – decays of beauty hadrons ('non-prompt' production)
- Any measurement can provide valuable input for NRQCD calculations for prompt production and FONLL for non-prompt production
- ATLAS performed a measurement of the differential production cross-sections of prompt and non-prompt J/ψ and $\psi(2S)$ mesons with transverse momenta between 8 and 360 GeV and rapidity in the range $|y| < 2$ using data with integrated luminosity of 140 fb^{-1}

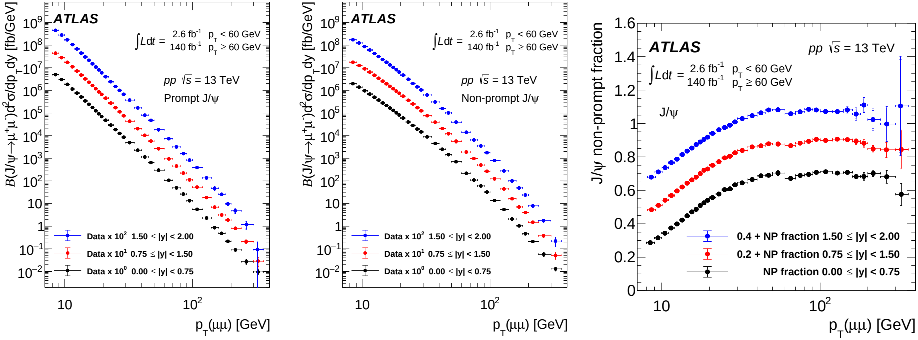




Production cross-section of J/ψ and $\psi(2S)$ mesons (2/3)

ATLAS-BPHY-2019-08

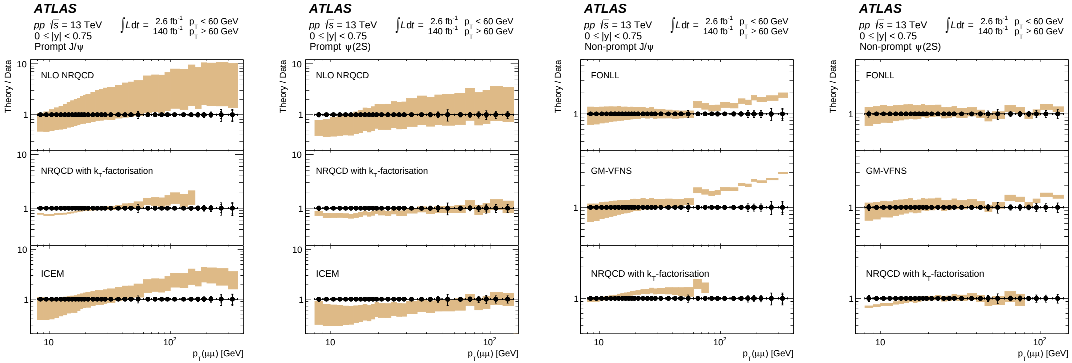
- The measured double-differential cross-sections assuming nominal isotropic spin-alignment scenario are presented
- The other result is non-prompt production fraction of J/ψ and $\psi(2S)$ mesons
- The $\psi(2S)$-to-J/ψ production ratio for the prompt and non-prompt production mechanisms was also measured



Production cross-section of J/ψ and $\psi(2S)$ mesons (3/3)

ATLAS-BPHY-2019-08

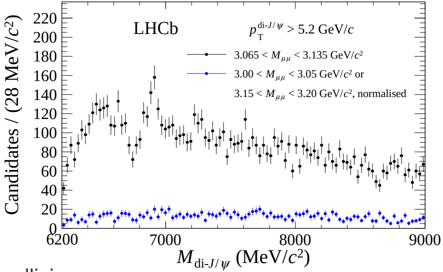
- The results were compared with several calculations
- Although "fair agreement" is generally true, there is definitely room for improvement in the prompt production predictions
- pT spectrum is noticeably harder in all predictions than in data for prompt production



Di-charmonium studies in the 4μ final state(1/2)

ATLAS-BPHY-2022-01

- The exotic hadrons composed of four ($qq\bar{q}\bar{q}$) or five ($qqqq\bar{q}$) quarks are allowed under color confinement in the SM
- First observed candidate was $X(3872)$ in 2003, and many other candidates were studied since then
- In 2020, LHCb observed a narrow structure $X(6900)$ in the di-J/ψ channel
- Since the energy is above the $J/\psi + \psi(2S)$ mass threshold, structure in $J/\psi + \psi(2S)$ is also possible



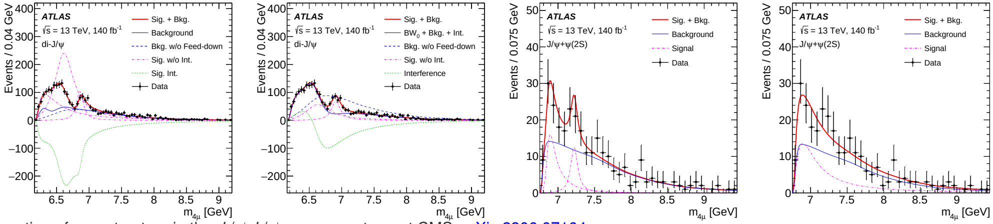
- ATLAS performed a search in the 4μ final state using 140 fb^{-1} of pp collisions
- For the signal, two models are used
  - A uses three interfering S-wave Breit-Wigner resonances
  - B considers two resonances. First interferes with SPS background while second is standalone
- Models A and B are analogous to models I and II of the LHCb study
- $J/\psi + \psi(2S)$ also considers two models α and β, where α is analogous to A with additional standalone resonance and β assumes single resonance
- For model α parameters of the first three resonances are fixed to their values from di-J/ψ fit
- In di-J/ψ channel, feed-down needs to be accounted

Di-charmonium studies in the 4μ final state(2/2)

ATLAS-BPHY-2022-01

- In di-J/ψ channel, the significance of all resonances far exceeds 5σ
- However, the broad structure at the lower mass could result from other physical effects such as feed-down from other resonances
- The mass of the third resonance, m_2 , is consistent with the LHCb mass
- This decay channel was also studied by the CMS experiment[1], where the resonances $X(6600)$ and $X(6900)$ were measured with significance above 5σ and the third peak at $X(7300)$ with 4.1σ
- In $J/\psi + \psi(2S)$, significance of model $\alpha(\beta)$ is $4.7\sigma(4.3\sigma)$
- In the fit with model α, the significance of the second resonance alone is found to be 3.0σ.

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
J/ψ+$\psi(2S)$	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$



[1] Observation of new structure in the $J/\psi J/\psi$ mass spectrum at CMS, arXiv:2306.07164

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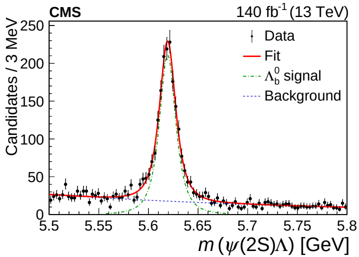
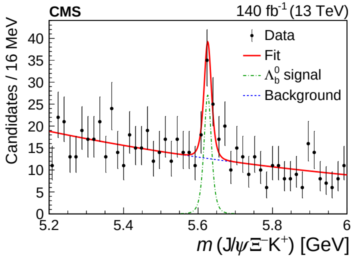
Observation of the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay (1/2)

CMS-BPH-22-002

- Multibody decays of beauty hadrons present a rich laboratory to search for intermediate resonances in the decay products
- LHCb reported various exotic states in $\Lambda_b^0 \to J/\psi p K^-$, $\Xi_b^- \to J/\psi \Lambda K^-$, $B_s^0 \to J/\psi p \bar{p}$ and $B^- \to J/\psi \Lambda \bar{p}$ decays
- CMS performed a search for the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay where $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$
- The normalization channel $\Lambda_b^0 \to \psi(2S)\Lambda$ is used due to similar topology
- The unbinned maximum likelihood fit results in $N(\Lambda_b^0 \to J/\psi \Xi^- K^+) = 46 \pm 11$ and lambda parameters in agreement with world average values
- The signal significance is evaluated using various techniques all resulting in $> 5\sigma$





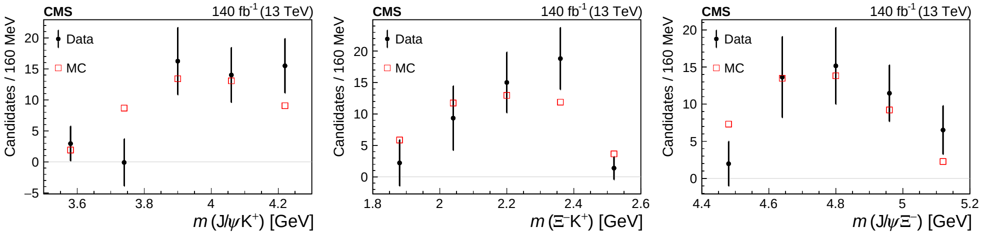
Observation of the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay (2/2)

CMS-BPH-22-002

- The sensitivity to potential pentaquark signals in the intermediate invariant mass distributions is limited by the low signal yield
- The background subtracted two-body invariant mass distributions do not show any narrow peaks and agree with simulation
- The branching fraction of the newly observed $\Lambda_b^0 \to J/\psi \Xi^- K^+$ with respect to $\Lambda_b^0 \to \psi(2S)\Lambda$ is measured to be:

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

where the last uncertainty is related to the uncertainties in the branching fractions



Conclusion

- There is many new results in B Physics at both the ATLAS and CMS experiments
- They are testing various aspects of the SM
- The LFU measurements and tests showing promising results, however, more data needs to be included to increase precision
- The precision measurement of $B_s^0 \to \mu\mu$ effective lifetime probes various BSM scenarios while the measurement of production cross-sections of J/ψ and $\psi(2S)$ is providing valuable inputs for QCD calculations
- There is also very active searches for exotic resonances and pentaquark candidates

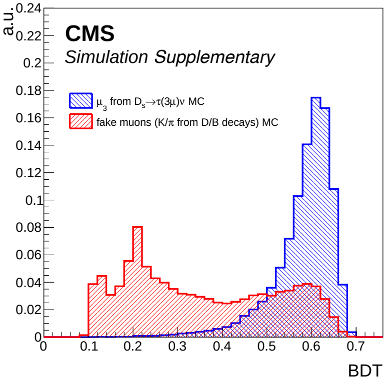
Stay tuned for new results!

Backup slides

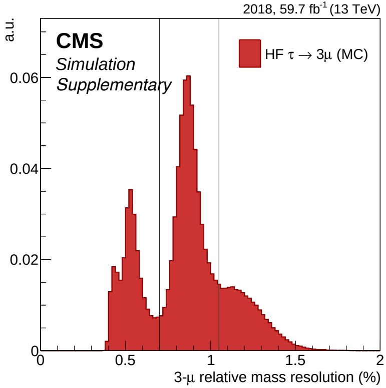
Lepton flavor violating in $\tau \to 3\mu$ decay (4/3)

CMS-BPH-21-005

- Distribution of muon reconstruction quality BDT score for the lowest-p_T muon in signal MC (blue) and for simulated kaons or pions from D and B meson decays misidentified as global muons (red)



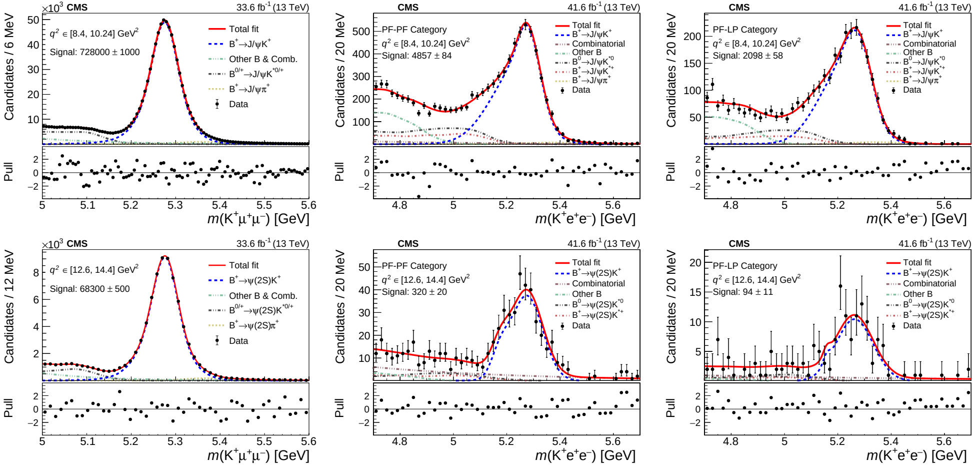
- Mass resolution categories:
  - $\sigma_m/m < 0.7\%$ ....A
  - $0.7 < \sigma_m/m < 1.05\%$ ....B
  - $1.05 < \sigma_m/m\%$ C



LFU in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ decays (4/3)

CMS-BPH-22-005

Invariant mass plots for J/ψ and $/\psi(2S)$ control regions



Production cross-section of J/ψ and $\psi(2S)$ mesons (4/3)

ATLAS-BPHY-2019-08