Status and prospects of rare decay searches at ATLAS and CMS

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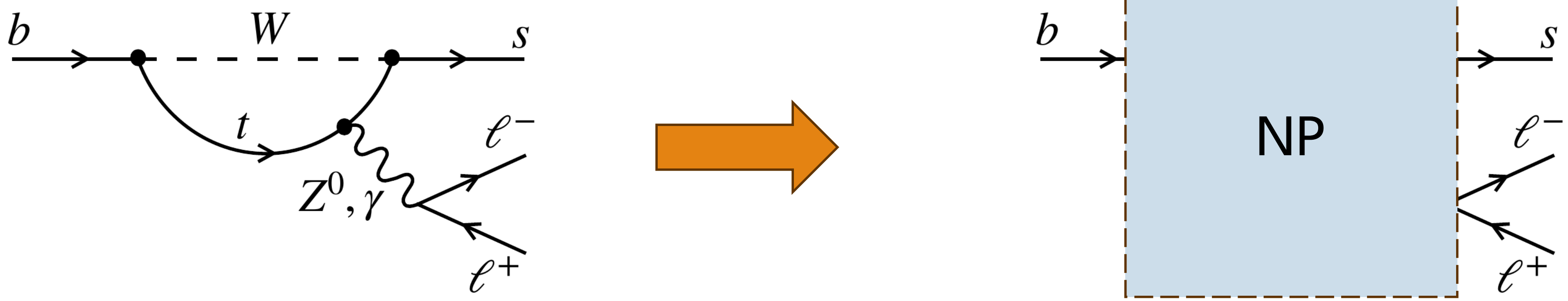
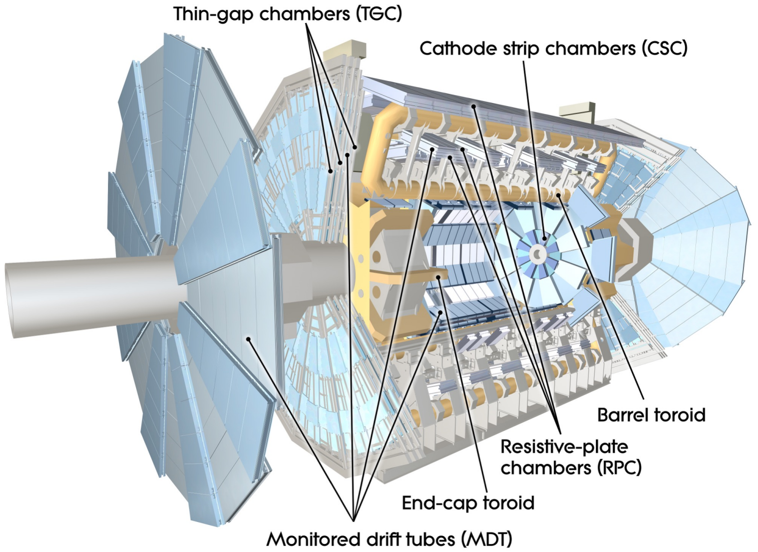
Rare flavour decays

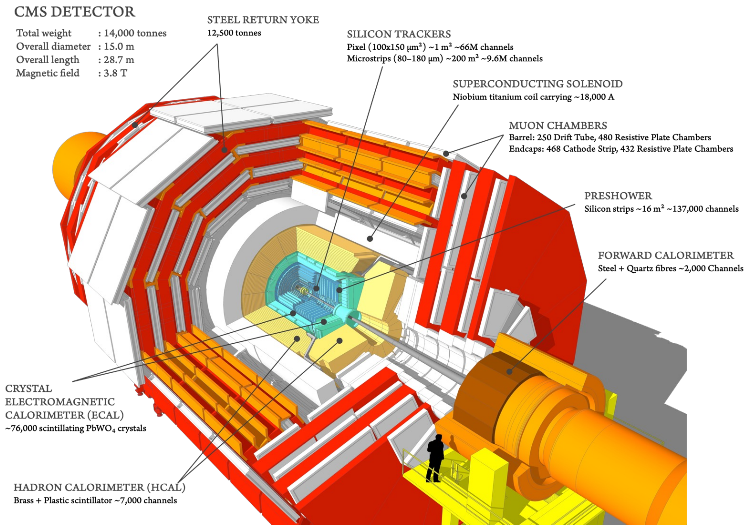
- Suppressed in the SM
  - Process involving FCNC transitions
    - e.g. $b \to s l^+ l^-$
  - Violation of fundamental symmetries (LUV, LFV and LNV)
    - Not discussed in this contribution, see [tomorrow's talk]
  - Other rare decays
    - e.g. radiative multilepton decays of neutral mesons
- Sensitive to New Physics scenarios
  - Deviations in BF or angular distributions



B Physics at ATLAS and CMS

- Differences wrt B-factory (e^+e^-)
  - ▲ Abundant production of B_s^0, B_c^+ and b baryons
  - ▼ More challenging event reconstruction in pp collisions
- Comparison with LHCb
  - ▲ Higher integrated luminosity
  - ▼ Trigger thresholds restrict low-$\mathrm{p_T}$ acceptance
  - ▼ Limited particle identification (PID) (no K/π distinction)
- B Physics searches mainly relies on muon triggers!





Outline

- Process involving FCNC transitions
  - $B^0_{(s)} \to \mu^+\mu^-$ **decay and properties**
    - CMS full Run2 analysis (Phys. Lett. B 842 (2023) 137955) & ATLAS partial Run2 analysis (JHEP 04 (2019) 098 and JHEP 09 (2023) 199)
  - $D^0 \to \mu^+\mu^-$ CMS Run3 (CMS-PAS-BPH-23-008)
  - Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ at CMS (Phys. Lett. B 864 (2025) 139406)
- Other rare decays
  - Observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay (Phys. Rev. D **109**, L111101)
  - First observation of the rare 4μ decay of the η meson (Phys. Rev. Lett. 131 (2023) 091903)
  - Observation of the $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ decay (Eur. Phys. J. C 84 (2024) 1062)
- Prospects for rest of Run3 and HL-LHC

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

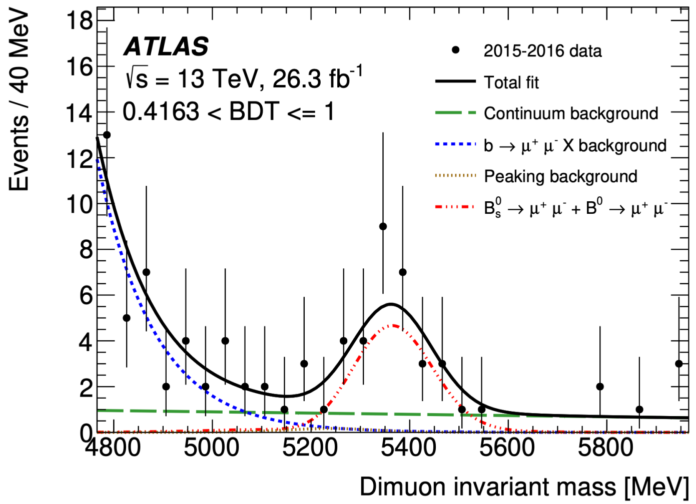
Motivations:

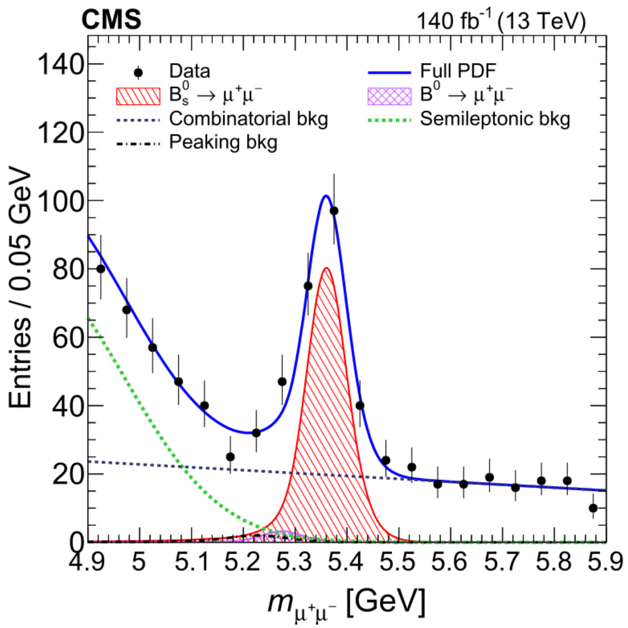
- Highly suppressed in the SM (Penguin and box diagrams, helicity suppressed)
- Clean final state, precise theoretical predictions
- Small deviations already observed $b \to sll$ processes (see $B^0 \to K^*\mu^+\mu^-$)

Analysis strategy:

- pp collisions at 13 TeV
  - Partial Run 2 dataset for ATLAS (2015-2016)
  - Full Run 2 for CMS
- Similar strategy for both experiments
- Main background suppression via MVA techniques
  - Trained with data sidebands for CMS and $bb \to \mu\mu X$ MC for ATLAS
- BF measured as a function of $B^+ \to J/\psi K^+$

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





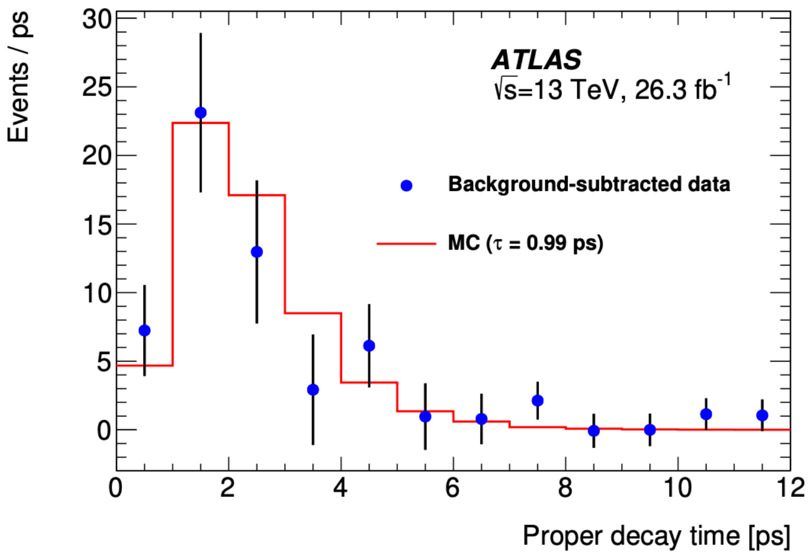
$B_s^0 \to \mu^+\mu^-$: effective lifetime

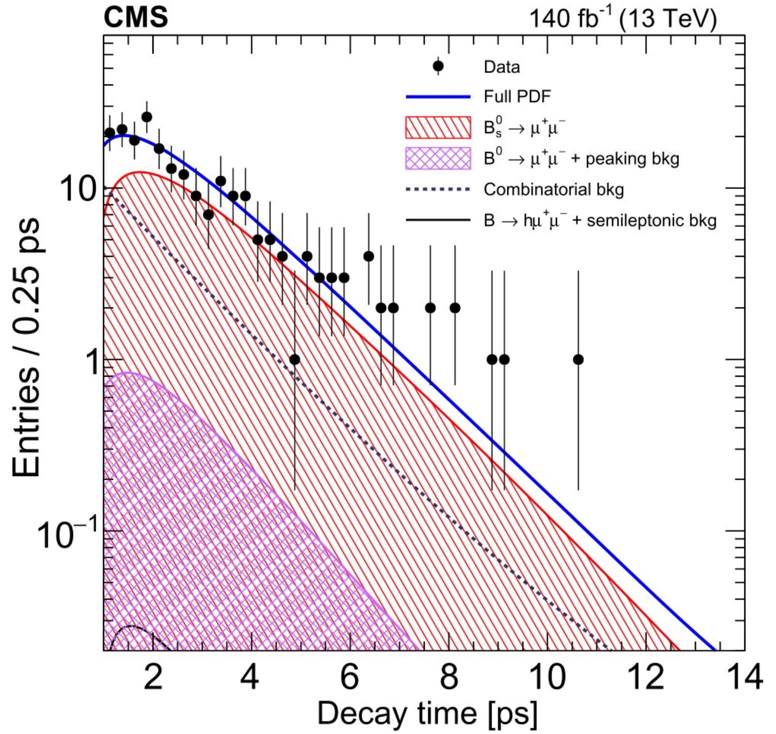
Motivations:

- In the SM only the heavy mass eigenstate of B_s^0 (${B_s^0}_{\mathrm{H}}$) can decay in 2 muons
  - In new physics scenarios, like minimal supersymmetric SM extensions, also ${B_s^0}_{\mathrm{L}}$ can contribute
  - $\tau_{{B_s^0}_{\mathrm{H}}} - \tau_{{B_s^0}_{\mathrm{L}}} = 1.624 - 1.431 = 0.193\,ps$ → A ${B_s^0}_{\mathrm{L}}$ should be observable
  - Complementary observable to BF (related to different set of effective operators)

Analysis strategy:

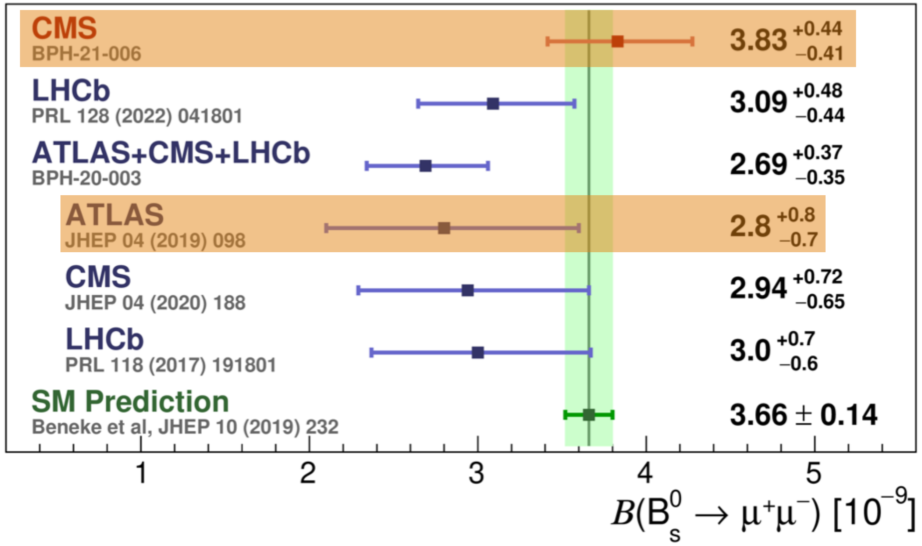
- Same datasets and similar selections as previous slide
- Lifetime estimation:
  - CMS: unbinned 3D ML fit to mass, lifetime and lifetime error
  - ATLAS: fit bkg-subtracted lifetime distribution with MC template

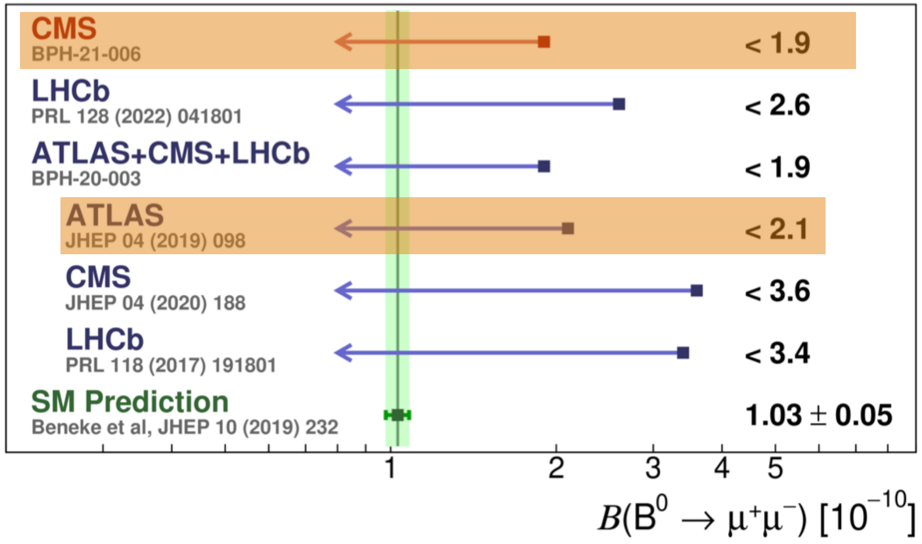




$B_s^0 \to \mu^+\mu^-$: Results

- $B_s^0 \to \mu^+\mu^-$ BF:
  - Similar precision for CMS and LHCb using full Run2 searches
  - ATLAS full Run2 still underway
  - Full LHC combination once ATLAS will be published
- $B^0 \to \mu^+\mu^-$ BF:
  - No sensitivity yet, only ULs
  - CMS has current best ULs (excluding combination)
  - Improvement expected with Run3 data
- $B_s^0 \to \mu^+\mu^-$ effective lifetime:
  - ATLAS: $\tau_{\mu\mu}^{obs} = 0.99^{+0.42}_{-0.07}\,(stat.) \pm 0.17\,(syst.)\,ps$
  - CMS: $\tau = 1.83^{+0.23}_{-0.20}(stat) \pm 0.04\,(syst)\,ps$
  - Compatible with SM expected $\tau_{B^0_{s\,H}} = 1.624 \pm 0.009$ ps





Search for $D^0 \to \mu^+\mu^-$

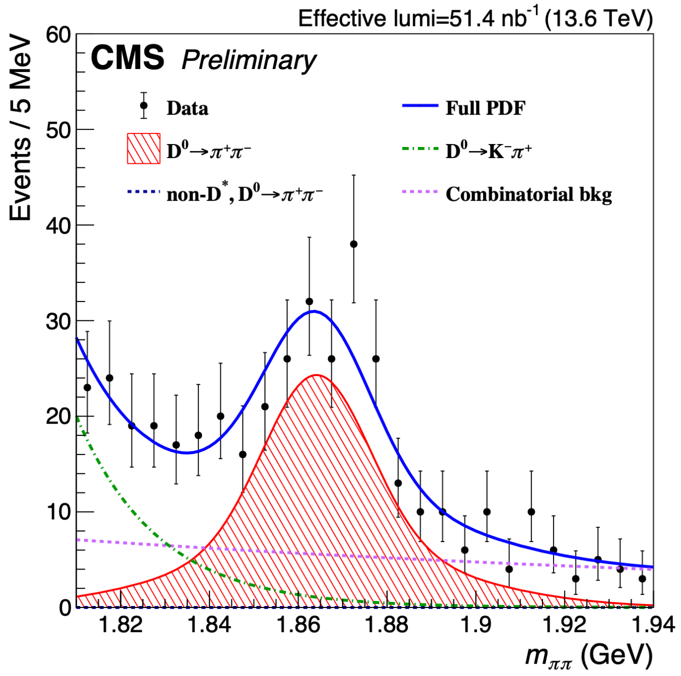
Motivations:

- Rare charmed hadrons decays involves $c \to u$ transitions
- More challenging theoretical computations due to long-distance contributions
  - Expected BF for $\boldsymbol{D^0 \to \mu^+\mu^-}$ = $\mathcal{O}(3\times10^{-13})$
  - Various physics models R-parity violating supersymmetry, and extra fermions or gauge bosons, predict enhancements in this decay rate

Analysis strategy:

- pp collisions at 13.6 TeV (64.5 /fb) (CMS 2022-2023 Run3 dataset) collected via new inclusive dimuon trigger
- Looking for D^0 produced from $D^{*+} \to D^0\pi^+$ to reduce combinatorial background
- Normalization relies on $\boldsymbol{D^0} \to \pi^+\pi^-$channel
  - Collected via zero bias trigger

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



Search for $D^0 \rightarrow \mu^+\mu^-$

Analysis strategy:

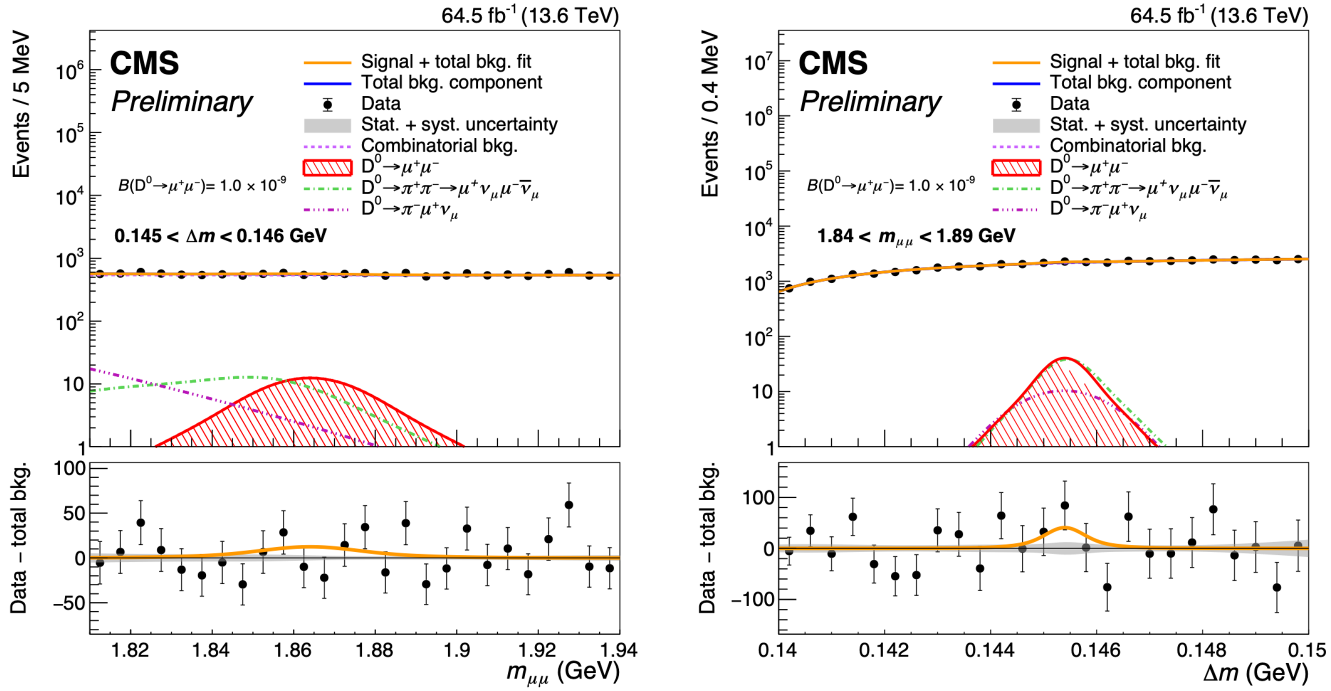
- Variables of interest $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
- Background rejected via pre-selections and a custom MVA discriminator trained with right side bands of the Δm distribution as background proxy and simulations for signal

Results:

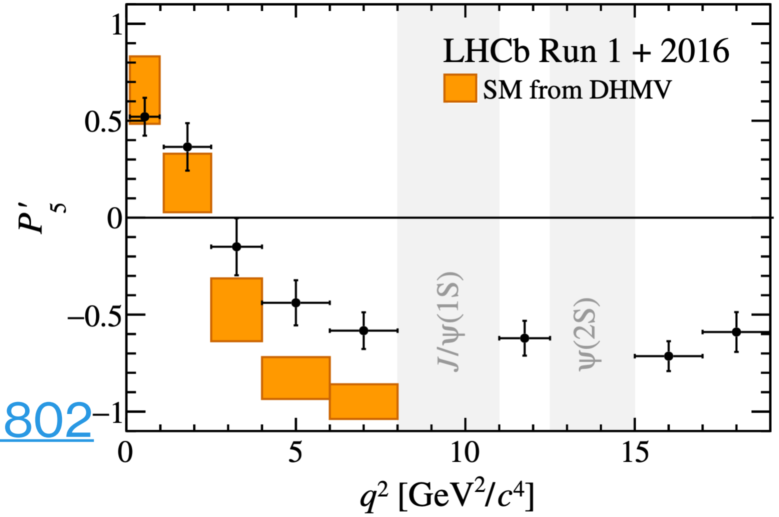
- No significant excess is observed
- Limits on the BF are extracted via 2D unbinned maximum likelihood fit of $m(D^0)$ and Δm

$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 2.6\times10^{-9}$ @ 95% C.L.

Best limit up to date thanks to the use of the new Run 3 di-muon trigger



Angular analysis of the $B^0 \to K^*(892)^0\mu^+\mu^-$ decay



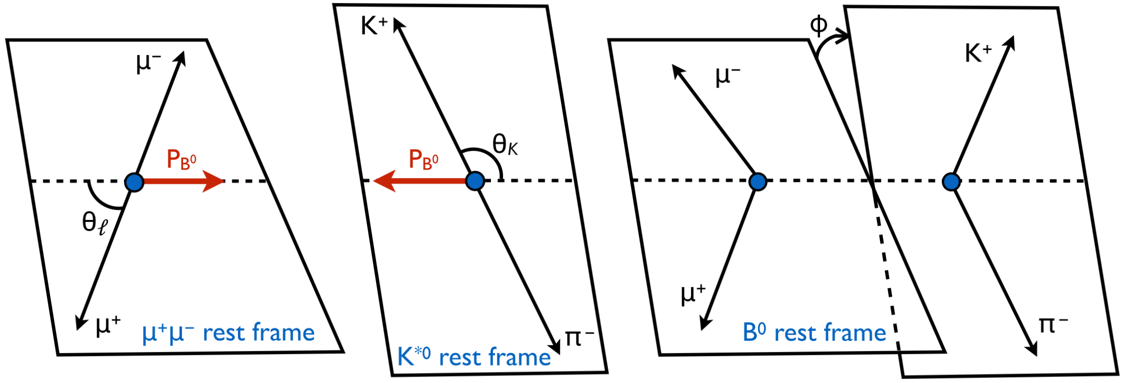
Motivations:

- Compared to simpler modes, such as $B_s^0 \to \mu^+\mu^-$, provides access to a **larger set of observables**
  - High sensitivity to deviations from SM expectations
- Tensions with the SM have arisen from recent results (e.g. LHCb)

Phys. Rev. Lett. **125**, 011802

Analysis strategy:

- pp collisions at 13 TeV (140 /fb) (Full CMS Run2 dataset) collected via dimuon + track triggers
- Decay rate expressed in terms of angular variables, invariant mass and a set of observables ($P_i^{(\prime)}$) related to the Wilson coefficients [as in JEP 01 (2013) 048]



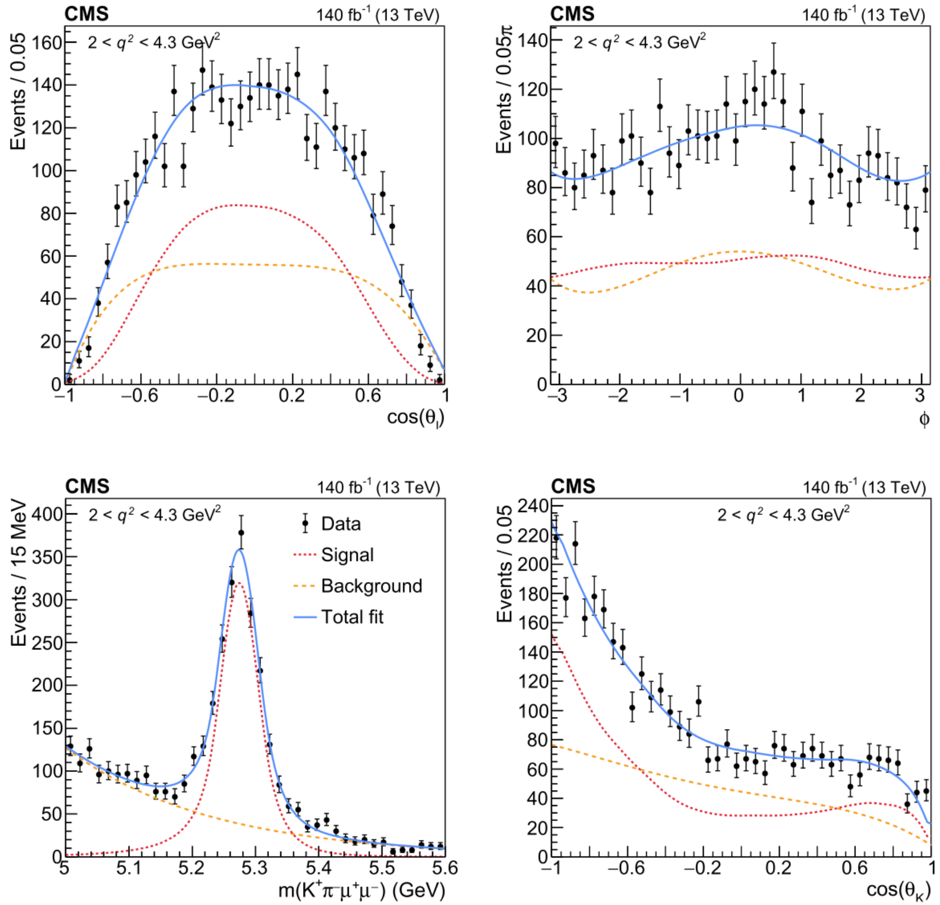
angular variables

Angular analysis of the $B^0 \to K^*(892)^0\mu^+\mu^-$ decay

Results:

- Simultaneously fit the mass and angular variables distributions for different in 6 different q^2 bins

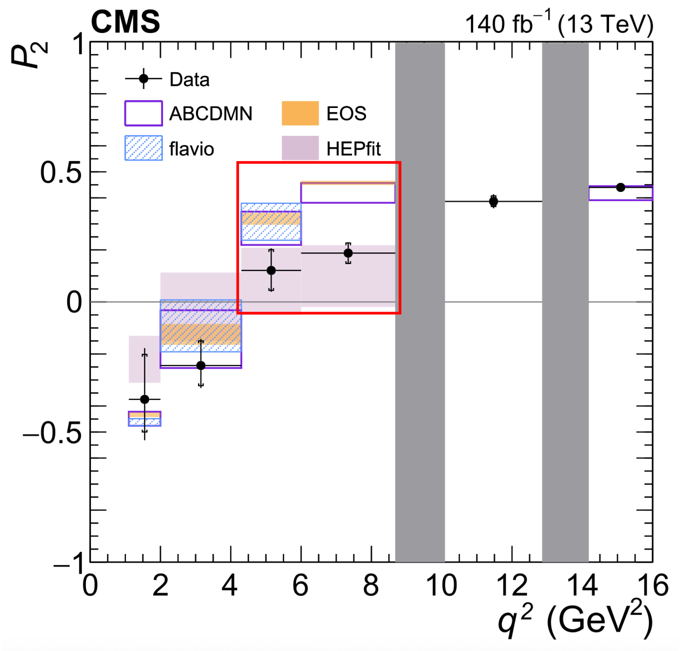
	$1.1 < q^2 < 2\,\text{GeV}^2$	$2 < q^2 < 4.3\,\text{GeV}^2$	$4.3 < q^2 < 6\,\text{GeV}^2$
F_L	$0.709\ ^{+0.073}_{-0.054} \pm 0.021$	$0.810\ ^{+0.036}_{-0.030} \pm 0.016$	$0.714\ ^{+0.032}_{-0.030} \pm 0.012$
P_1	$0.09\ ^{+0.23}_{-0.20} \pm 0.04$	$-0.29\ ^{+0.19}_{-0.21} \pm 0.05$	$-0.30\ ^{+0.15}_{-0.17} \pm 0.04$
P_2	$-0.37\ ^{+0.17}_{-0.13} \pm 0.10$	$-0.244\ ^{+0.094}_{-0.077} \pm 0.039$	$0.121\ ^{+0.080}_{-0.076} \pm 0.030$
P_3	$-0.05\ ^{+0.21}_{-0.22} \pm 0.04$	$-0.19\ ^{+0.20}_{-0.22} \pm 0.09$	$-0.03 \pm 0.14 \pm 0.08$
P'_4	$-0.44\ ^{+0.29}_{-0.32} \pm 0.11$	$-0.43\ ^{+0.16}_{-0.19} \pm 0.08$	$-0.72\ ^{+0.15}_{-0.16} \pm 0.07$
P'_5	$0.36\ ^{+0.17}_{-0.13} \pm 0.03$	$-0.14\ ^{+0.10}_{-0.09} \pm 0.04$	$-0.44 \pm 0.10 \pm 0.03$
P'_6	$0.000\ ^{+0.094}_{-0.097} \pm 0.021$	$0.108\ ^{+0.075}_{-0.071} \pm 0.018$	$0.129\ ^{+0.074}_{-0.071} \pm 0.011$
P'_8	$0.16 \pm 0.37 \pm 0.11$	$0.73\ ^{+0.18}_{-0.19} \pm 0.06$	$-0.01 \pm 0.22 \pm 0.04$

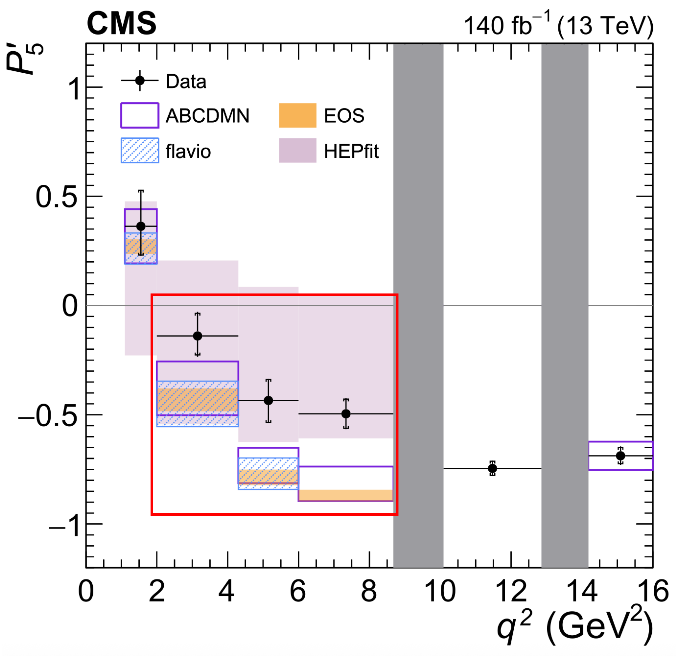


Angular analysis of the $B^0 \to K^*(892)^0\mu^+\mu^-$ decay

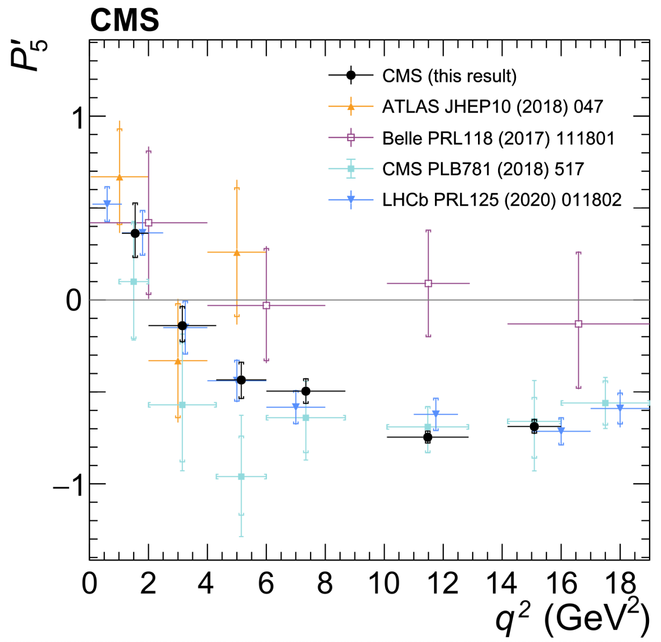
Results:

- Simultaneously fit the mass and angular variables distributions for different in 6 different q^2 bins
- Main discrepancies observed in P_2 and P_5'
- Result still limited statistically

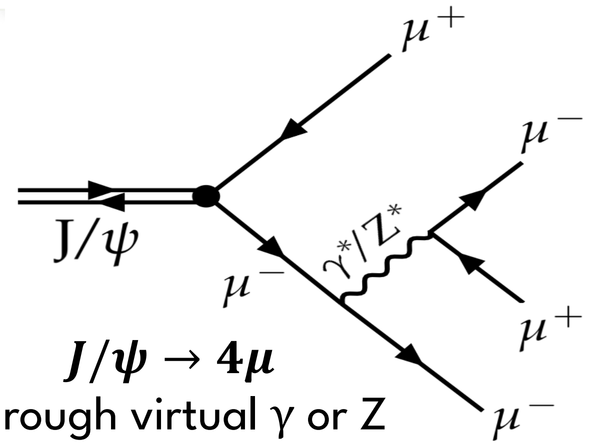




- Discrepancies in P_5' consistent with previous results:



Observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay



$\boldsymbol{J/\psi \to 4\mu}$
Through virtual γ or Z

Motivations:

- Predicted by the Standard Model (SM) with decay fraction (BR): $\mathcal{B}(J/Psi \longrightarrow 4\mu) = (9.74 \ \pm 0.05)\times 10^{-7}$ [PhysRevD.104.094023]
- Sensitive to the presence of new physics [s10052-020-08816-9]

Analysis strategy:

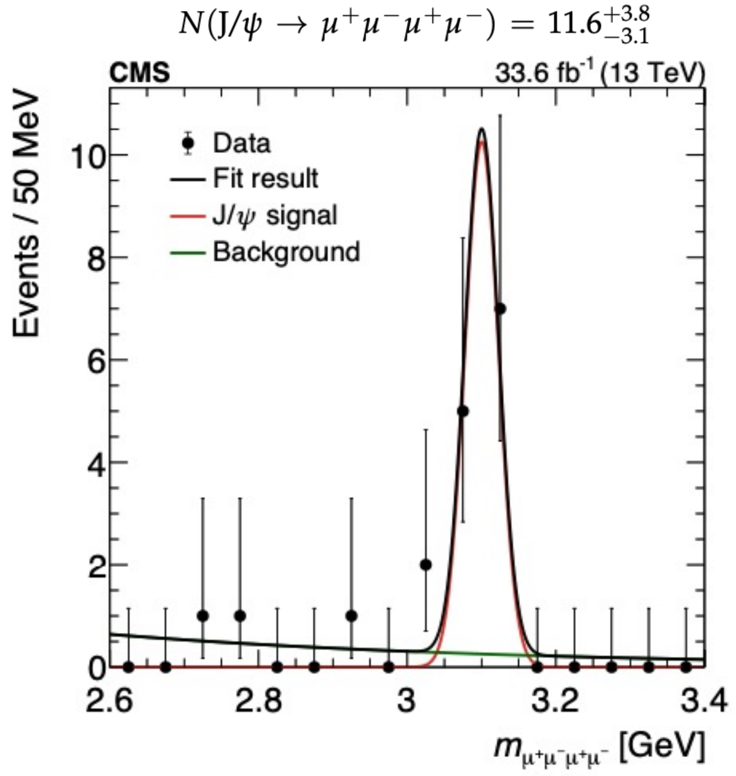
- pp collisions at 13 TeV (33.6 /fb) (2018 B Parking: high rate (~3 kHz), delayed processing)
- Offline selections based on common vertex, vertex probability and on the kinematics of the J/ψ
- The BR of $J/\psi \to 4\mu$ is determined in terms of that of $J/\psi \to 2\mu$:

$$\frac{\mathcal{B}_{J/\psi\to4\mu}}{\mathcal{B}_{J/\psi\to2\mu}} = \frac{N_{J/\psi\to4\mu}}{N_{J/\psi\to2\mu}} \Big/ \frac{\varepsilon_{J/\psi\to4\mu}}{\varepsilon_{J/\psi\to2\mu}}$$

$\mathcal{B}(J/\psi \longrightarrow 2\mu) = (5.961 \pm 0.033)\times 10^{-2}$ [PDG]

Obtained from MC

Observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay



Results:

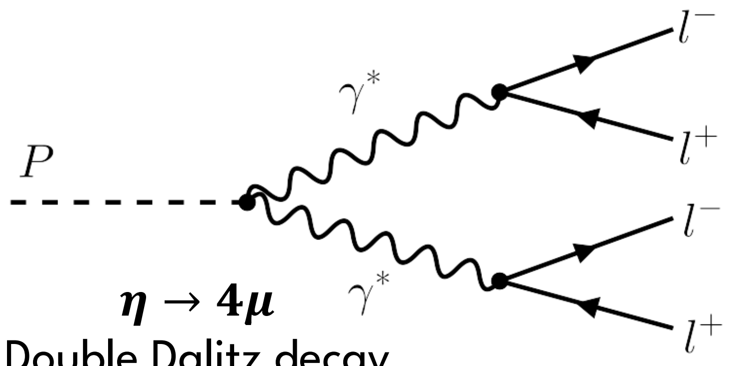
- A peak in the spectrum of the invariant mass of the 4 muons is observed
  - Statistical significance > 7σ

$$\frac{\mathcal{B}_{J/\psi\to4\mu}}{\mathcal{B}_{J/\psi\to2\mu}} = (16.9^{+5.5}_{-4.6}(\text{stat}) \pm 0.6(\text{syst}))\times10^{-6}$$

$$\mathcal{B}(J/\psi \to 4\mu) = (10.1^{+3.3}_{-2.7}(\text{stat}) \pm 0.4(\text{syst}))\times10^{-7}$$

- Compatible with the expected value of the SM:
  - $\mathcal{B}(J/\psi \longrightarrow 4\mu) = (9.74 \pm 0.05)\times10^{-7}$

Observation of the rare 4μ decay of the η meson



$\eta \to 4\mu$

Double Dalitz decay

Motivations:

- Double-Dalitz decay used as test of the SM
  - Sensitive to new physics [Rep. Prog. Phys. 86 016201]
  - Contribute to light-by-light hadronic component of the muon anomalous magnetic moment

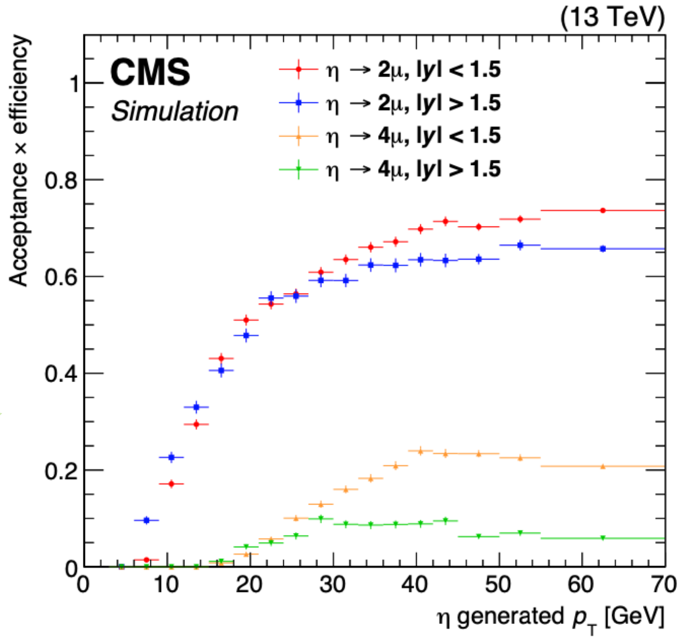
Analysis strategy:

- pp collisions at 13 TeV (~101/fb) (Run2 high rate «**Scouting stream**», save only a part of the info per event)
- The BR of $\eta \to 4\mu$ is determined in terms of that of $\eta \to 2\mu$:

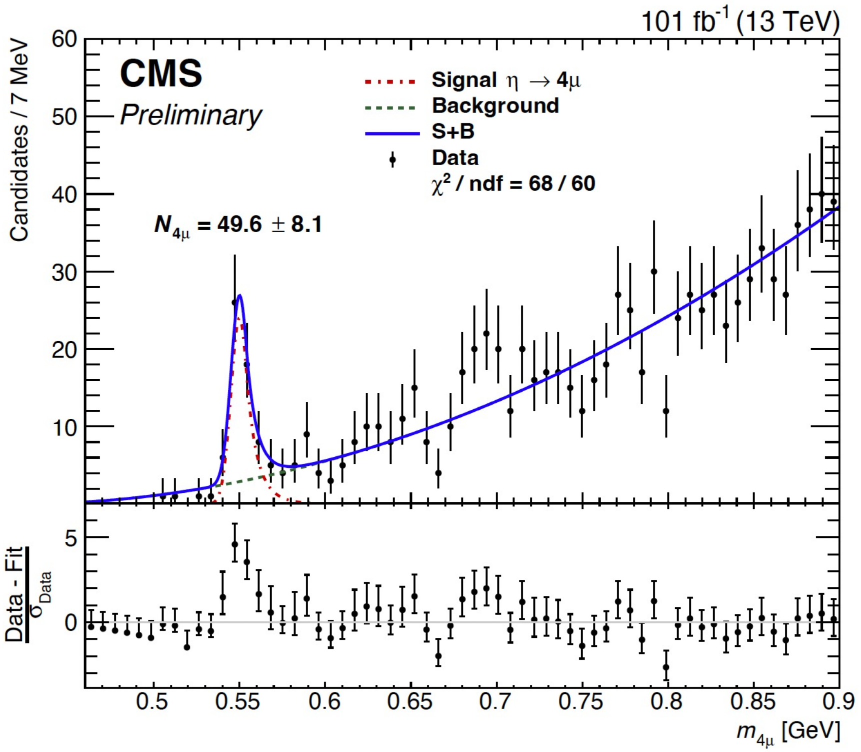
$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}},$$

$\mathcal{B}(\eta \longrightarrow 2\mu) = (5.8 \pm 0.8)\times 10^{-6}$ [PDG]

Acceptance and efficiency for η⟶4μ and η⟶2μ measured in simulations for p_T and pseudorapidity bins



Observation of the rare 4μ decay of the η meson



Results:

- A peak in the spectrum of the invariant mass of the 4 muons is observed
  - Statistical significance > 5σ

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.9 \pm 0.1(\text{stat}) \pm 0.1(\text{syst}))\times 10^{-3}$$

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

- Compatible with the expected value of the SM:
  $\mathcal{B}(\eta \longrightarrow 4\mu) = (3.98 \pm 0.15)\times 10^{-9}$

[Chinese Phys. C 42 (2018) 023109]

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

Motivations:

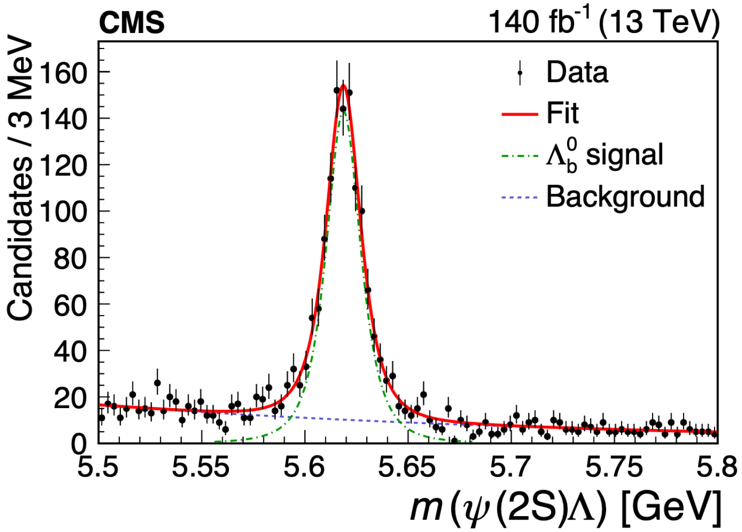
- Recent discovery of pentaquark-like structures in $J/\psi p$ and $J/\psi\Lambda^0$
- Study of heavier baryons in the decay products, like Ξ^- could unveil the existence of doubly or triply strange pentaquarks

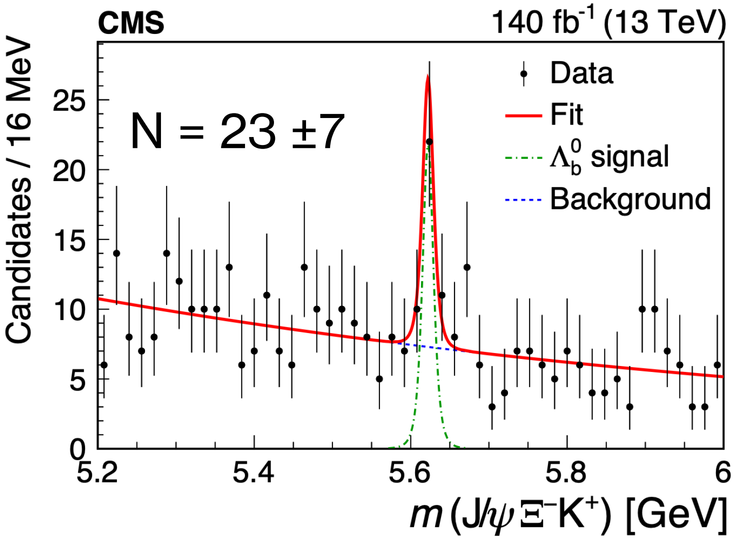
Analysis strategy:

- pp collisions at 13 TeV (140 /fb) (Full CMS Run2 dataset)
- Challenging reconstruction due to 3-vertex cascade decay
- Similar to previous analysis, measure $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ BF relative to $\Lambda_b^0 \to \psi(2s)\Lambda$ via:

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi\Xi^-K^+}} \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}$$

$$[3.38 \pm 1.02\,(\text{stat}) \pm 0.61\,(\text{syst}) \pm 0.03\,(\mathcal{B})]\%$$





Summary and perspectives

Great progress in reconstructing di-muon signatures at CMS and ATLAS

- Performance now almost comparable to dedicated experiments such as **LHCb**
- Most of the current results are based on **Run 2 datasets**
- **Run 3** dedicated trigger strategies are already expanding the physics reach
  - CMS: the new **Run 3 di-muon trigger** shows impressive performance in rare decays (like $D^0 \rightarrow \mu\mu$)

Prospects for the future

- Searches for $\eta \rightarrow \mu\mu ee$ and $B^0_{(s)} \rightarrow 4\mu$ are expected to be **published next year** by CMS
- **Full Run 3 analyses** of the rare decay channels discussed here ($B/D \rightarrow \mu^+\mu^-$) will be performed by both CMS and ATLAS, further improving **limits and precision**
- The **Phase-2 tracker upgrades** will improve **mass resolution by a factor ~1.5** in both experiments, boosting sensitivity to rare processes

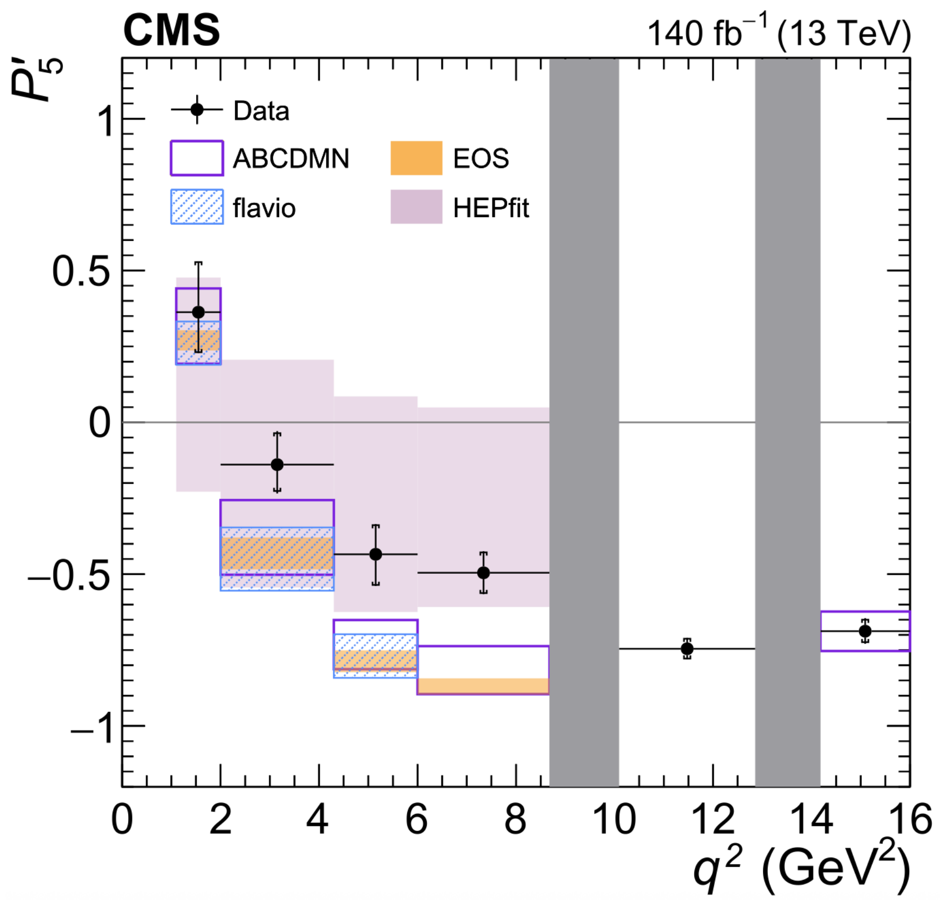
Thanks for your attention!

Backup

Angular analysis of the $B^0 \to K^*(892)^0\mu^+\mu^-$ decay

[*Eur. Phys. J. C* **80**, 456 (2020)](#)

- The predictions calculated with the **HEPfit software** package adopt a conservative estimation of non-local hadronic matrix elements and their uncertainties, to account for a possible large impact from charm-loop penguin diagrams.
- The HEPfit predictions, given the large uncertainties, are compatible with the measurements.



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