# Rare Heavy Flavor Decays from ATLAS/CMS


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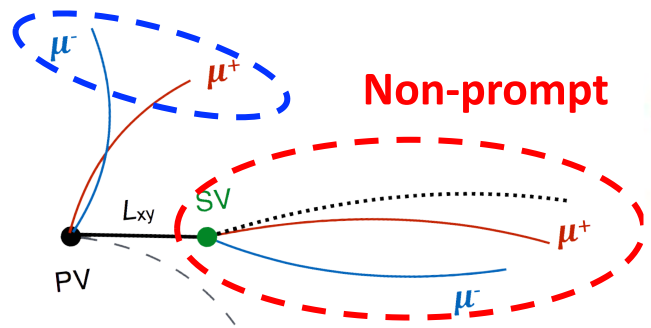
# ATLAS and CMS for HF studies

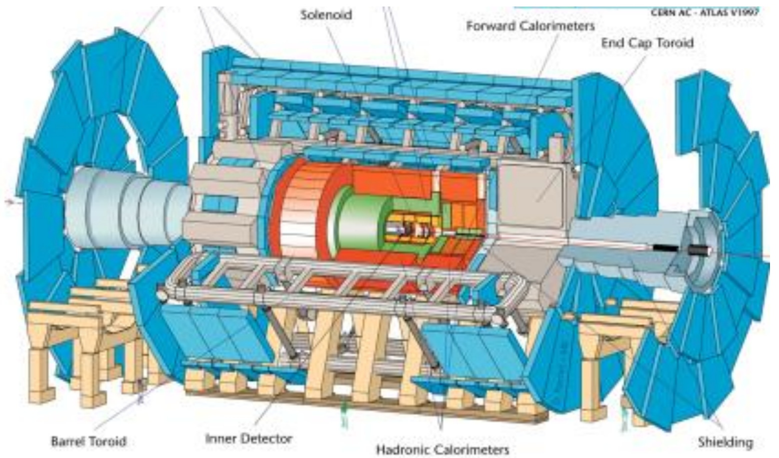
- Large silicon tracker
- Strong magnetic field
- Broad acceptance
- Superb muon systems

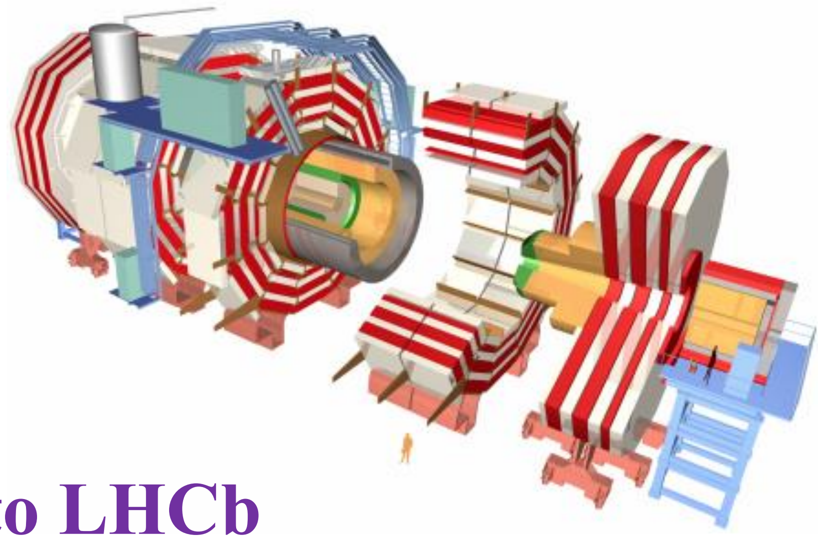
(CMS parameters, ATLAS similar)

- Three different devices, coverage up to $|\eta|<2.4$
- Dimuon mass resolution ~0.6-1.5% (depending on $|y|$).
- Fake rate ≤0.1% for pi,K; ≤0.05% for proton, with very tight ID

- Flexible triggers, novel & dedicated data-taking schemes

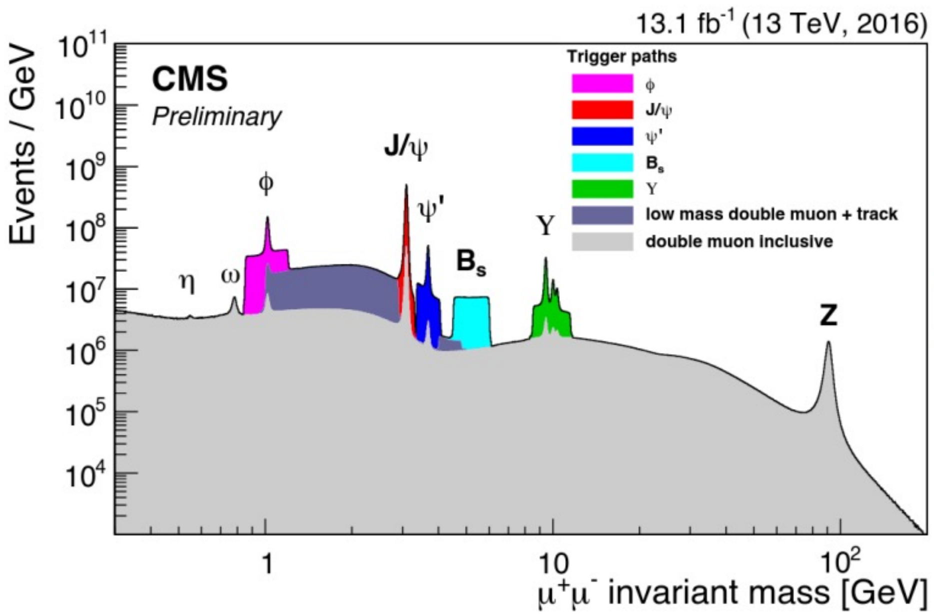


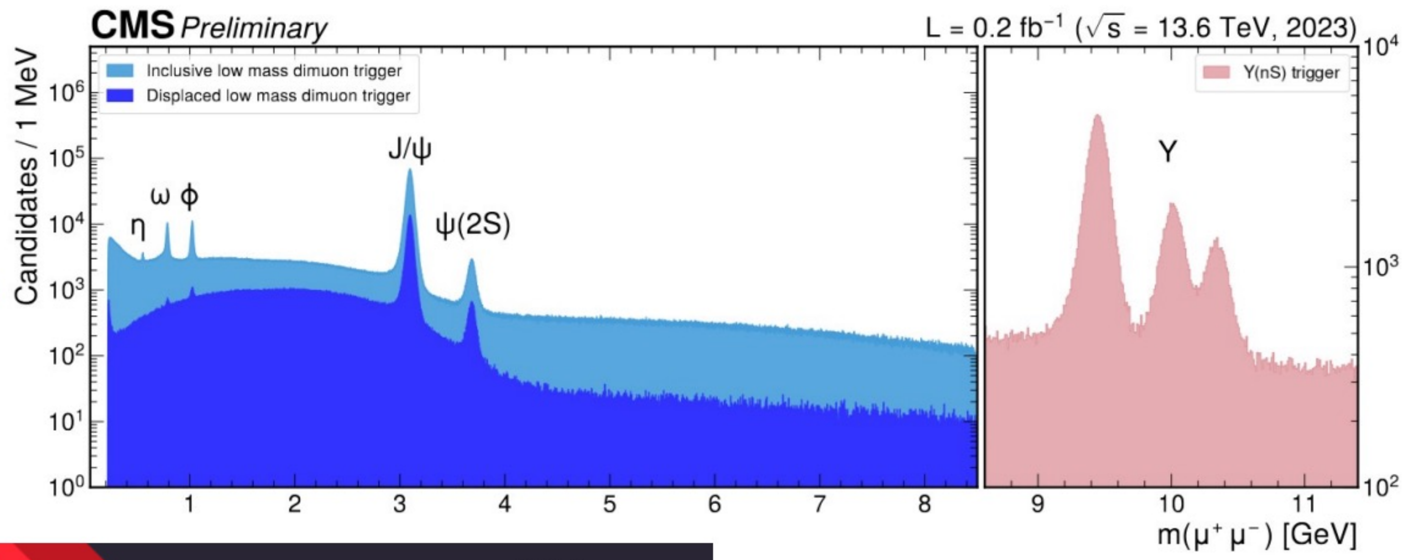



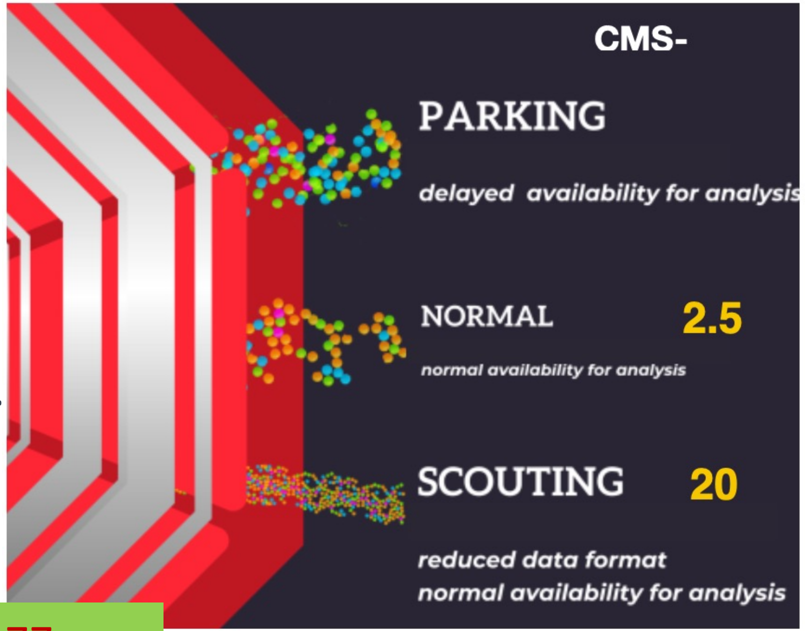



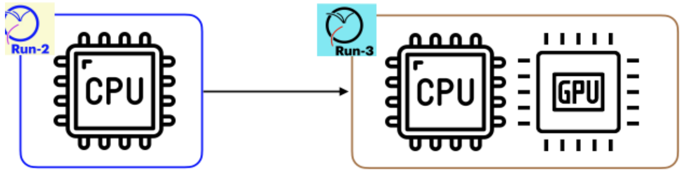
**Complementary to LHCb**

# Evolution of BPH triggers and data-taking schemes



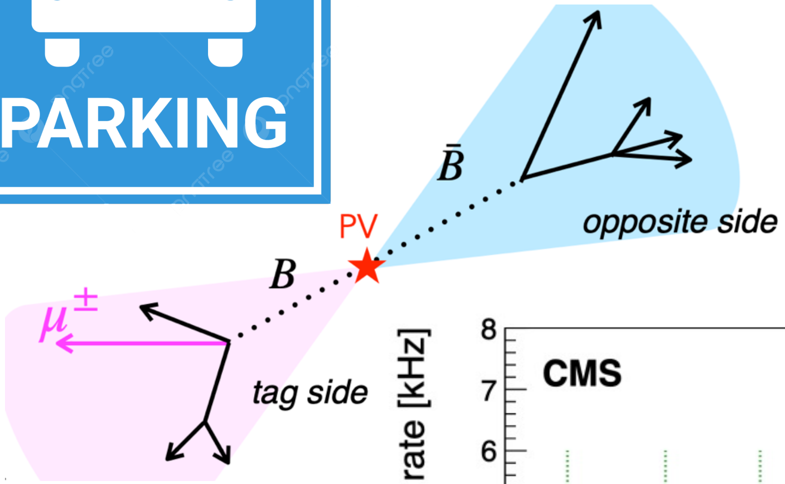



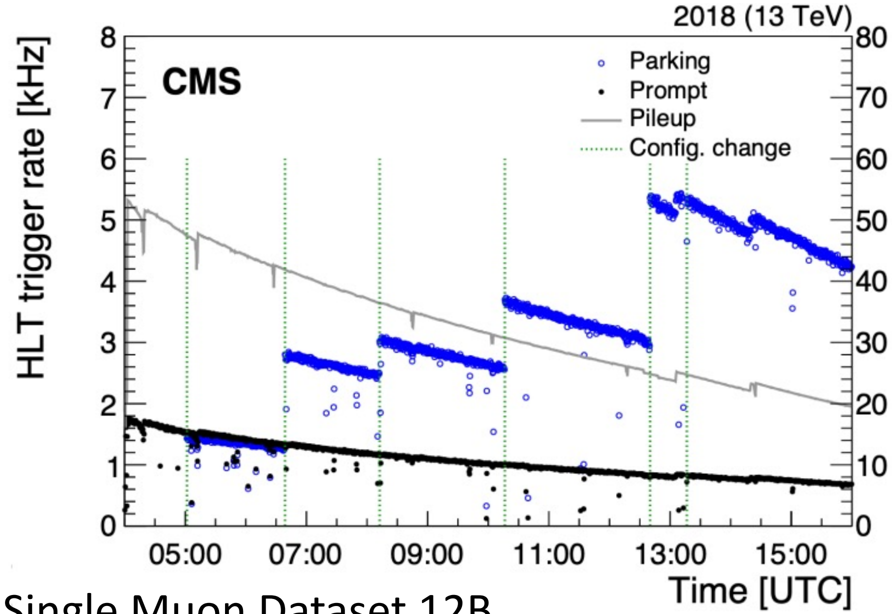

NexTGen
Next Generation Triggers

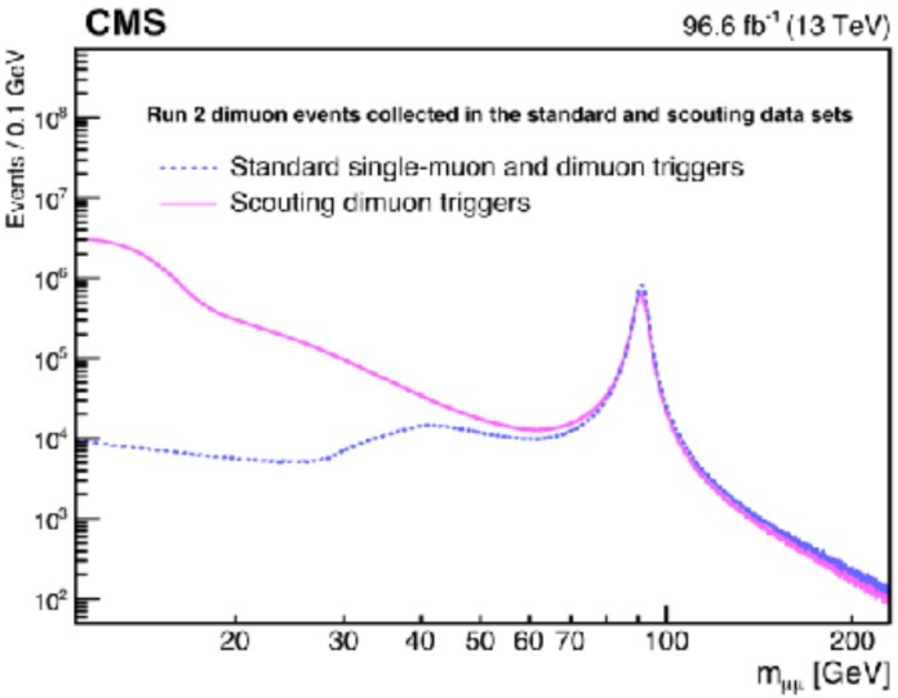
- Many heavy-flavor analyses on dimuon triggers
- a set of triggers dedicated to specific dimuon mass regions or topologies=> inclusive dimuon trigger with loose requirements on the momenta

Physics Reports 1115 (2025) 678–77


# Data Parking and scouting




Run2018 Displaced Single Muon Dataset 12B events useful events were collected

Greatly increase the event rate for analysis

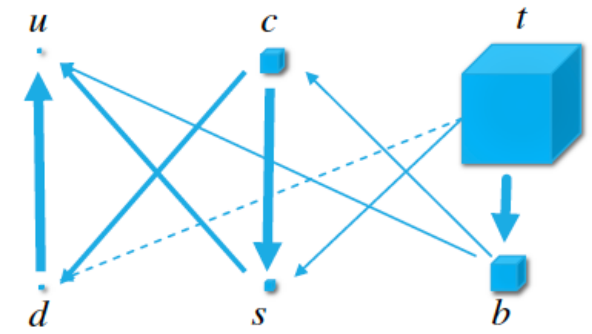
opening up otherwise inaccessible low-mass phase space

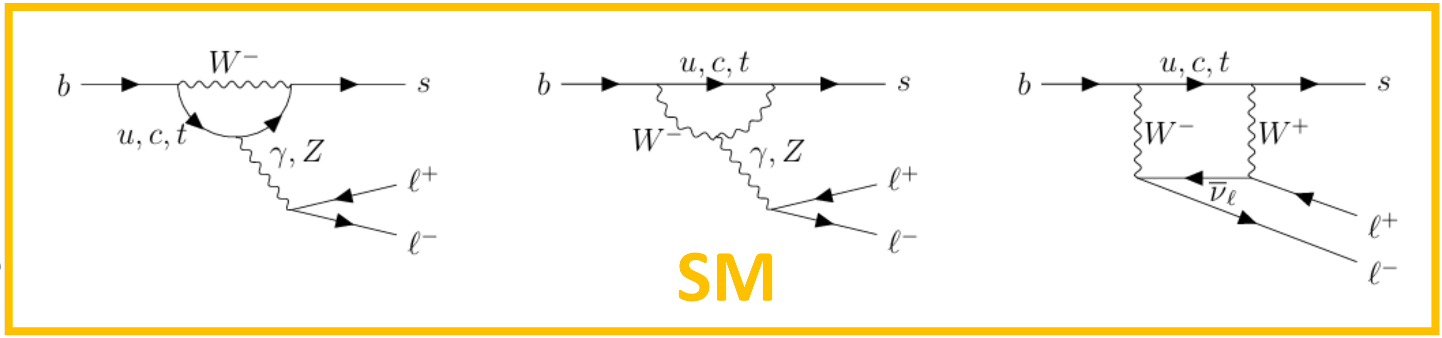
$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)$ : PRD109, L111101 (2024)

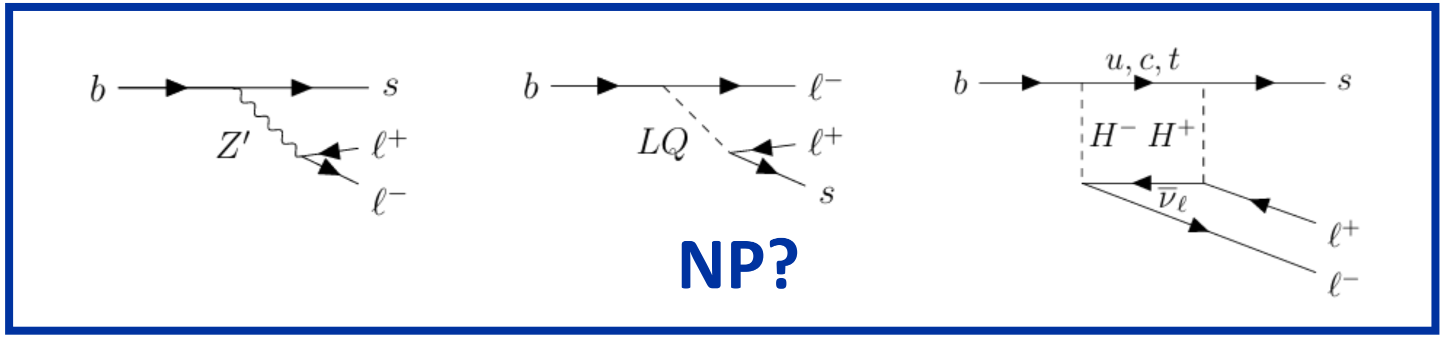
$\eta \to \mu^+\mu^-\mu^+\mu^-$ PRL131, 091903 (2023)

# Flavor-changing neutral current(FCNC) transitions

- Flavour-changing neutral current (FCNC) transition: transitions between quarks of the same electric charge
- SM: forbidden at tree level, need more complex diagrams to achieve
- Enhanced in many BSM theories: new particles can contribute at the loop or tree level
- NP can modify angular parameters, decay rates …

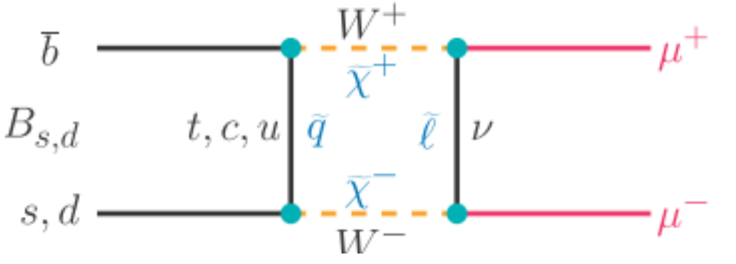


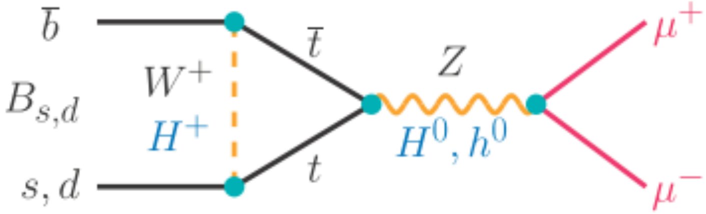



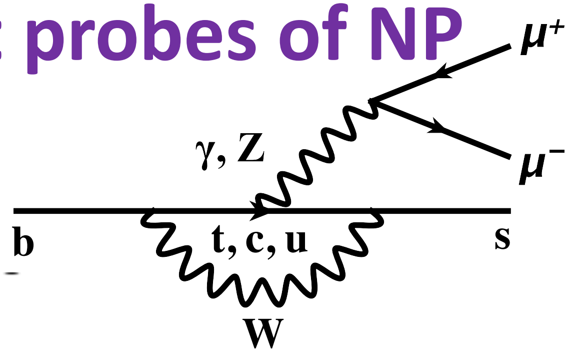



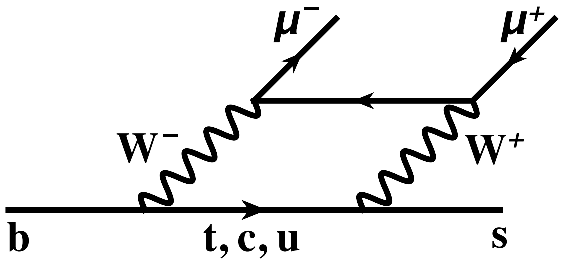
# FCNC processes b→μ+μ− and b→sμ+μ−

## golden indirect probes of NP




$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm tq}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\rm NP}^2} \mathcal{O}_{\rm NP}$$

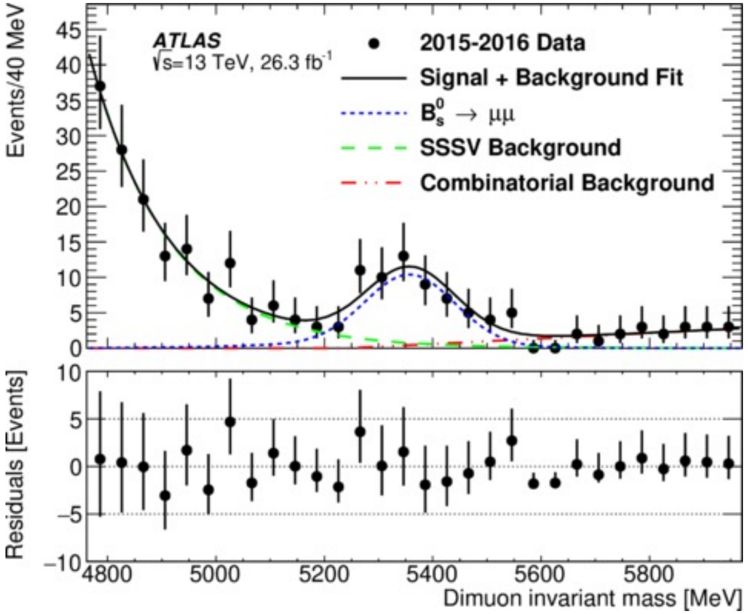
- $i = 1, 2$ Tree
- $i = 3 - 6, 8$ Gluon penguin
- $i = 7$ Photon penguin
- $i = 9, 10$ EW penguin
- $i = S, P$ (Pseudo)scalar penguin

| Operator $\mathcal{O}_i$ | $B_{s,d} \to X_{s,d}\mu^+\mu^-$ | $B_{s,d} \to \mu^+\mu^-$ | $B_{s,d} \to X_{s,d}\gamma$ |
|---|---|---|---|
| $\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$ | ✓ | | ✓ |
| $\mathcal{O}_9 \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$ | ✓ | | |
| $\mathcal{O}_{10} \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu \ell)$ | ✓ | ✓ | |
| $\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$ | (✓) | ✓ | |

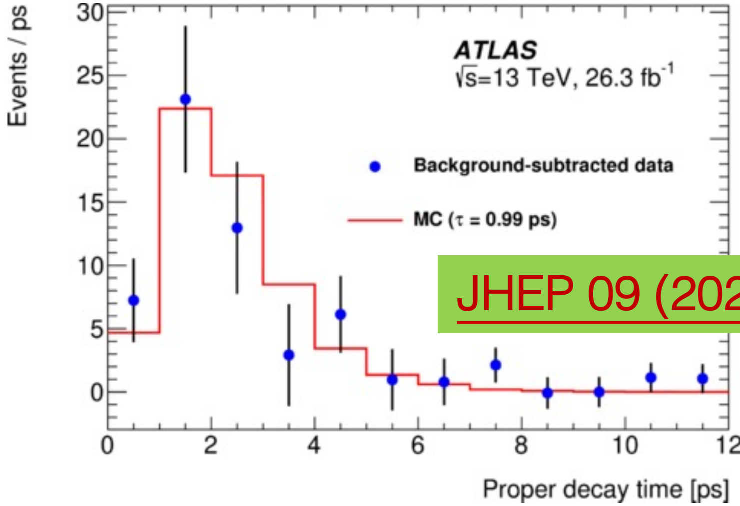
- ✓ clean experimental signatures;
- ✓ robust theory calculations;
- ✓ high sensitivity

different processes are sensitive to different operators

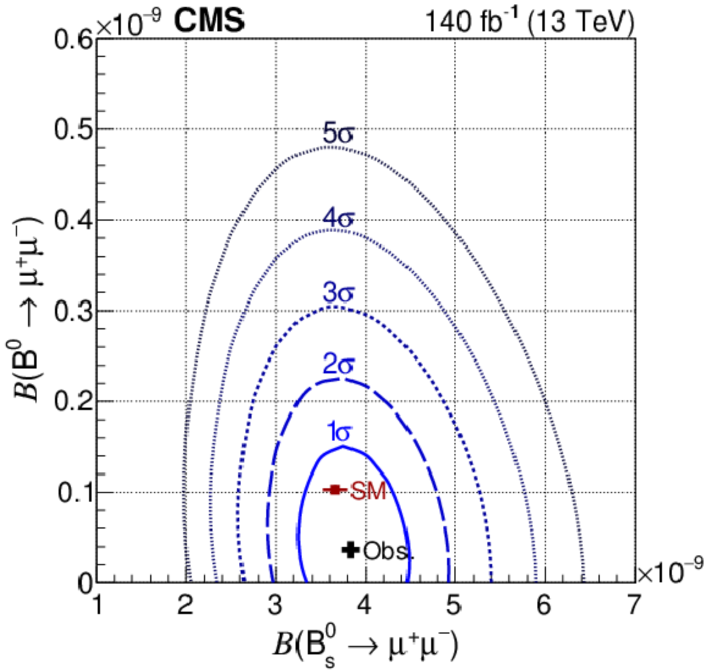
# ATLAS/CMS Run-II results on $B_{(s)} \rightarrow \mu\mu$ decays




$$\tau_{\mu\mu}^{\mathrm{Obs}} = 0.99^{+0.42}_{-0.07}\ (\mathrm{stat.}) \pm 0.17\ (\mathrm{syst.})\ \mathrm{ps}.$$

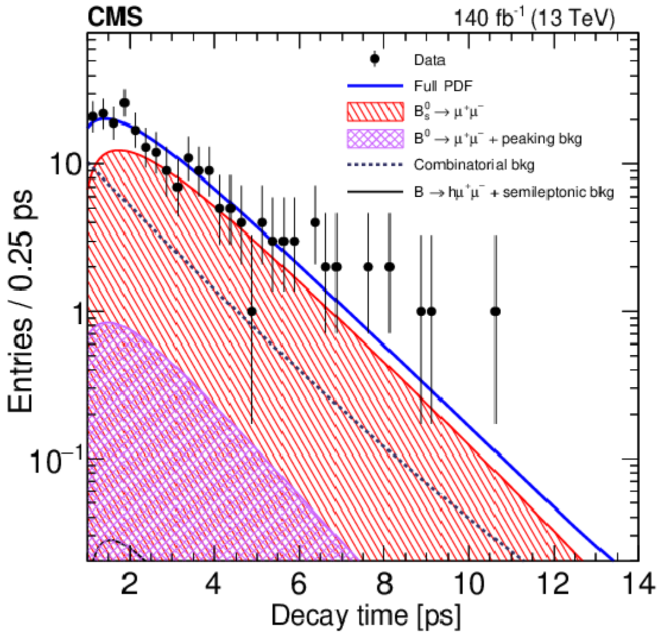



JHEP 09 (2023) 199

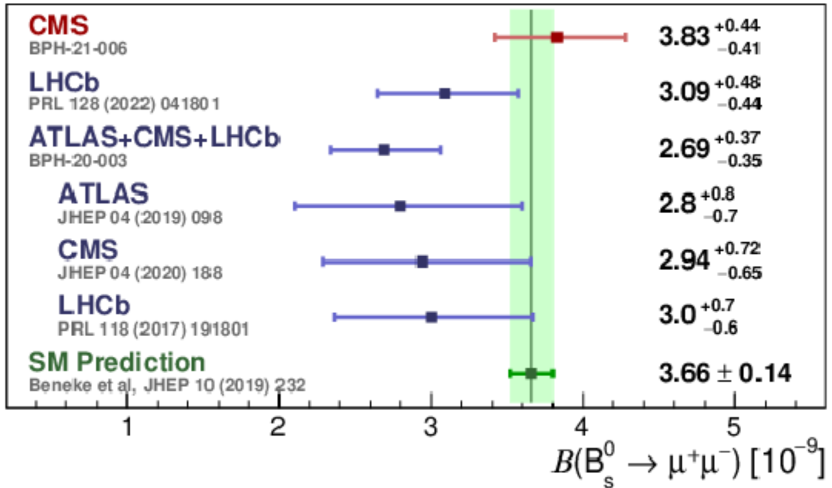



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = [\, 3.83^{+0.38}_{-0.36}\ (\mathrm{stat})\ {}^{+0.19}_{-0.16}\ (\mathrm{syst})\ {}^{+0.14}_{-0.13}\ (f_s/f_u)\,] \times 10^{-9},$$
$$\tau = 1.83\ {}^{+0.23}_{-0.20}\ (\mathrm{stat})\ {}^{+0.04}_{-0.04}\ (\mathrm{syst}$$

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




CMS-BPH-21-006
PLB 842 (2023) 137955



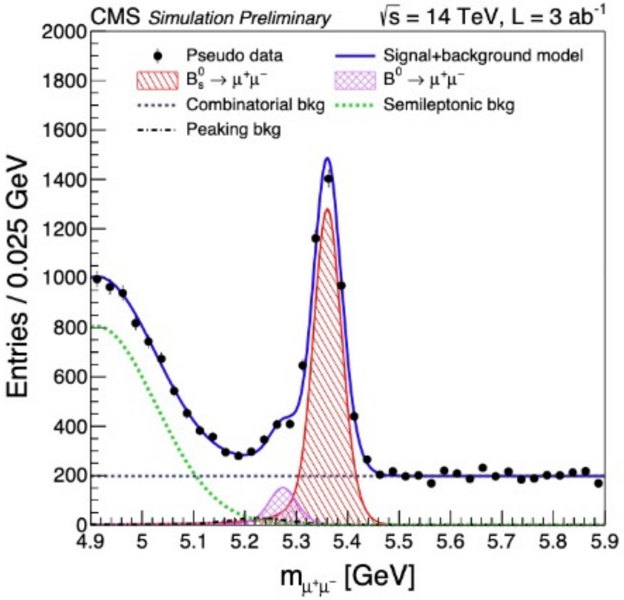
# ATLAS/CMS $B_s$ and $B^0 \rightarrow \mu\mu$ : HL-LHC projections

Flavour inputs to ESPPU

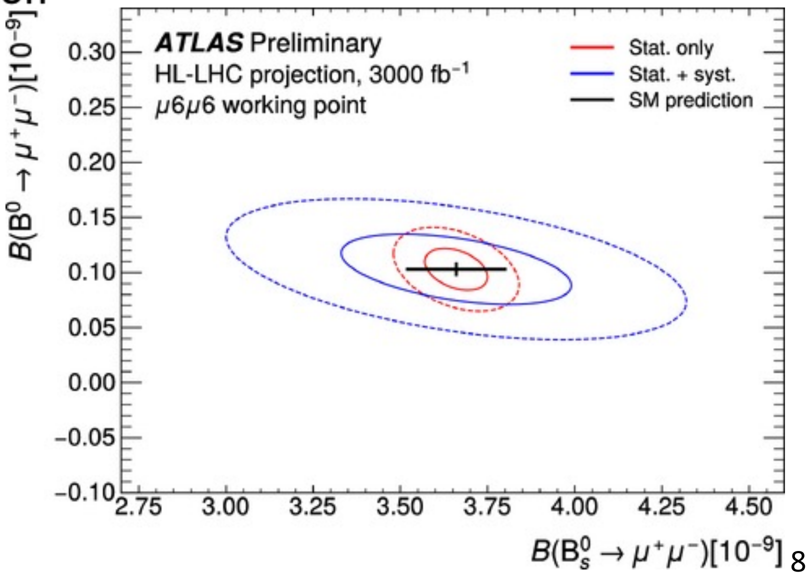
**ATLAS-PHYS-PUB-25-016**
**CMS-BPH-25-004**
**arXiv:2503.24346**

New projection:

- Yields scaled for $\int L$ and cross section (14/13 TeV) ratio
- Improved mass resolution included as scaling factor
- Same integrated S/B ratio as in the current analysis
- Stat. uncertainty from fits to pseudo-data
  - with s-plots weights for the lifetime
- Same syst. uncertainty as in Run2. Exceptions:
  - 1.5% instead 2.3% in tracking efficiency
  - 2.4% trigger efficiency uncertainty, uniform across categories
  - *Total: 3.5% from fs/ fu ratio; 4.3% for all other sources*
  - x2 improvement for lifetime fit bias and the mismodeling of the decay time distribution




| | ATLAS | CMS | LHCb |
|---|---|---|---|
| $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ $[10^{-9}]$ | $(0.33 - 0.40)$ | 0.22 | 0.16 |
| $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ $[10^{-10}]$ | $(0.32 - 0.48)$ | 0.12 | 0.12 |
| $\tau_{\text{eff}}(B_s^0 \rightarrow \mu^+\mu^-)$ [ps] | $+(0.07-0.11)$ $-(0.05-0.08)$ | 0.05 | 0.05 |



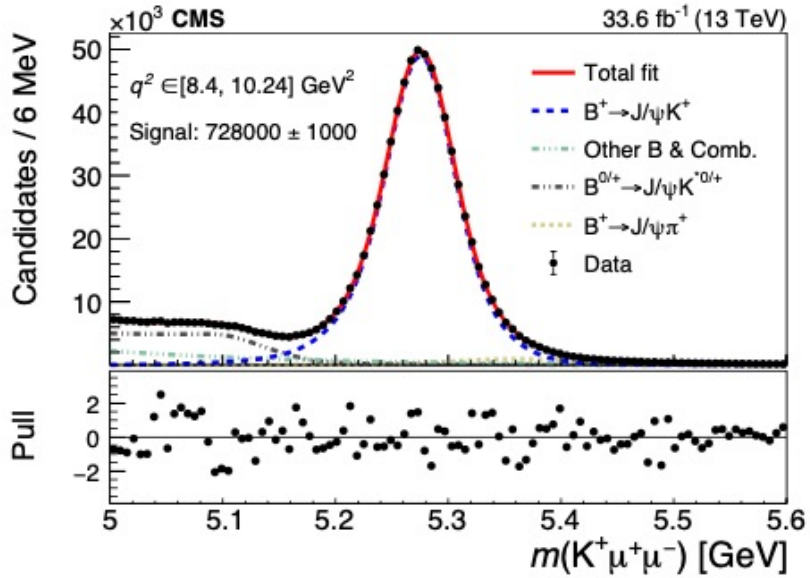

Systematics becomes relevant for Bs; Clear observation of $B_0 \rightarrow \mu\mu$ possible

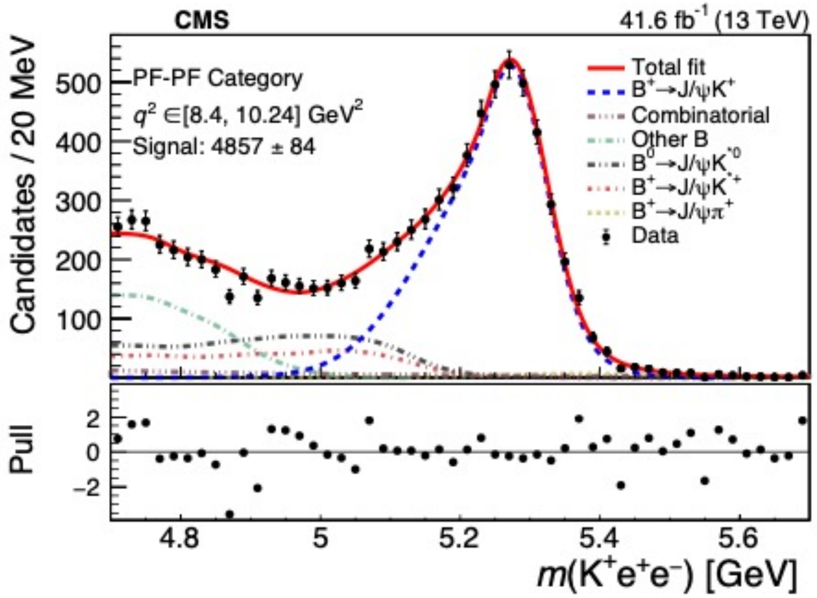
# Measurements of B⁺→K⁺ l l with B parking data

$$\mathcal{R}(K) = \frac{\mathcal{B}(B \to \mu\mu K)}{\mathcal{B}(B \to J/\psi(\to \mu\mu)K)} \Big/ \frac{\mathcal{B}(B \to ee K)}{\mathcal{B}\big(B \to (B \to J/\psi(\to ee)K)\big)}$$

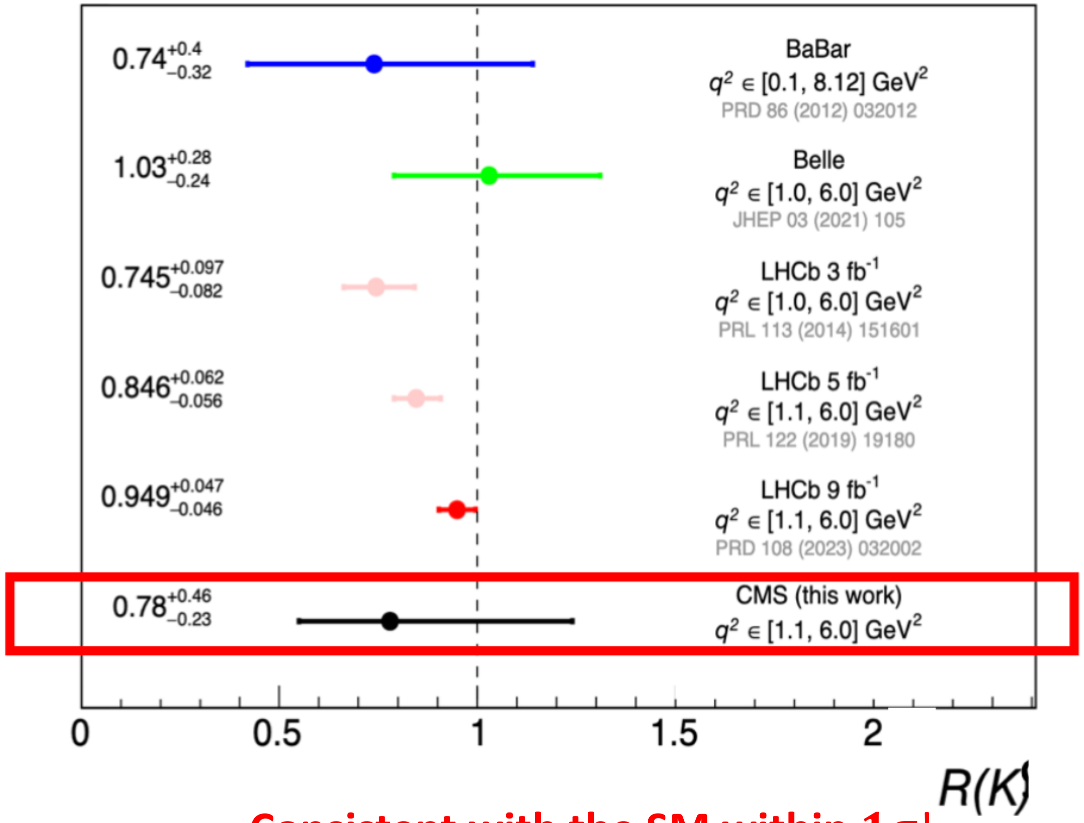
- Theoretical precision:1.00±0.01
- New data-acquisition technique: 2018 B-Parking
- Fit to Kll invariant mass in 3 $q^2$ regions,
  - SR: (1.1, 6.0) GeV, $J/\psi$ CR: (8.41, 10.24 )GeV $\psi(2S)$CR: (12.6,14.4) GeV
- Dedicated low-pT ID for electrons
- Main Backgrounds suppressed mostly through ID BDTs:
  - Partially reconstructed $B \to K^*(892)$ll
  - $J/\psi$ leakage and any other B decays
  - Combinatorial
- Ratio extracted from profile likelihood

$$R(\mathrm{K}) = 0.78^{+0.46}_{-0.23}\,(\mathrm{stat})^{+0.09}_{-0.05}\,(\mathrm{syst}) = 0.78^{+0.47}_{-0.23},$$

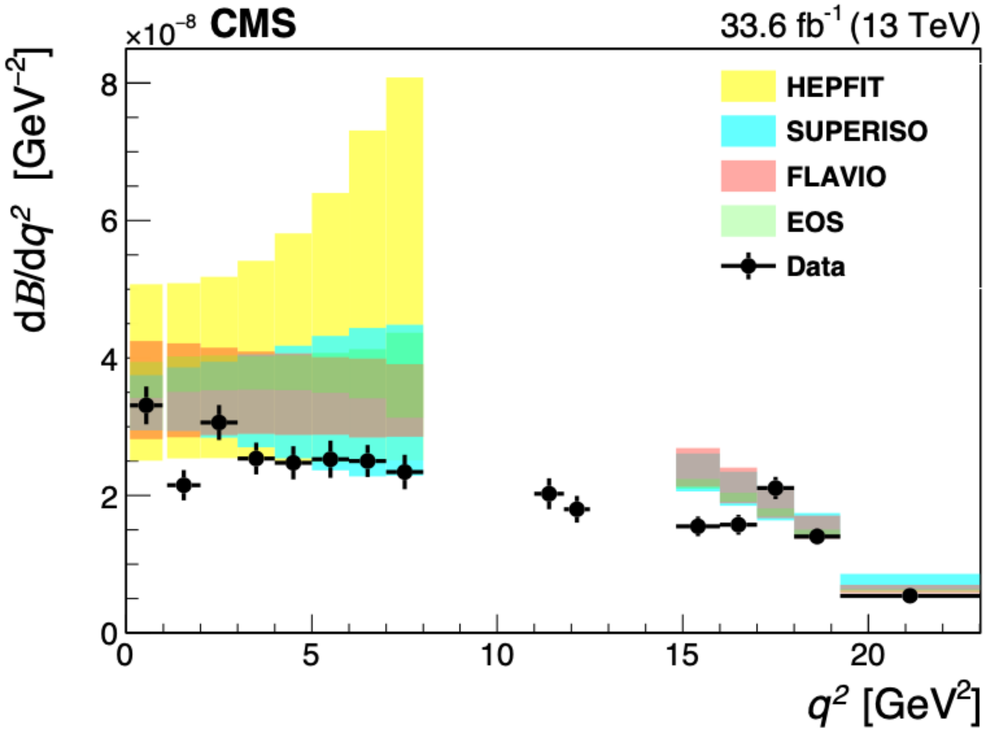


| Source | Impact on the $R(\mathrm{K})$ ratio [%] PF-PF | PF-LP |
|---|---|---|
| Signal and background description | 5 | 5 |
| $J/\psi$ event leakage to the low-$q^2$ bin | 4 | 9 |
| BDT efficiency stability | 2 | 5 |
| BDT cross validation | 2 | 3 |
| Trigger efficiency | 1 | 4 |
| BDT data/simulation difference | 1 | 2 |
| $J/\psi$ meson radiative tail description | 1 | 1 |
| Total systematic uncertainty | 7 | 13 |
| Statistical and total uncertainty | 40 | 200 |




**Electron channel limiting precision**




**Consistent with the SM within 1σ!**

$$\mathcal{B}(\mathrm{B}^{\pm} \to \mathrm{K}^{\pm}\mu^{+}\mu^{-}) = (12.42 \pm 0.68) \times 10^{-8}$$

consistent with and has a comparable precision to the present world average

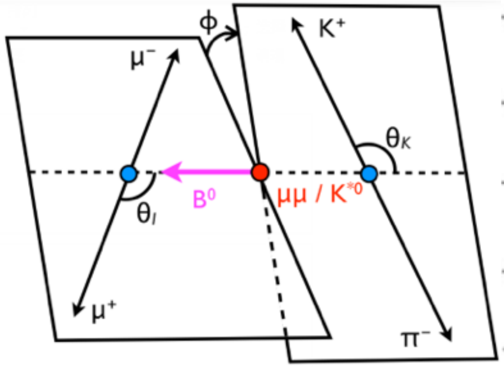
CMS-BPH-22-005
Rep. Prog. Phys. 87 (2024) 077802

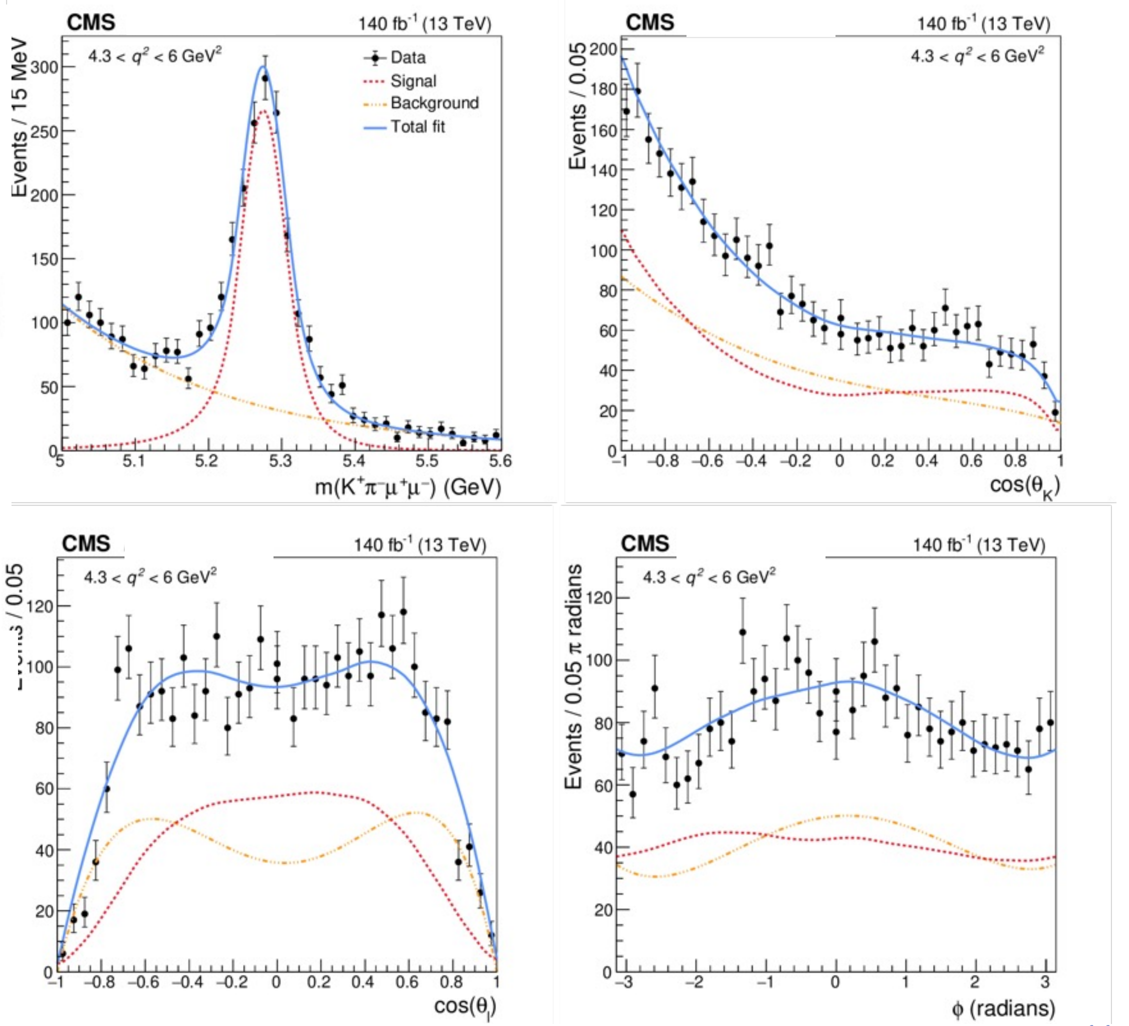
# Run2: Full angular analysis of $B^0 \to K^{*0}\mu\mu$

**More details:**
**X.Qin' s poster**

**CMS-BPH-21-002**
**PLB 864 (2025) 139406**

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\,d\cos\theta_l\,d\cos\theta_K\,d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\left(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right)\cos 2\theta_l$$
$$+\frac{1}{2}P_1(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\sqrt{(1-F_L)F_L}\left(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{(1-F_L)F_L}\left(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$
$$+2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big],$$



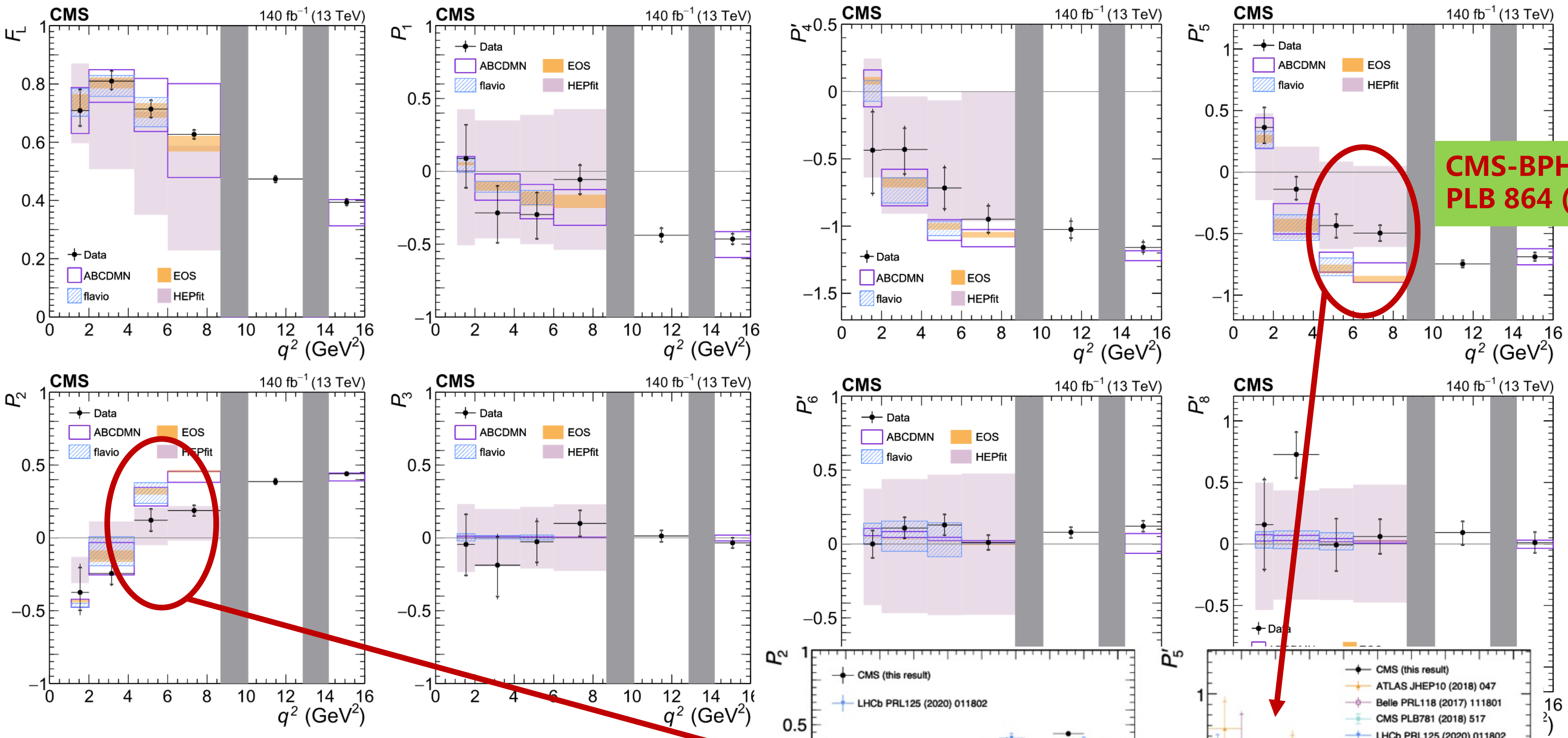

$$\text{pdf}(m,\cos\theta_K,\cos\theta_l,\phi) = Y_S\Big[S^C(m)S^a(\cos\theta_K,\cos\theta_l,\phi)\epsilon^C(\cos\theta_K,\cos\theta_l,\phi)$$
$$+R\cdot S^M(m)S^a(-\cos\theta_K,-\cos\theta_l,-\phi)\epsilon^M(\cos\theta_K,\cos\theta_l,\phi)\Big]$$
$$+Y_B B^m(m)B^a(\cos\theta_K,\cos\theta_l,\phi)$$

**Angular rate**

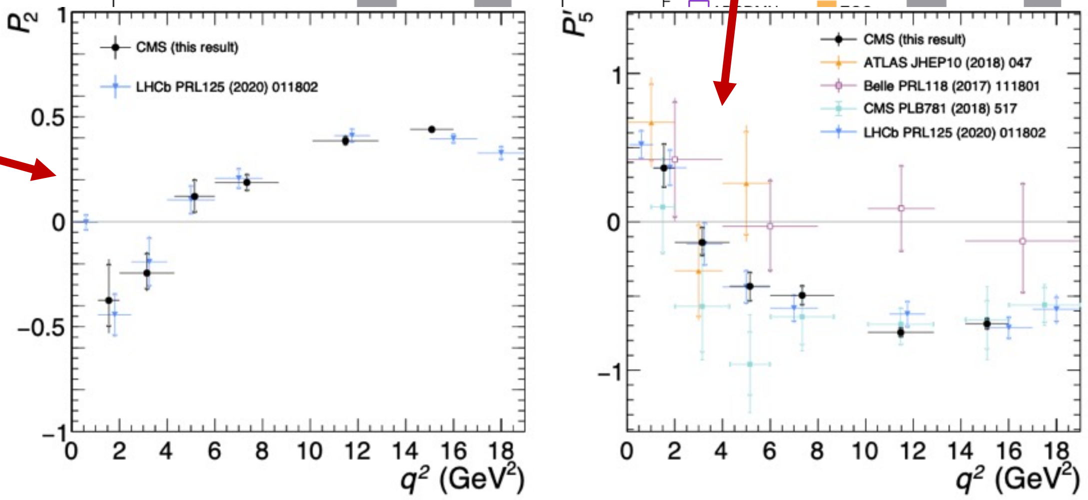
**Signal and bkg mass shapes**

**KDE efficiency**

**Bkg angular shape**




**CMS-BPH-21-002**
**PLB 864 (2025) 139406**



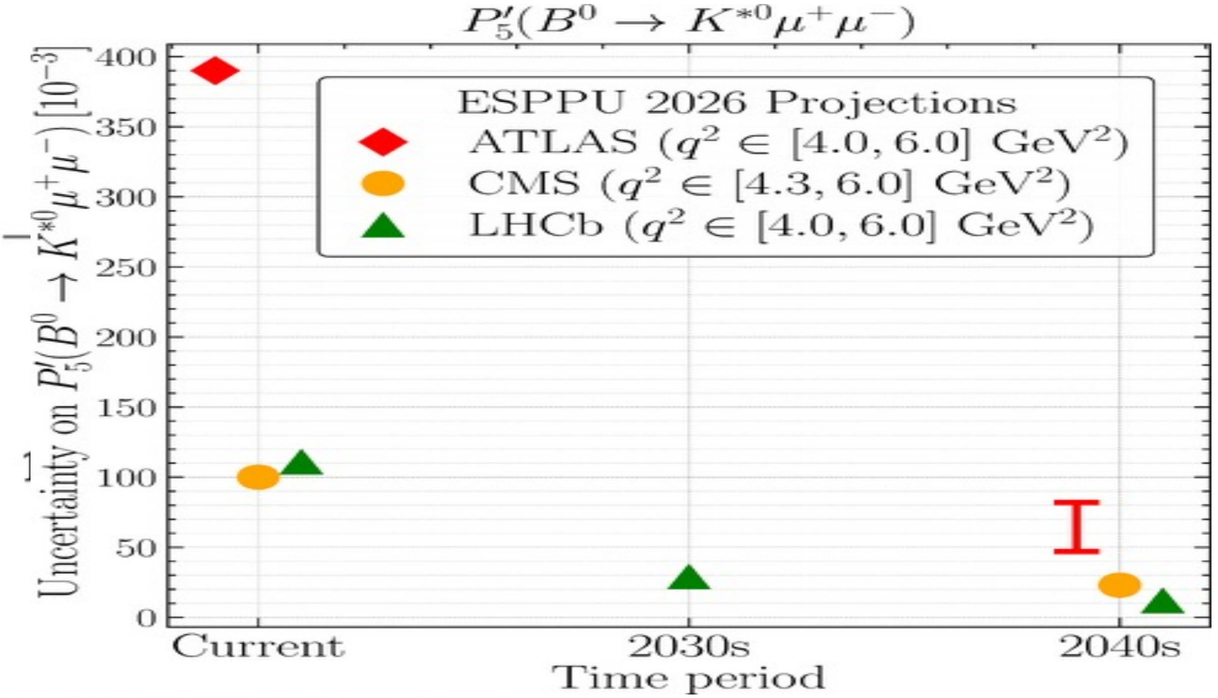

- ✓ among the most precise measurements of the angular observables of this decay
- ✓ valuable contribution to the understanding of the b → sl⁺l⁻

# ATLAS/CMS $B^0 \to K^{*0}\mu\mu$ : HL-LHC projections

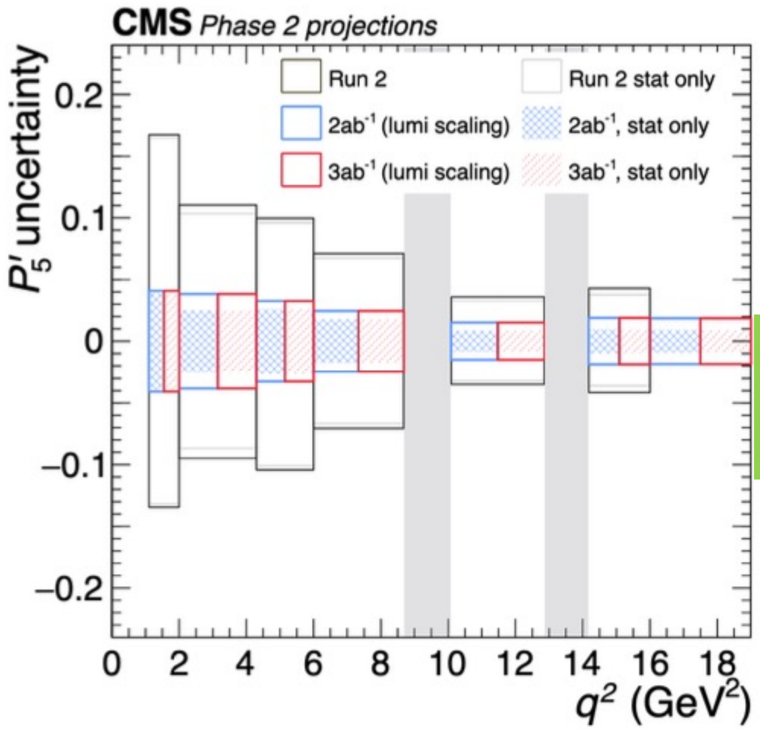
New projection. For each q$^2$ bin:

- Yields scaled for $\int L$ and bb-cross section (14/13 TeV) ratio
- Stat. error obtained scaling the Run2 uncertainty by √L ratio
- Syst. error related to N(B) in the sideband scaled by √L ratio
- No syst. related to MC statistics
- For other systematics 2 scenarios: same as Run2 or reduced by a factor 2 wrt Run2

| P5’ ($10^{-3}$) | ATLAS | CMS | LHCb |
|---|---|---|---|
| Now | 390 | 100 | 111 |
| HL-LHC | 47-82 | 23 | 12 |



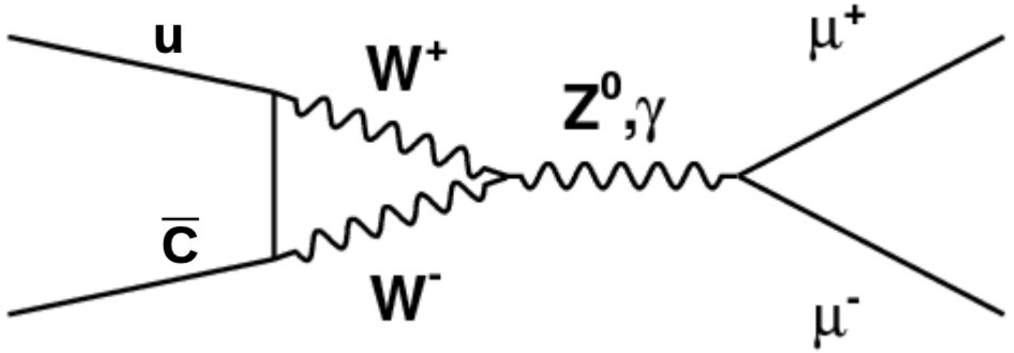

Statistical error still dominant




**ATLAS-PHYS-PUB-25-020**
**CMS-BPH-25-004**
**arXiv:2503.24346**

# Search for $D^0 \rightarrow \mu\mu$ decay

- Heavily suppressed in the SM (loop diagram + helicity)
  - BR prediction ~ $10^{-13}$
  - High sensitivity to new-physics phenomena
  - Previous best limit at: BR($D^0 \rightarrow \mu\mu$) < 3.5 $\times 10^{-9}$ (95% CL) by LHCb
- This analysis uses 2022+2023 CMS data with new low-momentum dimuon trigger
  - a newly developed inclusive dimuon trigger, expanding the scope of the CMS flavor physics program.



# Key points of the search

- Analysis Strategy
  - uses D0 from cascade decays: $D^{*+} \to D^0\pi^+$
  - Exploits mass difference $\Delta m = m(D^{*+}) - m(D^0)$ to strongly suppress combinatorial $D^{*+}$ produced promptly or from B-hadron decays
  - Final state: opposite charged muons + track
- $D^0 \to \pi^+\pi^-$ used as normalization channel:

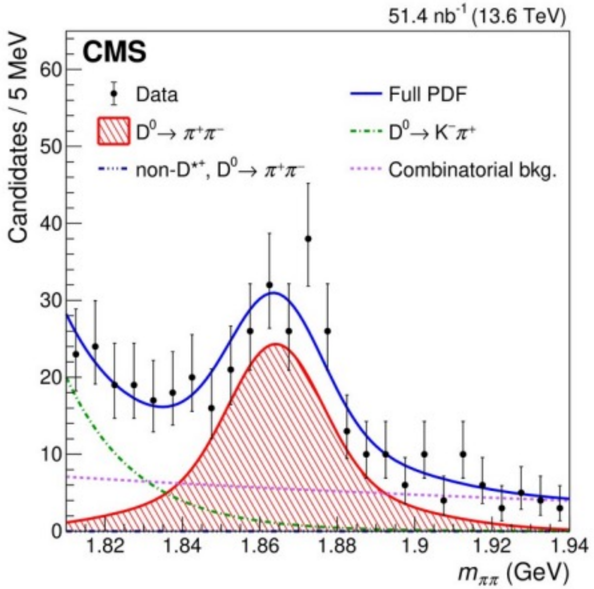
$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-)\frac{N_{\mathrm{D}0\to\mu\mu}}{N_{\mathrm{D}0\to\pi\pi}}\frac{\varepsilon_{\mathrm{D}0\to\pi\pi}}{\varepsilon_{\mathrm{D}0\to\mu\mu}}$$

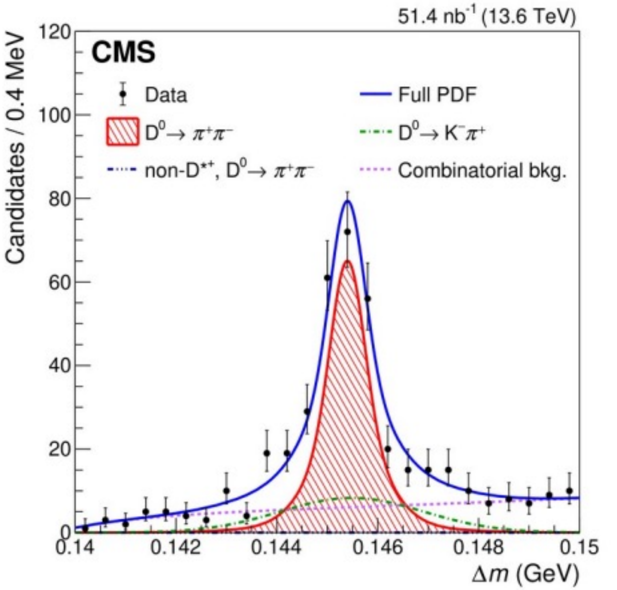
- Source of backgrounds
  - Combinatorial: suppressed via gradient BDT, exploiting topological features
  - Peaking backgrounds for signal:
    - $D^{*+} \to D^0 (\pi\pi)\pi \to \mu\mu + X$
    - $D^{*+} \to D^0 (\pi\mu\nu)\pi$
  - Peaking background for normalization channel:
    - $D^{*+} \to D^0 (K\pi)\pi$

# Search results

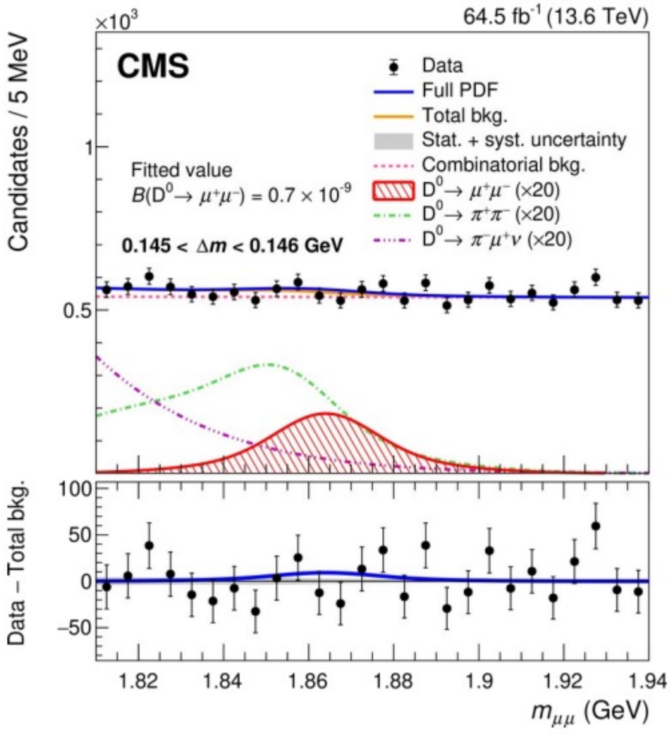
2D UML fits:

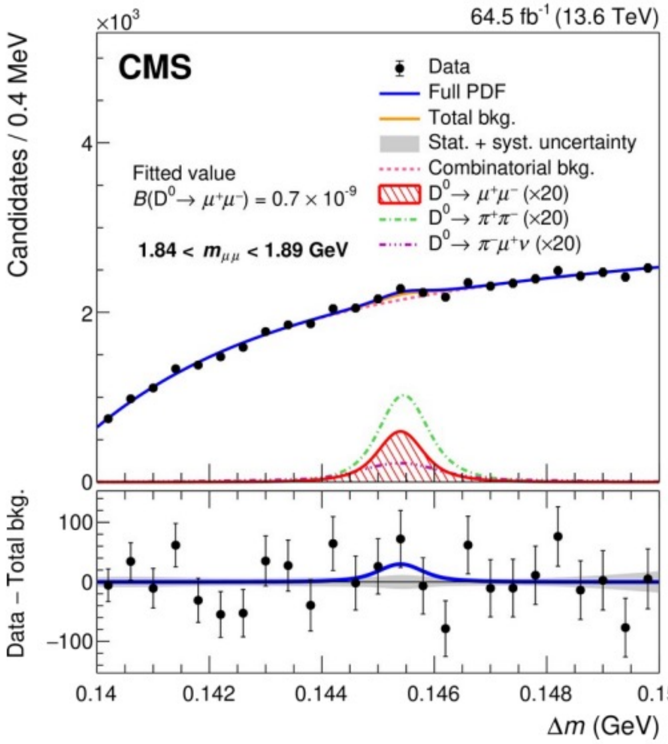
- to [m(ππ), Δm] in normalization sample
- to [m(μμ), Δm] in signal sample




$B(D^0 \to \mu^+\mu^-) < 2.1(2.4)\times10^{-9}$ at 90(95)% CL,
upper limit improved by ~40%

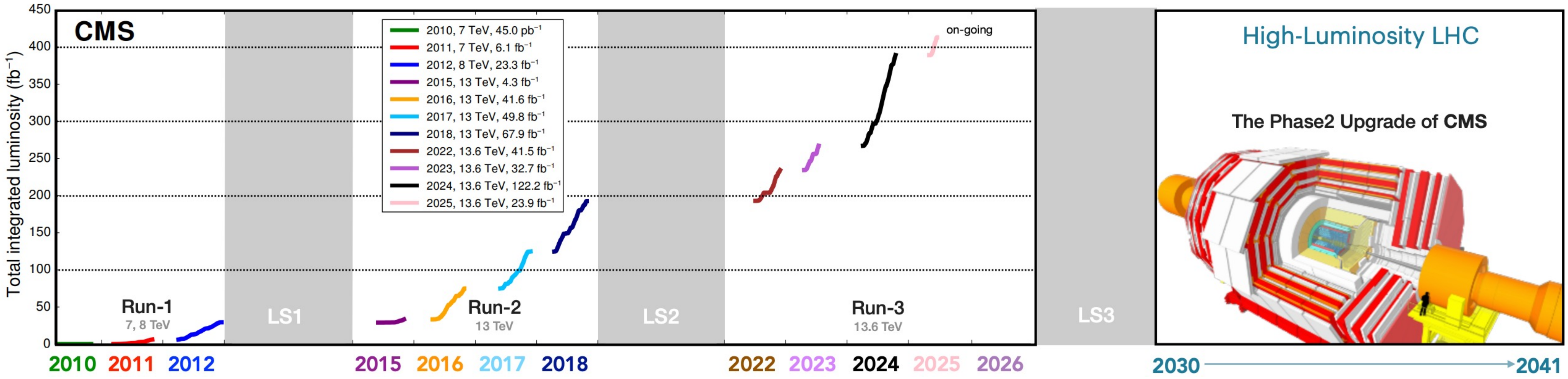


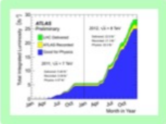




the most stringent upper limit set on any flavor changing neutral current decay in the charm sector

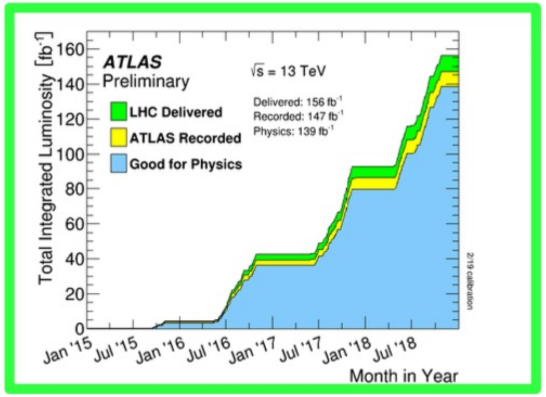
CMS-BPH-23-008
arxiv:2506.06152
PRL accepted

Still 4 order of magnitude above SM prediction

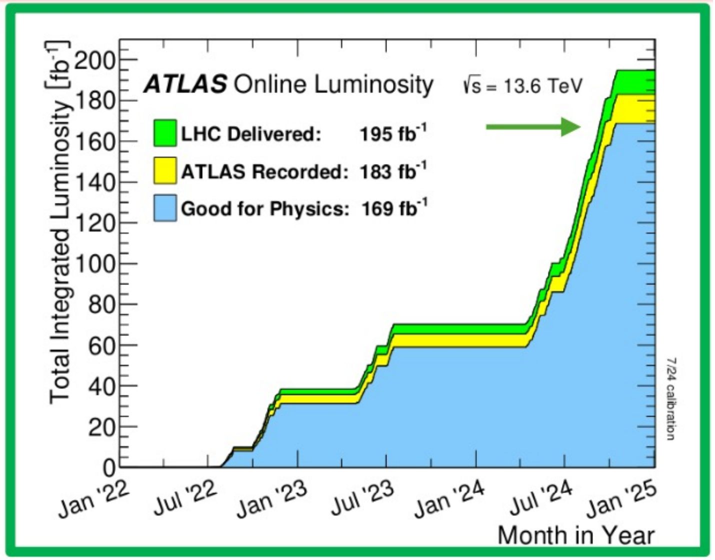


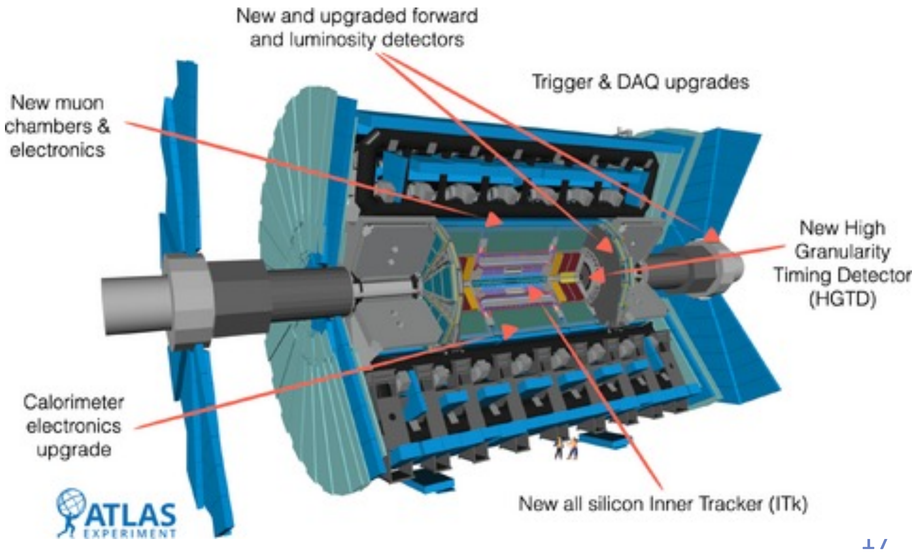
Run 1:
25 $fb^{-1}$ @ 7+8 TeV




Run 2:
140 $fb^{-1}$ @ 13 TeV




Run 3: 2022-2024
168 $fb^{-1}$ @ 13.6 TeV



# Summary

- ATLAS/CMS is probing SM with heavy flavor rare decays extensively
- Some recent results from B and D FCNC processes
  - $B_{(s)} \rightarrow \mu\mu$: BF and lifetime measurements
  - Run2: Full angular analysis of $B^0 \rightarrow K^{*0}\mu\mu$, PLB 864 (2025) 139406
  - BF measurement and LFU test of $B^+ \rightarrow K^+ l\, l$ : Rep. Prog. Phys. 87 (2024) 077802
  - $D^0 \rightarrow \mu\mu$: arxiv:2506.06152
- More flexible trigger and data-taking schemes implemented in Run3, more sensitive results expected
  - HL-LHC coming in ~5 years, projections updated

More:
ATLAS HF Public Results
CMS HF Public Results