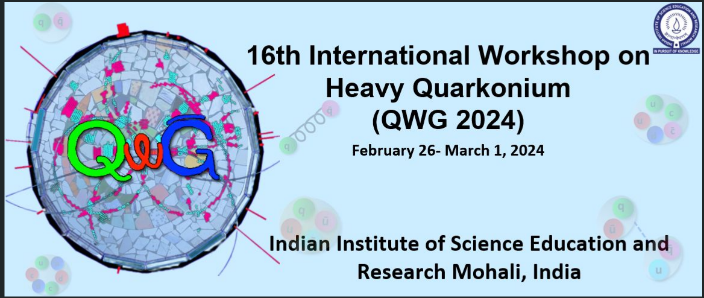


Rare decays at CMS

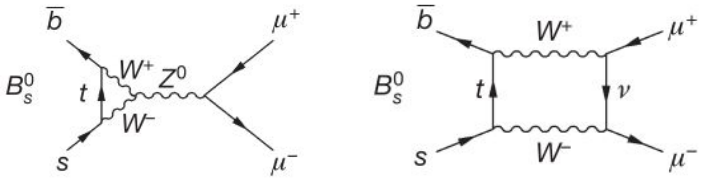
Rishabh Raturi, On behalf of CMS Collaboration
Indian Institute of Technology Bhubaneswar

Outline

- Introduction
- CMS detector
- Test of lepton flavor universality in $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ and $B^{\pm} \to K^{\pm}e^{+}e^{-}$ decays
- Measurement of $B_s^0 \to \mu^{+}\mu^{-}$ decay properties and search for $B^0 \to \mu^{+}\mu^{-}$ decay
- Search for lepton flavor violating $\tau \to 3\mu$ decay
- Search for long-lived particles decaying in the CMS detector
- Search for long-lived heavy flavor leptons decay to jets and a charged lepton
- Search for pair production of scalar and vector leptoquarks

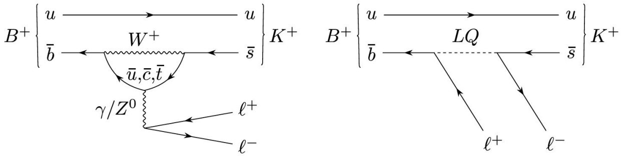
Introduction

- Leptonic and semi-leptonic **flavor changing neutral currents** (eg: b➔sll transitions)
  - forbidden at tree level
  - proceed via higher order loop diagrams



- Yet undiscovered particles, not predicted by SM, may enter these diagrams and alter the decay amplitude

- Rare decays also provide a way to test **Standard Model** (SM) and explore beyond SM physics
  - lepton flavor universality
  - leptoquarks
  - long-lived neutral particles



- Recent measurements of B meson decays have reported **tensions** with the SM predictions

- Searches for intermediate resonances like **pentaquarks**

images source: [Nature 522 (2015) 68], [arXiv:2104.07090]

CMS Detector

- CMS detector is a **superconducting solenoid** of 6m internal diameter: 3.8T
- Silicon **pixel** and **strip** tracker
- **Lead tungstate** crystal electromagnetic calorimeter (**ECAL**)
- Brass and scintillator **HCAL**
- Muon chambers: (outside steel return yolk)
  - Drift tubes (**DTs**)
  - Cathode strip chambers (**CSCs**)
  - Resistive-plate chambers (**RPCs**)
- Two-level trigger system (**L1+HLT**)

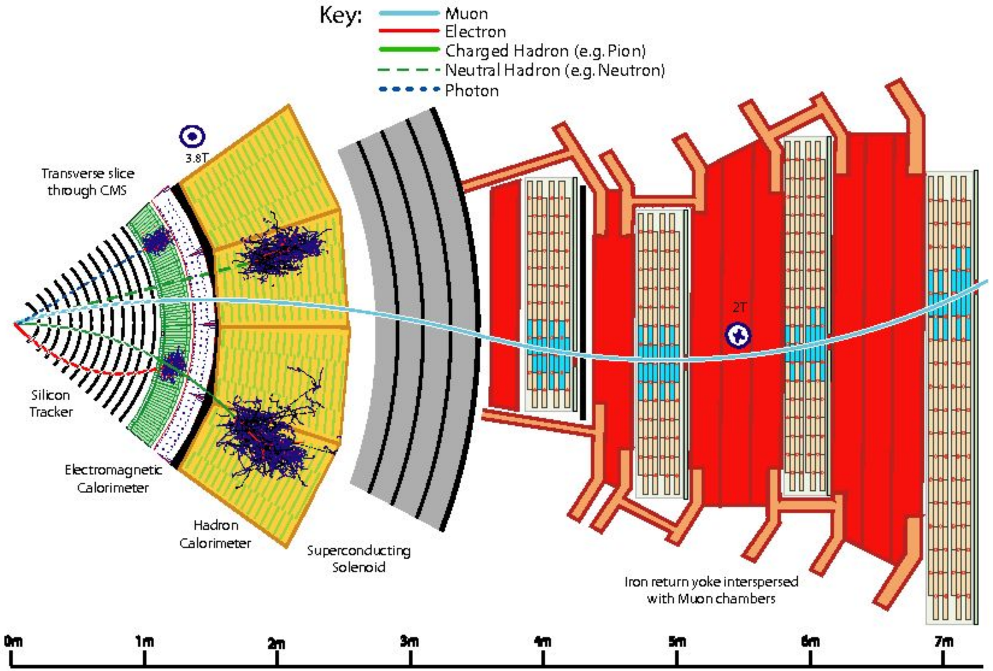
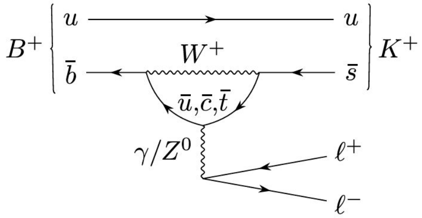


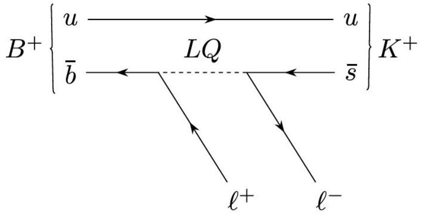
image source: JINST 12 (2017) P10003

Test of lepton flavor universality in $B^{\pm} \to K^{\pm} l^+ l^-$ decays

- In SM, leptons have identical couplings to gauge boson→ **lepton flavor universality**

- $B^{\pm} \to K^{\pm} l^+ l^-$ forbidden at tree level (flavor changing neutral current)
  - proceed via loop level diagrams
  - BSM: **leptoquarks** with flavor-dependent couplings





- As compared to B meson e and μ have negligible masses
  - same phase space
  - ratio of branching fraction ~1 in SM

- LHCb Collaboration had reported LFU violation in $B^{\pm} \to K^{\pm} l^+ l^-$ with a significance of 3.1σ

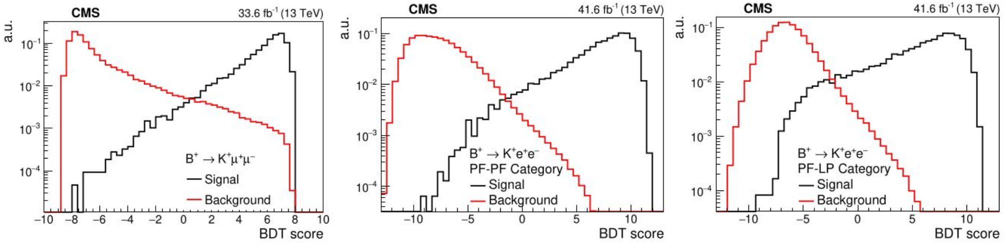
- CMS reports
  - R(K) measurement
  - integrated branching fraction $\mathcal{B}(B^{\pm} \to K^{\pm}\mu^+\mu^-)$ in q^2: 1.1-6.0 GeV^2 [$q^2 = m(\mu^+\mu^-)^2$]

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

images source: arXiv:2104.07090

Analysis overview

- Dedicated 2018 pp collision dataset at $\sqrt{s}$=13TeV and $\mathcal{L}$ = 41.6 ± 1.0 fb^{-1}
    - special high-rate data stream
    - 10b unbiased b hadron decays (**B-parking dataset**)
- $B^+ \to K^+ \mu^+ \mu^-$ decay reconstructed from two oppositely charged muons and positively charged track fitted to a common vertex
- Final selection based on BDT for both μ and e channel
    - p_T of decay products, isolation variables
    - $\Delta R(\mu, K^{\pm})$, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
    - $\Delta z(e_i, K^+)$ etc.



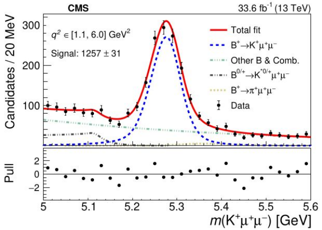
separate category for low-p_T electrons

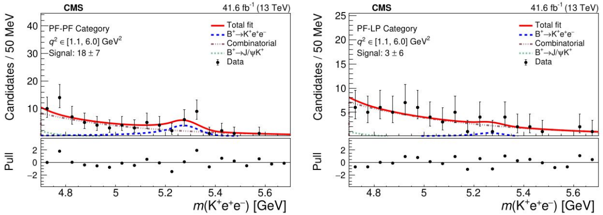
- Good agreement between data and MC using the **splot** technique

plots source: **arXiv:2104.07090**

Results

- Yields extracted through UML fit to B candidates
  - signal: double Crystal Ball function
  - background: exponential





q^2 range [GeV^2]	Signal yield	Branching fraction [10^{-8}]
0.1–0.98	260 ± 20	2.91 ± 0.24
1.1–2.0	197 ± 19	1.93 ± 0.20
2.0–3.0	306 ± 23	3.06 ± 0.25
3.0–4.0	260 ± 21	2.54 ± 0.23
4.0–5.0	251 ± 23	2.47 ± 0.24
5.0–6.0	264 ± 27	2.53 ± 0.27
6.0–7.0	267 ± 21	2.50 ± 0.23
7.0–8.0	256 ± 23	2.34 ± 0.25
11.0–11.8	207 ± 19	1.62 ± 0.18
11.8–12.5	172 ± 16	1.26 ± 0.14
14.82–16.0	272 ± 20	1.83 ± 0.17
16.0–17.0	246 ± 17	1.57 ± 0.15
17.0–18.0	317 ± 19	2.11 ± 0.16
18.0–19.24	242 ± 19	1.74 ± 0.15
19.24–22.9	158 ± 19	2.02 ± 0.30

- R(K) in q^2: 1.1-6.0 GeV^2

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

1σ from SM prediction

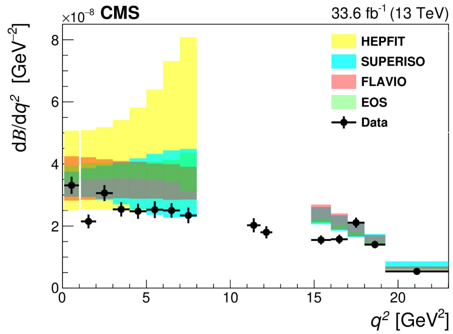
- Differential branching fractions

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

- Integrated branching fraction

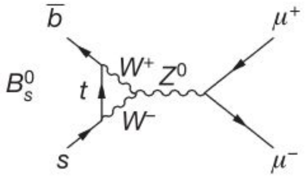
$$\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)[1.1, 6.0]\,\mathrm{GeV}^2 = (12.42 \pm 0.54\,(\mathrm{stat}) \pm 0.11\,(\mathrm{MC\ stat}) \pm 0.40\,(\mathrm{syst})) \times 10^{-8} = (12.42 \pm 0.68) \times 10^{-8}.$$

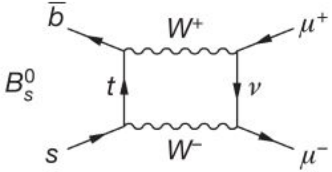
In agreement with world-average value and LHC Collaboration result



plots source: arXiv:2104.07090

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays





- Another **flavor changing neutral current**
  - loop level transition
  - further helicity suppressed $m^2(\mu)/m^2(B)$
  - precise theoretical predictions

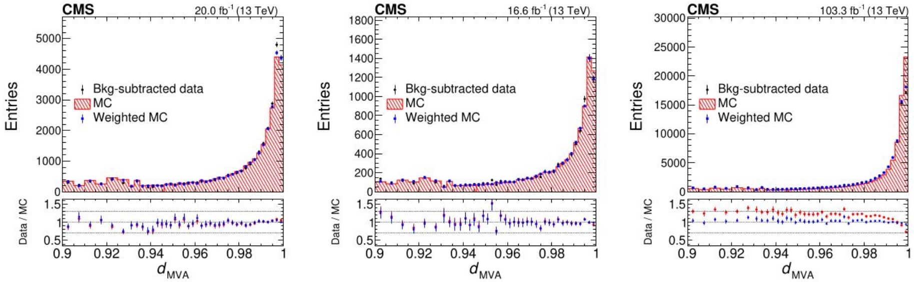
	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
Nature 522 (2015) 68 **CMS+LHCb**	$2.8^{+0.7}_{-0.6} \times 10^{-9}$
JHEP 04 (2019) 098 **ATLAS**	$2.8^{+0.8}_{-0.7} \times 10^{-9}$
JHEP 04 (2020) 188 **CMS**	$(2.9 \pm 0.7 \pm 0.2) \times 10^{-9}$
PRD 105 (2022) 012010 **LHCb**	$3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$

- Recent measurements from $b \to sll$ decays reported 2-3σ deviation from SM predictions
- Precise measurements of $B_s^0 \to \mu^+\mu^-$ and its decay properties is sensitive to **BSM** physics

images source: Nature 522 (2015) 68

Analysis overview

- Run II pp collision dataset at $\sqrt{s}$=13TeV and $\mathscr{L}$ = 140 fb^{-1}
- Two high-quality oppositely charged muons with p_T>4 GeV and $|\eta|$<1.4
- Mis-identification suppressed via tight muon identification criteria
- B-candidate from the kinematic fitter with constraints on the SV
- Multivariate analysis to discriminate between signal and background (d_{MVA})
  - pointing angles
  - SV observables
  - No of tracks compatible with $\mu^+\mu^-$ candidates , isolation variables
- Good agreement between data and MC using **splot** technique



plots source: PLB 842 (2023) 137955

Results

- The branching fraction measurement equations:

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}) \frac{N_{\mathrm{B_s^0}\to\mu^+\mu^-}}{N_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}} \frac{\varepsilon_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}}{\varepsilon_{\mathrm{B_s^0}\to\mu^+\mu^-}} \frac{f_\mathrm{u}}{f_\mathrm{s}},$$

$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) = \mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}) \frac{N_{\mathrm{B^0}\to\mu^+\mu^-}}{N_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}} \frac{\varepsilon_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}}{\varepsilon_{\mathrm{B^0}\to\mu^+\mu^-}} \frac{f_\mathrm{u}}{f_\mathrm{d}},$$

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\mathrm{stat})\,^{+0.19}_{-0.16}\,(\mathrm{syst})\,^{+0.14}_{-0.13}\,(f_\mathrm{s}/f_\mathrm{u})\right] \times 10^{-9}$$

$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\,(\mathrm{stat})\,^{+0.08}_{-0.09}\,(\mathrm{syst})\right] \times 10^{-10}.$$

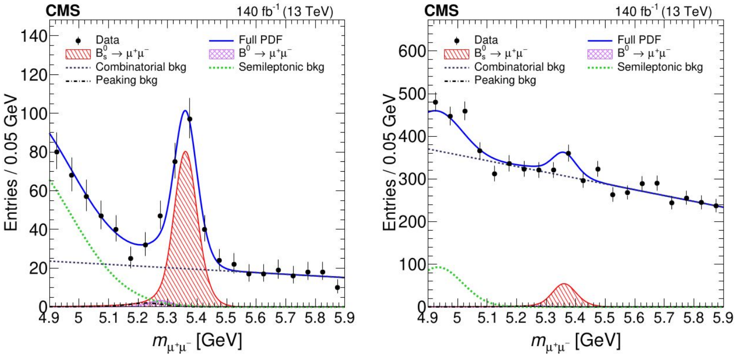
- Upper limits on $\mathcal{B}(B^0 \to \mu^+\mu^-)$ evaluated through CLs criterion

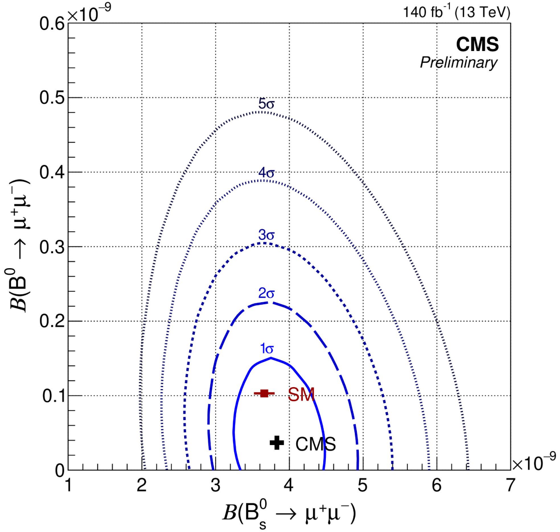
$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at } 90\% \text{ CL},$$

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

- Lifetime measurement $\tau = 1.83\,^{+0.23}_{-0.20}\,(\mathrm{stat})\,^{+0.04}_{-0.04}\,(\mathrm{syst})$ ps.

- All results consistent with the SM predictions and previous measurements





plots source: PLB 842 (2023) 137955

LFU violating $\tau \to 3\mu$ decay

- LFU violation in SM
  - neutrino transitions
  - branching fraction around 10^{-55}
- Various extension of SM predicts $\mathcal{B}(\tau \to 3\mu)$ around 10^{-10}-10^{-8}
- The most **stringent** upper limit from the Belle experiment
- τ leptons are explored in
  - **heavy-flavor** (b and c) hadron decays characterized by low-p_T < 10 GeV
  - **W boson decays:** large p_T muons accompanied by p_T^{miss}

PLB 687 (2010) 139 **Belle**	**< 2.1 x 10^{-8}**
PRD 81 (2010) 111101 **Babar**	**< 3.3 x 10^{-8}**
JHEP 02 (2015) 121 **LHCb**	**< 4.6 x 10^{-8}**
EPJC 76 (2016) 232 **ATLAS**	**< 38 x 10^{-8}**
JHEP 01 (2021) 163 **CMS**	**< 8.0 x 10^{-8}**

Upper limits on $\mathcal{B}(\tau \to 3\mu)$ at 90% CL

Analysis overview

- pp collision data at $\sqrt{s}$ = 13 TeV (2017-2018) and $\mathscr{L}$ = 97.7 fb^{-1}
- Results combined with already published 2016 data to obtain total $\mathscr{L}$ = 131 fb^{-1}
- Three mass resolution categories σ_m/m [<0.7% (A), 0.7-1.05% (B), >1.05% (C)]

Heavy-flavor decays

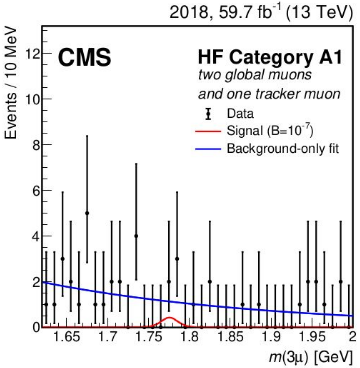
- ➔ Dedicated HLT paths
  - ◆ two muons $p_T(\mu)$>3 GeV
  - ◆ one track p_T> 1.2 GeV
- ➔ Invariant mass 1.60 < m(3μ) < 2.02 GeV
- ➔ Muon reconstruction quality BDT using observables from silicon tracker and muon detectors
- ➔ Analysis BDT to improve signal-to-background ratio
  - ◆ trimuon p
  - ◆ muon reconstruction BDT
  - ◆ no. of hits in muon detectors etc.

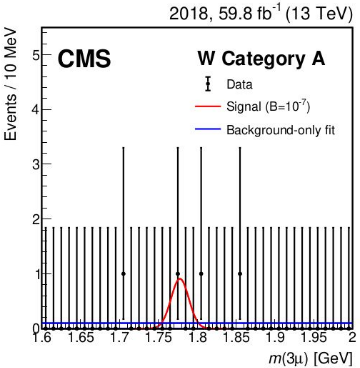
W boson decays

- ➔ Dedicated HLT paths
  - ◆ Three global muons (at least one $p_T(\mu)$>7 GeV)
- ➔ Invariant mass 1.3 < m(3μ) < 2.1 GeV
- ➔ Largest transverse mass $m_T = \sqrt{2p_T^{\tau}p_T^{miss}(1-\cos\Delta\phi(\vec{p}_T^{\tau},\vec{p}_T^{\tau}))}$
- ➔ Analysis BDT to improve signal-to-background ratio
  - ◆ $W^+ \rightarrow \tau^+ \nu_\tau$ decay: $p_T(\tau)$, $\eta(\tau)$, p_T^{miss}, $p_T(W)$ etc
  - ◆ decay vertex: χ^2 of vertex fit, α_{2D}
  - ◆ quality of muon: tight muon identification

Results

- Signal strength extracted through simultaneous UML fit to m(3μ) across three different mass resolution categories
  - Heavy flavor: Gaussian+Crystal Ball+exponential
  - W boson: Gaussian+flat polynomial

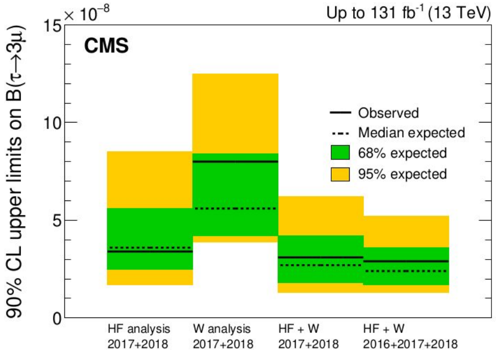




- The combined results
  (heavy flavor+W boson (2017-2018)+**2016**)

$$\mathcal{B}(\tau \to 3\mu) < 2.9(2.4) \times 10^{-8}$$ at 90% CL

$$\mathcal{B}(\tau \to 3\mu) < 3.6(3.0) \times 10^{-8}$$ at 95% CL



plots source: [arXiv:2312.02371]

Search for long-lived particles decaying in the CMS detector

- Extensions to SM predicts existence of **neutral, weakly coupled long-lived particles (LLPs)**

- LLP decays can be identified using the CMS muon detectors
  - hadronic and em showers
  - large multiplicity of hits→ **muon detector showers (MDS)** objects

- The results are interpreted in two models
  - **Twin Higgs:** SM Higgs → pair of long-lived scalars (S) → $b\bar{b}, d\bar{d}, K^+K^-, K^0K^0, \pi^+\pi^-, \pi^0\pi^0, \gamma\gamma, e^+e^-, \tau^+\tau^-$
  - **Dark shower:** SM Higgs → pair of **dark-sector quarks**→ short and long-lived **dark-sector mesons**→ SM particles through gluon, photon, vector, Higgs and dark-photon **portals**

- pp collision dataset $\sqrt{s}$ = 13 TeVand $\mathscr{L}$ = 138 fb^{-1}

- Dominant backgrounds: punch-through jets, muons that undergo bremsstrahlung

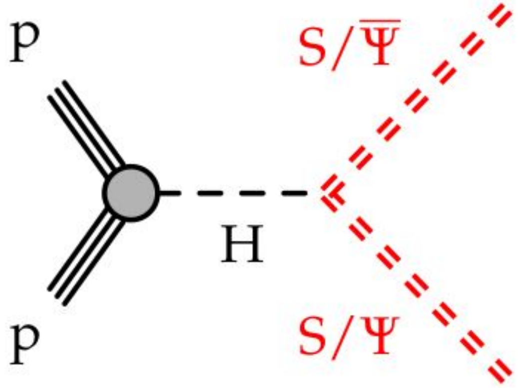


image source: arXiv:2402.01898

Analysis overview

- **DT** and **CSC** play a crucial role: hits are clustered together to form MDS objects (N_{hits}>50)

- At least 1 jet with p_T> 30 GeV and $|\eta|$<2.4, clustered from reconstructed particles using **infrared and collinear anti-k_T algorithm**

- Large p_T^{miss} (> 120 GeV)
  - improper momentum measurement
  - not associated with a particle by PF

- Excellent shielding provided by the CMS magnet and its steel flux-return yoke from backgrounds

- $\Delta\phi(\vec{p}_T^{miss}, \text{cluster})$ and N_{hits} are used to discriminate between signal and backgrounds

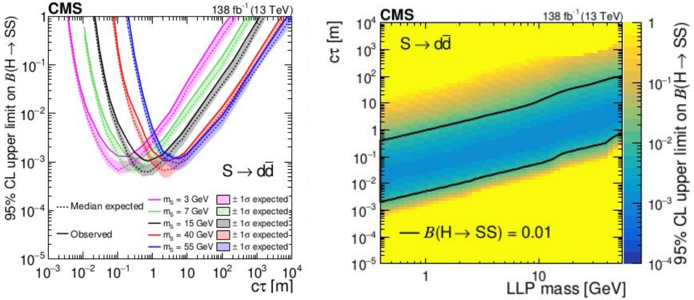
- Events are categorized into
  - two clusters
  - one CSC cluster
  - one DT cluster

Results

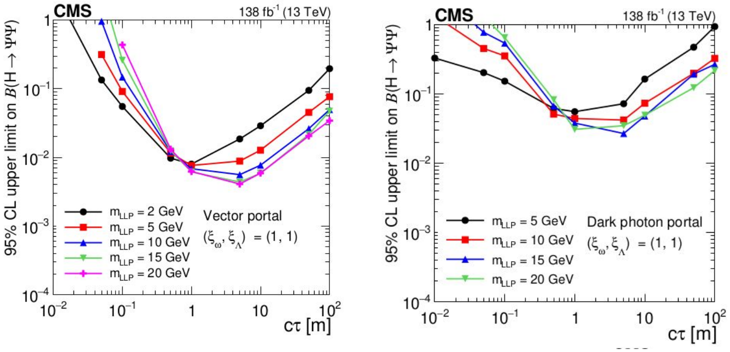
- No significant deviation in any of the categories with respect to the SM
- This sets the first LHC limits on models of dark showers produced via Higgs boson decay

LLP decay mode, mass proper decay length	CSC-CSC	DT-DT	DT-CSC	Single CSC	Single DT
$d\bar{d}$, 3 GeV, $c\tau = 1$ m	0.3	1.3	1.2	12.3	21.2
$d\bar{d}$, 7 GeV, $c\tau = 1$ m	1.5	5.7	4.3	22.5	35.8
$d\bar{d}$, 15 GeV, $c\tau = 1$ m	4.7	13.6	11.1	32.0	46.8
$d\bar{d}$, 40 GeV, $c\tau = 1$ m	6.6	12.9	8.8	23.4	19.3
$d\bar{d}$, 55 GeV, $c\tau = 1$ m	0.5	1.4	2.1	9.8	5.9
$\tau^+\tau^-$, 7 GeV, $c\tau = 1$ m	0.6	1.8	1.6	14.2	22.5
$\tau^+\tau^-$, 15 GeV, $c\tau = 1$ m	1.7	5.2	3.9	20.1	28.9
$\tau^+\tau^-$, 40 GeV, $c\tau = 1$ m	3.3	4.5	3.3	21.3	17.0
$\tau^+\tau^-$, 55 GeV, $c\tau = 1$ m	0.3	0.9	1.0	10.6	6.0
$\pi^0\pi^0$, 0.4 GeV, $c\tau = 0.1$ m	0.1	0.4	0.4	6.8	19.2
$\pi^0\pi^0$, 1 GeV, $c\tau = 0.1$ m	0.4	1.3	1.1	11.6	30.7

Expected no. of signal events assuming $\mathcal{B}(H \to SS)$=1%



Twin Higgs: 95% CL upper limits on $\mathcal{B}(H \to SS)$



Dark shower: 95% CL upper limits on $\mathcal{B}(H \to \psi\psi)$

plots source: arXiv:2402.01898

Search for long-lived heavy flavor leptons

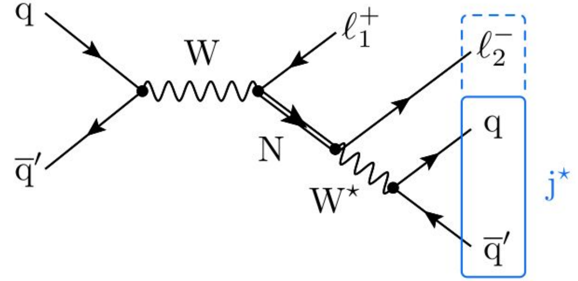
- BSM mechanism to explain fundamental nature of neutrinos
  - observation of neutrino oscillations
  - expectation value of Higgs potential

- **Seesaw** mechanism
  - existence of **additional neutral leptons** with arbitrary mass
  - through Higgs field they mix with SM neutrinos
  - mass eigenstates→ SM neutrinos and **heavy neutral leptons** (HNLs)

- Long-lived as their decay widths are proportional to $m^5_N |V_{lN}|^2$ $l \in \{e, \mu, \tau\}$

- Signature: prompt lepton l_1, a displaced lepton l_2, and at least one displaced jet j^*

- pp collision dataset $\sqrt{s}$ = 13 TeVand $\mathscr{L}$ = 138 fb^{-1}



➔ l_1 used to trigger the events (stringent criteria)

➔ jets with $|\eta|<2.4$, $p_T>20$ GeV
  - ◆ jets closest to l_2→ HNL decay

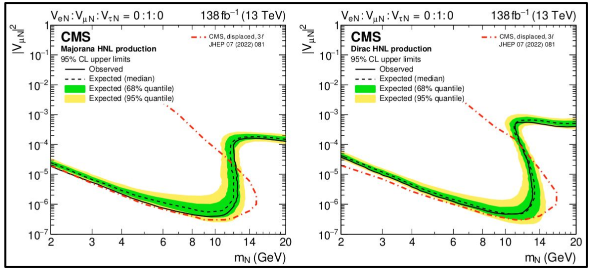
➔ Jets from HNL decay identified through **deep neural network** (DNN)

➔ Dominant backgrounds: (Z/γ^*+jets, W+jets, $V\gamma^*$+jets etc)

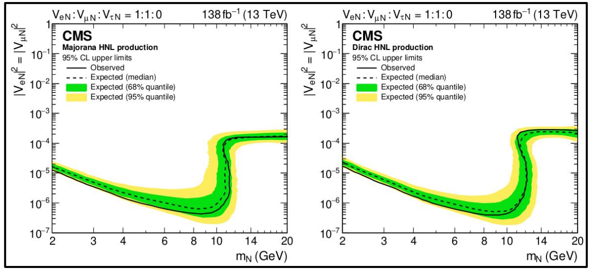
image source: arXiv:2312.07484

Results

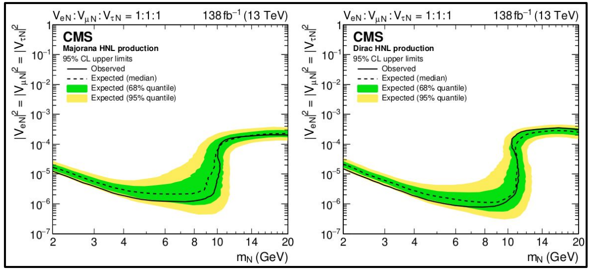
pure μ



e-μ



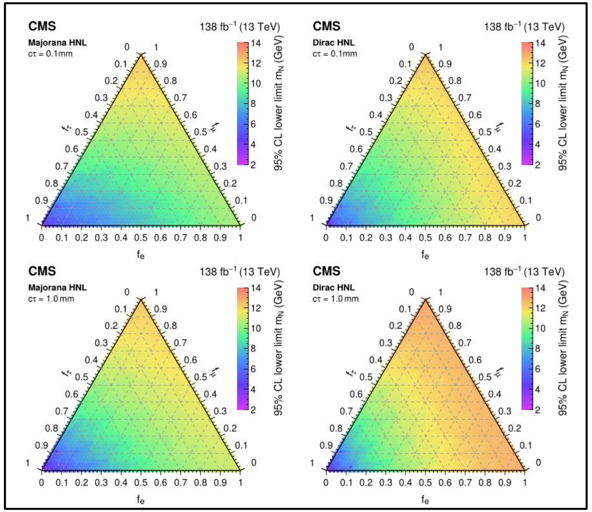
Democratic coupling



- The **most stringent limits** on the coupling strength is obtained for pure muon at m_N=10 GeV: $|V_{\mu N}|^2$>5(4)x10^{-7} Dirac(Majorana)

- The limits on m_N and proper lifetime as a function of relative coupling:

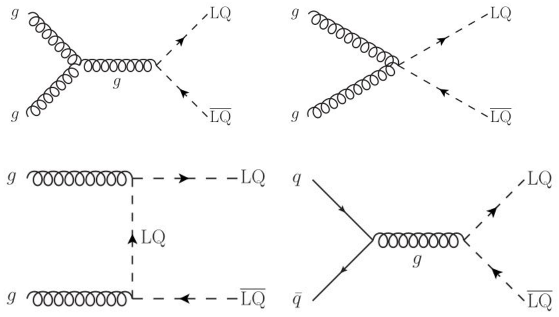
$$f_l = \frac{|V_{lN}|^2}{|V_{eN}|^2+|V_{\mu N}|^2+|V_{\tau N}|^2}$$



plots source: [arXiv:2312.07484](https://arxiv.org/abs/2312.07484)

Search for pair production of scalar and vector leptoquarks

- In models BSM
  - symmetry between quarks and leptons
  - particles that bridge these two families (**leptoquarks** LQs)



- Tensions in recent B meson decays and LFU test have increased interest in LQ

- Their interaction with SM particles completely described by:
  - $\mathbf{m_{LQ}}$
  - Yukawa coupling at LQ-lepton-quark vertex $\boldsymbol{\lambda_{LQ}}$
  - Branching fraction $\boldsymbol{\beta}$ of a LQ decay to a lepton and a quark
  - $\boldsymbol{\kappa}$ (vector LQs) relates anomalous magnetic and electric quadrupole moment

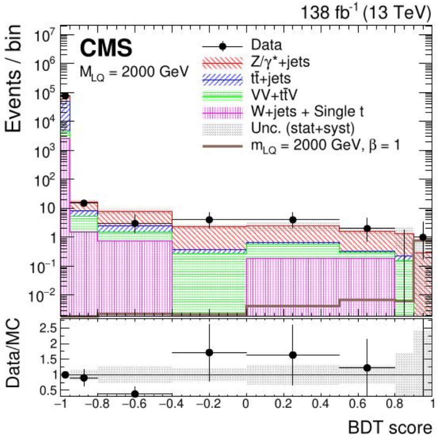
- pp collision dataset $\sqrt{s}$ = 13 TeVand $\mathscr{L}$ = 138 fb^{-1}

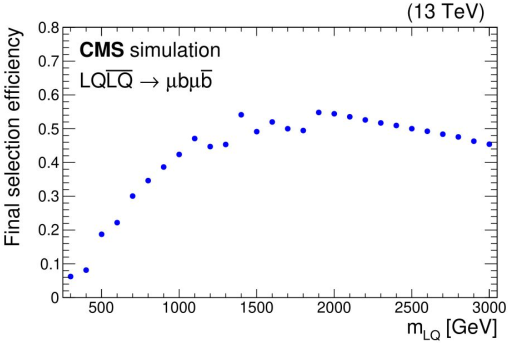
signature: $\mathrm{LQ\bar{LQ}} \to \mu b \mu \bar{b}$

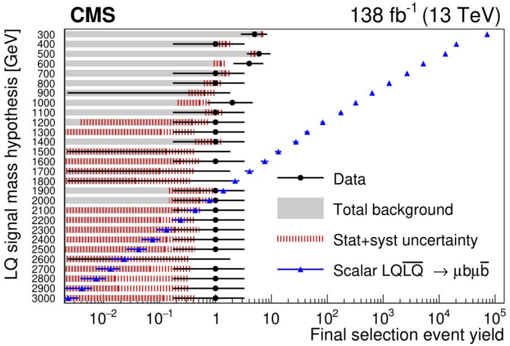
- BDT used to discriminate between signal and background (Z/γ+jets, tt+jets, diboson production)

image source: CMS-EXO-21-018-003

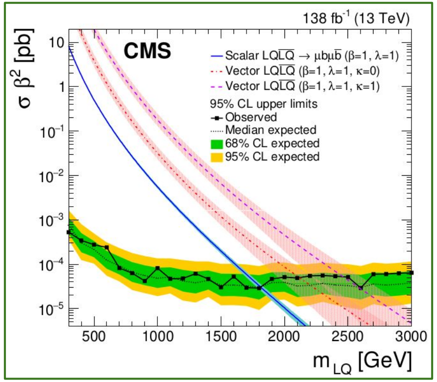
Results

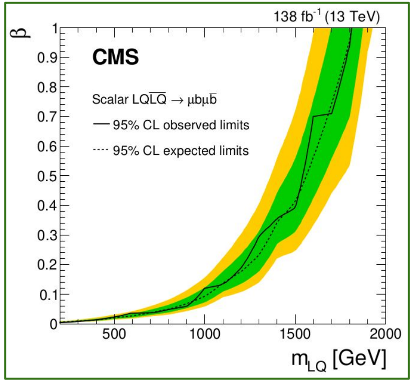






- Scalar LQ with m_{LQ}<1810 GeV are excluded for **β**=1
- Vector LQ with m_{LQ}<2120 GeV are excluded for **β**=1
- These represents the most stringent limits to date on these models





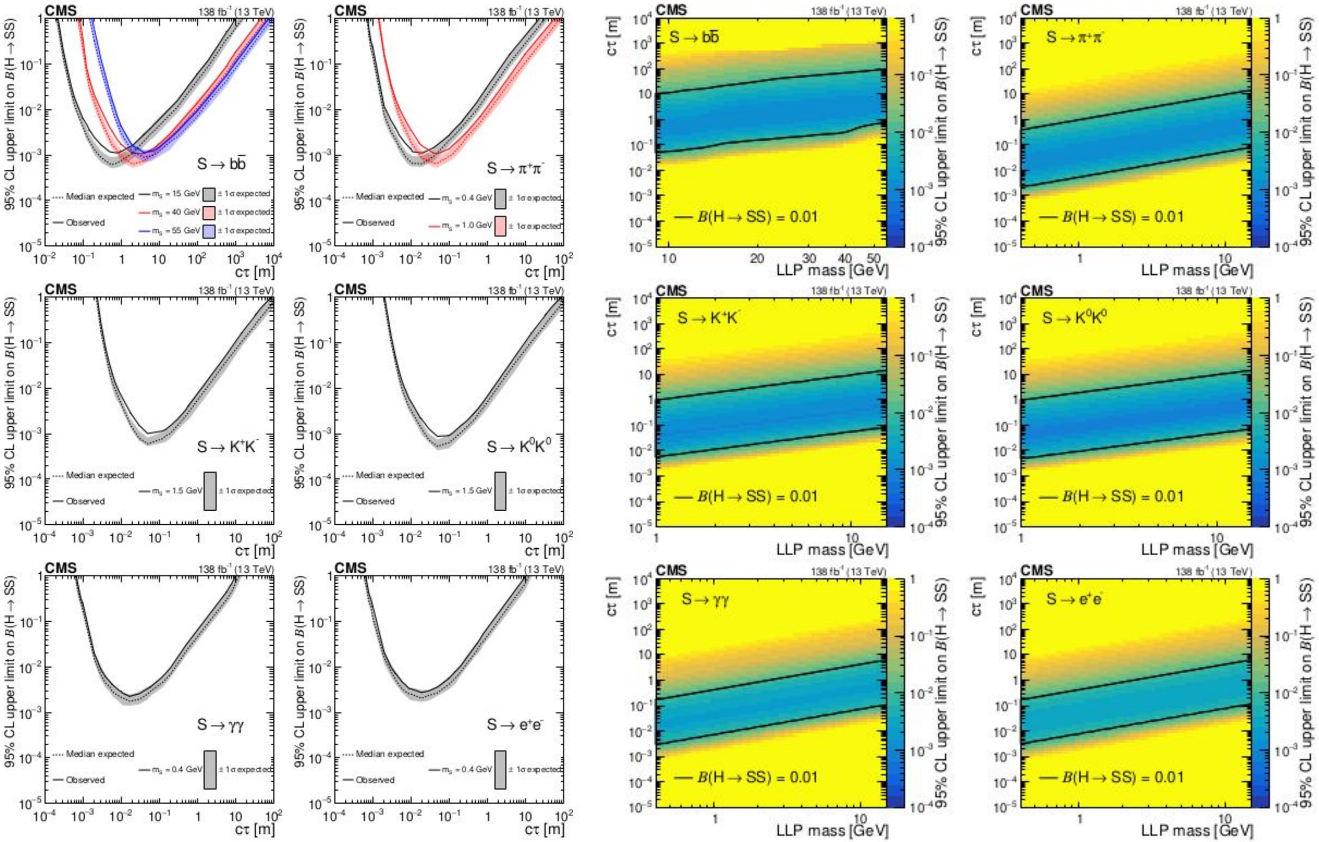
plots source: CMS-EXO-21-018-003

Summary

- Recent results from CMS are presented for rare decays
- First observation of $\Lambda^0_b \to J/\psi p K^-$ with branching fraction measurement which also opens the path for doubly-strange hidden-charm pentaquarks searches
- LFU test with results in agreement with SM and other collaboration results
- LFV decay $\tau \to 3\mu$ with limits on its branching fraction
- Searches for long-lived heavy particles (LLPs) , long-lived heavy neutral leptons (HNLs) and pair production of leptoquarks (LQs)
- No statistical deviation with respect to SM is observed

BackUp

Search for long-lived particles decaying in the CMS detector



Search for long-lived heavy flavor leptons

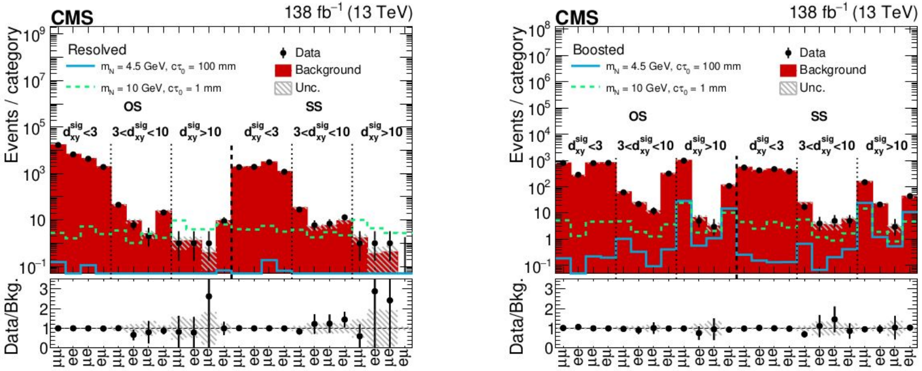


Figure 5: Observed number of events and predicted number of background events per category for (left) resolved and (right) boosted categories. The bin label denotes the flavour of the prompt (ℓ_1) and displaced (ℓ_2) lepton as $\ell_1\ell_2$. Two representative signal scenarios for Majorana HNL production with equal coupling to all lepton generations are overlaid. The lower panels show the ratio of the data to the predicted background. The hatched band shows the total systematic uncertainty in the predicted background.

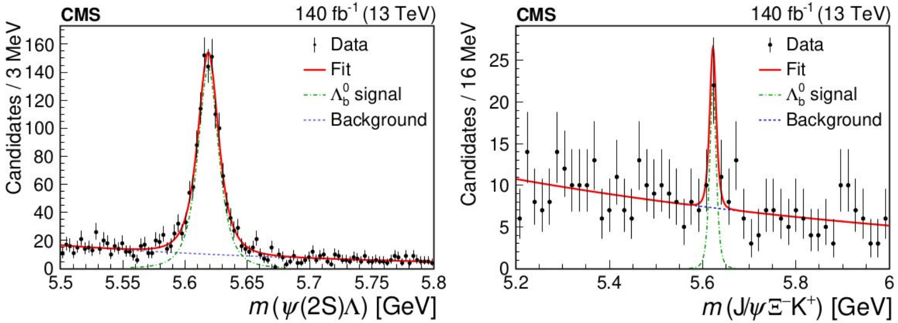
Observation of $\Lambda^0_b \to J/\psi \Xi^- K^+$ decay

- Opportunity to search for **intermediate resonances**
- LHCb Collaboration reports the observation of **pentaquark-like** structures in $\Lambda^0_b \to J/\psi pK$
- Additional exotic structures in $\Lambda^0_b \to J/\psi pK$, $\Xi_b^- \to J/\psi \Lambda K^-$, $B^0_s \to J/\psi p\bar{p}$ and $B^- \to J/\psi \Lambda \bar{p}$
- **Hidden-charm pentaquarks** reported only in $J/\psi p$ and $J/\psi \Lambda$ system
- Decays with Ξ^- and Ω^- could unveil the existence of **double or triply strange pentaquarks**
- CMS reports the first observation for such decay $\Lambda^0_b \to J/\psi \Xi^- K^+$
- pp collision data at $\sqrt{s}$=13TeV and $\mathcal{L}$ = 140 fb^{-1}

Results

- Offline muons selections: $p_T(\mu^{\pm})$>3 GeV, $|\eta(\mu^{\pm})|$<2.4, $P_{vtx}(\mu^+\mu^-)$>1% (χ^2 fit probability to a common vertex)

- Yields extracted from unbinned maximum likelihood fit (UML)
  - signal: Student's t-distribution
  - background: exponential
  - $N(J/\psi\Xi^-K^+) = 46 \pm 11$



- $\Lambda^0_b \to \psi(2S)\,\Lambda$ used as the normalization channel

- Additional selections applied to measure $\mathfrak{R}$
  - $p_T(\mu^{\pm})$>4 GeV, $p_T(J/\psi)$>6.9 GeV, $P_{vtx}(\mu^+\mu^-)$>5% , track IP>2σ
  - $N(J/\psi\Xi^-K^+) = 23 \pm 7$

- Efficiencies(ϵ) calculated from simulation
  - detector acceptance
  - reconstruction and trigger efficiency

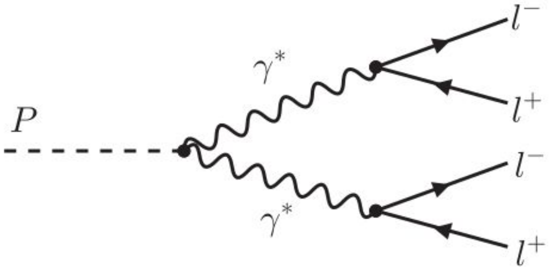
$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi\Xi^-K^+}} \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\Xi^-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

- First observation with a statistical significance of 5.8σ

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

plots source: arXiv:2401.16303

Observation of the rare **$\eta \rightarrow 4\mu$** decay



- Radiative decay
  - **electromagnetic coupling** of pseudoscalar meson to photon
  - photons internally convert into pair of leptons

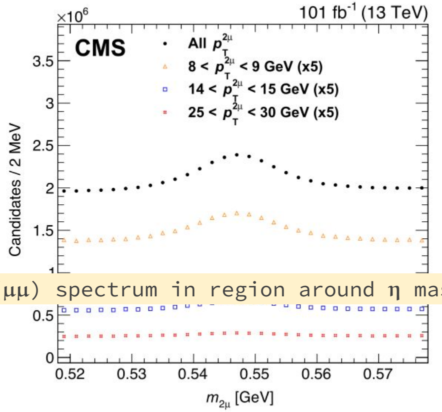
- Highly suppressed: proceed only through em instead of strong interaction

- The predicted branching fraction is extremely small $\mathcal{B}(\eta \to 4\mu) = (3.98 \pm 0.15) \times 10^{-9}$

- pp collision data (2017-2018) at √s = 13 TeV (2017-2018) and $\mathcal{L}$ = 101 fb^{-1}

- Dedicated high-rate triggers
  - Low p thresholds
  - Events only with muons reconstruction at HLT: **data-scouting**

- CMS reports first observation with branching fraction measurement $\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$,



m(μμ) spectrum in region around η mass

plots source: [PRL 131 (2023) 091903]

Results

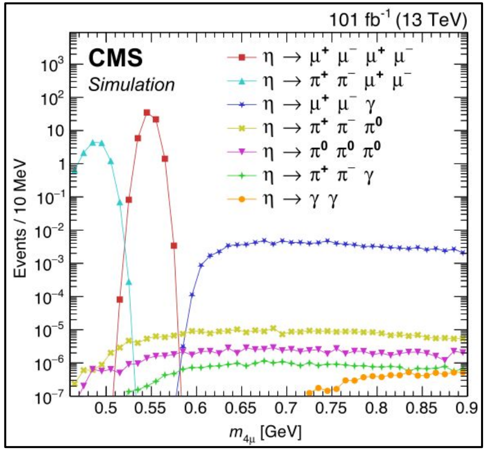
- A binned maximum likelihood fit:
  - signal: single-sided Crystal Ball function
  - background: threshold function
  - $N_{4\mu} = 49.6 \pm 8.1$; $N_{bkg} = 16.6 \pm 0.6$
- Branching fraction results

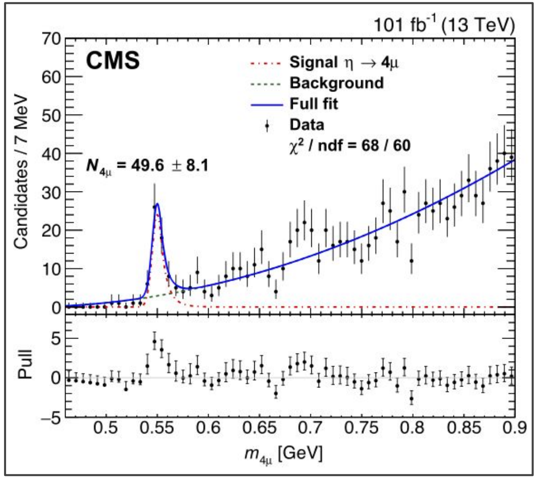
$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = [0.86 \pm 0.14(\text{stat}) \pm 0.12(\text{syst})] \times 10^{-3},$$

$$\mathcal{B}(\eta \to \mu^+\mu^-) = (5.8 \pm 0.8) \times 10^{-6}$$ PDG

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

- In agreement with SM prediction $(3.98 \pm 0.15) \times 10^{-9}$





plots source: PRL 131 (2023) 091903