Heavy Flavour Decays & LFV (& LFU)

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on **behalf on the ATLAS, CMS and LHCb collaborations**

LHCP 2023

Introduction

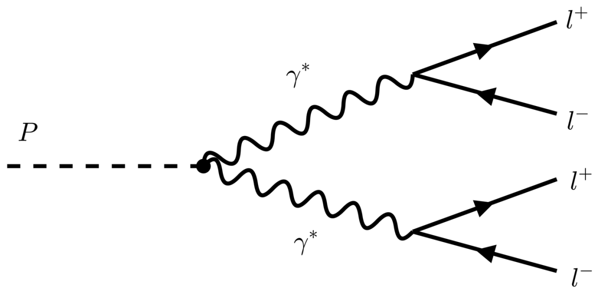
- A very broad title, so inevitable omissions
- In consultation with the HF convenors the scope was shifted as the LFV and LFU is so rich. We also interpret HF to include top processes for LFV and LFU studies
- As a result I direct you to the excellent talks in the parallel sessions
- Guided by responses from the experiments, some of which are now not covered here, but many thanks for their input
- Thanks to contributors, blame the speaker!

Part 1: Rare decays (excluding LFV)

- $\eta \to \mu^+\mu^- \mu^+\mu^-$
- $D^0 \to \mu^+\mu^-$
- $D^{*0} \to \mu^+\mu^-$
- $B^0_s \to \mu^+\mu^-$

- X(6900), new structures in the di-charmonium mass spectrum

First observation of the rare 4μ decay of the η meson



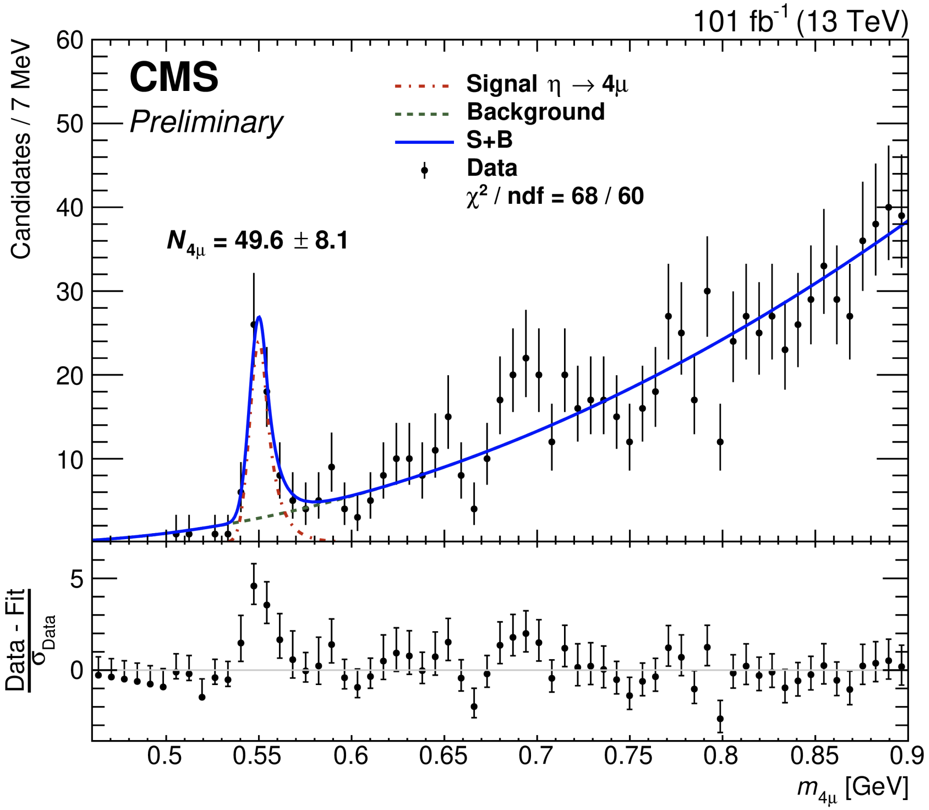
- >5 sigma observation of double-Dalitz decay $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Data from high-rate low-pt muon triggers saving only HLT-level info, corresponding to 101 fb^{-1} (2017+2018).

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

- Using world average:

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

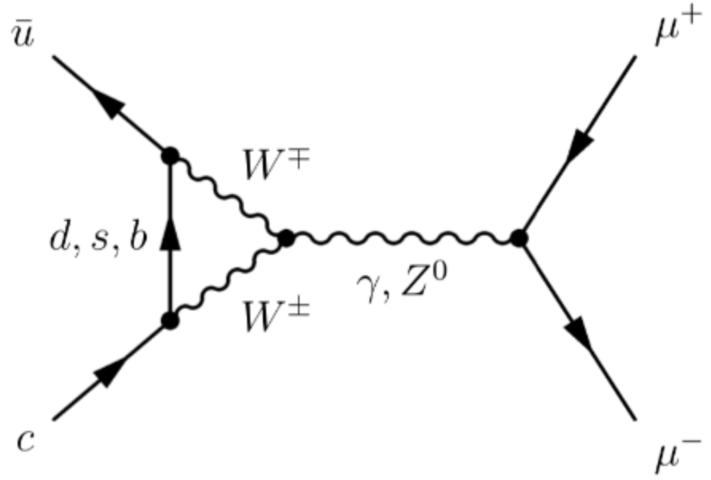
- Branching fraction is higher than predicted but within uncertainty.



LHCb-PAPER-2022-029

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

Z-penguin contribution in the SM



FCNC decay with GIM and helicity suppression

- Key in constraining non-SM physics
- 2 SM contributions (PRD.93.074001):
  - Short distance: B(D^0)→ $\mu^+\mu^-$ < 10^{-18} (Z-penguins, W-boxes)
  - Long distance : B($D0 \to \mu^+\mu^-$) < 10^{-11} ($D^0 \to \gamma\gamma$ transitions)

Previous upper limit by LHCb (1fb^{-1}) B($D^0 \to \mu^+\mu^-$)<6.2 ·10^{-9} at 90%CL PLB.2013.06.37

Analysis Strategy

- Reconstruct tagged $D^{*+} \to D^0\pi^+$ decays
- Use a BDT against combinatorial background
- Use PID info to suppress hh → $\mu\mu$ misID background
- Perform ML fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
- Norm. yield obtained from fit to Δm of $D^{*+} \to D_0(h^-\pi^+)\pi^+$ decays

Efficiency ratio — Norm. BF

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^0\to\mu^+\mu^-}}{N_{D^0\to h^+h^-}} \cdot \frac{\varepsilon_{h^+h^-}}{\varepsilon_{\mu^+\mu^-}} \cdot p \cdot \mathcal{B}(D^0 \to h^+h^-)$$

Norm. yield — Trigger prescale on norm. mode

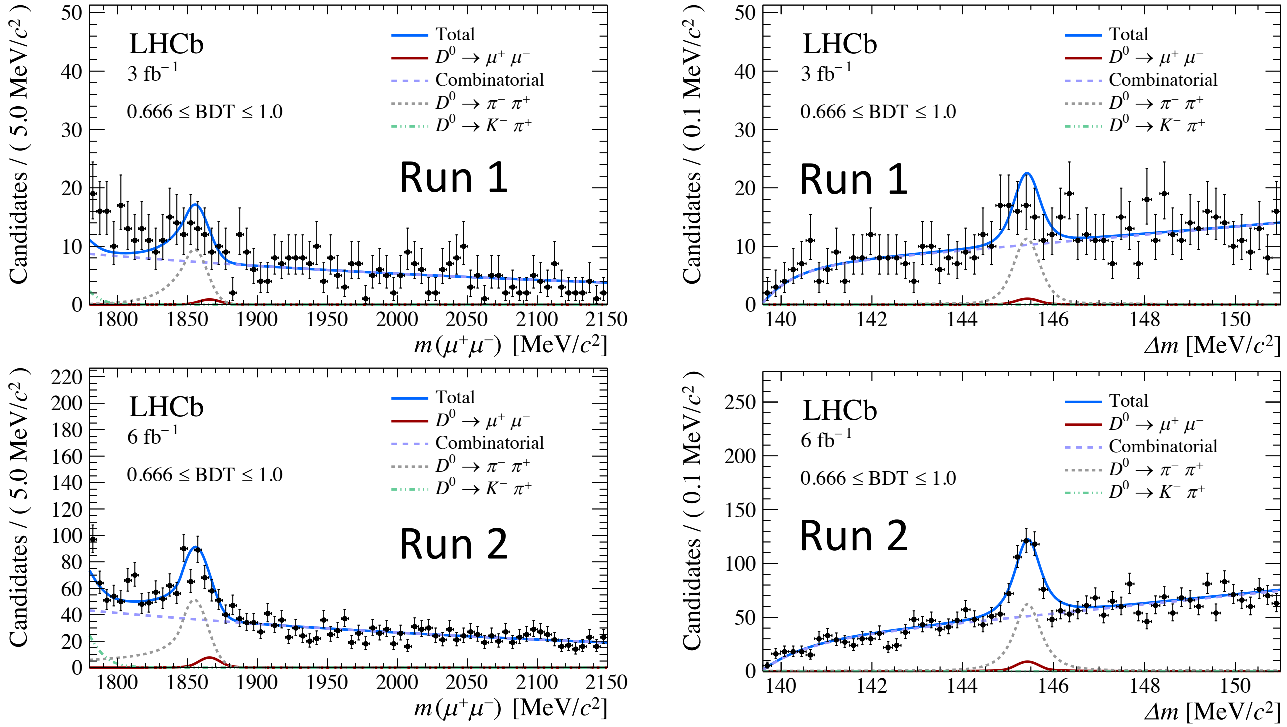
$h = K$ or π

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

Result in most sensitive BDT region

Signal mode fit performed simultaneously in 3 BDT intervals

- MisID background yields constrained based on simulation and PDG



- Results from fit $N(D^0) \to \mu^+\mu^-$ =79±45

$\Rightarrow \mathcal{B}(D^0 \to \mu^+\mu^-) = (1.7 \pm 1.0) \cdot 10^{-9}$

Derive upper limit on BF

$\Rightarrow \mathcal{B}(D^0 \to \mu^+\mu^-) < 2.94\ (3.25) \cdot 10^{-9}$ at 90(95)% CL

Improvement by factor ≈ 2 wrt. previous result and most stringent limit of FCNC in charm sector

LHCb-PAPER-2023-004

Search for $D^{*0} \to \mu^+\mu^-$

- **Analysis Strategy**
- Reconstruct $B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-$ decays
- Use a BDT against combinatorial bkg.
- Use PID info to suppress $K \to \pi$ and hh $\to \mu\mu$ misID bkgs.
- Perform simultaneous ML fit to $m(D^{*0})$ and $m(B^-)$
- Signal yield $N(B^- \to D^{*0}\pi^-)$ from fit translated into BF via

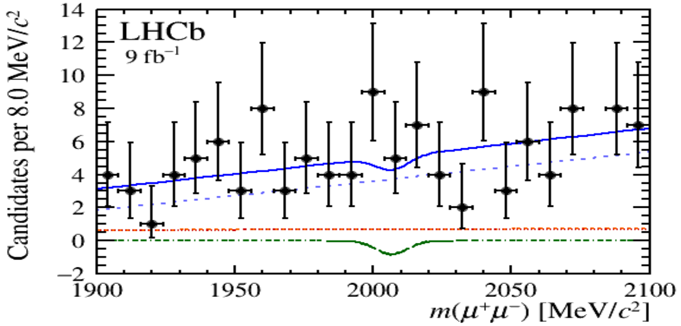
$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) =$$

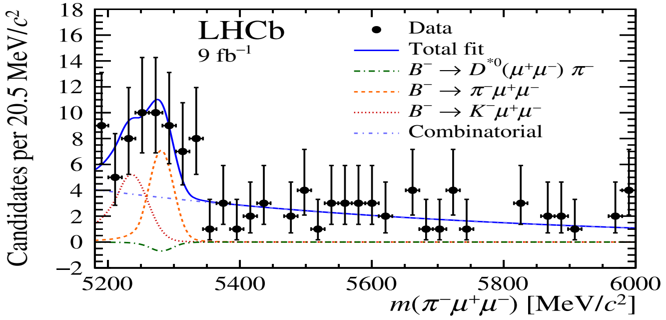
Efficiency ratio — Known BFs

$$\frac{N_{D^{*0}\pi^-}}{N_{J/\psi K^-}} \cdot \frac{\varepsilon_{J/\psi K^-}}{\varepsilon_{D^{*0}\pi^-}} \cdot \frac{\mathcal{B}\left(B^- \to J/\psi K^-\right)}{\mathcal{B}\left(B^- \to D^{*0}\pi^-\right)} \cdot \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$$

Normalisation yield

- Normalisation yield from fitting m(J/ψ) and m(B^-) in $B^- \to J/\psi(\mu\mu)\,K^-$ decays





Slightly negative signal yield
N(B^-)→$D^{*0}\pi^-$ = −2±3

$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = (-1.06 \pm 1.85) \cdot 10^{-8}$$

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\%\ \text{CL}\,.$$

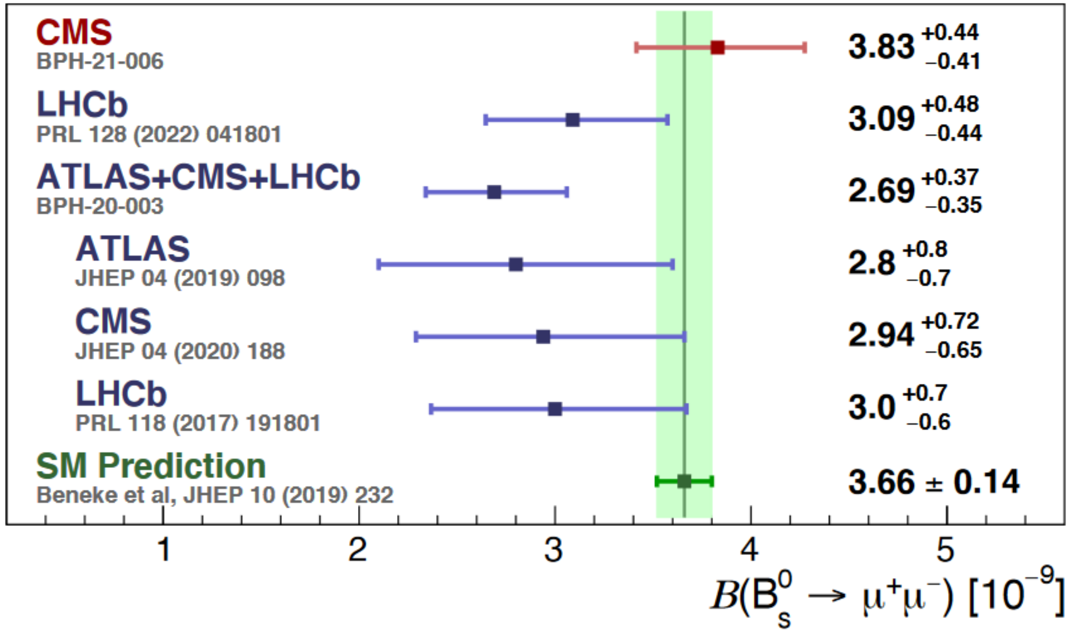
Most stringent upper limit on $D^{*0} \to l^+l^-$ decays
First search of a rare charm-hadron decay exploiting production in beauty decays

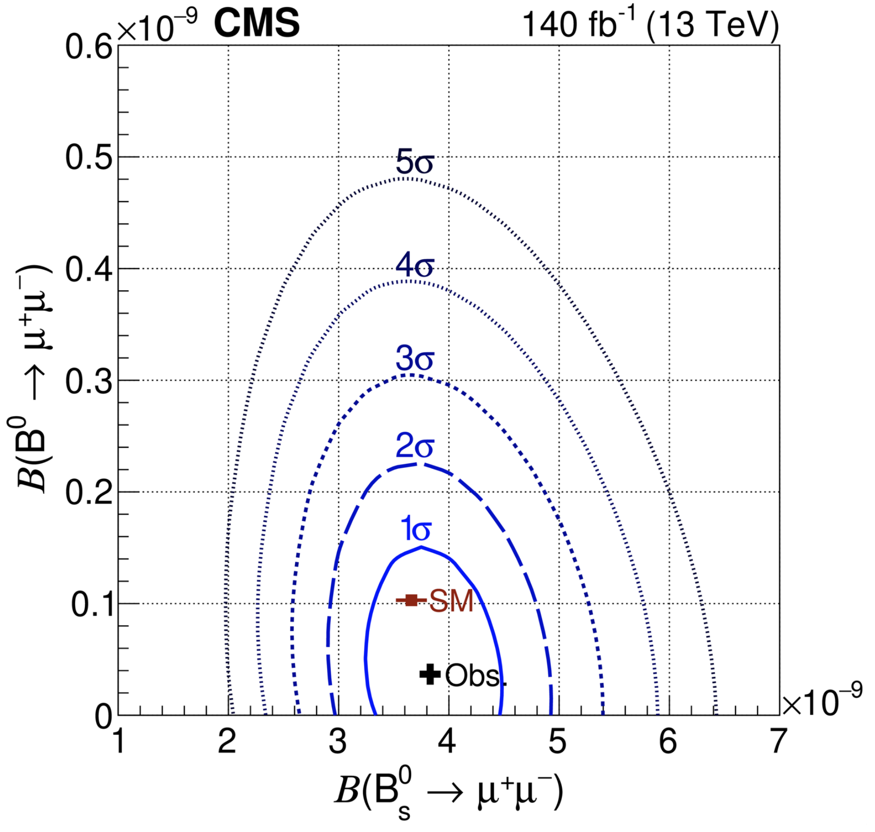
Measurement of the $B^0_s \to \mu^+\mu^-$ decay properties

- Integrated luminosity of $140 fb^{-1}$.
- The relative uncertainty is reduced from 23 to 11% compared with previous CMS measurement.

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

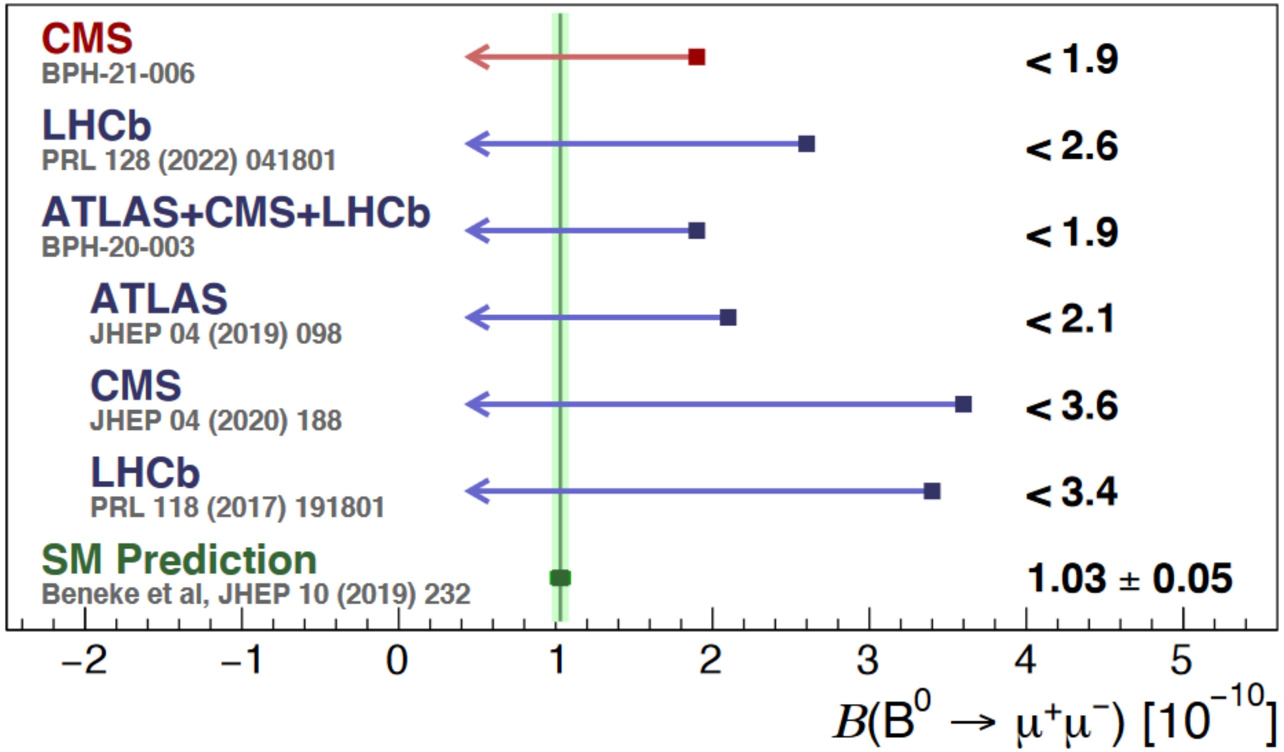
$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\,\text{ps}.$$

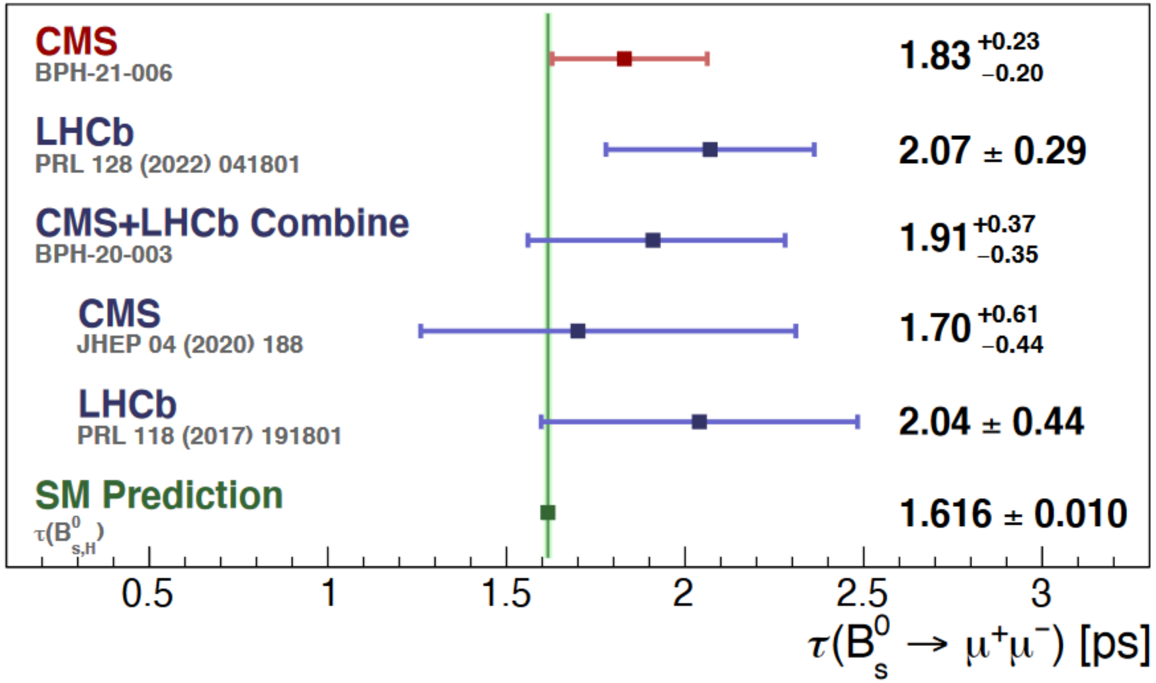




CMS is about 1.2 S.D. higher than LHCb
Some tension with previously combined result

$B^0_s \to \mu^+\mu^-$ decay properties, $B^0_d \to \mu^+\mu^-$ search





The main challenge with $B^0 \to \mu\mu$ is the combinatorial background.
It will require more data and analysis improvements to reach discovery level.

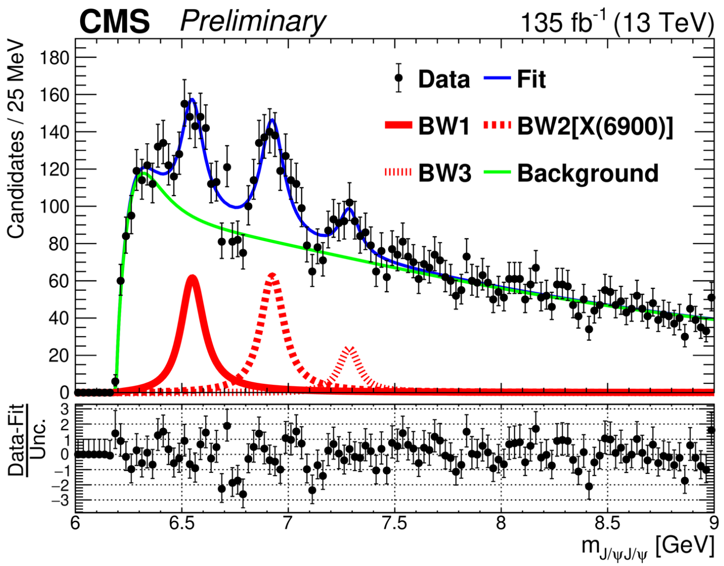
CMS-PAS-BPH-21-003

arXiv:2304.08962 BPHY-2022-01

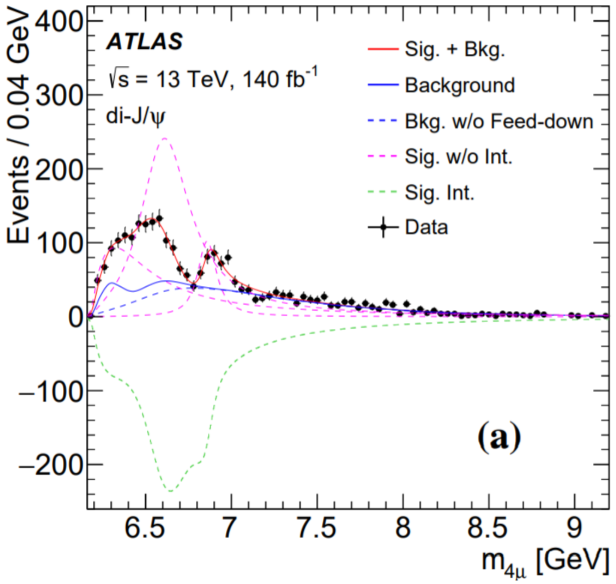
Observation of new structures in the di-charmonium mass spectra

- Motivated by LHCb discovery of resonant-like signal X(6900) in di-J/ψ spectrum.
- Goal: search for potential tetraquarks decaying into a pair of charmonia in the 4μ final state
- Observation of the X (6900) structure is confirmed by both experiments.
- CMS see clear structure at 6552MeV and 7287MeV; ATLAS also see a broad structure at the lower mass
- More data needed to explore the structures and any exotic nature

135 fb^{-1} recorded with the CMS



139 fb^{-1} recorded by ATLAS



Part 2: LFV and LFU from Heavy Flavour

From LHCb

- $B^0{}_{(s)} \to p\ \mu^-$
- $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$
- $b \to sl\nu$
- $b \to cl\nu$

- LFV from $\tau \to \mu\mu\mu$ (CMS – late addition)
- LFV in top sector in the trilepton final state (ATLAS, CMS)
- LFV $B(t \to \tau\mu q)$ from dileptonic tt decays (ATLAS)
- LFU in b-decay from 2l+(0/1)b-jet (ATLAS)

LHCb-PAPER-2022-022

Search for $B^0_{(s)} \to p\mu^-$

If seen, violates lepton and baryon number

Non-observation of proton decay suggests

$\mathcal{B}(\bar{b} \to uul^-) \lesssim 10^{-27}$ PRD.72.095001

Analysis Strategy

Reconstruct $B^0 \to p\,\mu^-$ decays (s)

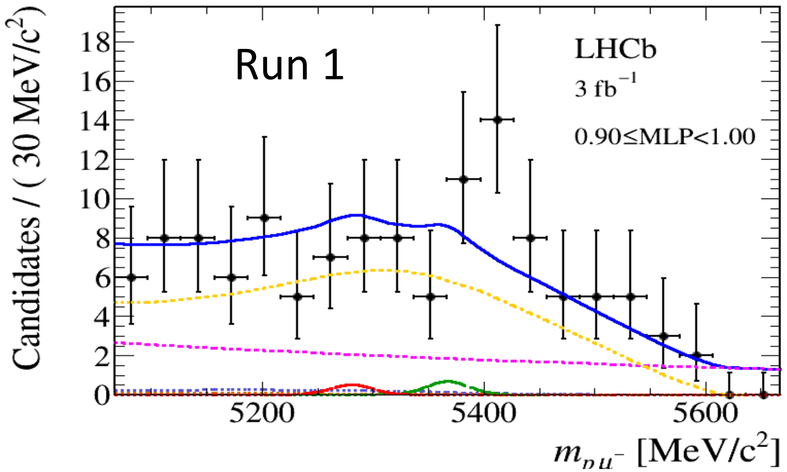
- MultiLayer Perceptron for combinatorial background
- Use PID info to suppress hh $\to p\mu$ misID background
- Perform ML fit to $m(p\,\mu^-)$
- Use $B^- \to J/\psi(\mu^+\mu^-)K^-$ & $B^0 \to K^+\pi^-$ as normalisation modes

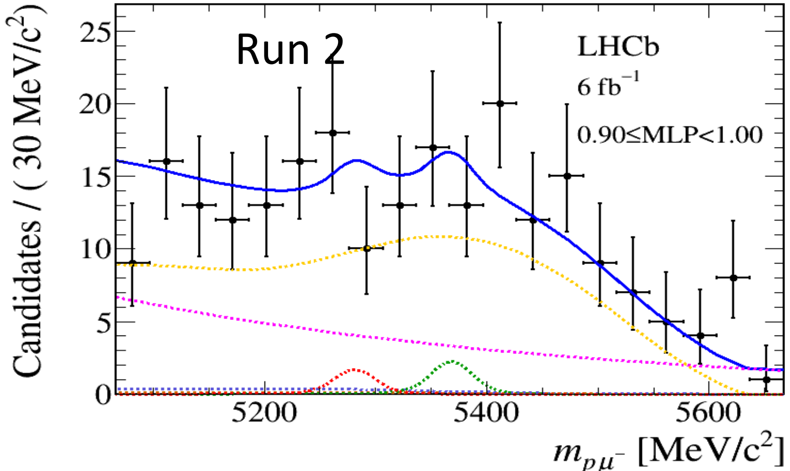
Signal simultaneous fit performed in 7 MLP intervals

Semileptonic decays are dominant bkg. source

$$\mathcal{B}(B^0 \to p\mu^-) = (0.84 \pm 1.17 \pm 0.57) \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to p\mu^-) = (4.28 \pm 3.99 \pm 2.29) \times 10^{-9}$$

$\Rightarrow$



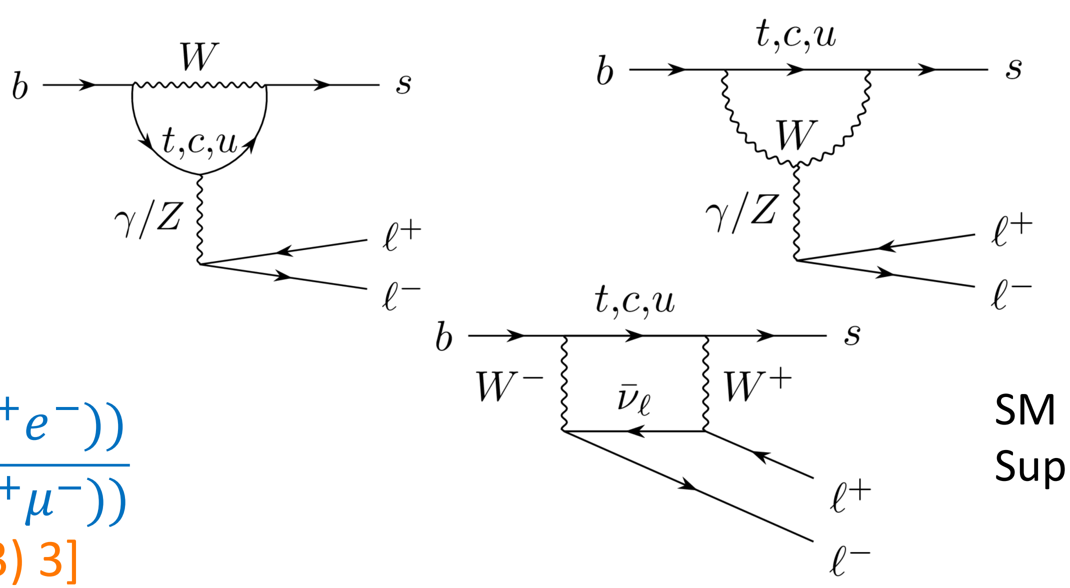


1st upper limits based on CLs method at 90% (95)% CL

$$\mathcal{B}(B^0 \to p\mu^-) < 2.6\ (3.1) \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to p\mu^-) < 12.1\ (14.0) \times 10^{-9}$$

arXiv:2212.09153

b→sll: R(K) and R(K*)



SM LO Suppressed

$9 fb^{-1}$ from Run 1 and 2

Analysis Strategy

Electron and muon recon v different ⇒

Use **double** ratio of rare to resonant decay modes

$$R_k = \frac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to K^+e^+e^-)} \times \frac{B(B^+ \to K^+ J/\psi(\to e^+e^-))}{B(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}$$

Resonant ratio from BESIII and BEPCII [PRD 88 (2013) 3]

Cross-check with this dataset and with $R_{\psi(2S)}$

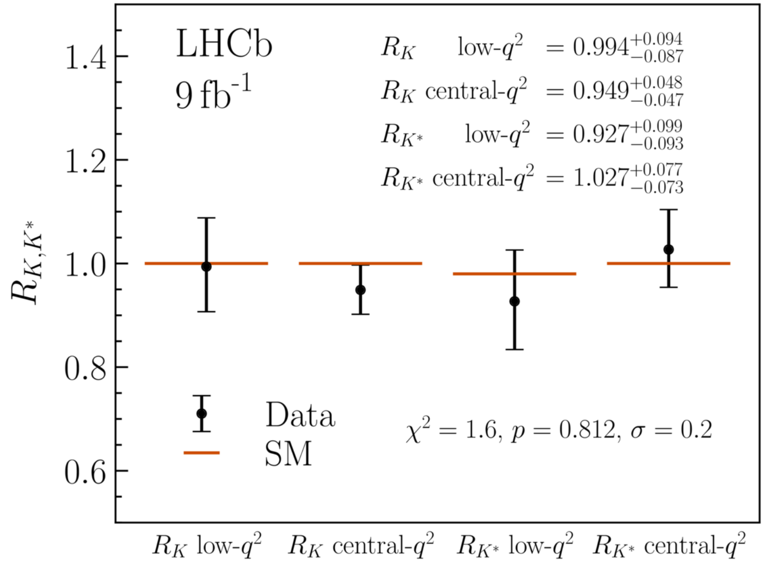
Analyse in low and high q^2 regions

Challenges

Brehm for electrons, requires recovery & modelling

Electron triggering efficiency (combine triggers)

Background modelling (mainly partial reconstruction of D decays



Result:

Compatible with the SM at 0.2σ

Statistical errors dominate

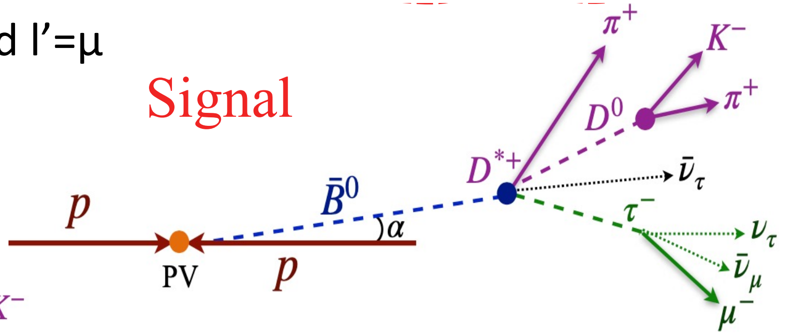
b→cll(i) Simultaneous R(D) & R(D*), muonic τ-decay

$$R(X_c) = \frac{BF(X_b \to X_c l \nu)}{BF(X_b \to X_c l' \nu)}$$

🙂 Good statistics
🙂 Clean, cancel systematics
😕 Missing ν
😕 Backgrounds

This study, l=τ and l'=μ

Signal



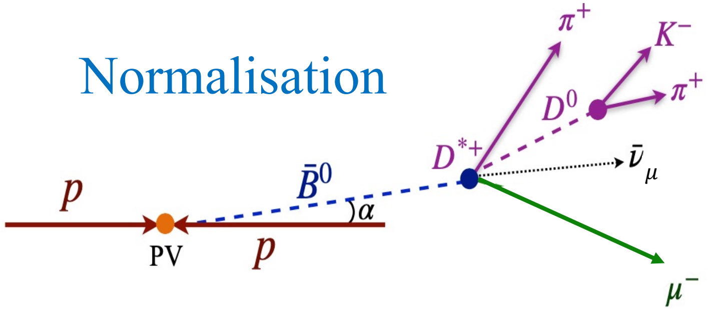
Analysis Strategy

Run 1 dataset

$\bar{B}^0 \to D^{*+}\tau^- \bar{\nu}_\tau$ $B^- \to D^{*0}\tau^-\bar{\nu}_\tau$ and $B^- \to D^0\tau^- \bar{\nu}_\tau$ decays

Use muonic τ→μ decays

Normalisation



[D*μ] – use $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$

[D μ] – use all 3 channels

Use analogue semi-muonic decays to normalise

Separate modes using $q^2 = (P_B - P_D)^2$, El, m^2_{miss}

Control feed-down (MVA), mis-ID and fake B, D

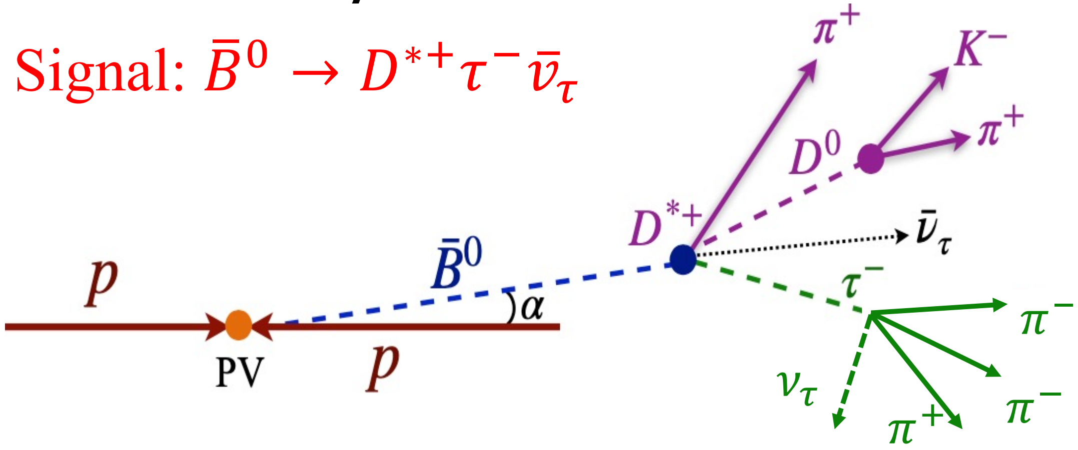
$$R(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$R(D) = 0.441 \pm 0.060 \pm 0.066$$
$$\rho = -0.43$$

Result is 1.9σ from SM

LHCb-PAPER-2022-052

(ii) R(D) & R(D*) with hadronic τ-decay

Signal: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



Analysis Strategy

Partial Run 2 dataset (2 fb^{-1})

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$, B- → $D^{*0}\tau^-\bar{\nu}$ and $B^- \to D^0\tau^-\bar{\nu}$ decays

Use τ→3h decays

Use hadronic D decay to normalise

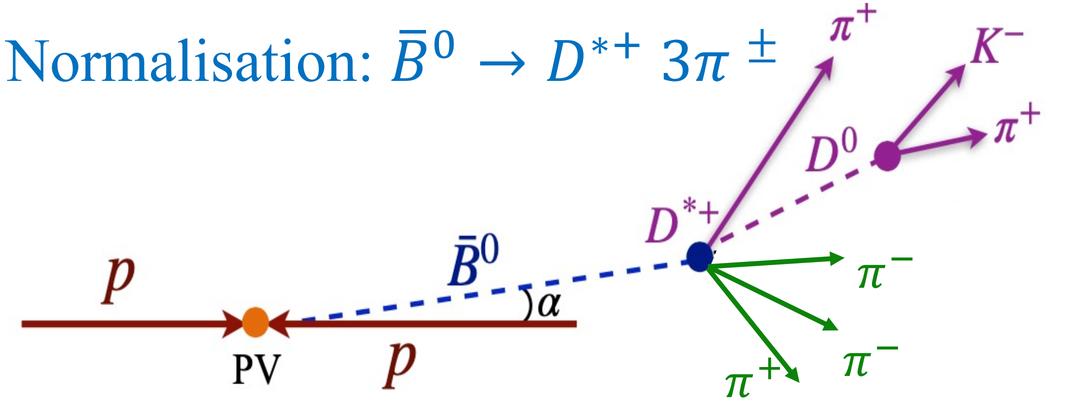
Measure:

$$K(D^*) = \frac{BF(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BF(\bar{B}^0 \to D^{*+}3\pi^\pm)}$$

Use external input to obtain:

$$R(D^*) = K(D^*) * \frac{BF(\bar{B}^0 \to D^{*+}3\pi^\pm)}{BF(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

Normalisation: $\bar{B}^0 \to D^{*+}\ 3\pi^\pm$

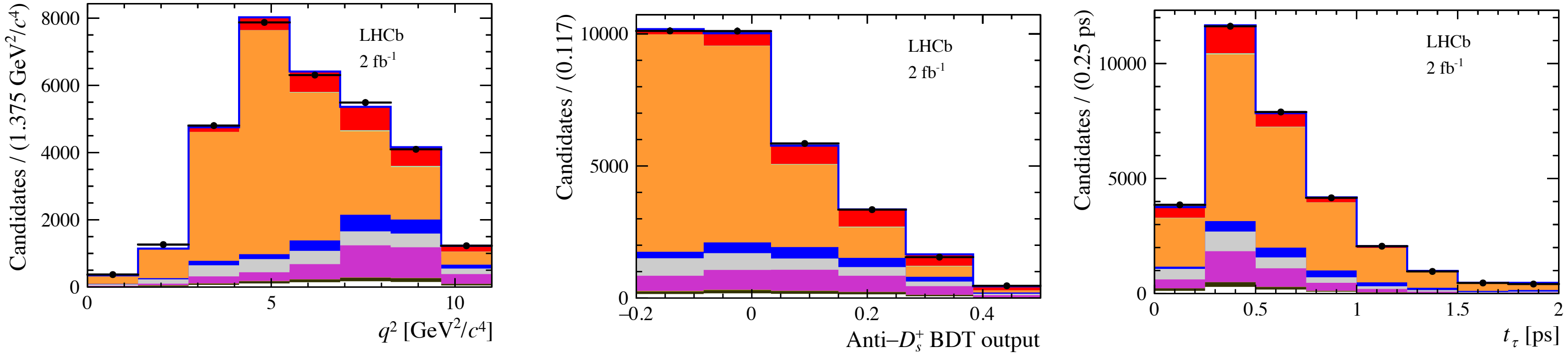


Dominant systematics:

- Simulation sample size
- Modelling of backgrounds ($\bar{B}^0 \to D^{*+}3\pi^\pm$X and double charm backgrounds)

(iii) R(D) & R(D*) with hadronic τ-decays

3D ML fit to q², τ lifetime and anti-D_s^+ BDT output



$K(D^*) = 1.700 \pm 0.101\ (\text{stat})^{+0.105}_{-0.100}(\text{syst})$

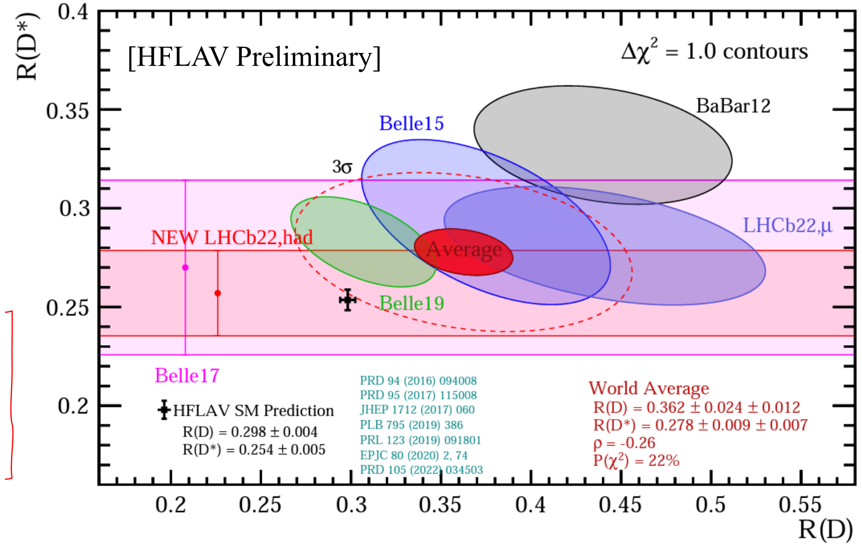
$R(D^*) = 0.247 \pm 0.015\ (\text{stat}) \pm 0.015\ (\text{syst}) \pm 0.012\ (\text{ext.})$

within 1σ of SM prediction

⤇ Combine with leptonic result

$R(D^*) = 0.257 \pm 0.012\ (\text{stat}) \pm 0.014\ (\text{syst}) \pm 0.012\ (\text{ext.})$

Leaves WA 3σ from SM



New this week

BPH-23-005
See Keith Ulmer, BSM/Flavour Thurs morning

LFV: $\tau \to \mu\mu\mu$ from HF and W boson decays

Existing LHC limits @ 90% CL

LHCb <4.6×10^{-8} *JHEP* **02** (2015) 121 ATLAS <38×10^{-8} *EPJ. C* **76** (2016) 232 CMS <8.0×10^{-8} *JHEP* **01** (2021) 163

Other Limits

Belle < 2.1 x 10^{-8} *PLB* **687** (2010) 139 Babar 3.3 x 10^{-8} *PRD* **81** (2010) 111101

τ sources:

HF (dominant): $D_s^+ \to \tau^+\nu$; $B^+/B^0 \to \tau^+ X$

Normalisation: $D_s^+ \to \varphi\pi^+ \to \mu^+\mu^-\pi^+$

L1 trigger: 2μ+1 track; L2 3μ and prescaled 2μ+1 track

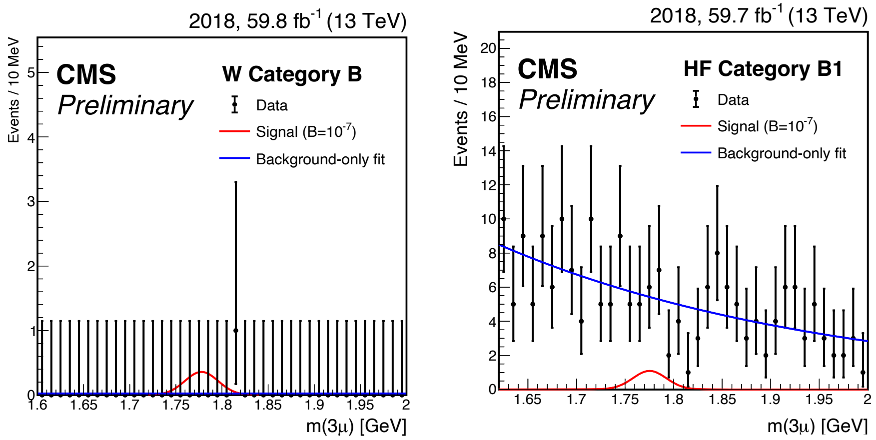
Obtain normalisation from data, fit proper lifetime for $B \to D_s^+$ fraction

BDT to supress backgrounds

Boson: $W^+ \to \tau^+\nu$

3μ signal, background reduced with BDT and veto di-μ near known resonances

Both sources: subsamples characterised by low, medium, high m(3τ) resolution



Results:

These studies

B($\tau \to 3\mu$) of 3.1(2.7) × 10^{-8} obs(exp) @ 90%

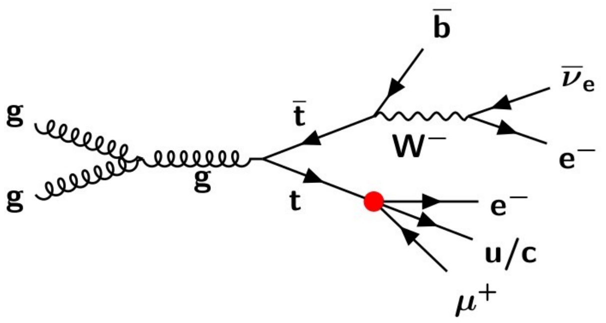
Combine with earlier result

B($\tau \to 3\mu$) of 2.9(2.4) × 10^{-8} obs(exp) @ 90%

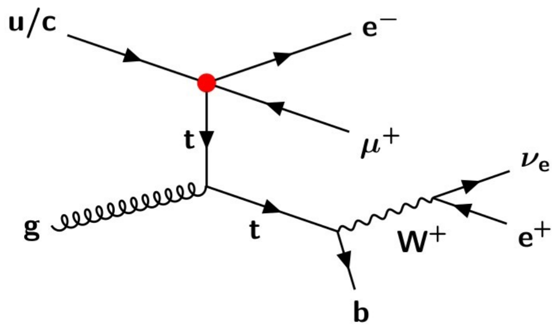
LFV in the top sector trilepton final state

Signature:

- 3 l in final state (eμ modes)
  - 1 l from SM top decay (**bachelor** l)
  - 2 l from the LFV interaction
- b-jet



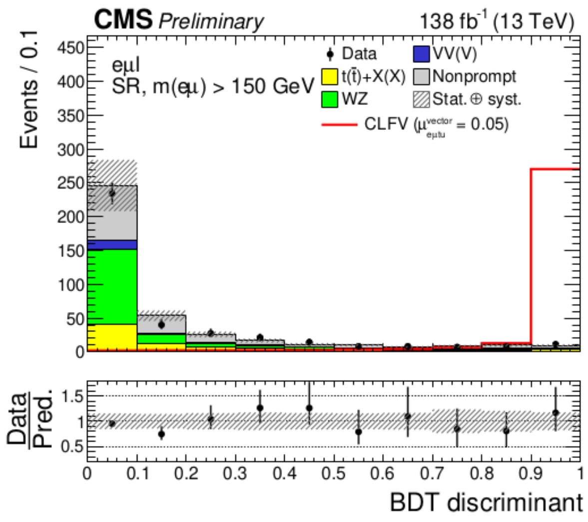
Production



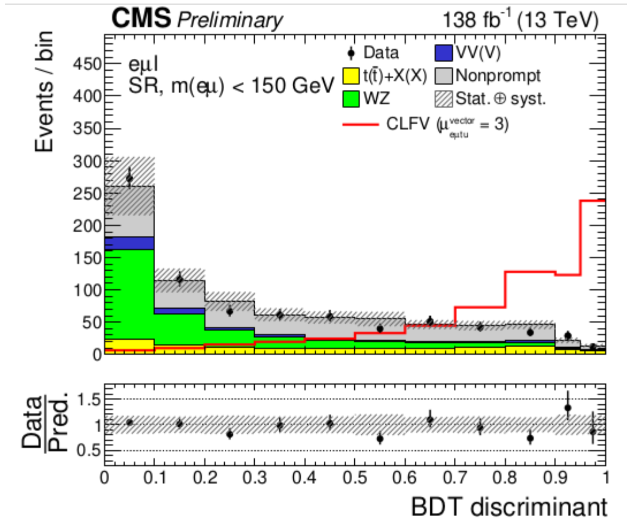
Decay

Strategy:

- Selection:
  - BDT to reject non-prompt l
  - Exactly 3 l: eμl
  - b-jet & MET>20GeV
- Background:
  - •prompt with MC & CR (WZ)
  - •non-prompt data-driven (DY Jets)
- LFV production: $m_{e\mu}$ >150GeV
- LFV decay: $m_{e\mu}$<150GeV



Production

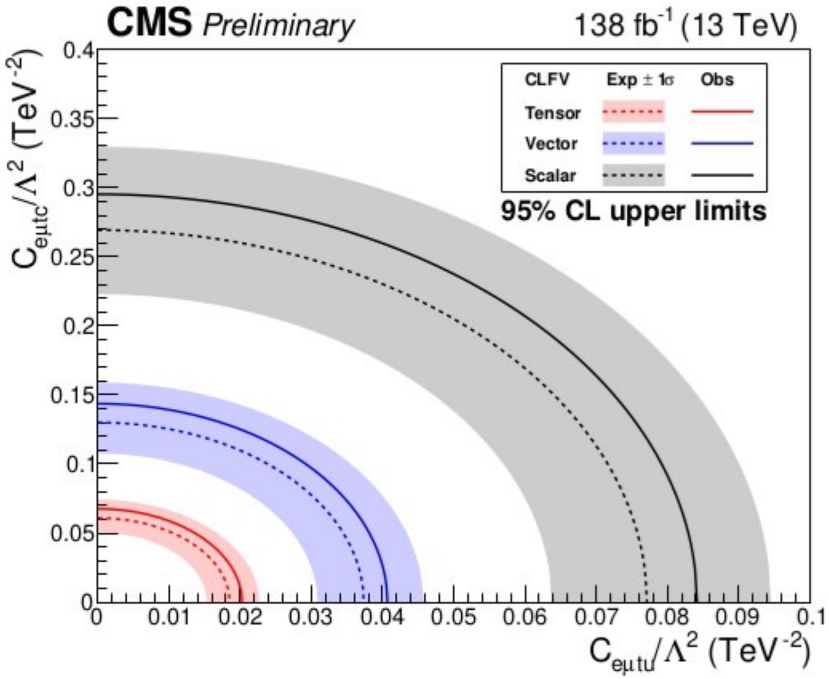


Decay

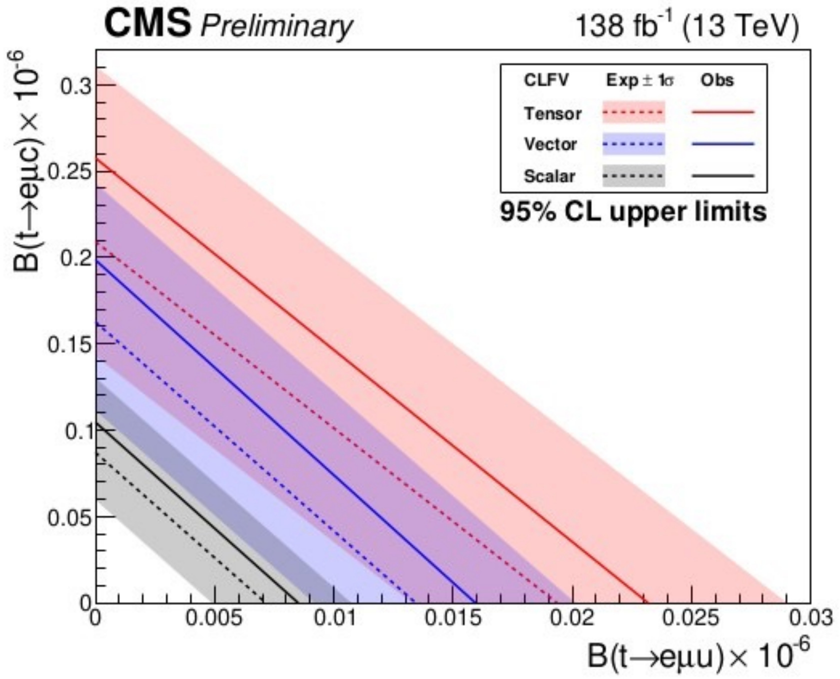
Dominant systematics: fake-rate method uncertainties, disagreement between data/MC in WZ control region

Results

Limit on Wilson Coefficients

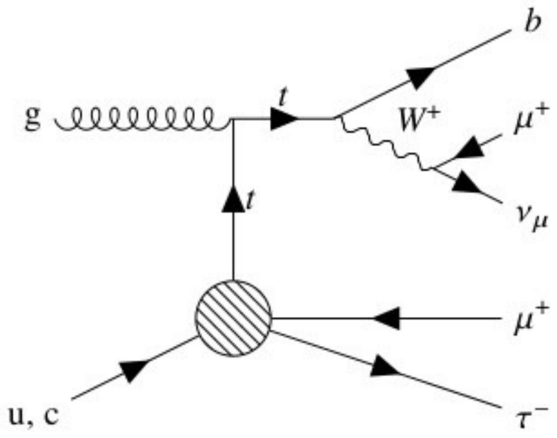


Limit on Branching Fraction



Structure	Scalar	Vector	Tensor
$B(t\to e\mu u)$	$0.009\ 10^{-6}$	$0.016\ 10^{-6}$	$0.023\ 10^{-6}$
$B(t\to e\mu c)$	$0.105\ 10^{-6}$	$0.199\ 10^{-6}$	$0.258\ 10^{-6}$

LFV in t→ μτq



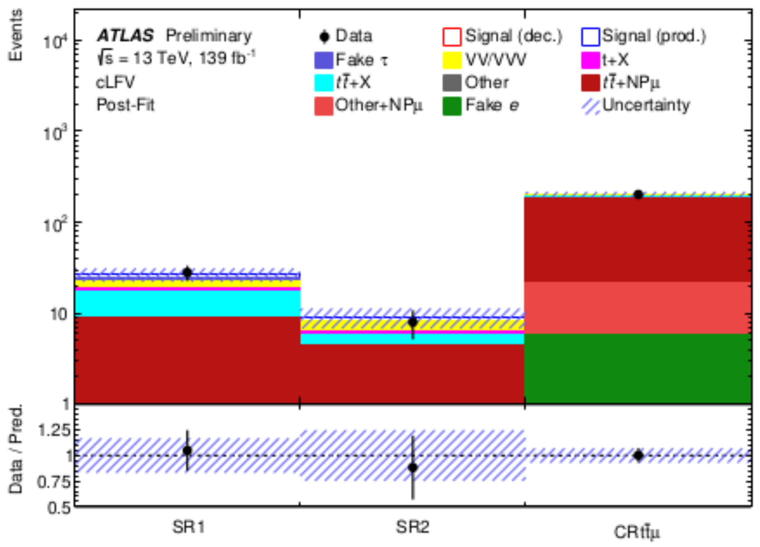
Signature:

- Similar to CMS case but with **<u>hadronic τ</u>** in final state
- μ from the SM top decay
- same charge μ from the LFV/production/decay

Strategy:

- Selection:
  - 1 b-tagged jet
  - Neural Network for τ ID
  - 2 same-charge μ
- Production SR: Selection & 1 jet
- Decay SR: Selection & >1 jet
- Backgrounds:
  - $t\bar{t}$ (fake μ), $t\bar{t}$ V, WZ
- Fake μ,τ estimated with Control Regions and transfer factors
- Dominant Systematics:
  - $t\bar{t}$ modelling
  - Signal modelling
  - MC statistics

Yield & SM expectation

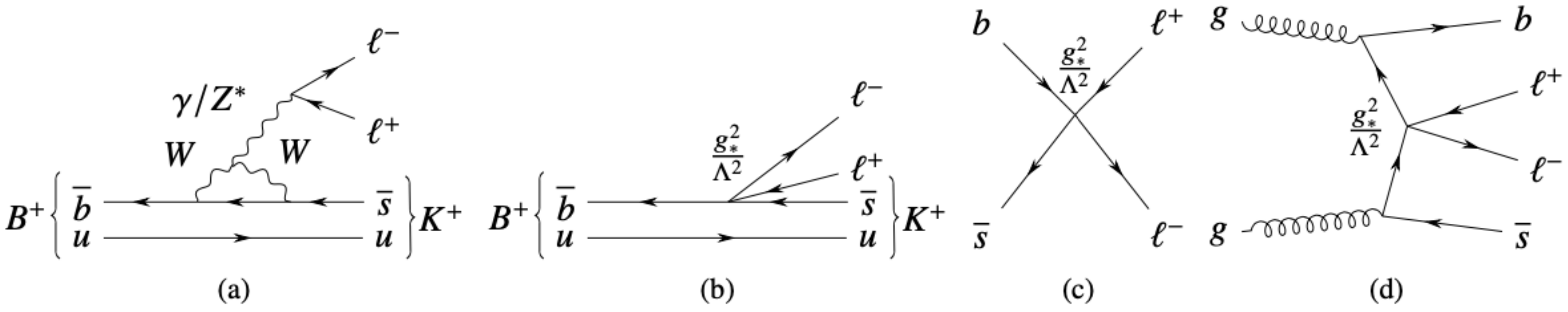


Result:

BR(t→τμq)<11 x 10^{-7} @95%CL

PRL 127, 141801 (2021)

LFU from ll+(0/1) b-jet



Model B decay LFU violation by contact interaction
Implies signals in ll+0 b-jets and ll+1 b-jet

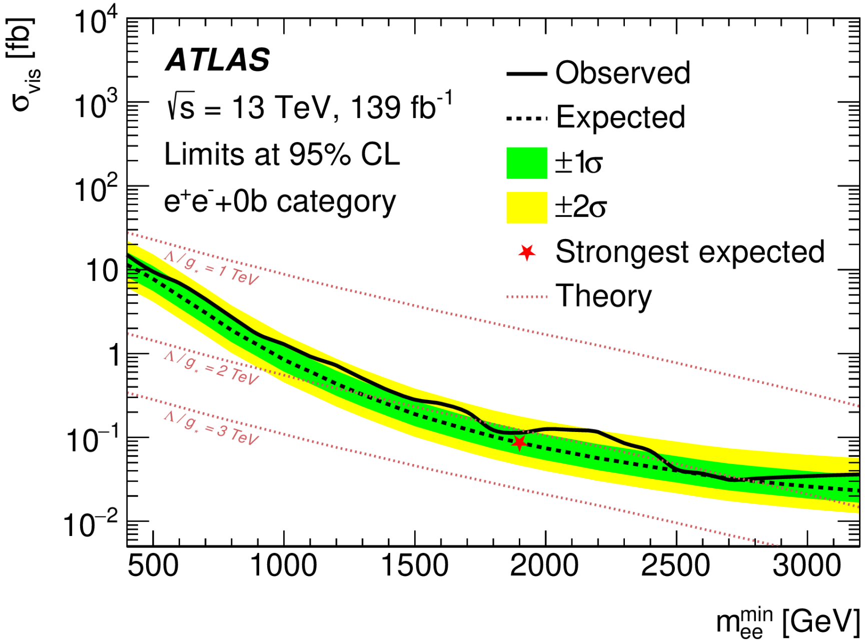
Signature:

- Identify the two samples
- High-pT leading lepton for efficiency
- High 2000(1500)GeV ll-mass

Strategy:

Selection

- 1 b-tagged jet or Strong veto on b jet
- 2 same-flavour/opp. charge leptons



Result:
Λ/g*< 2(2.4)TeV e(μ) @95%CL

Conclusions

- HF at the LHC continue to provide insights into new physics, including through rare decays and also through LFV and LFU studies
- I have presented a selection of results here, see parallel sessions and published results pages for more ATLAS , CMS and LHCb results
- Measurements of Charmonia as well as the open-heavy flavour hadron-production, provide valuable tests to multiple QCD production models.
- Measurements searching for LFV in HF sector see no unambiguous violation of SM - within the precision of data used so far.
- Hints of LFU breakdown remain, but with significance diminishing

Related non-HF studies

- **LFV in Higgs decays**
  - **(i) H → eμ search in ATLAS**
  - Phys. Lett. B 801 (2020) 135148 ATLAS
  - **(ii) H → eμ search in CMS**
  - HIG-22-002 CMS
  - **(iii) H → (eτ, μτ) search in ATLAS**
  - Phys. Lett. B 801 (2020) 135148 ATLAS

- **LFV in Z decays:**
  - **(i) eτ, μτ**
  - PRL127 141801 (2021) ATLAS
  - Nat. Phys. 17 (2021) 819 ATLAS
  - **(ii) eμ**
  - arXiv:2204.10783 ATLAS
- **LFV from heavy resonances** arXiv:2205.06709 CMS
- **LFU from W decays** Nat. Phys. 17 (2021) 813 ATLAS

Combination of the ATLAS, CMS and LHCb results on the $B_s \to \mu^+\mu^-$ decays