«Tests of lepton flavour universality violation with B_c meson decays at CMS»

12-15 December 2023,

Fermilab US LUA Meeting

(US LHC Users Association)

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ETH Zürich and Fermilab LPC (2024)

OUTLINE

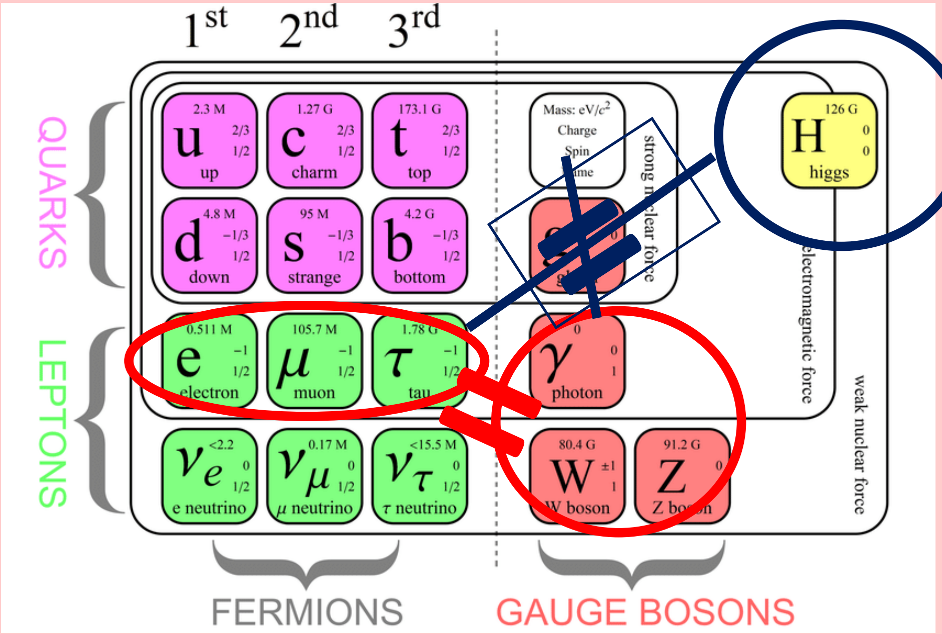
- Introduction to Lepton Flavour Universality
- Motivation
  - Experimental Motivation
  - Theoretical Motivation
- CMS results with B_c
  - Why B_c mesons?
  - Signal and Backgrounds
  - Discriminants
  - Analysis strategy
  - Results
- Conclusions

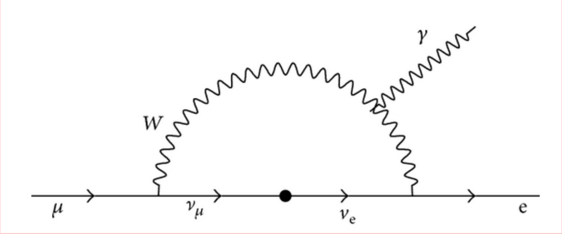
INTRODUCTION

➢ In the Standard Model (SM) *Lepton Flavour Universality (LFU) is not a* formal symmetry

- Charged *Lepton Flavour Universality (CLFU)*
  - ☑ Expected in the electroweak (EW) sector
  - ☑ Broken by Yukawa interactions of the Higgs boson with the three leptons
  - ☑ Violation *possible* only via neutrino mixing. *Very Rare* event:

    $\mathcal{B}(\mu^+ \to W^+\nu(\nu_\mu \to \nu_e) \to e^+\gamma < \mathbf{10^{-55}}$





Observation of LFU violation implies physics beyond the SM!

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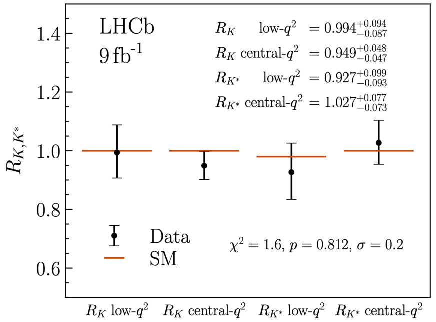
EXPERIMENTAL MOTIVATION

- Semi-leptonic decays of *B* mesons have proved to be an additional lever-arm to test LFU

$b \to s$ quark transition

$$\mathcal{R}(H_s) = \frac{\mathcal{B}(H_b \to H_s \mu^+ \mu^-)}{\mathcal{B}(H_b \to H_s e^+ e^-)}$$

- Some excitement in 2021 with a 3.1σ-deviation from the SM for $\mathcal{R}(K^{(*)})$ by LHCb:
  Nature Physics **volume 18**, pages 277–282 (2022)
- Updated result (Dec 2022):
- arXiv:2212.09152 and arXiv:2212.09153



SM Consistent!

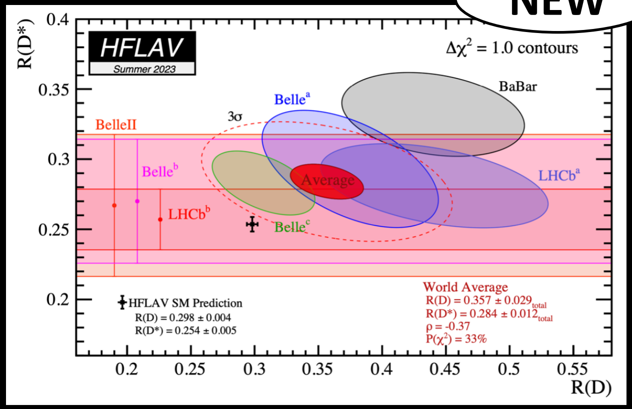
Not connected with $b \to c$!

$b \to c$ quark transition

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \nu_\mu)}$$

- Since 2012, three experiments reporting on $\mathcal{R}(D^{(*)})$: BaBar, Belle and LHCb
- Including the latest LHCb result (Feb 2023): arXiv:2302.02886

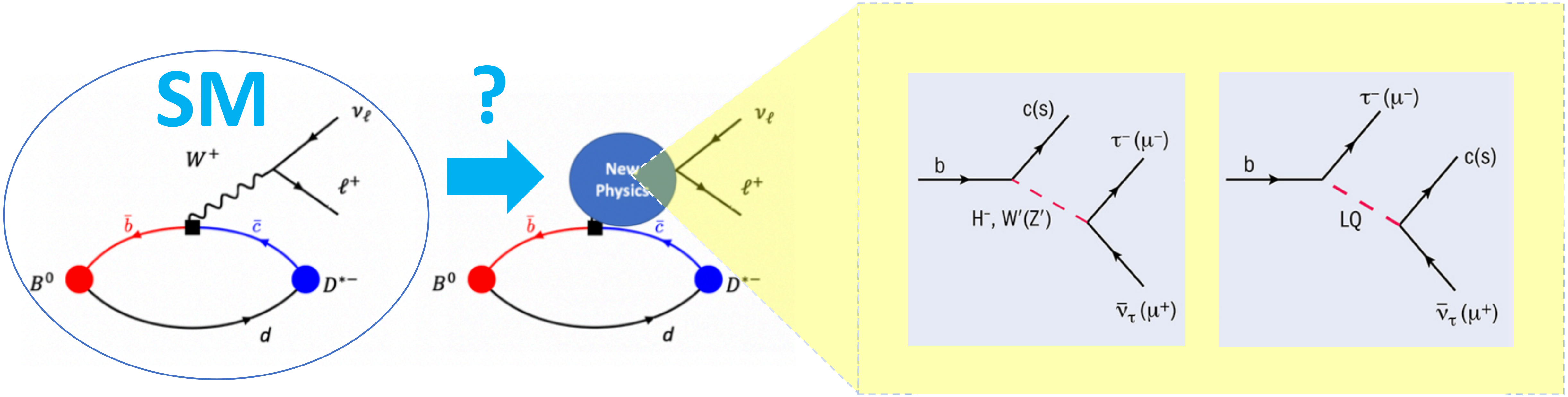
NEW



3.3σ-deviation from the SM!

THEORETICAL MOTIVATION

- Possible LFU violation will be clear indication of new Beyond-the-SM (BSM) physics:
  - **Extended Higgs** or **Gauge sector** or **LeptoQuarks**



- **Impact**: LeptoQuarks able to explain LUFV should have a mass of 30 TeV
- We are currently planning the the post-LHC era. Which machine should we build? Which Energy scale? For which physics program? Clear indication!

FCC
LHC

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WHY B_c MESONS?

- For the $b \to c$ quark transition, there is another interesting ratio

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

1

- B_c are "young" mesons. Discovered at CDF in 1998: Phys. Rev. Lett. 81, 2432
- B_c mesons cannot be produced at existing *B factories.* At the moment **unique opportunity for LHC**
- **Only one measurement from LHCb: 2σ away from the SM expectation** Phys. Rev. Lett. 120, 121801 (2018)

WHY B_c MESONS AT CMS?

- For the $b \to c$ quark transition, there is another interesting ratio

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)} = \frac{\mathcal{B}(B_c^+ \to \mu^+\mu^-\mu^+\nu_\mu\overline{\nu_\tau}\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

1

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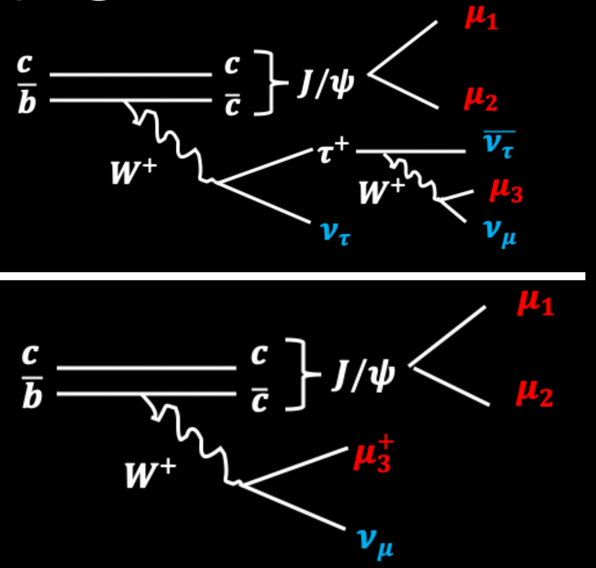
2

- Common uncertainties cancel out in ratios
- **Clear** $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ and $J/\psi \to \mu^+\mu^-$ decays, only muons and neutrinos:
  - CMS excellent in muon ID and reconstruction, even at low-p_T
  - CMS calorimeter hermiticity excellent for neutrino-final states

Key ingredients for precision measurements

SIGNALS

$\mathcal{R}(J/\psi) =$



- **Similar final states**

Similar reconstruction and Simultaneous fit

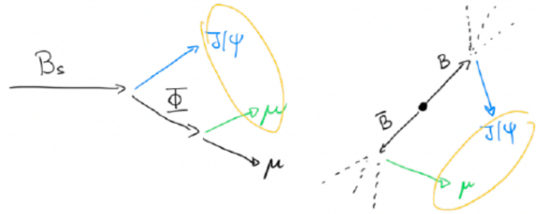
Due to neutrinos, **COLLINEAR APPROXIMATION** to reconstruct key kinematics: $p_{B_c} = \frac{m_{B_c}}{m_{3\mu}^{vis}} \cdot p_{3\mu}^{vis}$

BACKGROUNDS

- **Muon Fakes**
  - J/ψ **+ misidentified muons** (pions or kaons)

- **B$_c$ background**
  - Feedowns: excited $c\bar{c} \to J/\psi$
  - Other $B_c^+ \to J/\psi H_c^+ X$ decays

- **H$_b$ background**
  - $H_b \to J/\psi + \mu$ decays



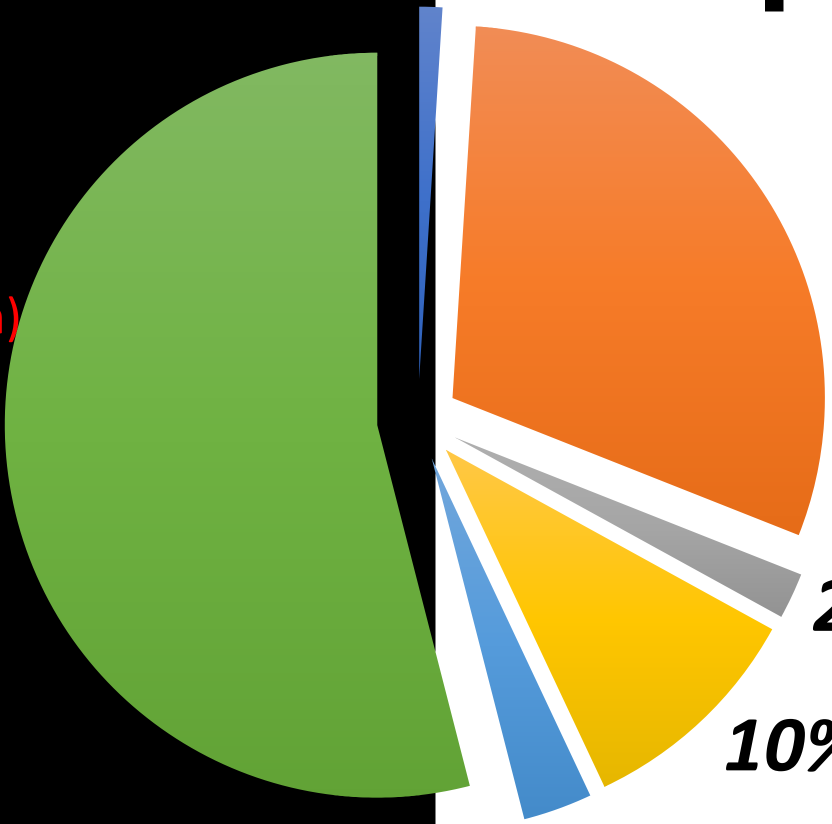
- **Combinatorial Dimuon + μ^+**
  - Unrelated muons, which reconstruct the J/ψ invariant mass

SIGNALS

- **Separation between signals**
  - lepton mass difference
  - neutrino contribution
  - ✓ $q^2 = (p_{B_c^+} - p_{J/\psi})^2$
  - ✓ $\frac{IP3D}{\sigma_{IP3D}}$ (3D-impact parameter)
  - ✓ $\frac{L_{xy}}{\sigma_{L_{xy}}}$ (transverse decay length)

BACKGROUNDS

- **Separation Signal Vs Background (Muon Fakes)**
  - Isolation (ISO) of the third muon



3% : $J/\psi\tau^+\nu_\mu$

54%* : $J/\psi\mu^+\nu_\mu$

30% : **Muon Fakes** **Data driven**

2% : **B$_c$ background** **MC based**

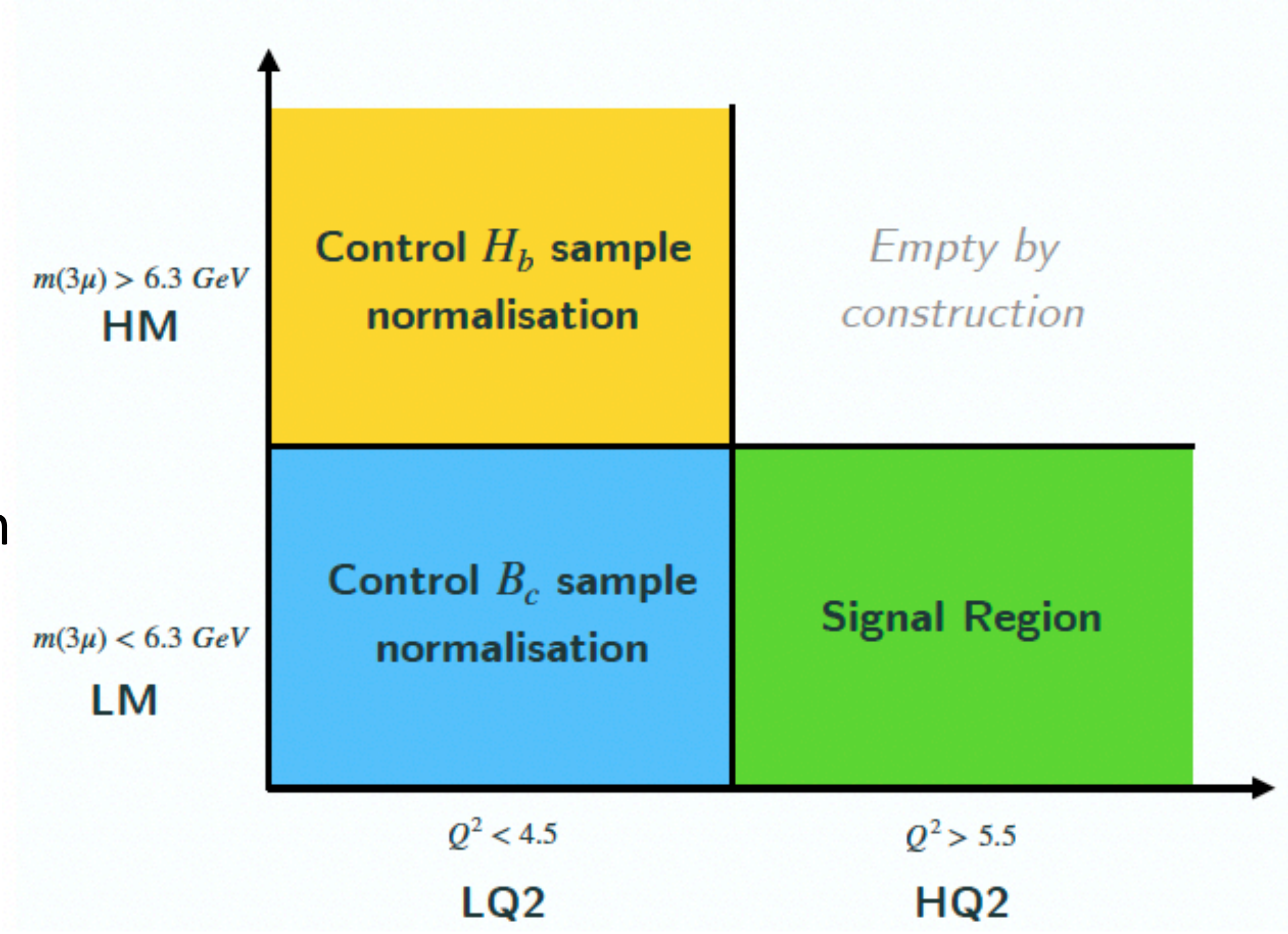
10% : **H$_b$ background** **MC based**

1% : **Comb. Dimuon +** μ^+ **Data driven**

** Numbers are based on the analysis inclusive category*

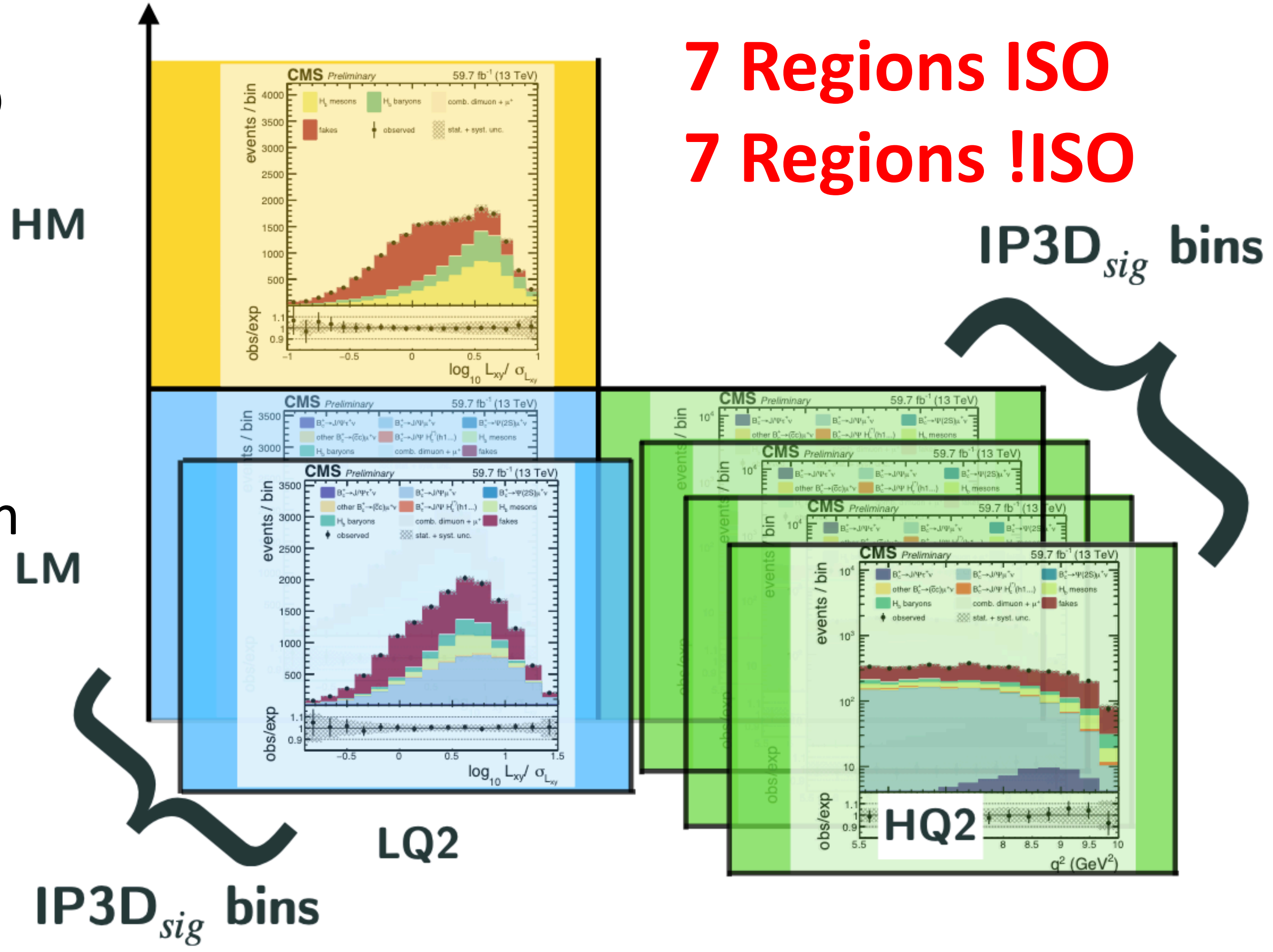
ANALYSIS STRATEGY I

- Binned maximum likelihood fit to q^2 and $L_{xy}/\ \sigma_{L_{xy}}$ distributions
  - Free floating parameters: B_c and H_b normalizations
  - Parameter-Of-Interest (POI) : $\mathcal{R}(J/\psi)$
  - **Blind strategy**: POI scaled by unknown random number

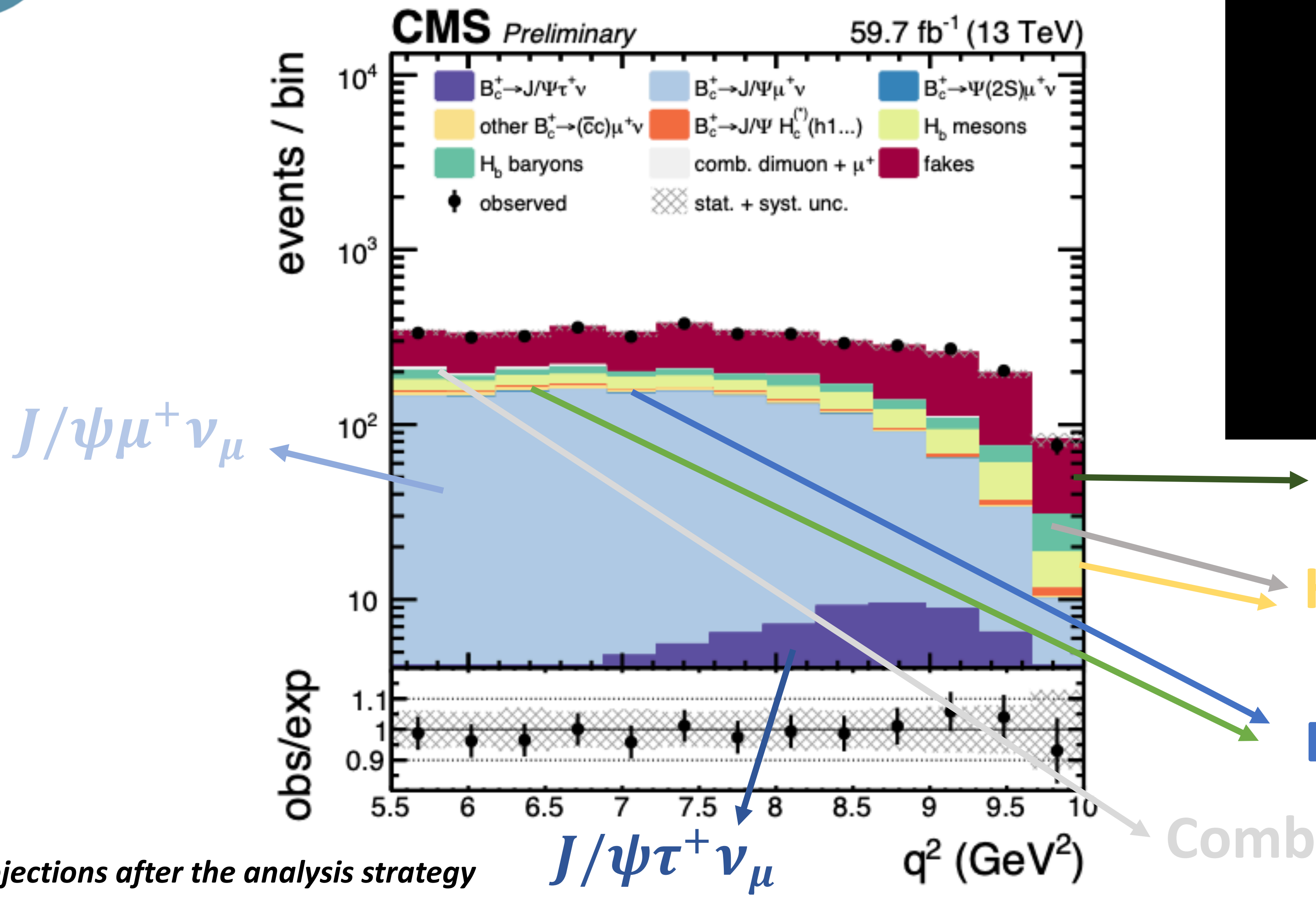


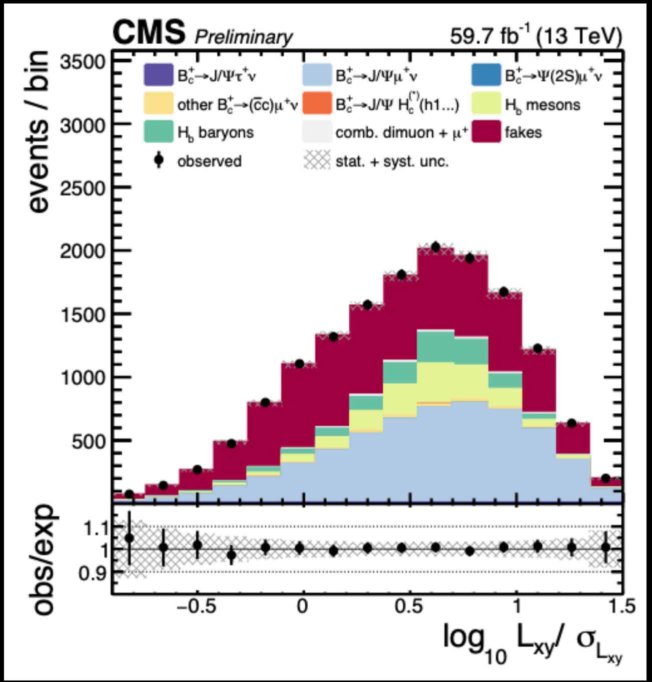
ANALYSIS STRATEGY II

- Binned maximum likelihood fit to q^2 and $L_{xy}/\ \sigma_{L_{xy}}$ distributions
  - Free floating parameters: B_c and H_b normalizations
  - Parameter-Of-Interest (POI) : $\mathcal{R}(J/\psi)$
  - **Blind strategy**: POI scaled by unknown random number
  - **14 categories to optimize S/B and control background contributions**



DISCRIMINANTS





** Projections after the analysis strategy*

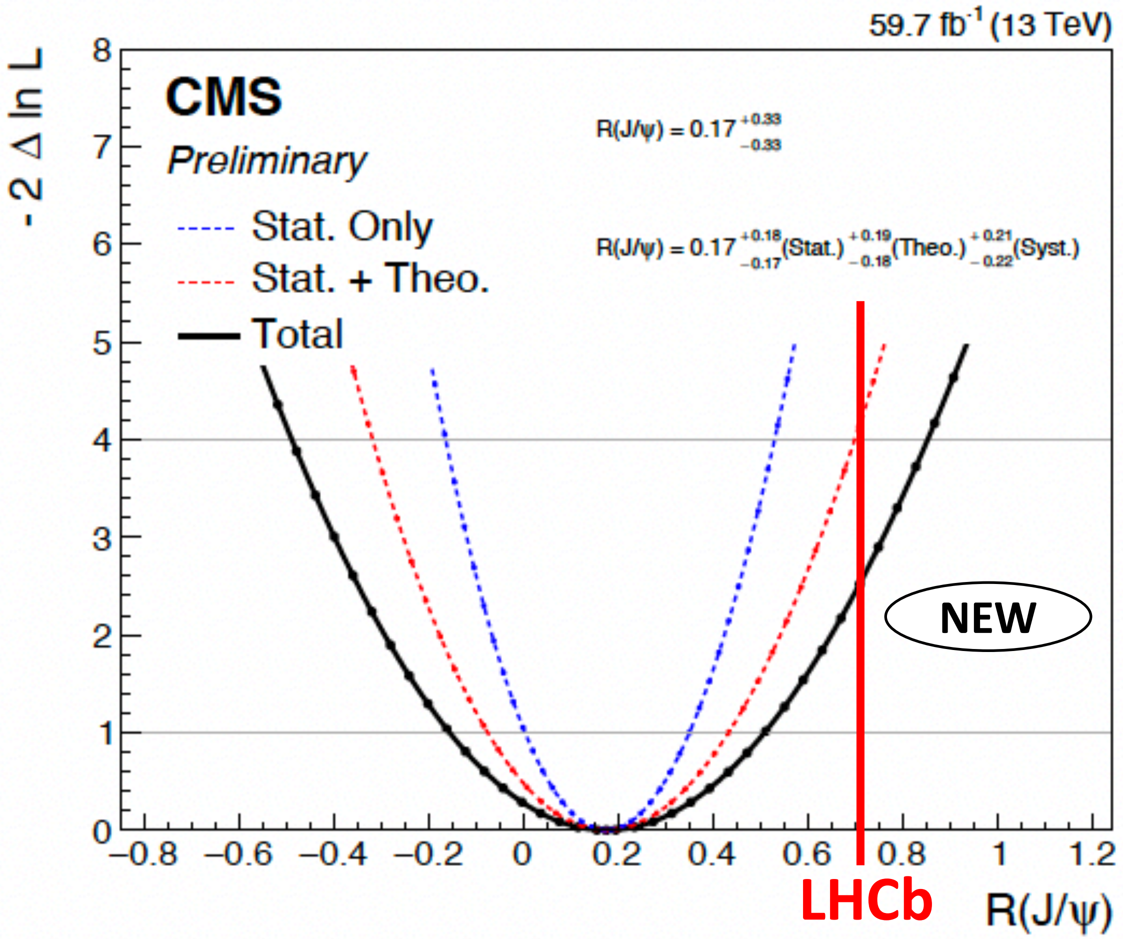
RESULTS

CERN-CMS-PAS BPH-22-012

$\mathcal{R}(J/\psi) = \mathbf{0.17 \pm 0.33}$

Compatible with the

- ➢ SM prediction within 0.3σ
- ➢ Some Beyond-the-SM (BSM) models
- ➢ LHCb result within 1.3σ
- ➢ **First CMS result for the $b \to c$ quark transition**
  - ▪ based only on 2018 data



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CONCLUSIONS

- LFUV is an interesting research area where to look for new physics

- Some experimental indications are puzzling the scientific community

- CMS recently released a result based on B_c mesons
  - **First CMS result for the $b \to c$ quark transition**
  - Result agrees with the SM within 0.3σ, but still compatible with some BSM models
  - Just a first result starting the CMS LFUV program
  - Sensitivity expected to significantly improve in the next interaction...

... STAY TUNED!

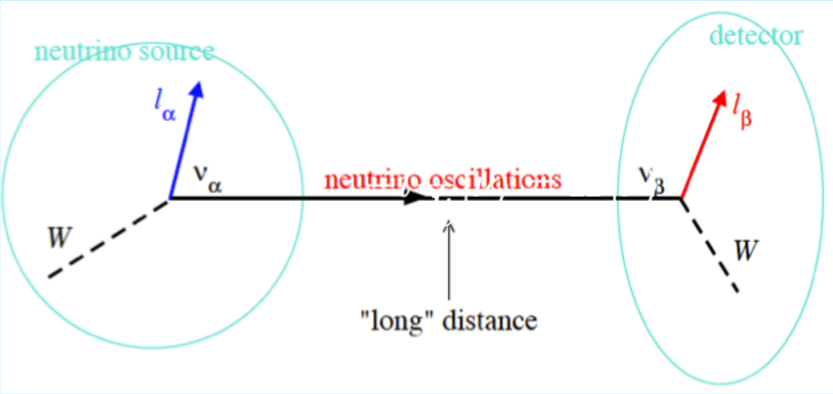
PARTICLE PHYSICS in the DISNEY WORLD

BACK-UP

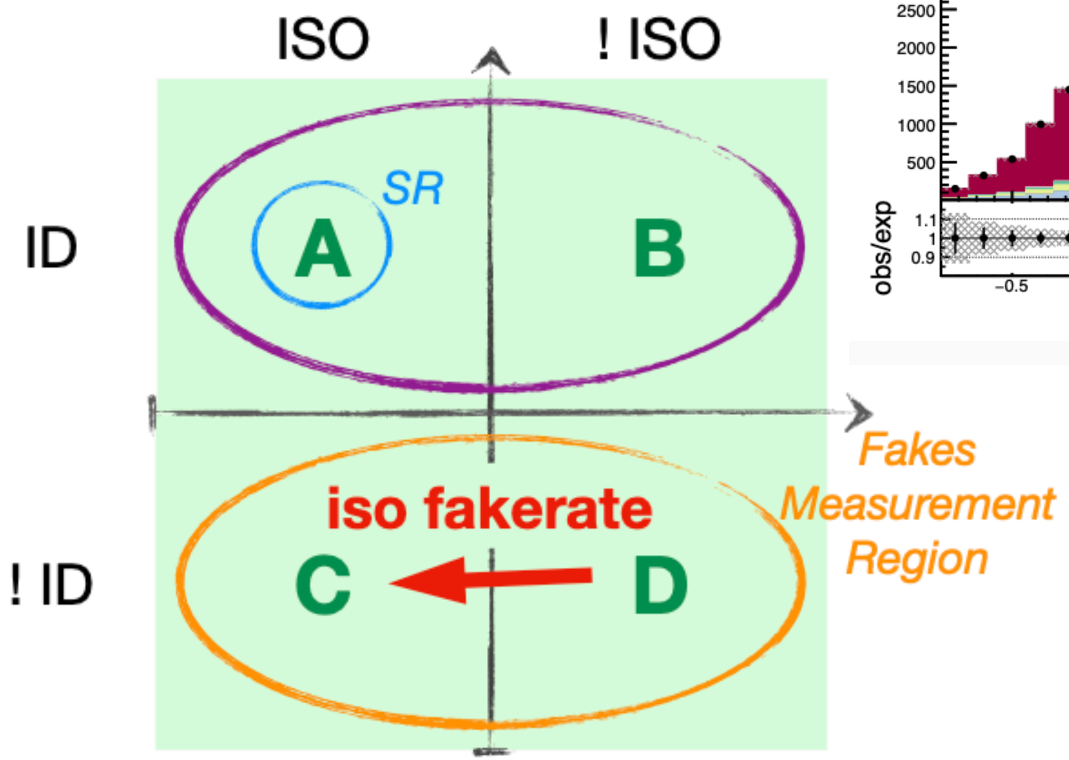
INTRODUCTION

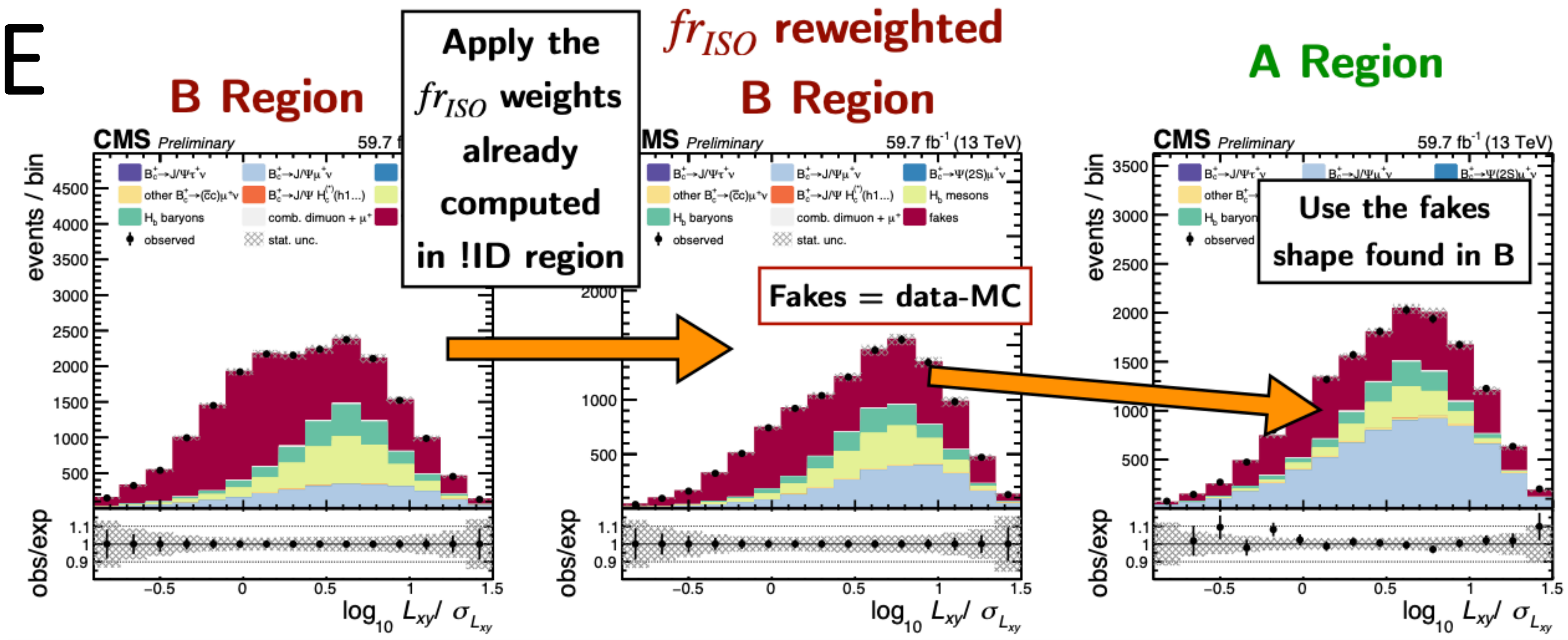
➢ In the Standard Model (SM) *Lepton Flavour Universality (LFU) is not a* formal symmetry

- *Neutral Lepton Flavour Universality (NLFU)* broken by the evidence of neutrino oscillations: [*Phys. Rev. Lett. 81:1562-1567, 1998*]
  - ☑ Proportional to neutrino masses



FAKES ESTIMATE





$$Fakes(SR) = fr_{iso} \cdot Data(B) - fr_{iso} \cdot MC(B)$$

SYSTEMATIC UNCERTAINTIES

Contribution	Unc. type	$\Delta R(J/\psi) \cdot 10^{-2}$
Theory	S	19
fakes stat. non closure	S (bin-by-bin)	13
fakes	N	8
fakes	S	7
finite MC size	S (bin-by-bin)	9
$IP3D/\sigma_{IP3D}$, $L_{xy}/\sigma_{L_{xy}}$ corr.	S	9
muon ID, iso, trigger	N	6
H_b sample	N	0.8
B_c^+ bkg. BRs	N	0.6
J/ψ comb. norm.	N	0.1
Other	N	< 0.1
Total systematic uncertainty		28

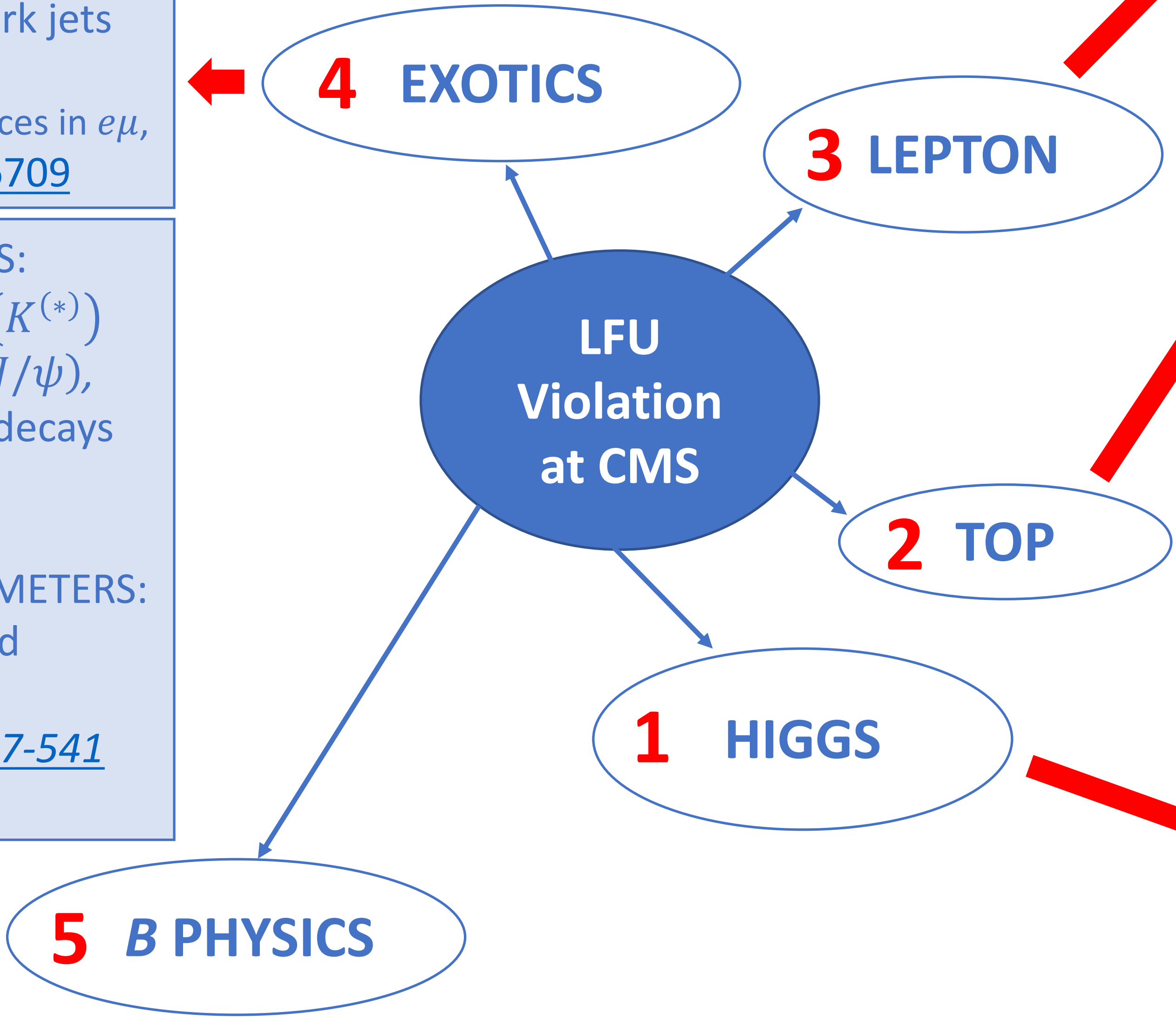
THE CMS LFU PROGRAM

TWO DIRECT SEARCHES:
1. Search for Z' with b-quark jets
   CMS-PAS-EXO-22-016
2. Search for Heavy resonances in $e\mu$, $\mu\tau$ and $e\tau$ arXiv:2205.06709

TWO R(X) MEASUREMENTS:
1. Ongoing efforts for $\mathcal{R}(K^{(*)})$
2. Ongoing efforts for $\mathcal{R}(J/\psi)$, leptonic and hadronic decays of τ-leptons
   - Results soon

TESTS ON ANGULAR PARAMETERS:
1. For $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$

Phys. Lett. B 781 (2018) 517-541 and *JHEP 04 (2021) 124*



ONE DIRECT SEARCH:
1. Search for $\tau \to 3\mu$
CMS-PAS-BPH-21-005

ONE DIRECT SEARCH:
1. Search for t→ $e\mu u$, t→ $e\mu c$ fopr tensor, vector and scalar interactions
CMS-PAS-TOP-22-005

TWO DIRECT SEARCHES:
1. Search for $H \to e\mu$
   arXiv:2305.18106
2. Search for $H \to e\tau$ and $H \to \mu\tau$
   Phys. Rev. D 104, 032013