Challenging Lepton Universality

Universality vs. Particularity

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Dominated by LHCb *results*

*Many **excellent COMHEP reviews/talks** addressing LU*
*Mine will be biased towards **b-physics***

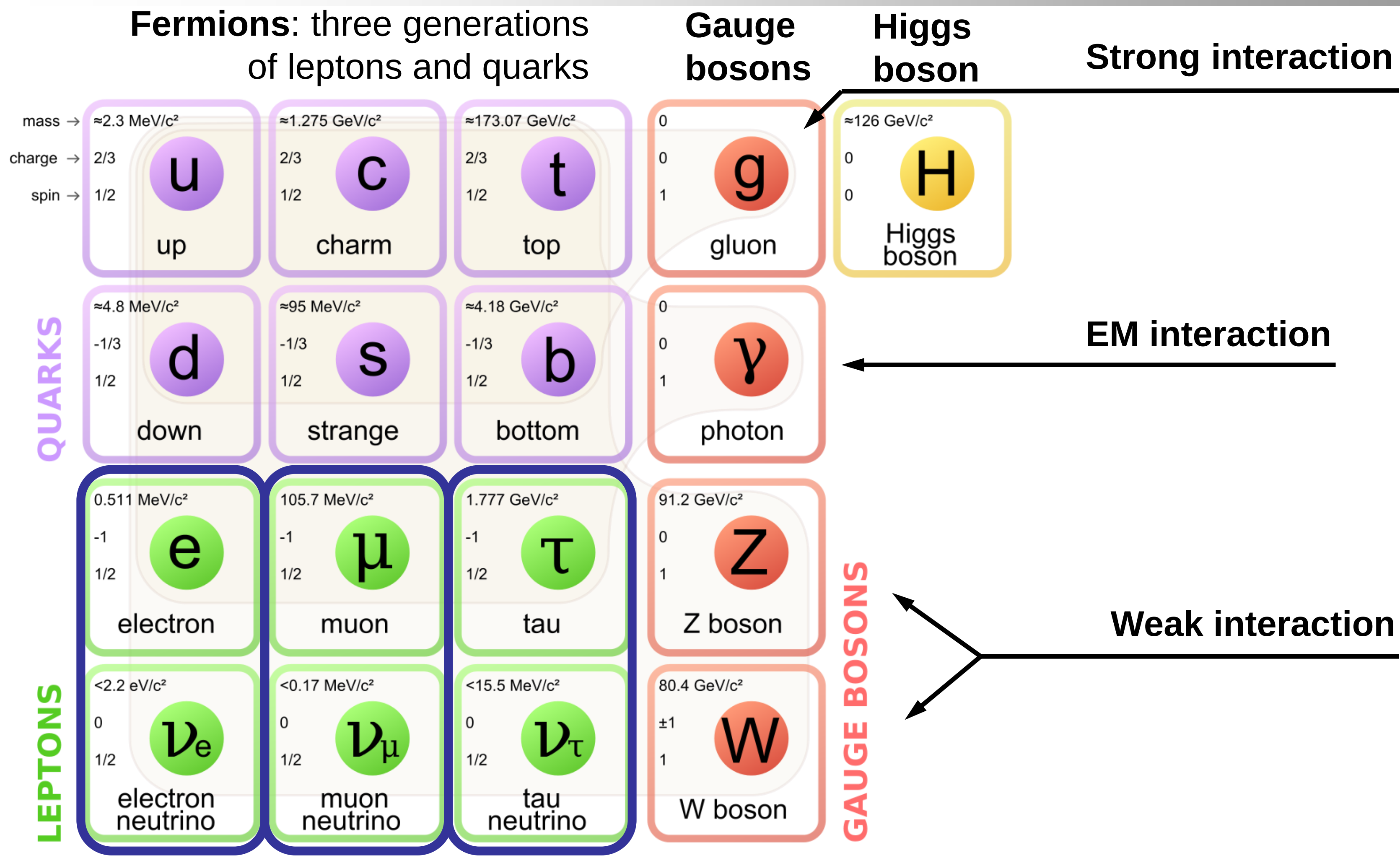
Many slides/material from M. Borsato, S. Decotes-Genon, K. Petridis, M.-H. Schune, J. Smeaton et al.

« On ne peut pas être précis, et être toujours vrai. »
« You cannot be precise, and be always true. »

Marc Chagall

Introduction

Standard Model



- **Three families of leptons are identical (except for masses);**
- The γ, the W, the Z couple in exactly the same way to three lepton generations (**universality**);
- Higgs mechanism for the breakdown of EW gauge symmetry does not affect universality of gauge coupling.

** kinematic differences due to different lepton masses to be accounted for*

- Standard Model – highly successful predictive theory
- However, explanations lacking for numerous observations: dark matter, matter-antimatter asymmetry, mass hierarchy, …

- Search for effects not described by the SM: new particles or interactions

- Search via direct production, ***energy path***
- Search indirectly, via contributions to loops, for modification of rates and/or angular distributions, ***quantum path***

Need **observables with well-understood SM predictions** and **where NP could give measurable effects**

- SM gauge group $SU_C(3) \times SU(2)_L \times U(1)_Y$

  breaking to $SU(3)_C \times U(1)_{em}$ via Higgs mechanism

  does not impact universality

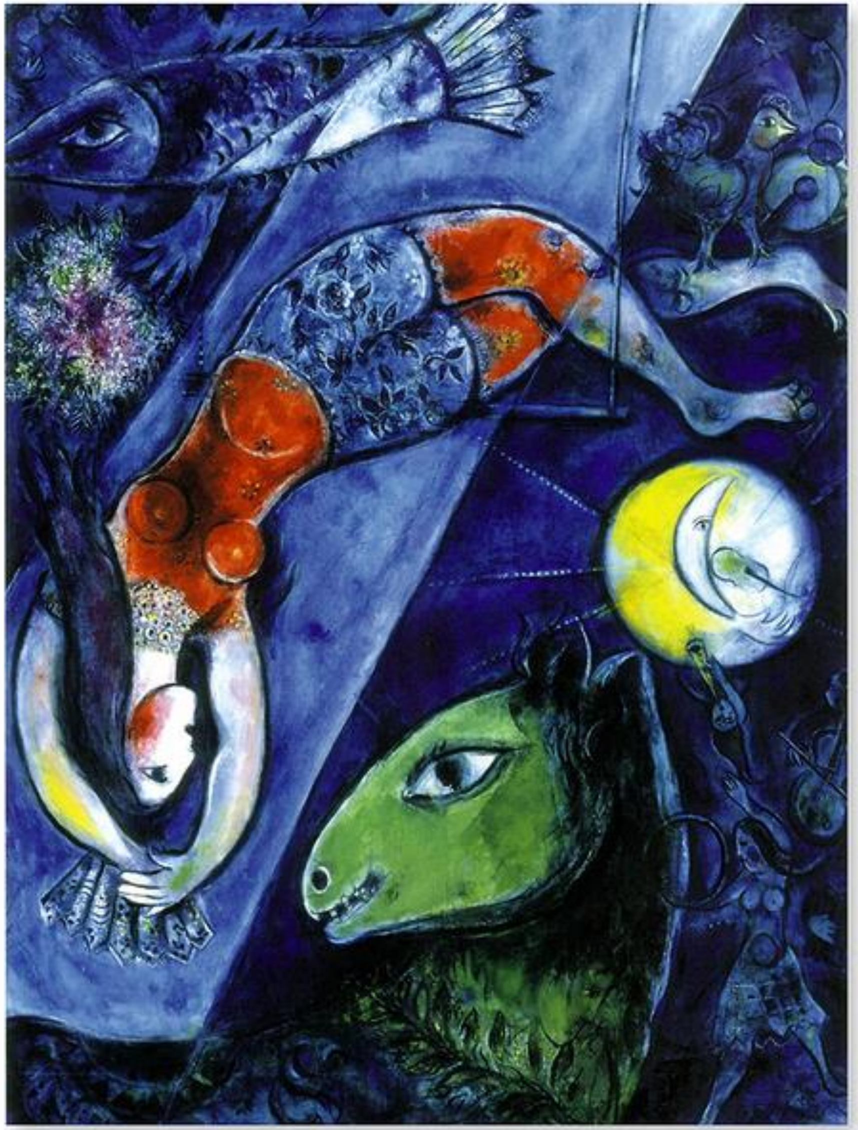
- The **difference between the three families comes from the Yukawa interaction between the Higgs field and the fermion fields**. The diagonalization of the mass matrices yields mixing matrices (CKM and PMNS) between weak and mass eigenstates occurring in the coupling of fermions to the weak gauge boson $W^{\pm}$
- **Flavour of the quarks** involved in a transition is **determined experimentally (mass and charge)**, so that the CKM matrix elements are determined unambiguously
- **Charged leptons are distinguished in the same way as quarks**, whereas most of the time the **neutrino mass eigenstates cannot be distinguished** (their mass differences are negligible compared to the other scales and they are not detected in experiments)

$$b \to c\, \tau^- \bar{\nu}_\tau$$

- Final state with unspecified (anti)neutrino mass eigenstate → **sum over amplitudes for all three possible (anti)neutrino mass eigenstates**
- Overlap of each mass eigenstate with the produced weak interaction eigenstate ν_τ via PMNS matrix U
- Decay width proportional to $\sum_{i=1,2,3} |U_{\tau i}|^2$. Equals to 1 due to PMNS unitarity

  → **PMNS matrix plays no role in the SM**
- Choose either **purely leptonic** or **semileptonic processes that involve leptons of different generations, but with the same quark transition**, so that there are no PMNS matrix elements and the CKM ones cancel out in ratios

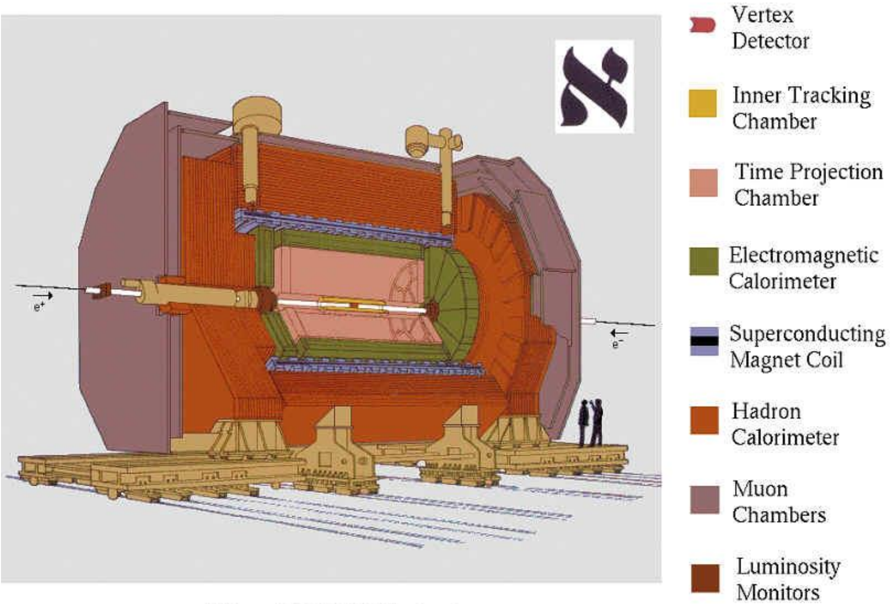
Detection features



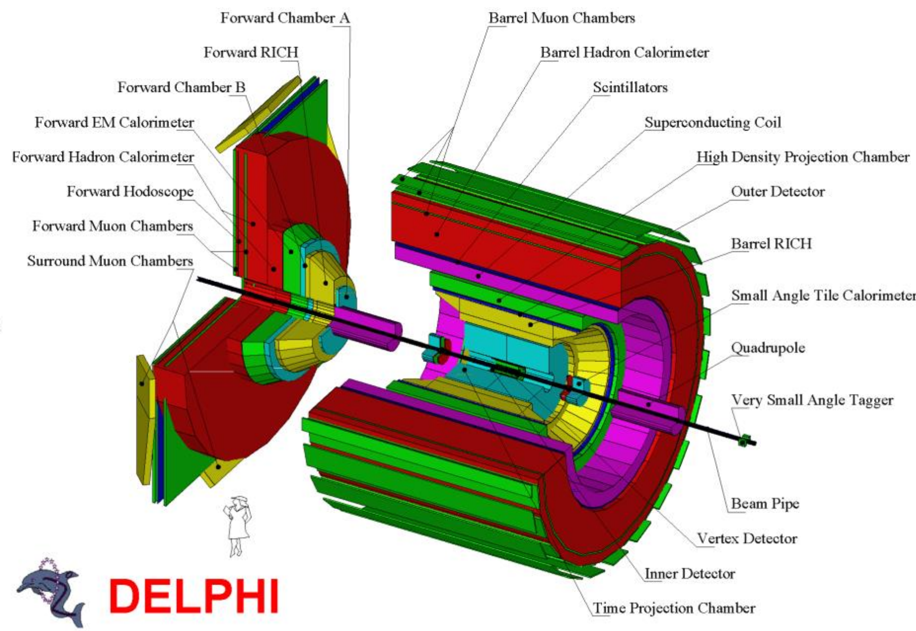
Clean environment

e^+e^- colliders, LEP experiments

- Real Z and W production, ideal environment for lepton coupling studies

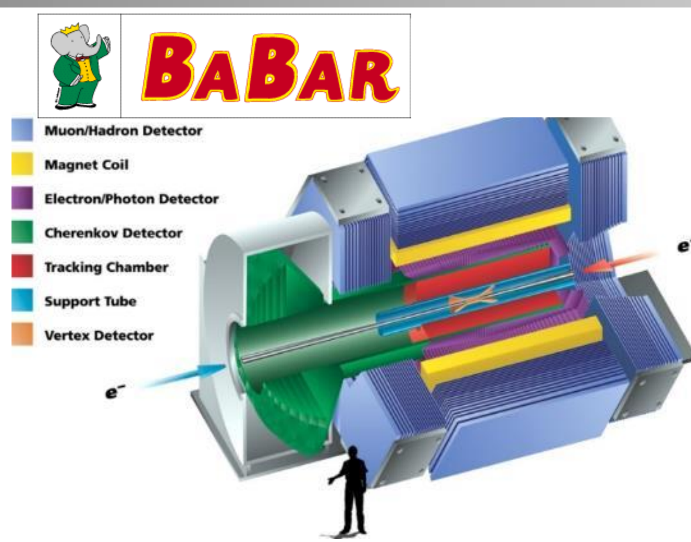


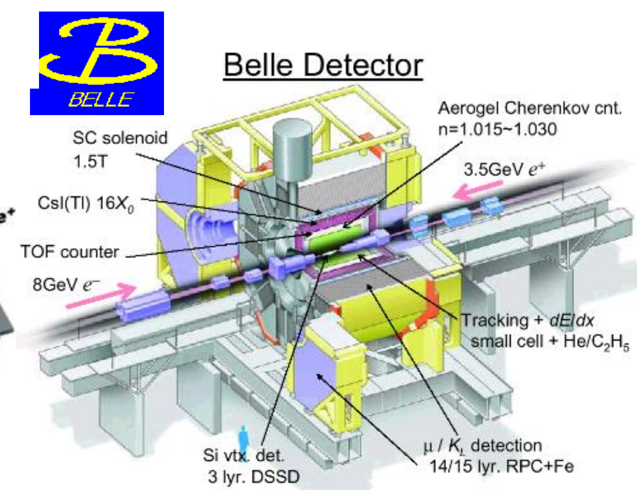
The ALEPH Detector



e^+e^- colliders, B-factories

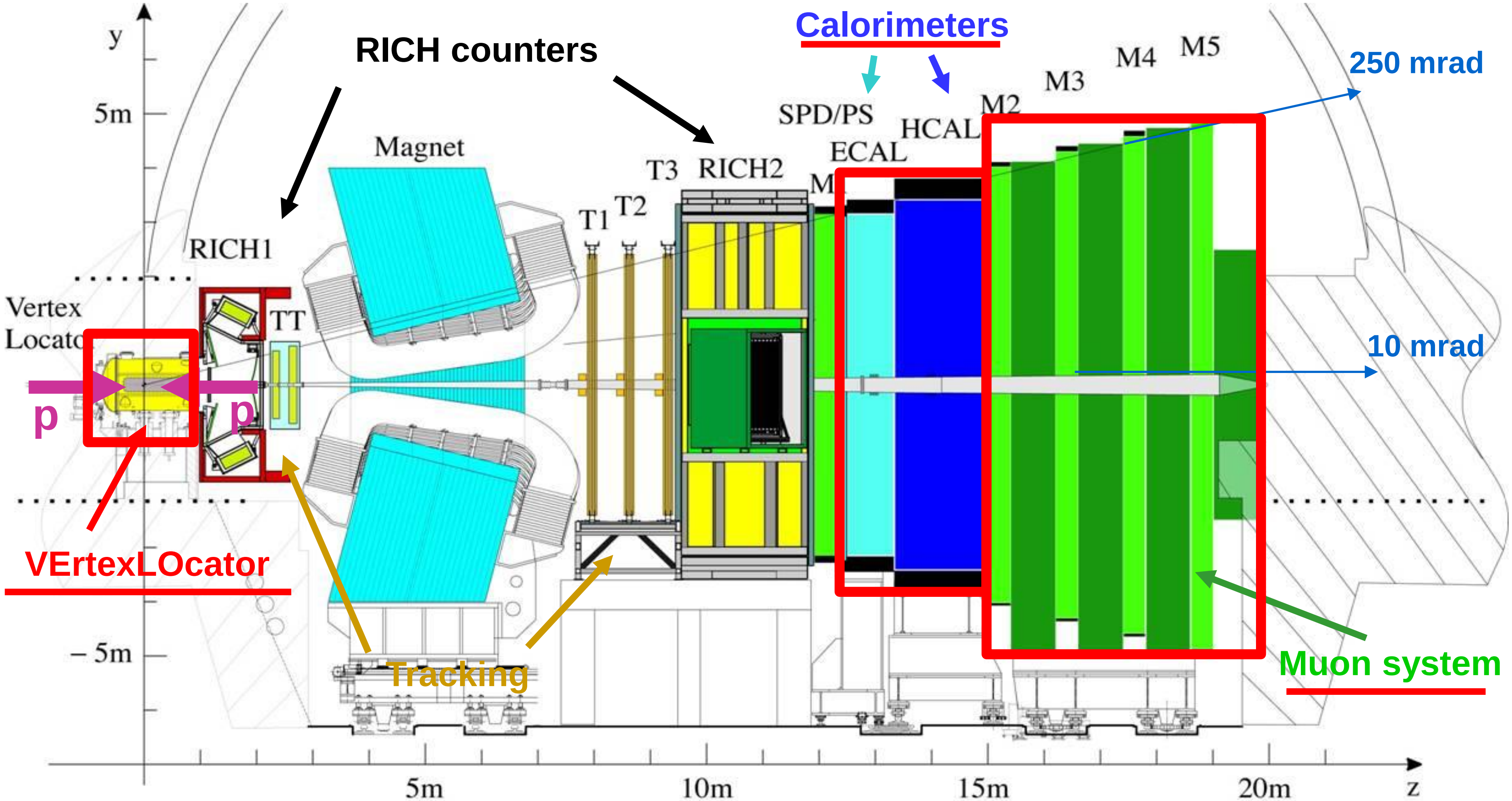
- Excellent performance for modes with neutrals/neutrinos
- Lower collision energy, poorer lifetime resolution





JINST 8 (2013) P08002, INT.J.MOD.PHYS.A30 (2015) 1530022

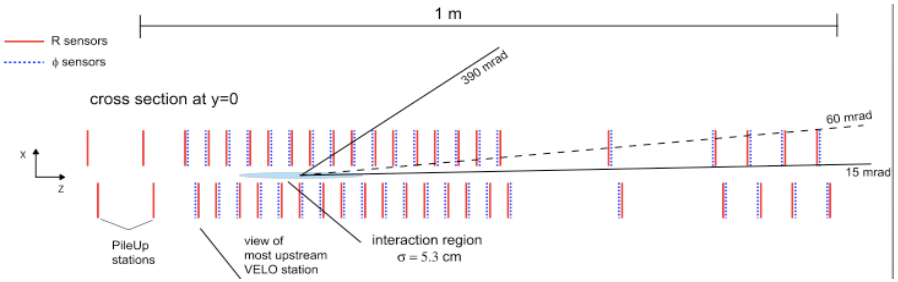
- **LHCb**: dedicated flavour physics experiment
- Acceptance 1.9 < η < 4.9, **~4% of solid angle**, but **~40% of beauty production x-section**



- Key detector systems for lepton universality studies: **vertex reconstruction (VELO), particle identification (electromagnetic calorimeter, muon detector), trigger**
- Excellent lifetime resolution due to large boost, ~0.03 τ_B

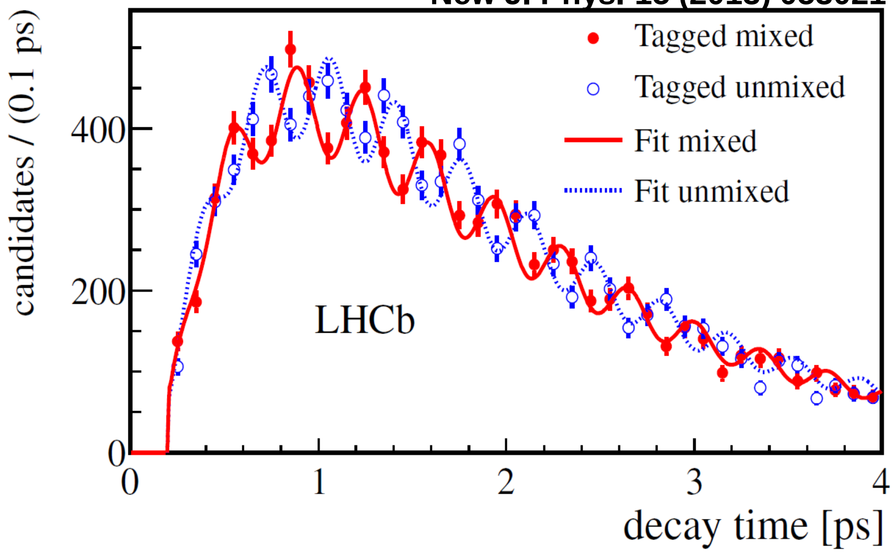
JINST 8 (2013) P08002, JINST 9 (2014) P09007

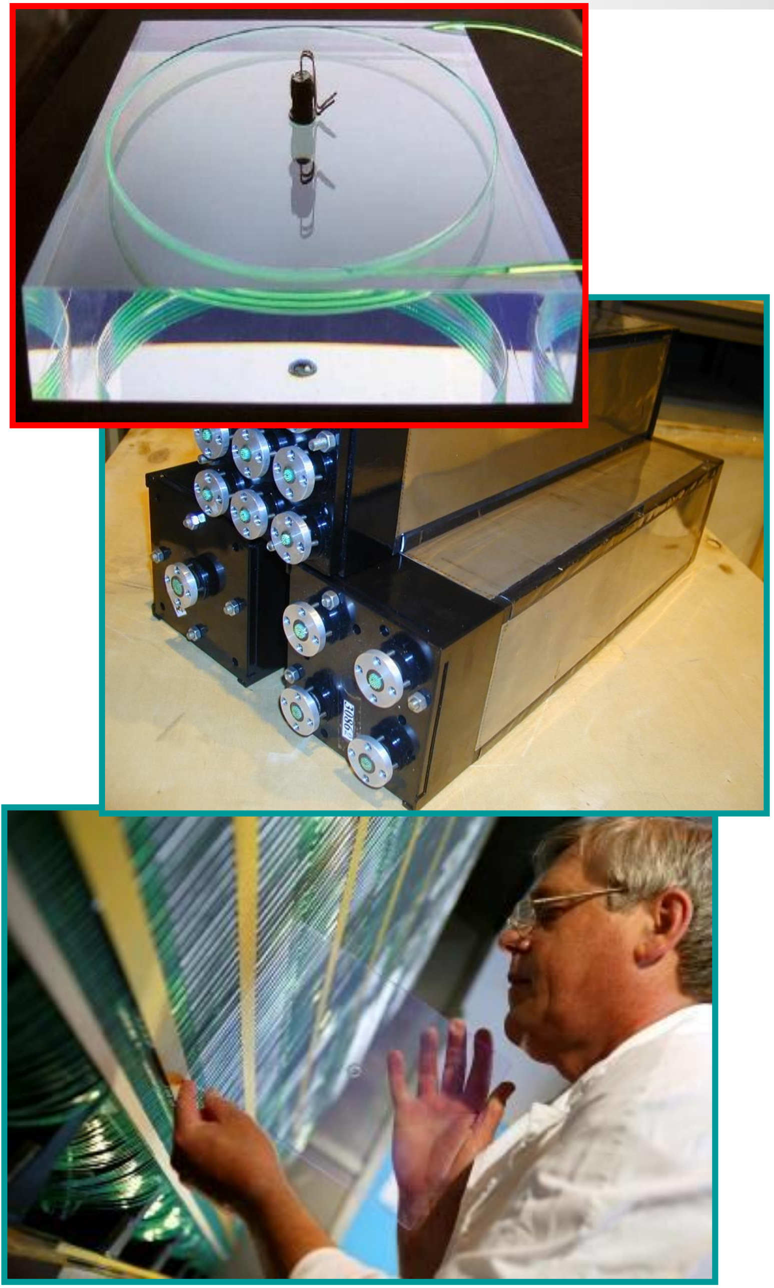
- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout
- 300μ*m* thick n-on-n sensors, strip pitches from 40 to 120μ*m*
- **First active strip at 8.2mm from beam axis**



- Excellent **spatial resolution**, down to 4μ*m* for single tracks
- Precise **impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT$ [μ*m*]
- Precise **primary vertex** reconstruction, $\sigma_{x,y} = 13\mu m$, $\sigma_z = 69\mu m$ for vertex of 25 tracks
- VELO provides excellent **proper time** resolution
- **Vertex resolution** allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

New J. Phys. 15 (2013) 053021





Three calorimeters PS, ECAL, HCAL
and one threshold device SPD

arranged in the pseudo-projective geometry, variable granularity

Preshower (PS) and Scintillator Pad Detector (SPD)

- PID for L0 electron and photon trigger
- electron, photon/pion separation by PS
- photon/MIP separation by SPD
- charged multiplicity veto by SPD

Shashlyk Electromagnetic Calorimeter (ECAL)

- E_T of electrons, photons and π^0 for L0 trigger
- reconstruction of π^0 and prompt γ offline
- particle ID

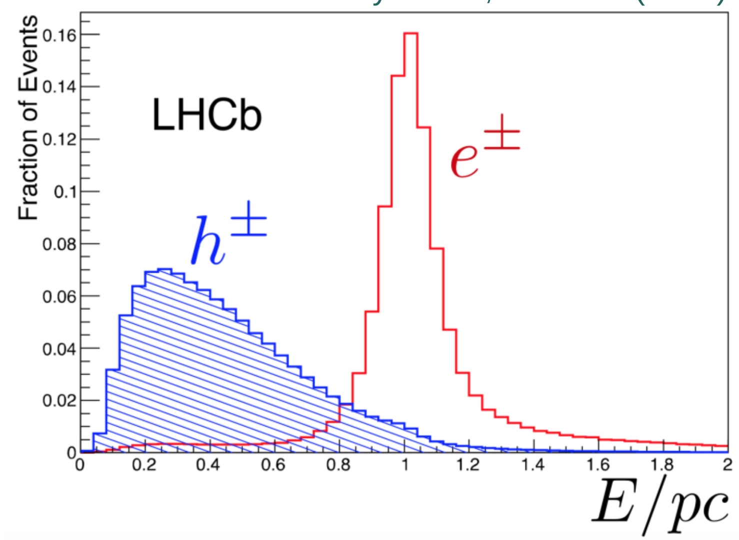
Tile Hadron Calorimeter (HCAL)

- E_T of hadrons for L0 trigger
- particle ID

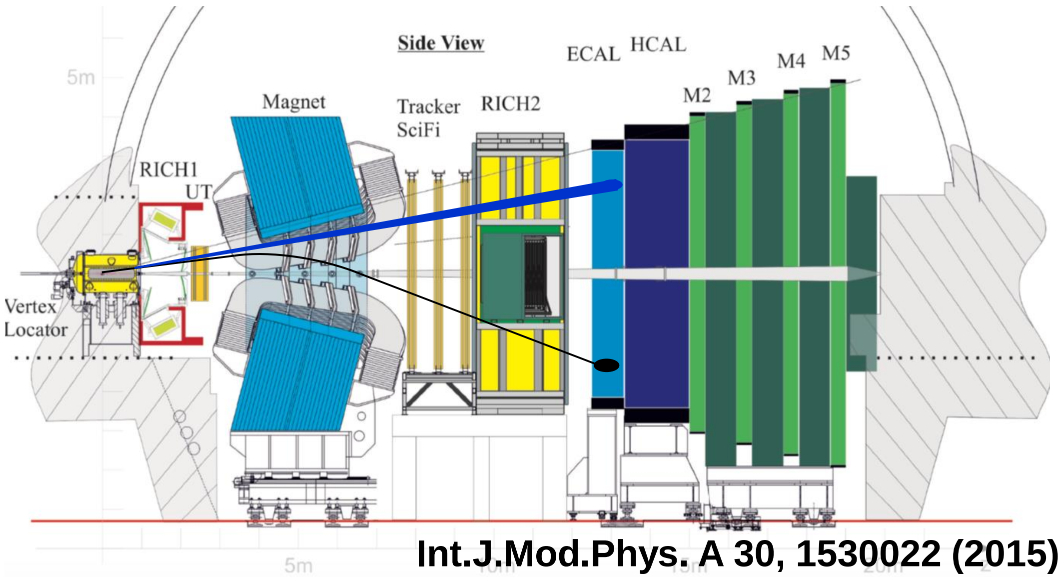
L0 trigger tools

- **Lepton identification** is anything but universal. based on ECAL vs. Muon detector and tracking
- **Electrons emit Bremsstrahlung photons**, degrading resolution. Energy recovery applied
- Higher occupancy in calorimeters requires **higher electron trigger threshold**
- Efficiency difference due to hardware trigger thresholds

Int.J.Mod.Phys. A 30, 1530022 (2015)



- Measurement of momentum affected by bremsstrahlung emission before magnet
- **Bremsstrahlung photon recovery procedure** with limited efficiency



Int.J.Mod.Phys. A 30, 1530022 (2015)

- Tests of LU, menu:
    - *Electroweak sector*
    - *Decays of pseudoscalar K and D mesons*
    - *Leptonic decays*
    - *Quarkonia decays*
    - ***b-hadron decays***

- Searching for a **consistent picture**:
    - Probing via decay branching fractions or decay asymmetries
    - LU tests for first Two generations vs. Three generations
    - Tree diagrams vs. Loop diagrams
    - Mesons vs. Baryons
    - CKM dependence: which matrix elements involved

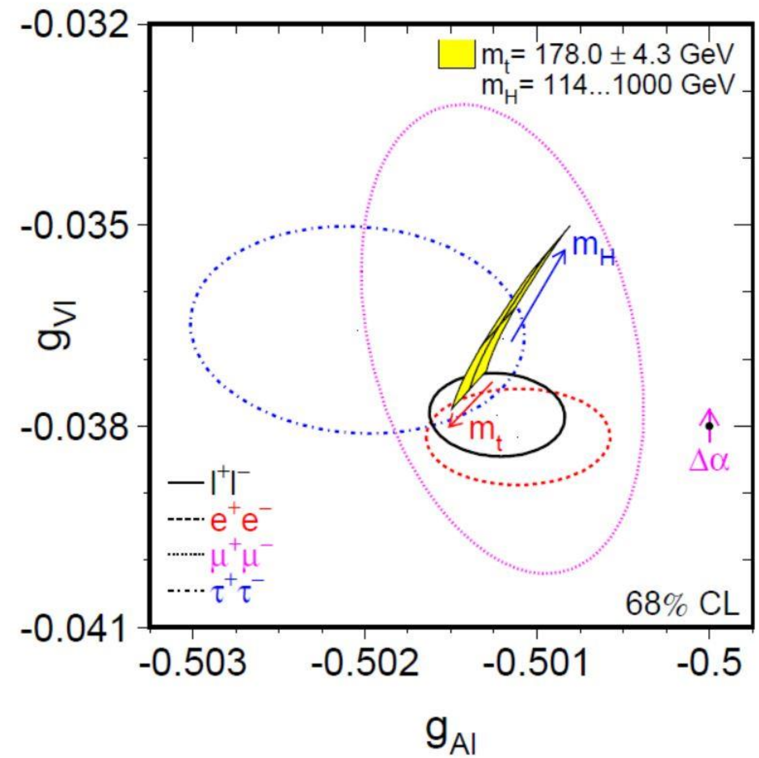
- Check that **couplings of the W and Z bosons to all lepton species** are identical (SM)
- Measure the **Z → e^+e^-, Z → $\mu^+\mu^-$ and Z → $\tau^+\tau^-$ partial widths** and their ratios

$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}} = 1.0019 \pm 0.0032$$

Experiments at LEP
Phys. Rept. 427 (2006) 257

- *LU tested to ~0.3%, both for 1-2 families and 1-3 and 2-3 families*

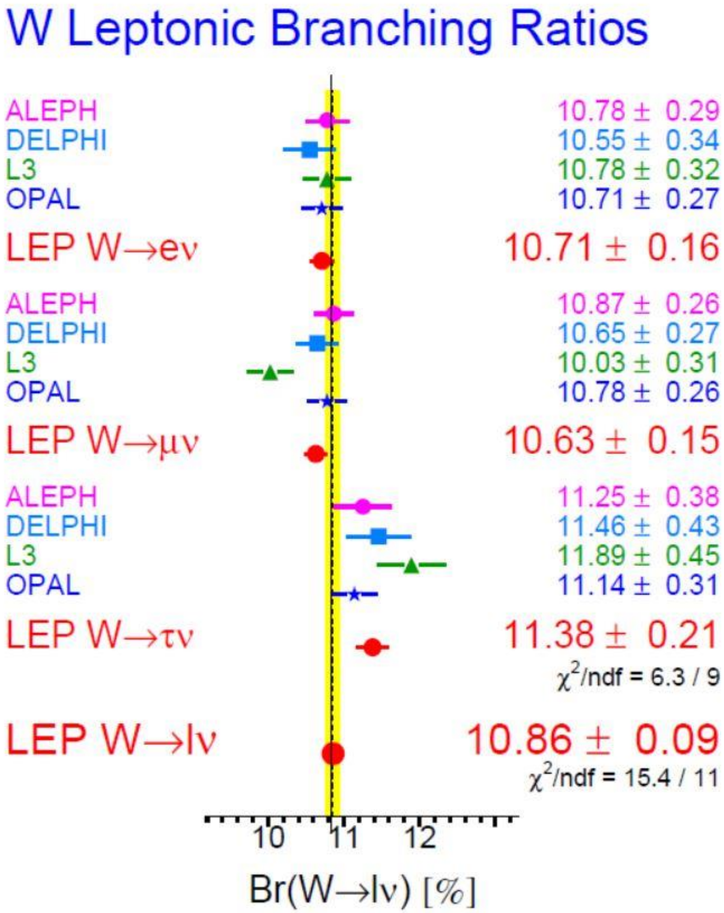


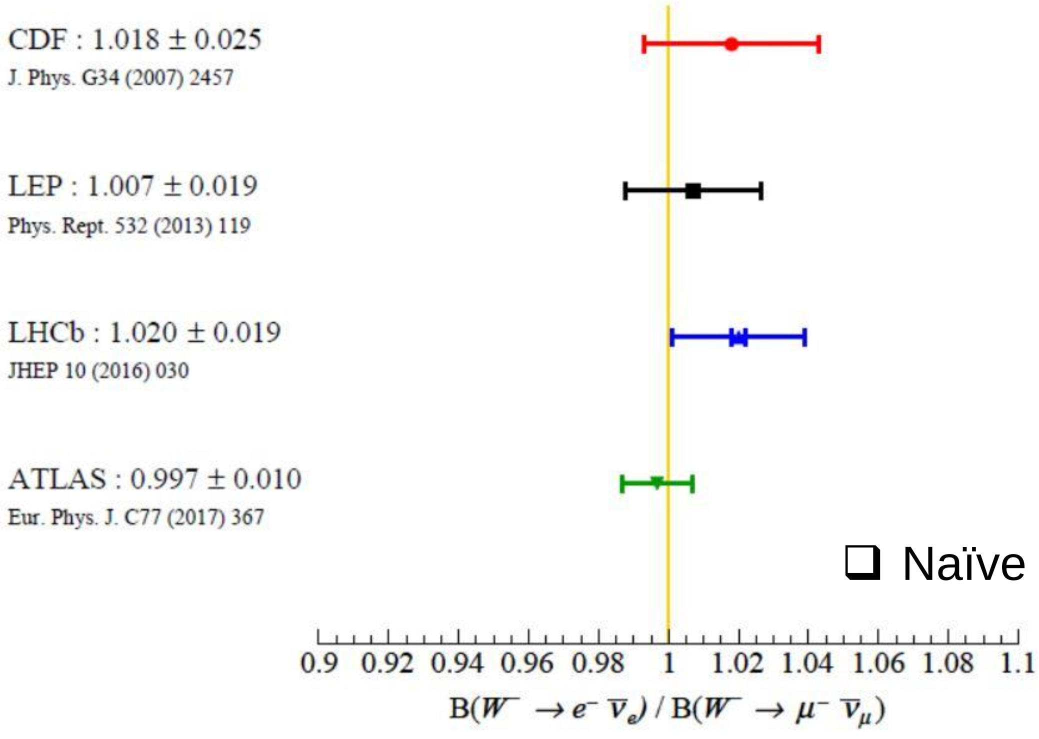
- From asymmetry measurements and partial Z decay widths: **effective vector and axial-vector coupling constants** for leptons
- Three light neutrino families with equal effective couplings and $g_{V\nu} \equiv g_{A\nu}$ are assumed
- **Good agreement** is observed

- LEP, Tevatron and LHC measurements using W boson decays can be interpreted as tests of LU
- Measure strength of the $W \to \ell\nu$, coupling, g_ℓ.
- All results agree with SM with an order of magnitude worse precision than for Z coupling.

LEP results from WW production

Phys. Rept. 532 (2013) 119





- Naïve average: $\frac{\mathcal{B}(W^- \to e^- \overline{\nu}_e)}{\mathcal{B}(W^- \to \mu^- \overline{\nu}_\mu)} = 1.004 \pm 0.008$
- *LU tested to ~0.8%, for 1-2 families*

- And involving 3rd family:

$$\frac{\Gamma_{W^- \to \tau^- \overline{\nu}_\tau}}{\Gamma_{W^- \to e^- \overline{\nu}_e}} = 1.063 \pm 0.027$$

$$\frac{\Gamma_{W^- \to \tau^- \overline{\nu}_\tau}}{\Gamma_{W^- \to \mu^- \overline{\nu}_\mu}} = 1.070 \pm 0.026$$

Dominated by LEP experiments
Phys. Rept. 532 (2013) 119

- *LU tested to ~3%, when third family involved*

- Assuming that LU holds between the first and the second families, an improved precision is obtained by the LEP experiments via the test:

$$\frac{2\Gamma_{W^- \to \tau^- \overline{\nu}_\tau}}{\Gamma_{W^- \to e^- \overline{\nu}_e} + \Gamma_{W^- \to \mu^- \overline{\nu}_\mu}} = 1.066 \pm 0.025$$

Phys. Rept. 532 (2013) 119

- *Tension with the SM expectation at the level of 2.6σ*

Decays of pseudoscalar mesons

- Leptonic decays of charged pions or kaons (helicity suppressed in the SM)
- Ratios test $(g_e/g_\mu)^2$
- SM prediction: $$\left(\frac{\Gamma_{K^- \to e^- \overline{\nu}_e}}{\Gamma_{K^- \to \mu^- \overline{\nu}_\mu}}\right) = (2.477 \pm 0.001) \times 10^{-5}$$

Cirigliano and Rosell, Phys. Rev. Lett. 99 (2007) 231801

- Good agreement with the experiment $$\frac{\Gamma_{K^- \to e^- \overline{\nu}_e}}{\Gamma_{K^- \to \mu^- \overline{\nu}_\mu}} = (2.488 \pm 0.009) \times 10^{-5}$$

dominated by NA62 PLB 719 (2013) 326

- Also good agreement from pion leptonic decays
- *LU tested to ~0.2%, families 1-2*
- Access third family with D_s leptonic decays

$$\frac{\Gamma_{D_s^- \to \tau^- \overline{\nu}_\tau}}{\Gamma_{D_s^- \to \mu^- \overline{\nu}_\mu}} = 9.95 \pm 0.61$$

HFLAV, EPJC 77 (2017) 895

SM: 9.76 ± 0.10

Dobrescu and Kronfeld, PRL 100 (2008) 241802
Burdman, Goldman and Wyler, PRD 51 (1995) 111

- *LU tested to ~6%, families 2-3*

- LU tests using **pure leptonic decays of the τ lepton** $\tau^- \to e^- \overline{\nu}_e \nu_\tau$
  $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$
- Tight constraint on the universality of the charged-current couplings to leptons:

$$g_\mu / g_e = 1.0018 \pm 0.0014$$

A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

- *LU at ~0.14%, for families 1-2 … one of the stringiest experimental tests*

- Combining τ and μ decay branching fractions and their lifetimes:

$$g_\tau / g_e = 1.0030 \pm 0.0015$$
$$g_\tau / g_\mu = 1.0011 \pm 0.0015$$

A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

- *LU at ~0.15%, the stringiest experimental tests of LU for couplings 1-3 and 2-3*

- Pure leptonic decay modes probe the couplings of a transverse W.
- **Semileptonic decays** $P^- \to \ell^- \nu_\ell$ **and** $\tau^- \to \nu_\ell P^-$ are only sensitive to the spin-0 piece of the charged current; thus, they probe the presence of possible scalar-exchange contributions with Yukawa-like couplings proportional to some power of m_ℓ
- Complementary studies

- Leptonic decays of quarkonia resonances
- The most precise test from the ratio of the J/ψ partial widths:

$$\frac{\Gamma_{J/\psi \to e^+e^-}}{\Gamma_{J/\psi \to \mu^+\mu^-}} = 1.0016 \pm 0.0031$$

- Dominated by BES III data PRD 88 (2013) 032007
- *LU at ~0.31%, for families 1-2*

$R^{Y(3S)}_{\tau\mu} = B(Y(3S) \to \tau^+\tau^-)/B(Y(3S) \to \mu^+\mu^-)$ ratio

PRL 125 (2020) 241801

122 million Y(3S) decays = integrated luminosity of 27.96 fb−1

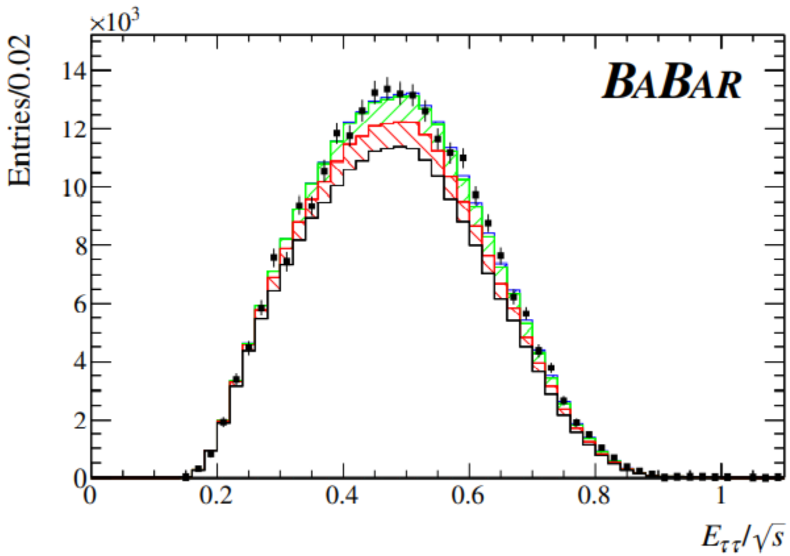
- **Ratio of widths to final state leptons** with different flavor is **free of hadronic uncertainties**, and for heavy spin 1 resonances differs from unity by a small phase-space correction
- Potential contribution from e.g. CP-odd Higgs boson with stronger coupling to heavier leptons: $Y(nS) \to A^0 \to \tau^+\tau^-$ vs. $Y(nS) \to A^0 \to \mu^+\mu^-$

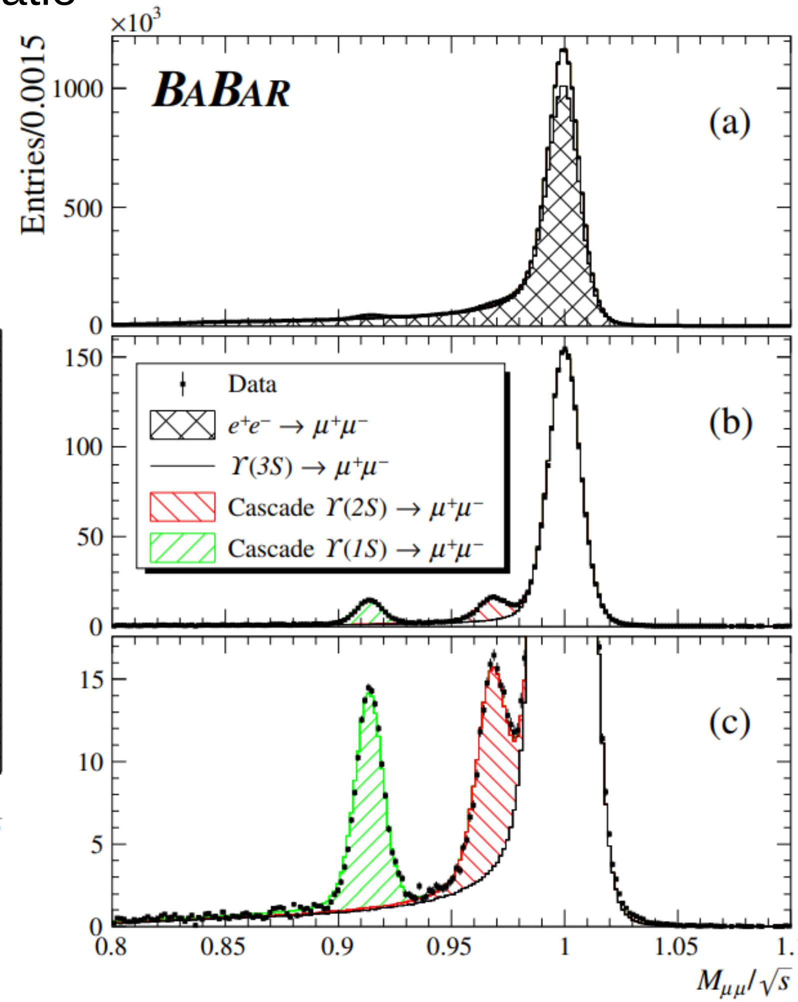
Sanchis-Lozano, Int. J. Mod. Phys. A19 (2004) 2183

- ISR suppressed for resonant production
- Continuum estimated using Y(4S) region
- Control samples: data collected at the Y(4S);
  below the Y(4S) resonance;
  below the Y(3S) resonance

$R^{\Upsilon(3S)}_{\tau\mu} = B(\Upsilon(3S) \to \tau^+\tau^-)/B(\Upsilon(3S) \to \mu^+\mu^-)$ ratio

PRL 125 (2020) 241801





- ❑ Measured ratio: $\mathcal{R}^{\Upsilon(3S)}_{\tau\mu} = 0.966 \pm 0.008_{\rm stat} \pm 0.014_{\rm syst}$
- ❑ Uncertainty order of magnitude improved compared to previous CLEO value
- ❑ *Consistent with SM prediction of 0.9948 to <2σ*

Aloni, Efrati, Grossman, Nir
JHEP 06 (2017) 019

$b \to \ell^+\ell^-$

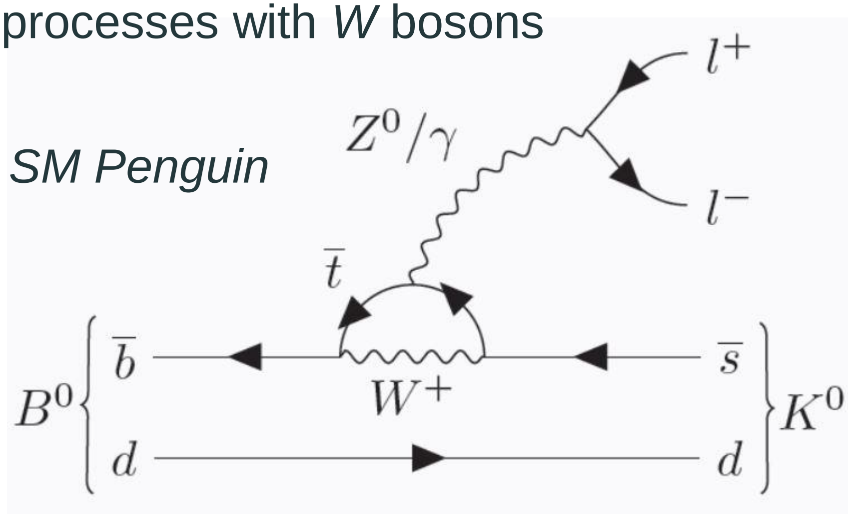
$b \to s\ell^+\ell^-$

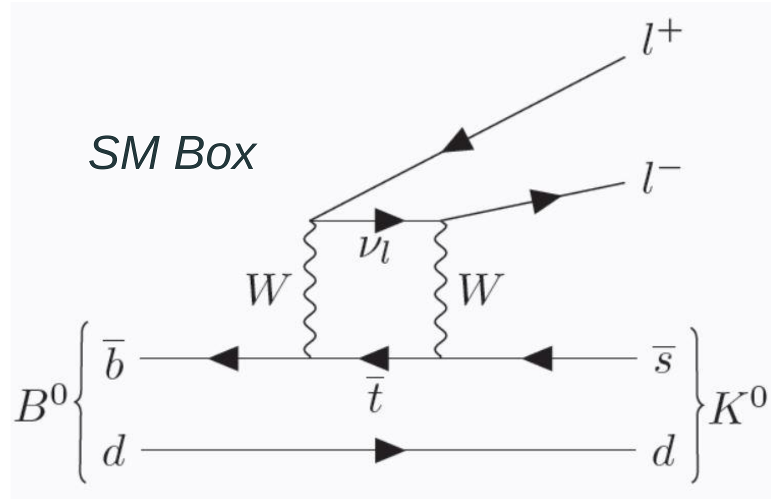
$b \to c\ell^+\ell^-$

$b \to cc\ell^+\ell^-$

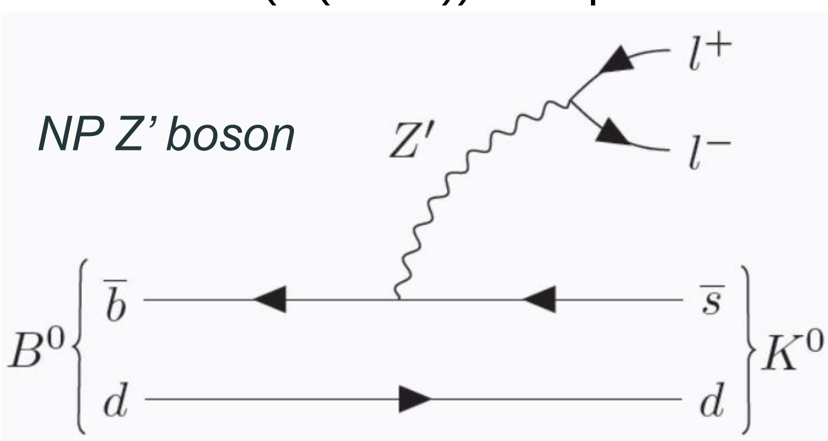
Why $b \to s\ell^+\ell^-$ decays

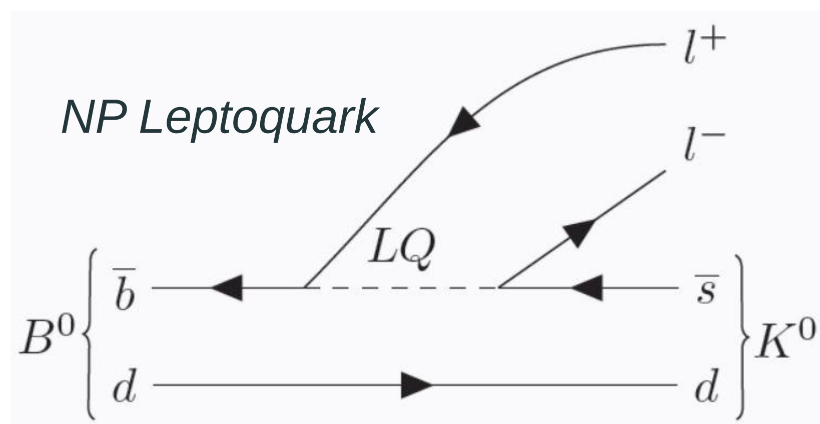
- $b \to s\ell^+\ell^-$ decays, FCNC **in SM** quark flavour
- Suppressed in the SM, branching fractions O(10^{-7})-O(10^{-6}), only occur via loop-level processes with *W* bosons



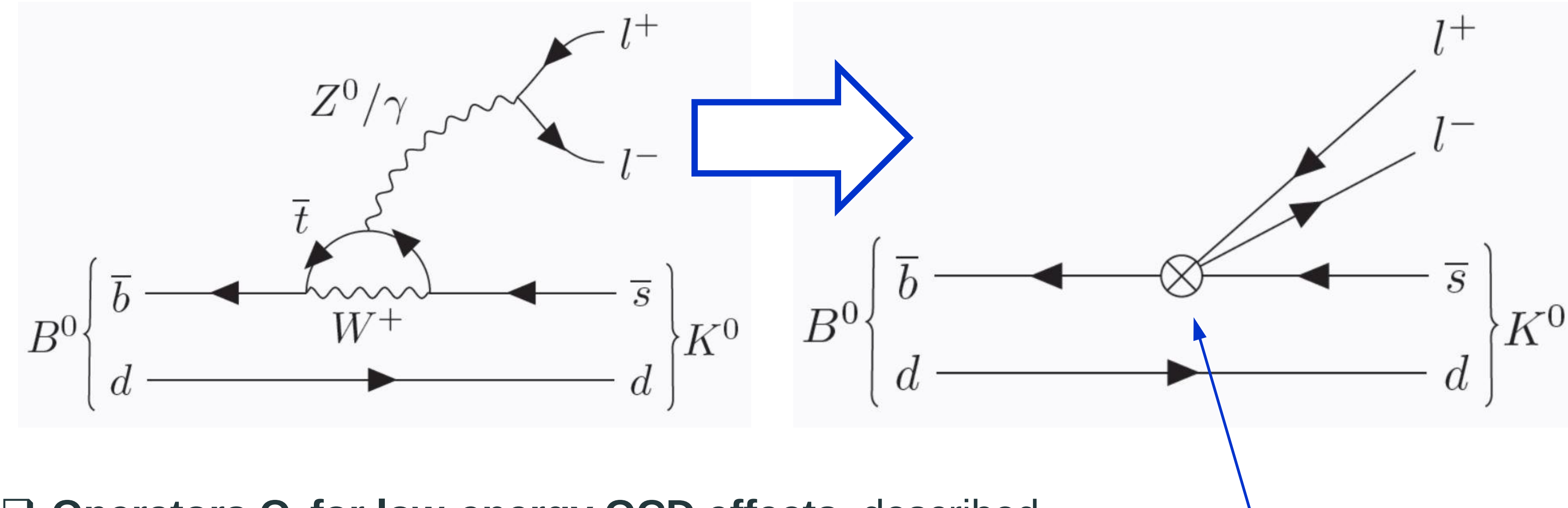


- **NP effects** could give sizeable contributions to $b \to s\ell^+\ell^-$
- Could be tree-level
- Sensitive to (O(>TeV)) new particle masses





- Zoom out to m_b scale and use an Effective Field Theory (EFT), valid at m_b



- **Operators O_i for low-energy QCD effects**, described using form factors, having large theory uncertainties
- Integrate out **short-distance (high-energy) effects**, parameterize them using **Wilson Coefficients $C_i(m_b)$**

C_9 - EW vector
C_{10} - EW axial-vector
C_7 - electromagnetic

- Hamiltonian defined in terms of Wilson Coefficients $C_i^{(')}$ and Operators $C_i^{(')}$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

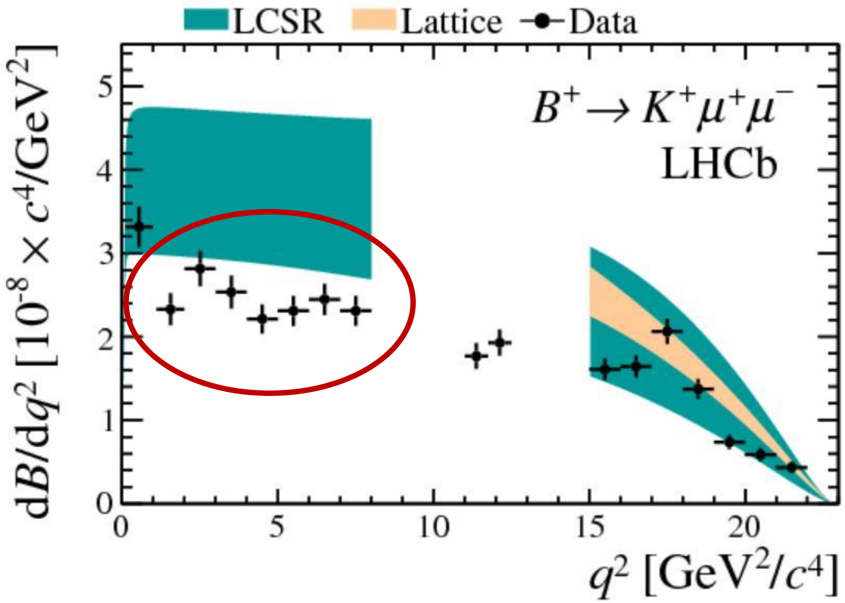
- *High-mass NP effects will modify values of C_i*

- **$b \to s\mu^+\mu^-$ branching fractions**

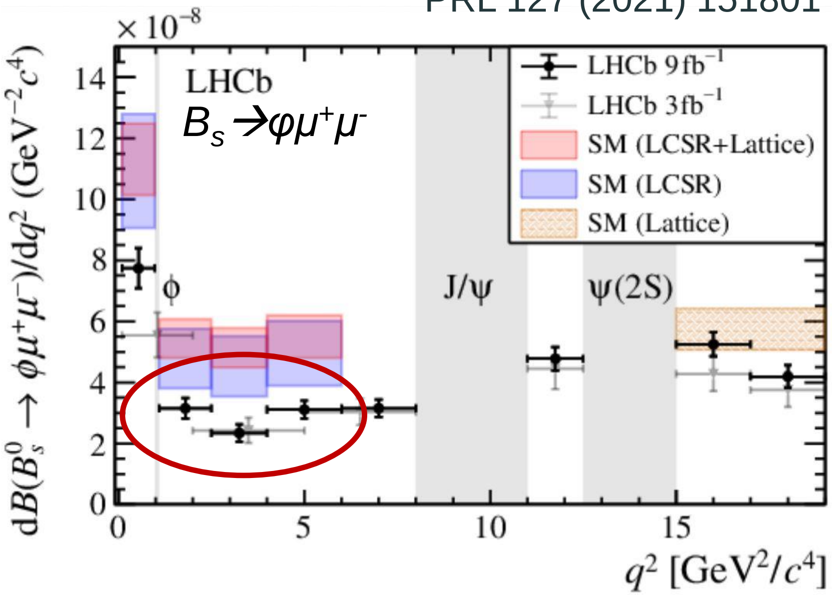
  in bins of $q^2 = m(\mu^+\mu^-)^2$

- Deviations in low q^2 region
- SM predictions suffer from large hadronic uncertainties

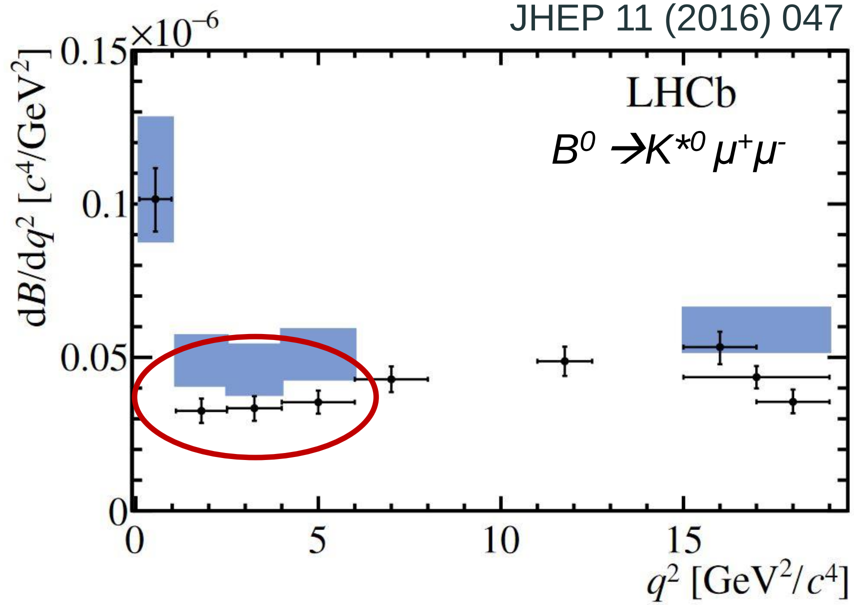
JHEP 06 (2014) 133



PRL 127 (2021) 151801

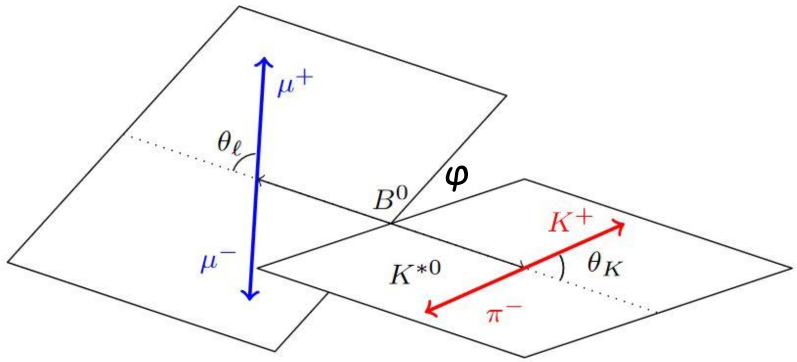


JHEP 11 (2016) 047

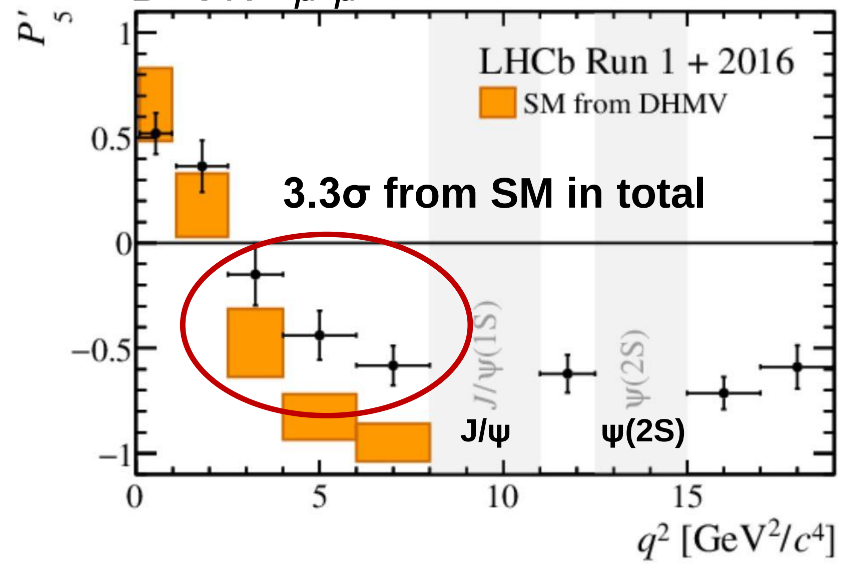


Flavour anomalies: $b \to s\mu^+\mu^-$ angular observables

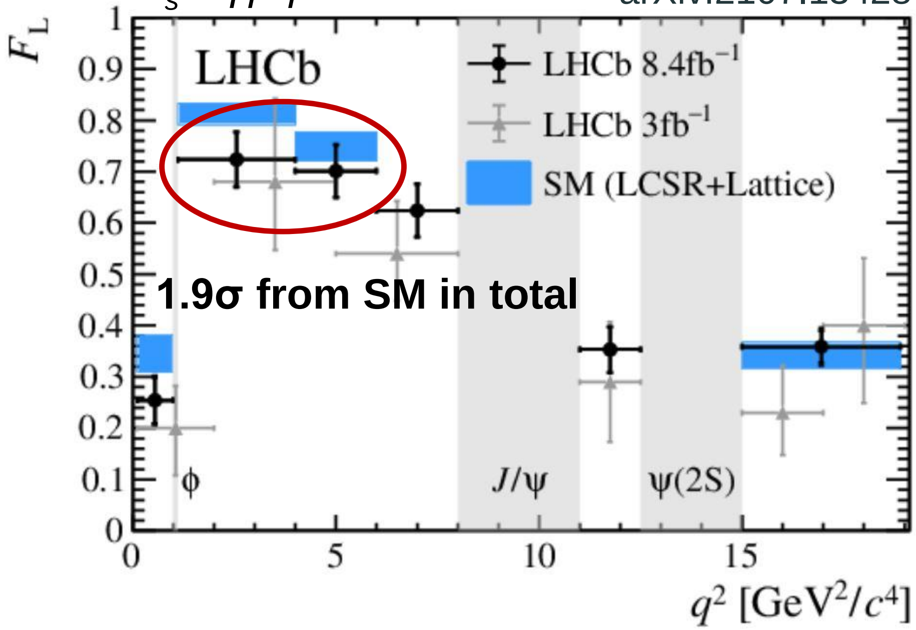
- Large number of observables offering complementary information on NP
- **Angular observables, F_L and P_5'**



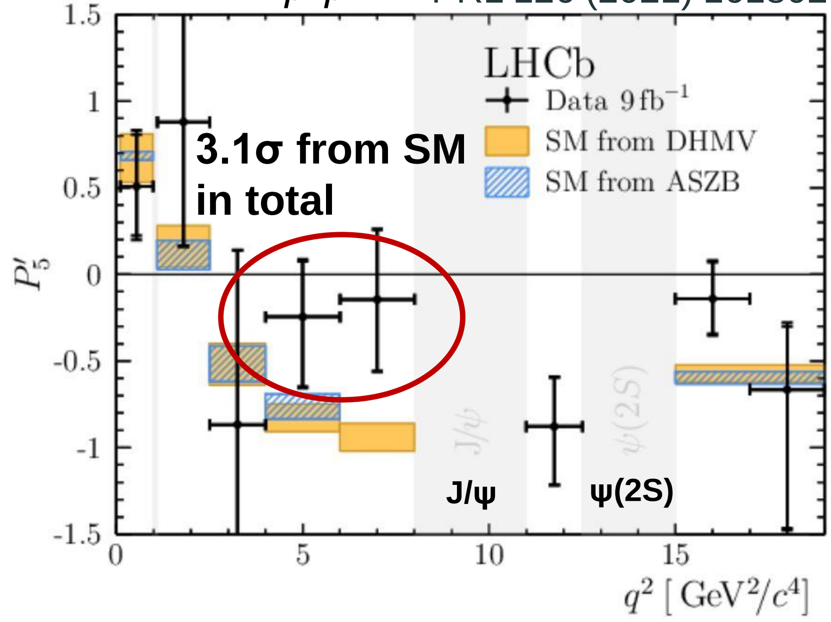
$B^0 \to K^{*0}\mu^+\mu^-$ PRL 125 (2020) 011802



$B_s \to \varphi\mu^+\mu^-$ arXiv:2107.13428

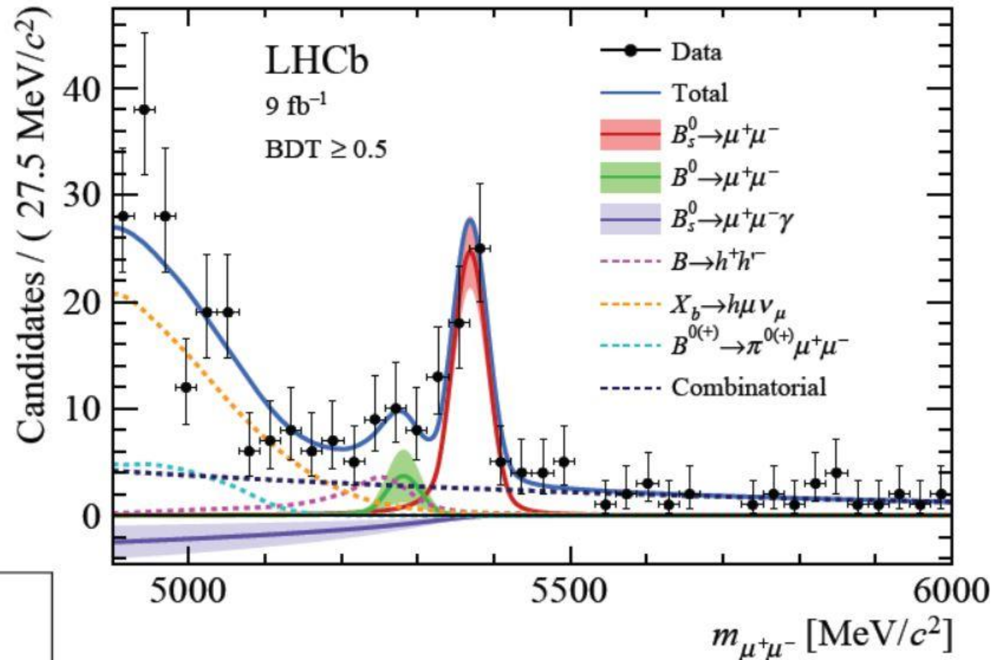


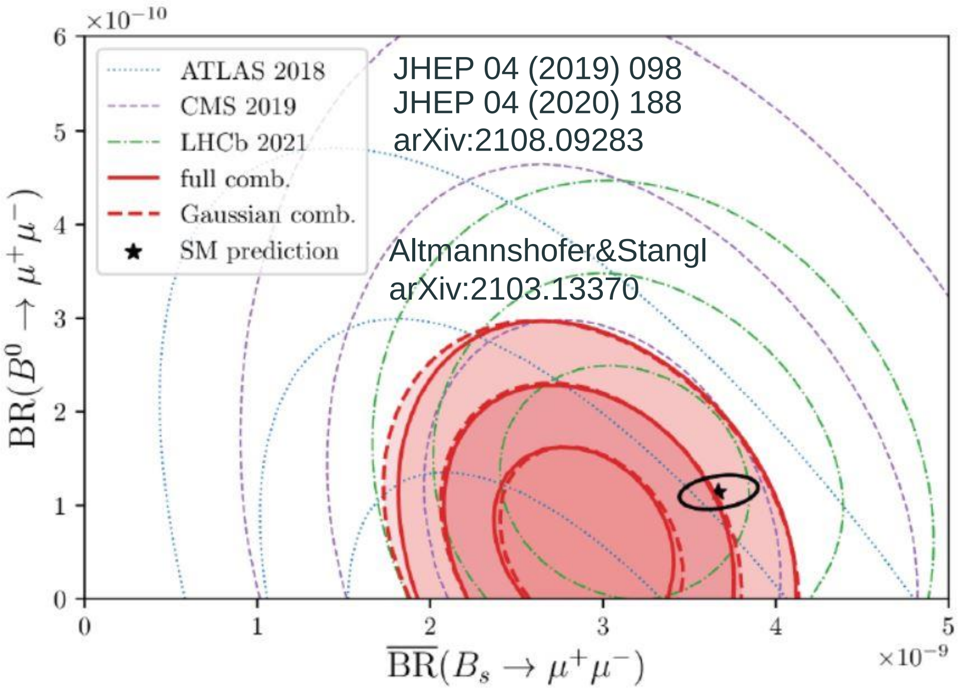
$B^+ \to K^{*+}\mu^+\mu^-$ PRL 126 (2021) 161802



- Purely leptonic final-state
- Low hadronic uncertainties for SM prediction
- Clean experimental signature

arXiv:2108.09283





- Average of LHCb, ATLAS, CMS branching fractions is **2.3σ from SM**

$b \to s\ell^+\ell^-$

- Lepton universality ratios

$$R_H \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2} \approx 1 \text{ (SM)}$$

- Extremely clean theoretically, any deviation from the SM prediction can point to NP

Hiller, Krüger, PRD 69 (2004) 074020
Bordone, Isidori, Pattori, EPJC 76 (2016) 44
Isidori, Nabeebaccus, Zwicky, JHEP 12 (2020) 104

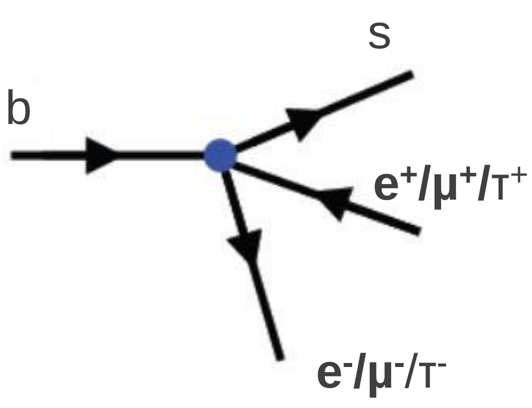
- Lepton universal in the SM → can point to LU violating NP

Hiller & Kruger arXiv:hep-ph/0310219

- $b \to s\tau^+\tau^-$ not observed yet → compare μ and e

- Precise predictions
  - QCD uncertainty cancels to 10^{-4}
  - Up to ~1% QED corrections

Bordone et al arXiv:1605.07633

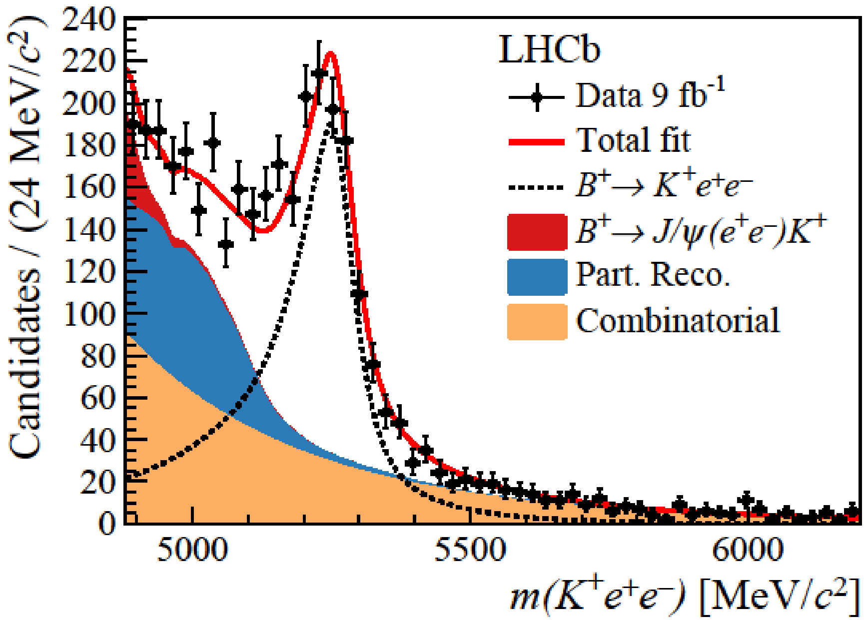


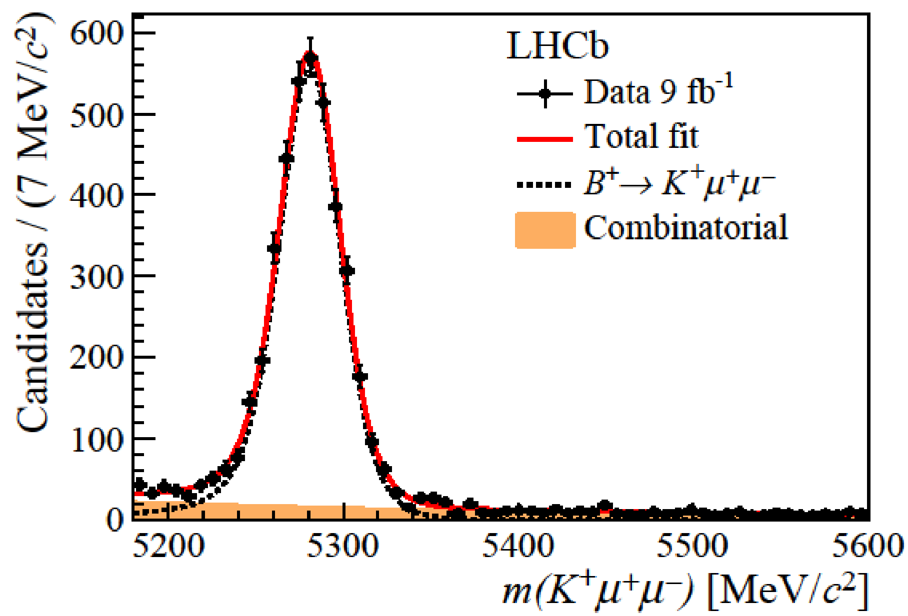
$B^+ \rightarrow K^+\ell^+\ell^-$

arXiv:2103.11769

- Electrons more difficult due to Bremsstrahlung photons:
  - Degrading resolution even after energy recovery applied
  - Higher electron trigger threshold
- Efficiency difference due to hardware trigger thresholds

$$\epsilon(B+ \rightarrow K+\mu+\mu-) \,/\, \epsilon(B+ \rightarrow K+e+e-) \sim 2.8$$





- **Double ratio** to reduce uncertainty due to efficiency modelling:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

- $J/\psi \rightarrow \ell^+\ell^-$ branching fractions respect lepton universality to within 0.4%

- Numerous **cross-checks**
- $r_{J/\psi} = \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)/\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+) = 0.981 \pm 0.020$

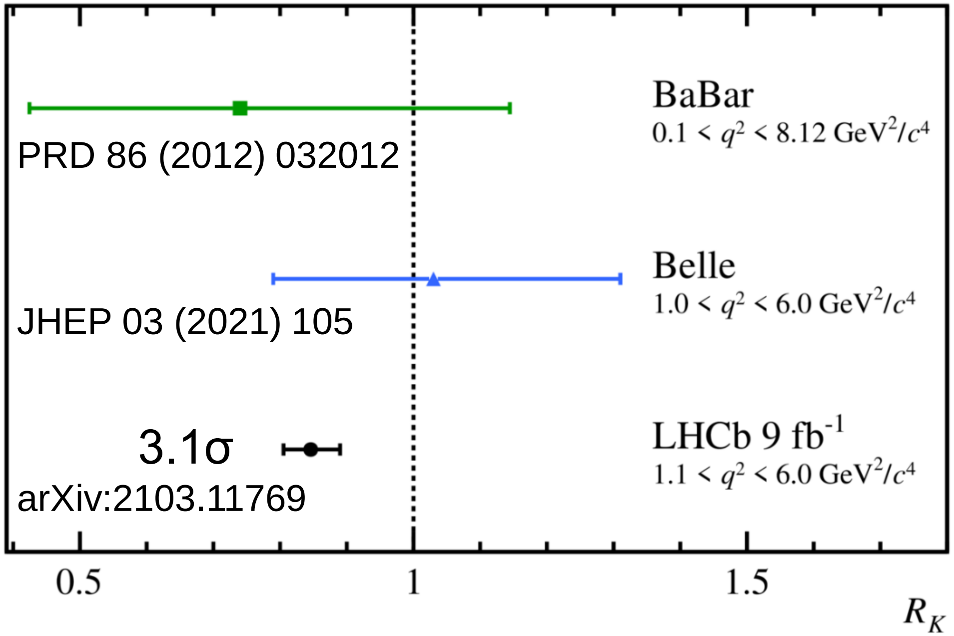
  → good control of the efficiencies

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.997 \pm 0.011$$

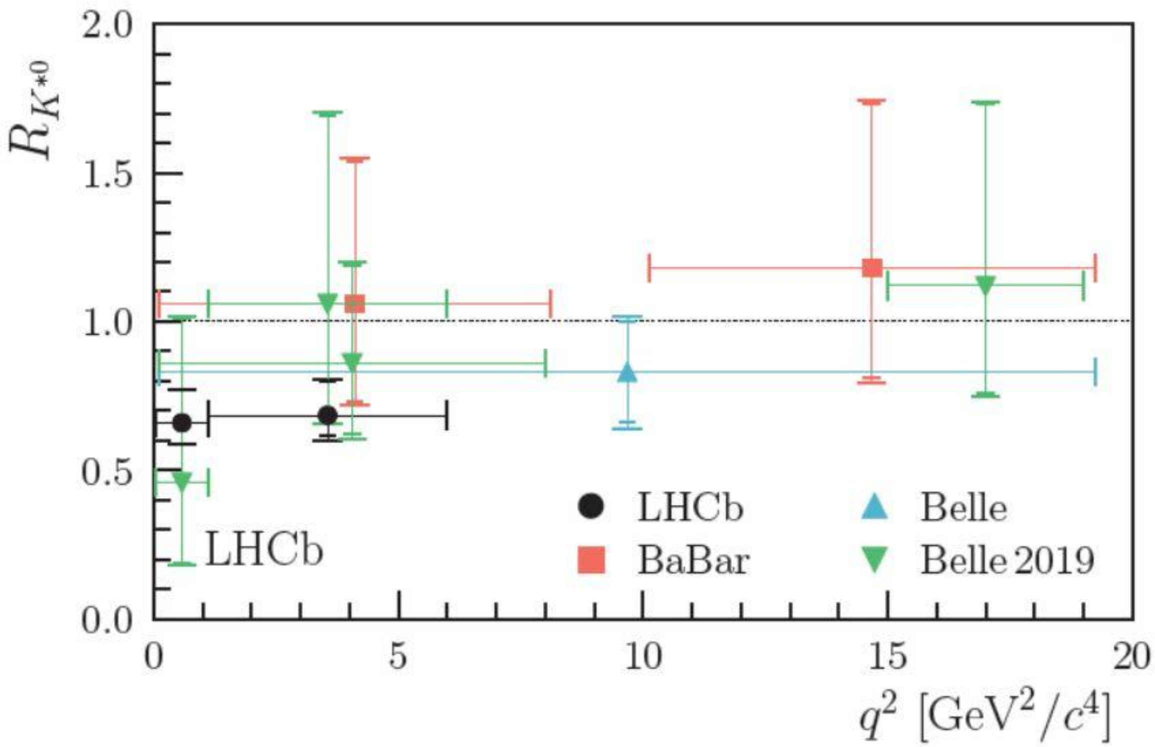
  → world-leading test of lepton flavour universality in $\psi(2S)\to\ell^+\ell^-$ decays

- $R_{K+} = 0.846\,^{+0.042}_{-0.039}\text{(stat)}\,^{+0.013}_{-0.012}\text{(syst)}$ in [1.1,6.0] GeV^2
- Most precise measurement of R_{K+} to date
- p-value of 0.10%
- ***3.1σ deviations from SM***

- Summary of the measurements
- BaBar and Belle measurements combine R_{K+} and R_{Ks}



$B^0 \to K^{*0} \ell^+ \ell^-$



LHCb: JHEP 08 (2017) 055
Belle 2019: PRL 126 (2021) 161801
Belle: PRL 103 (2009) 171801
BaBar: PRD 86 (2012) 032012

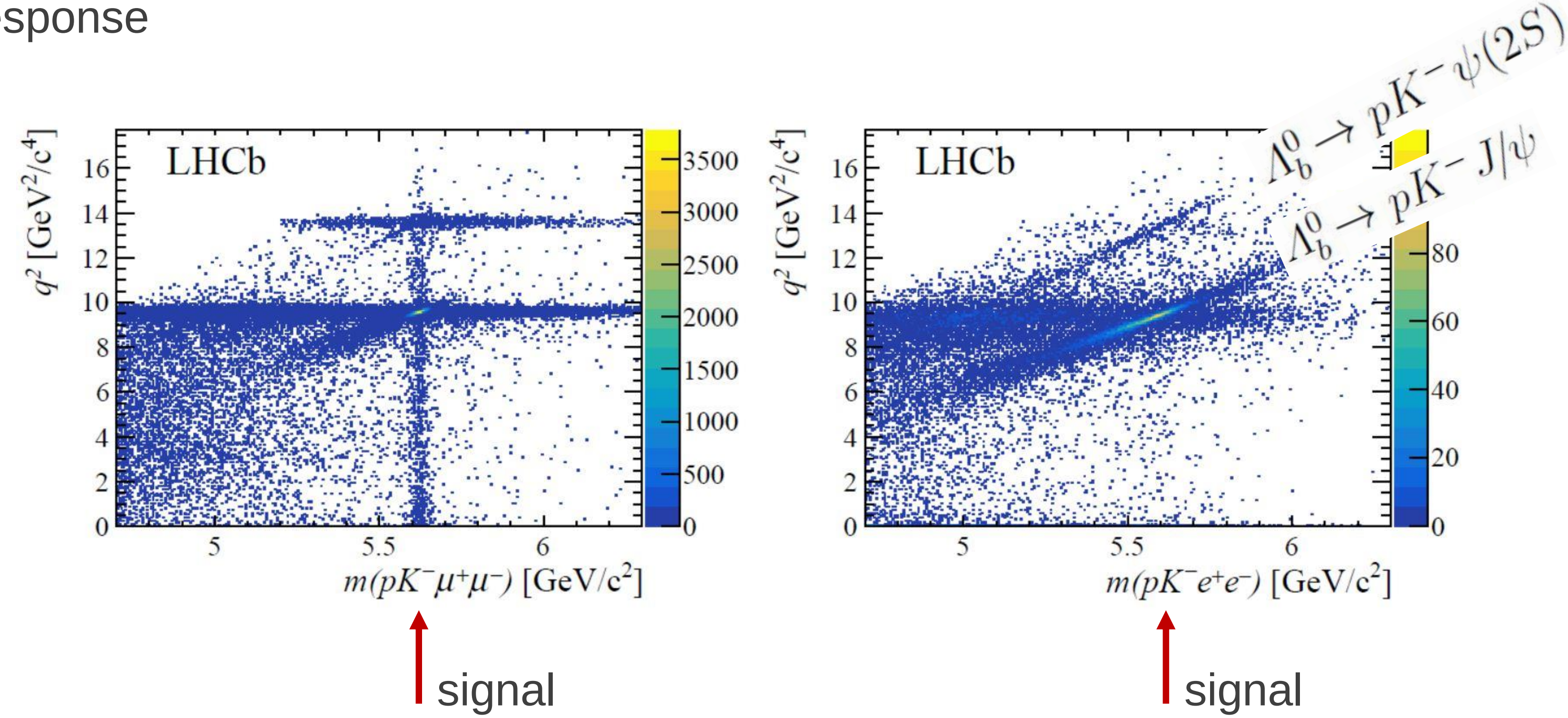
- ❑ $R_{K^{*0}} = 0.66^{+0.11}_{-0.07}$ (stat) ± 0.03 (syst) in [0.045,1.1] GeV^2
- ❑ $R_{K^{*0}} = 0.69^{+0.11}_{-0.07}$ (stat) ± 0.05 (syst) in [1.1,6.0] GeV^2
- ❑ ***2.2-2.5σ deviations from SM**, depending on q^2 bin*

$\Lambda_b \to pK^-\ell^+\ell^-$

JHEP 05 (2020) 040

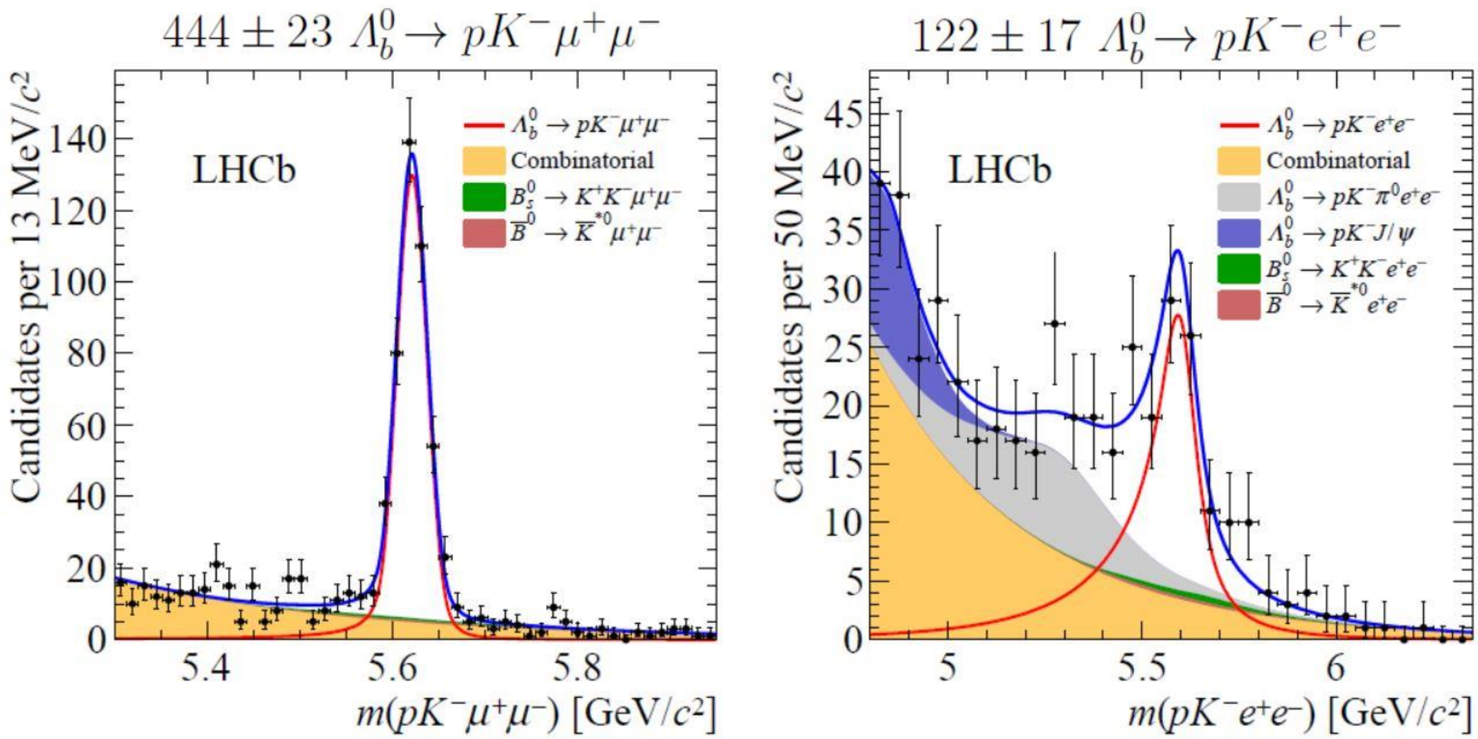
- At the LHC, the $b \to s\ell^+\ell^-$ study can be extended to baryons, independent test of the SM
- R_{pK} ($\Lambda_b \to pK^-\ell^+\ell^-$) - same pattern, complementary constraints, but pK resonant structure needed

- Electrons more difficult due to emission of Bremsstrahlung photons and trigger response



$\Lambda_b \to pK^- \ell^+ \ell^-$

JHEP 05 (2020) 040



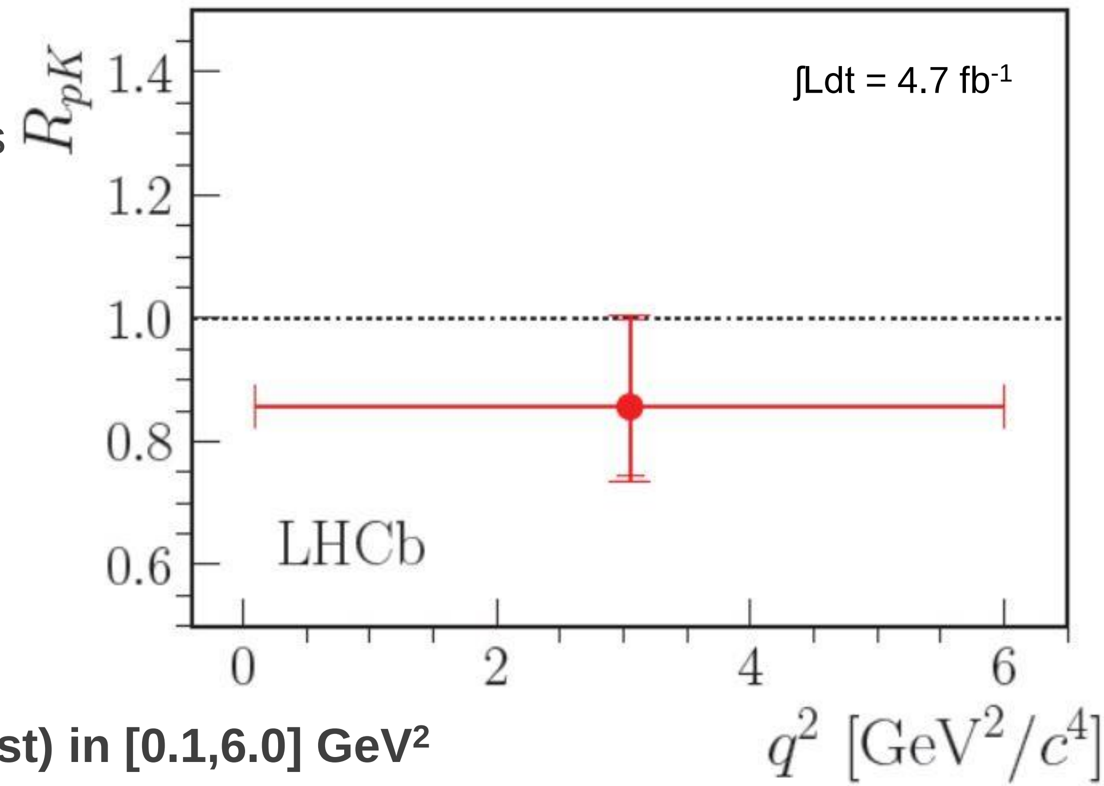
- **Double ratio** to reduce uncertainty due to efficiency modelling:

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))} \Bigg/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}$$

- $J/\psi \to \ell^+\ell^-$ branching fractions respect lepton universality to within 0.4%

$\Lambda_b \to pK^-\ell^+\ell^-$ JHEP 05 (2020) 040

- Cross-checks
- $r_{J/\psi}^{-1} = 0.96 \pm 0.05$
  → good control of the efficiencies



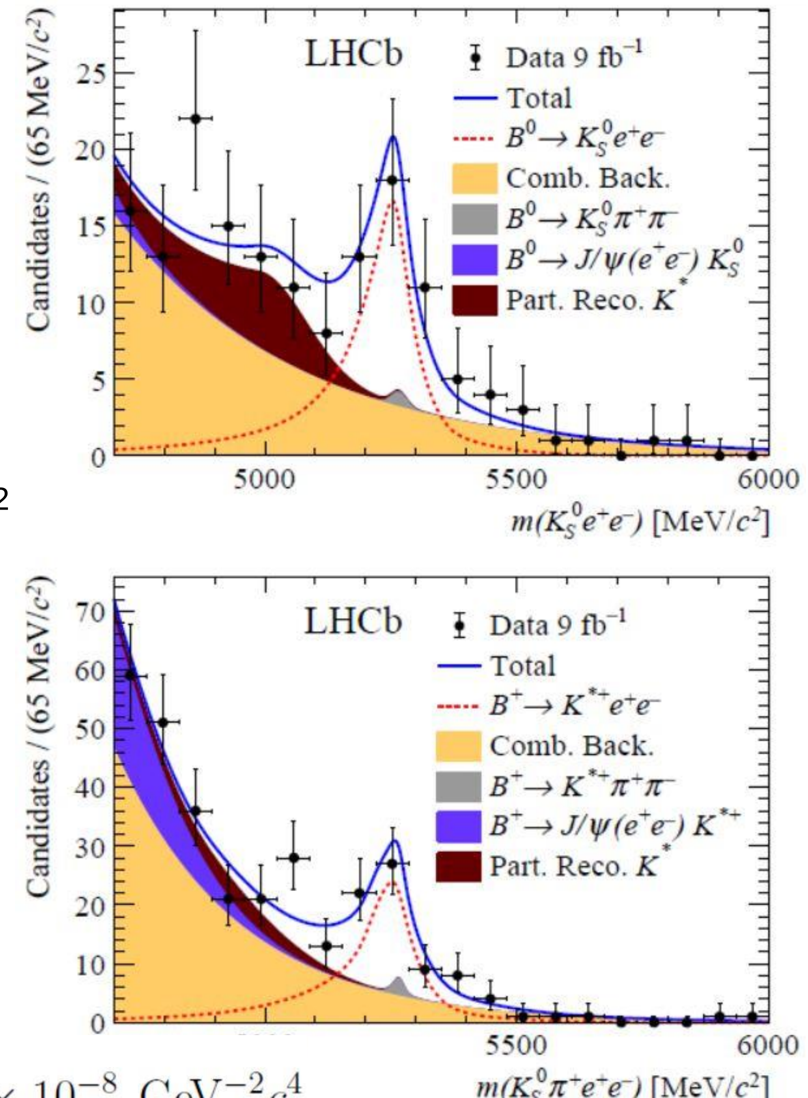
- **$R_{pK} = 0.86^{+0.14}_{-0.11}$ (stat) ± 0.05 (syst) in [0.1,6.0] GeV²**
- ***Agrees with SM at <1σ***
- *Also in agreement with the deviations observed in tests of R_K and $R_{K^{*0}}$*
- First measurements:

$$\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = \left(2.65 \pm 0.14 \pm 0.12 \pm 0.29^{+0.38}_{-0.23}\right) \times 10^{-7}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = \left(3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}\right) \times 10^{-7}$$

arXiv:2110.09501

$B^0 \rightarrow K^0_S \ell^+ \ell^-$

$B^+ \rightarrow K^{*+} \ell^+ \ell^-$



- Long-lived K^0_S, which often flies out of the tracker acceptance → lower signal yield
- Reconstruct $K^0_S \rightarrow \pi^+\pi^-$, $K^{*+} \rightarrow K^0_S\pi^+$
- q^2 range of $R_{K^{*+}}$ extended down to 0.045 GeV^2

- **First observations**:

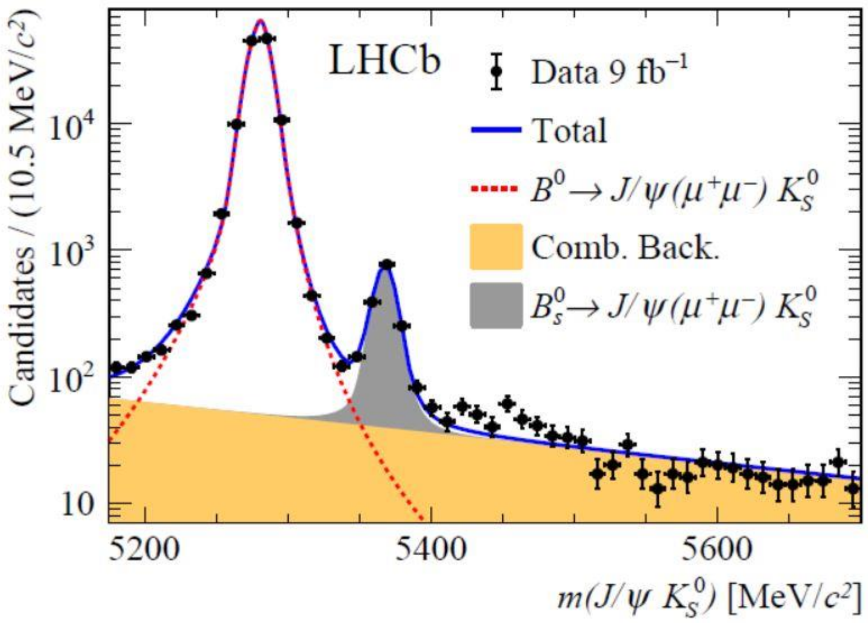
$$\frac{d\mathcal{B}(B^0 \rightarrow K^0 e^+ e^-)}{dq^2} = (2.6 \pm 0.6\,(\text{stat.}) \pm 0.1\,(\text{syst.})) \times 10^{-8}\ \text{GeV}^{-2}c^4$$

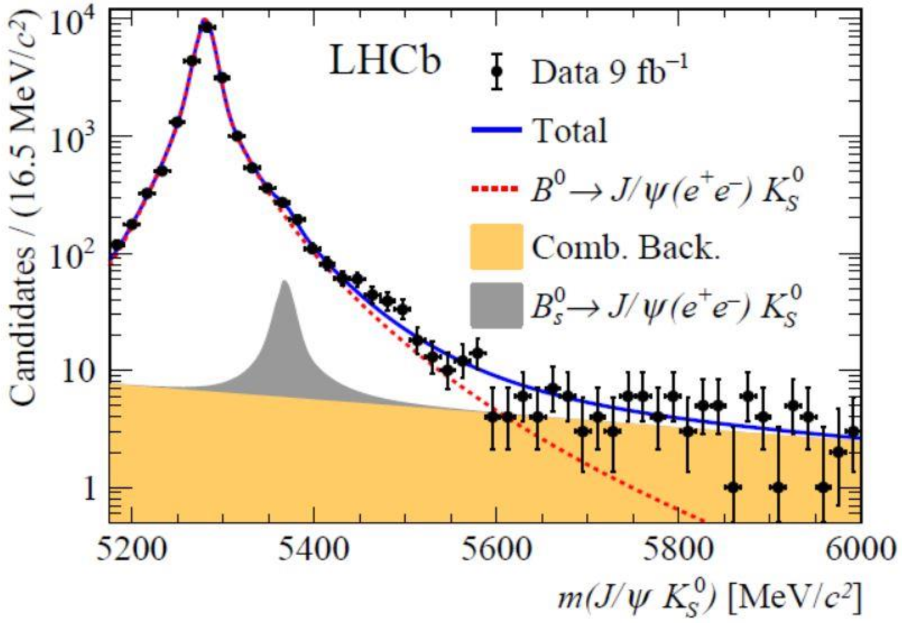
$$\frac{d\mathcal{B}(B^+ \rightarrow K^{*+} e^+ e^-)}{dq^2} = \left(9.2\,^{+1.9}_{-1.8}\,(\text{stat.})^{+0.8}_{-0.6}\,(\text{syst.})\right) \times 10^{-8}\ \text{GeV}^{-2}c^4,$$

- Reduce systematic effects by using control channel

arXiv:2110.09501

$$B \rightarrow K^{(*)} J/\psi(\rightarrow \ell^+\ell^-)$$

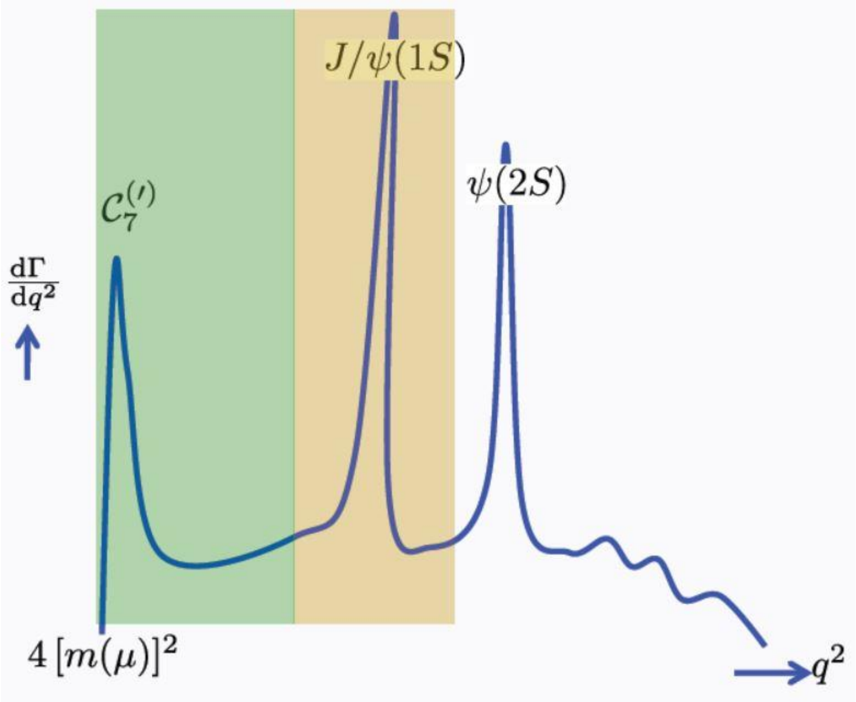




- Charmonium decays known to respect LU to within 0.4%
- High signal purity thanks to the $m(e^+e^-)$ constraint to the mass

arXiv:2110.09501

- Electron signal yields are limiting factor for precision
  - Drives choice of q^2 binning
- Upper q^2 limits minimise J/ψ pollution
- In $B^+ \rightarrow K^{*+}\ell^+\ell^-$, pole at low-$q^2$ from virtual photons
  - While lepton-universal, gives a large increase in signal yield



$B^0 \rightarrow K_S\,\ell^+\ell^-$

- q^2 bins

Decay mode	Min. q^2 [GeV^2]	Max. q^2 [GeV^2]
$B^0 \rightarrow K^0_S\ell^+\ell^-$	1.1	6.0
$B^+ \rightarrow K^{*+}\ell^+\ell^-$	0.045 ($4m_\mu^2$)	6.0

- **Double ratio to partly cancel μ/e response differences**

arXiv:2110.09501

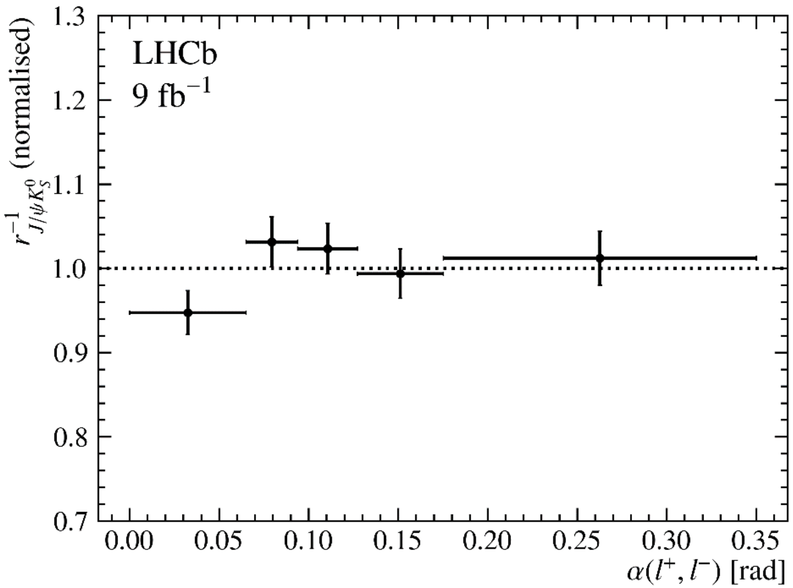
$$R_{K^{(*)}}^{-1} = \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$

$$= \left(\frac{N_{\rm sig}^{ee}}{\epsilon_{\rm sig}^{ee}} \cdot \frac{\epsilon_{\rm con}^{ee}}{N_{\rm con}^{ee}}\right) \Big/ \left(\frac{N_{\rm sig}^{\mu\mu}}{\epsilon_{\rm sig}^{\mu\mu}} \cdot \frac{\epsilon_{\rm con}^{\mu\mu}}{N_{\rm con}^{\mu\mu}}\right),$$

Dominates the total uncertainty

- **Ratios $r_{J/\psi\ K(*)}$:**

$$r_{J/\psi K^{(*)}}^{-1} \equiv \frac{\mathcal{B}\left(B\to J/\psi\,(e^+e^-)\,K^{(*)}\right)}{\mathcal{B}\left(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)}\right)}$$



$$r_{J/\psi K^0_{\rm S}}^{-1} = 0.977 \pm 0.008\,({\rm stat.}) \pm 0.027\,({\rm syst.})$$

$$r_{J/\psi K^{*+}}^{-1} = 0.965 \pm 0.011\,({\rm stat.}) \pm 0.034\,({\rm syst.})$$

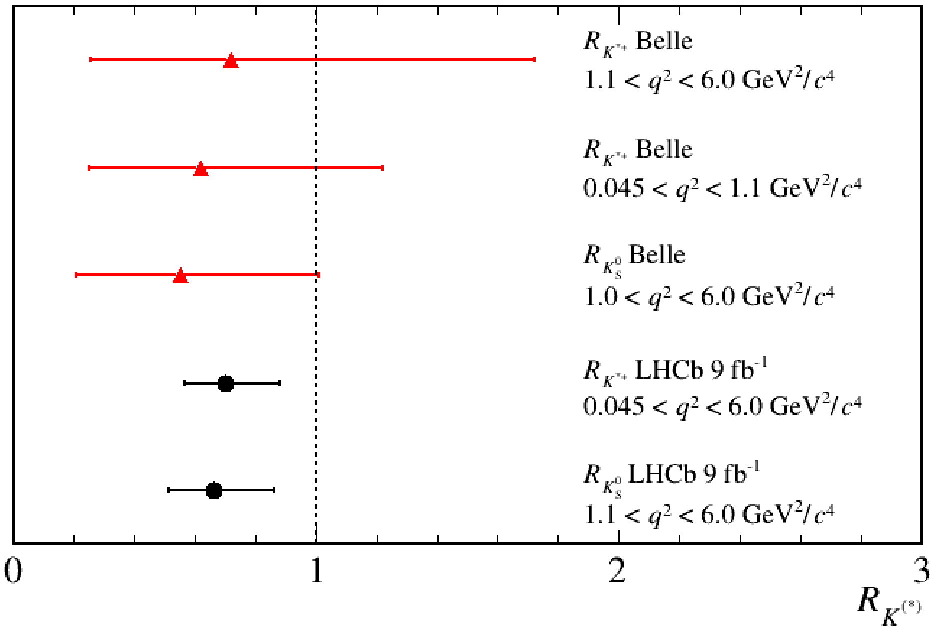
- Flat within statistical precision against opening angle between leptons, multivariate classifier, …

- **Double ratio to partly cancel μ/e response differences**

arXiv:2110.09501

$$R^{-1}_{K^0_S} = 1.51\,^{+0.40}_{-0.35}\,(\text{stat.})\,^{+0.09}_{-0.04}\,(\text{syst.})$$
$$R^{-1}_{K^{*+}} = 1.44\,^{+0.32}_{-0.29}\,(\text{stat.})\,^{+0.09}_{-0.06}\,(\text{syst.})$$

- The **most precise measurements** $\mathbf{R_{K0}}$ **and** $\mathbf{R_{K^{*+}}}$ to date
- Results **in agreement with SM** predictions and previous measurements at Belle
- Central values exhibit **same pattern of deviation as isospin partners** R_{K+} and $R_{K^{*}0}$

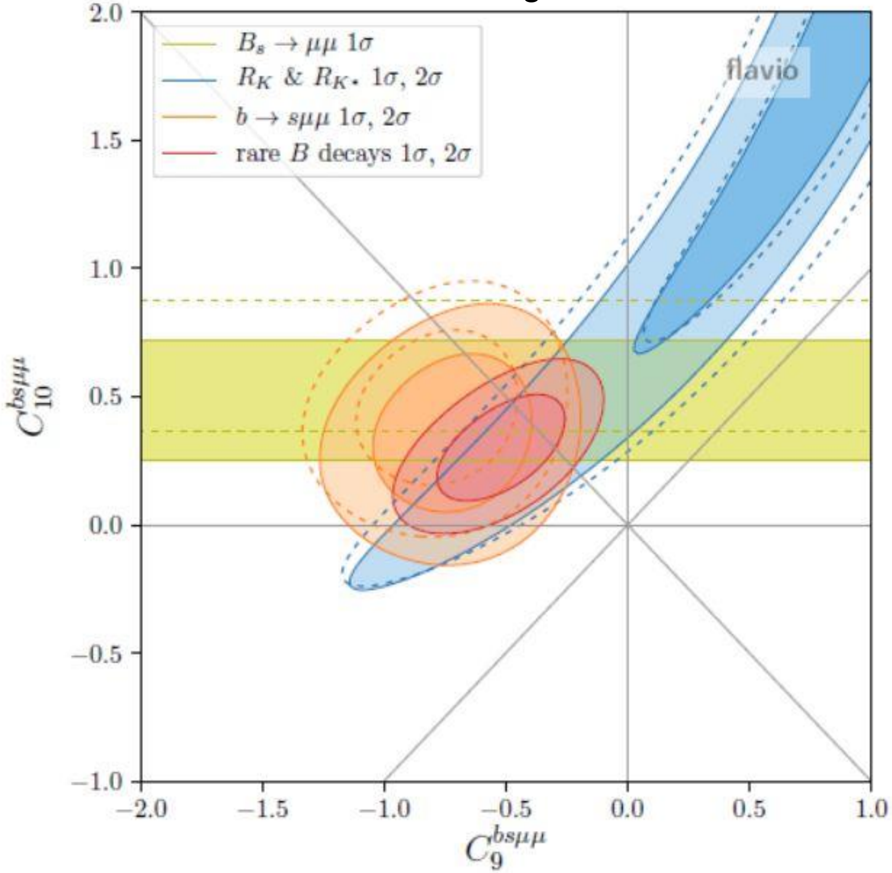


- Two results combined to evaluate total significance with respect to the SM:
  - Fit for Wilson Coefficients using Flavio, arxiv:1810.08132
  - Float $C_9^{bs\mu\mu} = - C_{10}^{bs\mu\mu}$ (LFU ratios cannot disentangle $C_9^{bs\mu\mu}$ and $C_{10}^{bs\mu\mu}$)
- ***Combined significance of 2.0σ compared to SM***
- *Best fit value:* $C_9^{bs\mu\mu} = -0.8^{+0.4}_{-0.3}$

- **Global fits** to examine possible NP in a model-independent way
- Different analyses with various approaches
- Negative shifts to C^{μ}_{9} or $C^{\mu}_{9} = - C^{\mu}_{10}$ favoured
- **Deviations of 3-5σ from SM, depending on theory assumptions**
- Anomalies can be explained coherently by:
  - new vector coupling $C_9^{bs\mu\mu}$
  - new vector-axial vector coupling with $C_9^{bs\mu\mu} = - C_{10}^{bs\mu\mu}$
- *Do we see a coherent pattern ?*

Altmannshofer and Stangl, arXiv:2103.13370

Muonic axial-vector coupling



Muonic vector coupling

- Other averages in:
  - Algueró *et. al.*, arXiv:2104.08921
  - Hurth *et. al.*, arXiv:2104.10058
  - Ciuchini *et. al.*: EPJ C79 (2019) 8, 719
  - ...

LFU tests with R(D*), R(D), R(J/ψ)

- **SM prediction**: R(D*) = 0.252 ± 0.003, Fajfer et al., PRD 85 (2012) 094025

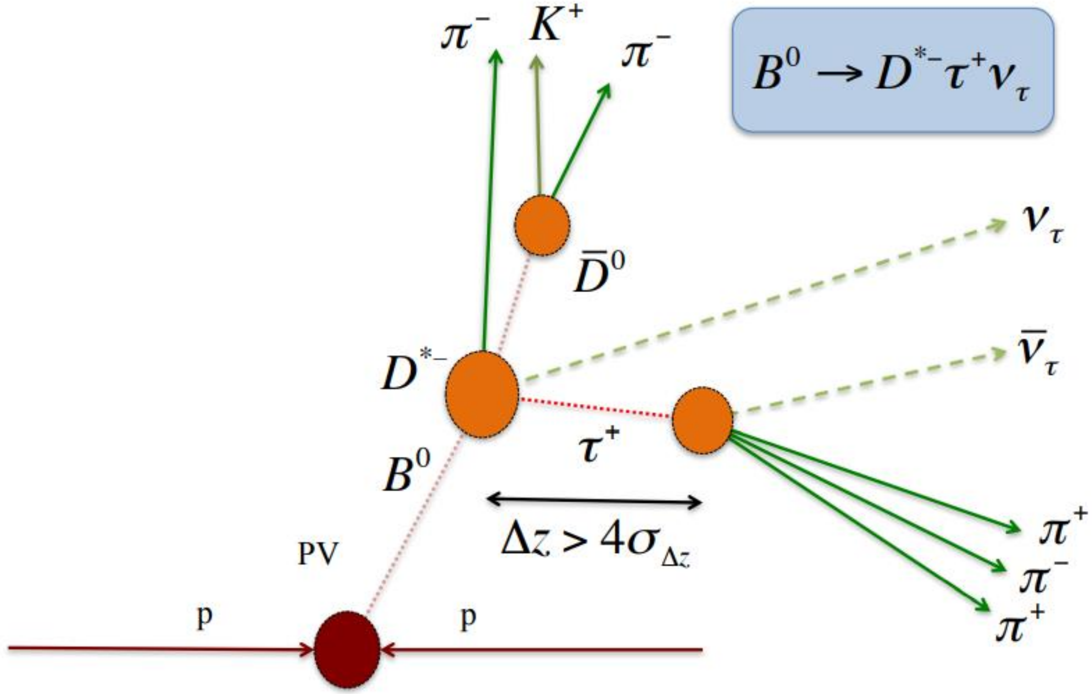
$$\mathcal{R}(D^{(*)-}) \equiv \mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)$$

- In order to reduce systematic uncertainty, **normalization with B⁰ hadronic decay**

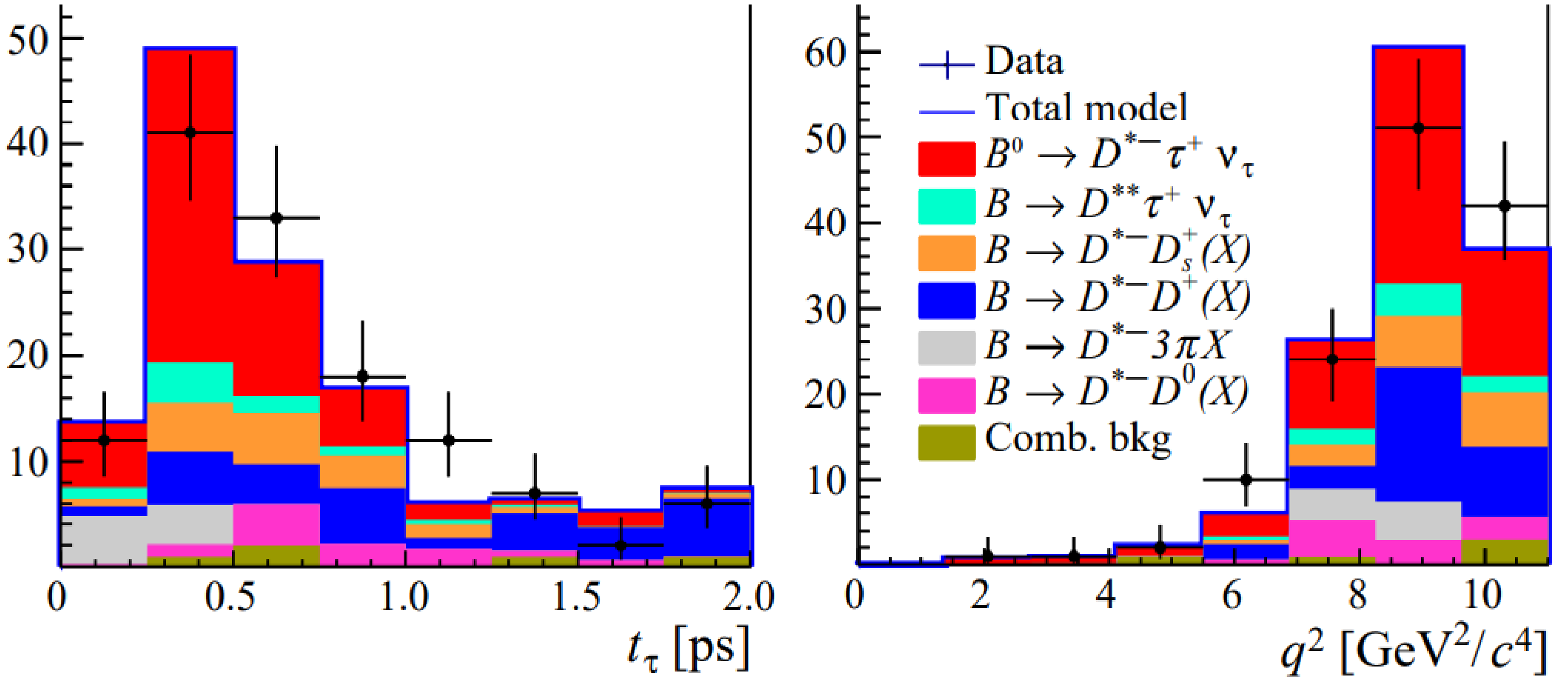
$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} = \frac{N_{\text{sig}}}{N_{\text{norm}}}\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}\frac{1}{\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\overline{\nu}_\tau)}$$

$$\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-}) \times \mathcal{B}(B^0 \to D^{*-}3\pi)/\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$$

- Signal **decay topology**



- Distributions of t_τ and q^2 in the BDT bin with highest BDT response



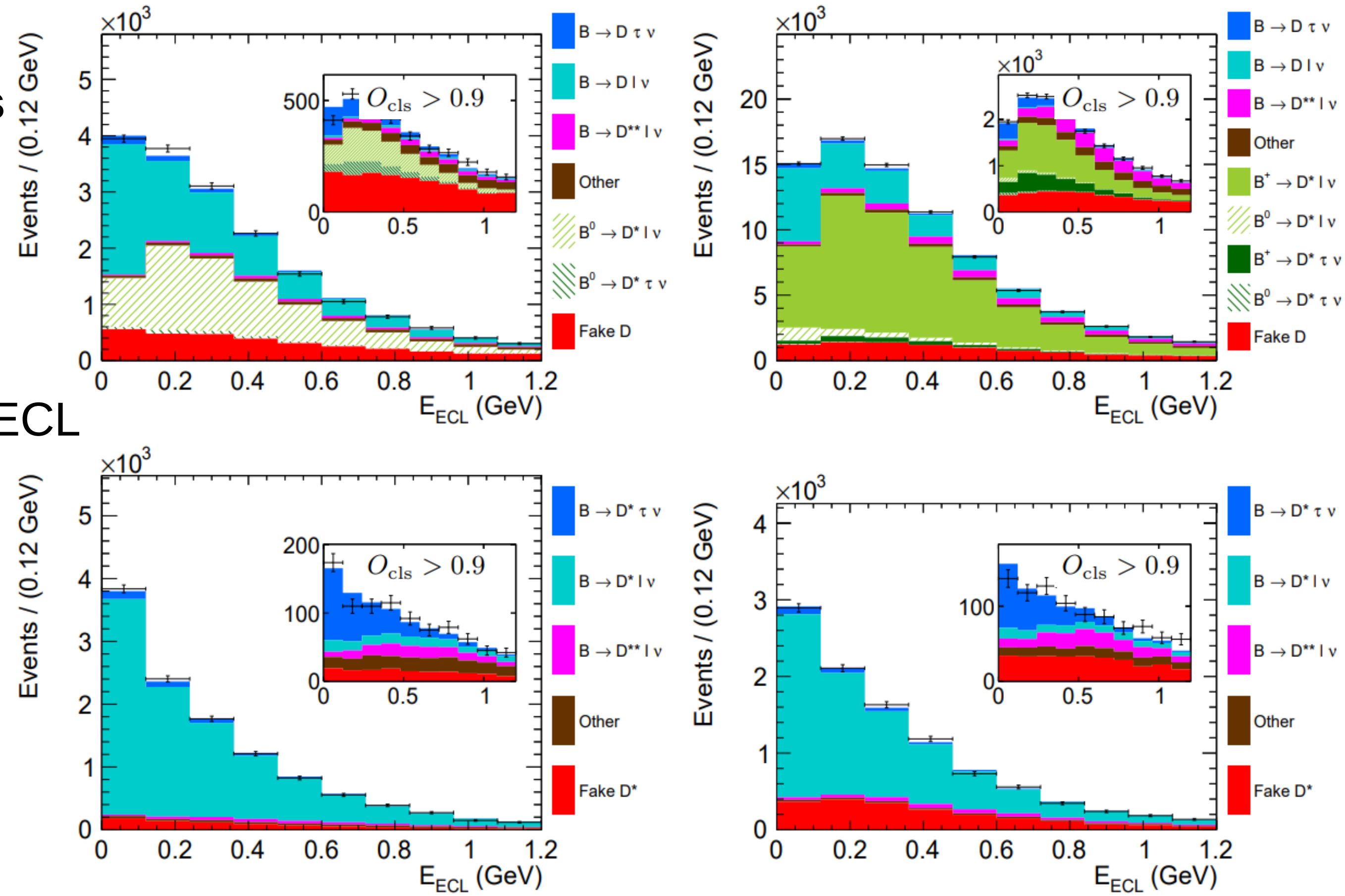
$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$$

- **Deviation from the SM prediction is 1.1σ**

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

$772 \times 10^6 B\bar{B}$

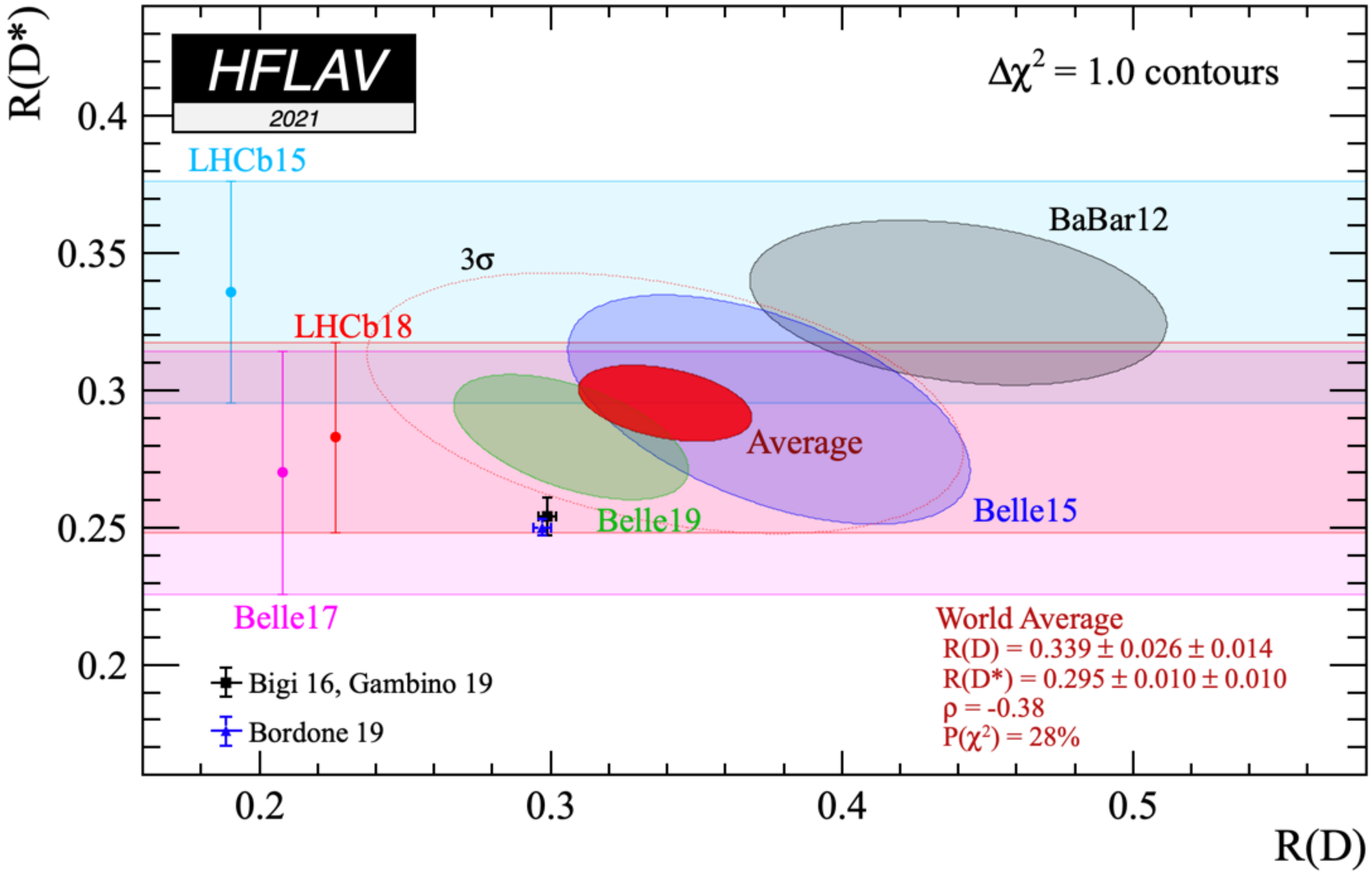
- **R(D$^{(*)}$)** with **semileptonic tagging** at Belle
- Fit simultaneously to **four D$^{(*)}\ell$ samples**
- Exploit isospin constraint R(D$^{(*)0}$) = R(D$^{(*)+}$)
- Fit projections to sum of neutral clusters in ECL not associated to reconstructed particles
- Classifier in entire and high regions



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

- **Deviation from the SM prediction is 0.2σ and 1.1σ**

- Combination of LHCb, Belle and BaBar results



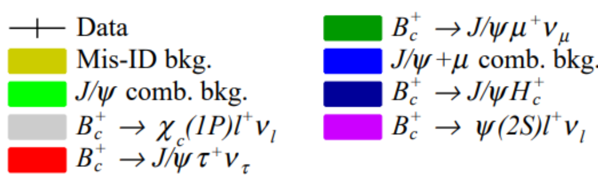
- **Flavour anomaly at >3σ**

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

- Tree diagram
- SM predictions between 0.25 and 0.28

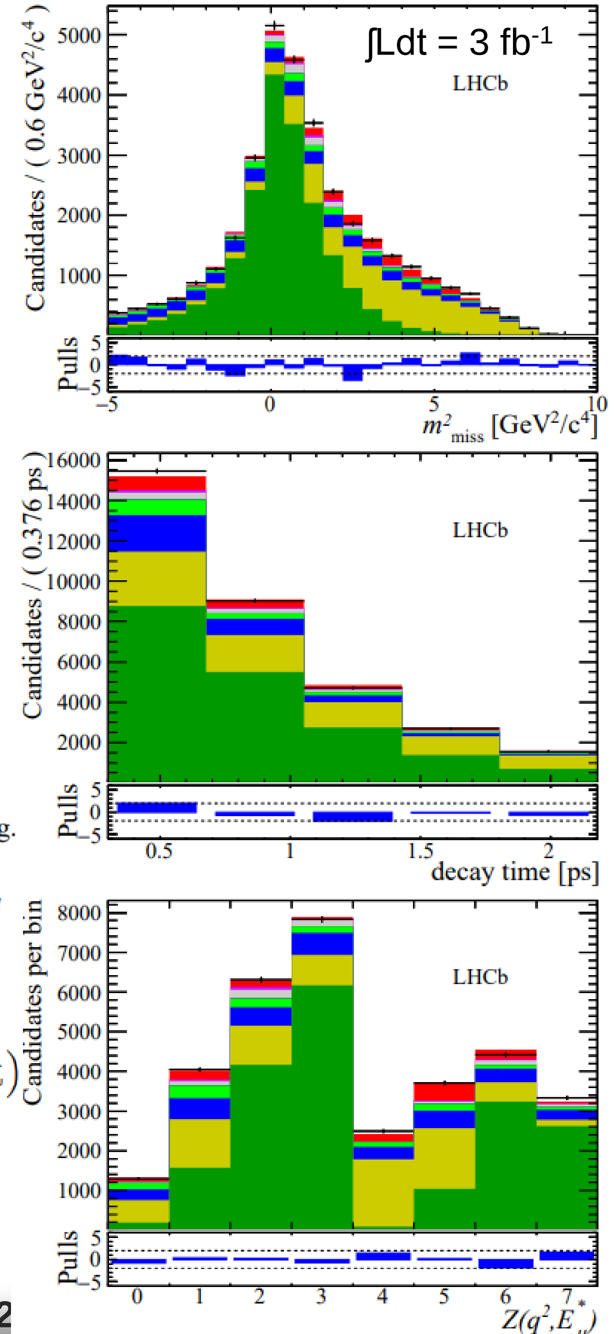
  Anisimov, Narodetskii, Semay, Silvestre-Brac, PLB 452 (1999) 129
  Kiselev, arXiv:hep-ph/0211021
  Ivanov, Korner, Santorelli, PRD 73 (2006) 054024
  Hernandez, Nieves, Verde-Velasco, PRD 74 (2006) 074008

- Identical visible final state $(\mu^+\mu^-)\mu^+$
- Form factors $V(q^2)$, $A_0(q^2)$, $A_1(q^2)$, $A_2(q^2)$ determined from fits to data

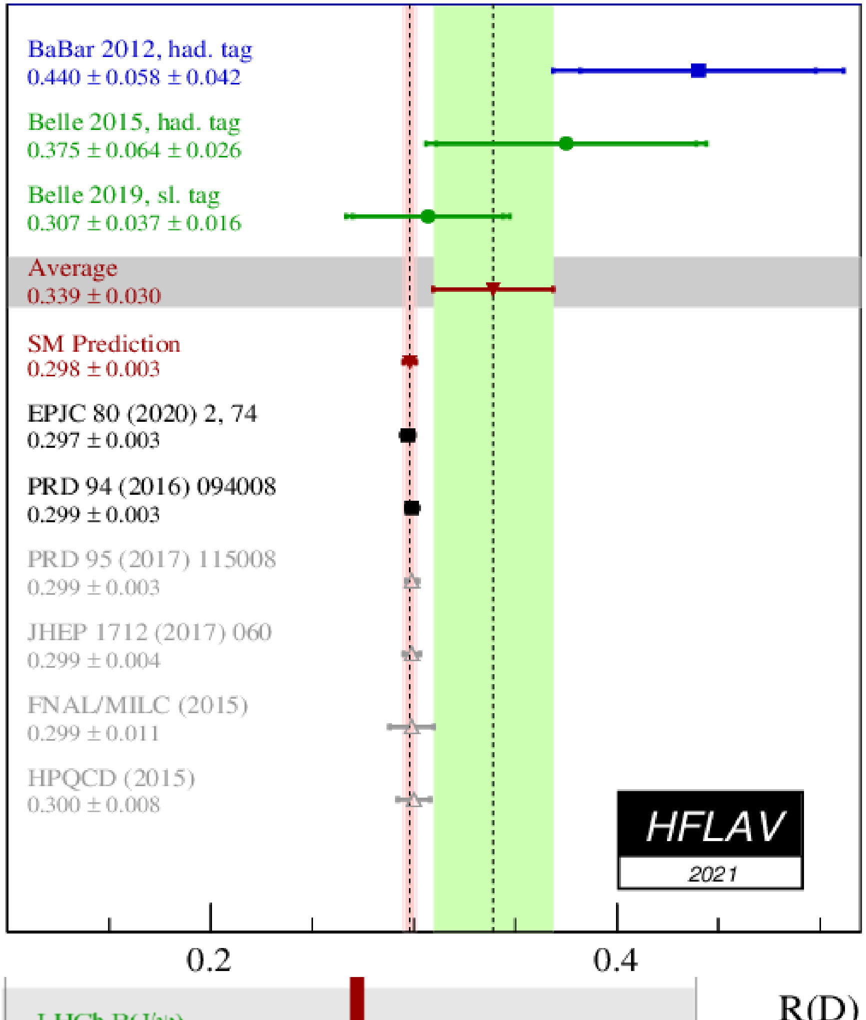


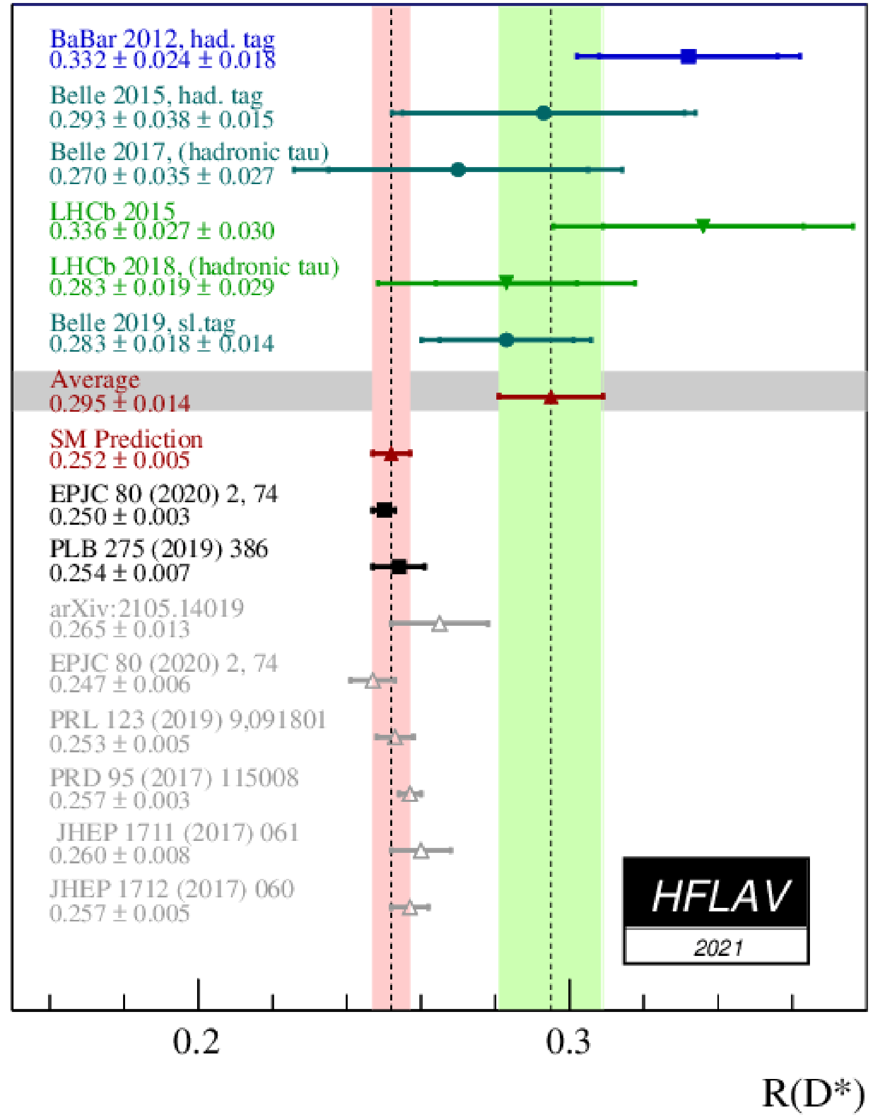
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})$$

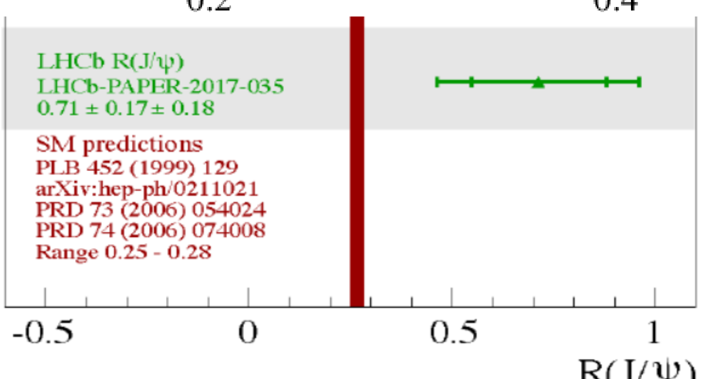
< 2σ above SM



LFU tests with R(D*), R(D), R(J/ψ)







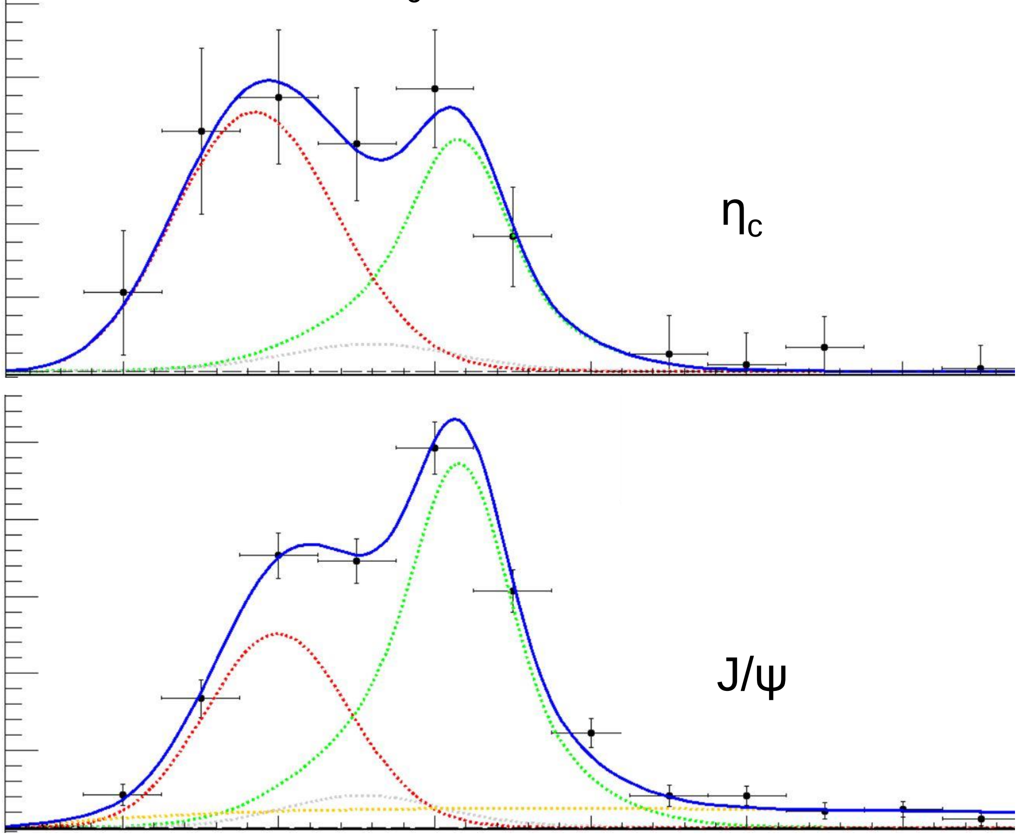
- **ALL** R(D), R(D*) and R(J/ψ) measurements lie **ABOVE** the SM expectations.

Preview = teaser slide

- Towards the test in B_c sector: **B_c semileptonic decays to charmonium**
- **Double ratio using charmonium decays to hadrons**

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

- Correction of B_c reconstructed mass



Corrected mass of B_c candidates

- First measurement of **B_c semimuonic branching fraction ratio** ongoing at Universidad Nacional de Colombia

- Assuming the anomalies become observations, what would be **possible interpretations** ? Major theory effort ongoing on extensions of the SM.
- Consistent (renormalizable) extensions with scalars, fermions or vectors

$b \to s\ell^+\ell^-$ channel

- Z' boson with a flavour violating couplings to bottom and strange quarks can account for the anomaly at tree-level (would expect an effect in B_s mixing)

Altmannshofer, Stangl, Straub, PRD 96 (2017) 055008

- LQ representations can contribute at tree-level to $b \to s\ell^+\ell^-$ while giving loop-suppressed effects in other observables. Can account for the anomaly without being in tension with other observables.

Hiller, Schmaltz, PRD 90 (2014) 054014

- Loops involving new heavy scalars and fermions

Gripaios, Nardecchia, Renner, JHEP 1606 (2016) 083

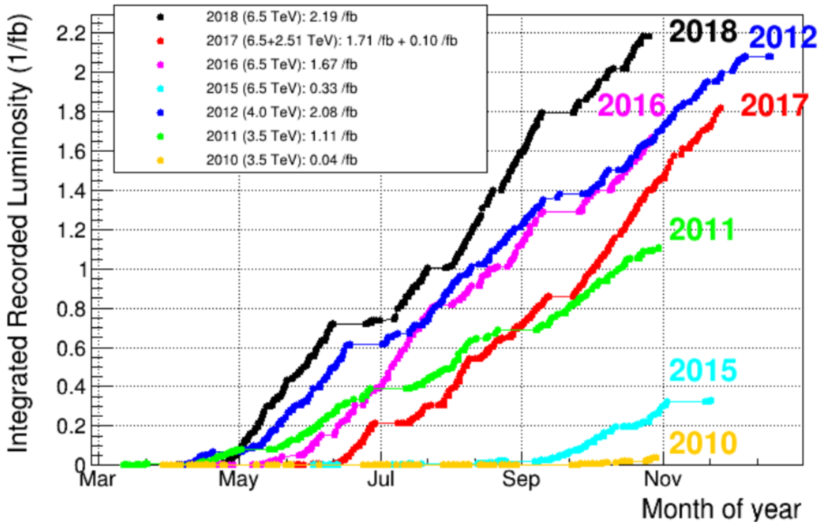
$b \to c\tau\nu$ process

- Mediated at tree-level in the SM: tree-level NP contribution needed of ~10% w.r.t SM
- Charged current process: charged Higgs, W' bosons (disfavoured by B_c lifetime and/or LHC searches) and LQs (constraints from B_s mixing, B->K*νν and LHC searches)

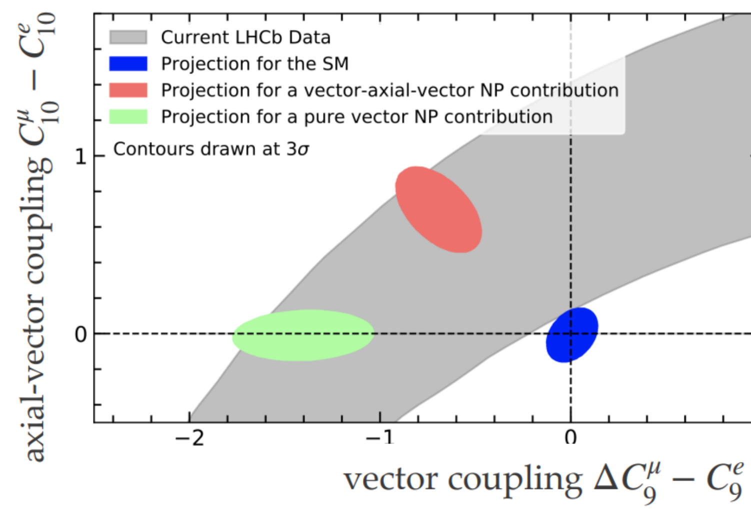
Hofer, Mescia, Crivellin, JHEP 1704 (2017) 043

- LQ option attractive but would not be able to explain e.g. Cabibbo angle anomaly

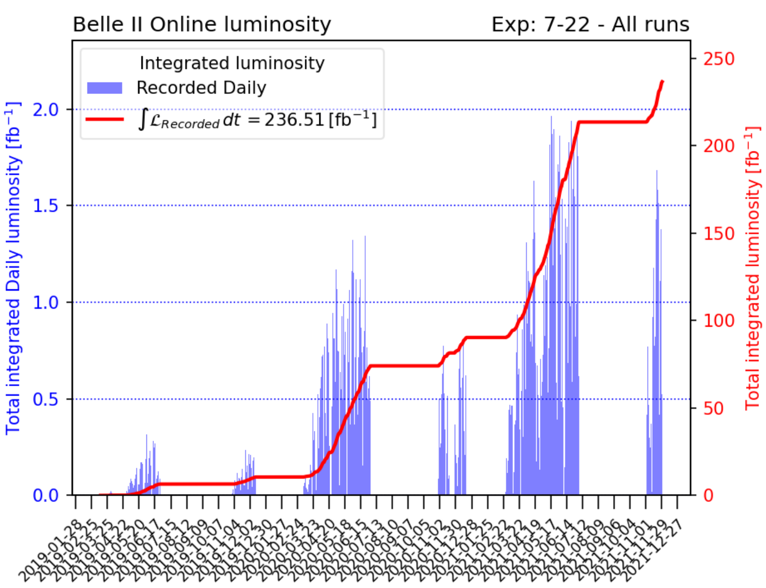
A. Crivellin, https://ep-news.web.cern.ch/

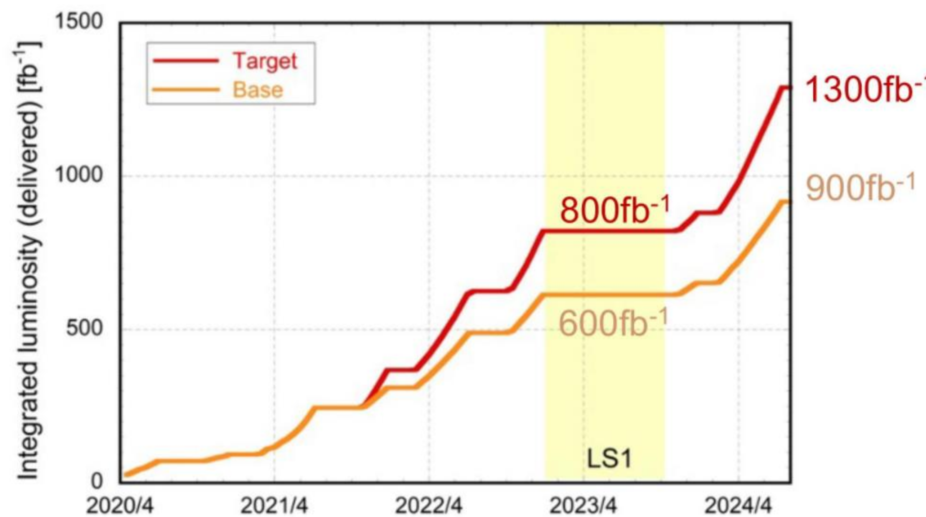


- ❑ Analysis with entire LHCb Run 2 data
- ❑ Upcoming LHCb upgrade I, then upgrade II luminosity = 10 x luminosity upgrade I

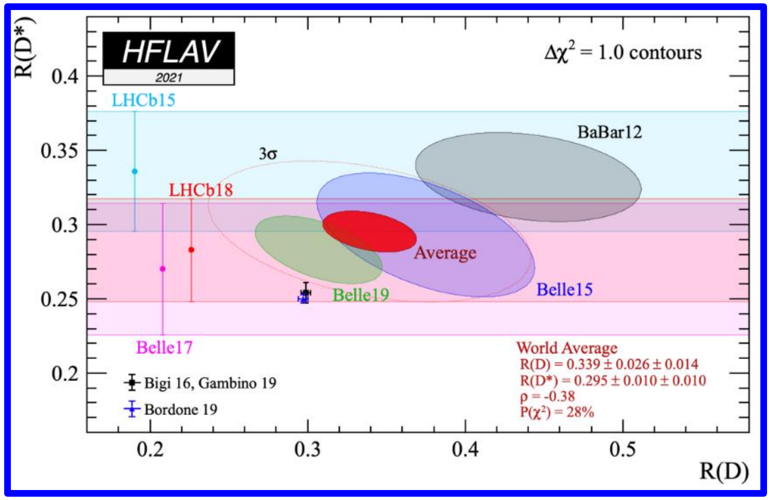


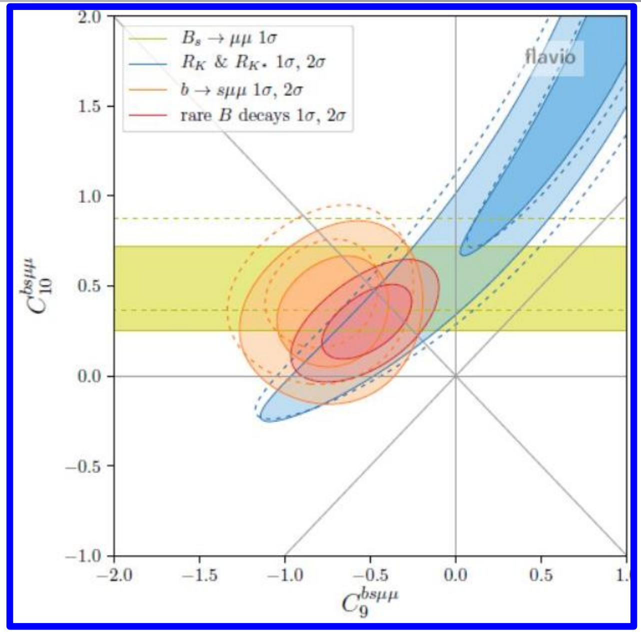
- ❑ New inputs from other experiments: Belle II, ATLAS, CMS
- ❑ Belle II taking data, 50 ab^{-1} by 2031-2032





- ❑ Lepton Universality tests probe fundamental predictions of Standard Model: same interactions and couplings for three fermion generations
- ❑ Experimental studies attacking all possible indications of effects beyond Standard Model





- ❑ Several measurements hint/tease a possible violation of Lepton Universality
- ❑ b-physics provide intrigueing results, in two classes of semileptonic b-decays

- ❑ Still suspense under improving experimental and theory precision and searching for new observables
- ❑ LFU violation often implies LFV → intense searches for $e^+\mu^-$, $\mu^+\tau^-$

S.Glashow et al., PRL 114 (2015) 091801

- In order to finally corner the Lepton Universality Violation, we need …

… STRONG …

… and …

… DEVOTED …

… LHCb physicists.

¡Muchas gracias a los organizadores y hospedadores de la conferencia!