Heavy Flavour Anomalies
(Hot topic in HF Physics)*

6th Colombian Meeting on High Energy Physics (COMHEP6)
November 29th - December 3rd, 2021
Hybrid meeting

Thanks the organizers for the invitation !

Alexis Pompili (virtual talk - 29.11.2021)

UNIVERSITÀ degli STUDI di BARI & I.N.F.N. Sezione di Bari

*Another hot topic is **Hadron Spectroscopy** (see talk by A. Correa Dos Reis)

New Physics searches in b-hadron decays

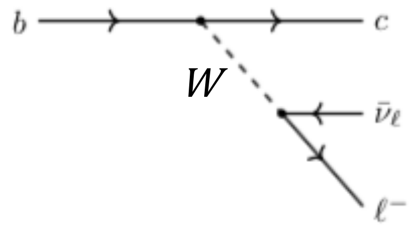
- Due to the large mass of the beauty quark, **b-hadron decays offer a rich phenomenology to explore.** A fertile ground for **indirect searches for New Physics,** namely **via virtual processes** allowing to probe **energies > TeV** which are **not directly accessible in collisions** (at the current colliders)

  - Historical example: charm-quark presence invoked - before the J/ψ discovery - from the suppression of $K^0 \to \mu^+\mu^-$ rate (GIM mechanism)

- **Precision measurements**

SM Tree-level decay

$b \to c\,\ell\,\nu$



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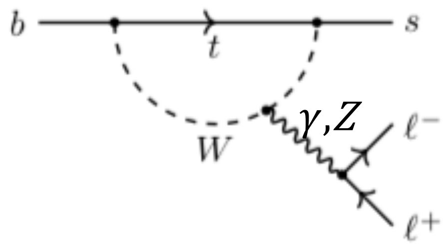

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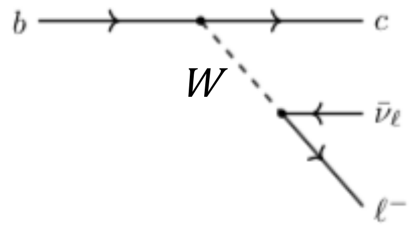

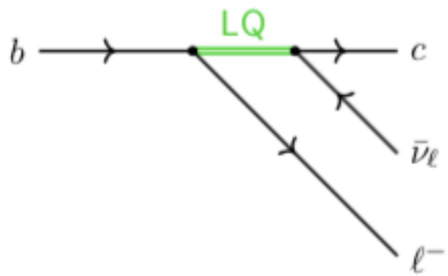

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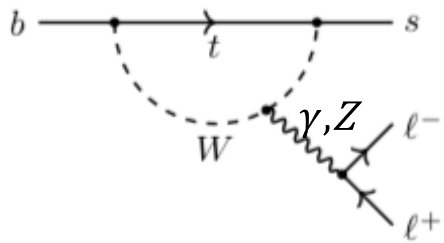

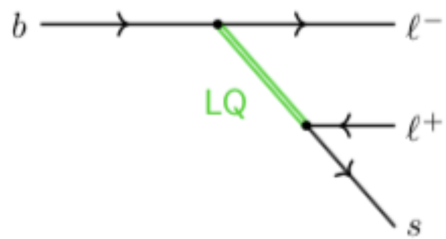

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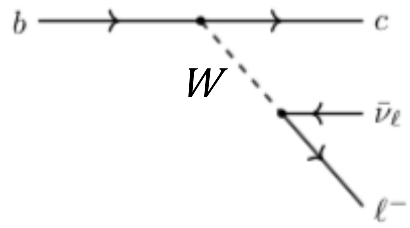

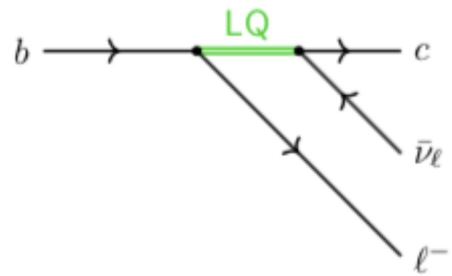

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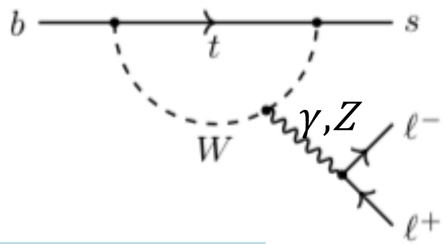
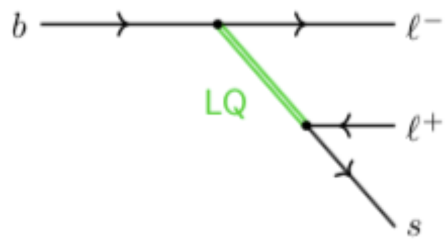




- Increasing experimental indications of deviations from SM **(**mainly from LHCb so far**)**

- **Particles associated with NP quantum fields can have masses above reach of direct searches at LHC**

Flavour Anomaly Workshop (FAW21) @ CERN

Flavour Anomaly Workshop 2021

https://indico.cern.ch/event/1055780/

Wednesday Oct 20, 2021, 8:00 AM → 6:00 PM Europe/Zurich

500/1-001 - Main Auditorium (CERN)

Alexander Lenz (Siegen University), Alexis Pompili (Universita e INFN, Bari (IT)), Aurelio Juste Rozas (ICREA and IFAE (ES)), Chris Parkes (University of Manchester (GB)), Danny van Dyk (TU München), Guy Wilkinson (University of Oxford (GB)), Jure Zupan (University of Cincinnati), Marcella Bona (Queen Mary University of London (UK)), Marco Pappagallo (Universita e INFN, Bari (IT)), Maurizio Pierini (CERN), Monica Pepe-Altarelli (CERN), Niels Tuning (Nikhef National institute for subatomic physics (NL)), Svjetlana Fajfer (Univ. of Ljubljana and Inst. J. Stefan), Yasmine Sara Amhis (IJCLab (Orsay))

Description The Flavour Anomaly and Implications Workshop is dedicated to the memory of Sheldon Stone.

- Obituary: https://cerncourier.com/a/sheldon-stone-1946-2021/

Goals of the workshop

- Increase the level of interest in flavour physics at the LHC.
- Discuss the experimental and theoretical status of the Flavour Anomalies in b->sll and semileptonic B-decays;
- Discuss the connection to high-pT searches;
- Discuss the future experimental and theoretical prospects.
- Zoom link: https://cern.zoom.us/j/65155243908?pwd=S0hHRVFTaXV4YVdLTmlvMWhPYWdpZz09

Scientific program contains contributions from Theory, ATLAS, CMS and LHCb on

1. FCNC b->sll decays
2. Semileptonic decays
3. High pT and LFV searches

- CERN EP Seminar
  - Tuesday 19 Oct 11:00 CET
  - *New tests of lepton universality using rare B decays with $K0S$ mesons in the final state at LHCb*
  - https://indico.cern.ch/event/1065152/

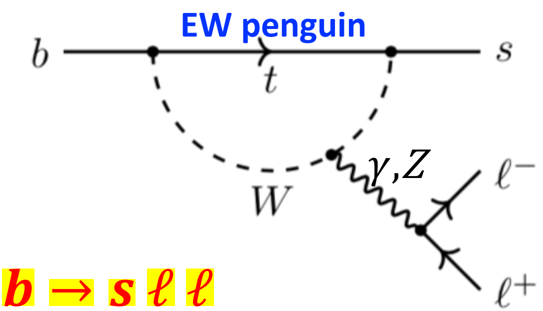
Participation: all interested theorists and members of experimental collaborations are welcome to participate, and are encouraged to register at the workshop INDICO page. **Registration will close Thu 14 Oct. Please contact <Lhcb.Secretariat@cern.ch> in case of problems.**

LFU tests & LFV in the Heavy Flavour sector

- **Lepton Universality**: in the SM, the 3 charged leptons have the same coupling constant in EW interactions.

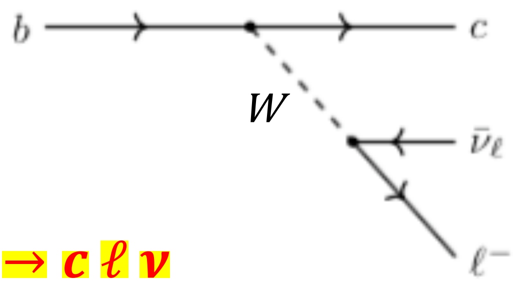
The two classes of B decays introduced provide two main ways to test the LFU :

$b \to s\ell^+\ell^-$ are FCNC processes that can only occur via loop in the SM



$\boldsymbol{b \to s\,\ell\,\ell}$

- suppressed ($BF \lesssim 10^{-6}$) → low statistics
- fully reconstructed signature



$\boldsymbol{b \to c\,\ell\,\nu}$

- large statistics
- not kinematically closed

- **Lepton Flavour Violation** is the non-conservation of lepton number. It is very suppressed in the SM.
  - Ex.: for $\tau \to 3\mu$ the SM $BF{\sim}10^{-54}$, BUT in some NP models the BF is enhanced to $BF{\sim}10^{-9}$
    - clean experimental signature

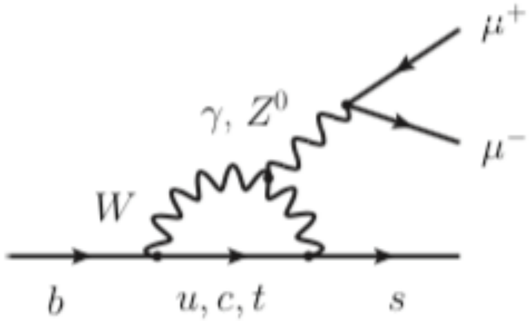
Outline

- **Anomalies & LFU tests :**
  - **Study of the $b \to s \ell \ell$ transitions** — **PART 1a** (focus mostly on this topic)
  - **Study of the $b \to c \ell \nu$ transitions** — **PART 1b**
- **Search for evidence of direct LFV in decays** — **PART 2**

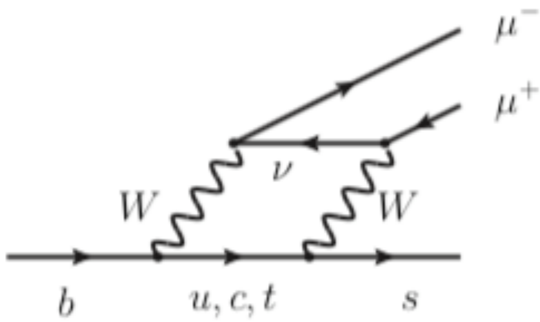
(*) Assuming flavour anomalies are a genuine NP effect, they can be the starting point to study **model building** in connection to EFT: from the global fits that we will discuss one knows the operator structure needed and try to understand what kinds of (heavy) states could be behind. This can guide also the **searches at high-p_T** and in a reasonable (non-pessimistic) scenario there can still be opportunities at the LHC.
See talks of S.Renner & A.Greljo at the FAW21!

PART 1a / $b \to s\ell\ell$: Anomalies & LFU tests

- $b \to sll$ are Flavour Changing Neutral Current (FCNC) processes: can only proceed via loop in the SM (GIM suppression)
- Rare decays, with branching fractions $\lesssim 10^{-6}$ → **Sensitive to NP**

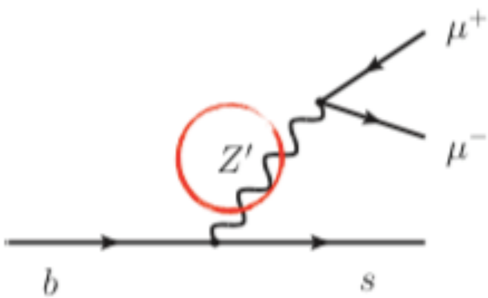


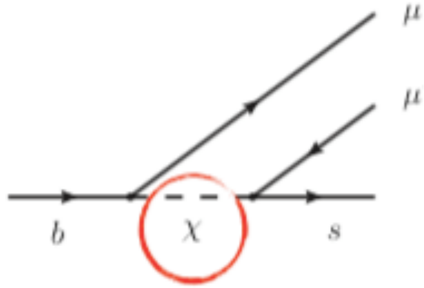
EW penguin



box

- Branching fractions or angular observables deviate from the SM prediction if new particles are present
- e.g. a Z' or a Leptoquark (χ) mediating FCNC at tree level

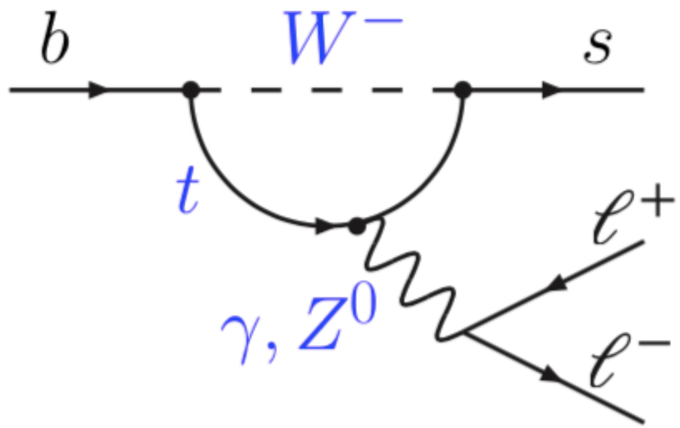




A possible new physics contribution to the decay with a hypothetical leptoquark (LQ) which, unlike the electroweak bosons, could have different interaction strengths with the different types of leptons.

Probing New Physics with $b \to s \ell \ell$ decays

$b \to s\ell^+\ell^-$ is an excellent probe of NP



- **It's rare** (decay rate $< 10^{-6}$)
  - Forbidden at tree-level, proceeds through loop
  - Small CKM elements and GIM mechanism
  - Heavy NP could enter at the same order as SM
- **It's friendly** (to experiments)
  - No neutrinos involved!
  - Several complementary channels
  - Several complementary observables
- **It's beautiful** (involves a b quark)
  - Small long-distance contributions ($m_b \gg \Lambda_{QCD}$)
  - Can interpret with effective theory ($m_b \ll m_W$)

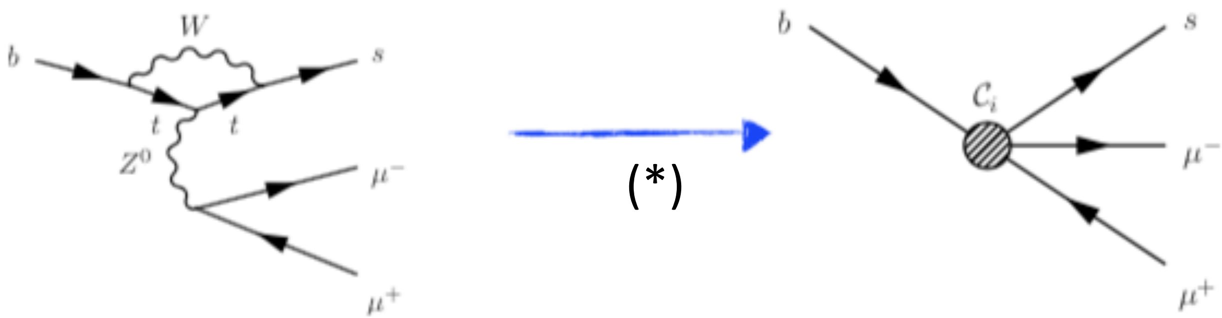
Several complementary channels → $B_s \to \ell^+\ell^-$, $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$, $B_s \to \phi\ell^+\ell^-$, $\Lambda_b \to pK^-\ell^+\ell^-$, …

Several complementary observables → Branching ratios, angular analyses, SM symmetry tests

Effective theory for rare B decays - I

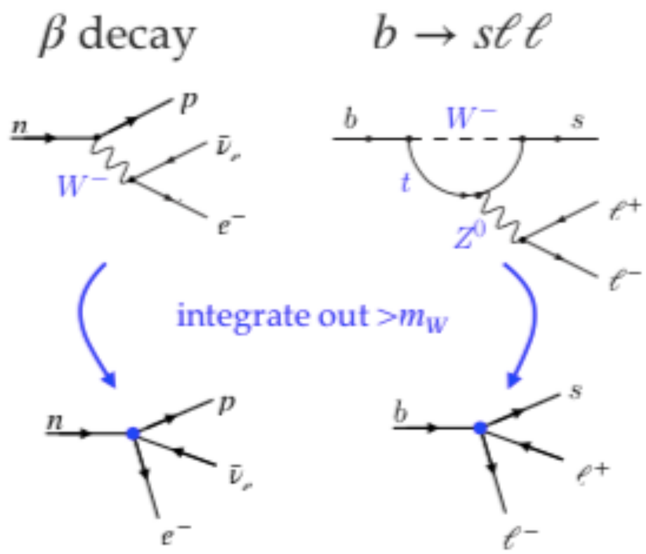
- QCD interactions are hard to evaluate at the b mass scale: since $M_b \ll M_W$, b-hadron decays can be described with an effective Hamiltonian, to factorise high and low energy contributions

Full theory | **Effective description**



point-like interaction
(as in the Fermi description of the neutron decay)

- Theory well established
  - 4fermion interaction once heavy degrees of freedom “integrated out”
  - Several effective operators (O) with their Wilson coefficients (C)
  - Absolute-rate calculations made complex by QCD effects but not relevant for ratios
  - Mind the charmonium: different diagrams (Os and Cs) enter there. Tree-level -> reduce NP sensitivity



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

Effective theory for rare B decays - II

- Hamiltonian defined in terms of ....

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\lambda) \mathcal{O}_i(\lambda)$$

- Local operators (long-distance): the corresponding form factor is computed with, e.g., lattice QCD → describe (using *form factors*) low-energy QCD which can have large uncertainties
- Wilson coefficients (short-distance): evaluated in perturbation theory
  → encode short-distance physics

- SM operators for $b \to sll$:

$$\mathcal{O}_9^{(\prime)} = (\bar{s} P_{\mathrm{L(R)}} b)\,(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s} P_{\mathrm{L(R)}} b)\,(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

corresponding to SM $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$

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

- Generic New Physics contribution:

$$\Delta\mathcal{H}_{\mathrm{NP}} = \frac{c_i}{\Lambda^2_{\mathrm{NP}}} \mathcal{O}_i$$

Precision measurements go well beyond collision energies!

can modify SM $C_i^{(\prime)}$ but also introduce new operators

- four-fermion interaction described by effective couplings

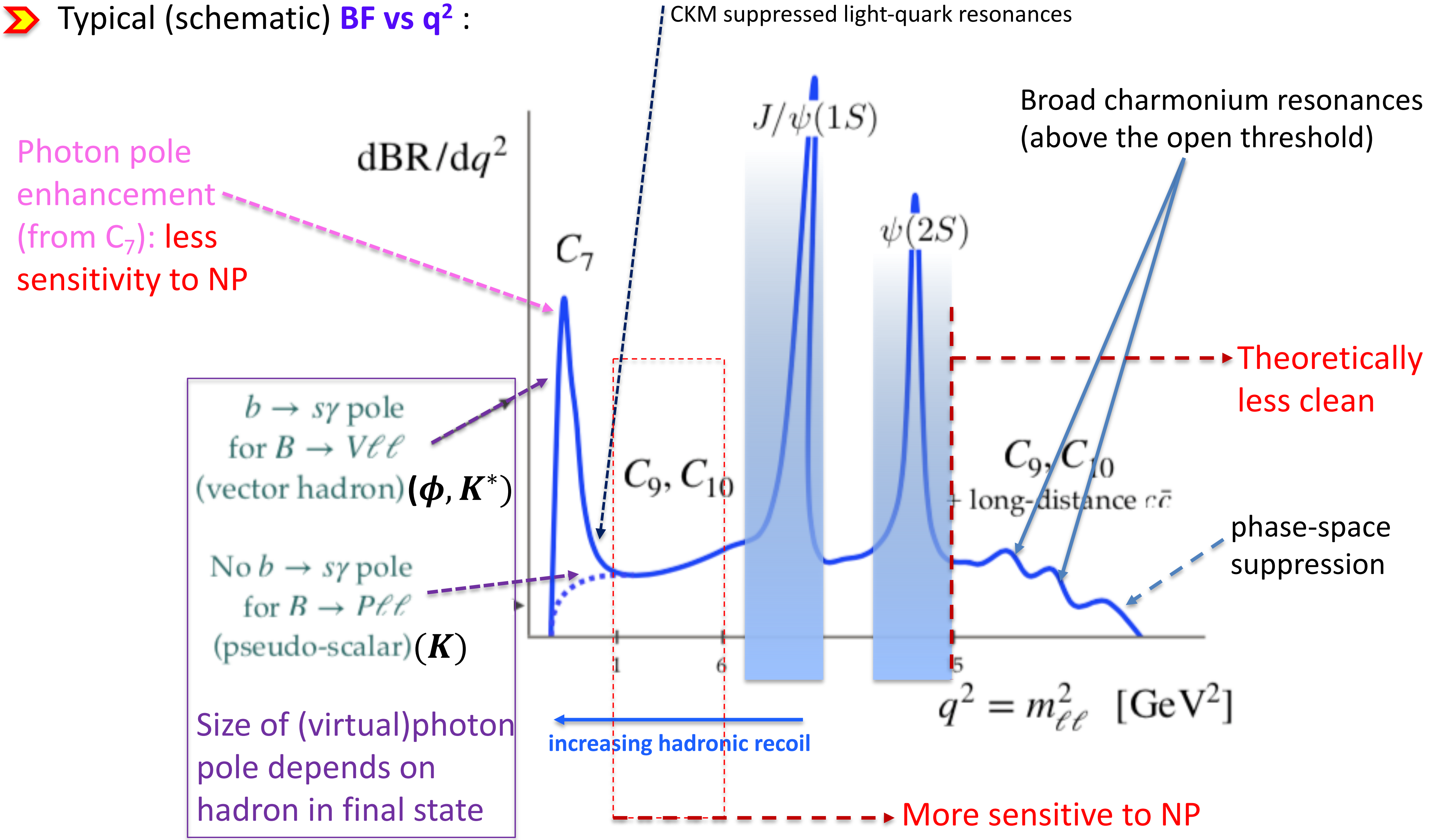
$$C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}$$

- Main SM contributions:
  - **Vector** (C_9) and **Axial-vector** (C_{10}) leptonic currents
  - Dipole $b \to s\gamma^*$ contribution in C_7 → very well constrained by radiative

- Vector coupling C_9 receives contribution from top and charm. Axial-vector couplings arise at weak scale are related to C_{10} and are dominated by top contribution

Typical q^2 spectrum of $b \to s\ell\ell$

- Typical (schematic) **BF vs q^2** :



Flavour Anomalies in $b \to s\ell\ell$ decays

- There are **several observables** for which LHCb performs measurements deviating from SM predictions by 2-3σ (these **deviations** are called **anomalies**):

  - **Branching Fractions** in **dimuon** decays : $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{(*)0}\mu^+\mu^-$, $B_s^0 \to \phi^+\mu^+\mu^-$
  - **Angular observable** (**P_5', ...**) in : $B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^-$
  - It should be added a golden (**fully leptonic**) flavour physics channel : **BF** of $B_s^0 \to \mu^+\mu^-$
  - **LFU tests** with **Ratios of (diff.) branching fractions** (μ **vs** e):

$$R_H = \frac{\int_{q^2_{\min}}^{q_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\int_{q^2_{\min}}^{q_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2}$$

$H = K^{(*)}$

growing theoretical "cleanliness" i.e.
increasing precision of the SM predictions

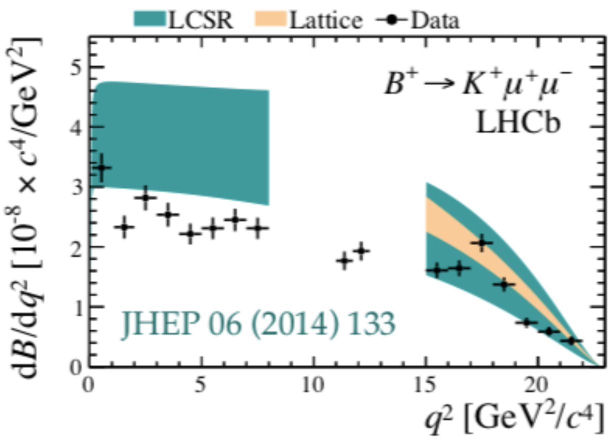
	parametric uncertainties	form factors	non-local matrix elements
$\mathcal{B}(B \to M\ell\ell)$	✗	✗	✗
angular observables	✓	✗	✗
$\overline{\mathcal{B}}(B_s \to \ell\ell)$	✗	✓	✓ (N/A)
LFU observables	✓	✓	✓

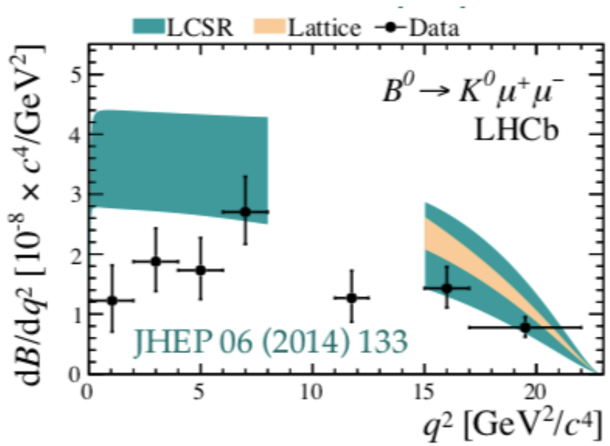
(as discussed a bit through next slides)

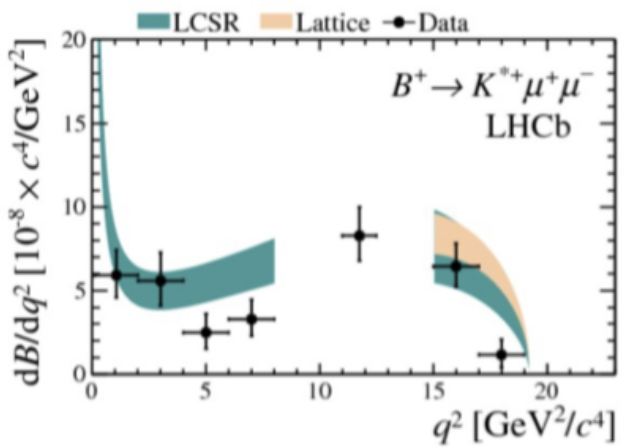
[P.Stangl *et al.* @ FAW21]

Branching Fractions for $b \rightarrow s\ell\ell$

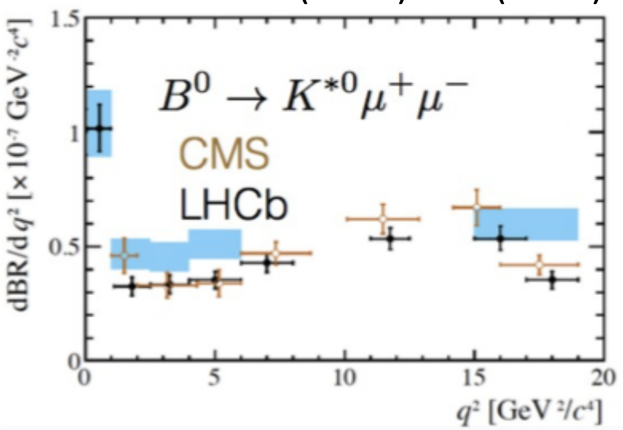
- A quite **consistent trend** w.r.t. SM predictions (undershooting) is present - in the LHCb measurements of the differential BFs (in bins of q^2) - **accross several decay modes**



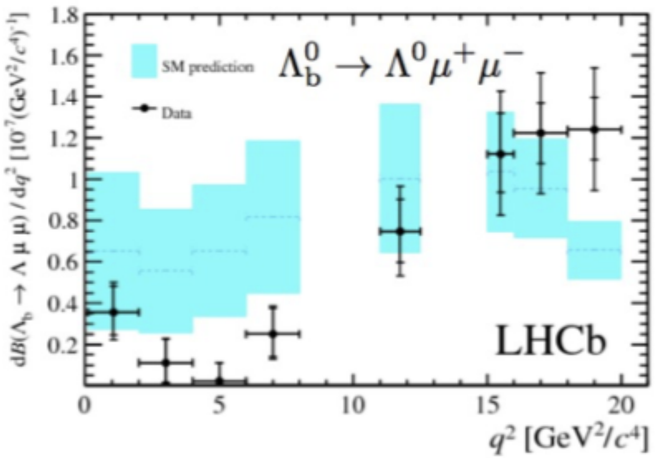




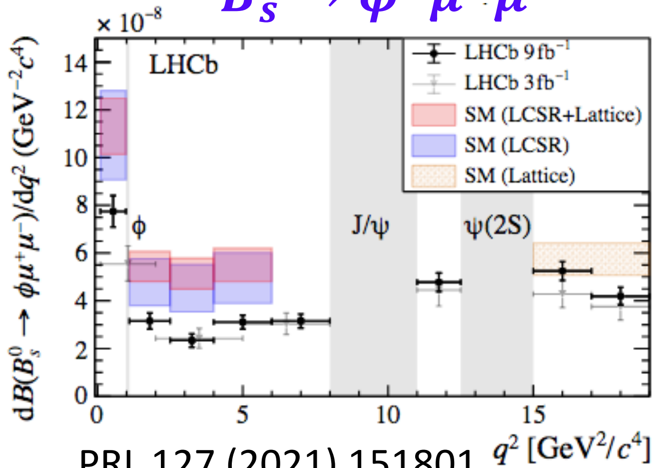
LHCb - JHEP 04 (2017) 142 (Run-1)
CMS - PLB 753 (2016) 424 (8TeV)



LHCb - JHEP 09 (2018) 146



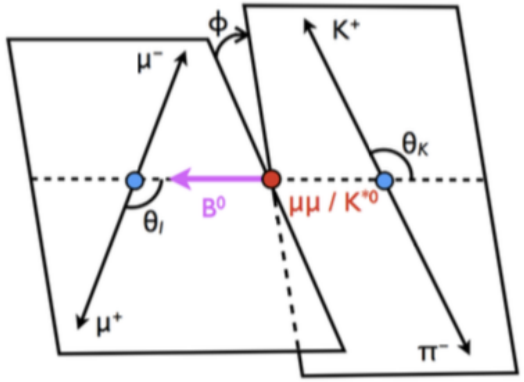
$B_s^0 \rightarrow \phi^+\mu^+\mu^-$



PRL 127 (2021) 151801

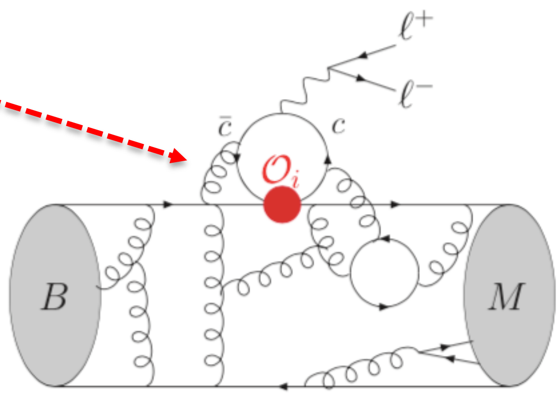
- In most channels the theoretical uncertainty (~20-30%) is dominant (**hadronic form factors**)

Angular analyses of $b \to s\ell\ell$ - I



- These 4body decays have **complex angular structure** that gives access to different operators in the effective Hamiltonian.
  - Kinematics can be described by **q^2** & **3 angles**:
- Resonant decays used as control q^2 regions
- Final state has contribution from P-wave (K*,…), S-wave and their interference

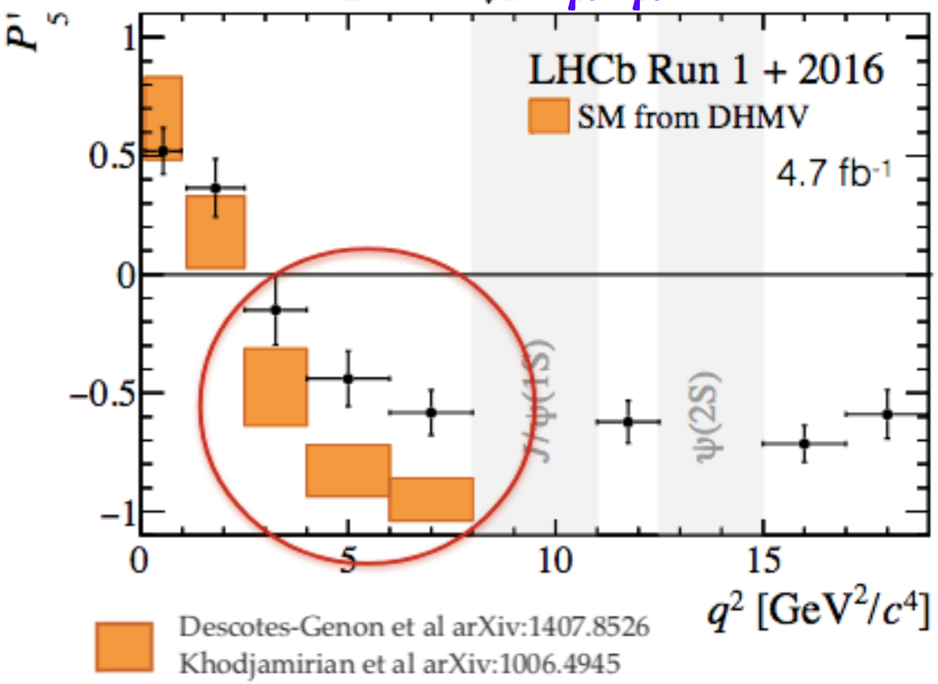
- **SM predictions are challenging, but uncertainties are smaller than for BFs**
  - Set of enough clean parameters $P_i' = S_i/\sqrt{F_L(1-F_L)}$ (*)
    (for instance P_5' is an optimised variable where hadronic uncertainties cancel out at 1st order)
  - **Theory uncertainties under scrutiny**. Special attention to the role of **non-local charm loops** that can cause a shift in the SM C_9



(*) F_L = fraction of longitudinal polarization of the K^{*0}
S_i = CP-averaged observables (JHEP 02 (2016) 104) [can be related to C_9 & C_{10}]

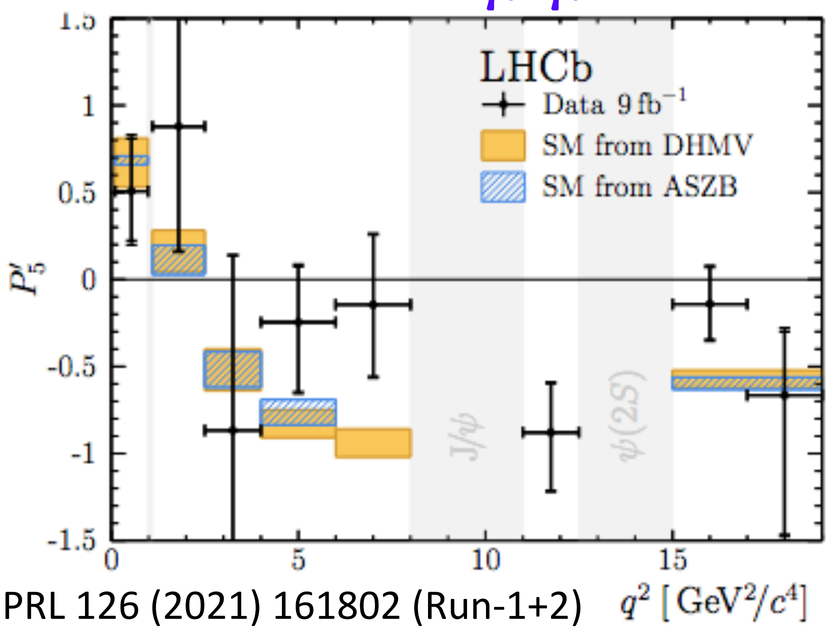
- **The angular analyses of LHCb show some tension with the SM predictions (the largest local deviation has significance of ~3σ)**

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



PRL 125 (2020) 011802 (Run-1+2016)

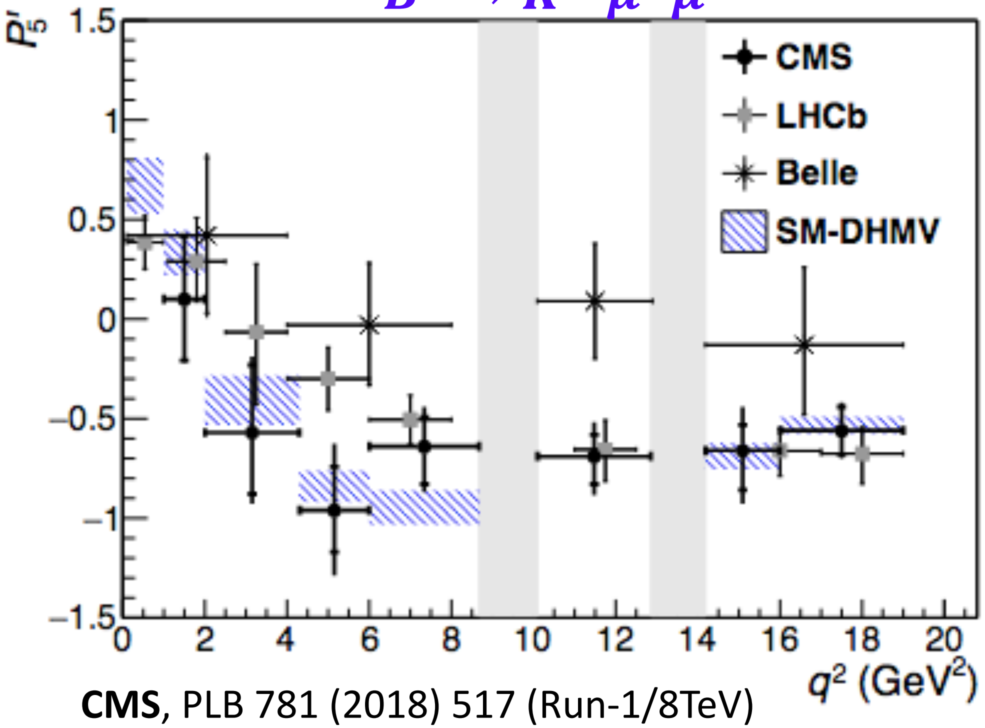
$B^+ \to K^{*+}\mu^+\mu^-$



PRL 126 (2021) 161802 (Run-1+2)

- **Older Belle-I and recent CMS results are also available :**

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



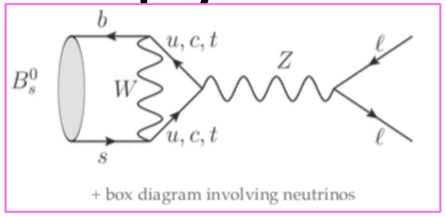
CMS, PLB 781 (2018) 517 (Run-1/8TeV)

- **For the $B^0 \to K^{*0}\mu^+\mu^-$ channel LHCb & CMS (& maybe ATLAS) are expected to deliver the full Run-2 results: stay tuned!**
  - Example (CMS) of projections on P'5 uncertainties at HL-LHC shown in the backup.

- **Because of the theoretical uncertainties there is no consensus if there is really a P'_5 anomaly due to the non-local charm contributions (*charming penguins*)** [HEPfit group, see backup]**.**
As discussed later **more consensus is on:**
  - **C_9^{NP} might break lepton universality** → LFU tests
  - **C_{10}^{NP} not plagues by long-distance contributions** → Importance of the BF of $B_s^0 \to \mu^+\mu^-$

BF of $B_s^0 \to \mu^+\mu^-$

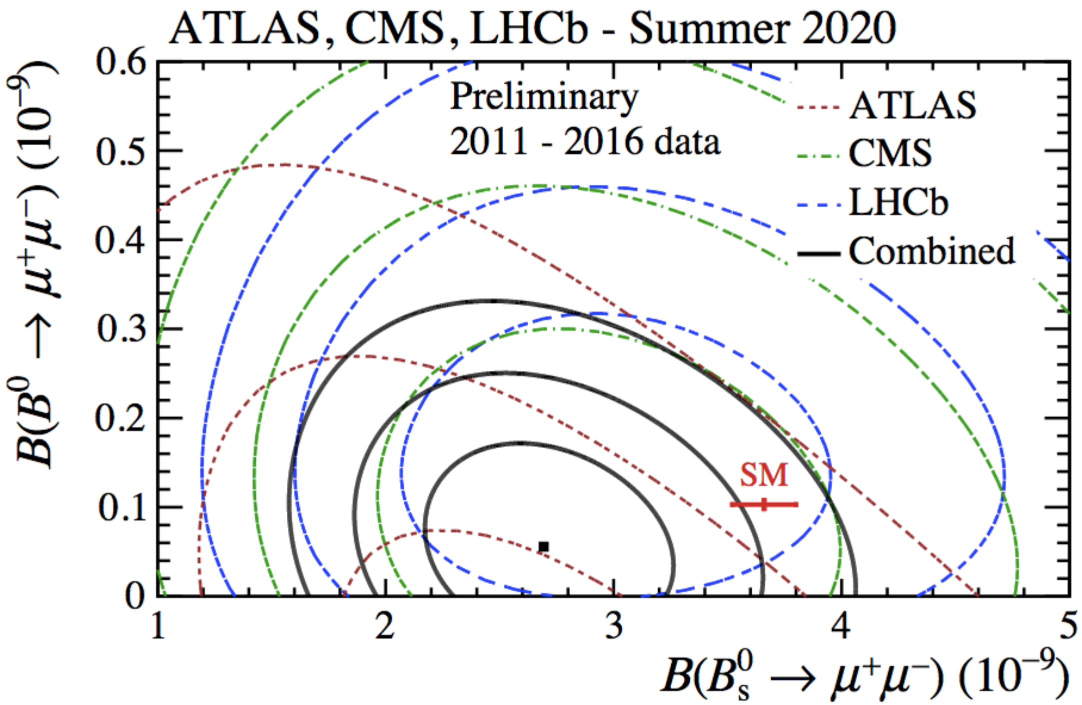
- **It's a golden flavour physics channel since:**
  - very rare (BF~10^{-9}) (FCNC+helicity suppression)
  - **precise (4%) BF prediction (being fully leptonic)**



- **Firstly observed in 2014 combining LHCb & CMS Run-1 data [** Nature 522 (2015) 68 **]**

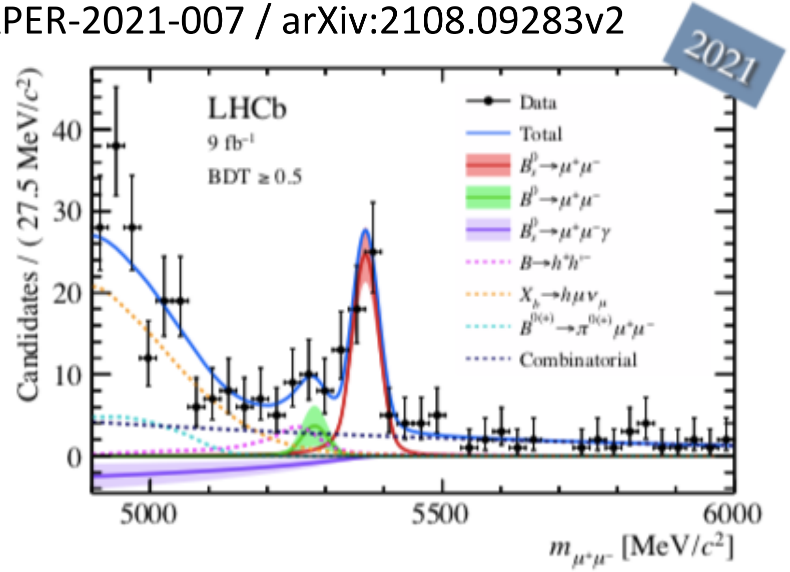
- Because of its suppression, it is a perfect channel for detecting NP contributions. Sensitive to axial-vector coupling C_{10} and thus plays a major role in $b \to s\ell\ell$ global fits (see later!)

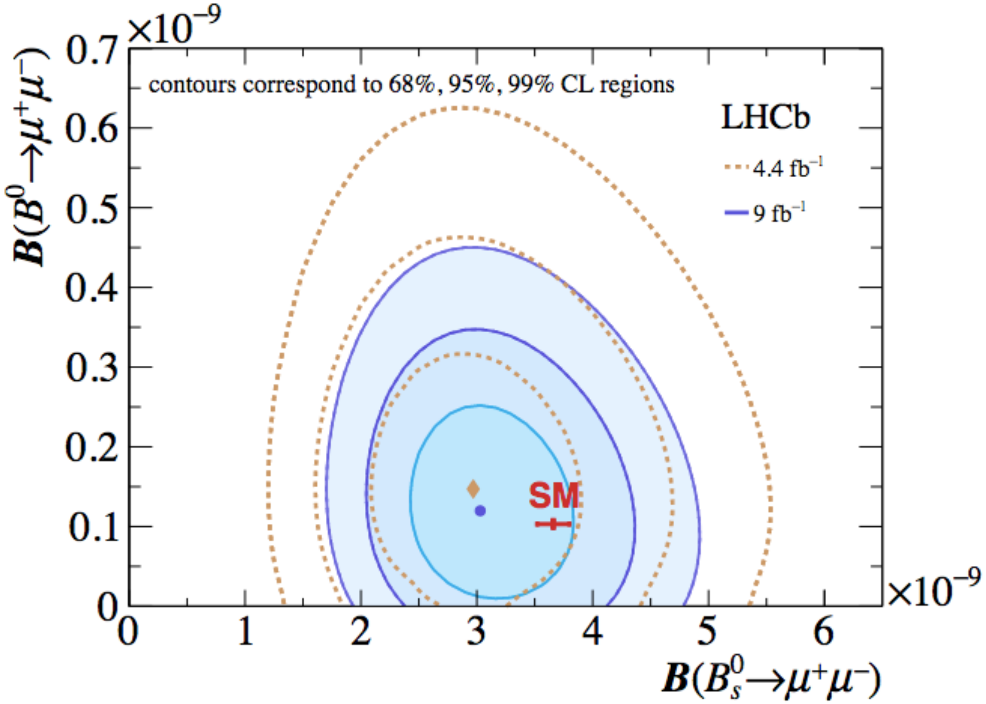
- **In 2020 summer, ATLAS, CMS & LHCb** [https://cds.cern.ch/record/2727216] combined measurements **of BFs based on Run-1+2016 dataset.** The combination was obtained summing binned 2D profile likelihoods. The result shows a **slight tension** with prediction for the B^0_s decay: compatible with SM predictions at 2.1σ in the 2D plane, when the theoretical uncertainties are included.



New LHCb result (full Run-2)

- LHCB-PAPER-2021-007 / arXiv:2108.09283v2





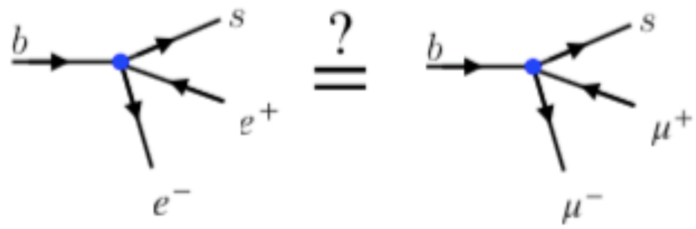
- Full Run-2 measurement reached 16% uncertainty (most precise single-exp):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

- Expect 10% precision when there will be the combination with ATLAS & CMS full Run-2 results

- **ATLAS & CMS full Run-2 analyses are ongoing: stay tuned!**

- LFU test in $b \to s\ell\ell$ represent a great way to extend the investigation on the tensions observed in the BF of the muonic channels:



  - $b \to s\ell\ell$ is lepton universal in the SM → can identify LU violating NP contributions!
  - $b \to s\tau\tau$ has not yet been observed → possible comparing μ to e

- Ratios of Branching Fractions are measured:

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

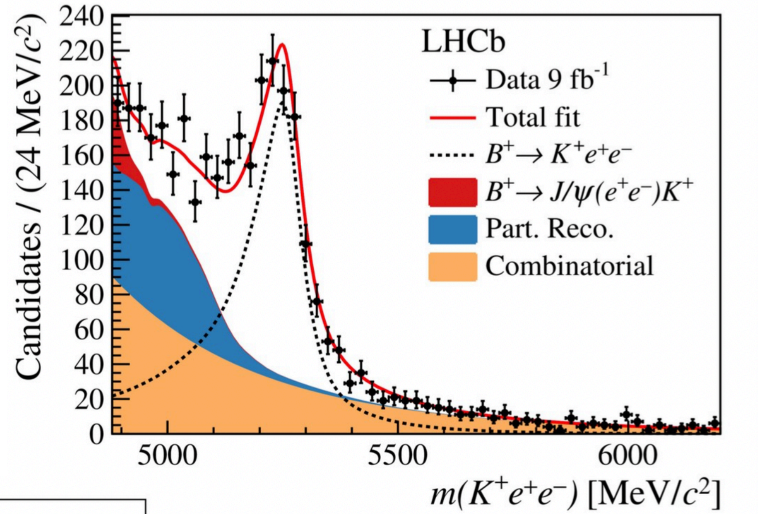
  - Theoretical predictions are robust and rather precise (QED corrections at the % level; QCD uncertainties mostly cancel out) [see Isidori *et al*. JHEP 12 (2020) 104]

  - **Experimentally is challenging :** μ & e behave differently in the detector.
    In particular electrons are affected by the *bremsstrahlung energy loss*.
    Mismodelling of the reconstruction efficiency in only one channel can bias the ratio.

- LHCb has performed R(K) and R(K^{*0}) analyses observing discrepancies w.r.t. the LFU hypothesis

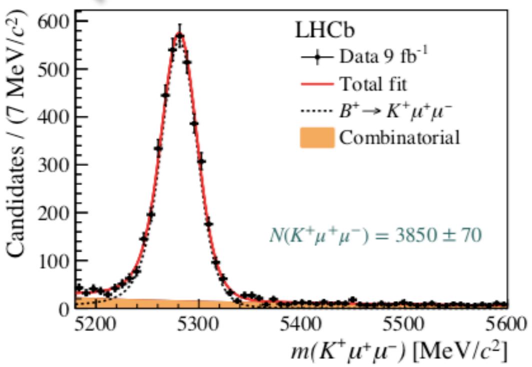
LFU tests in $b \to s\ell\ell$ - II

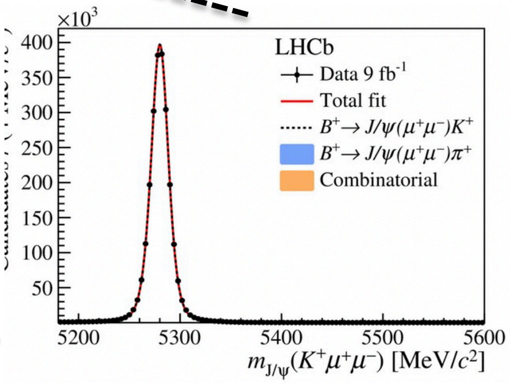
- As an example let's consider the most recent LHCb R(K) measurement:

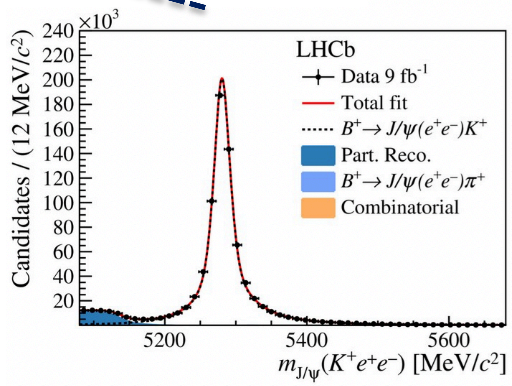


the **R(K) value is extracted using a double ratio** (to improve the control over the efficiency corrections):

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





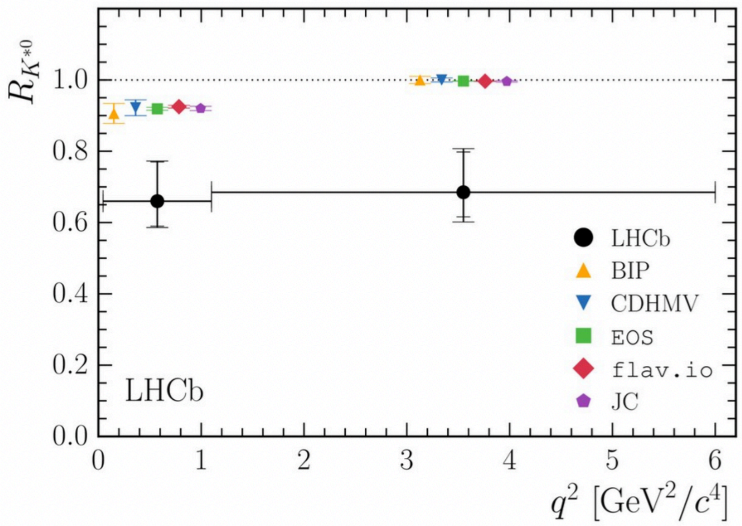


- **Main validation** is to verify that the ratio between the **resonant decays** is compatible with 1 :

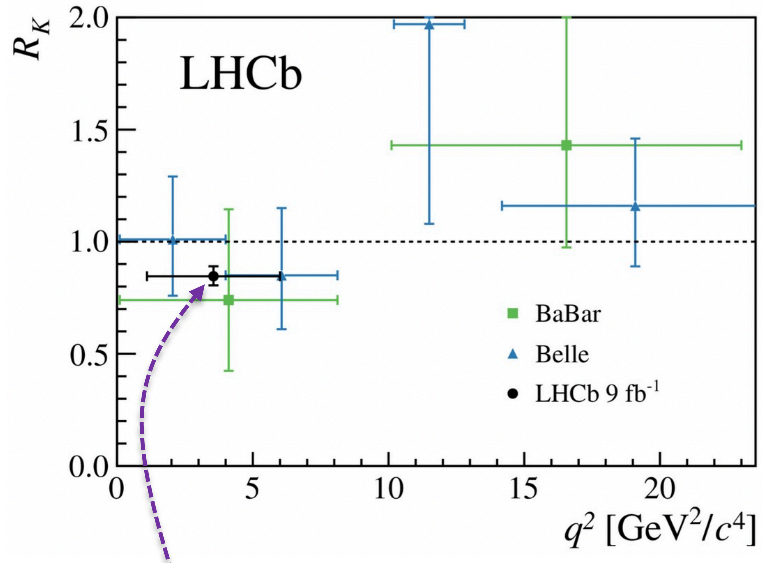
$$r_{J/\psi} \equiv \frac{\mathcal{B}(B^+ \to K^+(J/\psi \to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+(J/\psi \to e^+e^-))} = 0.981 \pm 0.020$$

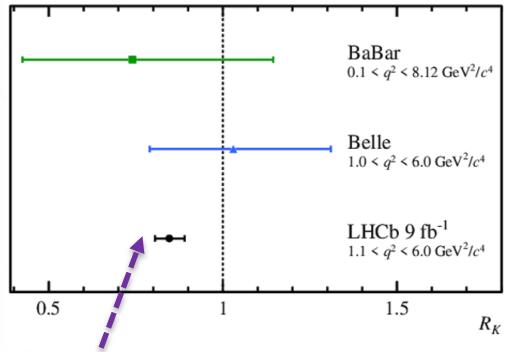
- **LHCb has performed R(K) and R(K*0) analyses observing discrepancies w.r.t. the LFU hypothesis**
  - **$R(K^{*0})$ shows a deviation from the SM by** { **2.3σ** / **2.5σ** } **… in the bins** { $0.045 < q^2 < 1.1$ GeV^2 / $1.1 < q^2 < 6$ GeV^2 }
  - **R(K) shows a deviation from the SM by 3.1σ in the bin** $1 < q^2 < 6$ GeV^2

JHEP 08 (2017) 055/ Run-1



arXiv:2103.11769 / Run-1+2





$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846^{+0.043+0.013}_{-0.039-0.012}$$

- **Recently LHCb performed also**

Remarks about *Global Fits*

Most important Wilson coefficients:

- C_9^μ: dominant contributions to angular observables, LFU observables
- C_{10}^μ: dominant contributions to $B_s \to \mu\mu$, LFU observables

Wilson coefficients not considered in the following:

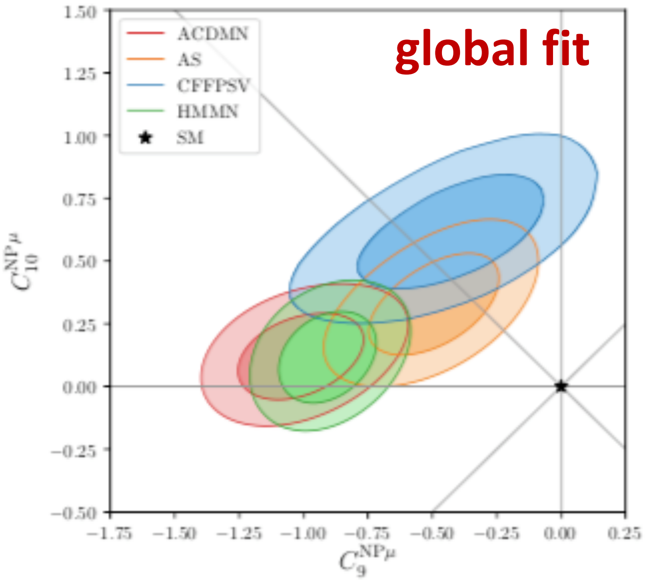
- $C_7^{(\prime)}$: strongly constrained by radiative decays and very low-q^2 bin of $B \to K^* e^+ e^-$
- C_i^e: current data does not indicate NP in electron coefficients, but not enough data to be conclusive
- $C'_{9,10}$: dominant contribution from coefficients with right-handed quarks disfavoured by $R_K \approx R_{K^*}$

Interesting NP scenarios:

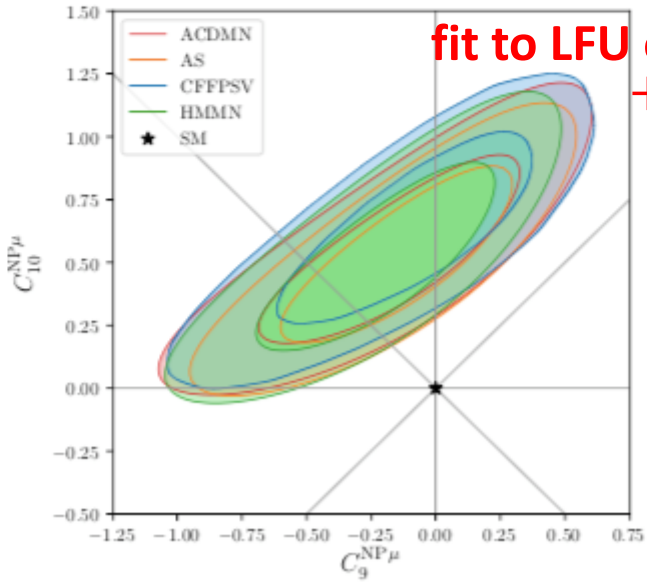
- 1D scenarios: $C_9^{\mathrm{NP}\mu}$ or $C_9^{\mathrm{NP}\mu} = -C_{10}^{\mathrm{NP}\mu}$
- 2D scenario: $C_9^{\mathrm{NP}\mu}$ and $C_{10}^{\mathrm{NP}\mu}$

EFT & NP effects in $b \to s\ell\ell$

- **For the FAW21 workshop, 4 groups** (see backup) **doing *global fits* not only compared them (left plot) but also made the great (!) exercise to identify a consensus area (right plot):**



P.Stangl talk @ FAW21



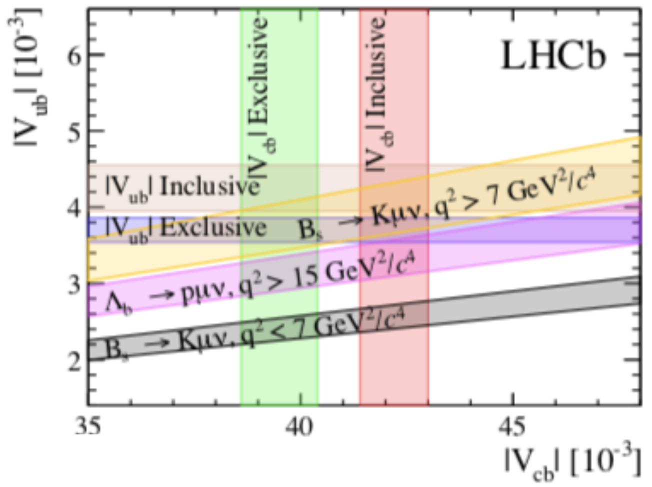
Fits show preference for NP contributions to C_9^μ and/or C_{10}^μ

- **What are the lesson learned?**
  - **Different groups with different methods were able to point to the same region using the same inputs ! (**different theoretical & statistical methodologies are not an issue**)**
  - Same groups diverge when adding further observables to the fit : assumptions in the inputs and in some related theoretical aspects do play a relevant difference.
  - It was pointed out that relevant shifts are due to the use of the rate in high-q2 bin (for P'5) and to the more or less conservative approch to evaluate the non-local hadronic contributions
  - $B_s^0 \to \mu^+\mu^-$ **is crucial !**

Part 1b : LFU tests : $b \to c \, \ell \, \nu$ transitions

R(D) & R(D*) with semileptonic decays - I

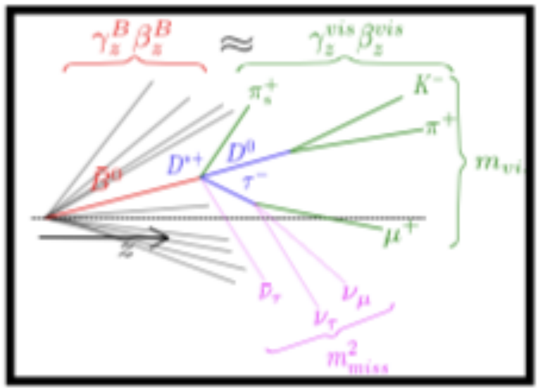
- $b \to c\ell\nu$ are FCCC decays tree level transitions → not where you would expect to find NP !
  - Traditionally used to measure V_{ub} & V_{cb} elements of the CKM matrix
    - … and the situation is already confused enough:
      inclusive and exclusive measurements disagree - - - - - - - - - →

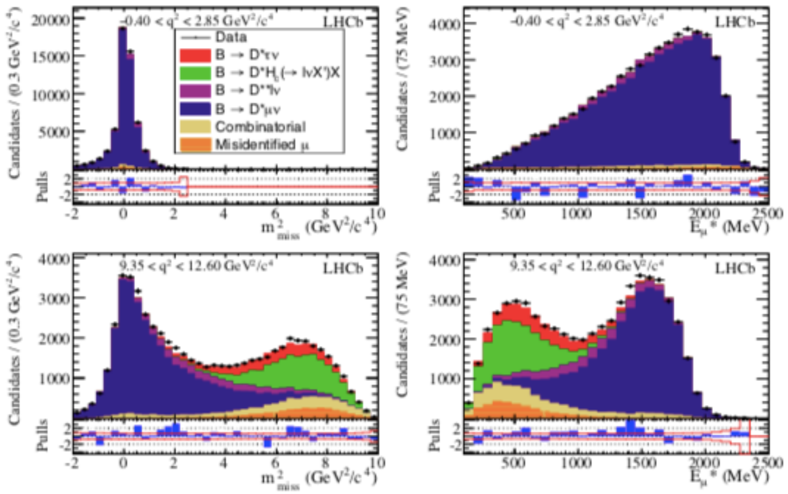


- **Even in this case it's possible to define flavour ratios and look from departures from the SM:**

$$\mathrm{R}(X) = \frac{\mathcal{B}(B \to X\tau\bar{\nu})}{\mathcal{B}(B \to X\ell\bar{\nu})} \qquad [X = D, D^*] \quad [\ell = \mu, e]$$

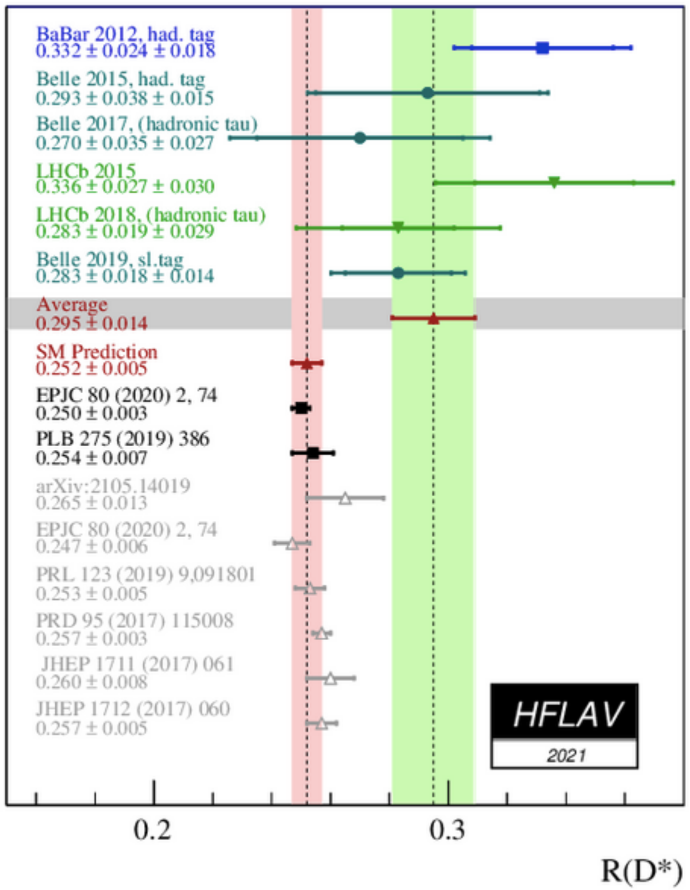
  - These are high-stat measurements: systematic uncertainties dominate!
    - BKG modelling is tricky

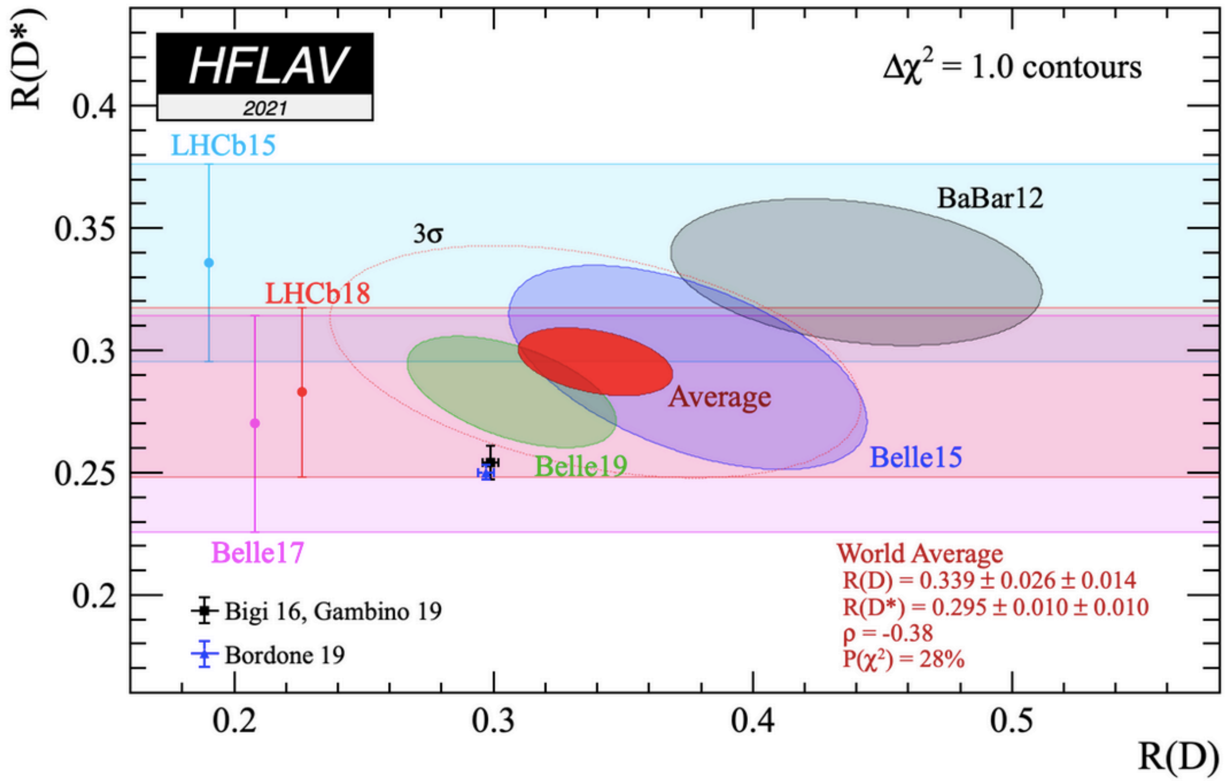




R(D) & R(D*) with semileptonic decays - II

- Since 2013 results in B decays started to exhibit **tensions with the SM predictions** connected with a possible violation of LVU, namely **a different behaviour** (besides pure kinematical effects) **of different lepton species**:





Deviations with the SM by 2.3σ & 3.4σ
(with an **overall 3.1σ discrrepancy**)

Part 2 : LFV searches @ LHC

LFV searches overview

- Searches for decays with explicit violation of charged lepton flavour conservation

- Decays of low mass particles : $\tau \to 3\mu$

  next few slides

$D^0 \to e\mu$, $B^0 \to e\mu$, $\mu\tau$

$B^+ \to K^+ e\mu$, $K^+ \mu\tau$

Many details in A. Korytov talk @ FAW21

- Decays of high mass particles: $H \to \mu\tau, e\tau$; $Z \to \mu\tau, e\tau, e\mu$; $t \to qe\mu$;
- Searches for new (BSM) particles: $X \to \mu\tau, e\tau, e\mu$ (Z', RPV SUSY $\tilde{\nu}_\tau$, Quantum BH, additional H, LLP)

$\tau \to 3\mu$

- **LHC is a prolific source of τ leptons :** $\sim 2\times10^{11}/fb^{-1}$

	Process	# of taus	Comment
PYTHIA	$pp \to cc$, $D \to \tau\nu$	1.2×10^{11}	95% D_s, 5% $D^{\pm}$
PYTHIA	$pp \to bb$, $B \to \tau + \ldots$	0.5×10^{11}	44% $B^{\pm}$, 45% B^0, 11% B_s
PYTHIA	$B \to D(\tau\nu) + \ldots$	0.2×10^{11}	98% D_s, 2% $D^{\pm}$
NNLO	$pp \to W \to \tau\nu$	2.0×10	
NNLO	$pp \to Z \to \tau\tau$	0.4×10^7	$60 < m_{\tau\tau} < 120$ GeV

Hadronic Taus (from HF)

- **lots of** (mainly $D_s \to \tau\nu$)
- **challenging**: low-p_T, not-isolated, forward
- **low S/B**

Taus from W/Z

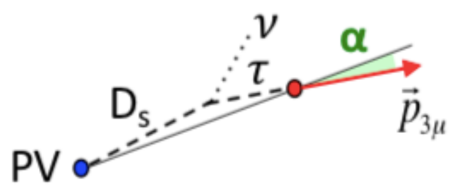
- **10^4 fewer**
- **… but cleaner:** high-p_T, isolated, central
- **better S/B**

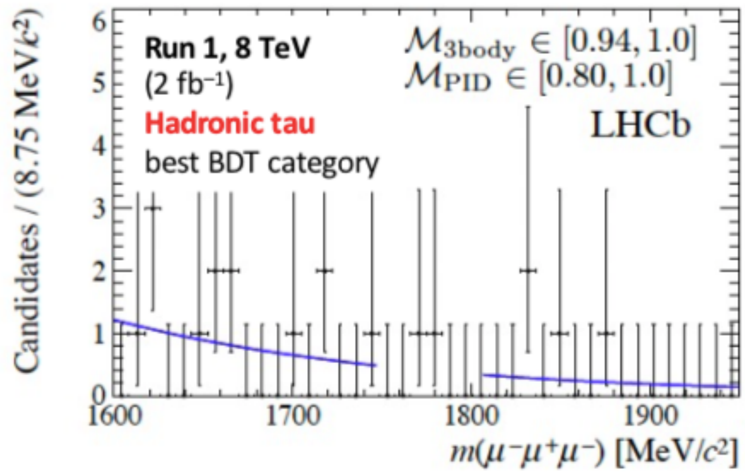
- **LHCb** published results for full Run 1 dataset (7+8 TeV, 3 fb^{-1}): ***Hadronic*** *Tau* JHEP 02 (2015) 121
  ATLAS published results with Run 1, 8-TeV dataset (20 fb^{-1}): ***W*** *Tau* EPJ C76 (2016) 232
  CMS published results with Run 2, 2016 dataset (33 fb^{-1}): ***Hadronic* + *W*** *Tau* JHEP 01 (2021) 163

No excess is observed so far: **upper limits** are given (see next slides)

Hadronic Tau analyses (main source $D_s \to \tau\nu \to 3\mu + \nu$)

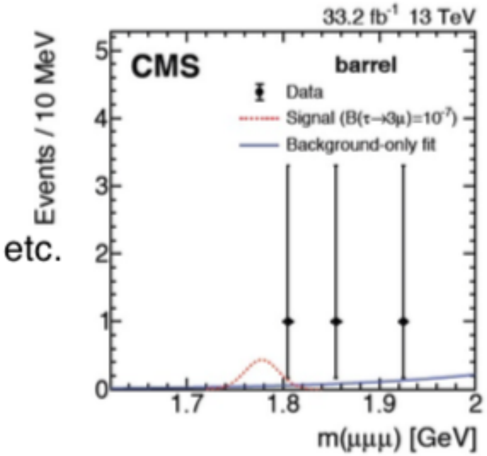
- *3 good-quality muons, veto events with* $m_{\mu^+\mu^-}$ *in vicinity of dimuon resonances*
- **BDT**: *3μ vertex χ^2, vertex displacement, angle α, muon quality, tau isolation*, etc.
  Use sidebands for background in BDT training
- **Signal extraction:** *BDT categories*, look for excess at $m_{3\mu} = m_\tau$
- **Normalization channel:** $D_s \to \phi\pi \to \mu\mu\pi$





W Tau analyses ($W \to \tau\nu \to 3\mu + \nu$)

- *3 good-quality muons, veto events with* $m_{\mu^+\mu^-}$ *in vicinity of dimuon resonances*
- **BDT**: *isolation, $\vec{p}_T^{\,3\mu}$, $m_T(\vec{p}_T^{\,miss}, \vec{p}_T^{\,3\mu})$, $|\vec{p}_T^{\,miss} + \vec{p}_T^{\,3\mu}|$, vertex χ^2, vertex displacement*, etc.
  Use sidebands for background in BDT training
- **Signal extraction:** *Cut on BDT*, look for excess at $m_{3\mu} = m_\tau$



Run 2, 2016
(33.2 fb⁻¹)
W tau
best BDT category

$\tau \to 3\mu$ limits

		Hadronic	W	Hadronic + W
LHCb	**Run 1 (3 fb^{-1})**, JHEP 02 (2015) 121	4.6×10^{-8}		
ATLAS	**Run 1 (8 TeV, 20 fb^{-1})**, Eur. Phys. J. C 76 (2016) 232		38×10^{-8}	
CMS	**Run 2 (2016, 33 fb^{-1})**, JHEP 01 (2021) 163	9.5×10^{-8}	20×10^{-8}	8.0×10^{-8}
Best limits so far (Belle): 2.1×10^{-8}				

- Searches with **full** Run-2 data are still **ongoing** (stay tuned for new results)

HL-LHC projections: $\mathcal{O}(10^{-9})$

ATLAS: ATL-PHYS-PUB-2018-032 (12 Dec 2018)

CMS: Phase 2 Muon Upgrade TDR, CMS-TDR-016 (2017)

LHCb: Physics case for an LHCb Upgrade II, LHCB-PUB-2018-009 (2018)

Sensitivity improvements scale better than $1/\sqrt{L}$ due to the foreseen detector/trigger upgrades

- Belle-II will be extremely competitive in few years: $O(10^{-9})$ …
  with an extended spectrum of leptonic final states (next slide)

2018 - 90% CL Upper Limits for BF of τ LFV decays / Belle-II projection

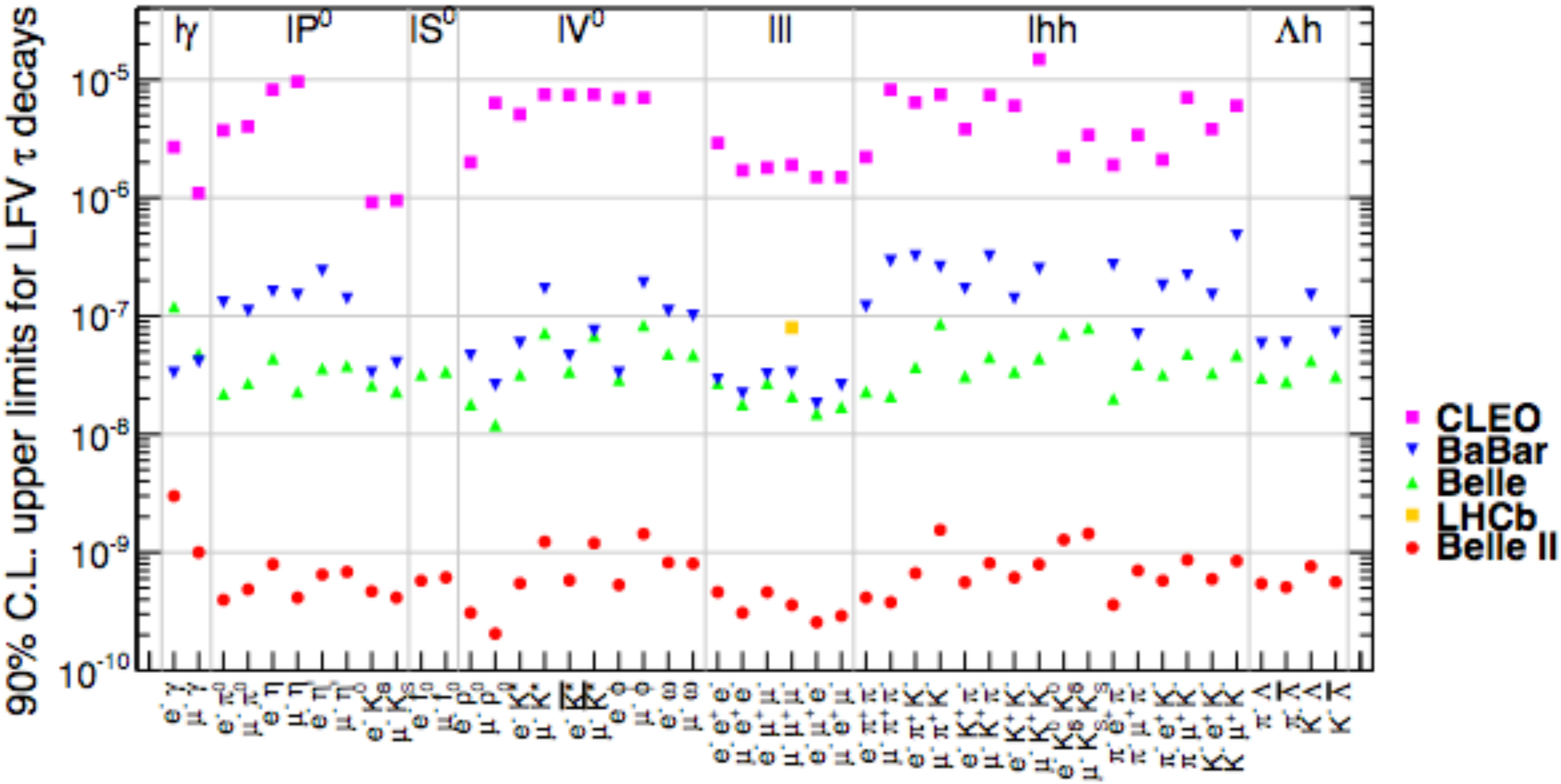


Fig. 189: Current 90% C.L. upper limits for the branching fraction of τ LFV decays obtained in the CLEO, BaBar, and Belle experiments. Purple boxes, blue inverted triangles, green triangles and yellow boxes show CLEO, BaBar, Belle and LHCb results, respectively, while red circles express the Belle II future prospects, where they are extrapolated from Belle results assuming the integrated luminosity of 50 ab^{-1}.

could be reached in 2031 (see backup)

Perspectives

- **On the theoretical side :**
  global fits can be based on improved parametrization of non-local matrix elements
  (van Dyk *et al.***)**

- **Experimental updates and new measurements, not only from LHCb but also CMS and ATLAS - and eventually from Belle-II - are needed.**
  - **LFU tests with new channels : R(ϕ), R(Λ), …**
  - **Update of angular analyses to full datasets & all possible updates ($B_s^0 \to \mu^+\mu^-$, …)**
  - $B \to K^* e^+ e^-$ **angular analyses; angular analyses with baryons ($\Lambda_b \to \Lambda\mu^+\mu^-$, …)**
  - $B_s^0 \to \tau^+\tau^-$ **… if we want to understand R(D) & R(D*)**
  - **Further LFV searches (in the most different leptonic final states)**

- **Still work to do from theoretical and experimental sides !**

- **Exciting short & long-term prospects (Run-3 + HL-LHC)**: 30 more time data w.r.t. Run-2
  - For low-mass signals, detectors & trigger upgrades may enhance the signals' acceptance

BACKUP / Additional Material

Results presented here by:

- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code — arXiv:2104.08921
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` — arXiv:2103.13370
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code `HEPfit` — arXiv:2011.01212
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code `SuperIso` — arXiv:2104.10058

See also similar fits by other groups:
Geng et al., arXiv:2103.12738, Alok et al., arXiv:1903.09617, Datta et al., arXiv:1903.10086, Kowalska et al., arXiv:1903.10932, D'Amico et al., arXiv:1704.05438, Hiller et al., arXiv:1704.05444, …

P.Stangl talk @ FAW21

Observables in $b \to s\ell\ell$ global analyses

- Inclusive decays
  - $B \to X_s\gamma$ ($\mathcal{B}$)
  - $B \to X_s\ell^+\ell^-$ ($\mathcal{B}$)
- Exclusive leptonic decays
  - $B_{s,d} \to \ell^+\ell^-$ ($\mathcal{B}$)
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$ ($\mathcal{B}, S_{K^*\gamma}, A_I$)
  - $B^{(0,+)} \to K^{(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu, R_K$, angular observables)
  - $B^{(0,+)} \to K^{*(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu, R_{K^{*0}}$, angular observables)
  - $B_s \to \phi\mu^+\mu^-$ ($\mathcal{B}$, angular observables)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ ($\mathcal{B}$, angular observables)
- Fits might include 150 $\sim$ 250 observables $\Rightarrow$ **global** $b \to s\ell\ell$ analyses

P.Stangl talk @ FAW21

Global fits - III

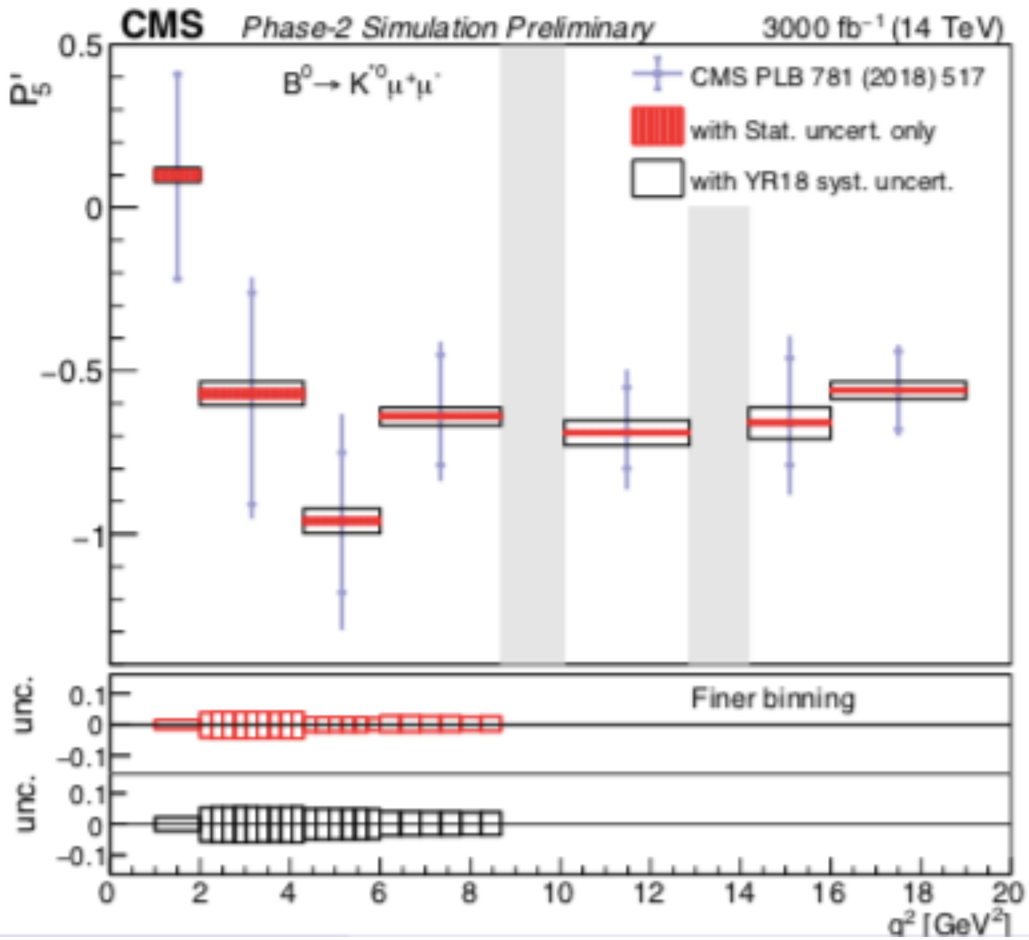
Comparison between the groups

- Different experimental inputs, e.g.
  - $q^2 \in [6, 8]$ GeV^2 data (ACDMN, CFFPSV, HMMN)
  - High-q^2 data (AS, ACDMN, HMMN)
  - Radiative decays (ACDMN, CFFPSV, HMMN)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ (AS, HMMN)
- Different form factor inputs
  - Low-q^2: form factors from LCSR, reduced with heavy-quark & large-energy symmetries + (uncorrelated) power corrections. High-q^2: lattice form factors (ACDMN)
  - Full q^2 region: form factors from combined LCSR + lattice fit, with full correlations (AS, HMMN)
  - Low q^2 region: form factors from combined LCSR + lattice fit, with full correlations (CFFPSV)
- Different assumptions about non-local matrix elements
  - Order of magnitude estimates based on theory calculations from continuum methods, with different parameterisations (ACDMN, AS, HMMN)
  - Direct fit to data in each scenario, relying on continuum methods only for $q^2 \leq 1$ GeV^2 while allowing them to freely grow for larger q^2 (CFFPSV)
- Different statistical frameworks

P.Stangl talk @ FAW21

Projections on P'_5 uncertainty in CMS (HL_LHC)

- Run 1 statistical uncertainty scaled according to the expected yield
- Systematic uncertainties based on data control channel scaled according to statistics
- Other systematic uncertainties are scaled by a factor of 2
- Total uncertainty is expected to improve by 15 times wrt Run 1 result
- Large signal yield allows to split the q^2 range in finer bins



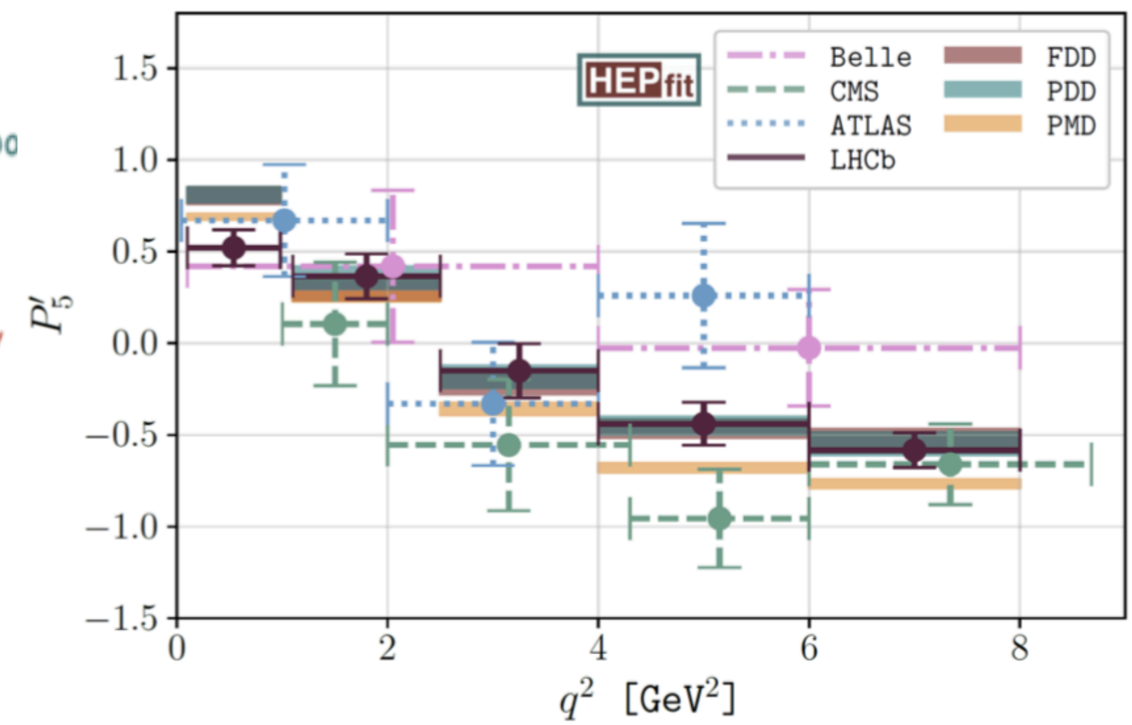
A.Boletti, talk @ Beauty2019

P'$_5$ & charming penguins

From L. Silvestrini talk @ CMS BPH Workshop 2021 (work from Ciuchini *et al.*)

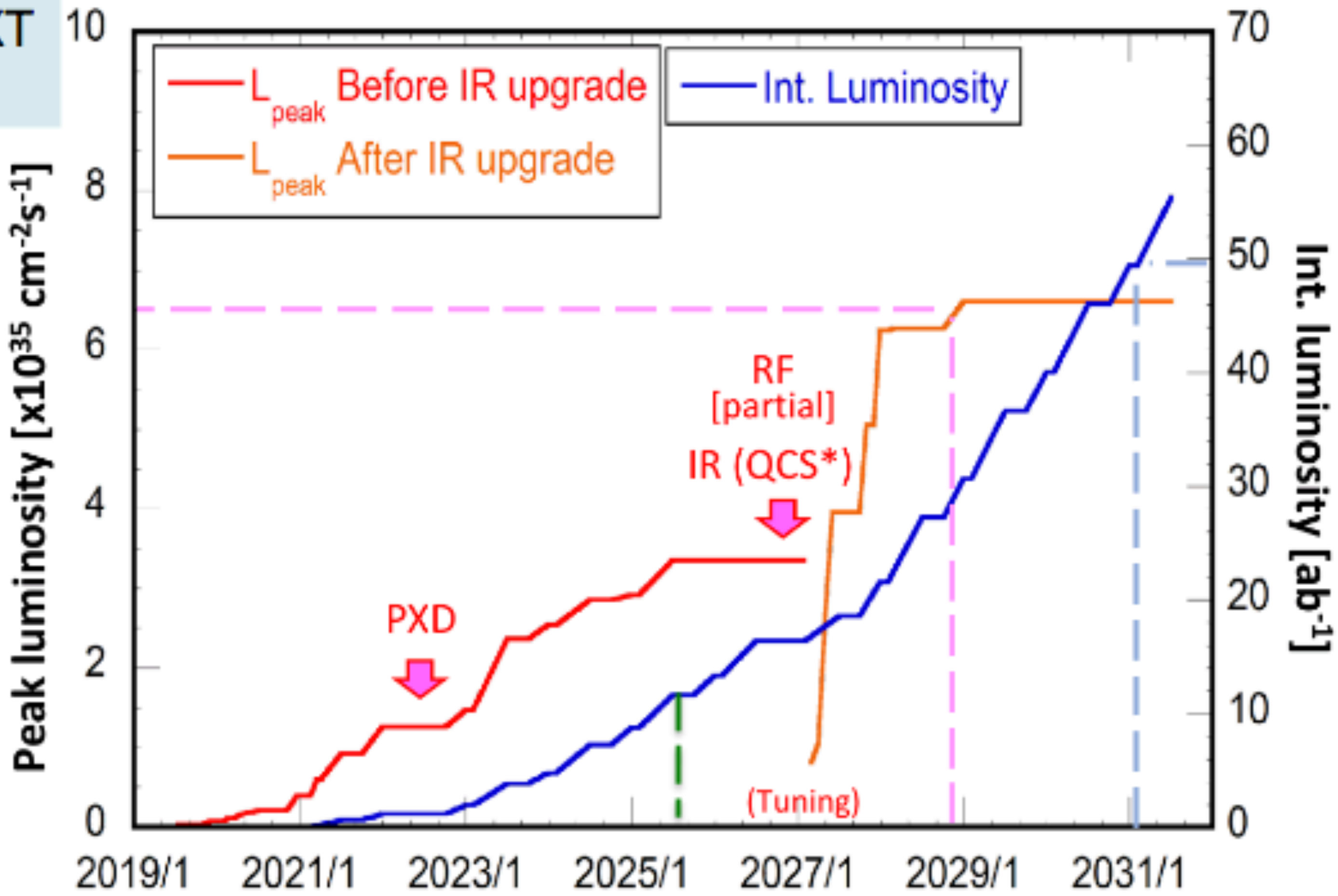
- Compute all amplitudes using QCD factorization and form factors from LQCD (at large q^2) and LCSR (at small q^2)
- "Optimized observables" such as P_5' are not independent on charm loo effects, nor on the form factors if the charm loop is not neglected
- Three approaches for the charm loop:
  - trust LCSR calculation at low q^2 and extrapolate to larger q^2 using unitarity (PMD)
  - trust LCSR calculation at low q^2 (1 GeV^2) only (PDD)

    or
  - let data determine the charm loop (FDD)
- fit all available experimental data using the HEPfit code



Belle-II luminosity plan

Submitted to MEXT roadmap 2020



$\int \mathcal{L} = 0.5 \div 1\ ab^{-1}$ in 2022

$\int \mathcal{L} = 10\ ab^{-1}$ in 2026

$\mathcal{L}_{peak} = 6\ 10^{35}\ cm^{-2}\ s^{-1}$ in 2029

$\int \mathcal{L} = 50\ ab^{-1}$ in 2031

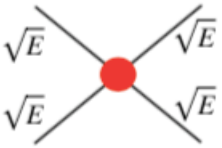
High-p_T implications: at which scale?

- Courtesy of M.Pierini by his wrap-up of the FAW21 (based on A.Grejo's talk)

- IF $b \to s\ell^+\ell^-$ anomalies are genuine new physics effect
  $\Longrightarrow$ Major Revolution in HEP

$\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ [See talk by Stangl et al]

4-fermion scattering at $E \gg v_{EW}$



$\mathscr{A} \sim \frac{E^2}{(40\ \mathrm{TeV})^2}$ $\Longrightarrow$ Violation of perturbative unitary $\lesssim 100\ \mathrm{TeV}$ Di Luzio, Nardecchia 1706.01868

- Observational evidence!
  (Argument stronger than EW naturalness)

The nightmare scenario

The high-p_T collider nightmare scenario assumptions:

- The only "big" operator in the SMEFT is: $\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2}(\bar{Q}_2\gamma^\mu Q_3)(\bar{L}_2\gamma_\mu L_2)$
- The mediator particle behind this operators is too heavy for an on-shell production

In the past the scale was lower

- However, the scale indicated from the perturbative unitary tends to be overly pessimistic
  - Example 1
    Weak interactions $\to G_F \sim (250\ \mathrm{GeV})^{-2}$ $\quad G_F \sim \frac{g_W^2}{m_W^2}$ $\quad m_W \approx 80\,\mathrm{GeV}$
  - Example 2
    "Super-weak" interaction [L. Wolfenstein]:
    $\frac{e^{i\delta}}{\Lambda^2}(\bar{s}\Gamma d)^2$ $\quad \frac{1}{\Lambda^2} \sim (10^4\ \mathrm{TeV})^{-2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$ $\quad m_t \approx 170\,\mathrm{GeV}$

[Taken from Isidori]

This could be true also this time

- In $b \to s\ell\ell$ case, $\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$
- $40\,\mathrm{TeV}$ could be "*a mirage*"
  $\Longrightarrow$ opportunities at high-p_T LHC