Rare Heavy Flavours decays at LHCb

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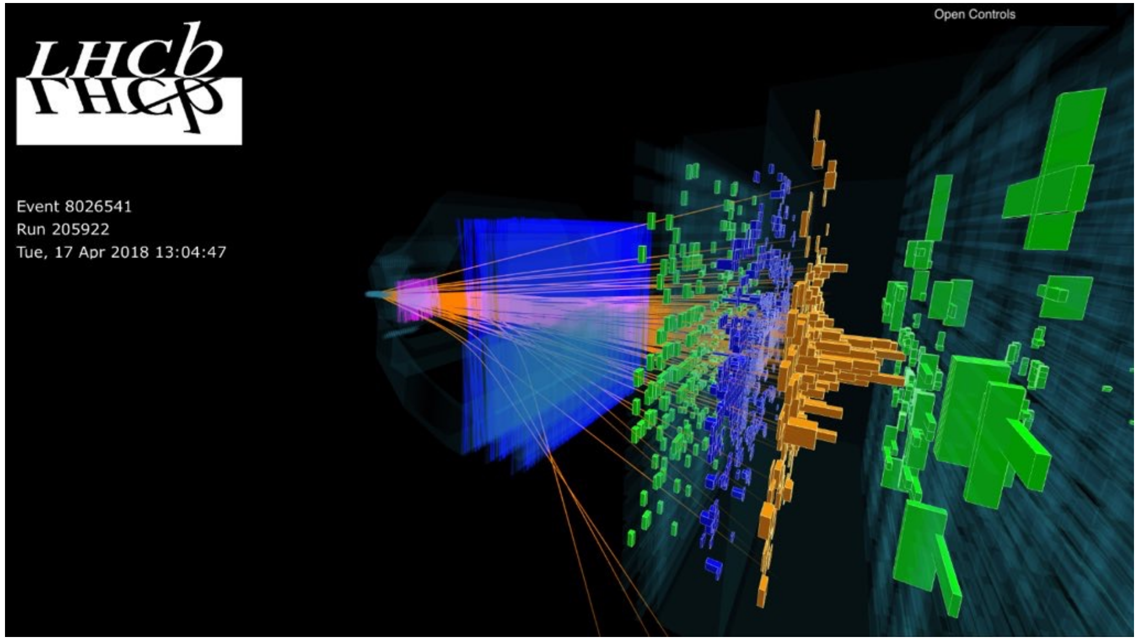


- *b*-hadron decays, focussing on $b \to s\ell^+\ell^-$ transitions
- Not so rare decays
 (for $B_{(s)} \to \ell^+\ell^-$ details see Jacco De Vries talk)

- As requested by the organizing committee, last three slides on $b \to c\ \tau\nu$

European Research Council
Established by the European Commission

CHIARO SCURO

Why rare $b \to q\ell^+\ell^-$ transitions interesting?

FCNC are forbidden at tree level in the SM

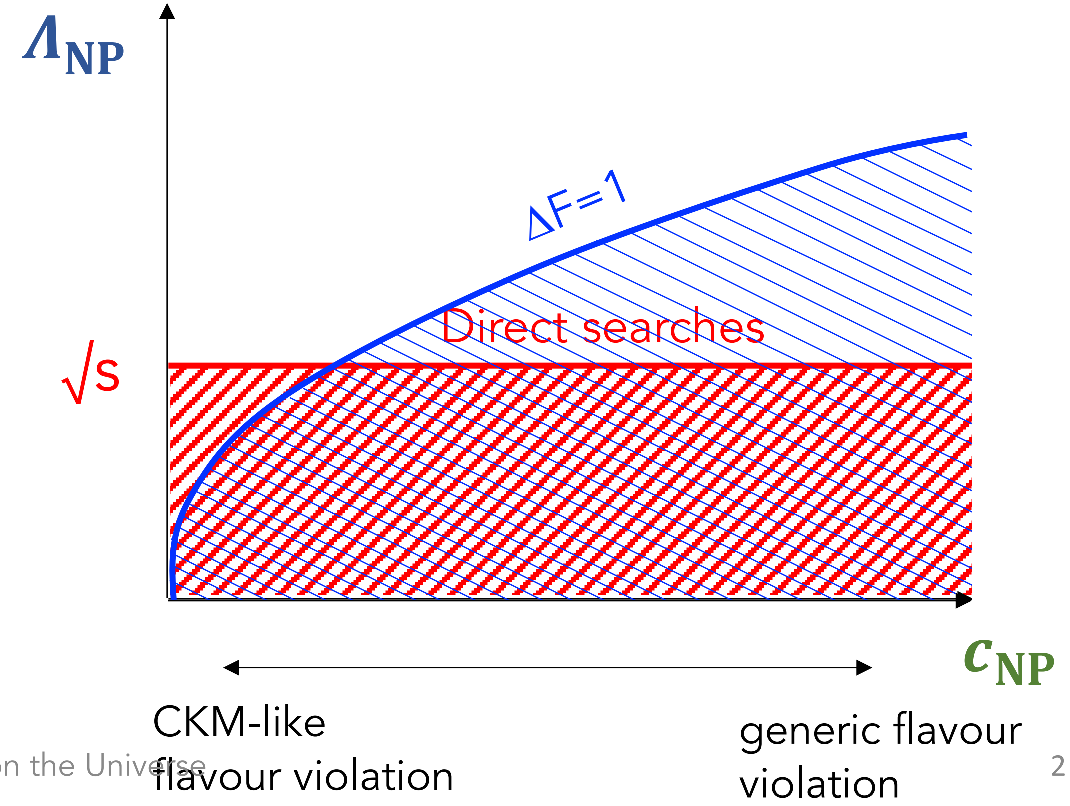
Mediated by box and loop diagrams ⇒ sensitive to indirect effects of New Physics (NP)

Access to larger scales than direct searches

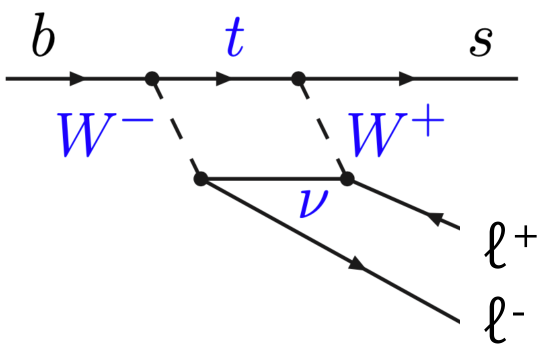
Tests of couplings to 3rd generation (*b*-quarks)

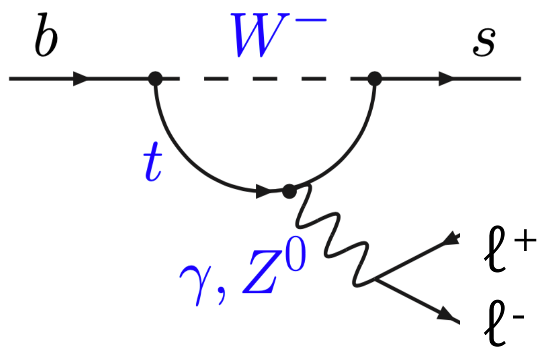
$$\mathcal{H}_{NP} \propto \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2}$$

NP scale and coupling

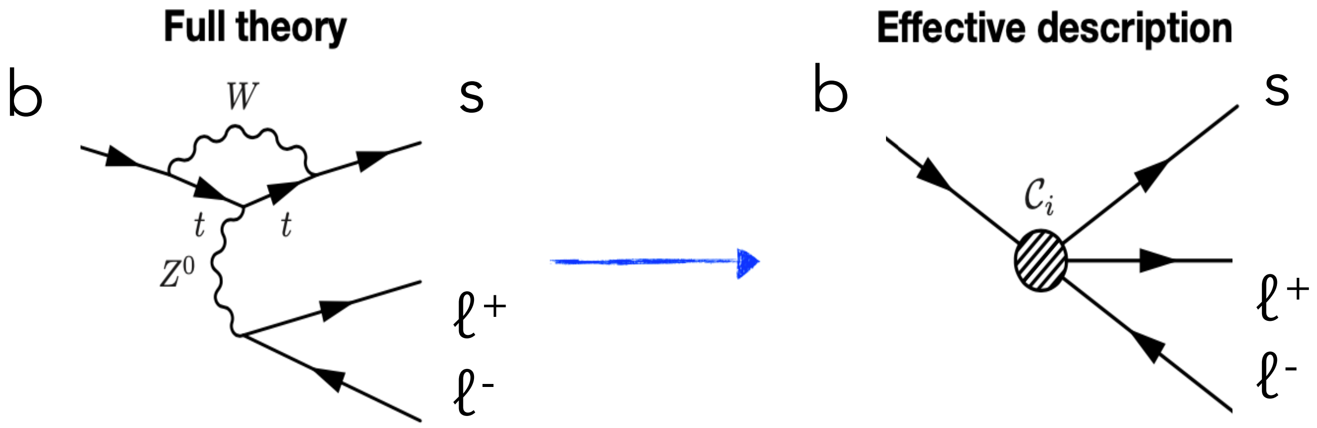


In the SM:





Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$



$$H_{\text{eff}} \propto V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

$O_i^{(\prime)}$ operator encoding Lorentz structure

$C_i^{(\prime)} = C_i^{SM\,(\prime)} + C_i^{NP\,(\prime)}$

~ Fermi's description of the neutron decay

Which operators ?

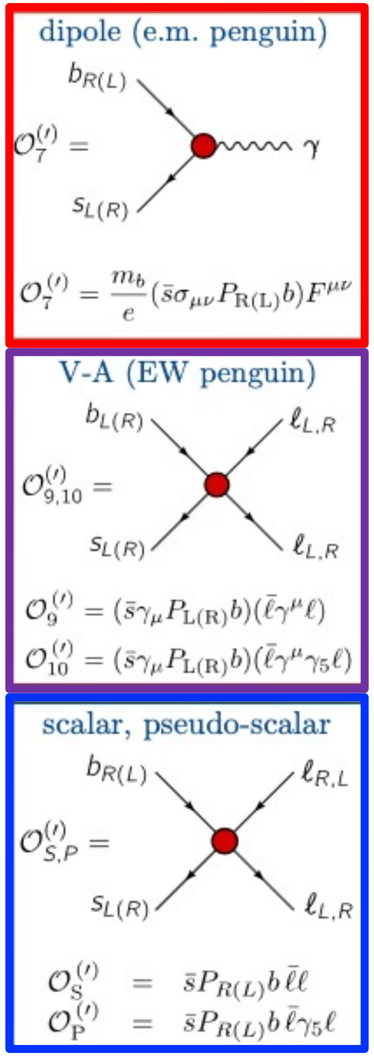
$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$

$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu l)$

$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu\gamma_5 l)$

$O_S^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\,l)$

$O_P^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\gamma_5 l)$

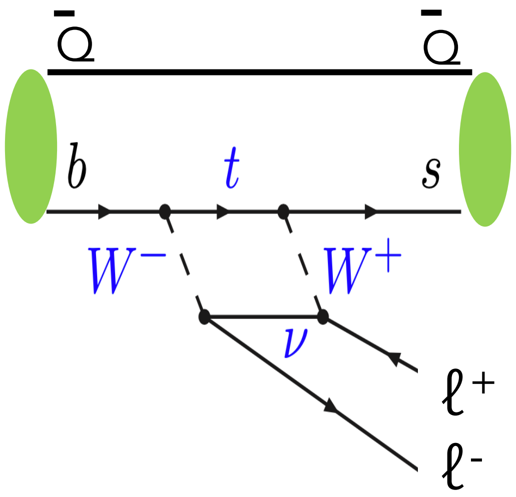


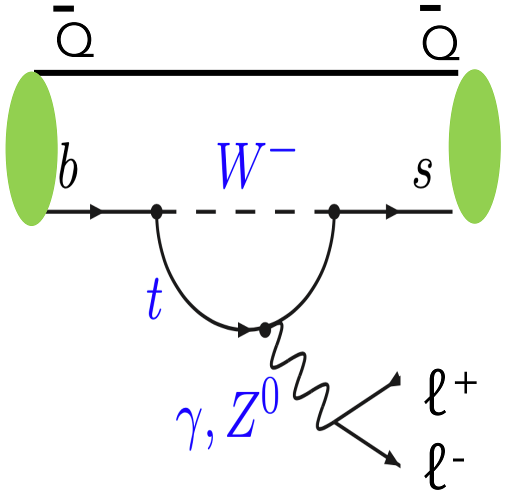
Coupling	b→sγ	b→sℓℓ	B→ℓℓ
$C_7^{(\prime)}$	■	■	
$C_9^{(\prime)}$		■	
$C_{10}^{(\prime)}$		■	■
$C_S^{(\prime)}$ & $C_P^{(\prime)}$			■

Left/Right differences : C/C′

Beyond Standard Model $C_i^{(\prime)}$ can also depend on the lepton type

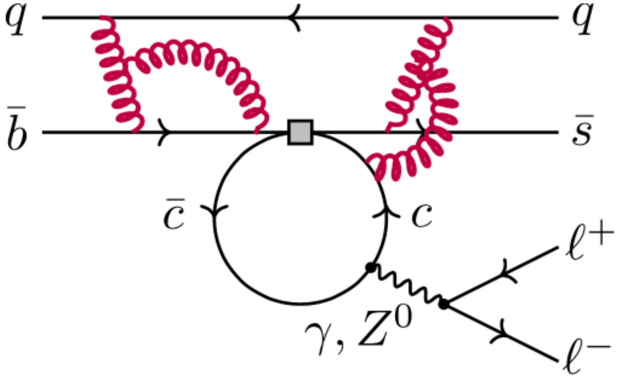
Real life is more complicated…





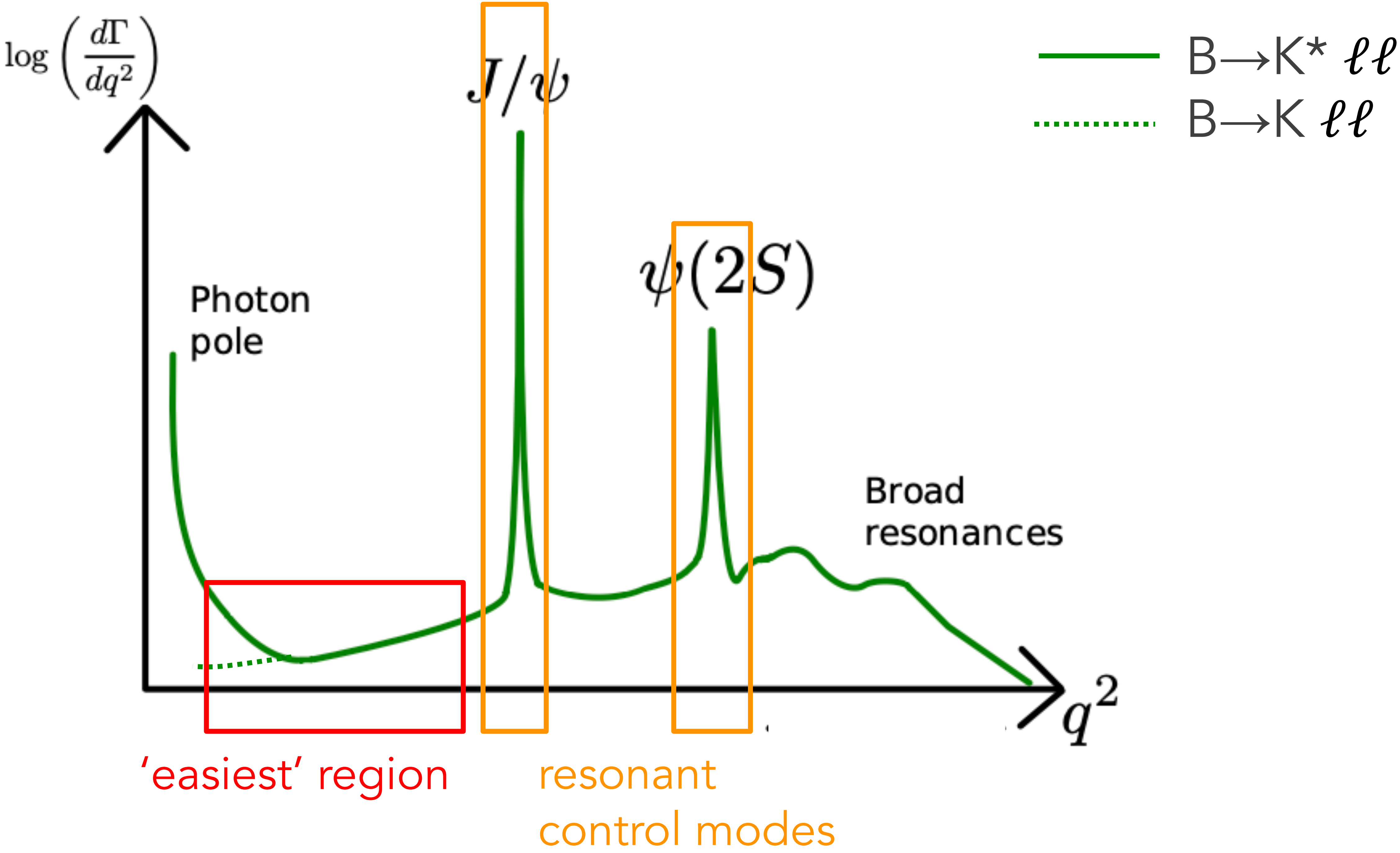
Q=u	Q=d	Q=s
$B^- \to K^- \ell\ell$ $B^- \to K^{*-} \ell\ell$	$B^0 \to K_s \ell\ell$ $B^0 \to K^{*0} \ell\ell$	$B_s \to \phi \ell\ell$

+ *b*-baryons ….
(and B_c)



QCD challenges:

- working with hadrons ⇒ local form factors
- $q\bar{q}$ loops ⇒ non-local form factors + non factorizable soft gluon corrections



$\log\left(\frac{d\Gamma}{dq^2}\right)$
J/ψ
$\psi(2S)$
Photon pole
Broad resonances
q^2
$B \to K^* \ell\ell$
$B \to K \ell\ell$
'easiest' region
resonant control modes

In general BR are $\mathcal{O}(10^{-7})$
→ LHC large production is clearly a plus
→ comes with the cost of a very challenging experimental environment

- $b \to s\,\mu\mu$ channels :
  - clean experimental signature
  - precise experimental results on a large number of BR and angular observables in a fine q^2 binning
- $b \to s\,ee$ channels :
  - low p_T electrons in the harsh LHC context
  - limited number of results (few LFU ratios, one very specific angular analysis)

Branching Ratios

Angular observables

LFU observables :
R-ratios
angular observables ratios

theoretical cleanness

there is no free lunch

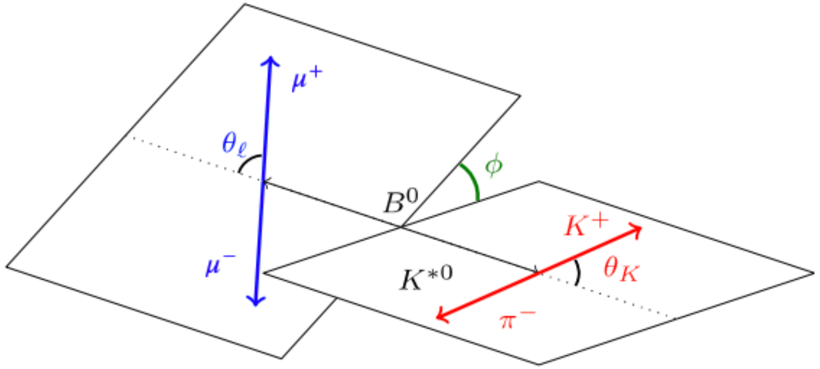
all LFV modes omitted even if they are very important to constraint NP models

Rich phenomenology:

- Branching Ratios (but large theoretical uncertainties due to non-perturbative QCD)
- Angular observables

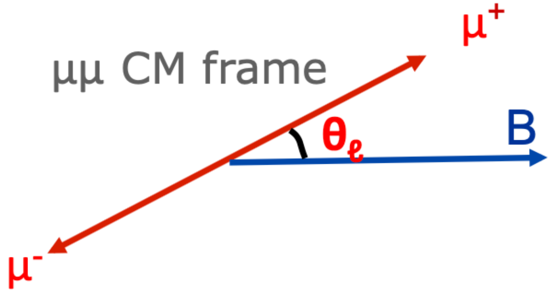
B→V $\ell\ell$

Described by 3 angles and $q^2 = M^2(\ell\ell)$

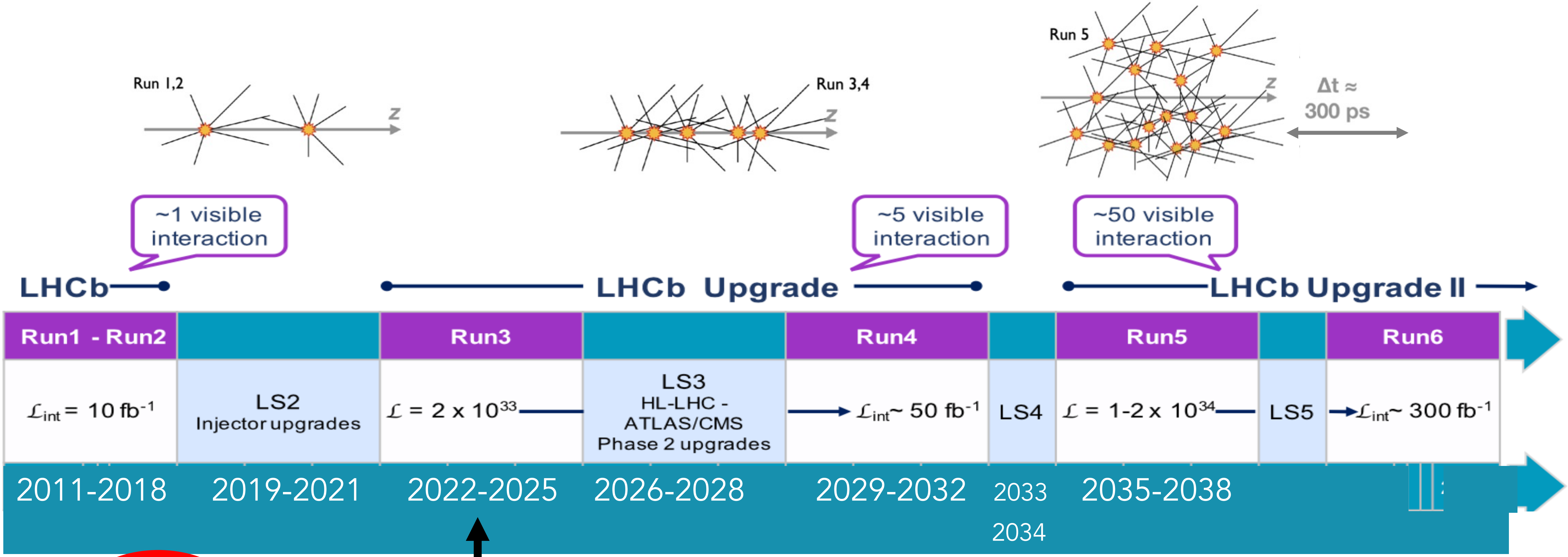


B→PS $\ell\ell$

Described by one angle and q^2



Schedule and datasets



9 fb^{-1}

23 fb^{-1}

50 fb^{-1}

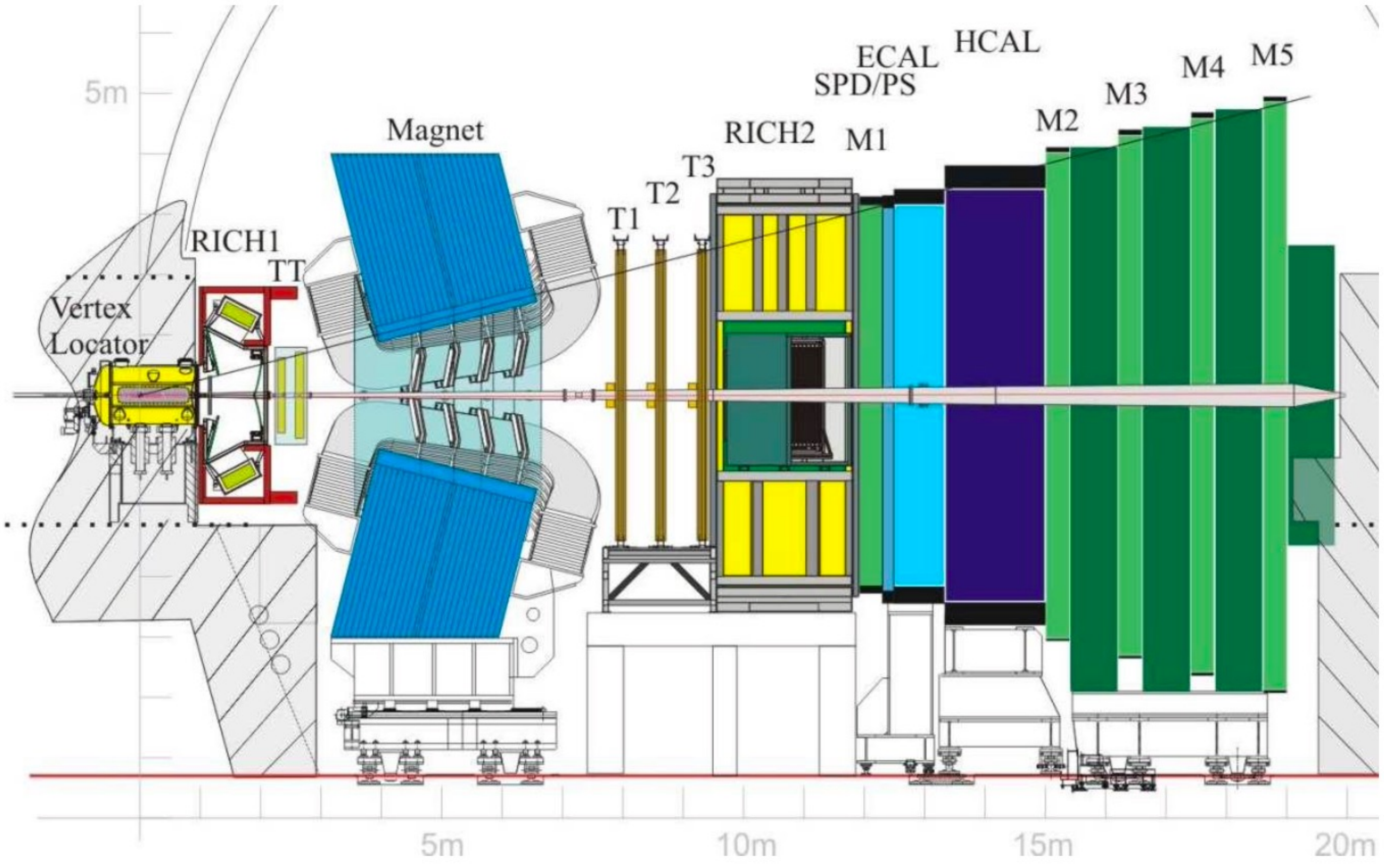
~300 fb^{-1}

the current results

We are here, commissioning our new detector

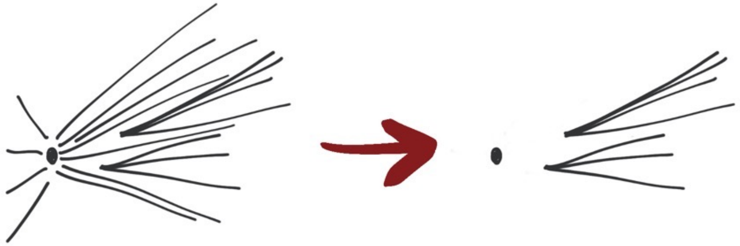
Run1 Run2 results

Experimental set-up and datasets



$\Delta p / p = 0.5 - 1.0\%$

$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$



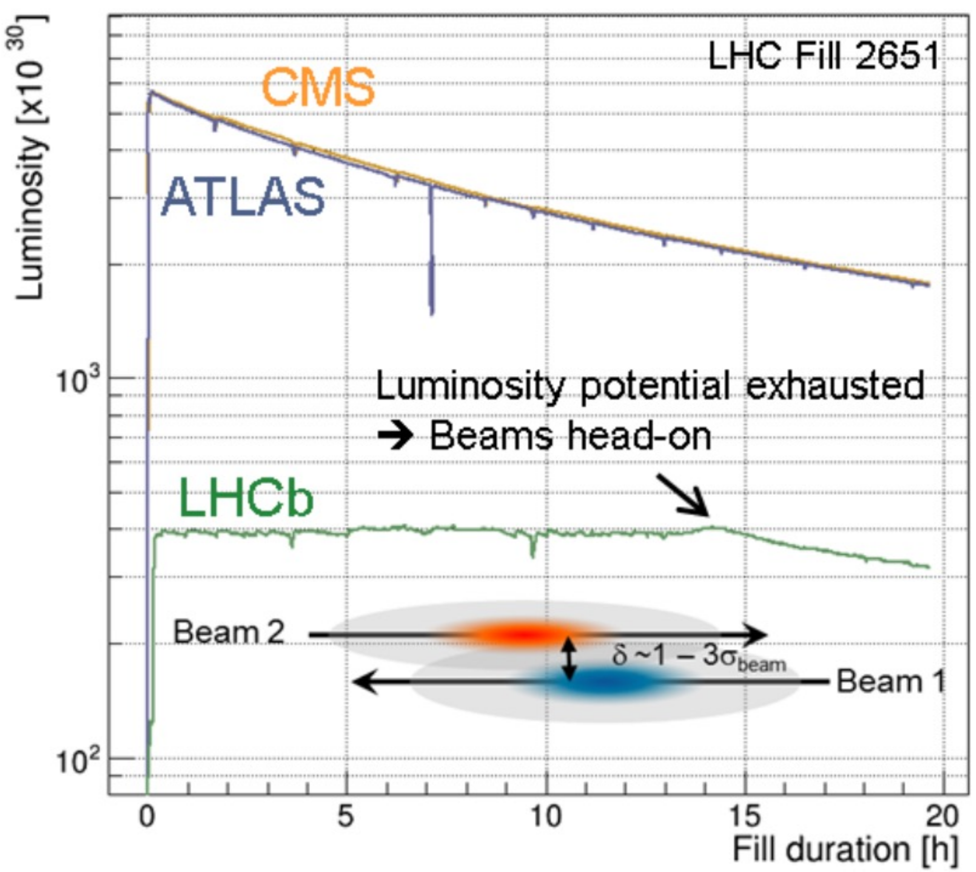
$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[GeV])}$

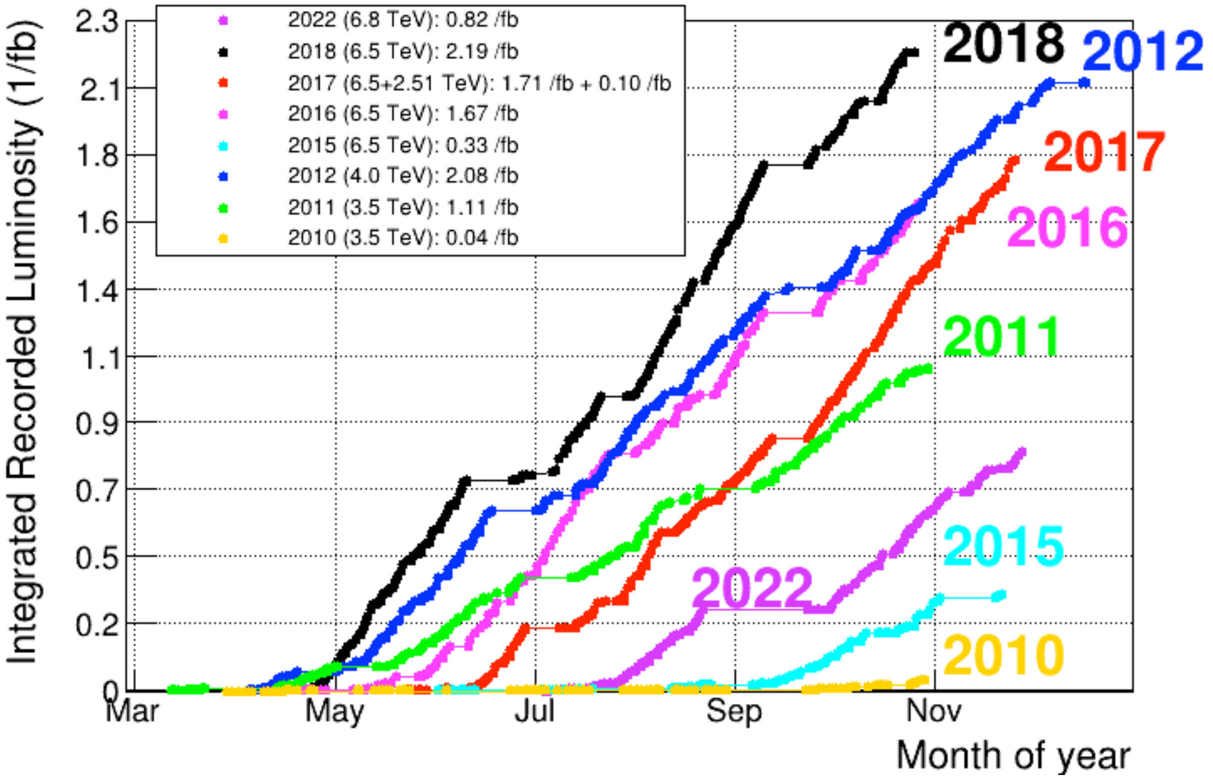
Electron ID ~90% for ~5% $h \rightarrow e^{\pm}$ mis-id probability

Muon ID ~ 97% for 1-3% $\pi \rightarrow \mu$ mis-id probability

Run1 and Run2 data taking

- Running with luminosity levelling at 4. 10^{32} $cm^{-2}s^{-1}$ (x2 design luminosity)
- About 1.5 interaction per bunch crossing
- 9 fb^{-1} collected

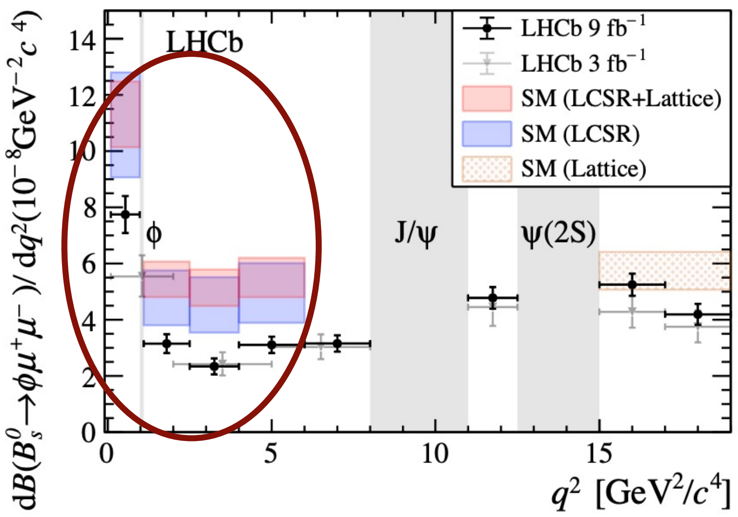




Branching fractions for b→s $\mu\mu$ transitions

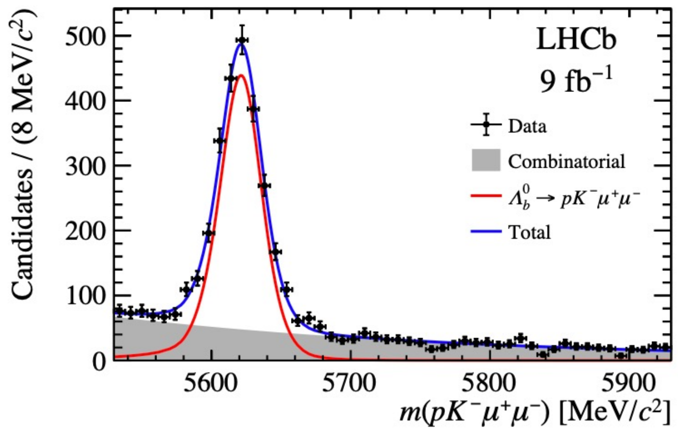
$B_s \to \phi\ \mu\mu$

PRL 127 (2021) 151801

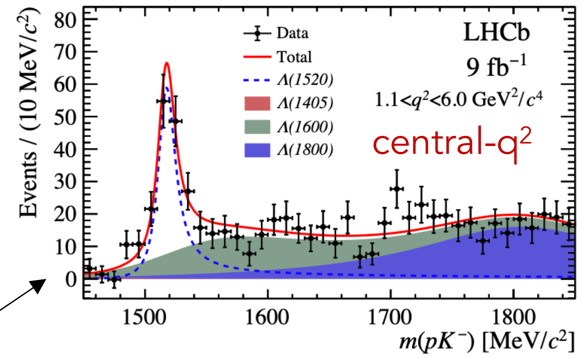


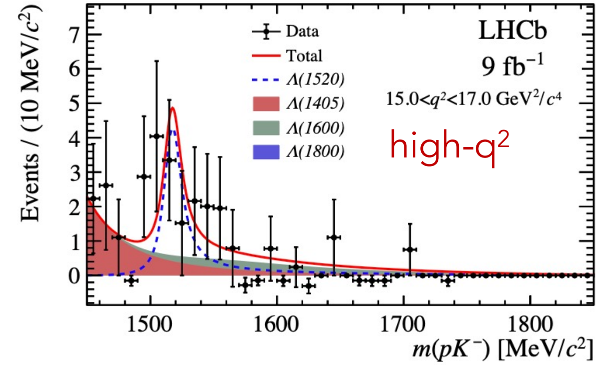
$\Lambda_b \to \Lambda(1520)\ \mu\mu$

arXiv:2302.08262



$N(\Lambda_b \to pK^-\mu^+\mu^-)$ =2250±57(stat)

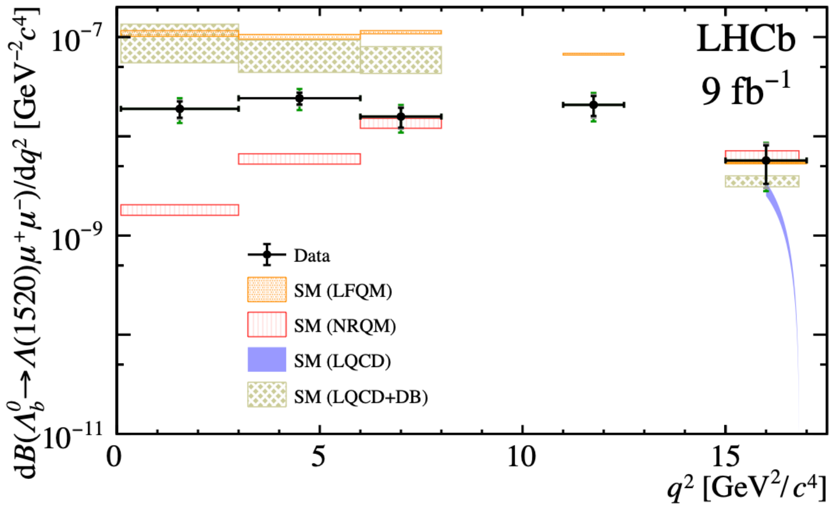




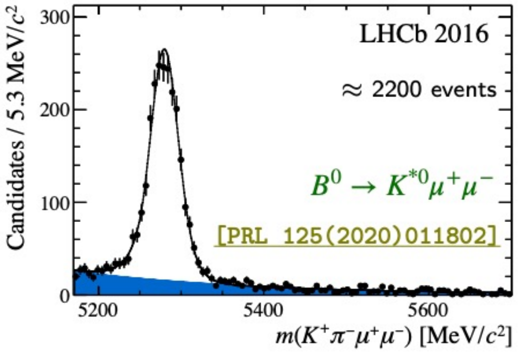
b-mesons: a tendency to measure BF lower than predictions (low and central q^2).

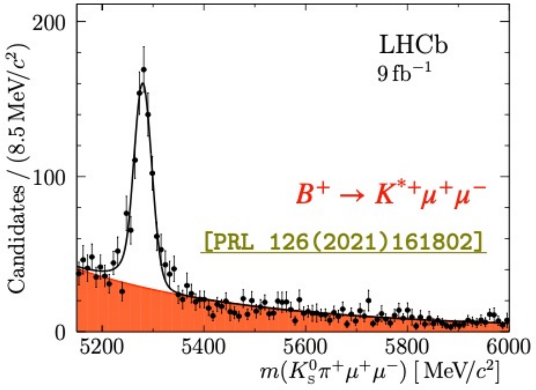
b-baryons: BF in agreement with LQCD (high-q^2). Lack of precise predictions in the rest of phase space.

Predictions uncertainties correlated between bins

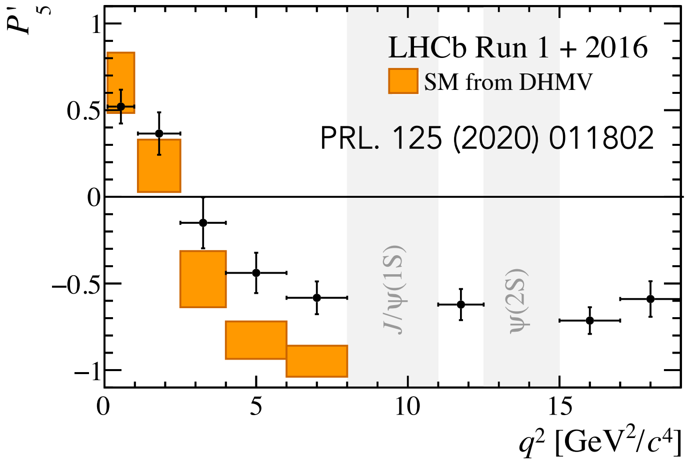


Angular analyses for b→s $\mu\mu$ transitions

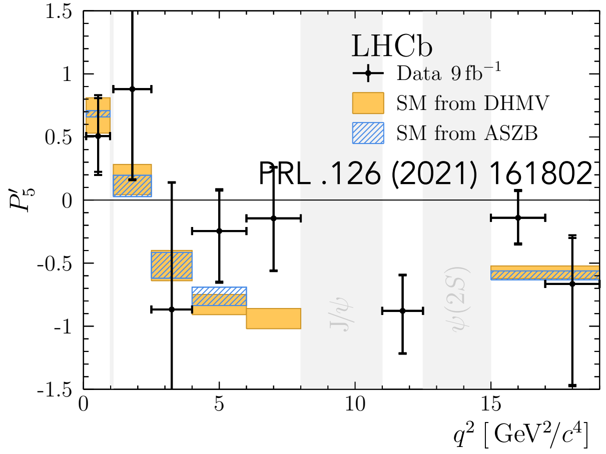




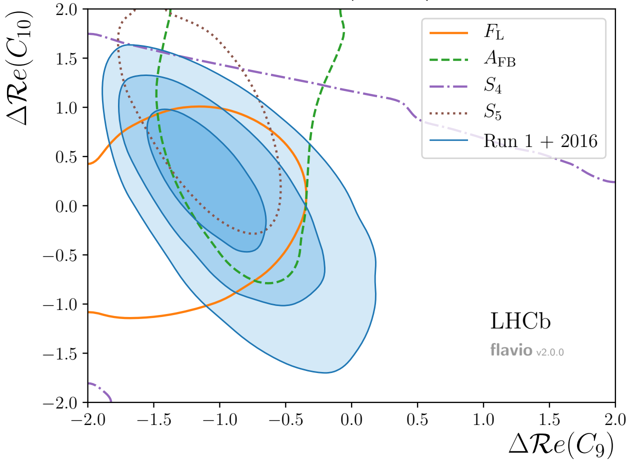
$B^0 \to K^{*0}\ \mu\mu$



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



PRL. 125 (2020) 011802

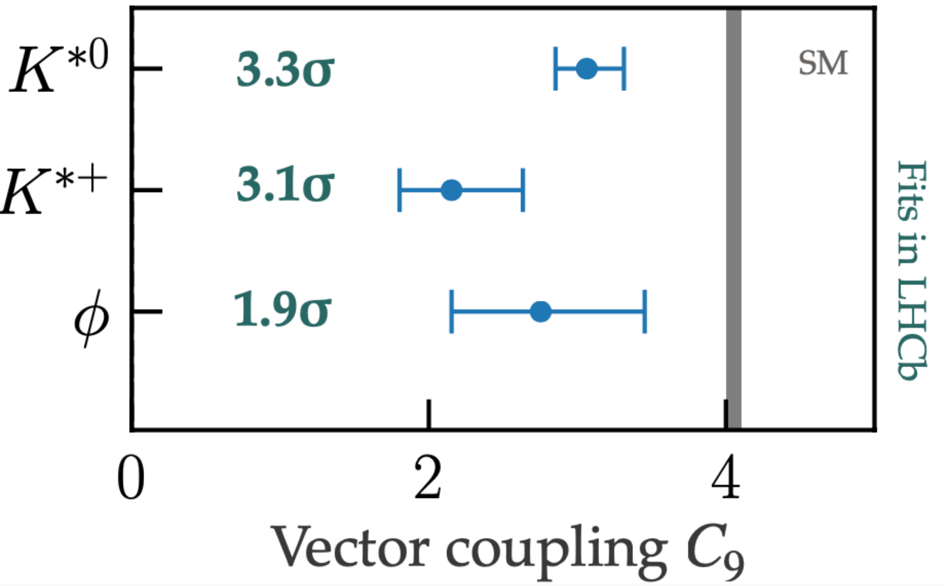


Very clean signal peaks.

Still round for improvements on the experimental side:

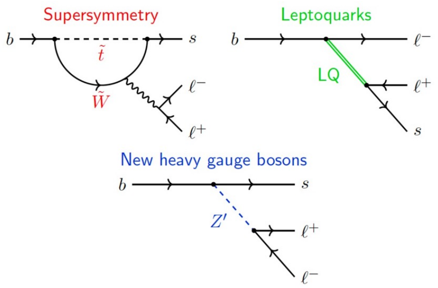
- whole Run1 + Run2 dataset for all the modes
- Add more modes (eg $\Lambda_b \to \Lambda(1520)\ \mu\mu$)

Persisting set of tensions in b→s $\mu\mu$ transitions



Global Wilson coefficients fit seems to indicate a pattern: different observables give a coherent picture

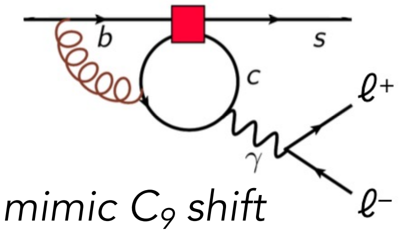
New Physics



or

QCD

$c\bar{c}$ loop



They can mimic C_9 shift

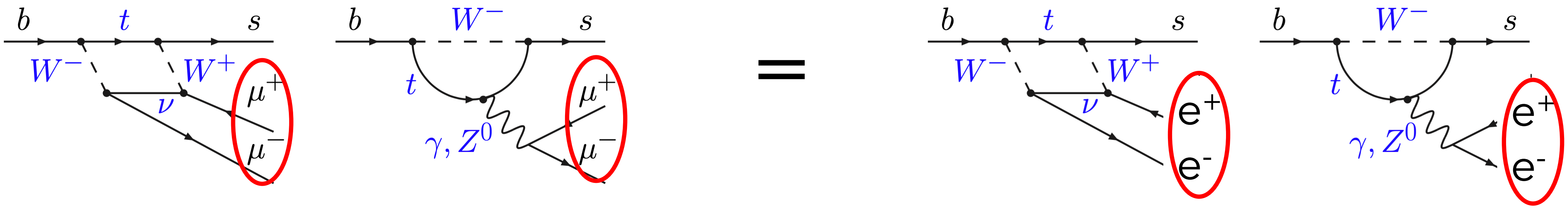
?

New inputs from analyses will help
(finer q^2 bins, unbinned fit over q^2 , other modes…)

Lepton Flavour Universality tests in b→sℓℓ transitions

ℓ=e, μ

SM



Only difference : kinematics (lepton masses)

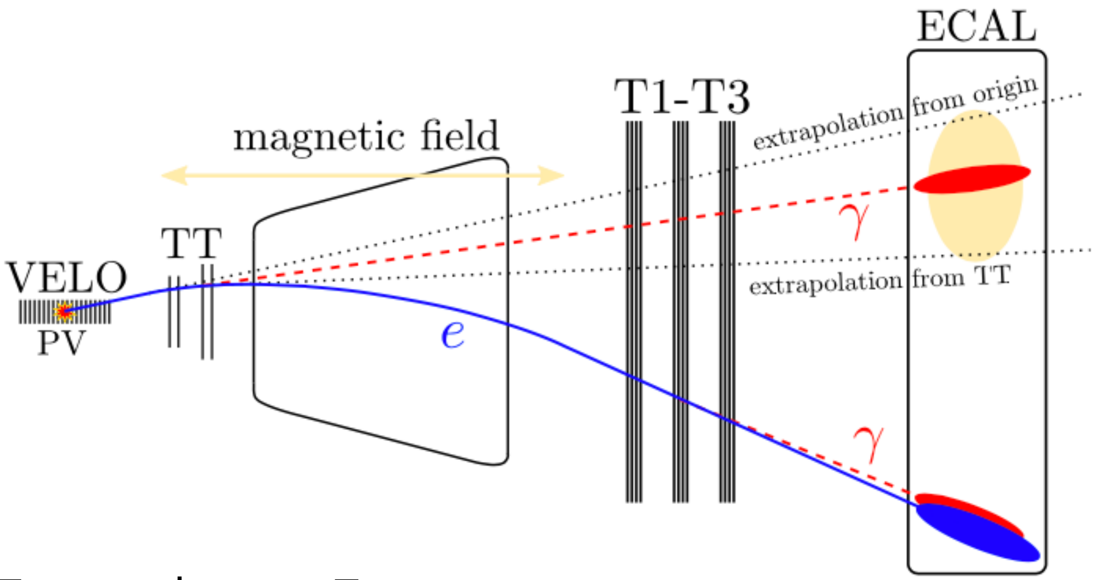
Any ratio of observables in principle

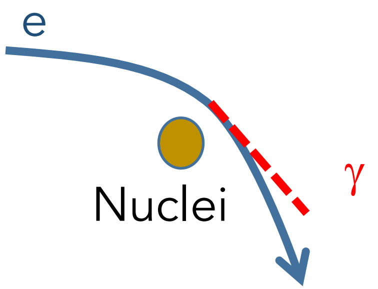
Start with the simplest (?) one: ratio of branching fractions

$B^{+,0}$, B_s, Λ_b → B ; K, K^*, ϕ, pK … → H_s

$$R_{H_s} = \frac{\int \frac{\mathrm{d}\Gamma(B \to H_s\, \mu^+ \mu^-)}{\mathrm{d}q^2}\, \mathrm{d}q^2}{\int \frac{\mathrm{d}\Gamma(B \to H_s\, e^+ e^-)}{\mathrm{d}q^2}\, \mathrm{d}q^2} \overset{SM}{\cong} 1$$

Bremsstrahlung emission is significant for electrons





Before the magnet

- electron can be swept out (=lost !)
- kinematics are "wrong"

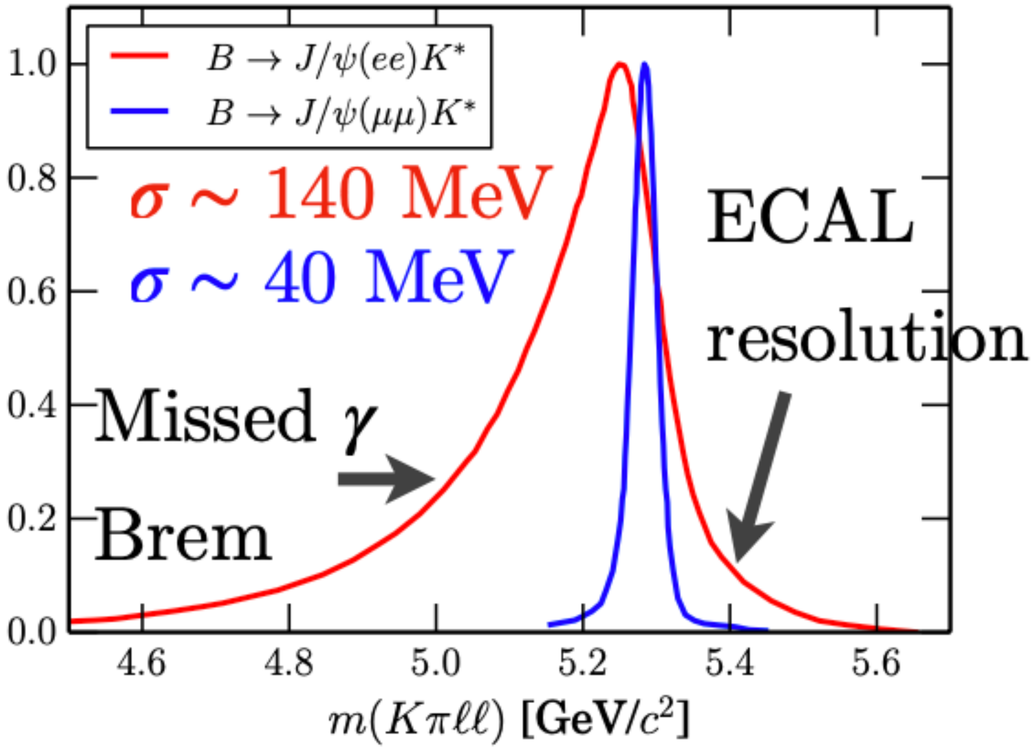
After the magnet

- not an issue

In both cases E/p is correct

Energy loss ∝ E_e
Energy loss ∝ material

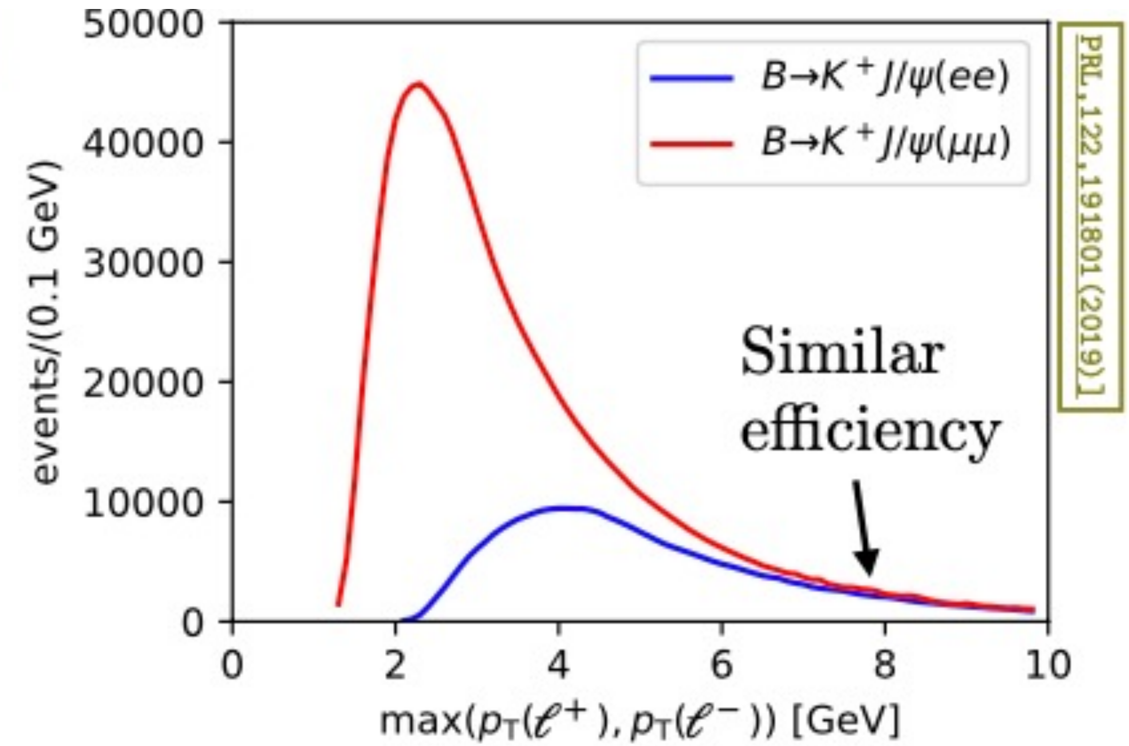
⇒ Use of a recovery algorithm



Hardware trigger is very different for electrons and muons

Larger ECAL occupancy → tighter thresholds for electrons than for muons:

- e pT > 2700/2400 MeV
- μ pT > 1700/1800 MeV



$$\varepsilon(e) \sim \frac{\varepsilon(\mu)}{3}$$

Effect mitigated triggering Independently of Signal

Practically at LHCb:

$$R_H = \frac{N(B\to H\mu^+\mu^-)}{N(B\to He^+e^-)} \times \frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to H\mu^+\mu^-)}$$

Yields from mass fits

Efficiencies from MC & data calibration samples

H = K, K*, pK …

+

$$r_{J/\psi} = \frac{BR(B\to HJ/\psi(\mu^+\mu^-))}{BR(B\to HJ/\psi(e^+e^-))} = 1$$

well tested LFU in J/ψ modes

⇒ Use of the double ratio using the resonant channels

$$R_H = \frac{\dfrac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\dfrac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\dfrac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\dfrac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}$$

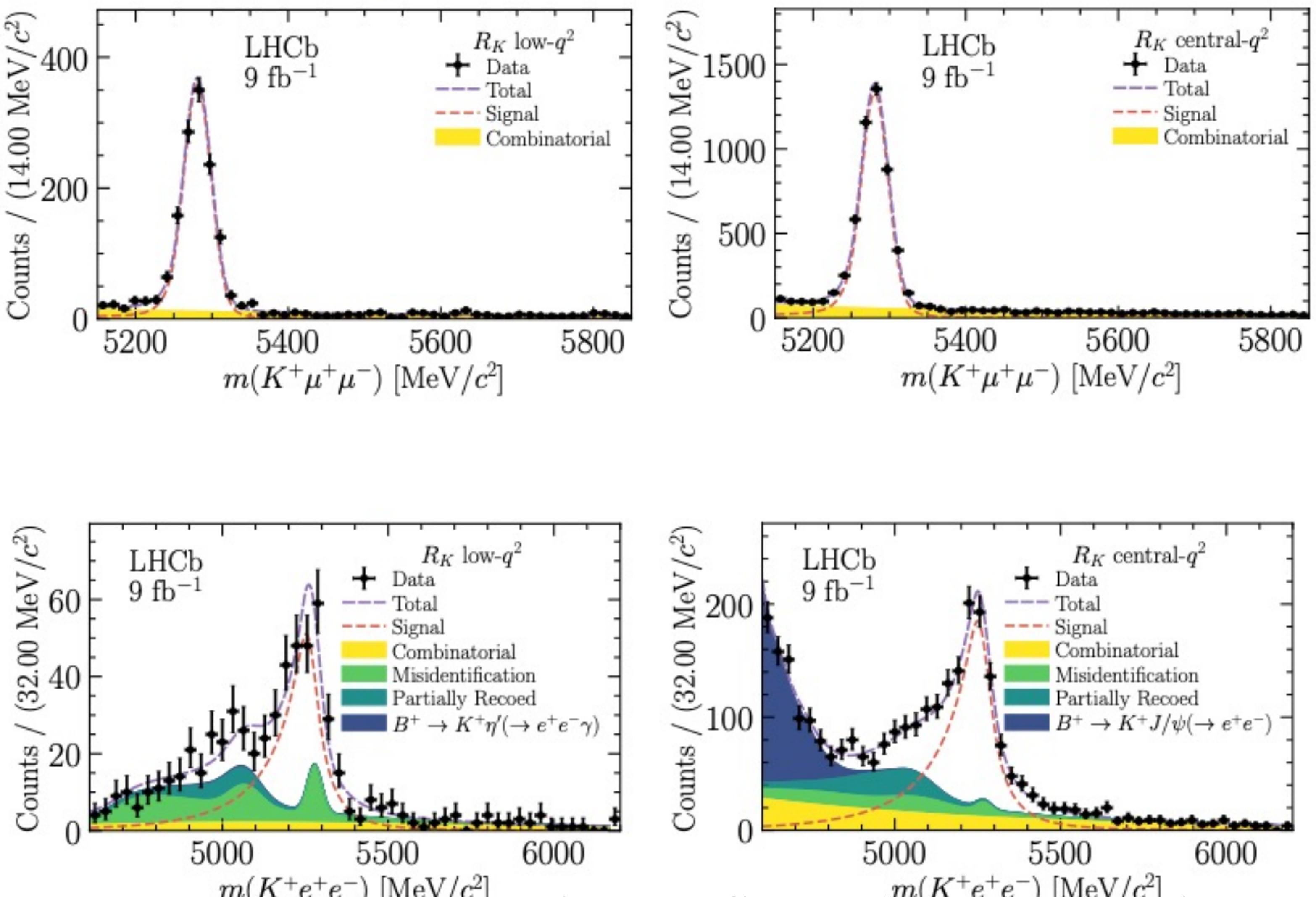
⇒ cancels out most of the systematics due to e/μ differences

Simultaneous fit of two decay modes ($B \to K \ell\ell$ and $B^* \to K^* \ell\ell$) and two kinematical regions (low and central-q^2)

Low-q^2 **Central-q^2**

μμ

ee



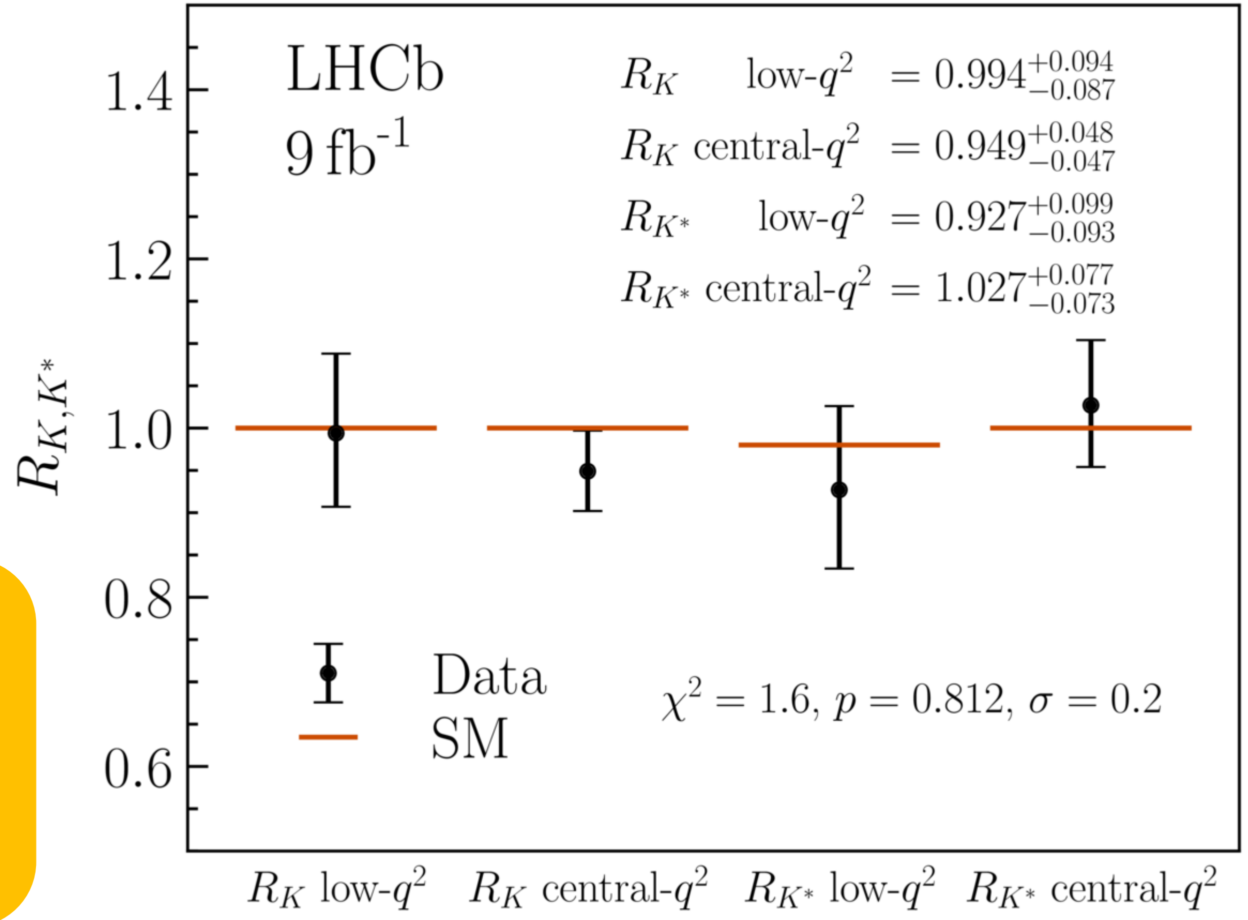
Example of $B^{\pm} \to K^{\pm} \ell\ell$

In depth revision and understanding of electron misidentification

$$\text{low-}q^2 \begin{cases} R_K &= 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\ ^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} &= 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\ ^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K &= 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\ ^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} &= 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\ ^{+0.027}_{-0.026}\,(\text{syst}), \end{cases}$$

Phys. Rev. Lett. 131, 051803 and Phys. Rev. D 108, 032002



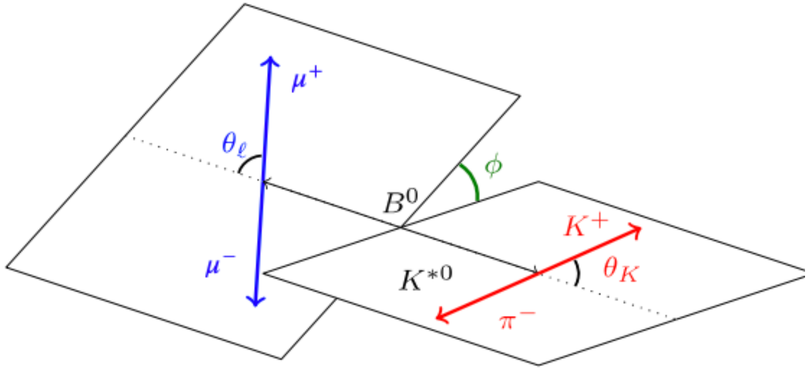
First or most precise test of LFU in $b \to s\ell\ell$
5 to 10% precision (stat dominated)
Compatible with the SM at 0.2 σ

Photon polarization in b →s γ transitions

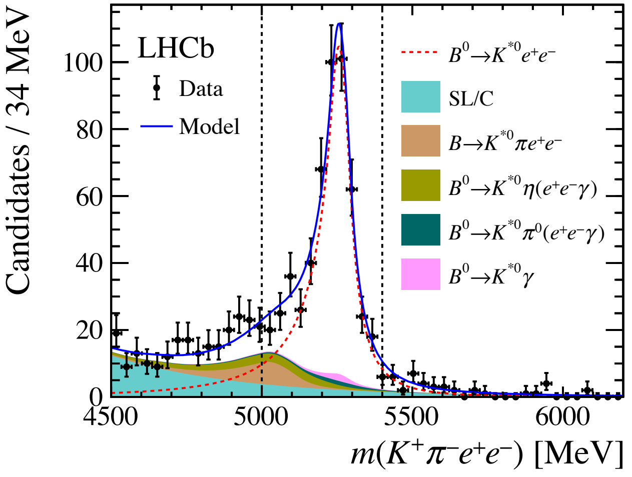
V-A structure of the SM ⇒ right-handed photon are suppressed in b →s γ transitions: $C'_7/C_7 \sim m_s/m_b$

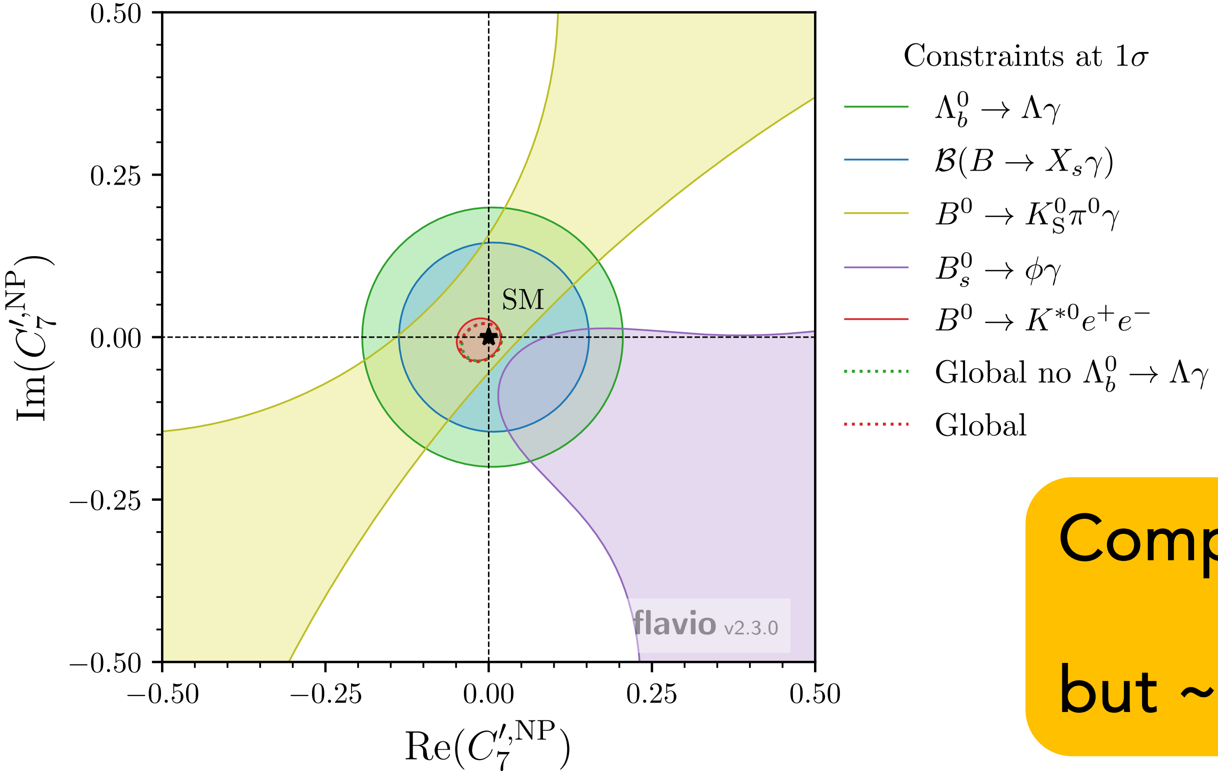
'Experimental polarimeter':

- ϕ distribution in $B^0 \to K^*ee$ in the very low-q^2 (photon pole)
- CP violation effects ($B^0 \to K^{*0} (\to K^0 \pi^0) \gamma$ [BFactories] & $B_s^0 \to \phi \gamma$)
- $\Lambda_b \to \Lambda\gamma$ due to Λ weak decay



$B^0 \to K^*ee$ [JHEP 12 (2020) 081]
$B_s^0 \to \phi \gamma$ [PRL 123 (2019) 8, 081802]
$\Lambda_b \to \Lambda \gamma$ [PRD 105 (2022) 5, L051104]





Compatible with the SM

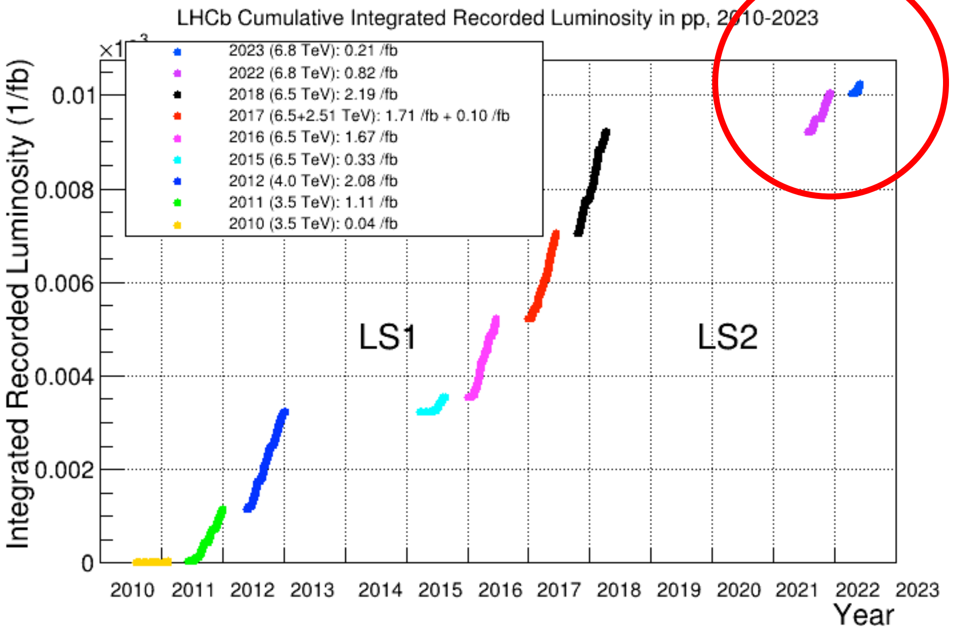
but ~ 5% precision only

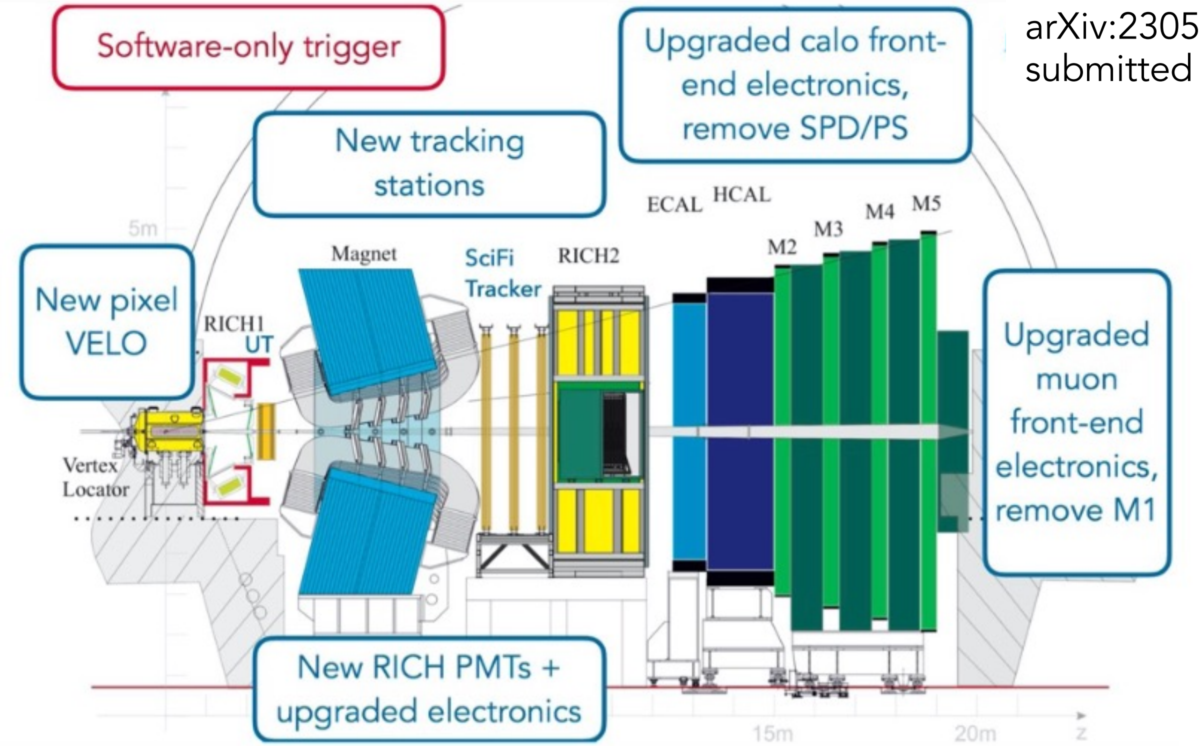
What's next ?

LHCb-Upgrade I

Luminosity x5 wrt Run2
5.5 visible interactions/crossing
Higher track multiplicity from ~<70> to ~<180>)

No more hardware trigger (full detector readout at 40 MHz)
Tracking & PID detectors modified/replaced
Higher grtanularity





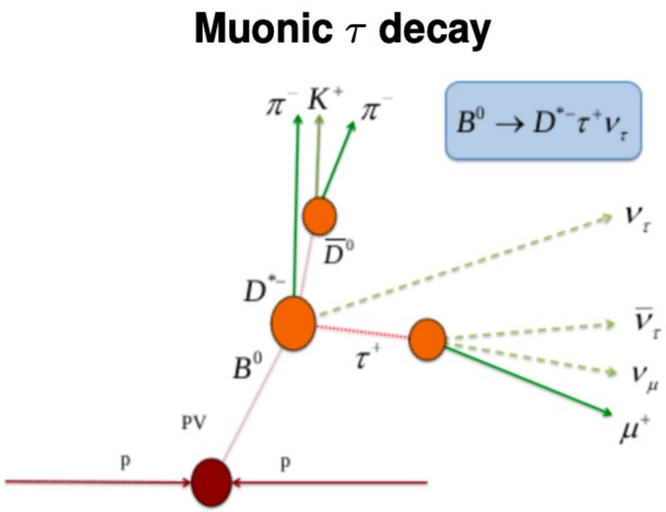
arXiv:2305.10515, submitted to JINST

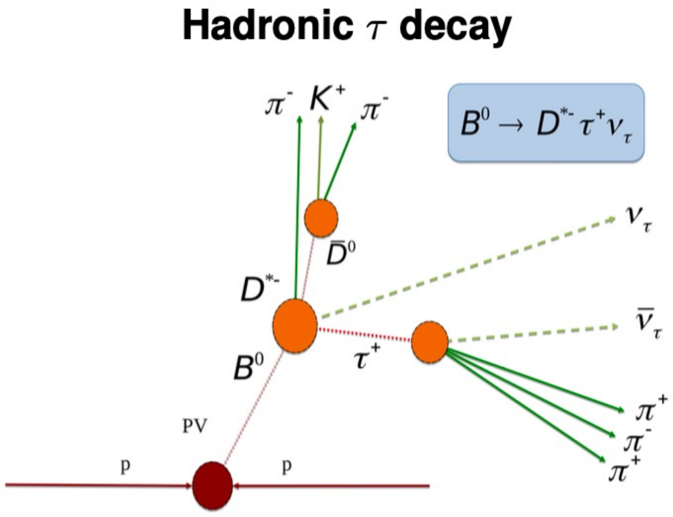
In January 2023, a loss of control of the LHC primary vacuum system
⇒ plastic deformation of the RF foil separating VELO from LHC.
⇒ significant impact on 2023 physics programme

2022 – 2023 : commissioning and understanding the new detector

b→c $\tau\nu$: test of LFU & angular analysis

Not a rare decay: BR($B^0 \to D^* \tau\nu$) ~ 10^{-4}





$$R(X_c) \equiv \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell^+ \nu_\ell)}$$

$X_b = B^{0,+}_{(s,c)}, \Lambda_b^0, \qquad \ell = \mu, e,$

$X_c = D^{(*)}_{(s)}, J/\psi, \Lambda_c^+$

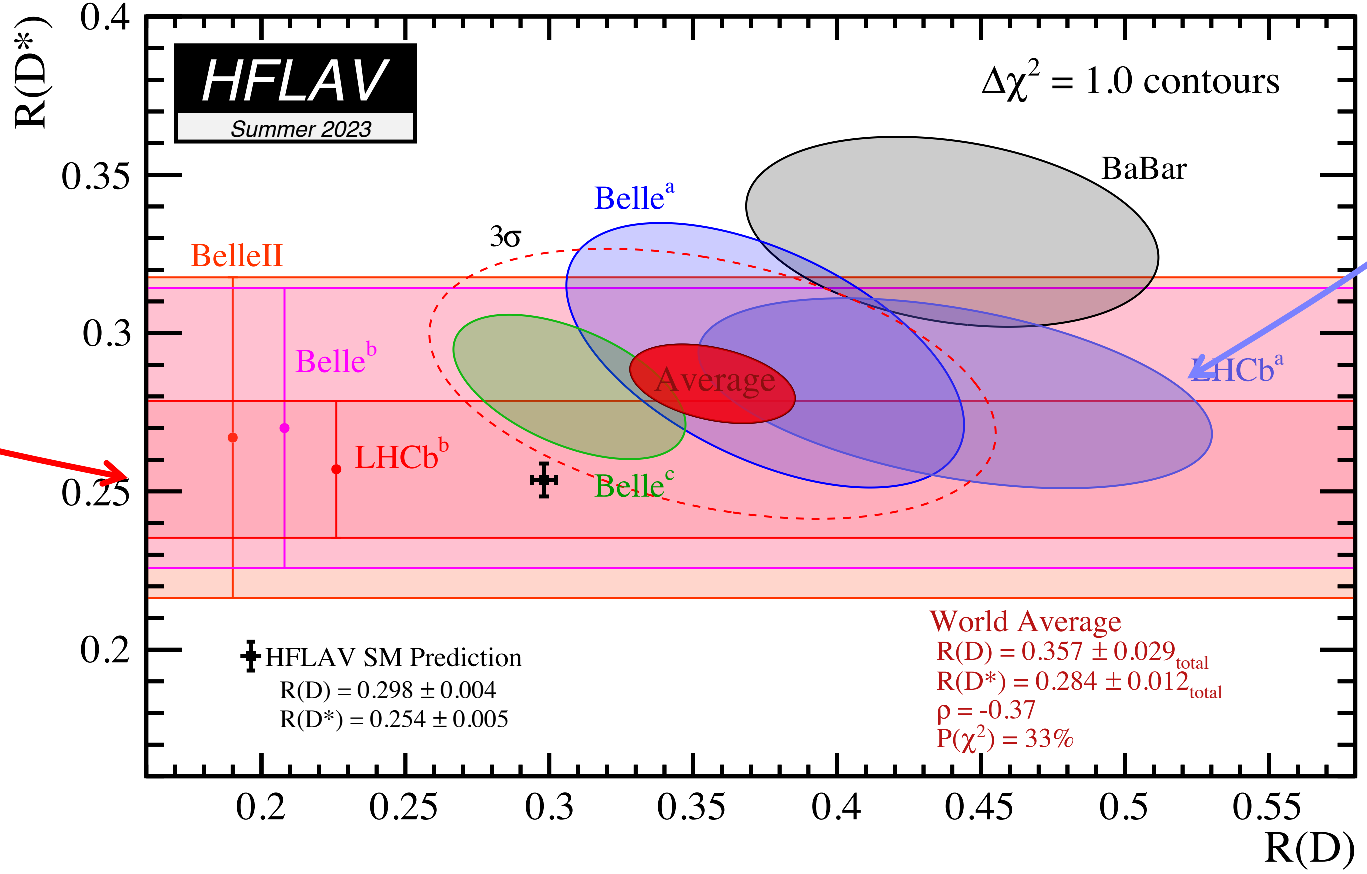
Very large boost→ flight distance reconstruction
→ kinematical constraints

A whole set of new results from LHCb

- Combined analysis for R(D*) and R(D) using $\tau \to \mu\nu\nu$ arXiv:2302.02886

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}, \qquad \tau^- \to \mu^-\nu_\mu\nu_\tau, \qquad D^{*-} \to D^0(\to \pi^+K^-)\pi^-$$

- New analysis for R(D*) using $\tau \to \pi\pi\pi(\pi^0)\ \nu$ (Run1 + part of Run2 dataset) arXiv:2305.01463



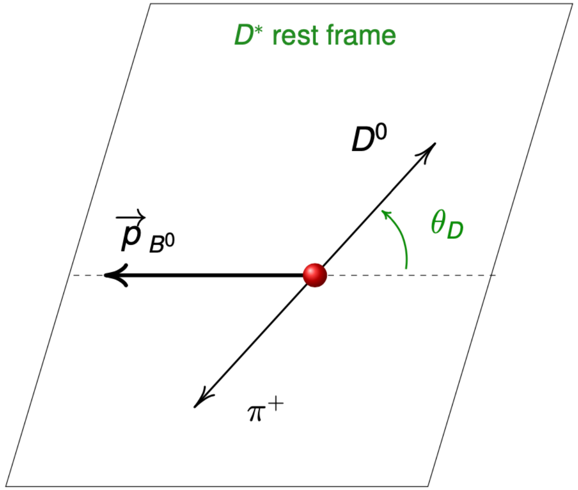
3.3 σ tension with the SM

but also :

Measurement of the D* polarization in B→D* $\tau\nu$ decay

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

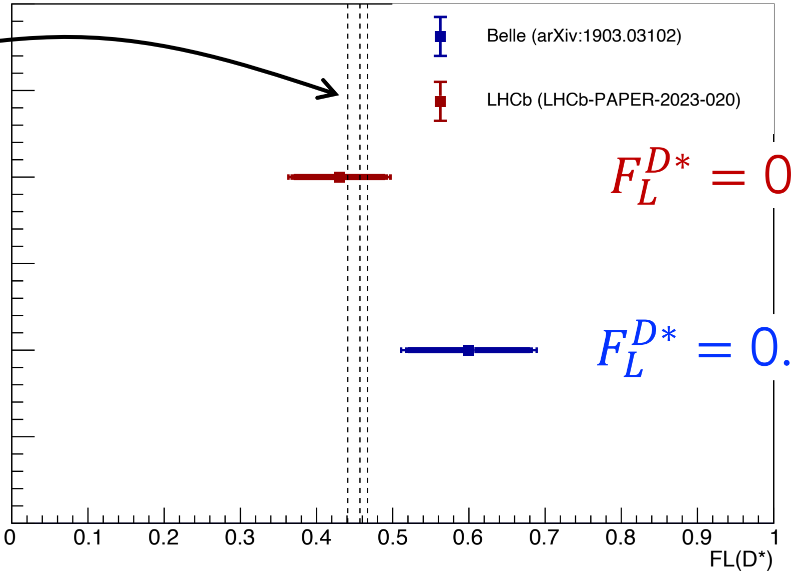


Two q² ($M^2(\tau\nu)$) regions:

$q^2 < 7\,\mathrm{GeV}^2/c^4$:	$0.51 \pm 0.07(stat) \pm 0.03(syst)$
$q^2 > 7\,\mathrm{GeV}^2/c^4$:	$0.35 \pm 0.08(stat) \pm 0.02(syst)$

In agreement with SM predictions and the pioneering result from Belle :

SM predictions:
0.441 ± 0.006 Phys. Rev. D 98 (2018) 095018
0.457 ± 0.010 The European Physical Journal C 79 (2019)
0.467 ± 0.009 The European Physical Journal C 80 (2020)



$F_L^{D*} = 0.43 \pm 0.06 \pm 0.03$

$F_L^{D*} = 0.60 \pm 0.08 \pm 0.04$

A last word on $b \to q \ell^+ \ell^-$

- Tensions persist in $b \to s\, \mu\mu$ branching fractions and (some) angular parameters. Showing up as a shift in C_9 . NP or hadronic issues ?

- $B_s \to \mu\mu$ is compatible with the SM: no obvious sign of NP in C_{10}

- No sign of large Lepton Flavour Universality violation in $b \to s\, \ell\ell$

- Photon polarization in $b \to s\, \gamma$ transitions compatible with SM expectation

SM agreement at the ~5% precision, tests statistically limited
Understanding of persisting tensions
Studies of $b \to d\, \ell\ell$ transitions have hardly started (Cabibbo suppression)

→More data and more analyses !

Stay tuned