Heavy flavour physics III

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Outline of the lectures

- Introduction to the CKM formalism and objectives
- Historical perspective
- LHCb: a flavour-physics detector at the LHC
- Selected *B*-physics results
- Future prospects

Selected *B*-physics results

Rare decays and

B-physics anomalies

Why studying rare decays

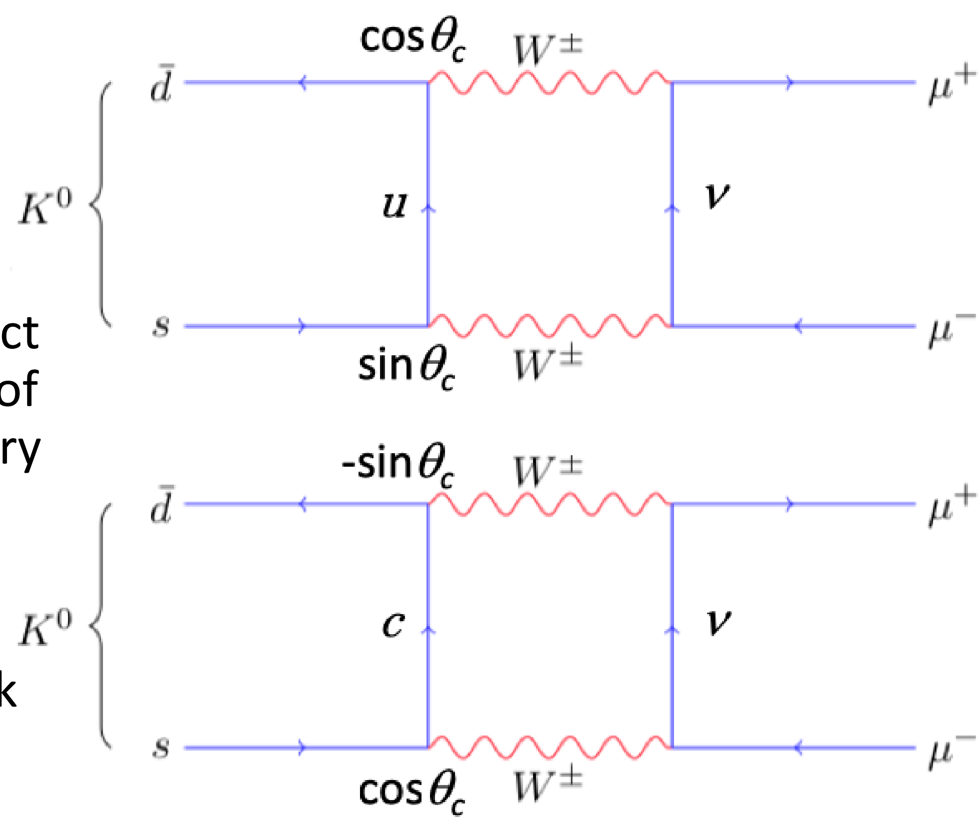
- Decays characterised by very small branching fractions in the Standard Model are excellent laboratories to look for new-physics effects

$$A = A_0 \left[\cancel{c_{SM} \frac{1}{M_W^2}} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- For example, flavour-changing neutral-current (FCNC) processes cannot proceed at tree level in the SM and so need higher order diagrams → strong suppression
  - And further suppressions may arise from additional mechanisms

Textbook example

- Take $K_L \to \mu^+\mu^-$
  - No tree-level diagram
  - Further suppression due to GIM cancellation
    - The cancellation is not perfect due to the different masses of up and charm quarks, yet very effective
    - Side note: at the time, this led to the prediction of the existence of the charm quark
  - $\mathfrak{B}(K_L \to \mu^+\mu^-) \approx 7 \times 10^{-9}$

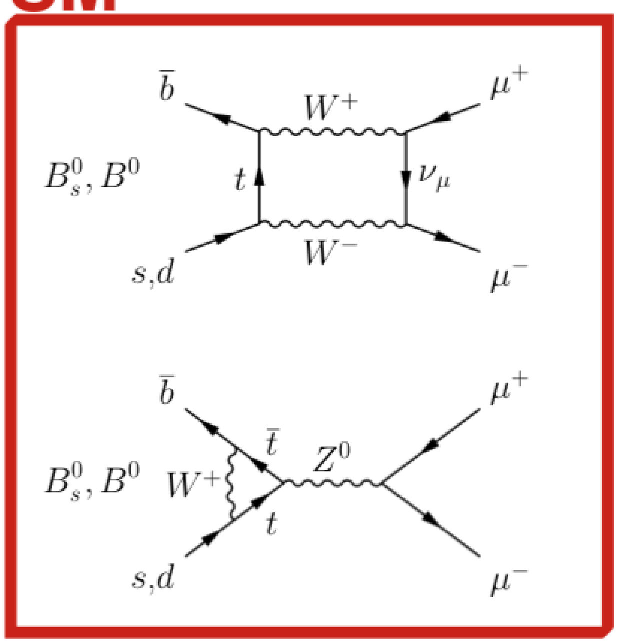


- If we consider $K_S \to \mu^+\mu^-$ this is even further suppressed, due to smallness of CP violation in kaon decays, since the S-wave component of the decay is forbidden when CP is conserved
  - $\mathfrak{B}(K_S \to \mu^+\mu^-) \approx 5 \times 10^{-12}$

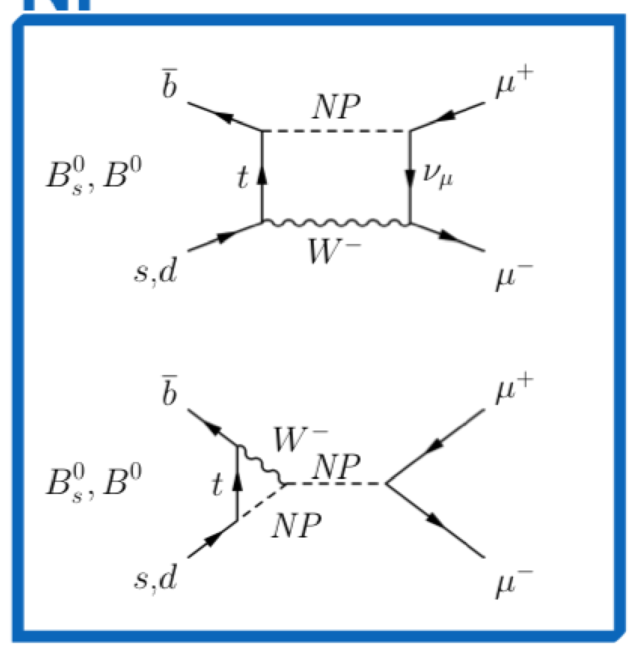
Measurement of $B \rightarrow \mu^+\mu^-$ decays

- Highly suppressed in the SM
  - FCNC- and helicity-suppressed, proceed via *Z* penguin and *W* box
- The helicity suppression of vector(-axial) terms make these decays particularly sensitive to new physics (pseudo-)scalar contributions, such as extra Higgs doublets, which can raise the branching fraction with respect to the Standard Model

SM



NP

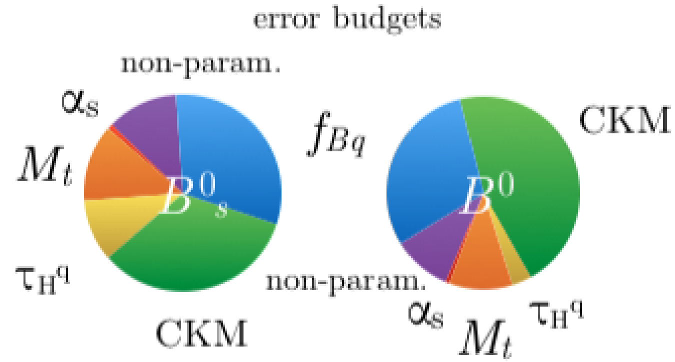


Measurement of $B \rightarrow \mu^+\mu^-$ decays

- Branching fractions for B^0 and B_s decays to two muons are precisely predicted in the SM

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.
[PRL 112 (2014) 101801]



- Some uncertainties cancel in the ratio between the two, which is also a very useful observable

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{1/\Gamma_H^s}\left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{M_{B_d}\sqrt{1-\frac{4m_\mu^2}{M_{B_d}^2}}}{M_{B_s}\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}}} = 0.0295^{+0.0028}_{-0.0025}$$

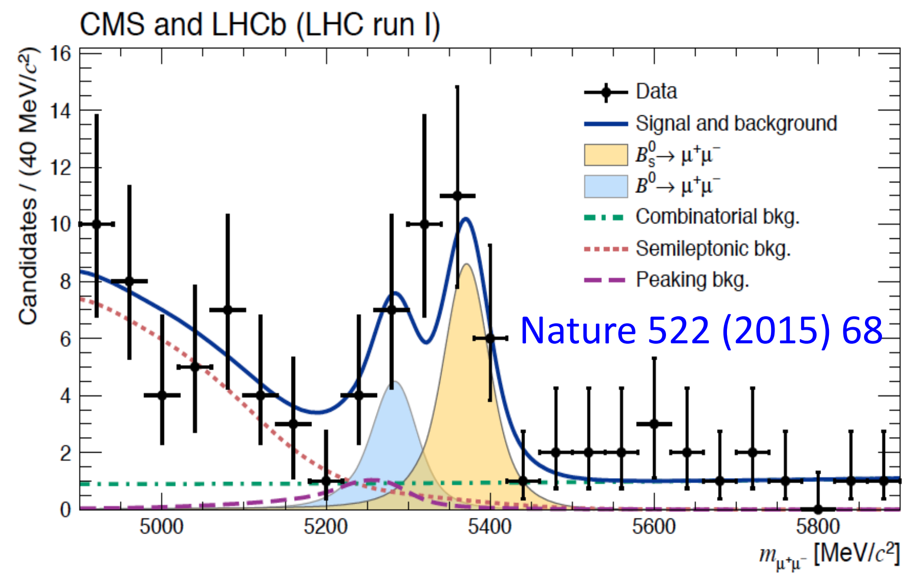
Measurement of $B \to \mu^+\mu^-$ decays

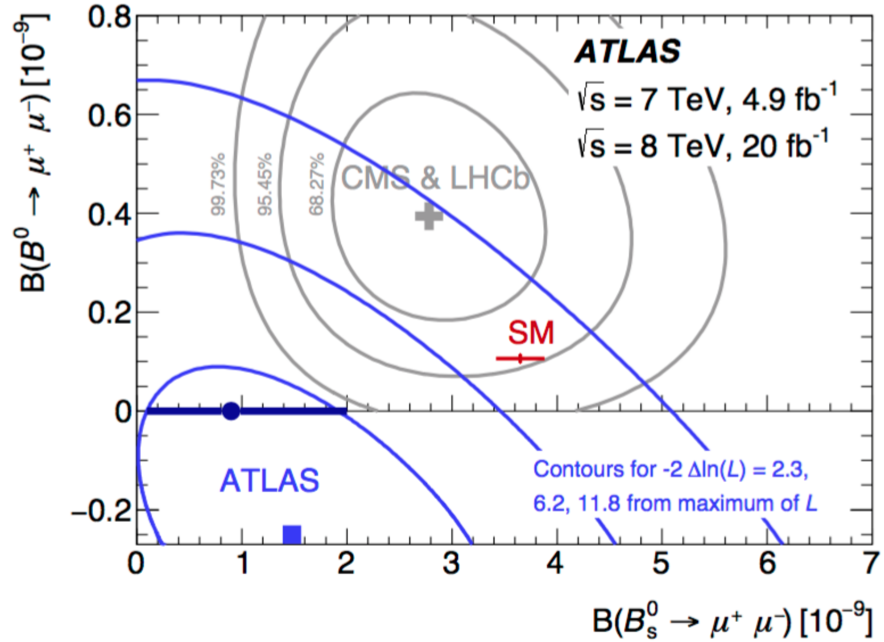
- CMS and LHCb have performed a combined fit to their full Run-1 data sets

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

- $B_s \to \mu\mu$ 6.2σ significance was first observation
  - Compatibility with the SM at 1.2σ
- Excess of events at the 3σ level for $B^0 \to \mu\mu$
  - Compatible with SM at 2.2σ
- A bit later, also ATLAS published a measurement with Run-1 data





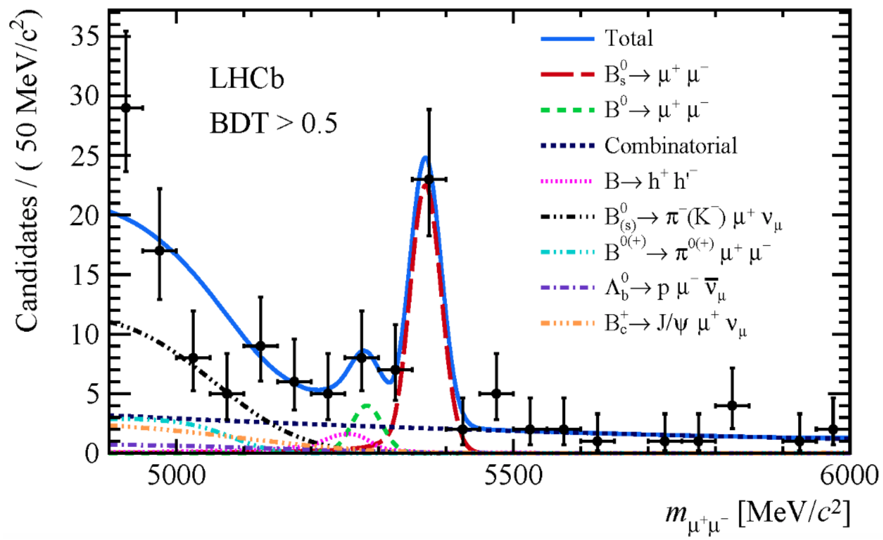
Measurement of $B \rightarrow \mu^+\mu^-$ decays

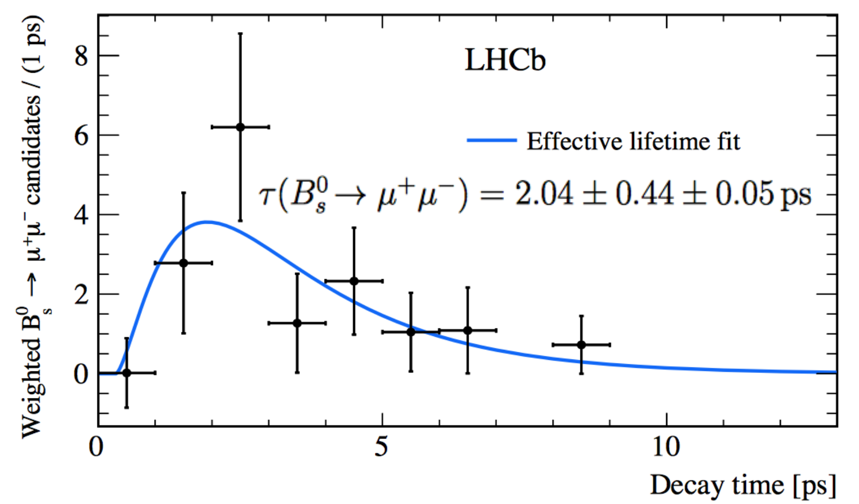
- New measurement from LHCb using Run-2 data has led in 2017 to the first observation of the $B_s \rightarrow \mu\mu$ decay from a single experiment

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

- Moreover, LHCb started to measure other properties, such as the effective lifetime of the decay, that will be useful when increasing the precision for discriminating between new physics models

Phys. Rev. Lett. 118, 191801 (2017)





$B \to \mu^+\mu^-$ first search 30 years ago…

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Two-body decays of B mesons

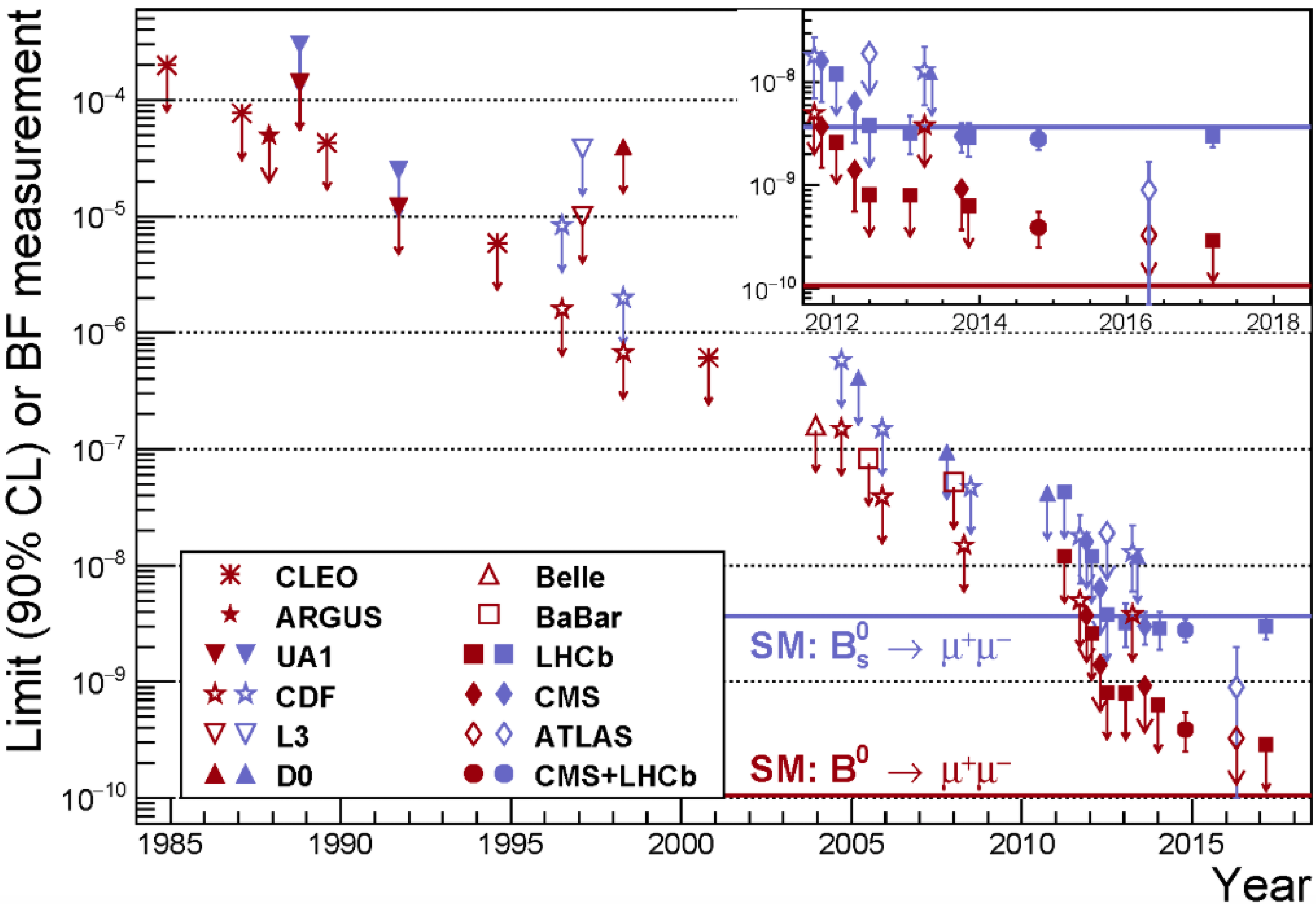
(Received 8 June 1984; revised manuscript received 10 September 1984)

Various exclusive and inclusive decays of B mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a B meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^{\pm}e^{\mp}$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\overline{B}^0 \to \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We improve our limit for $\overline{B}^0 \to e^+e^-$ by requiring that only one of the electrons be positively identified in the dE/dx and shower-chamber systems. One found candidate, coupled with a detection efficiency of 33%, gives a 90%-confidence-level upper limit of 0.03%. Finally, for the decay $\overline{B}^0 \to \mu^{\pm}e^{\mp}$, we require the muon to be identified but the electron needs to be positively identified if it is in the fiducial volume of the electron detectors. This pro-

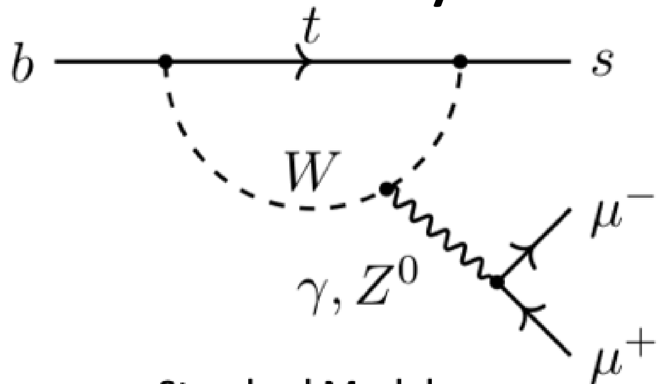
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2 \times 10^{-4} \text{ at } 90\% \text{ C.L.}$$

$B \to \mu^+\mu^-$ historical perspective

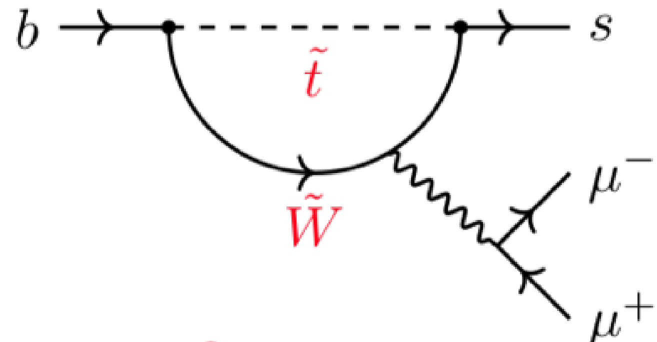


$b \to s\ell^+\ell^-$ transitions

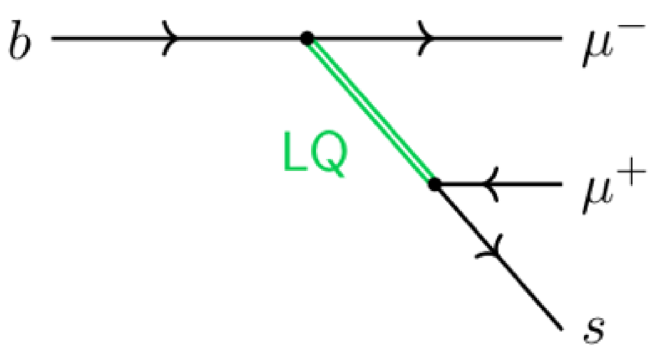
- $B \to \mu^+\mu^-$ decays belong to a more general family of quark-level diagrams which includes other relevant decays like $B \to K\mu^+\mu^-$



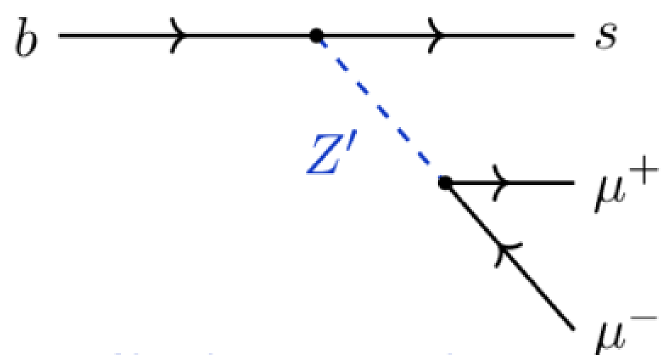
Standard Model



Supersymmetry



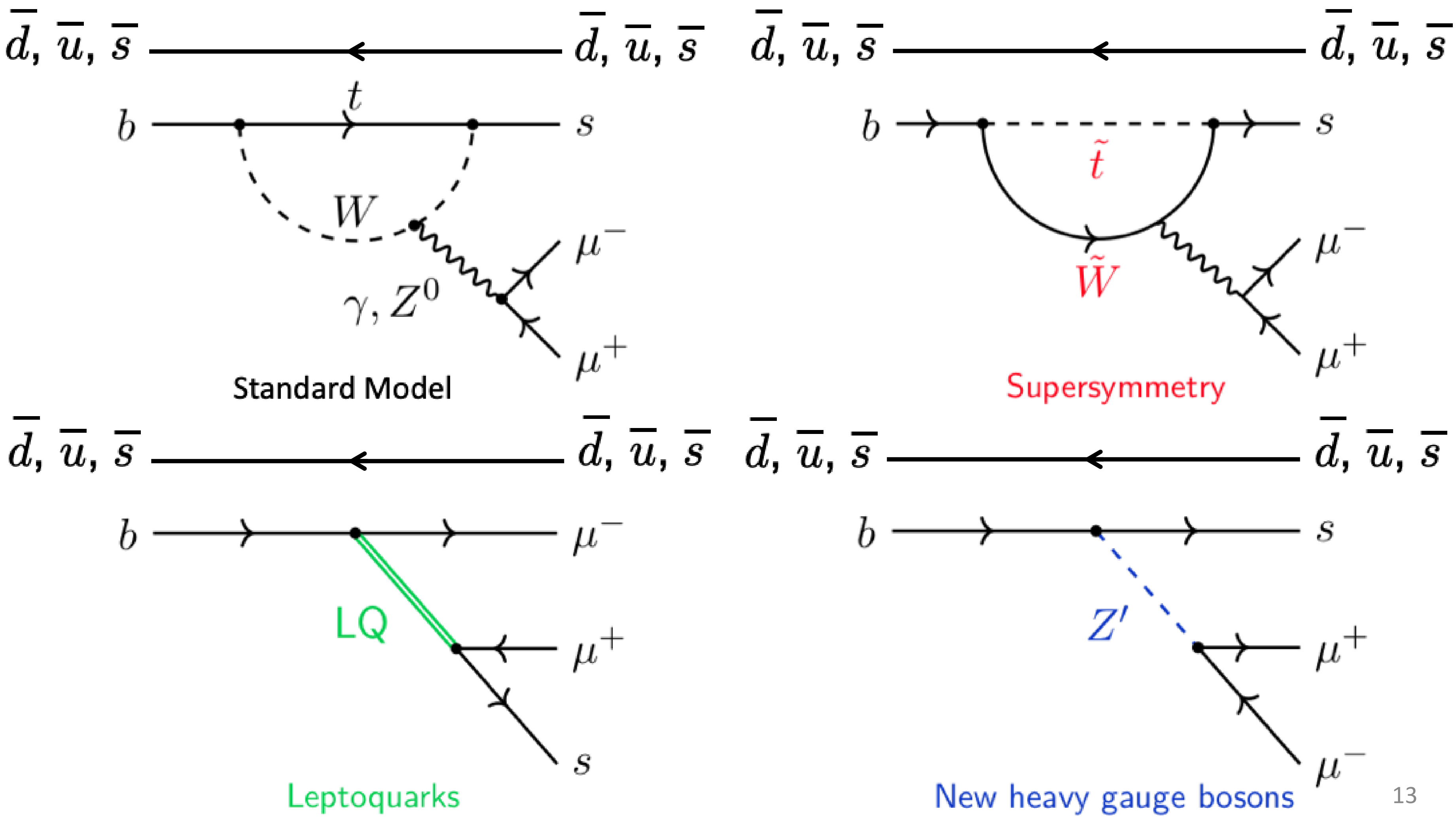
Leptoquarks



New heavy gauge bosons

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

- It's enough to add a spectator quark line to get the B hadron



Measurements that can be done with $b \rightarrow s\ell^+\ell^-$ channels

- Lepton-flavour universality (LFU) tests
  - I.e. checking that electrons and muons exhibit the same couplings, as expected in the Standard Model
- Differential branching fractions as a function of q^2
  - q is the invariant mass of the lepton pair
- Full decay rate including angular variables
  - This has quite a complicated expression, will have a look later

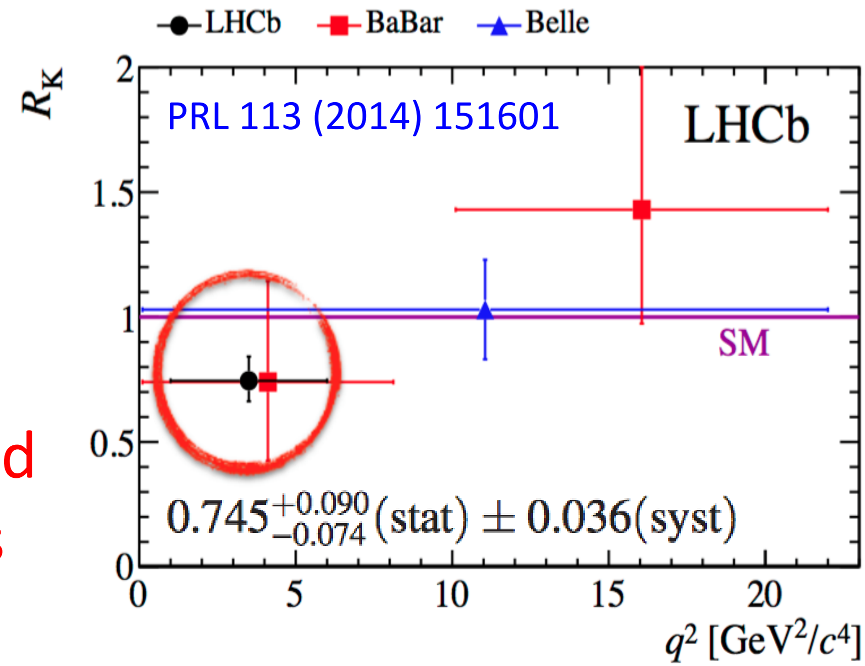
LFU tests in $b \to s\ell^+\ell^-$ transitions

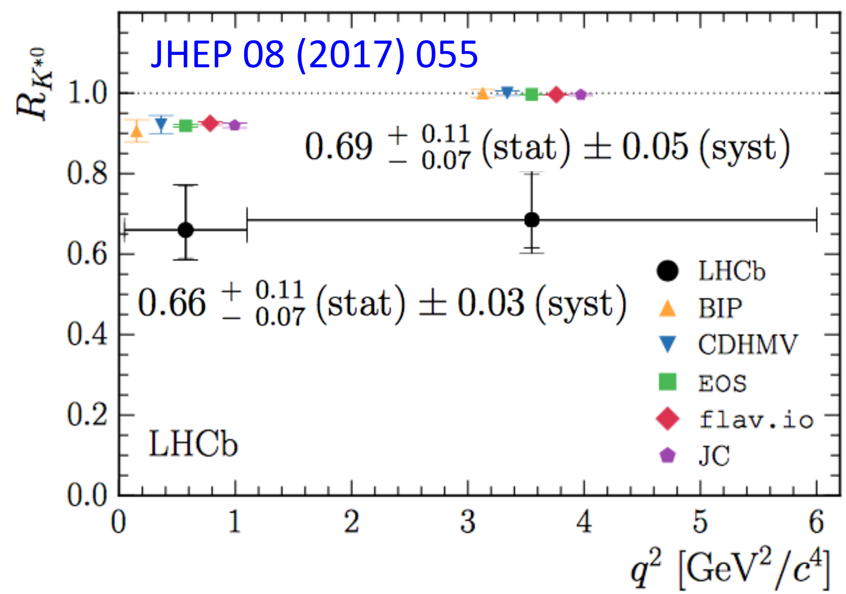
- Measured ratios

$R_K = \mathfrak{B}(B^+ \to K^+\mu^+\mu^-) \,/\, \mathfrak{B}(B^+ \to K^+e^+e^-)$

$R_{K^*} = \mathfrak{B}(B^0 \to K^{*0}\mu^+\mu^-) \,/\, \mathfrak{B}(B^0 \to K^{*0}e^+e^-)$

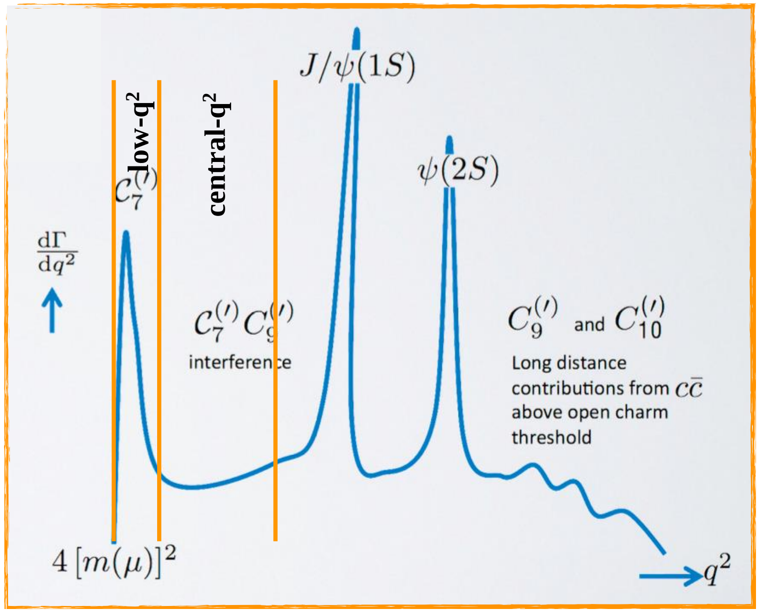
- Theoretically very clean
  - Observation of non-LFU would be a clear sign of new physics
- For the moment at the 3σ-ish level from the SM
- Updates with Run-2 as well as other new measurements with different decay modes coming this year





Let's examine more closely the measurement of R_{K*}

- Test of LFU with $B^0 \rightarrow K^{*0}\mu\mu$ and $B^0 \rightarrow K^{*0}ee$
- Two regions of q^2
  - Low [0.045-1.1] GeV$^2/c^4$
  - Central [1.1-6.0] GeV$^2/c^4$



- Challenging measurement due to significant differences in the way muons and electrons "interact" with the detector
  - Recovery of bremsstrahlung photons
  - Trigger efficiencies

Bremsstrahlung recovery

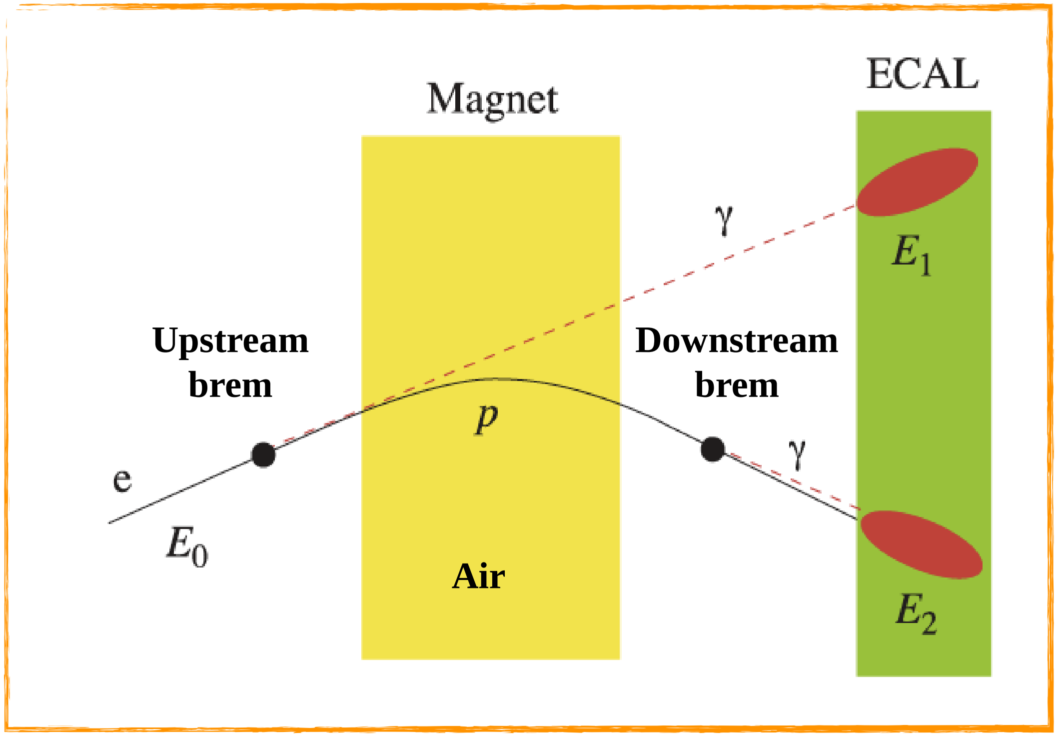
- Electrons emit a large amount of bremsstrahlung radiation while traversing the detector material that results in degraded momentum and mass resolutions
- Two types of bremsstrahlung

Downstream of the magnet

Photon energy in the same calorimeter cell as the electron and momentum correctly measured

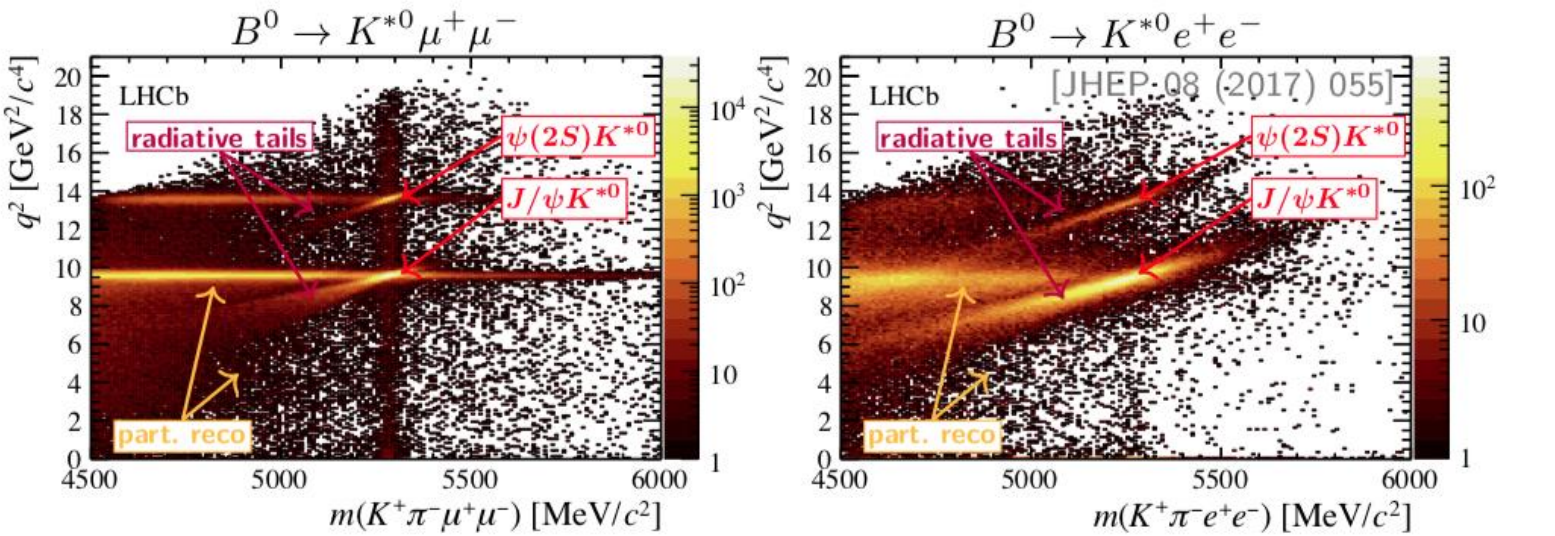
Upstream of the magnet

Photon energy in different calorimeter cells than electron and momentum evaluated after bremsstrahlung



Bremsstrahlung recovery

- A recovery of the energy deposits on the calorimeter is used to improve the momentum reconstruction
- Imperfect recovery due to
  - Energy threshold of the bremsstrahlung photon (E_T > 75 MeV)
  - Calorimeter acceptance
  - Presence of energy deposits mistaken as bremsstrahlung photons



- Incomplete recovery causes the reconstructed *B* mass to shift towards lower values and events to migrate in and out of the q^2 bins

Measure as a double ratio

- R_{K*} determined as a double ratio using the resonant mode to reduce systematic effects to the minimum possible

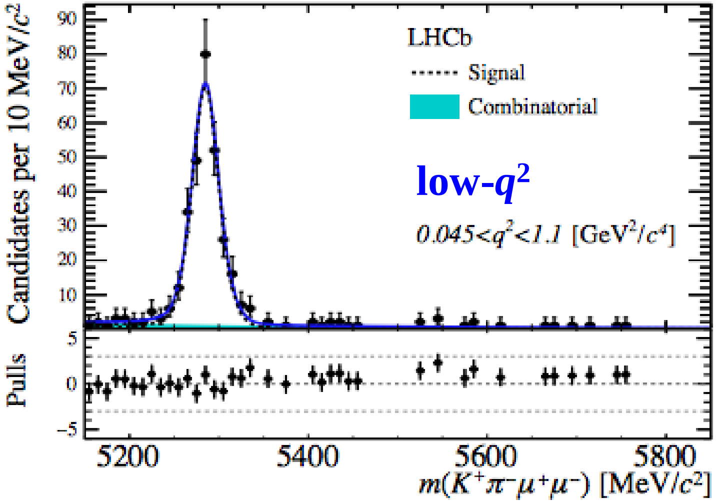
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

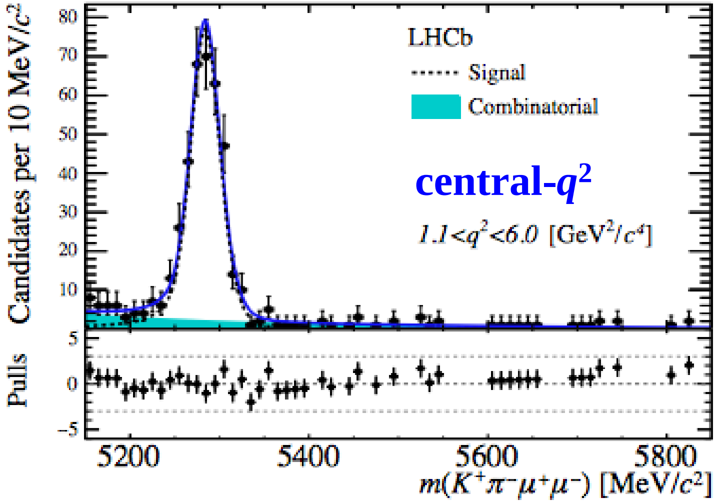
- Event selection as similar as possible between μμ and *ee*
- Efficiencies determined using simulation, but tuned using data

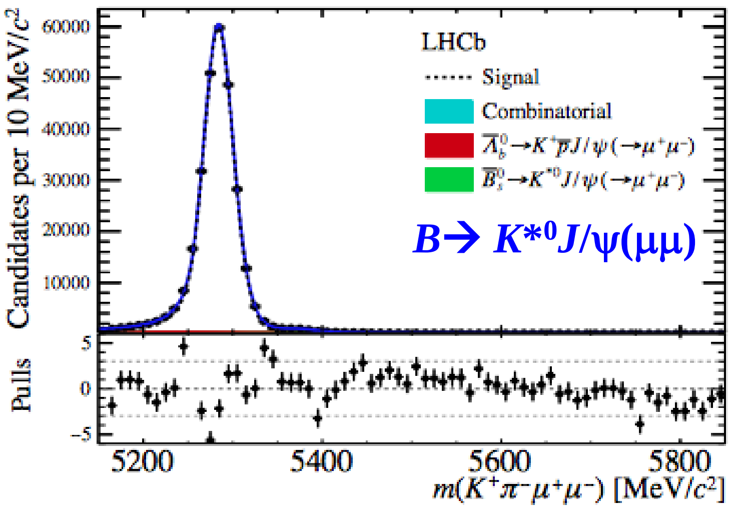
Tuning of simulation

- Particle identification
  - Particle identification response of each particle species tuned using dedicated calibration samples
- Generator
  - Event multiplicity and B^0 kinematics matched to data using $B^0 \rightarrow K^{*0} J/\psi(\mu\mu)$ decays
- Trigger
  - Hardware and software trigger responses tuned using $B^0 \rightarrow K^{*0} J/\psi(\mu\mu)$ and $B^0 \rightarrow K^{*0} J/\psi(ee)$ decays
- Data/MC differences
  - Residual discrepancies in variables entering the multivariate classifier reduced using $B^0 \rightarrow K^{*0} J/\psi(\mu\mu)$ and $B^0 \rightarrow K^{*0} J/\psi(ee)$ decays
- After tuning, very good data vs Monte Carlo agreement in all key variables

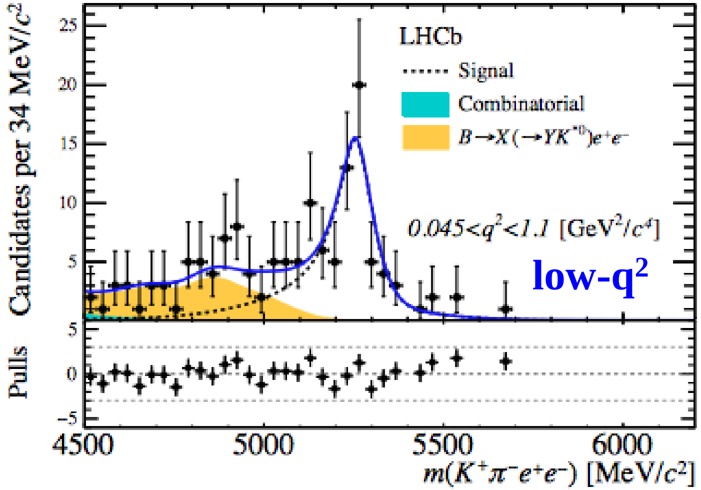
Fit results for muonic channel

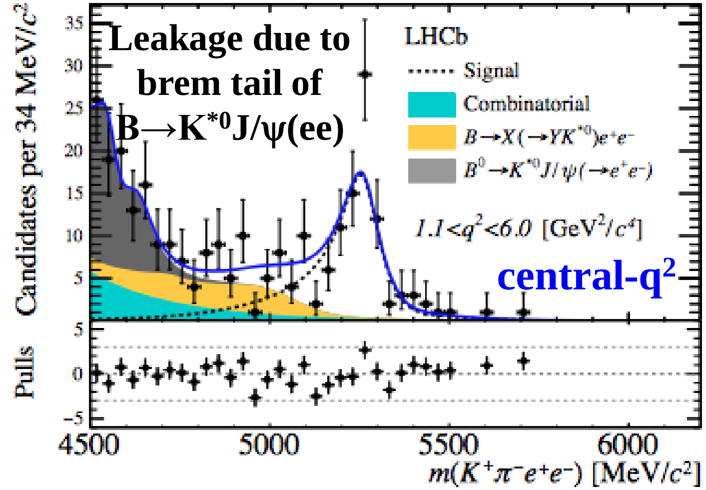


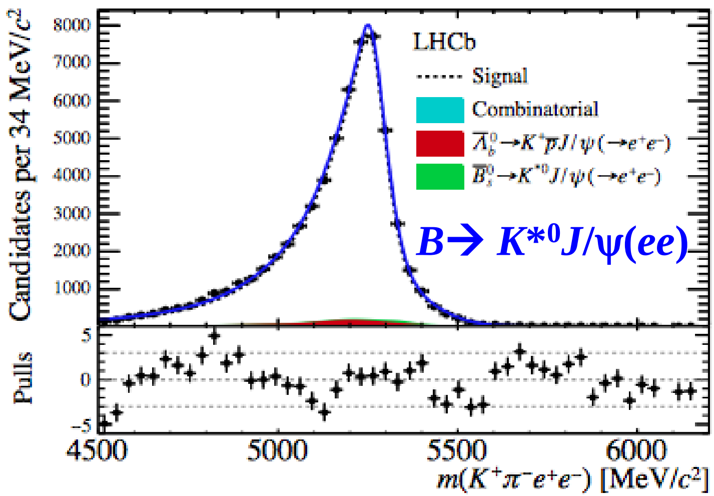




Fit results for electron channel







- Precision of the measurement driven by the electron statistics: in total, about 90 and 110 $B^0\to K^{*0}ee$ candidates at low- and central-q^2 bins, respectively

Important cross check: $r_{J/\psi}$

- Control of the absolute scale of the efficiencies via the ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

which is expected to be unity and is measured to be

$$1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

- Result observed to be independent of the decay kinematics and event multiplicity
- Very stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio

Other cross checks

- $\mathfrak{B}(B^0 \to K^{*0}\mu\mu)$ is determined and found to be in good agreement with previous LHCb publications
  - JHEP 11 (2016) 047, JHEP 04 (2017) 142
- If corrections to simulations are not accounted for, the ratio of the efficiencies changes by less than 5%
- Further checks performed by measuring the following ratios

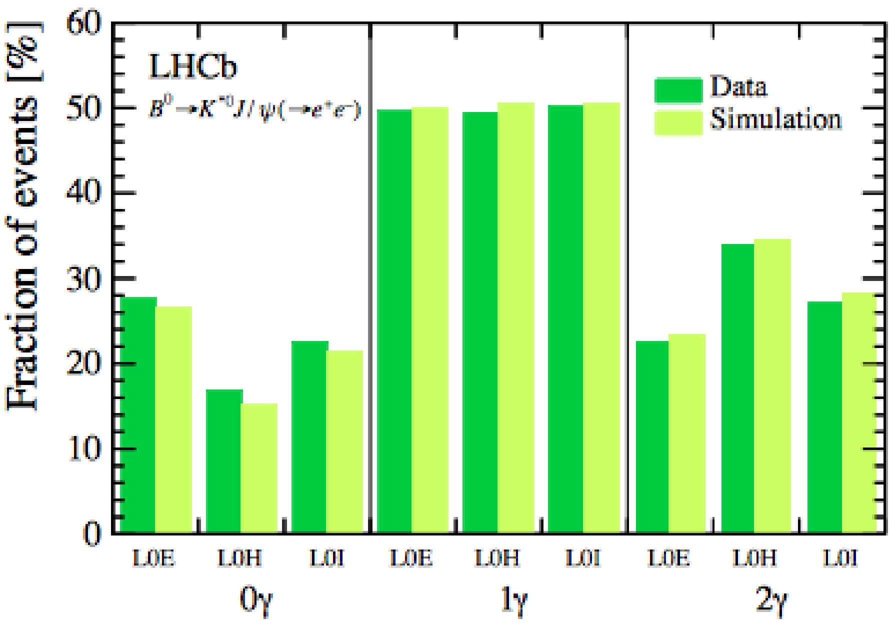
$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

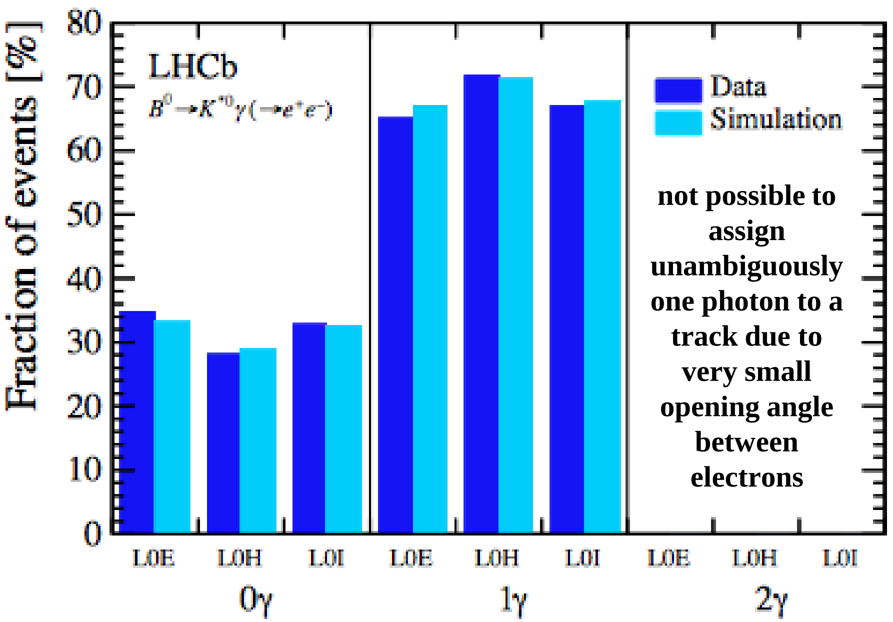
$$r_\gamma = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- These are found to be compatible with the expectations

Cross check on bremsstrahlung recovery

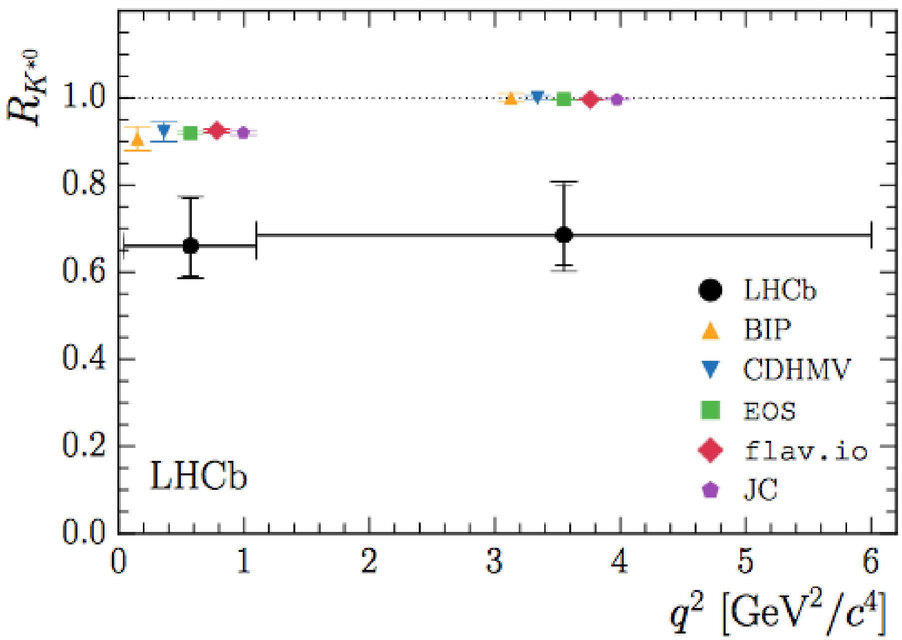
- Relative population of bremsstrahlung categories compared between data and simulation using $B^0 \to K^{*0} J/\psi(ee)$ and $B^0 \to K^{*0}\gamma(ee)$ events

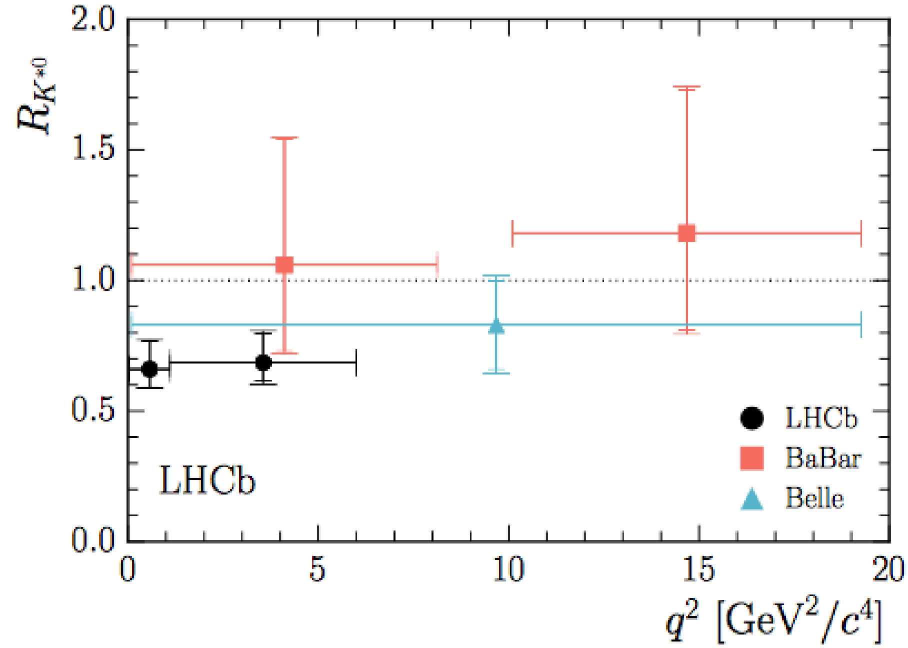




- Very good agreement is observed

Results for R_{K^*}





Central q^2: [1.1-6 GeV^2]: SM = 1.000(6)

$$R_{K^{*0}} = 0.69\,^{+\,0.11}_{-\,0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$$

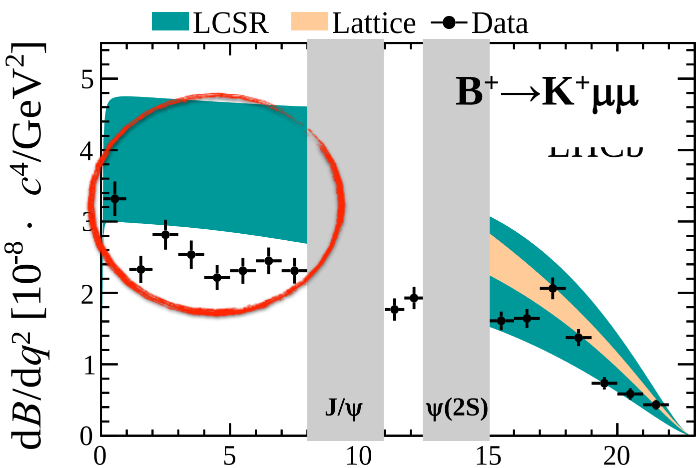
Low q^2 [0.045-1.1 GeV^2]: SM = 0.922(22)

$$R_{K^{*0}} = 0.66\,^{+\,0.11}_{-\,0.07}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

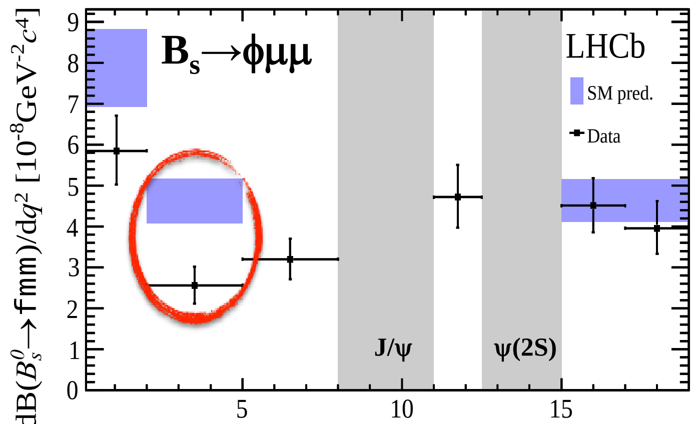
- Both bins between 2 and 2.5σ too low with respect to SM

Other anomalies in the $b \rightarrow s\ell^+\ell^-$ sector

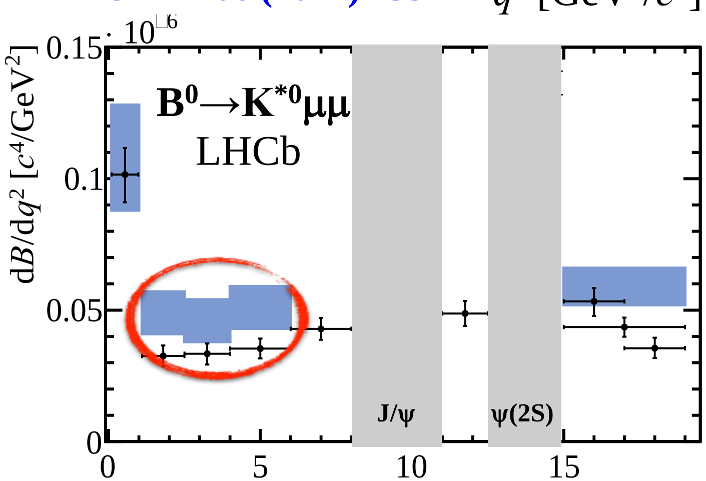
- Differential branching fractions consistently lower than SM expectations, although uncertainties in the predictions are matter of theoretical debates



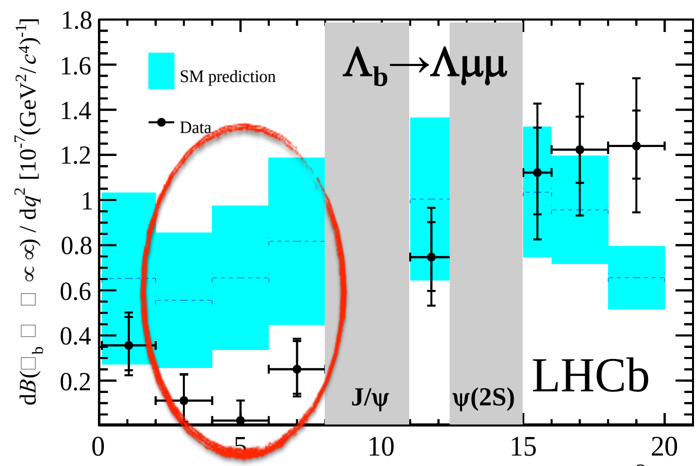
JHEP 06 (2014) 133



JHEP 09 (2015) 179



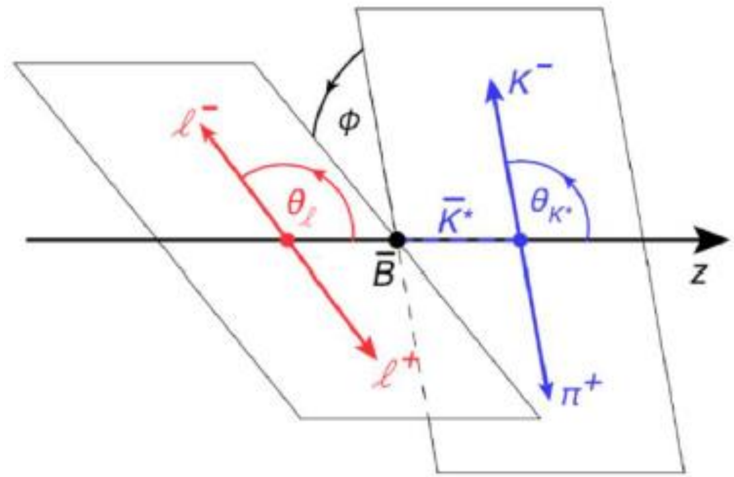
JHEP 11 (2016) 047, JHEP 04 (2017) 142



JHEP 06 (2015) 115

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

- Measure the decay rate as a function of helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and q^2



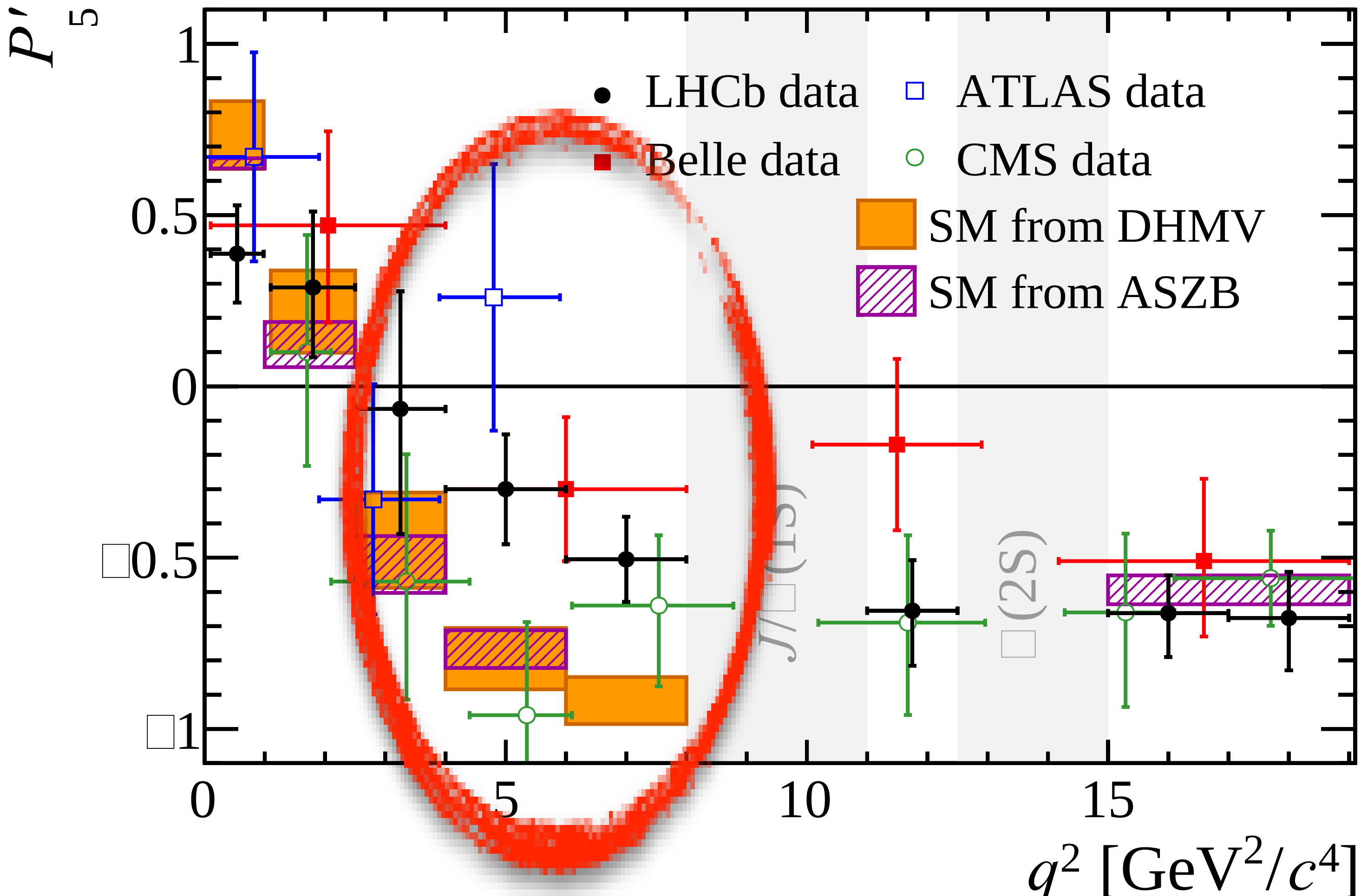
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- $F_\mathrm{L}, A_\mathrm{FB}, S_i$ are combinations of K^{*0} spin amplitudes
- One can even use ratios of observables where form factors cancel to first order, thus reducing the theoretical uncertainty of the Standard Model prediction, like

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Descotes-Genon *et al.* JHEP 05 (2013) 137

Another anomaly from $b \to s\ell^+\ell^-$ angular analysis



- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

Effective field theory and $b \to s\ell^+\ell^-$

- Effective field theory can be used to combine the all relevant observables in $b \to s\ell^+\ell^-$ decays
- This is an approximation valid below the scale of new physics
  - Analogous to Fermi theory of the beta decay, valid at low energy if compared to the mass of the W
- Amplitude of decay process calculated as an operator product expansion

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}}\sum_i V^i_{CKM} C_i(\mu)\langle F|O_i(\mu)|M\rangle$$

Hadronic Matrix Elements

Effective Hamiltonian

CKM couplings

Wilson coefficients (μ = scale)

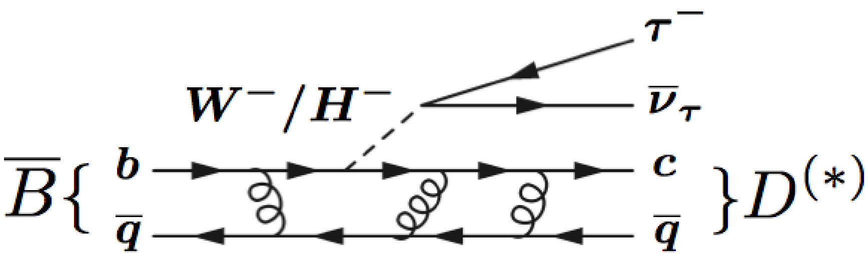
- Global fits of Wilson coefficients performed by several theory groups, taking into account more than 100 observables from various experiments, nicely get a consistent overall picture pointing to new physics at the 4-5σ level

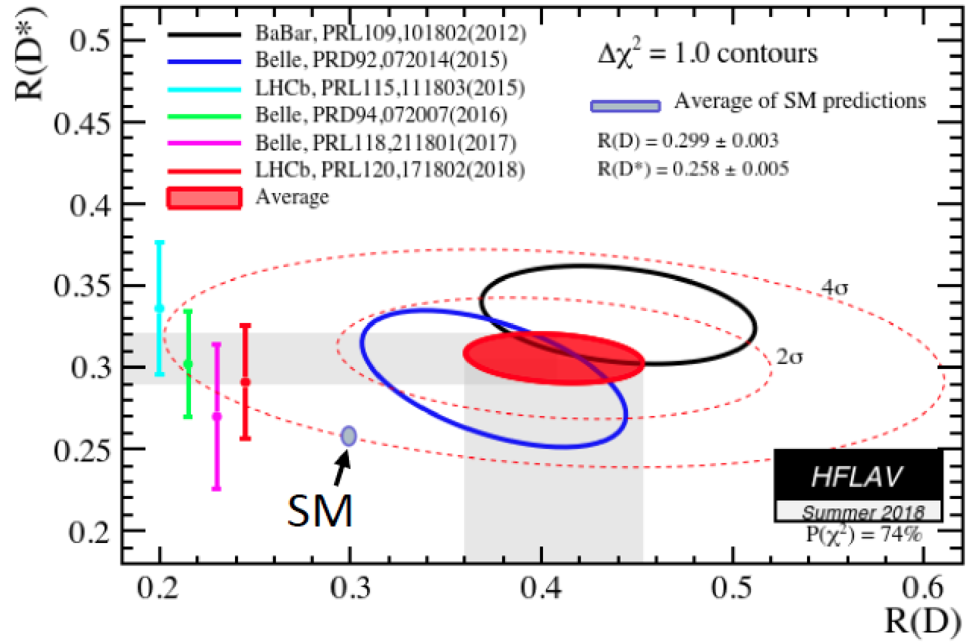
JHEP 06 (2016) 092, EPJC 77 (2017) 377, JHEP 1801 (2018) 093

LFU tests with semitauonic decays

$B \to D^{(*)}\tau\nu$

- Ratio $R_D^{(*)} = \mathfrak{B}(B\to D^{(*)}\tau\nu)$ / $\mathfrak{B}(B\to D^{(*)}\mu\nu)$ is sensitive e.g. to charged Higgs scenarios

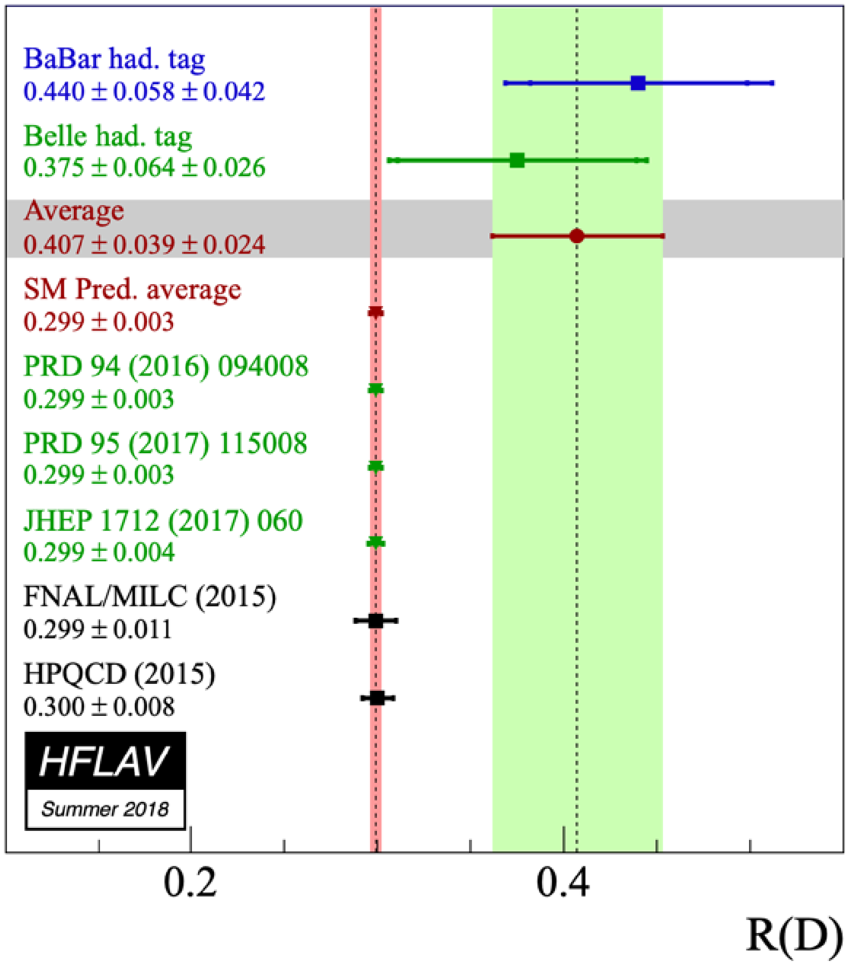


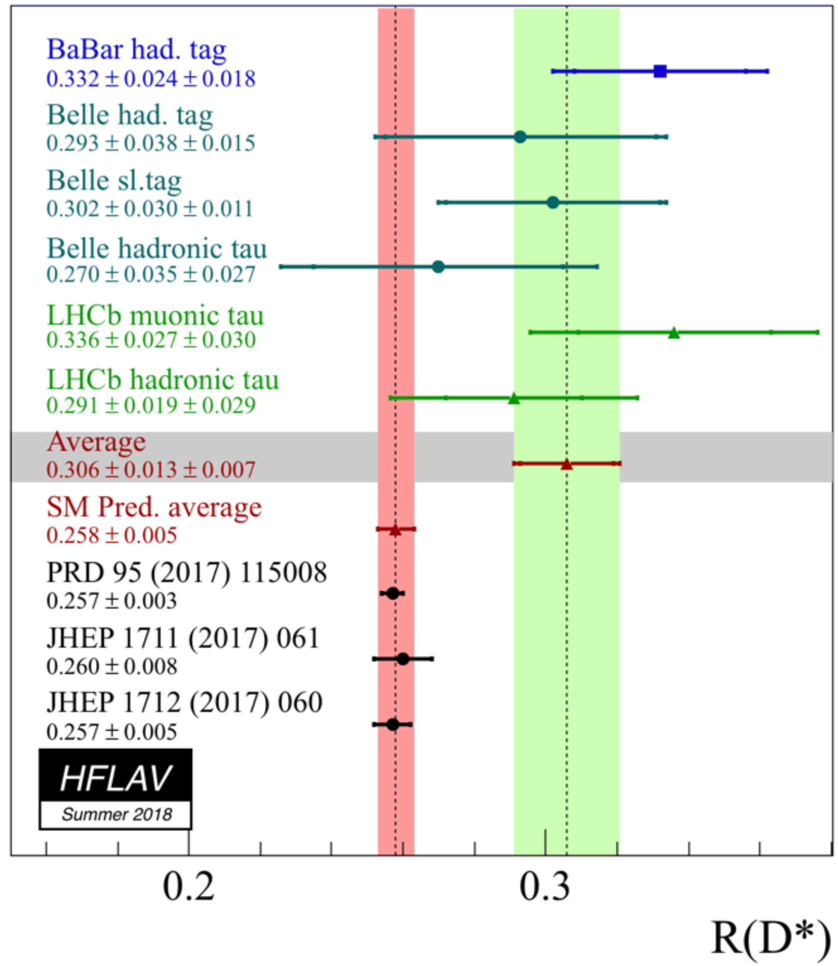


- Measurements of R_D and R_{D*} by BaBar, Belle and LHCb
  - Overall average shows a discrepancy from the SM between 3.5 and 4σ
- LHCb can also perform measurements with other *b* hadrons
  - e.g. B_s, B_c and Λ_b decays will help to better understand the global picture

LFU tests with semitauonic decays

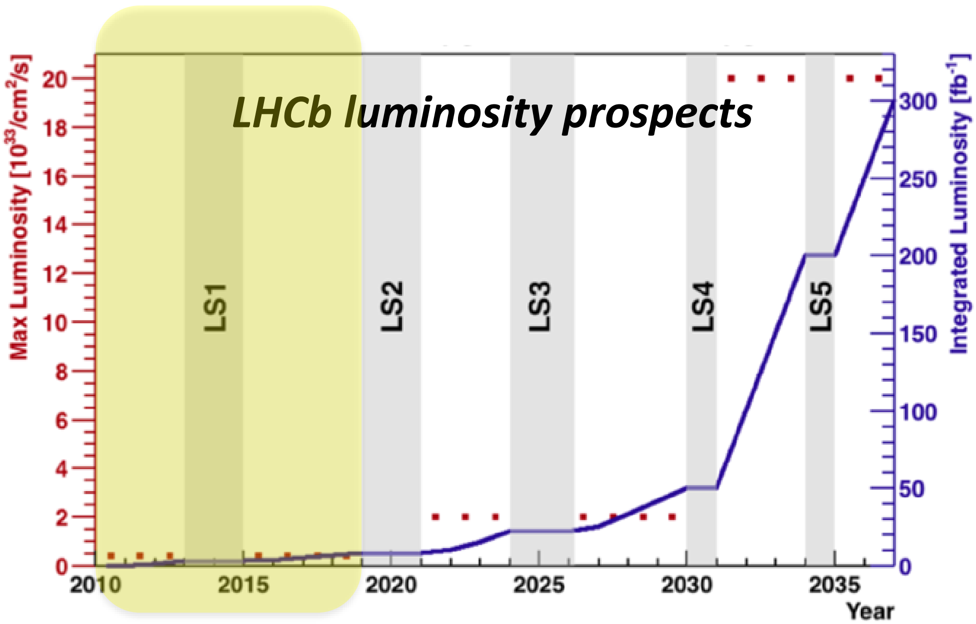
$B \rightarrow D^{(*)}\tau\nu$





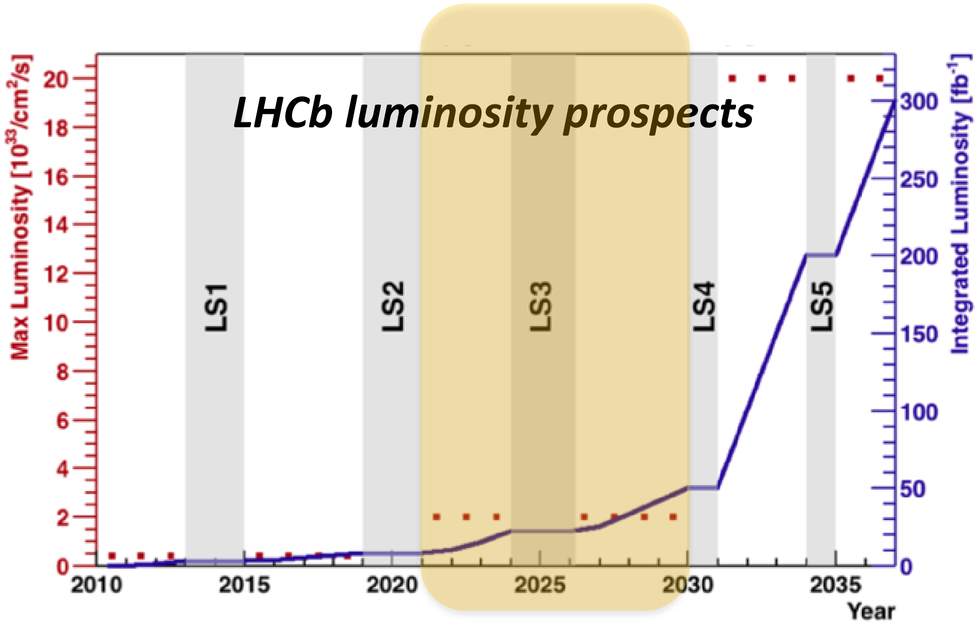
Future prospects

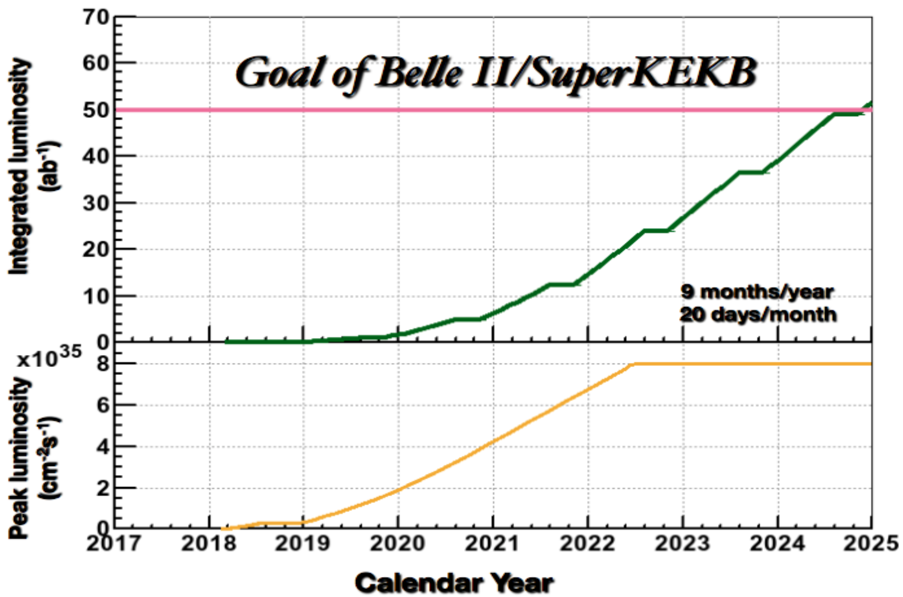
Where do we go



- LHCb has completed its first lifecycle in the years 2010–2018 collecting about 9 fb^{-1} of data
  - 1 fb^{-1} at 7 TeV
  - 2 fb^{-1} at 8 TeV
  - 6 fb^{-1} at 13 TeV

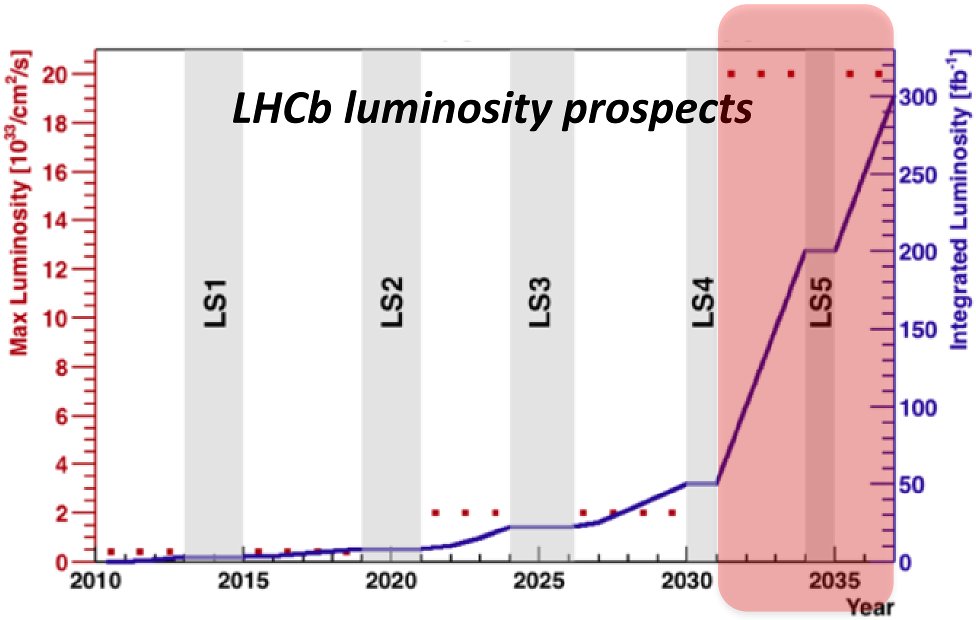
Where do we go

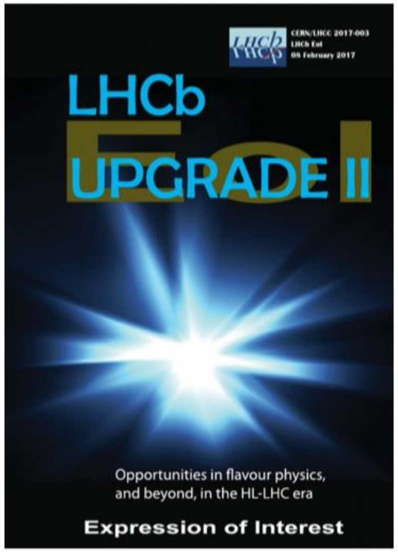




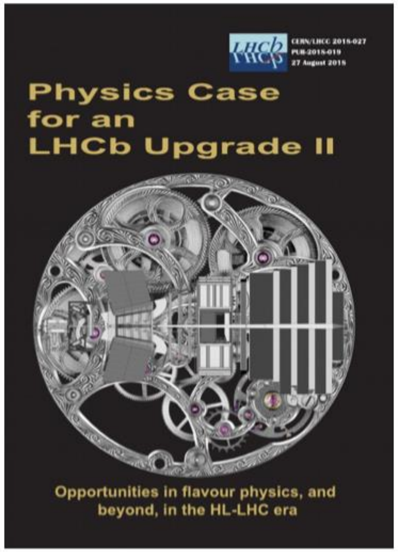
- Belle-2 has just started taking data and will run until 2025 to collect 50 ab^{-1} of luminosity at $\Upsilon(4S)$
- LHCb will resume operation in 2021 with an instantaneous luminosity increased by a factor 5 and run up to 2030 collecting a total of 50 fb^{-1}

Where do we go





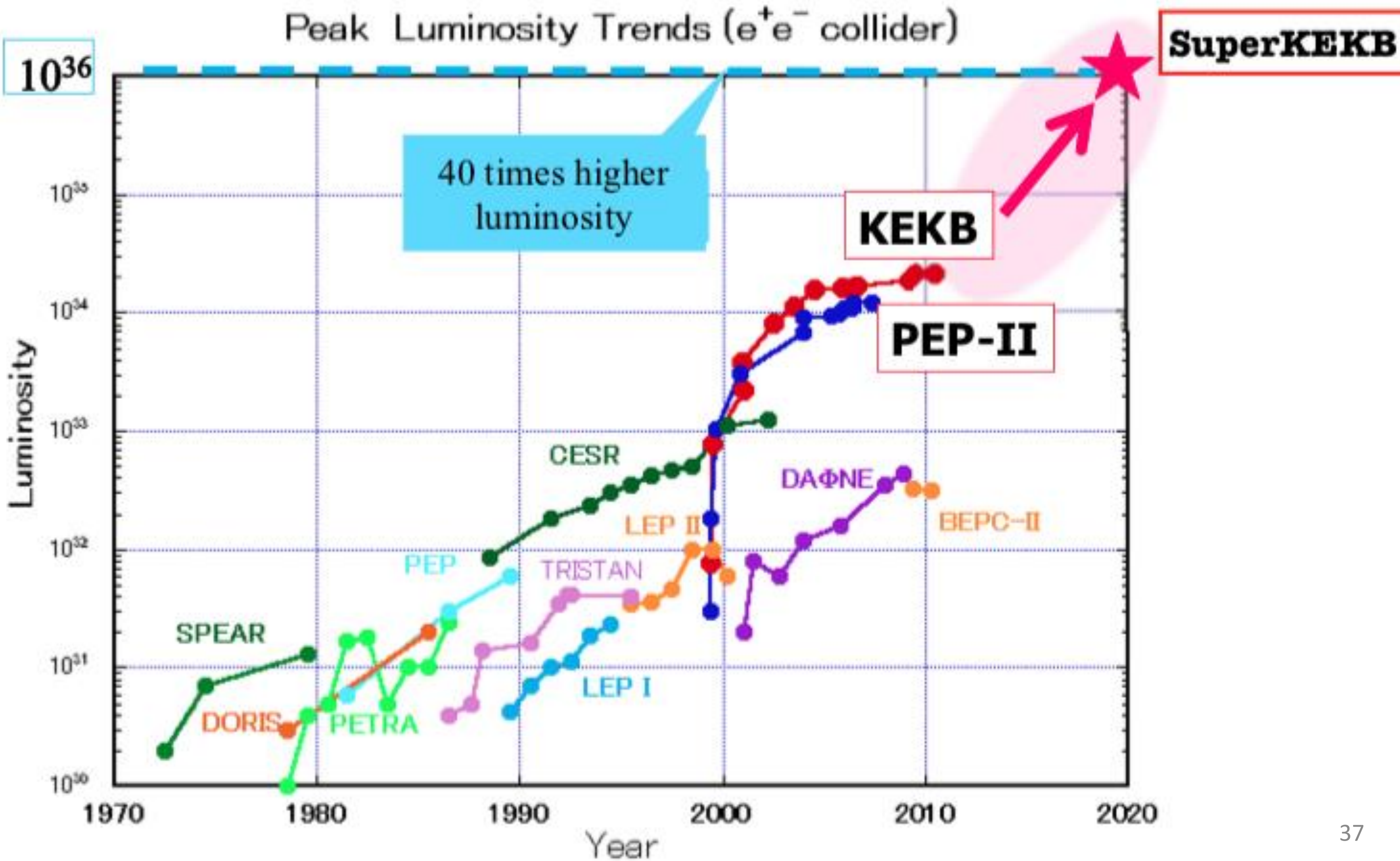
CERN-LHCC-2017-003



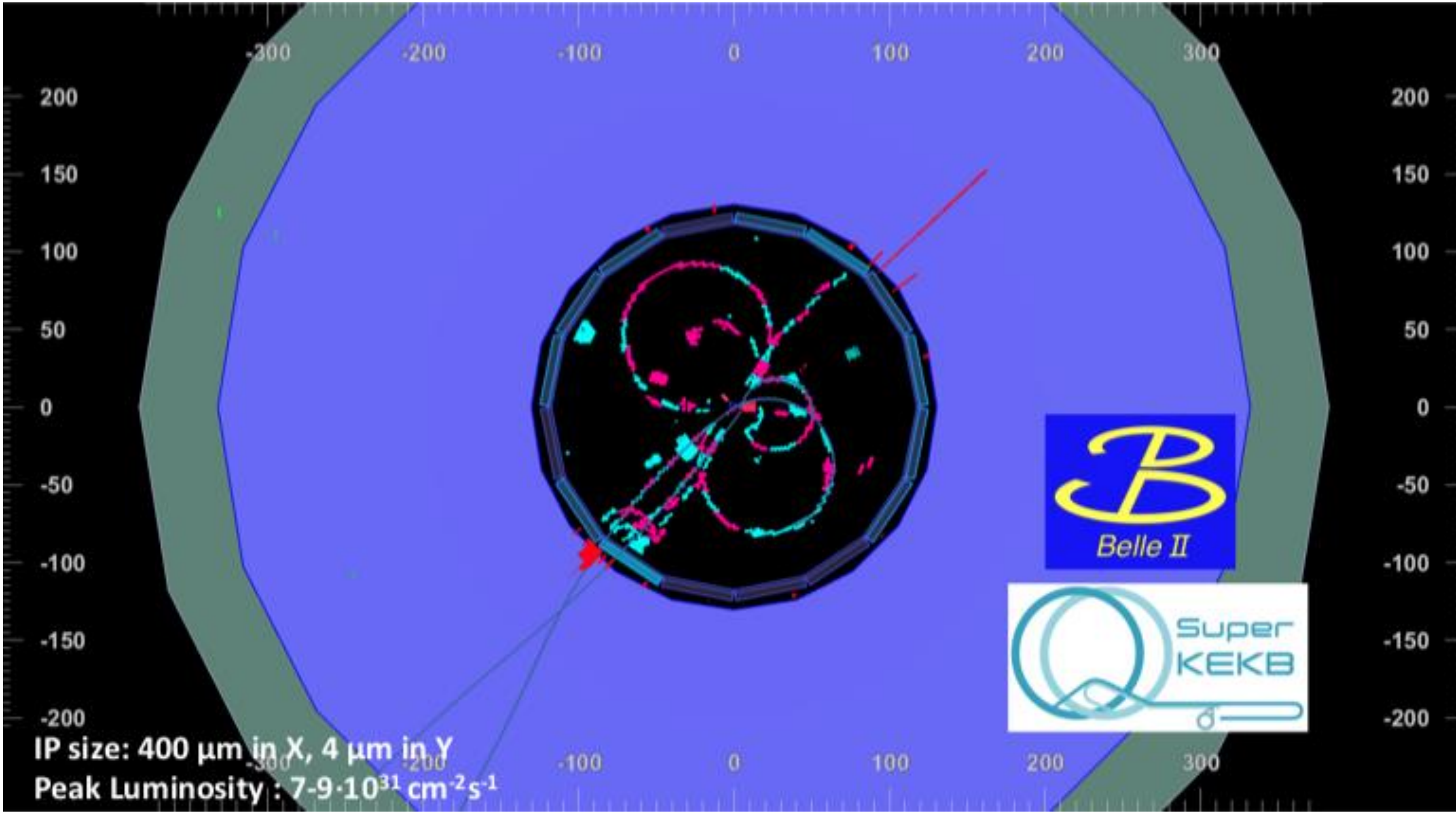
CERN-LHCC-2018-027
arXiv:1808.08865

- LHCb has now proposed a new upgrade for the early 2030's to reach an instantaneous luminosity of 2×10^{34} cm^{-2}s^{-1}, which is a factor 50 larger than what we have had so far, in order to collect at least 300 fb^{-1} by the end of the programme

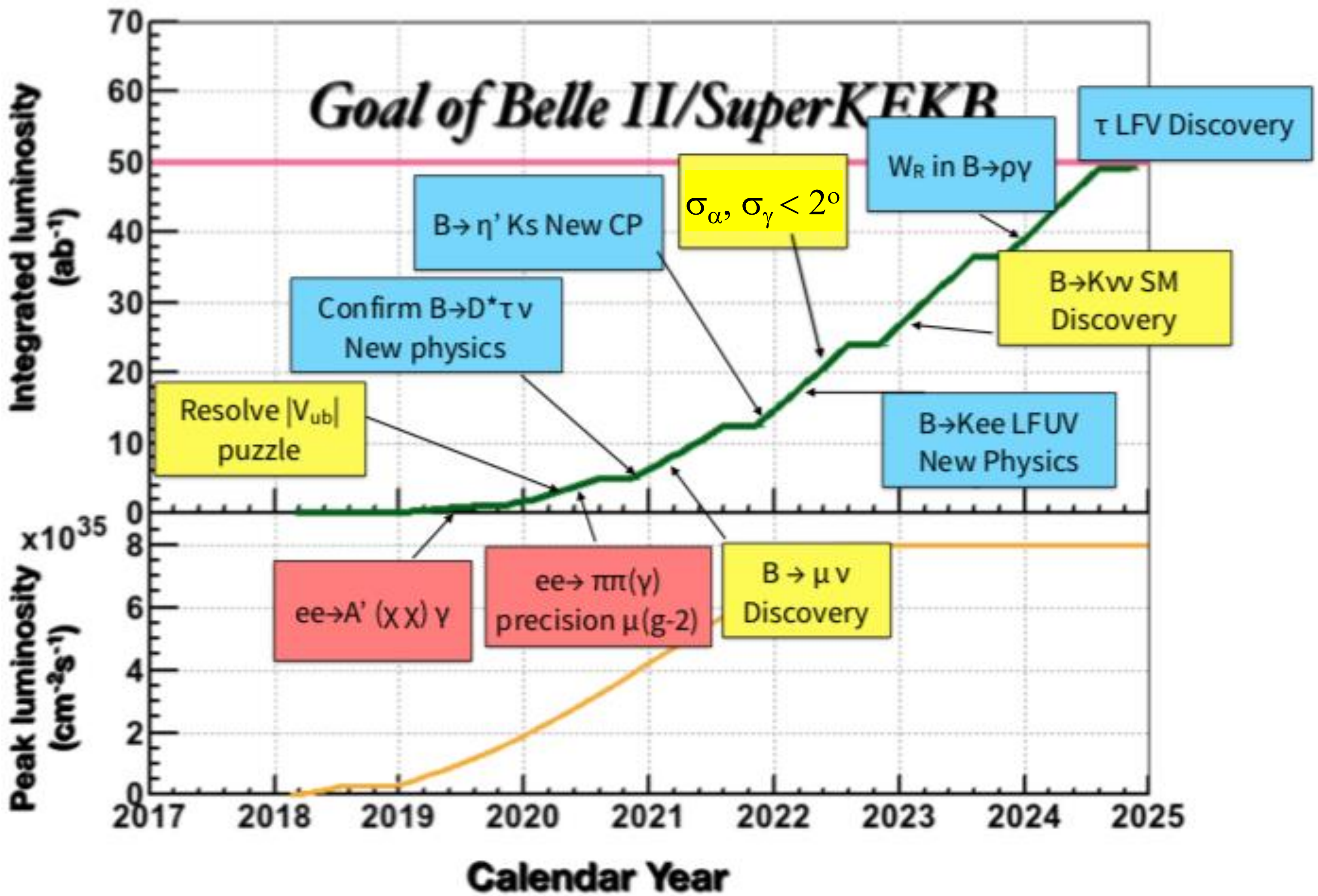
SuperKEKB machine goals



First collisions at Belle-2 on April 2018



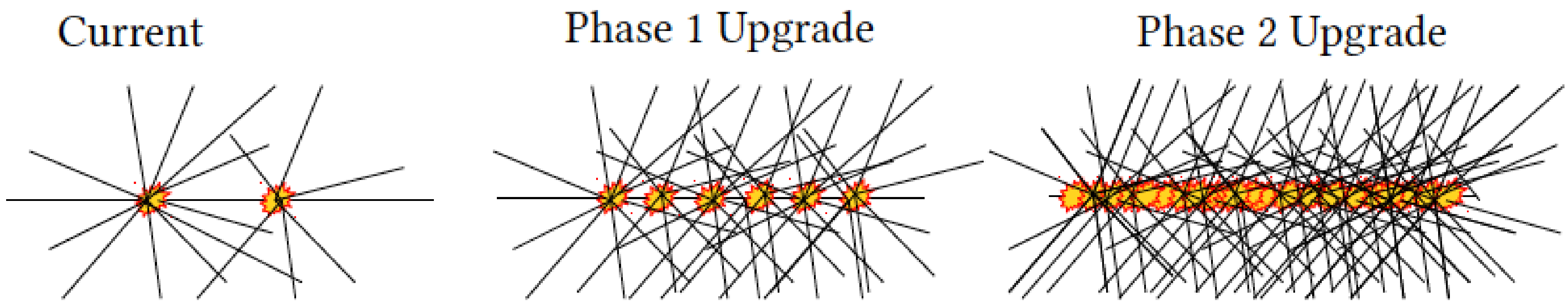
Physics goals of Belle-2



Physics goals of LHCb Upgrade-II

- The LHCb Upgrade-II will be capable of improving on a broad spectrum of important flavour-physics measurements
  - Measurement of γ with a precision of 0.4°
  - Measurement of ϕ_s with a precision of 3 mrad
  - A comprehensive programme of measurements of $b \to s\ell\ell$ and $b \to d\ell\ell$ transitions, employing both muon and electron modes
  - Measurement of the ratio $\mathcal{B}(B^0 \to \mu\mu)$ / $\mathcal{B}(B_s \to \mu\mu)$ with an uncertainty of about 10%, and precise measurements of relevant $B_s \to \mu\mu$ observables such as effective lifetime and *CP* violation
  - A wide-ranging set of lepton-universality tests in $b \to c\ell\nu$ decays, exploiting the full range of *b* hadrons
  - *CP*-violation measurements in charm with 10^{-5} precision

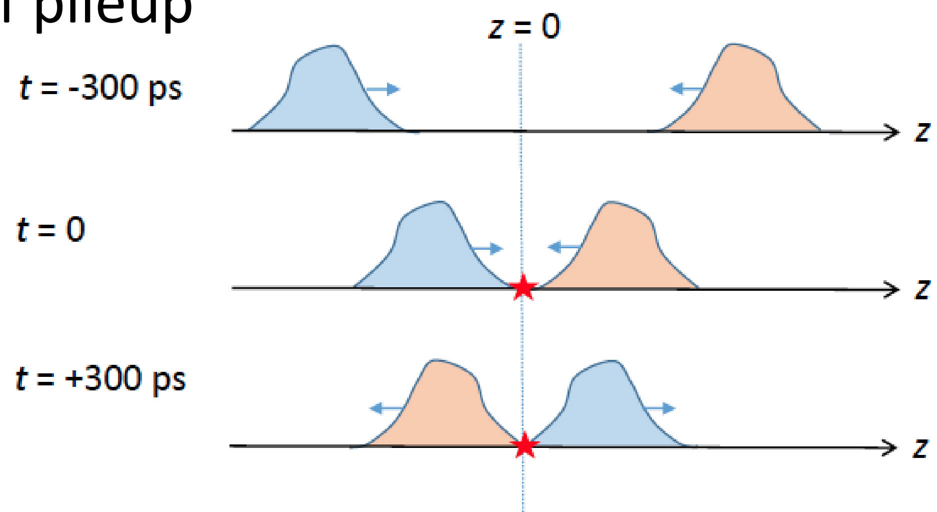
LHCb Upgrade-II: challenges



- The project is very challenging
  - otherwise we would have done it already...
- The mean number of interactions per event will be around 50
  - The increased particle multiplicity and rates will present significant problems for all detectors, notably including increased radiation damage
- An essential attribute will be precise timing in the VELO detector, and also downstream of the magnet for both charged tracks and neutrals
  - A time resolution of a few tens of ps for charged tracks and photons would dramatically simplify pattern recognition and improve association of particles to the correct interaction vertex where they were produced

Why timing information

- In high pileup conditions, detector occupancy, vertex reconstruction and assignment of a production vertex to a given reconstructed particle become limiting factors
- Time is an additional dimension for tracking particles that would allow the effective reduction of pileup
  - Particles produced at same position can have very different production times

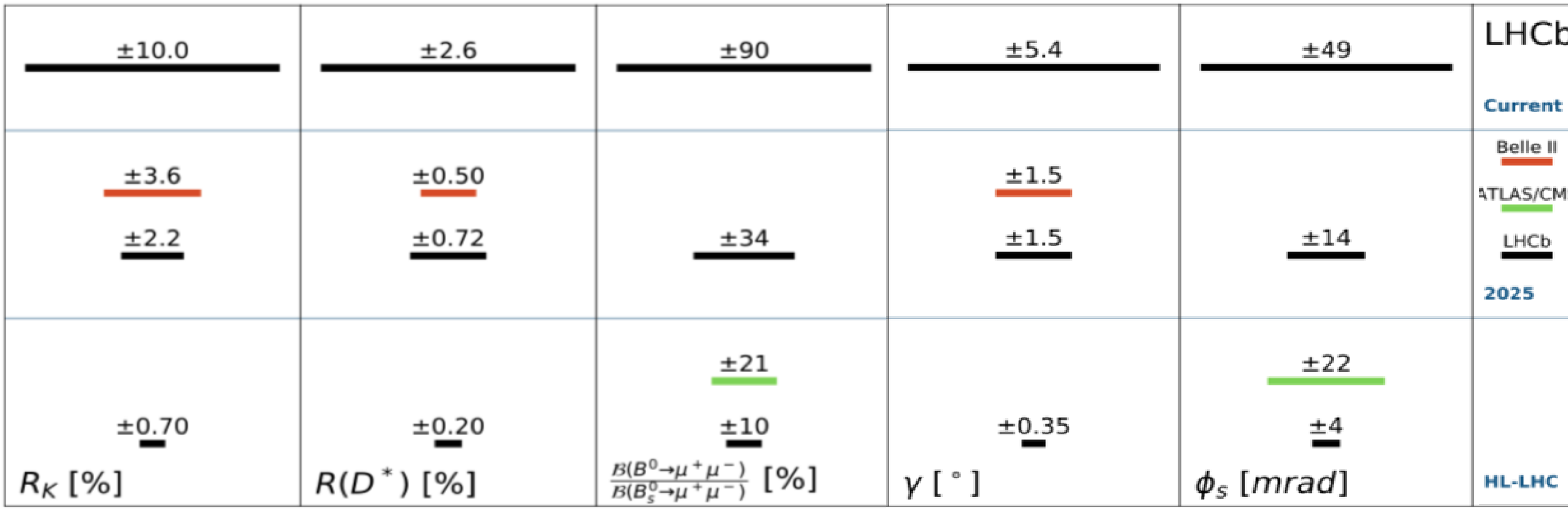


- Consider two beam bunches crossing at the interaction point as in the cartoon
- Here interactions are at same *z* but separated by 300 ps in time
- If we would have precise enough time information for charged particles and neutrals, the complexity of high-pileup events would be significantly reduced

How good the timing should be?

- The luminous region at the LHCb interaction point is approximately Gaussian-shaped in *z* with a width of 5 cm
- Thus about 70% of the interaction vertices are located in a window of 10 cm → 300 ps at light speed
- A timing resolution of a few tens of picoseconds would allow the separation of piled-up events into several time domains, thus effectively mitigating the pileup problem and possibly reducing the event complexity to the current situation
- Dedicated R&D efforts starting now

Prospects for a few key observables

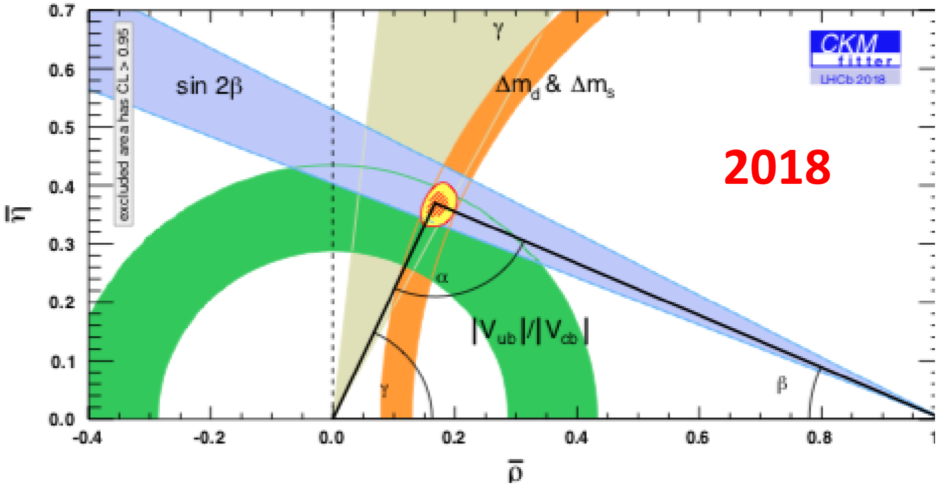


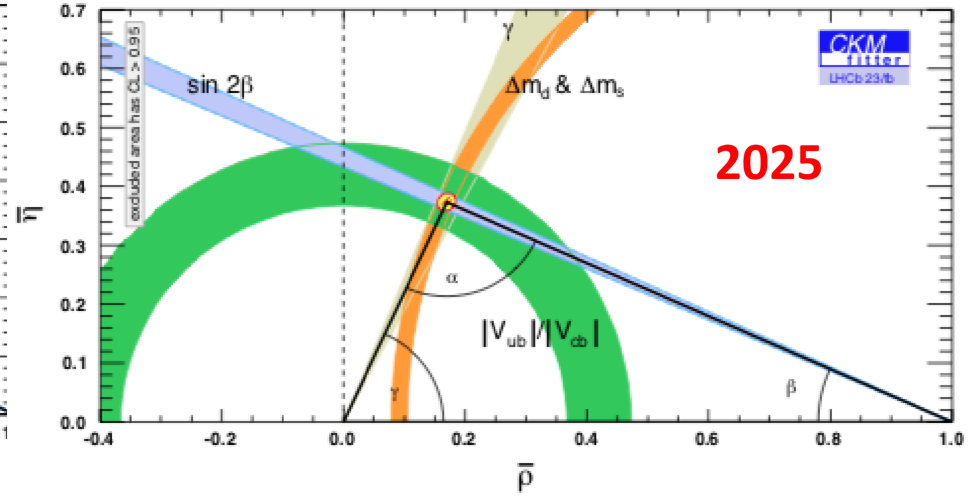
- The table compares, whenever information is available in public documents, the current precision to that expected at Belle-2 (ending in 2025), LHCb Upgrade-I (in 2025) and ATLAS/CMS/LHCb Upgrade-II at the end of the LHC high luminosity phase (beyond 2035)
- This is obviously not an exhaustive set, but includes measurements that we have discussed in these lectures

A more comprehensive table

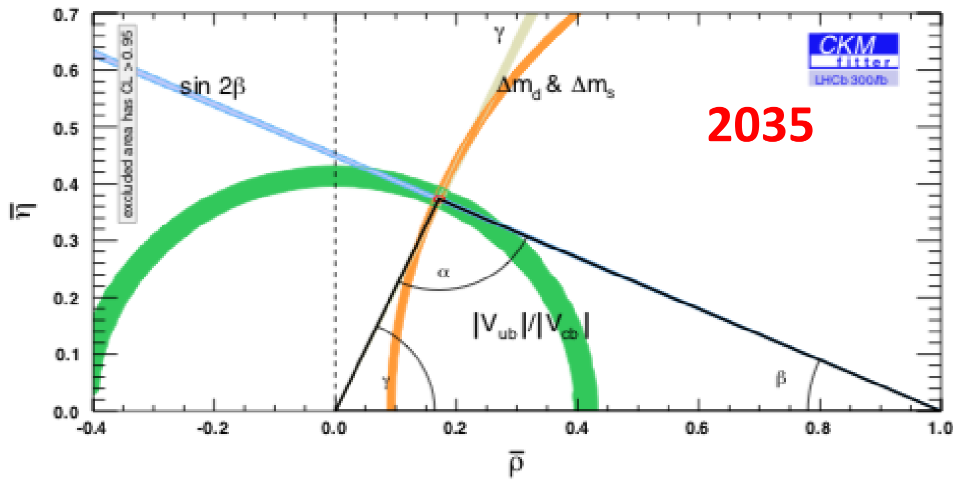
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad	22 mrad
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad	Under study
a_{sl}^s	33×10^{-4}	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%	21%
$\tau_{B_s^0\to\mu^+\mu^-}$	22%	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Expected evolution of the knowledge on the unitarity triangle (LHCb only)





- Also assuming reasonable improvements of non-perturbative quantities from Lattice QCD
- Will be this sufficient to crack the triangle?



Recap of the lectures

- What we have discussed
  - Introduction to flavour physics and the CKM matrix
  - Historical perspective on flavour physics
  - LHCb as an example of dedicated flavour-physics detector
  - Overview of selected *B*-physics results
    - CKM metrology, rare decays and present *B*-physics anomalies
  - Future prospects
- What we have overlooked due to lack of time
  - Many interesting things: kaon physics, charm physics, lepton flavour violation searches, heavy-flavour spectroscopy, heavy flavour in heavy-ion collisions, …

Concluding remarks

- In the current state with fundamental physics, it is necessary to have a programme as diversified as possible
- If *B*-physics anomalies will consolidate with further data, independent confirmation from multiple experiments will be of paramount importance
  - E.g. Belle-2 if new physics comes from $b \to s\ell^+\ell^-$ and (non) LFU, as well as performing other measurements not accessible at LHCb like $B \to \tau\nu$, $B \to \mu\nu$, …
- Furthermore, new physics should affect different modes coherently
  - Maintaining the broadest possible physics programme in the long term will be crucial → upgrade of LHCb to further raise the luminosity in the LHC Run 5

Concluding remarks

- In the unfortunate event that no direct evidence of new physics pops out of the LHC, flavour physics can play a key role in indicating the way for future developments of elementary particle physics
- If instead new particles will be detected in direct searches, flavour physics will be a fundamental ingredient to understand the structure of what lies beyond the Standard Model
- And don't forget: this has been, is and will remain a combined effort between theory and experiments!

Good luck!