LHCb RESULTS AND PERSPECTIVES

Opportunities at Future High Energy Colliders

IFT Madrid, June 2019

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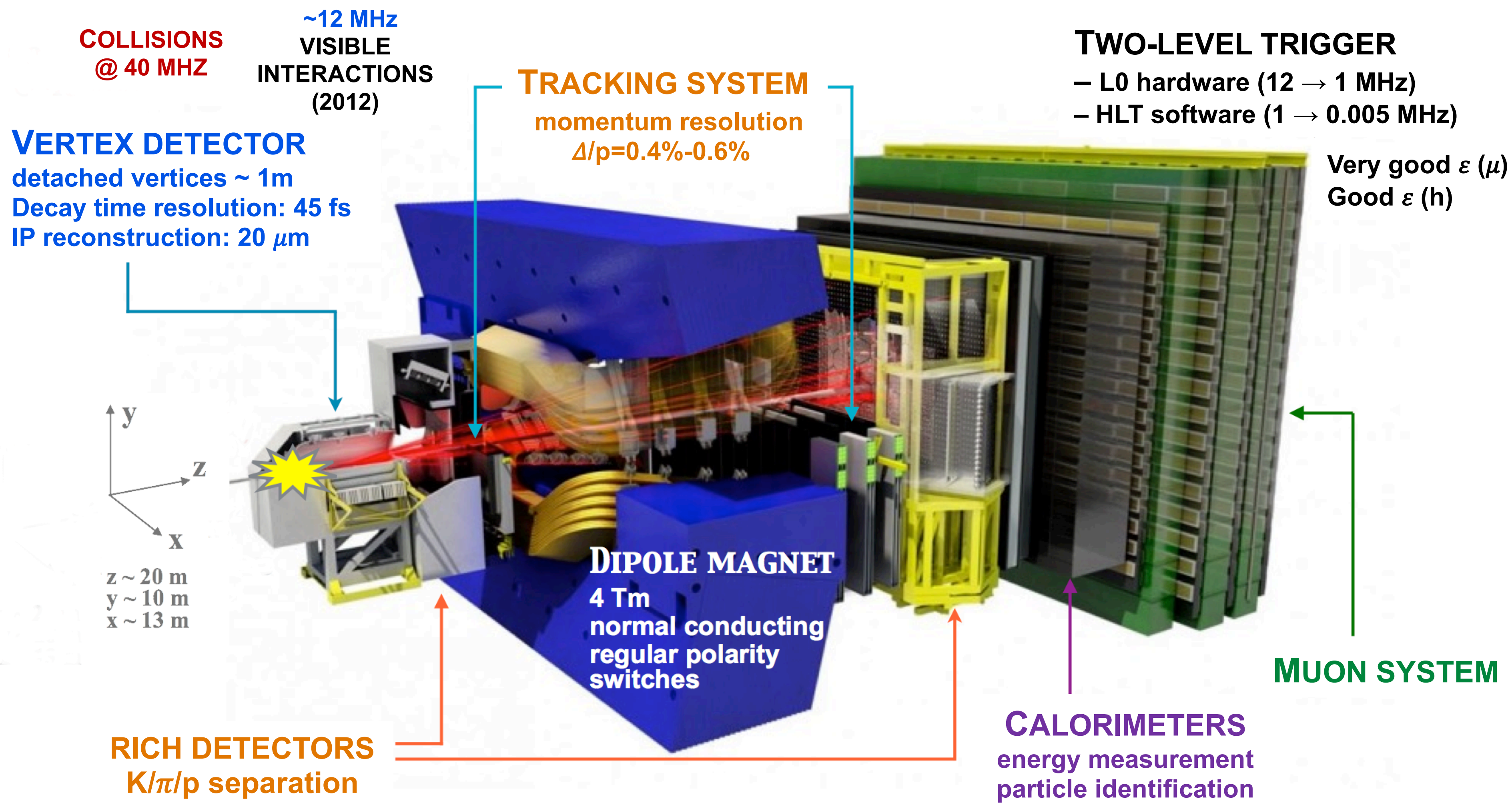
LHCb RESULTS AND PERSPECTIVES: TALK OUTLINE

1. LHCb apparatus and Upgrade
2. CP-violation in b-sector
3. CP-violation in c-sector
4. Lepton universality (LU) anomalies in charged currents
5. LU and other anomalies in flavor-changing neutral currents
6. Opportunities in K-physics and other new physics searches

LHCb and UPGRADE

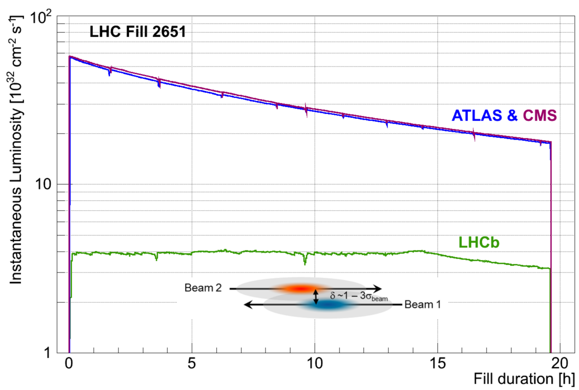
THE 2010-2018 LHCb APPARATUS



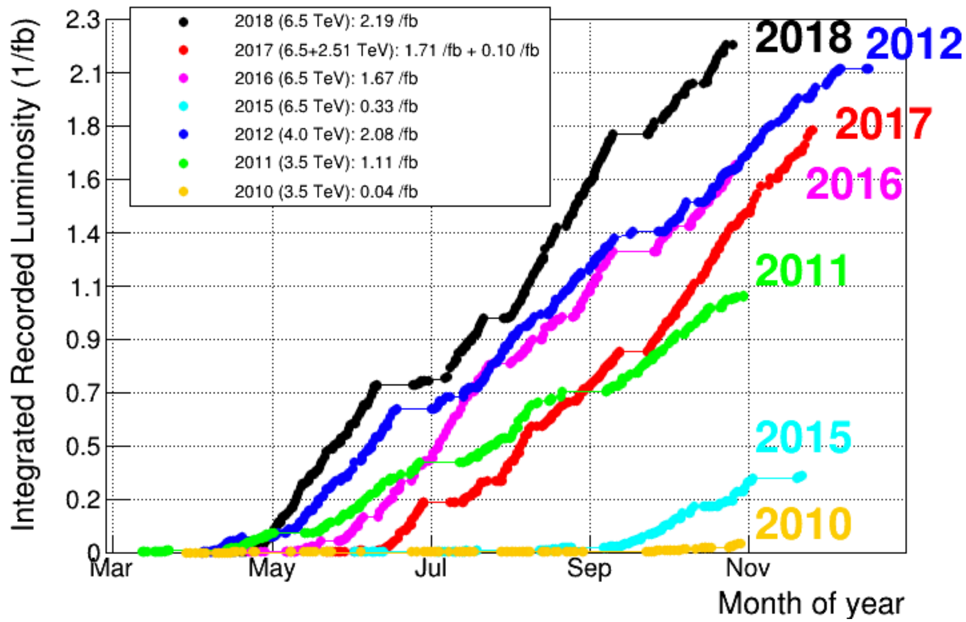
The LHCb detector at the LHC, JINST 3 (2008) S08005

DETECTOR OPERATION RUN 1 AND RUN 2

- LHCb designed to run at lower instantaneous luminosity $\mathcal{L}$ than ATLAS and CMS
- mean number of interactions per bunch crossing ~1
- pp beams displaced to reduce $\mathcal{L}$



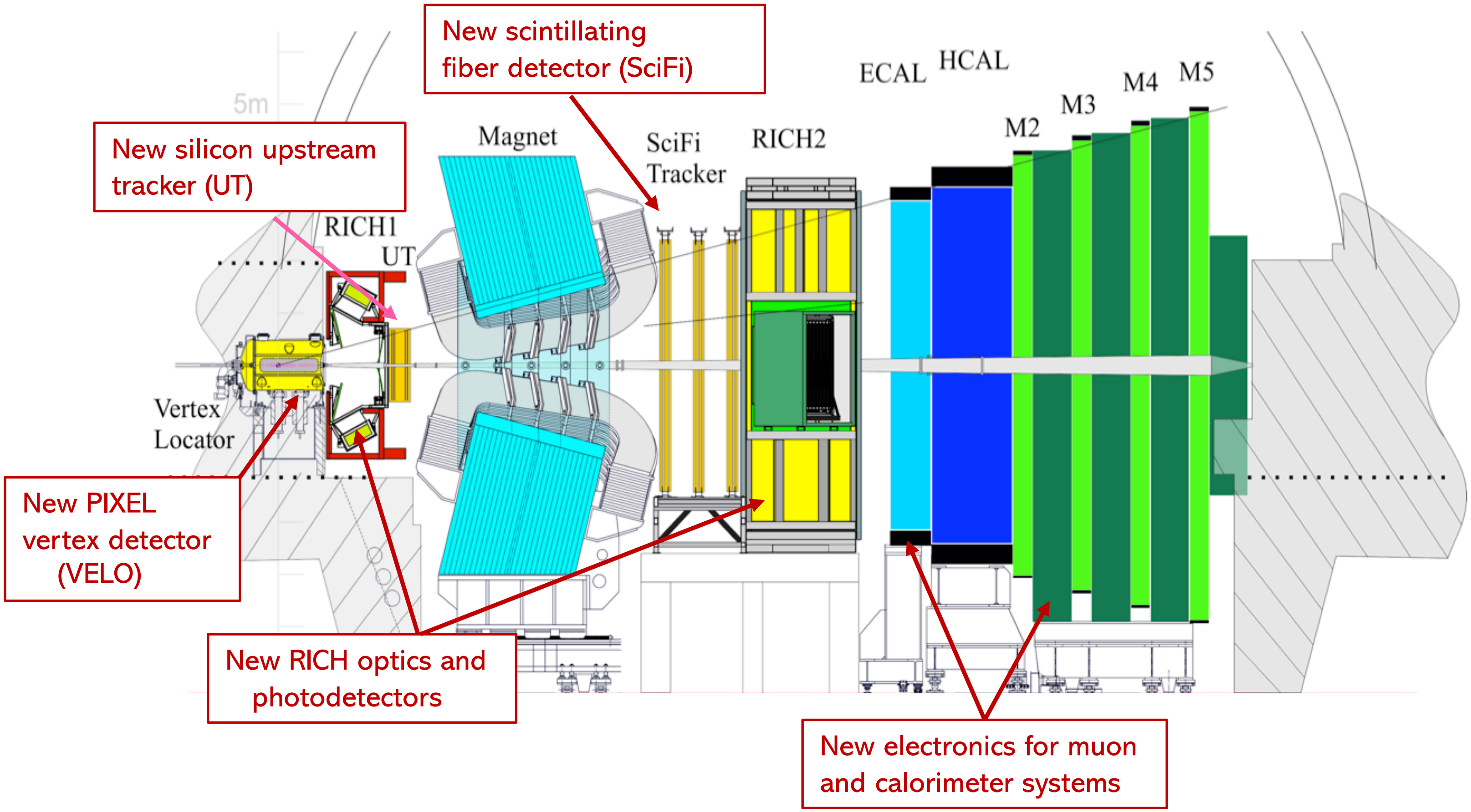
arXiv: 1412.6352



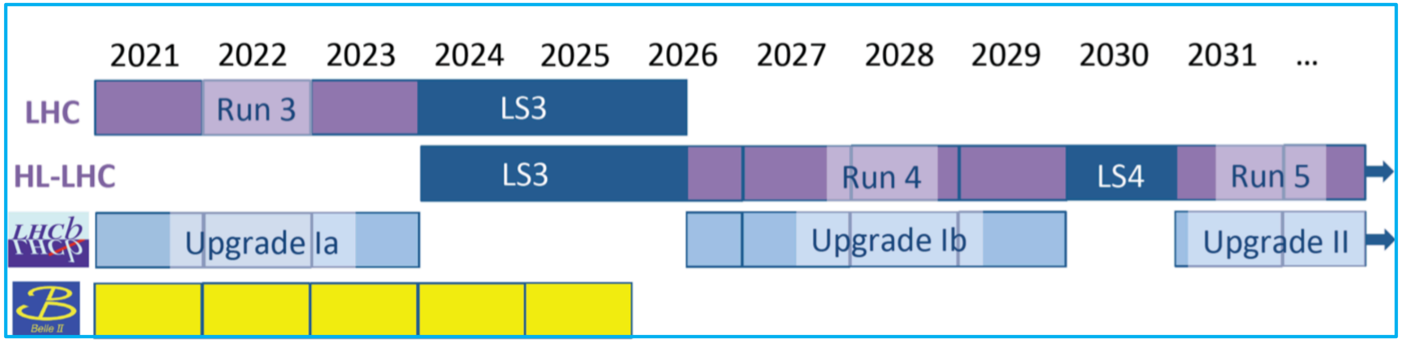
- ~ 3 fb^{-1} of pp collisions at 7-8 TeV in Run 1
- ~ 6 fb^{-1} of pp collisions at 13 TeV in Run 2
- ~ 9 fb^{-1} reached at the end of Run 2

THE LHCb UPGRADE I

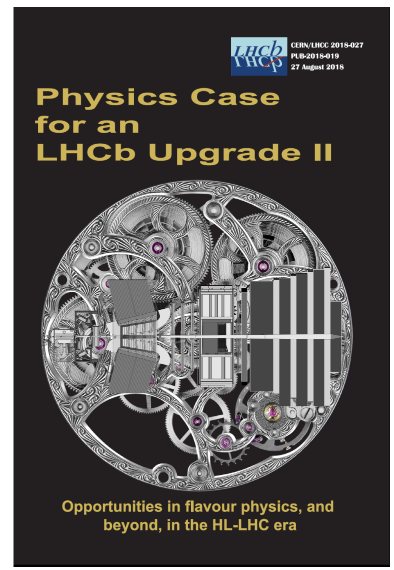
All sub-detectors read out at 40 MHz for a FULLY SOFTWARE trigger



THE LHCb UPGRADE II

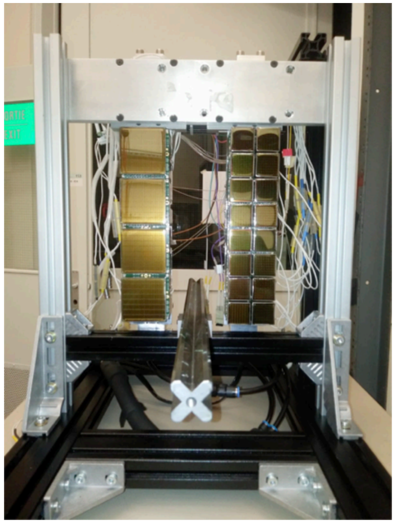


- Aims to **fully exploit the HL–LHC** for flavor physics in forward direction
- Expected to collect **> 300 fb^{-1}** at $\mathcal{L}=2\times10^{34}$, 10 times higher than Upgrade I
- Physics case document released arXiv: 1808.08865
- Green light from LHCC to proceed to detector TDR's (expected ~ late 2020)

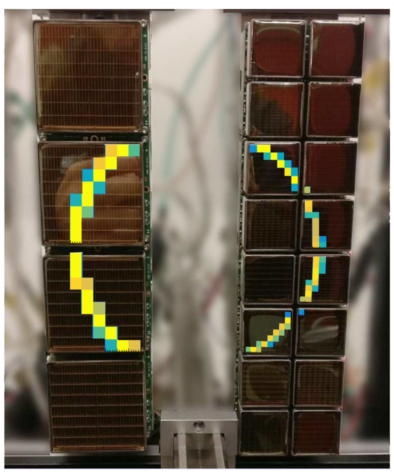


PROGRESS IN DETECTOR CONSTRUCTION

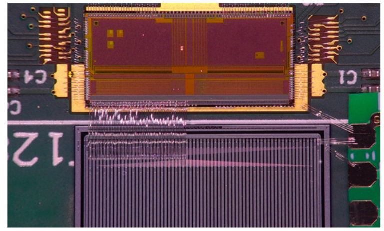
RICH MaPMT test stand



RICH photodetectors and readout

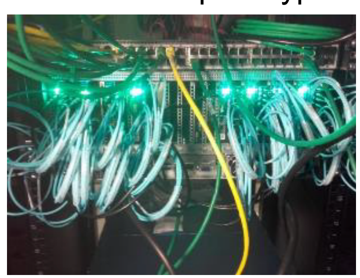


UT ASIC wire-bonded to a sensor

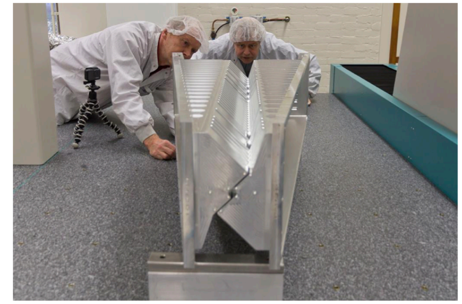


prototype stave of UT

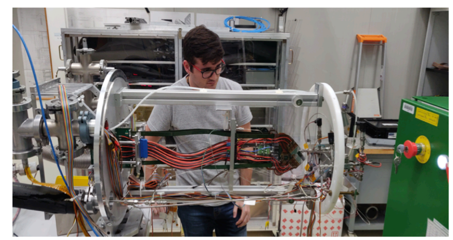
event builder prototype



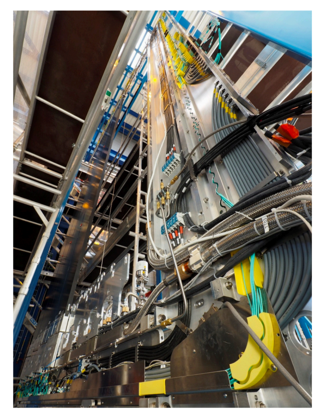
full size VELO RF boxes in “closed” position



VELO module test setup



prototype C-frame in construction at LHCb site



CP violation in b

THE KOBAYASHI-MASKAWA THEORY

- The CKM matrix must be UNITARY for a fixed number of quark generations (e.g. 3) :
  $V_{CKM}^{+} = V_{CKM}$ ⟺ SINGLE−PHASE hypothesis

- Which provides many relationships, such as **TRIANGLES** :

$$\underset{1\cdot\lambda^3}{V_{ud}V_{ub}^*} + \underset{\lambda\cdot\lambda^2}{V_{cd}V_{cb}^*} + \underset{\lambda^3\cdot 1}{V_{td}V_{tb}^*} = 0$$

$$\underset{\lambda\cdot\lambda^3}{V_{us}V_{ub}^*} + \underset{1\cdot\lambda^2}{V_{cs}V_{cb}^*} + \underset{\lambda^2\cdot 1}{V_{ts}V_{tb}^*} = 0$$

$$\underset{1\cdot\lambda}{V_{ud}V_{us}^*} + \underset{\lambda\cdot 1}{V_{cd}V_{cs}^*} + \underset{\lambda^3\cdot\lambda^2}{V_{td}V_{ts}^*} = 0$$

- Two independent phases characterize the first triangle: $\lambda \equiv \sin\theta_c$

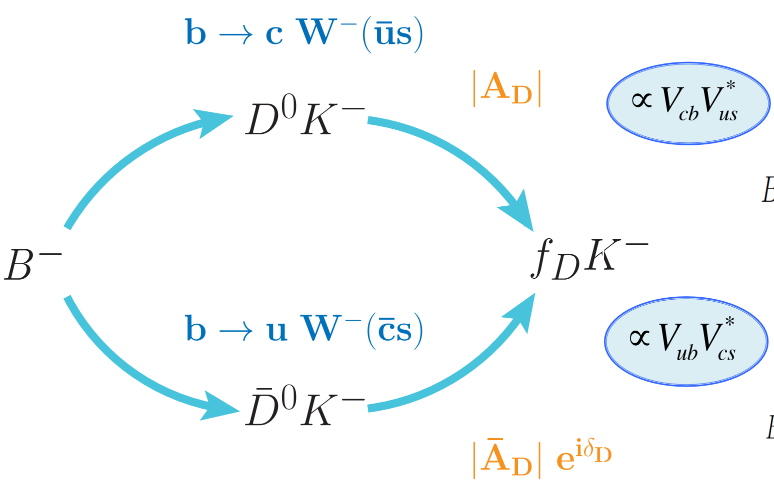
$$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/(V_{td}V_{tb}^*)\right]$$
$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)\right]$$

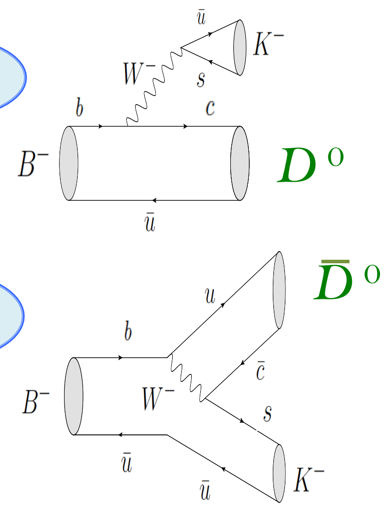
First evidence of CPV in B-mesons, BaBar 2001

- The **flat triangles** with a very small side mean very significant predictions:
  - the phase $\beta_s \equiv \arg\left[-V_{ts}V_{tb}^*/(V_{cs}V_{cb}^*)\right]$ must be very small ($\approx \lambda^4$)

NEW LHCb MEASUREMENT OF γ

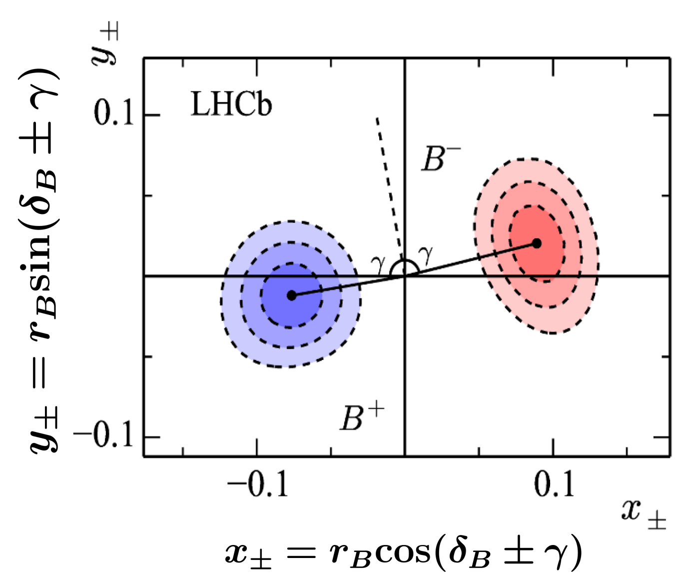
- γ is measured through interference in $B^- \to DK^-$. No assumptions on D decay amplitude are made





$$\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^+ \to D^0 K^+)} \equiv r_B e^{i(\delta_B - \gamma)}$$

LHCb, JHEP 08 (2018) 176



- Many K/π decay modes for D^0 meson are included

- Neutral B-mesons (B_s , B^0) are also used, time dependent analysis with $B_s \to D_s^{\mp}K^{\pm}$
  LHCb, JHEP 03 (2018) 059

CURRENT STATUS ON γ

- LHCb combination of tree-level measurements: $\gamma = (74.0\ ^{+5.0}_{-5.8})^{\circ}$

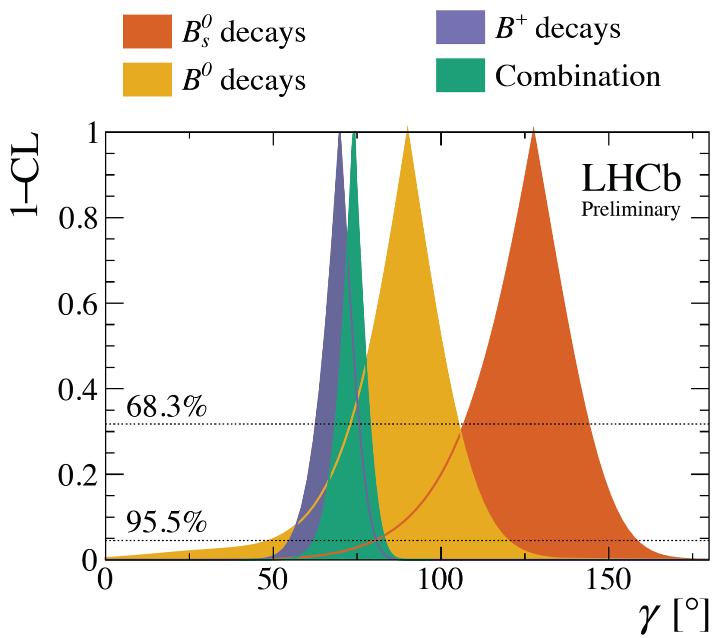
  It is the most precise measurement from a single experiment LHCb-CONF-2018-002

- World average of *direct* measurements: $\gamma = (73.5\ ^{+4.2}_{-5.1})^{\circ}$ HFLAV Winter 2018

- *Indirect* V_{CKM} measurements throw the result: $\gamma_{\text{indirect}} = (65.8 \pm 2.2)^{\circ}$

  UTFIT Summer 2018

- Both consistent within ~ 2σ. This is a most significant, and highly non trivial test, on:
  - the Kobayashi-Maskawa theory of CP-violation (*single-phase* hypothesis)
  - the contribution of *new physics* in tree-level diagrams

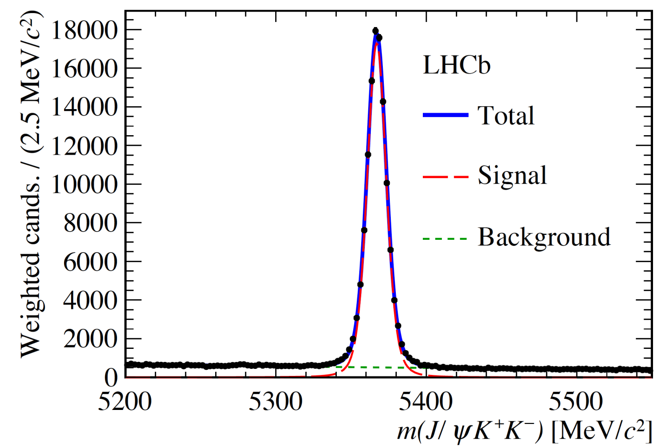


Small internal tensions between B_s and B^+ **will be followed** as more data are collected

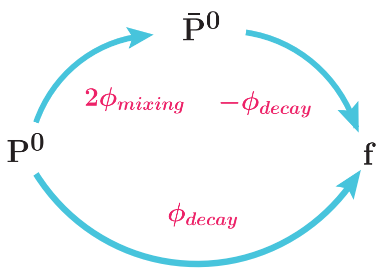
MEASUREMENT OF ϕ_s^{cc} WITH $B_s^0 \rightarrow J/\psi K^+K^-$

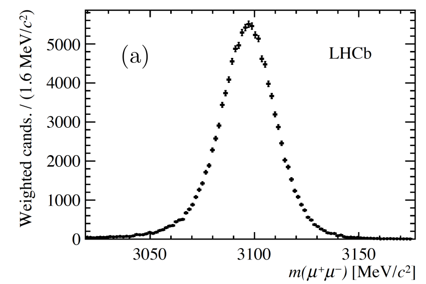
LHCb-PAPER-2019-013 preliminary

- LHCb updated measurement of time dependent CP-violating observables in $B_s^0 \rightarrow J/\psi K^+K^-$ decays, adding a new sample of 117000 signal events (2015-16)



- Interference between the decay and B_s^0 - $\bar{B}_s^0$ mixing amplitudes is governed in the SM by the very small CKM phase β_s (flat triangle) $\phi_s \approx -2\beta_s$ (ignoring sub-leading diagrams)

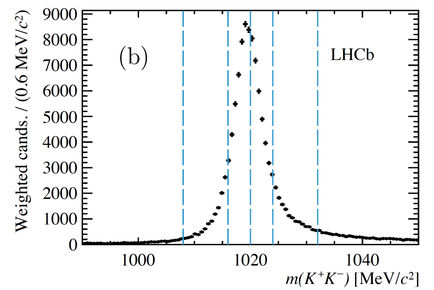




- Rather than predicted by the SM, the β_s phase is **strongly constrained** by the CKM unitarity to:

$$-2\beta_s^{SM} = -0.0368^{+0.00096}_{-0.00068} \text{ rad} \quad \text{CKMfitter group}$$

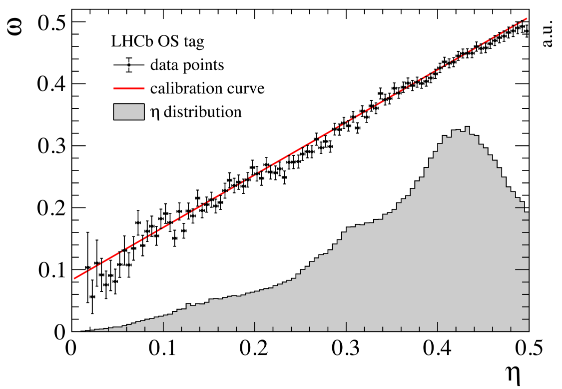
$$-2\beta_s^{SM} = -0.0370 \pm 0.0010 \text{ rad} \quad \text{UTfit collaboration}$$



- LHCb is well placed to approach such precision limit

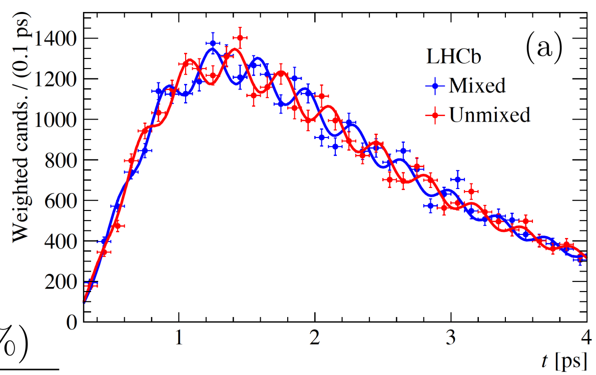
FLAVOR TAGGING AT LHCb

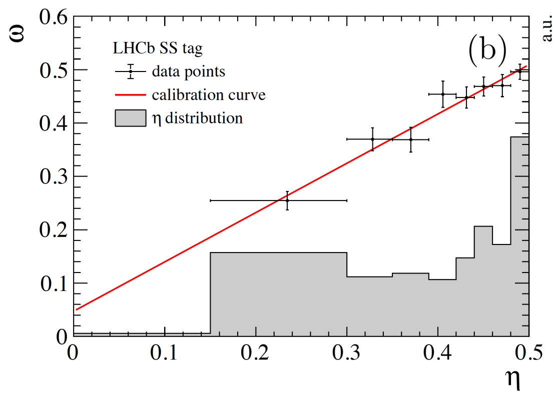
- Owing to very fast B_s^0 - $\bar{B}_s^0$ oscillations ($\Delta m_s \approx 17.77\ ps^{-1}$) two critical parameters need to be known very precisely, to attain the *mrad* precision at the LHC:
  - $B_s^0/\bar{B}_s^0$ *flavor* tagging efficiency and dilution at t=0
  - time resolution σ_t, better than $2\pi/\Delta m_s \approx 350$ fs



- LHCb has significantly improved flavor tagging since 2011, by refining both the **opposite side** (OS) muon/electron/kaon/multi plicity) and the **same side** (SS) kaon tagging

LHCb-PAPER-2019-013 preliminary





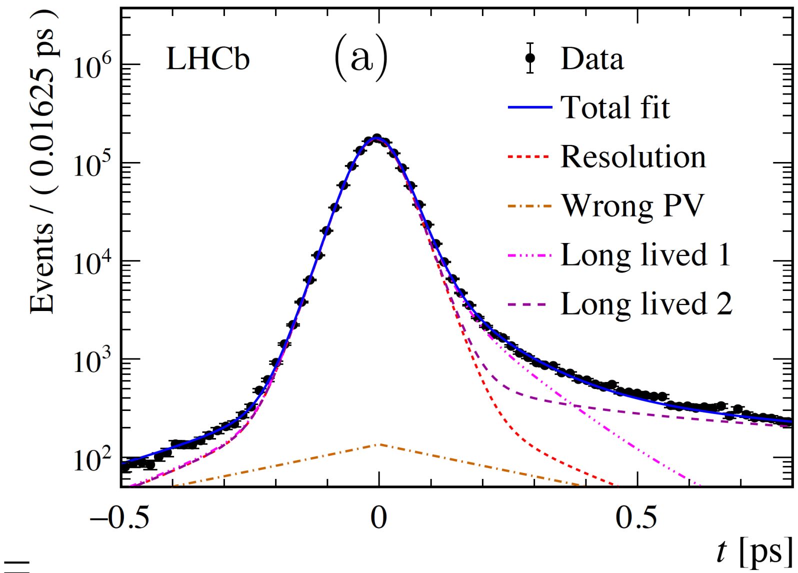
Category	$\varepsilon_{tag}(\%)$	$\mathcal{D}^2$	$\varepsilon_{tag}\mathcal{D}^2(\%)$
OS-only	11.35	0.078	0.88 ± 0.04
SSK-only	42.57	0.032	1.38 ± 0.30
OS&SSK	23.84	0.104	2.47 ± 0.15
Total	77.76	0.061	4.73 ± 0.34

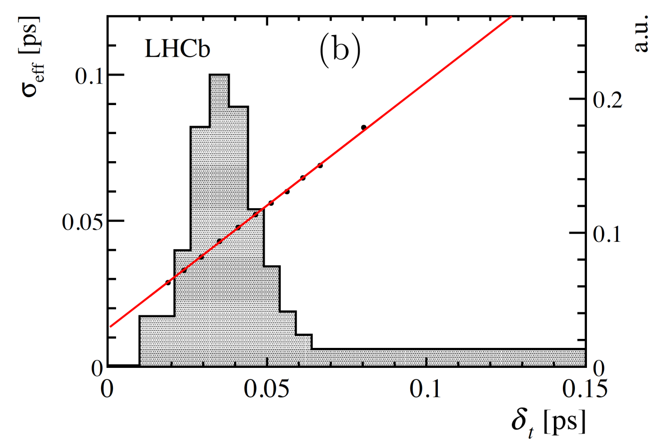
large control samples of $B+ \to J/\psi\ K^+$ and $B^0{}_s \to D_s^- \pi+$ are respectively used

TIME RESOLUTION AT LHCb

- With $\sigma_t \approx 45$ fs , the oscillation amplitude is damped by factor exp $(-\sigma_t^2 \Delta m_s^2/2)$ ($\approx$ 0.7 LHCb)
- A **prompt** sample of $B_s^0 \rightarrow J/\psi K^+K^-$ events, selected at the *primary pp* vertex (zero decay time), is used to calibrate the *effective* decay-time resolution, by correlating it (11 subsets) with the estimated per-event decay-time uncertainty: $\sigma_{eff}(\delta_t) = b_0 + b_1 t$
- The single Gaussian $\sigma_{eff} = \sqrt{(-2/\Delta ms^2)\ln D}$ is obtained from a 3-Gaussian fit, convolved as $P(t) = \varepsilon(t)\,(\Gamma(t') \otimes R(t-t'))$ with an analytical distribution $\Gamma(t)$ times a calibrated acceptance function $\varepsilon(t)$
- An averaged single-Gaussian resolution is obtained of $\boldsymbol{\sigma_{eff} = 45.54 \pm 0.04 \pm 0.05}$ **fs** for the $B_s^0 \rightarrow J/\psi K^+K^-$ simple.

LHCb-PAPER-2019-013 preliminary





AMPLITUDE ANALYSIS OF CP-EIGENSTATES

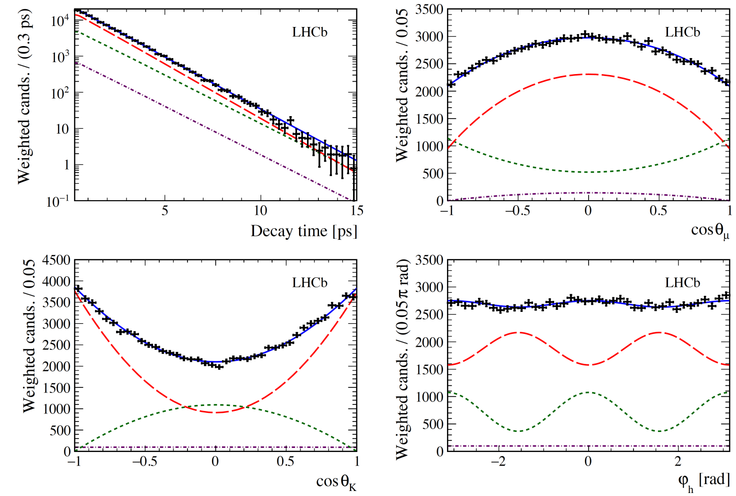
- The 3 VV helicity amplitudes $B_s^0 \to J/\psi\ \phi(K^+K^-)$ may also interfere with a $S(K^+K^-)=0$ scalar during the B_s^0 - $\bar{B}_s^0$ oscillation process:

LHCb-PAPER-2019-013 preliminary

$$\mathcal{A} = \sum \mathcal{A}_i = \mathcal{A}_0 + \mathcal{A}_{\parallel} + \mathcal{A}_{\perp} + \mathcal{A}_S$$

$$\overline{\mathcal{A}} = \sum \frac{q}{p}\overline{A}_i = \sum \lambda_i A_i = \sum \eta_i |\lambda_i| e^{-i\phi_s^i} A_i$$

$$\lambda_i \equiv \frac{q}{p}\frac{\overline{A}_i}{A_i} \qquad \phi_s^i \equiv -\arg(\eta_i \lambda_i)$$



- The flavor-tagged, time-convolved, background subtracted distributions are ML analysed

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t|B_s^0) = \frac{3}{4\pi} e^{-\Gamma t}\left(a_k \cosh\frac{\Delta\Gamma t}{2} + b_k \cosh\frac{\Delta\Gamma t}{2} + c_k \cos(\Delta m t) + d_k \sin(\Delta m t)\right)$$

$$h_k(t|\bar{B}_s^0) = \frac{3}{4\pi} e^{-\Gamma t}\left(a_k \cosh\frac{\Delta\Gamma t}{2} + b_k \cosh\frac{\Delta\Gamma t}{2} - c_k \cos(\Delta m t) - d_k \sin(\Delta m t)\right)$$

Parameter	Value
ϕ_s [rad]	$-0.083 \pm 0.041 \pm 0.006$
$\lvert\lambda\rvert$	$1.012 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0773 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.703 \pm 0.059 \pm 0.018$
$\lvert A_\perp\rvert^2$	$0.2456 \pm 0.0040 \pm 0.0019$
$\lvert A_0\rvert^2$	$0.5186 \pm 0.0029 \pm 0.0024$
$\delta_\perp - \delta_0$	$2.64 \pm 0.13 \pm 0.10$
$\delta_\parallel - \delta_0$	$3.062^{+0.082}_{-0.074} \pm 0.037$

- ϕ_s, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, $\Gamma_s - \Gamma_d$ ($\Gamma_s = \Gamma_L + \Gamma_H)/2$ are the most precise data today, along with a similar precision simultaneous measurement by ATLAS

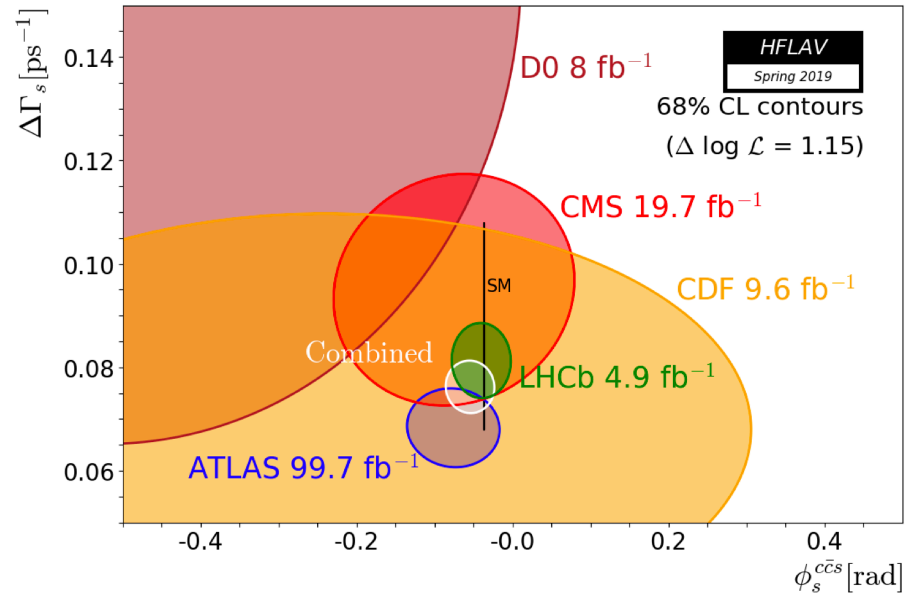
CURRENT STATUS OF ϕ_s^{cc} MEASUREMENTS

- LHCb has added other B_s^0 decays: $J/\psi\ \pi\pi$, $\psi\ (2s)\phi$, $D_s^+\ D_s$ all sensitive to ϕ_s^{cc}

LHCb-PAPER-2019-013 (prel)

ATLAS-CONF-2019-009 (prel)

$$\begin{aligned} \phi_s &= -0.041 \pm 0.025\,\text{rad}\,, \\ |\lambda| &= 0.993 \pm 0.010\,, \\ \Gamma_s &= 0.6562 \pm 0.0021\,\text{ps}^{-1} \\ \Delta\Gamma_s &= 0.0816 \pm 0.0048\,\text{ps}^{-1} \end{aligned}$$



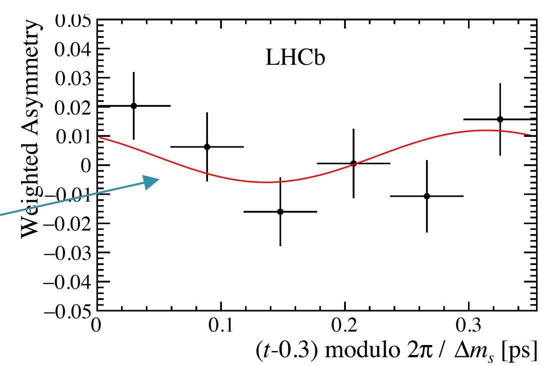
- Both main players yet to analyse full Run2. Some tension on absolute B_s^0 lifetime, and $\Delta\Gamma_s$

- LHCb result:

ϕ_s = -41 ± 25 mrad

begins to deviate from zero, but on the same side as the SM prediction: -37 ± 1 mrad

accumulated CP-asymmetry per oscillation cycle (2.4σ)

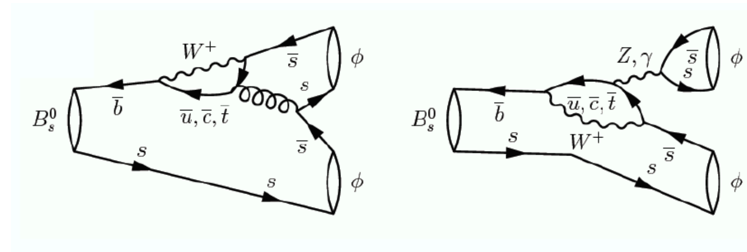


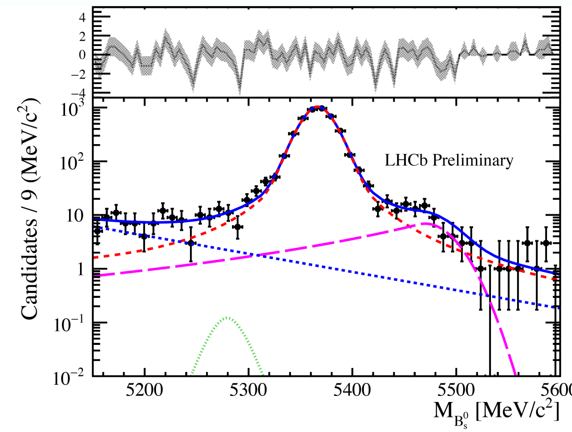
MEASUREMENT OF ϕ_s^{ss} FROM $B_s \rightarrow \phi\phi$

LHCb-PAPER-2019-019 , preliminary

- Copius signal, $\phi \rightarrow K^+ K^-$, subject in SM is to the same CKM phase as $B_s^0 \rightarrow J/\psi\phi$: $\phi_s^{ss} = -2\beta_s$. However, lowest order involves ***penguin*** $b \rightarrow ss\bar{s}$ diagrams, with potential contributions from NP particles from loops. Entirely similar *tagged* angular and time analysis, with 4 helicities: A_0, $A_{||}$,$A_\perp$ (CP-odd), A_S

$$\begin{aligned} \phi_s^{s\bar{s}s} &= -0.073 \pm 0.115\,(\text{stat}) \pm 0.027\,(\text{syst}) \text{ rad}, \\ |\lambda| &= 0.99 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst}). \end{aligned}$$





- Helicity dependent amplitudes have also been explored:

$$\begin{aligned} \phi_{s,\|} &= 0.014 \pm 0.055\,(\text{stat}) \pm 0.011\,(\text{syst}) \text{ rad}, \\ \phi_{s,\perp} &= 0.044 \pm 0.059\,(\text{stat}) \pm 0.019\,(\text{syst}) \text{ rad}. \end{aligned}$$

- Triple products are T-odd observables, a complementary search for CPV without flavor tagging or time analysis

$$\sin\Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1} \qquad U \equiv \sin\Phi\cos\Phi$$

$$\sin 2\Phi = 2(\hat{n}_{V_1} \cdot \hat{n}_{V_2})(\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1} \qquad V \equiv \sin(\pm\Phi)$$

$$A_U \equiv \frac{\Gamma(U>0) - \Gamma(U<0)}{\Gamma(U>0) + \Gamma(U<0)} \qquad A_V \equiv \frac{\Gamma(V>0) - \Gamma(V<0)}{\Gamma(V>0) + \Gamma(V<0)}$$

$$\begin{aligned} A_U &= -0.003 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst}) \\ A_V &= -0.012 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst}) \end{aligned}$$

- With 5.0 fb^{-1} (2011-2016), results are consistent with the hypothesis if CP conservation in $b \rightarrow s s\bar{s}$ transitions

CP-VIOLATING OBSERVABLES IN $B_s \to \phi\gamma$

- Time-dependent CP-asymmetries have been measured by LHCb for $B_s^0 \to \phi\,(K^+K^-)\,\gamma$ radiative decays, with 3 fb^{-1} (7+8 TeV)

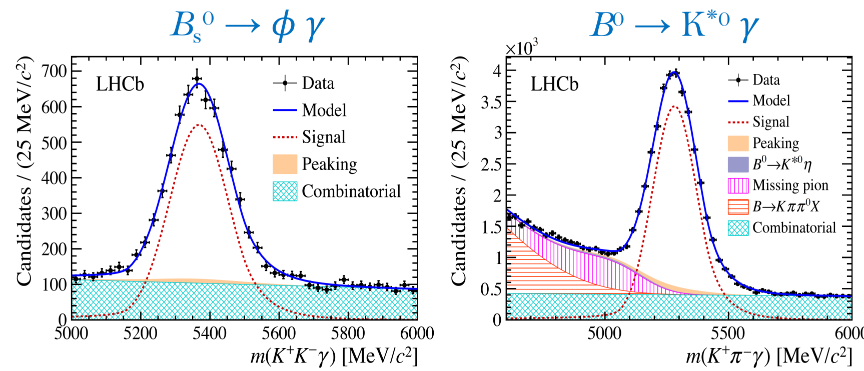
$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2) + \zeta\, C\cos(\Delta m_s t) - \zeta\, S\sin(\Delta m_s t)\}$$

- $\mathcal{A}^{\Delta}$ sensitive to *right-handed* currents in $b \to s\gamma$ transition (penguins) and *small* in the SM ($\propto A_L A_R$ photon amplitudes) arXiv:0802.0876

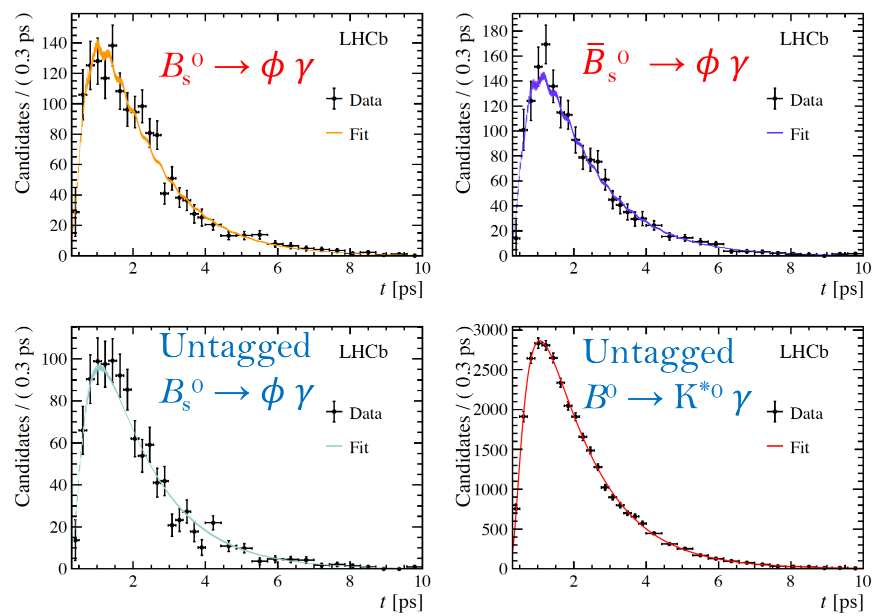
- $B^0 \to K^{*0}\gamma$ used as proxy for time acceptance calibration (single exponential)

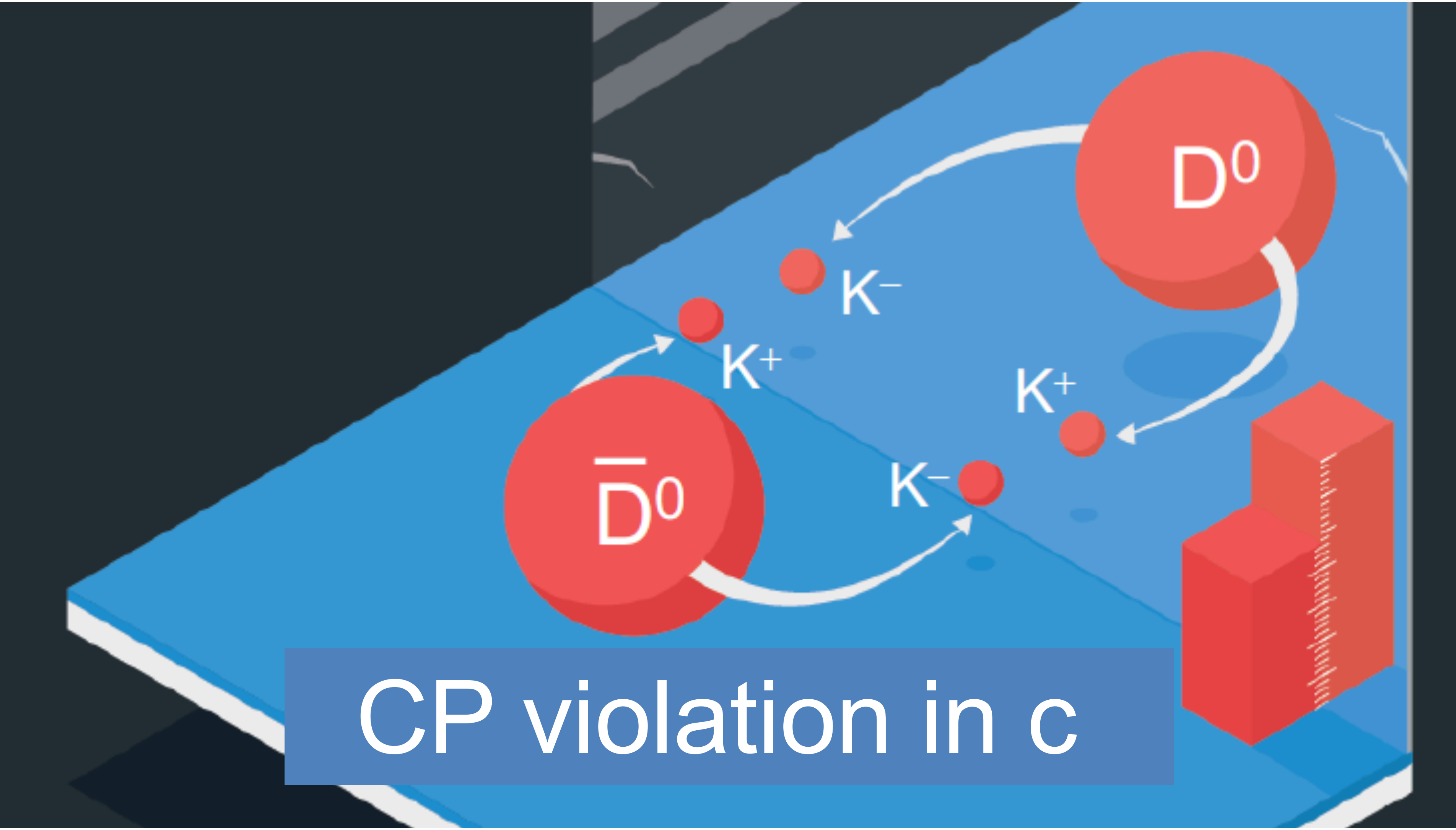
- Measured parameters compatible with SM expectation within $(1.3, 0.3, 1.7)\sigma$, respectively:

$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17$$



LHCb-PAPER-2019-015, arXiv: 1905.06284





CP violation in c

DISCOVERY OF CP VIOLATION IN CHARM

- LHCb has discovered a non zero *charmed* time integrated CP-violating asymmetry:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -(15.4 \pm 2.9) \times 10^{-4}$$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

R. Aaij et al. PRL 122, 211803 (2019)

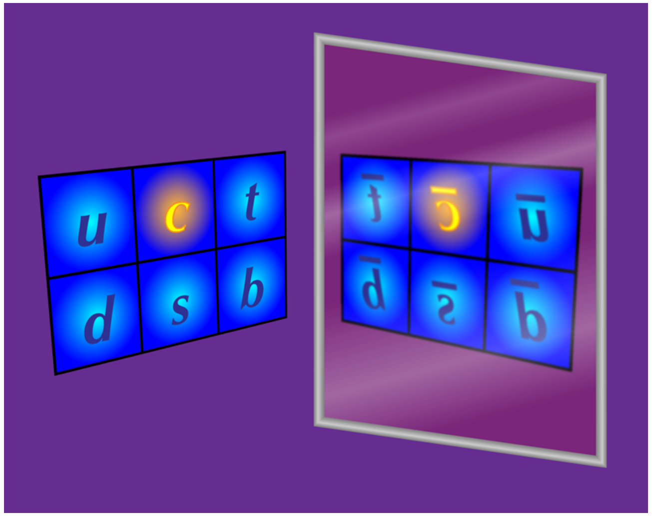
- Model independently, we know to $\mathcal{O}(10^{-6})$:

$$A_{CP}(f) \approx a_{CP}^{dir}(f)\left(1 + \frac{\langle t\rangle_f}{\tau_{D^0}} y_{CP}\right) - \frac{\langle t\rangle_f}{\tau_{D^0}} A_\Gamma$$

effective $\Gamma(CP = +1)$ different from $\Gamma(D^0)$

- LHCb has also performed a *time analysis* A_{CP} (t) to determine A_Γ and elucidate whether the CP-violating $D^0/\bar{D}^0$ mixing (modulus or phase) is responsible

LHCb-CONF-2019-001 April, 2019



Charm Reflects Poorly on Anticharm

- In addition an updated measurement of y_{CP} has been issued to accurately perform the correction to a_{CP}^{dir} , using *untagged semileptonic* B-decays

$a_{CP}^{ind} \approx - A_\Gamma$

R. Aaij et al. PRL 122, 011802 (2019)

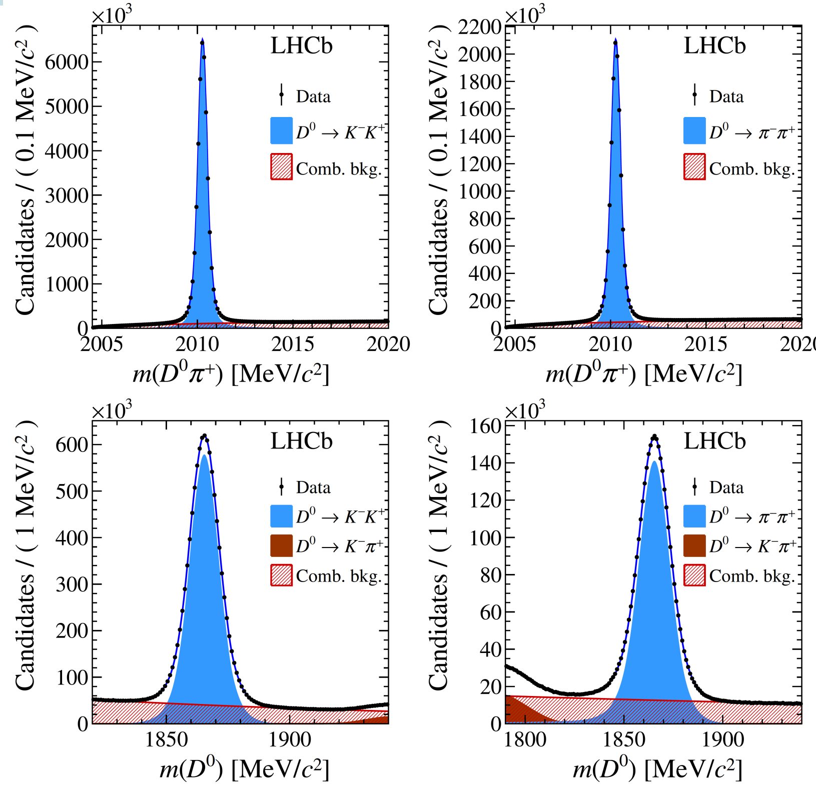
ASSESSMENT OF CP VIOLATION IN CHARM

- LHCb has used 6 fb^{-1} at pp $\sqrt{s}$=13 TeV, with CP=+1 eigenmodes $D^0 \to K^+K^-$, $\pi^+\pi^-$ (44 million $D^0 \to K^+K^-$ decays). Both $D^{*+}(\to D^0\pi^+)$ and semileptonic taggings were used.

  R. Aaij et al. PRL 122, 211803 (2019)

- The difference $A_{CP}(KK) - A_{CP}(\pi\pi)$ is chosen because detector and production CP-asymmetries largely cancel. Not unrelated, $A_{CP}(KK) = -A_{CP}(\pi\pi)$ is predicted from exact SU(3) symmetry. The outcome is then:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= -(15.4 \pm 2.9) \times 10^{-4}$$



- By using $y_{CP} = (5.7 \pm 1.5) \times 10^{-3}$ and $-A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4} \approx a_{CP}^{ind}$ (see next) we get:

  $\Delta a_{CP}^{dir} = (-15.6 \pm 2.9) \times 10^{-4}$ or A_{CP} PRIMARILY SENSITIVE TO *DIRECT* CPV

- The result is consistent with, although at the upper end of, SM expectations 10^{-4} -10^{-3} . Beyond the SM, the CPV rate could be enhanced. Present understanding does not allow more precise predictions, due to the difficulty of long-range strong interactions

SEARCH FOR TIME DEPENDENT CPV IN CHARM

LHCb-CONF-2019-001 April, 2019

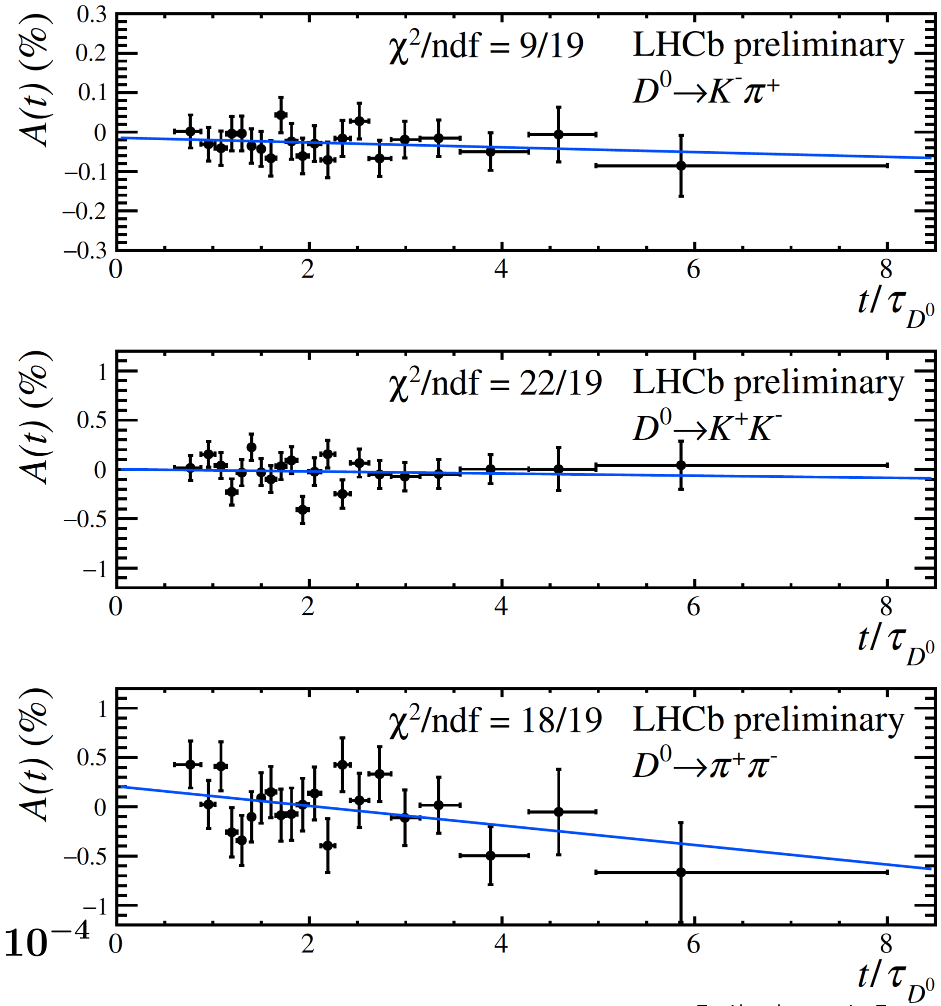
- Tagged $D(2010)^{*+} \rightarrow D^0 \pi^+$ decays are employed for *time analysis* of CP-asymmetries. Kinematic weighing is used for detector-induced asymmetries, with $D^0 \rightarrow K^- \pi^+$ as calibration

- Now the **measurement of A_Γ** is largely insensitive to time-independent detection and production asymmetries, so KK and $\pi\pi$ analyses *can* be separated.

$$\mathbf{A_\Gamma(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}}$$
$$\mathbf{A_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}}$$

- A_Γ is channel independent when decay phases are neglected, so a combined value (2011-2016) is meaningful:

$$\mathbf{A_\Gamma(K^+K^- + \pi^+\pi^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}}$$



➡ No evidence for CP violation in mixing or interference

$$A_\Gamma(f) \approx -x\phi_f + y\left[\left(\left|\frac{q}{p}\right| - 1\right)\right]$$

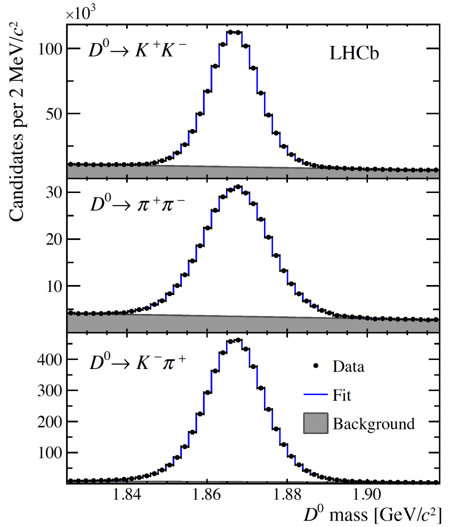
MEASUREMENT OF CHARM-MIXING PARAMETER y_{CP}

R. Aaij et al. PRL 122, 011802 (2019)

- In time analysis with D^0–$\overline{D^0}$ mixing, the effective decay widths (CP-even) $\Gamma(K^+K^-/\pi^+\pi^-)$ may *differ* from $\Gamma(D^0)$:

$$y_{CP} \equiv \frac{\Gamma_{CP+}}{\Gamma} - 1$$

CP conservation ⇔ $y_{CP} = y$

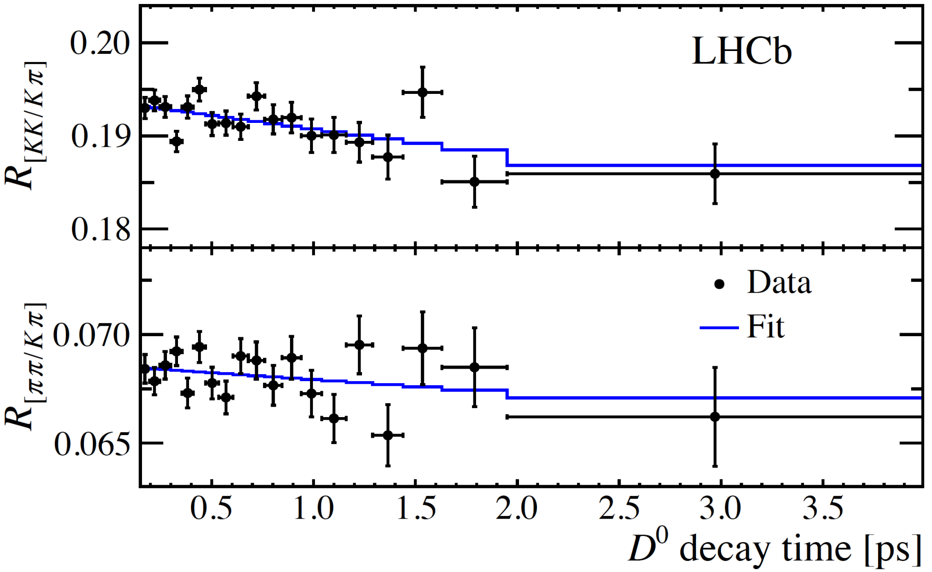


- LHCb has searched for CPV in mixing by requiring D^0 mesons to originate from semileptonic decays of B^- or $\overline{B^0}$: $\overline{B^0} \to D^0 \mu \bar{\nu} X$, and studying the time dependent RATIO between $D^0 \to K^+K^- / \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ signal yields

$$y_{CP} = (0.57 \pm 0.13 \pm 0.09) \times 10^{-2}$$

$$2y_{CP} \approx \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi$$

$$|D_{1,2} \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle \quad x \equiv (\Delta m)/\Gamma \quad y \equiv \Delta\Gamma/2\Gamma$$

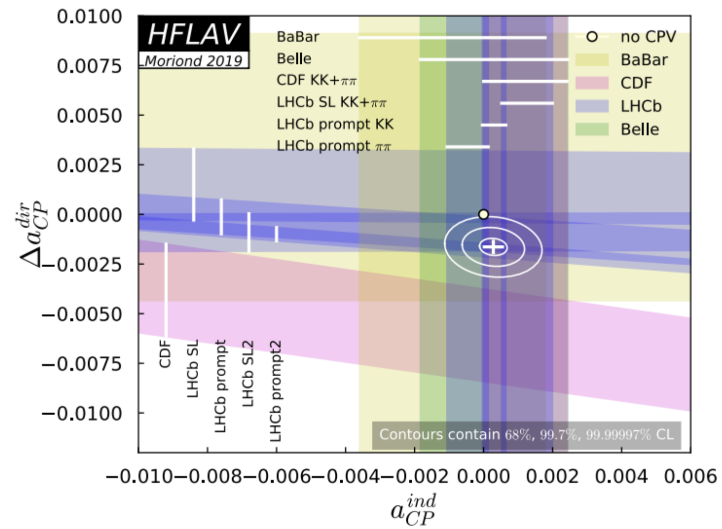


- y_{CP} is the most precise to date single experiment, being consistent with the w. a. mixing parameter $y = (0.62 \pm 0.07)\%$, hence **no evidence for CPV in D^0–$\overline{D^0}$ mixing**

NEW CHARM AVENUE

- The CP violation picture in the quark sector is now set for precision studies. Is the $\mathcal{O}(10^{-3})$ CPV found in charm the ultimate confirmation of Kobayashi-Maskawa theory, or a hint of new physics?

- Direct CPV in charm seems difficult to grasp, for challenging hadronic calculations with SM prediction $\mathcal{O}$ $(10^{-3}$-$10^{-4})$. But indirect CPV in A_Γ is predicted in the SM to be $A_\Gamma \approx 3 \times 10^{-5}$, offering a great **window of opportunity** for NP: its smallness may be turned into an advantage after all.



- Future measurements at HL-LHC (LHCb Upgrade II) will certainly improve the picture:

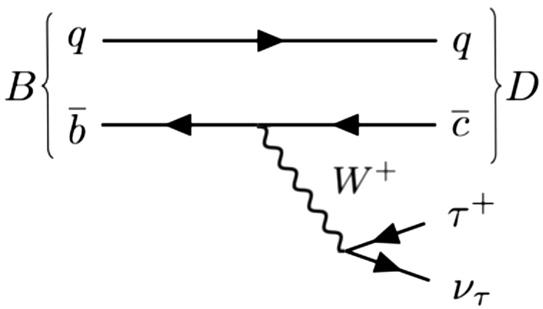
A. Cerri et al. CERN-LPCC-2008-06 arXiv: 1812.07638

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)_{K^+K^-}$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)_{\pi^+\pi^-}$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

LEPTON UNIVERSALITY anomalies in CC

LEPTON UNIVERSALITY IN CHARGED CURRENTS

- Very large data samples at LHCb, started and envisaged:

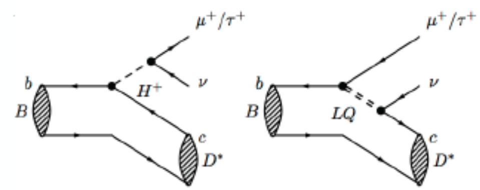


$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$

$$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s \quad \cdots$$

$$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \quad \cdots$$

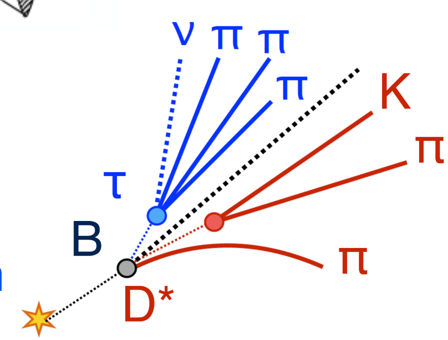
- Clean observables: hadronic uncertainties and $|V_{cb}|$ cancel out in the ratio. New operators may challenge universality:



- Generic difficulty at hadron colliders, due to missing neutrinos, partially solved by rest-frame approximation:

$$(p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

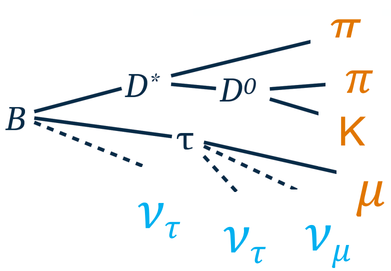
18% resolution on B momentum

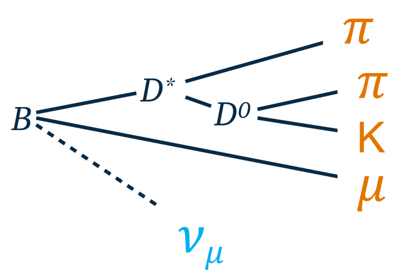


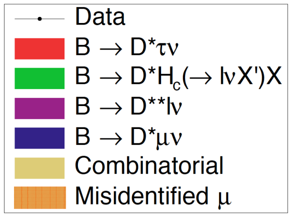
MUONIC R(D*)

R. Aaij et al. PRL 115, 111803 (2015)

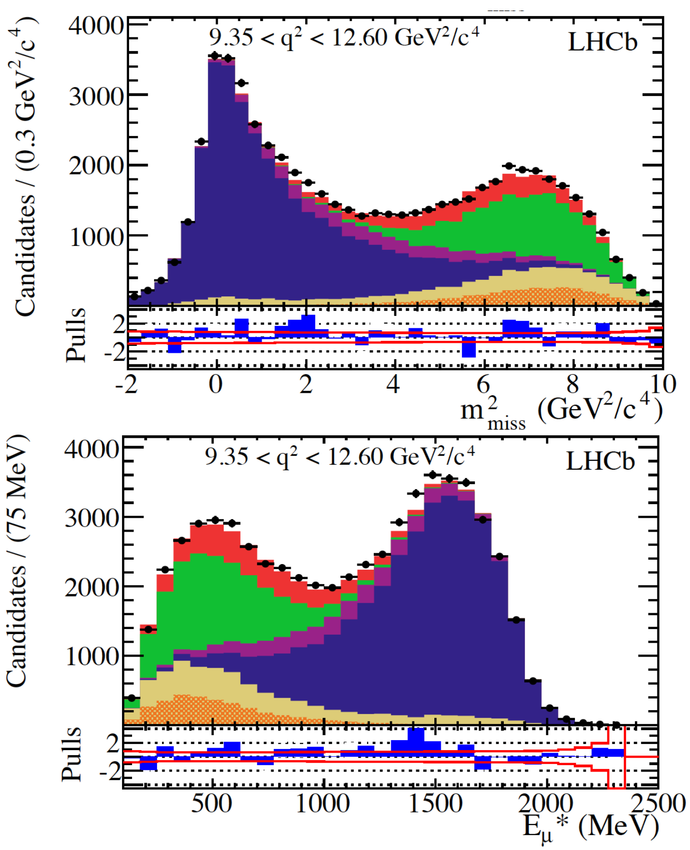
$$R(D^*) = \frac{\Gamma\left(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau\right)}{\Gamma\left(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu\right)}$$







Projections on one q^2-bin



- 3D fit to the data uses (m_{miss}^2, E_μ^*, $q^2 = (p_B - p_D)^2$)

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

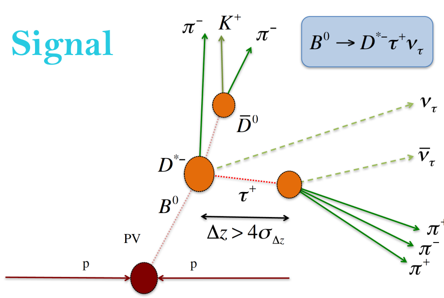
The result is 1.2σ above the SM 0.252±0.003

HADRONIC R(D*)

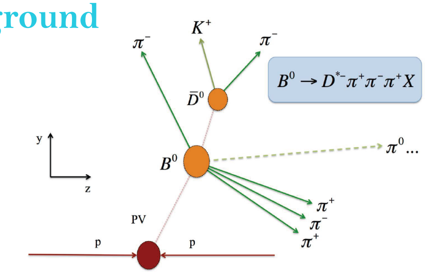
LHCb PRL 120 (2018) 171802 LHCb PRD 97 (2018) 072013

- Separation between B and 3π vertex ($\Delta z > 4\sigma_{\Delta z}$) crucial to achieve the required rejection of $B \to D^* 3\pi X$

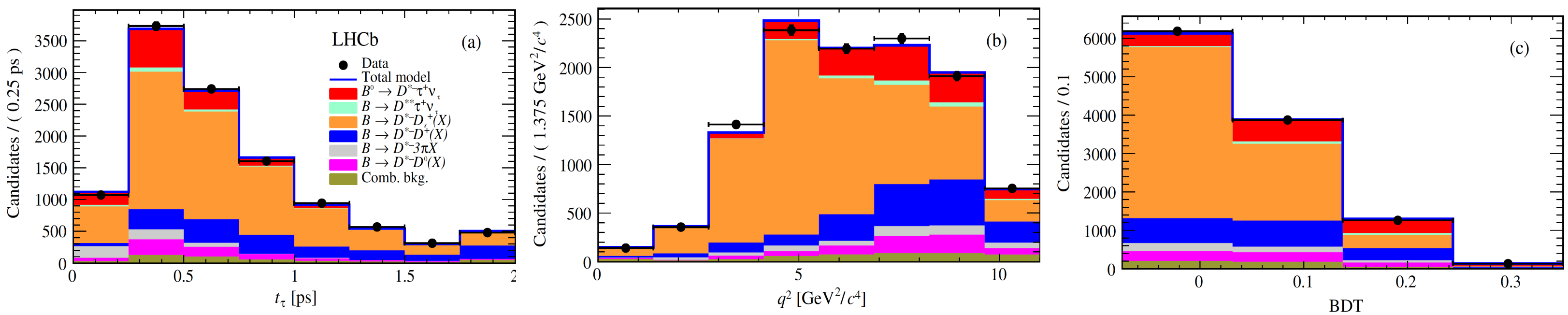
Signal



Background



- External knowledge of critical branching fractions is used ($B \to D^{*-} 3\pi$, BaBar+Belle+LHCb)



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

The result is $\sim 1\sigma$ above the SM 0.252 ± 0.003

LFU IN R(J/ψ) FROM B_c DECAYS

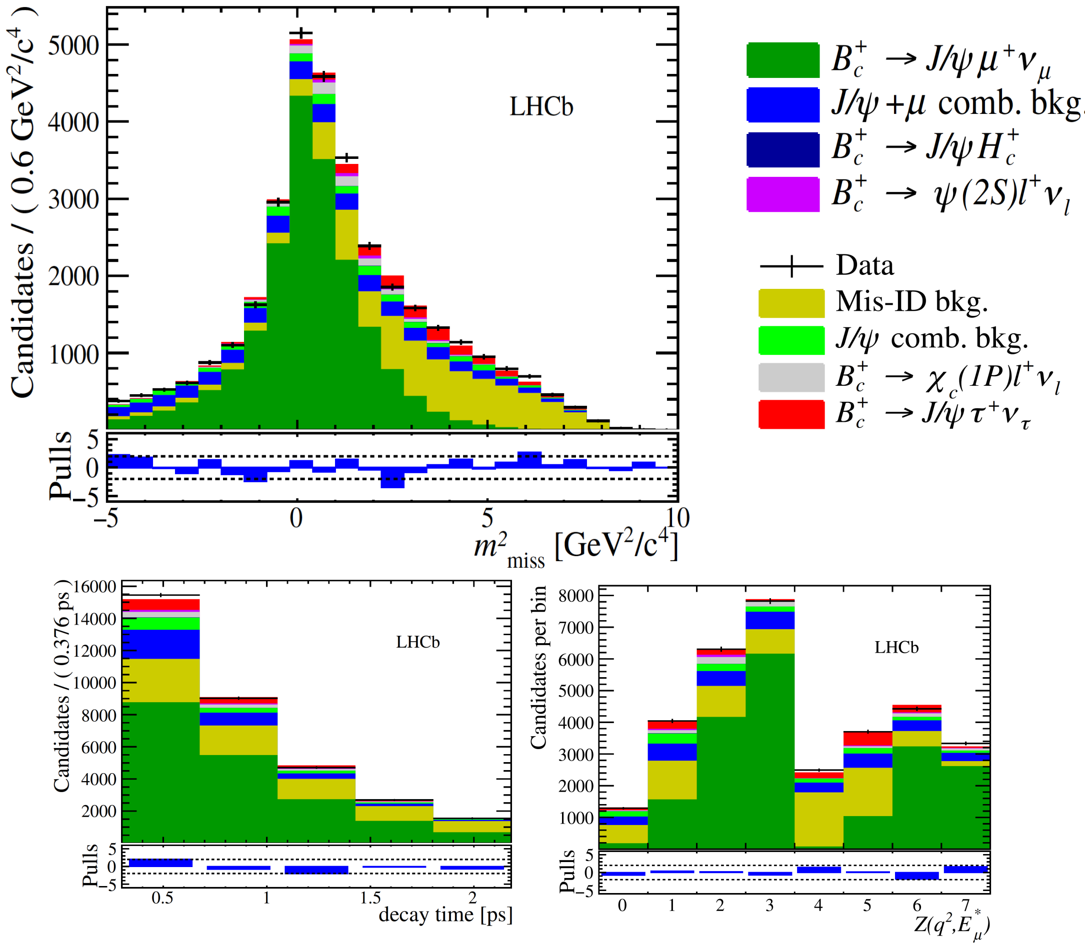
- New version of R(D*), charmed B-meson B_c^+: R. Aaij et al. PRL 120 (2018) 121801

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

- $B_c^+ \to J/\psi(\mu^+\mu^-)\mu^+\nu_\mu$ is used as normalization

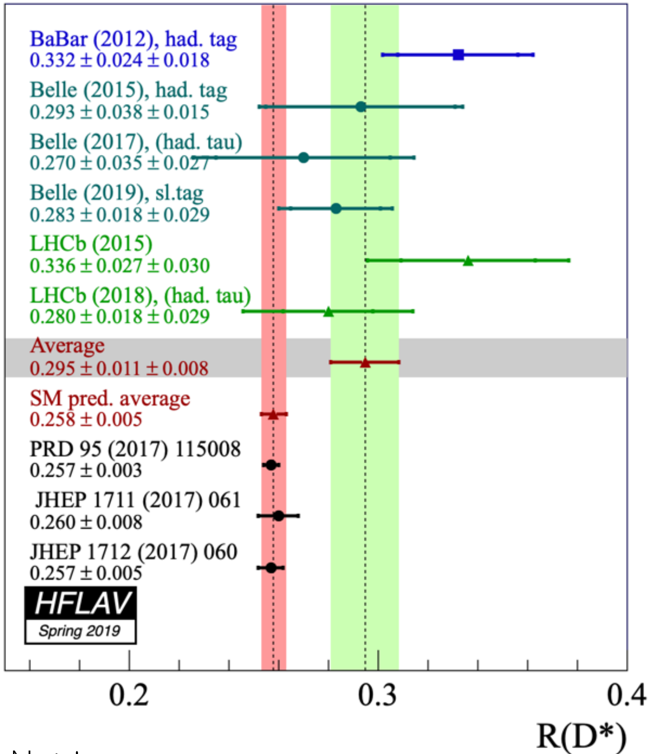
- Form factors not constrained from B-factories

- Measurement from 3D fit (m_{miss}^2, t_B, Z (q^2, E_μ^*))

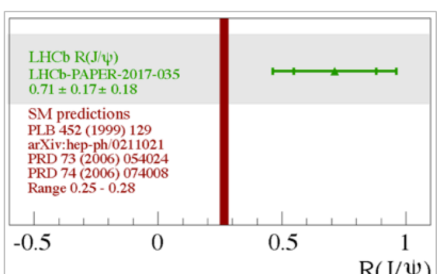


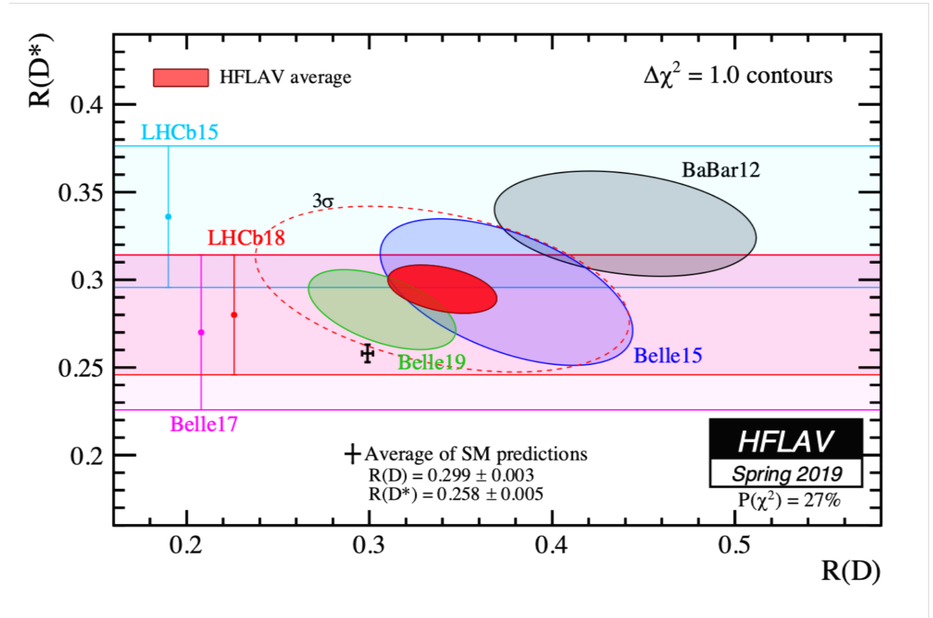
➡ R(J/ψ) = 0.71 ± 0.17 (stat) ± 0.18 (syst) above SM prediction by 2σ (0.25-0.28)

R(D) and R(D*) COMBINATION



Not in average:

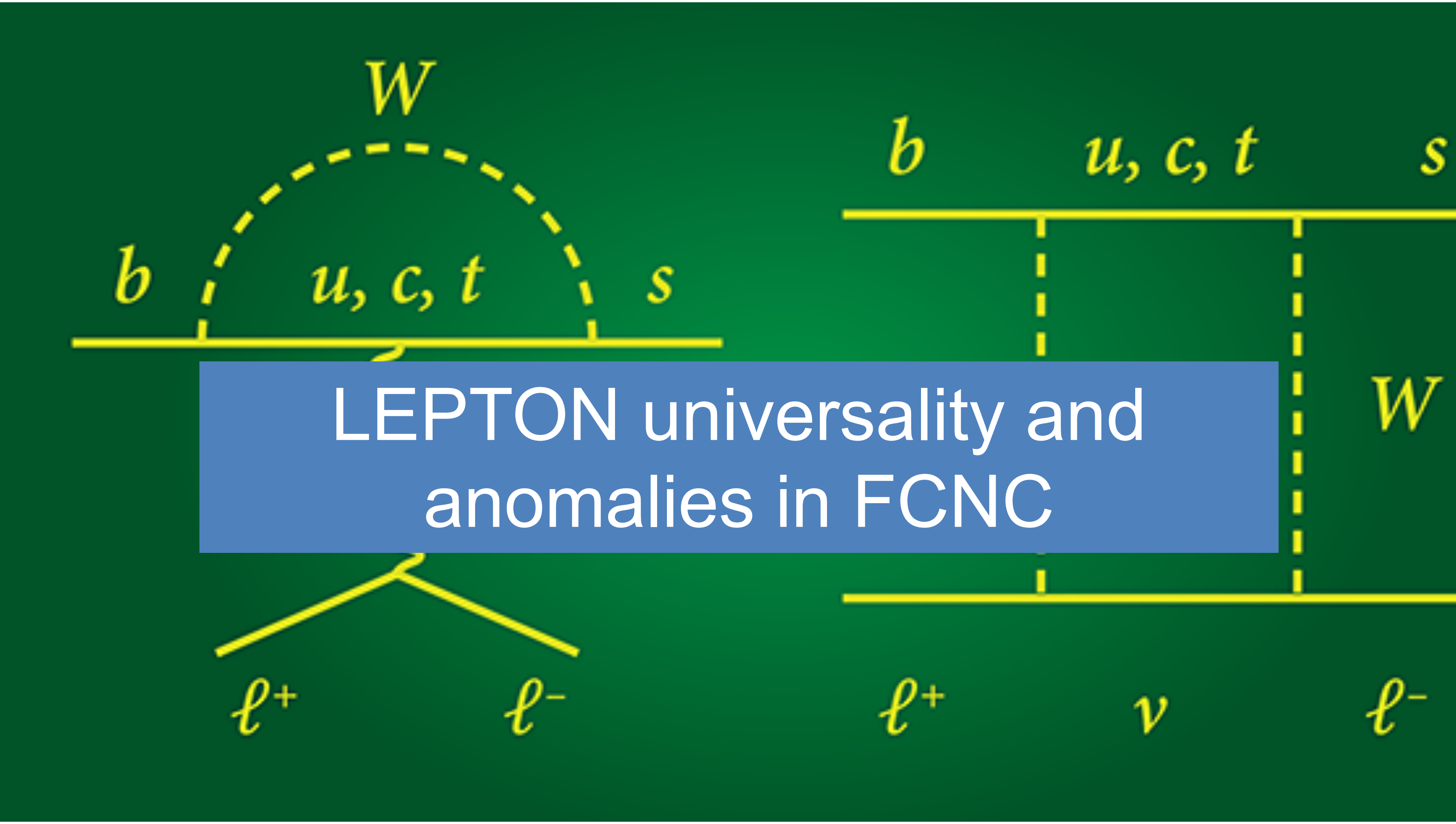




New R(D) and R(D*) measurements by Belle

arXiv:1904.08794

World average for R(D) and R(D*) 3.1σ from the SM



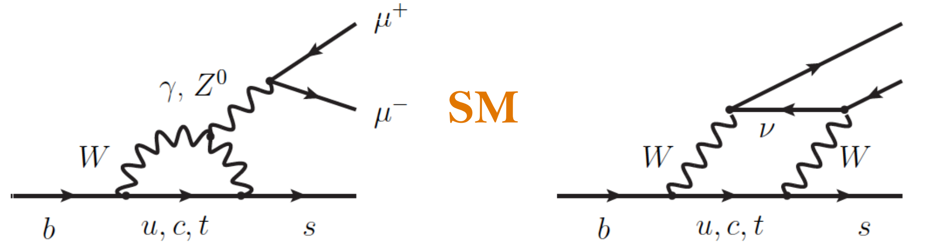
LEPTON universality and anomalies in FCNC

THE b → s $\mu\mu$ PROCESSES

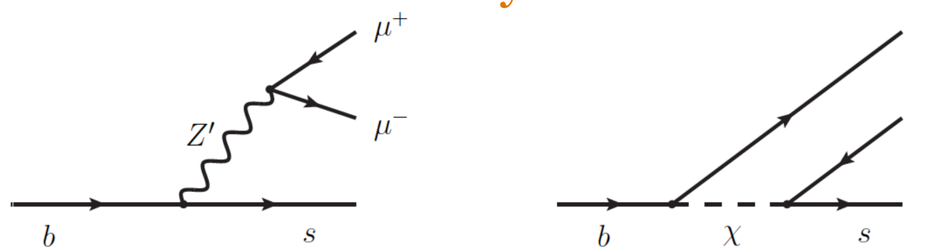
$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

- These rare processes are *forbidden* at tree level in the SM, because neutral currents (Z^0, γ) do not change flavour. They receive *calculable* loop contributions that are *small*
- These contributions are in SM normalized by the couplings of the Higgs/Yukawa sector (V_{CKM}), determined from other processes
- Beyond the SM, *new heavy particles* may contribute, altering the chiral couplings

SM



Beyond SM



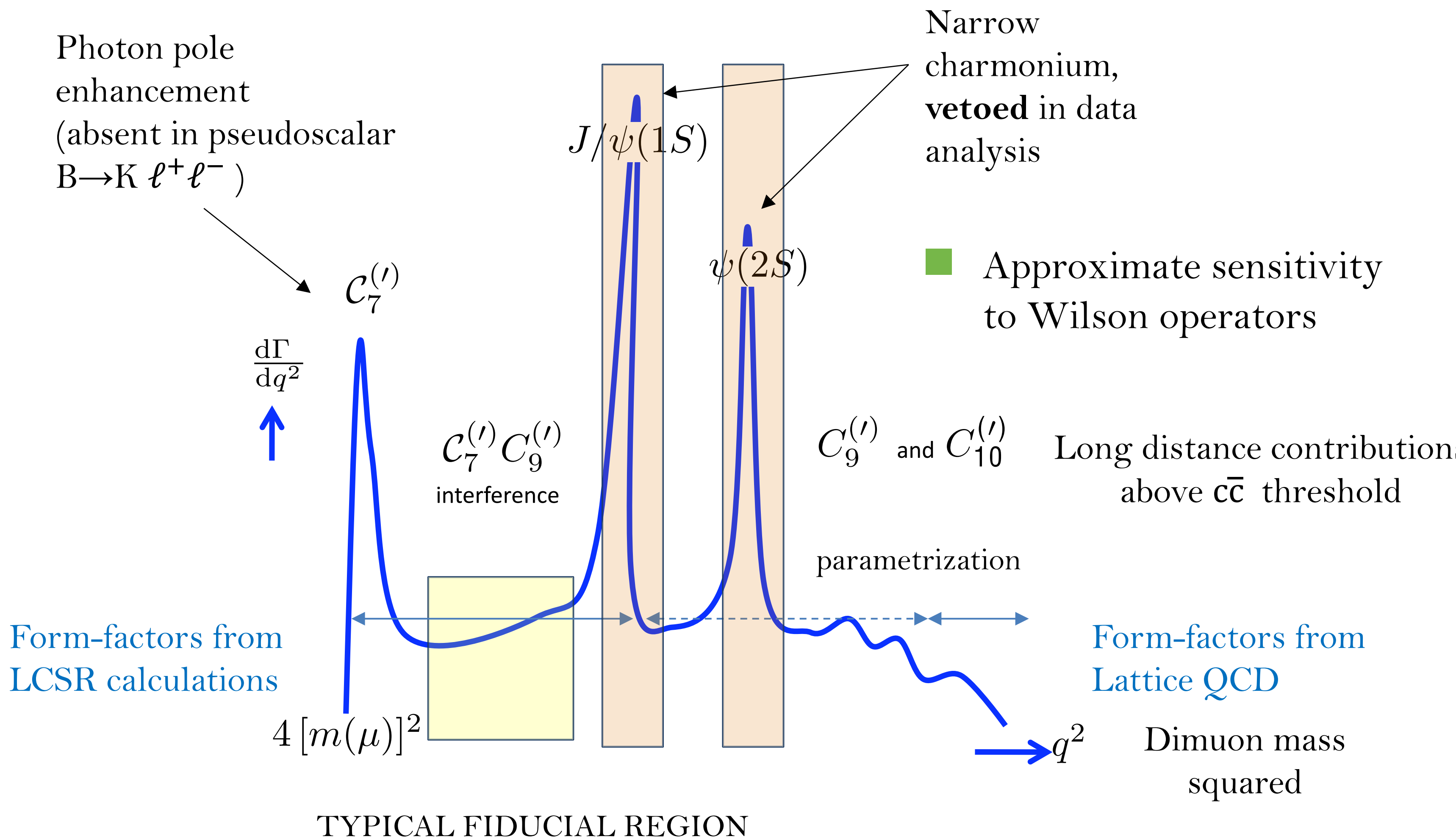
$$O_7 = \frac{e}{16\pi^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b \quad \text{[real or soft photon]}$$

$$O_9 = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu \ell \quad [\text{Z/hard } \gamma\ldots]$$

$$O_{10} = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu \gamma_5 \ell \quad [\text{Z}]$$

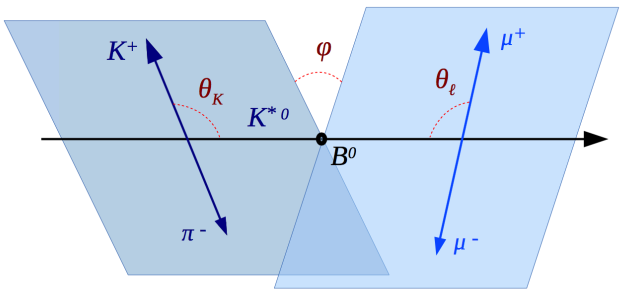
$O'_{7,9,10}$ → chirally-flipped $(1+\gamma_5)(\ldots)$

SENSITIVITY $d\Gamma(b \rightarrow s\mu\mu)/dQ^2$ SPECTRUM



ANGULAR ANALYSIS OF $B \to K^{*0}\mu\mu$

- Rare $b \to s\,\mu^+\mu^-$ decays are only allowed in the SM by calculable electroweak penguin and box diagrams, open to new heavy particles (Z', extra H…)



- Angular observables in $B^0 \to K^{*0}(K^+\pi^-)\,\mu^+\mu^-$ are characterized by 6 amplitudes: 3 K^{*0} helicities and 2 $\mu^+\mu^-$ chiralities (L,R)

$$A^{L,R}_{0,\|,\perp}$$

- The full set of 9 (CP-averaged) observables was analyzed by LHCb in 2013 arXiv:1304.6325 (1 fb^{-1}), as function of $q^2(\mu^+\mu^-)$, showing statistical agreement with the SM predictions in all of them, except *this* particular observable:

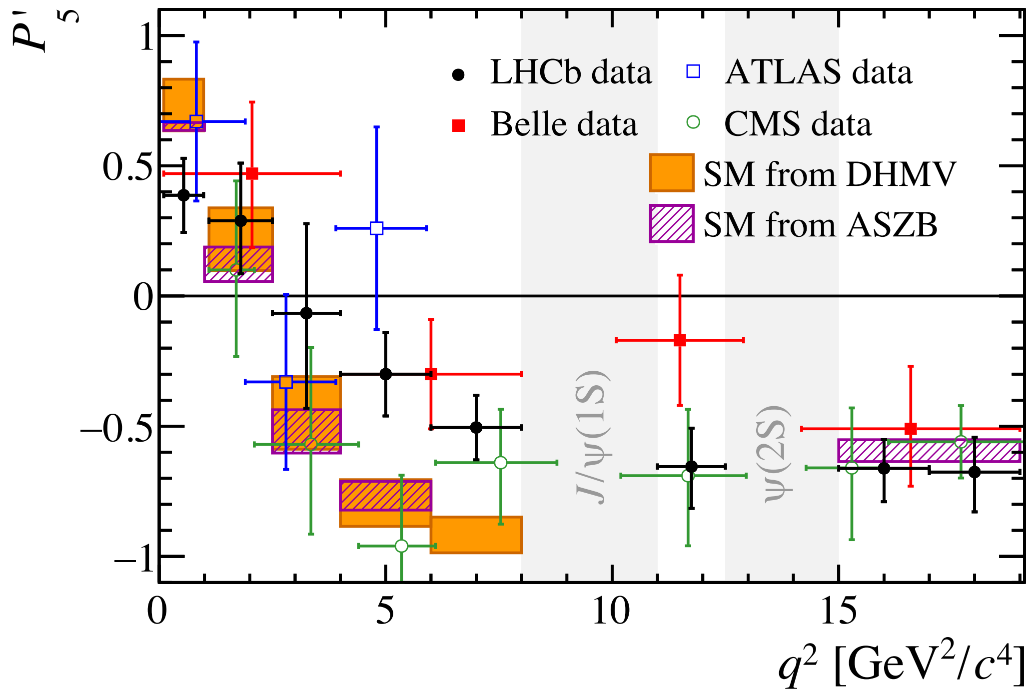
$$P_5{}' = \sqrt{2}Re\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right)/\sqrt{F_L(1-F_L)} \qquad F_L = |A_0^L|^2 + |A_0^R|^2$$

which showed a significant discrepancy (3.7σ)

- Since then, a great deal of attention has been devoted to this anomaly, both theoretically and experimentally (Belle, CMS, ATLAS)

CURRENT STATUS OF $K^{*0}\mu\mu$ ANOMALY

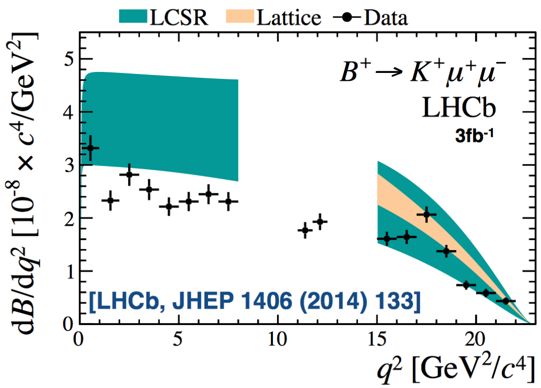
- Global significance is 3.4 σ, despite recent CMS results. Note the measurements show consistency with one another. The Belle result includes muons and electrons.



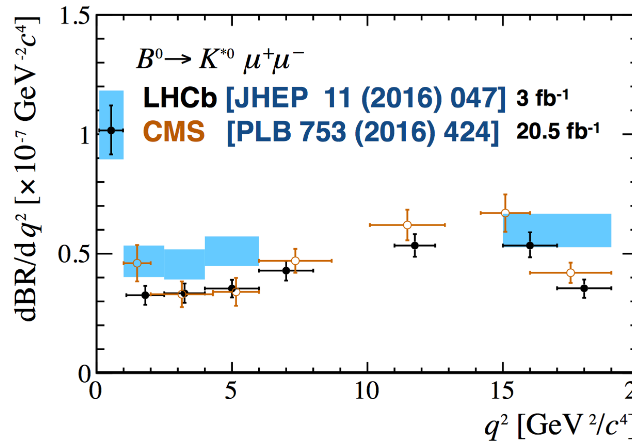
LHCb JHEP 02 (2016) 104
Belle PRL 118 (2017) 111801
ATLAS JHEP 10 (2018) 047
CMS PLB 781 (2018) 517

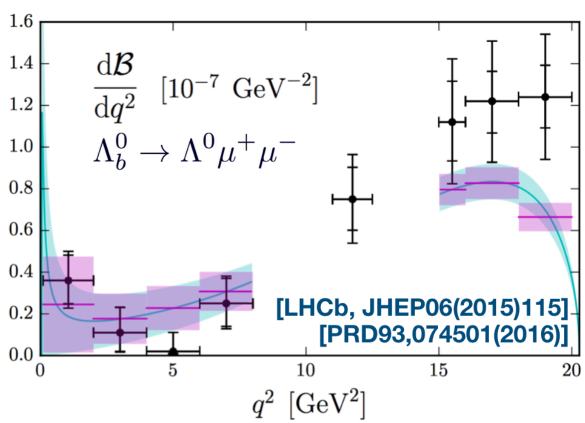
- The P'_5 observable is one of a set of so-called form-factor free observables that can be measured. SM DHMV: S. Descotes-Genon et al. JHEP 01 (2013) 048
SM ASZB: Proc. Sci. LATTICE2014 (2015) 372

OTHER $b \to s\mu\mu$ dB/dQ^2 MEASUREMENTS

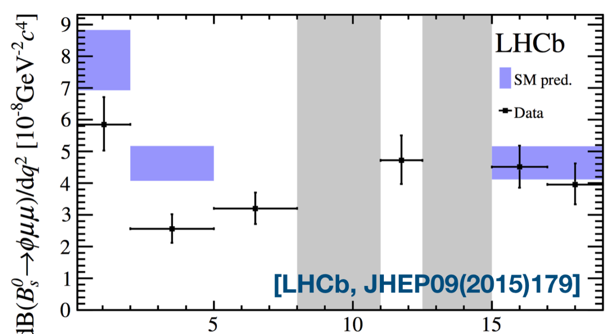


K+π-μμ (S-wave)





φ(K+K-)μμ



- various other LHCb branching fraction measurements in $b \to s\ \mu\mu$ processes have reported a similar behavior in the $0<6<q^2$ GeV^2 region

THE R_H OBSERVABLES FOR μ/e

- Lepton universality has been tested by comparing the rates $B \rightarrow H\,\mu^+\mu^-$ to $B \rightarrow H\,e^+e^-$:

$$\mathbf{R_H}\left[\mathbf{q^2_{min}}, \mathbf{q^2_{max}}\right] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \left[d\Gamma\left(B \rightarrow H\mu^+\mu^-\right)/dq^2\right]}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \left[d\Gamma\left(B \rightarrow He^+e^-\right)/dq^2\right]}\,,\quad \mathbf{q^2} = \mathbf{m^2}(l^+l^-) \quad \mathbf{H} = \mathbf{K}, \mathbf{K}^*, \phi \cdots$$

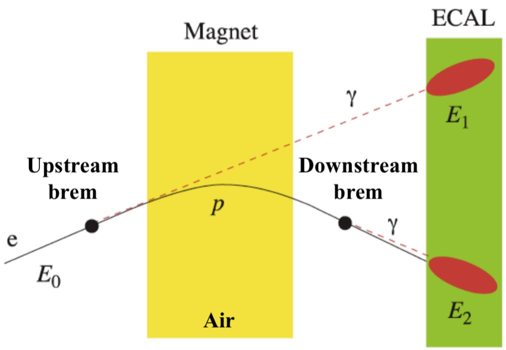
- These are flavour-changing neutral current processes of the form $b \rightarrow s\, l^+l^-$, with amplitudes involving *loop diagrams*

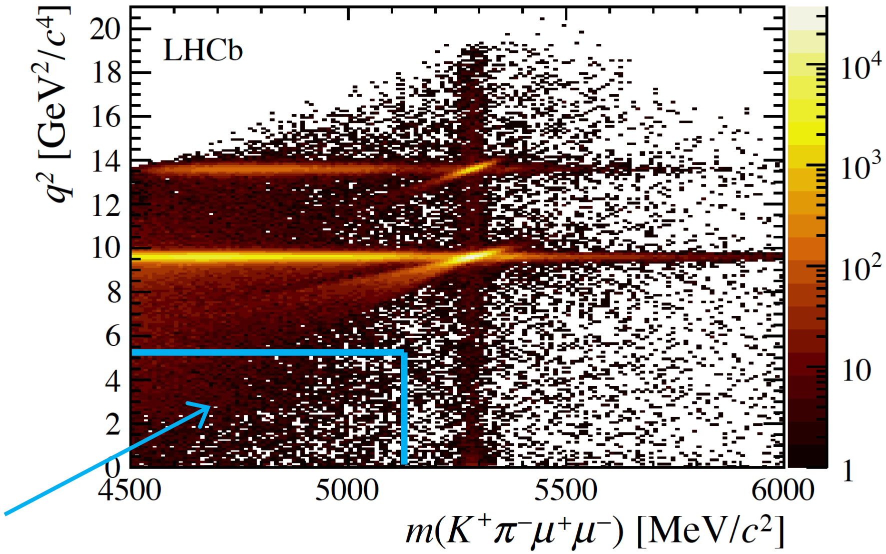
- They provide *clean probes* of New Physics, for two reasons:
  - new interactions may render *non-universal couplings* to μ and e
  - hadronic uncertainties as form factors, *cancel* in the SM (R_H=1), with QED corrections at ~ % level

JHEP 07 (2007) 040, EPJC 76 (2016) 8, 440

$\mu^+\mu^-$ VERSUS e^+e^- MEASUREMENT

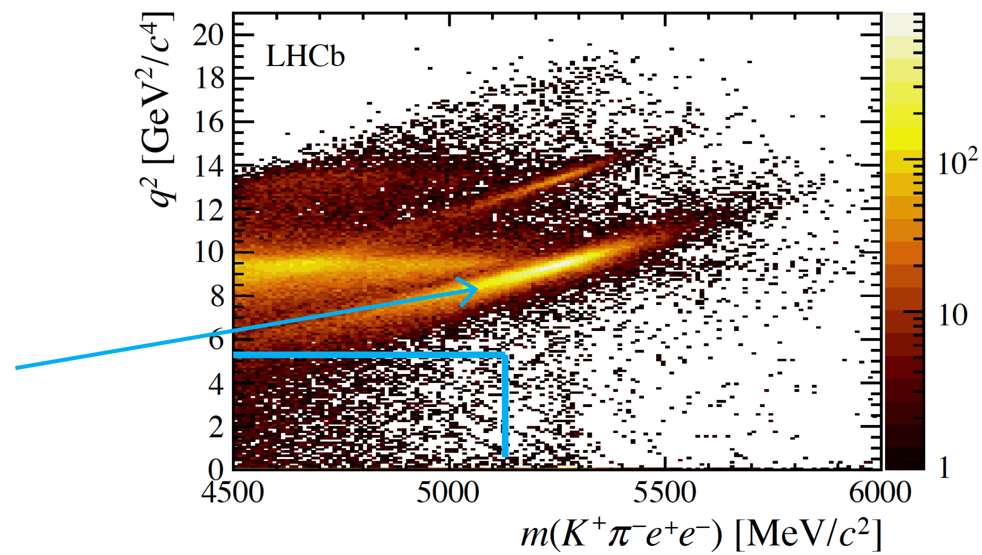
- photon-bremsstrahlung is accounted for





- upper cut of 6 GeV chosen to reduce J/ψ background

- reconstruction efficiency for e^+e^- about 5 times smaller than for $\mu^+\mu^-$

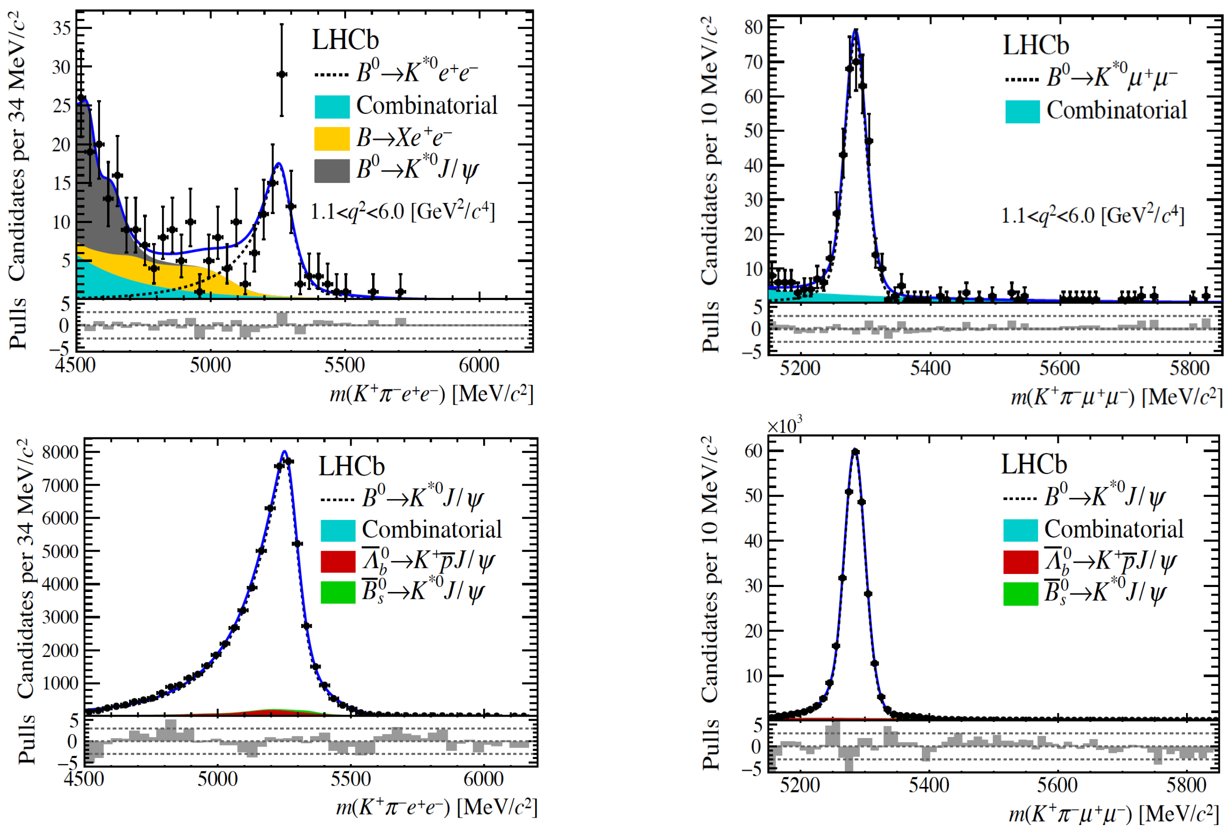


LHCb: JHEP 08 (2017) 055 (3 fb^{-1})

R_{K*} IS MEASURED AS A DOUBLE RATIO

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

R. Aaij et al. JHEP 08 (2017) 055 (3 fb^{-1})



SOME CHECKS ON R_{K^*}

R. Aaij et al., JHEP 08 (2017) 055

- $$r_{J/\psi} = \frac{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to \mu^+\mu^-\right)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to e^+e^-\right)\right)} = 1.043 \pm 0.006 \pm 0.045$$
  - very important independent test: when the same method is applied to J/ψ events, no deviation from unity is observed.
  - insensitive to kinematics (p_T, η of B^0 meson), and track multiplicity

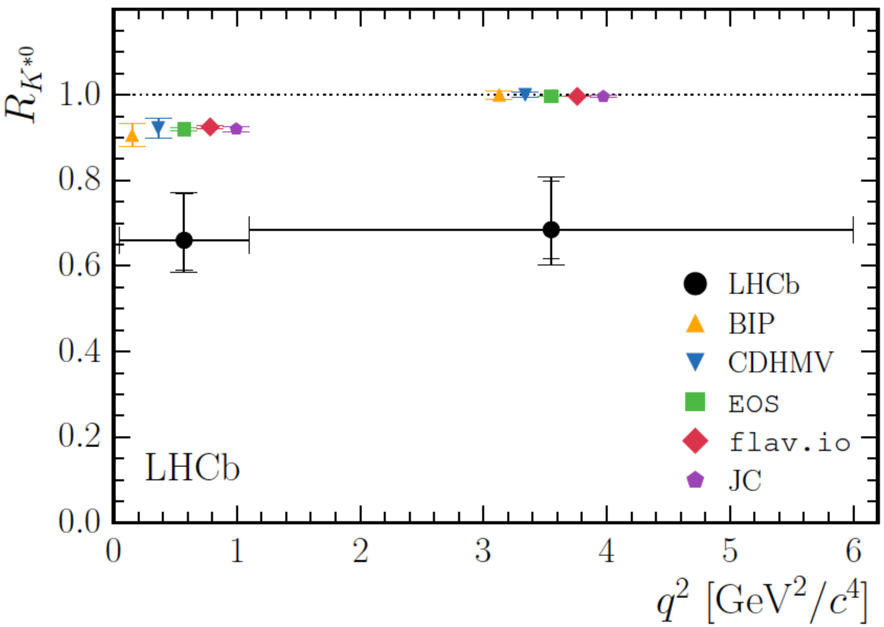
- $$R_{\psi(2s)} = \frac{\mathcal{B}\left(B^0 \to K^{*0}\psi(2s)(\to \mu^+\mu^-)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to \mu^+\mu^-\right)\right)} \Big/ \frac{\mathcal{B}\left(B^0 \to K^{*0}\psi(2s)(\to e^+e^-)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to e^+e^-\right)\right)}$$

  Compatible with 1 at 1σ (2%)

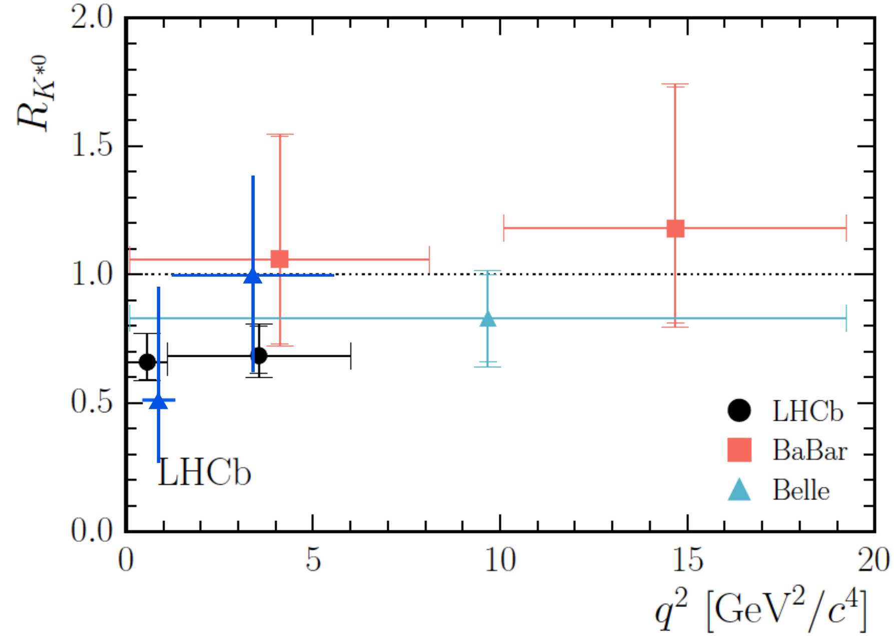
- If no correction is made to simulation, <5% change to efficiency ratio

R_{K^*} RESULT

Comparison with SM predictions



Comparison with Belle & BaBar



BIP: arXiv:1605.07633
CDHMV: arXiv:1510.04239, 1605.03156, 1701.08672
EOS: arXiv:1610.08761, https:eos.github.io
flav.io: arXiv:1503.05534, 1703.09189, flav-io/flavio
JC: arXiv:1412.3183

LHCb: JHEP 08 (2017) 055 (3 fb^{-1})
Belle: arXiv:1904.02440 (711 fb^{-1}) new result

BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

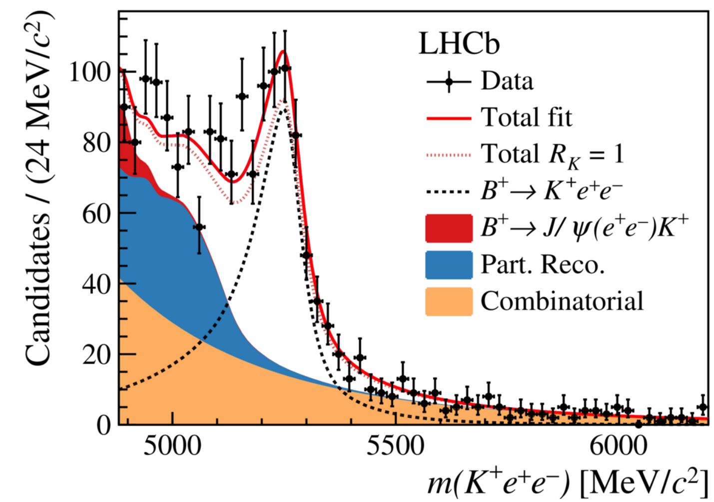
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2 \quad 2.1\text{–}2.3\,\sigma \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2 \quad 2.4\text{–}2.5\,\sigma \end{cases}$$

NEW MEASUREMENT OF R_K

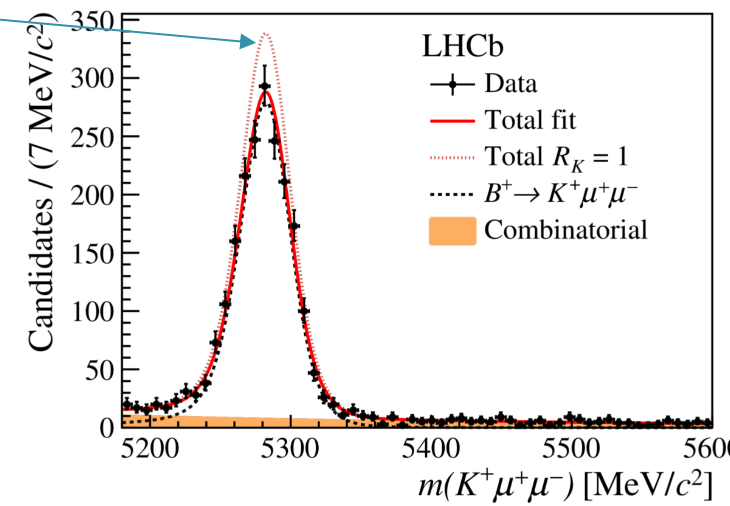
R. Aaij et al. 122 (2019) 191801

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

- LHCb has performed a thorough update of R_K measurements, with 5 fb^{-1}:
  - re-optimized analysis of Run 1 (3fb^{-1})
  - Added 2015&2016 Run 2 datasets (2fb^{-1})
- Electron/muon reconstruction assessment, in the *non resonant region*, follows similar strategy as for the R_{K*} measurement
- Simultaneous fit performed over the $\mu\mu$ and ee nonresonant candidates, using J/ψ as essential calibration tool: **partial reconstruction** background in *K*ee mainly from $B^0 \to K^{*0} e^+e^-$



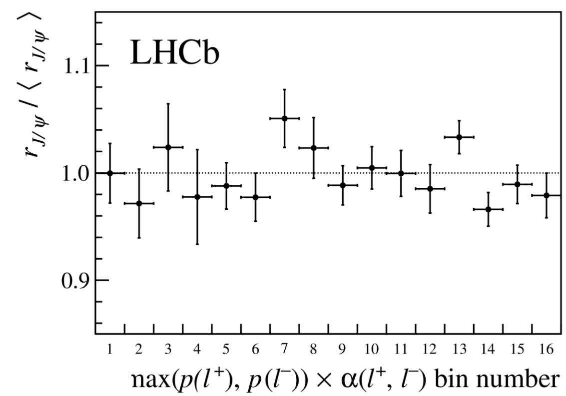
Expectation from $R_K = 1$ and $B^+ \to K^+ e^+e^-$ observed yield



R_K ANALYSIS CHECKS

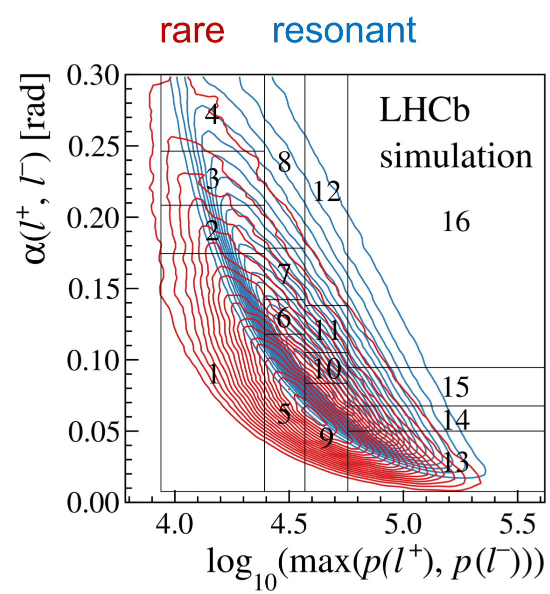
- Efficiencies computed from simulation, calibrated with several control channels selected from data
- Numerous cross-checks to ensure good understanding of efficiencies, in particular $r_{J/\psi} = 1$:

$r_{J/\psi}$ insensitive to kinematics



$$r_{J/\psi} = \frac{\mathcal{B}\left(B^+ \to K^+ J/\psi\left(\to \mu^+\mu^-\right)\right)}{\mathcal{B}\left(B^+ \to K^+ J/\psi\left(\to e^+e^-\right)\right)} = 1.014 \pm 0.035\ (\text{stat} + \text{syst})$$

- Kinematics of $J/\psi\,(\ell^+\ell^-)$ resonant and nonresonant pairs **do overlap considerably** in the laboratory frame, which facilitates calibration



$$R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.014}_{-0.016}\,(\text{syst})$$

Compatible with SM expectation at $2.5\ \sigma$

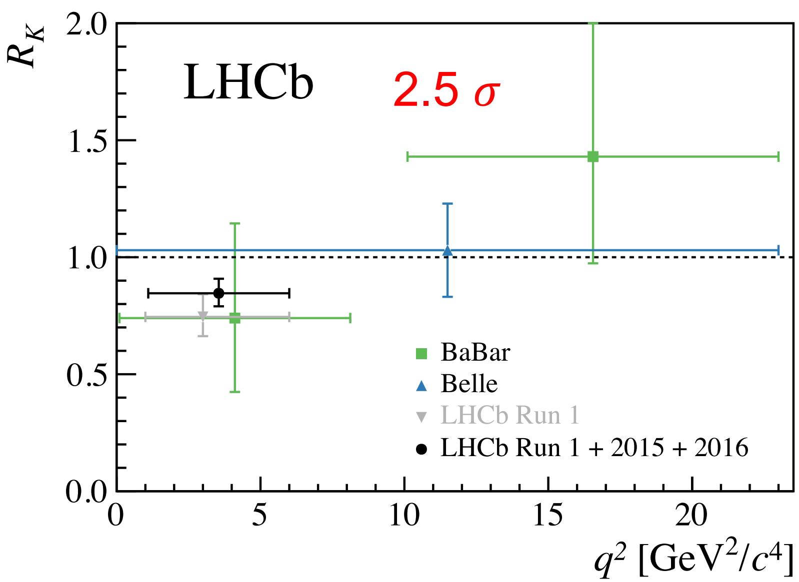
R. Aaij et al., PRL 122 (2019) 191801

SUMMARY OF LEPTON UNIVERSALITY IN $b \to s\ell^+\ell^-$

- **Ratios of muons/electrons extremely well predicted in the SM (R_K)**
  - Hadronic uncertainties of O(10^{-4}) JHEP 07 (2007) 040
  - QED uncertainties O(10^{-2}) EPJC 76 (2016) 8, 440

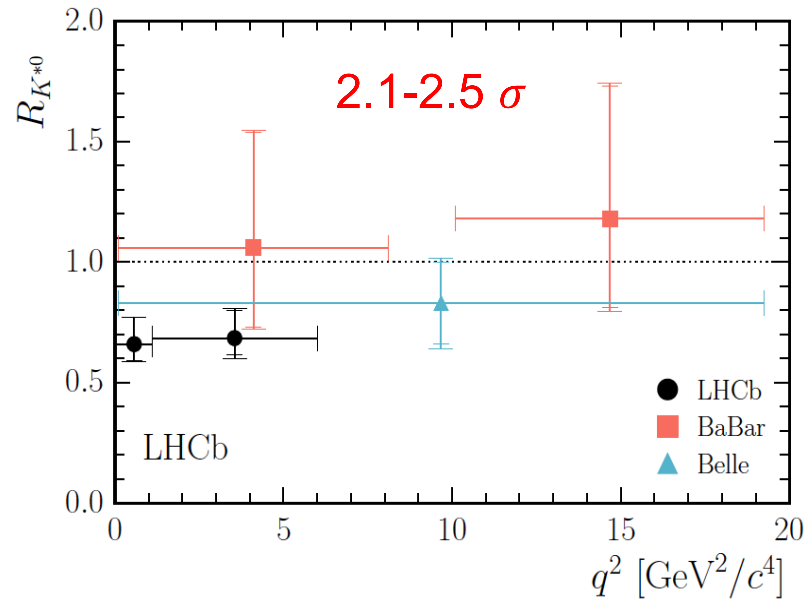
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{SM}{\cong} 1$$

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



Any statistically significant deviation from 1 indicates New Physics

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



Belle new result (K^{*0} + K^{*+}): arXiv: 1904.02440

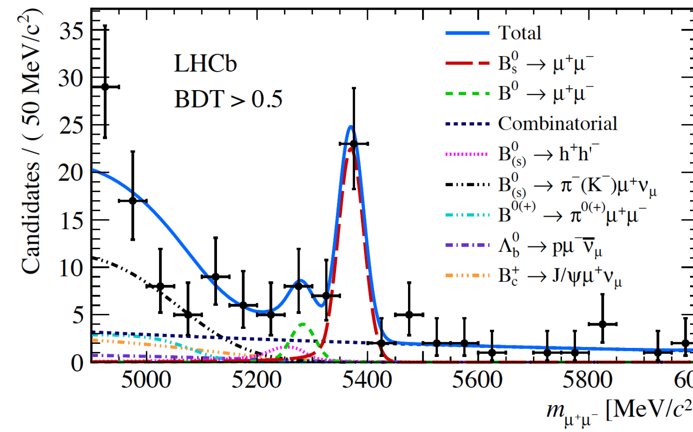
LHCb: JHEP 08 (2017) 055 LHCb: PRL 113 (2014) 151601 BaBar: PRD 86 (2012) 032012 Belle: PRL 103 (2009) 171801

$B_{(s)}^0 \to \mu^+\mu^-$ GOLDEN CHANNEL

- $B_{(s)}^0 \to \mu^+\mu^-$ is the cleanest exclusive $b \to s\, \ell^+\ell^-$ process, strongly constraining the scalar (S), pseudoscalar (P), and $C_{10}^{\mu\,\prime}$ operators, beyond the SM. All QCD effects encapsulated in a decay constant: $f_{Bs} = 230.7(1.3)$ MeV from lattice QCD
RBC-UKQCD collab. arXiv: 1311.0276, HPQCD, Fermilab Lattice and MILC collab.

- All LHC experiments have contributed to establishing the $B_s \to \mu^+\mu^-$ signal:

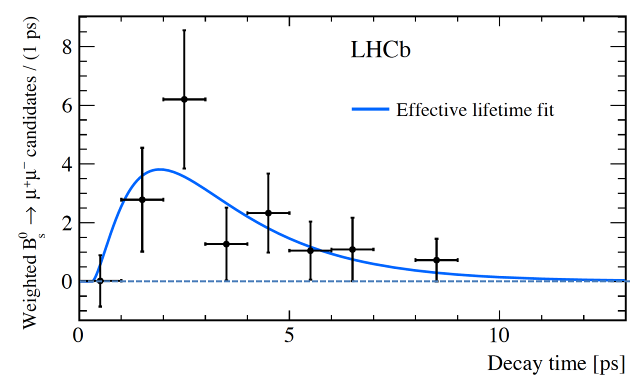
ATLAS collab. JHEP 04 (2019) 098 (**latest**, next)
R. Aaij et al., PRL 118 (2017) 191801, arXiv:1703.05747
CMS, LHCb collabs. Nature 522 (2015) 68-72



$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

- By exploiting $\Delta\Gamma_s \neq 0$, LHCb has accessed the effective B_s lifetime ($y_s \equiv \tau_{B_s^0}\Delta\Gamma/2$)

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right]$$



- Even if hardly constrained so far, a future measurement of $A^{\mu\mu}_{\Delta\Gamma} \neq +1$ (SM), would unveil NP scenarios for P, S operators
K. De Bruyn et al. PRL 109 (2012) 041801

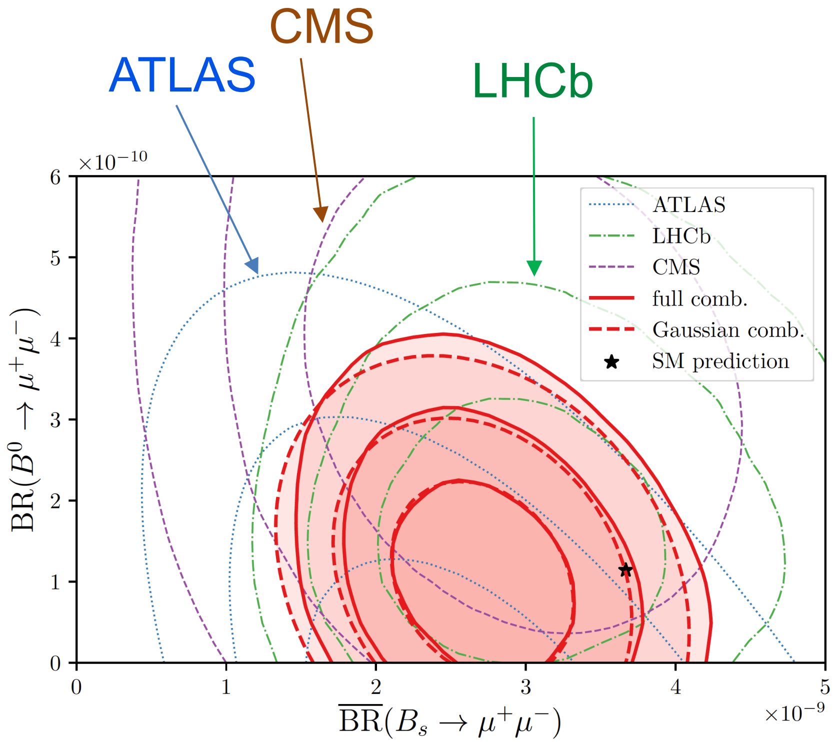
$B_{(s)}^0 \to \mu^+\mu^-$ UPDATE

- Latest measurement by ATLAS adds to the earlier results by LHCb and CMS. Because B^0 and B^0_s masses are close, some maximum likelihood unfolding is needed, that takes into account the resolution properties of each experiment

- Combined probabilities have been evaluated J. Aebischer et al. , arXiv:1903.10434 , and some tension appears with respect to the SM predictions, defined by:

$$BR(B_s^0 \to \mu^+\mu^-)_{SM} = 3.67 \pm 0.15) \times 10^{-9}$$
$$BR(B^0 \to \mu^+\mu^-)_{SM} = 1.14 \pm 0.12) \times 10^{-10}$$

- Interesting future *complementarity*, since LHCb and ATLAS/CMS seem to be measuring different linear combinations of BR's



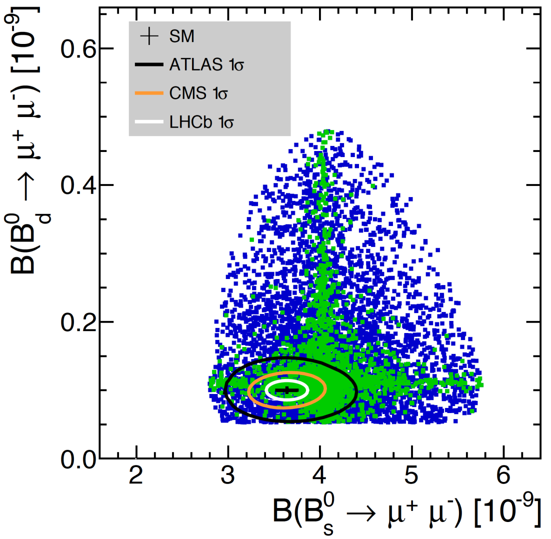
ATLAS collab. JHEP 04 (2019) 098, arXiv:1802.03017
LHCb collab. PRL 118 (2017) 191801, arXiv:1703.05747
CMS, LHCb collabs. Nature 522 (2015) 68-72

$B_{(s)}^0 \to \mu^+\mu^-$ FUTURE SCOPE

A. Cerri at al. CERN-LPCC-2018-06 , arXiv:1812.07638

- Latest LHCb and ATLAS results have reached ~ 25% uncertainty on $\mathfrak{B}(B_s \to \mu^+\mu^-)$
- Low-p_T of dimuon triggers and mass resolution will define the performance at HL–HE LHC, for $B_{s,d} \to \mu^+\mu^-$ analysis
- At LHCb, improved tracking and muon shielding will ensure non degraded performance with increasing pileup. The CMS inner tracker detector at HL–LHC will result in improved B_s/B_d separation
- The estimated experimental sensitivity at HL–LHC is close to the uncertainty of current SM *theory* prediction (dominated by f_{Bs})

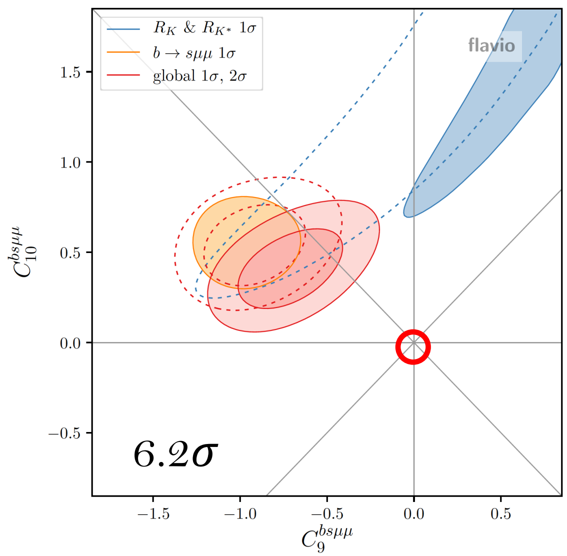
Blue, green points indicate predicted correlations from specific SUSY models, and from experimental constraints (arXiv:1501.02044)

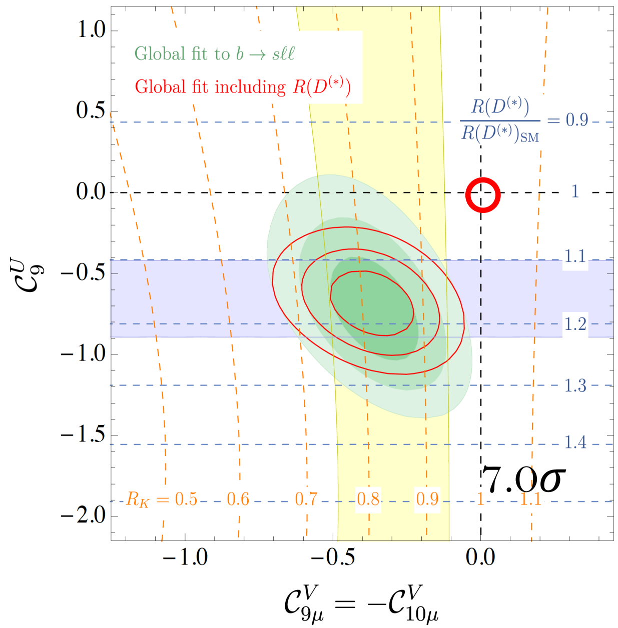


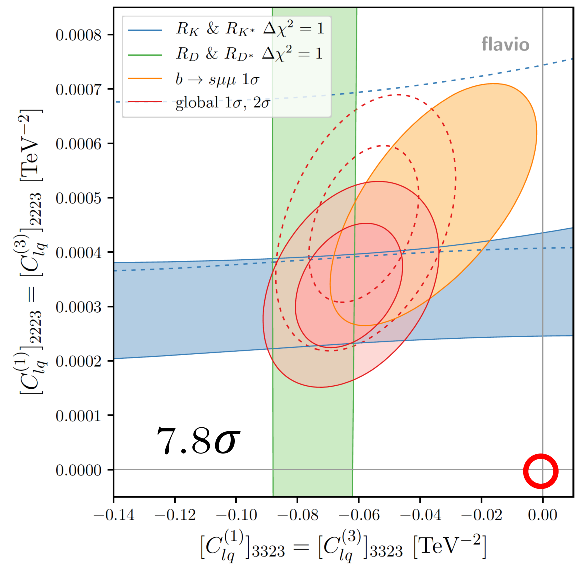
Experiment	Scenario	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ stat + syst %	$\mathcal{B}(B^0 \to \mu^+\mu^-)$ stat + syst %
LHCb	23 fb^{-1}	8.2	33
LHCb	300 fb^{-1}	4.4	9.4
CMS	300 fb^{-1}	12	46
CMS	3 ab^{-1}	7	16
ATLAS	Run 2	22.7	135
ATLAS	3 ab^{-1} Conservative	15.1	51
ATLAS	3 ab^{-1} Intermediate	12.9	29
ATLAS	3 ab^{-1} High-yield	12.6	26

MEASUREMENTS IMPACT ON SOME GLOBAL FITS

Some recent interpretations: J. Aebischer et al. [1903.10434], M. Algueró et al. [1903.09578]







- Data strongly prefer a solution with NP pointing at $C_9 = - C_{10}$
- Fits able to discriminate an additional LF-Universal *shift* in C_9
- Shift can be generated by 4-fermion operators (above EW scale), in particular a semi-tauonic operator (loop induced), also accounting for R_D , R_{D^*} data

➡ NP context: vector leptoquark, Z' models with vector-like quarks ...

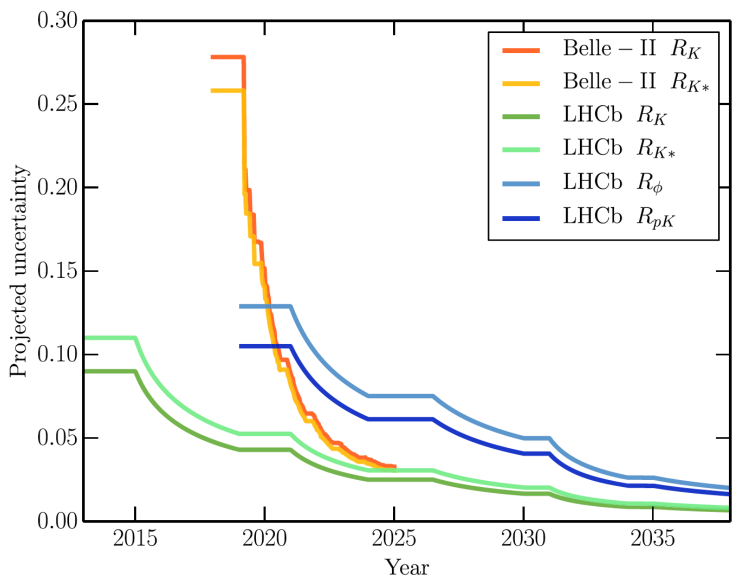
Other: A. K. Alok et al. arXiv:1903.09617, J. Kumar, D. London, R. Watanabe PR D99, 015007 (2019), M. Ciuchini et al. arXiv: 1903.09632, S. Glashow, D. Guadagnoli, K. Lane ,Phys. Rev. Lett. 114, 091801 AND MORE

PROSPECTS FOR LU TESTS IN R_{Hs} $(b \to s\ell^+\ell^-)$

- Precision in $R_{K(*)}$ expected to be comparable for Belle II and LHCb at the end of the former data taking (2025).
- For LHCb, significantly **higher efficiencies for e and μ channels** will be achieved from suppression of the hardware trigger bottleneck (after 2021). However larger pile-up in Upgrade II may increase backgrounds. Belle II precision is expected to be statistics dominated.

S. Bifani et al. J. Phys. G46 (2019) 023001
LHCb collaboration, arXiv: 1808.08865 (2018)
Belle II collaboration, arXiv: 1808.10567 (2018)

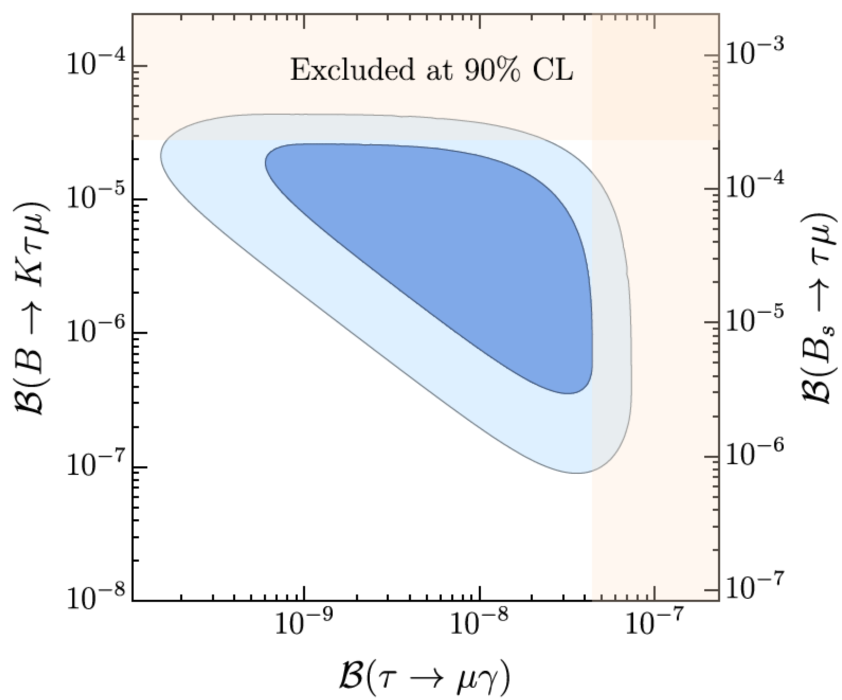
- New possibilities for LFU in $b \to s\ell\ell$ arise from R_ϕ and R_{pK} , due to the large production cross-sections. R_ϕ particularly interesting, free of backgrounds from higher hadronic resonances h→ ϕ.
- If no change in current central values of $R_{K(*)}$, both Belle II and LHCb **will be able to confirm LU violation with > 5σ** by 2025.



LEPTON FLAVOR VIOLATION SEARCHES

- In the SM, lepton flavor violation (LFV) may only occur from loop diagrams with neutrino oscillations (strong m_ν^2 suppression), unobservable at future facilities
- A presumptive breaking of lepton universality (LU) by the weak anomalies in CCs and FCNCs reinforces the importance of LFV searches, as LU violation usually implies LFV as well S.L. Glashow, D. Guadagnoli, K. Lane, PRL 114, 091801 (2015)
- LHCb has searched for $B_{(s)} \to \tau^+ \mu^-$ and $B^+ \to K^+ \mu^- e^+$ decays, with Run 1 data
- For definiteness, a three-site Pati-Salam model recently proposed, based on a vector leptoquark, can be tested

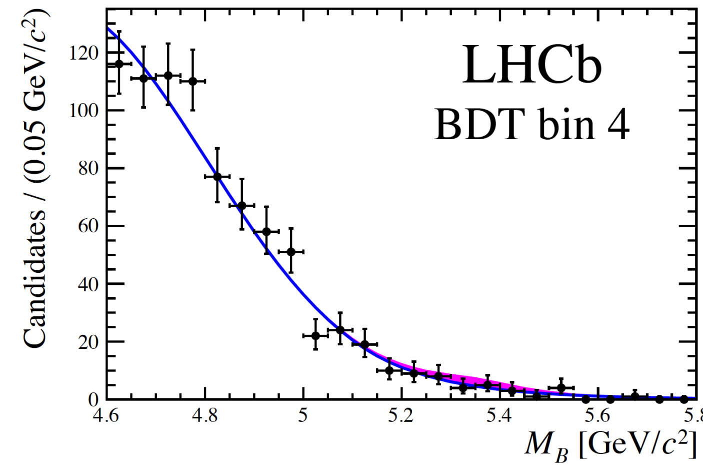
C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv: 1903.11517 (2019)



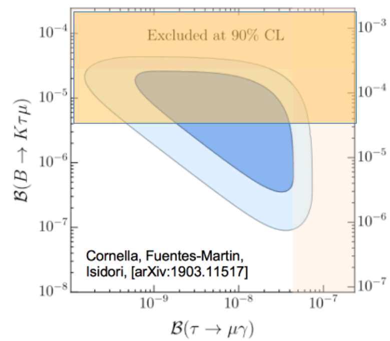
SEARCH FOR $B_{(s)} \to \tau^+ \mu^-$

LHCb-PAPER-2019-016 arXiv:1905.06614

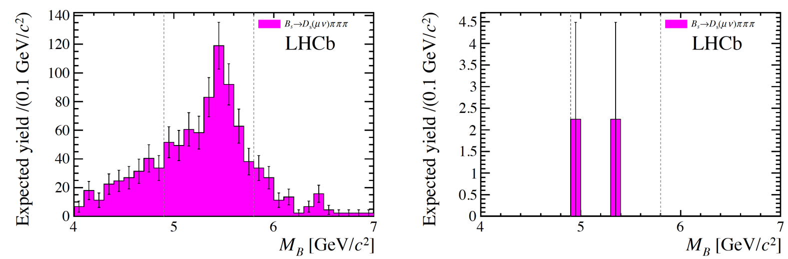
- $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ vertex detached from PV, good B-mass resolution, despite ν_τ (2-fold ambiguity). $B^0 \to D^- (\to K^+\pi^-\pi^-)\, \pi^+$ provides normalisation. Same sign $\tau^+\mu^+$ serves as background proxy.



- First measurement for the B^0_s meson, and factor ~ 2 improvement wrt to BaBar result for B^0. **Very significant constraint** to 3-site Pati-Salam model



Mode	Limit	90% CL	95% CL
$B_s^0 \to \tau^\pm\mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^\pm\mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}



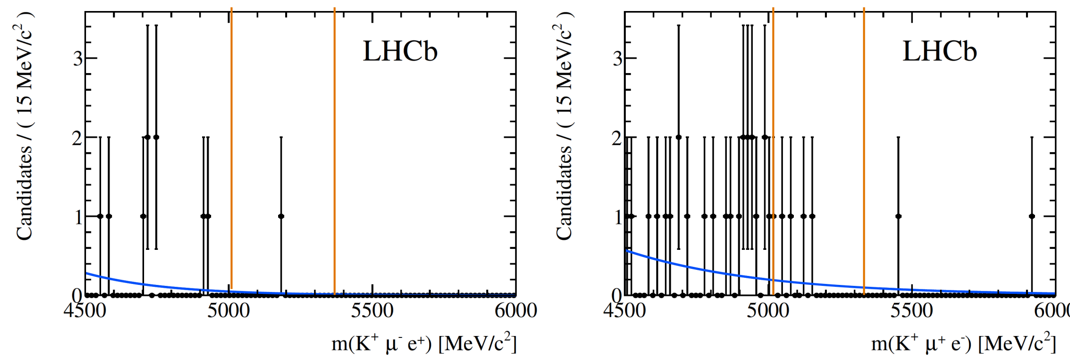
Peaking simulated sample $B_s \to D_s (\mu\bar{\nu})\, \pi\pi\pi$ before and after full selection criteria

SEARCH FOR $B^+ \to K^+ \mu^- e^+$

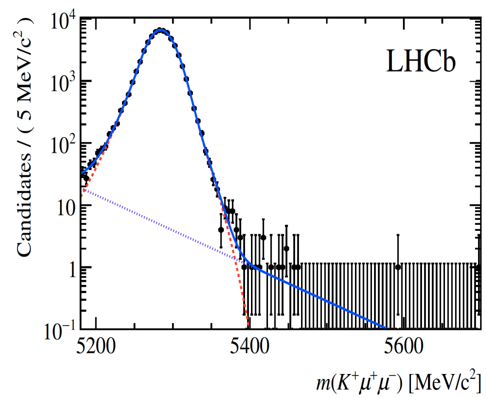
- LHCb has also searched for the LF violating decay $B^+ \to K^+ \mu^\pm e^\mp$, using 3 fb^{-1} .
- Displaced 3 charged tracks vertex, with well identified K,e, μ are required
- Normalisation is provided by $B^+ \to K^+ J/\psi\ (\to \mu^- \mu^- / e^+ e^+)$, accurately described in the analysis
- Current limits are **improved by an order of magnitude**, posing important constraints on leptoquark, extended gauge boson models, or CP violation in neutrino sector

$\mathcal{B}/10^{-9}$	90% C. L.	95% C. L.
$B^+ \to K^+\mu^- e^+$	6.3	8.2
$B^+ \to K^+\mu^+ e^-$	5.7	7.6
$B^+ \to K^+\mu^\pm e^\mp$	5.7	7.8

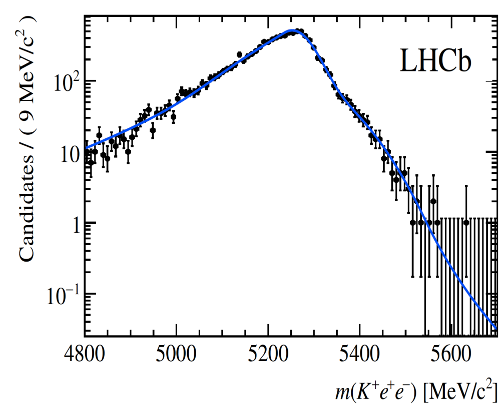
LHCb-PAPER-2019-022, preliminary



1(2) signal events observed after unblinding, respectively, in agreement with *background-only* hypothesis



Muon normalisation channel

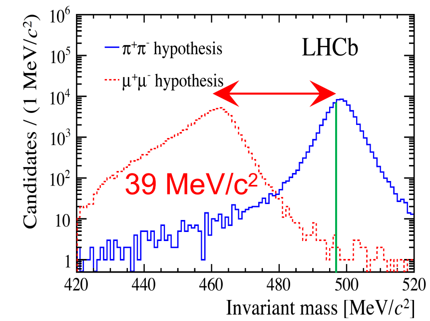


Electron normalisation channel, one bremss. photon recovered

RESULTS and OPPORTUNITIES in low-P_T TRIGGERS

SEARCH FOR $K_s^0 \rightarrow \mu^+\mu^-$

LHCb collaboration, EPJ C77 (2017) 678



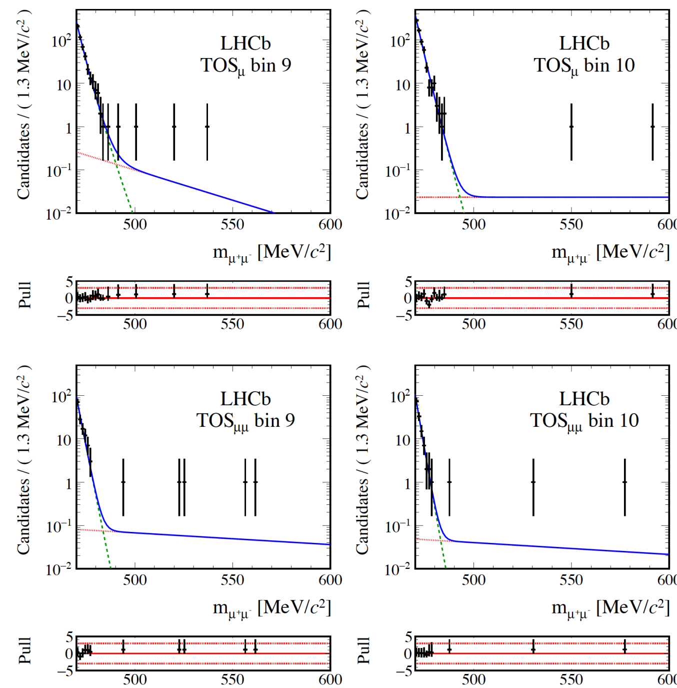
- The SM prediction for $K_s^0 \rightarrow \mu^+\mu^-$ is very strongly suppressed and dominated by long-distance contributions, which *can be constrained* using the observed $K_s^0 \rightarrow \gamma\gamma$ and $K_s^0 \rightarrow \pi^0\gamma\gamma$ leading to the prediction $\mathfrak{B}\,(K_s^0 \rightarrow \mu^+\mu^-) = (5.0 \pm 1.5)\times 10^{-12}$
  Isidori, Unterdorfer, JHEP 01 (2004) 009.

- LHCb trigger system not originally prepared for the very low-p_T s-quark physics, but drastic improvements took place for Run 2 F. Dettori, D. Martinez Santos, J. Prisciandaro, LHCb-PUB-2017-023

- LHCb with 3 fb^{-1} has obtained the *world's best upper limit* (overall improvement factor ~ 30)

$$\mathcal{B}(K_S^0 \rightarrow \mu^+\mu^-) < 0.8\ (1.0) \times 10^{-9} \text{ at } 90\%\ (95\%)\ \text{CL.}$$

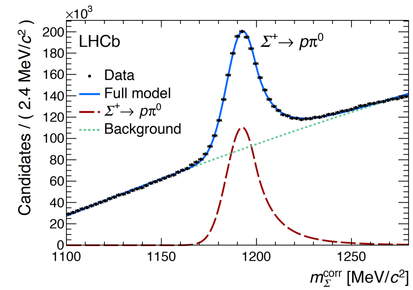
- $K_s^0 \rightarrow \pi^+\pi^-$ decays provide normalization and constitute the main background source, along with combinatorial random matchings. Dedicated multivariate clasifiers are used to strongly suppress both backgrounds.



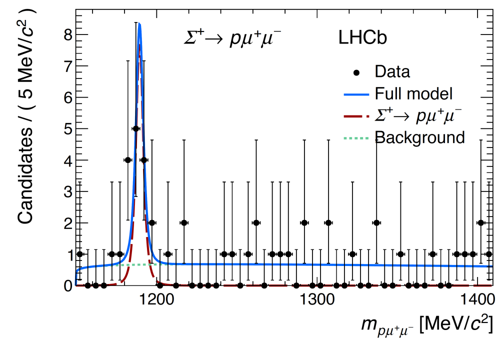
SEARCH FOR $\Sigma^+ \to p\,\mu^+\mu^-$

LHCb collaboration, PRL 120 (2018) 221803

- The HyperCP collaboration, H. Park et al. PRL 94 (2005) 021801 reported evidence of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5-4} \pm 5.5) \times 10^{-8}$ and observed 3 candidates $X^0 \to \mu^+\mu^-$ at nearly the same mass $m_{\mu\mu} = 214.3 \pm 0.5$ MeV/c^2

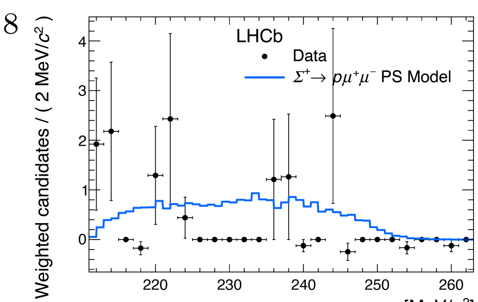


- Such particle was subject to several BSM interpretations, including a light pseudoscalar Higgs boson X.He, J. Jandeau, G. Valencia, PRL 98 (2007) 081802



- Despite the insufficient p_T of Σ^+ decays to pass the LHCb trigger, the $\Sigma^+ \to p\,\mu^+\mu^-$ signal is partially acquired independently of the signal (TIS), and so is the normalization channel $\Sigma^+ \to p\pi^0$ used in this analysis

- The decay fraction is seen $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$ compatible with the SM predictions



- A scan is steps of $\sigma_{\mu\mu}$ was made and no significant signal was found consistent with an intermediate particle, with limit:

$$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.7 \times 10^{-8}\,(95\%\mathrm{CL})$$

PROSPECTS FOR K-PHYSICS AT LHCb

- The LHCb prospects for searching $K_s^0 \to \pi^+\pi^-$ decays are excellent
- The theoretical prediction $\mathcal{B}(K_s^0 \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{LD} \pm 0.02_{SD}) \times 10^{-12}$ leaves room for small BSM contributions to interfere and compete with SM rate, such as leptoquark models (LQ), and MSSM

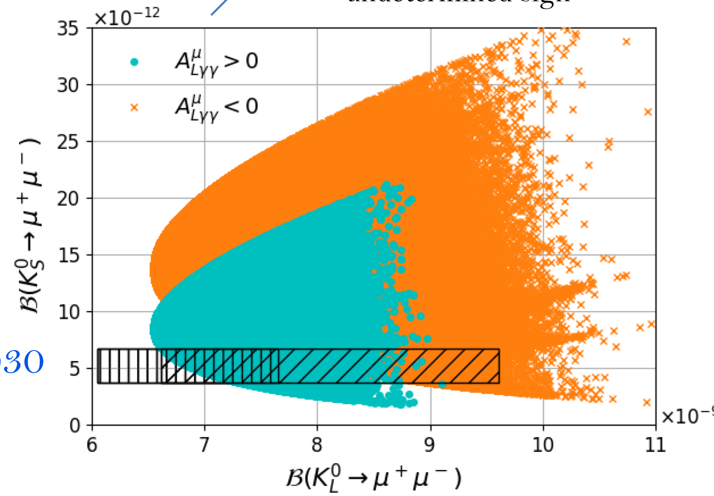
V. Chobanova et al. JHEP 05 (2018) 024. arXiv: 1711.11030

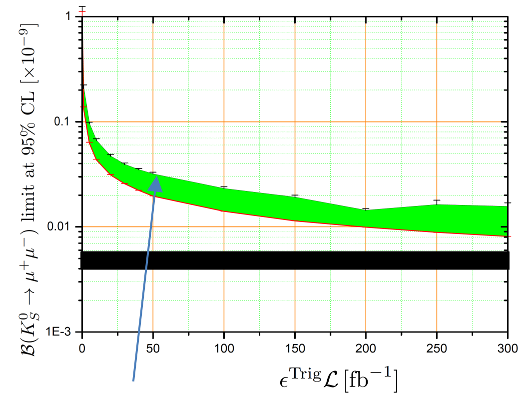
C. Bobeth, A. J. Buras, JHEP 02 (2018) 101.

- In LQ case, enhancements can reach up to the current limit, while for MSSM $\mathcal{B}(K_s^0 \to \mu^+\mu^-)$ can range within [0.78, 35.00] × 10^{-12}
- The full-software trigger, to operate at the Phase II of HL-LHC, will allow exploration of BF's below 10^{-10}. Provided $\varepsilon^{Trig} \approx 1$, LHCb could exclude BF's down to the *vicinity of the SM prediction*

A.A. Alves Junior et al. JHEP 05 (2019) 048

LD contribution is subject to undetermined sign





Estimated uncertainty on the sensitivity, due to model systematics, statistical subtraction of $K_L^0 \to \mu^+\mu^-$) background

D. Martínez Santos, LHCb collaboration EPJ Web Conf 179 (2018) 01013.

OTHER K-PHYSICS TOPICS AT LHCb UPGRADE

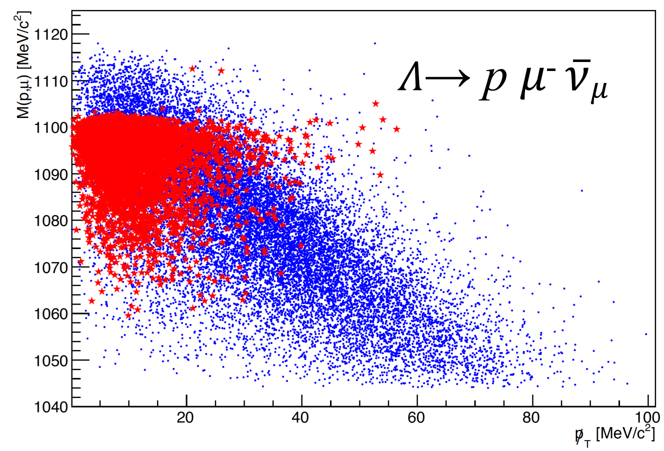
- At Run 2, LHCb trigger has provided access to muon p_T as low as **80 MeV/c** (minimum allowed by geometry and B-field), thus increasing trigger efficiency for $K_s^0 \to \mu^+\mu^-$, $K_s^0 \to \pi^0 \mu^+\mu^-$, $\Sigma^+ \to p\, \mu^+\mu^-$, $K^+ \to \pi^+ \mu^+\mu^-$, ... $\times\, \mathcal{O}(10)$ LHCb-PUB-2017-023

- With a full-software trigger (L0 removed) $\varepsilon^{\mathrm{Trig}} \approx \mathcal{O}(1)$ are attainable in the LHCb Upgrade (Phases I and II), for dimuons A.A. Alves Junior et al. , JHEP 05 (2019) 048

- Two examples of LHCb prospective measurements A. Cerri et al. CERN-LPCC-2018-06 arXiv:1812.07638 :
  - Tighter bounds on LFU can be set by improving the poorly known semimuonic hyperon decay BF's ($\Lambda \to p\, \mu\, \bar{\nu}_\mu$, $\Xi^- \to \Sigma^0 \mu\, \bar{\nu}_\mu$), since electron modes are already very well measured
  - Baryon-number and lepton-number violating decays (suppressed by $(m_W/\Lambda_{GUT})^4$) can be explored, beyond recently reported searches by CAS M. E. McCracken et al. , PR D92 (2015) 072002 , to reach sensitivities in $\Lambda \to hl$ modes of $\mathcal{O}(10^{-9})$

A.A. Alves Junior et al. , JHEP 05 (2019) 048

M($p\mu$)



background discrimination against $\Lambda \to p\pi^-$

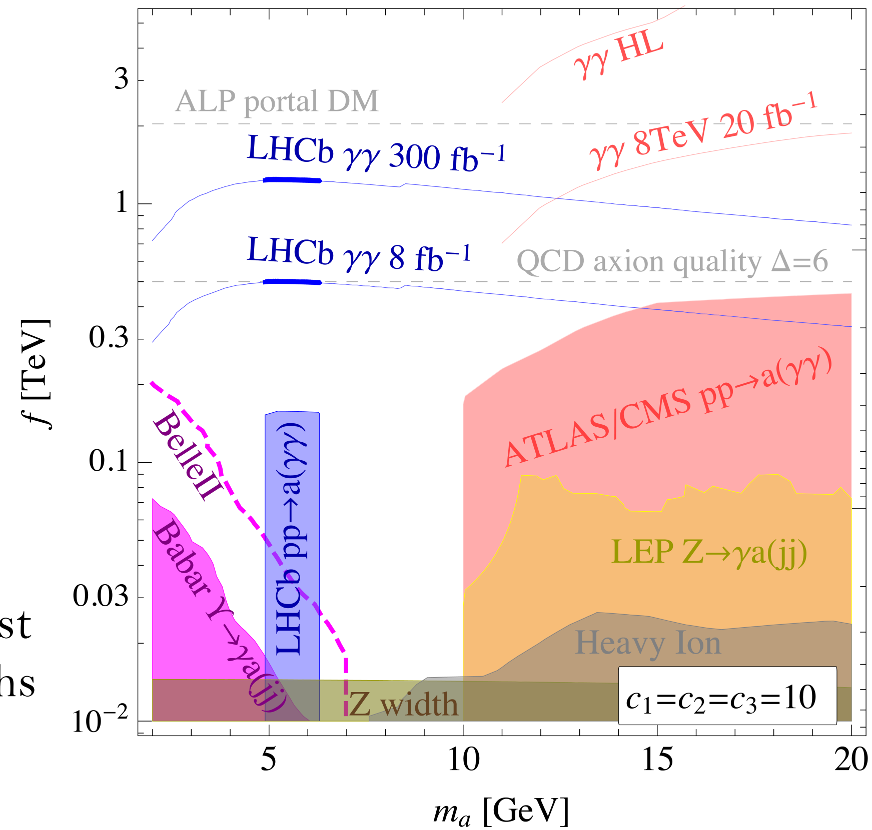
ν missing p_T in Λ plane

SEARCH FOR LOW–MASS AXION–LIKE PARTICLES

- $\mathcal{O}$(TeV) decay constants f_a for axion-like particles (ALP) are favored, both theoretically and from DM searches, with ALP's having $\gamma\gamma$ and gg couplings X. Cid Vidal et al. JHEP 1901 (2019) 113.
- LHCb has developed a low mass diphoton trigger, designed to look for the rare decay $B_s^0 \rightarrow \gamma\gamma$ LHCb-PUB-2018-006 , that motivates a dedicated LHCb search for $\gamma\gamma$ resonances in the broader mass range **$m_{\gamma\gamma} \in [3, 20]$ GeV/c²**
- Axions acquire a significant longitudinal boost and no extra E_T-jets are needed. Decay widths $\Gamma_{\gamma\gamma}$ and Γ_{gg} are very narrow, so that:

  $(0.1\text{mm})^{-1} \ll \Gamma_{\gamma\gamma} + \Gamma_{gg} \ll m_{\gamma\gamma}^{\text{bin}}$
- LHCb sensitivity to f_a in σ (pp→ a), for expected $\int\mathcal{L}dt$ values, is *very complementary* to that of ATLAS and CMS at higher masses

X. Cid Vidal et al. JHEP 1901 (2019) 113.



$$\mathcal{L}_{\text{eff}} \supset \frac{N\alpha_3}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{E\alpha_{\text{em}}}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

SUMMARY

- The LHCb experiment has successfuly completed Run 1 and Run 2 (2010-2018) and collected nearly 9 fb^{-1} of integrated luminosity, as originally conceived
- A program of *precision* measurements of CP-violation in the b- and c-sectors has been carried out. CP-violation has been observed in the charm sector at the level 10^{-3}, and ascribed to direct decay amplitudes. Searches for new physics will continue to even higher precision.
- Detailed investigations have been performed on LFU, both in charged currents and in flavor-changing neutral currents, and on weak anomalies and LF-violating decays. Studies will continue to elucidate whether amplitudes beyond the SM are required to understand the data.
- An Upgrade program is underway (Phase I), and the physics case has been made public for a Phase II, within a HL LHC, beyond 2030.
- QCD studies have not been discussed, where a very rich field of new measurements has been launched, both exotic and non exotic.

MEJORAS FUTURAS DE MADRID.

LA GRAN VIA:

VISTA, MIRANDO AL ESTE, DESDE SU ENCUENTRO CON LA CALLE DE LA CORREDERA BAJA DE SAN PABLO.

(Proyecto del arquitecto municipal D. Carlos Velasco.)