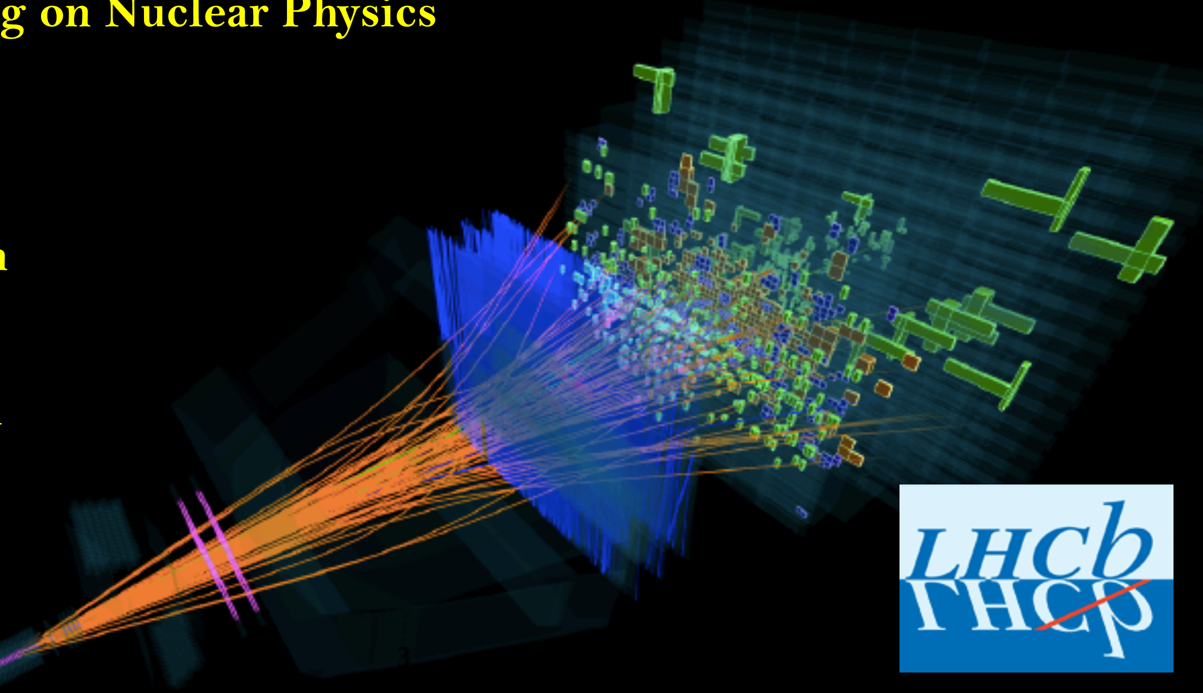
Flavor Results at LHCb

57th International Winter Meeting on Nuclear Physics



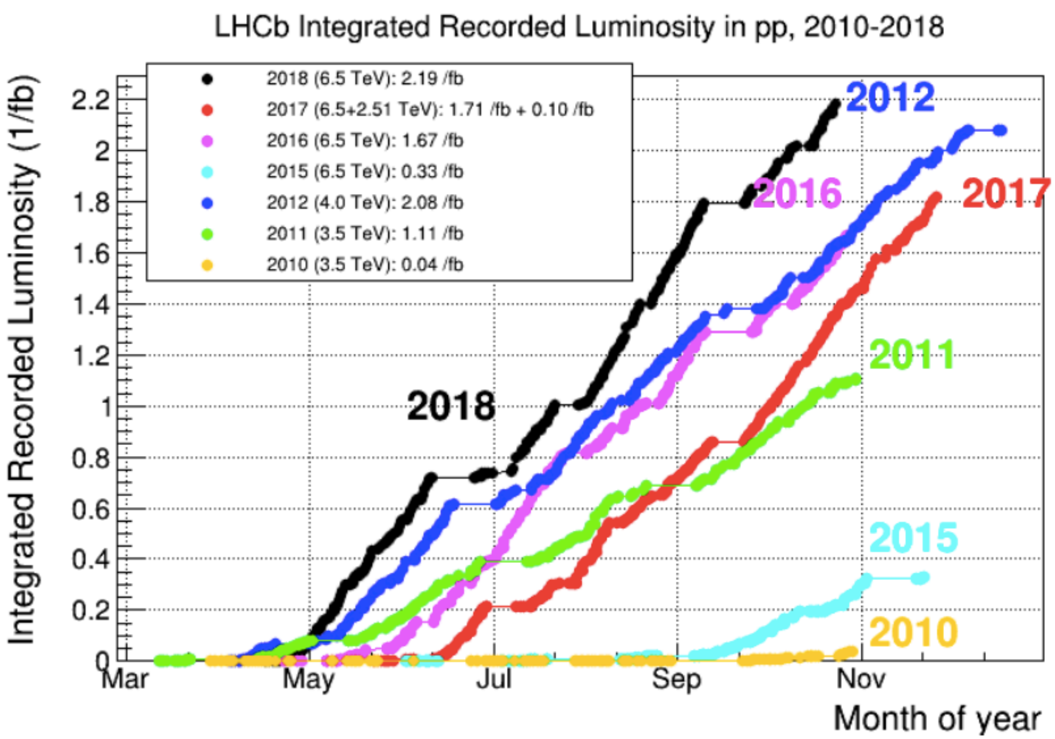
P. Campana (Frascati INFN)
on behalf of LHCb Collaboration

January 21st, 2019 - Bormio, Italy

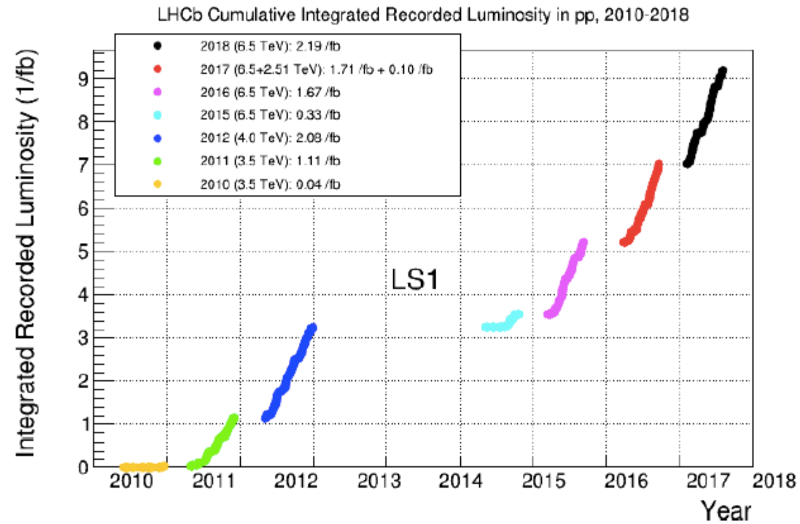
Talk outline

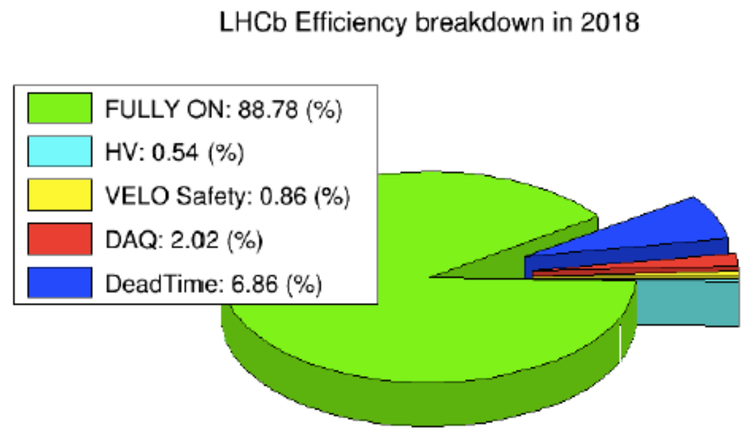
- Run 1 and Run 2 data taking
- Rare Decays
- Status of Weak Anomalies
- CP violation
- The LHCb Upgrade

Run 1 and Run 2 data taking



Since the start of LHCb
>10 fb^{-1} delivered, >9 fb^{-1} collected



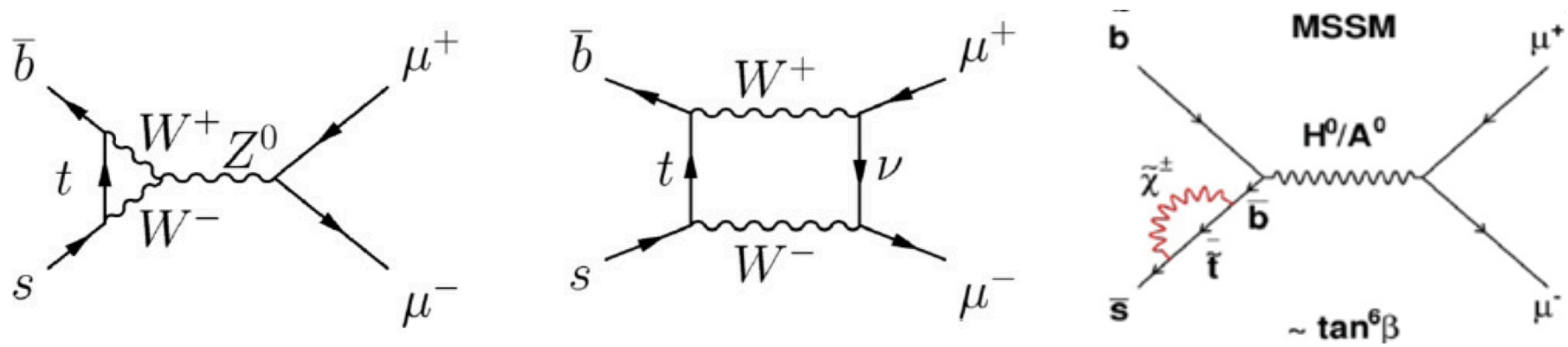


- Outstanding performance of LHC and of LHCb (~90% data taking efficiency)
- Run 1+2 statistics ~ 4 ÷ 6 x Run 1 (including higher b-quark production cross-section and higher selection efficiency of final states)
- LHCb Technical Proposal (1998) goal: **10/fb** (at 14 TeV)

Rare Decays

The golden channels: $B_{s(d)} \to \mu\mu$

At the beginning of LHC, a long-awaited FCNC process to demonstrate the existence of Supersymmetry, being possibly mediated by new currents which could modify the branching fractions



Theoretically very clean and very rare decays (C. Bobeth et al. PRL112 (2014) 101801)
BR ($B_s \to \mu\,\mu$) $= 3.6 \pm 0.2\ 10^{-9}$, BR ($B_d \to \mu\,\mu$) $= 1.1 \pm 0.2\ 10^{-10}$

$$\mathrm{Br}_{\mathrm{MSSM}}(B_q \to \ell^+\ell^-) \propto \frac{M_b^2 M_\ell^2 \tan^6\beta}{M_A^4}$$

Large contributions to BR in SUSY models

LHCb, CMS and ATLAS measurements. **1st single observation from LHCb**

BR($B_s \to \mu\,\mu$) at 7.8 σ significance !

A milestone in flavor physics

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

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

No NP effects observed. A first effective lifetime measurement also performed:

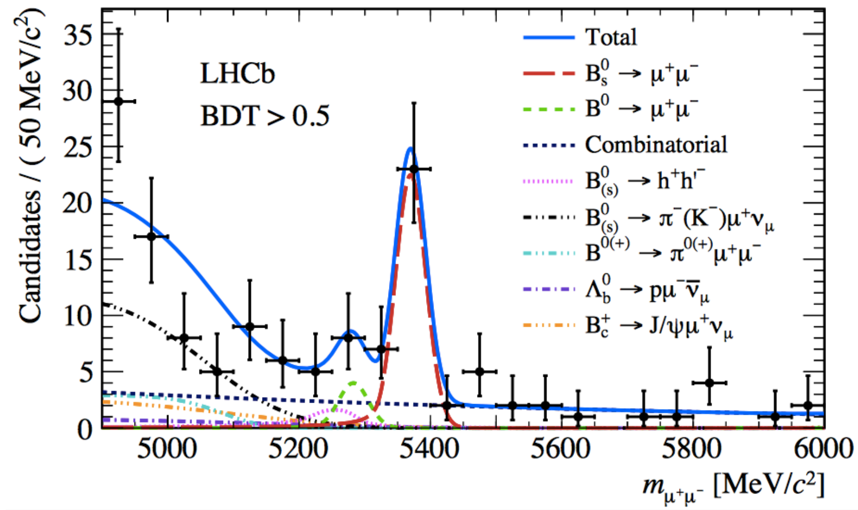
$$\tau_{\text{eff}}(B_s(t) \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\,ps$$

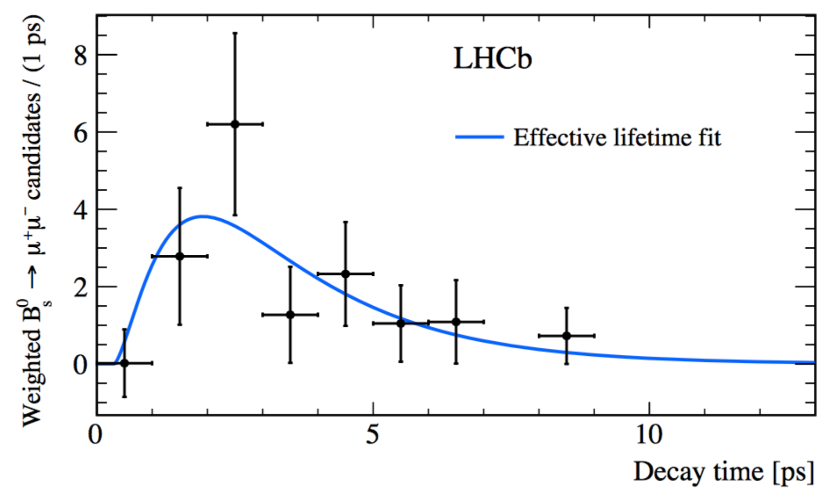
Average HFLAV $\tau(B_s)$=1.510±0.005 ps

In SM only heavy B_s mass eigenstate (B_s^H) decays to $\mu^+\mu^-$
Measurement of decay time can disentangle anomalous contribution from B_s^L and spot non-SM effects

Full Run 1+2 statistics = ~ x 3 this sample

PRL118 (2017) 191801





Dataset: Run 1 (3/fb) + Run 2 (1.4/fb)

Weak Anomalies

From the analyses of Run 1 data, **four** interesting anomalies appeared, pointing to possible violations of lepton universality

- In R_K and R_{K*} observables, from the FCNC $\mathbf{b \to s\, l^+l^-}$ process involving loops

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

- In R_{D*} (R_D) observables, testing universality in $B \to D^{(*)}\, \boldsymbol{\tau/\mu\ \nu}$ decays

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

- Same as before, but with B_c decays

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

- In dB/dq^2 and angular distributions of $B \to \mathbf{h}\ \mu\mu$ decays (h=K, K^*, $\boldsymbol{\phi}$, $\boldsymbol{\Lambda}$)

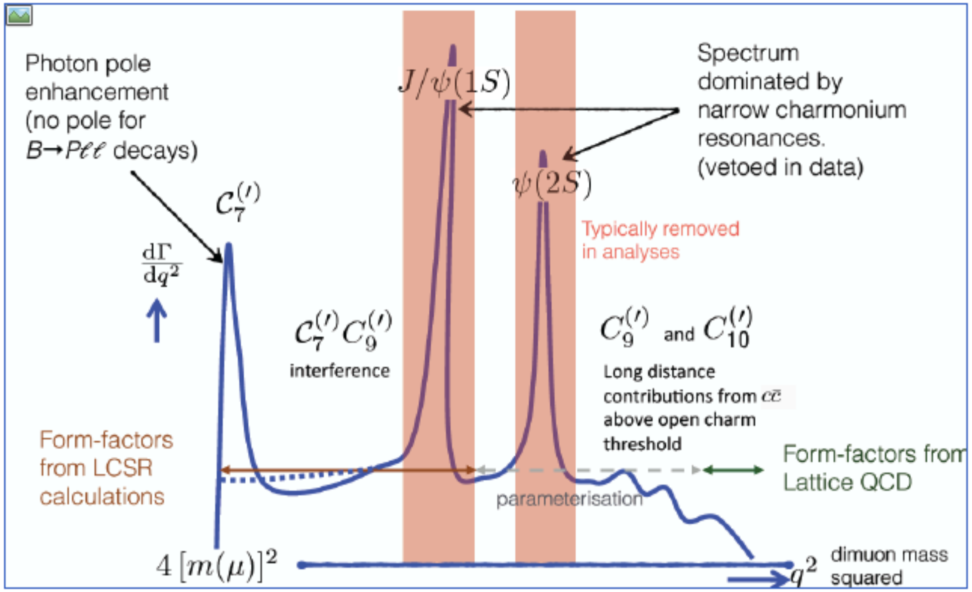
R_K and R_{K*} : a test of μ/e lepton flavor violation

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, with QED corrections at ~ % level

A complex $l^+ l^-$ spectrum (resonances, hadronic effects, ...) q^2 upper limit set to 6 GeV² to avoid J/ψ(1S)

μ and e reconstruction efficiencies very different (5:1) due to the bremsstrahlung effects

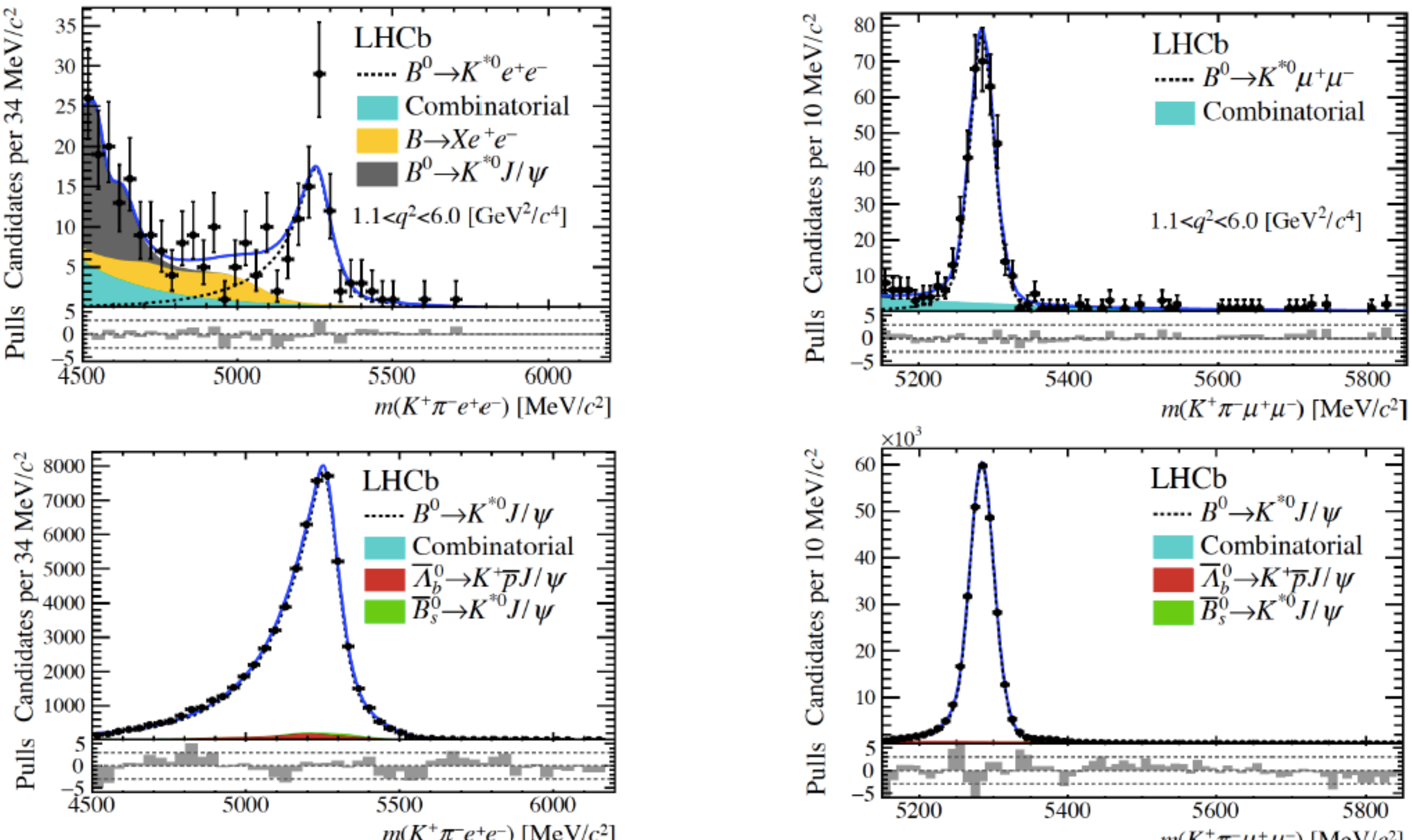


T. Blake CKM 2018

BRs normalized to control samples B→K$^{(*)}$ J/ψ (μμ / ee)

Measuring R_{K*} double ratio (Run 1 data)

JHEP08 (2017) 055



R_{K^*} measurement cross checks

- $$r_{J/\psi} = \frac{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to \mu^+\mu^-\right)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to e^+e^-\right)\right)} = 1.043 \pm 0.006 \pm 0.045$$

- $$R_{\psi(2s)} = \frac{\mathcal{B}\left(B^0 \to K^{*0}\psi(2s)(\to \mu^+\mu^-)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to \mu^+\mu^-\right)\right)} \Bigg/ \frac{\mathcal{B}\left(B^0 \to K^{*0}\psi(2s)(\to e^+e^-)\right)}{\mathcal{B}\left(B^0 \to K^{*0} J/\psi\left(\to e^+e^-\right)\right)}$$ *Compatible with 1 at 1σ (2%)*

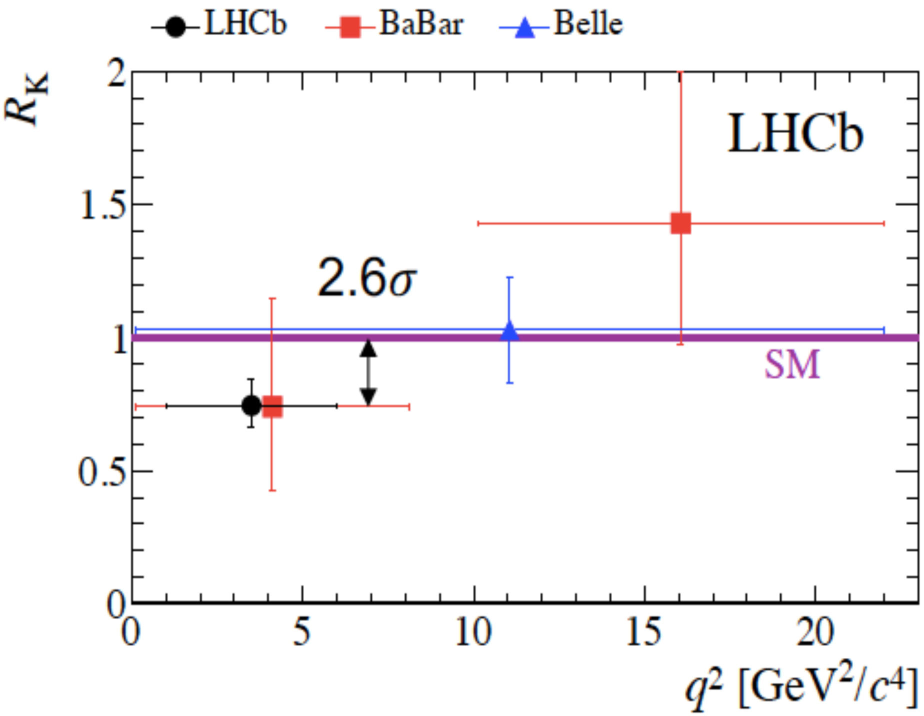
- $\mathcal{B}\left(B^0 \to K^{*0}\gamma\right)$ measured from γ-conversions (7%), agrees with expectations (2σ)

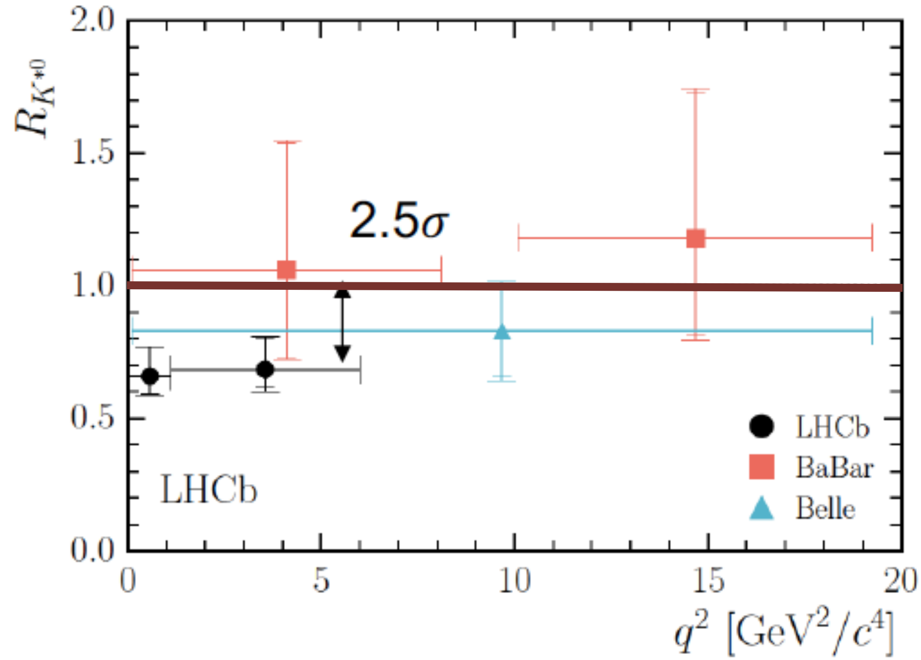
- If no correction is made to simulation, <5% change to efficiency ratio

- $\mathcal{B}\left(B^0 \to K^{*0}\mu^+\mu^-\right)$ is also measured, in agreement with JHEP11 (2016) 047

- Bremsstrahlung simulation is checked with $B \to K^* J/\psi\ (ee)$ *and* $B \to K^*\gamma\ (\to ee)$

R_K and R_{K*} LHCb results





$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ ~ 2.6 σ from SM PRL113 (2014) 151601 (3/fb)

$$R_{K^{*0}} = \begin{cases} 0.66 \, {}^{+\,0.11}_{-\,0.07} \, (\text{stat}) \pm 0.03 \, (\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \ \text{GeV}^2/c^4 \\ 0.69 \, {}^{+\,0.11}_{-\,0.07} \, (\text{stat}) \pm 0.05 \, (\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0 \ \ \text{GeV}^2/c^4 \end{cases}$$

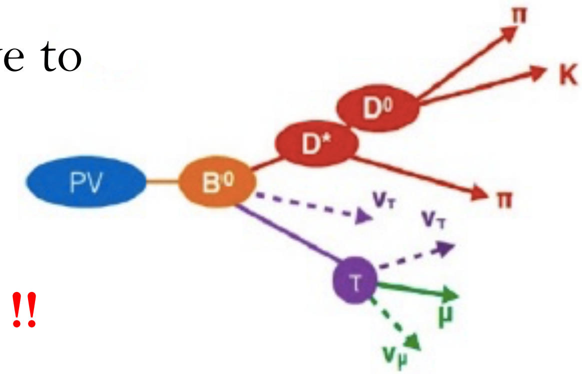
~ 2.5 σ from SM

JHEP08 (2017) 055 (3/fb)

Perspectives for Run 1 & 2 analyses: **σ_{stat} (R_{K*}) ~ 0.05 - σ_{stat} (R_K) ~ 0.04**

Tests of τ/μ LFV in $b \to c\, l\, \nu$

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)} \tau \bar{\nu}_\tau)}{BR(B \to D^{(*)} \mu \bar{\nu}_\mu)}$$



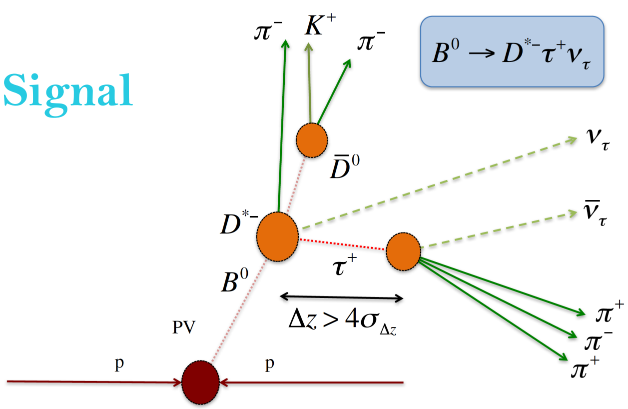
- R_{D*} (R_D) are theoretically clean observables, sensitive to NP, as τ can couple to new charged Higgs.
  In SM $R_{D*} = 0.252 \pm 0.003$, $R_D = 0.299 \pm 0.003$
- Hadronic uncertainties and $|V_{cb}|$ cancel in ratios
- τ are difficult: **1st time fully reconstructed at LHC !!**
  All tools of kinematical reconstruction in use

Two LHCb R_{D*} measurements:

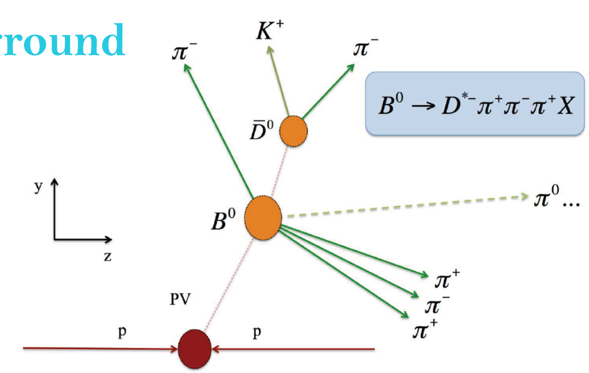
- PRL115 (2015) 111803, with $\tau \to \mu\nu\nu$ — $R_{D*} = 0.336 \pm 0.027 \pm 0.030$
- PRL120 (2018) 171802, with $\tau \to 3\pi(\pi^0)\nu\nu$ — $R_{D*} = 0.291 \pm 0.019 \pm 0.029$
  PRD 97 (2018) 072013

Separation between B and τ critical to disentangle signal from bkg ($B^0 \to D^* 3\pi X$)

Signal

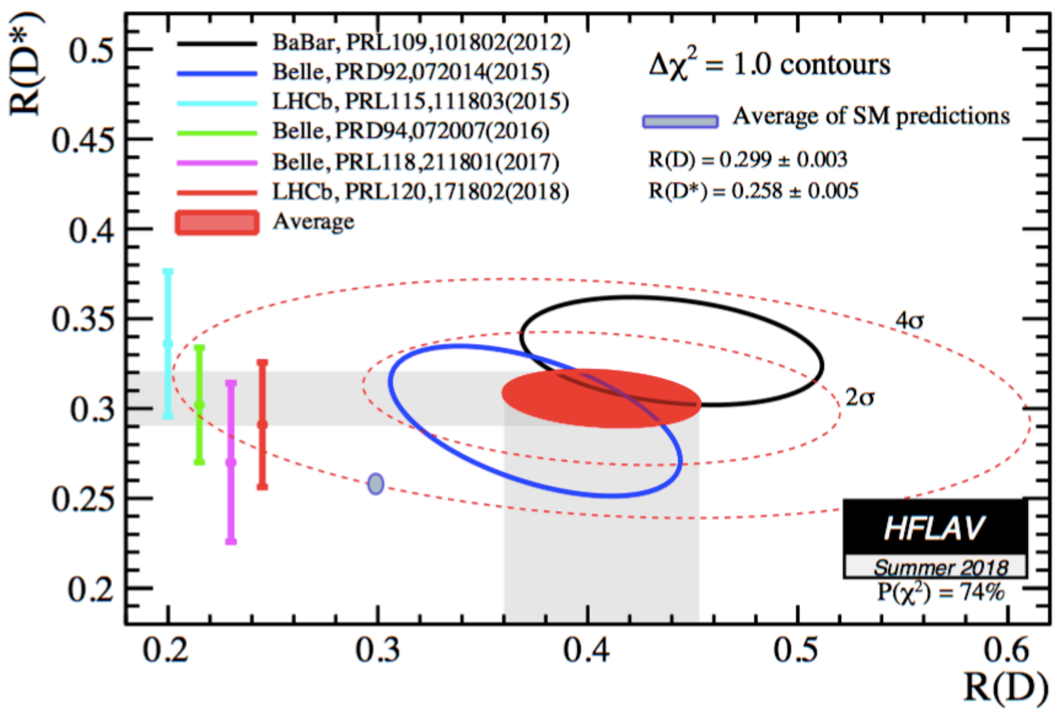


Background



Previous anomalous results from Belle and BaBar

Global fit currently 3.8 σ away from SM prediction in (R_D, R_{D^*}) plane



Future prospects:

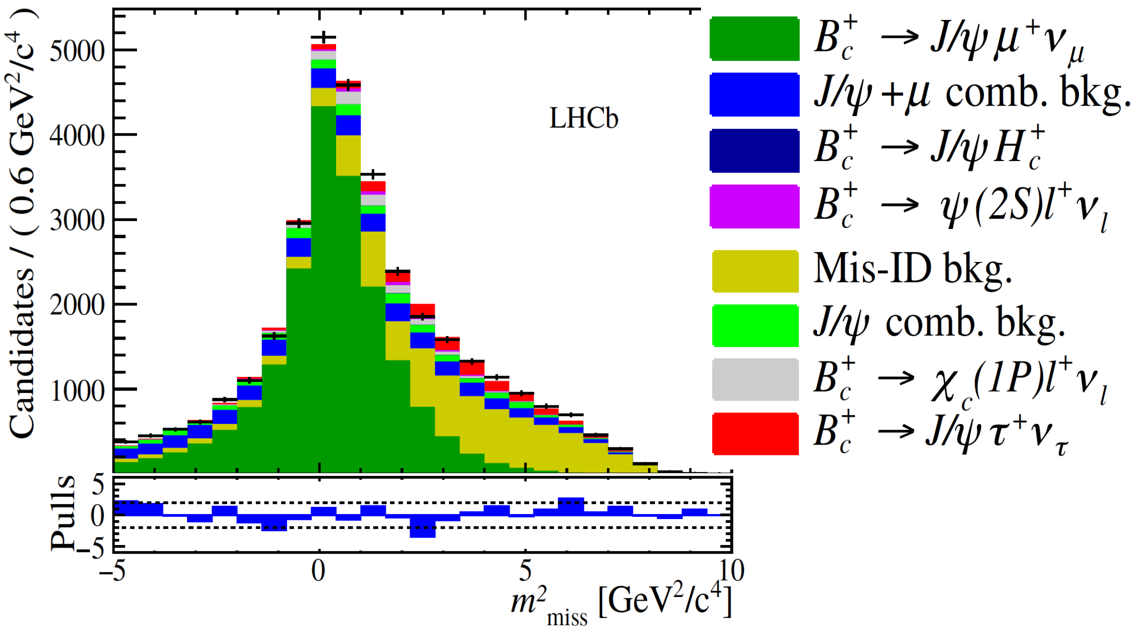
- with full Run2 luminosity, statistics will be x4 (1300 → 6000 events)
- new tauonic measurements will be incorporated, such as $R_{D_{s(*)}}$ ($B_s \rightarrow D_s^{(*)} \tau\nu$) , $R_{\Lambda_{c(*)}}$ ($\Lambda_b \rightarrow \Lambda_c^{(*)} \tau\nu$) and R_D

Tests of τ/μ LFV in $B_c \to J/\psi$ semi-leptonic decays

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} = 0.71 \pm 0.17 \pm 0.18 \quad (\text{SM } 0.25 \div 0.28)$$

PRL120 (2018) 121801

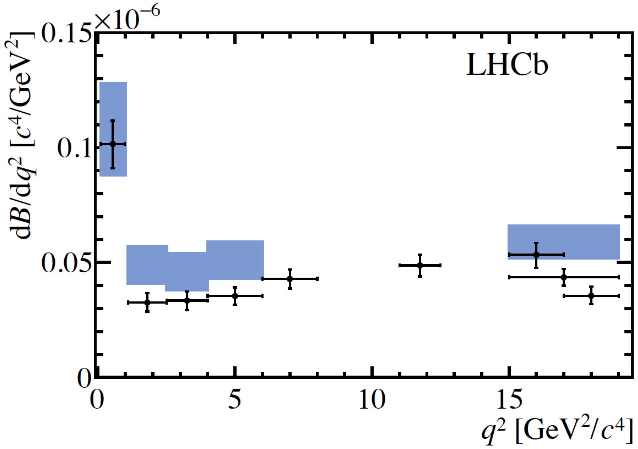
Main background originating from B hadrons (non charmed) decays into J/ψ with π/K misidentified as μ

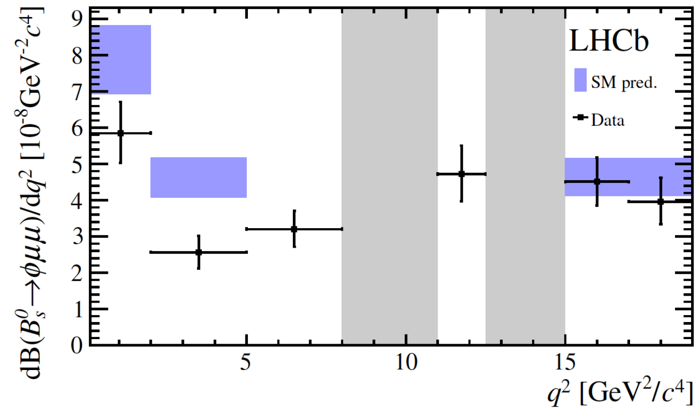


dB/dq^2 measurements of $b \rightarrow s\ \mu\mu$

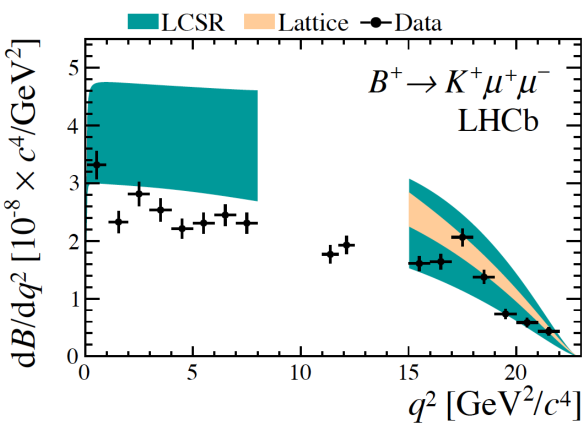
JHEP06 (2014) 133
JHEP06 (2015) 115
JHEP09 (2015) 179
JHEP11 (2016) 047
JHEP04 (2017) 142

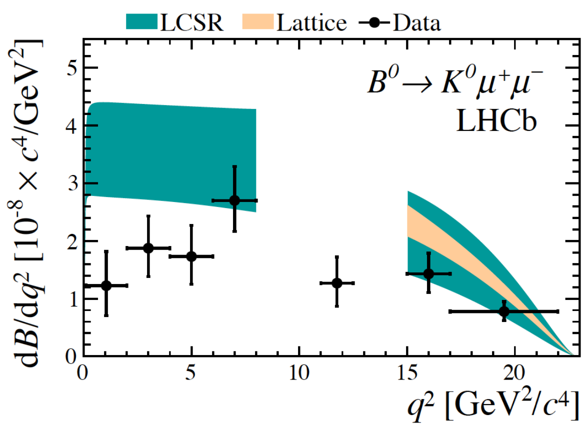
$K^+\pi^-\mu\mu$ (S-wave)

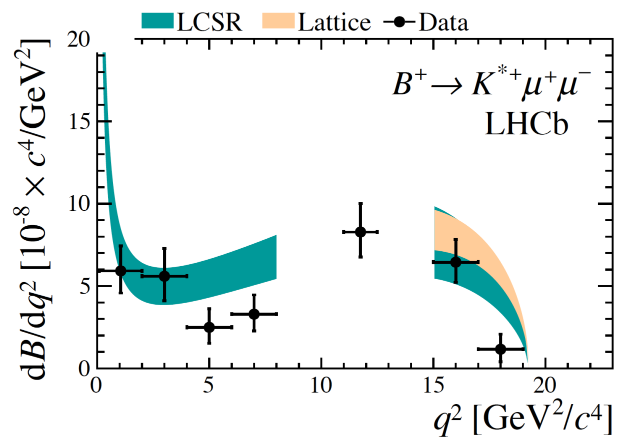




$\phi(K^+K^-)\mu\mu$

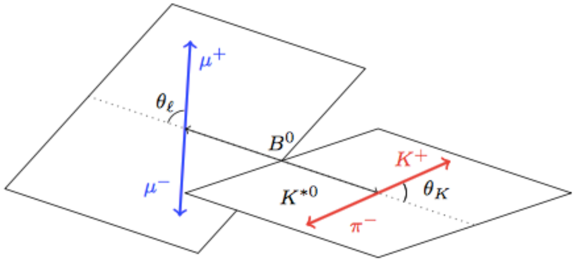




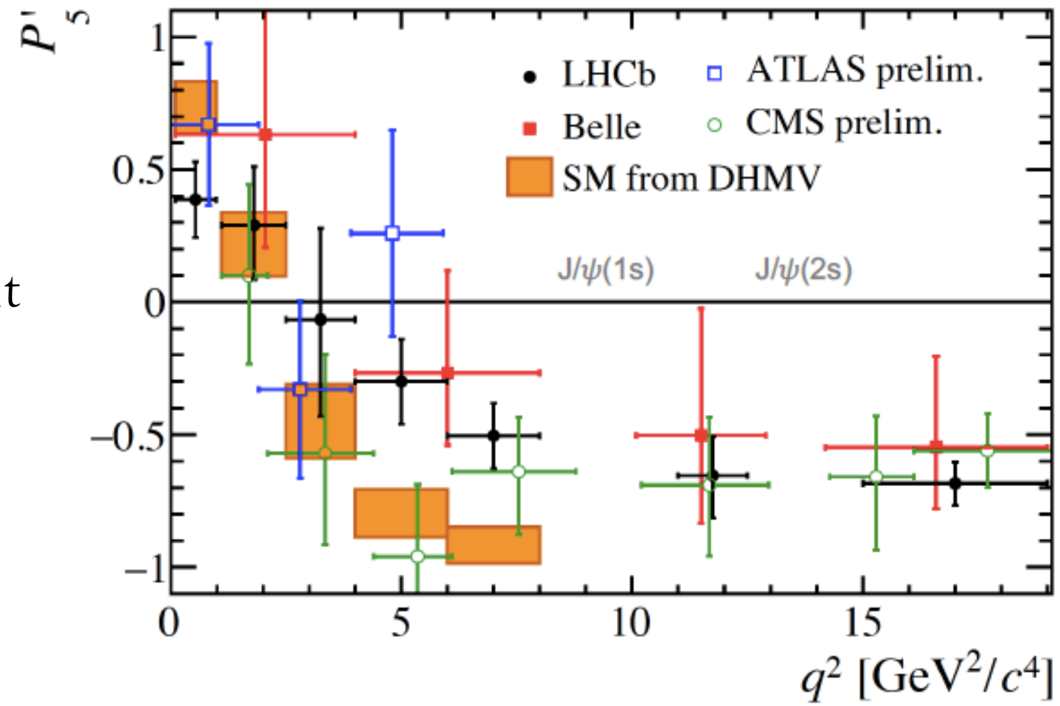


Data generally below model predictions at low q^2. Control mode with J/ψ
Low systematic experimental uncertainties. Relatively large theory errors

Angular analysis of $B \to K^* \mu\mu$



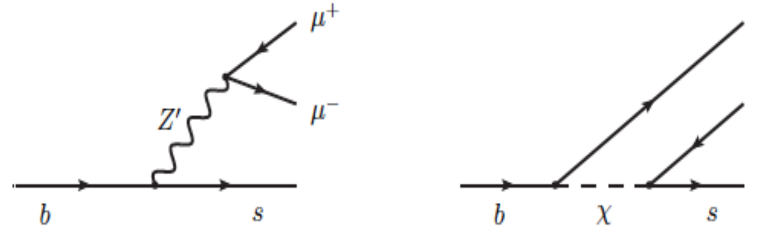
A laboratory to search for NP in asymmetries and angular distributions
Several observables can be build through 6 complex amplitudes $\mathcal{A}^{L,R}_{0,\|,\perp}$ corresponding to different transverse states of the $(K^*, \mu\mu)$ system



Large experimental effort of LHCb, Belle, ATLAS, CMS
Theory errors not negligible

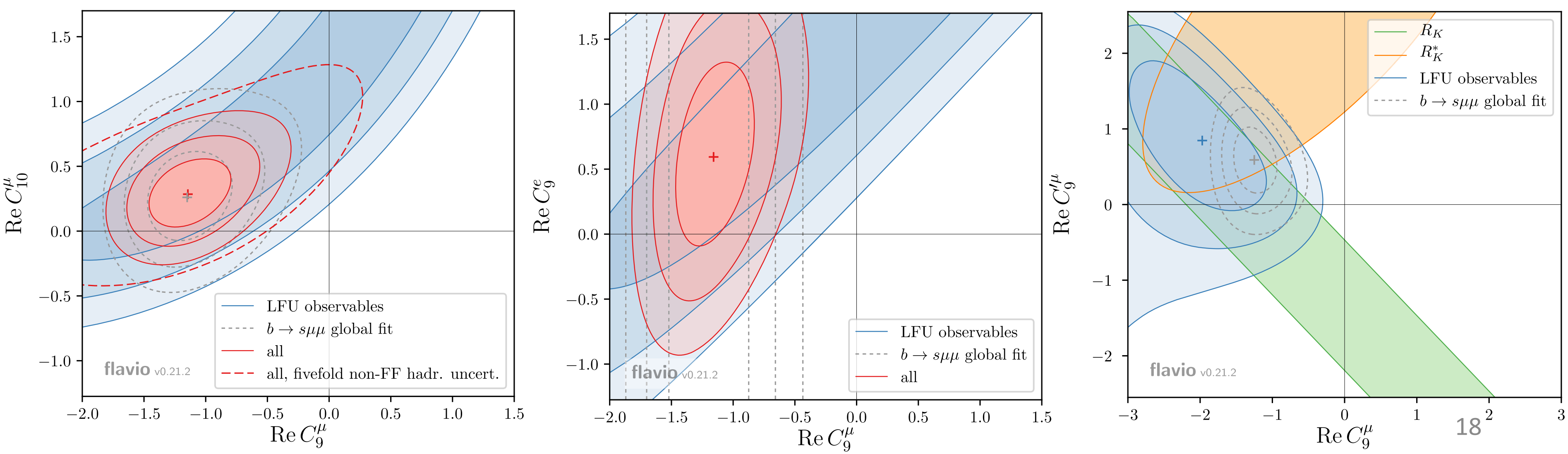
One of this variable ($\mathbf{P_5'}$) is chosen to be less affected by hadronic effects (form factors): current best global fit is **3.4 σ** away from SM (data from LHCb: JHEP02 (2016) 104). $\mathbf{P_5'}$ sensitive to NP in Wilson coefficients $C_9^{(')}$ and $C_{10}^{(')}$

Theory facing anomalies



A lot of excitement induced by LFV anomalies (R_{K*} LHCb paper >700 citations)

Model-independent H_{eff} approach (Altmannshofer et al. PRD96 (2017) 055008) suggests NP at Λ < 100 TeV affecting (mainly) C_9^μ Wilson coefficient mediated by 4-fermions contact interaction

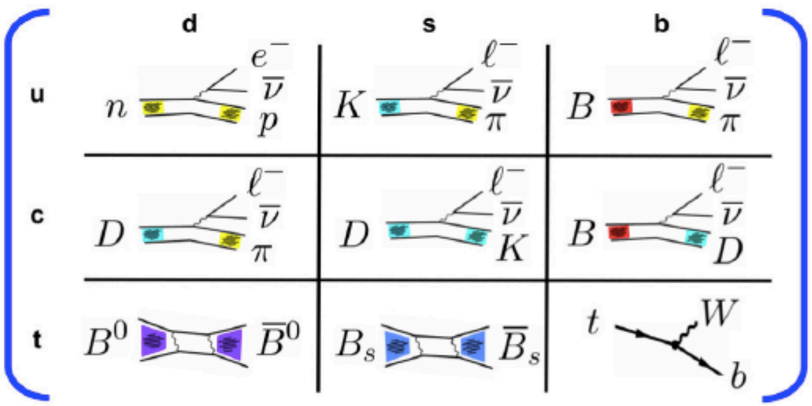


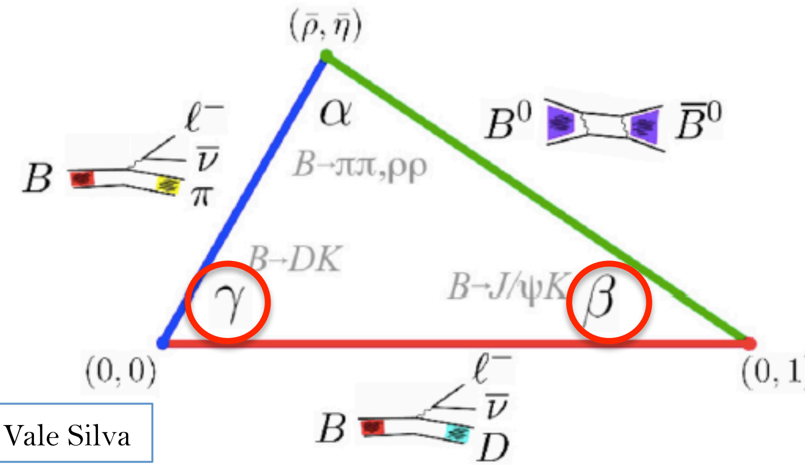
A large number of consistent new physics models have been proposed, with explicit mediators in the TeV mass range, that include a coloured vector lepto-quark as a particularly simple framework (Buttazzo et al. JHEP1711 (2017) 044)


CP violation

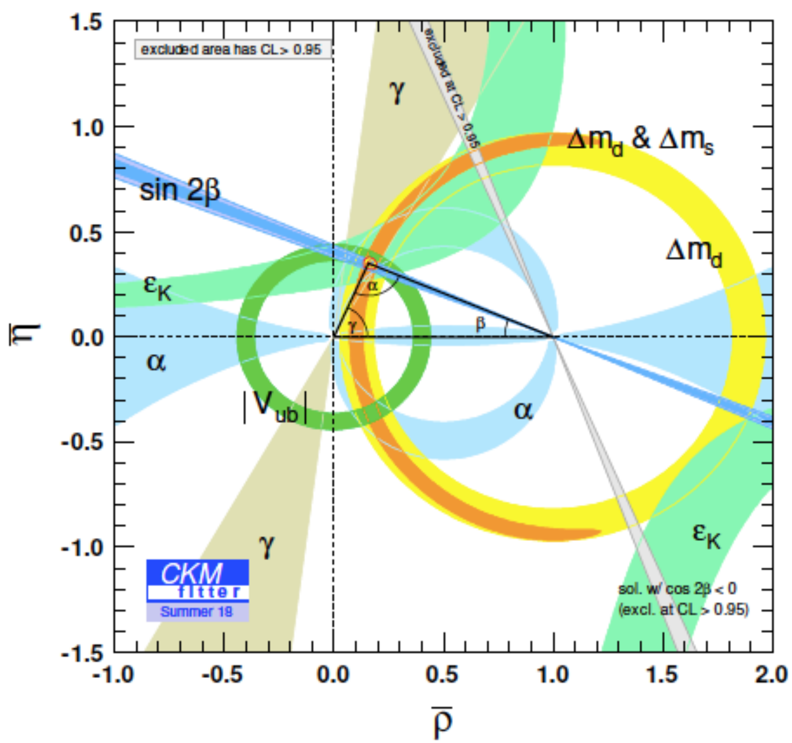
Testing CKM matrix

V =





Luiz Vale Silva



Sensitivity to NP comes from the global consistency of various measurements (tree vs loop / CP conserving vs CP violating channels)

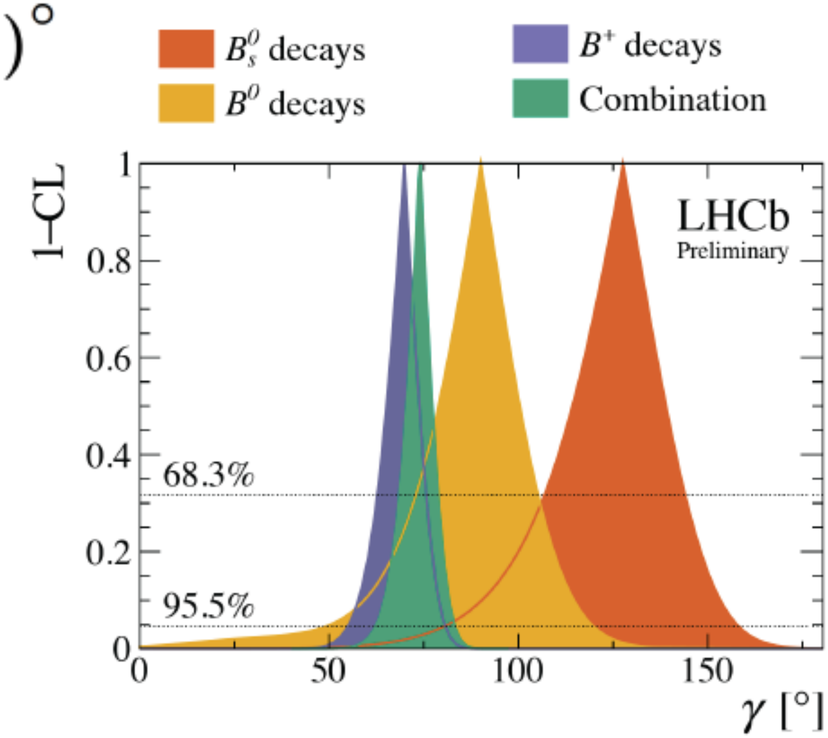
Excellent capabilities of LHCb to measure Unitarity Triangle angles **γ , β, β_s** (α is difficult in LHCb due to neutral in final states) and B_s B_d properties (Δm_d , Δm_s) in several modes

Status of γ

LHCb combination (mostly from Run 1 data) of tree-level measurements: the most precise one from a single experiment $\gamma = (74.0\ ^{+5.0}_{-5.8})^{\circ}$

LHCb-CONF-2018-002

HFLAV World Average $\gamma = (73.5\ ^{+4.2}_{-5.1})^{\circ}$



A large set of different ways of measuring γ:

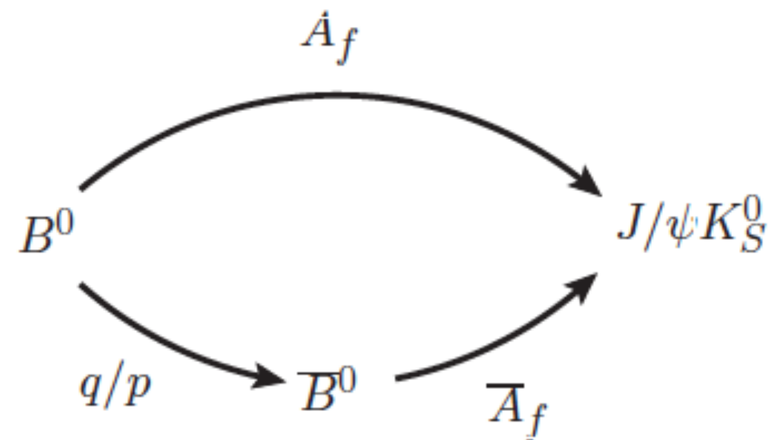
- Time integrated asymmetries in $B^+ \to DK^+$, $B^+ \to DK^{*+}$, $B^0 \to DK\pi$, PLB777 (2018) 16 with $D \to hh$, hhh (ADS, GLW methods)
- Time dependent analyses of $B_s \to D_s K$, $B^0 \to D\pi$ JHEP03 (2018) 176
- Dalitz plot analyses in $B^+ \to DK^+$, $B^0 \to DK^{*0}$, JHEP03 (2018) 059 with $D \to K_s h^+ h^-$ (GGSZ method)

Indirect measurement from V_{CKM} fit $\gamma_{\text{indirect}} = (65.8 \pm 2.2)^{\circ}$

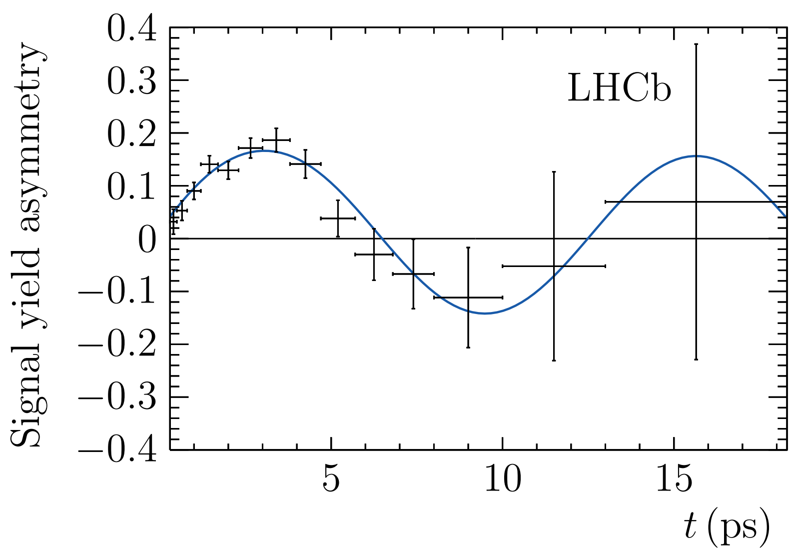
(UTFIT summer 2018)

Status of β

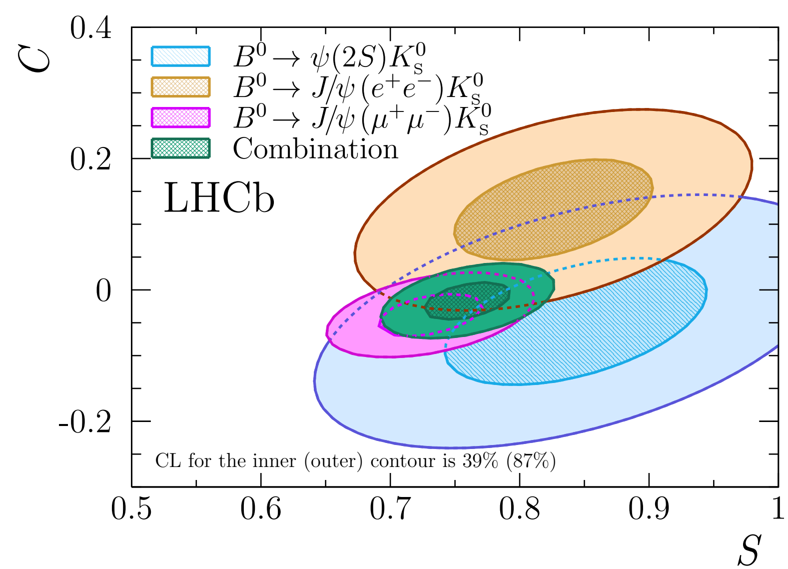
Measurement through time-dependent CP asymmetry: interference between decays with mixing and no mixing



Golden mode of b-factories
Precision of LHCb is now comparable
Measured by LHCb in $B^0 \to J/\psi\ (\mu\mu,\ ee)\ K_s$ and $B^0 \to \psi\ (2S)\ K_s$



PRL 115 (2015) 031601, JHEP11 (2017) 170



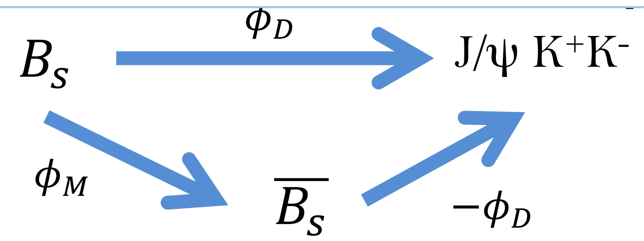
Combined result:

$$S_{c\bar{c}K^0_S} = 0.760 \pm 0.034$$

Status of β_s (the β angle for B_s decays)

Interference between mixing and decay gives rise to a CPV phase ($\phi_s = \phi_M - 2\,\phi_D \sim 0$ in SM)

$$\phi_s \overset{\text{SM}}{=} -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



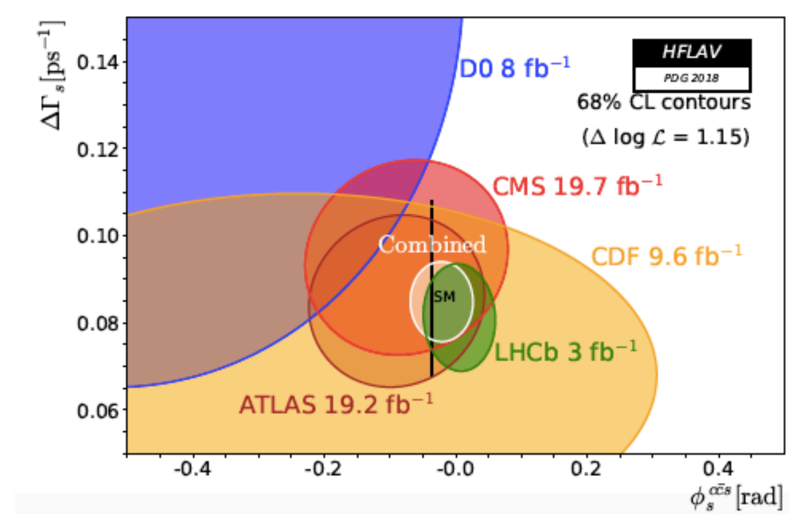
Powerful and theoretically clean test of SM
ϕ_s^{SM} = -36±1 mrad

LHCb measurement (PRL114 (2015) 041801) (Run 1) still dominated by statistics and not far from entering the precision level of SM

Sizeable decay widths difference of B_s^H, B_s^L (B_s mass eigenstates) is also measured ($\Delta\Gamma_s \neq 0$)

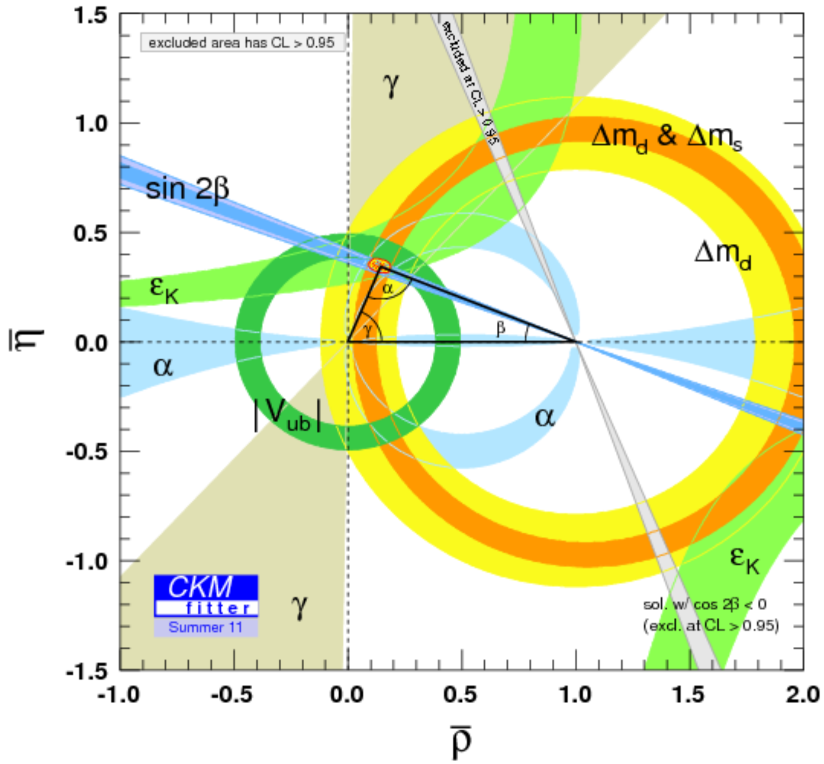
Measurement allowed by the excellent decay time resolution of vertex detector (~ 40 fs)

$$\begin{aligned}
\phi_s &= -58 \pm 49 \pm 6 \text{ mrad}\\
\Gamma_s &= 0.6603 \pm 0.0027 \pm 0.0015\\
\Delta\Gamma_s &= 0.0805 \pm 0.0091 \pm 0.0032\\
\Delta m_s &= 17.711^{+0.055}_{-0.057} \pm 0.0032\\
|\lambda| &= 0.964 \pm 0.019 \pm 0.007
\end{aligned}$$

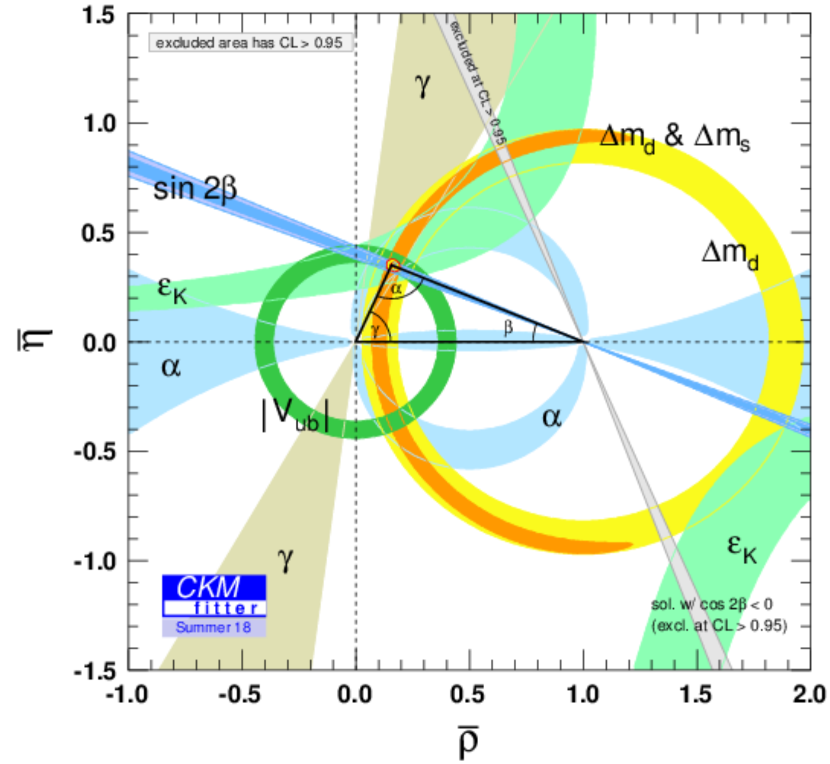


Evolution of UT triangle

CKM unitary triangle as of summer 2011



CKM unitary triangle as of summer 2018



Large impact of LHCb data on **γ , Δm_d , Δm_s** measurements

CP violation in charm decays

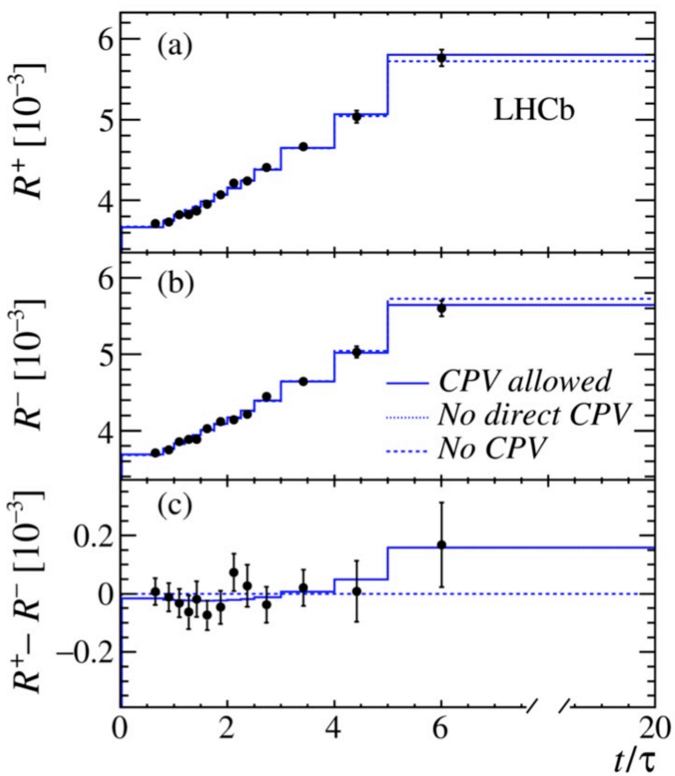
LHCb has collected a charm sample 100 ÷1000 larger than previous experiments

An independent way to probe New Physics (but not theoretically clean): c → u decays can reach very large mass scales $\Lambda \sim O(1000)$ TeV

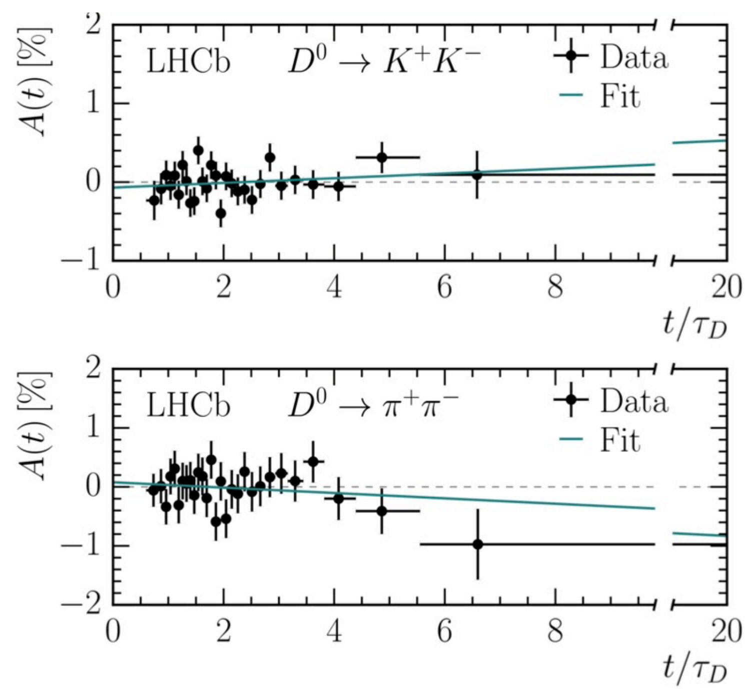
Several observables: direct CPV in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ (a_{CP}) ;

D-Dbar oscillations and CPV in mixing in $D^0 \to K^+\pi^-$ (x and y parameters)

D→Kπ - PRD97 (2018) 031101



D→KK, ππ – PRL118 (2017) 261803



No CP violation found in charm decays yet
Probing it at now at $10^{-2} \div 10^{-3}$ level

Credit: National Geographic

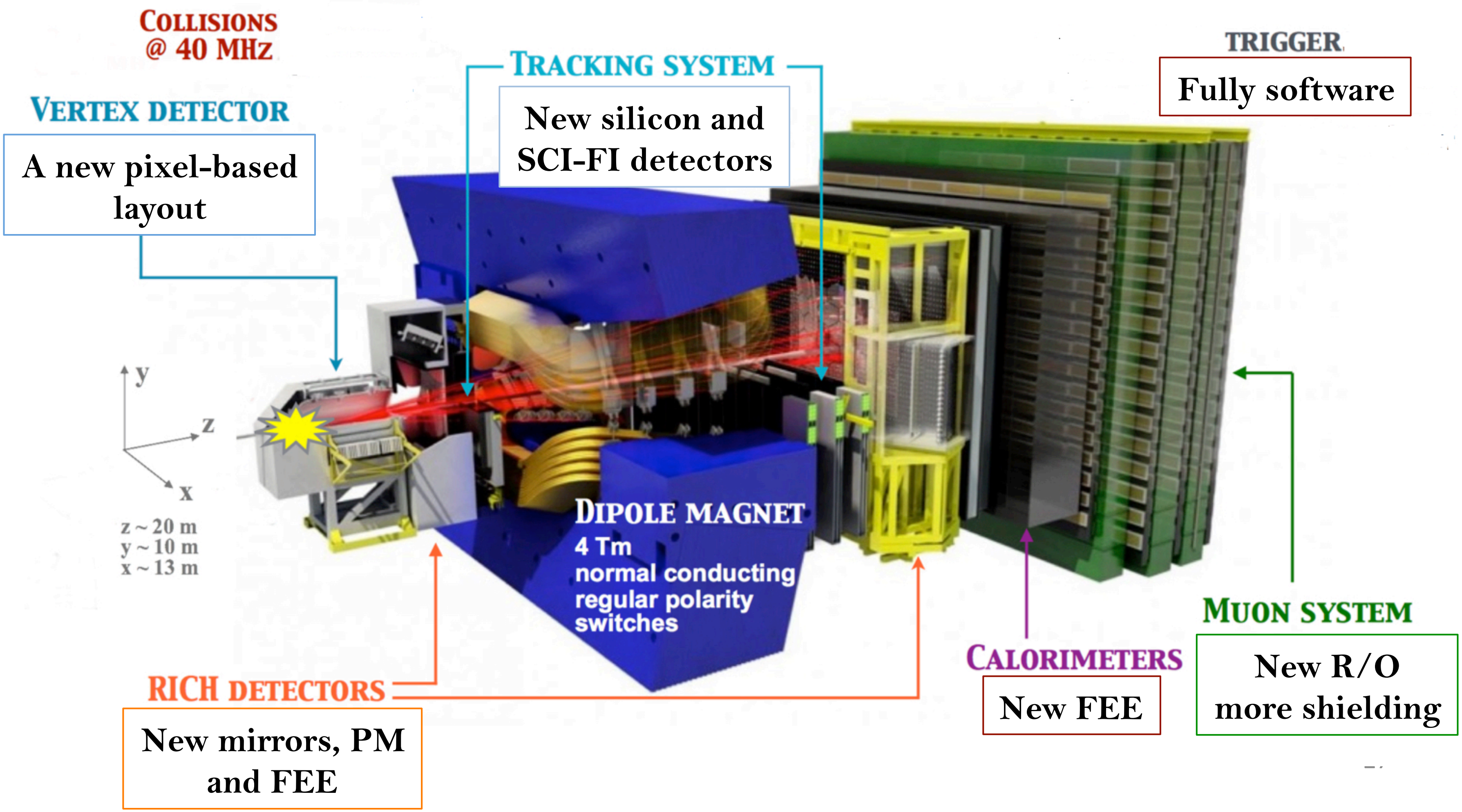
The LHCb Upgrade

LHCb will be upgraded to reach **L = 2 10^{33} cm^{-2} s^{-1}** (x 5 w.r.t. Run1 & 2, with higher trigger efficiency) during LS2 shutdown

Goal: ~ **15/fb** in Run 3 (2021-23) and ~ **25/fb** in Run 4 (2026-29)

Proposing a phased further upgrade in LS3 & LS4 (for HL-LHC)

Detector: CERN-LHCC-2017-003 - Physics case: arXiv:1808.08865



Physics prospects for Run 3 (and beyond)

Observable	Current LHCb	Run 3 [25/fb]	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	0.02, 0.02, 0.05
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	11 mrad
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	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% [264]	34%	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	2%
$S_{\mu\mu}$	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ LUV studies			
$R(D^*)$	0.026 [215, 217]	0.0072	0.002
$R(J/\psi)$	0.24 [220]	0.071	0.02
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K3\pi)$ 8.0×10^{-6}

$\sigma(R_{K,K^*}) \sim 3\%$

$\sigma(\gamma) \sim 1.5^0$

$\sigma(\phi_s) \sim 15$ mrad

$\sigma(B_d) \sim 30\%$

$\sigma(\tau_{Bs}) \sim 8\%$

$\sigma(CP_c) \sim 10^{-4}$

Conclusion

- In Run 1 & 2, the LHCb experiment has collected 9/fb. Larger data set will allow a significant error reduction (x 4 ÷ 6 depending on specific channel)
- Most of the analyses have still exploited only Run 1 sample. In the near future will be extracted from the full data set
- $B_s \rightarrow \mu\mu$ is entering the domain of precision tests, also looking to possible non SM effects in the measurement of effective lifetime
- Weak anomalies in LFV provide a consistent picture, to be verified by the larger statistics of Run 2, and by future Belle2 data
- A large set of CKM variables can be measured precisely at LHCb in many different ways. The search for SM inconsistencies is still open
- Starting to install the upgrade of LHCb, which will bring another ~15/fb by 2023