中国科学院大学

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Indirect search for New Physics at LHCb

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Outline

- Introduction
- Flavour anomalies
  - $B \to \mu^+\mu^-, b \to s\ell^+\ell^-$
  - R(D*)
- CP violation
  - ϕ_s, CKM-γ, charm ΔA_{CP}
- Summary

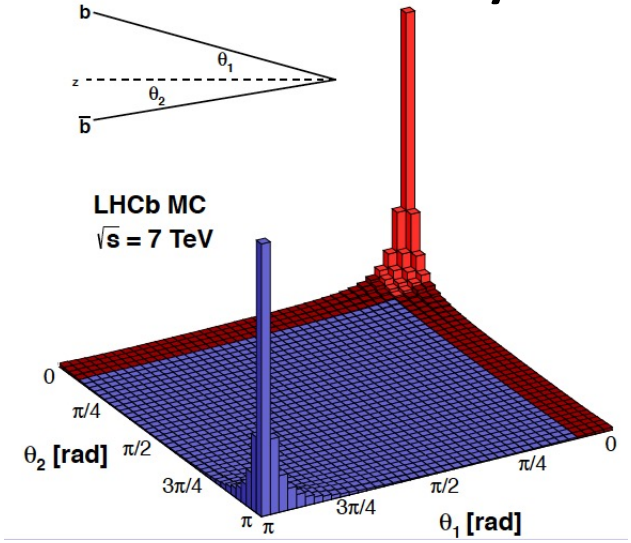
*sorry if I miss your favourite, more can be found in LHCb public page:
https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

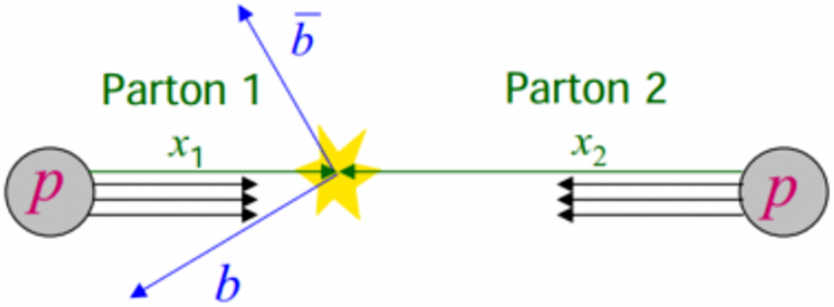
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb **c.f. 1nb @$\Upsilon(4S)$**

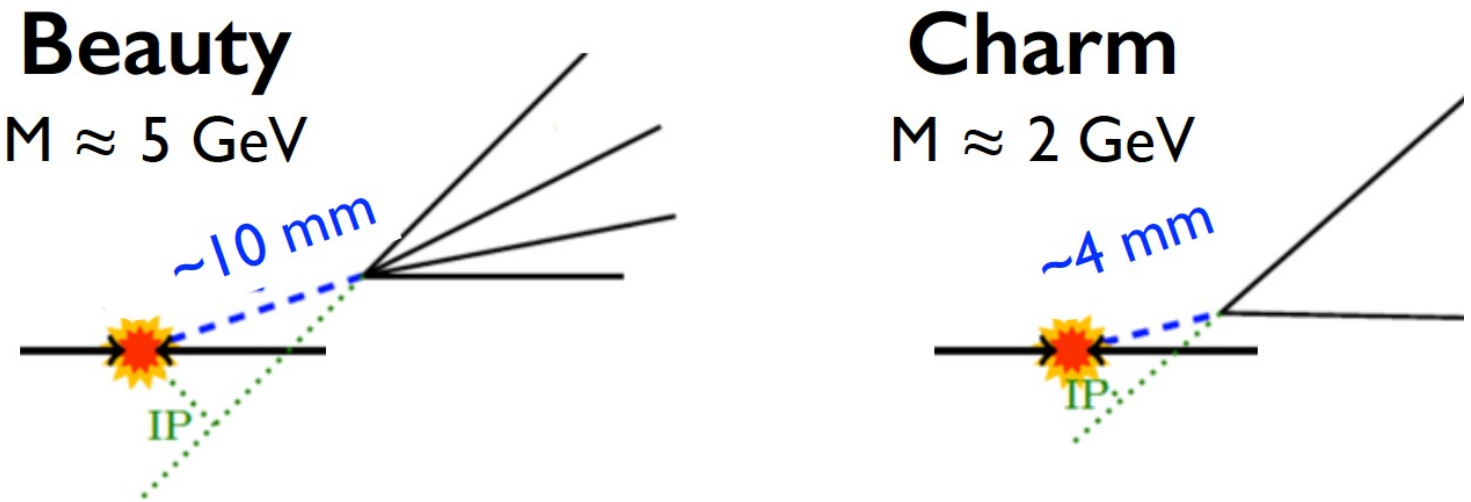
} Flavor factory!

- Predominantly in forward/backward cones



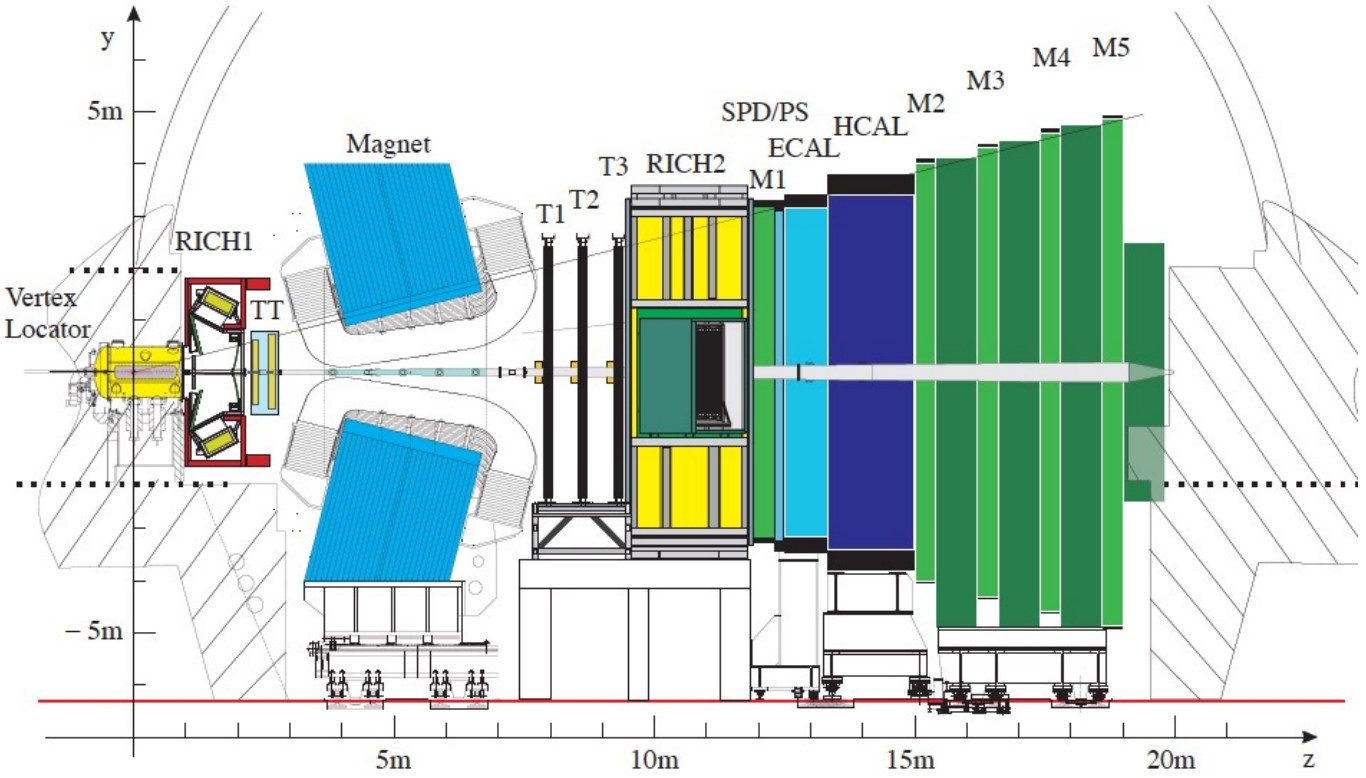


Beauty/charm signature



- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

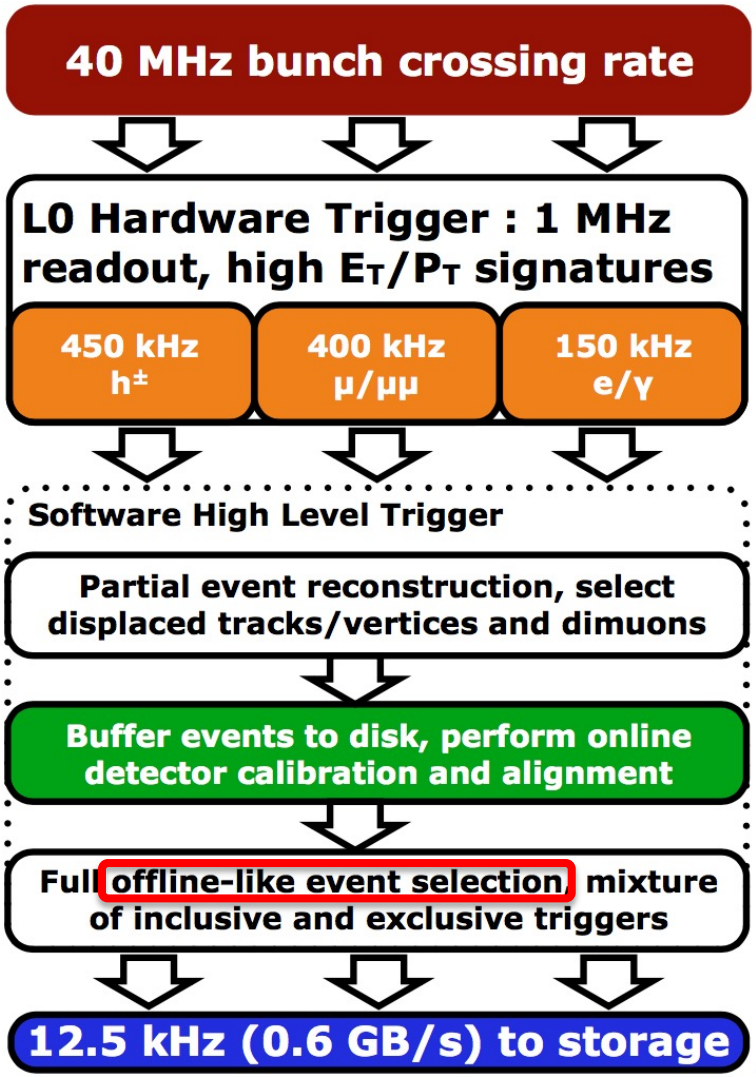
The LHCb experiment



[JINST 3 (2008) S08005]

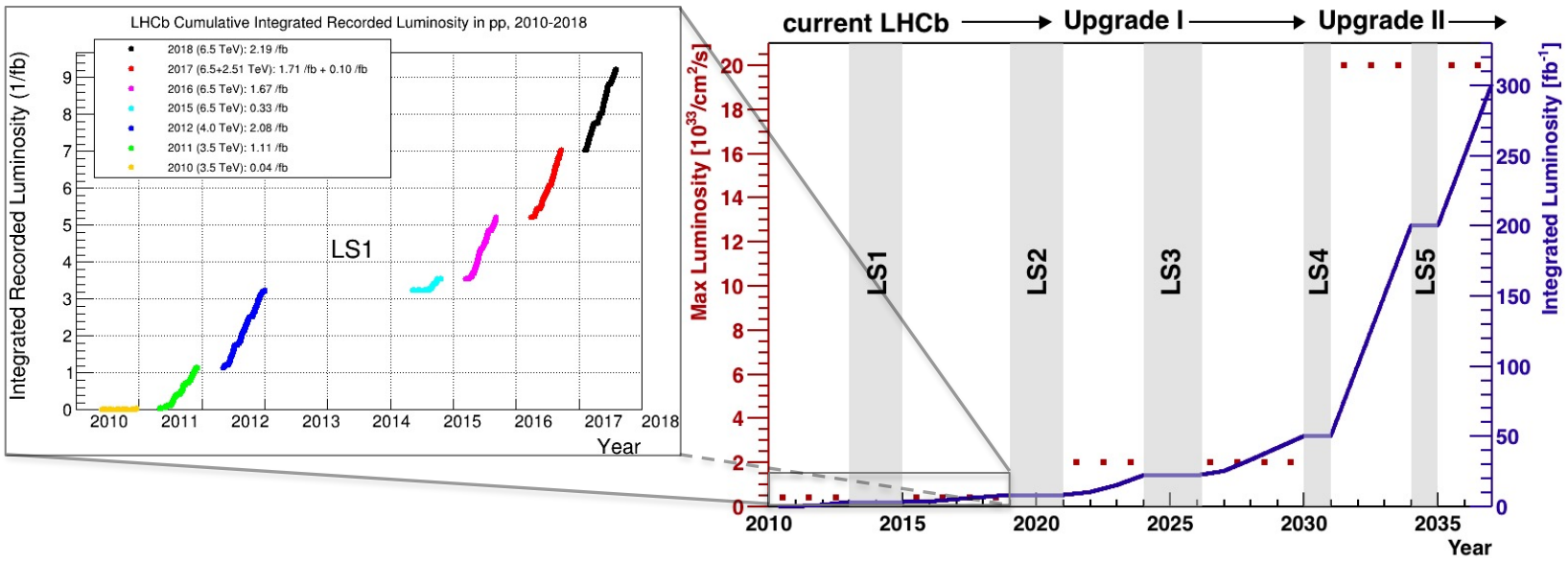
Vertex Locator	$\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (2018)



- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1)\times p_{\mathrm{T}}(\mu_2) >$ (1.5 GeV)^2
  - $p_{\mathrm{T}}(\mu) >$ 1.8 GeV
  - $E_{\mathrm{T}}(e) >$ 2.4 GeV
  - $E_{\mathrm{T}}(\gamma) >$ 3.0 GeV
  - $E_{\mathrm{T}}(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

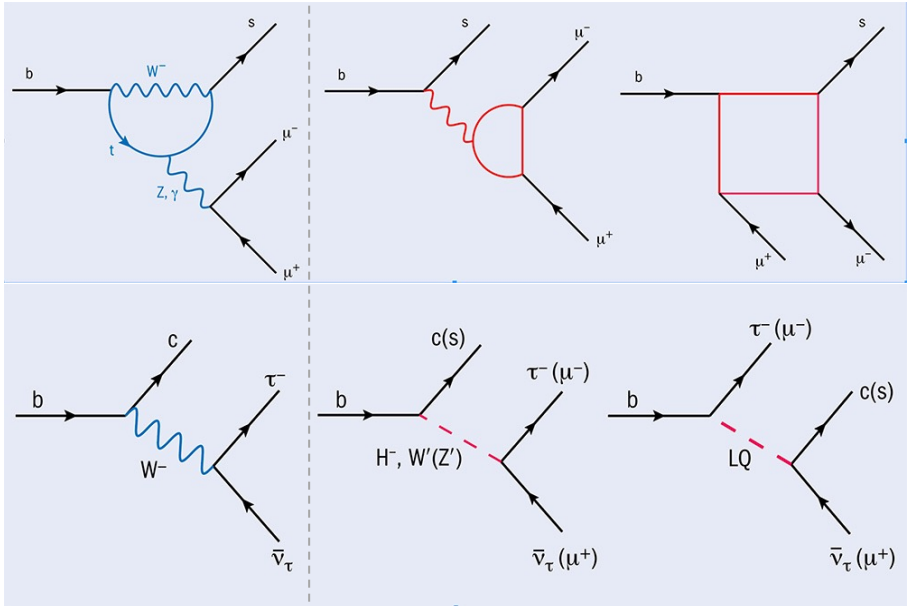
LHCb luminosity prospects

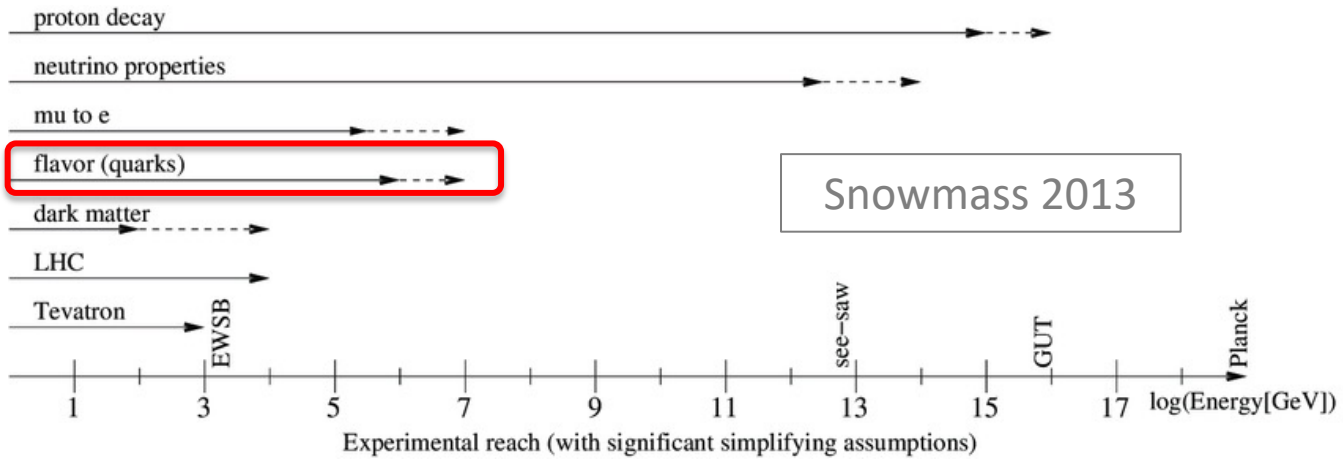


LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

Indirect search for New Physics

- Precision measurement of heavy hadron decays
  - Flavour-Changing NC
  - Flavour-Changing CC
- Probe New Physics at high energy scale

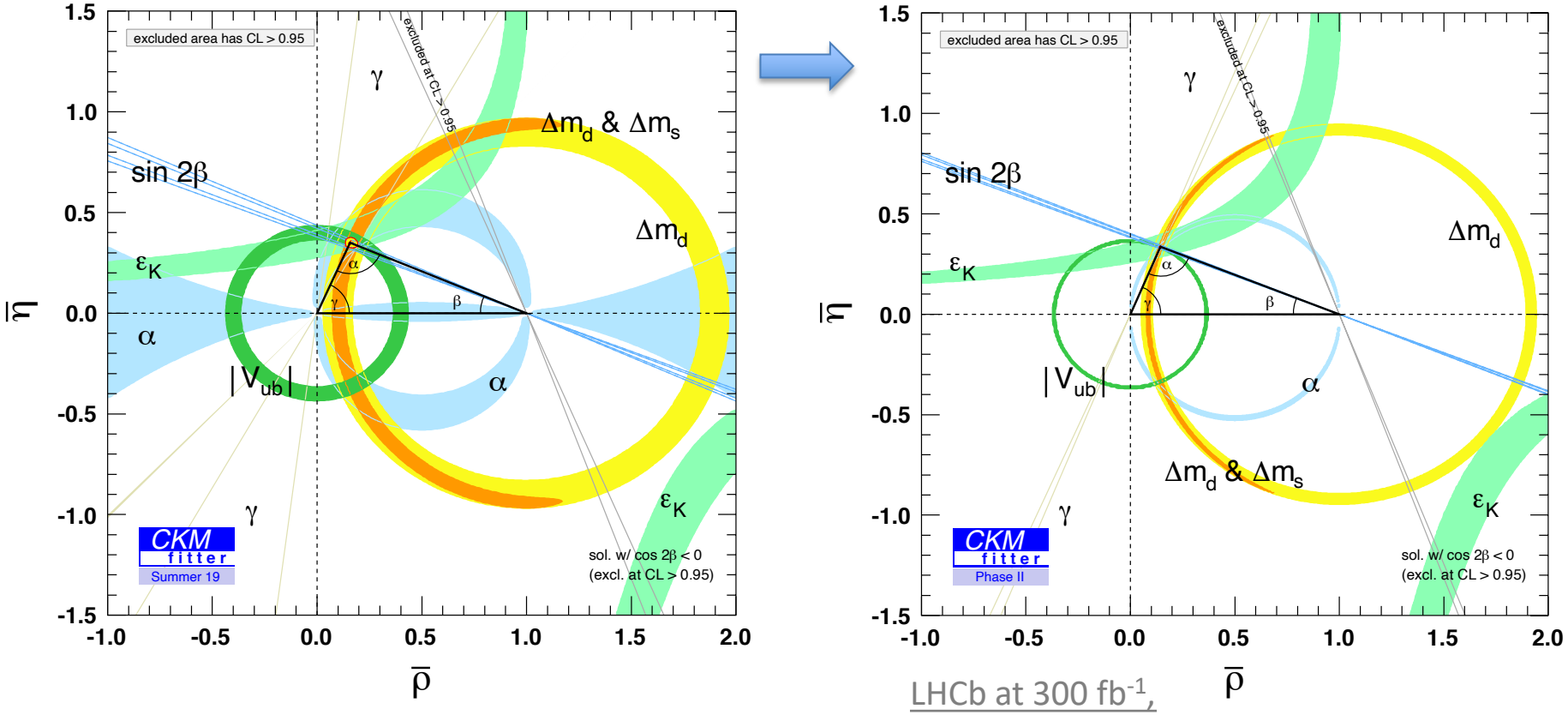




Snowmass 2013

Indirect search for NP (cont.)

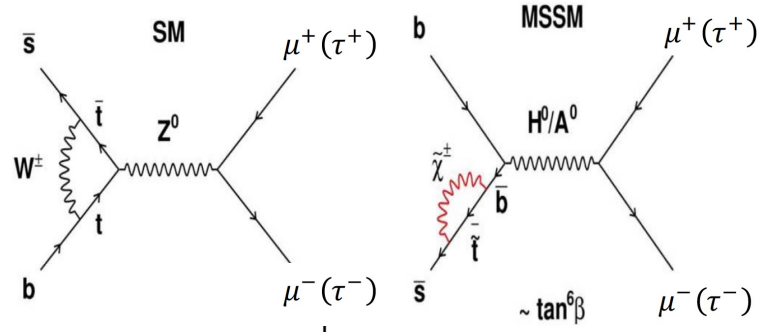
- Overconstrain the CKM triangle

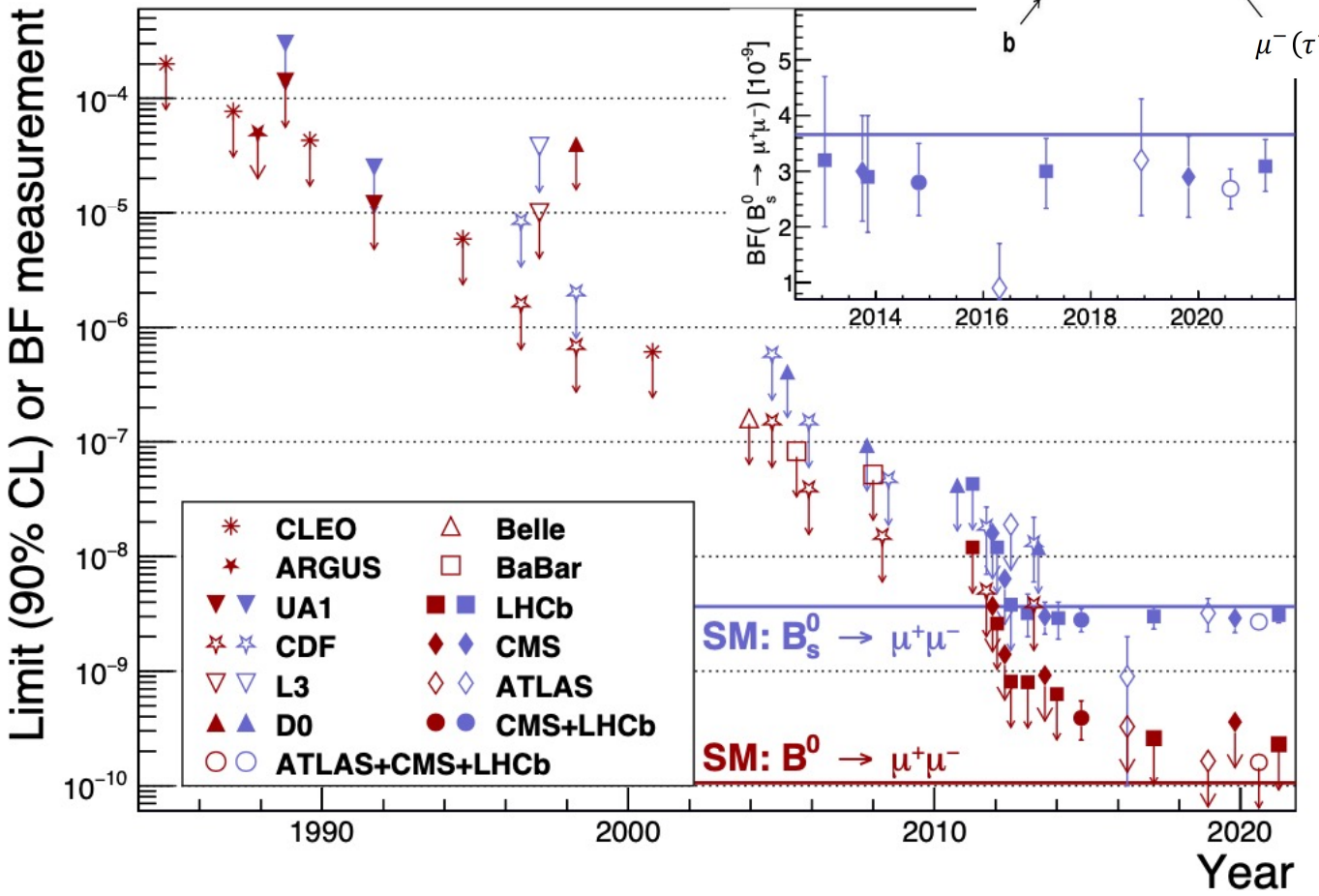


LHCb at 300 fb^{-1},
CMS/ATLAS at 3000 fb^{-1}, Belle II at 50 ab^{-1}.

$B^0_{(s)} \to \mu^+\mu^-$

- Road to $B^0_{(s)} \to \mu^+\mu^-$

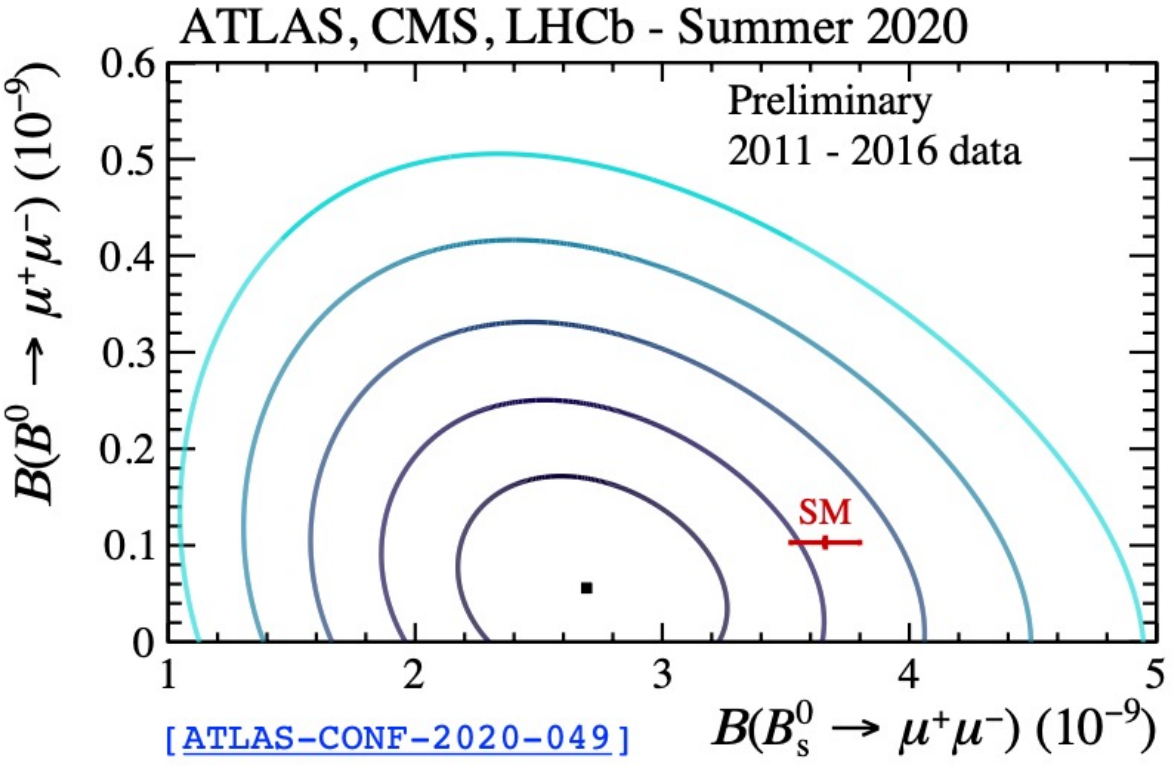




$B^0_{(s)} \to \mu^+\mu^-$, recent results

- $B^0_s \to \mu^+\mu^-$ observed in single experiment(s)

  LHCb (4.6 fb^{-1}): 7.8σ, ATLAS (26 fb^{-1}): 4.6σ, CMS (61 fb^{-1}): 5.6σ
- Still compatible with SM, start to be interesting



$B_s^0 \to \mu^+\mu^-$ effective lifetime

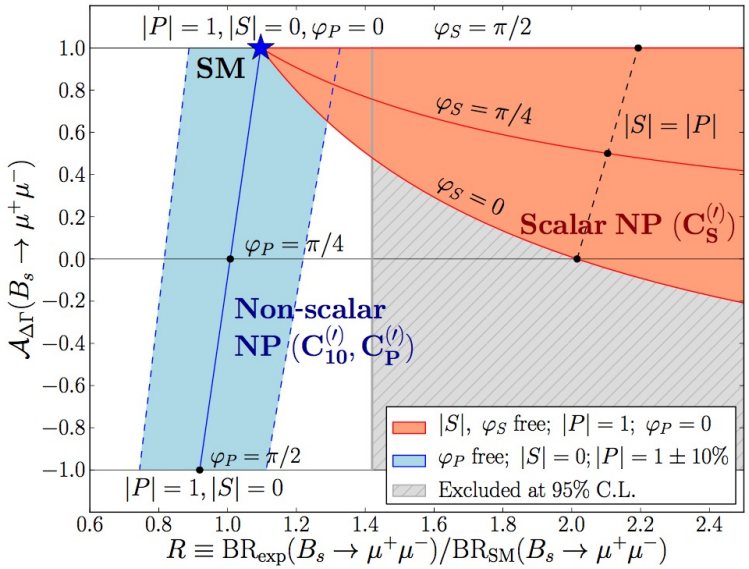
- B_s^0 mixing ⇒ effective τ

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

$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}} \qquad A_{\Delta\Gamma}=1 \text{ in SM}$$

$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

[PRL 118 (2017) 191801]



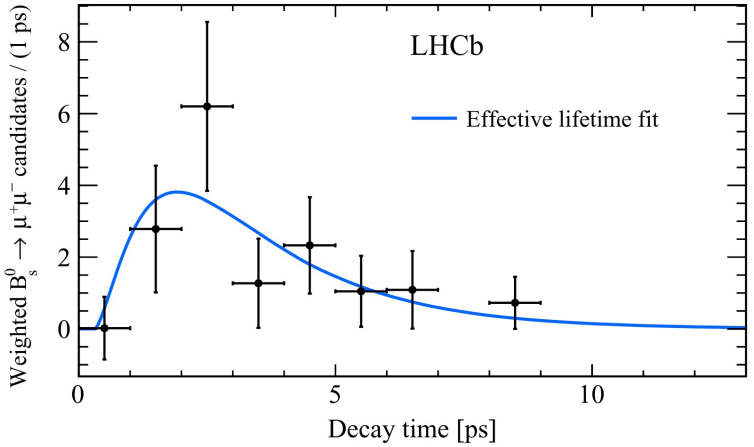
[De Bruyn *et al.*, PRL 109 (2012) 041801]

- First measurement, not yet sensitive to $A_{\Delta\Gamma}$

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

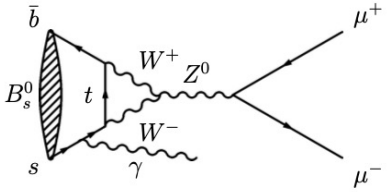
$1.70^{+0.61}_{-0.44}$ ps

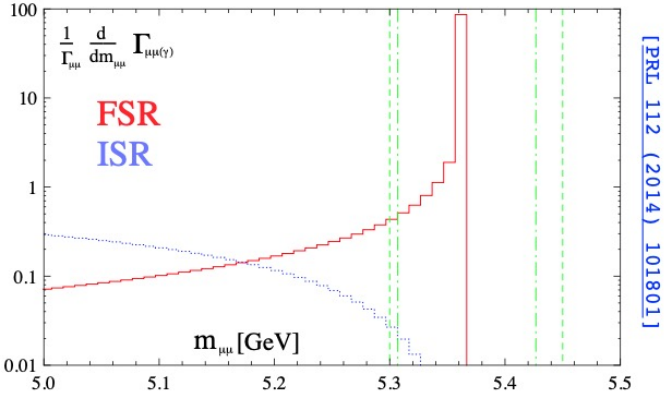
[CMS-PAS-BPH-16-004]



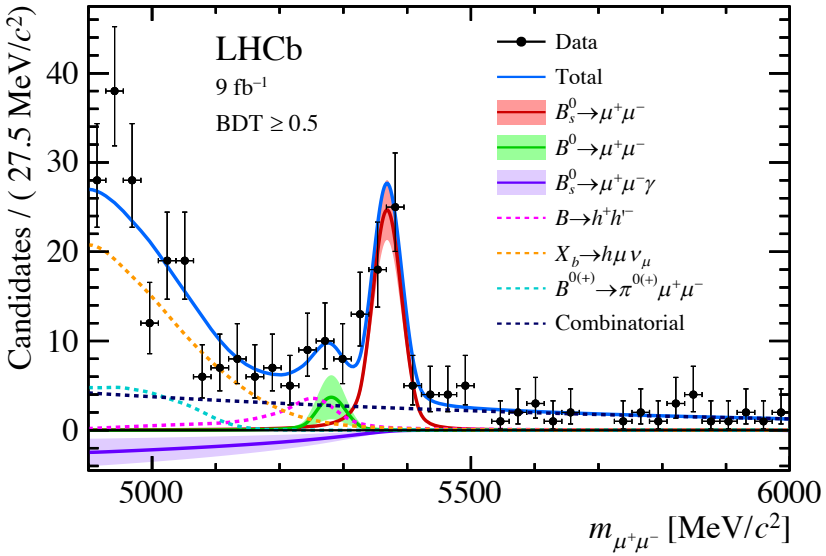
$B^0_{(s)} \to \mu^+\mu^-$

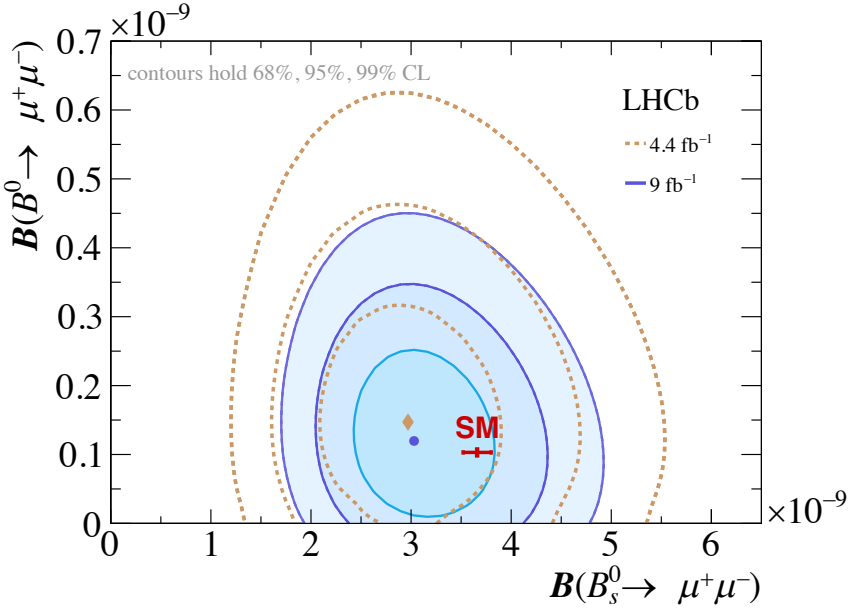
- Using all data, first limit on $B^0_s \to \mu^+\mu^-\gamma$





[LHCb-Paper-2021-007]





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

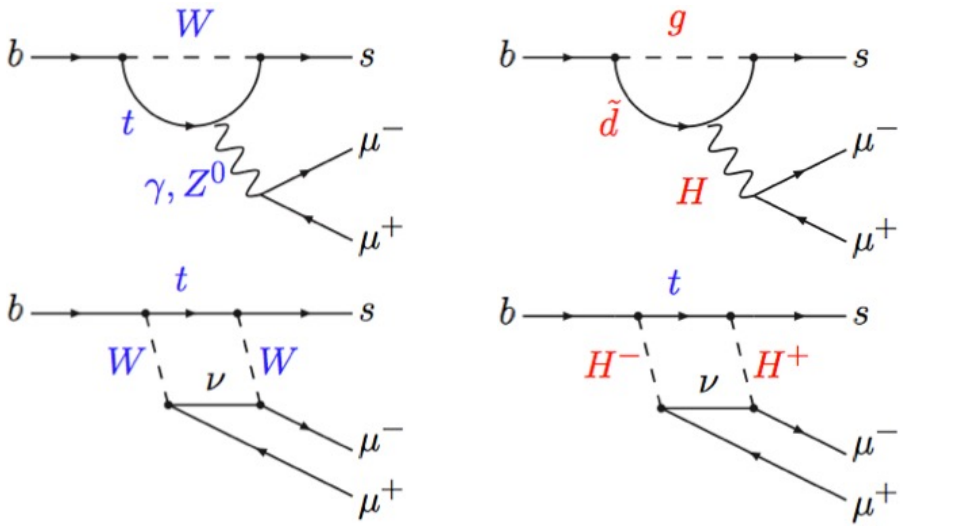
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6\times 10^{-10}$ (95% CL)

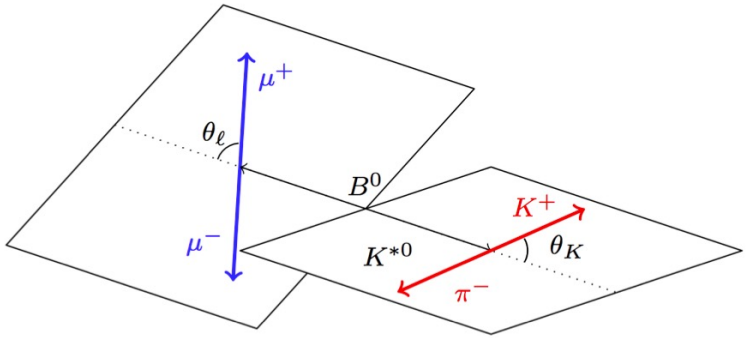
$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\ \text{GeV}} < 2.0\times 10^{-9}$ (95% CL)

$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03$ ps

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

- Rates and angular distributions sensitive to NP



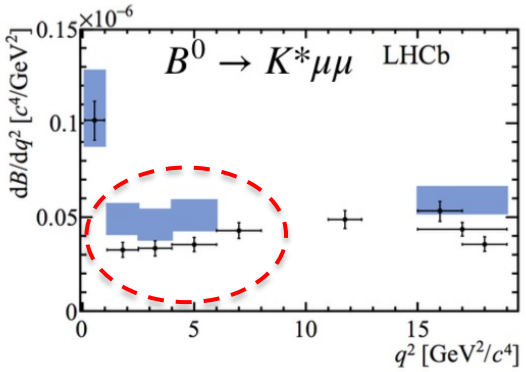


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

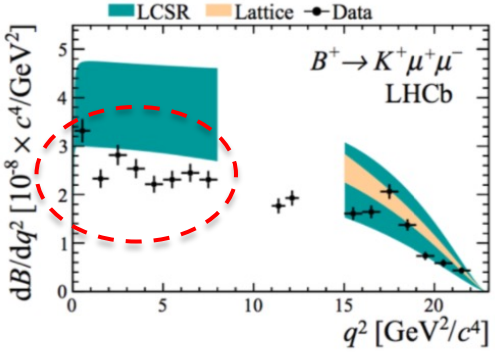
Branching fraction of $b \to s\mu^+\mu^-$

- Pattern of tensions seen, theo. uncertainty?

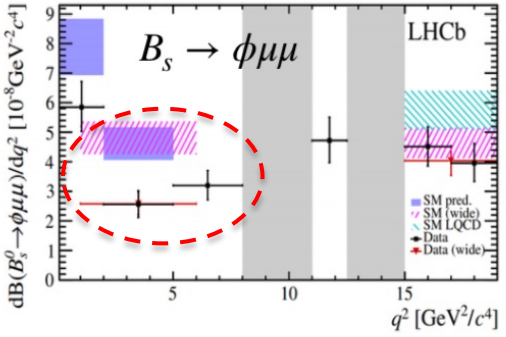
JHEP 11 (2016) 047



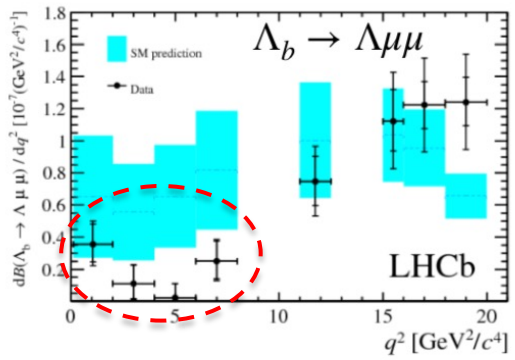
JHEP 06 (2014) 133



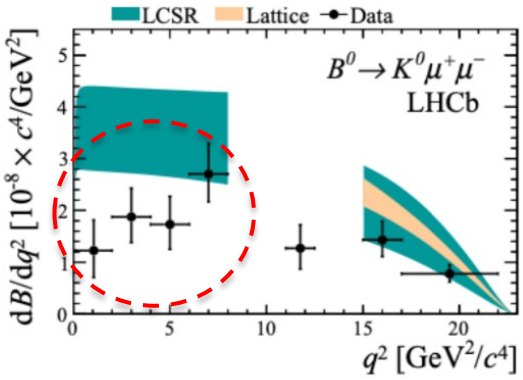
JHEP 09 (2015) 179



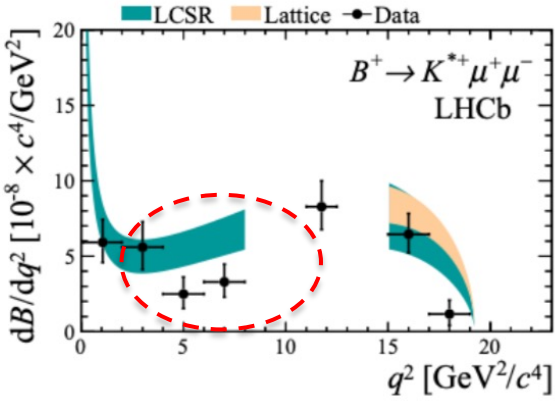
JHEP 06 (2015) 115



JHEP 06 (2014) 133



JHEP 06 (2014) 133

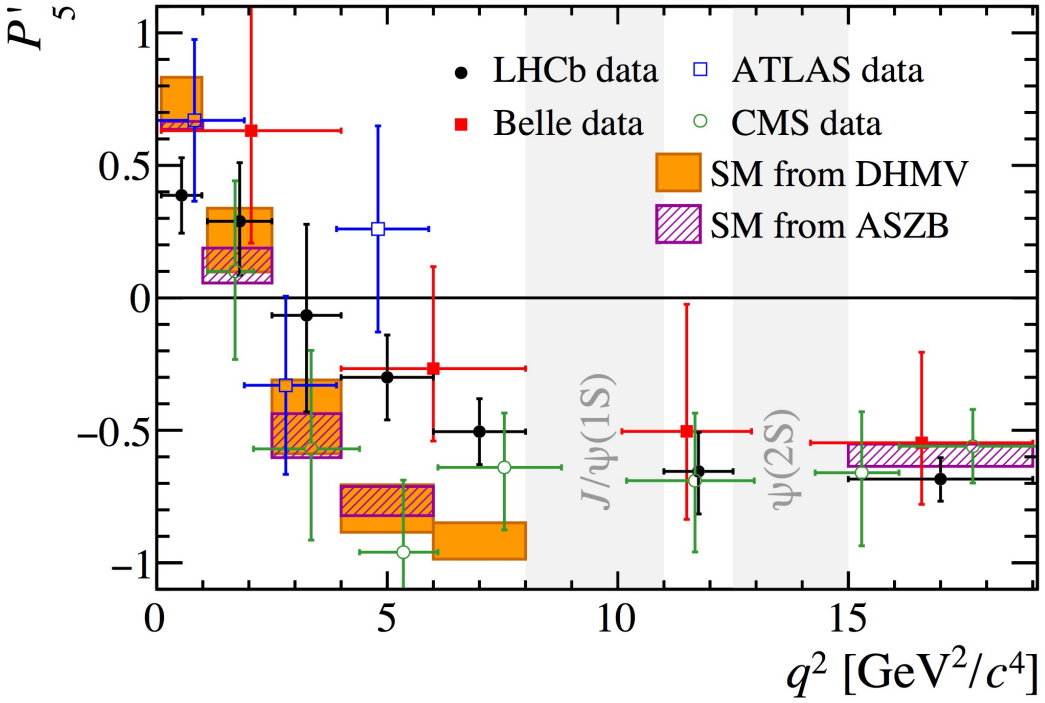


P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

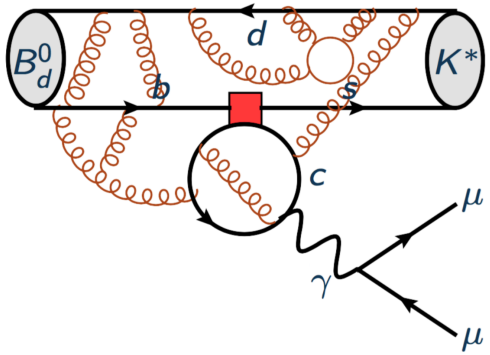
- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, less form-factor dependent

[S. Descotes-Genon, *et al.*, JHEP 01 (2013) 048]

- Also measured by Belle, ATLAS, CMS

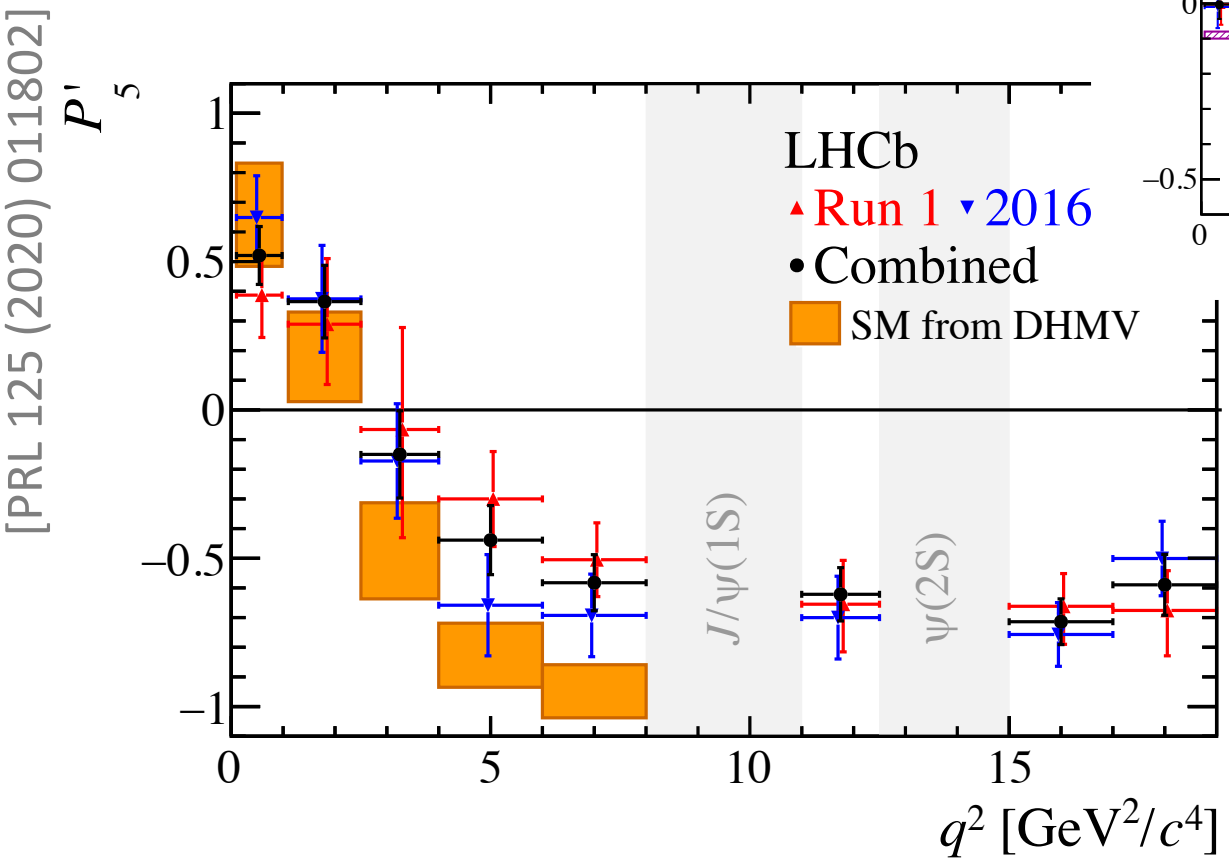


[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

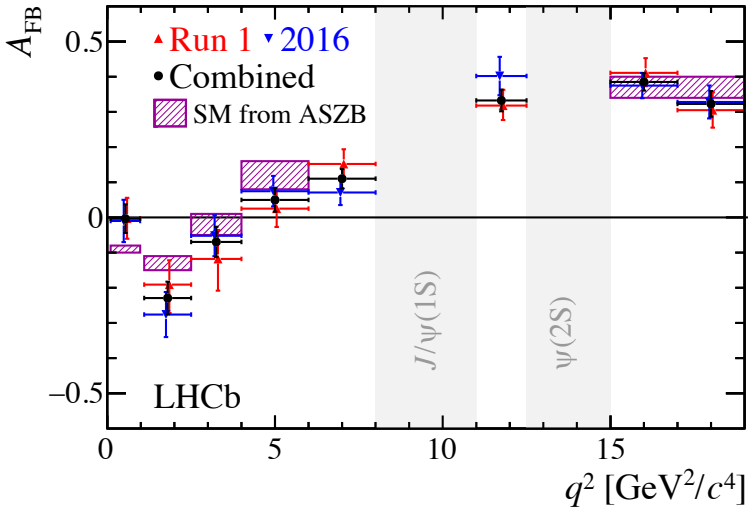


$B^0 \to K^{*0}\mu^+\mu^-$, latest results

- Updated with 2016 data

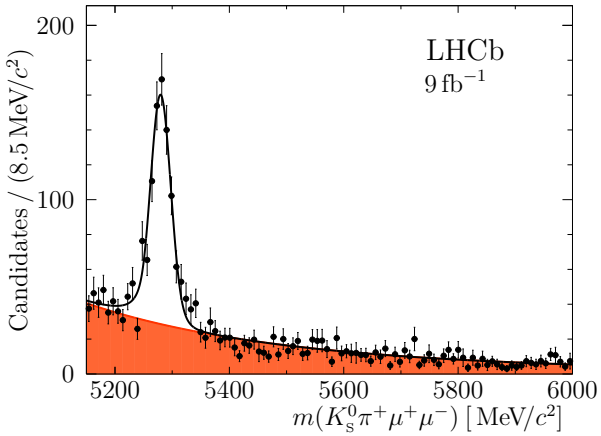


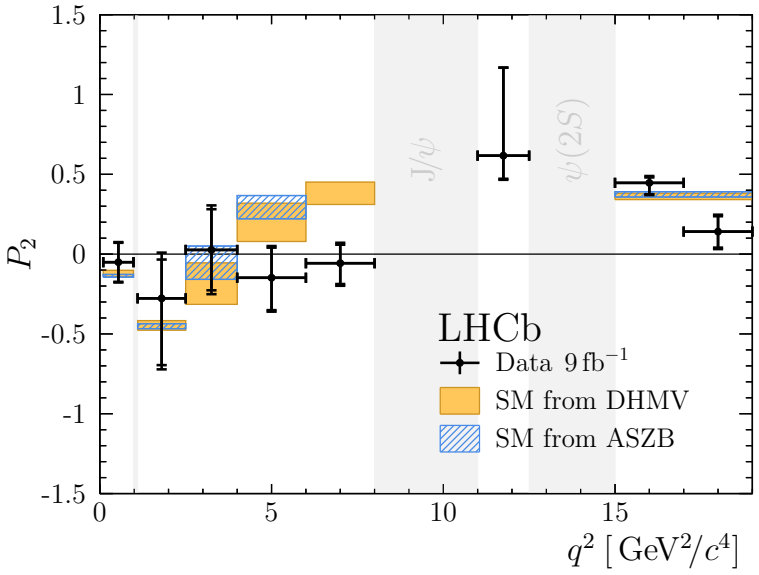
[PRL 125 (2020) 011802]

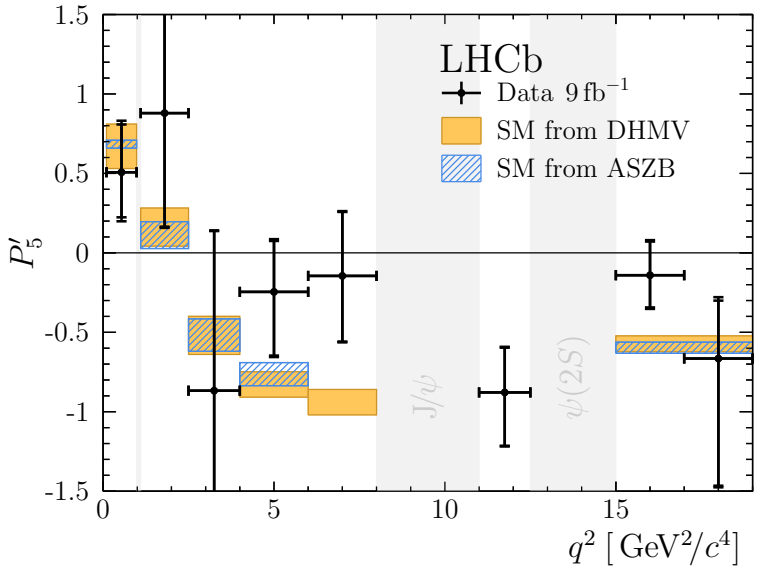


$P'_{5,2}$ with $B^+ \to K^{*+}\mu^+\mu^-$

- All data, $K^{*+} \to K^0_S\pi^+$
- Local deviation from SM, 3σ in $P'_2 = \frac{2}{3}A_{\mathrm{FB}}/(1-F_L)$



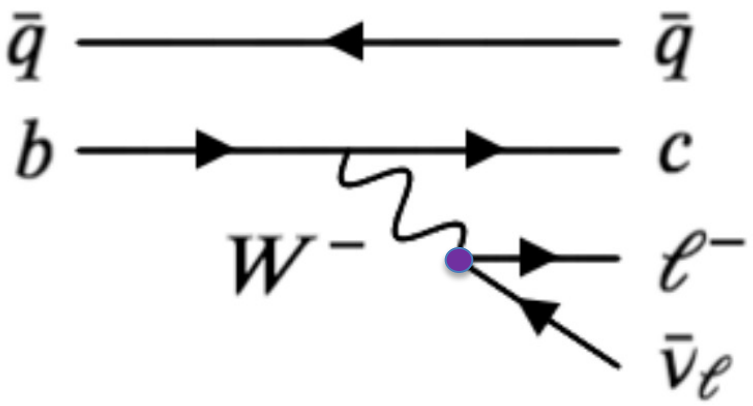


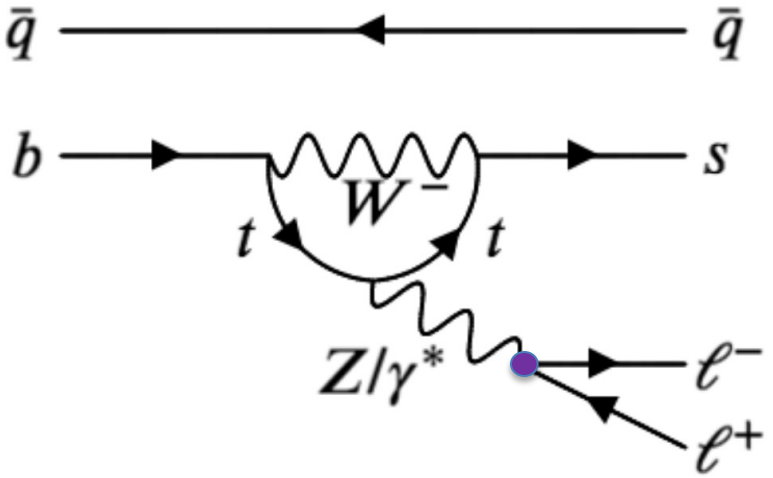


[PRL 126 (2021) 161802]

Lepton flavour universality

- In SM, three lepton families (e, μ, τ) have identical couplings to the gauge bosons





  - which means, e.g.,

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

$\mathcal{O}(10^{-4})$ uncertainty
[C. Bobeth *et al.*, JHEP 12 (2007) 040]

$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

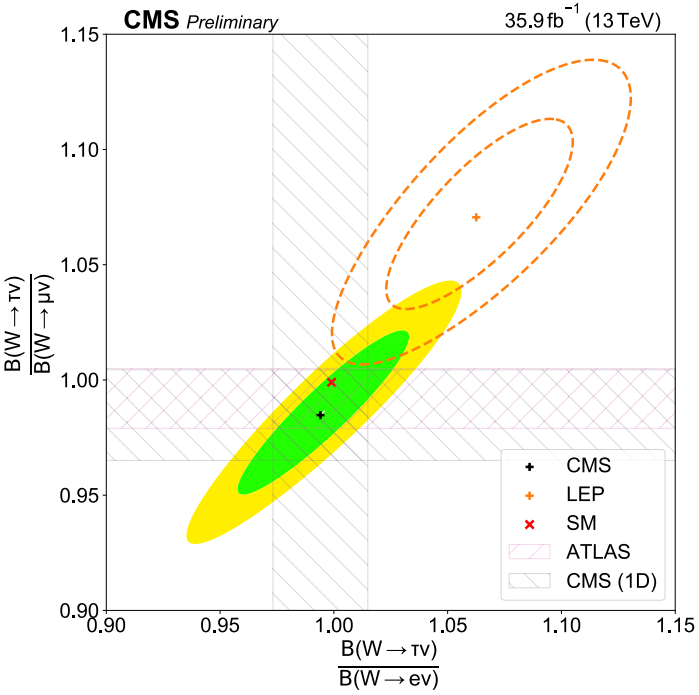
- Lepton flavor universality violation? New Physics!

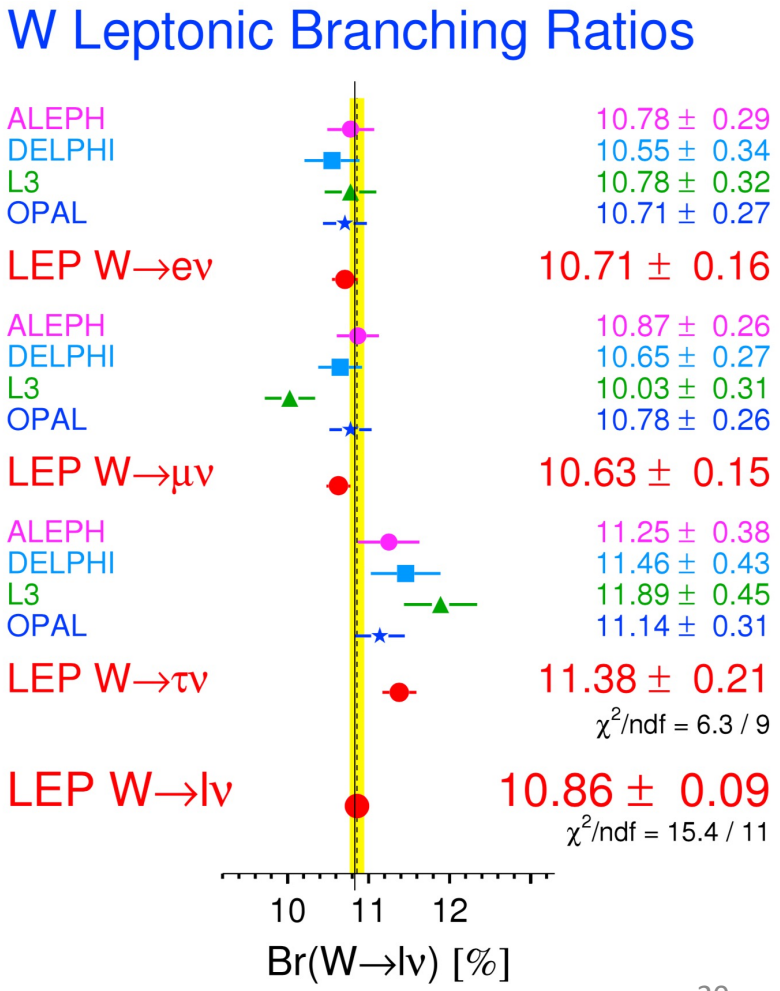
Experimental test of LFU

- Well established in SM, e.g. $W \to \ell\nu$
  - Some tension at LEP,

    addressed by ATLAS/CMS

[arXiv:2007.14040, CMS PAS SMP-18-011]



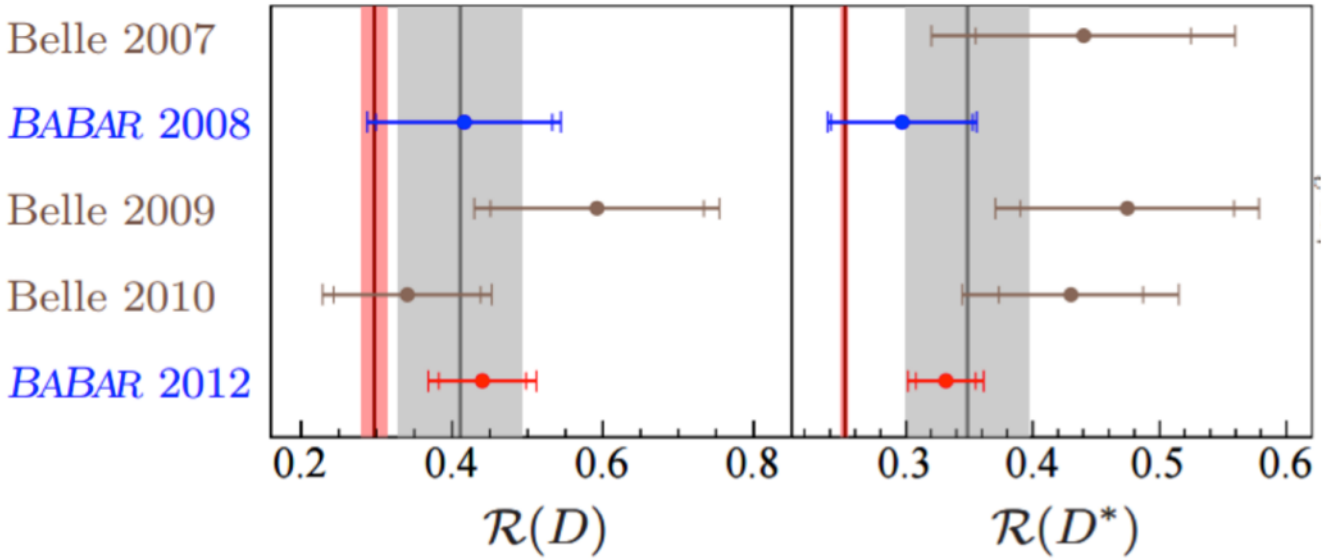


LFU in B system, pre-LHCb

- R($D^{(*)}$), Babar reported deviation of ~3.2 σ

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

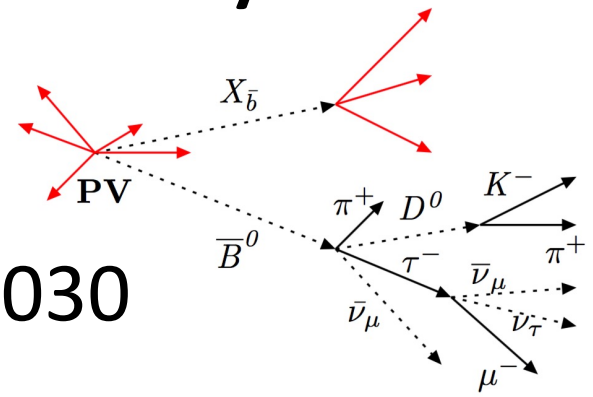
[Babar, PRD 88 (2013) 072012]



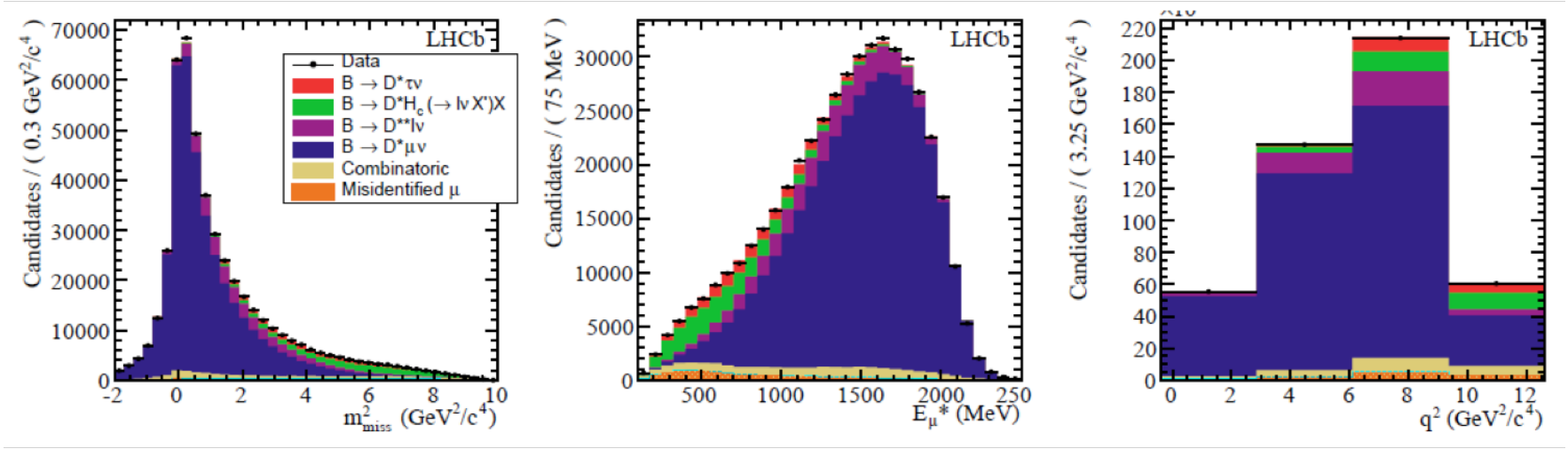
- No deviation seen in FCNC $b \to s\ell^+\ell^-$ decays

R(D*) using munoic τ decays

- $\mathcal{B}(\tau \to \mu X)$~17.4%
- 3D fits, R(D*)=0.336 ± 0.027 ± 0.030
  - Signal yields: 16 500 ± 1 670

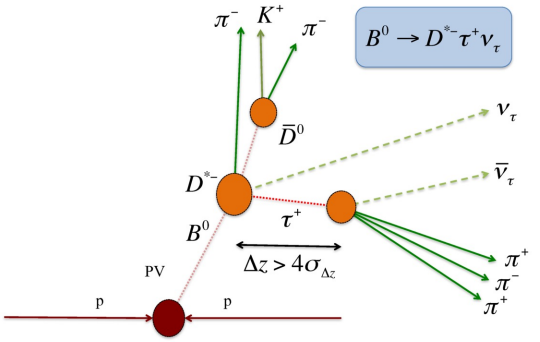


[PRL 115 (2015) 118003]



R(D*) using 3-prong τ decays

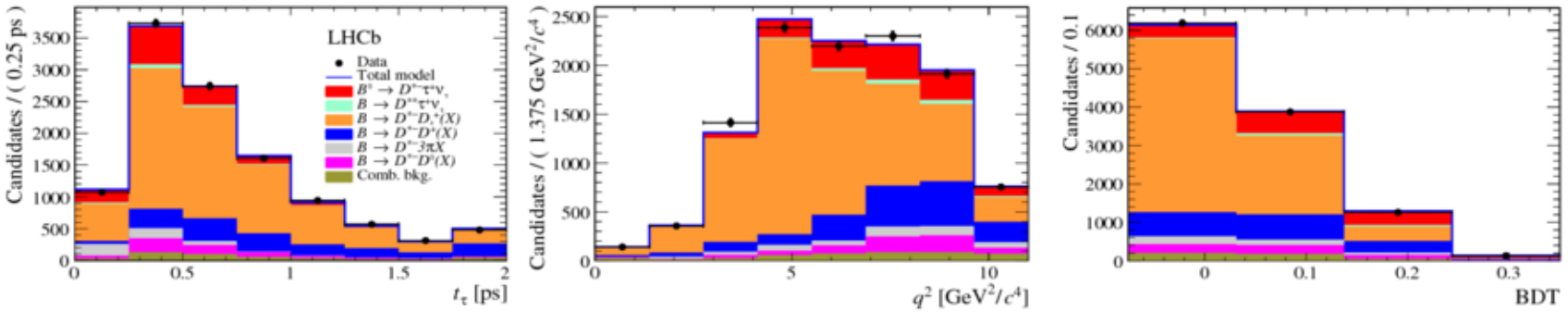
- $\mathcal{B}(\tau \to 3\pi^{\pm} X)$~9%+4%(≥1π⁰)
- Normalized to $B^0 \to D^{*-} 3\pi$



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

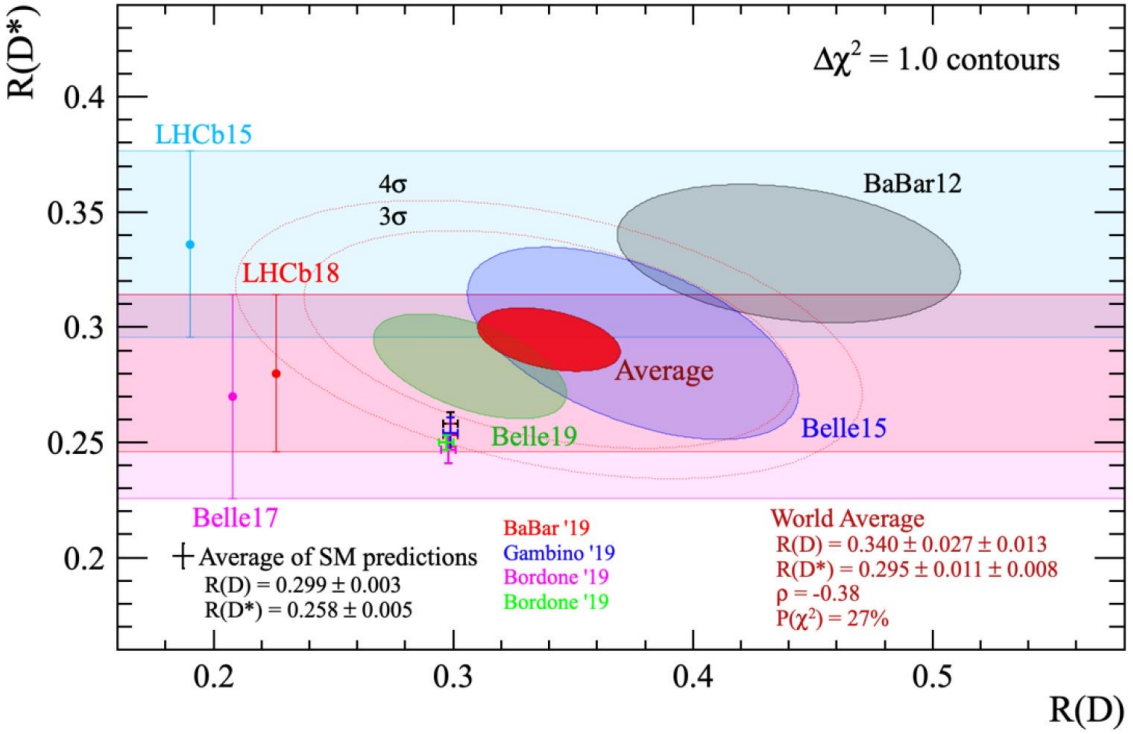
- 3D fits, R(D*)=0.286 ± 0.019 ± 0.025 ± 0.021
  - Signal yields: 1273 ± 85

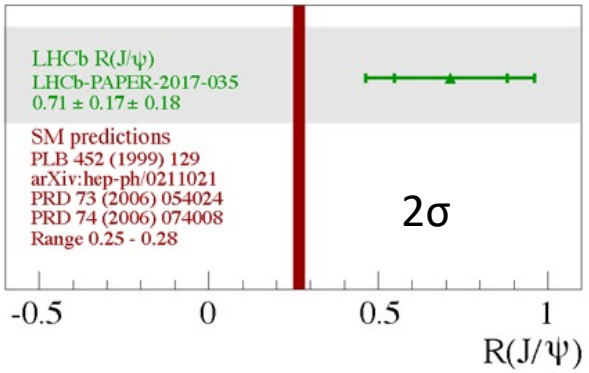
[PRL 120 (2018) 171802]



Summary of LFU in $b \to c\ell\nu$ decays

- Deviations from SM seen by Babar/Belle/LHCb

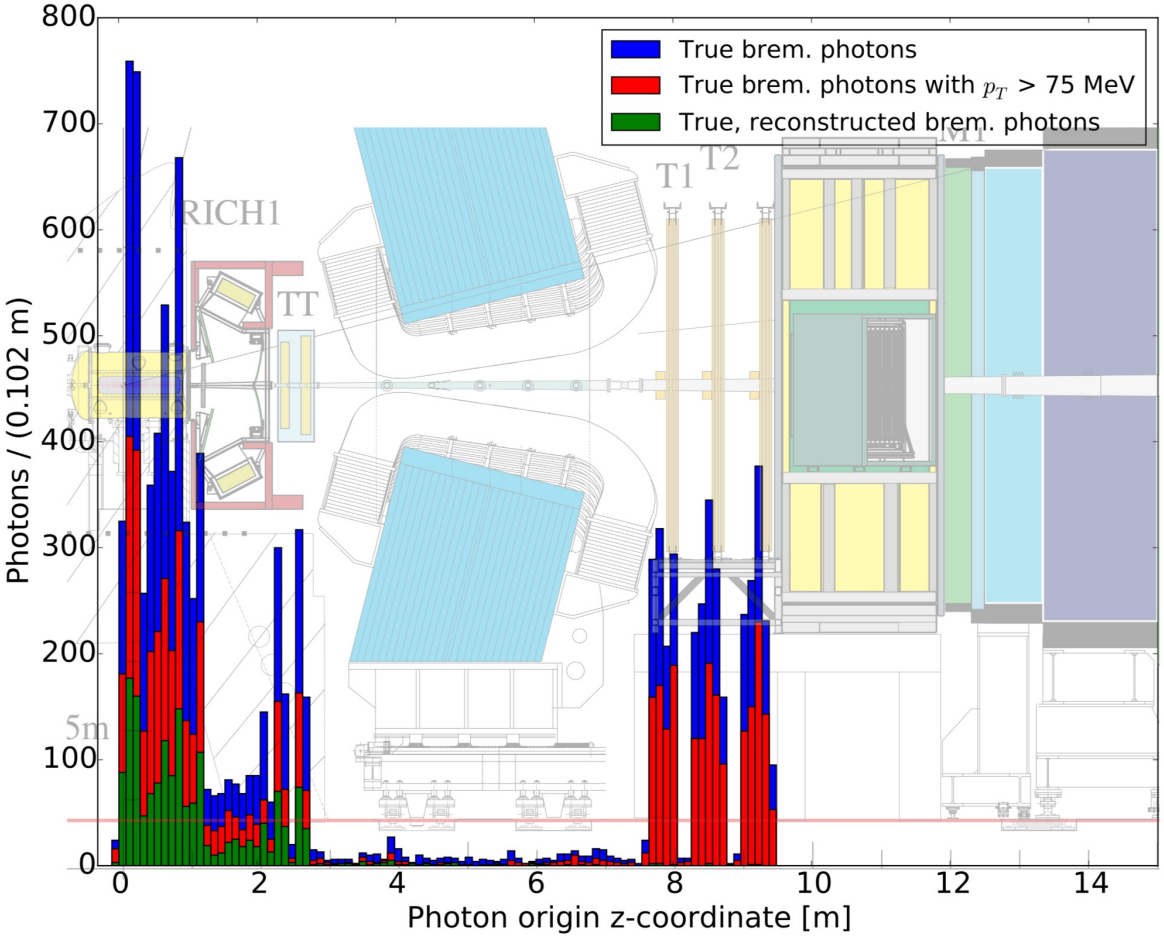


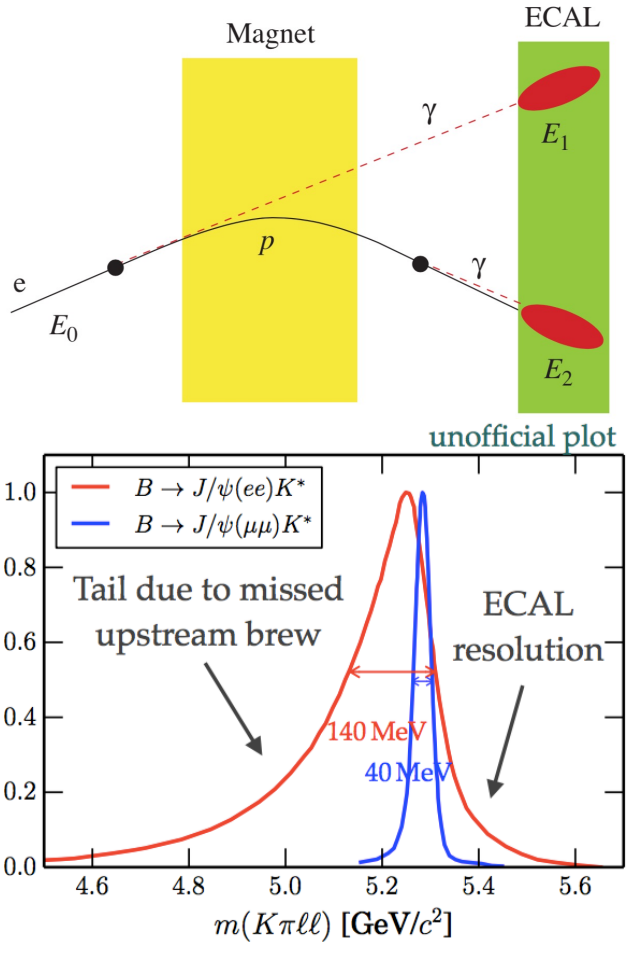


$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$

Back to 3.8σ?
[arXiv:1912.09335]

Bremsstrahlung corrections

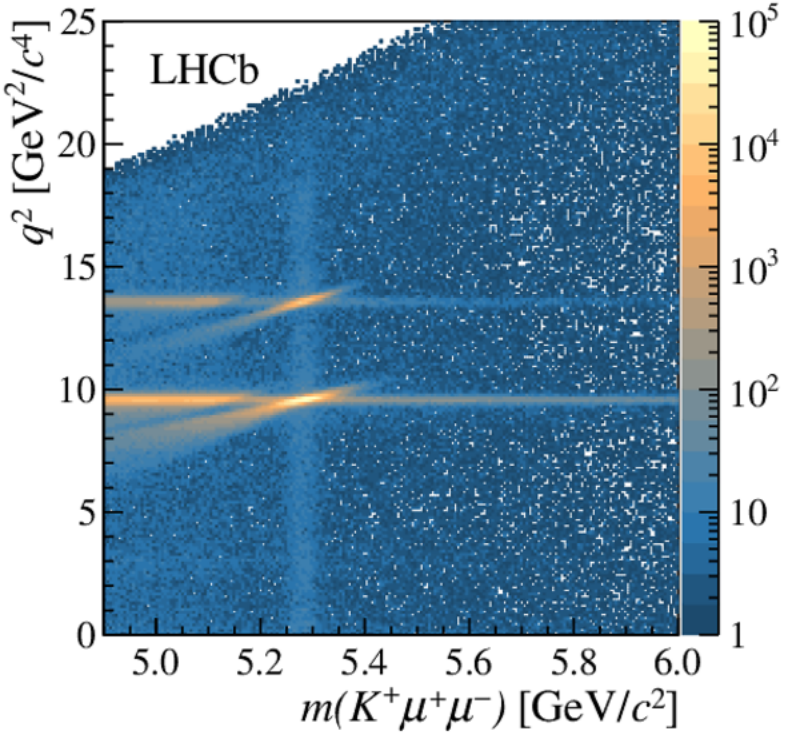


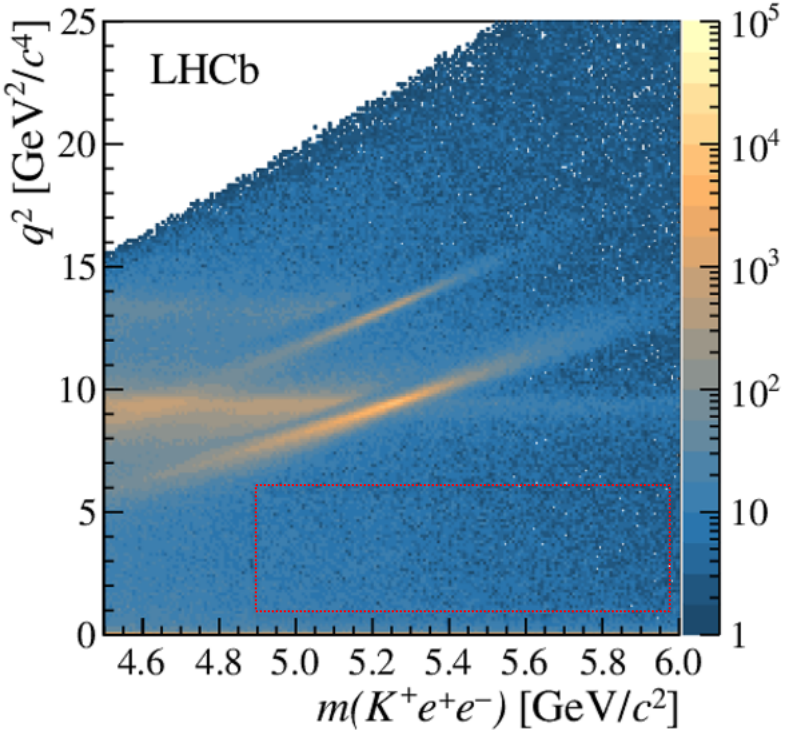


R(K), introduction

- Double ratio to control systematics

$$\mathcal{R}_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}} \right) \left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}} \right) \left(\frac{\varepsilon_{K^+e^+e^-}}{\varepsilon_{K^+\mu^+\mu^-}} \right) \left(\frac{\varepsilon_{J/\psi(\mu^+\mu^-)K^+}}{\varepsilon_{J/\psi(e^+e^-)K^+}} \right)$$



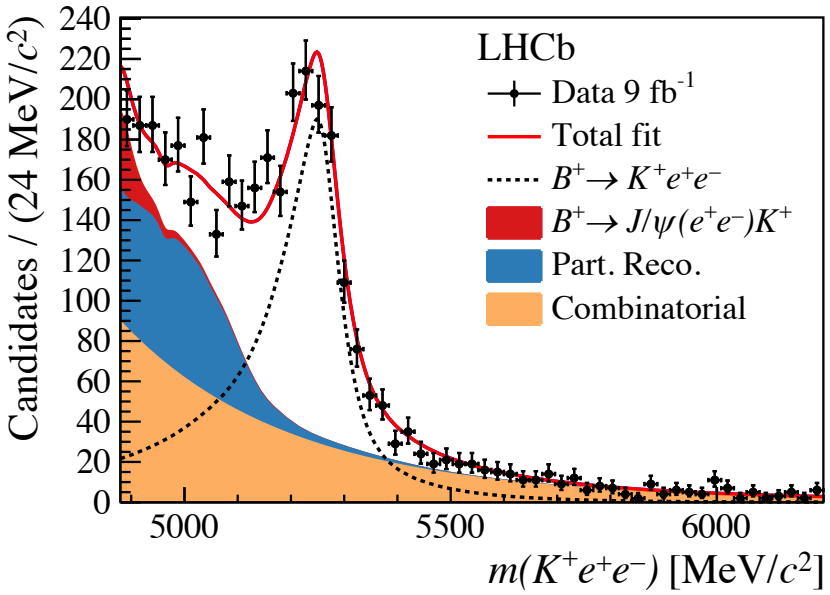


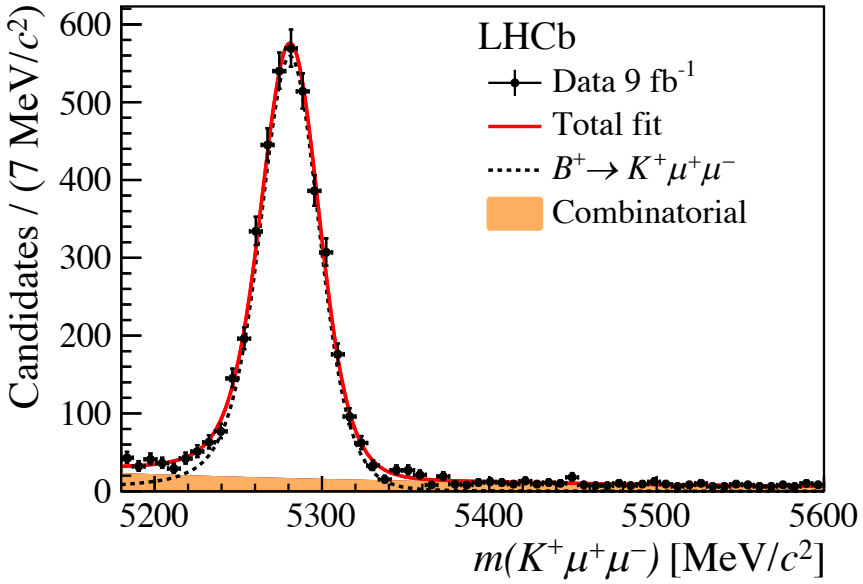
[PRL 122 (2019) 191801]

Signal yields with all data

- 9 fb^{-1} of data, $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
  - $N(B^+ \to K^+e^+e^-) = 1640 \pm 70$
  - $N(B^+ \to K^+\mu^+\mu^-) = 3850 \pm 70$

[arXiv:2103.11769]

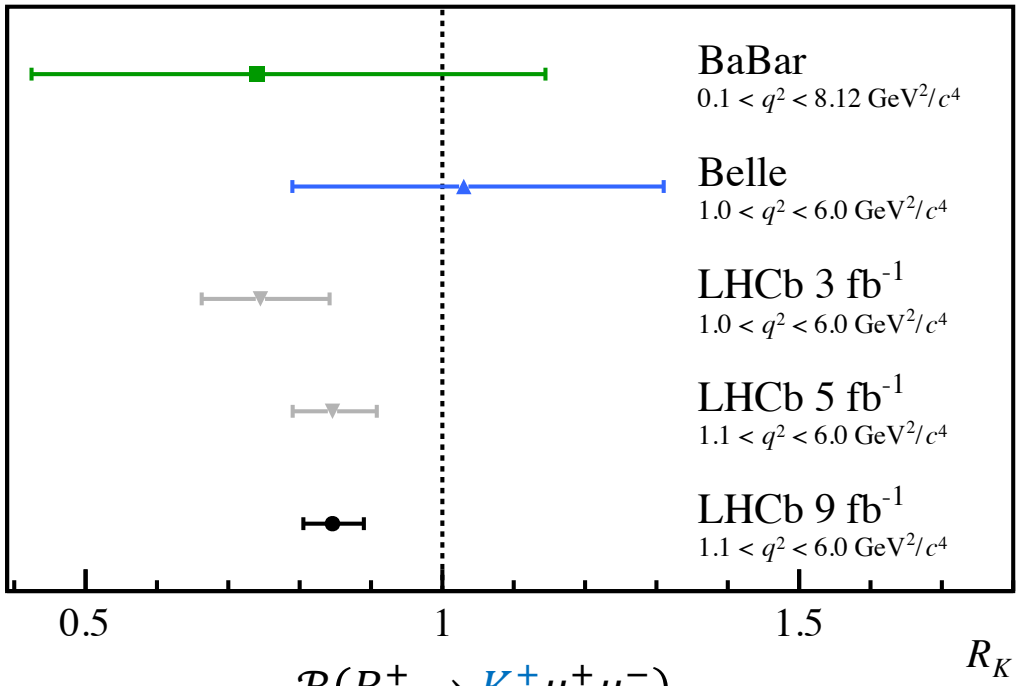




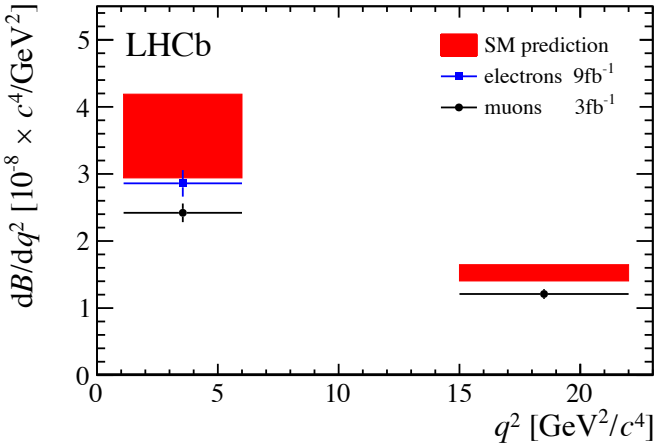
R(K), latest results

- Devivation from SM, 3.1σ by LHCb
- Electron mode more close to SM prediction?

[arXiv:2103.11769]

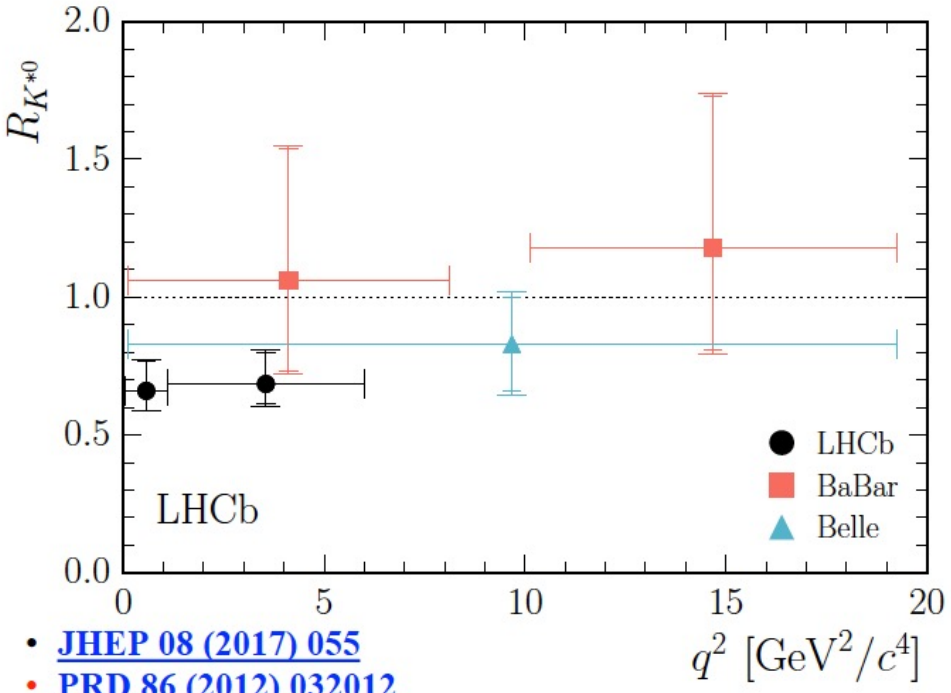


$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

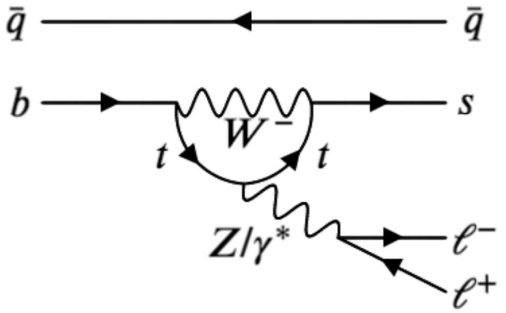


R(K^{*0}), results with Run-I data

- Deviations from SM seen by LHCb ($\sim 2.4\sigma$)



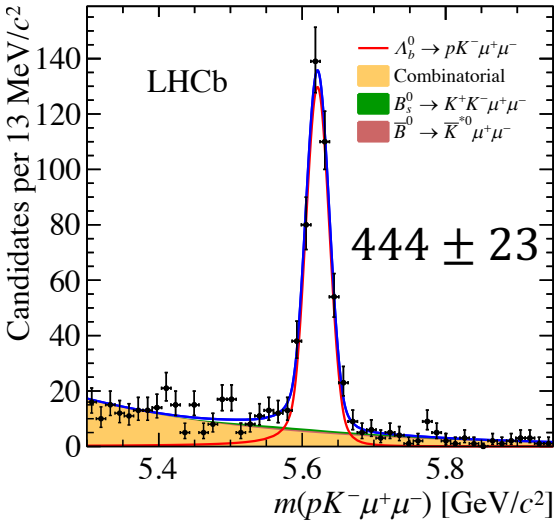
- JHEP 08 (2017) 055
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

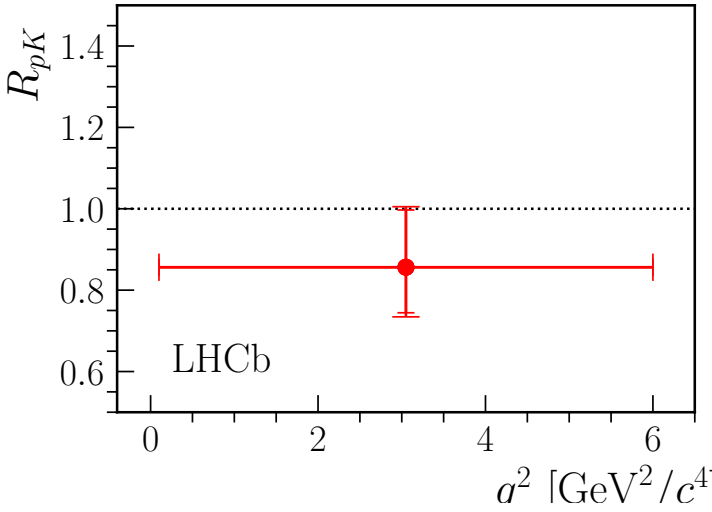


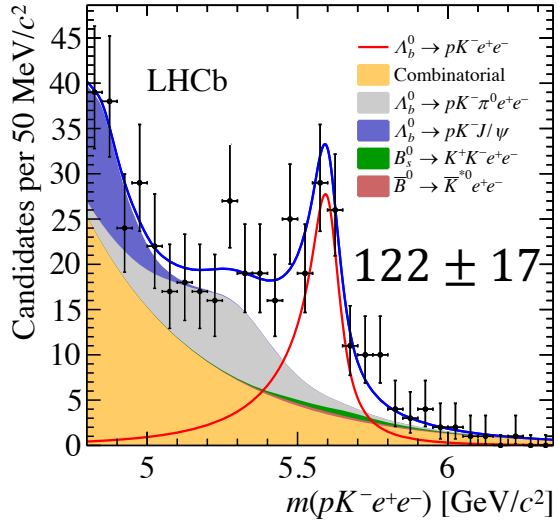
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

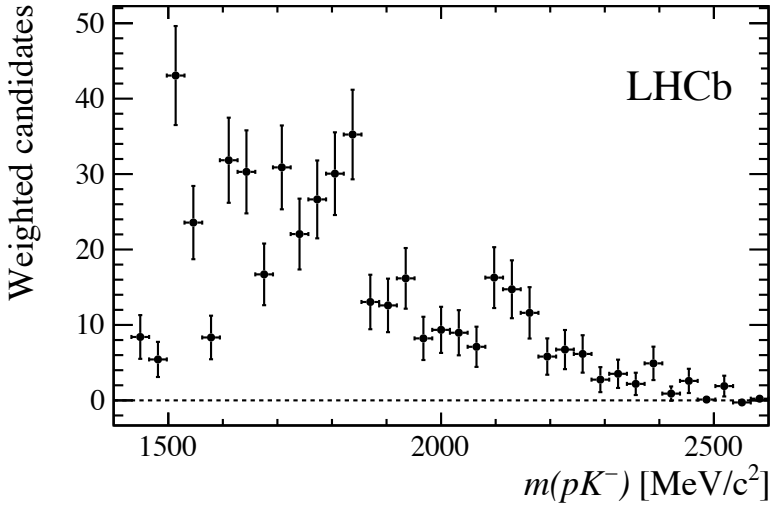
R(pK), results with Run-I+2016

- Compatible with 1, difficult to predict R(pK)?





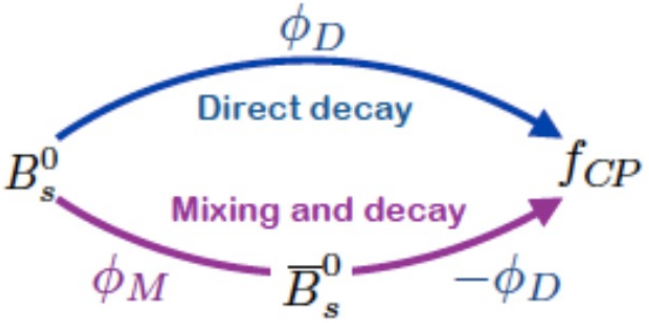




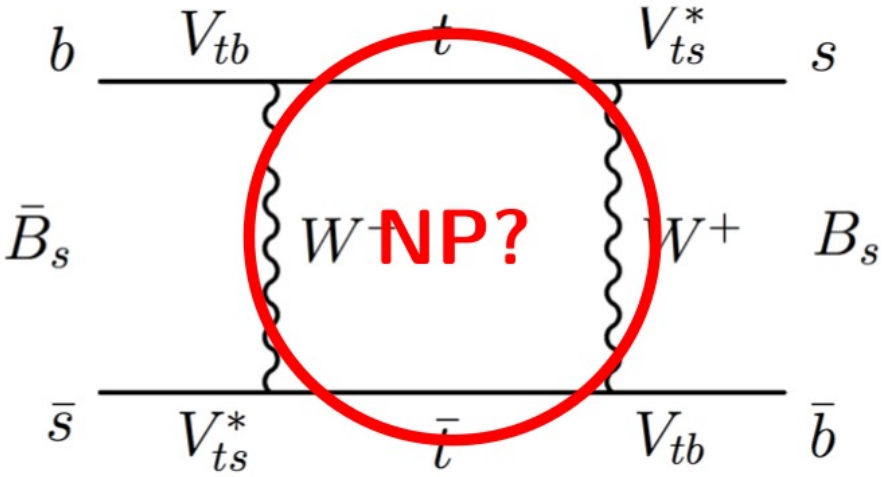
[JHEP 05 (2020) 040]

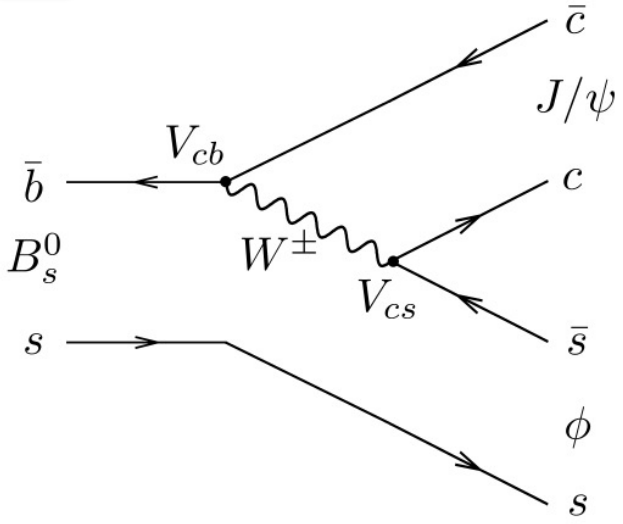
Mixing induced CPV

- $\phi_s = \phi_M - 2\phi_D$, small in SM, sensitive to NP
- Small penguin pollution



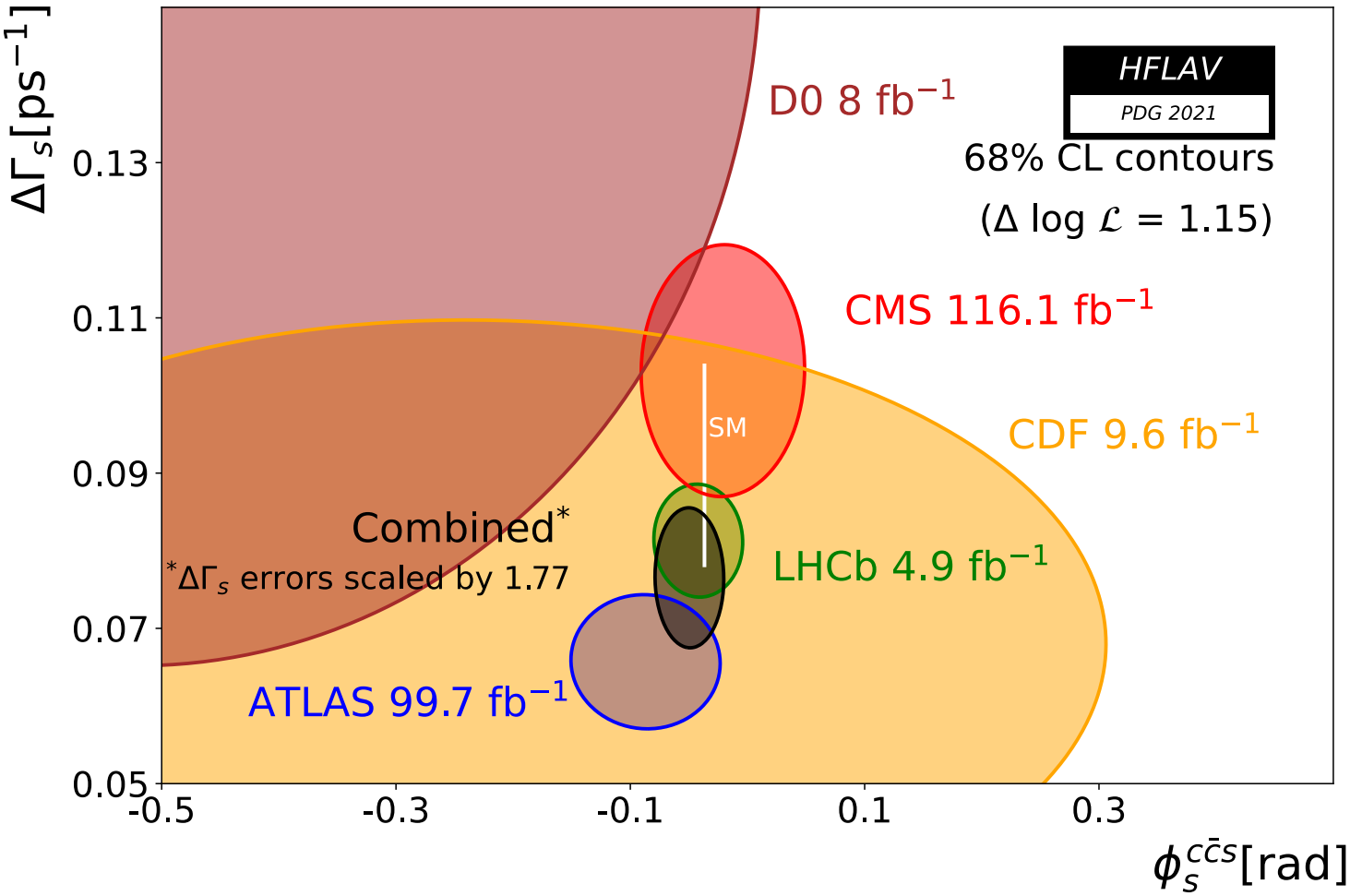
$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}, \text{ with } \phi_s^{\rm SM} = -2\beta_s + \delta P = (-0.0376^{+0.0008}_{-0.0007})\text{rad} + \delta P$$



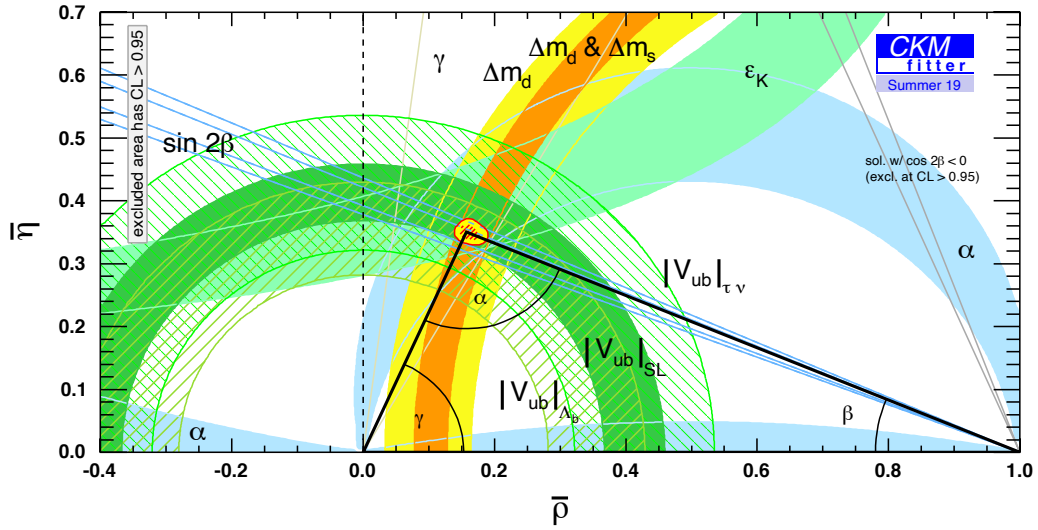


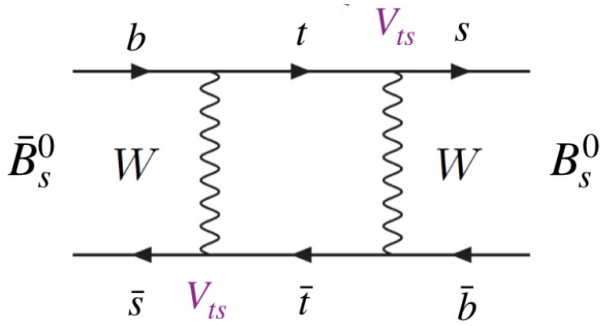
Latest results on ϕ_s

https://hflav-eos.web.cern.ch/hflav-eos/osc/PDG_2021/



B_s^0 mixing parameter Δm_s





$$\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2 \qquad q = d, s$$

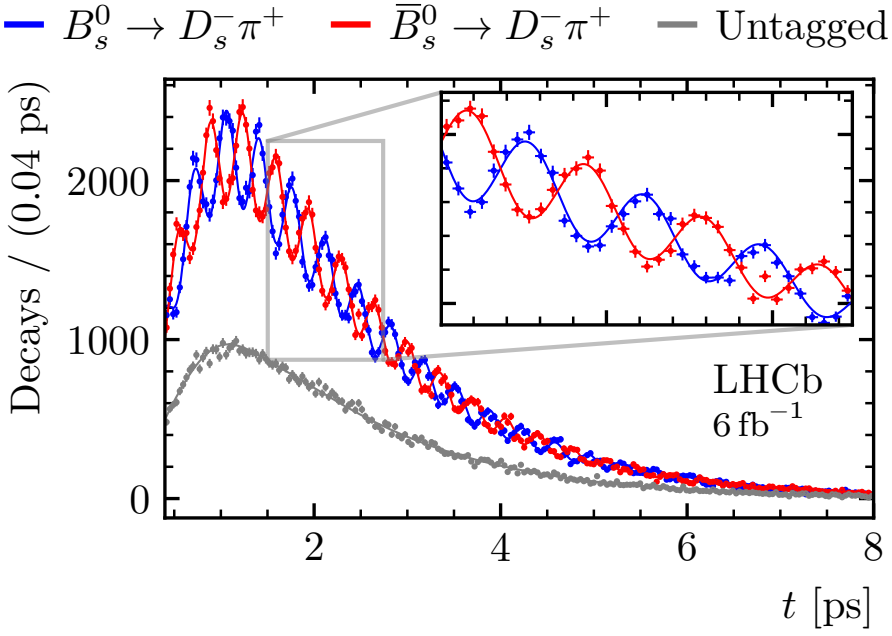
$$\frac{\Delta m_d}{\Delta m_s} = \frac{|V_{td}^2|}{|V_{ts}^2|} \frac{m_{B_d}}{m_{B_s}} \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} = \frac{|V_{td}^2|}{|V_{ts}^2|} \frac{m_{B_d}}{m_{B_s}} \xi^{-2}$$

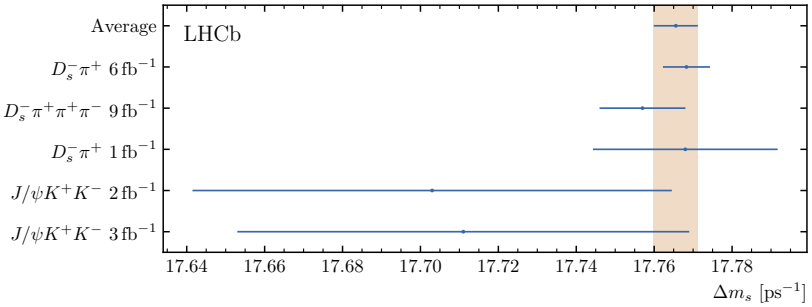
where $\xi = 1.200^{+0.0054}_{-0.0060}$ [L. Di Luzio *et al.*, JHEP 12 (2019) 009]

Δm_s, latest results from LHCb

- $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \mathrm{ps}^{-1}$, consistent with SM prediction $18.4^{+0.7}_{-1.2}\ \mathrm{ps}^{-1}$

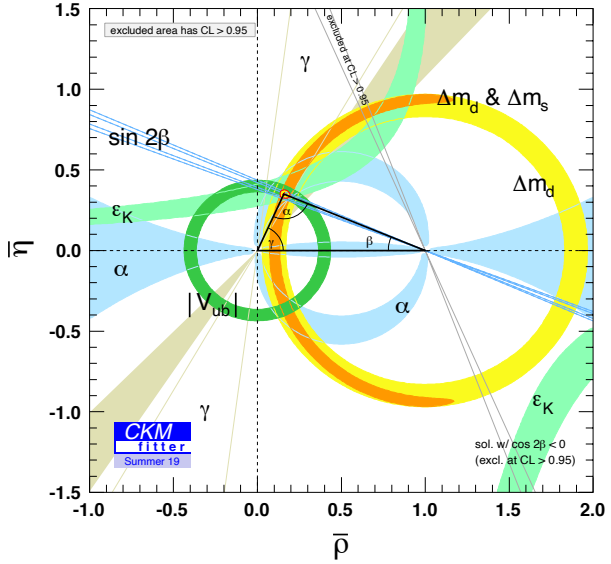
[arXiv:2104.04421]

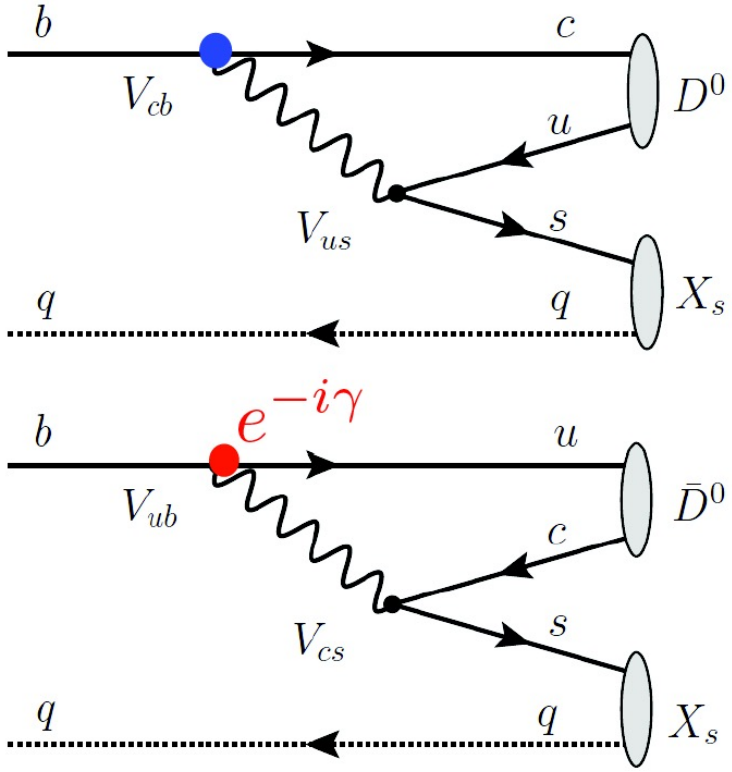




CKM-γ

- Least well-measured angle



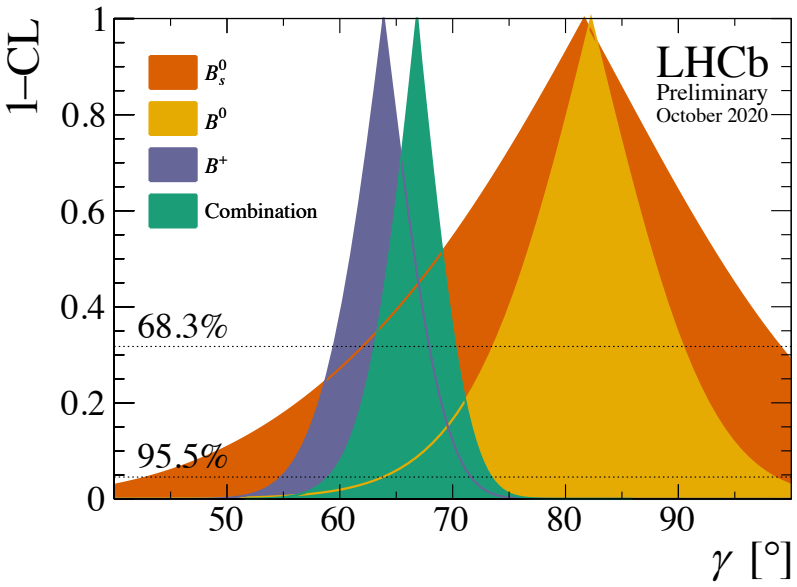


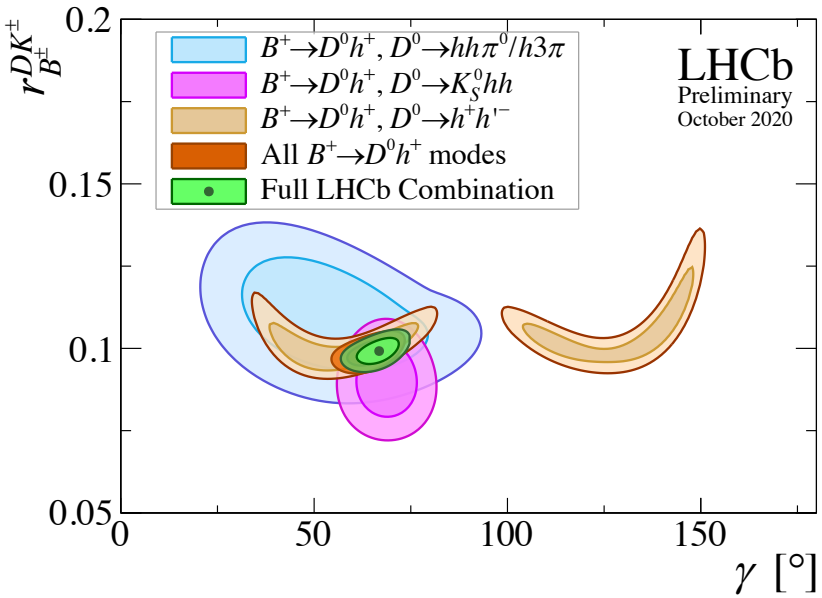
- Interference between $b \to u$ and $b \to c$ transitions
- CP observables $\Rightarrow \gamma$

CKM-γ, LHCb combination

- Most precise determination, $\gamma = (67 \pm 4)°$, c.f., indirect determination: $\gamma = (65.7^{+1.0}_{-2.5})°$
- Combined analysis with BES-III will help

[LHCb-CONF-2020-003]





ΔA_{CP} in charm

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

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

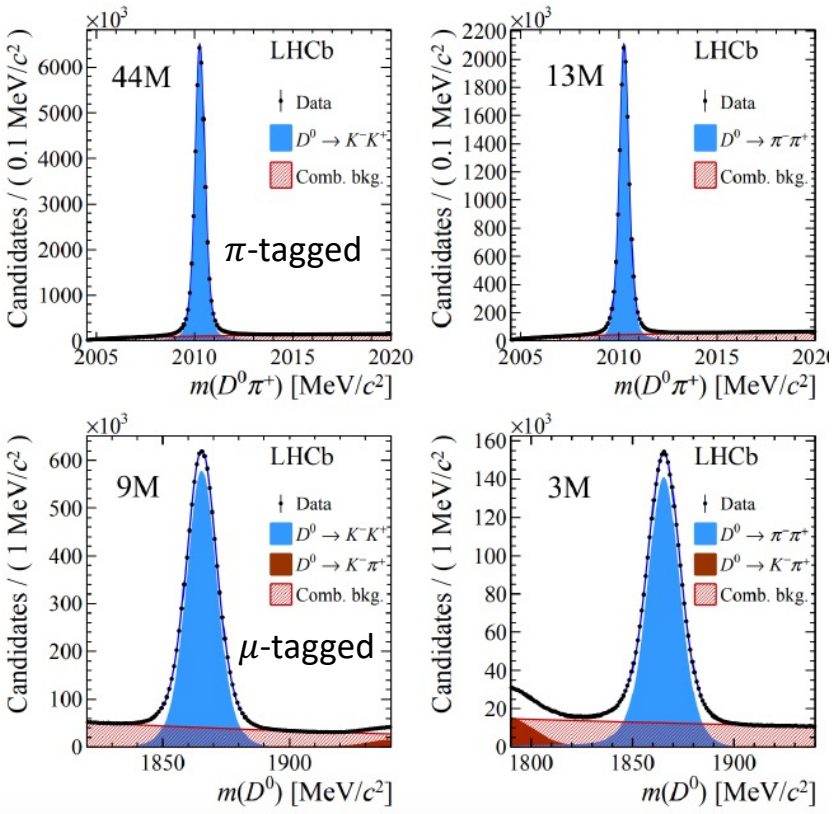
$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$

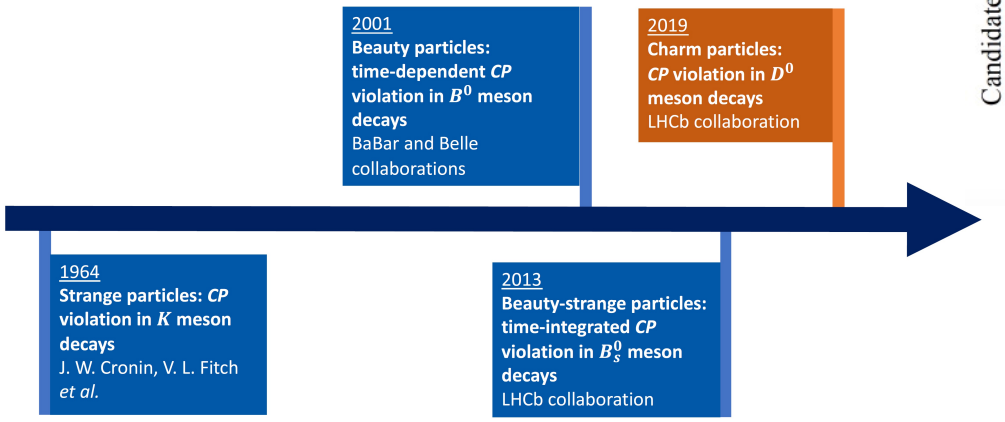
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

Combined one:

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

[PRL 122 (2019) 211803]





Prospects

- LHCb upgrades (2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

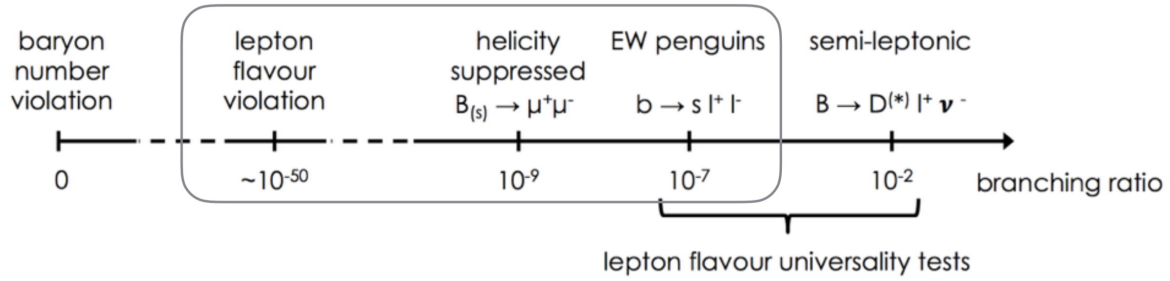
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
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	Under study [608]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B^0_s \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

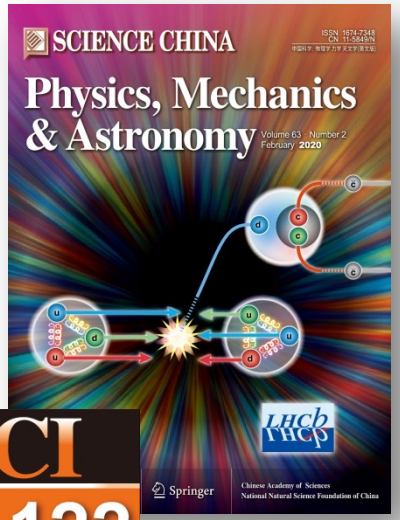
[CERN-LHCC-2018-027]

Summary

- Some anomalies seen at LHCb
  - $b \to s\ell^+\ell^-$, $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$, P_5' in $B \to K^*\mu^+\mu^-$, $\mathcal{R}_{K^{(*0)}}$
  - $b \to c\ell^-\bar{\nu}_\ell$, $\mathcal{R}_{D^*}$

  to be confirmed or refuted with more data
- Continuous efforts on CPV
  - ϕ_s, Δm_s, CKM-γ, charm ΔA_{CP}
- Your suggestions are always appreciated!





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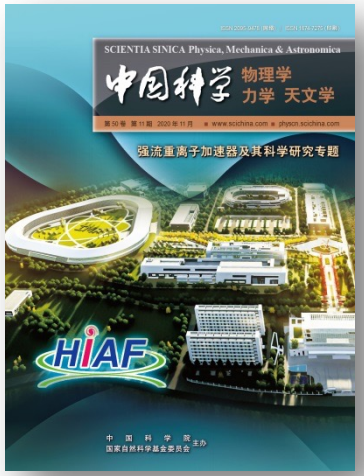

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