Universität Zürich[UZH]

Overview of neutral-current B anomalies at LHCb

Flavour at the Crossroads, MITP

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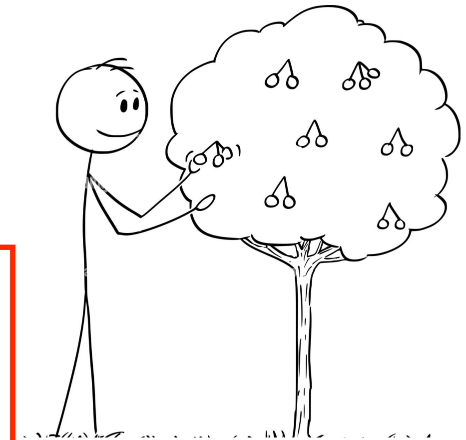
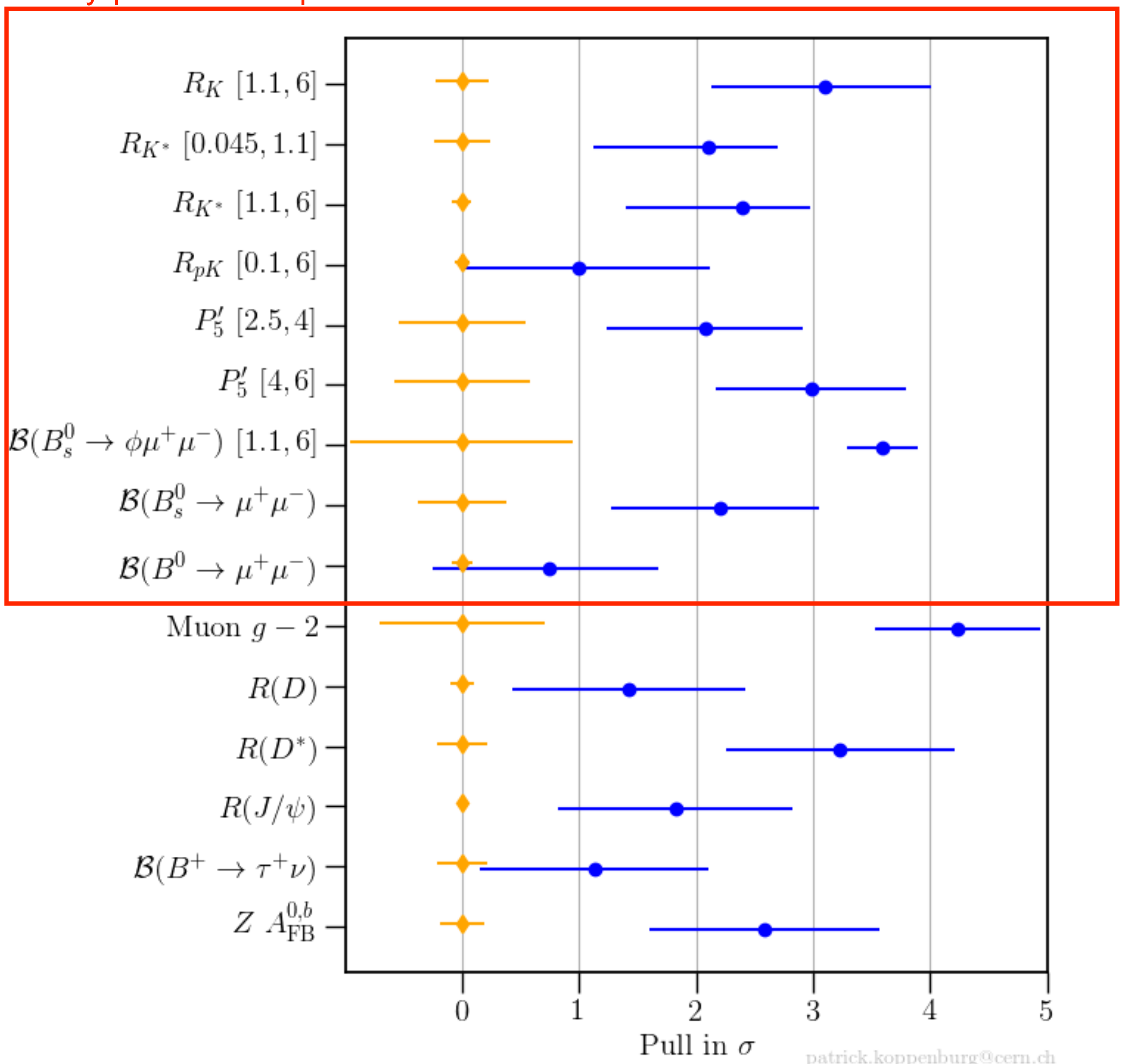
25.04.2022

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

What I will talk about



Cherry-picked examples

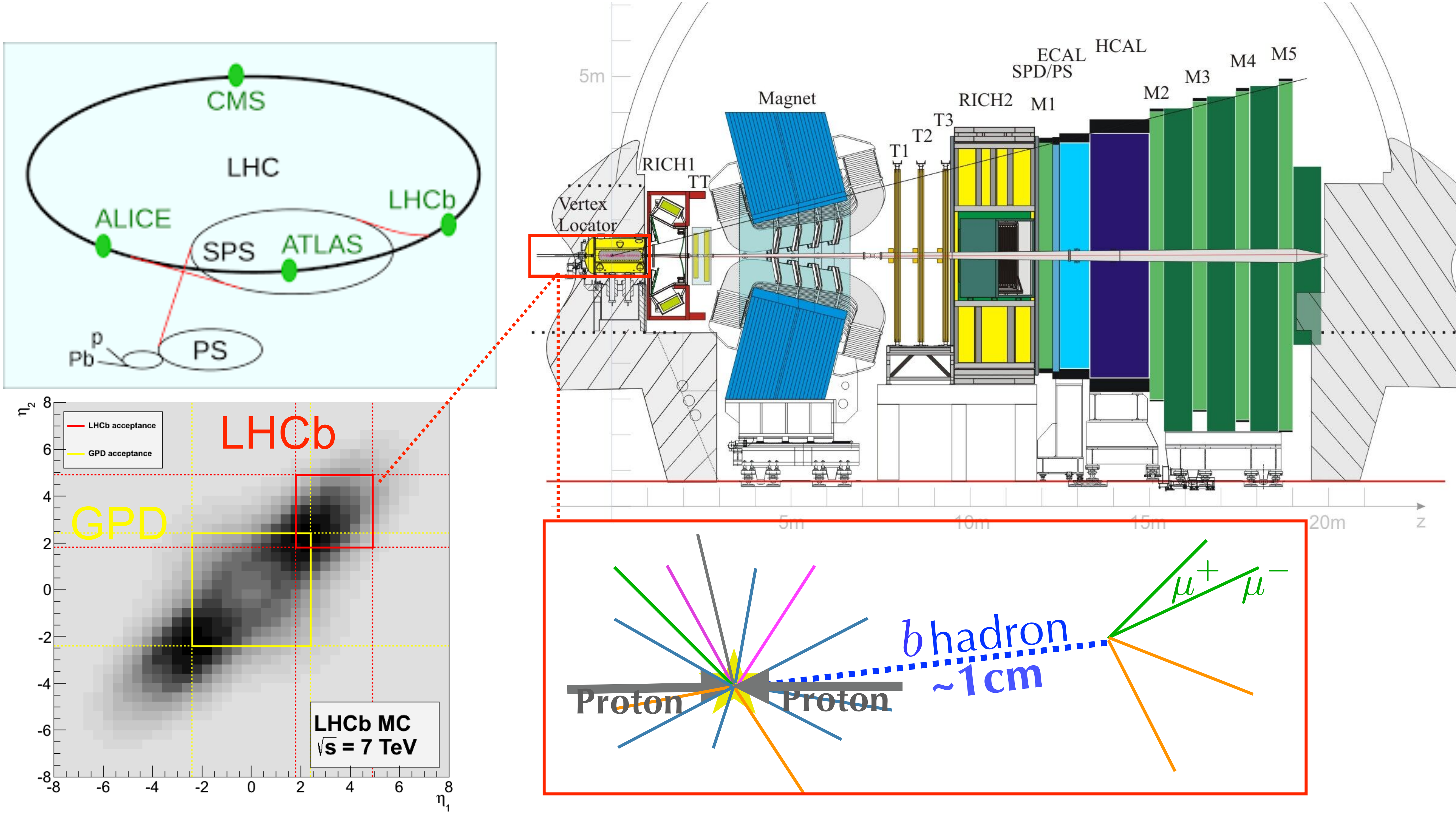


https://www.nikhef.nl/~pkoppenb/anomalies.html

- Brief introduction
- Recent results from LHCb on $b \to s\ell^+\ell^-$ decays
- Remaining Run 2 measurements expected in near-future
- Run 3 prospects

Why $b \to s(d)\ell^+\ell^-$ decays at LHCb?

- B-quarks produced at the LHC have a significant **boost in the forward direction**, exploited by LHCb experiment



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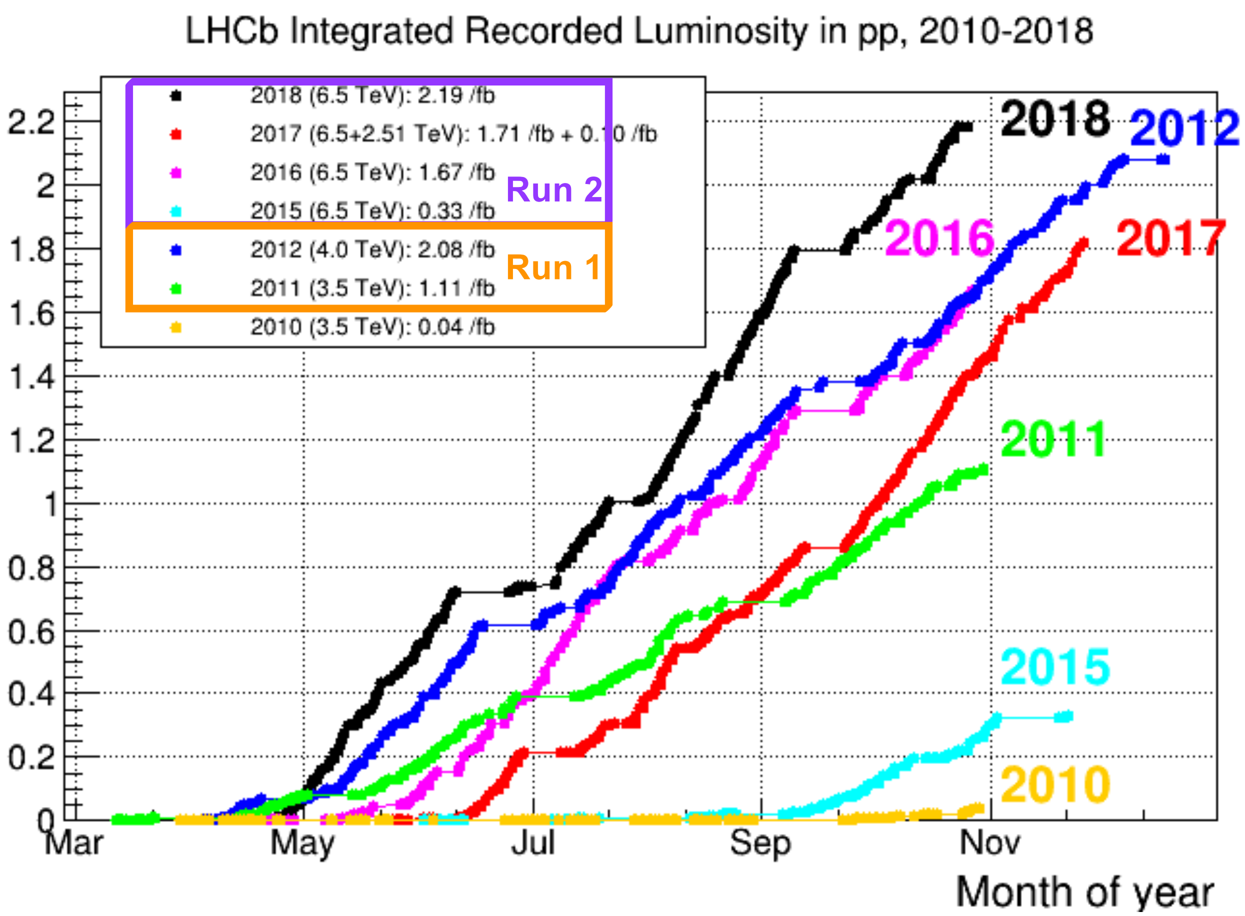
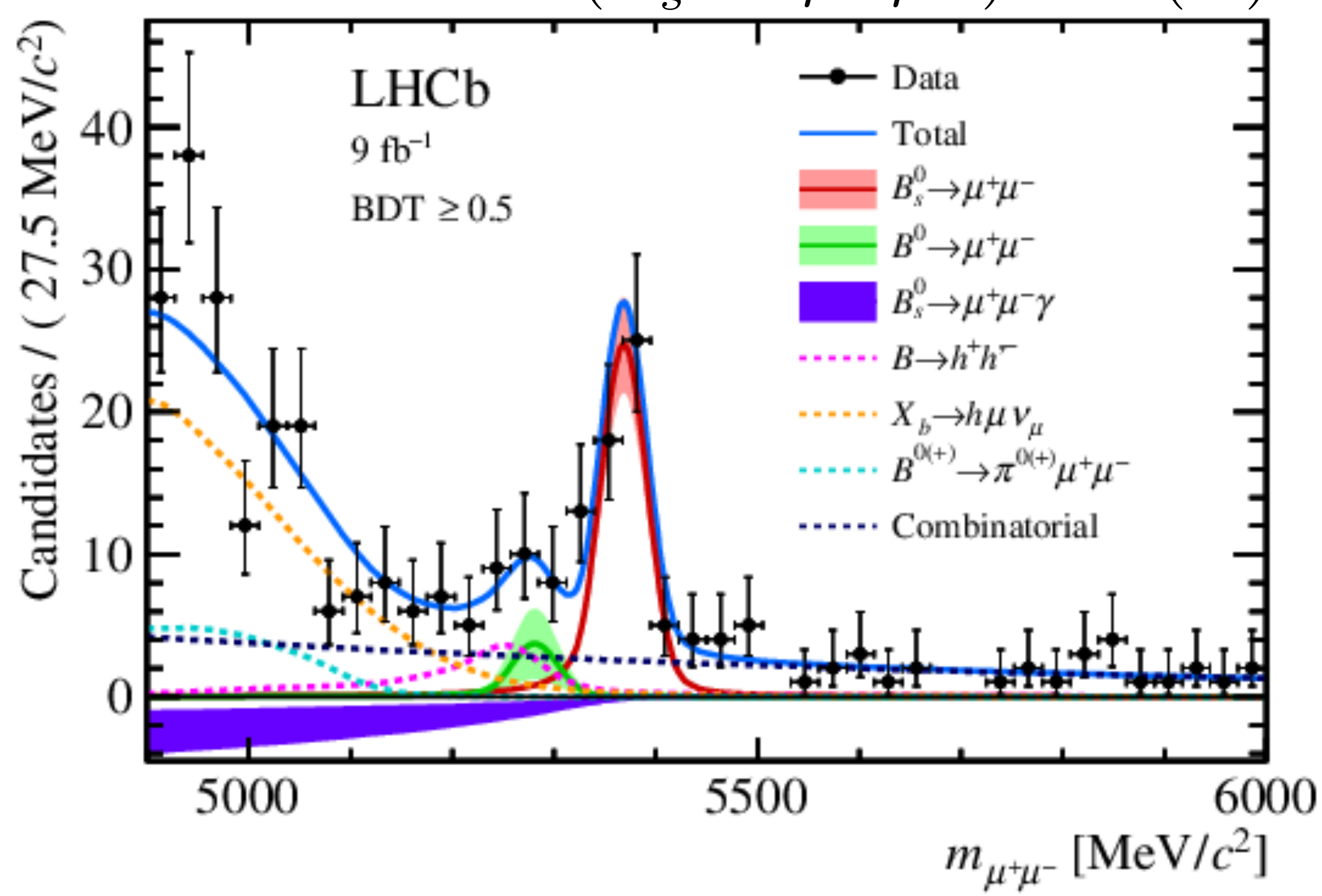
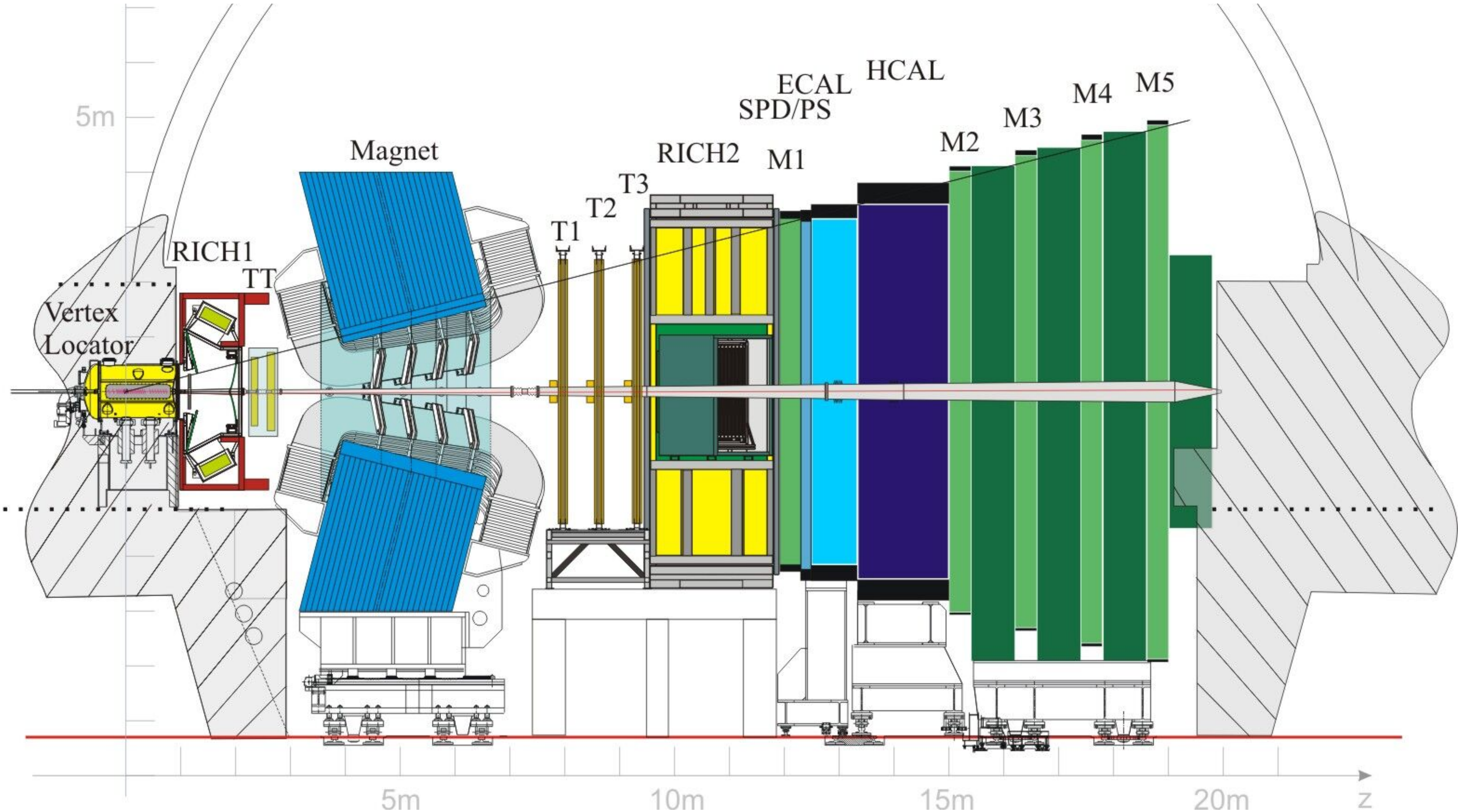


$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \mathcal{O}(\text{-}9)$



Current available LHCb data (LHC Run 1 (2011-2012) and Run 2 (2015-2018)) gives **upto 1% precision** on NP-sensitive $b \to s\ell^+\ell^-$ observables

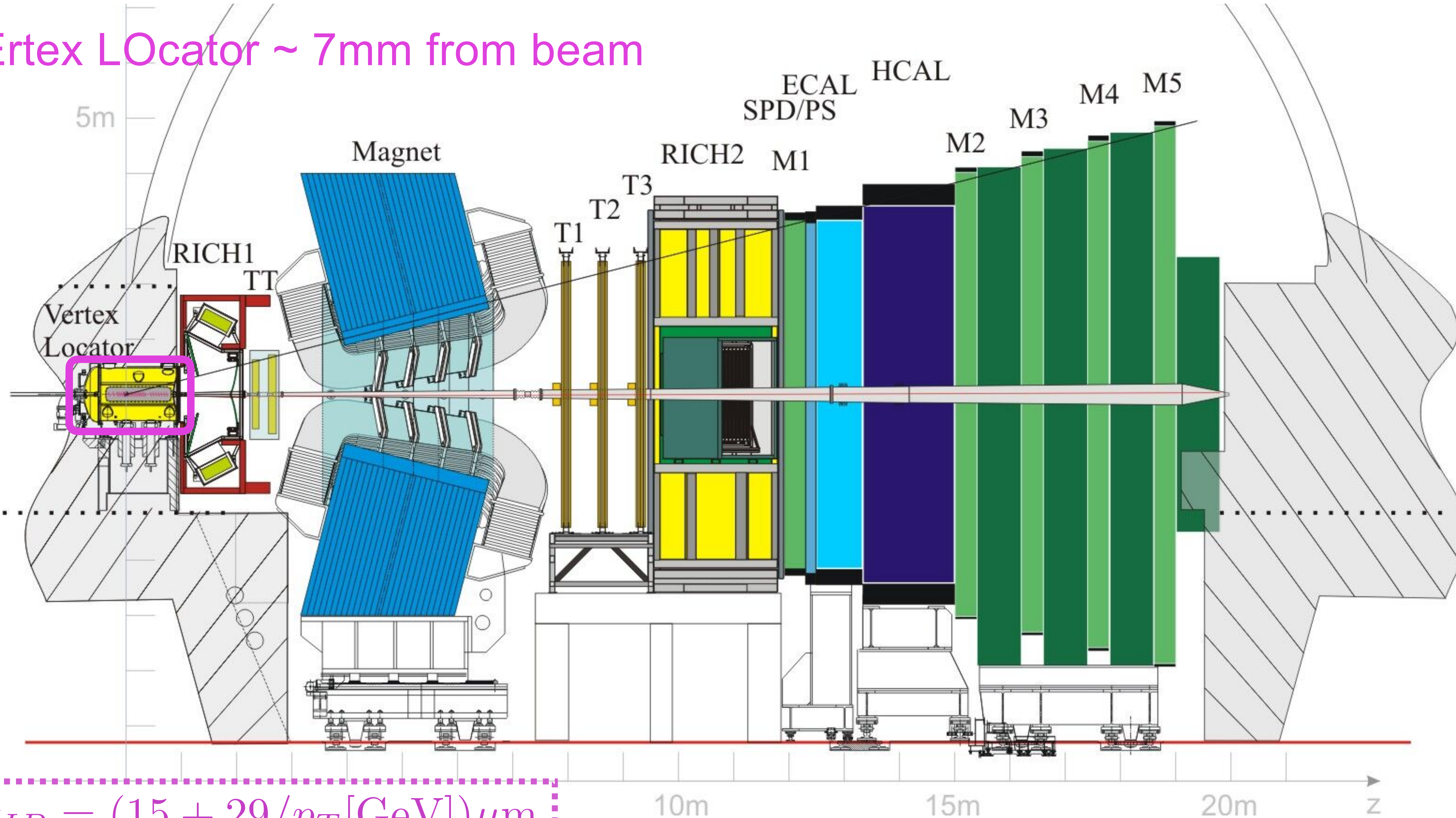
The LHCb detector



Int. J. Mod. Phys. A 30 (2015) 1530022

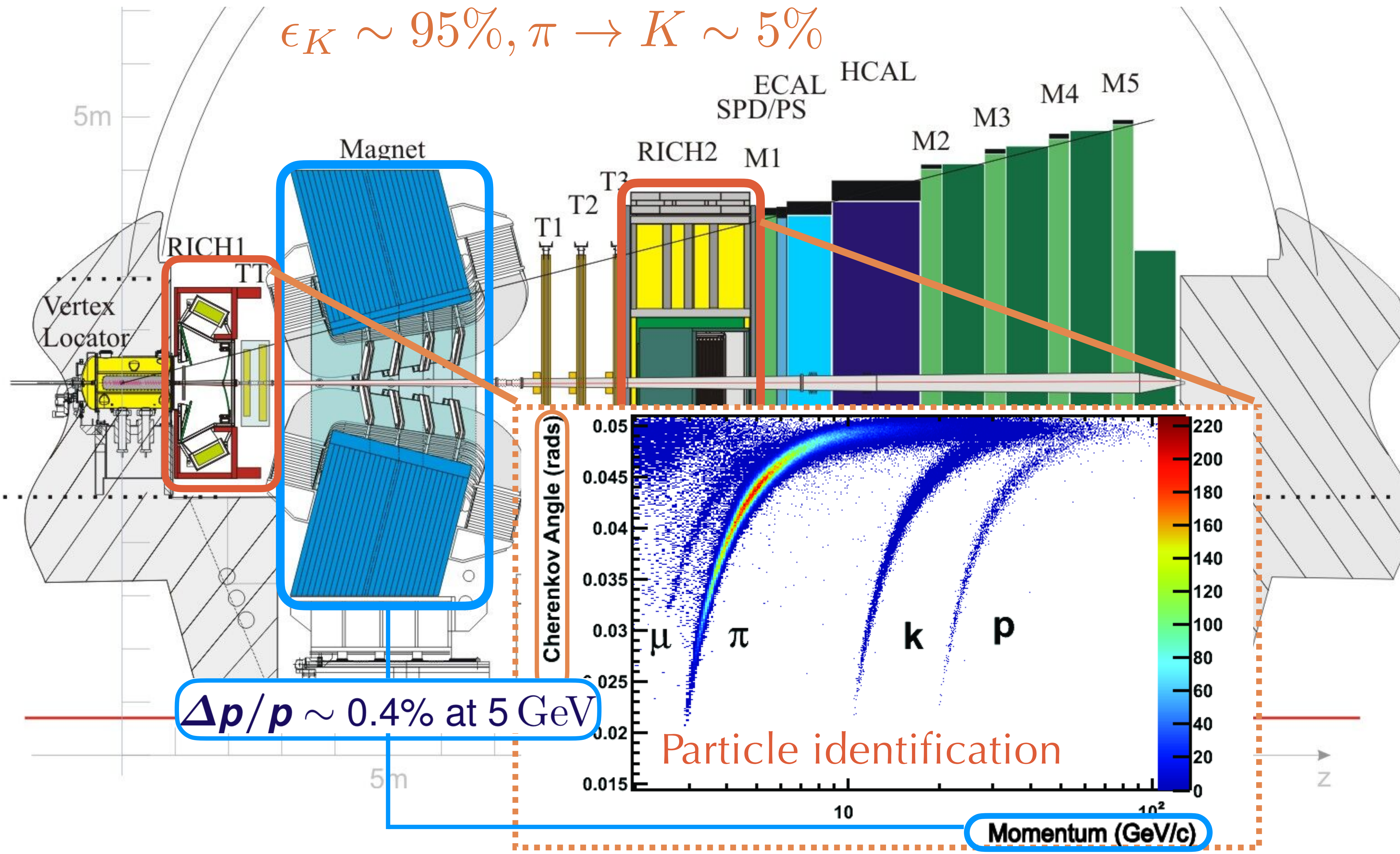
The LHCb detector

VErtex LOcator ~ 7mm from beam



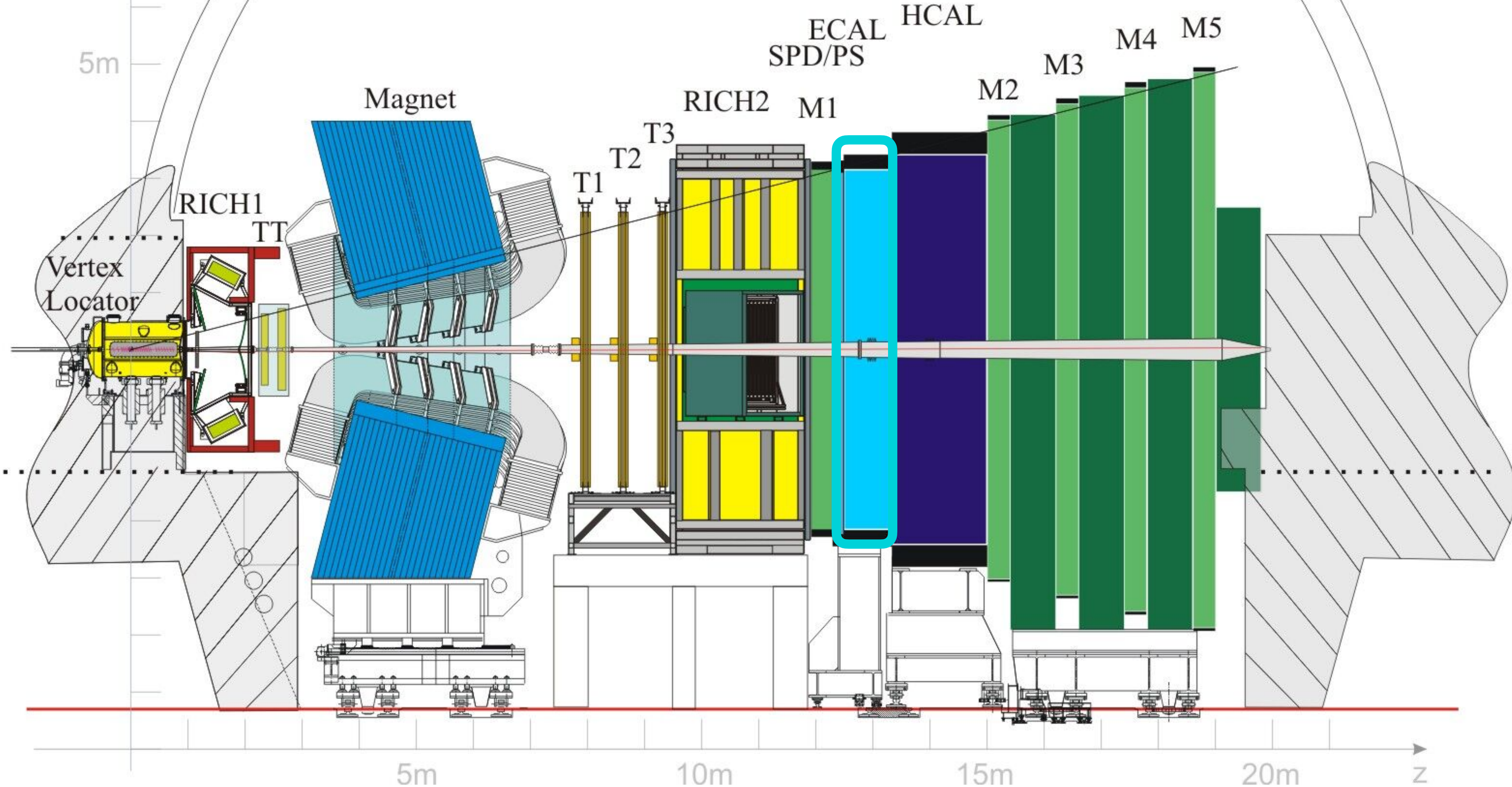
$$\sigma_{IP} = (15 + 29/p_T[\mathrm{GeV}])\mu\mathrm{m}$$

The LHCb detector



The LHCb detector

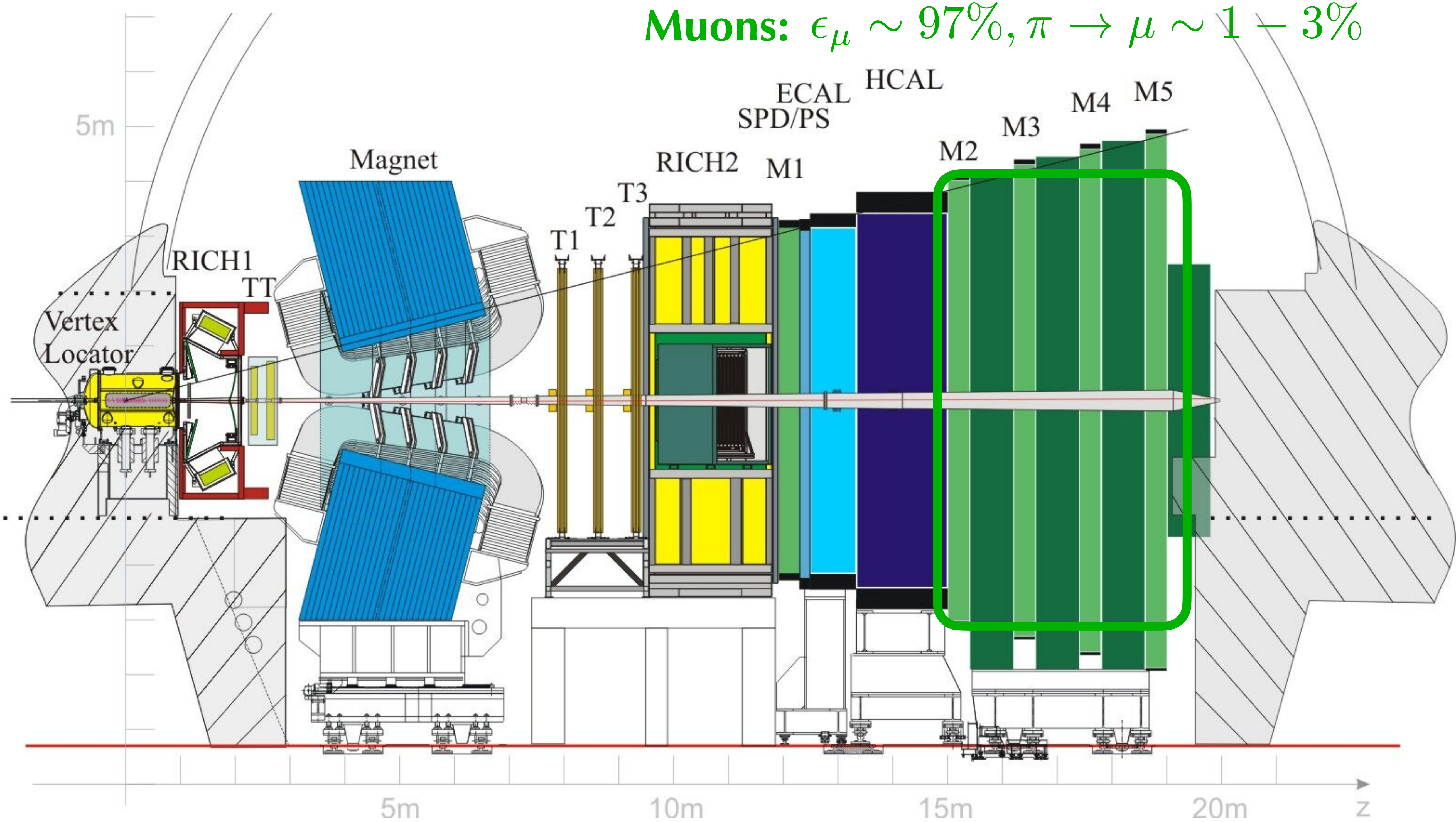
Electrons: $\epsilon_e \sim 90\%, e \rightarrow h \sim 5\%$



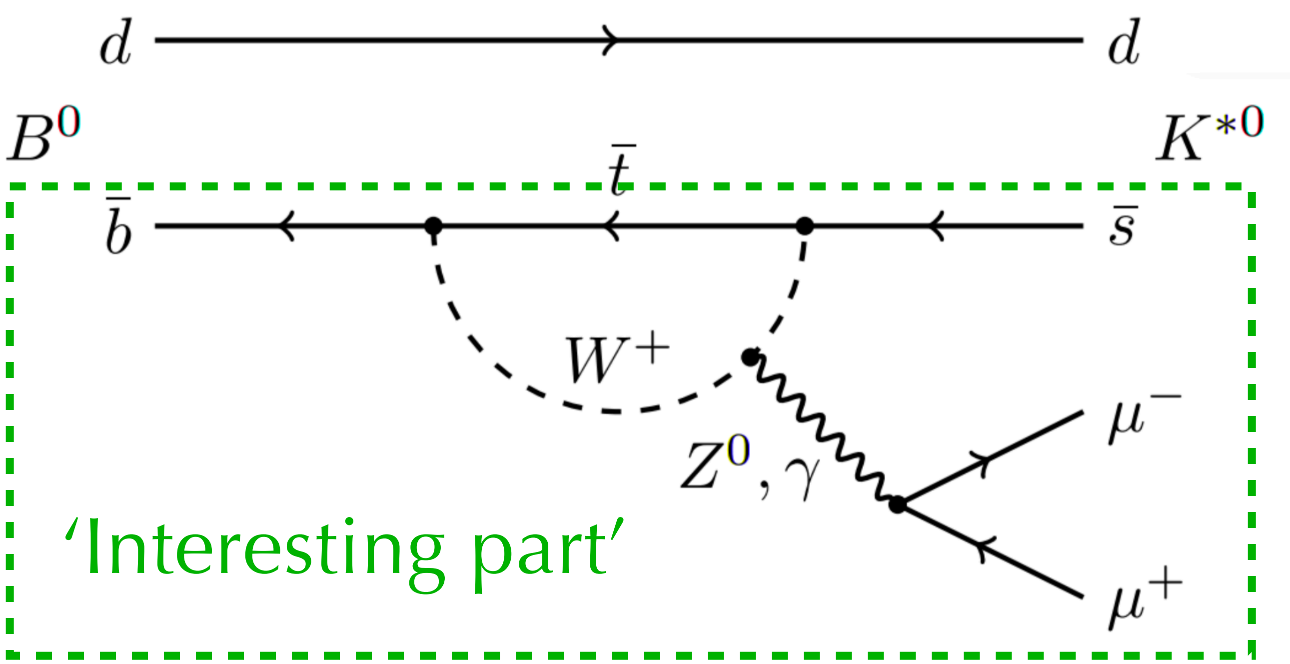
ECAL resolution: $1\% \pm \frac{10\%}{\sqrt{(E[GeV])}}$

The LHCb detector

Muons: $\epsilon_\mu \sim 97\%, \pi \to \mu \sim 1-3\%$

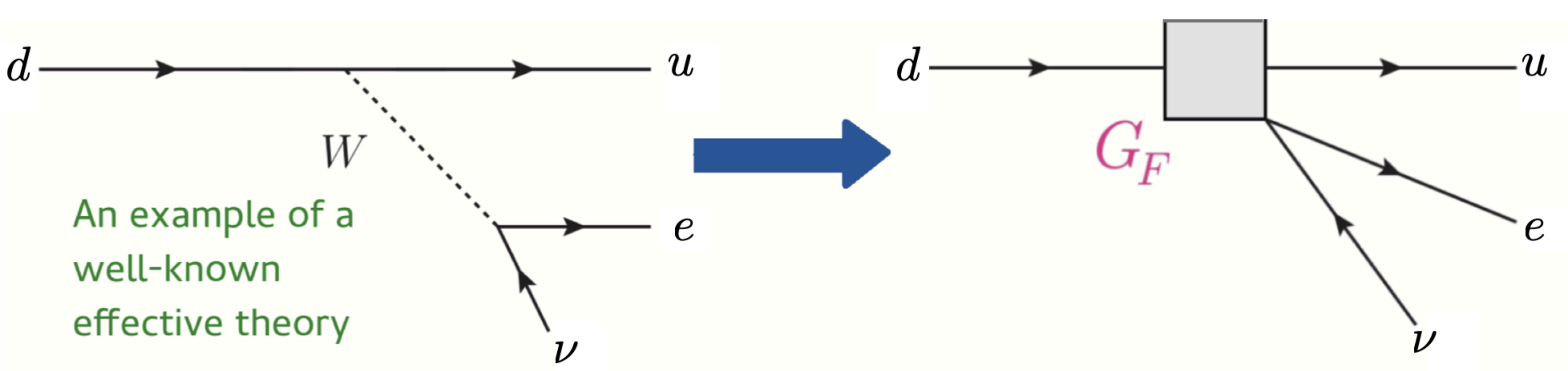


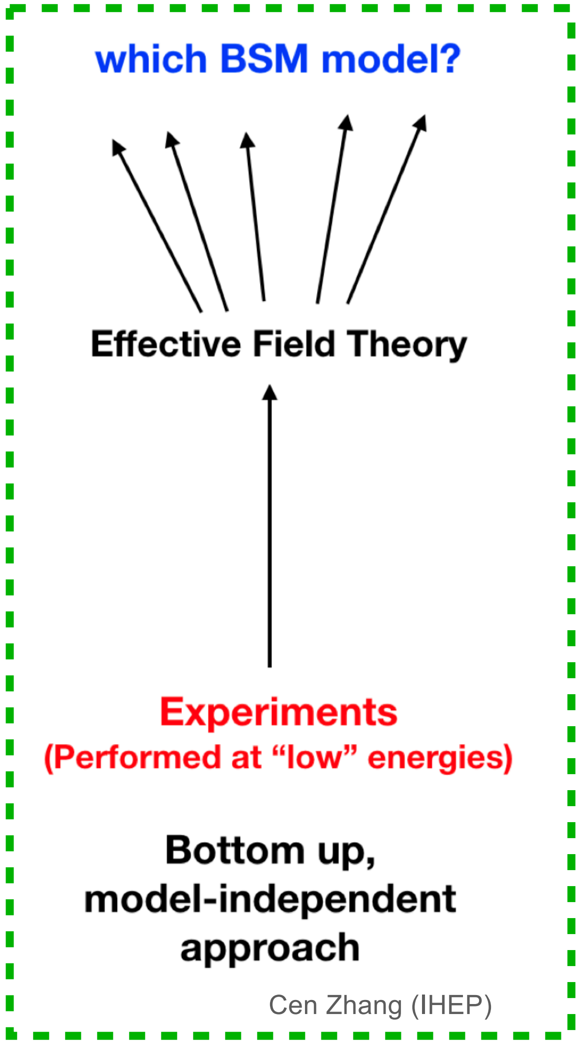
What do we actually want to measure?



Loop (or box) part of the diagram is sensitive to heavy NP

Much heavier energy scale than rest of diagram, use **effective field theory**





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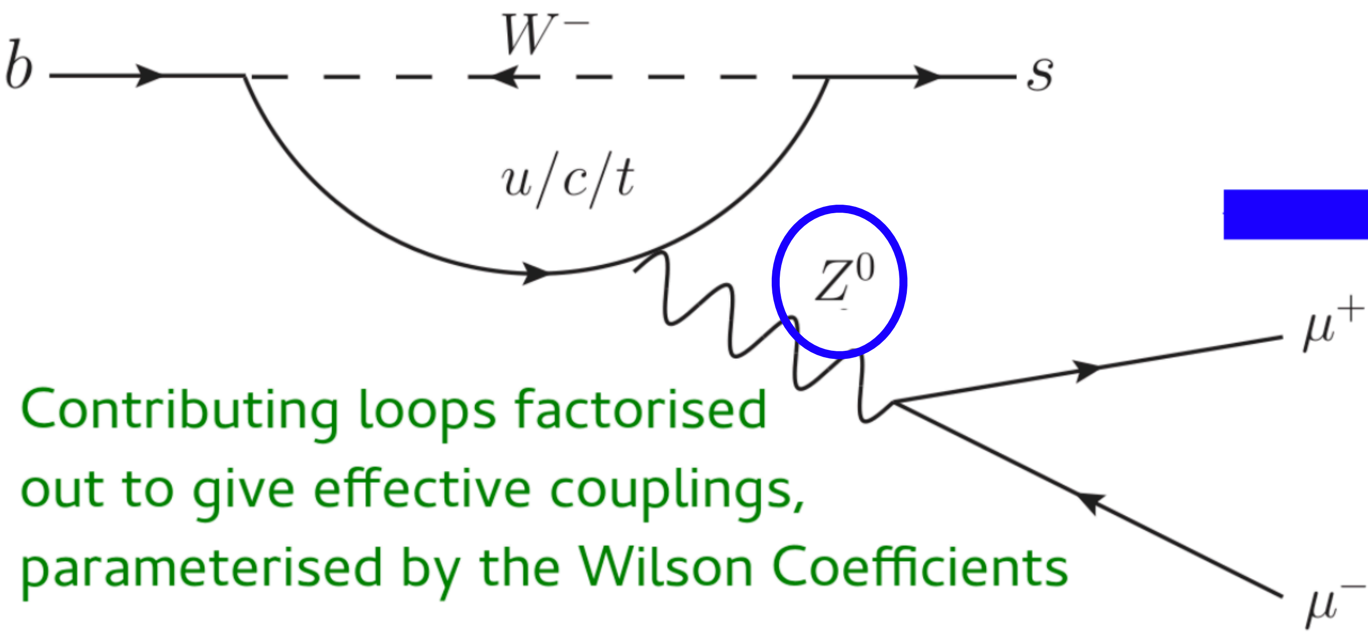
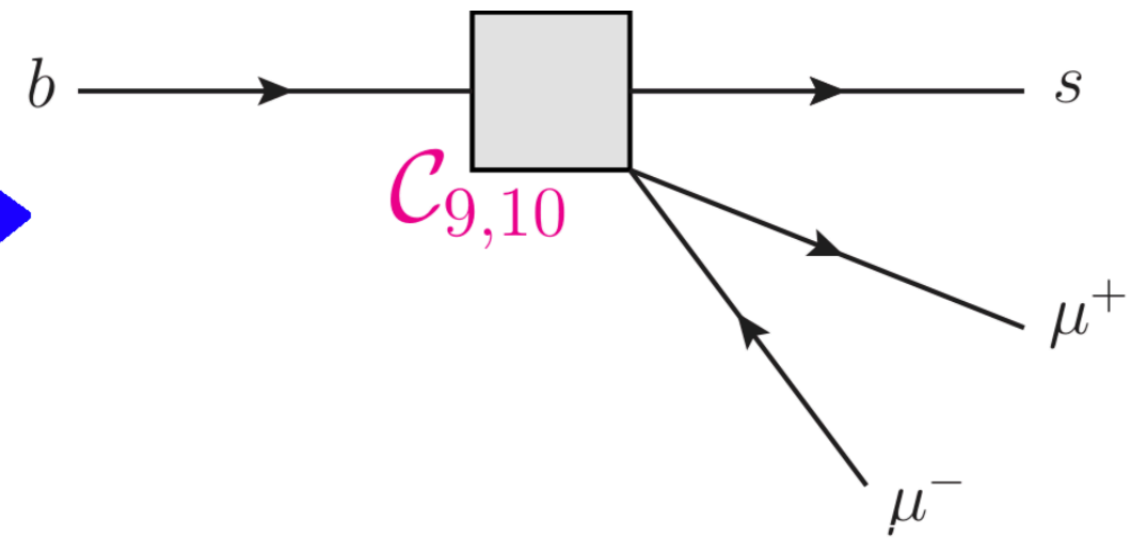
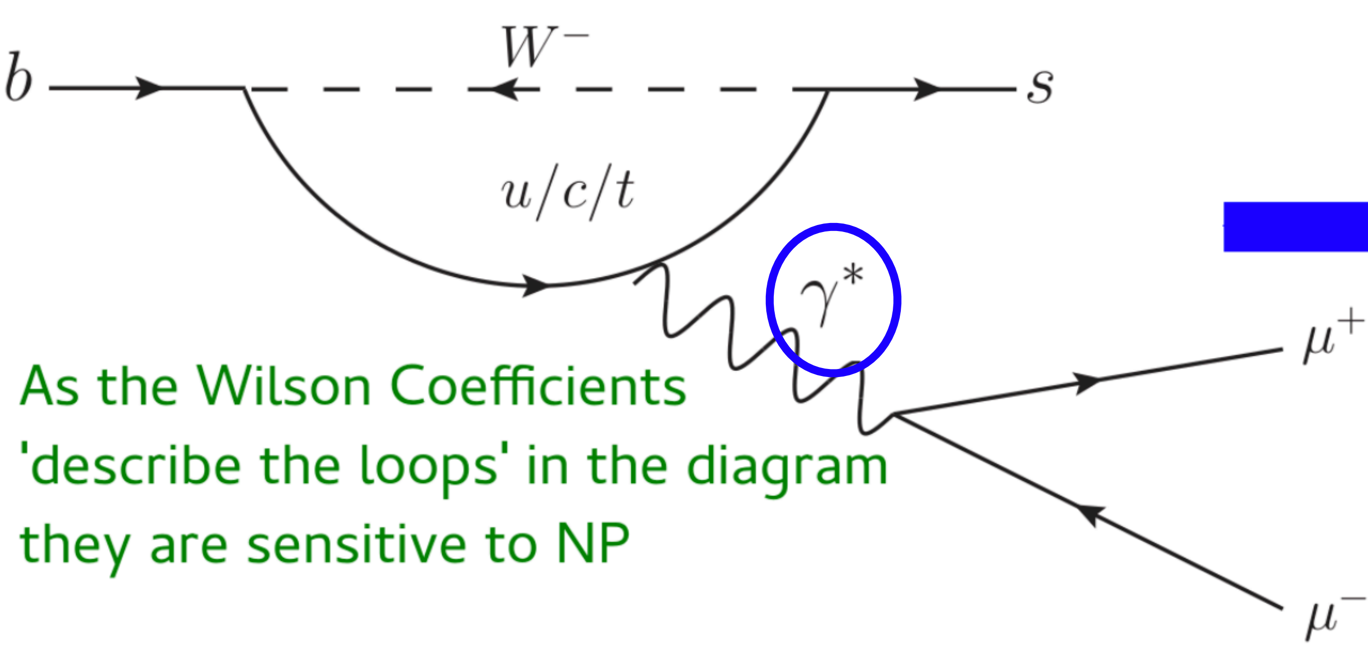
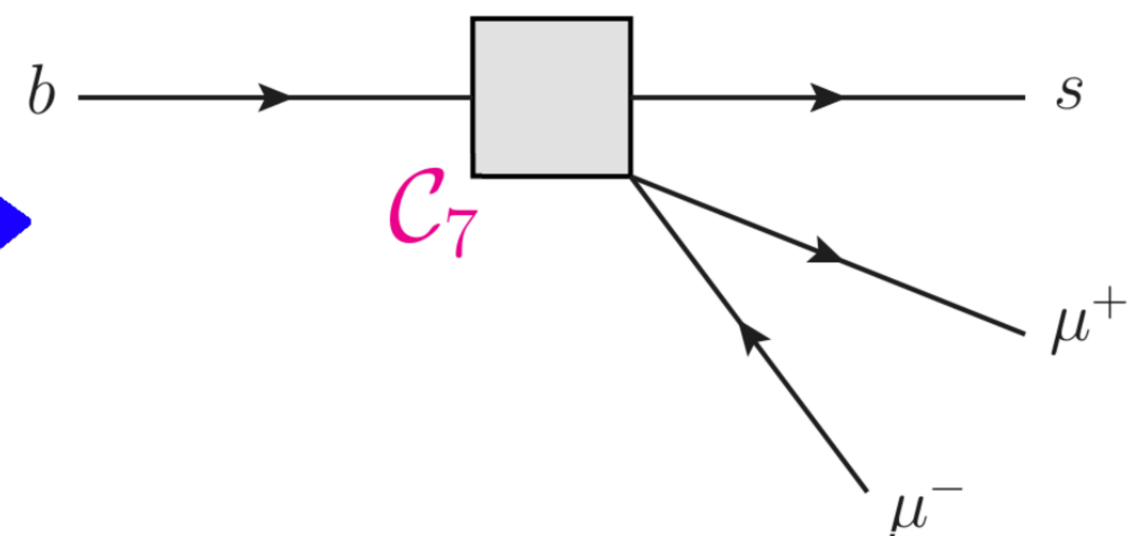




Contributing loops factorised out to give effective couplings, parameterised by the Wilson Coefficients

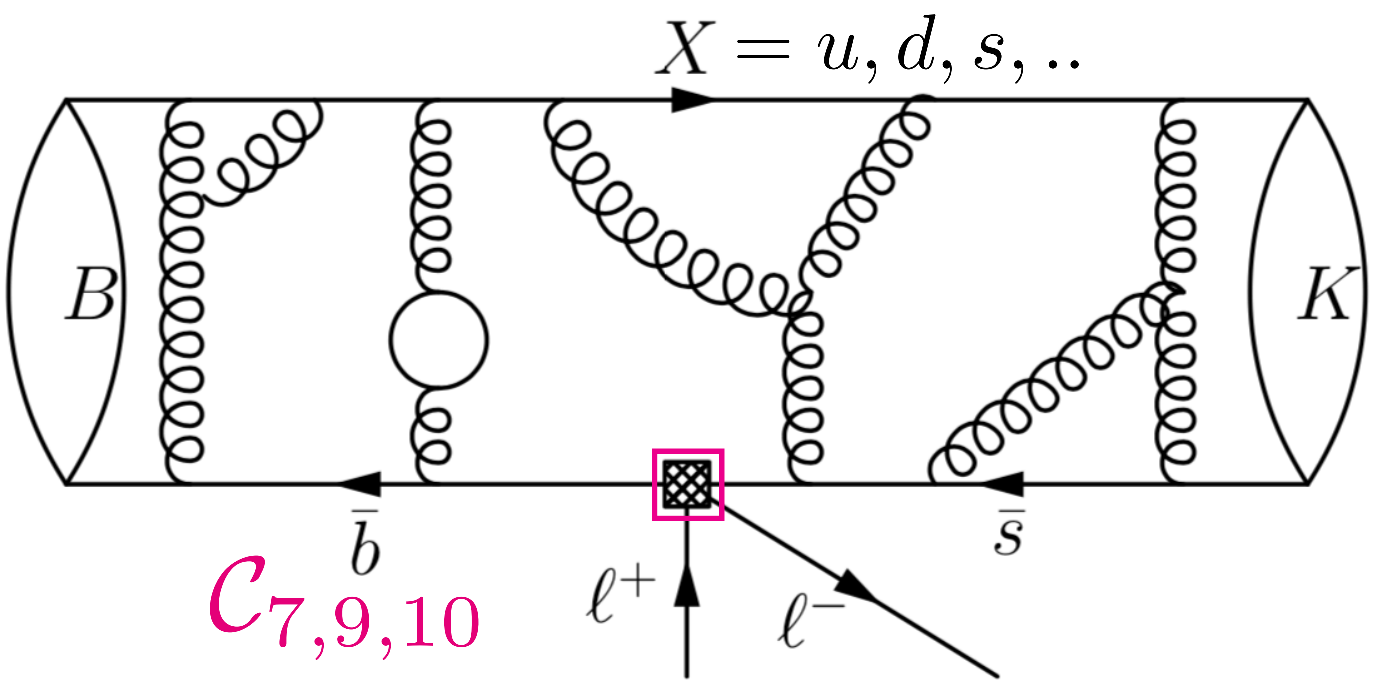




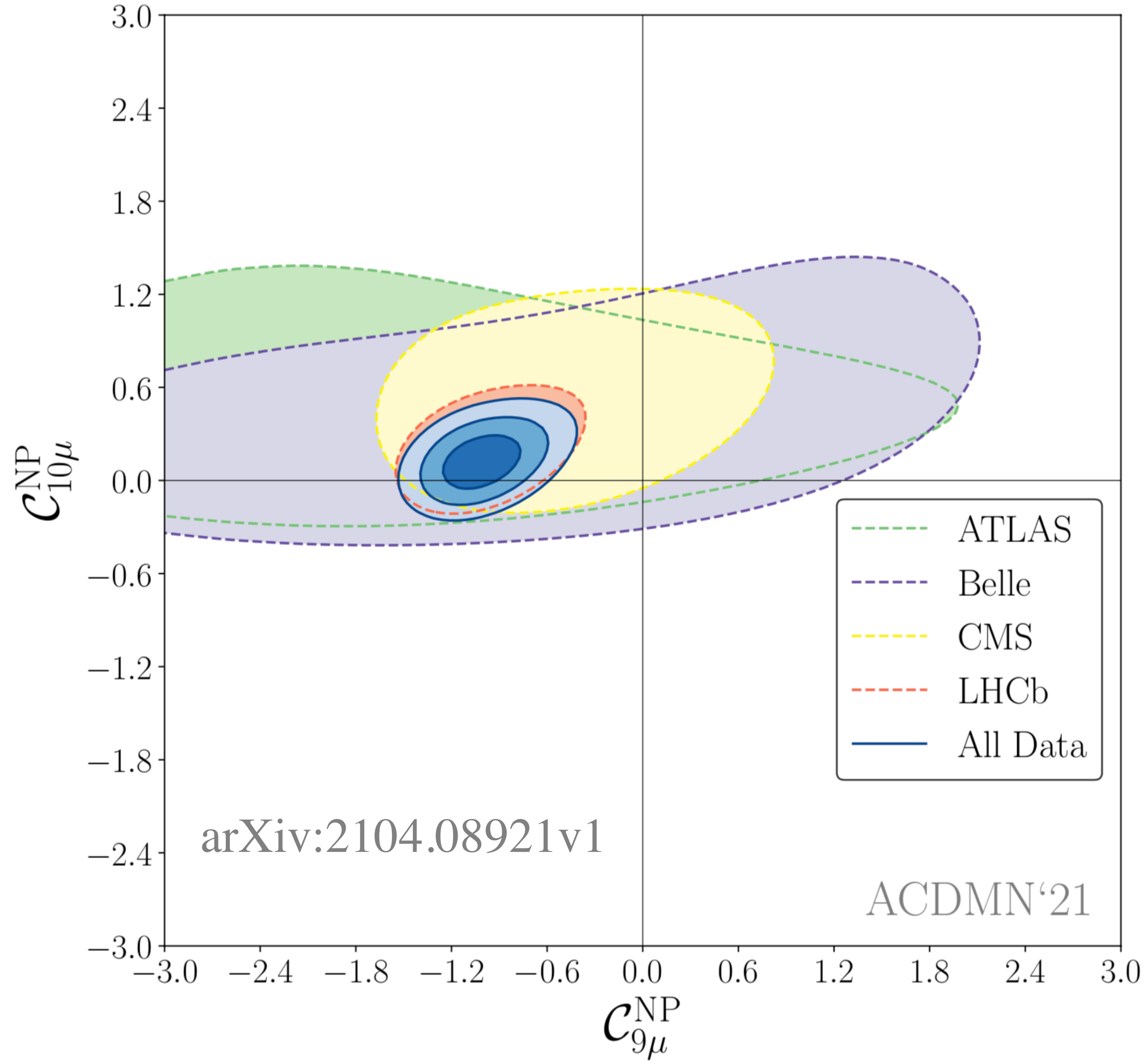
As the Wilson Coefficients 'describe the loops' in the diagram they are sensitive to NP

Combining observables

Combine all $b \to s\ell^+\ell^-$ measurements + observables together

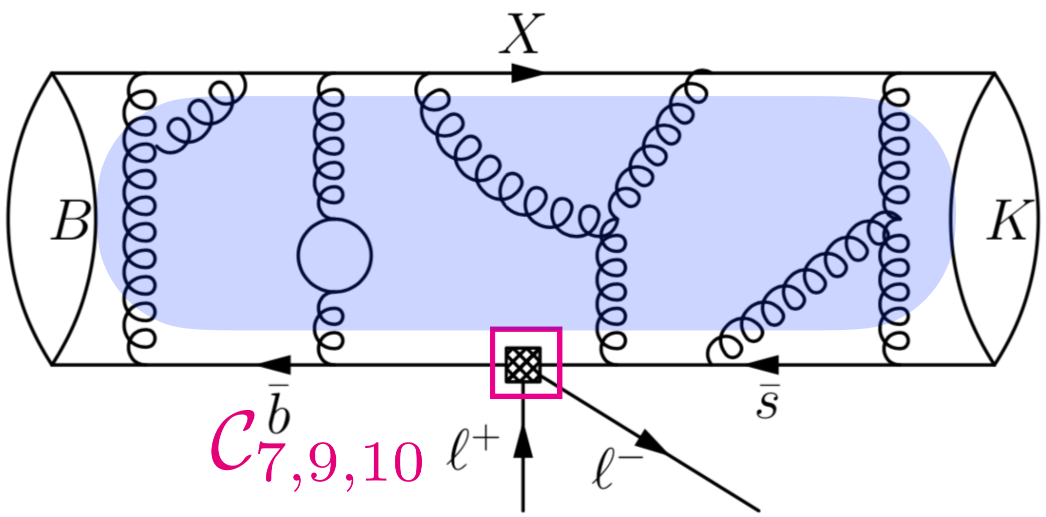


$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$



>5σ - why aren't we claiming discovery?

- Not all observables are made equal: robustness of predictions



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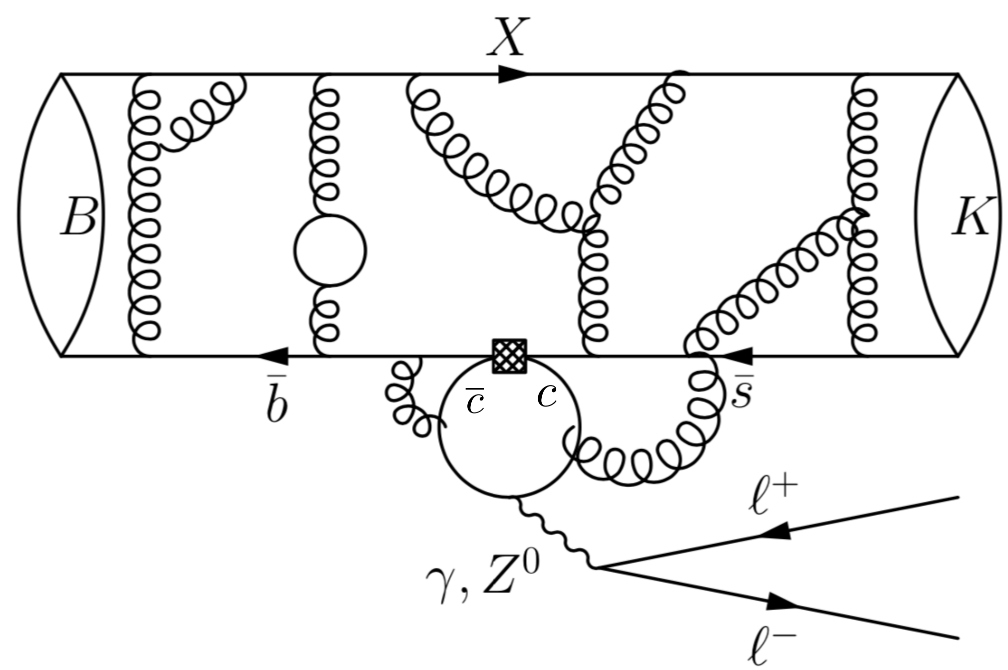
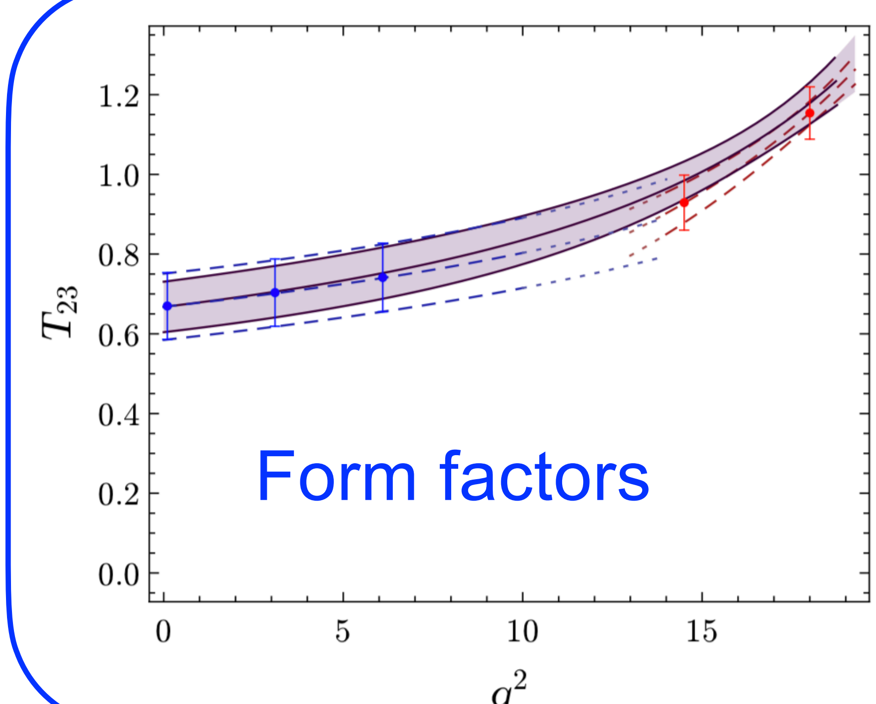
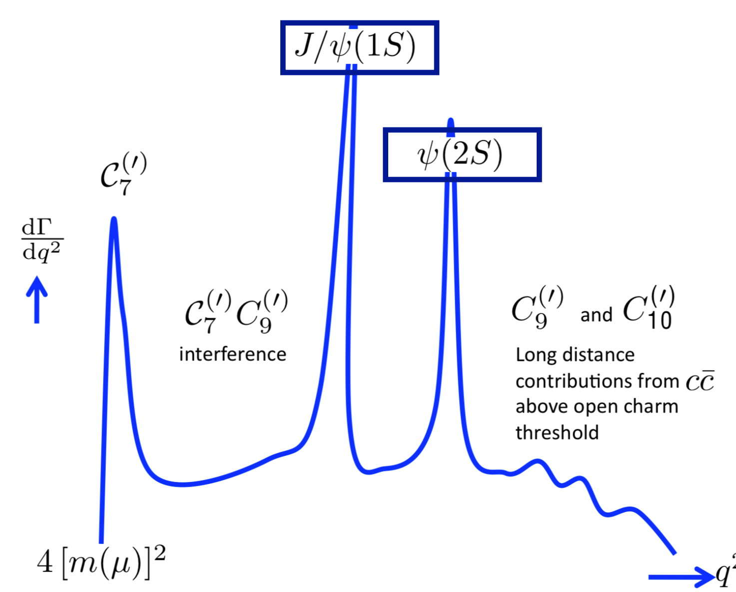


Non-perturbative "charm-loop" contributions





Mimic C_9

The more sensitive the variable to hadronic effects, the less "clean" the SM prediction

Hadronic cleanliness (not to scale)

Lepton Flavour Universality

Angular analyses

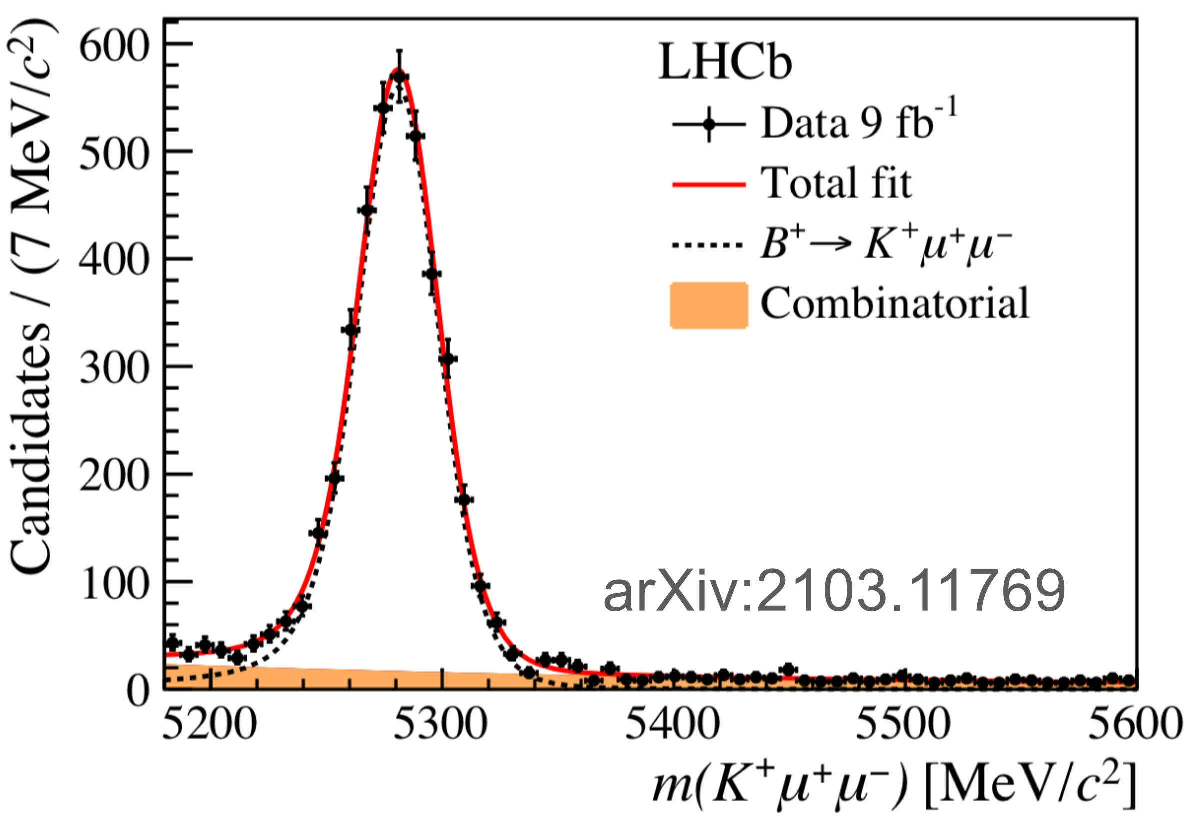
Branching fractions

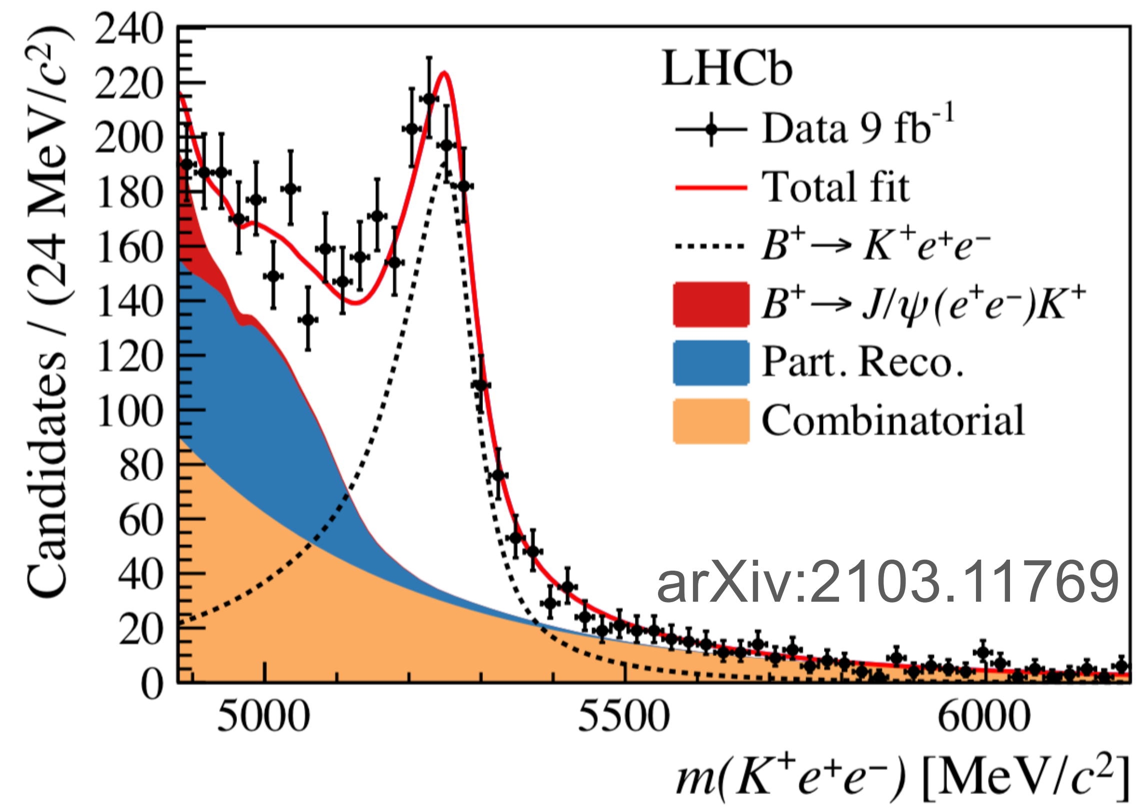
LFU and LFV

“Clean” Lepton Flavour Universality (LFU) observables

- Muons vs electron decay rates, **hadron uncertainties cancel**
- **Unambiguous sign of NP** if deviates from SM expectation

“Clean” observables: $$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$





LFU tests + electrons

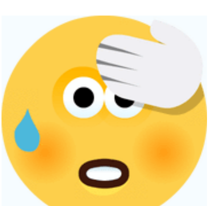
Lepton Flavour Universality tests defined as $R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$

In practice measure double-ratio:

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)} \Big/ \frac{\mathcal{B}(B \to XJ/\psi[\to \mu\mu])}{\mathcal{B}(B \to XJ/\psi[\to ee])}$$

- Double ratio very robust against systematic effects, single ratio:

$$r(J/\psi) \quad = 0.981 \pm 0.020$$



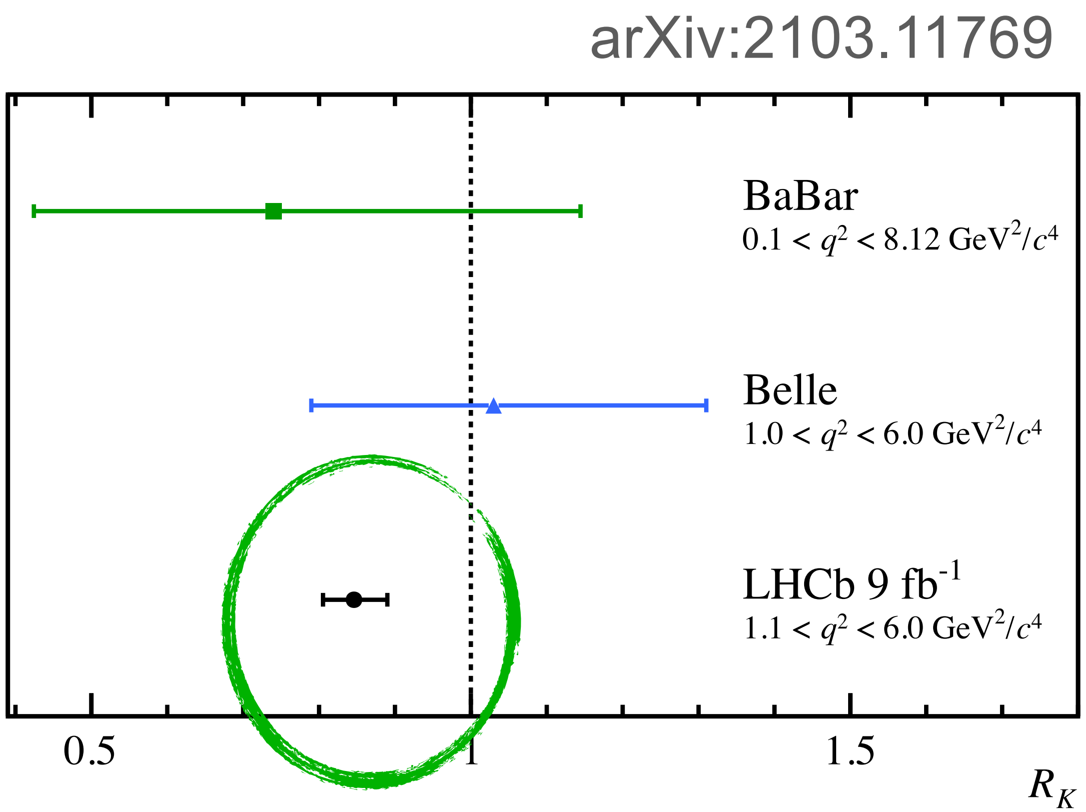
Although electrons more challenging, deviation from SM is largely due to the muon modes, not electrons

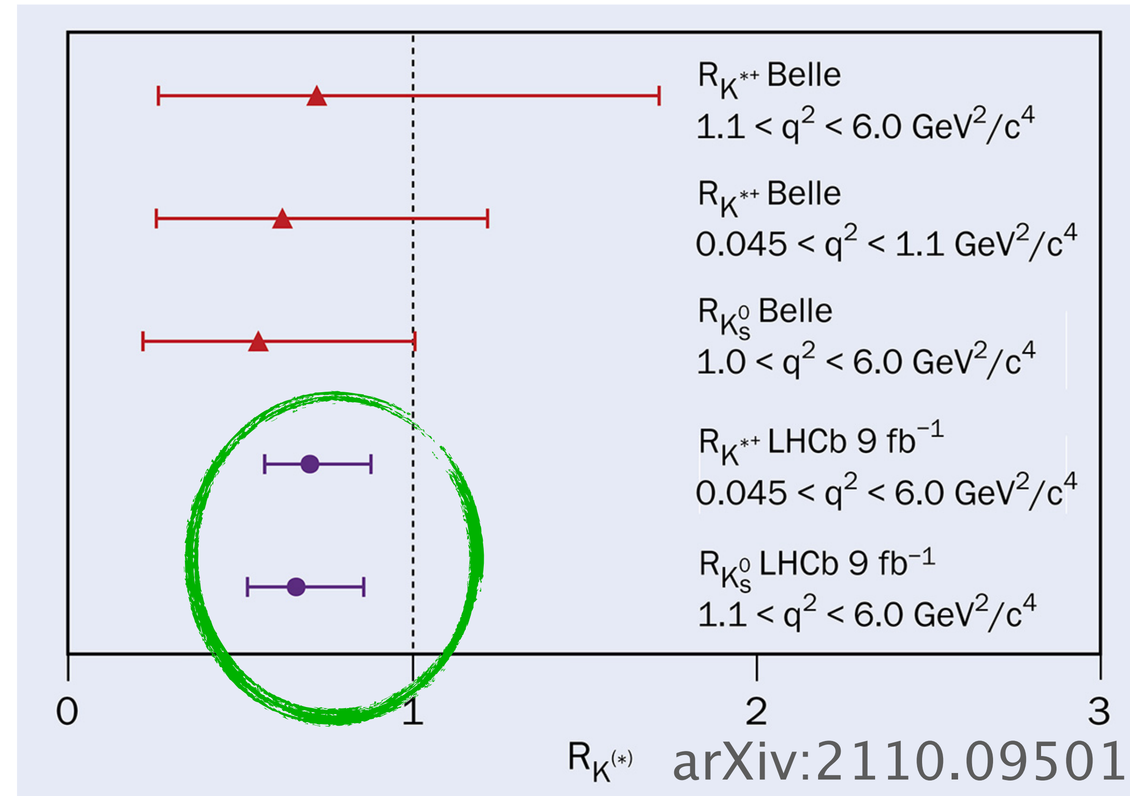
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

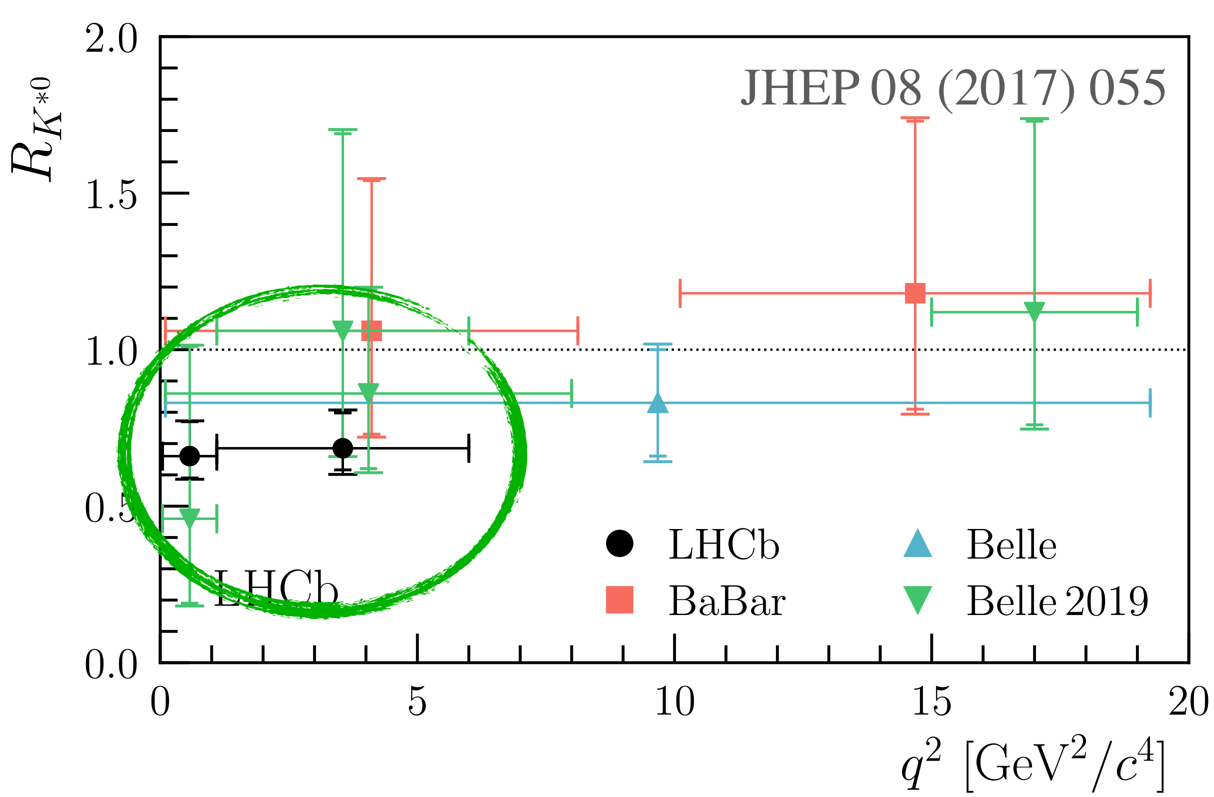
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = (28.6\,^{+1.5}_{-1.4} \pm 1.3) \times 10^{-9}\,c^4/\mathrm{GeV}^2$$

(arXiv:2103.11769)

Summary: Lepton Flavour Universality







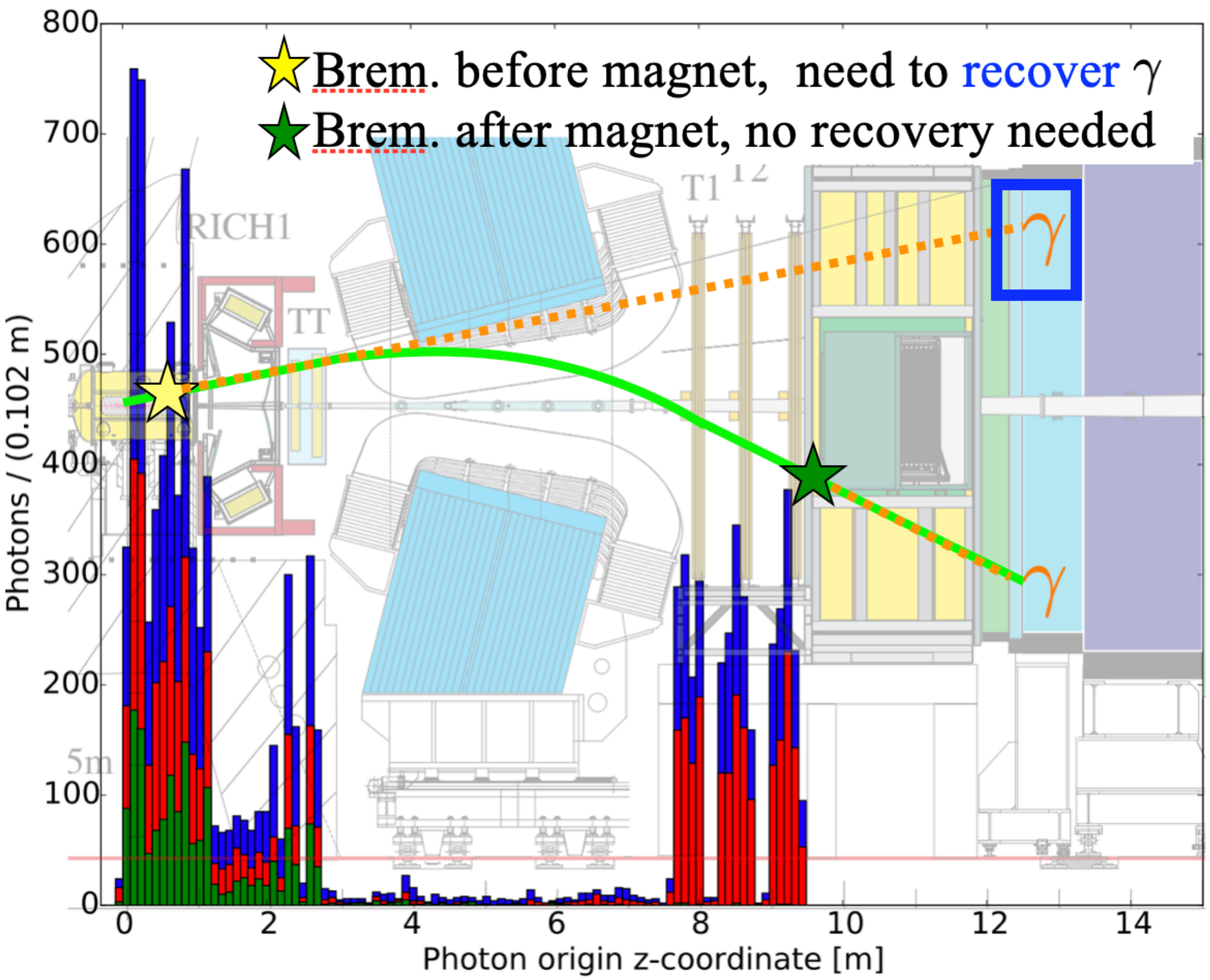
$\Lambda_b^0 \to pK\ell^+\ell^-$: JHEP 2020, 40 (2020)

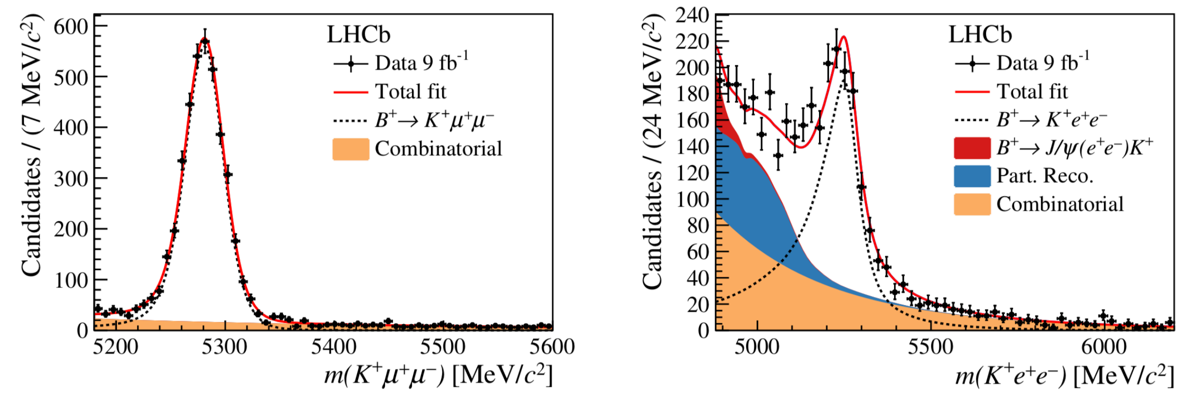
$$+ \quad R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

Same pattern, ratios below the SM prediction

Measuring electrons: Bremmstrahlung

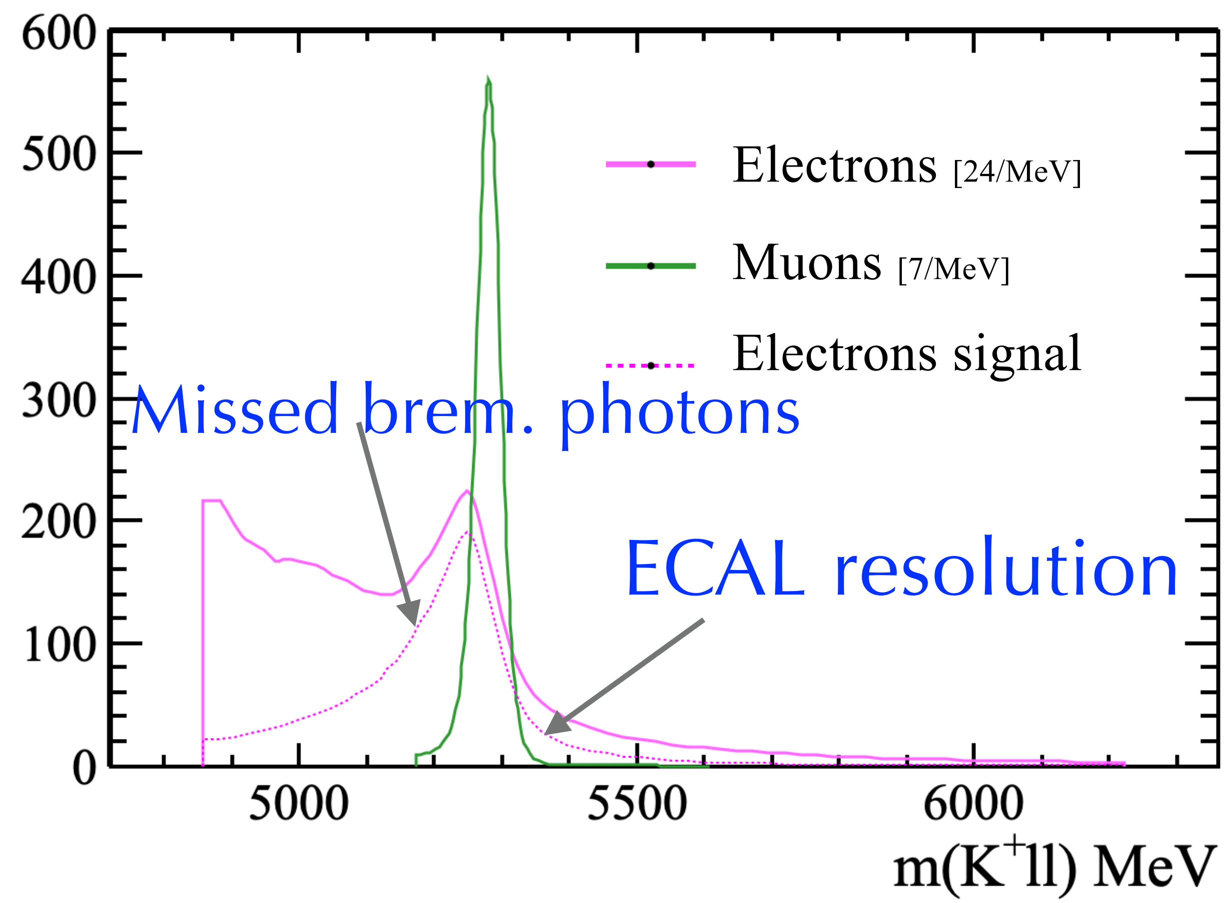
- Electrons at LHCb more challenging, smaller mass, much more Bremsstrahlung radiation





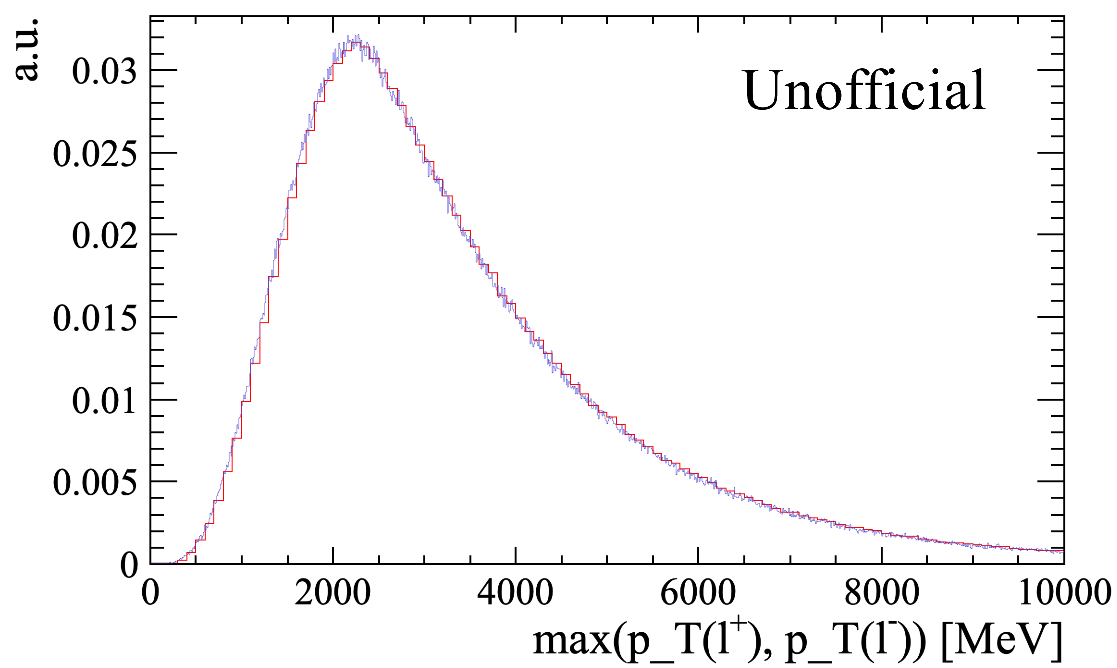
Muons

Electrons



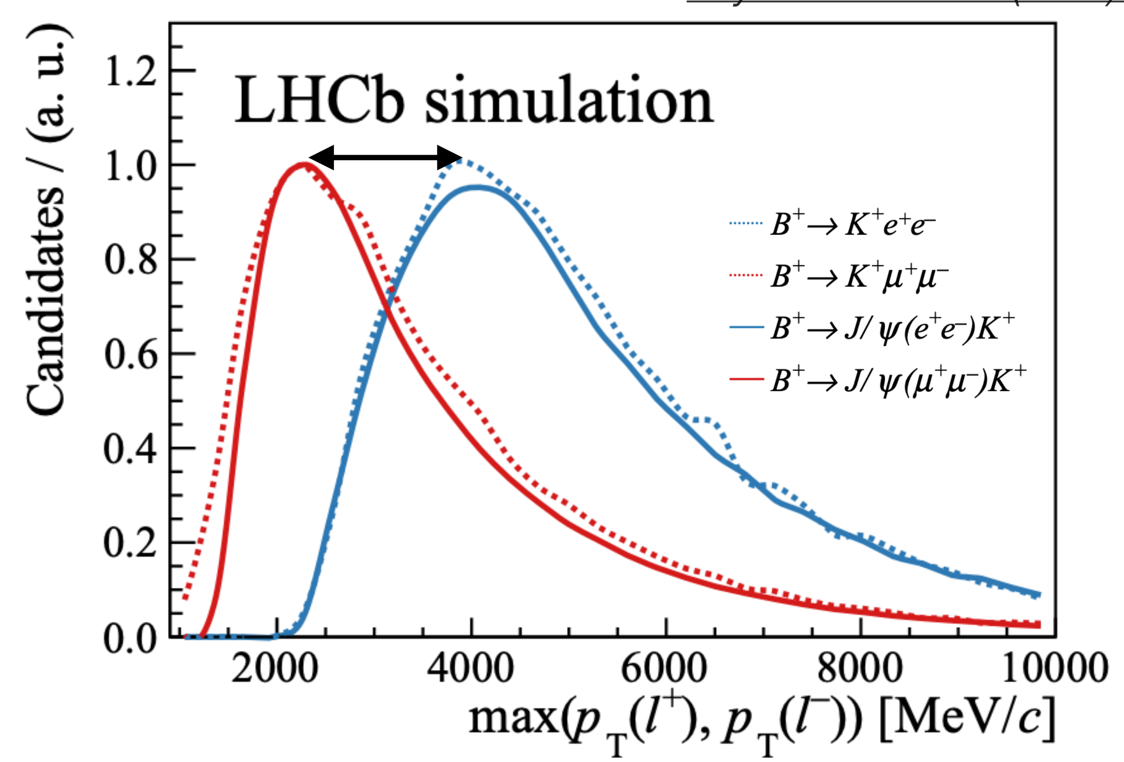
Measuring electrons: trigger

- Electrons are triggered via the signatures they leave in the ECAL
- High occupancy in the ECAL-> need higher trigger threshold to reduce throughput to acceptable level, **~40% of muon efficiency**



Before passing through detector

Phys.Rev.Lett. 122 (2019) 19

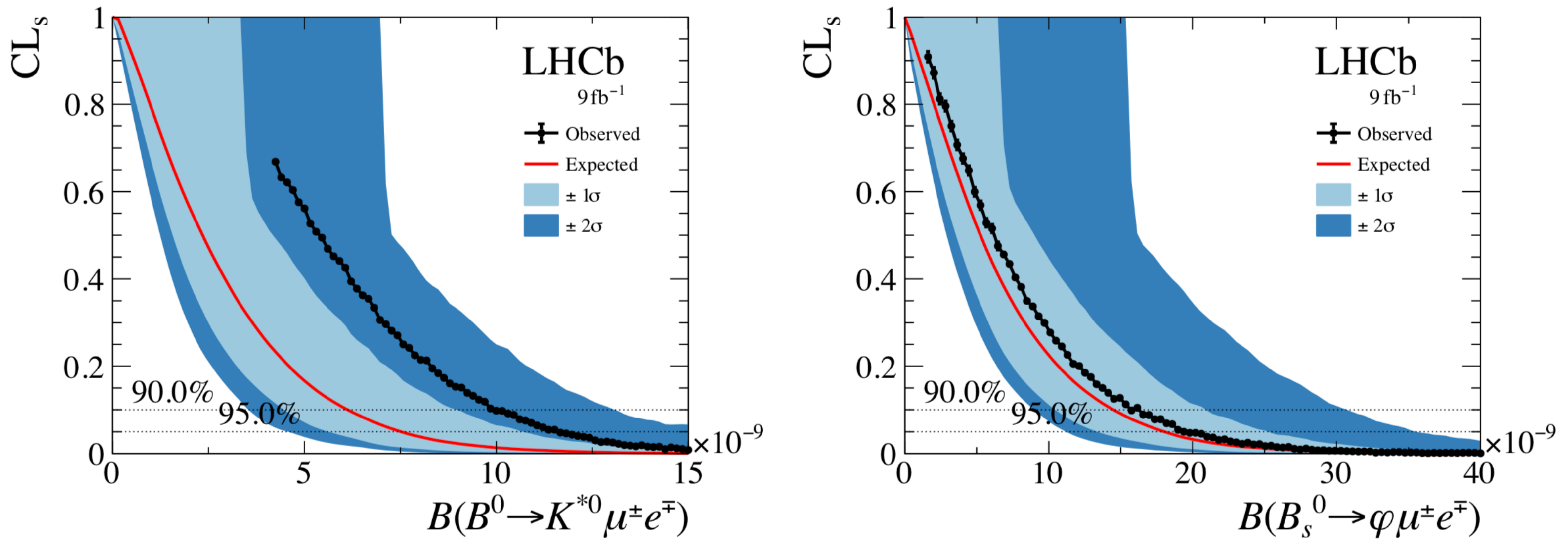


After trigger + selection

- Additionally, electrons loose energy through brem., increasing chance off being bent of acceptance by magnet

Tests of lepton flavour violation

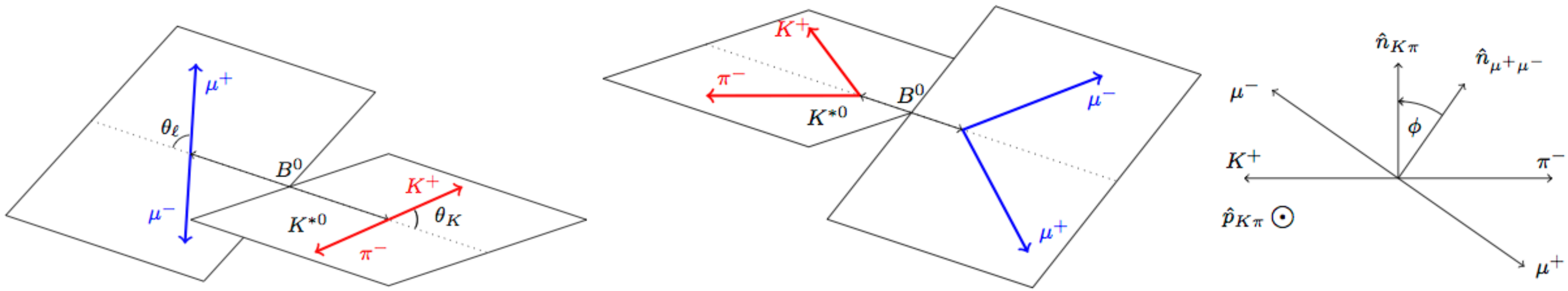
- New preliminary results on $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$, $B_s^0 \to \phi\mu^{\pm}e^{\mp}$



$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}\ (7.0 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.7 \times 10^{-9}\ (7.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 9.9 \times 10^{-9}\ (11.6 \times 10^{-9}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 15.9 \times 10^{-9}\ (19.4 \times 10^{-9})$$

Angular analysis

Angular analyses ($B \to V(\to hh)\ell^+\ell^-$)



(a) θ_K and θ_ℓ definitions for the B^0 decay

(b) ϕ definition for the B^0 decay

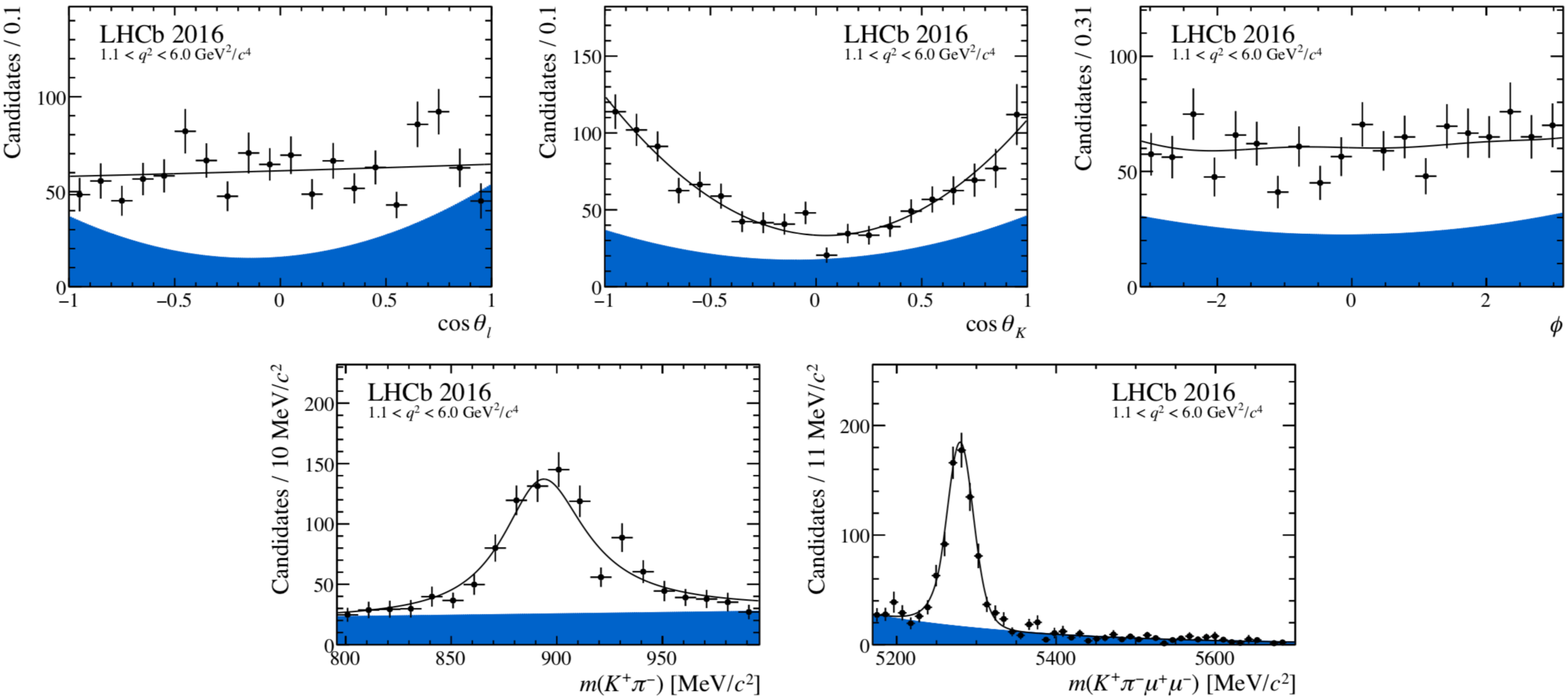
S_i basis *8 q² dependent observables describe 4D (3 angles + q²) distribution*

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]. \quad (29)$$

F_L : fraction of longitudinal polarisation

A_{FB} : forward-backward asymmetry of di-muon system

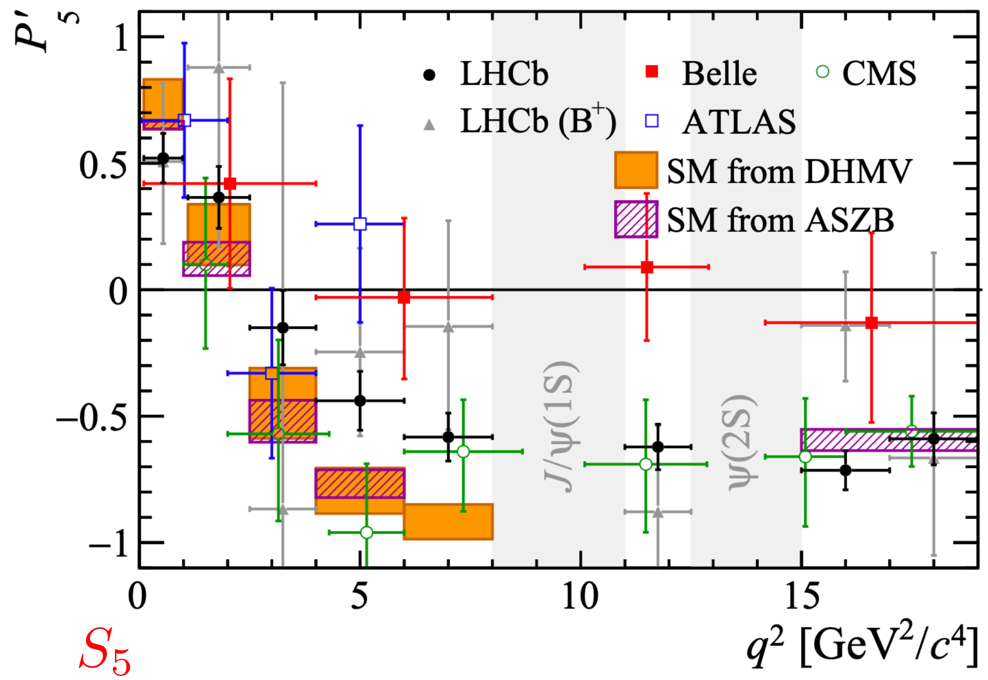
Example of projections from $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

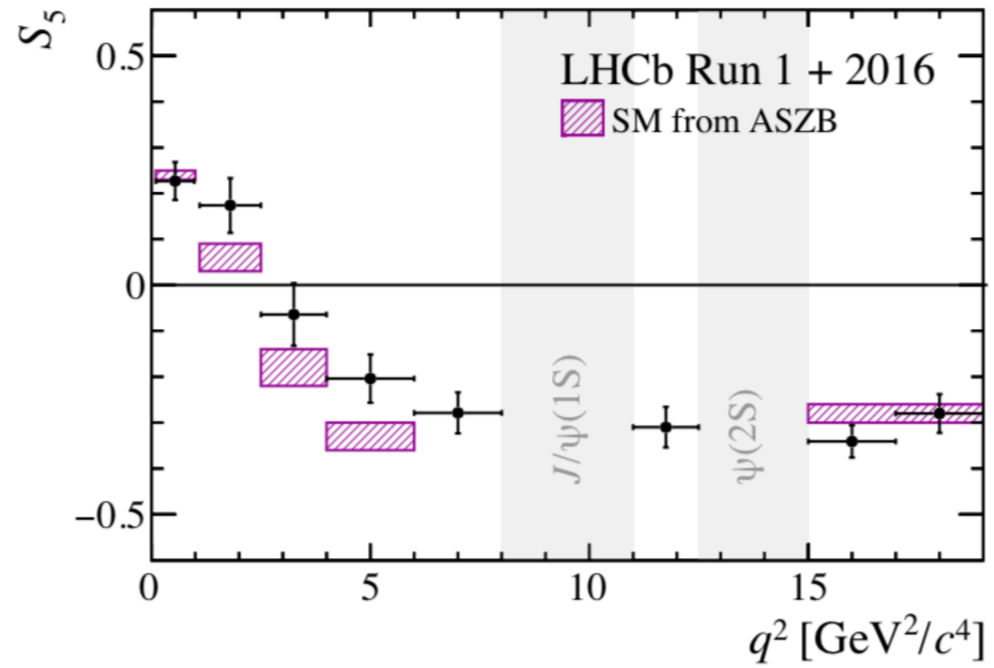


Phys.Rev.Lett. 125 (2020) 1, 011802

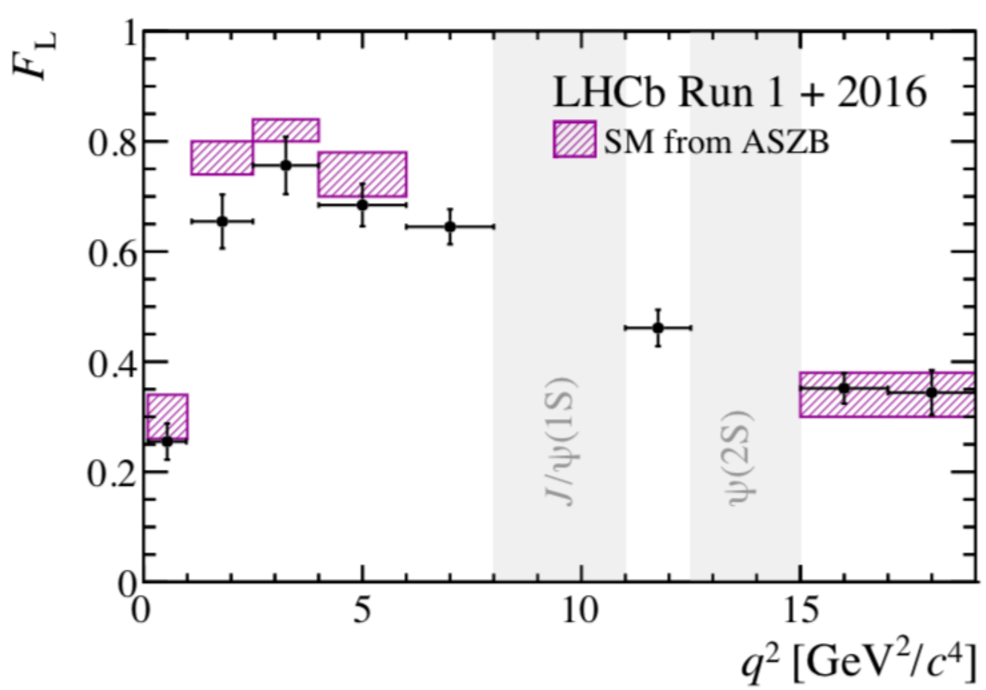
Example of results from $B^0 \to K^{*0}\mu^+\mu^-$

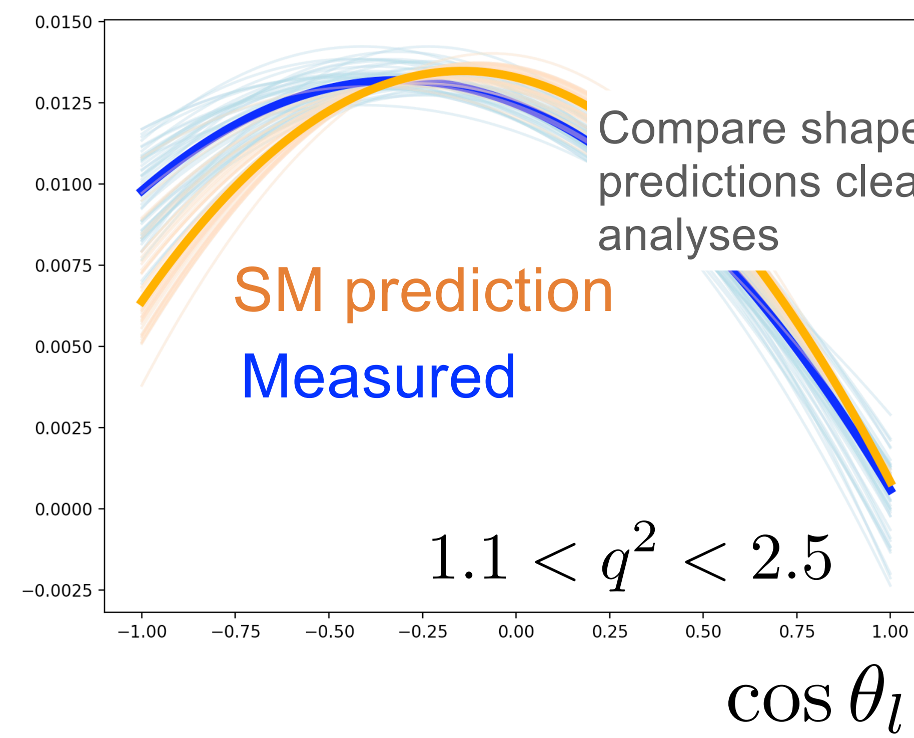
LHCb B0 PRL 125, 011802 (2020) . LHCb B+ PRL 161802 (2021) ATLAS: JHEP 10 (2018) 047
Belle: PRL 118 (2017), CMS:PLB 781 (2018) 517541





$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$



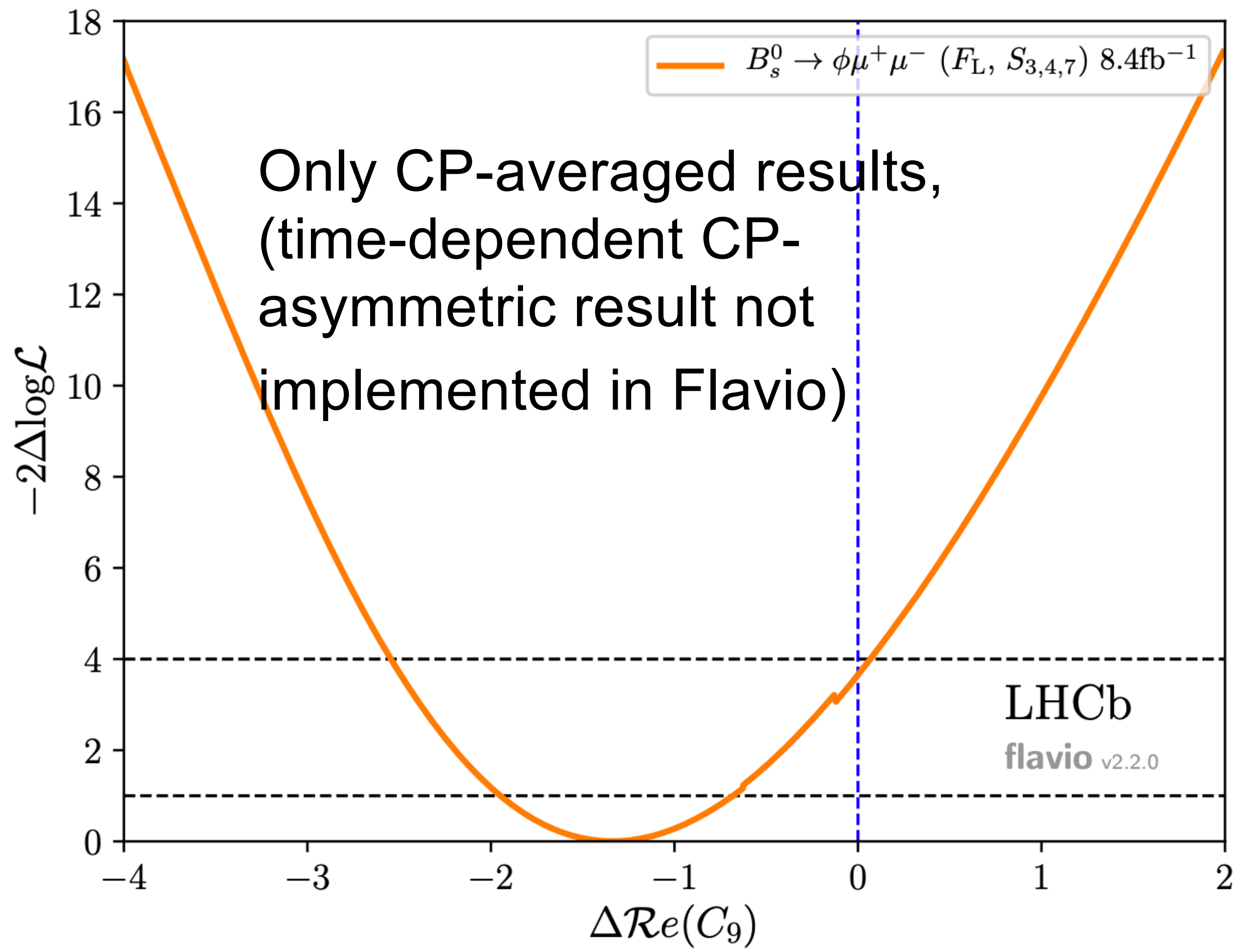


Compare shape not abs. rate, predictions cleaner than for BF analyses

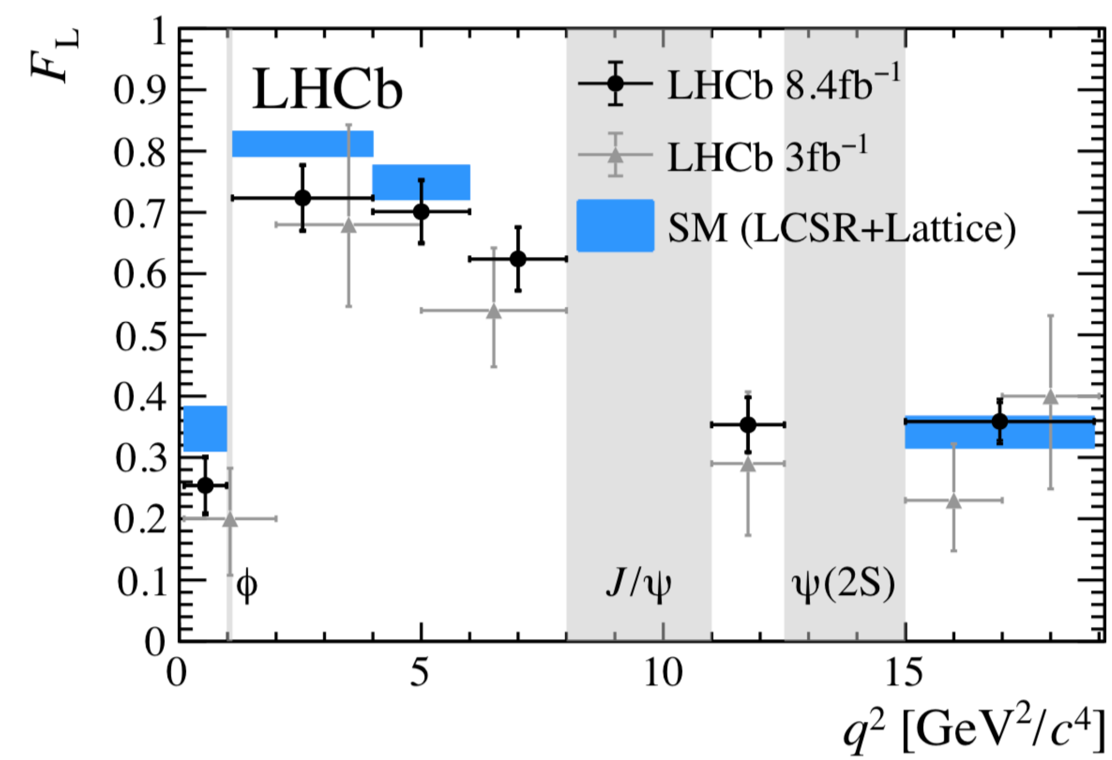
Phys.Rev.Lett. 125 (2020) 1, 011802

Results from $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$

Flavour-symmetric final-state, can only measure CP-averages (asymmetries) for CP-even (odd) terms, no P_5' term as CP-odd



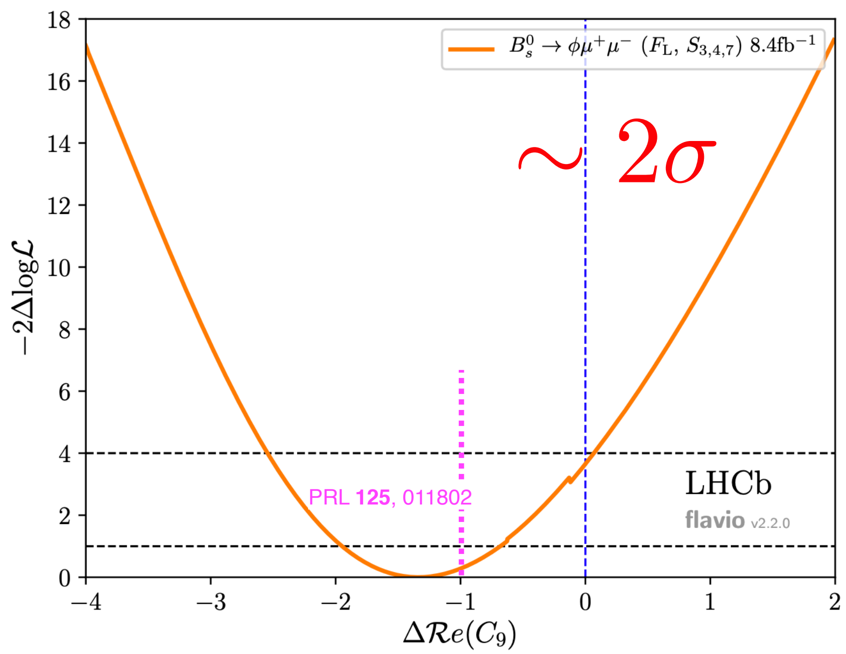
Only CP-averaged results, (time-dependent CP-asymmetric result not implemented in Flavio)

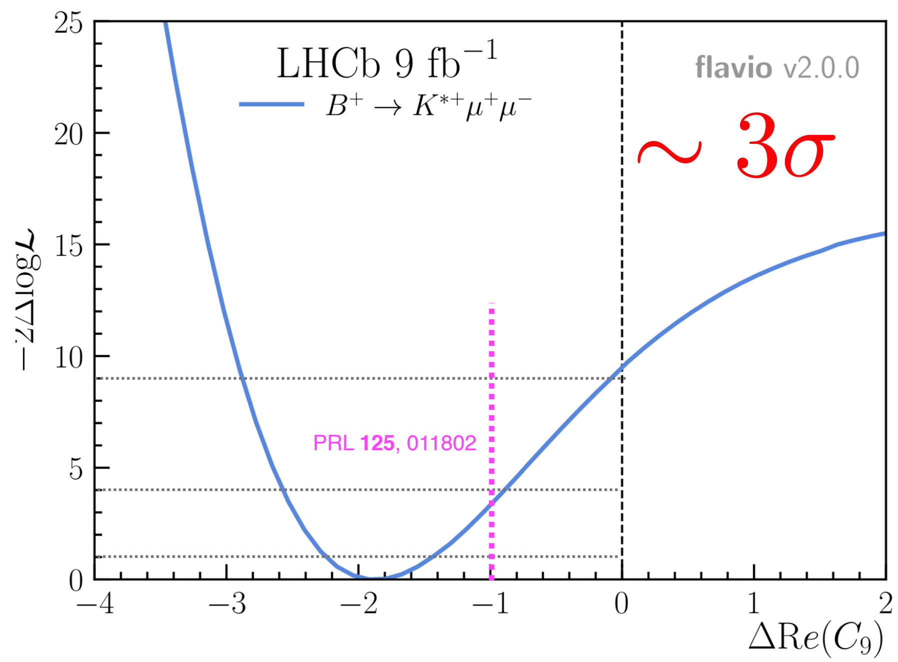


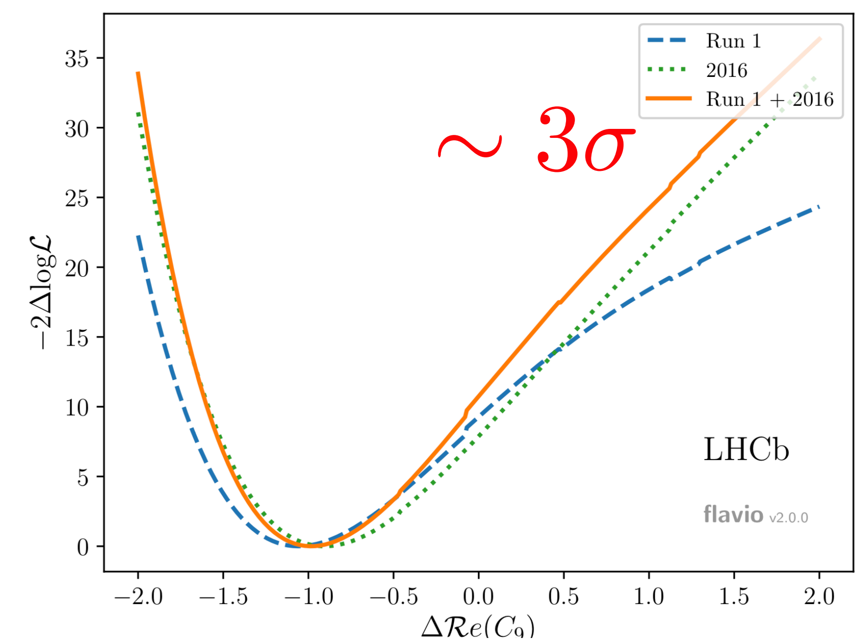
JHEP 11 (2021) 043

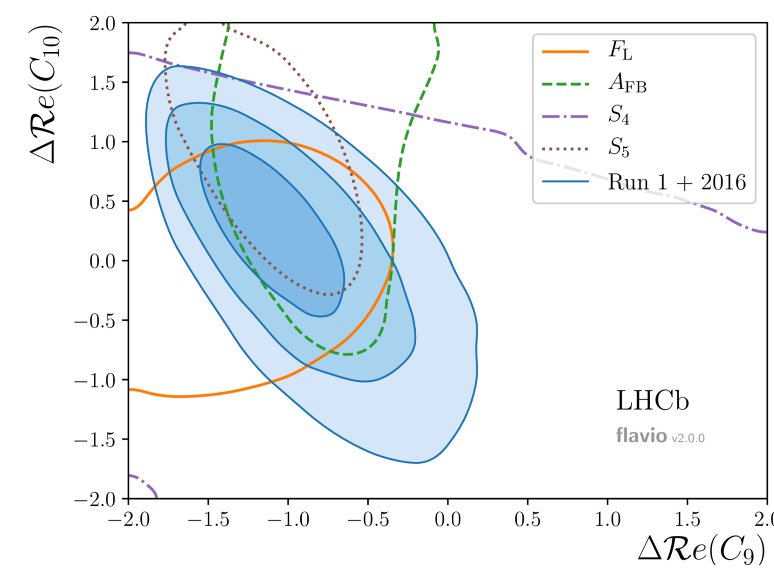
Summary of angular analyses (LHCb)

$B_s^0 \to \phi\mu^+\mu^-$	$B^+ \to K^{*+}\mu^+\mu^-$	$B^0 \to K^{*0}\mu^+\mu^-$
$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.3\,^{+0.7}_{-0.6}$	$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.9$	$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$
	Phys. Rev. Lett. **126**, 161802	Phys. Rev. Lett. **125**, 011802







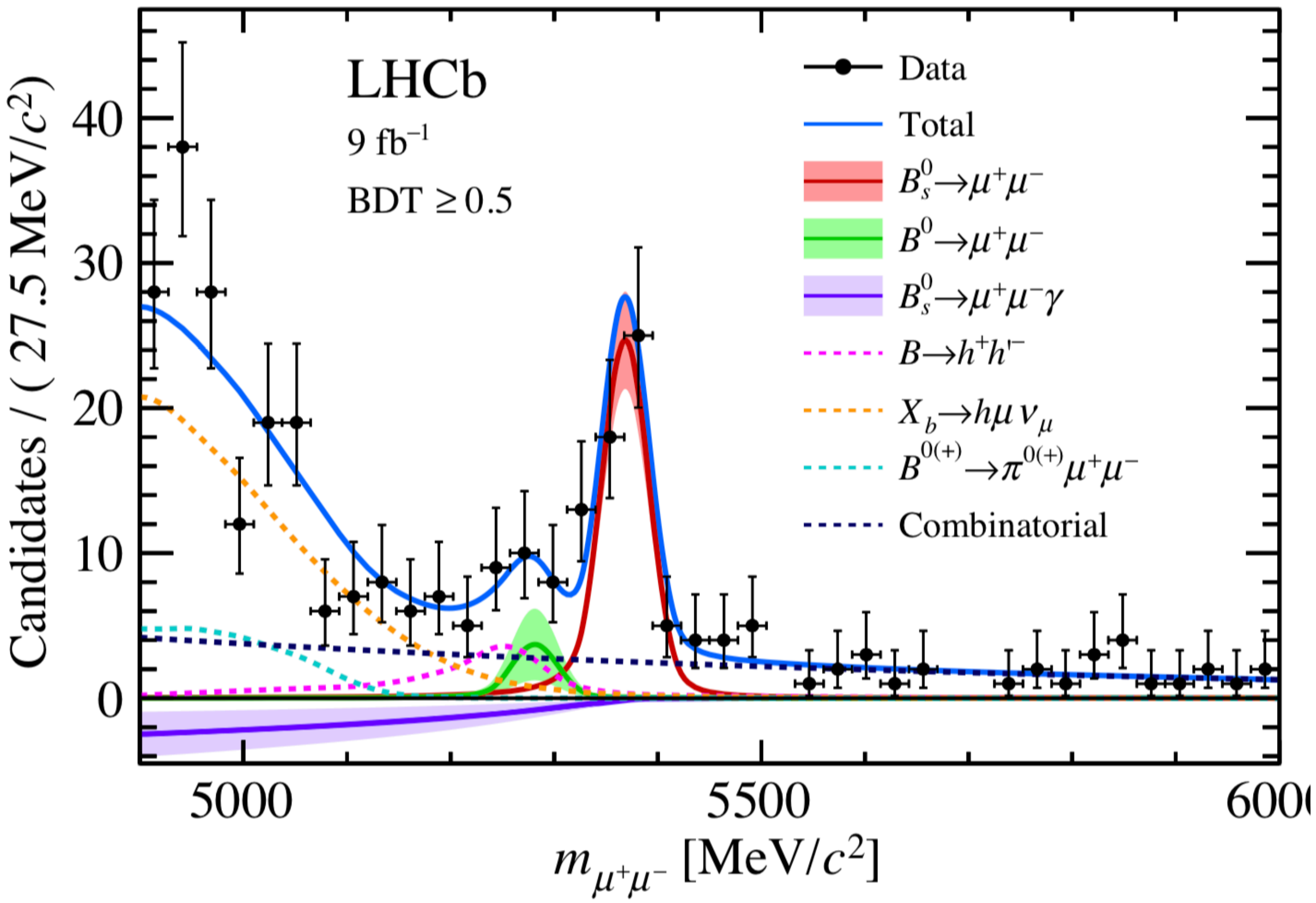


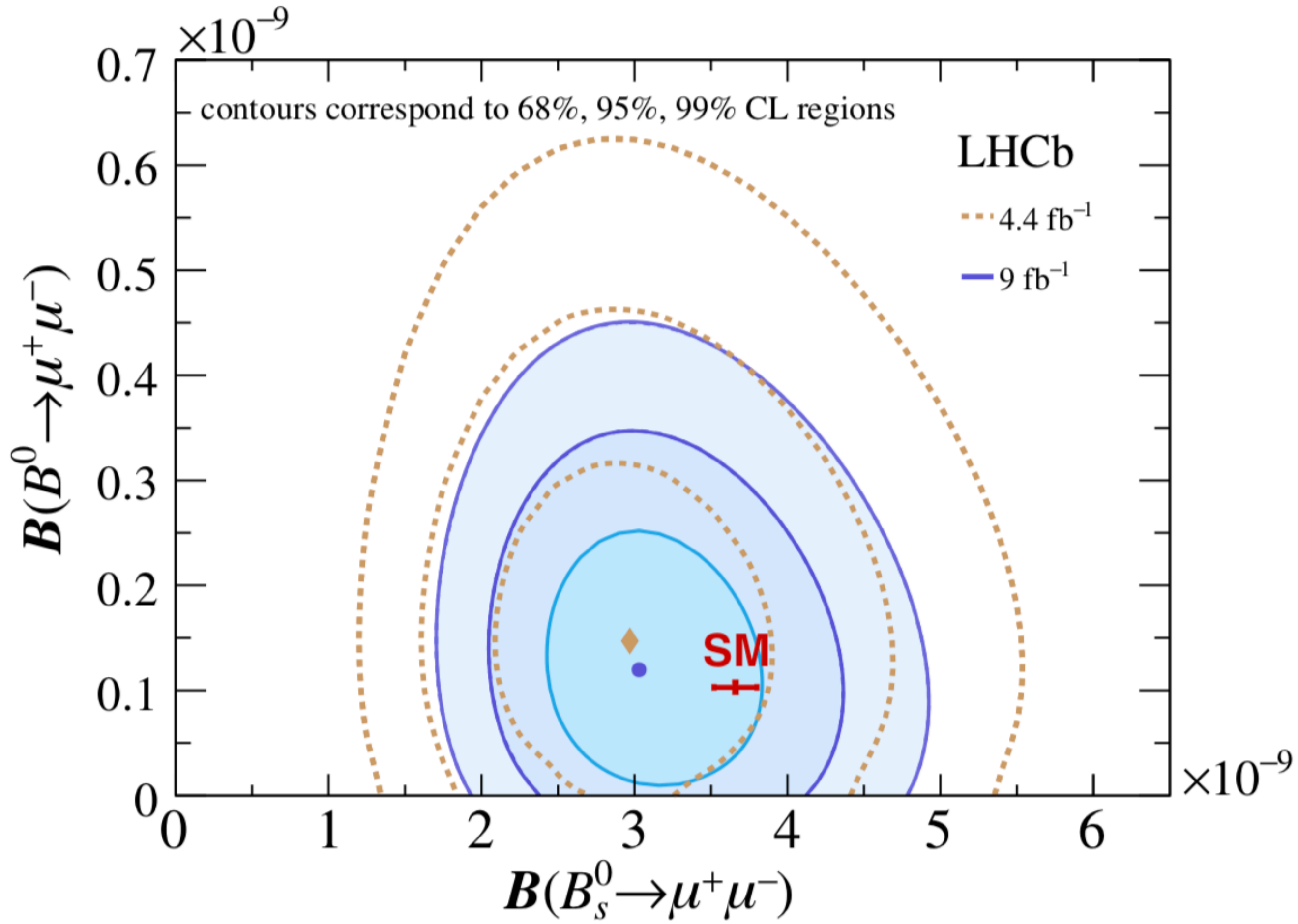
- Compare all 8 angular observables to SM using the underlying WC's
- Look at shift from the SM $\Delta\mathcal{R}e(\mathcal{C}_9) = 0$

Branching fractions

$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$

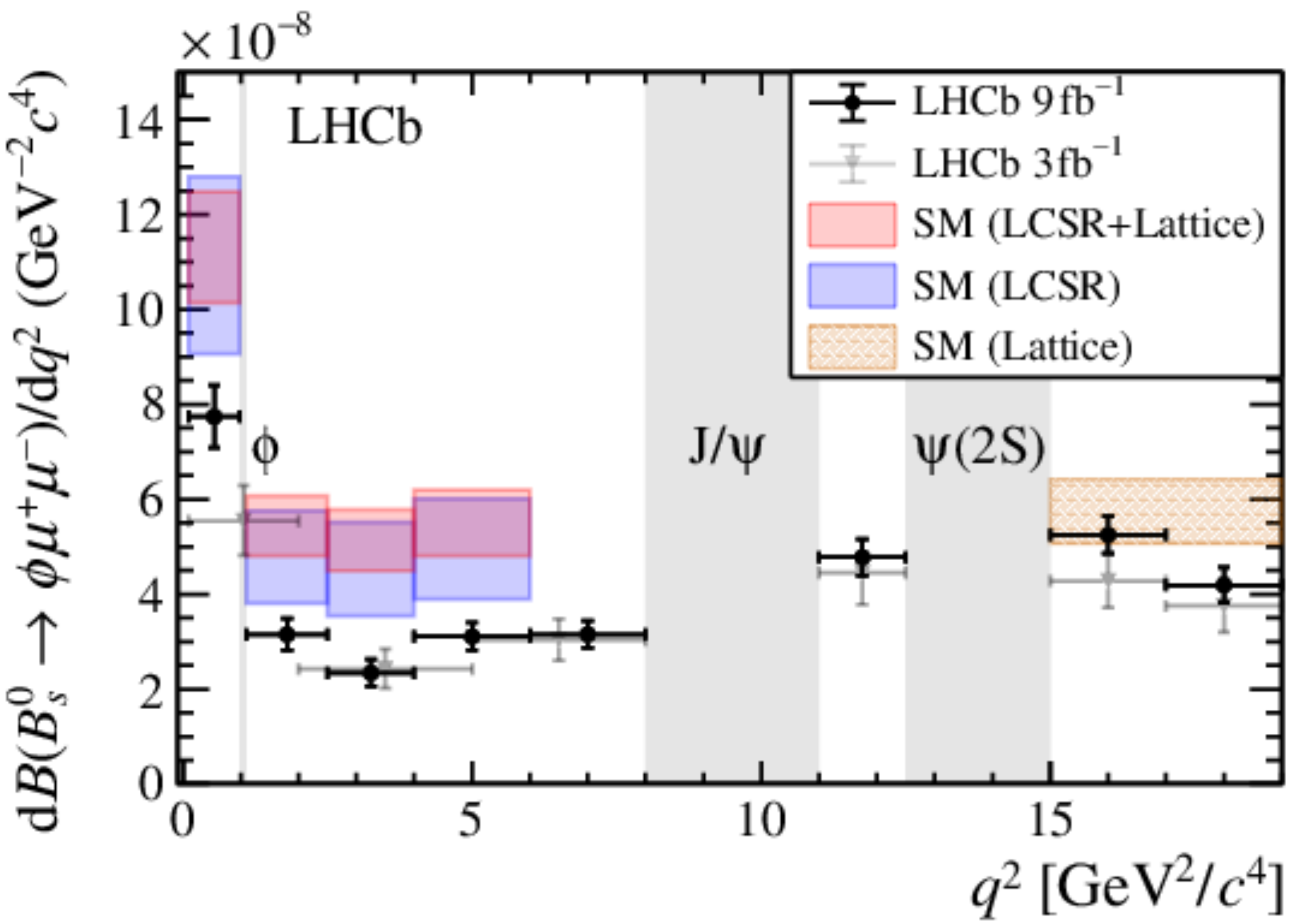
[PRL 128, (2022) 041801]

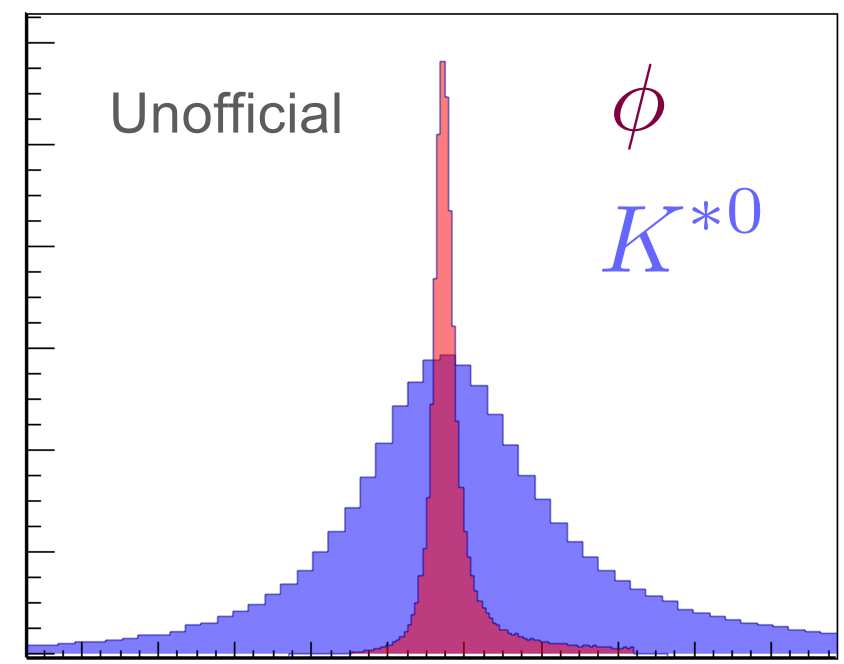




- Full Run 1 and Run 2 data sample
- Effective lifetime also measured: $2.07 \pm 0.29 \pm 0.03$ ps

$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$





Narrow width approximation more valid

Less background

$q^2 \in [1.1, 6.0]$ $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/dq^2 = (2.88 \pm 0.21) \times 10^{-8}\,\mathrm{GeV}^2/c^4$

Tension with SM at **3.6σ (LCSR+Lattice)** and **1.8σ (LCSR)**

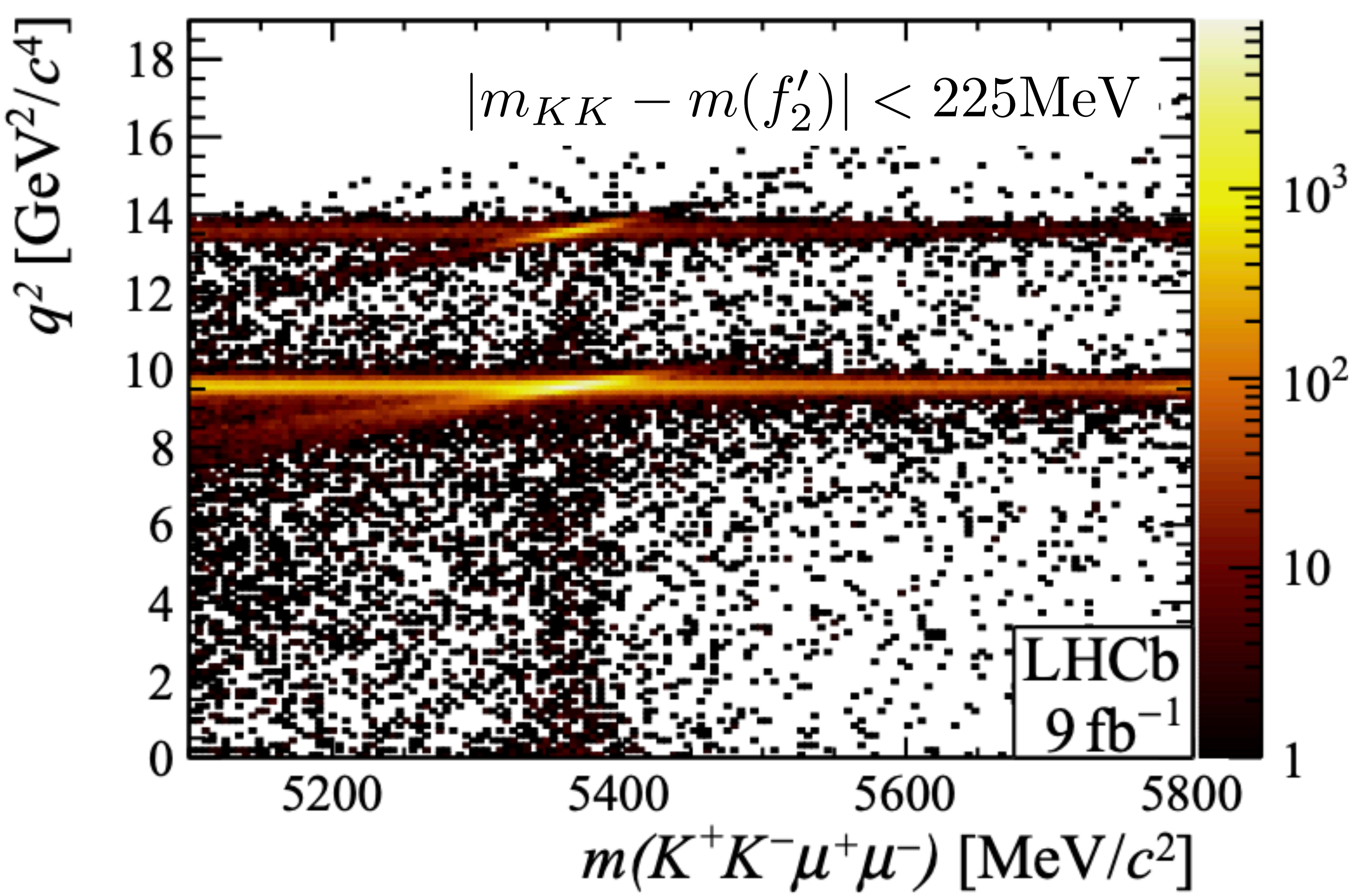
- WC pulled further from SM when adding to global fits, but overall significance drops
- Use inclusive Vcb for SM prediction

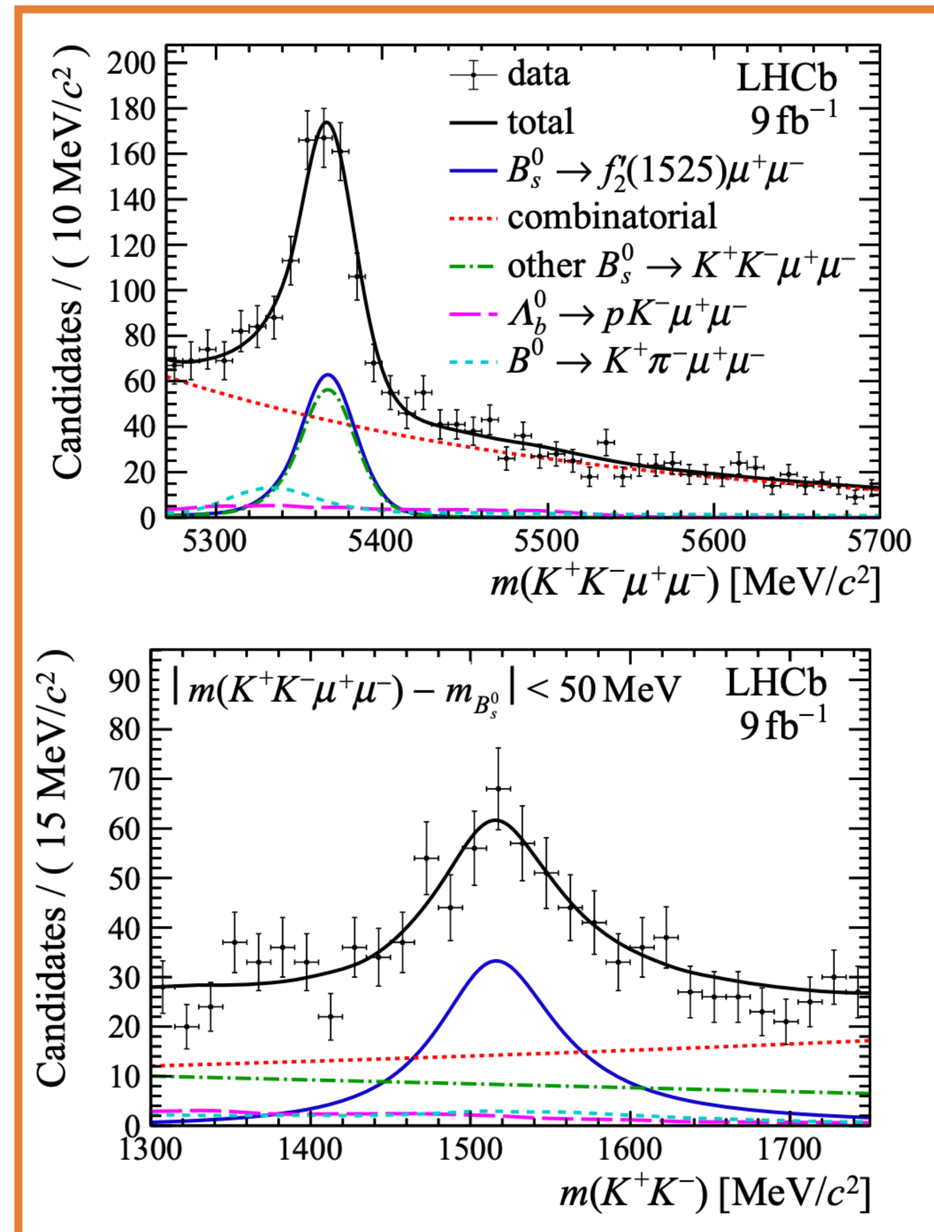
$\mathcal{B}(B_s^0 \to f_2^{'} \mu^+ \mu^-)$

- Same final state, higher dikaon mass, **first observation of a spin-2 FCNC**

$$\mathcal{B}(B_s^0 \to f_2' \mu^+ \mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$

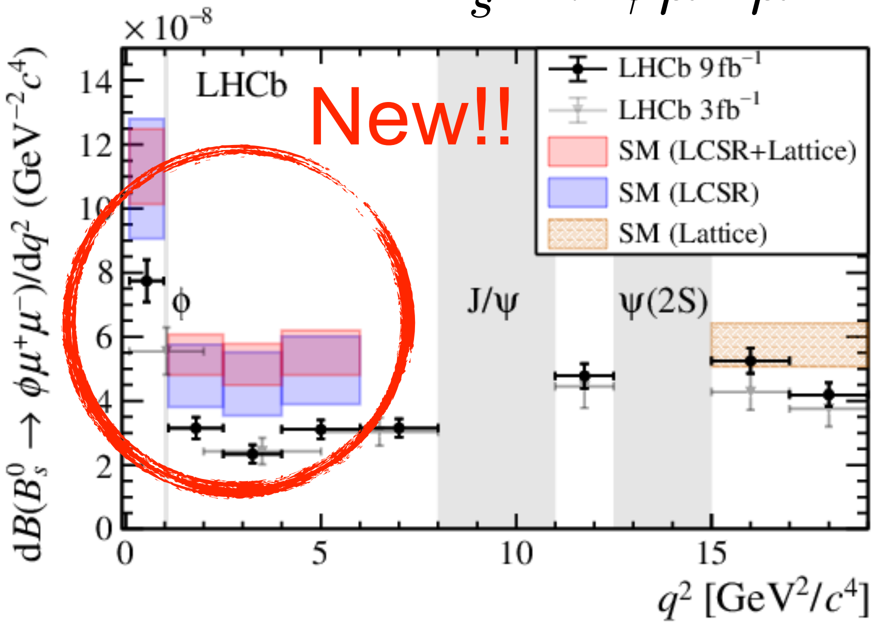
SM: $1.2 - 1.7 \times 10^{-7}$ [Phys. Rev. D83 (2011) 034034, Eur. Phys. J. C81 (2021) 30, arXiv: 2009.06213v2]



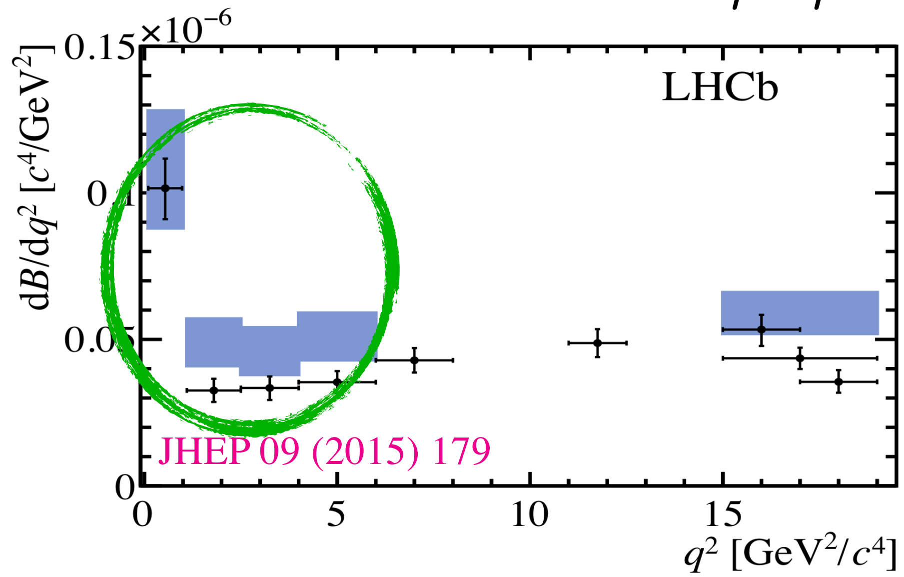


Branching fractions summary

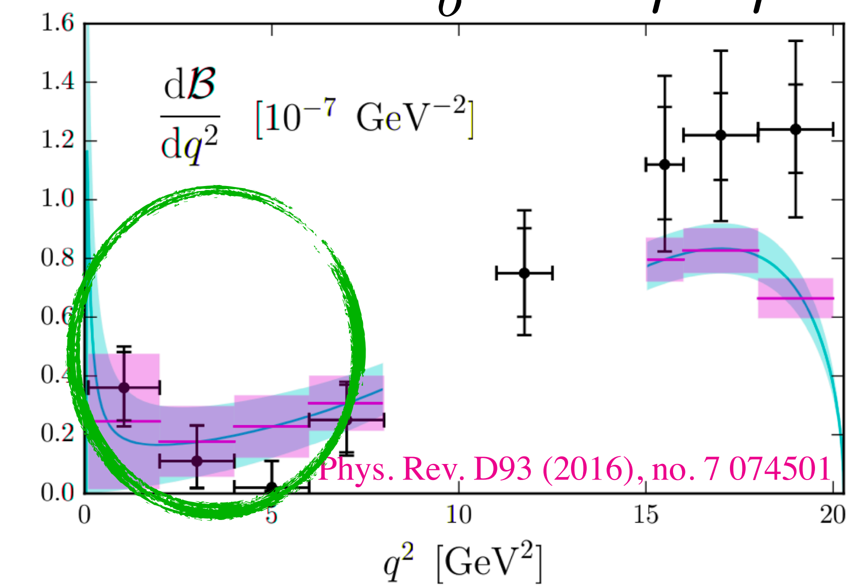
3.6σ $B_s^0 \to \phi\mu^+\mu^-$

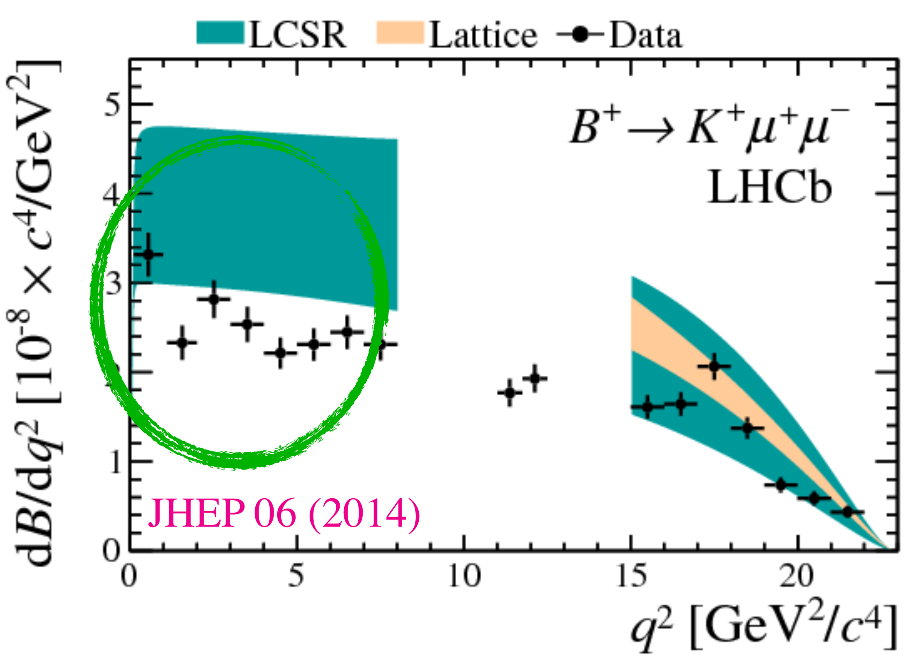


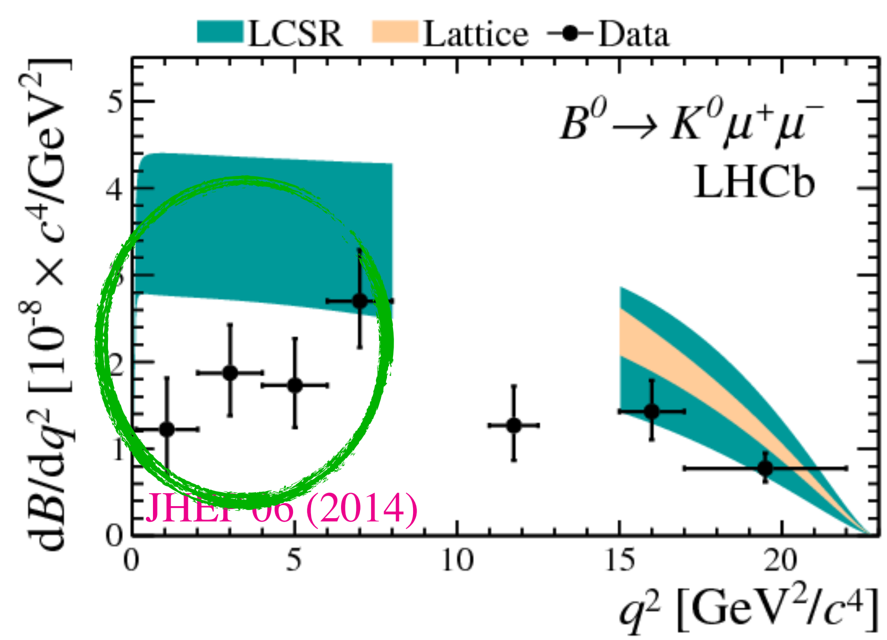
$B^0 \to K^{*0}\mu^+\mu^-$

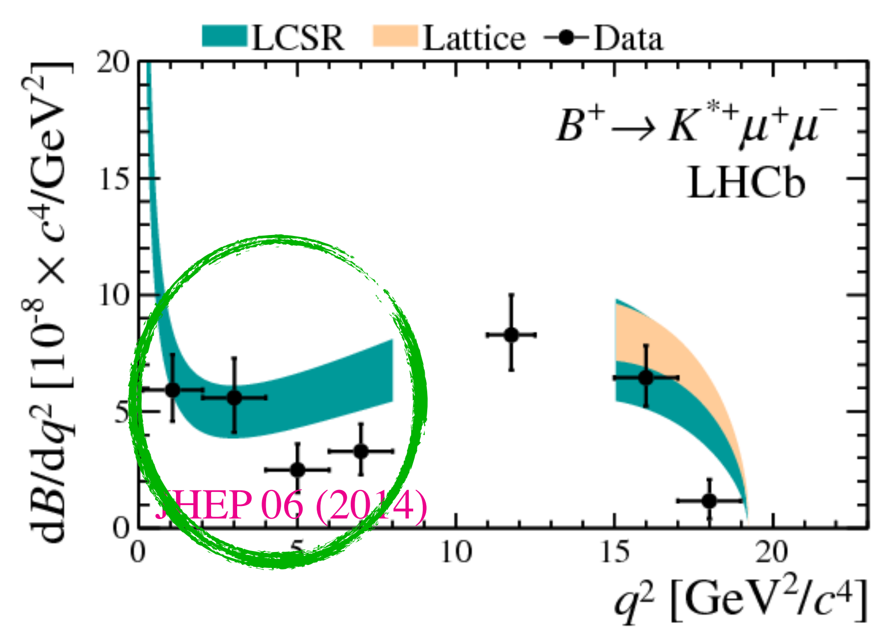


$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

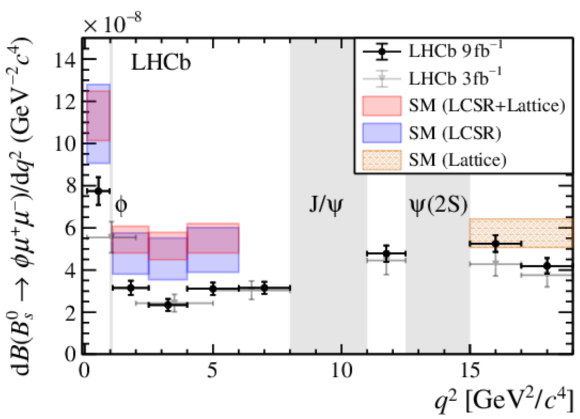


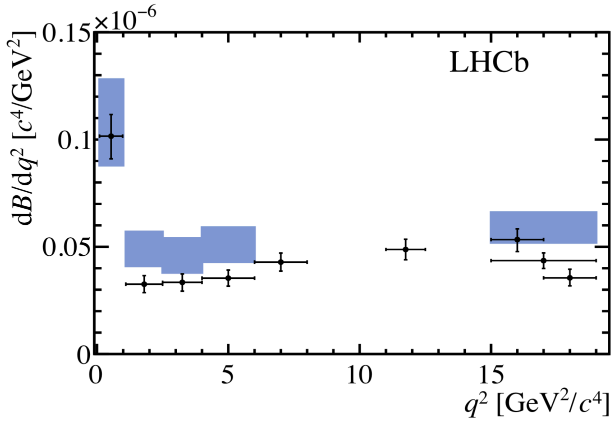


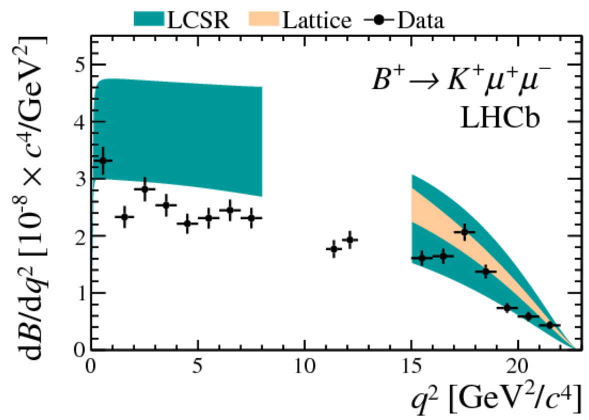




Interim recap: what $b \to s\ell^+\ell^-$ observables we have

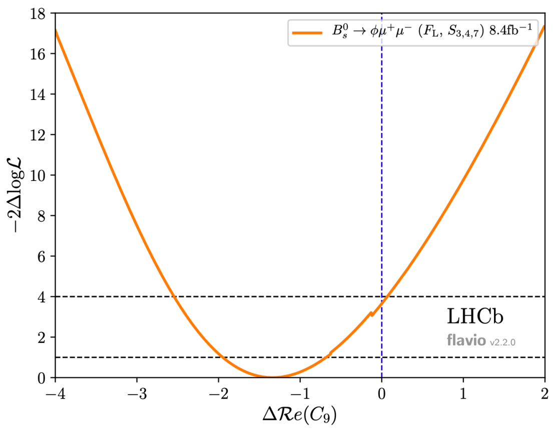


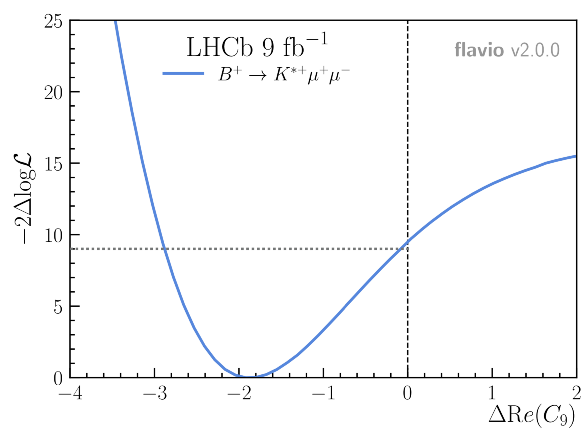


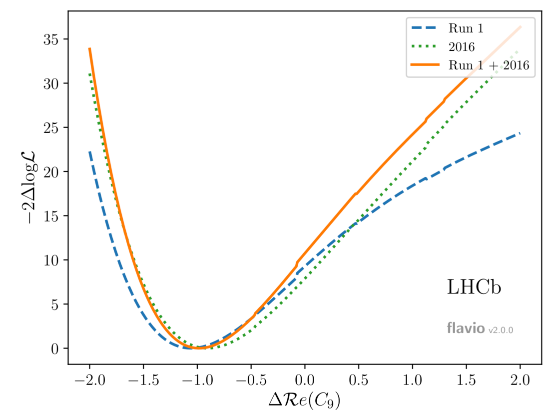


Branching fractions

$> 3\sigma$



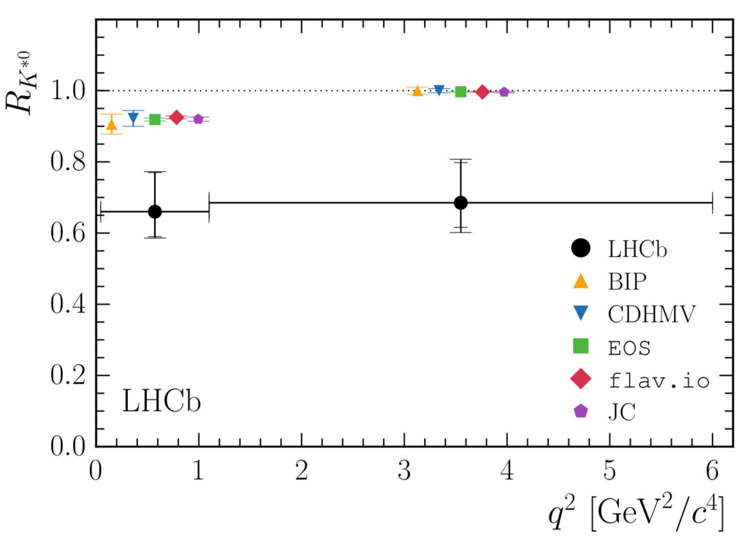


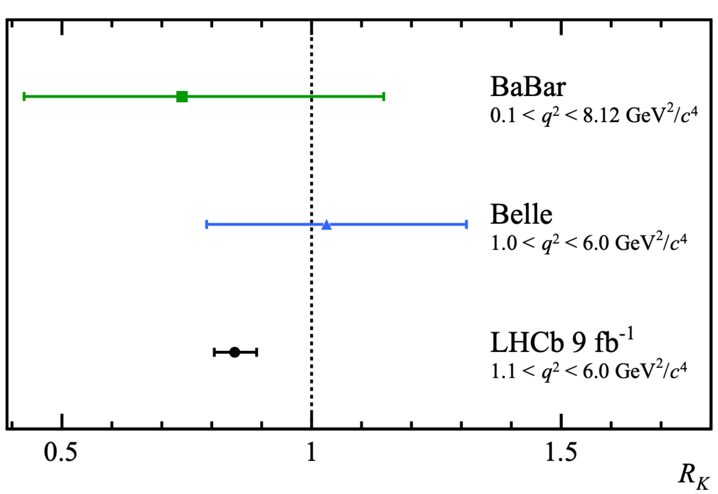


Angular analysis

$> 3\sigma$

Theoretical robustness

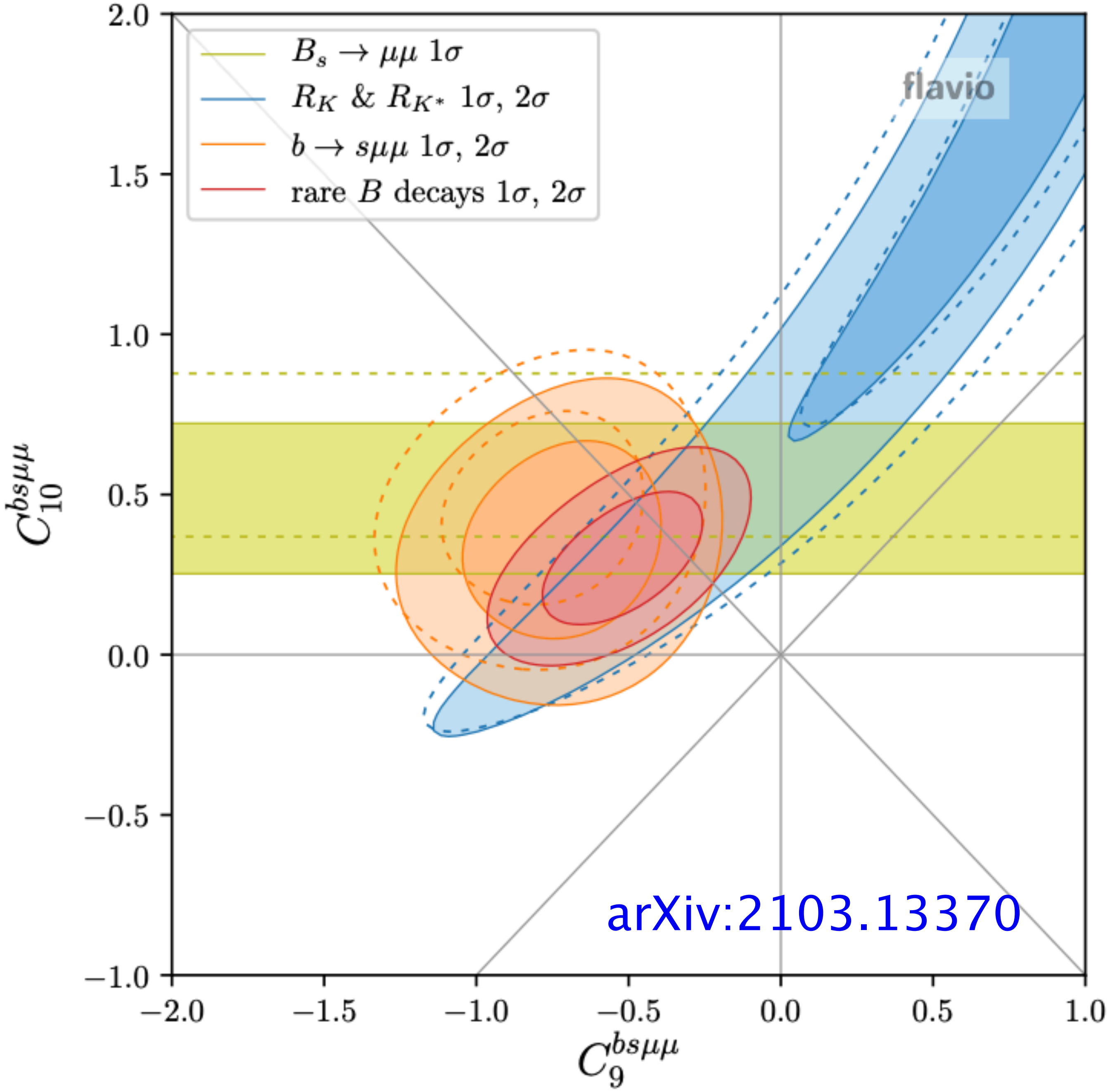




Lepton Flavour Universality (LFU)

$> 3\sigma$

Global fits summary



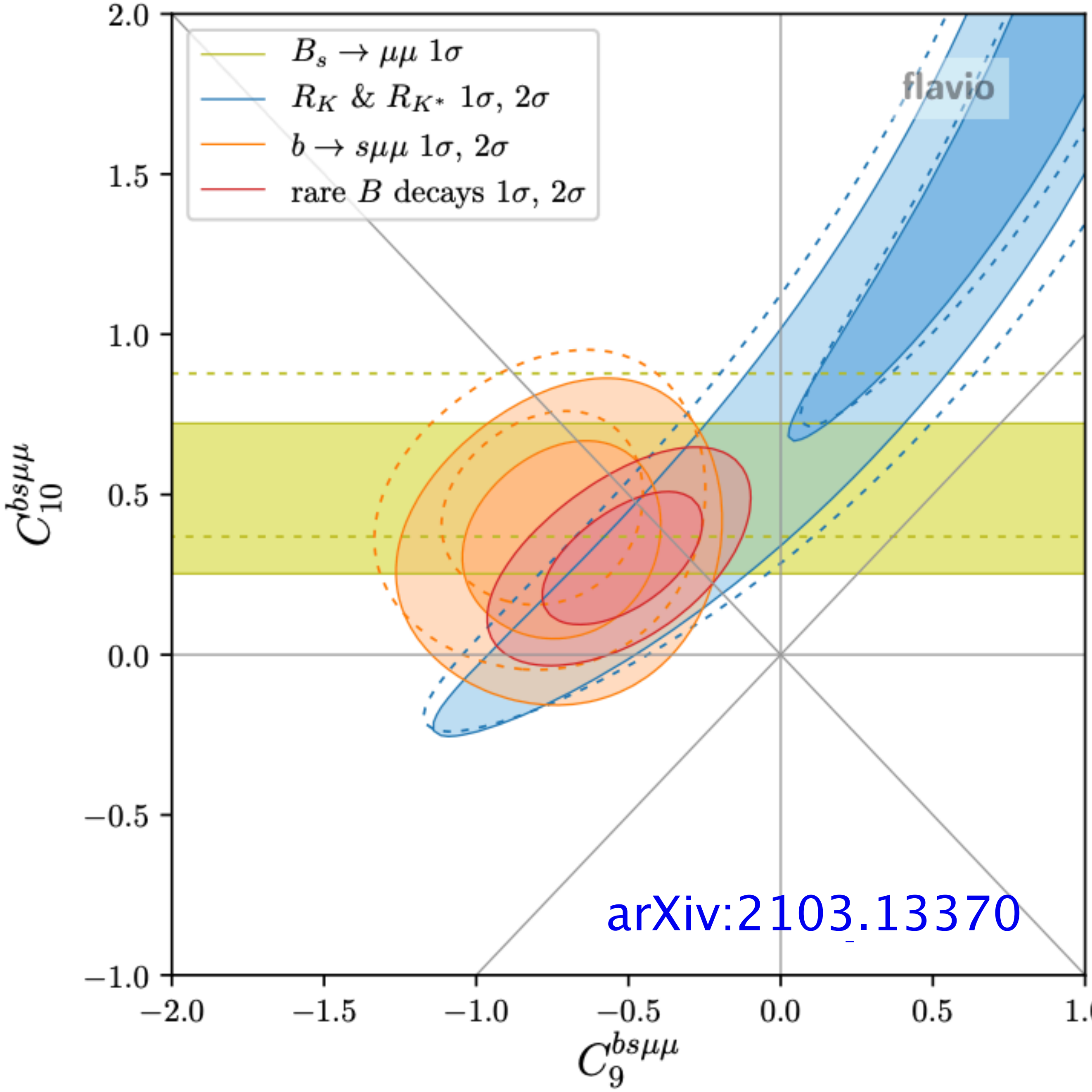
Lepton Flavour Universality

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$

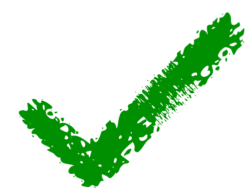
Very precisely known in SM

Gives a 4σ tension

Global fits summary



Lepton Flavour Universality

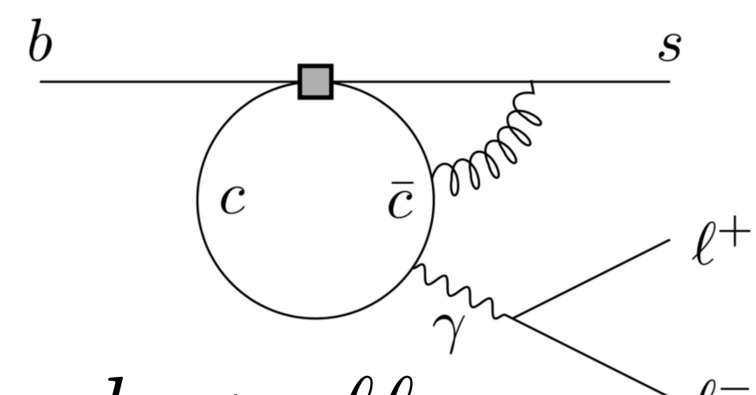


$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$

Very precisely known in SM

Gives a 4σ tension

$\mathcal{B}(b \to s\mu\mu), b \to s\mu\mu$ angular



$$b \to sc\bar{c} >> \ b \to s\ell\ell$$

Non-local charm-loop

Cannot be derived from first principles

Other things with Run 2 data

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

Binned analysis, extract $\int I_i(q^2)dq^2$ (normalised to decay rate)

Unbinned, directly fit for underlying Wilson Coefficients

i	$I_i(q^2)$	$f_i(\vec{\Omega})$
1s	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K$
1c	$\lvert\mathcal{A}_0^{\rm L}\rvert^2 + \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K$
2s	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \cos 2\theta_\ell$
2c	$-\lvert\mathcal{A}_0^{\rm L}\rvert^2 - \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K \cos 2\theta_\ell$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\rm L}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$
4	$\sqrt{\frac{1}{2}}{\rm Re}\left(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*}\right)$	$\sin 2\theta_K \sin 2\theta_\ell \cos\phi$
5	$\sqrt{2}{\rm Re}\left(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*}\right)$	$\sin 2\theta_K \sin\theta_\ell \cos\phi$
6s	$2{\rm Re}\left(\mathcal{A}_\parallel^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_\parallel^{\rm R}\mathcal{A}_\perp^{\rm R*}\right)$	$\sin^2\theta_K \cos\theta_\ell$
7	$\sqrt{2}{\rm Im}\left(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*}\right)$	$\sin 2\theta_K \sin\theta_\ell \sin\phi$
8	$\sqrt{\frac{1}{2}}{\rm Im}\left(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*}\right)$	$\sin 2\theta_K \sin 2\theta_\ell \sin\phi$
9	${\rm Im}\left(\mathcal{A}_\parallel^{\rm L*}\mathcal{A}_\perp^{\rm L} + \mathcal{A}_\parallel^{\rm R*}\mathcal{A}_\perp^{\rm R}\right)$	$\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$

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

Binned analysis, extract $\int I_i(q^2)dq^2$ (normalised to decay rate)

Unbinned, directly fit for underlying Wilson Coefficients

$$\mathcal{A}_0^{\mathrm{L,R}}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}}\left\{(C_9 \mp C_{10})A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}}C_7 T_{23}(q^2) + \boxed{\mathcal{G}_0(q^2)}\right\}, \quad (1)$$

$$\mathcal{A}_\parallel^{\mathrm{L,R}}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{(C_9 \mp C_{10})\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}C_7 T_2(q^2) + \boxed{\mathcal{G}_\parallel(q^2)}\right\}, \quad (2)$$

$$\mathcal{A}_\perp^{\mathrm{L,R}}(q^2) = N\sqrt{2\lambda}\left\{(C_9 \mp C_{10})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}C_7 T_1(q^2) + \boxed{\mathcal{G}_\perp(q^2)}\right\}, \quad (3)$$

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

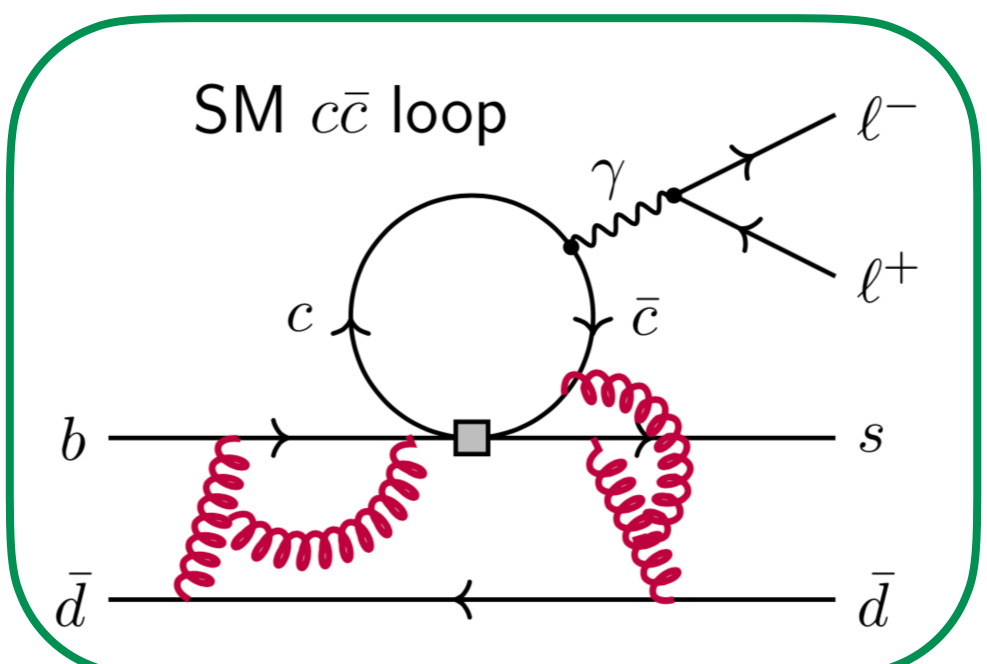
Binned analysis, extract $\int I_i(q^2)dq^2$ (normalised to decay rate)

Unbinned, directly fit for underlying Wilson Coefficients

$$\mathcal{A}_0^{\mathrm{L,R}}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}}\left\{(C_9 \mp C_{10})A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}}C_7 T_{23}(q^2) + \mathcal{G}_0(q^2)\right\}, \quad (1)$$

$$\mathcal{A}_\parallel^{\mathrm{L,R}}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{(C_9 \mp C_{10})\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}C_7 T_2(q^2) + \mathcal{G}_\parallel(q^2)\right\}, \quad (2)$$

$$\mathcal{A}_\perp^{\mathrm{L,R}}(q^2) = N\sqrt{2\lambda}\left\{(C_9 \mp C_{10})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}C_7 T_1(q^2) + \mathcal{G}_\perp(q^2)\right\}, \quad (3)$$



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

Eur. Phys. J. C (2018) 78: 453

Eur. Phys. J. C **80,** 1095 (2020)

Model non-local effects as distortion to C_9^{μ}

Fit for relative phase and magnitude

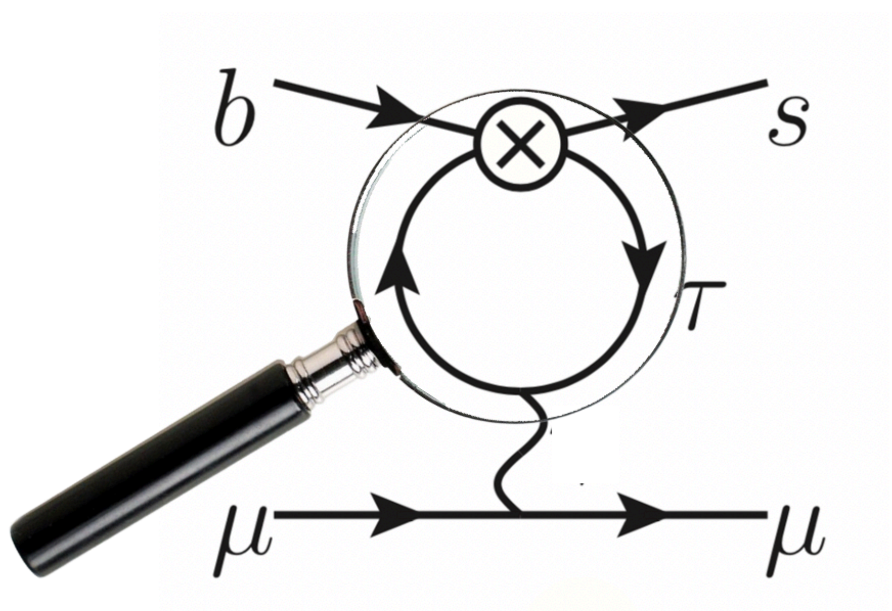
$$C_9^{eff} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{res}(q^2)$$

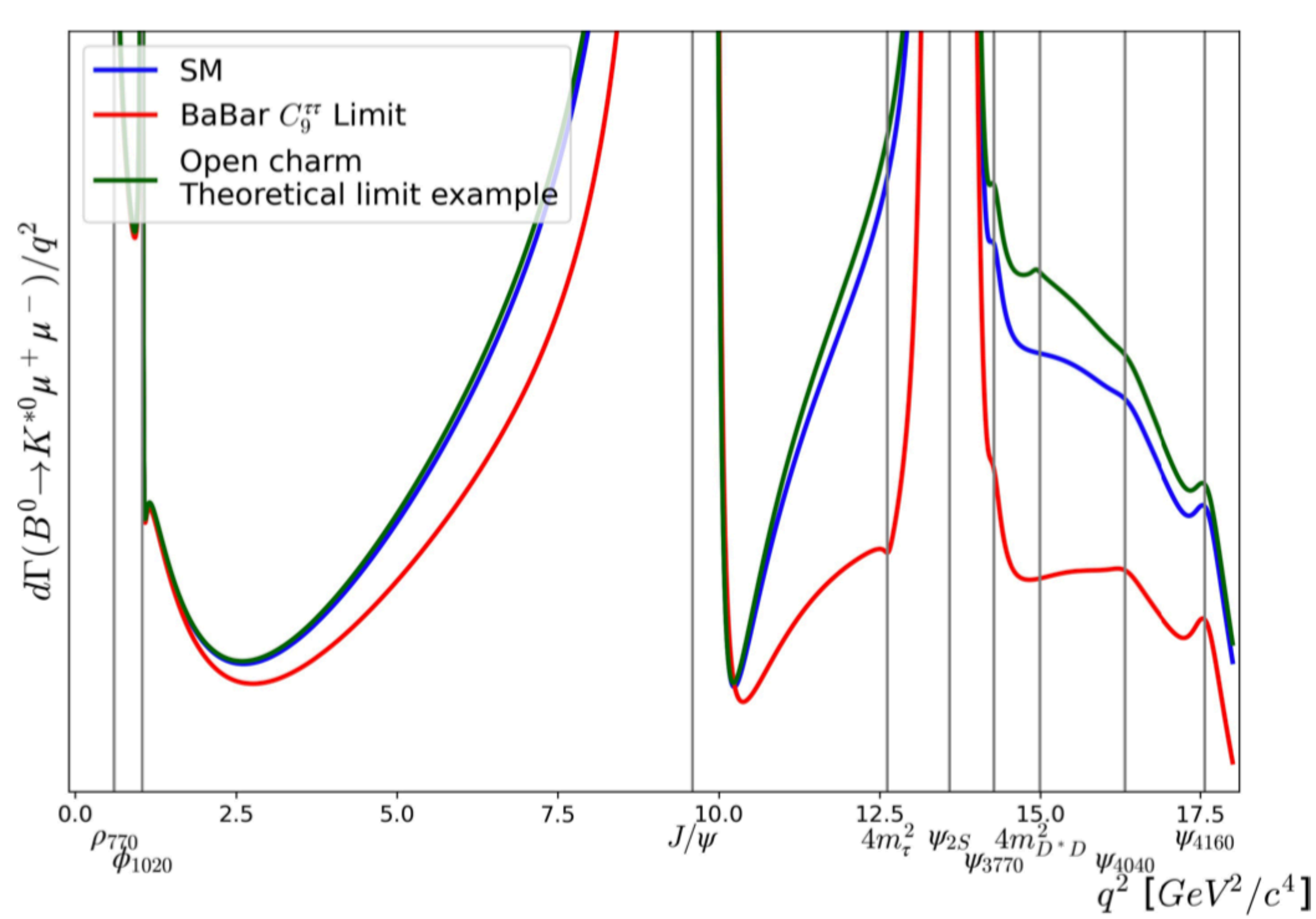
relative phase (δ_j), magnitude (η_j), lineshape ($A_j^{res}(q^2)$)

Lineshape modelled by Breitwigner

$(\rho, \omega, \phi, J/\psi, \psi(X))$ 1-particle states, modelled with BW

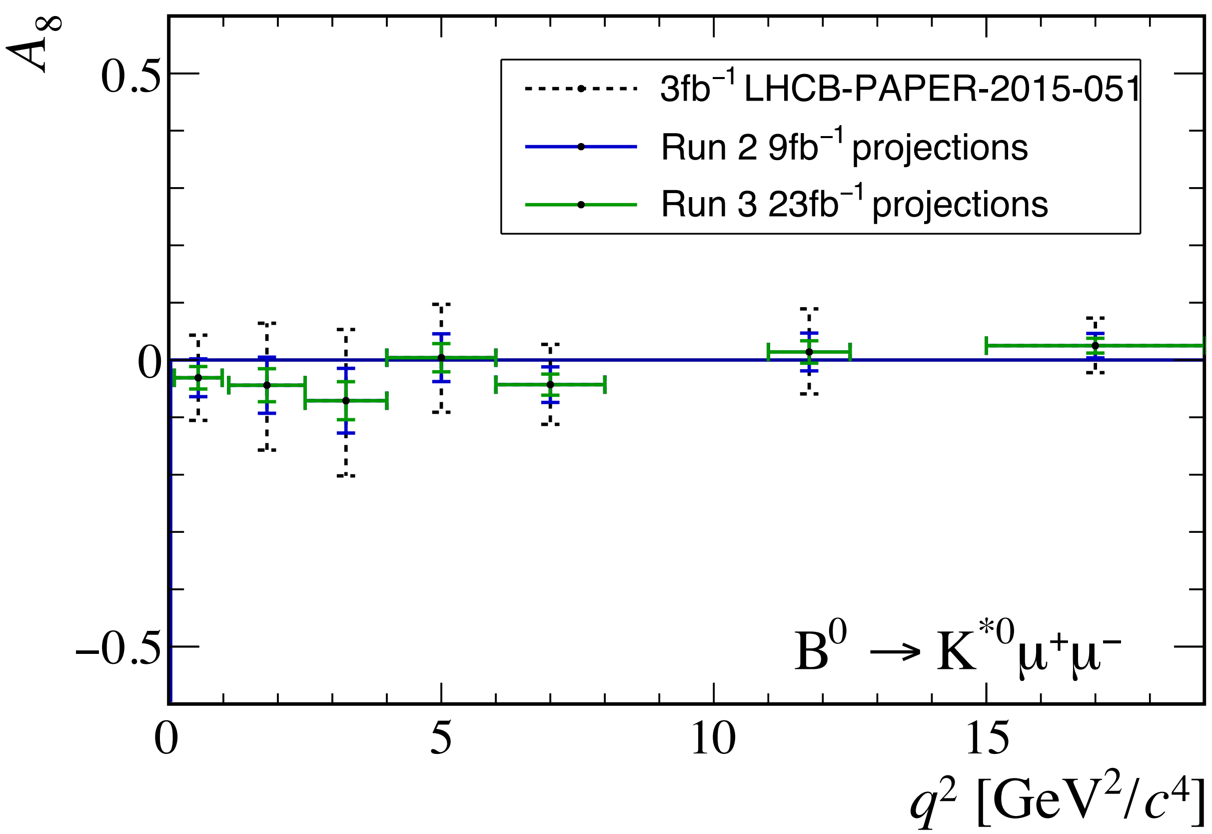
Model contributions above open-charm threshold and $B^0 \to K^{*0}\tau^+\tau^-$

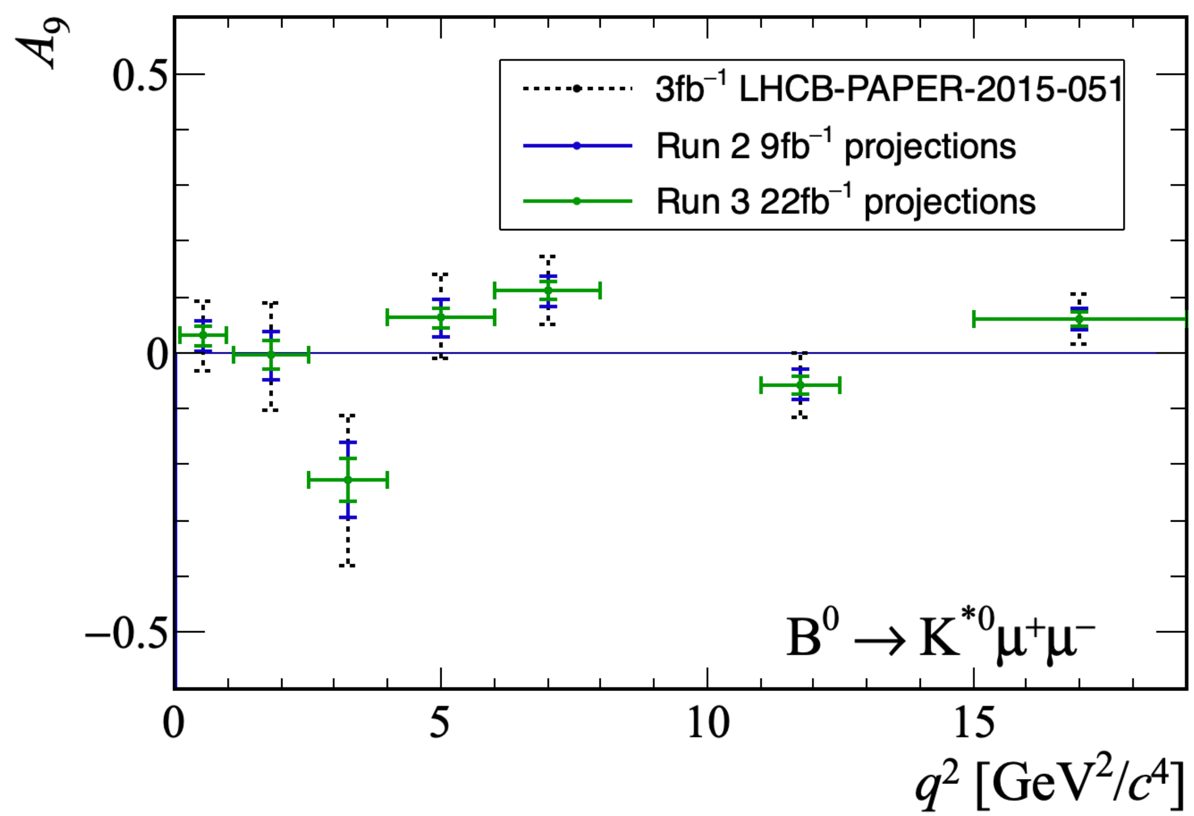




$B^0 \to K^{*0}\mu^+\mu^-$ binned analysis

- Full Run 1 and 2 data legacy analysis
- Provide CP-averages, asymmetries and correlations between them
- Also measure branching fraction



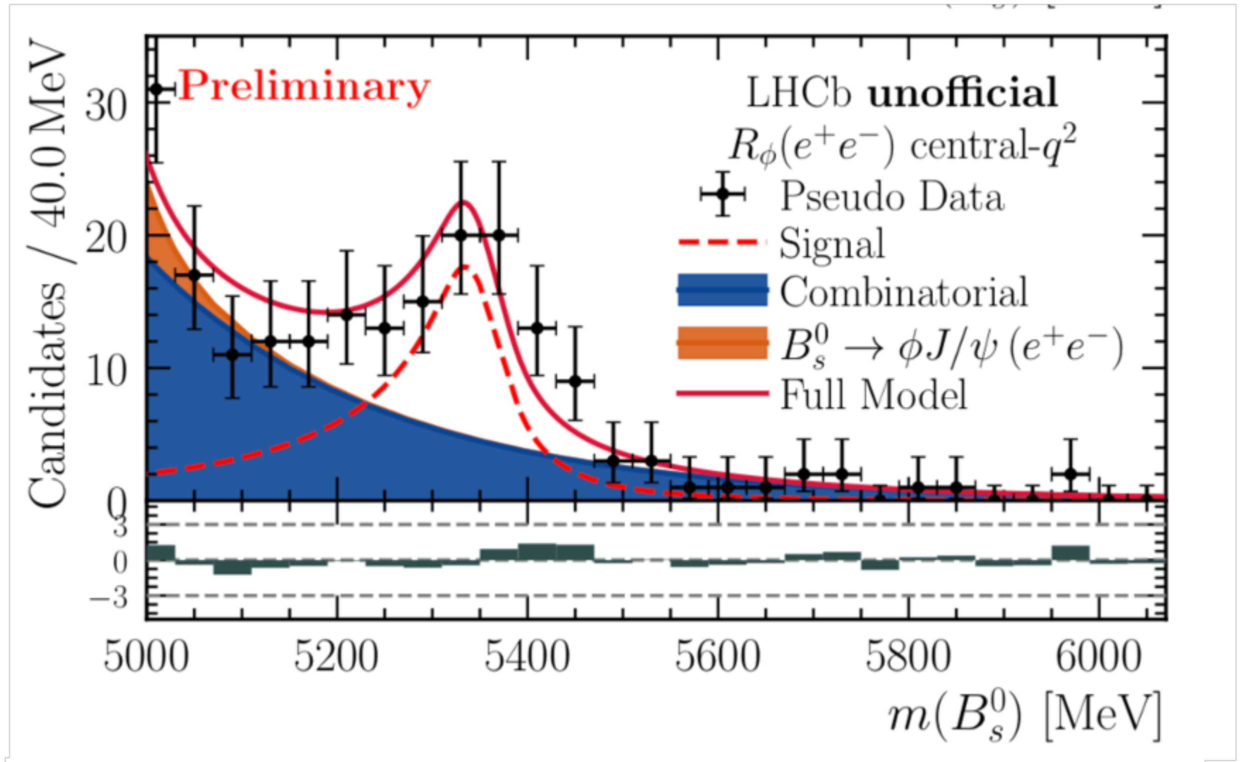


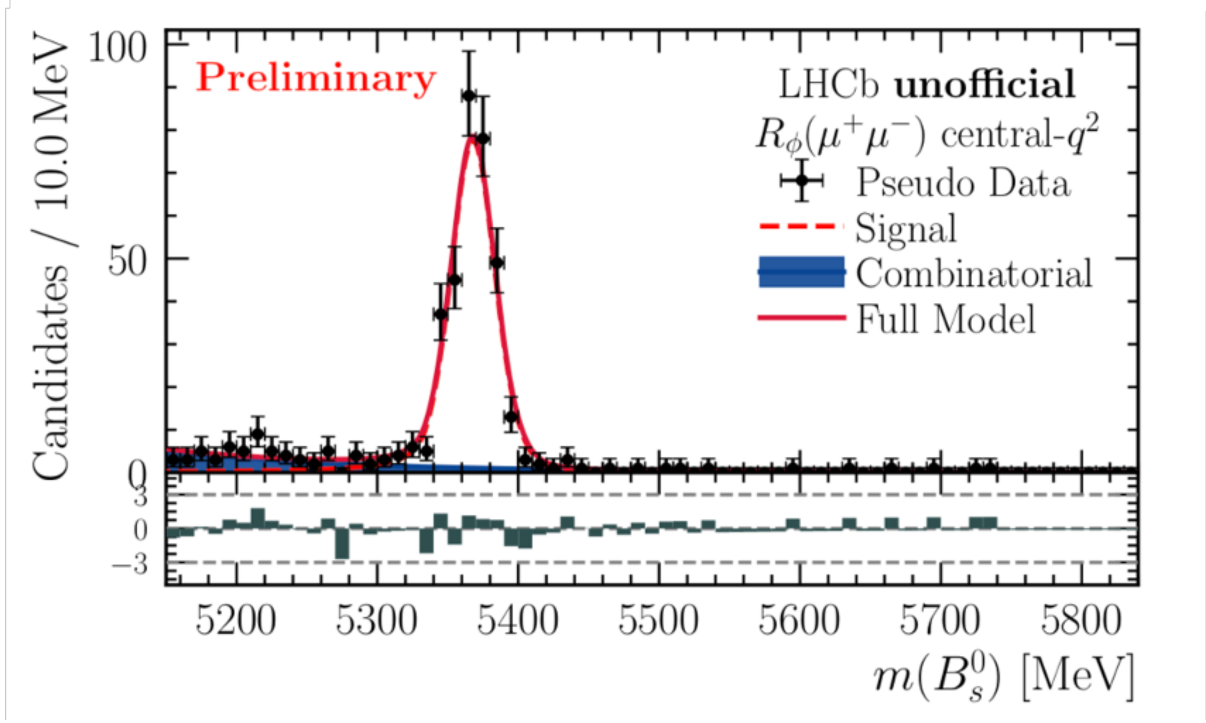
$R(\phi)$

$$R_\phi = \frac{\mathcal{B}\left(B_s^0 \to \phi\mu^+\mu^-\right)}{\mathcal{B}\left(B_s^0 \to \phi e^+e^-\right)} \Bigg/ \frac{\mathcal{B}\left(B_s^0 \to \phi J/\psi\left(\mu^+\mu^-\right)\right)}{\mathcal{B}\left(B_s^0 \to \phi J/\psi\left(e^+e^-\right)\right)}$$

- low q^2: $0.1 < q^2 < 1.1\,\mathrm{GeV}^2$
- central q^2: $1.1 < q^2 < 6\,\mathrm{GeV}^2$
- high q^2: $15 < q^2 < 19\,\mathrm{GeV}^2$

- **Expected Sensitivity** $\mathcal{O}(15\,\%)$





Run 3 data

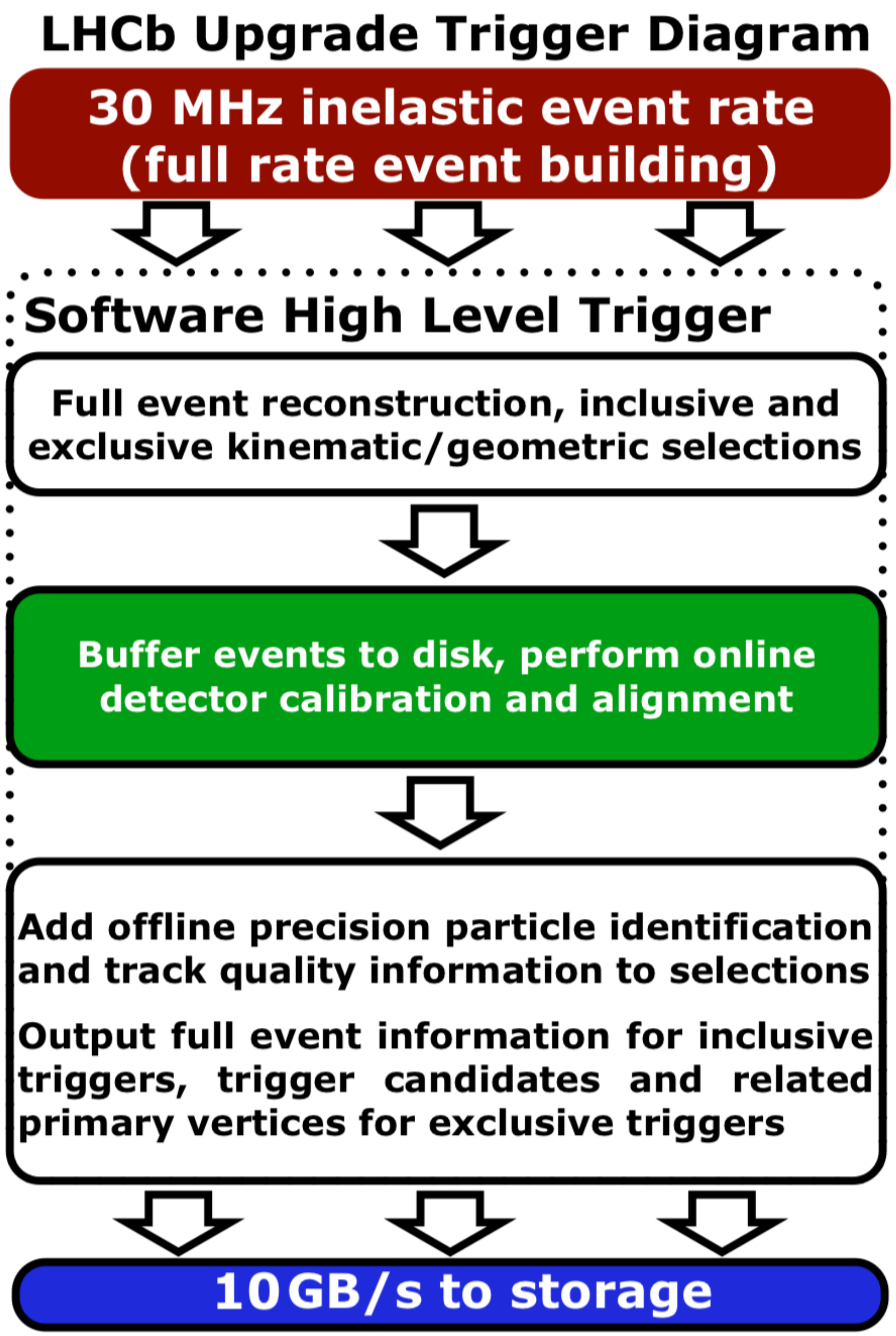
What can we expect from Run 3?

- We expect around 5 times the number of bb pairs by end of Run 3 compared to end of Run 2

Run 1&2	LS2	Run 3	LS3	Run 4
$\mathcal{L} = 4 \times 10^{32}/cm^2s$ $\int \mathcal{L}\, dt = 9$ fb^{-1}	LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 23$ fb^{-1}	LHCb Upgrade Ib	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 50$ fb^{-1}
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032

- Significant increase in the number of pp collisions per second -> different problems compared to Run 1+2
- The increase in luminosity in Run 3 means that ~24% of all events with have a reconstructable $c\bar{c}$ pair and 2% have a reconstructable $b\bar{b}$ pair (!)

New trigger for Run 3



- **Remove hardware trigger!**
- Make decision with more info, improve efficiencies
- Implement the trigger entirely in software
- First-level software trigger (HLT1) MVA based on inclusive one and two track selections

What does this mean for $b \to s\ell\ell$ decays?

- The ECAL hardware trigger is currently the major issue for electron analyses
- Removing this bottleneck should increase trigger efficiency relative to the muon mode

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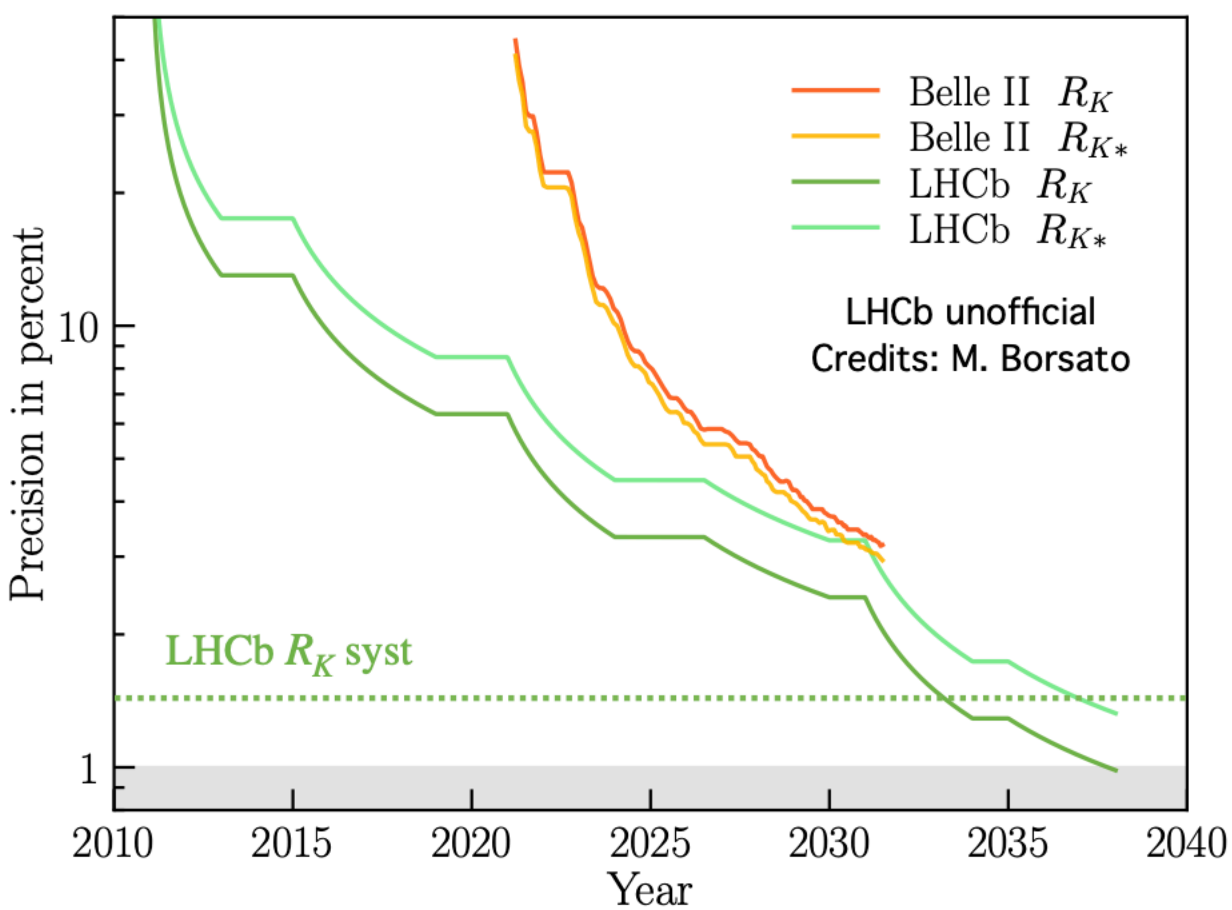
Signal	GEC	TIS -OR- TOS	TOS	GEC × TOS
$B^0 \to K^{*0}\mu^+\mu^-$	88.9 ± 2.0	90.6 ± 2.0	88.8 ± 2.1	79.0 ± 2.6
$B^0 \to K^{*0}e^+e^-$	84.2 ± 2.7	69.1 ± 3.8	61.7 ± 4.0	52.0 ± 3.8

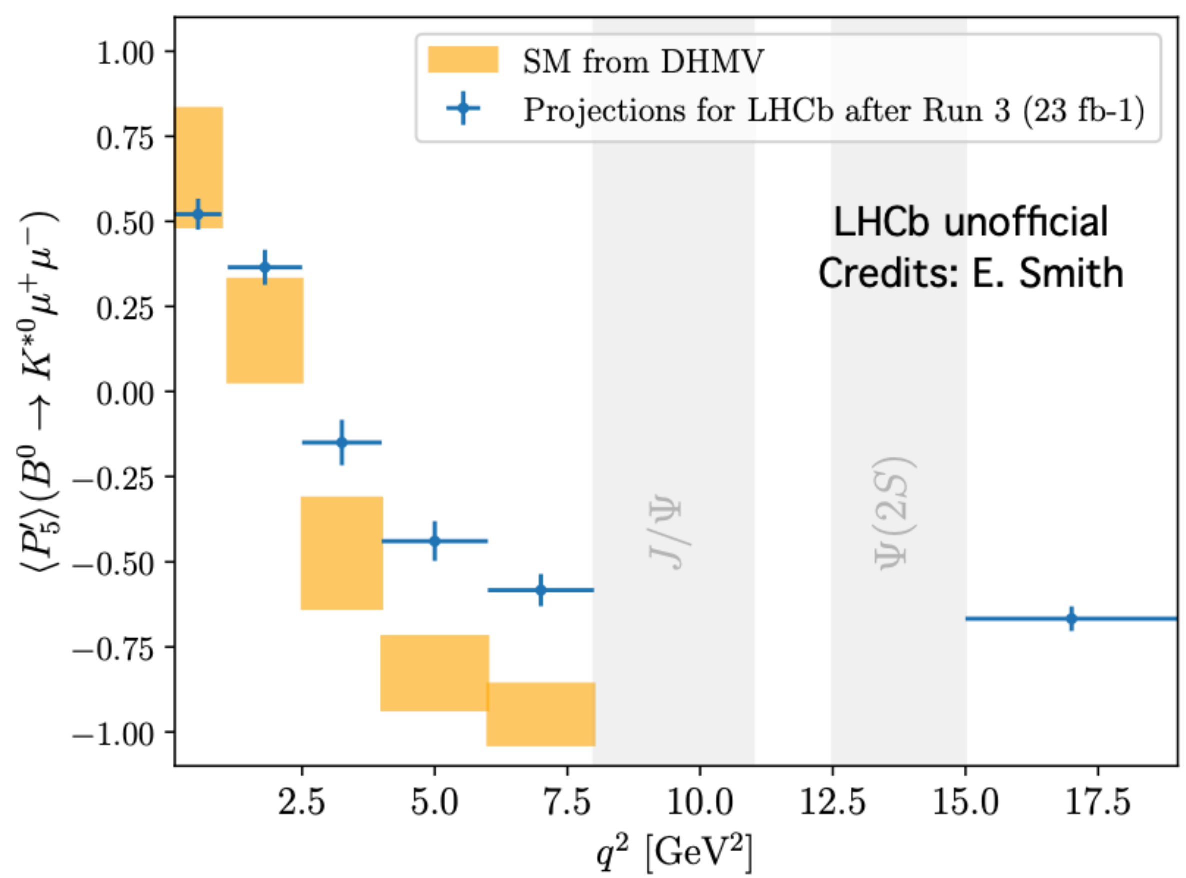
GEC: Global Event Cut, TIS: Trigger Independent of Signal, TOS: Trigger on Signal

- From ~40% of muon mode currently to ~ 60% of muon mode

Some outlook plots for Run 3

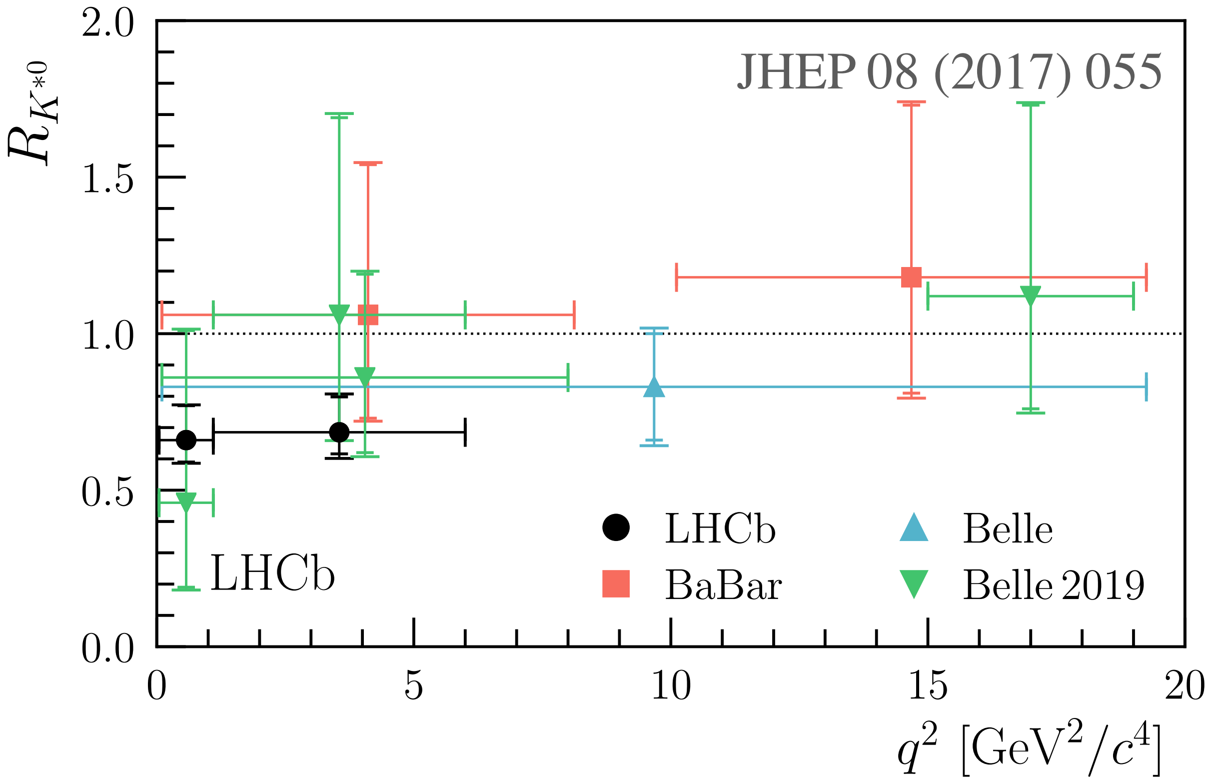
- Expect around 2.5% statistical uncertainty on RK by end of Run 3
- Angular muon modes will also significantly increase precision





Measurements with Run 3 data and beyond

Angular analysis of $b \to s e^+ e^-$ decays



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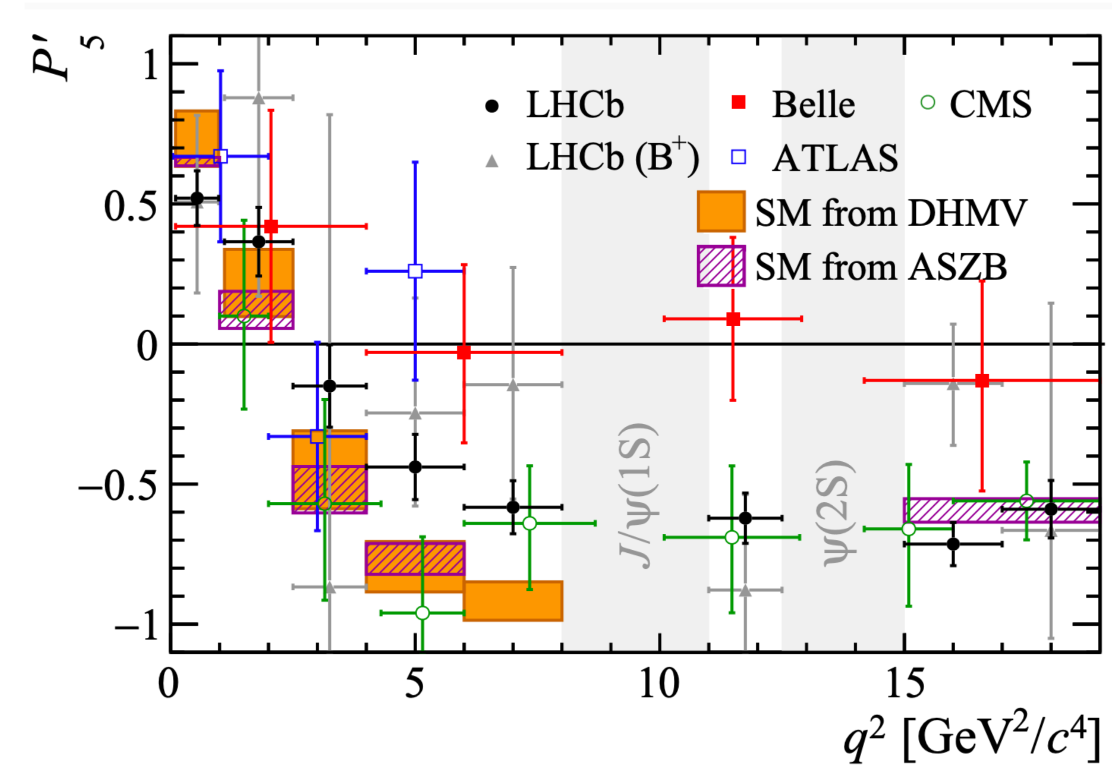
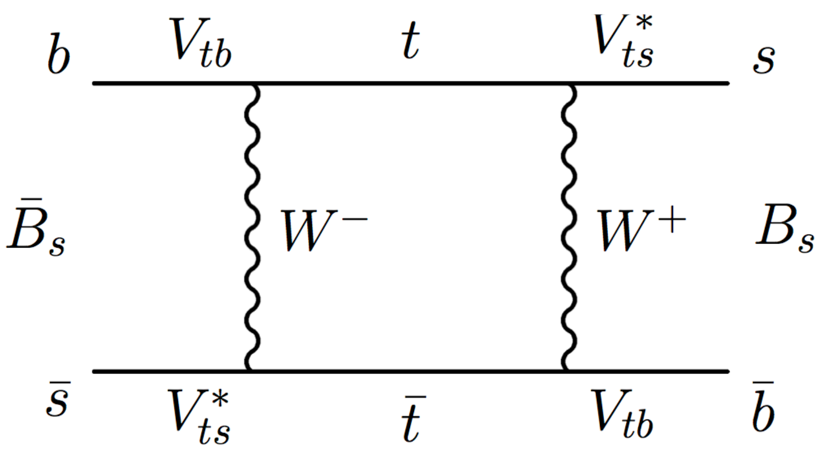


- A full angular analysis of $B \to V(\to hh)e^+e^-$ modes:
  - Confirm LFU results in **experimentally orthogonal way**
  - Gives far more in-depth info on the structure of NP
  - Can construct observables between electrons and muons with less dependence on charm loop

Time-dependent angular analysis



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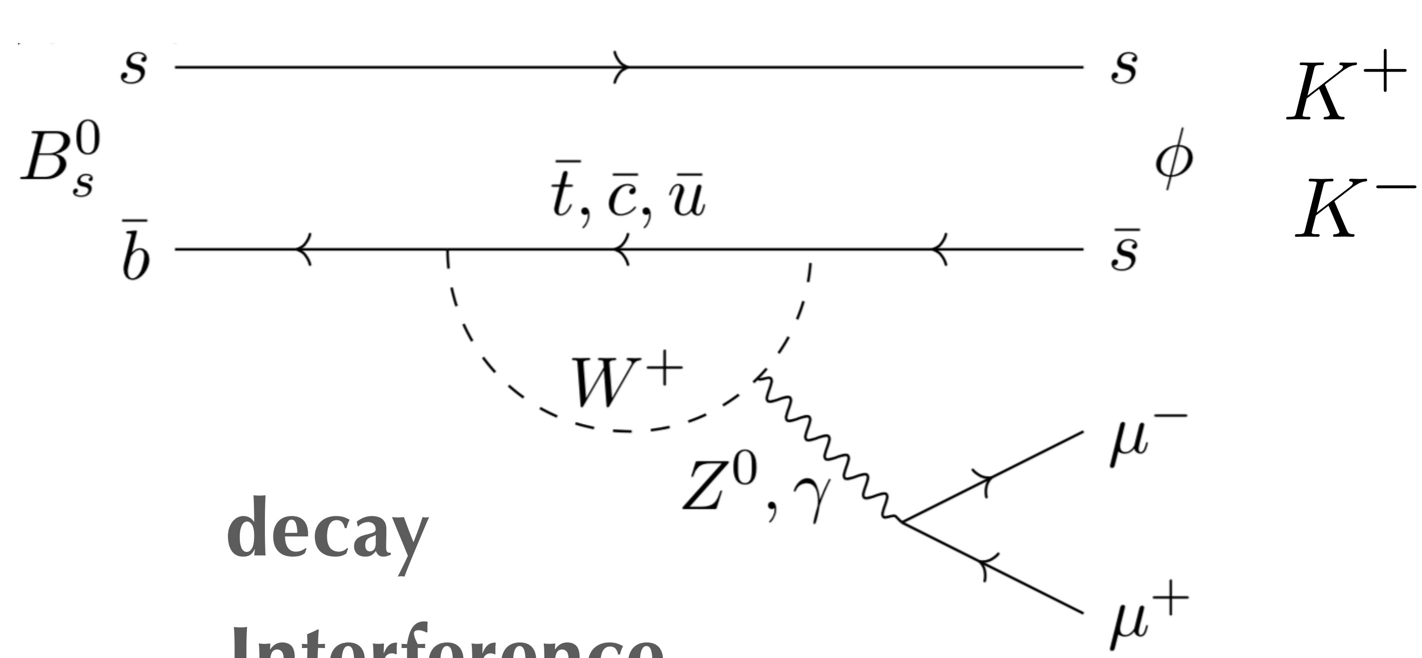
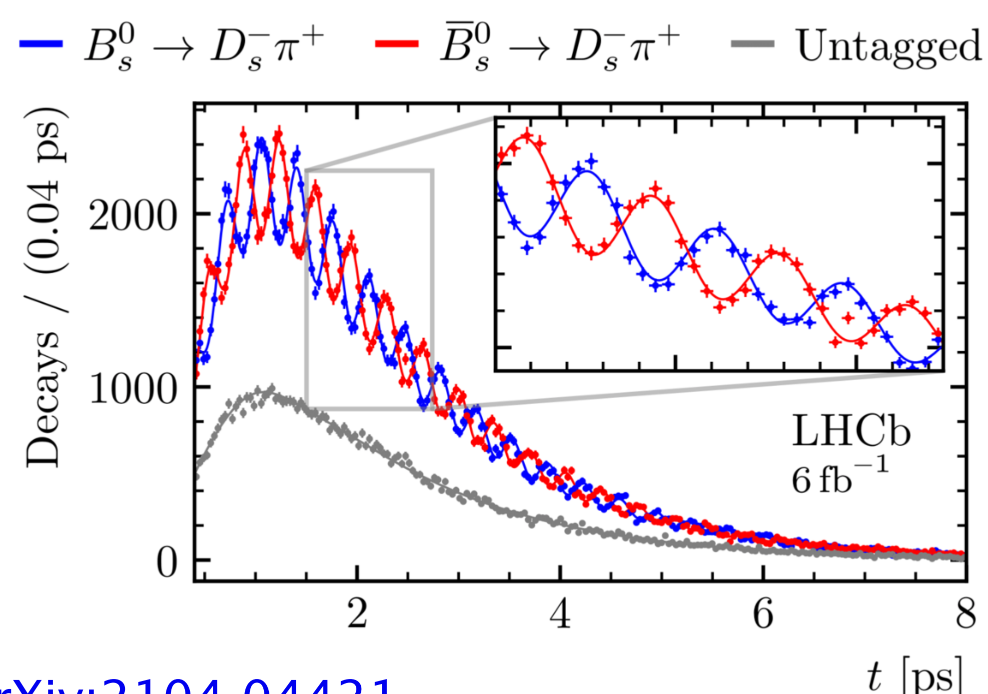


Mixing + **decay Interference**

= new observables from $b \to s\mu^+\mu^-$ decays with flavour-symmetric final-states



arXiv:2104.04421

$$J_i(t) + \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big]$$

$$J_i(t) - \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big] \,,$$

$$x \equiv \Delta m/\Gamma, \; y \equiv \Delta\Gamma/(2\Gamma)$$

Use rest of event to figure out the B_s flavour at production, this is called **Flavour-tagging**

$b \to s\mu^+\mu^-$ flavour-tagging

Yields, $\epsilon_{tag} \equiv 5\%$		Run 1 observed		Run 3 expected	
		Full q^2	$1.1 < q^2 < 6.0$	Full q^2	$1.1 < q^2 < 6.0$
$B_s^0 \to \phi(1020)\mu^+\mu^-$	untagged	432	101	5230	1220
	tagged	22	5	262	60
$B_d^0 \to K_s\mu^+\mu^-$	untagged	176	70	2200	850
	tagged	9	4	110	43

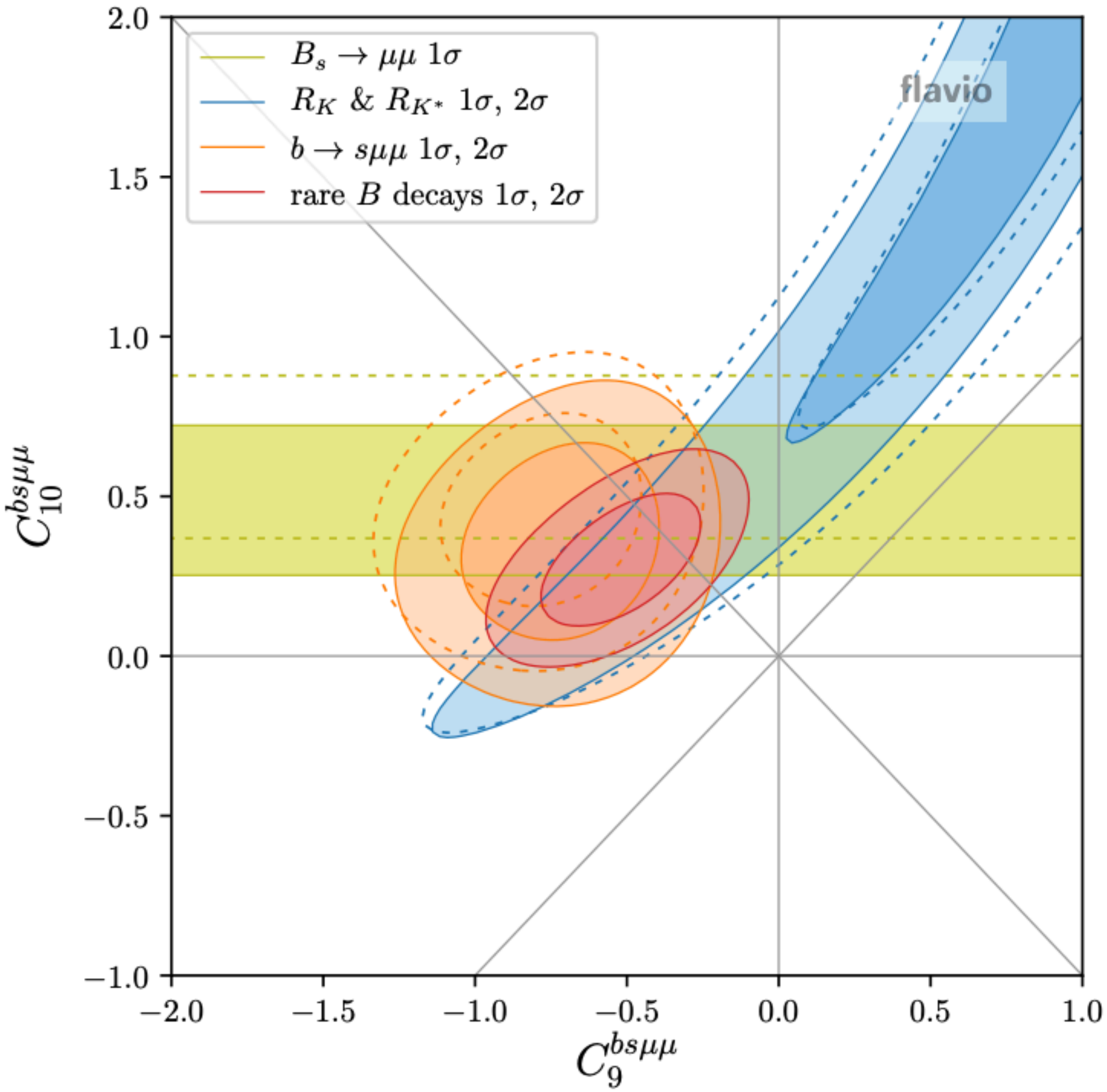
- Tagged angular analysis possible by end of Run 3 in wider q^2 bins at LHCb, full lifetime + angular analysis still somewhat limited
- Data collected in Run 4,5 and beyond needed to properly explore time-dependent angular analysis

What about $b \to d\ell^+\ell^-$ decays?

- Decay rates around $|V_{ts}/V_{td}|^2 \approx 25$ smaller than $b \to s\ell^+\ell^-$
- LFU tests possible by end of Run 3 but not angular analysis
- Many explanations for $b \to s\ell^+\ell^-$ anomalies predict effects in $b \to d\ell^+\ell^-$

R_X precision	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

Conclusions

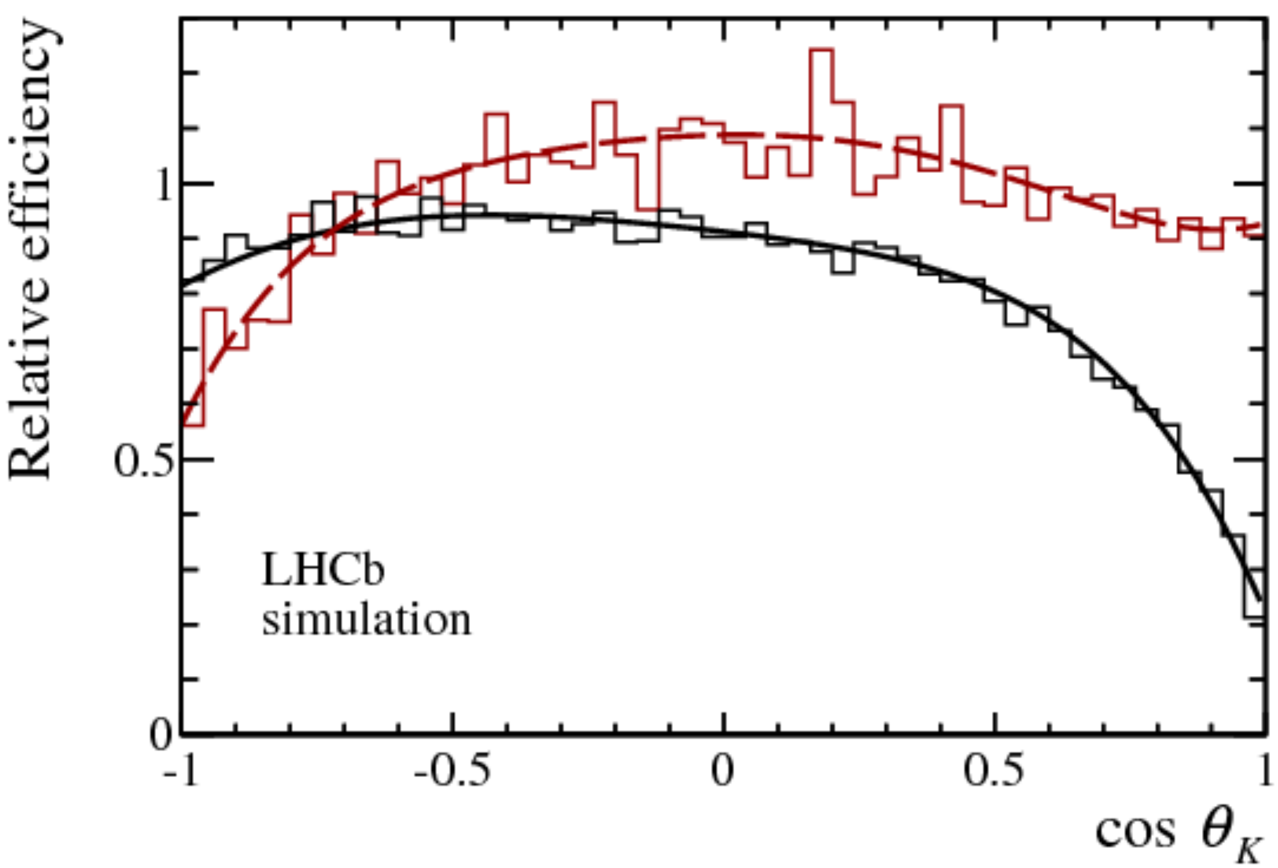


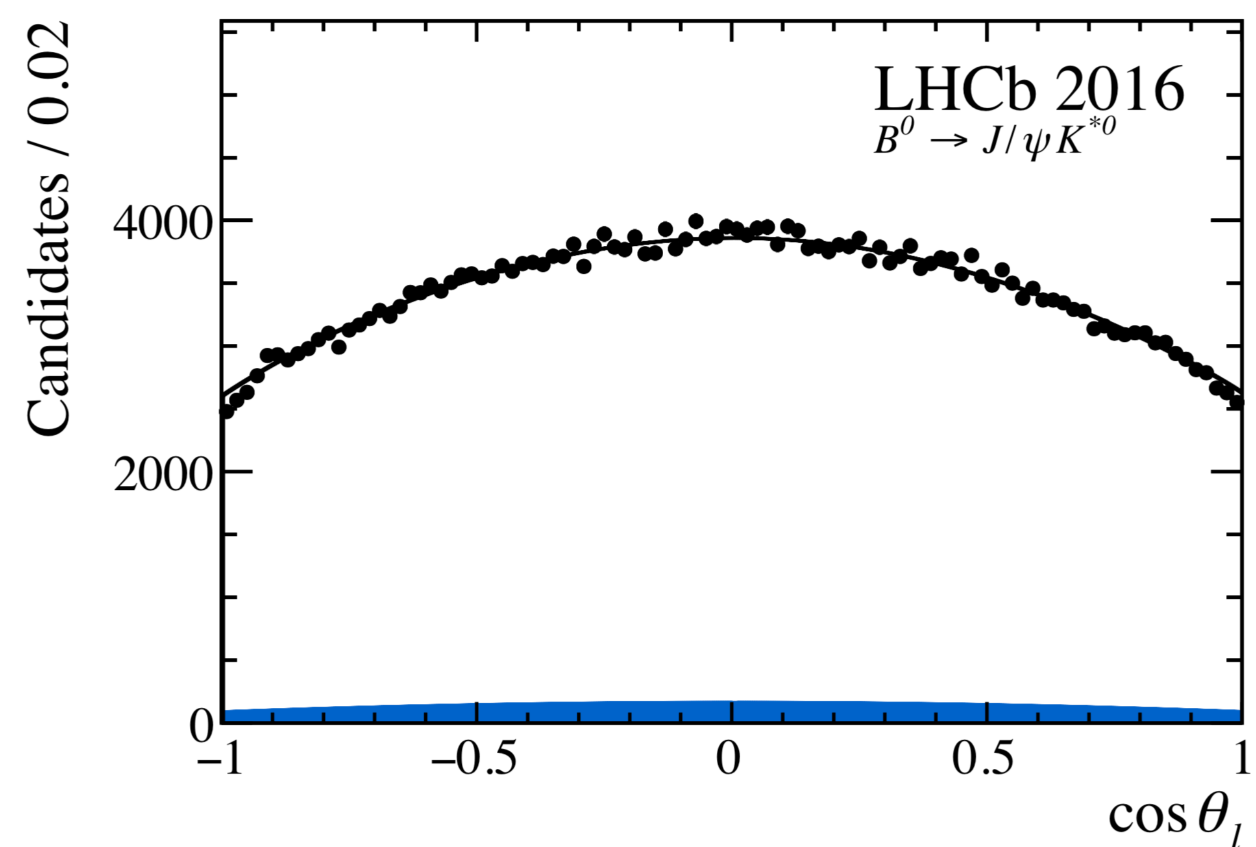
- Run 2 has been an exciting time for the neutral current anomalies at LHCb
- Still remains many measurements that can be performed with both existing and new data
- New measurements will shed more light on both key experimental and theory aspects of flavour anomalies

Back-ups

Experimental summary: angular analyses for muons

- Uncertainties dominated by statistics
- The efficiency shape as a function of all the angles and q2 is derived from simulation and validated on high-yield control modes in data
- Not dependent on absolute efficiency, no single dominate systematic



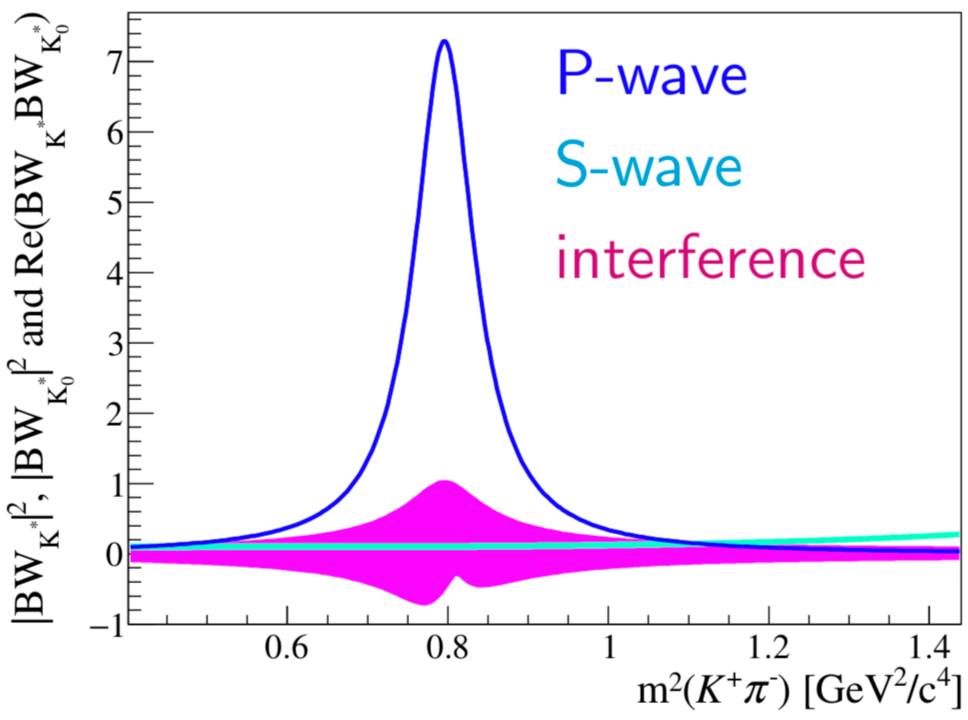


Complications: S-wave contribution

- Contribution from non-resonant $K\pi$'s and spin 0 resonances
- Must include additional angular terms (as nuisances)

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\Bigg|_{\mathrm{S+P}} = \boxed{(1-F_S)}\boxed{\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\Bigg|_{\mathrm{P}}}$$

$+$ **interference terms** P-wave



P-wave observables scaled by 1-F_s

- Use the $m_{K^+\pi^-}$ distribution to constrain S-wave

Complications: angular acceptance

- The reconstruction and selection efficiency must be calculated as a function of angles and q^2.
- Efficiency can be parametrised using Legendre polynomials

$$\varepsilon(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{k,l,m,n} c_{k,l,m,n} P(\cos\theta_\ell, k) P(\cos\theta_K, l) P(\phi, m) P(q^2, n)$$

- The coefficients $c_{k,l,m,n}$ are calculated via the method of moments using large statistic MC samples

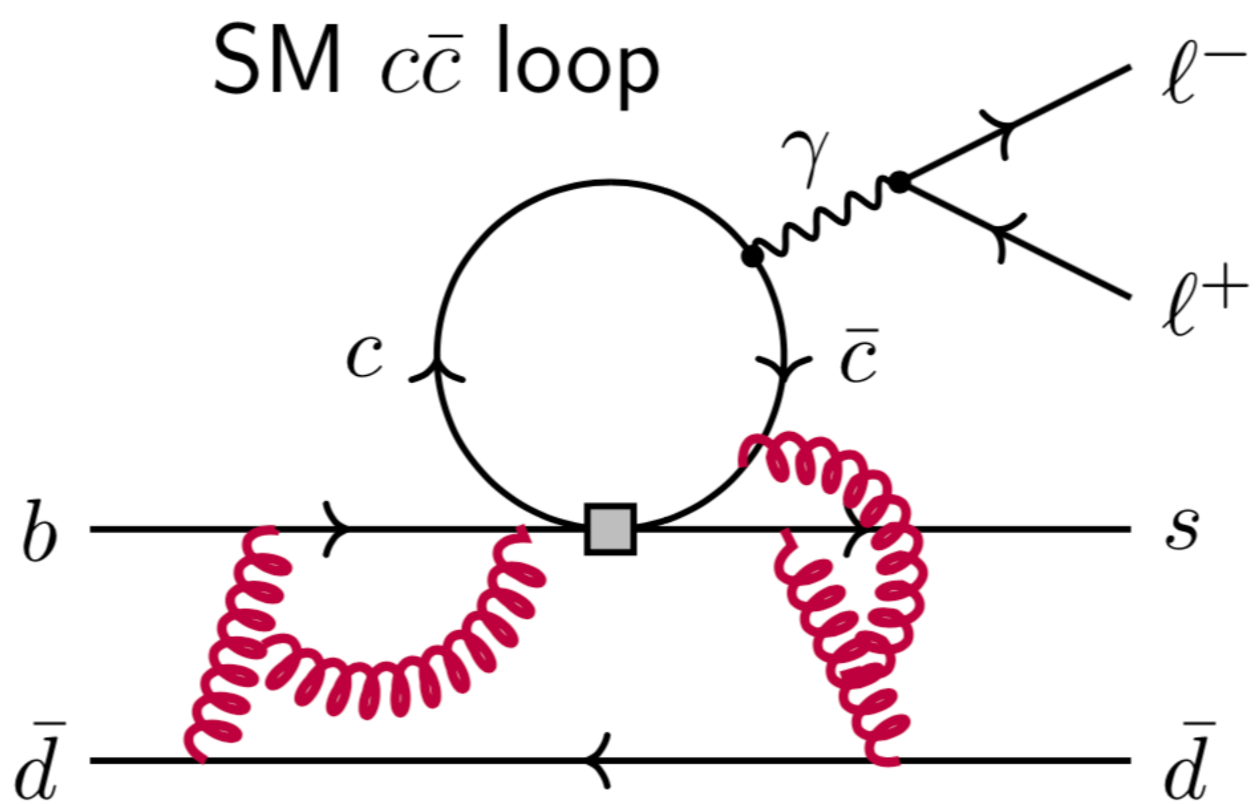
$$c_{k,l,m,n} = \frac{1}{N'} \sum_{i=1}^{N} w_i \left[\left(\frac{2k+1}{2}\right) \left(\frac{2l+1}{2}\right) \left(\frac{2m+1}{2}\right) \left(\frac{2n+1}{2}\right) \right. \\ \left. \times P(\cos\theta_\ell, k) P(\cos\theta_K, l) P(\phi, m) P(q^2, n) \right]$$

arXiv:1707.07305

Writing out expression for complex amplitudes in full:

$$\mathcal{A}^{L,R}_{\lambda=\perp,\|,0} = N_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}^T_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Wilson coefficients, form factors, effects from charm loop



arXiv:1707.07305

General idea -> parameterise the charm loops:

Taylor expandable

1. Perform some tricks to make $H_\lambda(q^2)$ an analytical function

Namely removing poles[*]: $J/\psi, \psi(2S)$

2. Exploit similar $H_\lambda(q^2), F_\lambda(q^2)$ properties, parametrise $H_\lambda(q^2)/F_\lambda(q^2)$

Need to get α_k^λ

$$\hat{\mathcal{H}}_\lambda(z) = [\sum_{k=0}^{2} \alpha_k^\lambda z^k]\mathcal{F}_\lambda(z)$$

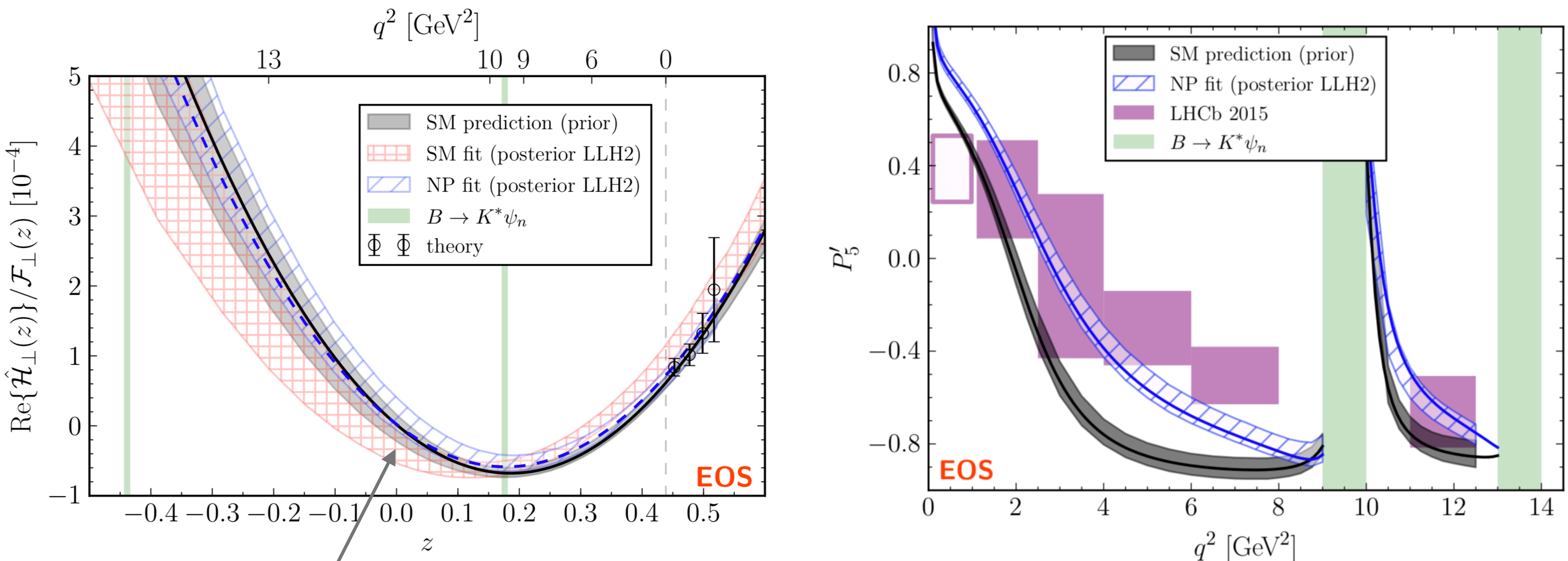
z is just remapping of q^2

Taylor expansion

3. Use information from theory where there is no charm: negative q^2
4. Use information from data (LHCb, Belle, Babar) for q^2 region corresponding to the poles $J/\psi, \psi(2S)$
5. Interpolate using info from [3][4] to get α_k^λ
6. Using knowledge of α_k^λ, apply to $B_0 \rightarrow K^{*0}\mu^+\mu^-$ region to get C_9

[*] and multi-branch decays, less dominate

arXiv:1707.07305



Interpolation between data and theory to extract $\vec{\alpha}^\perp$

Modelling the charm loop in fits

arXiv:1612.06764

Following the notation of Ref. [40], the *CP*-averaged differential decay rate of $B^+ \to K^+\mu^+\mu^-$ decays as a function of the dimuon mass squared, $q^2 \equiv m^2_{\mu\mu}$, is given by

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\}, \quad (1)$$

where $|\boldsymbol{k}|$ is the kaon momentum in the B^+ meson rest frame.
The parameters $f_{0,+,T}$ denote the scalar, vector and tensor $B \to K$ form factors.

$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + Y(q^2),$$

Insert term into eq. above

where the term $Y(q^2)$ describes the sum of resonant and continuum hadronic states appearing in the dimuon mass spectrum. In this analysis $Y(q^2)$ is replaced by the sum of vector meson resonances j such that

If n*pi/2 term disappears in eq.1

$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2), \quad (3)$$

assumes no continuum hadronic states (e.g. no DDbar)

where η_j is the magnitude of the resonance amplitude and δ_j its phase relative to C_9.

arXiv:1903.09578v2

	All				LFUV			
1D Hyp.	Best fit	$1\,\sigma/2\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	Best fit	$1\,\sigma/\,2\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-1.02	$[-1.18, -0.85]$ $[-1.34, -0.68]$	5.8	65.1 %	-1.02	$[-1.38, -0.69]$ $[-1.80, -0.40]$	3.5	50.6 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.49	$[-0.59, -0.40]$ $[-0.69, -0.30]$	5.4	55.5 %	-0.44	$[-0.55, -0.32]$ $[-0.68, -0.21]$	4.0	74.0 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}$	-1.02	$[-1.18, -0.85]$ $[-1.33, -0.67]$	5.7	61.3 %	-1.66	$[-2.15, -1.05]$ $[-2.54, -0.47]$	3.1	35.4 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -3\mathcal{C}_{9e}^{\mathrm{NP}}$	-0.92	$[-1.08, -0.76]$ $[-1.23, -0.60]$	5.7	62.7 %	-0.76	$[-1.02, -0.52]$ $[-1.30, -0.30]$	3.5	50.8 %

Table 1. Most prominent 1D patterns of New Physics in $b \to s\mu\mu$. The $\mathrm{Pull}_{\mathrm{SM}}$ is quoted in units of standard deviation. The p-value of the SM hypothesis is 8.6% for the fit "All" and 4.5% for the fit LFUV. We have checked also the scenario with only $\mathcal{C}_{10\mu}^{\mathrm{NP}}$ but its significance in the "All" fit is only at the 4.0σ level and 3.9σ for the LFUV fit.