EFT & Heavy Flavours : an experimentalist point of view

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Outline of the lectures

1

- Introduction (context, EFT as seen from an experimentalist, LHCb)
- $B \to \ell^+\ell^-$ what do we measure and how?
- $H_b \to H_s\, \ell^+\ell^-$ what do we measure and how?

2

- Why not electrons ?
- Some ideas to move forward

$B_{s/d} \to \mu^+\mu^-$:

- clean prediction (relative precision ~ 4 – 5 %)
- clean measurement for B_s (~ 10%) ; B_d not yet measured.

☺ clear road
C_{10} constraint

$H_b \to H_s\, \mu^+\mu^-$:

- clean measurements (~ 10% on BR in various q^2 bins)
- TH predictions not very precise for the BR. Better for angular observables.
- How to mitigate/constraint the impact of non-local contributions ?

?????

$$C_i = C_i^{SM} + C_i^{NP}$$

- In the SM Wilson coefficients are real, no necessarily the case for New Physics
- Many parameters fit… reduced configurations

B→ K*μμ alone

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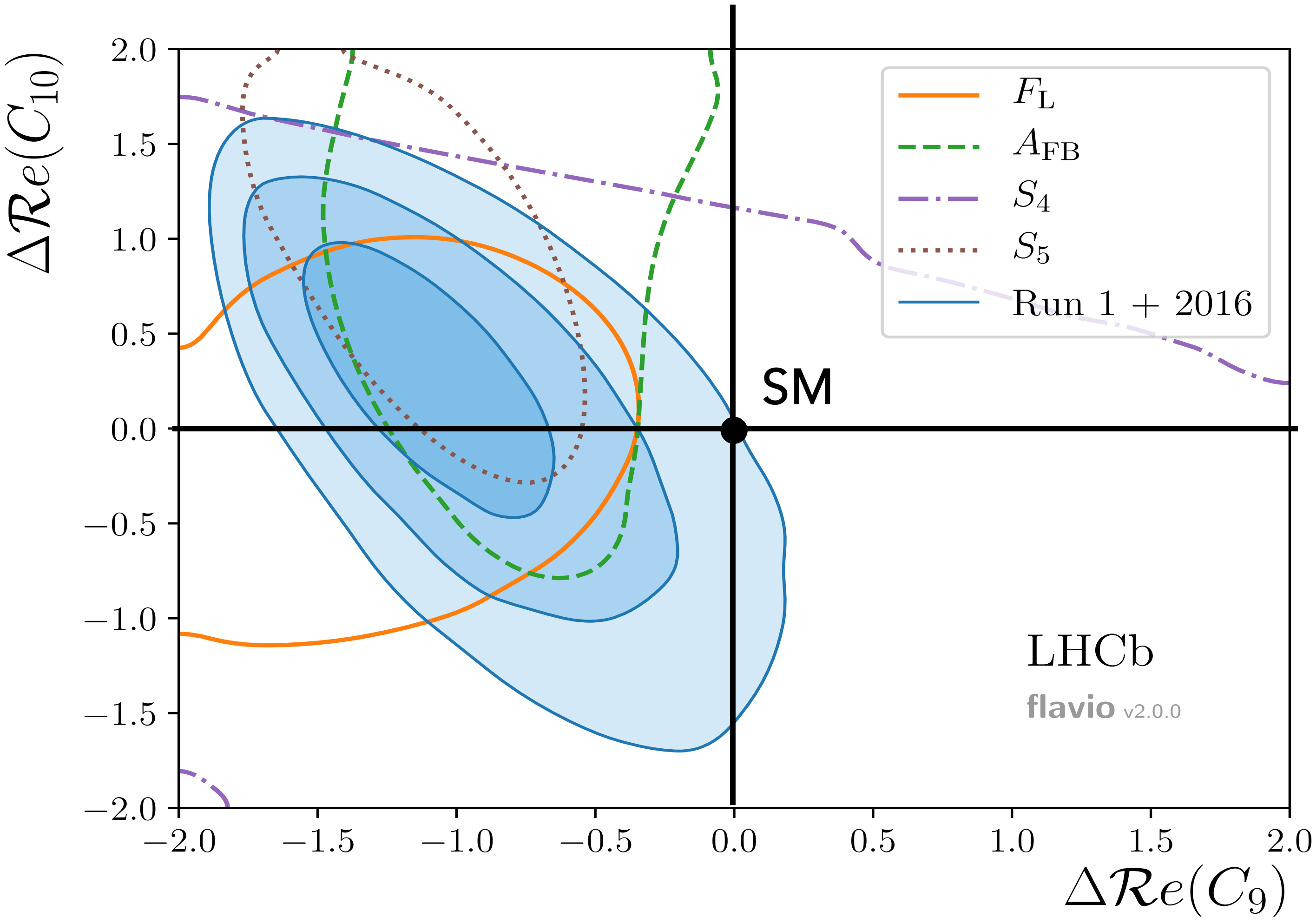
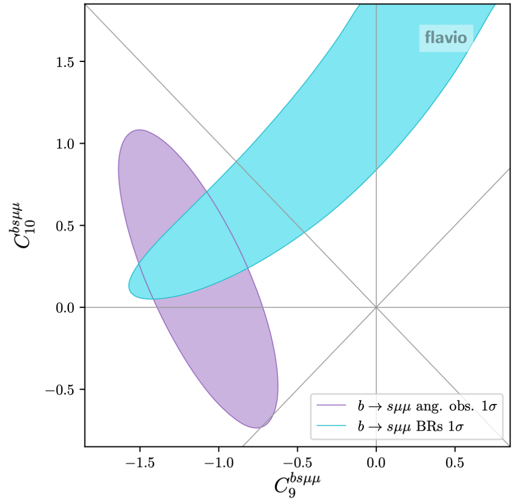
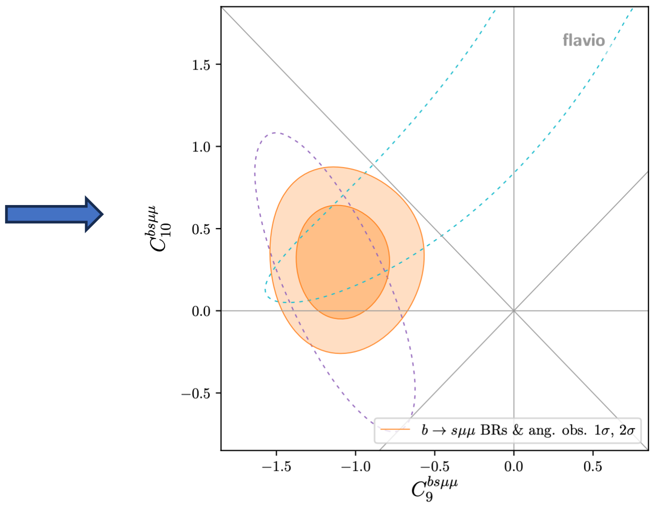
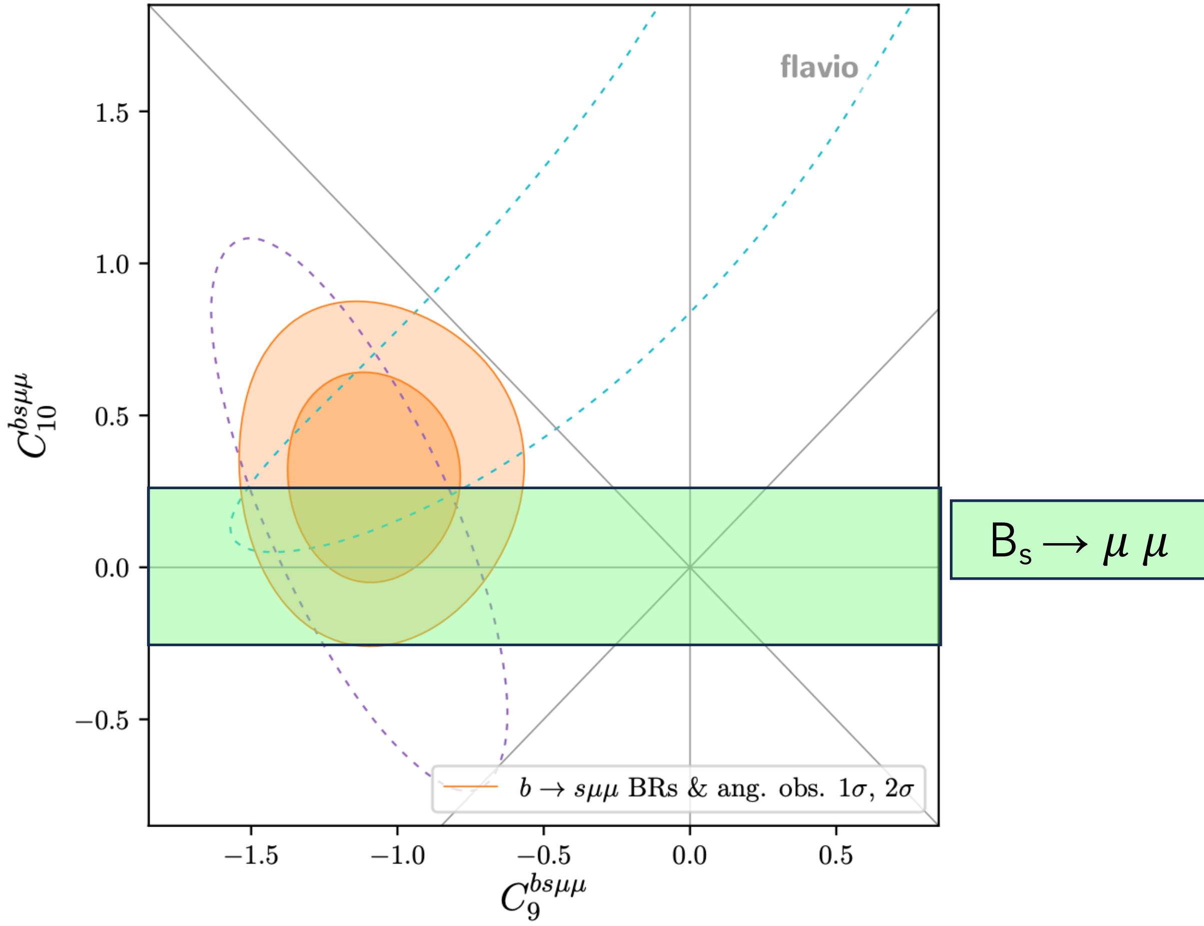


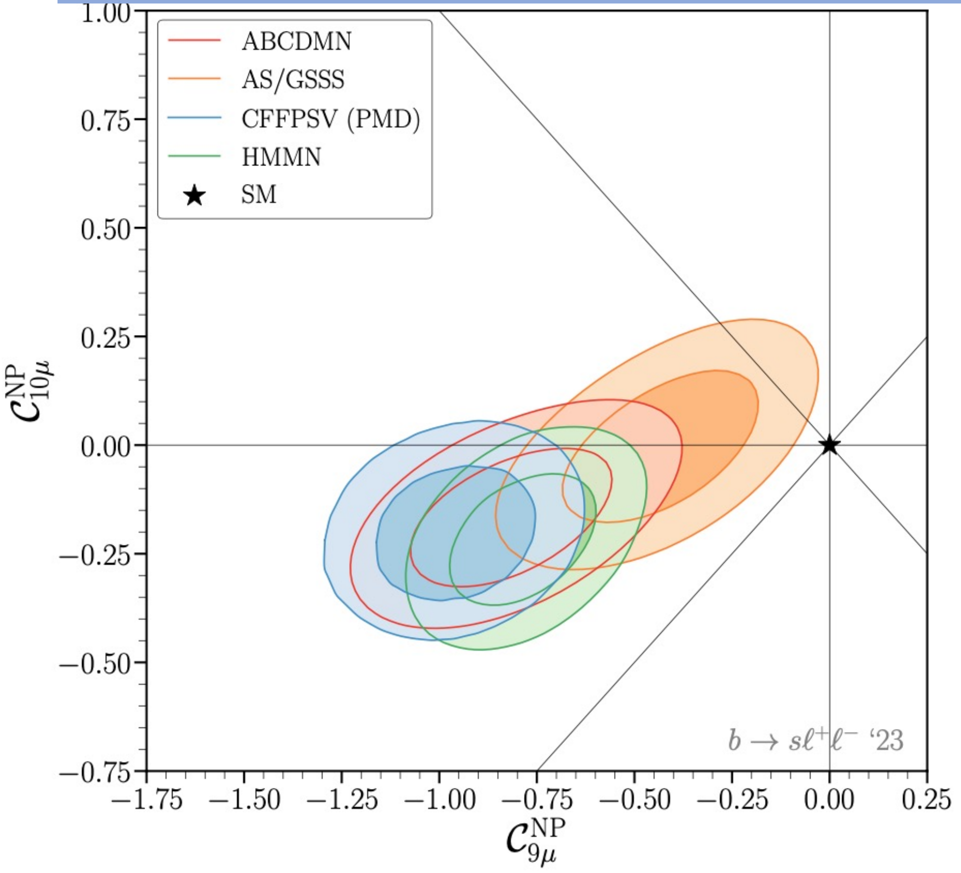




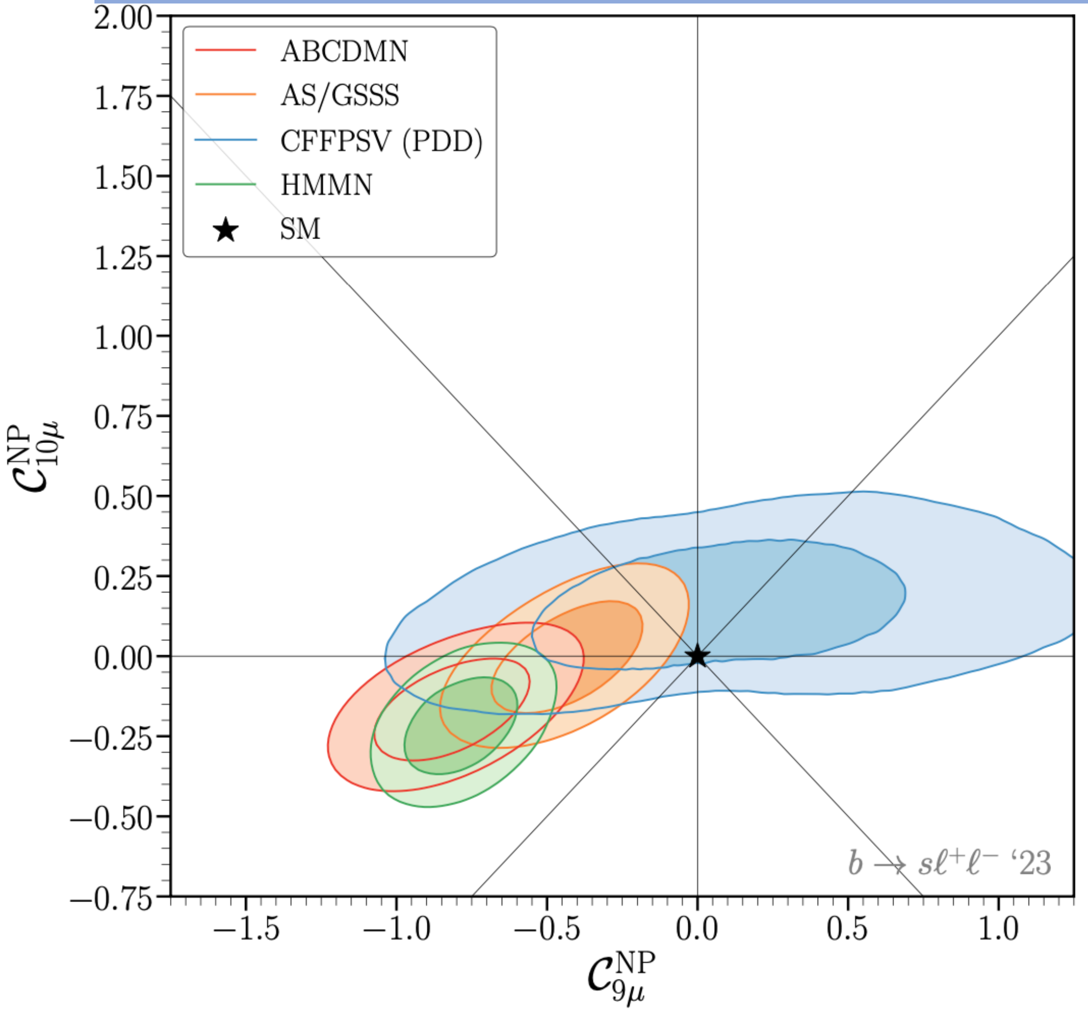
Adapted from plots from Peter Stangl La Thuile 2021



with TH input for the non-local contributions



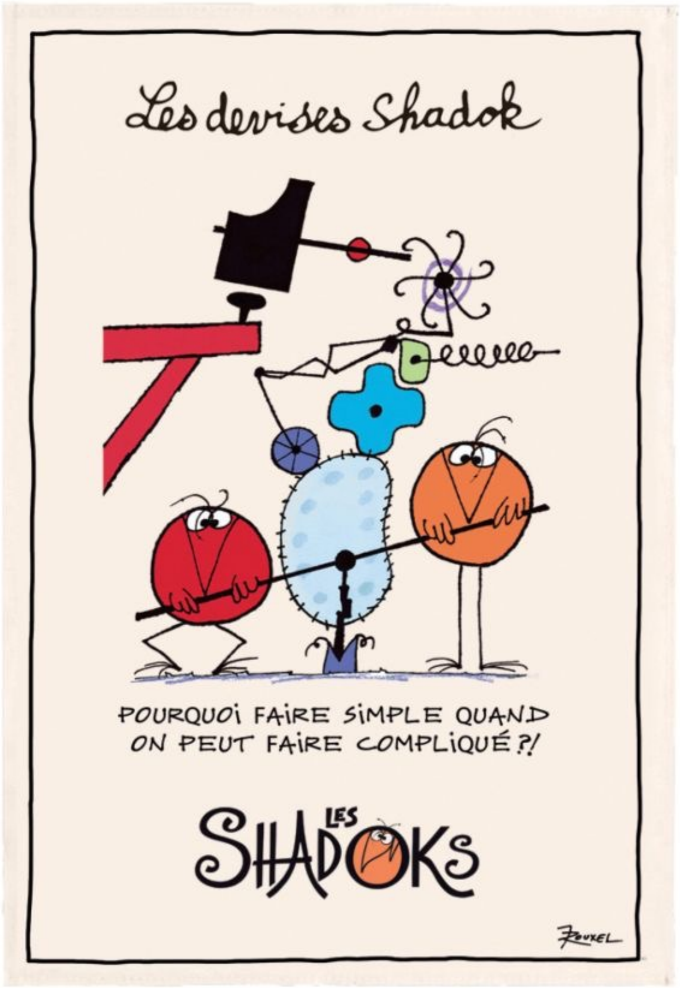
No TH input for the non-local contributions

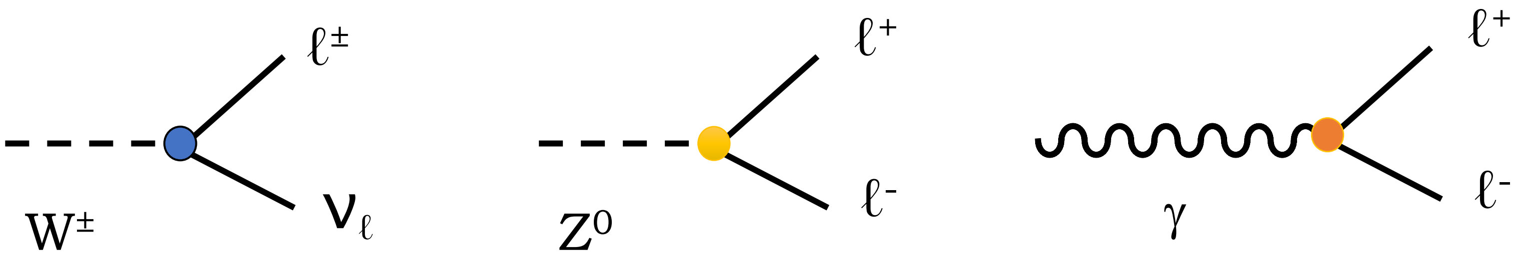


- ABCDMN (M. Algueró, A. Biswas, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code arXiv:2304.07330
- AS / GSSS (W. Altmannshofer, P. Stangl / A. Greljo, J. Salko, A. Smolkovic, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` arXiv:2212.10497.
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code `HEPfit` arXiv:2212.10516
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code `SuperIso` arXiv:23xx.xxxxx

From B. Capdevila
FPCP 2023

Why not electrons ?

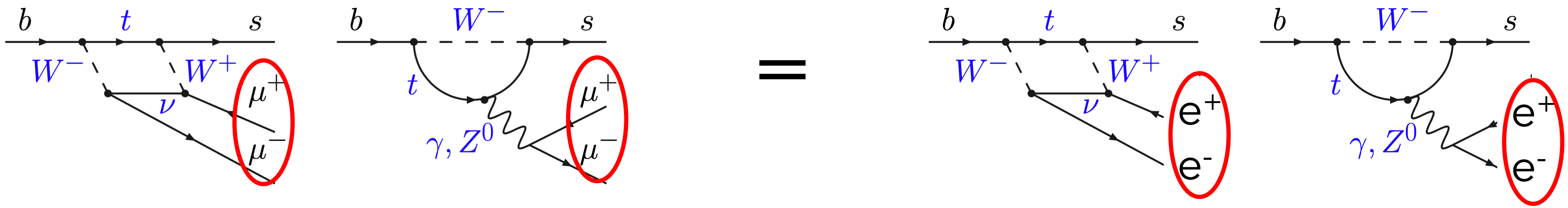




ℓ= e, μ or τ

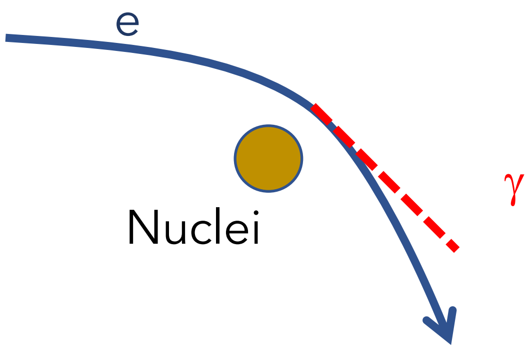
Only difference : kinematics (lepton masses)

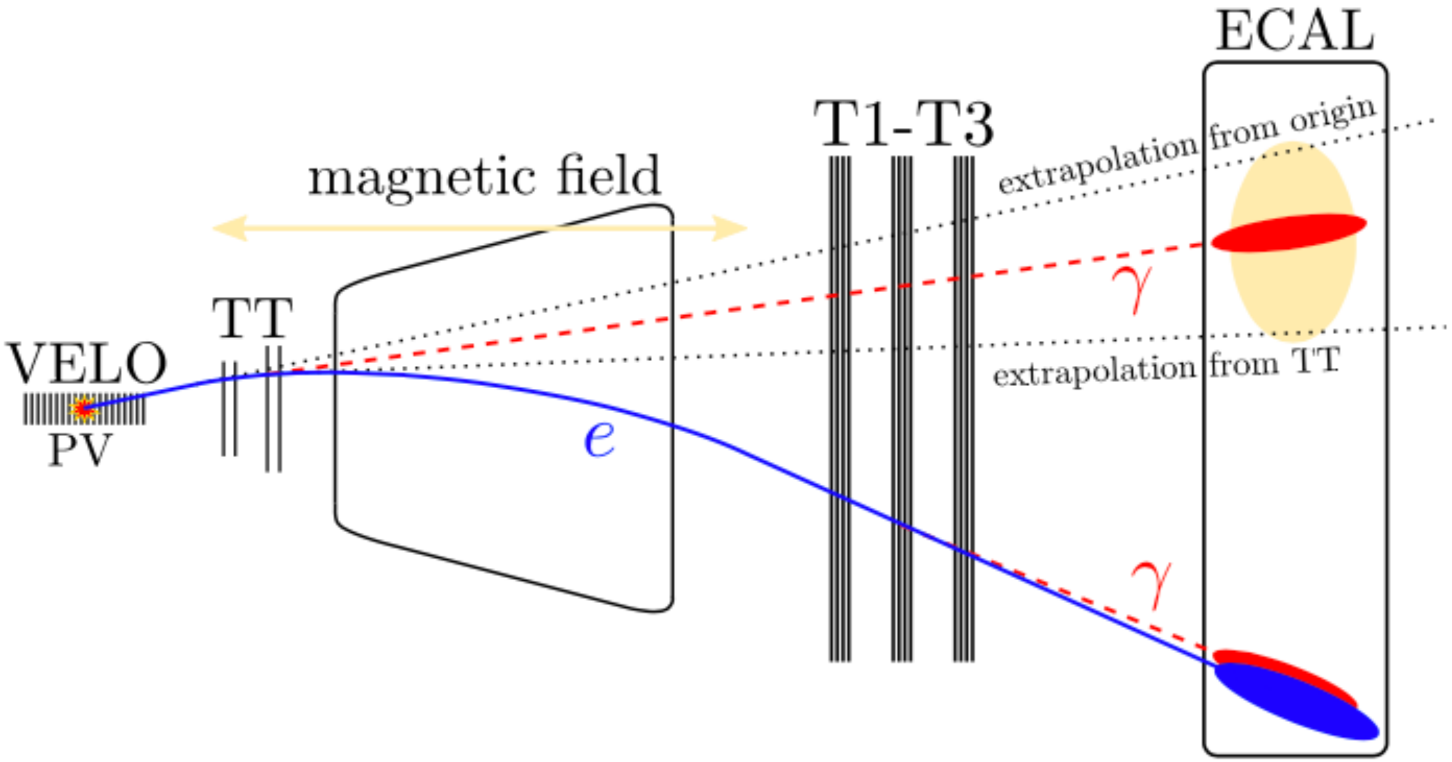
SM



Let’s use the electrons and double our statistics !

Electrons emit Bremsstrahlung





Before the magnet

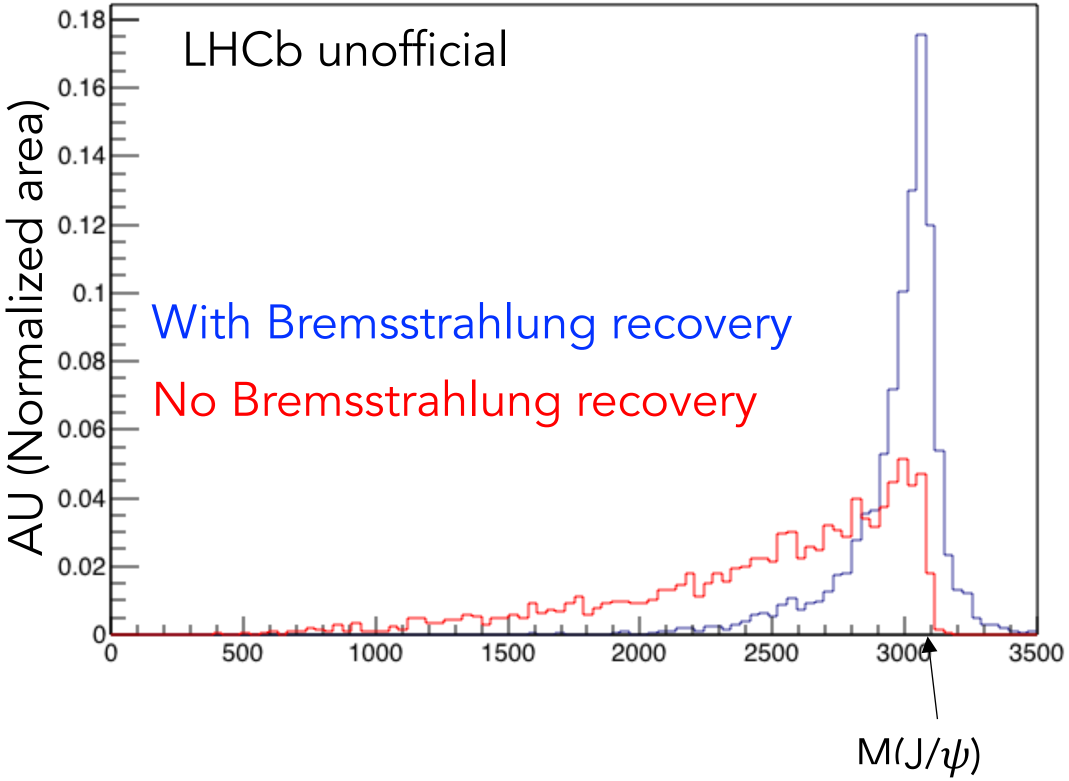
- electron can be swept out (=lost !)
- kinematics are "wrong"

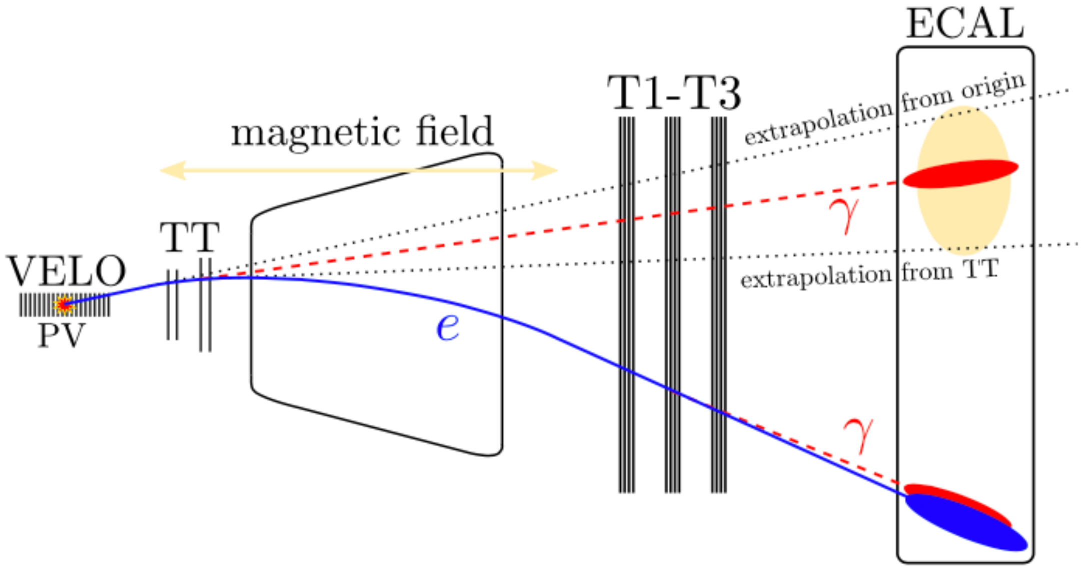
After the magnet

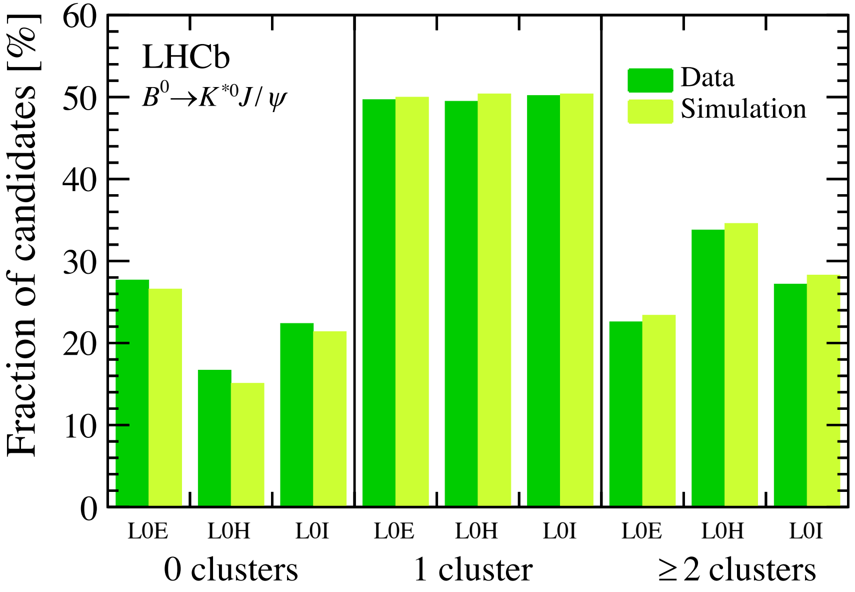
- not an issue

Energy loss ∝ E_e
Energy loss ∝ material

In both cases E/p is correct

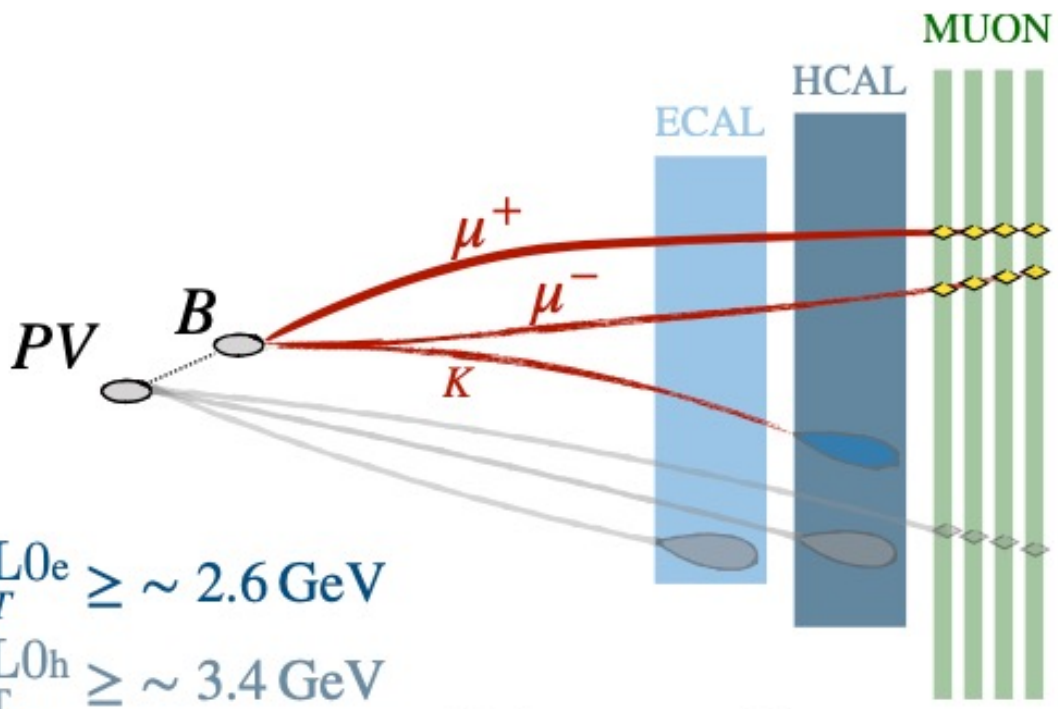






Bremsstrahlung recovery algorithm is ~ 50% efficient
Well described in simulation

Hardware trigger is very different for electrons and muons



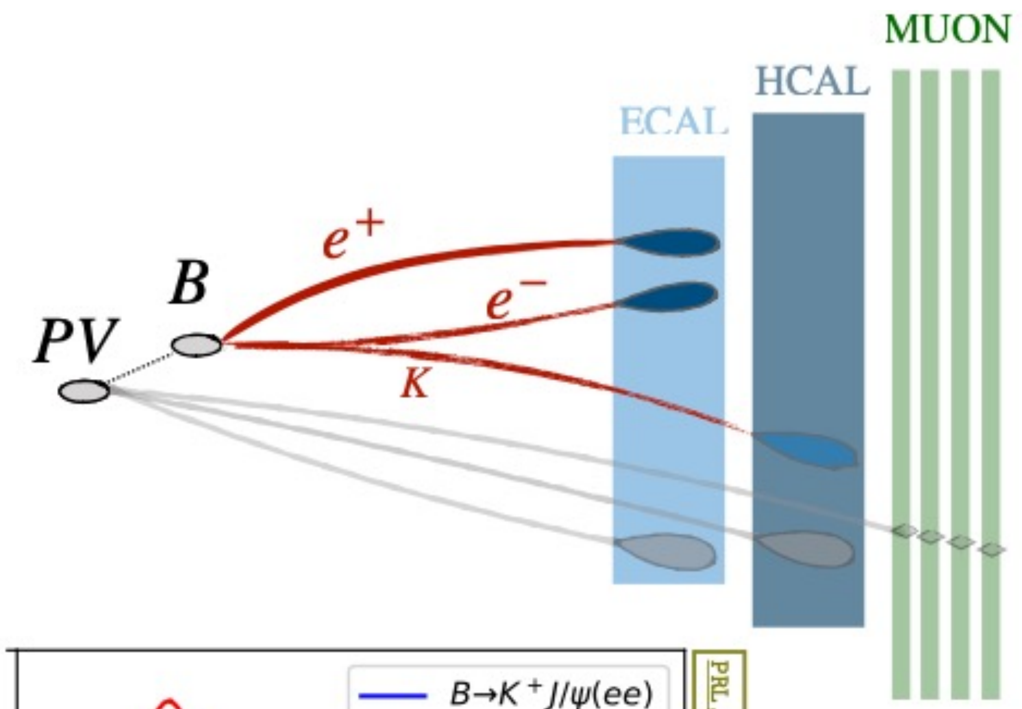
$E_T^{L0e} \geq \sim 2.6\,\mathrm{GeV}$

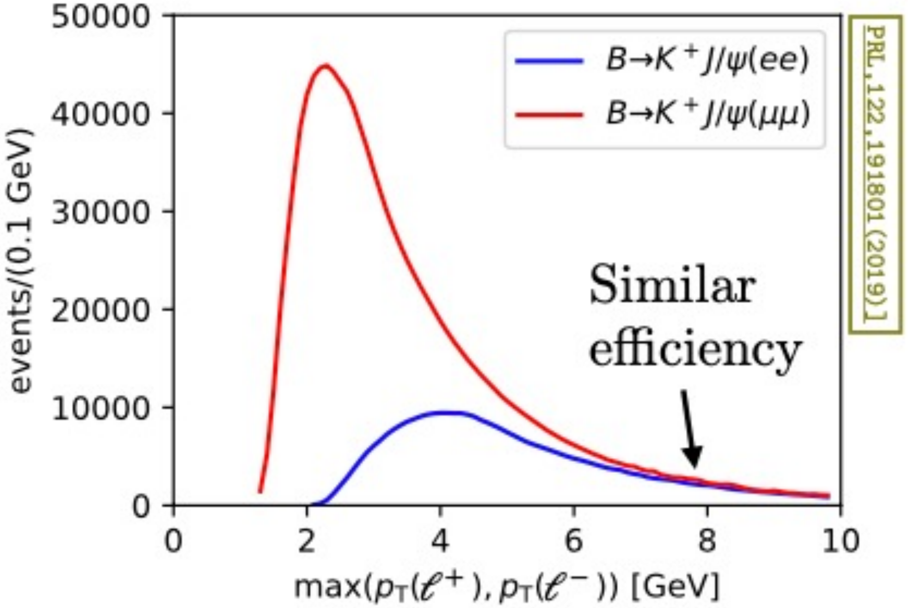
$E_T^{L0h} \geq \sim 3.4\,\mathrm{GeV}$

$p_T^{L0\mu} \geq \sim 1.4\,\mathrm{GeV}$

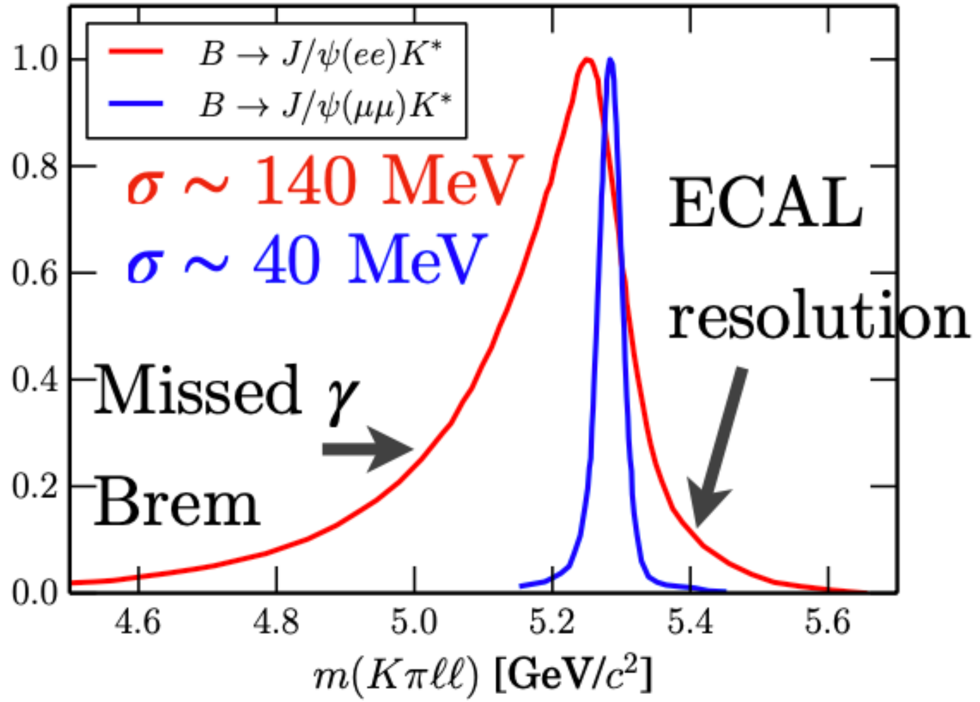
Selection effect from L0e vs L0μ

$\sim \frac{1}{3}$

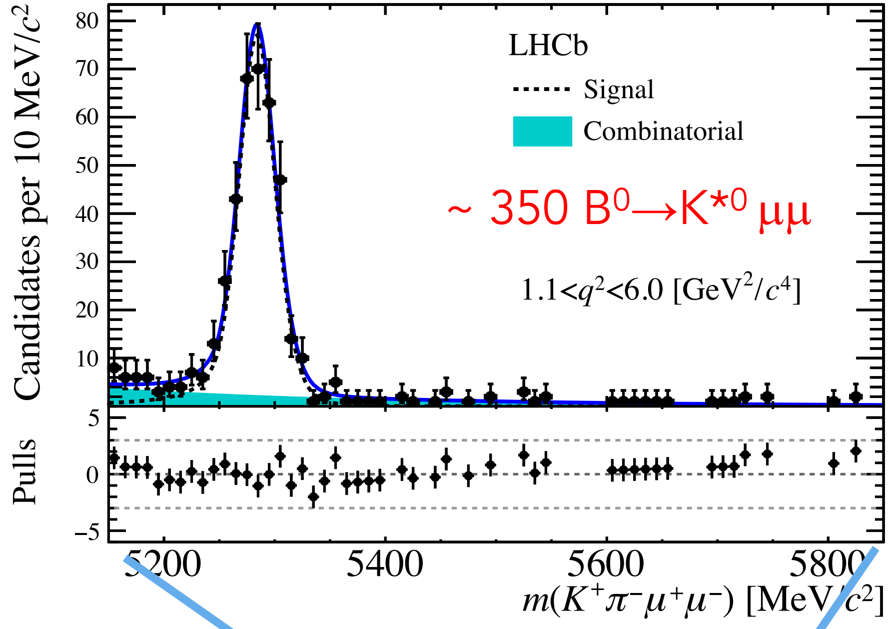


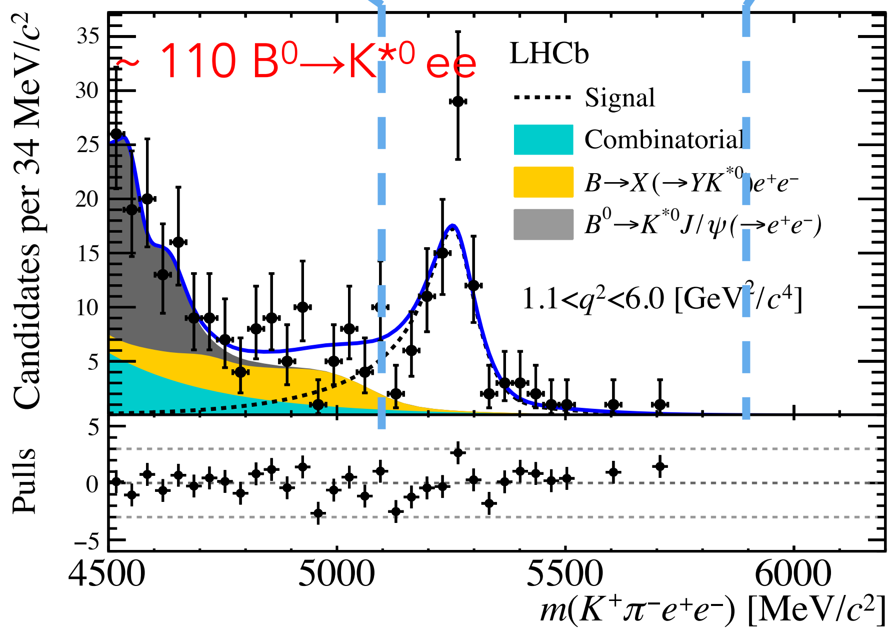


Slide borrowed from Renato Quagliani



JHEP 08 (2017) 055

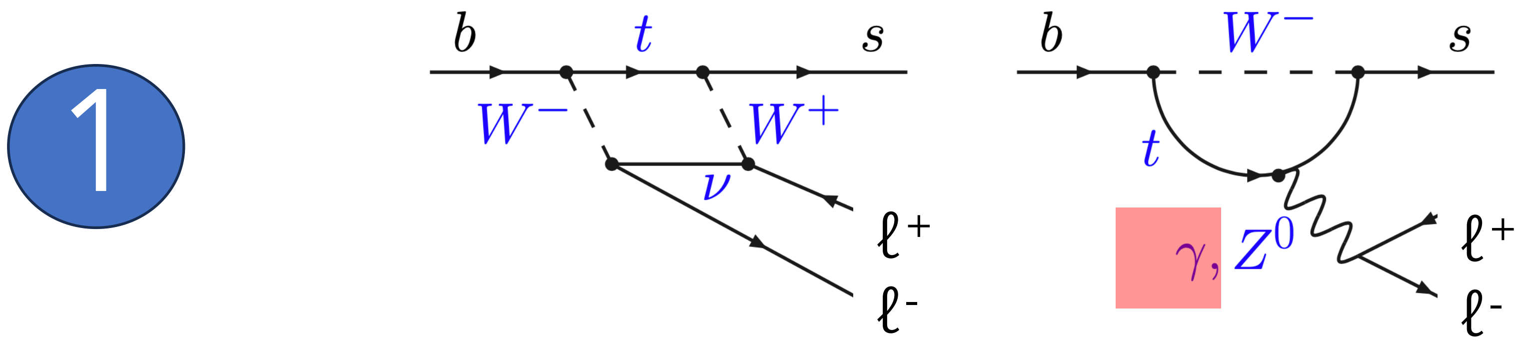




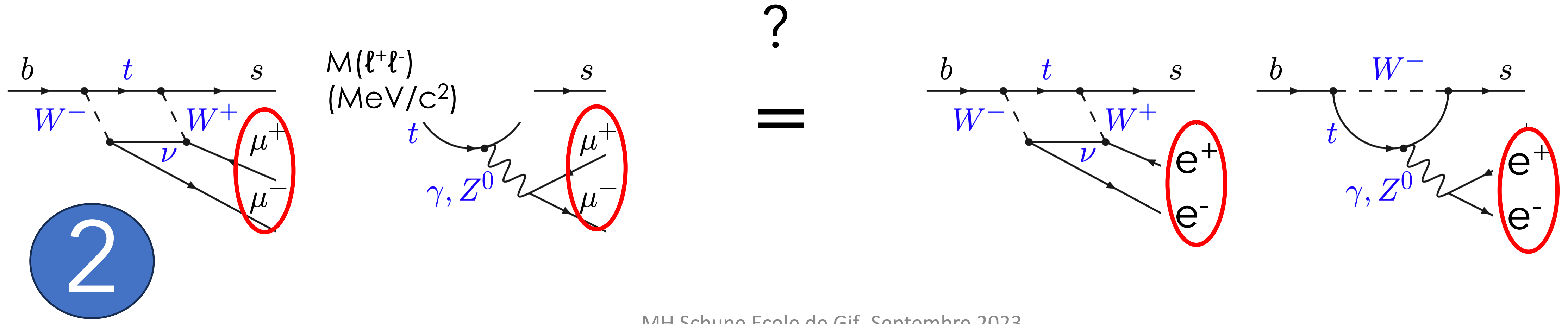
Using modes with electrons to increase the statistics is not the best idea

Use electrons for:

- measurements which **cannot** be done with muons



- search for New Physics



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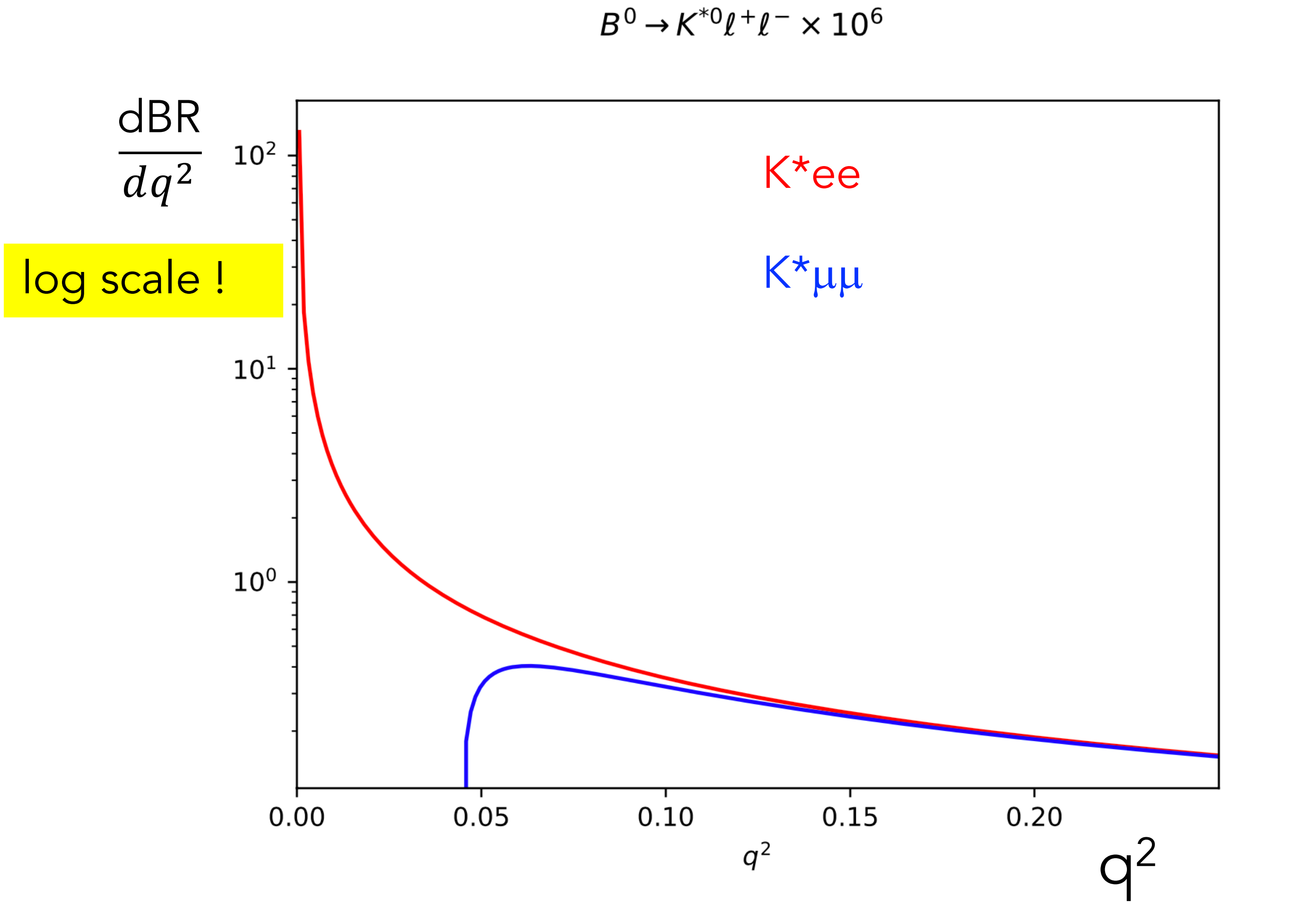

Electrons should give us access to C_7 and C'_7 Wilson coefficients (photon pole) in a privileged manner

Going back to

$s=q^2$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} =$$

$$\frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$

$$I_1 = \left\{\frac{3}{4}[|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)]\left(1 - \frac{4m_l^2}{3s}\right) + \frac{4m_l^2}{s}\mathrm{Re}(A_{\perp L}A_{\perp R}^* + A_{\parallel L}A_{\parallel R}^*)\right\}\sin^2\theta_{K^*} + \left\{(|A_{0L}|^2 + |A_{0R}|^2) + \frac{4m_l^2}{s}[|A_t|^2 + 2\mathrm{Re}(A_{0L}A_{0R}^*)]\right\}\cos^2\theta_{K^*}, \quad \text{(A.6a)}$$

$$I_2 = \left(1 - \frac{4m_l^2}{s}\right)\left[\frac{1}{4}(|A_{\perp L}|^2 + |A_{\parallel L}|^2)\sin^2\theta_{K^*} - |A_{0L}|^2\cos^2\theta_{K^*} + (L \to R)\right], \quad \text{(A.6b)}$$

$$I_3 = \frac{1}{2}\left(1 - \frac{4m_l^2}{s}\right)\left[(|A_{\perp L}|^2 - |A_{\parallel L}|^2)\sin^2\theta_{K^*} + (L \to R)\right], \quad \text{(A.6c)}$$

$$I_4 = \frac{1}{\sqrt{2}}\left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Re}(A_{0L}A_{\parallel L}^*)\sin 2\theta_{K^*} + (L \to R)\right], \quad \text{(A.6d)}$$

$$I_5 = \sqrt{2}\left(1 - \frac{4m_l^2}{s}\right)^{1/2}\left[\mathrm{Re}(A_{0L}A_{\perp L}^*)\sin 2\theta_{K^*} - (L \to R)\right], \quad \text{(A.6e)}$$

$$I_6 = 2\left(1 - \frac{4m_l^2}{s}\right)^{1/2}\left[\mathrm{Re}(A_{\parallel L}A_{\perp L}^*)\sin^2\theta_{K^*} - (L \to R)\right], \quad \text{(A.6f)}$$

$$I_7 = \sqrt{2}\left(1 - \frac{4m_l^2}{s}\right)^{1/2}\left[\mathrm{Im}(A_{0L}A_{\parallel L}^*)\sin 2\theta_{K^*} - (L \to R)\right], \quad \text{(A.6g)}$$

$$I_8 = \frac{1}{\sqrt{2}}\left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Im}(A_{0L}A_{\perp L}^*)\sin 2\theta_{K^*} + (L \to R)\right], \quad \text{(A.6h)}$$

$$I_9 = \left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Im}(A_{\parallel L}^*A_{\perp L})\sin^2\theta_{K^*} + (L \to R)\right]. \quad \text{(A.6i)}$$

Going back to

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$$I_1 = \left\{\frac{3}{4}[|A_{\perp L}|^2 + |A_{\| L}|^2 + (L \to R)]\left(1 - \frac{4m_l^2}{3s}\right) + \frac{4m_l^2}{s}\mathrm{Re}(A_{\perp L}A_{\perp R}^* + A_{\| L}A_{\| R}^*)\right\}\sin^2\theta_{K^*} + \left\{(|A_{0L}|^2 + |A_{0R}|^2) + \frac{4m_l^2}{s}[|A_l|^2 + 2\mathrm{Re}(A_{0L}A_{0R}^*)]\right\}\cos^2\theta_{K^*}, \quad \text{(A.6a)}$$

$$I_2 = \left(1 - \frac{4m_l^2}{s}\right)\left[\frac{1}{4}(|A_{\perp L}|^2 + |A_{\| L}|^2)\sin^2\theta_{K^*} - |A_{0L}|^2\cos^2\theta_{K^*} + (L \to R)\right], \quad \text{(A.6b)}$$

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$$I_4 = \frac{1}{\sqrt{2}}\left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Re}(A_{0L}A_{\| L}^*)\sin 2\theta_{K^*} + (L \to R)\right], \quad \text{(A.6d)}$$

$$I_5 = \sqrt{2}\left(1 - \frac{4m_l^2}{s}\right)^{1/2}\left[\mathrm{Re}(A_{0L}A_{\perp L}^*)\sin 2\theta_{K^*} - (L \to R)\right], \quad \text{(A.6e)}$$

$$I_6 = 2\left(1 - \frac{4m_l^2}{s}\right)^{1/2}\left[\mathrm{Re}(A_{\| L}A_{\perp L}^*)\sin^2\theta_{K^*} - (L \to R)\right], \quad \text{(A.6f)}$$

$$I_7 = \sqrt{2}\left(1 - \frac{4m_l^2}{s}\right)^{1/2}\left[\mathrm{Im}(A_{0L}A_{\| L}^*)\sin 2\theta_{K^*} - (L \to R)\right], \quad \text{(A.6g)}$$

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$4m_l^2 << q^2$

At low q^2 (FF simplification)

$$\hat{s} = \frac{q^2}{m_B^2}$$

$$A_{\perp L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\text{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} + C_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*}),$$

$$A_{\parallel L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\text{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*}),$$

$$A_{0L,R} = -\frac{N m_B}{2\hat{m}_{K^*}\sqrt{\hat{s}}} (1-\hat{s})^2 \left[(C_9^{\text{eff}} \mp C_{10}) + 2\hat{m}_b (C_7^{\text{eff}} - C_7^{\text{eff}\prime}) \right] \xi_\parallel(E_{K^*}),$$

Definition of observables:

$$F_L\ (q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

"clean"

$$A_T^{(\text{re})}(q^2) = \frac{2\,\text{Re}[A_\parallel^L(q^2) A_\perp^{L*}(q^2) - A_\parallel^R(q^2) A_\perp^{R*}(q^2)]}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$$

$$A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2 - |A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$$

$$A_T^{(\text{im})}(q^2) = \frac{2\,\text{Im}[A_\parallel^L(q^2) A_\perp^{L*}(q^2) + A_\parallel^R(q^2) A_\perp^{R*}(q^2)]}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2},$$

At low q² (FF simplification)

$$\hat{s} = \frac{q^2}{m_B^2}$$

$$q^2 \longrightarrow 0$$

$$A_{\perp L,R} = \sqrt{2} N m_B (1-\cancel{\hat{s}}) \left[\cancel{(C_9^{\mathrm{eff}} \mp C_{10})} + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\mathrm{eff}} + C_7^{\mathrm{eff}\prime}) \right] \xi_\perp(E_{K^*}),$$

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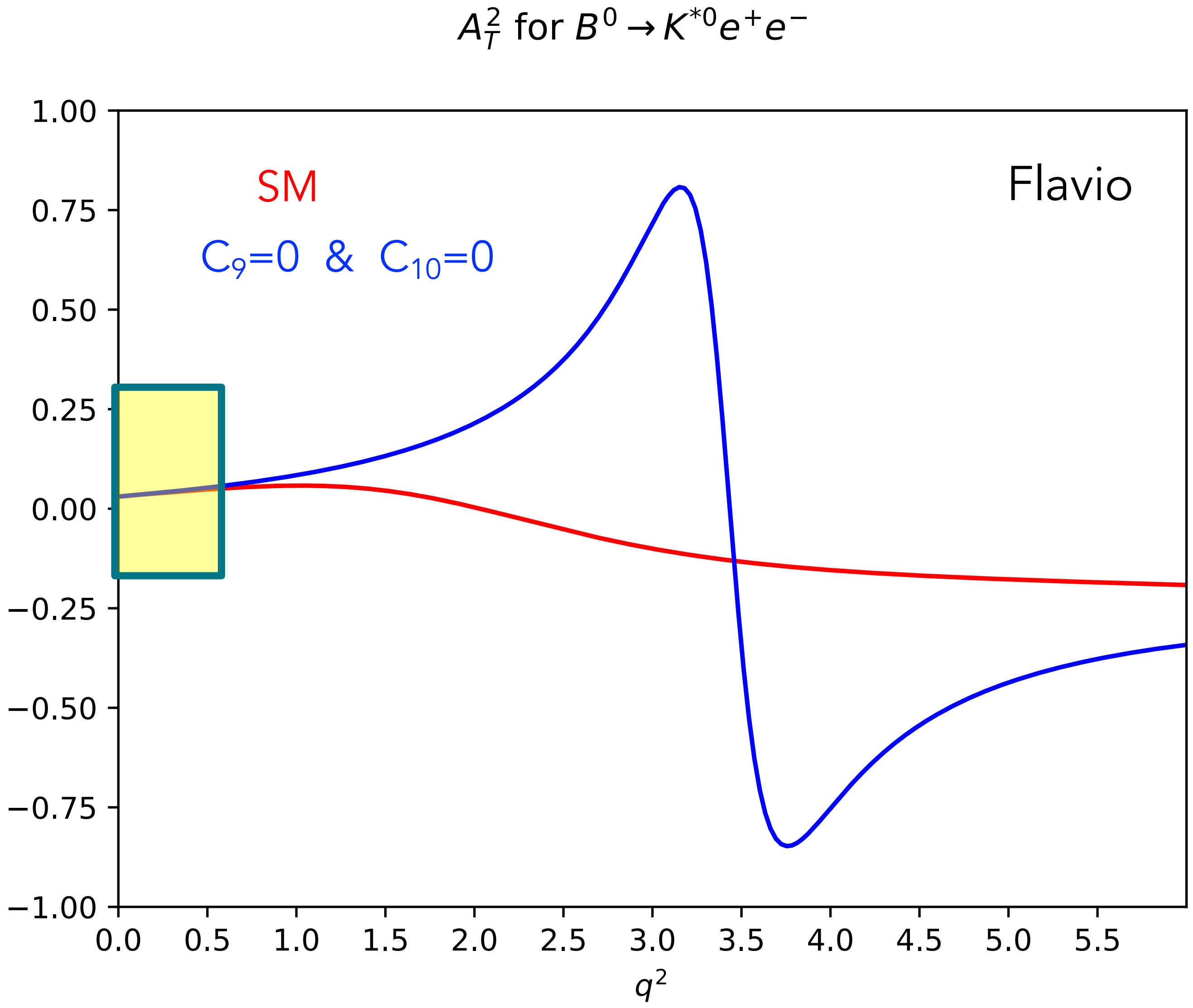
$$A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2 - |A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$$

sensitive to the photon polarisation

$$A_T^{(\mathrm{im})}(q^2) = \frac{2\,\mathrm{Im}[A_\parallel^L(q^2) A_\perp^{L*}(q^2) + A_\parallel^R(q^2) A_\perp^{R*}(q^2)]}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2},$$



$$A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2 - |A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$$

$$I_1 = \left\{\frac{3}{4}[|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)]\left(1 - \frac{4m_l^2}{3s}\right) + \frac{4m_l^2}{s}\mathrm{Re}(A_{\perp L}A_{\perp R}^* + A_{\parallel L}A_{\parallel R}^*)\right\}\sin^2\theta_{K^*}$$
$$+ \left\{(|A_{0L}|^2 + |A_{0R}|^2) + \frac{4m_l^2}{s}[|A_t|^2 + 2\mathrm{Re}(A_{0L}A_{0R}^*)]\right\}\cos^2\theta_{K^*},$$

$$I_2 = \left(1 - \frac{4m_l^2}{s}\right)\left[\frac{1}{4}(|A_{\perp L}|^2 + |A_{\parallel L}|^2)\sin^2\theta_{K^*} - |A_{0L}|^2\cos^2\theta_{K^*} + (L \to R)\right],$$

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$$I_4 = \frac{1}{\sqrt{2}}\left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Re}(A_{0L}A_{\parallel L}^*)\sin 2\theta_{K^*} + (L \to R)\right],$$

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$$I_8 = \frac{1}{\sqrt{2}}\left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Im}(A_{0L}A_{\perp L}^*)\sin 2\theta_{K^*} + (L \to R)\right],$$

$$I_9 = \left(1 - \frac{4m_l^2}{s}\right)\left[\mathrm{Im}(A_{\parallel L}^*A_{\perp L})\sin^2\theta_{K^*} + (L \to R)\right].$$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$

$+$

$$\tilde{\phi} \equiv \begin{cases} \phi \text{ if } \phi \geq 0 \\ \phi + \pi \text{ if } \phi < 0 \end{cases}$$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + \cancel{I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi} + \cancel{I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi} + I_6 \sin^2\theta_K \cos\theta_\ell + \cancel{I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi} + \cancel{I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi} + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$

Important simplification of the formulae without loss of precision on what we are interested in: the photon polarisation (C_7 and C'_7)

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell$$
$$+(1-F_{\mathrm{L}})A_T^{Re}\sin^2\theta_K\cos\theta_\ell$$
$$+\tfrac{1}{2}(1-F_{\mathrm{L}})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi}$$
$$+\tfrac{1}{2}(1-F_{\mathrm{L}})A_T^{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big]\,.$$

$$F_L\,(q^2) = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$

$$A_T^{(\mathrm{re})}(q^2) = \frac{2\,\mathrm{Re}[A_\parallel^L(q^2)A_\perp^{L*}(q^2) - A_\parallel^R(q^2)A_\perp^{R*}(q^2)]}{|A_\perp(q^2)|^2+|A_\parallel(q^2)|^2}$$

$$A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2-|A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2+|A_\parallel(q^2)|^2}$$

$$A_T^{(\mathrm{im})}(q^2) = \frac{2\,\mathrm{Im}[A_\parallel^L(q^2)A_\perp^{L*}(q^2) + A_\parallel^R(q^2)A_\perp^{R*}(q^2)]}{|A_\perp(q^2)|^2+|A_\parallel(q^2)|^2},$$

$$A_T^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e\left(\mathcal{C}_7\mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}$$

$$A_T^{Im}(q^2\to 0) = \frac{2\mathcal{I}m\left(\mathcal{C}_7\mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}$$

They vanish for purely left-handed polarisation

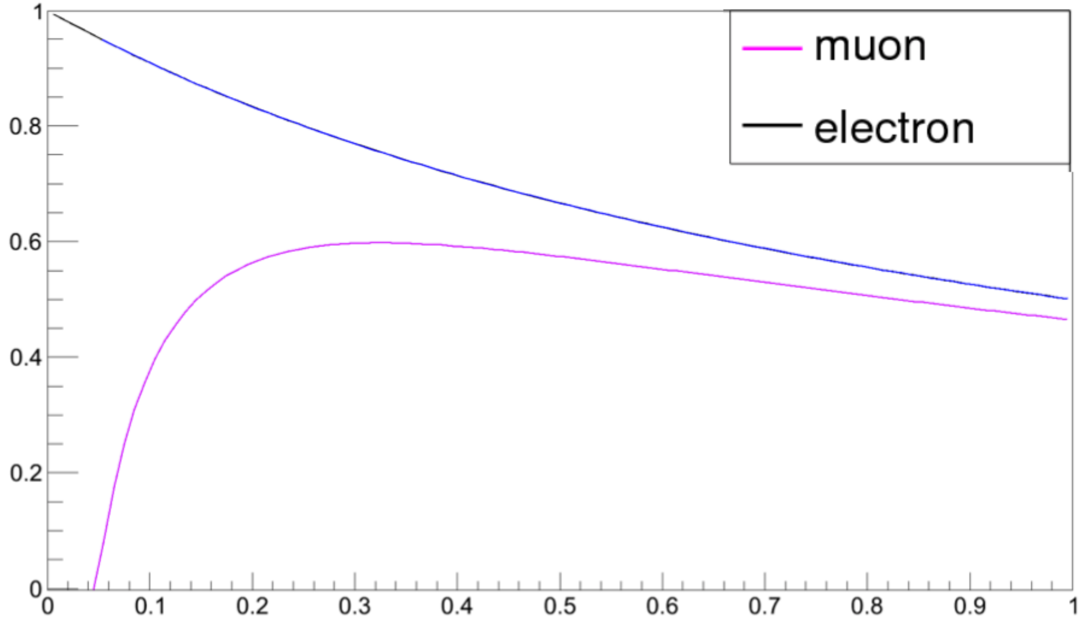
Beyond the yields, the precision on A_T^2 and A_T^{Im} is driven by $(1-F_L)$

$$
\begin{aligned}
\frac{9}{16\pi}\Big[&\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K \\
&+\tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell - F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell \\
&+(1-F_{\rm L})A_T^{Re}\sin^2\theta_K\cos\theta_\ell \\
&+\tfrac{1}{2}(1-F_{\rm L})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} \\
&+\tfrac{1}{2}(1-F_{\rm L})A_T^{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big].
\end{aligned}
$$

$$(1-F_L)$$

$$(1-F_L)\frac{1-x}{1+\frac{x}{2}}$$

$$x = \frac{4m_\ell^2}{q^2}$$



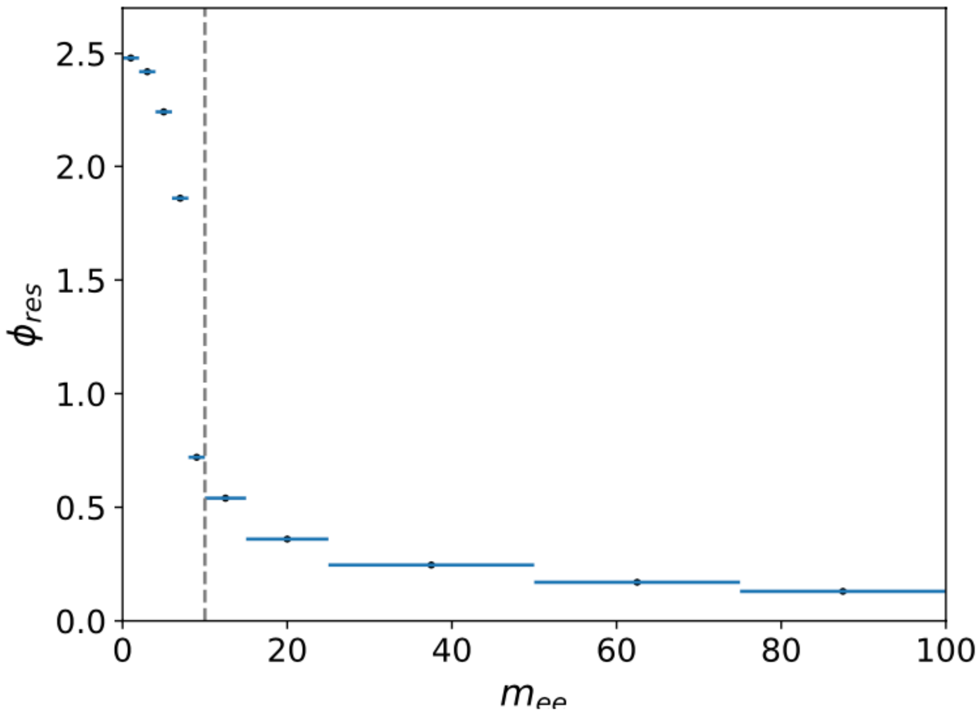
$q^2=M(\ell^+\ell^-)^2$ (GeV^2)

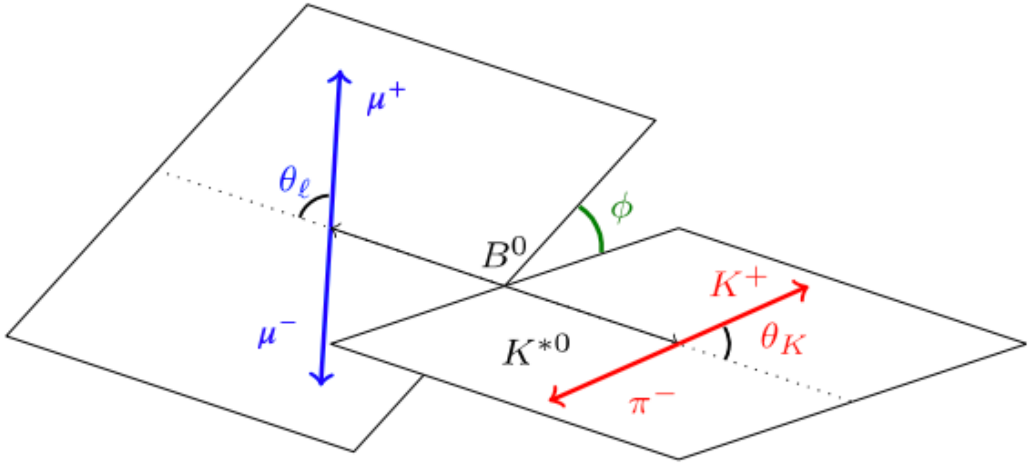
Given the experimental challenges, going above 0.5 GeV^2 with the electrons channel is not meaningful.

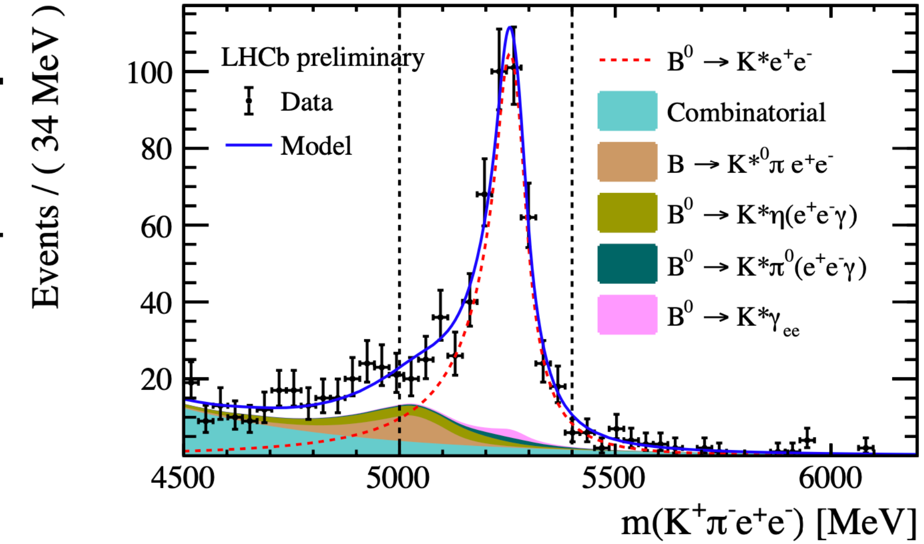
Lower Boundary In principle, can go to the threshold $m_{(ee)} = 2m_e \sim 1\text{MeV}/c^2$

→ Angle between leptons gets very small
→ Bad resolution on ϕ
→ Worse measurement of observables of interest

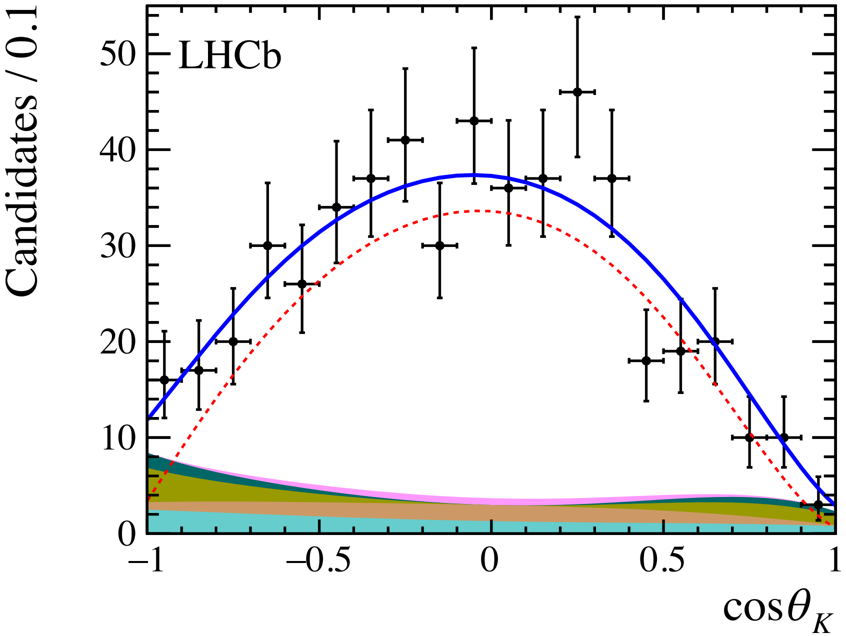
→ Cut at 10 MeV serves as a veto to converted γ



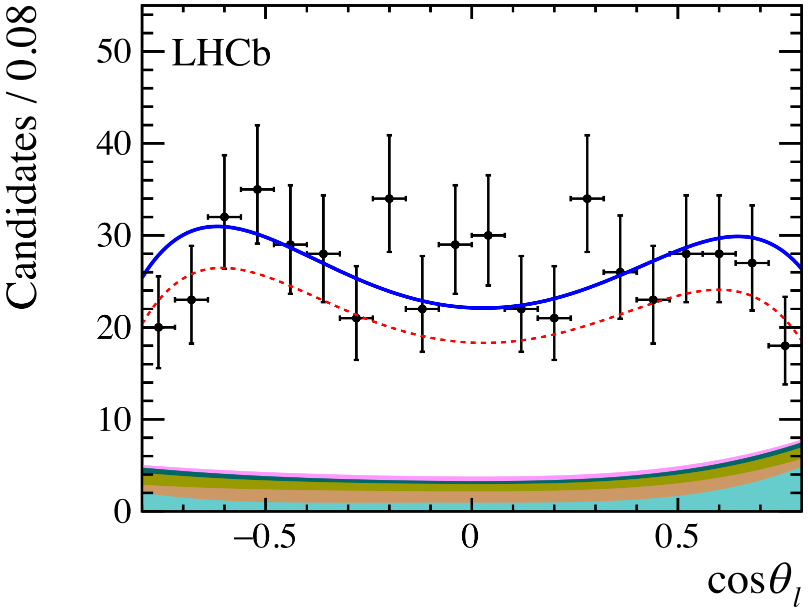




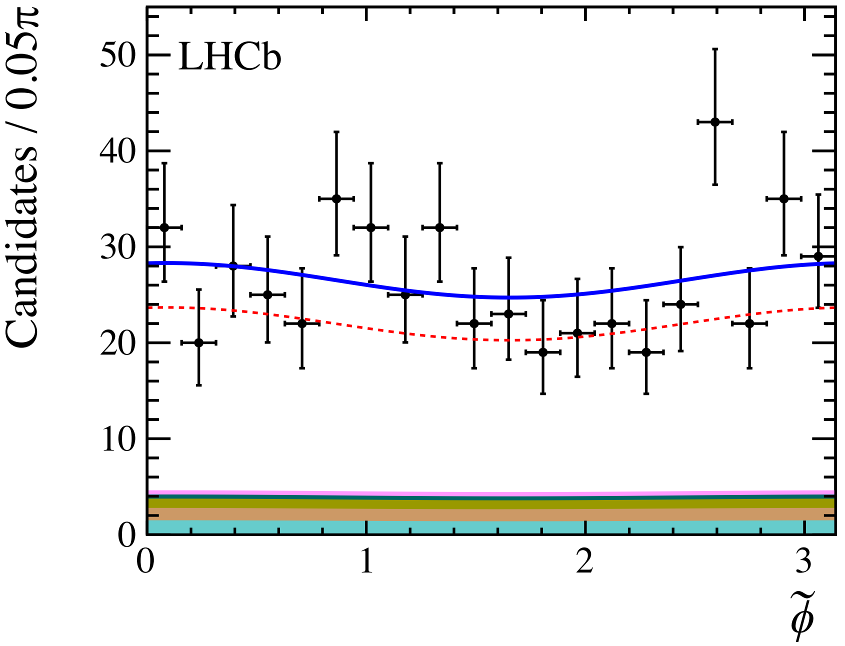
LHCb preliminary
Data
Model
$B^0 \to K^*e^+e^-$
Combinatorial
$B \to K^{*0}\pi e^+e^-$
$B^0 \to K^*\eta(e^+e^-\gamma)$
$B^0 \to K^*\pi^0(e^+e^-\gamma)$
$B^0 \to K^*\gamma_{ee}$
Events / (34 MeV)
$m(K^+\pi^-e^+e^-)$ [MeV]



LHCb
Candidates / 0.1
$\cos\theta_K$



LHCb
Candidates / 0.08
$\cos\theta_l$



LHCb
Candidates / 0.05π
$\tilde{\phi}$

$$F_{\mathrm{L}} = 0.044 \pm 0.026 \pm 0.014,$$
$$A_{\mathrm{T}}^{\mathrm{Re}} = -0.06 \pm 0.08 \pm 0.02,$$
$$A_{\mathrm{T}}^{(2)} = +0.11 \pm 0.10 \pm 0.02,$$
$$A_{\mathrm{T}}^{\mathrm{Im}} = +0.02 \pm 0.10 \pm 0.01,$$

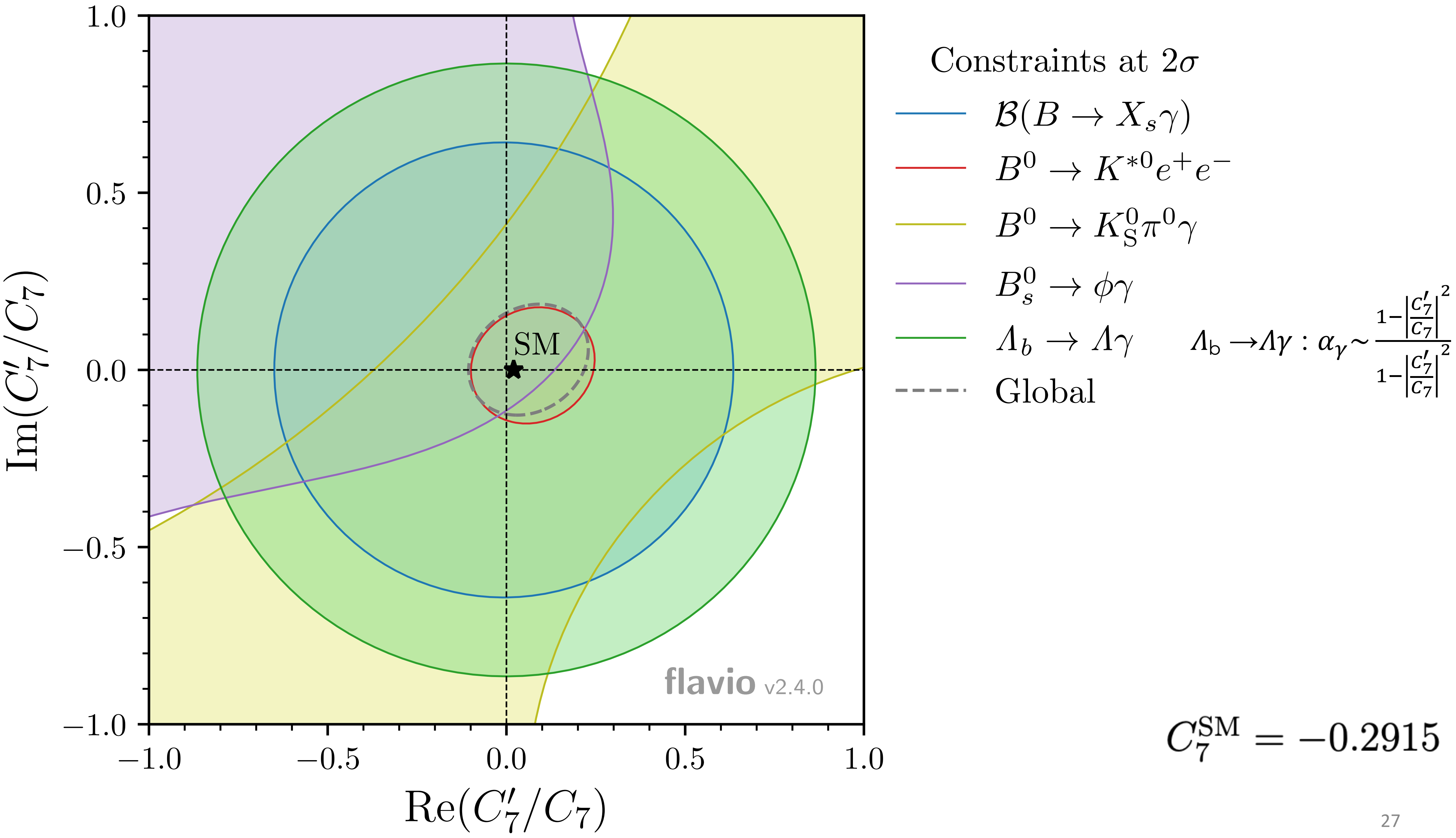
$$F_{\mathrm{L}}(\mathrm{SM}) = 0.051 \pm 0.013,$$
$$A_{\mathrm{T}}^{\mathrm{Re}}(\mathrm{SM}) = -0.0001 \pm 0.0004,$$
$$A_{\mathrm{T}}^{(2)}(\mathrm{SM}) = 0.033 \pm 0.020,$$
$$A_{\mathrm{T}}^{\mathrm{Im}}(\mathrm{SM}) = -0.00012 \pm 0.00034.$$

In good agreement with the SM predictions

$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e\left(\mathcal{C}_7\mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{Im}(q^2 \to 0) = \frac{2\mathcal{I}m\left(\mathcal{C}_7\mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

5% precision on the photon polarization in b→sγ transitions. Dominated by statistical uncertainties


Constraints at 2σ
$\mathcal{B}(B \to X_s\gamma)$
$B^0 \to K^{*0}e^+e^-$
$B^0 \to K^0_S\pi^0\gamma$
$B^0_s \to \phi\gamma$
$\Lambda_b \to \Lambda\gamma$
Global
SM
flavio v2.4.0
$\mathrm{Re}(C'_7/C_7)$
$\mathrm{Im}(C'_7/C_7)$
$\Lambda_b \to \Lambda\gamma : \alpha_\gamma \sim \frac{1-\left|\frac{C'_7}{C_7}\right|^2}{1-\left|\frac{C'_7}{C_7}\right|^2}$
$C_7^{SM} = -0.2915$

2

Branching Fractions

Angular observables

Lepton Flavour Universality observables:
Branching Fractions ratios
angular observables ratios

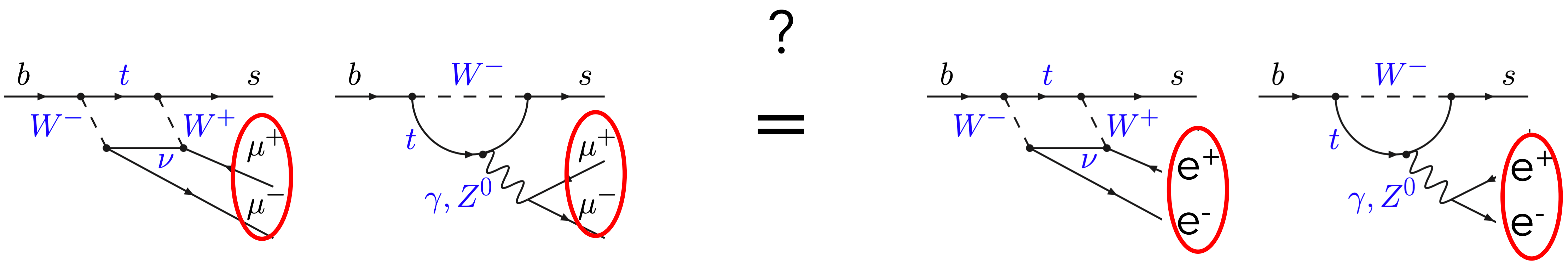
theoretical cleanness

Results in the $b \rightarrow s\mu\mu$ transitions:

- Extremely clean experimentally
- Large statistics
- not in perfect agreement with SM predictions (but uncertainties on these predictions sue to non-local contributions which are hard to estimate)

Lepton Flavour Universality tests in b→sℓℓ transitions

ℓ=e, μ



In the SM only difference : kinematics (lepton masses)

Any ratio of observables in principle

Start with the simplest (?) one: ratio of branching fractions

$$R_{H_s} = \frac{\int \frac{d\Gamma(B \to H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to H_s e^+ e^-)}{dq^2} dq^2} \overset{SM}{\cong} 1$$

Practically at LHCb:

$$R_H = \frac{N(B\to H\mu^+\mu^-)}{N(B\to He^+e^-)} \times \frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to H\mu^+\mu^-)}$$

Yields from mass fits

Efficiencies from MC & data calibration samples

H = K, K*, pK …

+

$$r_{J/\psi} = \frac{BR(B\to HJ/\psi(\mu^+\mu^-))}{BR(B\to HJ/\psi(e^+e^-))} = 1$$

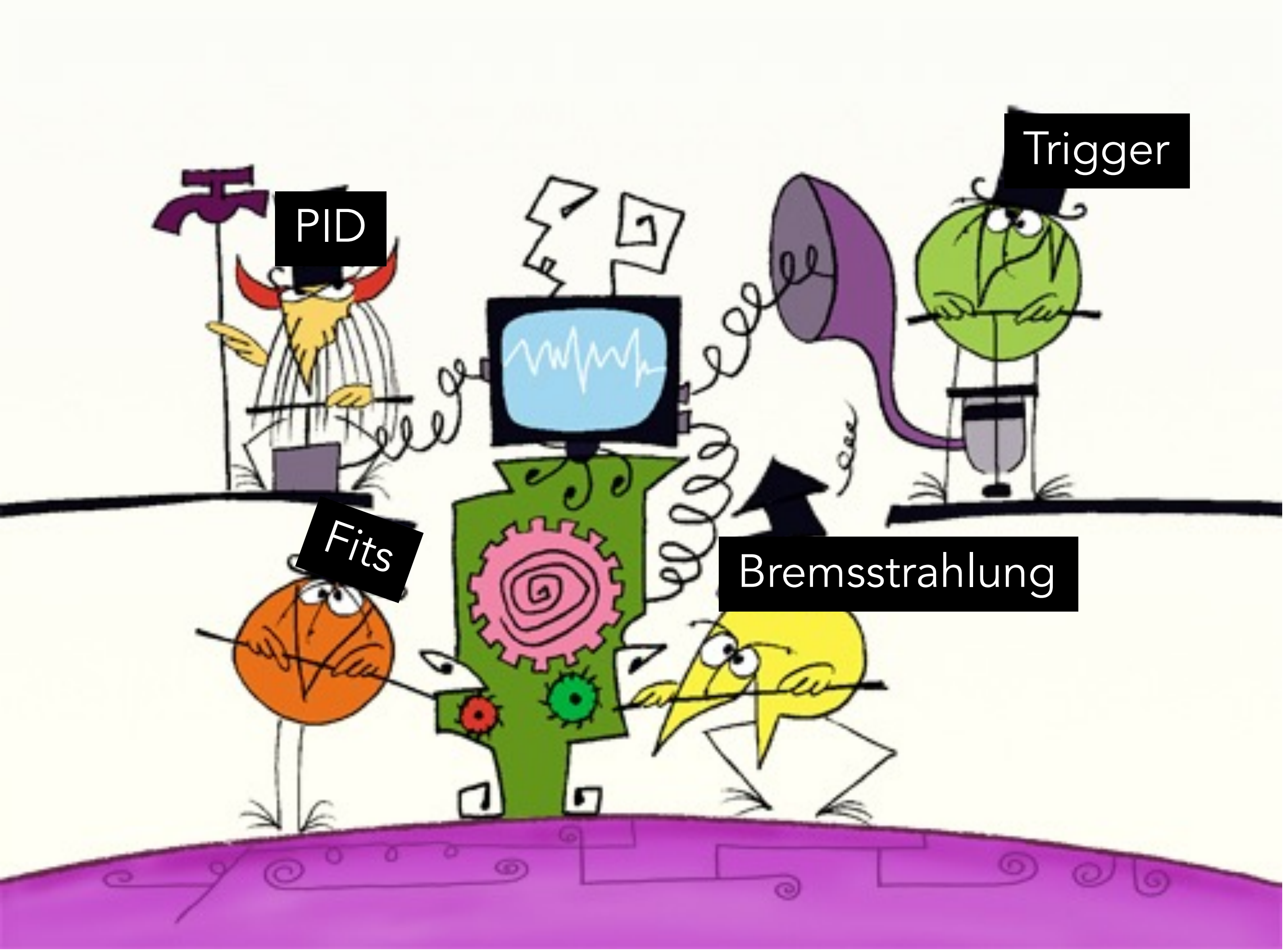
well tested LFU in J/ψ modes

⇒ Use of the double ratio using the resonant channels

$$R_H = \frac{\dfrac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\dfrac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\dfrac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\dfrac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}$$

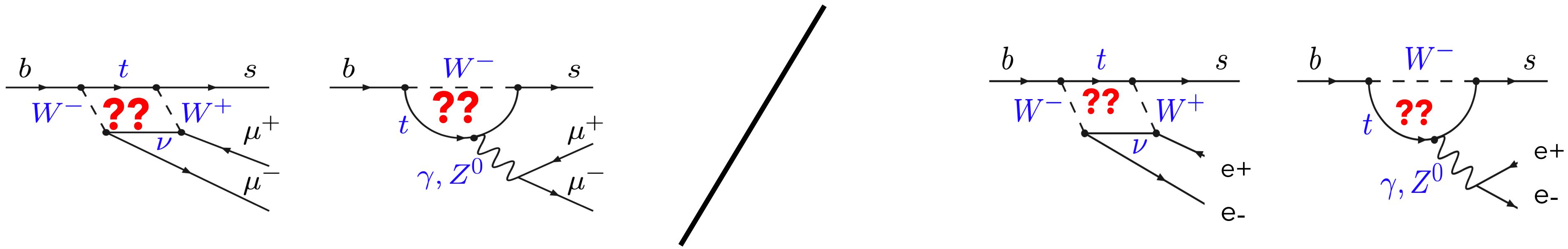
⇒ cancels out most of the systematics due to e/μ differences

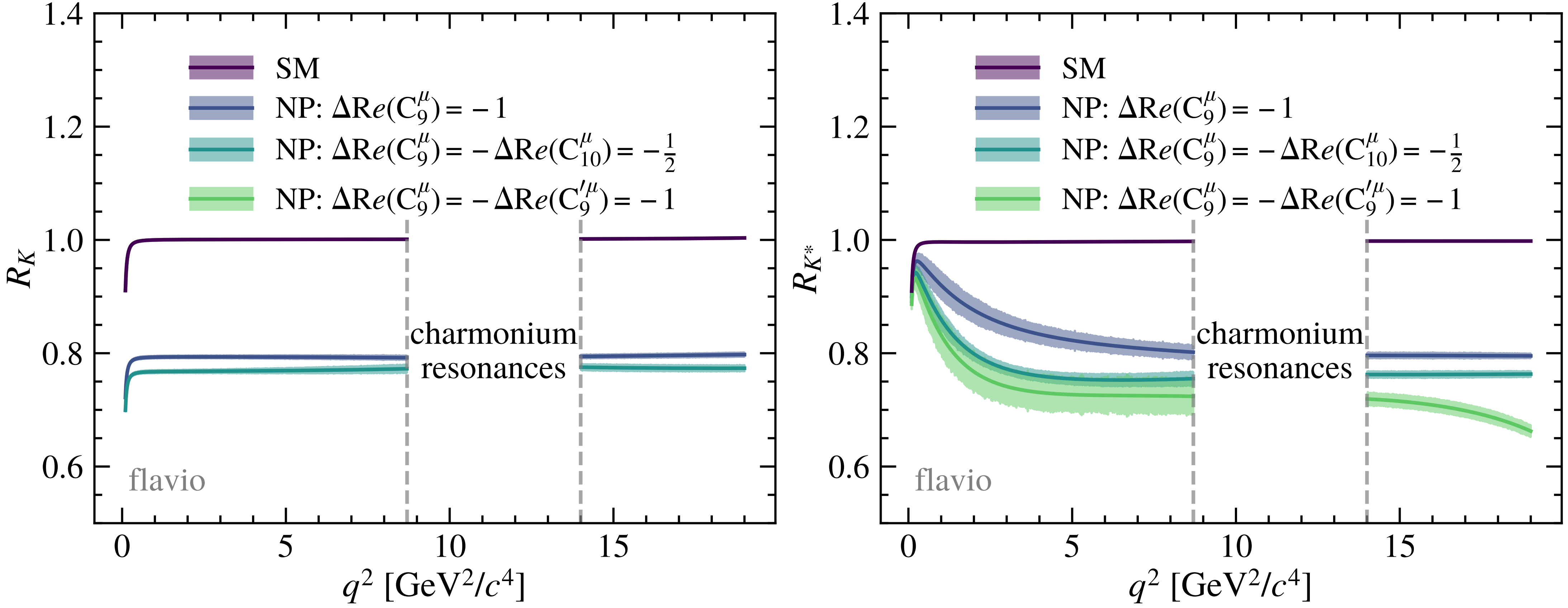
⇒the R_X analysis

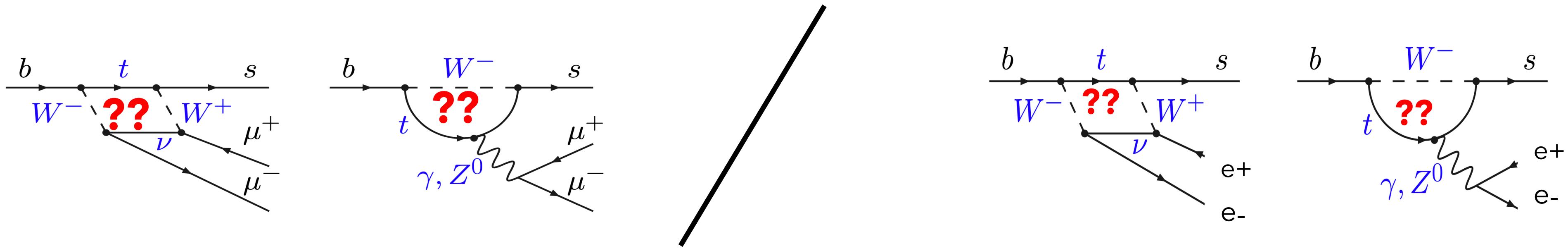


Simultaneous fit of

- $B \to K \ell\ell$ and $B \to K^* \ell\ell$
- in 2 kinematical regions (low and central-q^2)

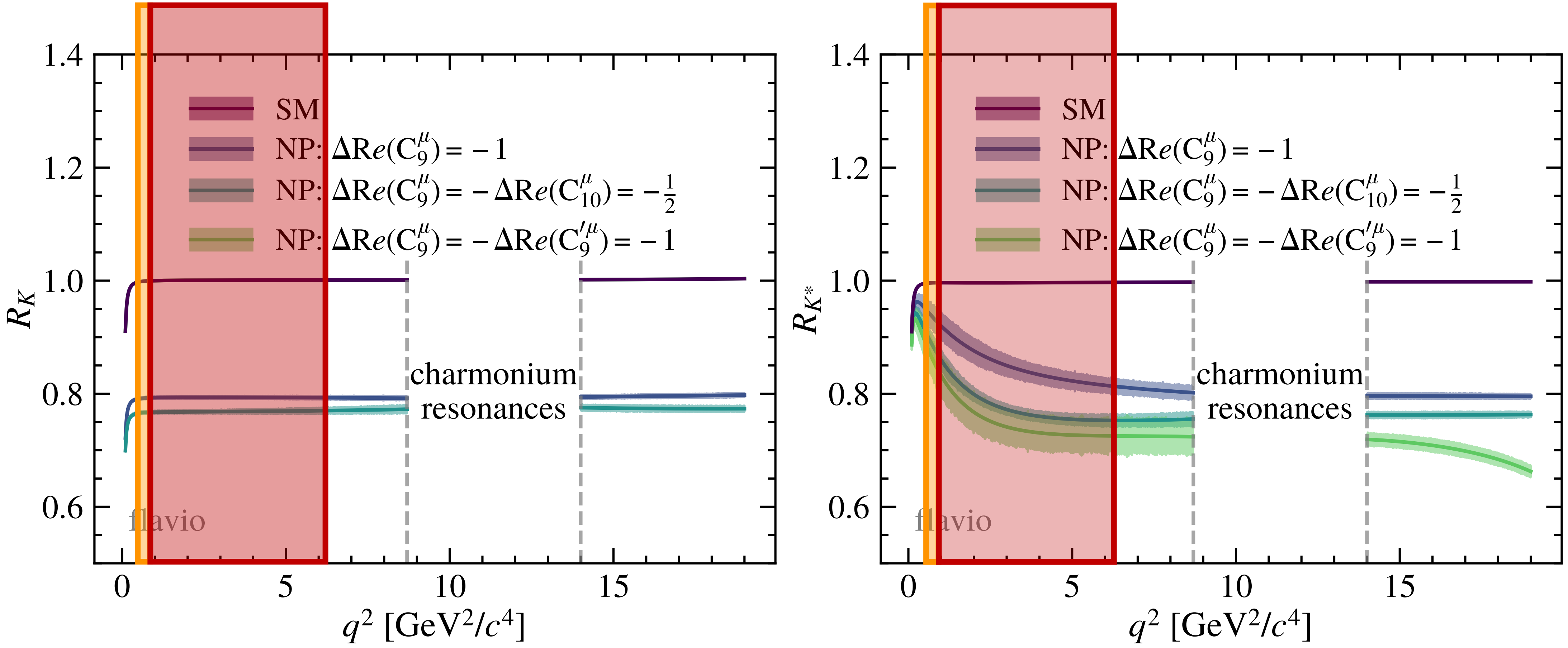

b
t
s
W−
??
W+
ν
μ+
μ−
b
W−
s
??
t
γ, Z0
μ+
μ−
b
t
s
W−
??
W+
ν
e+
e-
b
W−
s
??
t
γ, Z0
e+
e-


SM
NP: ΔRe(C9μ) = −1
NP: ΔRe(C9μ) = −ΔRe(C10μ) = −1/2
NP: ΔRe(C9μ) = −ΔRe(C′9μ) = −1
R_K
charmonium
resonances
flavio
q2 [GeV2/c4]
SM
NP: ΔRe(C9μ) = −1
NP: ΔRe(C9μ) = −ΔRe(C10μ) = −1/2
NP: ΔRe(C9μ) = −ΔRe(C′9μ) = −1
R_K*
charmonium
resonances
flavio
q2 [GeV2/c4]

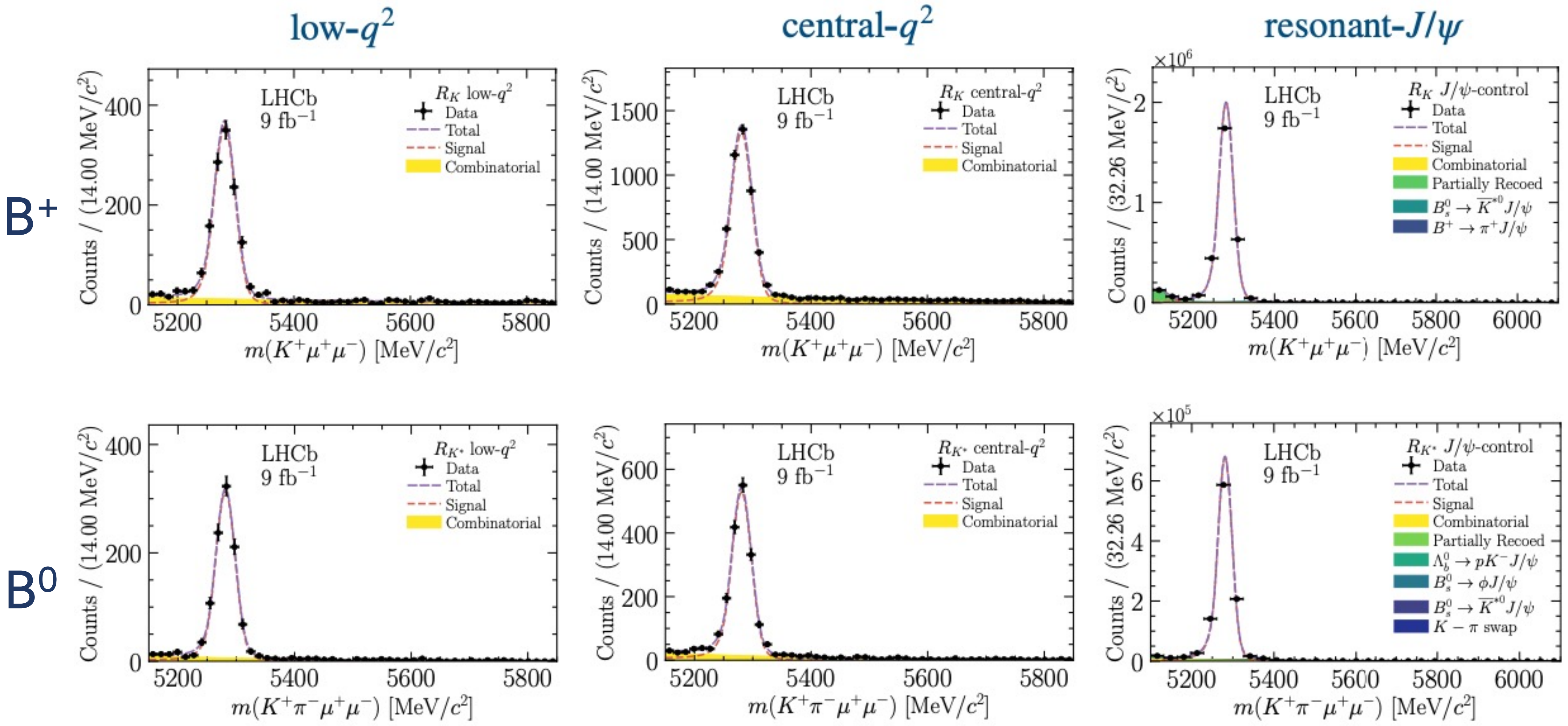


low-q²

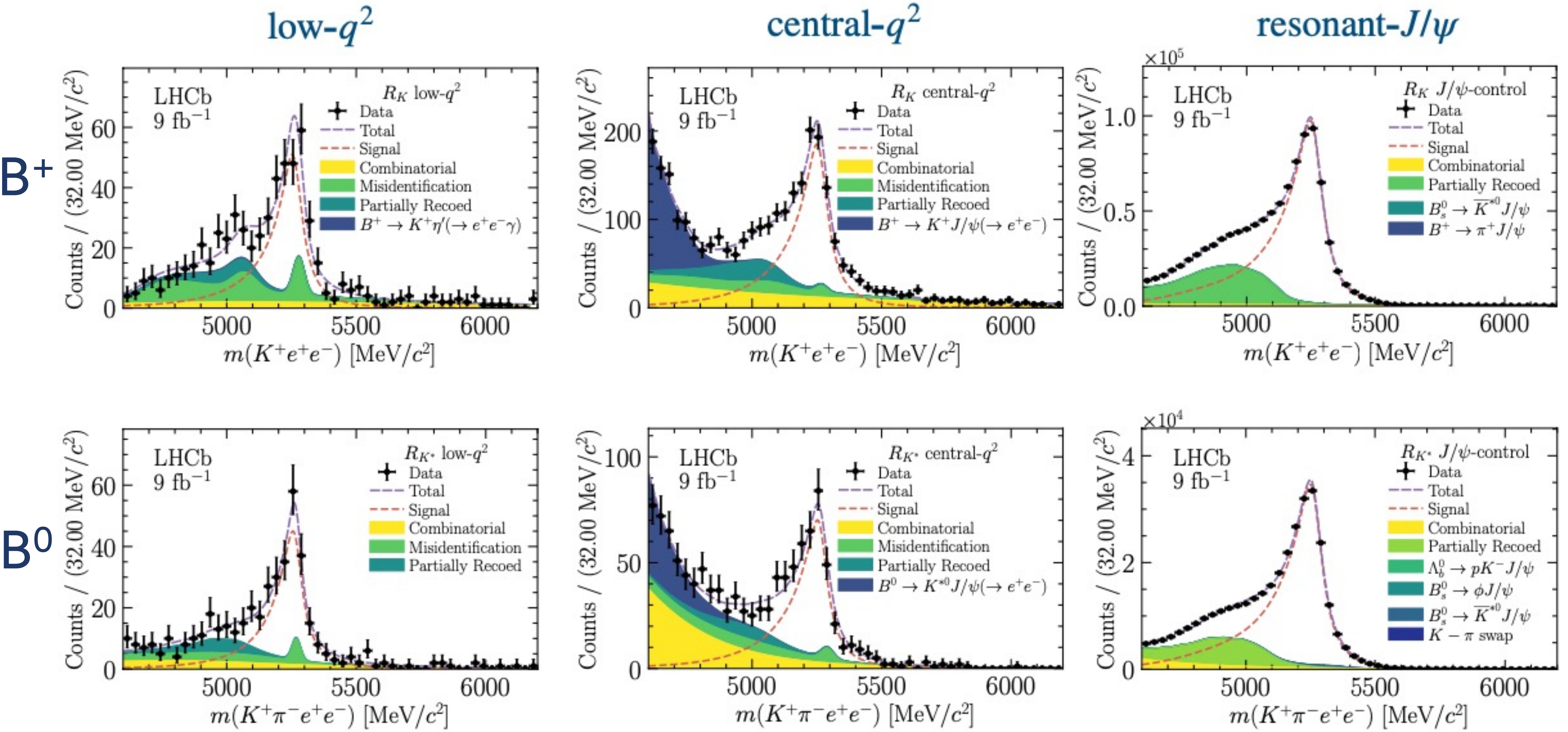
central-q²



Simultaneous fit for R_X extraction: muon modes



Simultaneous fit for R_X extraction: electron modes



A factor ~ 4 in yields between electron and muon modes

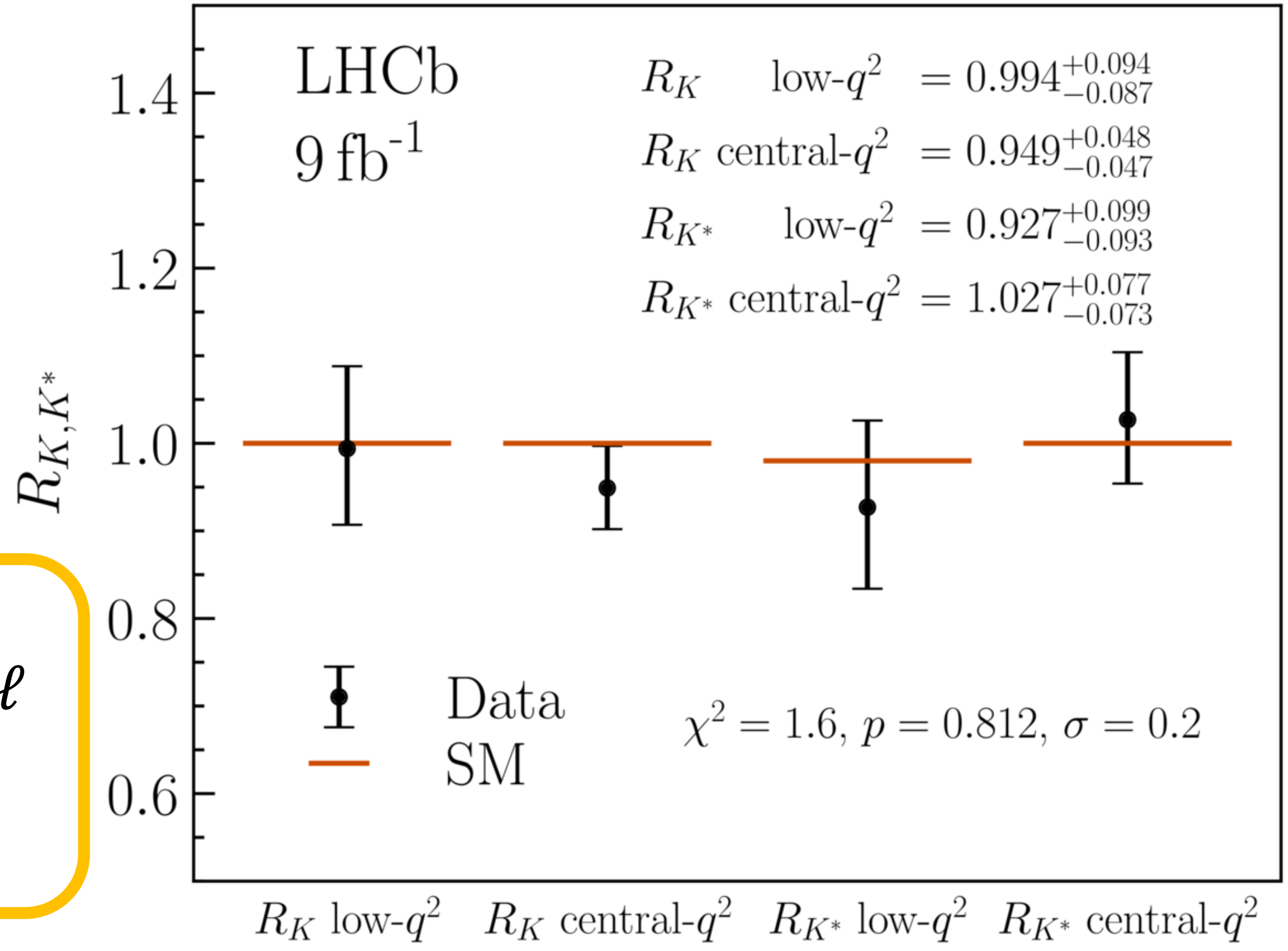
Measured yields from simultaneous fit to R_X

LU observable	Muon ($\times 10^3$)	Electron ($\times 10^3$)
low-q^2 R_K	1.25 ± 0.04	0.305 ± 0.024
low-q^2 R_{K^*}	1.001 ± 0.034	0.247 ± 0.022
central-q^2 R_K	4.69 ± 0.08	1.19 ± 0.05
central-q^2 R_{K^*}	1.74 ± 0.05	0.443 ± 0.028
J/ψ R_K	$(2.964 \pm 0.002) \times 10^3$	$(7.189 \pm 0.015) \times 10^2$
J/ψ R_{K^*}	$(9.733 \pm 0.010) \times 10^2$	$(2.517 \pm 0.009) \times 10^2$

Results

$$\text{low-}q^2 \begin{cases} R_K &= 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\ ^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} &= 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\ ^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K &= 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\ ^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} &= 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\ ^{+0.027}_{-0.026}\,(\text{syst}), \end{cases}$$



First or most precise test of LFU in $b \to s\ell\ell$

Compatible with the SM at 0.2 σ

To include Lepton Flavour Universality measurements in global fits:

$$C_i = C_i^{SM} + C_i^{NP}$$

$$i = 7, 9, 10$$

$$\Rightarrow \begin{cases} C_{i,e} = C_i^{SM} + C_{i,e}^{NP} \\ C_{i,\mu} = C_i^{SM} + C_{i,\mu}^{NP} \end{cases}$$

Some remarks:

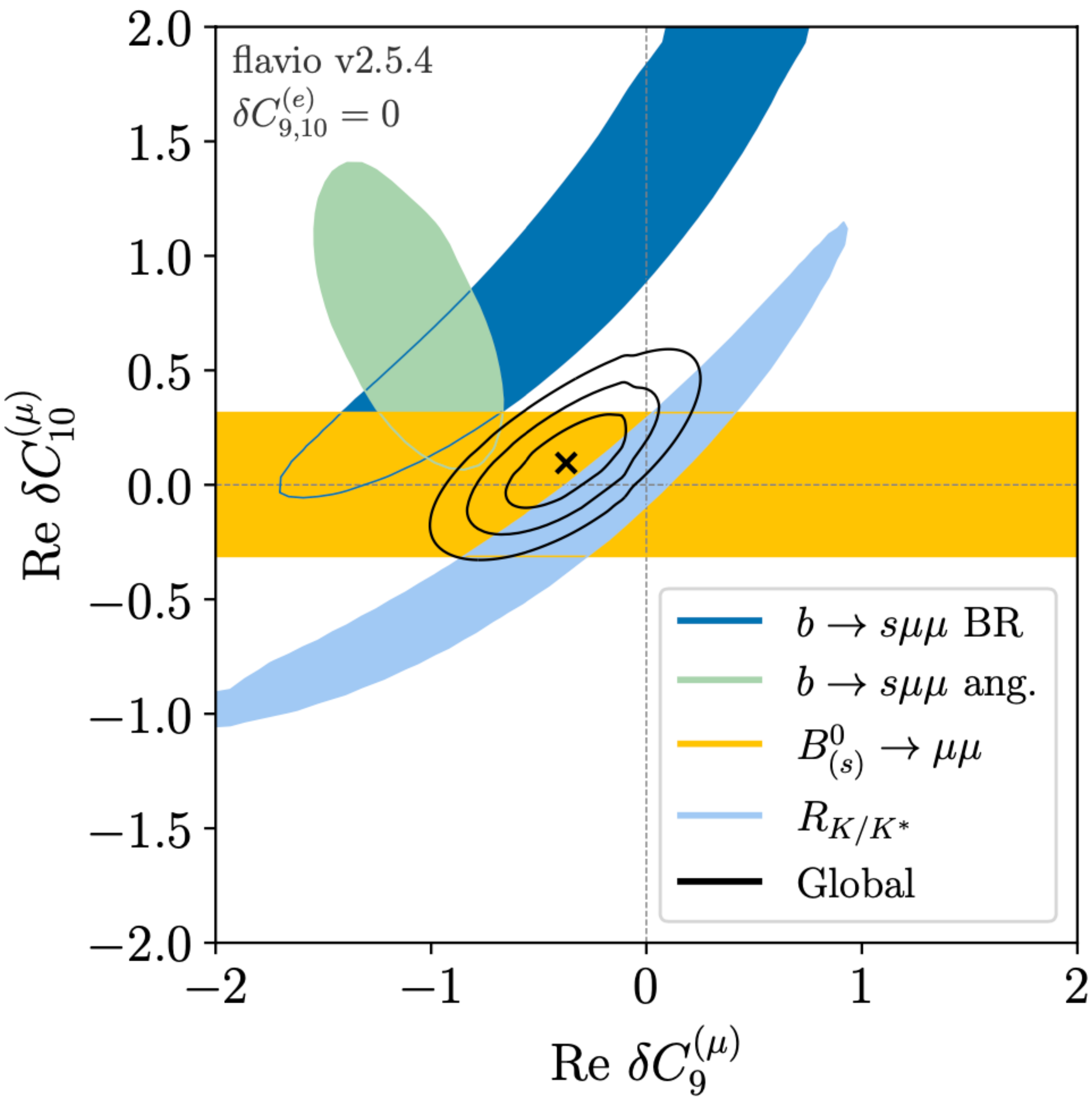
- $C^{(\prime)}_7$ strongly constraint from radiative decays and K*ee (very low-q^2)
- C'_9 and C'_{10} contributions disfavoured by $R_K \sim R_{K^*}$...

Some assumptions can be made:

- NP in muon modes only
- NP only in C_9
- ...

no NP in electrons

C_9 and C_{10} real



from Camille Normand PhD thesis (2023)

Disfavours a large shift on C_{10}

Some ideas to move forward

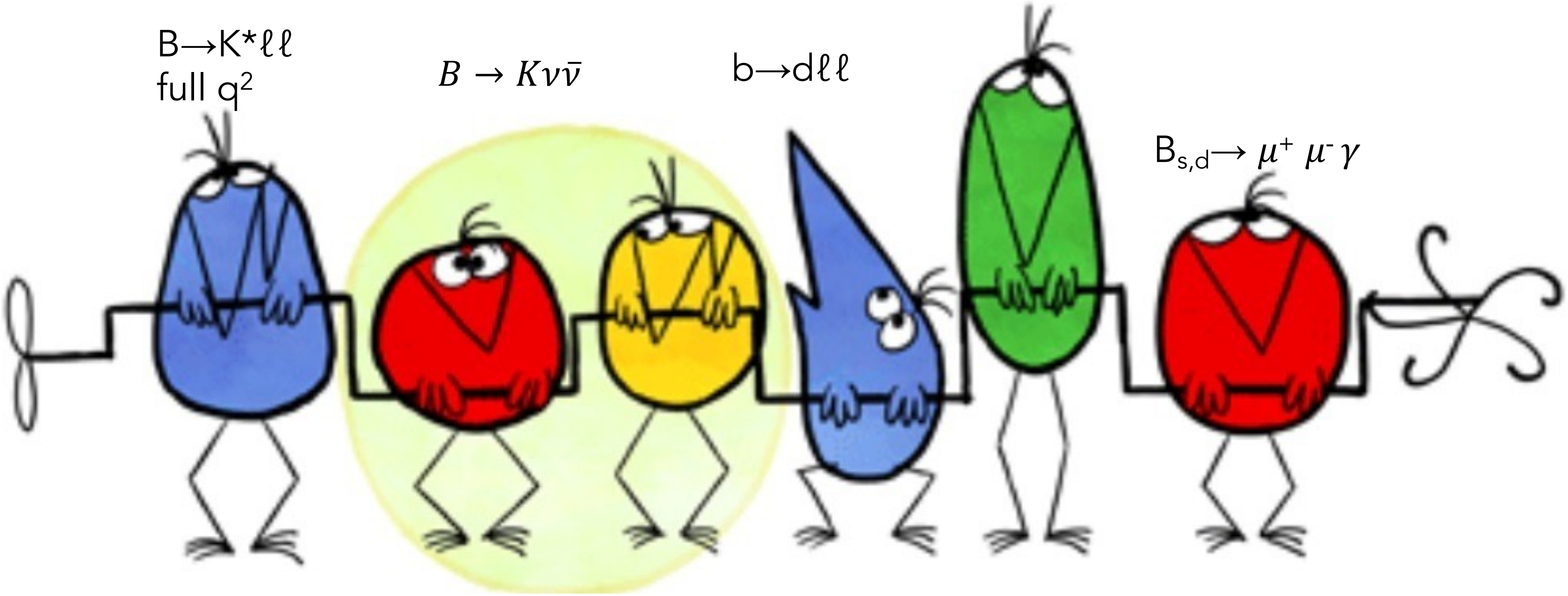
$B \to \mu\,\mu$: B_d , lifetime ..

$B \to K^*\ell\ell$
full q^2

$B \to K\nu\bar{\nu}$

$b \to d\ell\ell$

$B_{s,d} \to \mu^+ \mu^- \gamma$



$B_{s,d} \rightarrow \mu^+ \mu^-$

- More observables
- $B_{s,d} \rightarrow \mu^+ \mu^- \gamma$

and more stat !

More observables (one example)

NP ? NP ?

$$\mathcal{B}(\mathrm{B_s^0} \to \ell^+\ell^-) \;=\; \frac{1 + y_s \mathcal{A}_{\Delta\Gamma}}{1 - y_s^2} \times \mathcal{B}(\mathrm{B_s^0} \to \ell^+\ell^-)_{t=0}$$

$$\mathcal{B}(\mathrm{B^0_{(s)}}(\mathrm{t}) \to \ell^+\ell^-)_{t=0} \;\propto\; \left(1 - \frac{4m_\ell^2}{m_\mathrm{B}^2}\right) |C_S - C'_S|^2 + \left|(C_P - C'_P) + 2\frac{m_\ell}{m_\mathrm{B}^2}(C_{10} - C'_{10})\right|^2$$

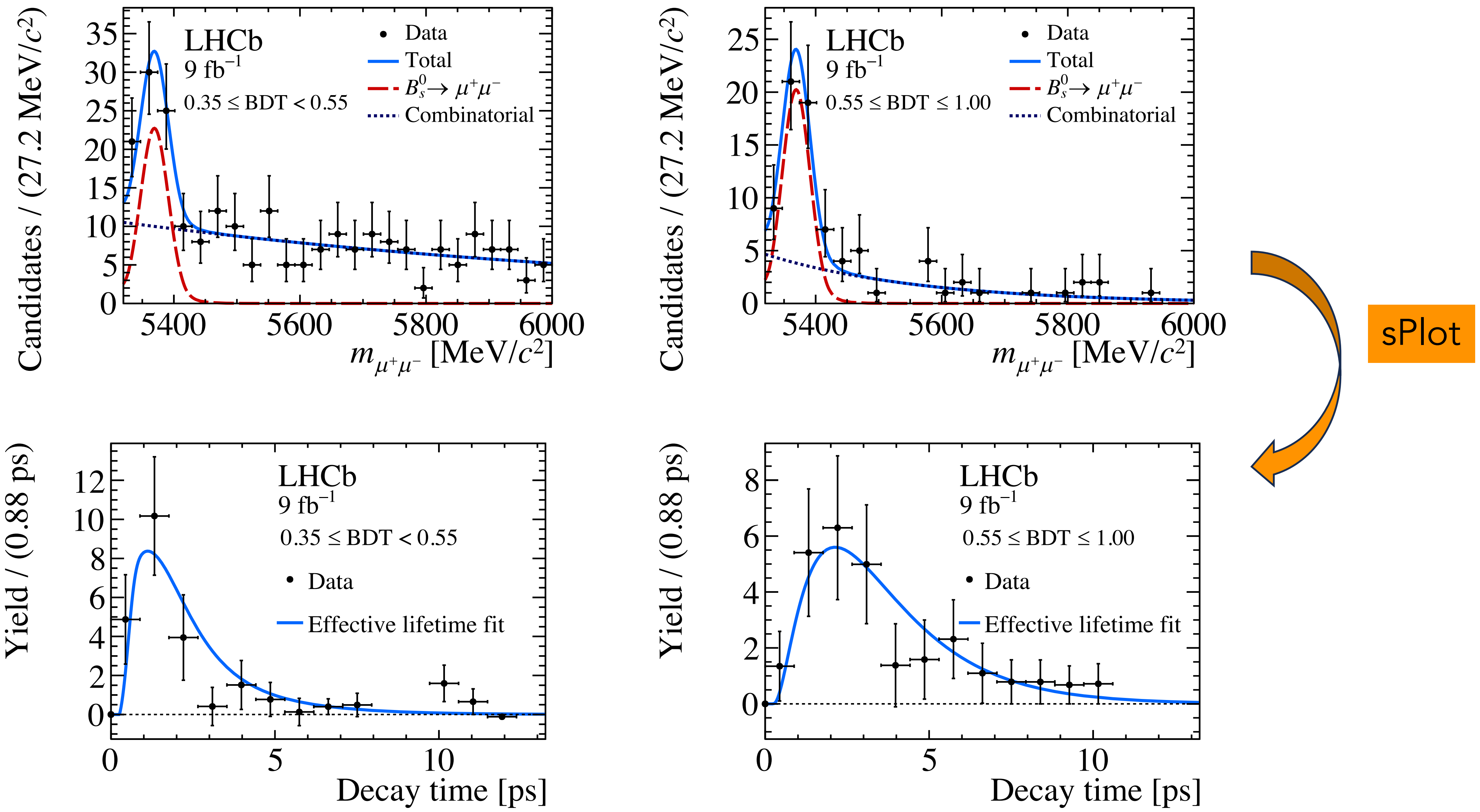
An additional variable : the effective lifetime

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\Gamma(B_s(t) \to \mu^+\mu^-)\,\mathrm{d}t}{\int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)\,\mathrm{d}t} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left[\frac{1 + 2A^{\mu\mu}_{\Delta\Gamma_s} y_s + y_s^2}{1 + A^{\mu\mu}_{\Delta\Gamma_s} y_s}\right]$$

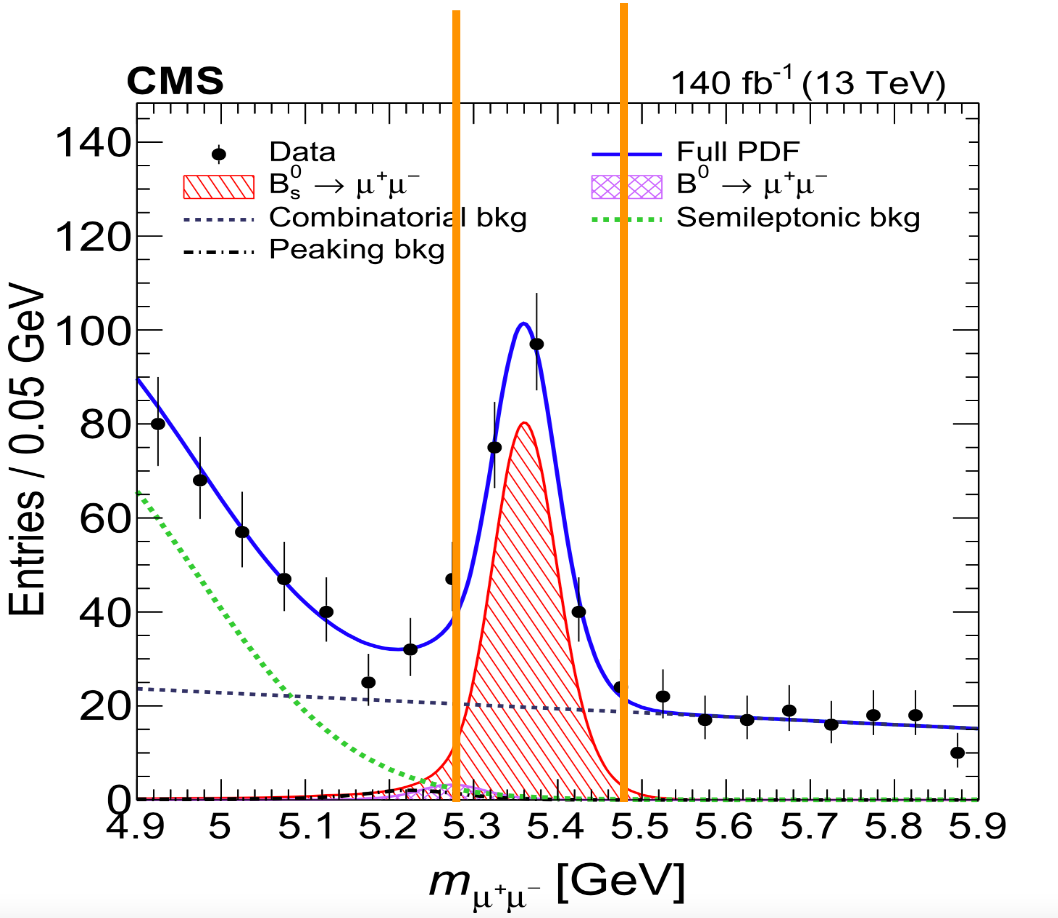
In the SM $\tau_{\mu\mu} = \tau_{B_s^H}$

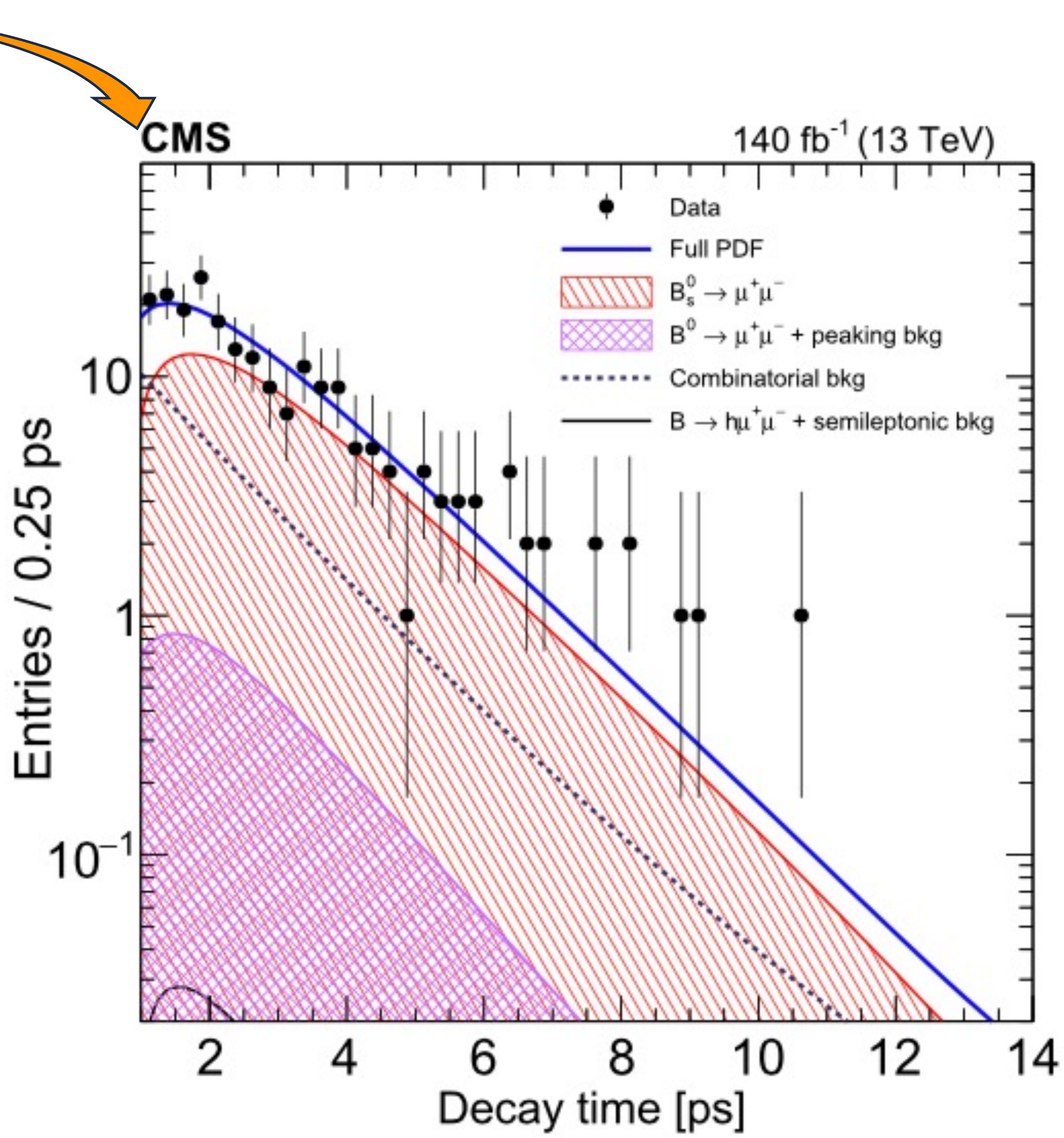
Enough statistics to start measuring the effective lifetime:

LHCb

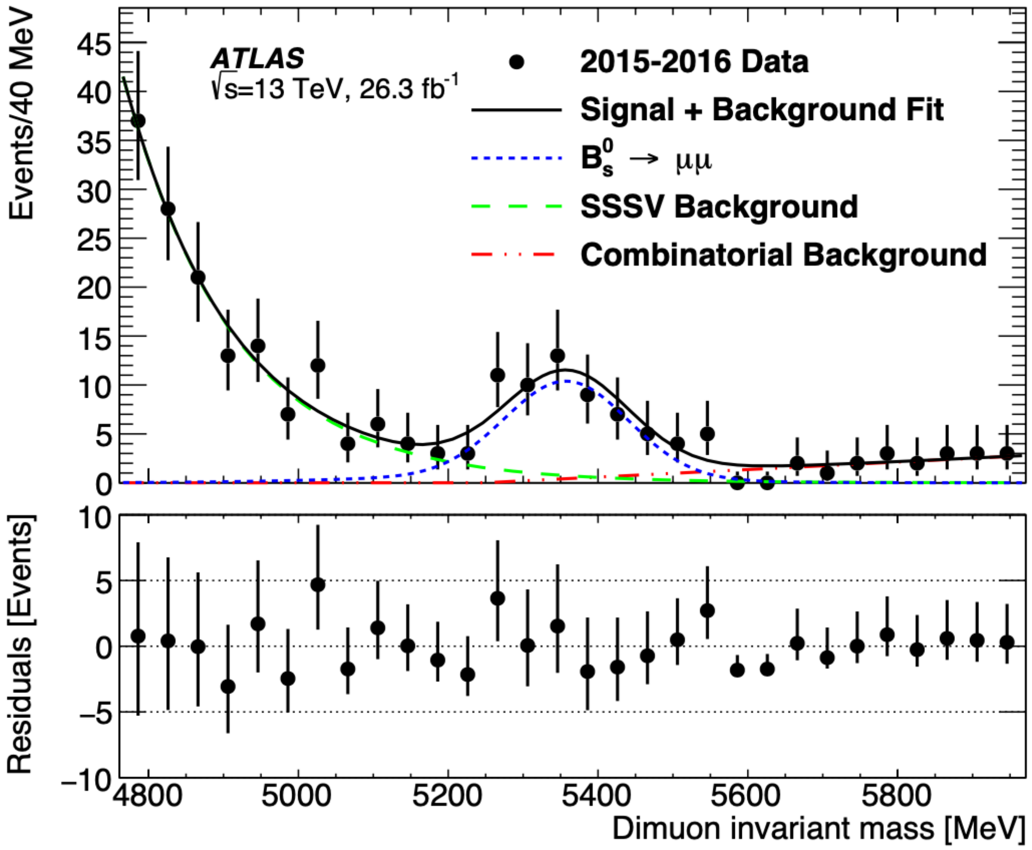


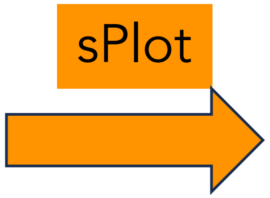
3D (dimuon invariant mass, decay time, and decay time uncertainty) Maximum Likelihood fit

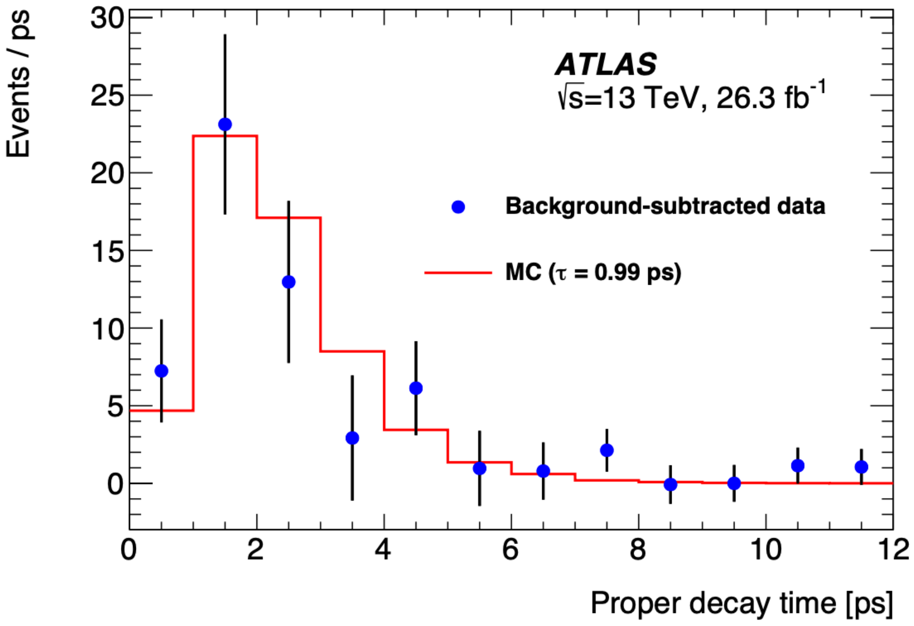




arXiv:2308.01171







Effective lifetime results:

Lifetime	Value [ps]
$\tau_{B_s^0 \to J/\psi\,\phi}$	$1.480 \pm 0.011 \pm 0.005$

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<1 % relative precision

$$2.07 \pm 0.29 \pm 0.03\,\text{ps}$$ LHCb

$$1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\,\text{ps}.$$ CMS

$$0.99^{+0.42}_{-0.07}\,(\text{stat.}) \pm 0.17\,(\text{syst.})\,\text{ps}$$ ATLAS

NB :

$$\tau_L = 1.423 \pm 0.005\,\text{ps} \text{ and } \tau_H = 1.620 \pm 0.007\,\text{ps}$$

Will play a role in future

What to expect with HL-LHC?

LHCb

BR($B_d \rightarrow \mu^+\mu^-$) still dominated by statistical uncertainty

BR($B_s \rightarrow \mu^+\mu^-$) : stat~ 1.8 % syst ~ 4 % (f_s/f_d)

BR($B_d \rightarrow \mu^+\mu^-$)/ BR($B_s \rightarrow \mu^+\mu^-$) : much more precisely predicted.
Measurement precision ~ 10%

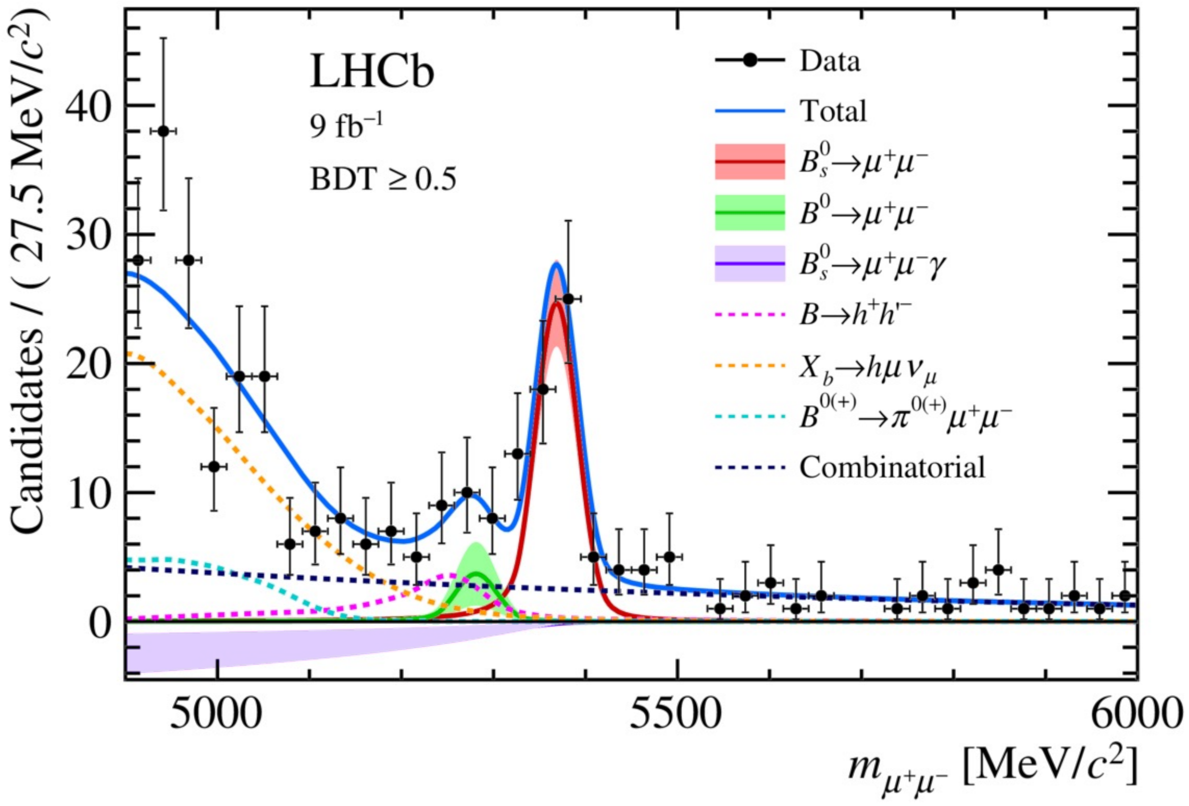
Additional observables:

- effective lifetime $\tau_{\mu\mu}$ precision for LHCb : 8% for 23 fb^{-1} and 2 % with 300 fb^{-1}
- time dependent CP asymmetry (sensitive to NP phase) . Accessible only to LHCb with 300 fb^{-1}

$B_{s,d} \to \mu^+ \mu^- \gamma$

When the photon is soft: test of the high-q^2 region (above $\psi(2S)$). Do not try to reconstruct it !

Nice interplay with the $B \to V \mu^+ \mu^-$ where the low-q^2 (below J/ψ) is exhibiting tensions with predictions



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

$$m_{\mu\mu} > 4.9\,\mathrm{GeV}/c^2$$

Need for a dedicated analysis going lower in $m_{\mu+\ \mu-}$

An analysis targeting the low-q^2 (energetic photon) ?

In any case: experimentally challenging !

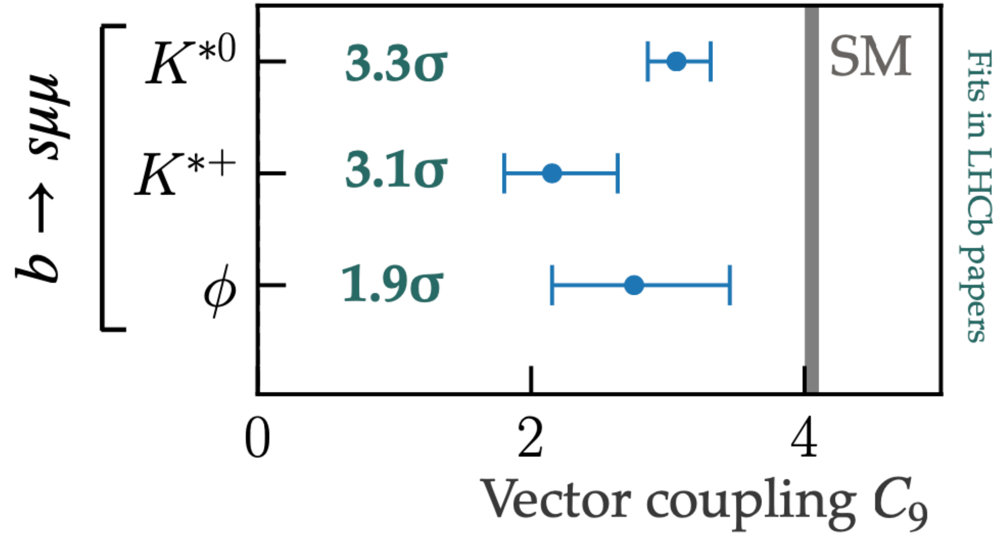
and predictions very sensitive to FF

$H_b \to H_{s,d}\, \ell^+ \ell^-$

- Constraining the non-local contribution from data ?
- More observables
- $b \to d\, \ell^+ \ell^-$

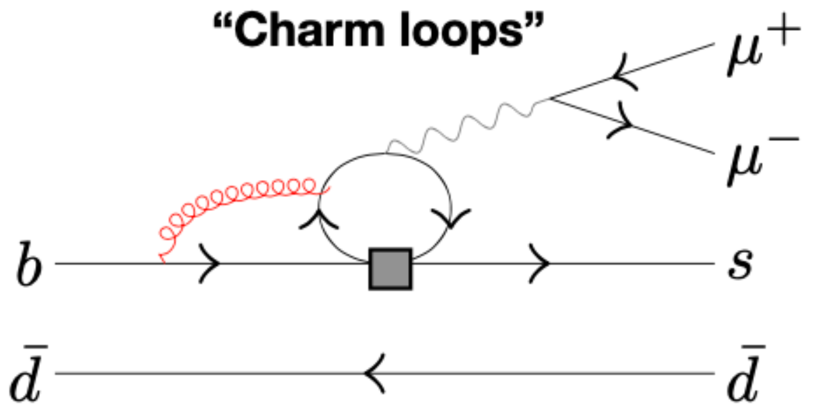
and more stat !

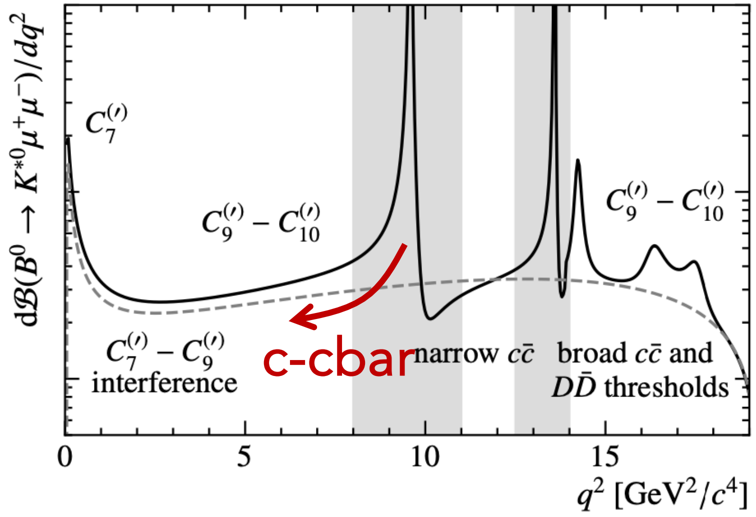
Constraining the non-local contribution from data ?



From Martino Borsato (SUSY2022)

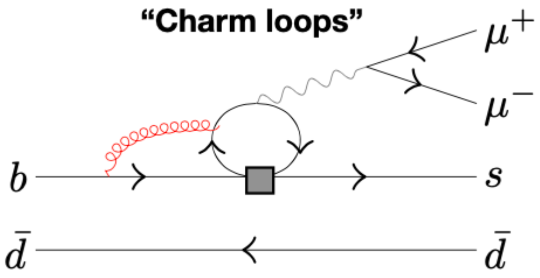
but :

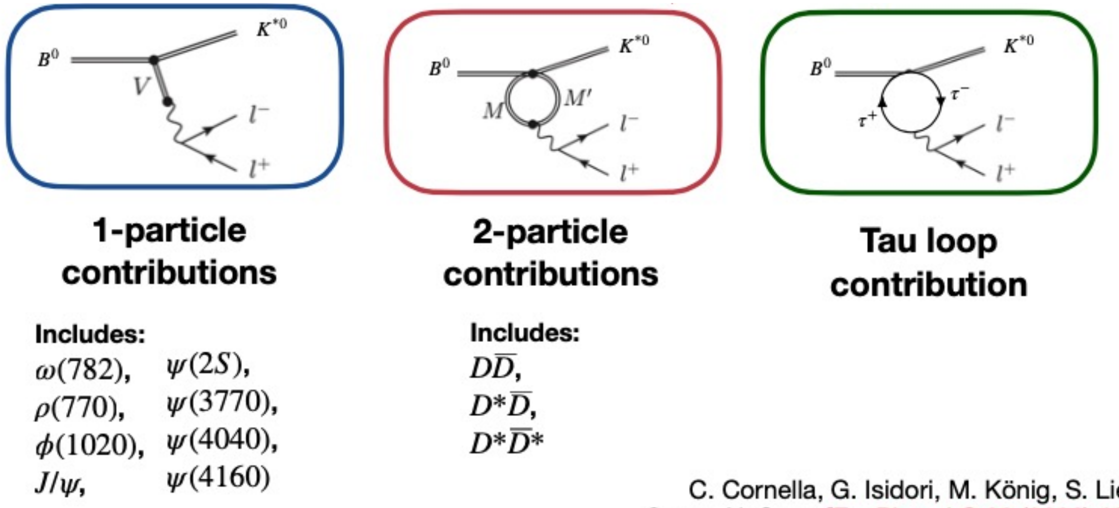




would act as a shift on C_9

Lively theoretical debate on the estimate of these non-local effects





C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]

- Computation of the exchange of one soft gluon (seems to increase more the tension)
- Problem: the phase difference between the long-distance charm contribution and the short-distance physics
  - nuisance parameters in the global fits
  - estimate from data fits (next two slides)

Various possibilities (most of them on their way for $B^0 \to K^* \mu\,\mu$)

$$A_\lambda^{L,R} = A_\lambda^{L,R,\text{Local}} + H_\lambda(q^2)$$

$$C_9^{\text{eff},\lambda}(q^2) = C_9^\mu + G_\lambda(q^2)$$

Model Independent ⟷ Model Dependent

Binned

Unbinned

Extract the angular observables from a 4D fit $(M,\vec{\Omega})$	Extract an amplitude ansatz ($A^{L,R}(q^2)$ modelled by polynomials) from a 4D fit $(q^2,\vec{\Omega})$	Extract $C_{9,10}^{(\prime)}$ + non-local contributions modelled by polynomials from a 4D fit $(q^2,\vec{\Omega})$	Extract $C_{9,10}^{(\prime)}$ C_9^τ + non-local contributions (magnitudes & phases) from a 4D fit $(q^2,\vec{\Omega})$

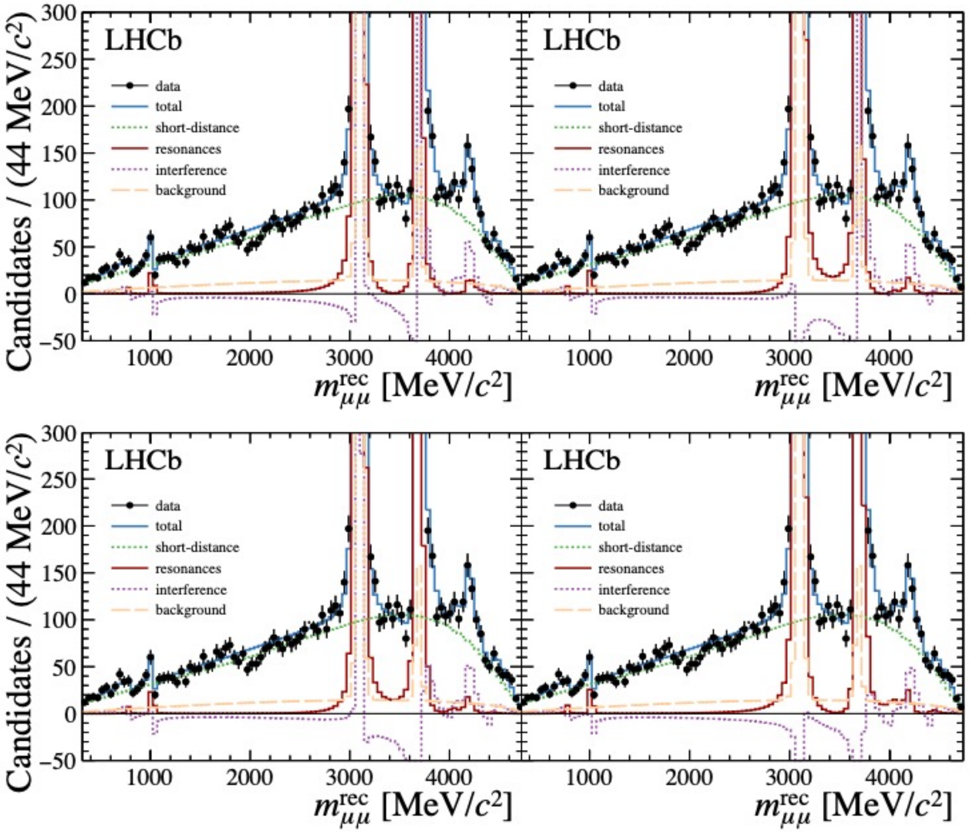
Eur.Phys.J.C 77 (2017) 3, 161

Estimate using data: B → K μ μ

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

magnitude of the resonance

phase of the resonance wrt C_9

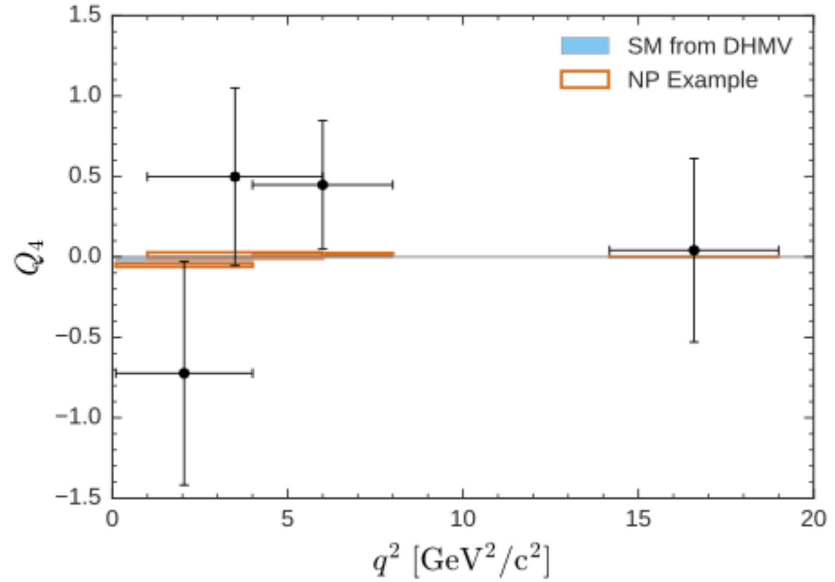


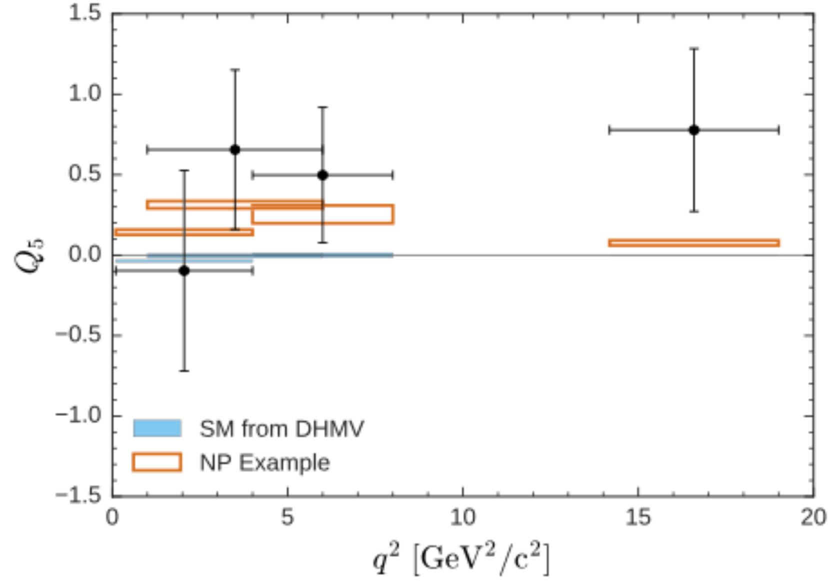
- Resonances added as relativistic BW
  Branching ratios of $B_+ \rightarrow VK_+$ constrained from the PDG (assuming factorization)
- Form-factors constrained from lattice QCD (Bailey et al., *Phys.Rev.D* 93 (2016) 2, 025026)
- Contribution of $D_{(*)}D_{(*)}$ ignored

4 ambiguities
interference with the rare mode far from the pole is small
can be improved with more contributions

More observables, more modes

Belle PRL 118 (2017) 111801





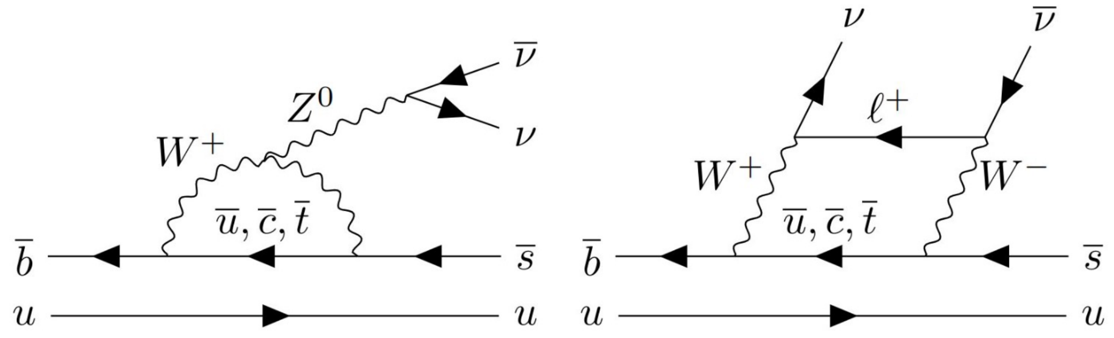
Dataset	$\sigma(Q_5)$ $1 < m^2_{\ell^+\ell^-} < 6\,\mathrm{GeV}^2/c^4$
Belle [32] ($\sim$0.7 ab^{-1})	$\sim$0.5
LHCb (9 fb^{-1})	~ 0.1 - 0.15 ?
Belle-II (25 ab^{-1})	$\sim$0.05
LHCb (23 fb^{-1})	~ 0.05 - 0.1 ?

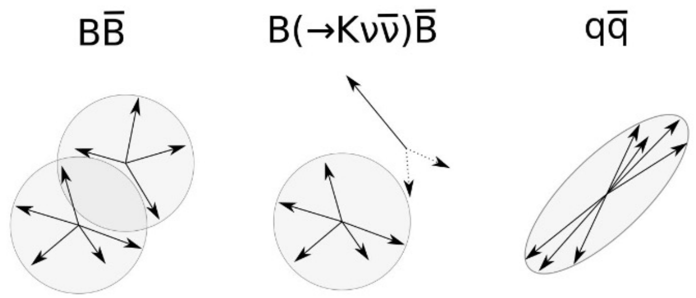
Are angular observables the same in b→ s μ μ and b→ s ee ?

- non-local contributions should be the same
- New Physics a priori different

$B \to K\nu\bar{\nu}$

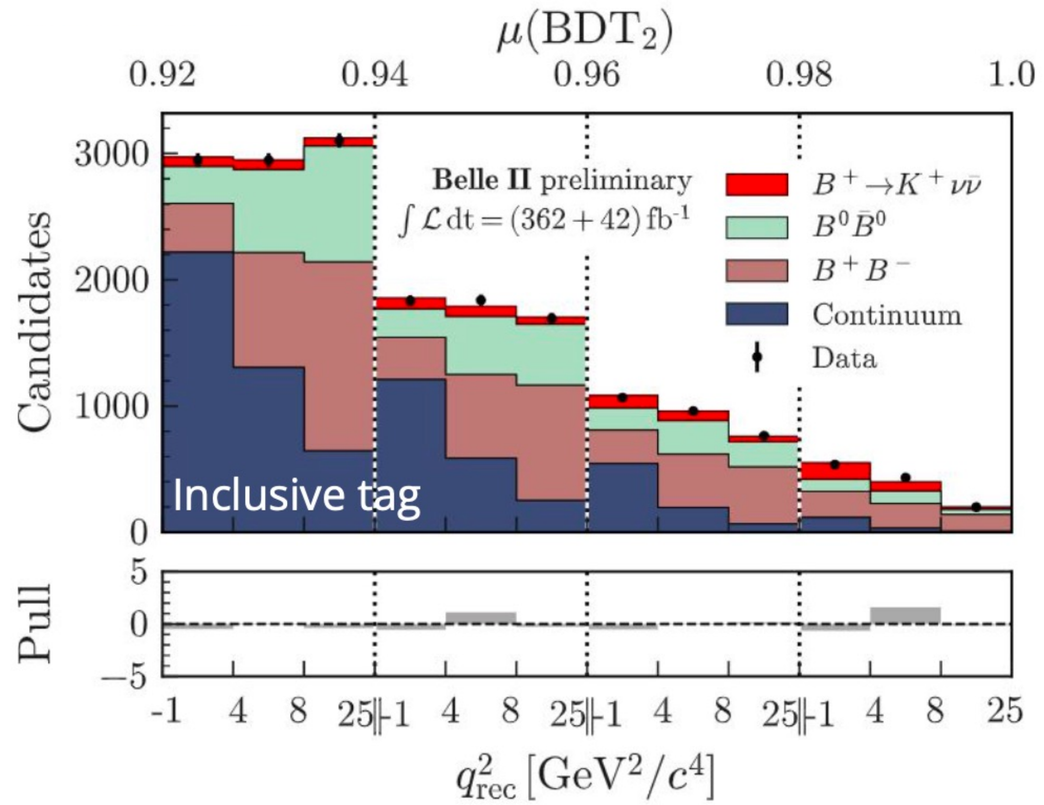
Belle-II @EPS 2023





Precisely predicted in the SM

B(B→K$^+$ νν) = (5.6 ± 0.4) x 10^{-6} (arXiv:2207.13371)



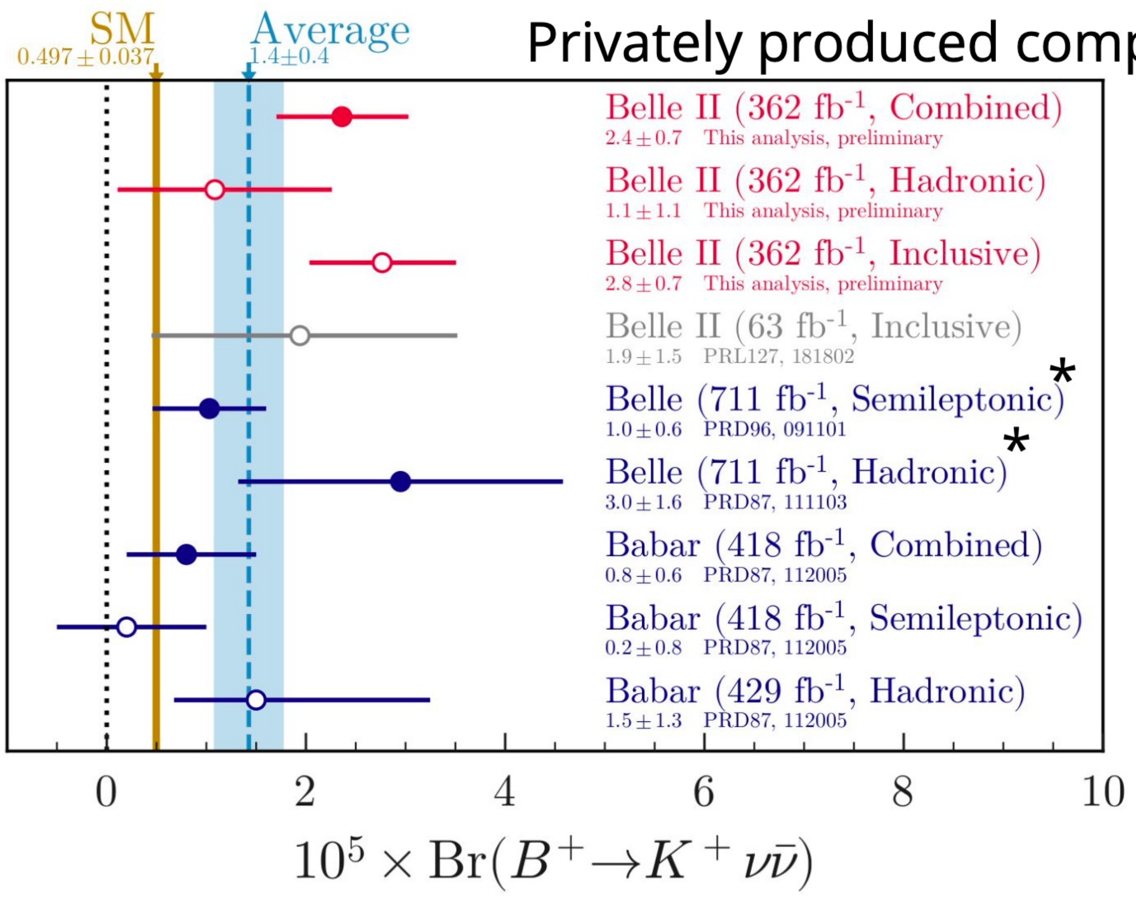
q^2 computed for the 2 neutrinos from K$^+$ recoil

global analysis using general event information (2 BDT)

Fit in bins of q^2 x BDT bins

plot from BELLE2-TALK-CONF-2023-123

Privately produced comparison

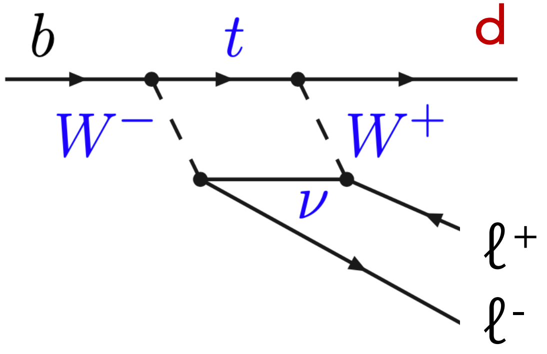


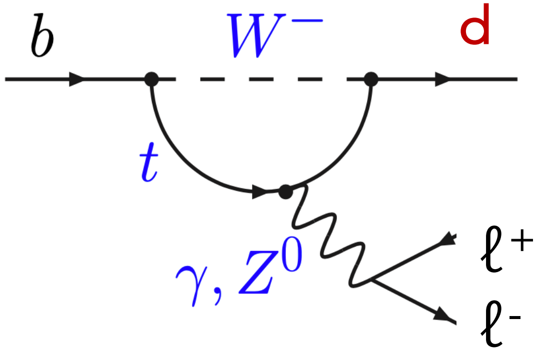
Not in significant tension with the SM

$b \to d\, \ell^+ \ell^-$

$H_b \to H_d\, \ell^+ \ell^-$

$B_d \to \ell^+ \ell^-$





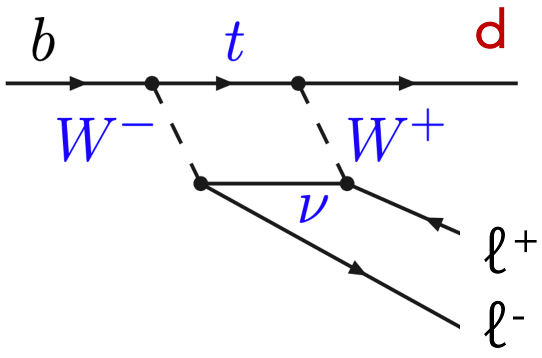
In the SM suppressed by $\left|\frac{V_{td}}{V_{ts}}\right|^2 \sim 0.04$

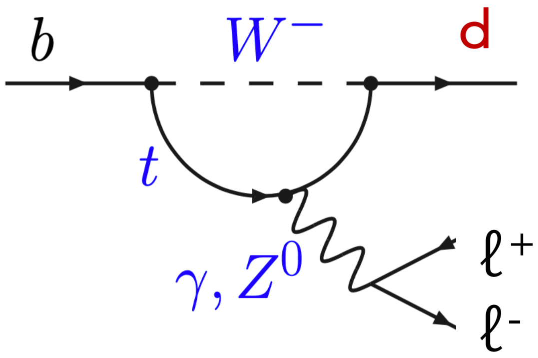
Rare modes are even more rare

But New Physics can couple differently: important to check

$B_d \to \ell^+ \ell^-$ "automatically" done (same final state)

What about $H_b \to H_d\, \ell^+ \ell^-$?





$B^+ \to K\,\ell\ell$ $B^+ \to \pi\,\ell\ell$

b→ s ℓ⁺ ℓ⁻	b→ d ℓ⁺ ℓ⁻
$B^+ \to K\,\ell\ell$	$B^+ \to \pi\,\ell\ell$
$B^0 \to K_S\,\ell\ell$	$B^0 \to \pi^0\,\ell\ell$
$B^0 \to K^{*0}\,\ell\ell$	$B^0 \to \rho^0\,\ell\ell$
$B_s \to \phi\ell\ell$	$B_s \to K^{*0}\,\ell\ell$

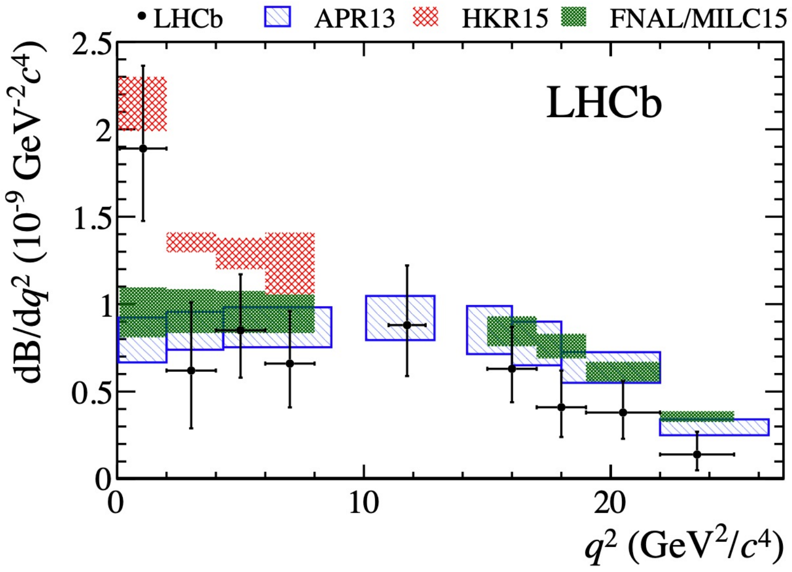
In most of the cases $b \to d\,\ell^+\,\ell^-$ transitions are experimentally and theoretically more challenging than $b \to s\,\ell^+\,\ell^-$

$b \to s\, \ell^+ \ell^-$	$b \to d\, \ell^+ \ell^-$
$B^+ \to K\, \ell\ell$	$B^+ \to \pi\, \ell\ell$

JHEP 10 (2015) 034

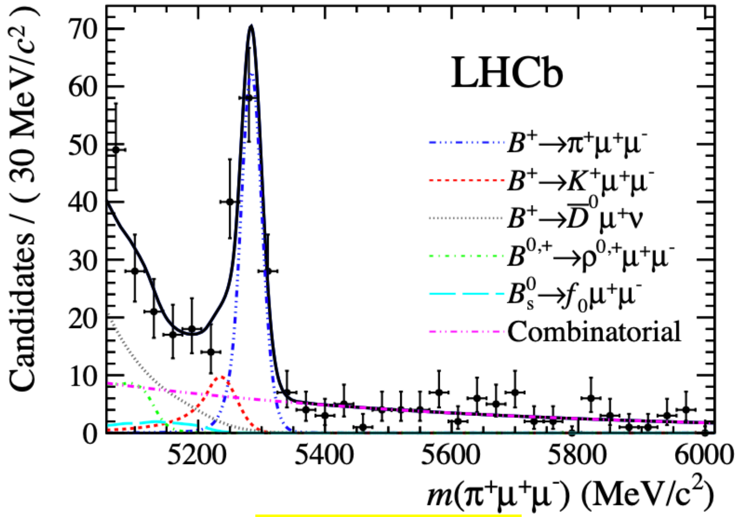
$$\mathcal{B}(B^\pm \to \pi^\pm \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$

full q^2 range (but J/ψ and $\psi(2S)$)



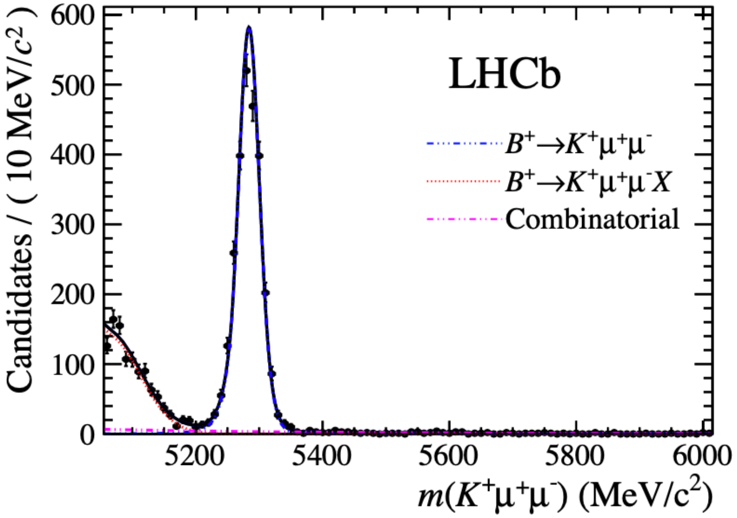
3 fb^{-1}

$B^+ \to \pi\, \ell\ell$



94 ± 12

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



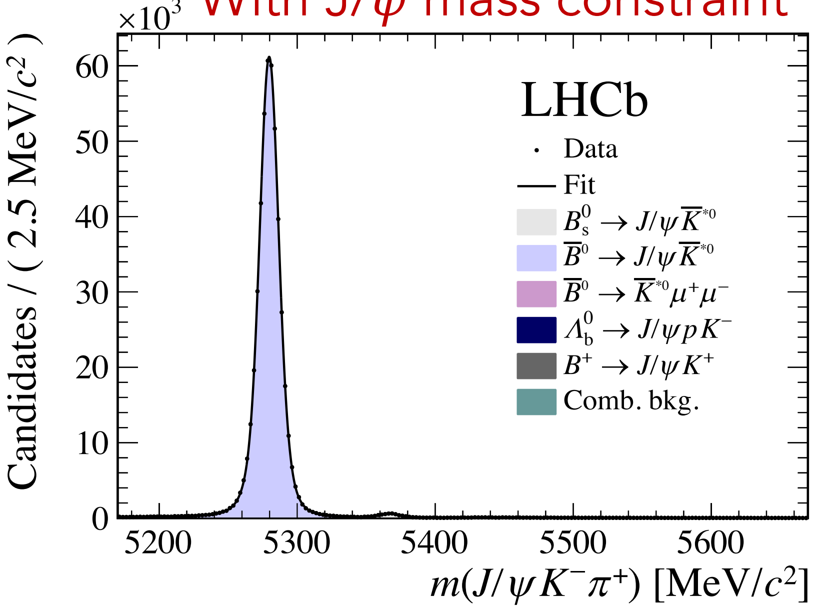
2922 ± 55

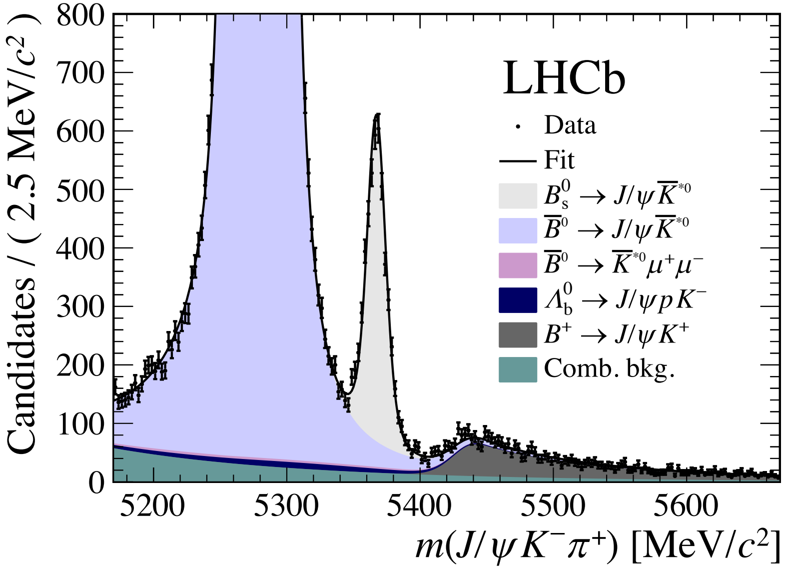
JHEP 07 (2018) 020

$b \to s \ell^+ \ell^-$	$b \to d \ell^+ \ell^-$
$B_s \to \phi \ell \ell$	$B_s \to K^{*0} \ell \ell$

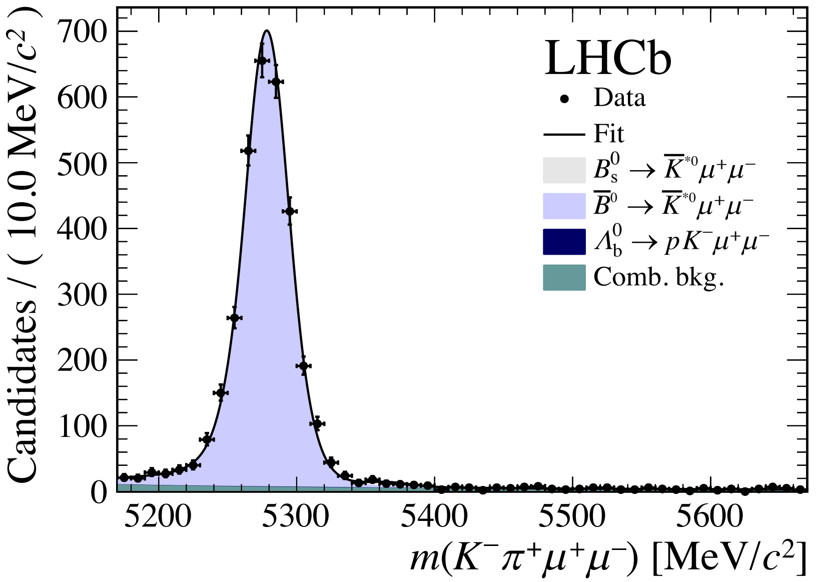
$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{norm})] \times 10^{-8}$$

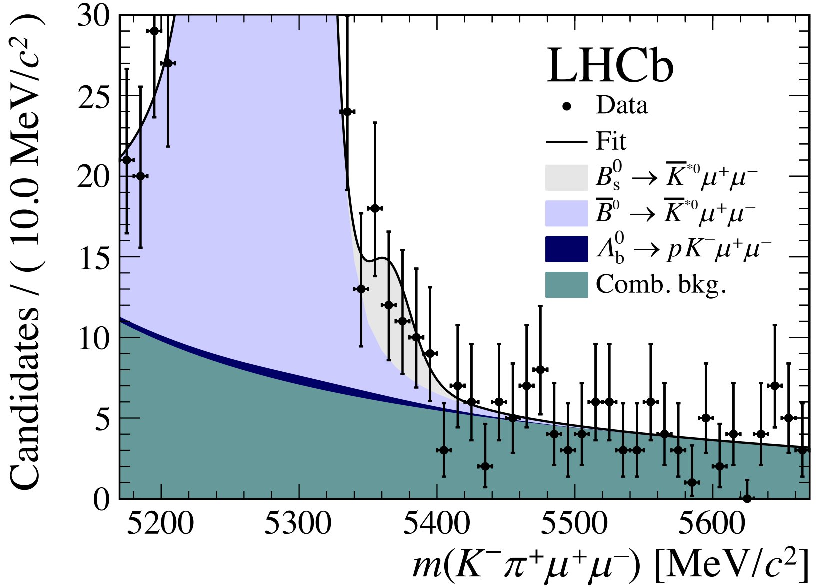
With J/ψ mass constraint





4.6 fb^{-1}





Will not work with electrons

Conclusion

- Experimentalists are more and more using EFT 'language' (specially useful for analyses with a lot of observables)
- A shift in C_9 ($b \rightarrow s\ \mu\mu$ branching fractions and (some) angular parameters). Situation unclear… Experiments & theory progressing together
- $B_s \rightarrow \mu\mu$ is compatible with the SM: no obvious sign of NP in C_{10}
- No sign of large Lepton Flavour Universality violation in $b \rightarrow s\ \ell\ell$
- Photon polarization in $b \rightarrow s\ \gamma$ transitions compatible with SM expectation

When SM agreement it is at the ~5% precision, tests statistically limited

→More data and more analyses !

Stay tuned

Many thanks to J. Rouxel & JP Couturier for the Shadoks

- 5 to 10% precision (stat dominated)

Looking back in the mirror

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

1961

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our results on the charge ratio and the degree of the 2π-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in K^0 decay.

Experiment stopped

In 1964 CP violation discovery: $(2.0 \pm 0.4)\ 10^{-3}$

Physical Review Letters, vol. 13, n° 4, 1964, p. 138

Backup slides

Why don't you look at $B_s \to ee$?

SM prediction   more helicity suppression !

$$\mathcal{B}(B_s^0 \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$

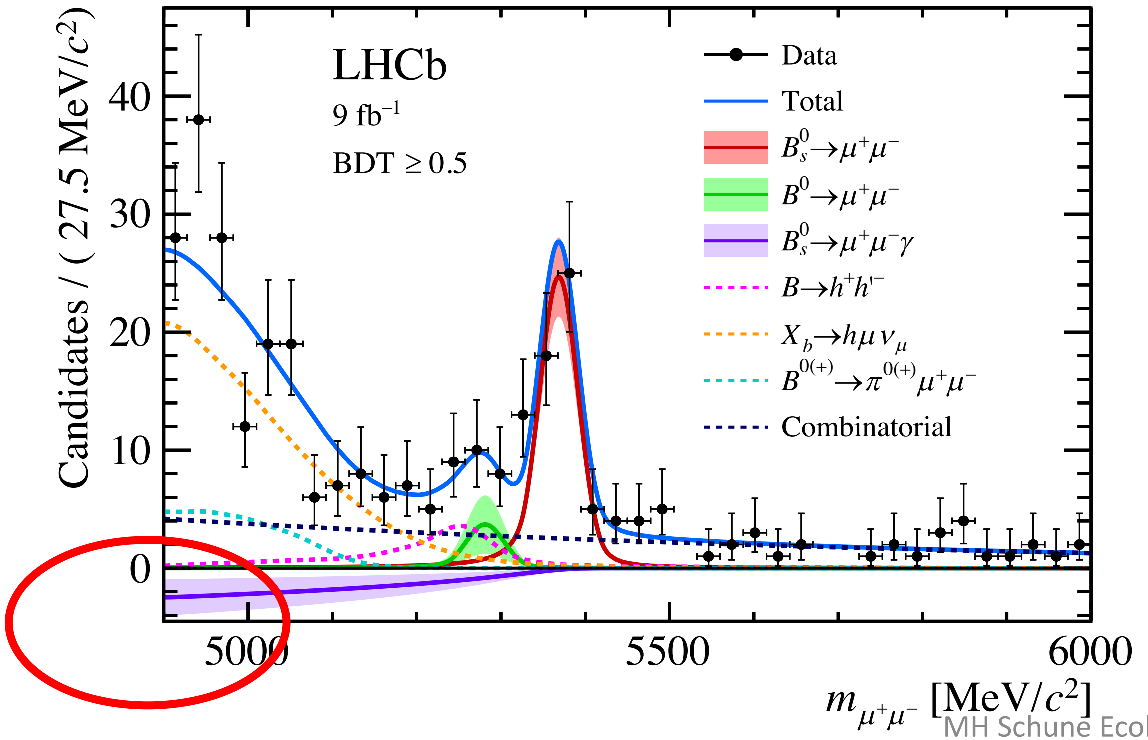
$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

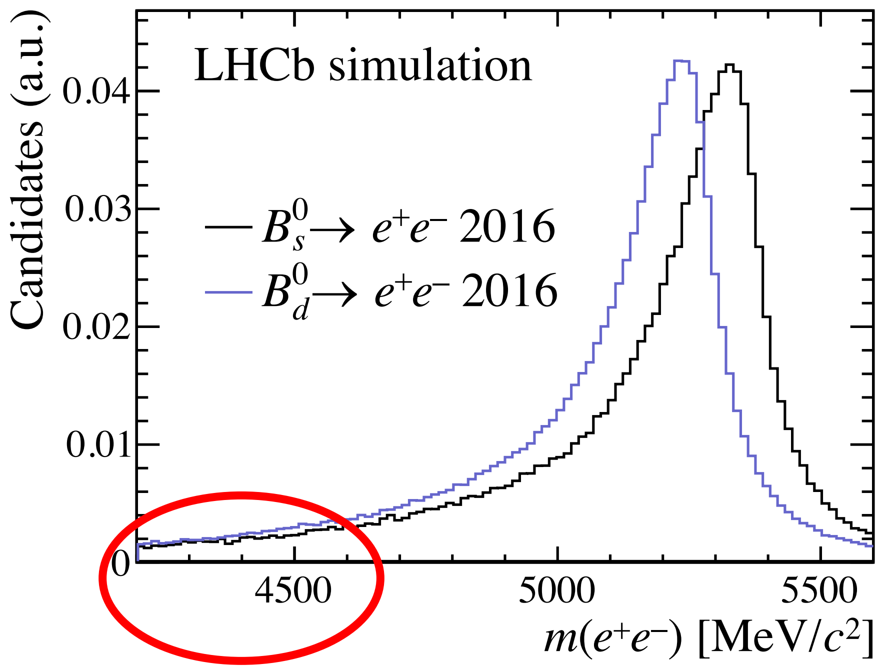
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

But electrons emit Bremsstrahlung photons ….

μμ

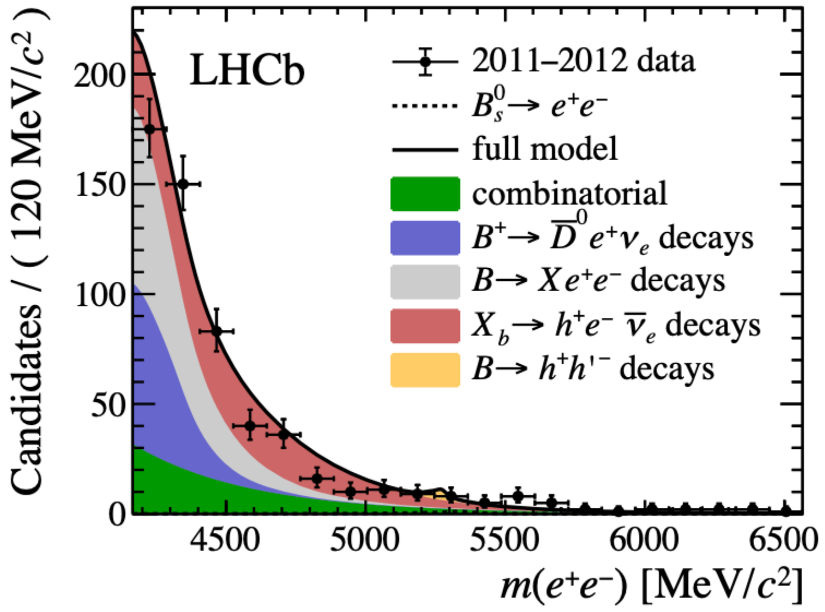


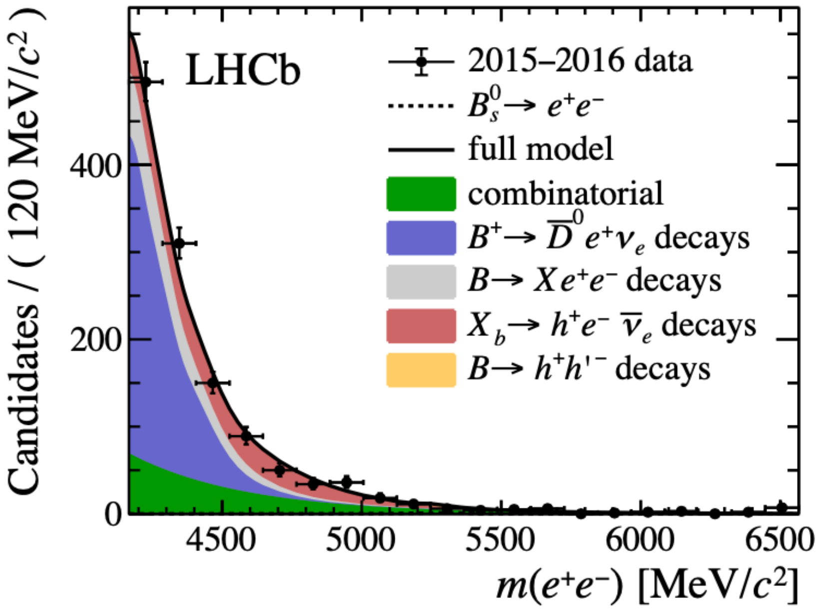
ee



LHCb-PAPER-2020-001

Not enough mass resolution to separate B_d from B_s





$$\mathcal{B}(B_s^0 \to e^+e^-) < 9.4\,(11.2) \times 10^{-9} \text{ at } 90\,(95)\,\% \text{ confidence level}$$

($5\ fb^{-1}$)

5 orders of magnitude wrt to SM

The top quark at an e+ e- collider with $\sqrt{s}$=10 GeV in 1987 !

$e^+ e^- \to \Upsilon(4S) \to B\bar{B}$ at $\sqrt{s}$ = 10.58 GeV

Production of coherent $B\bar{B}$ pairs

First hint of a *really large* m_{top}!

Argus Collaboration
Phys Lett B 192 p454

$$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$$

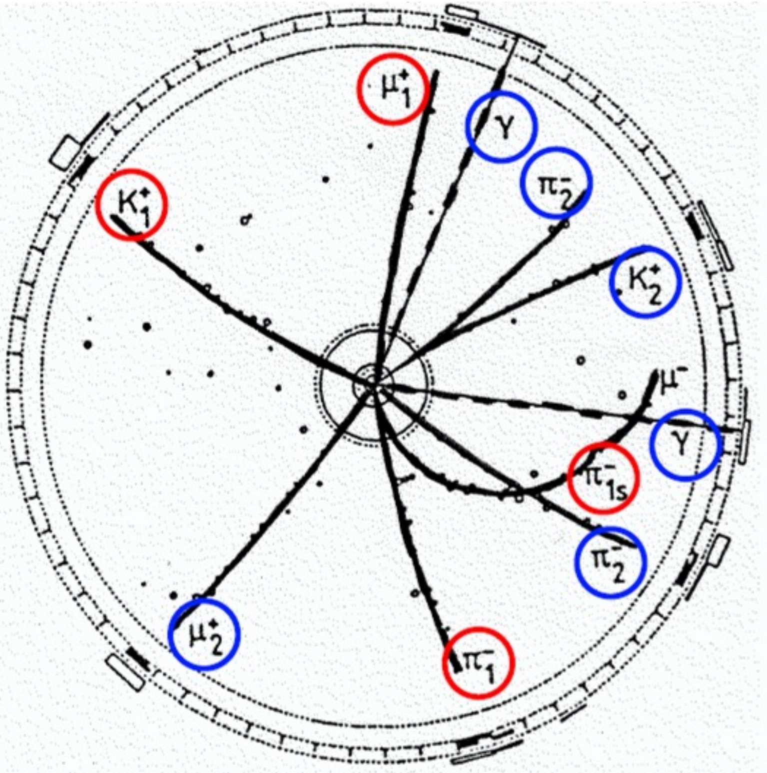
$$\approx 0.5 \mathrm{ps}^{-1}$$

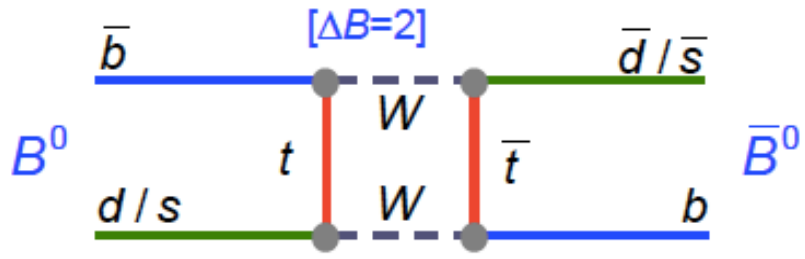
$\Rightarrow m_t > 50$ GeV

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

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

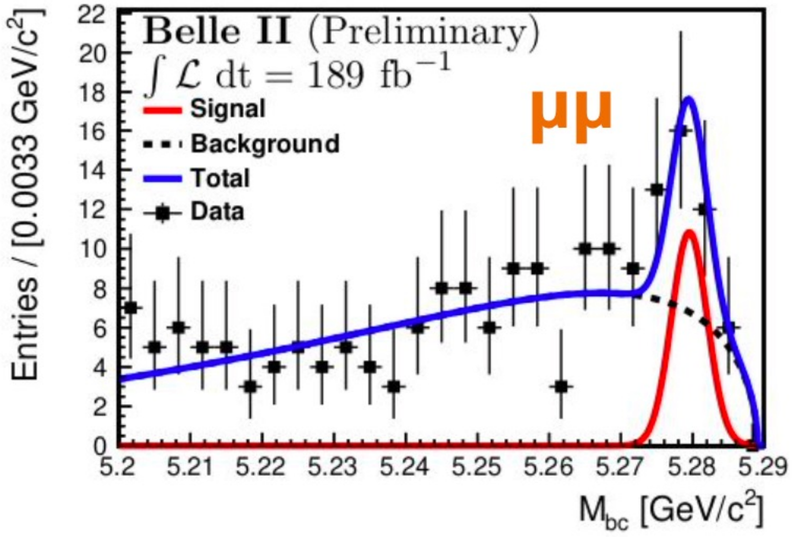
Fig. 11: The fully reconstructed ARGUS event [26] $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0 \to B^0 B^0$ as the first evidence for the occurance of $B^0\bar{B}^0$ oscillations.
$B^0 \to D_1^{*-} \mu_1^+ \nu_1$,
$D_1^{*-} \to \pi_{1s}^- \bar{D}^0$, $\bar{D}^0 \to K_1^+ \pi_1^-$.
$\bar{B}^0 \to B^0 \to D_2^{*-} \mu_2^+ \nu_2$,
$D_2^{*-} \to \pi^0 D_2^-$,
$\pi^0 \to \gamma\gamma$, $D_2^- \to K_2^+ \pi_2^- \pi_2^-$.

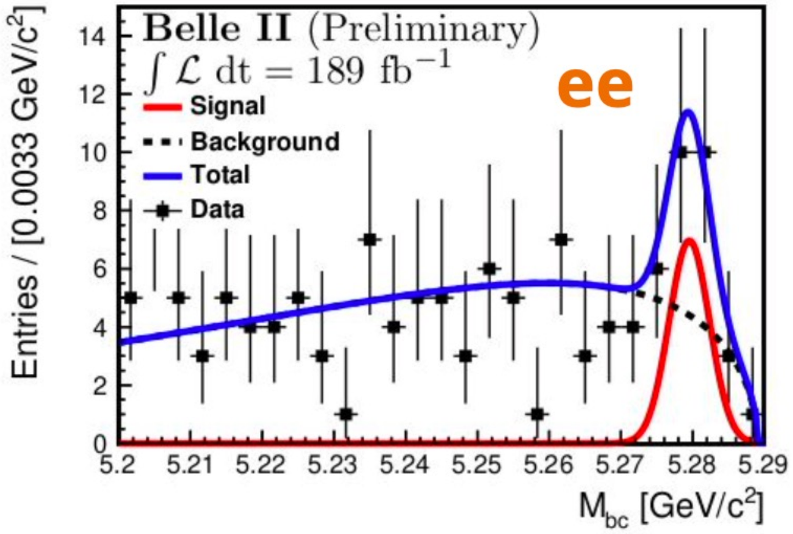




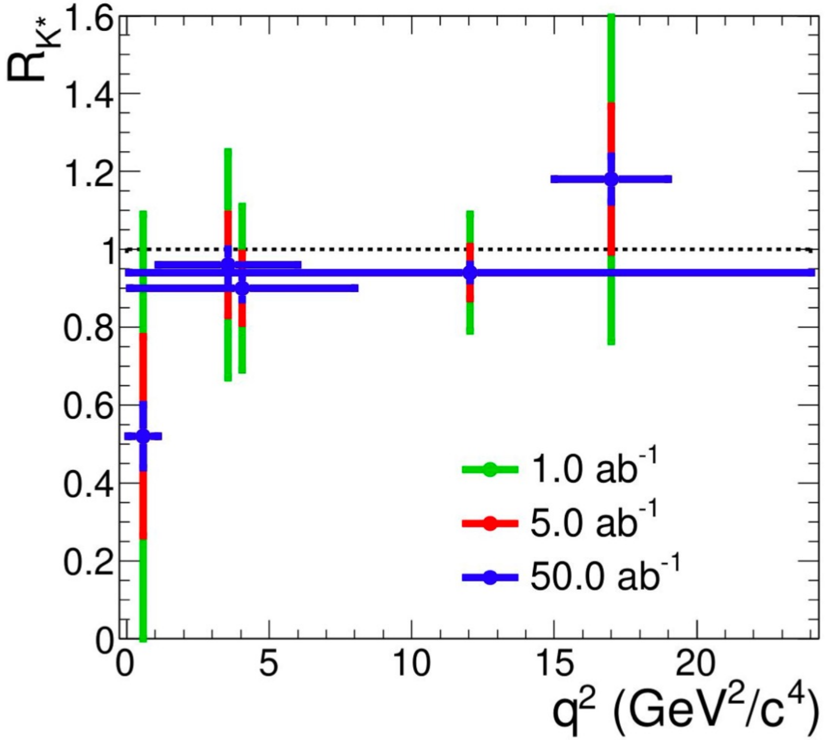
Belle-II prospects on R(K) and R(K*)

R(K*) status





~3% precision for q2 bin [1-6] for 50 ab^{-1} of data



(ee) and (μμ) similar !

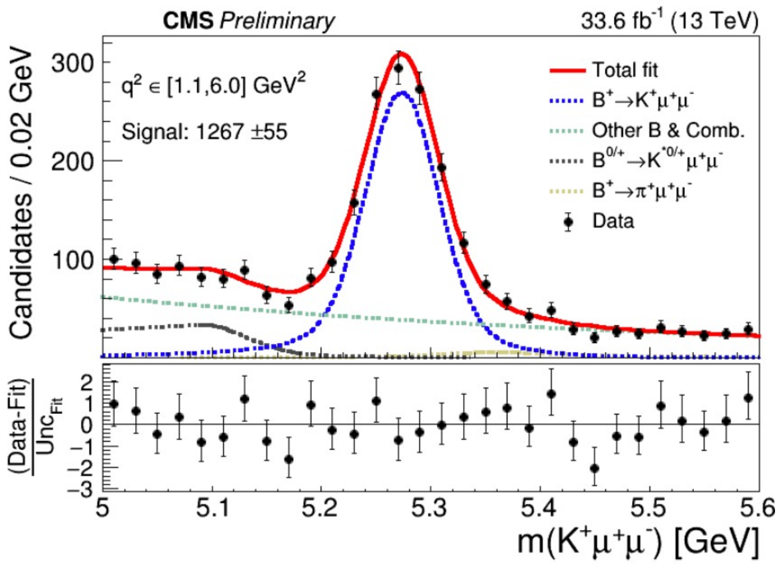
One recent CMS result (EPS 2023)

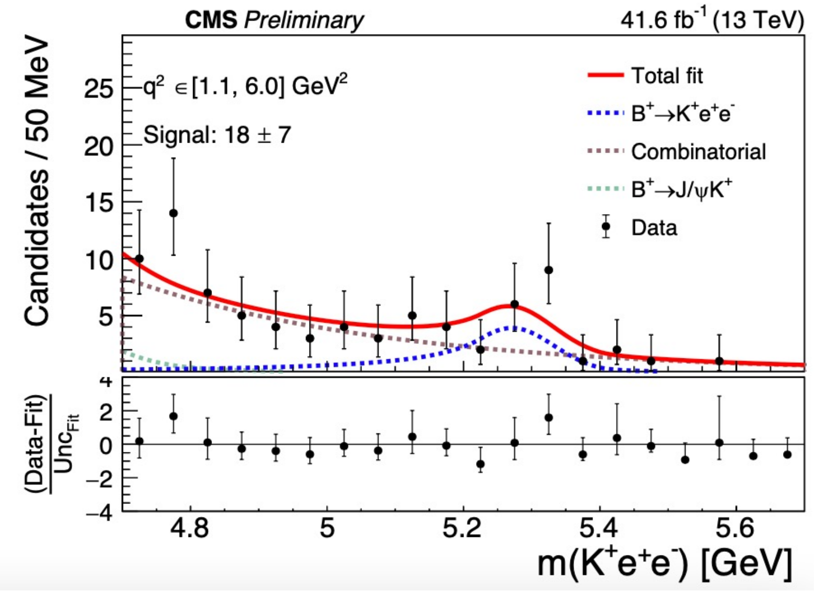
R(K) in the $1.1 < q^2 < 6.0$ GeV^2 range

$$R_K = \frac{BF(B \to \mu\mu K)}{BF(B \to J/\psi K, J/\psi \to \mu\mu)} \Big/ \frac{BF(B \to eeK)}{BF(B \to J/\psi K, J/\psi \to ee)}$$

$$R(K) = 0.78^{+0.46}_{-0.23}\,(\text{stat})^{+0.09}_{-0.05}\,(\text{syst})$$

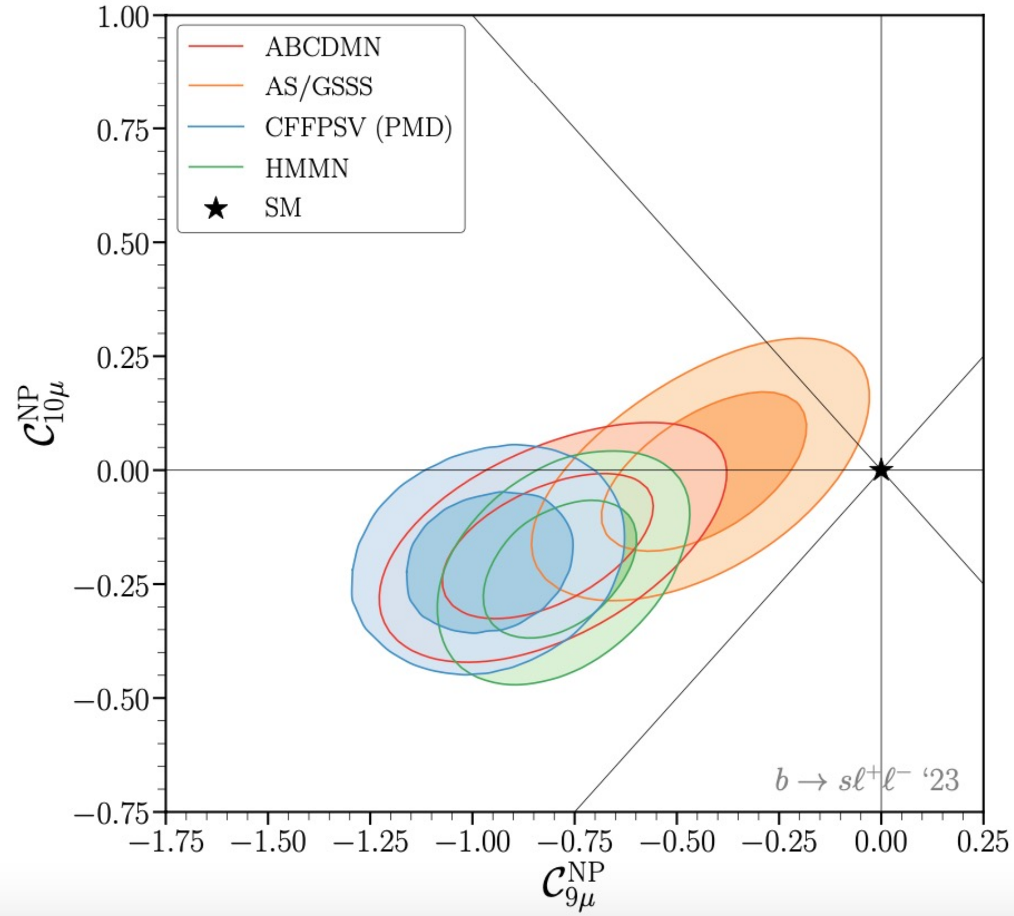
In agreement with SM





- Several fitters, they differs by:
  - Choice of experimental inputs
  - Form factors modelling
  - Treatment on non-local nuisance parameters
  - Statistical frameworks

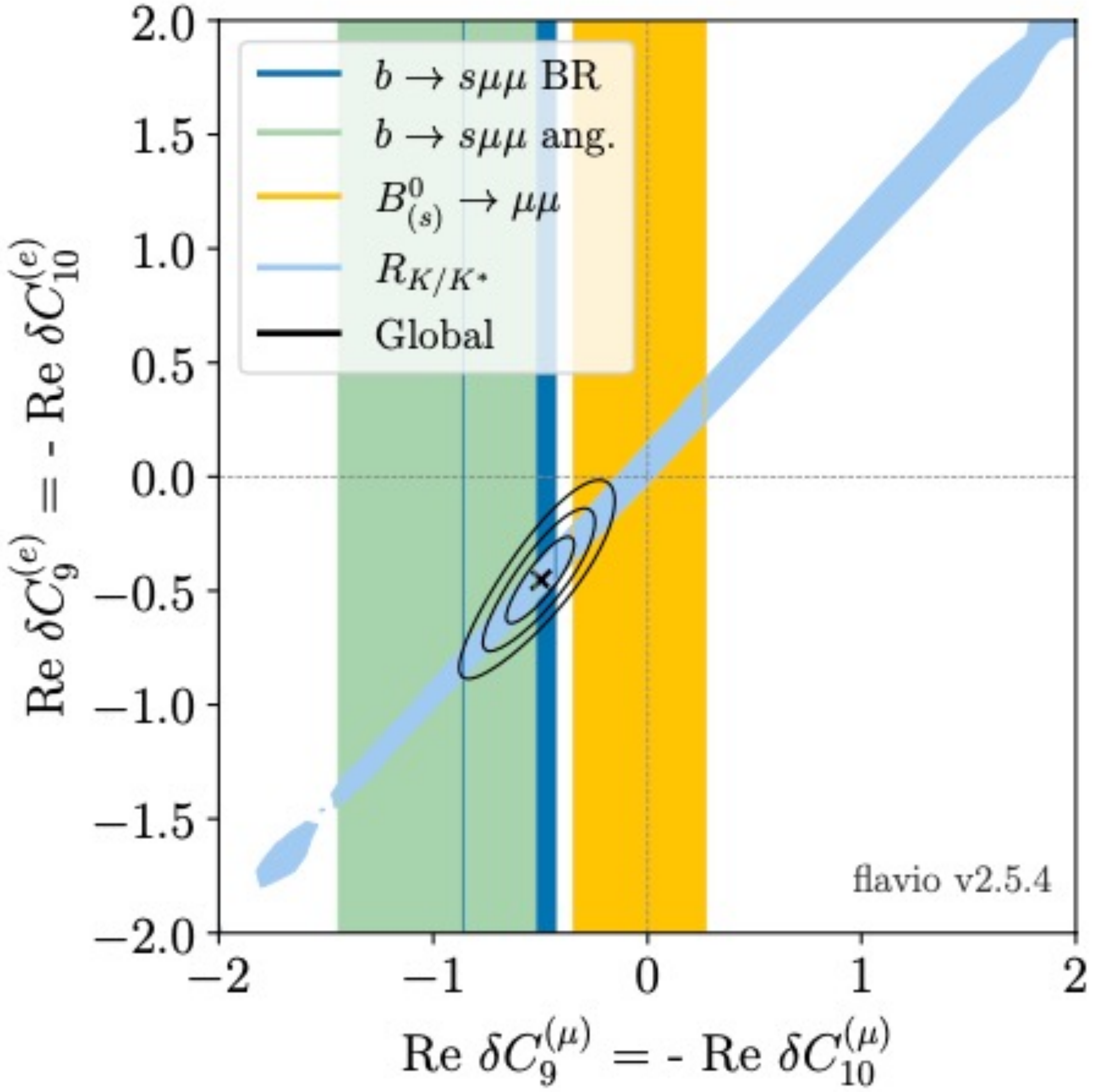
2-dimensional global fits



From B Capdevila FPCP2023

$\delta C_9^{(\ell)} = -\delta C_{10}^{(\ell)} \equiv \delta C_{LL}^{(\ell)}/2$ NP in e and μ

from Camille Normand
PhD thesis (2023)



shifts in Wilsons Coefficients should be the same for electrons and muons

What to expect with HL-LHC?

Additional observables:

- effective lifetime $\tau_{\mu\mu}$ precision for LHCb : 8% for 23 fb^{-1} and 2 % with 300 fb^{-1}

- time dependent CP asymmetry (sensitive to NP phase) . Accessible only to LHCb with 300 fb^{-1}

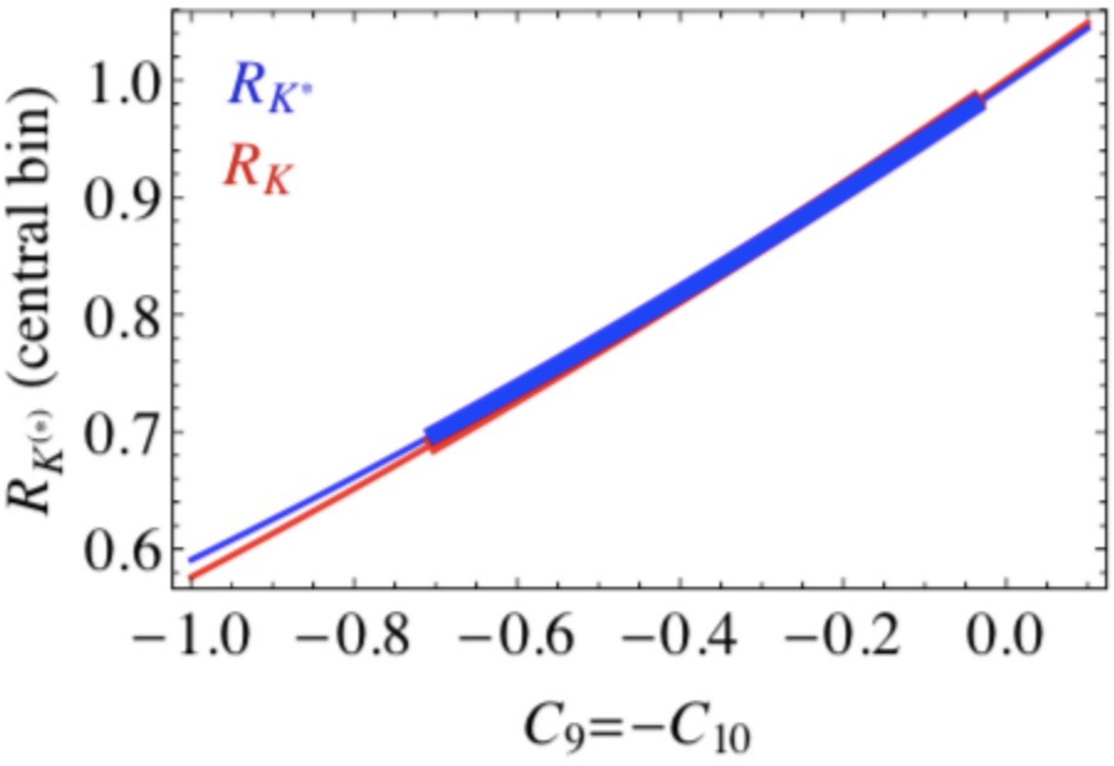
		$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
Experiment	Scenario	stat + syst %	stat + syst %
LHCb	23 fb^{-1}	8.2	33
LHCb	300 fb^{-1}	4.4	9.4
CMS	300 fb^{-1}	12	46
CMS	3 ab^{-1}	7	16
ATLAS	Run 2	22.7	135
ATLAS	3 ab^{-1} Conservative	15.1	51
ATLAS	3 ab^{-1} Intermediate	12.9	29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

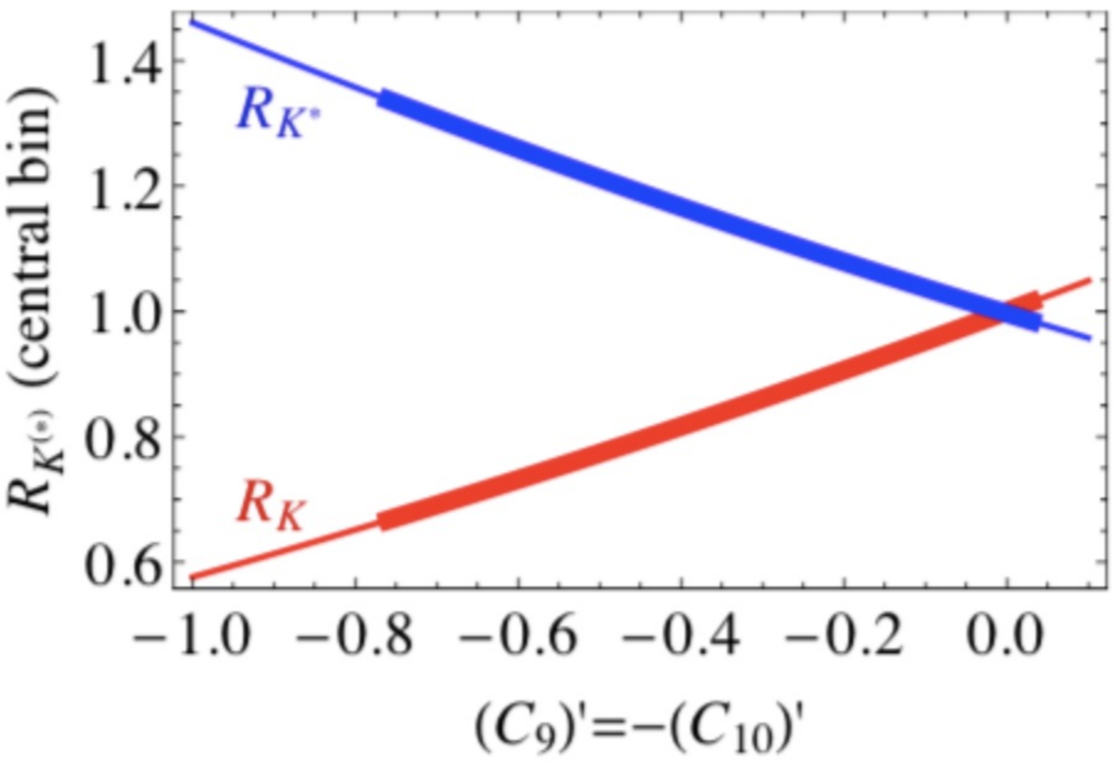
LHCb

$BR(B_d \to \mu^+\mu^-)$ still dominated by statistical uncertainty

$BR(B_s \to \mu^+\mu^-)$: stat~ 1.8 % syst ~ 4 % (f_s/f_d)

$BR(B_d \to \mu^+\mu^-)$/ $BR(B_s \to \mu^+\mu^-)$: much more precisely predicted. Measurement precision ~ 10%





From Damir Becirevic (Gif 2018)