UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

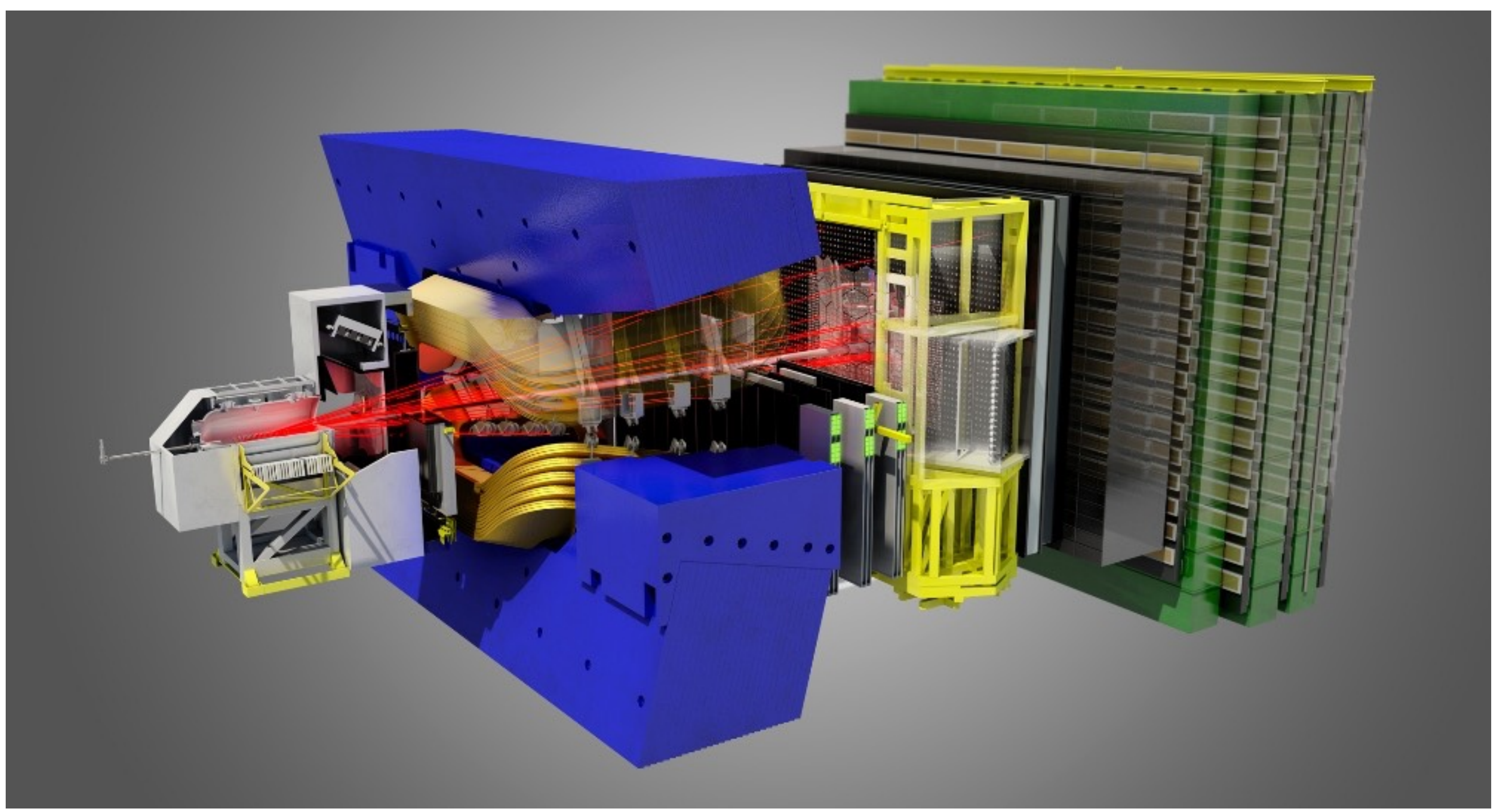
…based in Milano Bicocca from June

Status and perspectives of physics at high intensity

INFN Frascati - 9 Nov 2022

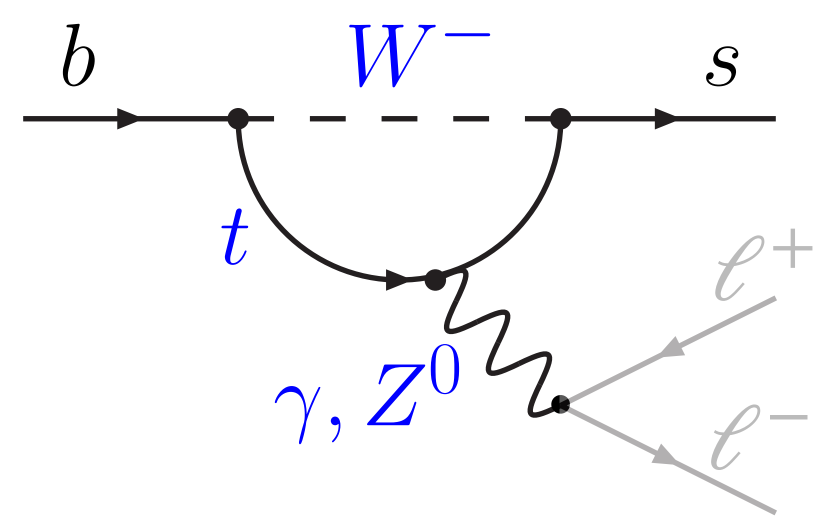
Electroweak penguin decays at LHCb

Martino Borsato



EW Penguins

EW penguins in $b \to s$ transitions



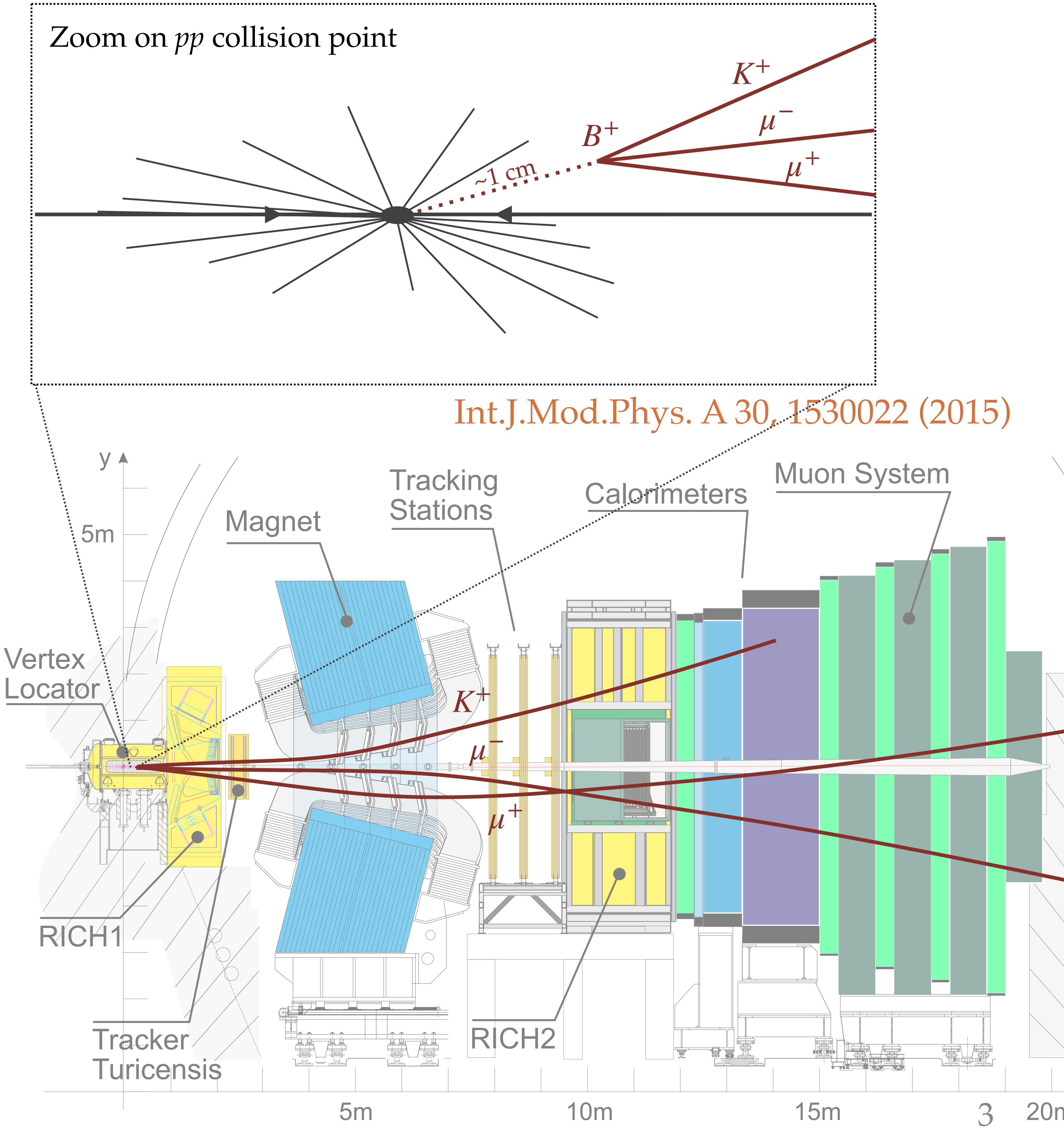
- **Rare** (decay rate 10^{-5} to 10^{-7})
  - Forbidden at tree-level, proceeds through loop
  - Small CKM elements and GIM mechanism
  - Heavy NP could enter at the same order as SM
- **Friendly** (to experiments)
  - No neutrinos involved (modulo $\nu\nu$ and $\tau\tau$)
  - Several complementary channels
  - Several complementary observables
- **Beautiful** (involves a b quark)
  - Small long-distance contributions ($m_b \gg \Lambda_{\text{QCD}}$)
  - Can interpret with effective theory ($m_b \ll m_W$)

$B \to K^*\gamma$, $B \to K^{(*)}\ell^+\ell^-$,
$B_s \to \phi\gamma$, $B_s \to \phi\ell^+\ell^-$
$\Lambda_b \to pK^-\ell^+\ell^-$, ...

Branching ratios,
angular analyses,
SM symmetry tests

(no time to cover LHCb contributions to Charm ($c \to u$) and Strange ($s \to d$) EW penguins)

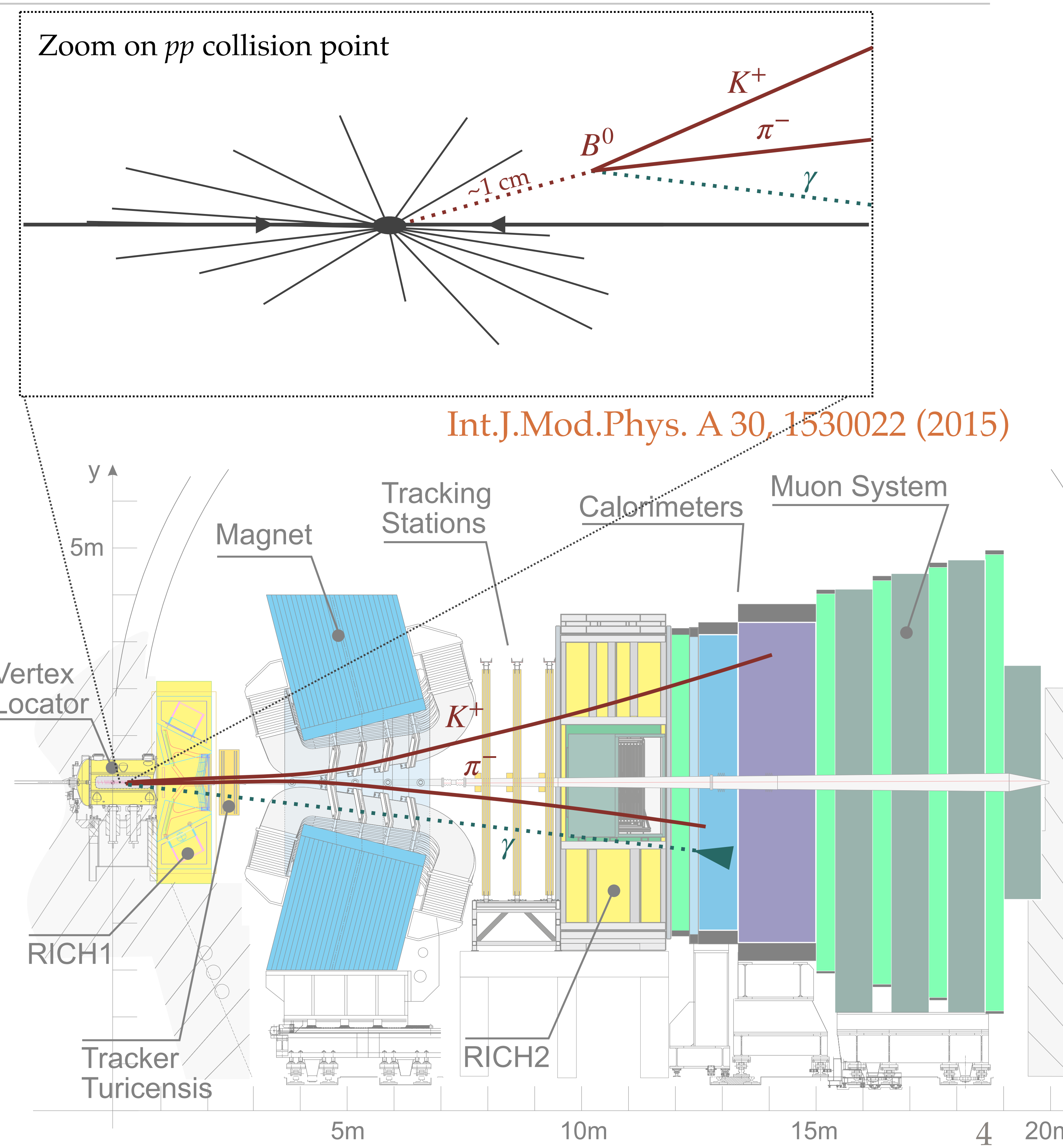
The LHCb experiment



Excellent for EW penguins

- About 10^{12} $b\bar{b}$ in the acceptance (integrated $\mathscr{L} = 9$ fb^{-1})
- Very displaced b vertices thanks to large forward boost $\beta\gamma \sim 20$
- Precise momentum and PID for charged tracks

The LHCb experiment

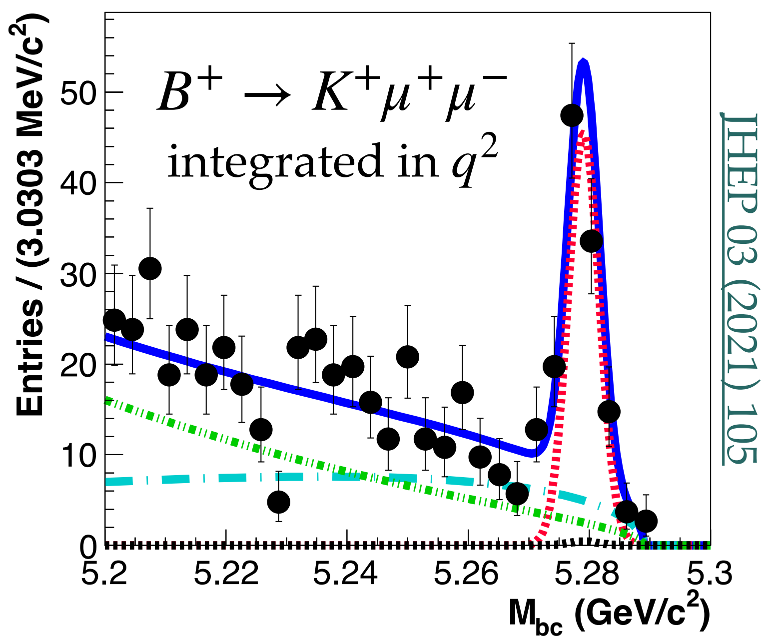


Excellent for EW penguins

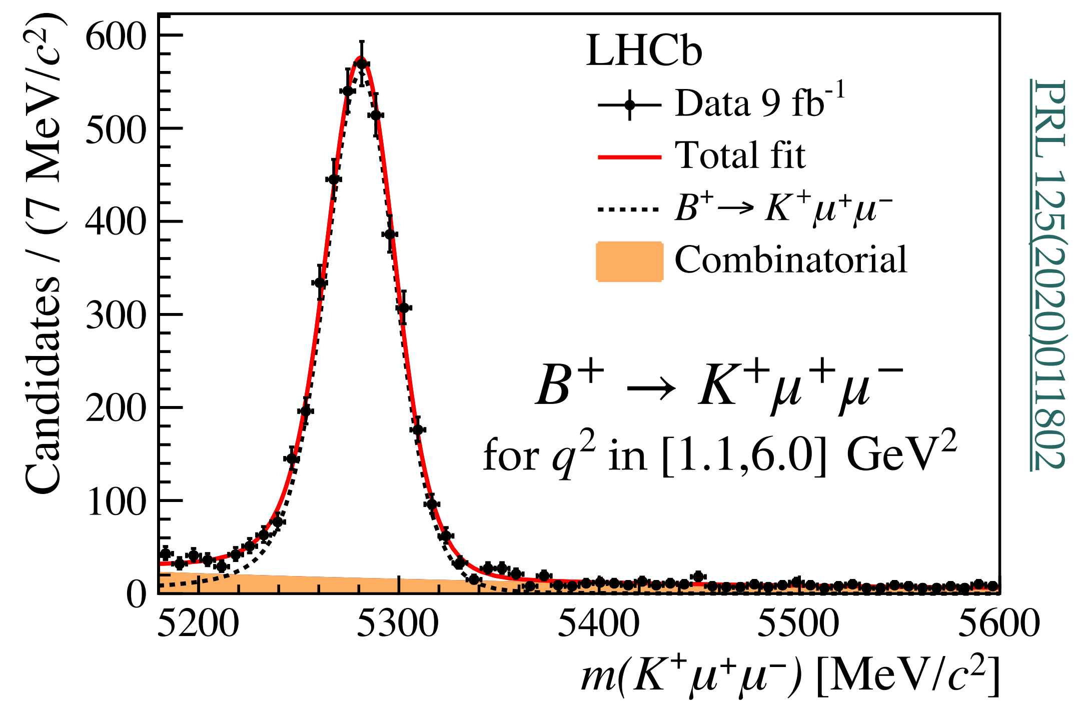
- About 10^{12} $b\bar{b}$ in the acceptance (integrated $\mathscr{L} = 9$ fb^{-1})
- Very displaced b vertices thanks to large forward boost $\beta\gamma \sim 20$
- Precise momentum and PID for charged tracks
- A bit more complicated for **photons**

The strength of LHCb

Belle



LHCb



- A comparison for $B \to K^+\mu^+\mu^-$ for $q^2 \in [1, 6]$ GeV^2
  - Belle could collect **~10 events/year** (assuming 200 fb^{-1}/year)
  - LHCb (Run2) collected **~1000 events/year** (assumig 2 fb^{-1}/year)
- Belle (2) contribution essential for other $b \to s\ell\ell$ channels: e.g. $b \to s\nu\nu$, $b \to s\tau\tau$, other final states with neutrals…

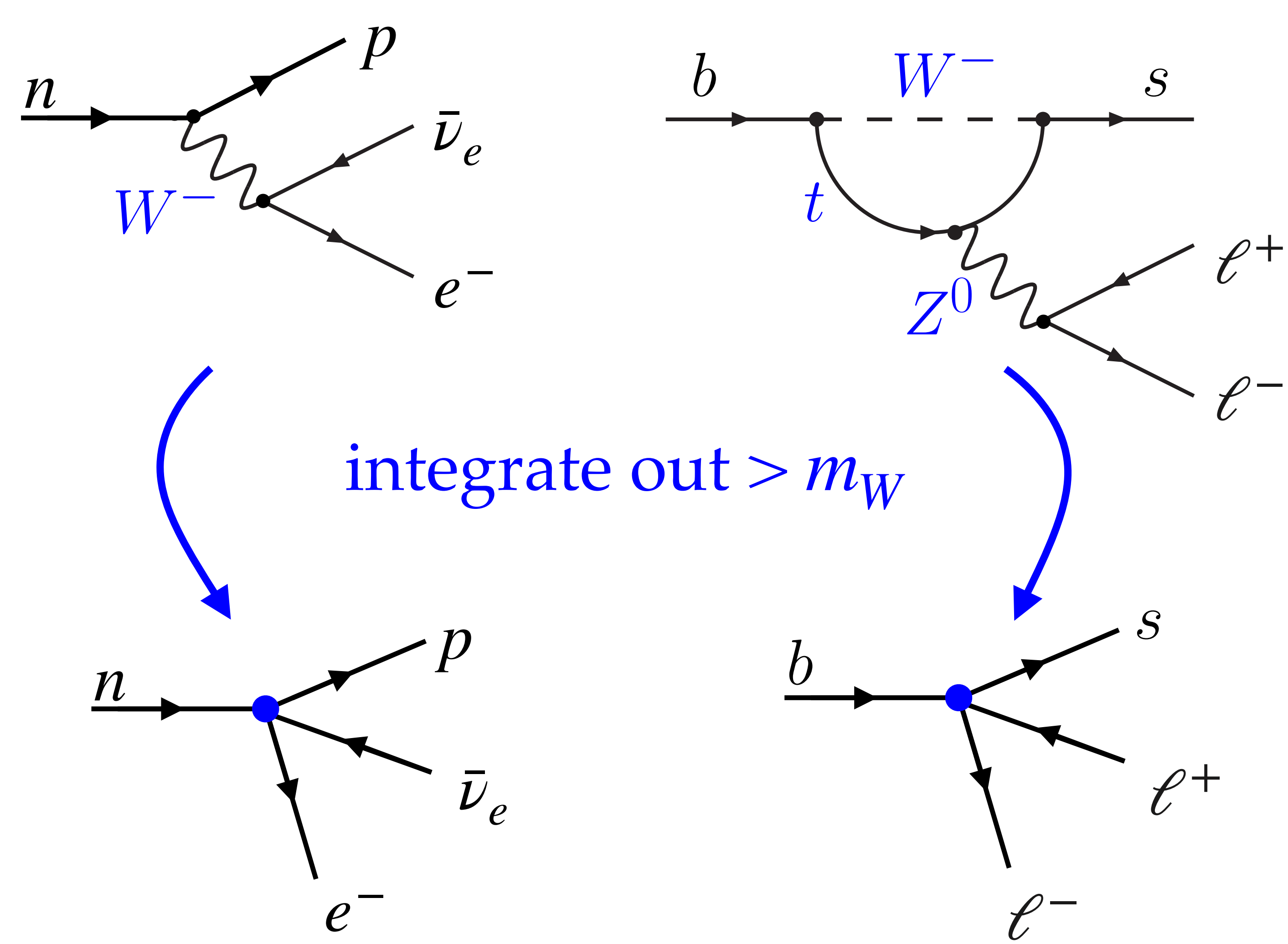
Weak effective theory

- Integrate out $> m_W$
- Four-fermion interaction described by effective couplings

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

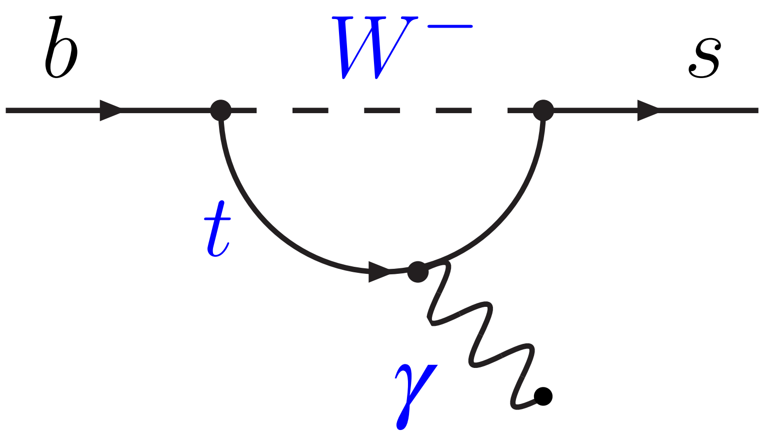
- Main SM contributions:
  - **Vector** (C_9) and **Axial-vector** (C_{10}) leptonic currents
  - Dipole $b \to s\gamma^*$ contribution in C_7 $\to$ well constrained by radiative
- Suppressed in the SM:
  - Right-handed quark currents C_i'
  - Spin-0 leptonic currents C_S and C_P

β decay $\qquad b \to s\ell\ell$



$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

$b \to s\gamma$ at LHCb



$C_7^{(\prime)}$ at LHCb

Left-handed C_7

$$\mathrm{BR} \propto (C_7^{\mathrm{SM}} + C_7^{\mathrm{NP}})^2 + (C_7^{\prime\,\mathrm{NP}})^2$$

- 5% precise prediction only for inclusive BR (quark-level)
  M. Misiak et al JHEP 06(2020)175
- 5% precise inclusive BR — B-factories
  HFLAV average 2022

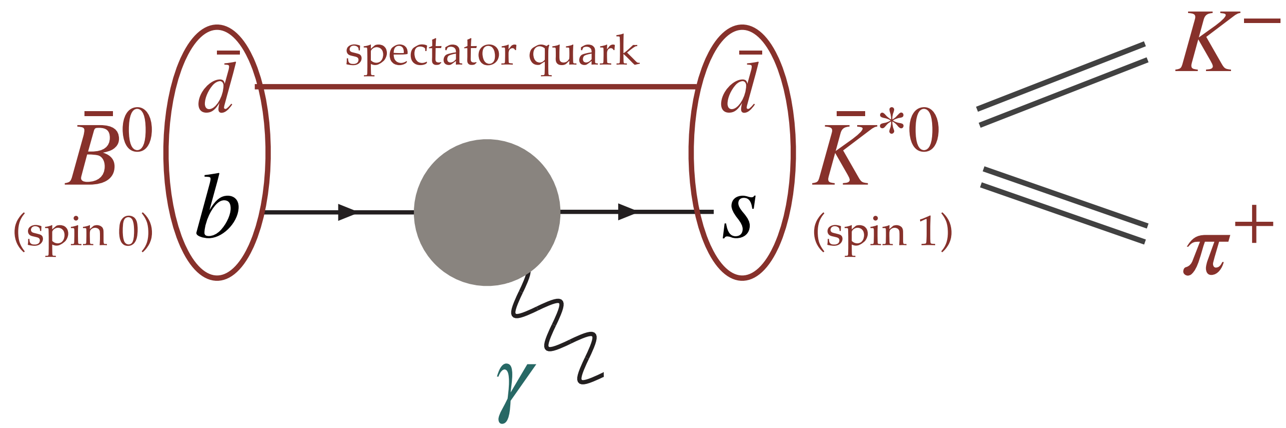
◉ ImC_7 measured with direct A_{CP}

- $B \to K_S\pi^0\gamma$ and similar — B-factories
  HFLAV average 2015
- Tagged time-dep. analysis of $B_s \to \phi\gamma$ — LHCb
  PRL 123 (2019) 8, 081802

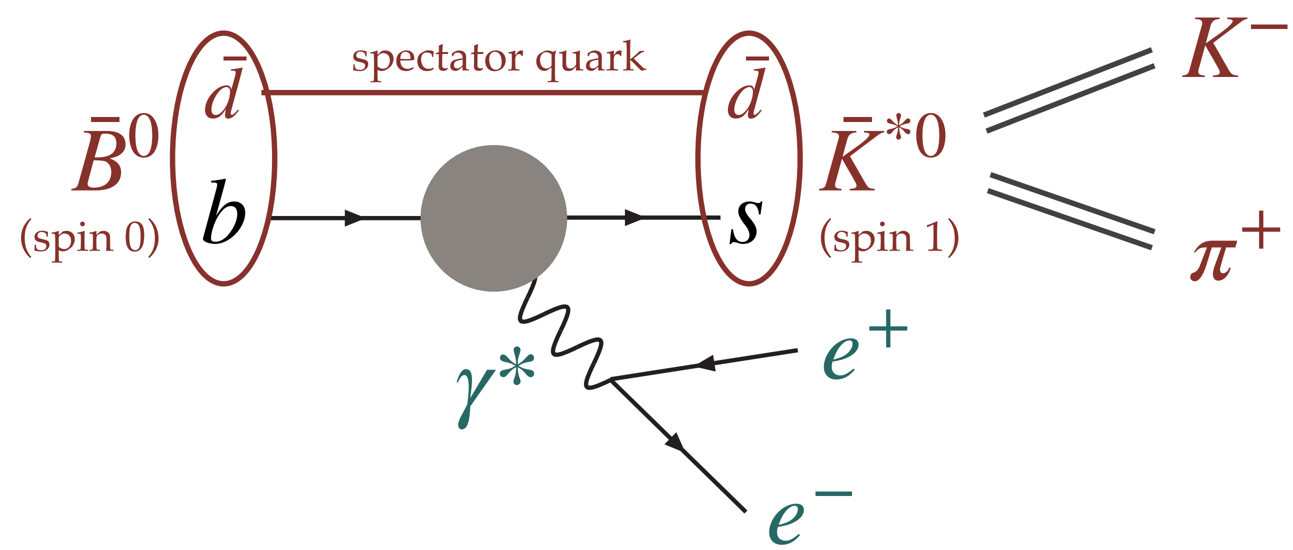
Right-handed C_7'

- Mixing induced CP asymm. in $B \to K_S\pi^0\gamma$ (et al) — B-factories
  HFLAV average 2015
- $\Delta\Gamma_s$ induced rate asymm. in $B_s \to \phi\gamma$ at LHCb — LHCb
  PRL 123 (2019) 8, 081802
- Transverse asymmetries in $B^0 \to K^* e^+e^-$ at LHCb — LHCb
  JHEP 12 (2020) 081
- Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb — LHCb
  PRD 105 (2022) 5, L051104
- Full amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ at LHCb — LHCb
  coming soon…

$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$



$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$



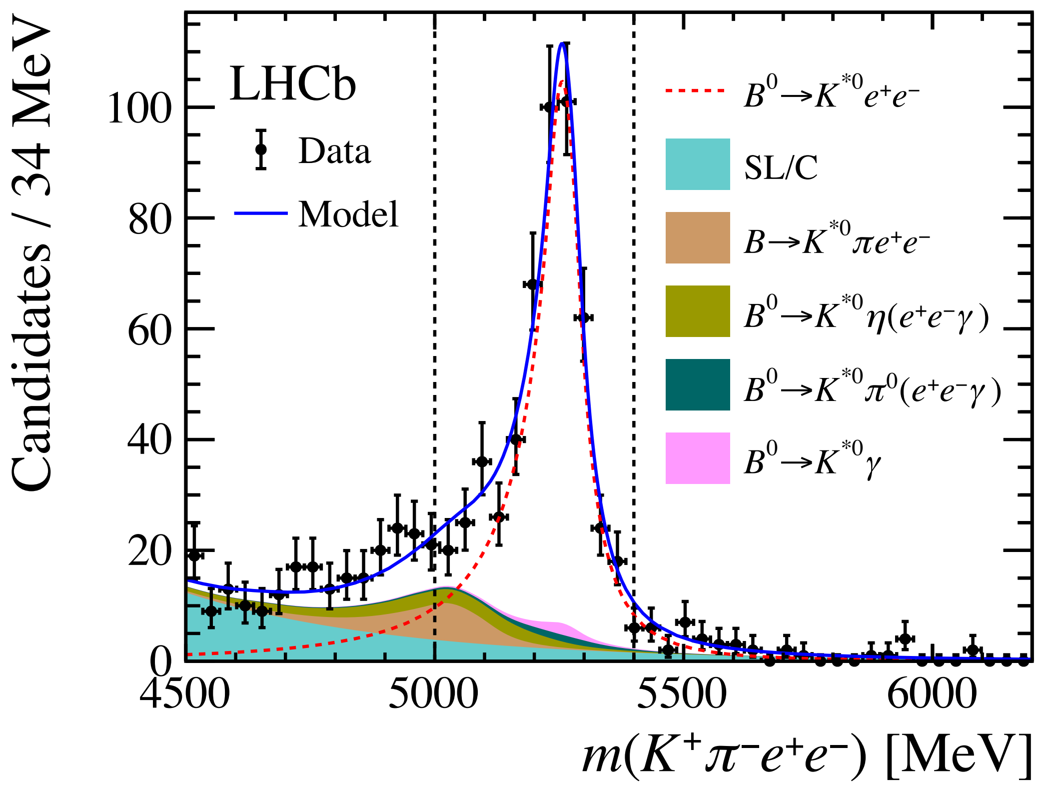
- ✓ Use $\gamma^* \to e^+e^-$ to measure photon polarisation!
- ✓ Get nice $K^-\pi^+e^-e^+$ final state
- ◉ Rate lower by $\alpha_{\text{e.m.}}$

$B^0 \to K^* e^+ e^-$ analysis

JHEP 12 (2020) 081

- Select $B^0 \to K^* \gamma^*$ with $\gamma^* \to e^+ e^-$ requiring $m(ee) < 0.5$ GeV
  - About 500 events with LHCb dataset despite BR $\sim 2 \times 10^{-7}$

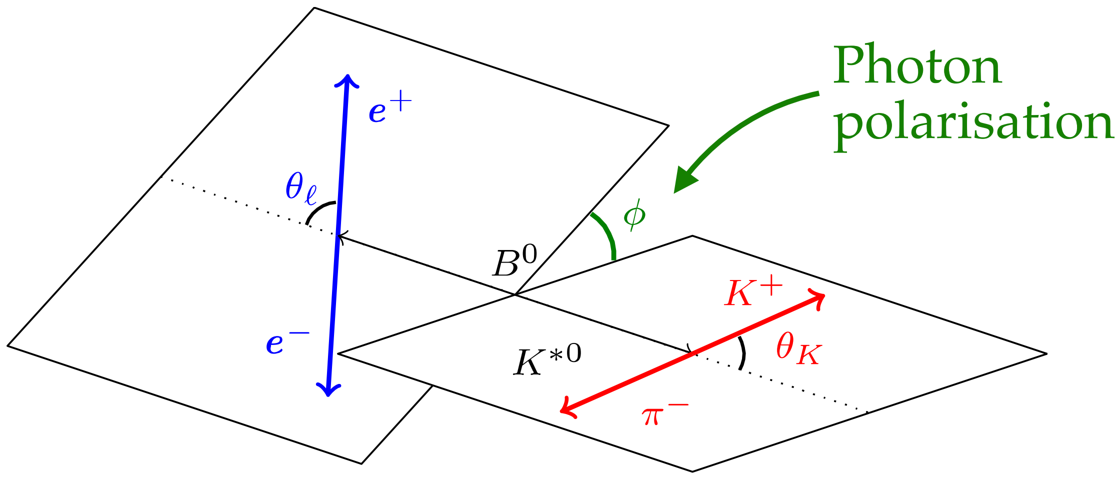
Made possible by developments in electron reconstruction at LHCb

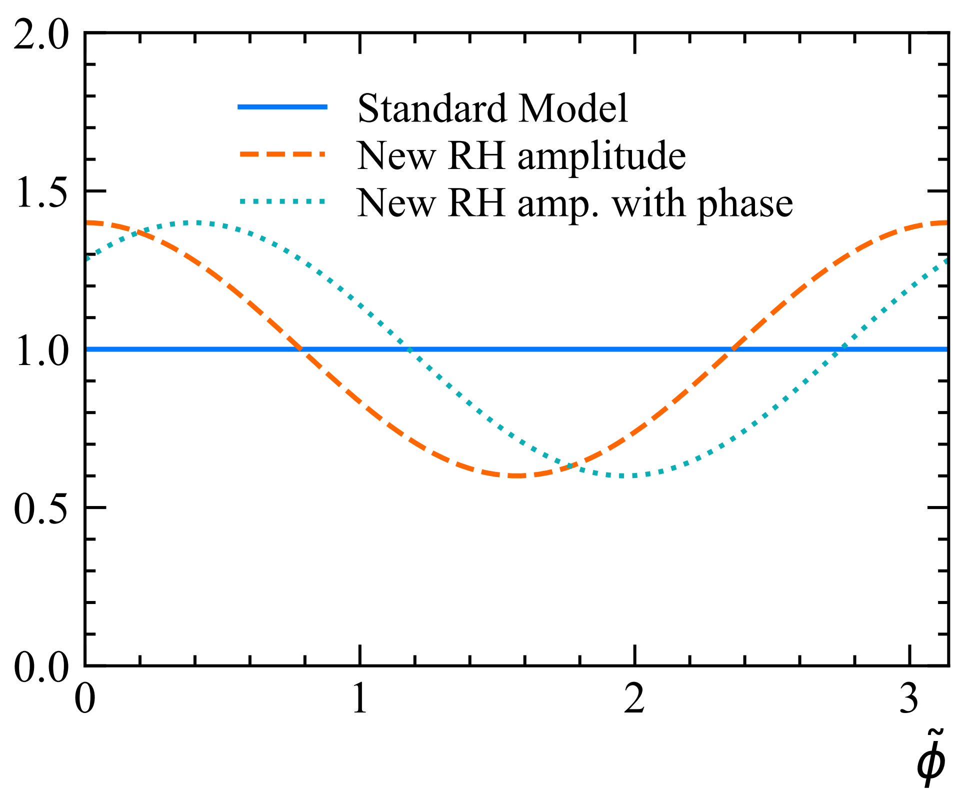


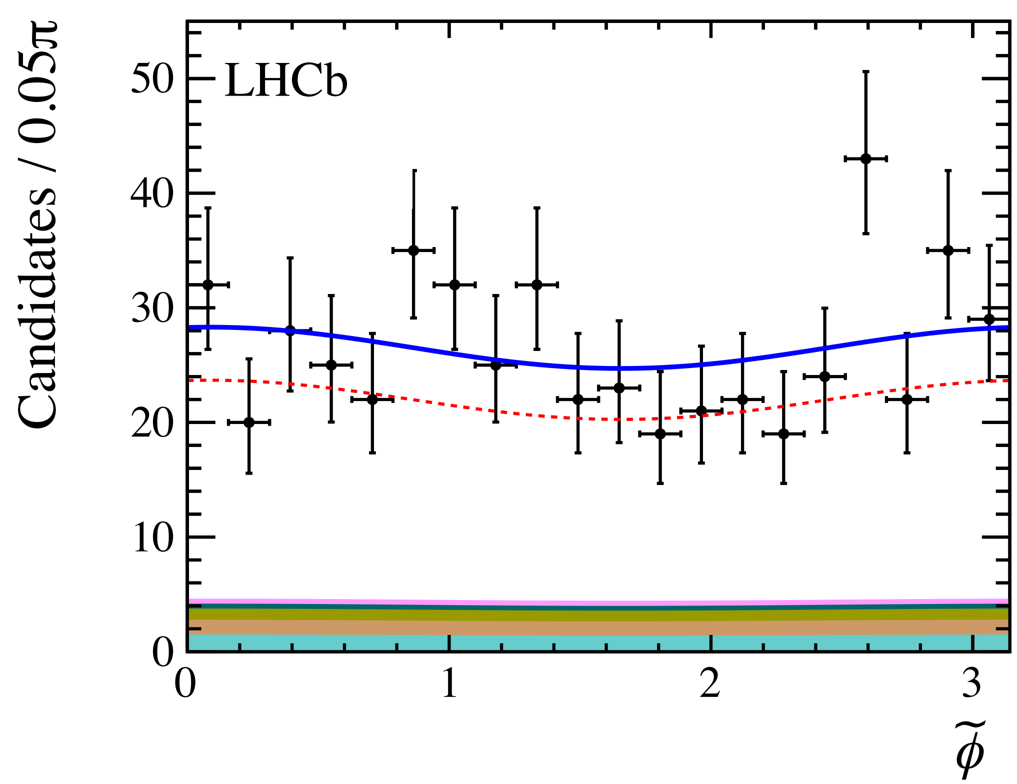
$B^0 \to K^* e^+ e^-$ analysis

JHEP 12 (2020) 081

- $B^0 \to K^+\pi^- e^+ e^-$ described by 3 angles
  $\to$ Full 3D angular analysis performed
- Photon polarisation measured with ϕ
  - $\cos 2\phi$ modulation (+phase) would signal right-handed contribution

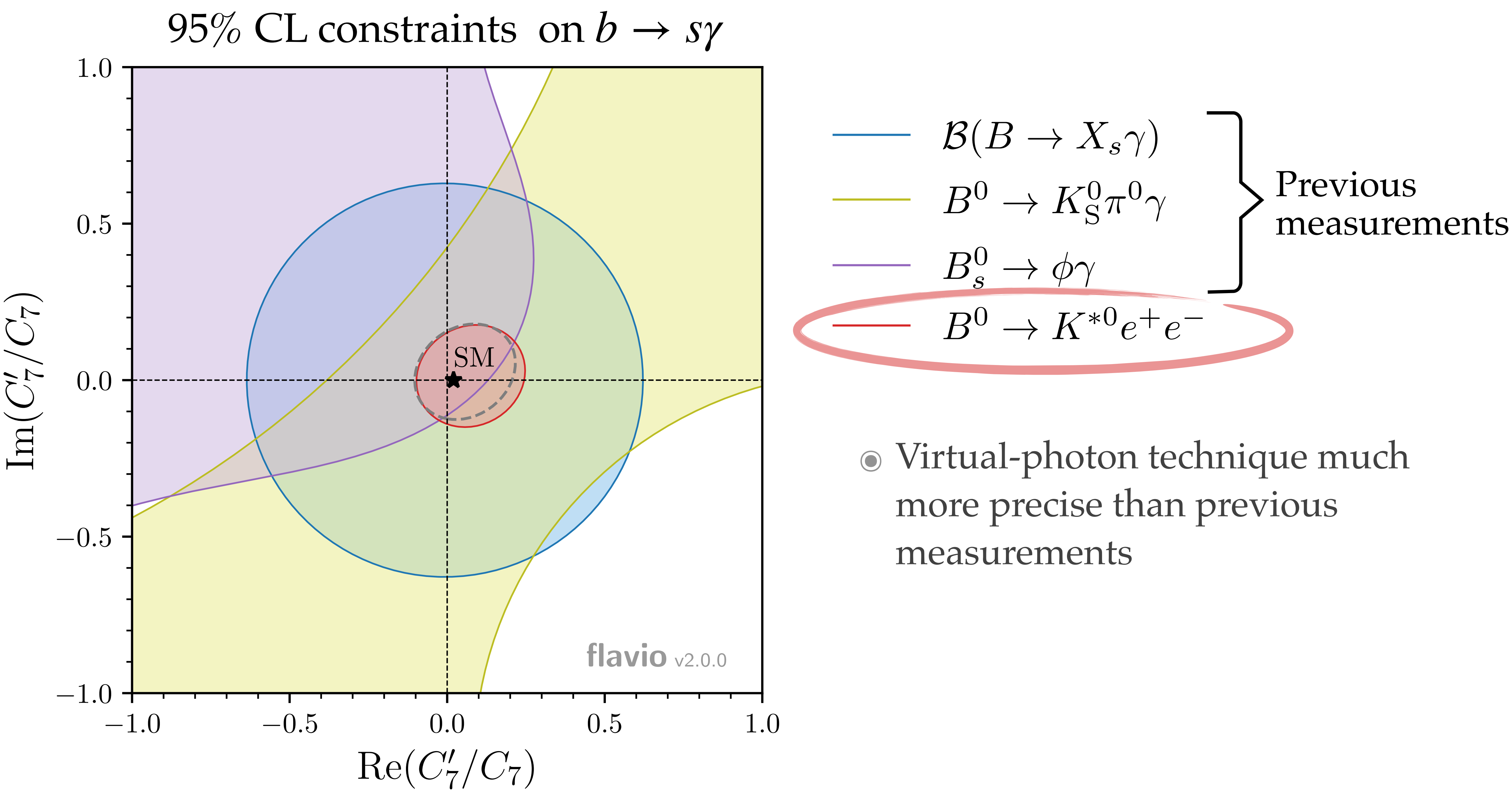






$B^0 \to K^* e^+ e^-$ analysis

JHEP 12 (2020) 081

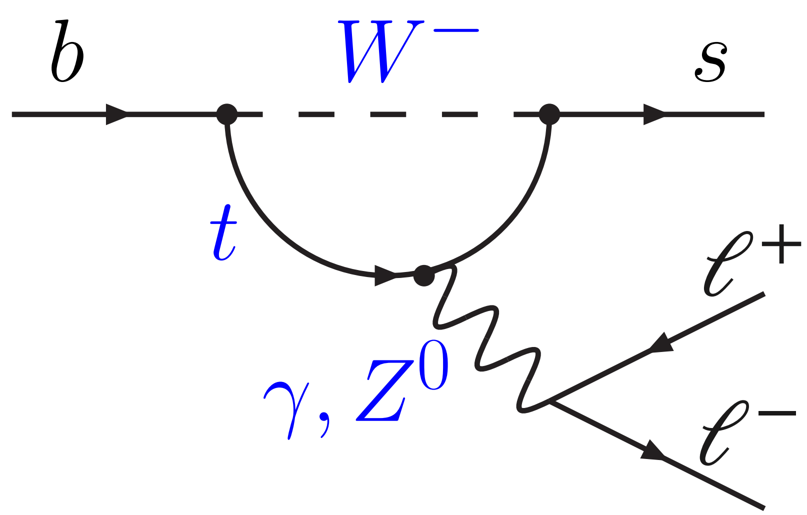


- Virtual-photon technique much more precise than previous measurements

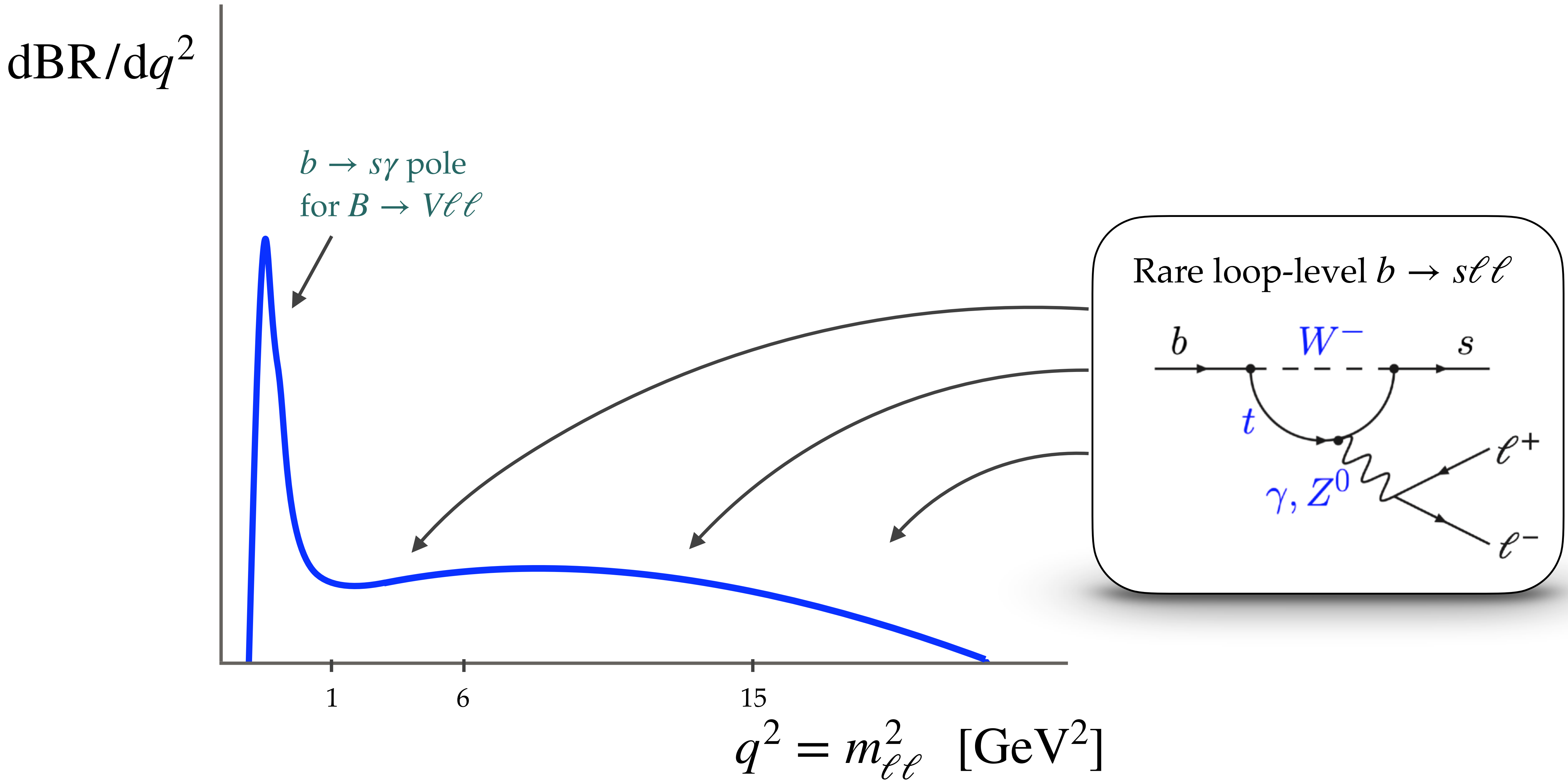
$C'_7/C_7 = \text{RH/LH}$

$C_7^{(\prime)}$ is $b \to s\gamma$ Wilson coefficient

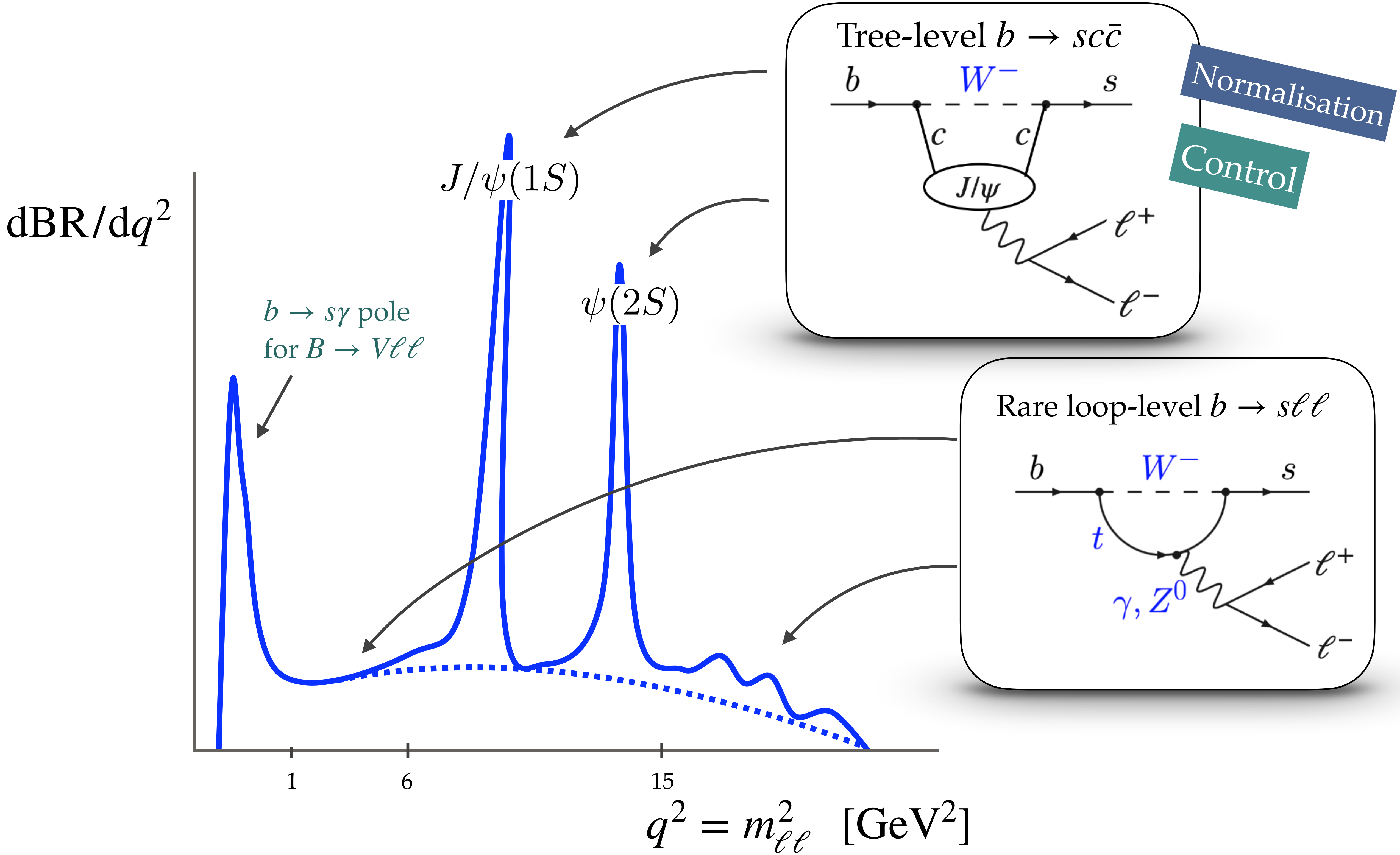
$b \to s\ell^+\ell^-$ at LHCb



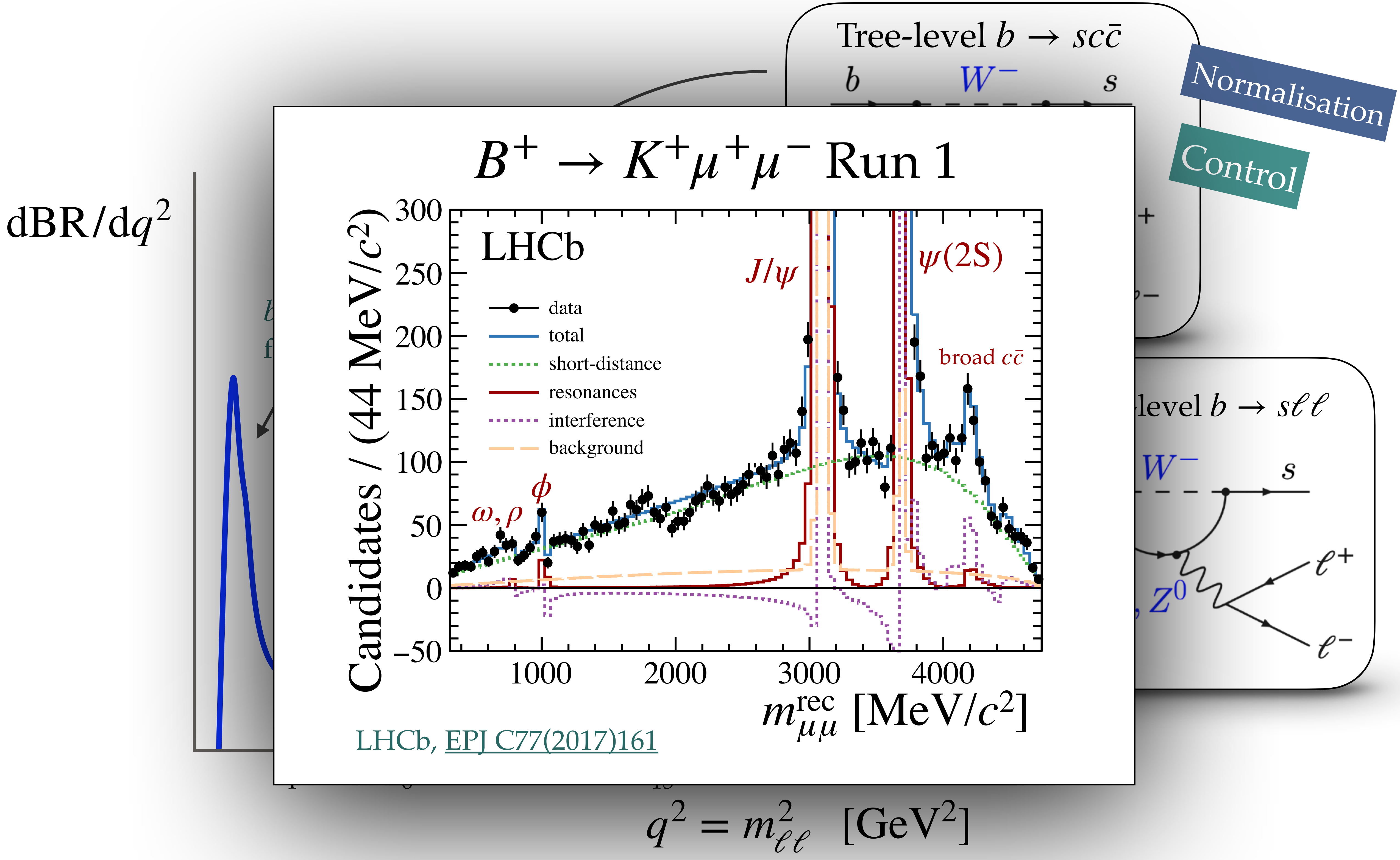
q^2 spectrum of $b \to s\ell\ell$



q^2 spectrum of $b \to s\ell\ell$

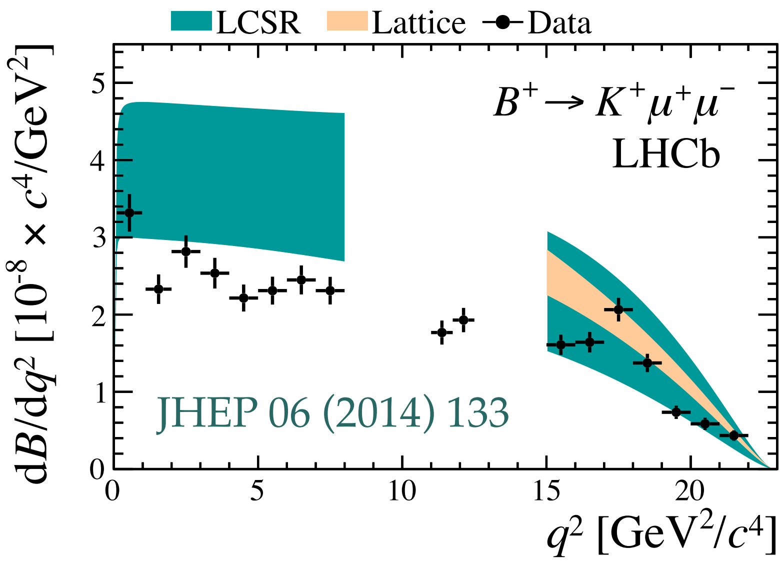


q^2 spectrum of $b \to s\ell\ell$

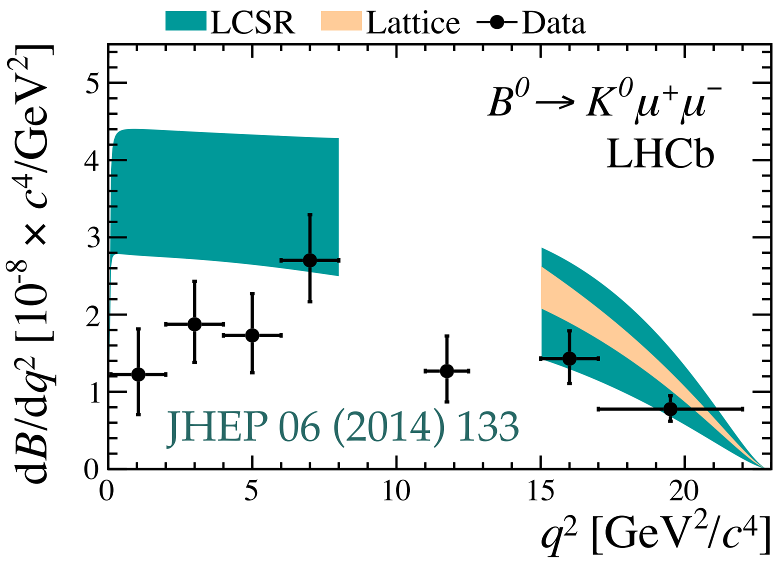


BR of semileptonic $b \to s\mu\mu$

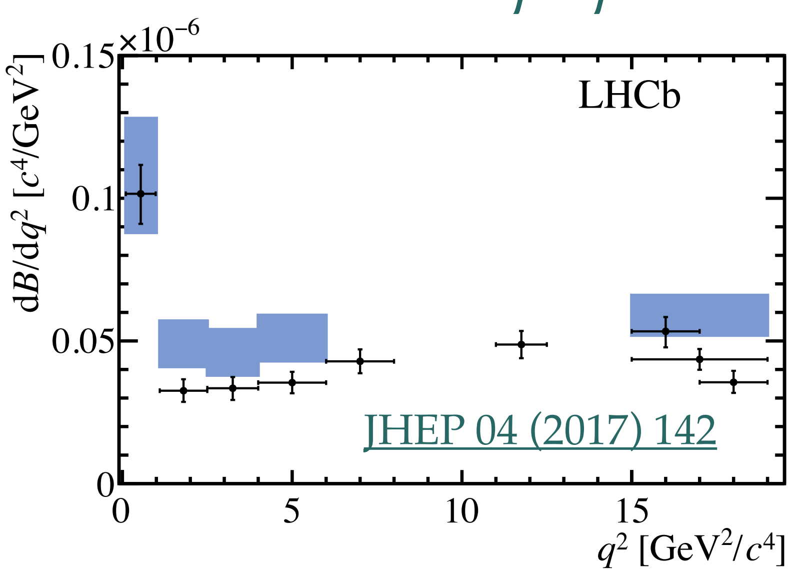
$B^+ \to K^+\mu^+\mu^-$



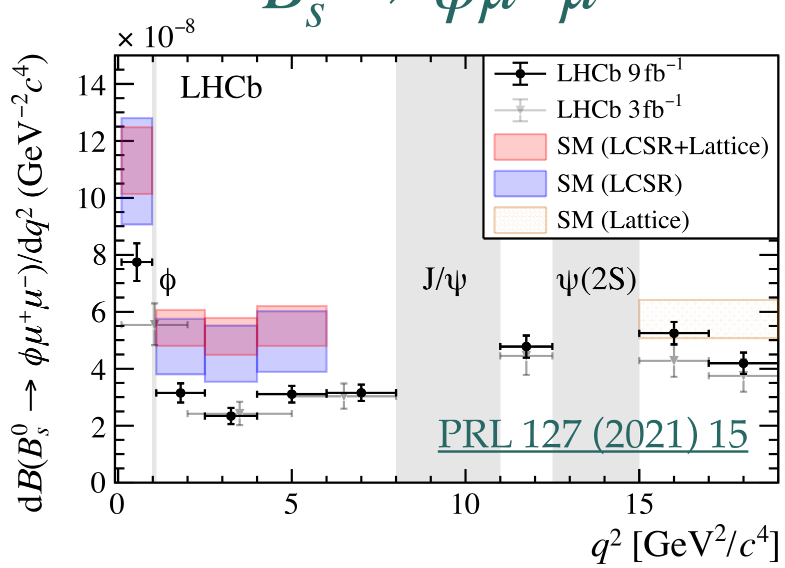
$B^0 \to K^0\mu^+\mu^-$



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



$B_s \to \phi\mu^+\mu^-$



dB/dq^2 in exclusive $b \to s\mu\mu$ seems to undershoot SM

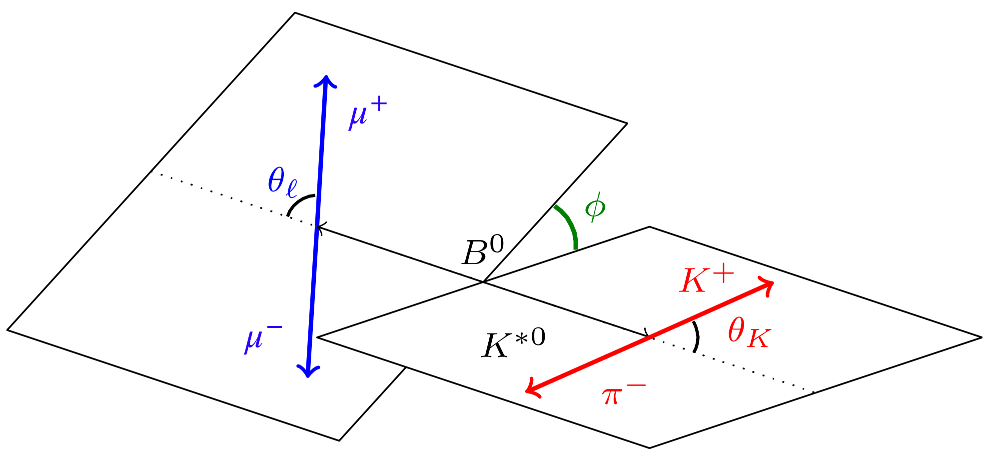
- Coherent undershooting, but predictions uncertainties are correlated
- Theory uncertainties ~20-30% (hadronic form factors)

Recent efforts to improve theoretical predictions

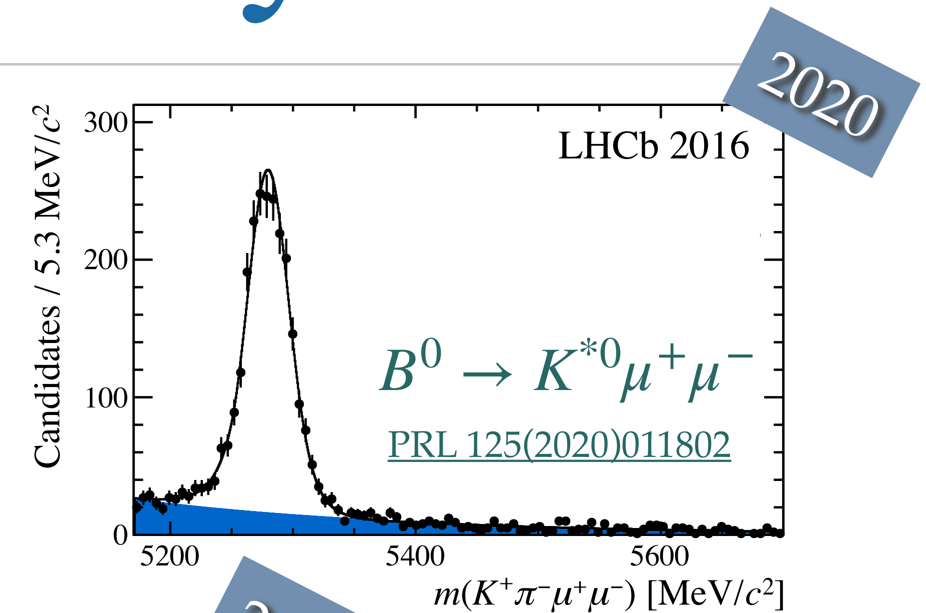
- Non-local corrections
  Gubernari et al, JHEP 09 (2022)
- Lattice QCD calculations
  HPQCD, arXiv:2207.13371

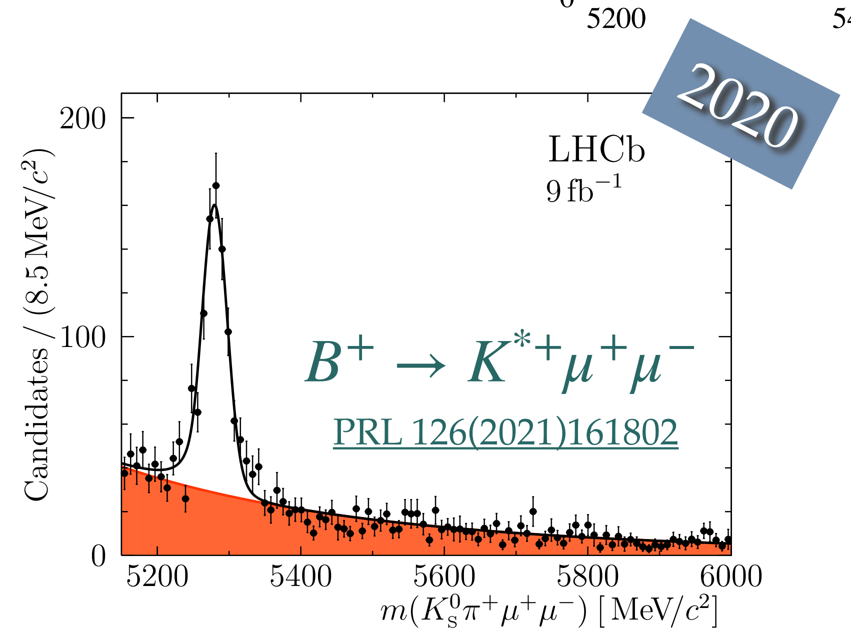
$b \to s\mu\mu$ angular analyses

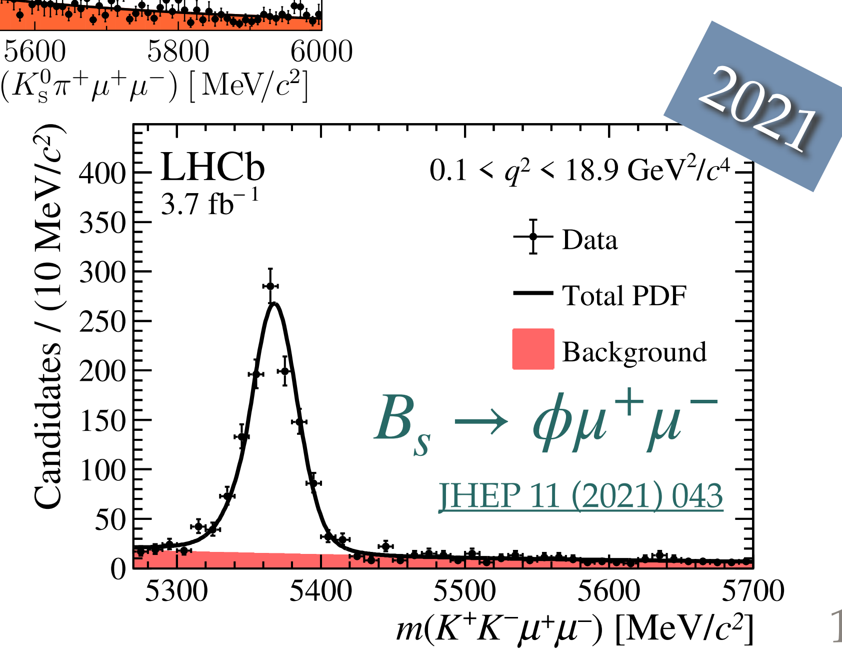
- $B \to V\mu^+\mu^-$ 4-body decay has rich kinematic structure to be studied
- Described by 3 angles and q^2



- Recent results:
  - $B^0 \to K^{*0}\mu^+\mu^-$ with 6/fb (~4600 events)
  - $B^+ \to K^{*+}\mu^+\mu^-$ with 9/fb (~700 events)
  - $B_s \to \phi\mu^+\mu^-$ with 9/fb (~1900 events)



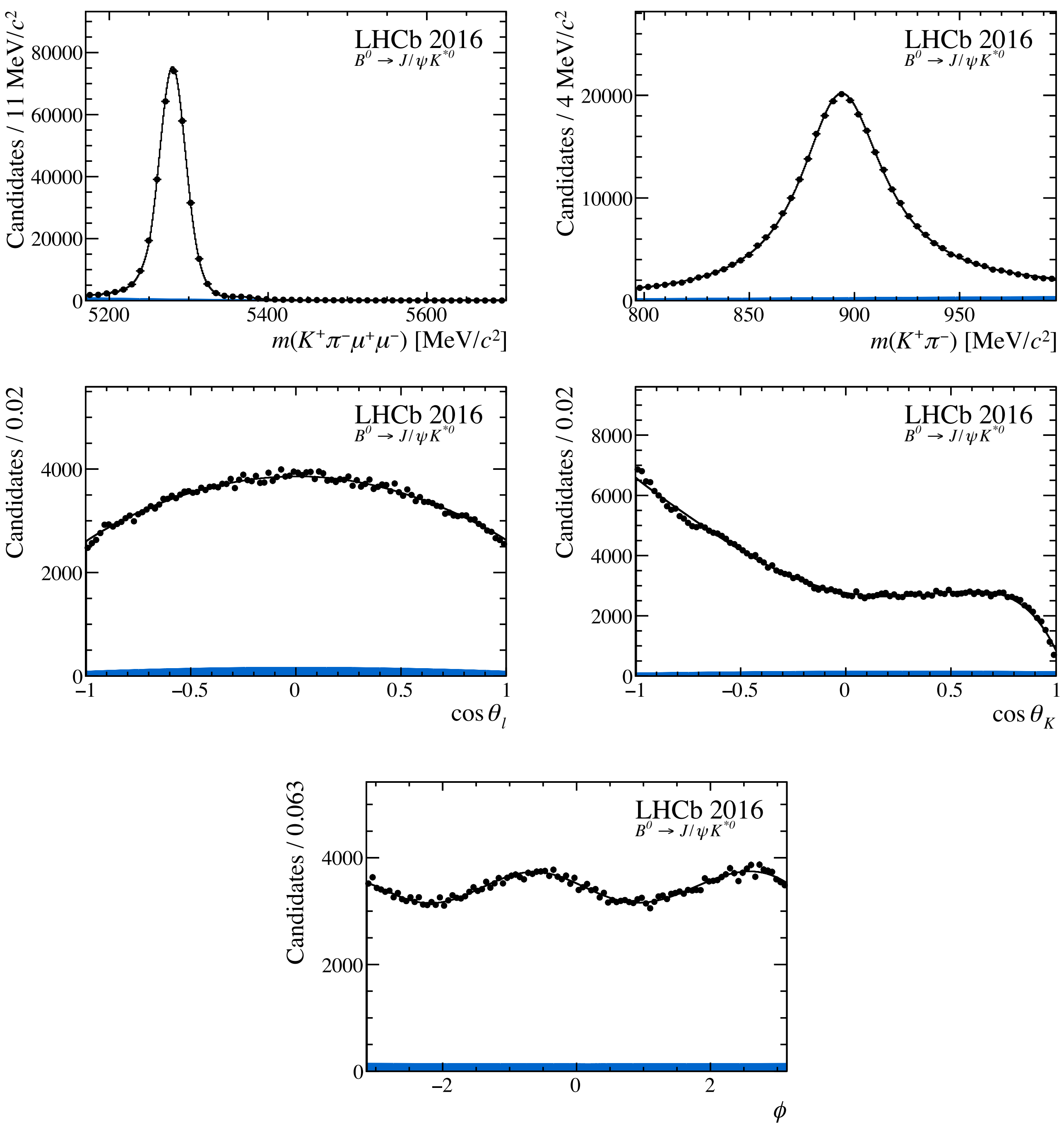




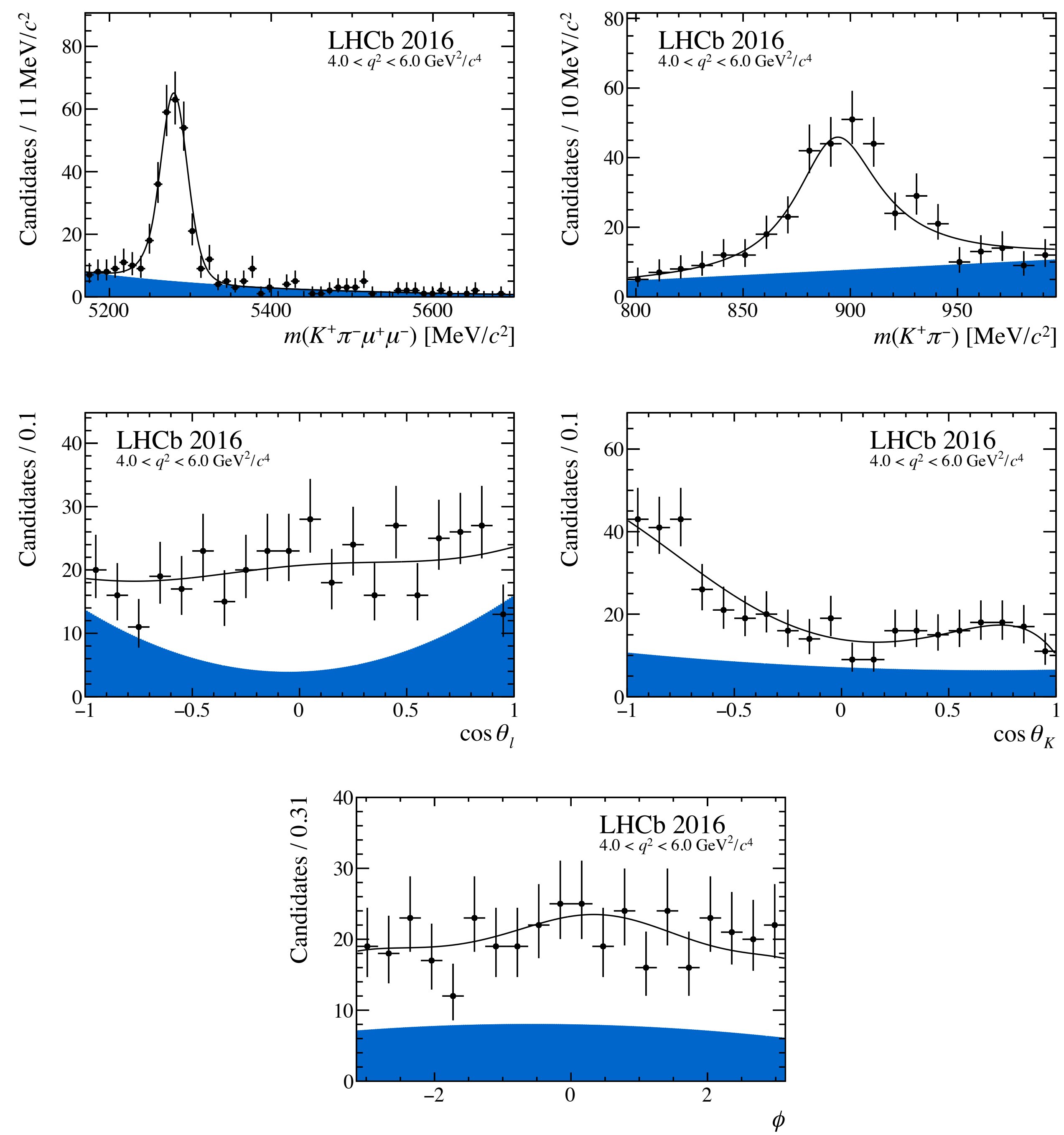
$b \to s\mu\mu$ angular analyses

PRL 125(2020)011802

$B^0 \to K^* J/\psi(\mu^+\mu^-)$ control channel



$B^0 \to K^*\mu^+\mu^-$ in $4.0 < q^2 < 6.0$ GeV^2



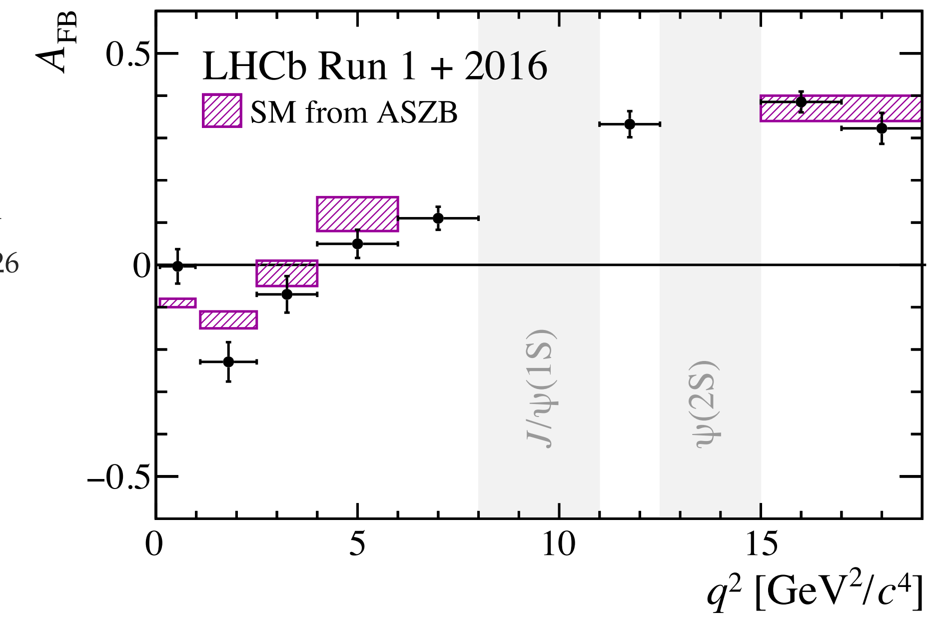
$b \to s\mu\mu$ angular analyses

PRL 125(2020)011802

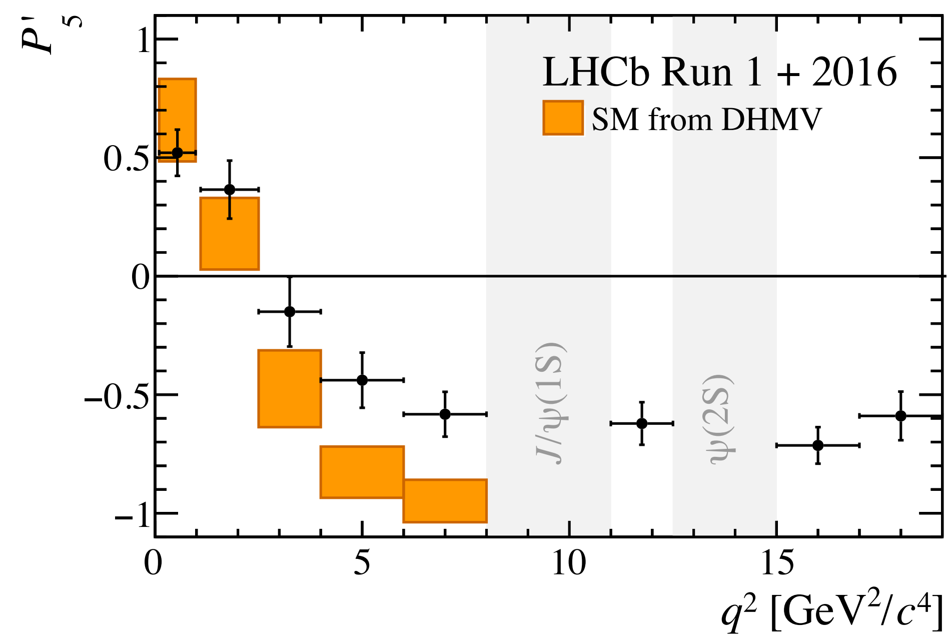
SM prections from:

Bharucha et al arXiv:1503.05534
Altmannshofer et al arXiv:1411.3161

Descotes-Genon et al arXiv:1407.8526
Khodjamirian et al arXiv:1006.4945



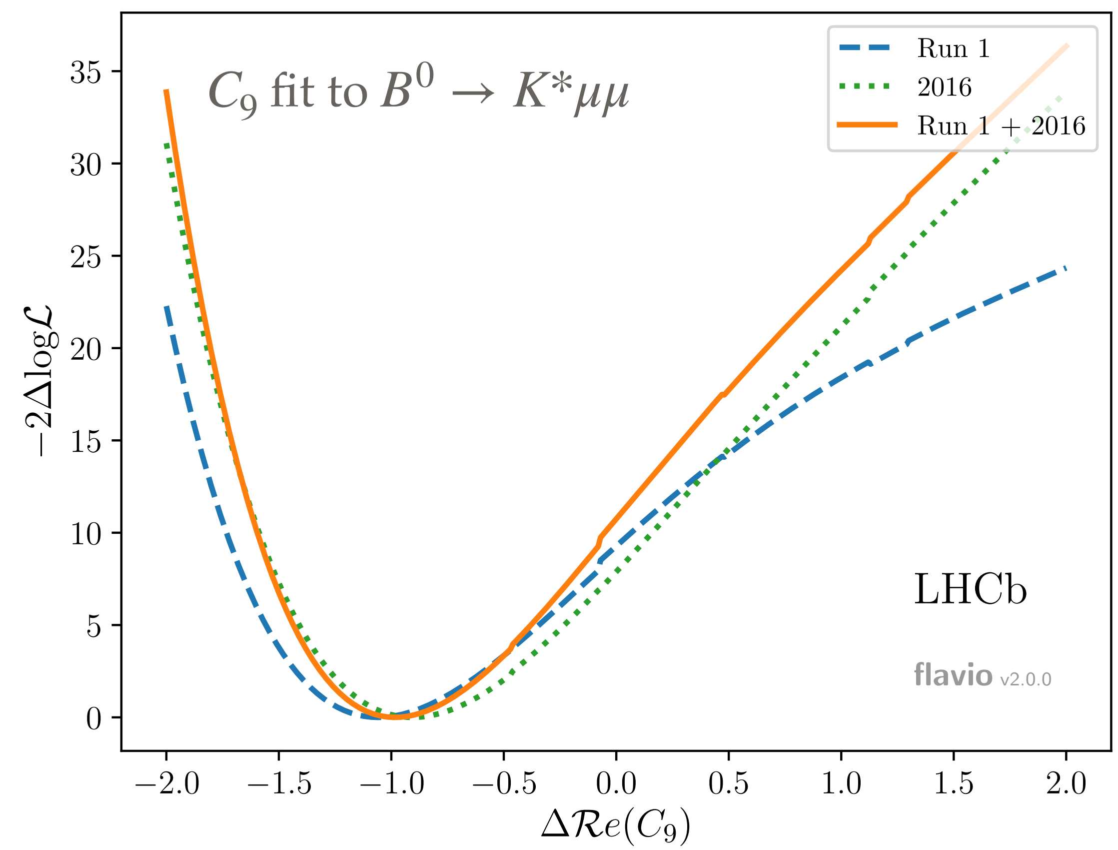
- Measure angular observables in q^2 bins
  - e.g. 8 CP-averaged angular observables in 8 q^2 bins in the $B^0 \to K^{*0}\mu^+\mu^-$
- SM predictions are challenging, but uncertainties are smaller than for BFs
- Optimised observables where hadronic uncertainties cancel out at 1st order (e.g. P_5')
- Some deviations at >2σ level observed → look-elsewhere effect?



…many more observables not shown here
+ results of $B^+ \to K^{*+}\mu\mu$ and $B_s \to \phi\mu\mu$

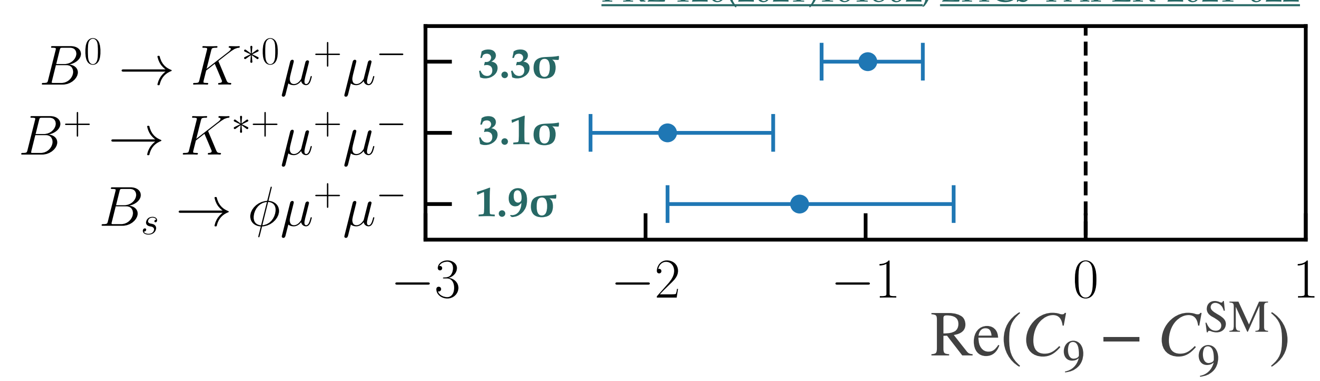
$b \to s\mu\mu$ angular analyses

PRL 125(2020)011802



- Simple fits of vector coupling C_9 reported with LHCb $b \to s\mu\mu$ angular analyses give consistent results
- Significantly better fit for $C_9 < C_9^{SM}$

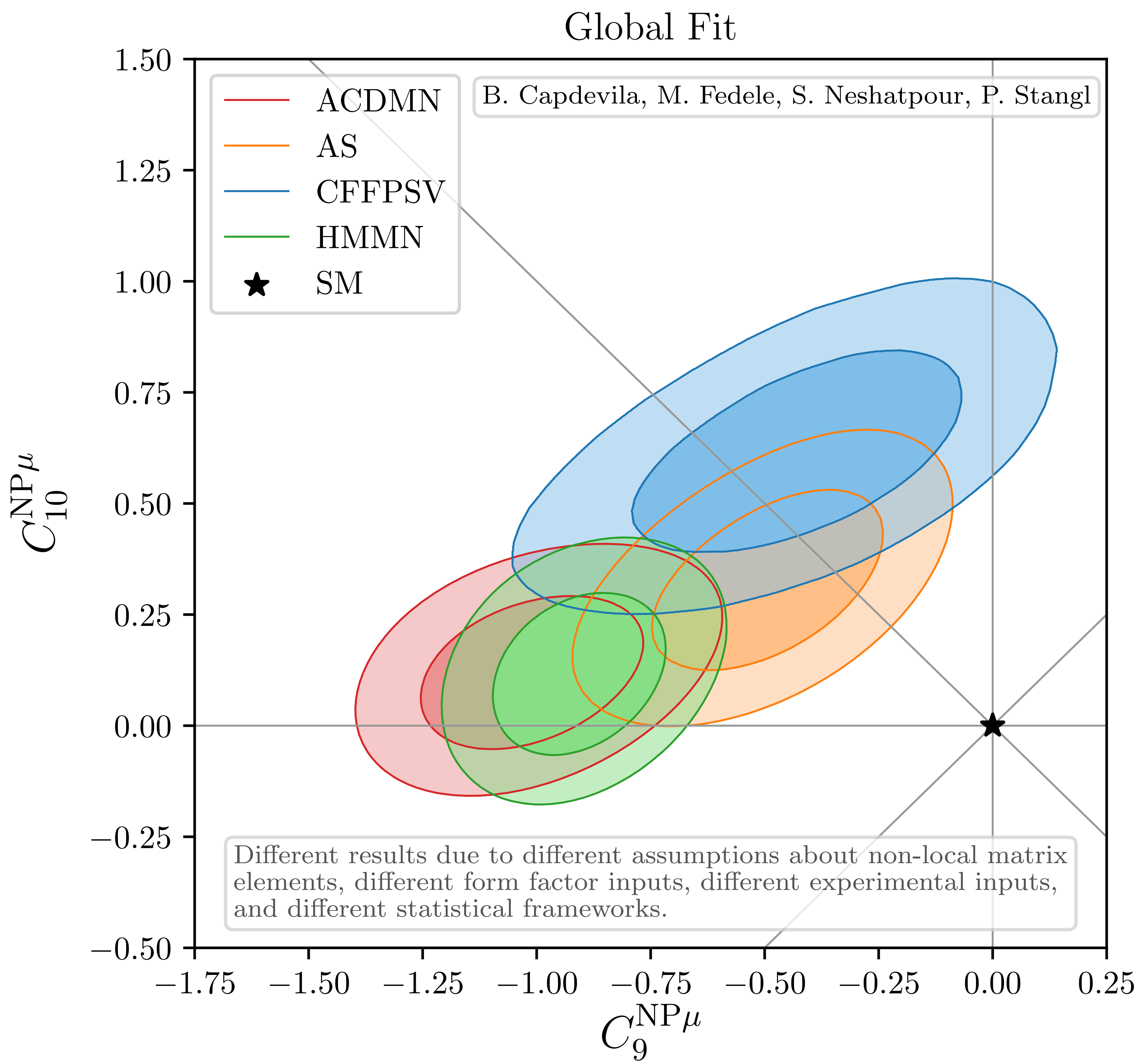
Private compilation of the Flavio fits results presented in from PRL 125(2020)011802, PRL 126(2021)161802, LHCb-PAPER-2021-022



$b \to s\mu\mu$ angular analyses

- Several groups performed fits to $b \to s\mu\mu$ results (and more)
  - Varying all relevant couplings
  - Taking into account Theo. and exp. uncertainties and correlations

A growing number of global fits:
Algueró et al: arXiv:2104.08921
Altmannshofer et al: arXiv:2103.13370
Ciuchini et al: arXiv:1903.09632
Geng et al arXiv:2103.12738
Hurth et al: arXiv:2104.10058
Kowalska et al: arXiv:1903.10932
and more…



- **Theory uncertaities under scrutiny**
  - Special attention to the role of non-local charmonium loops
  - Could cause a shift in SM C_9

$b \to s\mu\mu$ angular analyses

LHCb still has a lot to say

- More data → more sophisticated fits
  - Finer q^2 binning or unbinned
  - More floating parameters
  - Include CP-asymmetric observables
  - Parametrise non-local contributions and fit them to data (several methods)

Egede et al JHEP 06 (2015) 084
Bobeth et al EPJC 78 (2018) 6, 451
Gubernari et al JHEP 02 (2021) 088
Chrzaszcz et al JHEP 10 (2019) 236
Asatrian et al JHEP 04 (2020) 012
Cornella et al EPJC 80 (2020) 12, 1095

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

Hadronic form factors

Non local ($c\bar{c}$)

Lepton Universality in $b \to s \ell \ell$

Testing LU in $b \to s\ell^+\ell^-$

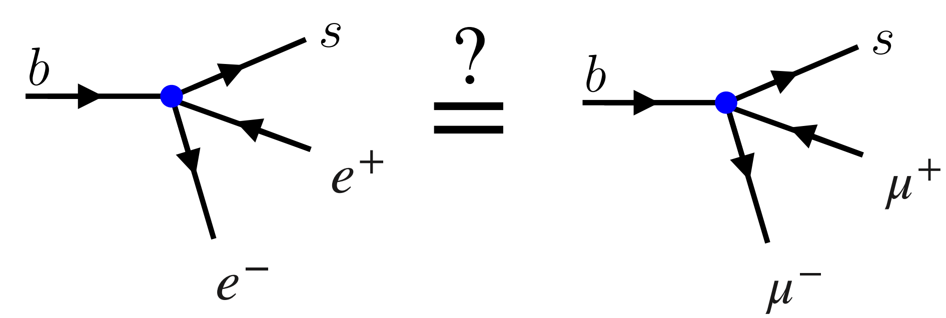
- $b \to s\ell^+\ell^-$ is lepton universal in the SM $\to$ use it to test if LU holds at high energy

  Hiller & Kruger arXiv:hep-ph/0310219

- $b \to s\tau\tau$ not observed yet $\to$ compare μ and e
- Predictions are extremely precise
  - QCD uncertainty cancels to 10^{-4}
  - Up to ~1% QED corrections

  Bordone et al arXiv:1605.07633

- Main challenge at LHCb is e/μ differences in the detector response



$$R_H = \frac{\int_{q^2_{min}}^{q_{max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{min}}^{q_{max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2}\, dq^2} \cong 1$$

SM

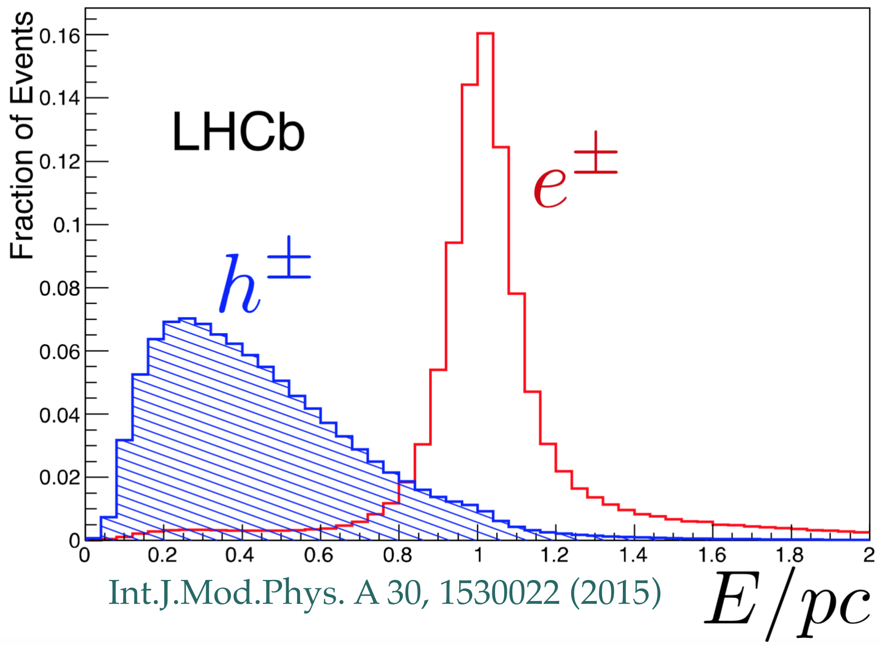
Electrons at LHCb

- Efficiency bottleneck at hardware trigger:
  - $p_{\mathrm{T}}(\mu^{\pm}) > 1.5 - 1.8$ GeV
  - $E_{\mathrm{T}}(e^{\pm}) > 2.5 - 3.0$ GeV
- Electron ID based on ECAL and tracking (harder and slower than μ ID)

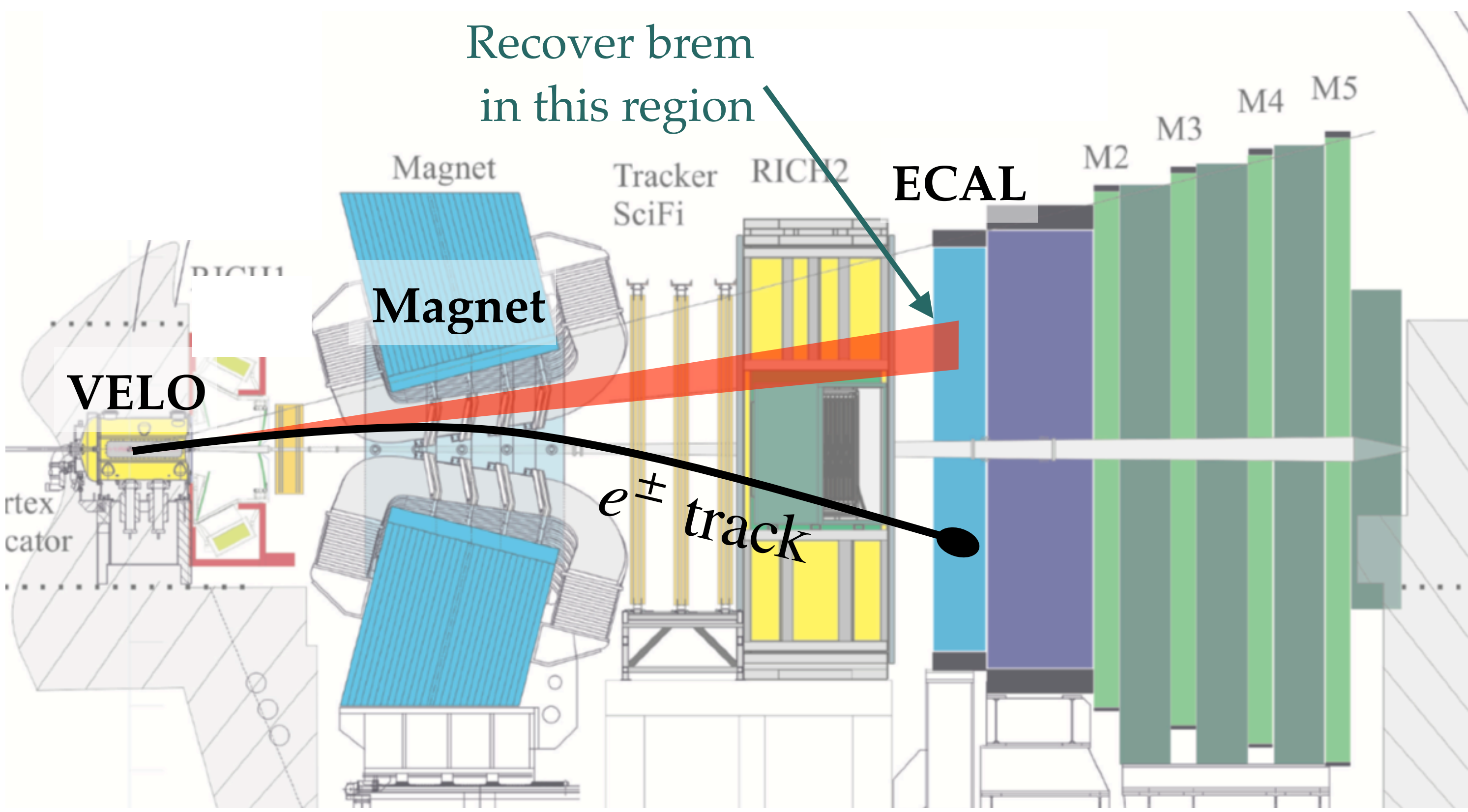
$$\frac{\epsilon(B^+ \to K^+\mu^+\mu^-)}{\epsilon(B^+ \to K^+e^+e^-)} \simeq 3$$

- Measurement of $p(e^{\pm})$ affected by bremsstrahlung emission before magnet
- Bremsstrahlung photon recovery procedure has limited efficiency

Electron ID



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

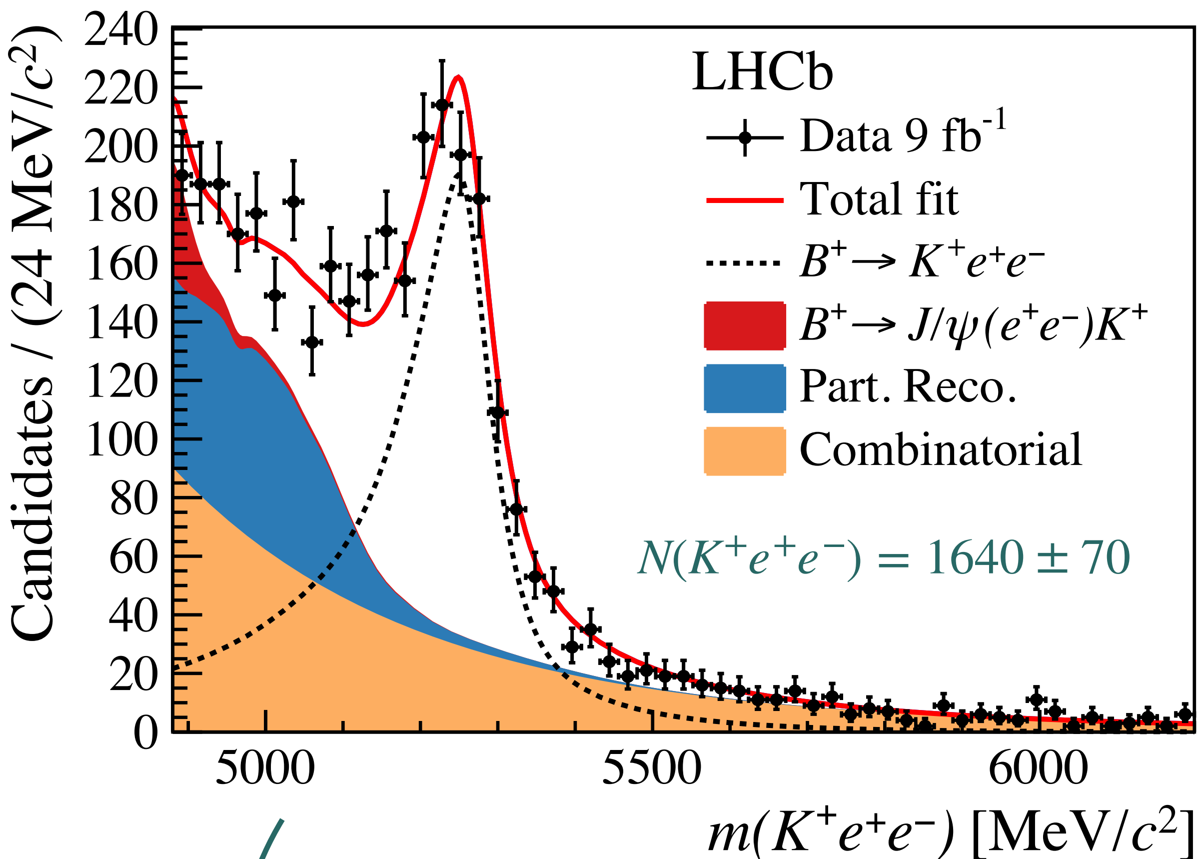


Int.J.Mod.Phys. A 30, 1530022 (2015)

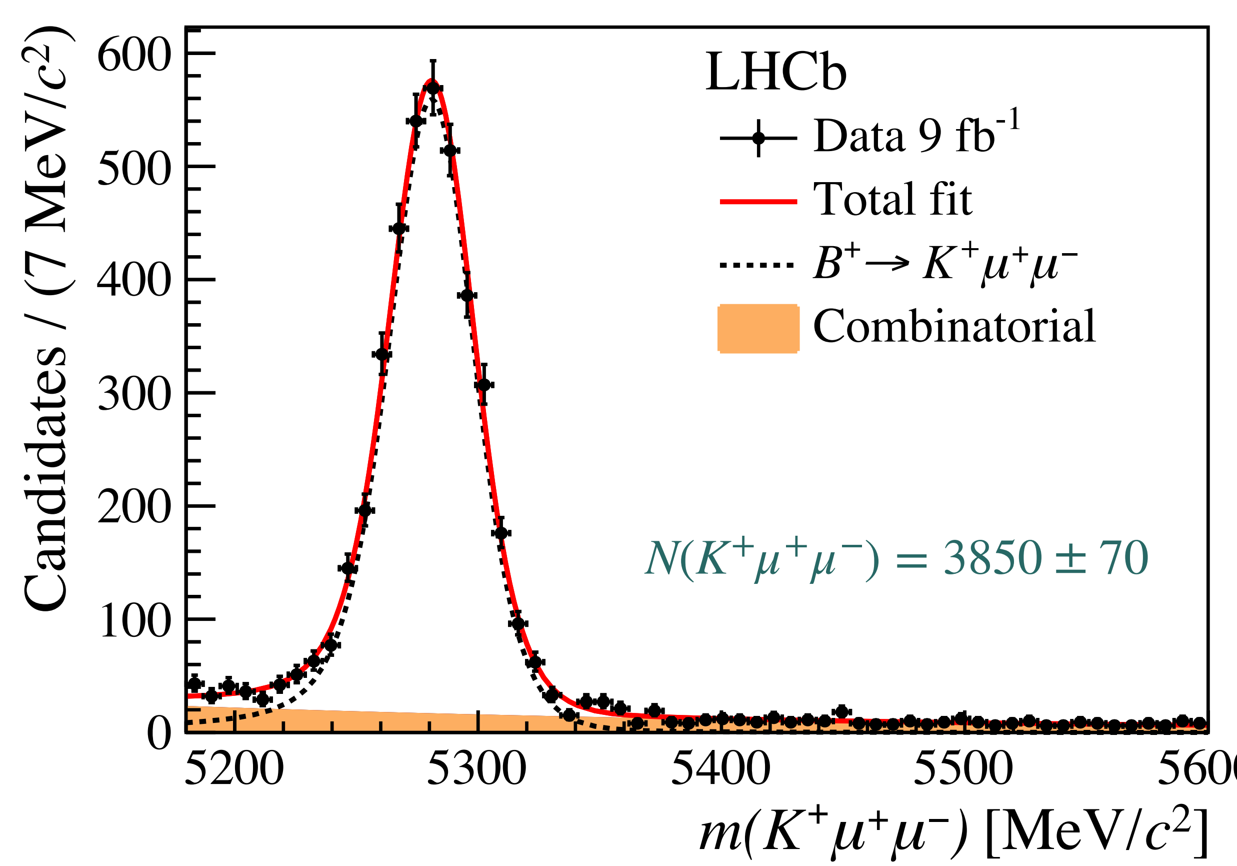
Electrons at LHCb

LHCb arXiv:2103.11769

Electrons



Muons



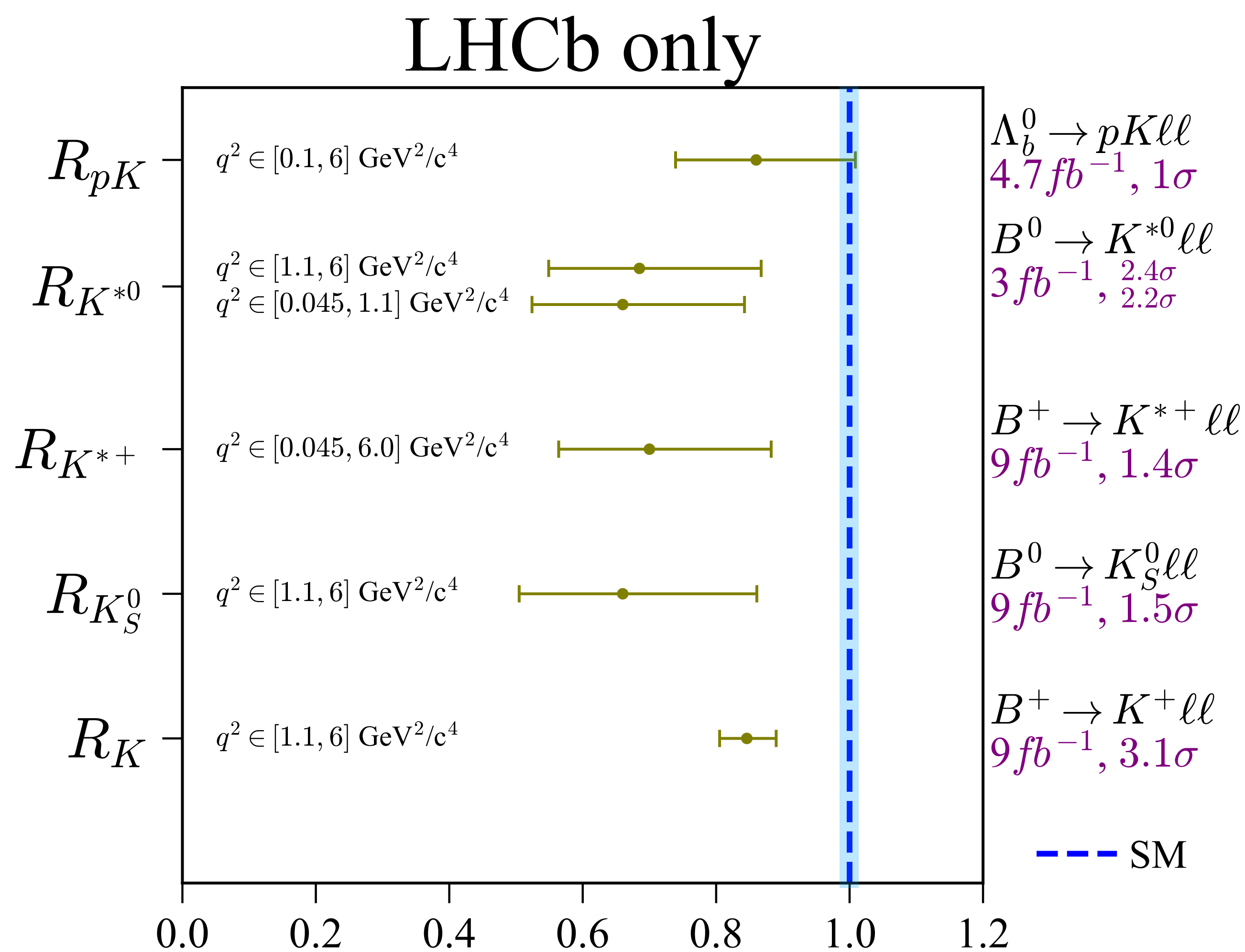
$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$

$$= \left(\frac{N^{ee}_{\rm sig}}{\epsilon^{ee}_{\rm sig}}\cdot\frac{\epsilon^{ee}_{\rm con}}{N^{ee}_{\rm con}}\right) \Big/ \left(\frac{N^{\mu\mu}_{\rm sig}}{\epsilon^{\mu\mu}_{\rm sig}}\cdot\frac{\epsilon^{\mu\mu}_{\rm con}}{N^{\mu\mu}_{\rm con}}\right),$$

Driving the total uncertainty

$b \to s\ell^+\ell^-$ tests of LU

- LU in $b \to s\ell\ell$ tested in several hadronic systems (more coming)
- Huge effort ongoing on **combined R_K and R_{K^*}** analysis
  - Full dataset, more q^2 bins
  - Better precision and deeper understanding of systematics
- High priority to $B^0 \to K^*ee$ **angular analysis** (and others)
  - Shed light on $K^*\mu\mu$ anomalies and their relation to LU tests
  - Main challenge is to control background angular shapes to the precision required

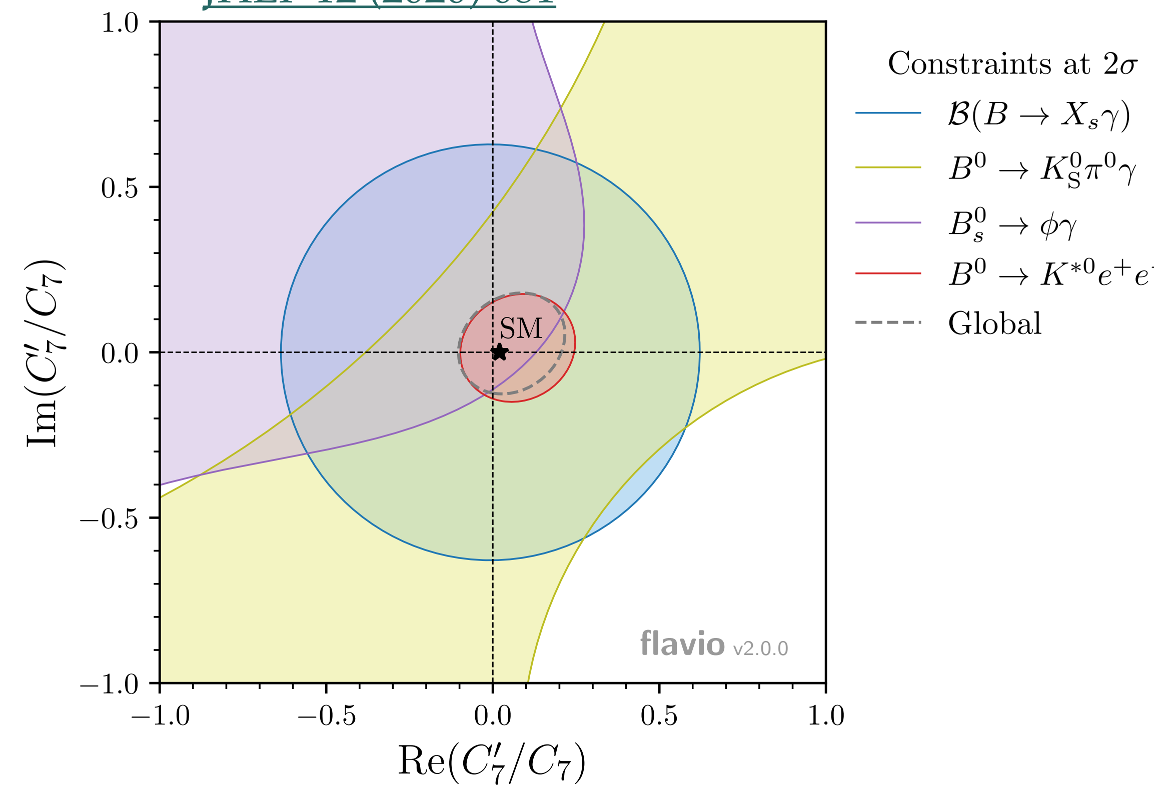


$$R_X = \frac{\mathcal{B}(b \to s\mu\mu)}{\mathcal{B}(b \to see)}$$

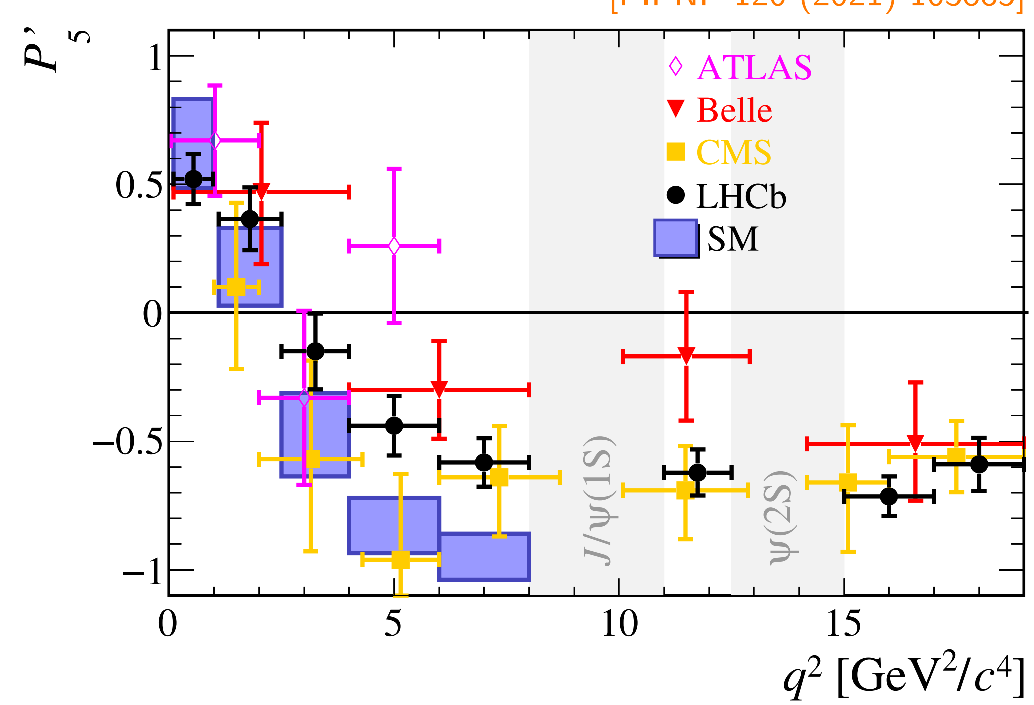
Summary

- Thanks to LHCb, EW penguins in $b \to s$ entered the **precision era**
  - Strong constraints on right-handed currents in $b \to s\gamma$
  - Sophisticated analyses of $b \to s\mu\mu$ transitions (BR+angular)
  - Precise LU tests in several $b \to s\ell\ell$ channels
- **Several anomalies** in $b \to s\ell\ell$ with a tantalising pattern
  - Upcoming run 1+2 analyses have the sensitivity to clarify the situation
- **Upgraded LHCb** being commissioned
  - $5\times$ the data rate and more precise trigger will translate in better precision
  - Opportunity to crosscheck anomalies with largely new detector

JHEP 12 (2020) 081

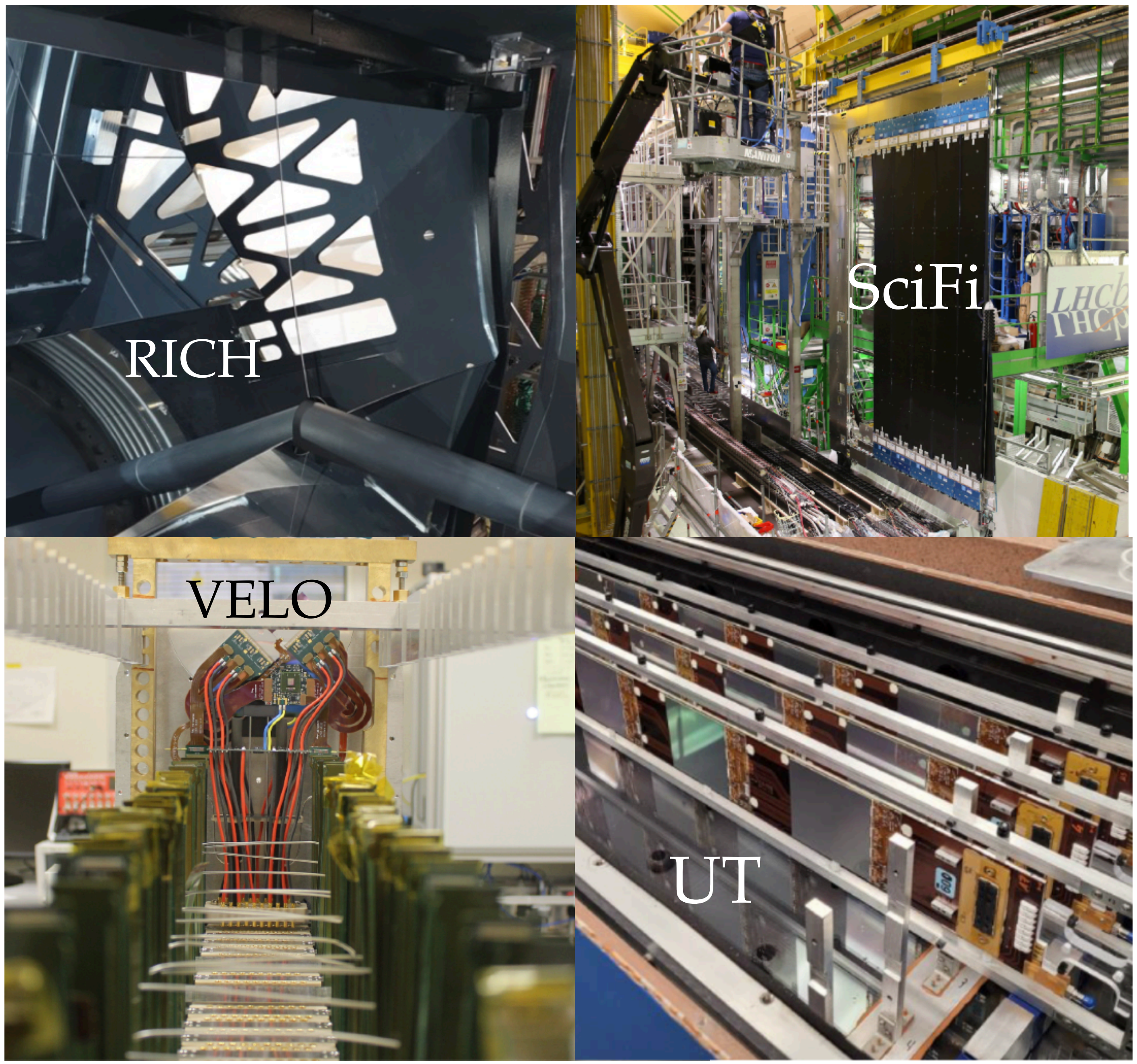


[PIPNP 120 (2021) 103885]



BACKUP

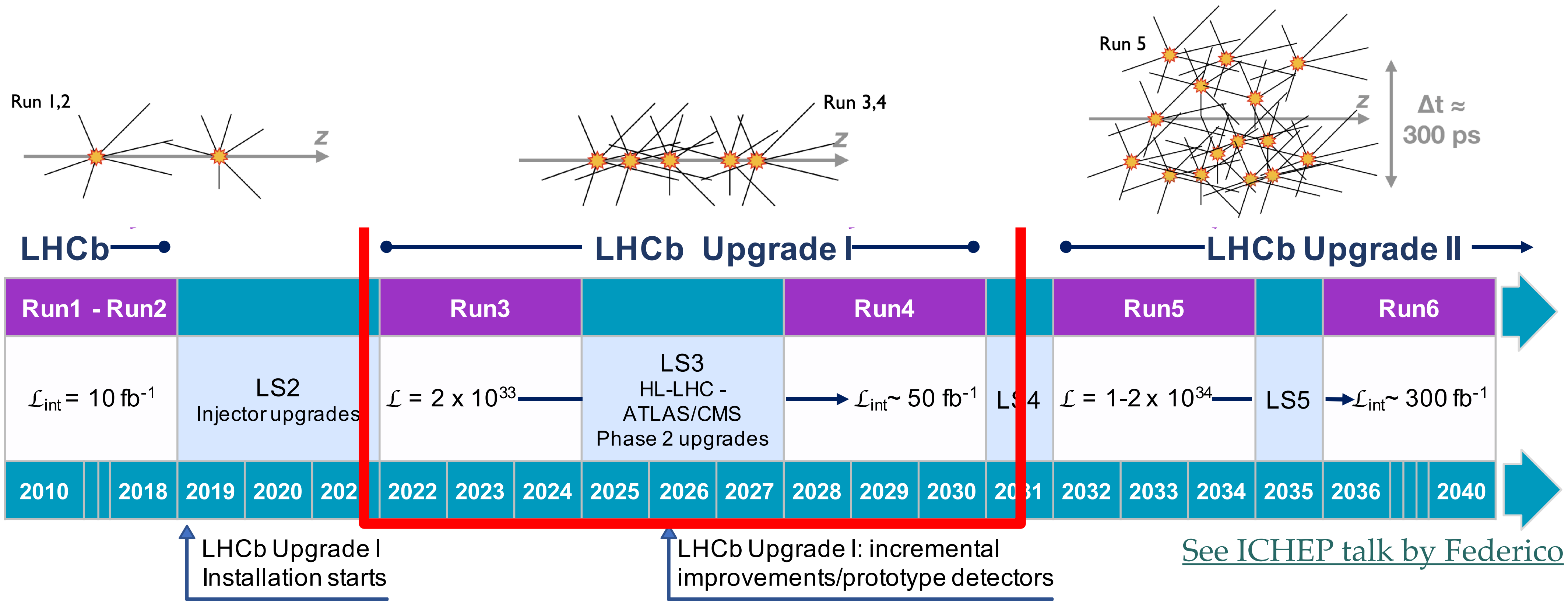
LHCb Upgrade I



More in Giovanni Cavallero's talk

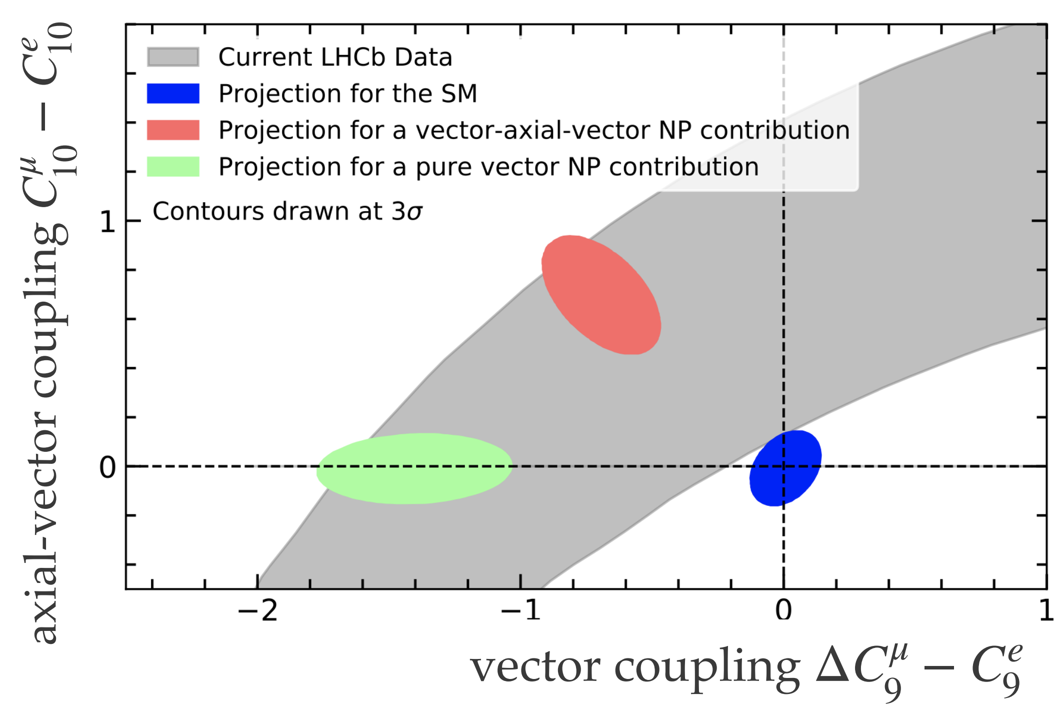
- Installing upgrade for Runs 3 and 4 (TDR)
  - Readout electronics and several subdetectors upgraded
  - Can run at 5x higher luminosity
  - Real-time trigger with GPUs
- Opportunity to crosscheck anomalies with largely new detector
- $B_{(s)} \to \mu\mu$, LU tests and LFV searches will directly profit from the higher statistics (about factor 3 with Run 3 only)
- Online electron selection will profit from new real-time analysis capabilities

LHCb Upgrade II



See ICHEP talk by Federico

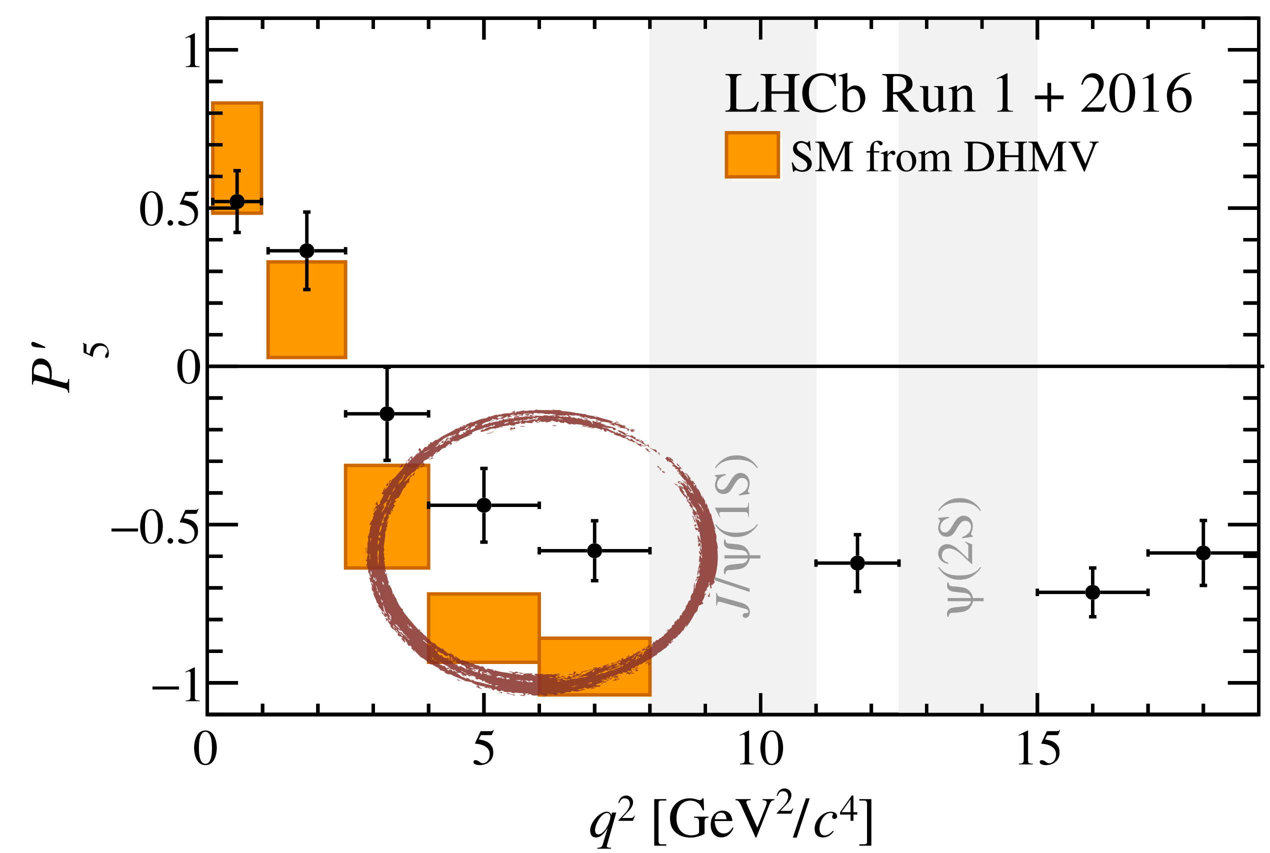
- Framework TDR for Upgrade II currently in review by the LHCC
  - 10x luminosity of Upgrade I
  - Can clearly check for consistency and distinguish NP scenarios



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

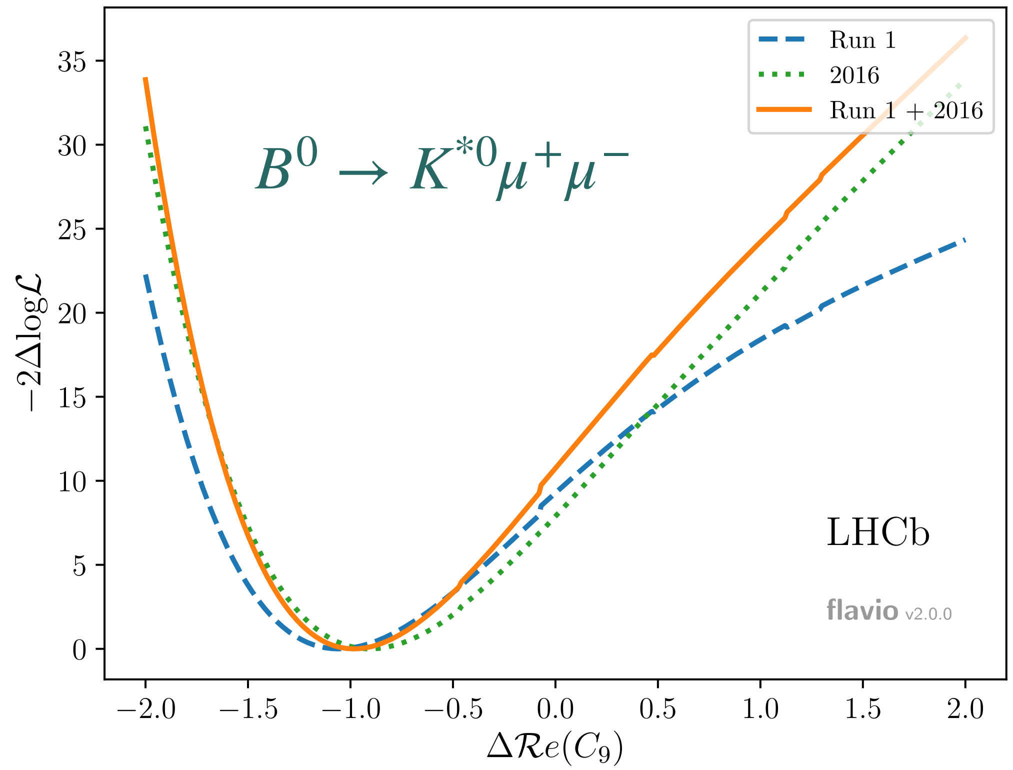
PRL 125(2020)01 1802

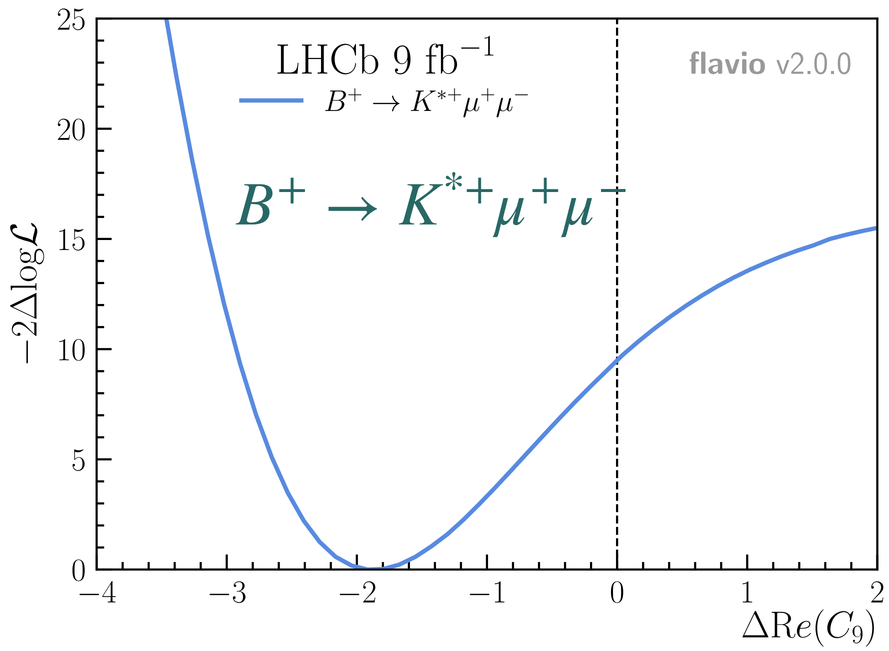
- Can construct theoretically cleaner angular observables such as
$$P'_5 = \frac{S_5}{F_L\sqrt{1-F_L}}$$
where hadronic uncertainties cancel out at first order
- If NP contributes to C_9 and C_{10} expect large deviations in P'_5
- Observed local discrepancies:
  - 2.5σ for $q^2 = [4.0 - 6.0]$ GeV^2
  - 2.9σ for $q^2 = [6.0 - 8.0]$ GeV^2
- Easier stat interpretation using global EFT fits → see later

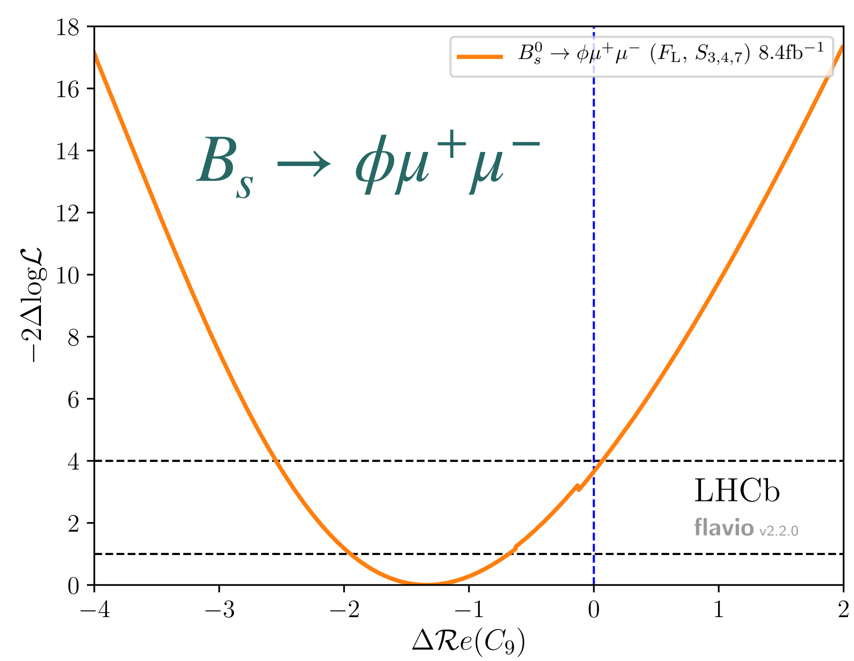


SM predictions by [JHEP12(2014)125] and [JHEP09(2010)089]

WC fits from angular analyses

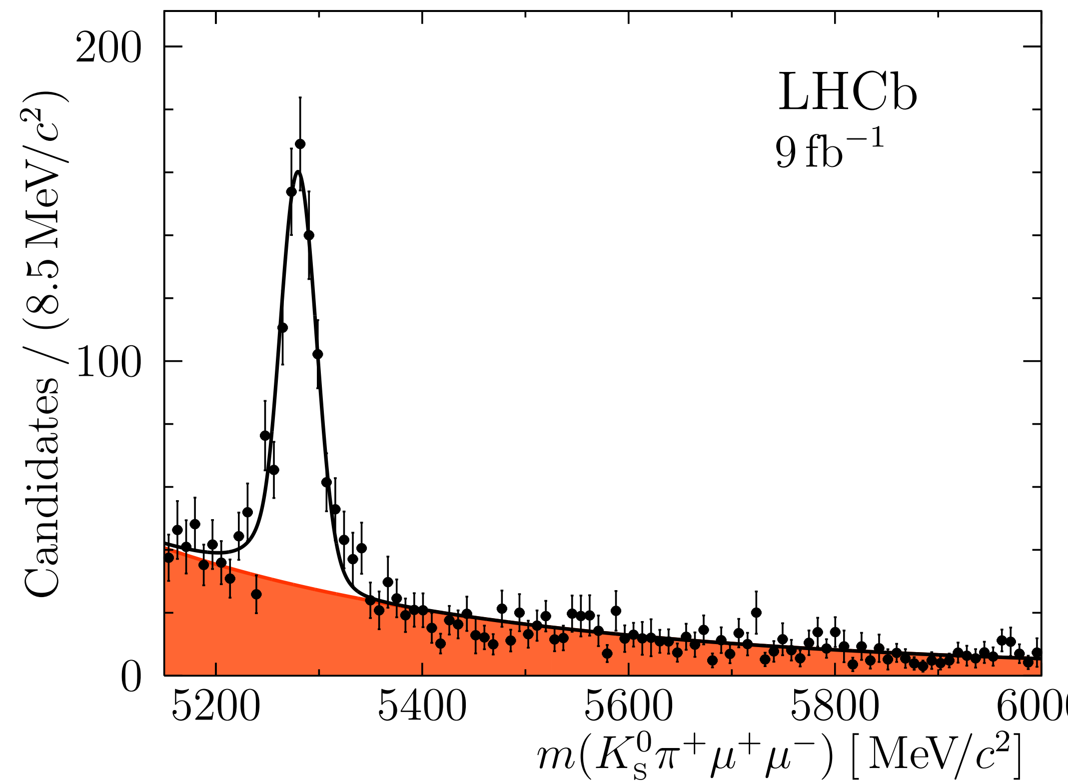






$B^+ \to K^{*+}\mu^+\mu^-$ angular analysis

- Recently analysed also isospin partner $B^+ \to K^{*+}(K_S\pi^+)\mu^+\mu^-$
- Challenging reconstruction of long-lived $K_S \to \pi^+\pi^-$
- Signal yield of 737 ± 34 events split in 8 q^2 bins for angular fit
- Angular folding technique used to reduce dimensionality of the fit



folding 0:

$$\phi \to \phi + \pi \quad \text{for } \phi < 0$$

folding 1:

$$\begin{aligned} \phi &\to -\phi && \text{for } \phi < 0 \\ \phi &\to \pi - \phi && \text{for } \cos\theta_L < 0 \\ \cos\theta_L &\to -\cos\theta_L && \text{for } \cos\theta_L < 0 \end{aligned}$$

folding 2:

$$\begin{aligned} \phi &\to -\phi && \text{for } \phi < 0 \\ \cos\theta_L &\to -\cos\theta_L && \text{for } \cos\theta_L < 0 \end{aligned}$$

folding 3:

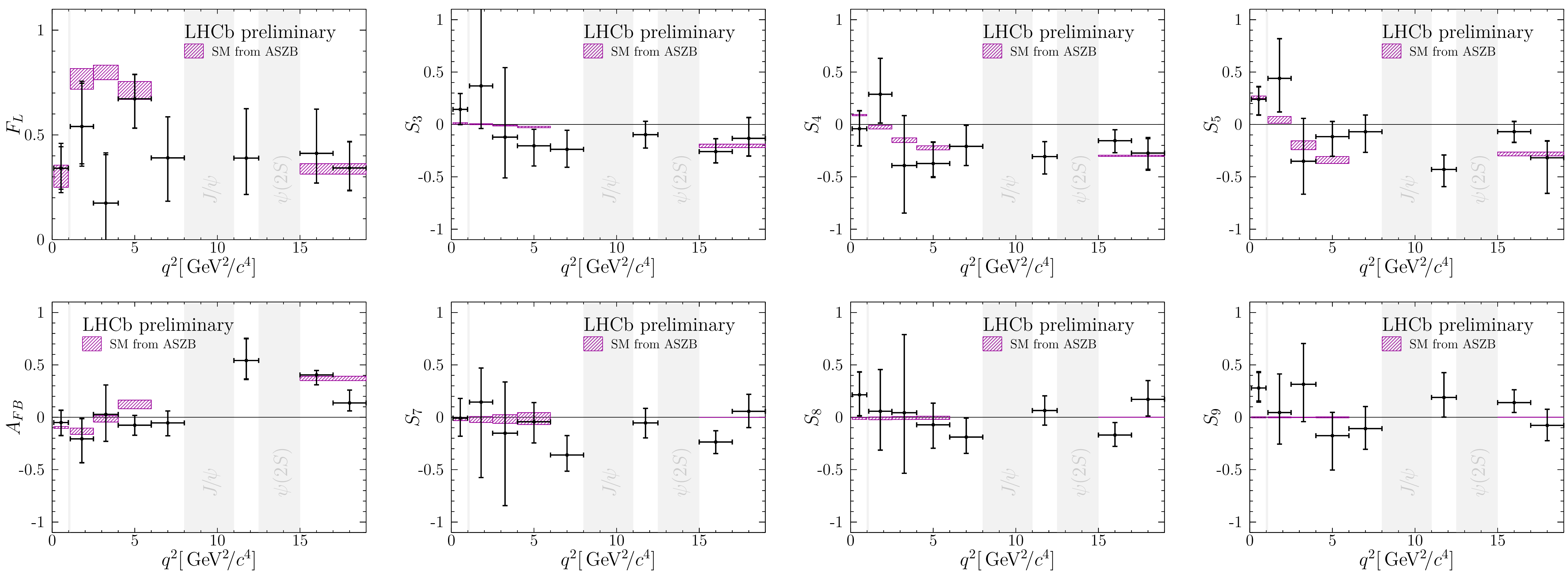
$$\begin{aligned} \cos\theta_L &\to -\cos\theta_L && \text{for } \cos\theta_L < 0 \\ \phi &\to \pi - \phi && \text{for } \phi > \tfrac{\pi}{2} \\ \phi &\to -\pi - \phi && \text{for } \phi < -\tfrac{\pi}{2} \end{aligned}$$

folding 4:

$$\begin{aligned} \cos\theta_L &\to -\cos\theta_L && \text{for } \cos\theta_L < 0 \\ \phi &\to \pi - \phi && \text{for } \phi > \tfrac{\pi}{2} \\ \phi &\to -\pi - \phi && \text{for } \phi < -\tfrac{\pi}{2} \\ \cos\theta_K &\to -\cos\theta_K && \text{for } \cos\theta_L < 0 \end{aligned}$$

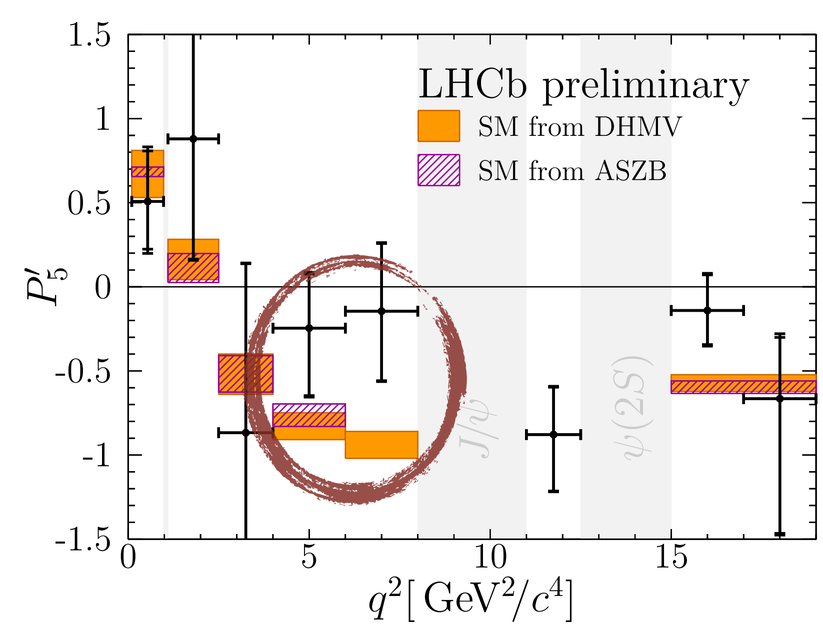
observable	moment	0	1	2	3	4
F_L	$\cos^2\theta_K$	(✓)	(✓)	(✓)	(✓)	✓
S_3	$\sin^2\theta_K \sin^2\theta_L \cos 2\phi$	(✓)	(✓)	(✓)	(✓)	✓
S_4	$\sin 2\theta_K \sin 2\theta_L \cos\phi$		✓			
S_5	$\sin 2\theta_K \sin\theta_L \cos\phi$			✓		
A_{FB}	$\sin^2\theta_K \cos\theta_L$	✓				
S_7	$\sin 2\theta_K \sin\theta_L \sin\phi$				✓	
S_8	$\sin 2\theta_K \sin 2\theta_L \sin\phi$					✓
S_9	$\sin^2\theta_K \sin^2\theta_L \sin 2\phi$	✓				

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



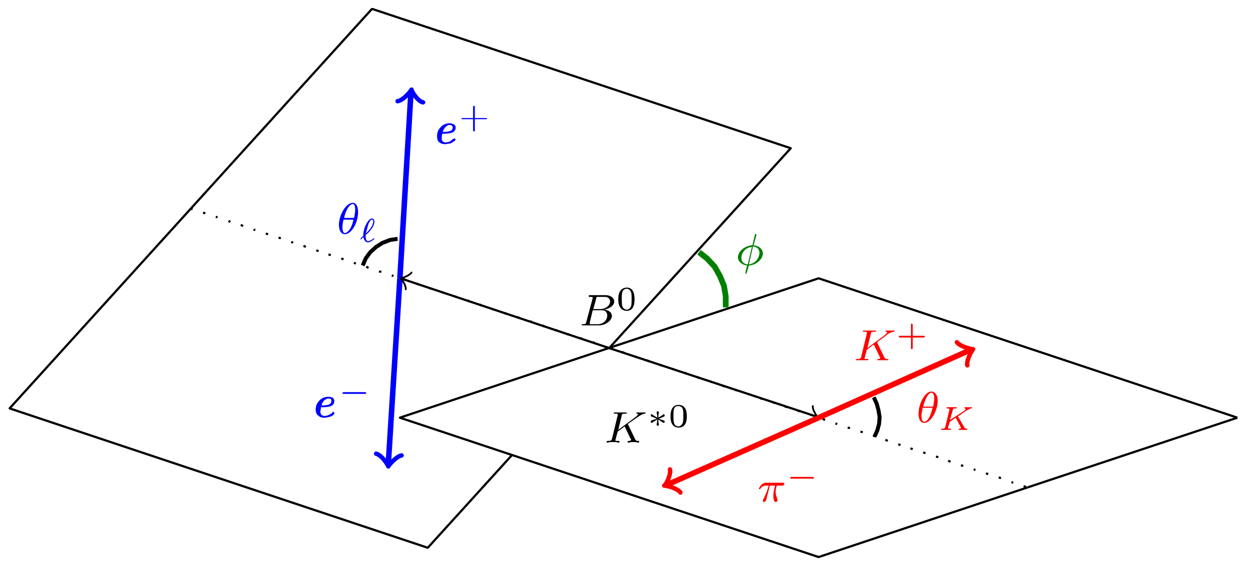
DHMV SM predictions by [JHEP06(2016)092] and [JHEP01(2018)093]
ASZB SM predictions by [JHEP08(2016)098] and [Eur.Phys.J.C75(2015)382]

- Results compatible with observations in B^0 channel
  - Similar pattern of deviations in P_5'
  - Uncertanties are much larger, but global EFT fit confirms same trend



$B^0 \to K^{*}e^+e^-$: Angular analysis

JHEP 12 (2020) 081



- Folding ϕ angle to simplify the 3D angular expression:

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

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

$B^0 \to K^{*}\gamma$ photon polarisation:

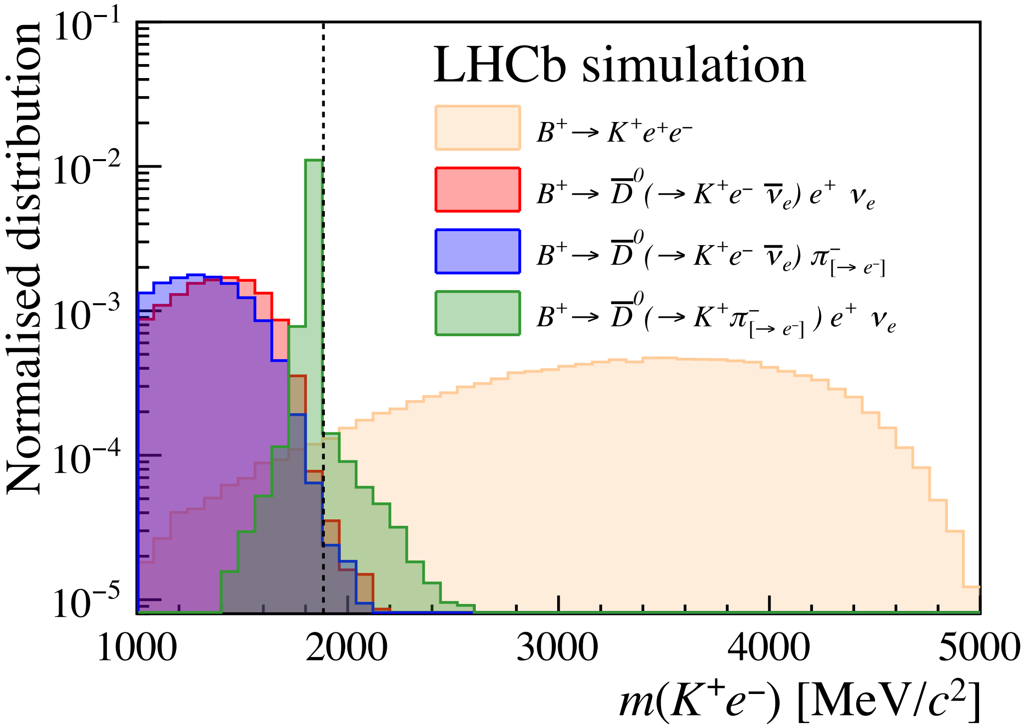
$$A_{\mathrm{R(L)}} \equiv |A_{\mathrm{R(L)}}|\,e^{i\phi_{\mathrm{R(L)}}}, \quad \tan\chi \equiv \left|A_{\mathrm{R}}/A_{\mathrm{L}}\right|$$

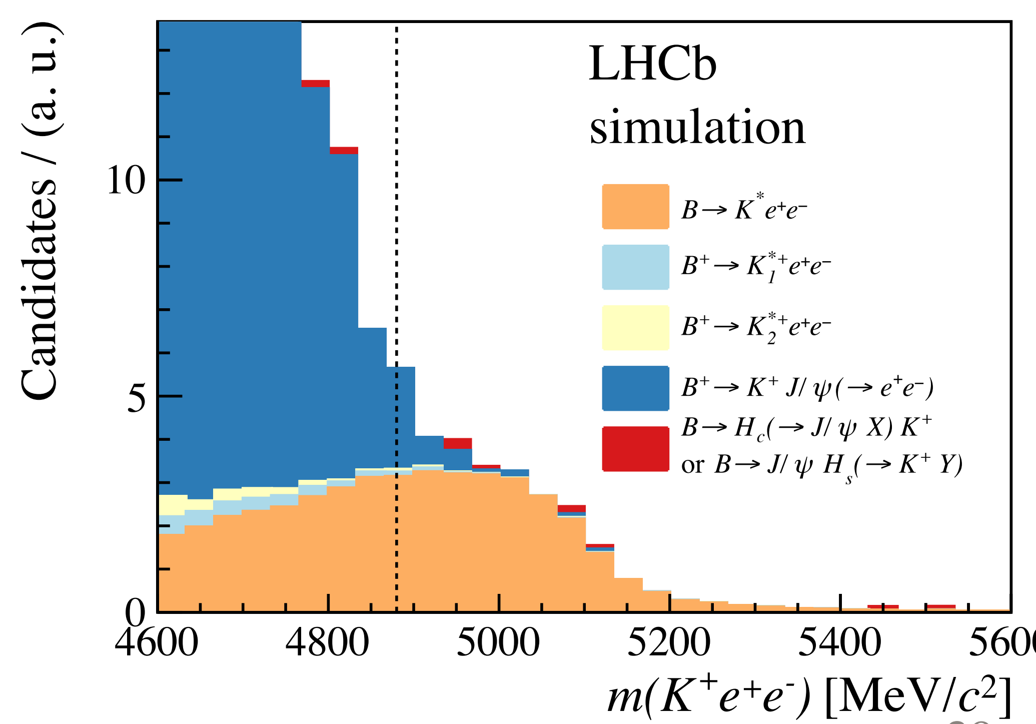
$$A_{\mathrm{T}}^{(2)} \simeq \sin(2\chi)\cos(\phi_{\mathrm{L}}-\phi_{\mathrm{R}}),$$
$$A_{\mathrm{T}}^{\mathrm{Im}} \simeq \sin(2\chi)\sin(\phi_{\mathrm{L}}-\phi_{\mathrm{R}}),$$

Backgrounds in electrons

LHCb arXiv:2103.11769

- Particle ID and mass vetoes to suppress bkg e.g:
  - cascade $B \to D \to K$ with $m(K^+e^-) > m_{D^0}$
  - remove $B^+ \to K^+\pi^+\pi^-$ with tight electron ID
- Reduce combinatorial background with multivariate analysis (Boosted Decision Tree)
- Choose $m(K^+e^+e^-)$ window to suppress other backgrounds



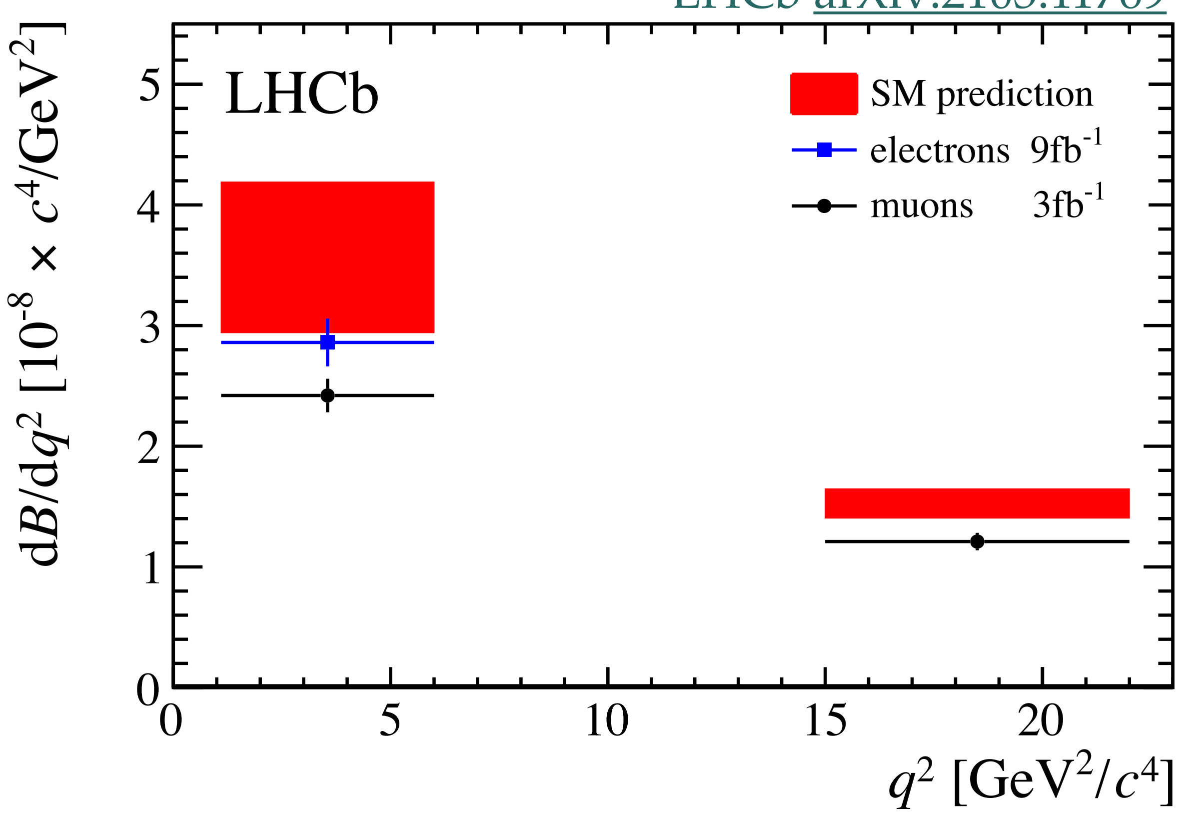


R_K result

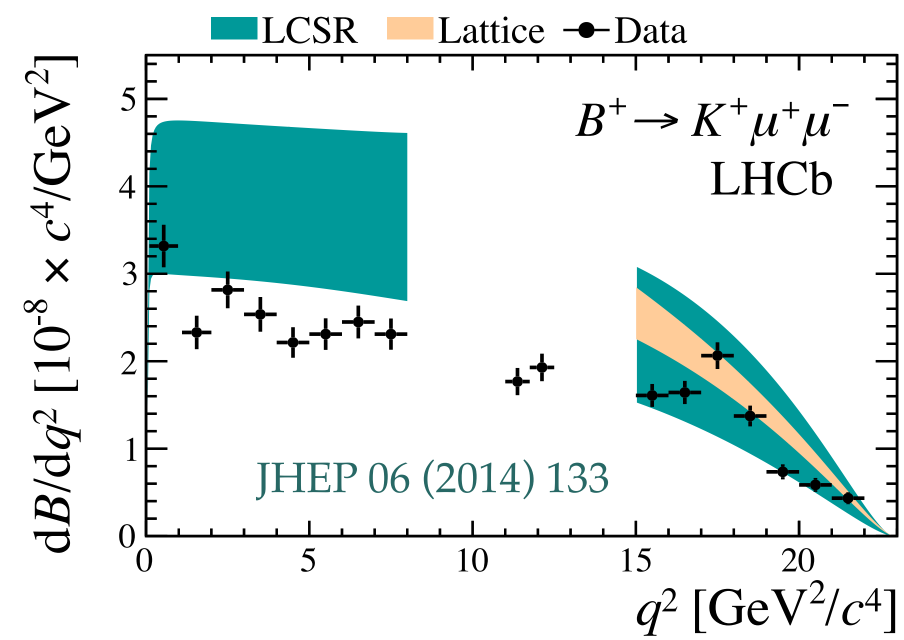
- Also measured electrons BR and compared to previous result on muons:

$$\frac{d\mathcal{B}\left(B^+ \to K^+ e^+ e^-\right)}{dq^2} = \left(28.6^{+1.5}_{-1.4}(\text{ stat }) \pm 1.4(\text{ syst })\right) \times 10^{-9} c^4/\text{GeV}^2$$

LHCb arXiv:2103.11769



$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ from 3/fb paper:



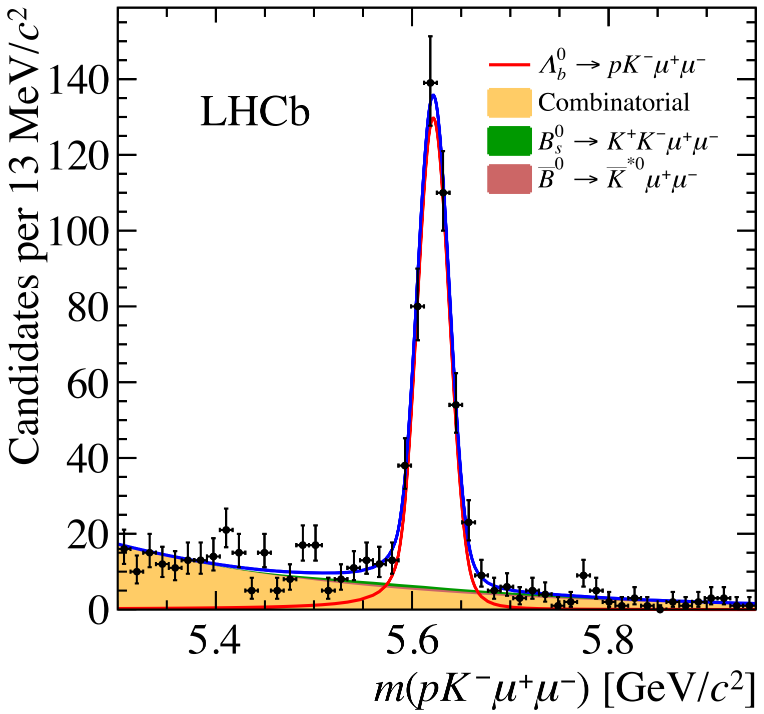
→ Electrons BR closer to SM prediction (but both compatible)

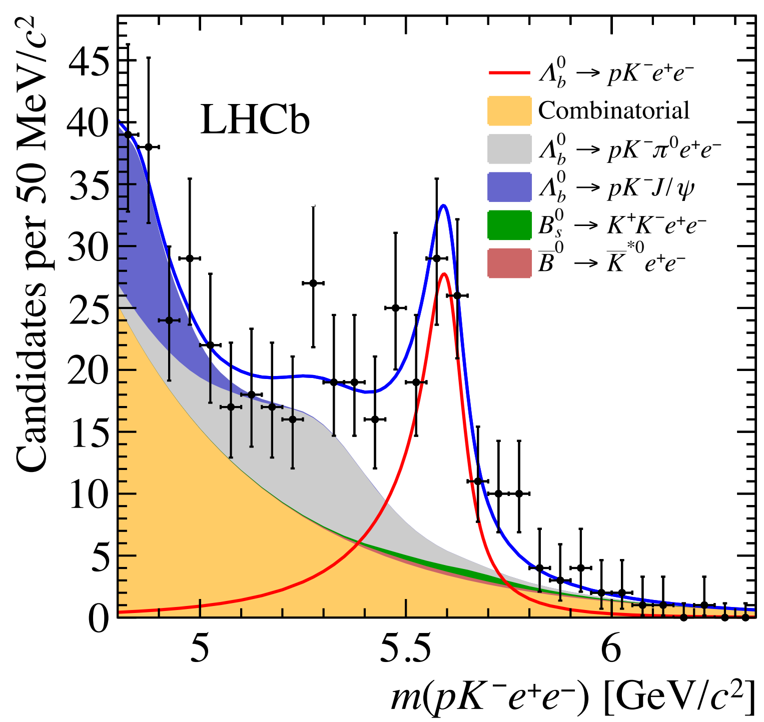
LFU test in baryons

LHCb, JHEP 05 (2020) 040

- New test of LFU in $\Lambda_b \to pK^-\ell^+\ell^-$
  - Using Run 1 + 2016 dataset (4.7/fb)
- Similar physics as R_K and
  - Different final state and selection
  - Different backgrounds and systematic uncertainties
- Crosscheck using $\Lambda_b \to pK^- J/\psi$
- Measured phase space region:
  - $m(pK^-) > 2.6$ GeV
  - $0.1 < q^2 < 6.0$ GeV^2

$$R_{pK}\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

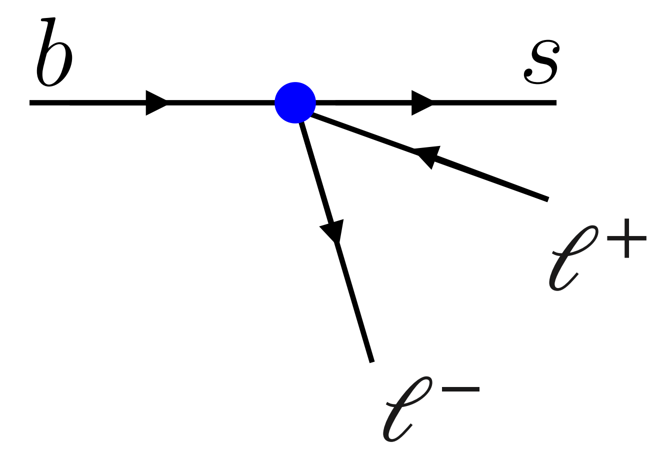




Weak effective theory

More details in next two talks

- Most important SM operators:
  - $O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \rightarrow$ Vector
  - $O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \rightarrow$ Axial-vector
  - O_7 dipole operator for $b \rightarrow s\gamma^*$ contributions
- Operators suppressed in the SM:
  - $O_{S(P)}$ (pseudo-)scalar op.s, suppressed by $m_\ell m_b / m_W^2$
  - O_i' primed right-handed op.s, suppressed by m_s / m_b



Found to be very SM like:
- C_7 determined to 5% precision with $B \rightarrow X_s\gamma$
- $C_7'/C_7 < 10\%$ from $B \rightarrow K^*\gamma$

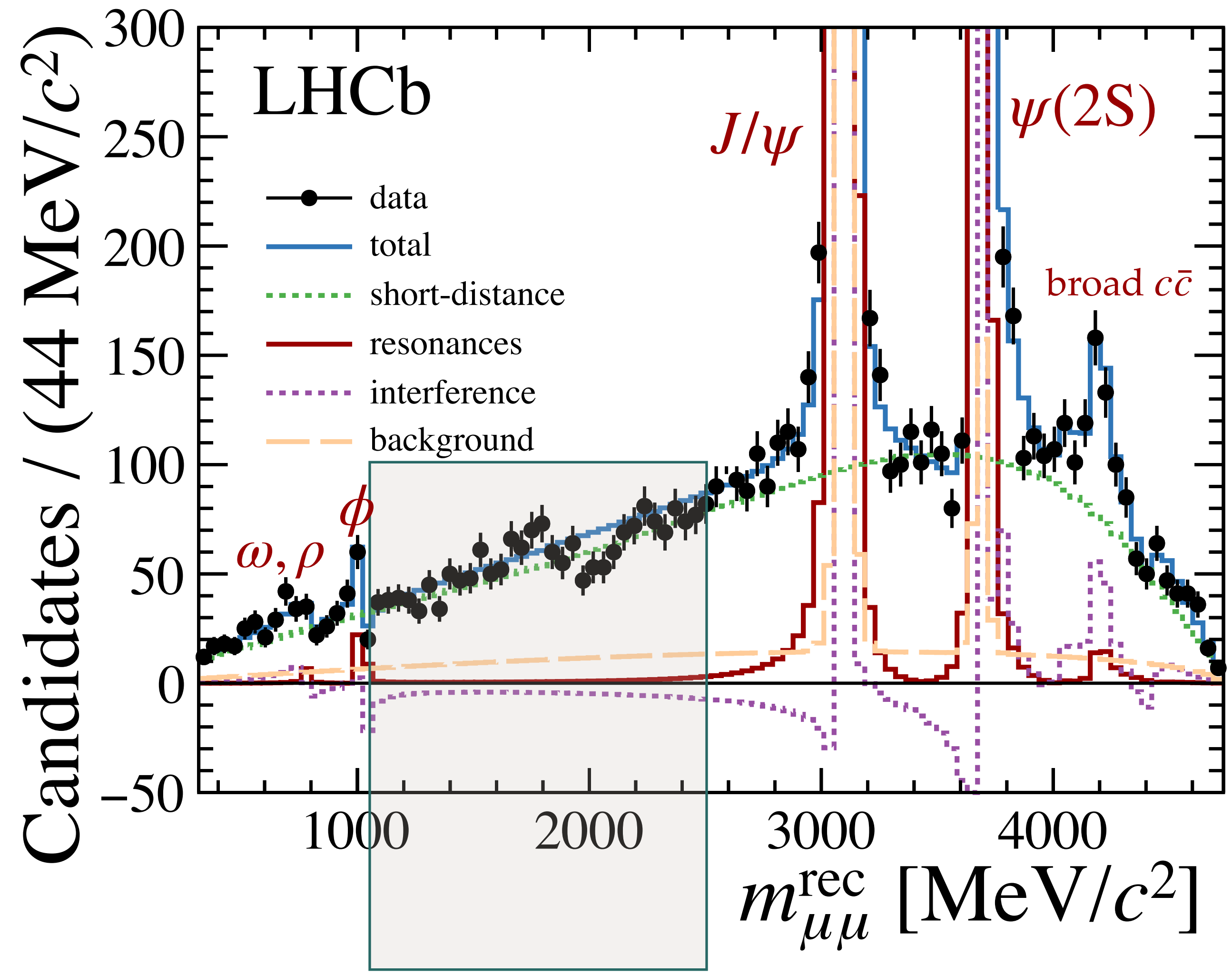
$\mathcal{C}_7^{(\prime)}$	$\mathcal{C}_9^{(\prime)}$	$\mathcal{C}_{10}^{(\prime)}$	$\mathcal{C}_{S,P}^{(\prime)}$	Experimental
✓				Radiative (e.g. $B \rightarrow X_s\gamma$)
✓	✓	✓		Semileptonic (e.g. $B \rightarrow K\ell\ell$)
		✓	✓	Leptonic (e.g. $B \rightarrow \mu\mu$)

Focus of today's talk

q^2 spectrum of $B^+ \to K^+\mu^+\mu^-$

LHCb, EPJ C77(2017)161

- Analysis of the q^2 spectrum
  - Modelling contributions from $K^+V(\mu^+\mu^-)$ with Breit-Wigners
  - Measure BR and phase differences
- Guidance for $b \to s\ell\ell$ measurements
  - Narrow J/ψ and $\psi(2S)$ are large and normally vetoed (also narrow ϕ)
  - Their interference with $b \to s\ell\ell$ (short distance) is small
  - Contributions from ω, ρ and broad charmonium above the $\psi(2S)$ are small and normally integrated
  - Region of $1.1 < q^2 < 6$ GeV^2 is the cleanest



$1.1 < q^2 < 6.0$ GeV^2
theo. favoured region