Rare B decays in the LHC era

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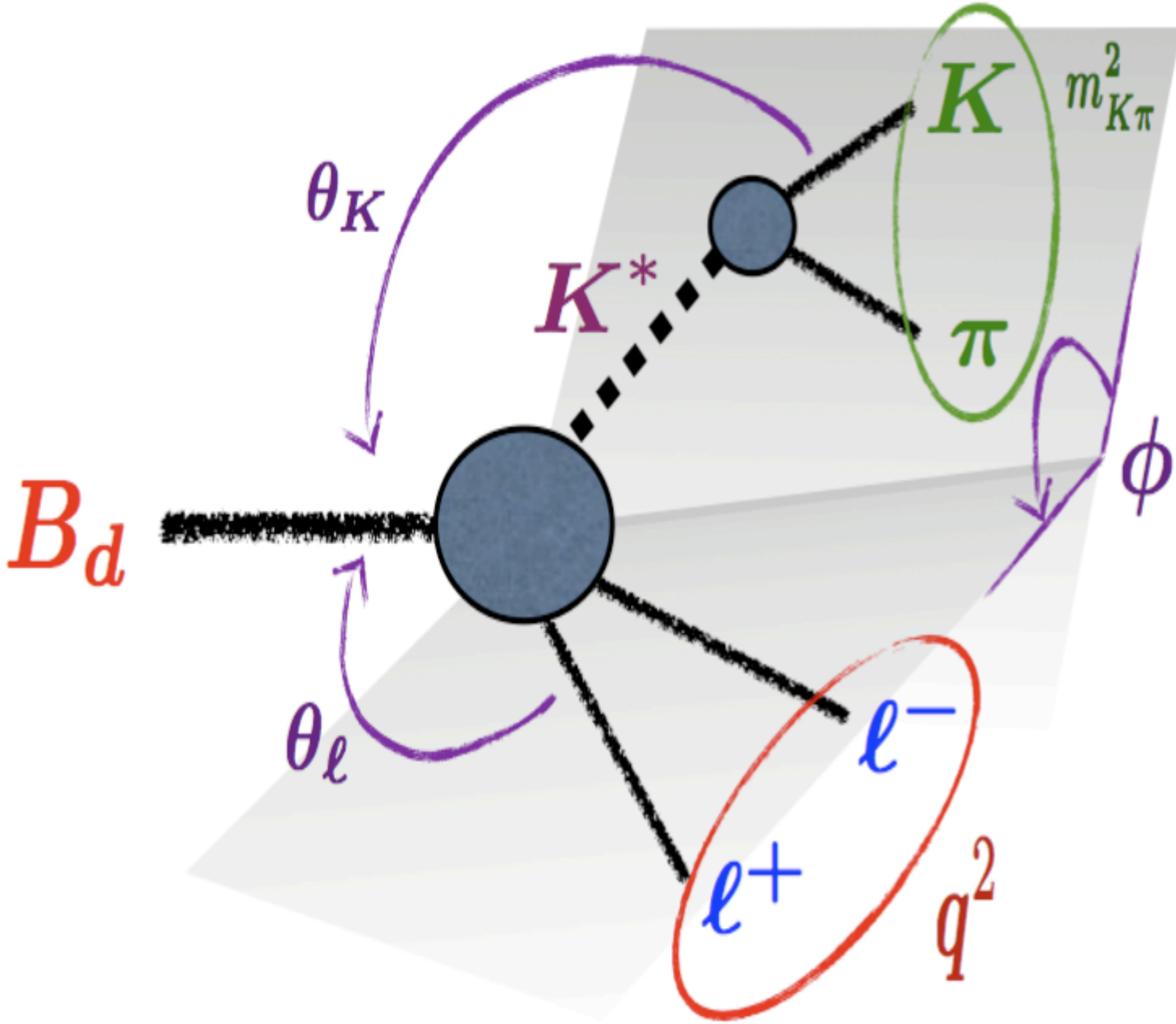
HADRON 2023 – June 9th, 2023

Will be discussing these type of decays:



literature | collaboration LHCb and not t detector and not t design

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays #1

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

pdf links DOI cite claim reference search 1,545 citations

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays #2

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)

Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]

pdf DOI cite claim reference search 1,297 citations

Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays #3

LHCb Collaboration • R. Aaij (CERN) et al. (May 16, 2017)

Published in: *JHEP* 08 (2017) 055 • e-Print: 1705.05802 [hep-ex]

pdf links DOI cite datasets claim reference search 1,220 citations

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ #4

LHCb Collaboration • Roel Aaij (CERN) et al. (Jun 29, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 11, 111803, *Phys.Rev.Lett.* 115 (2015) 15, 159901 (erratum) • e-Print: 1506.08614 [hep-ex]

pdf links DOI cite claim reference search 1,147 citations

Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity #5

LHCb Collaboration • Roel Aaij (CERN) et al. (Dec 14, 2015)

Published in: *JHEP* 02 (2016) 104 • e-Print: 1512.04442 [hep-ex]

pdf links DOI cite datasets claim reference search 901 citations

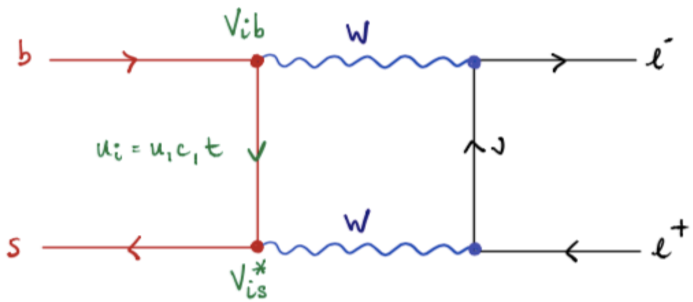
Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$ #6

LHCb Collaboration • R Aaij (NIKHEF, Amsterdam) et al. (Aug 7, 2013)

Published in: *Phys.Rev.Lett.* 111 (2013) 191801 • e-Print: 1308.1707 [hep-ex]

pdf DOI cite claim reference search 738 citations

SM is GIM/CKM and loop suppressed:



$$= \frac{g^2}{M_W^2} \sum_i V_{ib} V_{is}^* \, F(x_i)$$

$x_i = m_i^2 / M_W^2$

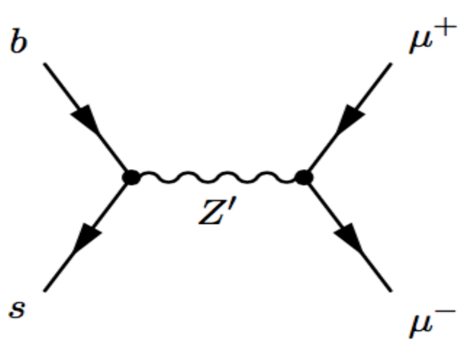
$$F(x_i) = F(0) + x_i \cdot F'(0) + \dots$$

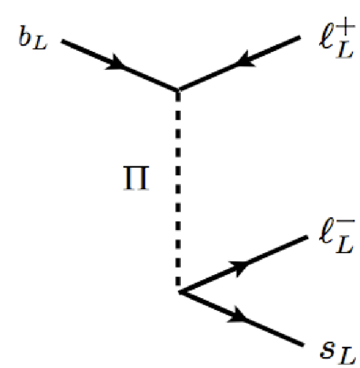
$$\sum_i V_{ib} V_{is}^* = 0$$

$$= \frac{g^2}{M_W^2} V_{tb} V_{ts}^* \, f(x_t) + \mathcal{O}(x_u - x_c)$$

4% ; Loop $\simeq \frac{1}{(4\pi)^2}$

Competes (potentially) with tree-level BSM contributions...





An order of magnitude estimate gives:

$$\frac{1}{(4\pi)^2}\frac{g^4}{M_W^2}\frac{m_t^2}{M_W^2}V_{tb}V_{ts}^* \sim \frac{1}{\Lambda_{NP}^2} \quad \Rightarrow \quad \Lambda_{NP} \sim 35\,\text{TeV}$$

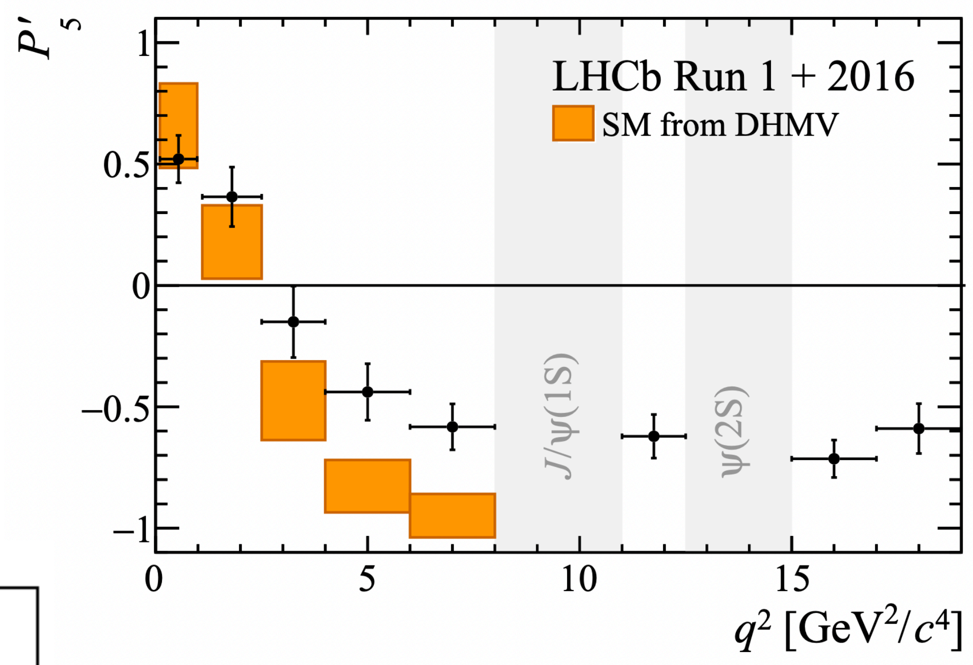
But in practice the important measure is **experimental + theoretical errors**

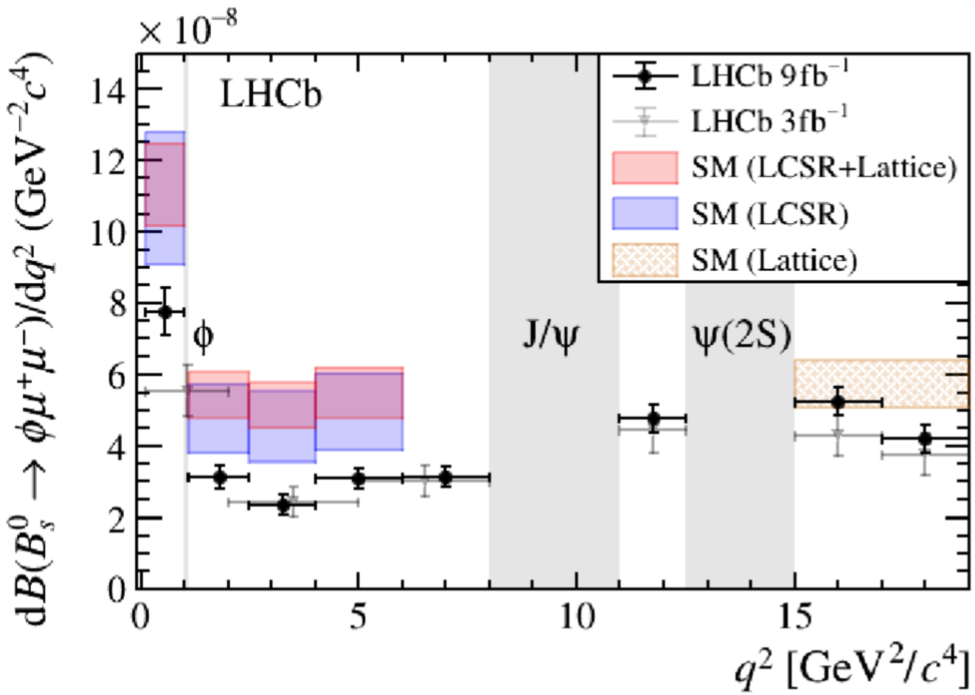
Experimentally the key is statistics ***

[*** It is actually a bit harder than that...]

Tensions in $b \to s\mu^+\mu^-$: BRs and AOs

Angular observables





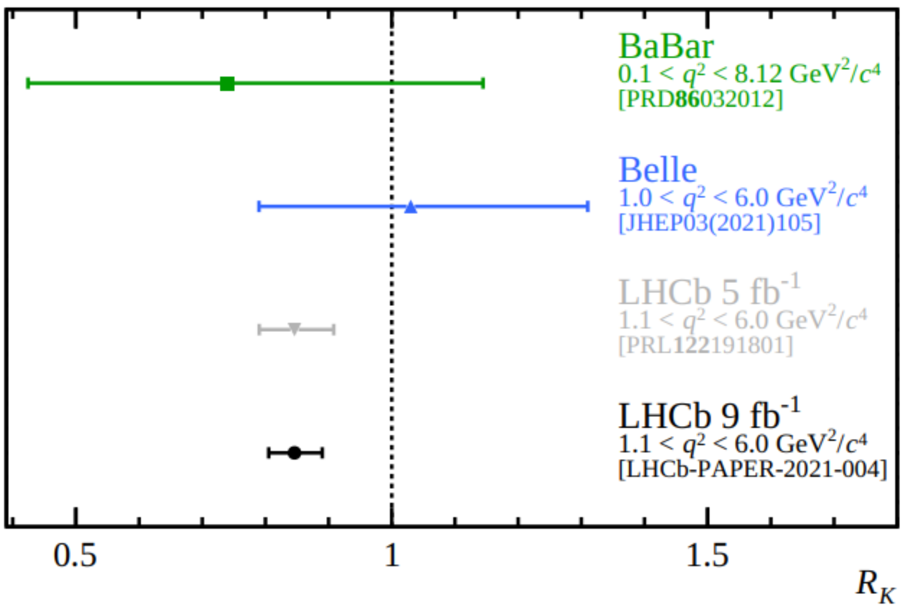
Branching fractions

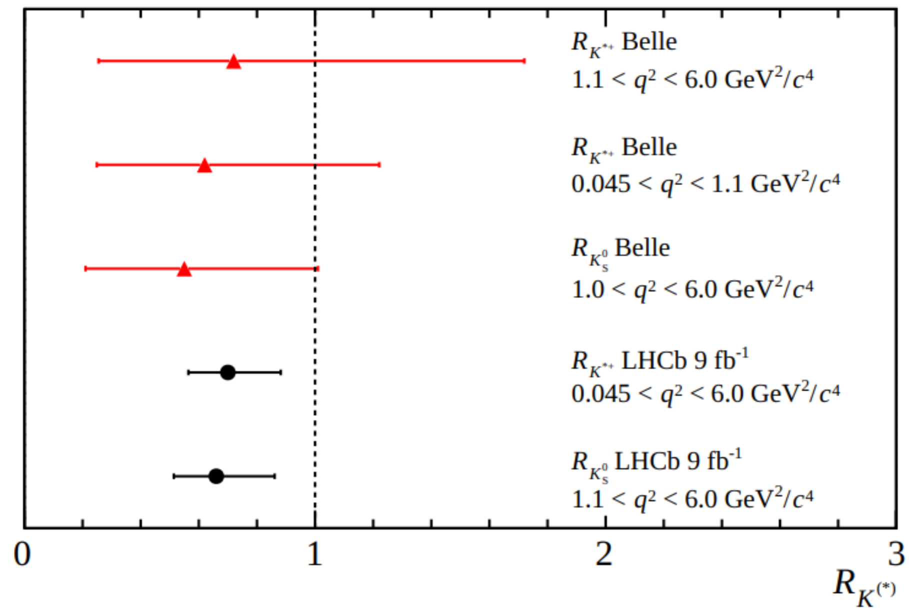
Tensions in $b \to s\mu^+\mu^-$: Two roads

- New Physics in $b \to se^+e^-$
  - Should see same type of deviations in both modes
  - Theoretically there is no particular advantage

- Lepton-Flavour Non-Universality
  - Theoretically clean (smoking gun)
  - Possible correlations to $b \to c\tau\nu$
  - Possible connection to LFV and effects elsewhere
  - Did not seem so well motivated at the time, but we got over it

LHCb 2103.11769, LHCb 2110.09501





$$R_H = \frac{\int_{\rm bin} dq^2\ BR(B \to H\mu^+\mu^-)}{\int_{\rm bin} dq^2\ BR(B \to He^+e^-)} \quad \overset{\rm SM}{- - - \longrightarrow} \quad \simeq 1$$

Hiller, Kruger

- **Anomalies in $b \to s\mu^+\mu^-$**: (LHCb, Belle, ATLAS, CMS)

$$P_5'(B \to K^*\mu^+\mu^-) \sim 3\sigma\ ; \quad \mathcal{B}(B_s \to \phi\mu^+\mu^-) \sim 2\sigma$$

$$\mathcal{B}(B \to K^{(*)}\mu^+\mu^-) \sim 1\sigma\ ; \quad \text{many others} \sim 0\sigma$$

Combined (180 Observables) $\sim 5\sigma$

Significantly alleviated if — Descotes, Matias, Virto 2013

$$\mathcal{L}_{NP} \simeq (35\,\mathrm{TeV})^{-2}\ [\bar{s}\gamma_\nu P_L b][\bar{\mu}\gamma^\nu \mu]$$

- **LFNU**: (LHCb, Belle)

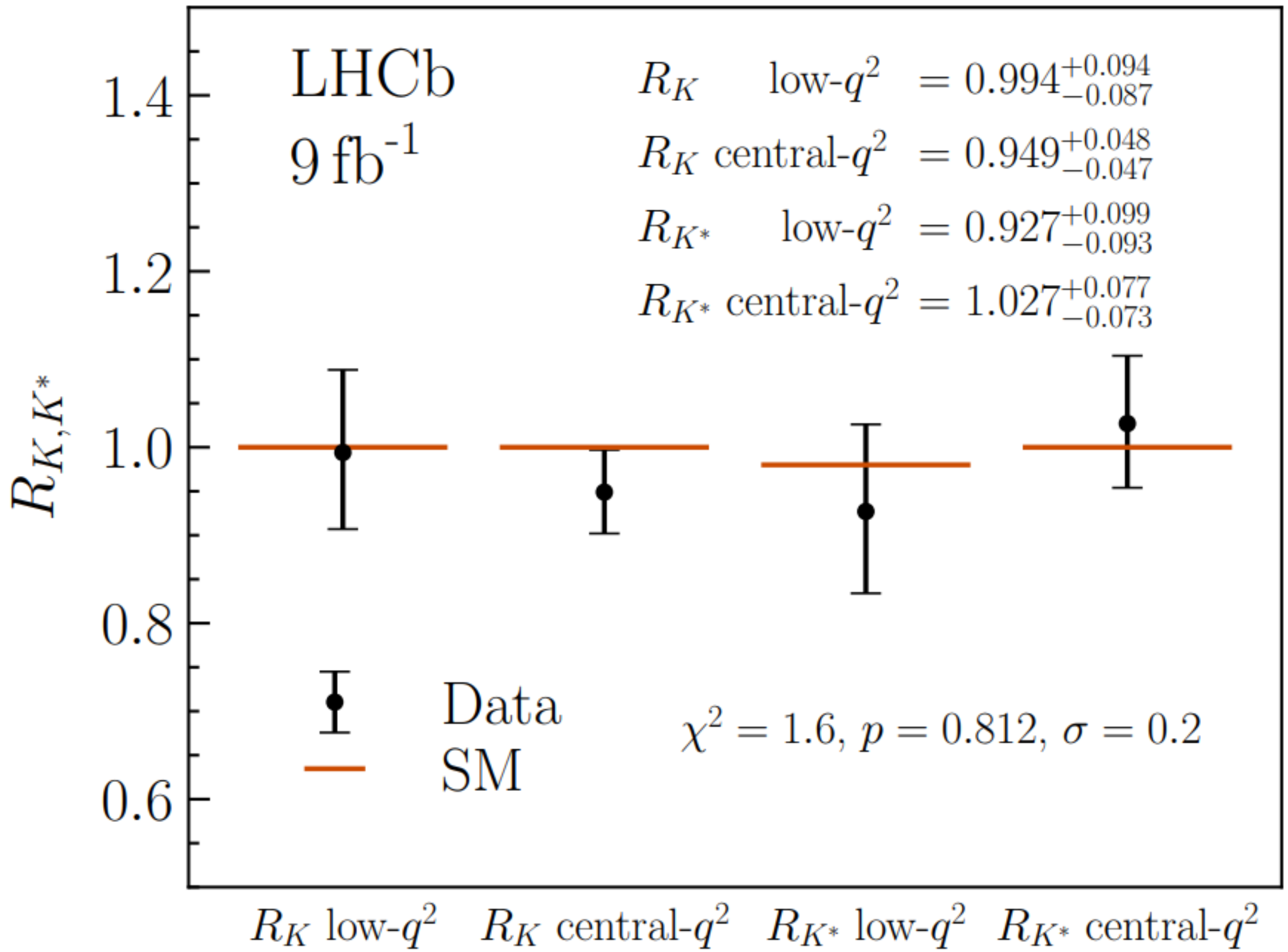
$$R_K, R_{K^*} \gtrsim 2\sigma\ ; \quad Q_5 \equiv P'_{5\mu} - P'_{5e} \gtrsim 1\sigma$$

Combined $\sim 4\sigma$

Consistent$^{(*)}$ with $b \to s\mu^+\mu^-$ — Alonso, Camalich, Grinstein 2014

NP interpretation requires accurate TH predictions of $B \to M\ell^+\ell^-$ obs

LHCb 2212.09153



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Significantly alleviated if

Descotes, Matias, Virto 2013

$$\mathcal{L}_{NP} \simeq (35\,\mathrm{TeV})^{-2}\,\{[\bar{s}\gamma_\nu P_L b][\bar{\mu}\gamma^\nu \mu] + [\bar{s}\gamma_\nu P_L b][\bar{e}\gamma^\nu e]\}$$

- LFNU: (LHCb, Belle)

$$R_K, R_{K^*} \gtrsim 2\sigma\,; \quad Q_5 = P'_{5\mu} - P'_{5e} \gtrsim 1\sigma$$

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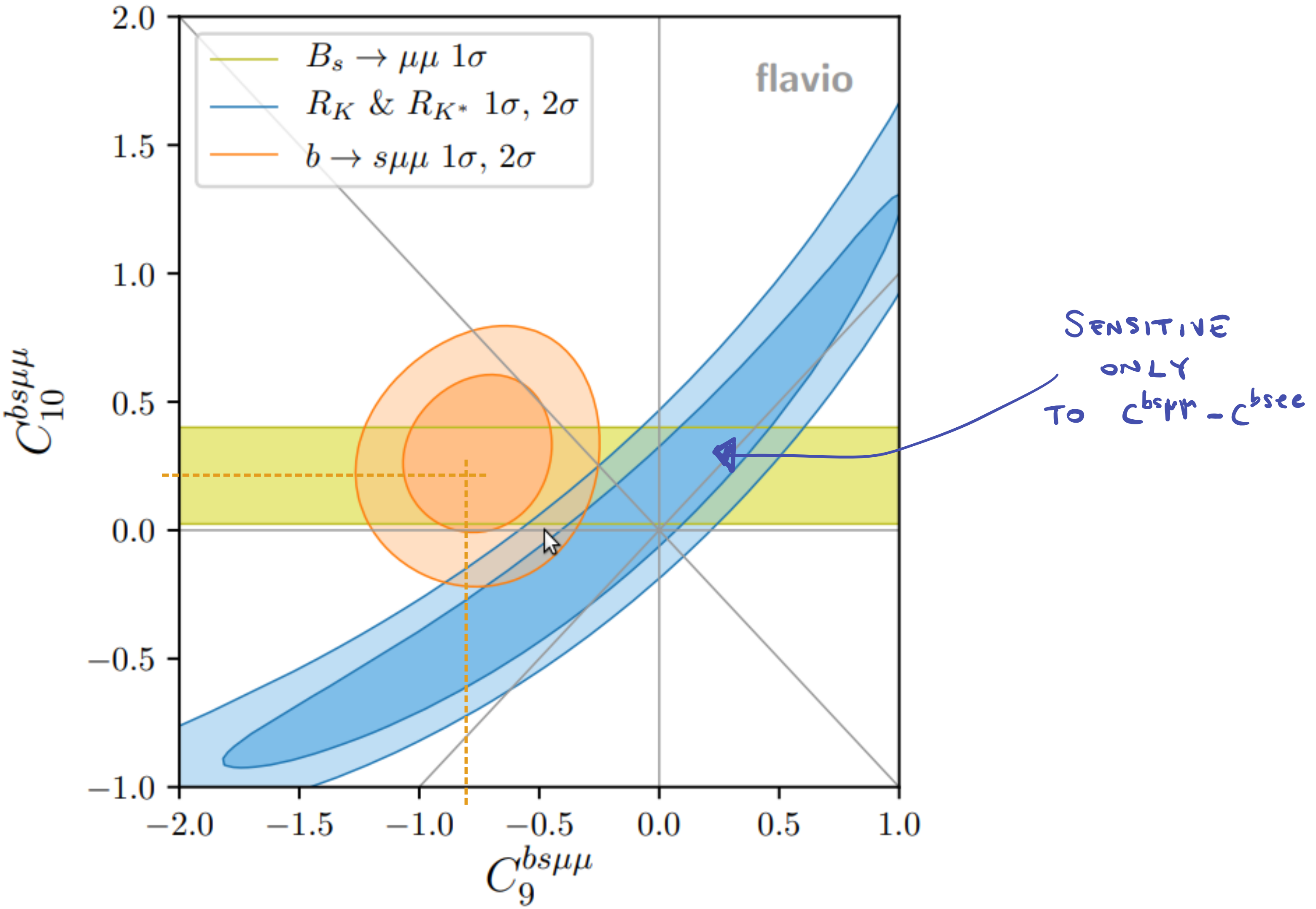
Consistent$^{(*)}$ with $b \to s\mu^+\mu^-$

Alonso, Camalich, Grinstein 2014

NP interpretation requires accurate TH predictions of $B \to M\ell^+\ell^-$ obs

Greljo, Salko, Smolkovic, Stangl 2022



Theory Calculations:

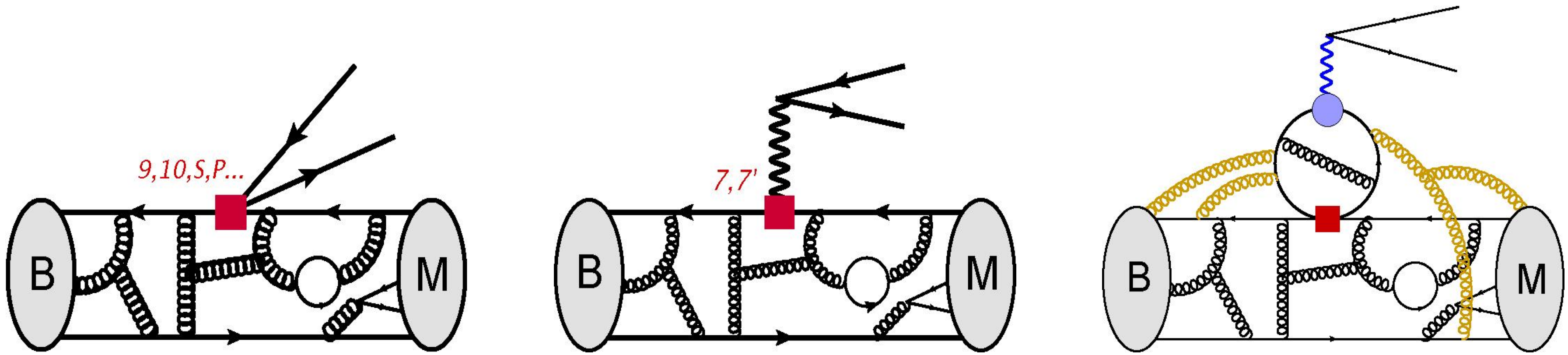
$$\mathcal{L}_{EFT} = \mathcal{L}_{QCD+QED} + \sum_i C_i \, \mathcal{O}_i$$

C_i = Calculated through a perturbative matching calculation

$$\mathcal{A}(B \to f) = \sum_i \underbrace{C_i}_{BSM} \; \underbrace{\langle f | T\{\cdots \mathcal{O}_i \cdots\} | B \rangle}_{QCD}$$

$\langle \mathcal{O}_i \rangle$ = Non-perturbative and difficult to calculate

Anatomy of $B \to M_\lambda \ell^+ \ell^-$ EFT Amplitudes



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

- Local (Form Factors): $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) | \, \bar{s}\, \Gamma_\lambda^{(T)}\, b \, | \bar{B}(k+q) \rangle$
- Non-Local: $\mathcal{H}_\lambda(q^2) = i\, \mathcal{P}_\mu^\lambda \int d^4x \, e^{iq\cdot x} \, \langle \bar{M}_\lambda(k) | T\{ j^\mu_{\rm em}(x), \mathcal{C}_i\, \mathcal{O}_i(0) \} | \bar{B}(q+k) \rangle$

In **both cases** the *"modern" strategy* is

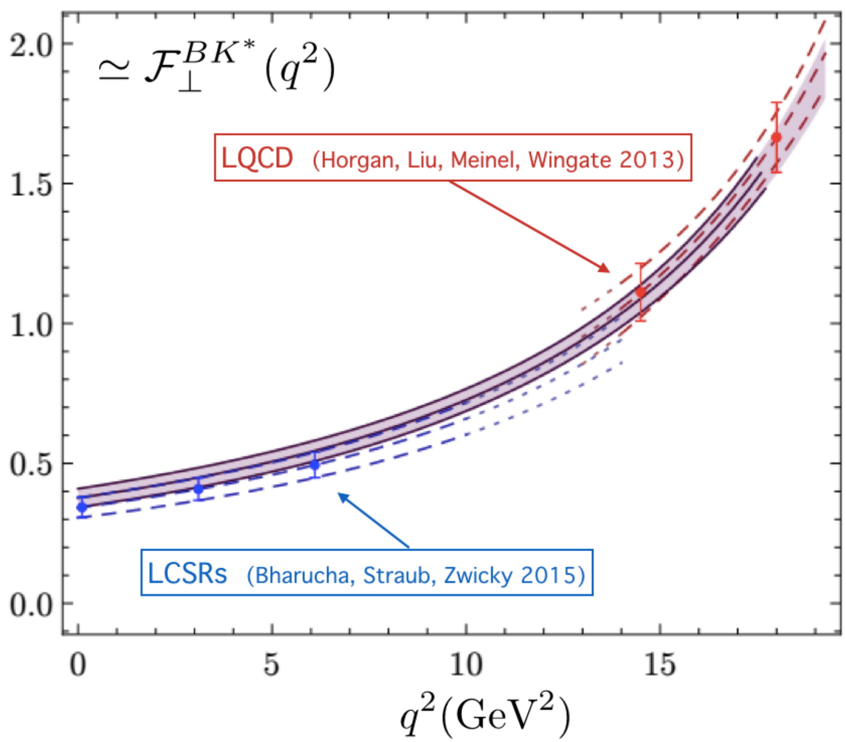
- **Calculate/extract** the form factors in optimal/feasible kinematic regions (**not** necessarily physical or the regions we are interested in)
  $\longrightarrow$ **"data"**

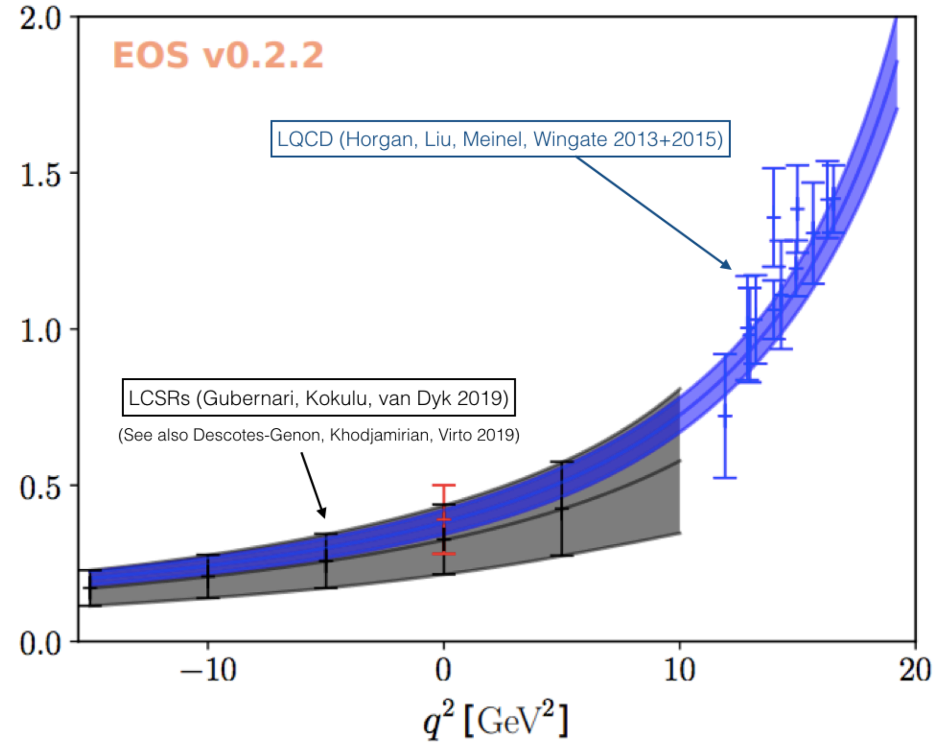
- **Parametrize** q^2 dependence by means of a rigorous **analytic expansion**

- **Fit** the (truncated) parametrization to the **"data"**

- Control the truncation error by means of a **dispersive bound**.

Local Form Factors



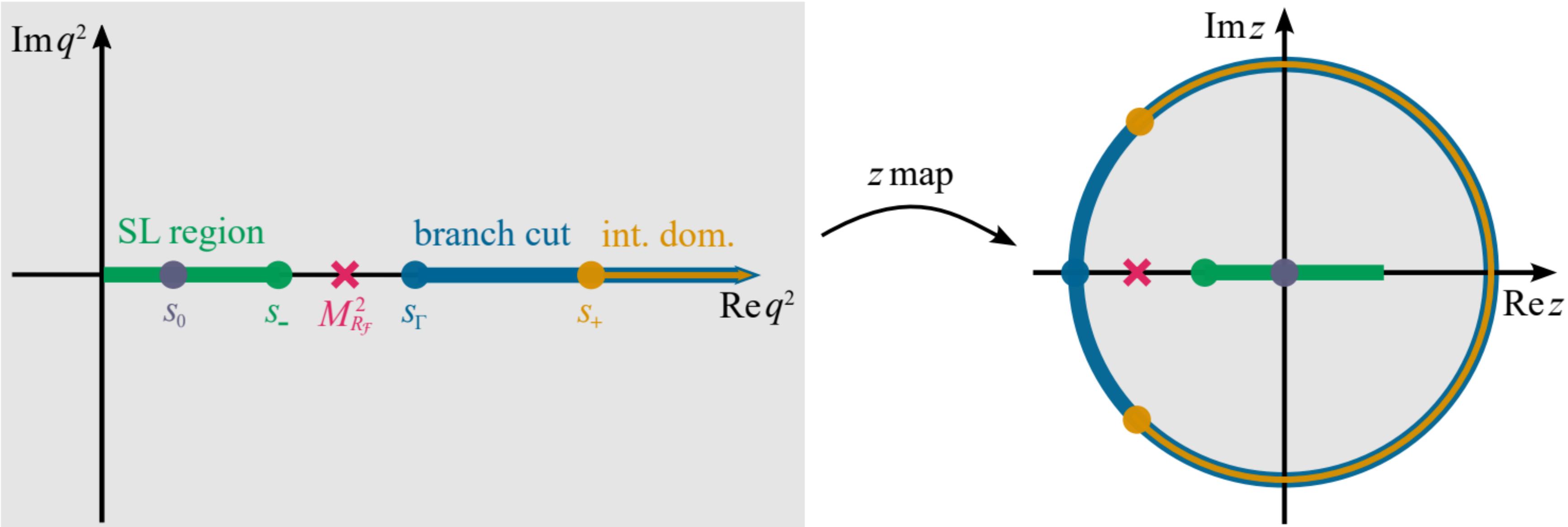


- Two main approaches: (1) Lattice QCD (large q^2 ***) (2) LCSRs (low q^2)
- Two approaches to LCSRs, in terms of (1) K^* LCDAs (2) B LCDAs
- q^2 dependence parametrized via a (dispersively-bounded) z-expansion

Form Factors : q^2-dependence from analyticity

Bourrely, Caprini, Lellouch; Boyd, Grinstein, Lebed; Caprini, Lellouch, Neubert; ...

- Conformal mapping : $$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$



- "z-parametrization" : $\hat{\mathcal{F}}_\lambda^{(T)}(q^2(z))$ is **analytic in** $|z| < 1$ $\qquad$ ($|z_{\rm phys}| < 0.15$)

$$\mathcal{F}_\lambda^{(T)}(q^2) = \frac{1}{(q^2 - m^2_{B_s^*})} \sum_k \alpha_k \, z(q^2)^k$$

Form Factors : Dispersive Bounds (BGL + improvement)

Boyd, Grinstein, Lebed 1997; Bharucha, Feldmann, Wick 2014, Gubernari, Reboud, van Dyk, Virto 2023

1. One starts with the two-point function

$$\Pi_\Gamma^{\mu\nu}(q) \equiv i\int d^4x\, e^{iq\cdot x}\langle 0|T\{J_\Gamma^\mu(x)J_\Gamma^{\dagger,\nu}(0)\}|0\rangle = \sum_{\lambda=t,\perp,\|,0} \epsilon_\lambda^\mu \epsilon_\lambda^{\nu*}\, \Pi_\Gamma^{(\lambda)}(q^2)$$

2. The invariant functions fulfil a once-subtracted dispersion relation:

$$\chi_\Gamma^{(\lambda)}(Q^2) = \left[\frac{\partial}{\partial q^2}\right]\Pi_\Gamma^{(\lambda)}(q^2)\bigg|_{q^2=Q^2} = \frac{1}{\pi}\int_0^\infty ds\,\frac{\mathrm{Im}\Pi_\Gamma^{(\lambda)}(s)}{(s-Q^2)^2}\,.$$

3. The function $\chi_\Gamma^{(\lambda)}(Q^2)$ can be calculated in an OPE at a suitable substraction point Q^2
Bharucha, Feldmann, Wick 2014

4. The discontinuity of $\Pi_\Gamma^{(\lambda)}(q^2)$ is the spectral function:

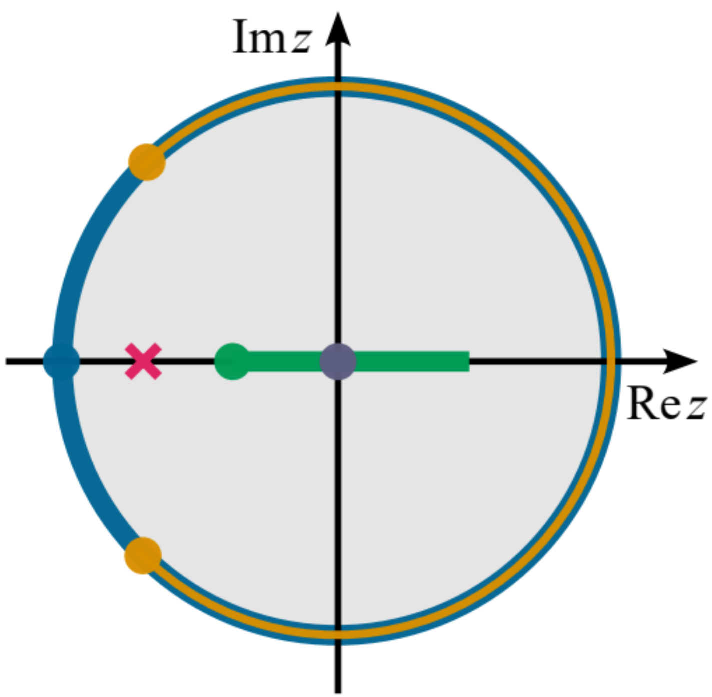
$$\mathrm{Im}\Pi_\Gamma^{(\lambda)}(s) \sim \sum_H \langle 0|J^\mu|H\rangle\langle H|J^{\nu\dagger}|0\rangle \sim f_{B_s^*}^2 + |F^{BK}|^2 + |F^{BK^*}|^2 + |F^{B_s\phi}|^2 + \cdots$$

(up to phase-space functions...)

Flynn, Jüttner, Tsang 2023; Gubernari, Reboud, van Dyk, Virto 2023

In order to simplify the bound, it is thus convenient to reparametrize:

$$\hat{\mathcal{F}}_\lambda^{B\to M}(q^2) = \mathcal{B}_\mathcal{F}(z)\phi_\mathcal{F}(z)\mathcal{F}_\lambda^{B\to M}(q^2) = \sum_k \alpha_k^\mathcal{F}\; p_k^\mathcal{F}(z)$$



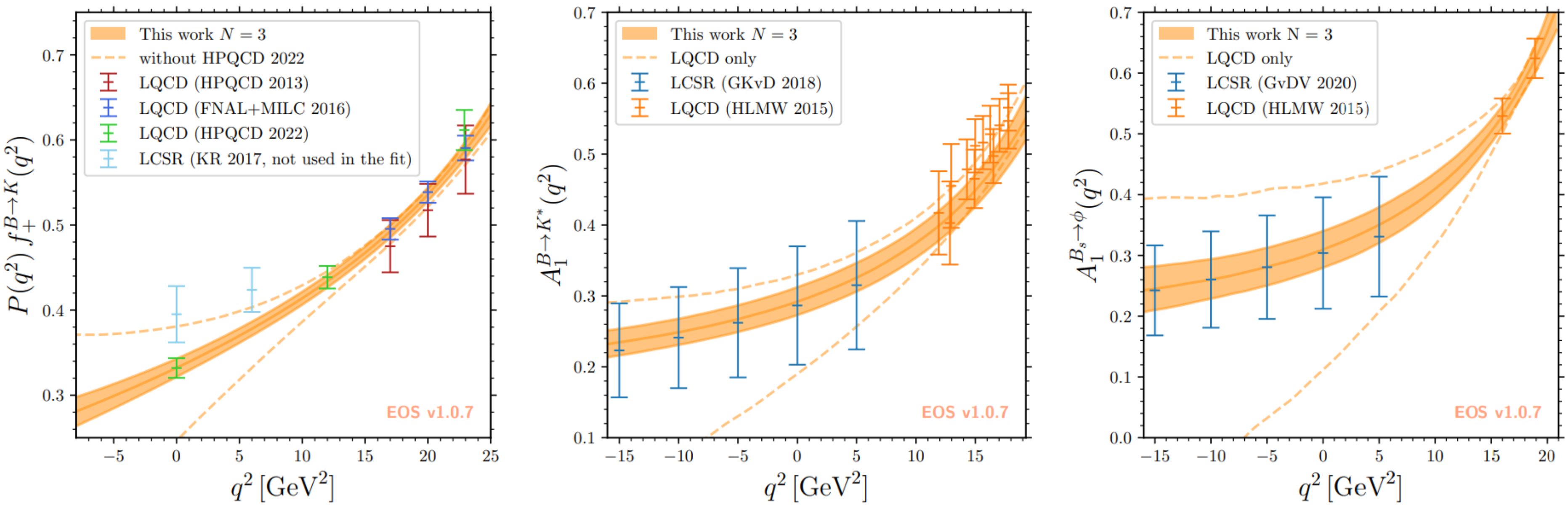
$$\int_{-\alpha_\mathcal{F}}^{+\alpha_\mathcal{F}} d\theta\, p_m^\mathcal{F}(e^{i\theta}) p_n^\mathcal{F}(e^{-i\theta}) = \delta_{mn}$$

$$\sum_{B\to M} \int_{-\alpha_\mathcal{F}}^{+\alpha_\mathcal{F}} d\theta \left|\hat{\mathcal{F}}_\lambda^{B\to M}(e^{i\theta})\right|^2 < 1$$

$$\sum_{\mathcal{F},k} |\alpha_k^\mathcal{F}|^2 < 1$$

Local Form Factors: Results

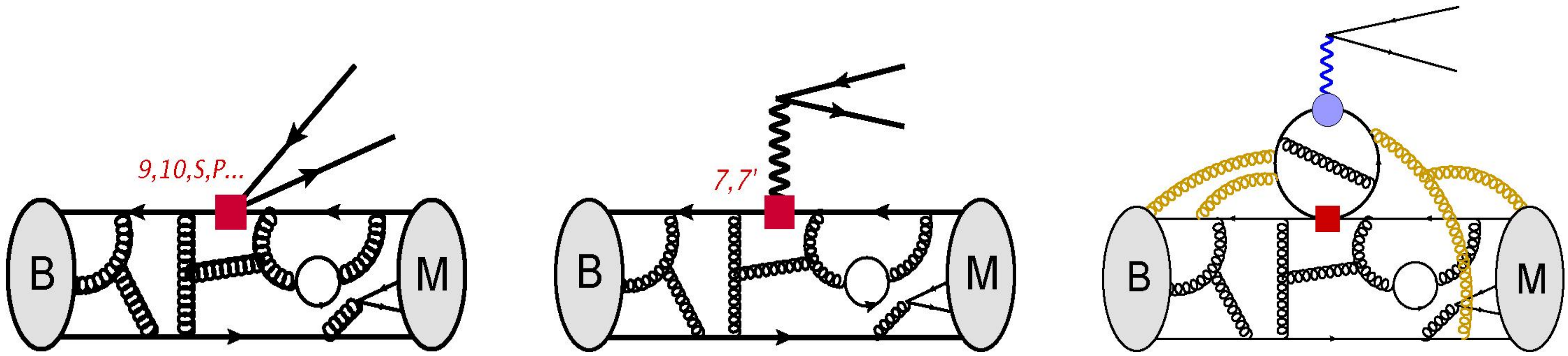
Gubernari, Reboud, van Dyk, Virto 2023



Truncate the series expansion to $N = 2, 3, 4$

Uncertainties stable for $N > 2$

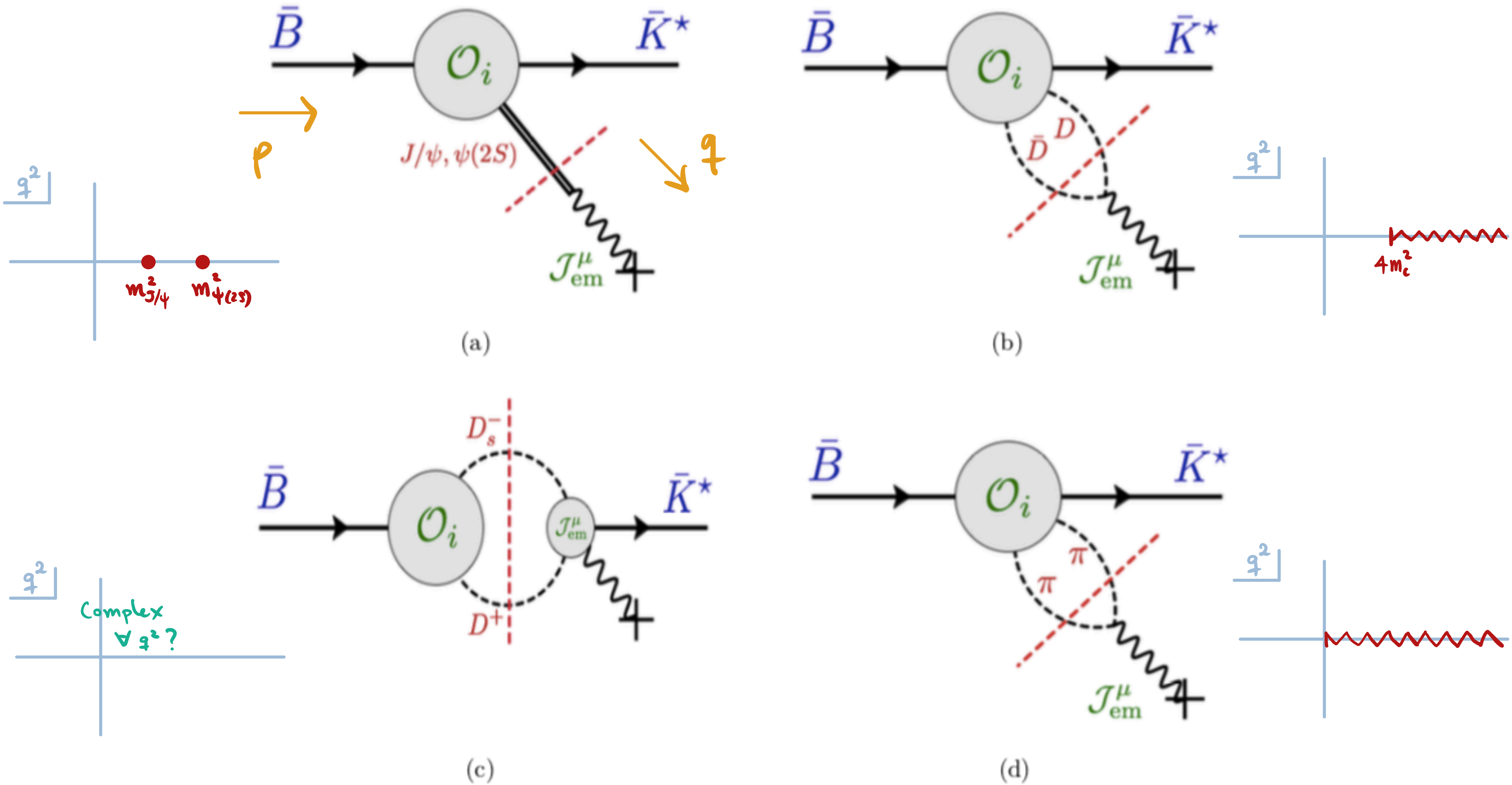
Non-Local Form Factors



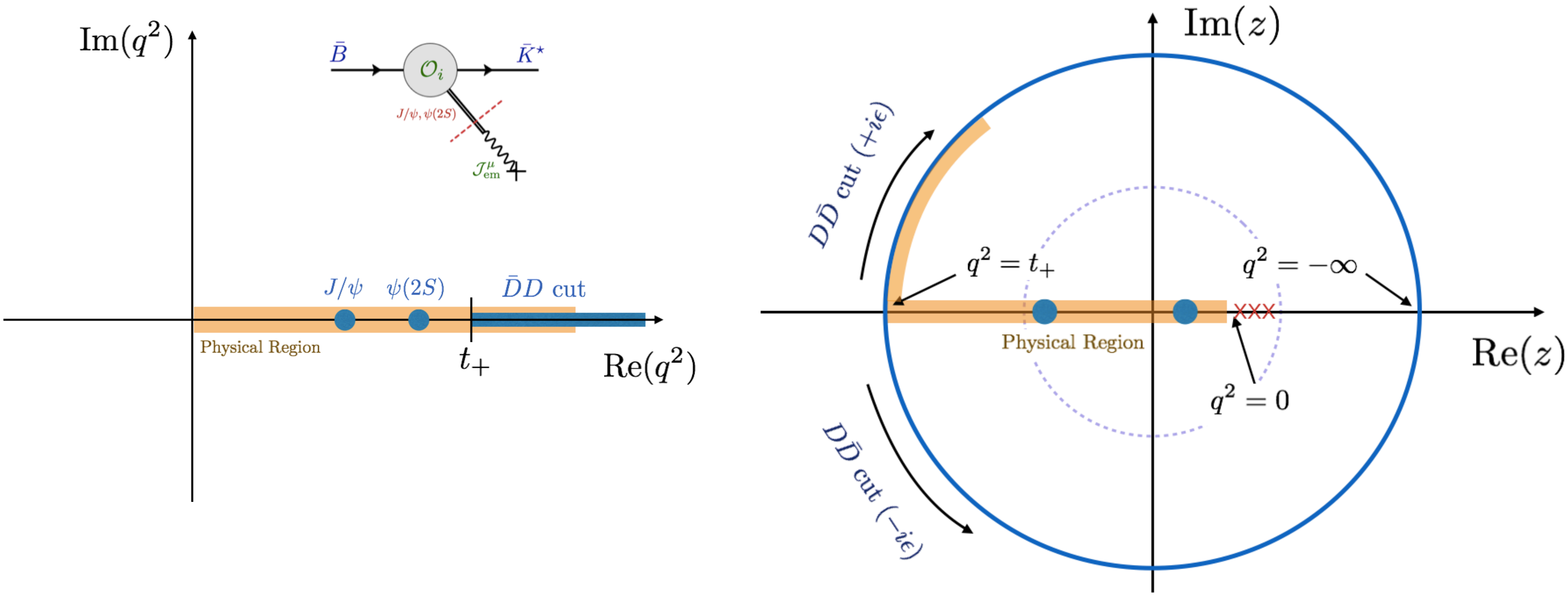
$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- Local (Form Factors) : $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) |\, \bar{s}\, \Gamma_\lambda^{(T)}\, b \,| \bar{B}(k+q) \rangle$
- Non-Local : $\mathcal{H}_\lambda(q^2) = i\, \mathcal{P}_\mu^\lambda \int d^4x\, e^{iq\cdot x} \langle \bar{M}_\lambda(k) | \mathcal{T}\{ \mathcal{J}^\mu_{\rm em}(x), \mathcal{C}_i\, \mathcal{O}_i(0) \} | \bar{B}(q+k) \rangle$

Non-Local Form Factors: Analytic structure



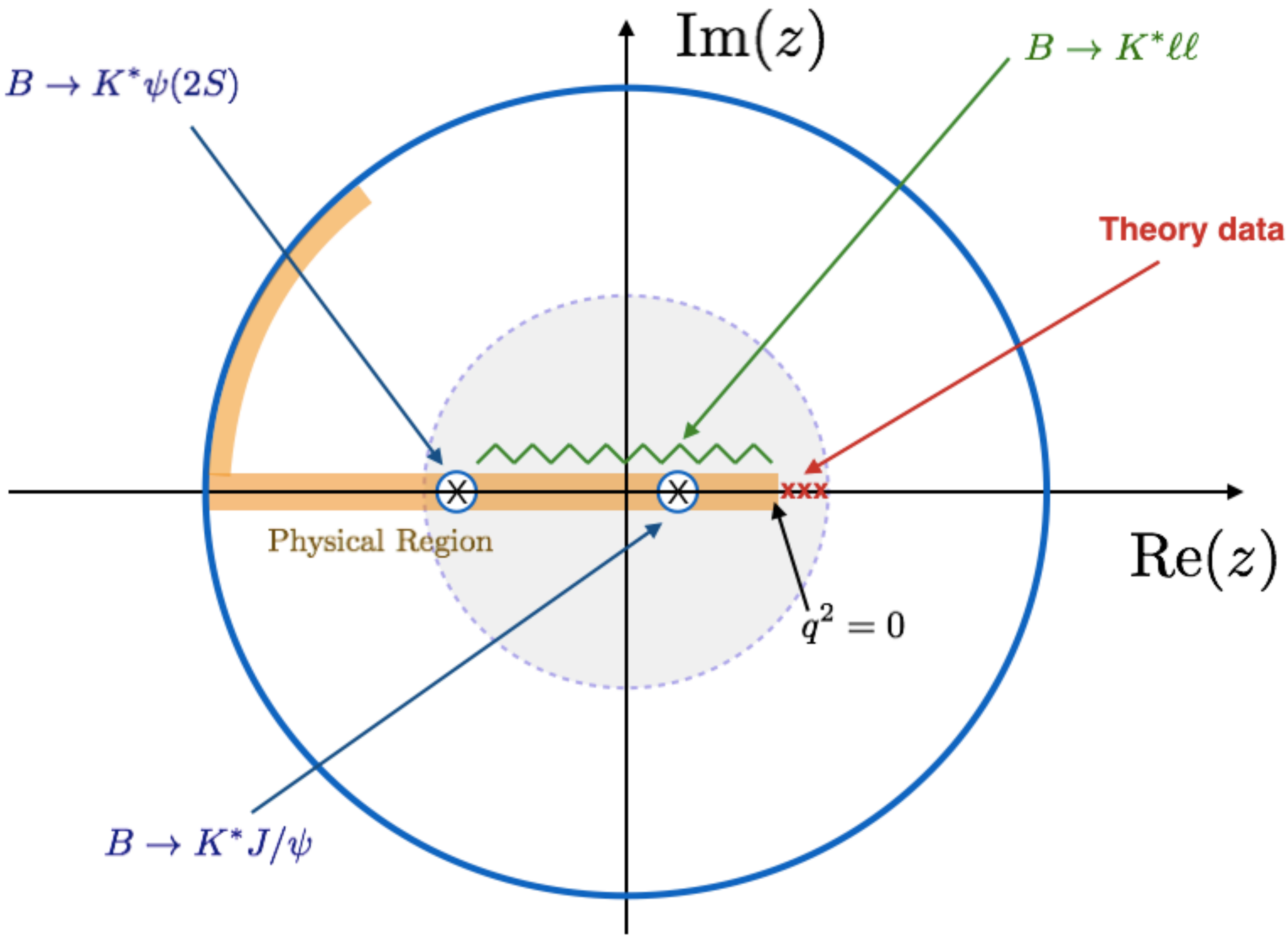
z-parametrisation for $\mathcal{H}_\lambda(q^2)$



- $\hat{\mathcal{H}}_\lambda(q^2(z)) = (q^2 - M^2_{J/\psi})(q^2 - M^2_{\psi(2S)})\,\mathcal{H}_\lambda(q^2)$ is **analytic in** $|z| < 1$
- Taylor expand $\hat{\mathcal{H}}_\lambda(z)$ around $z = 0$: $\hat{\mathcal{H}}_\lambda(z) = \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)} z^k\right]\mathcal{H}_\lambda(z)$
- Expansion needed for $|z| < 0.52$ ($-7\,\text{GeV}^2 \leq q^2 \leq 14\text{GeV}^2$)

Fit to z-parametrisation

Bobeth, Chrzaszcz, van Dyk, Virto 2017



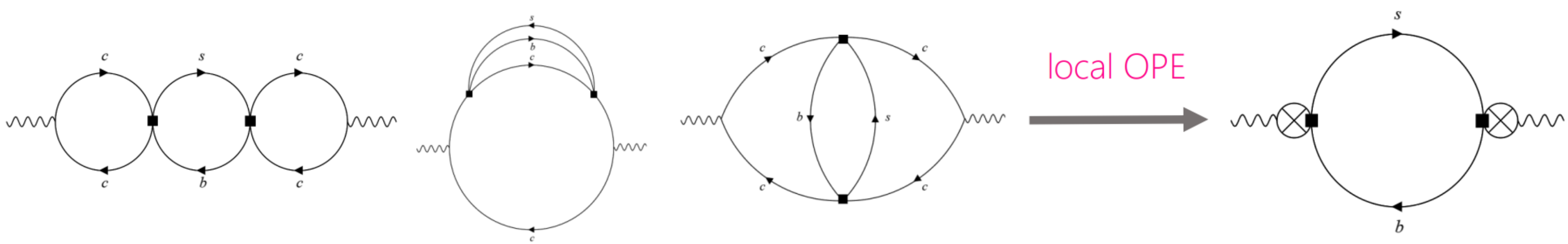
1. Use the correlation function

$$\Pi(q) \equiv i \int d^4x \, e^{iq\cdot x} \langle 0 | T \left\{ O^\mu(q;x), O^{\mu,\dagger}(q;0) \right\} |0\rangle$$

where

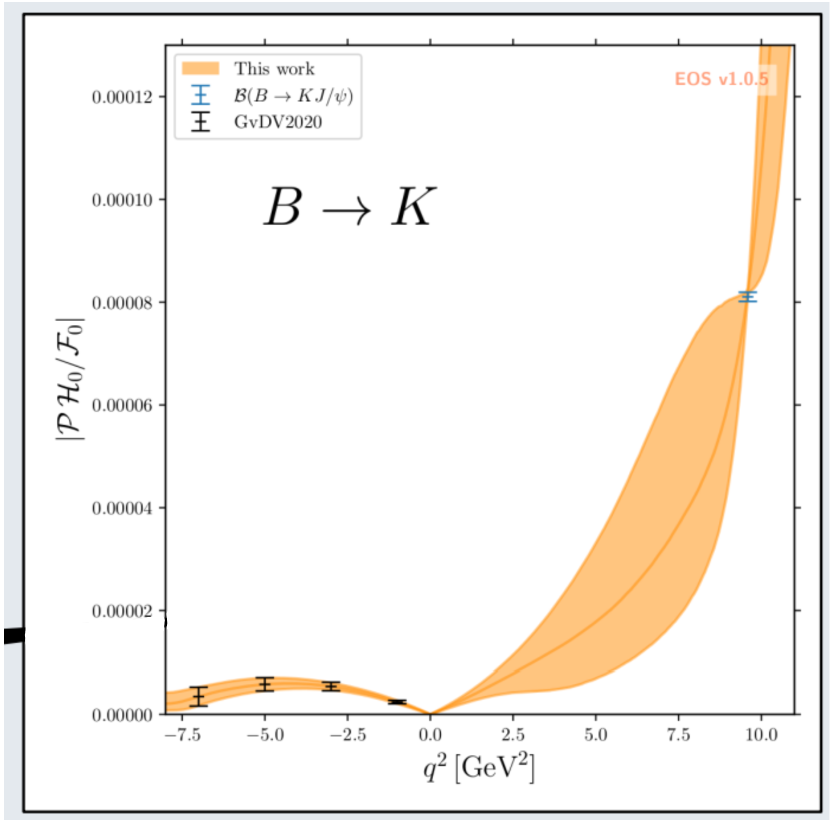
$$O^\mu(q;x) = -i \int d^4y \, e^{+iq\cdot y} \; T\{ j^\mu_{\rm em}(x+y), (C_1\mathcal{O}_1 + C_2\mathcal{O}_2)(x) \}$$

2. Calculate in OPE region



3. Note that (skematic) $\quad \mathrm{Im}\Pi(q^2) \sim \sum_\lambda |\mathcal{H}_\lambda|^2 + \text{positive}$

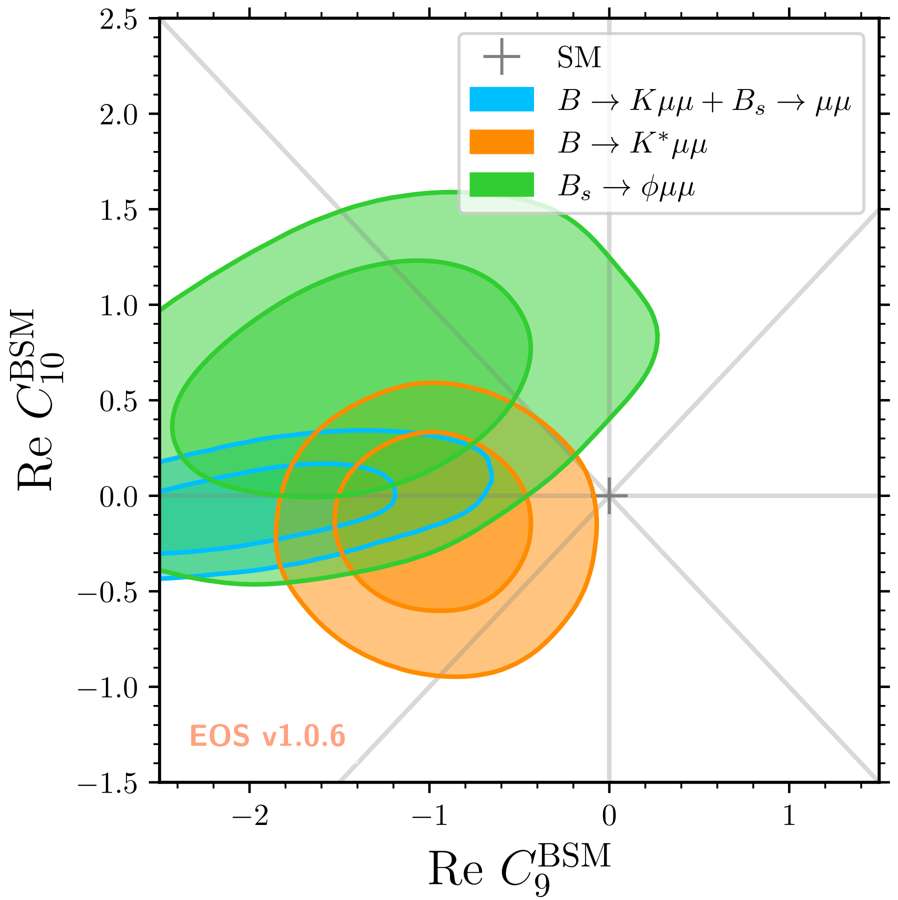
Non-local form factor fitted to LCOPE and J/Ψ data



Use under-constrained fit (N = 5) which saturates dispersive bound

All p-values are larger than 11%

Proof-of-concept fit to three modes separately.



Updated blue contour with:

- new HPQCD'22 [2207.12468] form factors
- new $B_s \to \mu\mu$ average [CMS 2212.10311]

Summary

Anomalies in $b \to s\mu\mu$ recently extended to $b \to see$

The understanding of rare B decay measurements requires the knowledge of **local and non-local form factors**

$$\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) | \, \bar{s}\, \Gamma_\lambda^{(T)}\, b \, | \bar{B}(k+q) \rangle$$

$$\mathcal{H}^\mu(q^2) = i \int d^4x \, e^{iq\cdot x} \, \langle \bar{M}_\lambda(k) | T\{ j^\mu_{\rm em}(x), [\bar{b}_L \gamma^\nu c_L][\bar{c}_L \gamma_\nu s](0) \} | \bar{B}(q+k) \rangle$$

Currently based on:

1. Calculation **2.** Analytic parametrizacion **3.** Dispersive bound

If you are into hadronic physics, you can try to get involved

END

B mesons mix and decay due to $\mathcal{L}_{Weak} + \mathcal{L}_{BSM?}$

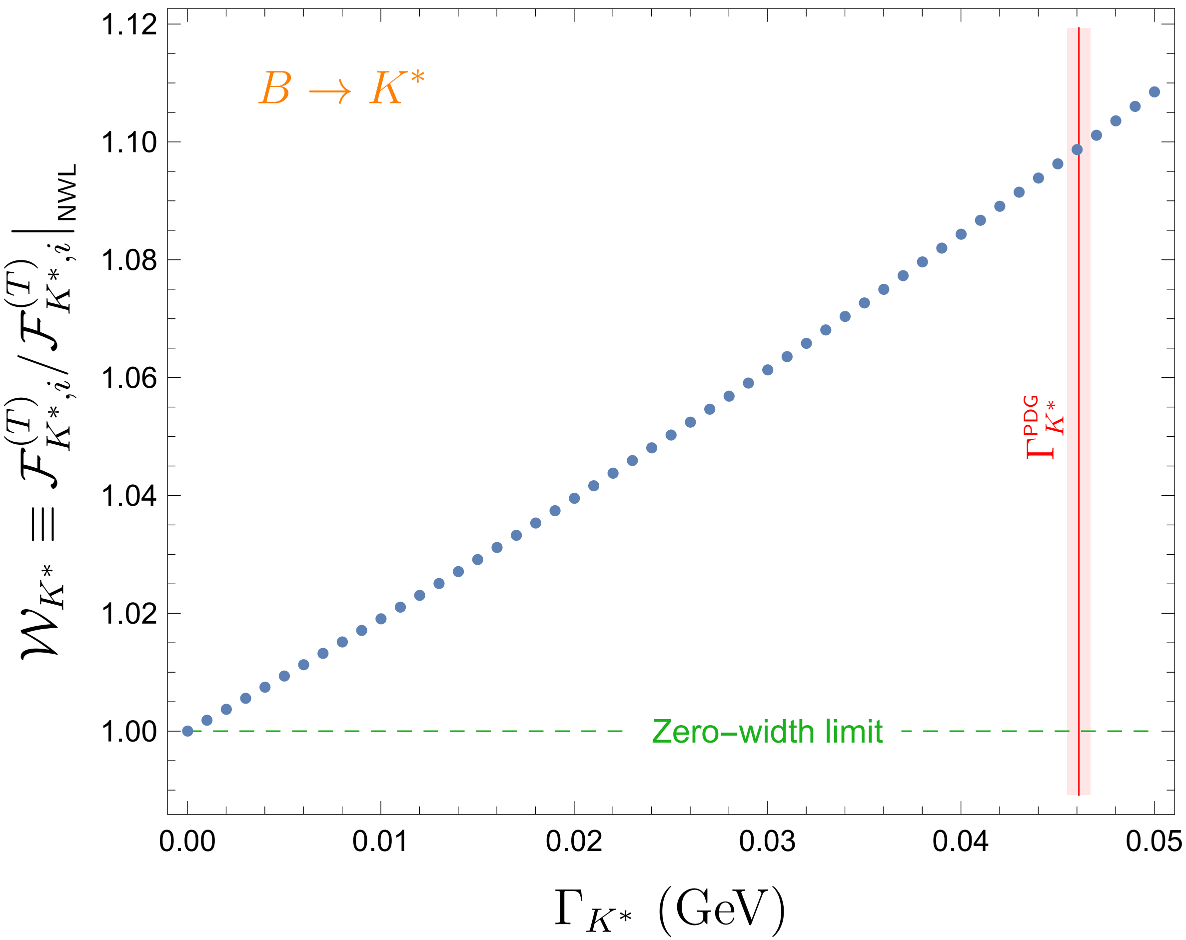
For $m_B \ll M_W, M_{BSM}$ we use an EFT : $\mathcal{L}_{EFT} = \mathcal{L}_{QCD+QED} + \sum_i C_i\, \mathcal{O}_i$

Class	Flavour structure	Number of Ops.	Other flavours	ADM	Example process
Class I	$\bar{s}b\,\bar{s}b$	5+3	$\bar{d}b\,\bar{d}b$	$\hat{\gamma}_{\rm I}$	$B_q - \overline{B}_q$ mixing
Class II	$\bar{u}b\,\bar{\ell}\nu_{\ell'}$	$(2+3)\times 9$	$\bar{c}b\,\bar{\ell}\nu_{\ell'}$	$\hat{\gamma}_{\rm II}$	$\overline{B}_d \to \pi^+\mu^-\bar{\nu}$
Class III	$\bar{s}b\,\bar{u}c$	10+10	$\bar{s}b\,\bar{c}u$ $\bar{d}b\,\bar{u}c$ $\bar{d}b\,\bar{c}u$	$\hat{\gamma}_{\rm III}$	$B^- \to \overline{D}^0 K^-$
Class IV	$\bar{s}b\,\bar{s}d$	5+5	$\bar{d}b\,\bar{d}s$ $\bar{b}s\,\bar{b}d$	$\hat{\gamma}_{\rm IV}$	$B^- \to \overline{K}^0 K^-$
Class V	$\bar{s}b\,\bar{q}q$ $\bar{s}b\,F,\ \bar{s}b\,G$ $\bar{s}b\,\bar{\ell}\ell$	57+57	$\bar{d}b\,\bar{q}q$ $\bar{d}b\,F,\ \bar{d}b\,G$ $\bar{d}b\,\bar{\ell}\ell$	$\hat{\gamma}_{\rm V}$	$\overline{B}_d \to D^+D_s^-$ $\overline{B}_d \to X_s\gamma$ $B^- \to K^-\mu^+\mu^-$
Class Vb	$\bar{s}b\,\bar{\ell}\ell',\ \ell \neq \ell'$	$(5+5)\times 6$	$\bar{d}b\,\bar{\ell}\ell'$	$\hat{\gamma}_{\rm Vb}$	$\overline{B}_s \to \mu^-\tau^+$
Class Vν	$\bar{s}b\,\bar{\nu}_\ell\nu_{\ell'}$	$(1+1)\times 9$	$\bar{d}b\,\bar{\nu}_\ell\nu_{\ell'}$	zero	$B^- \to K^-\bar{\nu}\nu$

Aebischer, Fael, Greub, Virto 2017

Form factors for unstable mesons (e.g., K^*): width effects

Descotes-Genon, Khodjamirian, Virto 2019



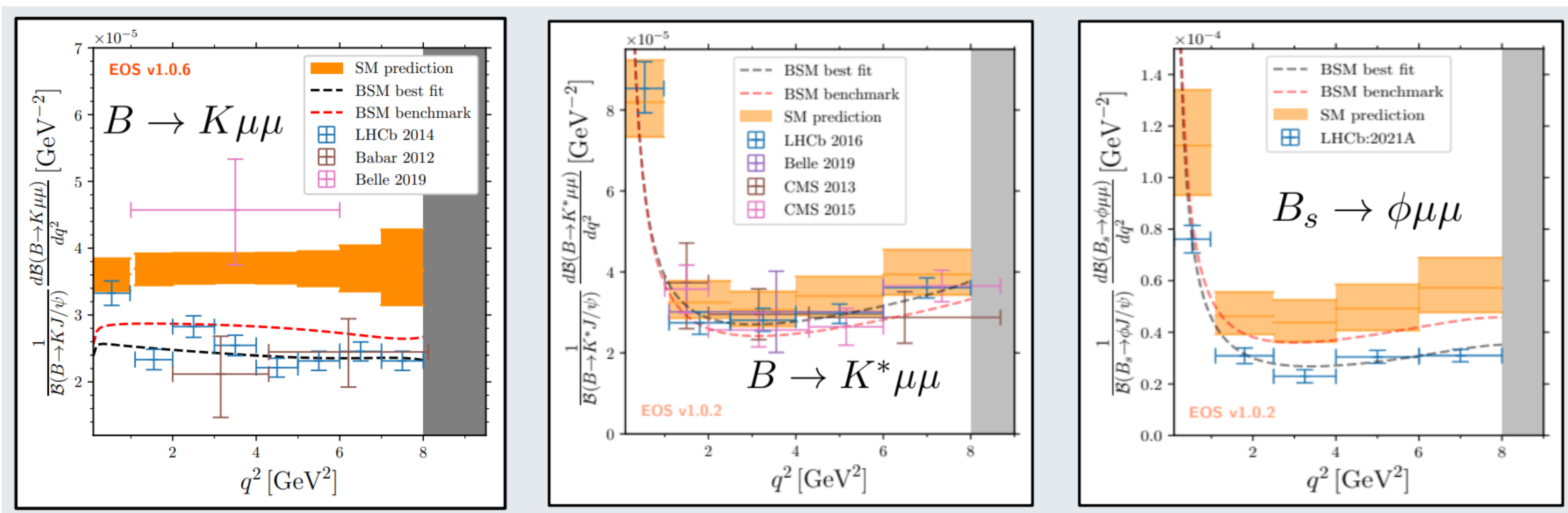
Crucial input: $\tau \to K\pi\nu$

$$\mathcal{W}_{K^*} \simeq 1 + 1.9\,\frac{\Gamma_{K^*}}{m_{K^*}}$$

$$\mathcal{W}_{K^*} = 1.09 \pm 0.01$$

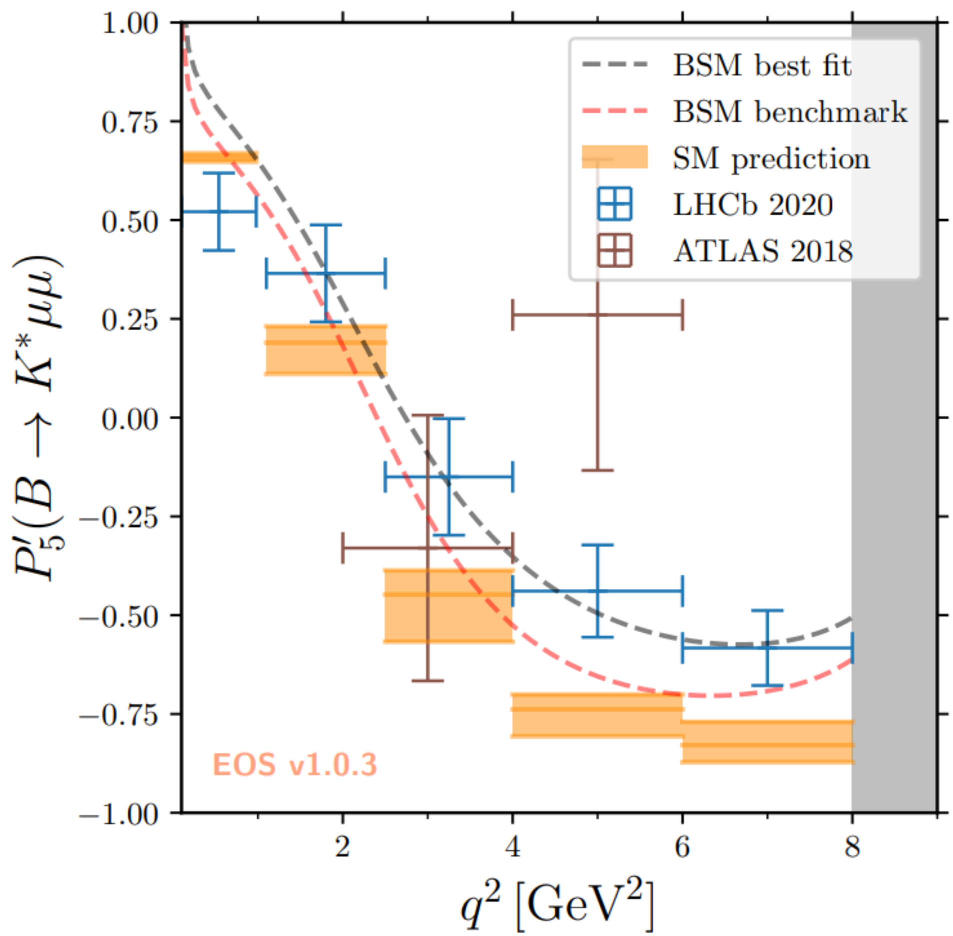
$\Rightarrow$ BRs are corrected by a factor $|\mathcal{W}_{K^*}|^2 \simeq 1.2$ (increasing anomalies)

Branching Fractions



Conservatively accounting for the non-local form factors does not improve agreement with data

Angular observables



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