Theoretical predictions for $b \to s\mu^+\mu^-$

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Based on
arXiv: 2011.09813, 2206.03797, 2305.06301, 2312.14146

in collaboration with
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58th Rencontres de Moriond
Electroweak Interactions & Unified Theories

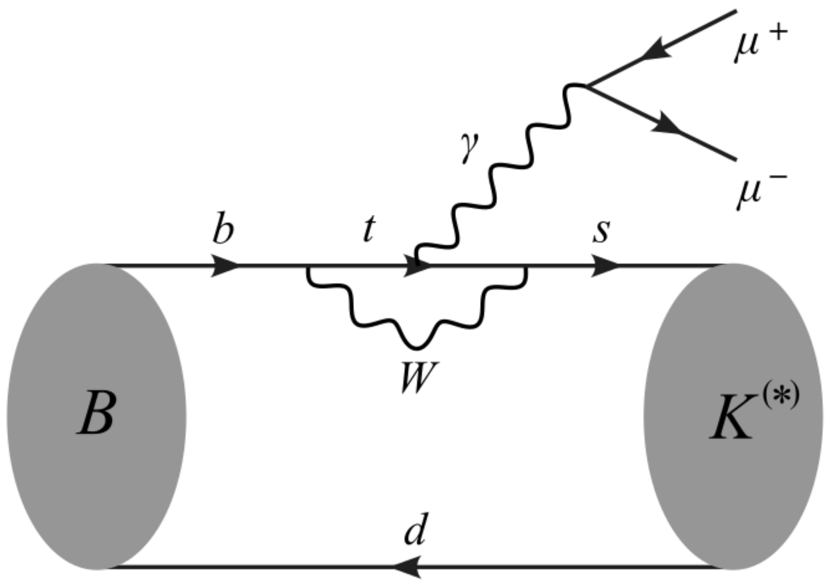
La Thuile, 27-March-2024

Introduction

$B \to K^{(*)}\mu^+\mu^-$ decays

flavour physics $\Longrightarrow$ probe the SM through **indirect searches**

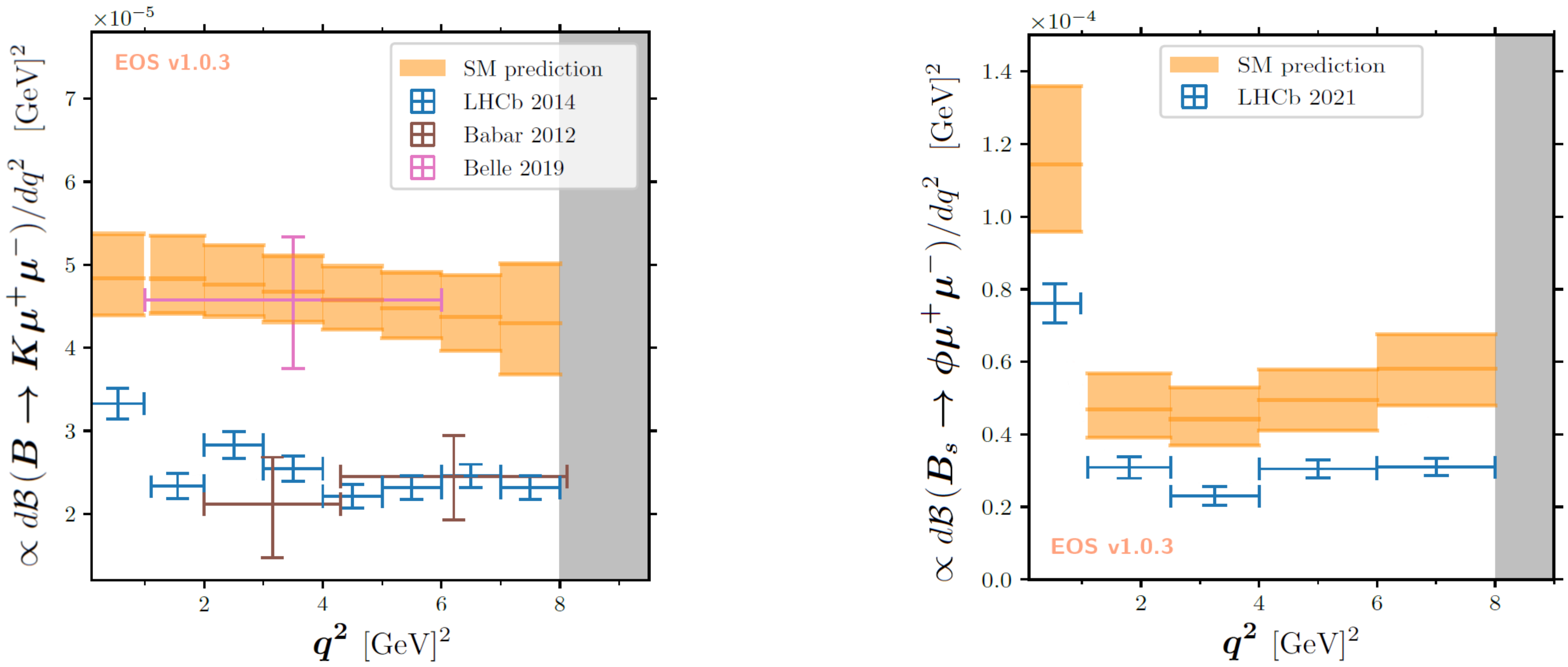
1. **measure** physical observables
2. **calculate** the observables in the SM
3. **compare** measurements and calculations
   $\Longrightarrow$ obtain constraints on NP (or new discovery?)



$B \to K^{(*)}\mu^+\mu^-$ decays excellent to perform indirect searches since they are suppressed in the SM $\Longrightarrow$ **sensitive to NP**
(loop, GIM and CKM suppressed)

Tensions in $b \to s\mu^+\mu^-$ decays

compare exp. measurements and theory predictions for
branching ratios and angular observables $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$



tension (or anomalies) in $b \to s\mu^+\mu^-$ observables $\Longrightarrow$ need to understand this tension
(independent from the LFU ratios R_K and R_{K^*})

Theoretical framework

Weak effective theory for FCNC

flavour changing neutral currents (FCNC)
are absent at tree level in the SM

integrate out DOF heavier than the b

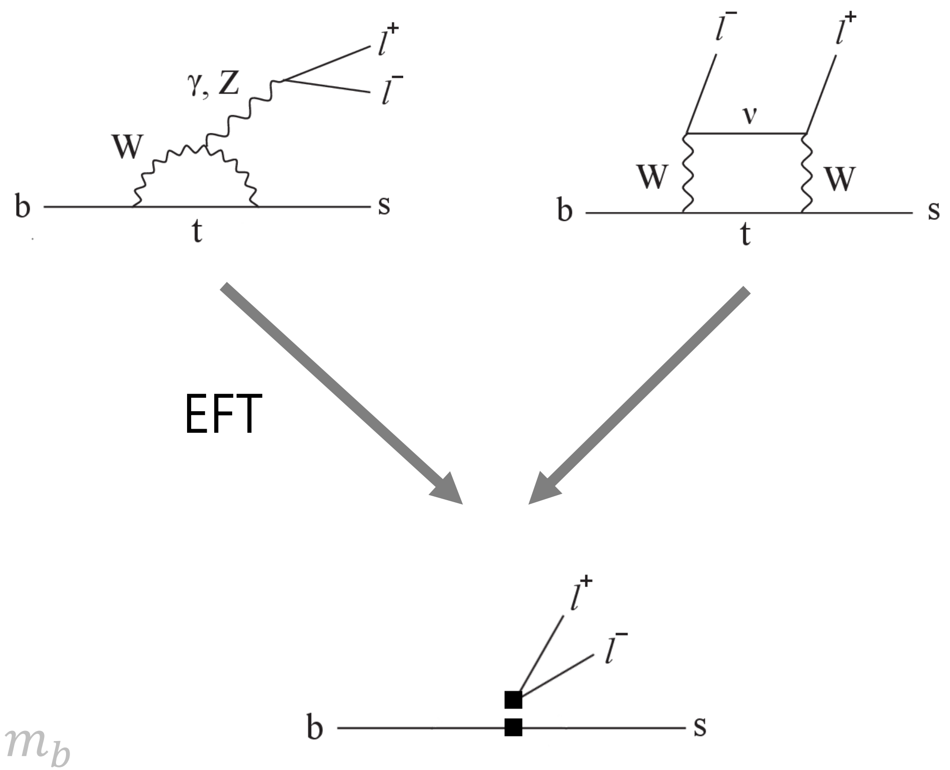
↓

weak effective field theory

transitions described by the **effective Hamiltonian**

$$\mathcal{H}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu) \qquad \mu = m_b$$

C_i Wilson coefficients, O_i effective operators



Decay amplitude for $B \to K^{(*)}\ell^+\ell^-$

calculate decay amplitudes precisely to probe the SM

$b \to s\mu^+\mu^-$ anomalies: NP or underestimated QCD uncertainties?

$$\mathcal{A}(B \to K^{(*)}\ell^+\ell^-) = \mathcal{N}\left[\underbrace{\left(C_9 L_V^\mu + C_{10} L_A^\mu\right)}\mathcal{F}_\mu - \underbrace{\frac{L_V^\mu}{q^2}}\left(C_7\,\mathcal{F}_{T,\mu} + \mathcal{H}_\mu\right)\right]$$

Wilson coefficients, leptonic matrix elements (and constants $\boldsymbol{\alpha}$, $\boldsymbol{V_{CKM}}$...)

perturbative objects, small uncertainties

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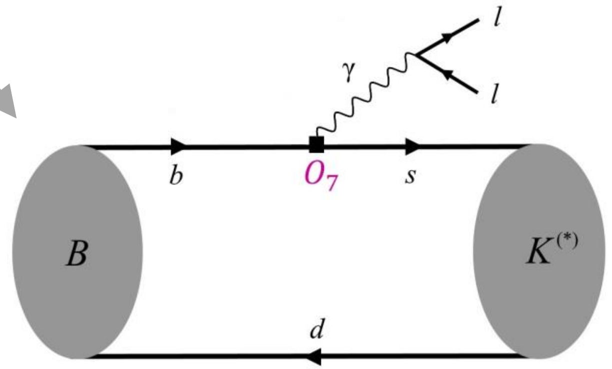
local hadronic matrix elements (MEs)

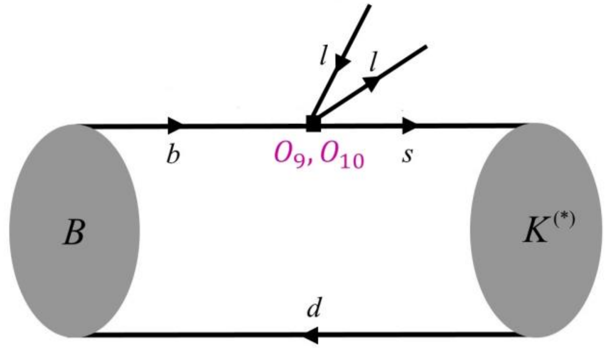
$$\mathcal{F}_\mu = \langle K^{(*)} | O_{7,9,10}^{\text{had}} | B \rangle \qquad O_{7,9,10}^{\text{had}} = (\bar{s}\,\Gamma\,b)$$

leading hadronic contributions

non-perturbative QCD objects

moderate uncertainties (3% – 15%)





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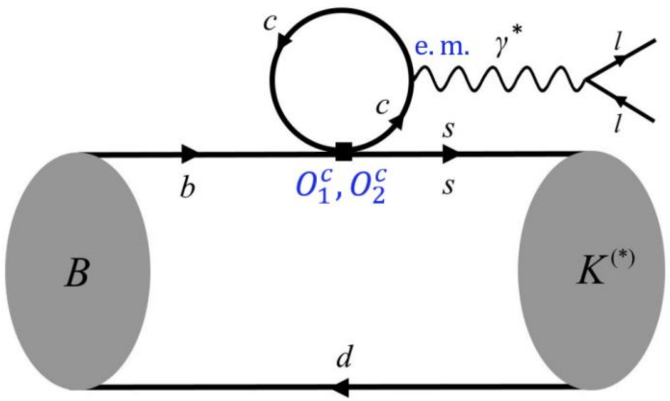
non-local hadronic MEs

$$\mathcal{H}_\mu = i\int d^4x\, e^{iq\cdot x}\langle K^{(*)}|T\{j_\mu^{\text{em}}(x), O_{1,2}^c(0)\}|B\rangle$$

$$O_{1,2}^c = (\bar{s}\,\Gamma\, b)(\bar{c}\,\Gamma\, c)$$



subleading (?) hadronic contributions

non-perturbative QCD objects

large uncertainties

Theoretical calculations

Local matrix elements calculations

MEs are functions of the momentum transfer squared q^2

non-perturbative techniques are needed to compute MEs $\mathcal{F}$:

1. lattice QCD (LQCD)

$B \to K^{(*)}$ and $B_s \to \phi$ at **high** q^2

[HPQCD 2013/2023] [FNAL/MILC 2015]
[Horgan et al. 2015] [HPQCD 2023]

small and reducible uncertainties

2. light-cone sum rules (LCSRs)

$B \to K^{(*)}$ and $B_s \to \phi$ at **low** q^2

[Bharucha et al. 2015] [Khodjamirian/Rusov 2017]
[NG/Kokulu/van Dyk 2018]

moderate uncertainties

$B \to K$ **MEs excellent** status (need independent calculation at low q^2)

more LQCD results needed for vector states (for high precision K^* width cannot be neglected)

how to **combine** different calculations and obtain result **whole** semileptonic region?

Local MEs parametrizations

we propose a **new parametrization**

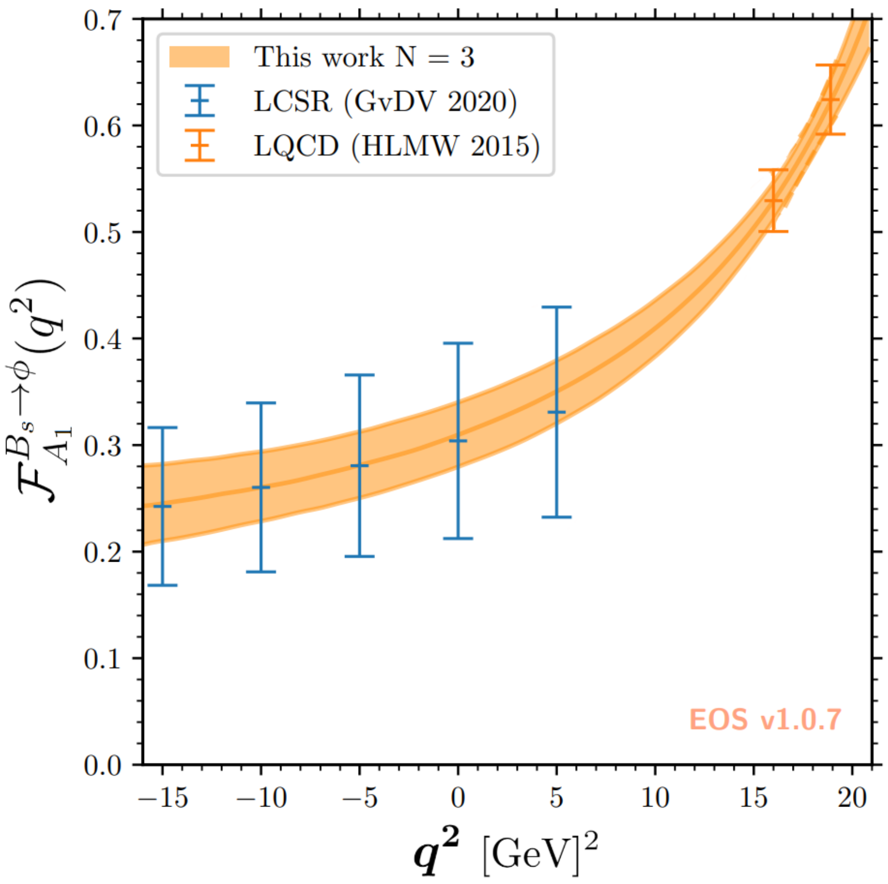
$$\mathcal{F}(q^2) \propto \sum_{k=0}^{\infty} \alpha_k\, p_k(q^2) \qquad \sum_{k=0}^{\infty} |\alpha_k|^2 < 1$$

p_k are known polynomials

fit α_k coefficients to LQCD (and LCSR) results
impose unitarity bounds

first parametrization that consistently implements analyticity and unitarity bounds
$\Longrightarrow$ **control systematic uncertainties**

obtain numerical results for $B \to K^{(*)}$ and $B_s \to \phi$ local MEs in the whole semileptonic region



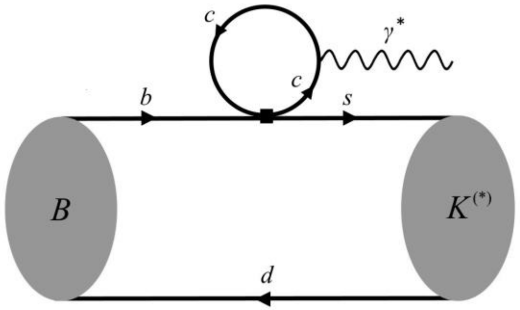
[NG/Reboud/van Dyk/Virto 2023]

Non-local MEs calculations

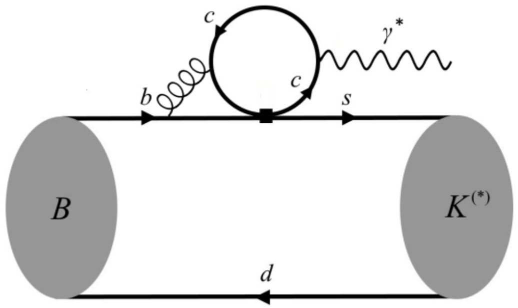
1. compute the $\mathcal{H}$ using a light-cone OPE at low q^2

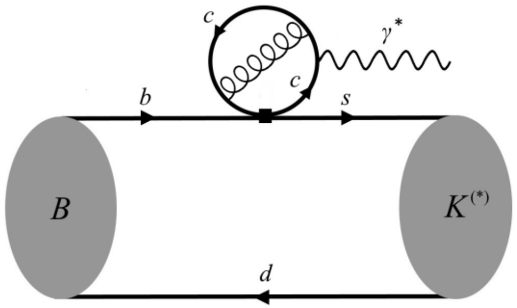
$$\mathcal{H}(q^2) = C(q^2)\mathcal{F}(q^2) + \tilde{C}(q^2)\mathcal{V}(q^2) + \cdots$$

leading power (LO in α_s)



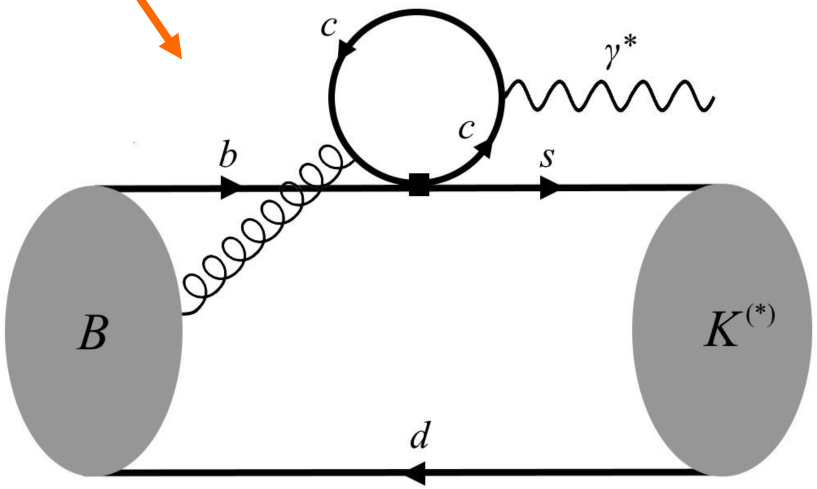
+ hard gluons (α_s) corrections





[Bell/Huber 2014] [Asatrian/Greub/Virto 2019]

soft gluon correction
non-perturbative
$\Longrightarrow$ not α_s suppressed



[Khodjamirian et al. 2010]
[NG/van Dyk/Virto 2020]

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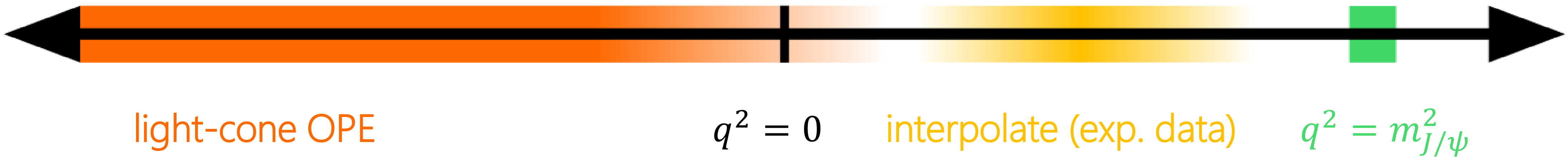
2. extract $\mathcal{H}_\lambda$ at $q^2 = m_{J/\psi}^2$ from $B \to K^{(*)} J/\psi$ and $B_s \to \phi\, J/\psi$ measurements (decay amplitudes independent of the local MEs)

3. **new approach: interpolate** these two results to obtain theoretical predictions in the low q^2 $(0 < q^2 < 8\ \mathrm{GeV}^2)$ region $\Longrightarrow$ compare with experimental data



Non-local MEs predictions

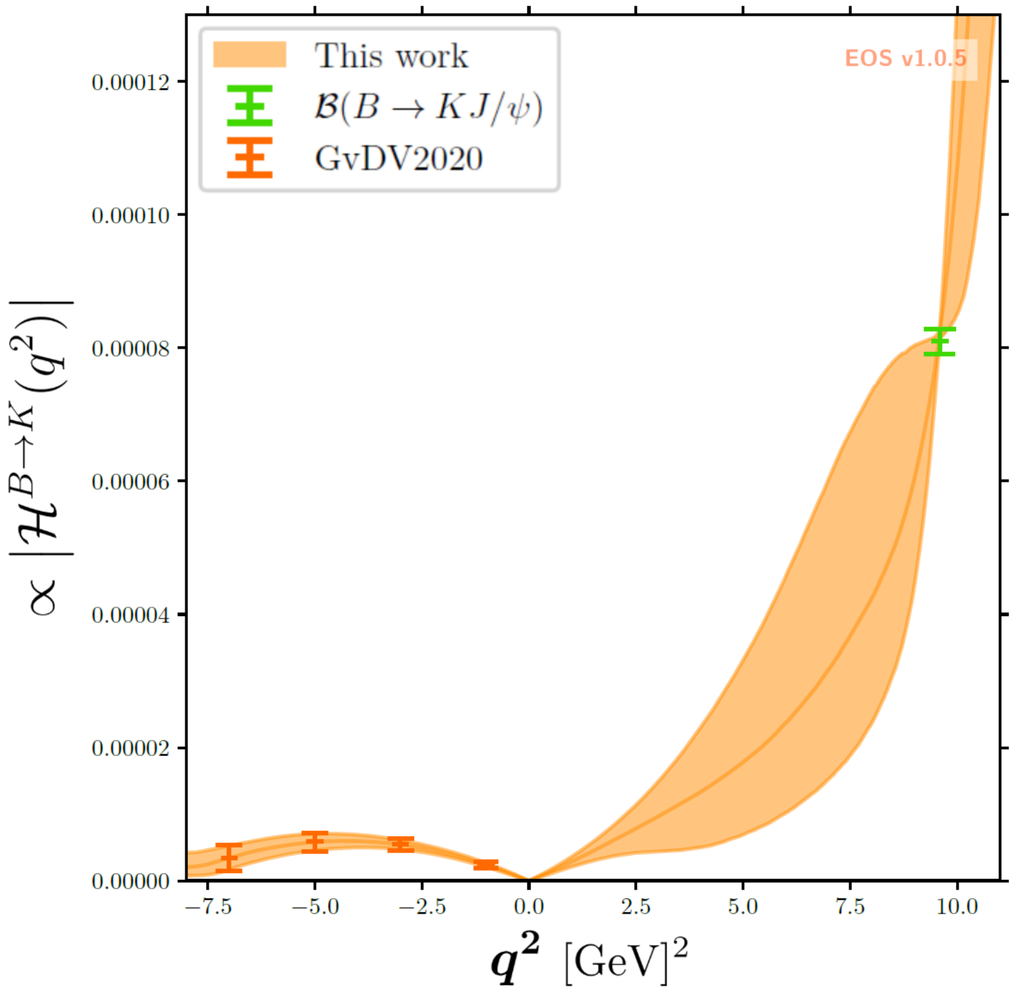
similar approach to local MEs $\mathcal{F}_\lambda$

$$\mathcal{H}(q^2) \propto \sum_{n=0}^{\infty} \beta_k p_k(q^2) \qquad \sum_{k=0}^{\infty} |\beta_k|^2 < 1$$

fit β_k coefficients to OPE and $B \to K^{(*)} J/\psi$ data
impose unitarity bounds

first unitarity bounds for non-local MEs $\mathcal{H}$
⟹control systematic uncertainties

obtain numerical results for $B \to K^{(*)}$ and $B_s \to \phi$ non-local MEs below 8 GeV^2



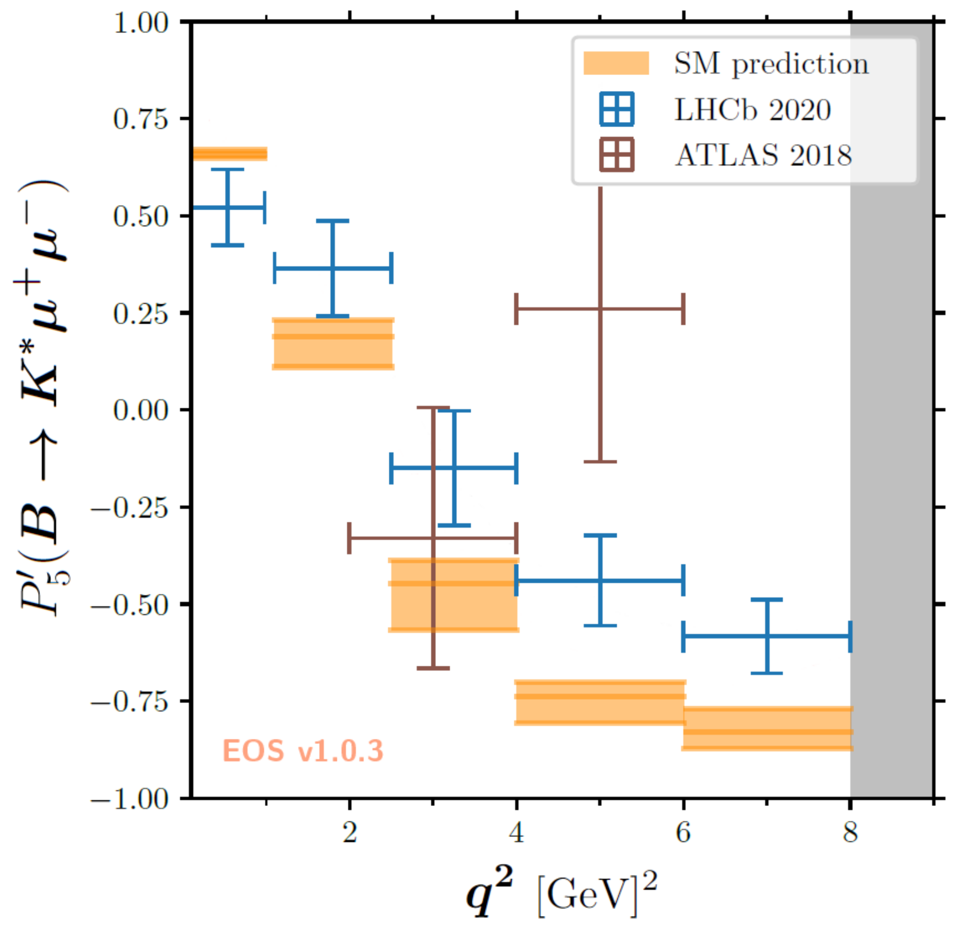
[NG/Reboud/van Dyk/Virto 2022]

SM predictions and confrontation with data

SM predictions vs. data

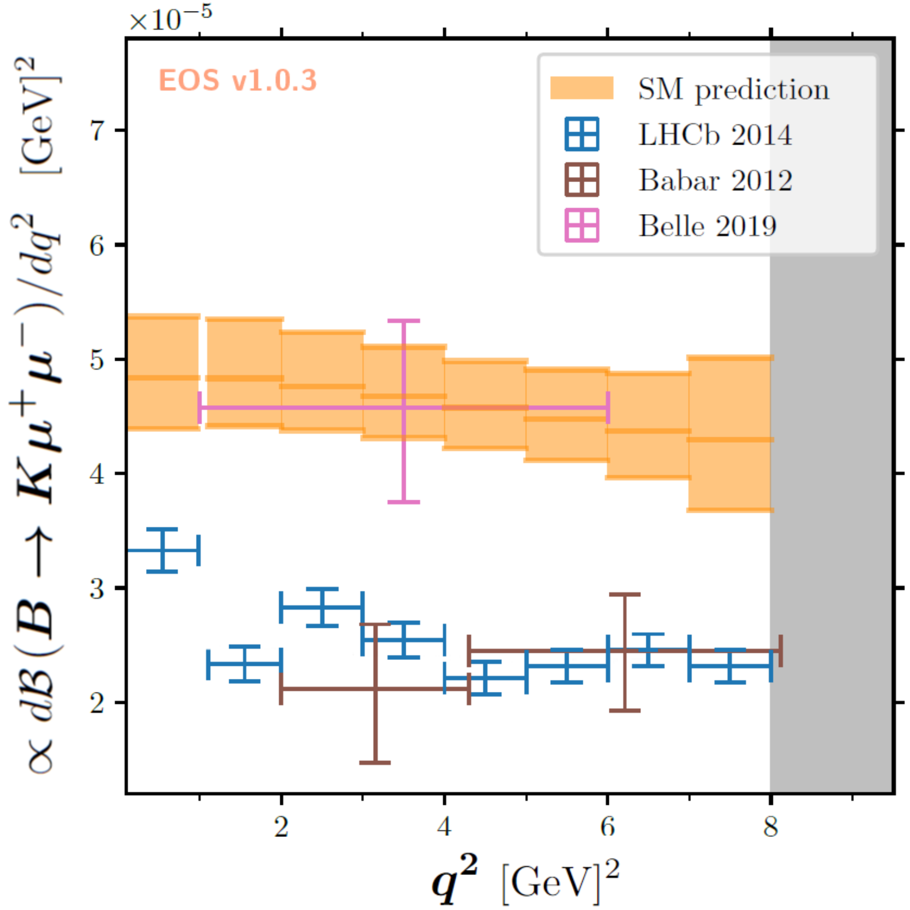
predict observables using our $\mathcal{F}_\lambda$ and $\mathcal{H}_\lambda$ results:
BRs and angular observables
for $B \to K^{(*)}\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$

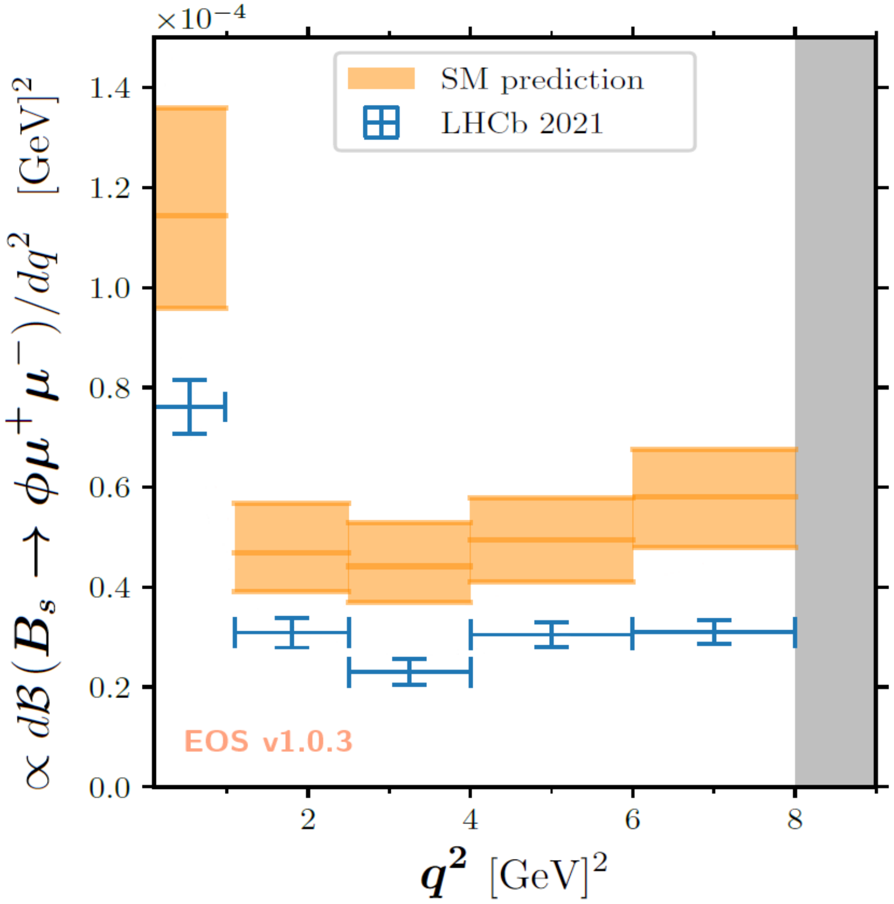
- theory uncertainties mostly due to $\mathcal{F}_\lambda$
- progress in $\mathcal{H}_\lambda$ calculations urgently needed
- more measurements on the way



[NG/Reboud/van Dyk/Virto 2022]

SM predictions vs. data





[NG/Reboud/van Dyk/Virto 2022]

coherent tensions between SM predictions and data

WET fits

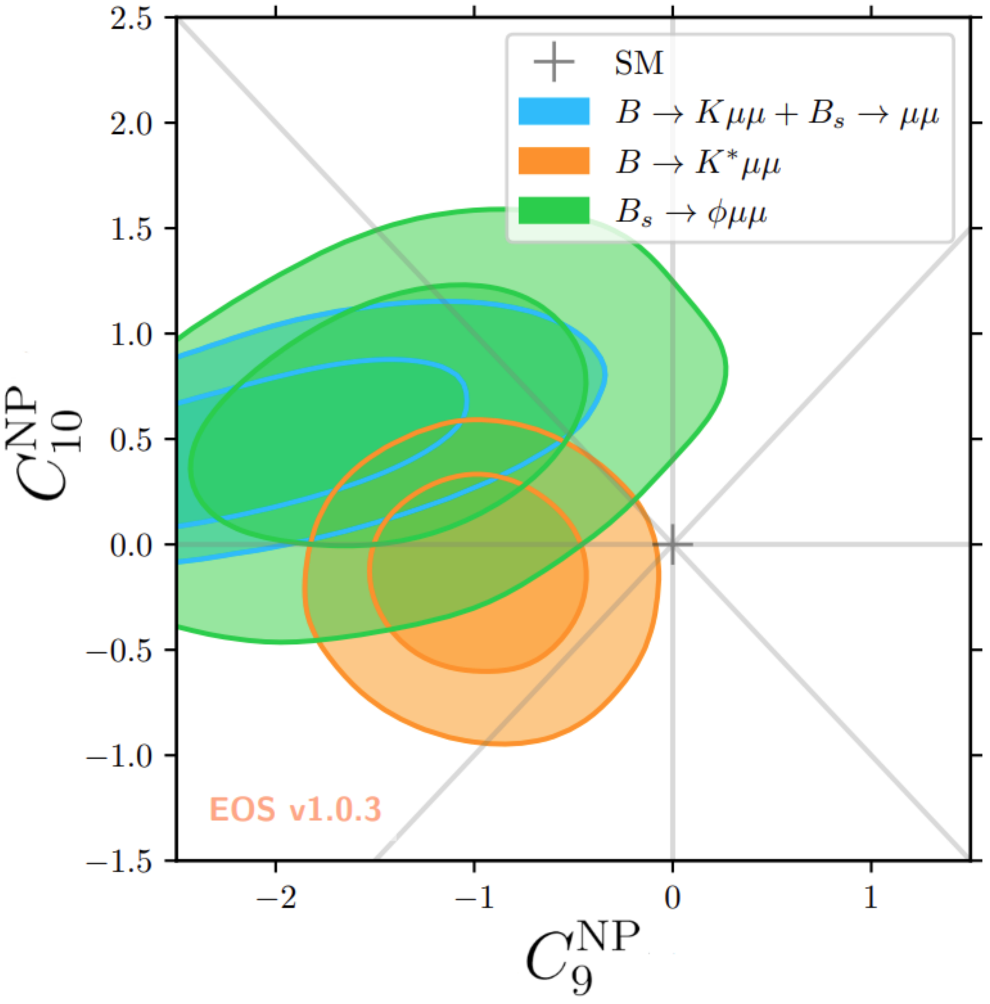
$$C_{9,10} = C_{9,10}^{\mathrm{SM}} + C_{9,10}^{\mathrm{NP}}$$

fit the Wilson coefficients C_9^{NP} and C_{10}^{NP}
to the available experimental measurements

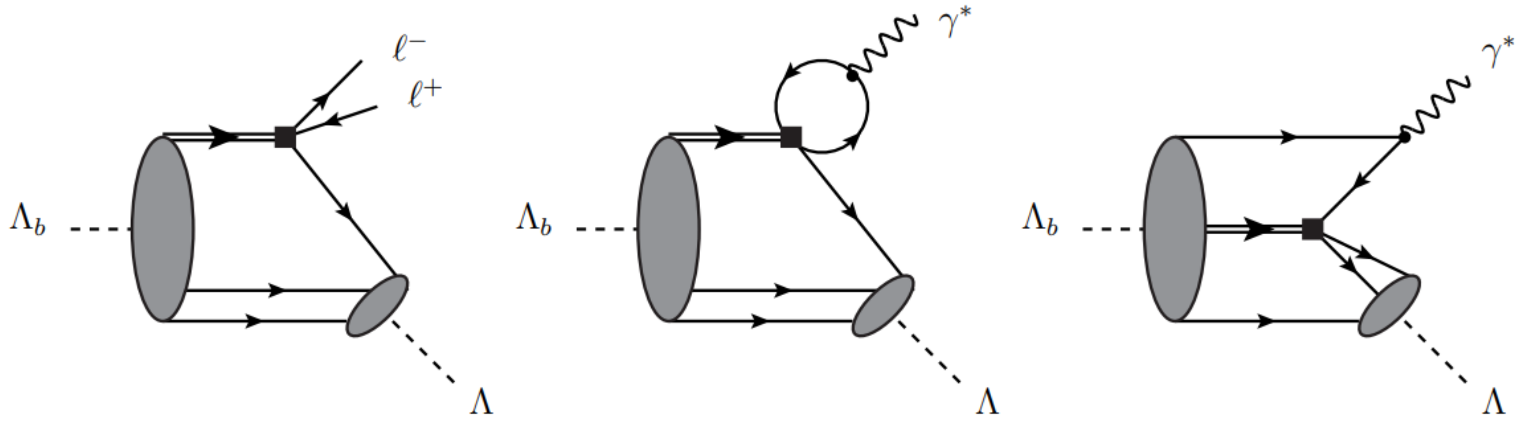
pulls (p value of the SM hypothesis):

- 5.7σ for $B \to K\mu^+\mu^- + B_s \to \mu^+\mu^-$
- 2.7σ for $B \to K^*\mu^+\mu^-$
- 2.6σ for $B_s \to \phi\mu^+\mu^-$

current predictions for
non-local MEs $\mathcal{H}_\lambda$ cannot explain this tension



Aside: $\Lambda_b \to \Lambda \ell^+ \ell^-$ decays



[Feldmann/NG 2023]

if $b \to s\mu^+\mu^-$ anomalies are due to New Physics $\Longrightarrow$ same shift expected in $\Lambda_b \to \Lambda\mu^+\mu^-$
but systematic effects are different

already measured by LHCb $\Longrightarrow$ new and more precise measurements on the way

progress needed in theory calculations (no estimate of charm-loop beyond naïve factorization)

first calculation of “annihilation” contributions in [Feldmann/NG 2024]

Summary and conclusion

Summary and conclusion

1. improved parametrization for local MEs $\mathcal{F}_\lambda$ with unitarity bounds

   combine LQCD (and LCSRs) inputs to get new results for $\mathcal{F}_\lambda$ in $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \phi\ell^+\ell^-$

2. new theoretical predictions for $\mathcal{H}_\lambda$ combining our OPE calculation and $B \to K^{(*)}J/\psi$ data

   innovative approach — use unitarity bound to control $\mathcal{H}_\lambda$ uncertainties

3. new and precise SM predictions for observables in $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \phi\ell^+\ell^-$ decays

   coherent deviations between SM and data in $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \phi\ell^+\ell^-$ decays

4. **progress on the theory side needed** more than ever

Thank you!