Discussion on the future of form factor computations

Felix Erben

Lattice@CERN 2024
19/7/2024

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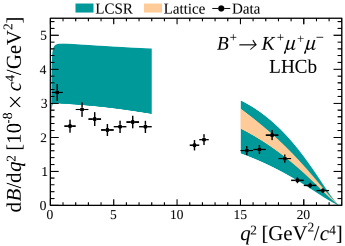
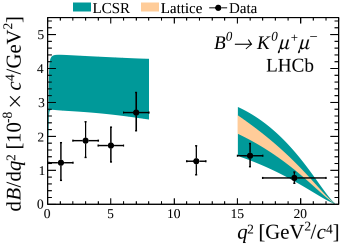
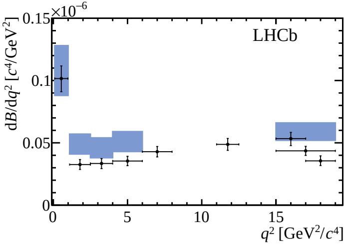
B-ANOMALIES



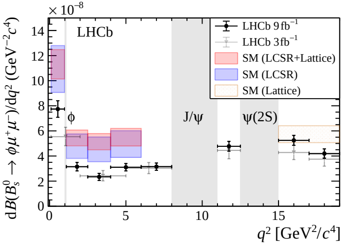
$B^+ \to K^+$ [LHCb, JHEP 14]



$B^0 \to K^0$ [LHCb, JHEP 14]



$B^0 \to K^{*0}$ [LHCb, JHEP 16]



$B_s \to \phi$ [LHCb, PRL 21]

- most recent LHCb measurements of $b \to s\ell^+\ell^-$ branching fractions
- low-q^2: LCSR
- high-q^2: lattice
- experiment consitently lower than theory, particularly at low q^2
- can we improve this picture with lattice?

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

LHCb

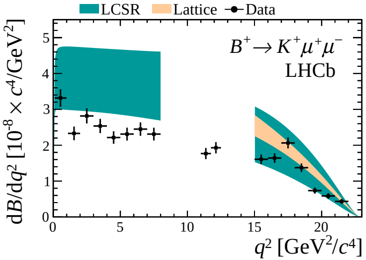
CERN-PH-EP-2013-137
LHCb-PAPER-2013-039
4 September 2013

Observation of a resonance in $B^+ \to K^+\mu^+\mu^-$ decays at low recoil

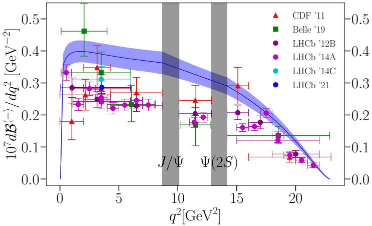
[LHCb, PRL 13]

The contribution of the $\psi(4160)$ resonance in the low recoil region, taking into account interference with the non-resonant $B^+ \to K^+\mu^+\mu^-$ decay, is about 20 % of the total signal. This value is larger than theoretical estimates, where the $c\bar{c}$ contribution is ∼10% of the vector amplitude, with a small correction from quark-hadron duality violation [23]. Results presented in this Letter will play an important role in controlling charmonium effects in future inclusive and exclusive $b \to s\mu^+\mu^-$ measurements.

B-ANOMALIES



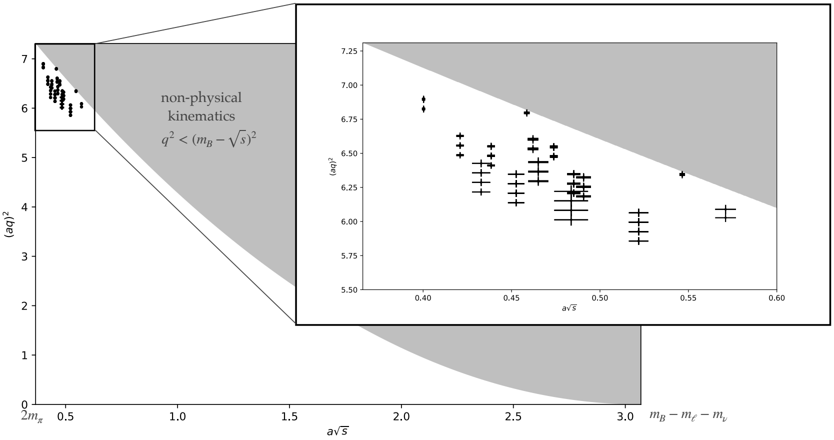
$B^+ \to K^+$ [LHCb, JHEP 14]



$B^0 \to K^+$ [Parrot, Bouchard, Davies, PRD 21]

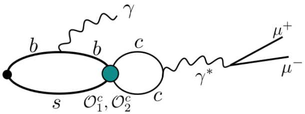
- progress with pseudoscalar final states
- 2021 HPQCD lattice calculation $B \to K\ell^+\ell^-$
- Results down to $q^2 = 0$
- tensions with LHCb $B^+ \to K^+\mu^+\mu^-$ in the low-q^2 region as high as 4.2σ

$\pi\pi$ FV spectrum - slide by Luka Leskovec [Fri 19/7 11:30]



- FV energies for Luka's $B \to \pi\pi\ell\nu$ calculation
- no 4-quark H_W, no charmonium resonances like in $B \to K^*\ell^+\ell^-$
- reach to $q^2 = 0$ significantly harder

Other Contributions - Charming Penguins



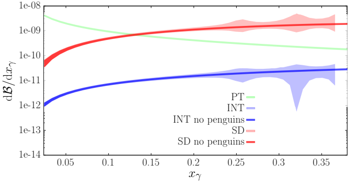
- Of the contributions we have not computed directly , the most significant one at large q^2 is expected to be that from the operators $O^c_{1,2}$ (charming penguins) and we are working on developing methods to overcome this. There are a number of new theoretical issues to be understood.

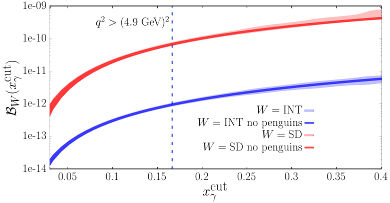
- In the meantime we follow previous ideas and estimate the contribution based on VMD inserting all $c\bar{c}$ resonances from the J/Ψ to the $\Psi(4660)$. It can be viewed as a shift in $C_9 \to C_9^{\text{eff}}(q^2) = C_9 + \Delta C_9(q^2)$:

$$\Delta C_9(q^2) = -\frac{9\pi}{\alpha_{\text{em}}^2}\left(C_1 + \frac{C_2}{3}\right)\sum_V |k_V|\,e^{i\delta_V}\,\frac{m_V\Gamma_V\,B(V\to\mu^+\mu^-)}{q^2 - m_V^2 + i m_V\Gamma_V}\,.$$

- k_V and δ_V parametrise the deviation from the factorisation approximation (in which $\delta_V = k_V - 1 = 0$). We allow δ_V to vary over $(0,2\pi)$ and $|k_V|$ to vary in the range 1.75 ± 0.75 .

Branching Fractions





$$\mathscr{B}(x_\gamma^{\rm cut}) = \int_0^{x_\gamma^{\rm cut}} dx_\gamma \, \frac{d\mathscr{B}(x_\gamma)}{dx_\gamma}$$

- Structure Dependent (SD) contribution dominated by F_V.
- The error from the charming penguins increases with x_γ (at $x_\gamma = 0.4$ it is about 30 %).
- Our Result - $\mathscr{B}_{\rm SD}(0.166) = 6.9(9) \times 10^{-11}$; LHCb - $\mathscr{B}_{\rm SD}(0.166) < 2 \times 10^{-9}$.

CHARMONIUM RESONANCES, B ANOMALIES

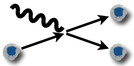
- B anomalies
- can lattice contribute?
- how to deal with charmonium resonances?

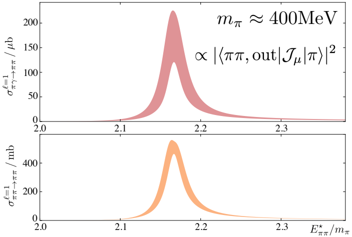
Transition amplitudes

$$\left|\langle n, L|\mathcal{J}|\pi, L\rangle\right|^2 = \langle \pi|\mathcal{J}|\beta, \mathrm{in}\rangle\, \mathcal{R}_{\alpha\beta}(P, L)\, \langle \beta, \mathrm{out}|\mathcal{J}|\pi\rangle$$

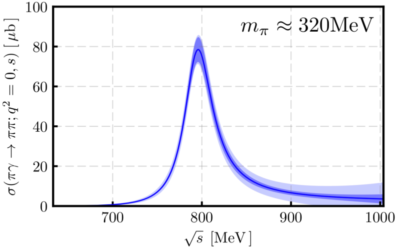
$$\mathcal{R}(P, L) = -\lim_{E \to E_n(L)} \frac{E - E_n(L)}{\mathcal{M}(s) + F^{i\epsilon}(P, L)^{-1}} = \frac{1}{\mu'(E)} \mathbf{v}^T \mathbf{v}$$

Briceño, Dudek, Leskovec

$\langle \pi\pi, \mathrm{out}|\mathcal{J}_\mu|\pi\rangle \equiv$ 



Briceño et. al., Phys. Rev. D93, 114508 (2016)



Alexandrou et. al., Phys. Rev. D98, 074502 (2018)

- Formalisms are understood and applied in calculations already

$\Rightarrow$ Large toolkit available

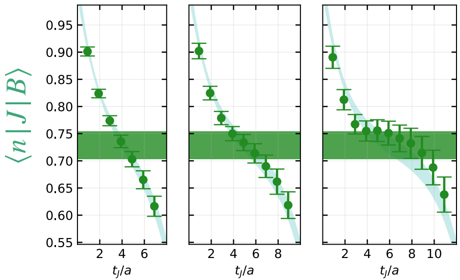
state projection

$$C_{3,i} = \sum_{n \in [\pi\pi]} Z_i^n \langle n | J | B \rangle Z_B \frac{e^{-E_n(\Delta t - t_J)} e^{-E_B t_J}}{2E_n 2E_B}$$

$$C_3^n = u_i^n C_{3,i}$$

weights from GEVP

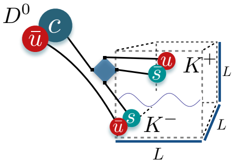
$$C_3^n = \langle n | J | B \rangle Z_B \frac{e^{-E_n(\Delta t - t_J)} e^{-E_B t_J}}{2E_B}$$



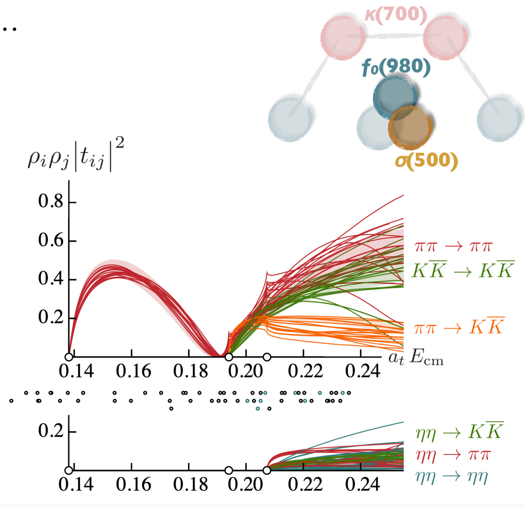
- same recipe works for B decays
- overall computation more costly, b-quark parametrista-tion, etc

Dreaming of the future...

$$I^G(J^{PC}) = 0^+(0^{++})$$



dreaming of the future



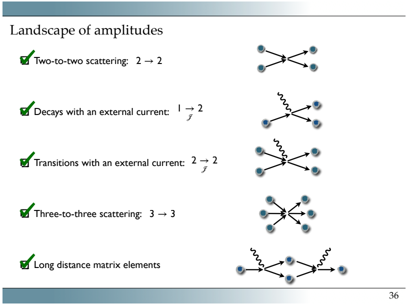
- We have the toolkit to do very involved calculations
- can we think of realistic dreams for the forseeable future?

❑ Biggest problem is >2 hadron states!

- currently, there are no scattering calculations in FLAG
- should we invest more effort into fulfilling relevant criteria?
  - continuum extrapolation
  - chiral extrapolation
  - full systematic error budget
- maybe the opposing dream: how do we ensure we can control what we know well?

- Which quantities would we like to see?
  - Resonance pole positions
  - form factors of e.g. $B \to \pi\pi\ell\nu$

- is it more tempting to keep exploring the massive toolbox we have been provided with?



DATA & CODE SHARING

- If we want to allow re-analysis, we could share all our correlator data & analysis code
- Arguably, if all 3 $B \to D^*$ calculations [Monday discussions] would have done this, a lot of good phenomenological work could have come out of it
- certainly, at least as much bad phenomenological work would have come out of it!
- is that a problem?

- Not impossible! We did it recently for K^*, ρ resonance work [FE et al., arXiv:2406.19193] [FE et al., arXiv:2406.19194]
- Correlator data published on CERN Document Server [FE et al.; CDS 2024]
- 800 GB of data - admittedly easier if at least one author has a CERN affiliation
- European grants often pay for cost
- If at least one author is living in Germany, PUNCH4NFDI [www.punch4nfdi.de]

PERSPECTIVES

- Ambitious lattice QCD physics programmes take years and people power
  - development of general formalisms
  - adaption of formalisms for specific processes
  - grant / computing time applications
  - gauge field generation
  - production runs
  - maintaining HPC clusters
  - data analysis

- Science / academia is a relatively precarious career path
- How do we ensure researchers at all career stages are
  - visible in the community? See a perspective for research jobs?
  - see a perspective for research jobs?
  - are motivated to have their work reproducible for future re-analysis / extensions?
  - Suggestion in yesterday's discussion to involve phenomenologists in author list

Last slide of Lattice@CERN 24

Thanks for participating!