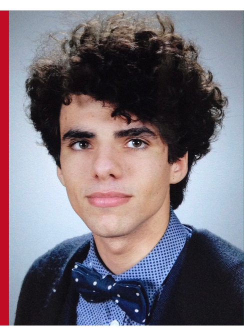
EXCLUSIVE LEPTONIC B DECAYS: VIRTUAL AND REAL QED CORRECTIONS



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Motivations

▶ **Why leptonic B decays ?**

– Direct determination of the CKM element $|V_{ub}|$.

– **Chirality-suppressed** in the SM → powerful probe of (pseudo) scalar new physics.

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \tau_B G_F^2 f_B^2 |V_{ub}|^2 \frac{m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_b^2}\right)^2$$

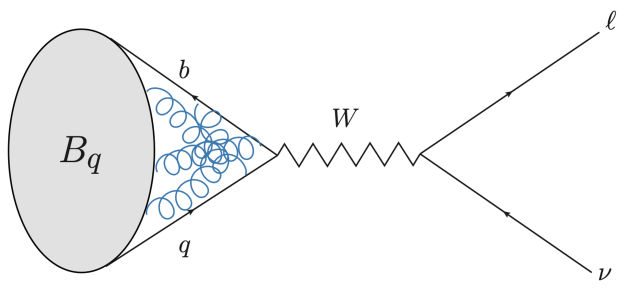
– Testing **flavor universality** in charged current : Belle II will measure the $\ell = \tau, \mu$ channels with $5 - 7\,\%$ uncertainties. [Belle II Physics Book]

▶ **Why QED corrections are needed?**

– Pure hadronic effects are simple and well understood :

$$\langle 0|\bar{q}\gamma^\mu\gamma_5 b|B_q(p)\rangle = i f_{B_q} p^\mu$$

[FNAL/MILC 1712.09262]



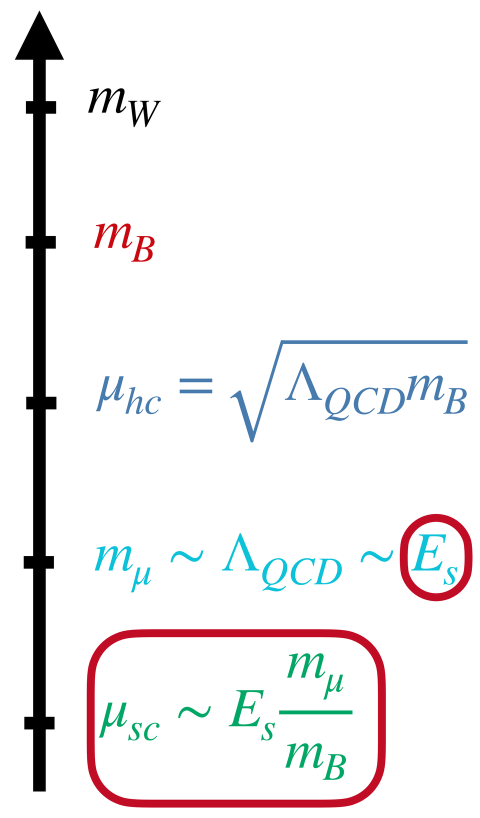
f_{B_q} is known with $\mathcal{O}(1\%)$ precision: $f_{B_q} = 189.4 \pm 1.4$ Mev

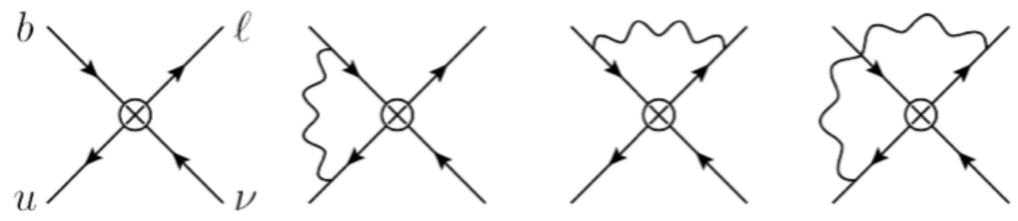
– **BUT** QED corrections are sensitive to the lepton mass and the restriction on additional radiation, yielding large (double) **logarithmic corrections** !

In the exclusive channel, with strong cuts on additional soft radiation, QED corrections can be **sizable** and compete with QCD uncertainties
⟶ need a **precise** estimation

A multi-scale problem

▶ Focusing on $\ell = \mu$ case, QED introduces new scales (both static and dynamic) to which $B^- \to \mu^- \bar{\nu}_\mu$ is sensitive :



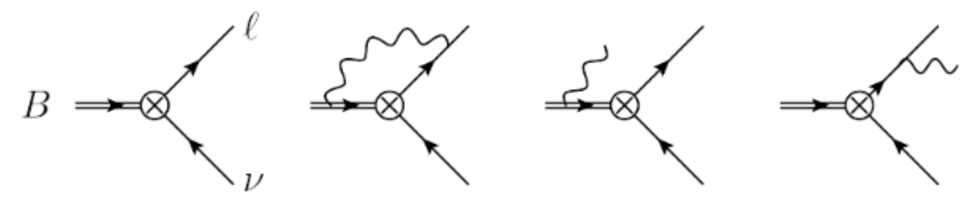


B-meson described as a superposition of Fock-states:

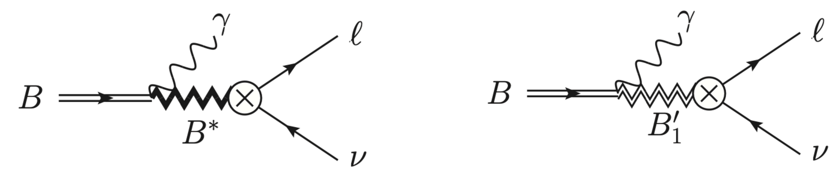
$|\bar{u}b\rangle \oplus |\bar{u}bg\rangle \oplus \cdots$ [Beneke et al(2019),JHEP10232]

→ virtual corrections can resolve the partonic substructure !

B-meson described as a point-like pseudo-scalar boson...



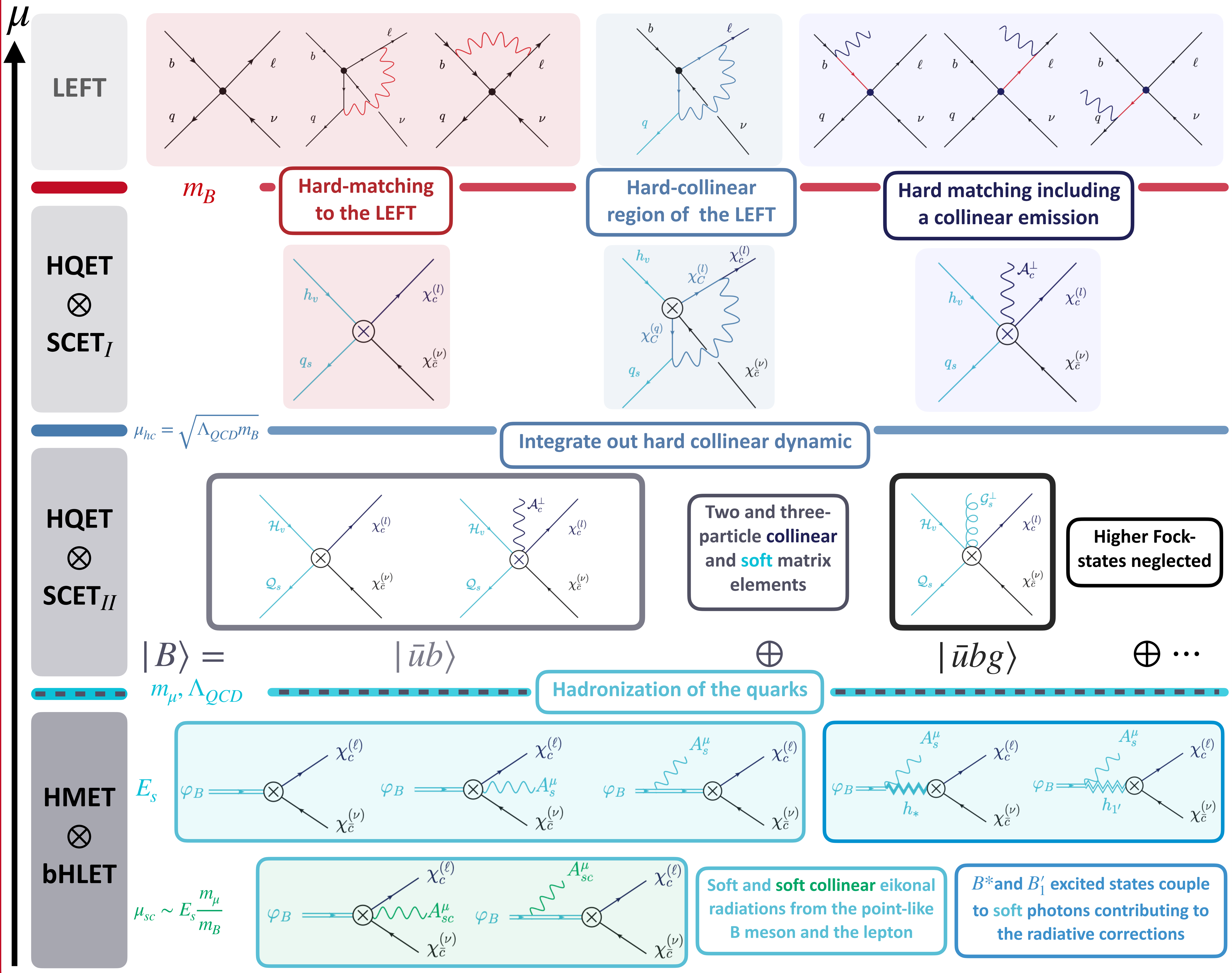
...including its first (pseudo) vector excited states as off-shell intermediate propagator ! [Becirevic et al (0907.1845)]



→ Scales dictated by the experimental energy cut on the additional final radiation.
→ FCC and Belle II could in principle achieve a resolution with $E_s \sim \mathcal{O}(\Lambda_{QCD}^2)$ ...
...BUT $E_s \sim \mathcal{O}(\Lambda_{QCD})$ is needed for Belle II to improve the statistics of the measurement !

We need to find the **appropriate effective description** at each scale including all the relevant scales. The aim is to evaluate each object at its **natural scale**, turning a multi-scale problem to a product of single scale objects. ⟶ **Factorization theorem**

The plan : embark in an EFT journey running down with the scale !



EFT toolbox

Power counting : $\lambda = \frac{m_\mu}{m_B} \sim \frac{\Lambda_{QCD}}{m_b}$

Light-cone directions :
$n^\mu = (1,0,0,1)$, $\bar{n}^\mu = (1,0,0,-1)$

Relevant scaling :
$p^\mu = (\bar{n}\cdot p, n\cdot p, p_\perp)$

Hard: $p^\mu \sim (1,1,1)m_b$
$p^2 \sim m_b^2 \sim \mathcal{O}(1)$ → **b-quark scale**

Hard-collinear : $p^\mu \sim (1,\lambda,\sqrt{\lambda})m_b$
$p^2 \sim m_\mu m_b \sim \mathcal{O}(\lambda)$
→ **Soft and collinear quark X-talk**

Collinear: $p^\mu \sim (1,\lambda^2,\lambda)m_b$
$p^2 \sim m_\mu^2 \sim \mathcal{O}(\lambda^2)$
→ **Lepton virtuality**

Soft: $p^\mu \sim (\lambda,\lambda,\lambda)m_b$
$p^2 \sim \Lambda_{QCD}^2 \sim E_s^2 \sim \mathcal{O}(\lambda^2)$
→ **Spectator virtuality and cut on soft radiations**

Soft-collinear: $p^\mu \sim (\lambda,\lambda^3,\lambda^2)m_b$
$p^2 \sim E_s^2(m_\mu^2/m_B^2) \sim \mathcal{O}(\lambda^4)$
→ **Soft photon to the muon boosted in the B frame**

Conclusion : factorization formula for the decay rate ...

$$\Gamma = \Gamma_0\left(|y_B(\mu)|^2\,|K(\mu)|^2\, S(E_s,\mu) + |y_B^*|^2 S_{B^*}(E_s) + |y_{B_1'}|^2 S_{B_1'}(E_s)\right)$$

Virtual corrections **Real corrections** **Structure-dependent radiative corrections**

Virtual corrections are factorized at the level of the amplitude : appear as an **effective Yukawa coupling**

$$y_B(\mu) = C_L(\mu) \times H(\mu) \times \mathcal{J}(\mu)$$

Real corrections factorize at the decay rate level : **convolution of radiative functions**

$$S(E_s,\mu) = W_s(E_s,\mu) \otimes W_{sc}(E_s,\mu)$$

...and estimation of the QED corrections !

$|y_b(\mu)|^2 S(E_s,\mu) \sim m_\mu^2 \log\frac{E_s}{m_B}\log\frac{m_\mu}{m_B}$

$|y_B^*|^2 S_{B^*}(E_s) \sim E_s^2$

$|y_{B_1'}|^2 S_{B_1'}(E_s)$: (numerical cancellation)

Structure-dependent radiative corrections enter via **additional Yukawa coupling** multiplied by a **soft radiative function**. They dominate for looser cuts!