The Role of Effective Field Theories in Precision Physics

Bahman Dehnadi

Fellow @ DESY Theory Group

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HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

Why Precision Physics?

New Physics can manifest itself as:

- signals in processes where the SM predictions are exceedingly small
- small corrections to Standard Model (SM) predictions

LHC and other modern experiments now often reach the percent level precision in their measurements

A high luminosity run of the LHC is expected to deliver integrated luminosity reaching inverse attobarns

To do list for theorists:

- Established theories must be understood better (in particular strong and weak interactions)
- Higher precision calculations (incl. resummation, control non-perturbative physics, improve MC-generators, ...)
- Precise measurements of fundamental parameters (coupling constants, particle masses, CKM, ...)

In this context Effective Field Theories (EFT) play a key role

Effective Field Theory

Effective Field Theory

Effective Field Theory is a field theory, very much like QED or QCD

Provides a coherent description of a system using only the relevant degrees of freedom

The power counting and symmetry arguments tells you which contributions are relevant

Example: Hydrogen Atom

Obviously, SM of particle physics contains everything (electromagnetic, strong and weak interaction)

In practice the SM-action is way too complicated and much of it is entirely irrelevant for describing the H-atom (quark structure of the proton, weak interaction, Higgs)

H-atom Hamiltonian contains only relevant dof's

Leading order: $\mathcal{O}(\alpha^2)$

- Non-relativistic electron
- Non-relativistic proton (the only property of the nucleus we need is the electric charge)
- Interacting via Coulomb potential

Higher order corrections

- Fine structure (m_e, m_p): relativistic correction, darwin correction, spin-orbit interaction $\mathcal{O}(\alpha^4)$
- Lamb shift (QED effects) $\mathcal{O}(\alpha^5)$
- ...

The effective theory for H-atom is non-relativistic QED

How to construct an EFT ?

- ✓ Identify the relevant degrees of freedom
- ✓ Identify the symmetries that constraint the interaction
- ✓ Identify the power counting (e.g. $\lambda = \Lambda_{\rm QCD}/E_{\rm cm}$)
- ✓ Do the expansion correctly (integrate out all the off-shell dof's)

$$L = L^{(0)} + \lambda\, L^{(1)} + \lambda^2\, L^{(2)} + \lambda^3\, L^{(3)} + \cdots$$

The key concept is **locality** which separates the high energy and the low energy dynamics (factorization)

The EFT Lagrangian is a sum of local, gauge and Lorentz invariant operators

$$L^{(n)} = \sum_{m=0}^{N} C_m\, O^{(m)}$$

Short distance coefficients accounts for off-shell dof's

Operators constructed from relevant dof's

Why are EFTs very powerful tools in QCD?

✓ Simplifies the calculation by only including relevant interactions and dealing with one scale at a time.
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- ✓ Sum large logarithms of the ratios of scales which could spoil the perturbative expansions

$$\sigma = \sum_{n \geq k} a_{nk}\, \alpha_s^n L^k \quad \text{with} \quad L = \log\left(\frac{M_w}{m_b}\right) \quad \text{or} \quad L = \log\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)$$

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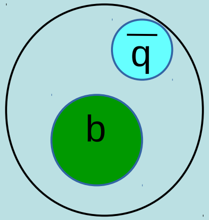
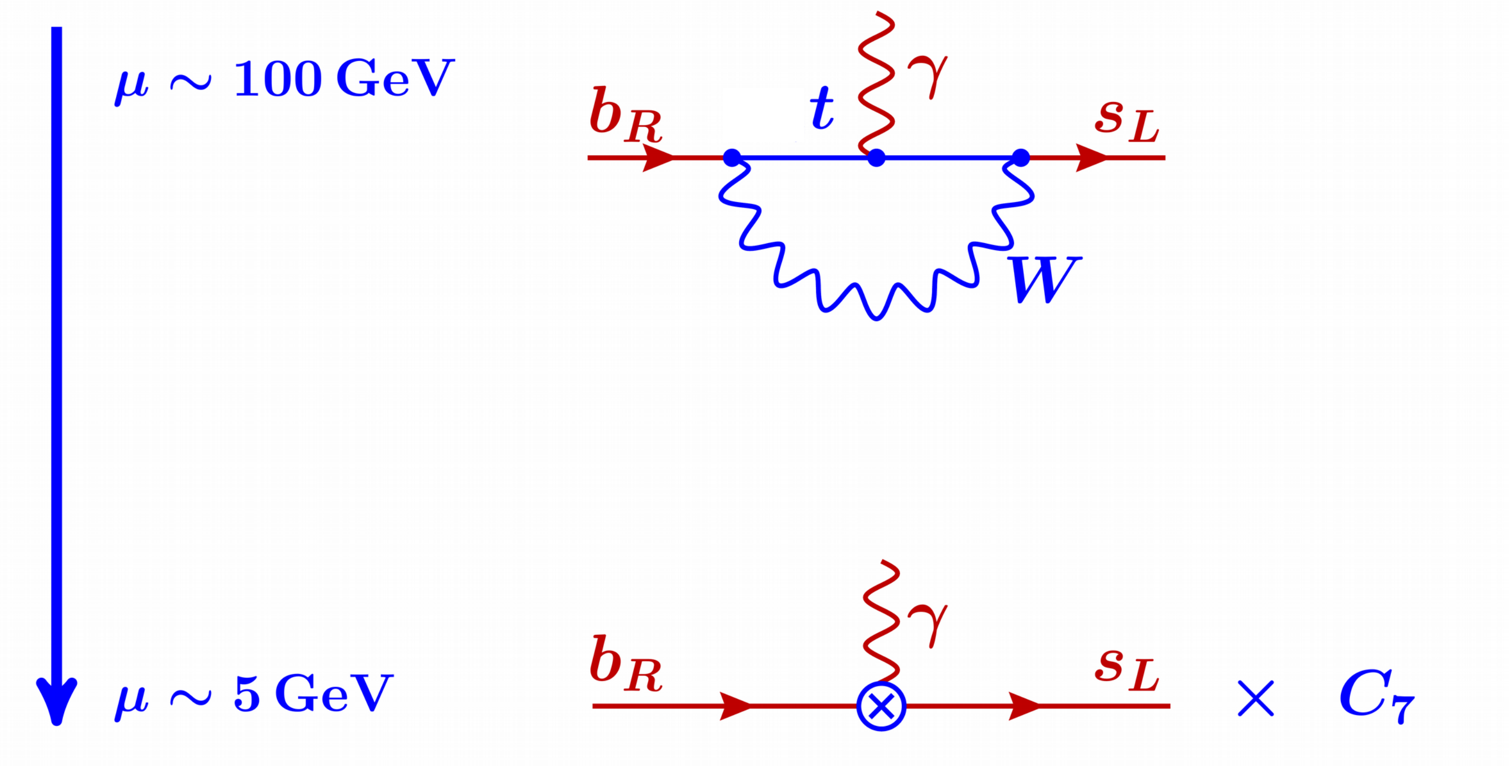
- ✓ Makes the relevant physics and symmetries manifest

Inclusive decays of B-mesons



EFT setup in inclusive B-meson decay

We wish to describe the photon energy spectrum in $\mathrm{B} \to X_s\,\gamma$



The bottom & strange quark masses and their momenta are much smaller than the W mass
Integrate out all the heavy particles i.e. W, Z, H, and top quark

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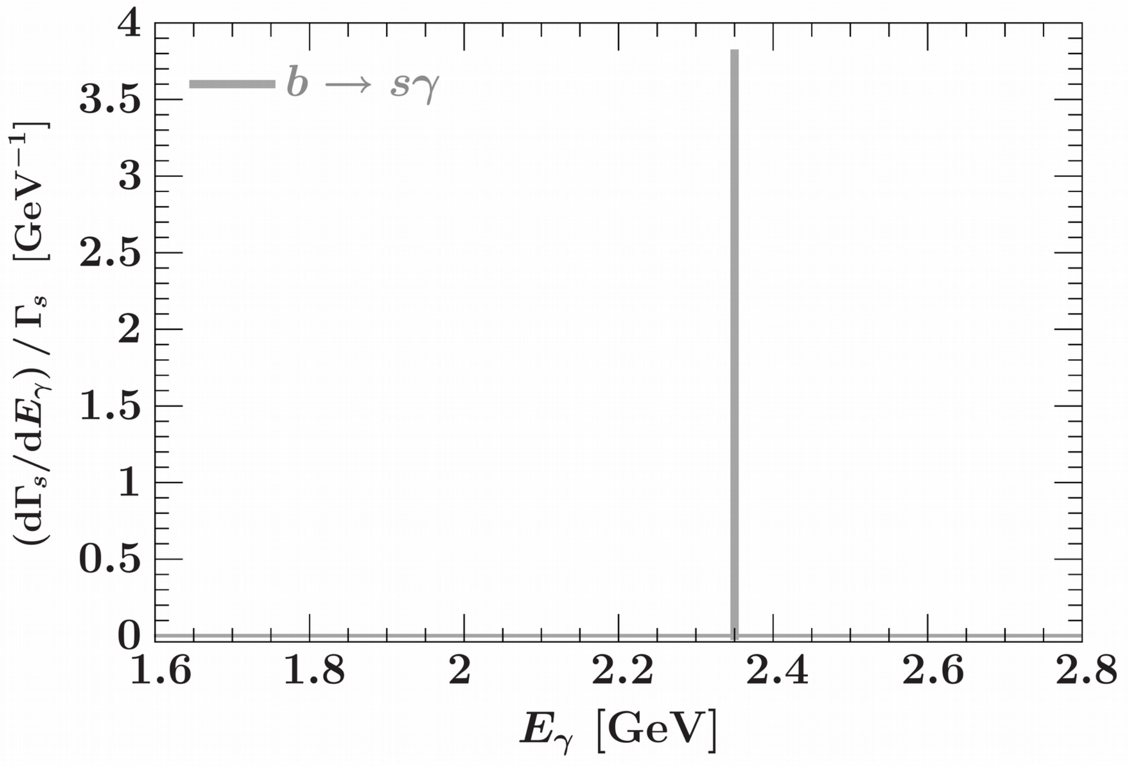

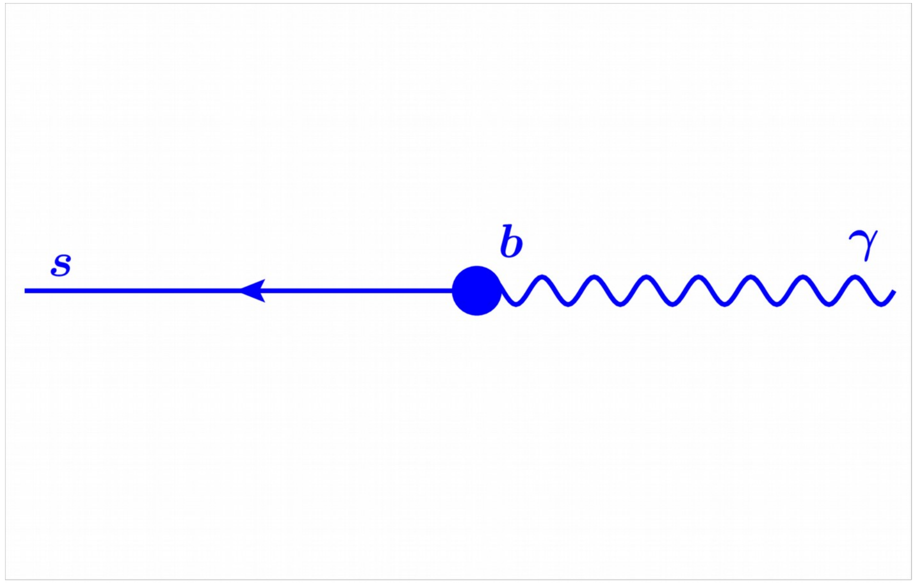

- Start with a stationary b-quark, the transition rate at tree level is: $\mathrm{d}\Gamma/\mathrm{d}E_\gamma = |C_7|^2\,\delta(E_\gamma - m_b/2)$

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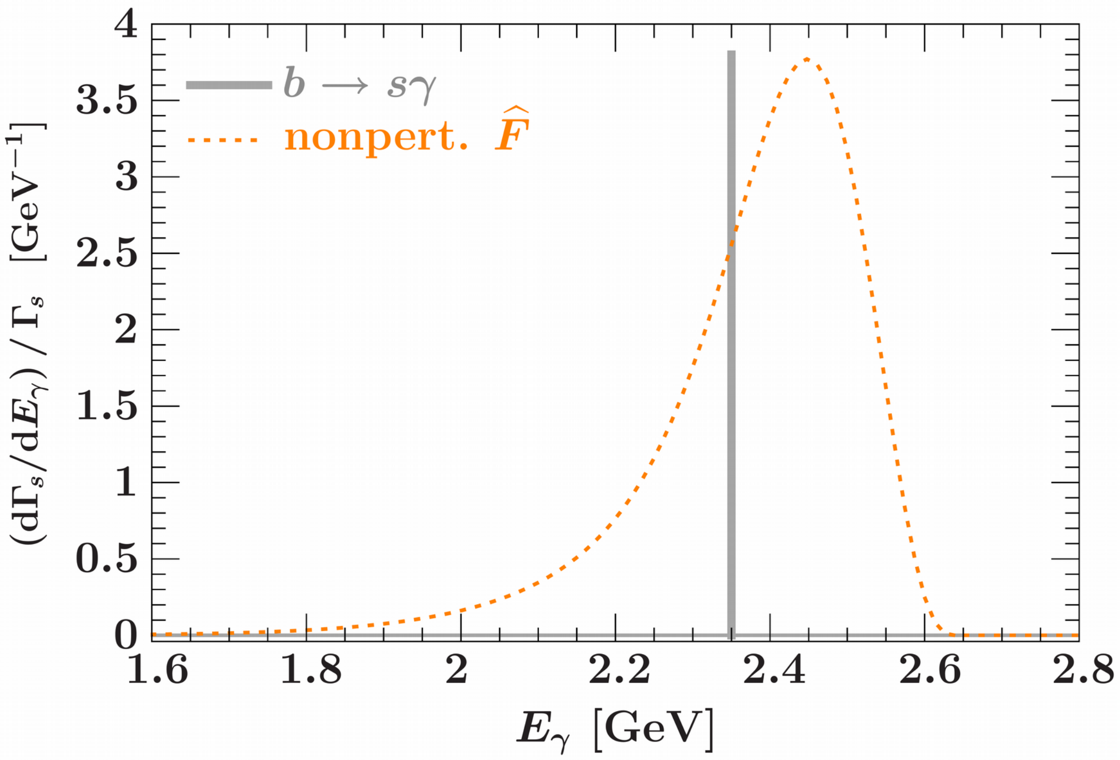

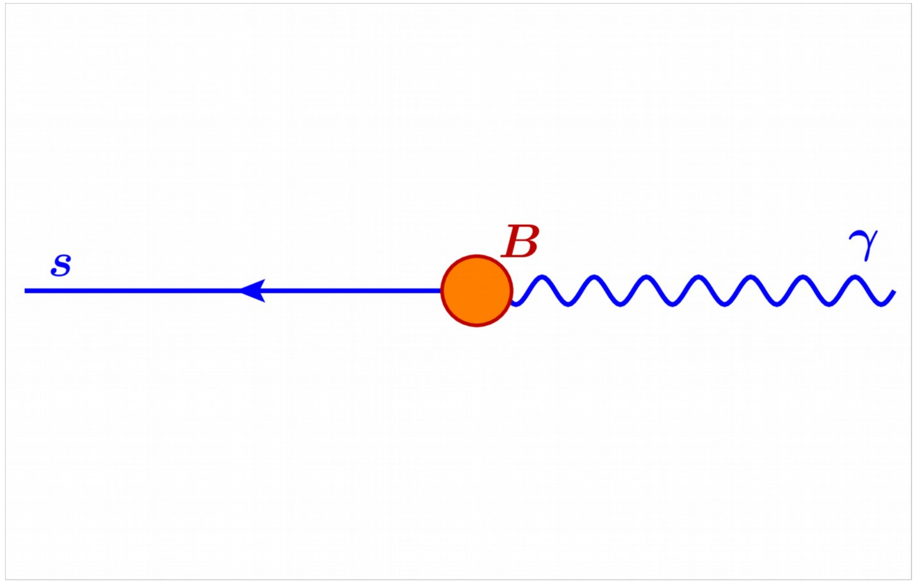

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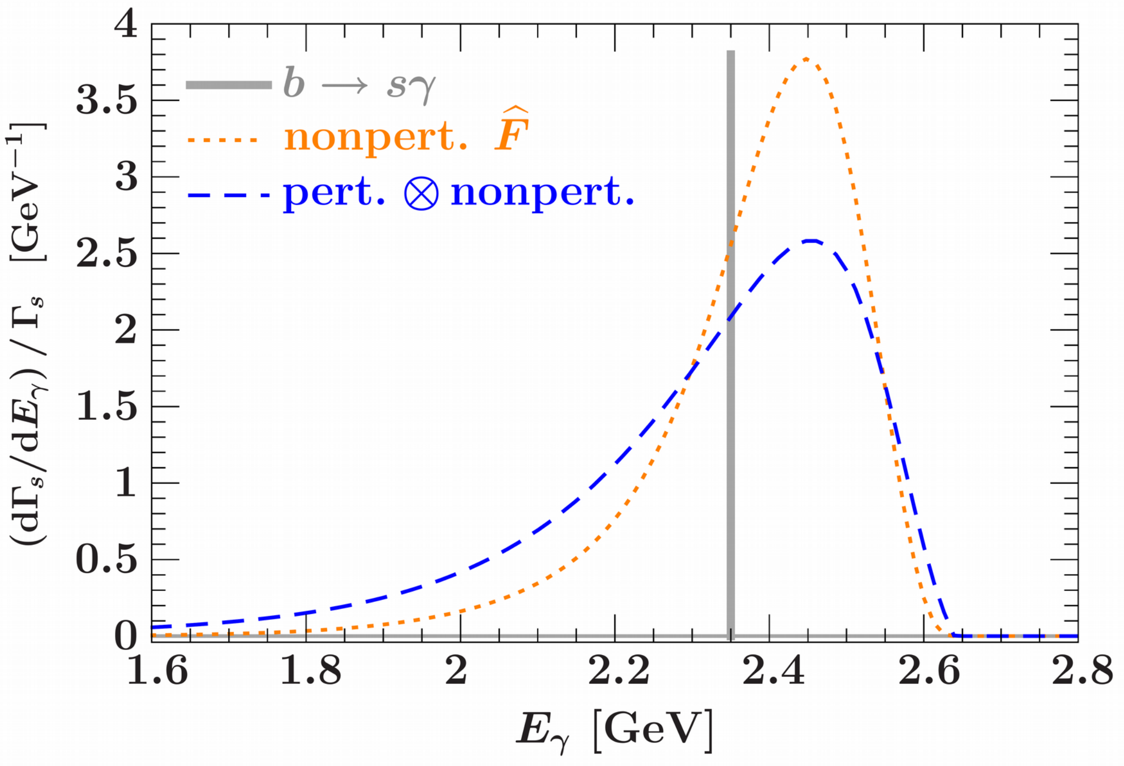

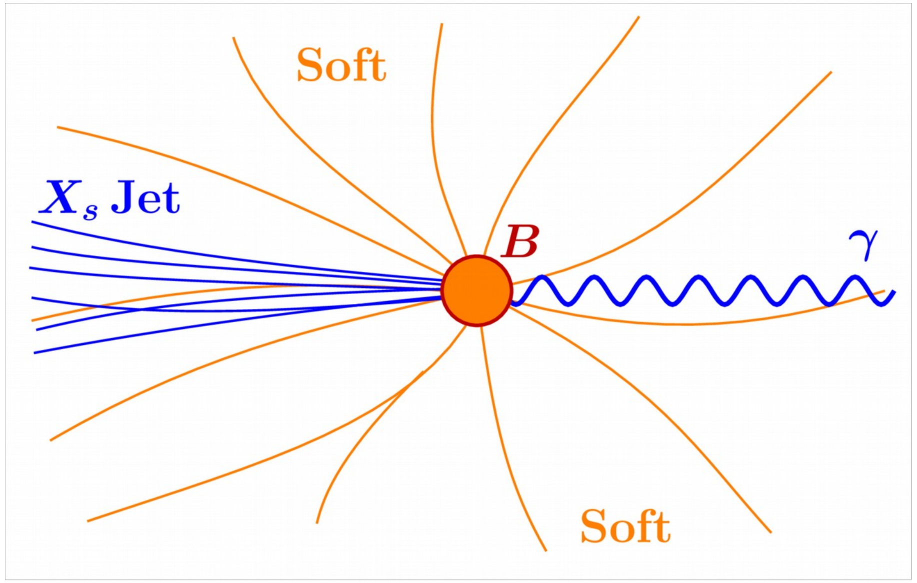

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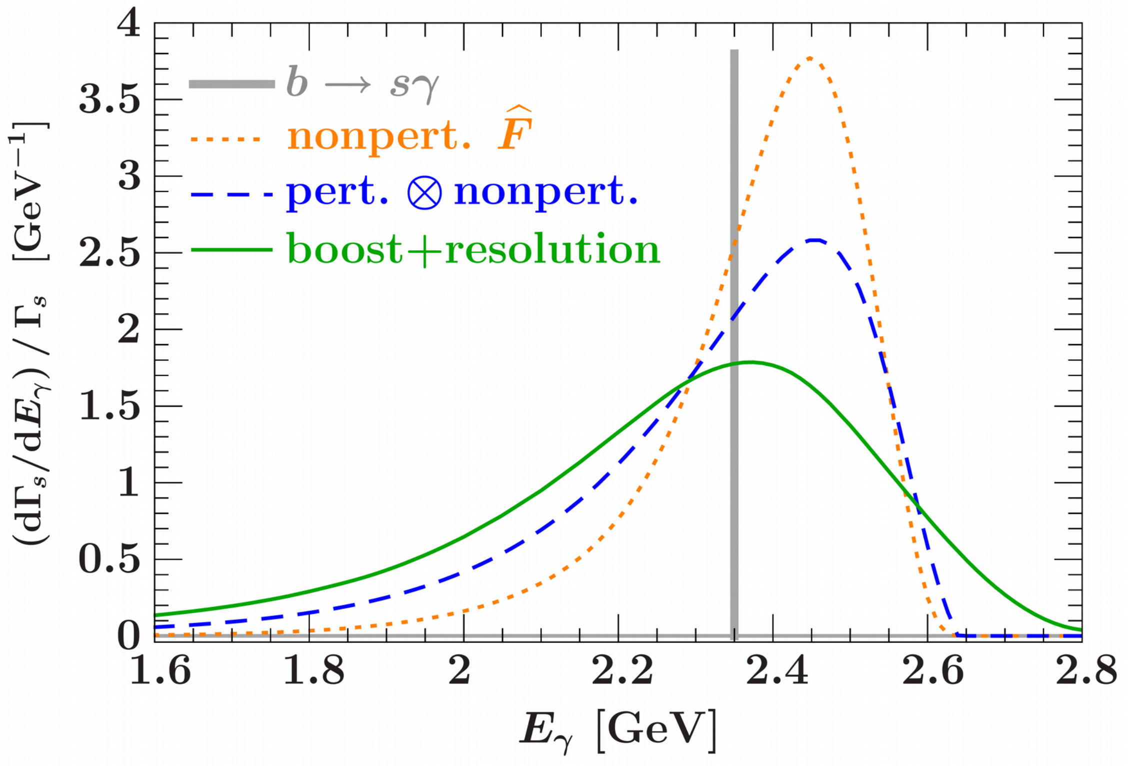

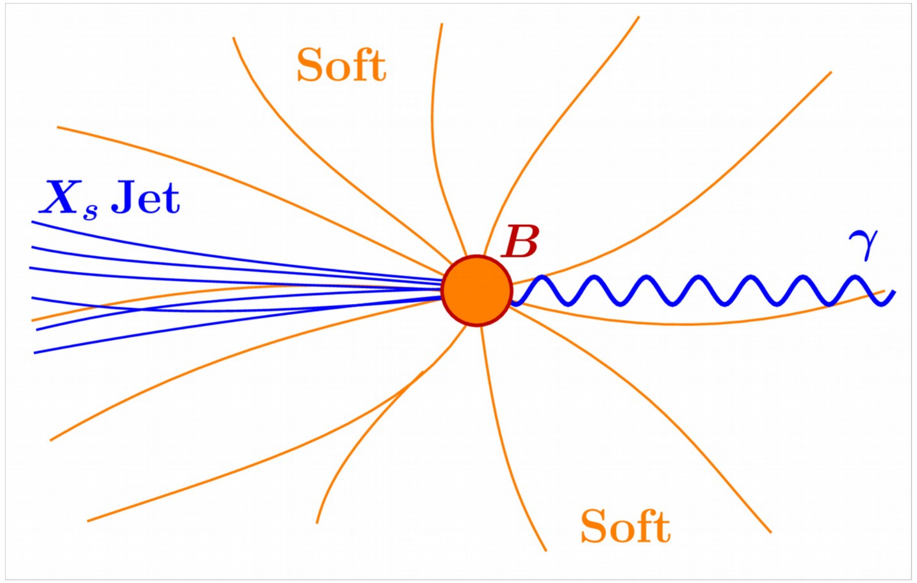

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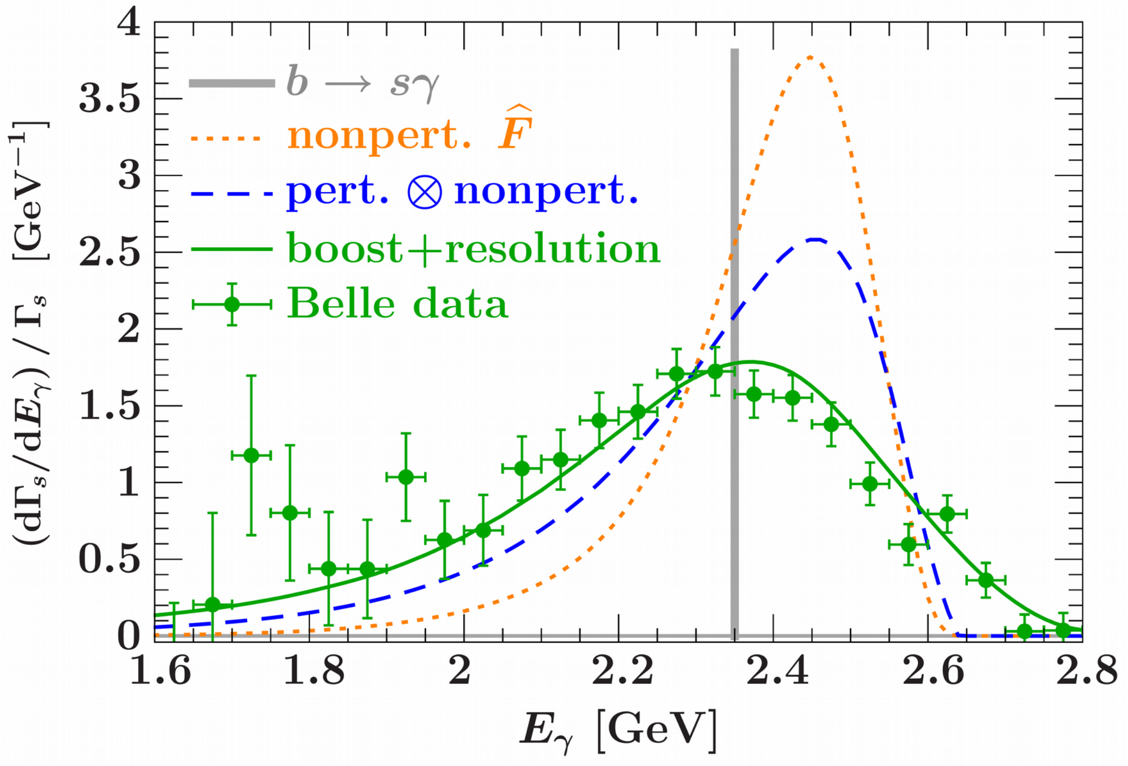

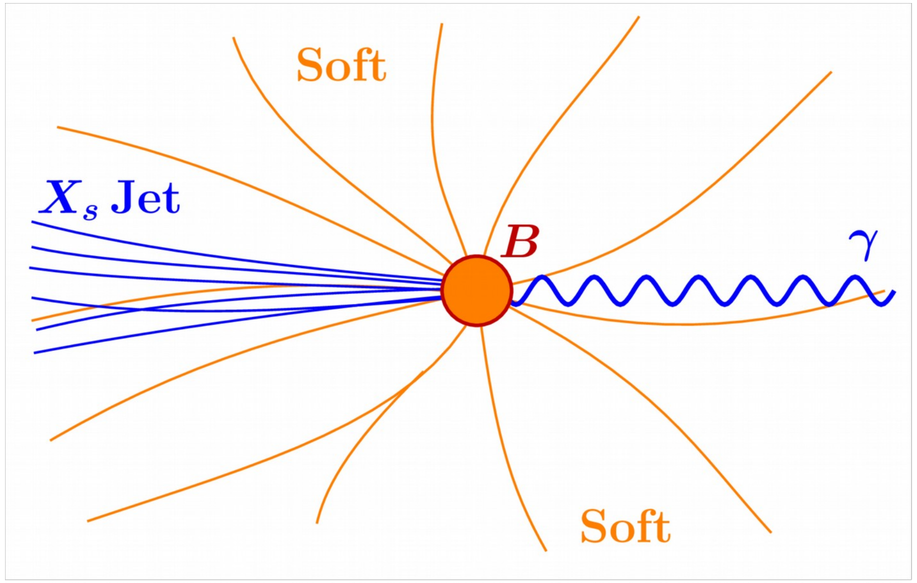

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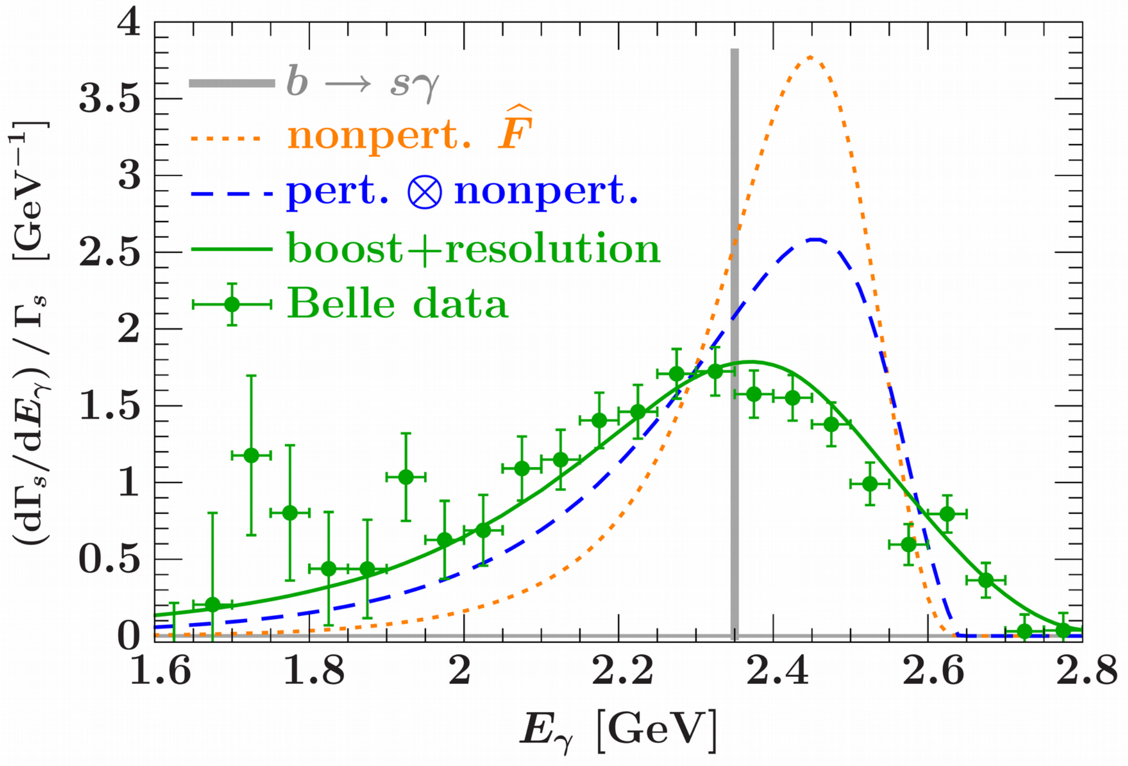

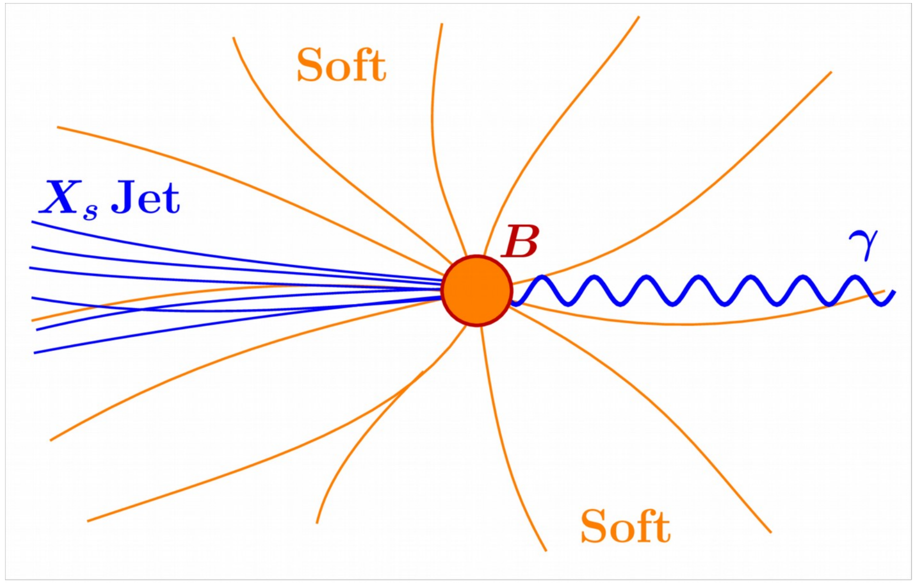

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- Analogous story for other inclusive B-meson decays: $\mathrm{B} \to X_u\, l\, \nu \quad \& \quad \mathrm{B} \to X_s\, l^+\, l^-$

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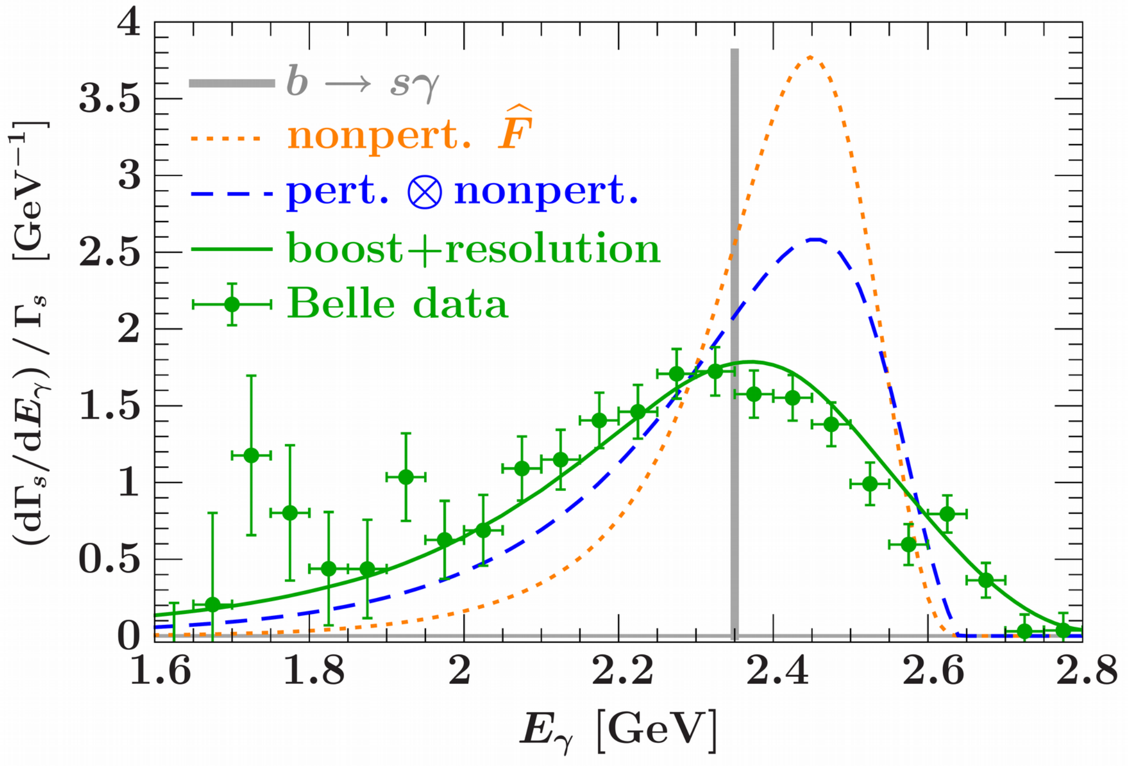

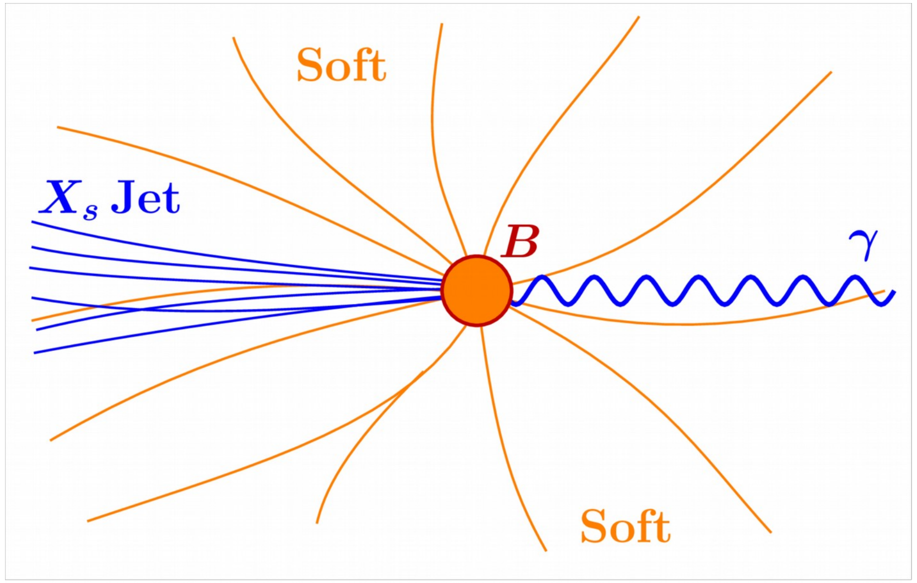

Effective theory setup:

Effective weak theory

Heavy quark effective theory (HQET)

Soft & collinear effective theory (SCET)

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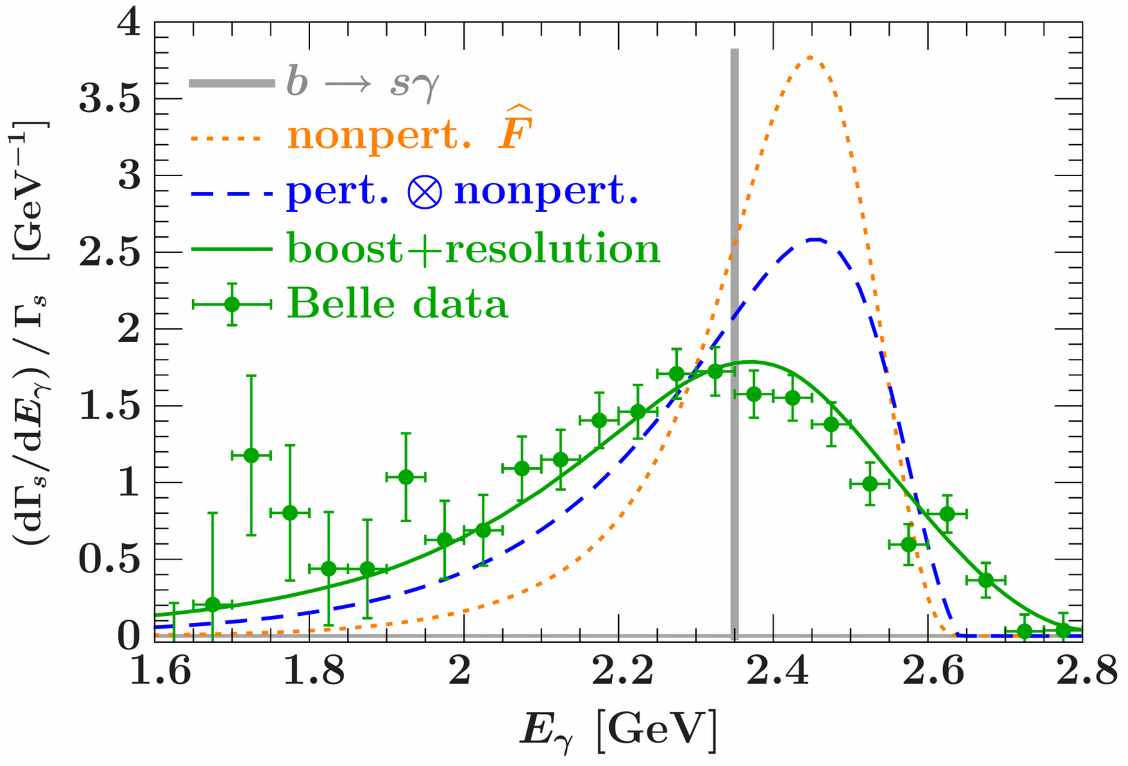

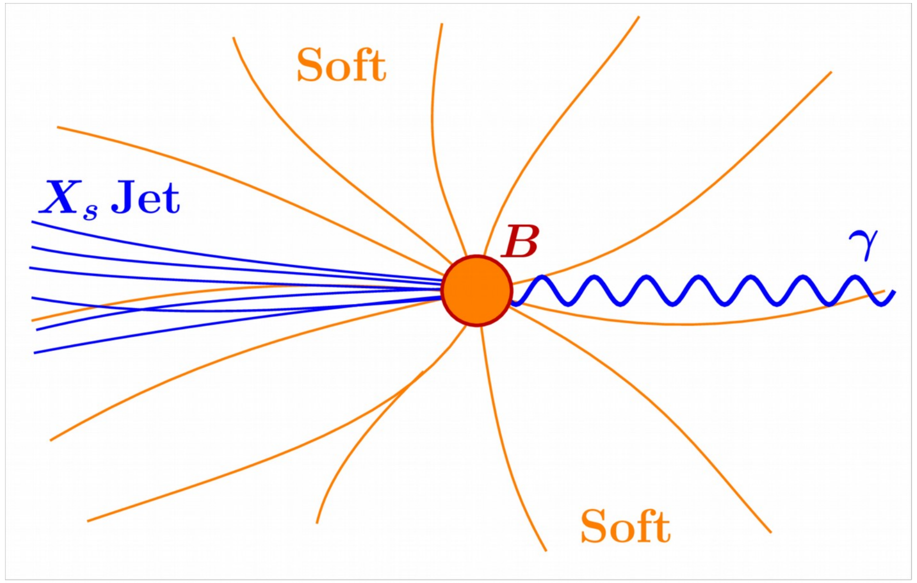

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Factorization Theorem

$$d\Gamma/dE_\gamma = |C_7|^2\, H \times J \otimes S \otimes F_B$$

Applications of EFTs in Precision Physics

Inclusive B-meson decays

Problem: persistent tension between the inclusive and exclusive determinations of $|V_{ub}|$

$$\sum_{X_u} d\Gamma(B \to X_u l\bar{\nu})$$

$$d\Gamma(B \to \pi l\bar{\nu})$$
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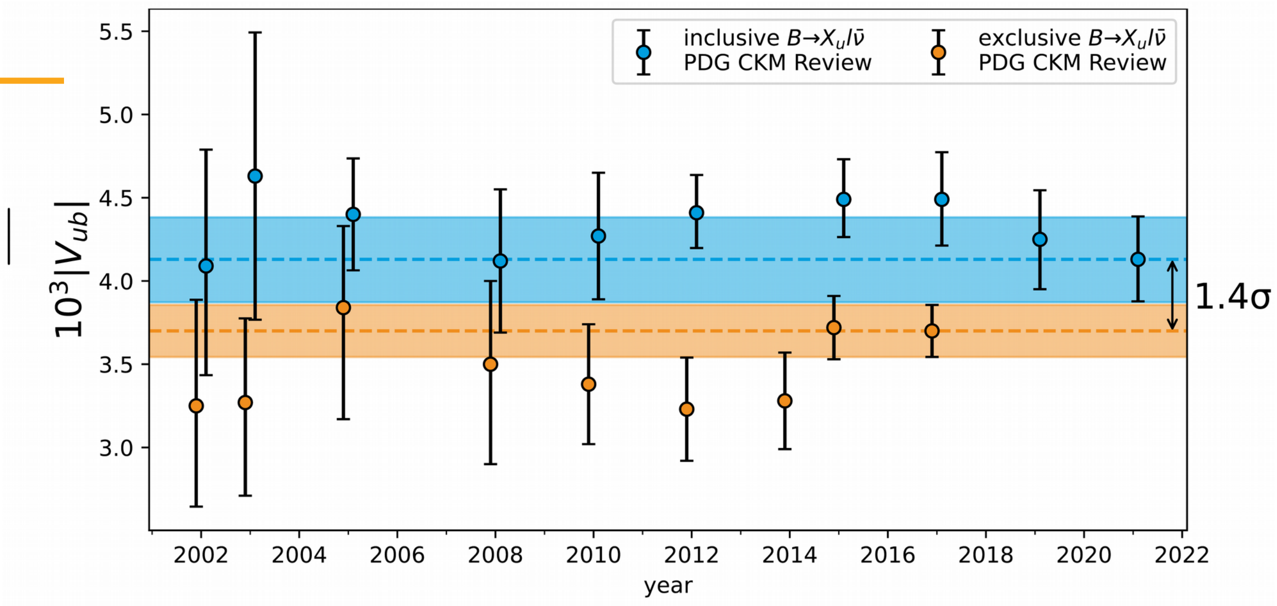

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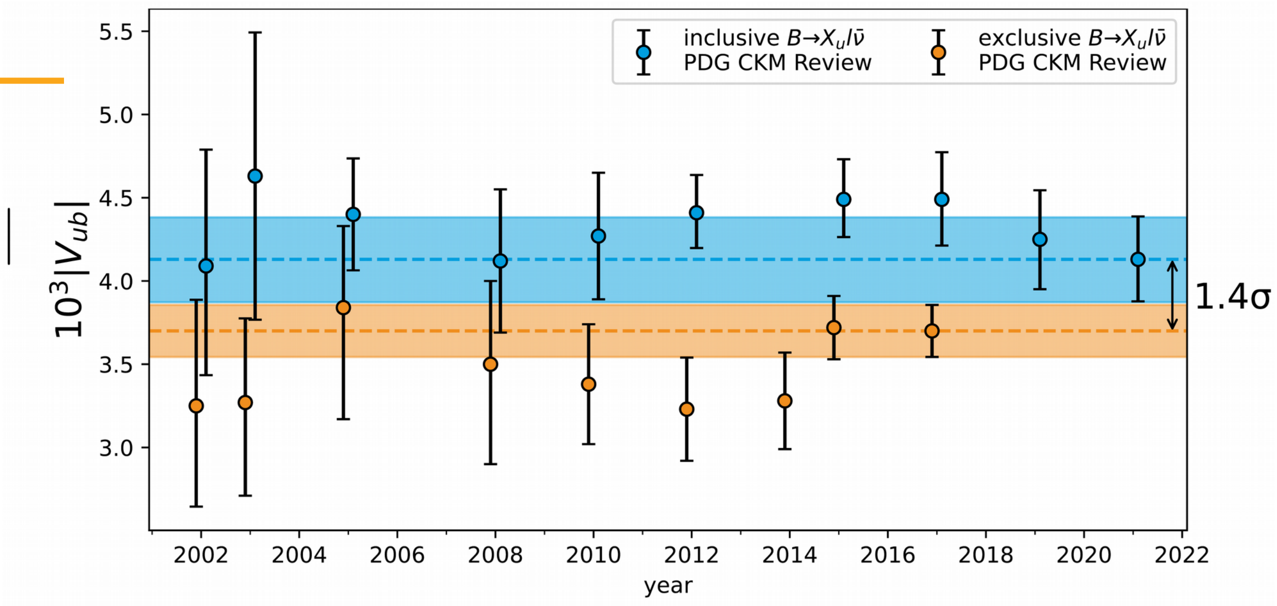

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✓ Factorization theorem separates the short-distance from the long distance physics

✓ $B \to X_s \gamma$ can be used to extract the universal non-perturbative shape function, then use it as an input for the other inclusive B-meson decay modes

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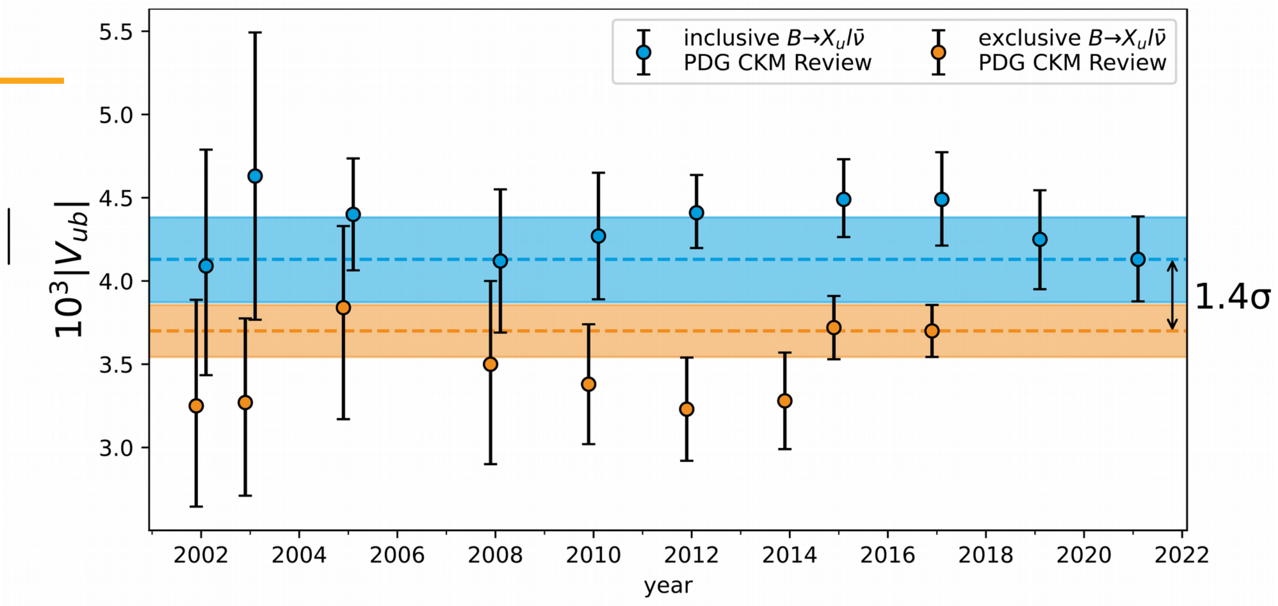

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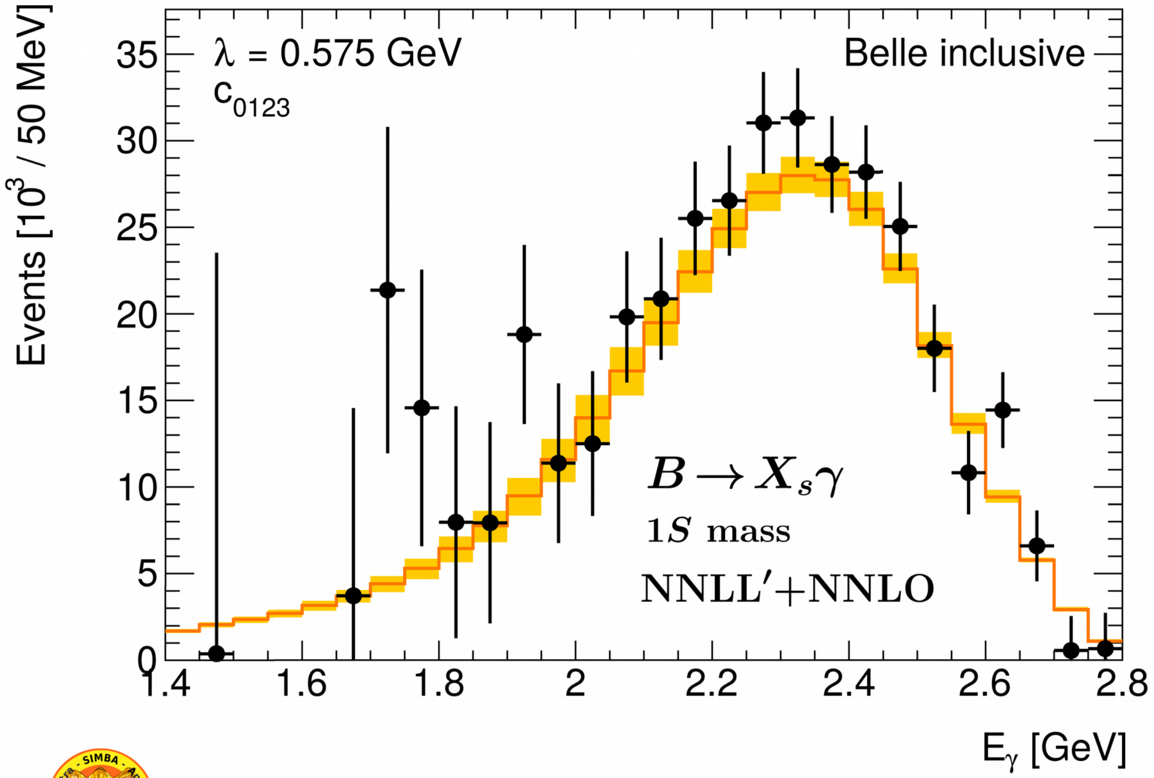
Aim: determine $|V_{ub}|$ from a global fit to inclusive B-meson decay

Inclusive B-meson decays

$B \to X_s \gamma$



SIMBA collaboration, F. U. Bernlochner, H. Lacker, Z. Ligeti, I. W. Stewart, F. J. Tackmann and K. Tackmann (2021)

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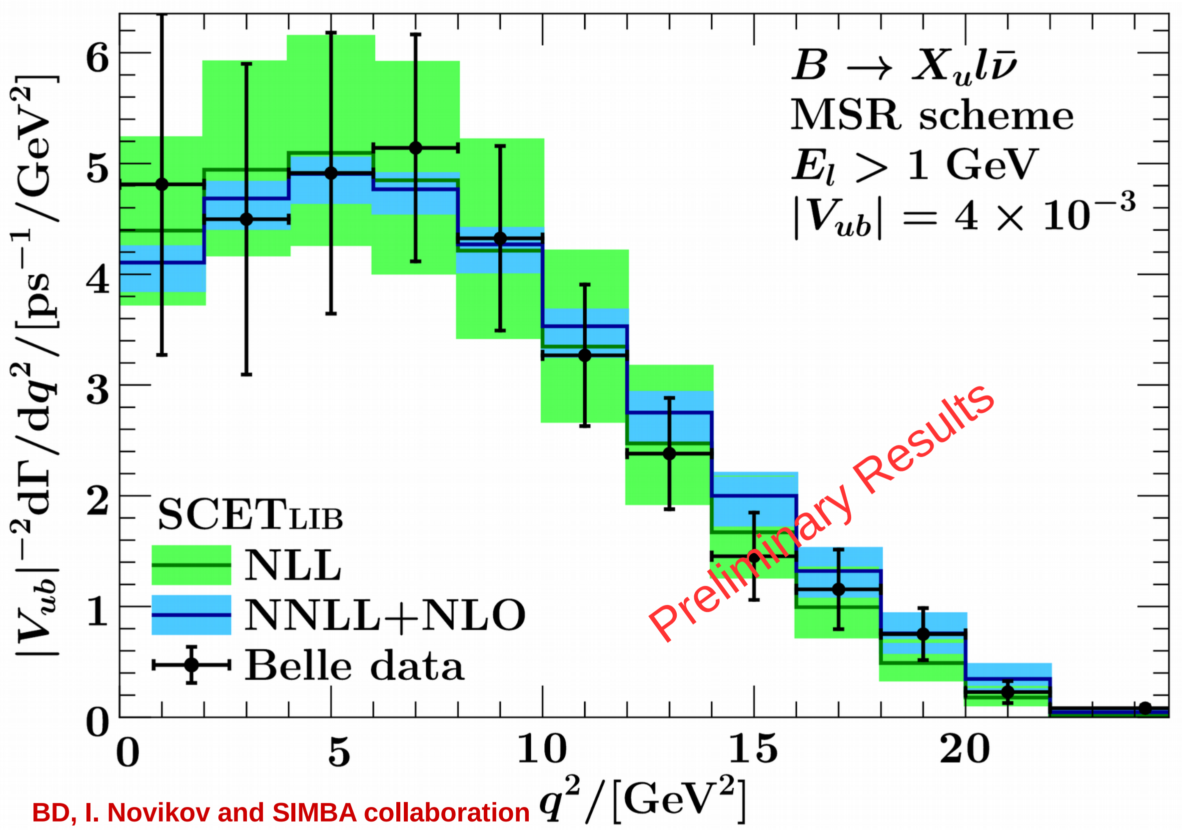
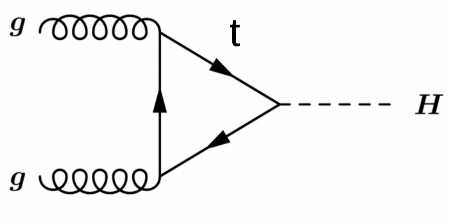


BD, I. Novikov and SIMBA collaboration

Total Higgs fiducial cross section



QCD correction to the total inclusive cross sections for $gg \to H$ is known up to N^{3}LO

Experimental measurements at LHC apply kinematic selection cuts on Higgs decay products

For example ATLAS fiducial cuts for $H \to \gamma\gamma$ $\longrightarrow$

$$p_T^{\gamma 1} \geq 0.35\, m_H\,, \qquad p_T^{\gamma 2} \geq 0.25\, m_H$$
$$|\eta^\gamma| \leq 1.37 \quad \text{or} \quad 1.52 \leq |\eta^\gamma| \leq 2.37$$

Problem: fiducial cuts break the azimuthal symmetry and introduce linear power corrections which increase the IR sensitivity of the fiducial obs.

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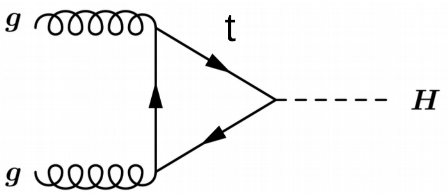

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Effective theory setup:

rEFT : integrate out the top quark

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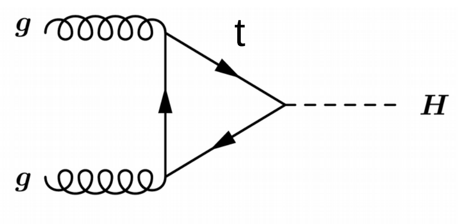

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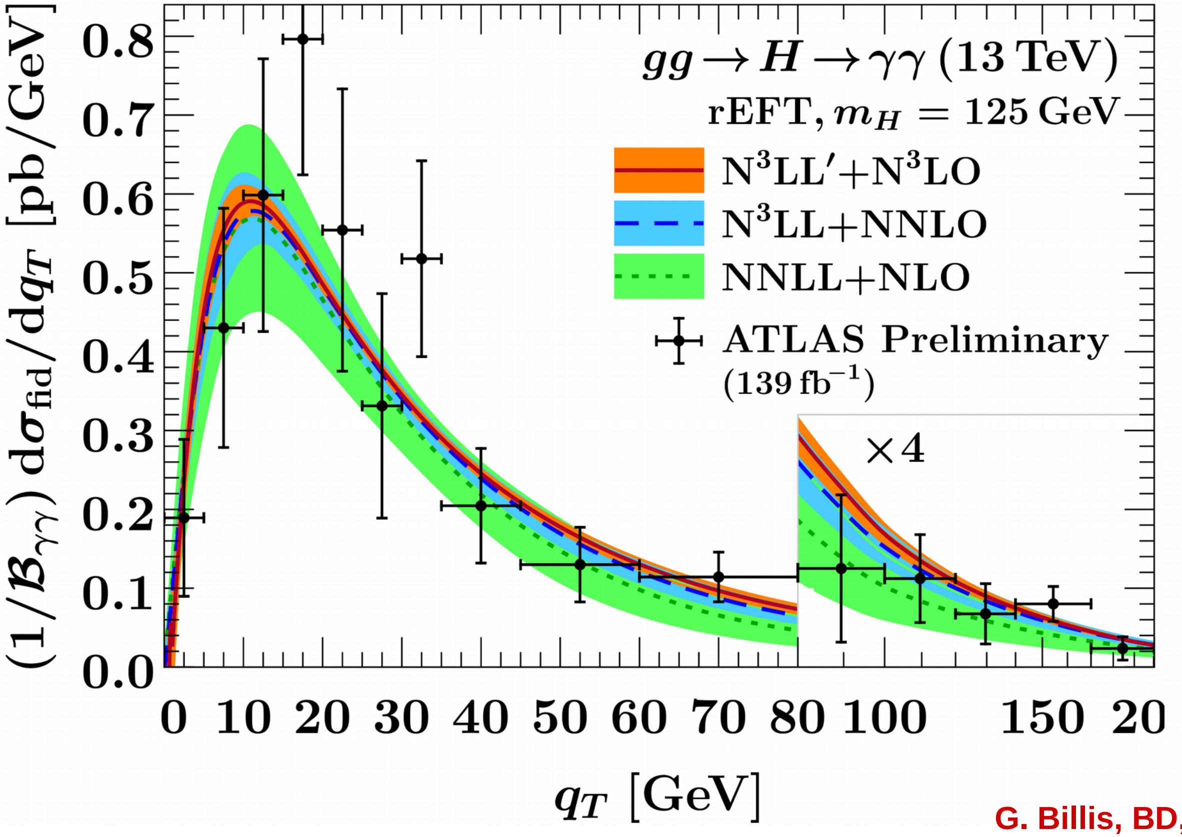
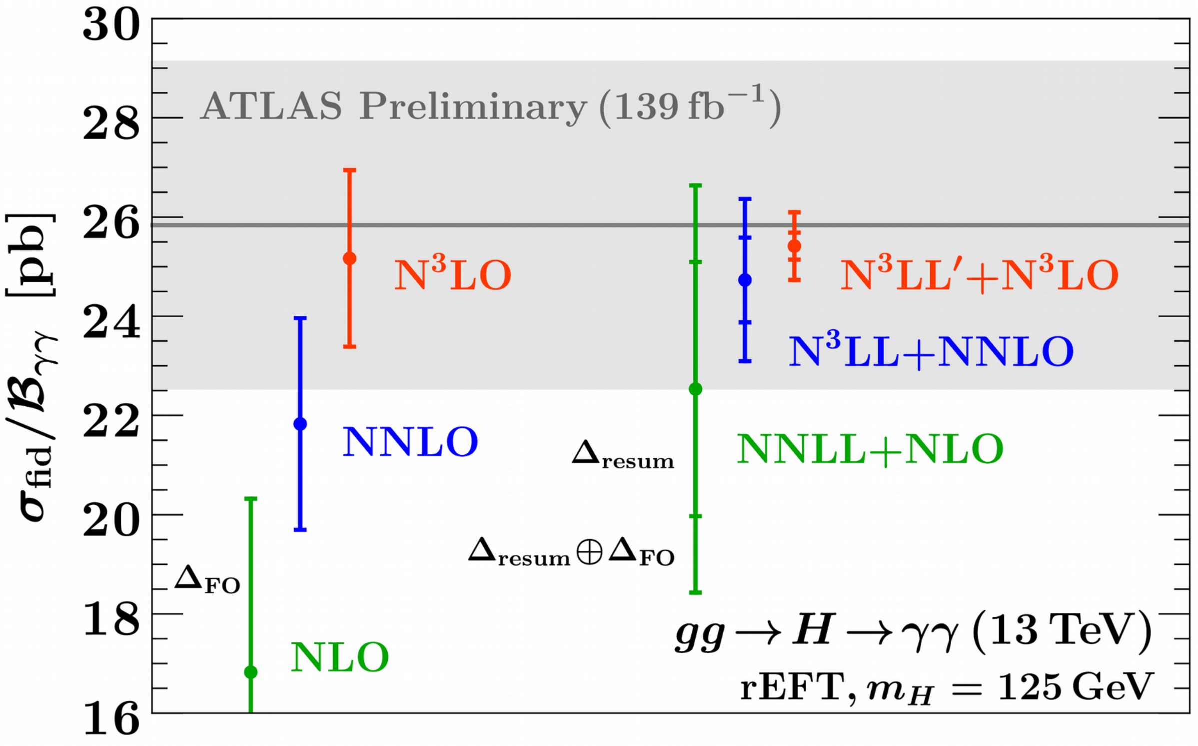
Aim: compute the total (and differential) Higgs cross section with fiducial cut including resummations

Total Higgs fiducial cross section

Higgs transverse momentum spectrum



total fiducial cross section



G. Billis, BD, M A. Ebert, J. K.L. Michel, F. J. Tackmann (2021)

Summary

- ✓ **Effective Field Theories** are very **powerful tools** in **precision physics**
- ✓ **Effective Field Theories** provide **coherent description** of a system using only the **relevant degrees of freedom**
- ✓ **Effective Field Theories** have often **more predictive powers** which can be **systematically improved**
- ✓ **Effective Field Theories** equip us with **factorization theorems** which allow us a to sytematically understand and control the physcis at lower energies (and non-perturbative dynamics)

Acknowledgment

Thank you all, for the nice memories!