Radiative Corrections to Semileptonic Meson Decays

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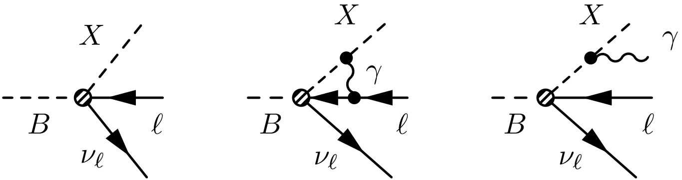
Contents

Motivation



- Determination of V_{xb}

$$\Gamma_{\text{measured}} = \eta^2_{\text{QCD}}\eta^2_{\text{QED}}|V_{xb}|^2\Gamma'_{\text{Born}}$$

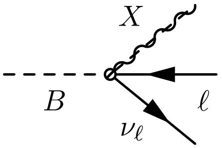
$\longrightarrow$ experiments extract rates which include radiative effects

- Corrections to measured kinematics

$\longrightarrow$ real and virtual photons alter momenta of involved particles

$\longrightarrow$ fits to kinematic variables can be very sensitive to slight changes Phys. Rev. D 79, 012002(2009)

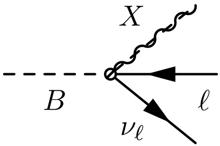
Model



$$\begin{aligned}\mathcal{M} &= \sqrt{2} G_F V_{xb} H_\mu L^\mu \\ L^\mu &= \bar{u}_\nu P_R \gamma^\mu v_\ell \\ H^\mu &= \langle X|V^\mu|B\rangle - \langle X|A^\mu|B\rangle\end{aligned}$$

1. QED corrections can be adequately described at $\mathcal{O}(\alpha)$
2. hadronic model fully characterises weak interaction
3. presence of QED radiation does not modify structure of form factors
4. momentum dependence of form factors negligible in loop integrations
5. scalar/vector QED is sufficient to describe meson-photon interaction

Model

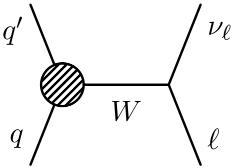


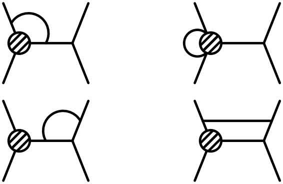
$$\mathcal{M} = \sqrt{2} G_F V_{xb} H_\mu L^\mu$$
$$L^\mu = \bar{u}_\nu P_R \gamma^\mu v_\ell$$
$$H^\mu = \langle X|V^\mu|B\rangle - \langle X|A^\mu|B\rangle$$

- supplement phenomenological model with QED
  - scalar, fermion, vector QED
  - emission off phen. vertex through minimal coupling
  - fully gauge invariant effective theory, Ward identities are fulfilled
- renormalise analoguous to QED
  - on-shell
  - G_F renormalised in short distance picture
    $\rightarrow$ match to muon decay Rev.Mod.Phys.50 (1978) 573
  - long distance corrections need to be matched to short distance corrections

Rev.Mod.Phys.50 (1978) 573

SD result – full EW SM

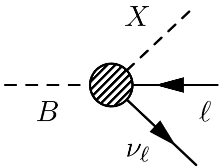


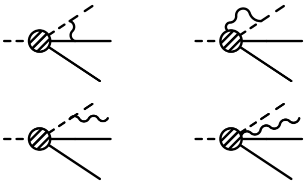


- full SM corrections $\mathcal{O}(\alpha^4_{\text{QED}})$ for partonic process
- needs an infrared cut-off $\Lambda \ll m_W$ at hadronic scale
- photon receives mass Λ
  $\rightarrow$ no real emissions if $\Lambda \geq \frac{1}{2}m_B$

$$\mathcal{M}^1_{0,SD} = \frac{\alpha}{\pi} \ln\frac{m_Z^2}{\Lambda^2} \mathcal{M}^0_0$$

LD result – pheno-LO$\otimes$QED





- $m_\gamma = 0 \;\rightarrow\;$ real and virtual emissions
- effective vertex may emit photons (gauge invariance)
- UV-regularisation using Pauli-Villars method
  $\rightarrow$ introduce heavy unphysical photon of mass M with negative propagator sign
- set $M = \Lambda$ to match to SD results

$\Gamma_{\text{measured}} = \eta^2_{\text{QCD}} \eta^2_{\text{QED}} |V_{xb}|^2 \Gamma'_{\text{Born}}$

$$\eta^2_{\text{QED}} = 1 + \delta^{SD}_{\text{QED}} + \delta^{LD}_{\text{QED}} = \frac{\Gamma\left[\mathcal{O}(\alpha G_F^2)\right]}{\Gamma\left[\mathcal{O}(G_F^2)\right]}$$

	$1+\delta^{LD}_{\text{QED}}$	stat. error	η_{QED}	error
$B^0 \to D^\mp e^\pm \nu_e$	1.00817	0.00025	1.0110	0.001
$B^0 \to D^\mp \mu^\pm \nu_e$	1.00757	0.00023	1.0108	0.001
$B^\pm \to D^0 e^\pm \nu_e$	0.99679	0.00023	1.0054	0.0005
$B^\pm \to D^0 \mu^\pm \nu_e$	0.99633	0.00021	1.0052	0.0005
$B^0 \to \pi^\mp e^\pm \nu_e$	1.04476	0.00079	1.0290	0.002
$B^0 \to \pi^\mp \mu^\pm \nu_e$	1.04544	0.00081	1.0292	0.002
$B^\pm \to \pi^0 e^\pm \nu_e$	0.99718	0.00046	1.0055	0.001
$B^\pm \to \pi^0 \mu^\pm \nu_e$	0.99598	0.00048	1.0049	0.001

$\rightarrow$ QED breaks isospin symmetry

Annals Phys.13(1961)379-452; JHEP12(2008)018

Resummation Effects – YFS-scheme

- resummation of soft limit ($k \to 0$)
- separation of soft limit of real and virtual amplitudes
  $\to$ YFS form factor $\exp[Y(\Omega)]$
- reorganisation of perturbative series
  $\to$ series in e with infrared divergent amplitudes into series in α with infrared subtracted squared amplitudes

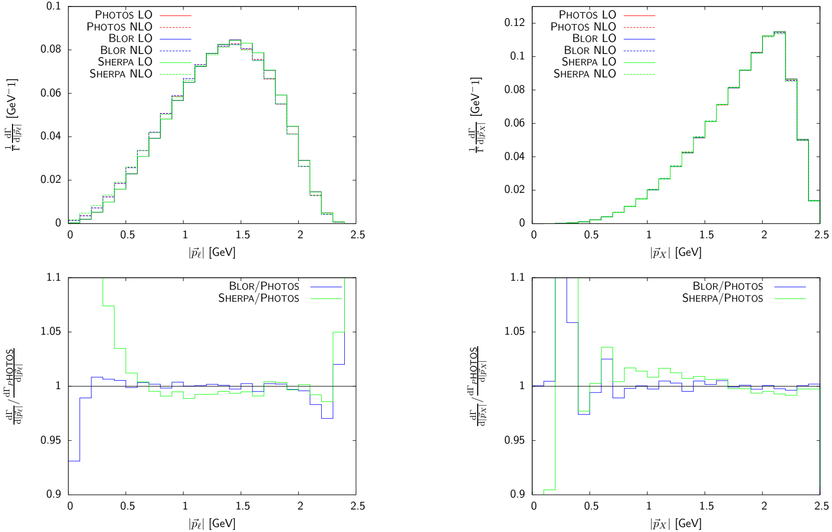
$$\left|\mathcal{M}_0^0 + \mathcal{M}_1^{\frac{1}{2}} + \mathcal{M}_0^1 + \ldots\right|^2$$

$$= \quad e^{Y(\Omega)} \prod_0^i \tilde{S}(k_i, \Omega) \left(\tilde{\beta}_0^0 + \tilde{\beta}_0^1 + \sum_i \frac{\tilde{\beta}_1^1(k_i)}{\tilde{S}(k_i)} + \ldots\right)$$

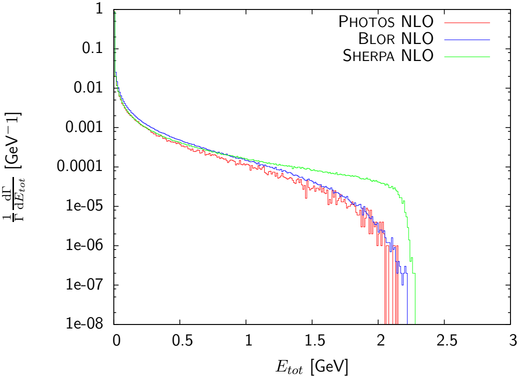
- improved predictions

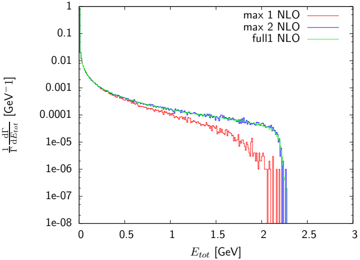
Comput.Phys.Commun.66:115-128,1991

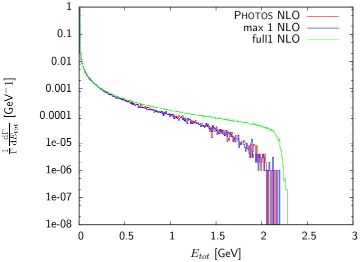
Differential distributions – $B^0 \to D^- e^+ \nu_e$



Origin of differences – $B^0 \to D^- e^+ \nu_e$







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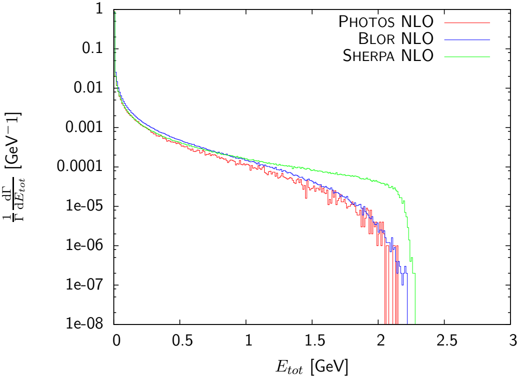
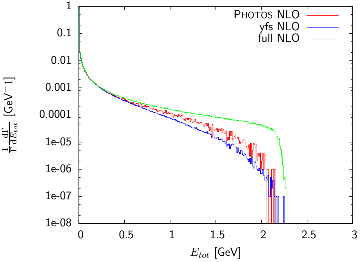
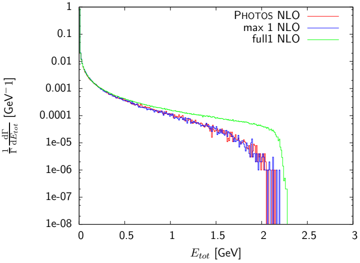




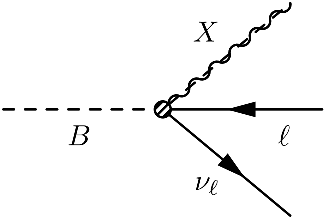


Conclusion

- corrections and smaller uncertanties to correction factor η_{QED} in V_{xb}
- some phase space regions receive much larger corrections
  $\rightarrow$ can only be adequately described using both fixed order ME and resummation
- quantify systematic uncertanties due to matching of SD and LD
- TODO: implement integration using YFS-improved calculation

Appendix

Phenomenological LO decay – $\mathcal{O}(G_F)$



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FS scalar
$$\begin{aligned}\langle X|V^\mu|B\rangle &= f_+(t)(p_B+p_X)^\mu + f_-(t)(p_B-p_X)^\mu \\ \langle X|A^\mu|B\rangle &= 0\end{aligned}$$

FS vector
$$\begin{aligned}\langle X|V^\mu|B\rangle &= 2ig(t)\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu p_{B\rho} p_{X\sigma} \\ \langle X|A^\mu|B\rangle &= f(t)\varepsilon^{\mu *} + a_+(t)(p_B+p_X)^\mu(p_B-p_X)^\nu\varepsilon^*_\nu \\ &\quad + a_-(t)(p_B-p_X)^\mu(p_B+p_X)^\nu\varepsilon^*_\nu\end{aligned}$$

Advantages over LL Factorization

		phen. model	PHOTOS
V	t dependency in FF	approximate	none
V	corrections on kinematics	yes	none
V	vertex emission	yes	none
V	contribution to decay rate	yes	none
R	t dependency in FF	yes	none
R	full photon emission coupling	yes	resummed soft limit
R	vertex emission	yes	none
R	parton level emission	none	none
R	emission ration at first order	yes	approximate
RV	total rate change	yes/no	none