Exclusive hadronic Z decays

Shan Cheng

In collaboration with Qin Qin, Man-qi Ruan and Fu-sheng Yu

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Exclusive hadronic Z decays arise from the $Z\bar{q}q$ interaction

$$\mathcal{L}_{Zq\bar{q}} = \frac{-e}{2\sin(2\theta_W)} \sum_f \left[q^\dagger_{\mathrm{L}f} \tilde{\sigma}^\mu q_{\mathrm{L}f} \left(T_3^f - Q_f \sin^2\theta_W \right) - q^\dagger_{\mathrm{R}f} \sigma^\mu q_{\mathrm{R}f} \left(Q_f \sin^2\theta_W \right) \right], \qquad (1)$$

and end up with the hadronization (i.e., LCDA)

$$\begin{aligned} & \int d^4 z_2\, e^{i\bar{k}_2 \cdot z_2} \left\langle \pi^+(p_2) \middle| \bar{u}_\delta(0)\, d_\alpha(z_2) \middle| 0 \right\rangle \\ = \quad & \frac{-if_\pi}{4N_c} \left\{ \gamma_5 \left[\not{p}_2\, \varphi_\pi(\bar{x}_2, b_2) + m_0^\pi\, \varphi_\pi^{\mathrm{p}}(\bar{x}_2, b_2) + m_0^\pi\, (\not{n}_+ \not{n}_- - 1)\, \varphi_\pi^{\mathrm{t}}(\bar{x}_2, b_2) \right] \right\}_{\alpha\delta} \\ \xrightarrow{\text{QCD asy}} \quad & \frac{-if_\pi}{4N_c} \left\{ \gamma_5 \left[\not{p}_2\, \varphi_\pi(x_2, b_2) + m_0^\pi\, \varphi_\pi^{\mathrm{p}}(x_2, b_2) - m_0^\pi\, (\not{n}_+ \not{n}_- - 1)\, \varphi_\pi^{\mathrm{t}}(x_2, b_2) \right] \right\}_{\alpha\delta} (2) \end{aligned}$$

Advantages with comparing to B physics

- The heavy-light system B meson is usually described by HQET,
  the scale $\mathcal{O}(m_B)$ is not large enough,
  the power corrections $\mathcal{O}(1/m_B)^n$ are indispensability,
  while the calculations are nontrivial.

- The point-like Z boson is much simpler than the B meson,
  power corrections only came from the final states.
- High energy scale $\mathcal{O}(m_Z)$, the power corrections $\mathcal{O}(1/m_Z)^n$ are highly suppressed.

Offer a precision test of SM and the factorization approach
Perturbative QCD approach VS QCD factorization
k_T factorization VS collinear factorization

$$\Gamma(Z \to \pi^+\pi^-) = \frac{m_Z}{48\pi}(g_{\rm V}^u - g_{\rm V}^d)^2 |\mathcal{G}_\pi(m_Z^2)|^2 \,. \qquad (3)$$

- Only relates to the pion electromagnetic form factor with $Q^2 = m_Z^2$.
- The QCD-based calculations for the pion electromagnetic form factor:

  Lattice QCD, $|q^2| \in [0, 1]$ GeV^2, [G. Wang, et.al., 2006.05431[hep-ph]]
  Light-cone sum rules, $|q^2| \in [1, 10]$ GeV^2, [SC, et.al., 2007.05550[hep-ph]]
  Perturbative QCD, $|q^2|, q^2 \in [\sim 10, \infty]$ GeV^2. [SC, 1905.05059[hep-ph]]

- The experiment data for the pion electromagnetic form factor:

  JLab $|q^2| \leqslant 2.5$ GeV^2, 12 GeV upgrade,
  BABAR: $e^+e^- \to \pi^+\pi^-(\gamma)$, $q^2 \in [4m_\pi^2, 8.7]$ GeV^2 , [J. Lees, et.al., 1205.2228[hep-ex]]
  Belle: $\tau \to \pi\pi\nu_\tau$, $q^2 \in [4m_\pi^2, 3.125]$ GeV^2. [M. Fujikawa, et.al., 0805.3773[hep-ex]]

- $\mathcal{B}(Z \to \pi^+\pi^-)_{PQCD} = (0.83 \pm 0.06) \times 10^{-12}$, [SC and Q.Qin, 1810.10524[hep-ex]]
  Future Z factories, to determine the leading twist pion LCDAs,
  and the QCD running behaviour at large $\mathcal{O}(m_Z)$ scale.

- Three-body decays are much more complicated,

$$d\Gamma(A(p) \to M_1(p_1)M_2(p_2)) = \frac{M_A\,|\mathcal{M}|^2}{64\pi^2}\,d\Omega\,, \tag{4}$$

$$d\Gamma(A(p) \to M_1(p_1)M_2(p_2)M_3(p_3)) = \frac{|\mathcal{M}|^2}{256\pi^3 M_A^3}\,dm_{12}^2 dm_{23}^2\,. \tag{5}$$

- Two independent Lorentz invariant variables

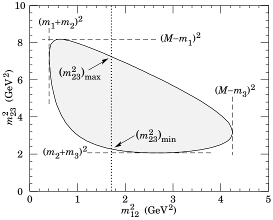

Figure: The Dalitz plots for the three-body final state $\pi^+\bar{K}^0 p$ at 3 GeV in the m_{12}^2-m_{23}^2 plane, cited from PDG.

i.e., $Z \to \pi^+\pi^-\pi^0$

- Three-body B decays receive many attentions, measured large local direct CPV.
- Only the resonance regions satisfies the requirement of factorization hypothesis,

  The non-resonant dynamics need to be addressed somewhere else, i.e., Z decays.
- Non-resonant backgrounds:

  $\lesssim 10\%$ in three-body D decays,
  large or even dominate in the penguin dominated B decays ($B \to K\pi\pi, KKK$),
  expectes to be overwhelmed in three-body Z decays.
- The Monte carlo study shows $\mathcal{B}(W^+ \to \pi^+\pi^-\pi^+) \in [10^{-8}, 10^{-5}]$,
  [M. Mangano et.al., 1410.7475[hep-ph]]
  CMS also report the upper limit $\mathcal{B}(W^\pm \to \pi^\pm\pi^\pm\pi^\mp) < 1.01 \times 10^{-6}$,
  [A. M. Sirunyan et.al., 1901.11201[hep-ex]]
- motivates the consideration of the similar channel $Z \to \pi^+\pi^-\pi^+$.
- key questions: how to calculate the contributions from non-resonant region ?
  how to quantitatively distinguish the kinematic boundaries for different regions in Dalitz plot ?

i.e., $Z \to \pi^0\gamma$

- The search of $Z \to \pi^+\pi^-\pi^0$ may be limited by the background, comments by Manqi.
- See the radiative decay modes

Decay mode	Branching ratio	CEPC Uncertainty	Current upper limit (PDG)
$Z \to J/\psi\gamma$	8.02×10^{-8}	$\sim 1.8\%$	$< 2.6 \times 10^{-6}$
$Z \to \Upsilon(1S)\gamma$	5.39×10^{-8}	$\sim 3.4\%$	
$Z \to \rho^0\gamma$	4.19×10^{-9}	$\sim 1.8\%$	
$Z \to \omega\gamma$	2.82×10^{-8}	$\sim 0.8\%$	$< 6.5 \times 10^{-4}$
$Z \to \phi\gamma$	1.04×10^{-8}	$\sim 1.6\%$	$< 8.3 \times 10^{-6}$
$Z \to \pi^0\gamma$	9.80×10^{-12}	$< 3.4 \times 10^{-8}$	$< 2.01 \times 10^{-5}$
$Z \to \eta\gamma$	$0.1 - 1.7 \times 10^{-10}$	$\sim 12\% - 50\%$	$< 5.1 \times 10^{-5}$
$Z \to \eta'\gamma$	$3.1 - 4.8 \times 10^{-9}$	$\sim 2.7 - 3.4\%$	$< 4.2 \times 10^{-5}$

Table: The SM predictions for radiative Z boson decays.

[Y. Grossman, et.al., 1501.06569[hep-ph]], [S. Alte, et.al., 1512.09135[hep-ph]]

- Radiative decay mode $Z \to \pi^0\gamma$ is almost background free @ CEPC.

The End, Thanks.