The potential of hadronic Z decays

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Overview

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

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

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

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

Factorisation theorem

- factorisation theorem stems from the temporal and spatial thinking.
- hard scattering happens in a short time and a minimal spacing.
- interacting partons are free to the onlooking partons in hadrons.
- detach the hard scale (pert.), the soft scale (nonpert.) physics.
- hadron wave function.

† idea of factorisation theorem in pion em. form factor, 1980s
Efremov-Radyushkin-Lepage-Brodsky theorem of hard elastic scattering
[G.P. Lepage and S.J. Brodsky., PRL 43.545(1979), PRD 22.2157(1980)]
[A.V. Efremov and A.V. Radyushkin, PLB 94.245(1980)]

† prosperity of the factorisation theorem in B physics, 2001-,
several approaches based on different factorisation hypothesises.
QCDF [M. Beneke, et al., PRL 83.1914(1999), NPB 591.313(2000)]
SCET [C.W. Bauer, et al., PRL 87.201806(2001), PRD 63. 114020(2001)]
LCSRs [A. Khodjamirian, et al., NPB 605.558(2001), PRD 67.054027(2003)]
pQCD [H.N. Li, et al., PLB 504.6(2001), PRD 63.054008(2001)]

Status of B physics study

- GREAT SUCCESS
- explain the vast majority of channels, predict a portion of channels, CP asymmetry, hadron inner structure $\cdots$
- SOME PUZZLES UNRESOLVED
- $B^0 \to \pi^0\pi^0$, $B^0 \to \rho^0\rho^0$, leptonic universality, $|V_{ub}|$ tension from inclusive and exclusive processes $\cdots$
- addressed in first by the precise examination in SM, and then by the new physics
- theoretical uncertainty in B sector
  - † high order hard amplitudes, QCD, EW calculations
  - † high power corrections, LCDAs and operators
  - † approaches themselves, factorisation scale
- many sources, focus on piece by piece

Z decays

- a key problem, pollution from large power corrections $\mathcal{O}(1/m_B)^n$
- indispensability, but difficult to calculate
- hard/impossible to fully complete the precise examination of factorisation theorem in B sector
- reason: B meson is usually described by HQET, the scale $\mathcal{O}(m_B)$ is not large enough.
- how to evade the power pollution ?
- hadronic Z decays provides a much cleaner environment
  - † point-like Z boson, much simple than B meson
  - † power corrections come from the final states and operators
  - † large scale, the power corrections $\mathcal{O}(1/m_Z)^n$ are negligible.
  - † leading power predictions are enough
- make the precise examination more solid, verify the factorisation approaches and hence to the small-x dynamics.

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

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

- only relates to the pion em. form factor at $Q^2 = m_Z^2$.
- The QCD-based calculations mainly worked in the spacelike regions
  - † LQCD, $|q^2| \in [0, 1]$ GeV^2, [G Wang, et.al., 2006.05431[hep-ph]]
  - † DSE-BSE, $|q^2| \in [0, 6]$ GeV^2, [M.Y Cheng, et.al., 1808.09461[hep-ph]]
  - † LCSRs, $|q^2| \in [1, 10]$ GeV^2, [SC, et.al., 2007.05550[hep-ph]]
  - † pQCD, $|q^2|, q^2 \in [\sim 10, \infty]$ GeV^2. [SC, 1905.05059[hep-ph]]
- The measurements are mainly in the timelike regions
  - † JLab: $|q^2| \leqslant 2.5$ GeV^2 and [0,9] GeV^2 is expected, [JLab 12 ungrade CDR]
  - † BES-III: $q^2 \in [0.36, 0.81]$ GeV^2 , [M. Ablikim, et.al., 1507.08188[hep-ex]]
  - † BABAR: $q^2 \in [4m_\pi^2, 8.7]$ GeV^2 , [J. Lees, et.al., 1205.2228[hep-ex]]
  - † Belle: $q^2 \in [4m_\pi^2, 3.125]$ 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]]
  $\mathcal{B}(Z \to K^+K^-)_{pQCD} = (1.74 \pm 0.06) \times 10^{-12}$
- $\mathcal{B}(Z \to \pi^+\pi^-) < 1.52 \times 10^{-5}$ [CDF, 1311.3282[hep-ex]]

- the factorisation scale dependence of approach itself

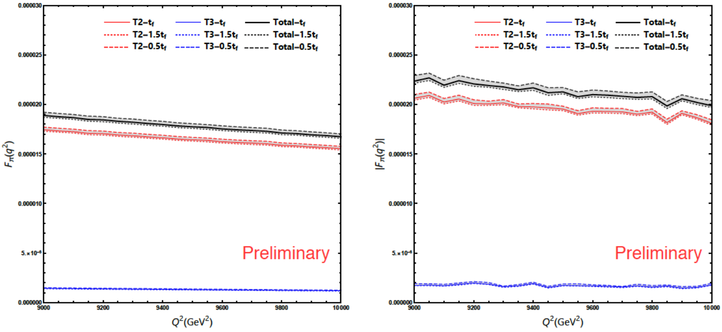

Figure: factorisation scale dependence

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

- the evolution of leading twist pion LCDA at $\mathcal{O}(m_Z)$ scale

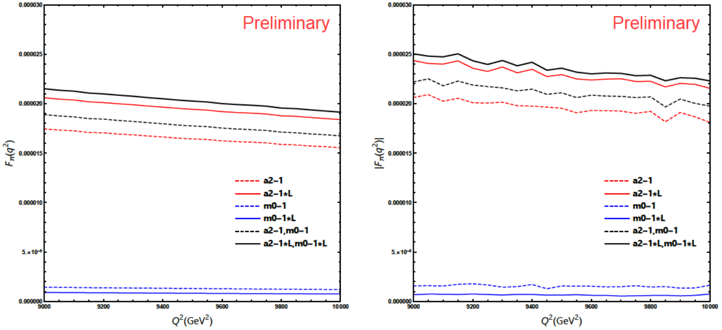

Figure: evolution dependence on the leading twist LCDA

- the uncertainty on the choice of parameters at $1\mathrm{GeV}$

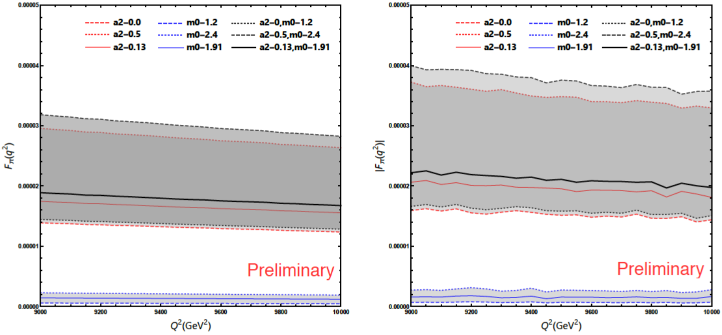

Figure: parameters dependence

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

- Three-body B decays is a hot topic, particular for the large local direct CPV.
- 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

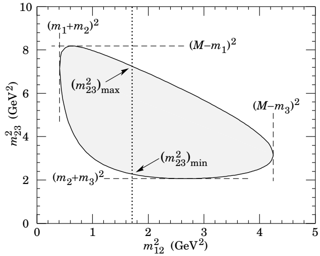

Figure: Dalitz plots for $\pi^+\bar{K}^0 p$ at 3 GeV in the m_{12}^2-m_{23}^2 plane, taken from PDG.

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

- factorisation hypothesis only holds in the resonance regions (R)
- a clear separation between R and NR regions is impossible in B sector
- The non-resonant dynamics need to be addressed somewhere else
- three-body Z decays is an ideal arena to study the non-resonant dynamics
- the different roles of NR contributions
  - † $\lesssim 10\%$ in three-body D decays
  - † large or dominate in the penguin dominated B decays ($B \to K\pi\pi, KKK$)
  - † expected 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]]

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

- motivates the consideration of the similar channel $Z \to \pi^+\pi^-\pi^0$.
- two open questions
  - † how to calculate the contributions from non-resonant region ?
  - † how to quantitatively distinguish the kinematic boundaries ?
- The search of $Z \to \pi^+\pi^-\pi^0$ may be limited by the background
  [comments by Manqi]
- need more clear analysis for the Dalitz plot

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

- Radiative decay mode $Z \to \pi^0\gamma$ is almost background free @ CEPC
- to precise test the factorisation theorem, to extract the pion LCDA
- The SM predictions for radiative Z boson decays

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}	$< 3.4 \times 10^{-8}$	$< 2.01 \times 10^{-5}$
$Z \to \eta\gamma$	$0.1 - 1.7 \times 10^{-10}$	$\sim 12\% - 50\%$	$< 5.1 \times 10^{-5}$
$Z \to \eta'\gamma$	$3.1 - 4.8 \times 10^{-9}$	$\sim 2.7 - 3.4\%$	$< 4.2 \times 10^{-5}$

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

Conclusion

- precise examination of factorisation theorem in two-body hadronic Z decays
- study the NR contribution in three-body hadronic Z decays
- precise measurement in radiative hadronic Z decays

The End, Thanks.