Enhancement of CP Violation by Final-State Interactions in $B_{(s)}$ Decays

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Collaborators: Xin-Yue Hu, Pengyu Niu, Wei Wang, in preparation

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Motivation

- CP violation, a prerequisite for the observed matter-antimatter asymmetry of the universe   A.D. Sakharov, Pisma Zh. Esp. Theos. Fiz. 5(1967)32

- CKM matrix elements ——fundamental parameters in SM
  - Non-leptonic B decays ⇒ CKM matrix elements
  - Hadronic decays of B meson ⇒ Weak angle

    The best channels for $\gamma \Leftarrow$ $B \to DK, \ \ B \to D\pi$ J. Brod, J. Zupan, JHEP01(2014)051
  - We propose other channels to measure weak angle γ
  - e.g. $\bar{B}^0 \to D\bar{D}, \bar{B}_s^0 \to D\bar{D}$ with FSI
- FSI
  - Whether FSI is important or not? ⇐ deBroglie wave lengths of the final particles

FSI is not important in B decays   H.Y. Cheng, C.K. Chuan, A. Soni, PRD71(2005)014030

Motivation

- FSI

  - For D mesons ($m_B - m_D \sim 4$ GeV), FSI is important

$\Rightarrow$ Long-distance rescattering effects are expected to influence CP asymmetry in $D \to PP$ decays

A. Pich, et.al, PRD108(2023)036026

$\Rightarrow$ FSI is important for the CP violation in both B and D decays

I. Bediaga et.al, PPNP114(2020)103808

$\Rightarrow$ FSI enhance CPV in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ processes

I. Bediaga, et.al, PRL131(2023)051802

$\Rightarrow$ The one-loop approximation of FSI in B decays

H.Y. Cheng, et.al, PRD72(2005)014006, C. Smith EPJC33(2004)523,…

- FSI in B decays

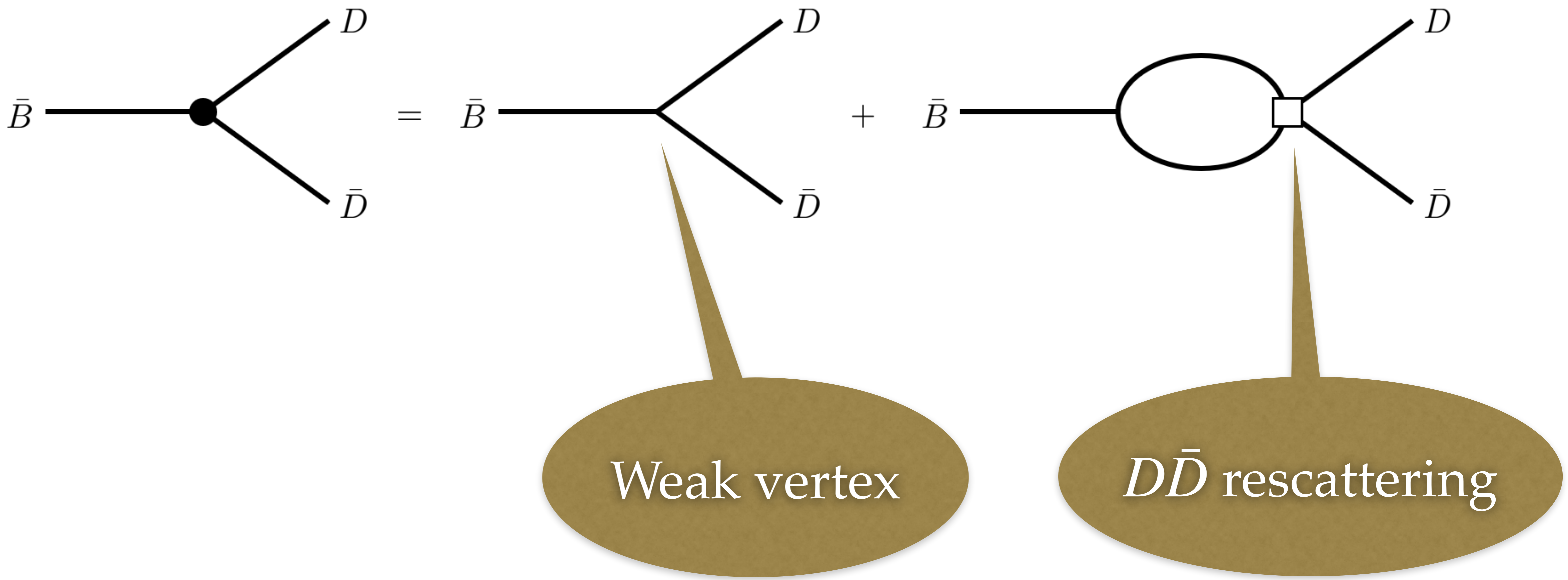
$$\mathscr{A}_{\rm CP}^{\rm dir}\left(\bar{B}^0 \to D_s^- D^+\right) = 0.0009 \pm 0.0053 \pm 0.0040$$

$$\mathscr{A}_{\rm CP}^{\rm dir}\left(\bar{B}_s^0 \to D_s^+ D^-\right) = 0.103 \pm 0.053 \pm 0.010$$

$\Rightarrow$ $m_P \to m_D$, phase space is sufficient small

$\Rightarrow$ Take advantage of the recent experimental measurements LHCb, arXiv:2603.28132

Motivation



$\bar{B}$
D
$\bar{D}$
$=$
$\bar{B}$
D
$\bar{D}$
$+$
$\bar{B}$
D
$\bar{D}$
Weak vertex
$D\bar{D}$ rescattering

Weak vertex

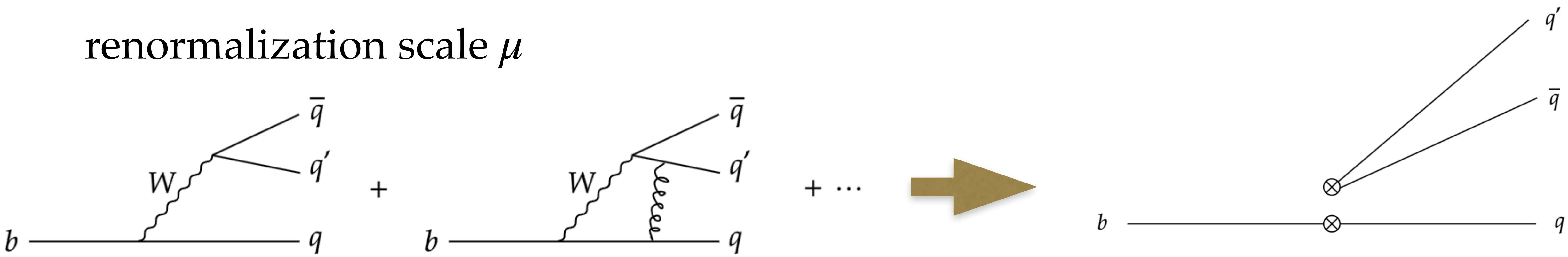
- Weak Effective Hamiltonian

$$H_{\text{eff}} = \frac{G_E}{\sqrt{2}} V^*_{qb} V_{qq'} \left(C_1(\mu)\mathcal{O}_1 + C_2(\mu)\mathcal{O}_2 \right)$$

$$\mathcal{O}_1 = \left(\bar{q}'_\alpha q_\beta\right)_{V-A} \left(\bar{q}_\beta b_\alpha\right) \quad q = (u, c)$$

$$\mathcal{O}_2 = \left(\bar{q}'_\alpha q_\alpha\right)_{V-A} \left(\bar{q}_\beta b_\beta\right) \quad q' = (d, s)$$

  - $C_1(\mu)$ and $C_2(\mu)$ are Wilson coefficients encoded physics larger than the renormalization scale μ



  - The coefficients of other eight penguin operators are much smaller (neglected)

- Decay Amplitude

A.J. Buras, et.al, NPB569(2000)3, M. Ciuchini, et.al, NPB501(1997)271

$$\mathcal{M}(B \to F) = \frac{G}{\sqrt{2}} V^*_{qb} V_{qq'} \sum_{n=1,2} C_n(\mu) \langle B | \mathcal{O}_n(\mu) | F \rangle$$

  - $\langle B | \mathcal{O}_n(\mu) | F \rangle$ hadronic matrix elements

Weak vertex

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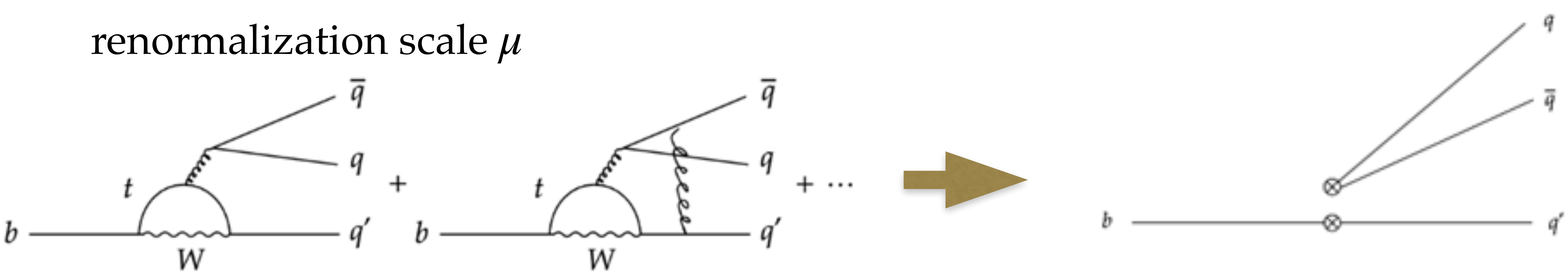

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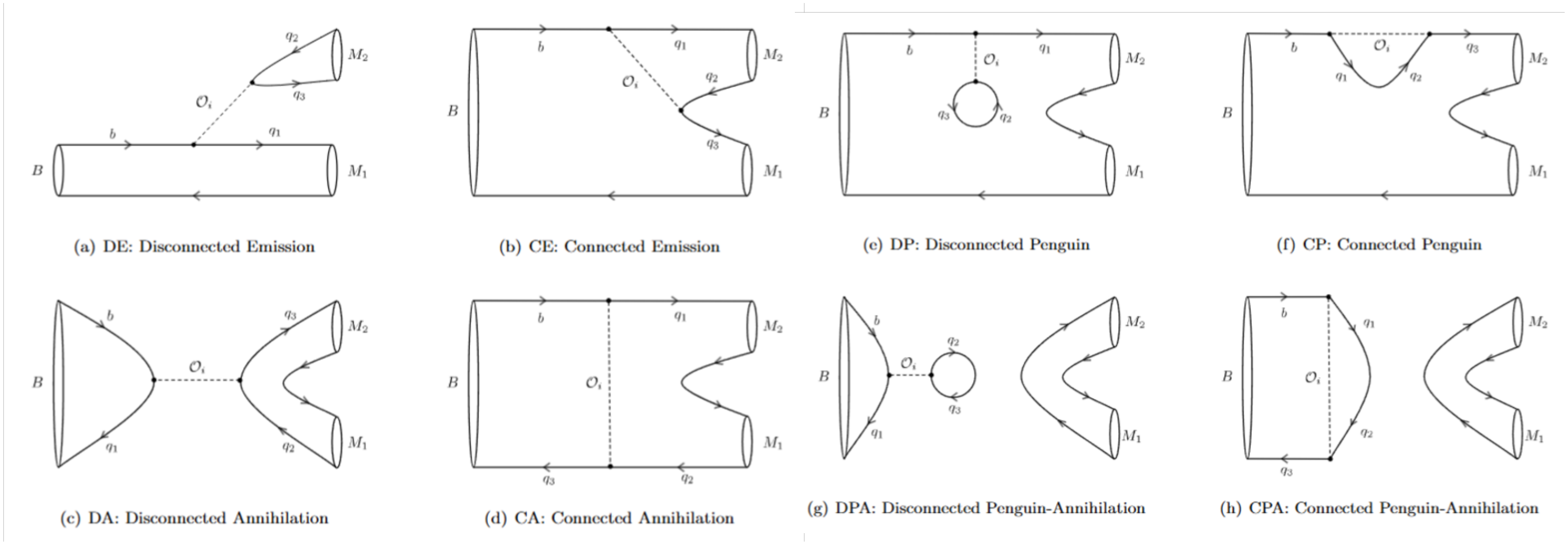
Weak vertex

- Different topologies of the matrix element



(a) DE: Disconnected Emission

(b) CE: Connected Emission

(e) DP: Disconnected Penguin

(f) CP: Connected Penguin

(c) DA: Disconnected Annihilation

(d) CA: Connected Annihilation

(g) DPA: Disconnected Penguin-Annihilation

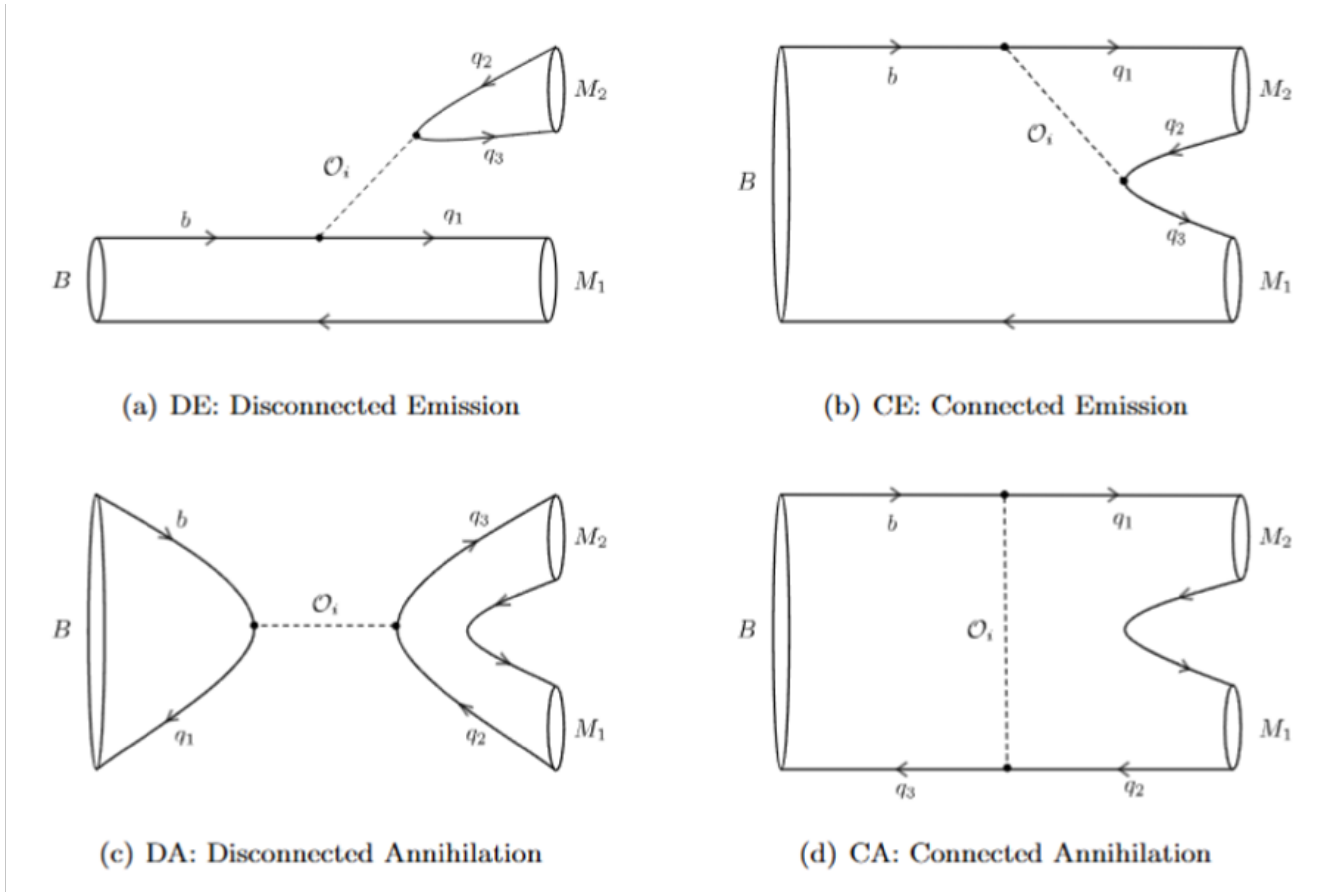
(h) CPA: Connected Penguin-Annihilation

- Eight topologies contribute to the $B_{(s)}$ to a pair of charmed mesons

Andrzej J. Buras and Luca Silvestrini, NPB 569 (2000) 3-52

Weak vertex

- Different topologies of the matrix element



$$E^c = C_1(\mu)\left\langle O_1(\mu)\right\rangle^c_{\mathrm{CE}} + C_2(\mu)\left\langle O_2(\mu)\right\rangle^c_{\mathrm{DE}}$$

$$A^c = C_1(\mu)\left\langle \mathcal{O}_1(\mu)\right\rangle^c_{\mathrm{DA}} + C_2(\mu)\left\langle \mathcal{O}_2(\mu)\right\rangle^c_{\mathrm{CA}}$$

- Eight topologies contribute to the $B_{(s)}$ to a pair of charmed mesons
- Different operators contribute to different topology diagrams

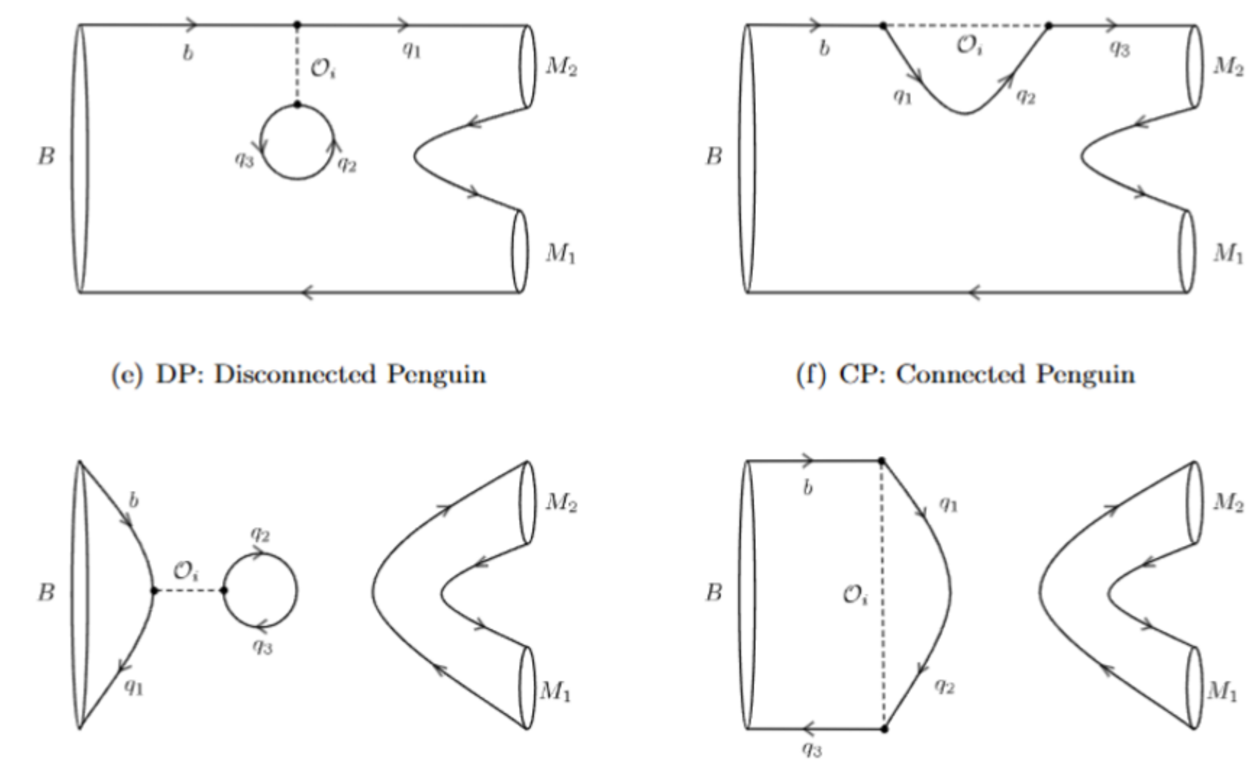
Andrzej J. Buras and Luca Silvestrini, NPB 569 (2000) 3-52

Weak vertex

- Different topologies of the matrix element

$$P^q = C_1(\mu)\left\langle \mathcal{O}_1(\mu)\right\rangle^q_{\mathrm{DP}} + C_2(\mu)\left\langle \mathcal{O}_2(\mu)\right\rangle^q_{\mathrm{CP}}$$

$$PA^q = C_1(\mu)\left\langle \mathcal{O}_1(\mu)\right\rangle^q_{\mathrm{DPA}} + C_2(\mu)\left\langle \mathcal{O}_2(\mu)\right\rangle^q_{\mathrm{CPA}}$$



(e) DP: Disconnected Penguin

(f) CP: Connected Penguin

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(h) CPA: Connected Penguin-Annihilation

- Eight topologies contribute to the $B_{(s)}$ to a pair of charmed mesons
- Different operators contribute to different topology diagrams
- For $B_{(s)} \to D\bar{D}$ process, only three combinations of those parameters appear

Andrzej J. Buras and Luca Silvestrini, NPB 569 (2000) 3-52

Weak vertex

- Bare decay amplitudes

$$T \equiv E^c + P^c, \quad A \equiv A^c + PA^c, \quad P \equiv P^u$$

Channel	Amplitude	Channel	Amplitude
$B^- \to D^0 D^-$	$Y_{cd}T + Y_{ud}P$	$\bar{B}^0 \to D_s^+ D_s^-$	$Y_{cd}A$
$B^- \to D^0 D_s^-$	$Y_{cs}T + Y_{us}P$	$\bar{B}_s^0 \to D^+ D^-$	$Y_{cs}A$
$\bar{B}^0 \to D^+ D^-$	$Y_{cd}(T + A) + Y_{ud}P$	$\bar{B}_s^0 \to D_s^+ D_s^-$	$Y_{cs}(T + A) + Y_{us}P$
$\bar{B}^0 \to D^+ D_s^-$	$Y_{cs}T + Y_{us}P$	$\bar{B}_s^0 \to D^0 \bar{D}^0$	$Y_{cs}A$
$\bar{B}^0 \to D^0 \bar{D}^0$	$Y_{cd}A$	$\bar{B}_s^0 \to D_s^+ D^-$	$Y_{cd}T + Y_{ud}P$

- Under CPT symmetry, the direct

$$A_{\rm CP}(\bar{B} \to F) \equiv \frac{\Gamma(\bar{B} \to F) - \Gamma(B \to F)}{\Gamma(\bar{B} \to F) + \Gamma(B \to F)}$$

$$A_{CP}\left(\bar{B}^0 \to D^0\bar{D}^0\right) = 0$$

$$A_{CP}\left(\bar{B}^0 \to D^+D^-\right) = \frac{2R\delta_p \sin\gamma}{1 + R^2 - 2R\cos\gamma} + \dots$$

$$A_{CP}\left(\bar{B}^0 \to D_s^+D_s^-\right) = 0$$

$$Y_{qq'} \equiv V_{qb}^* V_{qq'}$$

$$r \equiv |A|/|T|, R \equiv |Y_{ud}/Y_{cd}|,$$

$$\gamma \equiv \arg(-Y_{ud}/Y_{cd}), |T| \simeq |P|$$

$D\bar{D}$ rescattering

- LO $D\bar{D}$ interactions with respecting HQSS

$$\mathscr{L}_{4H} = \frac{1}{4}\,\mathrm{Tr}\left[\bar{H}^{(Q)a}H_b^{(Q)}\gamma_\mu\right]\mathrm{Tr}\left[H^{(\bar{Q})c}\bar{H}_d^{(\bar{Q})}\gamma^\mu\right]\left(F_A\delta_a^b\delta_c^d + F_A^\lambda\vec{\lambda}_a^b\cdot\vec{\lambda}_c^d\right)$$

$$+\frac{1}{4}\,\mathrm{Tr}\left[\bar{H}^{(Q)a}H_b^{(Q)}\gamma_\mu\gamma_5\right]\mathrm{Tr}\left[H^{(\bar{Q})c}\bar{H}_d^{(\bar{Q})}\gamma^\mu\gamma_5\right]\left(F_B\delta_a^b\delta_c^d + F_B^\lambda\vec{\lambda}_a^b\cdot\vec{\lambda}_c^d\right)$$

$$= v^2 P^{(Q)a\dagger}P_b^{(Q)}P^{(\bar{Q})c}P_d^{(\bar{Q})\dagger}(F_A\delta_a^b\delta_c^d + F_A^\lambda\vec{\lambda}_a^b\cdot\vec{\lambda}_c^d) + \cdots$$

M.B. Wise, PRD45(1992)R2188, M.T. AlFiky, et.al, PLB640(2006)238, T. Ji, et.al, PRD106(2022)094002

- The super field

$$H_a^{(Q)} = \frac{1+\not{v}}{2}(V_{a\mu}^{(Q)}\gamma^\mu - P_a^{(Q)}\gamma_5), \quad v\cdot V_a^{(Q)} = 0,$$

$$H_a^{(\bar{Q})} = (V_{a\mu}^{(\bar{Q})}\gamma^\mu - P_a^{(\bar{Q})}\gamma_5)\frac{1-\not{v}}{2}, \quad v\cdot V_a^{(\bar{Q})} = 0,$$

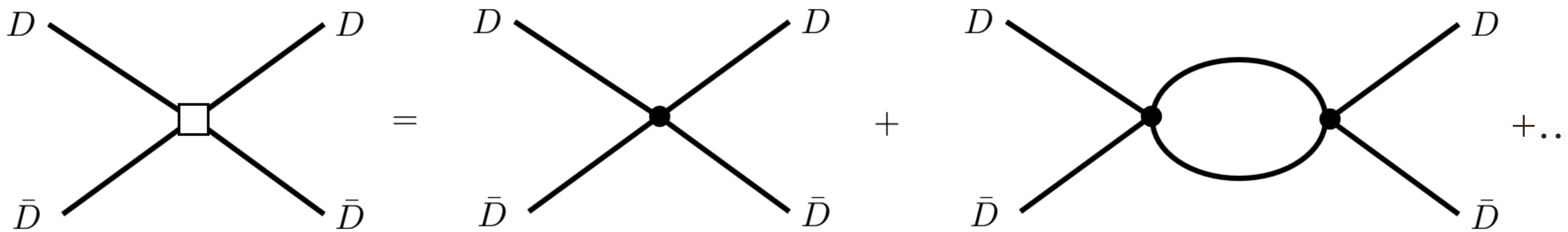
- S-wave $D\bar{D}$ contact potential

$$V_{\mathrm{CT}} = \begin{pmatrix} F_A + \frac{4}{3}F_A^\lambda & 2F_A^\lambda & 2F_A^\lambda \\ 2F_A^\lambda & F_A + \frac{4}{3}F_A^\lambda & 2F_A^\lambda \\ 2F_A^\lambda & 2F_A^\lambda & F_A + \frac{4}{3}F_A^\lambda \end{pmatrix}$$

- F_A and F_A^λ low-energy constants to be fitted from the $D\bar{D}$ scattering

$D\bar{D}$ rescattering

- LSE of $D\bar{D}$ scattering



- $\gamma\gamma \to D\bar{D}$ bare production amplitude

$$\mathscr{C}_i = (r\mathrm{U}, \mathrm{U}, \mathrm{U})$$

$$D^0\bar{D}^0, D^+D^-, D_s^+D_s^-$$

- The $D\bar{D}$ two-body propagator

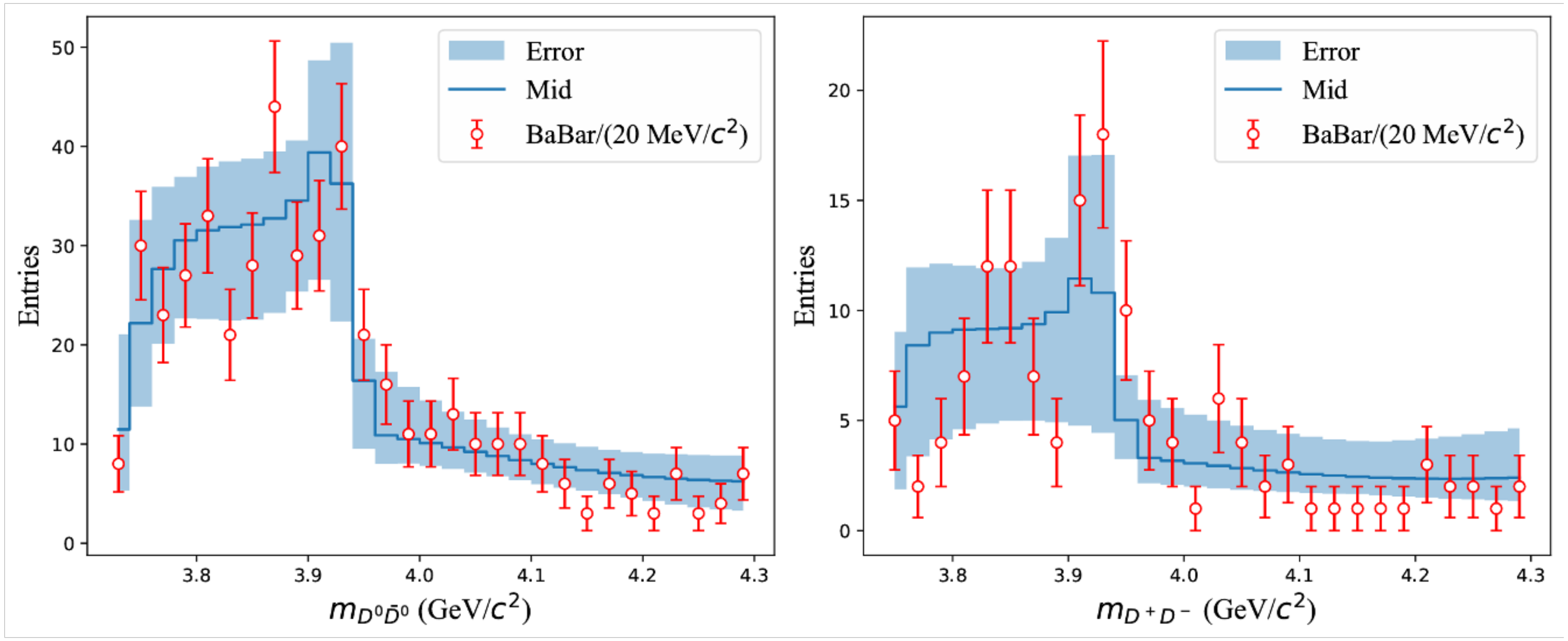
$$G_i^\Lambda(s) = -i \int \frac{d^4q}{(2\pi)^4} \frac{f^\Lambda(\mathbf{q}^2)}{(q^2 - m_i^2 + i\epsilon)[(P-q)^2 - m_i^2 + i\epsilon]}$$

$$= \frac{1}{4m_i^2}\left[\frac{\mu_i\Lambda}{(2\pi)^{3/2}} - \frac{\mu_i k_i}{2\pi} e^{-\frac{2k_i^2}{\Lambda^2}}\left(\mathrm{erfi}\left(\frac{\sqrt{2}k_i}{\Lambda}\right) - i\right)\right]$$

- The physical production amplitude $\mathscr{M}\left(\gamma\gamma \to D^i\bar{D}^i\right) = \mathscr{C}_j G_j^\Lambda(s) T_{ji}(s) + \mathscr{C}_i$

$D\bar{D}$ rescattering

- The fitted $D\bar{D}$ invariant mass



BaBar, PRD81(2010)092003

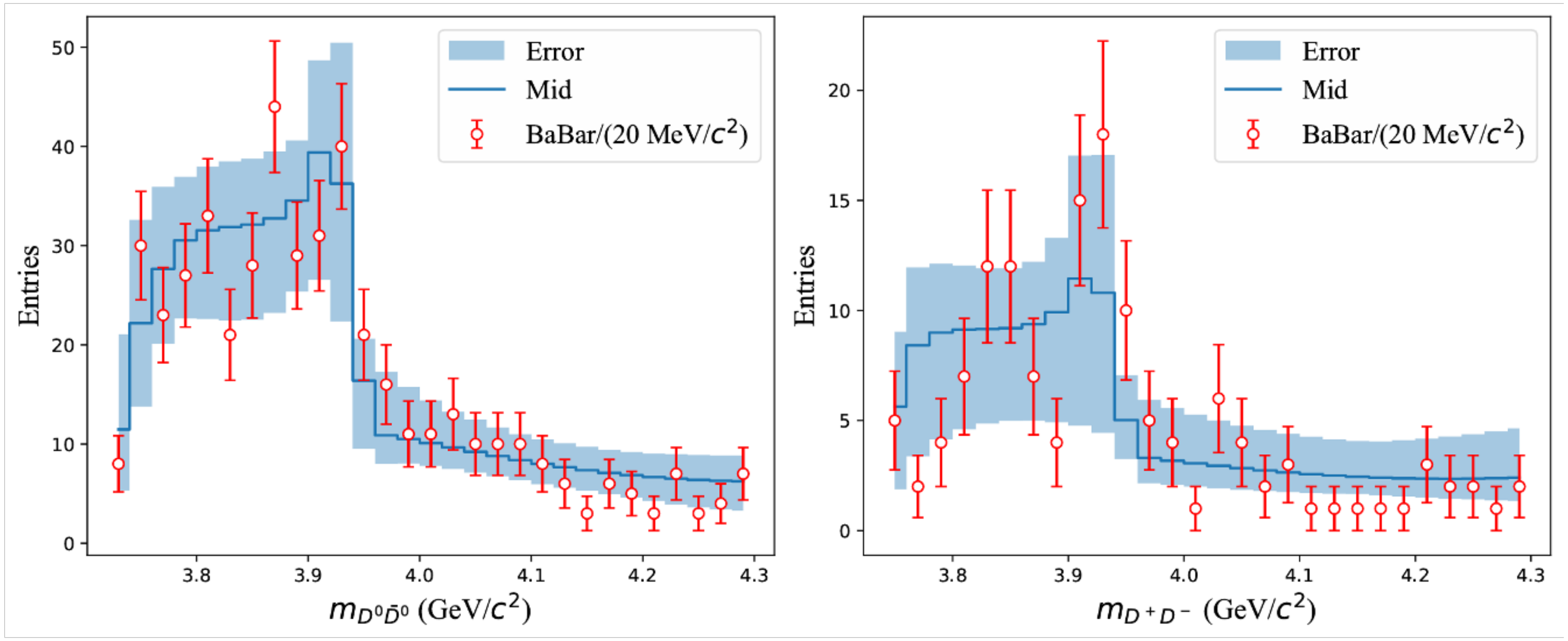
- The fitted parameters

Parameters	F_A (GeV^{-2})	F_A^λ (GeV^{-2})	Λ (GeV)	U (GeV^{-2})	r (GeV^0)	a (GeV^{-1})
Value	45.143 ± 39.667	-12.232 ± 7.646	1.942 ± 0.251	307.547 ± 33.112	0.823 ± 0.150	0.284 ± 0.036

- The errors are obtained by bootstrap
- $r < 1 \Rightarrow$ The magnetic force is typically much weaker than the electric force

$D\bar{D}$ rescattering

- The fitted $D\bar{D}$ invariant mass



BaBar, PRD81(2010)092003

- The poles

RSs	$+++$	$-++$	$--+$	$---$
E	3.65	$3.76 \pm 0.003i$	3.73 $3.94 \pm 0.003i$	3.73

- The $3.94 \pm 0.003i$ pole has physical impact.

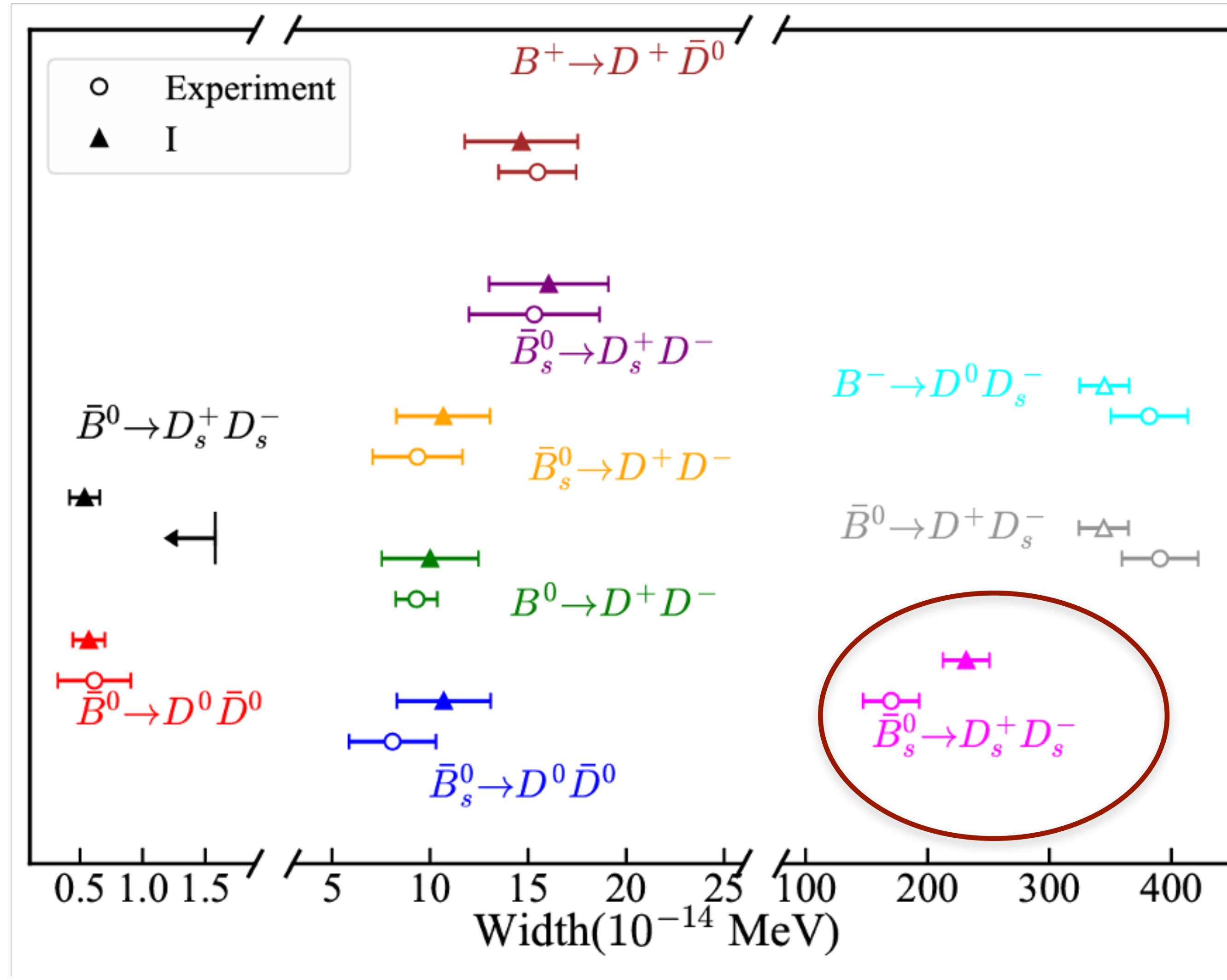
Results and Discussions

- Fit schemes
  - Scheme I: without FSI, fit to widths
  - Scheme II: with FSI, fit to widths
  - Scheme III, with FSI, fit to widths

  and A_{CP} of the channels

  $B^- \to D^- D^0 \quad B^- \to D^0 D_s^-$

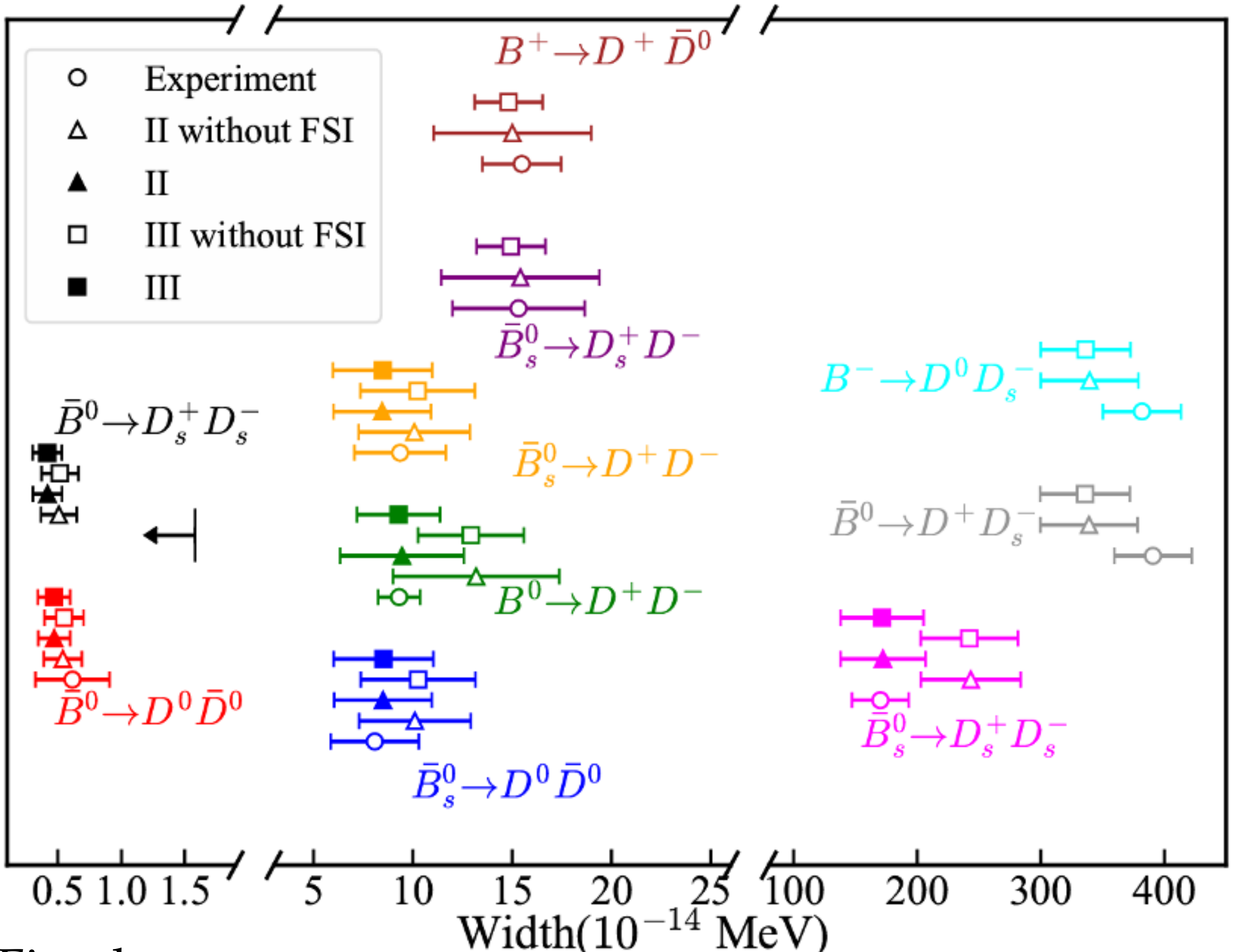
  $\bar{B}^0 \to D^+ D_s^- \quad \bar{B}_s^0 \to D_s^+ D^-$



- Scheme I: quark-level calculation cannot describe the $\bar{B}_s^0 \to D_s^+ D_s^-$ channel

Results and Discussions

- widths



- Errors in Scheme III is smaller than those of Scheme II
- The reduced chi-square becomes smaller
- FSI increase widths

- Fitted parameters

Schemes	$\|T\|$ [MeV]	$\|A\|$ [MeV]	$\|P\|$ [MeV]	δ_a[rad]	δ_p[rad]	χ^2/d. o. f
I	$(2.78 \pm 0.07) \times 10^{-2}$	$(4.88 \pm 0.54) \times 10^{-3}$	$(3.86 \pm 1.05) \times 10^{-2}$	3.25 ± 0.08	$(0.52 \pm 1.54) \times 10^{-1}$	2.30
II	$(2.76 \pm 0.16) \times 10^{-2}$	$(4.74 \pm 0.66) \times 10^{-3}$	$(4.06 \pm 0.99) \times 10^{-2}$	2.59 ± 0.37	$(0.23 \pm 1.91) \times 10^{-1}$	1.15
III	$(2.74 \pm 0.14) \times 10^{-2}$	$(4.78 \pm 0.67) \times 10^{-3}$	$(3.69 \pm 0.99) \times 10^{-2}$	2.55 ± 0.38	$(1.60 \pm 2.27) \times 10^{-2}$	1.00

Results and Discussions

- The reasonability of the parameters

Schemes	$\|T\|$ [MeV]	$\|A\|$ [MeV]	$\|P\|$ [MeV]	δ_a[rad]	δ_p[rad]	χ^2/d. o. f
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- The emission diagram is parameterized as

$$E \sim \frac{G_F}{\sqrt{2}} a_2 F^{B\to D}(m_D^2) f_D (m_B^2 - m_D^2) \sim 0.03 \text{ MeV} \quad \text{with} \quad F^{B\to D}(m_D^2) = \frac{F^{B\to D}(0)}{1 - \alpha_1 \frac{m_D^2}{m_{\text{pole}}^2} + \alpha_2 \frac{m_D^4}{m_{\text{pole}}^4}}$$

$$\alpha_1 = 1.71, \quad \alpha_2 = 0.52, \quad m_{\text{pole}} = m_B \qquad a_{1,2} = C_{1,2} + \frac{C_{2,1}}{N_c} = 0.090, 1.036$$

S.H. Zhou, et.al, PRD92(2015)094016, S.H. Zhou, et.al, PRD110(2024)056001

- The annihilation diagram cannot be calculated in quark-level, but estimated as

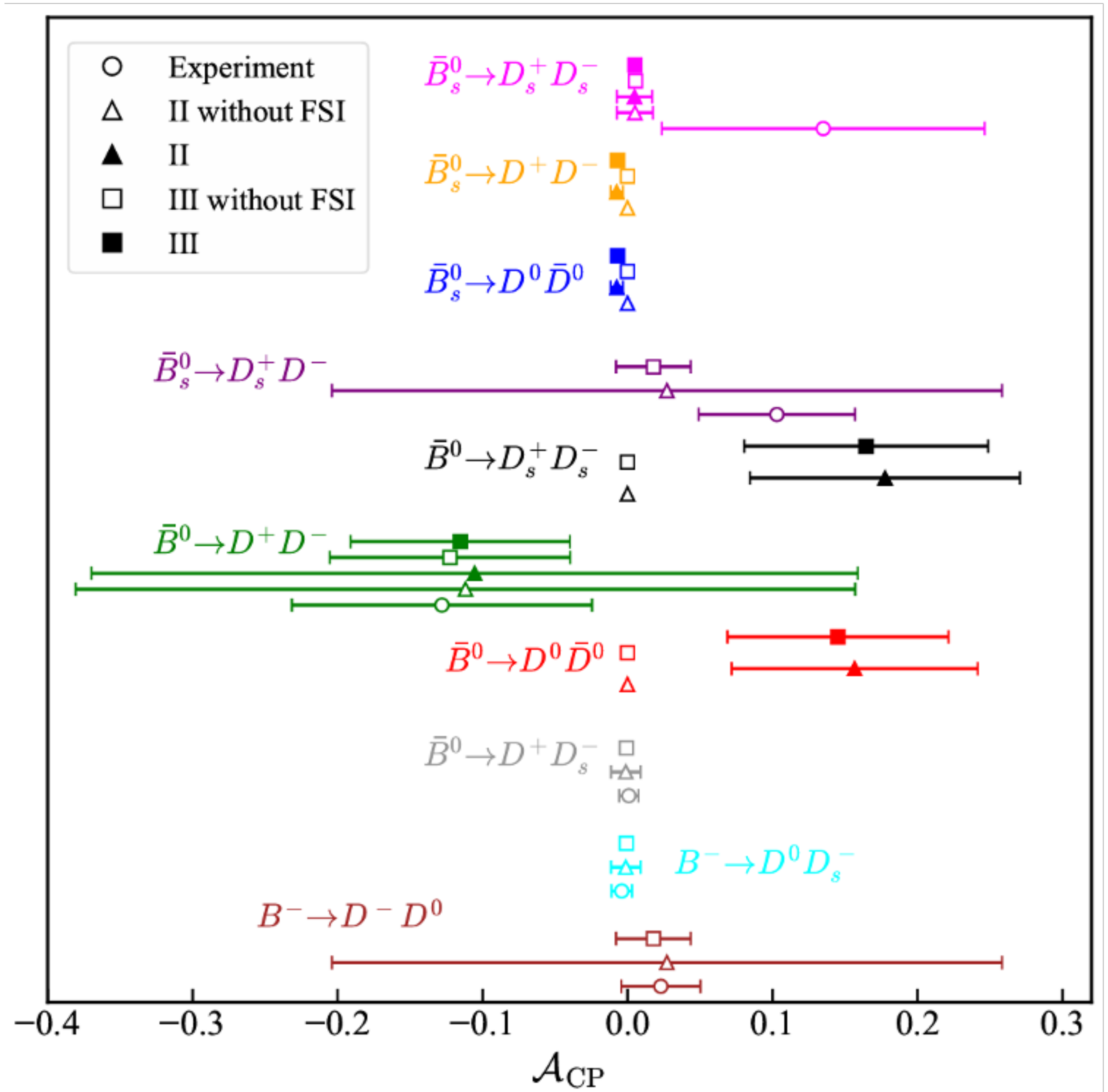
$$A \sim \frac{G_F}{\sqrt{2}} a_1 f_B f_{\chi_{c0}} g_{\chi_{c0} D\bar{D}} \frac{m_B^2 m_{\chi_{c0}}}{m_B^2 - m_{\chi_{c0}}^2} \sim 0.002 \text{ MeV}$$

Y.F. Sheng, et.al, PRD84(2011)074019, P. Colangelo, et.al, PRD69(2004)054023, PLB542(2002)71,

J. Ou-Yang, et.al, PRD112(2025)056005

Results and Discussions

- $A_{\rm CP}$



- $A_{\rm CP}$ without FSI

$$A_{CP}\left(\bar{B}^0 \to D^0 \bar{D}^0\right) = 0$$

$$A_{CP}\left(\bar{B}^0 \to D^+ D^-\right) = \frac{2R\delta_p \sin\gamma}{1 + R^2 - 2R\cos\gamma} +$$

$$A_{CP}\left(\bar{B}^0 \to D_s^+ D_s^-\right) = 0$$

- $A_{\rm CP}$ with FSI

$$A_{\rm CP}(\bar{B}^0 \to D^0 \bar{D}^0) \simeq f(\delta_p + \Delta^1_{12} + \Delta^1_{32} - \Delta^1_{22}),$$

$$A_{\rm CP}(\bar{B}^0 \to D^+ D^-) \simeq f(\delta_p + \Delta^2_{12} + \Delta^2_{32}),$$

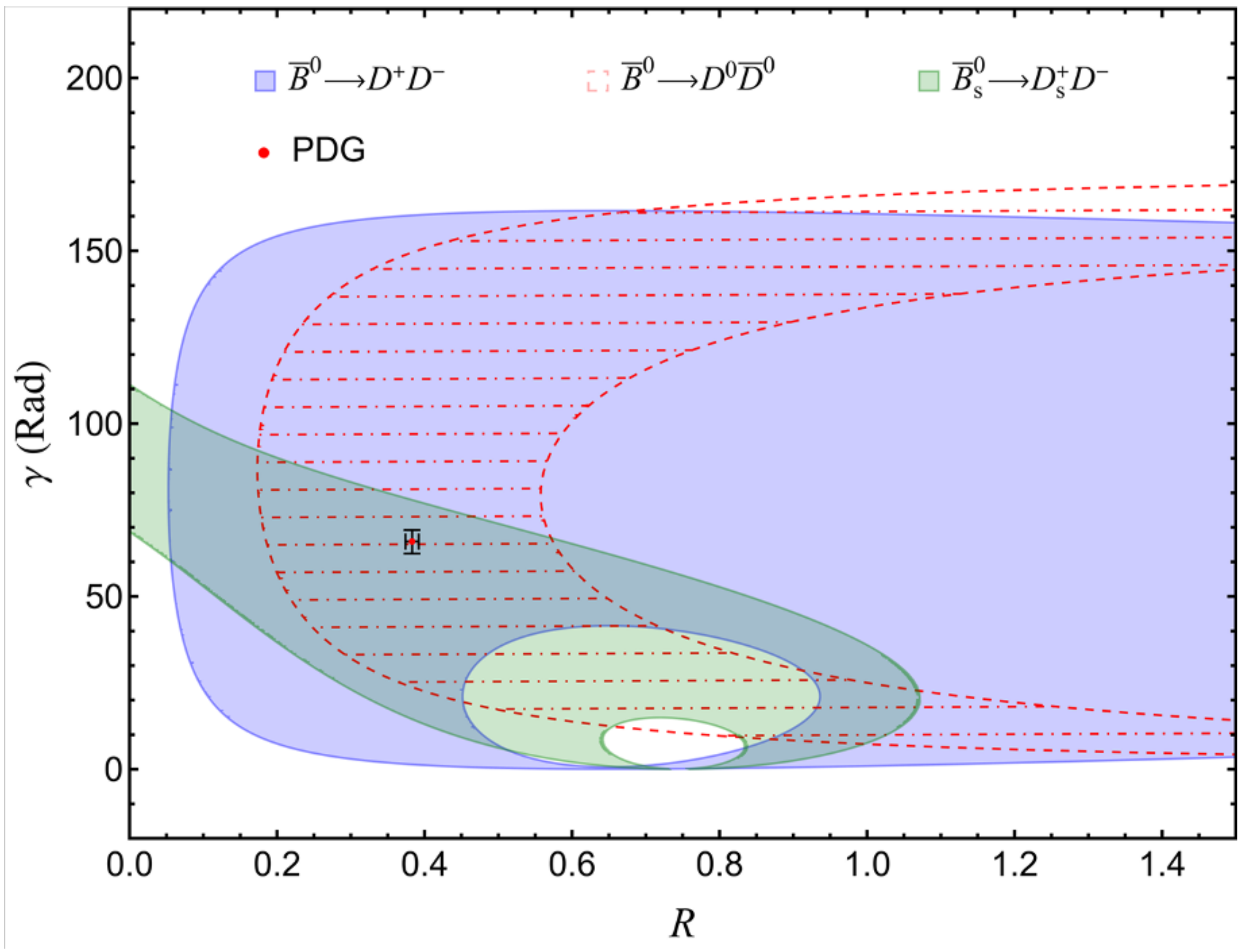
$$A_{\rm CP}(\bar{B}^0 \to D_s^+ D_s^-) \simeq f(\delta_p + \Delta^3_{12} + \Delta^3_{32} - \Delta^3_{22}),$$

$$f \equiv \frac{2R\sin\gamma}{1 + R^2 - 2R\cos\gamma}$$

- FSI significantly enhance the $A_{\rm CP}$ of the channels with only annihilation diagrams
- Predict $A_{\rm CP}$ of other channels
- Errors in III are smaller than that in II

Results and Discussions

- Precise measurements of A_{CP} can be used to determine the parameters in SM



- Filled band: Exp.
- Dashed band: Theory
- FSI makes channels with only annihilation diagrams can also be used for determine the parameters in SM

Summary and Outlook

- Summary
  - A comprehensive study of B decay to a pair of charmed mesons with FSI
  - Predict partial widths and asymmetries
  - A non-zero asymmetry of the channels solely governed by annihilation diagrams $\Rightarrow$ the importance of FSI
  - Any solid signals BSM should precisely deal with FSI

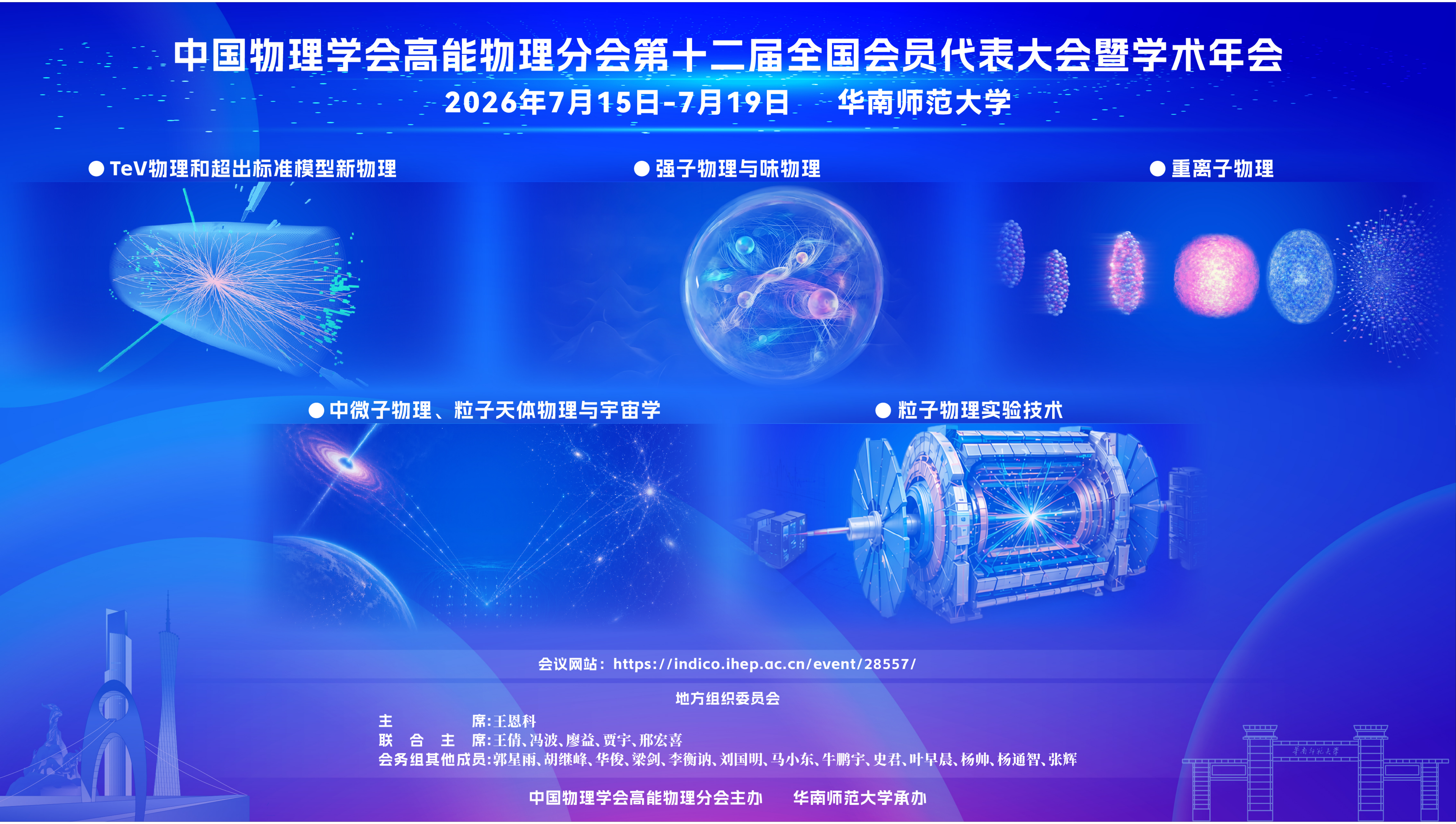
- Outlook
  - What do we expect from $\gamma\gamma$ fusion process?

    $\sigma(\gamma\gamma \to D^0\bar{D}^0), \sigma(\gamma\gamma \to D^+D^-), \sigma(\gamma\gamma \to D_s^+D_s^-)$

    $D\bar{D} - D^*\bar{D}^*$ coupled channel in 0^+ quantum number

    $\sigma(\gamma\gamma \to D^{*0}\bar{D}^{*0}), \sigma(\gamma\gamma \to D^{*+}D^{*-}), \sigma(\gamma\gamma \to D_s^{*+}D_s^{*-})$
  - What do we expect from BelleII and LHCb?

    $A_{\rm CP}(\bar{B}^0 \to D^0\bar{D}^0), A_{\rm CP}(\bar{B}^0 \to D_s^+D_s^-)$ $A_{\rm CP}(\bar{B}_s^0 \to D^0\bar{D}^0), A_{\rm CP}(\bar{B}_s^0 \to D^+D^-)$



Thank you very much!