

# Observation of a Threshold Enhancement in $\pi^+\pi^-$ Spectrum in $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ Decays



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重味物理与量子色动力学研讨会

# CONTENTS

**1**

**Introduction**

**2**

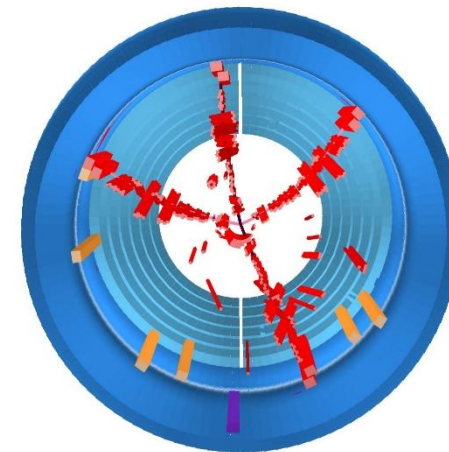
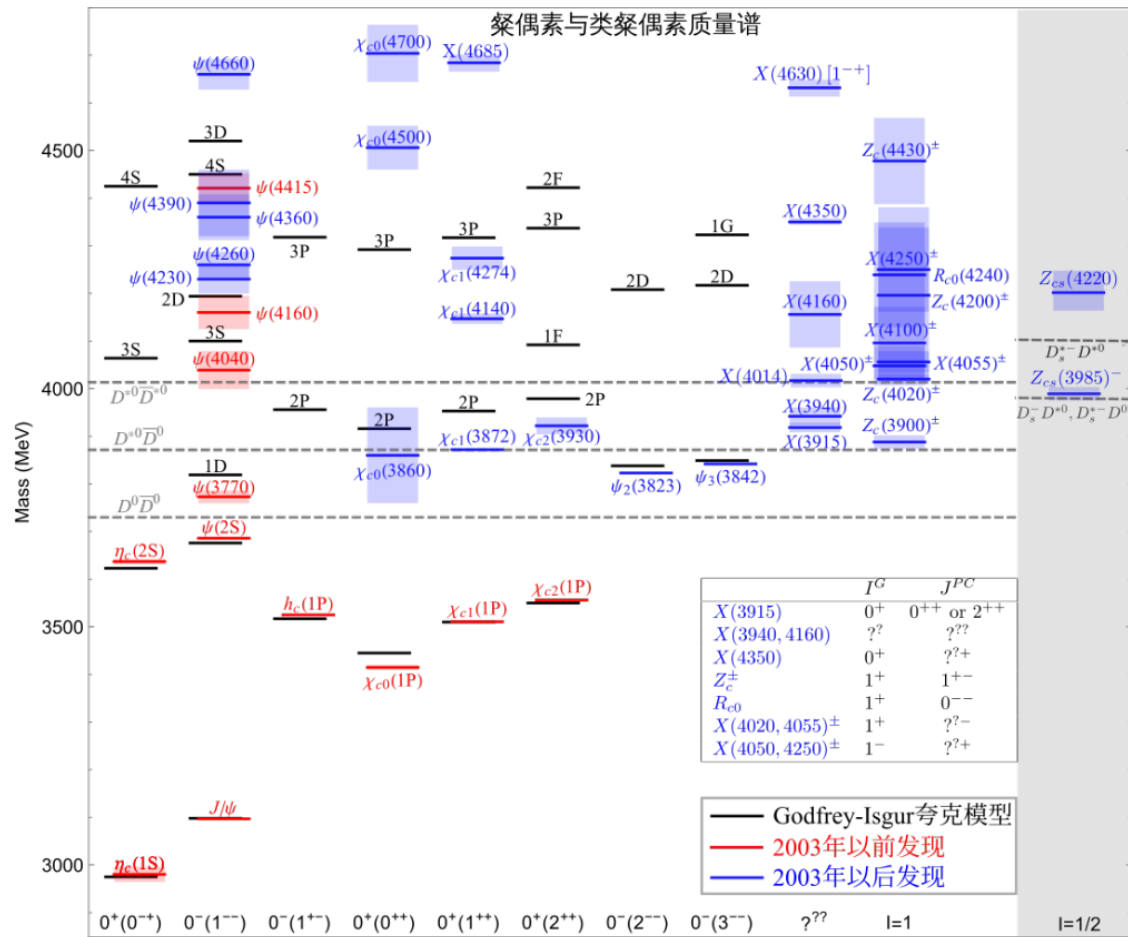
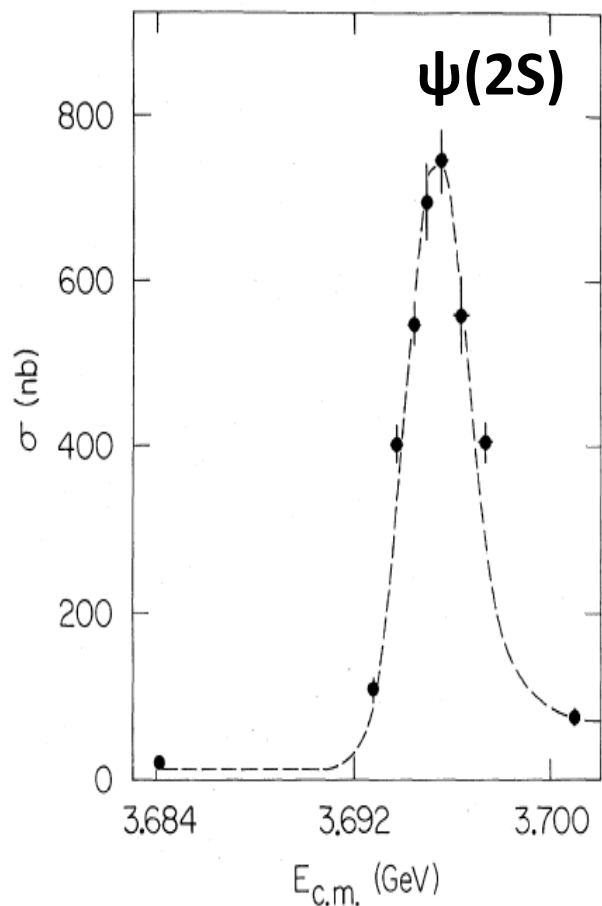
**$\pi^+ \pi^-$  threshold enhancement**

**3**

**Summary**

# Charmonium

PRL33, 1453 (1974)



A new field in HEP: Charmonium Physics

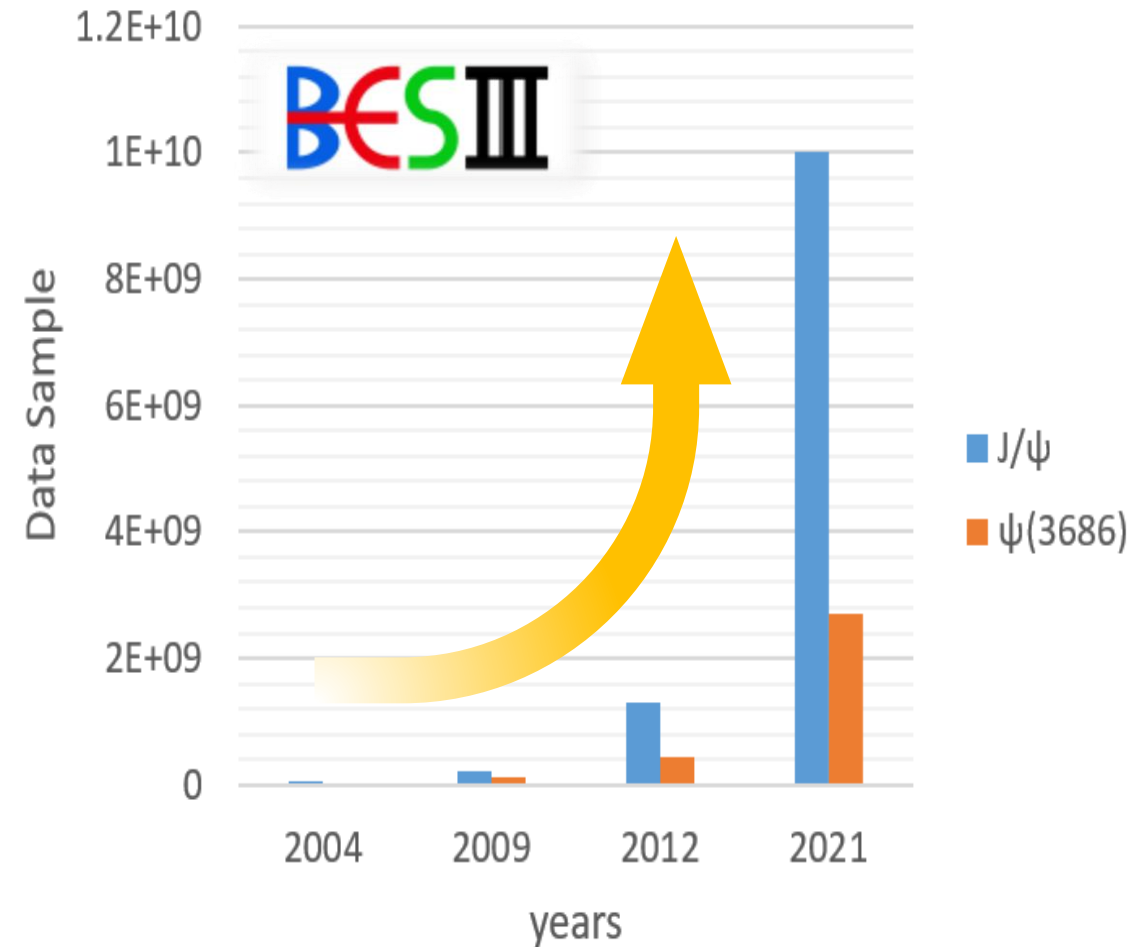
# Charmonium transition

- In recent years, BES has accumulated much large and clean statistics of  $J/\psi$ ,  $\psi(3686)$
- The transition of  $\psi(3686)$  to  $J/\psi$  are main part for  $\psi(3686)$  decay.

▼ Decays into  $J/\psi(1S)$  and anything

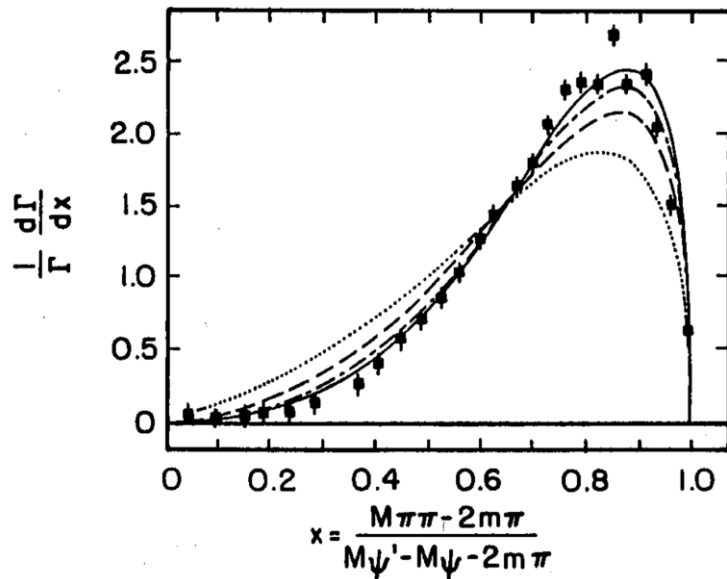
$\psi(2S)$  decays involving  $J/\psi$

$\Gamma_{10}$	$J/\psi(1S)$ anything	$(61.5 \pm 0.7) \%$
$\Gamma_{11}$	$J/\psi(1S)$ neutrals	$(25.4 \pm 0.5) \%$
$\Gamma_{12}$	$J/\psi(1S)\pi^+\pi^-$	$(34.69 \pm 0.34) \%$
$\Gamma_{13}$	$J/\psi(1S)\pi^0\pi^0$	$(18.2 \pm 0.5) \%$
$\Gamma_{14}$	$J/\psi(1S)\eta$	$(3.37 \pm 0.06) \%$
$\Gamma_{15}$	$J/\psi(1S)\pi^0$	$(1.268 \pm 0.032) \times 10^{-3}$



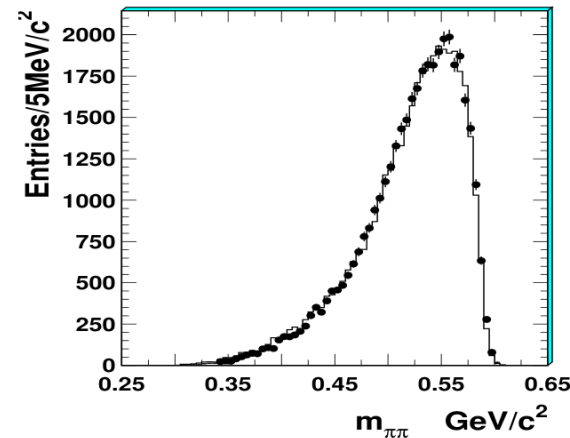
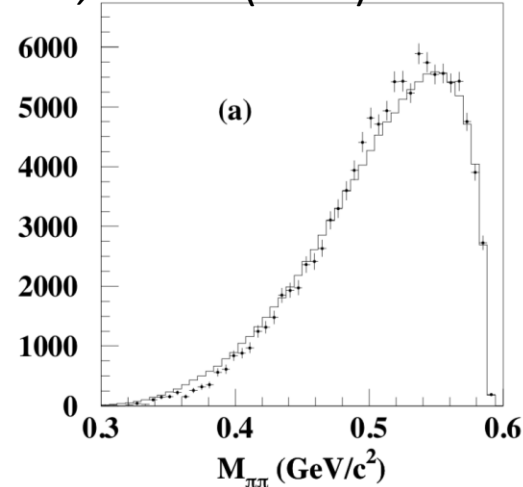
# Status of $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$

- Experimentally focusing on BF and cross section measurements
- Theoretically focusing on the shape of  $\pi\pi$  high invariant mass



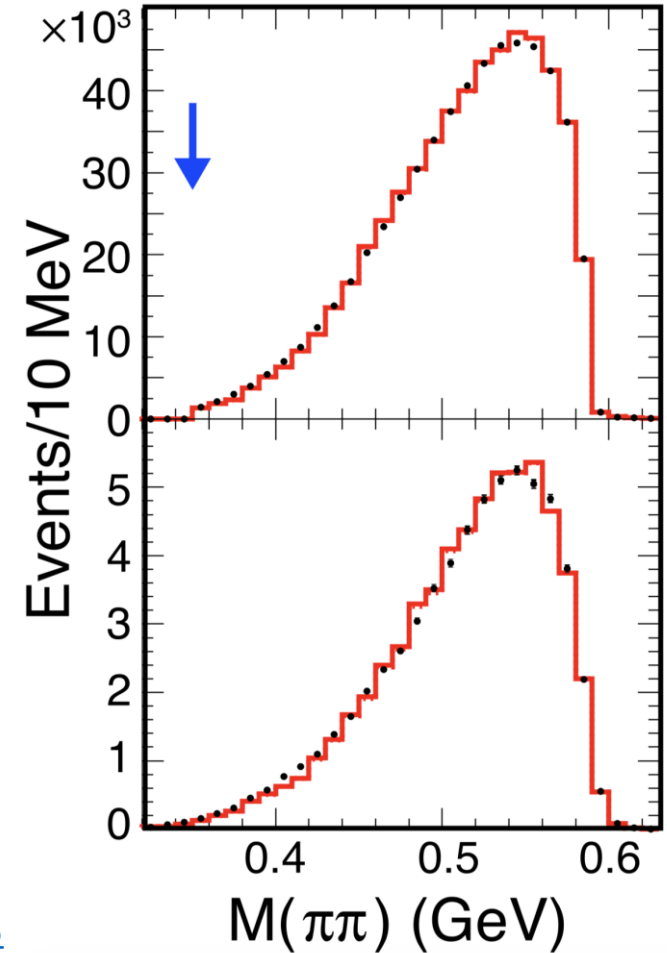
Y.P. Kuang, PRD44 (1991) 756-769

BES, PRD 62 (2000) 032002



[BES, PLB645 \(2007\) 19-25](#)

CLEO, PRD 78 (2008) 011102



# Motivation of $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$

- Mixture of Charmonium:

✓ Because of decay width of  $\frac{\Gamma_{\psi(3770) \rightarrow e^+ e^-}}{\Gamma_{J/\psi \rightarrow e^+ e^-}} \gg \frac{\Gamma_{1D \rightarrow e^+ e^-}}{\Gamma_{1S \rightarrow e^+ e^-}}$ . The observed  $\psi(3686)$  and  $\psi(3770)$  are mixtures of  $|2^3S_1 \rangle$  and  $|1^3D_1 \rangle$ :

$$\psi(3686) = |2^3S_1 \rangle \cos \theta - |1^3D_1 \rangle \sin \theta$$

$$\psi(3770) = |2^3S_1 \rangle \sin \theta + |1^3D_1 \rangle \cos \theta$$

where  $\theta$  is mixing angle.

- $\pi\pi$  transition:

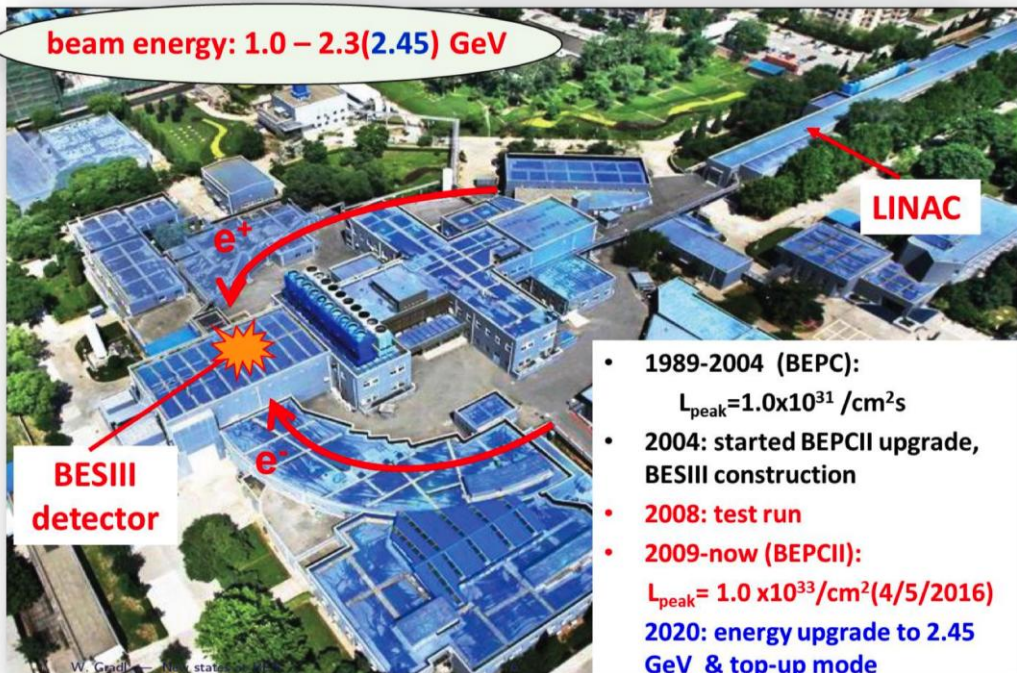
- ✓ A good place to study Chiral Symmetry and Final state interaction.
- ✓ Soft pion emission, e.g. Alder zero?
- ✓ High statistics of  $\pi\pi$  production provide chance to search for pionium.

- Test CPV and CEDM?

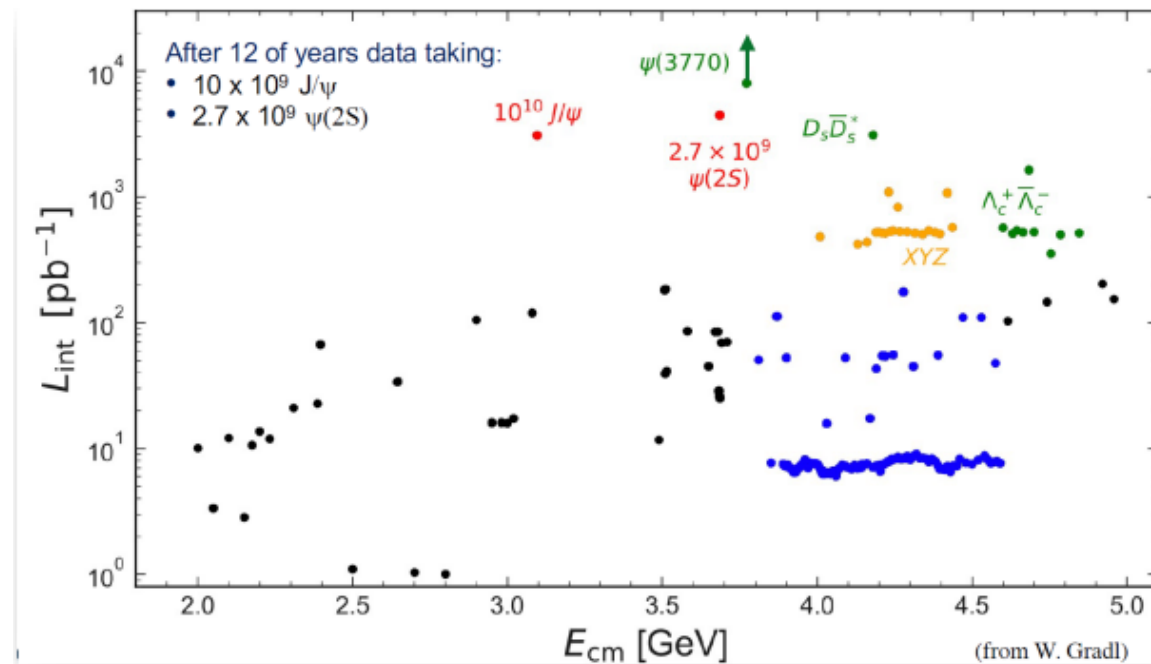
# BESIII status

## Beijing Electron Positron Collider (BEPCII)

beam energy: 1.0 – 2.3(2.45) GeV



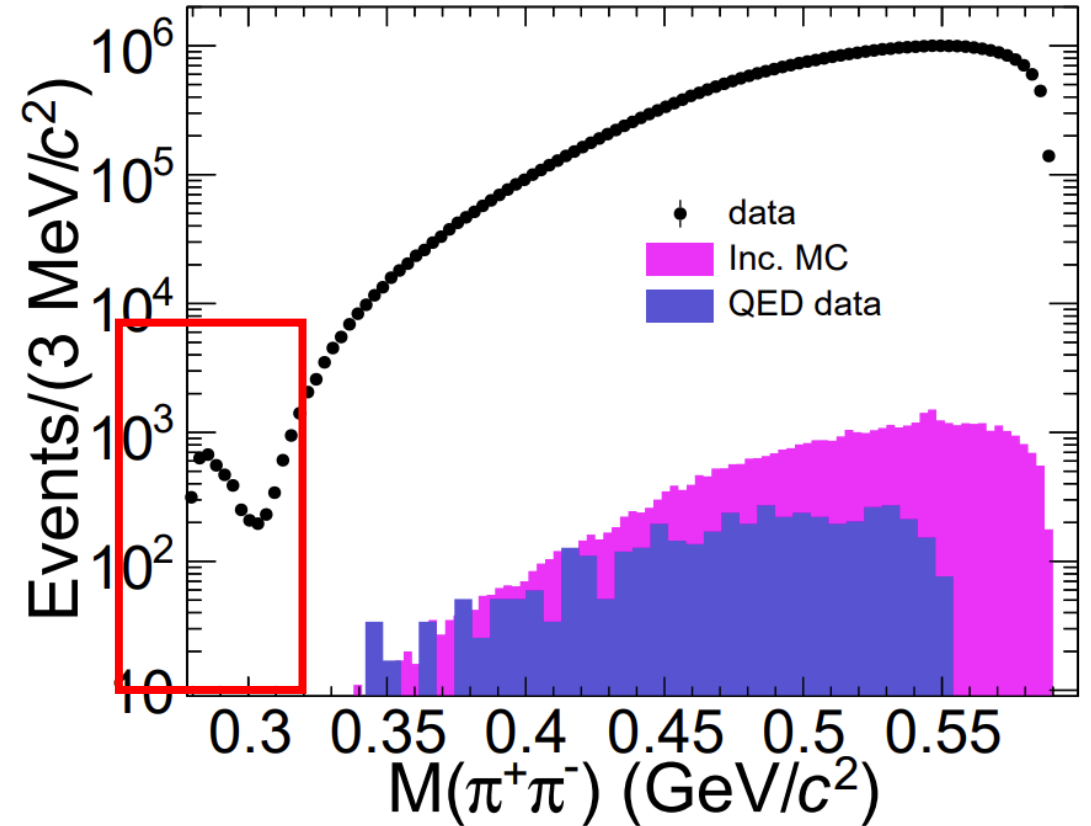
$2 \times 10^9 \psi(2S)$  events



World's Largest  $\tau$ -charm Data Sets in  $e^+ e^-$  Annihilation

# $\pi^+\pi^-$ enhancement

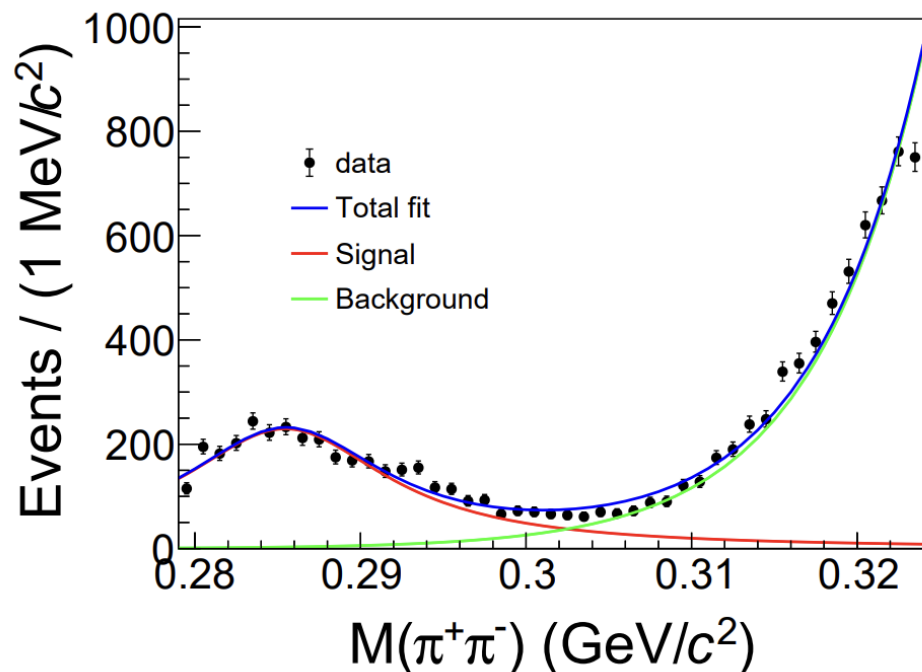
- $\psi(3686) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow l^+l^-$
- Selected  $3.7 \times 10^7$  events
- 99.8% purity



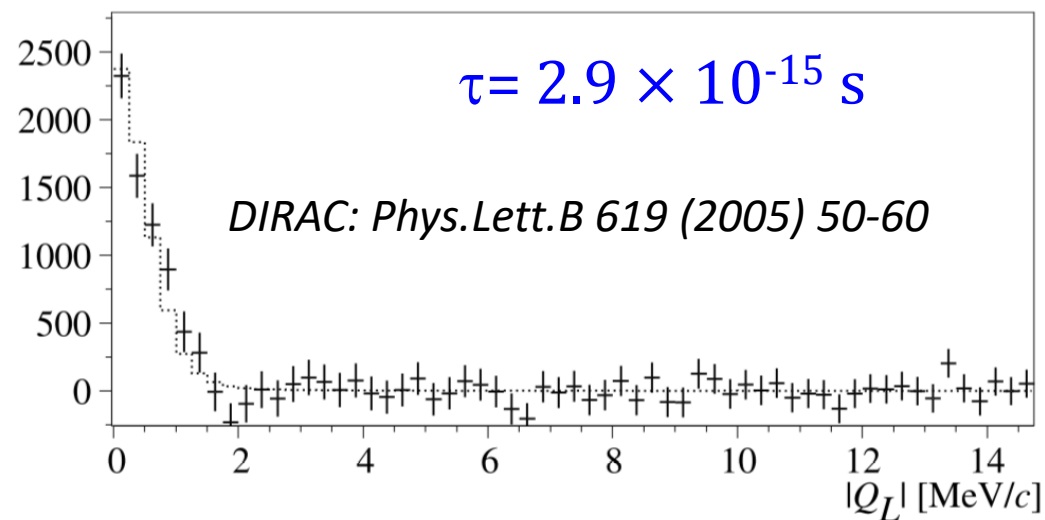
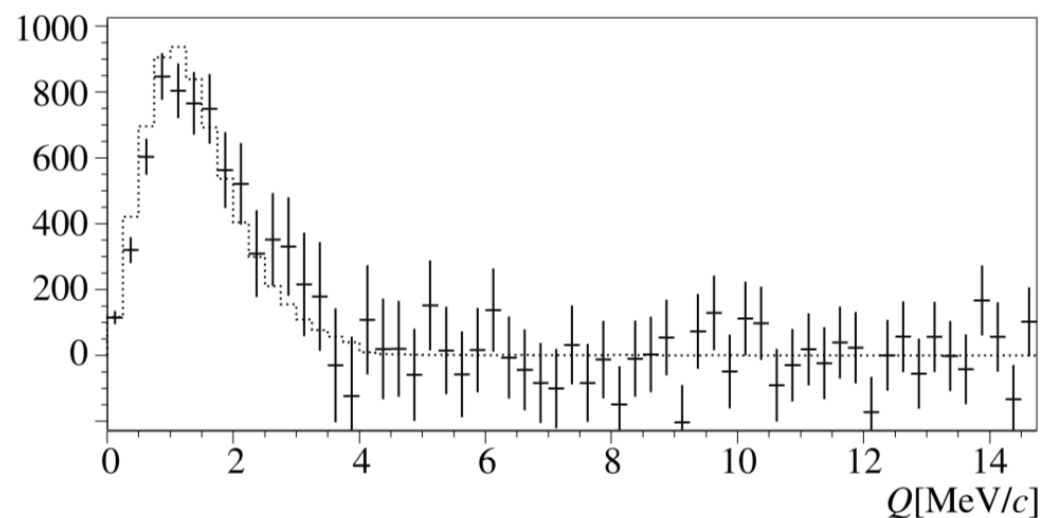
Phys. Rev. Lett. 136, 141902

**Clear  $\pi^+\pi^-$  threshold enhancement**

# Resonance model



- Take  $\pi^+\pi^-$  threshold as a resonance
- (Breit-Wigner  $\otimes$  Resolution)  $\times$  Efficiency
- $M = (285.5 \pm 2.6) \text{ MeV}/c^2$ ,  $\Gamma = (16.4 \pm 0.8) \text{ MeV}$
- $\tau = 4 \times 10^{-23} \text{ s}$ , much shorter than DIRAC !



# Theoretical model-ChPT

- ChPT:

- ✓ Heavy quark symmetry
- ✓ Chiral symmetry for  $\pi\pi$  production

- Lagrangian:

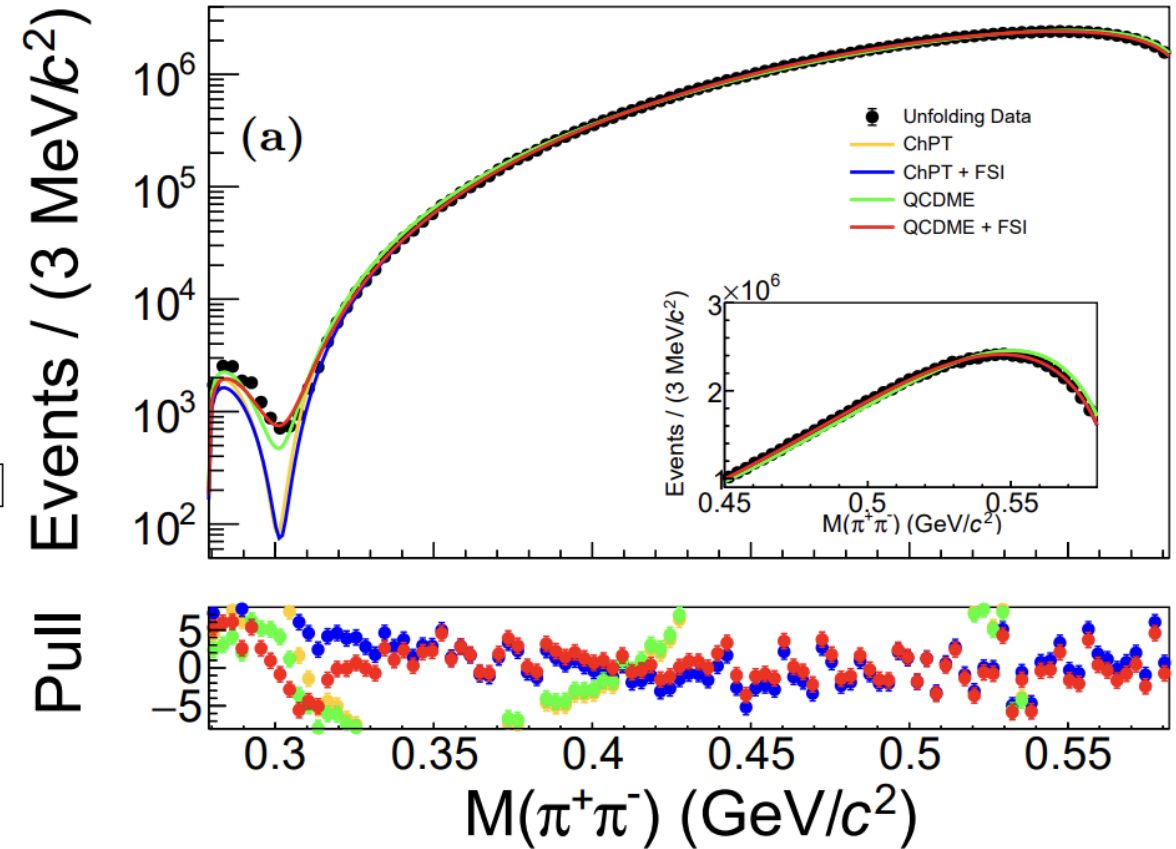
$$\mathcal{L}_0 = g_0 A_\mu^{(v)} B^{(v)\mu*} \text{Tr}[(\partial_\nu U)(\partial^\nu U)^\dagger] + g_1 A_\mu^{(v)} B^{(v)\mu*} \text{Tr}[(v \cdot \partial U)(v \cdot \partial U)^\dagger] + g_2 A_\mu^{(v)} B^{(v)\mu*} \text{Tr}[(\partial^\mu U)(\partial^\nu U)^\dagger + (\partial^\mu U)^\dagger(\partial^\nu U)] + \text{h.c.}$$

S-wave

D-wave

- Decay width:

$$\frac{d\Gamma}{dm_{\pi\pi} d\cos\theta_{\pi+}} = \frac{m_{\pi\pi}\sigma_\pi|\mathbf{q}|}{64\pi^3 m_\psi^2} |\mathcal{M}_S + \mathcal{M}_D|^2$$



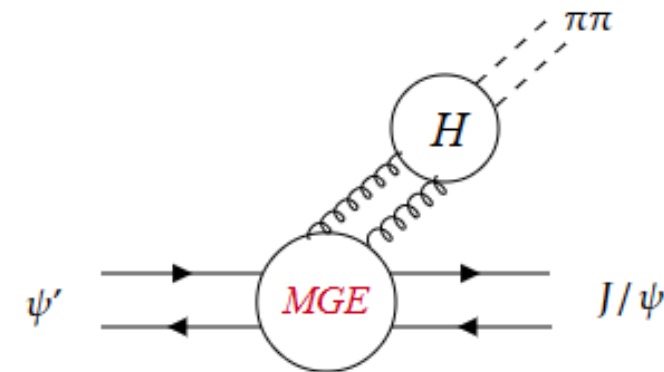
ChPT only can provide enhancement, but not full description

# Theoretical model-QCDME

- Amplitude:

$$\mathcal{M} = i \frac{g_E^2}{6} \sum_{KL} \frac{\langle \Phi_F | r_{m_1} | KL \rangle \langle KL | r_{m_2} | \Phi_I \rangle}{E_I - E_{KL}} \langle \pi\pi | E_{-m_1}^a E_{-m_2}^a | 0 \rangle$$

MGE factor
H factor



[Front.Phys.China 1 \(2006\) 19-37](#)

- Decay width:

$$\frac{d\Gamma}{dm_{\pi\pi} d\cos\theta_{\pi+}} = \cos^2\theta_{\text{mix}} \frac{dG_\alpha}{dm_{\pi\pi} d\cos\theta_{\pi+}} + \sin^2\theta_{\text{mix}} \frac{dH_\beta}{dm_{\pi\pi} d\cos\theta_{\pi+}}$$

- ✓  $2S \rightarrow 1S + \pi\pi$ :

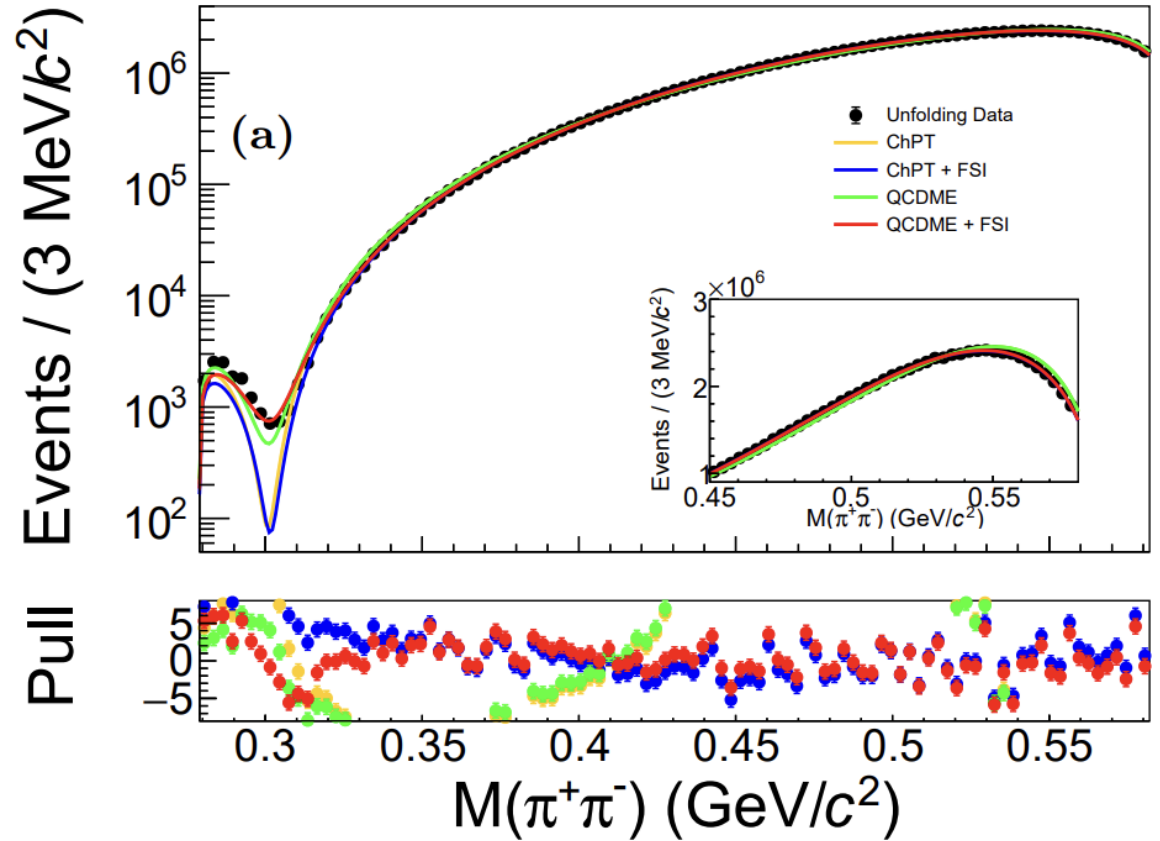
$$\frac{dG_\alpha}{dm_{\pi\pi} d\cos\theta_{\pi+}} = \frac{m_{\pi\pi} |\mathbf{q}| \sigma_\pi}{8\pi^3} \frac{m_{J/\psi}}{m_\psi^2} \left\{ \frac{1}{2} (m_{\pi\pi}^2 - 2m_\pi^2) + \alpha \left[ m_{\pi\pi}^2 + |\mathbf{q}|^2 - |\mathbf{q}|^2 \left( 1 - \frac{4m_\pi^2}{m_{\pi\pi}^2} \right) \cos^2\theta_{\pi+} \right] \right\}^2$$

- ✓  $1D \rightarrow 1S + \pi\pi$ :

$$\frac{dH_\beta}{dm_{\pi\pi} d\cos\theta_{\pi+}} = \frac{m_{\pi\pi} |\mathbf{q}| \sigma_\pi}{450\pi^3} \frac{m_{J/\psi}}{m_\psi^2} \beta^2 \left\{ (m_{\pi\pi}^2 - 4m_\pi^2)^2 + (m_{\pi\pi}^2 - 4m_\pi^2) |\mathbf{q}|^2 + |\mathbf{q}|^4 \right. \\ \left. - (2|\mathbf{q}|^2 + m_{\pi\pi}^2 + 8m_\pi^2) (m_{\pi\pi}^2 - 4m_\pi^2) \frac{|\mathbf{q}|^2}{m_{\pi\pi}^2} \cos^2\theta_{\pi+} + (m_{\pi\pi}^2 - 4m_\pi^2)^2 \frac{|\mathbf{q}|^4}{m_{\pi\pi}^4} \cos^4\theta_{\pi+} \right\}$$

# Theoretical model-QCDME

- QCDME:
  - ✓ Heavy quarkonium multipole expansion
  - ✓ Mixture of 2S-1D  $c\bar{c}$  charmonia.
  - ✓ Chiral symmetry of  $\pi\pi$  production.



The description is reasonable for low  $\pi^+\pi^-$  mass

# Theoretical model-FSI

## ● Final state interaction

✓ Chiral unitary approach: a good description of meson-meson interaction.

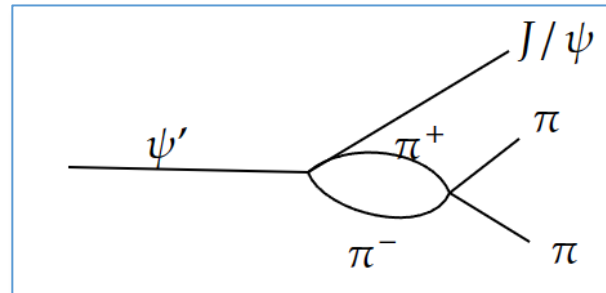
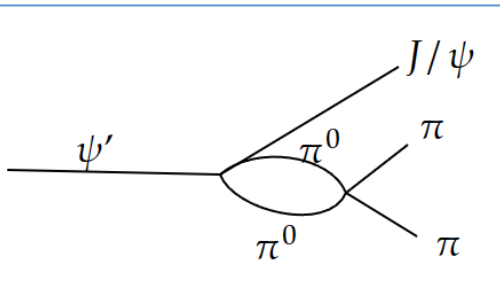
$$M_S = M_{S0} \cdot (1 + G \cdot t_{\pi\pi})$$

✓ For the  $t_{\pi\pi}$ :

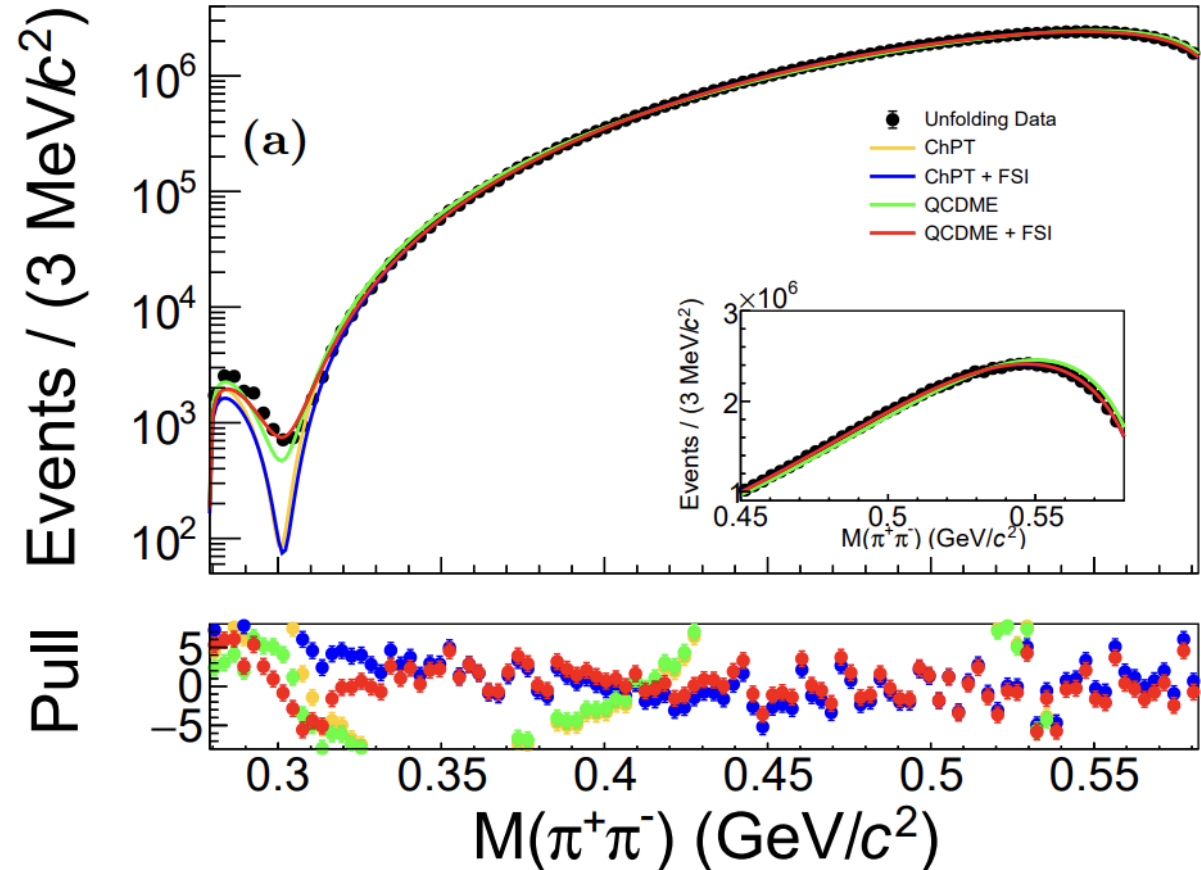
$$t_{\pi\pi} = \frac{1}{1/V_0 - G}$$

✓ And for  $G$  is to regularize the loop:

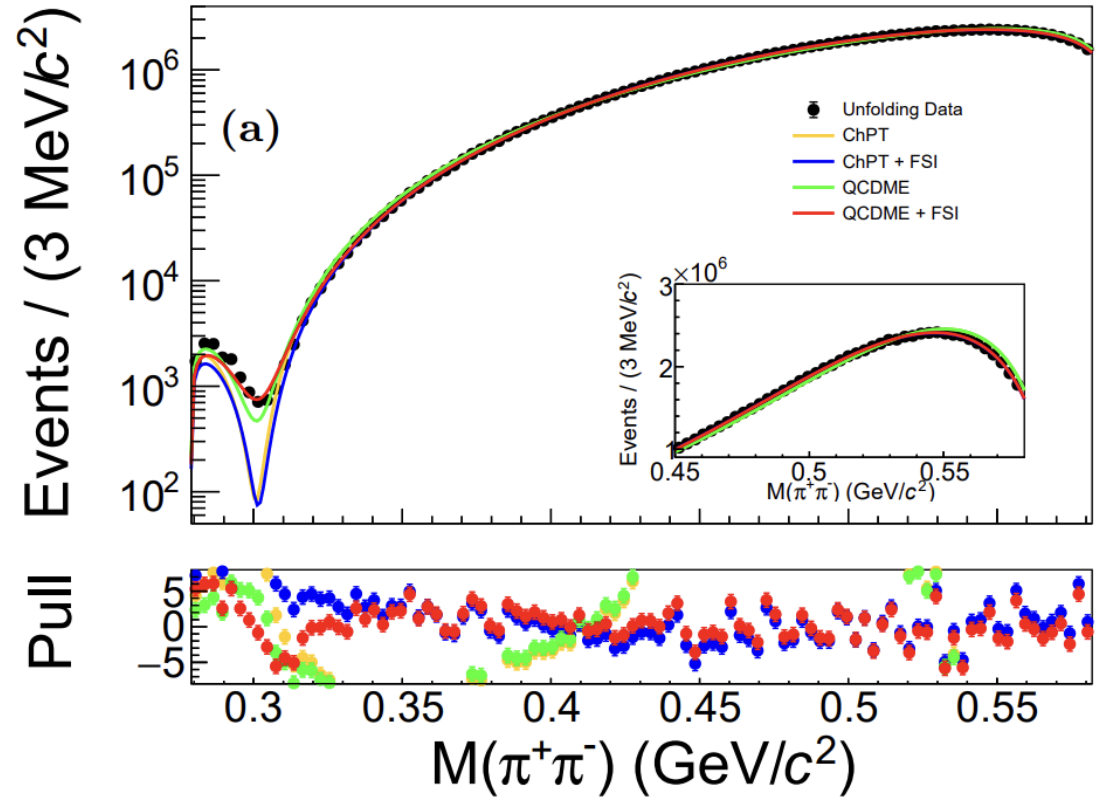
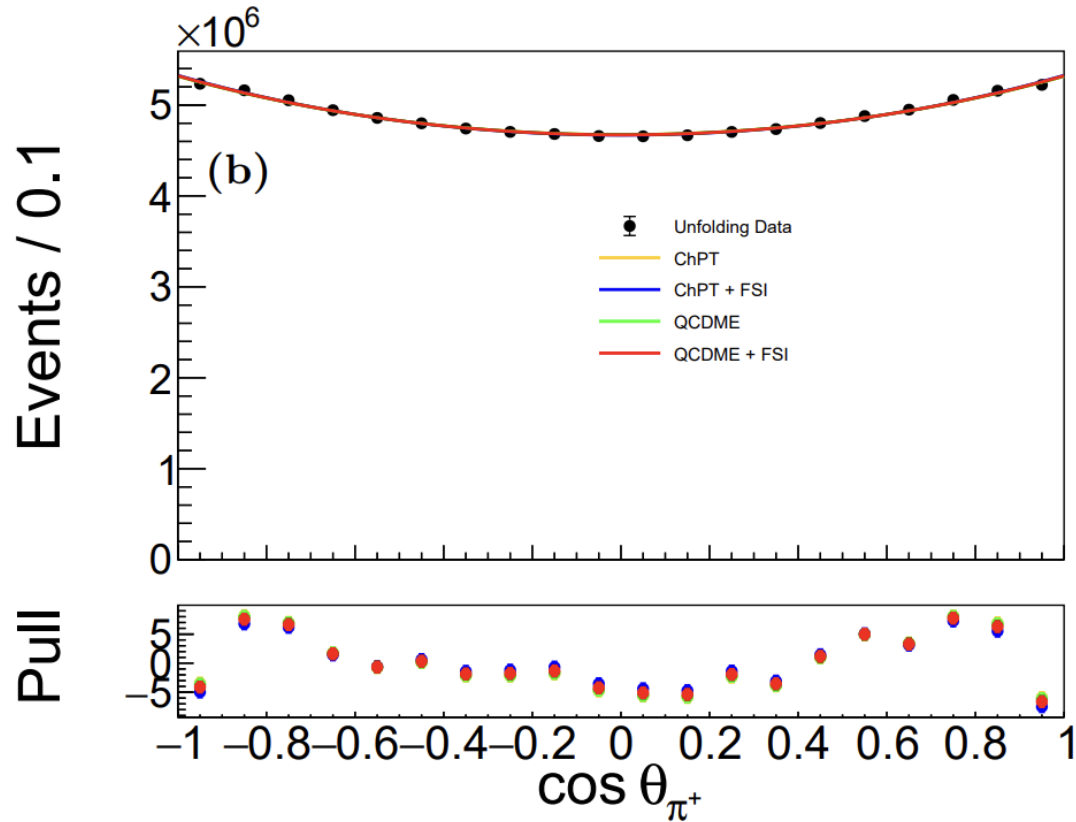
$$G = -\frac{1}{16\pi^2} \left[ \gamma + \sigma \log \frac{\sigma - 1}{\sigma + 1} \right]$$



[XH Liu et al, Eur.Phys.J.C 73 \(2013\) 1, 2284](#)



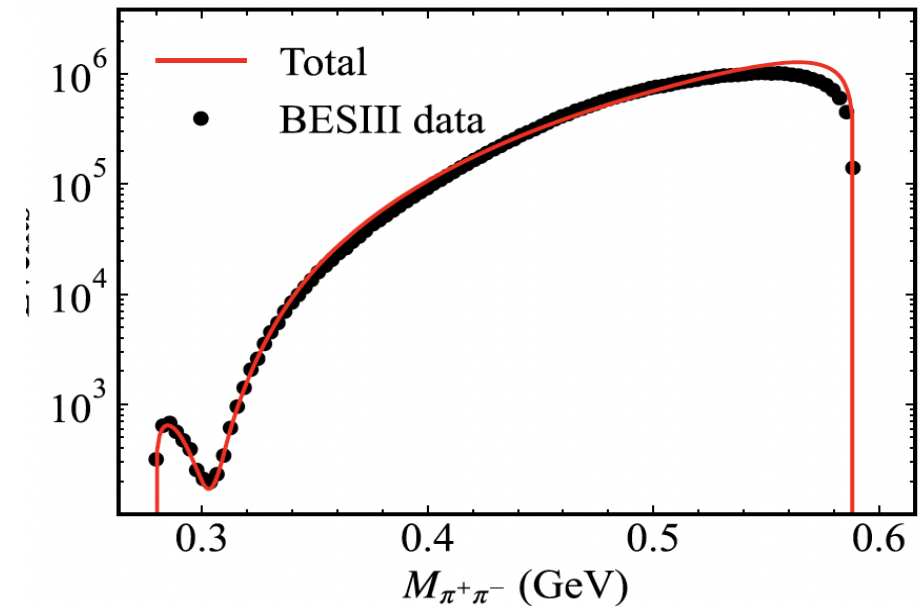
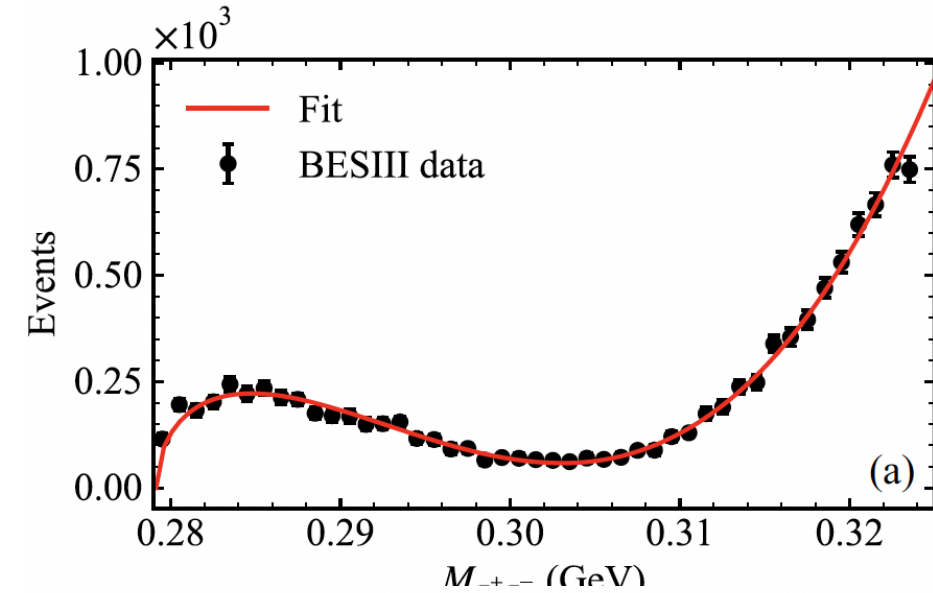
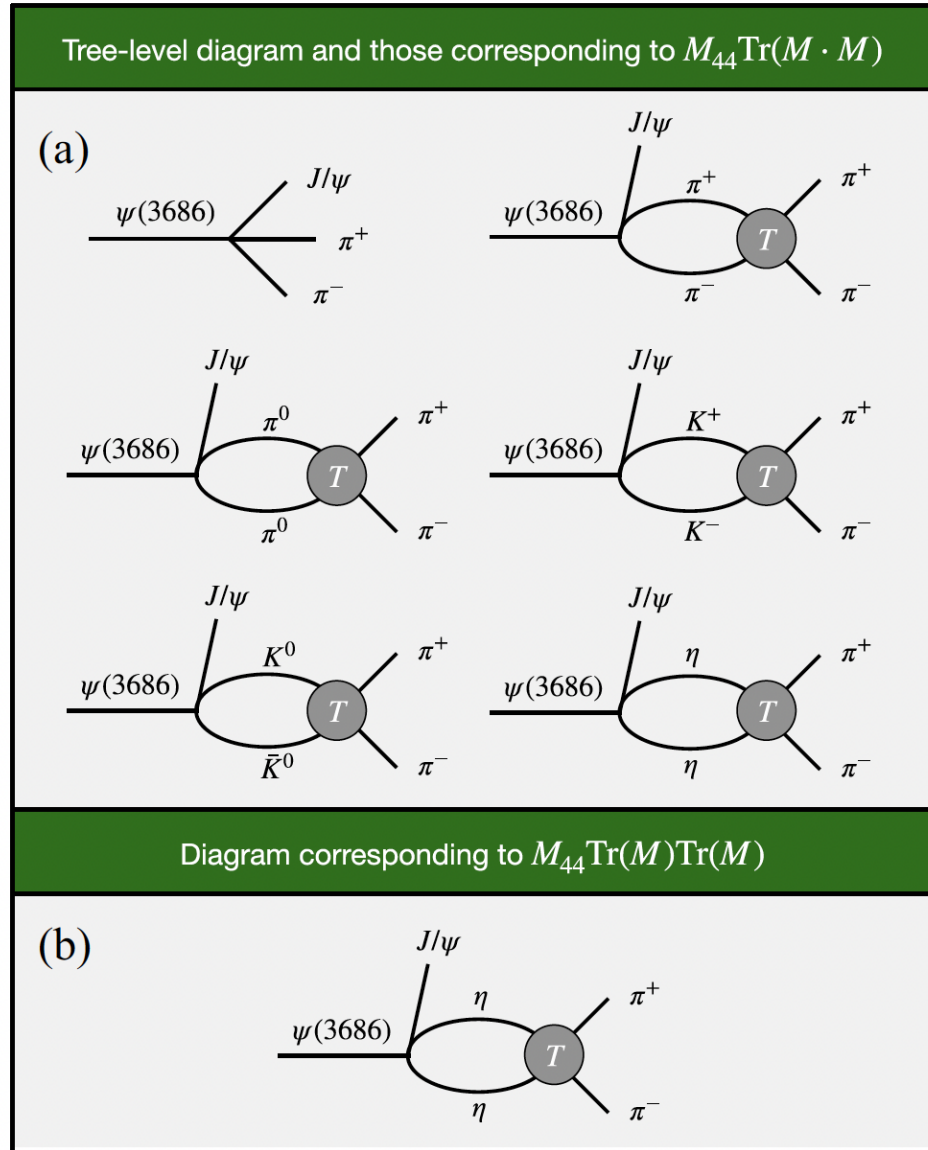
# Comparison

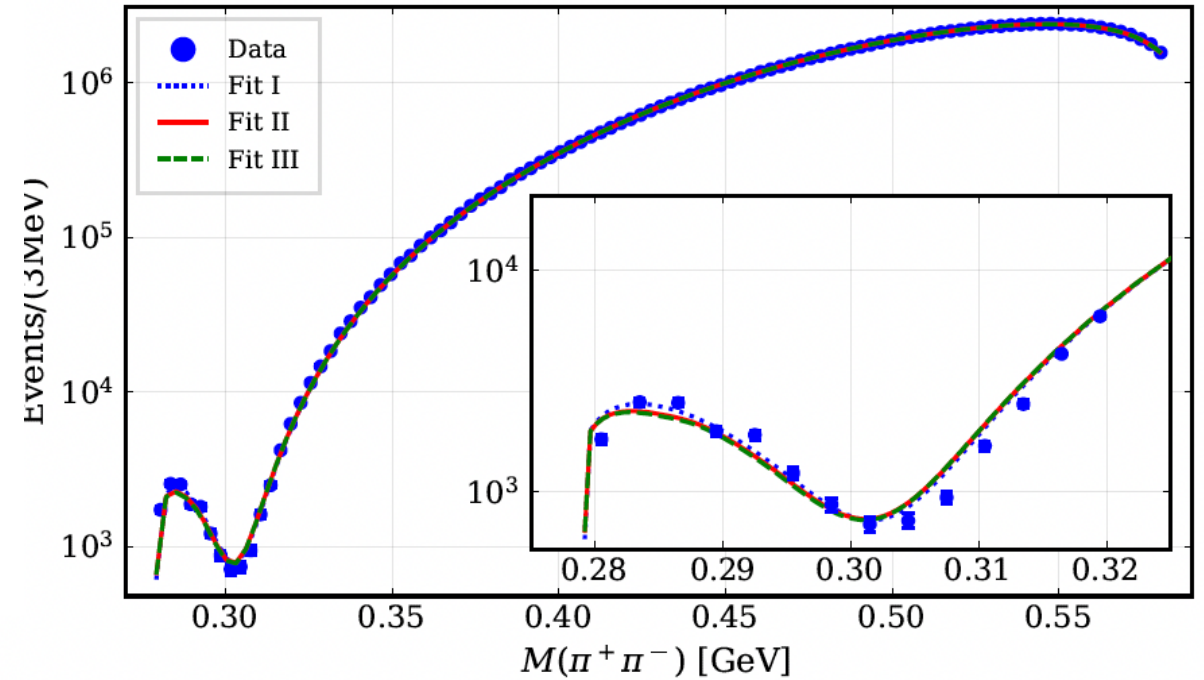
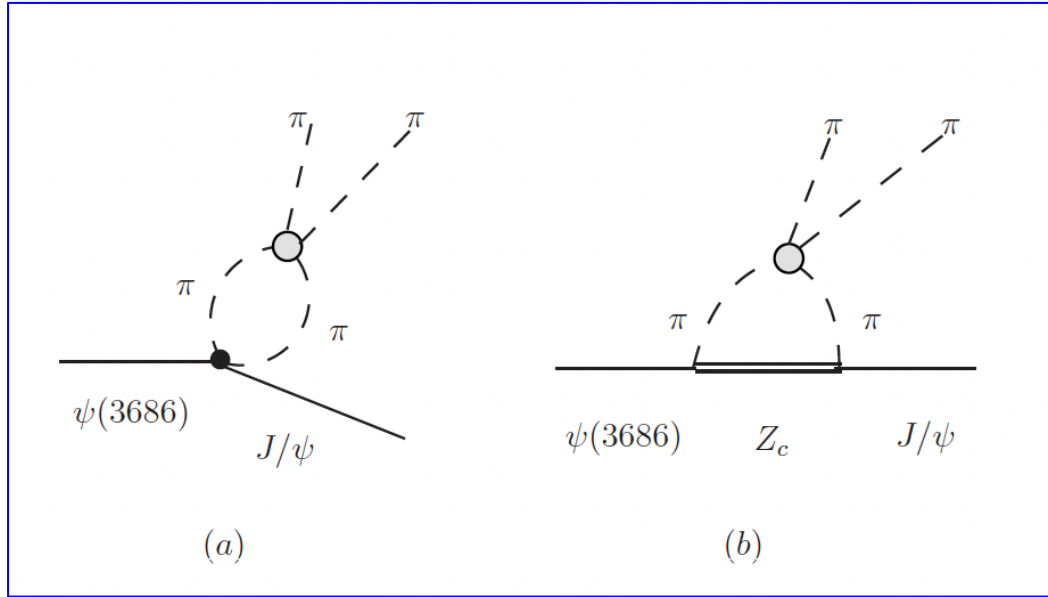


- FSI is necessary for high invariant mass spectrum
- QCDME :  $\psi(3686)$  is the mixture of S-wave and D-wave charmonium state !
- Chiral symmetry provide a reasonable description for  $\pi\pi$  threshold enhancement

# Theorists' work

ZY Wang, Z Liu, X Liu PRD 113, L031502 (2026)





$$\mathcal{L}_{\psi'\psi\Phi\Phi} = g_1 \langle \psi'^{\alpha} \psi_{\alpha}^{\dagger} \rangle \langle u_{\mu} u^{\mu} \rangle + h_1 \langle \psi'^{\alpha} \psi_{\alpha}^{\dagger} \rangle \langle u_{\mu} u_{\nu} \rangle v^{\mu} v^{\nu} \\ + j_1 \langle \psi'^{\mu} \psi_{\nu}^{\dagger} \rangle \langle u_{\mu} u^{\nu} \rangle + c_m \langle \psi'^{\mu} \psi_{\mu}^{\dagger} \rangle \langle \chi_{+} \rangle + \text{H.c.},$$

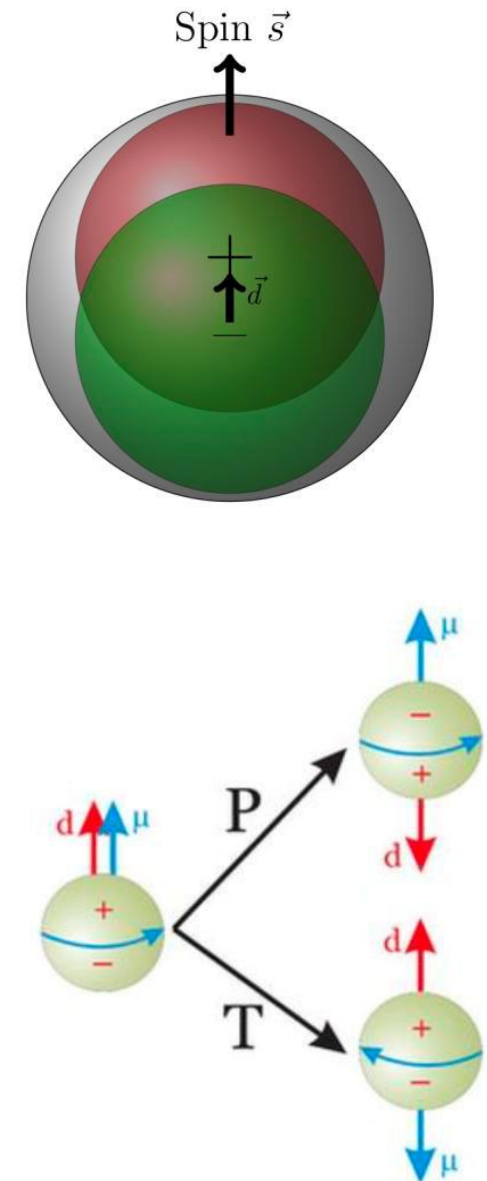
$$\mathcal{L}_{Z_c \psi' \pi} = C_{Z_c \psi' \pi} \psi'^i \langle Z_c^{i\dagger} u_{\mu} v^{\mu} \rangle + \text{H.c.},$$

$$\mathcal{L}_{Z_c \psi \pi} = C_{Z_c \psi \pi} \psi^i \langle Z_c^{i\dagger} u_{\mu} v^{\mu} \rangle + \text{H.c.}.$$

Provide a good description of data

# Chromo-EDM in $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$

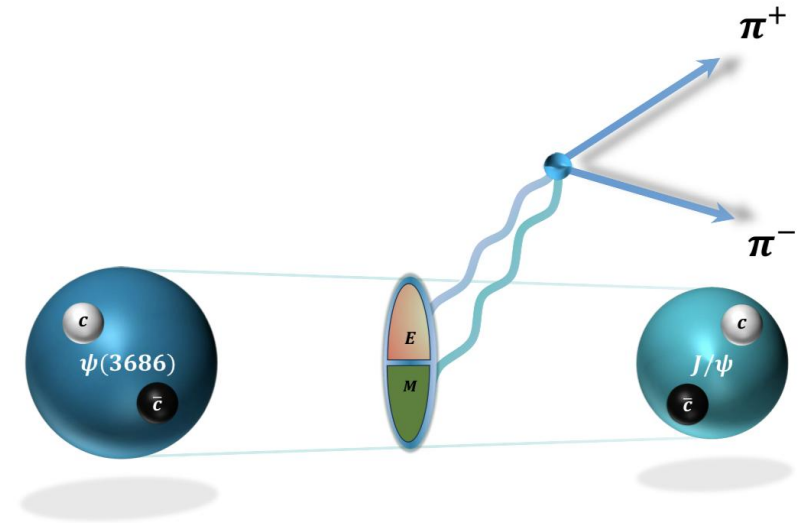
- The Electric Dipole Moment (EDM) of a fundamental particle or a subatomic system is a **measure of the asymmetric charge distribution within the particle volume**
- If the particle is not charged, then **a non zero EDM** implies that the center of charge of the particle is displaced from its center of mass.
- EDM exists relates to violations of time reversal and parity symmetry



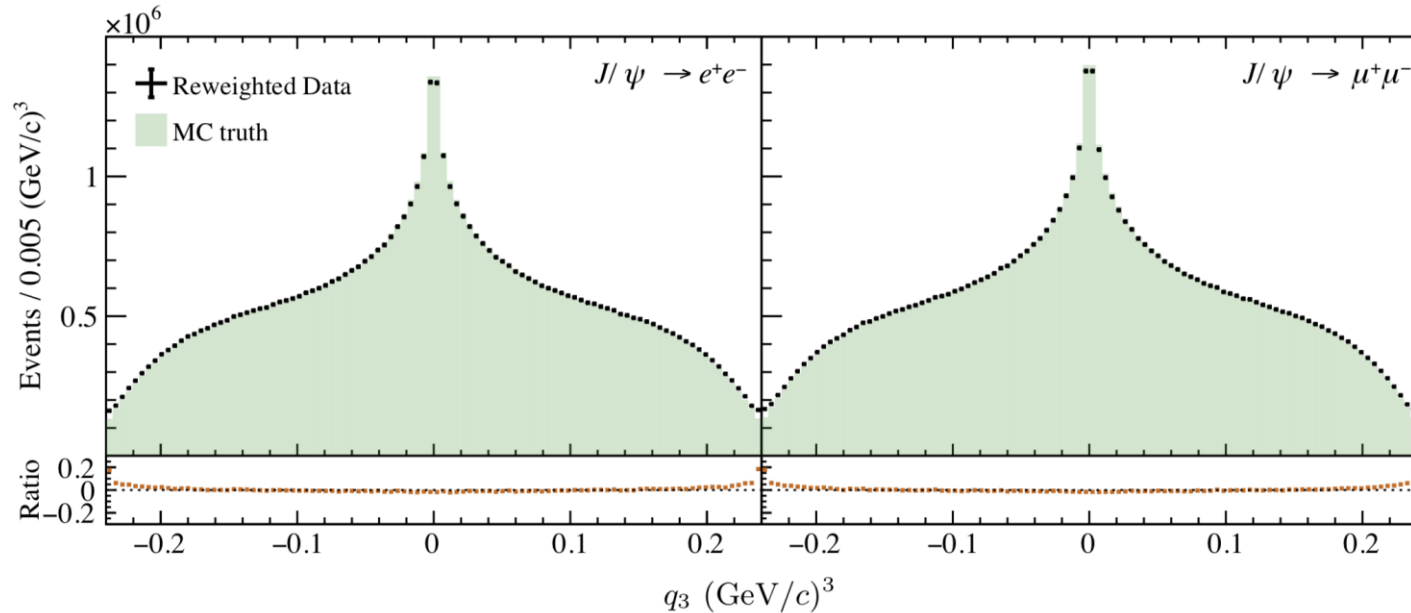
# Chromo-EDM in $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$

Based on QCDME, an extra contribution introduced:

$$\mathcal{L}_{CEDM} = -i/2 \boxed{d'_c} \bar{\psi}_c \sigma^{\mu\nu} \gamma_5 \lambda_a / 2 \psi_c G_{\mu\nu}^a$$



BESIII: arXiv: 2507.20618, accepted by PRL



Parameter	$J/\psi \rightarrow e^+e^-$	$J/\psi \rightarrow \mu^+\mu^-$
$A_{CP} (\times 10^{-4})$	$3.3 \pm 2.9 \pm 0.4$	$-1.2 \pm 2.4 \pm 0.1$
$\langle A_{CP} \rangle (\times 10^{-4})$	$0.6 \pm 1.8 \pm 0.1$	
$d'_c$ [CK] (e·cm)	$(2.6 \pm 7.8 \pm 0.4 \pm 0.6) \times 10^{-16}$	
$d'_c$ [Cornell] (e·cm)	$(3.5 \pm 10.5 \pm 0.6 \pm 0.5) \times 10^{-16}$	
$ d'_c $ (e·cm)	$< 2.1 \times 10^{-15}$	

# Summary

- Observed  $\pi^+\pi^-$  threshold enhancement structure
  - ✓ Mass:  $(285.5 \pm 2.6) \text{ MeV}/c^2$ , Width:  $(16.4 \pm 0.8) \text{ MeV}$
- Theoretical models
  - ✓ ChPT (QCDME) +FSI : reasonable description of  $\pi^+\pi^-$  mass spectrum
  - ✓ QCDME implies  $\psi(3686)$  is the mixture of S-wave and D-wave charmonium state
  - ✓ The 2D corrected data will be provided
  - ✓ Inspired theoretical discussions on this anomalous enhancement
- Precise test of CEDM of charm quark
- Prospects:  $\psi(3686) \rightarrow \pi^0\pi^0 J/\psi$  is in progress, released soon !



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**Thanks for listening!**

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