Observation of a resonance-like structure near the $\pi^+\pi^-$ mass threshold in $\psi(3686) \to \pi^+\pi^- J/\psi$

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Outline

- Introduction
- Data Sample
- Fitting results
- Summary

Introduction

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

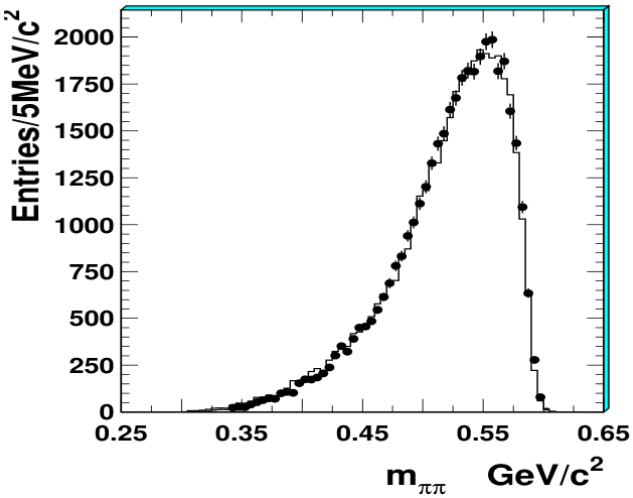
$$\psi(3686) = |2^3S_1> \cos\theta - |1^3D_1> \sin\theta$$
$$\psi(3770) = |2^3S_1> \sin\theta + |1^3D_1> \cos\theta$$

  where θ is mixing angle.

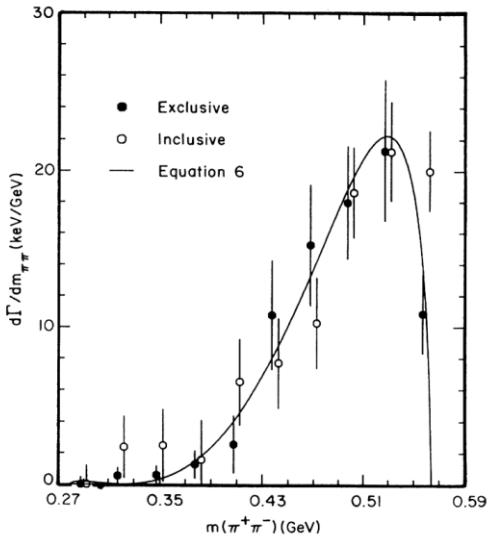
- $\pi\pi$ transition:
  - ✓ A good place to study Chiral Symmetry and Final state interaction.
  - ✓ Soft pion emission, e.g. Alder zero?
  - ✓High statistics of $\pi\pi$ production provide chance to search for pionium.

Introduction

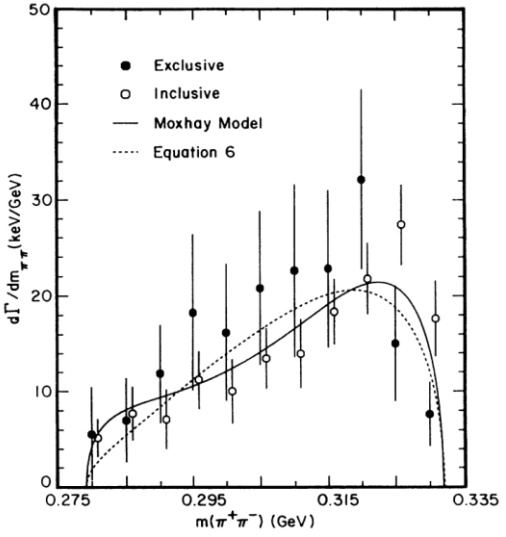
- Heavy quarkonium transition
  - ✓ Similar spectrum in charmonium and bottomonium transitions.
  - ✓ ChPT has great power to describe $\pi\pi$ production.



$\psi' \to \pi^+\pi^- J/\psi$



$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$



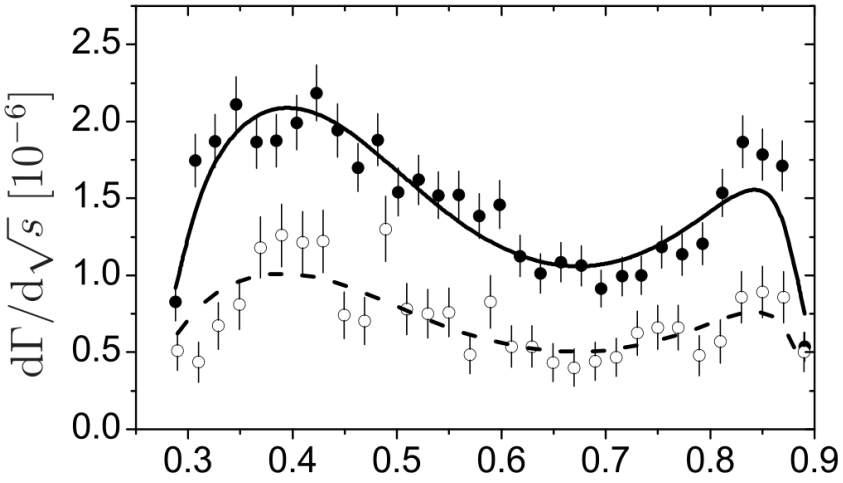
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$

[Phys.Lett.B 645 (2007) 19-25]

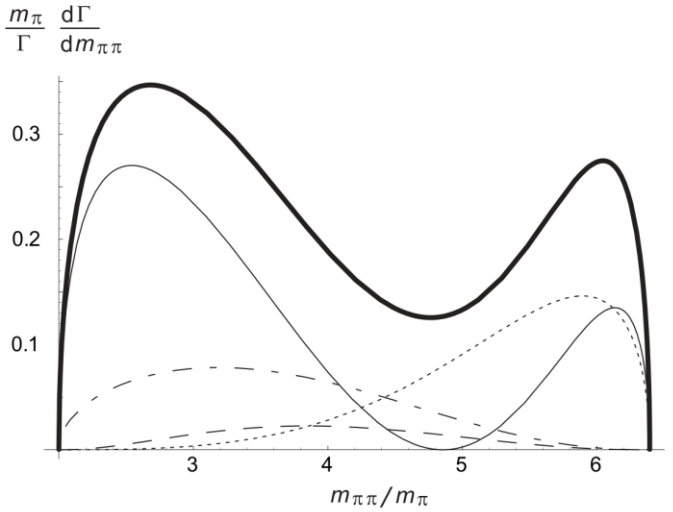
[Phys.Rev.D 49 (1994) 40-57]

Introduction

- Puzzle of $\Upsilon(3S) \to \pi\pi\Upsilon(1S)$
  - ✓ $\pi\pi$ spectrum much different from other quarkonium transitions.
- Tetraquark used to correct ChPT.
- QCD multipole expansion (QCDME) with S-D mixing quarkonium transition.

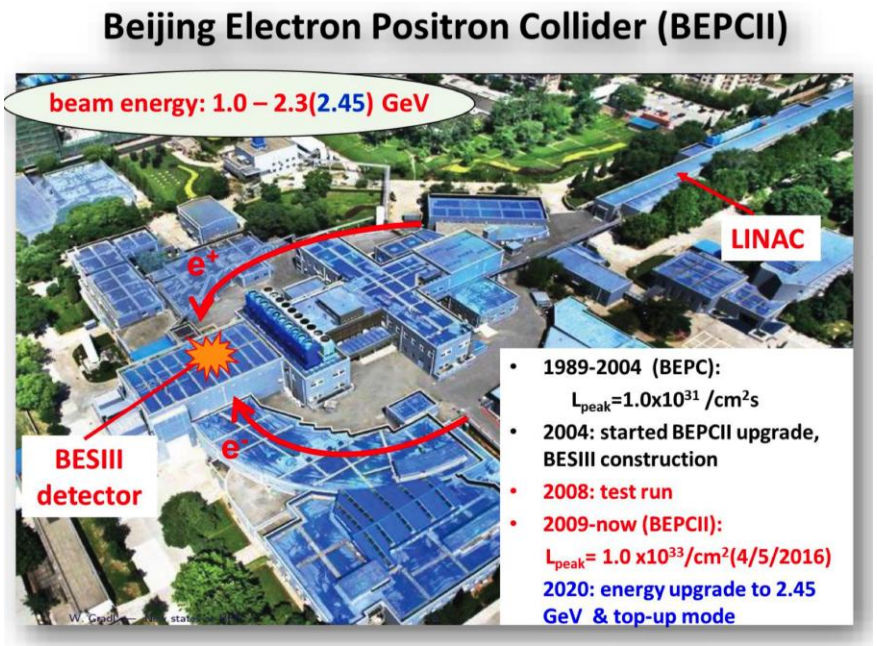


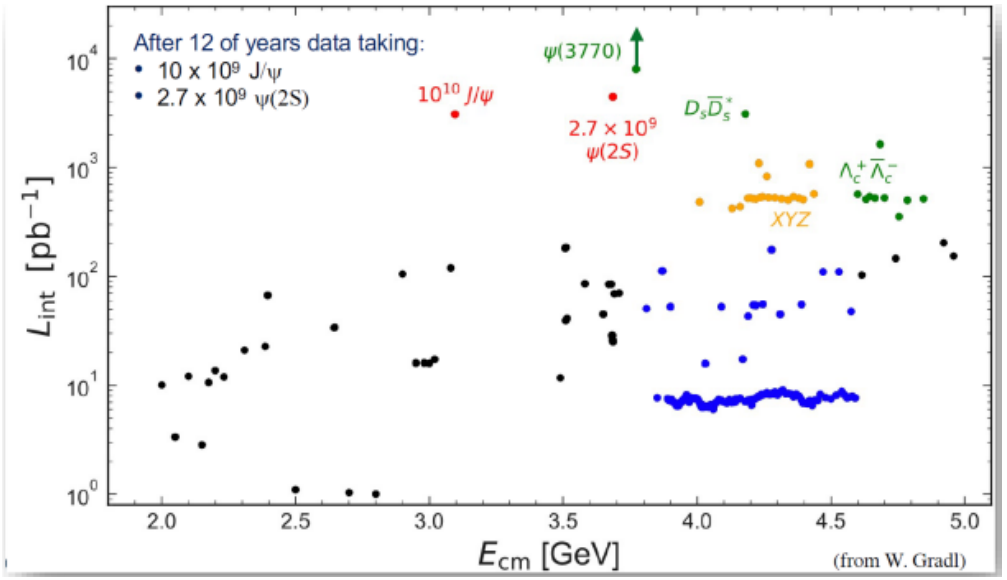
Phys.Rev.D 93 (2016) 3, 034030



Phys.Rev.D 74 (2006) 054022

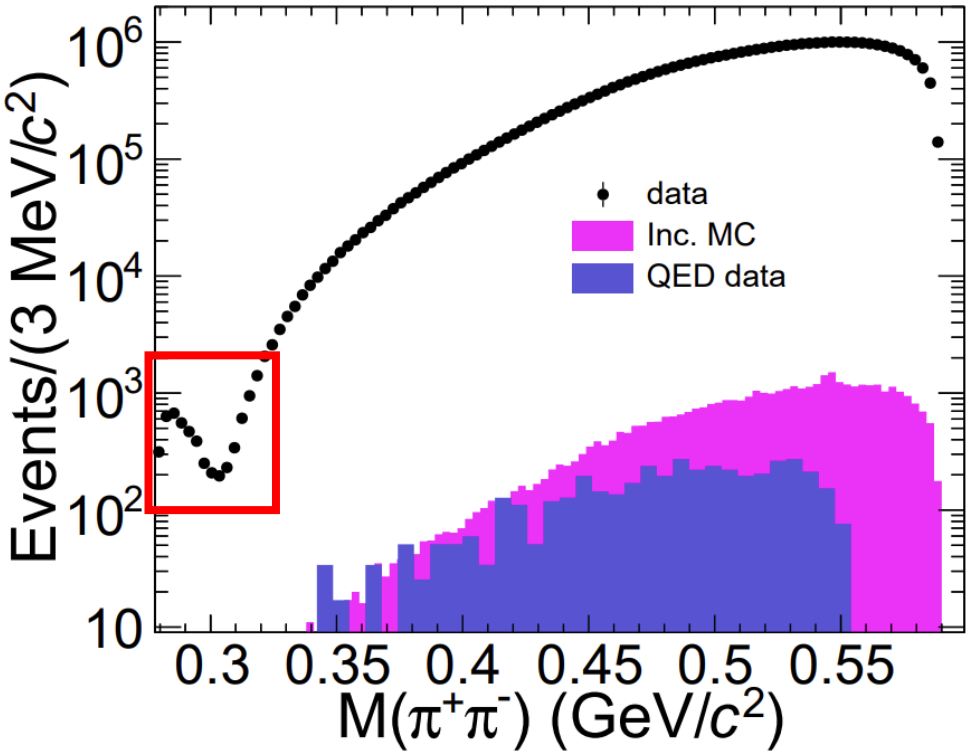
Data Sample





World's Largest τ-charm Data Sets in e^+e^- Annihilation

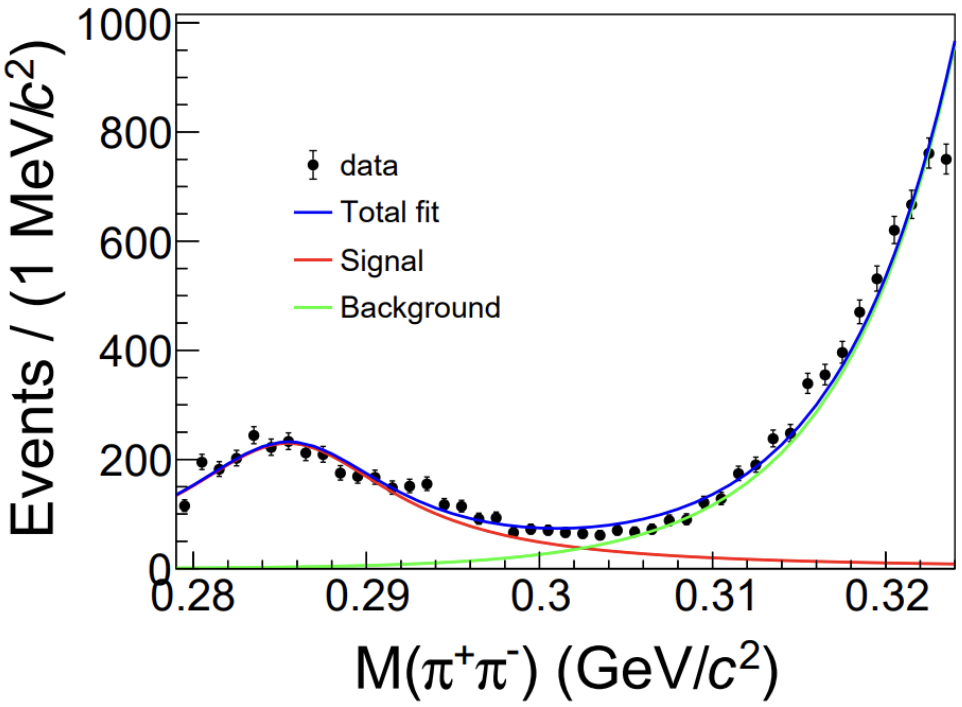
Data Sample



- 3.7×10^7 events
- 99.8% purity

First time observe $\pi^+\pi^-$ threshold enhancement in $\psi(3686) \to \pi^+\pi^- J/\psi$

Resonance-like hypothesis



- Take $\pi^+\pi^-$ threshold as a resonance
- (Breit-Wigner $\otimes$ Resolution) $\times$ Efficiency
- Mass: (285.5 ± 2.6) MeV/c^2, Width: (16.4 ± 0.8) MeV/c^2

Theoretical models

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

Z.Phys.C 73 (1997) 541-546

- Lagrangian:

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

S-wave

D-wave

- Decay width:

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

Theoretical models

Front.Phys.China 1 (2006) 19-37

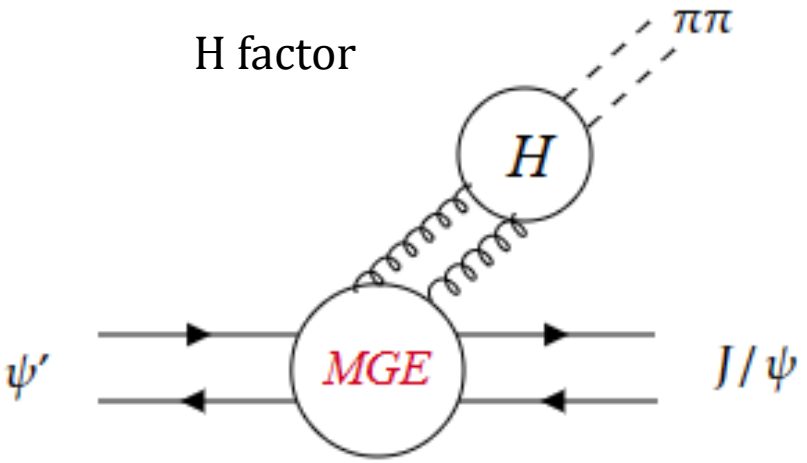
- QCDME:
  - ✓Heavy quarkonium multipole expansion.
  - ✓Mixture of 2S-1D $c\bar{c}$ charmonia.
  - ✓Chiral symmetry of $\pi\pi$ production.

- Amplitude:

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

MGE factor　　H factor

- H factor is similar as ChPT.



Theoretical models

- Decay width:

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

✓ $2S \to 1S + \pi\pi$:

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

✓ $1D \to 1S + \pi\pi$:

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

Theoretical models

- Final state interaction

Eur.Phys.J.C 73 (2013) 1, 2284

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

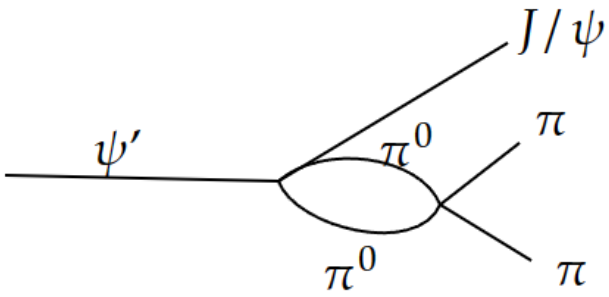
$$M_S = M_{S0} \cdot (1 + G \cdot t\_\pi\pi)$$

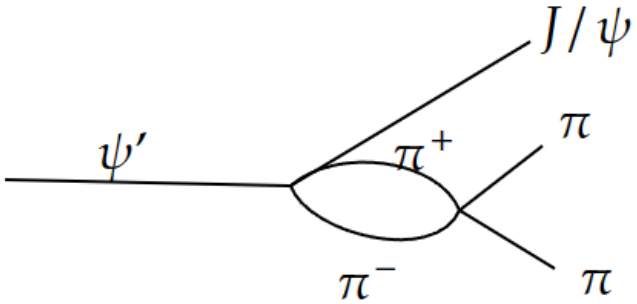
✓For the $t\_\pi\pi$:

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

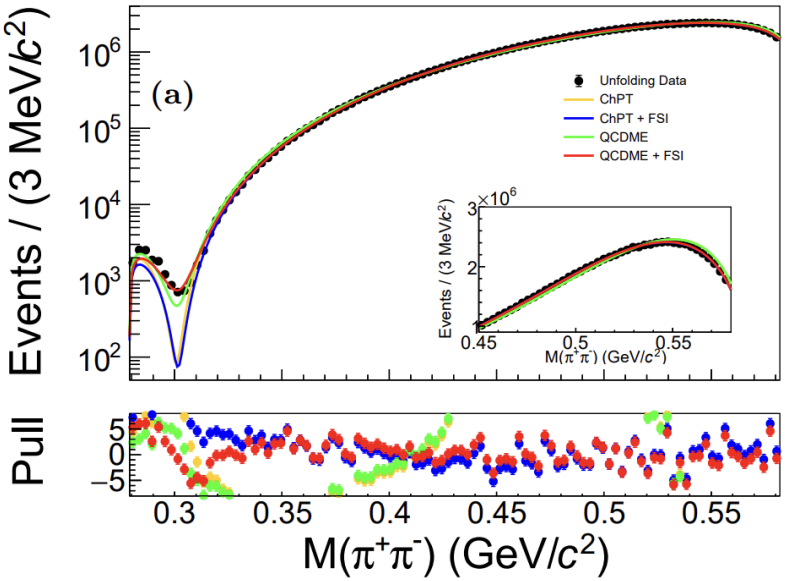
✓And for G is to regularize the loop:

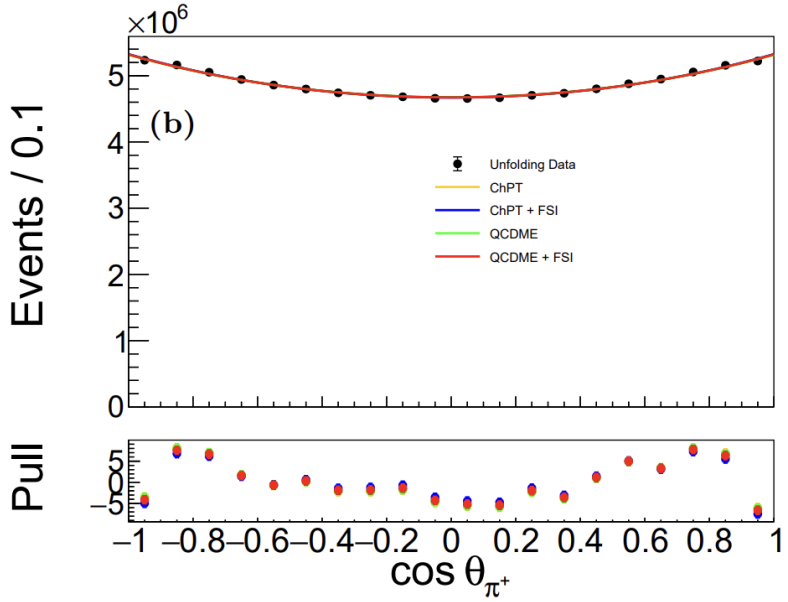
$$G = -\frac{1}{16\pi^2}\left[\gamma + \sigma \log\frac{\sigma - 1}{\sigma + 1}\right]$$





Fitting results





- FSI for high invariant mass
- QCDME for low invariant mass
- Chiral symmetry prediction $\pi\pi$ threshold enhancement.
- This shows $\psi(3686)$ is the mixture of S-wave and D-wave charmonium state!

Summary

- Resonance-like structure:
  - ✓ Mass: $(285.5 \pm 2.6)\ \mathrm{MeV}/c^2$, Width: $(16.4 \pm 0.8)\ \mathrm{MeV}/c^2$
- Theoretical model fitting result:
  - ✓ Chiral symmetry prediction $\pi\pi$ threshold enhancement.
  - ✓ QCDME + FSI can will describe $\pi\pi$ mass spectrum.
  - ✓ QCDME implies $\psi(3686)$ is the mixture of S-wave and D-wave charmonium state.
- Other hypothesis: Couple channel…
- Article: arxiv:2509.23761 (submitted to PRL).
- Welcome more discussions!

THANKS