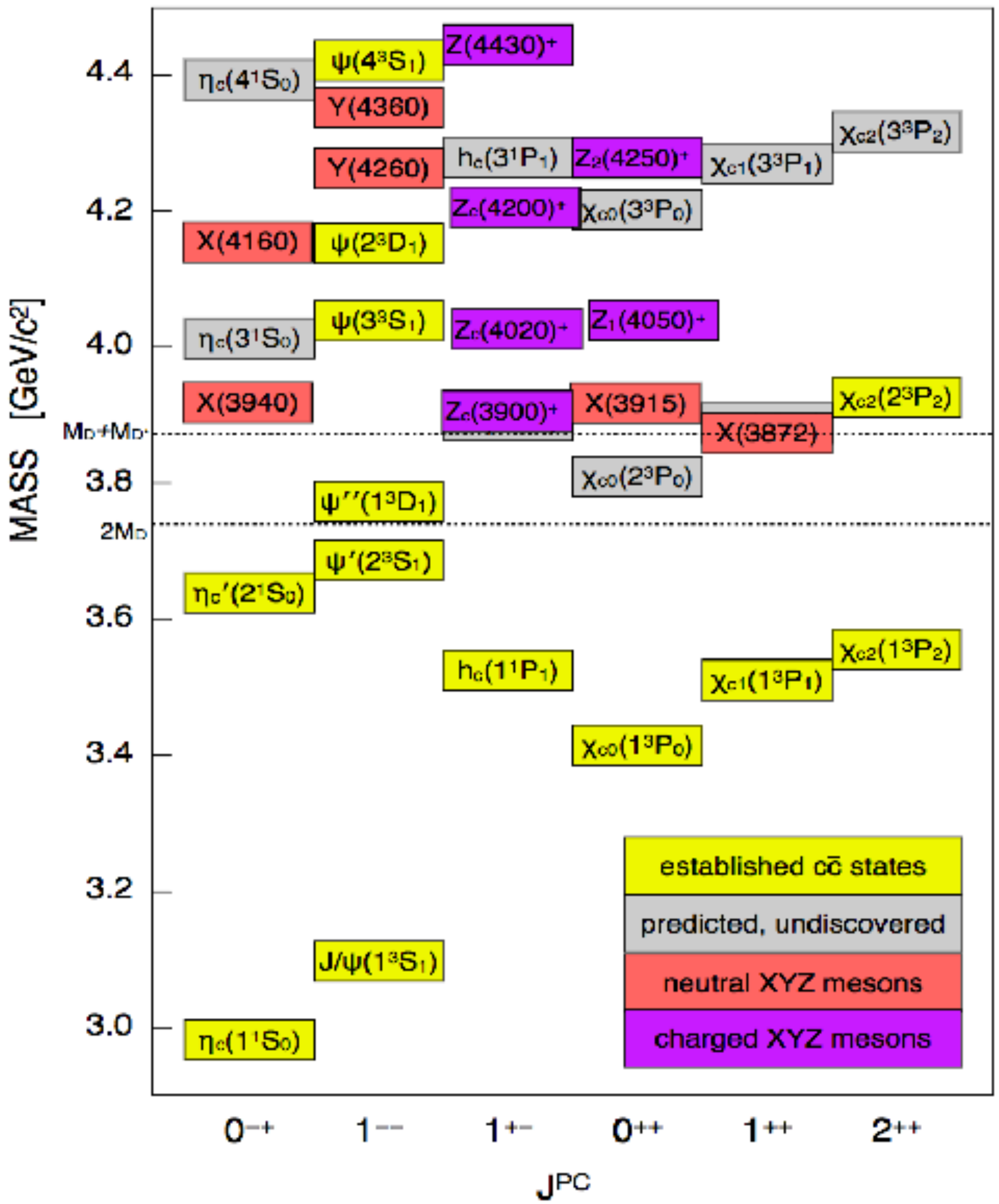
X(3872), XEFT, and $\bar{\text{P}}$ANDA

Thomas Mehen
Duke U.

Hadronic Physics with Lepton and Hadron Beams, Jefferson Lab
September 7, 2017

Exotic Charmonia



S. Olsen, **PoS Bormio** 050 (2015)

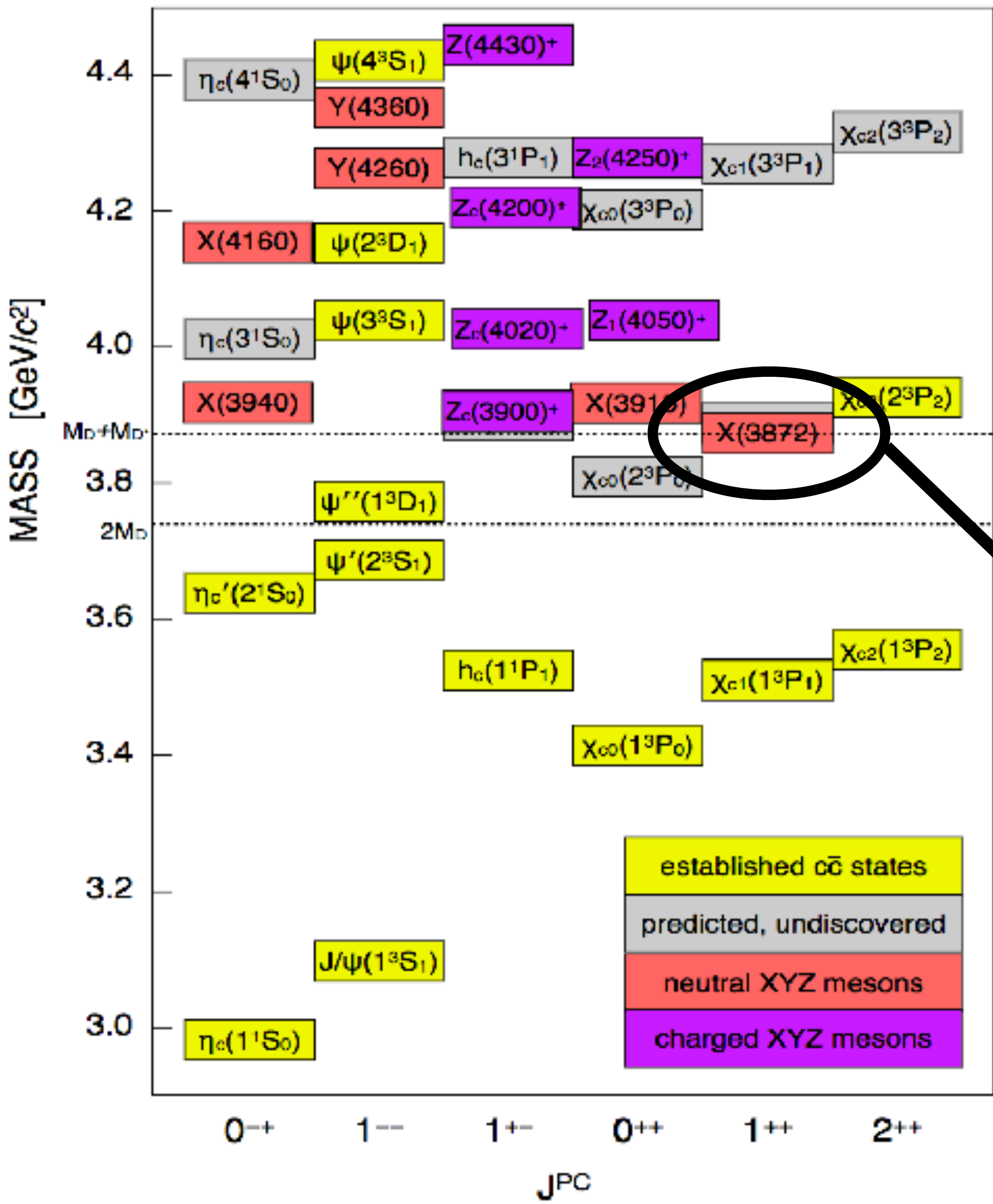
conventional onia?

tetraquarks?

hybrids?

hadronic molecules?

Exotic Charmonia



conventional onia?

tetraquarks?

hybrids?

hadronic molecules?

S. Olsen, **PoS Bormio** 050 (2015)

X(3872)

Decays: $X(3872) \to J/\psi\pi^+\pi^-$

$\to D^0\bar{D}^0\pi^0$

$\to D^0\bar{D}^0\gamma$

$\Gamma_X < 1.2\,\mathrm{MeV}$

$X(3872) \to J/\psi\pi^+\pi^-\pi^0$

$\to J/\psi\gamma$ (C=1)

$\to \psi(2S)\gamma$

angular distributions in $J/\psi\pi^+\pi^-$ require $J^{PC} = 1^{++}$

LHCb, PRL 110 (2013) 222001
arXiv:1302.6269 [hep-ex]

S-wave coupling to $D\bar{D}^* + \bar{D}D^*$

$$\frac{Br[X(3872) \to J/\psi\pi^+\pi^-\pi^0]}{Br[X(3872) \to J/\psi\pi^+\pi^-]} = 0.8 \pm 0.3$$

X(3872) is mixed state w/ I=0 and I=1?

Extremely Close to Threshold:

$$m_X = 3871.69 \pm 0.17\,\mathrm{MeV}$$

$$m_{D^0} = 1864.84 \pm 0.05\,\mathrm{MeV}$$

$$m_{D^{*0}} = 2006.85 \pm 0.05\,\mathrm{MeV}$$ (from PDG)

$$m_X - (m_{D^0} + m_{D^{*0}}) = 0.0 \pm 0.18\,\mathrm{MeV}$$

unique among proposed molecules:

Universality: $\psi_{DD^*}(r) \propto \frac{e^{-r/a}}{r}$ $\quad a \geq 10.6\,\mathrm{fm}$ $\quad B.E. = \frac{1}{2\mu_{DD^*}a^2}$

Long distance physics of X(3872) calculable in terms of scattering length, known properties of D mesons - Effective Range Theory (ERT)

(M. B. Voloshin, E. Braaten, et. al.)

Conventional Behavior of X(3872) I

$$\frac{Br[X(3872) \to \psi' \gamma]}{Br[X(3872) \to J/\psi \gamma]} = 2.46 \pm 0.70$$

Naturally expected for χ'_{c1}

Molecular Model: **3.8 10^{-3}** Swanson, Phy. Rep. **429** (2006) 243-305

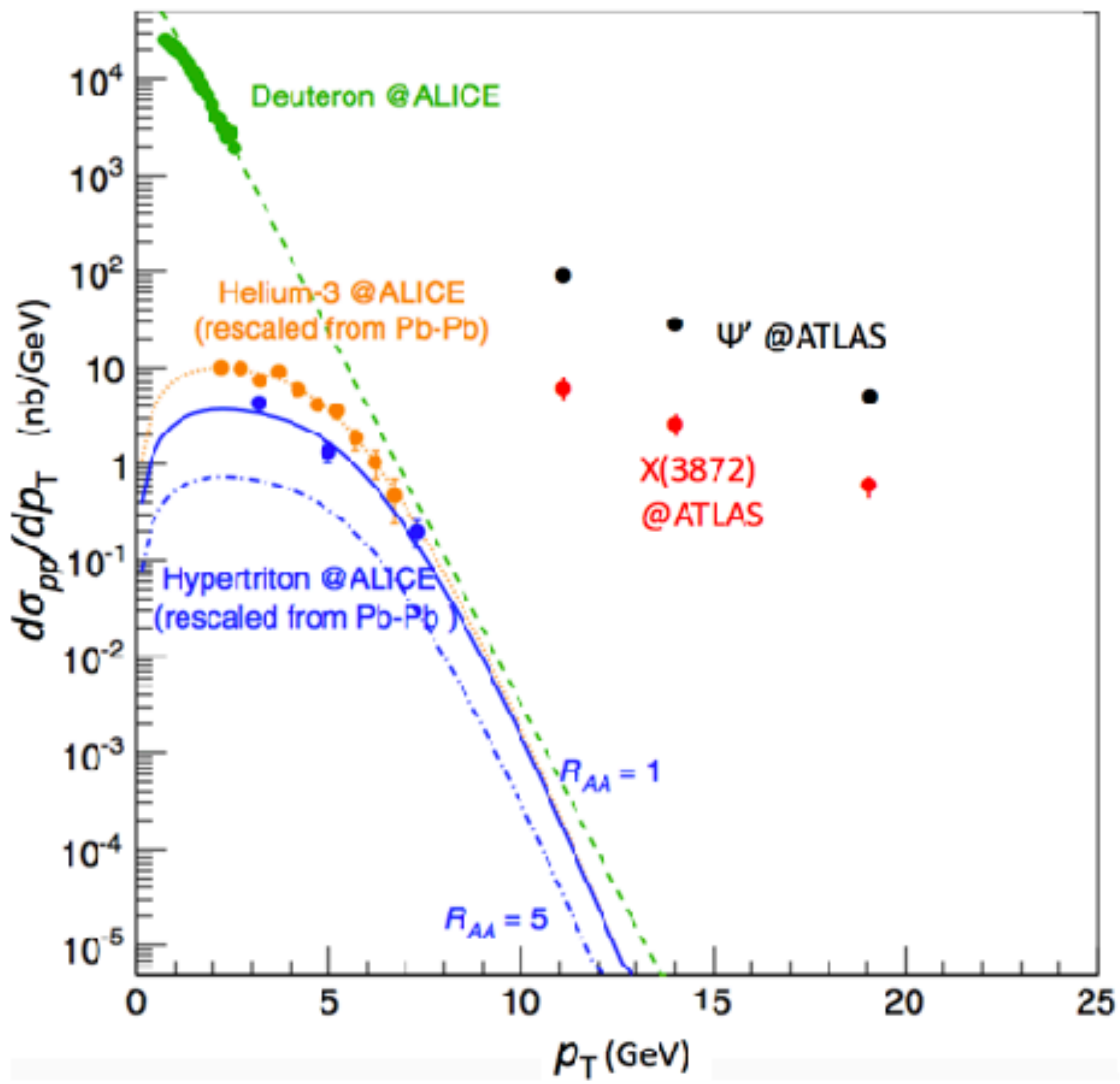
XEFT, EFT: depends on counterterms,
sensitive to short-distance structure of X(3872)

T.M., R.P. Springer, PR **D83** (2011) 094009

Guo, F.-K., et. al., PL **B742** (2015) 394-398

Conventional Behavior of X(3872) II

High p_T production in heavy ion collisions, hadron colliders



A. Esposito, et.al., PR **D92** (2015) 034028

C. Bignamini, et. al., PRL **103** (2009)162001,PL **B684** (22010) 228-230

P. Artoisenet, E. Braaten, et. al., PRD**81** (2010) 114018, PRD **83** (2011) 014019

Mixed Charmonium-Molecule

M. Suzuki, PRD **72** (2005) 114013

production at colliders

C. Meng, et. al., arXiv:1304.6710

M. Butenschoen, et. al. PR **D88** (2013) 011501

$$|X\rangle = \sqrt{Z_{c\bar{c}}}\,|\chi_{c1}(2P)\rangle + \sqrt{Z_{\rm mol}}\,|DD^*\rangle \qquad Z_{c\bar{c}} = (28-44)\%.$$

X(3872) on Lattice M. Padmanath, et. al., PR **D92** (2015) 034501

$c\bar{c}, D\bar{D}^*$ operators both required to obtain X(3872)

QCD sum rules analysis of mass, decays

R. Matheus, et. al., PR **D80** (2009) 056002

$$Z_{c\bar{c}} \sim 0.97, \quad Z_{\rm mol} \sim 0.03$$

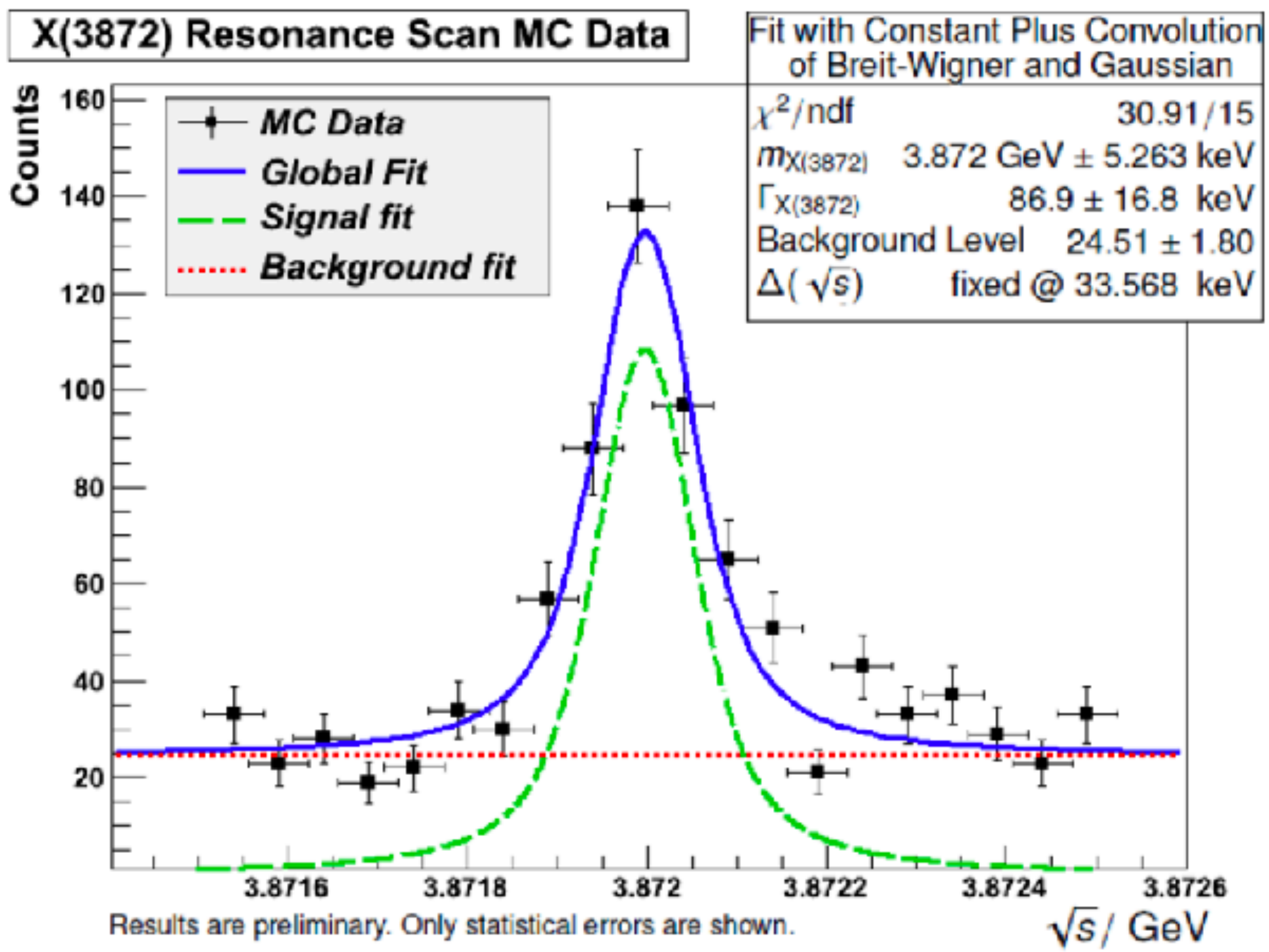
Diquark-Diquark Bound States

A. Esposito, A. Pilloni, A.D.Polosa,Phys. Rep. **668** (2016) 1-97

A. Esposito, et. al., Int. J. Mod. Phys. **A30** (2015) 1530002

X(3872) at $\bar{\text{P}}$ANDA

simulated resonance scan: $p\bar{p} \to X(3872) \to J/\psi\pi^+\pi^-$



M.Galuska et. al., POS(Bormio2012) 018

input $\Gamma_X = 100\,\text{keV}$

reconstruct $\Gamma_X \simeq 87 \pm 17\,\text{keV}$

Narrow Resonances

$$\sigma_{\mathrm{BW}}(\sqrt{s}) = \frac{(2J+1)\cdot 4\pi}{\sqrt{s}^2 - 4m_{\mathrm{p}}^2} \cdot \frac{\mathrm{BR}(\mathrm{X}(3872) \to \mathrm{p\bar{p}}) \cdot \Gamma_{\mathrm{X}(3872)}{}^2}{4(\sqrt{s} - m_{\mathrm{X}(3872)})^2 + \Gamma_{\mathrm{X}(3872)}{}^2}.$$

M.Galuska et. al., POS(Bormio2012) 018

Line shapes near threshold

E. Braaten, PRD **77** (2008) 034019

near threshold S-wave resonances, shallow bound states

will modify near threshold cross section

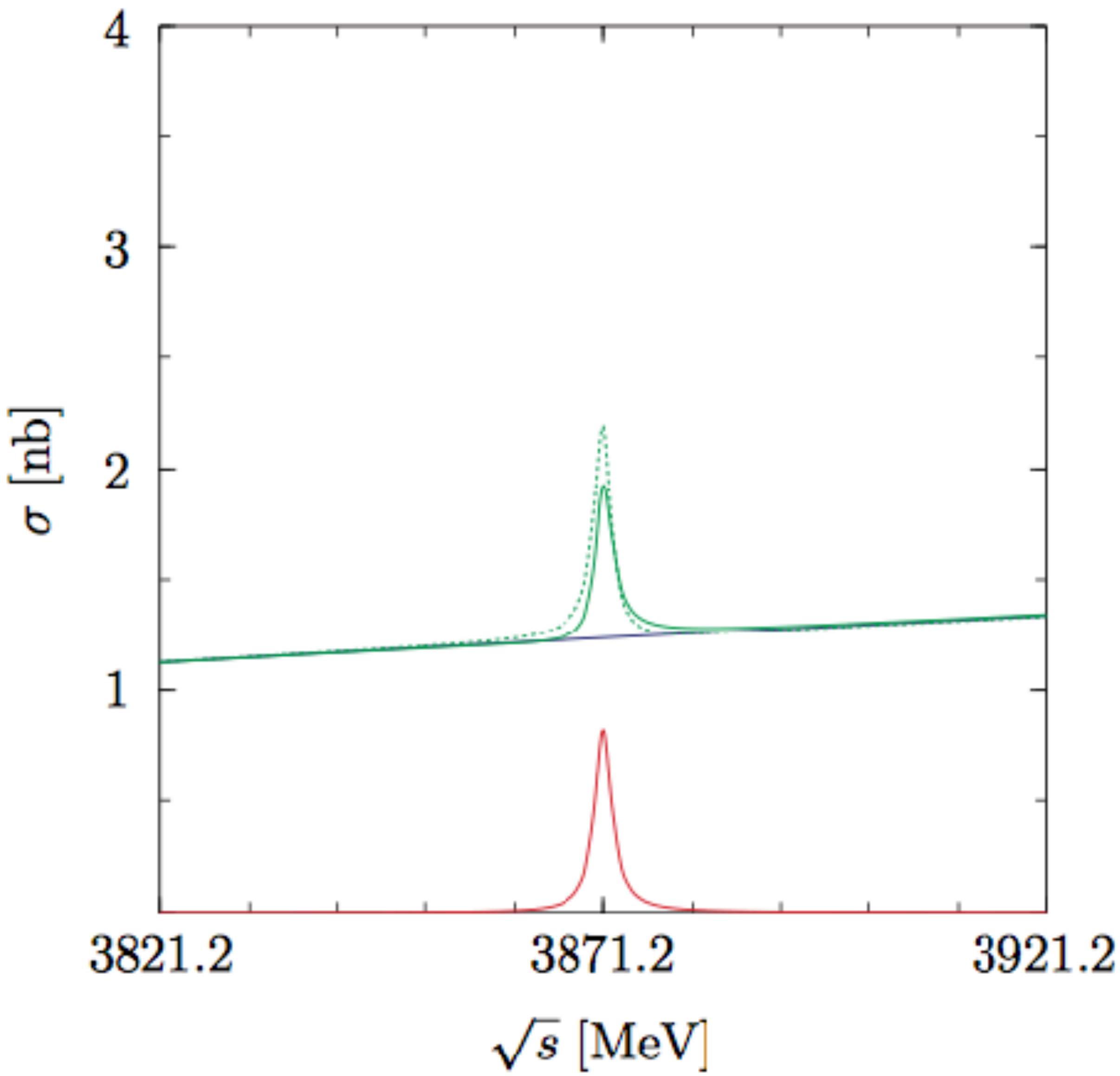
$$\times |f(E)|^2 \qquad f(E) = \frac{1}{-1/a + \sqrt{-2ME - i\epsilon}}$$

zero-range, single channel model

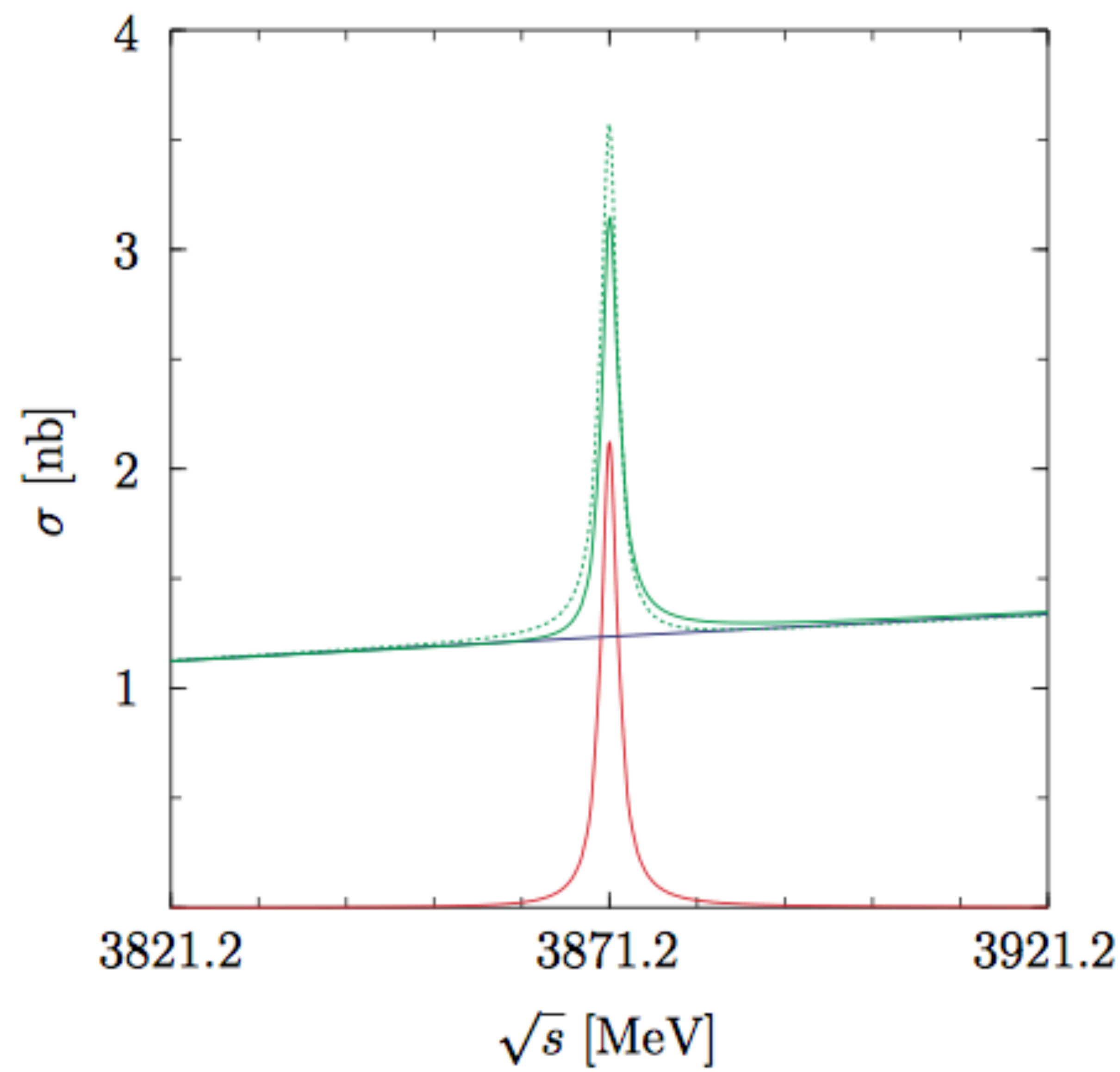
X(3872) Production at $\overline{\text{P}}$ANDA

G.Y.Chen, J.P. Ma, PRD **77** (2008) 097501

$\Gamma_X = 2.3\,\mathrm{MeV}$

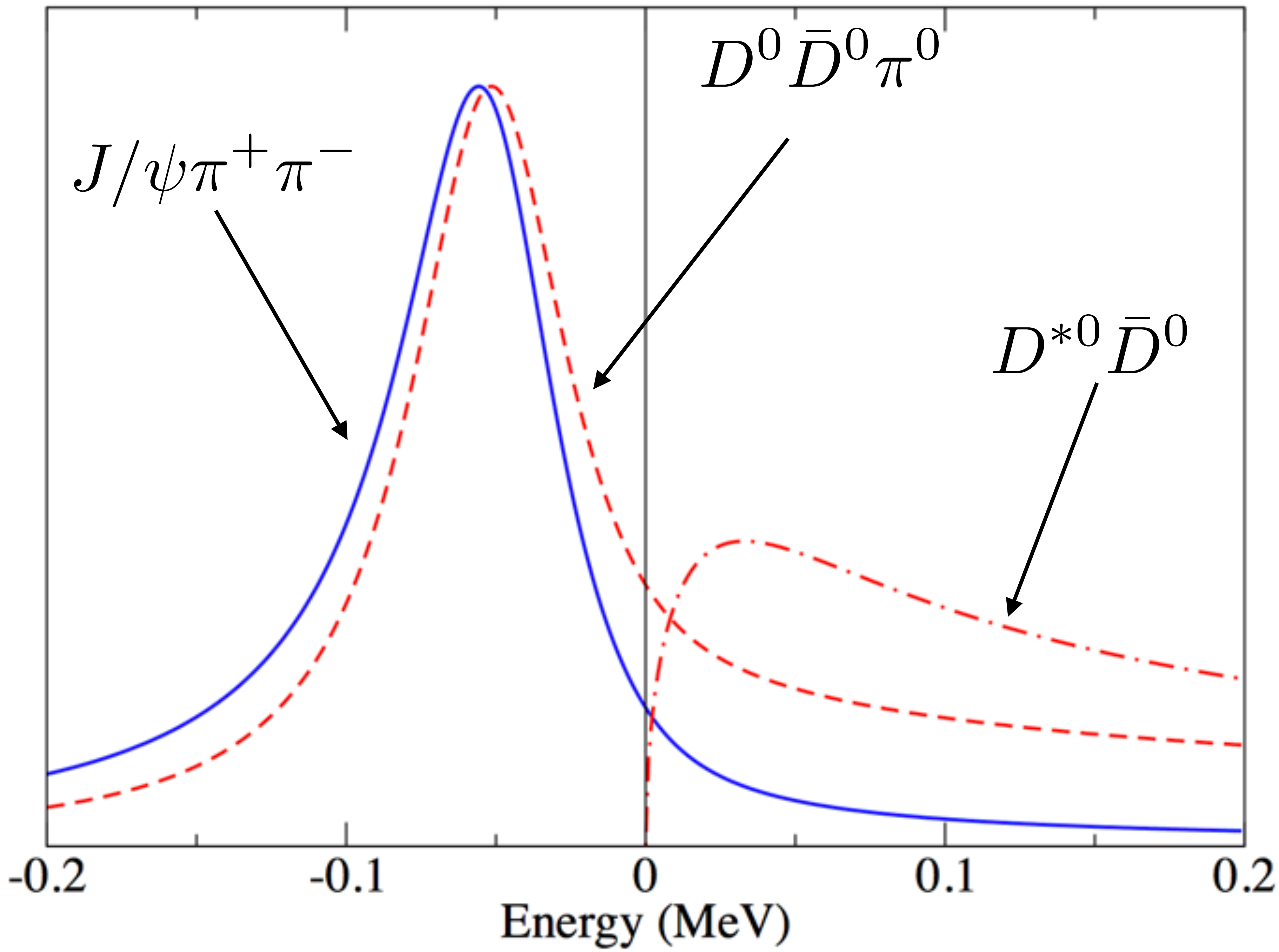


$\chi_{c1}(2P)$



molecule

Line shapes depend on channel



E. Braaten and J. Stapleton, PRD **81** (2010) 014019

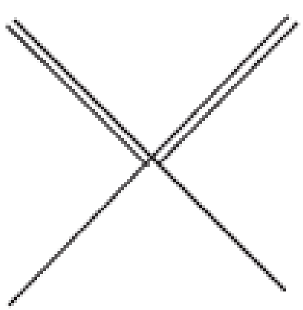
XEFT

S.Fleming, M.Kusunoki, T.M.,
U.van Kolck, PRD76:034006 (2007)

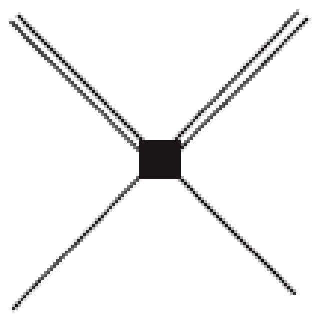
Non-Relativistic Propagators

D $\quad$ D^* $\quad$ π $\quad$ $\sim \dfrac{1}{Q^2}$

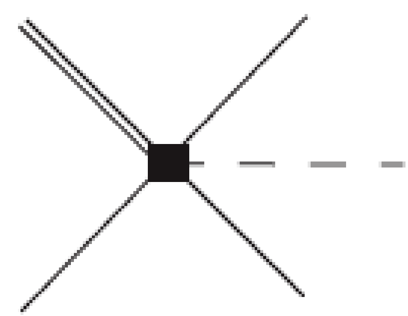
Contact Interactions, Pion Exchange



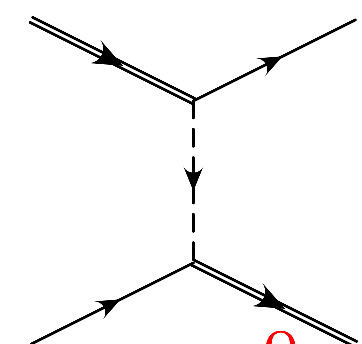
$C_0 \sim Q^{-1}$



$C_2\, p^2 \sim Q^0$



$B_1\, \epsilon \cdot p_\pi \sim Q^{-1}$



$\sim Q^0$

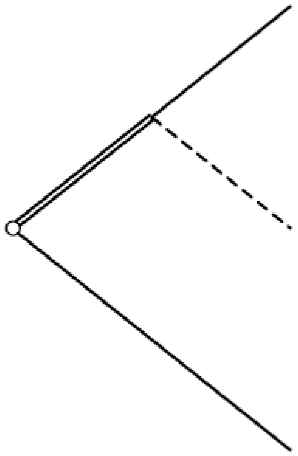
Power Counting

$p_D \sim p_\pi \sim \mu \sim \gamma \sim Q \qquad \gamma \equiv \sqrt{-2\mu_{DD^*}\mathrm{B.E.}} \leq 34\,\mathrm{MeV}$

$m_\pi \approx \Delta_H \approx 140\,\mathrm{MeV}$ are large scales in X-EFT

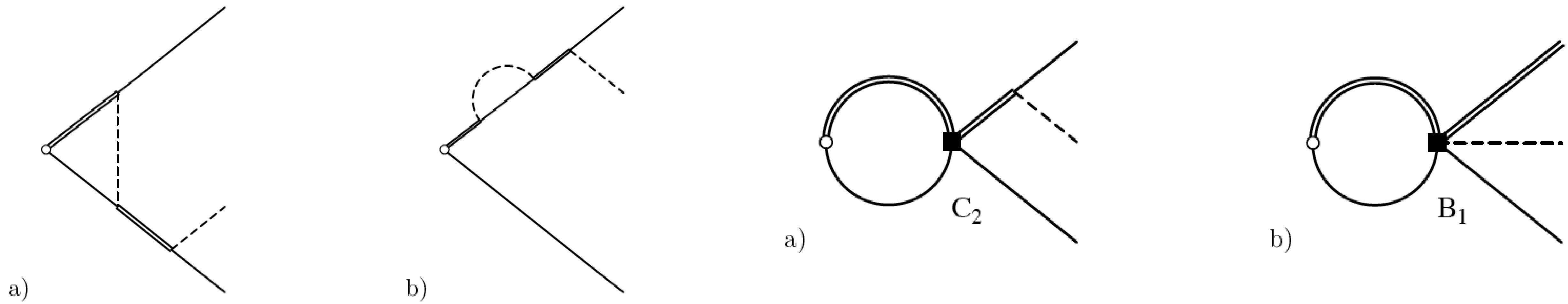
LO - reproduce ERT prediction for $X(3872) \to D^0 \bar{D}^0 \pi^0$

M.B.Voloshin, PLB 579: 316 (2004)

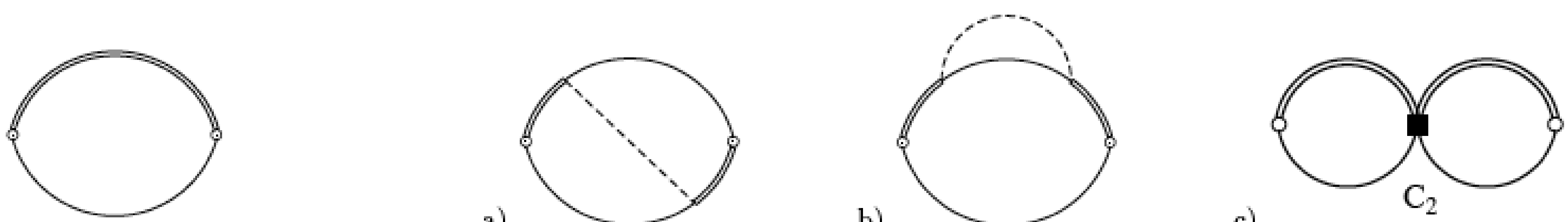


$$\frac{d\Gamma_{\rm LO}}{dp_D^2\, dp_{\bar{D}}^2} = \frac{g^2}{32\pi^3 f_\pi^2} 2\pi\gamma (\vec{p}_\pi \cdot \vec{\epsilon}_X)^2 \left[\frac{1}{p_D^2+\gamma^2} + \frac{1}{p_{\bar{D}}^2+\gamma^2} \right]^2$$

NLO - range corrections, non-analytic corr. from π^0 exchange



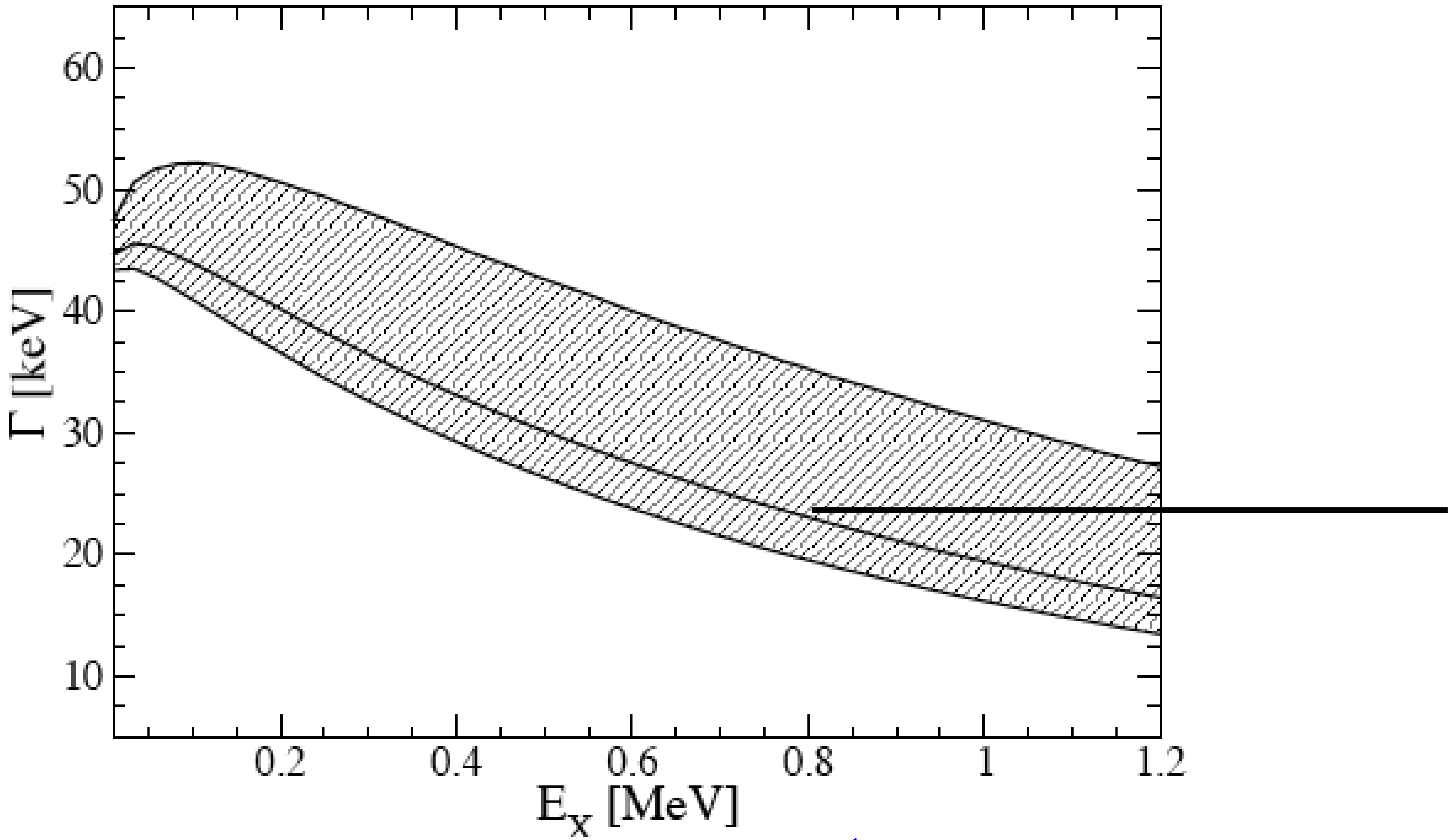
Wavefunction Renormalization



LO

NLO

$X(3872) \to D^0 \bar{D}^0 \pi^0$ at NNLO



$g = 0.6$ $\quad 0 \leq r_0 \leq (100\,\mathrm{MeV})^{-1}$ $\quad -1 \leq \eta \leq 1$

$$\left(\frac{g M_{DD^*}}{f_\pi} C_2(\Lambda_{\mathrm{PDS}}) + B_1(\Lambda_{\mathrm{PDS}})\right)(\Lambda_{\mathrm{PDS}} - \gamma) = \frac{\eta}{(100\,\mathrm{MeV})^3}$$

Corrections dominated by counterterms, pion loops are negligible

Agrees well with calculation with nonperturbative pions

Baru, et. al., PRD84:074029 (2011)

Bound on width of the X(3872)

TM,Phys.Rev. D92 (2015) no.3, 034019
arXiv:1503.02719

Zero binding energy: $\Gamma[X(3872) \to D^0 \bar{D}^0 \pi^0] = \Gamma[D^{*0} \to D^0 \pi^0]$
$= 36\,\mathrm{keV}$

XEFT + BE < 0.33 MeV:

$$28\,\mathrm{MeV} < \Gamma[X(3872) \to D^0 \bar{D}^0 \pi^0] < 42\,\mathrm{MeV}$$

PDG:

$$\frac{\Gamma[X(3872) \to D^0 \bar{D}^0 \pi^0]}{\Gamma[X(3872)]} > 32\%$$

Bound on total width:

$$\Gamma[X(3872)] < 131\,\mathrm{keV}$$

Why is $X(3872) \to \chi_{cJ}\pi^0$ **interesting?**

Heavy Quark Spin Symmetry (HQSS)
predicts relative rates

$$\Gamma_J \equiv \Gamma[X(3872) \to \chi_{cJ}\pi^0]$$

charmonium $\chi_{c1}(2^3P_1)$

$$\Gamma_0 : \Gamma_1 : \Gamma_2 :: 3p_\pi^3 : 5p_\pi^3 : 0 \approx 1 : 2.70 : 0$$

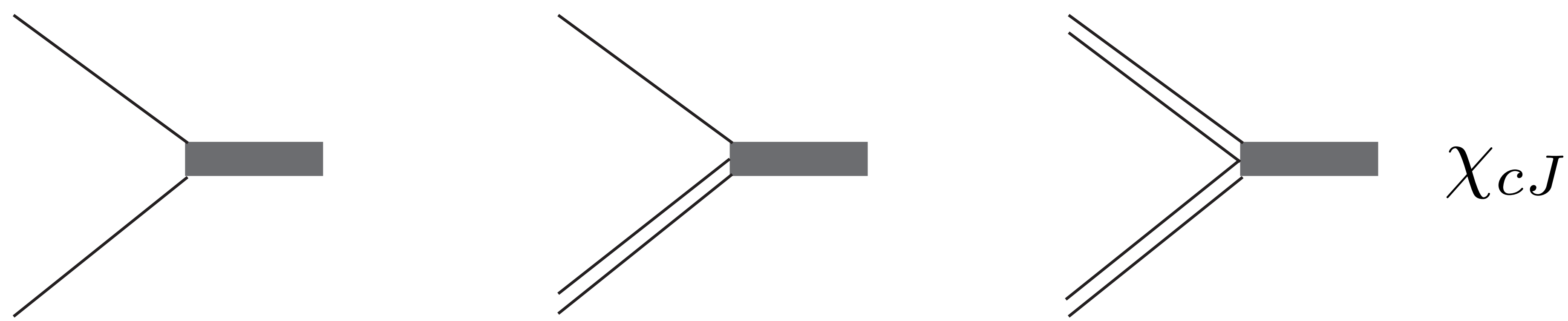
molecule

$$\Gamma_0 : \Gamma_1 : \Gamma_2 :: 4p_\pi^3 : 3p_\pi^3 : 5p_\pi^3 \approx 2.88 : 0.97 : 1$$

S. Dubynskiy,M.B. Voloshin, PRD 77, 014013 (2008)

Calculating $X(3872) \to \chi_{cJ}\pi^0$ in XEFT

coupling χ_{cJ} to D mesons, heavy quark spin symmetry



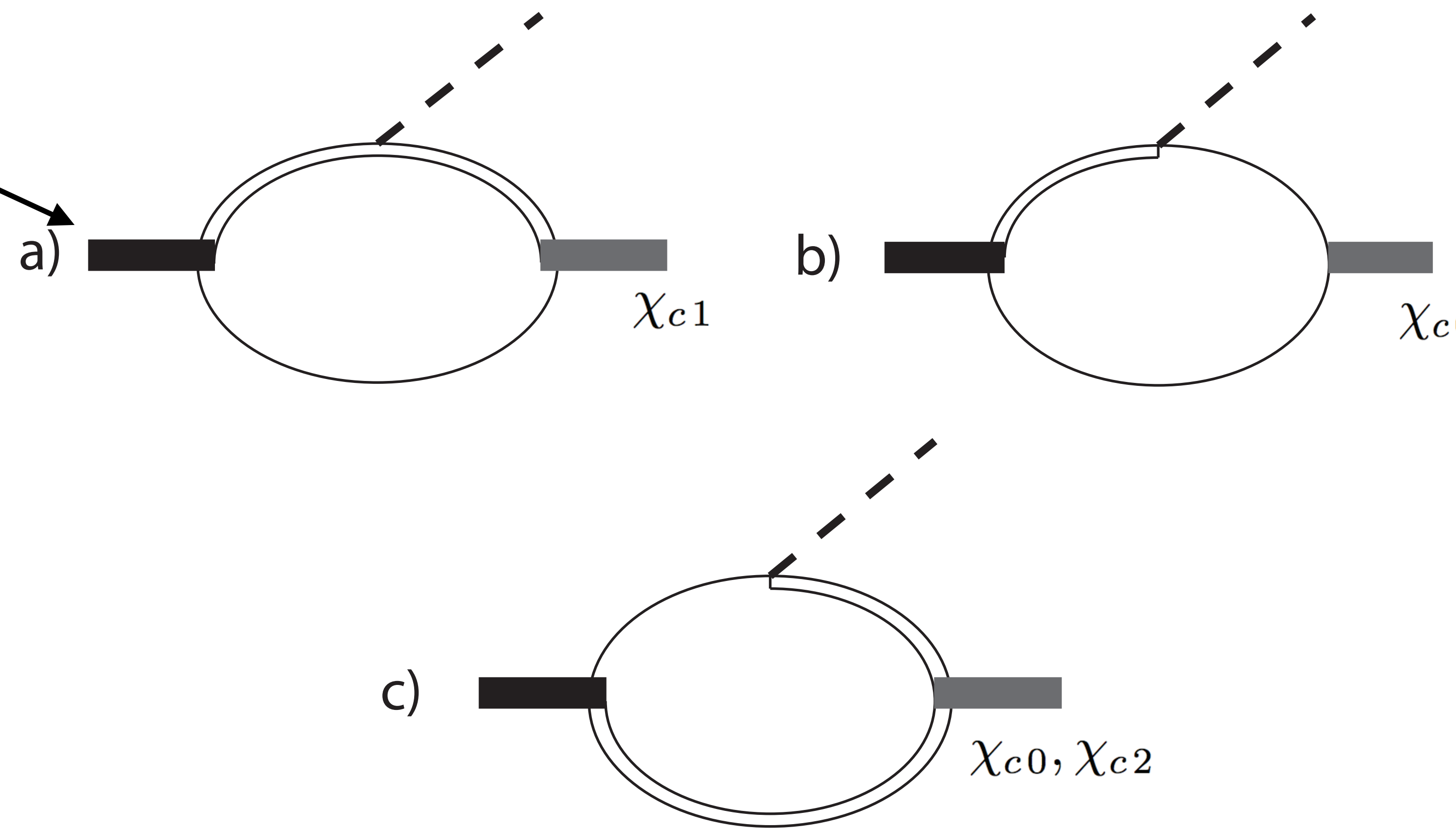
$$\langle D\bar{D}|\chi_{cJ}\rangle = 2\sqrt{6}\, g_1 \sqrt{m_{\chi_{c0}}} m_{D_0} \qquad g_1 \approx \frac{1}{457\,\mathrm{MeV}}$$

P. Colangelo, F. De Fazio, T. Pham, PRD69 (2004) 054023

contact interactions w/ onia, D mesons, pions (not shown)

Hadronic Loops

interpolating field
for X(3872)



coupling ~ $\sqrt{\dfrac{2\pi\gamma_n}{\mu_{DD^*}}}$

Nonrelativistic Power counting:

loops ~ v^5, propagators ~ v^{-2}, diagrams $\dfrac{p_\pi}{v}$

loops with contact interaction v^2 suppressed

Prediction

TM,Phys.Rev. D92 (2015) no.3, 034019
arXiv:1503.02719

$$\Gamma[X(3872) \to \chi_{c0}\pi^0] = \frac{2g^2 g_1^2}{9\pi^2 f_\pi^2}\gamma_n \mu_{DD^*}^2 \frac{m_{\chi_{c0}}}{m_{X(3872)}} p_\pi^3 F_0[\gamma_n, \Delta_0, E_\pi]^2 = 3.8\,\mathrm{MeV}$$

$$\Gamma[X(3872) \to \chi_{c1}\pi^0] = \frac{g^2 g_1^2}{6\pi^2 f_\pi^2}\gamma_n \mu_{DD^*}^2 \frac{m_{\chi_{c1}}}{m_{X(3872)}} p_\pi^3 F_1[\gamma_n, \Delta_0, E_\pi]^2 = 1.4\,\mathrm{MeV}$$

$$\Gamma[X(3872) \to \chi_{c2}\pi^0] = \frac{5g^2 g_1^2}{18\pi^2 f_\pi^2}\gamma_n \mu_{DD^*}^2 \frac{m_{\chi_{c2}}}{m_{X(3872)}} p_\pi^3 F_2[\gamma_n, \Delta_0, E_\pi]^2 = 1.2\,\mathrm{MeV}$$

exceeds total width! $\Gamma[X(3872)] < 1.2\,\mathrm{MeV}$

must include coupling to charged D mesons

Observed decays of X(3872) account for
>40% of branching fraction (PDG)

$$\sum_J \Gamma[X(3872) \to \chi_{cJ}\pi^0] < 0.6\,\Gamma[X(3872)] < 79\,\mathrm{keV}$$

neutral loops exceed this bound
by orders of magnitude

must be nearly cancelled by
loops w/ charged mesons

Including Charged Mesons

$$\Gamma[X(3872) \to \chi_{c0}\pi^0] = \frac{g^2 g_1^2}{9\pi^3 f_\pi^2}\mu_{DD^*}^4 \frac{m_{\chi_{c0}}}{m_{X(3872)}} p_\pi^3 \left(g_0 F_0[\gamma_n, \Delta_0, E_\pi] - g_+ F_0[\gamma_c, \Delta_+, E_\pi]\right)^2$$

$$\Gamma[X(3872) \to \chi_{c1}\pi^0] = \frac{g^2 g_1^2}{12\pi^3 f_\pi^2}\mu_{DD^*}^4 \frac{m_{\chi_{c1}}}{m_{X(3872)}} p_\pi^3 \left(g_0 F_1[\gamma_n, \Delta_0, E_\pi] - g_+ F_1[\gamma_c, \Delta_+, E_\pi]\right)^2$$

$$\Gamma[X(3872) \to \chi_{c2}\pi^0] = \frac{5g^2 g_1^2}{36\pi^3 f_\pi^2}\mu_{DD^*}^4 \frac{m_{\chi_{c2}}}{m_{X(3872)}} p_\pi^3 \left(g_0 F_2[\gamma_n, \Delta_0, E_\pi] - g_+ F_2[\gamma_c, \Delta_+, E_\pi]\right)^2$$

$$g_0^2\, \mathrm{Re}\Sigma_0'(-E_X) + g_+^2\, \mathrm{Re}\Sigma_+'(-E_X) = 1$$

$$g_0 = \sqrt{\frac{2\pi\gamma_n}{\mu_{DD^*}^2}}\cos\theta\,,\ g_+ = \sqrt{\frac{2\pi\gamma_c}{\mu_{DD^*}^2}}\sin\theta$$

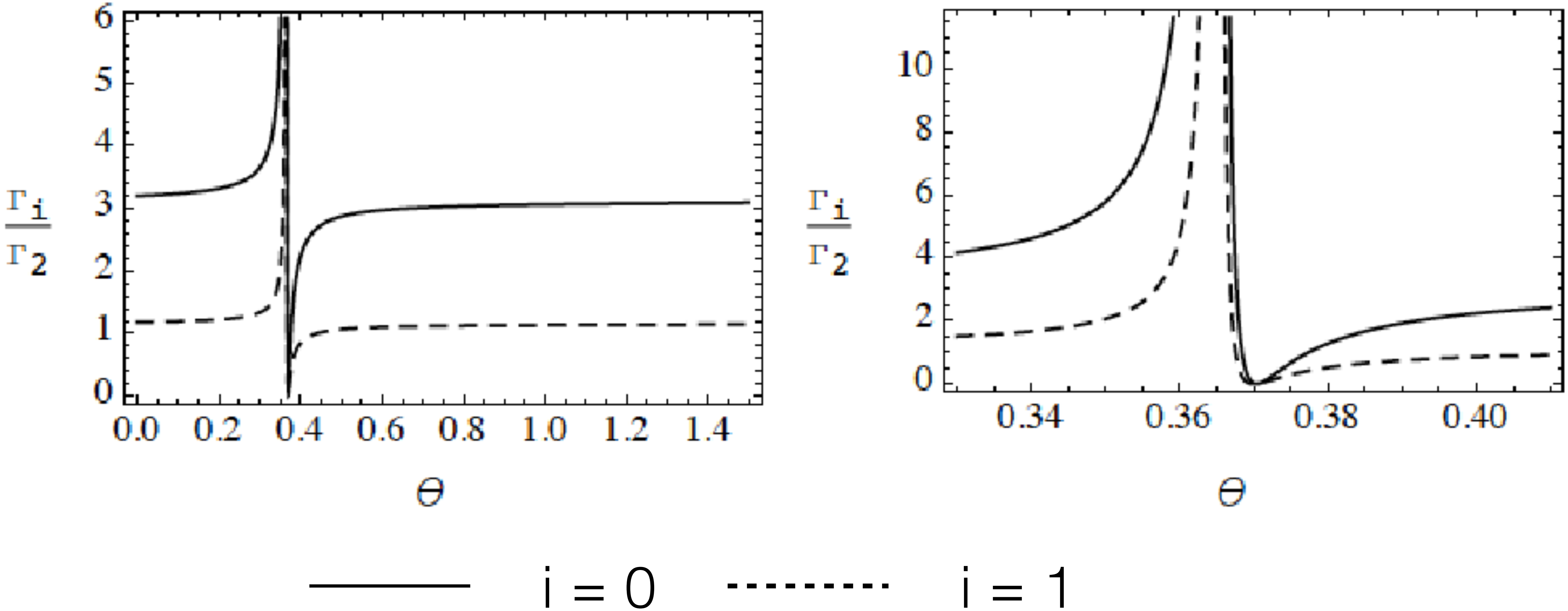
$$\gamma_c = 126\,\mathrm{MeV}$$

Bounds require $\theta = 0.37 \pm 0.04$

$$0.78 < g_0/g_+ < 0.99$$

I = 0

$$g_0/g_+ = 1$$

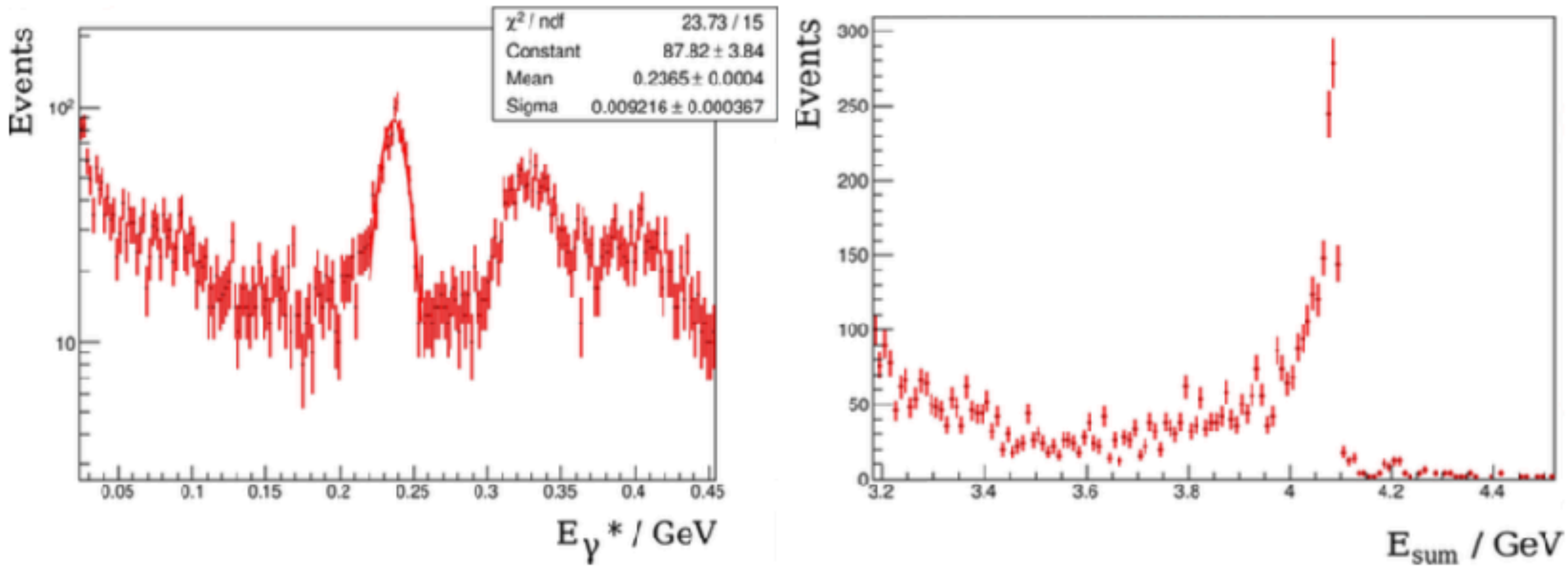


Predicted ratios differ from the HQSS predictions

$$\Gamma_2 : \Gamma_1 : \Gamma_0 :: 3.3 : 1.2 : 1$$

for allowed value of $\theta \approx 0.37$

Can $X(3872) \to \chi_{cJ}\pi^0$ be measured at PANDA?



S. Lange, et. al., arXiv:1311.7597

reconstructing ${}^3F_4$ charmonia in $J/\psi\gamma\gamma\gamma$

cut $E_\gamma > 150\,\mathrm{keV}$

Conclusions

Using XEFT calculation of $X(3872) \to D^0 \bar{D}^0 \pi^0$

$$\Gamma[X(3872)] < 131\,\mathrm{keV}$$

P̄ANDA: width & line shape will test XEFT, models

Hadronic loops for $X(3872) \to \chi_{cJ}\pi^0$ decays
must include couplings to charged mesons
$0.78 < g_0/g_+ < 0.99$ **near I = 0 state**

P̄ANDA: measurement tests HQSS, molecular interpretation, hadronic loops

Back Up Slides

Factorization

alternative approach to X(3872) decays

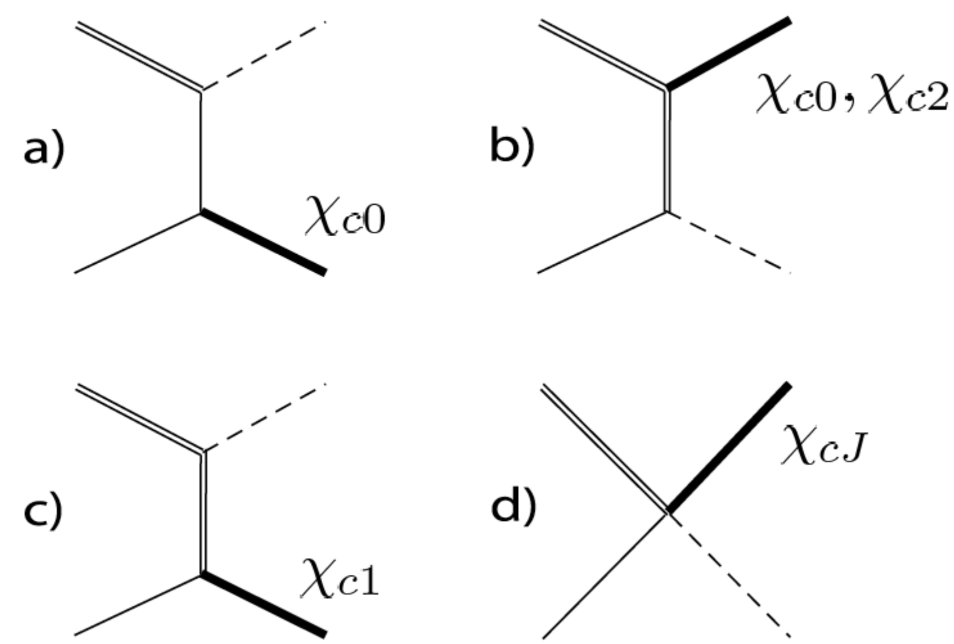
S.Fleming, T.M., PRD78 (2008) 094019

S.Fleming, T.M., PRD85 (2012) 014016

$$\Gamma[X(3872) \to F.S.] \propto \mathcal{O}_{XEFT} \times \sigma[D^0 \bar{D}^{*0} + c.c. \to F.S.]$$

$$\frac{1}{3}\sum_{\lambda} |\langle 0| \frac{1}{\sqrt{2}} \epsilon_i(\lambda)\,(V^i\,\bar{P} + \bar{V}^i\,P)|X(3872,\lambda)\rangle|^2$$

$$\sim |\psi(0)|^2$$



Relationship between Factorization, Hadronic Loops

hadronic loop integral

$$\mathcal{M}_{1b}[X(3872) \to \chi_{c0}\pi^0] = \int^{\Lambda} \frac{d^3 l}{(2\pi)^3} \psi_{DD^*}(\vec{l}\,)\, \mathcal{M}[D^{*0}(\vec{l}\,)\bar{D}^0(-\vec{l}\,) \to \chi_{c0}\pi^0]$$

$$\psi_{DD^*}(\vec{l}) = \frac{\sqrt{8\pi\gamma}}{l^2 + \gamma^2}$$

$$l^2 \sim m_D E_\pi \sim (850\,\mathrm{MeV})^2$$

$$\gamma_n = 14\,\mathrm{MeV}, \gamma_c = 126\,\mathrm{MeV}$$

For $\gamma_{n,c} \ll \Lambda \ll \sqrt{m_D E_\pi}$

expand in $l^2/(m_D E_\pi)$ recover results in factorization approach