Status of the X(3872)

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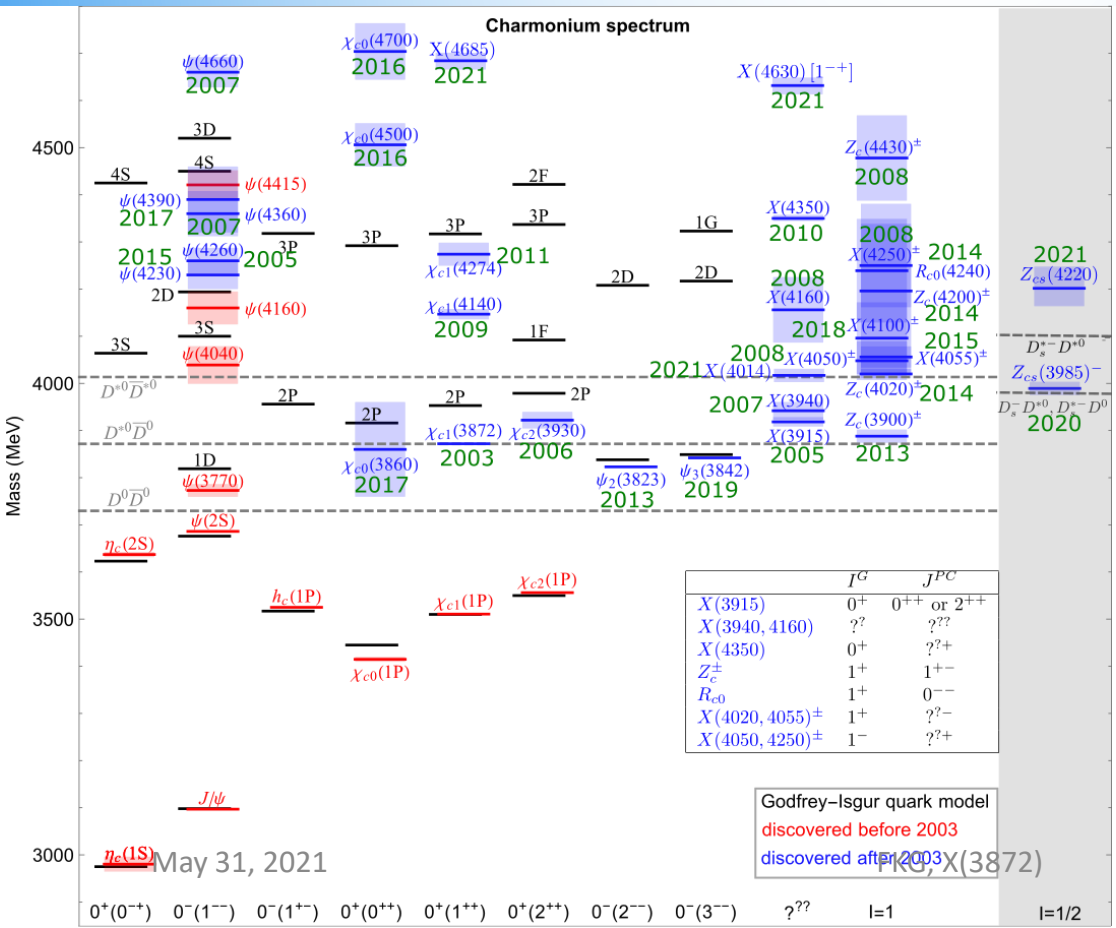


The 10th International Workshop on Charm Physics (CHARM 2020/2021)

31 May – 5 June 2021

$X(3872)$ aka $\chi_{c1}(3872)$

- Discovered in $B^{\pm} \to K^{\pm} J/\psi \pi^+ \pi^-$ Belle, PRL91(2003) 262001
- $J^{PC} = 1^{++}$ LHCb, PRL110(2013) 222001 couple to $D^0 \overline{D}^{*0} + c.c.$ in S-wave
- Mass: extremely close to the $D^0 \overline{D}^{*0}$ threshold, binding energy $\delta \equiv M_{D^0} + M_{D^{*0}} - M_X$

  $\delta = 0.01 \pm 0.14$ MeV LHCb, PRD102(2020)092005; $\delta = 0.12 \pm 0.13$ MeV LHCb, JHEP08(2020)123

  Inclusive b-hadron decays $B^+ \to K^+ X(3872)$

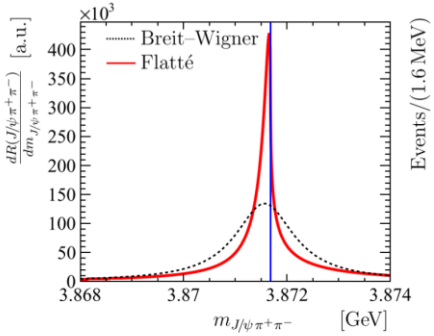
- BW width: < 1.2 MeV Belle, PRD84(2011)052004

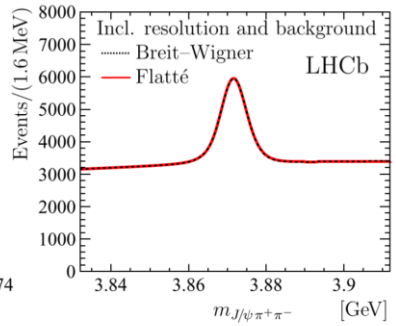
  1.39 ± 0.26 MeV LHCb, PRD102(2020)092005; 0.96 ± 0.28 MeV LHCb, JHEP08(2020)123

  from BW fits;

  width from the Flatté analysis is much smaller: LHCb, PRD102(2020)092005

Mode (MeV)	Mean (MeV)	FWHM (MeV)
$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$





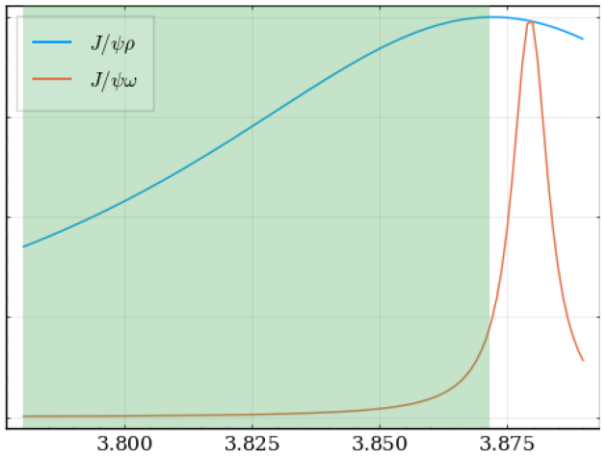
BW not suitable for near-threshold structures

- Strong coupling to $D^0 \overline{D}^{*0} + c.c.$: $\mathcal{B} > 30\%$ Belle, PRD81(2010)031103

$X(3872)$ aka $\chi_{c1}(3872)$

- Huge isospin breaking PDG2020, average of BESIII, 122(2019)232002 and BaBar, PRD82(2010)011101

$\frac{\mathcal{B}(X\to\omega J/\psi)}{\mathcal{B}(X\to\rho J/\psi)} = 1.1 \pm 0.4$, largely from phase space difference



$\frac{g_{X\rho J/\psi}}{g_{X\omega J/\psi}} = 0.26^{+0.08}_{-0.05}$ C. Hanhart et al., PRD85(2012)011501(R)

- Radiative decays

$\frac{\mathcal{B}(X\to\gamma\psi\prime)}{\mathcal{B}(X\to\gamma J/\psi)} = 3.4 \pm 1.4$ BaBar, PRL102(2009)132001

$= 2.46 \pm 0.70$ LHCb, NPB886(2014)665

< 2.1 @90% C.L. Belle, PRL107(2011)091803

< 0.59 @90% C.L. BESIII, PRL124(2020)242001

- Productions: found in $B \to KX, B \to K\pi X, e^+e^- \to \gamma X, pp/p\bar{p}$ inclusive, $\gamma^*\gamma$

Models and crucial quantities

- $D\bar{D}^*$ hadronic molecule, predicted by N.A.Törnqvist ZPC61(1993)525
- Diquark-antidiquark tetraquark L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, PRD71(2005)014028
- Mixture of $D\bar{D}^*$ hadronic molecule with $c\bar{c}$ Yu.S. Kalashnikova, PRD72(2005)034010; …
  E. Eichten et al., PRD17(1978)3090, D21(1980)203

Important quantities in determining the $D\bar{D}^*$ component (compositeness $1-Z$) inside $X(3872)$:

- width of long-distance processes: $X \to D^0\bar{D}^0\pi^0, D\bar{D}\gamma$ => coupling constant to $D\bar{D}^*$
- binding energy
- $D\bar{D}^*$ scattering length (from lattice)

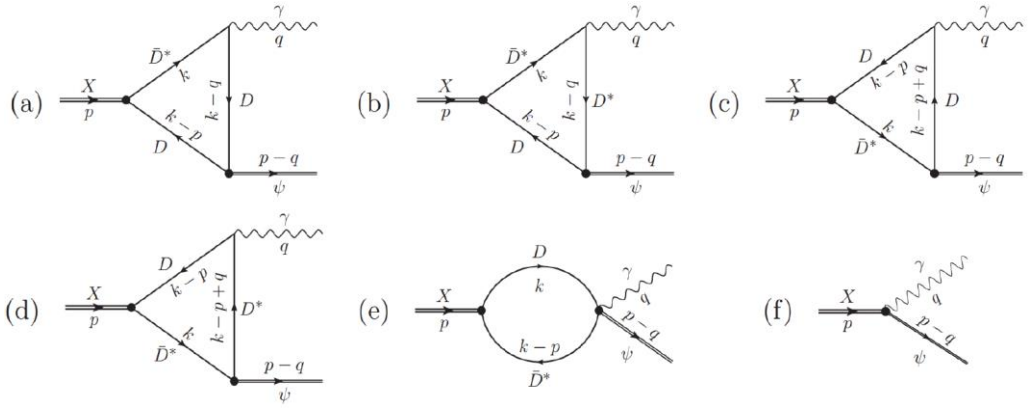
$$g_{\rm NR}^2 = (1-Z)\frac{2\pi}{\mu^2}\sqrt{2\mu\delta}\left[1+\mathcal{O}(\sqrt{2\mu\delta}/\beta)\right] \qquad a_0 = \frac{-2(1-Z)}{(2-Z)\sqrt{2\mu\delta}}$$

S. Weinberg, PR137(1965)B672;
FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, RMP90(2018)015004

Debates

Debates regarding processes involving short-distance physics, e.g.,

- radiative decays $X \to \gamma J/\psi$, $X \to \gamma \psi'$:
  ratio suggested to be sensitive to internal structure; however,
  - loops are sensitive to unknown couplings $g_{\psi' DD}/g_{J/\psi DD}$
  - UV divergent loops, needs a counterterm (short-distance physics)



FKG, Hanhart, Kalashnikova, Meißner, Nefediev, PLB742(2015)394
see also Mehen, Springer, PRD83(2011)094009

- productions at hadron colliders:
  the more extended, the more difficult to be produced, $\sigma \propto \delta^{1/2}$
  Often assumed that tetraquark is much more compact than molecule;
  the $X(3872)$ is extended by observation: $D^0\overline{D}^{*0}$ component

For more discussions, talk by Kevin Ingles in Session "Production"

Factorization into short-distance and long-distance parts E. Braaten, M. Kusunoki, PRD72(2005)014012

Spin partners

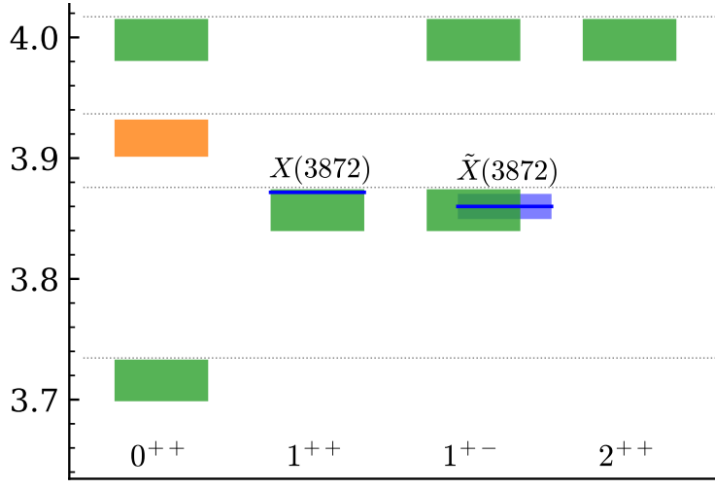
Different models normally lead to distinct heavy-quark spin structure

- $X_2(4013)$ $[D^*\bar{D}^*]$ expected in molecular models

  Törnqvist, ZPC61(1994)525; C.-Y. Wong, PRC69(2004)055202; E. Swanson, JPCS9(2005)79; J. Nieves, M.P. Valderrama, PRD86(2012)056004; FKG, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama, PRD88(2013)054007;…

  Heavy-quark spin symmetry:

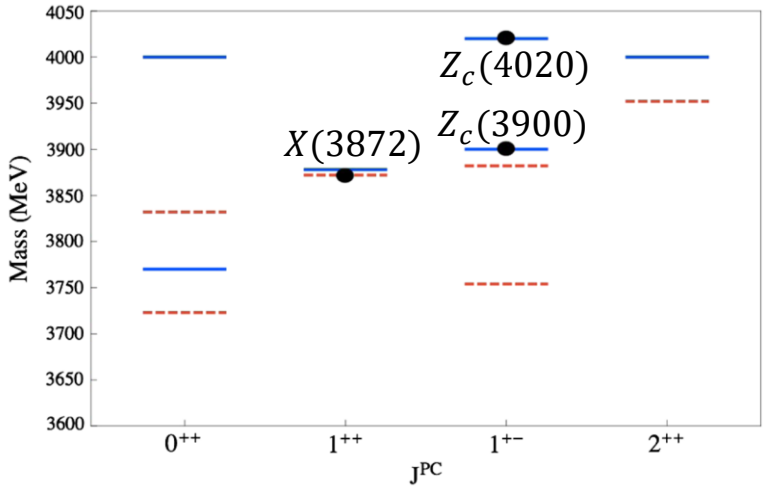
  $$M_{X_2} - M_X \approx M_{D^*} - M_D$$



  Mol. spectrum using a VMD interaction

  X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

- Tetraquark model



  L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, PRD89(2014)114010

  $$\mathcal{H} \approx 2\kappa_{qc}(s_q \cdot s_c + s_{\bar{q}} \cdot s_{\bar{c}})$$

  Spectrum similar with molecular model from fixing κ_{qc} using

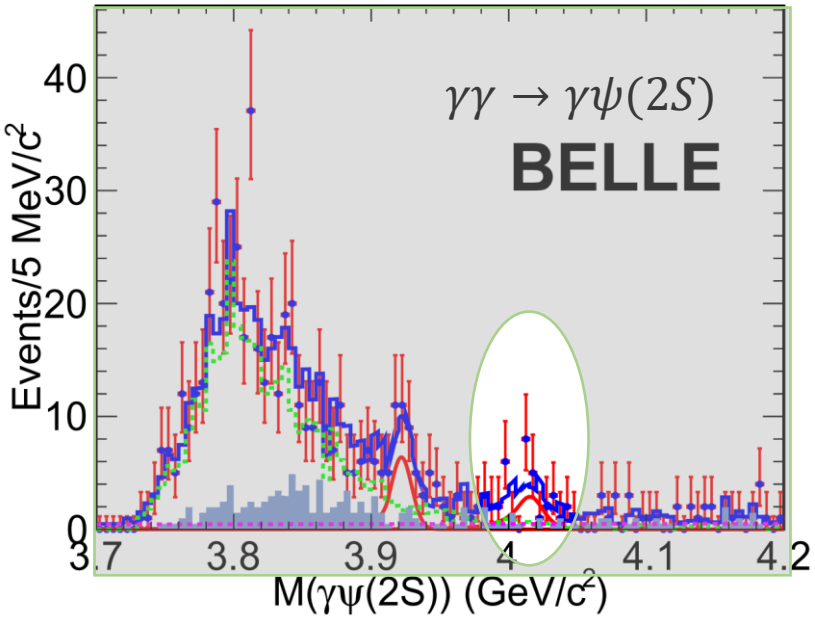
  $$M_{Z_c(4020)} - M_{Z_c(3900)} \approx M_{D^*} - M_D$$

Distinct spectra in the $P = -$ sector (backup)

Evidence for X_2?

- Structure observed in $\gamma\gamma \to \gamma\psi(2S)$

Belle, arXiv:2105.06605



$M = 4014.4 \pm 4.1 \pm 0.5$ MeV,

$\Gamma = 6 \pm 16 \pm 6$ MeV

significance: 3.0σ

- Width of $X_2 \to D\bar{D}, \bar{D}D^* + c.c.$ predicted in molecular model:

$\sim 2 - 8$ MeV M. Albaladejo, FKG, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama, EPJC75(2015)547

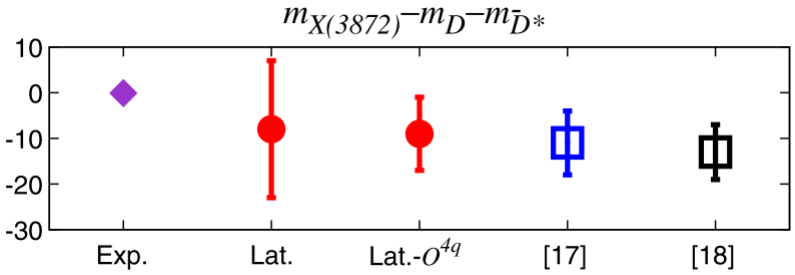
~ 50 MeV V. Baru, E. Epelbaum, A.A. Filin, C. Hanhart, U.-G. Meißner, A.V. Nefediev, PLB763(2016)20

Lattice results

Evidence found below $D\bar{D}^*$ threshold

- Isospin symmetric calculation
- Both $\bar{c}c$ and $D\bar{D}^*$ operators are needed

S. Prelovsek, L. Leskovec, PRL111(2013)192001;
M. Padmanath, C. Lang, S. Prelovsek, PRD92(2015)034501



[18] S.H. Lee et al. [Fermilab&MILC], arXiv:1411.1389

ERE parameters from S. Prelovsek, L. Leskovec (2013)

$$a_{D\bar{D}^*} = (-1.7 \pm 0.4)\ \text{fm}, \qquad r_{D\bar{D}^*} = (0.5 \pm 0.1)\ \text{fm}$$

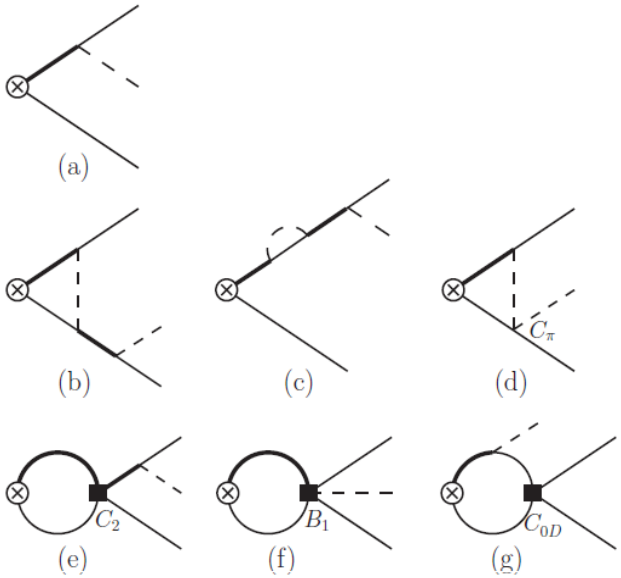
lead to an estimate of the compositeness $1 - Z \gtrsim 0.7$

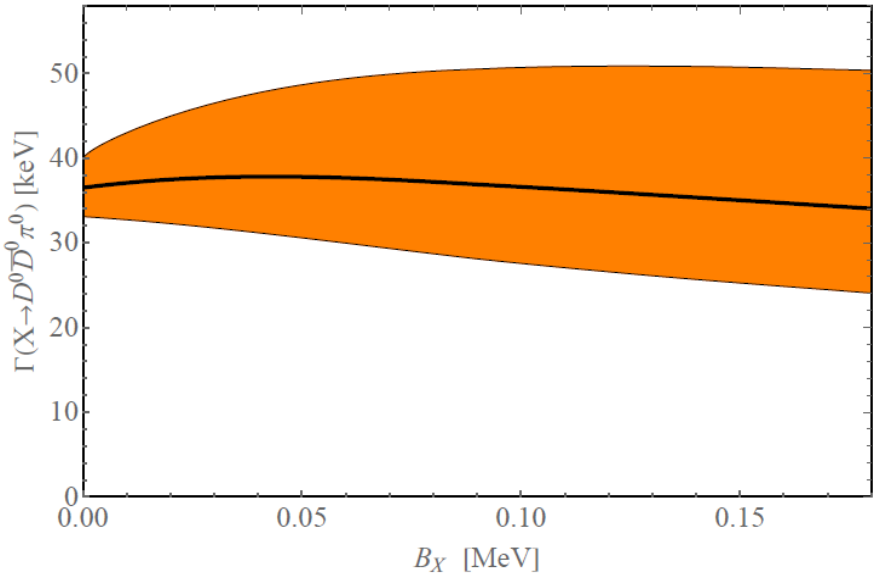
- But a small lattice volume was used: $L = 1.98$ fm

X(3872) width

- $X(3872) \to D^0 \bar{D}^0 \pi^0$ in XEFT:

S. Fleming et al., PRD76(2007)034006;
L. Dai, FKG, T. Mehen, PRD101(2020)054024





In the molecular picture: $\Gamma(X \to D^0 \bar{D}^0 \pi^0) = 36^{+14}_{-12}$ keV; would be smaller if $X(3872)$ is non-molecular

- Galilean invariant formulation of XEFT

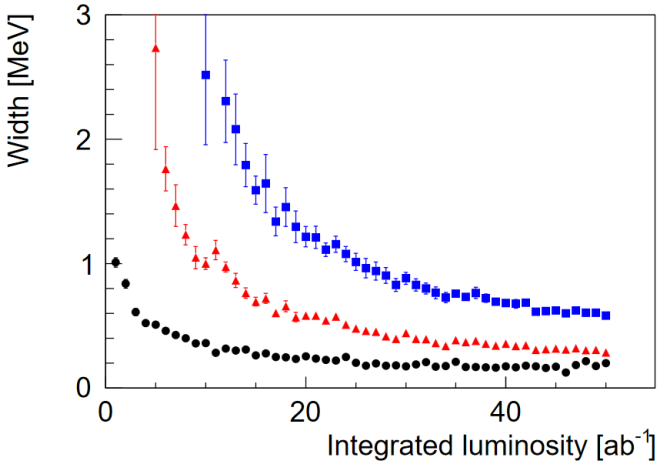
E. Braaten, L.-P. He, J. Jiang, PRD103(2021)036014

X(3872), precisely

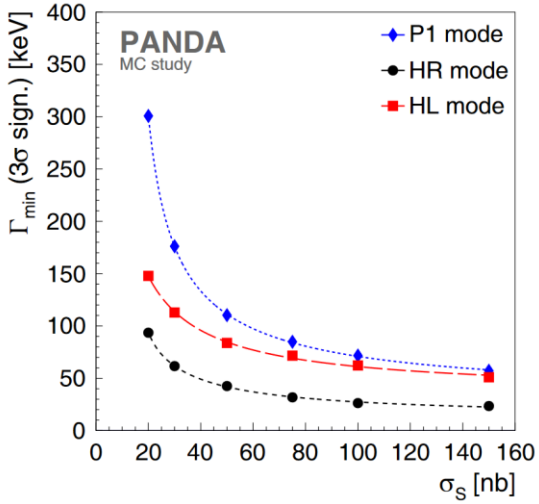
- Belle-II

  Sensitivity can reach 180 keV

H. Hirata, T. Iijima, Y. Kato [Belle II], JPS Conf. Proc. 26 (2019) 031008



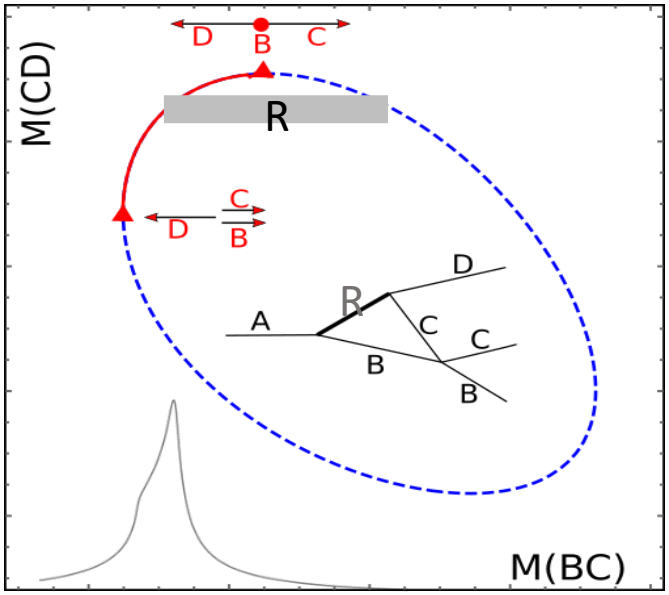
- PANDA EPJA55(2019)42



- PANDA can also measure the binding energy beyond the uncertainties of $M_{D^{(*)0}}$

S. Sakai, H.-J. Jing, FKG, PRD 102 (2020) 114041

Triangle singularity (TS)



- logarithmic branch point, can produce a peak, mimicking a resonance
- often close to a two-body threshold

$$m_A^2 \in \left[(m_R + m_B)^2,\ (m_R + m_B)^2 + \frac{m_B}{m_C}\left[(m_R - m_C)^2 - m_D^2 \right] \right]$$

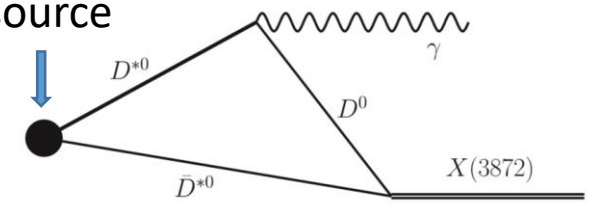
$$m_{BC}^2 \in \left[(m_B + m_C)^2,\ (m_B + m_C)^2 + \frac{m_B}{m_R}\left[(m_R - m_C)^2 - m_D^2 \right] \right]$$

- very sensitive to kinematic variables

Precision physics of X(3872)

FKG, PRL122 (2019) 202002

Short distance $D^{*0}\bar{D}^{*0}$ source



PHYSICAL REVIEW D **99,** 054028 (2019)

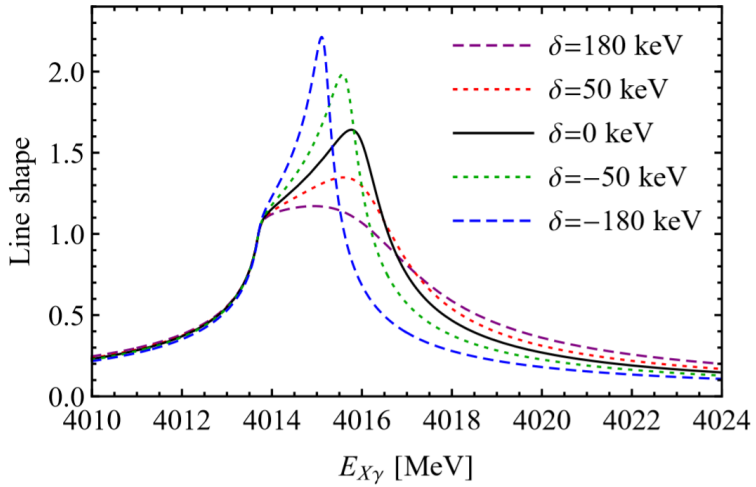
Radiative and pionic transitions $Z_c(4020)^0 \to X(3872)\gamma$ and $Z_c(4020)^\pm \to X(3872)\pi^\pm$

M. B. Voloshin

William I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis, Minnesota 55455, USA, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA, and Institute of Theoretical and Experimental Physics, Moscow 117218, Russia

(Received 12 February 2019; published 28 March 2019)

$$E_{X\gamma}^{\rm TS} \simeq 2M_{D^{*0}} + \frac{1}{2M_{D^0}}\left(M_{D^{*0}} - M_{D^0} - 2\sqrt{-M_{D^0}\delta} + \delta\right)^2$$



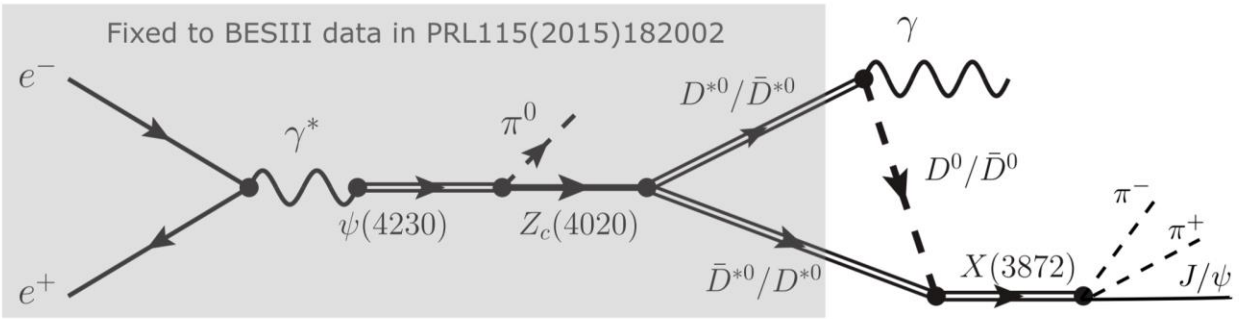
- Cusp fixed at the $D^{*0}\bar{D}^{*0}$ threshold
- Peak fixed at the TS energy:

δ (keV)	$E_{X\gamma}^{\rm TS}$ (MeV)
-180	$4015.2 - i0.1$
-50	$4015.7 - i0.2$
0	$4016.0 - i0.4$

Precision physics of X(3872)

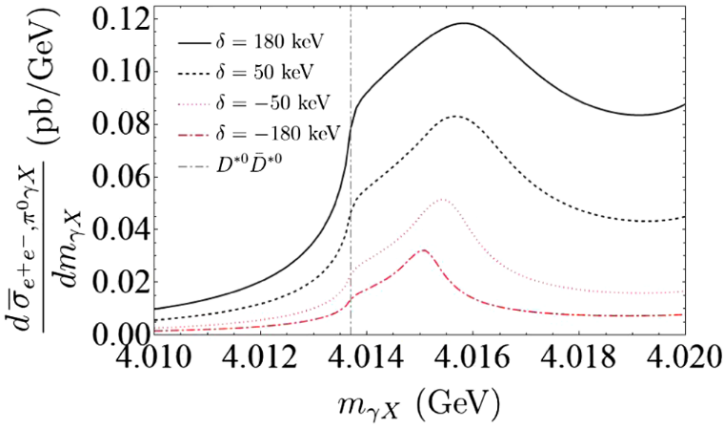
Cross section estimate (not precise prediction): S. Sakai, H.-J. Jing, FKG, PRD 102 (2020) 114041

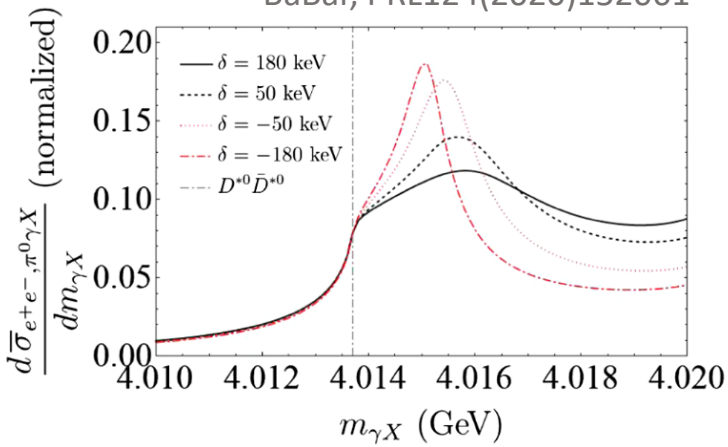
- Consider $e^+e^- \to \psi(4230) \to \pi^0 Z_c(4020)^0 \to \pi^0\gamma X(3872)$,



- Consider $X(3872) \to J/\psi\pi^+\pi^-$ with a $X(3872)$ width of 100 keV
  take $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 4.1\%$

BaBar, PRL124(2020)152001

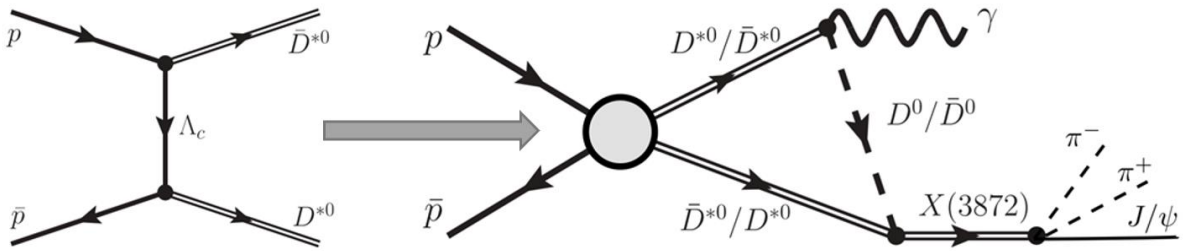




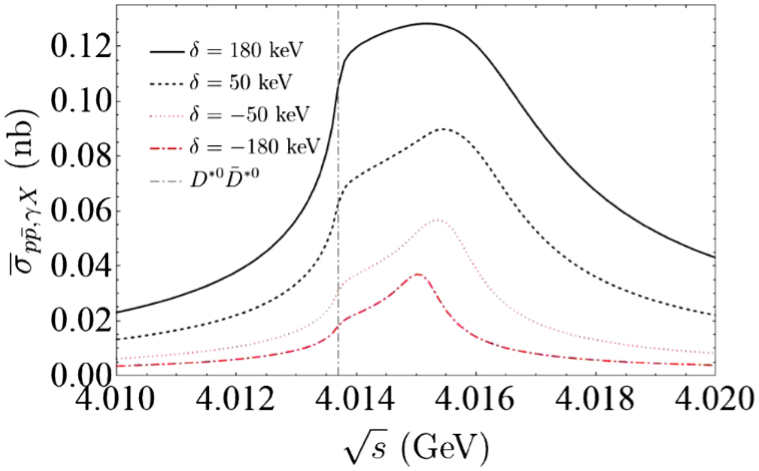
The cross section can be higher at higher energies, e.g. above 4.4 GeV, but seems still difficult for STCF/SCTF…

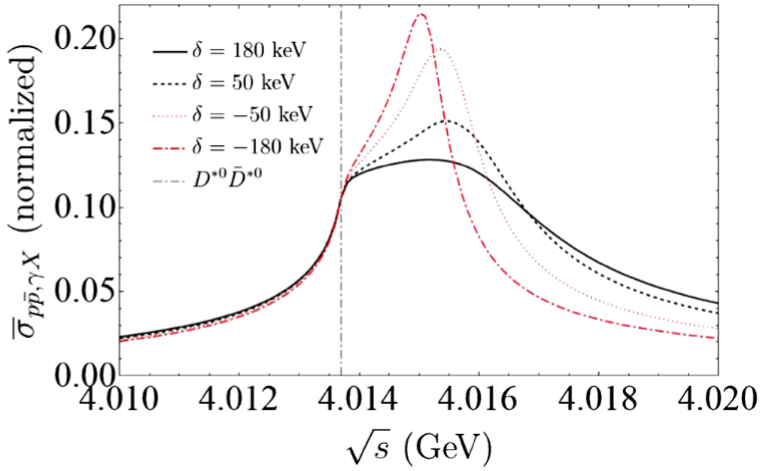
Precision physics of X(3872)

Cross section estimate: $p\bar{p} \to \gamma X(3872)$ S. Sakai, H.-J. Jing, FKG, PRD 102 (2020) 114041



- $\sigma(p\bar{p} \to \gamma X) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-) = \mathcal{O}(10\ \text{pb})$





- $\mathcal{O}(2 \times 10^3)$ events taking into account $\mathcal{B}(J/\psi \to \ell^+\ell^-) \simeq 12\%$ for an integrated luminosity of 2 fb^{-1} at PANDA

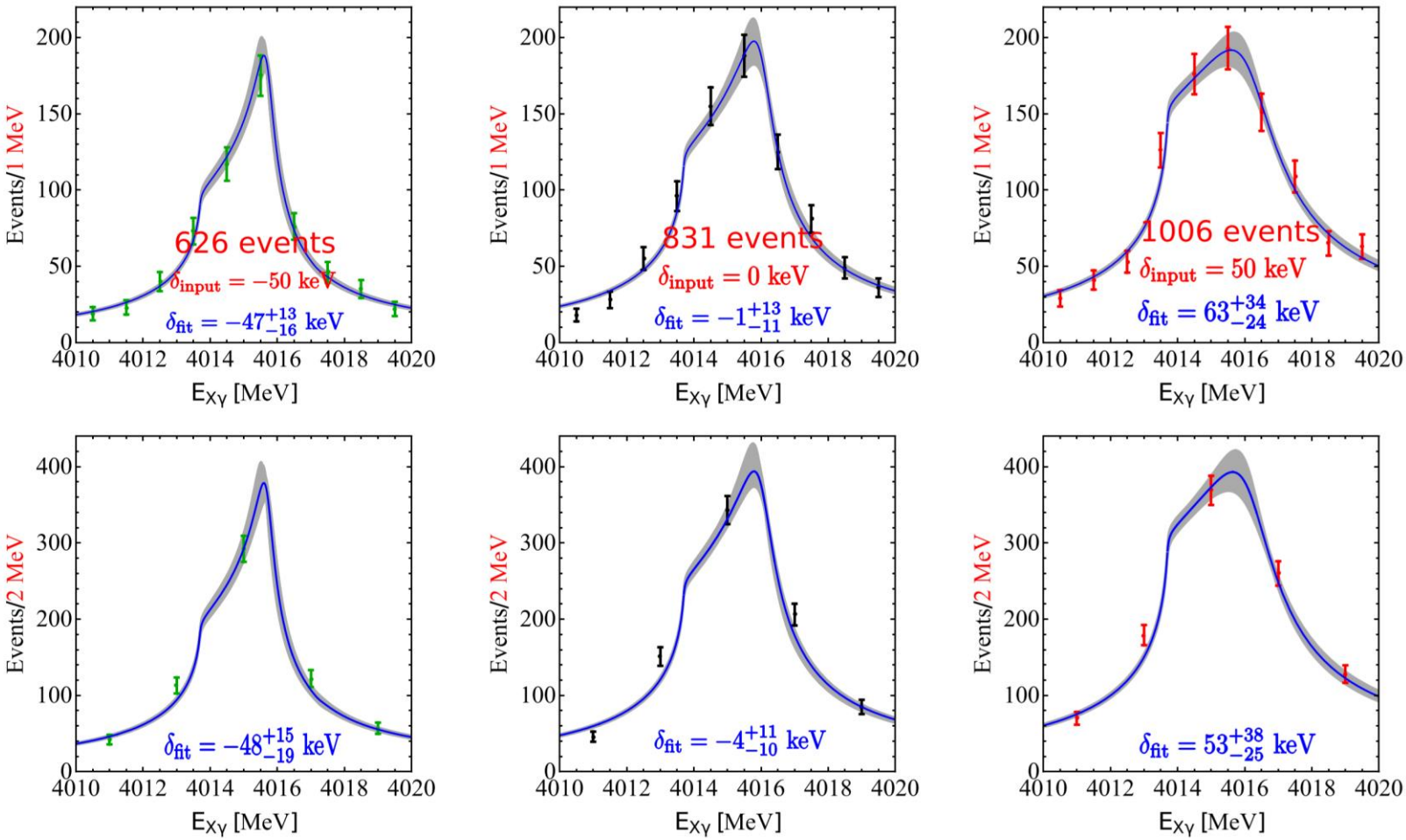
PANDA, EPJA55(2019)42

Precision physics of X(3872)

- Directly probe δ, uncertainty can be smaller than that of the $D^{(*0)}$ masses

Monte Carlo simulation of the sensitivity:

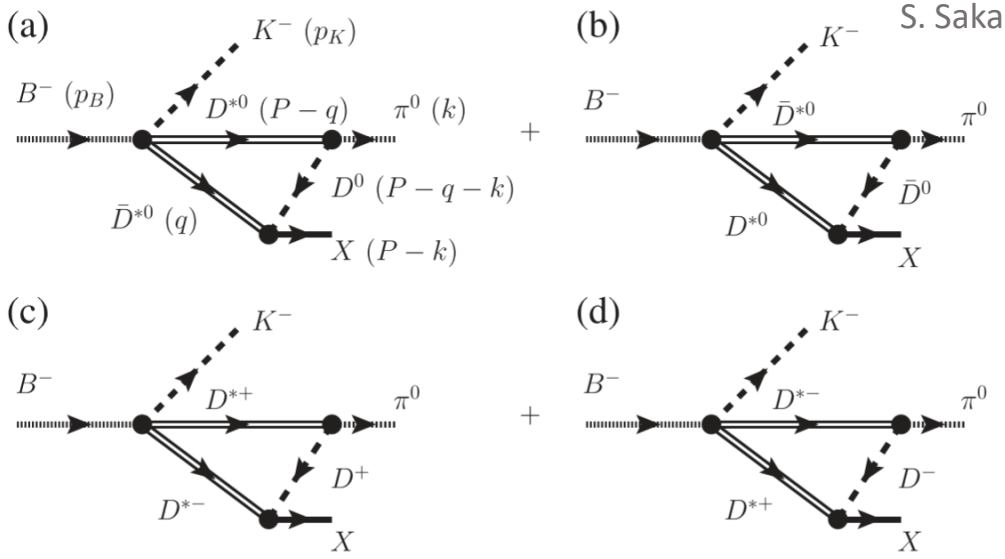
FKG, PRL122(2019)202002



Effects of energy resolution studied in P. G. Ortega, E. Ruiz Arriola, arXiv:2007.11608

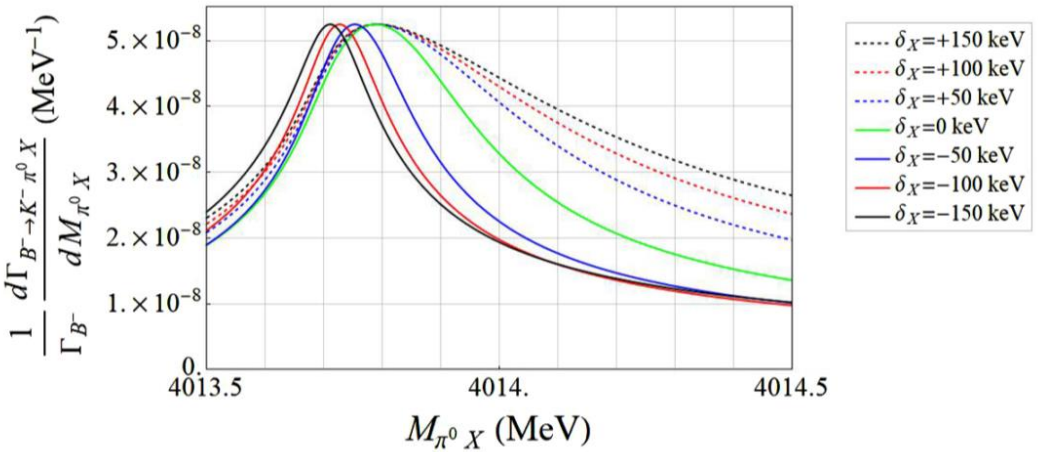
$B \to K\pi X(3872)$

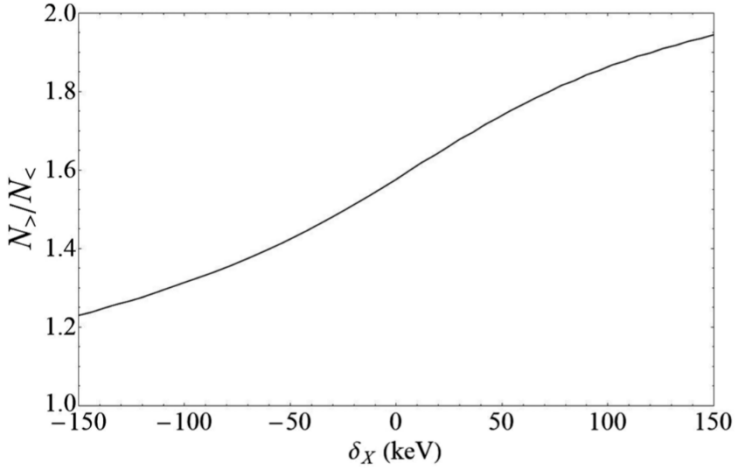
S. Sakai, E. Oset, FKG, Phys.Rev.D101(2020)054030



$$\frac{N_>}{N_<} \equiv \frac{\int_{M^{\max}}^{M^{\max}+\delta} dM_{\pi^0 X}\left(\overline{d\Gamma_{B^-\to K^-\pi^0 X}/dM_{\pi^0 X}}\right)}{\int_{M^{\max}-\delta}^{M^{\max}} dM_{\pi^0 X}\left(\overline{d\Gamma_{B^-\to K^-\pi^0 X}/dM_{\pi^0 X}}\right)}$$

Asymmetric line shape

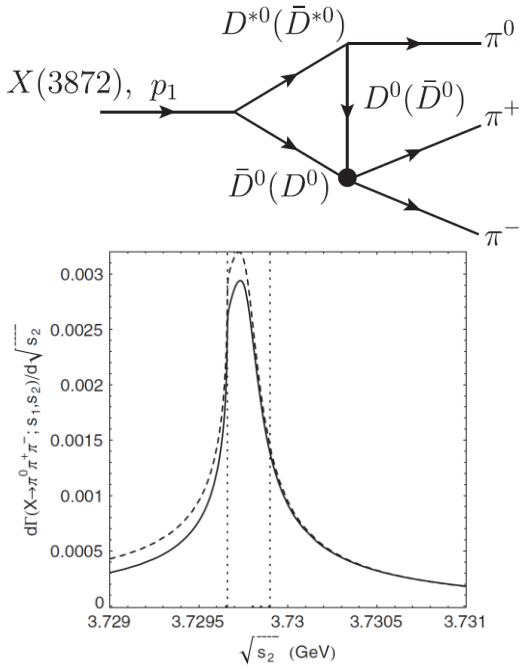




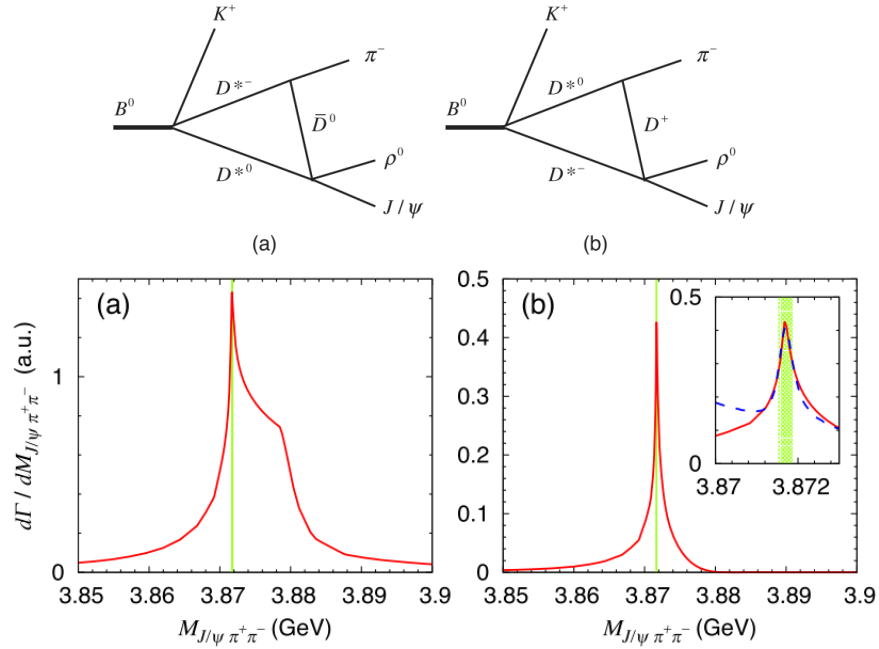
More TS effects for X(3872)

- TS peak in $X(3872) \to \pi^0\pi^+\pi^-$

  N. Achasov, G. Shestakov, PRD99 (2019) 116023



- Impact of TS in the X(3872) signal in $B \to (J/\psi\pi^+\pi^-)K\pi$: S. Nakamura, PRD 102 (2020) 074004



- More TS effects for the production of $X(3872)$

  Talk by Liping He, Session "Production"

  $B \to K\pi X(3872)$ E. Braaten, L.-P. He, K. Ingles, PRD 100 (2019) 074028

  Production of $X(3872)$ at hadron collider E. Braaten, L.-P. He, K. Ingles, PRD100 (2019) 094006

  $e^+e^- \to \gamma X(3872)$ E. Braaten, L.-P. He, K. Ingles, PRD 101 (2020) 014021

  $e^+e^- \to \gamma D^0\bar{D}^{*0}$ E. Braaten, L.-P. He, K. Ingles, PRD 101 (2020) 096020

X atom

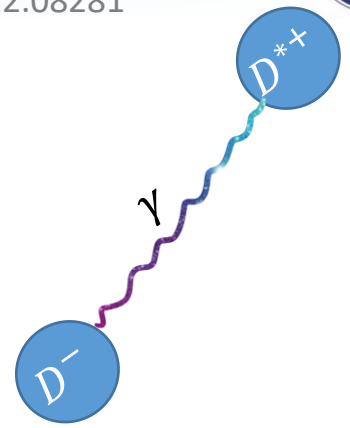
Z.-H. Zhang, FKG, arXiv:2012.08281

- Bohr radius of Coulomb bound state of D^-D^{*+}, D^+D^{*-} :

  hadronic atoms $$r_B = \frac{1}{\alpha\mu_c} = 27.86\ \text{fm}$$

- Coulomb binding energies:

$$E_n = \frac{\alpha^2\mu_c}{2n^2} = \frac{25.81\ \text{keV}}{n^2}$$



- X atom: The ground state $D^-D^{*+} - D^+D^{*-}$ atom with $C = +$; correction due to strong interaction
- Production:
  - the short-distance part is related to that of X(3872) via isospin symmetry
  - the long-distance part can be computed in NREFT

$$\frac{d\sigma[pp \to A + y]}{d\sigma[pp \to X + y]} = \frac{|g_{A,\text{str}}|^2}{|g_X|^2} \gtrsim 1 \times 10^{-3}$$

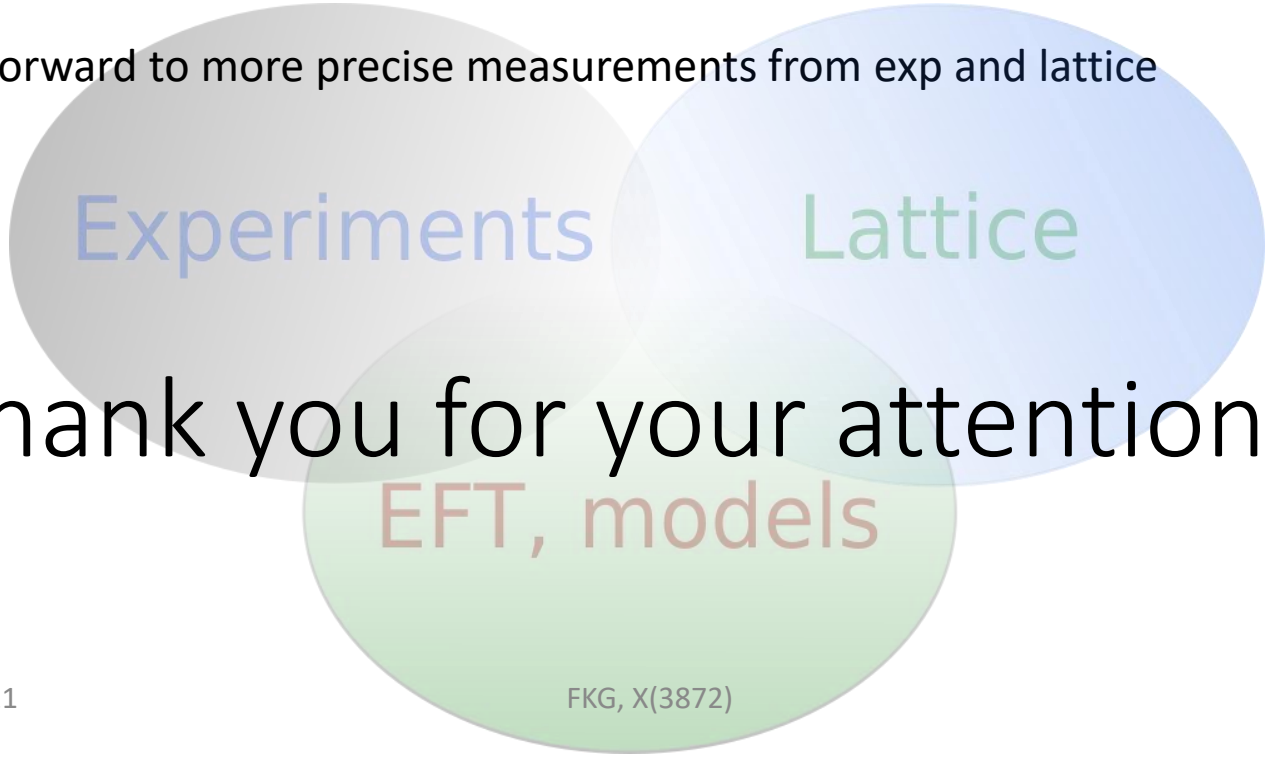
- X atom can be searched for at LHCb and PANDA

For more details, talk by Zhenhua Zhang, Session “Charm Spectroscopy”

Conclusion

- The X(3872) has been discovered for 18 years, debates continue
- Spin partner of the X(3872) observed?
- New insights regarding X(3872):
  - Measuring the binding energy using TS, uncertainty not limited by that of $D^{(*)0}$ masses, best at PANDA (high production rate and high energy resolution)
  - X atom may be used to settle the debates regarding the production

- Looking forward to more precise measurements from exp and lattice

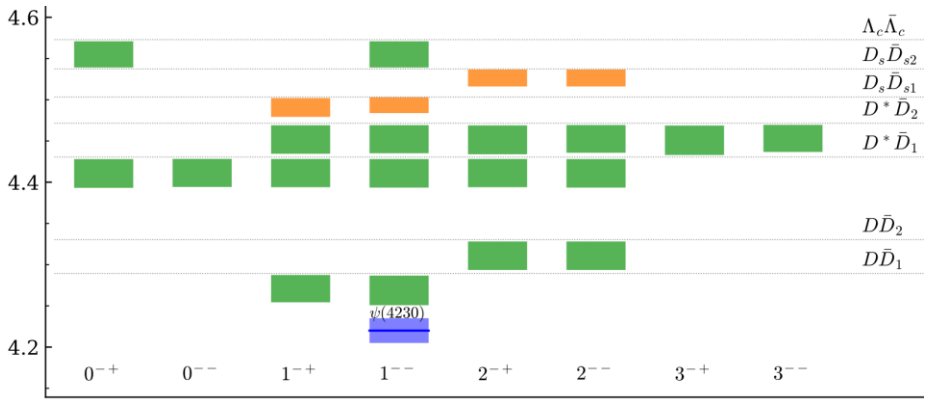


Thank you for your attention!

Spin partners

Needs to be distinguished from negative-parity sectors:

- Molecular model (VMD interaction)

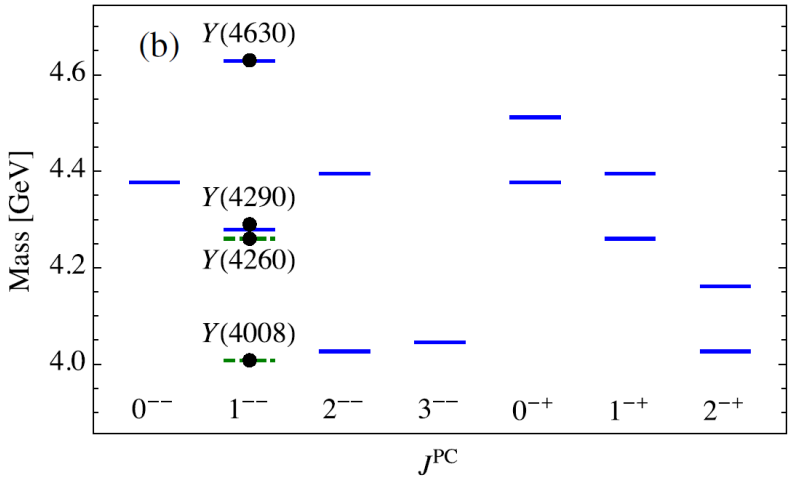


Mol. spectrum using a VMD interaction

X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

- Tetraquark model

$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}[s(s+1) + \bar{s}(\bar{s}+1) - 3].$$

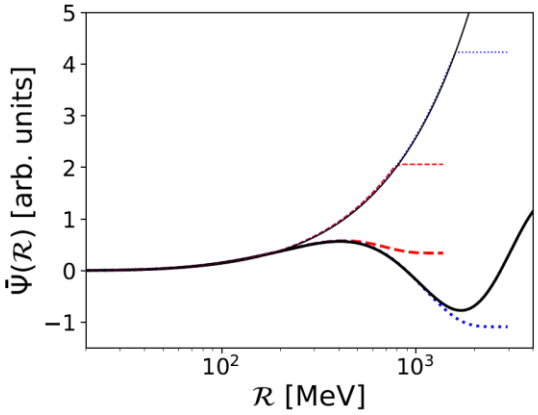


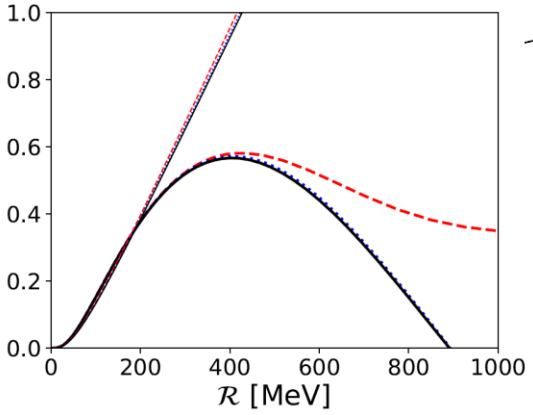
M. Cleven, FKG, C. Hanhart, Q. Wang, Q. Zhao, PRD92(2015)014005
using inputs from
L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, PRD89(2014)114010

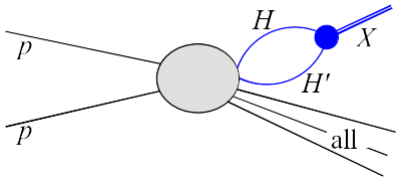
Production estimates

- Order-of-magnitude estimates of cross sections at hadron colliders in the molecular picture M. Albaladejo, FKG, C. Hanhart, U.-G. Meißner, J. Nieves, A. Nogga, Z. Yang, CPC41(2017)121001

  - The deuteron as an example







  - $\mathcal{R}$ must be much larger, $\mathcal{R} \sim 300$ MeV see also: Artoisenet, Braaten, PRD81(2010)114018

$\sigma(pp/\bar{p} \to X)$ [nb]	Exp.	Λ=0.1 GeV	Λ=0.5 GeV	Λ=1.0 GeV
CDF [IJMPA20(2005)3765]	37-115	0.07 (0.05)	7 (5)	29 (20)
CMS [JHEP1304(2013)154]	13-39	0.12 (0.04)	13 (4)	55 (15)

here $\Lambda \simeq 2\sqrt{2/\pi}\mathcal{R} \simeq 1.6\mathcal{R}$