On the photoproduction of X(3872):
insights from open-charm coupled-channel mechanism

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XHC, Meng-Lin Du, Feng-Kun Guo, arXiv: 2401.16112

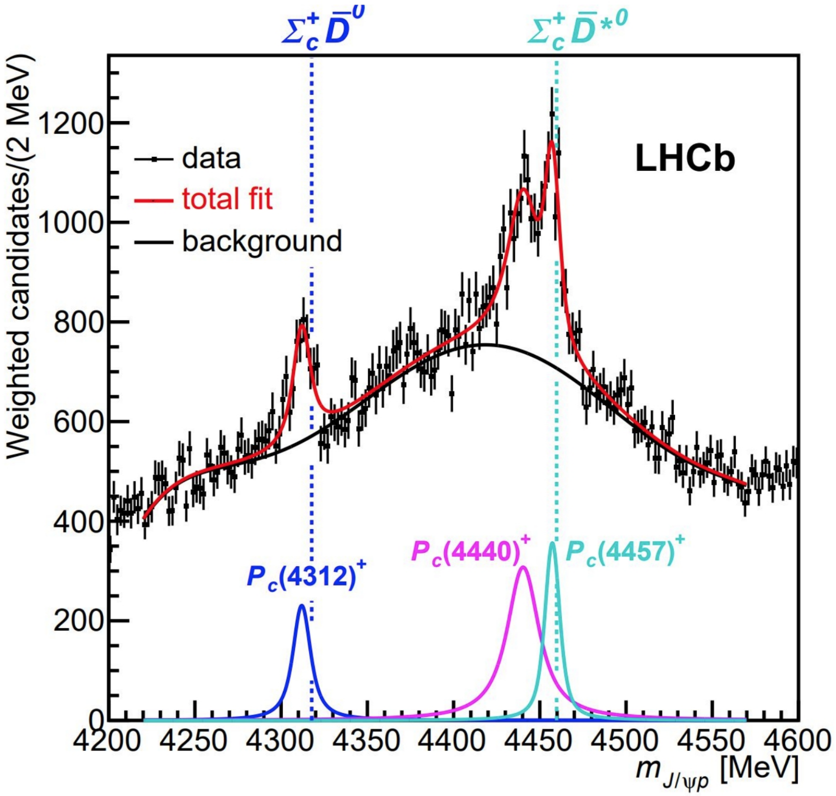
第七届强子谱与强子结构研讨会

2024/4/26–4/29

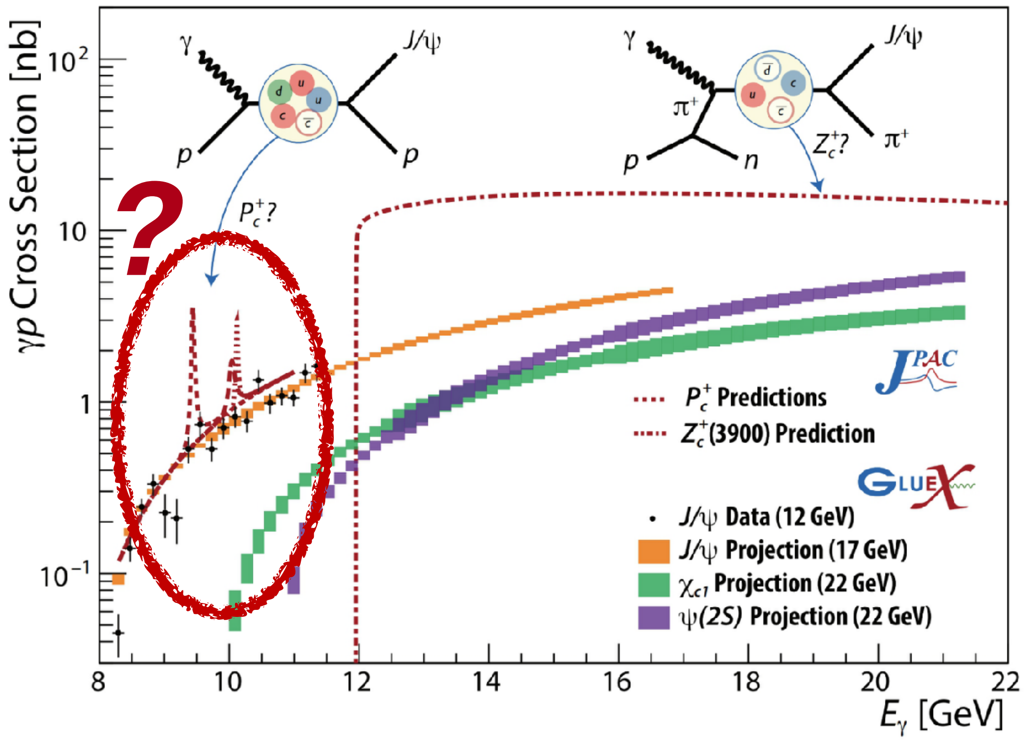
J/ψ photoproduction

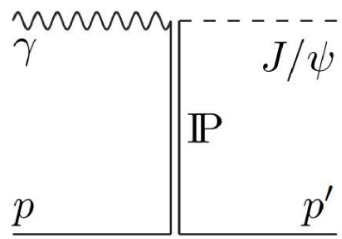
- Measurements at energies near threshold have attracted a lot of attention as potentially sensitive to key quantities relevant to **exotic hadrons**

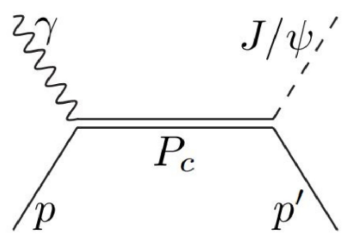
  - Observation of hidden charm pentaquark candidates by LHCb sparked interest in photoproduction searches



LHCb [Phys.Rev.Lett. 122 (2019) 22, 222001]

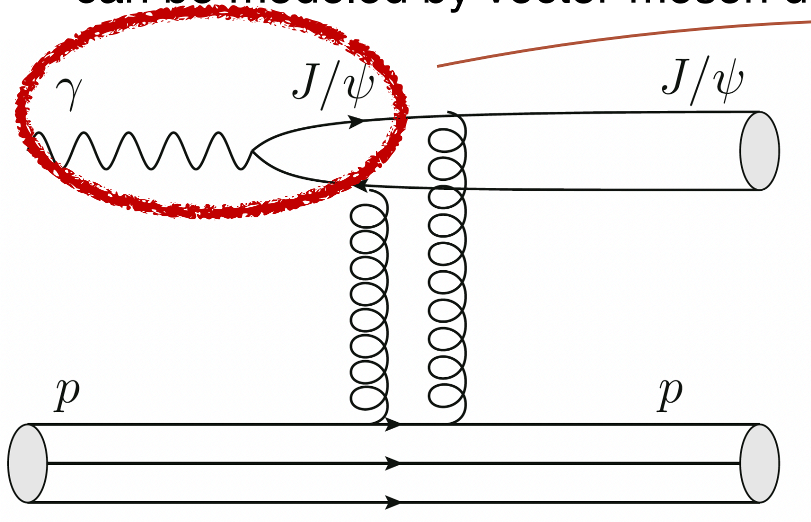






J/ψ-nucleon scattering and photoproduction

- The J/ψ photoproduction probes the gluonic contribution to the nucleon mass
  - if the mechanism of gluon exchanges is dominant, i.e., the J/ψ photoproduction can be modeled by vector-meson dominance (VMD)



$$\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}(s,t=0)=\frac{3\Gamma\left(J/\psi\to e^+e^-\right)}{\alpha m_\psi}\left(\frac{k_{J/\psi N}}{k_{\gamma N}}\right)^2 \times\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}(s,t=0)$$

D. Kharzeev, H. Satz, A. Syamtomov, G. Zinovjev, EPJC 9 (1999) 459

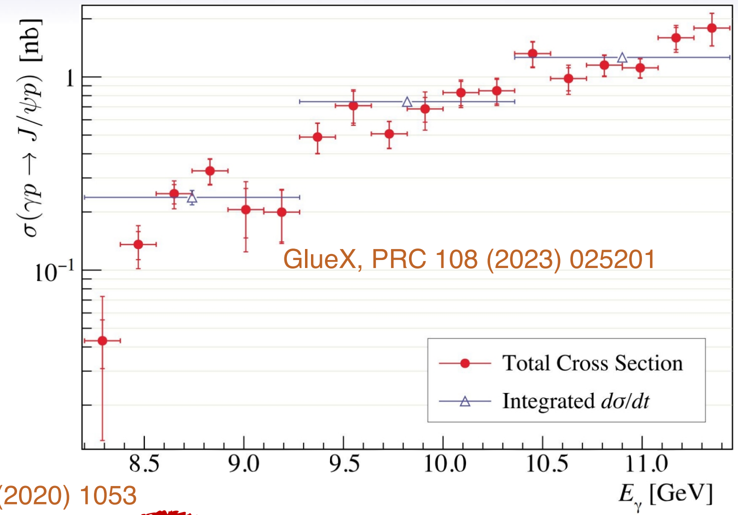
- Scattering length from VMD and photoproduction: $3\sim 25$ mfm L. Pentchev, I. Strakovsky, EPJA 57 (2021) 56
  21.3 ± 8.2 mfm GlueX, PRC 108 (2023) 025201

- Nucleon gluonic gravitational form factor, mass radius measured with this assumption Duran et al. [J/ψ-007], Nature 615 (2023) 813

J/ψ in the VMD model would be highly off-shell, but the scattering length and cross section are defined for real J/ψ

J/ψ photoproduction (near threshold)

- Process may not be as simple as it seems
  - Where are the pentaquarks?
  - Are there cusps? Open charm?

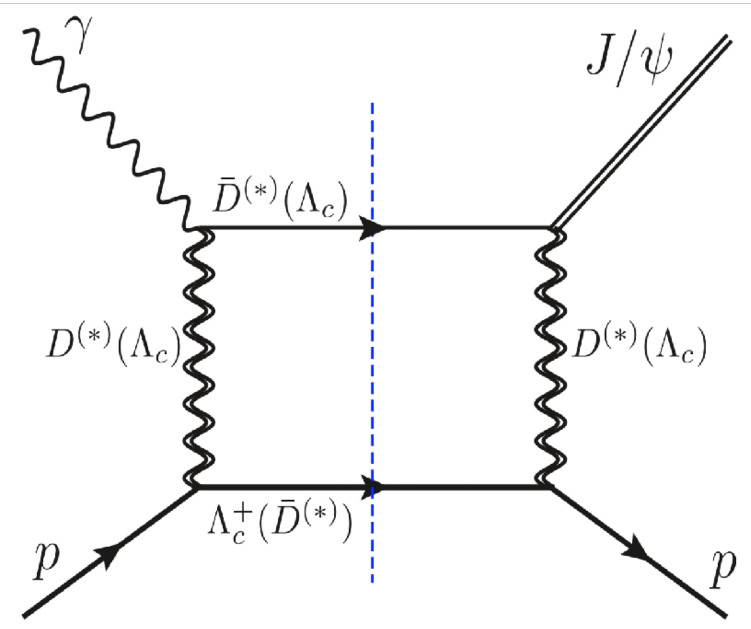


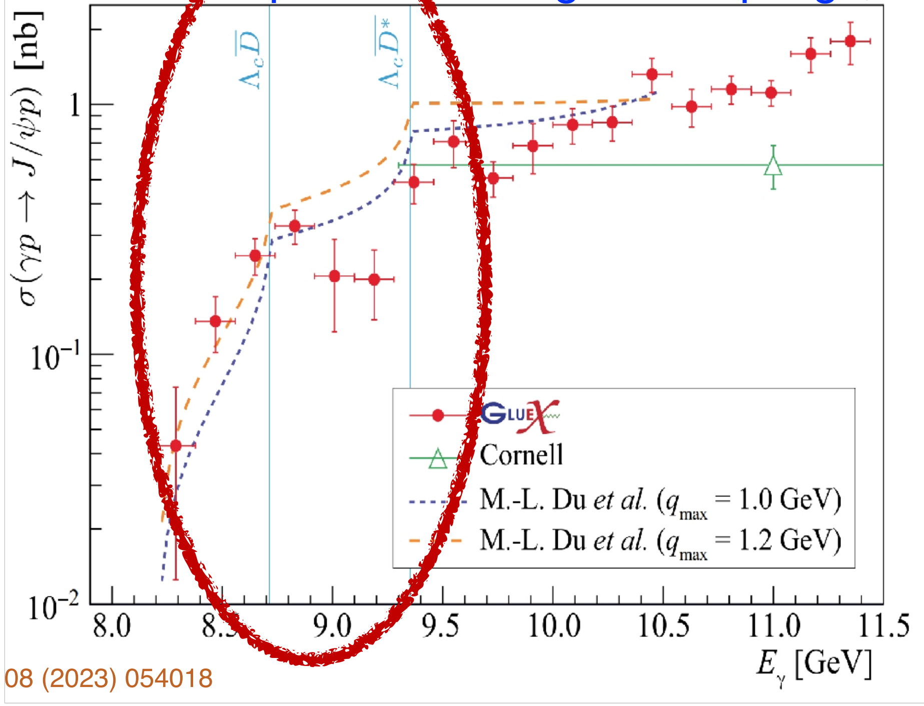
- Coupled-channel mechanism
  - Consider $\Lambda_c \bar{D}^{(*)}$ channels

M.-L. Du et al., EPJC 80 (2020) 1053

  - Unique feature: (S-wave) threshold cusps

With phenomenological couplings, not a fit.





See also JPAC analysis in D. Winney et al., PRD 108 (2023) 054018

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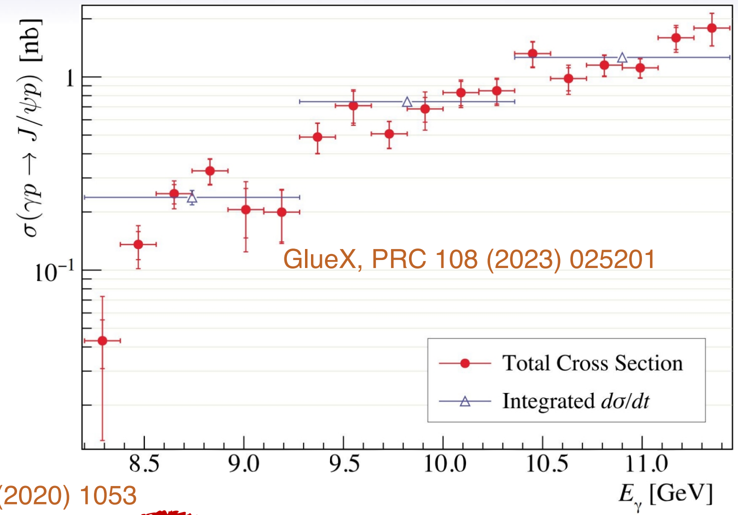

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M.-L. Du et al., EPJC 80 (2020) 1053

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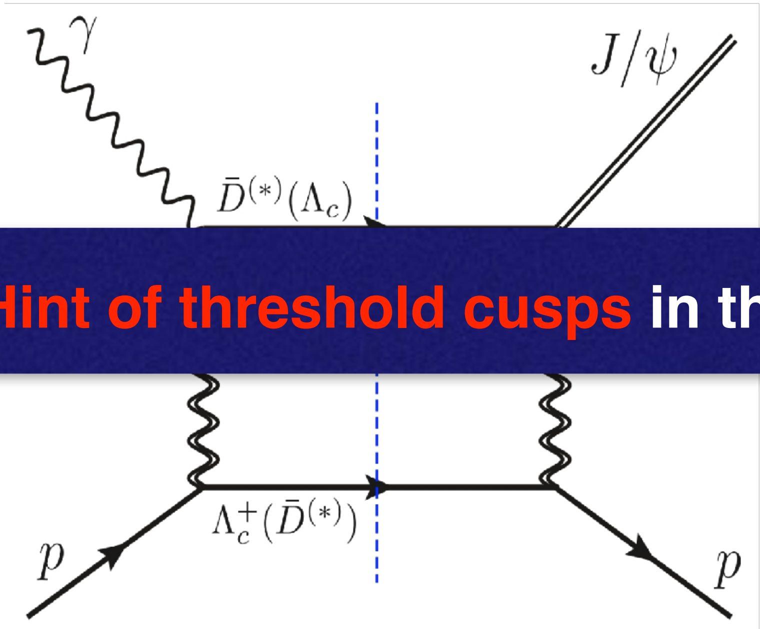
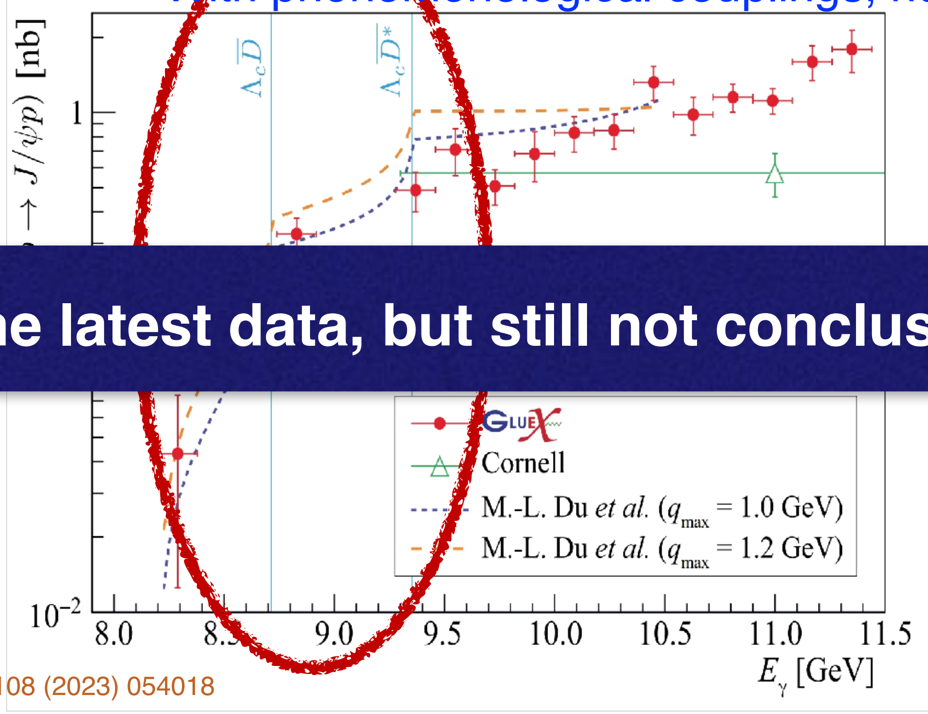




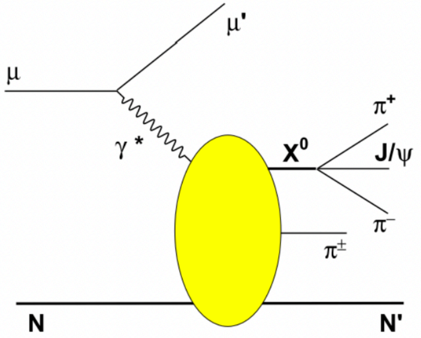
Hint of threshold cusps in the latest data, but still not conclusive

See also JPAC analysis in D. Winney et al., PRD 108 (2023) 054018

$X(3872)$ photoproduction: experimental efforts

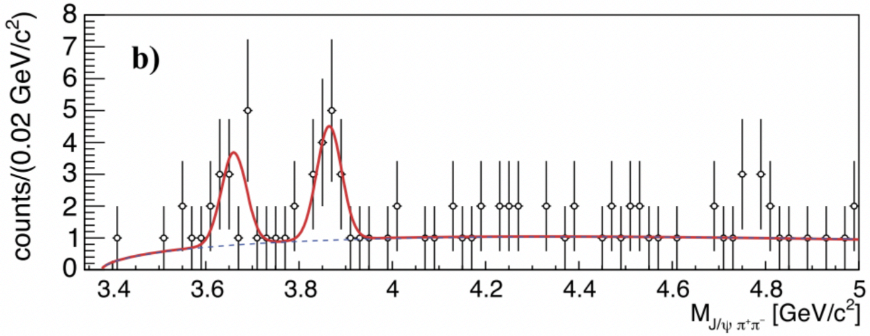
- Searched for at COMPASS, but not seen
  - Evidence of $\tilde{X}(3872)$ in $\gamma^* N \to X^0 \pi^\pm N'$ with 4.1σ

COMPASS, PLB783(2018)334

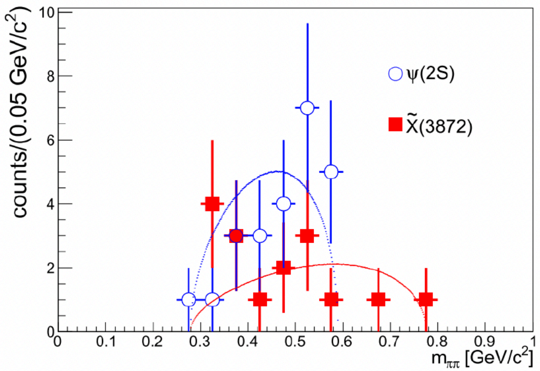


$\sqrt{s_{\gamma N}} \in [8, 18]$ GeV

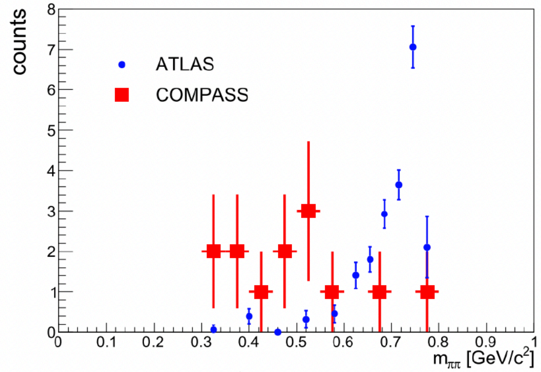
$M_{\tilde{X}} = (3860.4 \pm 10.0)$ MeV



  - The $\pi\pi$ invariant mass suggests $C(\tilde{X}) = -1$



(a)



(b)

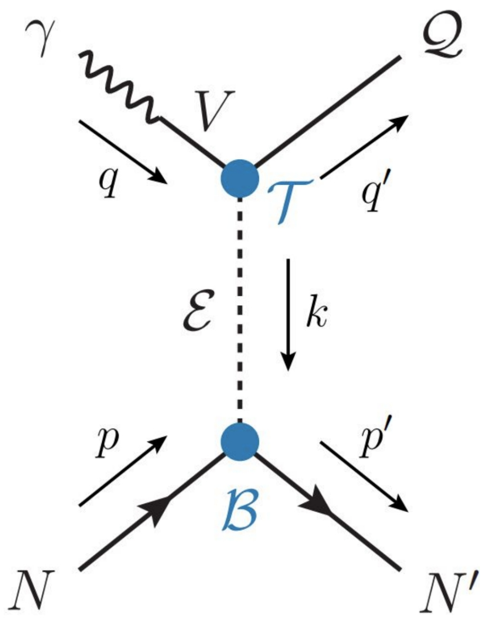
  - Cross sections at $\sqrt{s_{\gamma N}} = 13.7$ GeV : $\sigma(\gamma N \to \tilde{X}\pi N') \times \mathcal{B}(\tilde{X} \to J/\psi \pi^+ \pi^-) = (71 \pm 28 \pm 39)$ pb

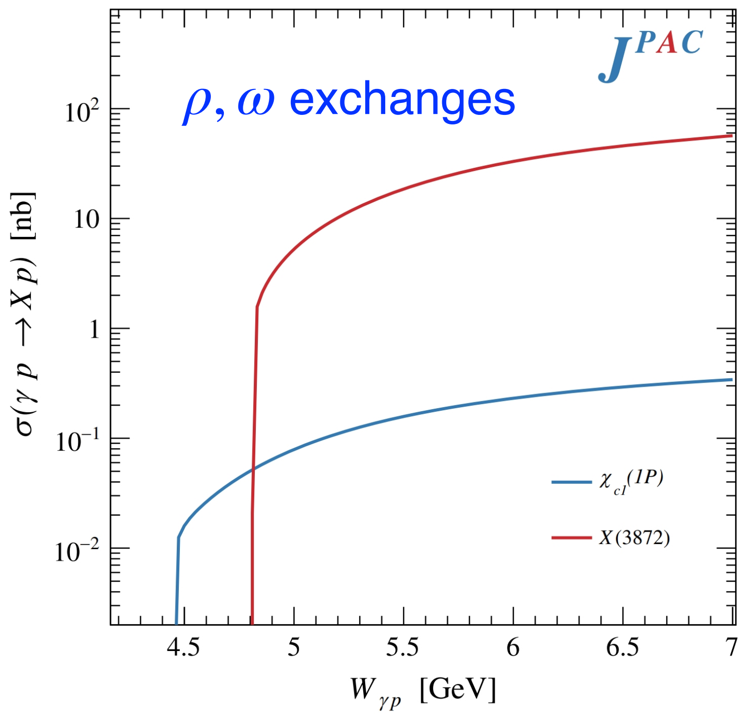
$\sigma(\gamma N \to X(3872) N') \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-) < 2.9$ pb (CL = 90%)

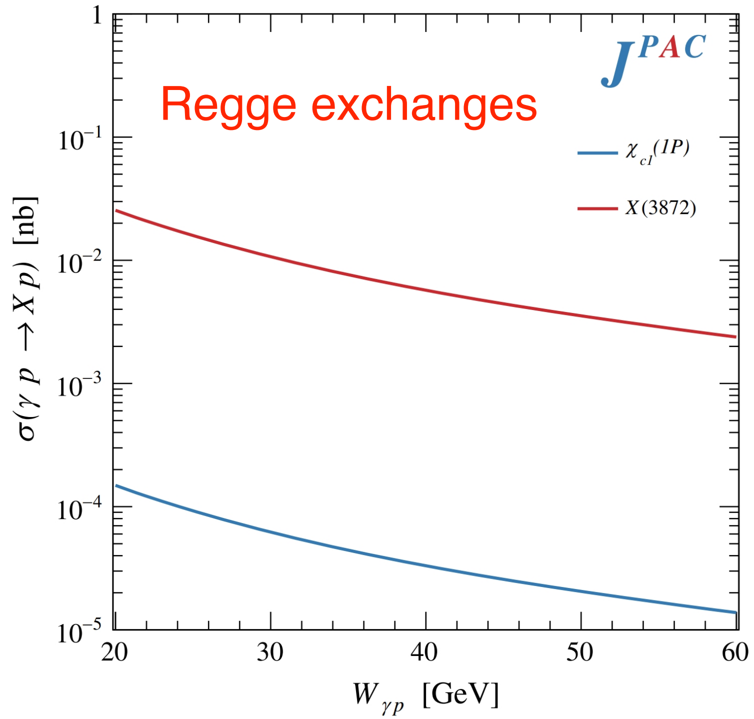
$X(3872)$ photoproduction with VMD

- Existing estimate for the $X(3872)$ photoproduction
  - VMD model: $\gamma \to J/\psi$
  - Low energy region: ρ, ω exchanges, $\mathcal{O}(10\ \text{nb})$
  - High energy region: Regge exchange

JPAC, PRD102(2020)114010







$X(3872)$ photoproduction with coupled channels

- Coupled-channel mechanism for the $X(3872)$ photoproduction in the near-threshold region
  - ☐ $X(3872)$ couples strongly to $D\bar{D}^*$
  - ☐ Nearby open-charm thresholds: $m_p + m_X = 4810$ MeV

$\bar{D}^0\Lambda_c(2940)^+$: 4804^{+2}_{-1} MeV

$\bar{D}^{*0}\Sigma_c(2800)^+$: 4799^{+14}_{-5} MeV

$D^{*-}\Sigma_c(2800)^{++}$: 4811^{+4}_{-6} MeV

$\bar{D}^{*0}\Lambda_c(2860)^+$: 4863^{+2}_{-6} MeV

$\bar{D}^{*0}\Lambda_c(2880)^+$: 4888^{+1}_{-0} MeV ×

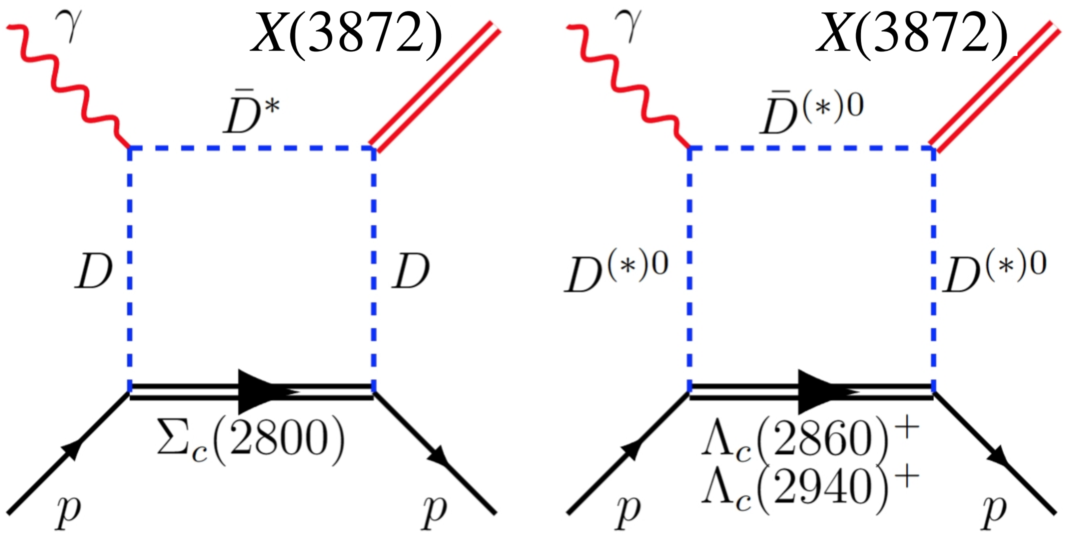
$\bar{D}^{*0}\Lambda_c(2940)^+$: 4946^{+1}_{-1} MeV

$\Lambda_c(2860)\,[3/2^+]$

$\Lambda_c(2940)\,[3/2^-]$

$\Sigma_c(2800)$ assumed to be $1/2^-$

S. Sakai, F.-K. Guo and B. Kubis PLB 808 (2020) 135623



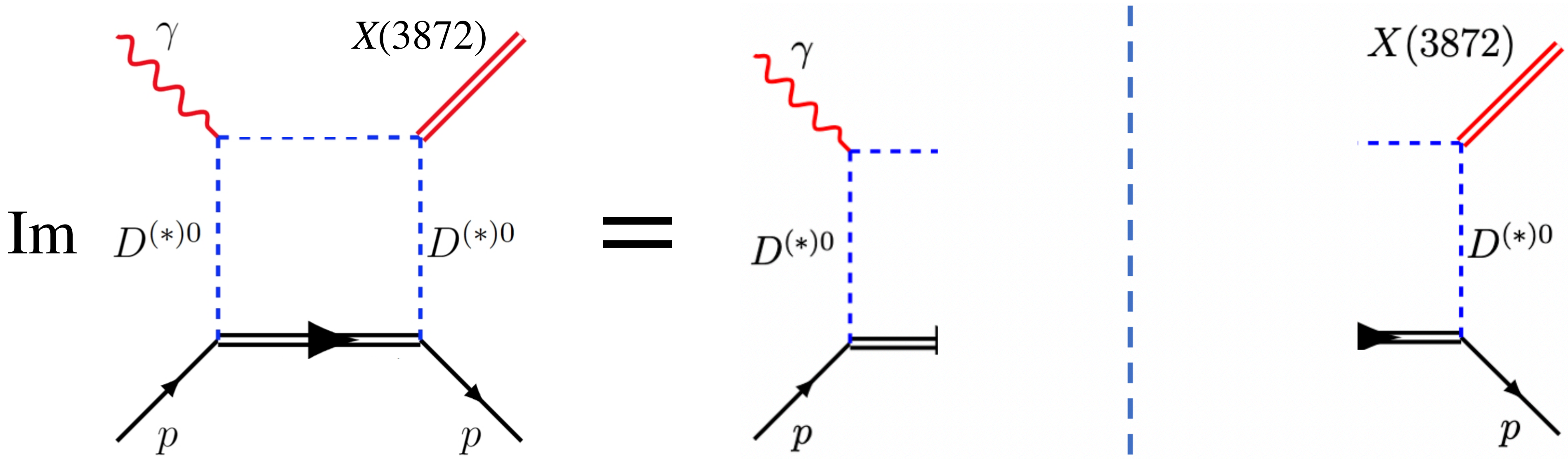
Couplings:

- Measured decay widths
- Heavy quark spin symmetry
- $X(3872)D\bar{D}^*$ coupling from combination fit of DD^* and $J/\psi\pi^+\pi^-$ spectrum

C. Meng et.al., PRD 92 (2015) 034020

Dispersive approach

- Evaluate the box diagrams with a dispersive approach:



$$\mathscr{A}^{(J)}_{\ell S;\bar{\ell}\bar{S}(\gamma p \to Xp)}(s) = \sum_{\ell',S'} \frac{1}{\pi} \int_{s_{\rm th}}^{s_{\rm cut}} ds' \frac{\mathscr{A}^{(J)}_{\ell' S';\overline{\ell S}(\gamma p \to \bar{D}^* \Sigma_c/\Lambda_c)}(s')\,\rho(s')\,\mathscr{A}^{(J)}_{\ell' S';\ell S(Xp \to \bar{D}^* \Sigma_c/\Lambda_c)}(s')}{s'-s}$$

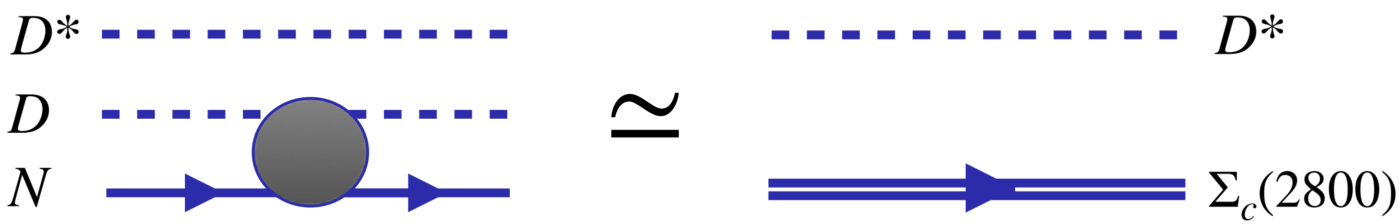
- Hard cutoff: $\sqrt{s_{\rm cut}} = \sqrt{q_{\rm max}^2 + m_{\Sigma_c/\Lambda_c}^2} + \sqrt{q_{\rm max}^2 + m_{D^{(*)}}^2}$ with $q_{\rm max} = 1$ GeV
- Monopole form factor for off-shell exchanged particles with $\Lambda = m_{\rm ex} + \eta \Lambda_{\rm QCD}$

$$F(t) = \frac{\Lambda^2 - m_{\rm ex}^2}{\Lambda^2 - t}$$

Finite width effects

- Complex mass scheme (isobar approximation)

Ex. $\Sigma_c(2800)$:



- Two-body approximation within a complex resonance pole mass is appropriate for calculating "enhancement" effects due to singularities of the three-body amplitude, near the physical region I.J.R. Aitchison, C. Kacser, *Phys.Rev.* 133 (1964) 5B, B1239

- Convolution with a Breit-Wigner (BW) distribution

R. Molina, D. Nicmorus, and E. Oset, PRD 78 (2008) 114018

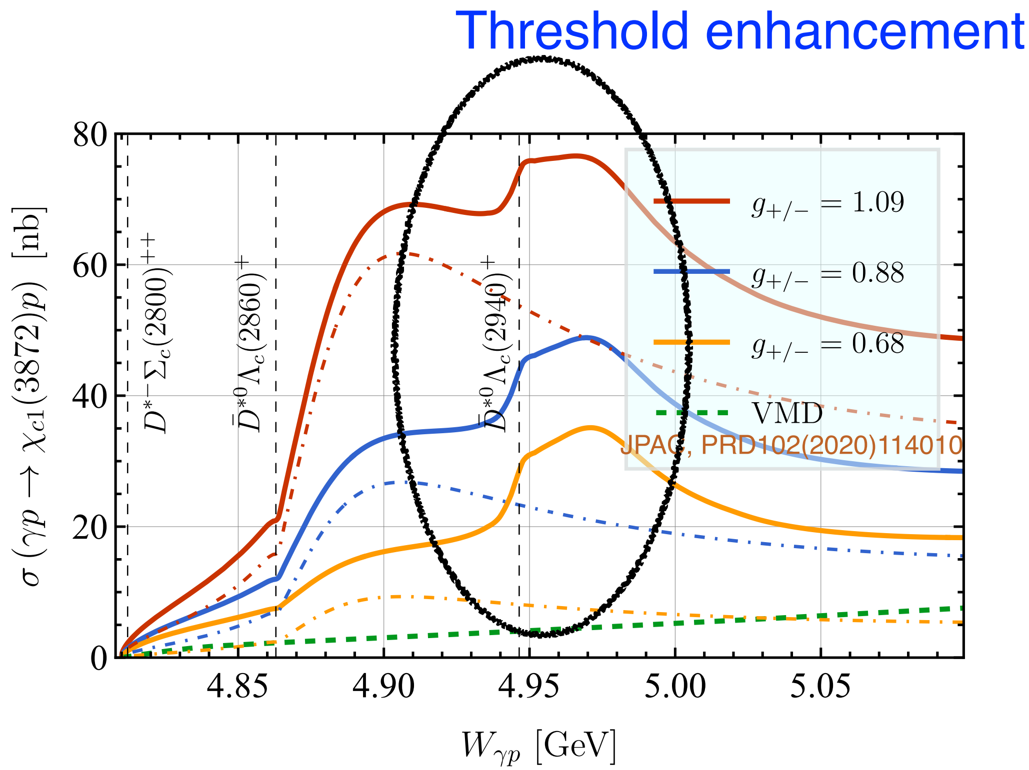
- Smearing the imaginary part:

$$\mathrm{Im}\,\tilde{\mathscr{A}}_{(\gamma p\to Xp)}\left(s, m_{\Lambda_c}^2\right) = \frac{1}{\mathcal{N}}\int_{\left(m_{\Lambda_c}-2\Gamma_{\Lambda_c}\right)^2}^{\left(m_{\Lambda_c}+2\Gamma_{\Lambda_c}\right)^2} \mathrm{d}m^2 \sigma\left(m_{\Lambda_c}^2, m^2\right)\mathrm{Im}\,\mathscr{A}_{(\gamma p\to Xp)}\left(s,m^2\right)\theta\left(s-\left(m+m_{D^*}\right)^2\right)$$

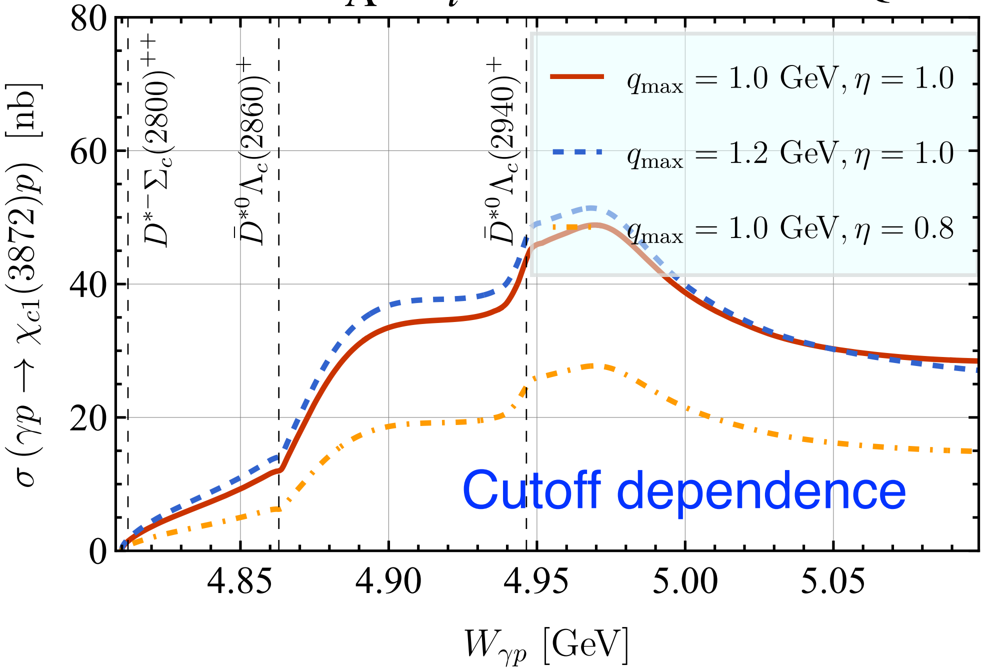
- The BW spectral function:

$$\sigma\left(s, m_{\Lambda_c}^2\right) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{s-m_{\Lambda_c}^2+im_{\Lambda_c}\Gamma_{\Lambda_c}}\right) = \frac{1}{\pi}\frac{m_{\Lambda_c}\Gamma_{\Lambda_c}}{\left(s-m_{\Lambda_c}^2\right)^2+m_{\Lambda_c}^2\Gamma_{\Lambda_c}^2},$$

Total cross sections



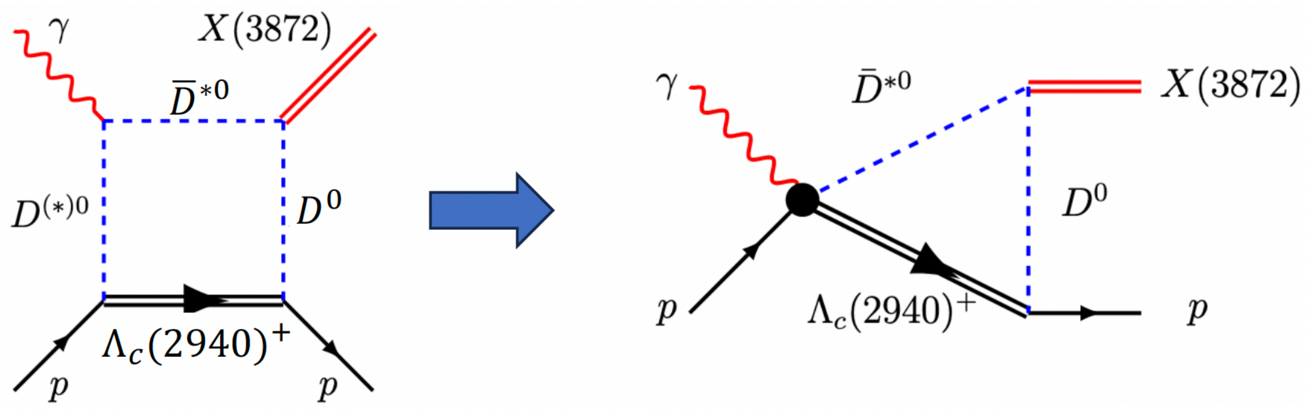
$$F(t) = \frac{\Lambda^2 - m_{ex}^2}{\Lambda^2 - t}, \quad \Lambda = m_{ex} + \eta\Lambda_{QCD}$$



- Here $g_{+/-}$ is the ratio of the $\Lambda_c(2860)D^{(*)}p$ and $\Lambda_c(2940)D^{(*)}p$ couplings
- Coupling constants constrained by the measured (predicted) decay widths

Triangle singularity (anomalous threshold)

- Triangle singularity (anomalous threshold): subleading Landau singularity of the box diagram L.D. Landau, Nucl. Phys.,13(1959)181



logarithmic singularity

↓

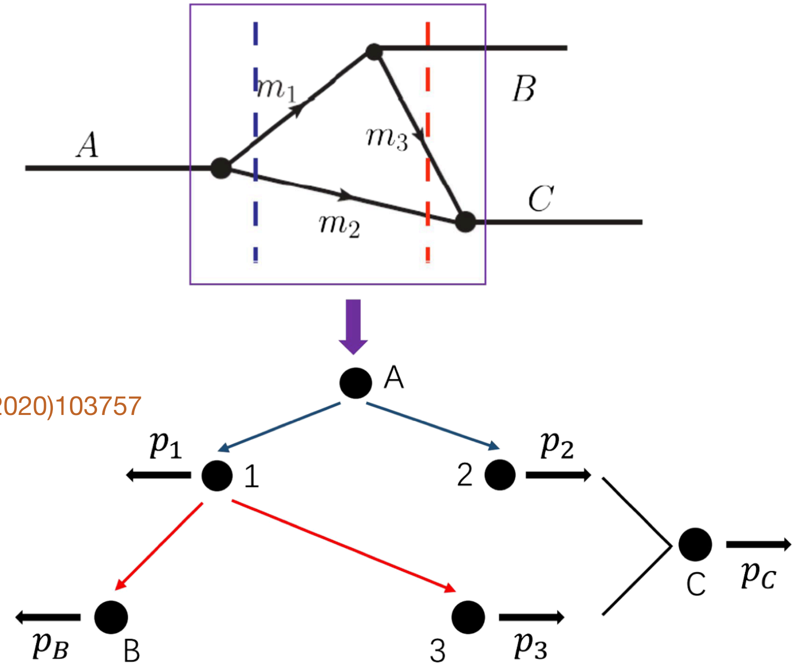
peak!

B. E. Norton, Phys. Rev.,135, B 1381(1964)
J. E. Aitchison:Phys. Rev.,133, B 1257 (1964)
S. Coleman, R.E. Norton, Nuovo Cim. 38(1965)438

- Conditions (Coleman-Norton theorem):
  - all three intermediate particles can go on-shell simultaneously
  - $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)

M. Bayar et.al., PRD 94(2016)074039; F.-K. Guo, X.-H. Liu and S. Sakai, PPNP, 112(2020)103757

- special kinematics → process dependent (contrary to pole positions)



Q. Huang, C.-W. Shen and J.-J. Wu, *PRD* 103(2021)016014

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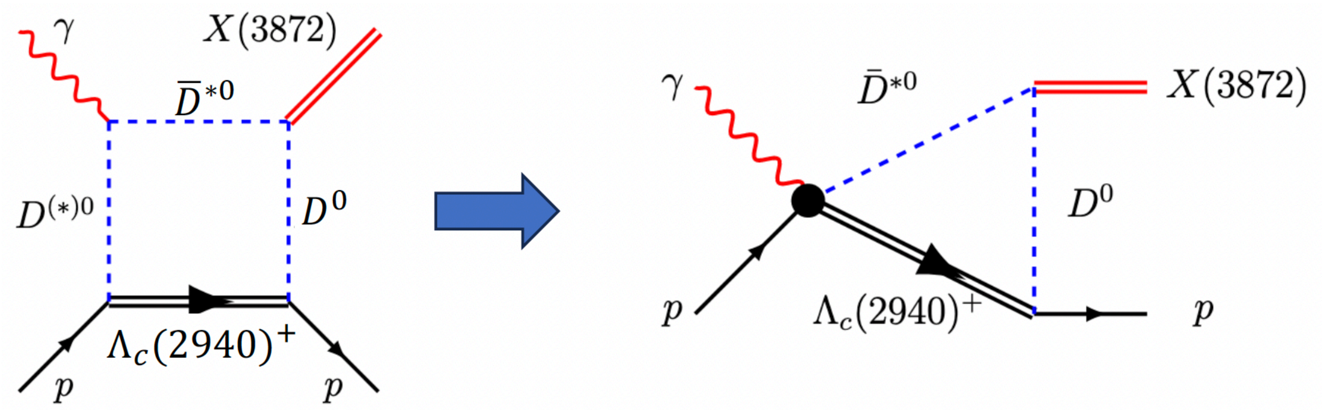


Logarithmic singularity

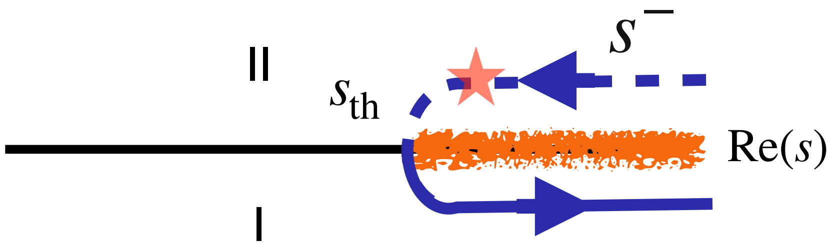
↓

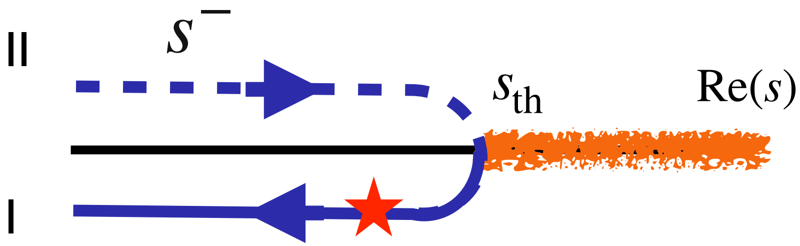
Peak!

- Trajectory of the anomalous threshold s^- with m_X increases from $\delta > 0$ to $\delta < 0$

Neglecting all widths

X(3872) binding energy ($\delta = m_{D^0} + m_{D^{*0}} - m_X$)



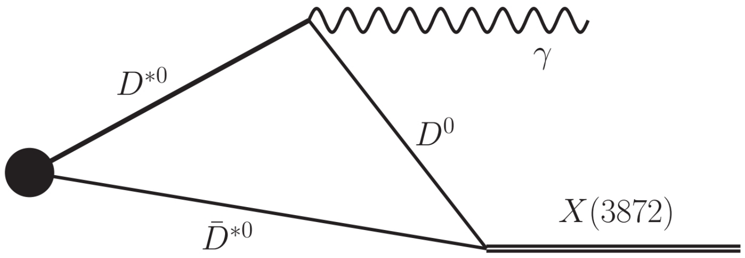


- $\pi\pi \to N\bar{N}$ or $\gamma \to N\bar{N}$ *S. Mandelstam, PRL* 4(1960)84
- long tail of the deuteron wave function

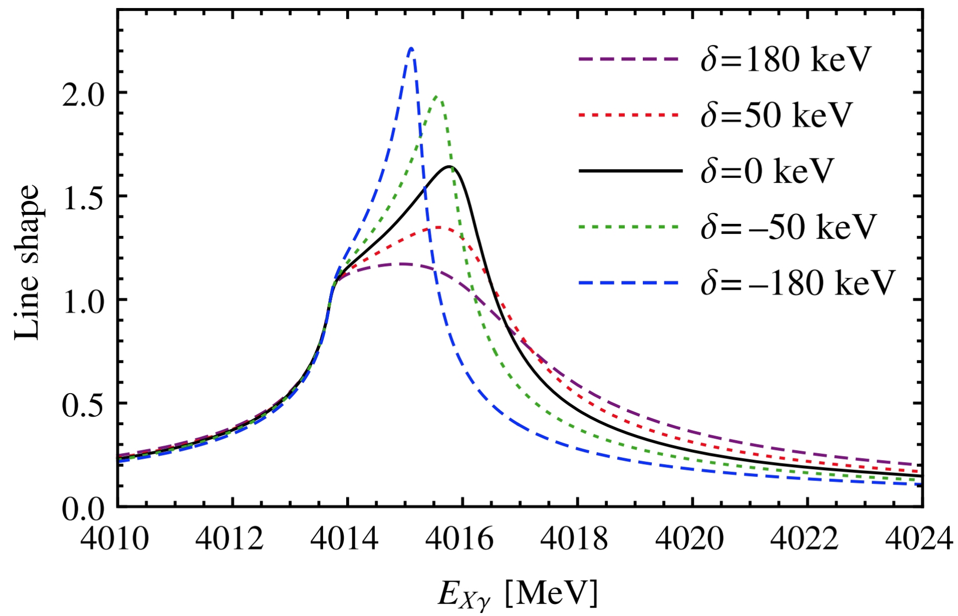
R. Blankenbecler and Y. Nambu, Nuovo Cim.,18(1960)595; L. Durand, Phys.Rev. 123(1961)1393

Triangle singularity (anomalous threshold)

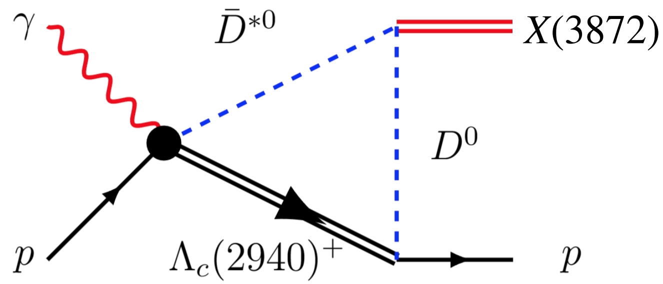
- Triangle singularity induced structure may be used to measure the X(3872) binding energy ($\delta = m_{D^0} + m_{D^{*0}} - m_X$)

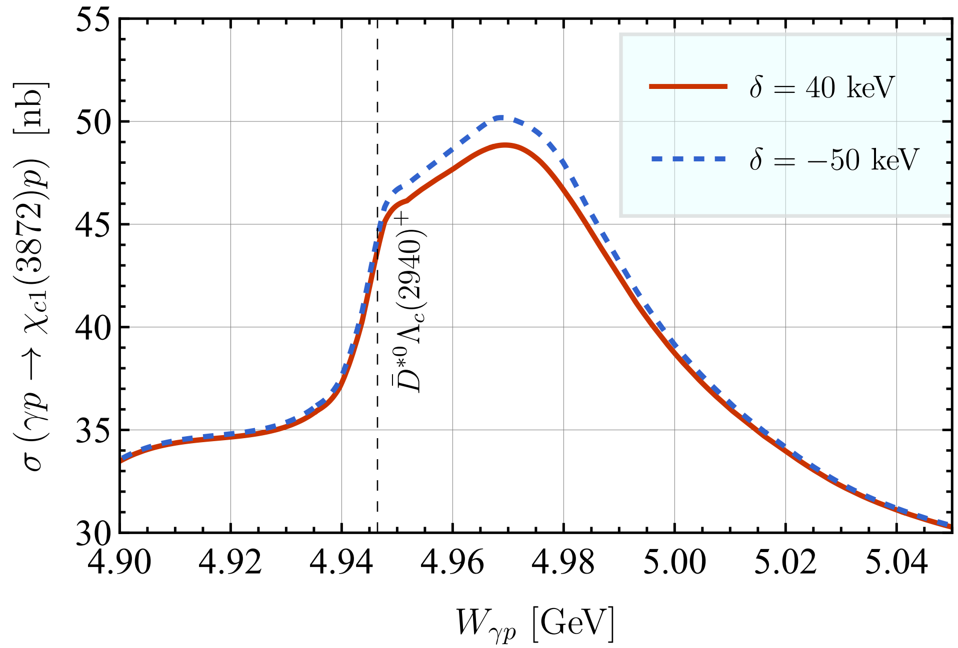


F.-K. Guo, PRL 122 (2019) 202002



- However, here the sensitivity is smeared out by the $\Lambda_c(2940)$ width (~20 MeV)





Summary

- ☑ Nontrivial structures in the total cross section: probe of the mechanism of the near-threshold production of hidden-charm mesons
- ☑ $\sigma(\gamma p \to X(3872)p) \sim \mathcal{O}(30\ \text{nb})$ at $\sqrt{s_{\gamma p}} \sim 5\text{GeV} \Rightarrow \mathcal{O}(0.3\ \text{nb})$ for electroproduction
- ☐ Calls for further study both experimentally and theoretically to understand model limitations and assumptions

Thank you for your attention!