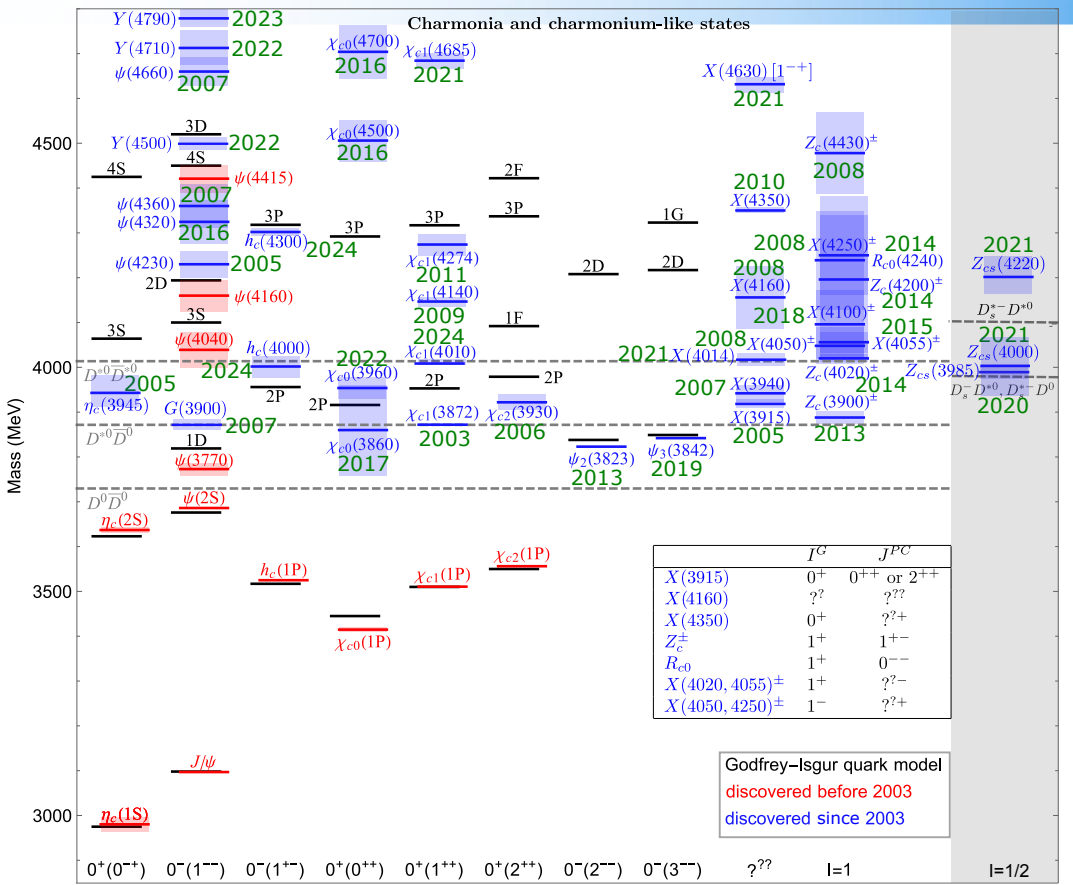
第三届“有道真论”
理论物理前沿研究与教学研讨会

Classification of near-threshold structures + Zotero-INSPIRE

Feng-Kun Guo

郭奉坤

Institute of Theoretical Physics, Chinese Academy of Sciences



X.-K. Dong, FKG, B.-S. Zou, PRL 126, 152001 (2021)

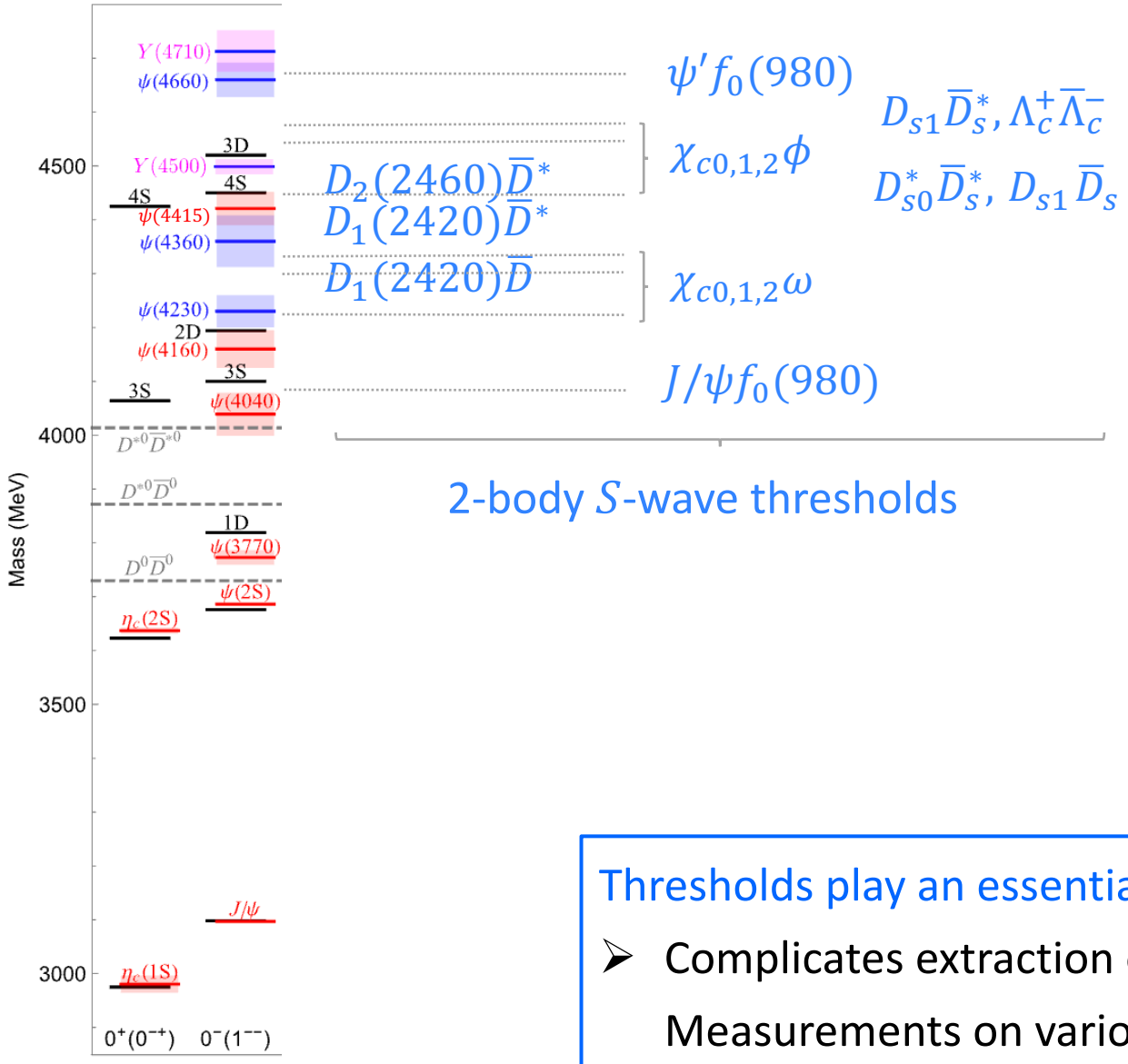
V. Baru, FKG, C. Hanhart, A. Nefediev, PRD 109, L111501 (2024)

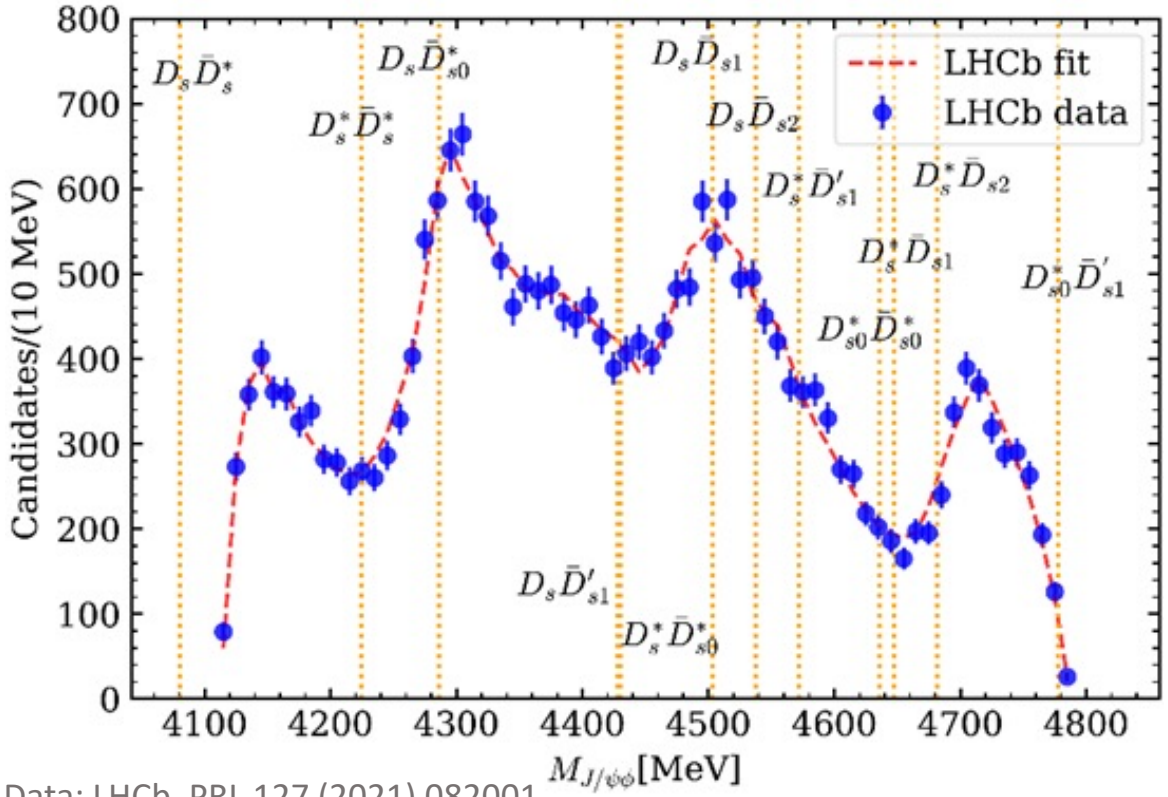
Z.-H. Zhang, FKG, PLB 863 (2025) 139387

https://github.com/fkguo/zotero-inspire/

Dec. 05, 2025

Many hidden-charm thresholds above 4 GeV





Data: LHCb, PRL 127 (2021) 082001

Plot: X.-K. Dong, FKG, B.-S. Zou, Progr. Phys. 41 (2021) 65 [arXiv:2101.01021]

Thresholds play an essential role

- Complicates extraction of resonance properties!

  Measurements on various final states are important
- Hadronic molecules?

Molecular line shapes at LO

- Scattering length approx.: $p \cot \delta = \frac{1}{a} + \cdots$
- Poles: bound (a<0) or virtual (a>0) state ($\kappa = 1/|a|$)
  - Bound and virtual state can hardly be distinguished above threshold ($E > 0$)

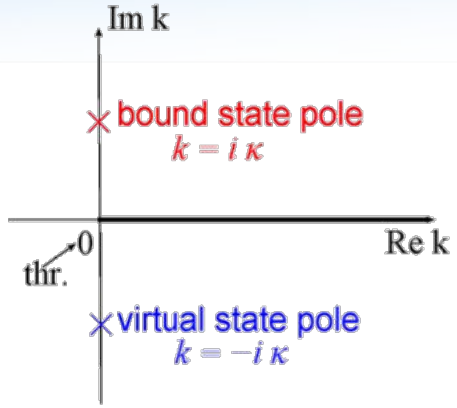
$$|T_{\rm NR}(E)|^2 \propto \left| \frac{1}{\pm\kappa + i\sqrt{2\mu E}} \right|^2 = \frac{1}{\kappa^2 + 2\mu E}$$

  - Different below threshold ($E < 0$)
    - bound state: peaked below threshold

$$|T_{\rm NR}(E)|^2 \propto \frac{1}{(\kappa - \sqrt{-2\mu E})^2}$$

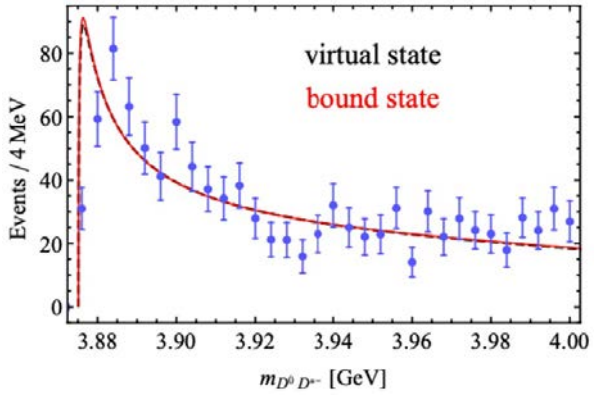
    - virtual state: sharp cusp at threshold

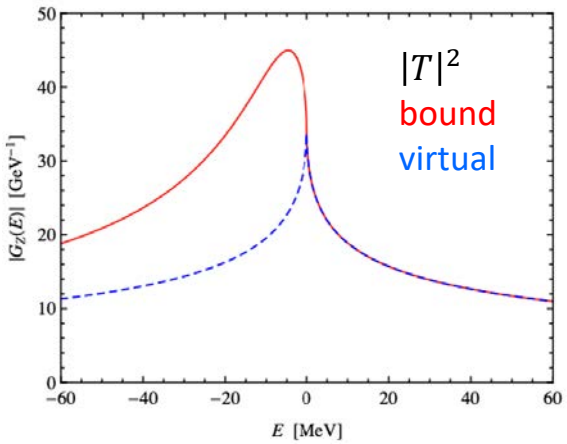
$$|T_{\rm NR}(E)|^2 \propto \frac{1}{(\kappa + \sqrt{-2\mu E})^2}$$

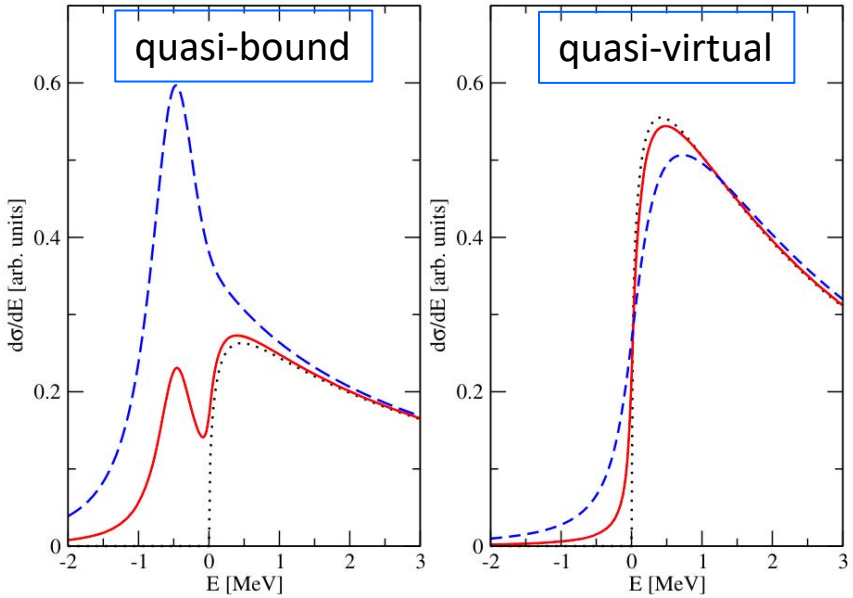


FKG, et al., RMP 90 (2018) 015004;
N. Brambilla et al., Phys.Rept. 873 (2020) 1

line shapes w/ phase space; one unstable constituent:



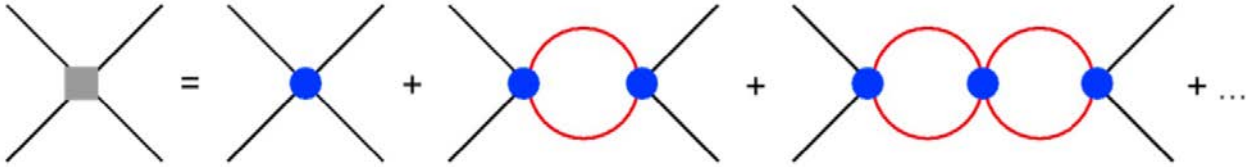




$\Gamma = 0$	0.1 MeV	1 MeV
dotted	dashed	solid

NREFT at LO for coupled channels

- Full threshold structure needs to be measured in a lower channel (ch-1) ⇒ coupled channels
- Consider a two-channel system, construct a "nonrelativistic" effective field theory (NREFT)
  - Energy region around the higher threshold (ch-2), Σ_2
  - Expansion in powers of $E = \sqrt{s} - \Sigma_2$
  - Momentum in the lower channel can also be expanded



$$T(E) = 8\pi\Sigma_2 \begin{pmatrix} -\frac{1}{a_{11}} + ik_1 & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & -\frac{1}{a_{22}} - \sqrt{-2\mu_2 E - i\epsilon} \end{pmatrix}^{-1} = -\frac{8\pi\Sigma_2}{\det} \begin{pmatrix} \frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon} & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & \frac{1}{a_{11}} - ik_1 \end{pmatrix}$$

$$\det = \left(\frac{1}{a_{11}} - ik_1\right)\left(\frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon}\right) - \frac{1}{a_{12}^2}$$

- a_{22}: single-ch. scattering length of ch-2
- a_{11}: single-ch. interaction strength of ch-1 at Σ_2

Effective scattering length with open-channel effects becomes complex, $\mathrm{Im}\frac{1}{a_{22,\mathrm{eff}}} \leq 0$

$$T_{22}(E) = -\frac{8\pi}{\Sigma_2}\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}$$

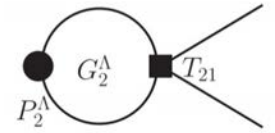
$$\frac{1}{a_{22,\mathrm{eff}}} = \frac{1}{a_{22}} - \frac{a_{11}}{a_{12}^2(1 + a_{11}^2 k_1^2)} - i\frac{a_{11}^2 k_1}{a_{12}^2(1 + a_{11}^2 k_1^2)}.$$

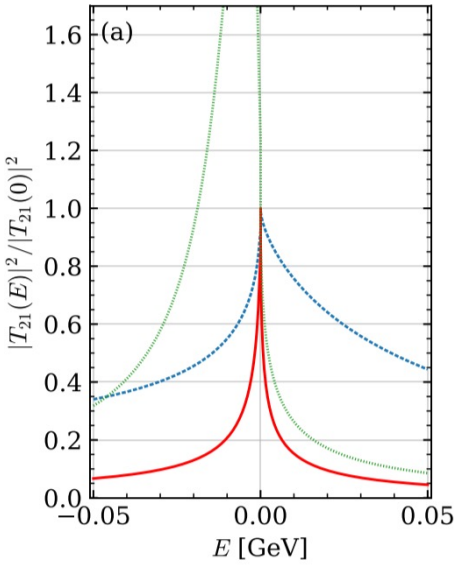
Distinct line shapes of the same pole

X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001

Line shapes of the same pole depend on the production mechanism. Consider production of particles in ch-1

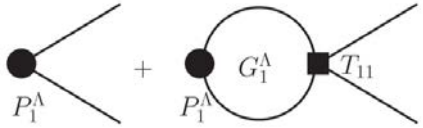
- Dominated by ch-2
  - Maximal at threshold for positive $\mathrm{Re}(a_{22,\mathrm{eff}})$ (attraction), FWHM $\propto 1/\mu$
    - ➢ more pronounced for heavier hadrons and stronger interactions
  - Peaking at pole for negative $\mathrm{Re}(a_{22,\mathrm{eff}})$

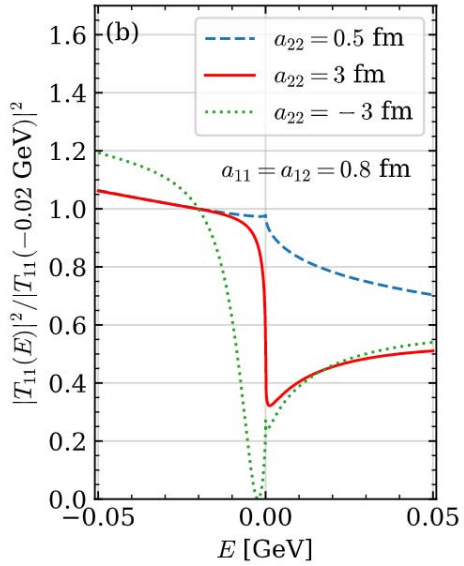




$$T_{21} \propto \frac{1}{a_{22,\mathrm{eff}}^{-1} - i\sqrt{2\mu_2 E}}$$

- Dominated by ch-1
  - One pole and one zero
  - Universality for large scattering length: for large $|a_{22}|$, there must be a dip around threshold (zero close to threshold)





$$T_{11} \propto \frac{a_{22}^{-1} - i\sqrt{2\mu_2 E}}{a_{22,\mathrm{eff}}^{-1} - i\sqrt{2\mu_2 E}}$$

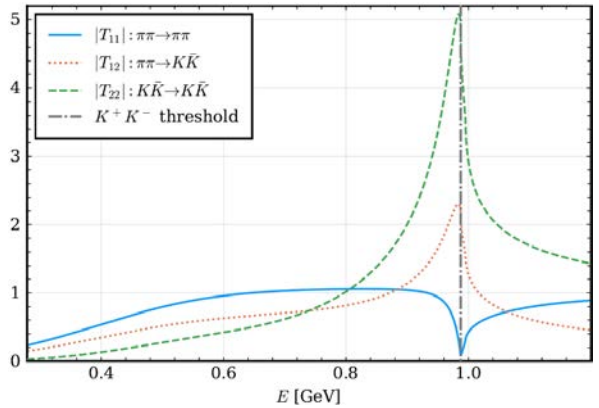
Process-dependent line shapes known since long; see, e.g., J. Taylor, *Scattering Theory*

✓ Classification of near-threshold structures and pole trajectories for two heavy channels: Z.-H. Zhang, FKG, PLB 863 (2025) 139387

Distinct line shapes of the same pole

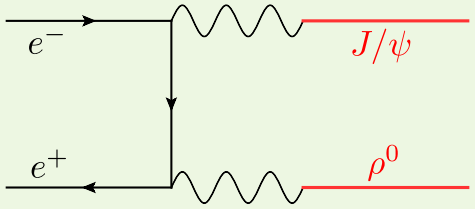
- Example-1: $f_0(980)$
  - T-matrix for $\pi\pi$ and $K\bar{K}$ coupled channels

    with the T-matrix from L.-Y. Dai, M. R. Pennington, PRD 90 (2014) 036004

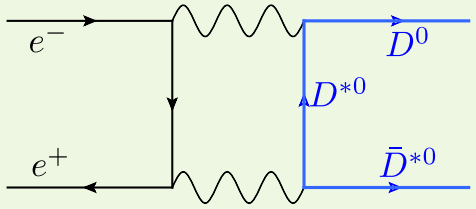


- Example-2: direct production of $X(3872)$ in e^+e^-

  V. Baru, FKG, C. Hanhart, A. Nefediev, PRD 109 (2024) L111501



(a)

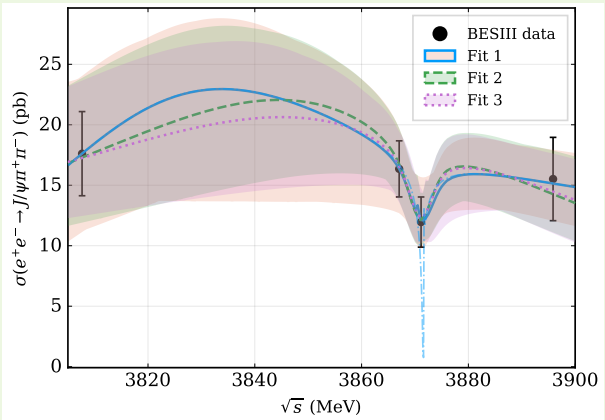


(b)

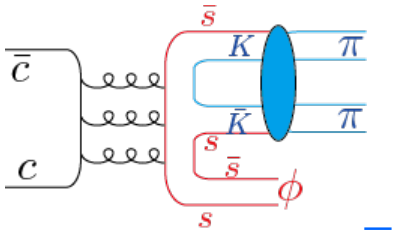
  - Driving channel:

    J/ψ +light vector
  - Prediction: dip around

    $D^*\bar{D}^*$ threshold

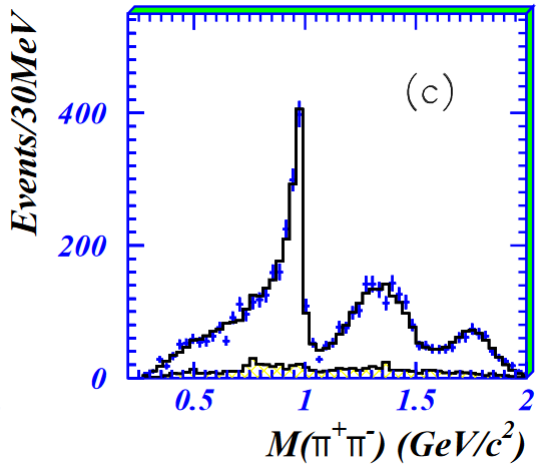


- $J/\psi\to\phi\pi^+\pi^-$



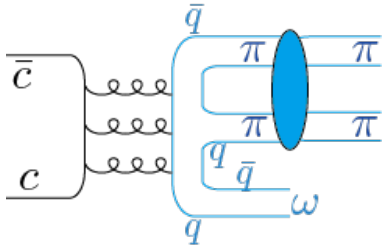
Driving channel: $K\bar{K}$

$J/\psi\to\phi K\bar{K}\to\phi\pi^+\pi^-$



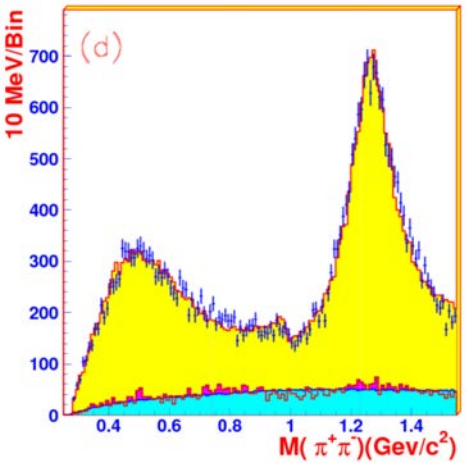
BES, PLB 607 (2005) 243

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



Driving channel: $\pi\pi$

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



BES, PLB 598 (2004) 149

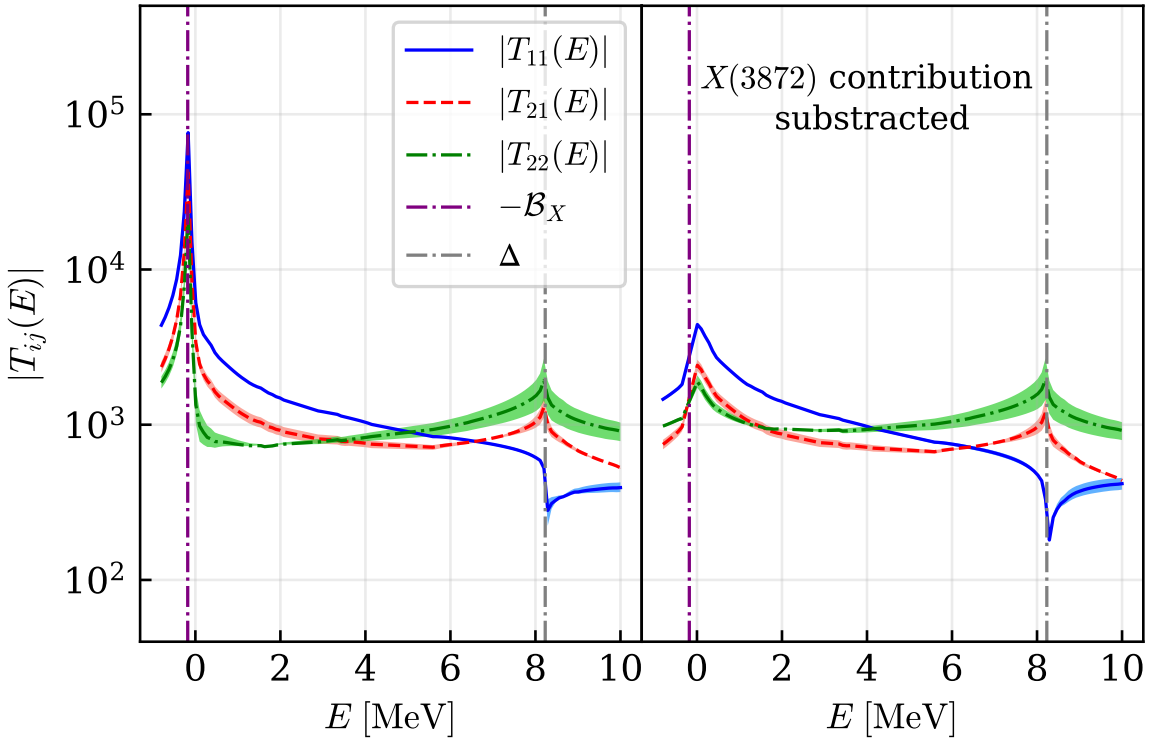
Prediction of an isospin vector partner of $X(3872)$

Z.-H. Zhang, T. Ji, X.-K. Dong, FKG, C.Hanhart, U.-G. Meißner, A. Rusetsky, JHEP 08 (2025) 130

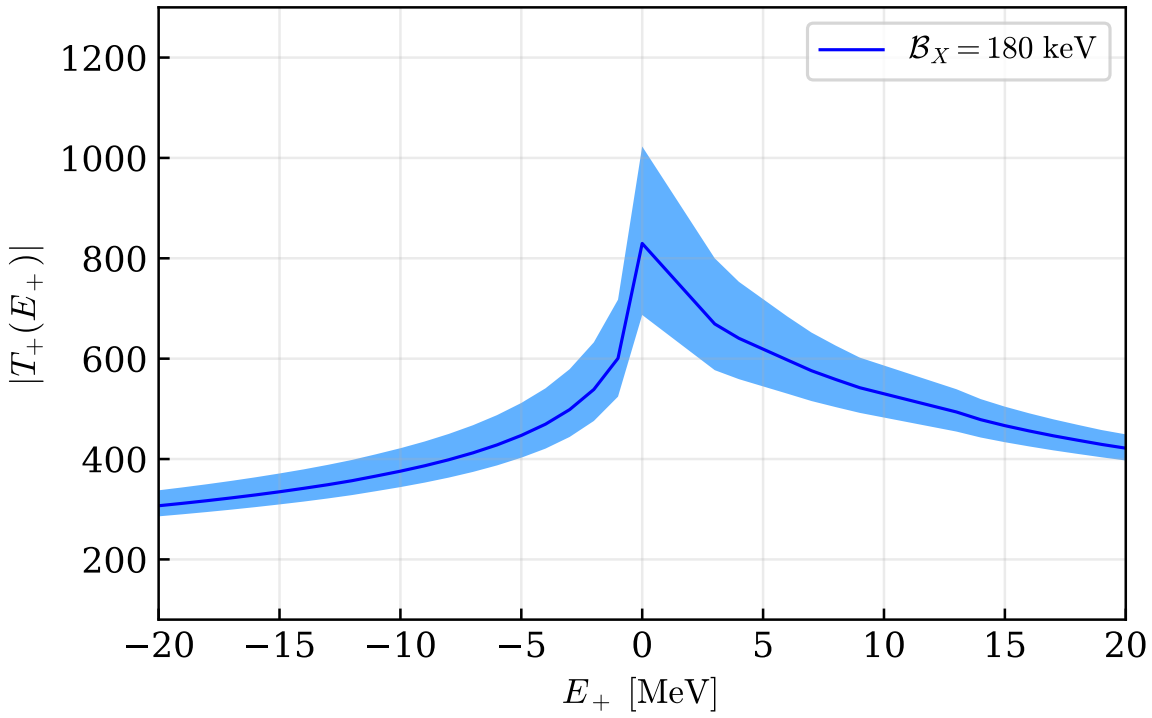
Teng Ji, X.-K. Dong, FKG, C. Hanhart, U.-G. Meißner, arXiv:2502.04458

- There must be an isospin vector partner W_{c1}
  - Virtual state pole in the stable D^* limit $\Rightarrow$ explains why it has not observed so far!

➢ W_{c1}^0 in $D^0\bar{D}^{*0} - D^+D^{*-}$ scattering amplitudes



➢ W_{c1}^+ in $D^+\bar{D}^{*0}$ scattering amplitude



➢ to be searched for in high-statistic $J/\psi\pi^+\pi^0$ data

➢ Compact tetraquark (Maiani et al. (2005)) cannot be virtual state!

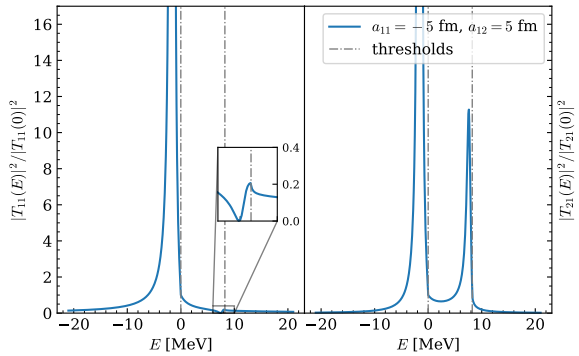
Classification of coupled-channel near-threshold structures

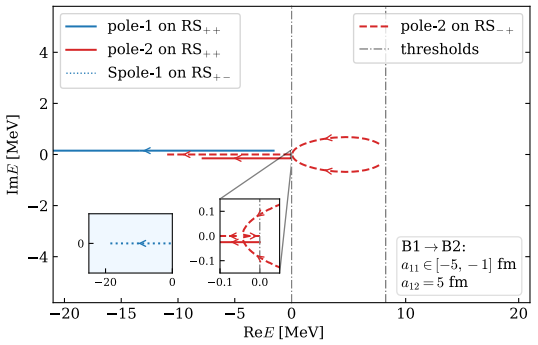
Starting from RGE fixed point with two zero-energy bound state:

Two-channel cases (B): $a_{11} < 0$

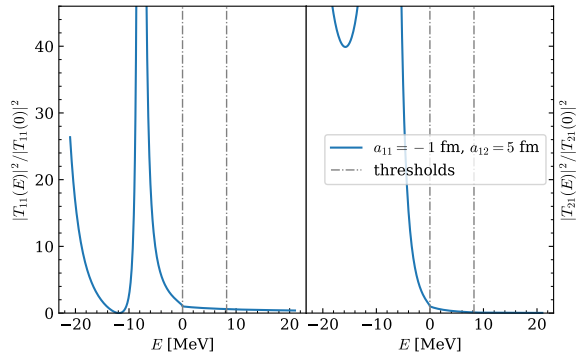
Here, $\delta \equiv \sqrt{2\mu_2\Delta}$,
Spole: shadow pole

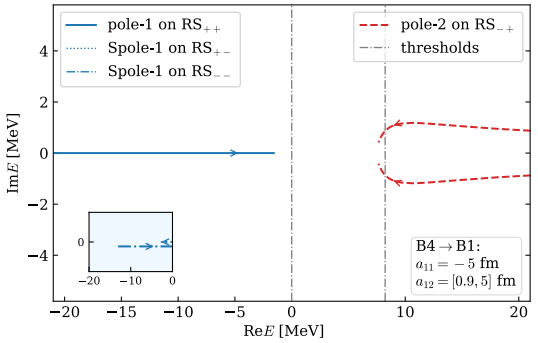
B1: $a_{11}\delta \ll -1, |a_{12}|\delta \gg 1$

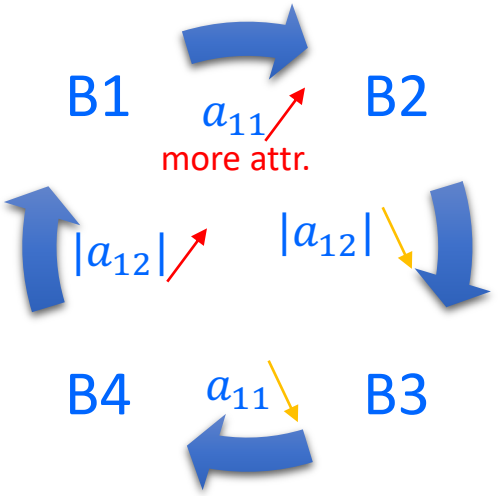


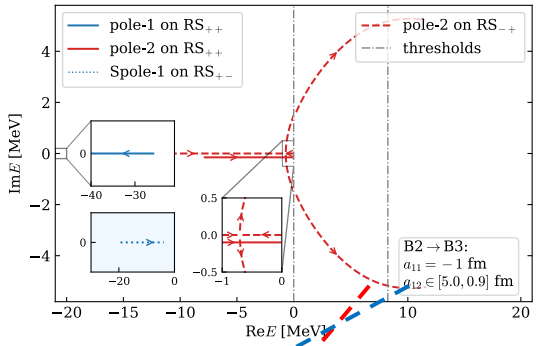


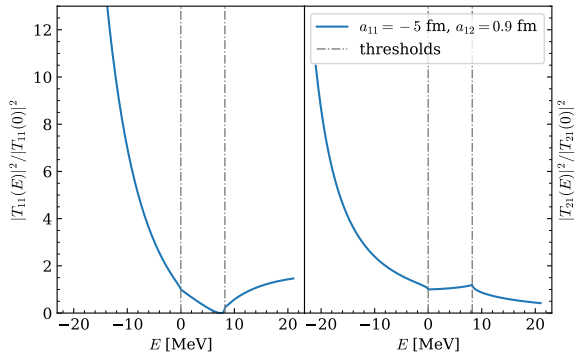
B2: $a_{11}\delta \in (-1,0), |a_{12}|\delta \gg 1$



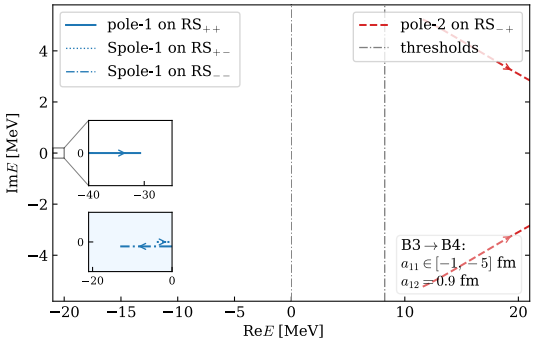


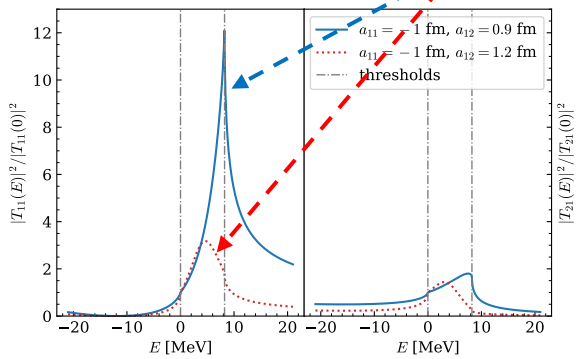






B4: $a_{11}\delta \ll -1, |a_{12}|\delta \in (0,1)$





B3: $a_{11}\delta \in (-1,0), |a_{12}|\delta \in (0,1)$

Z.-H. Zhang, FKG, PLB 863 (2025) 139387

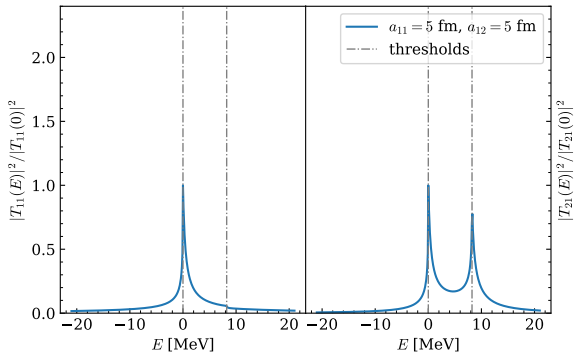
Classification of coupled-channel near-threshold structures

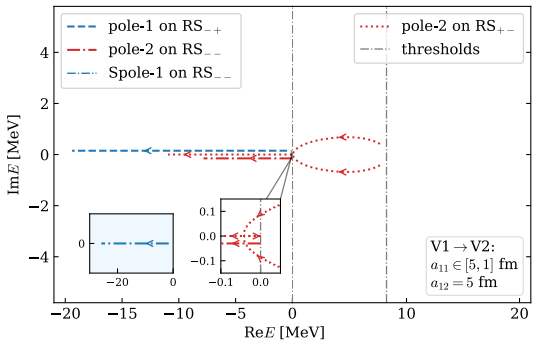
Starting from RGE fixed point with two zero-energy bound state:

Two-channel cases (V): $a_{11} > 0$

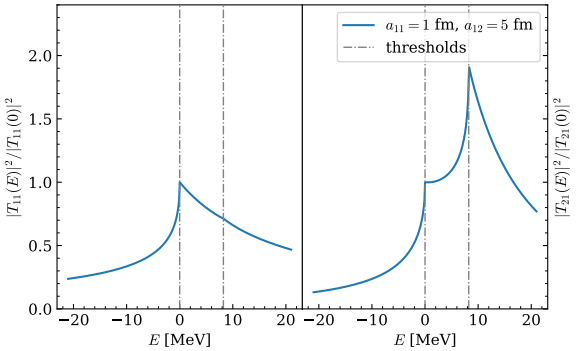
Here, $\delta \equiv \sqrt{2\mu_2\Delta}$,
Spole: shadow pole

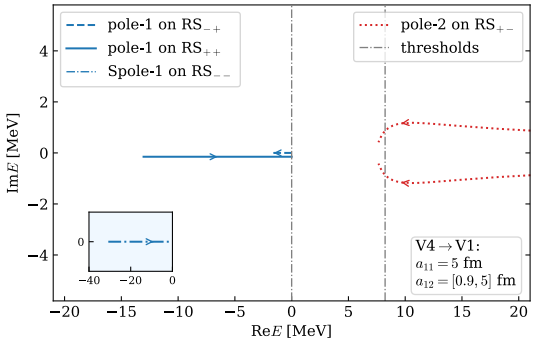
V1: $a_{11}\delta \gg 1, |a_{12}|\delta \gg 1$

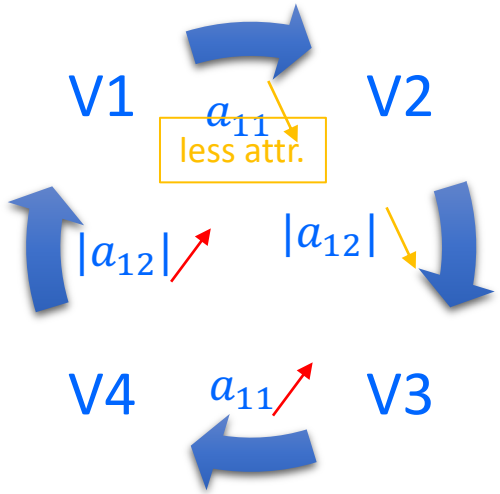


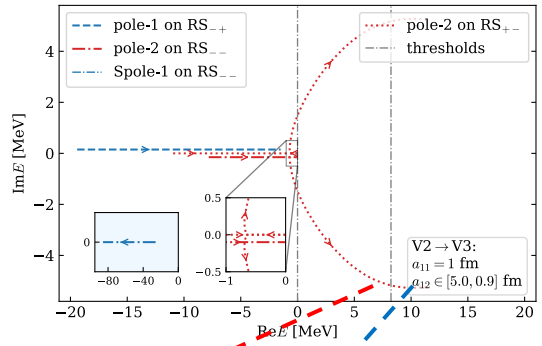


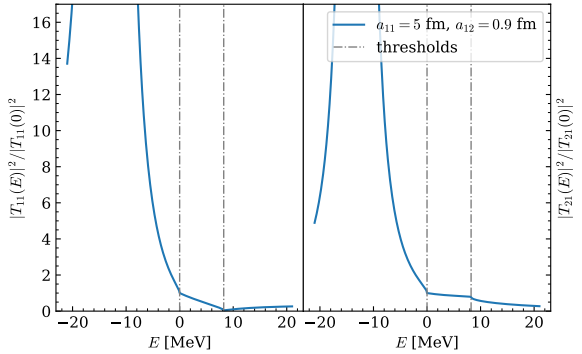
V2: $a_{11}\delta \in (0,1), |a_{12}|\delta \gg 1$



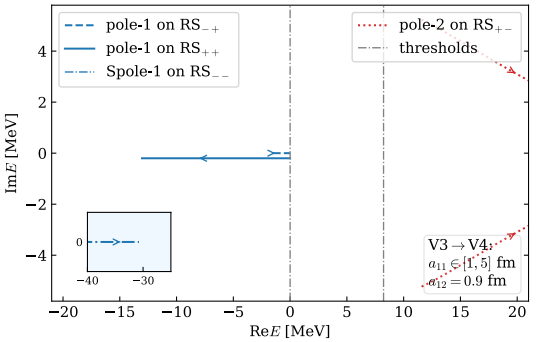


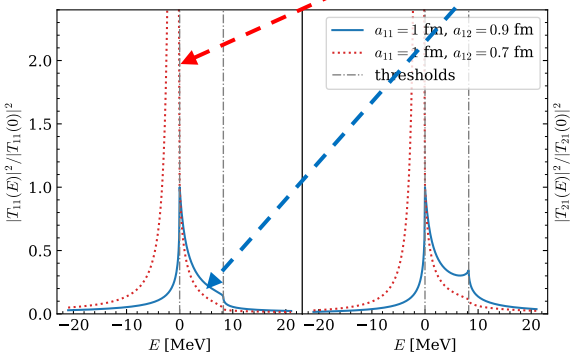






V4: $a_{11}\delta \gg 1, |a_{12}|\delta \in (0,1)$





V3: $a_{11}\delta \in (0,1), |a_{12}|\delta \in (0,1)$

Z.-H. Zhang, FKG, PLB 863 (2025) 139387

Poles dual to those in the B cases, on opposite RSs.

Summary

- General rules for (near-)threshold structures
  - S-wave attraction, more prominent for heavier particles and stronger attraction
  - Pole behavior: distinct line shapes depending on reaction mechanism
  - Universality: a dip (for large $|a_{22}|$) at the higher channel threshold in T_{11}

- Zotero-INSPIRE: brings INSPIRE into your zotero, and more!

Thank you for your attention!

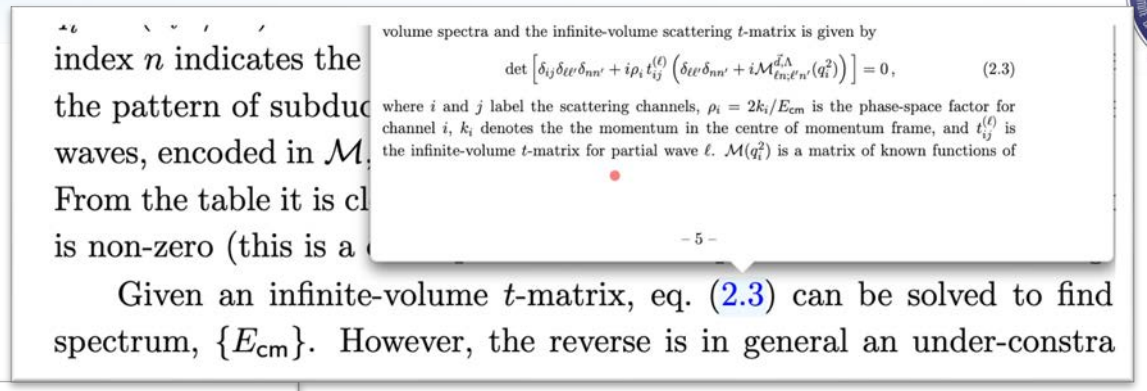
More interesting stuff

Zotero

- 开源免费 （若用它的官方云端存储超过一定额度，需要付年费）、多系统 (windows, linux, mac, ios, android)
- 标签、多层级 collection（同一个文献可以同时存在于多个 collections）、可设置有关联的文献
- pdf 批注 (支持手写)
- 多样化地添加文献方式
- 非常多的插件
  - 国内 Zotero 社区维护的插件市场：https://plugins.zotero-chinese.com
  - Better BibTeX (BBT): 提供 citekey 功能
    - 在设置中将 Citation key formula 设为 `inspireHep`
  - Zotero-INSPIRE: 任给 arXiv 号或 doi 或 INSPIRE 标准 citekey 等信息，可从 INSPIRE 数据库更新文献的元数据，包括发表信息、引用次数（及他引次数）等，插件页面有更多使用说明
  - ...
- 可以将某个 collection 的文献信息输出 .bib 文件，并自动更新 （后面有对写文章来说更便捷的更新 bib 文件的方式）
- 构建好文献库后，可以结合 vs code (+ vs code 的 LaTeX workshop 插件) 实现边写边引，极大节省精力！

Zotero

- 稳定版: 7
- Beta 版: 8


index n indicates the
the pattern of subduc
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From the table it is cl
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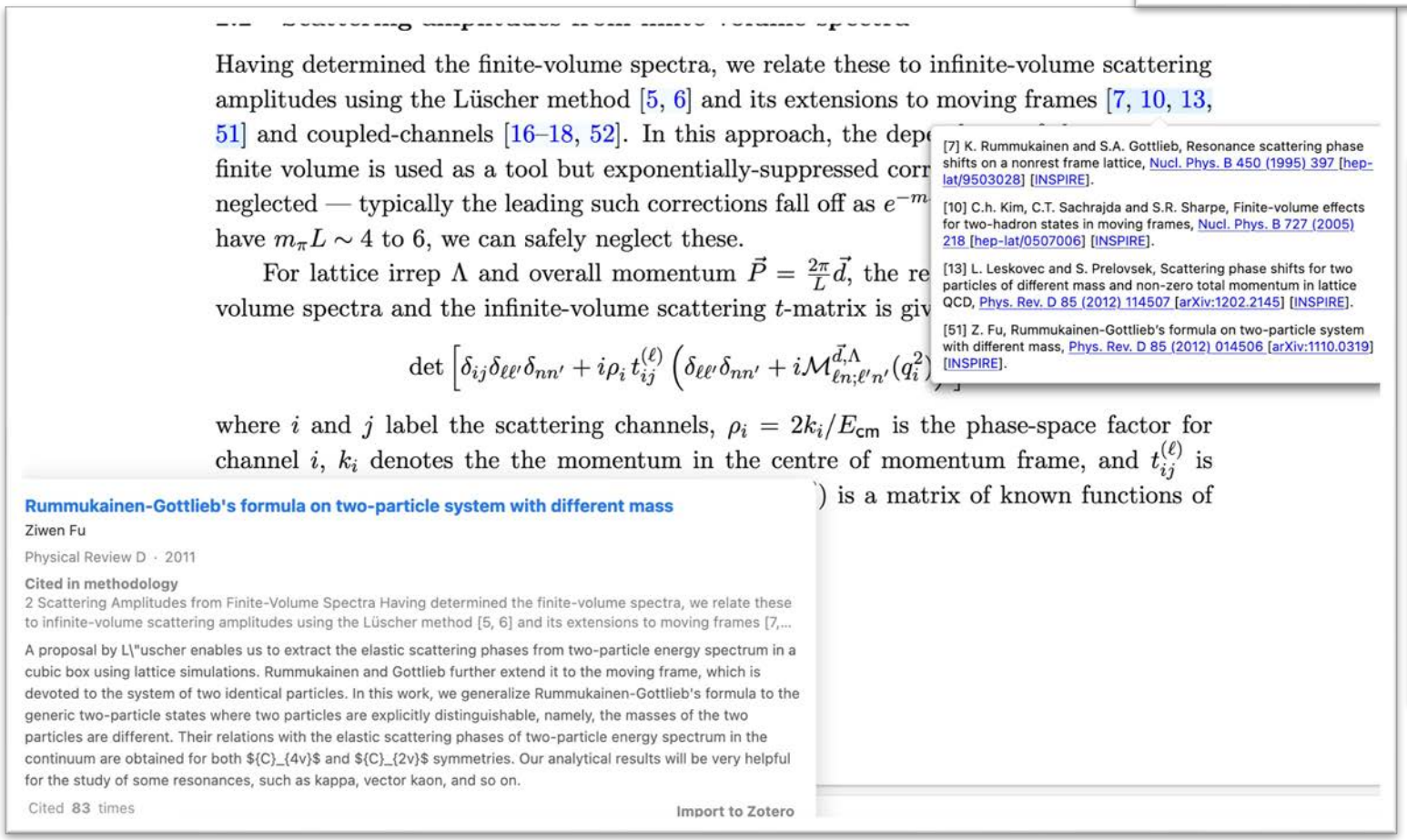
volume spectra and the infinite-volume scattering t-matrix is given by

$$\det\left[\delta_{ij}\delta_{\ell\ell'}\delta_{nn'} + i\rho_i t_{ij}^{(\ell)}\left(\delta_{\ell\ell'}\delta_{nn'} + i\mathcal{M}^{\vec{d},\Lambda}_{\ell n;\ell' n'}(q_i^2)\right)\right] = 0\,, \qquad (2.3)$$

where i and j label the scattering channels, $\rho_i = 2k_i/E_{\text{cm}}$ is the phase-space factor for channel i, k_i denotes the the momentum in the centre of momentum frame, and $t_{ij}^{(\ell)}$ is the infinite-volume t-matrix for partial wave ℓ. $\mathcal{M}(q_i^2)$ is a matrix of known functions of

– 5 –

Given an infinite-volume t-matrix, eq. (2.3) can be solved to find spectrum, $\{E_{\text{cm}}\}$. However, the reverse is in general an under-constra


Having determined the finite-volume spectra, we relate these to infinite-volume scattering amplitudes using the Lüscher method [5, 6] and its extensions to moving frames [7, 10, 13, 51] and coupled-channels [16–18, 52]. In this approach, the depe
finite volume is used as a tool but exponentially-suppressed corr
neglected — typically the leading such corrections fall off as e^{-m}
have $m_\pi L \sim 4$ to 6, we can safely neglect these.

For lattice irrep Λ and overall momentum $\vec{P} = \frac{2\pi}{L}\vec{d}$, the re
volume spectra and the infinite-volume scattering t-matrix is giv

$$\det\left[\delta_{ij}\delta_{\ell\ell'}\delta_{nn'} + i\rho_i t_{ij}^{(\ell)}\left(\delta_{\ell\ell'}\delta_{nn'} + i\mathcal{M}^{\vec{d},\Lambda}_{\ell n;\ell' n'}(q_i^2)\right)\right]$$

where i and j label the scattering channels, $\rho_i = 2k_i/E_{\text{cm}}$ is the phase-space factor for channel i, k_i denotes the the momentum in the centre of momentum frame, and $t_{ij}^{(\ell)}$ is
) is a matrix of known functions of

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[51] Z. Fu, Rummukainen-Gottlieb's formula on two-particle system with different mass, Phys. Rev. D 85 (2012) 014506 [arXiv:1110.0319] [INSPIRE].

Rummukainen-Gottlieb's formula on two-particle system with different mass

Ziwen Fu

Physical Review D · 2011

Cited in methodology

2 Scattering Amplitudes from Finite-Volume Spectra Having determined the finite-volume spectra, we relate these to infinite-volume scattering amplitudes using the Lüscher method [5, 6] and its extensions to moving frames [7,...

A proposal by L\"uscher enables us to extract the elastic scattering phases from two-particle energy spectrum in a cubic box using lattice simulations. Rummukainen and Gottlieb further extend it to the moving frame, which is devoted to the system of two identical particles. In this work, we generalize Rummukainen-Gottlieb's formula to the generic two-particle states where two particles are explicitly distinguishable, namely, the masses of the two particles are different. Their relations with the elastic scattering phases of two-particle energy spectrum in the continuum are obtained for both ${C}_{4v}$ and ${C}_{2v}$ symmetries. Our analytical results will be very helpful for the study of some resonances, such as kappa, vector kaon, and so on.

Cited 83 times

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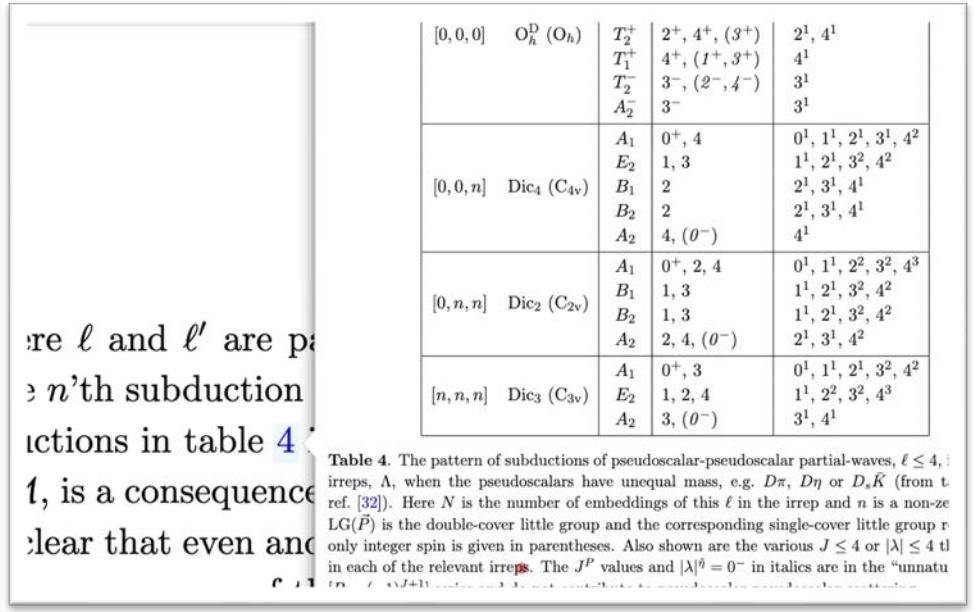
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$[0,0,0]$	O_h^D (O_h)	T_2^+ T_1^+ T_2^- A_2^-	$2^+, 4^+, (3^+)$ $4^+, (1^+, 3^+)$ $3^-, (2^-, 4^-)$ 3^-	$2^1, 4^1$ 4^1 3^1 3^1
$[0,0,n]$	Dic_4 (C_{4v})	A_1 E_2 B_1 B_2 A_2	$0^+, 4$ $1, 3$ 2 2 $4, (0^-)$	$0^1, 1^1, 2^1, 3^1, 4^2$ $1^1, 2^1, 3^2, 4^2$ $2^1, 3^1, 4^1$ $2^1, 3^1, 4^1$ 4^1
$[0,n,n]$	Dic_2 (C_{2v})	A_1 B_1 B_2 A_2	$0^+, 2, 4$ $1, 3$ $1, 3$ $2, 4, (0^-)$	$0^1, 1^1, 2^2, 3^2, 4^3$ $1^1, 2^1, 3^2, 4^2$ $1^1, 2^1, 3^2, 4^2$ $2^1, 3^1, 4^2$
$[n,n,n]$	Dic_3 (C_{3v})	A_1 E_2 A_2	$0^+, 3$ $1, 2, 4$ $3, (0^-)$	$0^1, 1^1, 2^1, 3^2, 4^2$ $1^1, 2^2, 3^2, 4^3$ $3^1, 4^1$

Table 4. The pattern of subductions of pseudoscalar-pseudoscalar partial-waves, $\ell \leq 4$, irreps, Λ, when the pseudoscalars have unequal mass, e.g. $D\pi$, $D\eta$ or $D_s\bar{K}$ (from t ref. [32]). Here N is the number of embeddings of this ℓ in the irrep and n is a non-ze $\text{LG}(\vec{P})$ is the double-cover little group and the corresponding single-cover little group r only integer spin is given in parentheses. Also shown are the various $J \leq 4$ or $|\lambda| \leq 4$ tl in each of the relevant irreps. The J^P values and $|\lambda|^\eta = 0^-$ in italics are in the "unnatu

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    https://www.zotero.org/download/connectors
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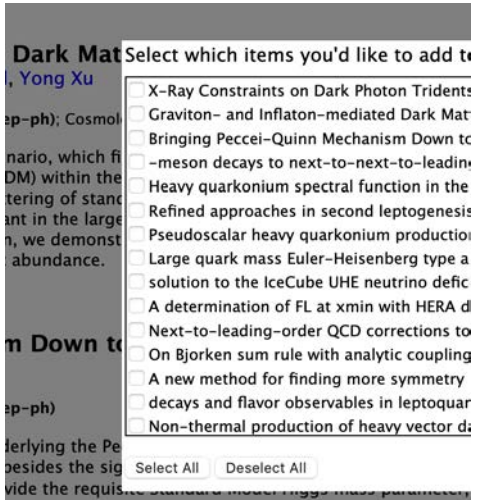

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  - arXiv:1706.04100
  - 或 Citation Key: BESIII:2017bua

更多小技巧及说明，参见
https://github.com/fkguo/zotero-inspire/tree/main?tab=readme-ov-file

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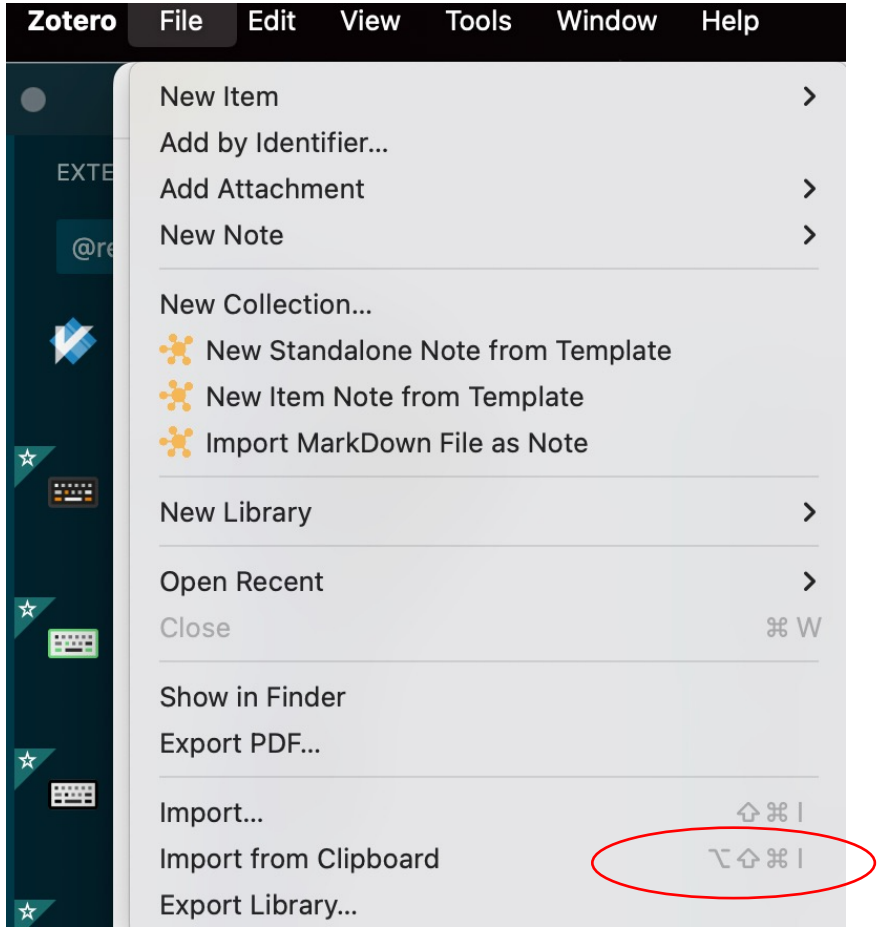
- 多种方式
  - 能处理特殊符号的方式: 从 INSPIRE 中复制文献条目的 bibtex，用 Import from clipboard 的快捷键导入，可自动将上下标、希腊字母等从 latex 格式转化成特殊符号的形式

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    eprint = "1706.04100",
    archivePrefix = "arXiv",
    primaryClass = "hep-ex",
    doi = "10.1103/PhysRevLett.119.072001",
    journal = "Phys. Rev. Lett.",
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    year = "2017"
}
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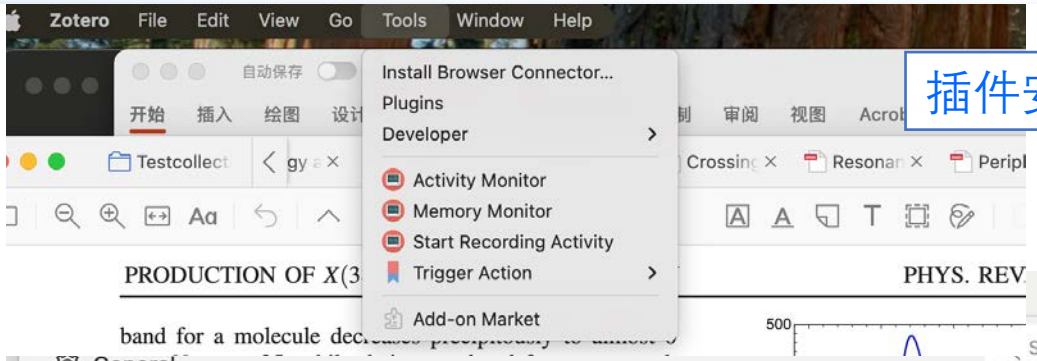

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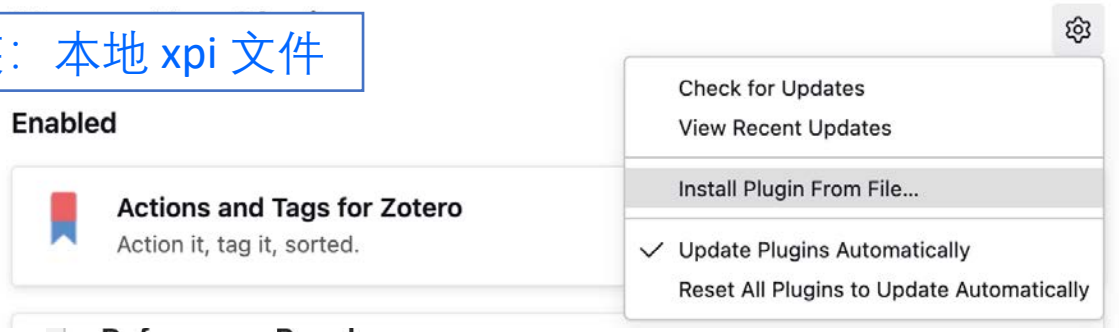

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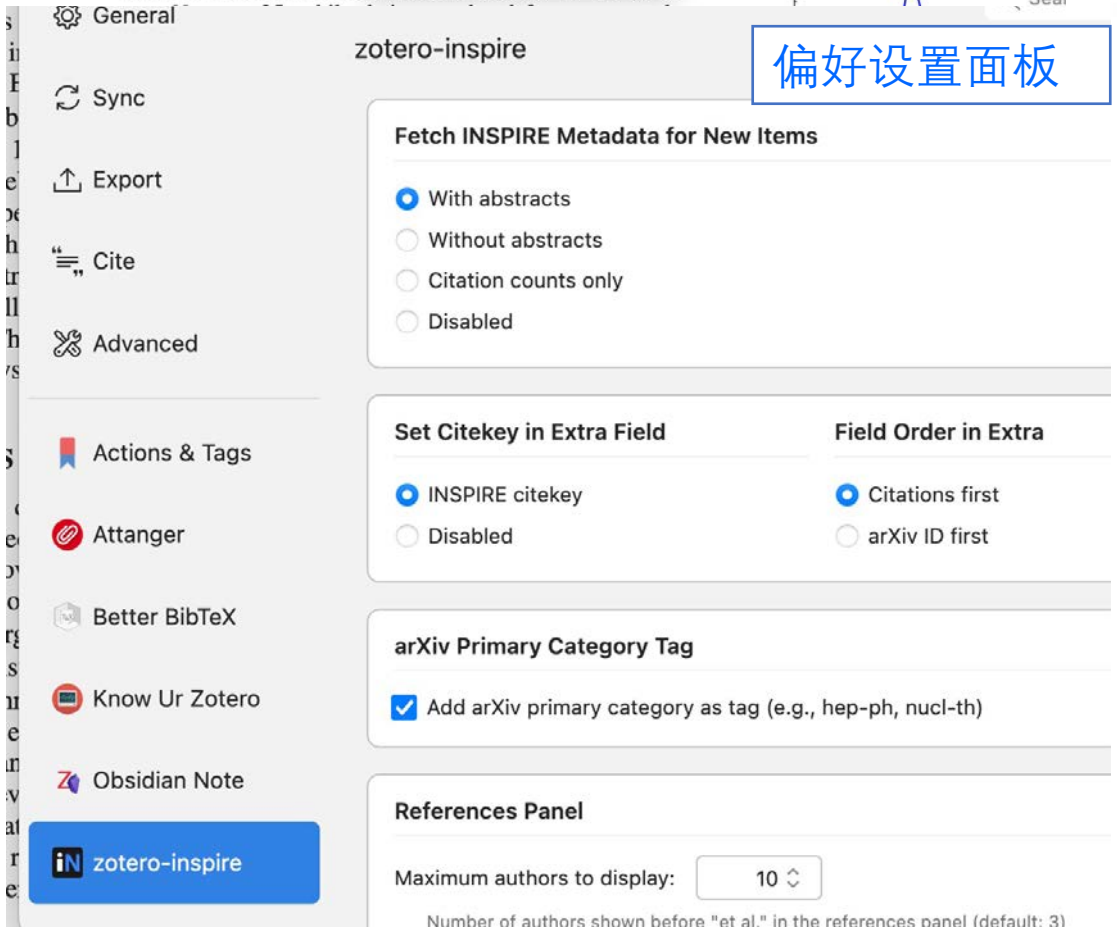

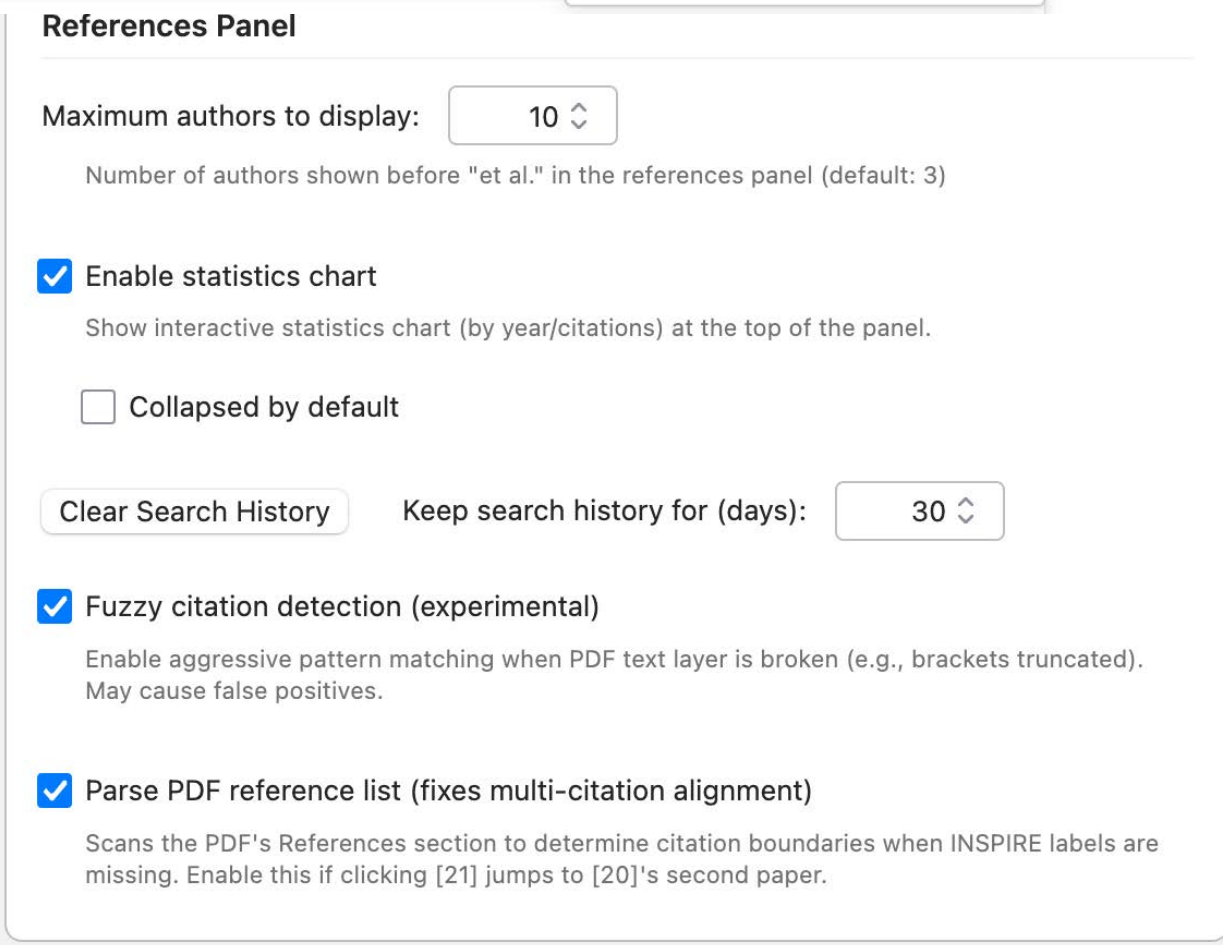

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Zotero-inspire中文说明

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- [x] Enable local cache for offline access

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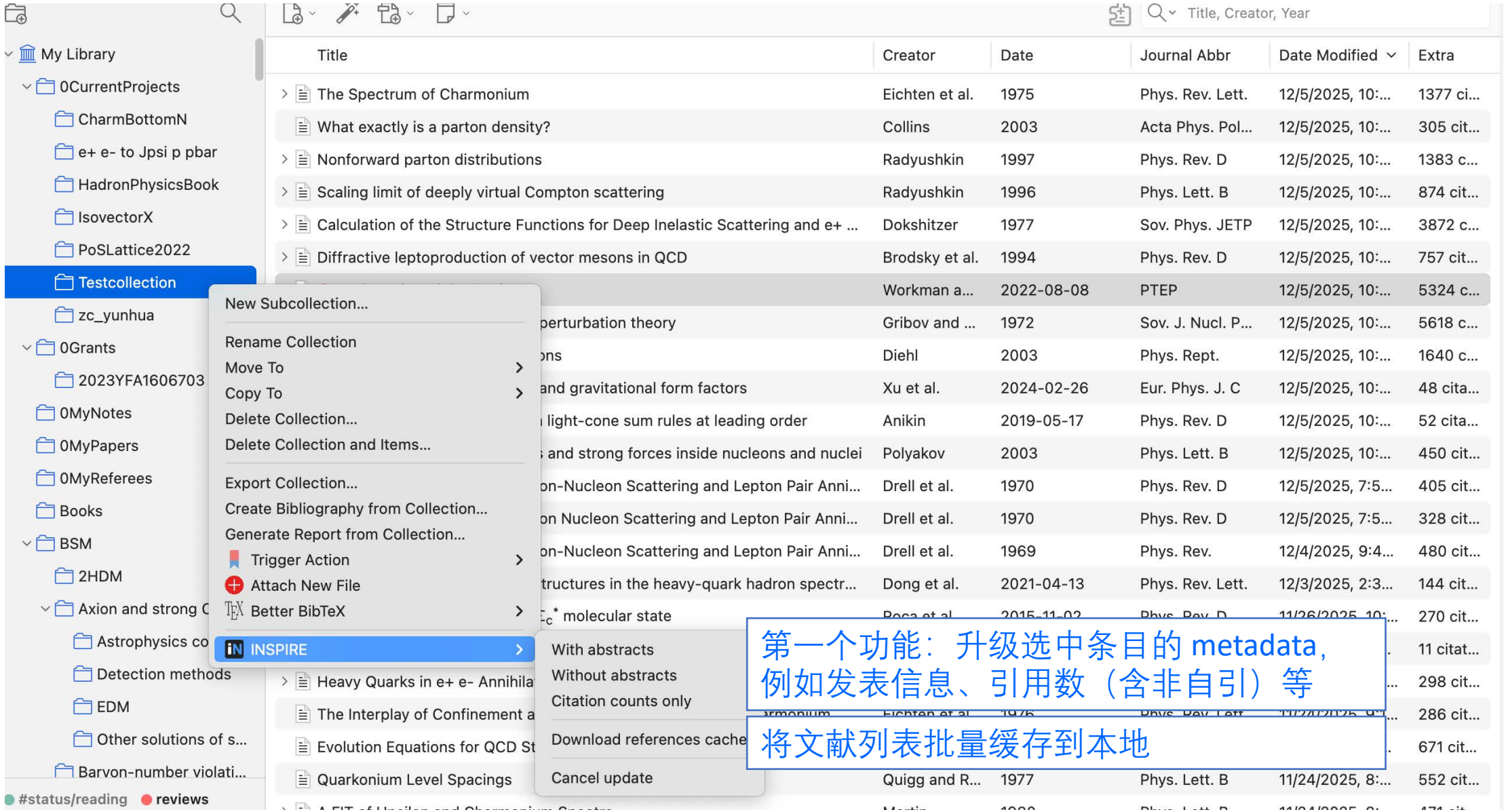

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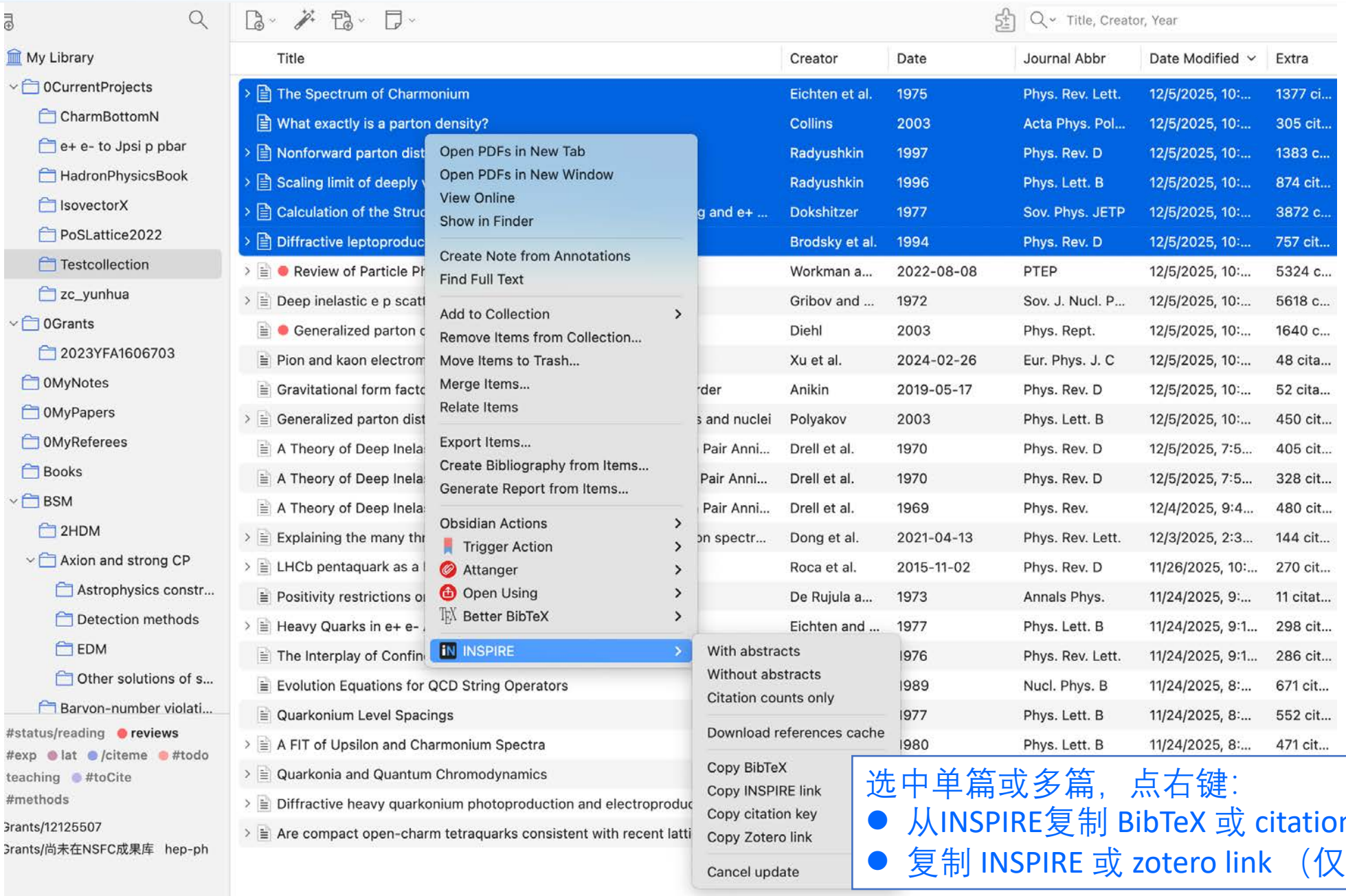

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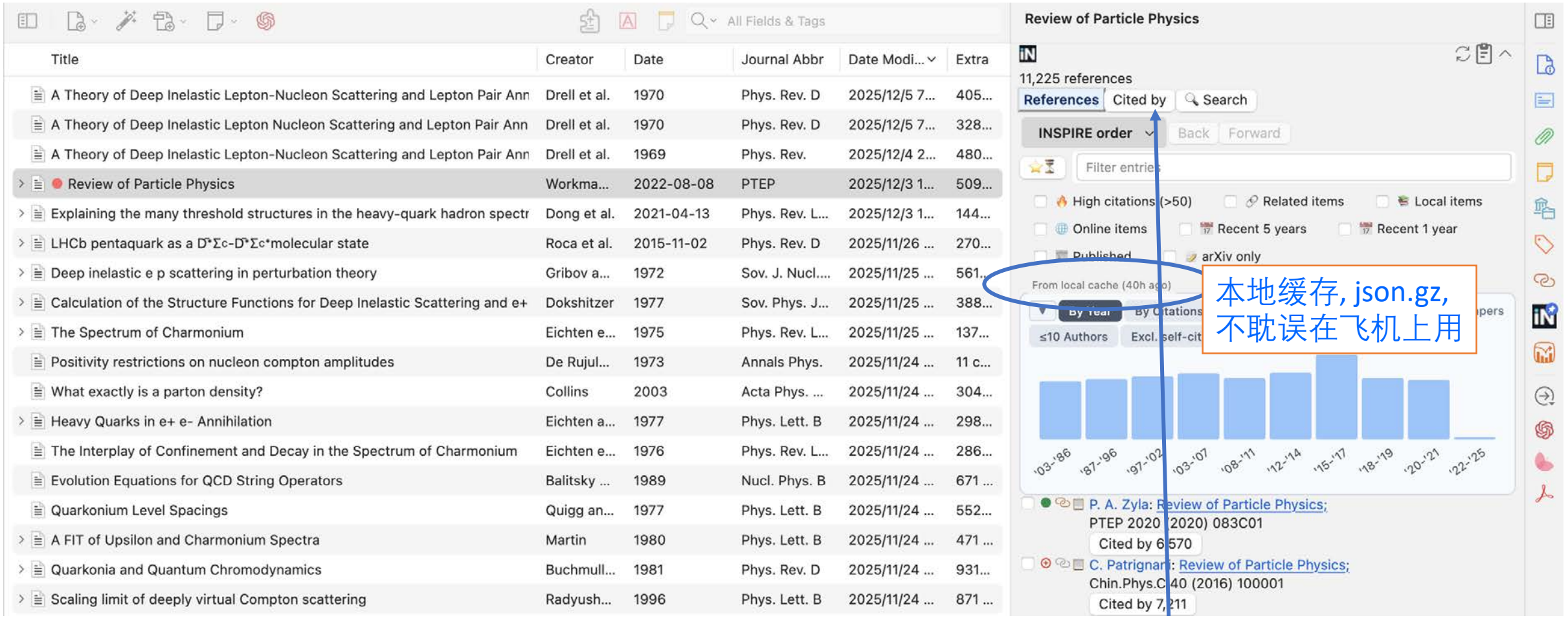

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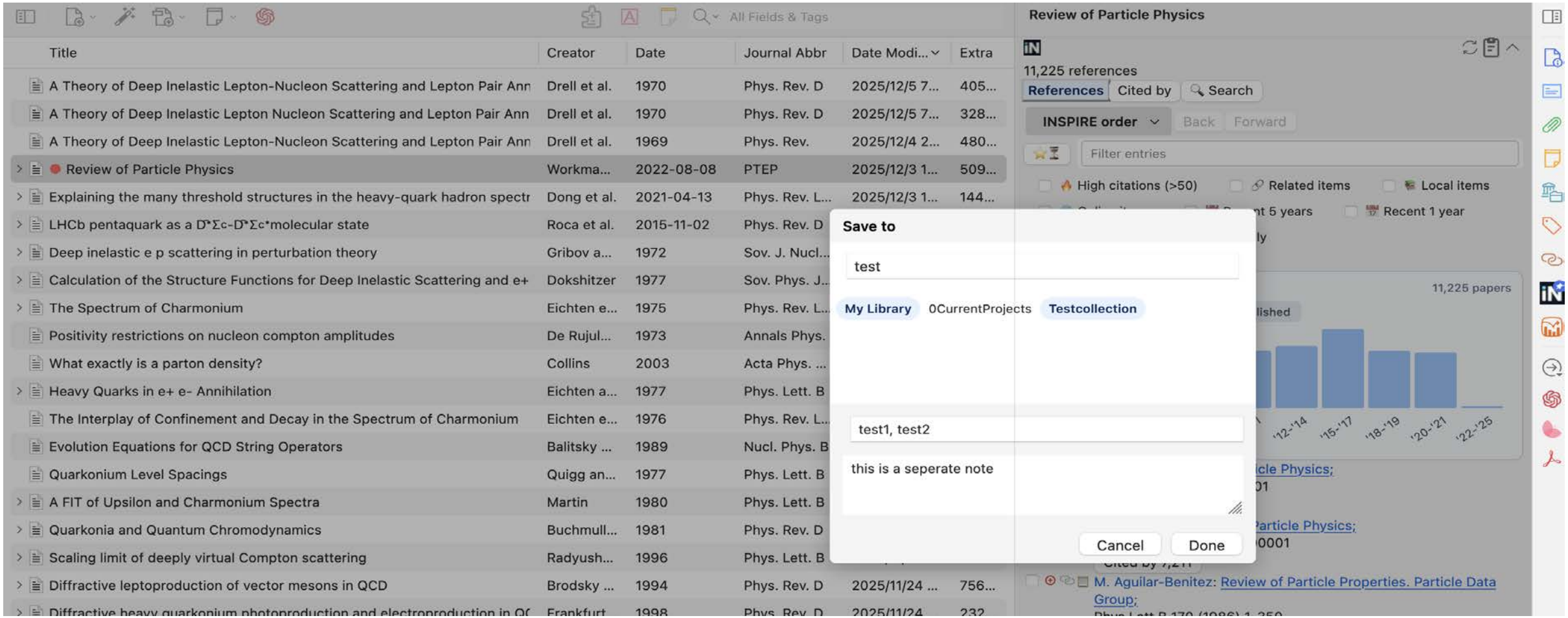

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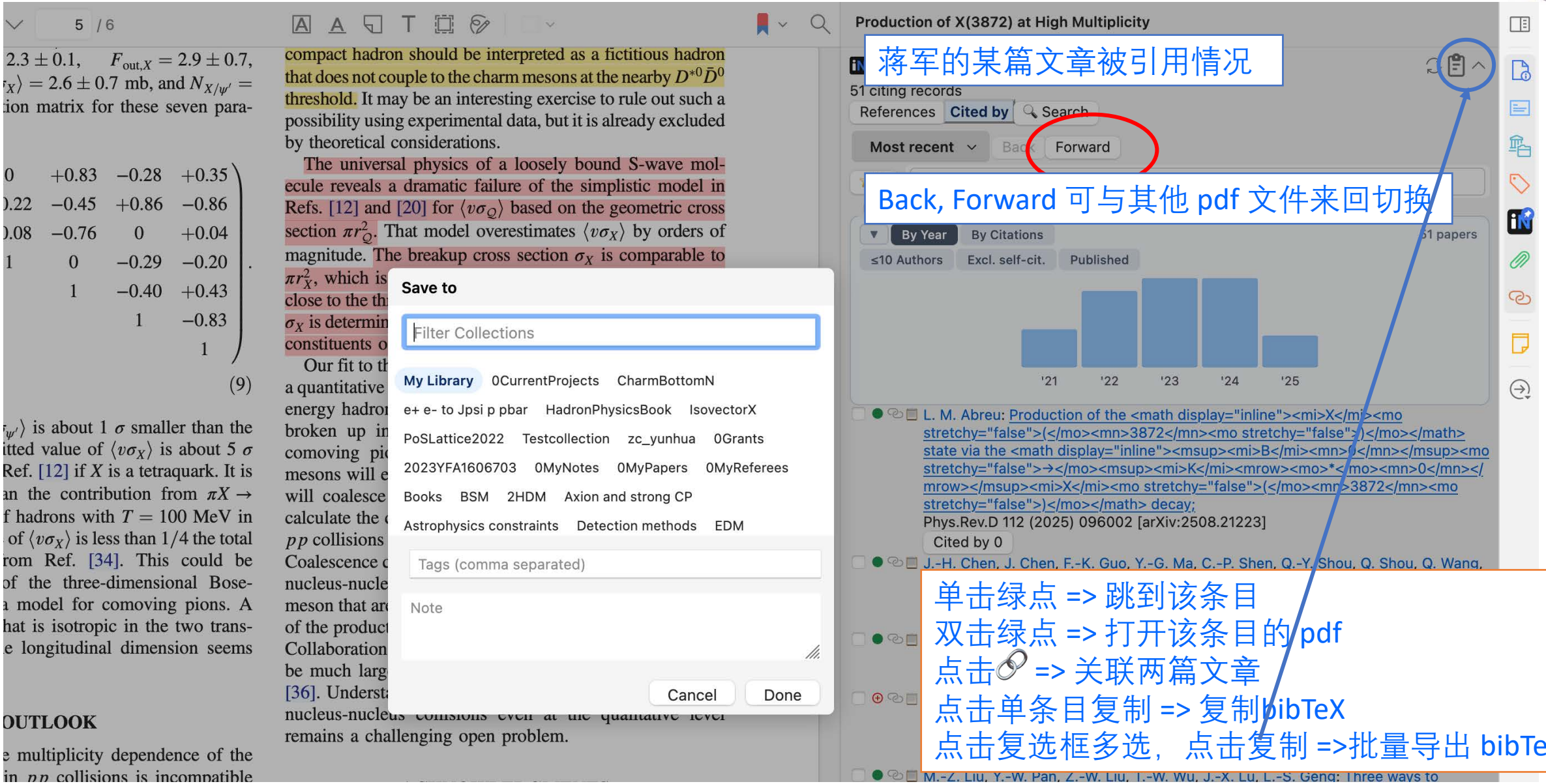

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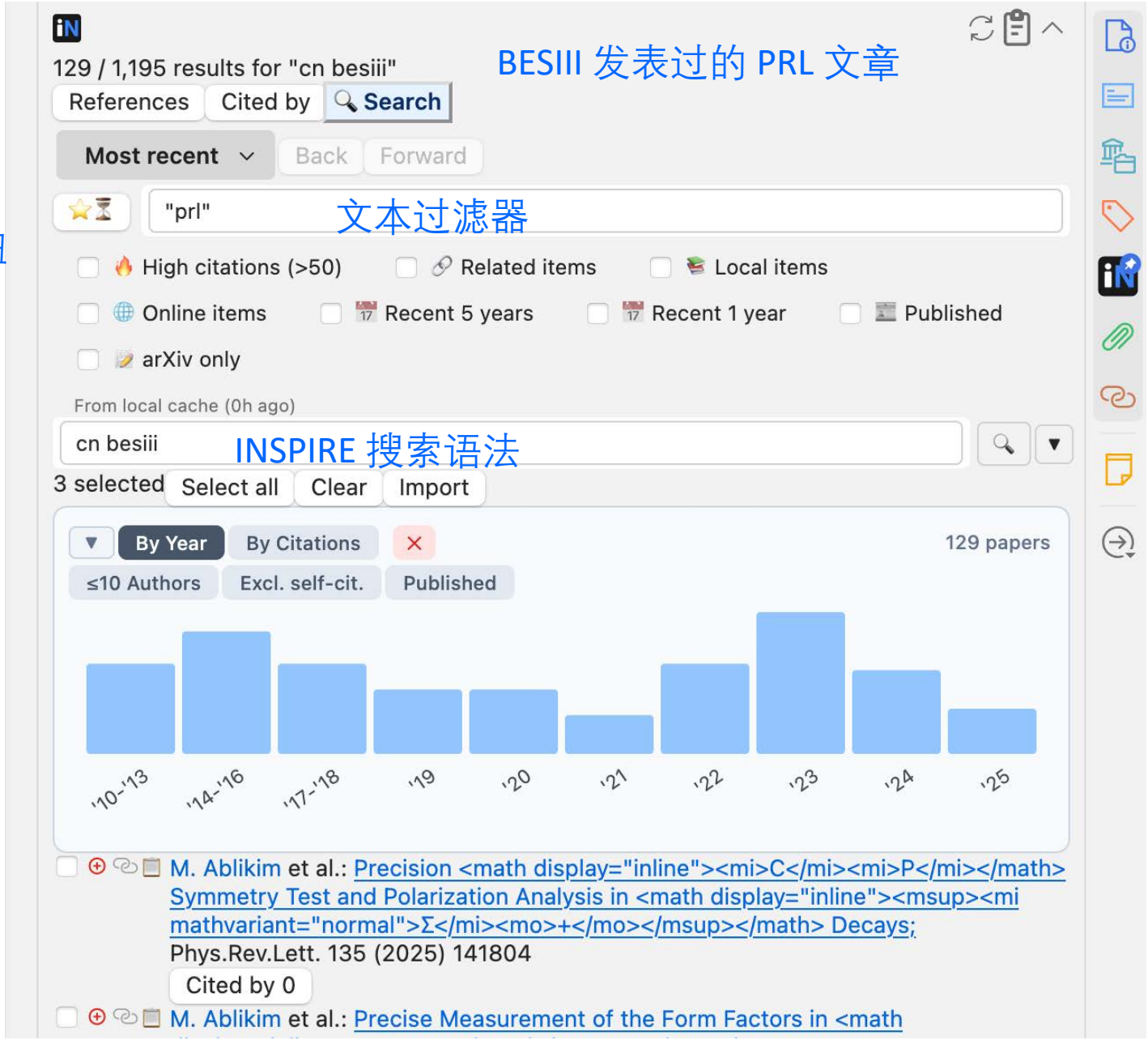

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and with universal properties determined by ε_X [9]. The mean separation of its constituents is $r_X = (8\mu|\varepsilon_X|)^{-1/2}$, where μ is the reduced mass of $D^{*0}\bar{D}^0$. The upper bound $|\varepsilon_X| < 0.22$ MeV implies $r_X > 4.8$ fm. Thus, this amazing hadron has a radius more than an order of magnitude larger than that of ordinary hadrons. More relevant to the other exotic heavy hadrons is what X would have been if not for the fine-tuning of its mass to the $D^{*0}\bar{D}^0$ threshold. The possibilities that have been proposed include the P-wave charmonium state $\chi_{c1}(2P)$, an isospin-0 charm-meson molecule, and an isospin-1 compact tetraquark. In all these cases, the tuning of the mass to the $D^{*0}\bar{D}^0$ threshold produces resonant couplings to $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$ that transforms X into a loosely bound molecule of neutral charm mesons.

Shortly after the discovery of X in B-meson decays [1], its existence was confirmed in $p\bar{p}$ collisions [10]. The production of X at a hadron collider can be resolved into two contributions: *prompt* production by strong interactions at the d the *b-decay* contribution fr s containing a bottom quark c ondary vertex. The behavior may provide evidence for t ant difference is the l he decay ns emerg at the LH m the primary vertex. Collisions with comoving hadrons

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[4] M. Karliner, J. L. Rosner, T. Skwarnicki: Multiquark States;
Ann.Rev.Nucl.Part.Sci. 68 (2018) 17-44 [arXiv:1711.10626]
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Eur.Phys.J.C 81 (2021) 669 [arXiv:2006.15044]

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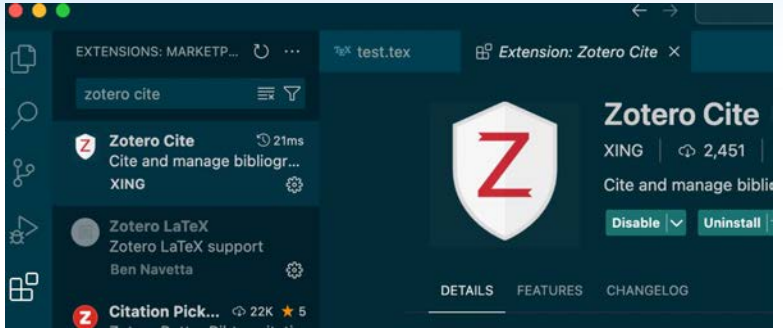

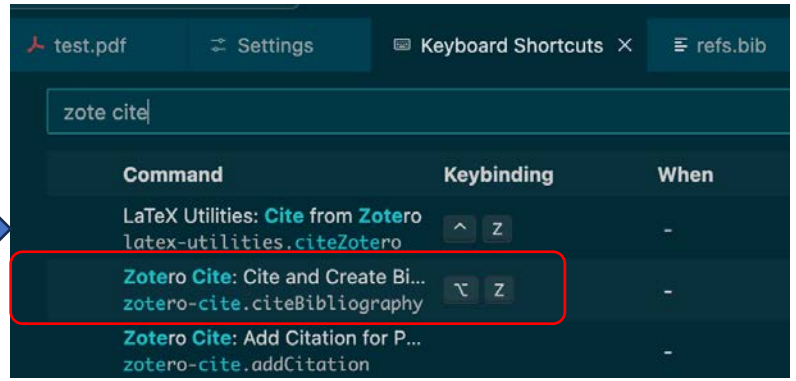

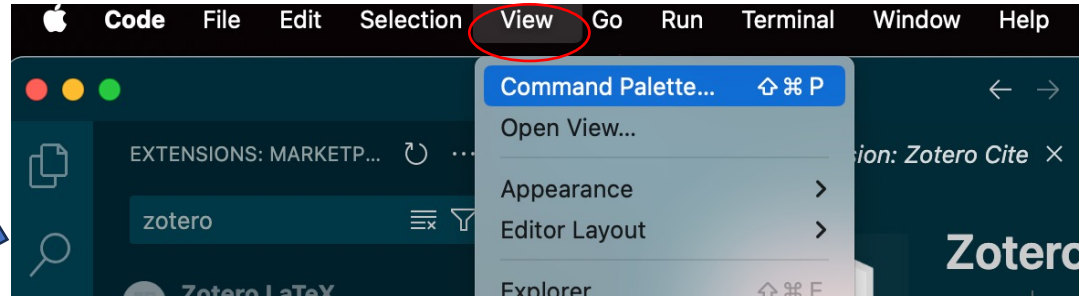

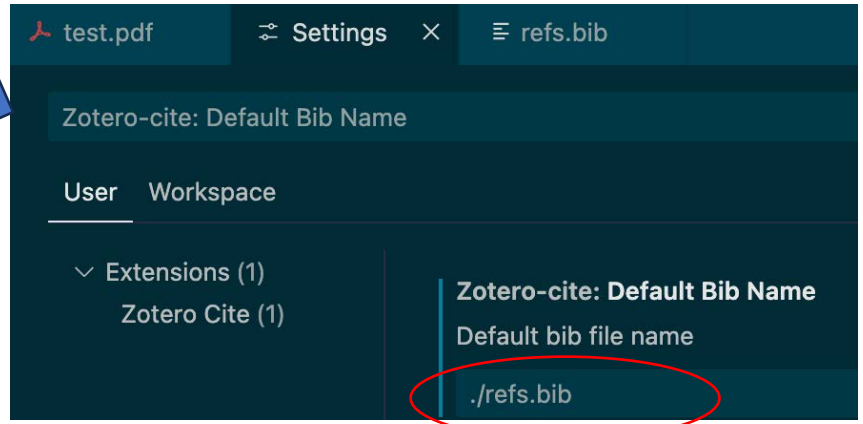

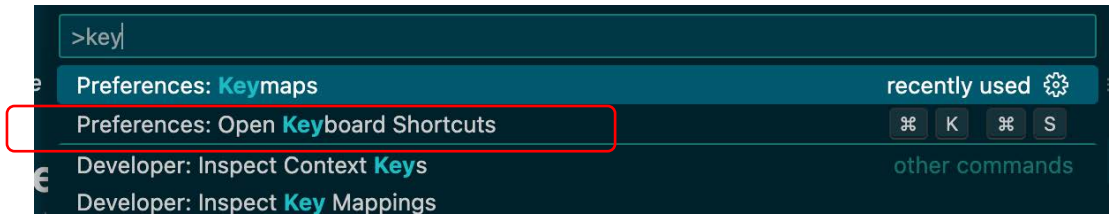

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  - 需要系统中已经安装过 latex 编译软件，如
    - TeXLive https://tug.org/texlive/
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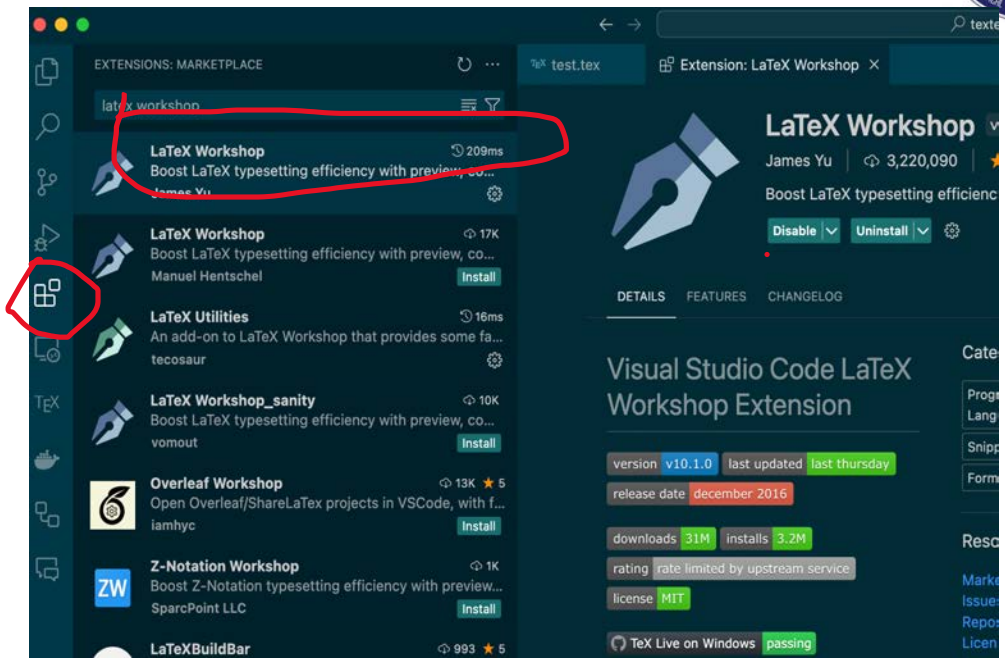

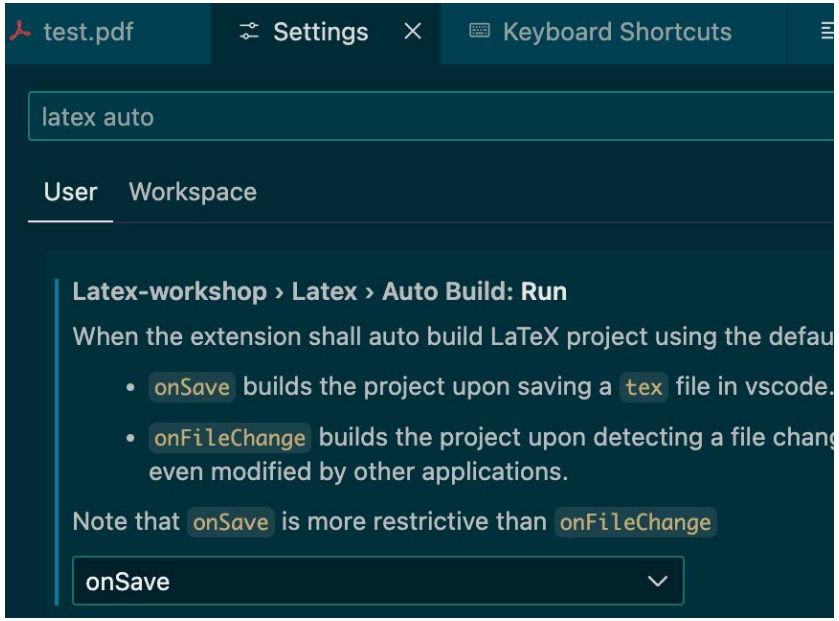

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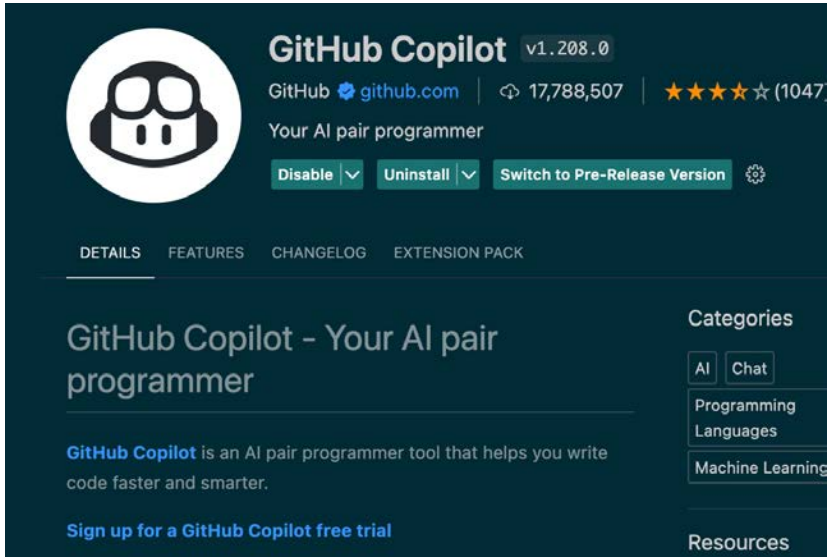

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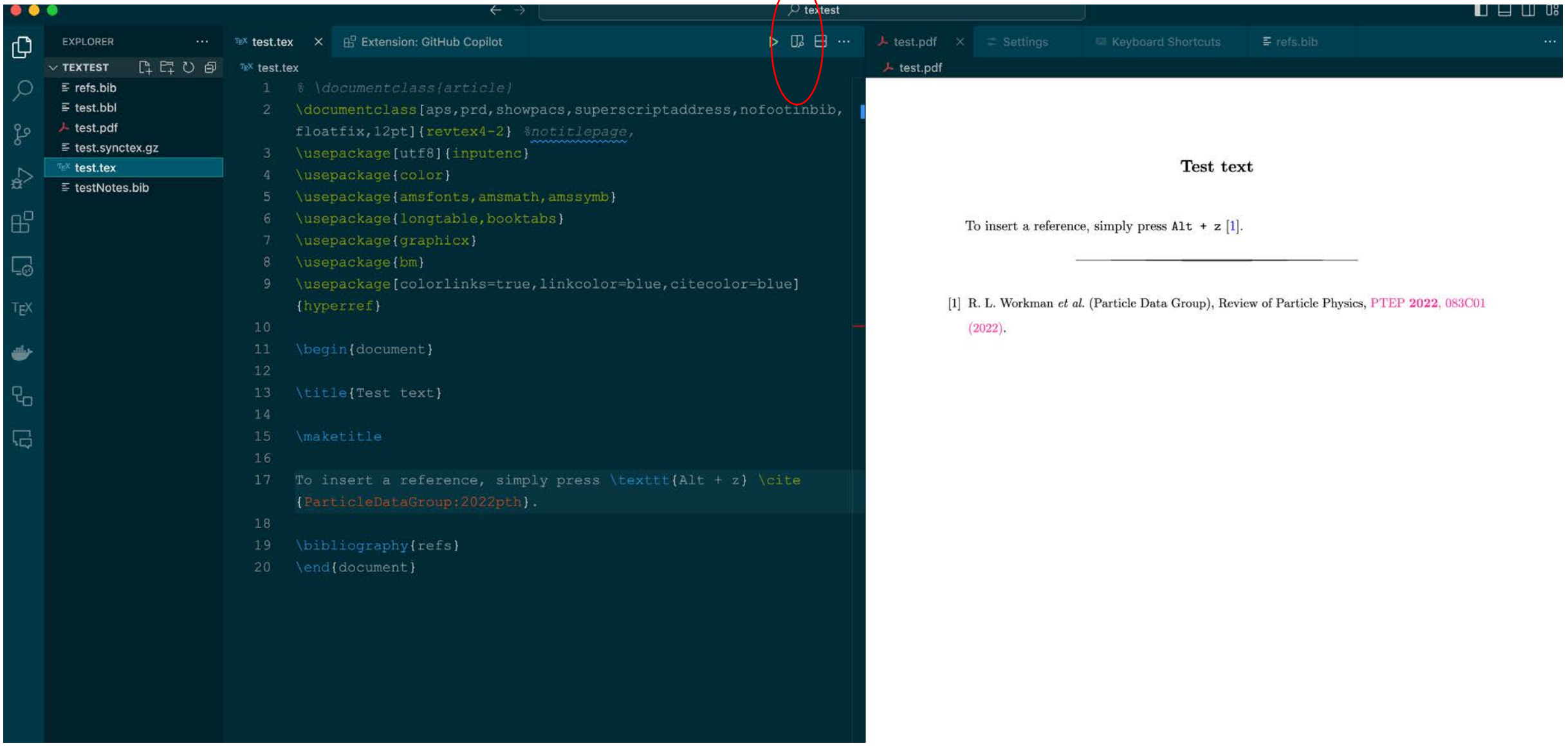
- 点击 View LaTeX PDF file，可实现 tex 源文件和 pdf 文件同屏显示，分屏线可拖拽调整



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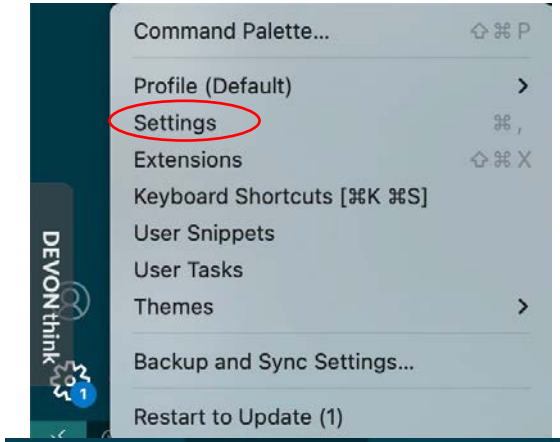

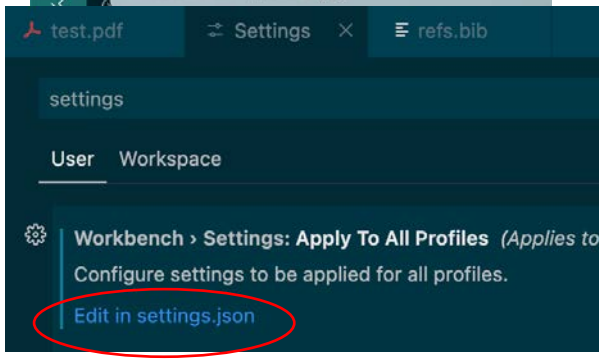

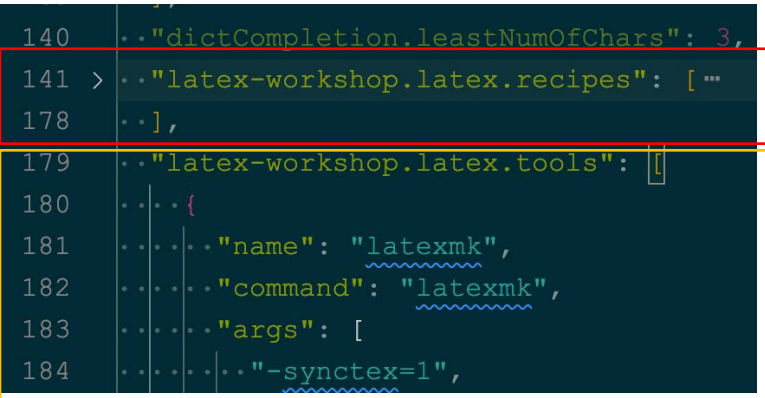

我的配置文件中的相关设置

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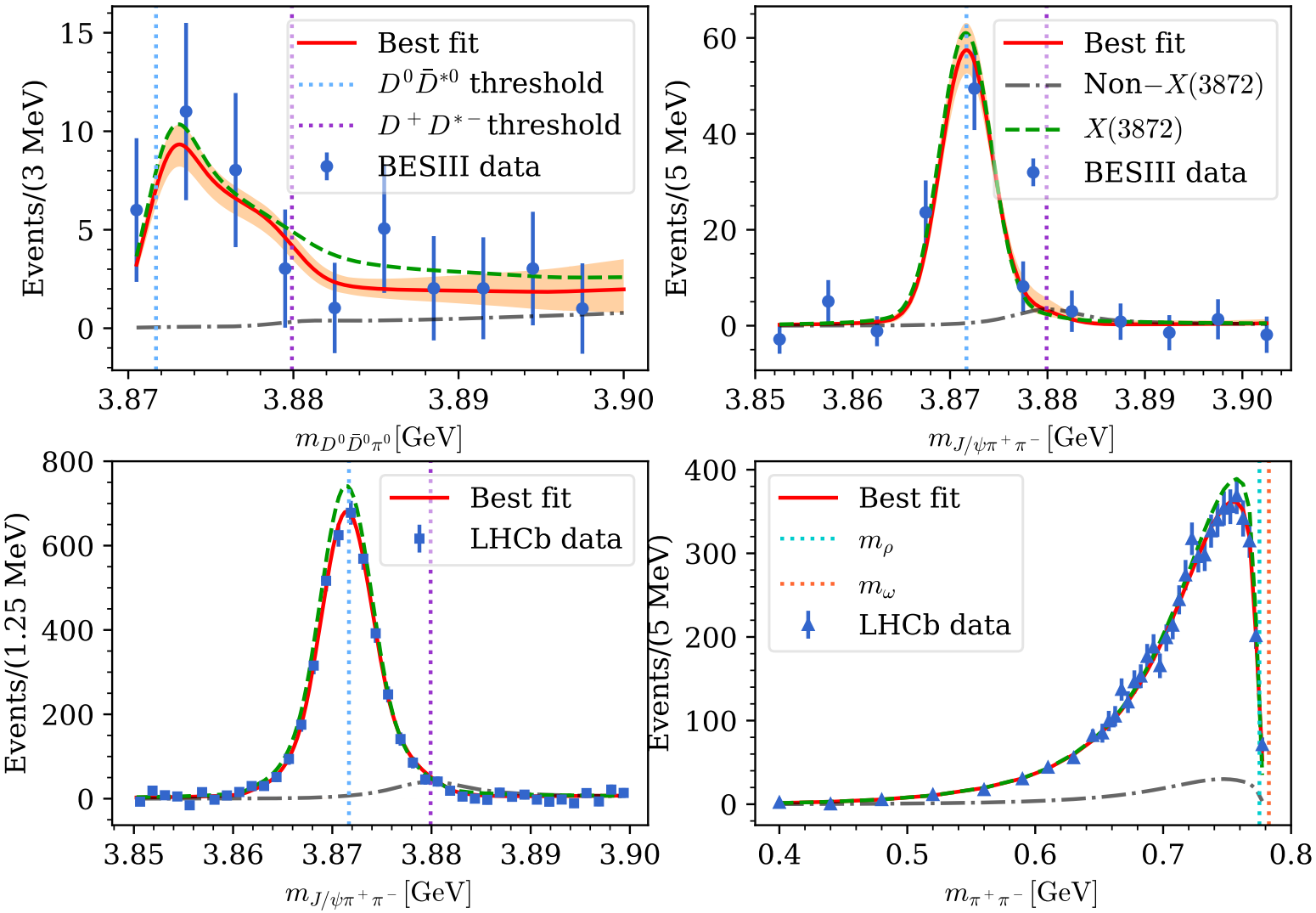
Combined analysis of BESIII and LHCb data for $X(3872)$



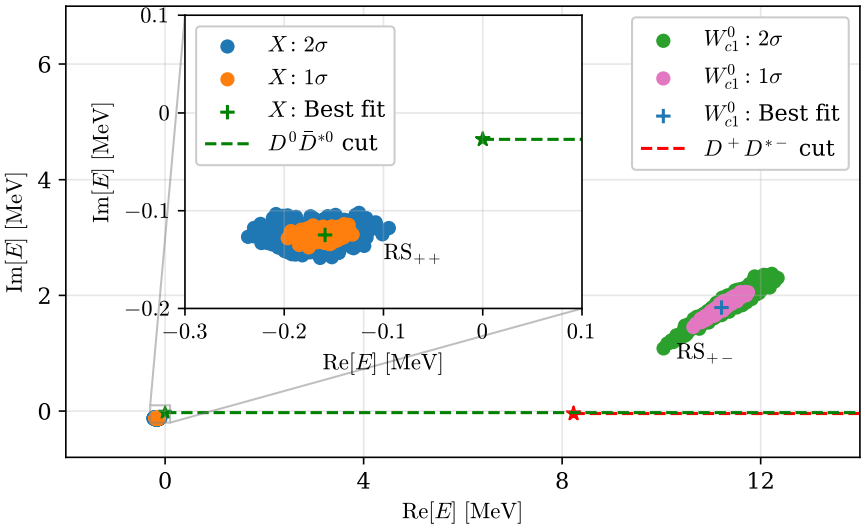
Best fit: $\chi^2/\text{dof} = 57/(96-10) = 0.66$

- Poles
  - $X(3872)$ as a bound state below $D^0\bar{D}^{*0}$ threshold (2.8σ)

$$E_X = \left(-160^{+43+38}_{-47-57} - 125^{+18+15}_{-25-28}i\right)\ \text{keV}$$

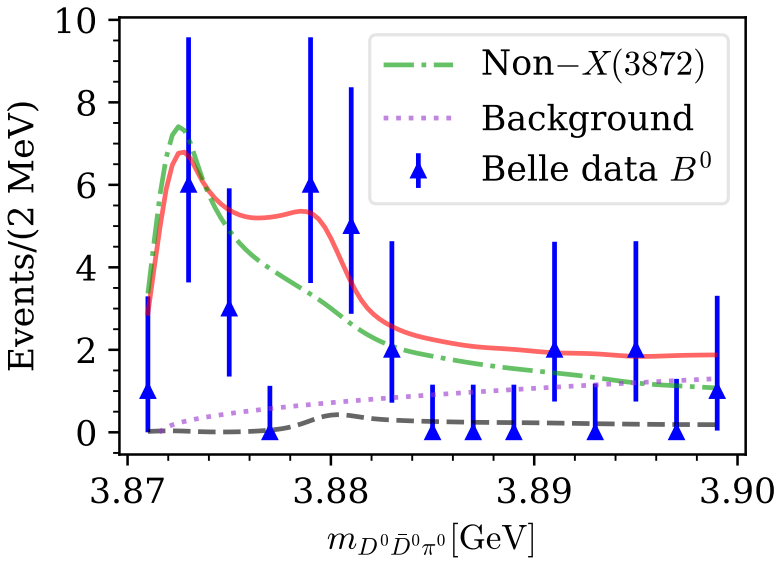
  - $W_{c1}(3880)^0$ pole on RS_{+-}, relative to the D^+D^{*-} threshold:

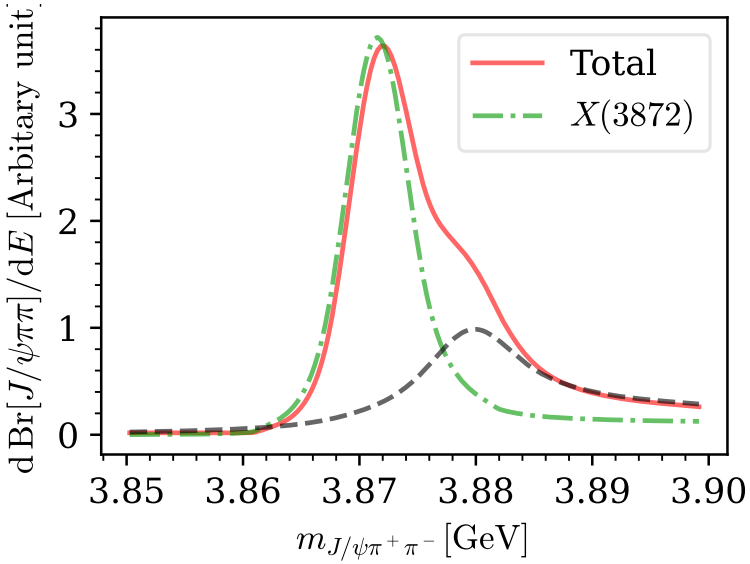
$$E_W = \left(3.1 \pm 0.7 + 1.3^{+1.9}_{-0.6}i\right)\ \text{MeV}$$



Implications of the existence of $W_{c1}(3880)$

- $W_{c1}(3880)^0$ signal should be stronger in $B^0 \to K^0[D^0\bar{D}^0\pi^0, J/\psi\pi^+\pi^-]$ decays, to be checked @ LHCb, Belle II





- Cusp at $D^+\bar{D}^{*0}/D^{*+}\bar{D}^0$ threshold in $J/\psi\pi^{\pm}\pi^0$