Novel Approaches to the Internal Structure of Exotic Hadrons

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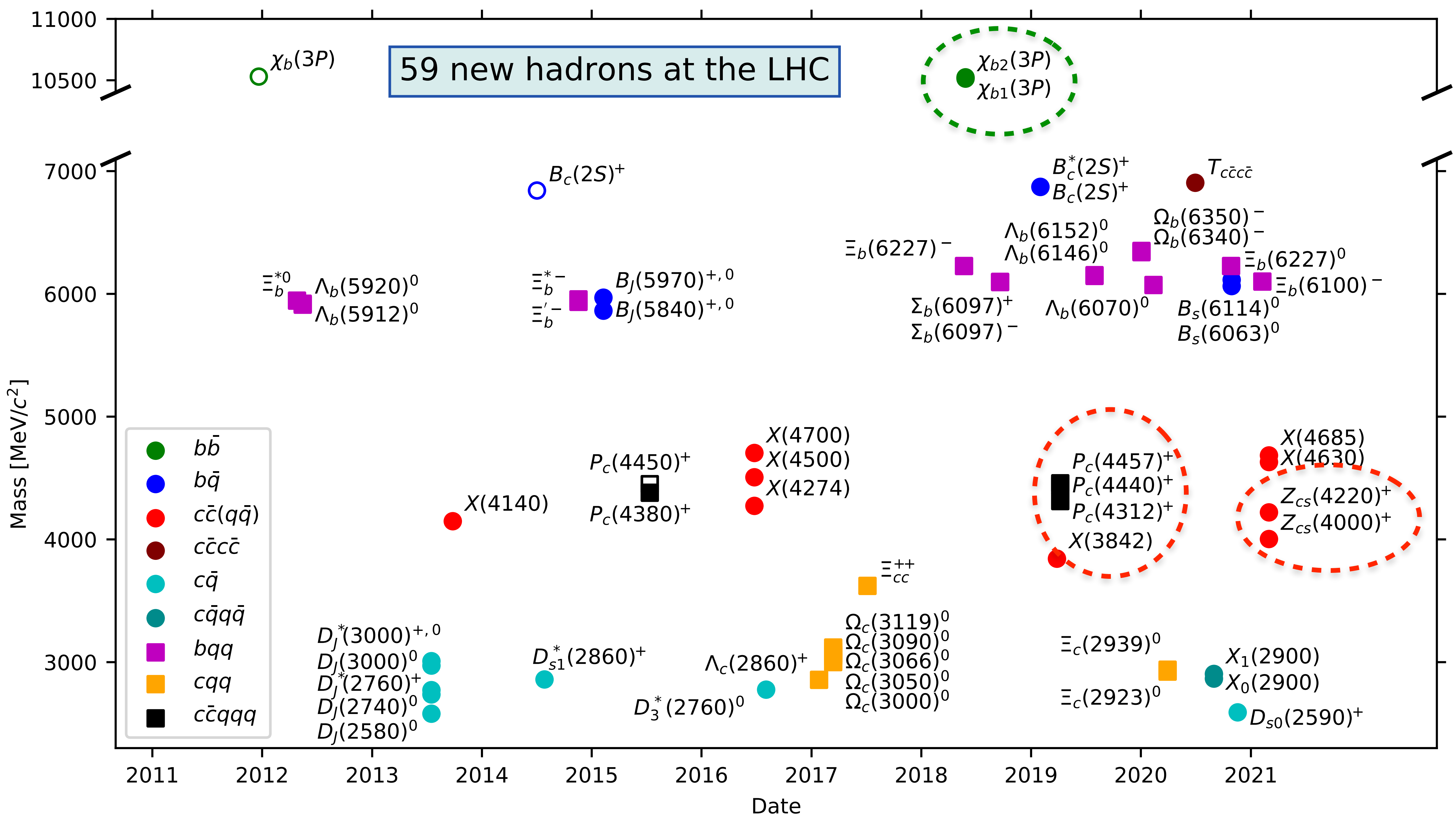
CCNU, Wuhan, 16th-18th October, 2025

Outline

- Status of Exotic Hadrons
- Hadrons at finite temperature
- Hadron properties in ML approach
- Summary and Outlook

Status of Exotic Hadrons

New hadrons at the LHC



Status of Exotic Hadrons

One of the important topics at high-energy facilities

Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

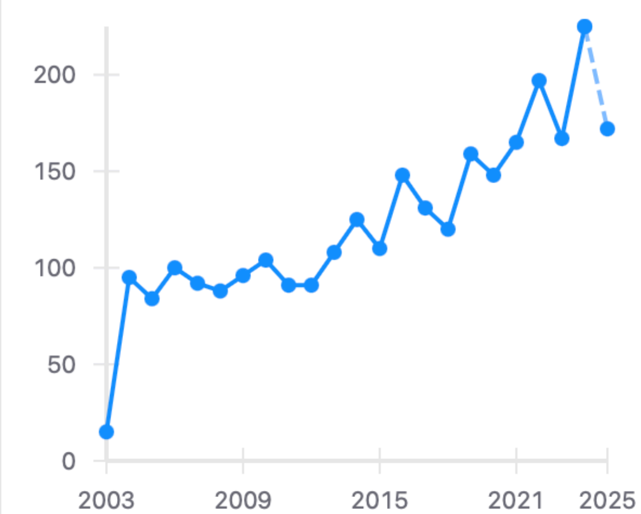
Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) Show All(174)
Sep, 2003

10 pages
Published in: *Phys.Rev.Lett.* 91 (2003) 262001
e-Print: hep-ex/0309032 [hep-ex]
DOI: 10.1103/PhysRevLett.91.262001
PDG: $\chi_{c1}(3872) \to \pi^{+}\pi^{-}J/\psi(1S)$ Show All(5)
Experiments: KEK-BF-BELLE
View in: ADS Abstract Service

pdf links cite claim reference search 2,831 citations

$X(3872)$

Citations per year



Observation of a Charged Charmoniumlike Structure in $e^{+}e^{-} \to \pi^{+}\pi^{-}J/\psi$ at $\sqrt{s}$ =4.26 GeV

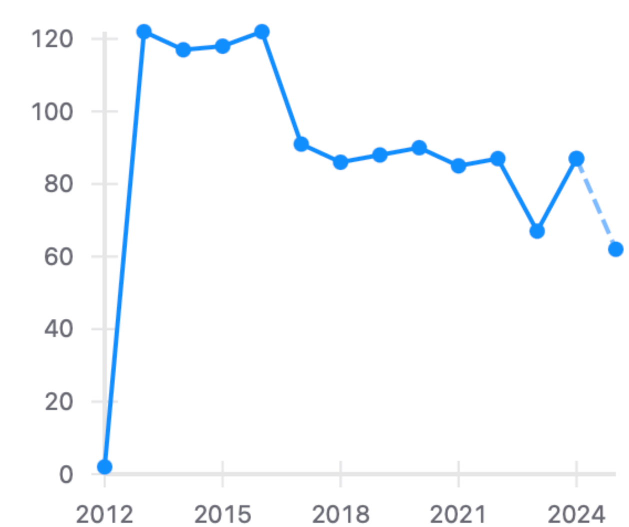
BESIII Collaboration • M. Ablikim (Beijing, Inst. High Energy Phys.) Show All(369)
Mar 24, 2013

7 pages
Published in: *Phys.Rev.Lett.* 110 (2013) 252001
Published: Jun 17, 2013
e-Print: 1303.5949 [hep-ex]
DOI: 10.1103/PhysRevLett.110.252001, 10.1142/9789811217739_0033
PDG: $\psi(4230) \to J/\psi\pi^{+}\pi^{-}$ Show All(5)
Experiments: BEPC-BES, BEPC-BES-III
View in: OSTI Information Bridge Server, ADS Abstract Service

pdf links cite claim reference search 1,224 citations

$Z_c(3900)$

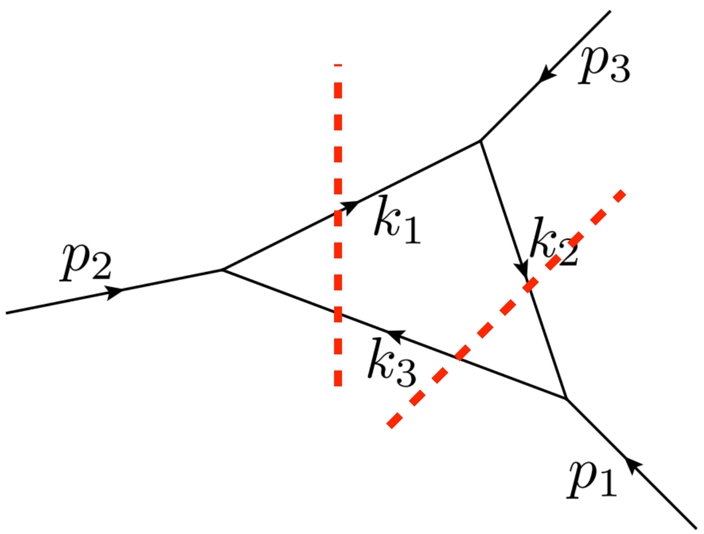
Citations per year



Status of Exotic Hadrons

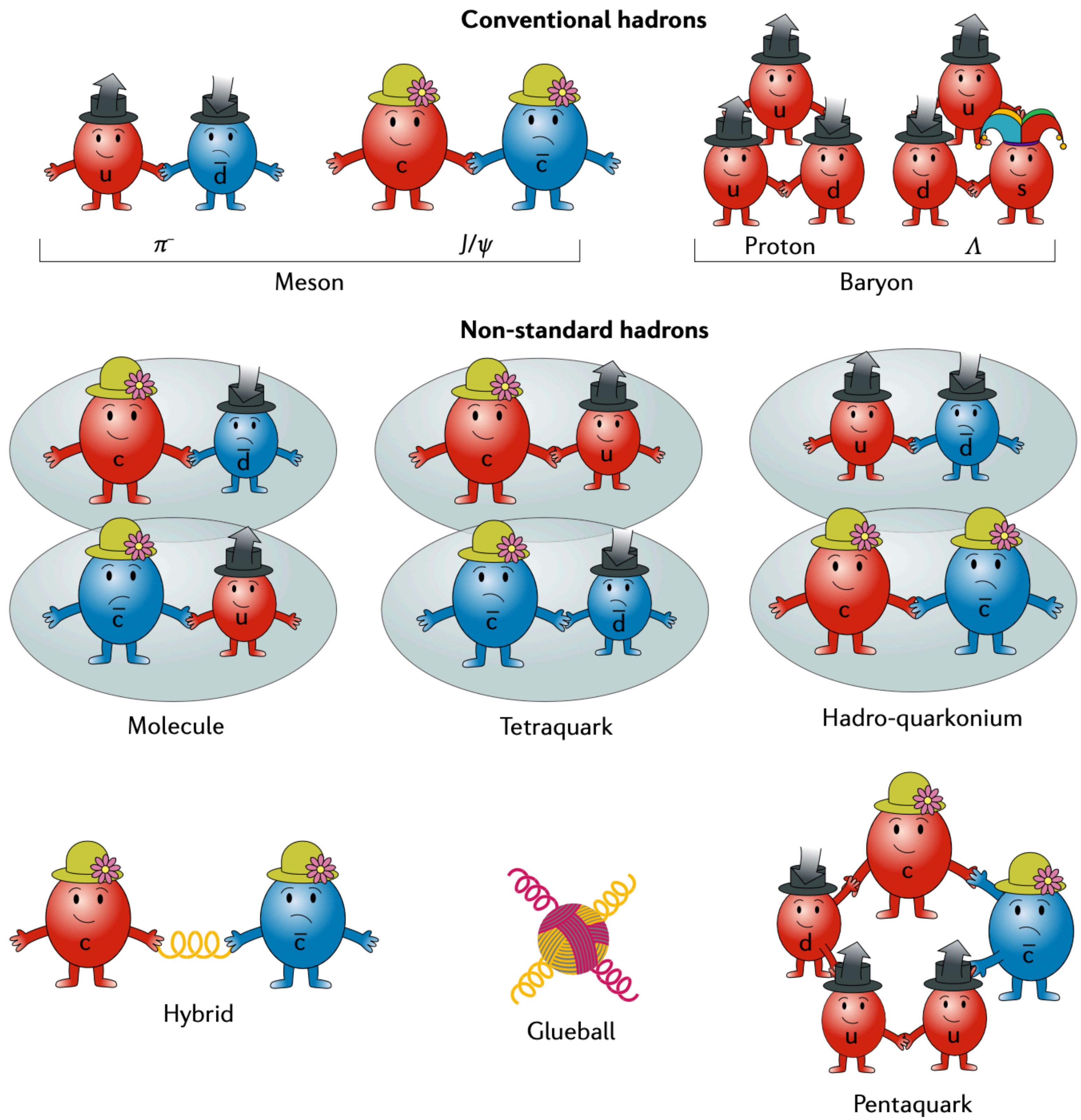
The interpretations

Triangle Singularity



(a)

Guo, Liu and Sakai, PPNP112(2020)103757

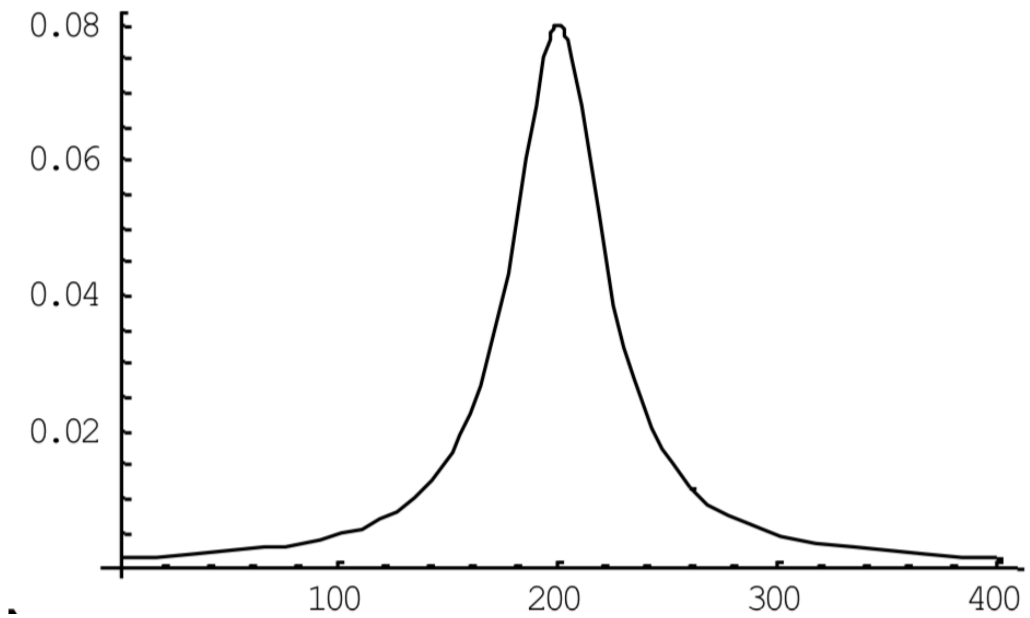


- All of them can produce a peak structure
- How to distinguish them?

Yuan and Olsen, Nature Rev. Phys.1(2019)480

Status of Exotic Hadrons

A state defined in experiment



Unstable particle

$$|t\rangle = e^{-i(M-i\Gamma/2)t}|0\rangle$$

The distribution in momentum domain

$$\rho(m) \sim \frac{\Gamma}{(m-M)^2 + \Gamma^2/4}$$

A state defined in theory

- The pole of S-matrix

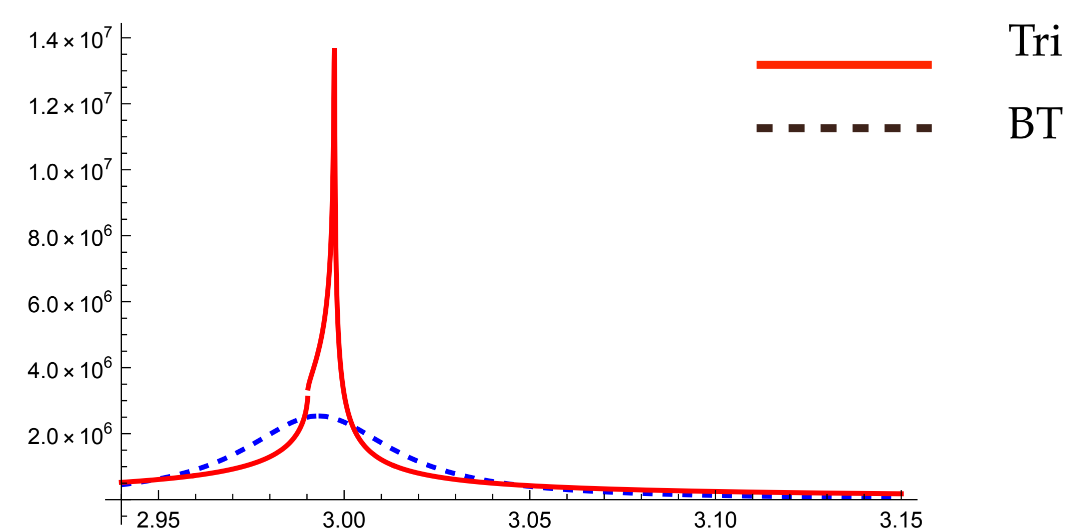
→ Consistent with BT formula

$$\frac{1}{m-M+i\Gamma/2}$$

- Other cases

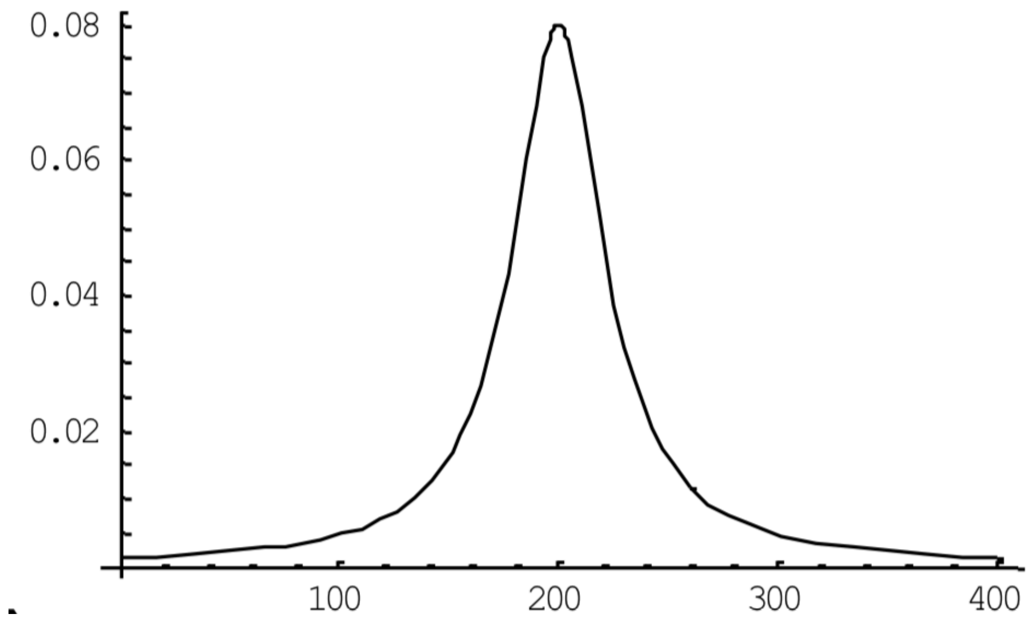
→ dynamic states

→ triangle singularity



Status of Exotic Hadrons

A state defined in experiment



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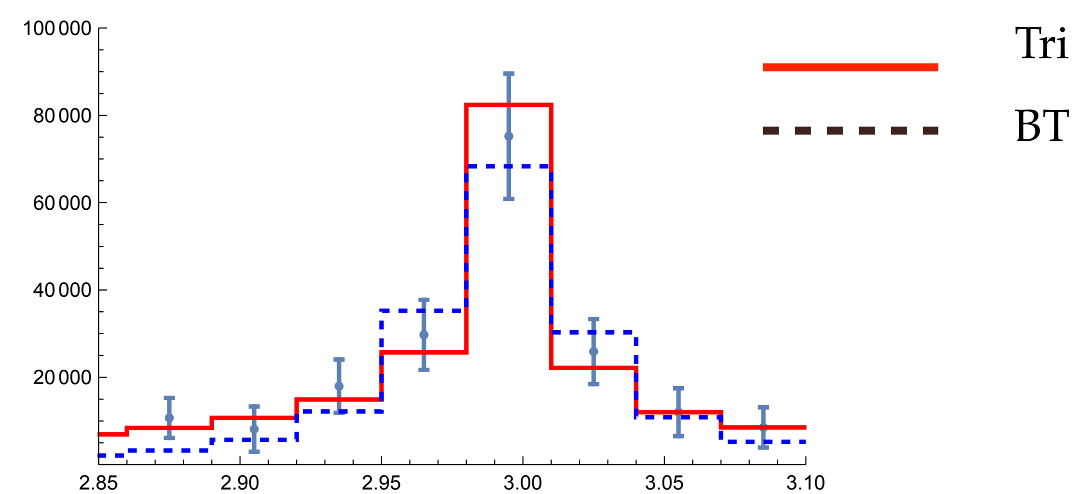
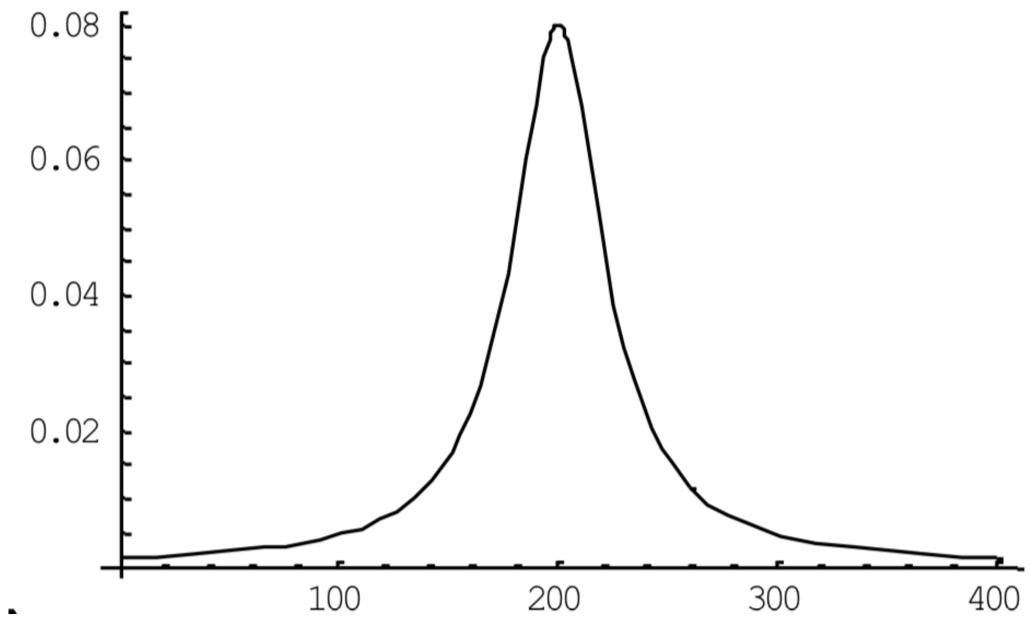


Indistinguishable for insufficient statistic

Status of Exotic Hadrons

A state defined in experiment



Unstable particle

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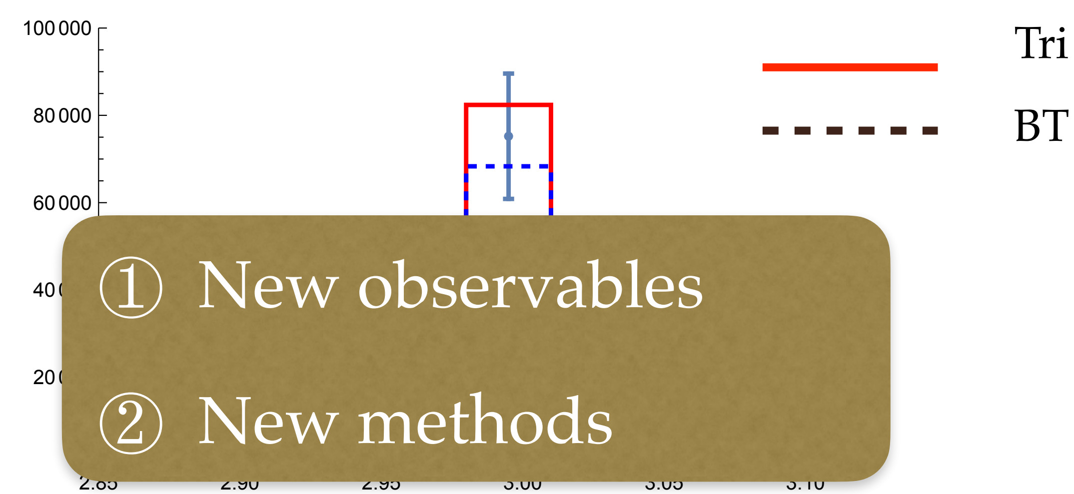


① New observables

② New methods

Indistinguishable for insufficient statistic

Hadrons at finite temperature

- The advantage of finite temperature

→ The observation of $X(3872)$ in Pb-Pb collision — CMS, PRL128(2022)032001

→ Provide another dimension to probe hadron property

- $X(3872)$, $X(4014)$ and their bottom partners at finite temperature

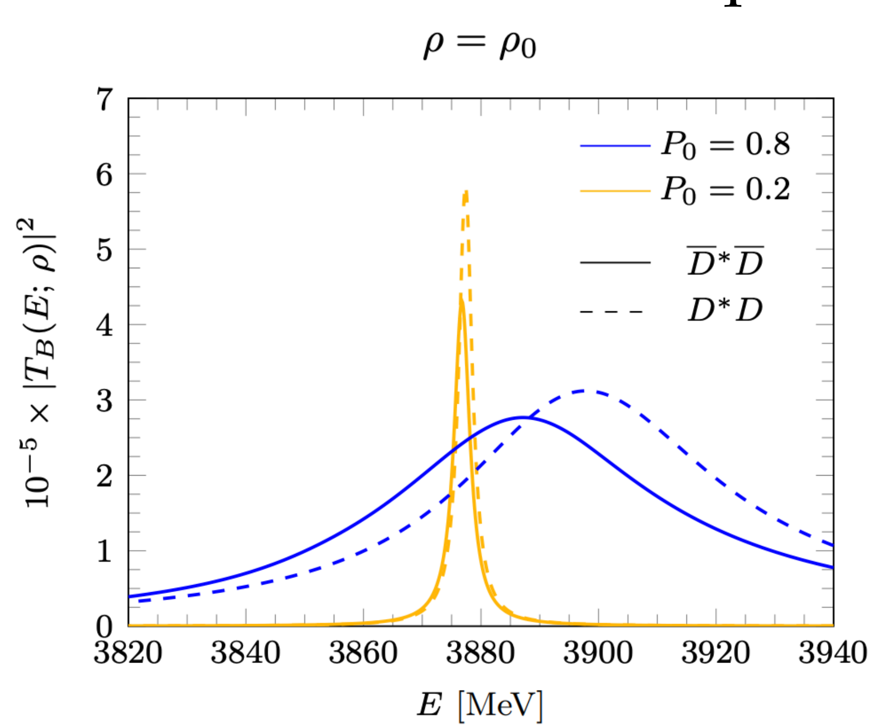
Montana et al., PRD107(2023)054014

- The centrality can be used to distinguish large size HM from compact object

Zhang et al., PRL126(2021)012301

- The different behaviors of double charm tetraquark and its anti partner in hot environment

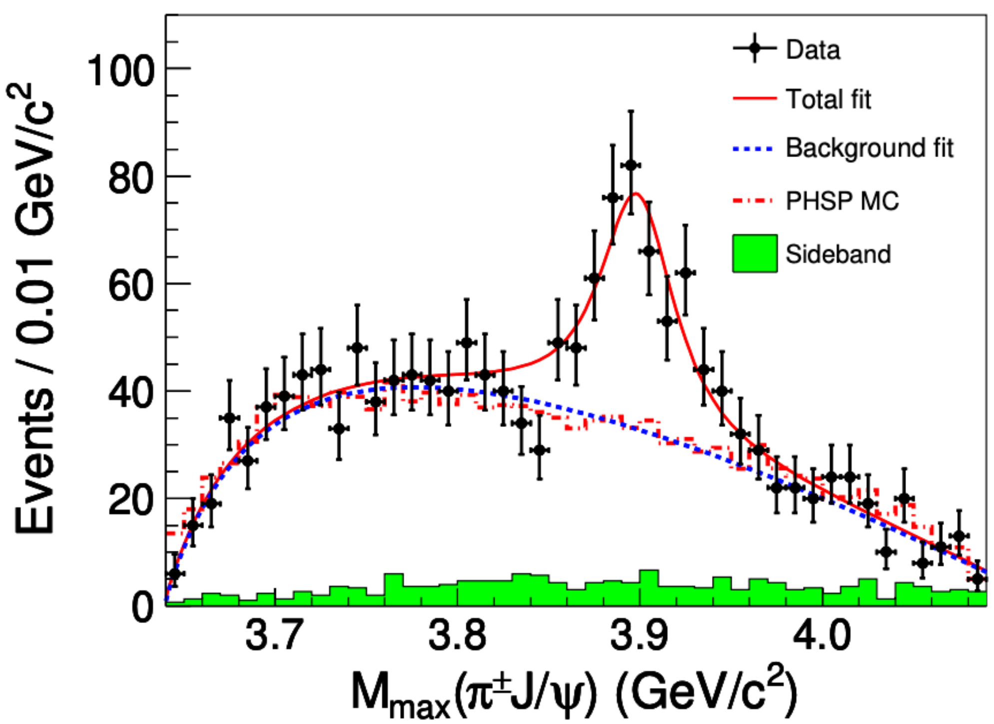
Montesinos et al., PRC108(2023)035205



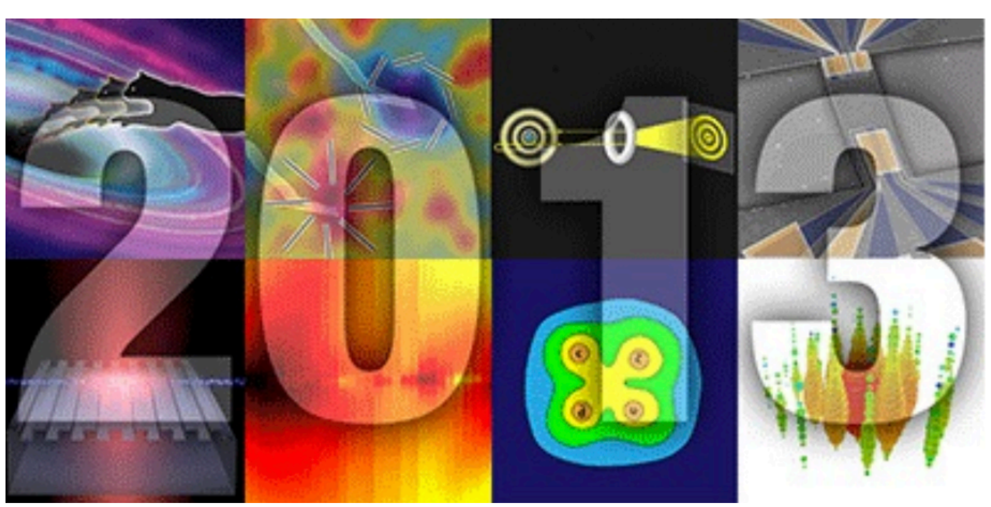
Hadrons at finite temperature

- The $Z_c(3900)$ in vacuum

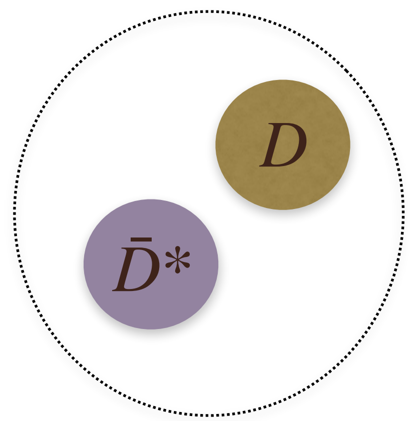
The observation of $Z_c(3900)$



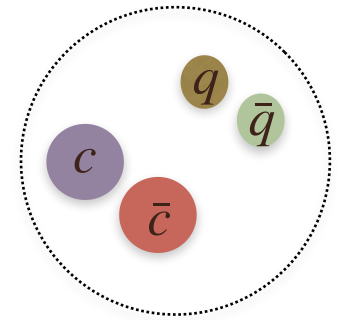
BESIII, PRL110,252001



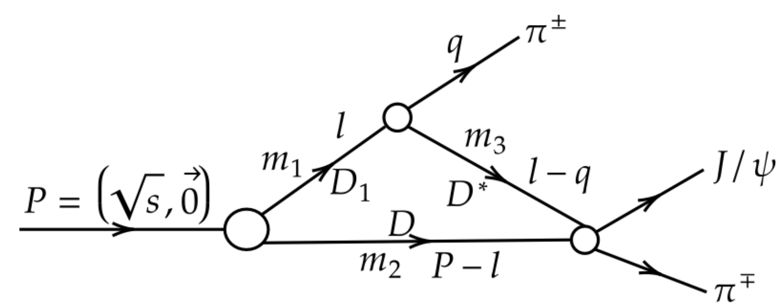
Hadronic Molecule



Compact tetraquark



Triangle singularity



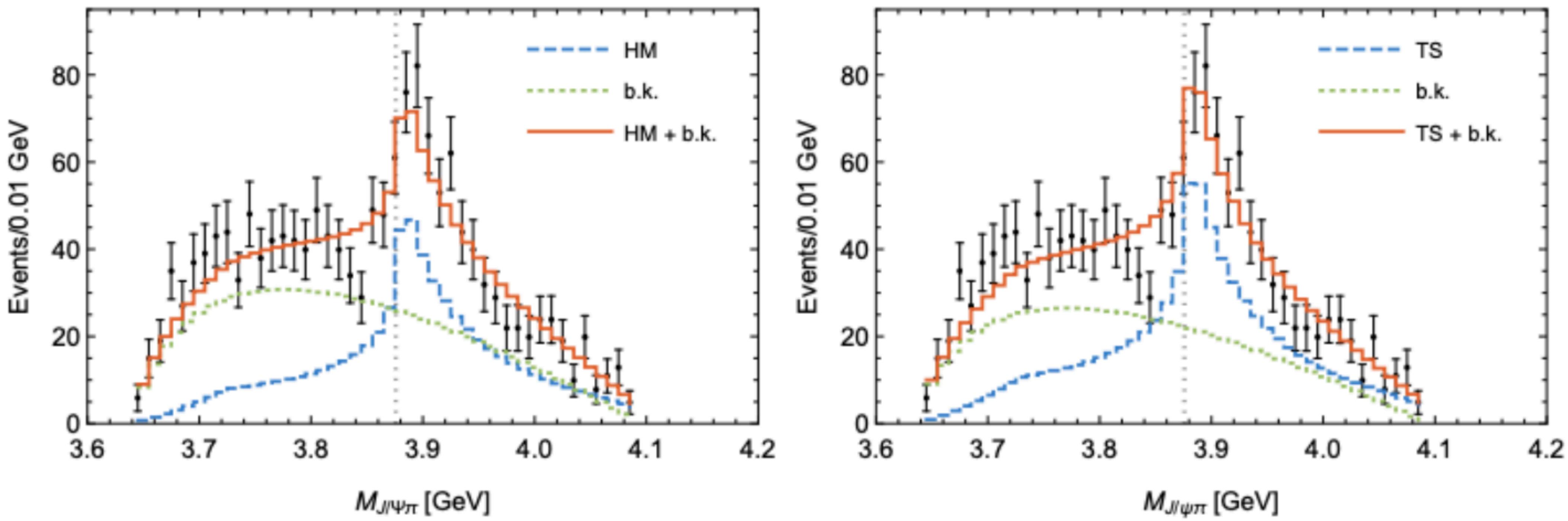
Wang:2013cya, Guo:2013sya, Wilbring:2013cha, He:2013nwa, Dong:2013iqa, Zhang:2013aoa, Aceti:2014uea, Albaladejo:2015lob, Albaladejo:2016jsg, Gong:2016hlt, He:2017lhy, Ortega:2018cnm, Du:2020vwb, Meng:2020ihj, Wang:2020dgr

Hadrons at finite temperature

- The $Z_c(3900)$ in vacuum

Zhang, Hosaka, QW, Yasui, PRD112(2025)016014

- The line shapes of $Z_c(3900)$ in vacuum



① Experimental resolution is not sufficient to distinguish the two scenarios, i.e. $D\bar{D}^* - J/\psi\pi$ dynamic state or triangle singularity

Wang:2013cya, Guo:2013sya, Wilbring:2013cha, He:2013nwa, Dong:2013iqa, Zhang:2013aoa, Aceti:2014uea, Albaladejo:2015lob, Albaladejo:2016jsg, Gong:2016hlt, He:2017lhy, Ortega:2018cnm, Du:2020vwb,,Meng:2020ihj

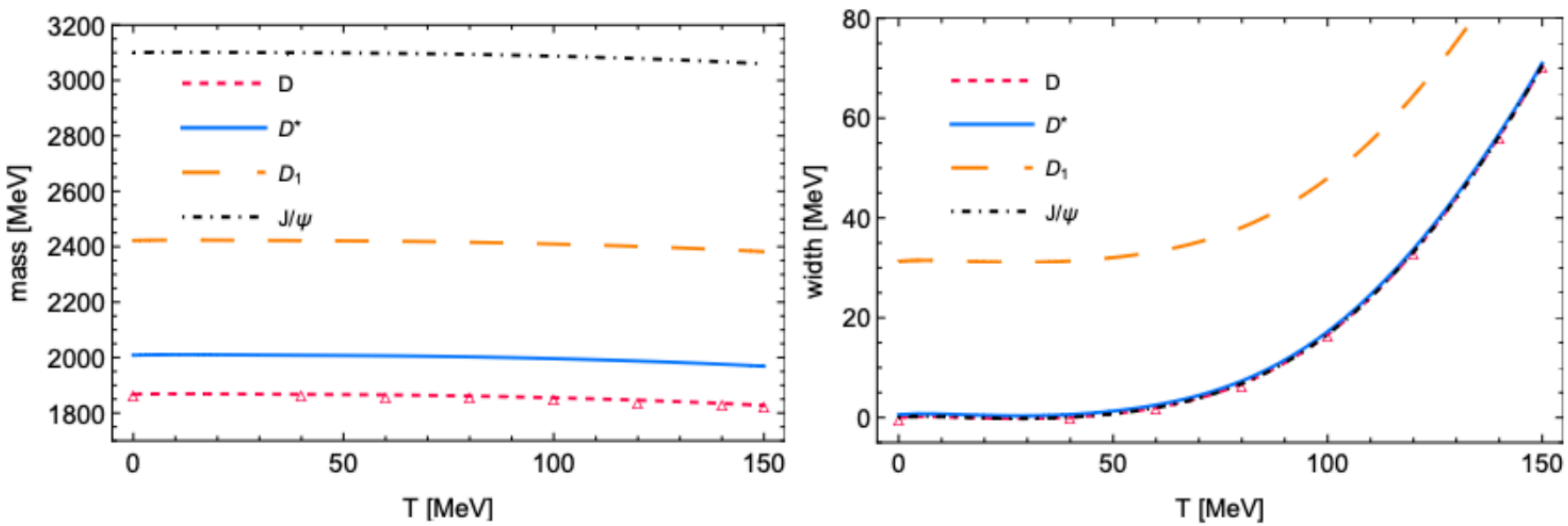
② Finite temperature effect: variable in coth(…) function and intermediate meson mass

Hadrons at finite temperature

- The $Z_c(3900)$ at finite temperature

  - The mass and with at finite temperature

Montana et al., PLB806(2020)135464



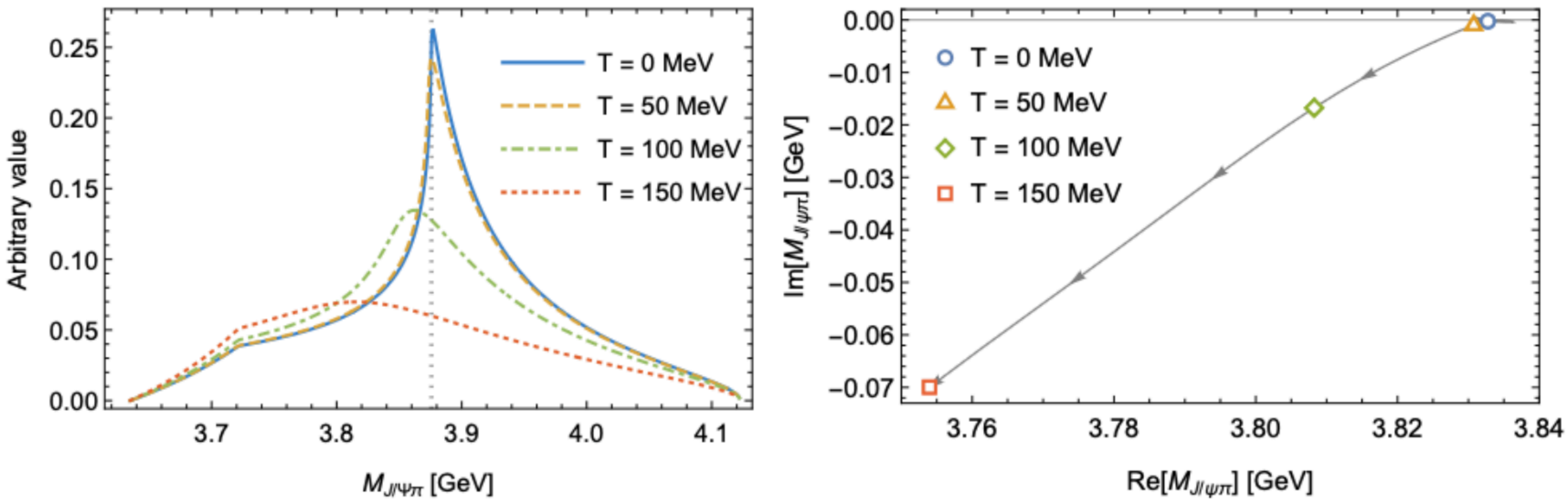
Fuchs et al., PRC73(2006)035204, Sasaki, PRD90(2014)114007

① Experimental resolution is not sufficient to distinguish the two scenarios

② Finite temperature effect: variable in coth(…) function and intermediate meson mass

Hadrons at finite temperature

- The $Z_c(3900)$ at finite temperature
  - The line shapes of $Z_c(3900)$ at finite temperature in HM



Zhang, Hosaka, QW, Yasui, PRD112(2025)016014

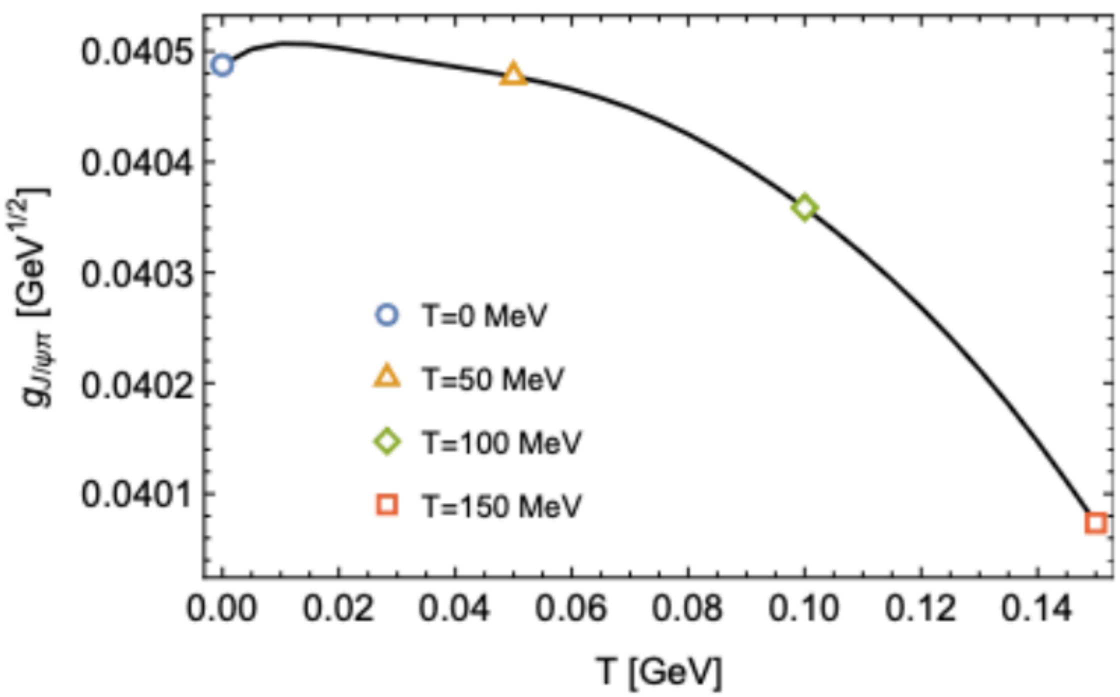
① Assume that the potentials do not depends on the temperature

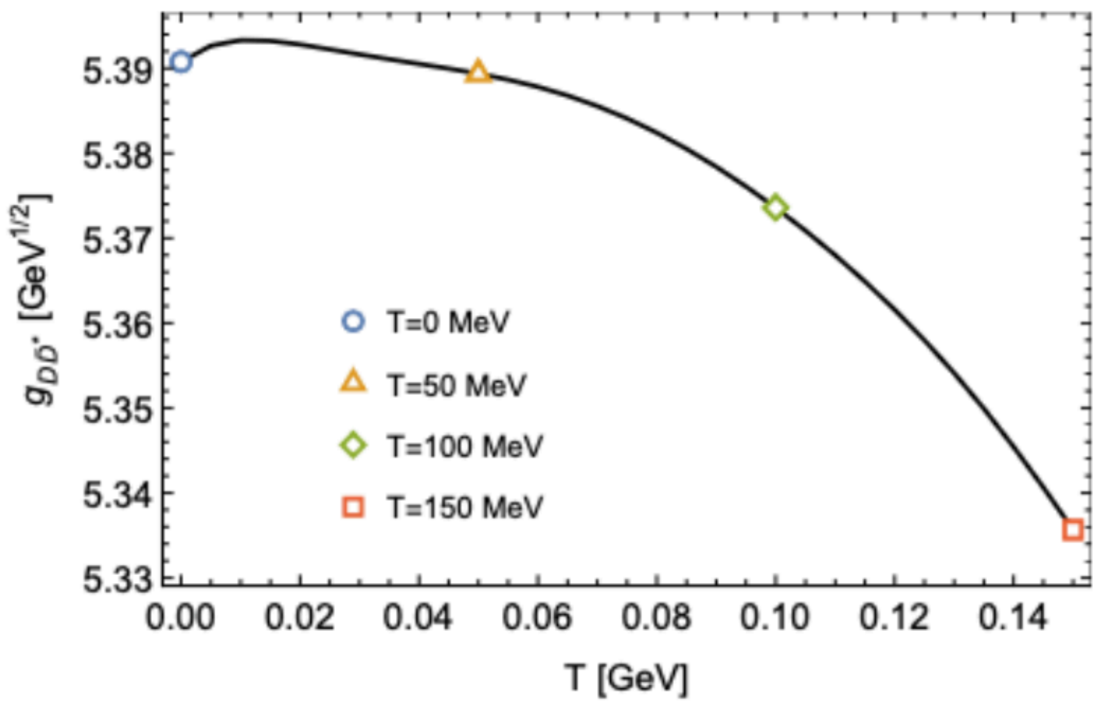
② The peak shift to lower energy region

③ The width becomes broader with the increasing temperature

Hadrons at finite temperature

- The $Z_c(3900)$ at finite temperature
  - The effective couplings at finite temperature





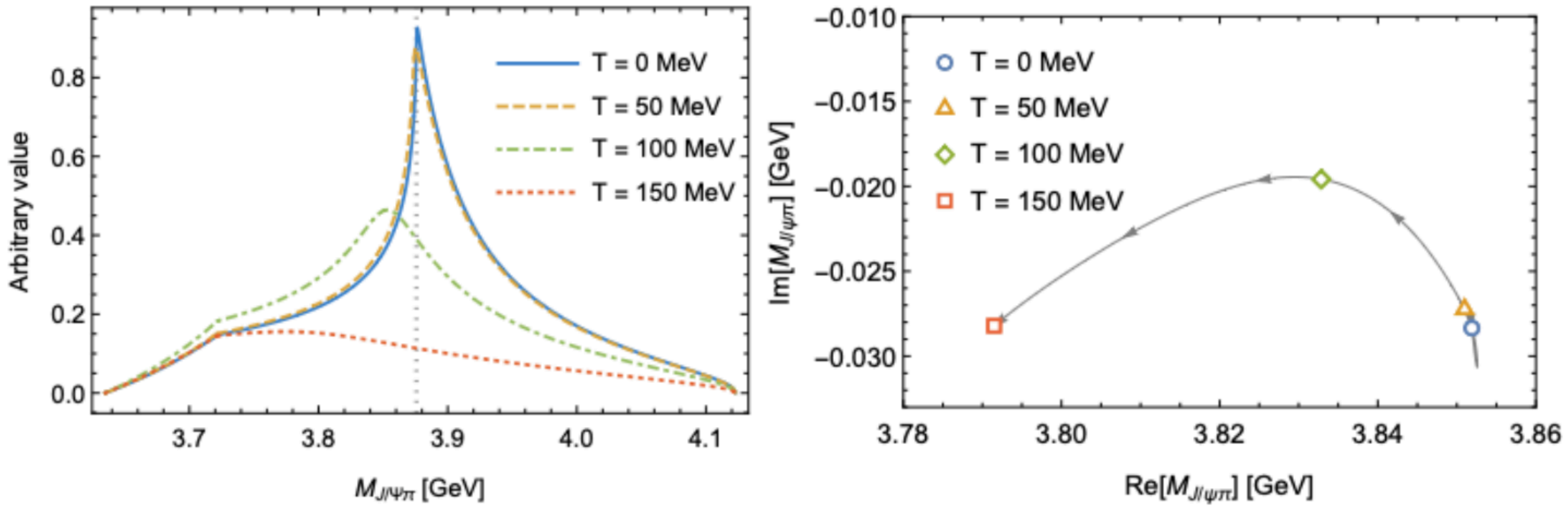
Zhang, Hosaka, QW, Yasui, PRD112(2025)016014

① Both effective couplings decrease with the increasing temperature

② Suggests the HM decouple with all the channels at sufficient high temperature, and will be dissociated

Hadrons at finite temperature

- The $Z_c(3900)$ at finite temperature
  - The line shapes of $Z_c(3900)$ at finite temperature in TS



Zhang, Hosaka, QW, Yasui, PRD112(2025)016014

① Assume that the couplings in TS do not depends on T

② The peak shift to lower energy region

③ The width becomes broader with the increasing temperature

Abreu et al., NPPP318(2022)32, Llanes-Estrada et al., arXiv2110.14707

Hadron properties in ML approach

The $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular picture

Liu et.al., PRL122(2019)242001

Solution A (χ^2/d.o.f. = 1.01)

Solution B (χ^2/d.o.f. = 1.03)

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	13.1 – 14.5	4306.3 – 4307.7
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	13.6 – 14.8	4370.5 – 4371.7
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
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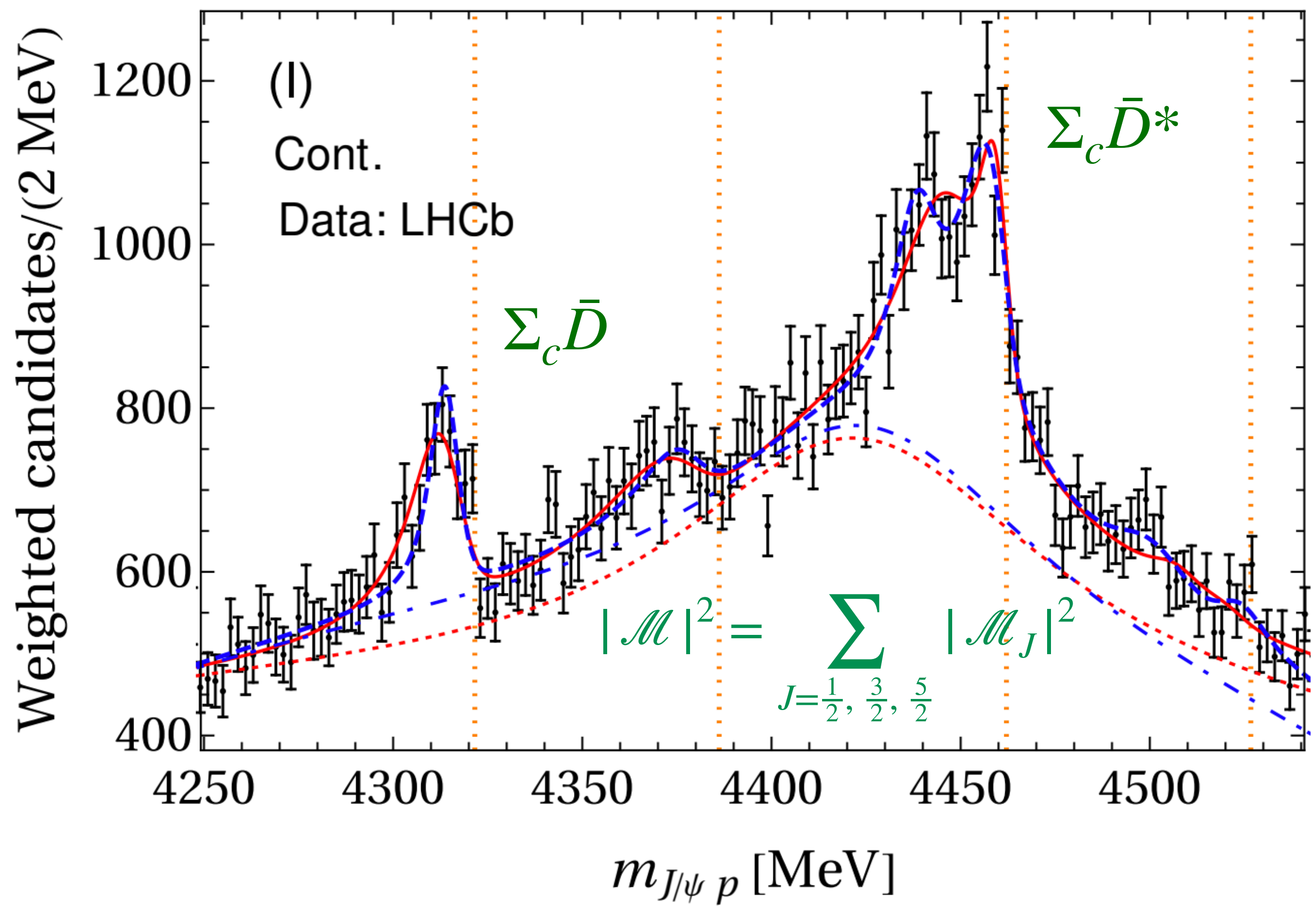
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	3.1 – 3.5	4523.2 – 4523.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	10.1 – 10.2	4516.5 – 4516.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	25.7 – 26.5	4500.2 – 4501.0



- Two parameters determined by

$P_c(4440)$, $P_c(4457)$

- Two solutions

- Two parameters g_S, g_D for $J/\psi p$, $\eta_c p$
- Predict pole positions accurately
- $\chi_A^2 < \chi_B^2$
- The effect of each data point is different

Du, Baru, Guo, Hanhart, Meißner, Oller, **QW,** PRL124(2020)072001

Hadron properties in ML approach

The $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular picture

Liu et.al., PRL122(2019)242001

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Solution B ($\chi^2/\text{d.o.f.} = 1.03$)

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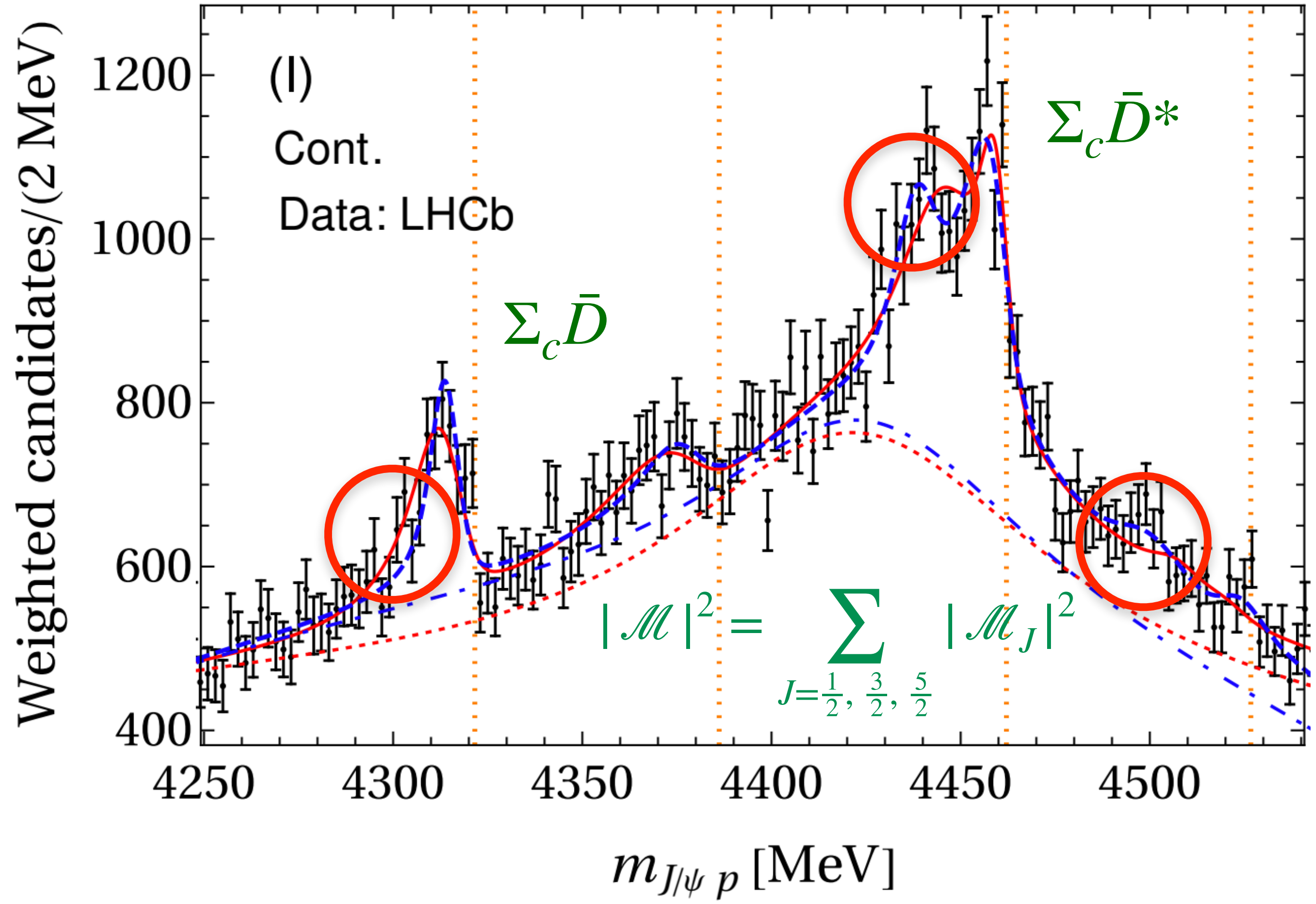

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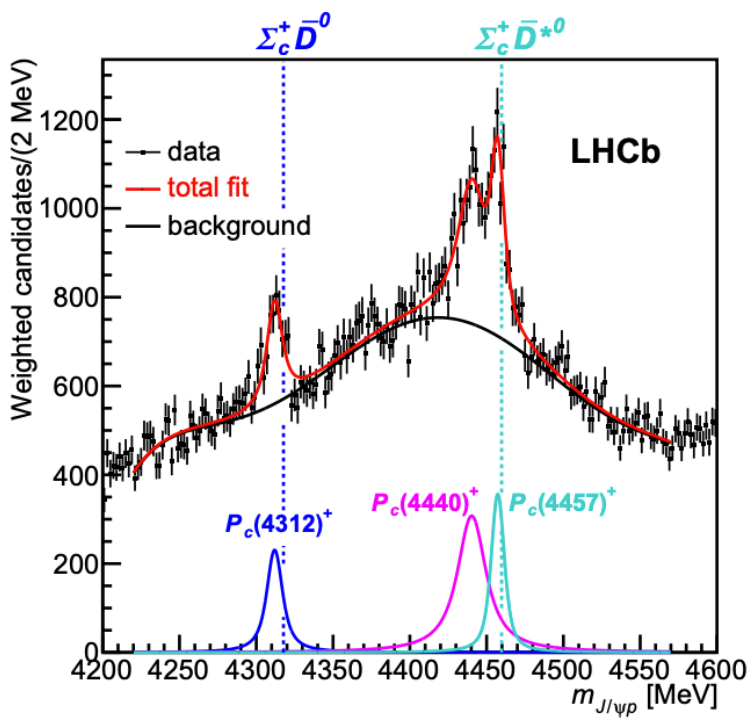
Du, Baru, Guo, Hanhart, Meißner, Oller, **QW,** PRL124(2020)072001

Hadron properties in ML approach

LHCb, PRL122(2019)222001

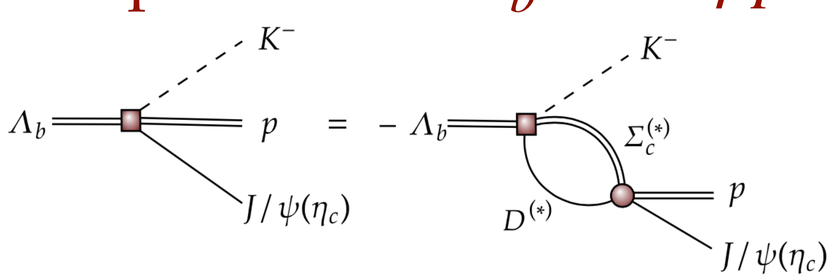


The $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular picture

- $P_c(4312)$ bound state or virtual state?
- Spin assignment of $P_c(4440)$ and $P_c(4457)$?
- The pole situations for all the P_c states?
- Whether NN approach obtains more than the normal fitting approach?

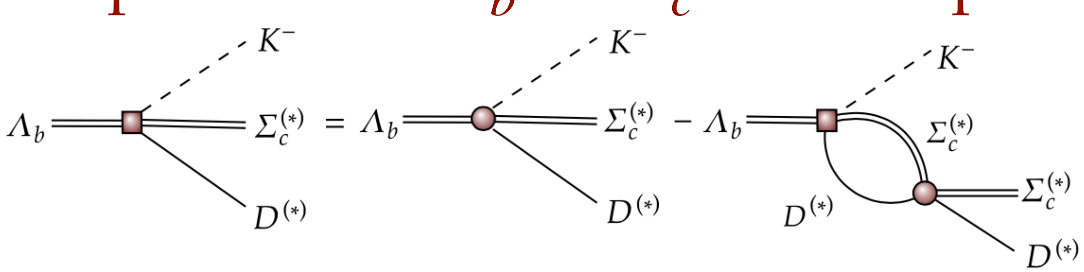
LO HQEFT, Du, Baru, Guo, Hanhart, Meißner, Oller, **QW,** PRL124(2020)072001

The decay amplitude for $\Lambda_b \to J/\psi p K^-$ process



Zhang, Liu, Hu, **QW, Meißner**, Sci.Bull.68(2023)981-989

The decay amplitude for $\Lambda_b \to \Sigma_c^{(*)}\bar{D}^{(*)}K^-$ process

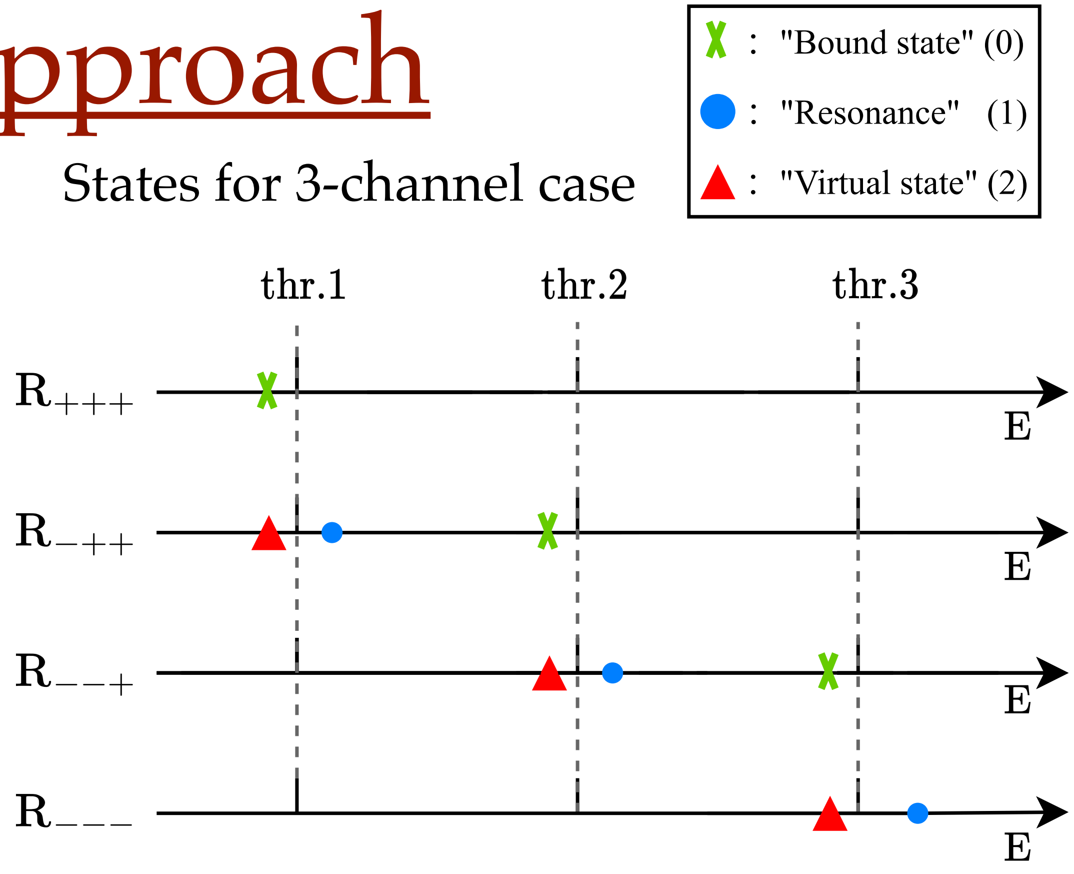


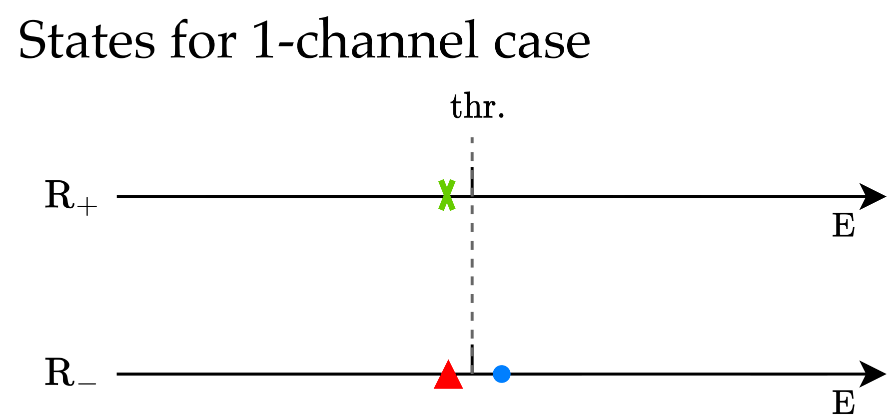
Hadron properties in ML approach

States and labels

- "+" and "-" for phy. and unphy. sheets
- $\frac{1}{2}^-$ dyn. Channels: $\Sigma_c\bar{D}$, $\Sigma_c\bar{D}^*$, $\Sigma_c^*\bar{D}^*$
- $\frac{3}{2}^-$ dyn. Channels: $\Sigma_c^*\bar{D}$, $\Sigma_c\bar{D}^*$, $\Sigma_c^*\bar{D}^*$
- $\frac{5}{2}^-$ dyn. Channel: $\Sigma_c^*\bar{D}^*$

LHCb, PRL122(2019)222001





Bound state for $J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ channels

Solution B 0000

Zhang, Liu, Hu, **QW,** Meißner, Sci.Bull.68(2023)981-989

- Mass label 1 and 0 for $J_{P_c(4440)} = \frac{1}{2}$, $J_{P_c(4457)} = \frac{3}{2}$ and $J_{P_c(4440)} = \frac{3}{2}$, $J_{P_c(4457)} = \frac{1}{2}$,

i.e. solution A and B in PRL122(2019)242001, PRL124(2020)072001, JHEP08(2021)157

Hadron properties in ML approach

Predicted probability

Training and verification

240184 samples

Mass Relation Label	State Label	Number of Samples
0	000	46951
1	000	4283
1	001	1260
1	002	4360
0	100	3740
0	110	4320
0	111	7520
1	111	360
0	200	9590
1	200	280
1	210	3980
1	211	2690
1	220	50240
1	221	50512
1	222	50098

Output(%) Label / NN	0000	1000	1001	1002	100X	others
prediction of NN trained with $\{S^{90}\}$ samples.						
NN 1	0.69	89.13	1.42	8.75	99.30	0.01
NN 2	0.03	5.83	38.47	55.30	99.60	0.37
NN 3	0.03	5.39	15.79	78.41	99.59	0.11
NN 4	0.01	1.9	27.01	70.95	99.86	0.13
NN 5	2.40	94.45	0.15	2.99	97.59	0.01
5 NNs Average	0.63(1.03)	39.34	16.57	43.28	99.19(0.91)	0.13(0.15)
10 NNs Average	0.36(0.74)	21.16	20.69	57.62	99.47(0.68)	0.12(0.13)
prediction of NN trained with $\{S^{92}\}$ samples.						
NN 1	0.00	0.15	5.37	94.47	99.99	0.00
NN 2	0.00	0.07	4.11	95.81	99.99	0.00
NN 3	0.00	0.78	13.57	85.61	99.96	0.03
NN 4	0.00	0.81	19.02	80.16	99.99	0.00
NN 5	0.14	15.13	16.91	67.80	99.84	0.00
5 NNs Average	0.03(0.06)	3.39	11.80	84.77	99.95(0.06)	0.01(0.01)
10 NNs Average	0.01(0.04)	1.78	9.50	88.70	99.97(0.04)	0.00(0.01)

- 5 and 10 NN models with an identical structure under different initialization
- The uncertainties decrease with the increasing number of NNs
- Top 3 probabilities, 1000,1001,1002 favor solution A
- Bound states in $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ channels, Undetermined for $J^P = \frac{5}{2}^-$ channel
- The NNs successfully retrieve the state label with an accuracy (standard deviation) of

$75.91(1.18)\,\%$, $73.14(1.05)\,\%$, $65.25(1.80)\,\%$, $54.35(2.32)\,\%$ for the samples $\{\mathcal{S}^{90}\}, \{\mathcal{S}^{92}\}, \{\mathcal{S}^{94}\}, \{\mathcal{S}^{96}\}$

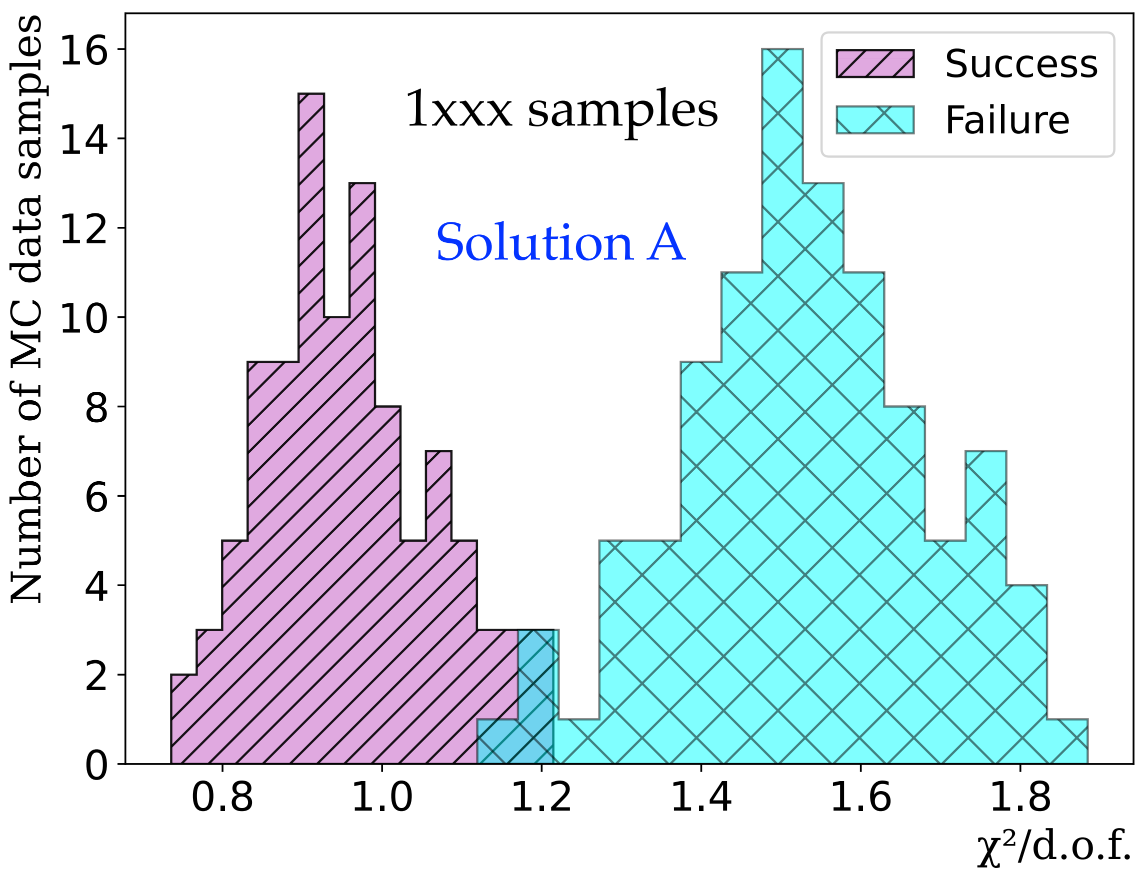
Zhang, Liu, Hu, **QW,** Meißner, Sci.Bull.68(2023)981-989

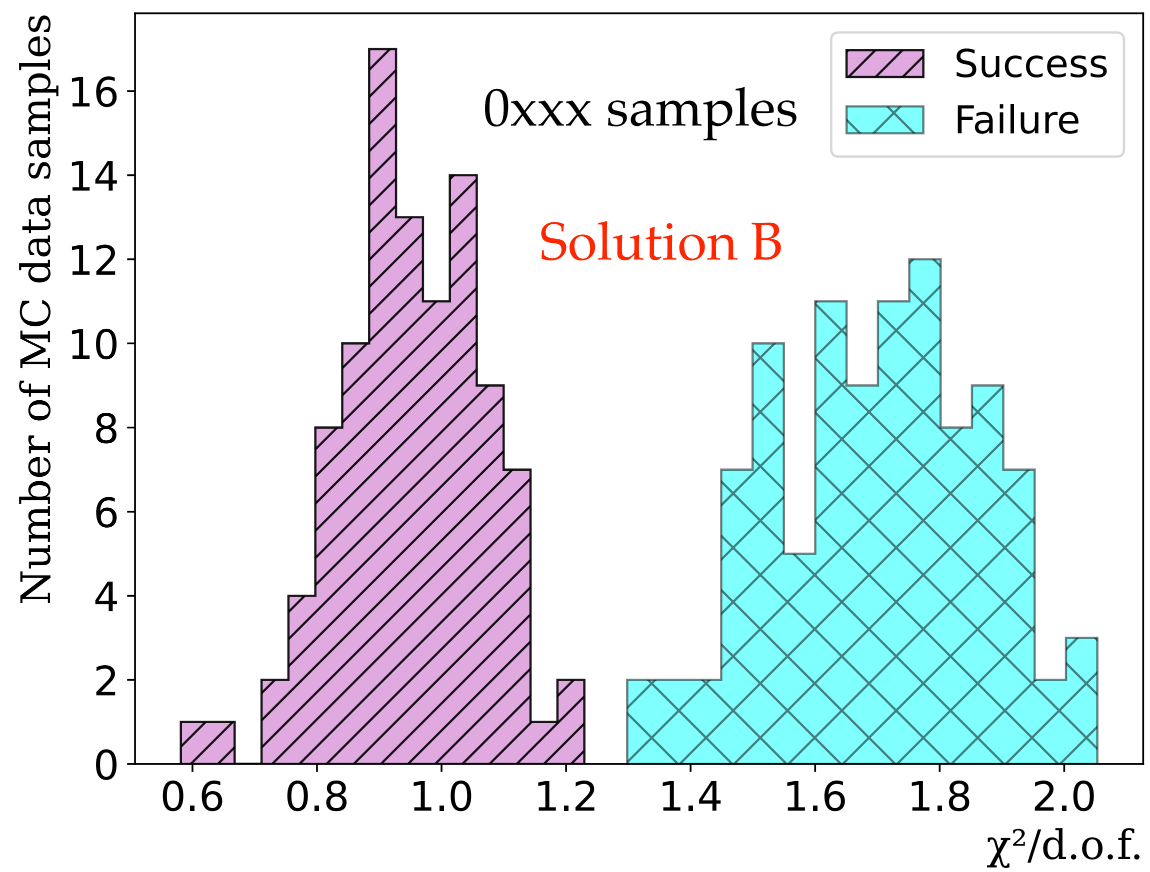
Hadron properties in ML approach

Why NN favors Solution A?

Generate 100 1xxx samples and 100 0xxx samples

Reduced chisq from the normal fitting





- A 3% misidentification for 1xxx samples

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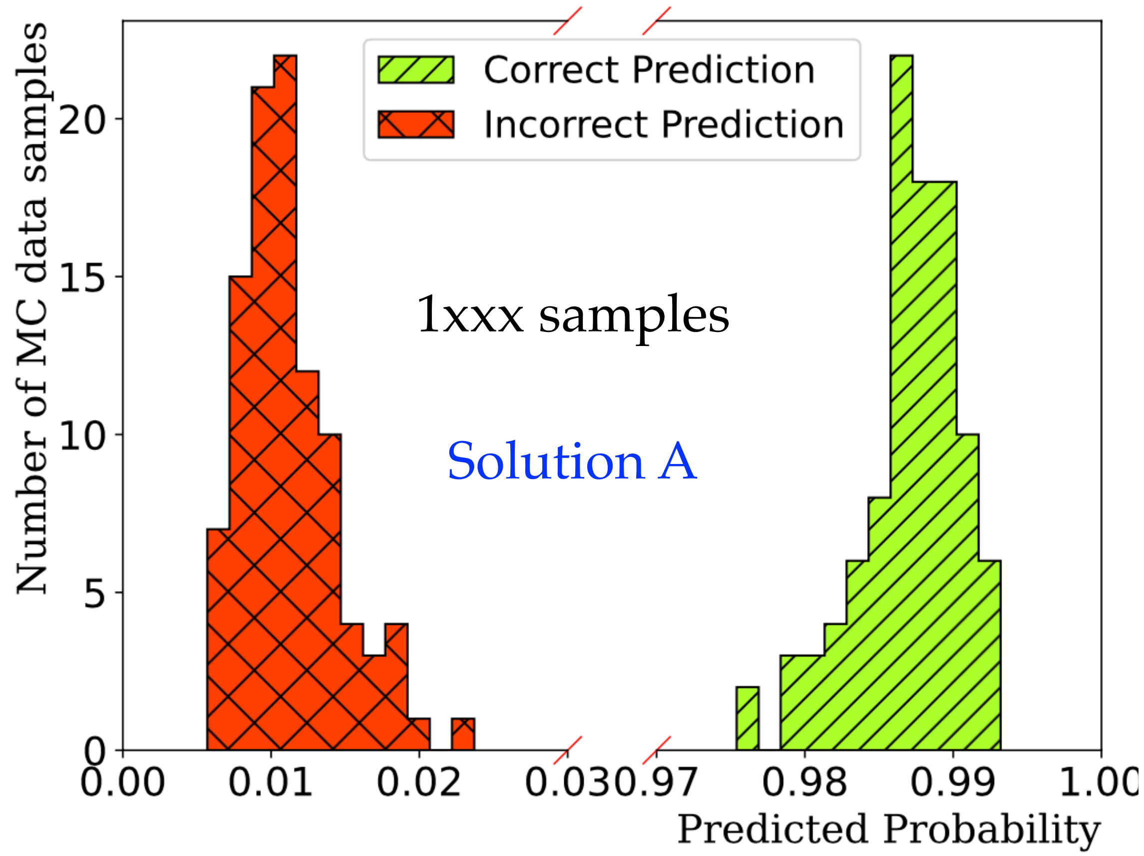
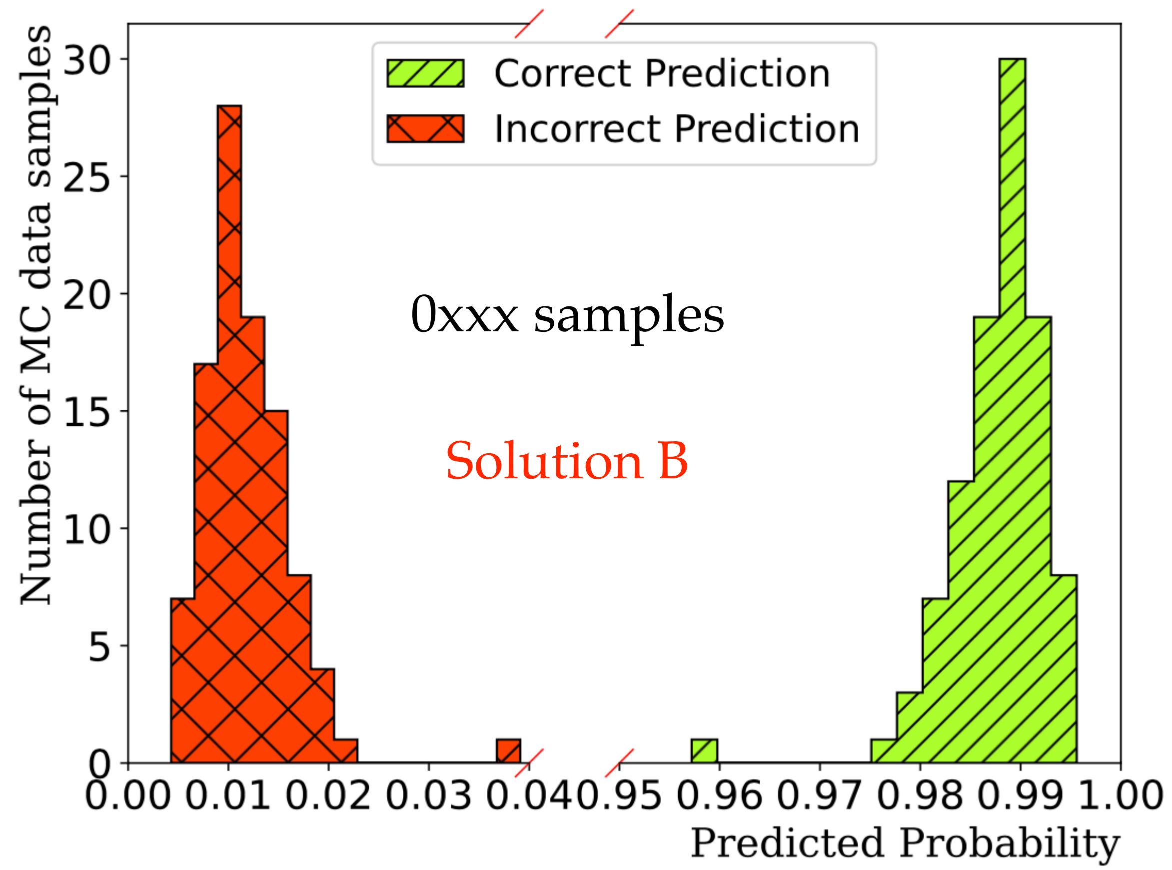
Probabilities from NN





- The NN can make a good prediction
- The two solutions are well distinguished for both samples

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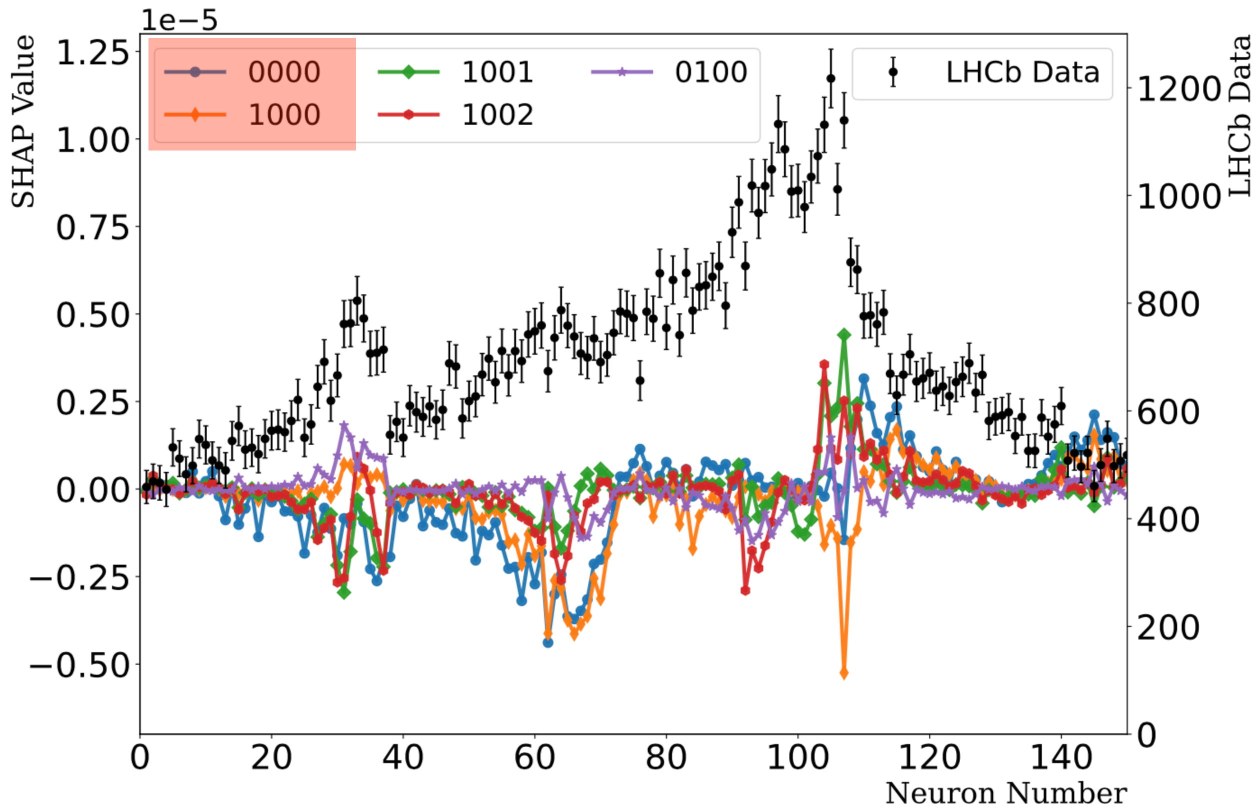
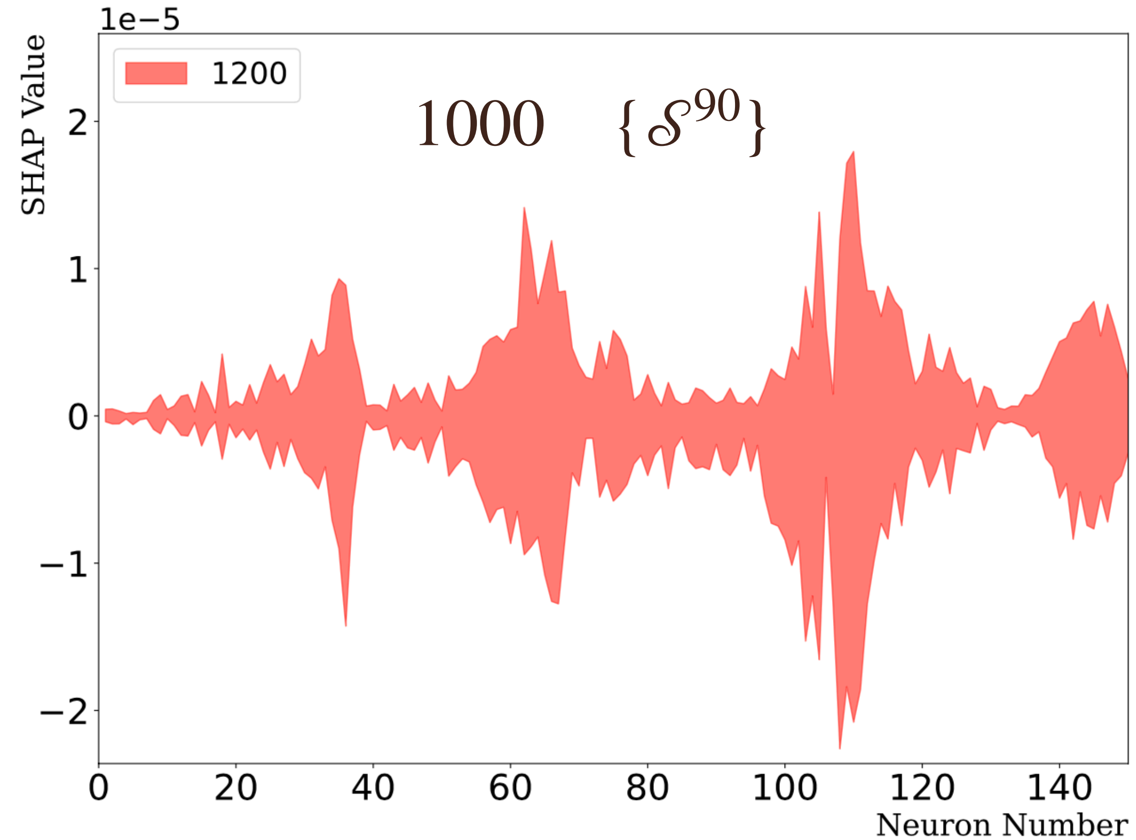
The impact of each experimental data point in NN





- The Shapley Additive exPlanation (SHAP) is investigated.
- A positive (negative) SHAP value indicates that a given data point is pushing the NN classification in favor of (against) a given class.
- The data points around the peaks in the mass spectrum have a greater impact.

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Summary and outlook

- HIC is a unique probe for hadron property
- New observables can be defined as additional criteria for hadron structures

→ The pole dependences of HM and triangle singularity interpretation of $Z_c(3900)$ on the temperature are different

→ However, the lineshapes at finite temperature are similar

- New method can also help to deepen our understanding of non-perturbative dynamics

→The ML approach help to distinguish the quantum numbers of $P_c(4440)$ and $P_c(4457)$

Thank you very much for your attention