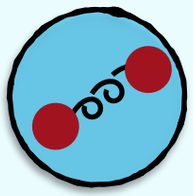
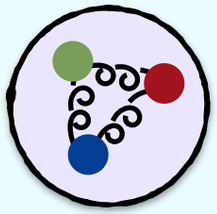
Theory Overview of Heavy Exotic Spectroscopy

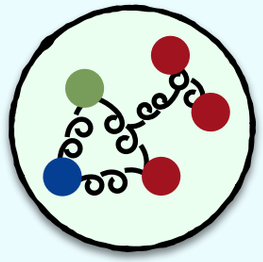
Ciaran Hughes (chughes@fnal.gov)



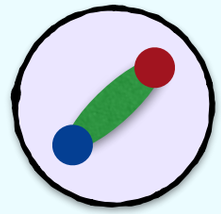
Mesons



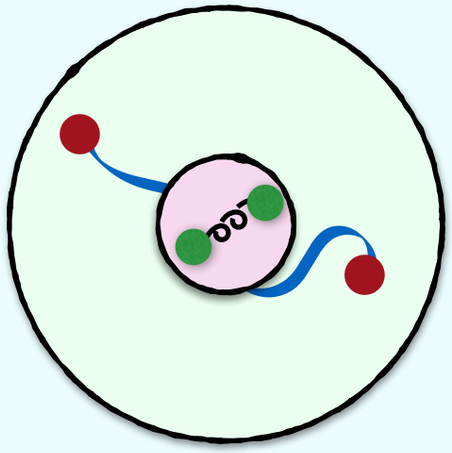
Baryons



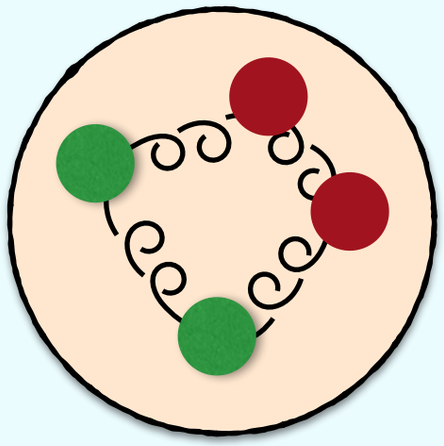
Pentaquarks



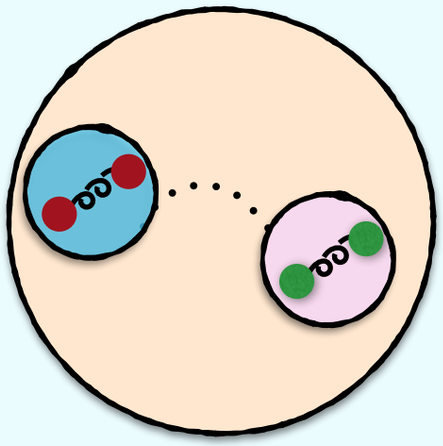
Hybrids



Hadro-Quarkonium



Compact Tetraquarks



Molecular

Beauty, 2020

Pre 2003 Heavy Spectroscopy  

- Def^{n}: "Conventional States" = Mesons (valence $\overline{q}q$) and Baryons (valence qqq) in line with quark potential model expectations

Post 2003 Heavy Spectroscopy

- $Def^{\underline{n}}$: "Exotic States" = "States we **do not** understand yet (but not new physics)"

Post 2003 Heavy Spectroscopy

- Def^{n}: "Exotic States" = States which are not in line with quark potential model expectations, e.g., not mesons or baryons.

Post 2003 Heavy Spectroscopy

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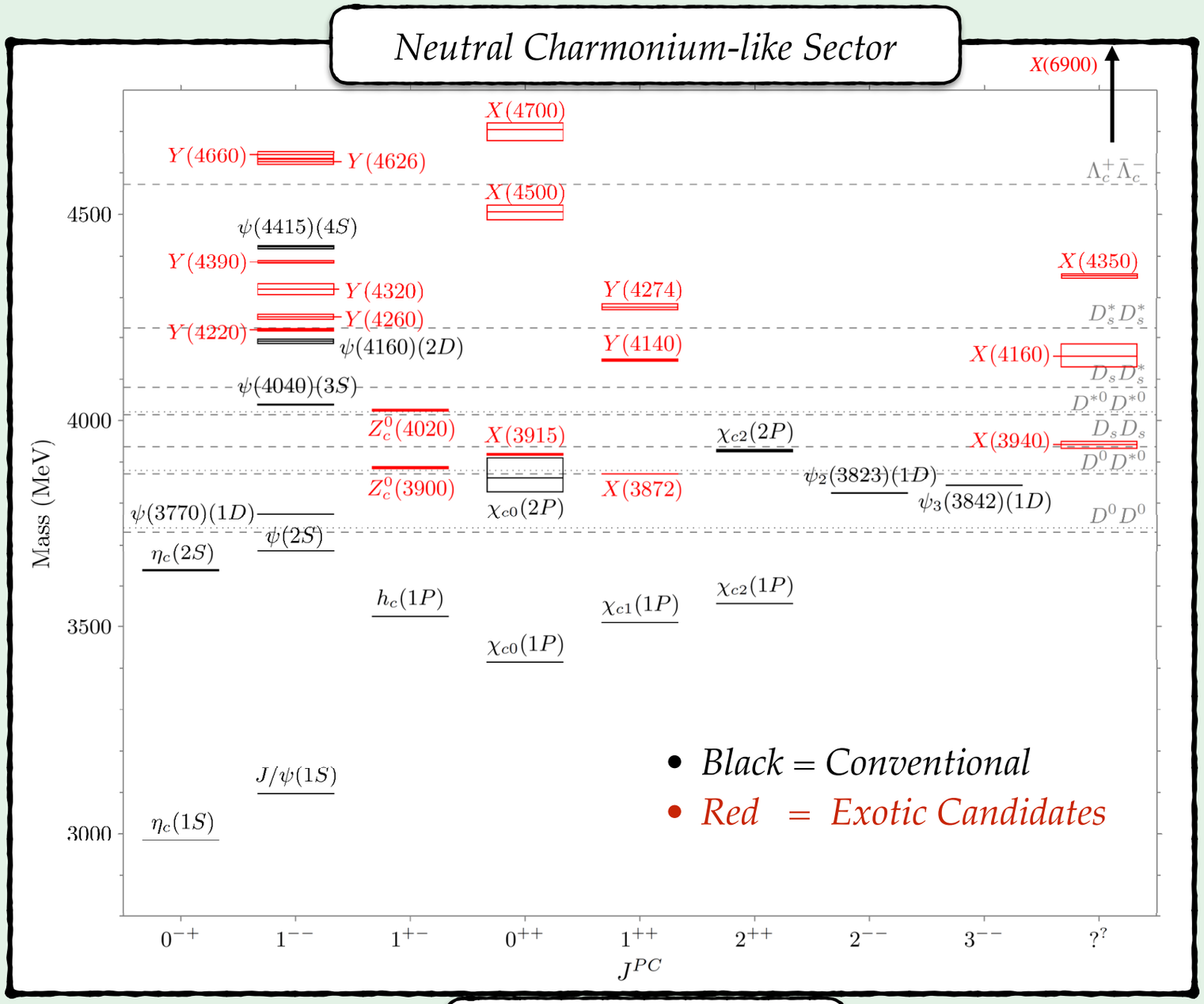

R. Lebed, 2020

Post 2003 Heavy Spectroscopy

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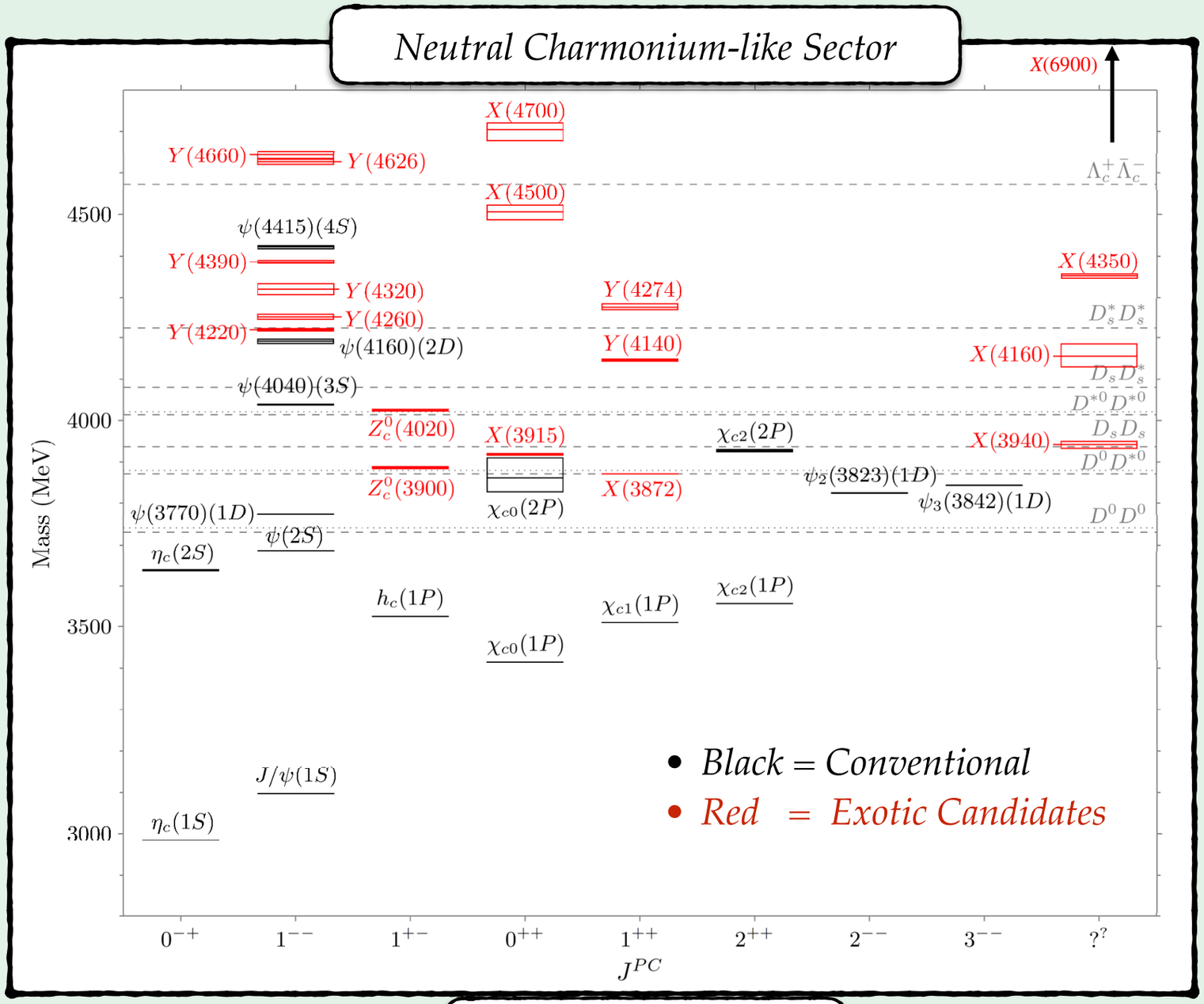

R. Lebed, 2020

- Total of 15 Experimentally Established Exotics PDG

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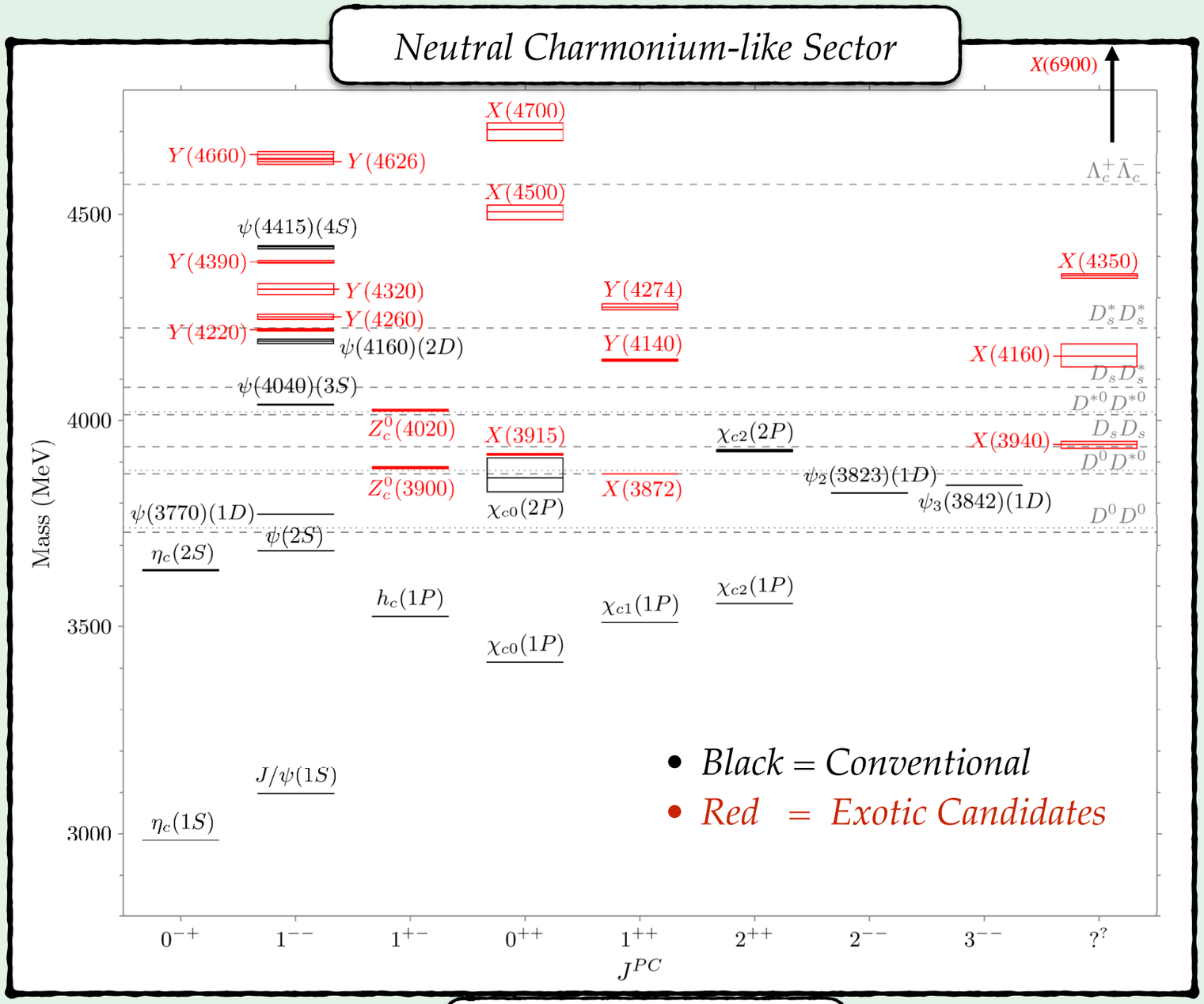

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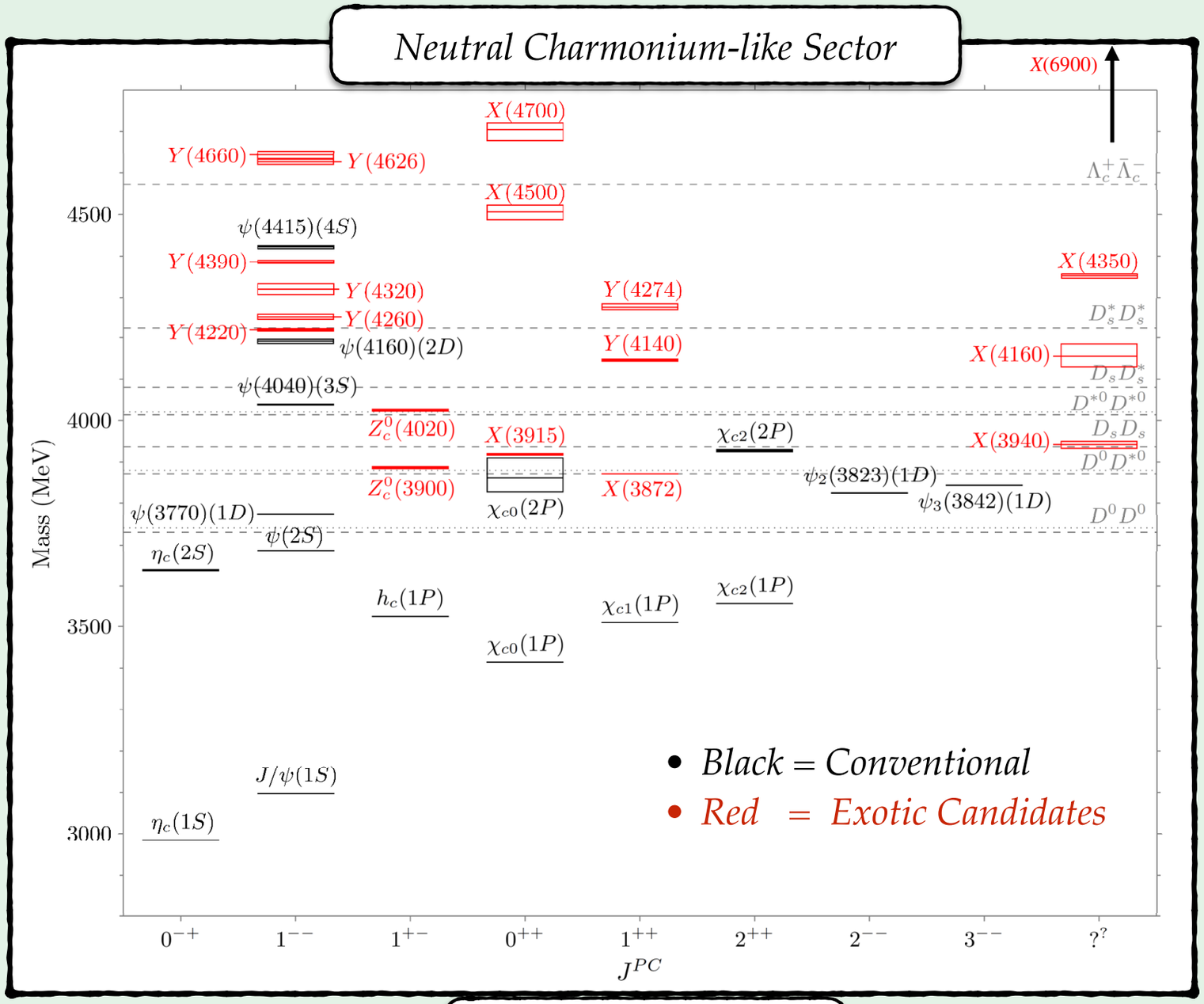

R. Lebed, 2020

- Total of 15 Experimentally Established Exotics PDG
- Commonly called XYZ states (PDG has official naming convention)
- 44 Observed Exotic Candidates

Exotic States: What Can They Be?

- Gell-Mann (1964) : "Color Confinement allows $\overline{q}gq, \overline{q}\overline{q}qq, \overline{q}qqqq, \ldots$ "

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Mesons

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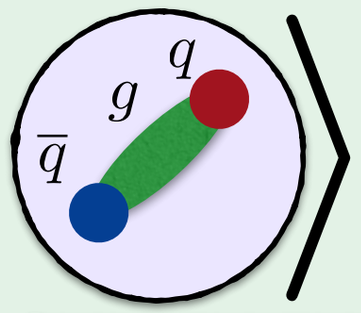

$\overline{q}gq$: *Hybrids*

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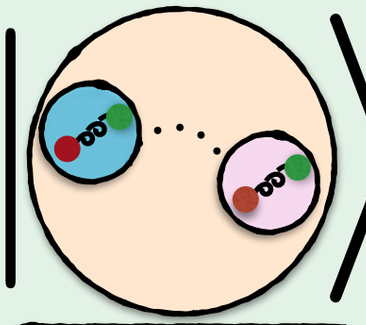

Molecular

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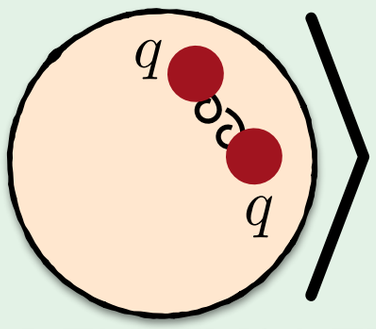

Diquark Tetraquarks

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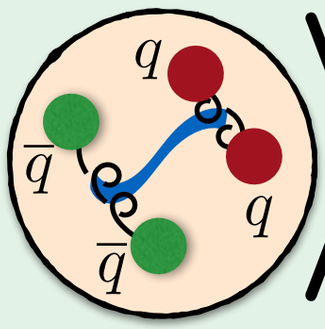

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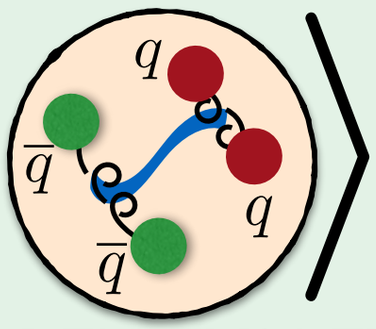

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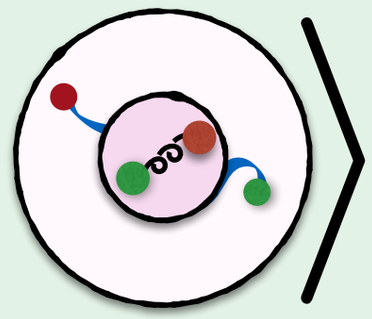
$$a_5 \left| \; \right\rangle$$



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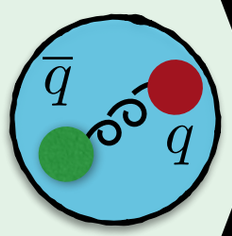
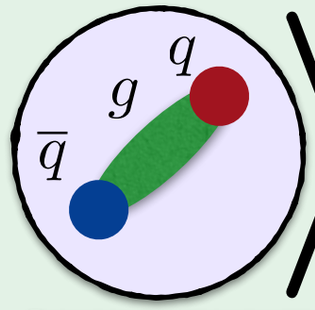
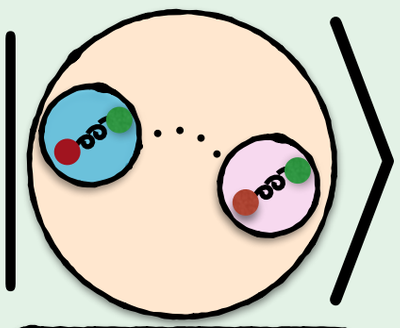
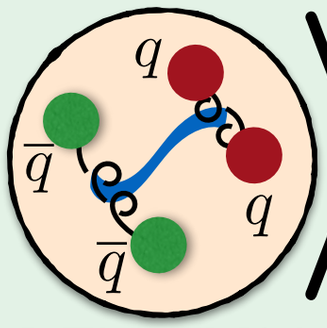
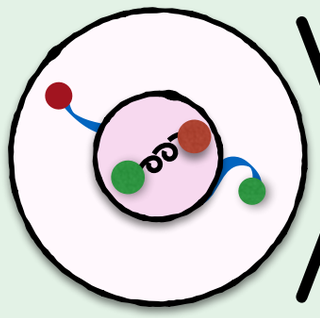
$$|\Psi\rangle = a_1 \Big|$$ 

$$\Big\rangle + a_2 \Big|$$ 

$$\Big\rangle + a_3 \Big|$$ 
$$\Big\rangle + a_4 \Big|$$ 

$$\Big\rangle + a_5 \Big|$$ 
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Molecular

Compact Tetraquarks

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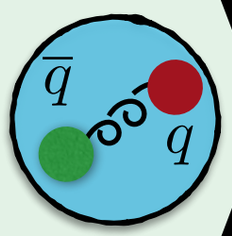
$$|\Psi\rangle = a_1 \Big|$$ 

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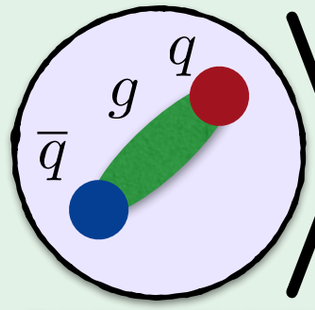
$$+ a_2 \Big|$$ 

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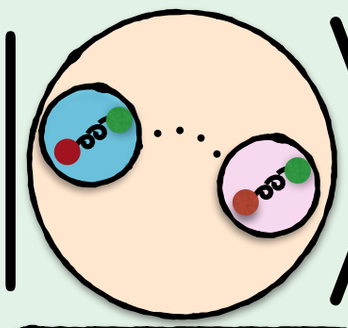
$$+ a_3 \Big|$$ 
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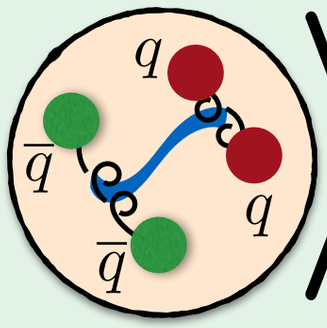
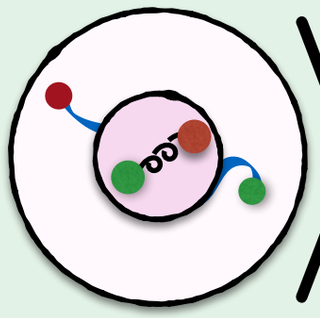
$$+ a_4 \Big|$$ 

$$\Big\rangle + a_5 \Big|$$ 
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📌 Exotic Spectroscopy = Which of These Hopeful Exotic Configurations Can Explain The Experimentally Determined States?

Scattering Overview: What Is A State?

📌 $Def^{\underline{n}}$: "State" = A Pole Singularity of the Scattering Matrix

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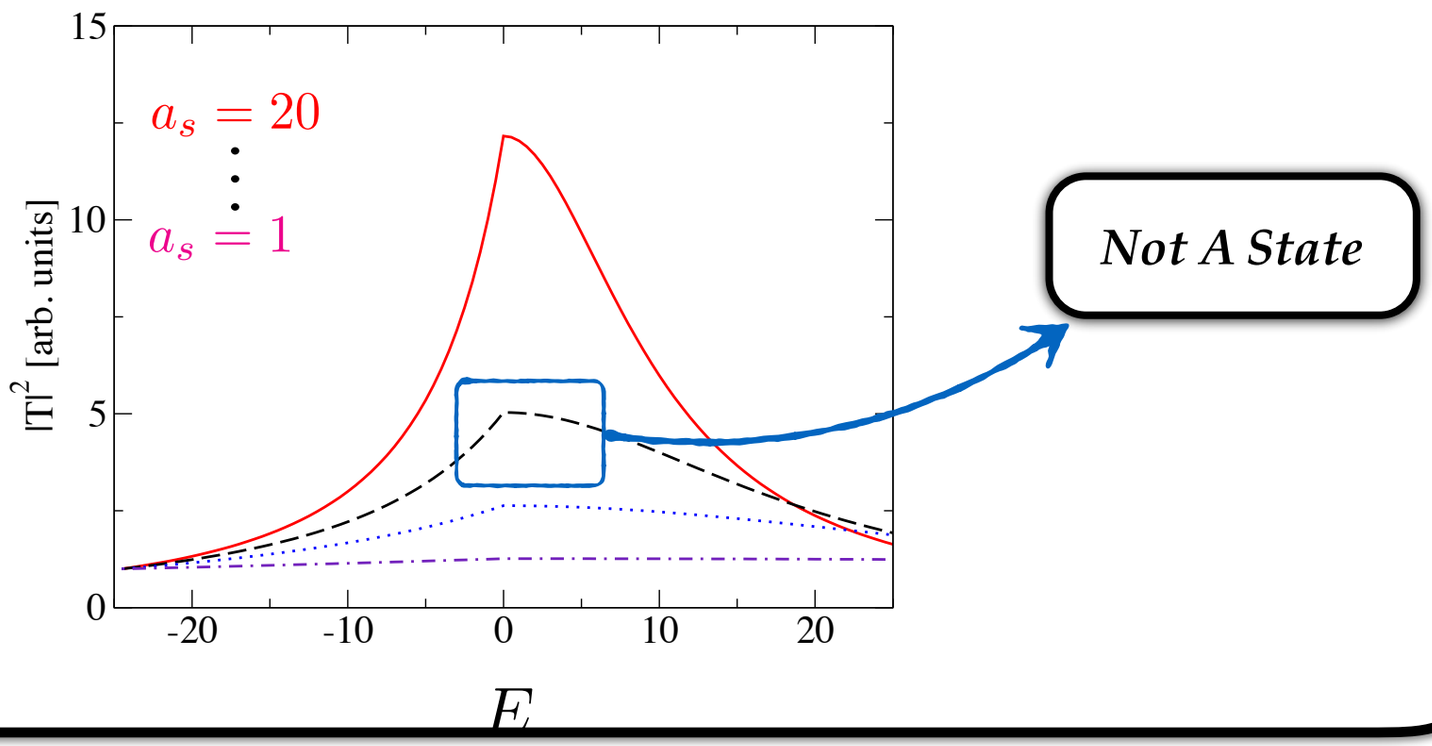

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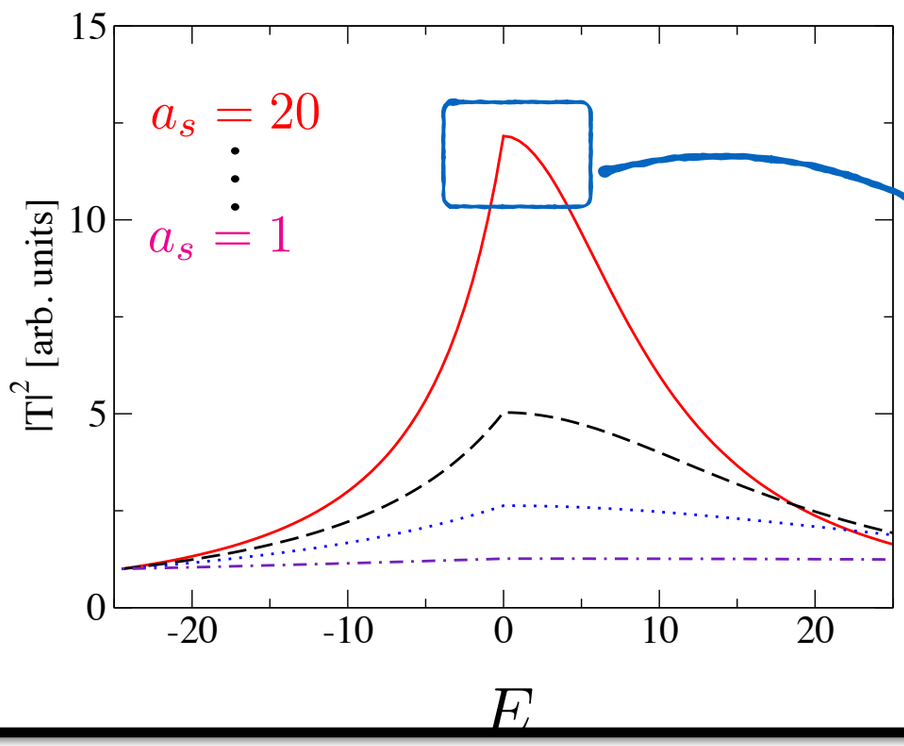

Prominent Cusp => Virtual State

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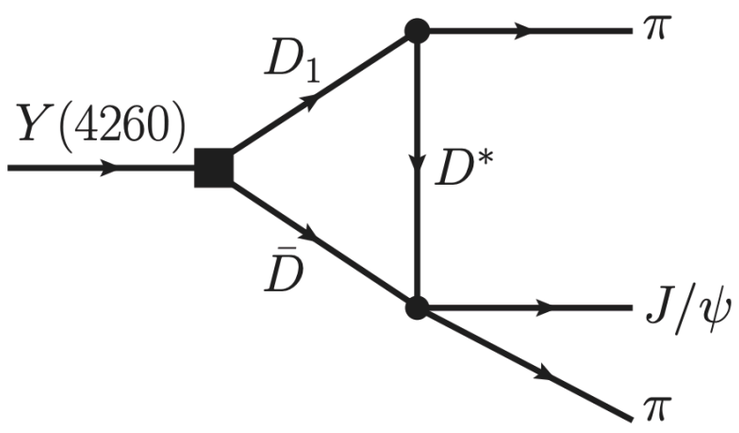

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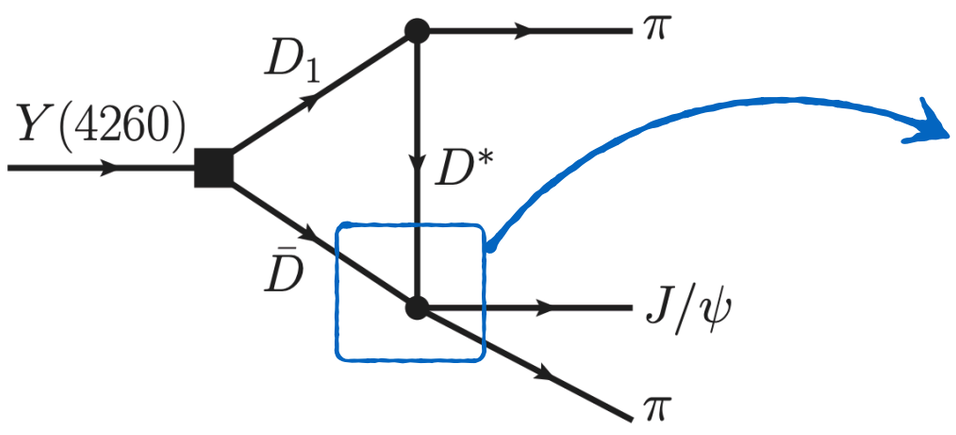

Rescattering Can Cause Logarithmic Singularity

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- Cusp/Triangle Singularity and State (which is a Pole) may both be Present in Experimental Data

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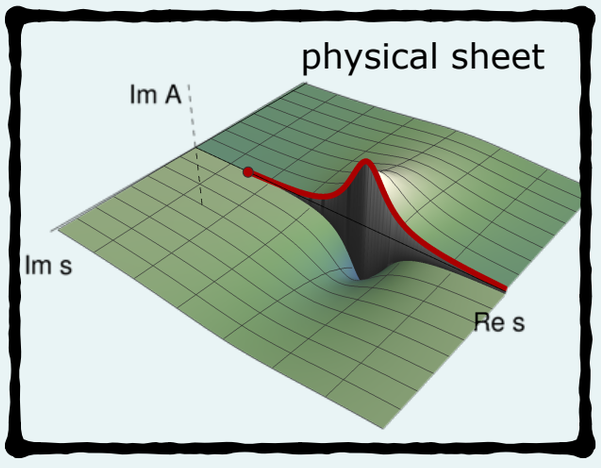

PDG, resonances review

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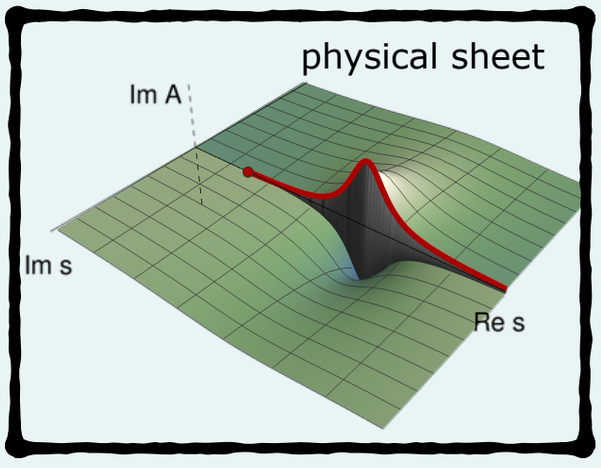

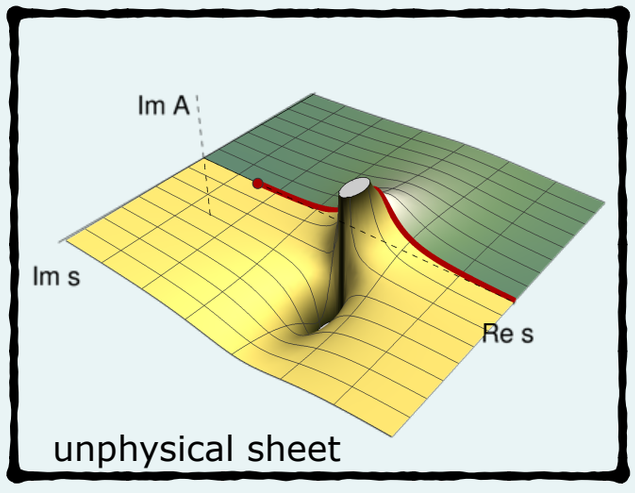

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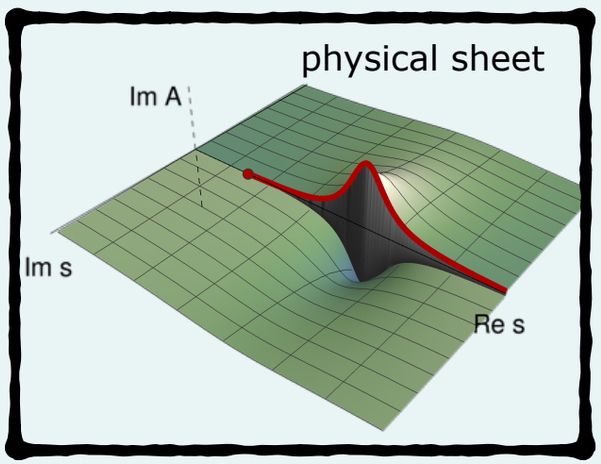
3. Virtual States: Poles on the real axis below threshold on Unphysical Sheet. E.g., $I = 1,\ S = 0$ nucleon-nucleon scattering (arxiv:1705.00141)



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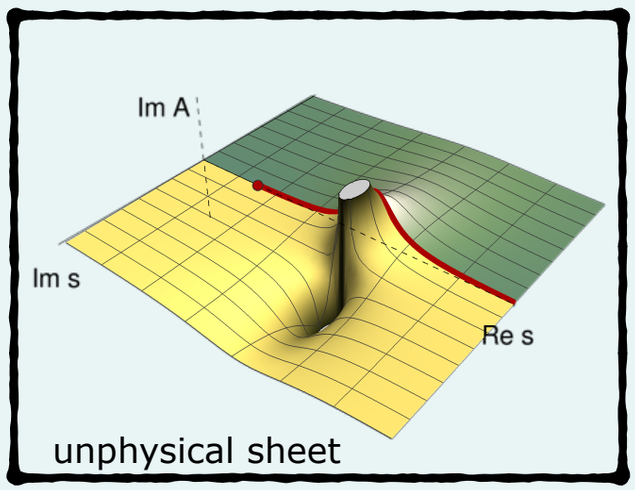

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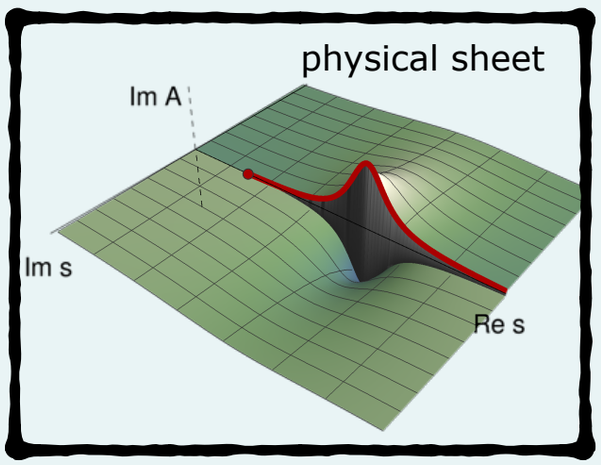
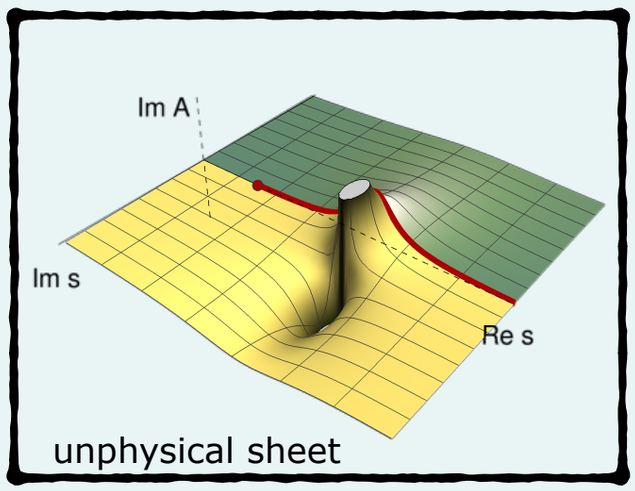
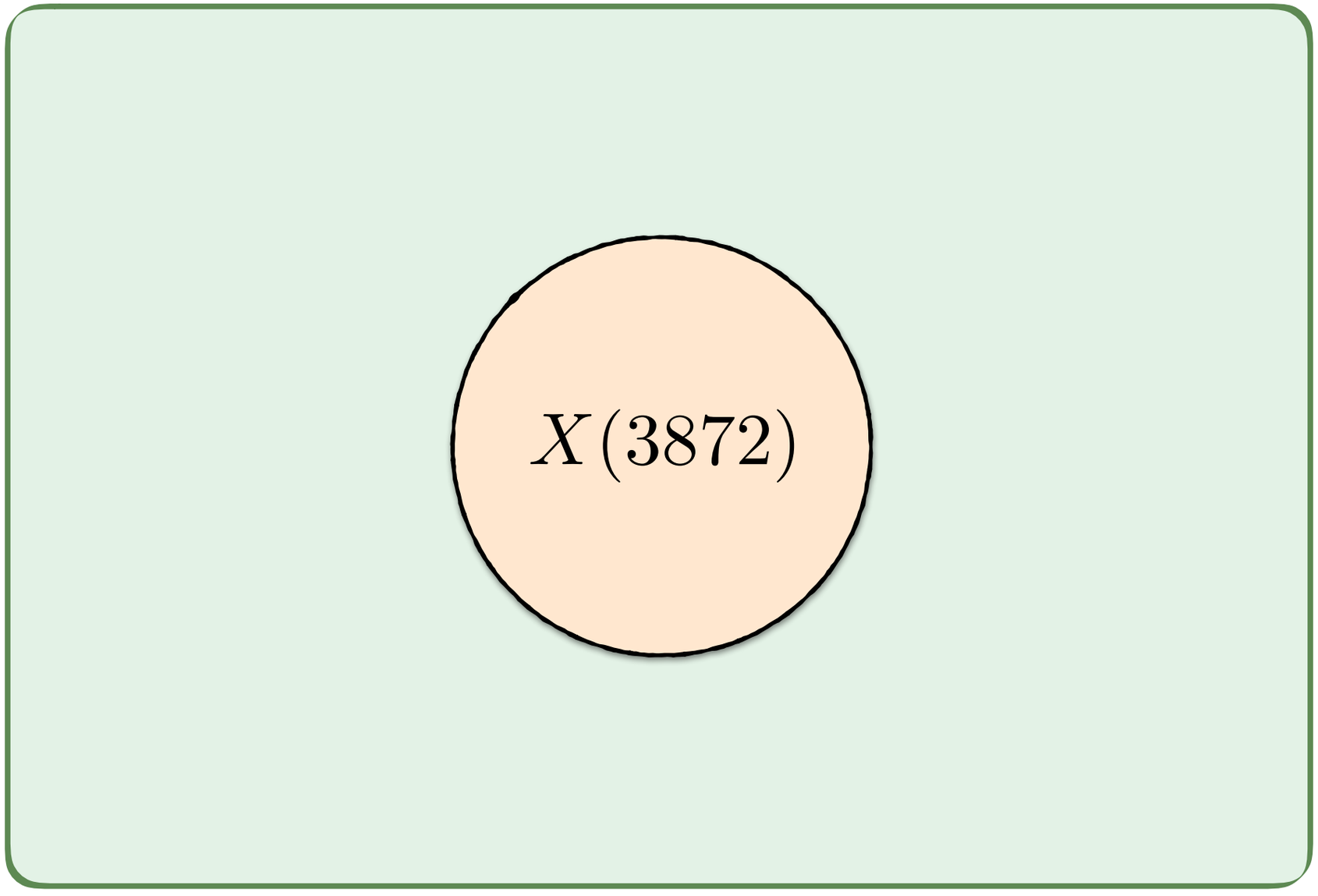


PDG, resonances review



arvix:2007.05329
Shallow Virtual States are predominantly Molecular.

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



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- Notable Decays

$\mathcal{B}(\pi^+\pi^- J/\psi) > 3.2\%$ $\mathcal{B}(D^0\overline{D^*}) > 30\%$ $\mathcal{B}(\rho^0 J/\psi) \sim \mathcal{B}(\omega J/\psi)$

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$\Gamma_{PDG} < 1.2$MeV

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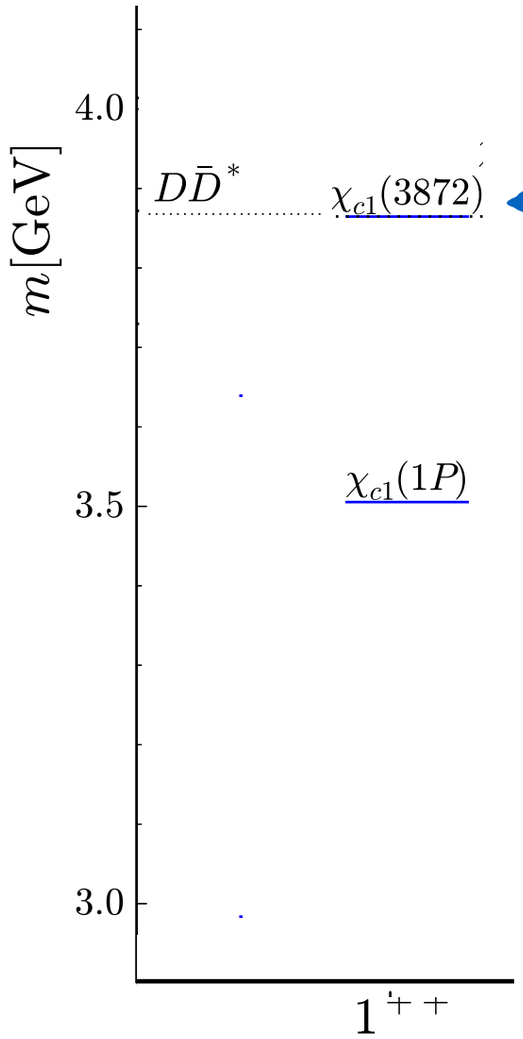

S-wave Threshold = Kinematical Singularities Possible

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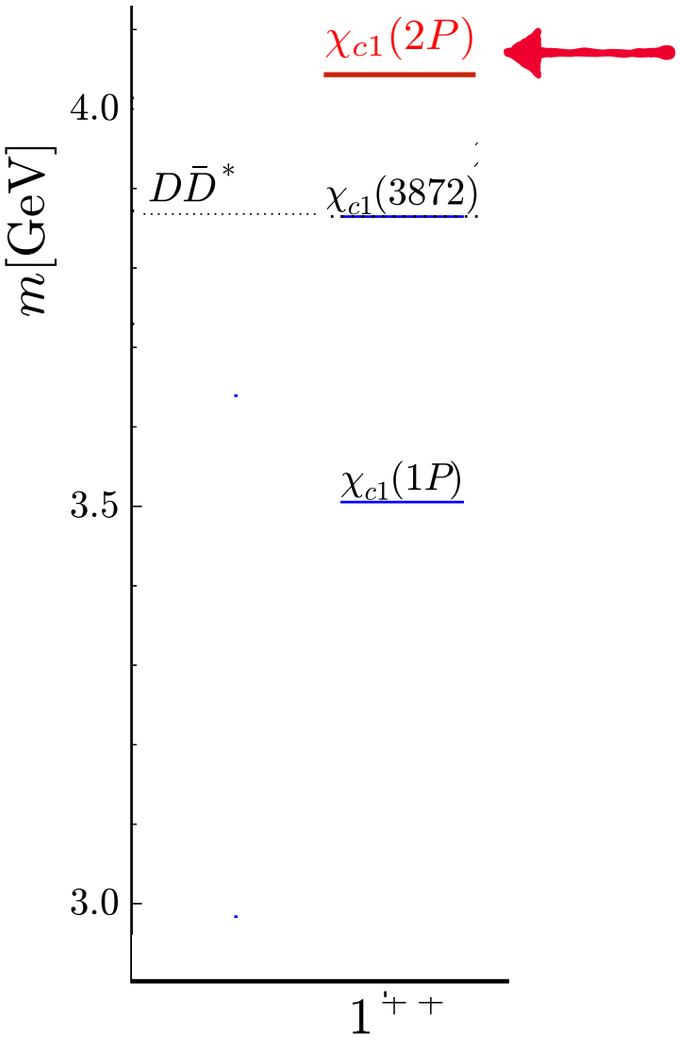

Potential Model with $\bar{c}c$

arxiv:1302.6857

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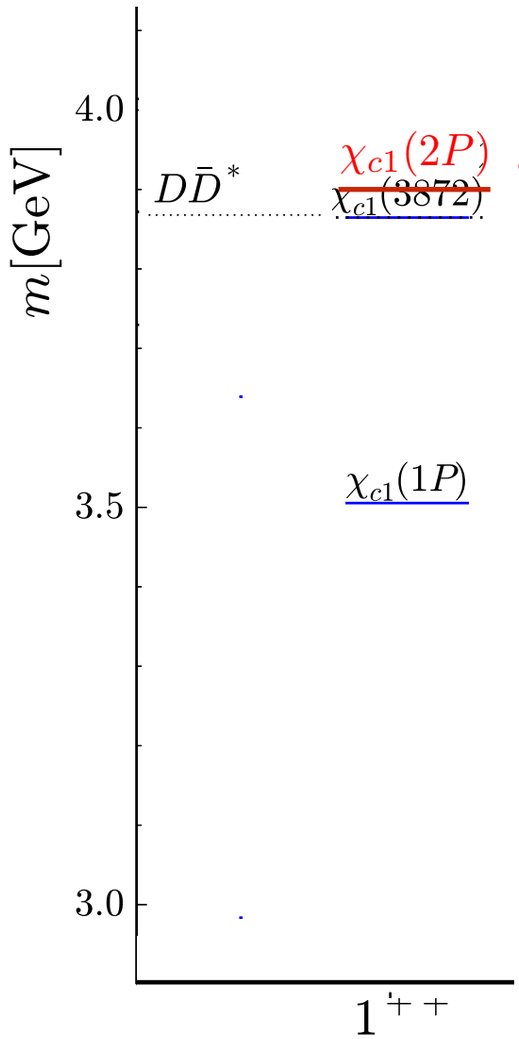

Potential Model with $\bar{c}c$ and meson-meson couplings

arxiv:1302.6857

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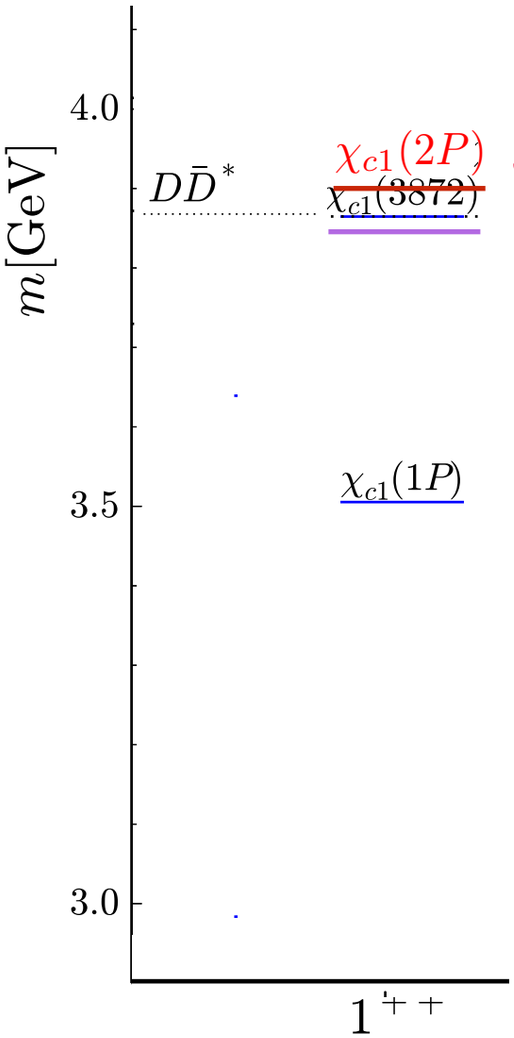
arxiv:1503.03257

$X(3872)$	$m_X - m_{D_0} - m_{D_0^*}$
Lat.	-8(15)
Lat. - O^{4q}	-9(8)
LQCD [17]	-11(7)
LQCD [18]	-13(6)

Lattice QCD



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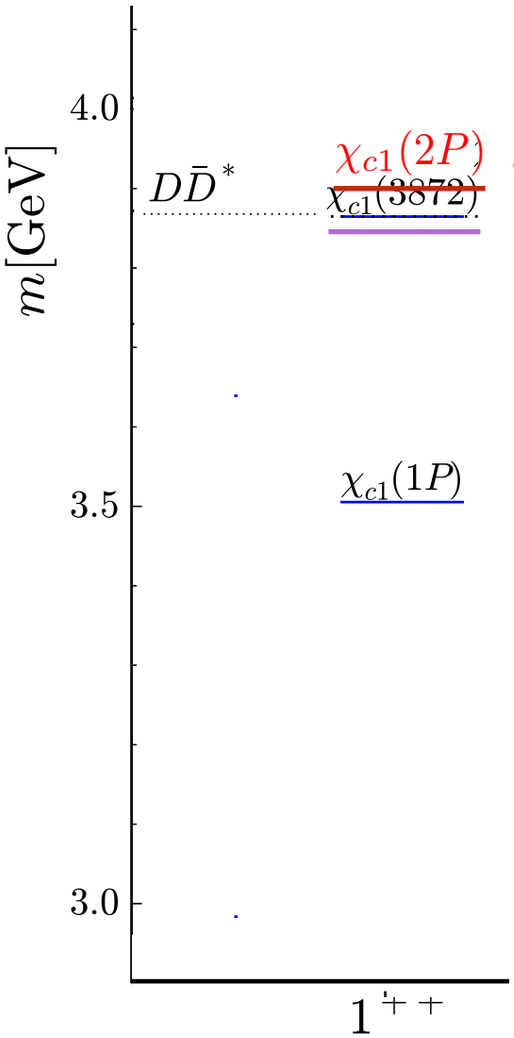
- $\bar{c}c$ and $D\bar{D}^*$ important
- Diquarks not important
- Find Bound State Pole

Lattice QCD



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Kinematically Allowed since 5 MeV $< M_X$ ***and*** $\Gamma(\rho)$ ***= 150 MeV***

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Kinematically Suppressed as 7 MeV $> M_X$ ***and*** $\Gamma(\omega) =$ ***8 MeV***

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- X(3872) is $I = 0$, if molecular then ~$|D^0 \bar{D}^{0*}\rangle + |D^+ D^{*-}\rangle +$ c.c.
- Isospin violations occurs in decays due to 8 MeV mass difference between $|D^0 \bar{D}^{0*}\rangle$ and $|D^+ \bar{D}^{*-}\rangle$ (arxiv:1711.01930)

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Pole Structure: arxiv:2005.13419

- Pure Cusp ruled out.
- Virtual or Bound State Compatible With Data

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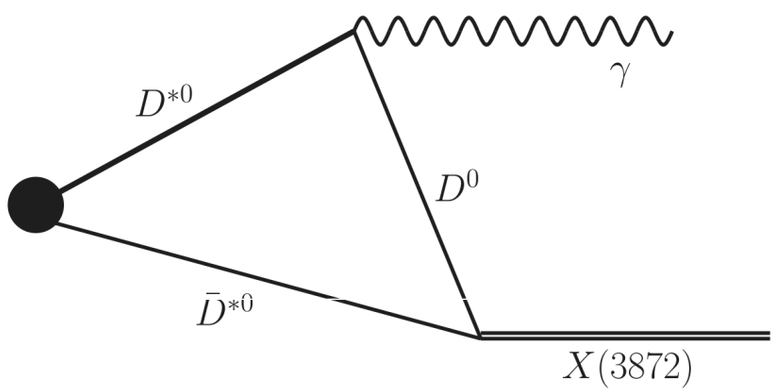
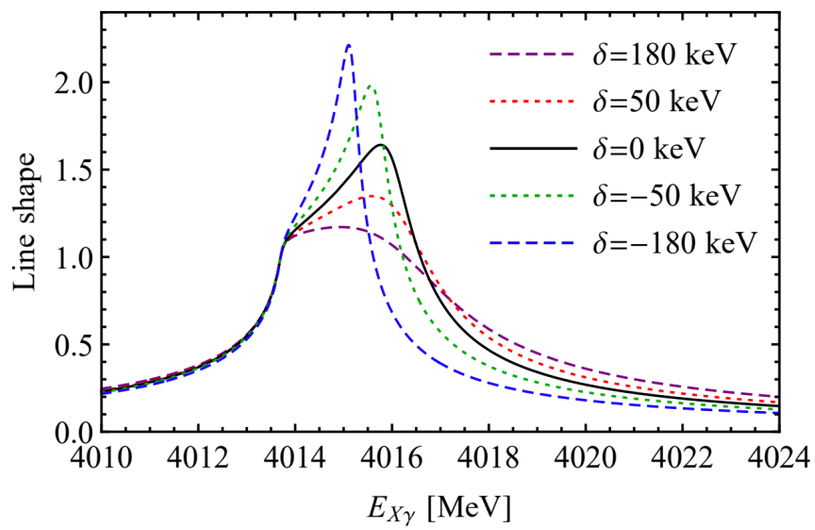
- Triangle Singularity gives enhancement. Order of magnitude more precise δ (arxiv:1902.11221)





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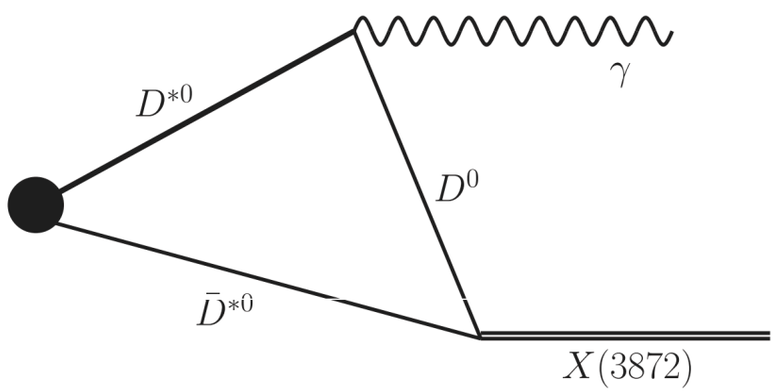
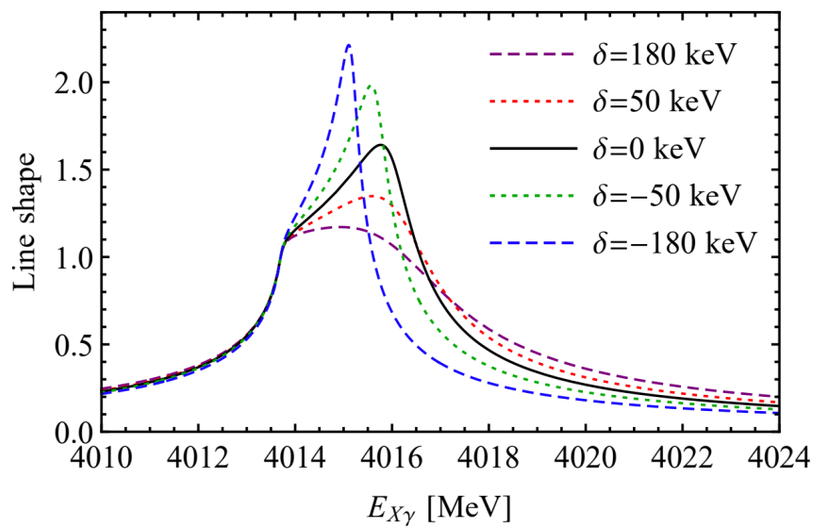
- Needs large number of low energy $D^{0*}\bar{D}^{0*}$





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Spatial Structure (my guess)

- Molecular $D^0\bar{D}^{0*}+ \chi_{c1}(2P)$: Lattice/Pheno/(Sum Rules arxiv:1812.08207)

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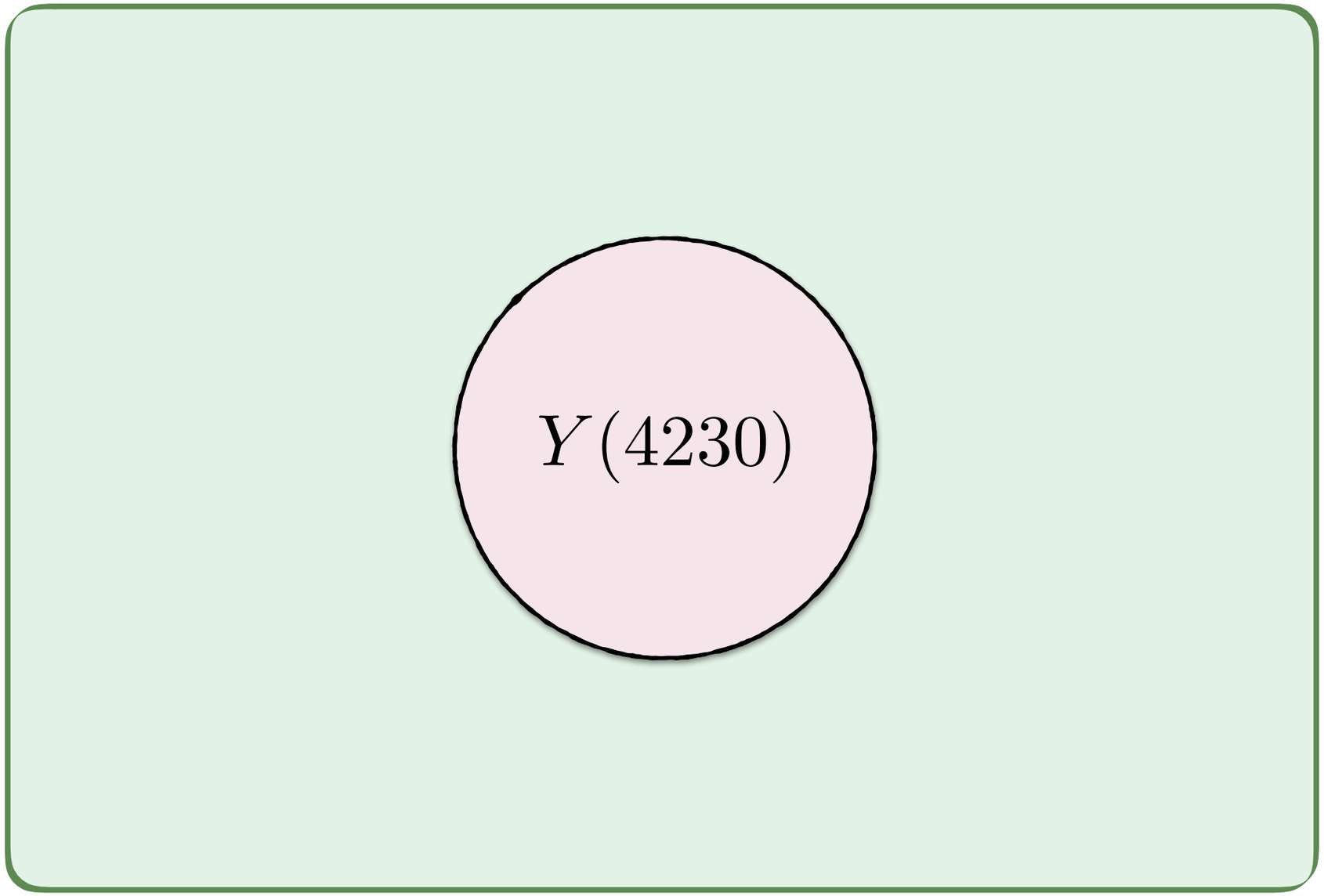
- Debates: Prompt Production arxiv:1709.09631, arxiv:1709.09101

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$



$\psi(4230)\ aka\ Y(4230)\ aka\ Y(4260)$

- Quantum Numbers

$$J^{PC} = 1^{--} \qquad Q = 0 \qquad I^G = 0^-$$

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

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$J^{PC} = 1^{--}$ $Q = 0$ $I^G = 0^-$

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- $M_{PDG} = 4220 \pm 15$ MeV
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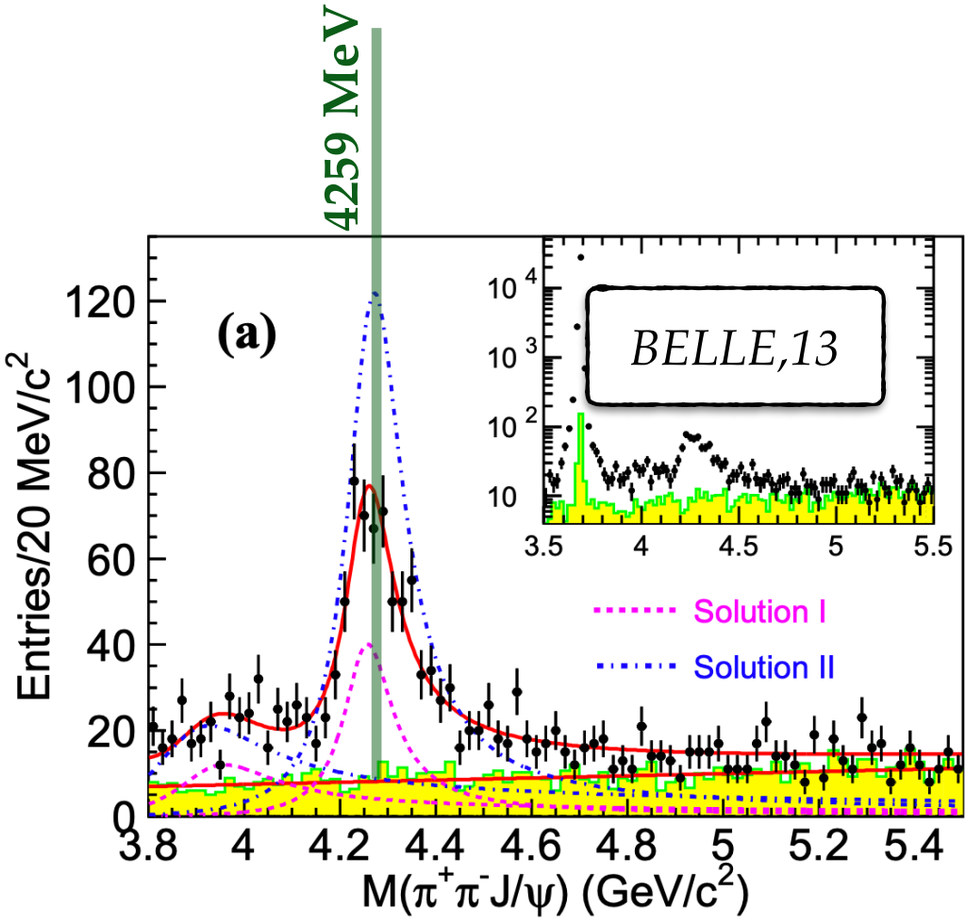

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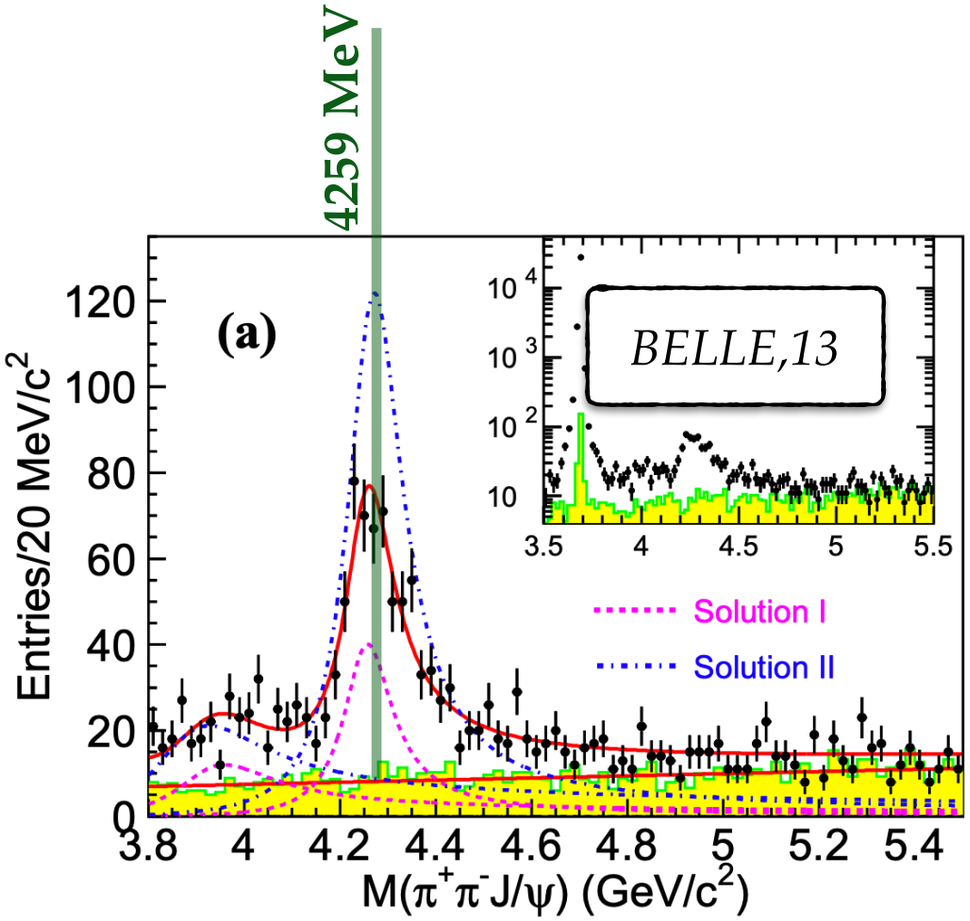

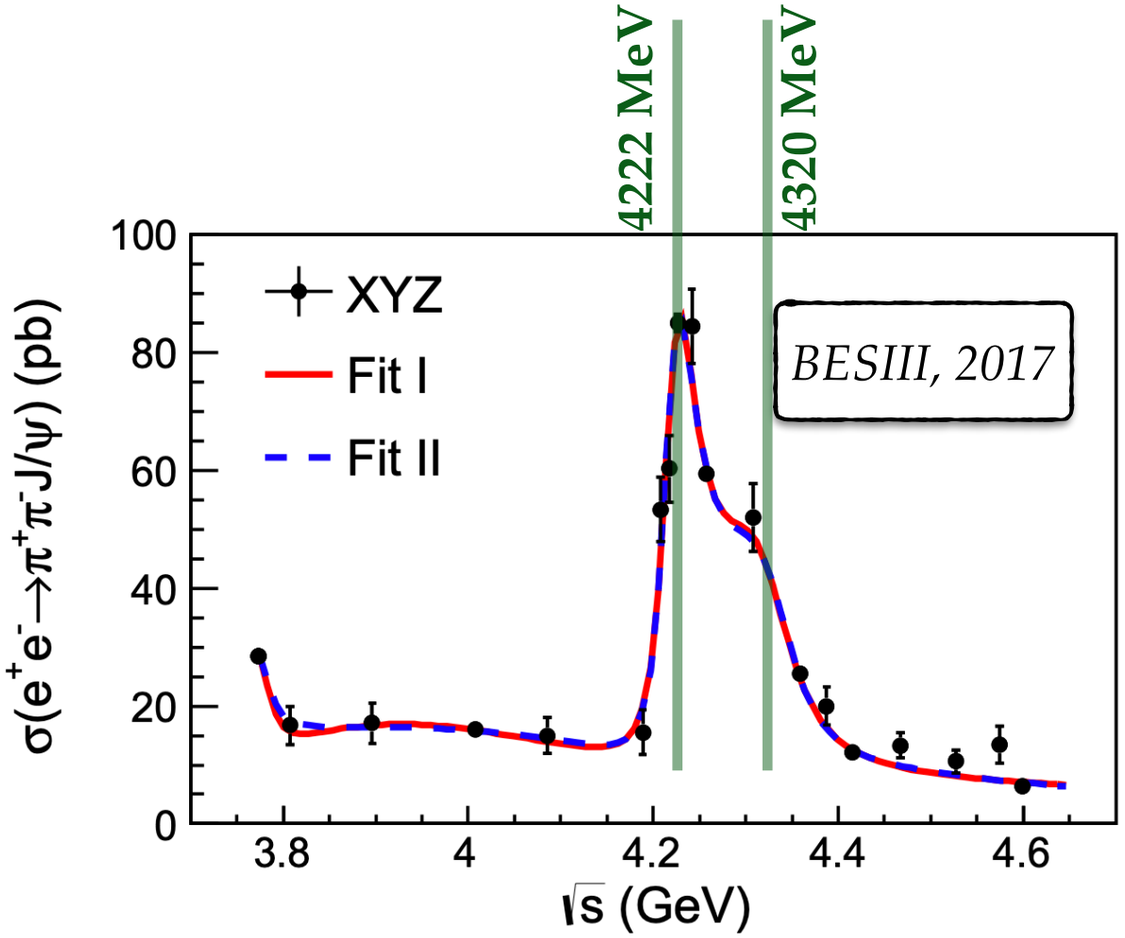

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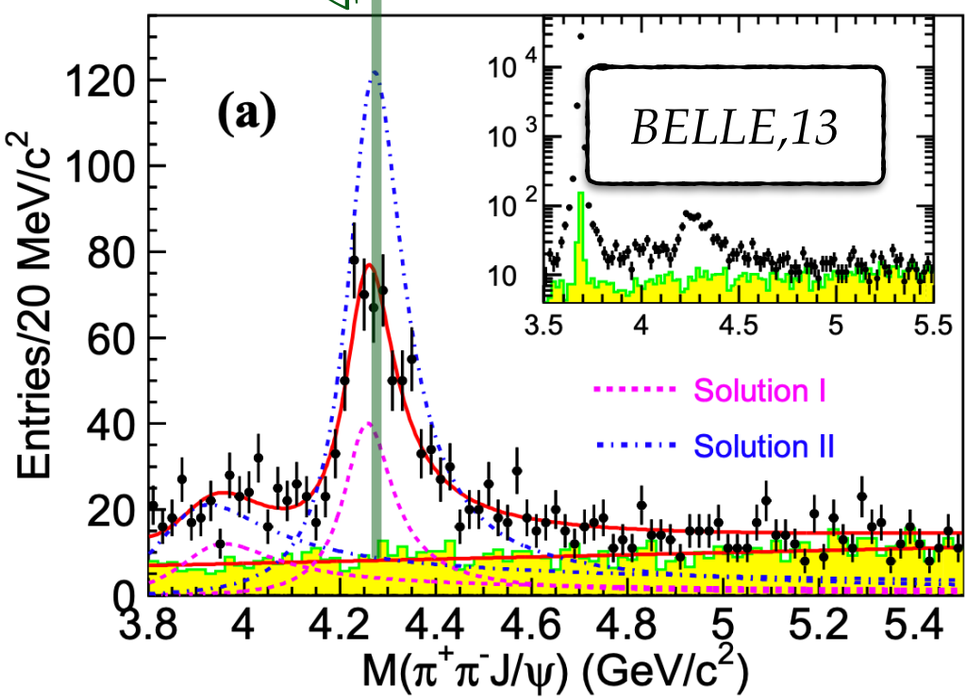
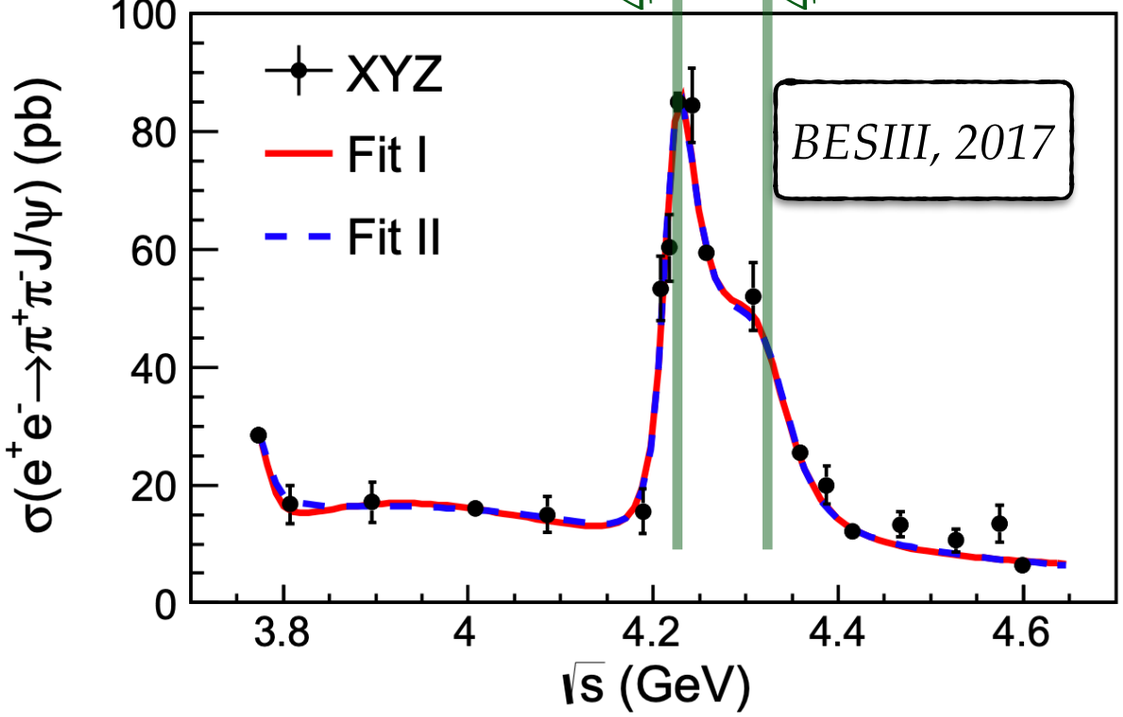
4259 MeV → *PDG 2020 Replaced* → 4222 MeV, 4320 MeV





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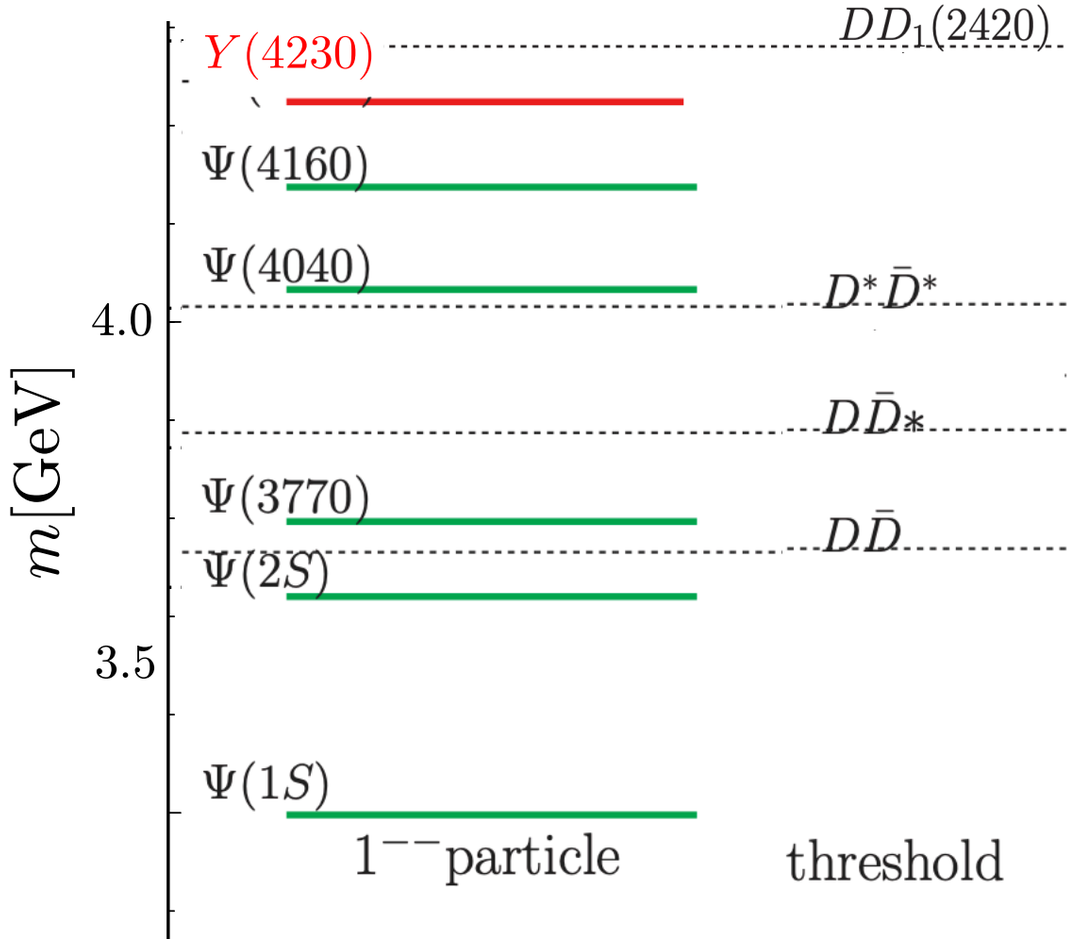

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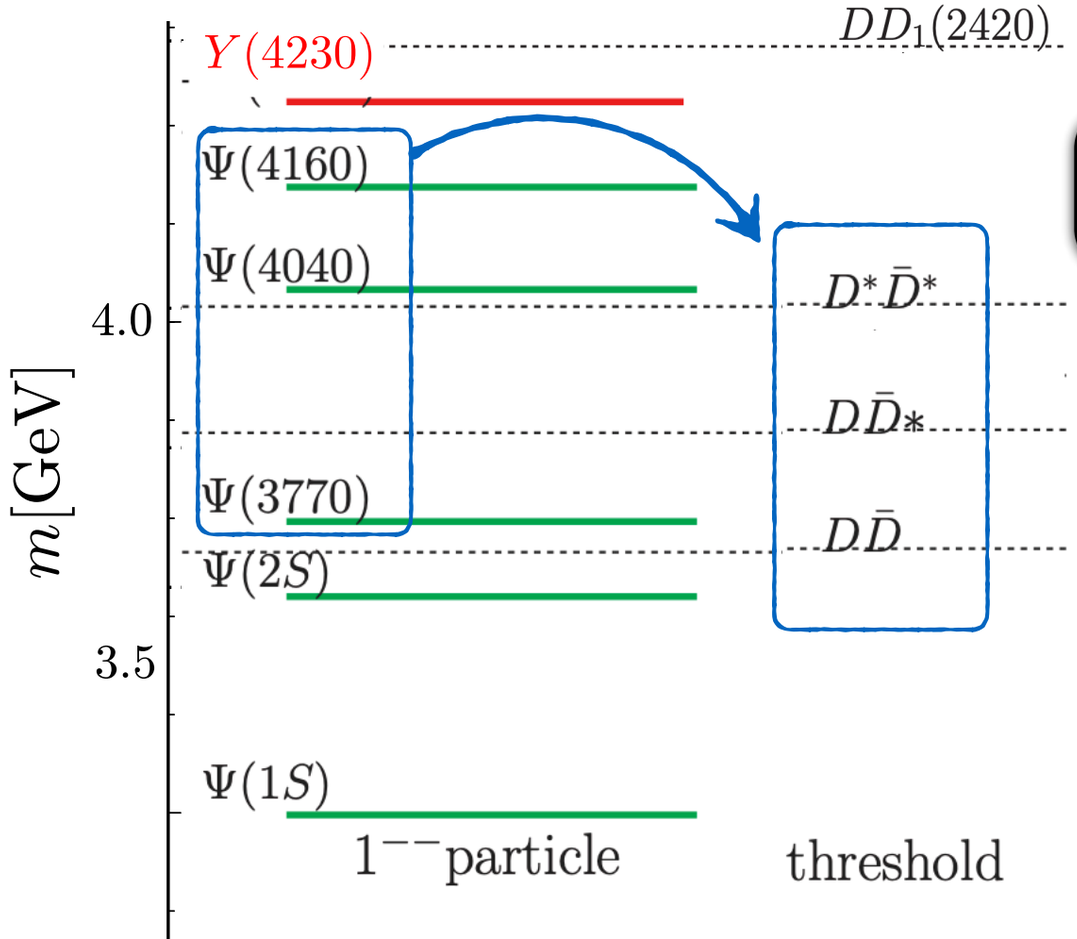
Notable Decays

- Seen $\mathcal{B}(\pi^+\pi^- J/\psi)$ $\mathcal{B}(\pi^+\pi^- h_c)$ $\mathcal{B}(\pi^+ D^{*-} D^0)$ $\mathcal{B}(\gamma X(3872))$
- Not Seen: Any Open-Charm Decays, e.g, $\mathcal{B}(D\bar{D})$

- $M_{PDG} = 4220 \pm 15$ MeV
- $\Gamma_{PDG} = 20 - 100$ MeV



Charmonium states decay to open flavour thresholds

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

Quantum Numbers

$J^{PC} = 1^{--}$ $\quad Q = 0$ $\quad I^G = 0^-$

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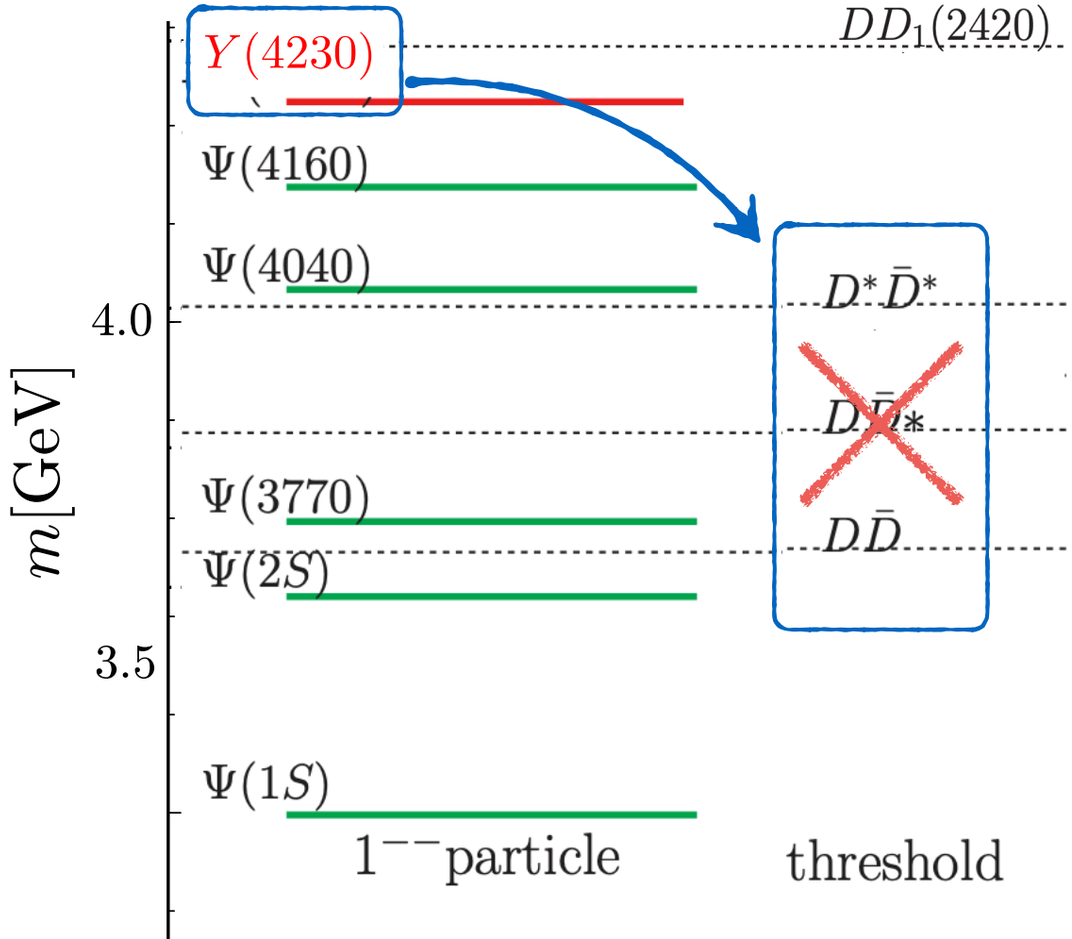

$Y(4230)$ cannot contain $\bar{c}c$ as it does not decay to open charm!

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

Quantum Numbers

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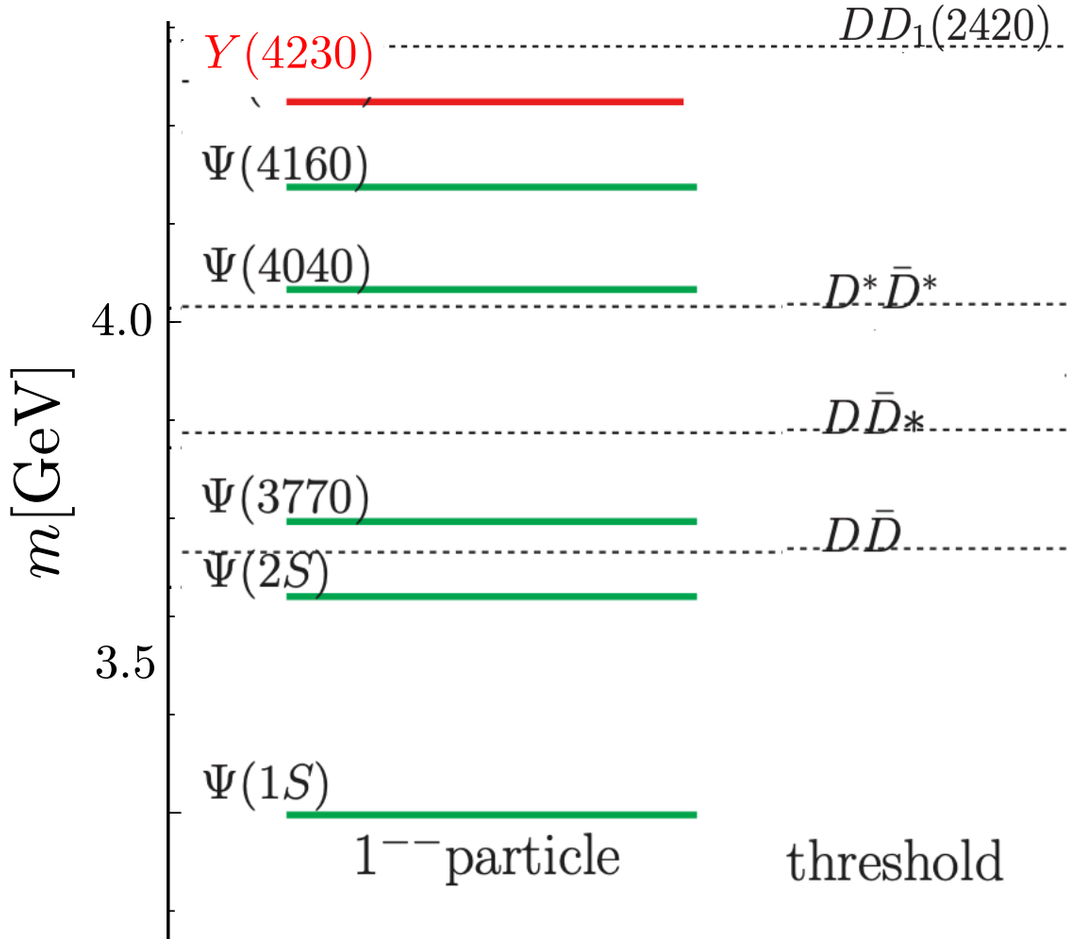

Scenario 1: $D\bar{D}_1(2420)$ Molecular State

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

Quantum Numbers

$J^{PC} = 1^{--}$ $Q = 0$ $I^G = 0^-$

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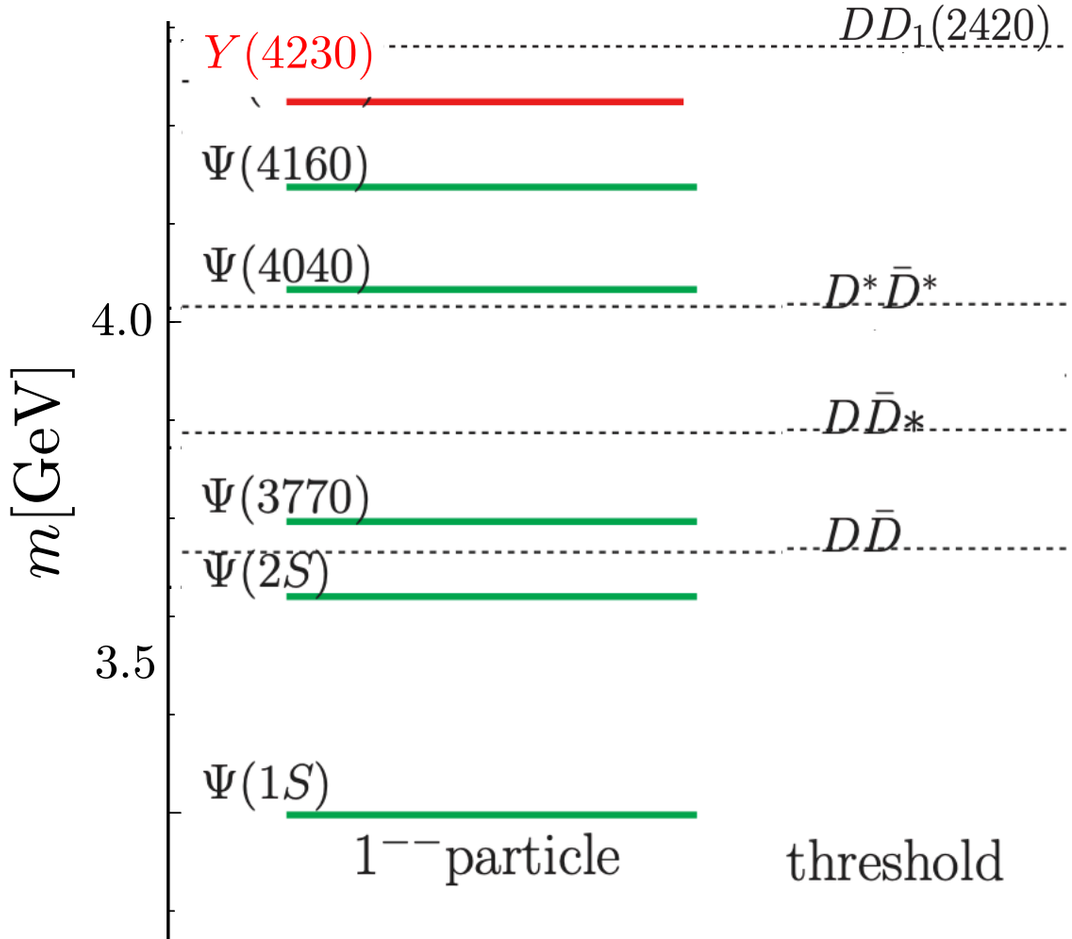

Scenario 1: $D\bar{D}_1(2420)$ Molecular State

- $M_Y - M_{D\bar{D}_1} = -65$ MeV within reason for potential models (arxiv:1910.14455)

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

Quantum Numbers

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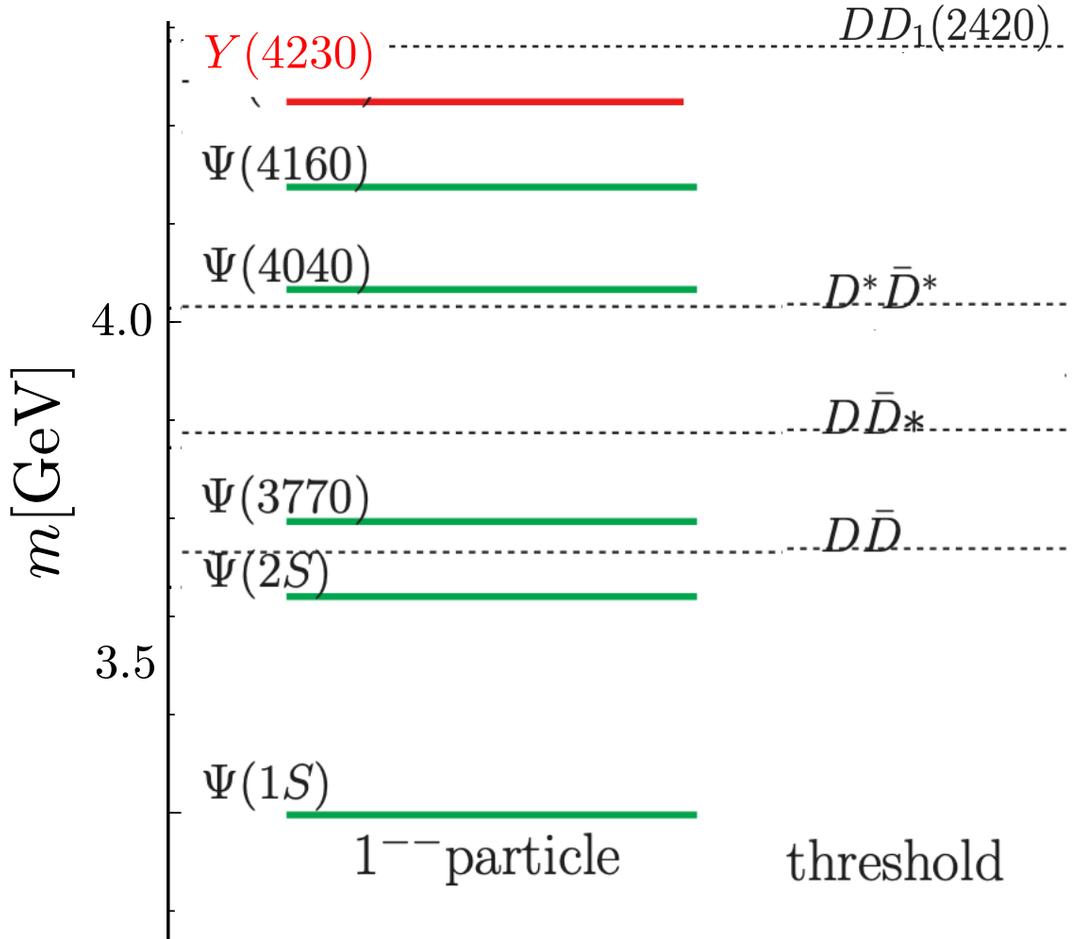

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- $M_Y - M_{D\bar{D}_1} = -65$ MeV within reason for potential models (arxiv:1910.14455)
- Molecular States decay through constituents: explains decay patterns (arxiv:1306.3096)

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Quantum Numbers

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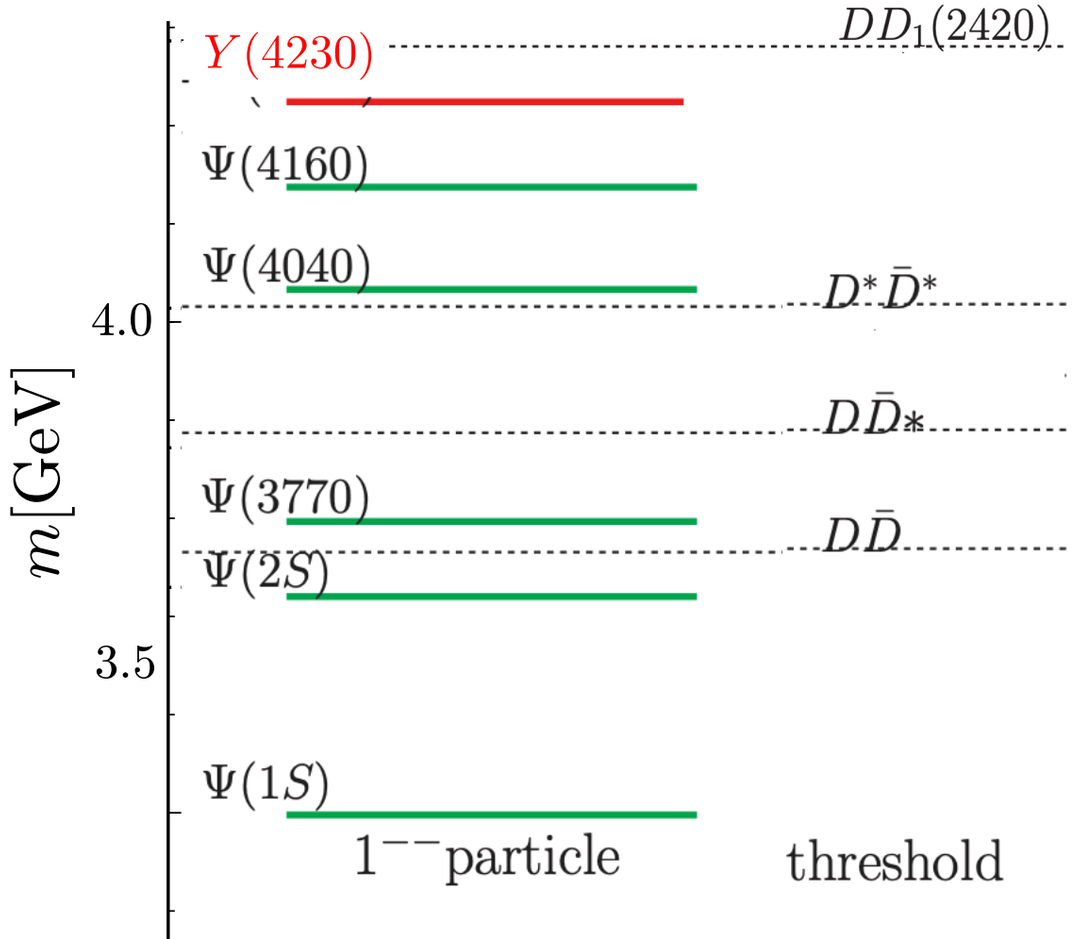

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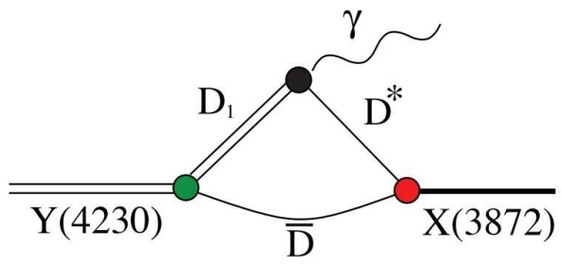
- $M_Y - M_{D\bar{D}_1} = -65$ MeV within reason for potential models (arxiv:1910.14455)
- Molecular States decay through constituents: explains decay patterns (arxiv:1306.3096)
  - $Y(4230) = D^0\bar{D}_1 \to D^0\pi^+ D^{*-}$
  - 

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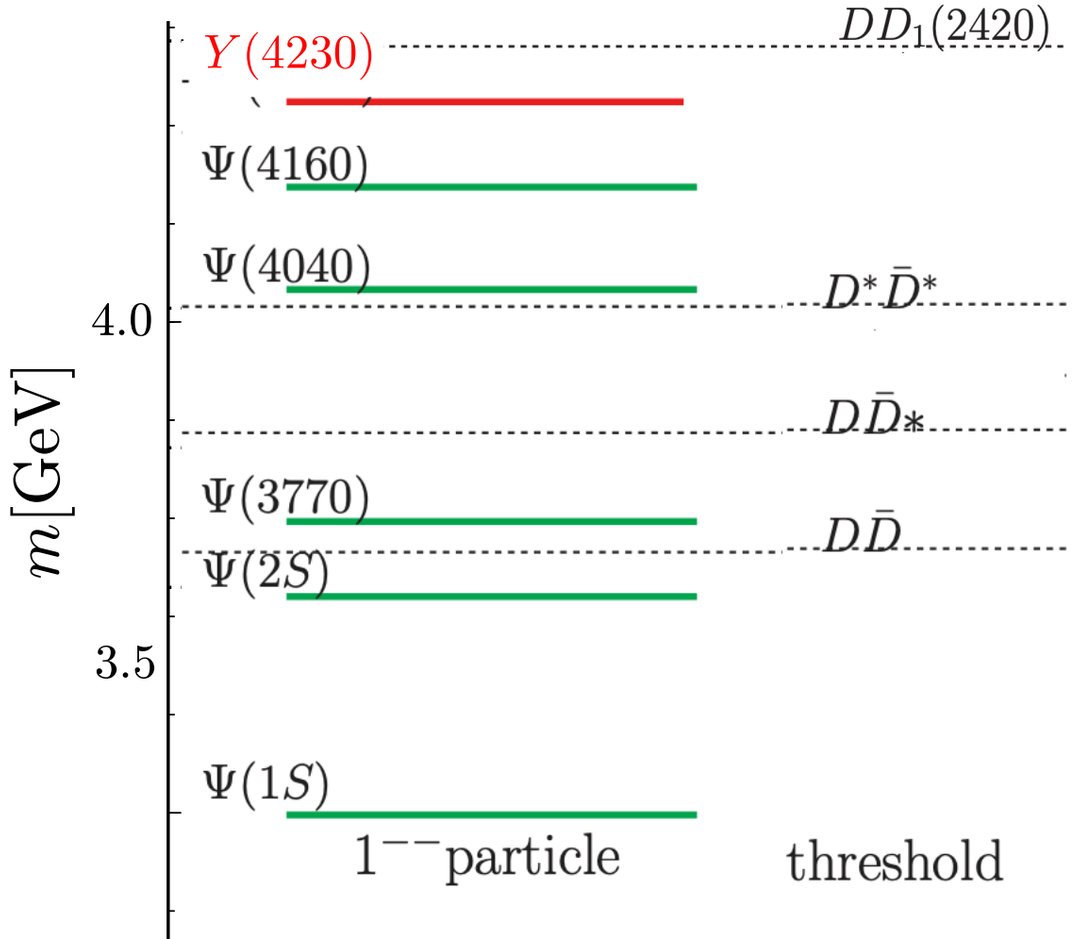

Scenario 1: $D\bar{D}_1(2420)$ Molecular State

- (arxiv:1902.10957) By studying $\pi\pi, Y(4230)$

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

Quantum Numbers

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Notable Decays

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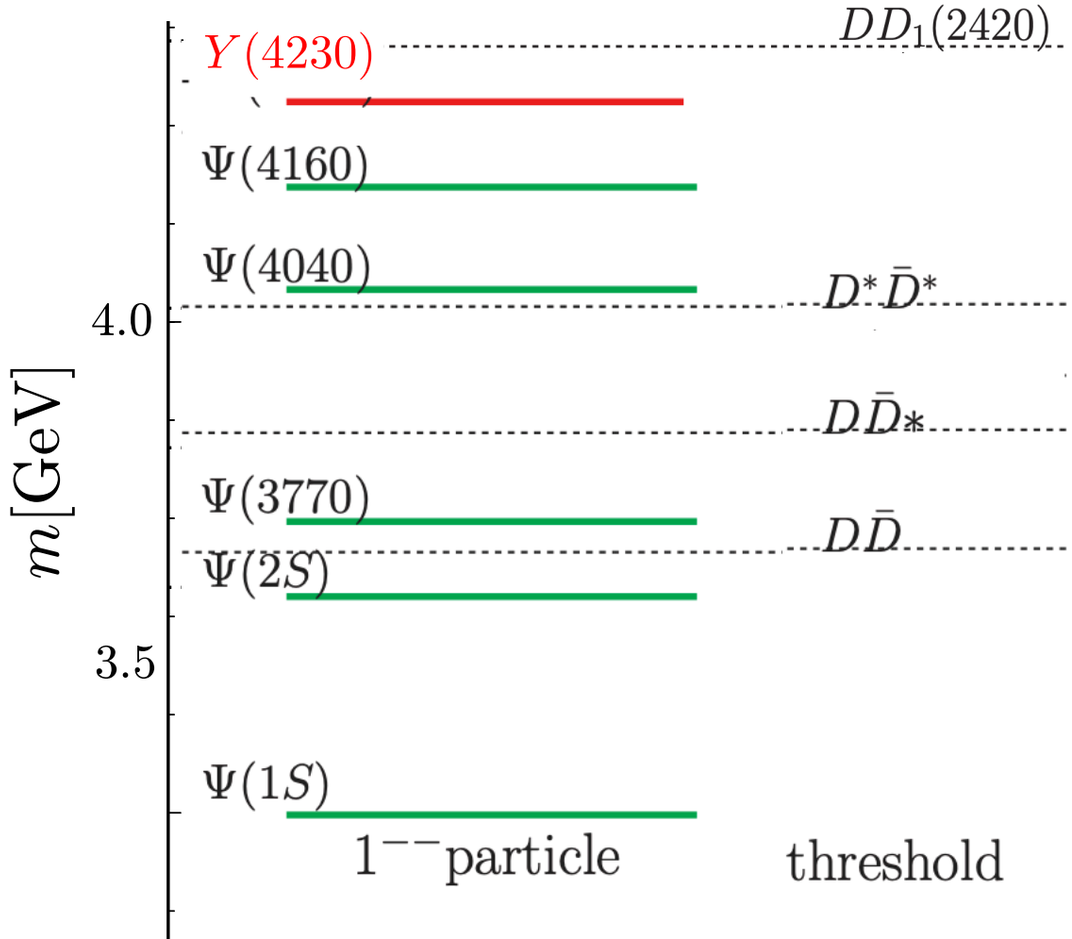

Scenario 1: $D\bar{D}_1(2420)$ Molecular State

- (arxiv:1902.10957) By studying $\pi\pi$, $Y(4230)$
  - cannot be fully molecular
  - has sizable SU(3) flavour octet component
    => Cannot be dominated by $\bar{c}c$ or hybrid.

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

Quantum Numbers

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Notable Decays

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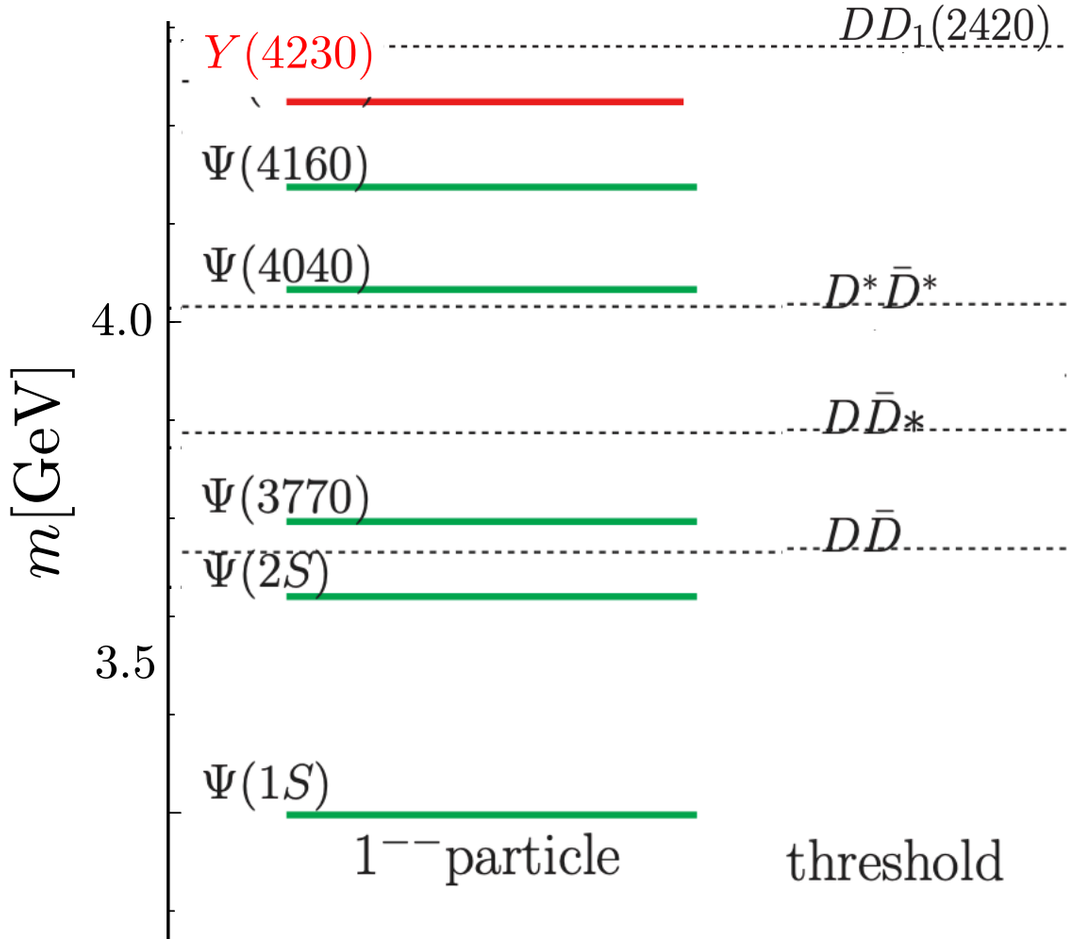

Scenario 2: $\bar{c}gc$ hybrid

- Lattice hybrid energy 180 MeV high, but with systematics roughly correct (arxiv:1610.01073)

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

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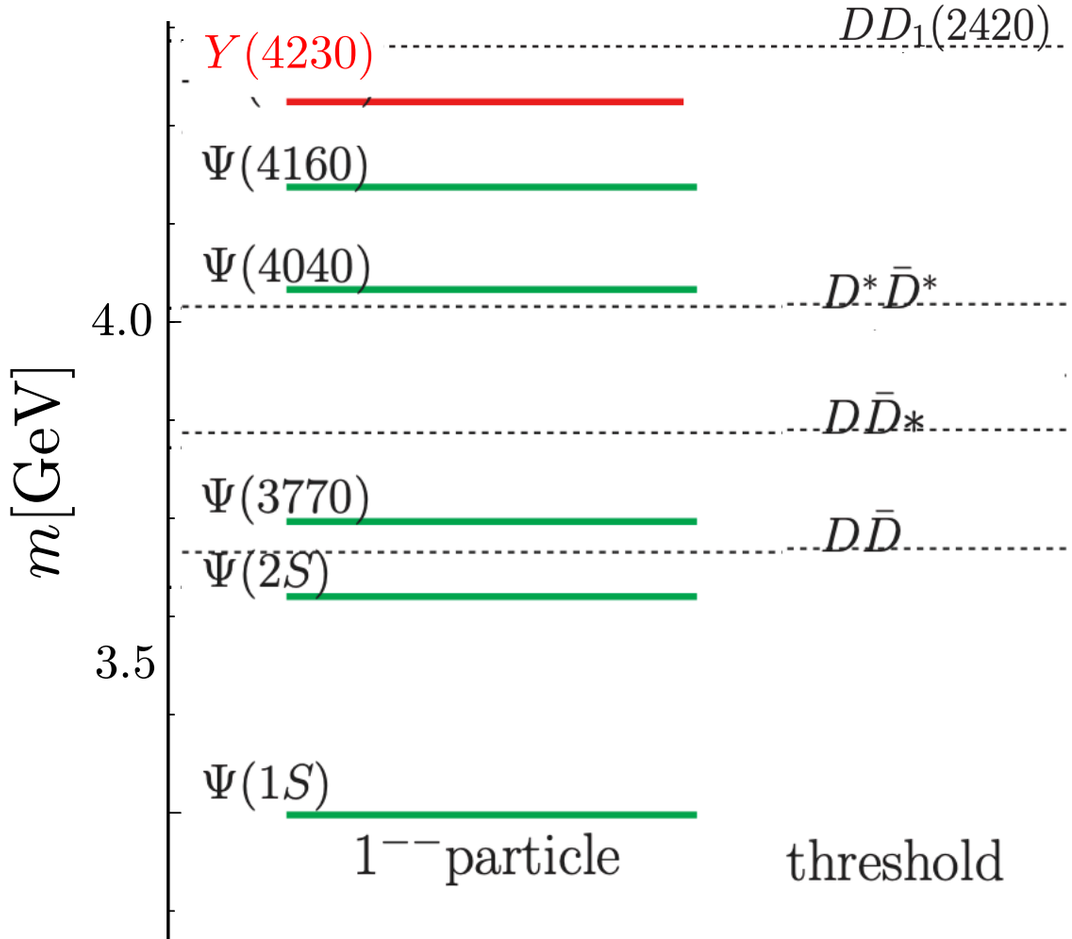

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- Lattice Potential + pNRQCD energy consistent (arxiv:1510.04299)

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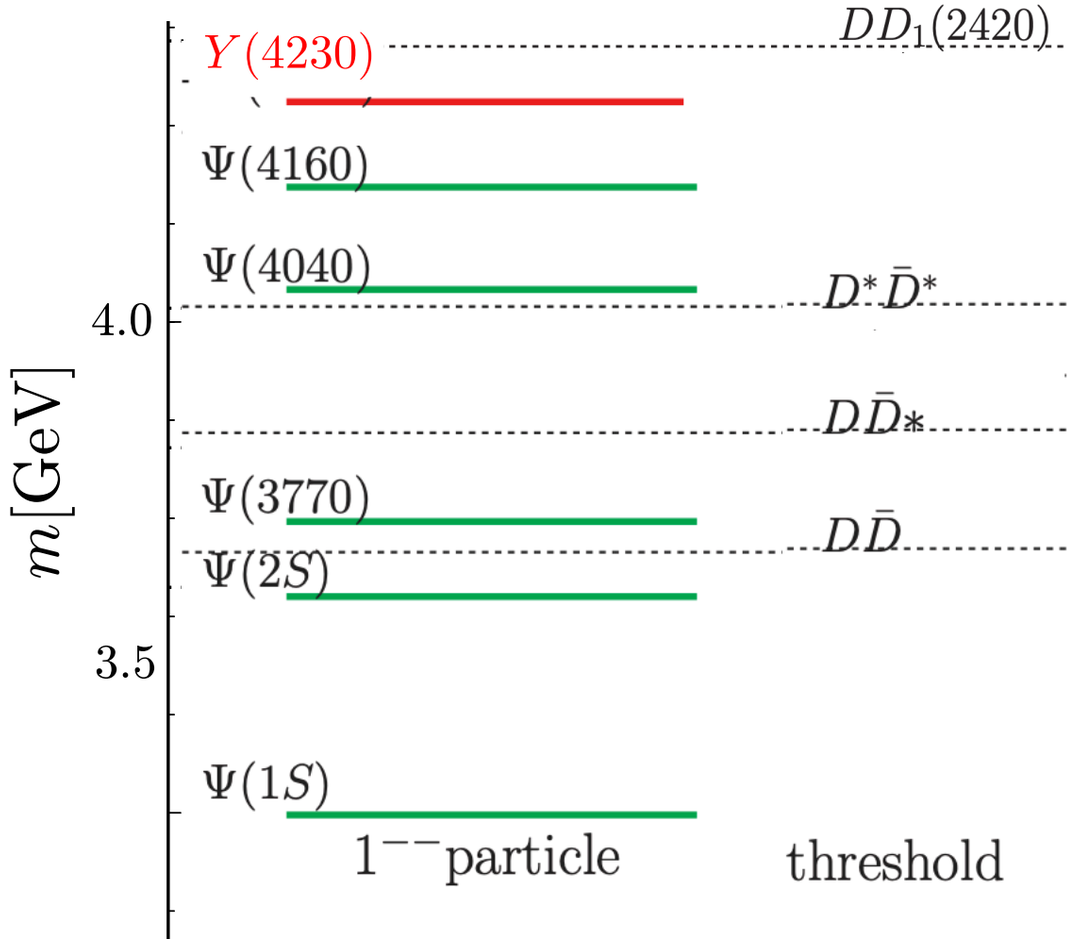

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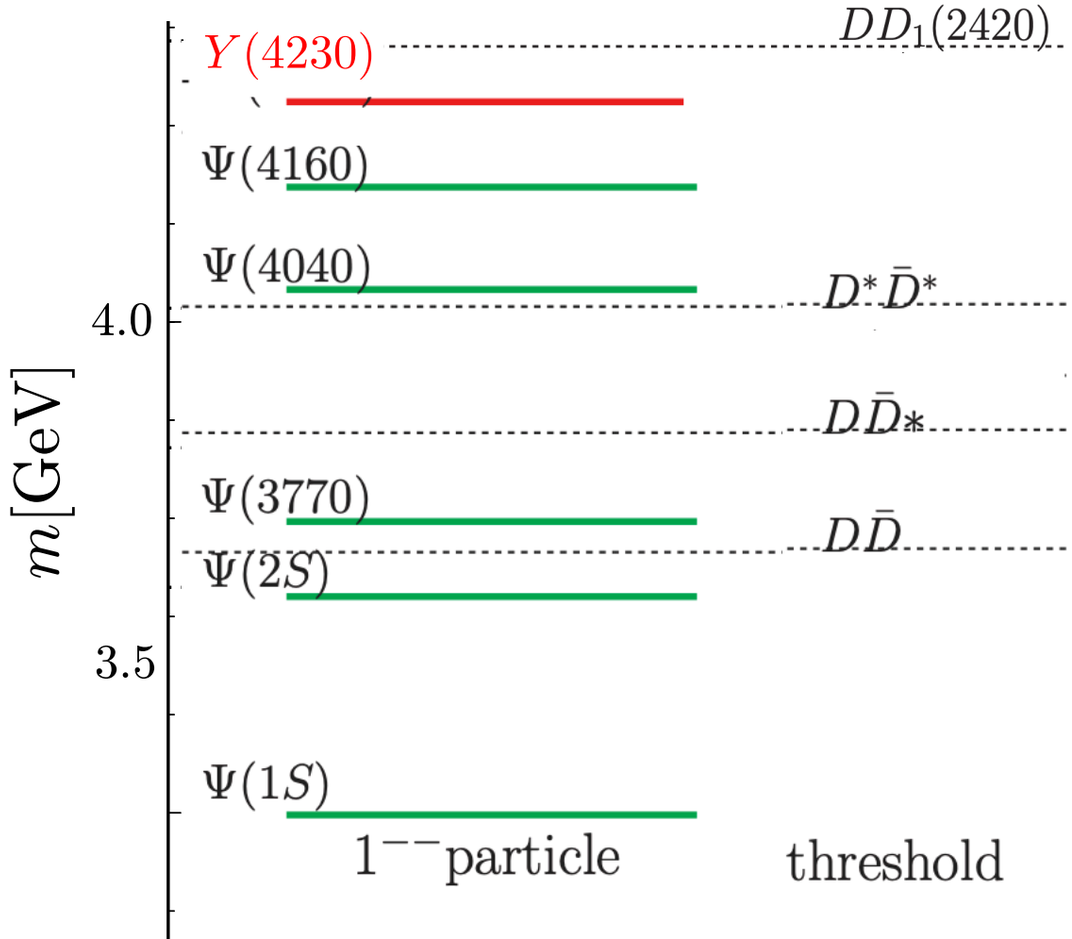

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- Decays to S-wave open charm forbidden (arxiv:0507119) => S-P mesons $D_1\bar{D}$ important
- Heavy quark spin symmetry less broken than in quarkonia: $\Lambda_{\rm QCD}/m_Q$

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Spatial Structure

- Molecular + Hybrid most probable

$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

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- Hydrocharmonium proposed (arxiv:1309.1681)

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- Compact Tetraquarks proposed (arxiv:1405.1551)

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Pole Structure: Bound State (if molecular)

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Spatial Structure

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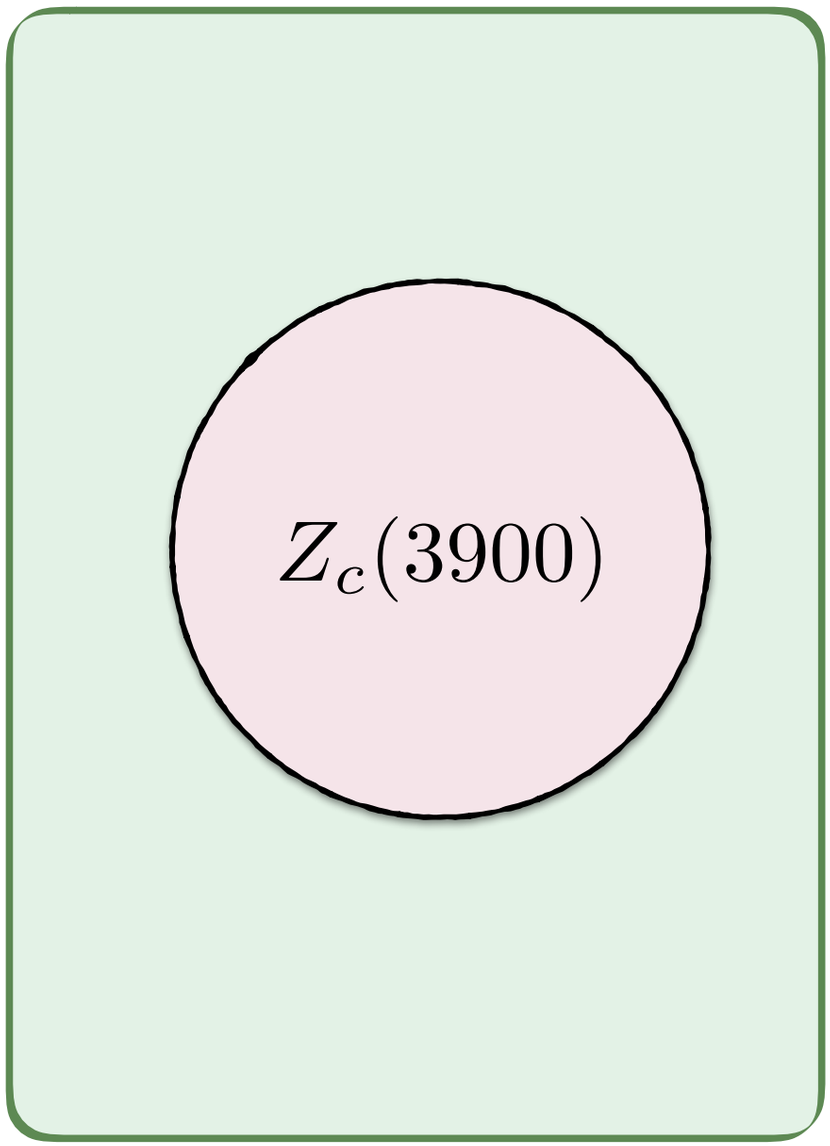
Pole Structure: Bound State (if molecular)

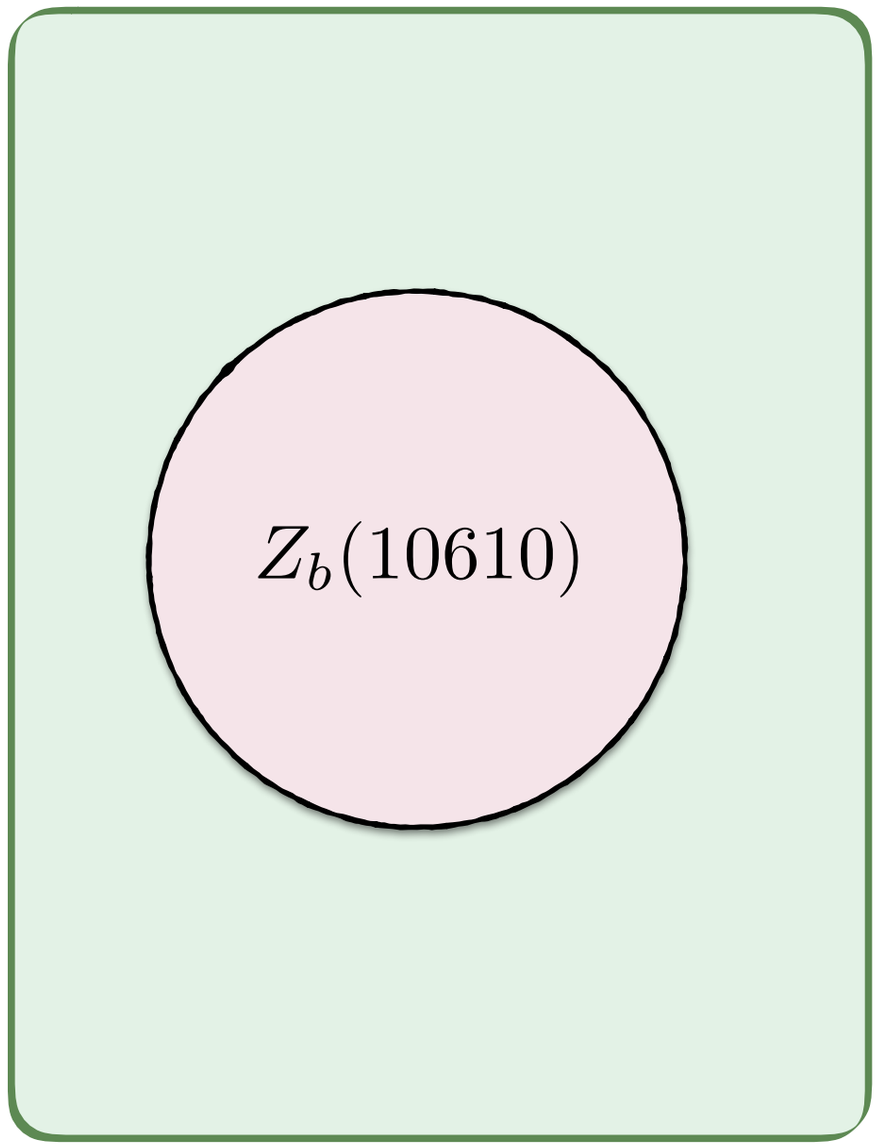
Leptonic Width to Distinguish Measurements $\Gamma_{e^+e^-}[Y(4230)] > 29.1 \pm 7.4$ eV

- Molecular: ~500 eV
- Hybrid : ~40 eV

arxiv:1907.07583

$Z_c(3900)$ and $Z_b(10610)$





$Z_c(3900)$ and $Z_b(10610)$

- Quantum Numbers

  $Q = \pm, 0$ $\qquad$ $I^G = 1^+$ $\qquad$ $J^{PC} = 1^{+-}$

$Z_c(3900)$ and $Z_b(10610)$

- Quantum Numbers

  $Q = \pm, 0$

$I^G = 1^+$

$J^{PC} = 1^{+-}$

Has Isospin charge
=> cannot be quarkonia

$Z_c(3900)$ and $Z_b(10610)$

- Quantum Numbers

  $Q = \pm, 0$ $\qquad I^G = 1^+$ $\qquad J^{PC} = 1^{+-}$

- Notable Decays
  - $Z_b(10610)$: $\quad \mathcal{B}((B\bar{B}^*)^+) = 86\%,\quad \mathcal{B}(\Upsilon(nS)\pi^+) \sim 3\%$

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Annihilation Effects Suppressed = minimal valence components

$\bar{Q}Q\bar{q}q$

$Z_c(3900)$ and $Z_b(10610)$

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- Lattice QCD Studies
  - $Z_b(10610)$ (arxiv:1912.02656)
    - Extracted potential between B and B^* (assuming eigenstate exclusively BB^*)
    - Sizable attraction for small r
    - Virtual State found for certain parameterizations of extracted potential

$Z_c(3900)$ and $Z_b(10610)$

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- $M_{Z_c} = 3888.4 \pm 2.5$ MeV $\quad \Gamma_{Z_c} = 28.3 \pm 2.5$ MeV $\quad \delta = M_{D\bar{D}^*} - M_{Z_c} = 13$ MeV

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- Lattice QCD Studies
  - $Z_c(3900)$: (arxiv:1907.07583)
    - Lattice includes diquark and two meson operators but does not find a bound state or narrow resonance

$Z_c(3900)$ and $Z_b(10610)$

- Quantum Numbers

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  - $Z_c(3900)$: $\quad \mathcal{B}((D\bar{D}^*)^\pm)\ /\ \mathcal{B}(J/\psi\pi^\pm) = 6.2$

- $M_{Z_b} = 10607.2 \pm 2.0$ MeV $\quad \Gamma_{Z_b} = 18.4 \pm 2.4$ MeV $\quad \delta = M_{B\bar{B}^*} - M_{Z_b} = 3(3)$ MeV
- $M_{Z_c} = 3888.4 \pm 2.5$ MeV $\quad \Gamma_{Z_c} = 28.3 \pm 2.5$ MeV $\quad \delta = M_{D\bar{D}^*} - M_{Z_c} = 13$ MeV

- Lattice QCD Studies
  - $Z_c(3900)$: (arxiv:1907.07583)
    - Lattice includes diquark and two meson operators but does not find a bound state or narrow resonance
    - arxiv:1606.03008: consistent with both resonance and virtual states
      => Lattice studies done at multiple volumes can distinguish these cases

$Z_c(3900)$ and $Z_b(10610)$

- Quantum Numbers

  $Q = \pm, 0$ $\qquad I^G = 1^+ \qquad J^{PC} = 1^{+-}$

- Pole Structure:
  - $Z_b(10610)$ (arxiv:1805.07453): virtual state ~1 MeV below threshold

$Z_c(3900)$ and $Z_b(10610)$

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  - $Z_c(3900)$ (arxiv:1512.03638): virtual state or resonance

$Z_c(3900)$ and $Z_b(10610)$

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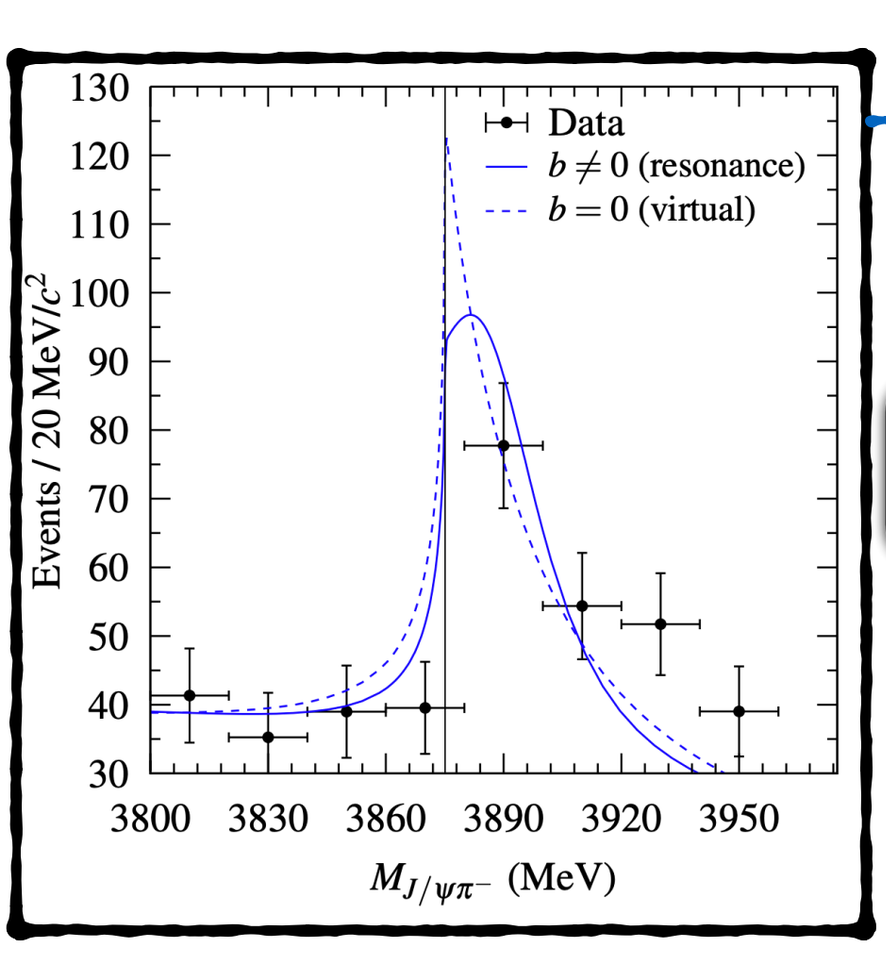


Smaller bin sizes and good energy resolution needed to distinguish

$Z_c(3900)$ and $Z_b(10610)$

- Quantum Numbers

  $Q = \pm, 0$ $\qquad I^G = 1^+ \qquad J^{PC} = 1^{+-}$

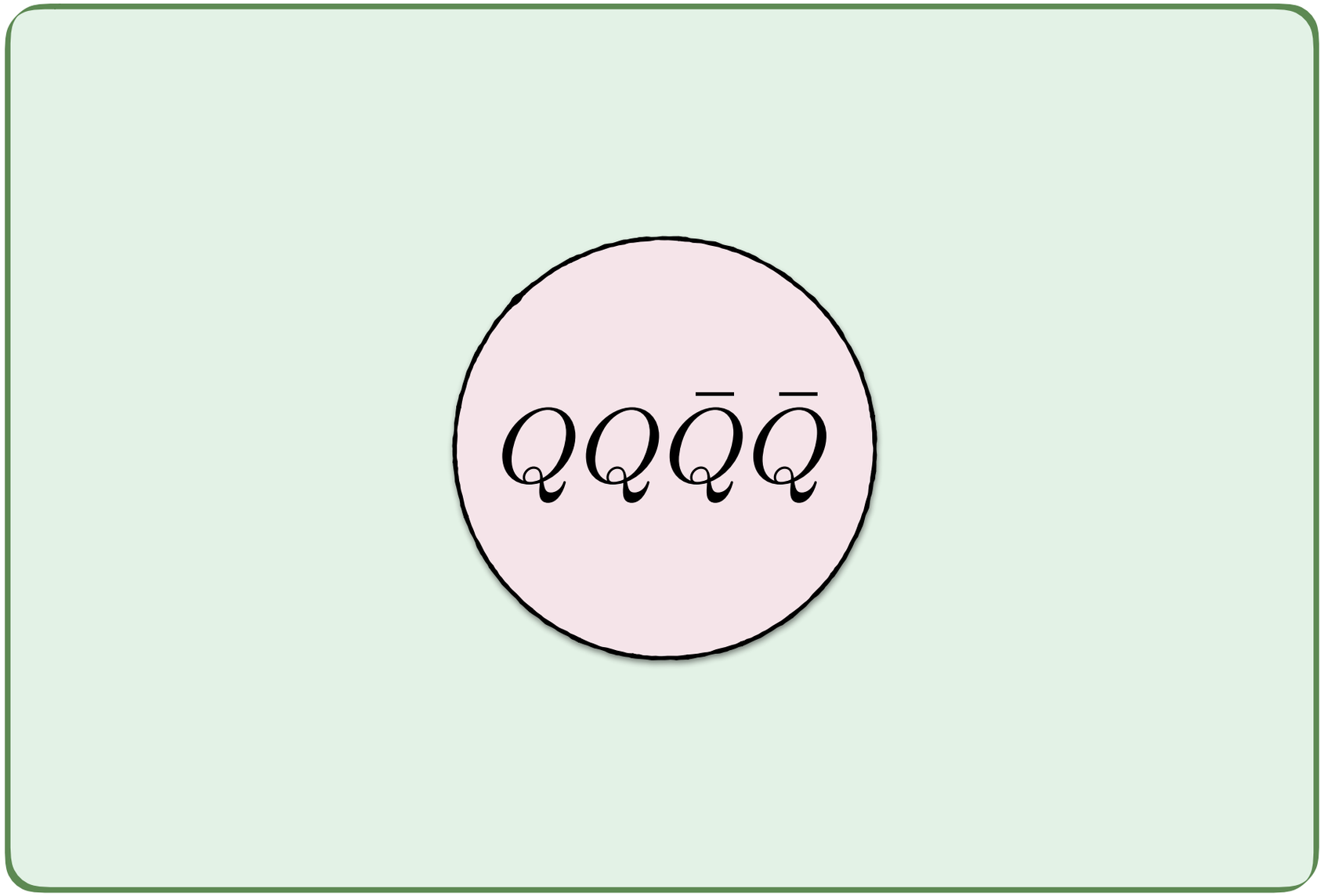
- Pole Structure:
  - $Z_b(10610)$ (arxiv:1805.07453): virtual state ~1 MeV below threshold
  - $Z_c(3900)$ (arxiv:1512.03638): virtual state or resonance

- Spatial Structure
  - (Multi) Molecular
  - (arxiv:1808.00914) $\pi J/\psi(\rho\eta_c) - D\bar{D}^*$ mixing just as important as diagonal parts of potential for $Z_c(3900)$

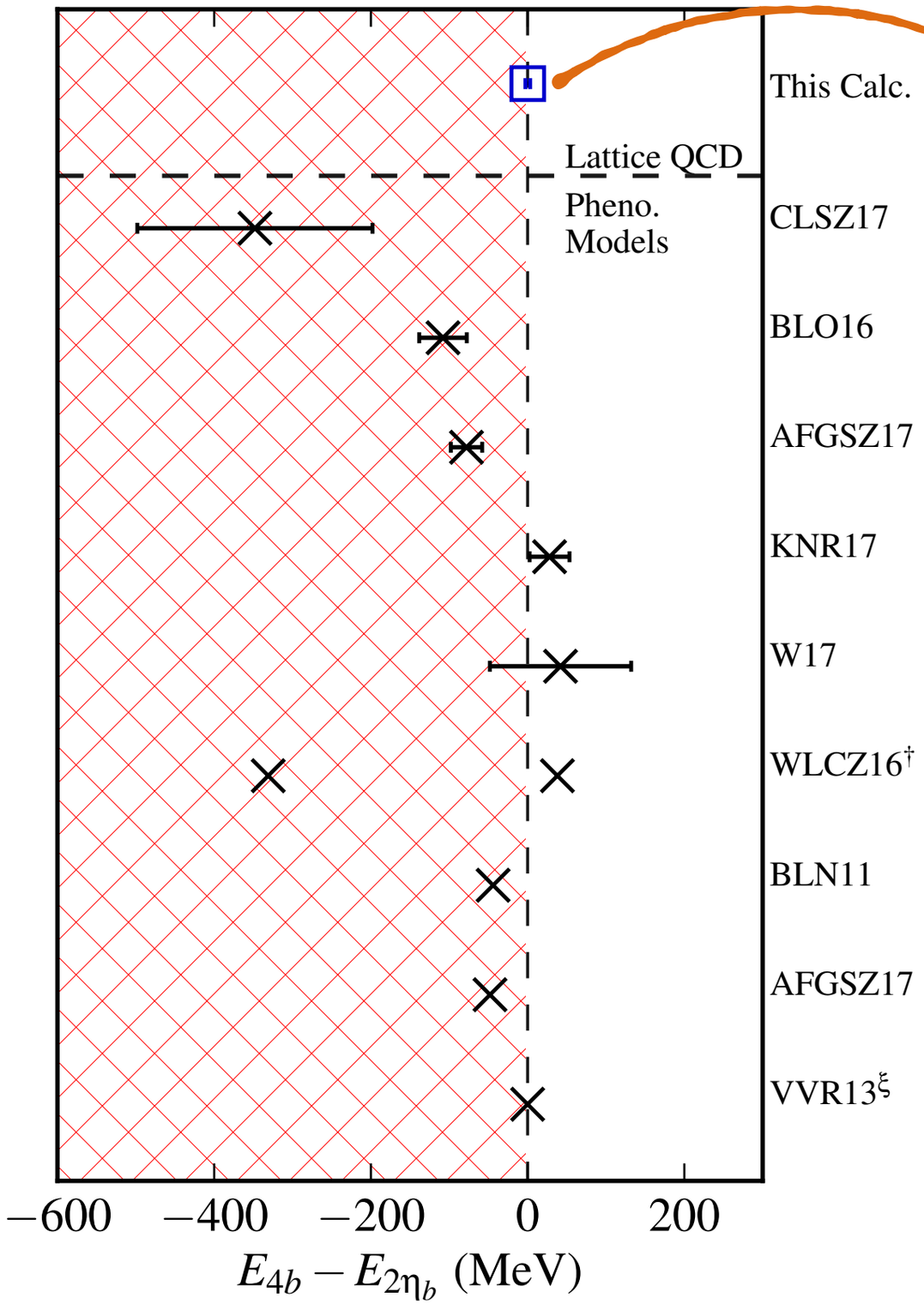
Other States I Won't Discuss

- $Z_b(10650)$ the B^*B^* partner to $Z_b(10610)$
- $Z_c(4020)$ the D^*D^* partner to $Z_c(3900)$
- X_b partner to $X(3872)$ not seen as $h_b(2P)$ below open threshold
- Pentaquarks P_c molecule of $\bar{c}c$ and p
- Exotic Flavour $cs\bar{u}\bar{d}$: HadSpec $D\bar{K}$, $I = 0$, $J^P = 0^+$ (arxiv:2008.06432)
  compared to X(2900) LHCb prelim results
- $\bar{b}b+$ Spectrum from HadSpec (arxiv:2008.02656)

- More experimental data needed to nullify models for
  - *Y(4360)* ($D_1 D^*$ partner of *Y(4230)?)*
  - *Y(4660)* ($D_s D_{s1}$ strange partner of *Y(4230)*)?
  - *Z(4430)*

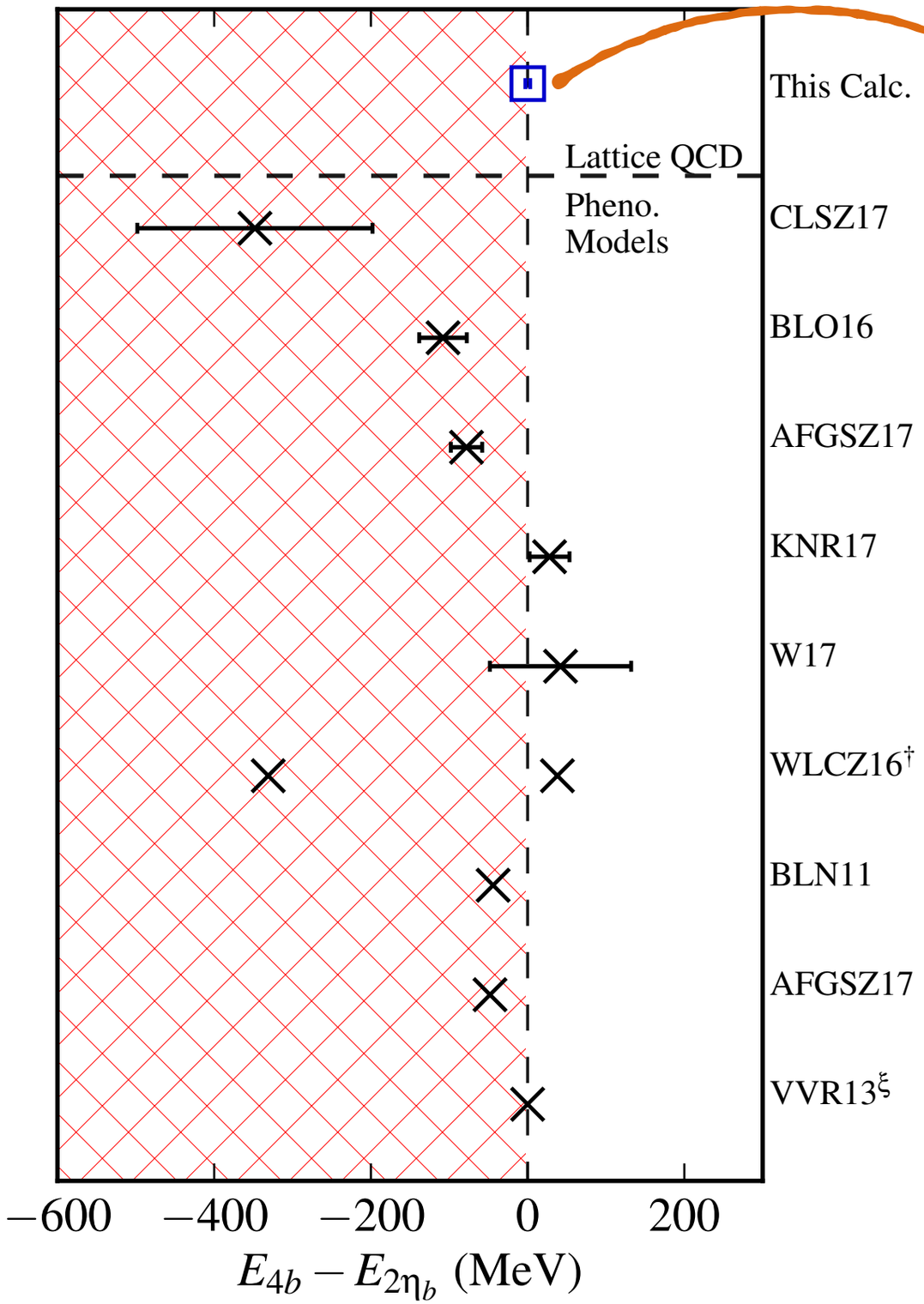

$QQ\bar{Q}\bar{Q}$

$\bar{b}\bar{b}bb$ S-wave Bound State Doesn't exist arxiv:1710.03236



No evidence of 0^{++} ***below*** $2\eta_b$ ***threshold***

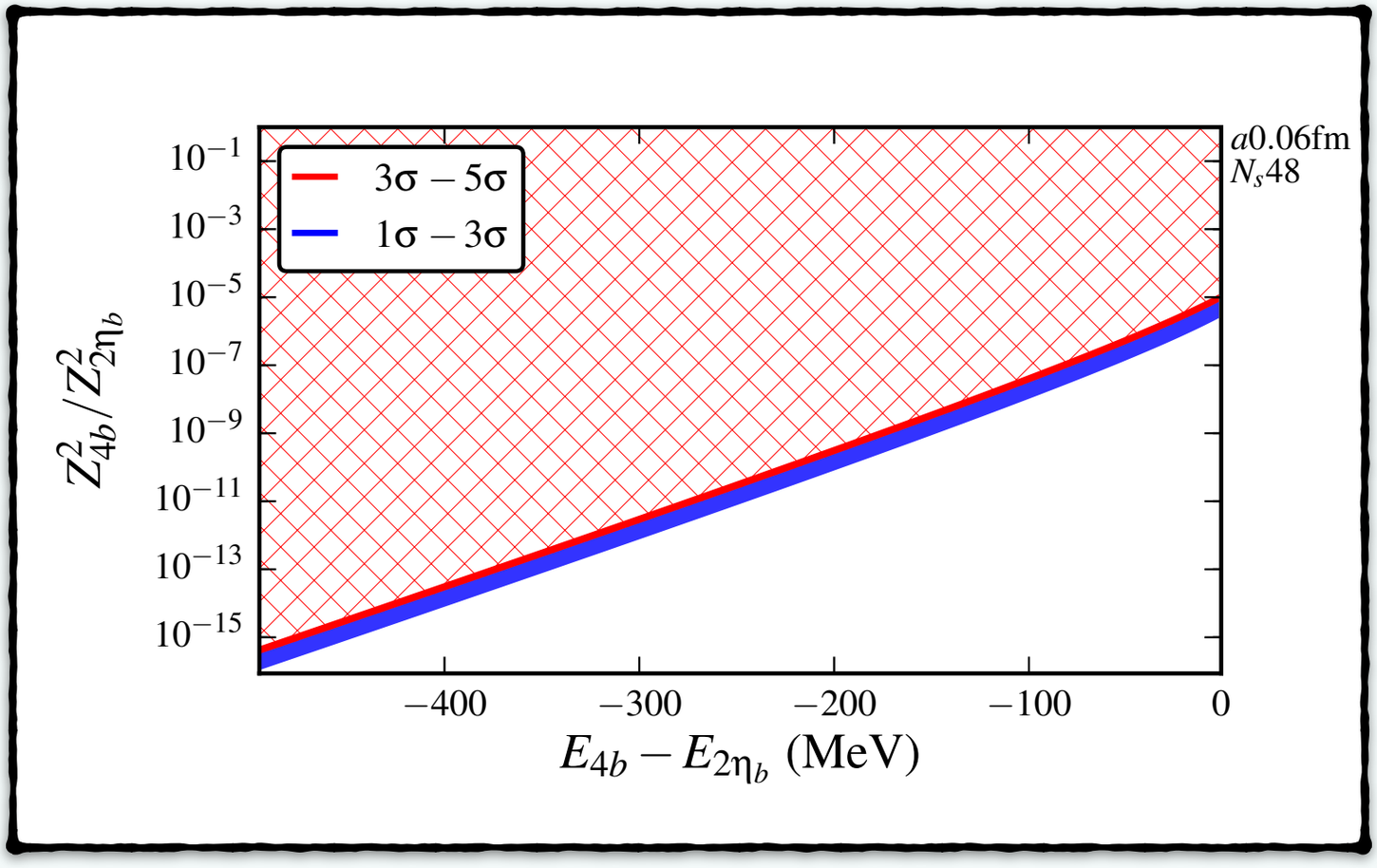
$\bar{b}\bar{b}bb$ S-wave Bound State Doesn't exist arxiv:1710.03236



No evidence of 0^{++} ***below*** $2\eta_b$ ***threshold***

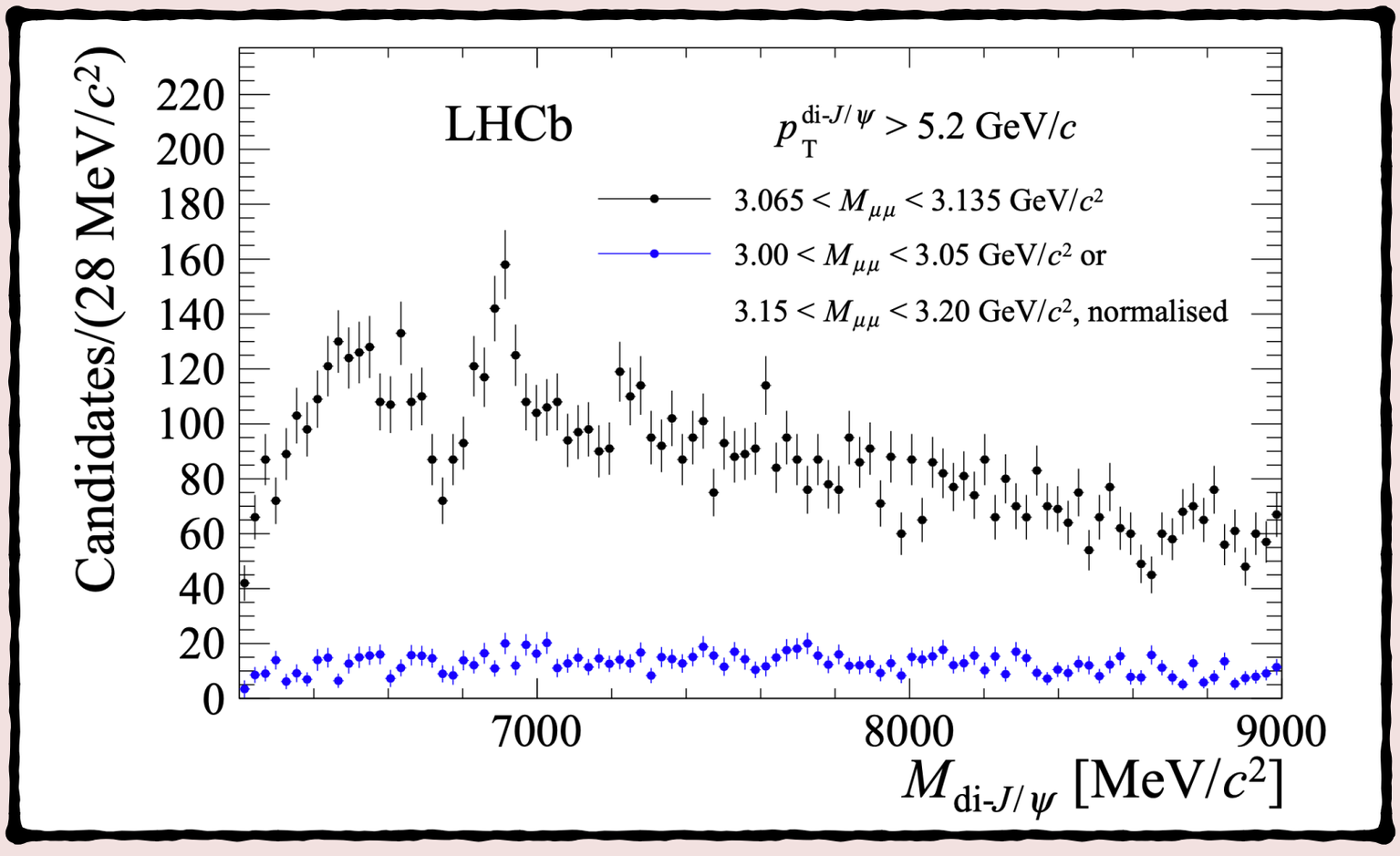
If you don't observe a process, need to determine a bound, e.g, proton decay.

$\bar{b}\bar{b}bb$ S-wave Bound State Doesn't exist arxiv:1710.03236



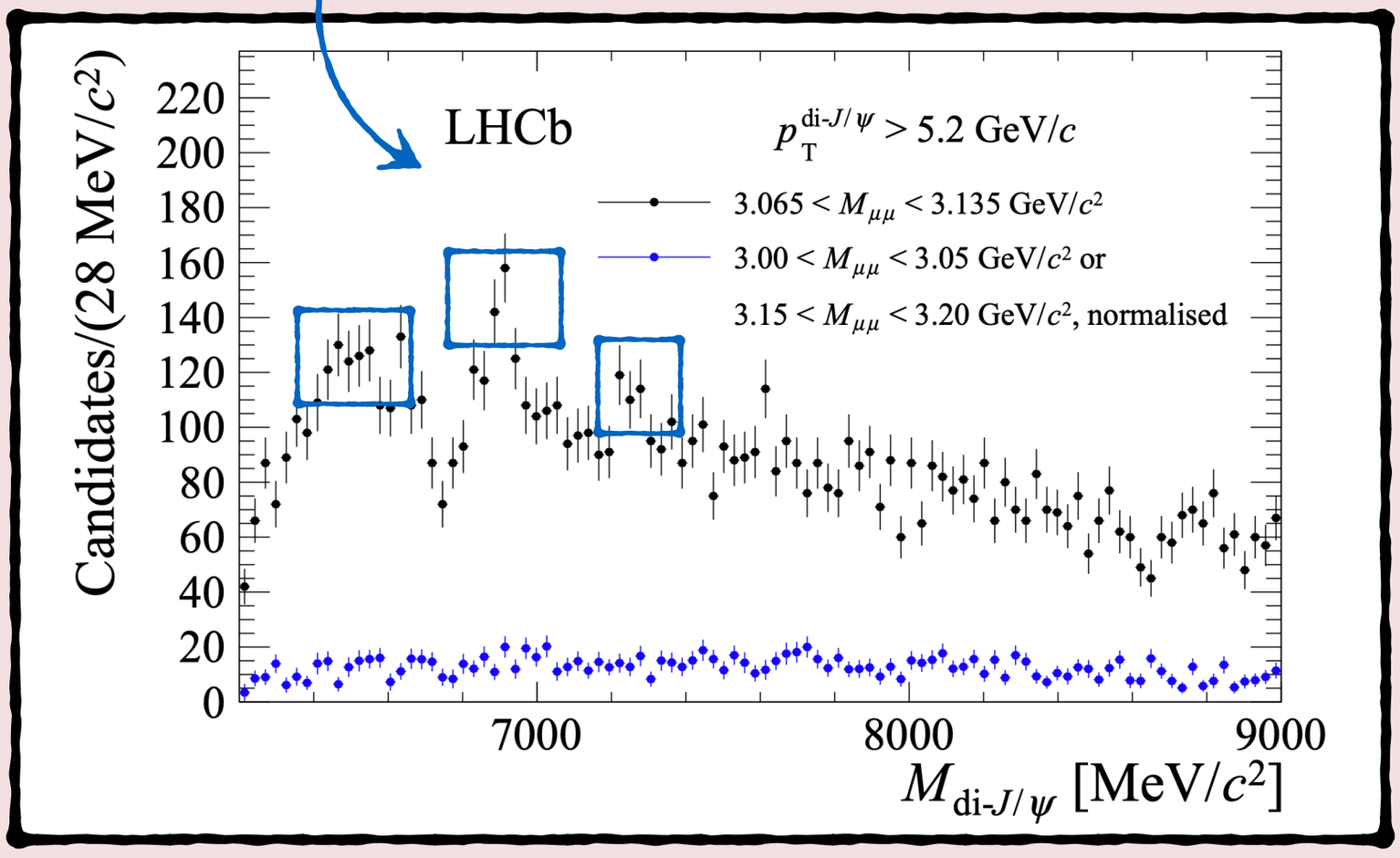
What is the probability we missed the bound state?

$\overline{c}\overline{c}cc$ - X(6900) arxiv: 2006.16957



$\overline{c}\overline{c}cc$ - X(6900) arxiv: 2006.16957

3 Possible Bumps



$\overline{c}\overline{c}cc$ - X(6900) arxiv: 2006.16957

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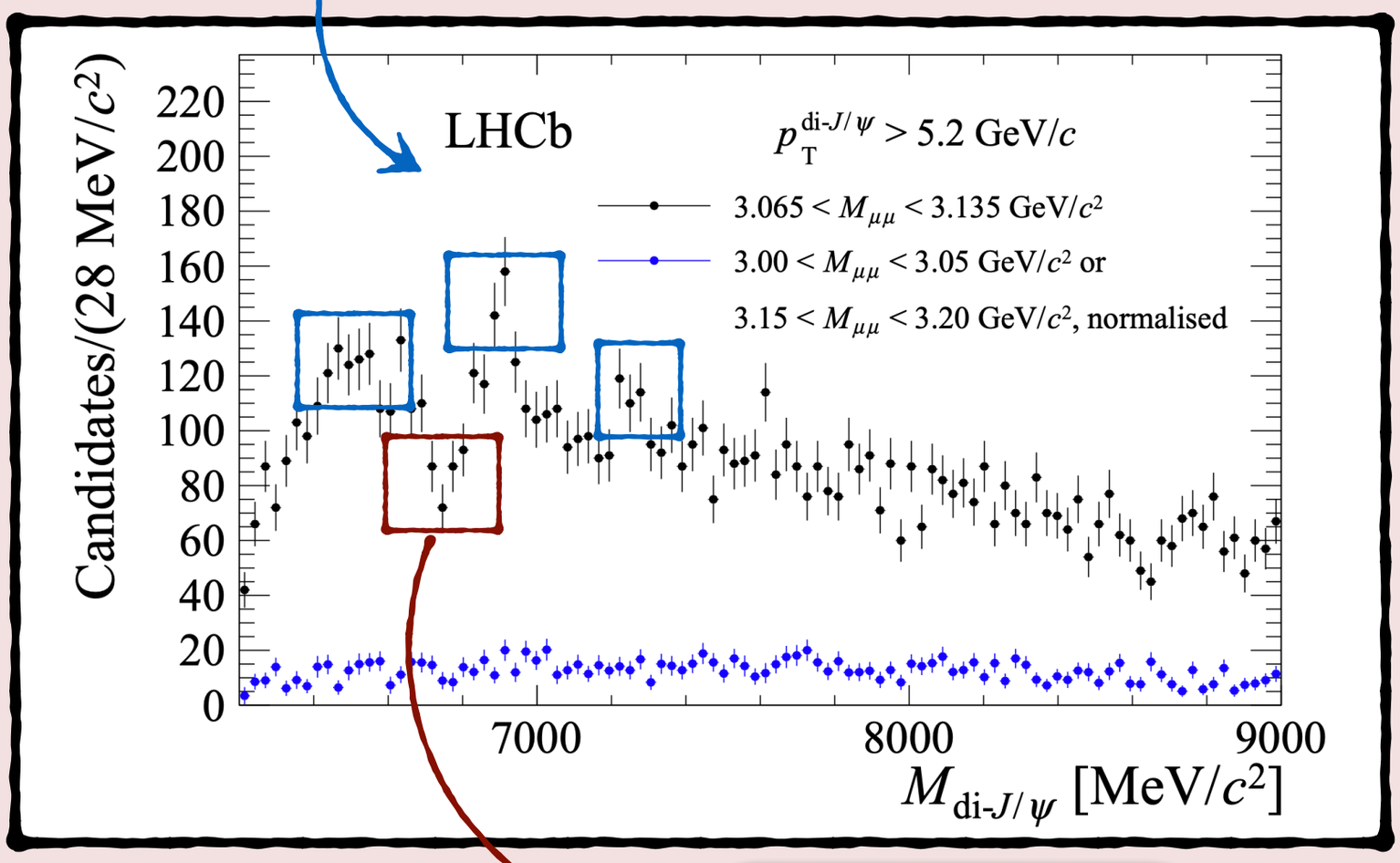
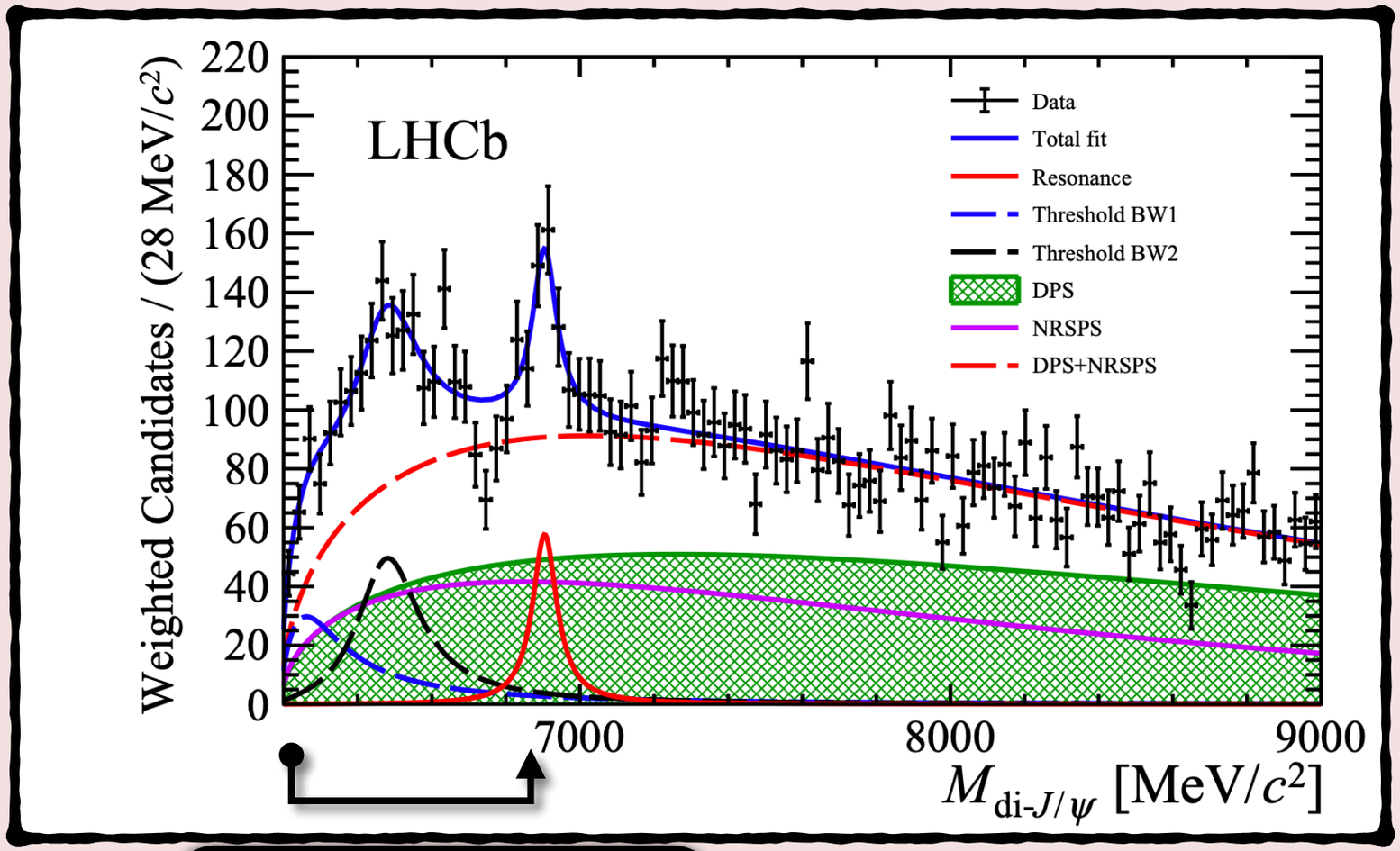


1 dip

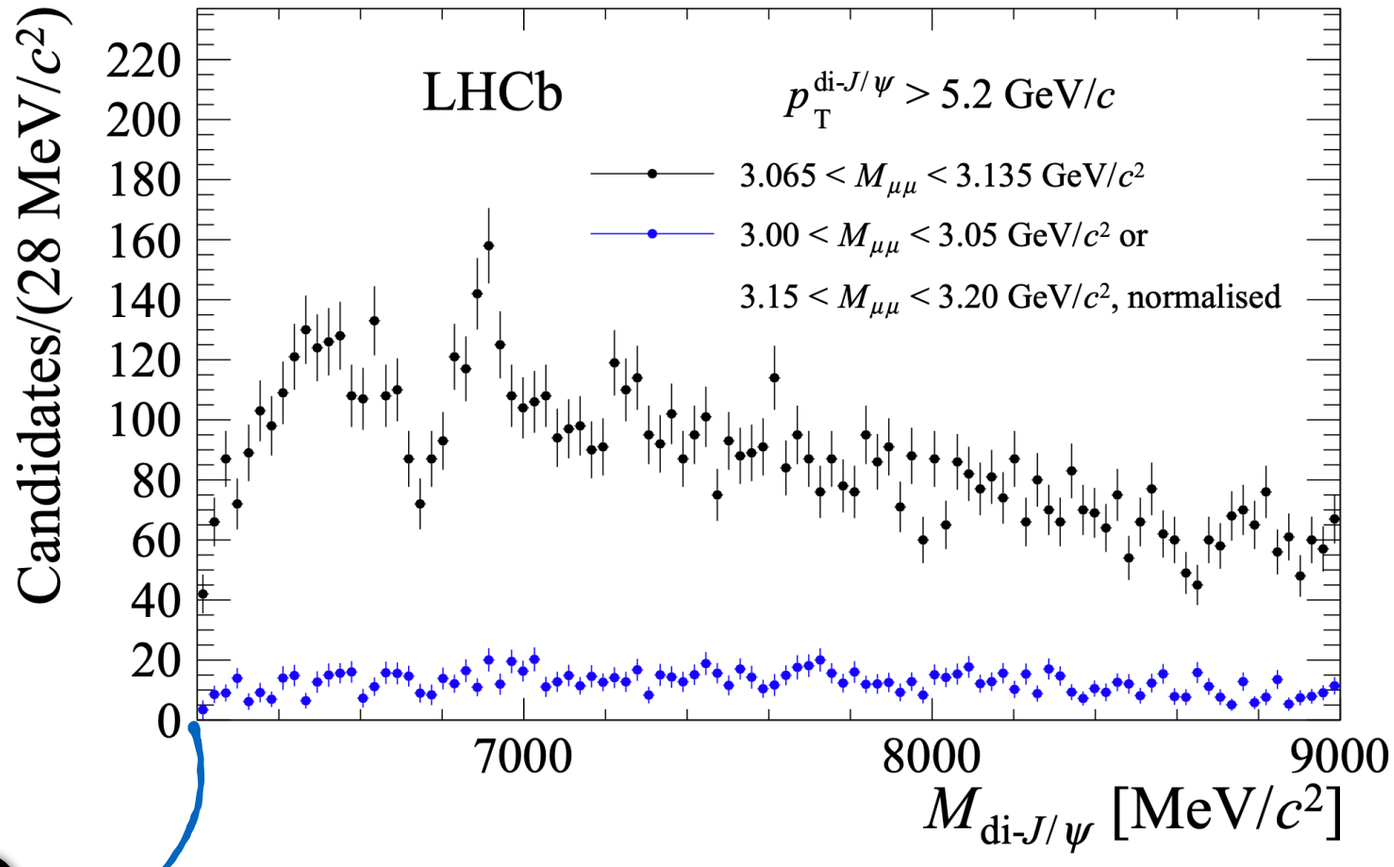
$\overline{c}\overline{c}cc$ - X(6900) arxiv: 2006.16957



700 MeV above $2J/\psi$

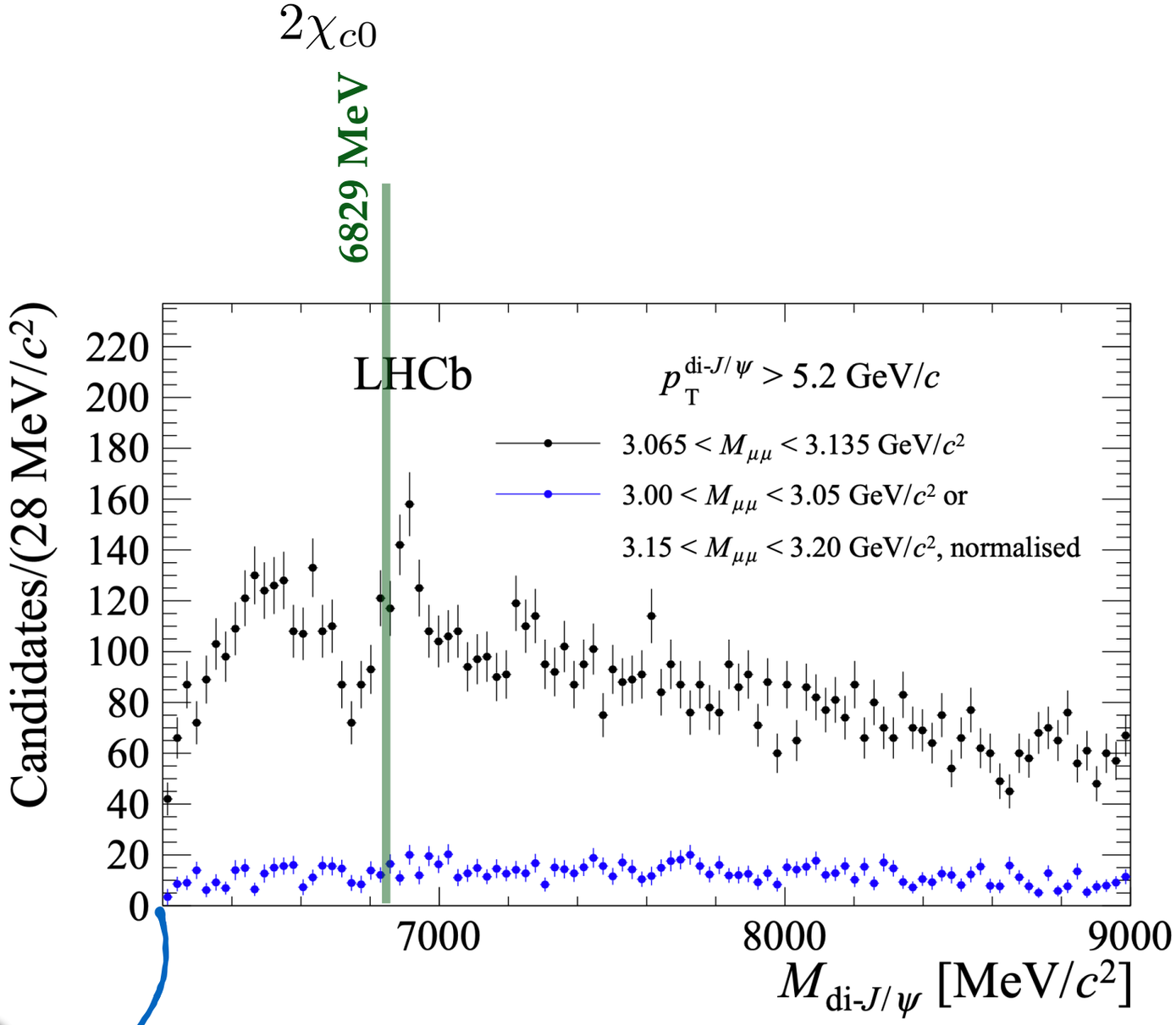
Only Viable Model = diquarks!!!!

$\overline{c}\overline{c}cc$ - X(6900) arxiv: 2006.16957



S-wave $2J/\psi$ *threshold*

$\overline{c}\overline{c}cc$ - X(6900) [arxiv: 2006.16957]



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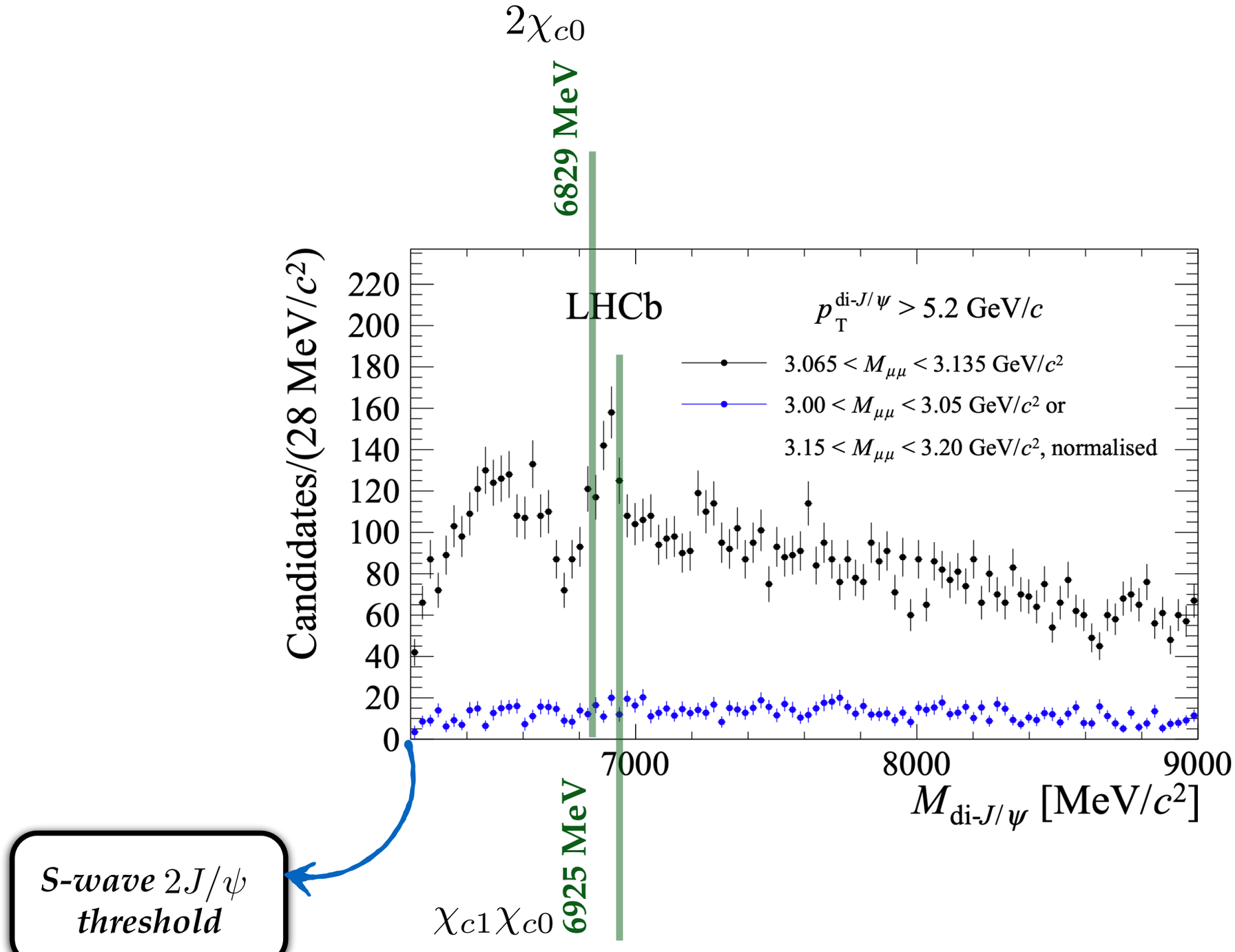
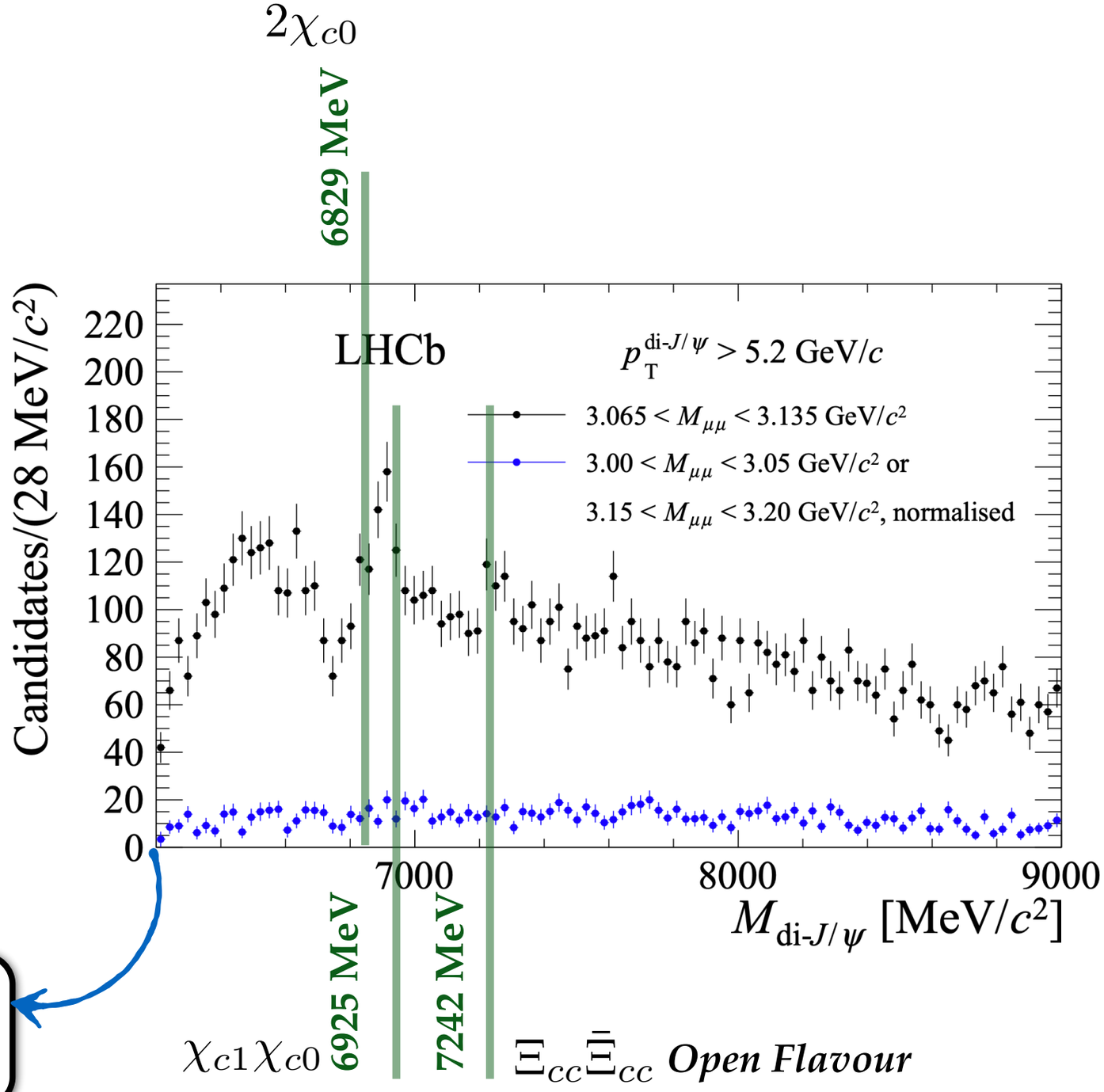


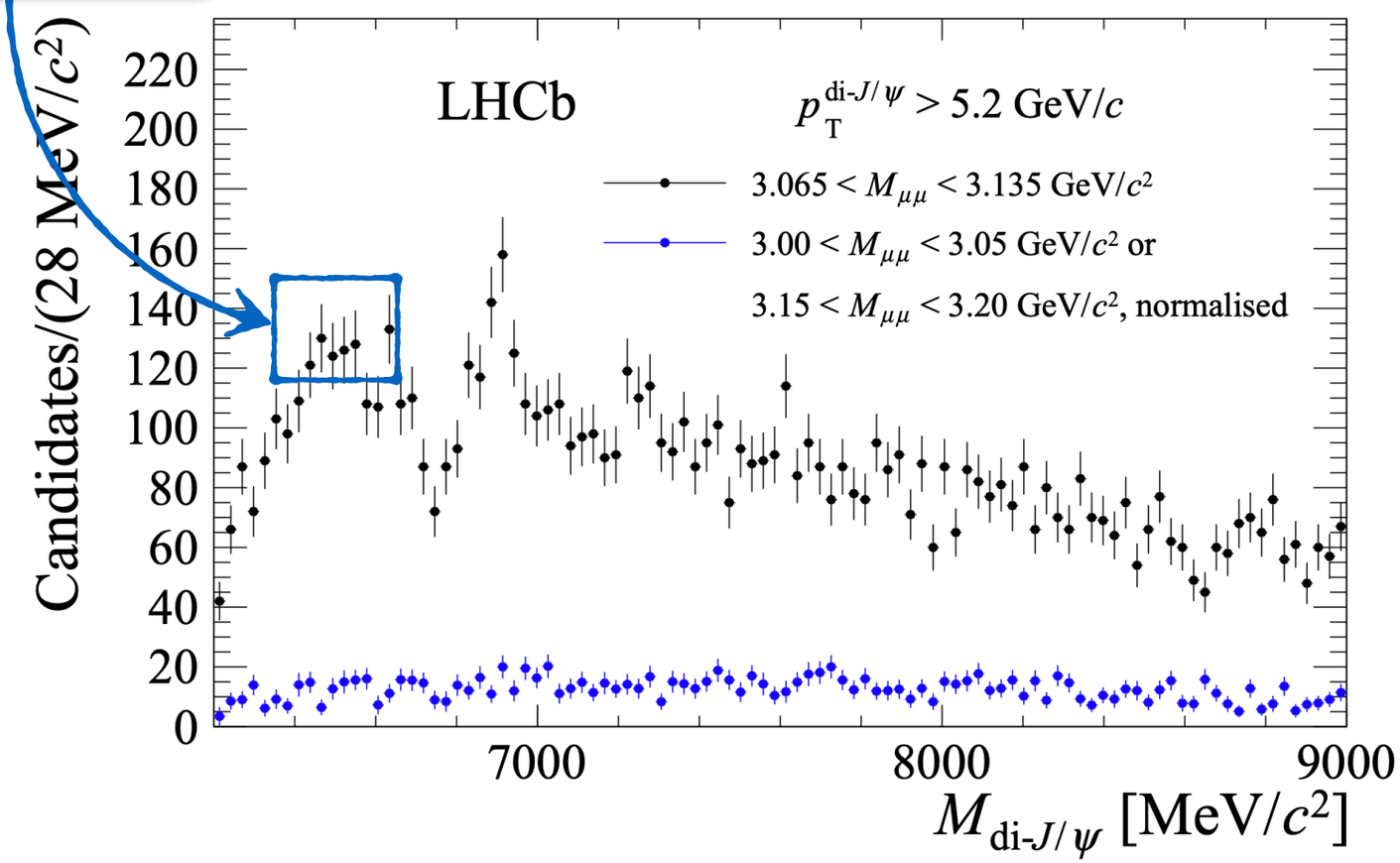
$\overline{c}\overline{c}cc$ - X(6900) arxiv: 2006.16957



$\bar{c}\bar{c}cc$ - X(6900) arxiv: 2006.16957

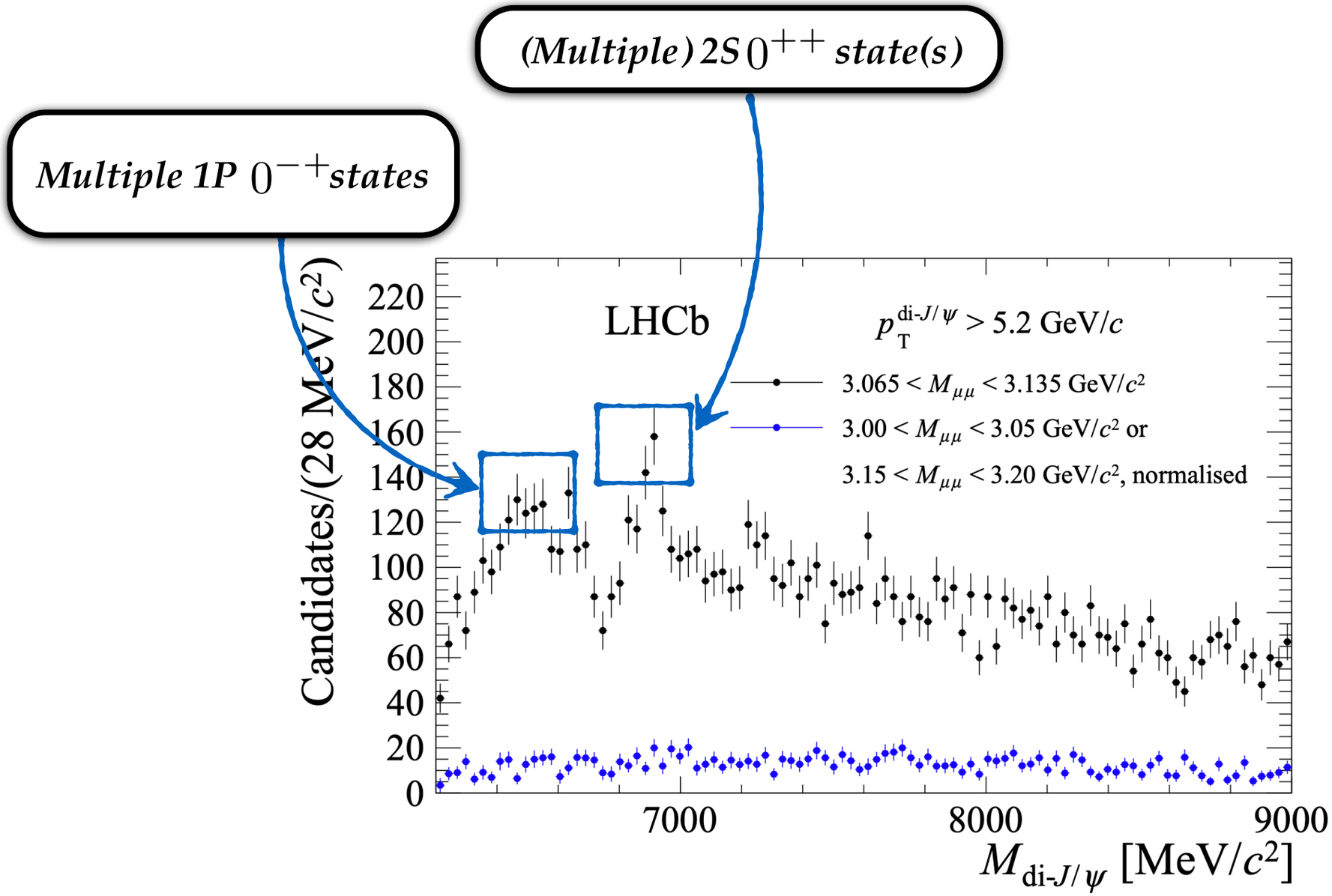
Dynamical Diquark Model arxiv:2008.01631

Multiple 1P 0^{-+}***states***



$\bar{c}\bar{c}cc$ - X(6900) arxiv: 2006.16957

- Dynamical Diquark Model arxiv:2008.01631



$\bar{c}\bar{c}cc$ - X(6900) arxiv: 2006.16957

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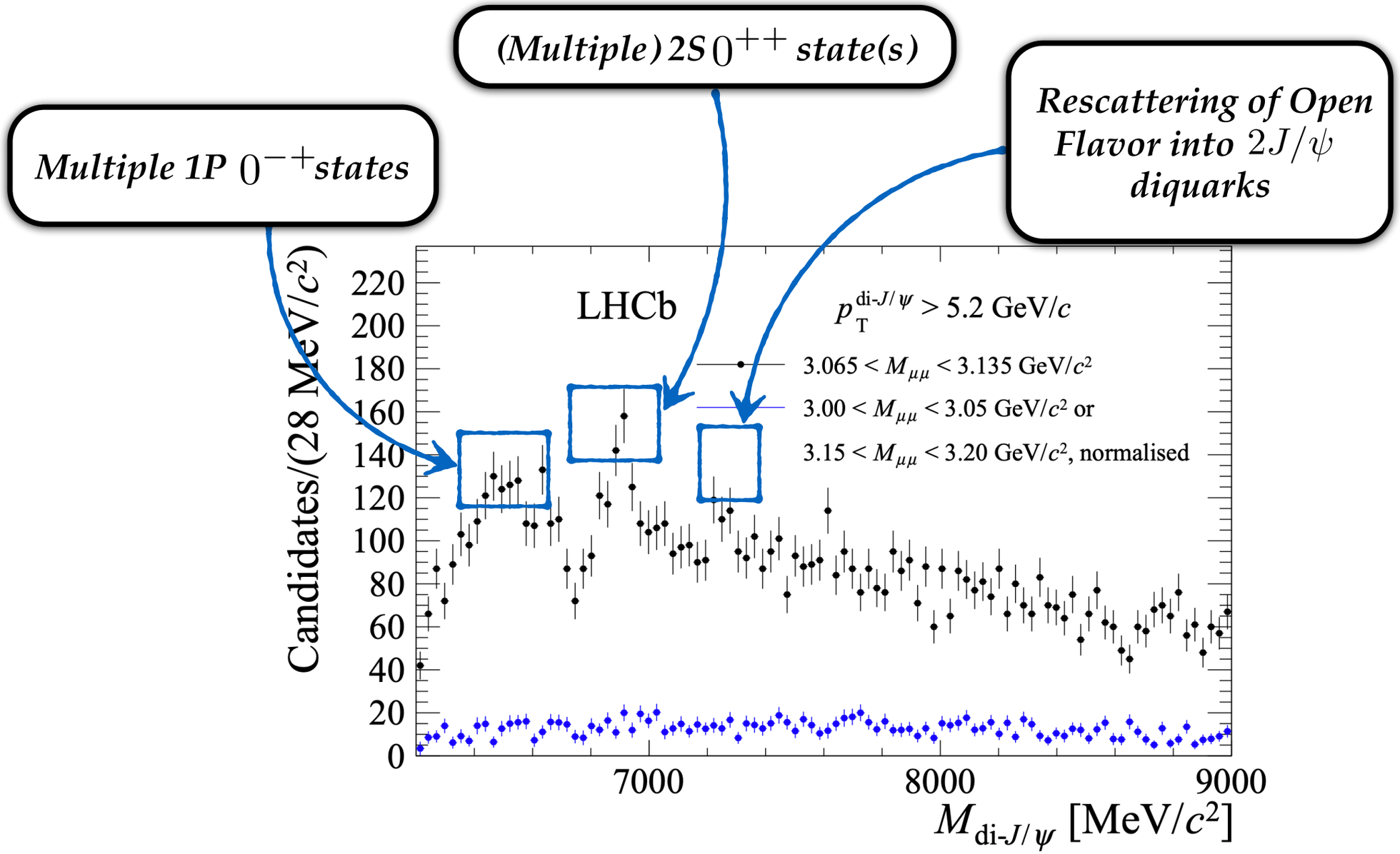
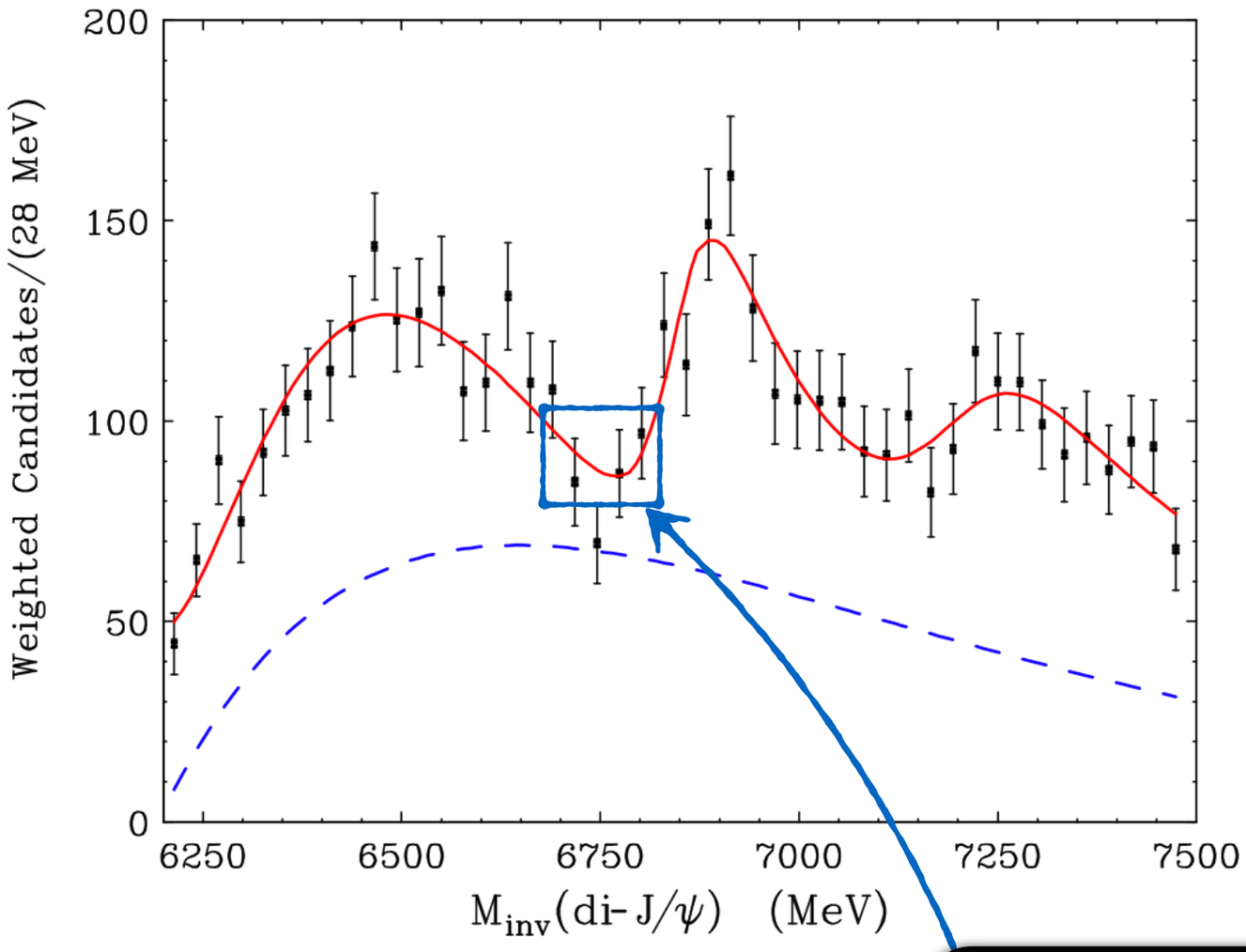


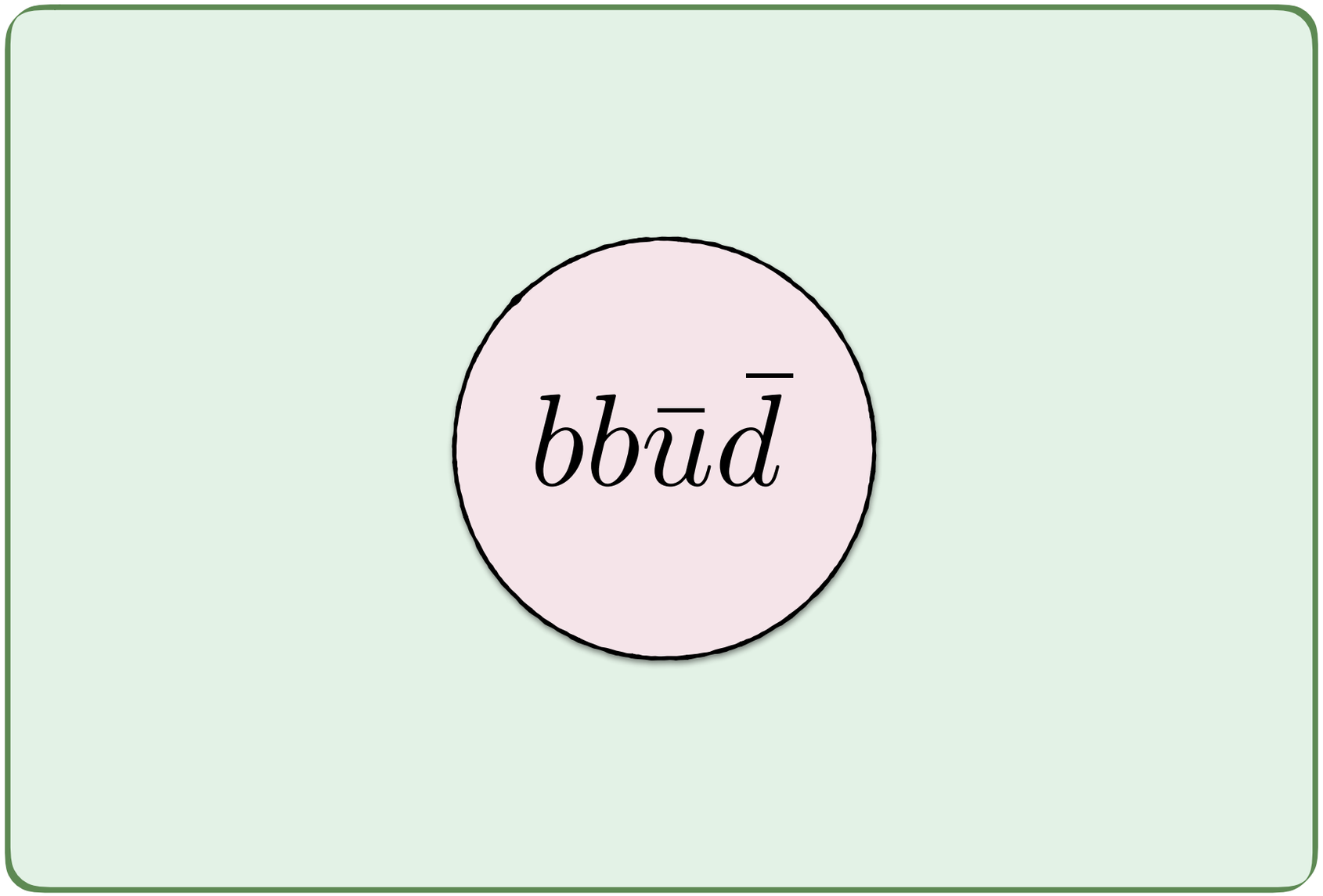
$\bar{c}\bar{c}cc$ - X(6900) arxiv: 2006.16957

- Pheno model arxiv:2009.4429



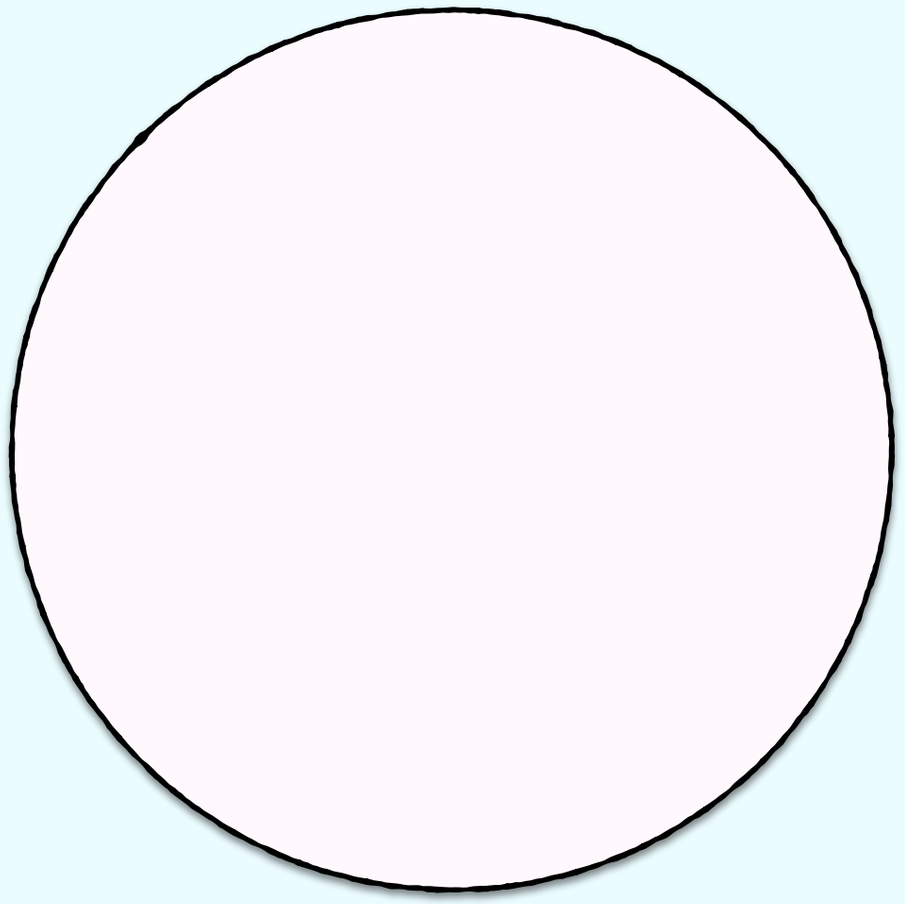
Dip due to Interference from $2\chi_{c0}$ threshold turning on

$bb\bar{u}\bar{d},\ I = 0,\ J^P = 1^+$ is bound



$bb\bar{u}\bar{d},\ I=0,\ J^P=1^+$ is bound

- Intuitive Understanding (arxiv:1707.09575)



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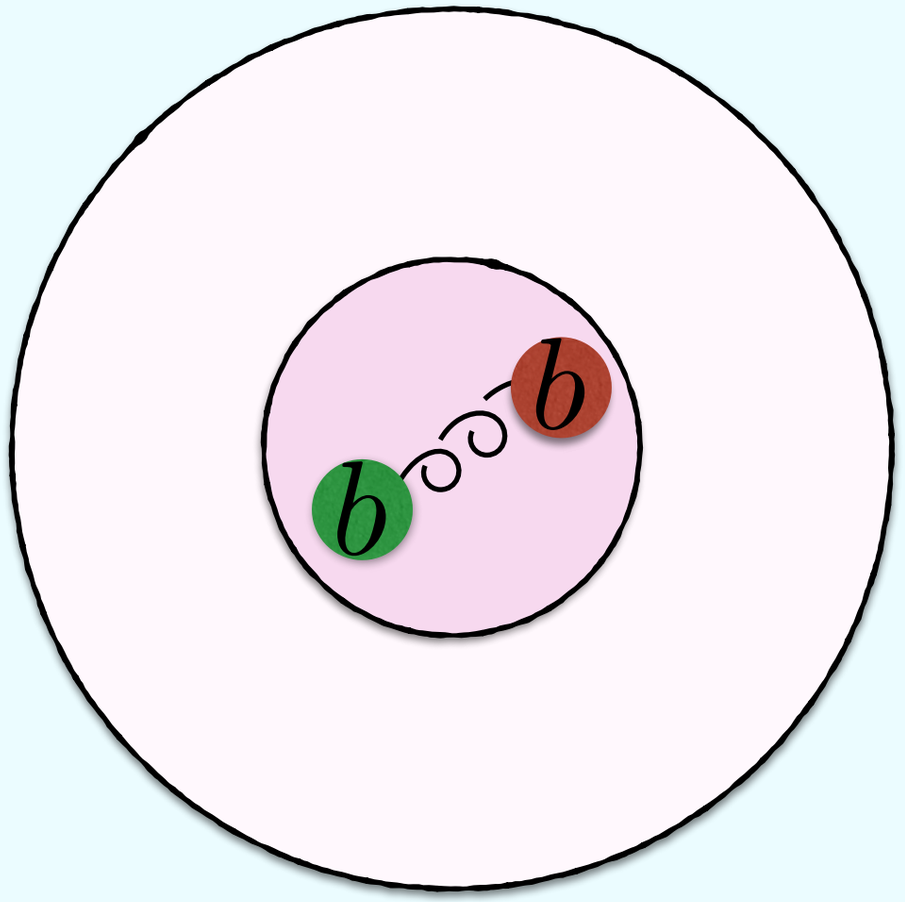

$bb\bar{u}\bar{d},\ I = 0,\ J^P = 1^+$ is bound

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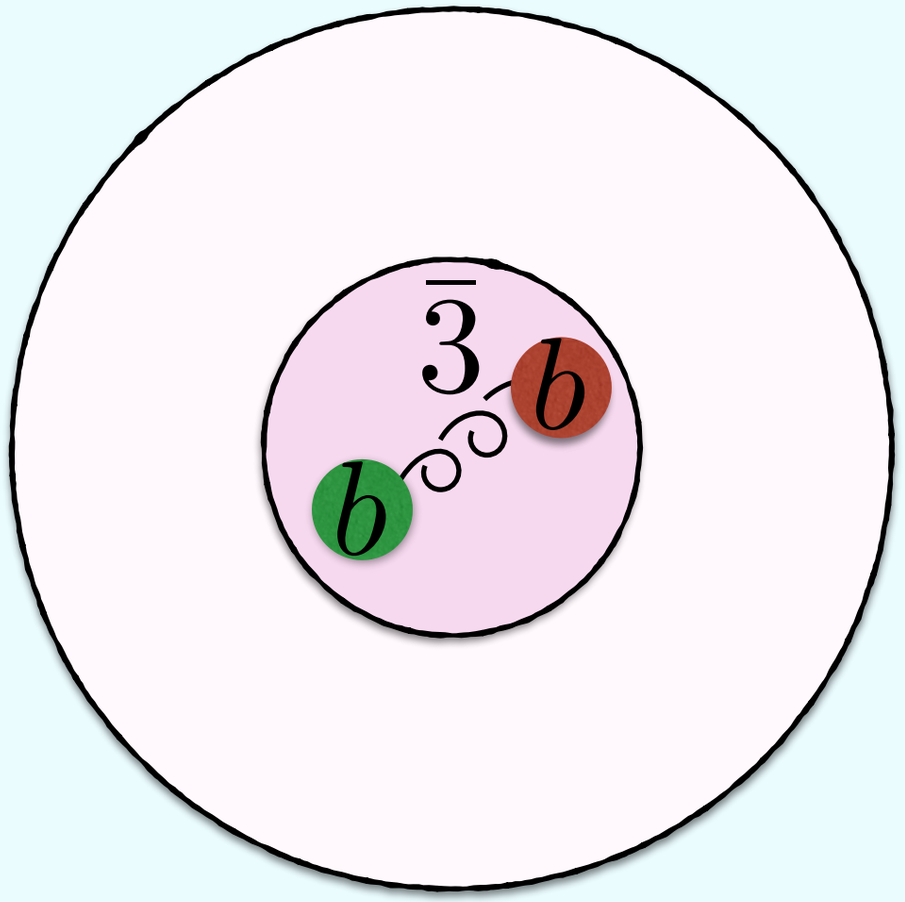

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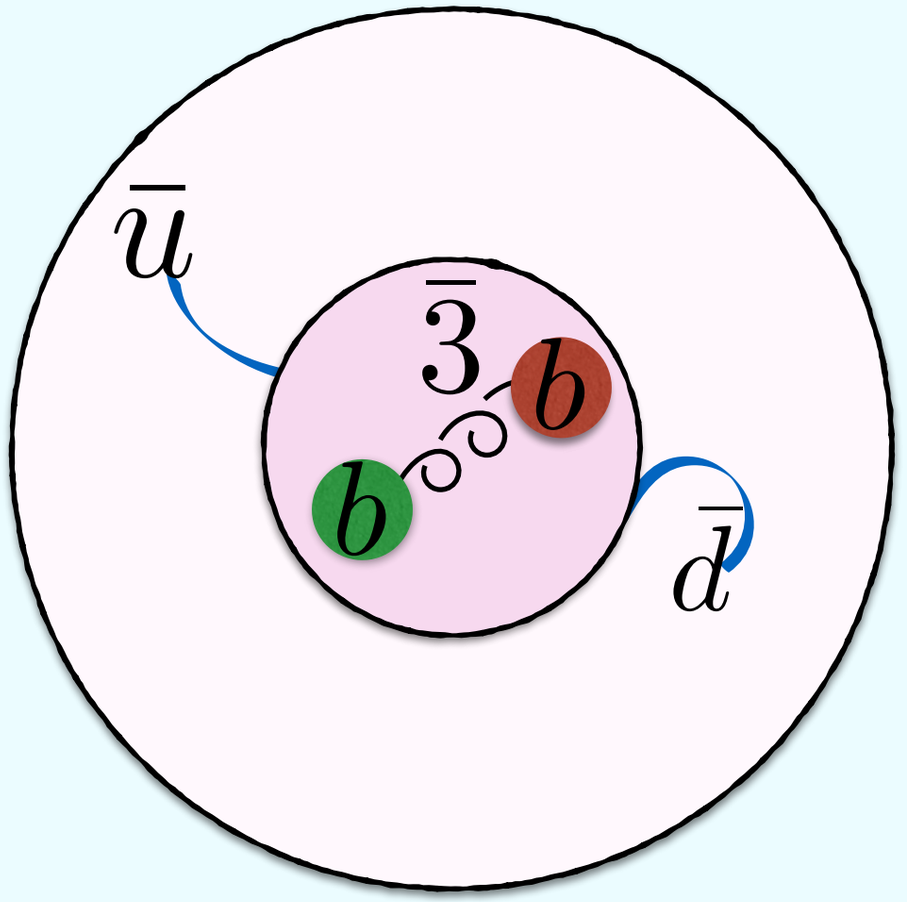

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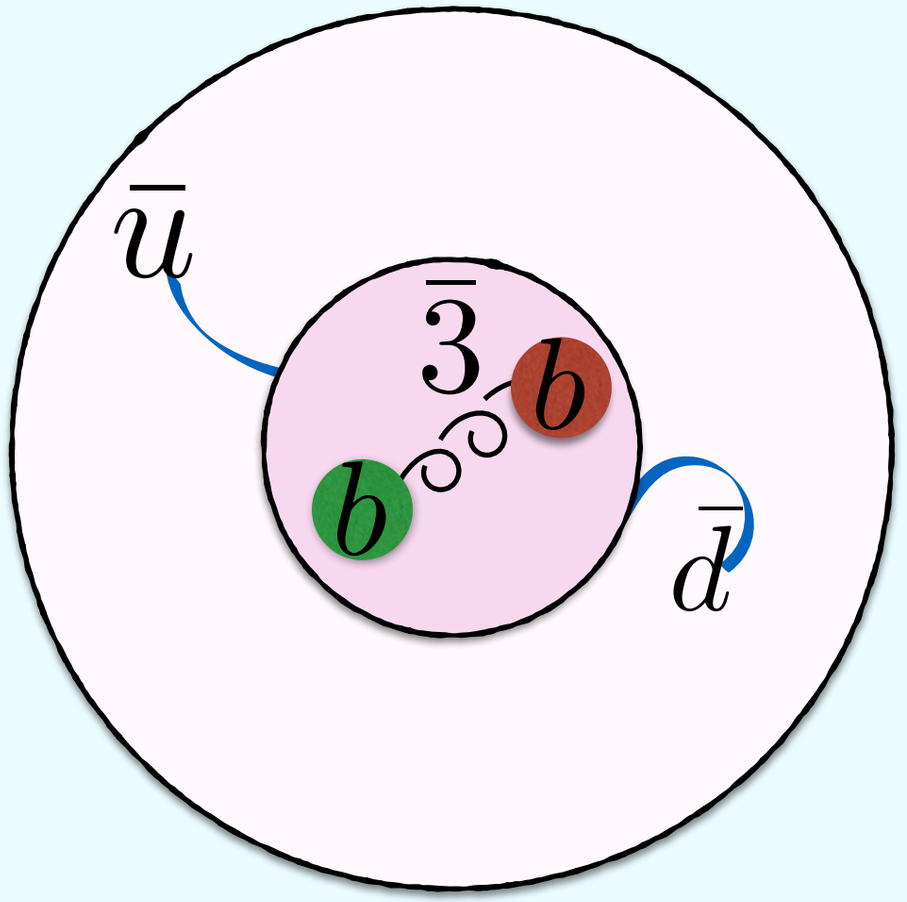
  - in attractive $\bar{3}$ channel
  - light quarks in cloud screen bb interaction
  - Finite b mass does not change picture



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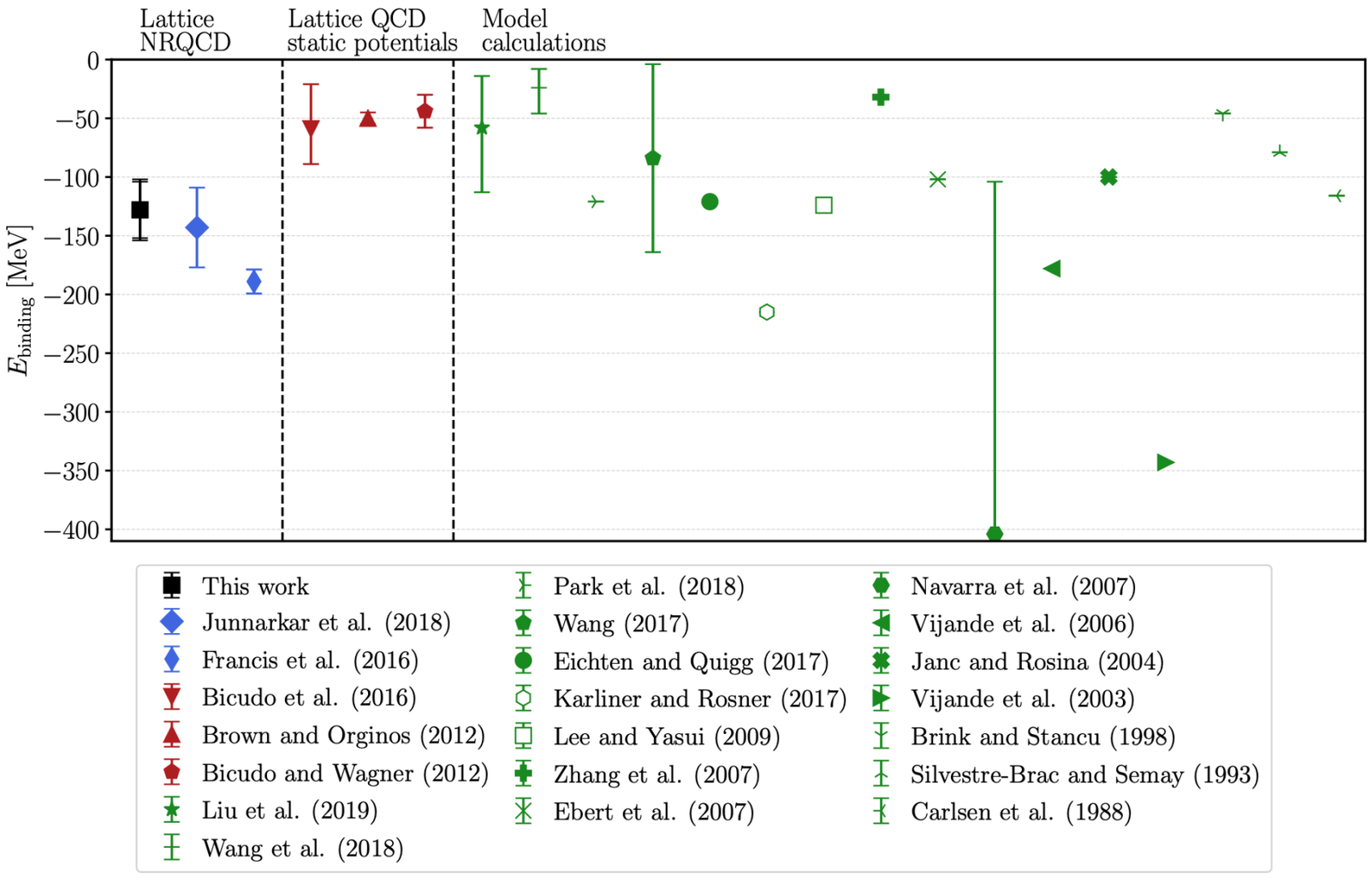
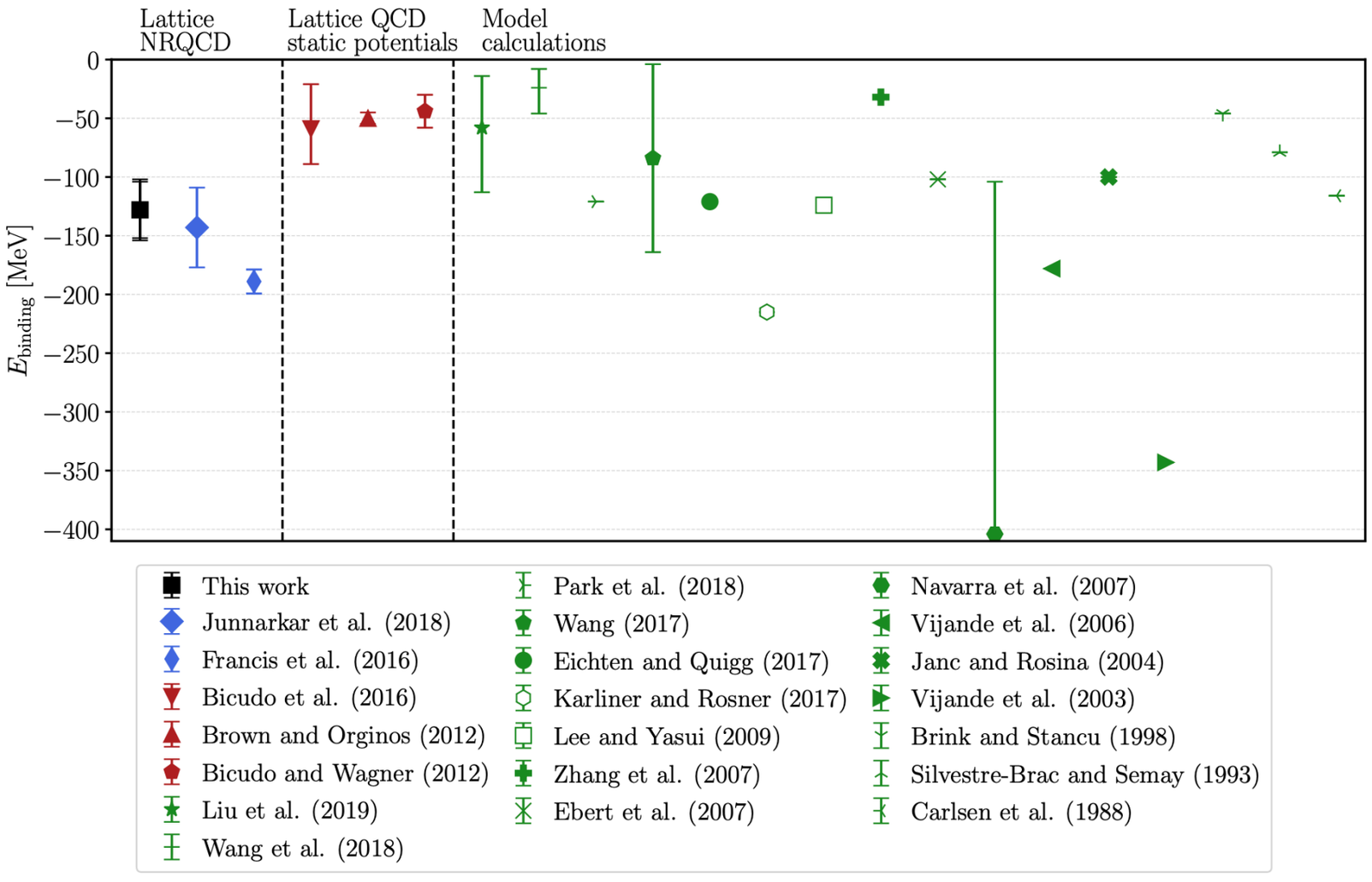


- Broad theoretical consensus that this state is bound

arxiv:1904.04197

$bb\bar{u}\bar{d},\ I = 0,\ J^P = 1^+$ is bound



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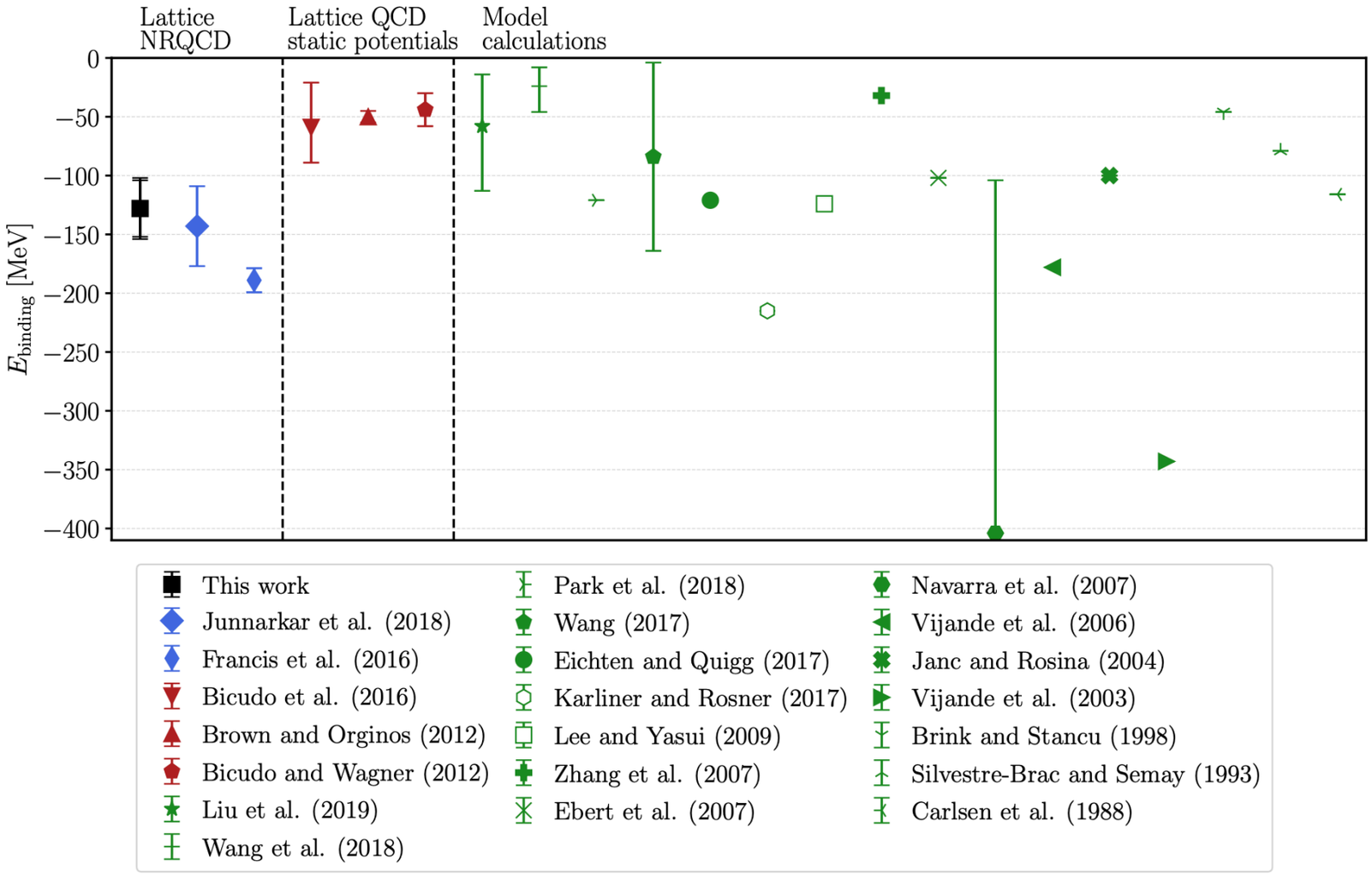

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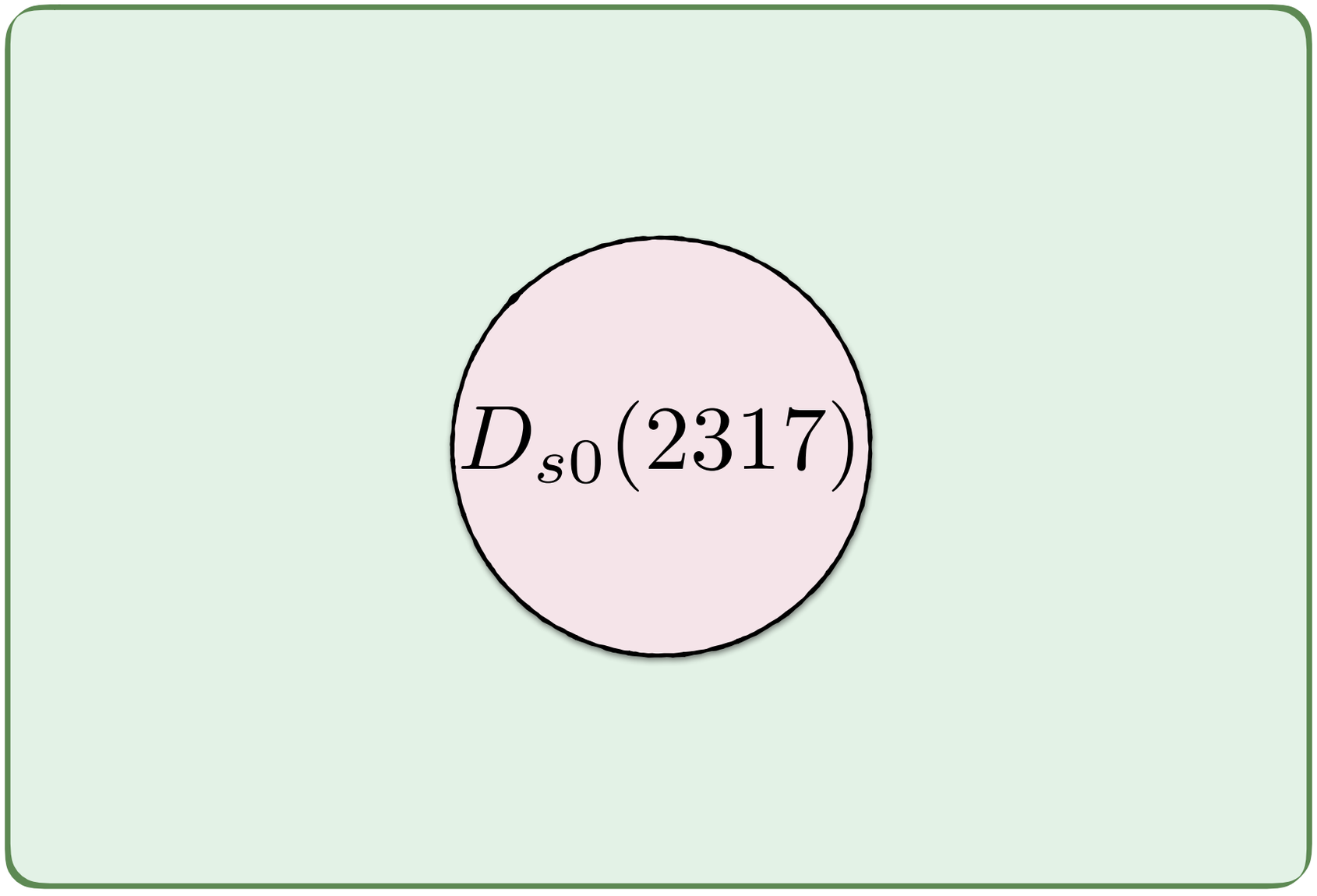
- For review talk of these types of tetraquarks see A. Francis talk here

arxiv:1904.04197

$D_{s0}(2317)$



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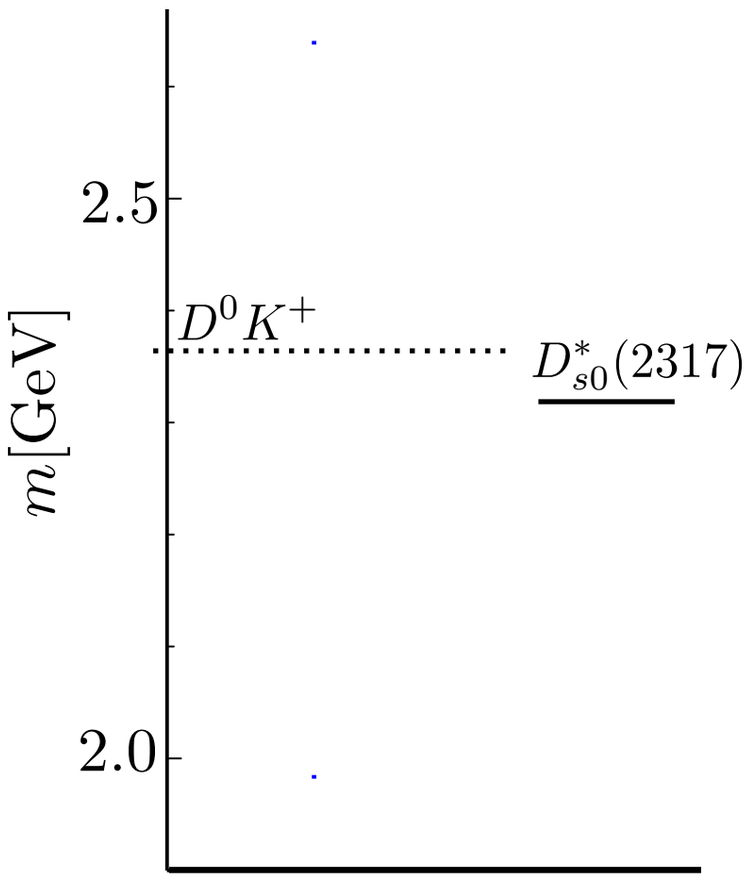

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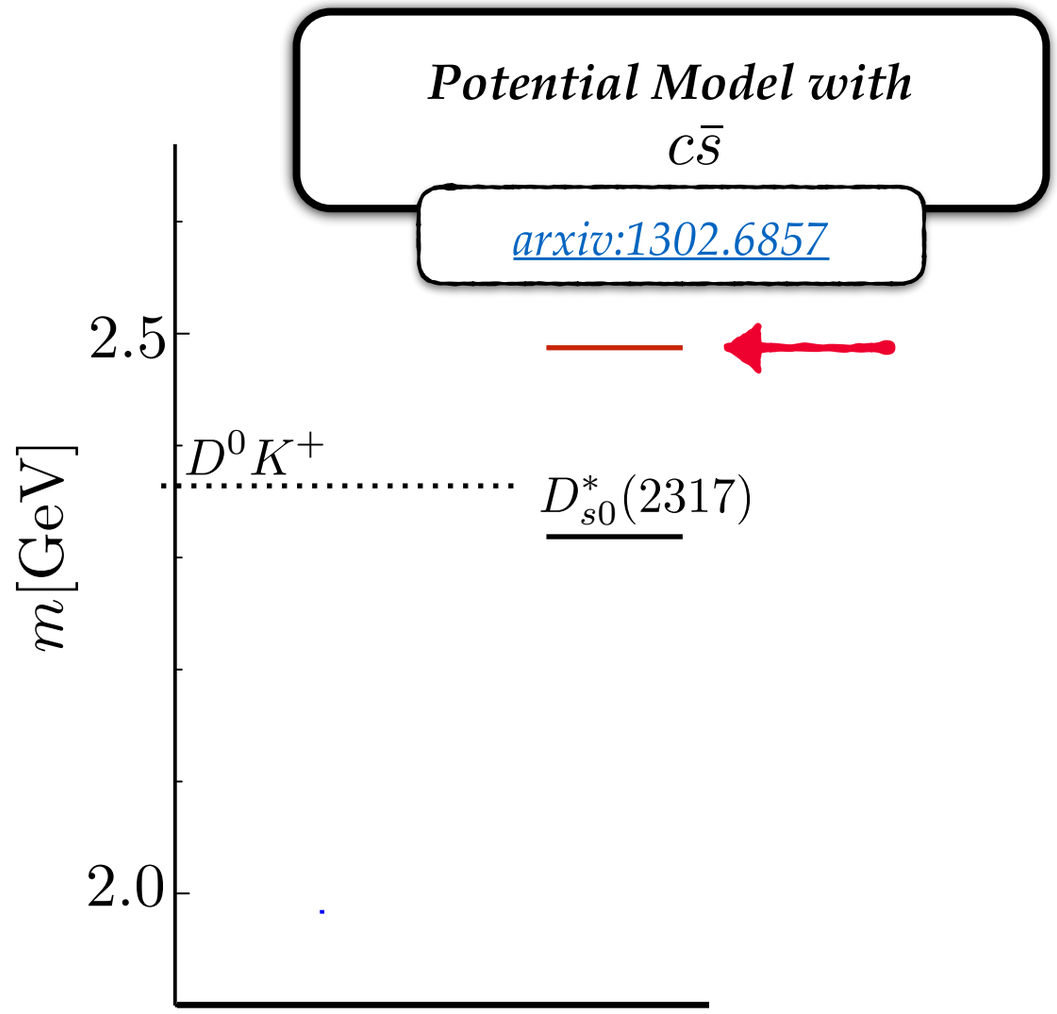
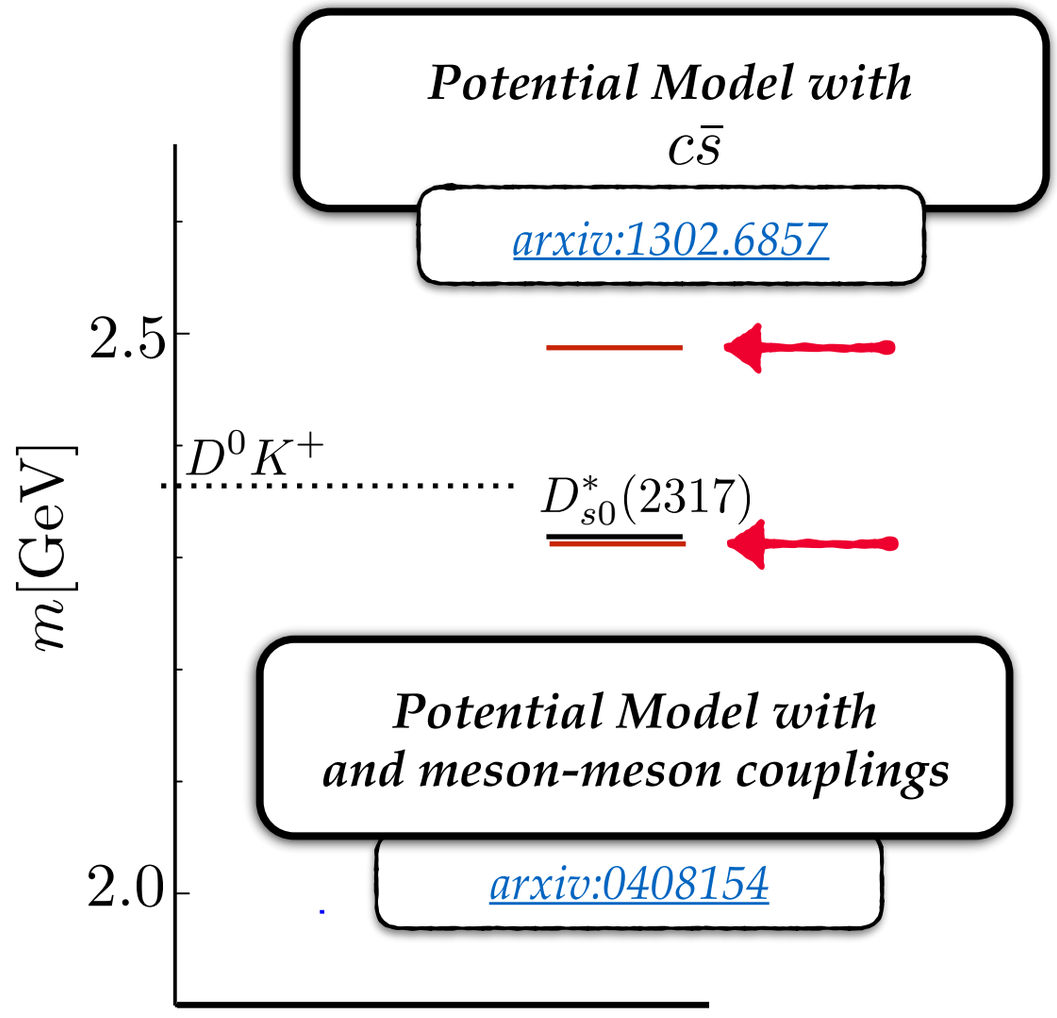

Potential Model with
$c\bar{s}$
arxiv:1302.6857
2.5
D^0K^+
$D^*_{s0}(2317)$
m[GeV]
2.0

$D_{s0}(2317)$


Potential Model with
$c\bar{s}$
arxiv:1302.6857
2.5
D^0K^+
$D^*_{s0}(2317)$
m[GeV]
Potential Model with
and meson-meson couplings
arxiv:0408154
2.0

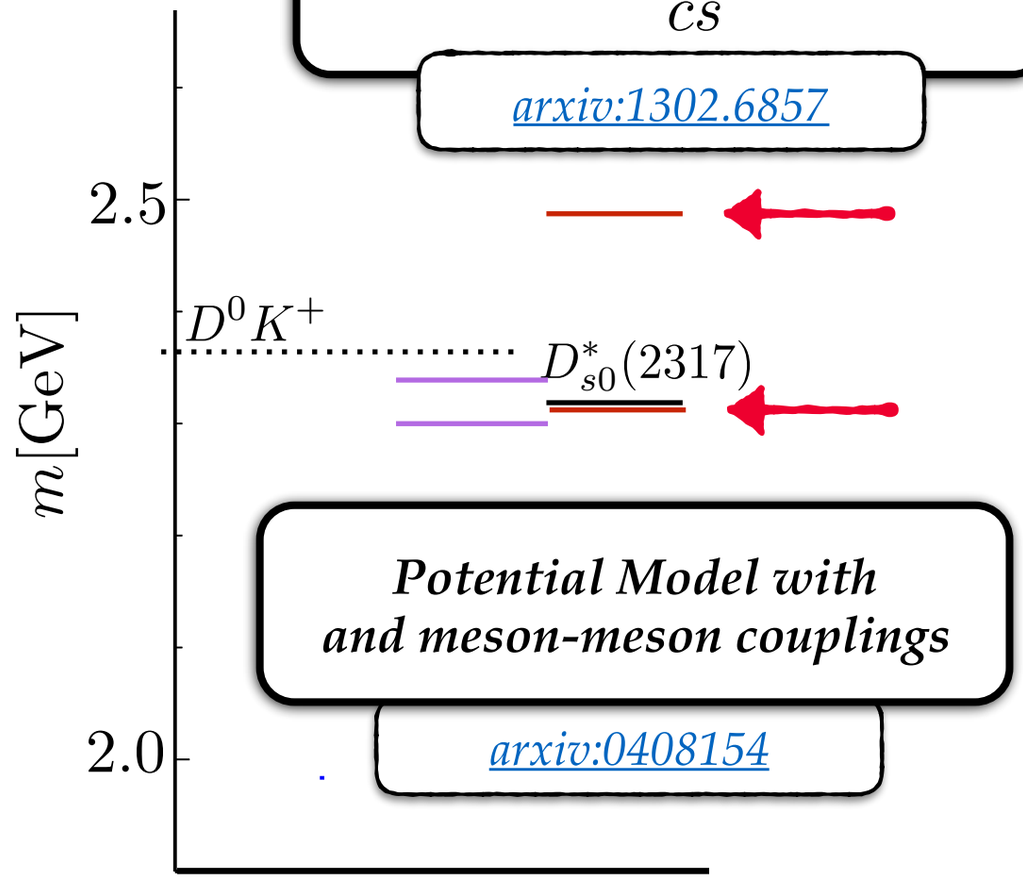
$D_{s0}(2317)$

- arxiv:1308.3175, arxiv:1706.01247, arxiv:2008.06432, arxiv:1911.08435
- $c\bar{s}$ and DK important
- Diquark not important
- Bound State Pole

Lattice QCD

Potential Model with $c\bar{s}$

arxiv:1302.6857



Potential Model with and meson-meson couplings

arxiv:0408154

$D_{s0}(2317)$

- Practical Proposal: Supplement Experimental Data with Lattice QCD

arxiv:1911.02024

$D_{s0}(2317)$

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- Use HQET and χ-PT to study

$$D_{s0} \to D \quad K$$

as a function of m_s

arxiv:1911.02024

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HQET: $M_D = m_c + m_l + C$

χ-PT : $M_K^2 \propto m_l + m_s$

arxiv:1911.02024

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1. Take $m_s' = m_s - \epsilon$
   - M_D changes as $-\epsilon$
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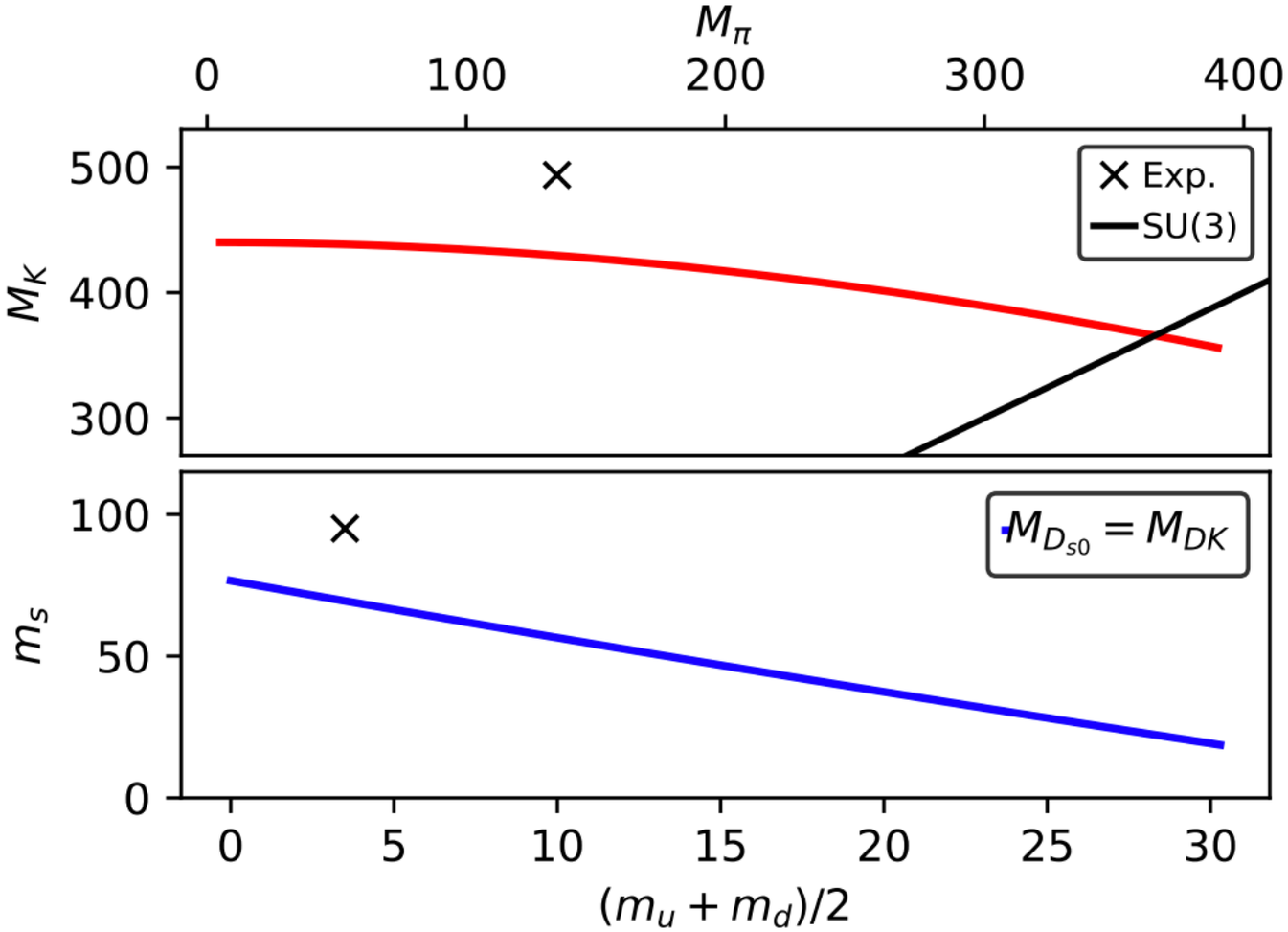
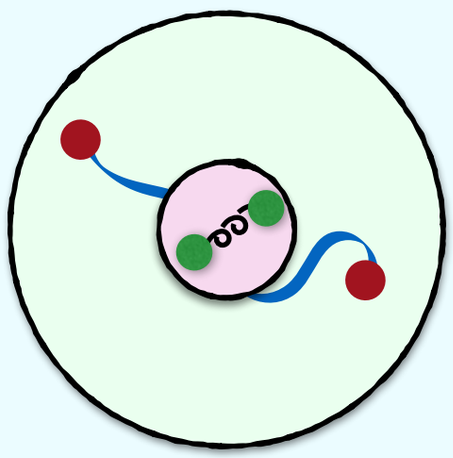


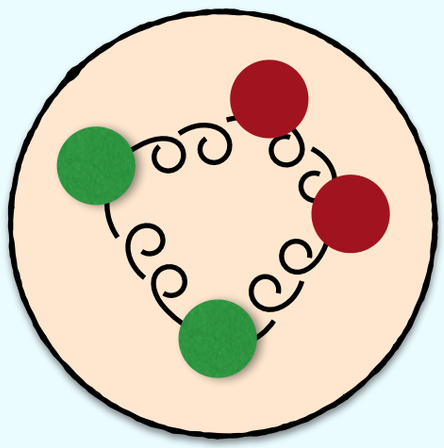
arxiv:1911.02024

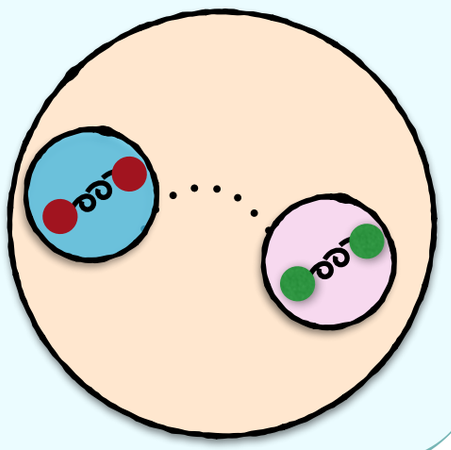
Theory Overview of Heavy Exotic Spectroscopy

Ciaran Hughes: chughes@fnal.gov

Future Looking Bright With Lots of New Experimental Data combined with Exciting Theory Understanding!







Beauty, 2020

Back-Up Slides

Scattering Overview: What Is A State?

Def^{n}: "State" = A Pole Singularity of the Scattering Matrix

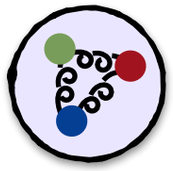
What A State is *Not* : A Bump In Experimental Data

- Non-Pole Singularities of S-Matrix Due To Kinematical Effects (which are not a state) can cause Data to go bump, e.g., arxiv:1912.07030
  - Cusps (Opening of Nearby Multi-Particle Thresholds)
  - Triangle Singularity
- Cusp/Triangle Singularity and State (which is a Pole) may both be Present in Experimental Data

Breit-Wigner theoretically motived if only one resonance in one channel
(*pdg mini-review on resonances)*

N.B.: Unitarity and Analyticity give rise to non-trivial line shapes. Cannot use sum of Breit-Wigners, use eg., K-matrix, see inspire:1519654

Conventional States



- $Def^{\underline{n}}$: "Conventional States" = "States we understand well enough"

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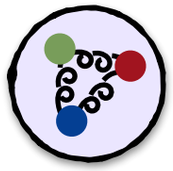

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$$V(r) = -\frac{\kappa}{r} + \sigma r + C + \cdots$$

Pheno: (1978) Phys. Rev. D 17 3090

Lattice: arxiv:0001312
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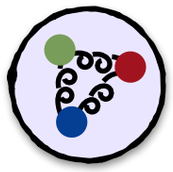
Conventional States



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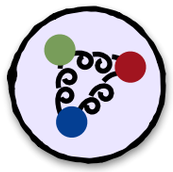

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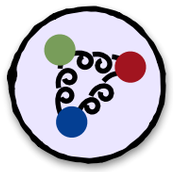

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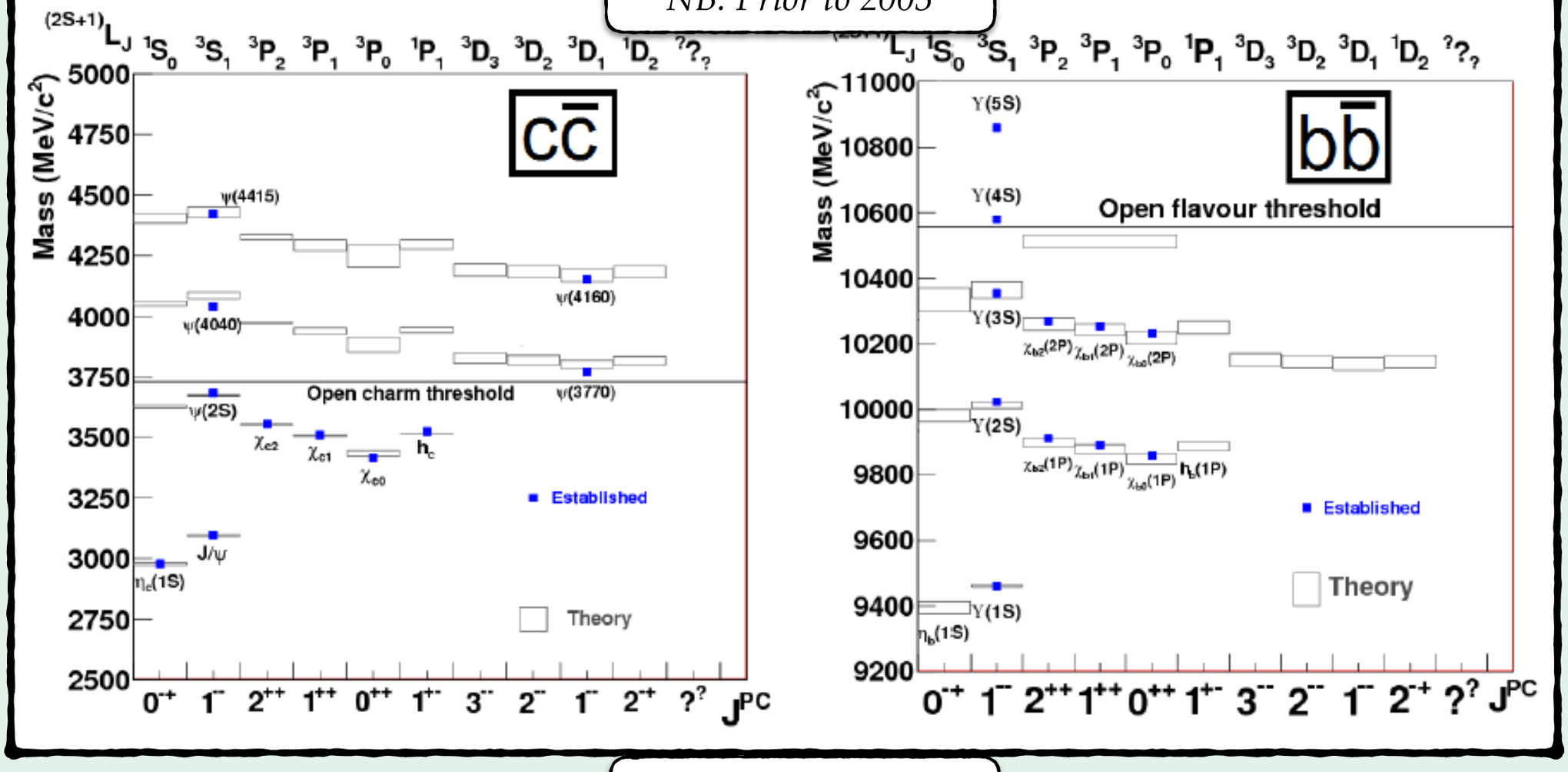
NB: Prior to 2003



E. Prencipe, 2019

Conventional States

Def^{n}: "Conventional States" = Mesons (valence $\bar{q}q$) and Baryons (valence qqq) in line with quark potential model expectations

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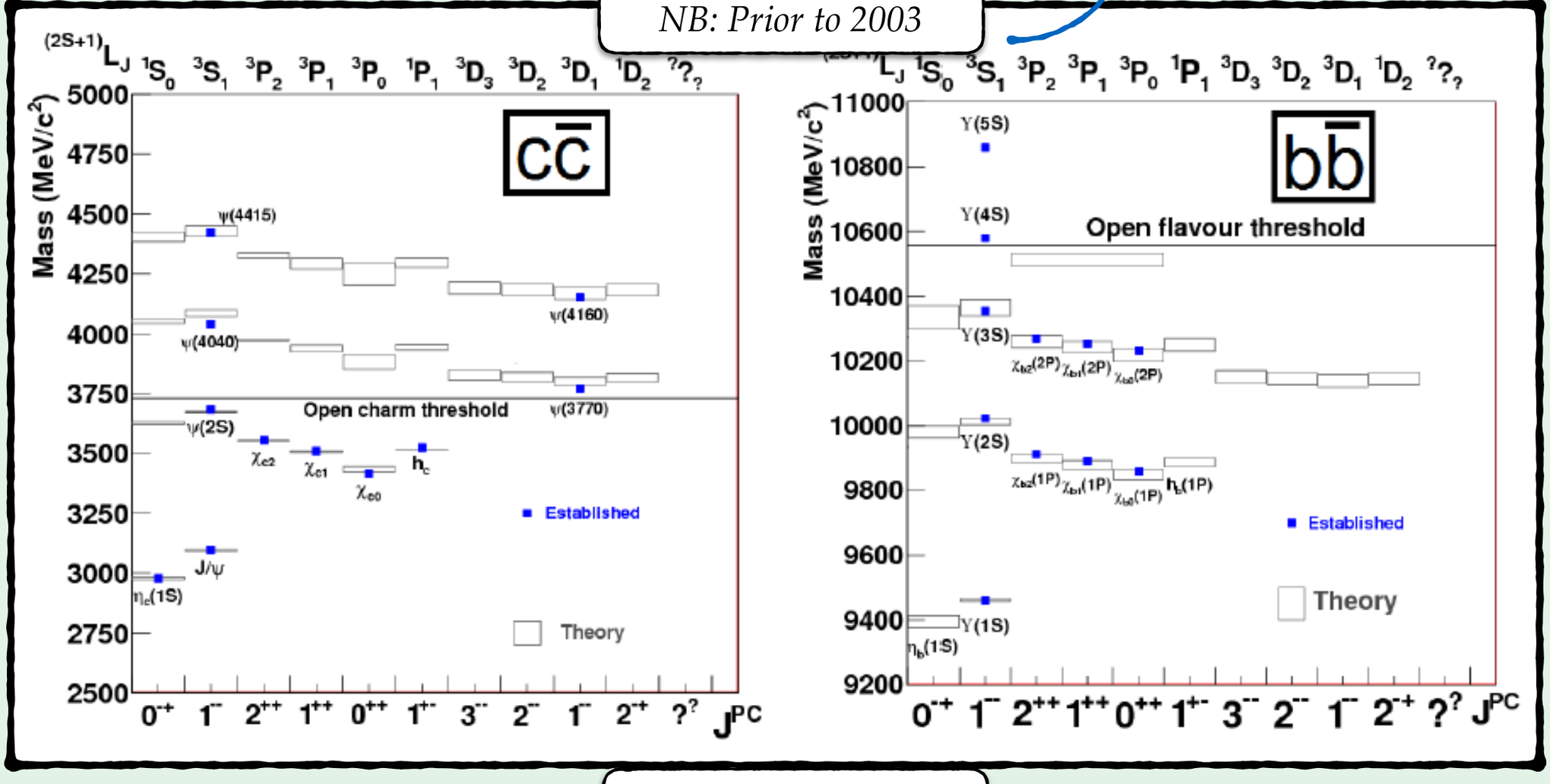

E. Prencipe, 2019

Classification

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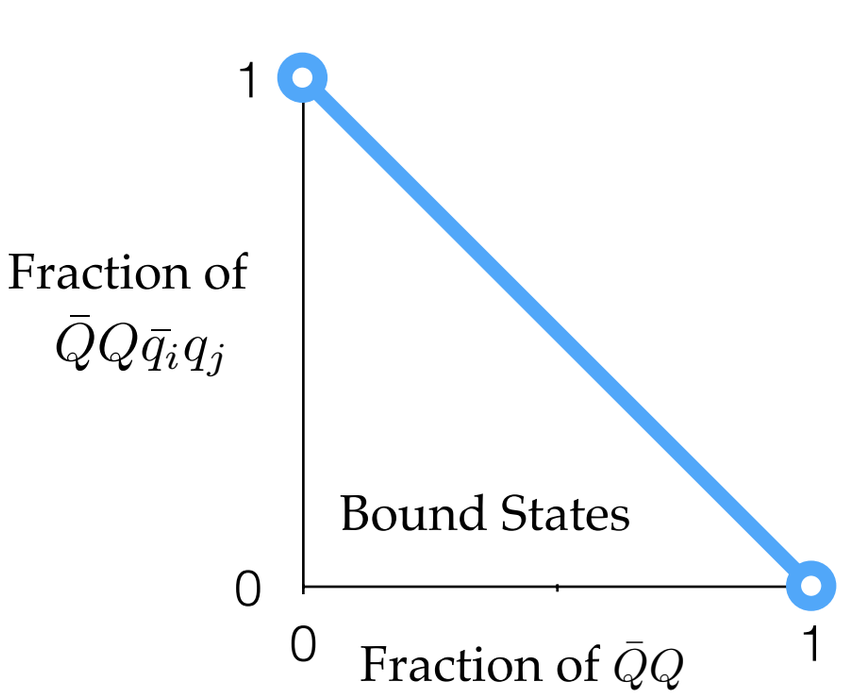

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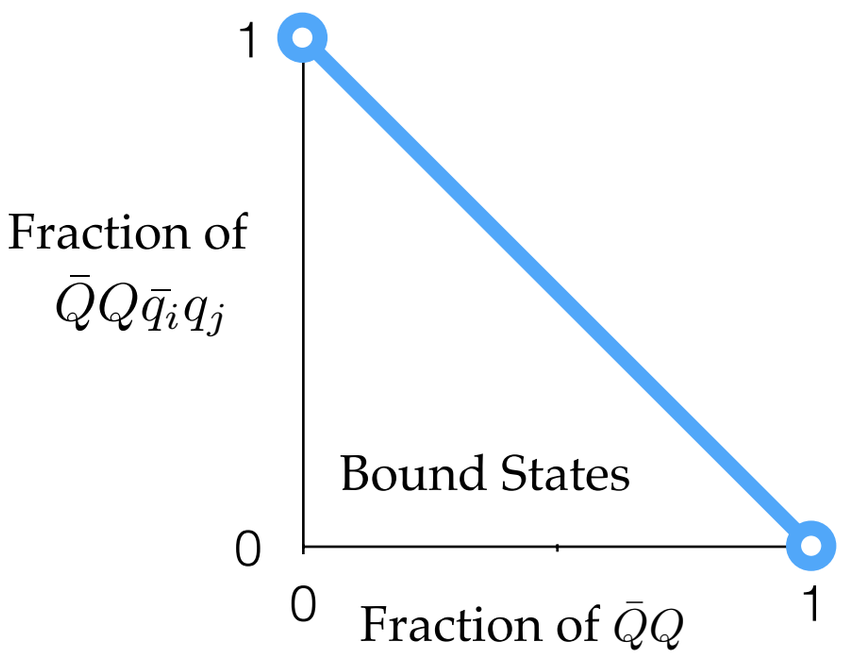

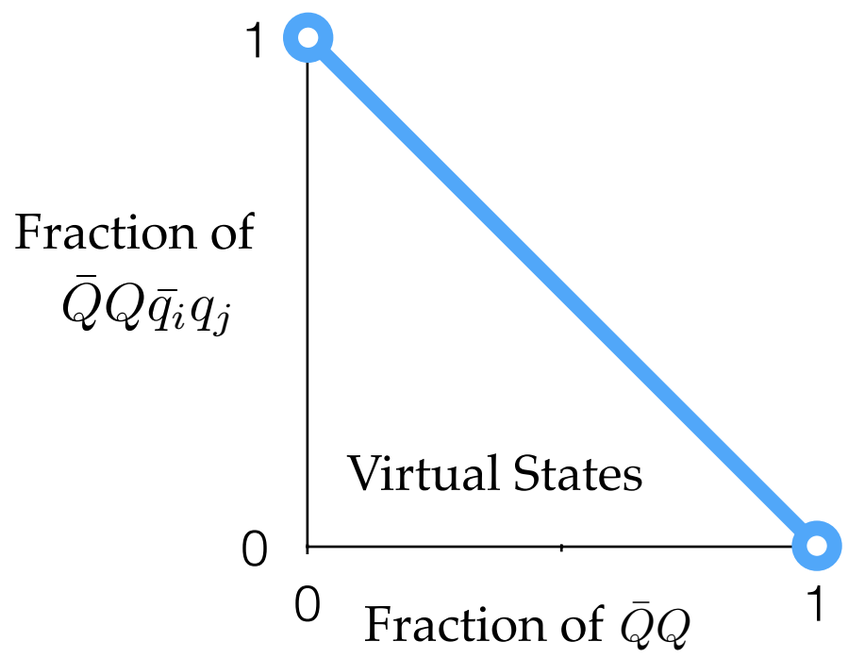

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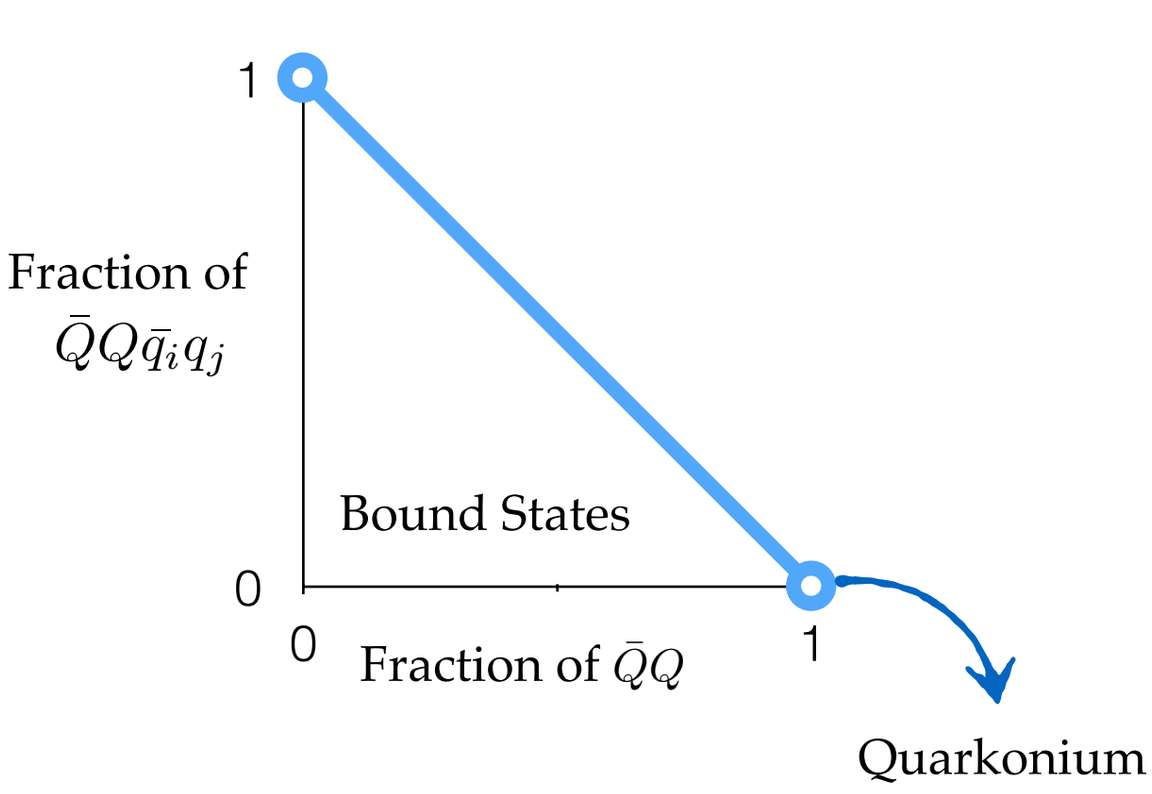

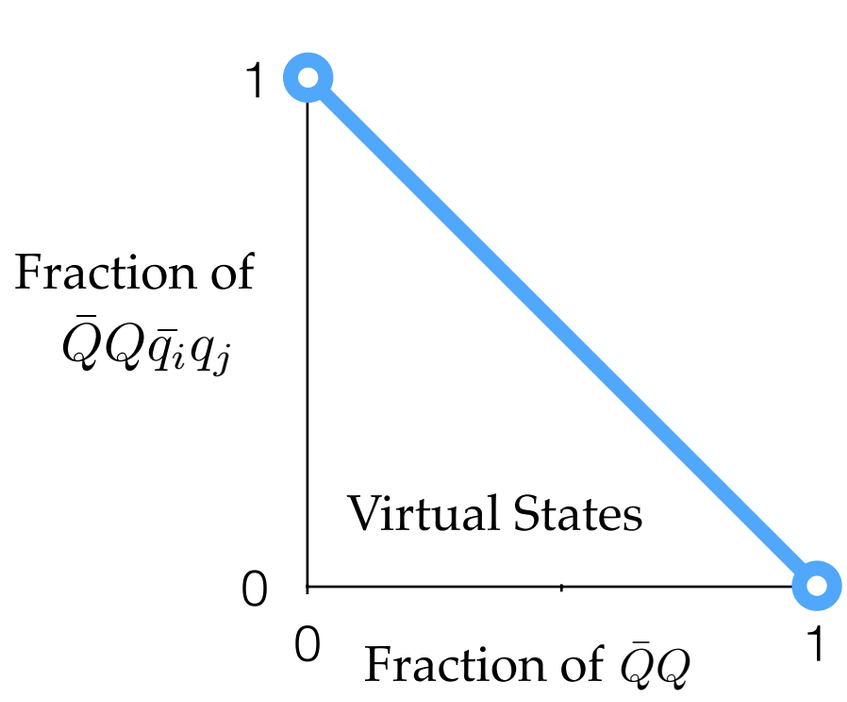

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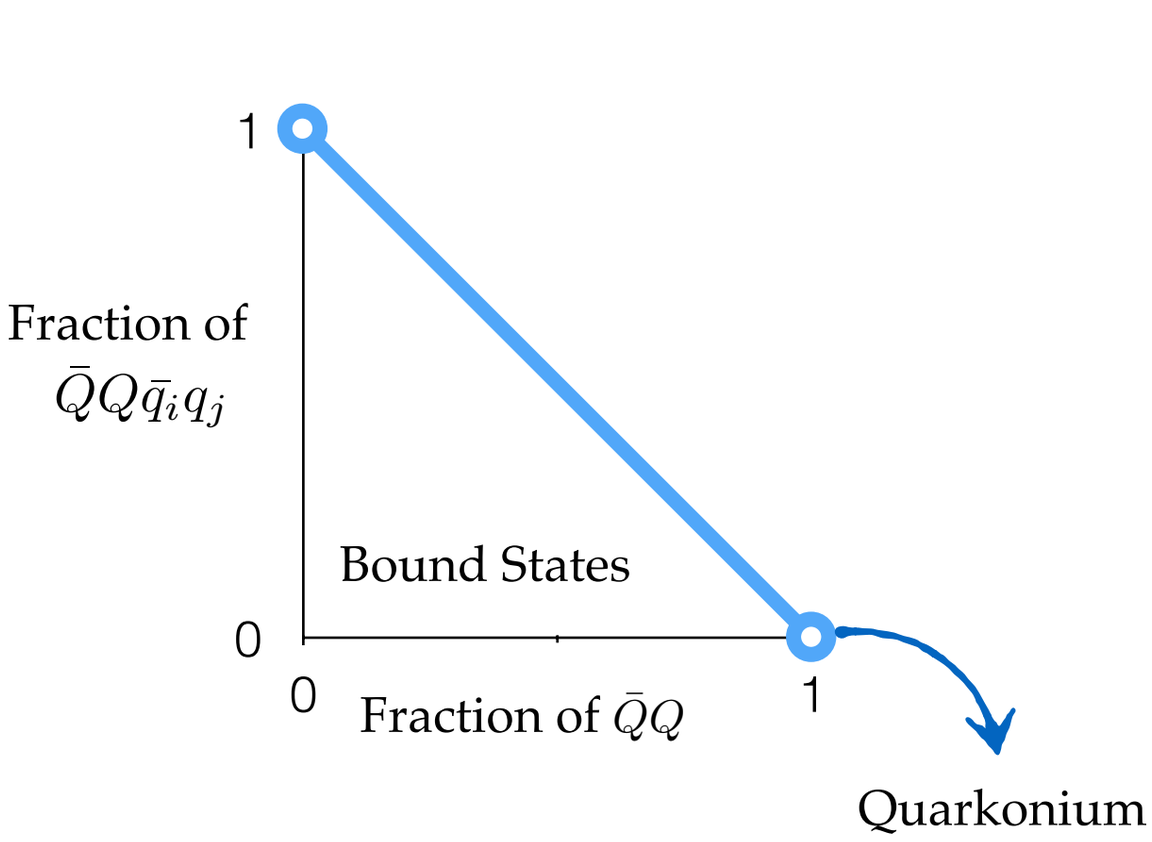

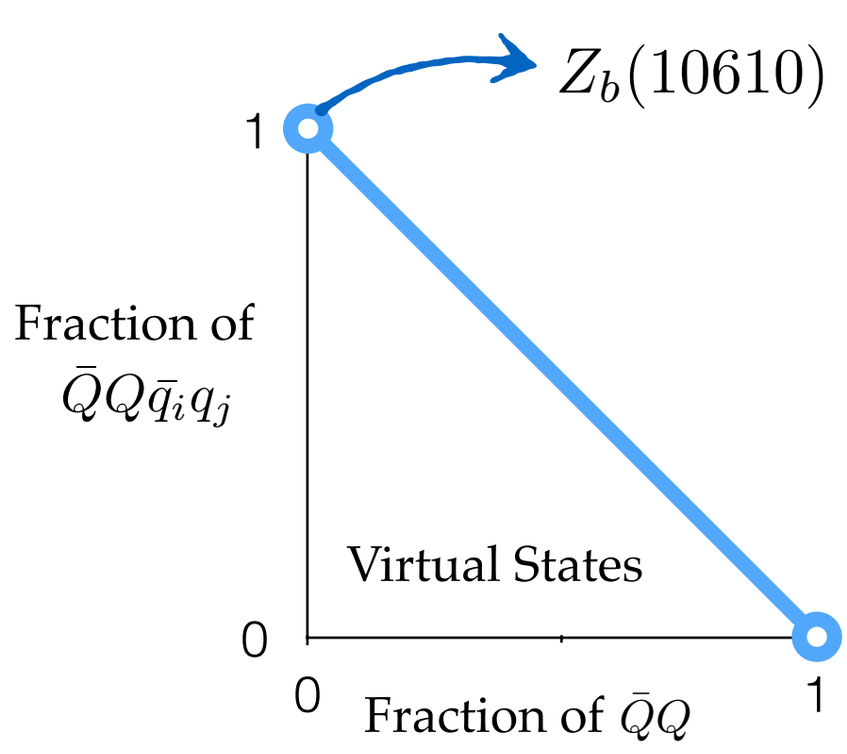

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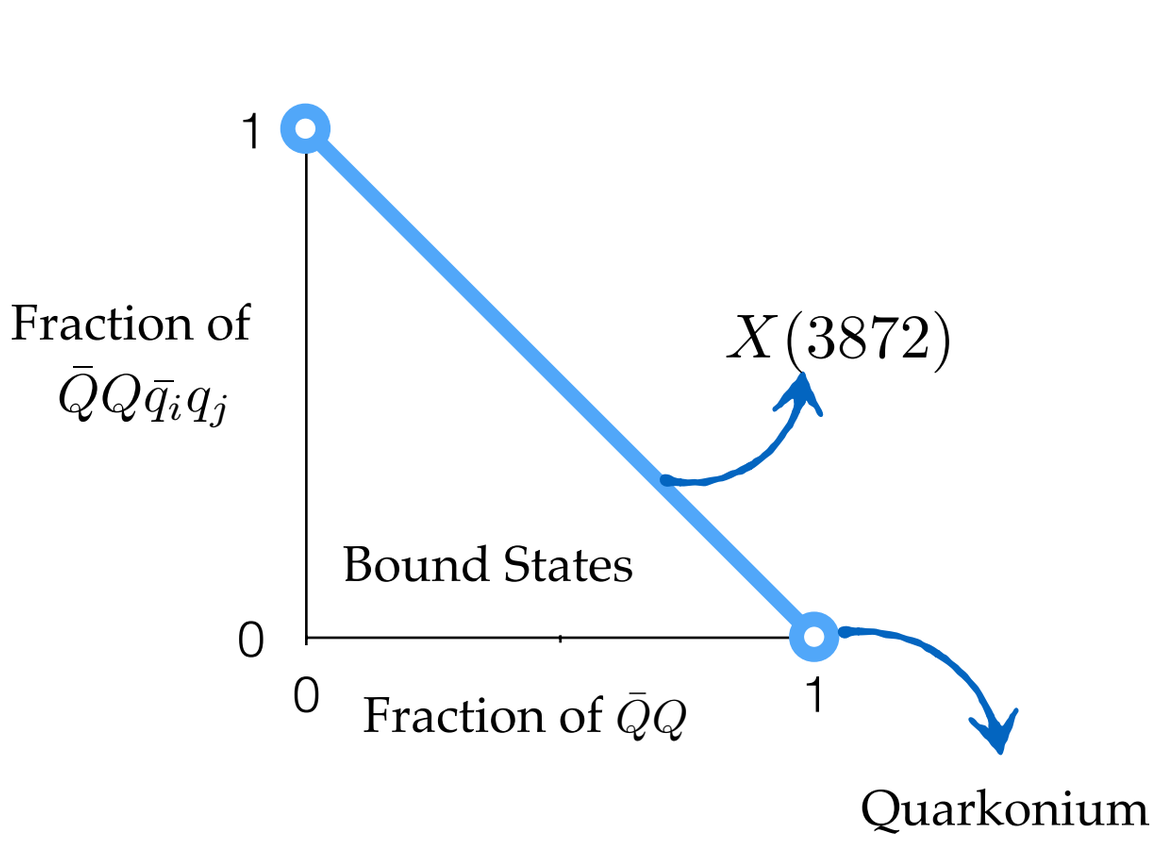

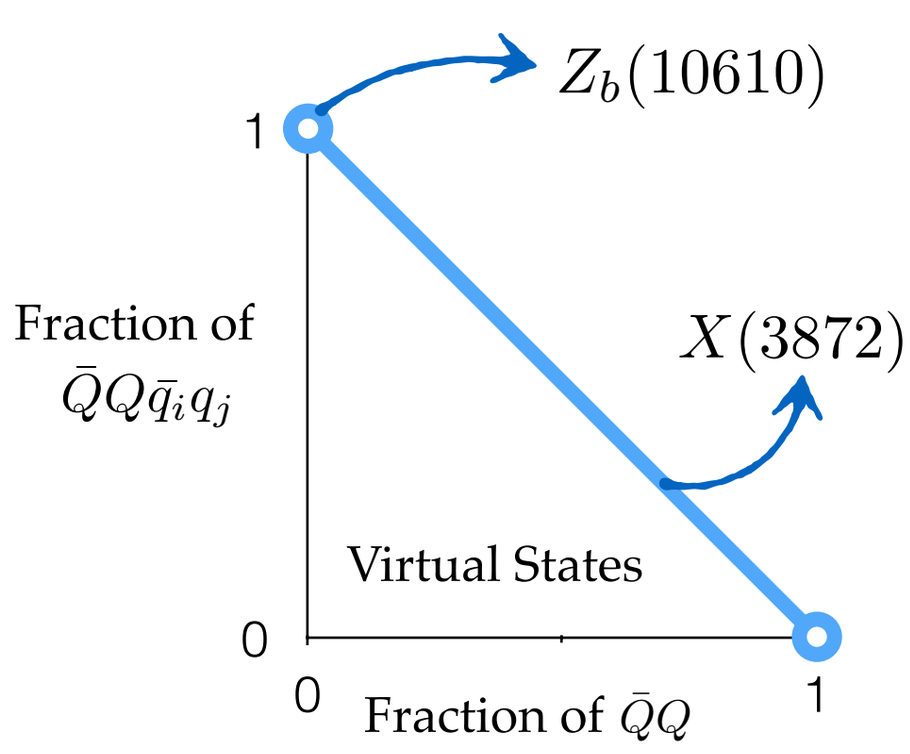

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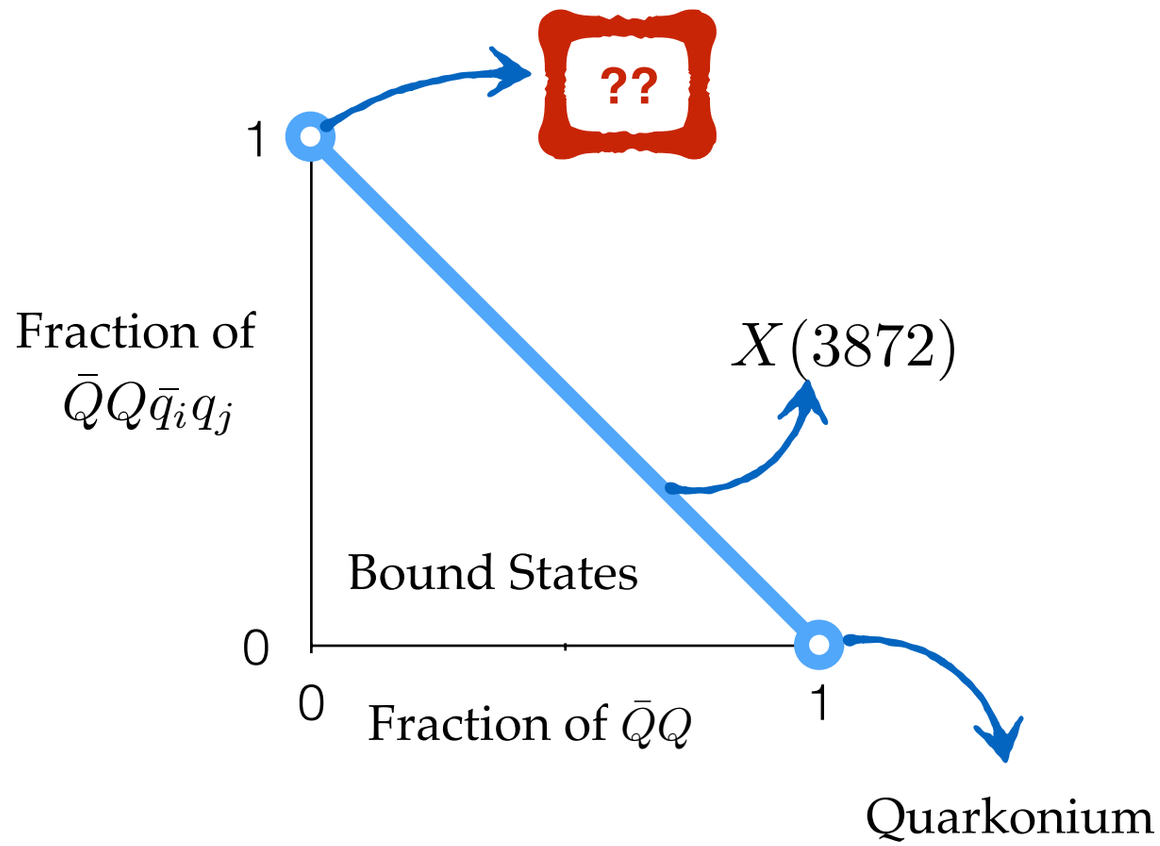

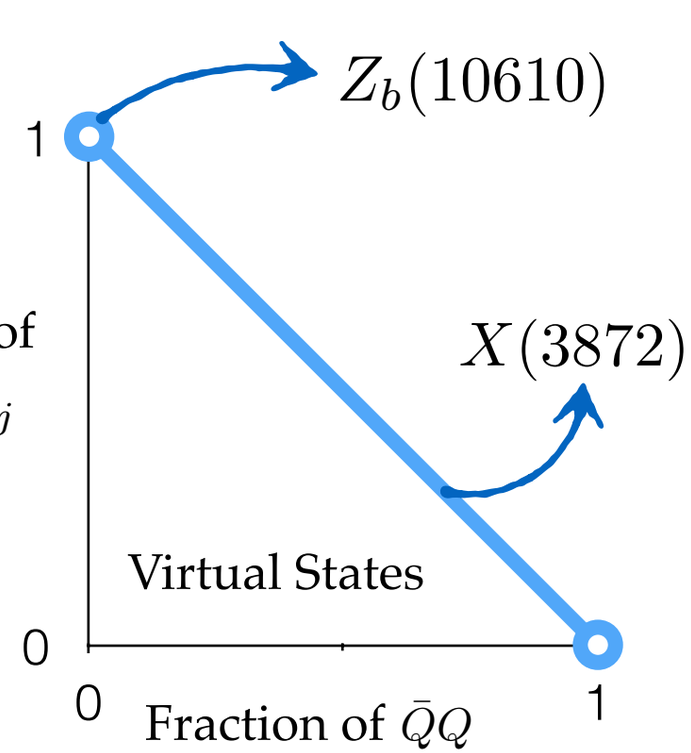

Classification

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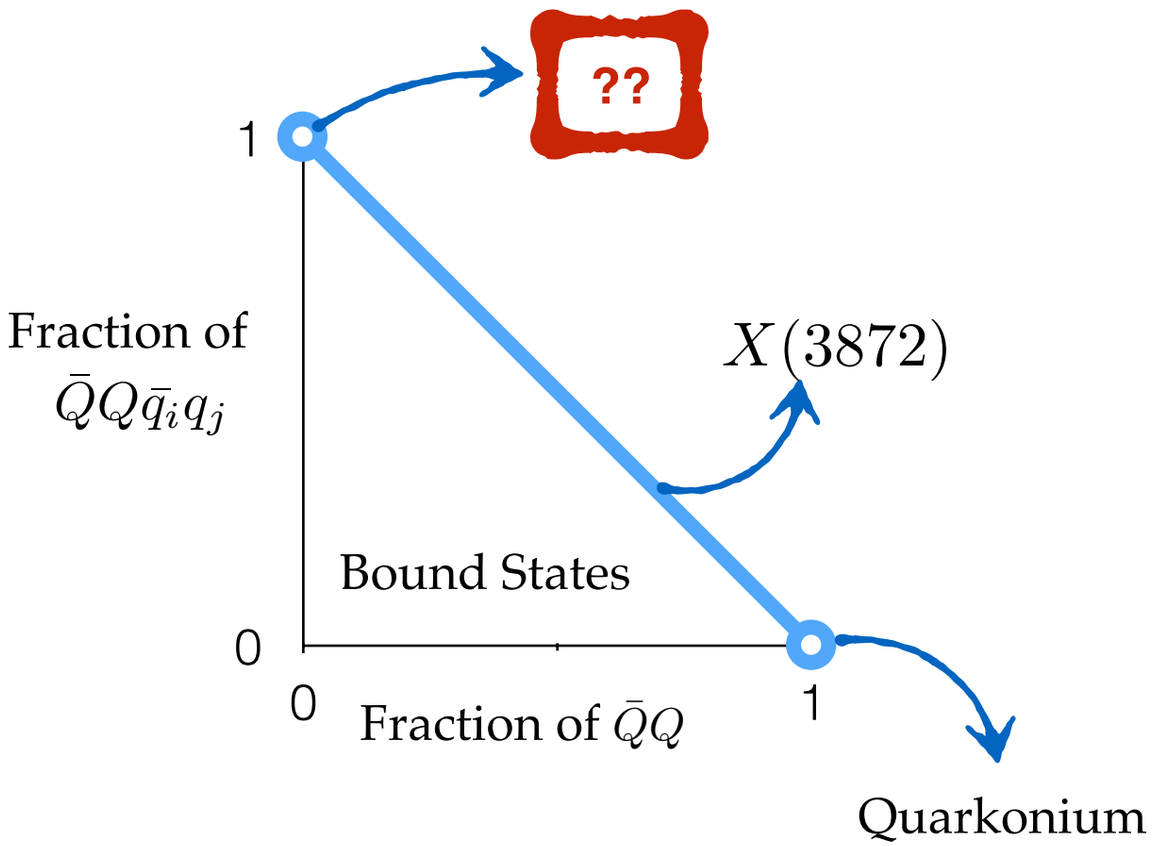
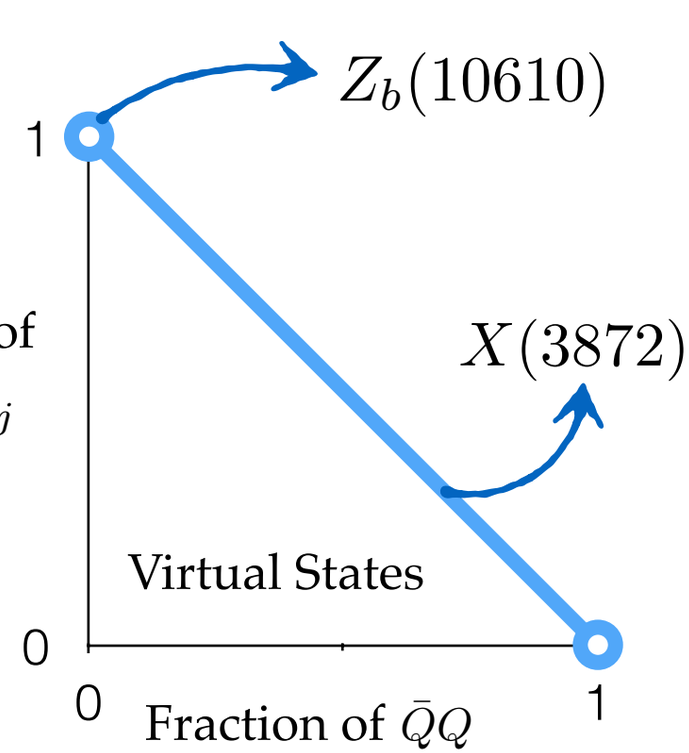
- Need no mixing, deeply bound, and experimentally testable.
  => Clean and simple system to understand, which can be used to understand more complicated XYZ





$\psi(4230)$ *aka* $Y(4230)$ *aka* $Y(4260)$

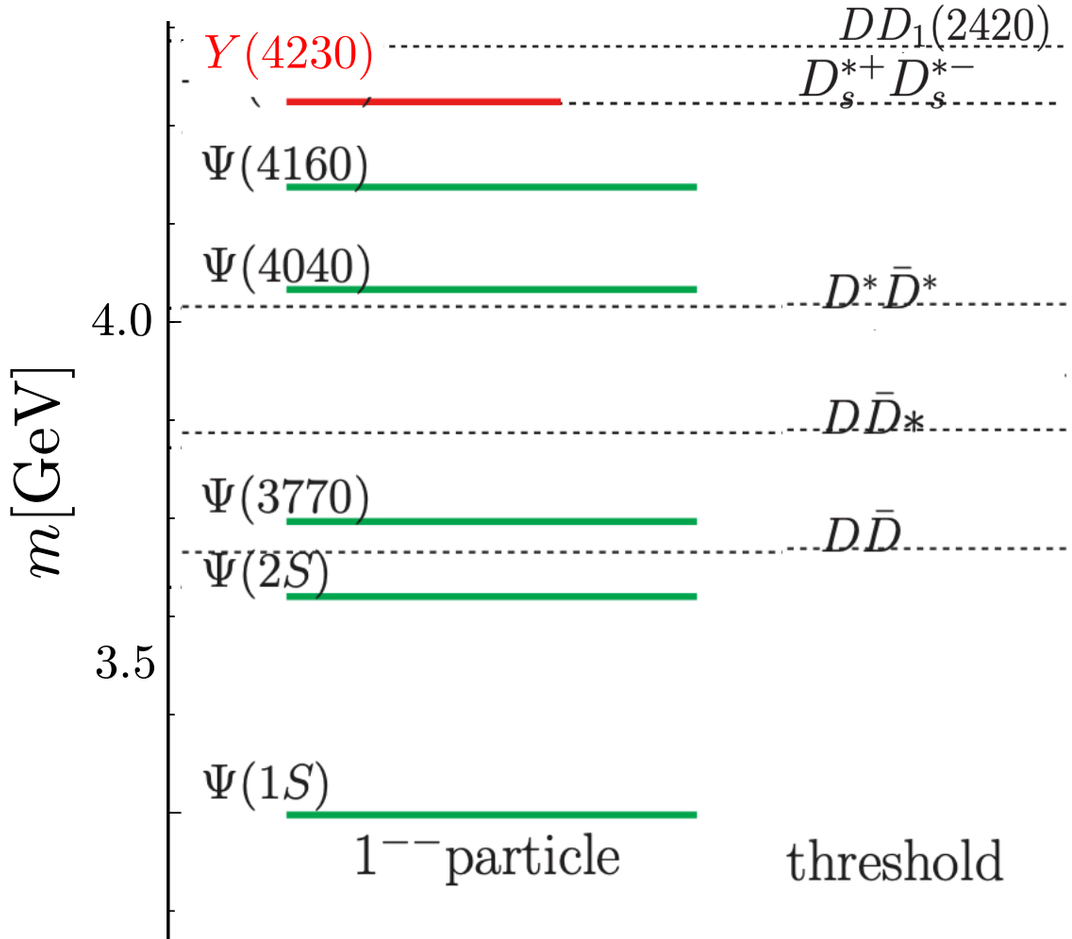
Quantum Numbers

$J^{PC} = 1^{--}$ $Q = 0$ $I^G = 0^-$

Notable Decays

- Seen $\mathcal{B}(\pi^+\pi^- J/\psi)$ $\mathcal{B}(\pi^+\pi^- h_c)$ $\mathcal{B}(\pi^+ D^{*-} D^0)$ $\mathcal{B}(\gamma X(3872))$
- Not Seen: Any Open-Charm Decays, e.g, $\mathcal{B}(D\bar{D})$

- $M_{PDG} = 4220 \pm 15$ MeV
- $\Gamma_{PDG} = 20 - 100$ MeV



Scenario 3: $Y(4230) = \psi(4160)$ (arxiv:1902.09268)

- $Y(4230)$ is not a new state at all!
  - $\psi(4160)$ is strongly coupled to
  - $D_s^* \bar{D}_s^*$ threshold (+30 MeV above)

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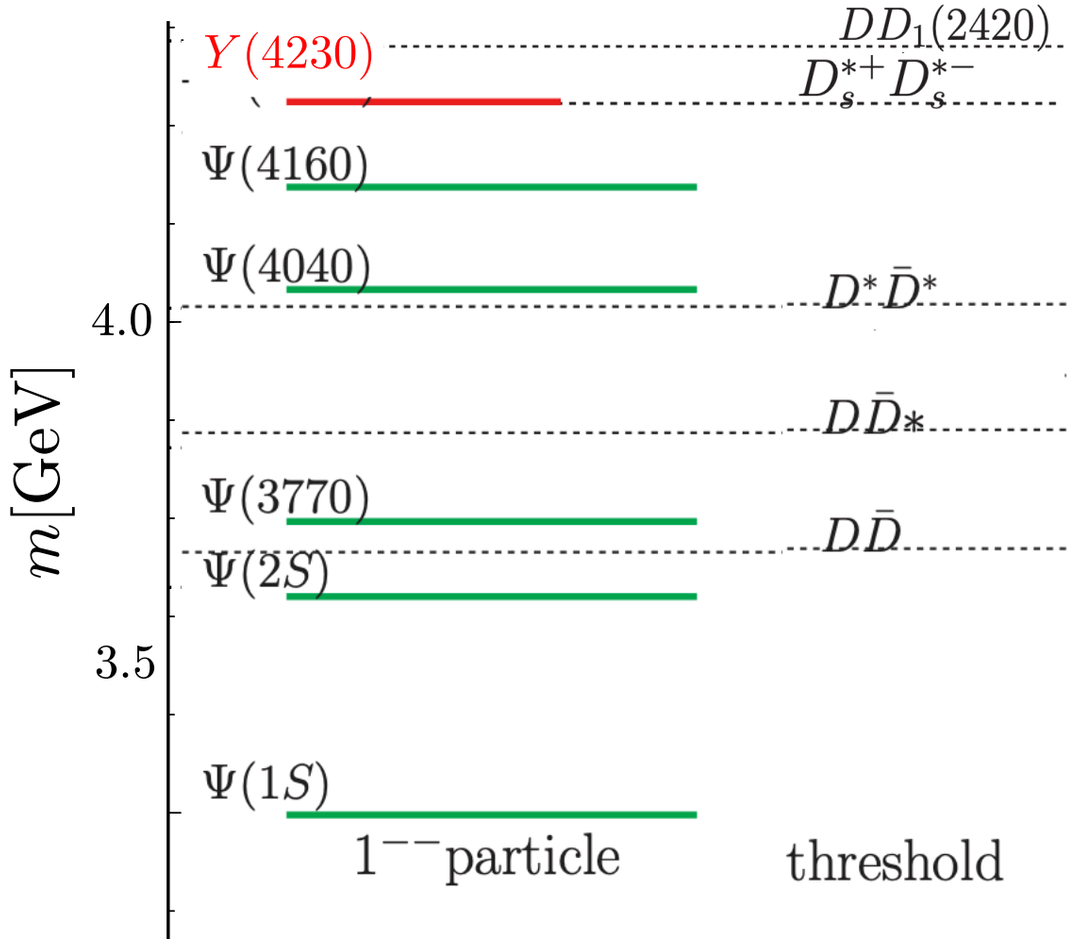

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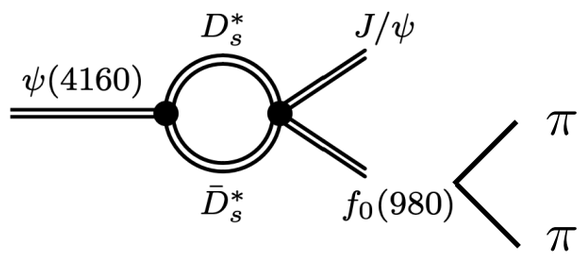

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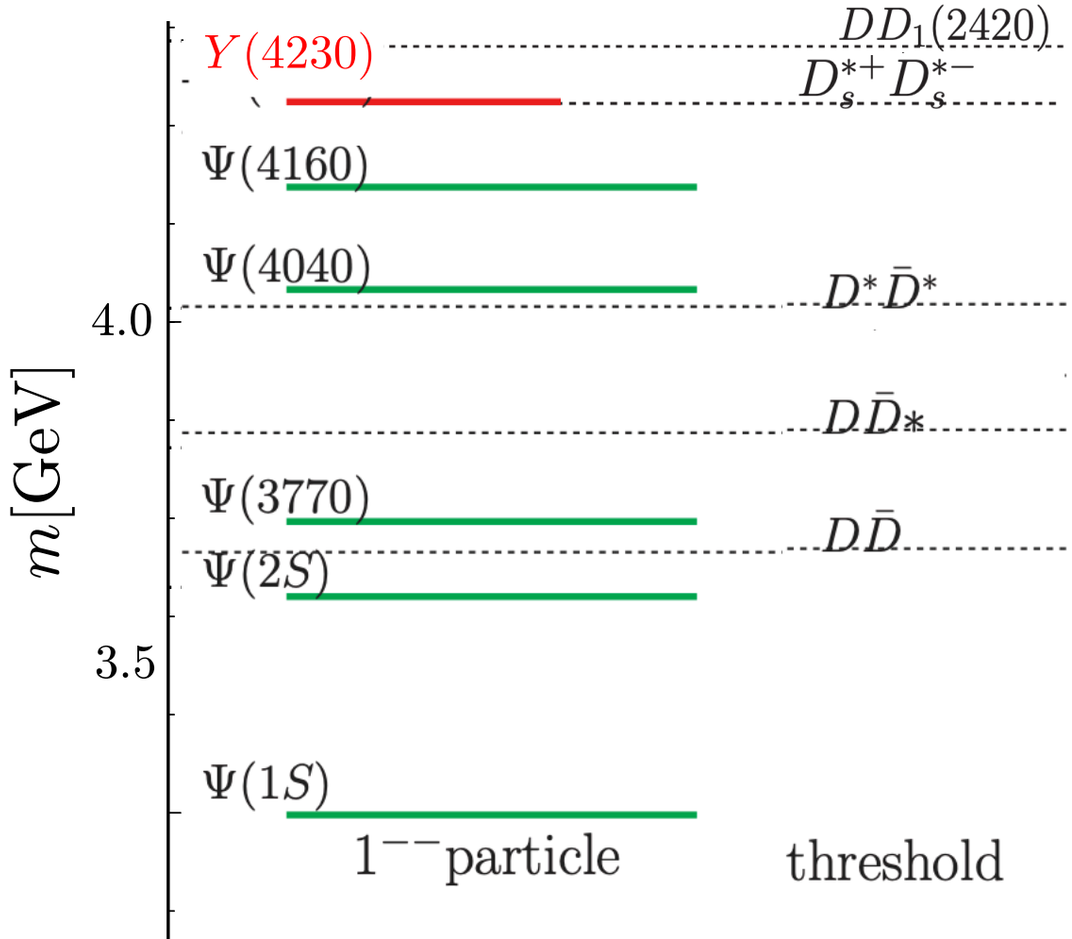

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  - Causing $Y(4230)$ structure in data, but only one pole from $\psi(4160)$