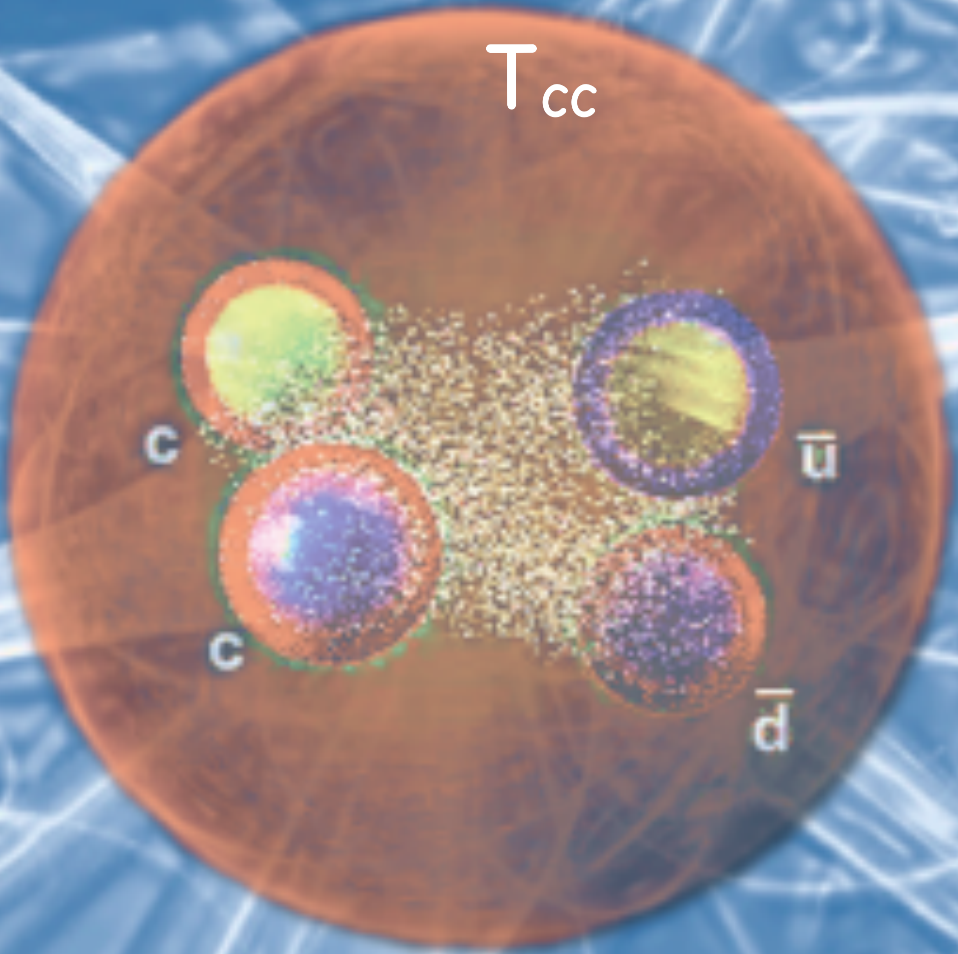
QCD22

25th HIGH-ENERGY PHYSICS
INTERNATIONAL CONFERENCE
IN QUANTUM CHROMODYNAMICS

MONTPELLIER · 4-7 july 2022 ·



Exotics from QCD Sum Rules

Marina Nielsen

Universidade de São Paulo

Candidates to Exotic Charmonium States

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	experiment	Year
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [22–24], BaBar [25]	2003
				$p\bar{p} \to (\pi^+\pi^- J/\psi)$ (...)	CDF [26–28], DØ [29]	
				$B \to K(\omega J/\psi)$	Belle [30], BaBar [31]	
				$B \to K(D^{*0}\bar{D}^0)$	Belle [32, 33], BaBar [34]	
				$B \to K(\gamma J/\psi)$	Belle [30], BaBar [35, 36]	
				$B \to K(\gamma\psi(2S))$	BaBar [36], LHCb [37]	
				$e^+e^- \to \pi^+\pi^- J/\psi$	BESIII [38]	
				$pp \to (\pi^+\pi^- J/\psi)$ (...)	LHCb [39, 40], CMS [41]	
$Z_c^+(3900)$	3886.6 ± 2.4	28.2 ± 2.6	1^{+-}	$Y(4260) \to (J/\psi\, \pi^+)\pi^-$	BESIII [42], Belle [43], CLEO-c [44]]	2013
				$Y(4260) \to (D\bar{D}^*)^+\pi^-$	BESIII [45]	
$Y(3940)$	3918.4 ± 1.9	20 ± 5	$0/2^{++}$	$B \to K\,(J/\psi\omega)$	Belle [46], BaBar [31, 47]	2004
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [48], BaBar [49]	
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi$ (...)	Belle [50]	2005
				$e^+e^- \to J/\psi\,(DD^*)$	Belle [51]	
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to \pi^+\pi^- J/\psi$	Belle [43, 52], BESIII [53]	2007
$Z_c^+(4020)$	4024.1 ± 1.9	13 ± 5	$?^{?-}$	$e^+e^- \to \pi^-(\pi^+ h_c)$	BESIII [54]	2013
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BESIII [55]	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?-}$	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [56], BaBar [57]	2008
$Z_c^+(4055)$	4054 ± 3	45	$(?^{?-})$	$e^+e^- \to \pi^-(\pi^+\psi(2S))$	Belle [58]	2014
$Z_c^-(4100)$	$(4096\pm^{+28}_{-32})$	$152^{+70}_{-45})$	$0^{++}/1^{-+}$	$B^0 \to K^+(\pi^-\eta_c(1S))$	LHCb [59]	2018
$Y(4140)$	4146.8 ± 2.4	22^{+8}_{-7}	1^{++}	$B \to K(\phi J/\psi)$	CDF [60, 61], D0 [62], LHCb [63], BESIII [64, 65]	2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$	Belle [51]	2007
$Z_c^+(4200)$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$B \to K(\pi^+ J/\psi)$	Belle [66]	2014
$Y(4220)$	4218^{+5}_{-4}	59^{+12}_{-10}	1^{--}	$e^+e^- \to \chi_{c0}\,\omega$	BESIII [67]	2014
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [56], BaBar [57]	2008
$Y(4260)$	4230 ± 8	55 ± 19	1^{--}	$e^+e^- \to \pi^+\pi^- J/\psi$	BaBar [71, 72], CLEO-c [73], Belle [43, 52], BESIII [53]	2005
				$e^+e^- \to K^+K^- J/\psi$	CLEO-c [74], BESIII [45]	
				$e^+e^- \to \pi^0\pi^0 J/\psi$	CLEO-c [74]	
				$e^+e^- \to Z_c(3900)^\pm\,\pi^\mp$	Belle [43], BESIII [42]	
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$?^{?+}$	$e^+e^- \to \phi J/\psi$	Belle [75]	2009
$Y(4360)$	4368 ± 13	96 ± 7	1^{--}	$e^+e^- \to \pi^+\pi^-\psi(2S)$	BaBar [76, 77], Belle [58, 78], BESIII [69]	2007
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$Y(4390)$	$4391.5^{+7.3}_{-7.8}$	$139.5^{+16.3}_{-20.7}$	1^{--}	$e^+e^- \to h_c\,\pi^+\pi^-$	BESIII [68]	2016
$Z^+(4430)$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$B \to K^-(\pi^+\psi(2S))$	Belle [79–81], BaBar [82], LHCb [83]	2007
				$B \to K^-(\pi^+ J/\psi)$	Belle [66], BaBar [82]	
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \Lambda_c^+\Lambda_c^-$	Belle [84]	2008
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \pi^+\pi^-\psi(2S)$	Belle [58, 78], BaBar [77]	2007

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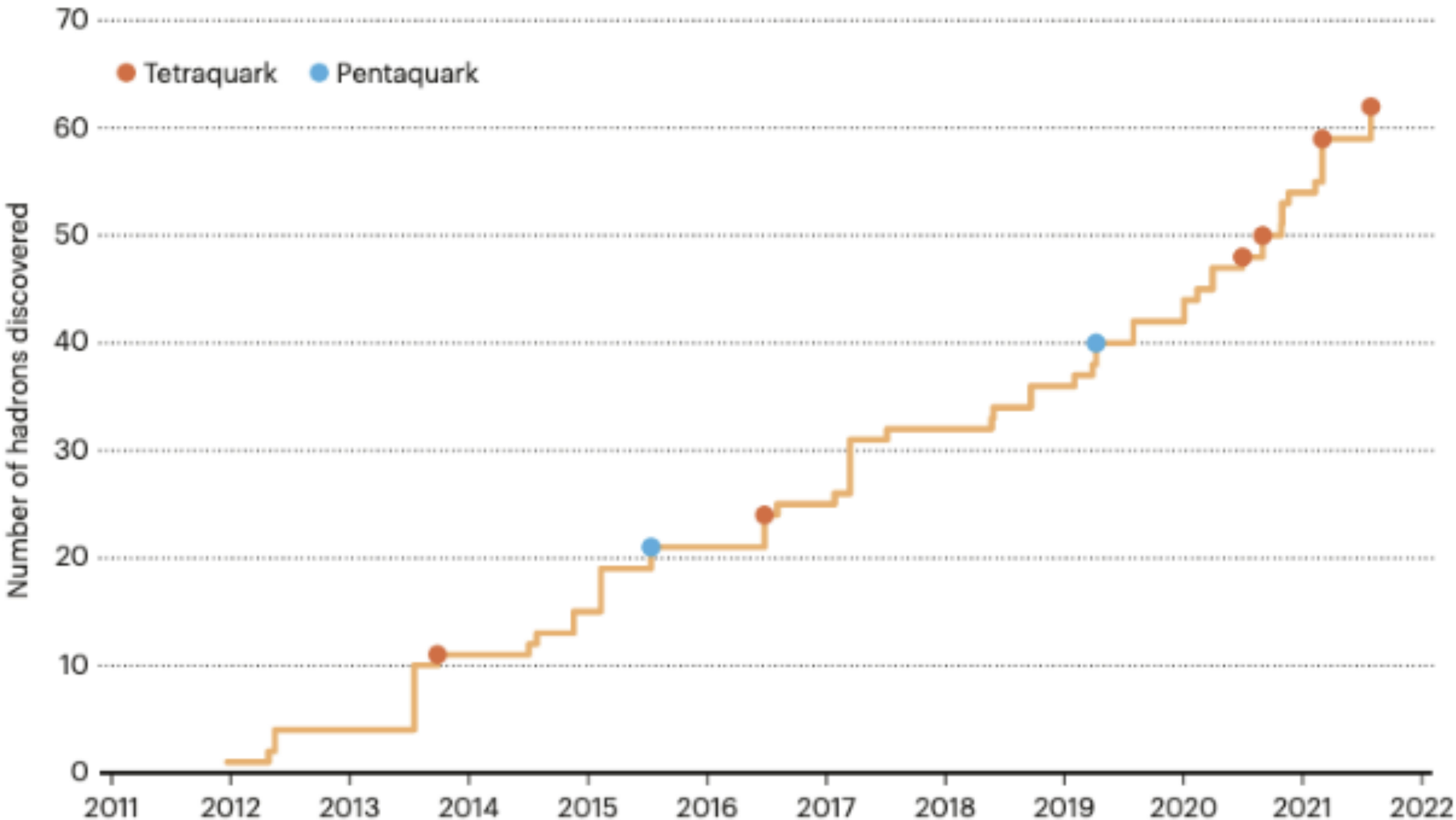
first one

and more ...

Hadrons discovered at LHC:

62 new hadrons were discovered at LHC, including many exotic states



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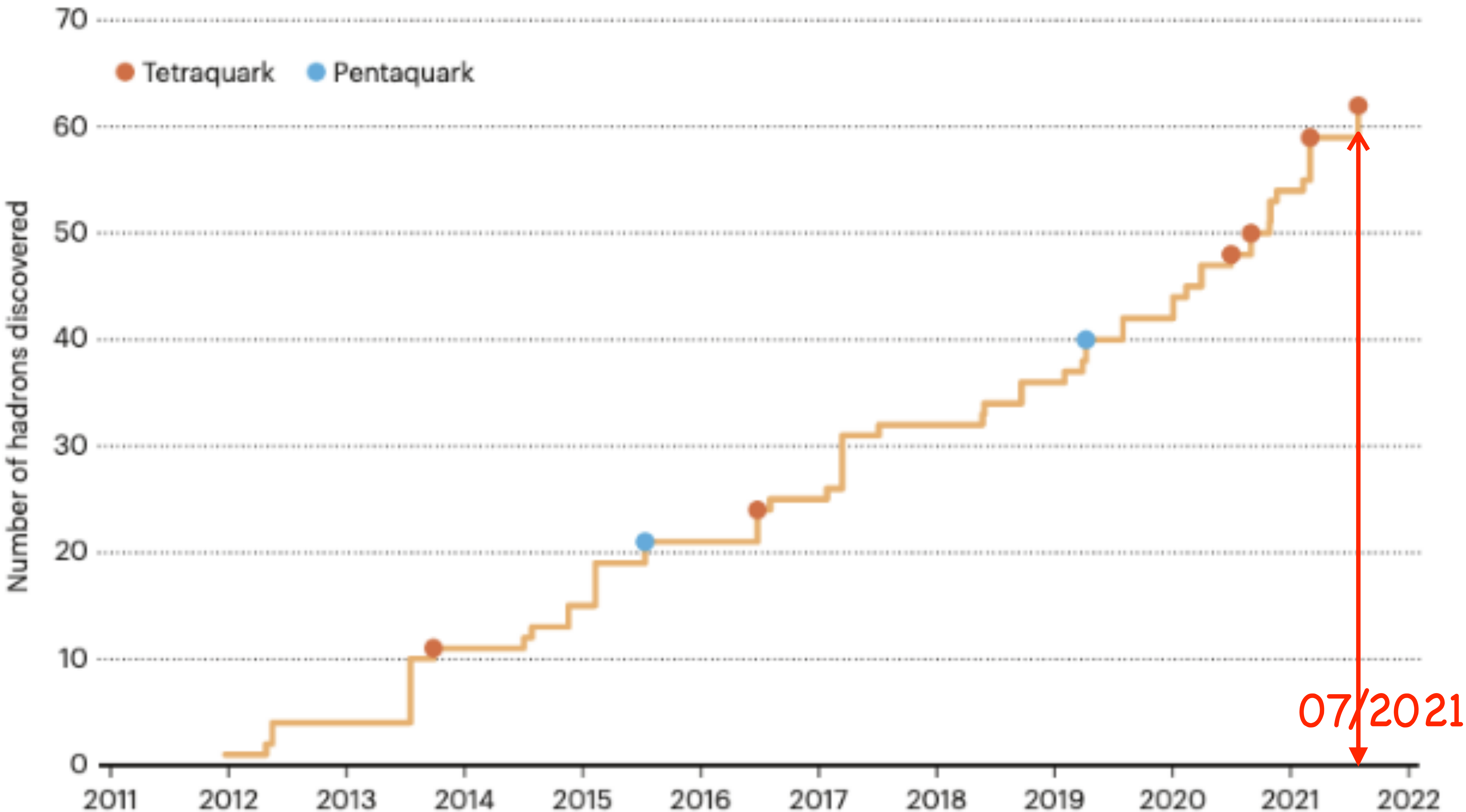
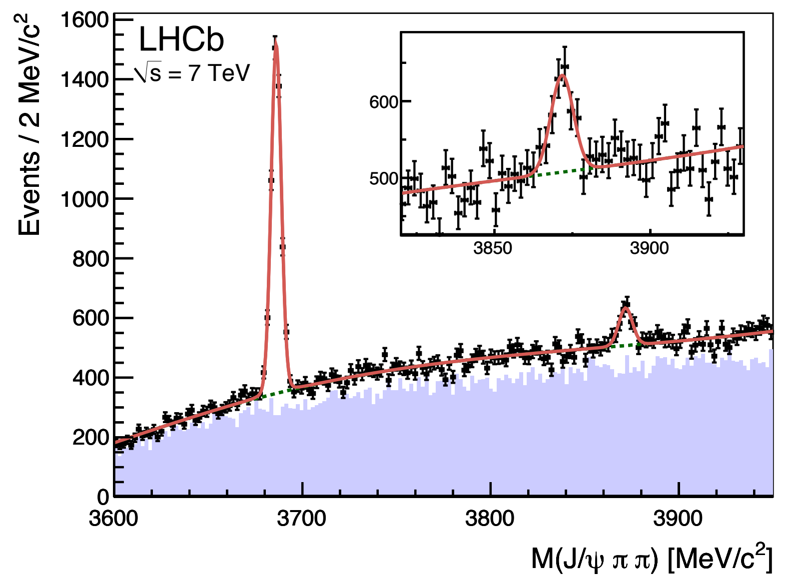


Exotic Spectroscopy: "my" overview

- 2003: Discovery of X(3872) by Belle started a new era in exotic spectroscopy.



M_X = (3871.65 ± 0.06) MeV
Γ = (1.19 ± 0.21) MeV

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

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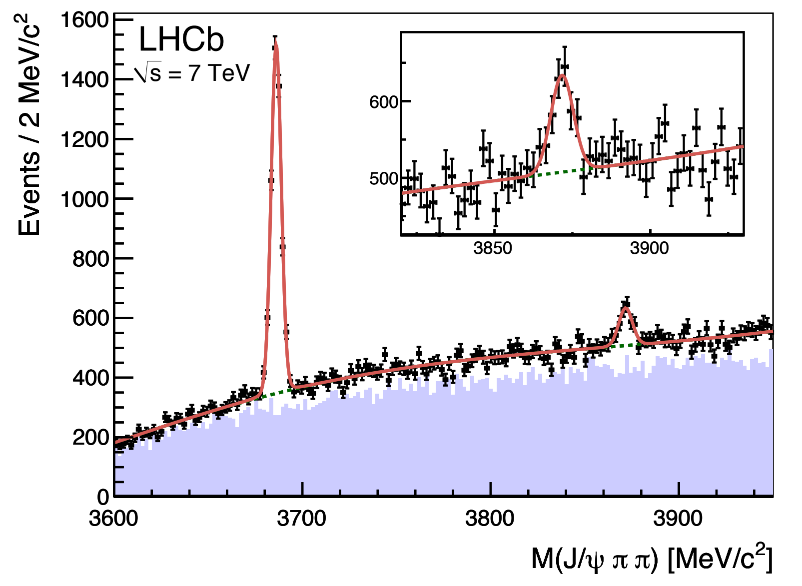

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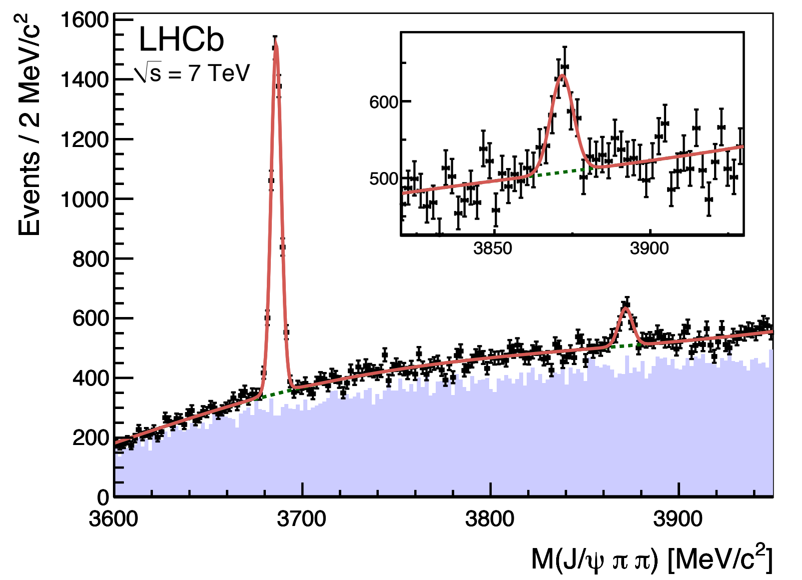

CDF LHCb CMS DØ

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M = (4478±16) MeV

Γ = (181±31) MeV

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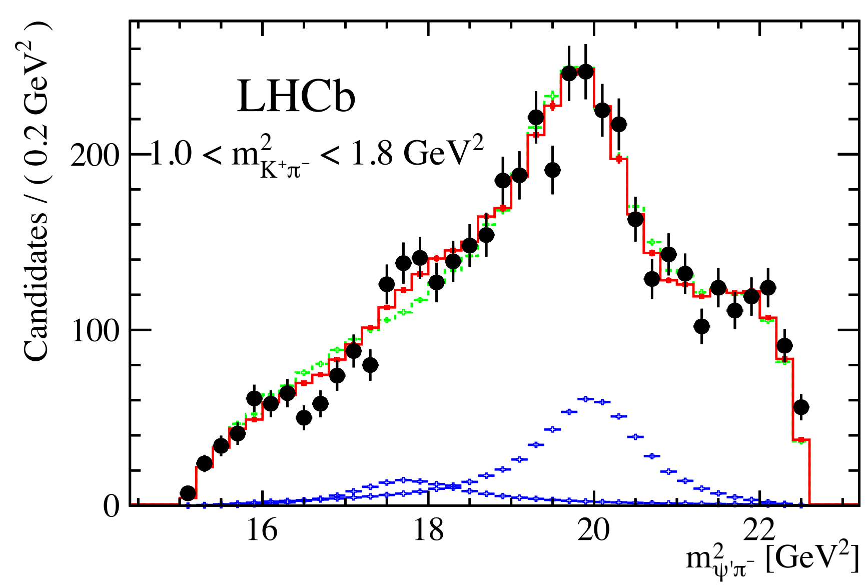
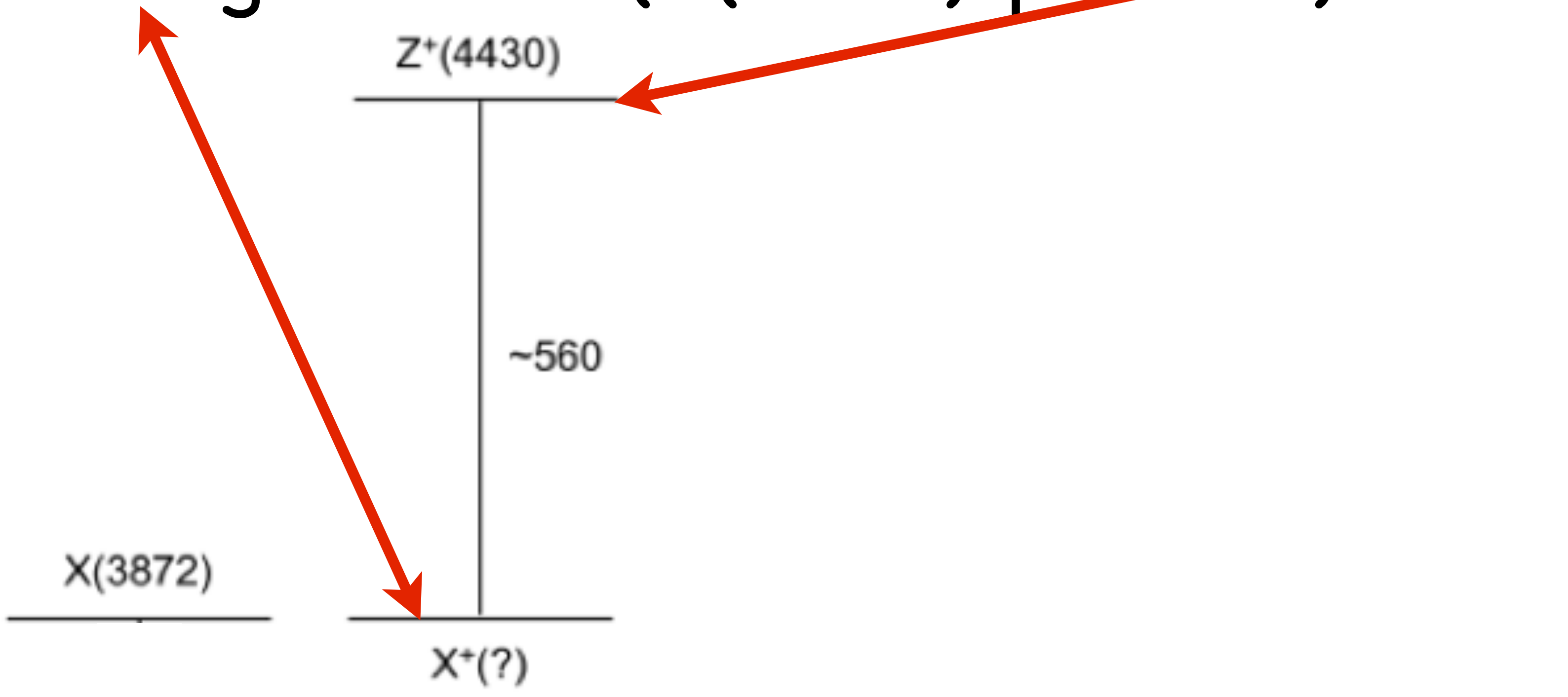


Maiani et al. (arXiv:0708.3997) : four-quark radial excitation of the 1^+ charged state (X(3872) partner)



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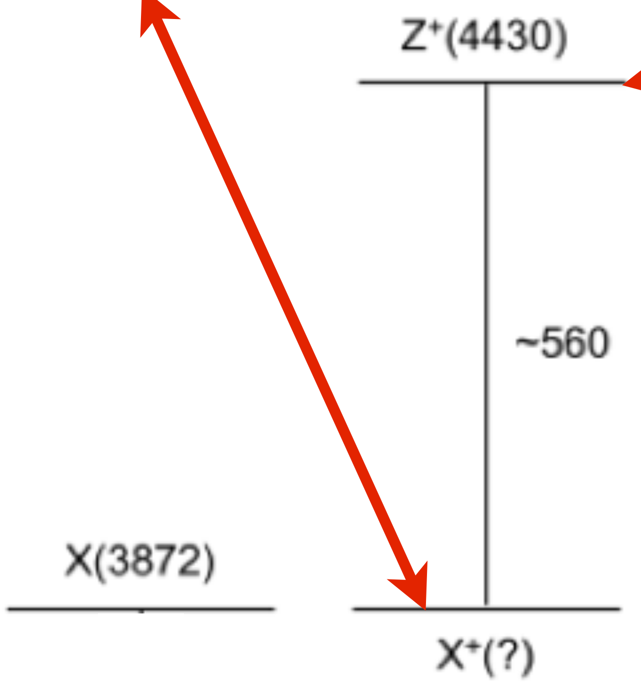

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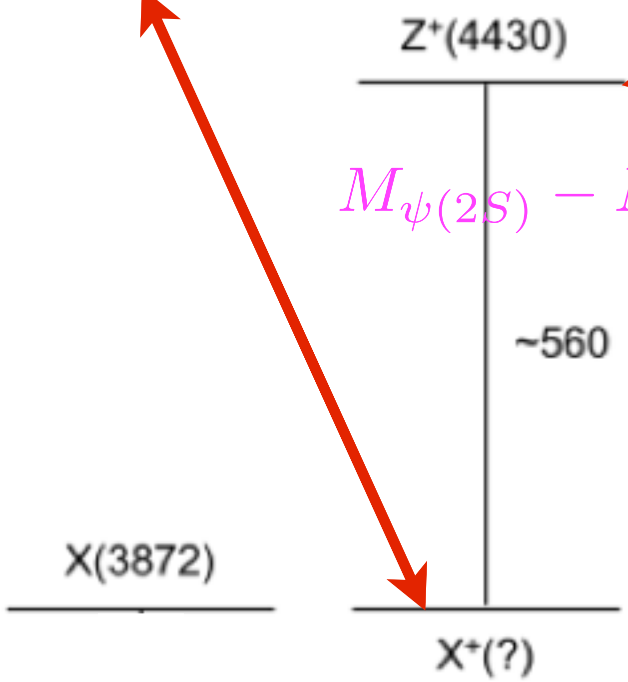
$M_{\psi(2S)} - M_{\psi(1S)} \sim 590 \text{ MeV} \sim M_{Z^+} - M_X$



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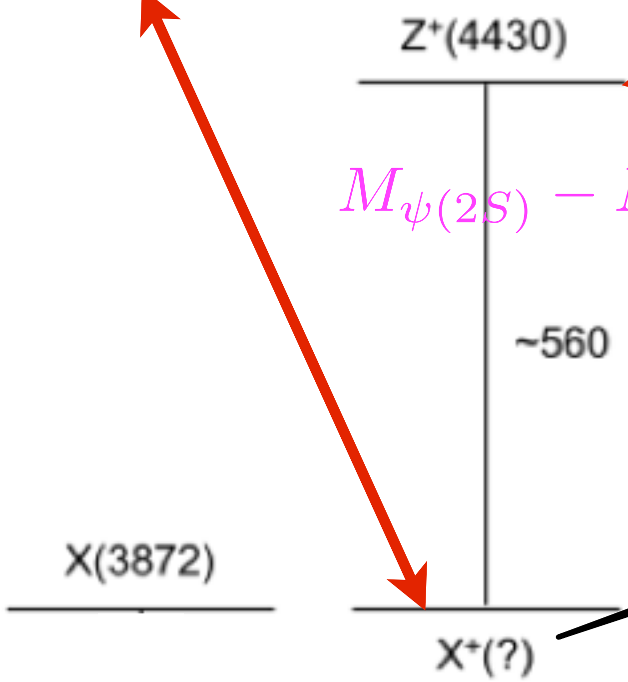

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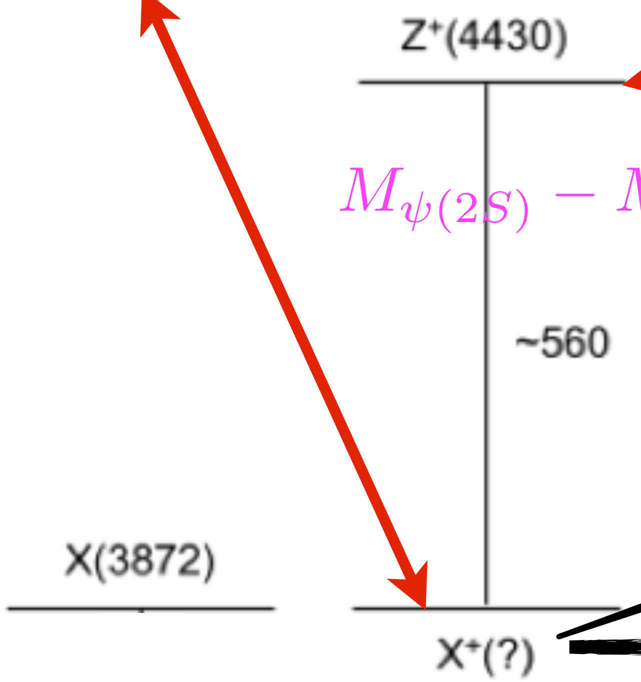

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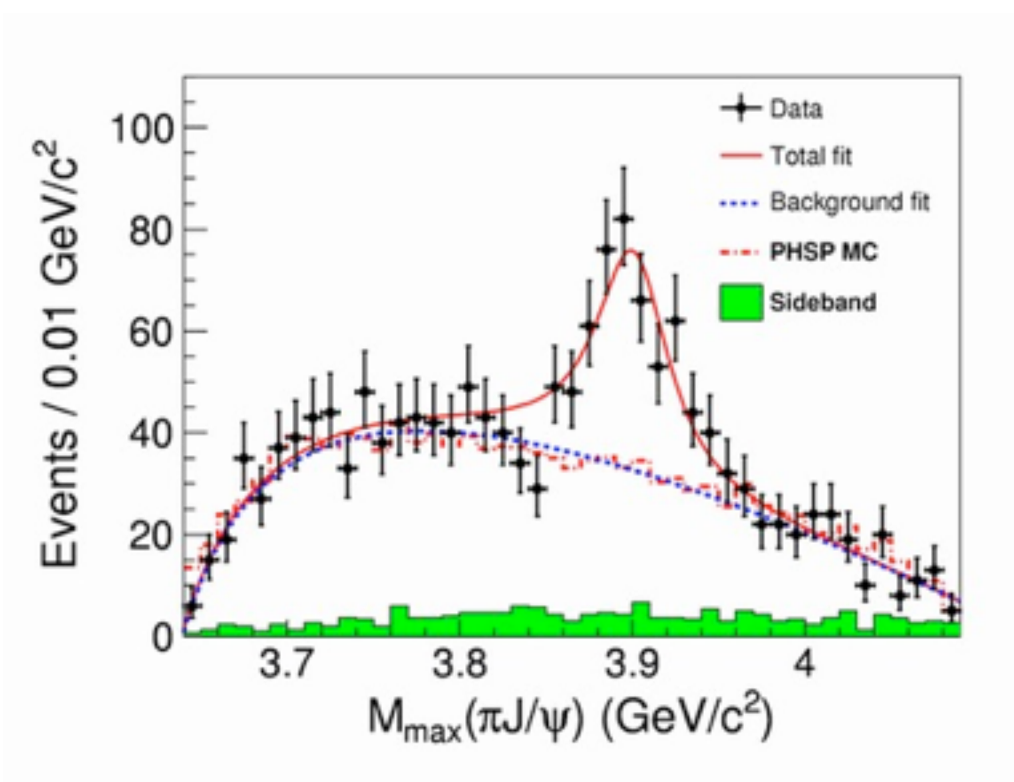
$Z_c^+(3900)$

- 2013: Observation of $Z_c^+(3900)$ by Belle and BESIII



$Z_c^+(3900)$

BES III arXiv:1303.5949

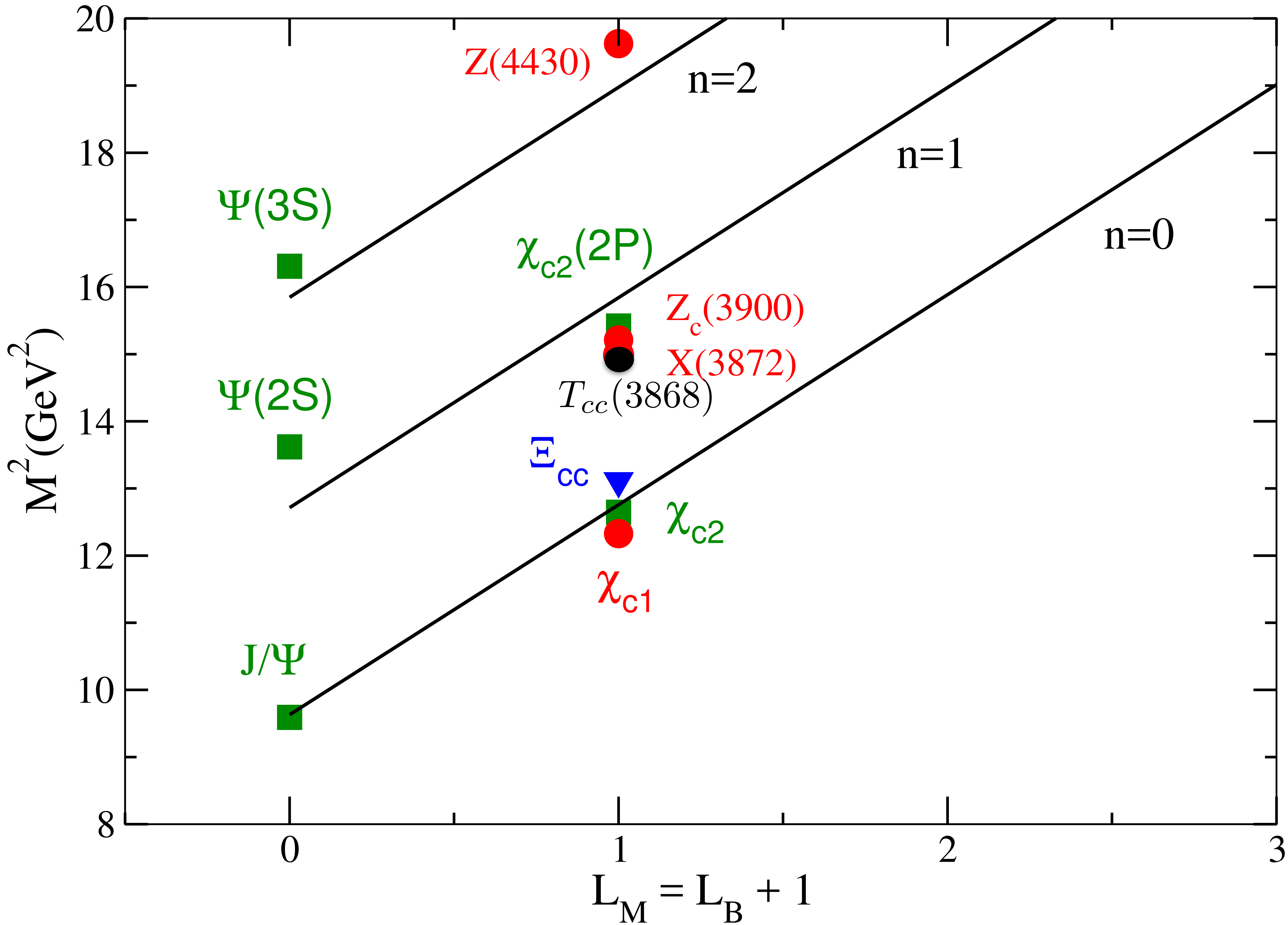
BELLE arXiv:1304.0121

$$Y(4260) \to (J/\psi\pi^+)\pi^-$$

M = (3887.1±2.6) MeV
Γ = (28.4±2.6) MeV
$J^P=1^+$

SuSyLFHQCD

MN, Brodsky, Téramond, Dosch, Navarra, Zou (arXiv:1805.11567)



- 2011: Observation of $Z_b^+(10610)$ by Belle: the first beauty charged tetraquark state: $J^P=1^+$, $M=(10{,}607\pm2)$ MeV, $\Gamma=(18.4\pm2.4)$ MeV

$$M_{B^*} + M_B = 10{,}605 \text{ MeV} \Rightarrow Z_b^+(10610) \leftrightarrow Z_c^+(3900)$$

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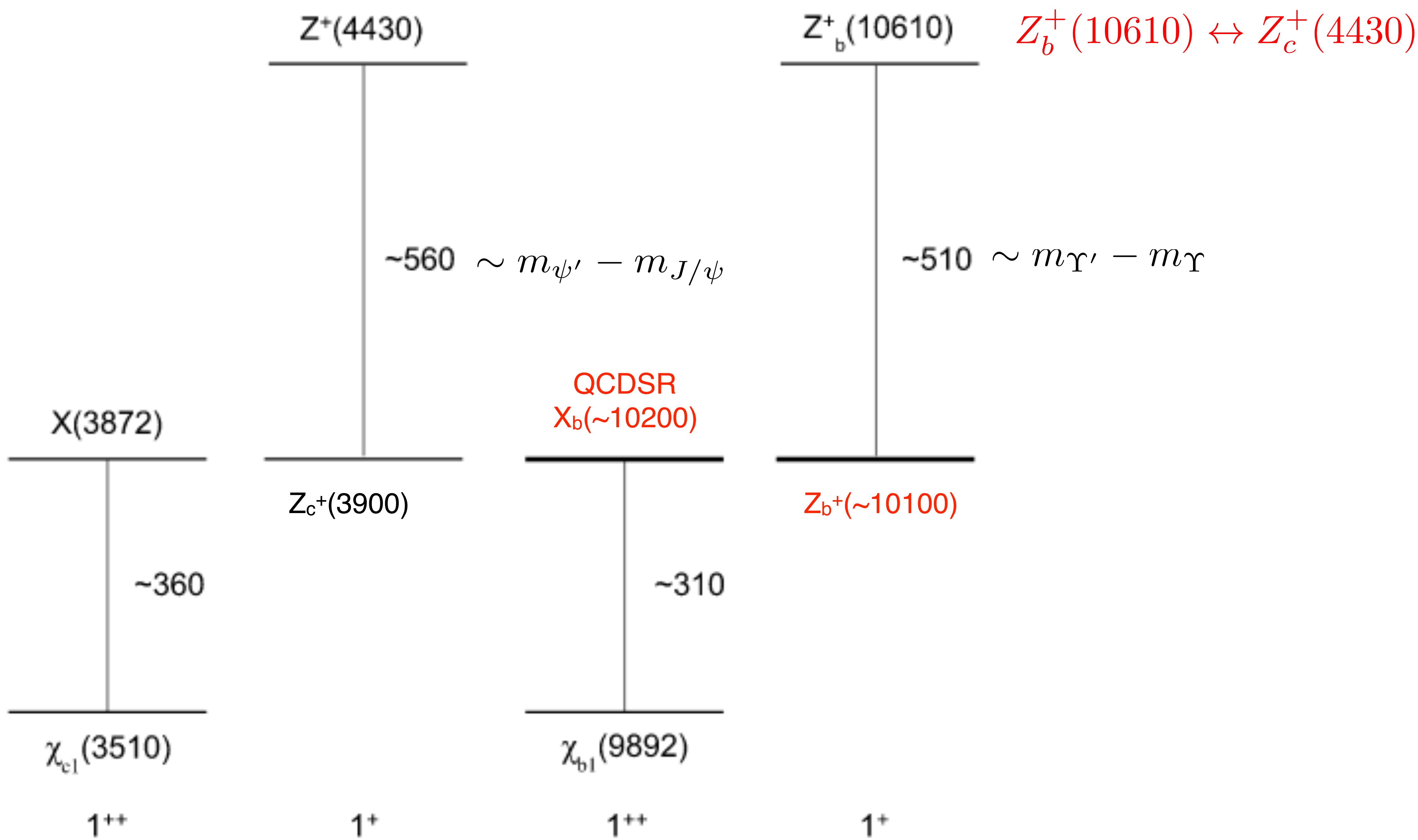

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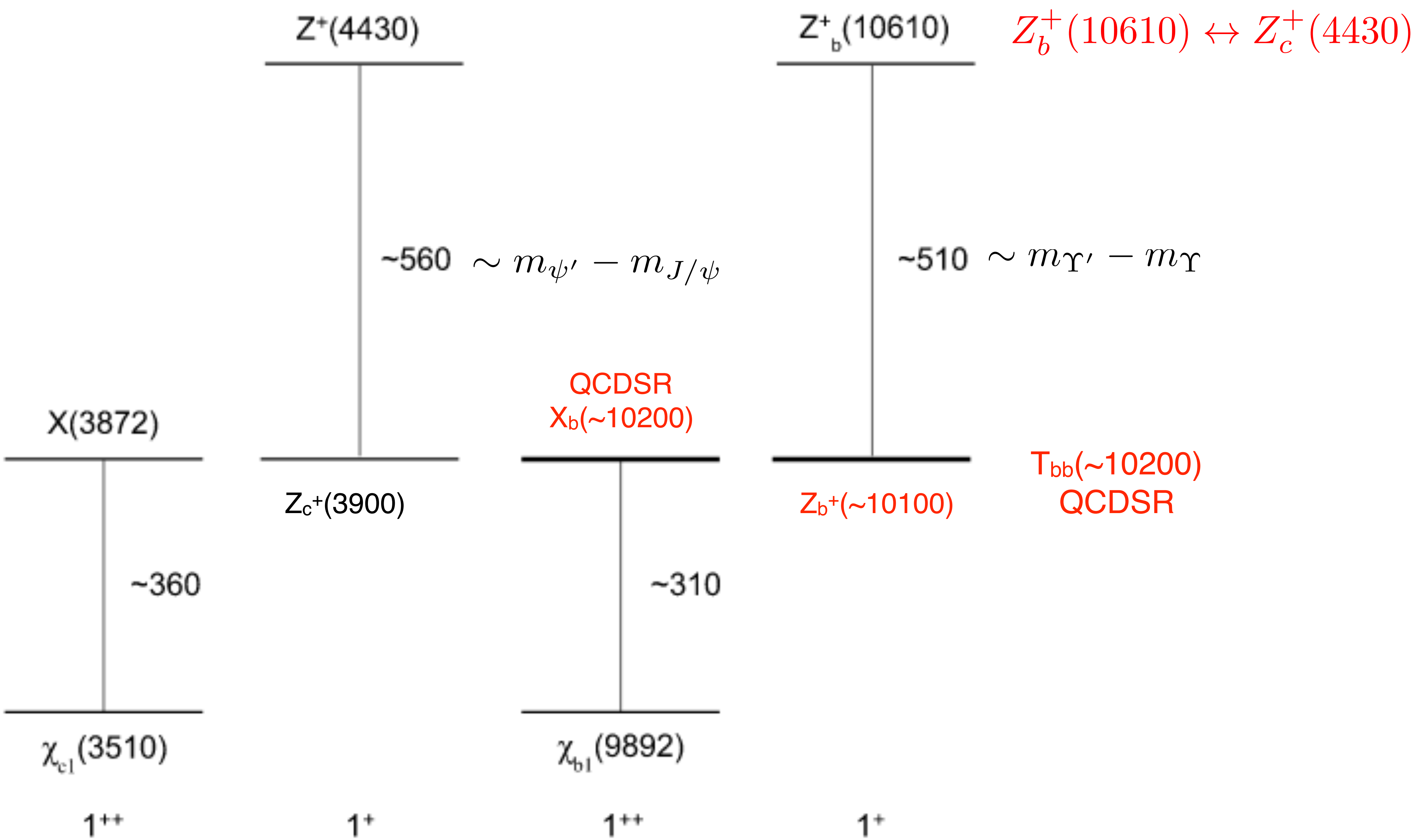
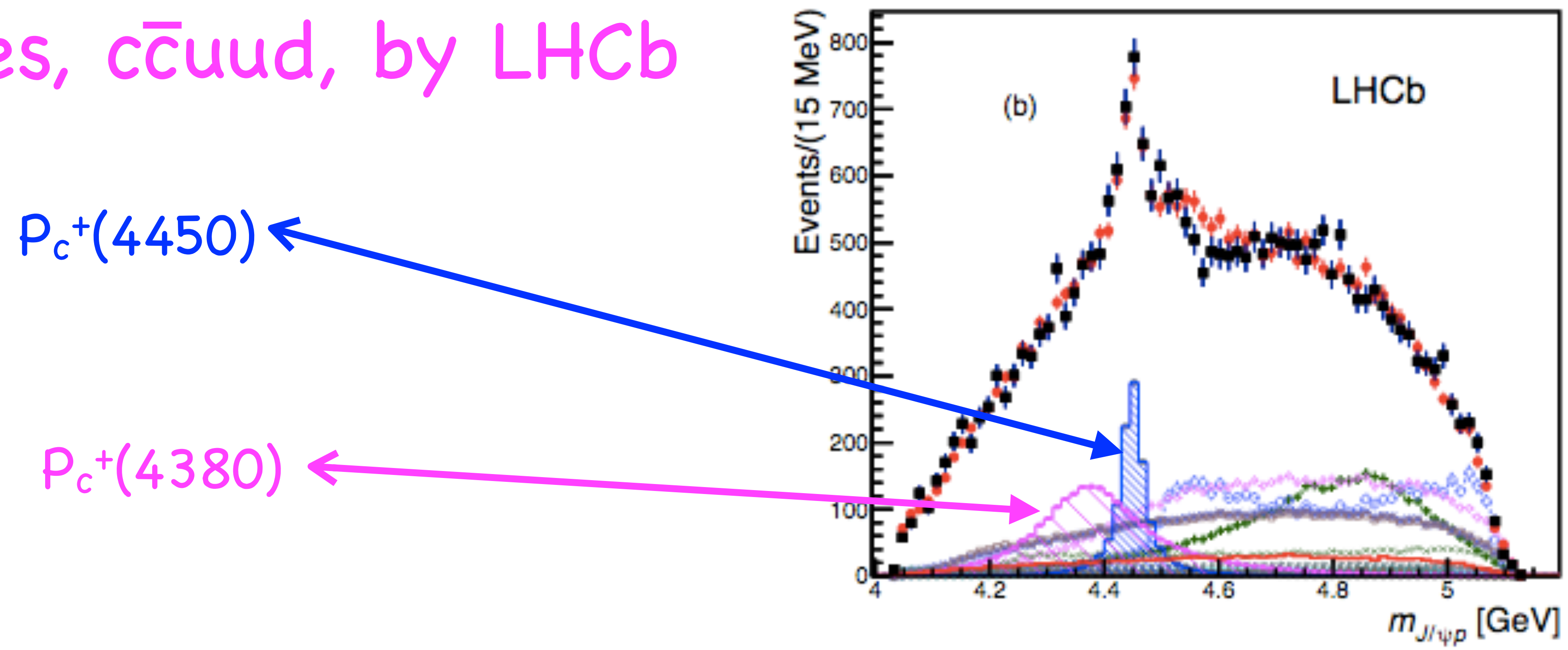


- 2015: Observation of the first charmed pentaquark states, $c\bar{c}uud$, by LHCb



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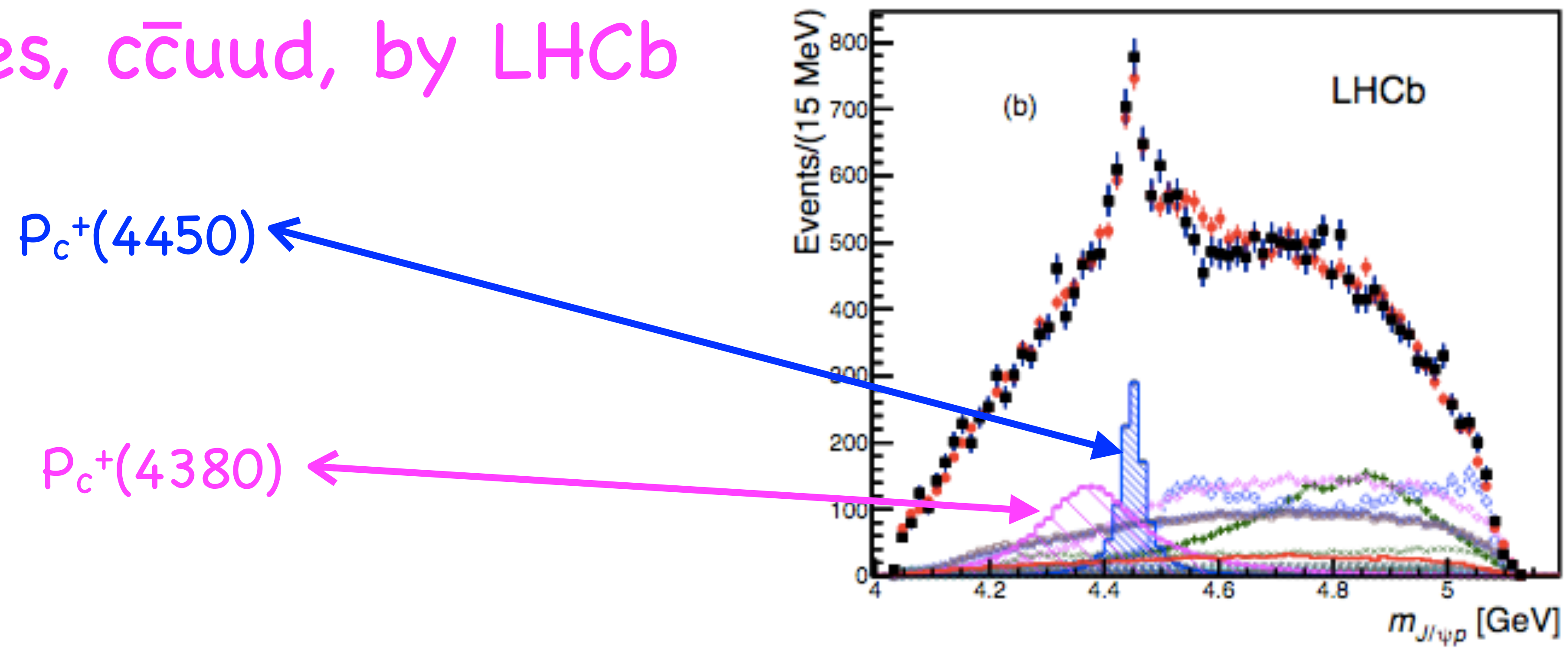
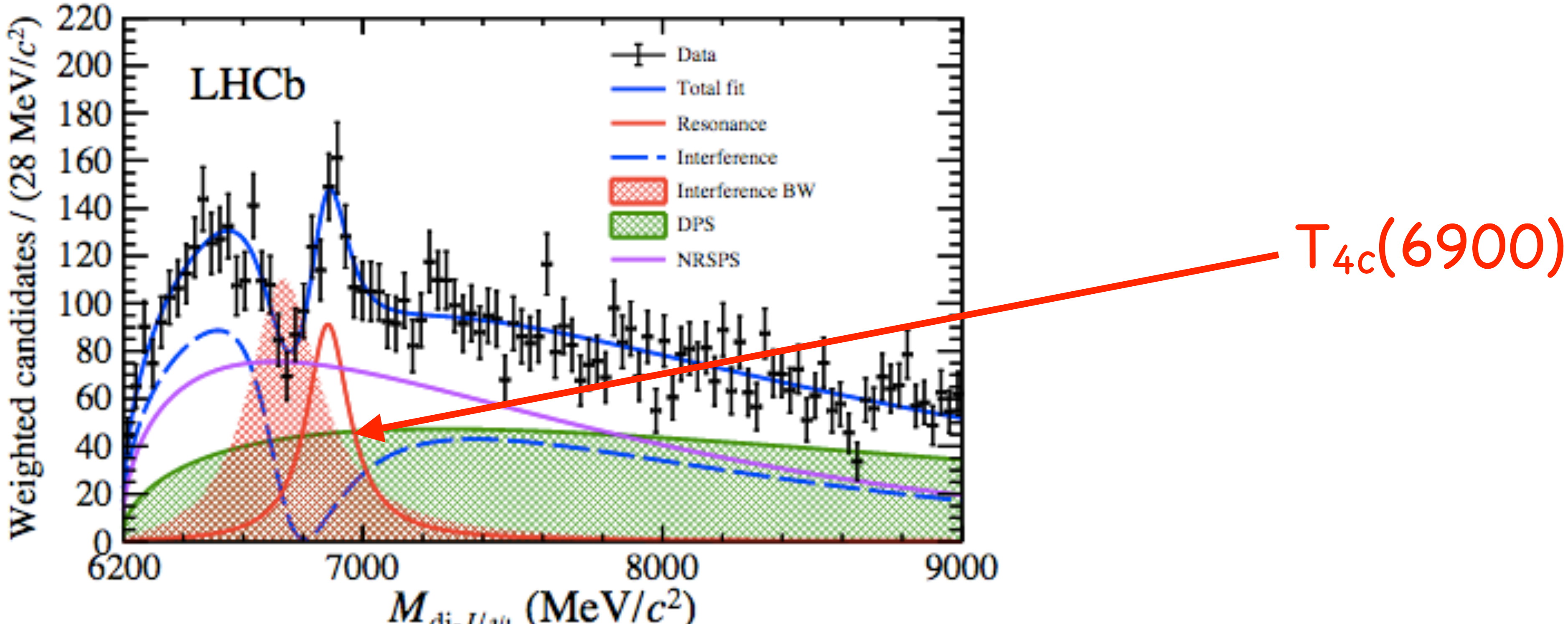
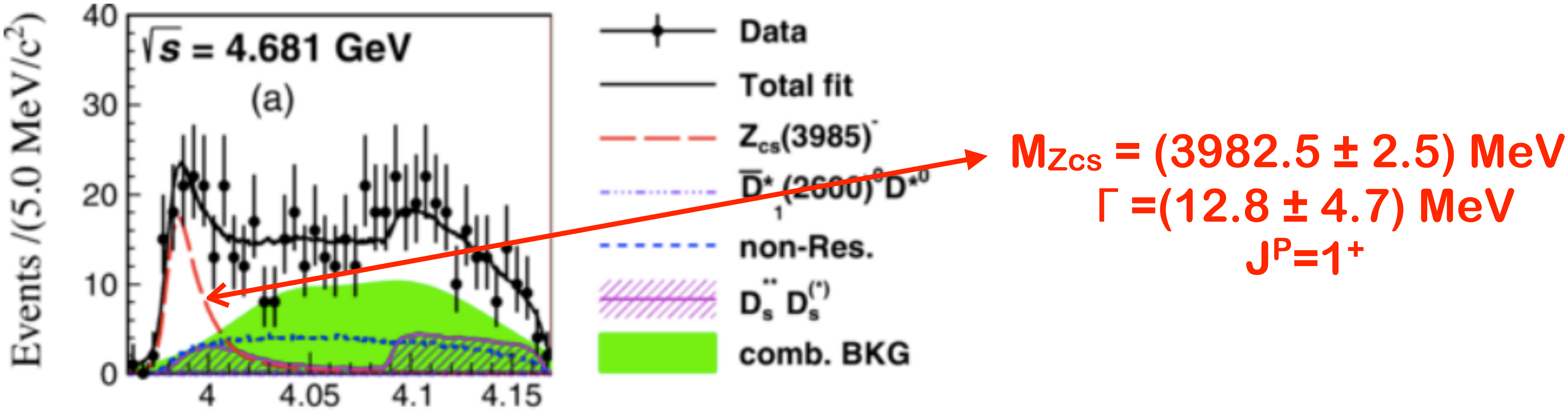


- 2020: Observation of the $X(cc\bar{c}\bar{c})$ by LHCb.



- 2020: Observation of $Z_{cs}^{-}(3985) \rightarrow D_s^{-(*)} D^{0(*)}$ by BESIII. The first strange charged tetraquark state.



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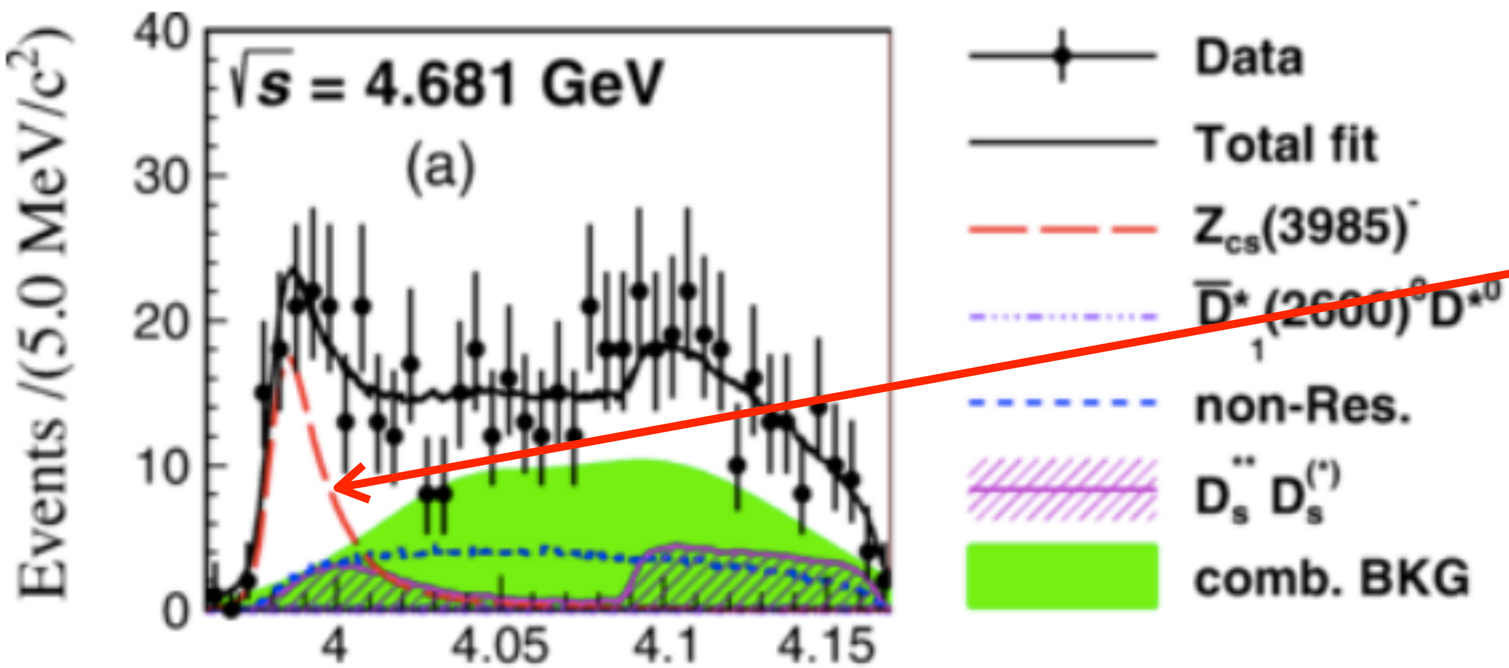
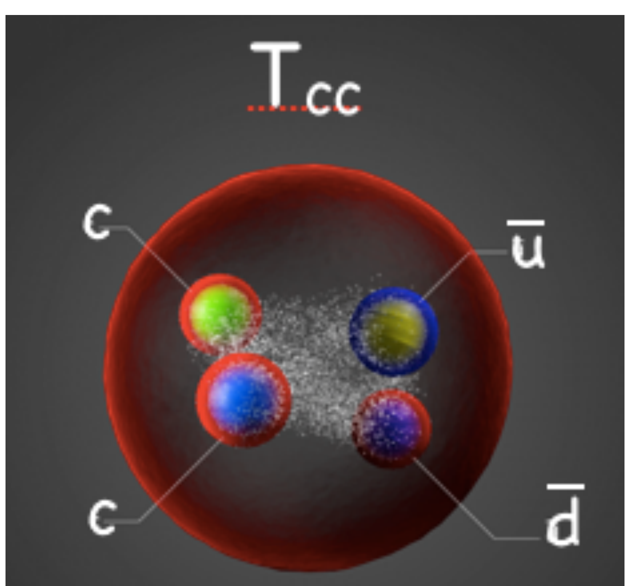
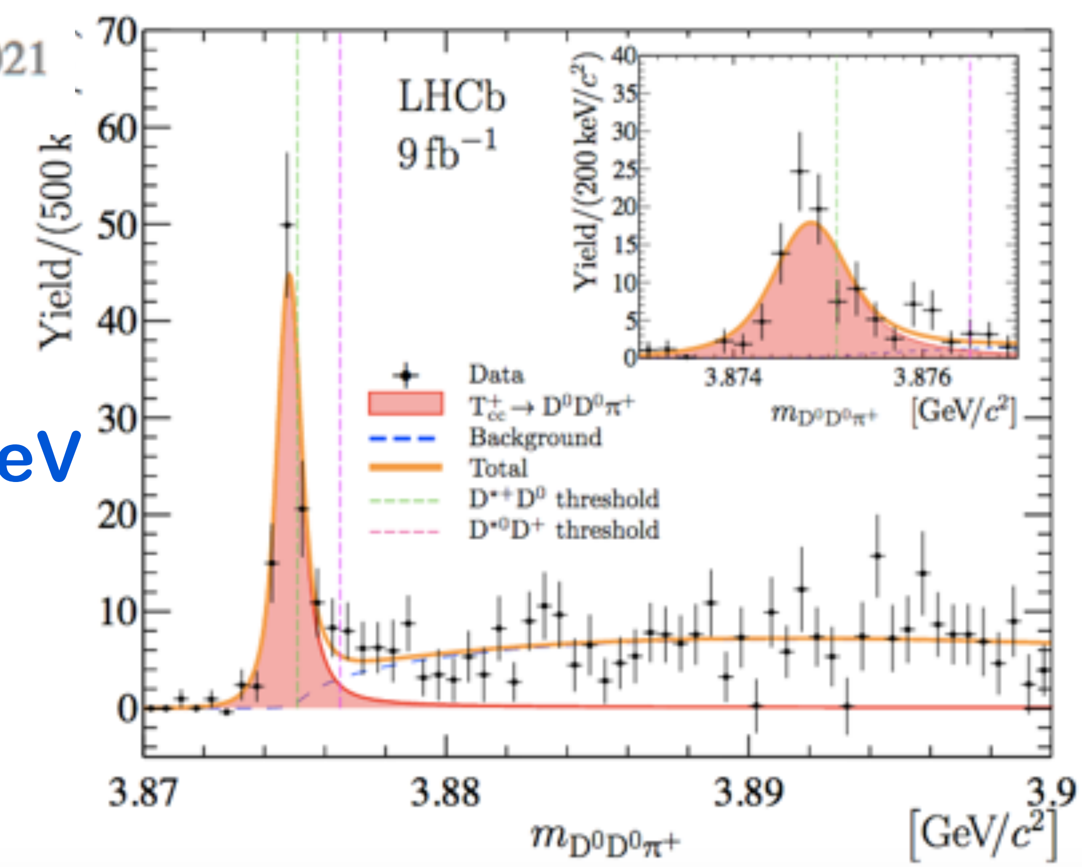


$M_{Z_{cs}}$ = (3982.5 ± 2.5) MeV
Γ =(12.8 ± 4.7) MeV
$J^P=1^+$

- 07/2021: Observation of T_{cc}: a double charmed tetraquark arXiv:2109.01038v2 [hep-ex] 3 Sep 2021



M = (3874.817±0.061) MeV
Γ = (0.410±0.170) MeV
$J^P=1^+$



Theoretical Predictions for T_{cc}

Reference		Year	$\delta' m$ [MeV/c^2]
J. Carlson, L. Heller and J. A. Tjon	[36]	1987	~ 0
B. Silvestre-Brac and C. Semay	[37]	1993	$+19$
C. Semay and B. Silvestre-Brac	[38]	1994	$[-1, +13]$
S. Pepin, F. Stancu, M. Genovese and J. M. Richard	[39]	1996	< 0
B. A. Gelman and S. Nussinov	[40]	2002	$[-25, +35]$
J. Vijande, F. Fernandez, A. Valcarce, A. and B. Silvestre-Brac	[41]	2003	-112
D. Janc and M. Rosina	[42]	2004	$[-3, -1]$
F. Navarra, M. Nielsen and S. H. Lee	[43]	2007	$+91$
J. Vijande, E. Weissman, A. Valcarce	[44]	2007	$[-16, +50]$
D. Ebert, R. N. Faustov, V. O. Galkin and W. Lucha	[45]	2007	$+60$
S. H. Lee and S. Yasui	[46]	2009	-79
Y. Yang, C. Deng, J. Ping and T. Goldman	[47]	2009	-1.8
G.-Q. Feng, X.-H. Guo and B.-S. Zou	[48]	2013	-215
Y. Ikeda, B. Charron, S. Aoki, T. Doi, T. Hatsuda, T. Inoue, N. Ishii, K. Murano, H. Nemura and K. Sasaki	[49]	2013	$[-70, +124]$
S.-Q. Luo, K. Chen, X. Liu, Y.-R. Liu and S.-L. Zhu	[50]	2017	$+100$
M. Karliner and J. Rosner	[51]	2017	$7 \pm 12 \to 1$
E. J. Eichten and C. Quigg	[52]	2017	$+102$
Z. G. Wang	[53]	2017	$+25 \pm 90$
G. K. C. Cheung, C. E. Thomas, J. J. Dudek and R. G. Edwards	[54]	2017	$\lesssim 0$
W. Park, S. Noh and S. H. Lee	[55]	2018	$+98$
A. Francis, R. J. Hudspith, R. Lewis and K. Maltman	[56]	2018	~ 0
P. Junnarkar, N. Mathur and M. Padmanath	[57]	2018	$[-40, 0]$
C. Deng, H. Chen and J. Ping	[58]	2018	-150
M.-Z. Liu, T.-W. Wu, V. Pavon Valderrama, J.-J. Xie and L.-S. Geng	[59]	2019	-3^{+4}_{-15}
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S. Noh, W. Park and S. H. Lee	[66]	2021	$+13$
R. N. Faustov, V. O. Galkin and E. M. Savchenko	[67]	2021	$+64$

Theoretical Predictions for T_{cc}

1987

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C. Semay and B. Silvestre-Brac	[38]	1994	[−1, +13]
S. Pepin, F. Stancu, M. Genovese and J. M. Richard	[39]	1996	< 0
B. A. Gelman and S. Nussinov	[40]	2002	[−25, +35]
J. Vijande, F. Fernandez, A. Valcarce, A. and B. Silvestre-Brac	[41]	2003	−112
D. Janc and M. Rosina	[42]	2004	[−3, −1]
F. Navarra, M. Nielsen and S. H. Lee	[43]	2007	+91
J. Vijande, E. Weissman, A. Valcarce	[44]	2007	[−16, +50]
D. Ebert, R. N. Faustov, V. O. Galkin and W. Lucha	[45]	2007	+60
S. H. Lee and S. Yasui	[46]	2009	−79
Y. Yang, C. Deng, J. Ping and T. Goldman	[47]	2009	−1.8
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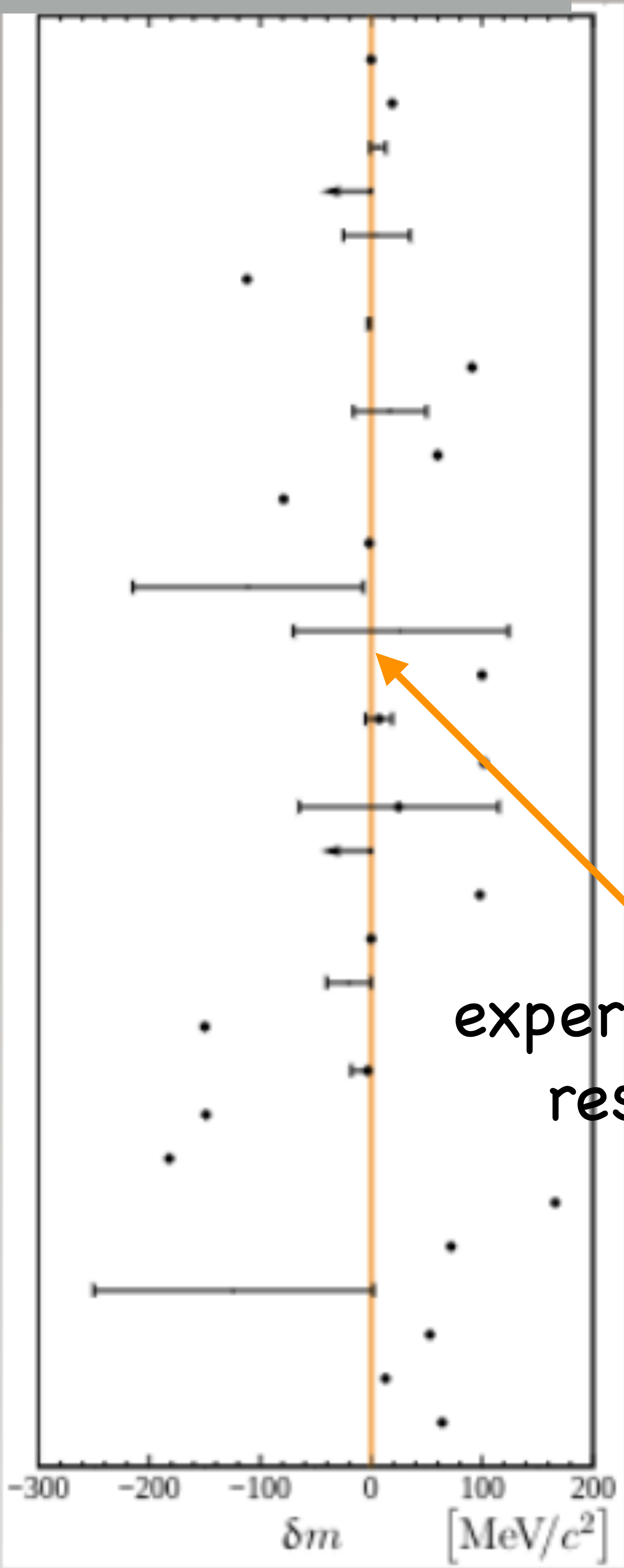

experimental result

Theoretical Predictions for T_{cc}

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2021

experimental result

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experimental result

QCD Sum Rule

Fundamental Assumption: Principle of Duality

$$\Pi(q) = i \int d^4x \, e^{iq.x} \, \langle 0|T[j(x)j^\dagger(0)]|0\rangle$$

Theoretical side

quark level
quark and gluon
degrees of freedom

Wilson OPE

Phenomenological side

hadron level
hadron parameters
(masses, couplings,
form-factors,...)

dispersion relation

$$\Pi_i^{phen} \leftrightarrow \Pi_i^{OPE}$$

$$\Pi^{phen} = -\lambda^2 \frac{1}{m^2 - q^2} + continuum$$

$\lambda \Rightarrow$ coupling current-state

$$\Pi^{OPE}(q^2) = \int_{s_{min}}^{\infty} ds \; \frac{\rho^{OPE}(s)}{s - q^2}, \;\; \rho^{OPE}(s) = \frac{1}{\pi} Im[\Pi^{OPE}]$$

$$\Pi^{phen} = -\lambda^2 \frac{1}{m^2 - q^2} + continuum$$

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$$\boldsymbol{continuum = \int_{s_0}^{\infty} ds \, \frac{\rho^{OPE}(s)}{s - q^2}}$$

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$$continuum = \int_{s_0}^{\infty} ds \, \frac{\rho^{OPE}(s)}{s - q^2}$$

s_0: continuum parameter

$$\Pi^{phen}(Q^2) \leftrightarrow \Pi^{OPE}(Q^2)$$

valid at small Q^2

valid at large Q^2

To improve the matching $\Rightarrow$ Borel transform

Borel Transform
- eliminates subtraction terms
- suppresses higher order condensates
- increases importance pole contribution

$$\lambda^2 e^{-m^2/M^2} = \int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ \rho^{OPE}(s)$$

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$$m^2 = \frac{\int_{s_{min}}^{s_0} ds\ s\ \rho_i^{OPE}(s)\ e^{-s/M^2}}{\int_{s_{min}}^{s_0} ds\ \rho_i^{OPE}(s)\ e^{-s/M^2}}$$

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Good Sum Rule ➡ Borel window such that:

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Good Sum Rule ➡ Borel window such that:

- pole contribution > continuum contribution
- good OPE convergence
- good Borel stability

To improve the matching $\Rightarrow$ Borel transform

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Good Sum Rule ➡ Borel window such that:

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OPE side: condensates
- quark condensate
- gluon condensate
- mixed condensates
- four-quark condensate

First QCD Sum Rule Calculation for X(3872)

Matheus, Narison, MN, Richard: tetraquark current (PRD75(07)014005)

$$j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T) + (q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)]$$

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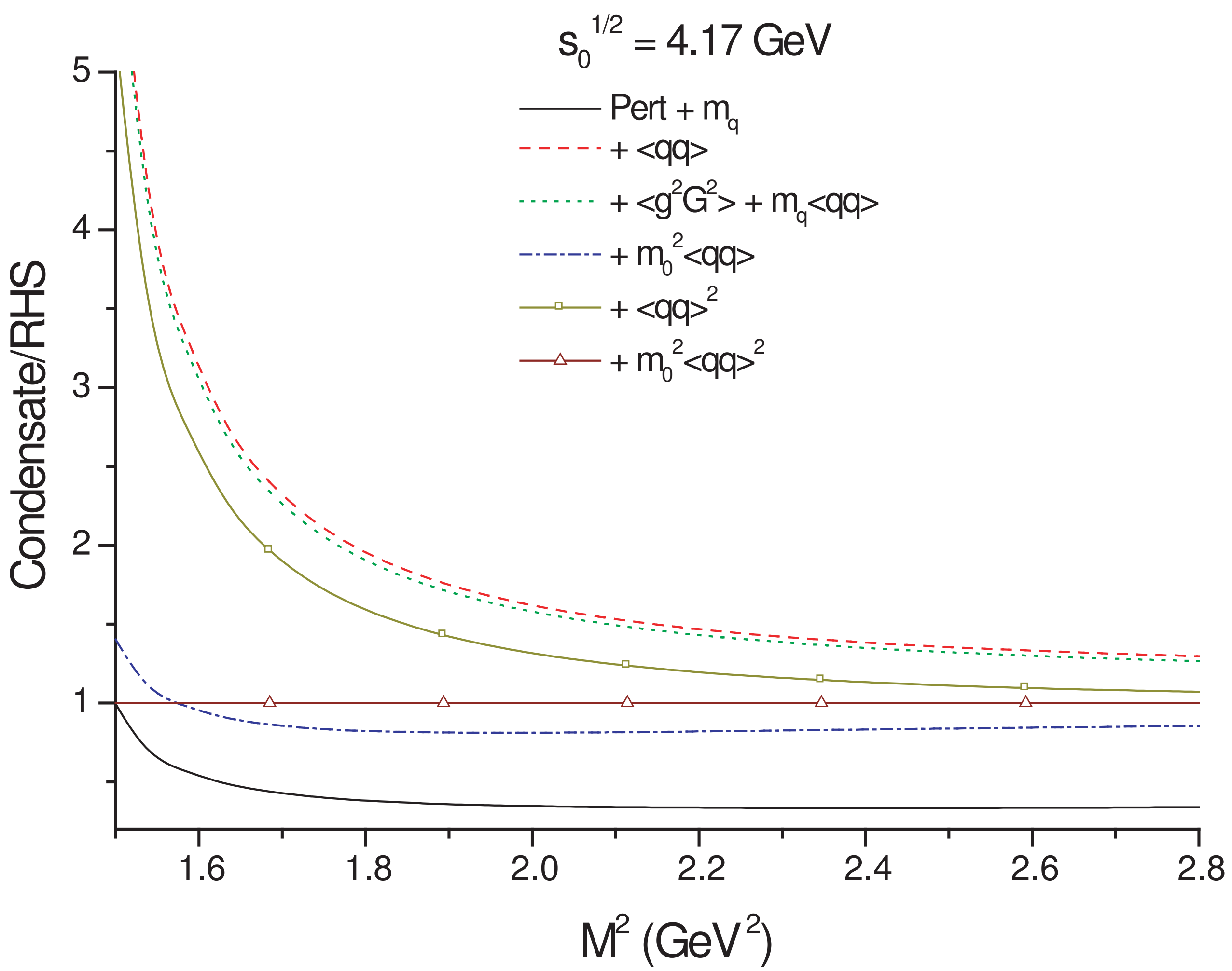

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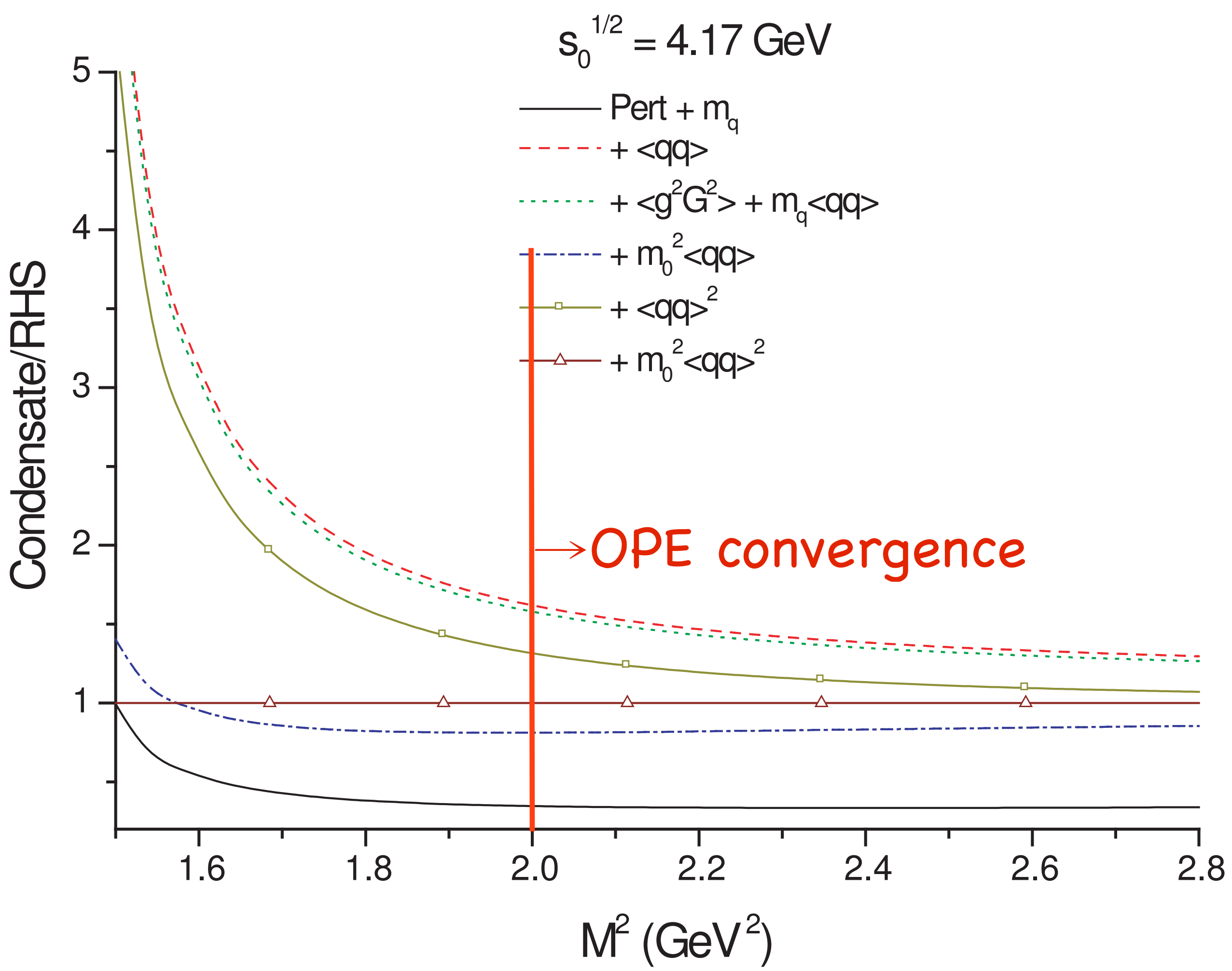

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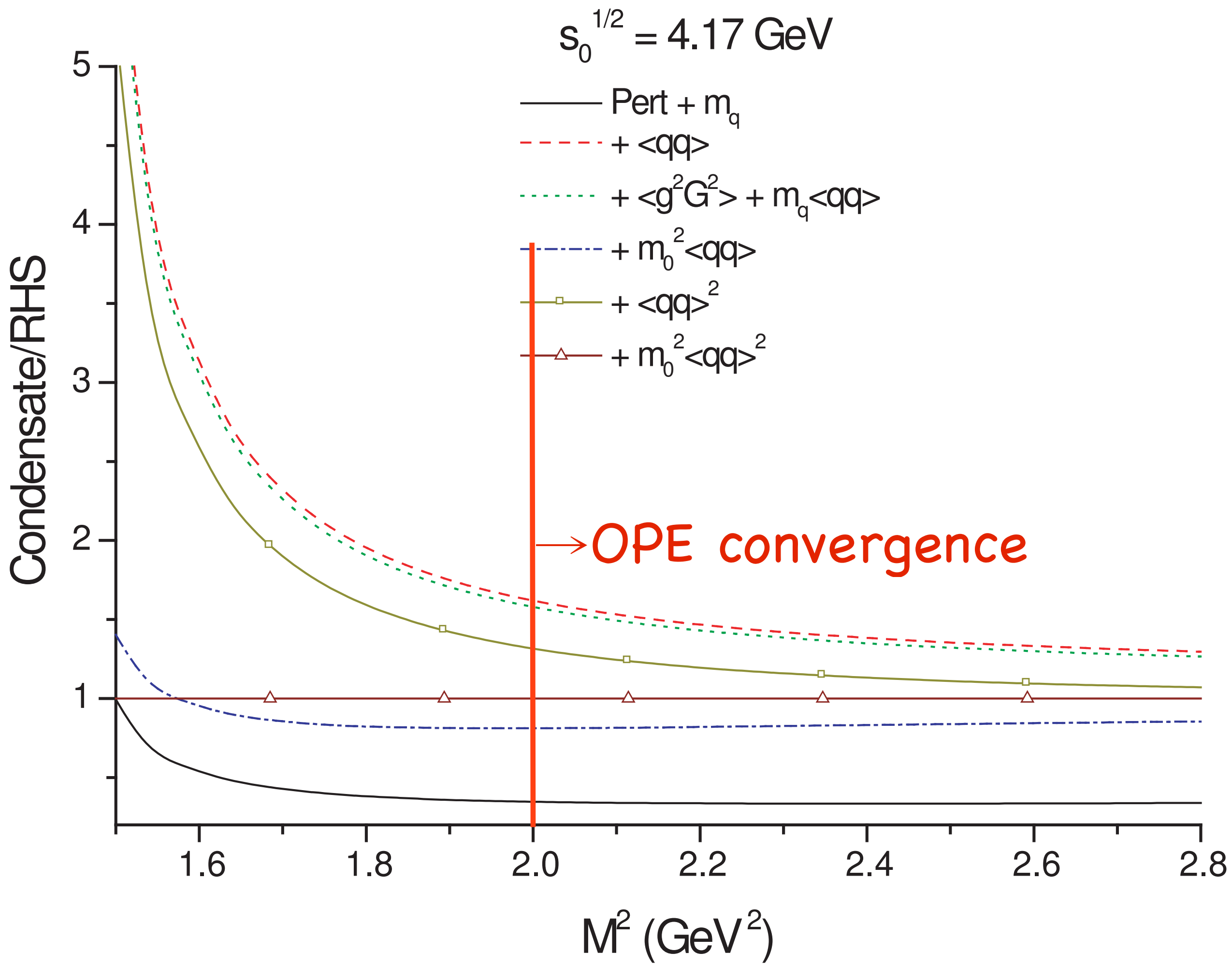

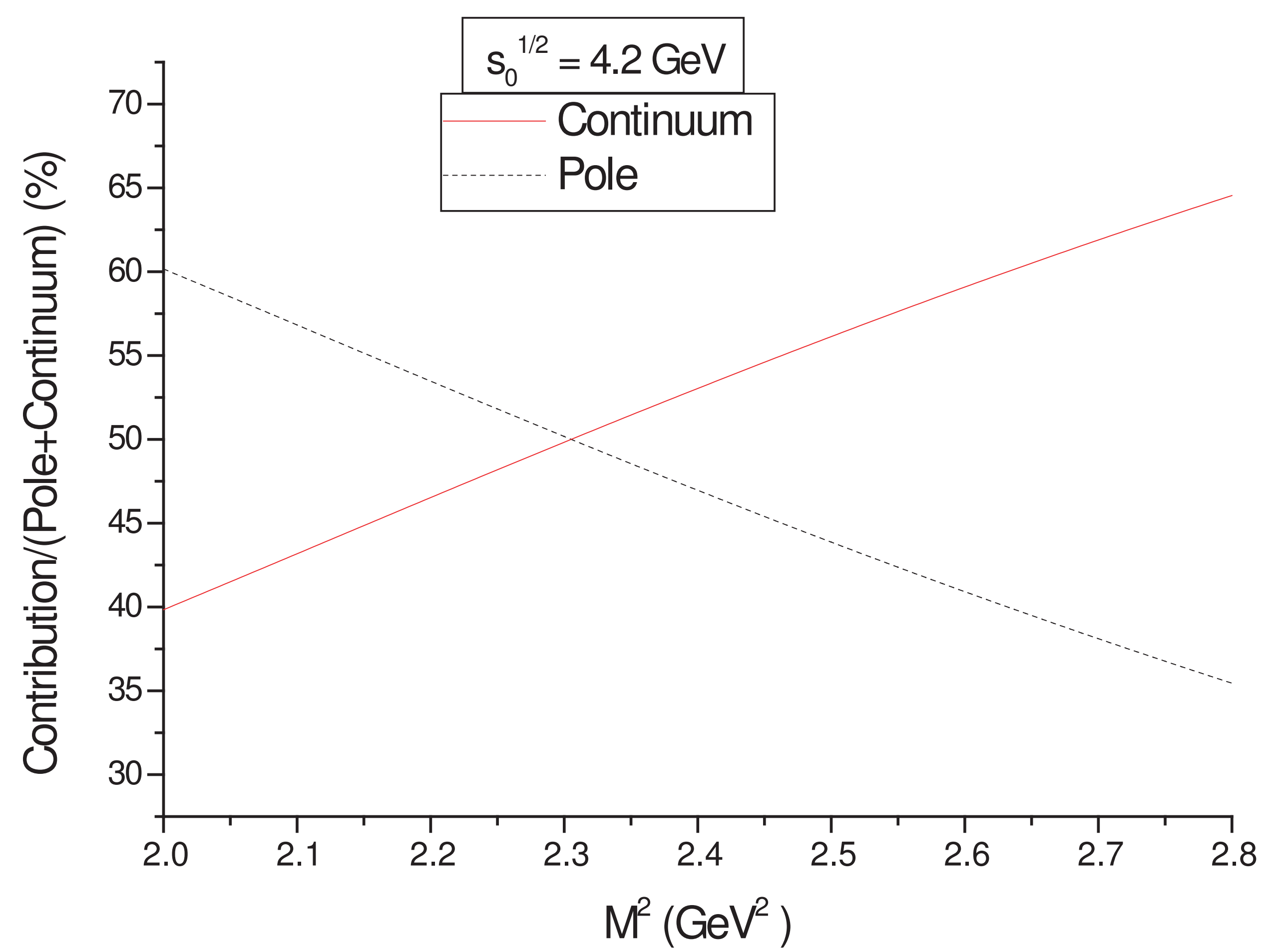

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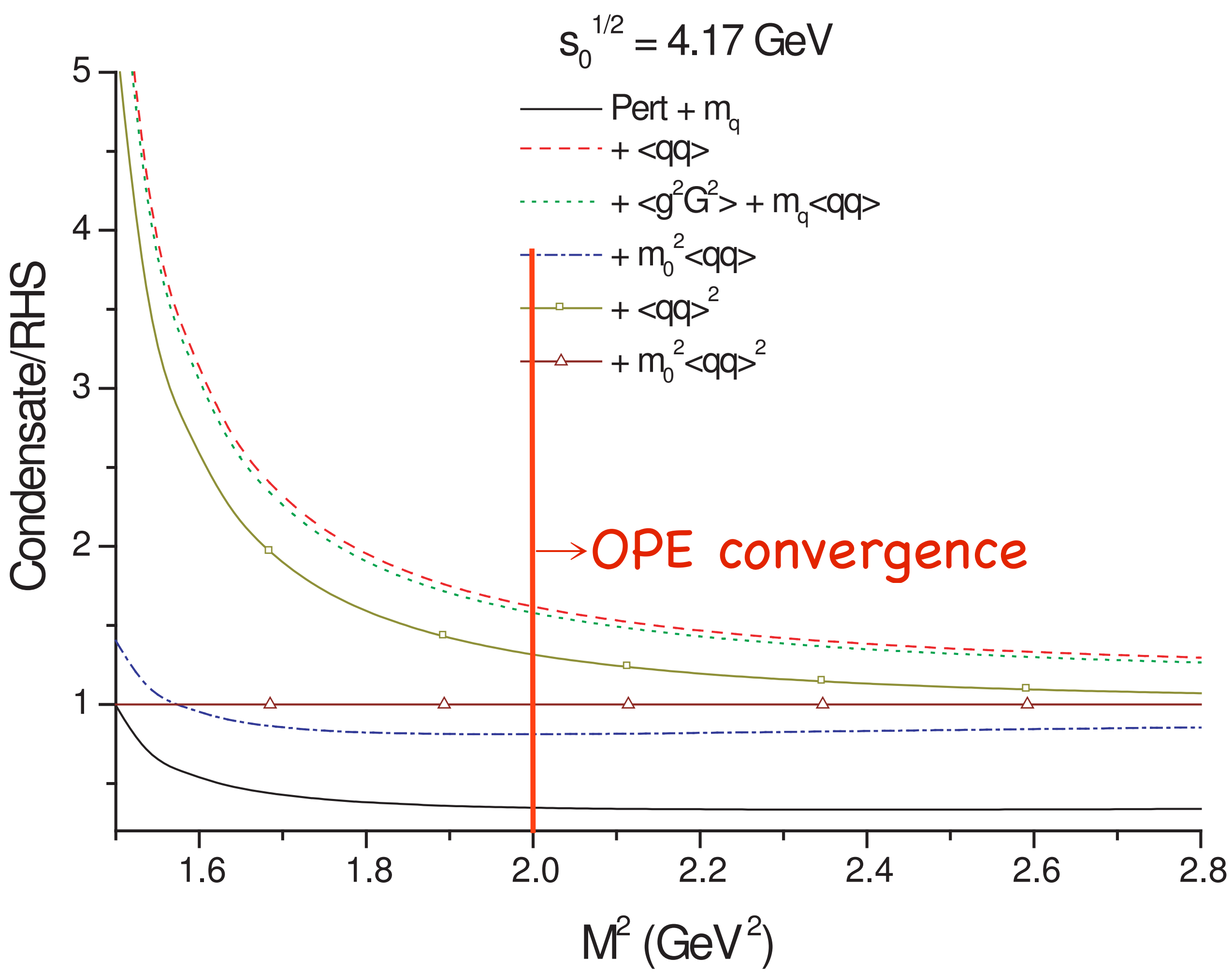
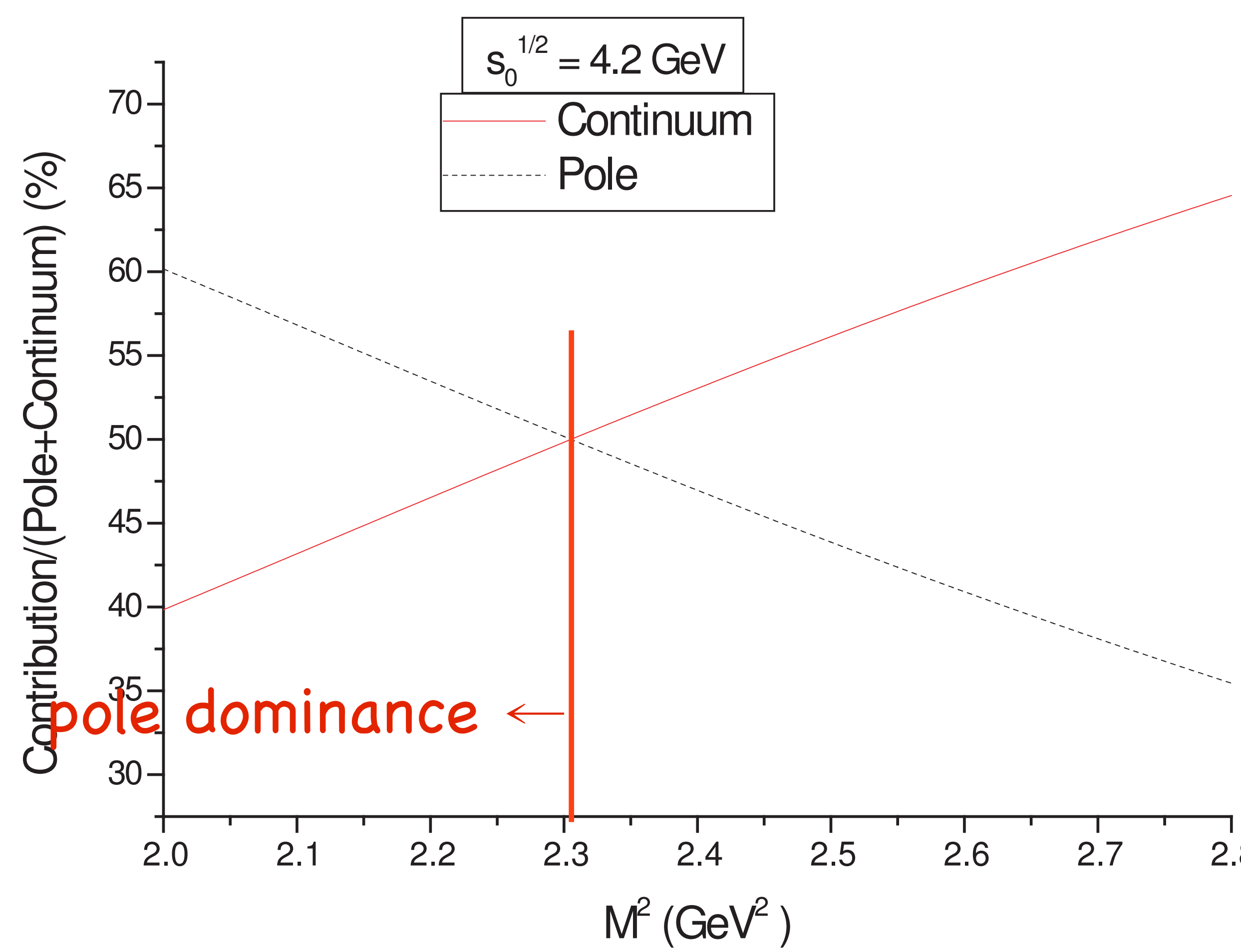
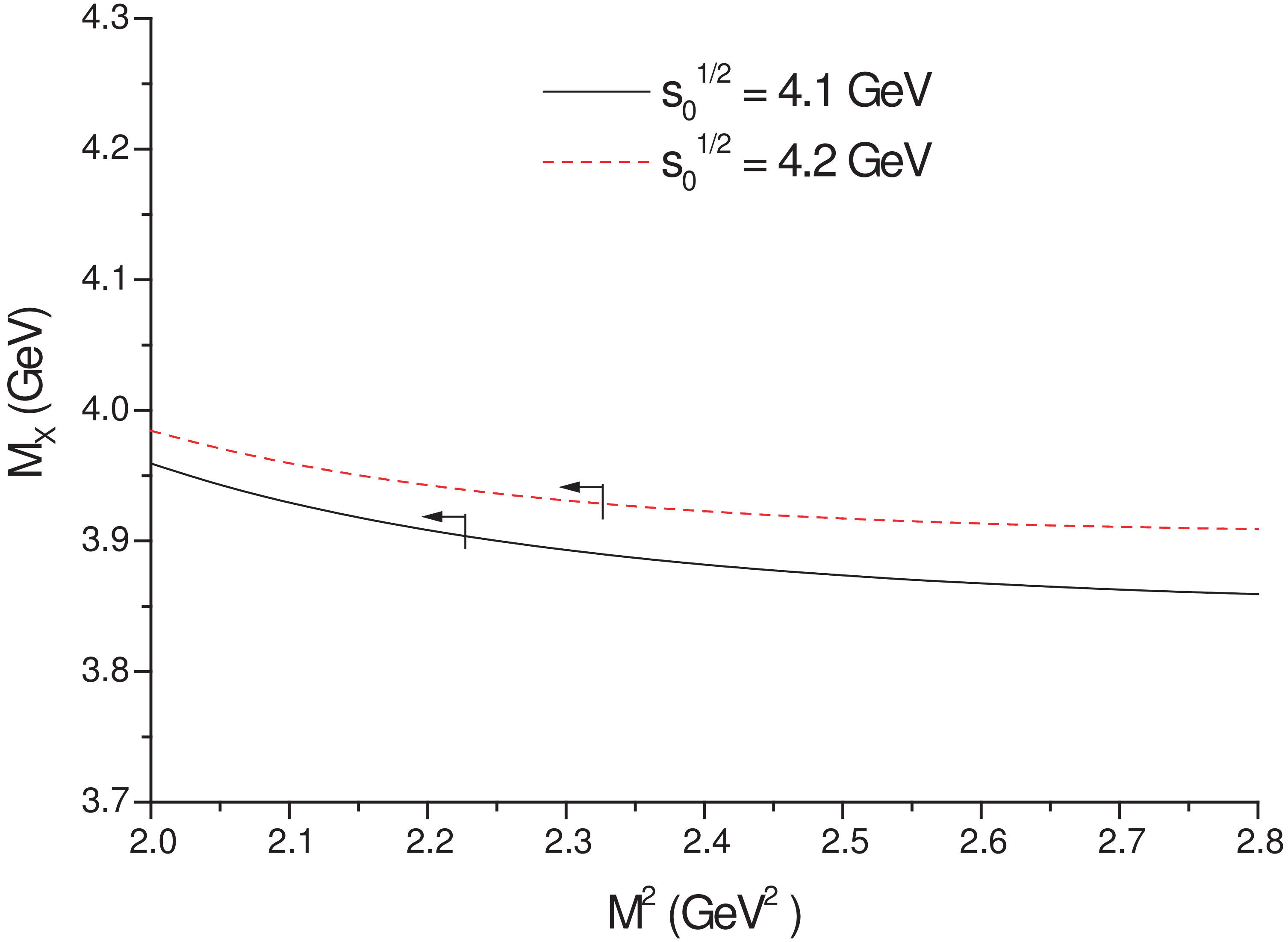
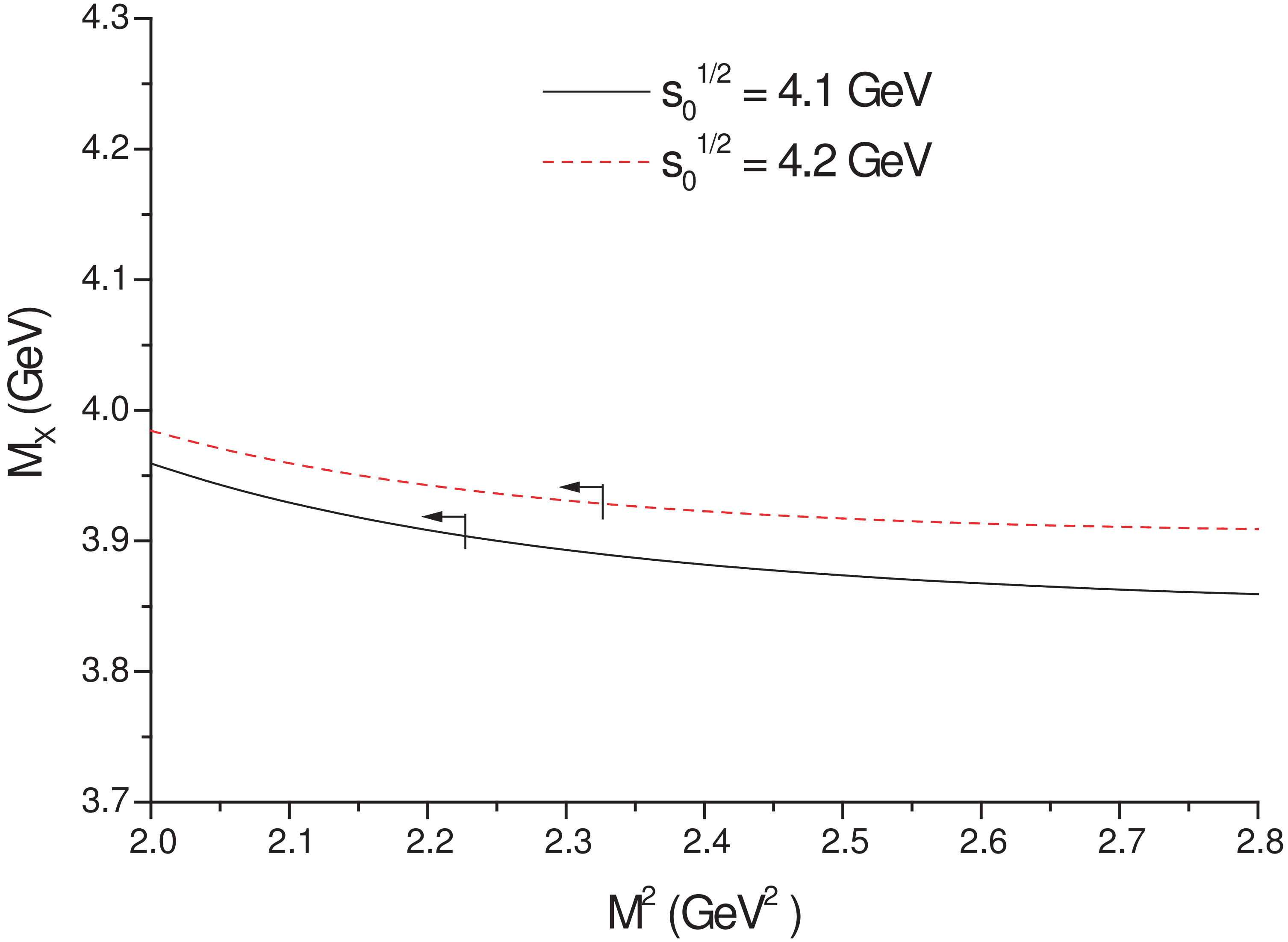






$$m_X = (3.92 \pm 0.13) \text{ GeV}$$



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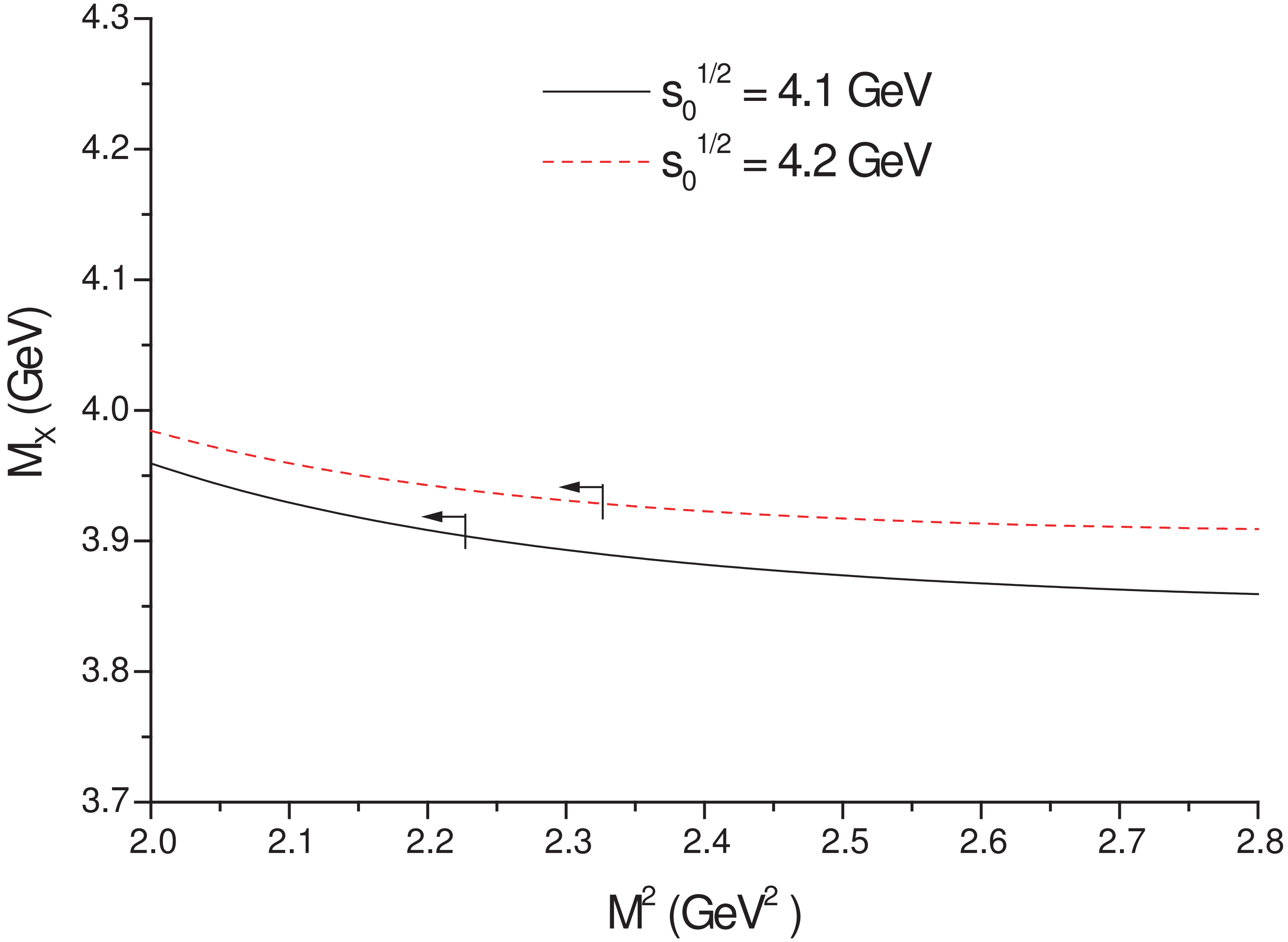
Prediction for X_b:

$$m_{X_b} = (10.26 \pm 0.30)\ \text{GeV}$$



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Lee, MN, Wiedner: $D^0 \bar{D}^{*0}$ molecular current (arXiv:0803.1168)

$$j_\mu^{(q,mol)}(x) = \frac{1}{\sqrt{2}}\Big[(\bar{q}_a(x)\gamma_5 c_a(x)\bar{c}_b(x)\gamma_\mu q_b(x)) - (\bar{q}_a(x)\gamma_\mu c_a(x)\bar{c}_b(x)\gamma_5 q_b(x)) \Big]$$

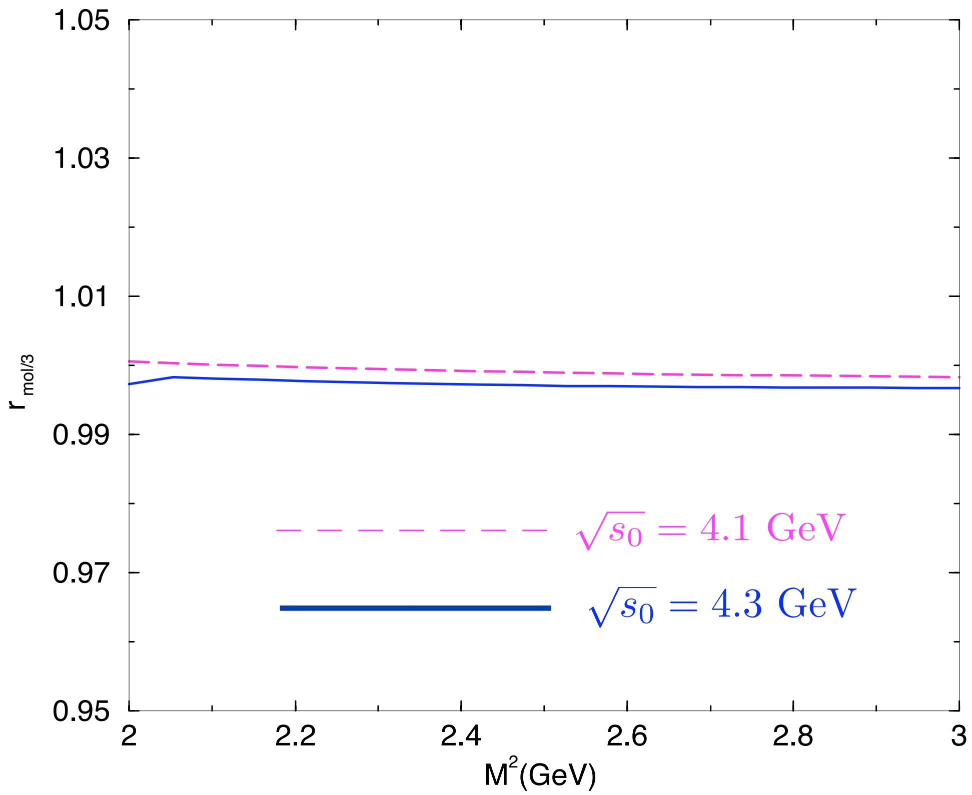
$$m_X = (3.87 \pm 0.07)\ \text{GeV}$$

double-ratio sum rules:

$$r_{mol/3} = \frac{M_{mol}}{M_3}$$

Narison, Navarra, MN, PRD83(11)016004

differences smaller than 0.01%



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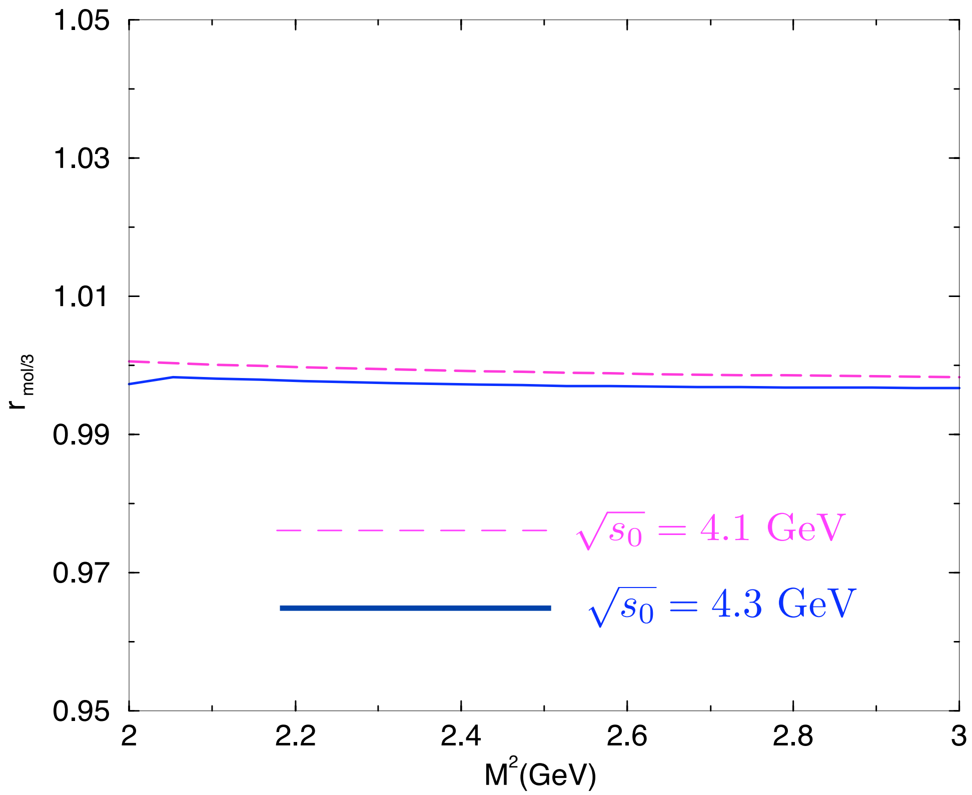

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Since T_{cc} ($cc\bar{q}\bar{q}$) can be described by a DD^* current and X(3872) ($c\bar{c}q\bar{q}$) by a $\bar{D}D^*$ current, similar comparison can also be made for X and T_{cc} states.

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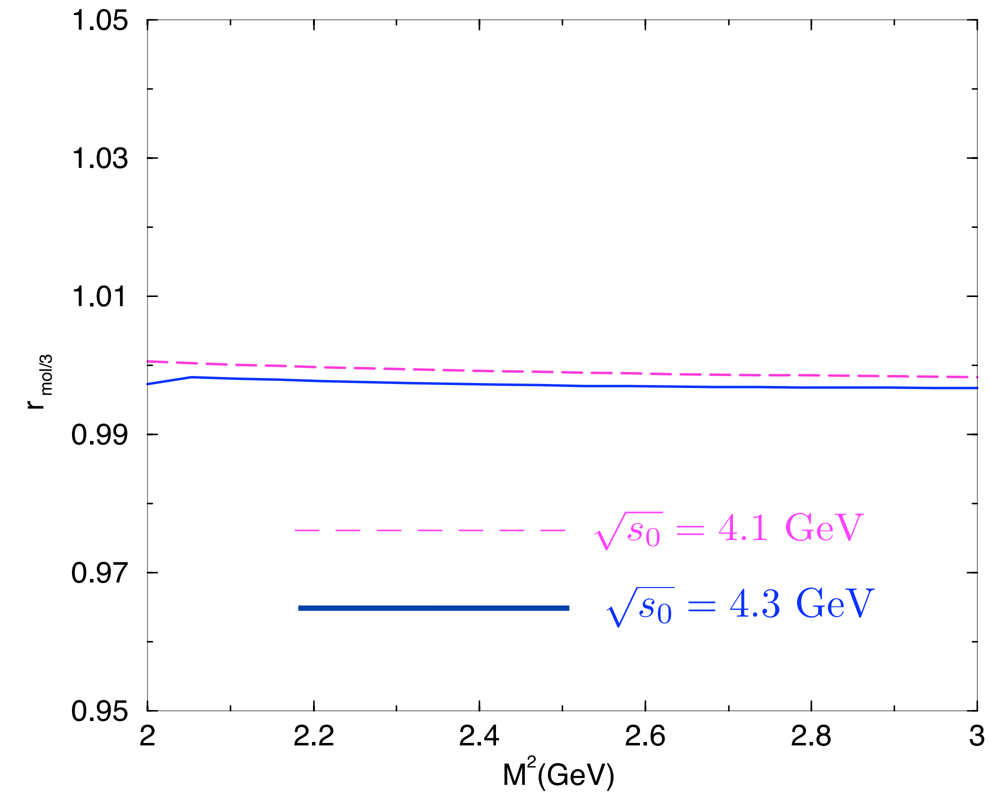

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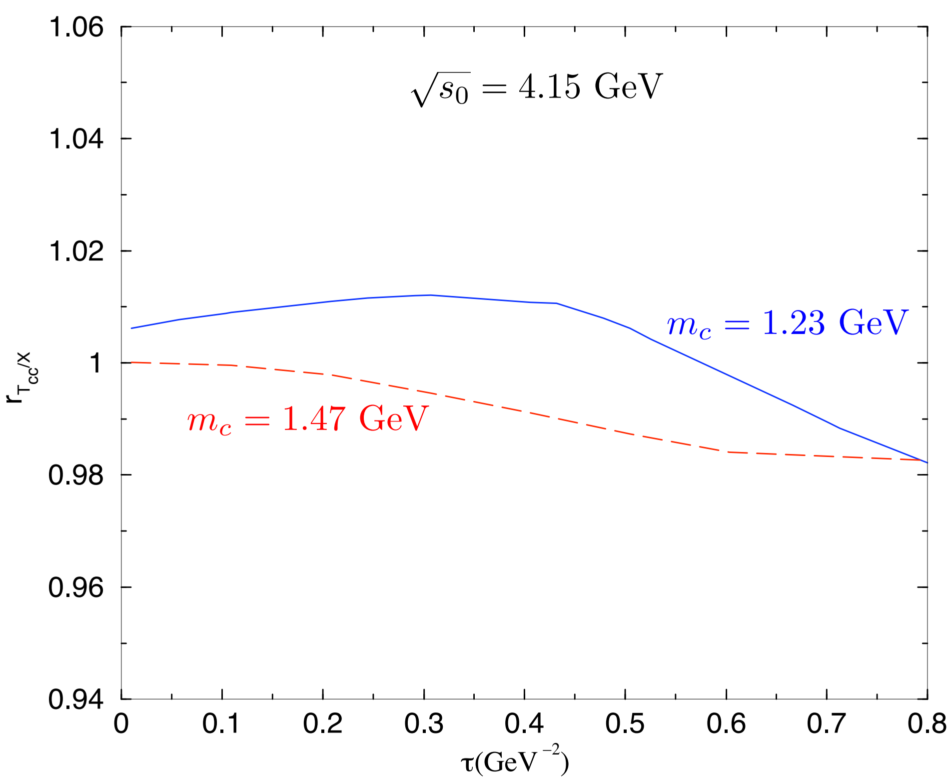

Dias, Narison, Navarra, MN, Richard

(arXiv:1105.5630)

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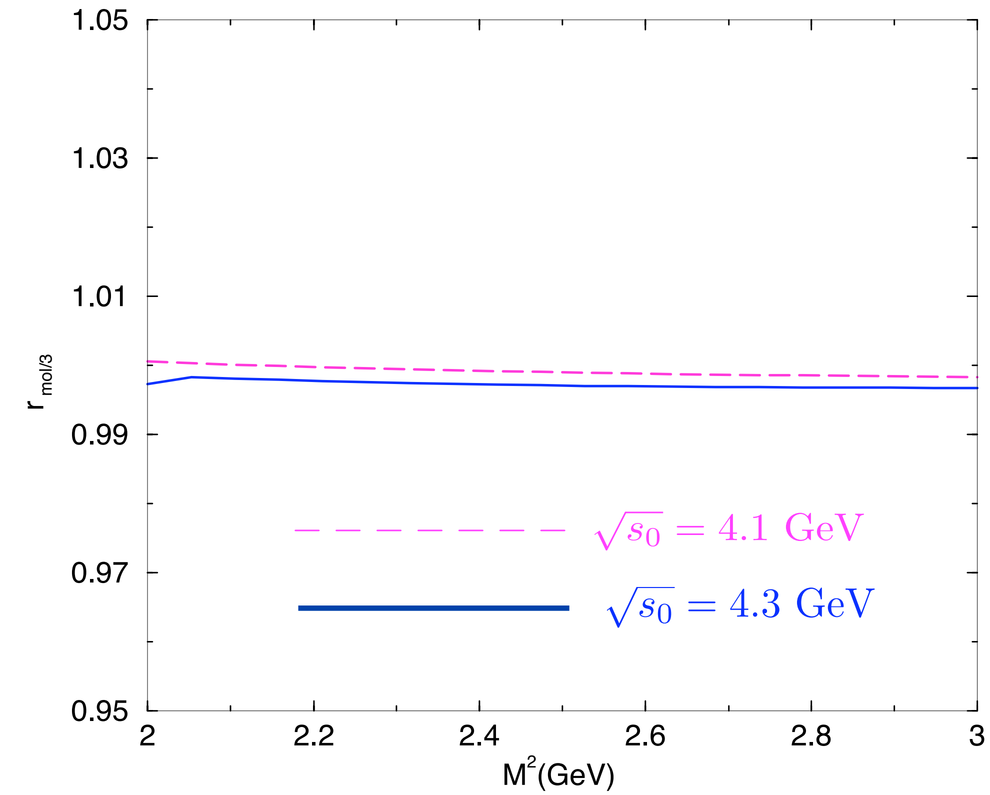

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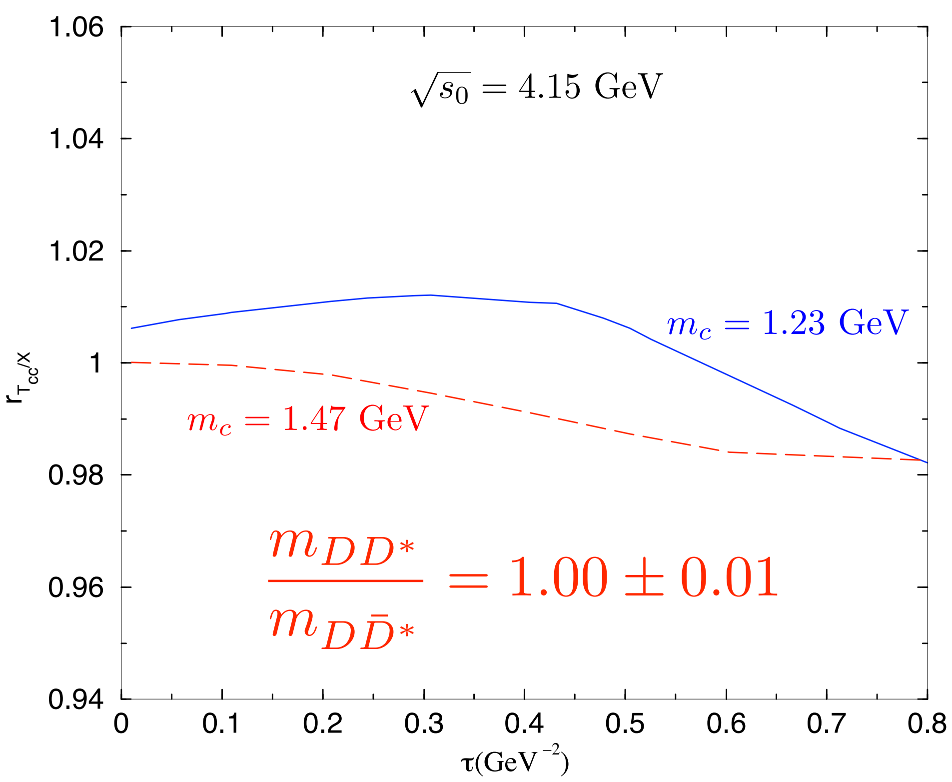
Since T_{cc} ($cc\bar{q}\bar{q}$) can be described by a DD^* current and X(3872) ($c\bar{c}q\bar{q}$) by a $\bar{D}D^*$ current, similar comparison can also be made for X and T_{cc} states.



Dias, Narison, Navarra, MN, Richard

(arXiv:1105.5630)

double-ratio sum rules:

$$r_{mol/3} = \frac{M_{mol}}{M_3}$$

Narison, Navarra, MN, PRD83(11)016004

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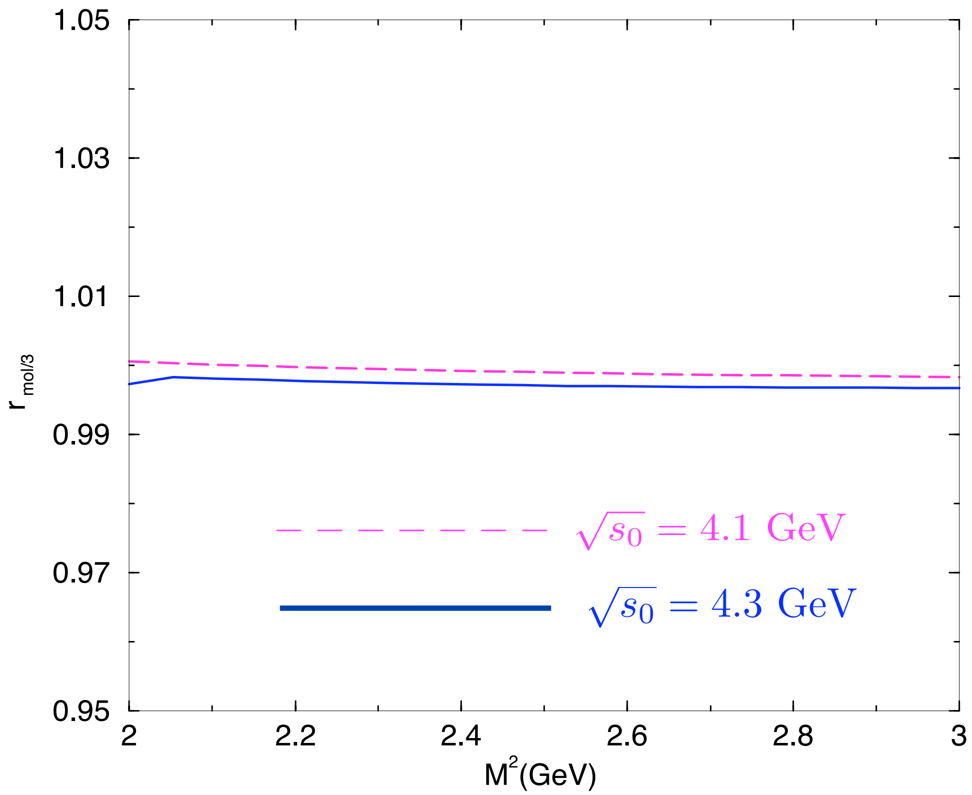

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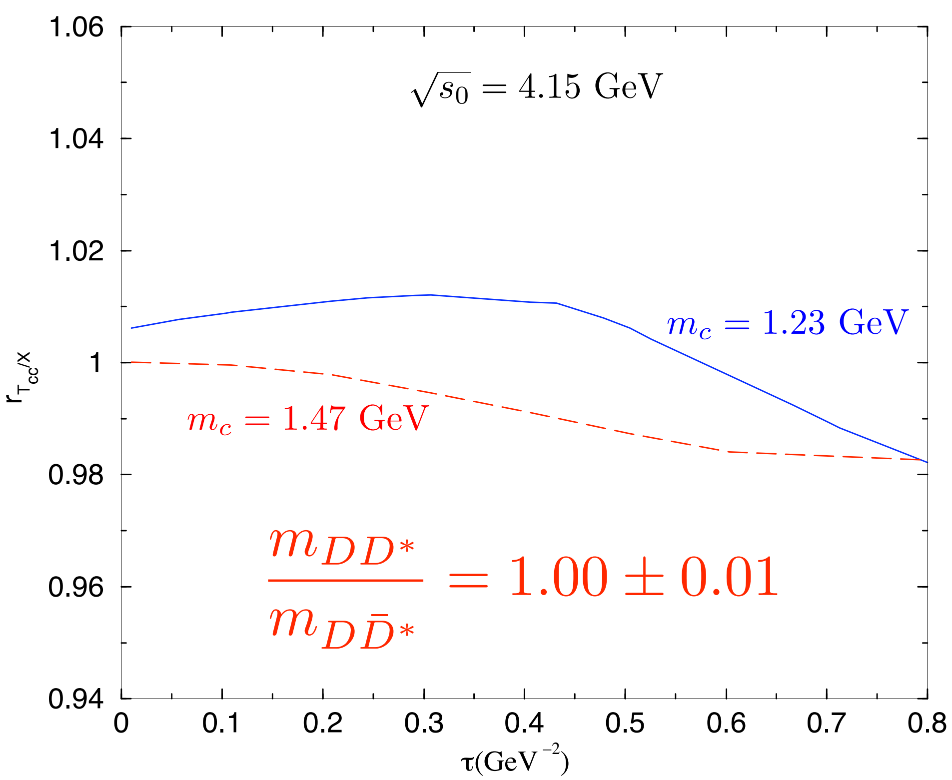

Dias, Narison, Navarra, MN, Richard

(arXiv:1105.5630)

Using the X(3872) experimental mass our prediction for the T_{cc} mass is:

$$M_{T_{cc}} = (3872.2 \pm 39.5)\ \text{MeV}$$

First QCD Sum Rule Prediction for T_{cc}

Navarra, MN, Lee, hep-ph/0703071

$$T_{cc}^{+}([cc][\bar{u}\bar{d}])\ J^P = 1^+$$

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Tetraquark current with $J^P = 1^+$

→ light antidiquark: $\epsilon_{abc}[\bar{u}_b \gamma_5 C \bar{d}_c^T]$

→ heavy diquark: $\epsilon_{aef}[c_e^T C \gamma_\mu c_f]$

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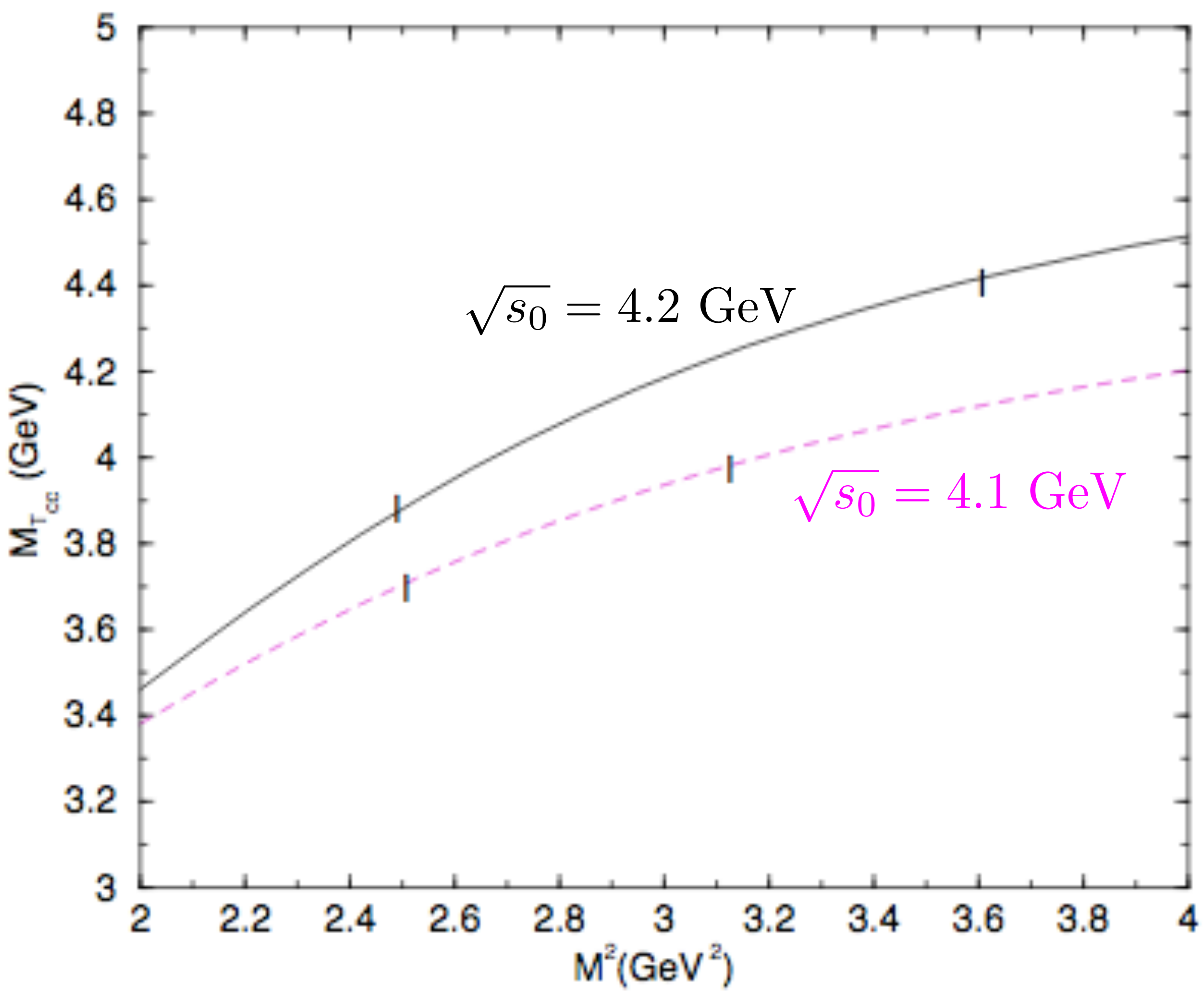

$$m_{T_{cc}} = (4.0 \pm 0.2)\ \text{GeV}$$

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Navarra, MN, Lee, hep-ph/0703071

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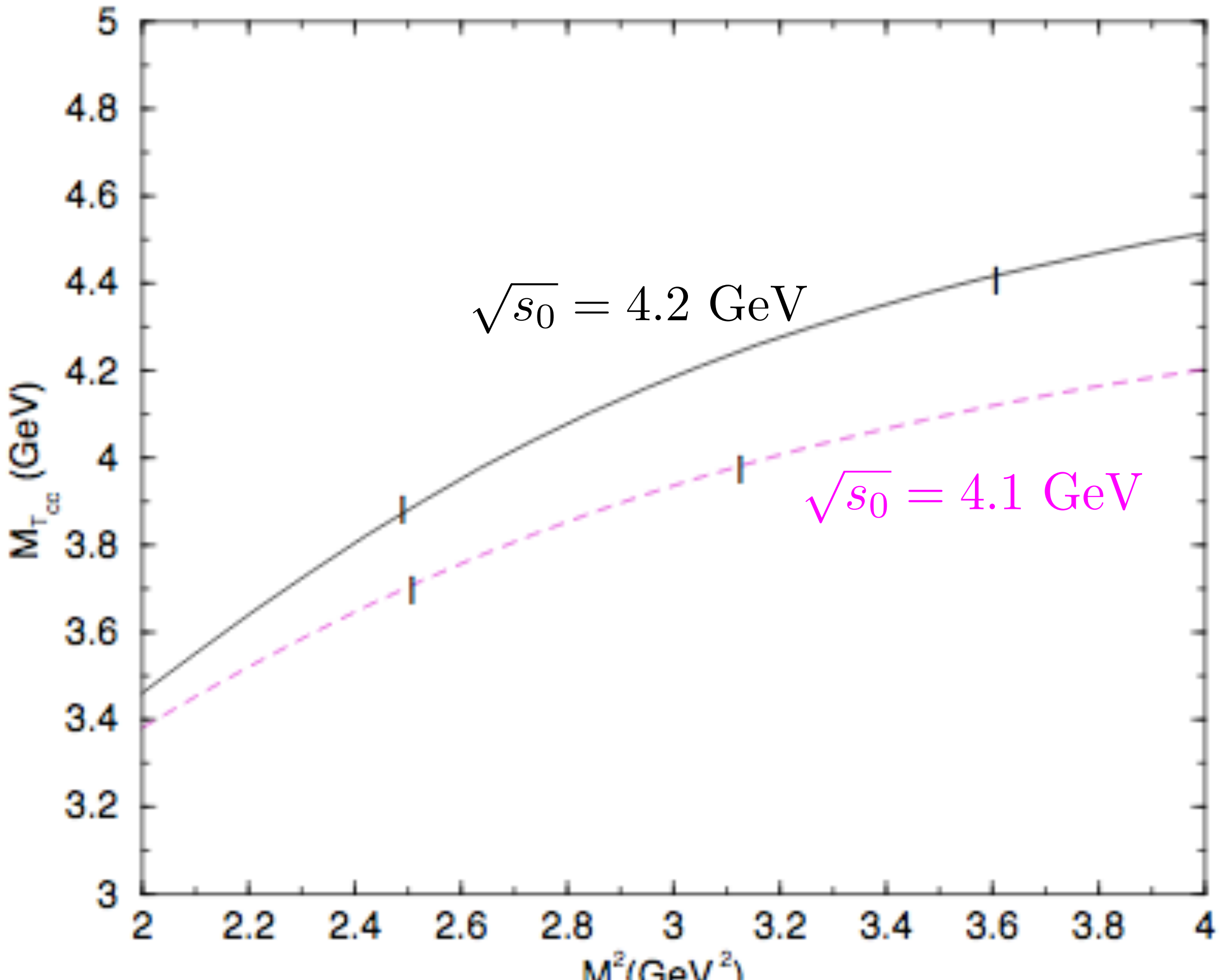


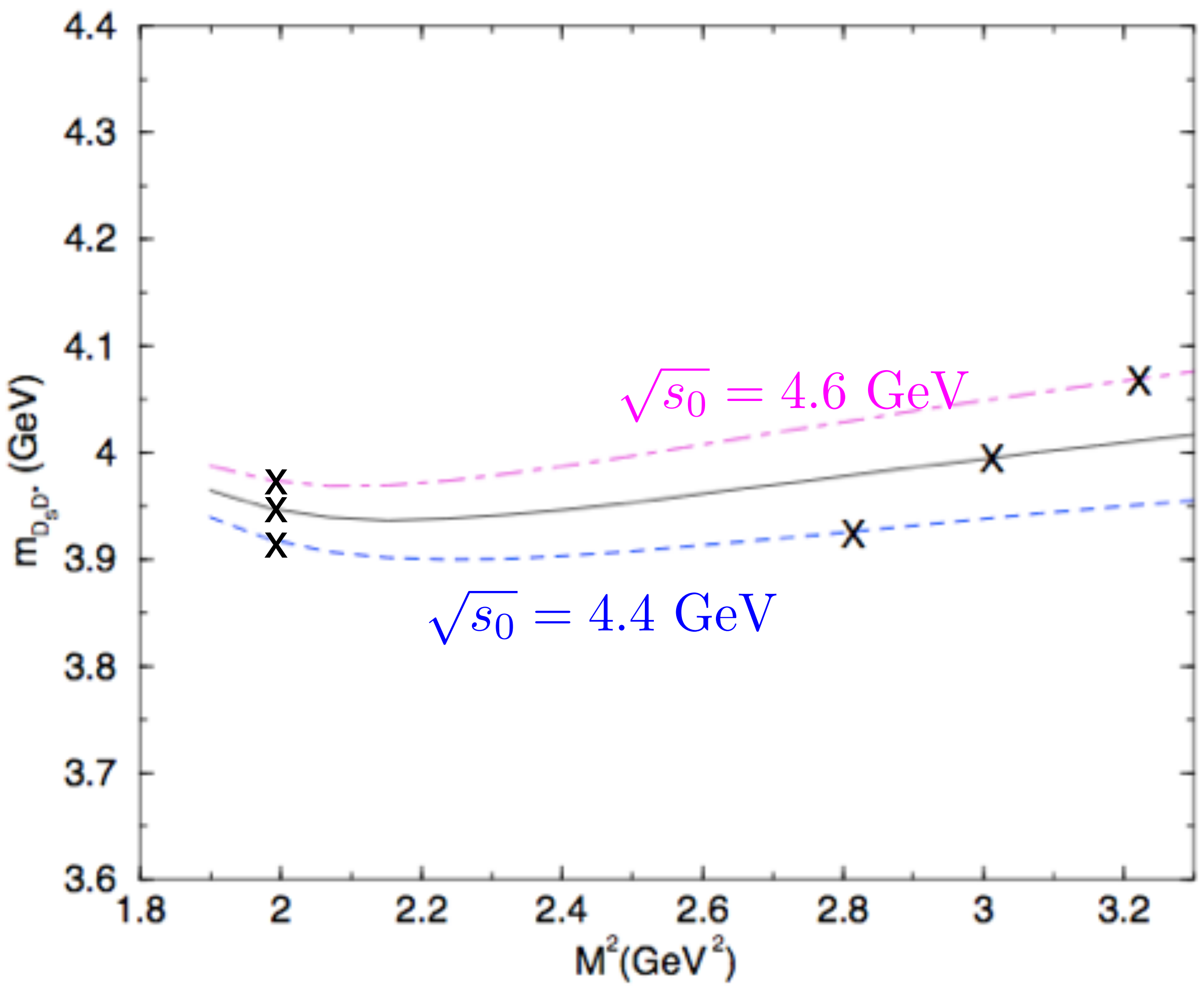
$$m_{T_{cc}} = (4.0 \pm 0.2)\ \text{GeV}$$

Prediction for T_{bb}:

$$m_{T_{bb}} = (10.2 \pm 0.3)\ \text{GeV}$$

Prediction for a Z_{cs}^+ state from QCD Sum Rule

Lee, MN, Wiedner, arXiv:0803.1168, $D_s^+\bar{D}^*$ molecular current $(J^P = 1^+)$



$$m_{Z_{cs}} = (3.97 \pm 0.08)\ \text{GeV}$$

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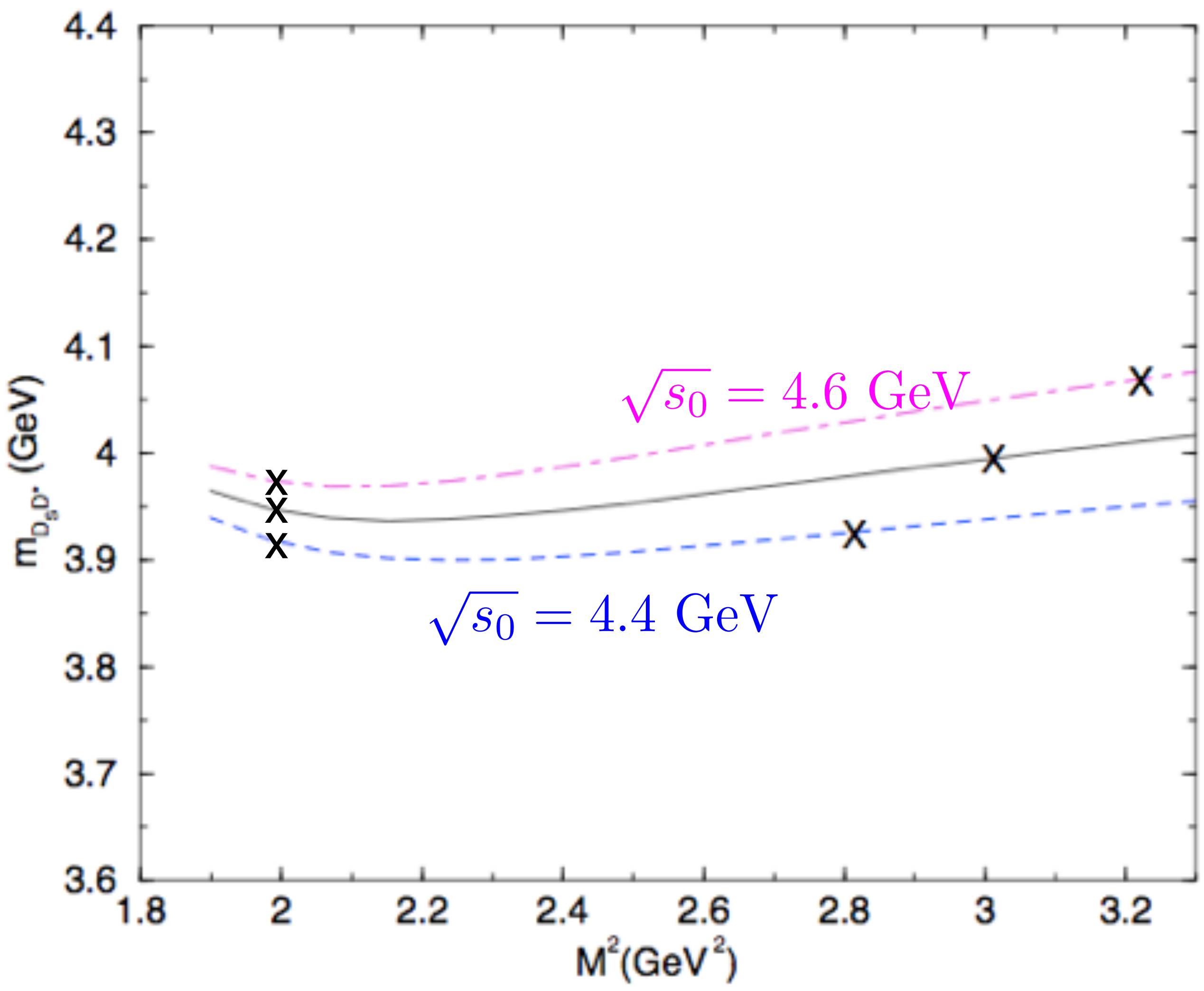

$$m_{Z_{cs}} = (3.97 \pm 0.08)\ \text{GeV}$$

Lee, MN, Wiedner, arXiv:0803.1168

$$m_{Z_{cs}}^{exp} = (3.983 \pm 0.002)\ \text{GeV}$$

arXiv:2011.07855

Decay width from QCD Sum Rule

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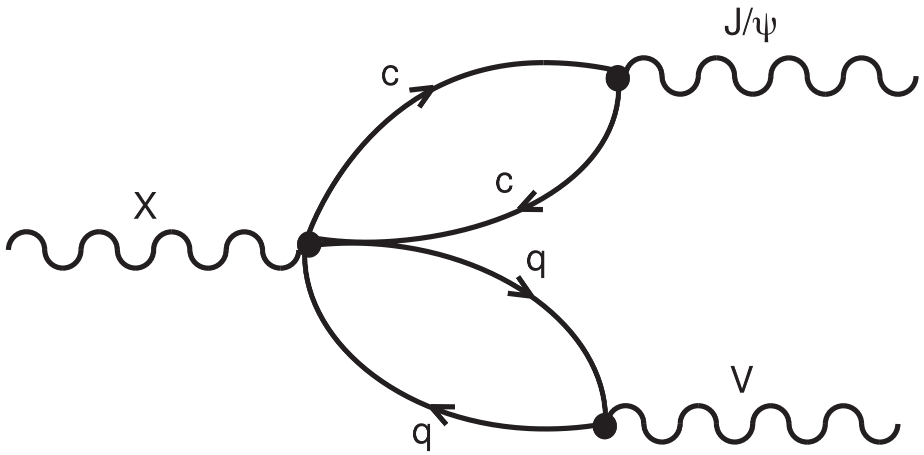

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y} \Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0 | T[j^{\psi}_{\mu}(x) j^{V}_{\nu}(y) j^{X\,\dagger}_{\alpha}(0)] | 0 \rangle$$

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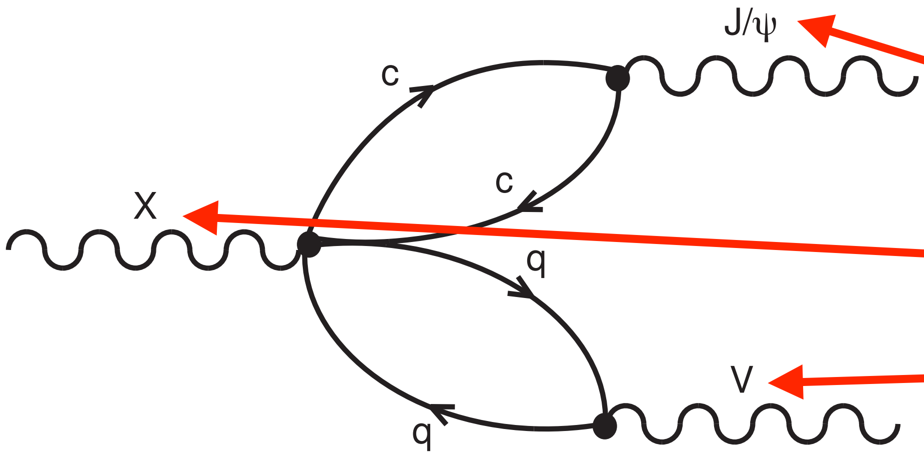

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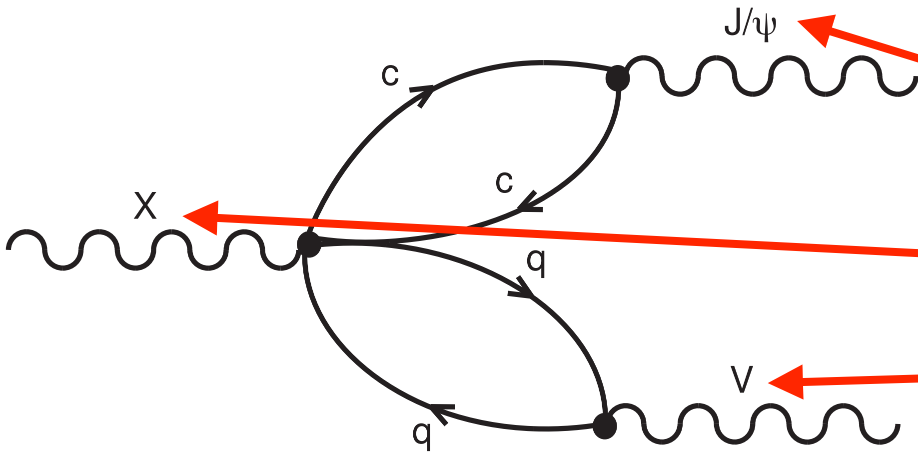

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OPE side: if X(3872) is a genuine tetraquark state, only color-conected diagrams will contribute

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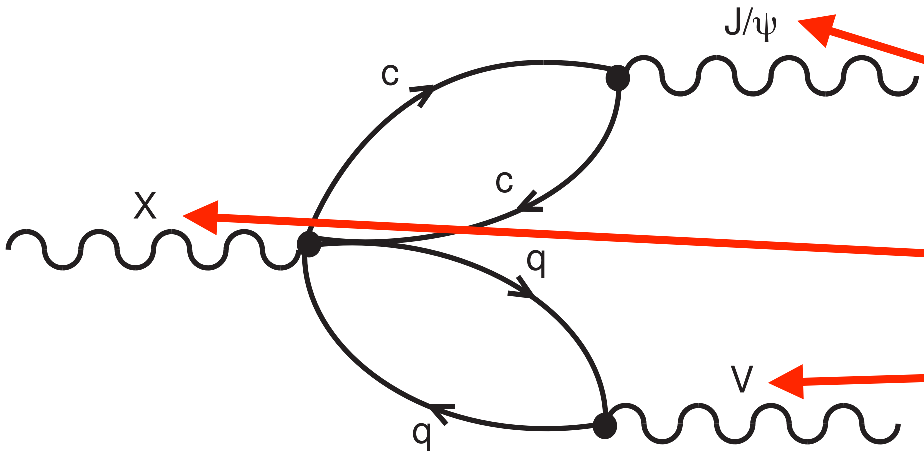

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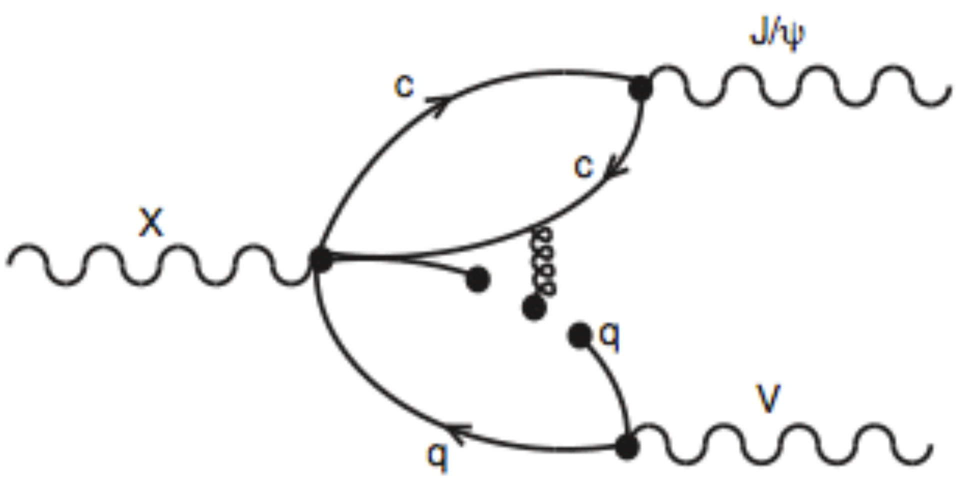

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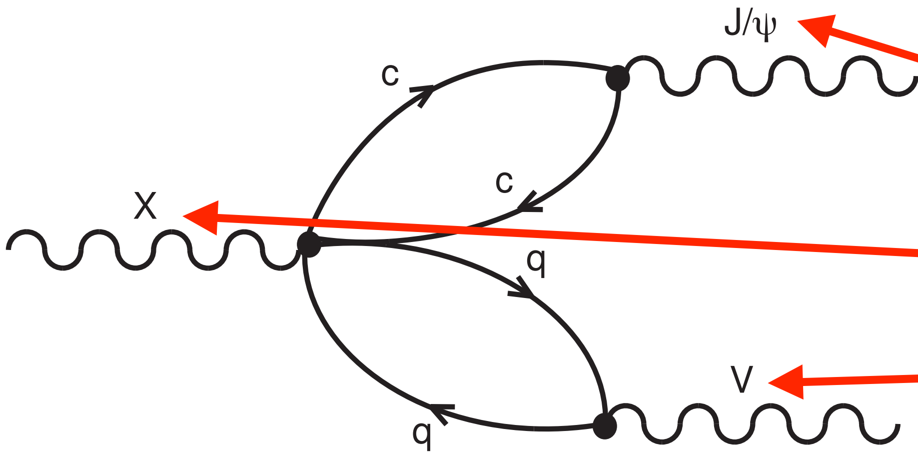

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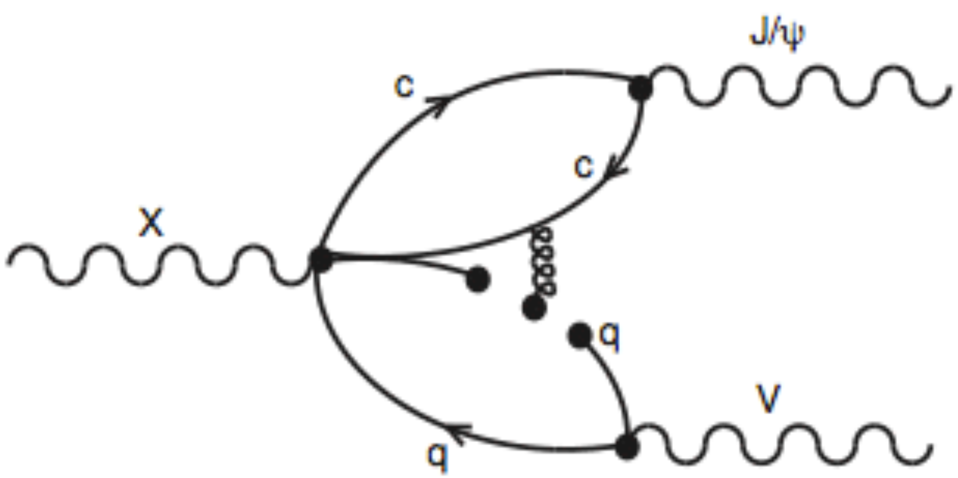

$$\Gamma_{CC}(X \to J/\psi \; (n\pi)) = (0.7 \pm 0.2) \;\; \mathrm{MeV}.$$

Navarra, MN, (PLB639(06)272)

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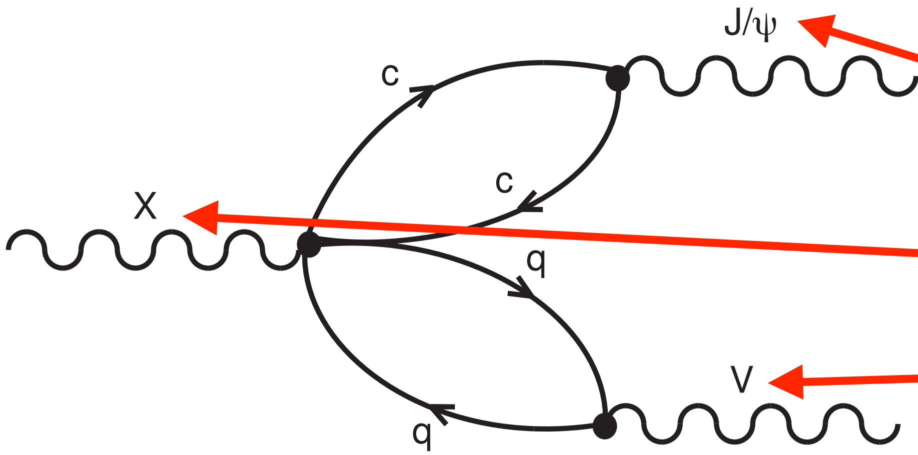

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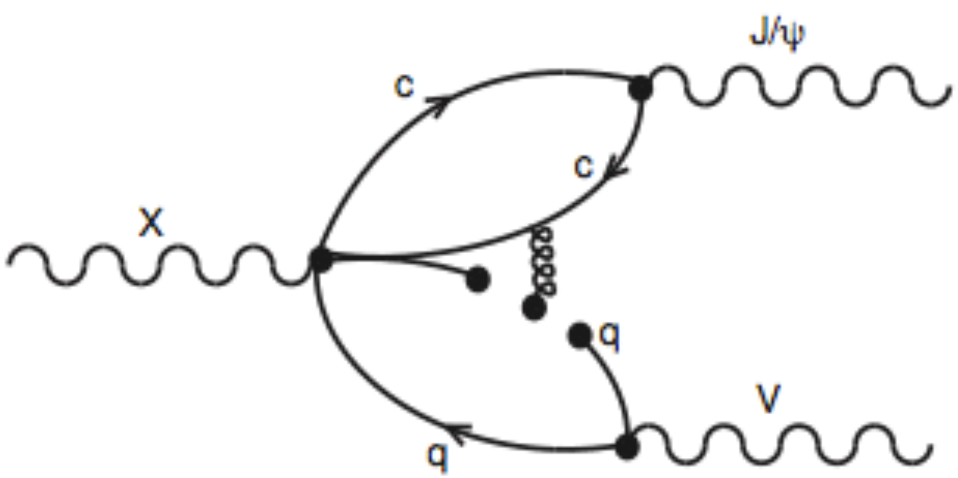

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Navarra, MN,(PLB639(06)272)

Compatible with the experimental X(3872) width: Γ<1.2 MeV

QCDSR Results for decay widths of the $Z_c^+(3900)$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

OPE side: only color-connected diagrams

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Vertex	coupling constant (GeV)	decay width (MeV)
$Z_c^+(3900) J/\psi \pi^+$	3.89 ± 0.56	29.1 ± 8.2
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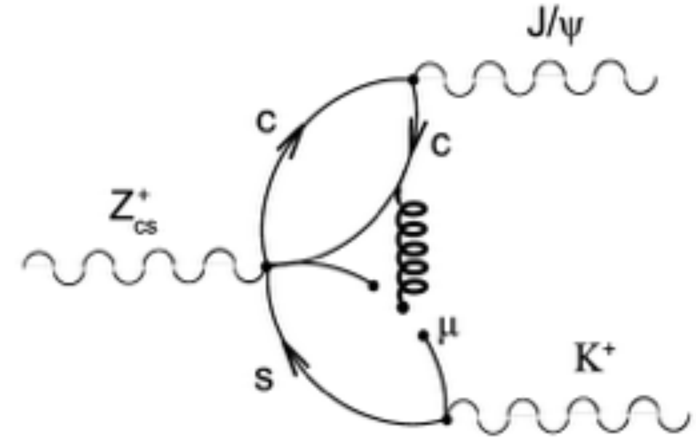
$$\Gamma_{Z_c^+}^{BELLE} = (63 \pm 35)\ \text{MeV}$$

Very good agreement

QCDSR Prediction for the decay width of Z_{cs}^+

Dias, Liu, MN, arXiv:1307.7100

Again only color-connected diagrams were considered



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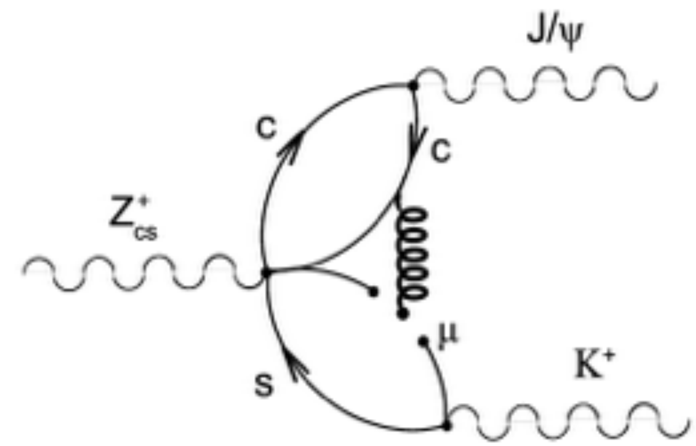

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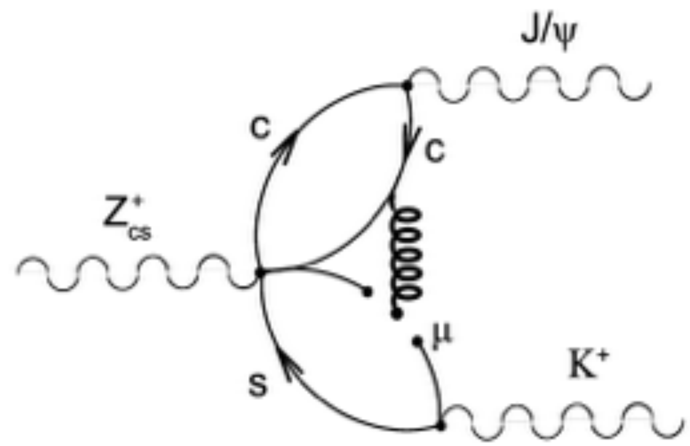

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$$\Gamma_{Z_{cs}} = (24.9 \pm 12.6)\ \text{MeV}$$

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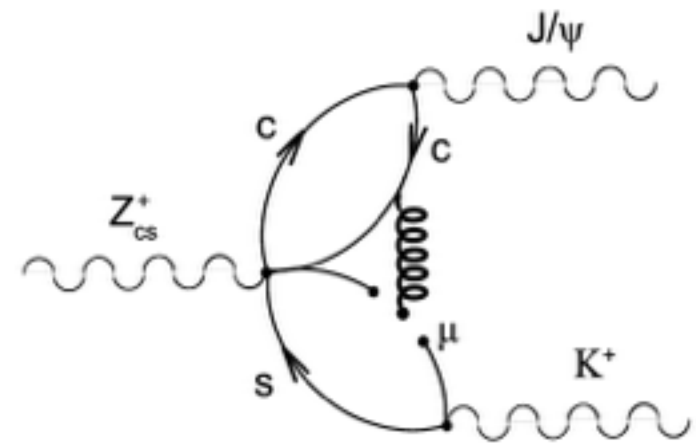

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Γ^{BES}=(12.8 ± 4.7) MeV

arXiv:2011.07855

Very good agreement

Conclusions

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$Z_c^+(4430)$ ➜ First observed charged tetraquark state. Possible first radial excitation of $Z_c^+(3900)$

$Z_{cs}^{+}(3985)$ ➜ first $[c\bar{c}u\bar{s}]$ observed $J^P=1^+$ tetraquark state. Predictions by QCDSR are consistent with its mass and decay width.

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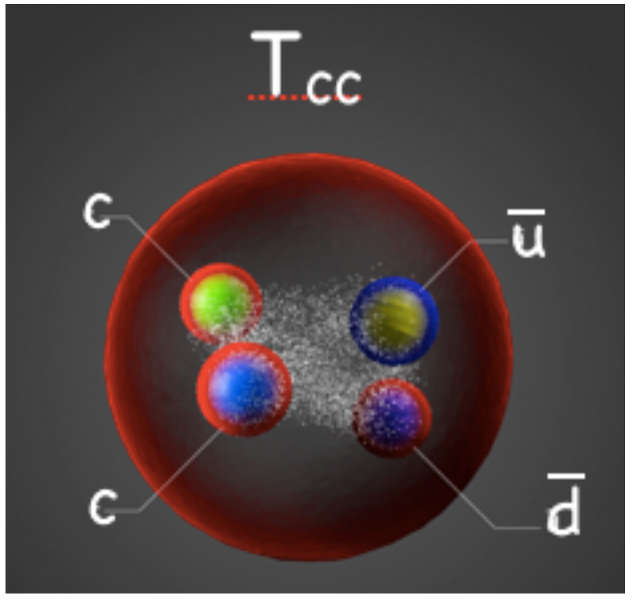
$T_{cc}^+(3875)$ ➜ The most expected tetraquark state. First prediction in 1987. First QCDSR prediction in 2007. Finally observed by LHCb in 2021 with a mass compatible with predictions.



Thank you!