Mesons and Tetraquarks

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Mesons and the quark model

From mesons spectroscopy you end up quite quickly into talking about constituent quarks

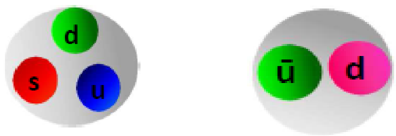
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

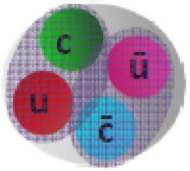
A SCHEMATIC MODEL OF BARYONS AND MESONS *

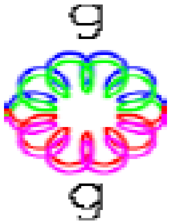
M. GELL-MANN
California Institute of Technology, Pasadena, California

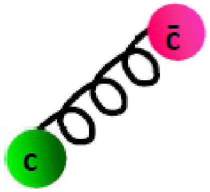
Received 4 January 1964

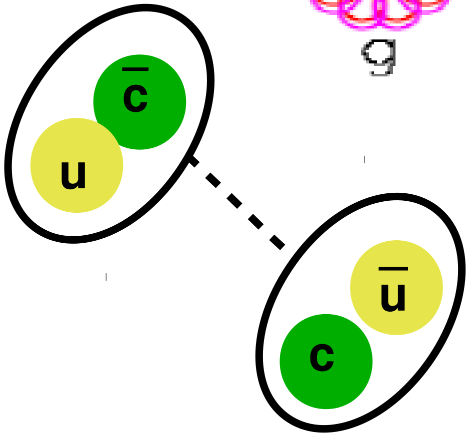
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.







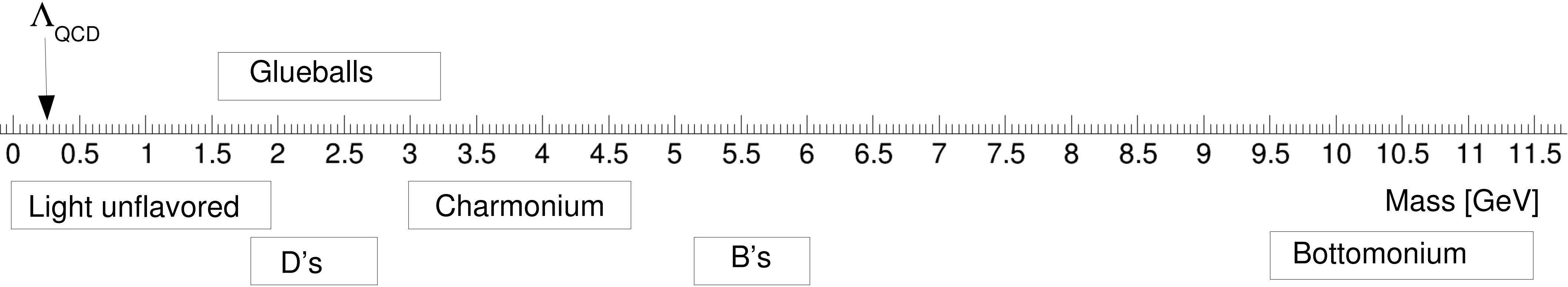




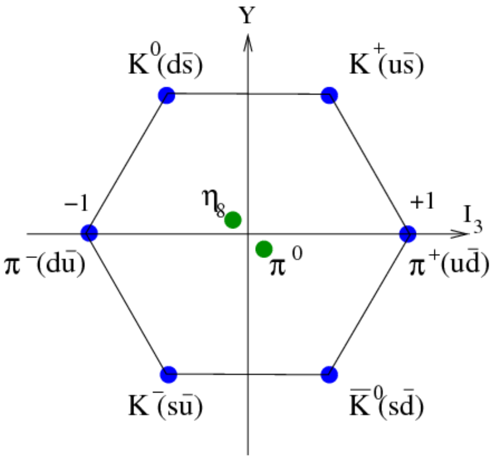
"Exotics" are not really exotic.
However, where are they?

The meson family

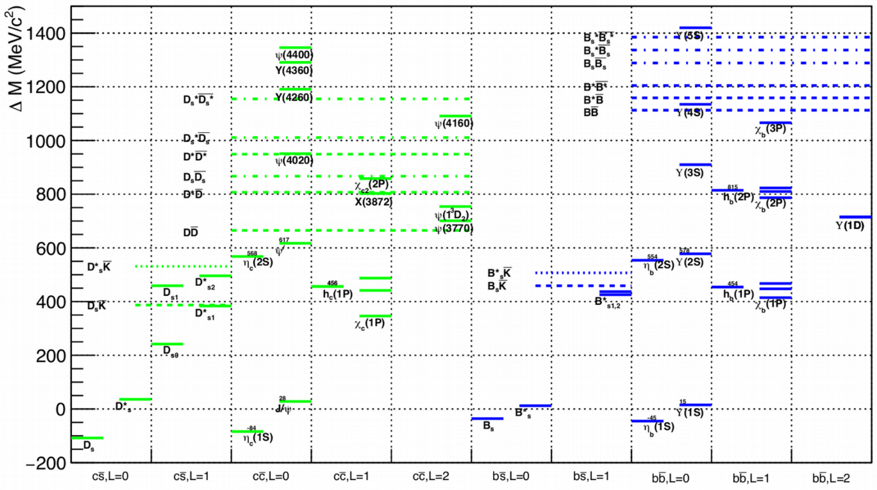
Mesons span over a wide range of masses and energy scales



SU(3) flavour domain



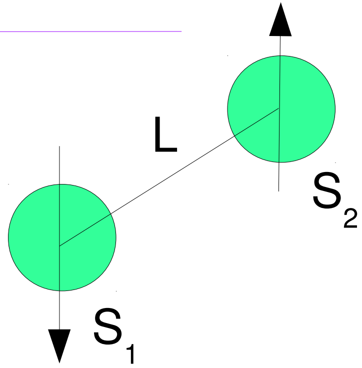
"Quark constituent" domain

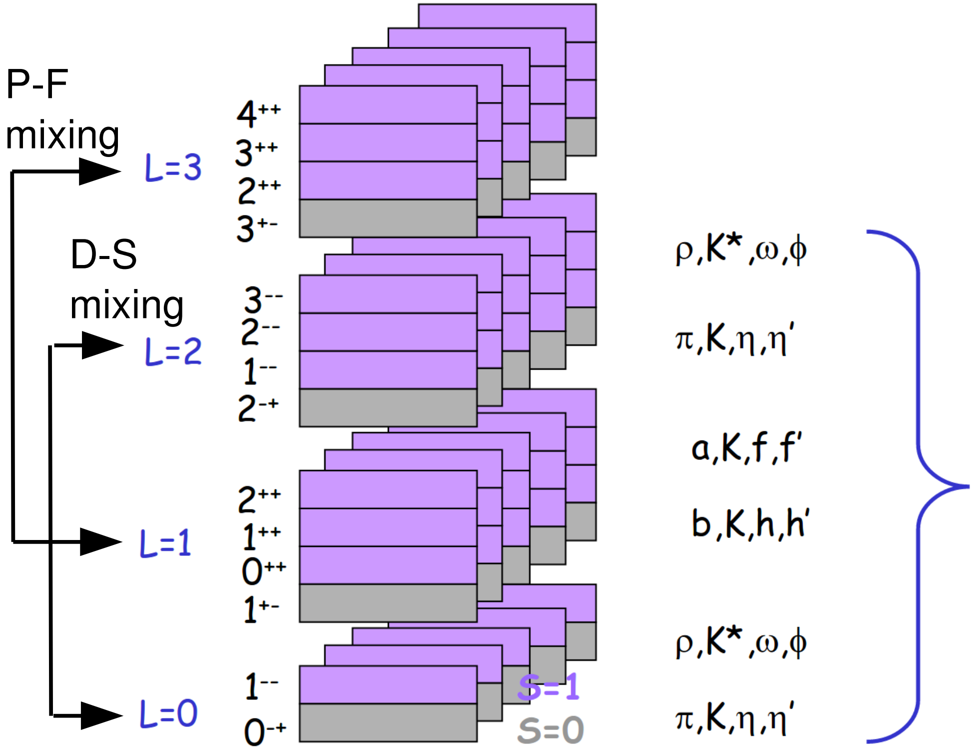


Low mass

- $\Lambda_{QCD}/m_q >> 1$
- $v/c \sim 1$
- **L is not a good quantum number**

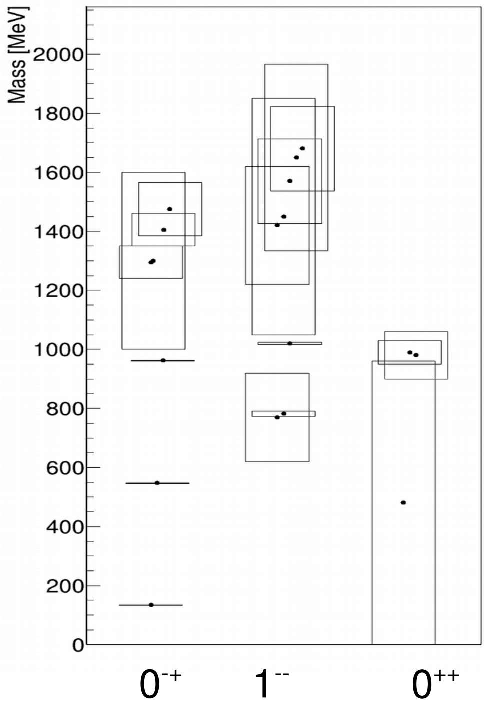
Broad resonances
$\Gamma \sim \Delta M \sim M$





Mesons come in nonets of the same J^{PC} Quantum Numbers

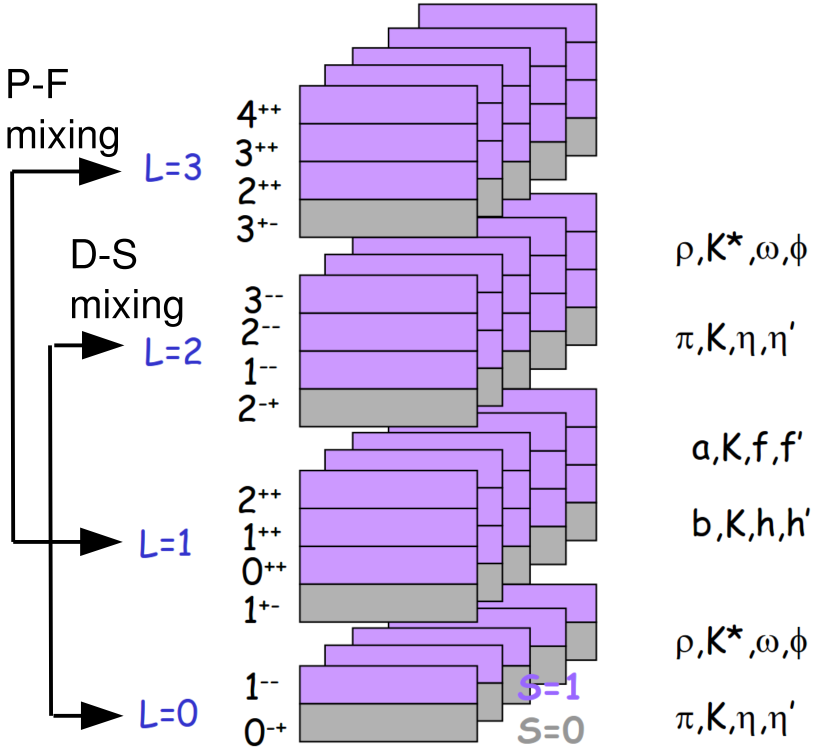
SU(3) is broken
last two members mix



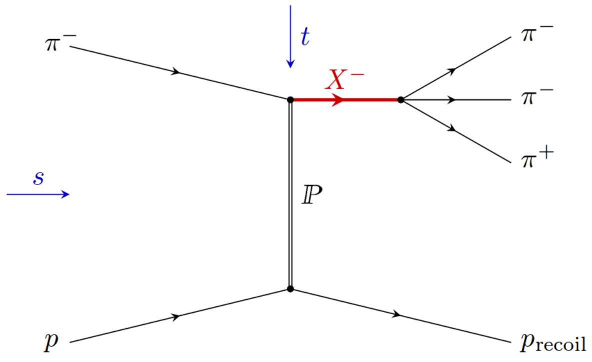
Low mass: experimental tools

- $\Lambda_{QCD}/m_q >> 1$
- $v/c \sim 1$
- **L is not a good quantum number**

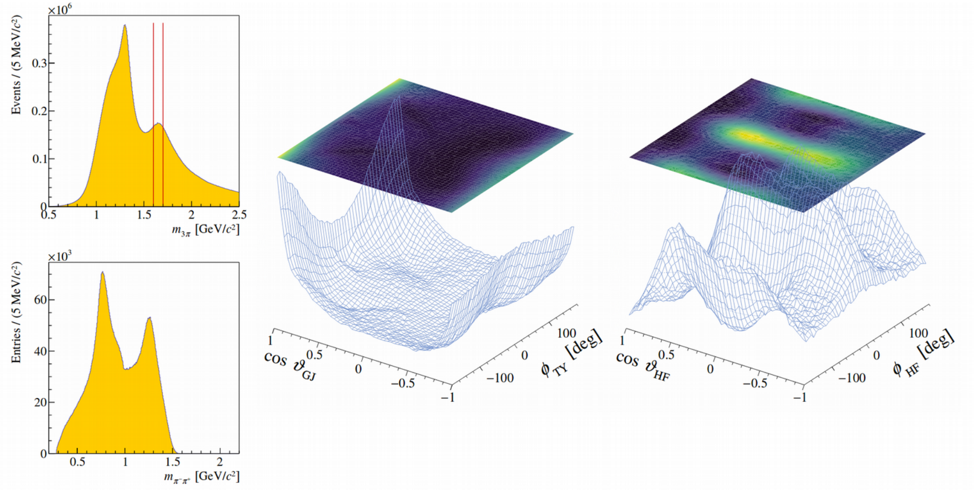
Exotic quantum numbers: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$ ...



Experimental tools: Partial Wave analysis

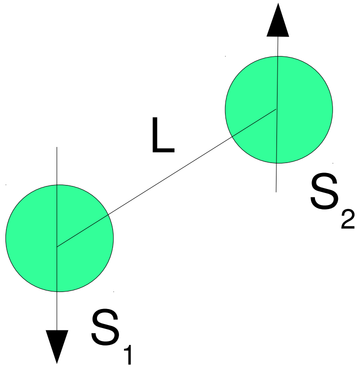


Compass @ CERN
CLAS @ JLAB
...



High mass

- $\Lambda_{QCD}/m_q < 1$
- $v/c << 1$
- **L is a good quantum number**

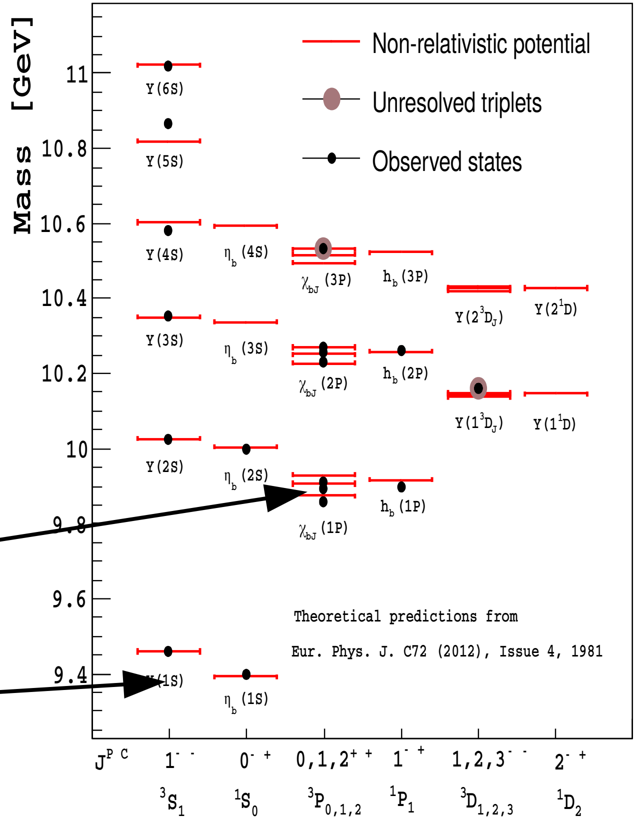


Narrow resonances
$\Gamma < \Delta M << M$

Quarkonium as a prototype of a simple QCD-based bound state

$$V(r) \sim \frac{-4}{3}\frac{\alpha_s}{r} \quad \text{for} \quad r << \frac{1}{\Lambda}$$

$$\begin{aligned} V_{spin}(r) &= \left(\frac{1}{2m_1^2}\vec{L}\cdot\vec{S}_1 + \frac{1}{2m_2^2}\vec{L}\cdot\vec{S}_2\right)\frac{1}{r}\frac{d}{dr}\left(V(r)+2V_1(r)\right) \\ &+ \frac{1}{m_1 m_2}\vec{L}\cdot(\vec{S}_1+\vec{S}_2)\frac{1}{r}\frac{dV_2(r)}{dr} \\ &+ \frac{1}{m_1 m_2}(\hat{r}\cdot\vec{S}_1\ \hat{r}\cdot\vec{S}_2 - \frac{1}{3}\vec{S}_1\cdot\vec{S}_2)V_3(r) + \frac{1}{3m_1 m_2}\vec{S}_1\cdot\vec{S}_2\ V_4(r) \end{aligned}$$



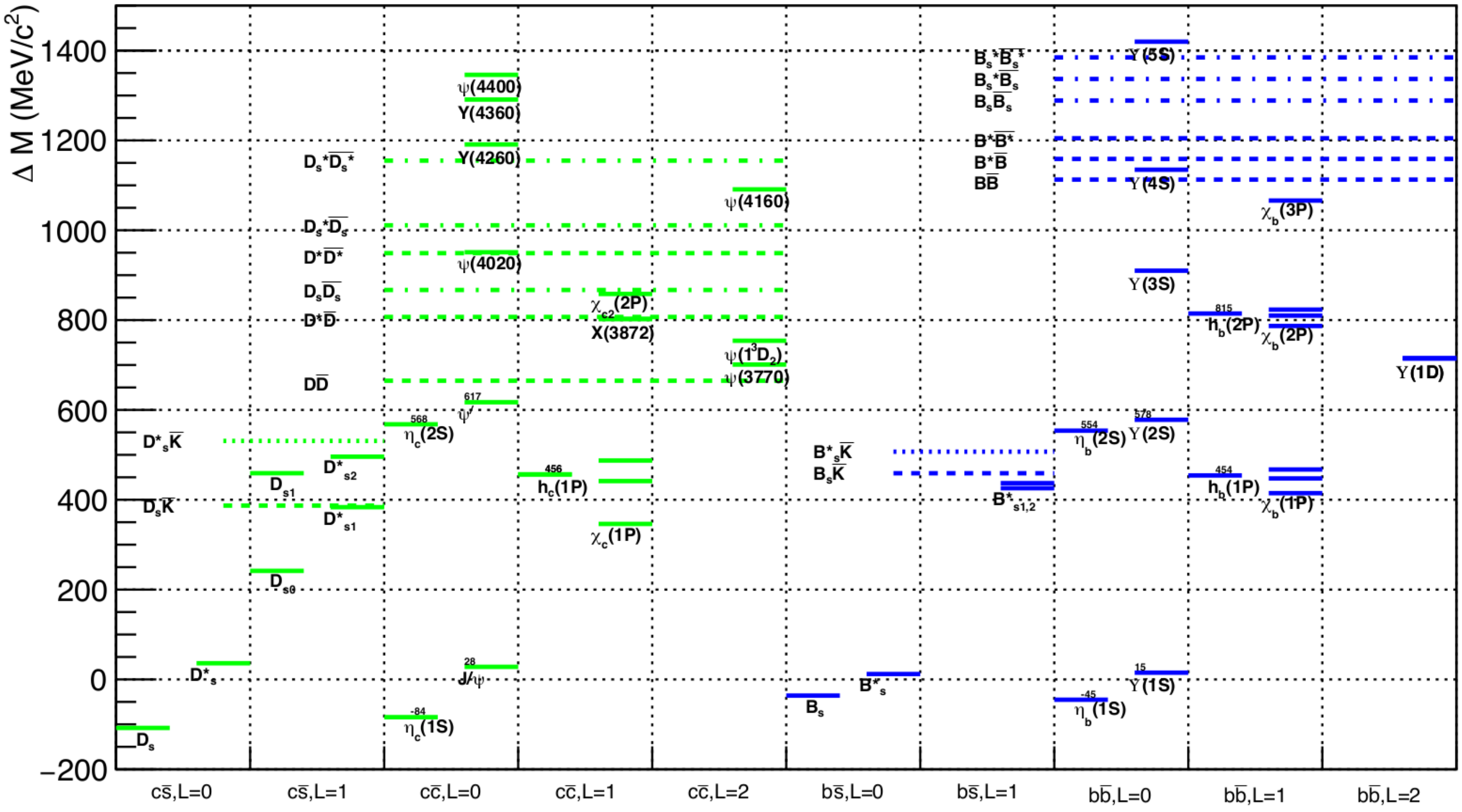
Fine splitting

Hyperfine splitting

High mass

- $\Lambda_{QCD}/m_q < 1$
- $v/c << 1$
- **L is a good quantum number**

Similarities between heavy and heavy-light states
→ heavy quark drives the dynamic
→ QCD potential is flavor-independent



High mass: experimental tools

- $\Lambda_{QCD}/m_q < 1$
- $v/c << 1$
- **L is a good quantum number**

Search for narrow peaks not fitting the expected spectra

Unique signatures:

→ Narrow states $\Gamma < \Delta M << M$

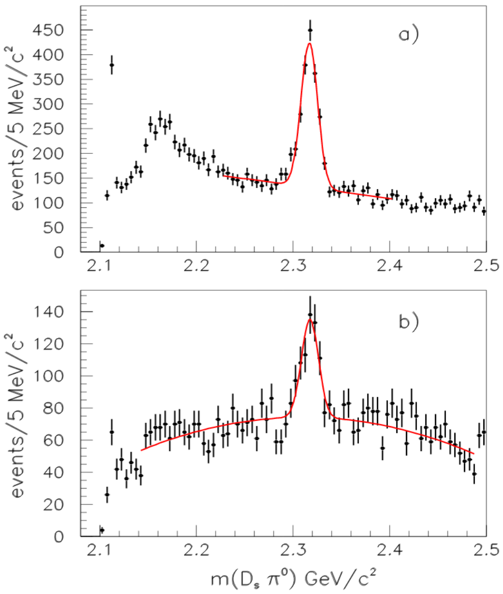
→ Flavored (open or hidden) final states

→ Spin effects decouple

→ Net charge in bottomonium- like implies at least 4 quarks involved!

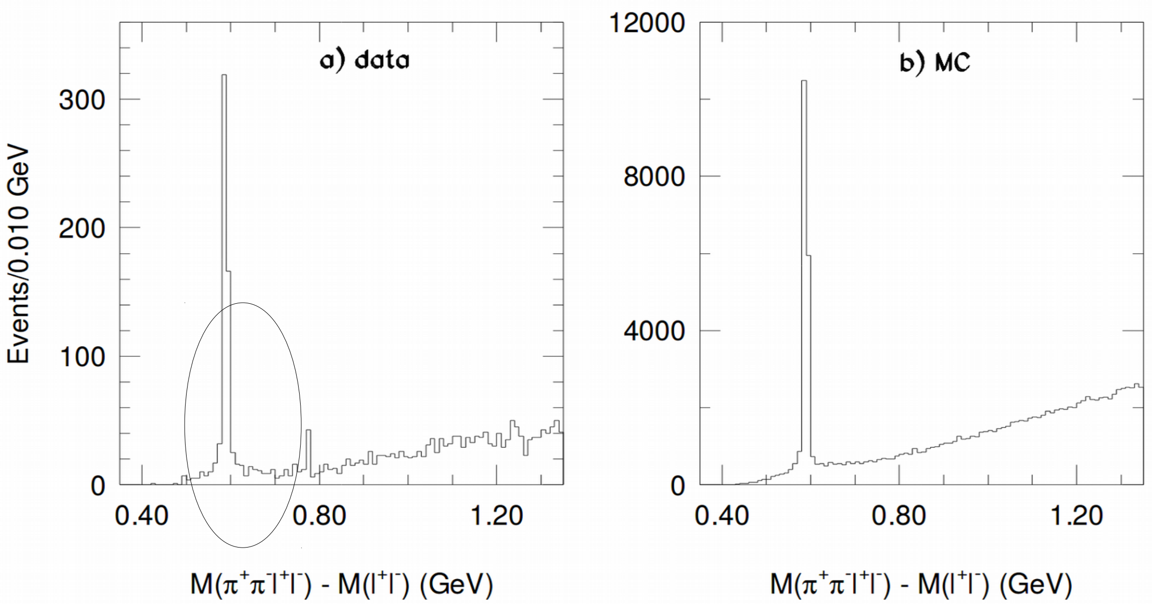
BaBar: D_{sJ}(2317)

Phys.Rev.Lett. 90 (2003) 242001



Belle: X(3872)

Phys.Rev.Lett. 91 (2003) 262001



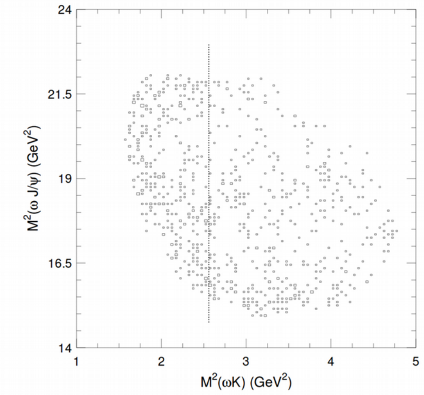
The uniqueness of quarkonia: the X(3915) saga

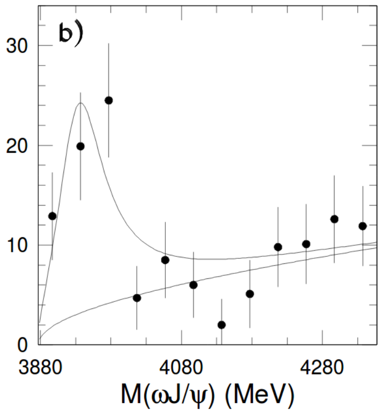
Seen by Belle in $B \to \omega\, J/\psi\, K$

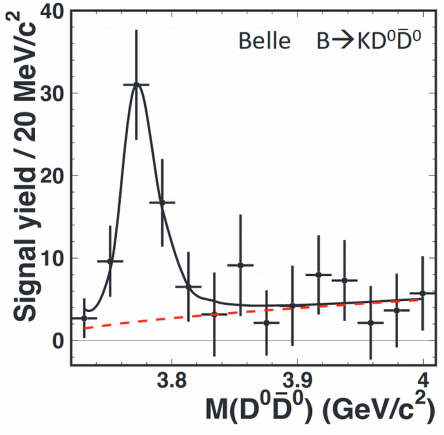
Phys.Rev.Lett. 94 (2005) 182002

NOT seen $B \to KDD$

Phys.Rev.Lett. 94 (2005) 182002

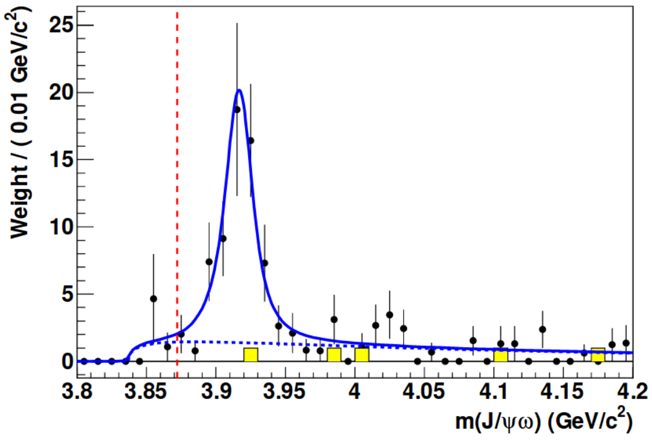


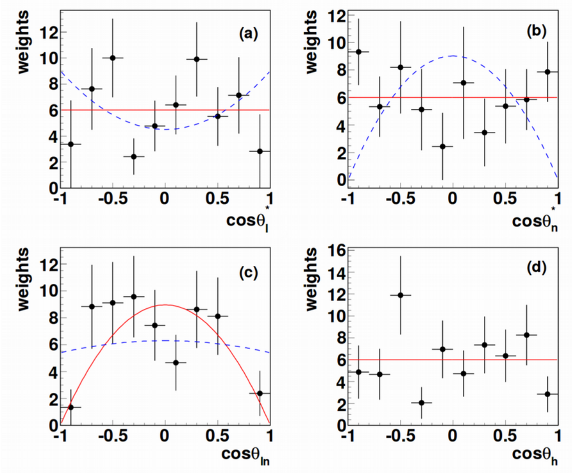




Confirmed by BaBar in $\gamma\gamma \to \omega\, J/\psi$

Phys.Rev. D86 (2012) 072002





Angular analysis favours 0++ over 2++ (if helicity 2 is dominating)

The X(3915) is the conventional state $\chi_{cJ0}(2P)$ (?)

The uniqueness of quarkonia: the X(3915) saga

Phys.Rev. D91 (2015) no.5, 057501

Is the $X(3915)$ the $\chi_{c0}(2P)$?

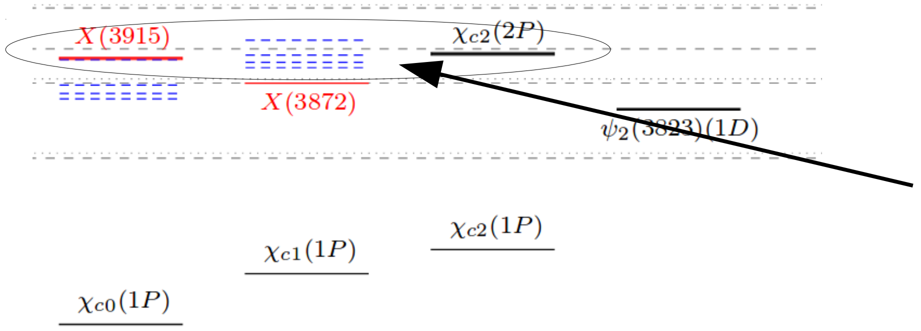
Stephen Lars Olsen[1]

[1] *Center for Underground Physics, Institute for Basic Science, Daejeon 305-811, Korea*

(Dated: October 27, 2014)

The Particle Data Group has assigned the $X(3915)$ meson, an $\omega J/\psi$ mass peak seen in $B \to K\omega J/\psi$ decays and $\gamma\gamma \to \omega J/\psi$ two-photon fusion reactions, as the $\chi_{c0}(2P)$, the 2^3P_0 charmonium state. Here it is shown that if the $X(3915)$ is the $\chi_{c0}(2P)$, the measured strength of the $\gamma\gamma \to X(3915)$ signal implies an *upper* limit on the branching fraction $\mathcal{B}(\chi_{c0}(2P) \to \omega J/\psi) < 7.8\%$ that conflicts with a $> 14.3\%$ *lower* limit derived for the same quantity from the $B \to KX(3915)$ decay rate. Also, the absence any signal for $X(3915) \to D^0\bar{D}^0$ in $B^+ \to K^+D^0\bar{D}^0$ decays is used to establish the limit $B(X(3915) \to D^0\bar{D}^0 < 1.2 \times \mathcal{B}(X(3915) \to \omega J/\psi)$. This contradicts expectations that $\chi_{c0}(2P)$ decays to $D^0\bar{D}^0$ would be a dominant process, while decays to $\omega J/\psi$, which are Okubo-Zweig-Iizuka suppressed, would be relatively rare. These, plus reasons given earlier by Guo and Meissner, raise serious doubts about the $X(3915) = \chi_{c0}(2P)$ assignment.

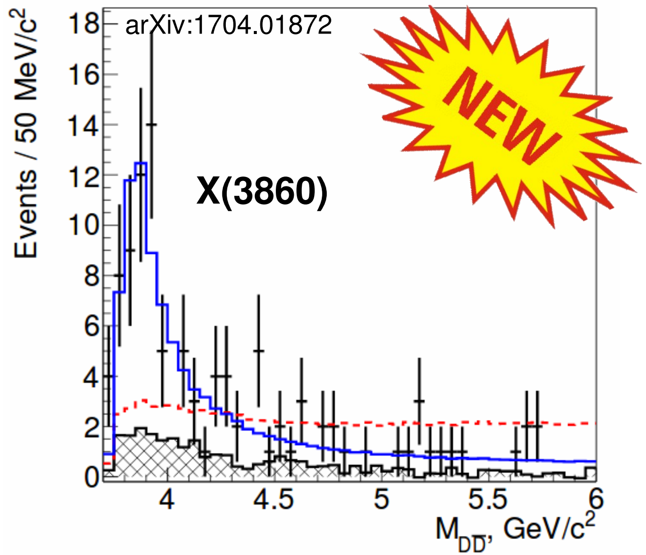
χ_{cJ0}(2P) should have:	X(3915)
1) Dominant decay to $D^0\bar{D}^0$	✗
2) Be 80-120 MeV below χ_{cJ2}(2P)	✗
3) $\mathcal{B}(\chi'_{c0} \to \omega J/\psi) < 7.8\%$.	✗



$$\Delta M(2P) = 8.8 \pm 3.2 \text{ MeV}$$

The uniqueness of quarkonia: the X(3915) saga

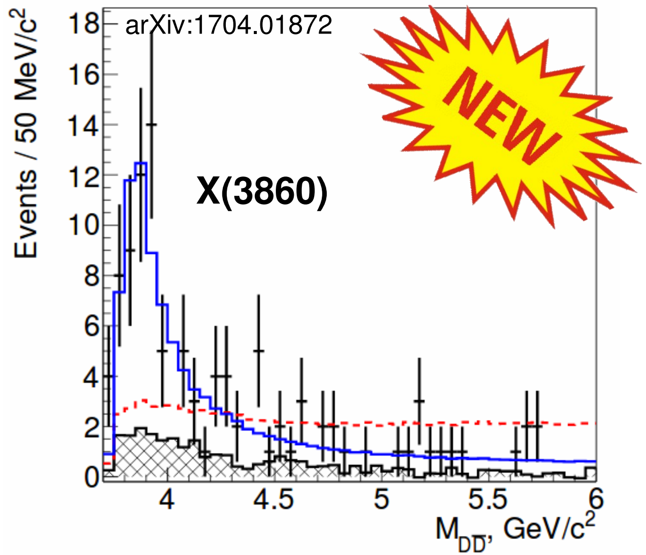
Belle 2017: New analysis of $e^+e^- \to J/\psi\ D^0\overline{D}^0$: **X(3860)**

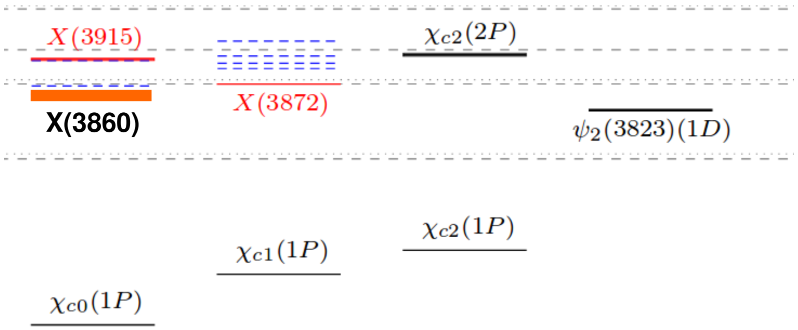


χ_{cJ0}(2P) should have:

	X(3915)	X(3860)
1) Dominant decay to $D^0\overline{D}^0$	✗	✓
2) Be 80-120 MeV below χ_{cJ2}(2P)	✗	
3) $\mathcal{B}(\chi'_{c0} \to \omega J/\psi) < 7.8\%$.	✗	

Belle 2017: New analysis of $e^+e^- \to J/\psi\, D^0\bar{D}^0$: **X(3860)**

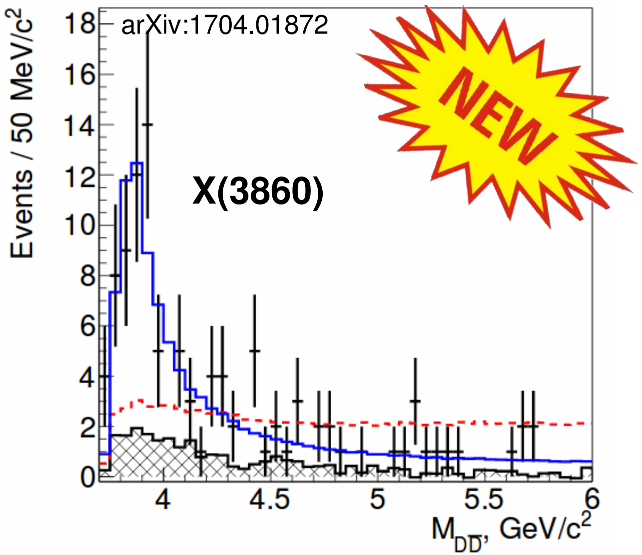




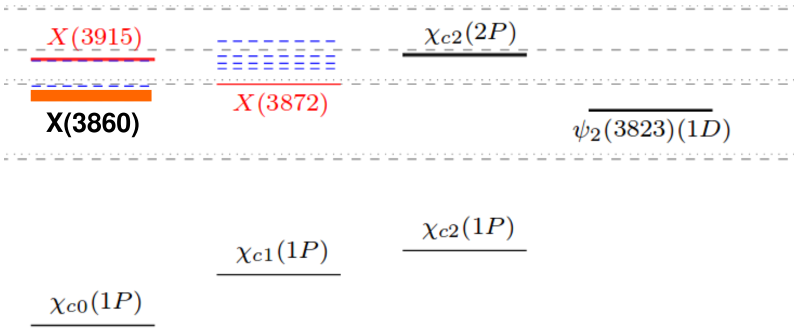
χ_{cJ0}(2P) should have:	X(3915)	X(3860)
1) Dominant decay to $D^0\bar{D}^0$	✗	✓
2) Be 80-120 MeV below χ_{cJ2}(2P)	✗	✓
3) $\mathcal{B}(\chi'_{c0} \to \omega J/\psi) < 7.8\%$.	✗	

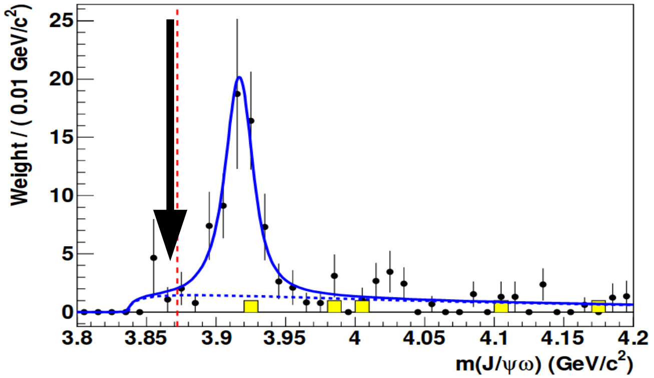
The uniqueness of quarkonia: the X(3915) saga

Belle 2017: New analysis of $e^+e^- \to J/\psi\, D^0\overline{D}^0$: **X(3860)**



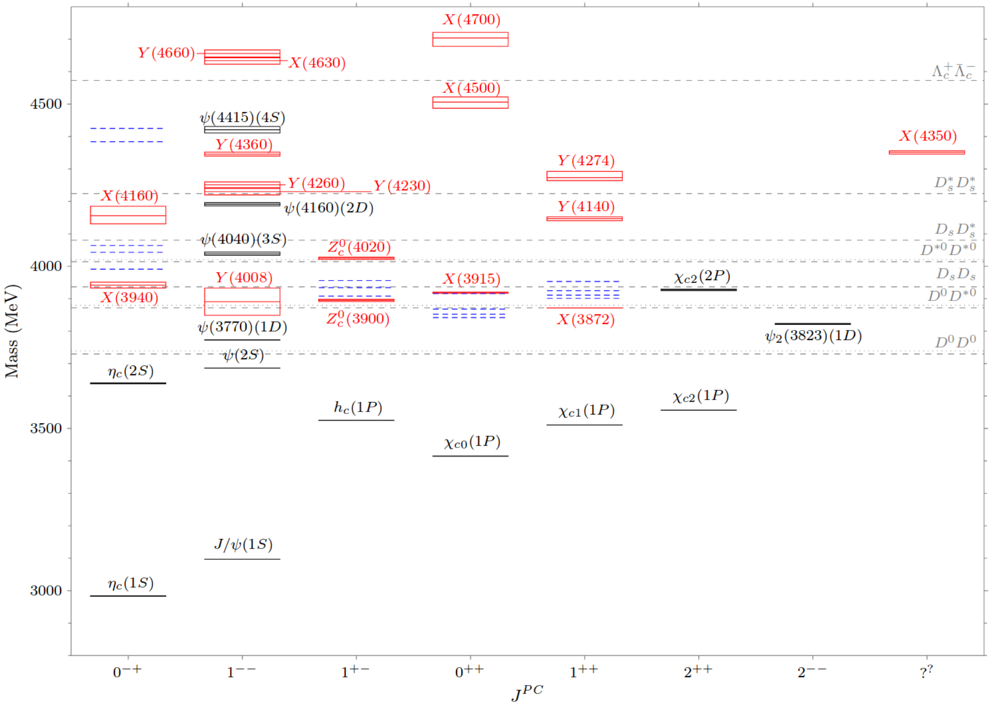
$\chi_{cJ0}(2P)$ ***should have:***	X(3915)	X(3860)
1) Dominant decay to $D^0\overline{D}^0$	✗	✓
2) Be 80-120 MeV below $\chi_{cJ2}(2P)$	✗	✓
3) $\mathcal{B}(\chi'_{c0} \to \omega J/\psi) < 7.8\%.$	✗	✓



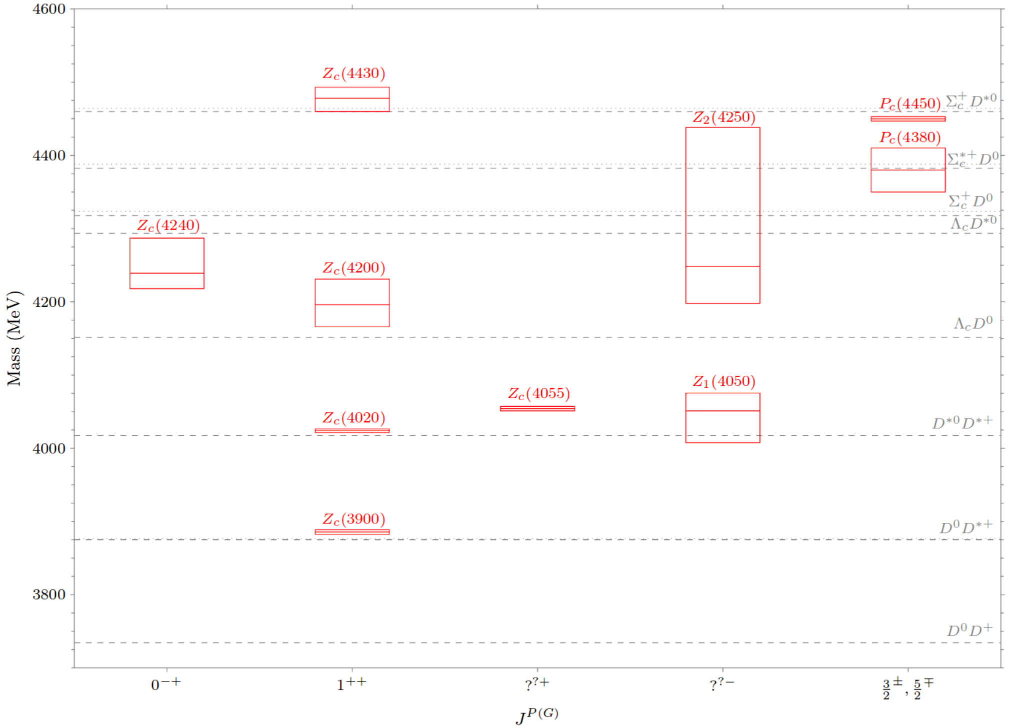


Part I: tetraquarks and exotica

Exotica in charmonia



Charged charmonia.
Minimal quark content is $c\bar{c}q\bar{q}$

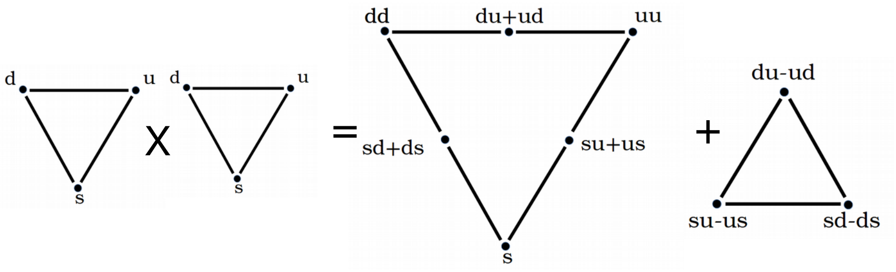


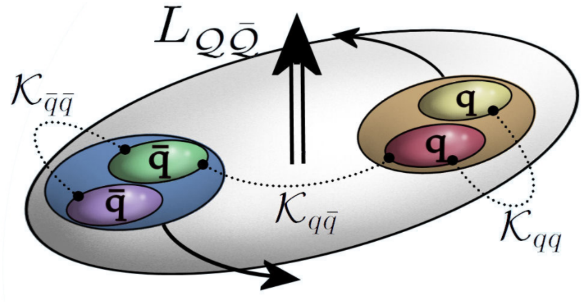
Intriguing patterns:

$M_{Z(4430)} - M_{Z(3900)} \sim M_{\psi} - M_{J/\psi}$

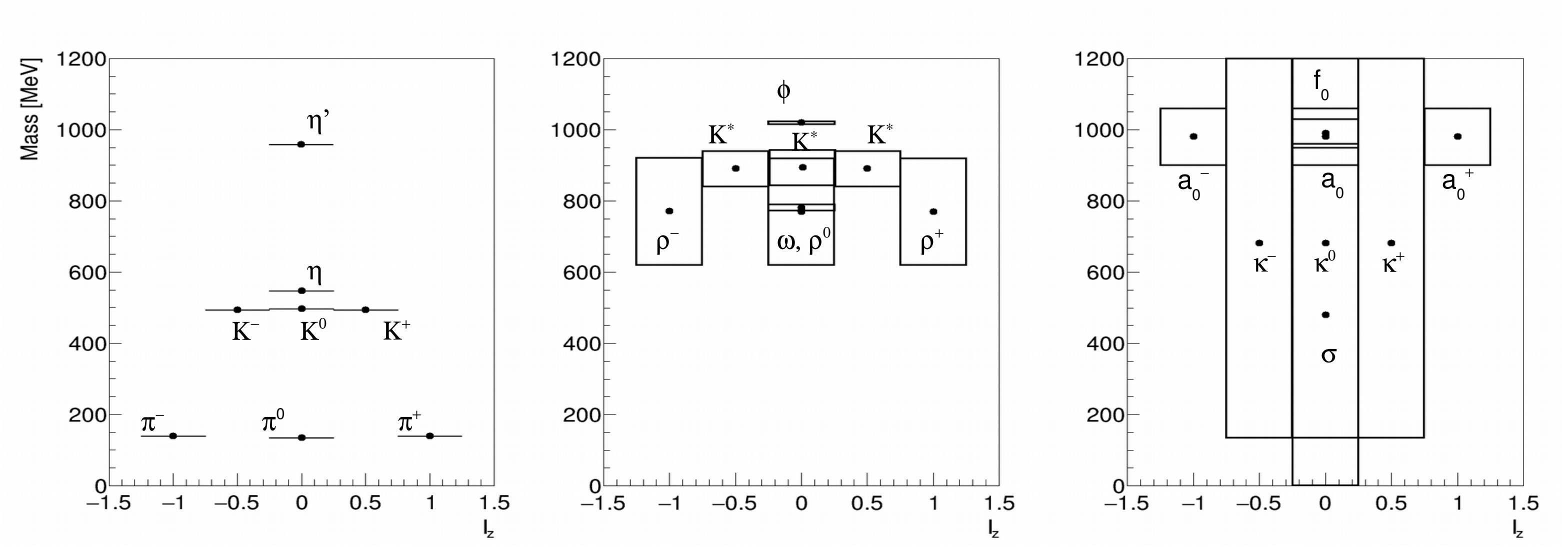
Understanding exotica: the tetraquark model

Based on the idea of di-quark





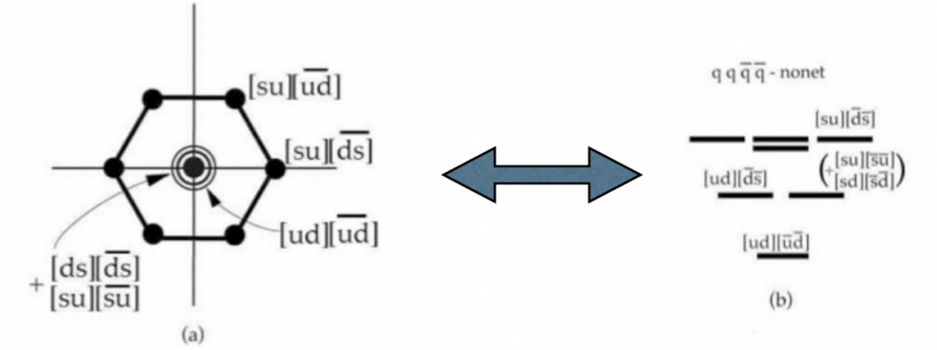
Originally motivated by the scalar mesons puzzle (Maiani et al, 2004)



Understanding exotica: the tetraquark model

Maiani et al, Phys.Rev.Lett. 93 (2004) 212002

t'Hooft et al, Phys.Lett. B662 (2008) 424-430



$$\sigma^{[0]} = [ud][\bar{u}\bar{d}]$$

$$\kappa = [su][\bar{u}\bar{d}];\ [sd][\bar{u}\bar{d}]\ (+\text{ conjugate doublet})$$

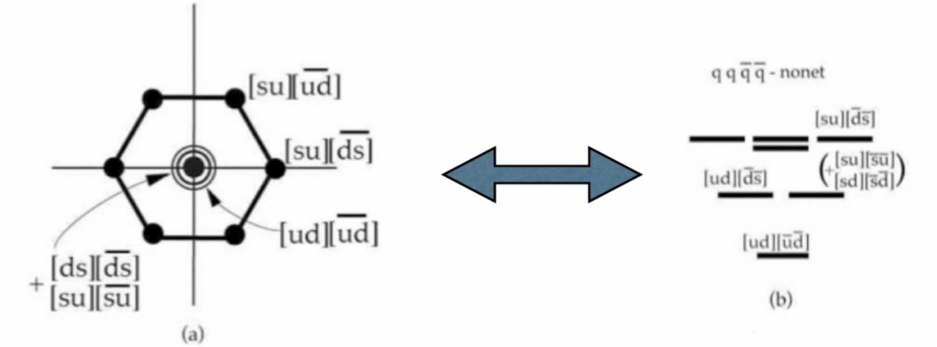
$$f_0^{[0]} = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$

$$a_0 = [su][\bar{s}\bar{d}];\ \frac{[su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]}{\sqrt{2}};\ [sd][\bar{s}\bar{u}]$$

Understanding exotica: the tetraquark model

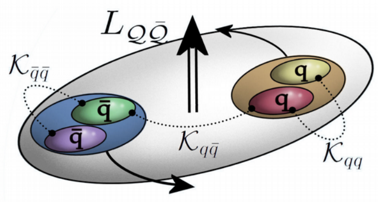
Maiani et al, Phys.Rev.Lett. 93 (2004) 212002

t'Hooft et al, Phys.Lett. B662 (2008) 424-430



$$\sigma^{[0]} = [ud][\bar{u}\bar{d}]$$
$$\kappa = [su][\bar{u}\bar{d}];\ [sd][\bar{u}\bar{d}]\ (+\text{ conjugate doublet})$$
$$f_0^{[0]} = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$
$$a_0 = [su][\bar{s}\bar{d}];\ \frac{[su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]}{\sqrt{2}};\ [sd][\bar{s}\bar{u}]$$

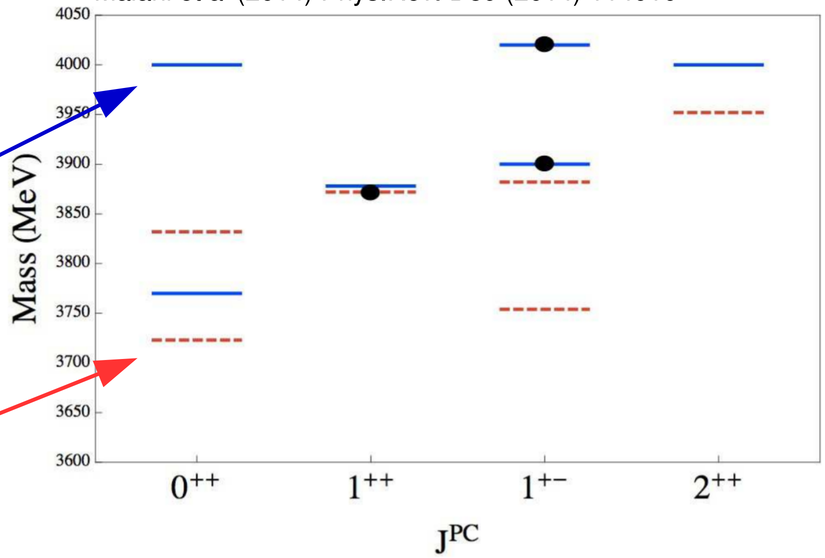
Tetraquark in the heavy sector



Interaction within di-quark dominates
$H \sim 2\kappa_{qc}(s_q.s_c + s_{\bar{q}}.s_{\bar{c}})$

Interaction across di-quarks dominates
$H \sim 2\kappa_{q\bar{q}}s_{q\bar{q}}(s_{q\bar{q}} + 1)$

Maiani et al (2014) Phys.Rev. D89 (2014) 114010

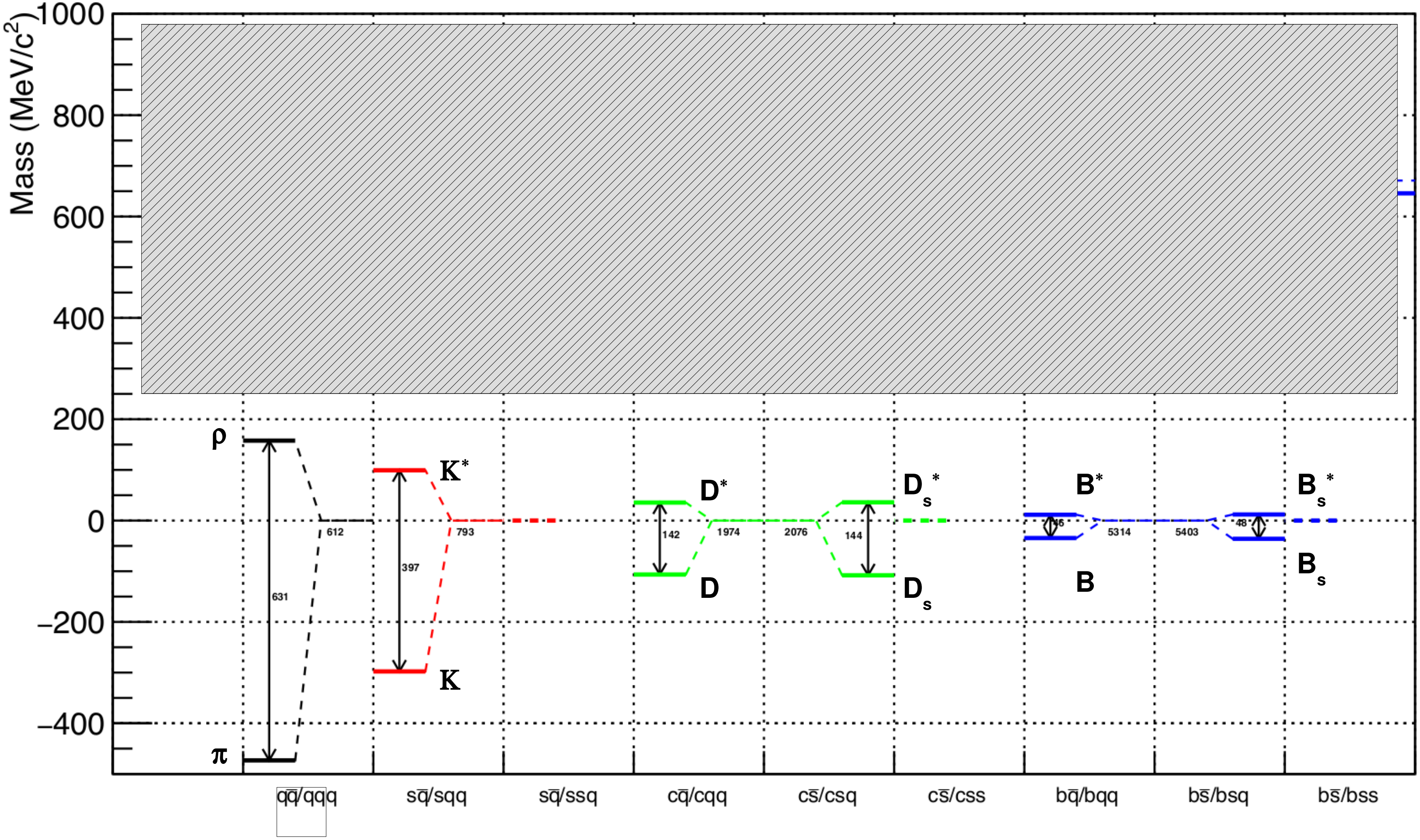


κ_{qc} fixed by mass difference between Z(3900) and Z(4430)

κ_{qq} fixed by mass difference baryons

Di-quarks: something more?

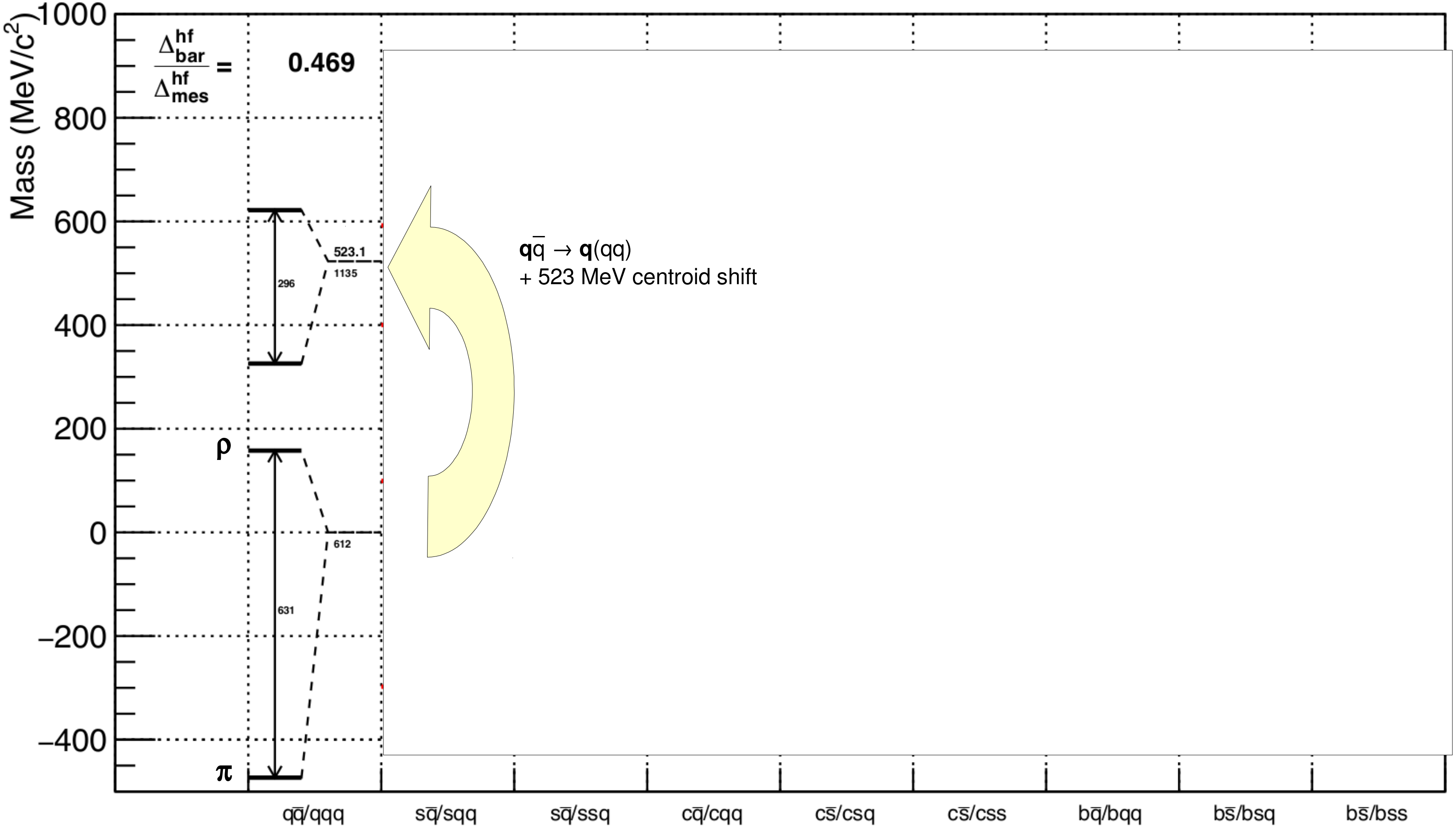
Frascati Phys.Ser. 60 (2015) 1-302



Nice scaling of the hyperfine splitting. Potential model not so bad even at low mass?

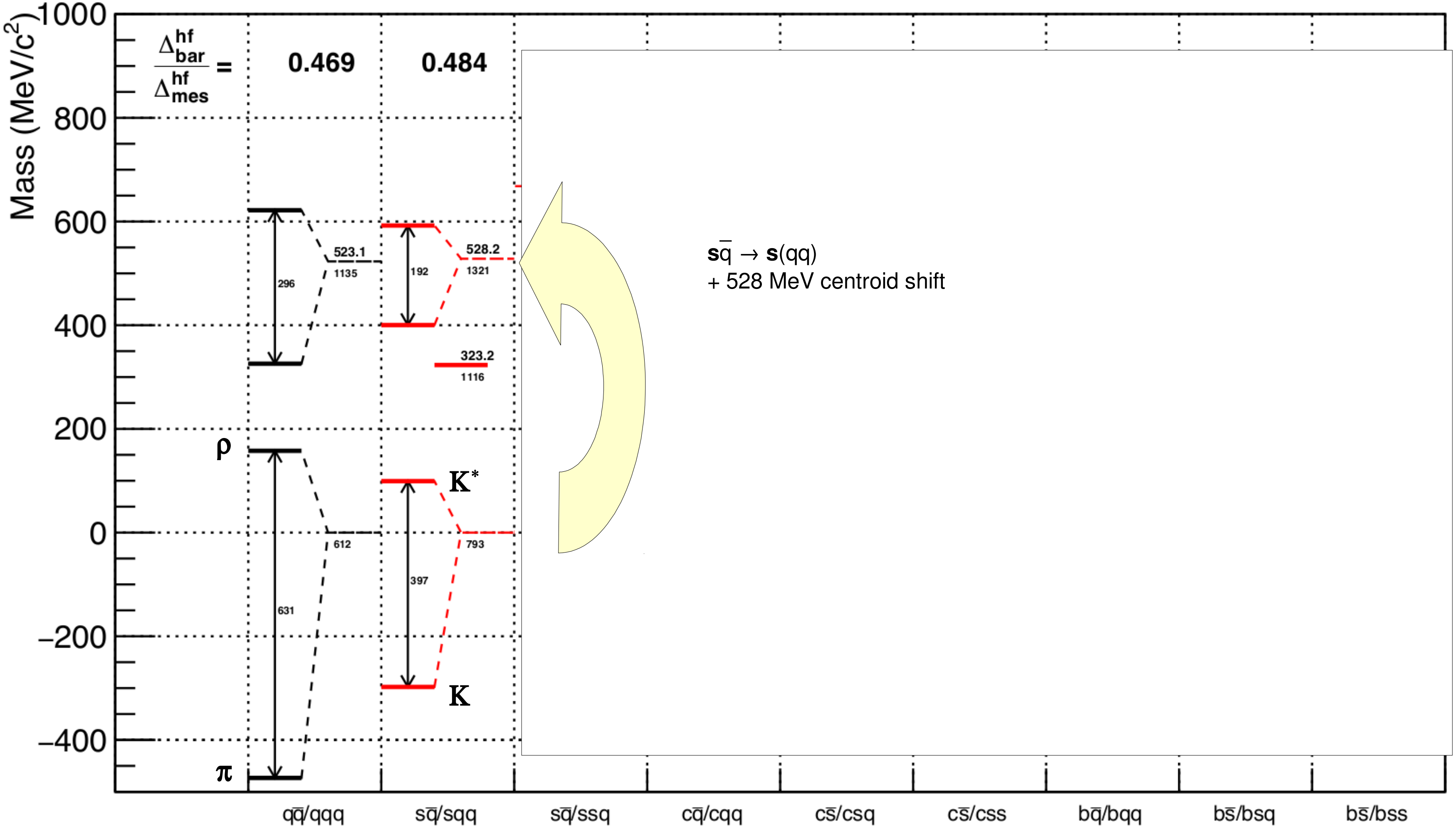
Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302



Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302

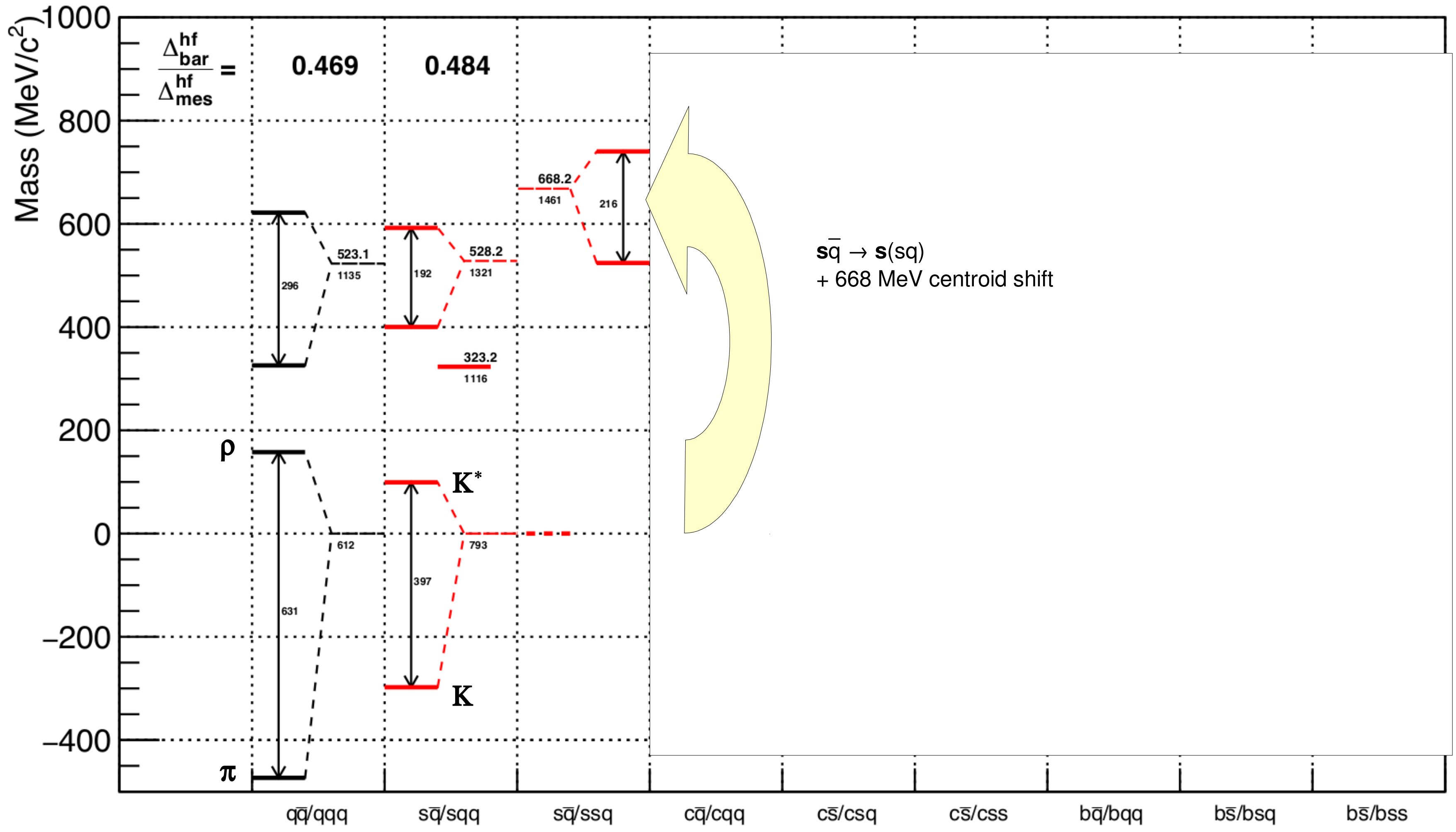


$s\bar{q}$ → **s**(qq)
+ 528 MeV centroid shift

q$\bar{q}$ → **q**(qq)
+ 523 MeV centroid shift

Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302

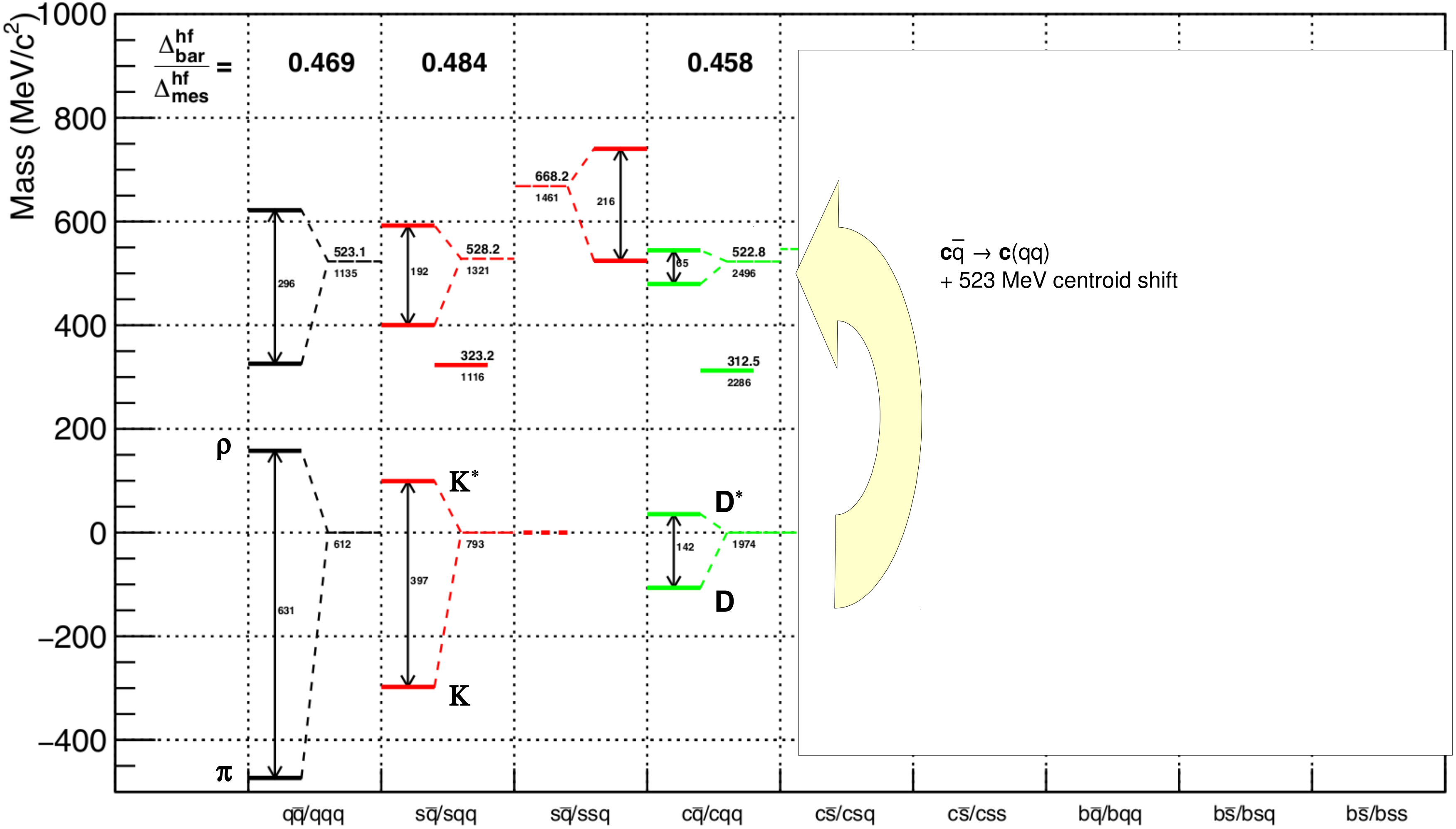


qq̄ → **q**(qq)
+ 523 MeV centroid shift

sq̄ → **s**(qq)
+ 528 MeV centroid shift

Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302



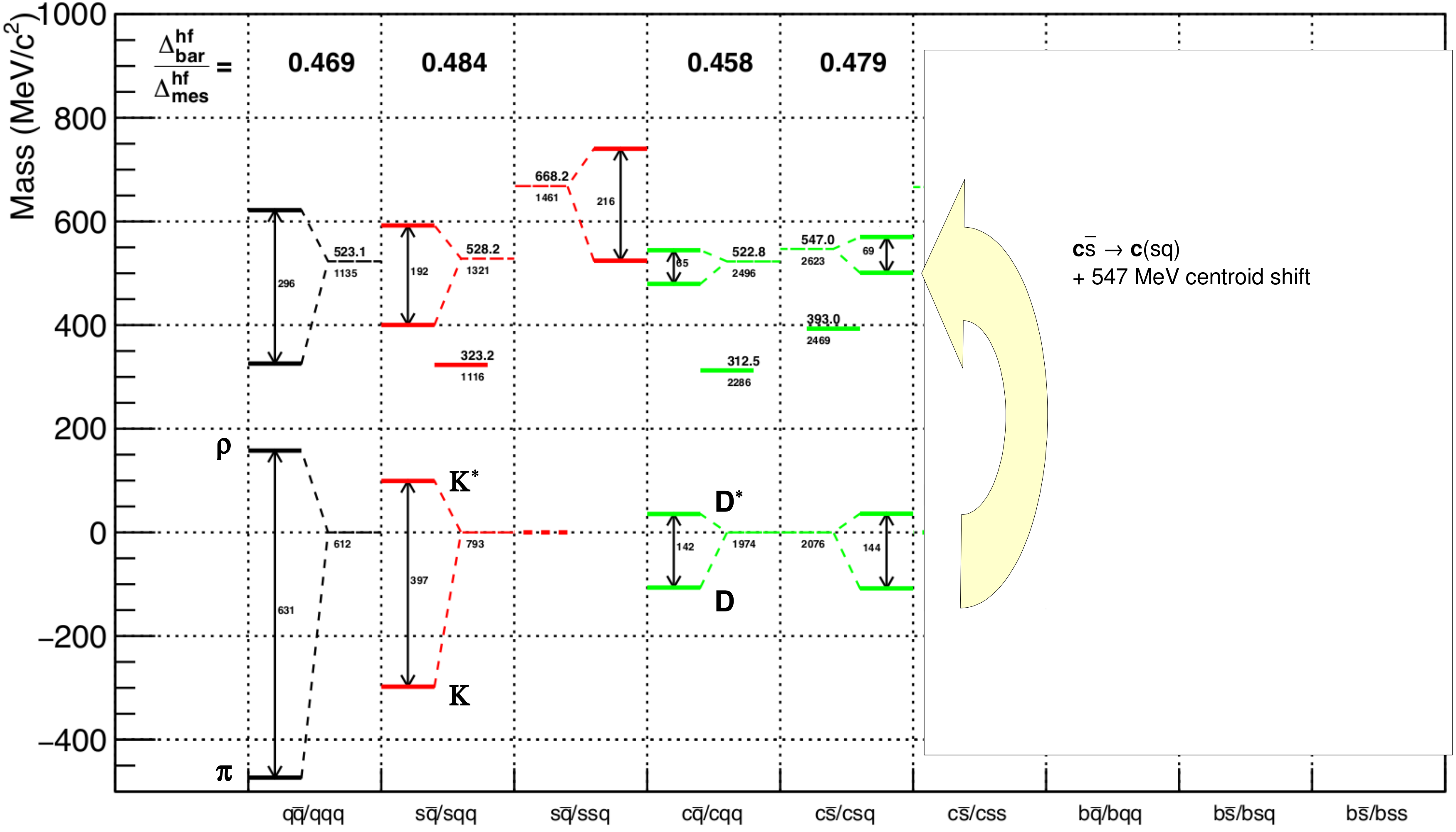
$q\bar{q} \to q(qq)$
+ 523 MeV centroid shift

$s\bar{q} \to s(qq)$
+ 528 MeV centroid shift

$s\bar{q} \to s(sq)$
+ 668 MeV centroid shift

Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302



qq̄ → **q**(qq)
+ 523 MeV centroid shift

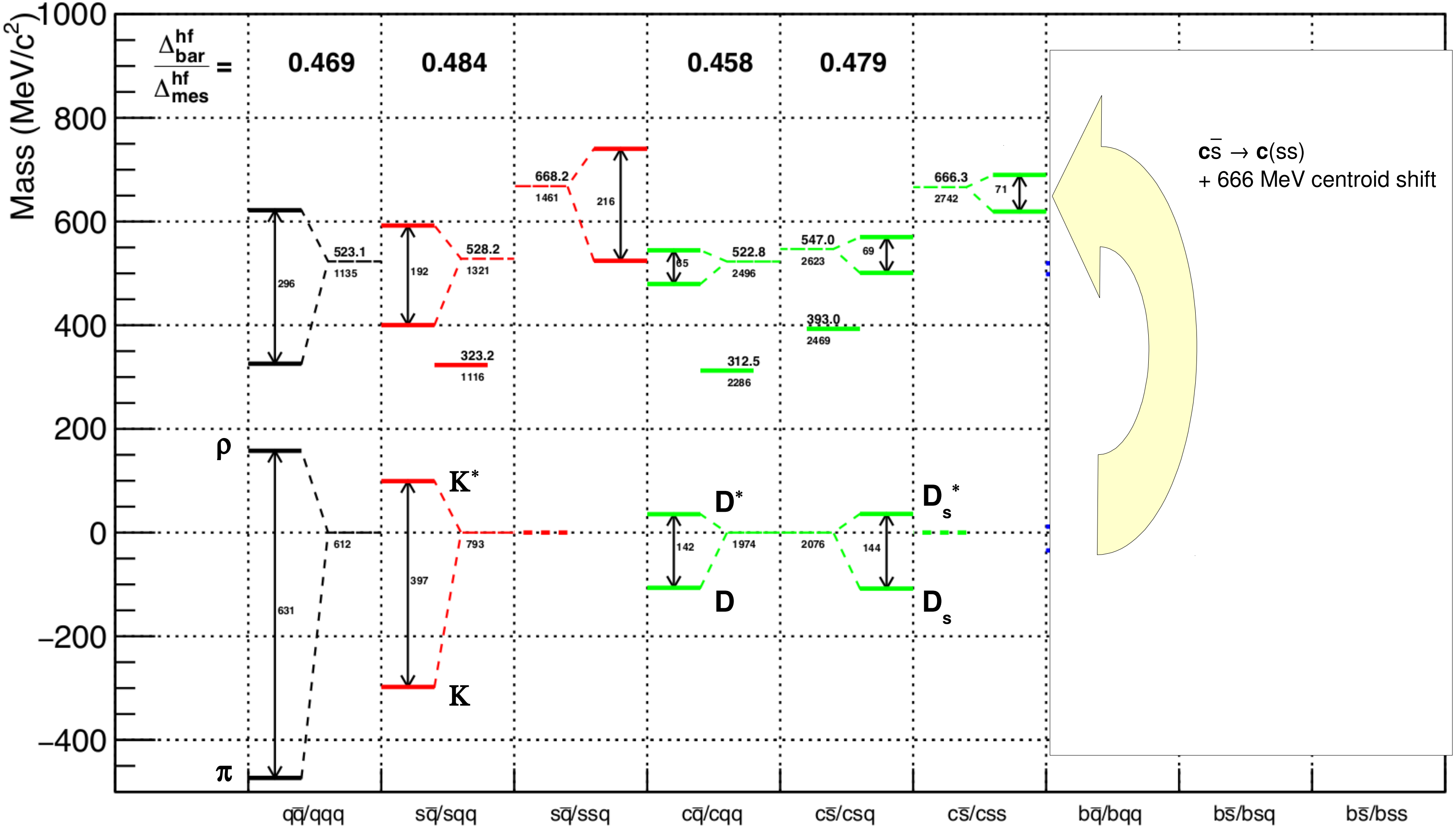
sq̄ → **s**(qq)
+ 528 MeV centroid shift

cq̄ → **c**(qq)
+ 523 MeV centroid shift

sq̄ → **s**(sq)
+ 668 MeV centroid shift

Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302



qq̄ → **q**(qq)
+ 523 MeV centroid shift

sq̄ → **s**(qq)
+ 528 MeV centroid shift

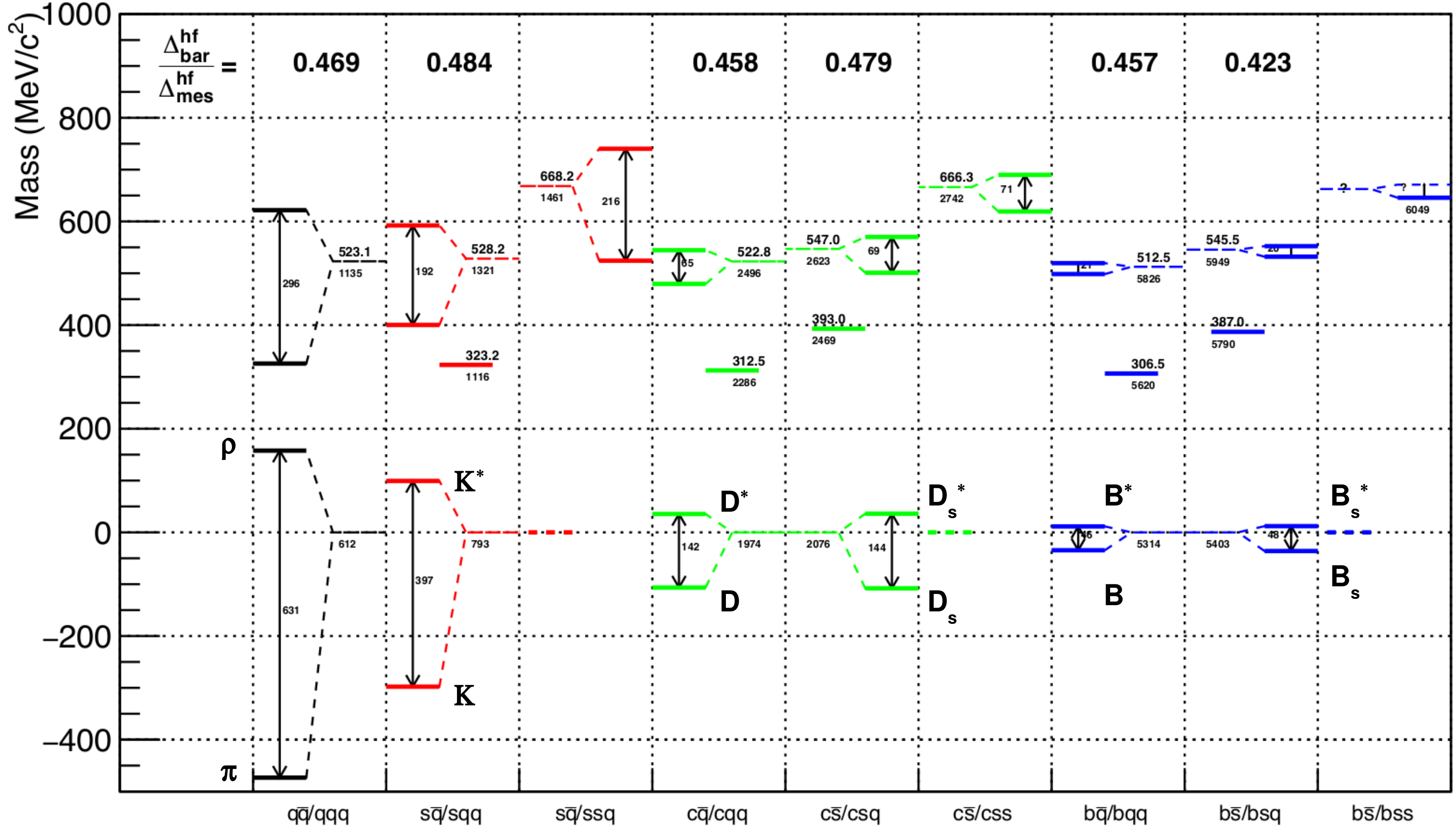
cq̄ → **c**(qq)
+ 523 MeV centroid shift

cs̄ → **c**(sq)
+ 547 MeV centroid shift

sq̄ → **s**(sq)
+ 668 MeV centroid shift

Di-quarks: something more?

Frascati Phys.Ser. 60 (2015) 1-302



S=0 → S=0

$q\bar{q} \to$ **q**(qq)
+ 523 MeV centroid shift

$s\bar{q} \to$ **s**(qq)
+ 528 MeV centroid shift

$c\bar{q} \to$ **c**(qq)
+ 523 MeV centroid shift

$b\bar{q} \to$ **b**(qq)
+ 512 MeV centroid shift

S=1 → S=1

$c\bar{s} \to$ **c**(sq)
+ 547 MeV centroid shift

$b\bar{s} \to$ **b**(sq)
+ 547 MeV centroid shift

S=1 → S=2

$s\bar{q} \to$ **s**(sq)
+ 668 MeV centroid shift

$c\bar{s} \to$ **c**(ss)
+ 666 MeV centroid shift

Tetraquark candidates: matching the data

$Q\bar{Q}q\bar{q}$ (q = u,d)

A.Ali, talk @ B2TiP workshop 2015

Label	J^{PC}	charmonium-like State	charmonium-like Mass [MeV]	bottomonium-like State	bottomonium-like Mass [MeV]
X_0	0^{++}	—	3756	—	10562.2
X_0'	0^{++}	—	4024	—	10652.2
X_1	1^{++}	$X(3872)$	3890	—	10607.2
Z	1^{+-}	$Z_c^+(3900)$	3890	$Z_b^{+,0}(10610)$	10607.2
Z'	1^{+-}	$Z_c^+(4020)$	4024	$Z_b^+(10650)$	10652.2
X_2	2^{++}	—	4024	—	10652.2
Y_1	1^{--}	$Y(4008)$	4024	$Y_b(10891)$	10891.1
Y_2	1^{--}	$Y(4260)$	4263	$Y_b(10987)$	**10987.5**
Y_3	1^{--}	$Y(4290)$ (or $Y(4220)$)	4292	—	**10981.1**
Y_4	1^{--}	$Y(4630)$	4607	—	11135.3
Y_5	1^{--}	—	6472	—	13036.8

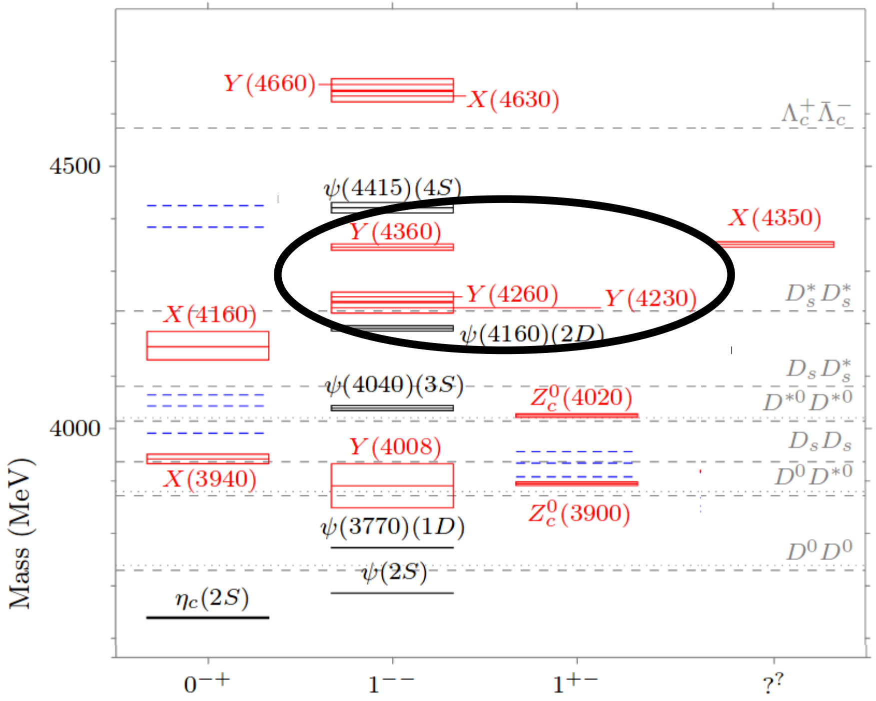
More states than observed ones….

$Q\bar{Q}s\bar{s}$

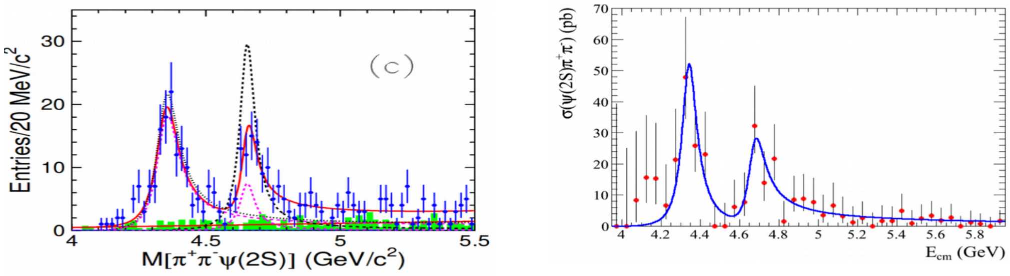
Phys.Rev. D93 (2016) no.9, 094024

State		Pred. Mass	Observed
X_0	$\|0^{++}\rangle_1$	3920	$\chi_{c0}(3915)^*$
X_0'	$\|0^{++}\rangle_2$	4360	$X(4350)$?
X_1	$\|1^{++}\rangle$	4140	$Y(4140)^*$
Z	$\|1^{+-}\rangle_1$	4140	
Z'	$\|1^{+-}\rangle_2$	4360	
X_2	$\|2^{++}\rangle$	4360	$X(4350)$?
	$\|0^{--}\rangle$	4320	$Y(4274)$?
	$\|0^{-+}\rangle_1$	4320	$Y(4274)$?
	$\|0^{-+}\rangle_2$	4540	
Y_1	$\|1^{--}\rangle_2$	3920	$Y(4008)$
Y_2	$\|1^{--}\rangle_1$	4230	$Y(4230)^*$
	$\|1^{-+}\rangle_1$	4230	
	$\|1^{-+}\rangle_2$	4450	
Y_3	$\|1^{--}\rangle_3$	4360	$Y(4360)^*$
Y_4	$\|1^{--}\rangle_4$	4630	$Y(4660)$
	$\|2^{-+}\rangle_1$	4050	
	$\|2^{-+}\rangle_2$	4270	$Y(4274)$?
	$\|2^{--}\rangle_1$	4050	
	$\|2^{--}\rangle_2$	4450	
	$\|3^{--}\rangle$	4180	

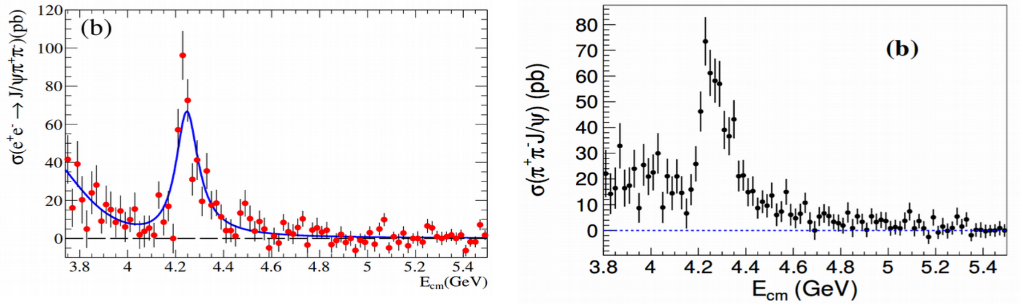
The case of vector charmonia



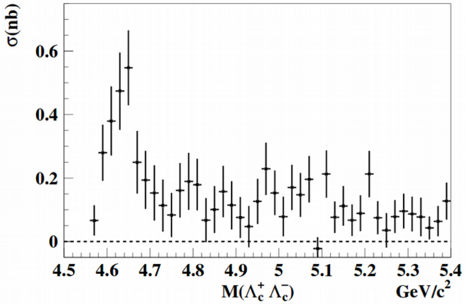
$e^+e^- \to \pi\pi\,\psi(2S)$



$e^+e^- \to \pi\pi\,J/\psi$



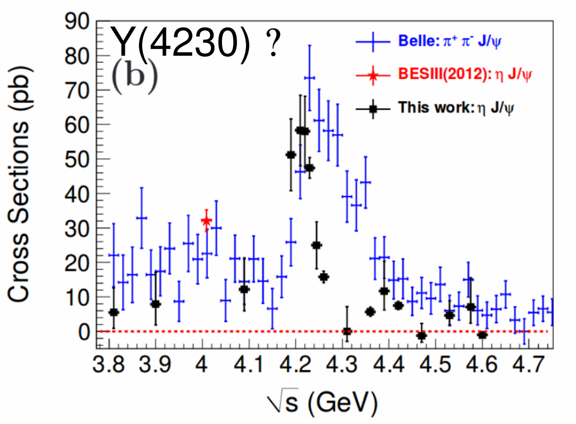
$e^+e^- \to \Lambda_c\overline{\Lambda}_c$



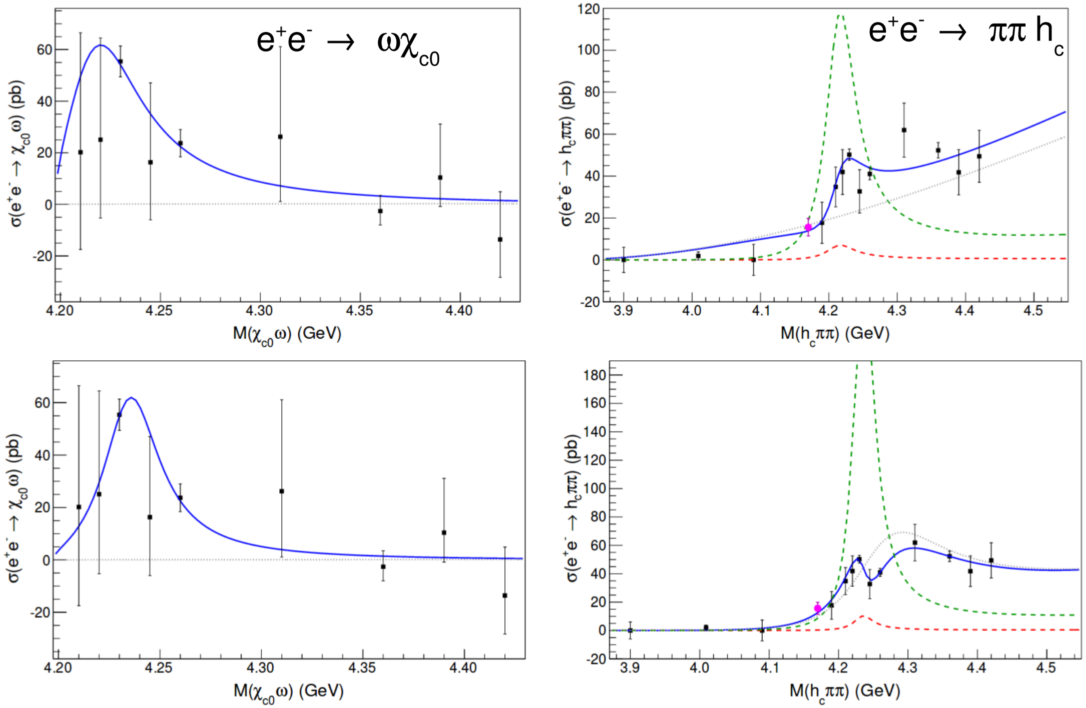
→ Several states piled up
→ Little (or none) overlap of decay modes

→ Y(4360) only in ππ ψ(2S)
→ Y(4260) only in ππ J/ψ

Y(4260): how many states?



Phys.Rev. D91 (2015) no.11, 117501

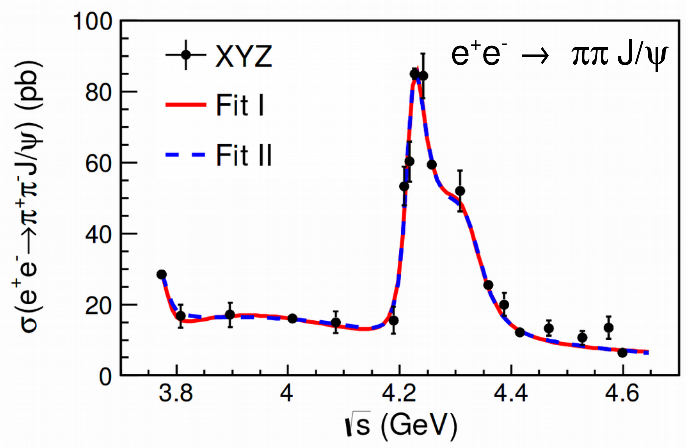


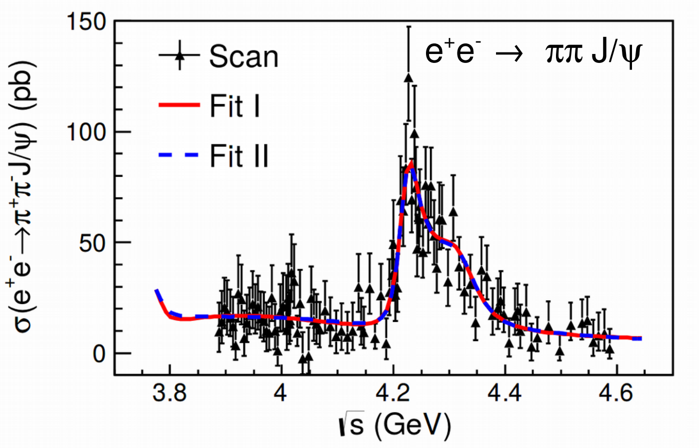
→ Y(4360) only in ππ ψ(2S)
→ Y(4260) only in ππ J/ψ
→ Y(4230) ηJ/ψ
  → also in ππ h_c, $\omega\chi_c$
  → better fit with Y(4230) + Y(4260)

m_1	(4234.4 ± 5.7) MeV
Γ_1	(34 ± 16) MeV
m_2	(4255 ± 18) MeV
Γ_2	(158 ± 52) MeV

Y(4260): yet other states!

BESIII scan: Phys. Rev. Lett. 118, 092001 (2017)





M = 4222 MeV, Γ = 44 MeV
M = 4320 MeV, Γ = 101 MeV

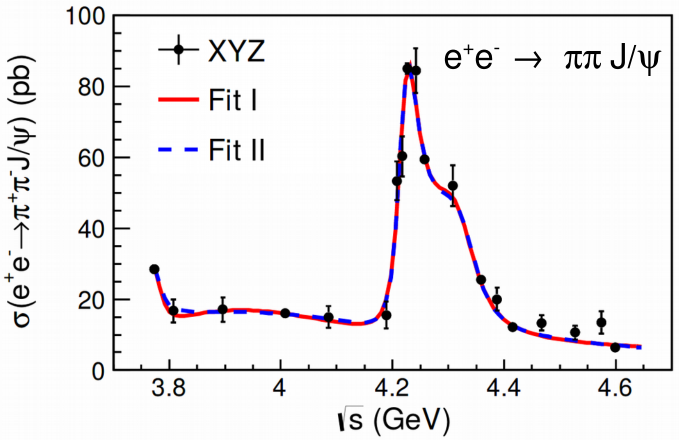
The Y(4260) simply does not exists!

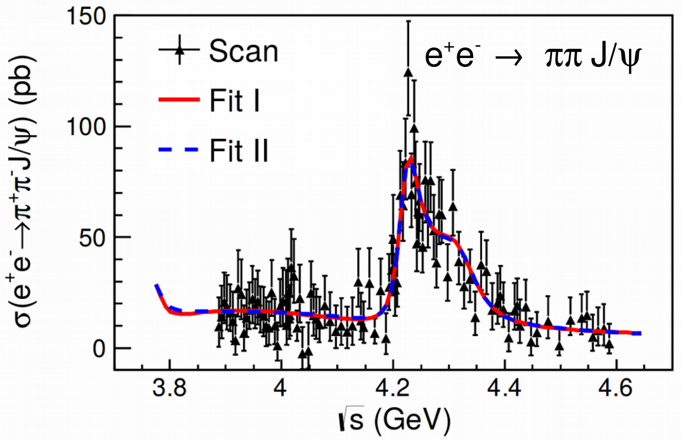
Parameters	Fit result
~~$M(R_1)$~~	~~$3812.6^{+61.9}_{-96.6}$ $(\cdots)$~~
~~$\Gamma_{tot}(R_1)$~~	~~$476.9^{+78.4}_{-64.8}$ $(\cdots)$~~
$M(R_2)$	4222.0 ± 3.1 (4220.9 ± 2.9)
$\Gamma_{tot}(R_2)$	44.1 ± 4.3 (44.1 ± 3.8)
$M(R_3)$	4320.0 ± 10.4 (4326.8 ± 10.0)
$\Gamma_{tot}(R_3)$	$101.4^{+25.3}_{-19.7}$ $(98.2^{+25.4}_{-19.6})$

Background PDF

Y(4260): yet other states!

BESIII scan: Phys. Rev. Lett. 118, 092001 (2017)

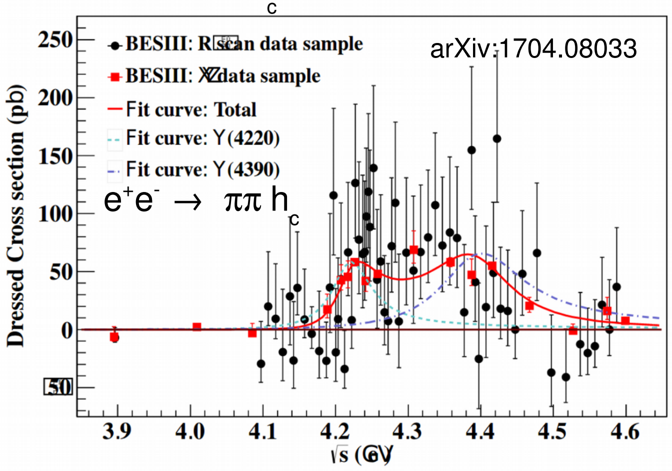




M = 4222 MeV, Γ = 44 MeV
M = 4320 MeV, Γ = 101 MeV

The Y(4260) simply does not exists!

$e^+e^- \to \pi\pi h_c$



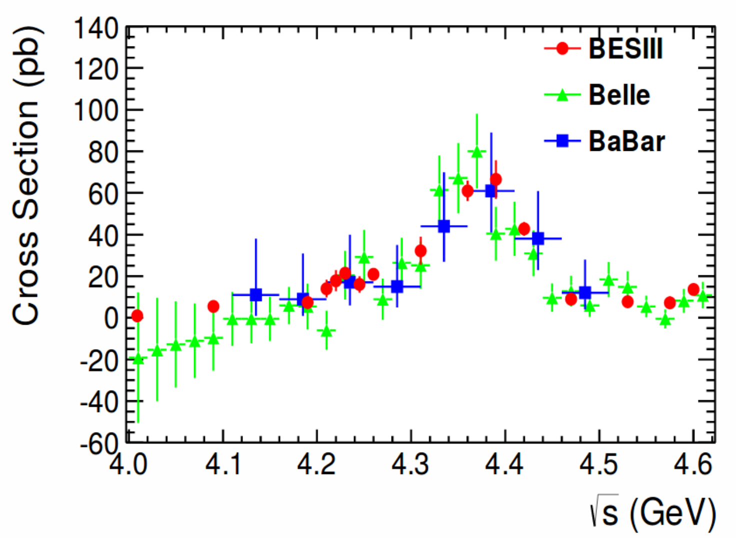
M = 4218 MeV, Γ = 66 MeV
M = 4391 MeV, Γ = 140 MeV

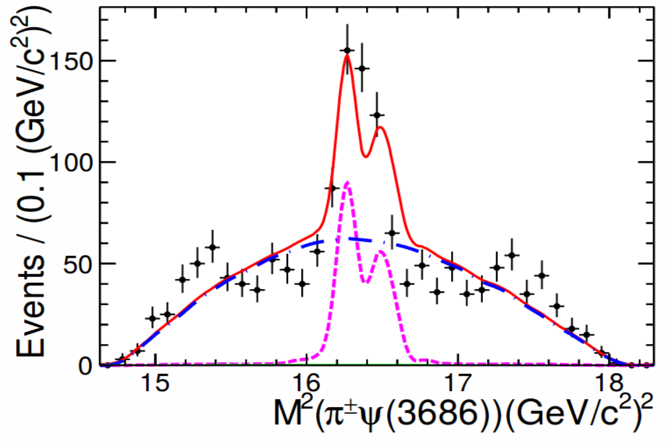
In summary, Y(4260) region hosts in total 4 $J^{PC} = 1^{--}$ states:

→ Y(4230) [Γ ~ 50 MeV] in all the decay modes, including $\omega\chi_c$ and $\eta J/\psi$
→ Y(4320) [Γ ~ 100 MeV] only in $\pi\pi J/\psi$
→ Y(4360) [Γ ~ 50 MeV] only in $\pi\pi \psi'$
→ Y(4390) [Γ ~ 140 MeV] only in $\pi\pi h_c$

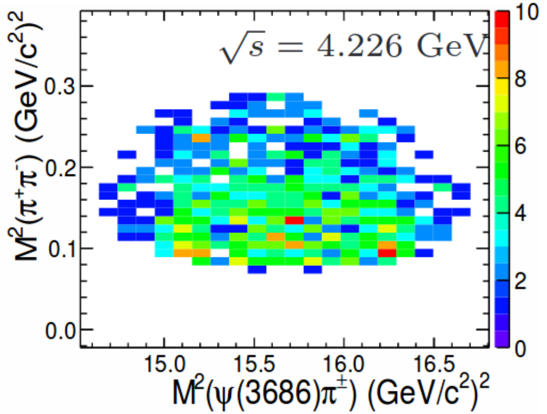
Breaking news!

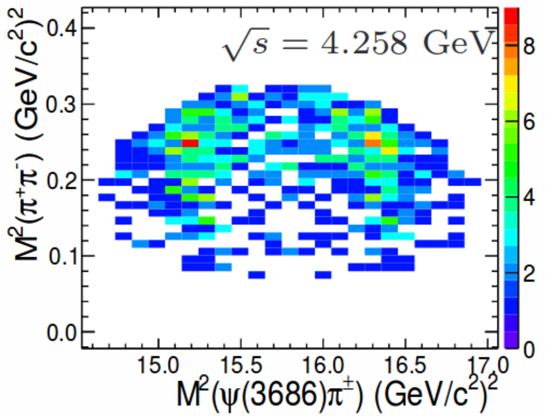
arXiv:1703.08787 [hep-ex], $e^+e^- \to \pi\pi\,\psi'$

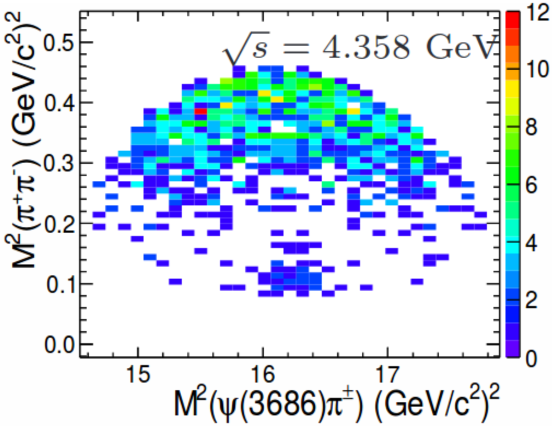


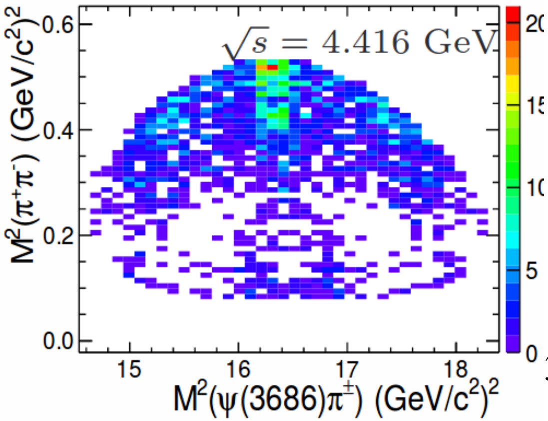


Some structures are there, but a good fit has not been found yet







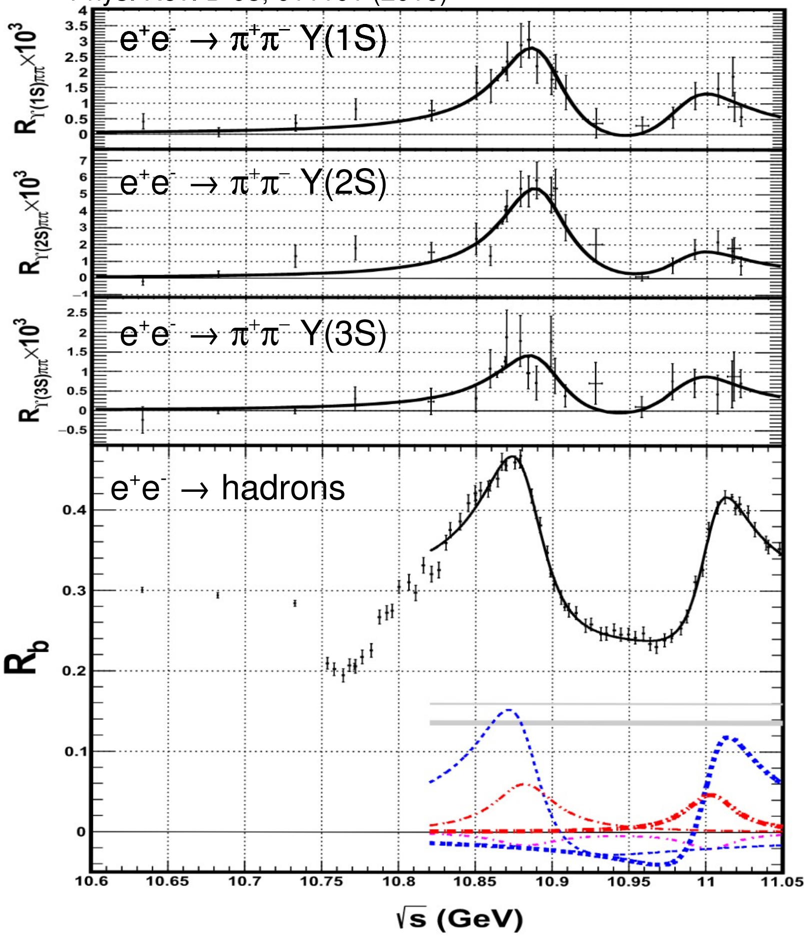


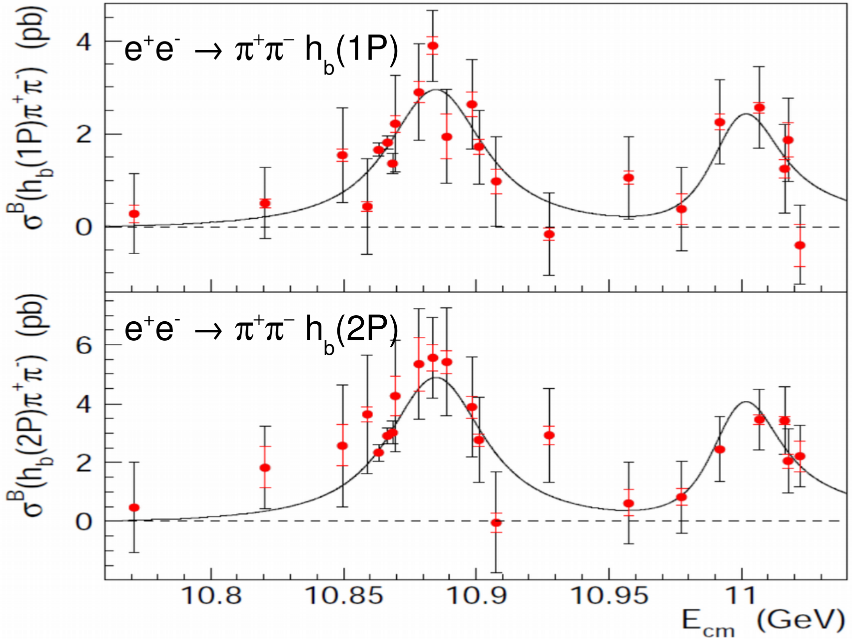
A look at Bottomonium

Comparing the spectra it is reasonable (at first) to relate Y(4260) and ϒ(5S)

Yet, the situation is rather different!

Phys. Rev. D 93, 011101 (2016)





Part II: what's next

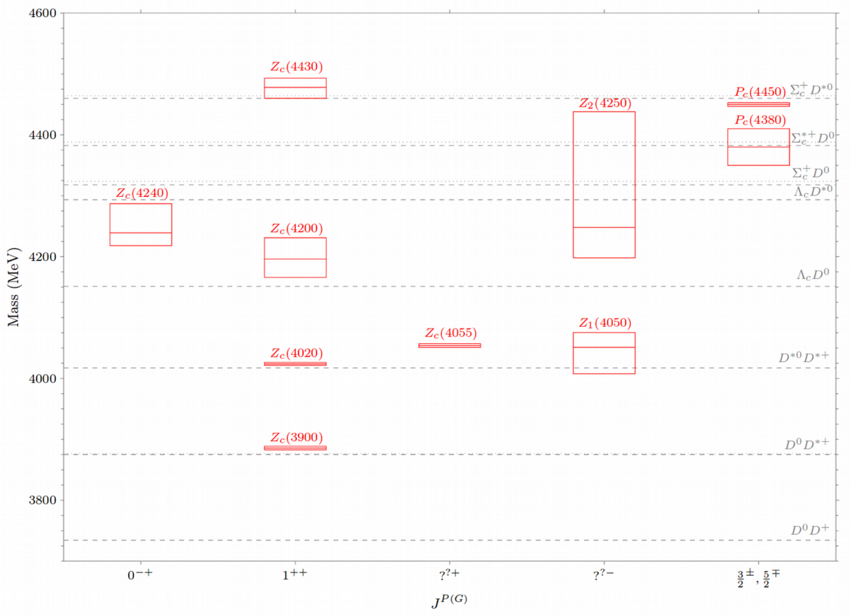
$\rightarrow$ Probing the exotic's nature

$\rightarrow$ New approaches to the light sector?

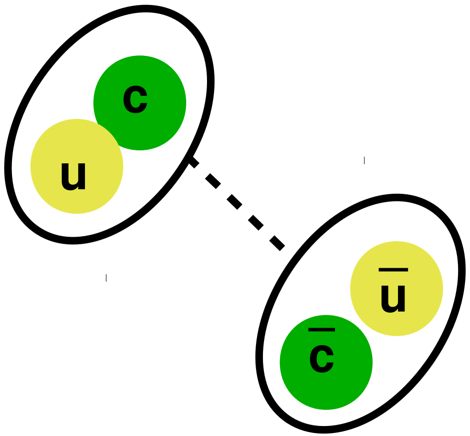
$\rightarrow$ Heavy meson annihilations as probes for collective effects

Exotica: alternative models

Compact tetraquarks are not the only model on the market



Several exotica are on a meson-meson threshold.
→ Hadronic molecules?



Loosely bound states of color singlets

Powerful model: describes effects in light mesons and baryon sector as well ***(very recent review: arXiv:1705.00141)***

Matches well with data in some cases
Zb, Zc ✓
X(3872) ✗

Phys. Rev. Lett. 116, 212001

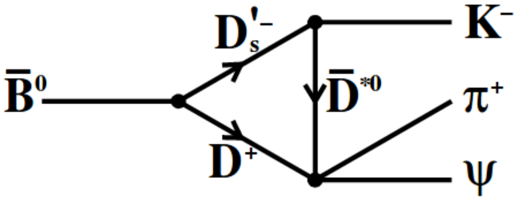
Channel	Fraction, % $Z_b(10610)$	Fraction, % $Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	...
$B^{*+}\bar{B}^{*0}$	...	$73.7^{+3.4+2.7}_{-4.4-3.5}$

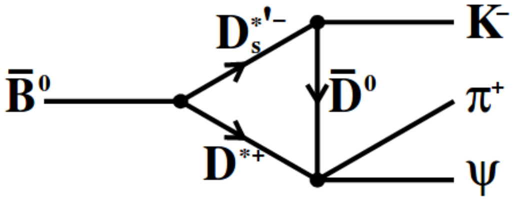
Decay of a molecule into its components

Exotica: alternative models

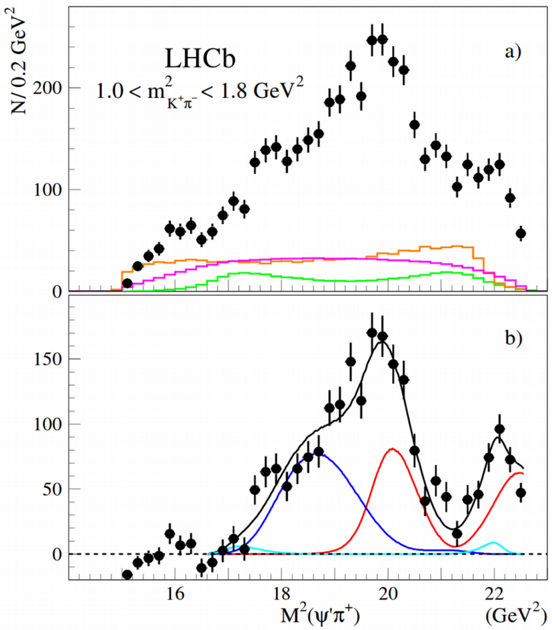
Several exotica are on a meson-meson threshold.
→ Dynamic effects?

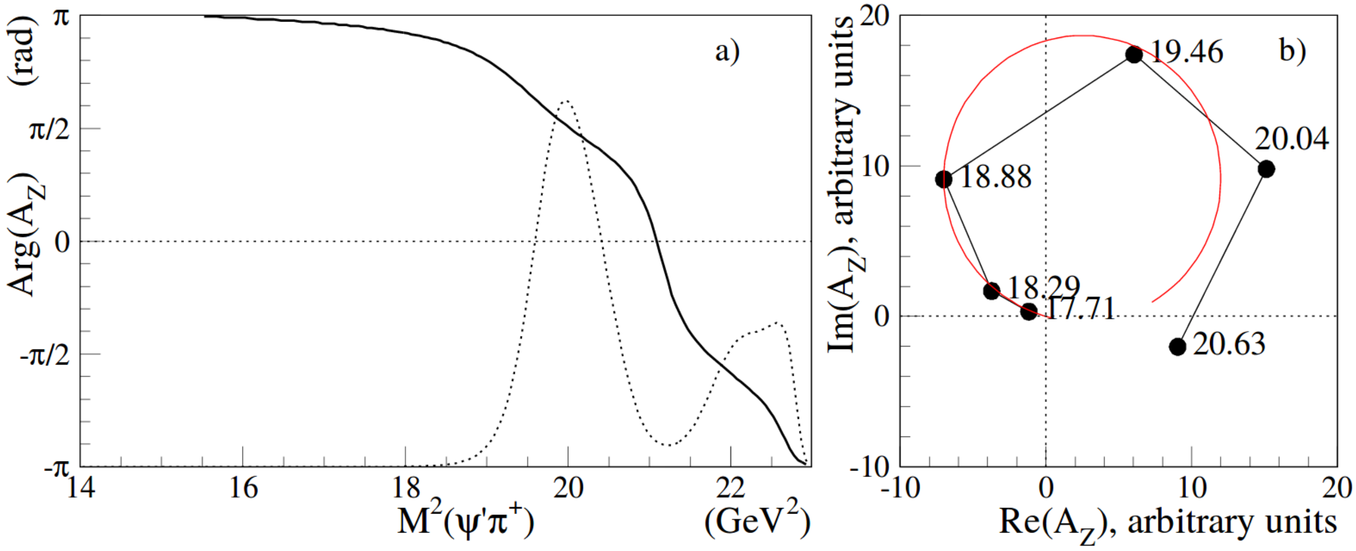
Phys.Lett. B748 (2015) 183-186





Can describe the Z(4430) even in the phase structure



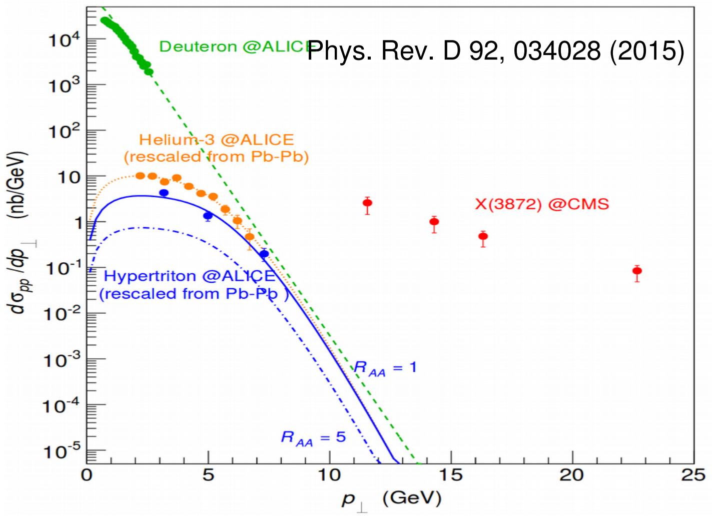


X(3872) in hadronic events

Esposito et Al, Phys. Rev. D 92, 034028 (2015)

If the X(3872) is a loosely bound molecule like deuteron, it's not likely to be produced at high p_T in hadron collisions, while If the X(3872) is a compact tetraquark, it can.

Inclusive production as probe of the exotic's nature



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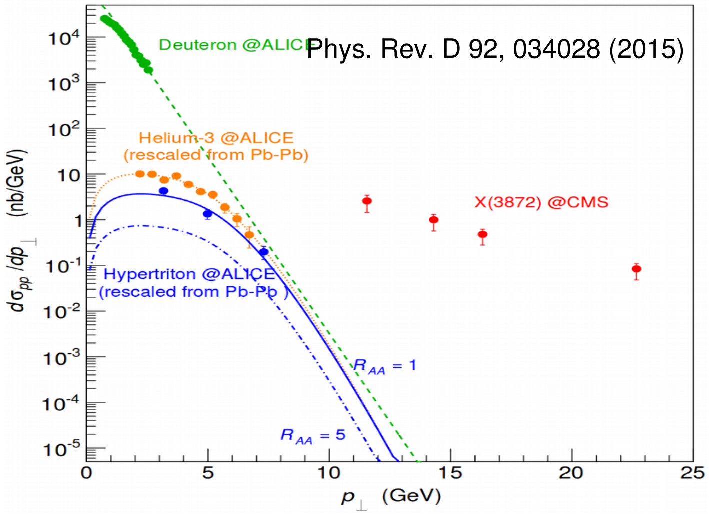
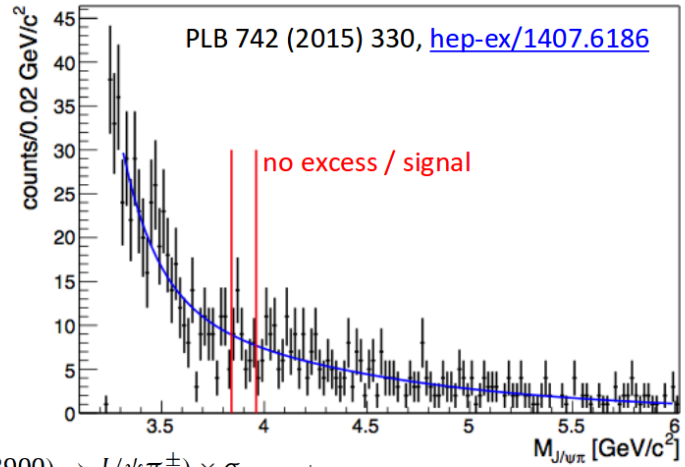


Compass 2015: no Zc(3900)!



$$\frac{BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma N \to Z_c^{\pm}(3900) N}}{\sigma_{\gamma N \to J/\psi N}} < 3.7\ 10^{-3}$$

Inclusive production as probe

Esposito et Al, Phys. Rev. D 92, 034028 (2015)

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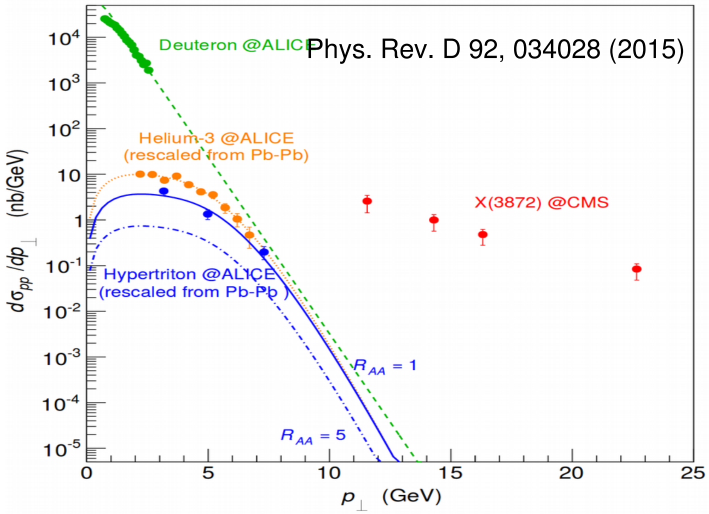
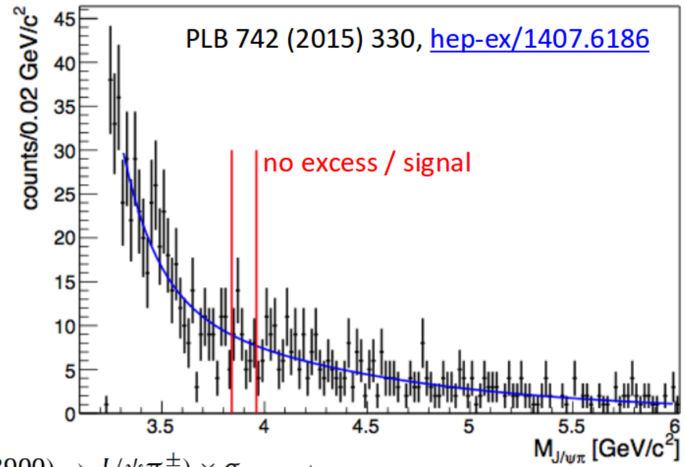


Compass 2015: no Zc(3900)!



$$\frac{BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma N \to Z_c^{\pm}(3900) N}}{\sigma_{\gamma N \to J/\psi N}} < 3.7\ 10^{-3}$$

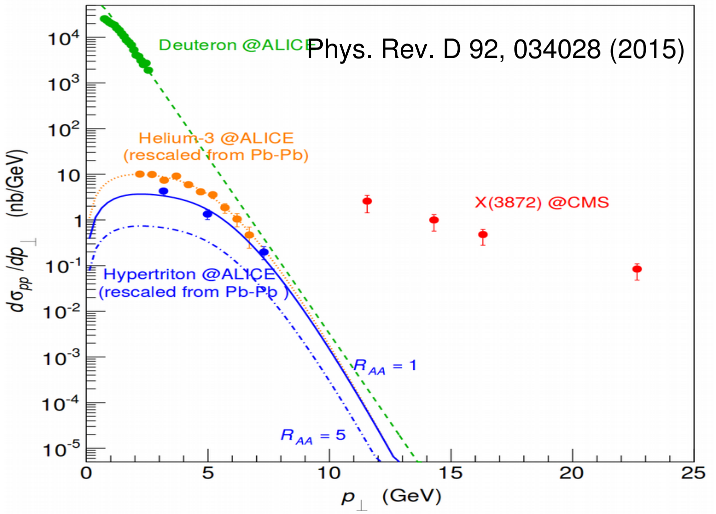
Results on other exotica from low-energy hadronic events?

Inclusive production as probe in Y(1S) decays

Esposito et Al, Phys. Rev. D 92, 034028 (2015)

If the X(3872) is a loosely bound molecule like deuteron, it's not likely to be produced at high p_T in hadron collisions, while If the X(3872) is a compact tetraquark, it can.

Inclusive production as probe of the exotic's nature

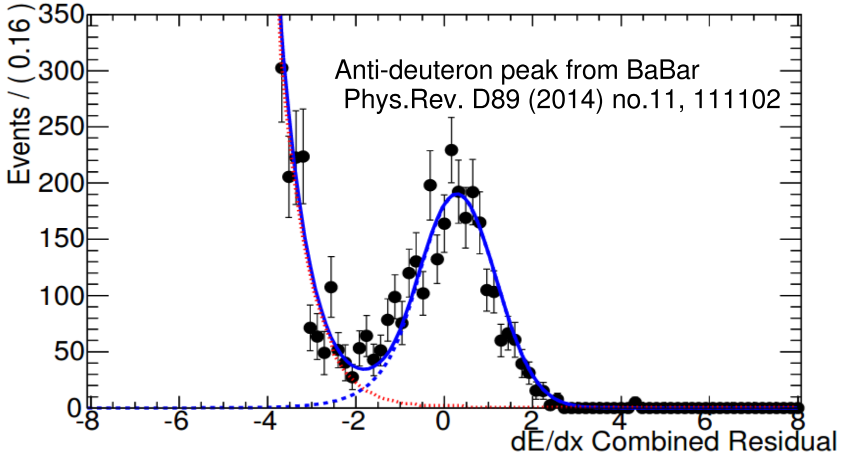


Y(nS) annihilations provide hadronic events
Small phase space, <u>but very high partonic density</u>
10 GeV in r ~ 0.1 fm

<u>Known production of deuteron</u>

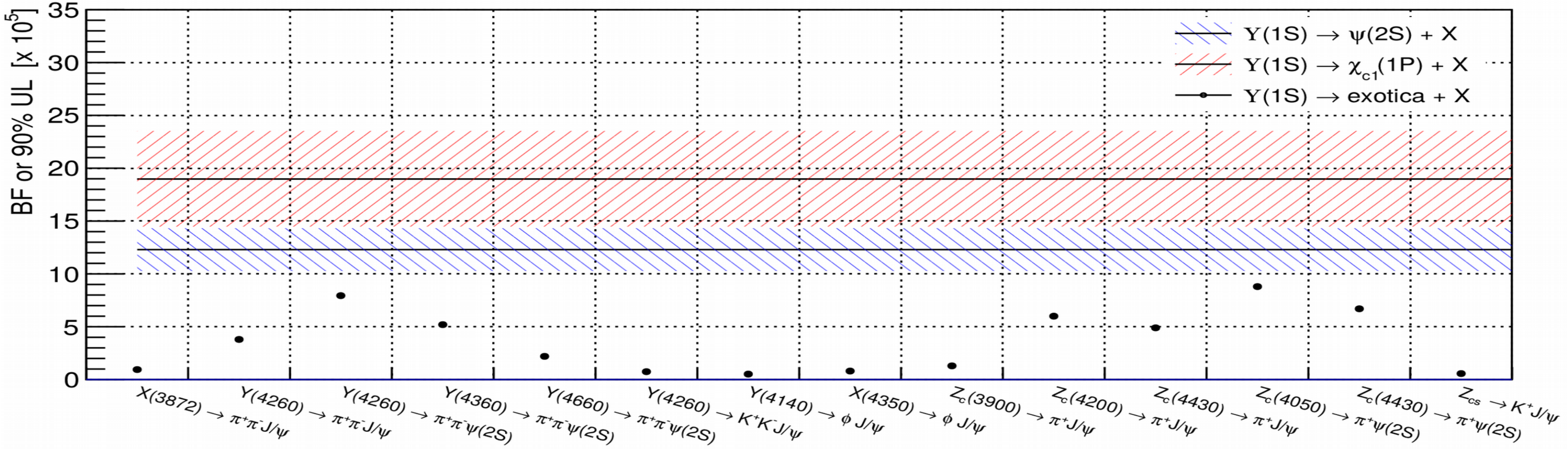
Phys.Rev. D89 (2014) no.11, 111102

Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ [$\sqrt{s} \approx 10.58\,\mathrm{GeV}$]	$(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb
$\frac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \mathrm{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$



Exotic $c\bar{c}$ in Y(1S)

Belle, Phys. Rev. D 93, 112013



Belle 2017: Inclusive production of exotic and conventional charmonia in Y(1S) annihilations

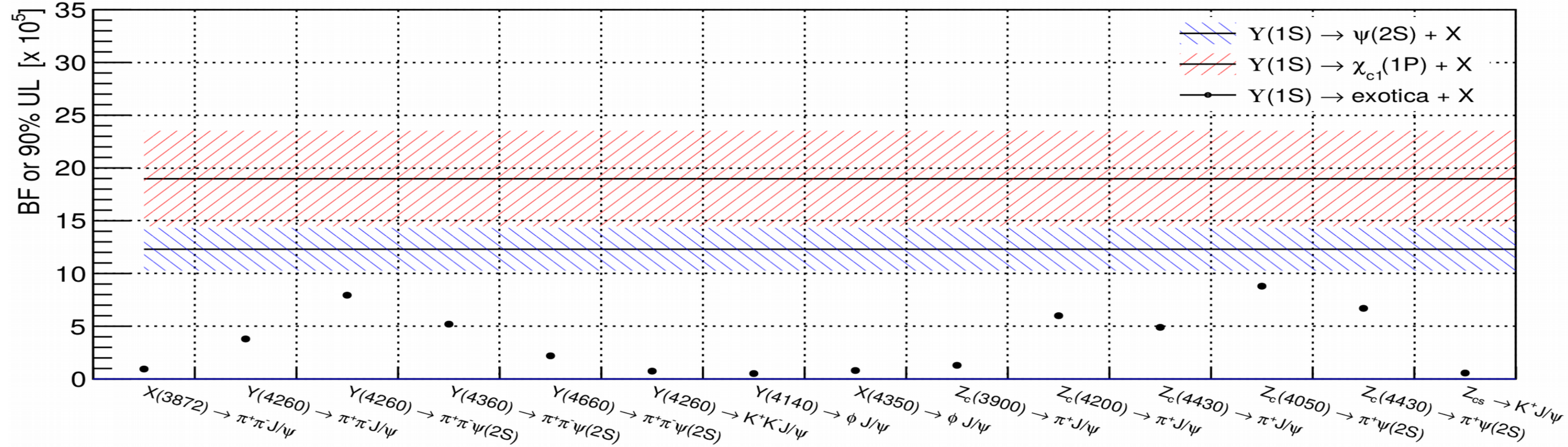
→ No exotica

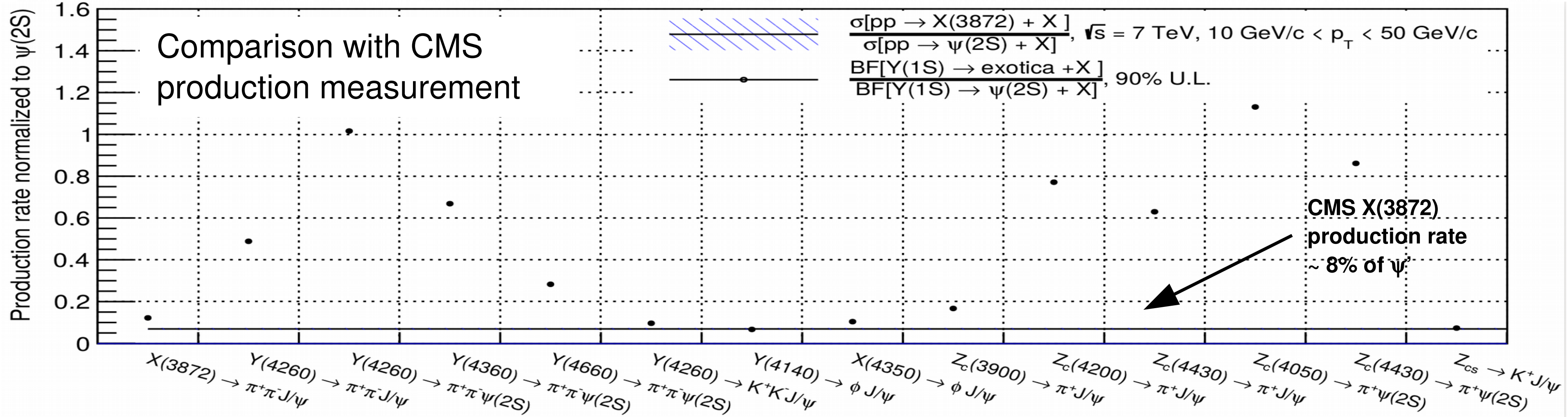
→ What can we compare with?

→ CMS measurement of X(3872) production

Exotic $c\bar{c}$ in $\Upsilon(1S)$

Belle, Phys. Rev. D 93, 112013

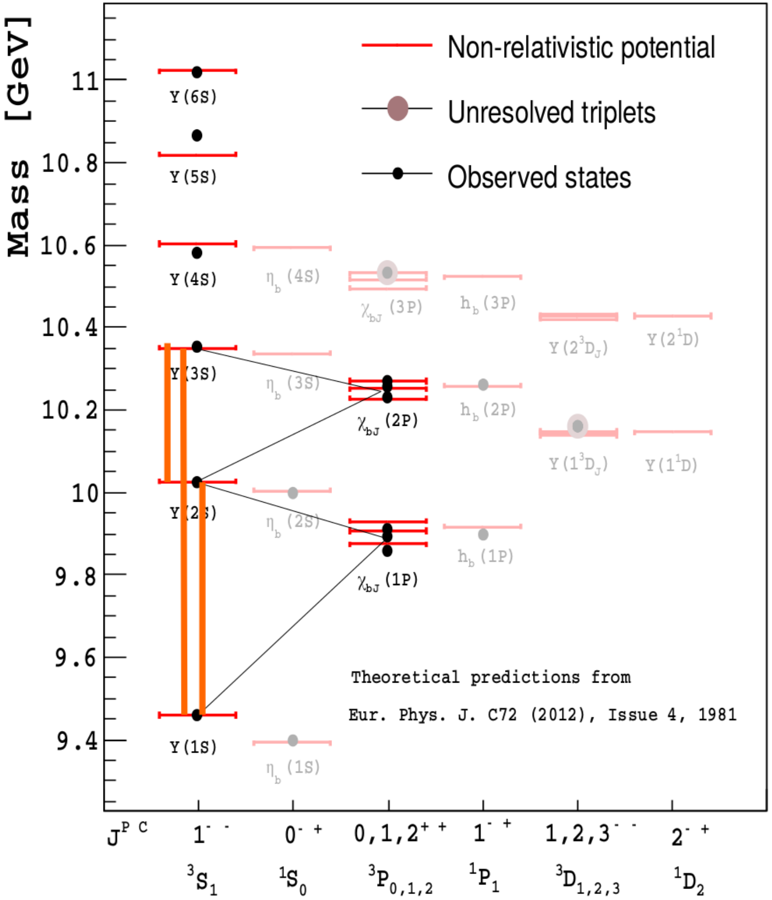




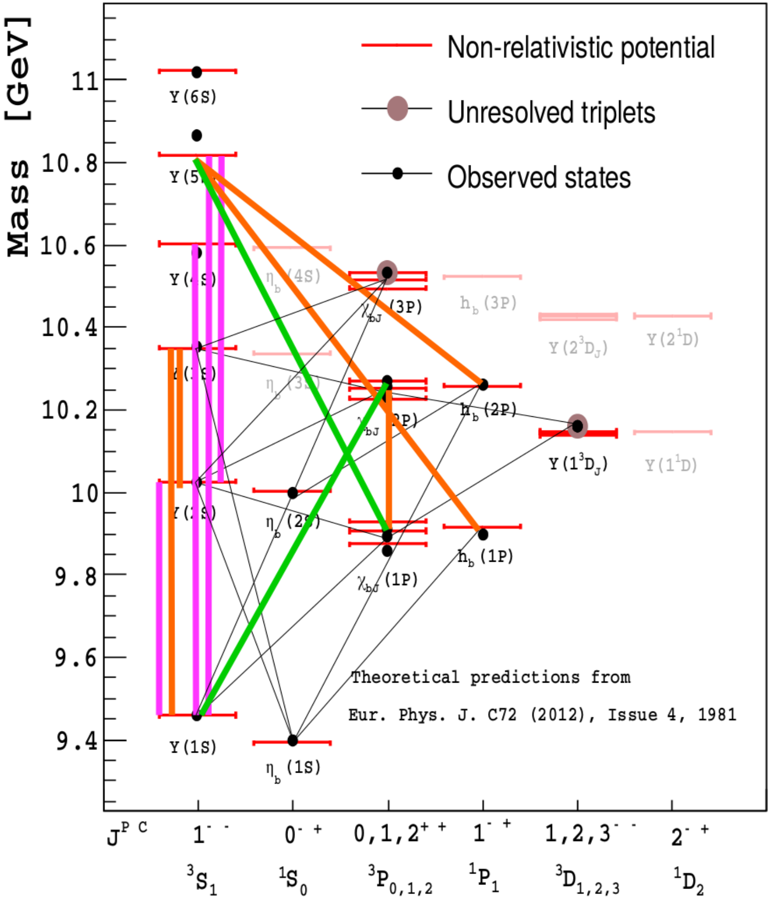
Transitions as a new probe

… and outstanding progresses in the study of transitions with the discovery of several selection rule violations.

Transitions pattern circa year 2000

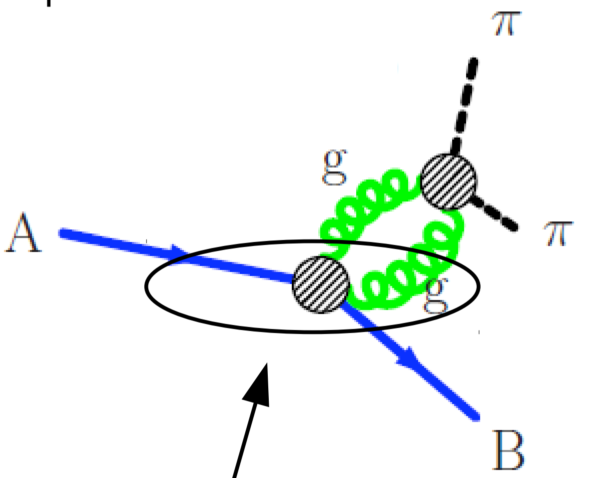


Transitions pattern year 2015



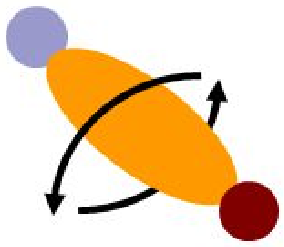
Transitions as a new probe for light exotica

Di-pion transitions among quarkonia can me modeled as the emission of a gluon pair in the the **QCD Multipole Expansion** formalism



Intermediate $q\bar{q}g$ states can be factorized

$$\mathcal{M}(\Phi_i \to \Phi_f + h) = \frac{1}{24}\sum_{KL} \frac{\langle f|d_m^{ia}|KL\rangle\langle KL|d_{ma}^{j}|i\rangle}{E_i - E_{KL}} \langle h|\mathbf{E}^{ai}\mathbf{E}_a^{j}|0\rangle$$



Phys.Rev. D76 (2007) 074035

The transition of higher excited states of quarkonia into lower ones (including the ground state) without flavor change but emitting photon or light mesons is believed to offer rich information on the hadron structure and governing dynamics, especially for the heavy quarkonia physics, for example, Brambilla *et al.*[23] studied the quarkonium radiative decays which are realized via electromagnetic interactions.

Our studies indicate that the transitions of $\psi(ns)(\Upsilon(ns)) \to \psi(ms)(\Upsilon(ms)) + \pi\pi$ may provide valuable information about the hybrid structures which have so far not been identified in experiments yet.

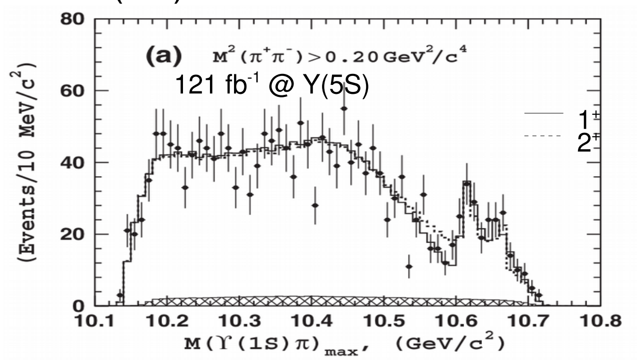
Scalar mesons in di-pion transitions

Phys.Rev. D91 (2015) no.7, 072003

$\Upsilon(5S) \to \pi\pi\ \Upsilon(1S)$

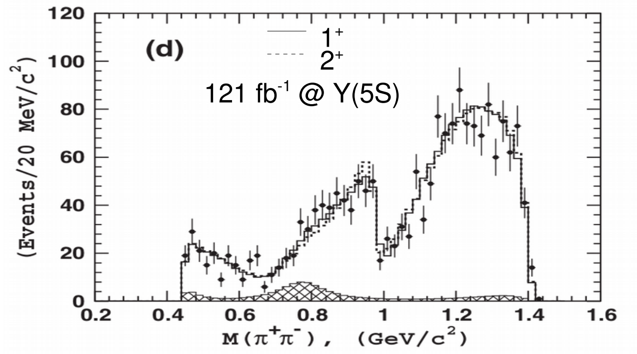
$$\mathcal{M}_{\Upsilon\pi\pi} = \mathcal{A}_{Z_1\pi} + \mathcal{A}_{Z_2\pi} + \mathcal{A}_{\Upsilon\sigma} + \mathcal{A}_{\Upsilon f_0} + \mathcal{A}_{\Upsilon f_2} + \mathcal{A}_{\rm NR}$$

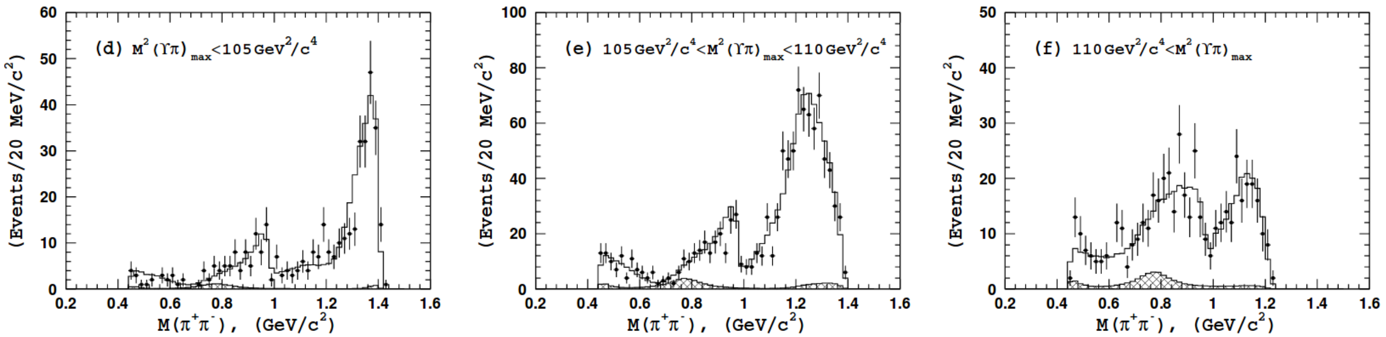
$\Upsilon(1S)\pi^+\pi^-$



→ Dalitz structure contains several 0^{++} contributions
→ Statistics is too limited to fit them now

→ Possibility for BelleII to contribute to solve the scalar meson puzzle?





Pion scattering length from di-pion transitions

At low energy the ππ interaction is described by two scattering lengths who vanish in the chiral limit:

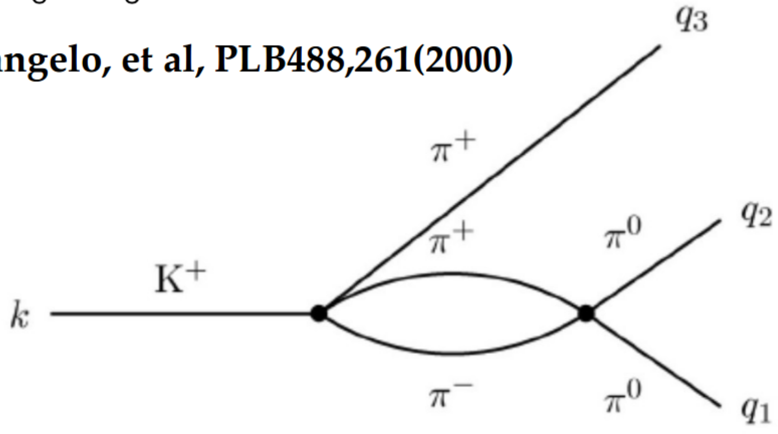
$$a_0^0 = \frac{7M_\pi^2}{32\pi F_\pi^2} + \mathcal{O}(m_q^2) \qquad a_0^2 = -\frac{M_\pi^2}{16\pi F_\pi^2} + \mathcal{O}(m_q^2)$$

Weinberg, PRL17,616(1966)

Using ChPT, theory predicts:

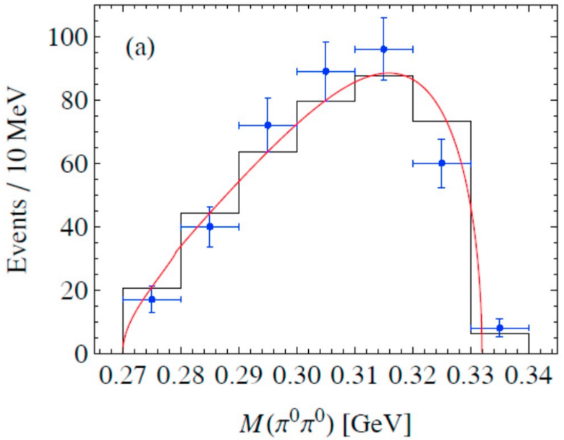
$$a_0^0 - a_0^2 = 0.265 \pm 0.004$$

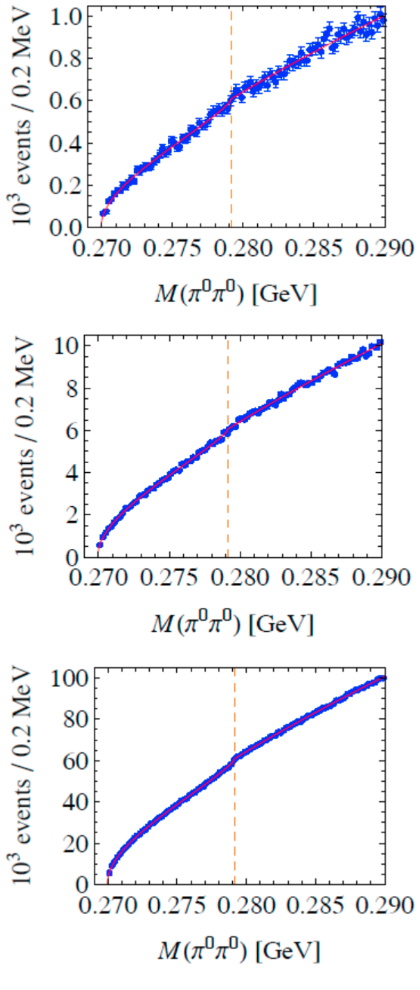
Colangelo, et al, PLB488,261(2000)



Q-value for Y(3S) → ππ Y(2S) is only 50 MeV

Liu et al,EPJC73, 2284 (2013)





Conclusions

<u>The phenomenology of exotica is broad and not confined to the discovery of new resonances</u>

What we need now is:

→ *Systematic, high statistics measurement of the hadronic transitions*
  → *New way to access the hybrids?*

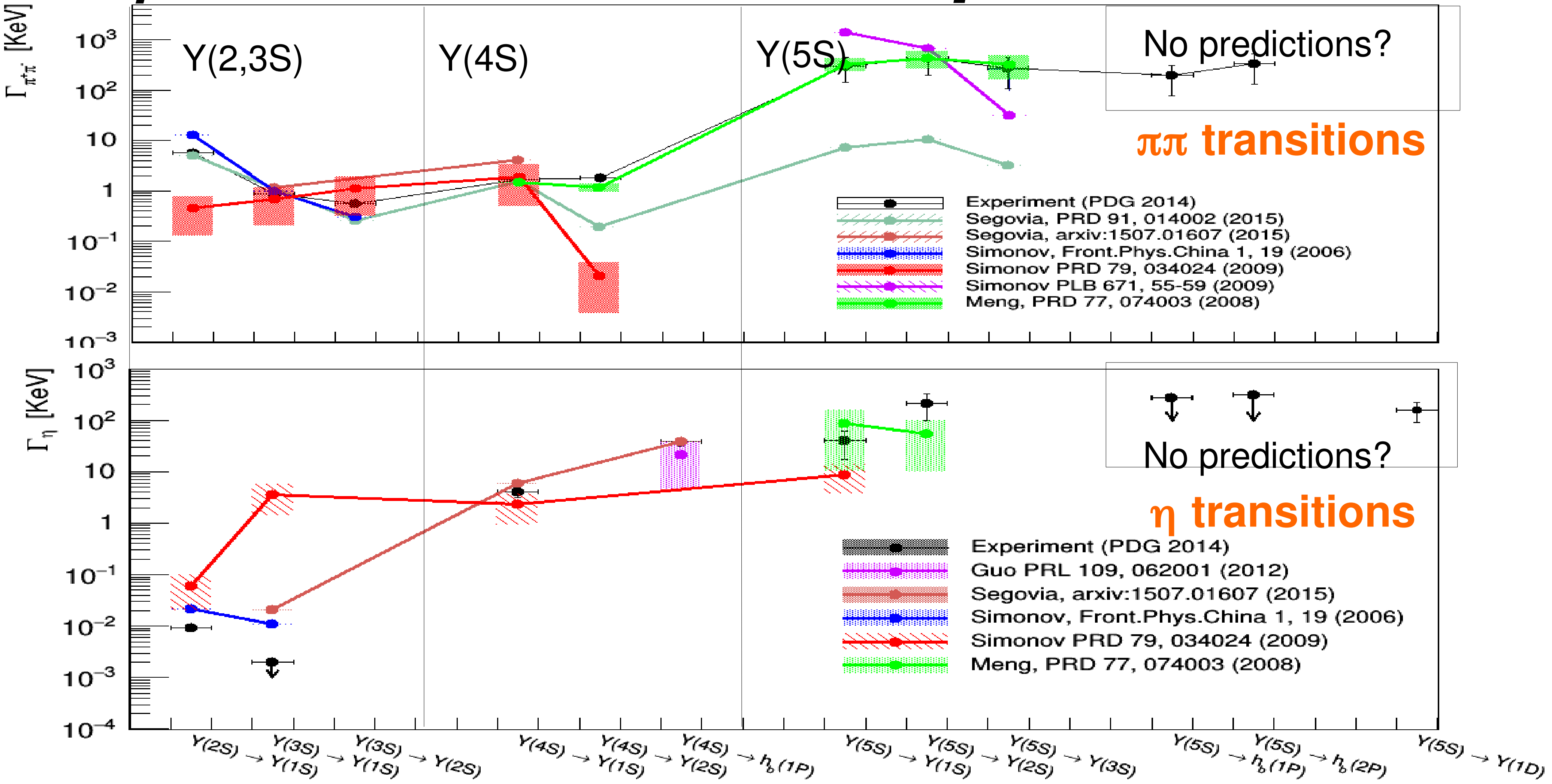
→ *Theoretical breakthroughs*
  → *Prominent role of di-quark correlations?*
  → *Meson – Baryon – Tetraquark symmetries ?*
  → *Common models?*

→ *Measurement of inclusive production in hadronic events*

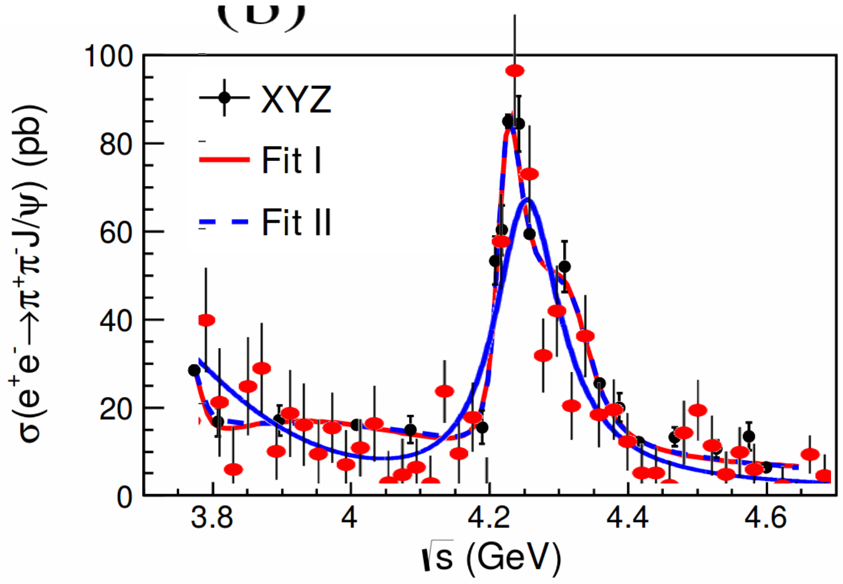
→ *Waiting for more results form JLAB and COMPASS!*

Backup

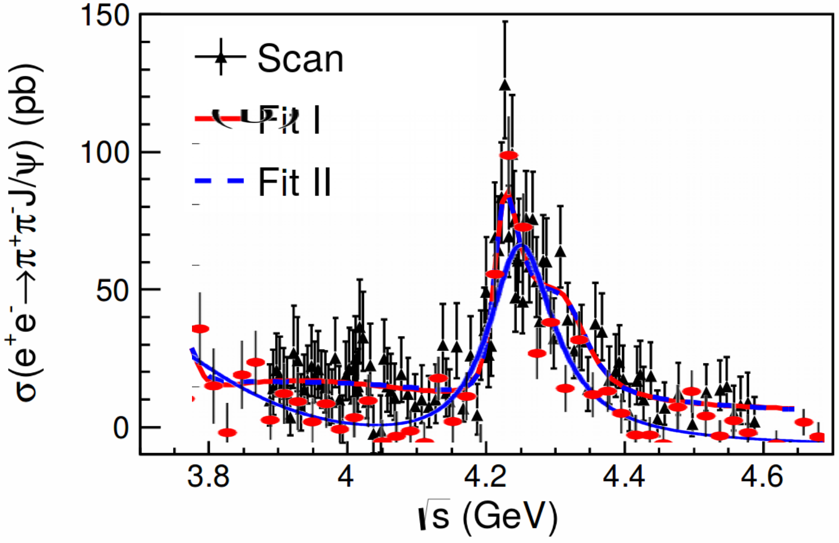
ππ/η transitions: Th. VS Exp



Y(4260)

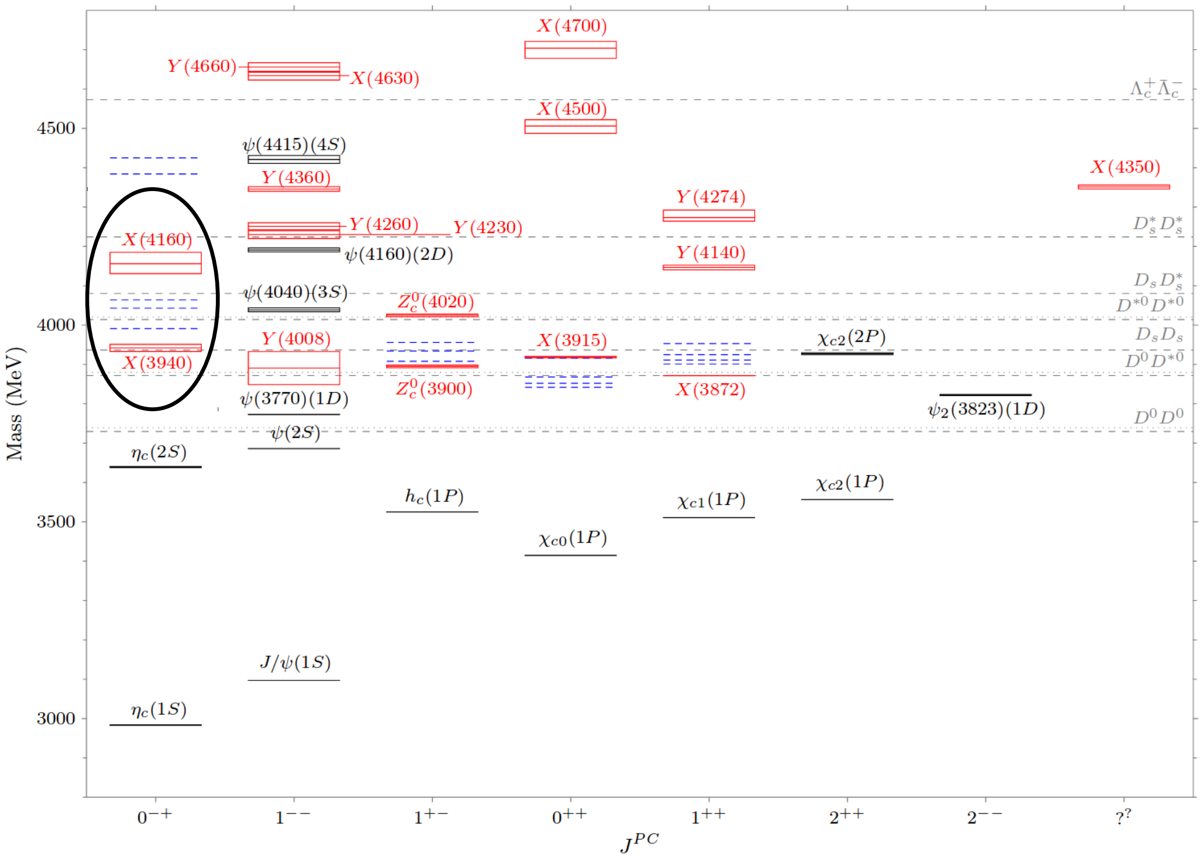


XYZ
Fit I
Fit II
σ(e+e-→π+π-J/ψ) (pb)
√s (GeV)



Scan
Fit I
Fit II
σ(e+e-→π+π-J/ψ) (pb)
√s (GeV)

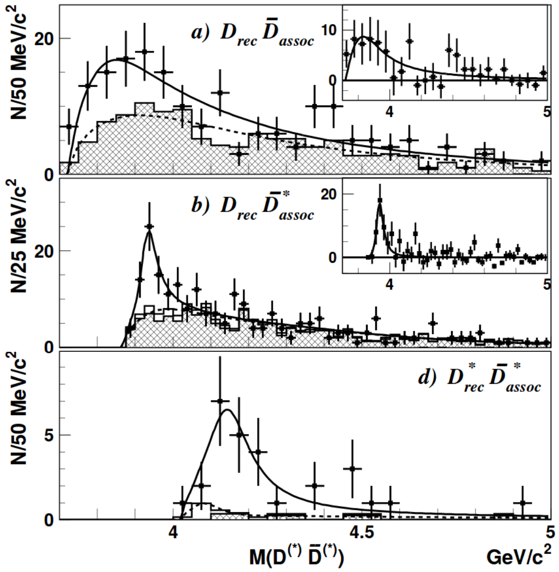
Charmonium exotica



Pseudo-scalar: X(3940), X(4160)

Seen in

e+e- → J/y + D*D(*)



e+e- → J/y + DD

No signals

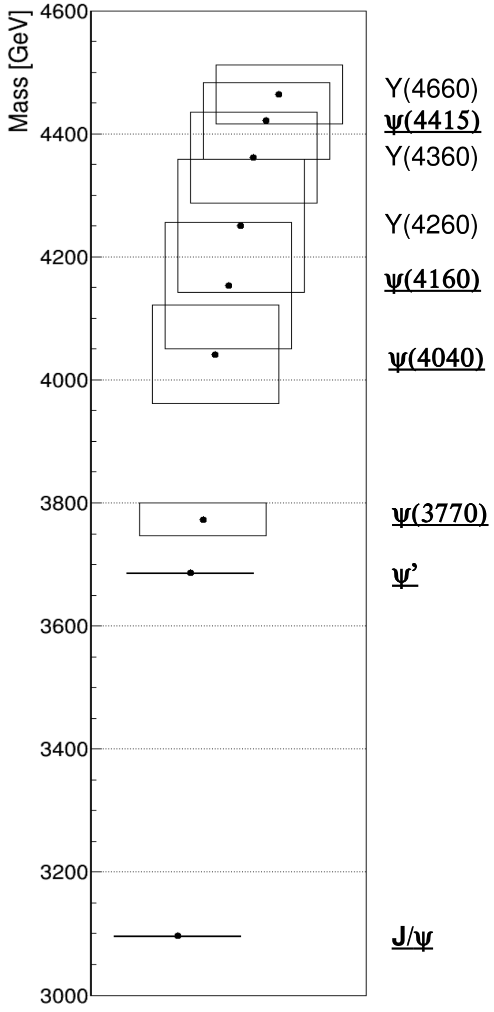
e+e- → J/y + DD

X(3940) only

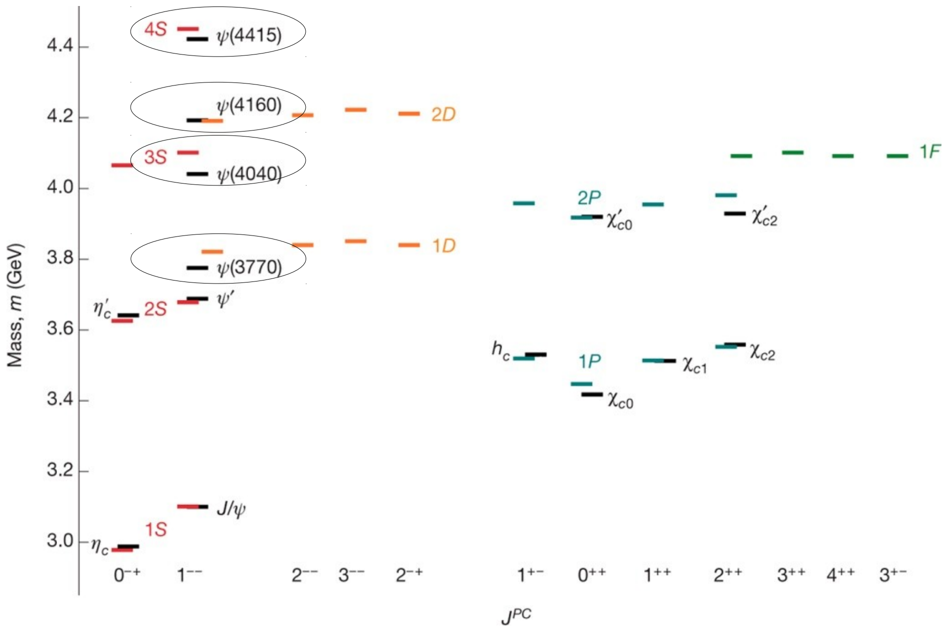
e+e- → J/y + DD

X(4160)

Vector Charmonia



Nature **534,** 487–493 (2016)

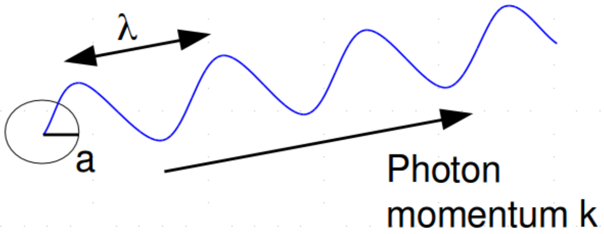


Some are (rougly) matching the expected cc resonances in S and D wave

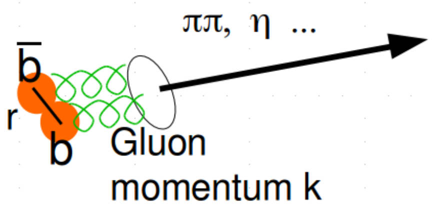
Vector Charmonia

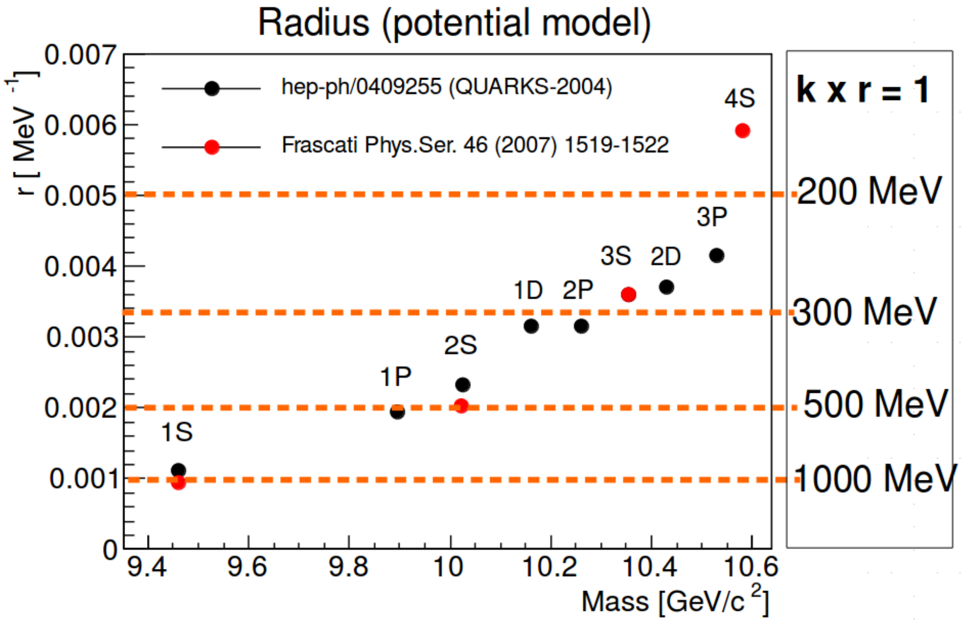
Kuang, Front.Phys.China 1, 19 (2006)

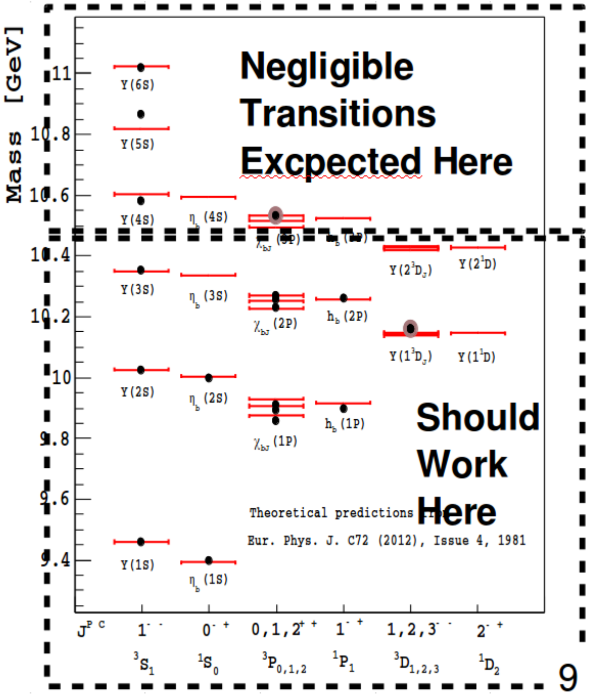
QED multipole expansion term:
$a/\lambda \sim ak < 1$



In quarkonia:
$r \sim 0.1$ fm
$k \sim 100$ MeV
$rk < 1$







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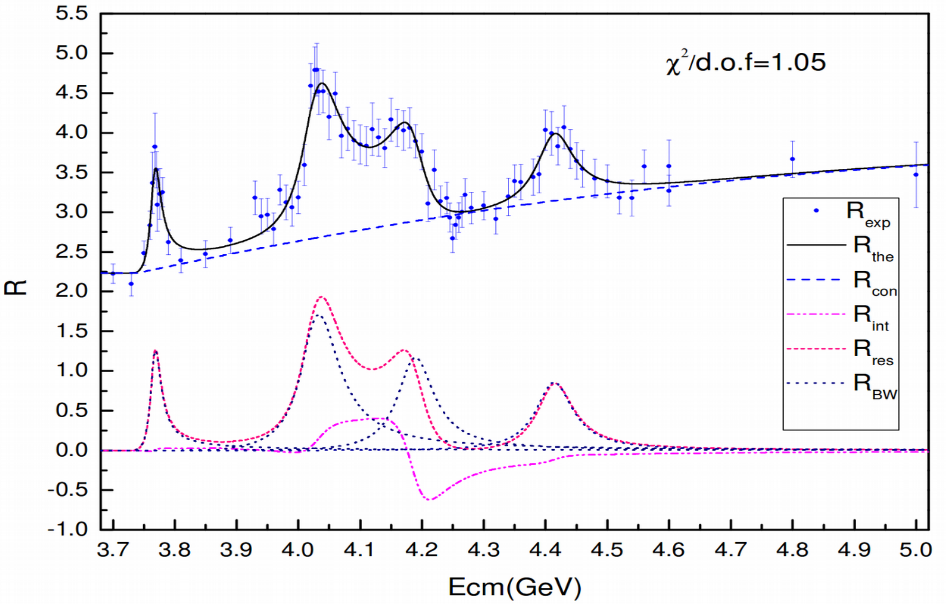
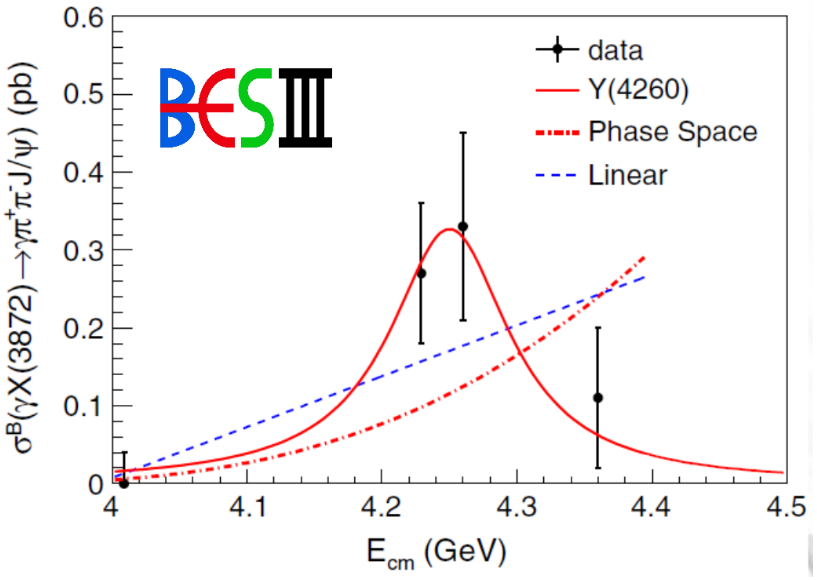
Y(4260): different models

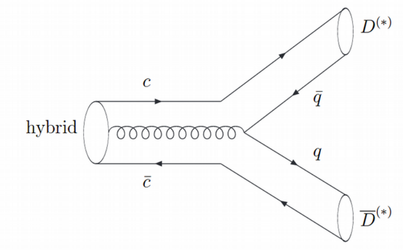




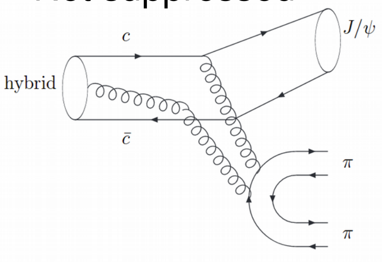
$$\frac{B(Y(4260)\to\gamma X(3872))}{B(Y(4260)\to\pi^+\pi^- J/\psi)} \sim 0.1$$

Hybrid interpretation?

Suppressed by ~ $1/m_c^2$



Not suppressed



→ No signal of Y(4360)

→ OK with tetraquark model

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