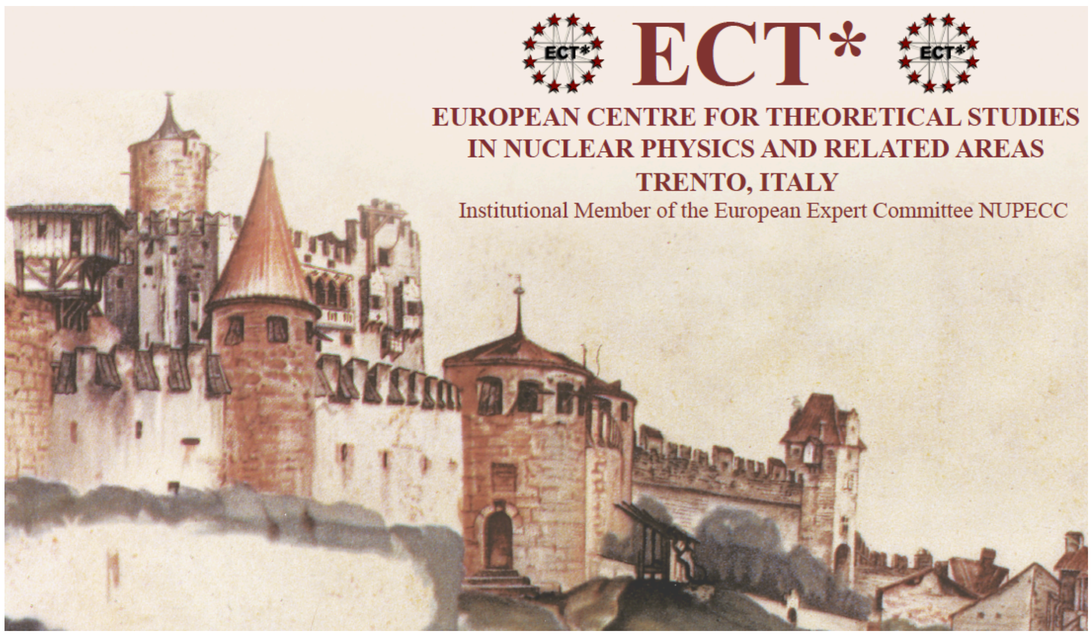
Exotic Charmonium in Photon-Photon Collisions at the LHC

Fernando S Navarra

University of São Paulo (USP)

B.D. Moreira, C.A. Bertulani, V.P. Gonçalves and F.S. N., arxiv:1610.06604



QCD challenges in pp, pA and AA collisions at high energies

Trento, February 27 - March 3, 2017

Exotic charmonium

Exotic Charmonium

Before 2003:

Cornell potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma\, r + \ldots$$

Schrödinger equation:

$$H\,\Psi = \left(-\frac{\nabla^2}{2\mu} + V\right)\Psi = E\,\Psi$$

$$M_n = 2m_Q + E_n$$

"Good" quarkonium spectrum

Exotic Charmonium

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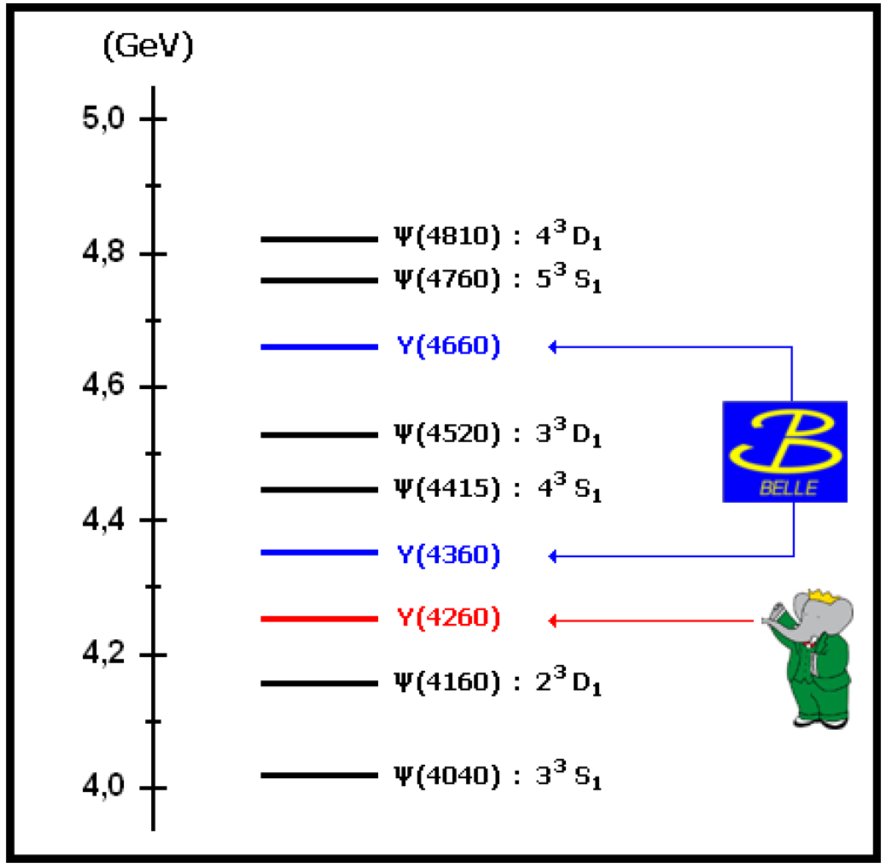

States with "wrong" masses

Exotic Charmonium

Nielsen, Navarra, Lee,
arXiv:0911.1958

Table 1: Charmonium states observed in the last years.

state	production mode	decay mode
$X(3872)$	$B \to KX(3872)$	$J/\psi\pi\pi$
$X(3915)$	$\gamma\gamma \to X(3915)$	$J/\psi\omega$
$Z(3930)$	$\gamma\gamma \to Z(3930)$	$D\bar{D}$
$Y(3930)$	$B \to KY(3930)$	$J/\psi\omega$
$X(3940)$	$e^+e^- \to J/\psi X(3940)$	$D\bar{D}^*$
$Y(4008)$	$e^+e^- \to \gamma_{ISR}Y(4008)$	$J/\psi\pi\pi$
$Z_1^+(4050)$	$B^0 \to K^- Z_1^+(4050)$	$\chi_{c1}\pi^+$
$Y(4140)$	$B \to KY(4140)$	$J/\psi\phi$
$X(4160)$	$e^+e^- \to J/\psi X(4160)$	$D^*\bar{D}^*$
$Z_2^+(4250)$	$B^0 \to K^- Z_1^+(4250)$	$\chi_{c1}\pi^+$
$Y(4260)$	$e^+e^- \to \gamma_{ISR}Y(4260)$	$J/\psi\pi\pi$
$X(4350)$	$\gamma\gamma \to X(4350)$	$J/\psi\phi$
$Y(4360)$	$e^+e^- \to \gamma_{ISR}Y(4260)$	$\psi'\pi\pi$
$Z^+(4430)$	$B^0 \to K^- Z^+(4430)$	$\psi'\pi^+$
$X(4630)$	$e^+e^- \to \gamma_{ISR}X(4630)$	$\Lambda^+\Lambda^-$
$Y(4660)$	$e^+e^- \to \gamma_{ISR}Y(4660)$	$\psi'\pi\pi$

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$Z_1^+(4050)$	$B^0 \to K^-Z_1^+(4050)$	$\chi_{c1}\pi^+$
$Y(4140)$	$B \to KY(4140)$	$J/\psi\phi$
$X(4160)$	$e^+e^- \to J/\psi X(4160)$	$D^*\bar{D}^*$
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$Y(4260)$	$e^+e^- \to \gamma_{ISR}Y(4260)$	$J/\psi\pi\pi$
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After 2013:

Nielsen, Navarra, arXiv:1401.2913

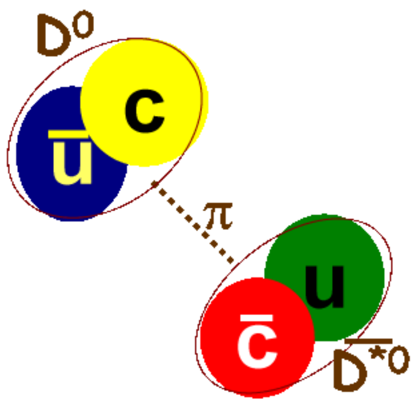
Table 1. Charged exotic charmonium states

State (Mass)	Experiment (Year)	J^P	Decay Mode
$Z^+(4430)$	BELLE (2008)	1^+	$B^+ \to K\psi'\pi^+$
$Z_1^+(4050)$	BELLE (2008)	?	$\bar{B}^0 \to K^-\pi^+\chi_{c1}$
$Z_2^+(4250)$	BELLE (2008)	?	$\bar{B}^0 \to K^-\pi^+\chi_{c1}$
$Z_c^+(3900)$	BESIII (2013)	1^+	$Y(4260) \to (J/\psi\pi^+)\pi^-$
$Z_c^+(4025)$	BESIII (2013)	?	$e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$
$Z_c^+(4020)$	BESIII (2013)	?	$e^+e^- \to (\pi^+h_c)\pi^-$
$Z_c^+(3885)$	BESIII (2013)	?	$e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$

Exotic Charmonium: multiquark states

S. Cho et al. arXiv:1702.00486 M. Nielsen et al. arXiv:1611.03300

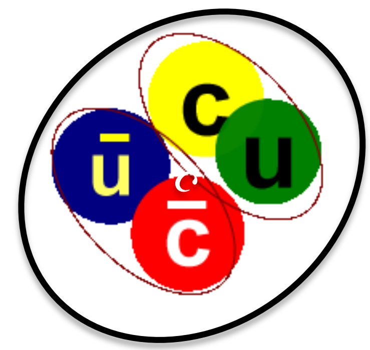
Meson molecule



Large object: ~ 10 fm

X (3872)

Tetraquark



Compact object: ~ 1 fm

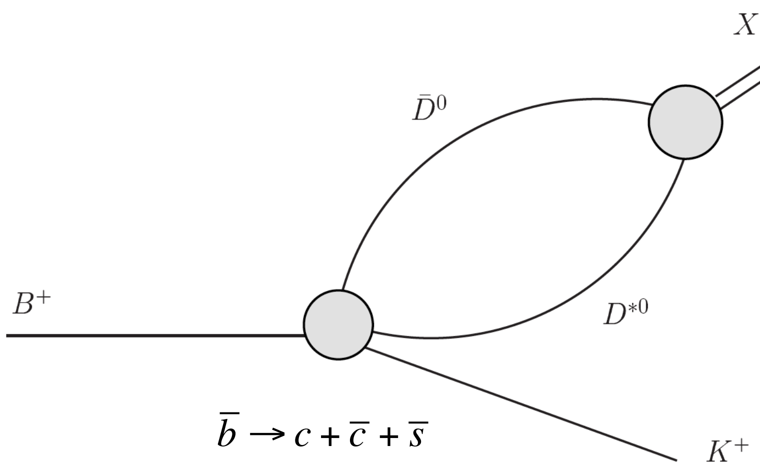
Mixture

$$\begin{cases} X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle \\ X = a\,|\chi'_{c1}\rangle + b\,|D\bar{D}^*\rangle \end{cases}$$

X(3872) production

B decays

Meson Molecule

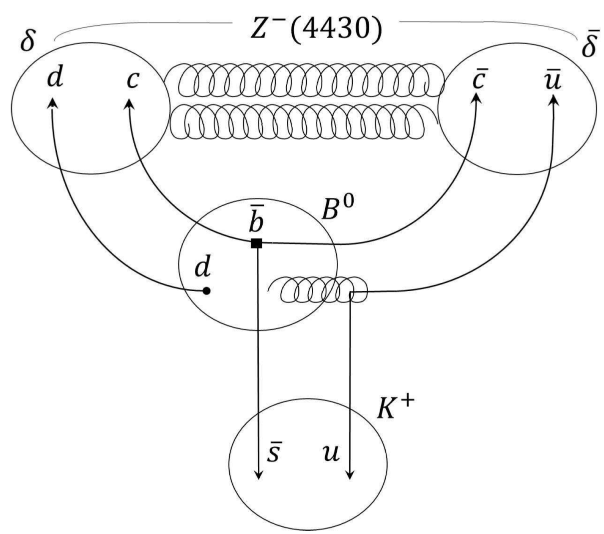


Meson coalescence

Small binding energy

E. Braaten, M. Kusunoki, hep-ph/0404161

Tetraquark



Diquark-antidiquark picture

Non-relativistic potential

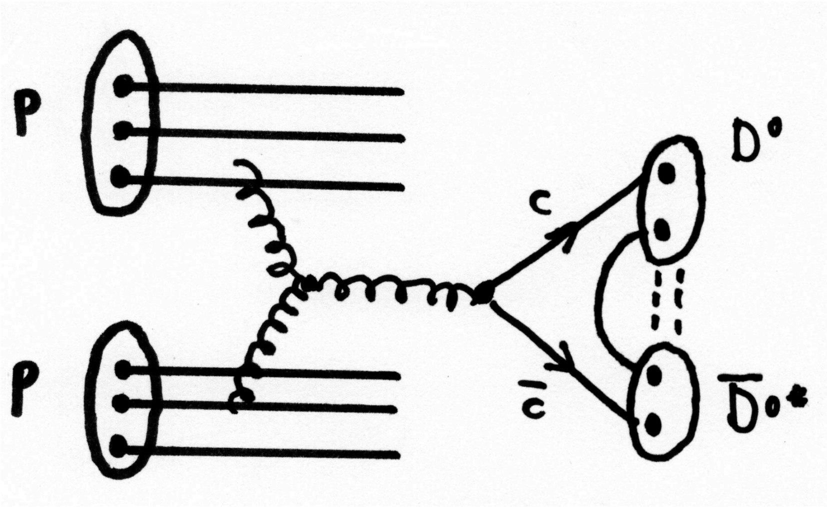
S.J. Brodsky, D.S. Hwang, R.F. Lebed, arXiv:1406.7281

Both approaches work !

Proton-proton

Meson molecule

Bignamini et al., arXiv:0906.0882, arXiv:09012.5064 Guerrieri et al., arXiv:1405.7929



Charm quark pairs generated with PYTHIA

Fragmentation into D and D*

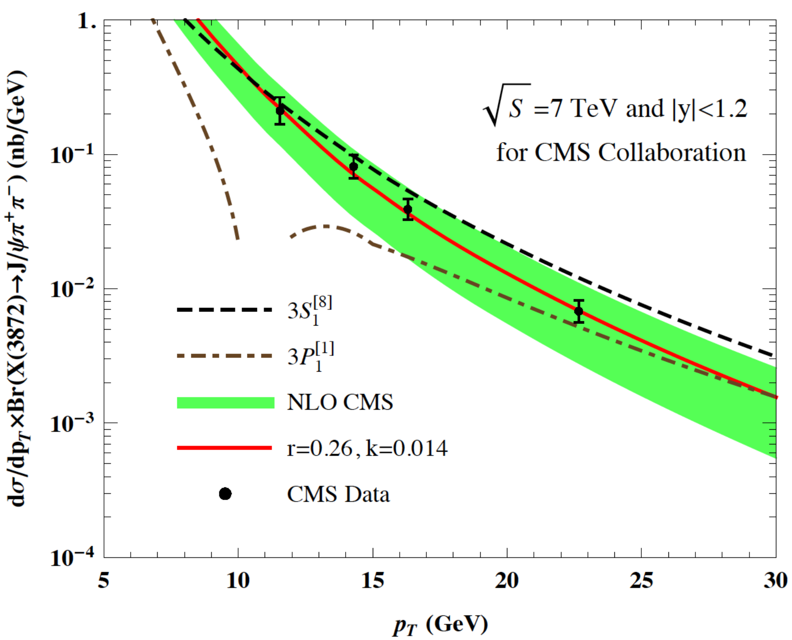
Model for binding D and D*

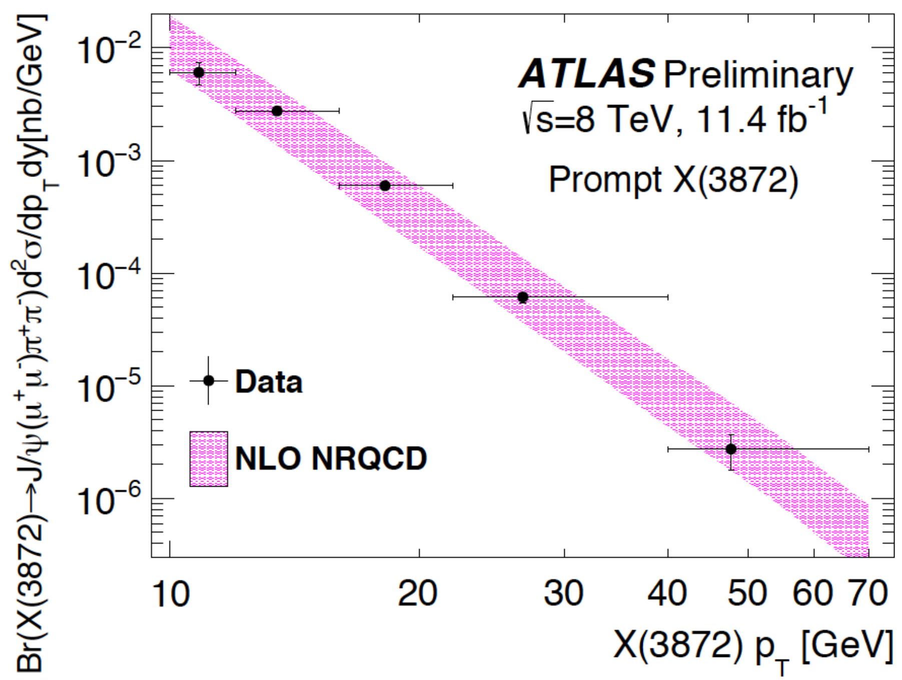
$$\sigma_{\rm th} \simeq 0.01\,\sigma_{\rm exp} \quad \text{(CDF)}$$

Charmonium - Molecule Mixture

Meng, Han, Chao, arxiv:1304.6710

$$X = a\,|\chi'_{c1}\rangle + b\,|D\bar{D}^*\rangle$$ (NRQCD)





ATLAS - CONF - 2016 - 028

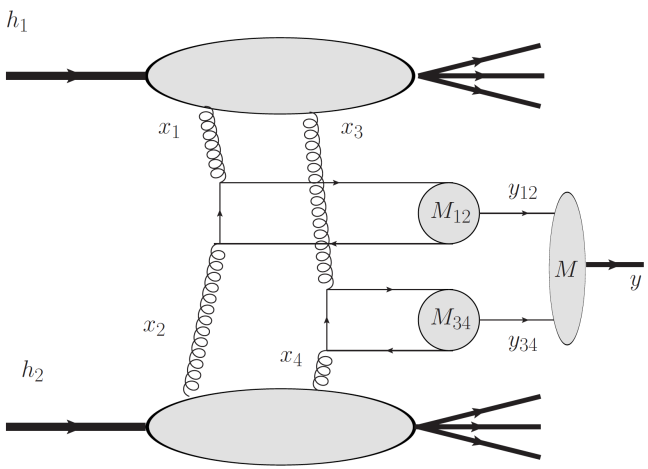
K. Toms, ICHEP 2016 Chicago

Charmonium with ~ 40 % probability

Pure D D* molecule ruled out !

Tetraquark

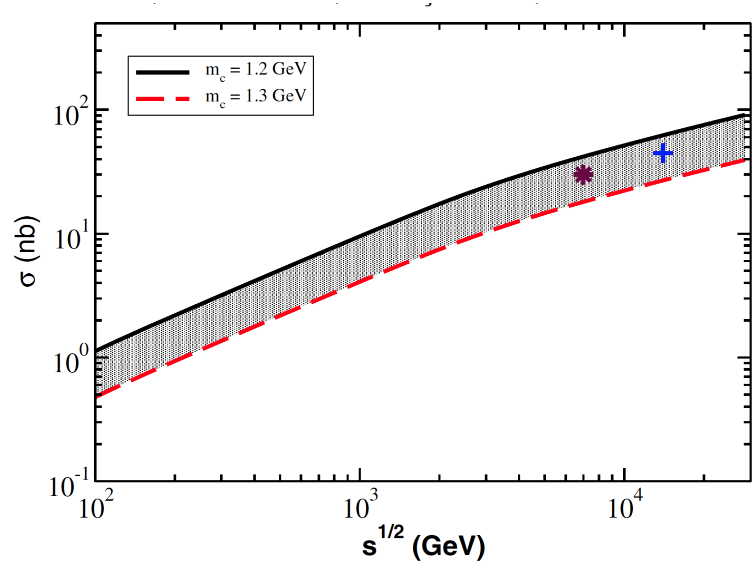
Carvalho, Cazaroto, Gonçalves, FSN, arxiv:1511.05219



Double parton scattering

Binding as in the Color Evaporation Model

Energy (TeV)	$\sigma_{c\bar{c}}$ (mb)	σ_{inel} (mb)	σ_X (nb)
7	8.5 [28]	73.2 [27]	30.0 [9]
14			44.6 ± 17.7



Prediction of the energy dependence

So far...

Mass $X(3872)$

Hadronic decay width $X(3872) \to J/\psi\, \pi\, \pi$

Production in B decays $B \to K\, X(3872)$

Can be understood in both approaches !

but...

So far...

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Hadronic decay width $X(3872) \to J/\psi\, \pi\, \pi$

Production in B decays $B \to K\, X(3872)$

Can be understood in both approaches !

but...

Production in hadronic collisions $p\, p \to X(3872)\, +\, X$

Molecular picture disfavored

Production in nucleus-nucleus collisions

- central : from QGP
  EXHIC arXiv:1702.00486
- peripheral : photon-photon

Production of exotic charmonium in two photon processes

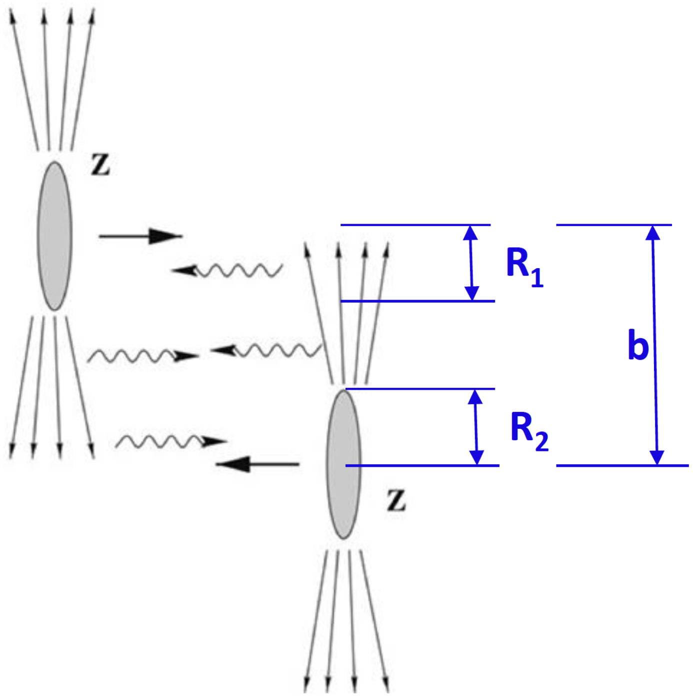
Exclusive production in peripheral pp or AA collisions

$$p\,p \to p\,p\,R$$

$$A\,A \to A\,A\,R$$

Production by Two Photons $\gamma\gamma \to R$

Photon-Photon Collisions at the LHC



Ultra-peripheral (UPC) collisions: b > R_1+R_2

$\rightarrow$ hadronic interactions strongly suppressed

High photon flux

$\rightarrow$ well described in Weizsäcker-Williams approximation (quasi-real photons)

$\rightarrow$ flux proportional to Z^2

$\rightarrow$ high cross section for γ-induced reactions

Bertulani,Klein,Nystrand,
arXiv:nucl-ex/0502005

The cross section

$$\sigma = \int N(\omega_1, b_1)\, N(\omega_2, b_2)\, \hat{\sigma}(\gamma\gamma \to R)\, S(b)\, d^2b_1\, d^2b_2\, d\omega_1\, d\omega_2$$

Equivalent photon spectrum

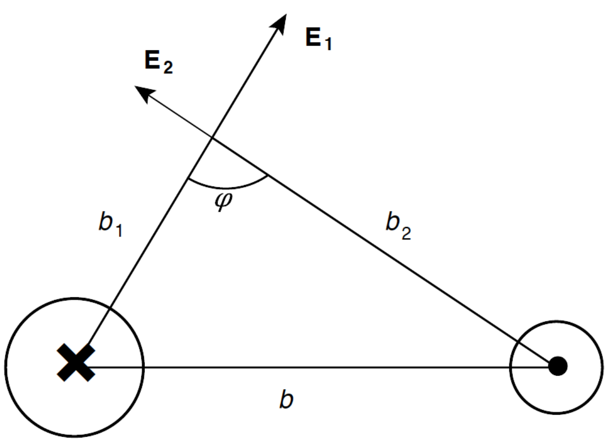
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 b^2 \omega} \left[\int du\, u^2 J_1(u)\, F\left(\sqrt{\frac{(b\omega/\gamma)^2 + u^2}{b^2}} \right) \frac{1}{(b\omega/\gamma)^2 + u^2} \right]^2$$

Photon fusion cross section

$$\hat{\sigma}(\gamma\gamma \to R) = 8\pi^2 (2J+1) \frac{\Gamma_{R\to\gamma\gamma}}{M_R} \delta(4\omega_1\omega_2 - M_R^2)$$

Geometric factor

$$S(b) = \Theta(|\mathbf{b}| - R_1 - R_2)$$
$$= \Theta(|\mathbf{b_1} - \mathbf{b_2}| - R_1 - R_2)$$



The cross section

$$\sigma = \int N(\omega_1, b_1)\, N(\omega_2, b_2)\, \hat{\sigma}(\gamma\gamma \to R)\, S(b)\, d^2 b_1\, d^2 b_2\, d\omega_1\, d\omega_2$$

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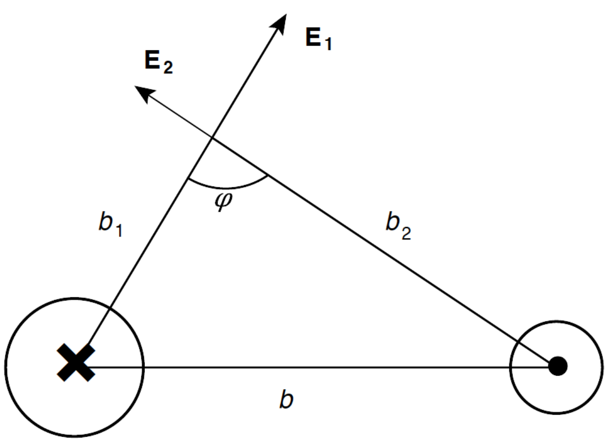
Absorption factor

$$S(b) = \Theta(|\mathbf{b}| - R_1 - R_2)$$
$$= \Theta(|\mathbf{b_1} - \mathbf{b_2}| - R_1 - R_2)$$



Form factor F

Pointlike

$$F(q^2) = 1$$

Proton

$$F(q^2) = \frac{1}{\left[1 + \frac{q^2}{\Lambda^2}\right]^2} \qquad \Lambda = 0.71 \text{ GeV}$$

dipole

Nucleus

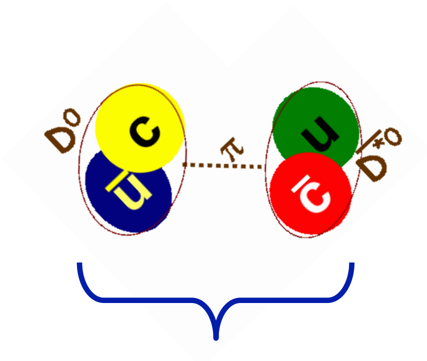
$$F(q^2) = \frac{\Lambda^2}{\Lambda^2 + q^2} \qquad \Lambda = 0.088 \text{ GeV}$$

monopole

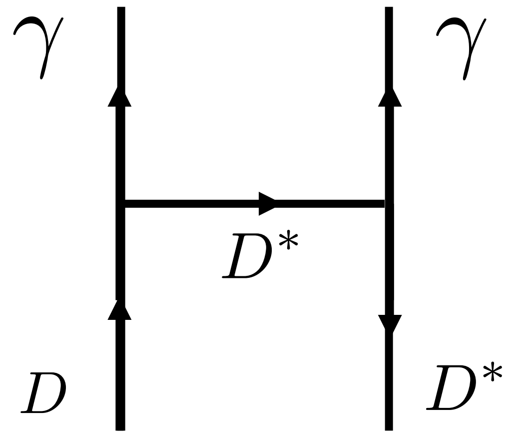
realistic

Klusek-Gawenda, Szczurek,
arXiv:1004.5521

Decay width into two Photons $\Gamma(R \to \gamma\gamma)$



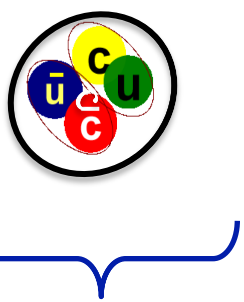
~ 10 fm



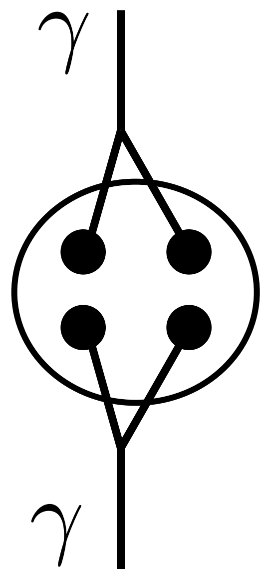
Heavy meson exchange
is short distance

$\simeq 1/m_{D^*} \simeq 0.2\, fm$

Suppressed ?



~ 1 fm



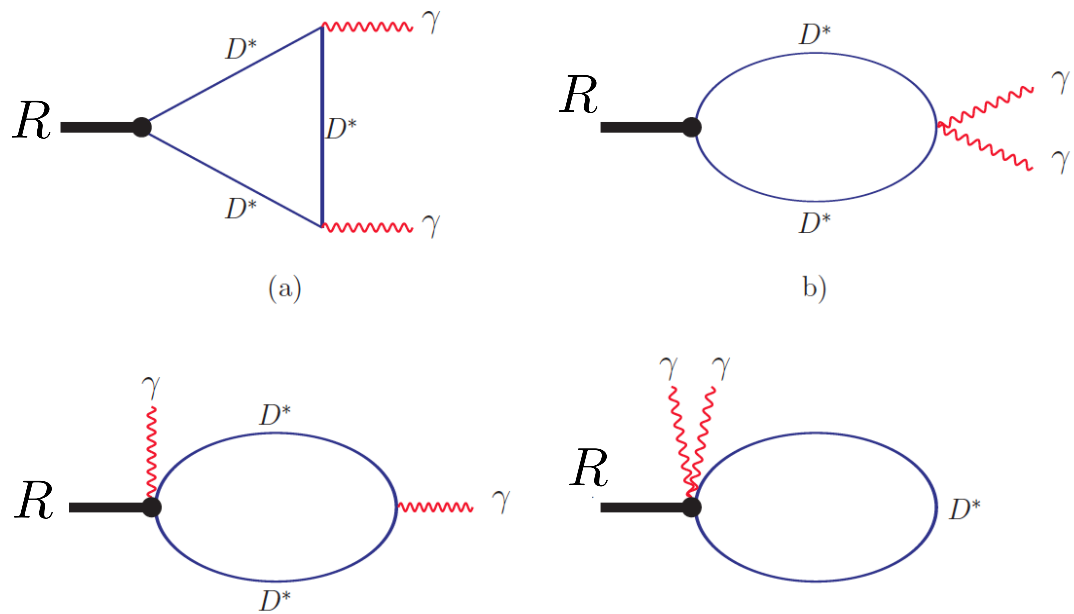
Unsuppressed ?

Decay width into two Photons $\Gamma(R \to \gamma\gamma)$

Meson molecule

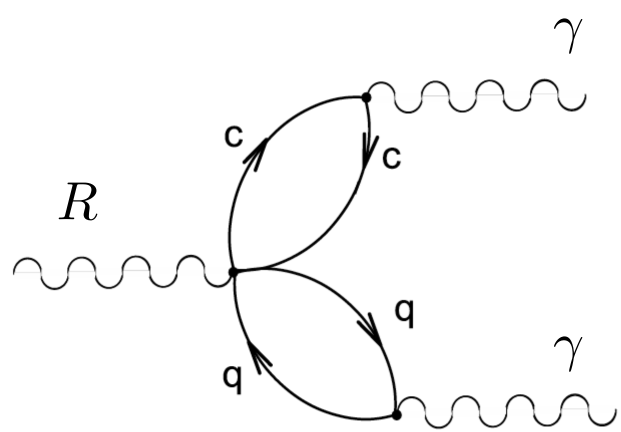
T. Branz et al., arXiv:0903.5424

$$\Gamma(R \to \gamma\gamma) \simeq 10^{-3}\ \mathrm{keV}$$



Tetraquark

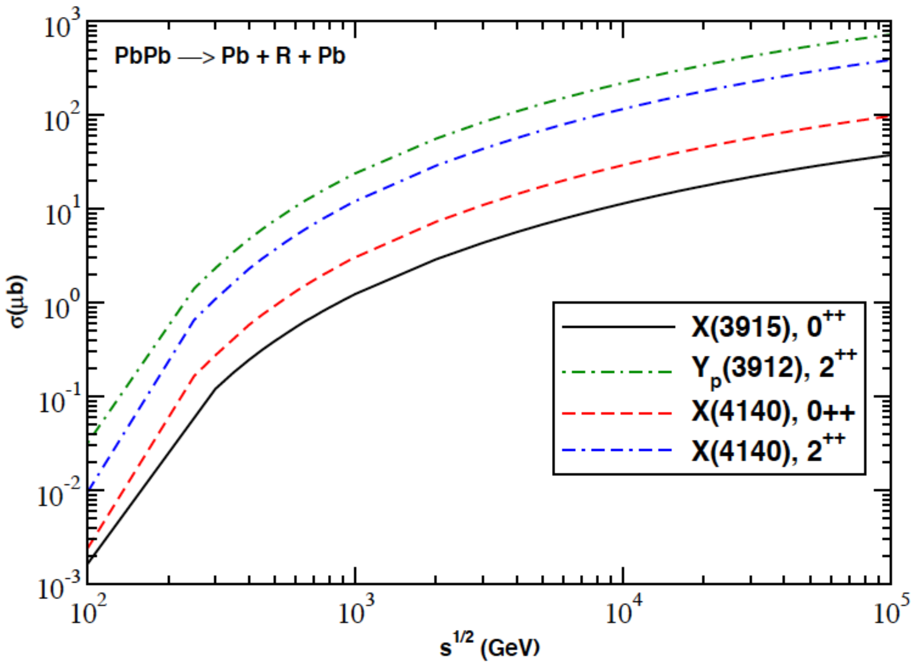
$$\Gamma(R \to \gamma\gamma) = ?$$

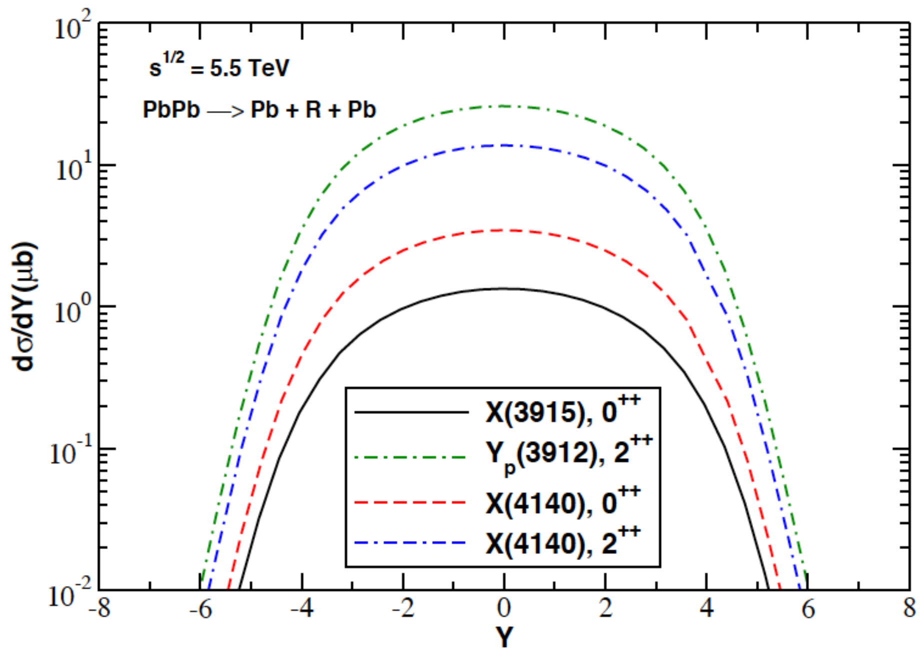


Results

Meson molecule

Moreira, Bertulani, Gonçalves, FSN, arxiv:1610.06604





Proton-proton

V. Gonçalves,
D. Silva,
W. Sauter,
arXiv:1209.0701

State	Mass (MeV)	$\Gamma^{th.}_{\gamma\gamma}$ (keV) $H \to \gamma\gamma$	$\sigma_{Electric}$ (pb) 7 TeV	$\sigma_{Electric}$ (pb) 14 TeV	σ_{DZ} (pb) 7 TeV	σ_{DZ} (pb) 14 TeV
$f_0(1370)$	1523	1.3	108.7	144.1	131.3	172.2
$f_0(1710)$	1721	0.05	2.7	3.6	3.3	4.4
$X(3940)$, 0^{++}	3943	0.33 ± 0.01	1.01	1.4	1.3	1.7
$X(3940)$, 2^{++}	3943	0.27 ± 0.01	4.1	5.7	5.1	7.0
$X(4140)$, 0^{++}	4143	0.63 ± 0.01	1.6	2.3	2.02	2.8
$X(4140)$, 2^{++}	4143	0.50 ± 0.01	6.4	8.9	8.02	11.0

This work
arXiv:1610.06604

pointlike — dipole

State	Mass	$\Gamma^{theor}_{\gamma\gamma}$ (keV)	$\sigma_{b_{min}}$ (pb) 7 TeV	$\sigma_{b_{min}}$ (pb) 14 TeV	$\sigma_{b_{min}}$ (pb) 100 TeV	σ_F (pb) 7 TeV	σ_F (pb) 14 TeV	σ_F (pb) 100 TeV
X(3940), 0^{++}	3943	0.33	0.98	1.3	2.8	1.0	1.5	2.8
X(3940), 2^{++}	3943	0.27	4.0	5.6	11.4	4.1	5.7	11.6
X(4140), 0^{++}	4143	0.63	1.6	2.2	4.5	1.6	2.2	4.6
X(4140), 2^{++}	4143	0.50	6.2	8.7	18.0	6.4	8.9	18.3
Z(3930), 2^{++}	3922	0.083	1.2	1.7	3.6	1.3	1.8	3.6
X(4160), 2^{++}	4169	0.363	4.4	6.1	12.8	4.5	6.3	13.0
$Y_p(3912)$, 2^{++}	3919	0.774	11.7	16.3	33.4	12.0	16.7	34.0
X(3915), 0^{++}	3919	0.20	0.60	0.84	1.7	0.62	0.86	1.8

$\eta_c(1S)$	$6.7^{+0.9}_{-0.8}$	58.0	80.0	72.0	97.0
$\chi_{c0}(1P)$	2.28 ± 0.3	11.0	15.9	14.0	19.0
$\chi_{c2}(1P)$	0.504 ± 0.06	11.0	15.0	13.7	18.6
$\eta_c(2S)$	1.30 ± 0.6	5.0	7.0	6.0	8.9

p - Pb

State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (nb)			σ_F (nb)		
			5 TeV	8.8 TeV	63 TeV	5 TeV	8.8 TeV	63 TeV
X(3940), 0^{++}	3943	0.33	2.8	4.0	10.6	3.3	4.5	11.3
X(3940), 2^{++}	3943	0.27	11.4	16.3	43.4	12.9	18.3	46.3
X(4140), 0^{++}	4143	0.63	4.4	6.3	16.6	5.0	7.1	18.3
X(4140), 2^{++}	4143	0.50	17.6	25.2	65.9	20.0	28.4	72.5
Z(3930), 2^{++}	3922	0.083	3.6	5.1	13.2	4.0	5.7	14.5
X(4160), 2^{++}	4169	0.363	12.5	17.9	46.9	14.2	20.1	63.3
Y_p(3912), 2^{++}	3919	0.774	33.5	47.7	123.3	37.9	53.6	132.0
X(3915), 0^{++}	3919	0.20	1.7	2.5	6.4	2.0	2.8	7.0

Pb - Pb

pointlike

monopole

Klusek-Gawenda, Szczurek, arXiv:1004.5521

State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (μb)			σ_F (μb)			σ_R (μb)		
			2.76 TeV	5.5 TeV	39 TeV	2.76 TeV	5.5 TeV	39 TeV	2.76 TeV	5.5 TeV	39 TeV
X(3940), 0^{++}	3943	0.33	4.2	8.2	31.6	6.5	11.8	40.9	5.7	10.8	39.6
X(3940), 2^{++}	3943	0.27	17.2	33.6	129.2	26.5	48.4	167.4	23.4	44.2	162.0
X(4140), 0^{++}	4143	0.63	6.5	12.9	51.2	10.2	18.7	65.7	9.0	17.1	63.6
X(4140), 2^{++}	4143	0.50	26.0	51.2	201.0	40.3	74.3	260.6	35.5	67.7	252.3
Z(3930), 2^{++}	3922	0.083	5.4	10.5	40.9	8.3	15.2	52.4	7.4	13.9	50.5
X(4160), 2^{++}	4169	0.363	18.4	36.4	144.2	28.6	52.7	185.3	25.2	48.1	178.7
Y_p(3912), 2^{++}	3919	0.774	50.5	98.6	382.4	77.9	142.2	490.1	68.9	129.9	473.7
X(3915), 0^{++}	3919	0.20	2.6	5.1	19.8	4.0	7.3	25.3	3.6	6.7	24.5

Bertulani, arXiv:0903.3174

Mesons η, χ and h ($c\bar{c}$)	J^{PC}	$\Gamma_{\gamma\gamma}^{th}$ [keV]	$\Gamma_{\gamma\gamma}^{\exp}$ [keV]	Obs.	$\sigma_{\gamma\gamma}^{X}$
η_c	(0^{-+})	3.4 - 4.8	$6.7^{+0.9}_{-0.8}$	$m_c = 1.4 - 1.6$ GeV	0.26 - 0.34 mb

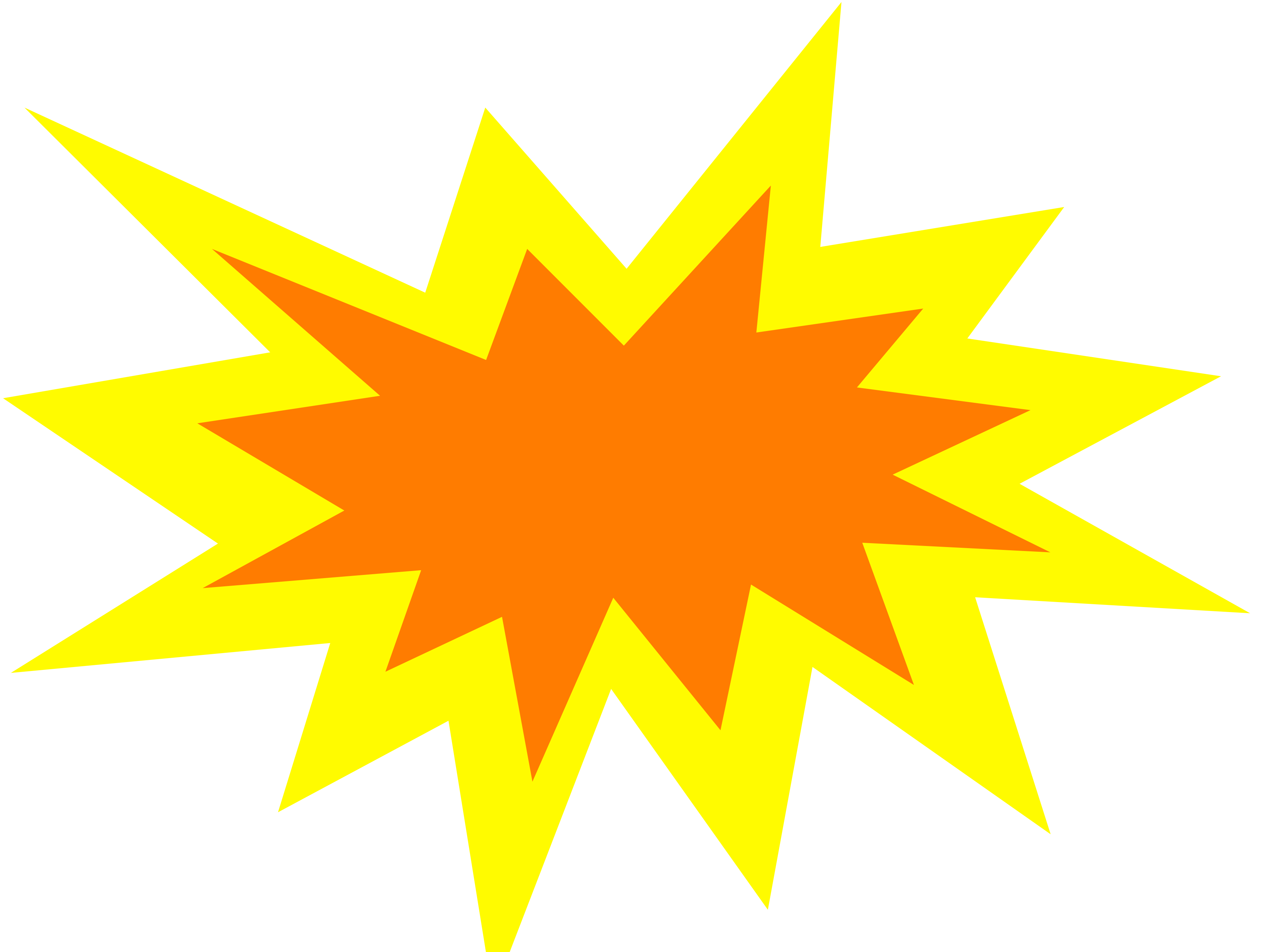
Conclusion

Y(3940) , Y(4140) in p-Pb and Pb-Pb for the first time

Z(3930) , X(4160) , Y(3912), X(3915) for the first time

Since we know that the R states exist and since everything else is known the measurement of the cross section will determine the decay width and therefore the R structure

Thank you !

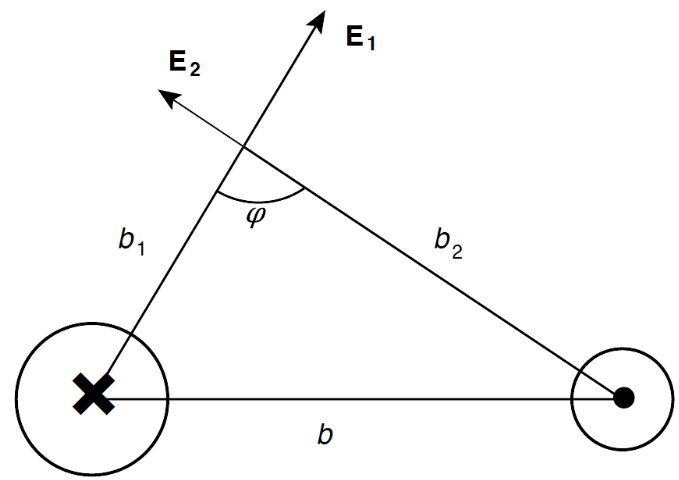


The cross section

$$\sigma\left(h_1 h_2 \to h_1 \otimes R \otimes h_2; s\right) = \int \hat{\sigma}\left(\gamma\gamma \to R; W\right) N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_2\right) S^2_{abs}(\mathbf{b}) \mathrm{d}^2\mathbf{b}_1 \mathrm{d}^2\mathbf{b}_2 \mathrm{d}\omega_1 \mathrm{d}\omega_2$$

$$S^2_{abs}(\mathbf{b}) = \Theta\left(|\mathbf{b}| - R_{h_1} - R_{h_2}\right)$$
$$= \Theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - R_{h_1} - R_{h_2}\right)$$

$$\omega_1 = \frac{W}{2} e^{Y} \qquad \omega_2 = \frac{W}{2} e^{-Y}$$

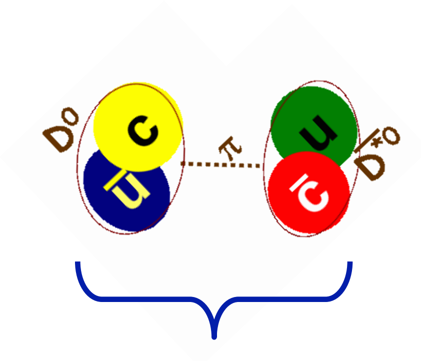


$$\sigma_{\gamma\gamma\to R}(\omega_1, \omega_2) = 8\pi^2 (2J+1) \frac{\Gamma_{R\to\gamma\gamma}}{M_R} \delta(4\omega_1\omega_2 - M_R^2)$$

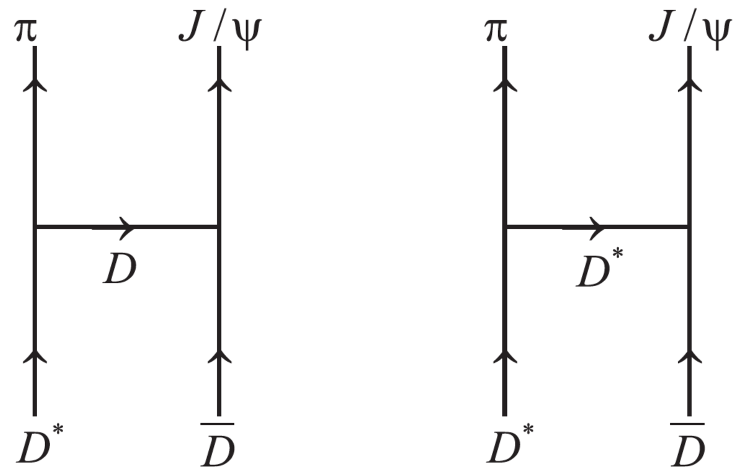
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2} \frac{1}{b^2 \omega} \left[\int u^2 J_1(u) F\left(\sqrt{\frac{(b\omega/\gamma)^2 + u^2}{b^2}} \right) \frac{1}{(b\omega/\gamma)^2 + u^2} \mathrm{d}u \right]^2$$

$$F(q) = \frac{\Lambda^2}{\Lambda^2 + q^2} \qquad F(q) = 1/\left[1 + q^2/(0.71\mathrm{GeV}^2)\right]^2$$

Molecule decay



~ 10 fm



heavy meson exchange is short distance: $\approx 1/m_D \approx 0.2\ fm$

Mahajan, arXiv:1304.1301

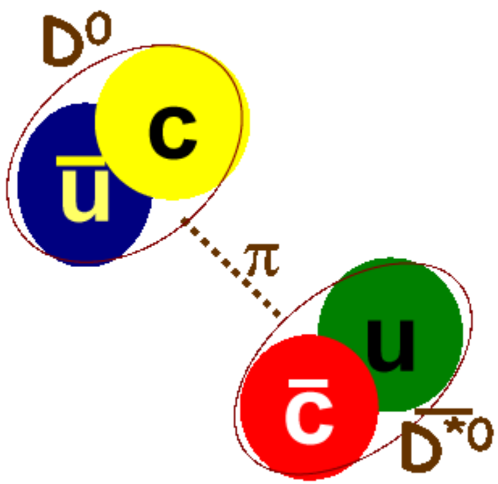
$$\Gamma \sim E_B \frac{4}{3}\sqrt{\frac{m_Q}{E_B}}\left(\alpha_s \frac{1}{r_{eff}m_Q}\right)^2 \longrightarrow \Gamma < 10\ MeV$$

$(\ \Gamma_{exp} \approx 29\ MeV\ )$

Decay into charmonium is suppressed !

The X (3872) structure

Meson molecule

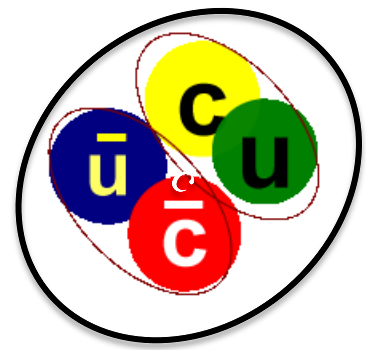


large

loosely bound

meson exchange

Tetraquark



compact

color exchange

Mixture ?

$$\begin{cases} X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle \\ X = a\,|\chi'_{c1}\rangle + b\,|D\bar{D}^*\rangle \end{cases}$$

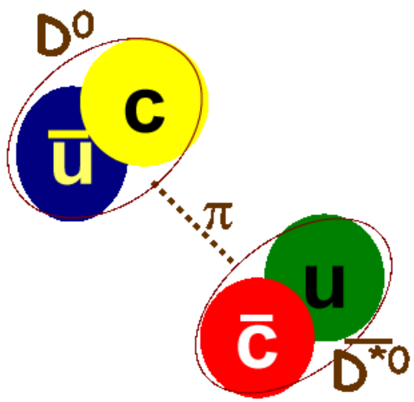
Exotic Charmonium: multiquark states

S. Cho et al. arXiv:1702.00486

M. Nielsen et al. arXiv:1611.03300

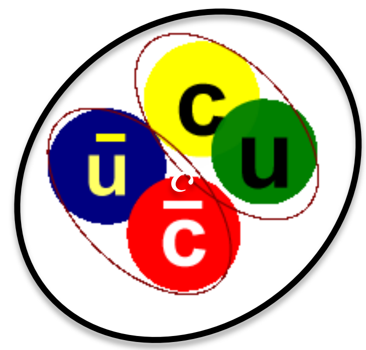
X (3872)

Meson molecule



Large object: ~ 10 fm

Tetraquark



Compact object: ~ 1 fm

$\approx 1/m_{D^*} \approx 0.2\ fm$

Exotic charmonium

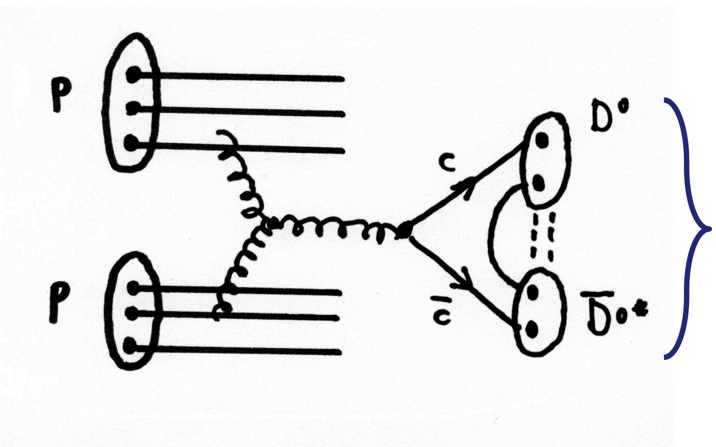
$$\gamma\gamma \to Y$$

$$\sigma_Y \;\propto\; N(\omega_1)\, N(\omega_2)\, \Gamma(Y \to \gamma\gamma)$$

new !

Proton-proton

Meson molecule



~ 10 fm

Charm quark pairs generated with PYTHIA

Fragmentation into D and D*

Model for binding D and D*

$$\sigma_{\rm th} \simeq 0.01\,\sigma_{\rm exp} \quad \text{(CDF)}$$

Bignamini et al., arXiv:0906.0882

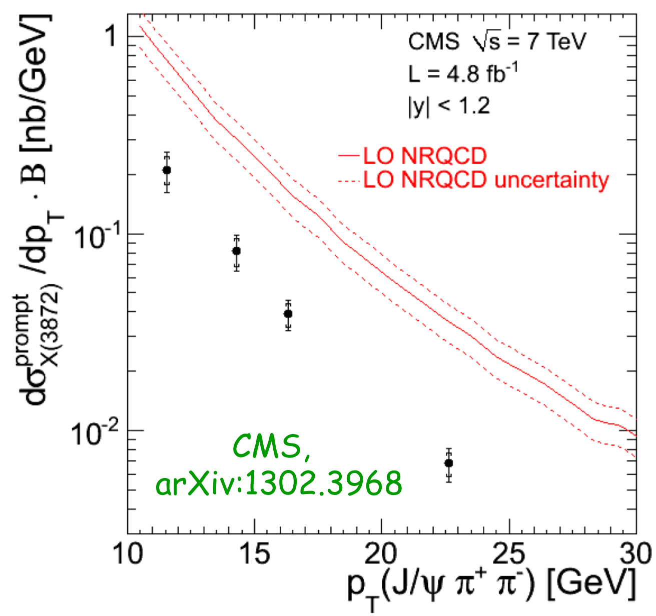
Bignamini et al., arXiv:09012.5064

Guerrieri et al., arXiv:1405.7929

NRQCD

D D* rescattering

Relative momentum ~ pion mass



Artoisenet, Braaten, arXiv:0911.2016

Artoisenet, Braaten, arXiv:1007.2868

Dall'Osso et al., POS (Beauty 2013) 066

X (3872) production

B decays : $e^+ + e^- \to B^+ + B^-$

$\hookrightarrow B^+ \to X + K^+ \quad \longrightarrow \quad X \to J/\psi + \pi^+ + \pi^-$

Proton-proton: $g + g \to c + \bar{c}$

(prompt production)

$\hookrightarrow$
$c \to D$
$\bar{c} \to \bar{D}^*$
$\longrightarrow \quad D + \bar{D}^* \to X$

Nucleus-nucleus: **?**

ExHIC Collab., Cho et al., PRL 106, 212001 (2011) ; PRC 84, 064910 (2011).

Comparison with other works

Pb Pb

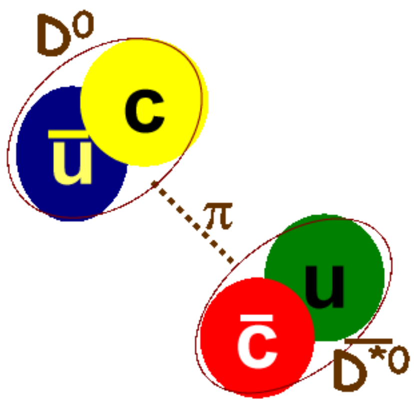
Bertulani, arXiv:0903.3174

Mesons η, χ and h $(c\bar{c})$	J^{PC}	$\Gamma_{\gamma\gamma}^{th}$ [keV]	$\Gamma_{\gamma\gamma}^{\exp}$ [keV]	Obs.	$\sigma_{\gamma\gamma}^{X}$
η_c	(0^{-+})	3.4 - 4.8	$6.7^{+0.9}_{-0.8}$	$m_c = 1.4 - 1.6$ GeV	0.26 - 0.34 mb
$\eta_c(3790)$		1.85 - 8.49	1.3 ± 0.6	$m_c = 1.4$ GeV	0.06 - 0.1 mb
$\eta'_c(3790)$		3.7	unknown	$m_c = 1.4$ GeV	0.11 mb
$\eta_c(4060)$		3.3	unknown		0.09 mb
$\eta_{c2}^{1D}(3840)$		$20. \times 10^{-3}$	unknown		0.15 μb
$\eta_{c2}^{2D}(4210)$		$35. \times 10^{-3}$	unknown		0.14 μb
$\eta_{c4}^{1G}(4350)$		0.92×10^{-3}	unknown		0.08 μb
χ_2	(2^{++})	0.56	0.258 ± 0.019	$(\lambda = 2) / (\lambda = 0) = 0.005$	82 μb
χ_0	(0^{++})	1.56	0.276 ± 0.033	$\Gamma_{\gamma\gamma}(\chi_0) / \Gamma_{\gamma\gamma}(\chi_2) = 2.79$	0.05 mb
χ'_2	(2^{++})	0.64	unknown		0.09 mb
$h_{c2}(3840)$		20×10^{-3}	unknown	$^1D_2$	82 μb
$\chi_2(4100)$		30×10^{-3}	unknown	$^3F_2$	0.11 μb

Exotic Charmonium: multiquark states

S. Cho et al. arXiv:1702.00486 M. Nielsen et al. arXiv:1611.03300

Meson molecule



X (3872)

Large object: ~ 10 fm