Novel aspects of particle production in UPCs

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I - Production of charm molecules in UPCs

II - Production of very forward pions in UPCs

I) Charm Molecule is Exotic Charmonium !

Not a state like: $c\,\bar{c}$

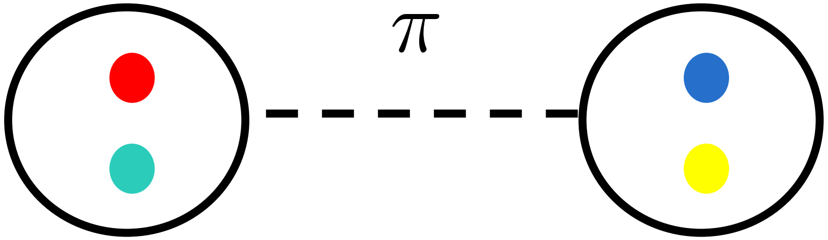
Multiquark state : $c\,\bar{c}\,q\,\bar{q}'$

Meson molecule

Large object: ~ 5 - 10 fm

Loosely bound

Meson exchange

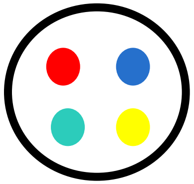


Tetraquark

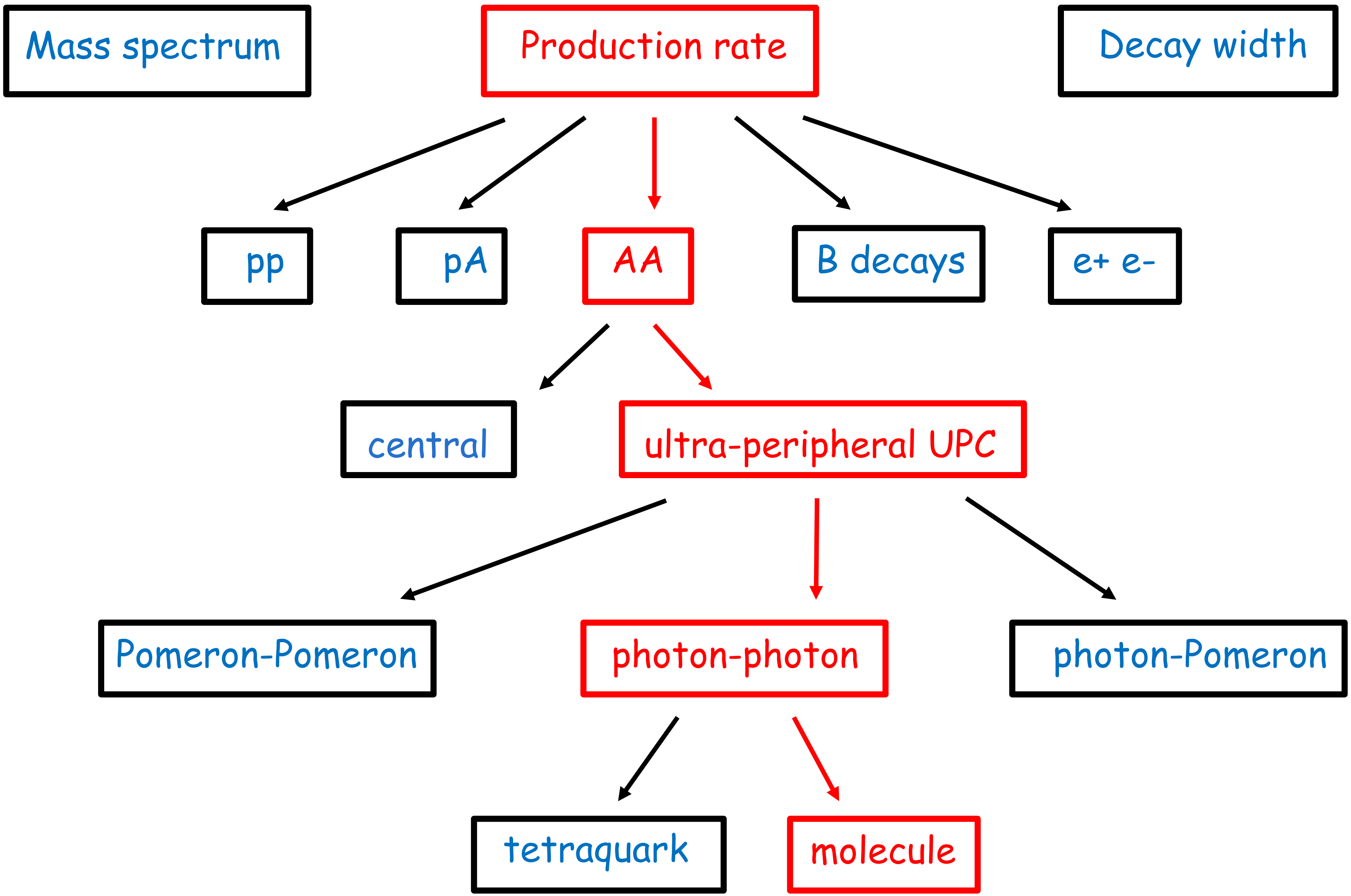
Compact object: ~ 0.5 - 1 fm

Deeply bound

Color exchange



Studying Exotic Charmonium



Lightest Charm Molecule : scalar D^+D^- bound state

Known as $X(3700)$ $M \approx 3723$ MeV

Predicted in:

D. Gamermann, E. Oset, D. Strottman and M. J. Vicente Vacas, Phys. Rev. D 76, 074016 (2007).

C. Hidalgo-Duque, J. Nieves and M. P. Valderrama, Phys. Rev. D 87, 076006 (2013).

J. Nieves and M. P. Valderrama, Phys. Rev. D 86, 056004 (2012).

S. Prelovsek, S. Collins, D. Mohler, M. Padmanath and S. Piemonte, JHEP 06, 035 (2021).

Experimental evidence (not conclusive) in:

S. Uehara et al. (Belle Collaboration), Phys. Rev. Lett. 96, 082003 (2006).

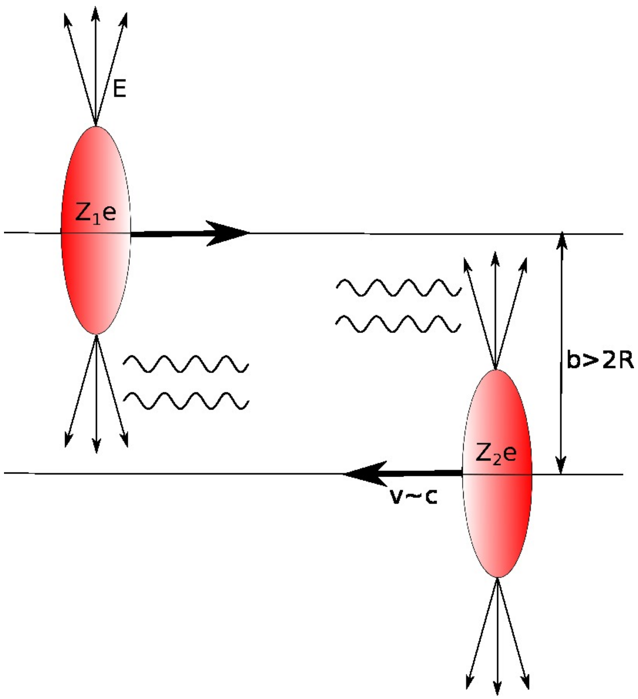
B. Aubert et al. (BaBar Collaboration), Phys. Rev. D81, 092003 (2010).

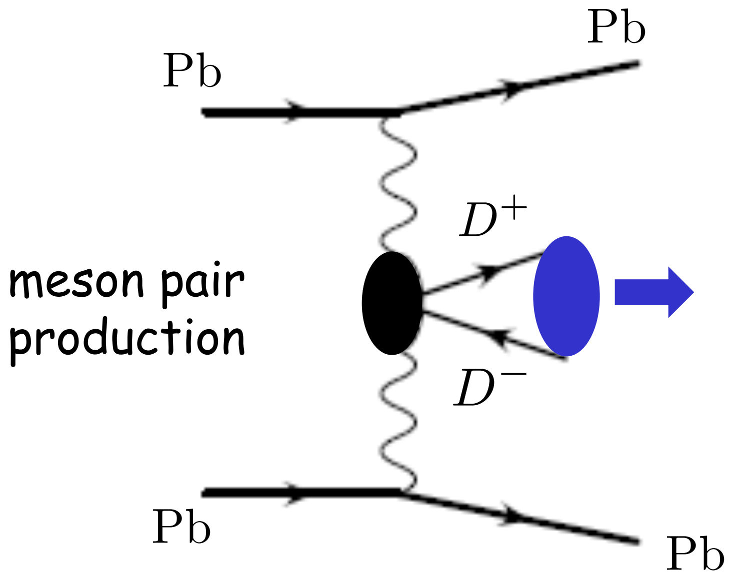
Recent works:

M.~Ablikim et al. [BESIII], Phys. Rev. D 108, 052012 (2023)

P. C. S. Brandao, J. Song, L. M. Abreu and E. Oset, Phys. Rev. D 108, 054004 (2023)

Charm Production in Ultra-Peripheral Collisions





C. A. Bertulani, S. R. Klein, and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55, 271 (2005), arXiv:nucl-ex/0502005.

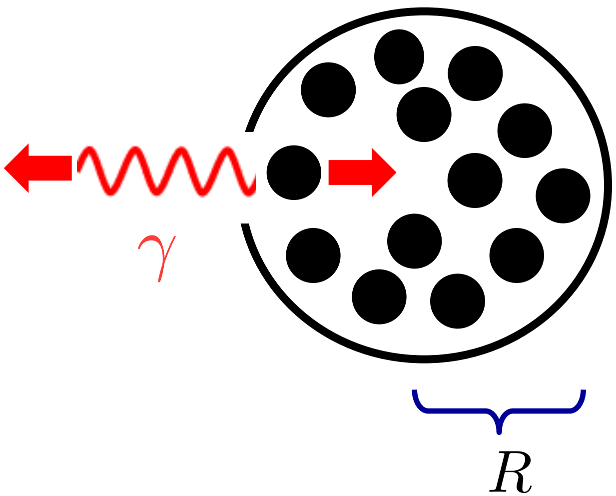
A. J. Baltz, Phys. Rept. 458, 1 (2008), arXiv:0706.3356

The Number of Equivalent Photons

M. I. Vysotskii and E. Zhemchugov, arXiv:1806.07238

$$n(\vec{q})d^3q = \frac{Z^2\alpha}{\pi^2}\frac{(\vec{q}_\perp)^2}{\omega\, q^4}d^3q = \frac{Z^2\alpha}{\pi^2\omega}\frac{(\vec{q}_\perp)^2}{\left((\vec{q}_\perp)^2 + (\omega/\gamma)^2\right)^2}d^3q$$

Integrate over $\vec{q}_\perp$ keeping the projectile intact $\max \vec{q}_\perp = \hat{q}$



$$\hat{q} = \frac{1}{2R}$$

For a Pb nucleus :

$$\hat{q} = 0.014\,\text{GeV}$$

For a proton :

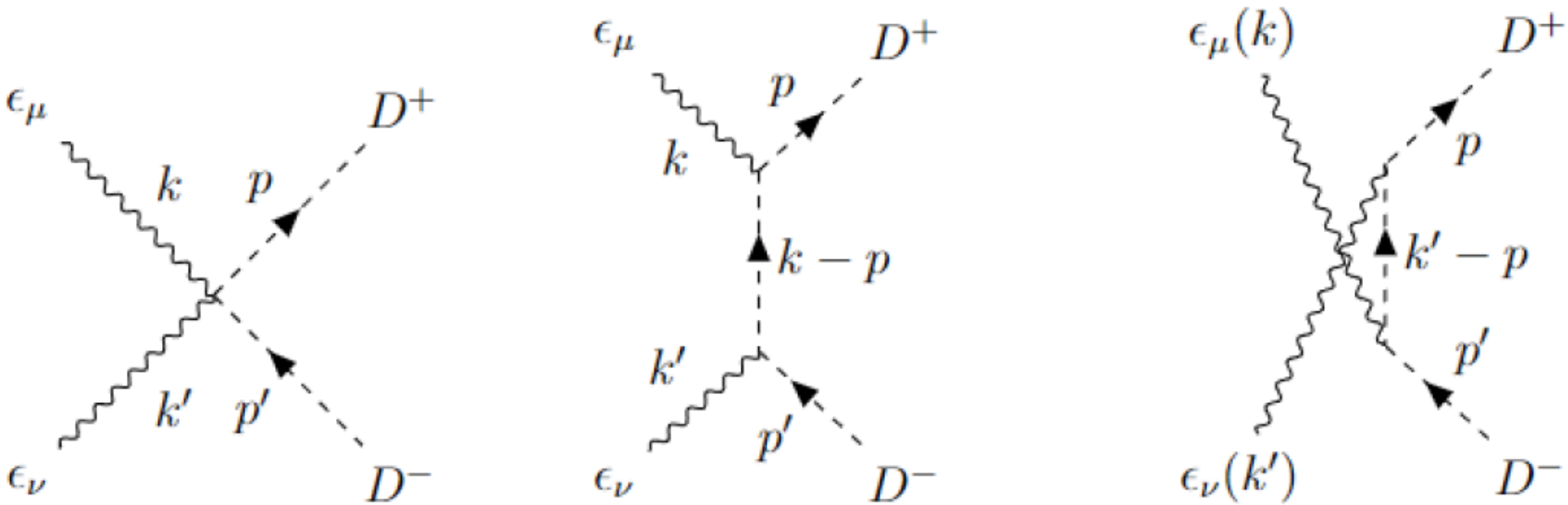
$$\hat{q} = 0.1\,\text{GeV}$$

$$n(\omega)d\omega = \frac{2Z^2\alpha}{\pi}\ln\left(\frac{\hat{q}\gamma}{\omega}\right)\frac{d\omega}{\omega}$$

Meson Pair Production in Photon-Photon Collisions

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - m_D^2 \phi^* \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$D_\mu \phi = \partial_\mu \phi + ieA_\mu \phi \qquad\qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$



Form factors in the vertices: $$F(q^2) = \frac{\Lambda^2 - m_D^2}{\Lambda^2 - q^2} \qquad F(m_D^2) = 1$$

Parameter !

Meson Pair Production in Photon-Photon Collisions

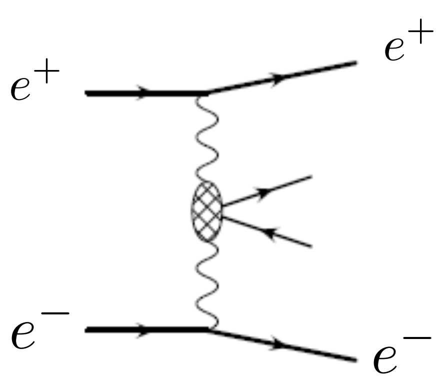
$$|M(\gamma\gamma \to D^+D^-)|^2 = \frac{e^4}{4}\Bigg[16F^4(\bar{q}) + \frac{(-2p+k)^2(2p'-k')^2}{4(k\cdot p)^2}F^4(\hat{t}) + \frac{(-2p+k')^2(2p'-k)^2}{4(k'\cdot p)^2}F^4(\hat{u})$$
$$+ 2\frac{(-2p+k)\cdot(2p'-k')}{(k\cdot p)}F^2(\bar{q})F^2(\hat{t}) + 2\frac{(-2p+k')\cdot(2p'-k)}{(k'\cdot p)}F^2(\bar{q})F^2(\hat{u})$$
$$+ \frac{[(-2p+k)\cdot(2p'-k)][(2p'-k')\cdot(-2p+k')]}{2(k\cdot p)(k'\cdot p)}F^2(\hat{t})F^2(\hat{u})\Bigg]$$

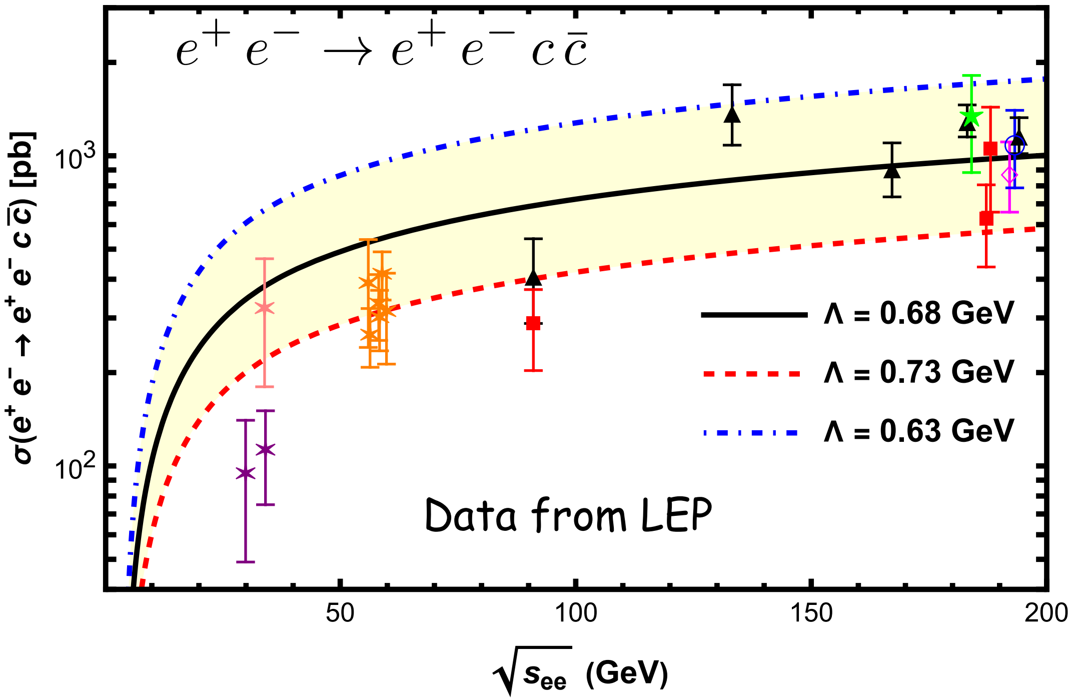
$$\sigma_P = \frac{1}{64\pi^2}\frac{1}{\hat{s}}\sqrt{1-\frac{4m_D^2}{\hat{s}}}\int |M(\gamma\gamma\to D^+D^-)|^2 d\Omega$$

$$\sigma(e^+e^- \to e^+e^- D^+ D^-) = \int d\omega_1\, d\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma_P$$

One parameter: Λ

Fixed using LEP data





Production of Bound States in Photon-Photon Collisions

Take the average over the bound state wave function :

(QFT, Peskin, page 150)

$$\frac{M(\gamma\gamma \to B)}{\sqrt{2E_B}} = \int \frac{d^3q}{(2\pi)^3} \tilde{\psi}^*(\vec{q}) \frac{1}{\sqrt{2E_{D+}}} \frac{1}{\sqrt{2E_{D-}}} M(\gamma\gamma \to D^+ D^-)$$

If relative momentum q is small: $M(\gamma\gamma \to B) = \psi^*(0)\sqrt{\frac{2}{E_B}} M(\gamma\gamma \to D^+ D^-)$

$$d\sigma = \frac{1}{H} \frac{d^3 p_B}{(2\pi)^3} \frac{1}{2E_B} (2\pi)^4 \delta^{(4)}(k + k' - p_B) |M(\gamma\gamma \to B)|^2$$

The Wave Function at the Origin

D. Gamermann, J. Nieves, E. Oset and E. Ruiz Arriola, Phys. Rev. D 81, 014029 (2010)

Bethe-Salpeter Equation for a two (heavy) particle system: $T = V + VGT$

$$\psi(0) = \frac{g}{(2\pi)^{3/2}} G \quad \begin{cases} G = -8\mu\pi \left(\Lambda_0 - \gamma \arctan\left(\frac{\Lambda_0}{\gamma} \right) \right) & \text{(Loop function)} \\ g^2 = \dfrac{\gamma}{8\pi\mu^2 (\arctan(\frac{\Lambda_0}{\gamma}) - \frac{\gamma\Lambda_0}{\gamma^2+\Lambda_0^2})} & \gamma = \sqrt{2\mu E_b} \end{cases}$$

$$\begin{cases} \Lambda_0 & \text{cut-off} \\ \mu = m_D/2 & \text{reduced mass} \\ E_b & \text{binding energy} \end{cases} \longrightarrow \quad \psi(0) = f(E_b)$$

Final Cross Sections

$$\sigma_P(A\,A \to A\,A\,D^+D^-) = \int_{m_D^2/\hat{q}\gamma}^{\hat{q}\gamma} d\omega_1 \int_{m_D^2/\omega_1}^{\hat{q}\gamma} d\omega_2\, \sigma_P(\omega_1,\omega_2)\, n(\omega_1)\, n(\omega_2)$$

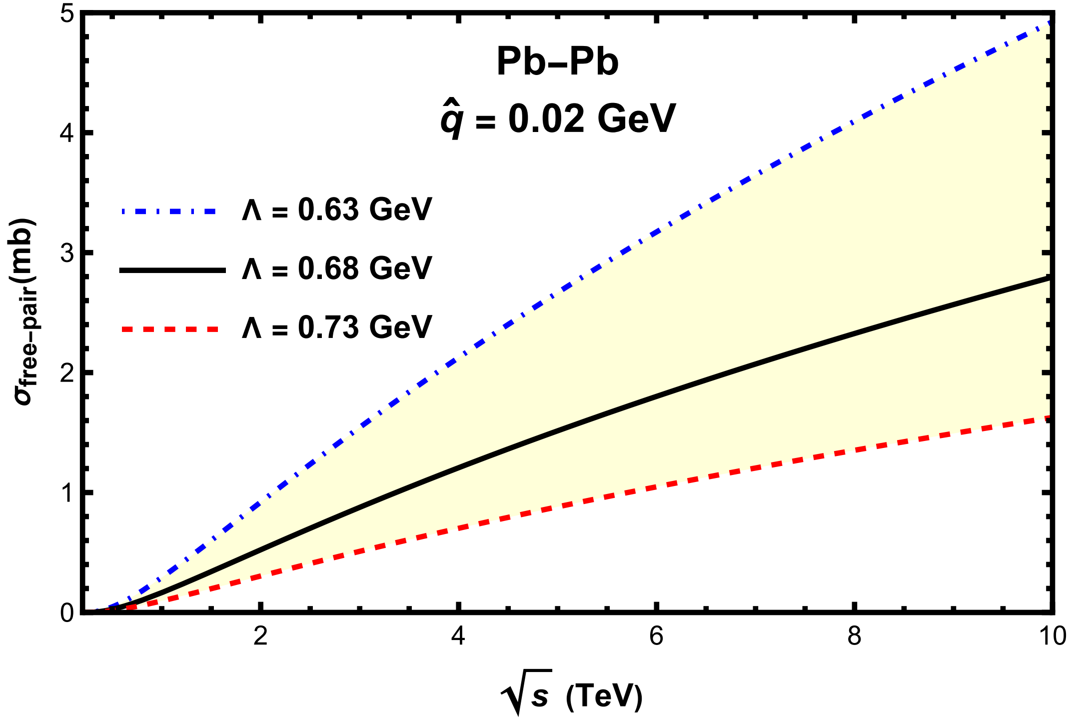
Two parameters: Λ $\hat{q}$

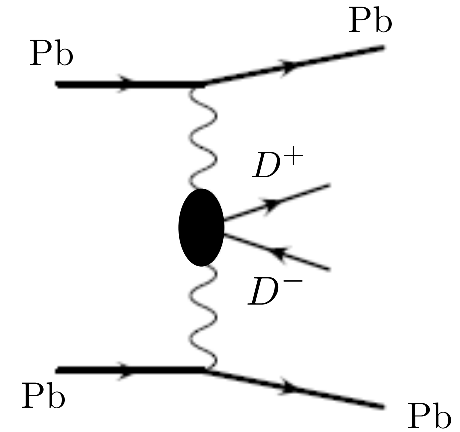
$$\sigma_B(A\,A \to A\,A\,B) = \int_{m_D^2/\hat{q}\gamma}^{\hat{q}\gamma} d\omega_1 \int_{m_D^2/\omega_1}^{\hat{q}\gamma} d\omega_2\, \sigma_B(\omega_1,\omega_2)\, n(\omega_1)\, n(\omega_2)$$

Three parameters: Λ $\hat{q}$ $\psi(0)$

Results

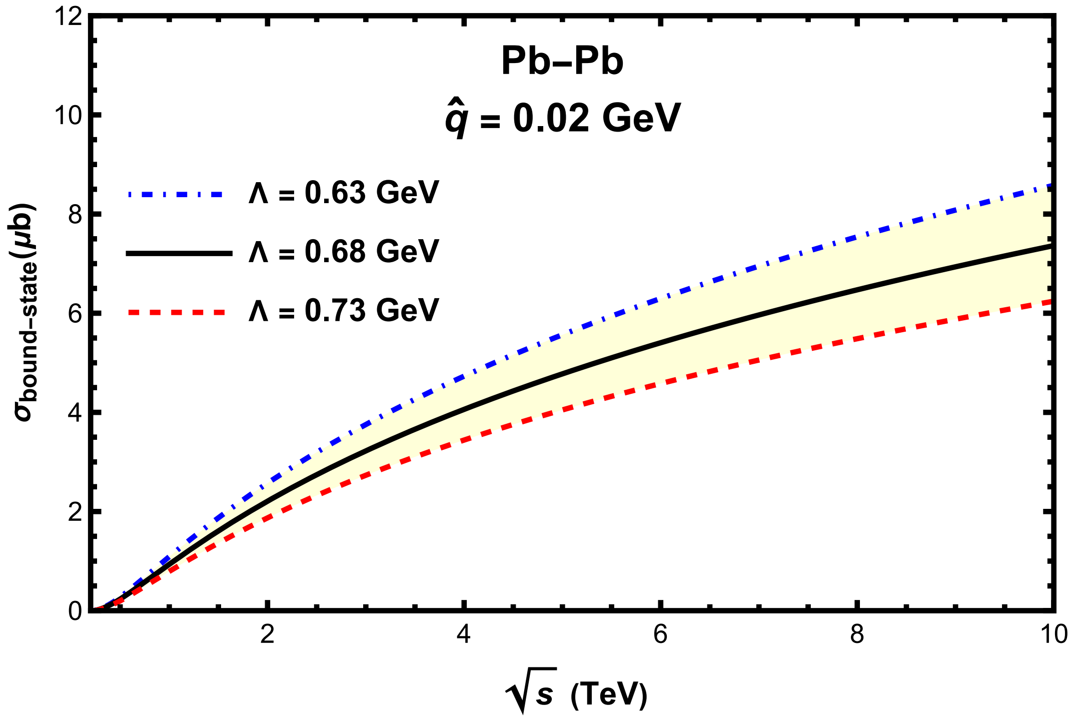
Free pair production





$\sqrt{s} = 5.02$ TeV → $\sigma(Pb\,Pb \to Pb\,Pb\,D^+D^-) = 1.5^{+1.2}_{-0.6}$ mb

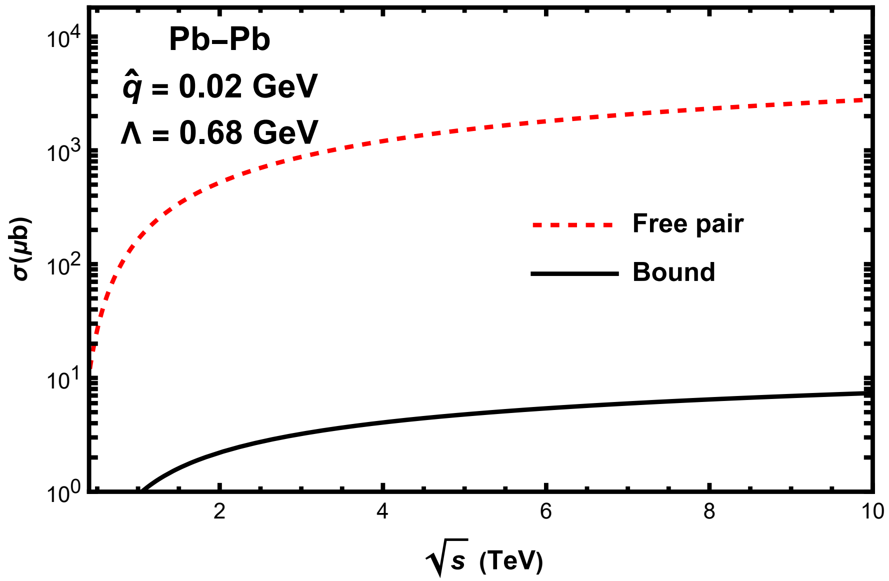
Bound state production in Pb Pb



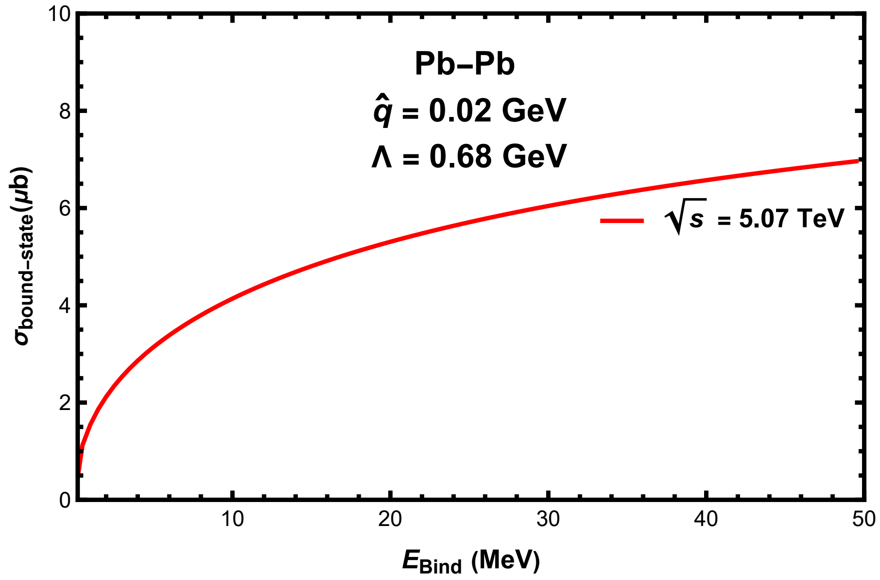
$$E_b = 17 \text{ MeV}$$

$$|\psi(0)|^2 \simeq 0.008 \text{ GeV}^3$$

$$\sqrt{s} = 5.02 \text{ TeV} \longrightarrow \boxed{\sigma(Pb\,Pb \to Pb\,Pb\,B) = 4.82^{+0.8}_{-0.7}\ \mu b}$$



Cross section for bound state is only 1/300 of the cross section for free pair production !



Cross section increases with the binding energy !

Comparison with previous results

Two photon fusion in the impact parameter formalism

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

b-dependent equivalent photon spectrum

Form factor

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

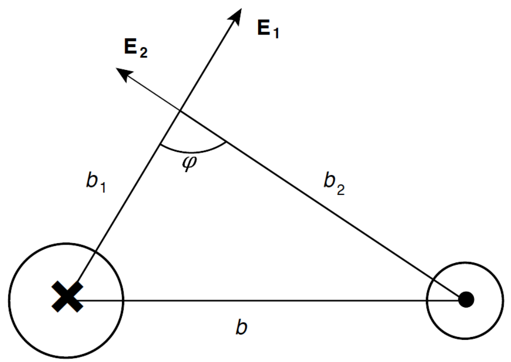
Photon fusion cross section : Low formula

Decay width

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

Geometric factor

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



Exotic scalar charmonium production

Klusek-Gawenda, Szczurek, arXiv:1004.5521

State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (μb) pointlike			σ_F (μb) monopole			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(3915), 0^{++}	3919	0.20	2.6	5.1	19.8	4.0	7.3	25.3	3.6	6.7	24.5

Moreira, Bertulani, Gonçalves, FSN, arxiv:1610.06604

molecules

State	Mass	$\Gamma_{\gamma\gamma}$[keV]	$\sigma[\mu$b]		
			2.76 TeV	5.02 TeV	39 TeV
X(3940), 0^{++}	3943	0.33	5.5	9.7	32.5
χ_{c0}(3915) , 0^{++}	3919	0.20	3.4	6.0	20.1

Fariello, Bhandari, Bertulani, F.S.N., arXiv:2306.10642

$$5 \leq \sigma \leq 11 \ \mu b$$

Summary-I

We introduced a prescription to produce charm meson molecules in photon-photon collisions

Use effective Lagrangians and the bound state wave function

Three parameters: $\Lambda \quad \hat{q} \quad \psi(0)$ Can be better constrained !

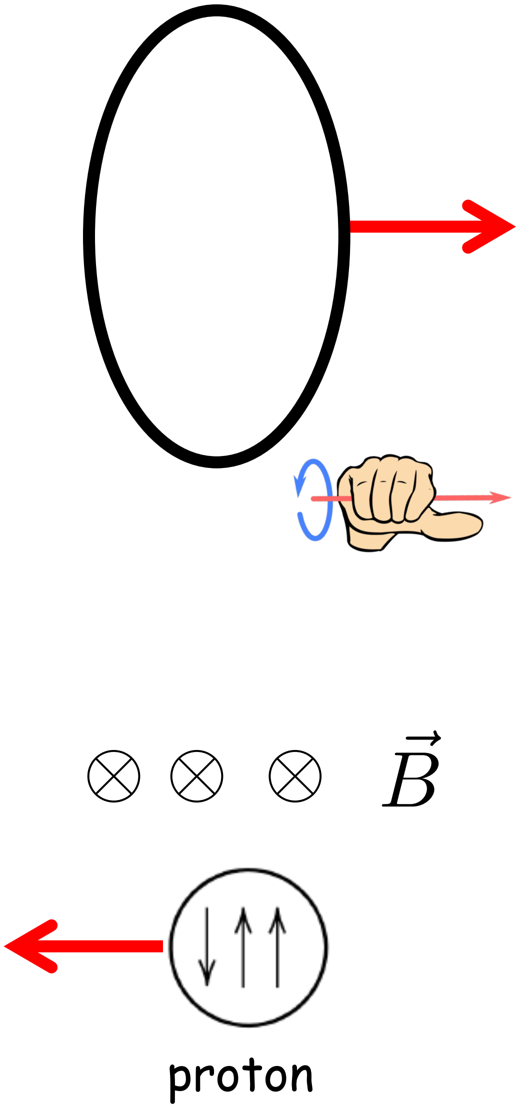
Production of the molecule $D^+ D^-$ $\sigma \simeq 4.8 \ \mu b$

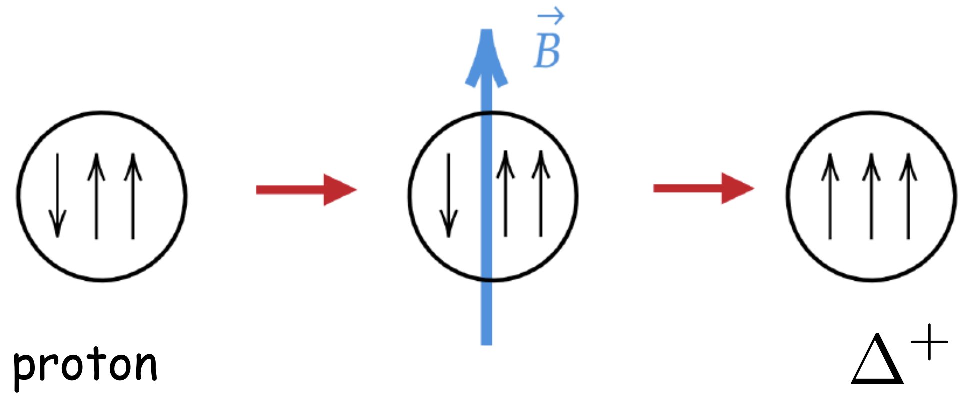
Production of similar states with a similar method $5 \leq \sigma \leq 11 \ \mu b$

Towards a theory of molecule production in UPCs

II - Production of forward pions in UPCs

Magnetic Transitions





$$\Delta^+ \rightarrow p + \pi^0$$ ~ 99%

$$\pi^0 \rightarrow \gamma + \gamma$$ ~ 99%

Pions are very close to the beam!

Magnetic Transitions in Perturbation Theory

$$\begin{cases} eB \simeq m_\pi^2 \qquad \sqrt{eB} \simeq m_\pi \\ M_\Delta - M_N \simeq 2 m_\pi \end{cases}$$

$M_\Delta - M_N \simeq 2 m_\pi$ → Energetically possible

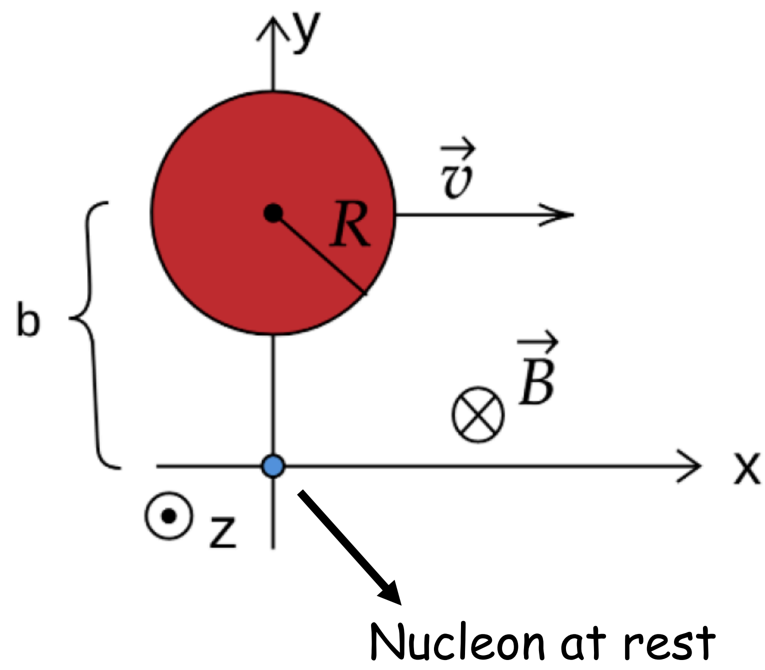
$m_\pi << M_N$ → Time dependent perturbation theory

$$a_{fi} = -i \int_{-\infty}^{+\infty} e^{iE_{fi}t'} \langle \Delta | H_{int} | N \rangle \, dt'$$

$$H_{int} = -\vec{\mu}.\vec{B}$$

$$\vec{B} = \frac{Z\, e\, \gamma\, v\, b}{4\,\pi\,(R^2 + \gamma^2\, v^2\, t^2)^{3/2}}\,\hat{z}$$

$$\vec{\mu} = \sum_{i=u,d} \vec{\mu}_i = \sum_{i=u,d} \frac{q_i}{m_i} \vec{S}_i$$



The matrix element $\langle \Delta | H_{int} | N \rangle$

Wave functions of $SU(2)_{spin} \otimes SU(2)_{isospin}$

$$
\begin{aligned}
|p \ \uparrow\rangle &= \frac{1}{3\sqrt{2}}[udu(\downarrow\uparrow\uparrow + \uparrow\uparrow\downarrow -2 \uparrow\downarrow\uparrow) + duu(\uparrow\downarrow\uparrow + \uparrow\uparrow\downarrow -2 \downarrow\uparrow\uparrow) \\
&+ \ uud(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2 \uparrow\uparrow\downarrow)]
\end{aligned}
$$

$$
\begin{aligned}
|n \ \uparrow\rangle &= \frac{1}{3\sqrt{2}}[dud(\downarrow\uparrow\uparrow + \uparrow\uparrow\downarrow -2 \uparrow\downarrow\uparrow) + udd(\uparrow\downarrow\uparrow + \uparrow\uparrow\downarrow -2 \downarrow\uparrow\uparrow) \\
&+ \ ddu(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2 \uparrow\uparrow\downarrow)]
\end{aligned}
$$

$$
|\Delta^+ \uparrow\rangle = \frac{1}{3}(uud + udu + duu)(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow)
$$

$$
|\Delta^0 \uparrow\rangle = \frac{1}{3}(ddu + dud + udd)(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow)
$$

Cross section

$$\langle \Delta^0 \downarrow | H_{int} | n \downarrow \rangle = \frac{\sqrt{2} B e \hbar}{3m}$$

$$\langle \Delta^+ \uparrow | H_{int} | p \uparrow \rangle = \frac{\sqrt{2} B e \hbar}{3m}$$

$$\langle \Delta^+ \downarrow | H_{int} | p \downarrow \rangle = -\frac{\sqrt{2} B e \hbar}{3m}$$

$$\langle \Delta^0 \uparrow | H_{int} | n \uparrow \rangle = -\frac{\sqrt{2} B e \hbar}{3m}$$

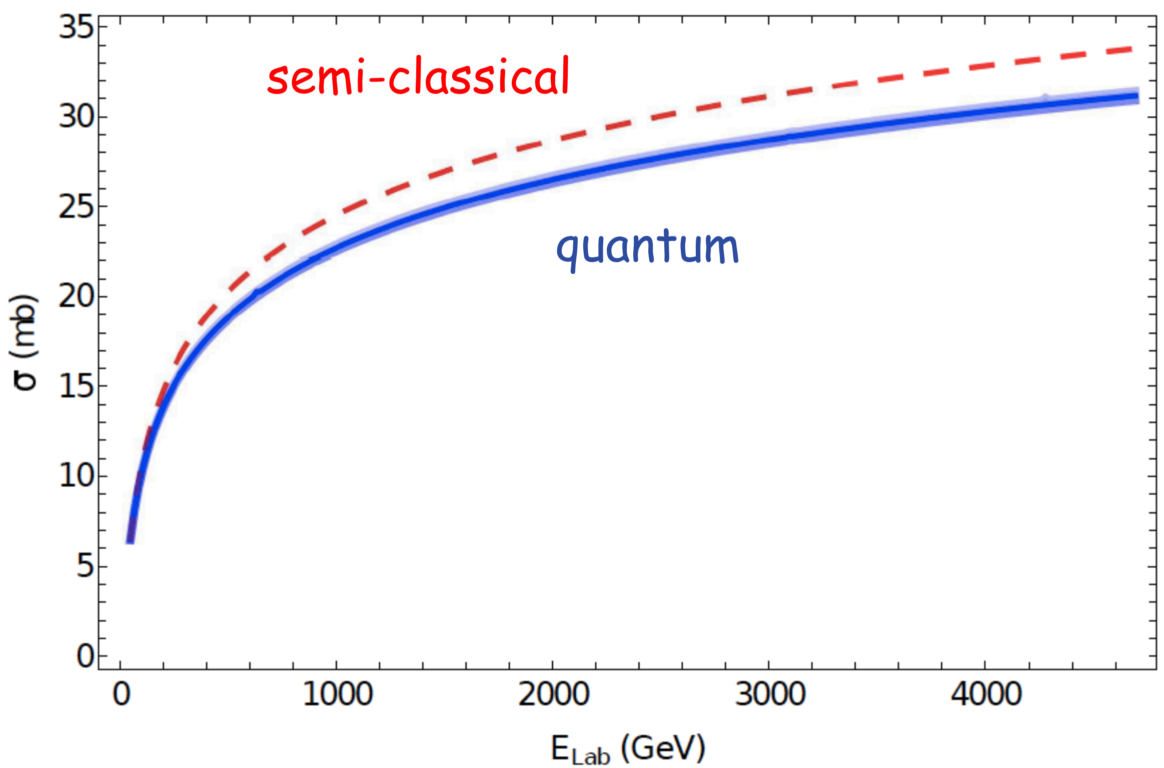
$$a_{fi} = -i \int_{-\infty}^{+\infty} e^{iE_{fi}t'} \langle \Delta | H_{int} | N \rangle \, dt'$$

$$\sigma = \int_R^{\infty} |a_{fi}|^2 d^2 b$$

Large cross sections !

I. Danhoni, F.S. N,

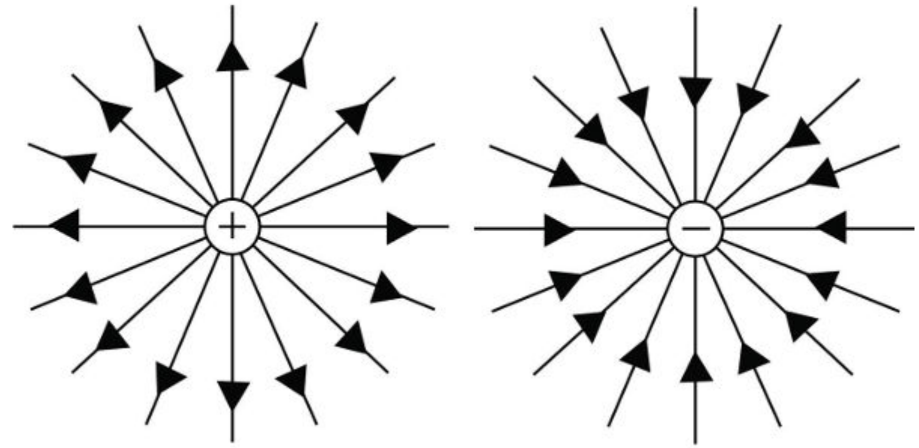
PLB 805 (2020) 135463



On the validity of the classical field approximation

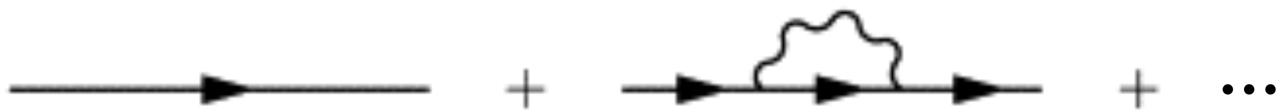
Classical picture

Continuous fields



Quantum picture:

Electron propagator



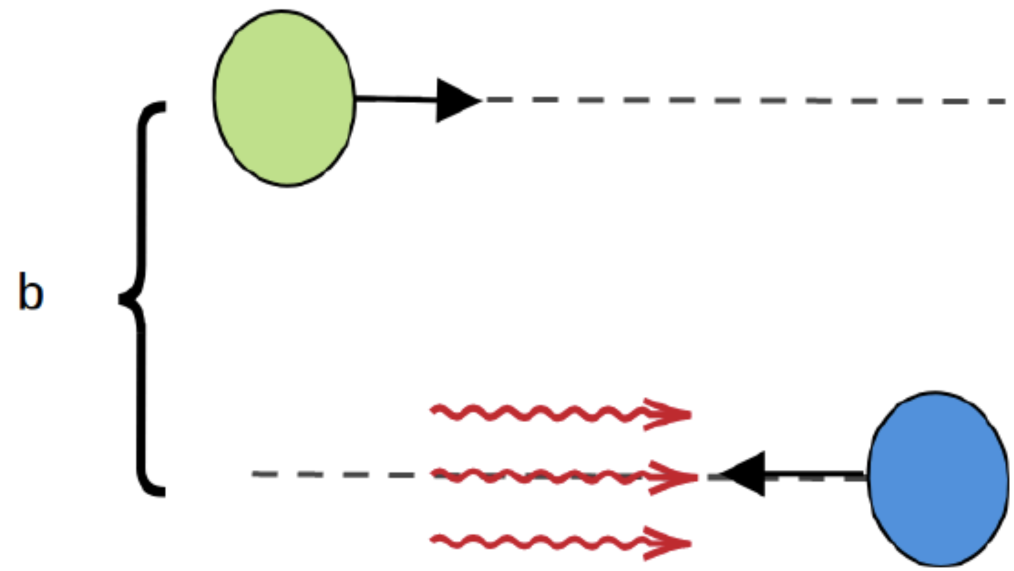
"Classical field is the limit of a quantum field when all the energy levels have a large occupation number"

Do we reach this limit in relativistic heavy ion collisions ?

A test

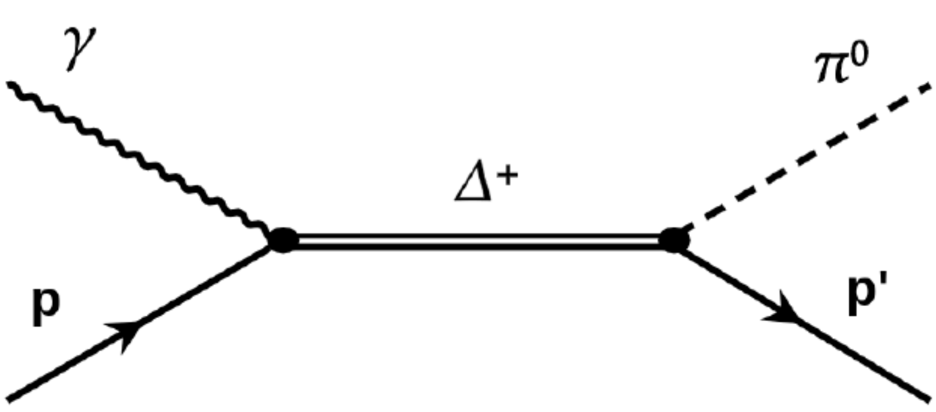
I. Danhoni, F.S. N., PRC 103 (2021) 024902

The projetile emits photons



Photon flux computed with the Weizsäcker-Williams method

A photon interacts with a nucleon in the target

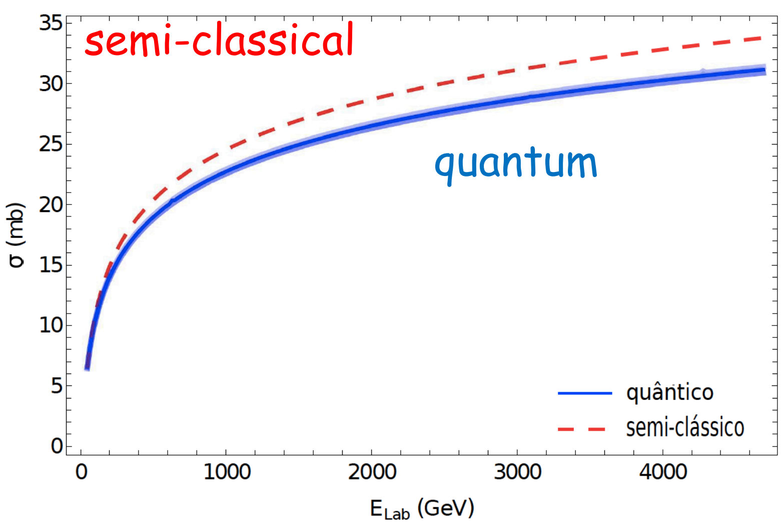


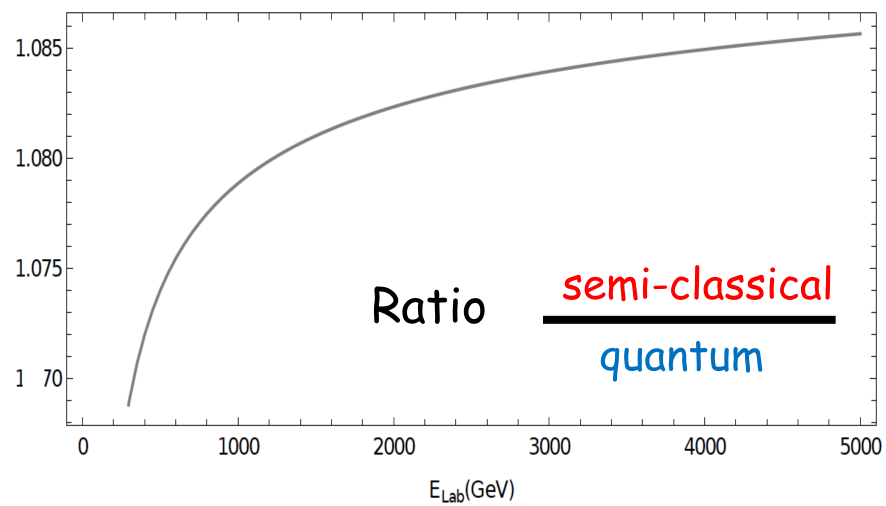
Cross section

$$\sigma = \int \frac{dw}{w} \sigma_\gamma(w) n(w)$$

$$n(w) = \frac{Z_1^2 \alpha}{\pi} \left[2\xi K_0(\xi) K_1(\xi) - \xi^2 (K_1^2(\xi) - K_0^2(\xi)) \right] \qquad \xi = \frac{w(R_A + R_B)}{\gamma}$$

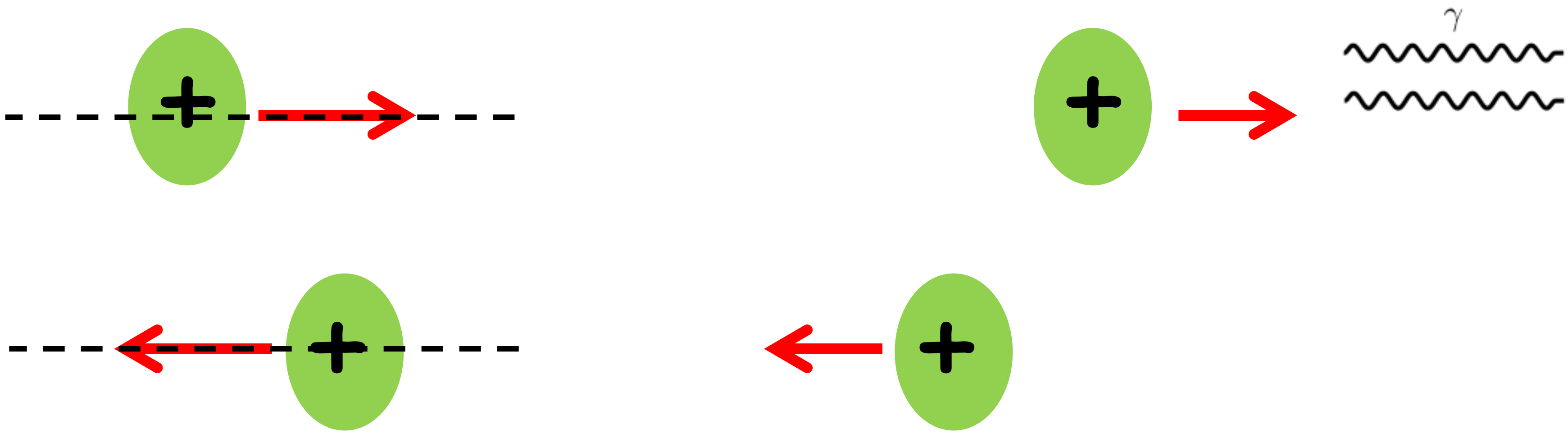
$\sigma_\gamma(\omega)$ taken from the literature and extrapolated to higher energies





Classical approximation is not bad !

Measurement



Measure very forward photons $(\eta \simeq 9 - 11)$ in a segmented detector

Reconstruct the neutral pions

Use the LHCf and RHICf detectors for ultra-peripheral collisions

Background: either suppressed by small cross sections (diffraction)
or appearing in other regions of phase space (smaller rapidities)

Measurements of longitudinal and transverse momentum distributions for neutral pions in the forward-rapidity region with the LHCf detector

O. Adriani, E. Berti, M. Bongi, R. D'Alessandro, M. Del Prete, and A. Tiberio
INFN Section of Florence, Italy and
University of Florence, Italy

Inspiration !

arXiv:1507.08764

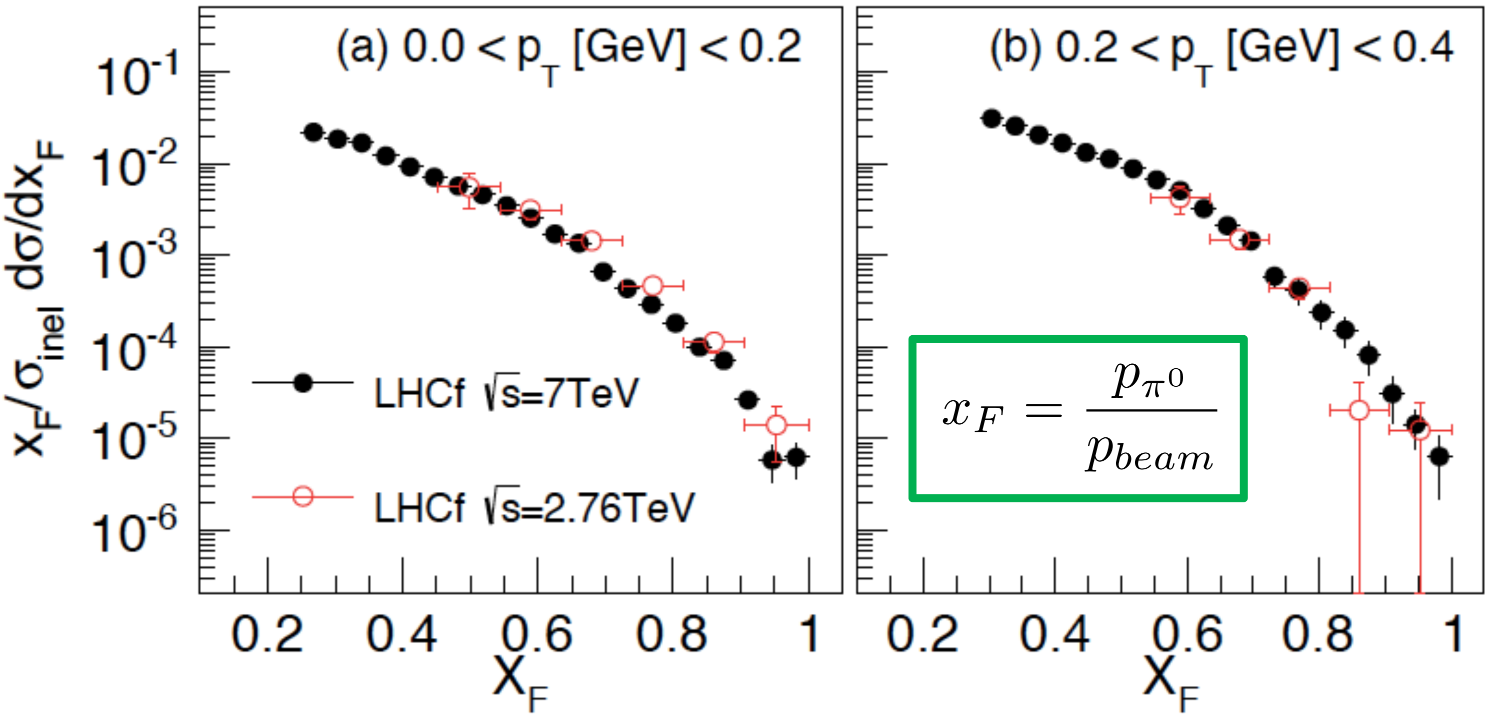


FIG. 21. (color online). The π^0 yield in each p_T range as a function of x_F. Left: the distributions for $0.0 < p_T < 0.2$ GeV. Right: the distributions for $0.2 < p_T < 0.4$ GeV. Open red circles and filled black circles indicate LHCf data in $p + p$ collisions at $\sqrt{s} = 2.76$ and 7 TeV, respectively.

Summary-II

Magnetic transitions have large cross sections

Very particular distribution in phase space

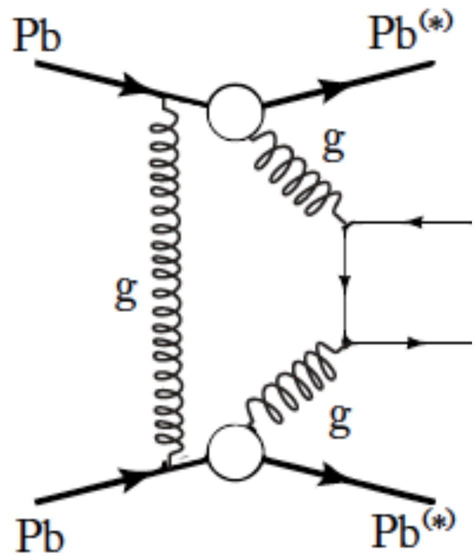
Classical magnetic field is a reasonable approximation

Measurement might be feasible : RHICf for UPC's

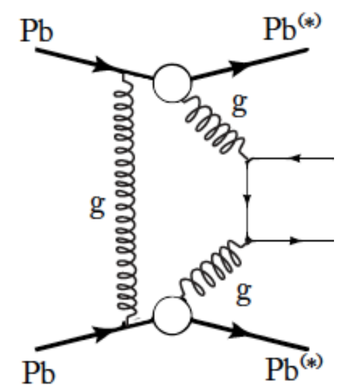
Manifestation of the strong magnetic field !

Thank you for your attention

Back-ups

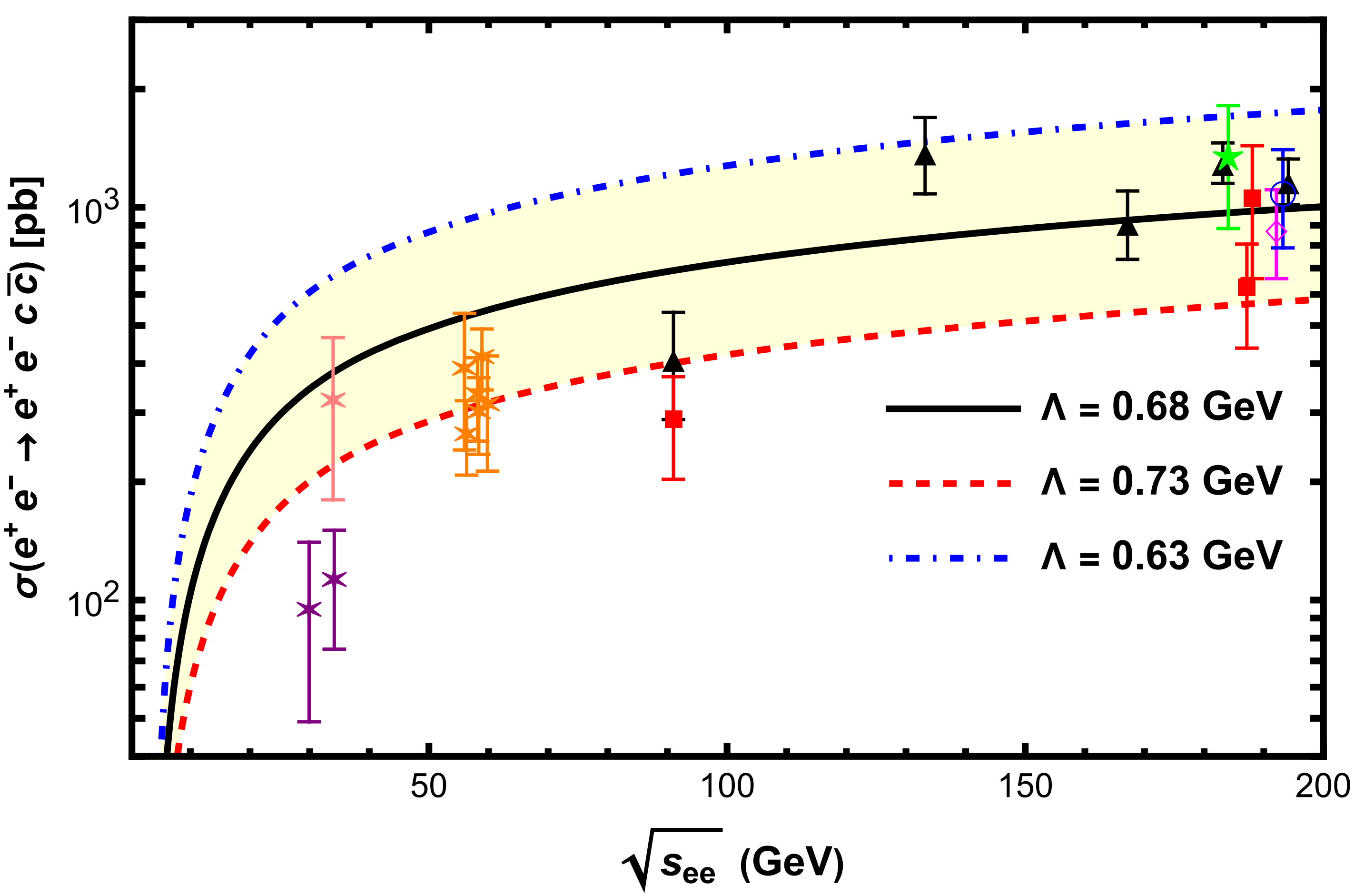


Pb
Pb(*)
g
g
g
Pb
Pb(*)



Pb
Pb(*)
g
g
g
Pb
Pb(*)

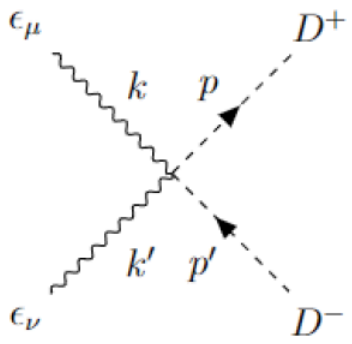
$$\frac{|B\rangle}{\sqrt{2E_B}} \equiv \int \frac{d^3q}{(2\pi)^3}\tilde{\psi}^*(\vec{q})\frac{1}{\sqrt{2E_q}}\frac{1}{\sqrt{2E_{-q}}}|\vec{q},-\vec{q}\rangle$$



$\sigma(e^+e^- \to e^+e^- c\bar{c})$ [pb]
10^3
10^2
50
100
150
200
$\sqrt{s_{ee}}$ (GeV)
Λ = 0.68 GeV
Λ = 0.73 GeV
Λ = 0.63 GeV

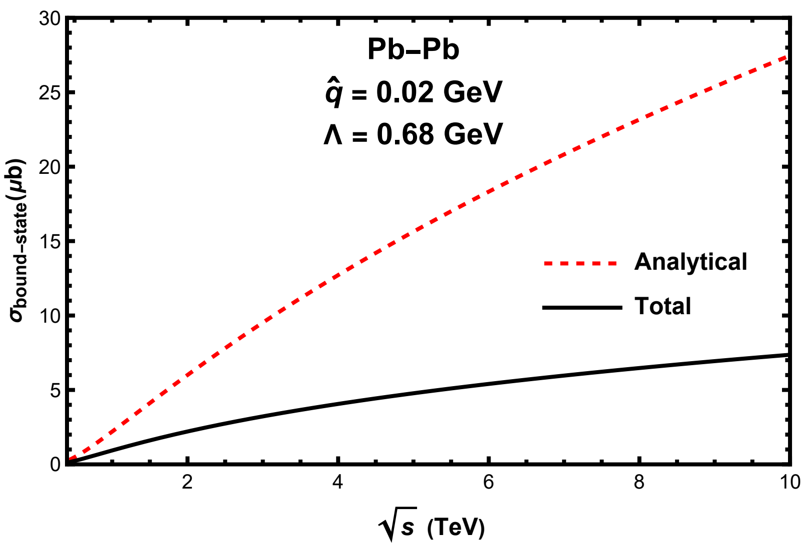
Low Energy Analytical Expression

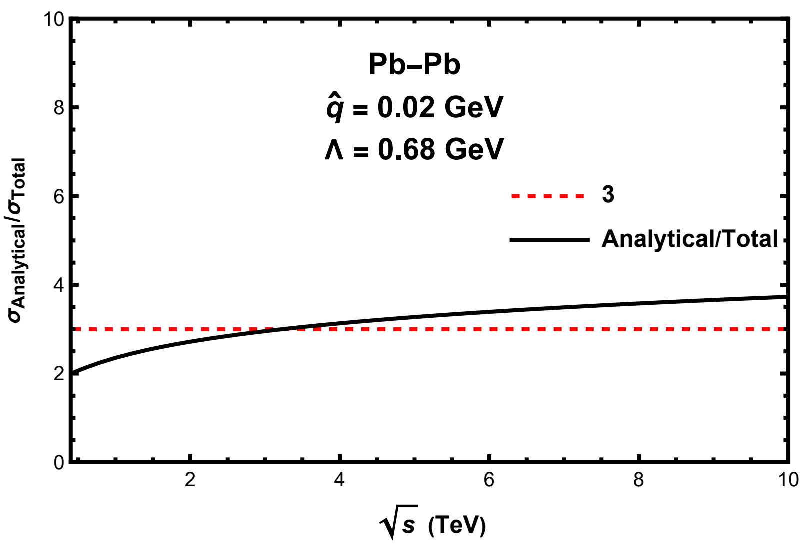
$$\frac{1}{(k-p)^2 - m_D^2} \approx \frac{1}{0 - m_D^2 - m_D^2} = \frac{-1}{2m_D^2}$$



$$|M(\gamma\gamma \to D^+D^-)|^2 = 4e^4F^4(-m_D^2)$$

$$\sigma_B(A\,A \to A\,A\,B) = \frac{256\pi|\psi(0)|^2 Z^4\alpha^4 F^4(m_D^2)}{3m_B^5}\left[\ln\left(\frac{s\hat{q}^2}{m_p^2 m_B^2}\right)\right]^3$$





AA in QED versus pp in QCD

$$\sigma(pp \to ppc\bar{c}) = \int_{\frac{4m_c^2}{s}}^{1} dx_1 f(x_1) \int_{\frac{4m_c^2}{x_1 s}}^{1} dx_2 f(x_2)\sigma(x_1, x_2)$$

$$f(x_1) = \frac{1}{x_1^a}; \quad f(x_2) = \frac{1}{x_2^a}$$

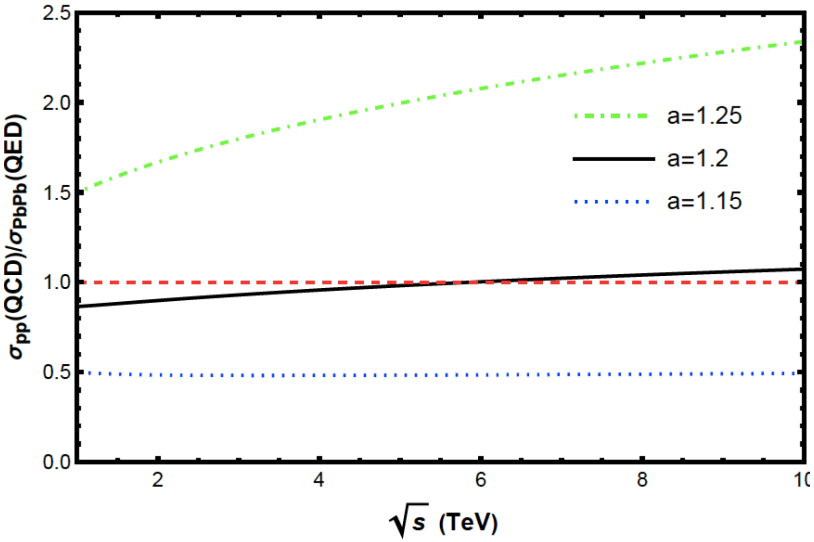
$$\sigma(x_1, x_2) = \frac{\alpha_s^2}{x_1 x_2 s}$$

$$\sigma(PbPb \to PbPbc\bar{c}) = \int_{\frac{2m_c^2}{\sqrt{s}}}^{\frac{\sqrt{s}}{2}} d\omega_1 n(\omega_1) \int_{\frac{m_c^2}{\omega_1}}^{\frac{\sqrt{s}}{2}} d\omega_2 n(\omega_2)\sigma(\omega_1, \omega_2)$$

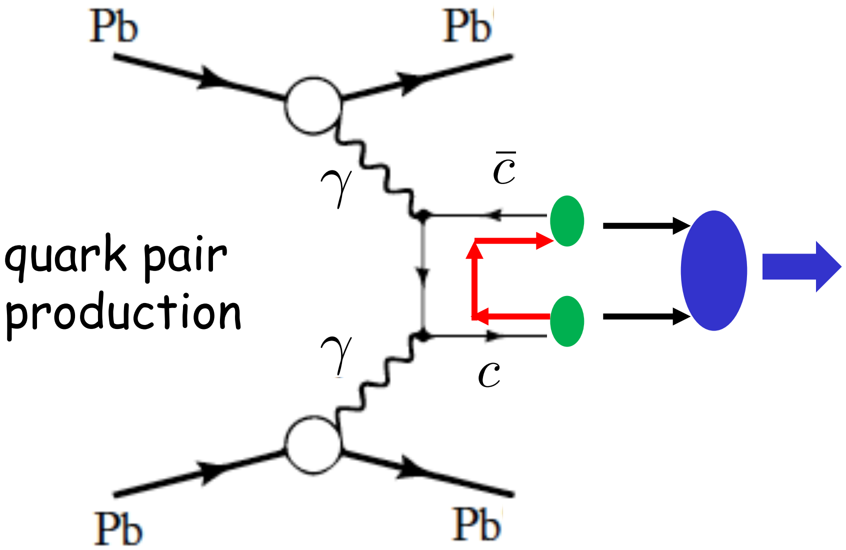
$$n(\omega_1) = \frac{2Z^2\alpha}{\pi\omega_1} \ln\left(\frac{\sqrt{s}}{2\omega_1}\right)$$

$$n(\omega_2) = \frac{2Z^2\alpha}{\pi\omega_2} \ln\left(\frac{\sqrt{s}}{2\omega_2}\right)$$

$$\sigma(\omega_1, \omega_2) = \frac{\alpha_s^2}{4\omega_1\omega_2}$$



$$\sigma_{QED}(Pb\,Pb \to Pb\,Pb\,c\,\bar{c}) \approx \sigma_{QCD}(p\,p \to p\,p\,c\,\bar{c})$$


Pb
Pb
γ
c̄
quark pair
production
γ
c
Pb
Pb

$$\sigma(pp \to c\bar{c}) = \int dx_1\, dx_2\, f_g(x_1)\, f_g(x_2)\, \sigma(gg \to c\bar{c})$$

$$m^2 = x_1\, x_2\, s$$

$$\sigma(gg \to c\bar{c}) = \frac{\pi\alpha_s^2}{3m^2} \left\{ \left(1 + \frac{4m_c^2}{m^2} + \frac{m_c^4}{m^4}\right) ln\frac{1+\lambda}{1-\lambda} - \frac{1}{4}\left(7 + \frac{31m_c^2}{m^2}\right)\lambda \right\}$$

$$\lambda = \sqrt{1 - \frac{4m_c^2}{s}}$$

$$f(x) \simeq \frac{1}{x}$$

$$\sigma(pp \to c\bar{c}) \propto \alpha_s^2$$

$$\sigma(A\,A(\gamma\gamma) \to A\,A\,c\,\bar{c}) = \int d\omega_1\, d\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma(\gamma_1\gamma_2 \to c\bar{c})$$

$$\sigma(\gamma_1\gamma_2 \to c\bar{c}) = \frac{4\pi\alpha^2}{m^2} \left\{ \left(1 + \frac{4m_c^2}{m^2} - \frac{8m_c^4}{m^4}\right) ln\frac{1+\lambda}{1-\lambda} - \left(1 + \frac{4m_c^2}{m^2}\right)\lambda \right\}$$

$$m^2 = \omega_1\, \omega_2$$

$$n(\omega) = \frac{2}{\pi} Z^2 \alpha \frac{1}{\omega} ln(\frac{\mu\gamma}{\omega})$$

$$\sigma(AA \to c\bar{c}) \propto Z^4\, \alpha^4$$

For Pb: $Z\,\alpha \simeq 0.6$

$$Z^4\, \alpha^4 \simeq 0.13 \qquad \alpha_s^2 \simeq 0.1$$

Charm production: QCD proton versus QED lead

$$m^2 = x_1\, x_2\, s$$

$$\sigma(gg \to c\bar{c}) = \frac{\pi\alpha_s^2}{3m^2}\left\{\left(1+\frac{4m_c^2}{m^2}+\frac{m_c^4}{m^4}\right) ln\frac{1+\lambda}{1-\lambda} - \frac{1}{4}\left(7+\frac{31m_c^2}{m^2}\right)\lambda\right\}$$

$$\lambda = \sqrt{1-\frac{4m_c^2}{s}}$$

$$f(x) \simeq \frac{1}{x}$$

$$\sigma(pp \to c\bar{c}) \propto \alpha_s^2$$

$$\sigma(A\,A(\gamma\gamma) \to A\,A\,c\,\bar{c}) = \int d\omega_1\, d\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma(\gamma_1\gamma_2 \to c\bar{c})$$

$$\sigma(\gamma_1\gamma_2 \to c\bar{c}) = \frac{4\pi\alpha^2}{m^2}\left\{\left(1+\frac{4m_c^2}{m^2}-\frac{8m_c^4}{m^4}\right) ln\frac{1+\lambda}{1-\lambda} - \left(1+\frac{4m_c^2}{m^2}\right)\lambda\right\}$$

$$m^2 = \omega_1\, \omega_2$$

$$n(\omega) = \frac{2}{\pi}\, Z^2\alpha\, \frac{1}{\omega}\, ln(\frac{\mu\gamma}{\omega})$$

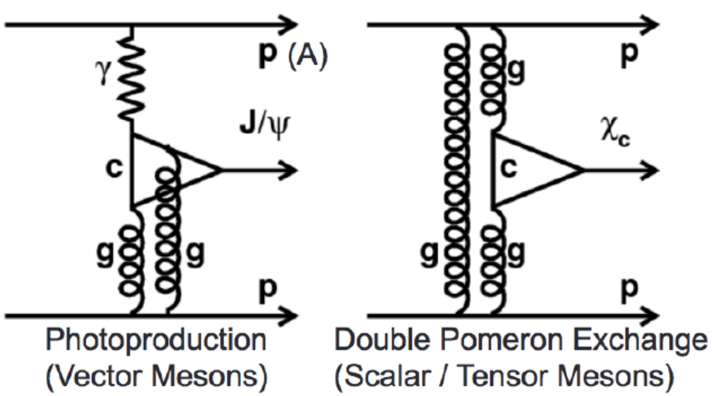
$$\sigma(AA \to c\bar{c}) \propto Z^4\, \alpha^4$$

For Pb: $Z\,\alpha \simeq 0.6$

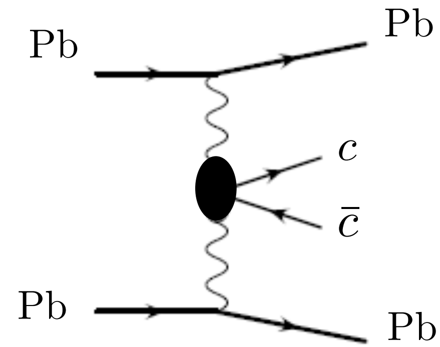
$$Z^4\,\alpha^4 \simeq 0.13 \qquad \alpha_s^2 \simeq 0.1$$

Charmonium Production in UPCs

Photon-Pomeron Pomeron-Pomeron

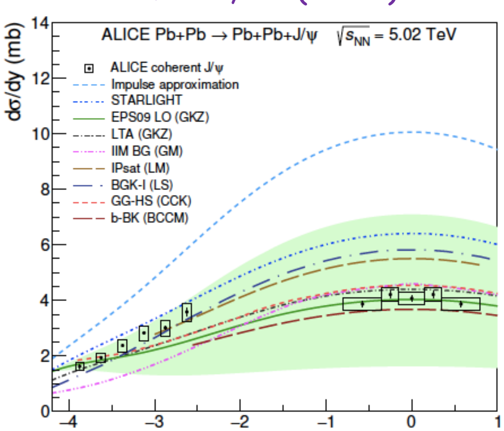


Photon-Photon

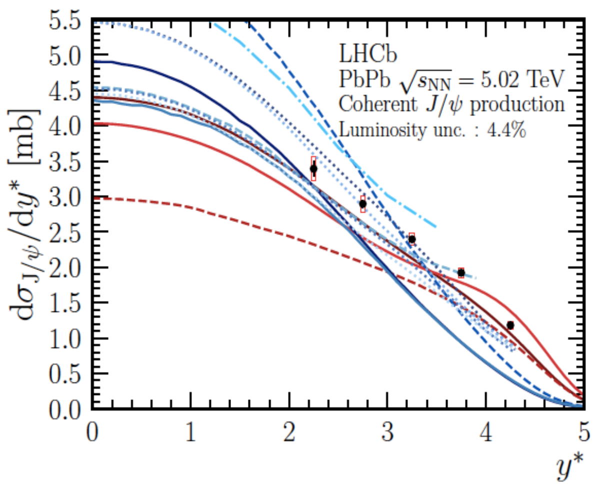


Cross section of microbarns

A. Matyja, Nucl. Part. Phys. Proc. 324, 22 (2023)

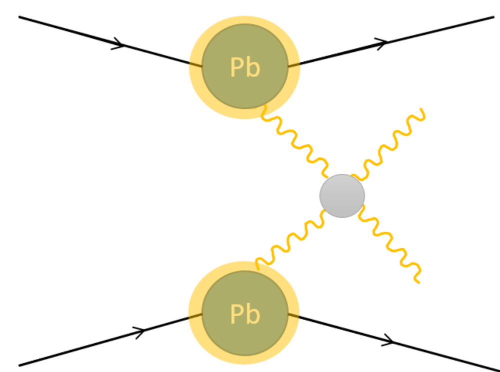


X. Wang, arXiv:2301.00222



Cross section of milibarns

LHCb, arXiv:1810.04602



Cross section ~ 100 nanobarns

Two photon fusion

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

Two photon fusion

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

Equivalent photon spectrum

Form factor

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

Two photon fusion

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

Equivalent photon spectrum

Form factor

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

Photon fusion cross section : Low formula

Decay width

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

Two photon fusion in the impact parameter formalsim

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

b-dependent equivalent photon spectrum

Form factor

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

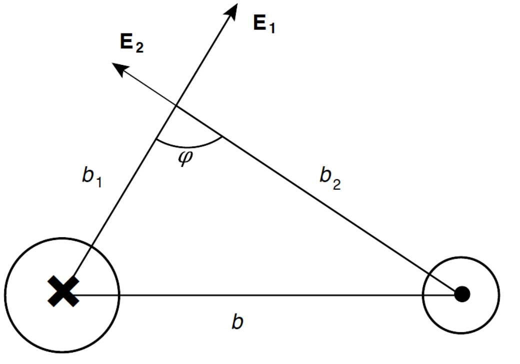
Photon fusion cross section : Low formula

Decay width

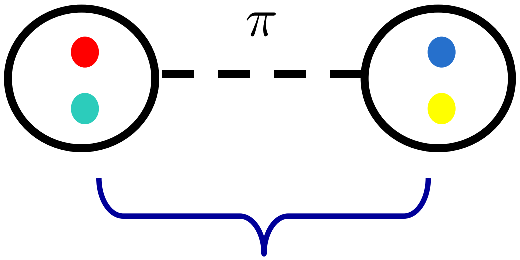
$$\hat{\sigma}(\gamma\gamma \to R) = 8\pi^2 (2J+1) \frac{\Gamma_{R\to\gamma\gamma}}{M_R} \delta(4\omega_1\omega_2 - M_R^2)$$

Geometric factor

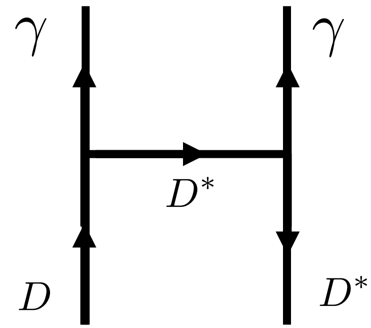
$$S(b) = \Theta(|\mathbf{b_1} - \mathbf{b_2}| - R_1 - R_2)$$



Decay width into two photons



~ 10 fm



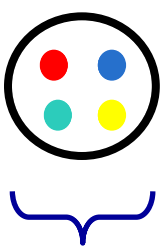
Heavy meson exchange
is short distance

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

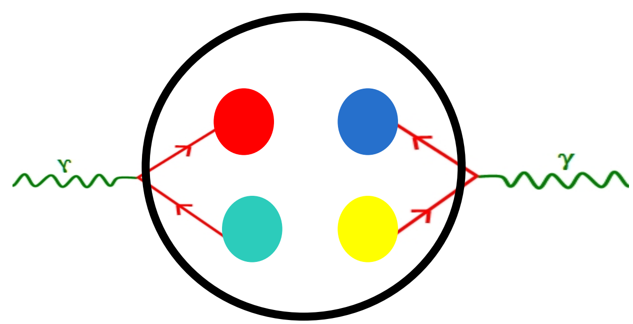
$$\Gamma \sim E_B \frac{4}{3}\sqrt{\frac{m_Q}{E_B}}\left(\alpha_s \frac{1}{r_{eff} m_Q}\right)^2$$

M. Shmatikov, hep-ph/9503471

Suppressed ?



~ 1 fm



Unsuppressed ?

X(3940) decay into two photons

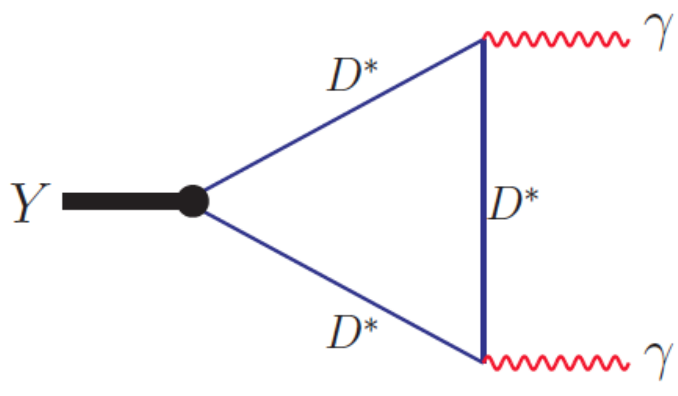
Meson molecule (EFT)

Branz, Gutsche, Lyubovitskij
arXiv:0903.5424

$$\Gamma(Y \to \gamma\gamma) = 0.33 \pm 0.01 \text{ keV}$$

Branz, Molina, Oset arXiv:1010.0587

$$\Gamma(Y \to \gamma\gamma) = 0.013 - 0.085 \text{ keV}$$



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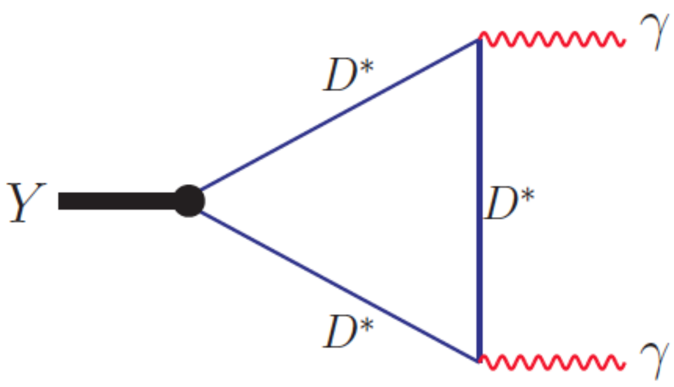
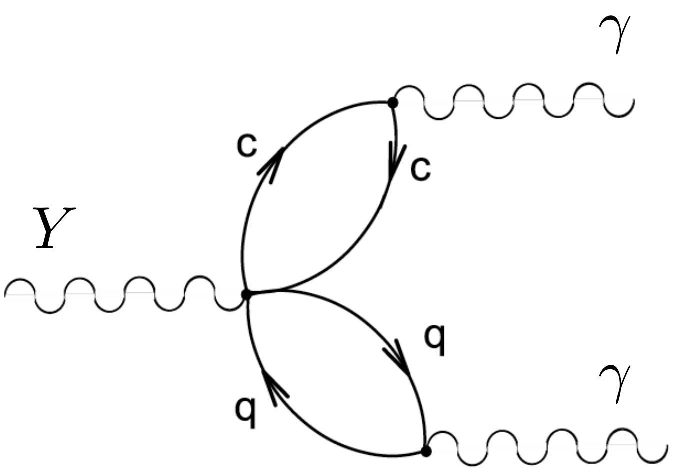


Branz, Molina, Oset arXiv:1010.0587

$$\Gamma(Y \to \gamma\gamma) = 0.013 - 0.085 \text{ keV}$$

Tetraquark (QCDSR)



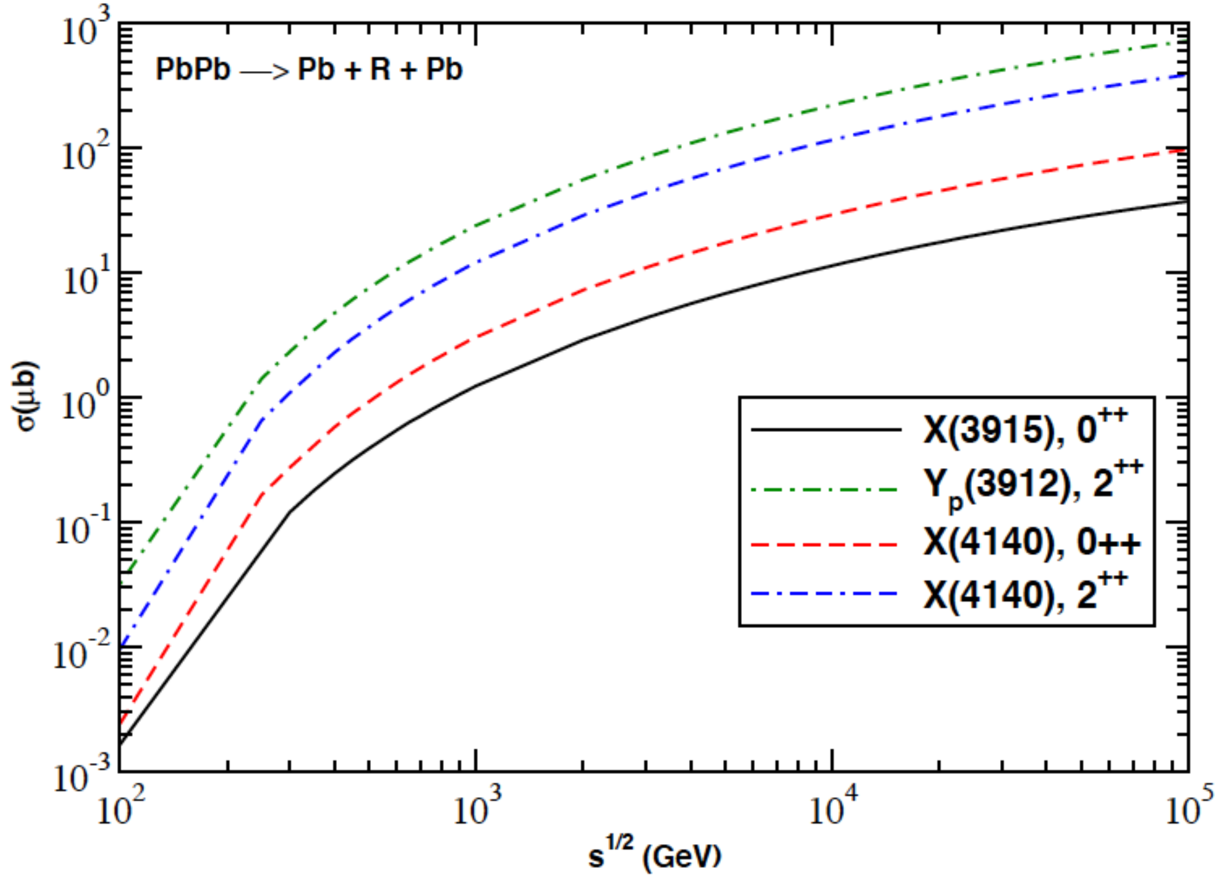
Albuquerque, Dias, Nielsen, Zanetti,
arXiv:1209.6592

$$\Gamma(Y \to \gamma\gamma) = 1.6 \pm 1.3 \text{ keV}$$

Cross sections

Meson molecule

Moreira, Bertulani, Gonçalves, FSN, arxiv:1610.06604

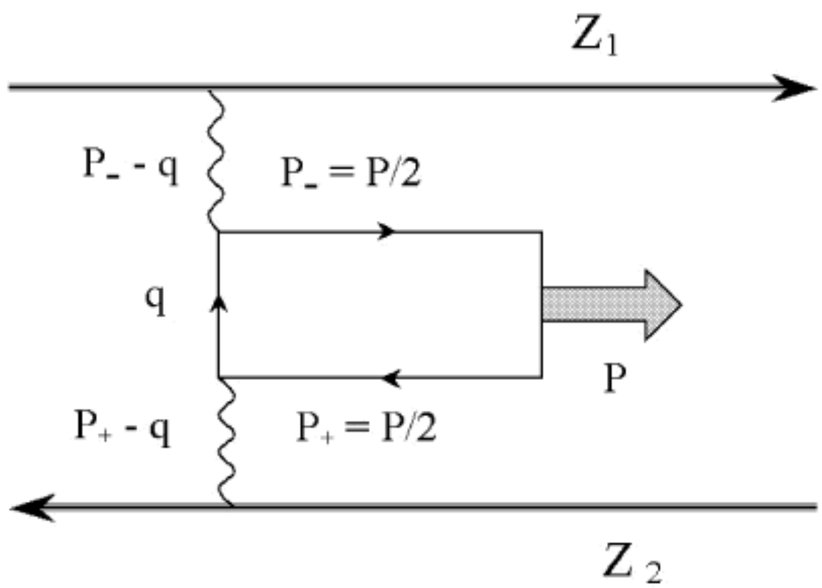


Charmonium production

Classical Field Approximation

C. Bertulani and FSN, Nucl. Phys. A 703 861 (2002)

Production of C even mesons



$$A_0^{(1)}(q) = -8\pi^2 Ze\ \delta(q_0 - \beta q_3)\frac{e^{i\mathbf{q}_t.\mathbf{b}/2}}{q_t^2 + q_3^2/\gamma^2} \qquad A_3^{(1)} = \beta A_0^{(1)}$$

$$\mathcal{M} = -ie^2\bar{u}(\frac{P}{2})\left[\int \frac{d^4q}{(2\pi)^4} \not{A}^{(1)}(\frac{P}{2}-q)\frac{\not{q}+M/2}{q^2-M^2/4}\not{A}^{(2)}(\frac{P}{2}+q)+\not{A}^{(1)}(\frac{P}{2}+q)\frac{\not{q}+M/2}{q^2-M^2/4}\not{A}^{(2)}(\frac{P}{2}-q)\right]v(\frac{P}{2})$$

Projection onto a bound state ("coalescence")

$$\bar{u}\cdots v \longrightarrow \frac{\Psi(0)}{2\sqrt{M}}\,\mathrm{tr}\left[\cdots(\not{P}+M)i\gamma^5\right]$$

(Peskin pg. 150)

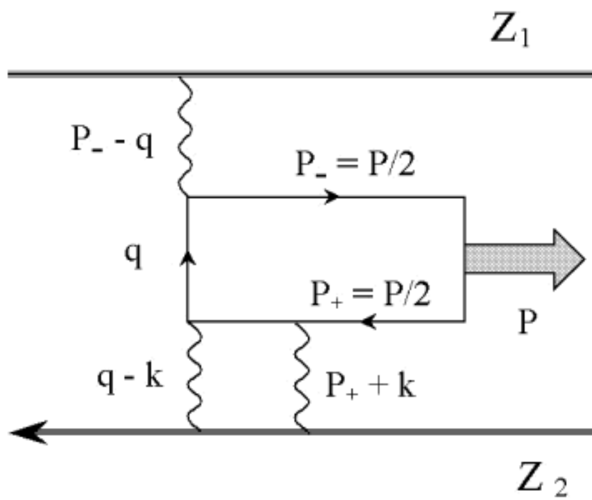
$$\Gamma_{\gamma\gamma} = 16\pi\alpha^2\left|\Psi(0)\right|^2/M^2 \cdot 3\sum_i Q_i^4$$

$$d\sigma = \sum_{\mu}\left[\int d^2b\,|\mathcal{M}(\mu)|^2\right]\frac{d^3P}{(2\pi)^3\,2E}$$

$$\frac{d\sigma}{dP_z} = \frac{16(2J+1)}{\pi^2}\frac{Z^4\alpha^2}{M^3}\frac{\Gamma_{\gamma\gamma}}{E}\int d\mathbf{q}_{1t}d\mathbf{q}_{2t}\,(\mathbf{q}_{1t}\times\mathbf{q}_{2t})^2\,\frac{\left[F_1(q_{1t}^2)F_2(q_{2t}^2)\right]^2}{\left(q_{1t}^2+\omega_1^2/\gamma^2\right)^2\left(q_{2t}^2+\omega_2^2/\gamma^2\right)^2}$$

$$F(q^2) = \frac{4\,\pi\,\rho_0}{A\,q^3}\,\left[\sin(qR)-qR\cos(qR)\right]\left[\frac{1}{1+q^2a^2}\right]$$

Production of C odd mesons



$$\bar{u}\cdots v \longrightarrow \frac{\Psi(0)}{2\sqrt{M}}\,\mathrm{tr}\left[\cdots(\not{P}+M)i\,\not{\epsilon}^{*}\right]$$

(Peskin pg. 150)

$$\mathcal{M}_a = e^3\bar{u}(\frac{P}{2})\int\frac{d^4q}{(2\pi)^4}\int\frac{d^4k}{(2\pi)^4}\,\not{A}^{(1)}(\frac{P}{2}-q)\frac{\not{q}+M/2}{q^2-M^2/4}\,\not{A}^{(2)}(q-k)\frac{\not{k}+M/2}{k^2-M^2/4}\,\not{A}^{(2)}(\frac{P}{2}+k)v(\frac{P}{2})$$

$$\frac{d\sigma}{dP_z} = 1024\,\pi\left|\Psi(0)\right|^2(Z\alpha)^6\frac{1}{M^3E}\int\frac{dq_{1t}\;q_{1t}^3\;\left[F(q_{1t}^2)\right]^2}{\left(q_{1t}^2+\omega_2^2/\gamma^2\right)^2}$$

$$\times\int\frac{dq_{2t}\;q_{2t}\;\left[F(q_{2t}^2)\right]^2}{\left[q_{2t}^2+(2\omega_1-\omega_2)^2/\gamma^2\right]^2}\left[\int\frac{dk_t\;k_t\;F(k_t^2)}{(k_t^2+(\omega_1-\omega_2)^2/\gamma^2)}\right]^2$$

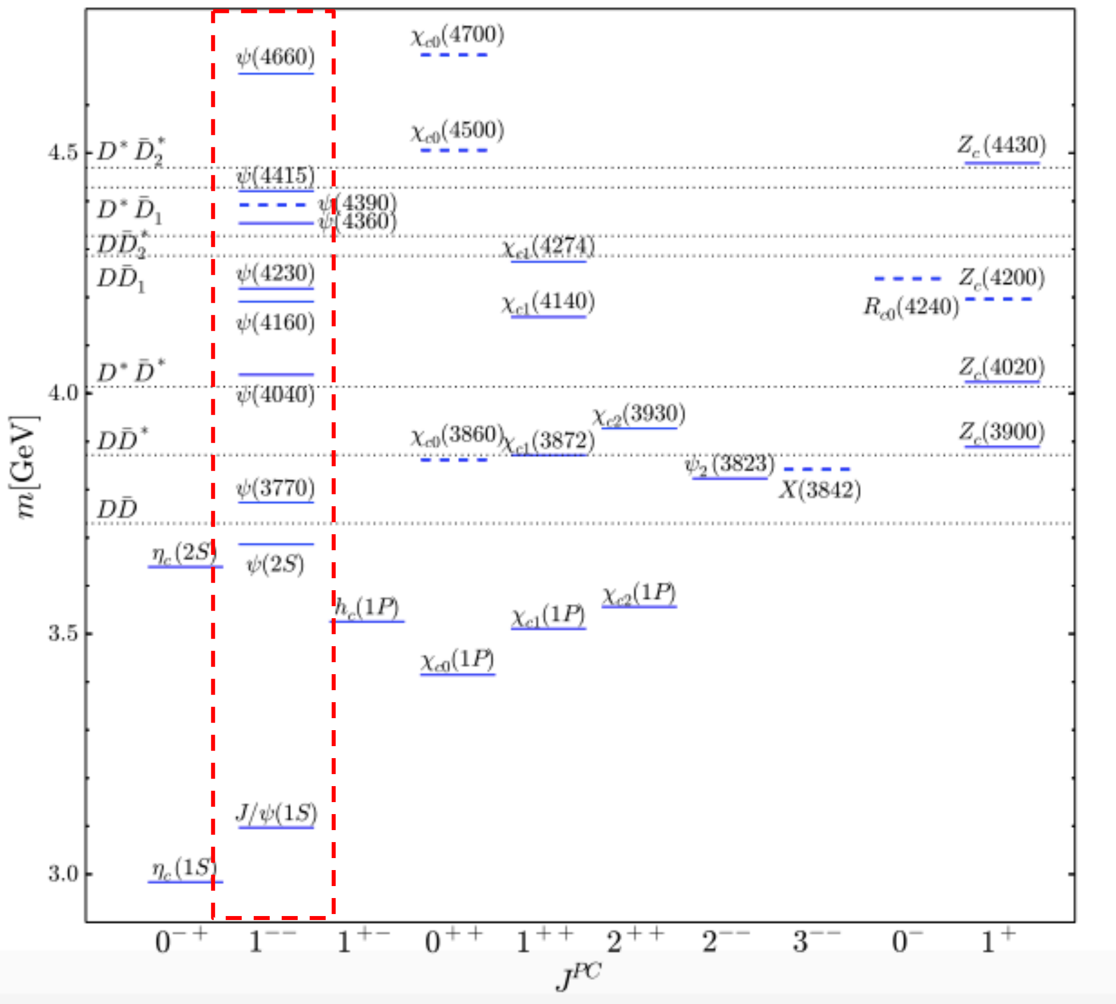
$$E=\omega_1+\omega_2$$

$$\omega_1-\omega_2=P_z$$

$$\Gamma_{e^+e^-} = 16\pi\alpha^2\left|\Psi(0)\right|^2/3M^2\;(3\cdot\textstyle\sum_i Q_i^2)$$

Cross sections

N. Brambilla et al. arXiv:1907.07583



Pb - Pb $\sqrt{s} = 5.02\,\mathrm{TeV}$

State	Mass	$\Gamma_{e^+e^-}$ [keV]	σ[nb]
ρ^0	770	6.77	2466.9
ω	782	0.6	215.3
J/ψ	3097	5.3	476.5
$\psi(2S)$	3686	2.1	161.4
$\psi(3770)$	3770	0.26	19.5
$\psi(4040)$	4040	0.86	59.7
$\psi(4160)$	4160	0.48	32.4
$\psi(4230)$	4230	1.53	101.5
$\psi(4415)$	4415	0.58	36.9

R. Fariello, D. Bhandari, C.A. Bertulani and F.S.N., arXiv:2306.10642

Summary

UPCs are clean and measurable processes

Can help in understanding the nature of (exotic) quarkonium

Photon fusion from QED : cross section is large enough

Might be visible in some part of the phase space : light-by-light scattering

Exotic charmonium

Two-photon (and three photon) decay width needs to be better calculated

Conventional charmonium

Here we study them as quark-antiquark states and produced with QED !

Bound state formation is well defined !

Some states still under discussion: 3770 , 4160 , 4230

Measurement would confirm q-qbar nature !

QCD versus QED

$$\sigma(pp \to c\bar{c}) = \int dx_1\, dx_2\, f_g(x_1)\, f_g(x_2)\, \sigma(gg \to c\bar{c})$$

$$f(x) \simeq \frac{1}{x} \qquad \sigma(gg \to c\bar{c}) = \frac{\pi\alpha_s^2}{3m^2} \qquad m^2 = x_1\, x_2\, s$$

$$\sigma(pp \to c\bar{c}) \propto \alpha_s^2$$

$$\sigma(A\,A(\gamma\gamma) \to A\,A\,c\,\bar{c}) = \int d\omega_1\, d\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma(\gamma_1\gamma_2 \to c\bar{c})$$

$$n(\omega) = \frac{2}{\pi} Z^2\alpha \frac{1}{\omega} ln(\frac{\mu\gamma}{\omega}) \qquad \sigma(\gamma_1\gamma_2 \to c\bar{c}) = \frac{4\pi\alpha^2}{m^2} \qquad m^2 = \omega_1\, \omega_2$$

$$\sigma(AA \to c\bar{c}) \propto Z^4\, \alpha^4$$

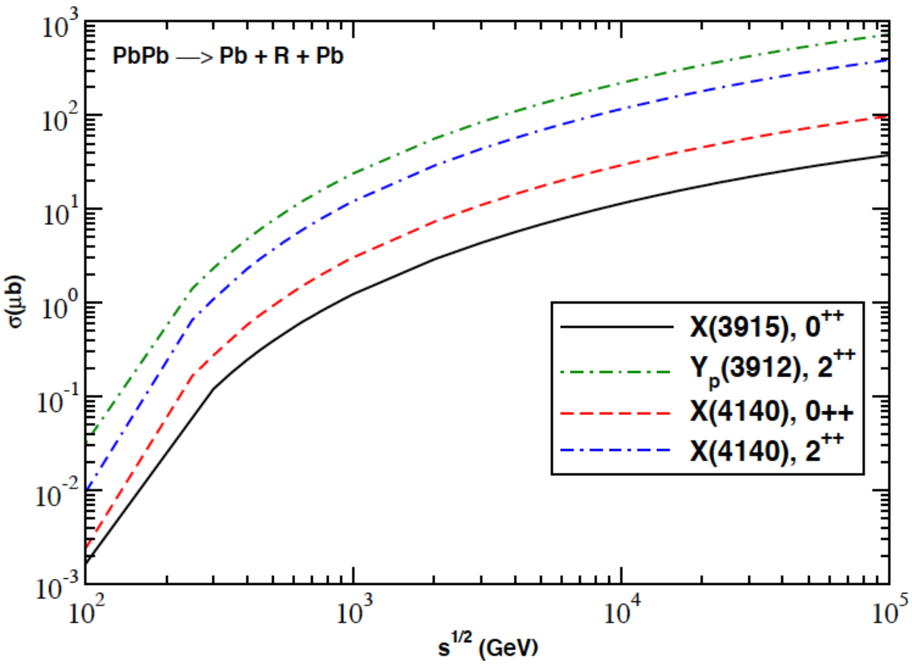
For Pb: $Z\,\alpha \simeq 0.6$ $\longrightarrow$ $Z^4\,\alpha^4 \simeq 0.13$ $\qquad \alpha_s^2 \simeq 0.1$

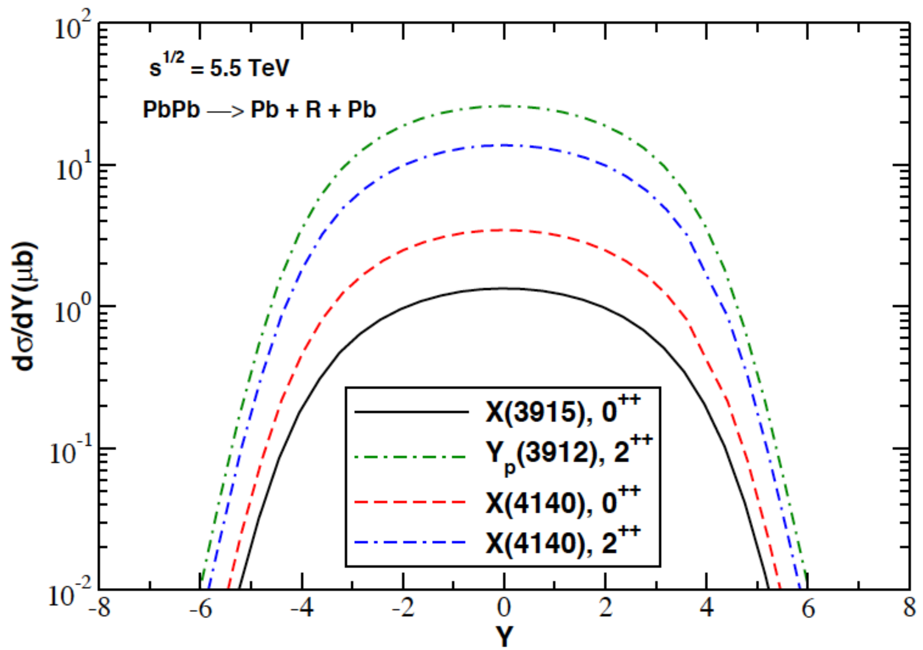
"QCD-proton is equivalent to QED-lead"

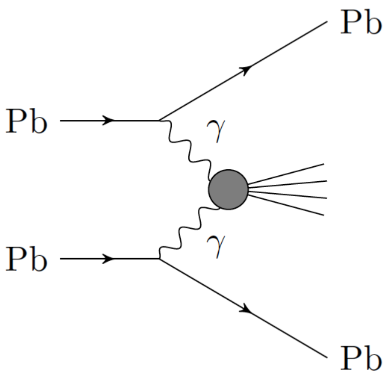
Results

Meson molecule

Moreira, Bertulani, Gonçalves, FSN, arxiv:1610.06604






Pb
Pb
γ
γ
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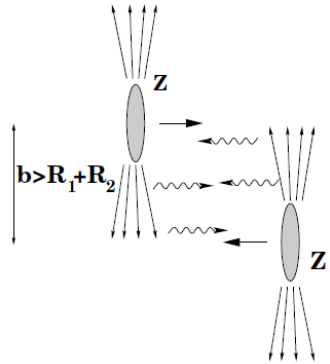
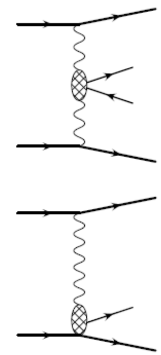
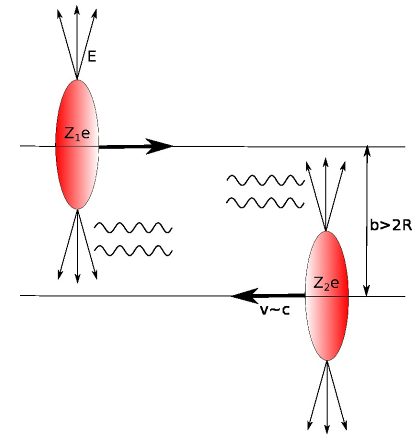
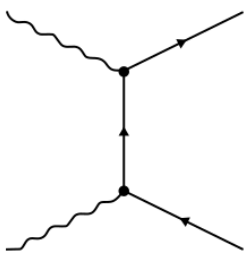
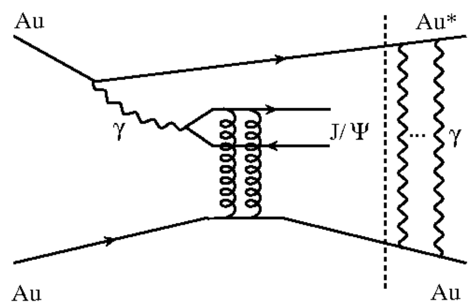
Pb


Z
b>R1+R2
Z

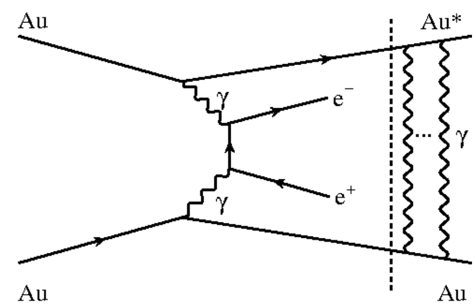



E
Z1e
b>2R
Z2e
v~c

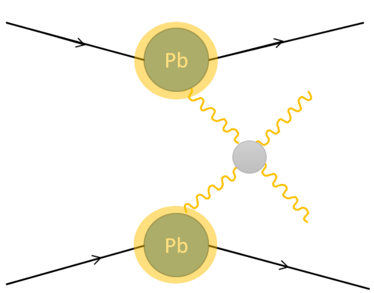


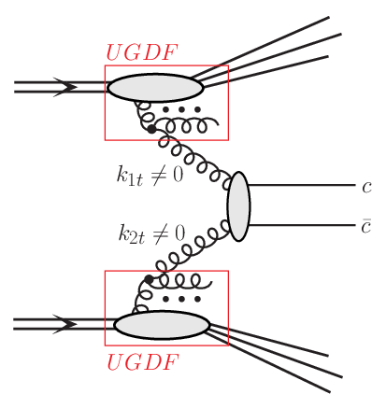

Au
Au*
γ
J/Ψ
γ
Au
Au

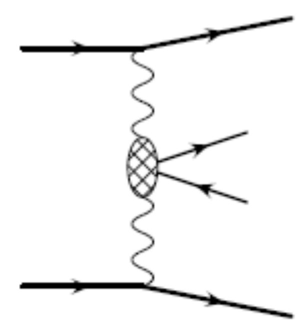
a)


Au
Au*
γ
e⁻
γ
e⁺
γ
Au
Au

b)


Pb
Pb

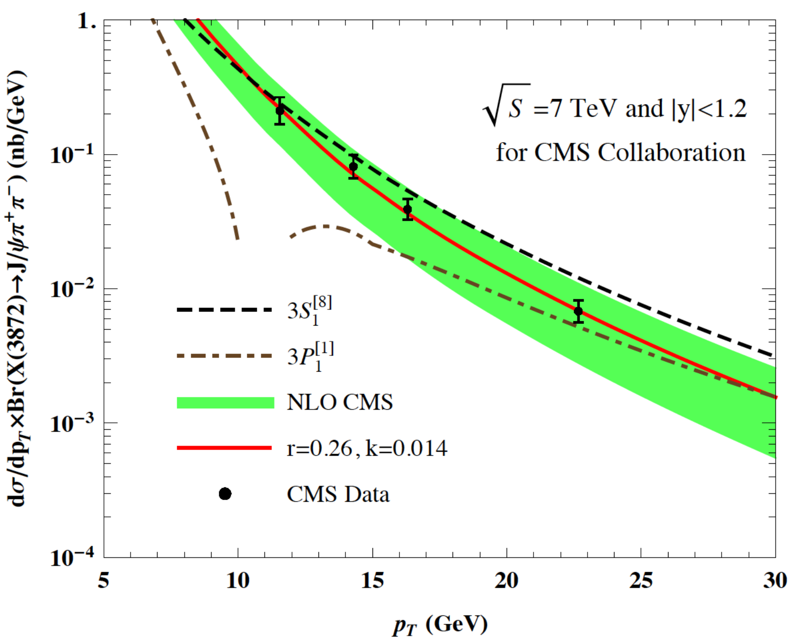

UGDF
k1t ≠ 0
c
k2t ≠ 0
c̄
UGDF

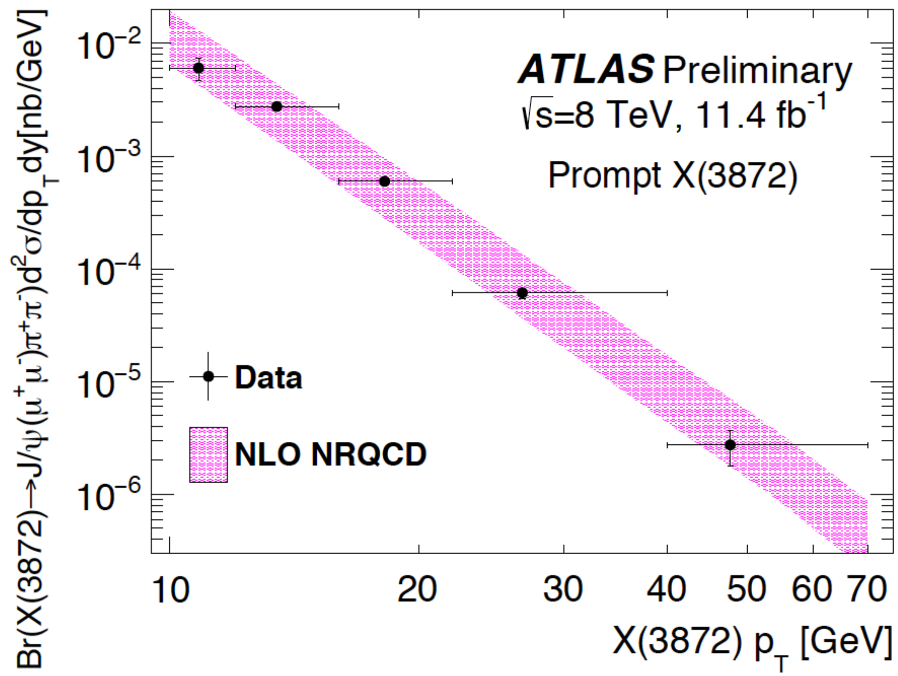


Charmonium - Molecule Mixture

Meng, Han, Chao, arxiv:1304.6710

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





ATLAS - CONF - 2016 - 028

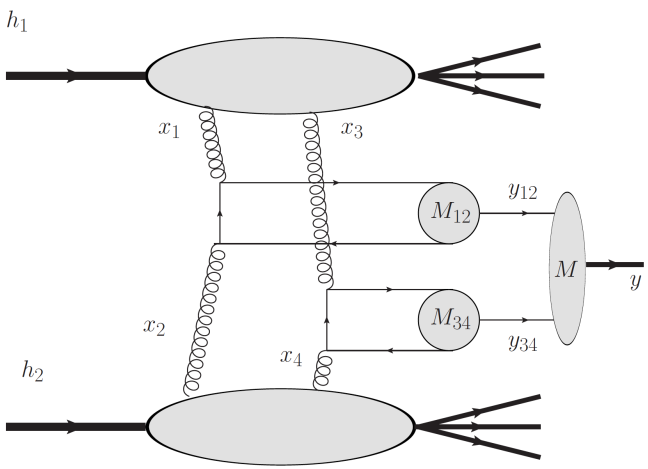
K. Toms, ICHEP 2016 Chicago

Charmonium with ~ 40 % probability

Pure D D* molecule ruled out !

Tetraquark

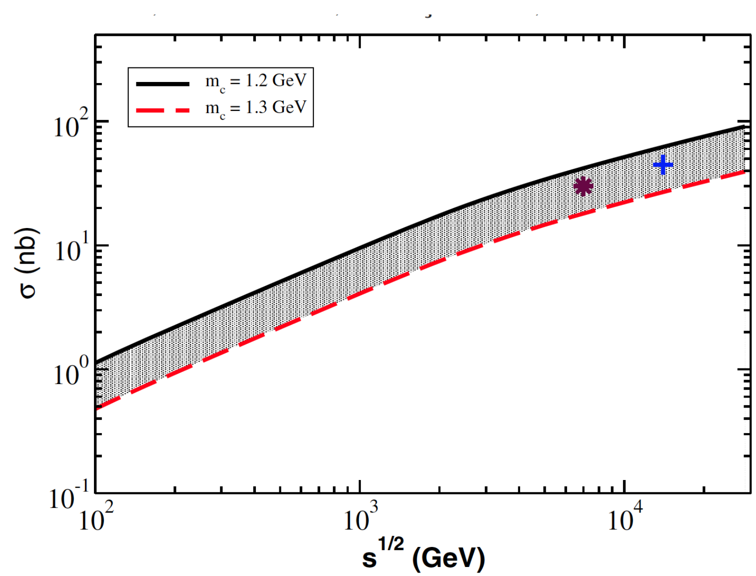
Carvalho, Cazaroto, Gonçalves, FSN, arxiv:1511.05219



Double parton scattering

Binding as in the Color Evaporation Model

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



Prediction of the energy dependence