Particle Production in Photon-Induced Processes

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UFRGS

Outline

- Introduction
- γh processes
  - Photoproduction of Vector Mesons
- $\gamma\gamma$ processes
  - Dilepton Production
  - Bound States Production
- Conclusions

Introduction

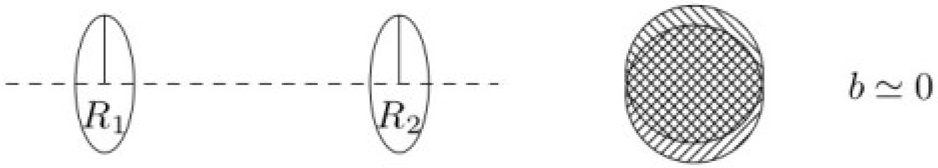
Introduction

- Initial stages at hadronic collisions

Introduction

- Initial stages at hadronic collisions

Central collisions



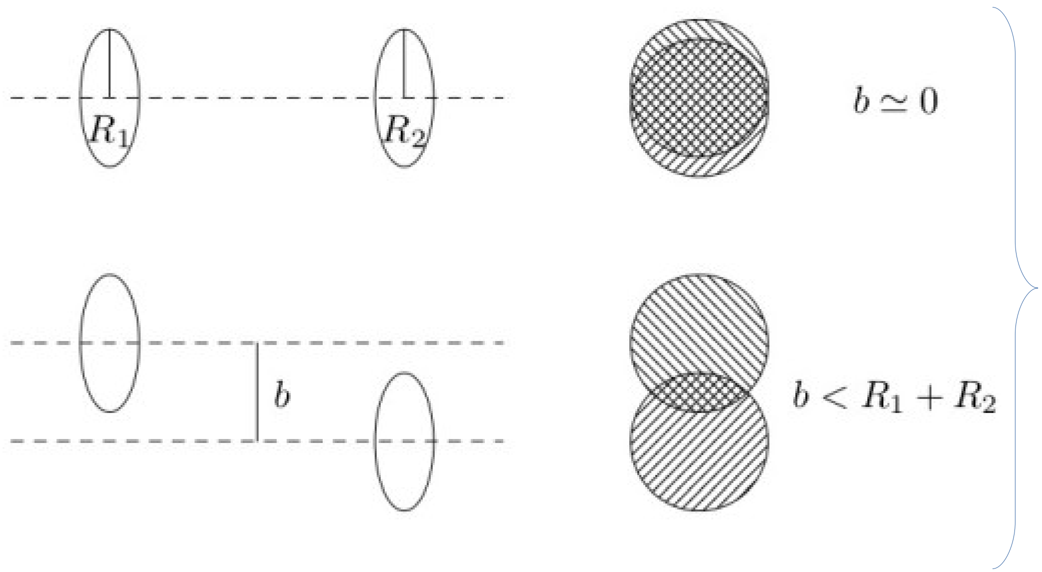
Dominated by gluon exchange.

Introduction

- Initial stages at hadronic collisions

Central collisions

Peripheral collisions



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(But non negligible photon exchange).

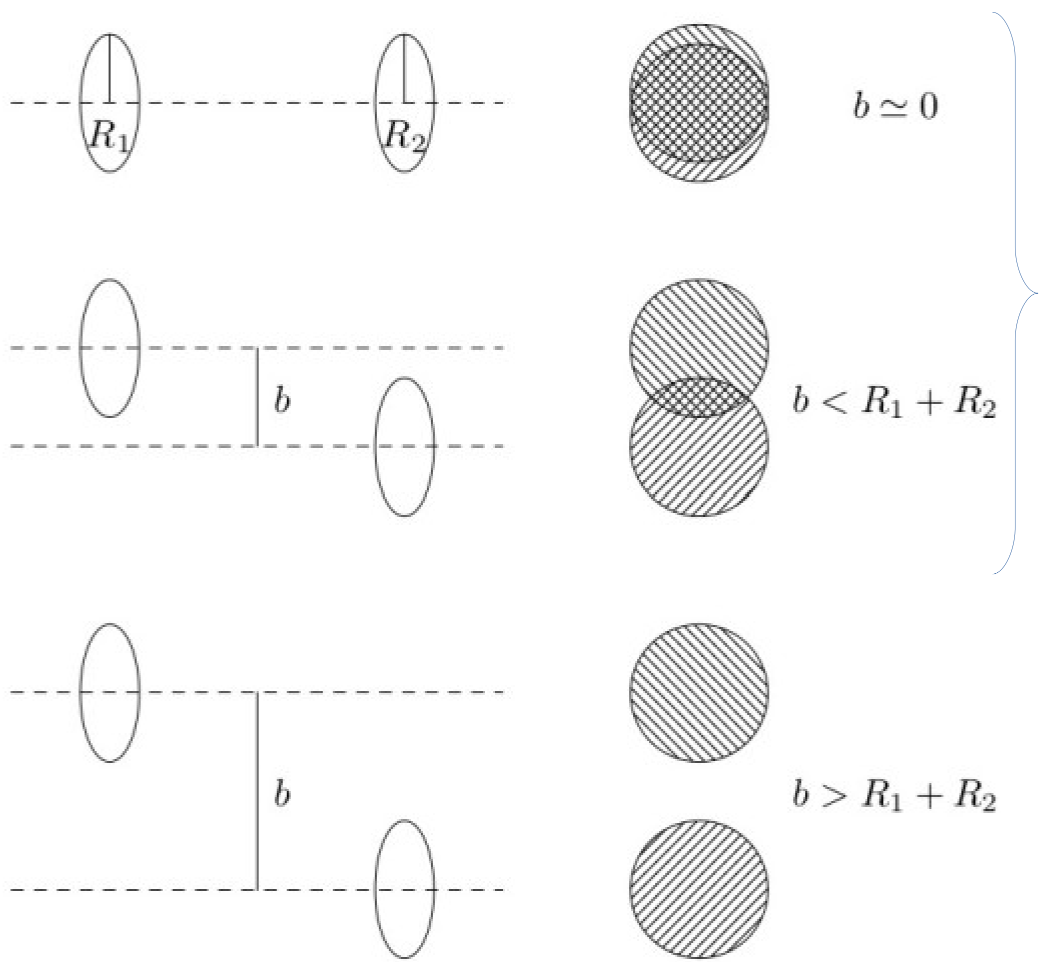
Introduction

- Initial stages at hadronic collisions

Central collisions

Peripheral collisions

Ultraperipheral collisions



Dominated by gluon exchange.

Dominated by gluon exchange.
(But non negligible photon exchange).

Dominated by photon exchange.

Introduction

- Ultraperipheral collisions allows the study of photon-induced processes!

$\sigma_{\gamma h}$ photon-hadron/nucleus interactions

$\sigma_{\gamma\gamma}$ photon-photon interactions

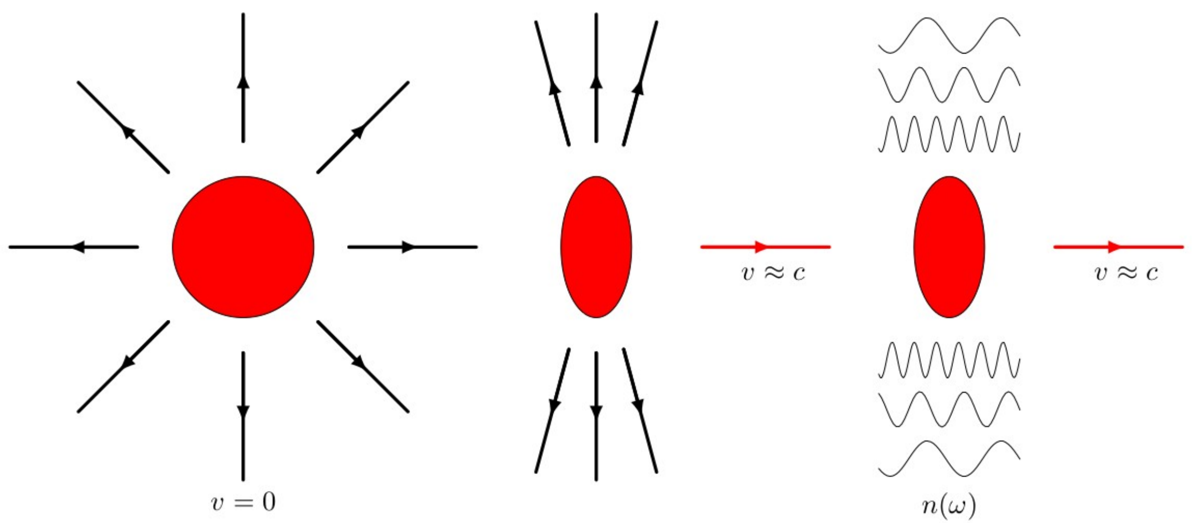
Introduction

- Characteristics of photon-induced processes
  - several processes have high event rates.
  - provide a clean environment for particle detection.
    - Characterized by rapidity gaps.

γh Processes

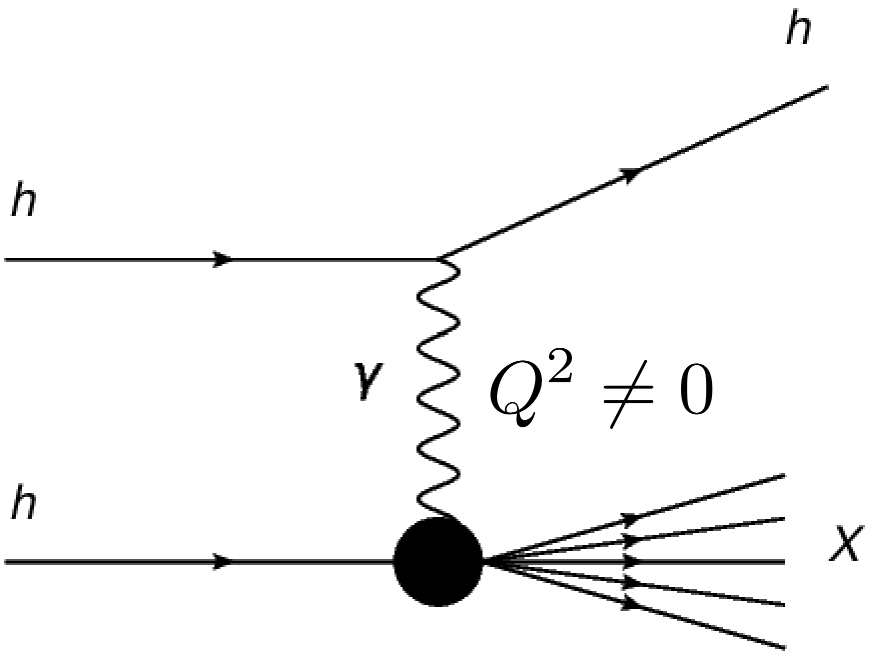
Equivalent Photon Approximation

- Behavior of the electromagnetic field of a fast moving charge.



Equivalent Photon Approximation

$$h + h \to h + X$$



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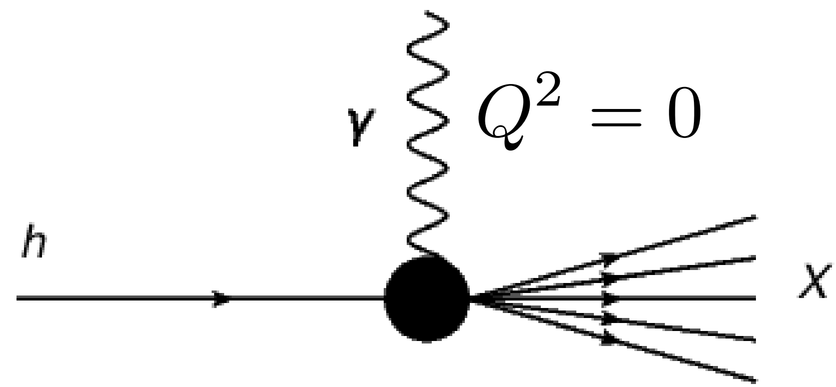

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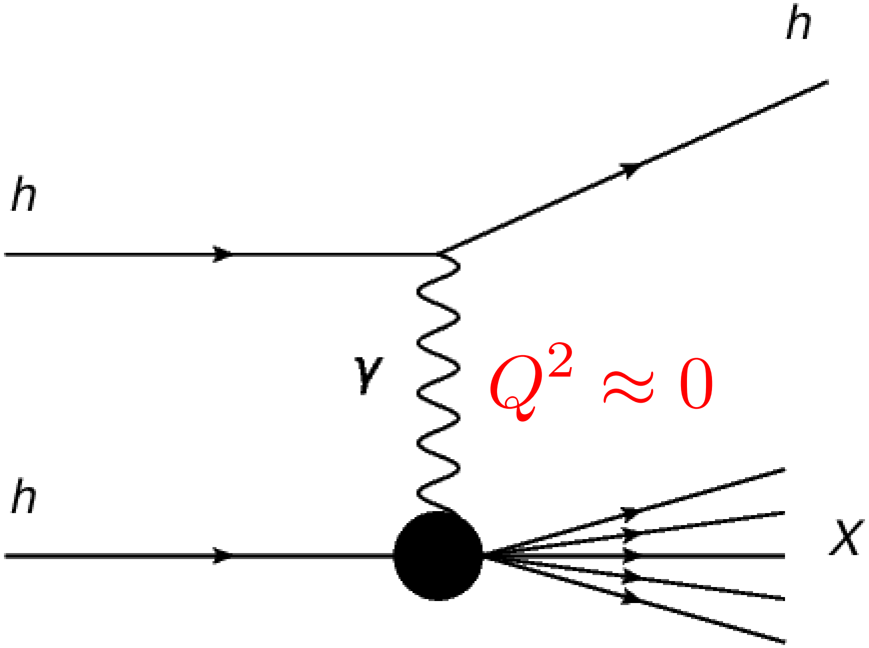

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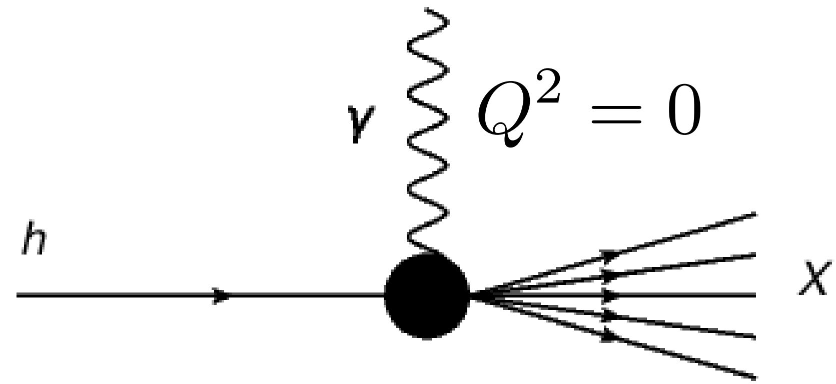

$$\sigma_{hh\to hX}(\sqrt{s}) = \int d\omega \frac{n(\omega)}{\omega} \sigma_{\gamma h \to X}\left(W = \sqrt{2\omega\sqrt{s}}\right)$$

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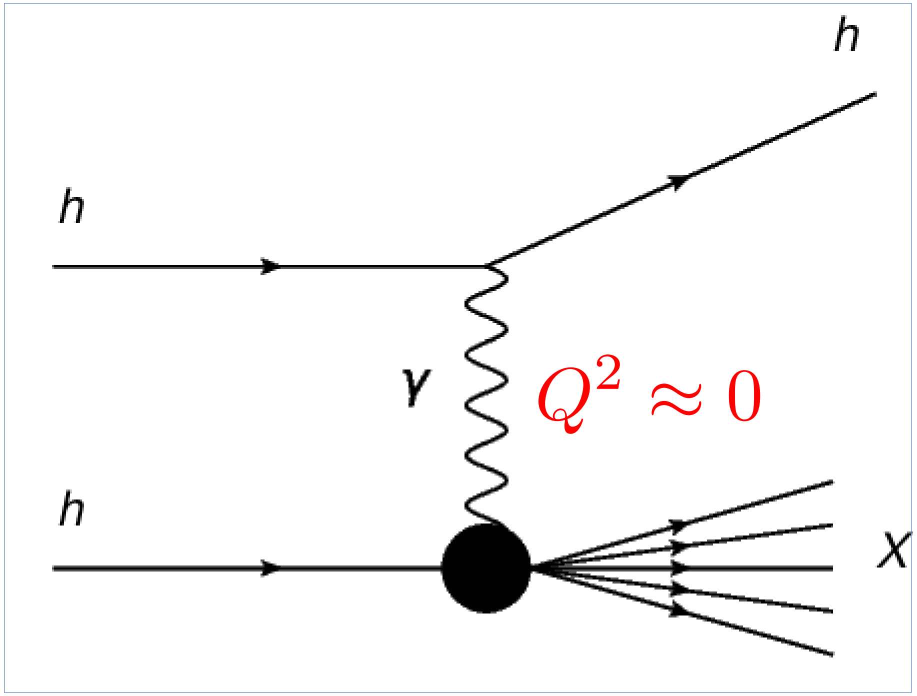

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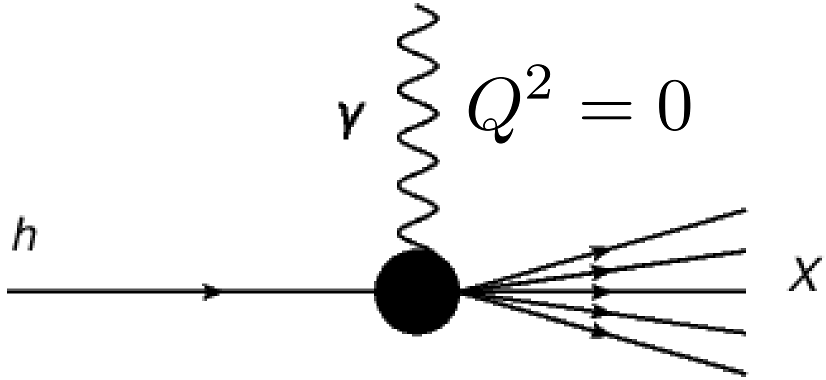

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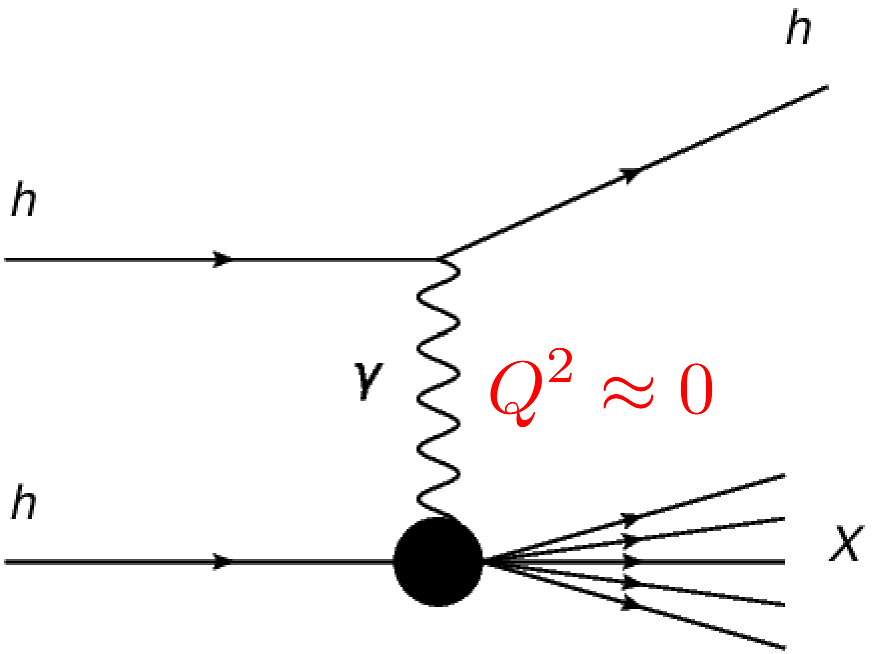

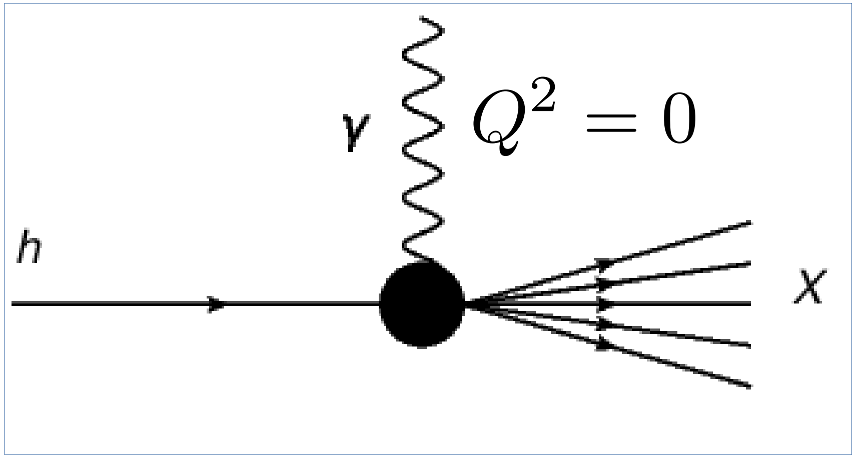

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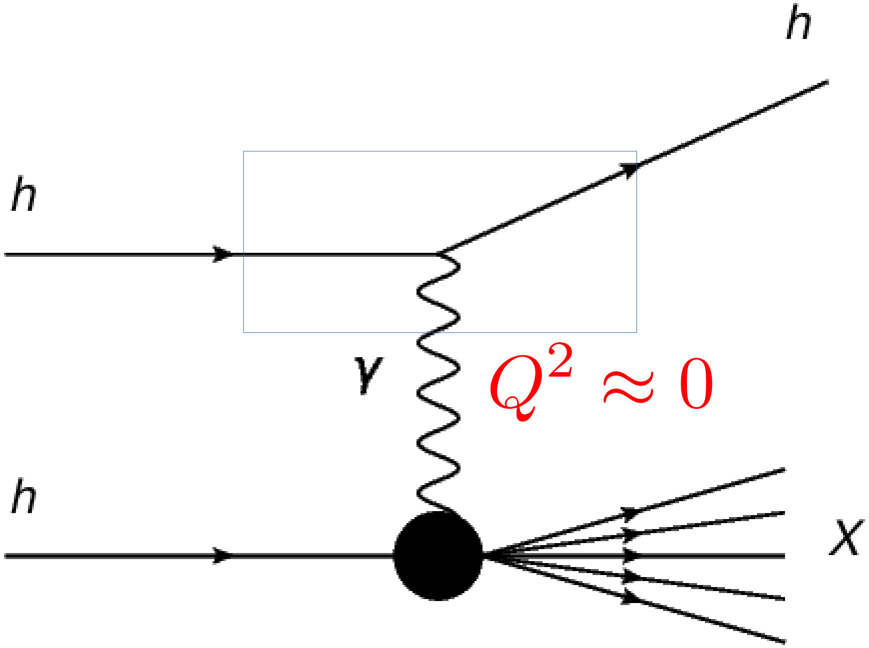

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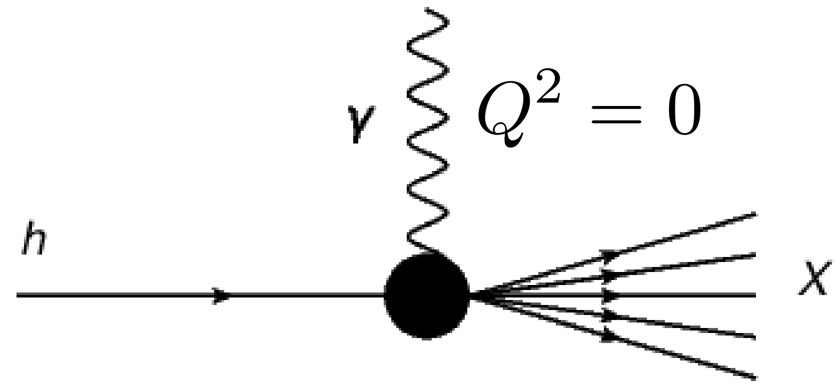

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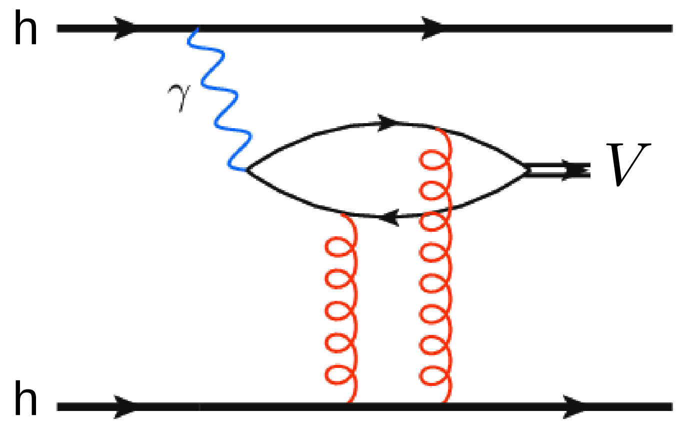
Photoproduction of Vector Mesons

Photoproduction of Vector Mesons

- Photoproduction of vector mesons in hadronic colliders.
  - Study of the QCD dynamics in high energies.



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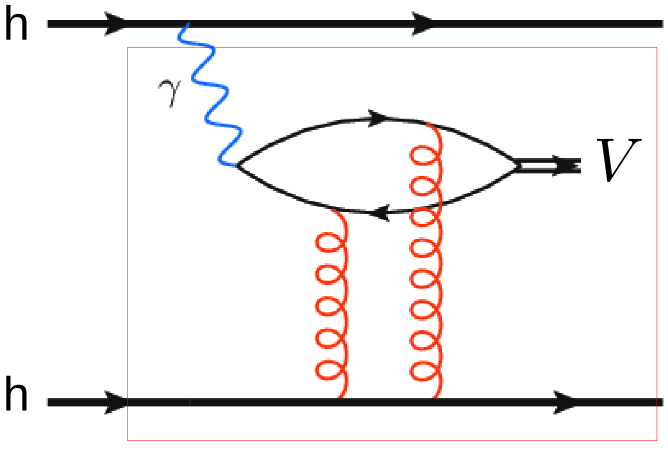
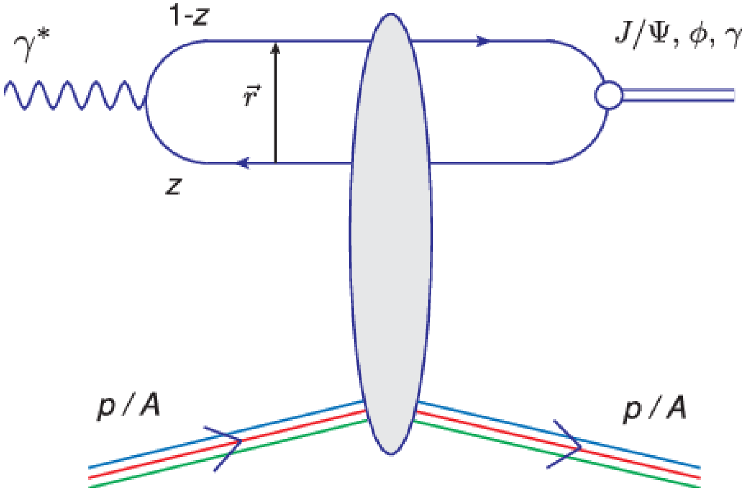


Photoproduction of Vector Mesons

- Color dipole picture

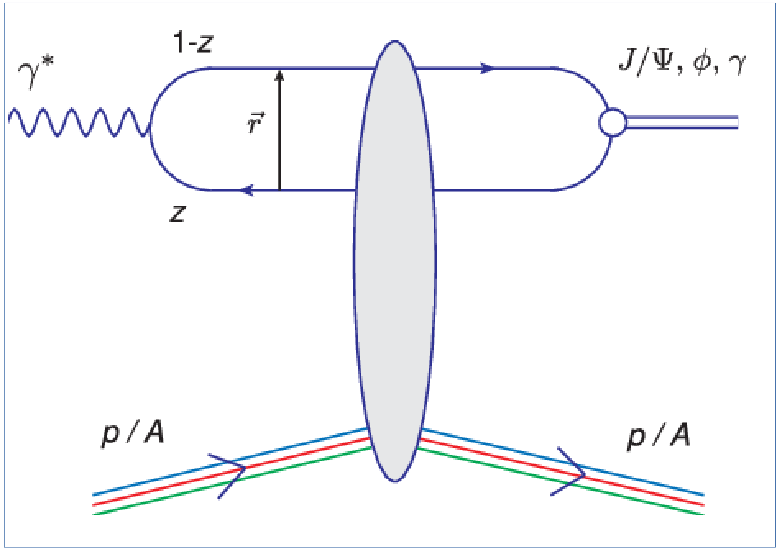


$$\sigma(\gamma h \to Vh) = \frac{1}{16\pi} \int_{-\infty}^{0} \left| \mathcal{A}^{\gamma h \to Vh}(x, \Delta) \right|^2 dt$$

$$\mathcal{A}^{\gamma h \to Vh}(x, \Delta) = i \int dz d^2 r d^2 b \, [\psi_V^*(r, z)\psi_\gamma(r, z)]_T \, e^{-i[\vec{b}-(1-z)\vec{r}]\cdot\vec{\Delta}} \, 2\mathcal{N}(x, r, b)$$

Photoproduction of Vector Mesons

- Color dipole picture



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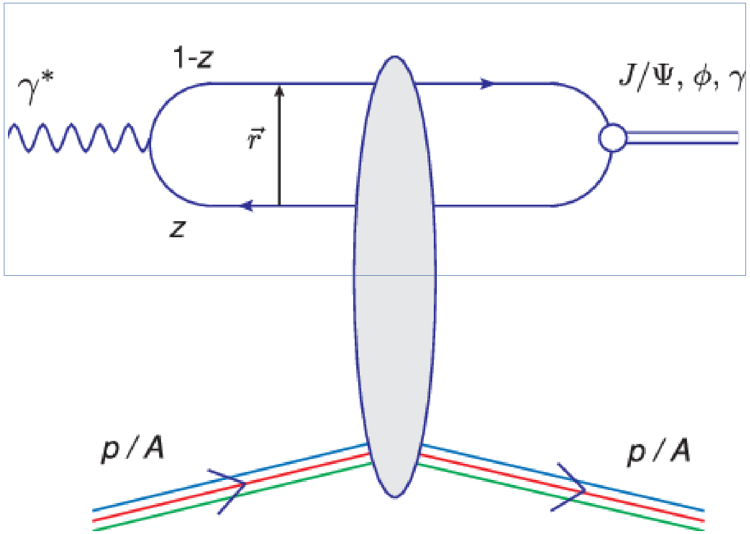

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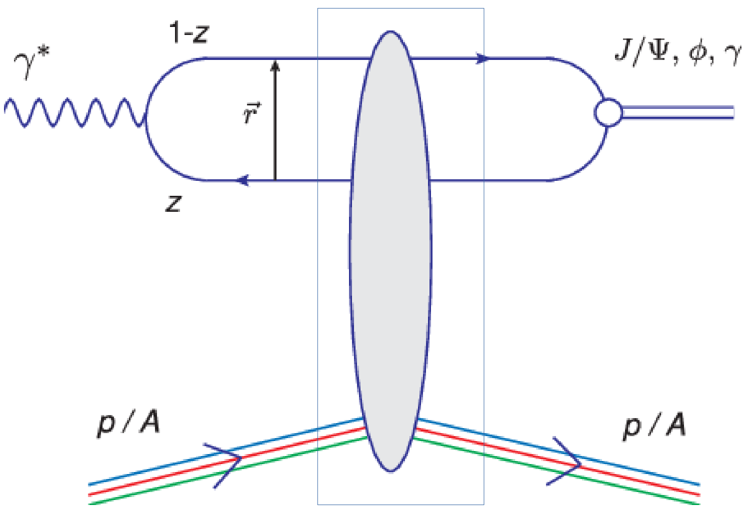

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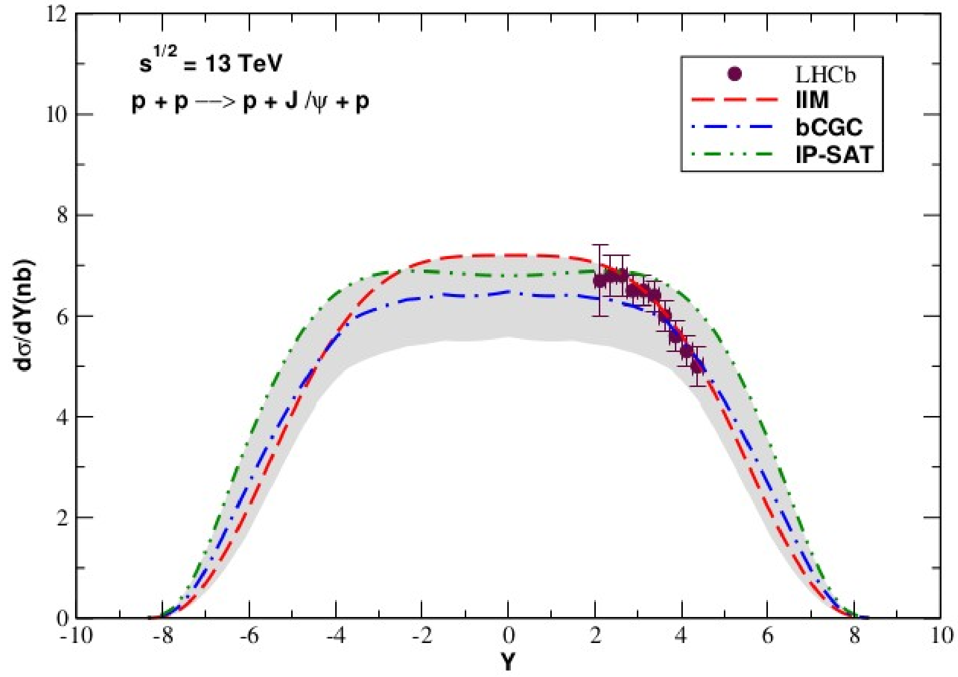
Photoproduction of Vector Mesons

- Results for the J/ψ production in pp collisions.

$$\omega = \frac{M_V}{2} e^y$$

$$\frac{d\sigma_{pp}(\sqrt{s})}{dy} = n(y)\sigma_{\gamma p}(y) + n(-y)\sigma_{\gamma p}(-y)$$

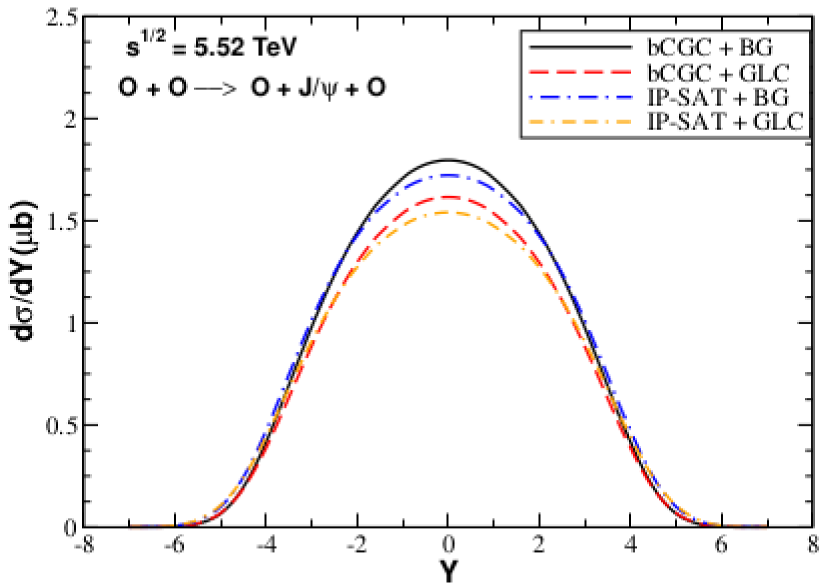


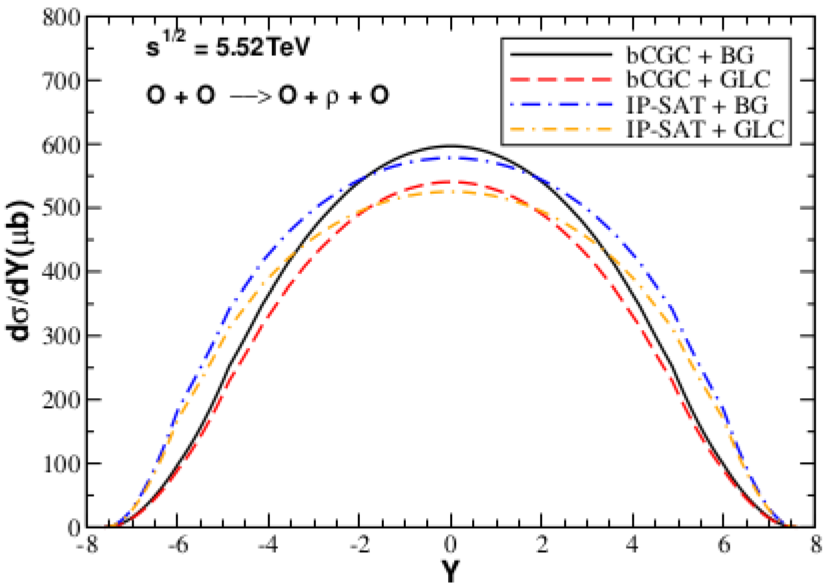
Phys.Rev.D 96 (2017) 9, 094027

V. P. Gonçalves, M. V. T. Machado, B.D.M, F. S. Navarra, G. Sampaio dos Santos

Photoproduction of Vector Mesons

- Results for the J/ψ and ρ production in OO collisions.





Phys.Rev.C 107 (2023) 5, 055205

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Photoproduction of Vector Mesons

- Results for the J/ψ and ρ production in OO collisions.

ALICE ($-2.5 \le Y \le 2.5$)	$\rho(\mu b)$	$J/\psi(\mu b)$
bCGC+BG	2837.62	8.06
bCGC+GLC	2571.39	7.25
IP-SAT+BG	2800.92	7.85
IP-SAT	2545.44	7.01

Cross sections in μb.

Phys.Rev.C 107 (2023) 5, 055205

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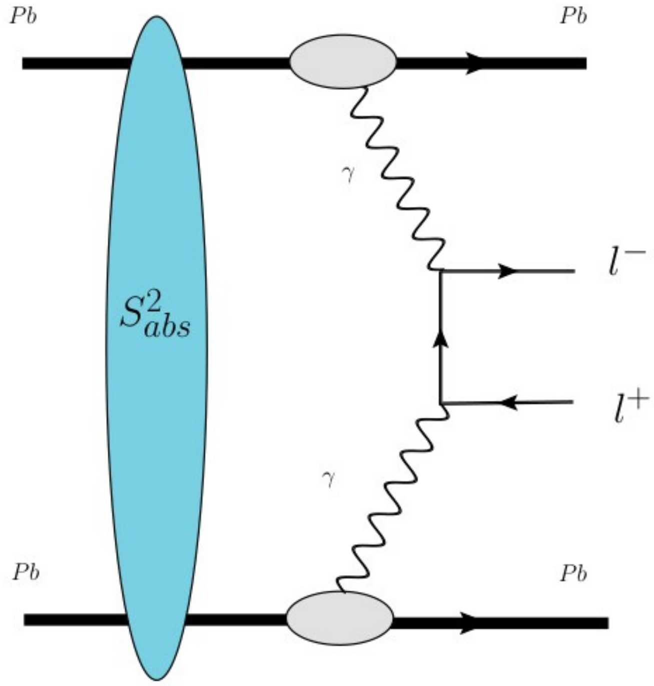
$\gamma\gamma$ Processes

Production of Dileptons

Production of Dileptons

- Process $\gamma\gamma \to l^+ l^-$
  - Interesting process to test the equivalent photon approximation.



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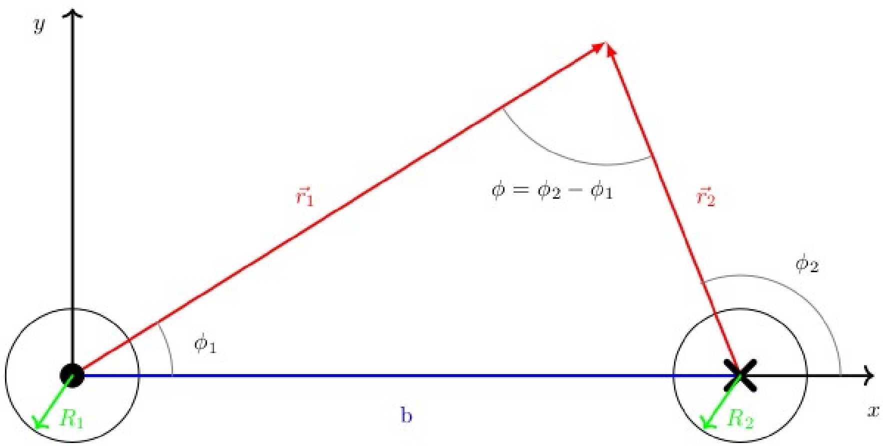
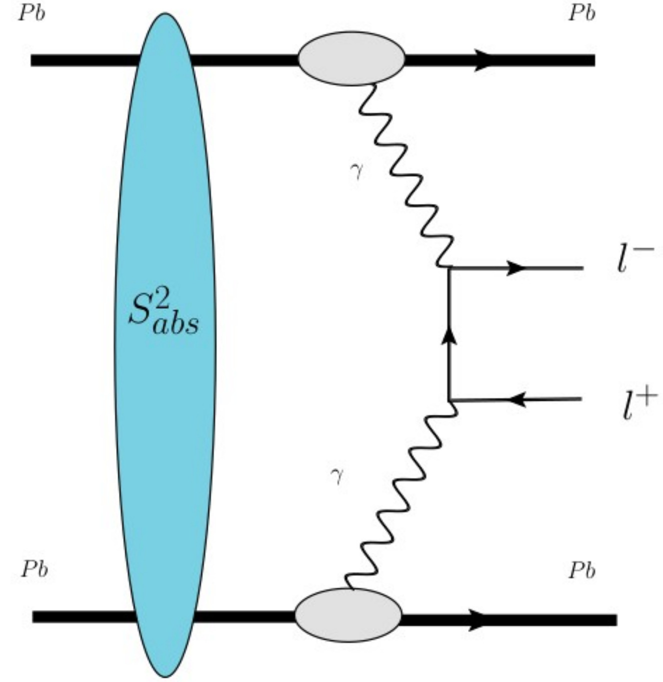
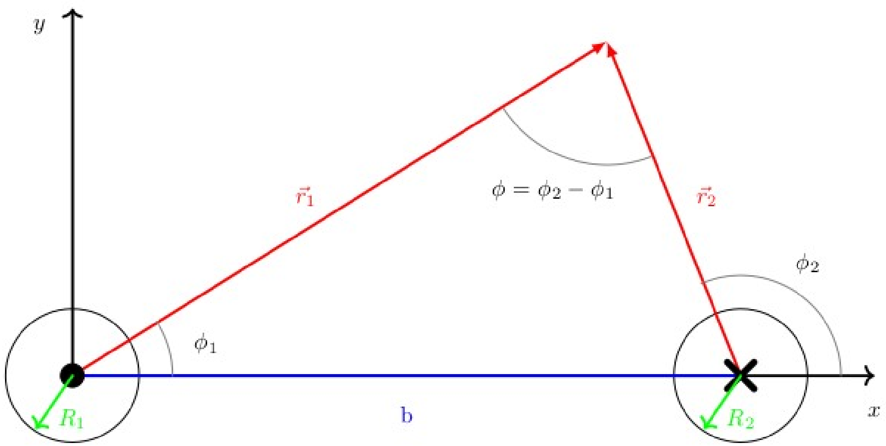


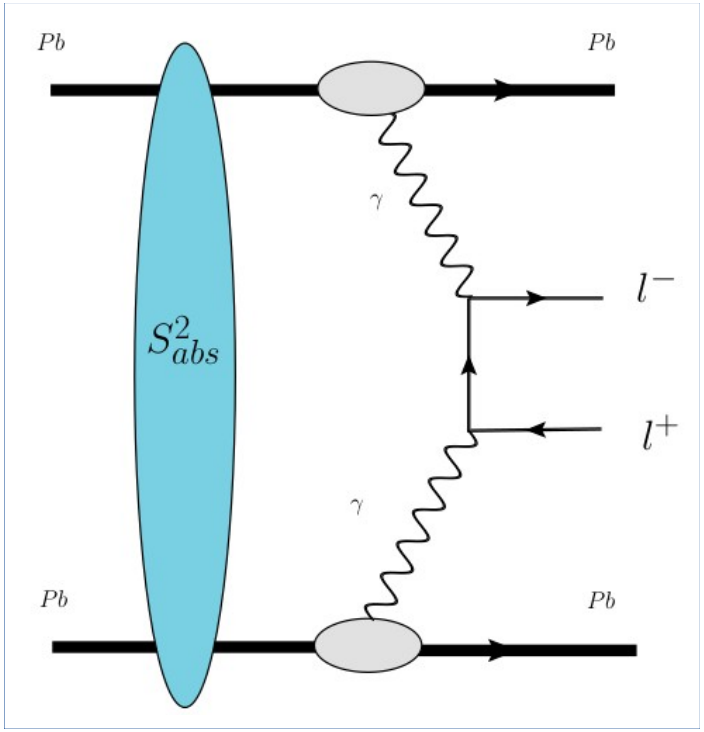


$$\frac{d\sigma_{AA}}{dW}(\sqrt{s}) = \int d^2r_1 d^2r_2 dy \frac{W}{2}\hat{\sigma}_{\gamma\gamma}(W)N(\omega_1, r_1)N(\omega_2, r_2)S^2_{abs}(b)$$

Production of Dileptons

- Process $\gamma\gamma \rightarrow l^+l^-$





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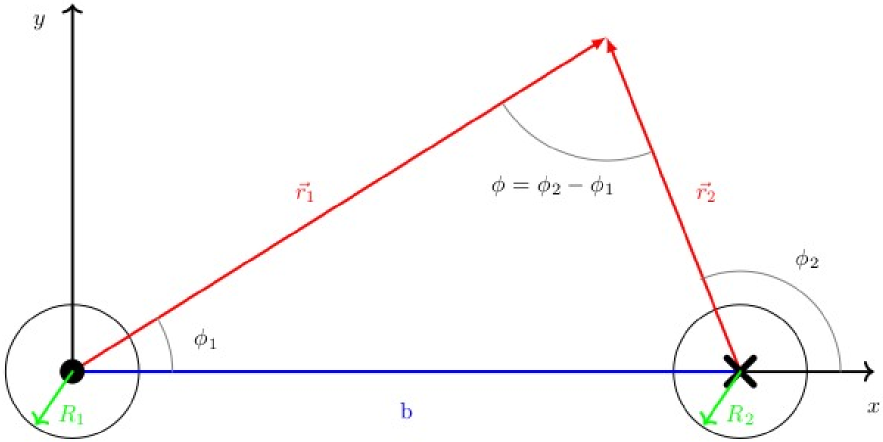

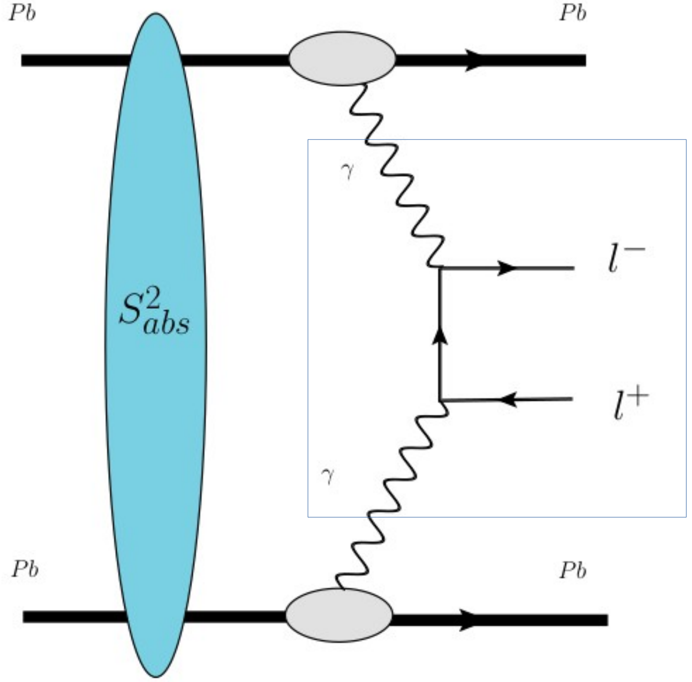

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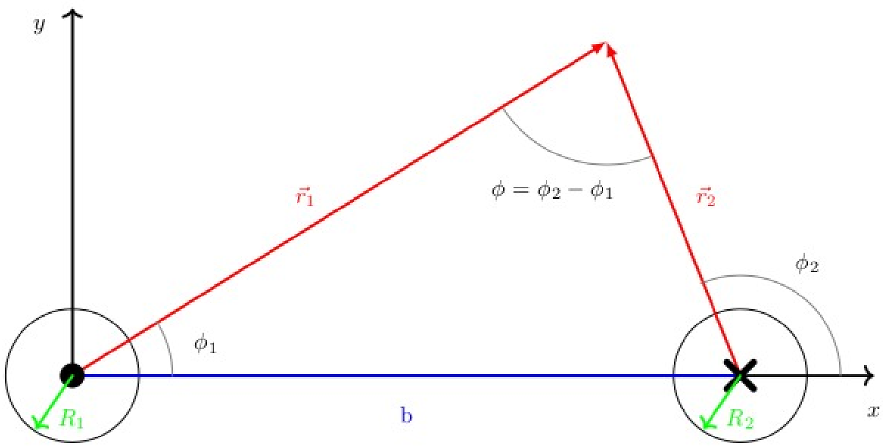

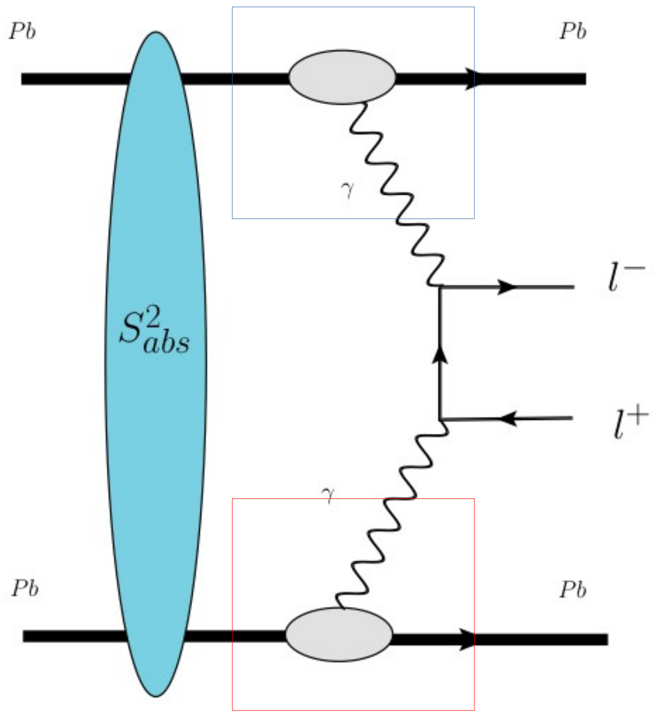

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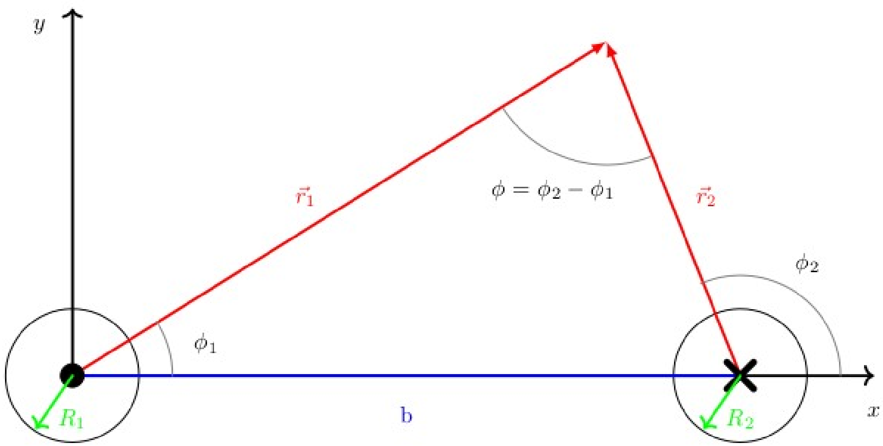
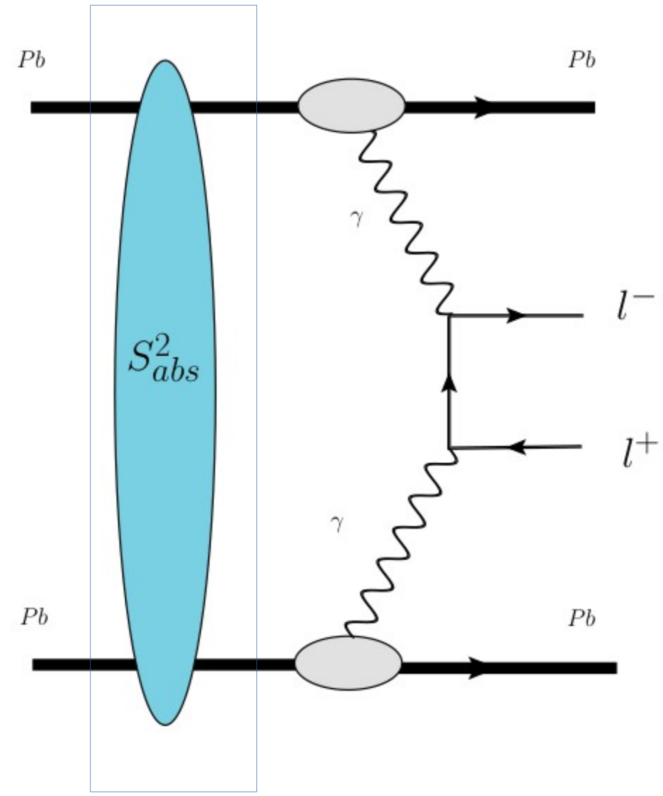
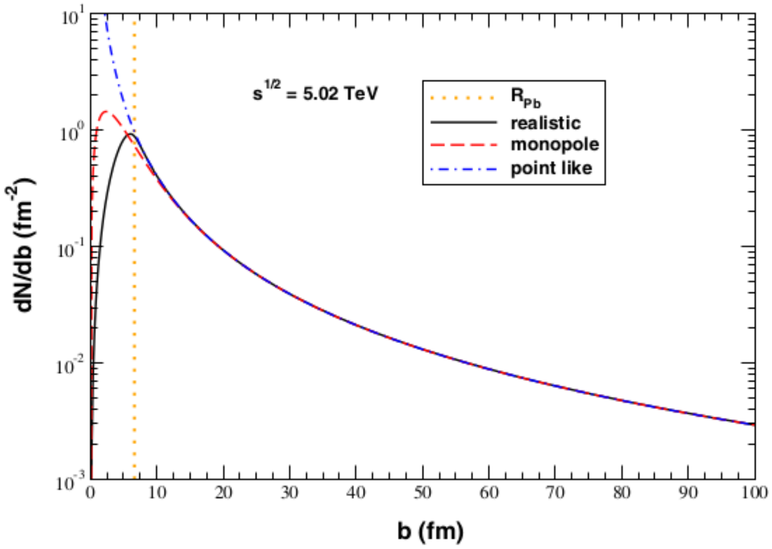




$$\frac{d\sigma_{AA}}{dW}(\sqrt{s}) = \int d^2r_1 d^2r_2 dy \frac{W}{2} \hat{\sigma}_{\gamma\gamma}(W) N(\omega_1, r_1) N(\omega_2, r_2) S^2_{abs}(b)$$

Production of Dileptons

- Results for the invariant mass distribution for electron pairs



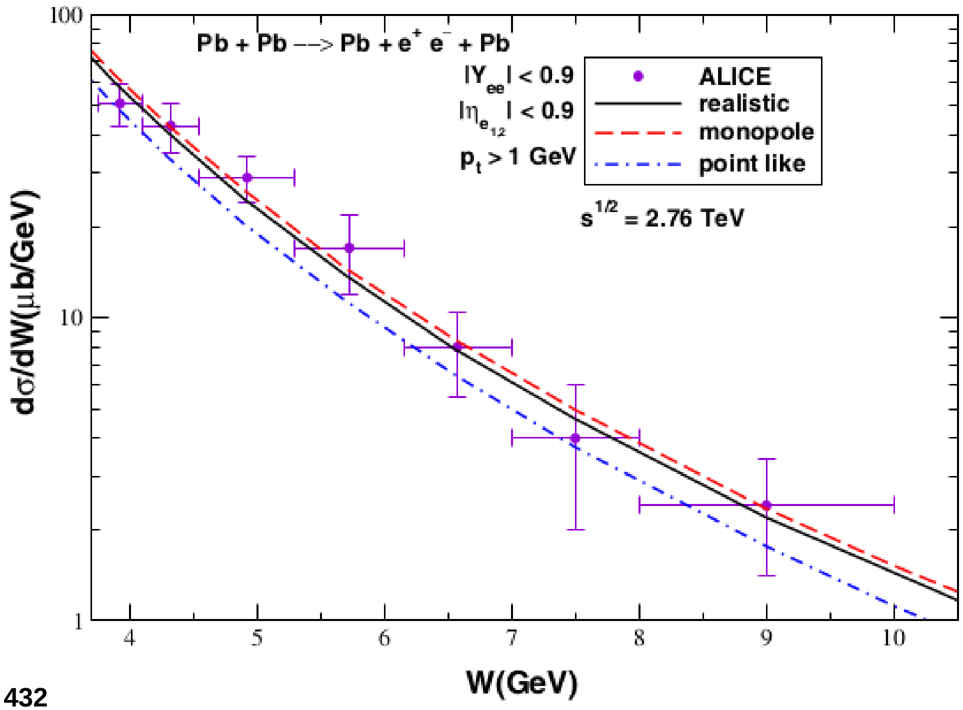
$$N(\omega, r) = \frac{Z^2\alpha}{\pi^2}\frac{1}{r^2\omega}\left[\int du u^2 J_1(u) F\left(\sqrt{\frac{\left(\frac{r\omega}{\gamma}\right)^2 + u^2}{r^2}}\right)\frac{1}{\left(\frac{r\omega}{\gamma}\right)^2 + u^2}\right]^2$$

Eur.Phys.J.C 79 (2019) 5, 432

Celsina Azevedo, Victor P. Gonçalves, B.D.M.

Production of Dileptons

- Results for the invariant mass distribution for electron pairs



Cross sections ~ 100 kb.

Eur.Phys.J.C 79 (2019) 5, 432

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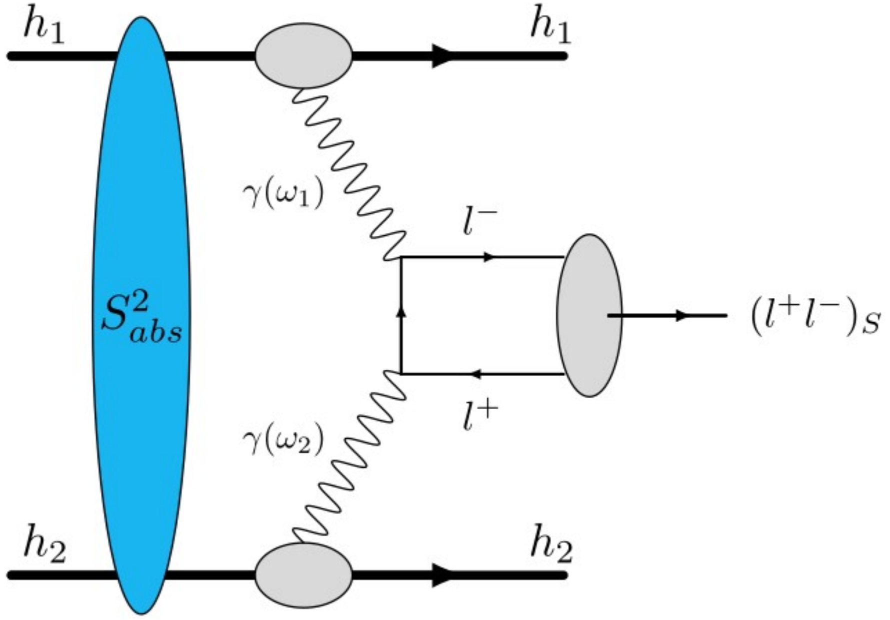
Production of Bound States

Positronium Production

Positronium Production

- Production of positronium
  - Test of QED and search for the new physics.



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

Positronium Production

- Rapidity distribution for positronium production in nuclear collisions.

Eur.Phys.J.A 58 (2022) 2, 35

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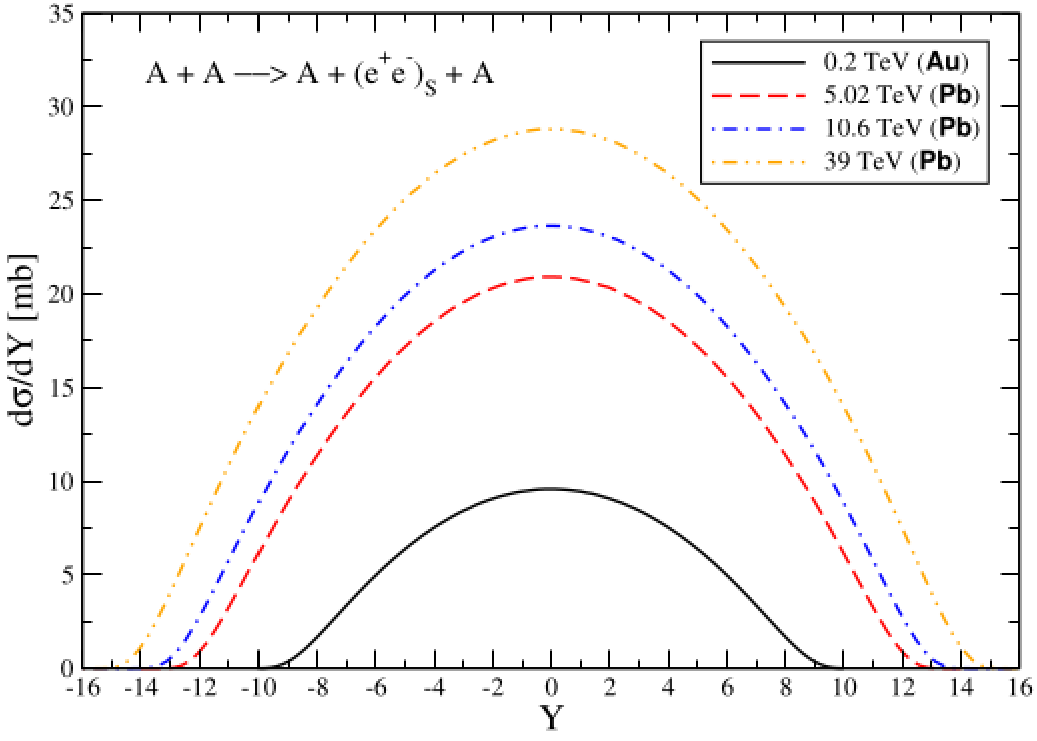
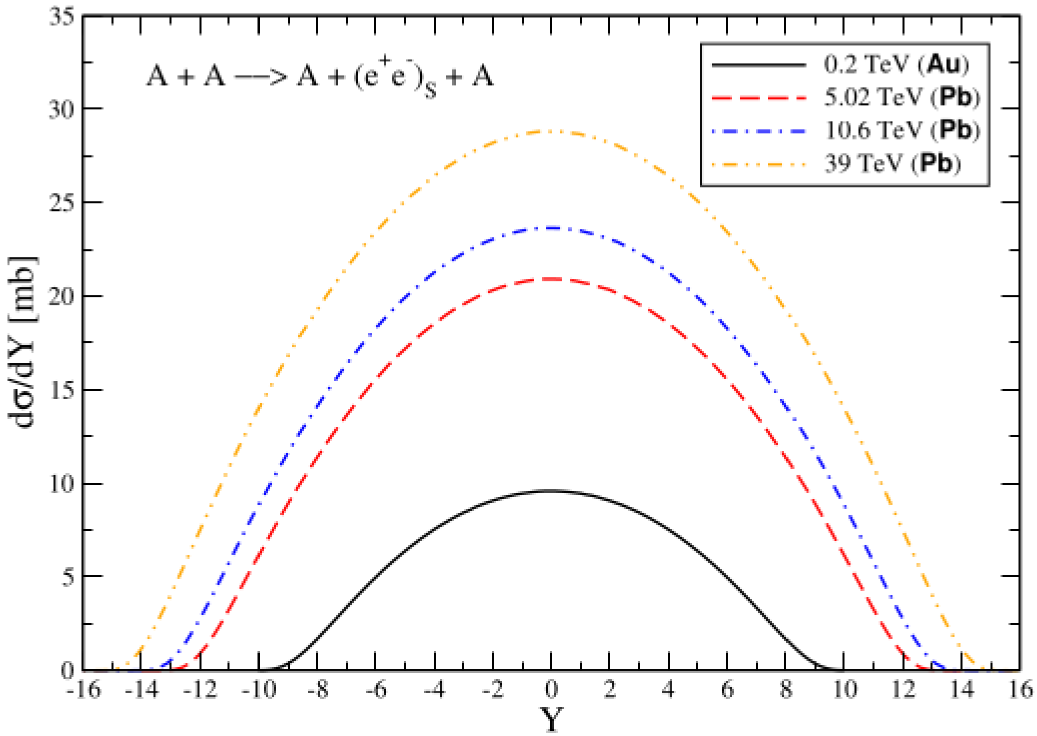


Positronium Production

- Rapidity distribution for positronium production in nuclear collisions.

Cross sections in fb (event rates per year)

	Parapositronium
AuAu ($\sqrt{s_{NN}} = 0.2$ TeV)	112.1×10^{12} (11.2×10^{8})
PbPb ($\sqrt{s_{NN}} = 5.02$ TeV)	333.2×10^{12} (33.3×10^{8})
PbPb ($\sqrt{s_{NN}} = 10.6$ TeV)	400.3×10^{12} (40.0×10^{8})
PbPb ($\sqrt{s_{NN}} = 39.0$ TeV)	537.6×10^{12} (59.1×10^{9})



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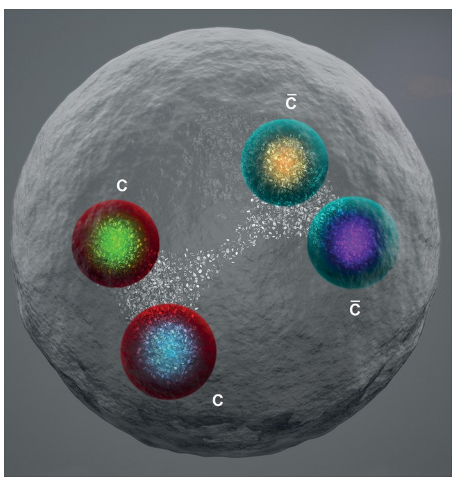
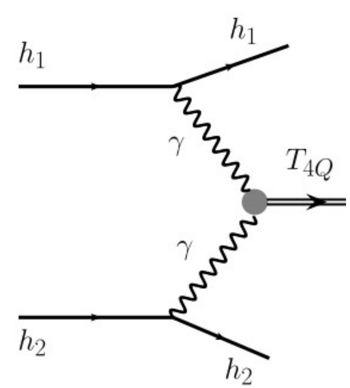
Production of Exotic States

Production of Exotic States

- Exotic states in $\gamma\gamma$ interactions
  - Fully charmed tetraquark production.

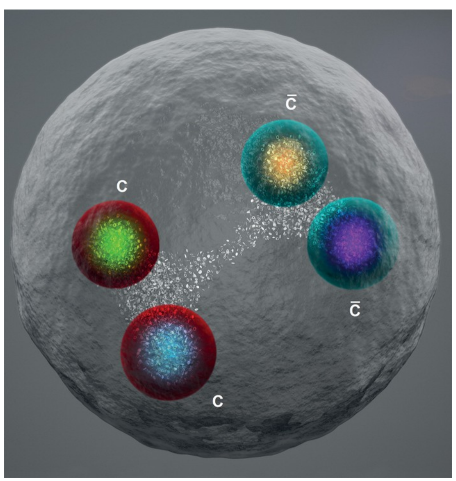


$$\hat{\sigma}(\gamma\gamma \to X) = 8\pi^2(2J+1)\frac{\Gamma_{(X)\to\gamma\gamma}}{M}\delta(W^2 - M^2)$$

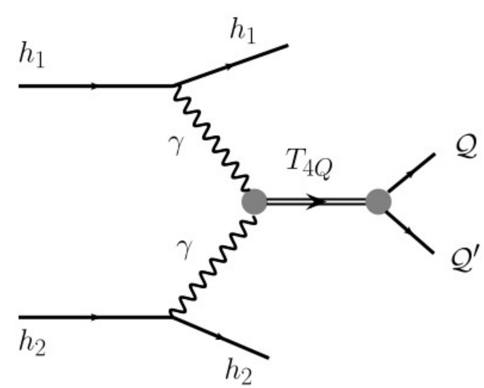


Production of Exotic States

- Exotic states in $\gamma\gamma$ interactions
  - $T_{4C} \rightarrow$ di-J/ψ production.

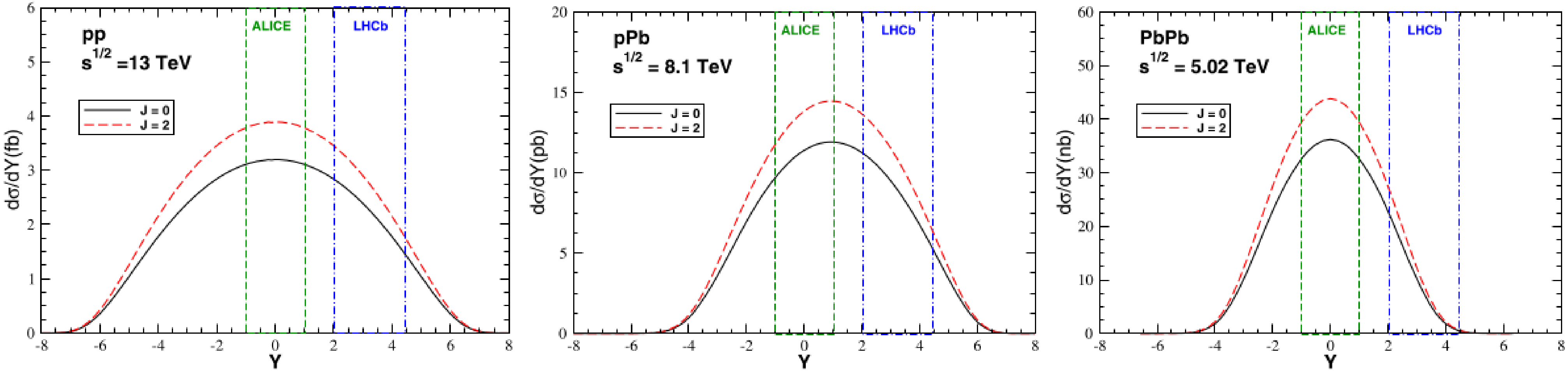


$$\hat{\sigma}(\gamma\gamma \to X) = 8\pi^2(2J+1)\frac{\Gamma_{T_{4Q}\to\gamma\gamma} \times \mathcal{B}(T_{4Q} \to J/\psi J/\psi)}{M}\delta(W^2 - M^2)$$



Production of Exotic States

- T_{4c} production in pp, pPb and PbPb collisions



(a) (b) (c)

Phys.Lett.B 816 (2021) 136249

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Production of Exotic States

- T_{4c} production in pp, pPb and PbPb collisions

Collision	Resonance	LHC Full rapidity range
pp ($\sqrt{s} = 13$ TeV)	$X(6900)$, 0^{++}	26.3 fb
	$X(6900)$, 2^{++}	31.9 fb
pPb ($\sqrt{s} = 8.1$ TeV)	$X(6900)$, 0^{++}	76.3 pb
	$X(6900)$, 2^{++}	92.4 pb
$PbPb$ ($\sqrt{s} = 5.02$ TeV)	$X(6900)$, 0^{++}	171.0 nb
	$X(6900)$, 2^{++}	206.0 nb

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Conclusions

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- Photon-induced interactions provides a way to study different kind of processes.
- The formalism of the equivalent photon approximation is well known and under theoretical control.
- Experimentally, the photon-induced processes are clean and, in several cases, show large cross sections.
- Can be used for the study of the interactions in high energies, the structure of the hadrons, nuclear effects and multiple scattering and for the search of new particles and new physics.

Thank you!!!

Extras

Photon Fluxes

- b independent

$$n_A(\omega) = \frac{2Z^2\alpha_{em}}{\pi}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}(K_1^2(\xi) - K_0^2(\xi))\right], \quad (3)$$

where

$$\xi = \omega(R_{h_1} + R_{h_2})/\gamma_L, \quad (4)$$

$$n_p(\omega) = \frac{\alpha_{em}}{2\pi}\left[1 + \left(1 - \frac{2\omega}{\sqrt{s}}\right)^2\right] \times \left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right), \quad (5)$$

where

$$\Omega = 1 + [(0.71\ \mathrm{GeV}^2)/Q^2_{\min}] \quad (6)$$

and

$$Q^2_{\min} = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{s})] \approx (\omega/\gamma_L)^2. \quad (7)$$

Photon Fluxes

- b dependent

$$N(\omega_i, r_i) = \frac{Z^2\alpha}{\pi^2}\frac{1}{r_i^2 v^2 \omega_i} \cdot \left[\int u^2 J_1(u) F\left(\sqrt{\frac{\left(\frac{r_i\omega_i}{\gamma_L}\right)^2 + u^2}{r_i^2}}\right) \frac{1}{\left(\frac{r_i\omega_i}{\gamma_L}\right)^2 + u^2} \mathrm{d}u\right]^2, \quad (3)$$

point like

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

monopole

$$F(\vec{q}) = \frac{\Lambda^2}{\Lambda^2 + q^2}$$

real

$$\rho(r) = \frac{\rho_0}{1 + \mathrm{e}^{\frac{r-R}{a}}}$$

$$F(\vec{q}) = \int \rho(\vec{r}) \mathrm{e}^{i\,\vec{r}\cdot\vec{q}} d^3\vec{r}.$$

Photon Fluxes

- Absorption factor in $\gamma\gamma$ interactions

$$S^2_{abs}(\mathbf{b}) = \Theta\left(|\mathbf{b}| - 2R\right) = \Theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R\right), \qquad (5)$$

$$S^2_{abs}(\mathbf{b}) = 1 - P_H(\mathbf{b}), \qquad (6)$$

where

$$P_H(\mathbf{b}) = 1 - \exp\left[-\sigma_{nn}\int d^2\mathbf{r}\, T_A(\mathbf{r}) T_A(\mathbf{r}-\mathbf{b})\right]. \qquad (7)$$

with σ_{nn} being the total hadronic interaction cross section and T_A the nuclear thickness function. As in Ref. [18] we will assume that $\sigma_{nn} = 88$ mb at the LHC. In Fig. 2a we

Dipole Formalism

- IIM

$$\mathcal{N}_p(x,r) = \begin{cases} \mathcal{N}_0\left(\frac{rQ_s}{2}\right)^{2[\gamma_s + (1/(\kappa\lambda Y))\ln(2/rQ_s)]}, & rQ_s \leq 2, \\ 1 - e^{-A\ln^2(BrQ_s)}, & rQ_s > 2 \end{cases} \tag{14}$$

where $Y = \ln(1/x)$ and

$$Q_s(x) = \left(\frac{x_0}{x}\right)^{\lambda/2}, \tag{15}$$

Dipole Formalism

- bCGC

$$\mathcal{N}_p(x,r) = \begin{cases} \mathcal{N}_0\left(\frac{rQ_s}{2}\right)^{2[\gamma_s + (1/(\kappa\lambda Y))\ln(2/rQ_s)]}, & rQ_s \le 2, \\ 1 - e^{-A\ln^2(BrQ_s)}, & rQ_s > 2 \end{cases} \tag{14}$$

where $Y = \ln(1/x)$ and

$$Q_s \equiv Q_s(x,b) = \left(\frac{x_0}{x}\right)^{\lambda/2}\left[\exp\left(-\frac{b^2}{2B_{CGC}}\right)\right]^{1/(2\gamma_s)}. \tag{18}$$

Dipole Formalism

- IP-SAT

$$\mathcal{N}_p(x,\boldsymbol{r},\boldsymbol{b}) = 1 - \exp\left[\frac{\pi^2 r^2}{N_c}\alpha_s(\mu^2)xg\left(x, \frac{4}{r^2} + \mu_0^2\right)T_G(b)\right], \tag{19}$$

with a Gaussian profile

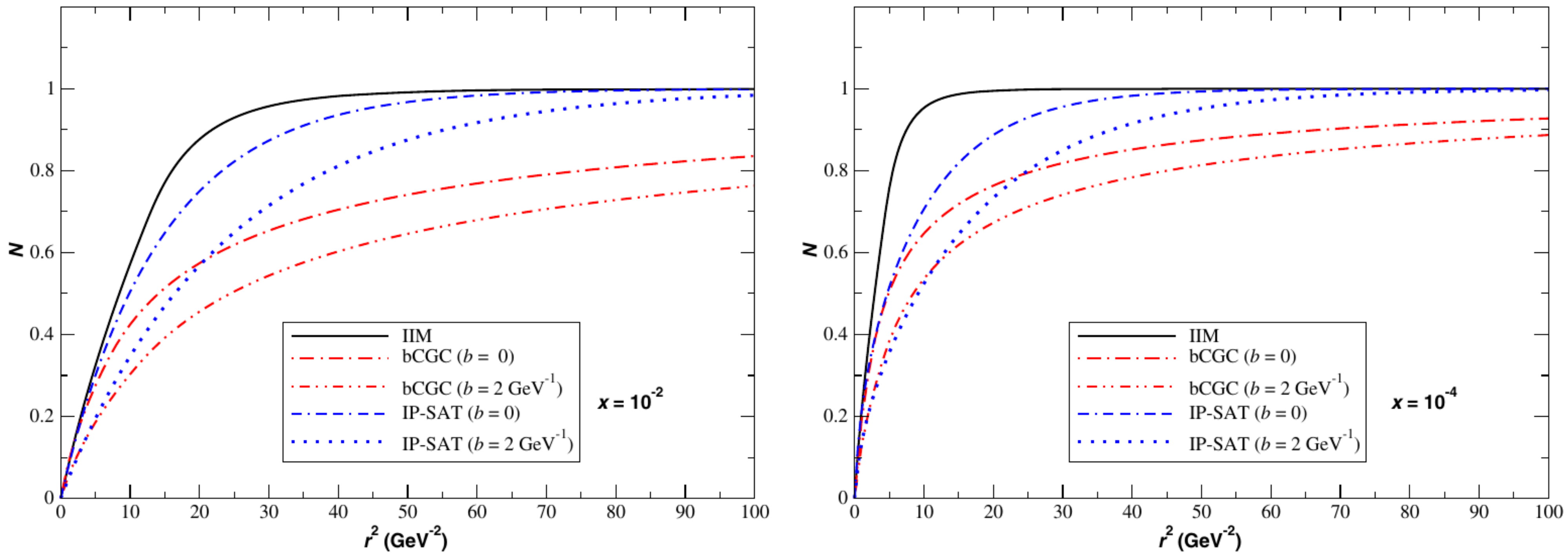
$$T_G(b) = \frac{1}{2\pi B_G}\exp\left(-\frac{b^2}{2B_G}\right). \tag{20}$$

The initial gluon distribution evaluated at μ_0^2 is taken to be

$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{5.6}. \tag{21}$$

Dipole Formalism

- Dipole-proton amplitude



Dipole Formalism

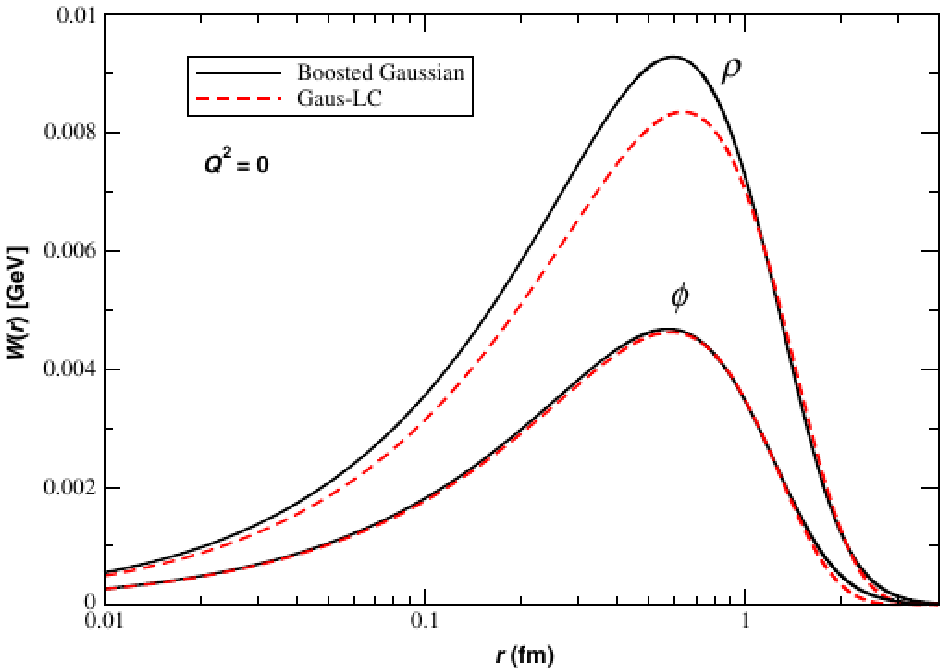
- Vector mesons wave function

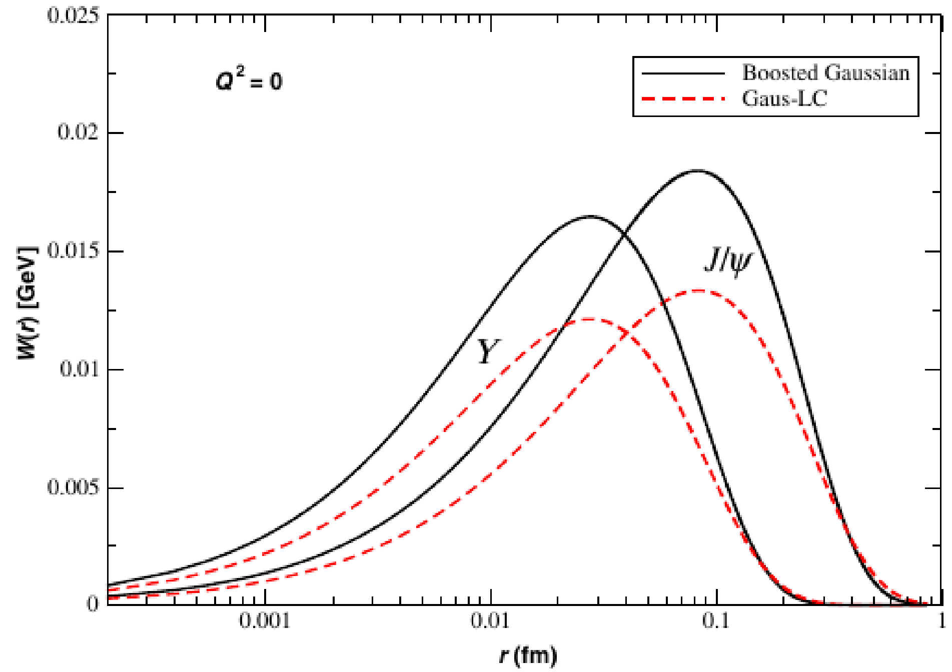
$$(\Psi_V^*\Psi)_T = \hat{e}_f e \frac{N_c}{\pi z(1-z)} \{m_f^2 K_0(\epsilon r)\phi_T(r,z) - [z^2 + (1-z)^2]\epsilon K_1(\epsilon r)\partial_r \phi_T(r,z)\}, \quad (10)$$

Gaus LC	Boosted Gaussian
$\phi_T(r,z) = N_T[z(1-z)]^2 \exp\left(-\frac{r^2}{2R_T^2}\right)$	$\phi_T(r,z) = N_T z(1-z) \times \exp\left(-\frac{m_f R^2}{8z(1-z)} - \frac{2z(1-z)r^2}{R^2} + \frac{m_f^2 R^2}{2}\right)$

Dipole Formalism

- Vector mesons wave function





T_{4C} Production

- Properties

$$\Gamma_{T_{4c(0)}} \approx \Gamma_{\chi_{c_0}} = 10.8 MeV$$

$$B_{T_{4c(0)}\to\gamma\gamma} \approx B_{\chi_{c_0}\to\gamma\gamma} = 2.04 \times 10^{-4}$$

$$\Gamma_{T_{4c(2)}} \approx \Gamma_{\chi_{c_2}} = 1.97 MeV$$

$$B_{T_{4c(2)}\to\gamma\gamma} \approx B_{\chi_{c_2}\to\gamma\gamma} = 2.85 \times 10^{-4}$$

T_{4C} Production

- Properties

$$B(T_{4c} \to J/\psi J/\psi) \approx 2\%$$