MESON2016

PHOTOPRODUCTION OF VECTOR MESONS: FROM ULTRAPERIPHERAL TO SEMI-CENTRAL HEAVY ION COLLISIONS

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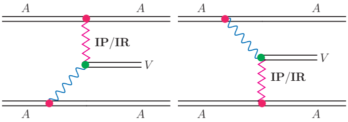
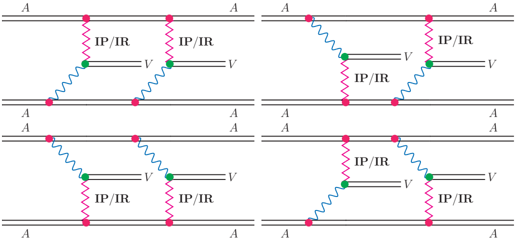
THEORETICAL PREDICTIONS

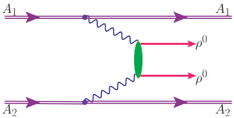
- Single ρ^0 & J/ψ production



- Double-scattering mechanism



- $\gamma\gamma$ fusion



$$\mathrm{Br}\left(\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-\right) \simeq 100\%$$

- Ultraperipheral $\to$ Peripheral $\to$ Semi-central

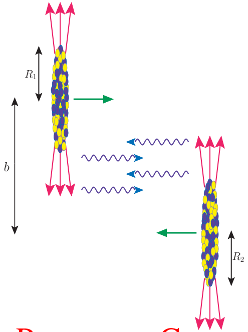
THEORETICAL PREDICTIONS

- RHIC ($\sqrt{s_{AuAu}} = 130, 200$ GeV) & LHC ($\sqrt{s_{PbPb}} = 2.76, 3.5, 5.5$ TeV)

REFERENCES

1. M. K-G and A. Szczurek,
   Double-scattering mechanism in the exclusive $AA \to AA\rho^0\rho^0$ reaction in ultrarelativistic collisions,
   Phys. Rev. **C89** (2014) 024912
2. M. K-G and A. Szczurek,
   Photoproduction of J/ψ mesons in peripheral and semicentral heavy ion collisions,
   Phys. Rev. **C93** (2016) 044912

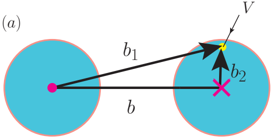
EQUIVALENT PHOTON APPROXIMATION



The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.

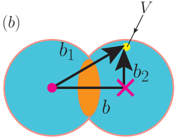
ULTRAPERIPHERAL COLLISIONS

$$b > R_{min} = R_1 + R_2$$

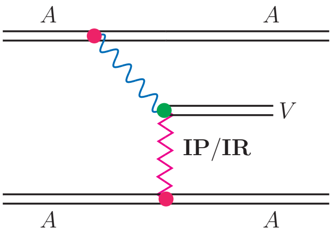


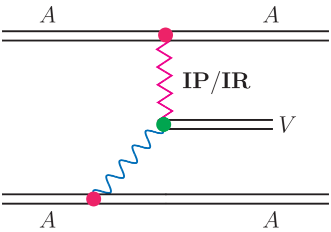
SEMI-CENTRAL COLLISIONS

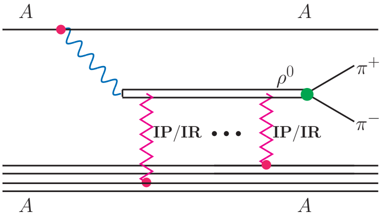
$$b \leq R_{min}$$

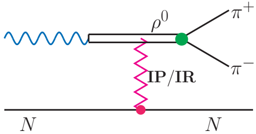


PHOTOPRODUCTION OF VECTOR MESON





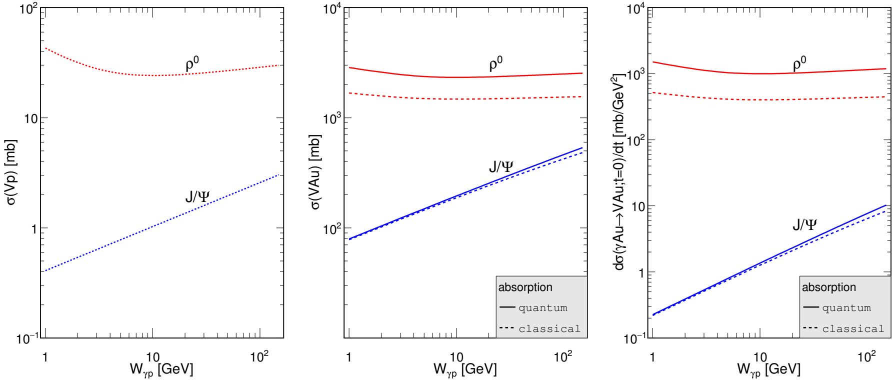




Parameters fixed to describe HERA data

we expect: $\frac{d\sigma(\gamma n \to Vn)}{dt} \approx \frac{d\sigma(\gamma p \to Vp)}{dt}$

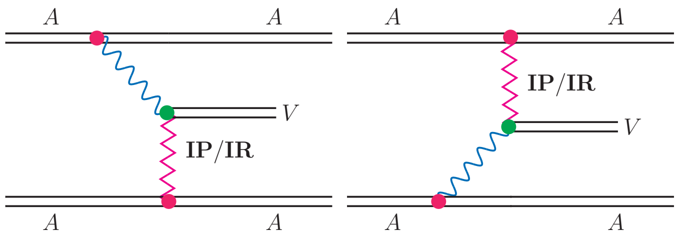
$\frac{d\sigma_{\gamma p \to Vp}(t=0)}{dt}$ $\leftarrow$ HERA data



- $\sigma^{CM}_{tot}(VA) = \int d^2\mathbf{r}\,\left(1 - \exp\left(-\sigma_{tot}(Vp)\,T_A(\mathbf{r})\right)\right)$
- $\sigma^{QM}_{tot}(VA) = 2\int d^2\mathbf{r}\,\left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(Vp)\,T_A(\mathbf{r})\right)\right)$

$$\sigma_{\gamma A \to VA}(W_{\gamma A_{2/1}}) = \frac{d\sigma_{\gamma A \to VA}(t=0)}{dt} \int_{-\infty}^{t_{max}} dt \left| \boxed{F_A(t)} \right|^2$$

SINGLE VECTOR MESON PRODUCTION

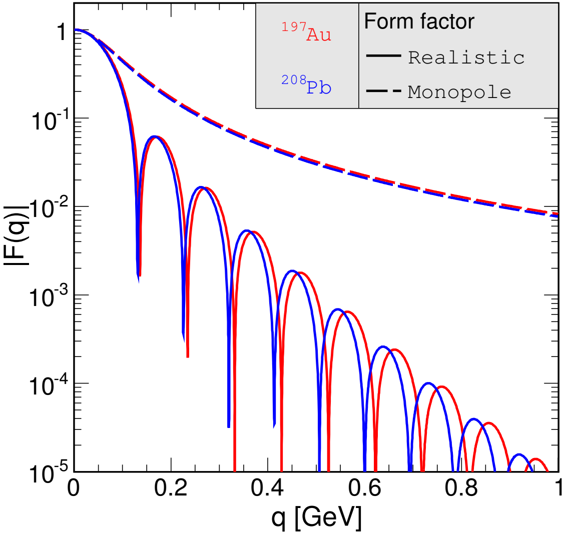


$$\frac{d\sigma_{A_1A_2\to A_1A_2V}}{d^2b\,dy} = \frac{dP_{\gamma\mathbf{P}}(b,y)}{dy} + \frac{dP_{\mathbf{P}\gamma}(b,y)}{dy} \qquad (1)$$

$$\frac{dP_{1/2}(b,y)}{dy} = \omega_{1/2} N(\omega_{1/2}, b)\,\sigma_{\gamma A_{2/1}\to VA_{2/1}}(W_{\gamma A_{2/1}}) \qquad (2)$$

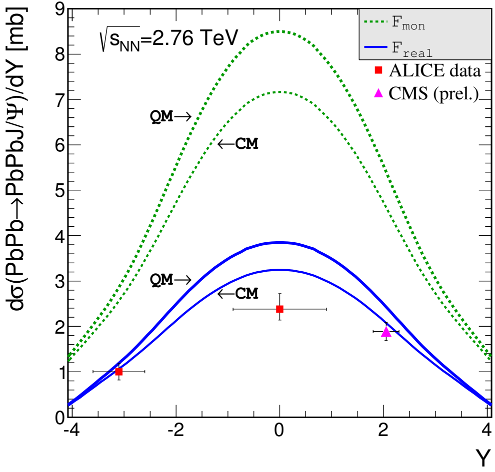
- point-like $F(q) = 1$
- realistic $F(q) = \frac{4\pi}{q}\int \rho(r)\sin(qr)\,r\,dr$
- monopole $F(q) = \frac{\Lambda^2}{\Lambda^2+q^2}$ $\quad \Lambda = \sqrt{\frac{6}{<r^2>}}$

FORM FACTOR



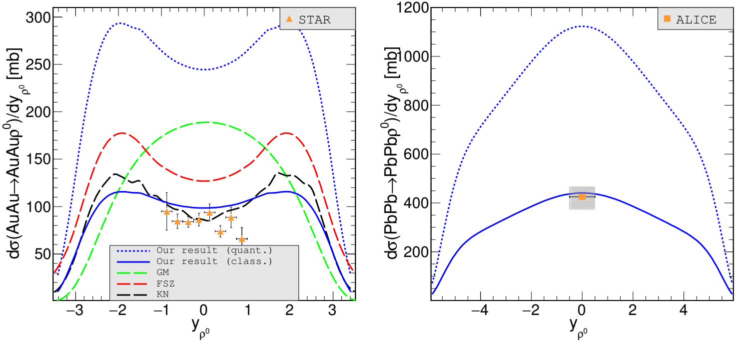
^{197}Au
^{208}Pb
Form factor
Realistic
Monopole
|F(q)|
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.2
0.4
0.6
0.8
1
q [GeV]

J/ψ MESON PRODUCTION (UPC)



REALISTIC FORM FACTOR AND CLASSICAL MECHANICS APPROACH TO THE $\sigma_{tot}(J/\psi A)$

ρ^0 MESON PRODUCTION (UPC)

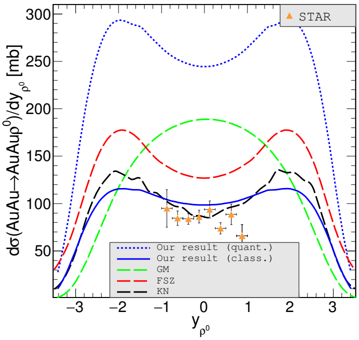


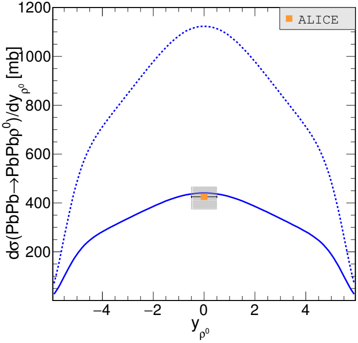
LEGEND
GM - V.P. Gonçalves and M.V.T. Machado, Eur. Phys. J. **C40** (2005) 519,
FSZ - L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. **B537** (2002) 51,
KN - S. Klein and J. Nystrand, Phys. Rev. **C60** (1999) 014903

CLASSICAL MECHANICS APPROACH TO THE $\sigma_{tot}(\rho^0 A)$

- $\gamma \mathbf{P} \to \rho^0$
- $\mathrm{Br}(\rho^0 \to \pi^+\pi^-) \approx 100\%$
- $\gamma\gamma \to \pi^+\pi^-$
- $AA \to AA\pi^+\pi^-$

ρ^0 MESON PRODUCTION (UPC)





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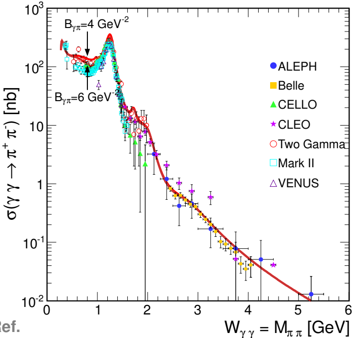
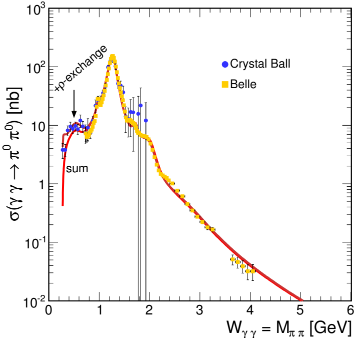
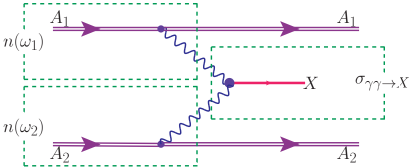
- $AA \to AA\pi^+\pi^-$

$\pi\pi$ PRODUCTION - $\gamma\gamma$ FUSION





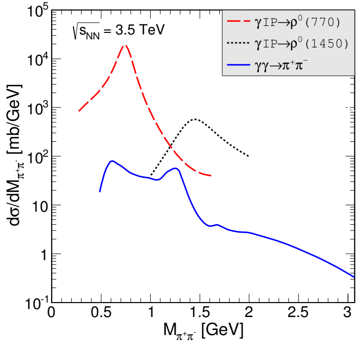
Ref.
M. Kłusek and A. Szczurek, Phys. Rev. **C87** (2013) 054908,
"$\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy ion collisions"

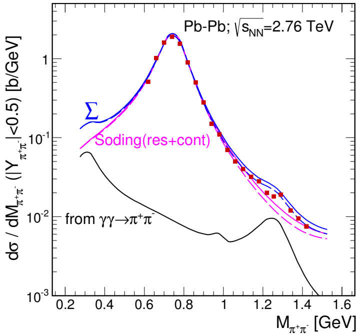


NUCLEAR CROSS SECTION

$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b)$$

ρ^0 PRODUCTION VS. TWO-PION PRODUCTION





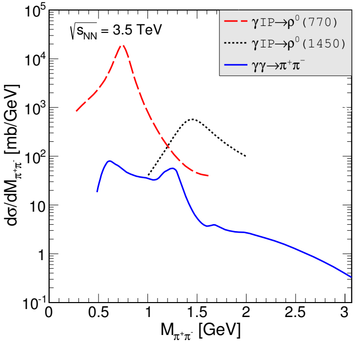
$\gamma\gamma$ FUSION IS NOT NEGLIGIBLE

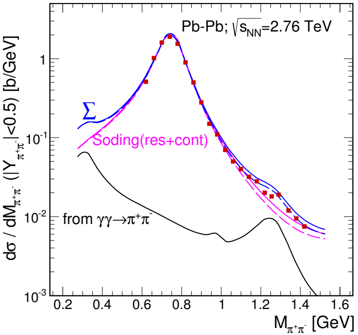
Drell-Söding+$f_2(1270)$

colored solid lines - $\Gamma_{\rho^0} = 150.2$ MeV
colored dashed lines - $\Gamma_{\rho^0} = 140$ MeV

ALICE data, JHEP 1509 (2015) 095

ρ^0 PRODUCTION VS. TWO-PION PRODUCTION





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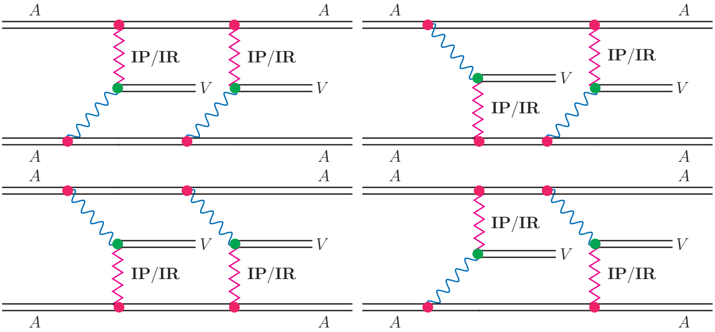
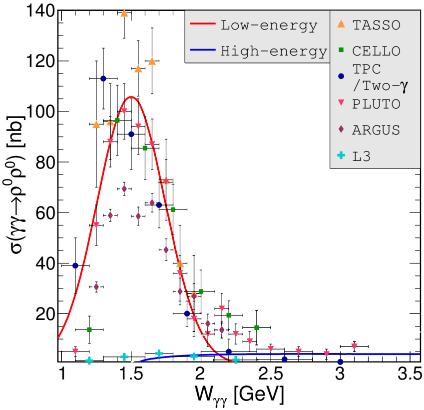
DOUBLE-SCATTERING MECHANISM



$$\frac{d\sigma_{A_1A_2\to A_1A_2\rho^0\rho^0}}{dy_1 dy_2} = \frac{1}{2}\int \left(\frac{dP_{\gamma \mathbf{P}}(b,y_1)}{dy_1} + \frac{dP_{\mathbf{P}\gamma}(b,y_1)}{dy_1} \right) \times \left(\frac{dP_{\gamma \mathbf{P}}(b,y_2)}{dy_2} + \frac{dP_{\mathbf{P}\gamma}(b,y_2)}{dy_2} \right) d^2b$$

(ρ^0's have negligibly small transverse momenta)

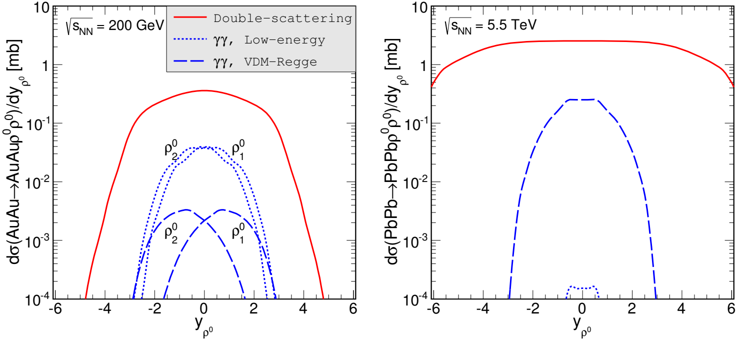
$\rho^0\rho^0$ PRODUCTION - $\gamma\gamma$ FUSION



Ref.
M. Kłusek, W. Schäfer and A. Szczurek, Phys.Lett. **B674** (2009) 92,
"Exclusive production of $\rho^0\rho^0$ pairs in $\gamma\gamma$ collisions at RHIC"
+ back-up slide

LOW-ENERGY AND VDM-REGGE COMPONENT

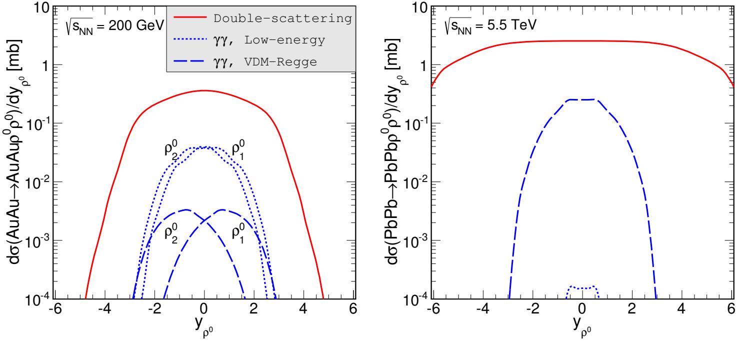
DOUBLE-SCATTERING MECHANISM VS. $\gamma\gamma$ FUSION



A DOMINANCE OF THE DS COMPONENT OVER THE $\gamma\gamma$ FUSION

- $Br(\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-) \simeq 100\%$
- A smearing of the ρ^0 mass

DOUBLE-SCATTERING MECHANISM VS. $\gamma\gamma$ FUSION



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- $\mathrm{Br}\left(\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-\right) \simeq 100\%$
- A smearing of the ρ^0 mass

SMEARING OF ρ^0 MASS

Drell-Söding contribution:

$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}} \frac{\sqrt{m m_{\rho^0} \Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0} \Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi}$$

$$\Gamma_{\rho^0}(m) = \Gamma_{\rho^0} \frac{m_{\rho^0}}{m} \left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2}$$

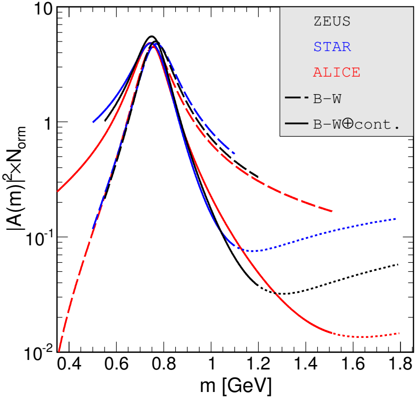
Parameter	ZEUS	STAR	ALICE
m_{ρ^0} [GeV]	0.77 ± 0.002	0.775 ± 0.003	0.761 ± 0.0023
Γ_{ρ^0} [GeV]	0.146 ± 0.003	0.162 ± 0.007	0.1502 ± 5.5
$\left\lvert \frac{\mathcal{B}_{\pi\pi}}{\mathcal{A}_{\mathcal{BW}}} \right\rvert$ [GeV$^{-1/2}$]	0.669	0.89 ± 0.08	0.5 ± 0.04
m [GeV]	$(0.55 - 1.2)$	$(0.5 - 1.1)$	$(0.28 - 1.512)$

SMEARING OF ρ^0 MASS

Drell-Söding contribution:

$\mathcal{A}$ ... $+ \mathcal{B}_{\pi\pi}$

3/2



Paramete...	...	ALICE
m_{ρ^0} [GeV...	...3	0.761 ± 0.0023
Γ_{ρ^0} [GeV...	...7	0.1502 ± 5.5
$\left\lvert \frac{\mathcal{B}_{\pi\pi}}{\mathcal{A}_{\mathcal{BW}}} \right\rvert$ [G...		0.5 ± 0.04
m [GeV]	....1)	$(0.28 - 1.512)$

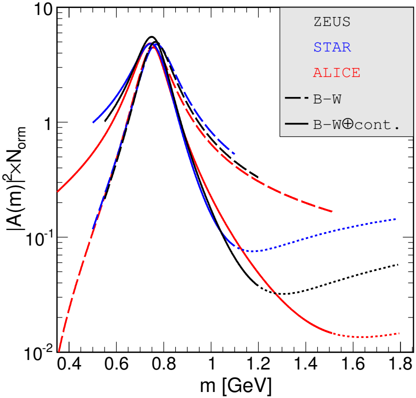
ALICE PARAMETRIZATION "WINS"

SMEARING OF ρ^0 MASS

Drell-Söding contribution:

$\mathcal{A}$ … $+ \mathcal{B}_{\pi\pi}$

3/2



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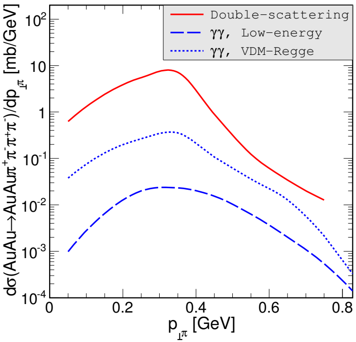
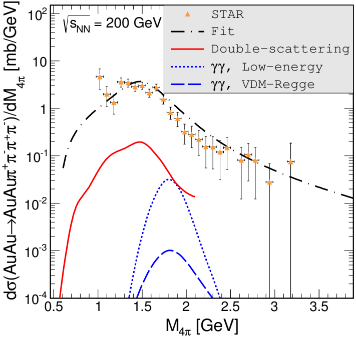
m [GeV]	…1)	$(0.28 - 1.512)$

ALICE PARAMETRIZATION "WINS"

$\pi^+\pi^-\pi^+\pi^-$ PRODUCTION @ RHIC

$|\eta_\pi| < 1$





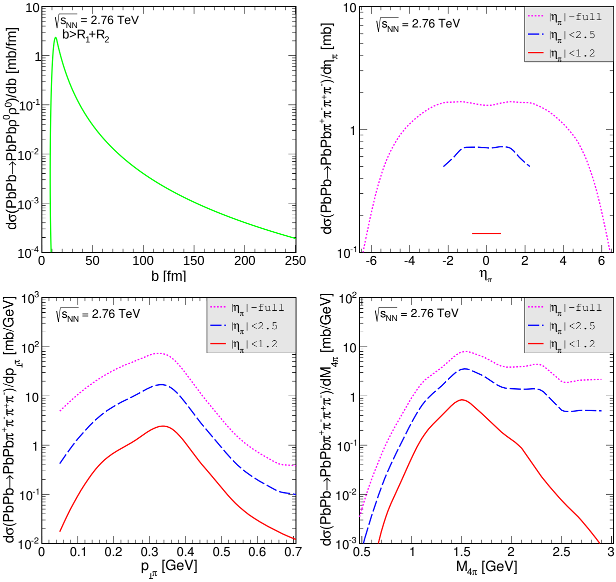
missing mechanisms:

$AA \to AA\rho^0(1450) \to 4\pi$

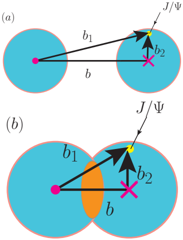
$AA \to AA\rho^0(1700) \to 4\pi$

?

$\pi^+\pi^-\pi^+\pi^-$ PRODUCTION @ LHC



Centrality



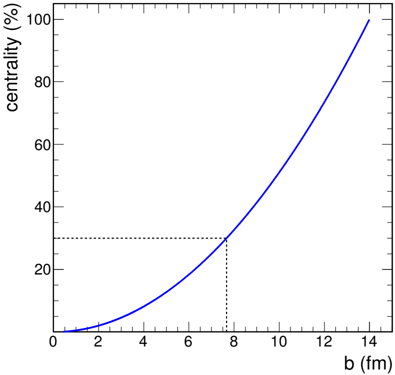
0 $$N(\omega,b)=\frac{Z^2\alpha_{em}}{\pi^2}\left|\int u^2 J_1(u)\,\frac{F\left(\frac{\left(\frac{\omega b}{\gamma}\right)^2+u^2}{b^2}\right)}{\left(\frac{\omega b}{\gamma}\right)^2+u^2}\right|^2 ,$$

1st $$N(\omega,b)=\int N^{(0)}(\omega,b_1)\,\frac{\theta(R_A-\mathbf{b_2})}{\pi R_A^2}\,\mathrm{d}^2 b_1 ,$$

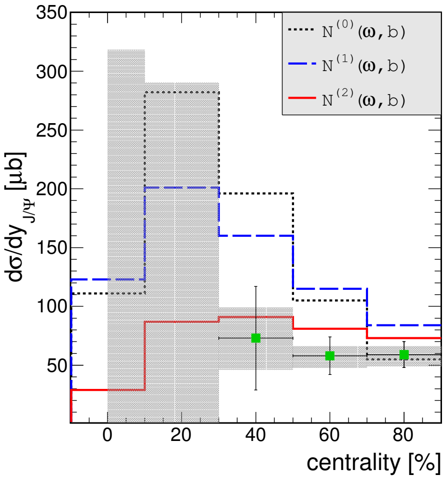
2nd $$N(\omega,b)=\int N^{(0)}(\omega,b_1)\,\frac{\theta(R_A-\mathbf{b_2})\times\theta(\mathbf{b_1}-R_A)}{\pi R_A^2}\,\mathrm{d}^2 b_1 .$$

(a) UPC
(b) Semi-central

Photon from emitter hits the nucleus medium.
Region of overlapping nuclei $\rightarrow$ quark-gluon plasma.



PbPb→PbPbJ/Ψ (semi-central/peripheral)



Analysis for a forward rapidity range - good agreement

Conclusions

1. **EPA** - strong el-mag field $\rightarrow$ photons that can induce el-mag reactions in $A - A$ collisions
2. Impact parameter space approach
3. Realistic form factor
4. **UPC:** Good description of
   - STAR and ALICE data for $\rho^0(770)$ production
   - CMS and ALICE data for J/ψ production

$$\boxed{\frac{d\sigma_{PbPb \to PbPbJ/\psi}(y=0;UPC)}{dy} \approx 2 \text{ mb}}$$

5. **More central:** Good description of
   - ALICE data for J/ψ production

$$\boxed{\frac{d\sigma^{photoprod.}_{PbPb \to J/\psi}(y=0;\, b<R_A+R_B)}{dy} \sim (1.00/1.55) \text{ mb}^*}$$

$$* \quad \frac{d\sigma_{pp \to J/\psi}(y=0)}{dy} \approx 4.31 \pm 0.99\ \mu\text{b} \oplus \text{no. of binary collisions}$$

$\oplus$ experimental nuclear modification factor

$$\rightarrow \quad \boxed{\frac{d\sigma_{PbPb \to J/\psi}(y=0)}{dy} \sim 1 \text{ mb}}$$

Conclusions

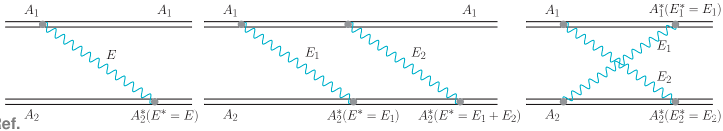
6. Smearing of ρ^0 meson
7. Comparison of four-pion production via $\rho^0\rho^0$ production
   - $\gamma\gamma$ fusion
   - nuclear double-photoproduction (very large)

Energy	mechanism	σ_{tot} [mb]
RHIC ($\sqrt{s_{NN}} = 200$ GeV)	$\rho^0\rho^0$ in double-scattering	1.6
$-\|\|-$	$\rho^0\rho^0$ in $\gamma\gamma$ fusion	0.1
$-\|\|-$	$\pi^+\pi^-\pi^+\pi^-$ in $\gamma\gamma$ fusion	0.1
LHC ($\sqrt{s_{NN}} = 3.5$ TeV)	ρ^0 in photoproduction	4089.3
$-\|\|-$	$\pi^+\pi^-$ in $\gamma\gamma$ fusion	46.7

Conclusions

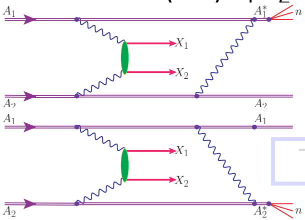
8. Coherent V production in AA UPC
   with electromagnetic dissociation of heavy ions

Single Double Mutual excitation

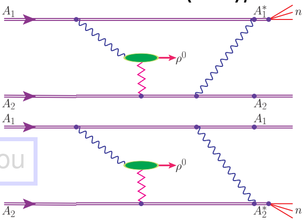


Ref.
M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek, Phys. Rev. **C89** (2014) 054907, ”Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions”

$$AA \to AA^*(kn)X_1X_2$$



$$AA \to AA^*(kn)\rho^0$$

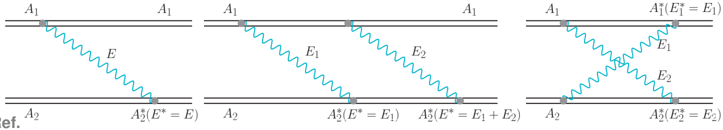


Thank you

Conclusions

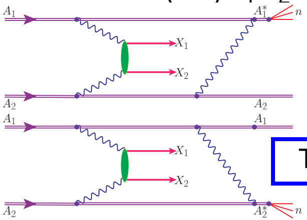
8. Coherent V production in AA UPC
   with electromagnetic dissociation of heavy ions

Single | Double | Mutual excitation

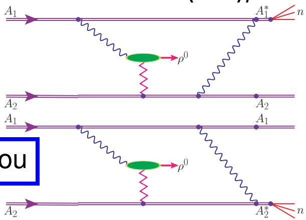


Ref.
M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek, Phys. Rev. **C89** (2014) 054907, "Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions"

$$AA \to AA^*(kn)X_1X_2$$



$$AA \to AA^*(kn)\rho^0$$

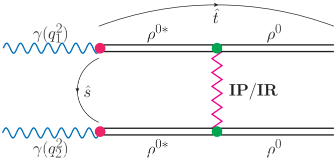


$\boxed{\text{Thank you}}$

Back-up slides

ELEMENTARY CROSS SECTION $\gamma\gamma \to \rho^0\rho^0$

$$\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0} = \int_{\hat{t}_{min}(\hat{s})}^{\hat{t}_{max}(\hat{s})} \frac{d\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} d\hat{t} \tag{3}$$



$$\frac{d\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} = \frac{1}{16\pi\hat{s}} \left| \mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right)\right|^2 \tag{4}$$

$$\mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) = C_{\gamma\to\rho^0} C_{\gamma\to\rho^0} \mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) \tag{5}$$

$$\mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) = \left(\eta_{\mathbf{P}}\left(\hat{s},\hat{t}\right) C_{\mathbf{P}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{P}}\left(\hat{t}\right)-1} + \eta_{\mathbf{R}}\left(\hat{s},\hat{t}\right) C_{\mathbf{R}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{R}}\left(\hat{t}\right)-1}\right)$$

$$\times \hat{s}\, F\left(\hat{t};q_1^2\approx 0\right) F\left(\hat{t};q_2^2\approx 0\right) \tag{6}$$

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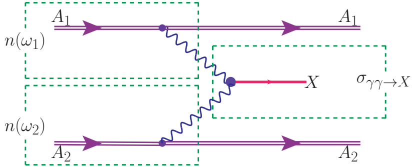
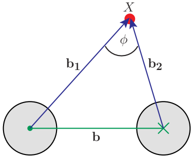
NUCLEAR CROSS SECTION



$$n(\omega) = \int\limits_{R_{min}}^{\infty} 2\pi b\, \mathrm{d}b\, N(\omega, b) \qquad (7)$$

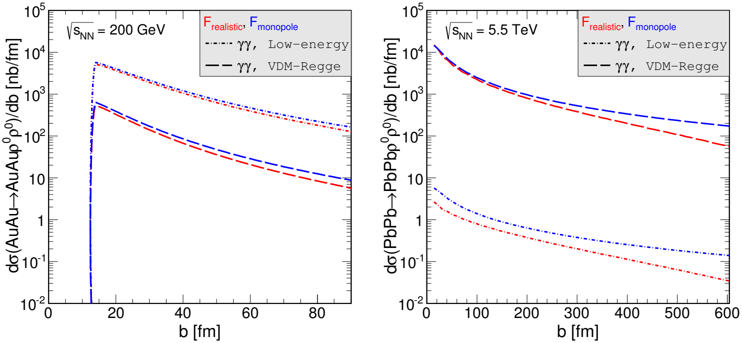
$$\begin{aligned}
\sigma_{A_1 A_2 \to A_1 A_2 X} &= \int \mathrm{d}\omega_1\, \mathrm{d}\omega_2\, n(\omega_1) n(\omega_2) \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2) \\
&= \ldots \\
&= \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \\
&\times \sigma_{\gamma\gamma\to X}\left(\sqrt{s_{A_1 A_2}}\right) \\
&\times 2\pi b\, \mathrm{d}b\, \mathrm{d}\bar{b}_x\, \mathrm{d}\bar{b}_y\, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma}\, \mathrm{d}Y_X \qquad (8)
\end{aligned}$$



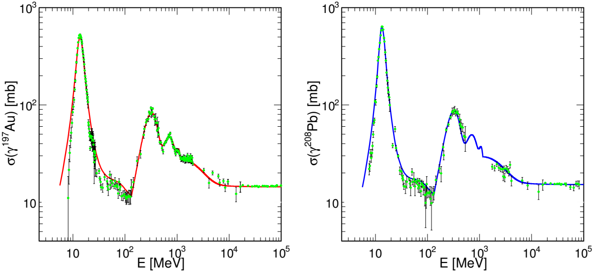
AA→AA$\rho^0\rho^0$ - FORM FACTOR

$N(\omega_{1/2}, \mathbf{b}_{1/2})$ depends on the form factor

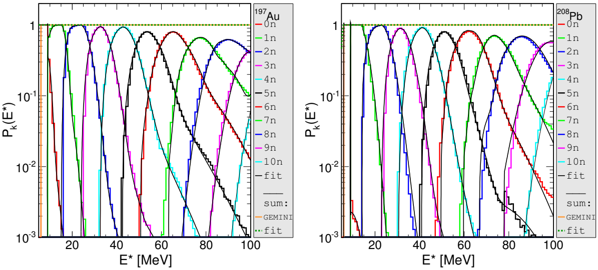
- realistic
- monopole



Photoabsorption $\sigma(\gamma A \to A) \downarrow$



Probability of neutron multiplicity $\downarrow$



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Nuclear production of single vector meson
Single meson production
J/ψ meson production
ρ^0 meson production
Nuclear production of vector mesons
Double-scattering mechanism
$\gamma\gamma$ fusion
Smearing of ρ^0 mass
$\rho^0\rho^0 \to 4\pi$
Not only UPC
Conclusion

Excitation function $\gamma^{A}X \rightarrow kn^{A-1}X\downarrow$