WPCF2018

Recent theoretical results for electromagnetically induced ultraperipheral reactions of heavy ions

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Introduction

Our recent works related to UPC:

1. $PbPb \to PbPbe^+e^-$ and $PbPb \to PbPb\mu^+\mu^-$
2. $PbPb \to PbPb\rho^0$
3. $PbPb \to PbPb\rho^0\rho^0$
   single versus double scattering
4. $PbPb \to PbPb\pi^+\pi^-$ and $PbPb \to PbPb\pi^0\pi^0$
5. $PbPb \to PbPb\gamma\gamma$ (UPC)
   extraction of $\gamma\gamma \to \gamma\gamma$ cross section
6. $PbPb \to PbPbp\bar{p}$ (UPC)
   $\gamma\gamma \to p\bar{p}$ as a background to $J/\psi \to p\bar{p}$ process.
7. $PbPb \to PbPbe^+e^-e^+e^-$ and $PbPb \to PbPb\mu^+\mu^-\mu^+\mu^-$
8. $PbPb \to PbPbJ/\psi$
   photoproduction not only in UPC

UltraPeripheral heavy-ion Collisions

EPA

Vector meson photoproduction

Photon-photon scattering

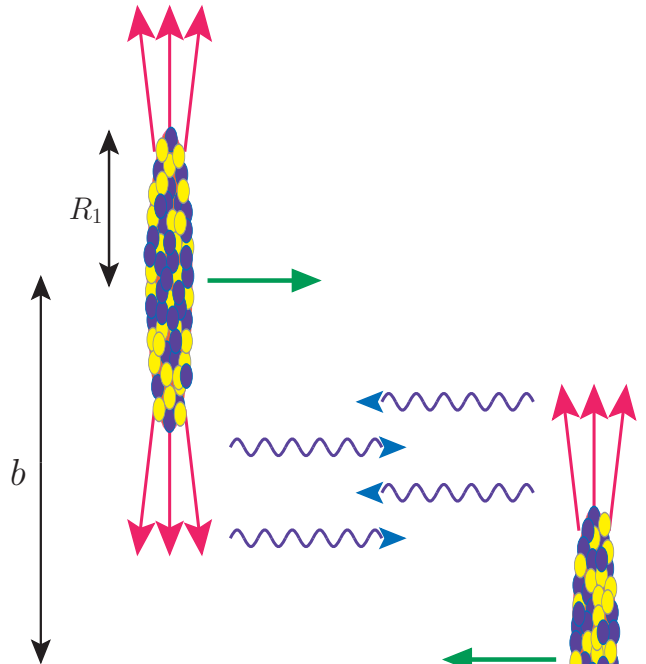
Four-lepton production

- Electrons
- Muons

Proton-antiproton production

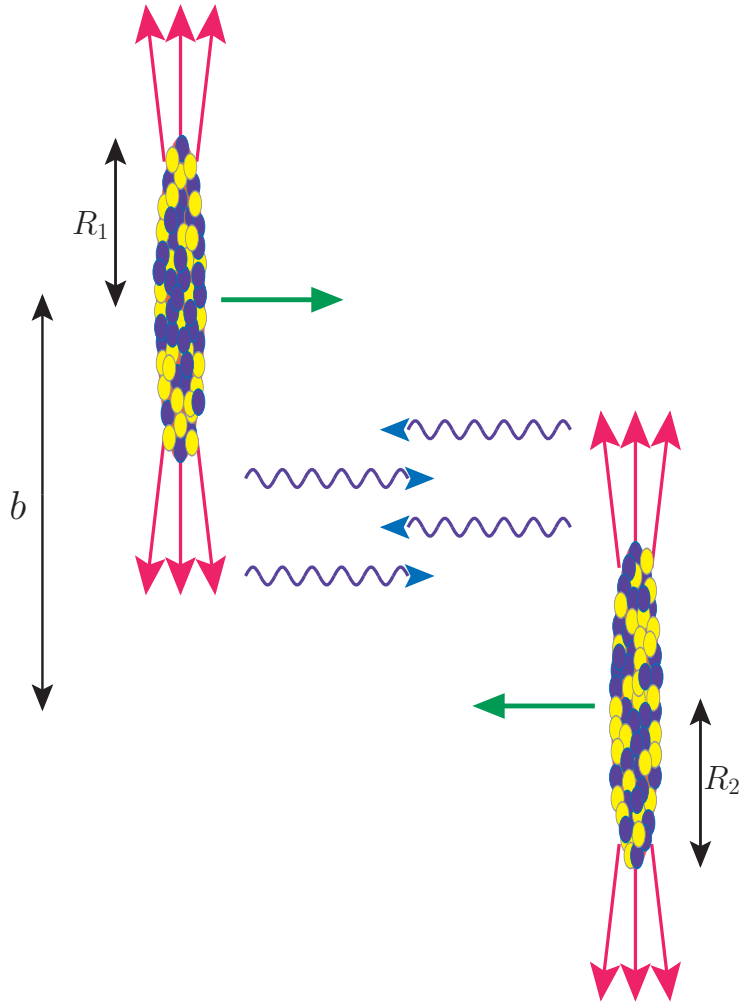
Not only UPC

Conclusion



1. M. K-G, P. Lebiedowicz, A. Szczurek,
Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collide,
Phys. Rev. **C93** (2016) 044907,
2. M. K-G, W. Schäfer, A. Szczurek,
Two-gluon exchange contribution to elastic $\gamma\gamma \longrightarrow \gamma\gamma$ scattering and production of two-photons in ultraperipheral ultrarelativistic heavy ion and proton-proton collisions,
Phys. Lett. **B761** (2016) 399,
3. M. K-G, A. Szczurek,
Double scattering production of two positron–electron pairs in ultraperipheral heavy-ion collisions,
Phys. Lett. **B763** (2016) 416,
4. A. van Hameren, M. K-G, A. Szczurek,
From the Single- and double-scattering production of four muons in ultraperipheral PbPb collisions at the Large Hadron Collider,
Phys. Lett. **B776** (2018) 84,
5. M. K-G, P. Lebiedowicz, O. Nachtmann, A. Szczurek,
From the $\gamma\gamma \longrightarrow p\bar{p}$ reaction to the production of $p\bar{p}$ pairs in ultraperipheral ultrarelativistic heavy-ion collisions at the LHC

UltraPeripheral heavy-ion Collisions

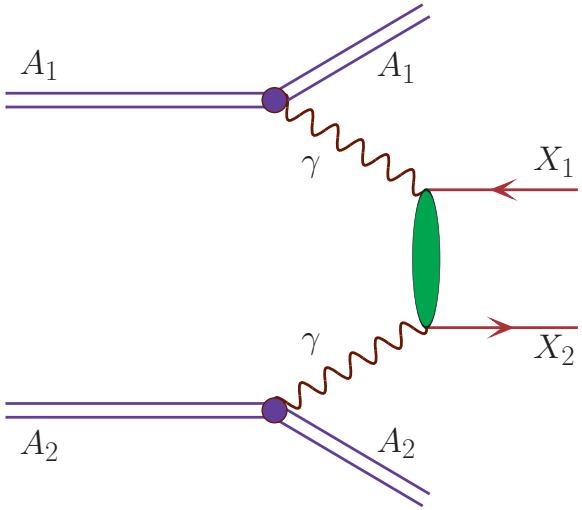


Two categories of processes:

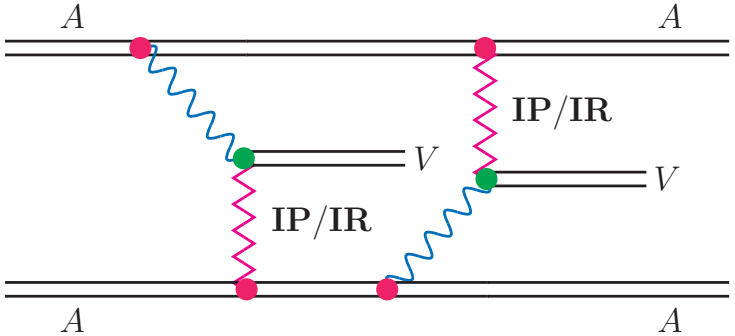
(a) photon-photon processes

(b) photon (or its hadron fluctuation) rescattering in the second nucleus

$\gamma\gamma$ fusion



Photoproduction



✓ $\rho^0, J/\psi$

✓ $\rho^0\rho^0, J/\psi J/\psi$

✓ $\pi^+\pi^-, \pi^0\pi^0$

✓ $c\bar{c}, b\bar{b}$

✓ $e^+e^-, \mu^+\mu^-$

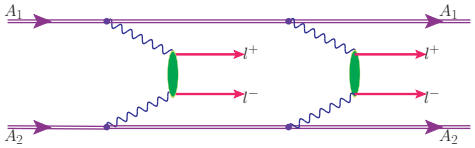
✓ $\gamma\gamma$

✓ $p\bar{p}$

✓ $\pi^+\pi^-\pi^+\pi^-$

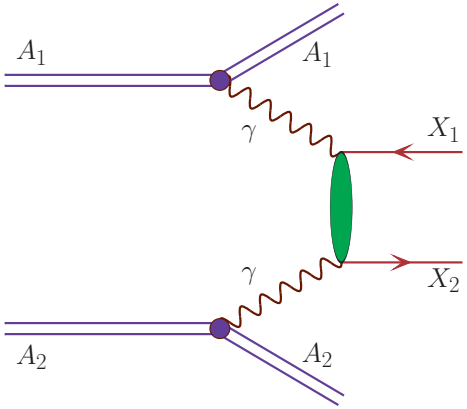
✓ $e^+e^-e^+e^-$

✓ $\mu^+\mu^-\mu^+\mu^-$



ALICE, ATLAS, CMS, LHCb (^{208}Pb+^{208}Pb @ $\sqrt{s_{NN}} = 2.76, 3.5, 5.02, 5.5$ TeV)

Nuclear Cross Section



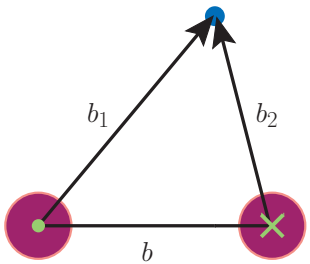
$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \ldots$$

$$\text{NAIVELY} \Rightarrow \ldots = \int \mathrm{d}\omega_1\,\mathrm{d}\omega_2\, n(\omega_1)n(\omega_2) \times \sigma_{\gamma\gamma\to X_1X_2}(\omega_1,\omega_2)$$

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

MORE

$$\text{CORRECTLY} \Rightarrow \ldots = \int N(\omega_1,\mathbf{b_1})\,N(\omega_2,\mathbf{b_2})S^2_{abs}(\mathbf{b}) \times \sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma}) \times \mathrm{d}^2b\,\mathrm{d}\bar{b}_x\,\mathrm{d}\bar{b}_y\,\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}$$



Photon flux & Form factor

✗ charge distribution in nucleus

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times \left| \int \mathrm{d}\chi\, \chi^2 \frac{F\left(\frac{\chi^2+u^2}{b^2}\right)}{\chi^2+u^2} J_1(\chi) \right|^2$$

$$\beta = \frac{p}{E},\ \gamma = \frac{1}{\sqrt{1-\beta^2}},\ u = \frac{\omega b}{\gamma\beta},\ \chi = k_\perp b$$

- point-like $F\left(\mathbf{q}^2\right) = 1$

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u)\right]$$

- monopole $F\left(\mathbf{q}^2\right) = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2}$

$$\sqrt{\langle r^2 \rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1\ \text{fm}\ A^{1/3}$$

Form factor

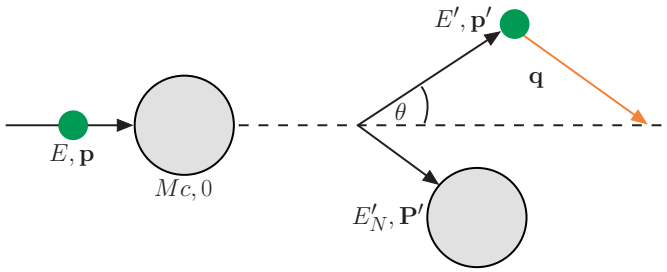
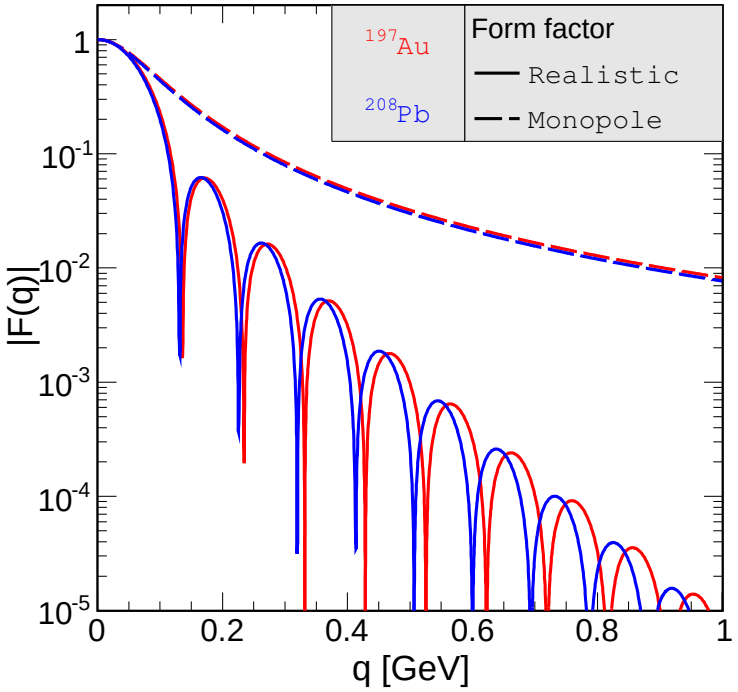


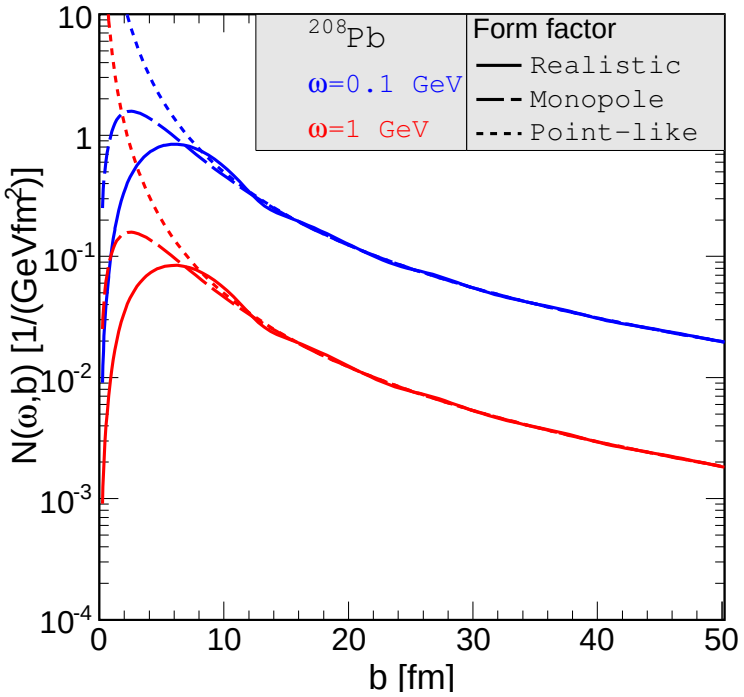
Figure: Elastic scattering of electron-nucleus

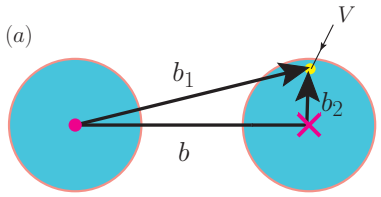
Form factor & Photon flux

- realistic charge distribution

$$F\left(\mathbf{q}^2\right) = \frac{4\pi}{|\mathbf{q}|}\int \rho(r)\sin(|\mathbf{q}|\,r)\,r\,\mathrm{d}r$$





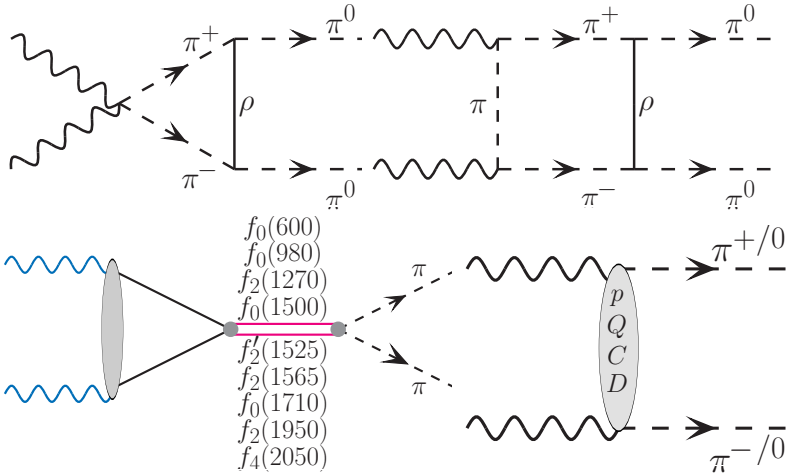


$\gamma\gamma \to \pi\pi$

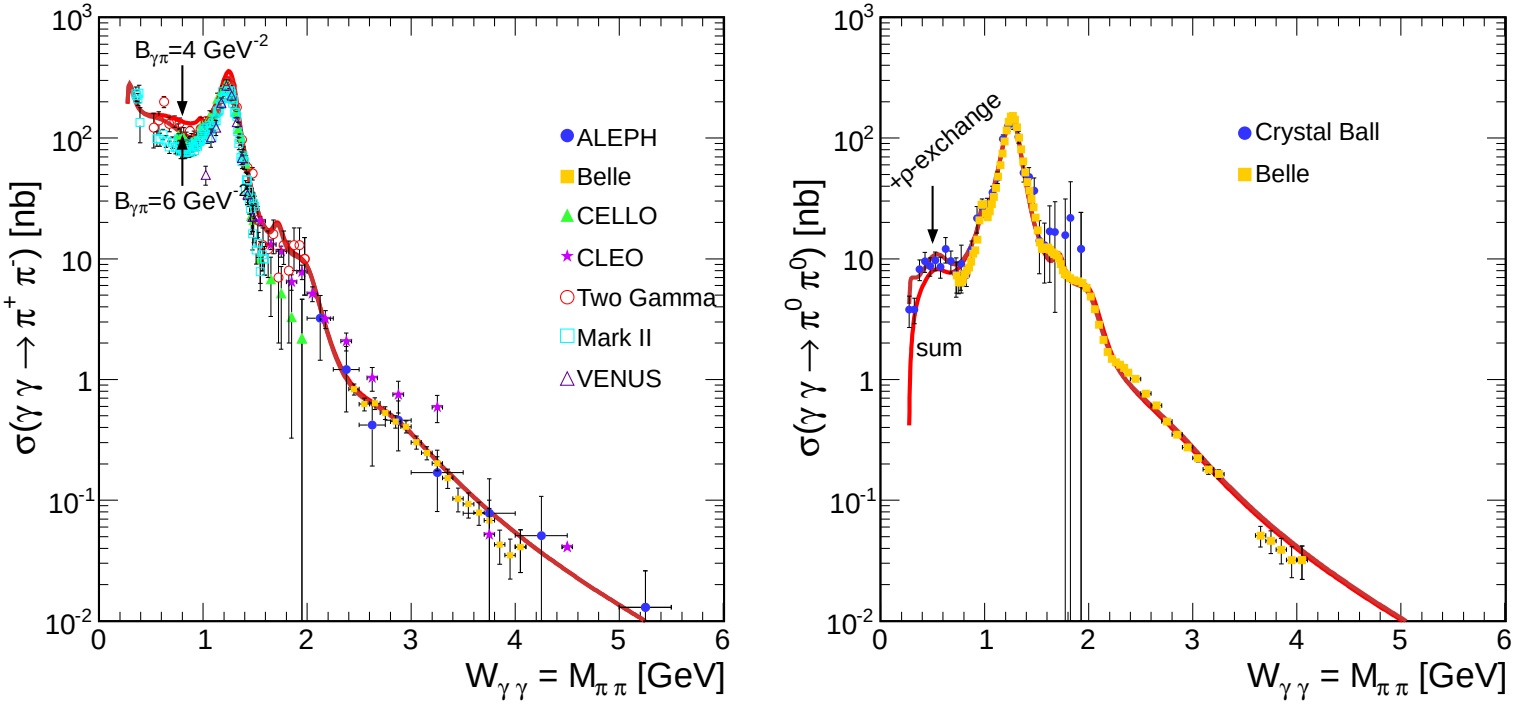
- M. K-G and A. Szczurek,
  $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy ion collisions,
  Phys. Rev. **C87** (2013) 054908

Both $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$ subprocesses

Several resonances (scalar, tensor), continuum, pQCD ala Brodsky-Lepage, hand-bag mechanism



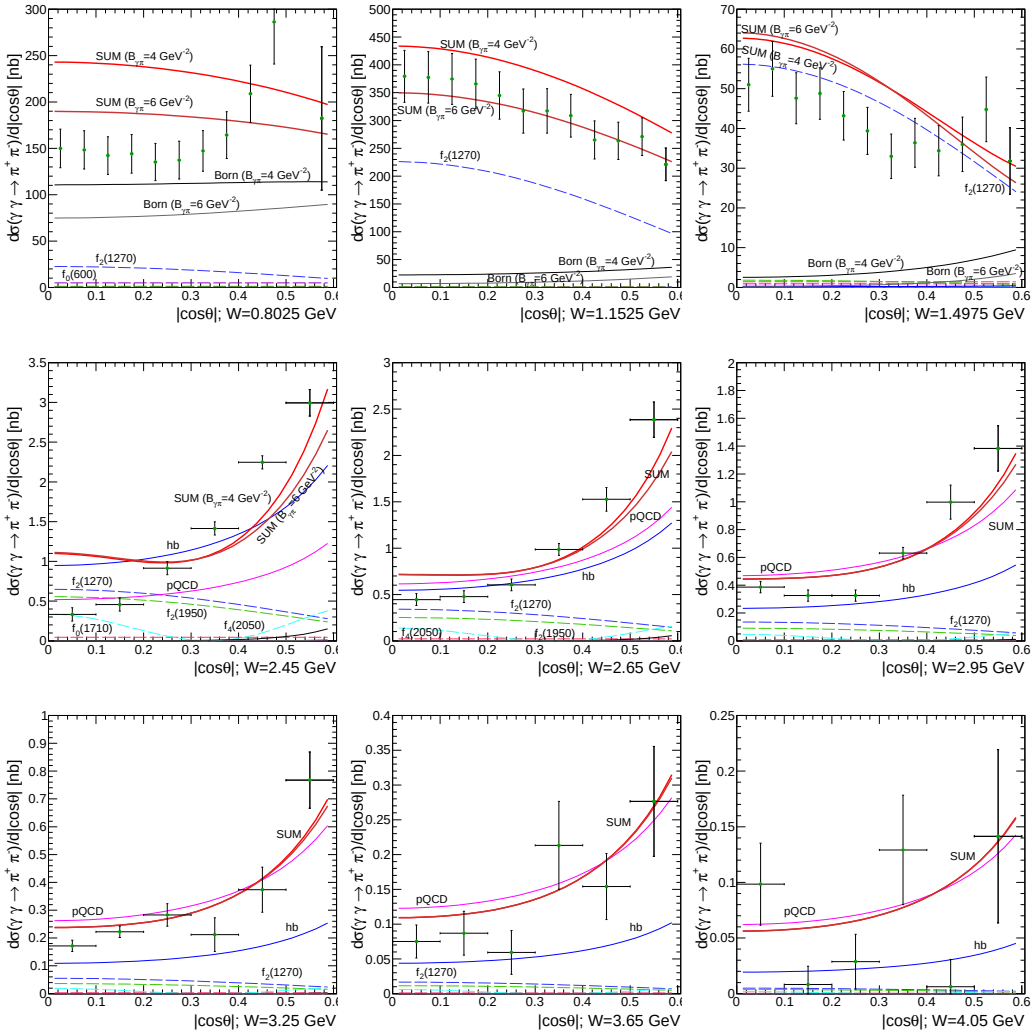
Total cross section

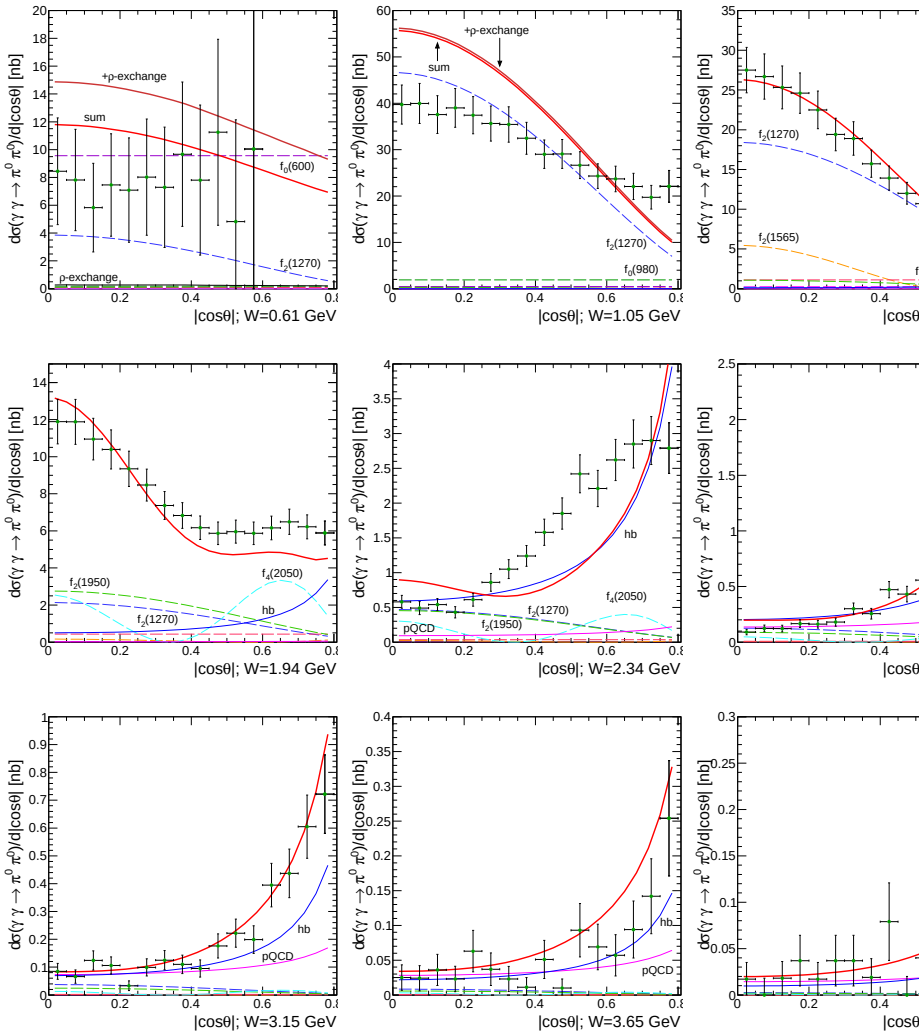


Good description of the data

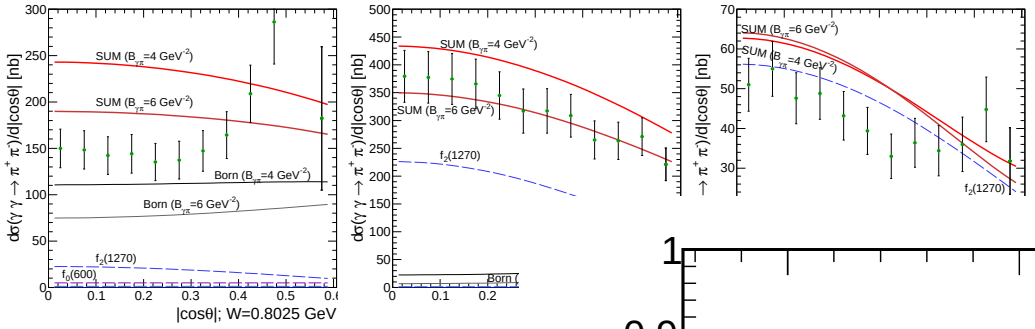
$\gamma\gamma \to f_2(1270) \to \pi\pi$ resonance contribution is dominant

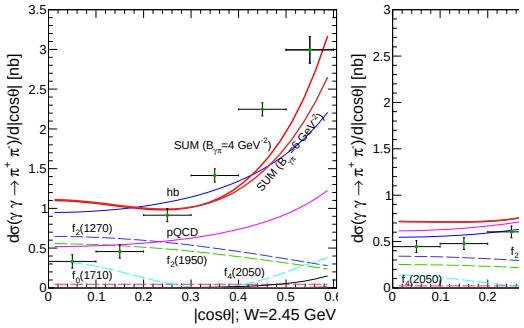
Angular distributions

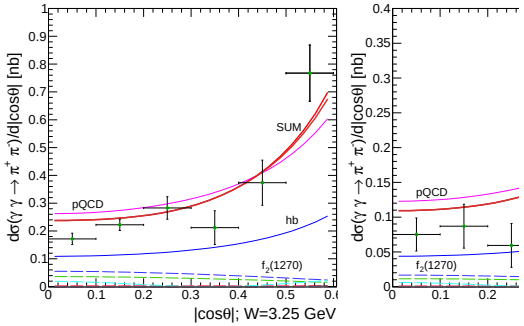


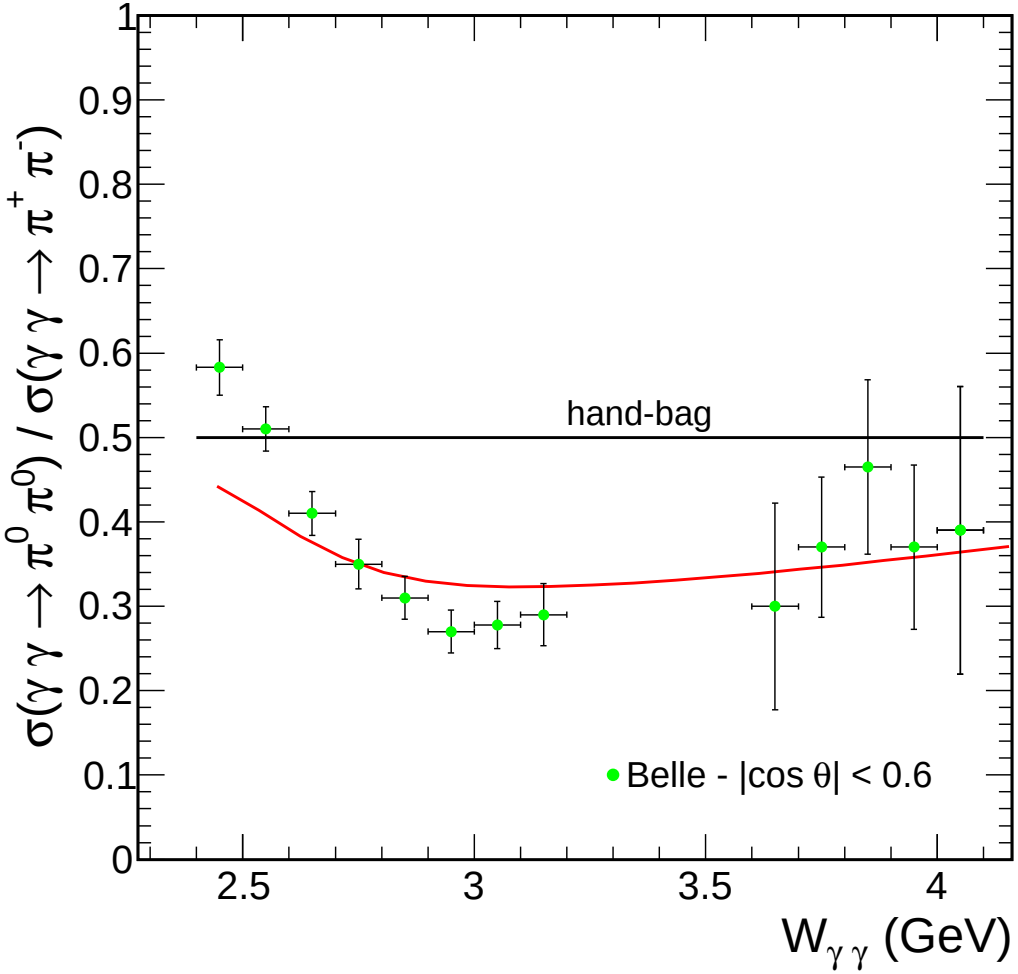


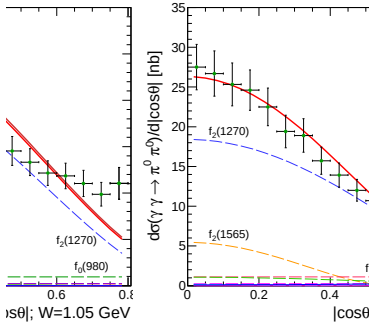
Angular distributions

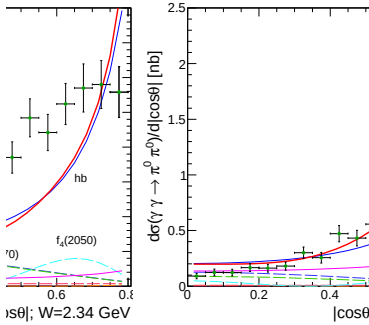


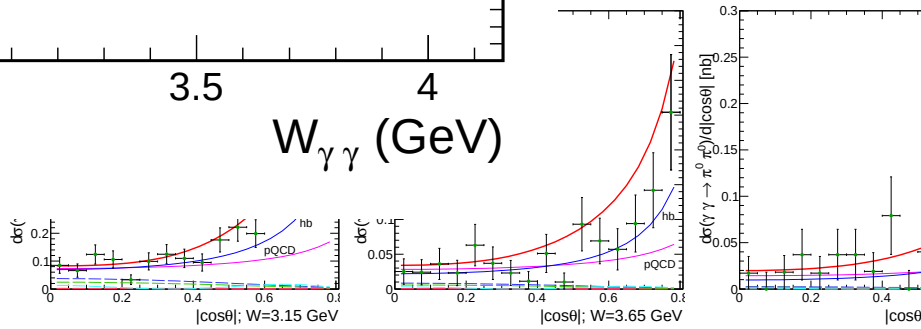




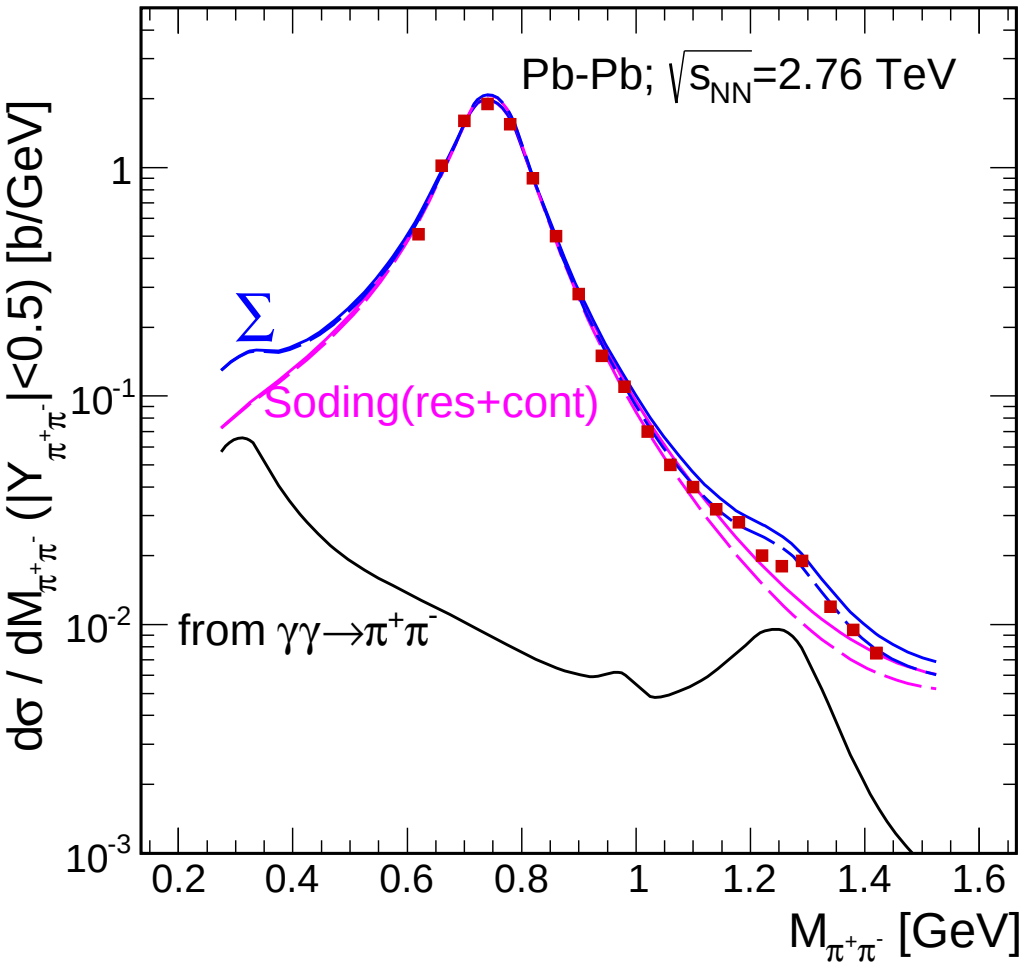






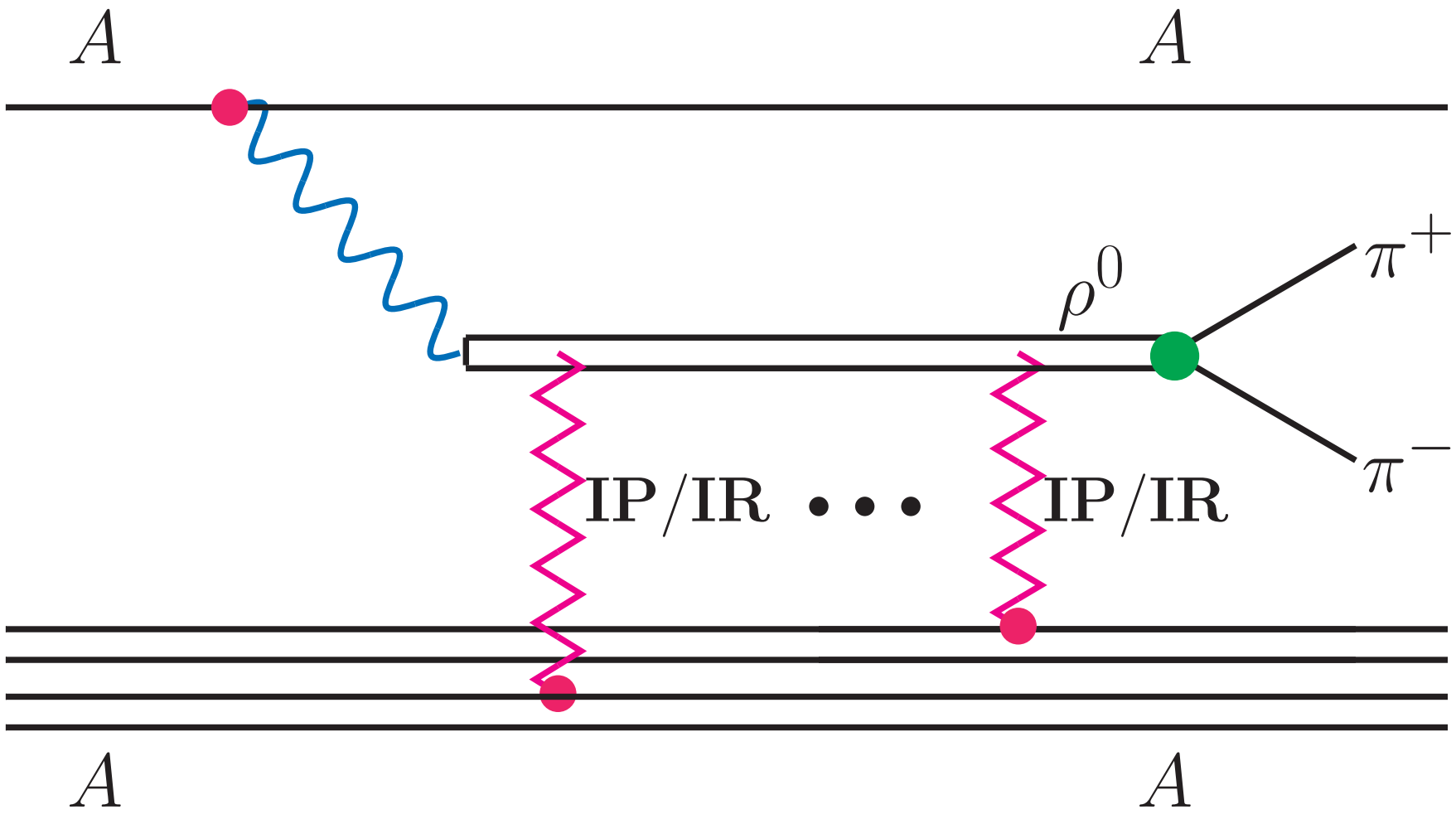


$AA \to AA\rho^0$

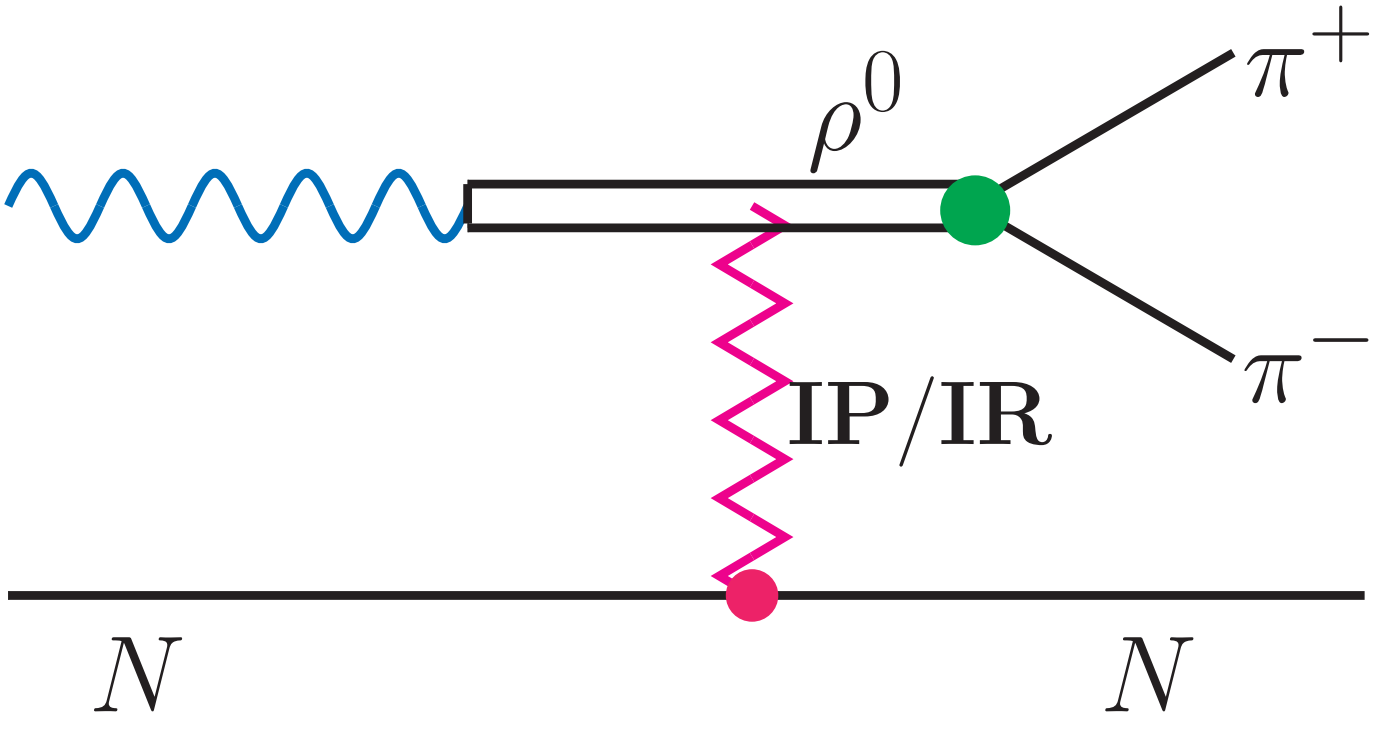


ALICE data

AA→AAρ^0



$\gamma N \to \rho^0 N$

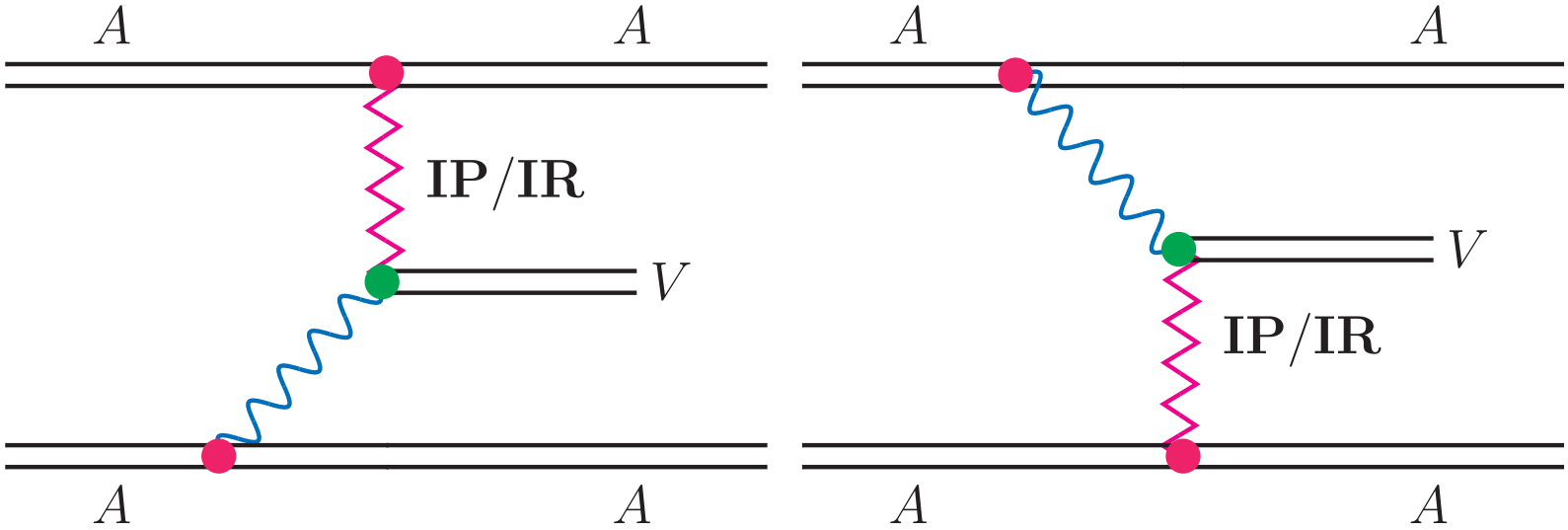


$N = n, p$

Parameters fixed to describe HERA data:

we expect: $\frac{d\sigma(\gamma n \to \rho^0 n)}{dt} \approx \frac{d\sigma(\gamma p \to \rho^0 n)}{dt}$

Single ρ^0 meson production



$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2V}}{\mathrm{d}^2b\mathrm{d}y} = \frac{\mathrm{d}P_{\gamma\mathbf{P}}(b,y)}{\mathrm{d}y} + \frac{\mathrm{d}P_{\mathbf{P}\gamma}(b,y)}{\mathrm{d}y}$$

$$P_{1/2}(b,y) = \omega_{1/2}\tilde{N}\left(\omega_{1/2},b\right)\sigma_{\gamma A_{2/1}\to VA_{2/1}}(W_{\gamma A_{2/1}})$$

$$\sigma_{\gamma A\to\rho^0 A} = \frac{d\sigma_{\gamma A\to\rho^0 A}(t=0)}{dt}\int_{-\infty}^{t_{max}}\mathrm{d}t\left|F_A(t)\right|^2$$

nuclear form factor

A rescattering model for $\gamma A \to \rho^0 A$ reaction

$$\sigma_{\gamma A \to \rho^0 A} = \frac{d\sigma_{\gamma A \to \rho^0 A}(t=0)}{dt} \int_{-\infty}^{t_{max}} \mathrm{d}t \, |F_A(t)|^2 \, \frac{d\sigma_{\gamma A \to \rho^0 A}(t=0)}{dt} = \frac{\alpha_{em} \sigma_{tot}^2 (\rho^0 A)}{4 f_{\rho^0}^2}$$

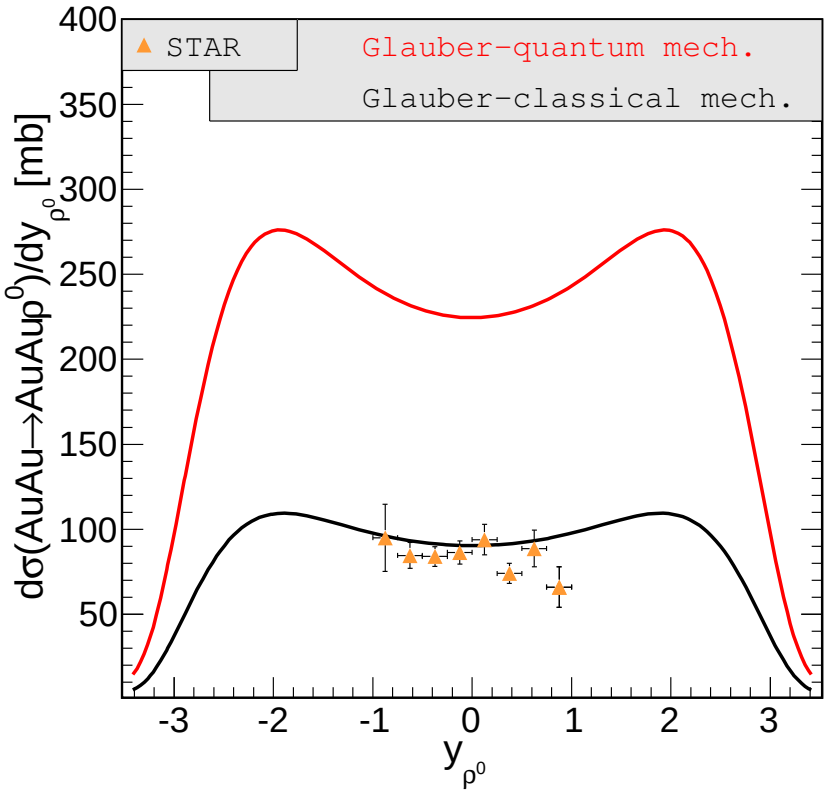
- classical mechanics Glauber:
  $\sigma_{tot}(\rho^0 A) = \int \mathrm{d}^2\mathbf{r} \left(1 - \exp\left(-\sigma_{tot}(\rho^0 p) \, T_A(\mathbf{r})\right)\right)$
- quantum mechanical Glauber:
  $\sigma_{tot}^{qm}(\rho^0 A) = 2 \int \mathrm{d}^2\mathbf{r} \left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(\rho^0 p) \, T_A(\mathbf{r})\right)\right)$

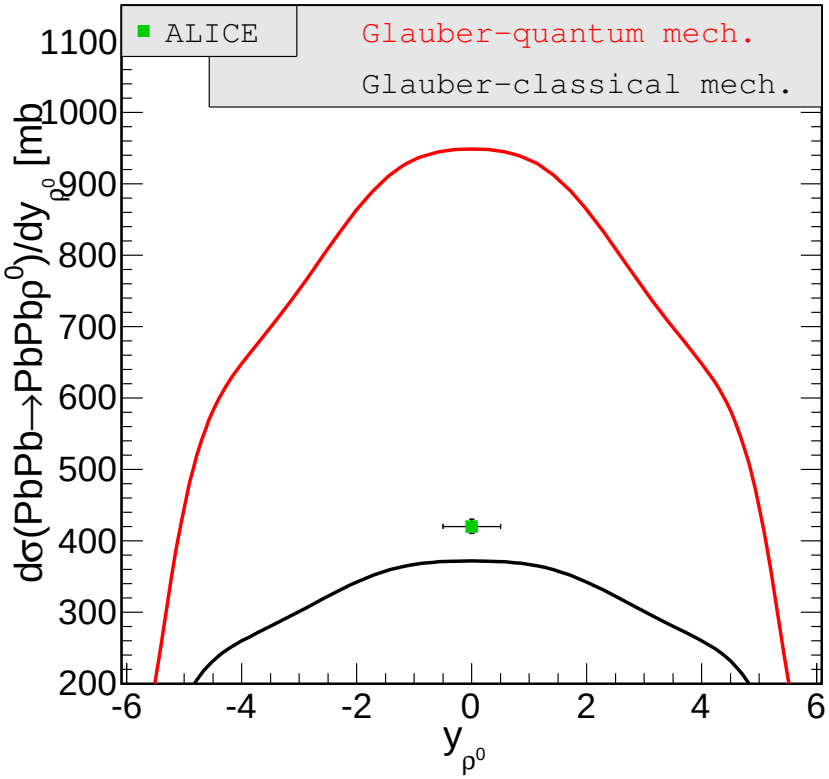
nucleus thickness: $T_A(\mathbf{r}) = \int \mathrm{d}z \, \rho_A\left(\sqrt{|\mathbf{r}|^2 + z^2}\right)$

$$\sigma_{tot}^2(\rho^0 p) = 16\pi \frac{\mathrm{d}\sigma_{\rho^0 p \to \rho^0 p}(t=0)}{\mathrm{d}t} \frac{\mathrm{d}\sigma_{\rho^0 p \to \rho^0 p}(t=0)}{\mathrm{d}t} = \frac{f_{\rho^0}^2}{4\pi\alpha_{em}} \frac{\mathrm{d}\sigma_{\gamma p \to \rho^0 p}(t=0)}{\mathrm{d}t}$$

(VDM) $\frac{\mathrm{d}\sigma_{\gamma p \to \rho^0 p}(t=0)}{\mathrm{d}t} = B_{\rho^0}\left(XW^{\epsilon} + YW^{-\eta}\right)$ $\leftarrow$ HERA data

AA→AAρ^0 vs Glauber model





Smearing of ρ^0 mass

$$\frac{\mathrm{d}\sigma_{AA\to AA\rho_0}}{\mathrm{d}m\,\mathrm{d}y} = f(m)\frac{\mathrm{d}\sigma_{AA\to AA\rho_0}(y,m)}{\mathrm{d}y}$$

$$f(m) = \frac{|\mathcal{A}(m)|^2 N_{orm}}{\int |\mathcal{A}(m)|^2 N_{orm}\mathrm{d}m}$$

$$\int N_{orm}\,|\mathcal{A}(m)|^2\,\mathrm{d}m = 1$$

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

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

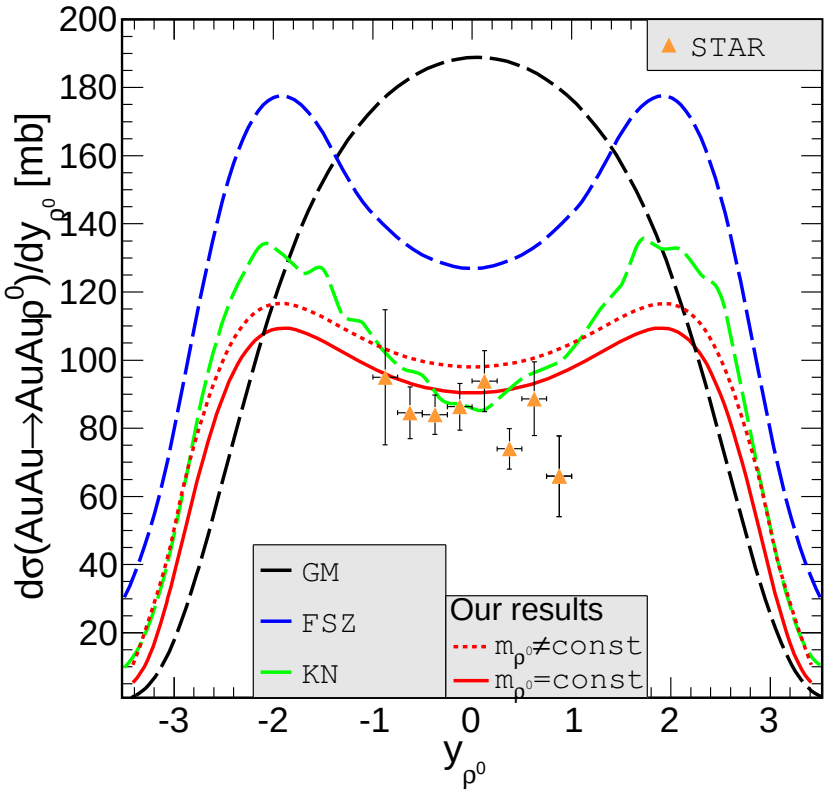
Smearing of ρ^0 mass

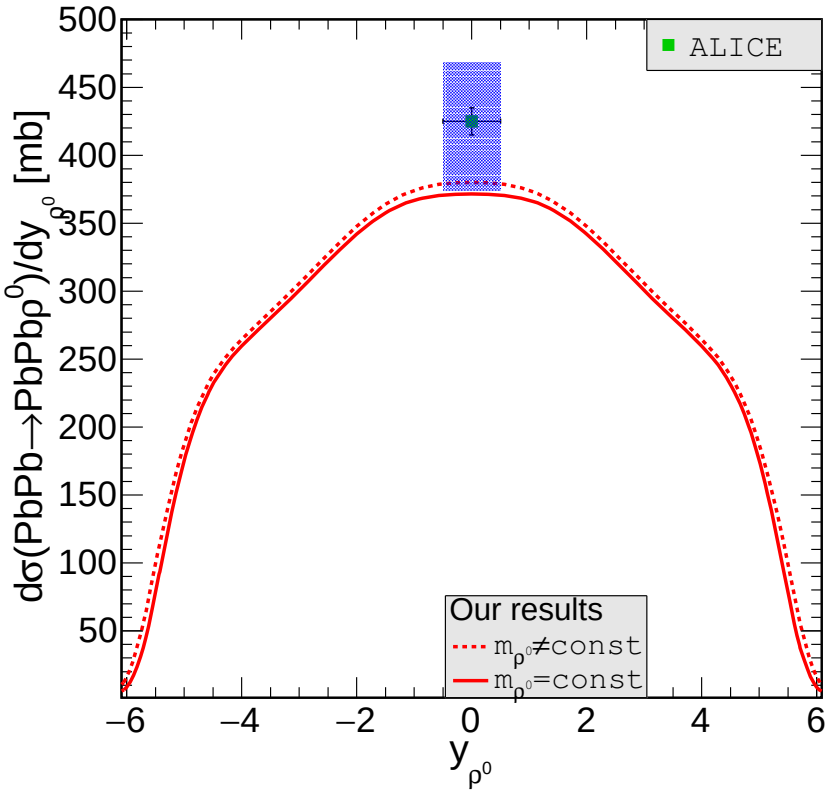
$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}} \frac{\sqrt{m m_{\rho^0} \Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0} \Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi}$$

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

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]	$(0.55 - 1.2)$	$(0.5 - 1.1)$	$(0.28 - 1.512)$

Single ρ^0 meson production



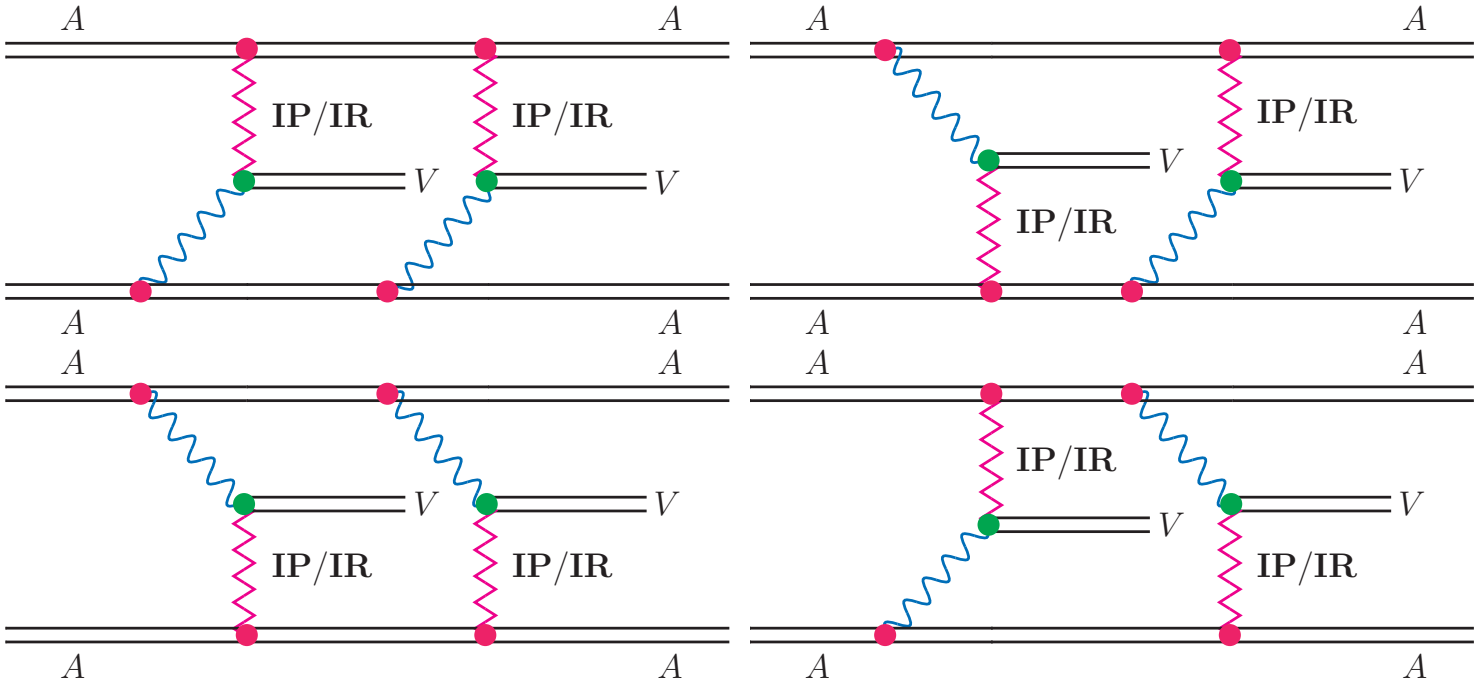


Single ρ^0 meson production

GM	FSZ	KN	Our result		Experimental data
			$m_{\rho^0} = \text{const}$	$m_{\rho^0} \neq \text{const}$	
$\sqrt{s_{NN}} = 130$ GeV; full $\lvert y_{\rho^0} \rvert$					STAR
	490		359	407	$370 \pm 170 \pm 80$
$\sqrt{s_{NN}} = 130$ GeV; $\lvert y_{\rho^0} \rvert < 1$					STAR
	140		130	143	$106 \pm 5 \pm 14$
$\sqrt{s_{NN}} = 200$ GeV; full $\lvert y_{\rho^0} \rvert$					STAR
876	934	590	590	646	$391 \pm 18 \pm 55$
$\sqrt{s_{NN}} = 2.76$ TeV; full $\lvert y_{\rho^0} \rvert$					ALICE
			3309	3405	$4200 \pm 100^{+500}_{-600}$
$\sqrt{s_{NN}} = 2.76$ TeV; $\lvert y_{\rho^0} \rvert < 0.5$					ALICE
			371	380	$425 \pm 10^{+42}_{-50}$

GM - V.P. Gonçalves and M.V.T. Machado, "The QCD pomeron in ultraperipheral heavy ion collisions. IV. Photonuclear production of vector mesons", Eur. Phys. J. **C40** (2005) 519,
FSZ - L. Frankfurt, M. Strikman and M. Zhalov, "Signals for black body limit in coherent ultraperipheral heavy ion collisions" Phys. Lett. **B537** (2002) 51,
KN - S. Klein and J. Nystrand, "Exclusive vector meson production in relativistic heavy ion collisions", Phys. Rev. **C60** (1999) 014903

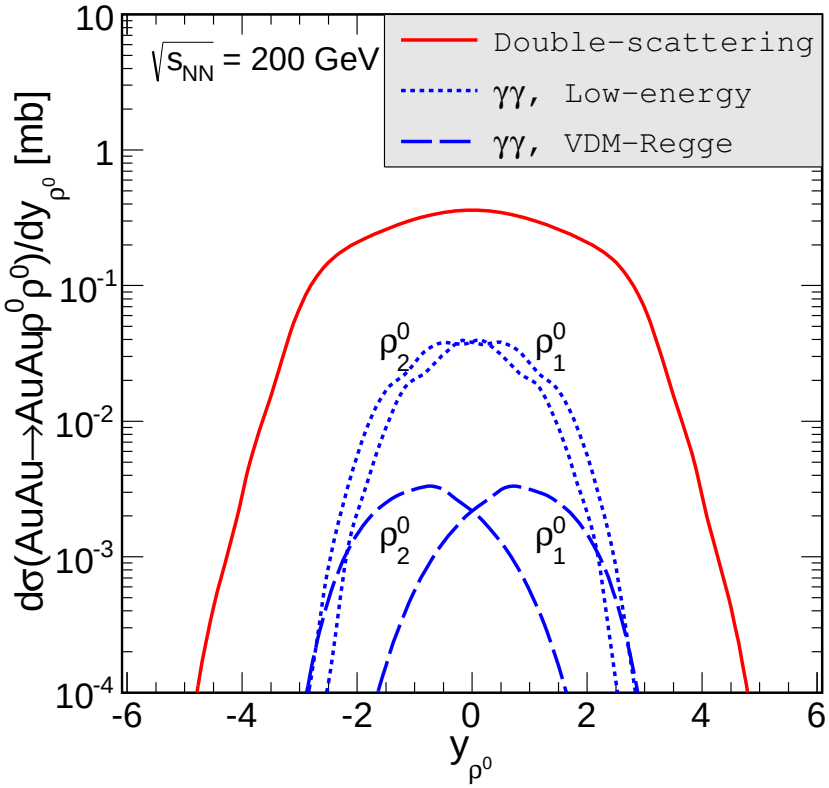
Double-scattering mechanism

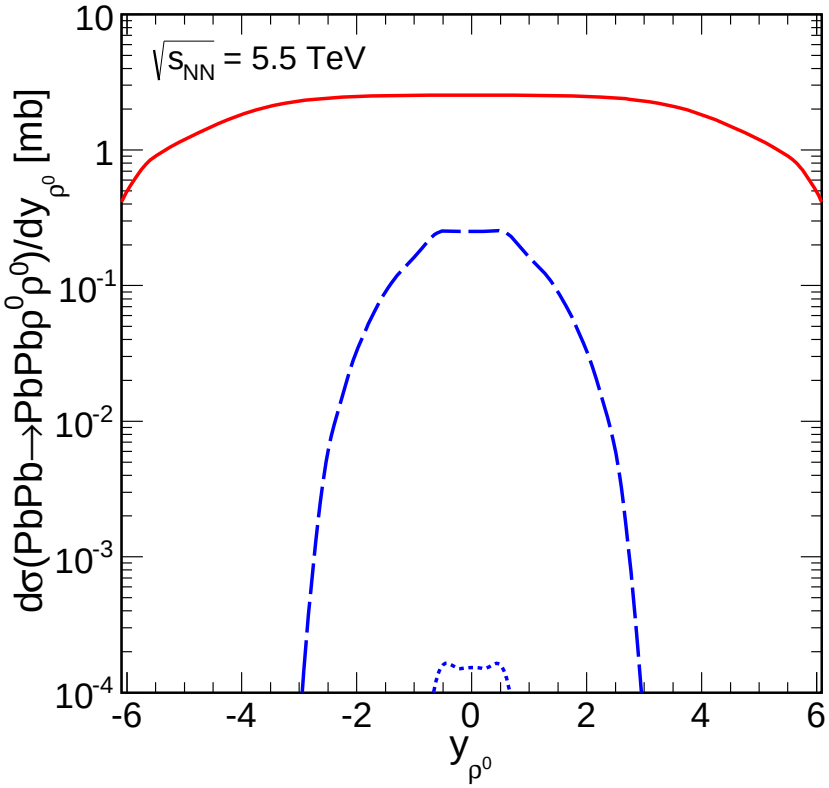


$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2\rho^0\rho^0}}{\mathrm{d}y_1\mathrm{d}y_2} = \frac{1}{2}\int\left(\frac{\mathrm{d}P_{\gamma\mathbf{P}}(b,y_1)}{\mathrm{d}y_1} + \frac{\mathrm{d}P_{\mathbf{P}\gamma}(b,y_1)}{\mathrm{d}y_1}\right) \times \left(\frac{\mathrm{d}P_{\gamma\mathbf{P}}(b,y_2)}{\mathrm{d}y_2}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

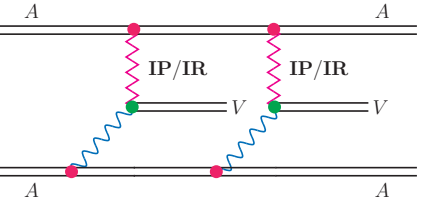
(ρ^0's have negligibly small transverse momenta)

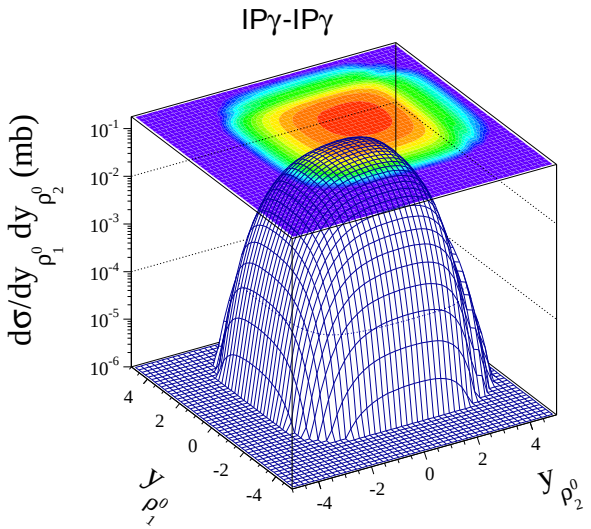
Double-scattering mechanism vs $\gamma\gamma$ fusion

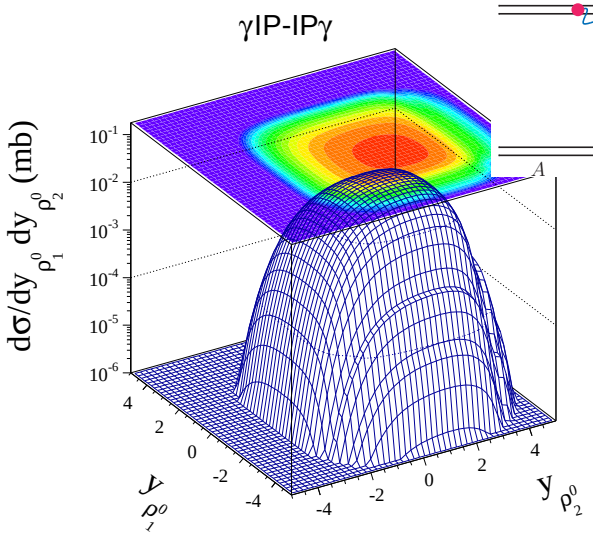


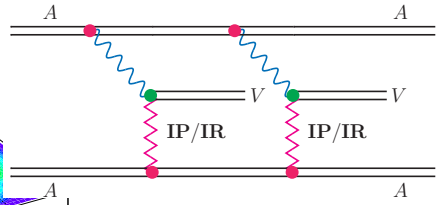


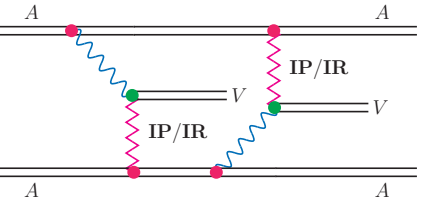
Double-scattering mechanism

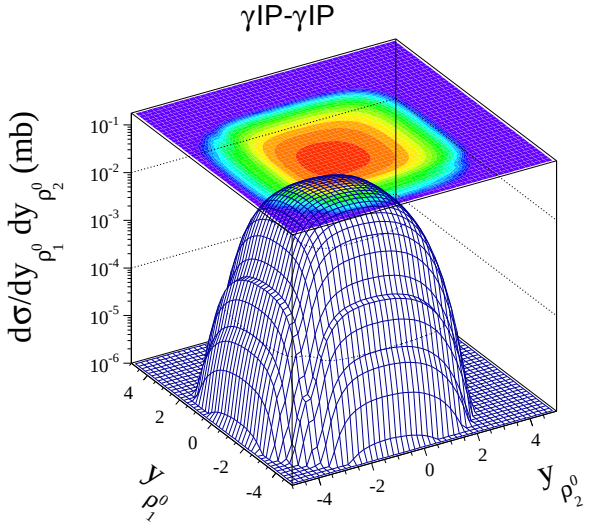


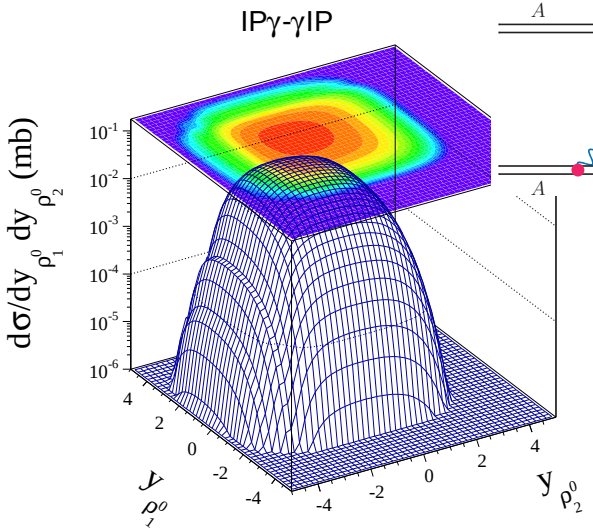


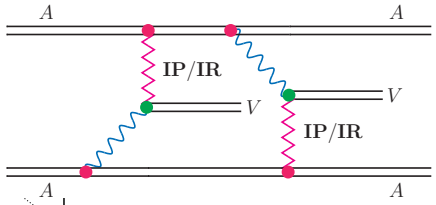










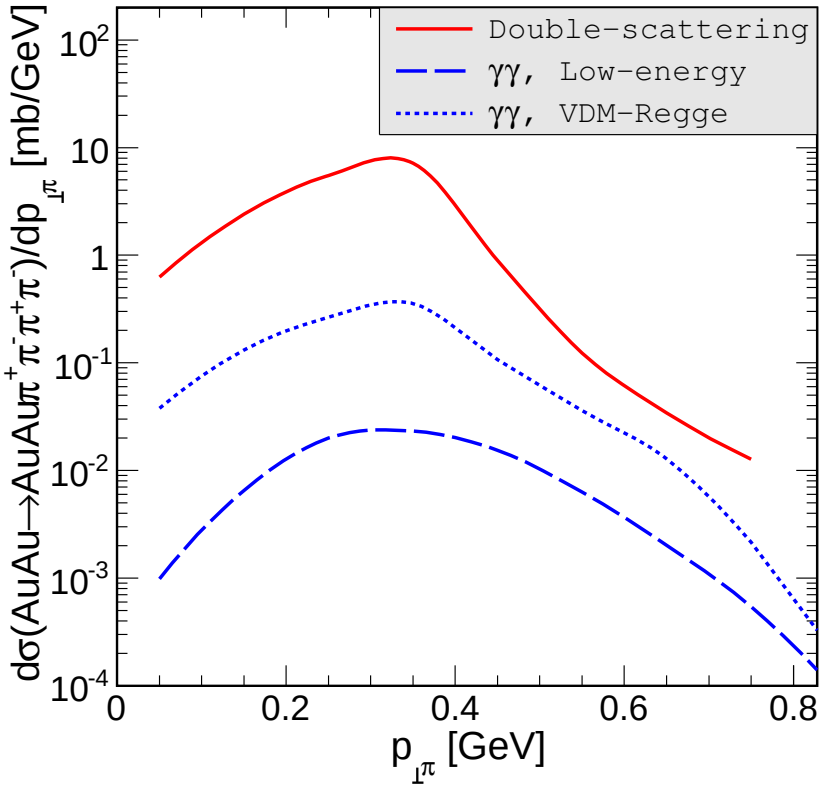


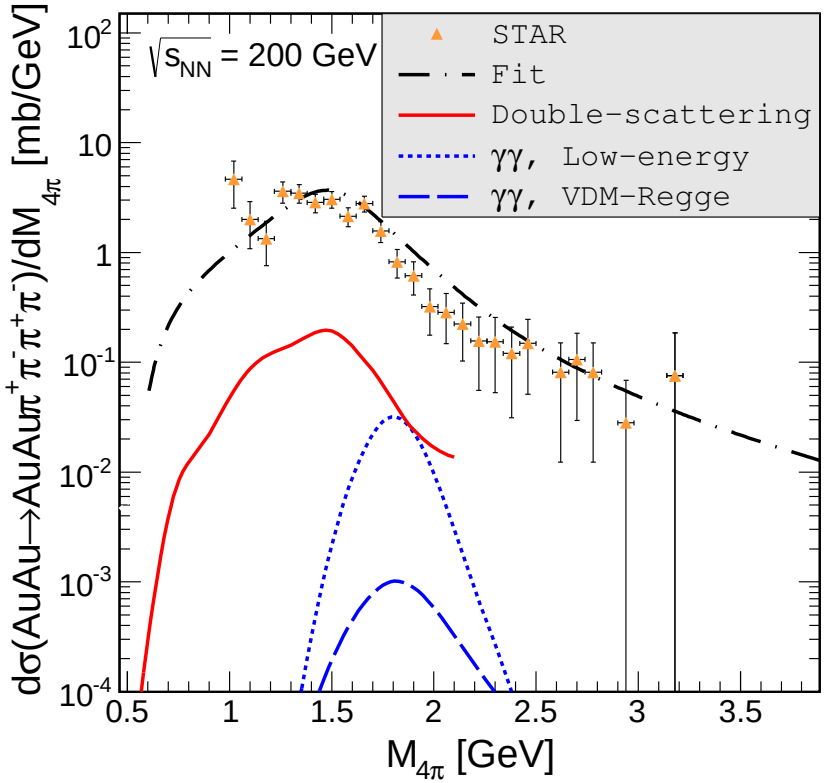
Broad distributions in $y_1 x y_2$

This reguires broad pseudorapidity coverage (ATLAS, CMS)

Double-scattering mechanism at RHIC

$|\eta_\pi| < 1$

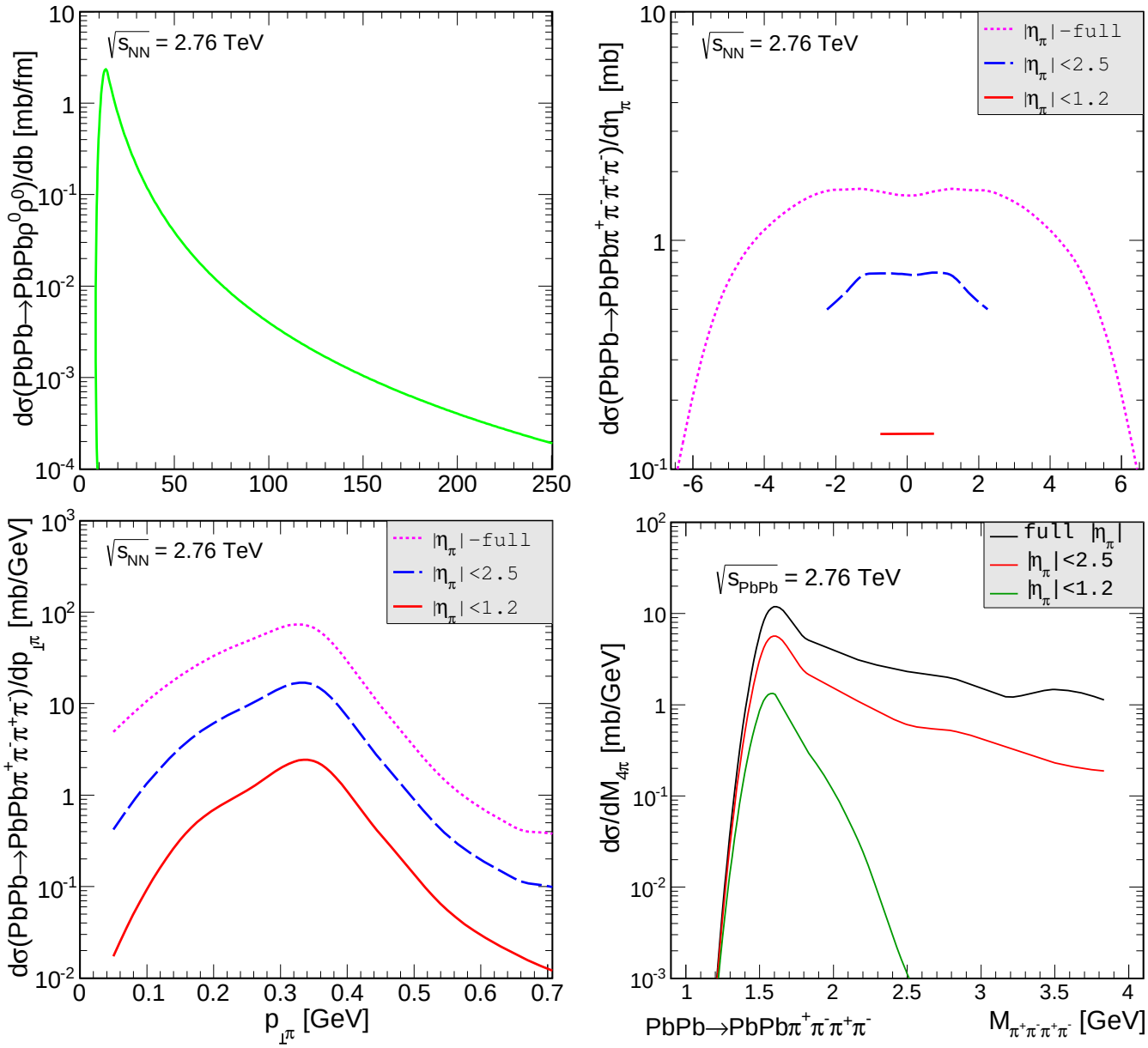




missing mechanisms: $AA \to AA\rho^0(1450) \to 4\pi$
$AA \to AA\rho^0(1700) \to 4\pi$ **?**

New results on $\gamma p \to \rho' p$ from H1

Double-scattering mechanism at LHC

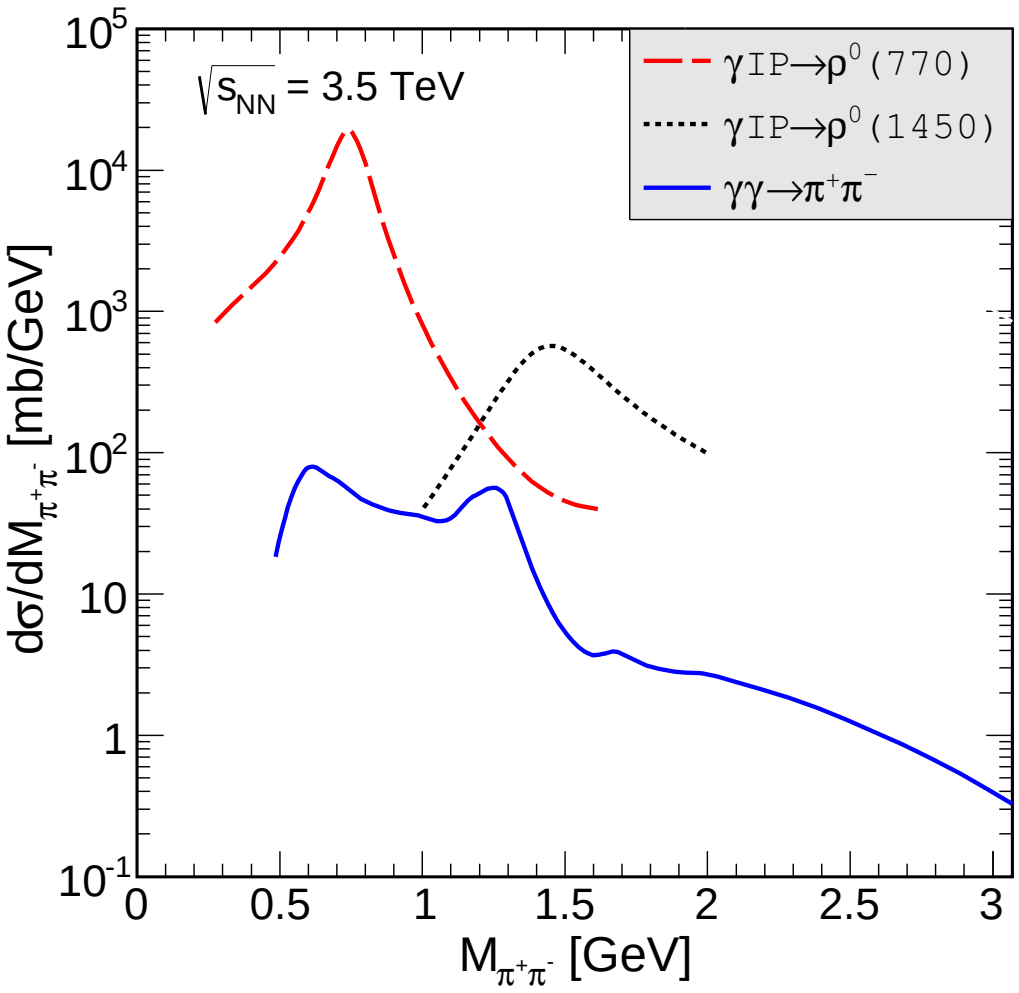


Comparison of the mechanisms

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

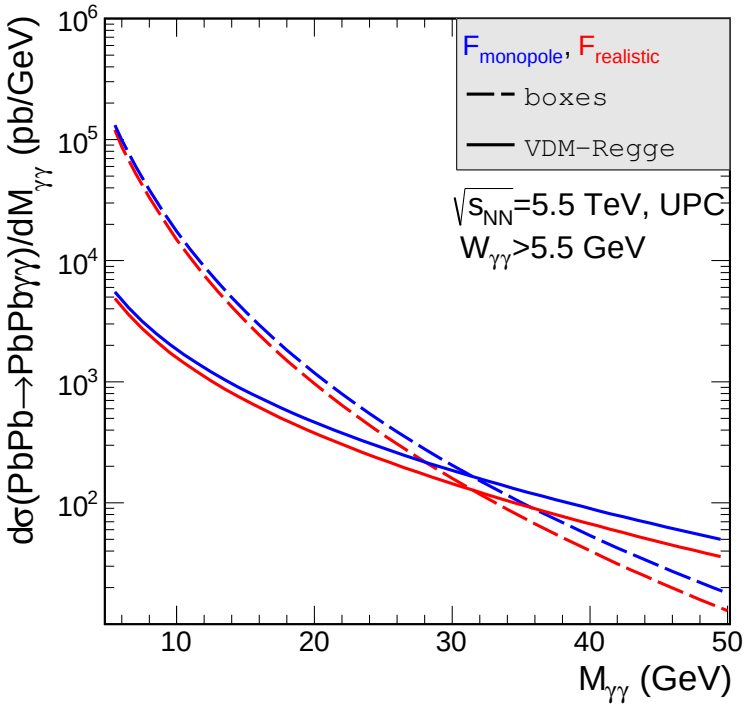
Reference: M. Kłusek-Gawenda and A. Szczurek "Double-scattering mechanism in the exclusive $AA \to AA\rho^0\rho^0$ reaction in ultrarelativistic collisions",
Phys. Rev. **C89** (2014) 024912

Two-pion production



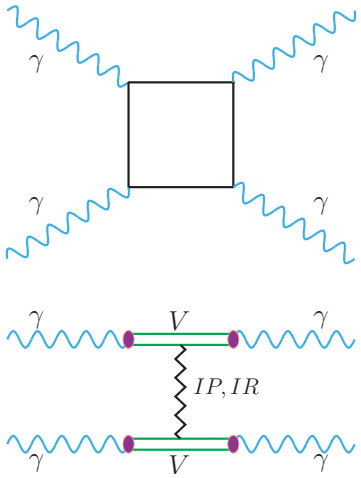
Reference: M. Kłusek-Gawenda and A. Szczurek, "$\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy ion collisions", Phys. Rev. **C87** (2013) 054908

AA→AA$\gamma\gamma$ - form factor dependence



⇨ realistic

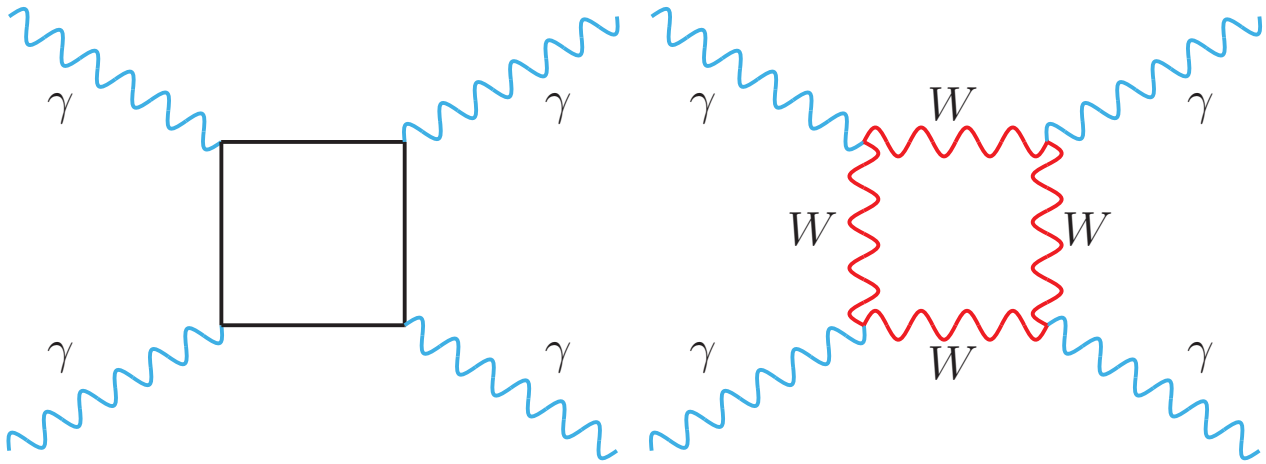
⇨ monopole



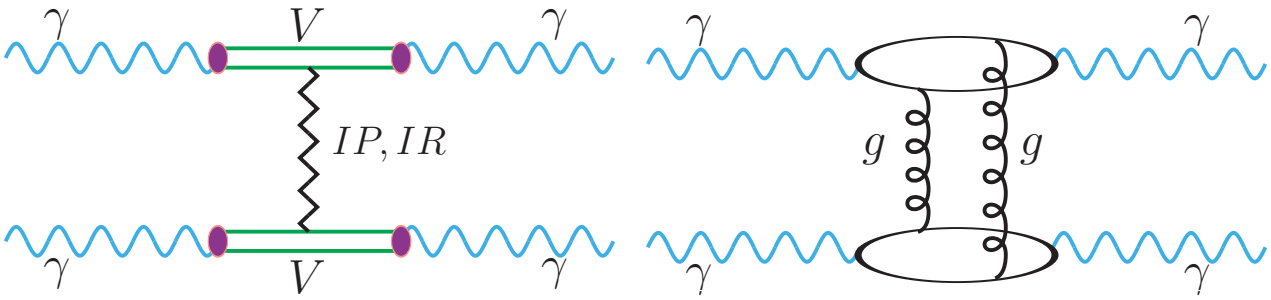
$\frac{\sigma_{monopole}}{\sigma_{realistic}}$ ↗ for larger values of $M_{\gamma\gamma}$

$\gamma - \gamma$ elastic scattering

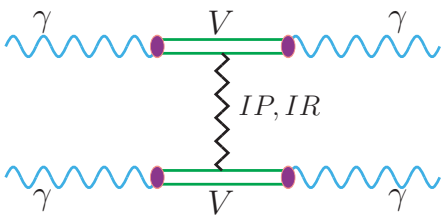
WELL-KNOWN



WE ADD



VDM-Regge contribution



$$\mathcal{A}_{\gamma\gamma\to\gamma\gamma}(s,t) = \sum_i^3 \sum_j^3 C_{\gamma\to V_i} \mathcal{A}_{V_iV_j\to V_iV_j} C_{\gamma\to V_j}$$

$$\approx \left(\sum_{i=1}^3 C_{\gamma\to V_i}\right) \mathcal{A}_{VV\to VV}(s,t) \left(\sum_{j=1}^3 C_{\gamma\to V_j}\right)$$

$$\boxed{i,j = \rho,\omega,\phi}$$

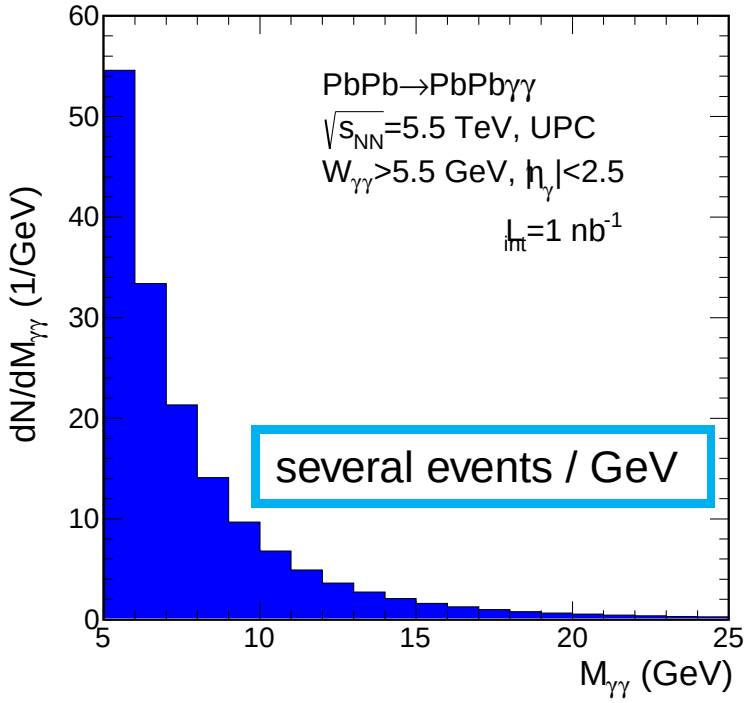
$$\mathcal{A}_{VV\to VV}(s,t) = \mathcal{A}(s,t) \exp\left(\frac{B}{2}t\right)$$

$$\mathcal{A}(s,t) \approx s\left((1+i)\, C_{\mathbf{R}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{R}}(t)-1} + i C_{\mathbf{P}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{P}}(t)-1}\right)$$

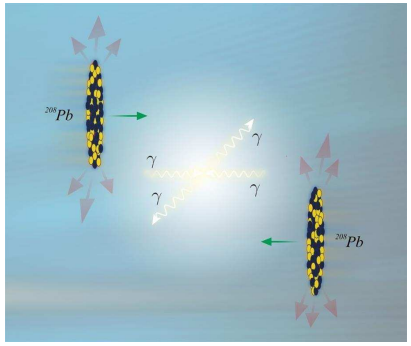
- $C^2_{\gamma\to V_i} = \frac{e}{f_{V_i}}$
- $C_{\mathbf{P}}$, $C_{\mathbf{R}}$ - Donnachie-Landshoff
- $\alpha_{\mathbf{R}}(t)$, $\alpha_{\mathbf{P}}(t)$ - trajectories

Photon collisions:
Photonic billiards might be the newest game!

number of count



www.eurekalert.org/pub_releases/2016-05/thni-pcp0

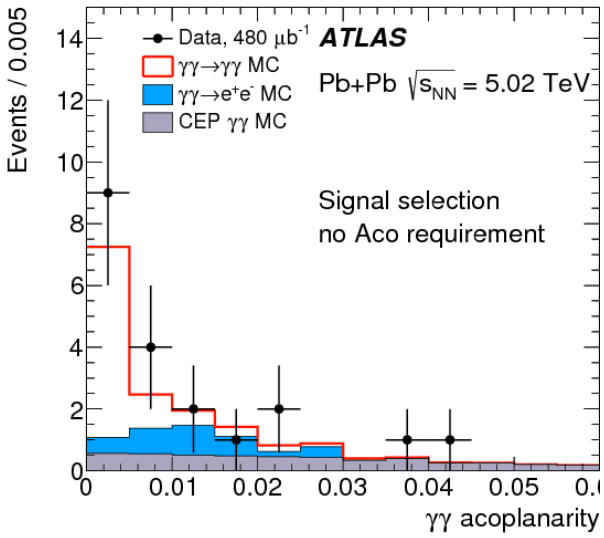


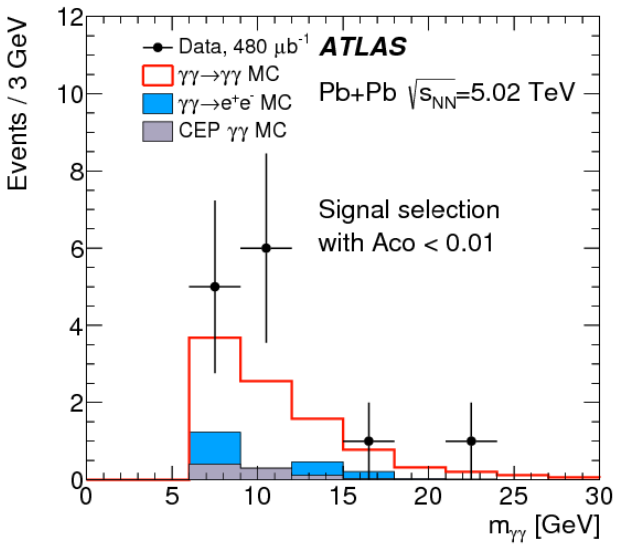
σ(PbPb→PbPb$\gamma\gamma$) [nb] at LHC ($\sqrt{s_{NN}}$ = 5.5 TeV) and FCC ($\sqrt{s_{NN}}$ = 39 TeV)

	cuts	boxes $F_{realistic}$	boxes $F_{monopole}$	VDM-Regge $F_{realistic}$	VDM-Regge $F_{monopole}$
	$W_{\gamma\gamma} > 5$ GeV	306	349	31	36
	$W_{\gamma\gamma} > 5$ GeV, $p_{t,\gamma} > 2$ GeV	159	182	7E-9	8E-9
L	$E_\gamma > 3$ GeV	16 692	18 400	17	18
	$E_\gamma > 5$ GeV	4 800	5 450	9	611
H	$E_\gamma > 3$ GeV, $\lvert y_\gamma \rvert < 2.5$	183	210	8E-2	9E-2
	$E_\gamma > 5$ GeV, $\lvert y_\gamma \rvert < 2.5$	54	61	4E-4	7E-4
C	$p_{t,\gamma} > 0.9$ GeV, $\lvert y_\gamma \rvert < 0.7$ (ALICE cuts)	107			
	$p_{t,\gamma} > 5.5$ GeV, $\lvert y_\gamma \rvert < 2.5$ (CMS cuts)	10			
F	$W_{\gamma\gamma} > 5$ GeV	6 169		882	
C	$E_\gamma > 3$ GeV	4 696 268		574	
C					

AA→AA$\gamma\gamma$ - theoretical predictions vs. experiment

- ATLAS Collaboration (M. Aaboud et al.), Nature Phys. **13** (2017) 852
  Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC





✗ $p_{t_\gamma} > 3$ GeV
✗ $|\eta_\gamma| < 2.4$
✗ $M_{\gamma\gamma} > 6$ GeV
✗ $p_{t_{\gamma\gamma}} < 2$ GeV
✗ Aco < 0.01

✔ $\gamma\gamma \to \gamma\gamma$ - using our calculations
✔ background:
  ✔ $\gamma\gamma \to e^+e^-$
  ✔ $gg \to \gamma\gamma$
  ✔ $\gamma\gamma \to q\bar{q}$
✔ 13 events were observed

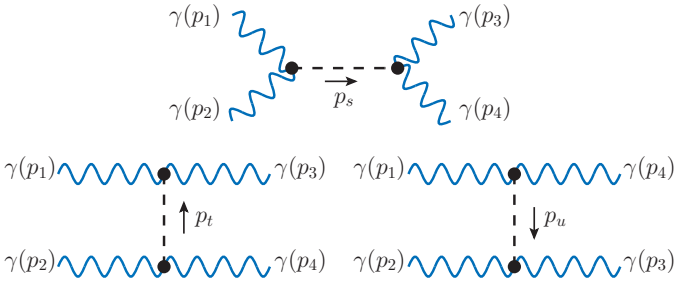
ATLAS ⇒ $\sigma = 70 \pm 20(\text{stat.}) \pm 17(\text{syst.})$ nb

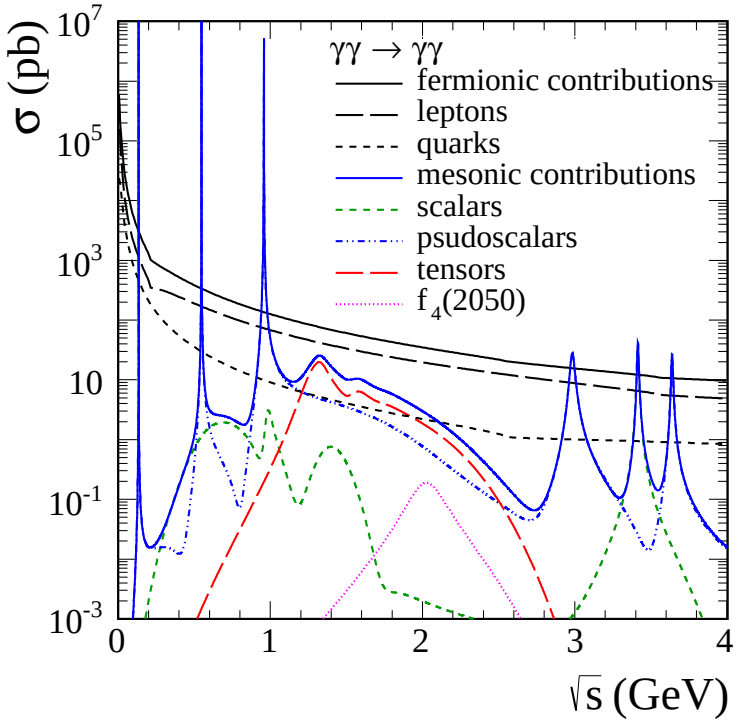
from ours model ⇒ $\sigma = 49 \pm 10$ nb

PRL (2013)/(2016) ⇒ $\sigma = 45 \pm 9$ nb

New result from CMS, Quark Matter 2018

$M_{\gamma\gamma} < 5$ GeV $\Rightarrow$ Meson excha





$f_0(500)$	π^0	$f_2(1270)$	
$f_0(980)$	η	$a_2(1320)$	
$a_0(980)$	$\eta'(958)$	$f_2'(1525)$	$f_4(2050)$
$f_0(1370)$	$\eta_c(1S)$	$f_2(1565)$	
$\chi_{c0}(1P)$	$\eta_c(2S)$	$a_2(1700)$	

$s-$channel diagrams (leading to peaks at $\sqrt{s} \cong m_M$)

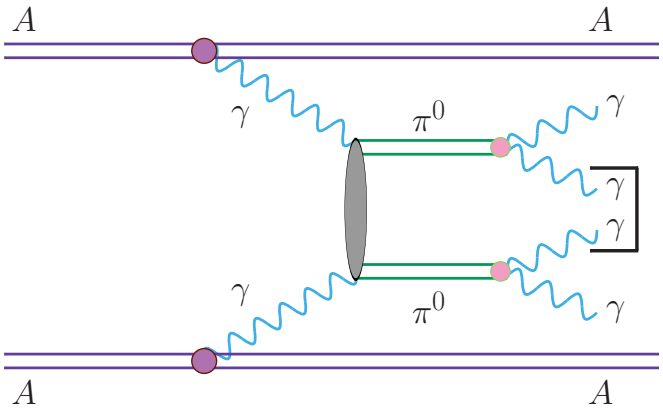
$t-$ and $u-$channels (leading to broad continua)

- P. Lebiedowicz, A. Szczurek,
  The role of meson exchanges in light-by-light scattering,
  Phys. Lett. **B772** (2017) 330

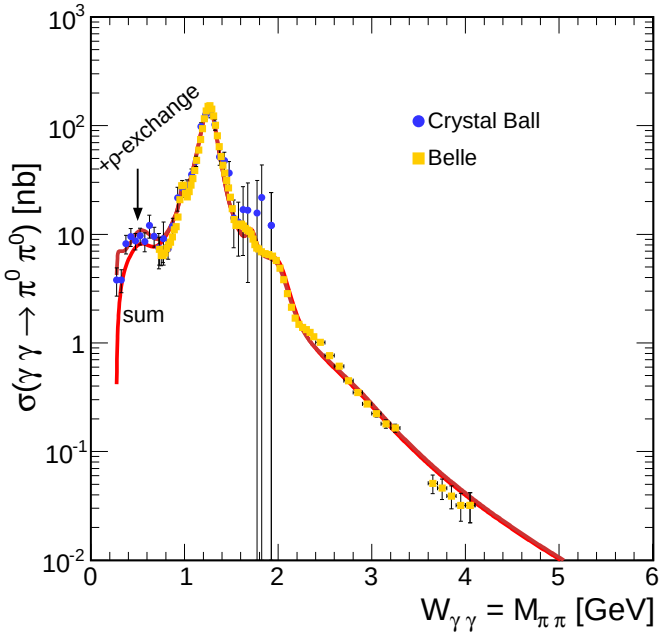
η & η' at UPC of AA...

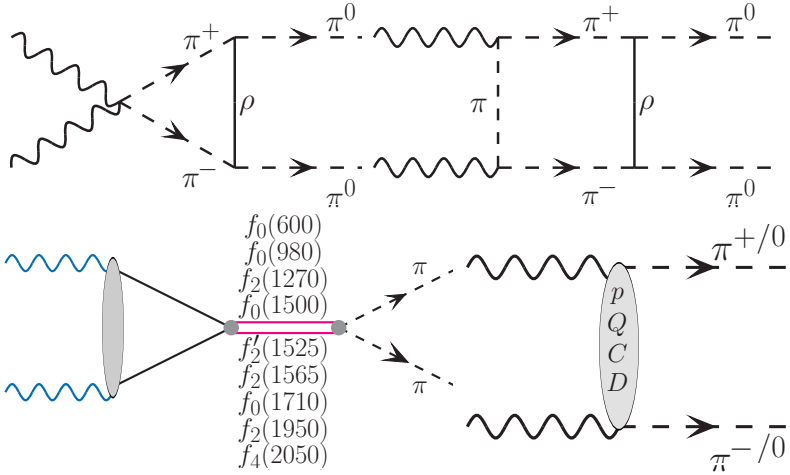
$M_{\gamma\gamma} < 5$ GeV $\Rightarrow \pi^0\pi^0$ Background

- M. K-G, A. Szczurek, $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy ion collisions, Phys. Rev. **C87** (2013) 054908
  - $W_{\gamma\gamma} \in (2m_\pi - 6)$ GeV
  - total cross section & angular distributions
  - simultaneously for $\gamma\gamma \to \pi^+\pi^-$ & $\pi^0\pi^0$



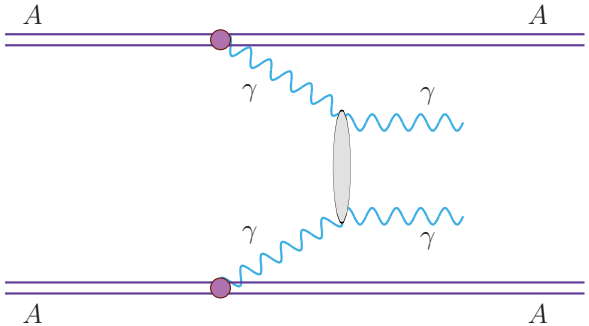
$\gamma\gamma \to \pi^0\pi^0$



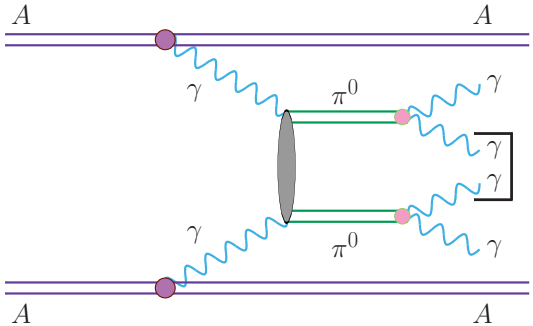


AA→AA$\gamma\gamma$ for $M_{\gamma\gamma} < 5$ GeV ? NEW

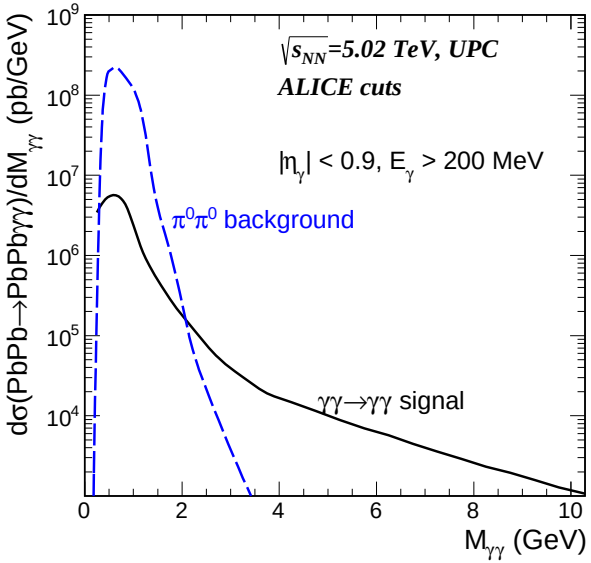
signal

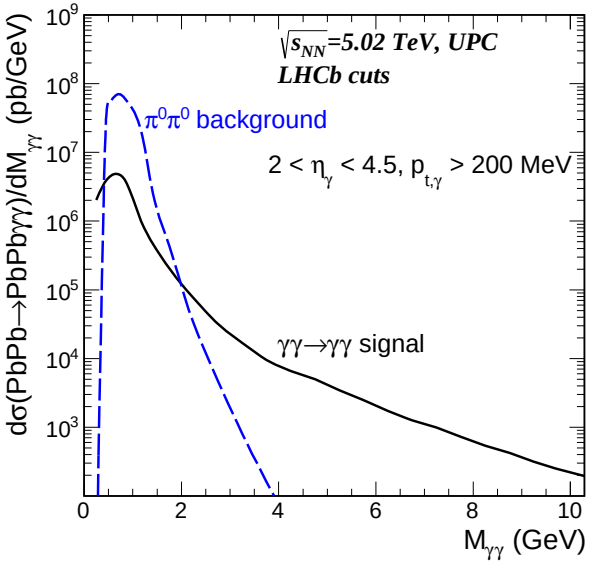


background



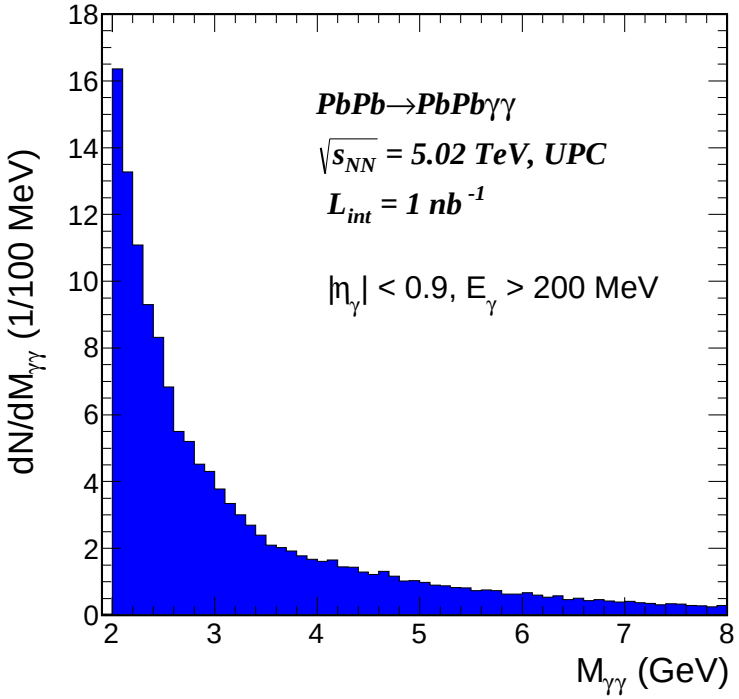
experiment	pseudorapidity range	other condition
ALICE	$-0.9 < \eta_\gamma < 0.9$	$E_\gamma > 200$ MeV
LHCb	$2.0 < \eta_\gamma < 4.5$	$p_{t,\gamma} > 200$ MeV

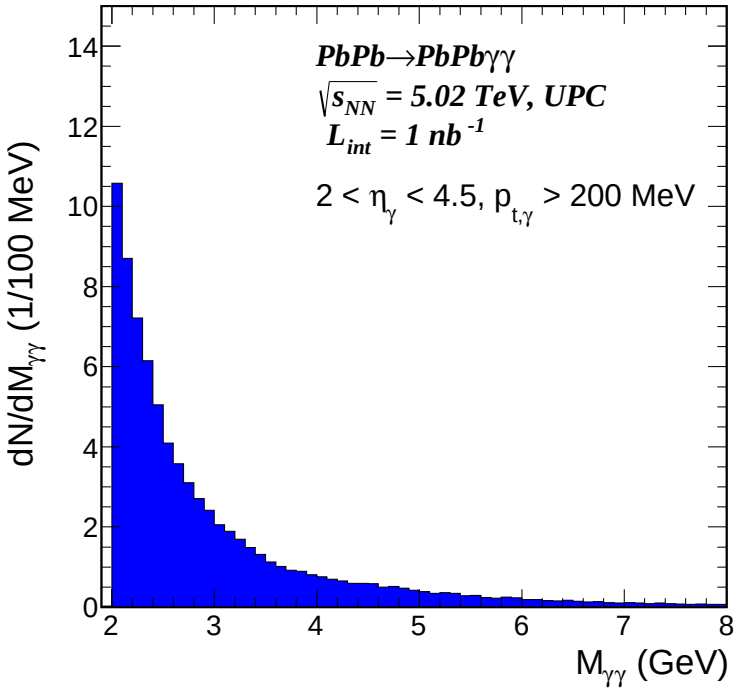




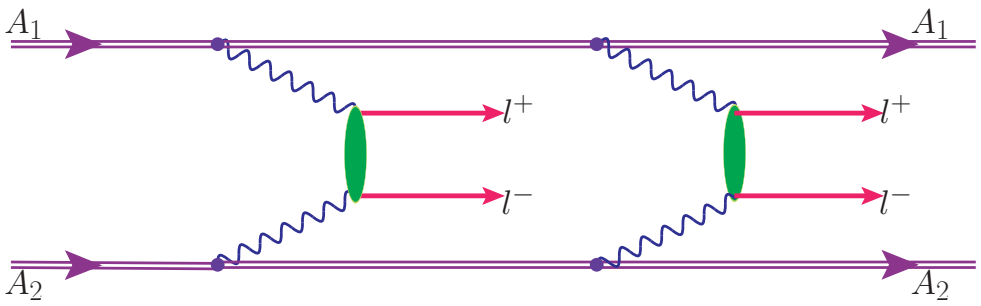
AA→AA$\gamma\gamma$ for $M_{\gamma\gamma} > 2$ GeV ?

Our Predictions





Four-lepton production

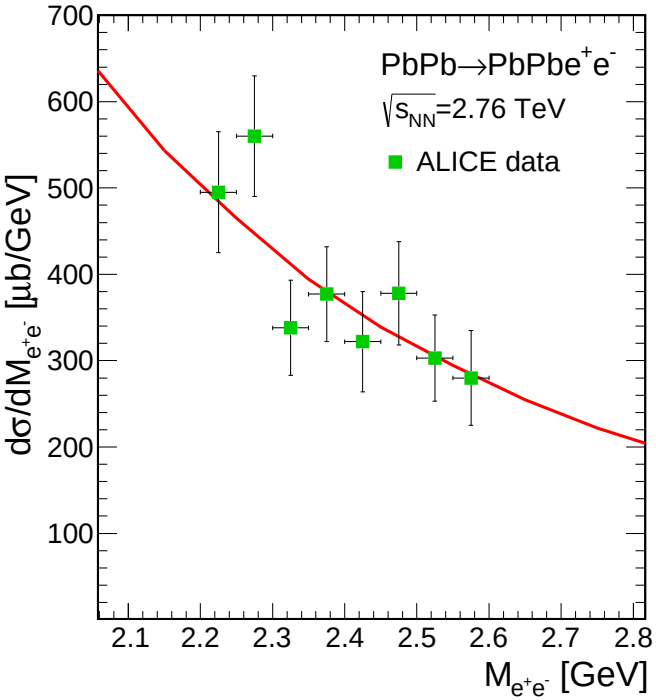


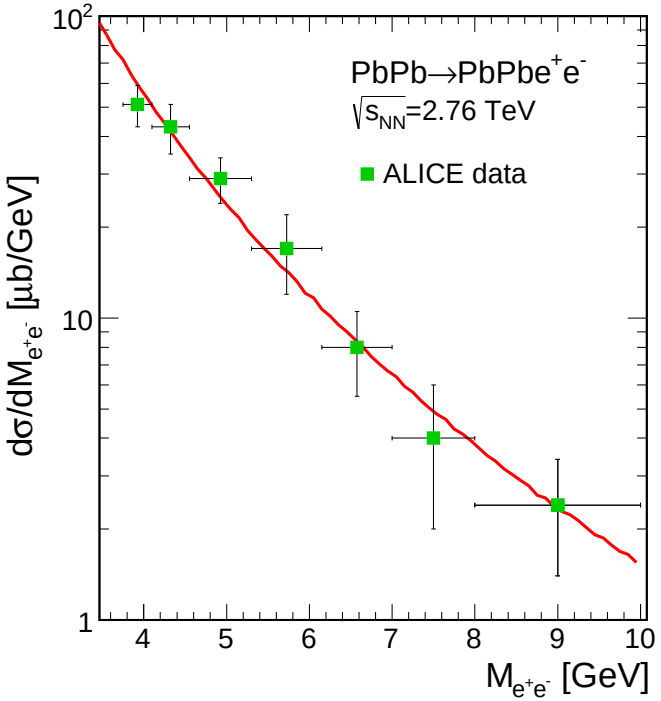
$$
\begin{aligned}
P_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b;y_{l^+},y_{l^-},p_{t,l}) &= \int N(\omega_1,\mathbf{b_1})\,N(\omega_2,\mathbf{b_2})S^2_{abs}(\mathbf{b}) \\
&\times \frac{\mathrm{d}\sigma_{\gamma\gamma\to l_1 l_2}(W_{\gamma\gamma})}{\mathrm{d}z}\,\mathrm{d}\bar{b}_x\,\mathrm{d}\bar{b}_y\,\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{l_1 l_2} \\
\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2 l_1^+ l_2^- l_3^+ l_4^-}}{\mathrm{d}y_{l^+}\,\mathrm{d}y_{l^-}\,\mathrm{d}p_{t,l}\,\mathrm{d}y_{l^+}\,\mathrm{d}y_{l^-}\,\mathrm{d}p_{t,l}} &= \frac{1}{2}\int \frac{\mathrm{d}P^{I}_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b;y_{l^+},y_{l^-},p_{t,l})}{\mathrm{d}y_{l^+}\,\mathrm{d}y_{l^-}\,\mathrm{d}p_{t,l}} \\
&\times \frac{\mathrm{d}P^{II}_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b;y_{l^+},y_{l^-},p_{t,l})}{\mathrm{d}y_{l^+}\,\mathrm{d}y_{l^-}\,\mathrm{d}p_{t,l}}\,\mathrm{d}^2b \\
\sigma_{A_1A_2\to A_1A_2 l^+l^-} &= \int \frac{\mathrm{d}P_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b;y_{l^+},y_{l^-},p_{t,l})}{\mathrm{d}y_{l^+}\,\mathrm{d}y_{l^-}\,\mathrm{d}p_{t,l}}\mathrm{d}^2b \\
&\times \mathrm{d}y_{l^+}\,\mathrm{d}y_{l^-}\,\mathrm{d}p_{t,l}
\end{aligned}
$$

$AA \to AAe^+e^-$ - calculations vs. data

- ALICE Collaboration (Abbas, E. et al.),
  Charmonium and e^+e^- pair photoproduction at mid-rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,
  Eur. Phys. J. **C73** (2013) 2617

$2.2\ \text{GeV} < M_{ee} < 2.6\ \text{GeV}$ $|y_e| < 0.9$ $3.7\ \text{GeV} < M_{ee} < 10\ \text{GeV}$

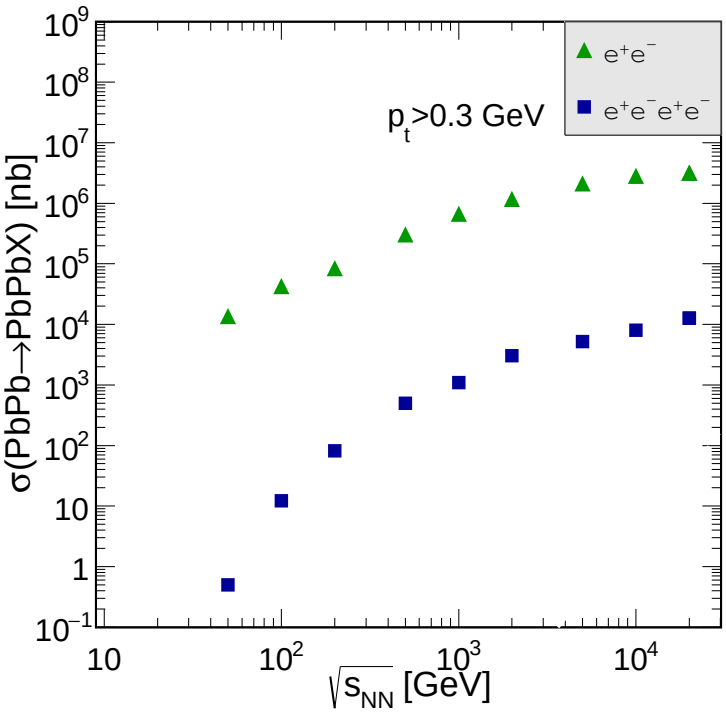




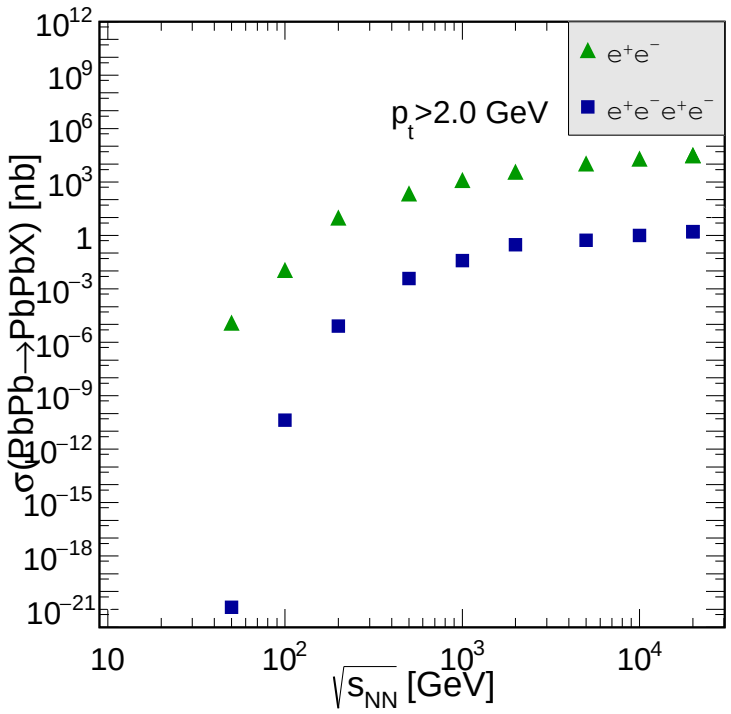
Good description of single pair production $\Rightarrow$ two e^+e^- pair production

$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

$p_t > 0.3$ GeV

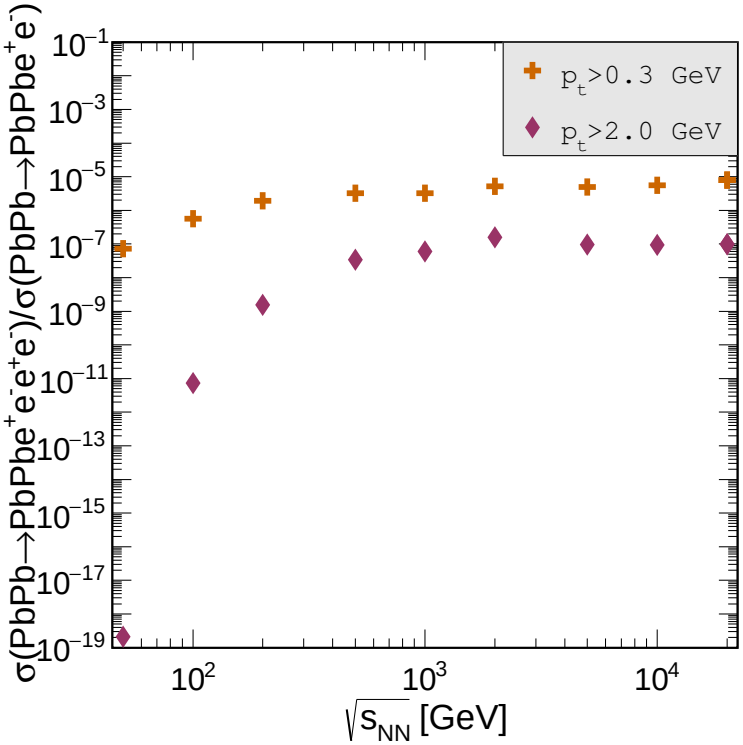


$p_t > 2.0$ GeV



$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

$$\frac{\sigma_{AA\to AAe^+e^-e^+e^-}}{\sigma_{AA\to AAe^+e^-}}$$



Ratio depends on $\sqrt{s_{NN}}$ and $p_{t,min}$

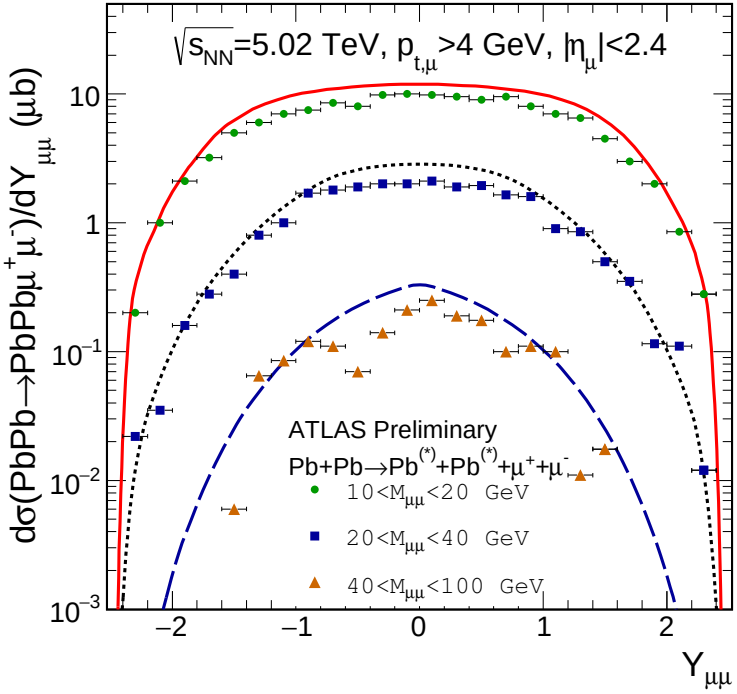
$AA \to AA\mu^+\mu^-$ - calculations vs. data

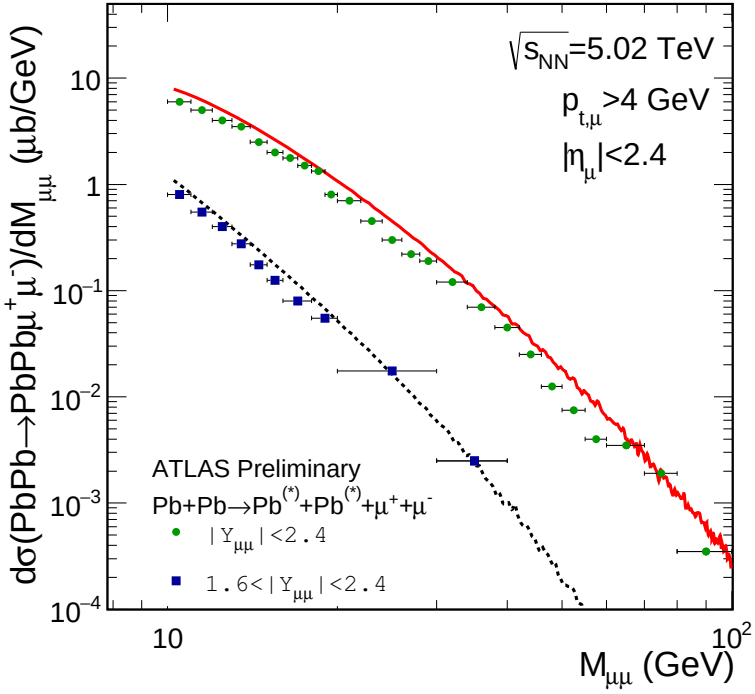
- ATLAS Collaboration,
  Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ *TeV with the ATLAS detector at the LHC*,
  ATLAS-CONF-2016-025

$$\frac{d\sigma}{dY_{\mu^+\mu^-}}$$

$$p_{t,\mu} > 4 \text{ GeV}, \ |\eta_e| < 0.9$$

$$\frac{d\sigma}{dM_{\mu^+\mu^-}}$$





Our results above preliminary ATLAS data

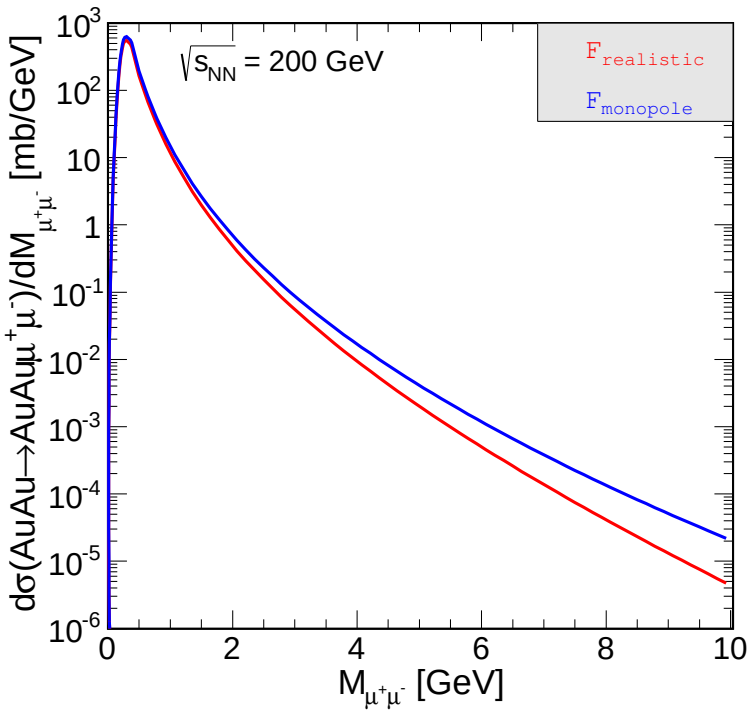
AA→AA$\mu^+\mu^-$ - form factor

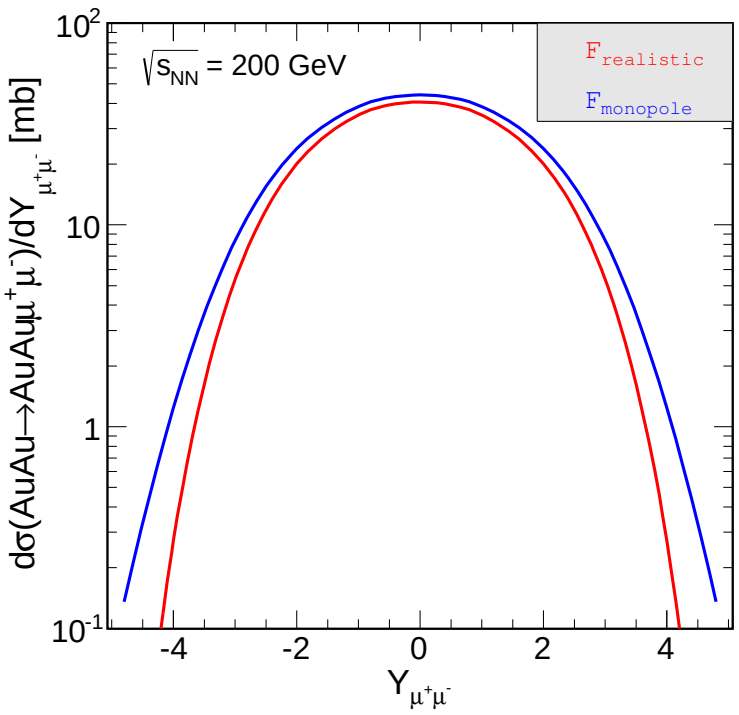
$M_{\mu^+\mu^-}$

⇨ realistic

⇨ monopole

$Y_{\mu^+\mu^-}$

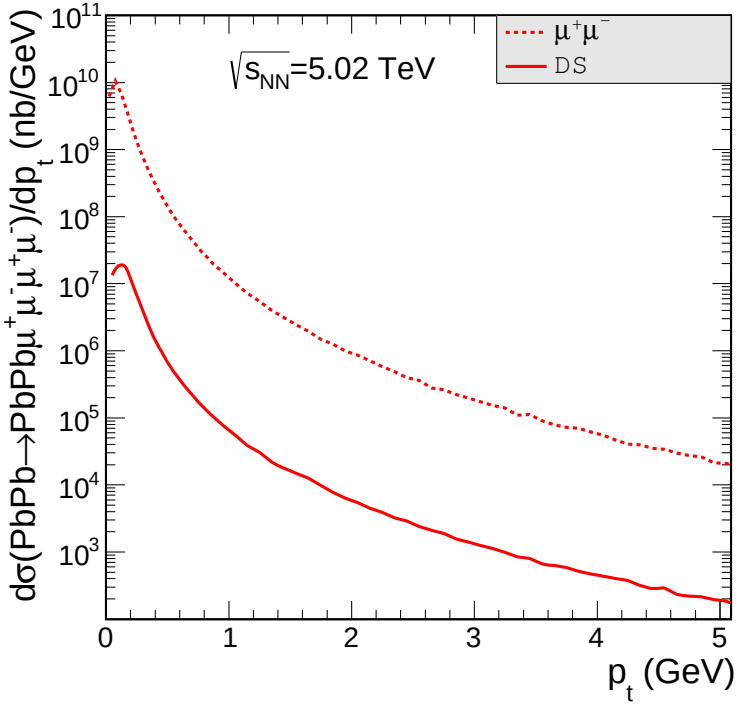




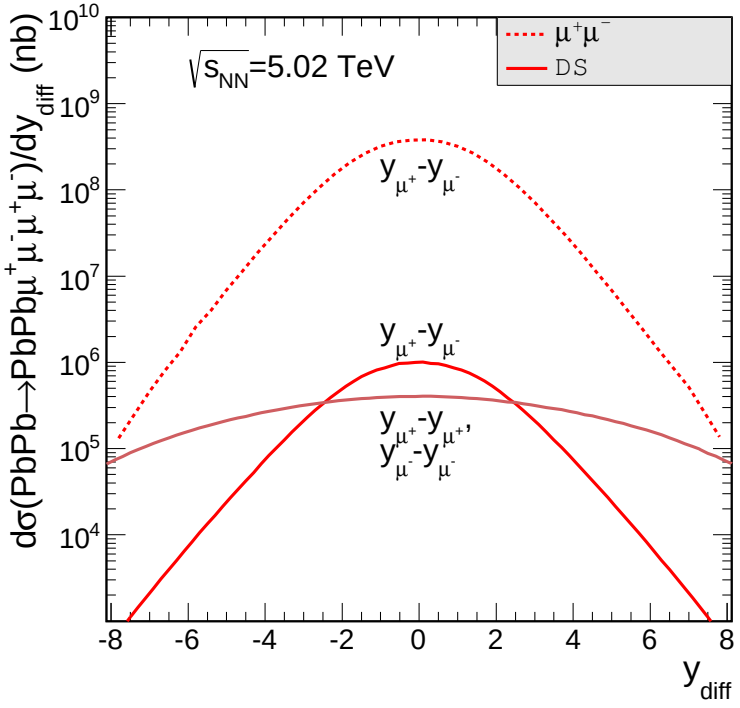
RHIC energy

$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

$p_{t,\mu}$



y_{diff}

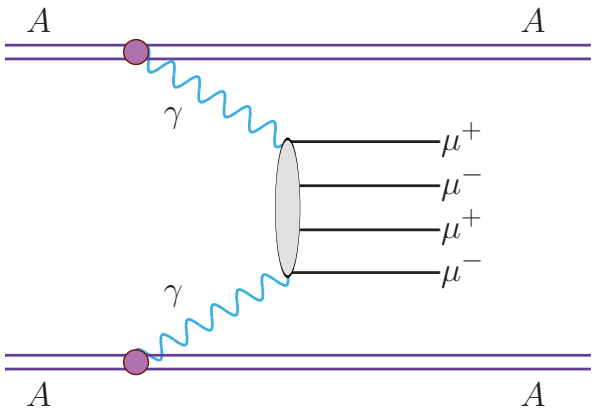


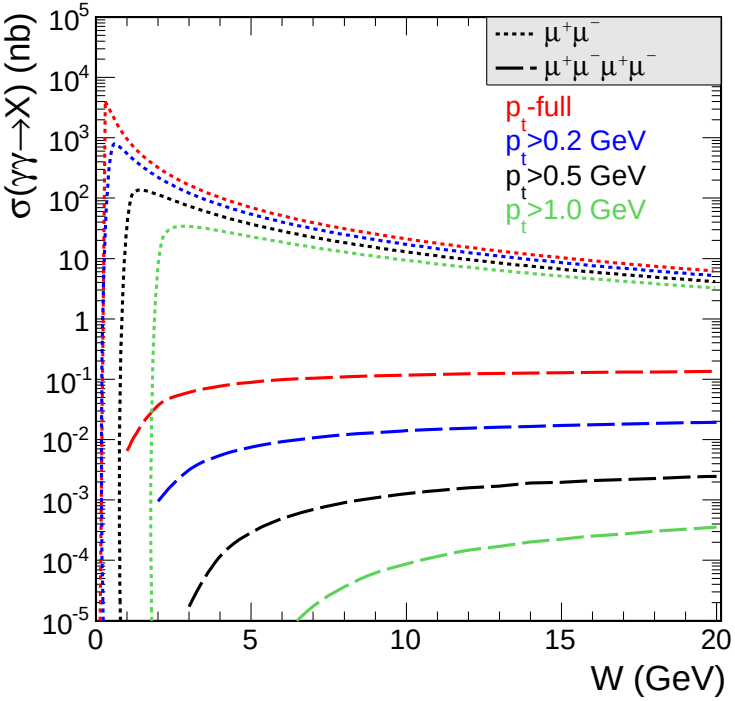
Similar like for electron-positron production: $\sigma_{\mu^+\mu^-} \simeq 1000 \times \sigma_{\mu^+\mu^-\mu^+\mu^-}$

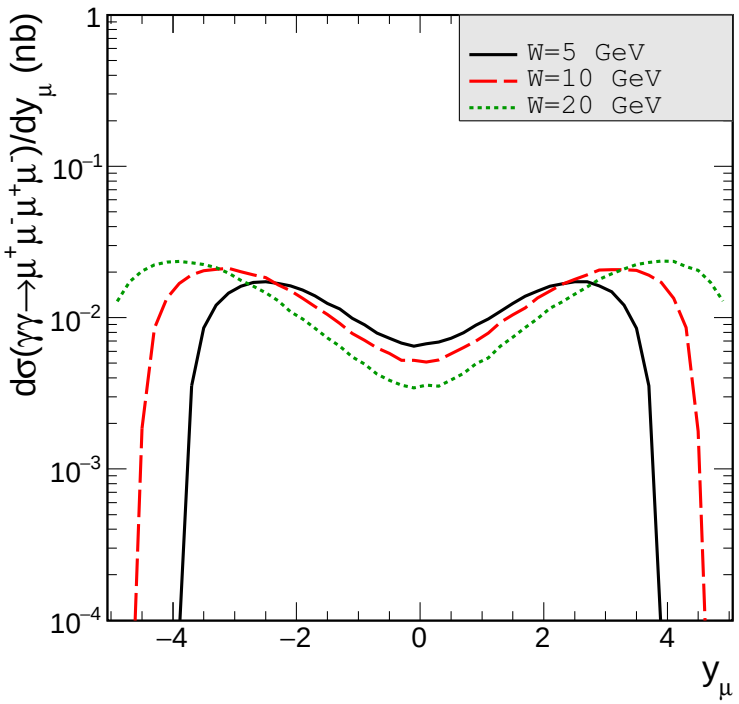
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - single scattering

$\Uparrow$

KATIE- an event generator that is specially designed to deal with initial states that have an explicit transverse momentum dependence, but can also deal with on-shell initial states. KATIE is a parton-level generator for hadron scattering, but requires only a few adjustments to deal with photon scattering.



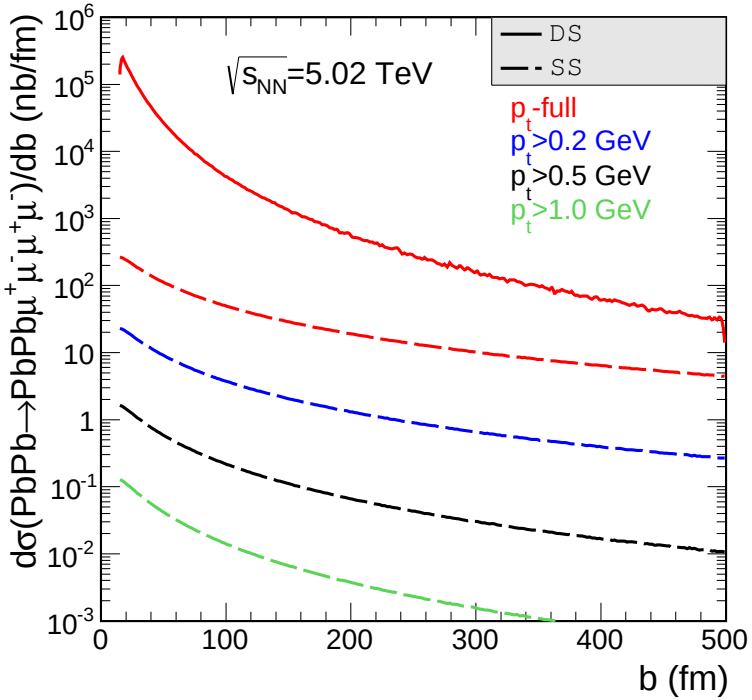


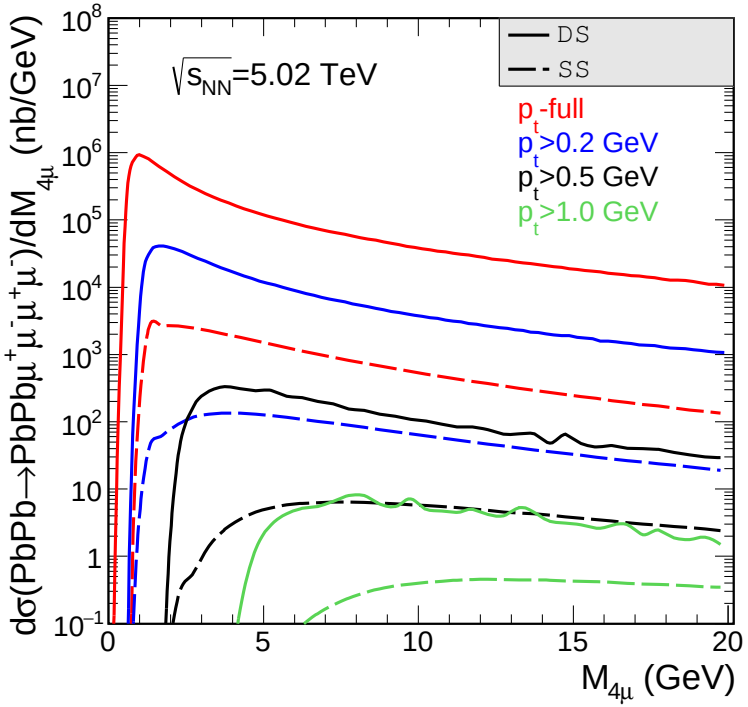


AA→AA$\mu^+\mu^-\mu^+\mu^-$

impact parameter

$W_{\gamma\gamma} = M_{4\mu}$





↑ purely theoretical distribution

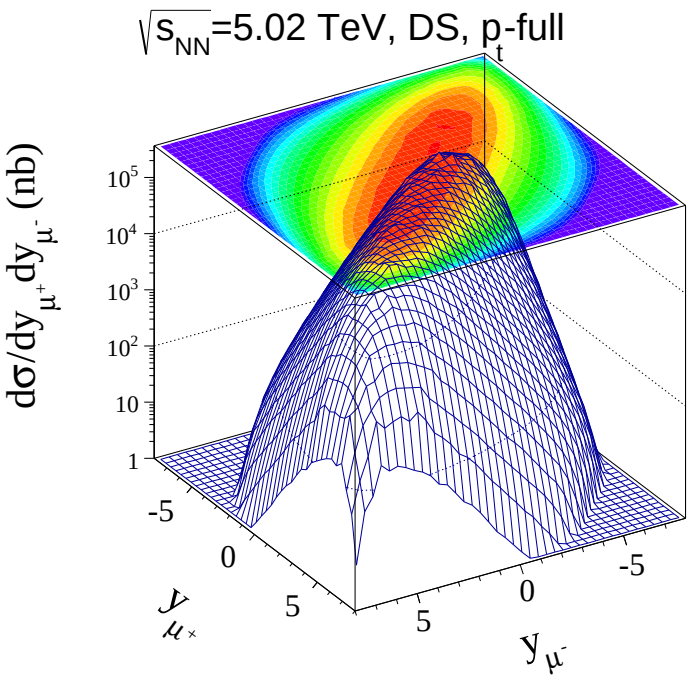
↑ DS dominates

It is difficult to isolate range of SS domination

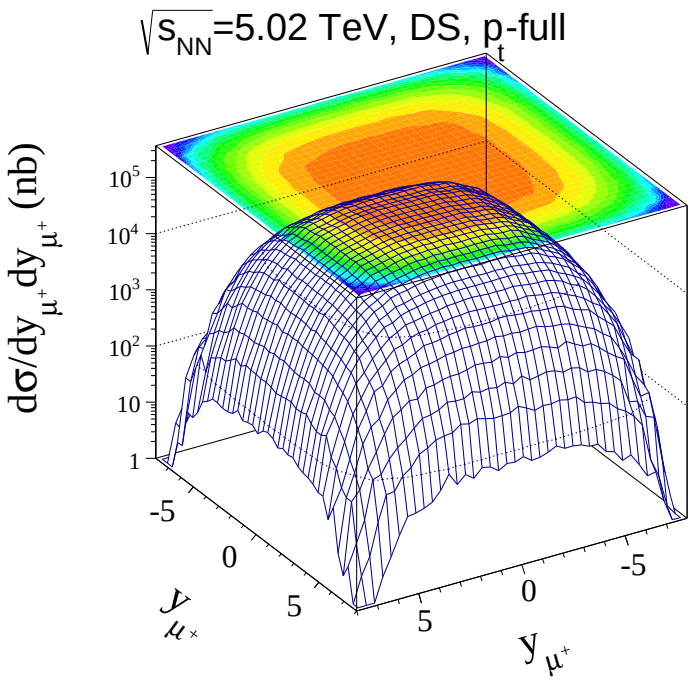
*DS - double-scattering mechanism
*SS - a NEW single-scattering mechanism

AA→AA$\mu^+\mu^-\mu^+\mu^-$

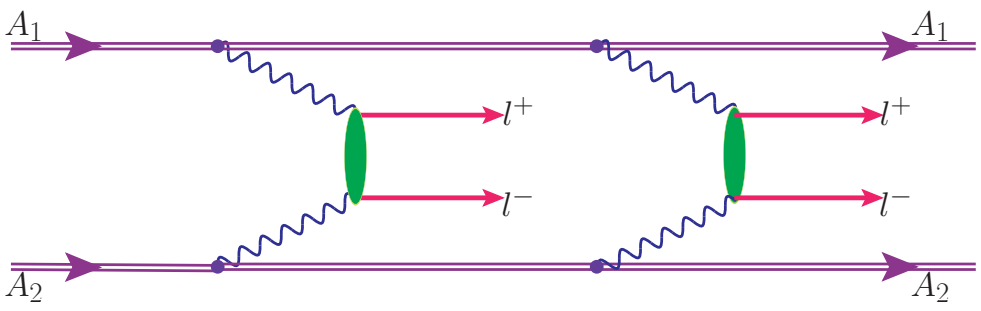
y_{μ^+}, y_{μ^-}



$y_{\mu^\pm}, y_{\mu^\pm}$



$p_{t,\mu^+} \simeq p_{t,\mu^-} \Rightarrow$ construction of similar distributions by ALICE or CMS?



The number of counts for L_{int} = 1 nb^{-1}

(4μ), $\sqrt{s_{NN}} = 5.02$ TeV		$(4e)$, $\sqrt{s_{NN}} = 5.5$ TeV	
experimental cuts	N	experimental cuts	N
$\lvert y_i \rvert < 2.5$, $p_t > 0.5$ GeV	815	$\lvert y_i \rvert < 2.5$, $p_t > 0.5$ GeV	235
$\lvert y_i \rvert < 2.5$, $p_t > 1.0$ GeV	53	$\lvert y_i \rvert < 2.5$, $p_t > 1.0$ GeV	10
$\lvert y_i \rvert < 0.9$, $p_t > 0.5$ GeV	31	$\lvert y_i \rvert < 1.0$, $p_t > 0.2$ GeV	649
$\lvert y_i \rvert < 0.9$, $p_t > 1.0$ GeV	2	$\lvert y_i \rvert < 1.0$, $p_t > 1.0$ GeV	1
$\lvert y_i \rvert < 2.4$, $p_t > 4.0$ GeV	$\ll 1$		

CMS and ALICE $\Rightarrow p_{t,\text{cut}} = 1$ GeV

ALICE $\Rightarrow p_{t,\text{cut}} = 0.2$ GeV

ATLAS $\Rightarrow p_{t,\text{cut}} = 4$ GeV

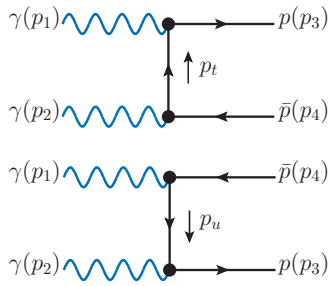
Potential background

$\downarrow \sqrt{s_{NN}} = 5.5$ TeV, $\lvert y \rvert < 4.9$

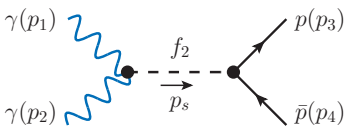
Reaction	$p_{t,min}$ = 0.3 GeV	$p_{t,min}$ = 0.5 GeV
$PbPb \to PbPb\pi^+\pi^-\pi^+\pi^-$	2.954 mb	8.862 μb
$PbPb \to PbPbe^+e^-e^+e^-$	7.447 μb	0.704 μb

Proton-antiproton pair production

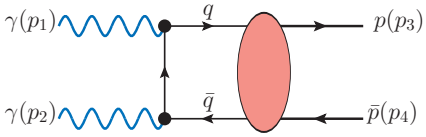
$$\gamma(p_1,\lambda_1)+\gamma(p_2,\lambda_2)\to p(p_3,\lambda_3)+\bar{p}(p_4,\lambda_4)$$



$$\begin{aligned}\mathcal{M}^{p-exchange}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = \quad & (-i)\,\epsilon_{1\mu}(\lambda_1)\epsilon_{2\nu}(\lambda_2)\\ & \times\bar{u}(p_3,\lambda_3)\Big(i\Gamma^{(\gamma pp)\,\mu}(p_3,p_t)\frac{i(/p_t+m_p)}{t-m_p^2+i\epsilon}i\Gamma^{(\gamma pp)\,\nu}(p_t,-p_4)\\ & +i\Gamma^{(\gamma pp)\,\nu}(p_3,p_u)\frac{i(/p_u+m_p)}{u-m_p^2+i\epsilon}i\Gamma^{(\gamma pp)\,\mu}(p_u,-p_4)\Big)v(p_4,\lambda_4)\end{aligned}$$



$$\begin{aligned}\mathcal{M}^{f_2(1270),f_2(1950)}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = \quad & (-i)\,\epsilon_{1\mu}(\lambda_1)\,\epsilon_{2\nu}(\lambda_2)\,i\Gamma^{(f_2\gamma\gamma)\,\mu\nu\kappa\lambda}(p_1,p_2)\,i\Delta^{(f_2)}_{\kappa\lambda,\alpha\beta}(p_s)\\ & \times\bar{u}(p_3,\lambda_3)i\Gamma^{(f_2p\bar{p})\,\alpha\beta}(p_3,p_4)\,v(p_4,\lambda_4)\end{aligned}$$



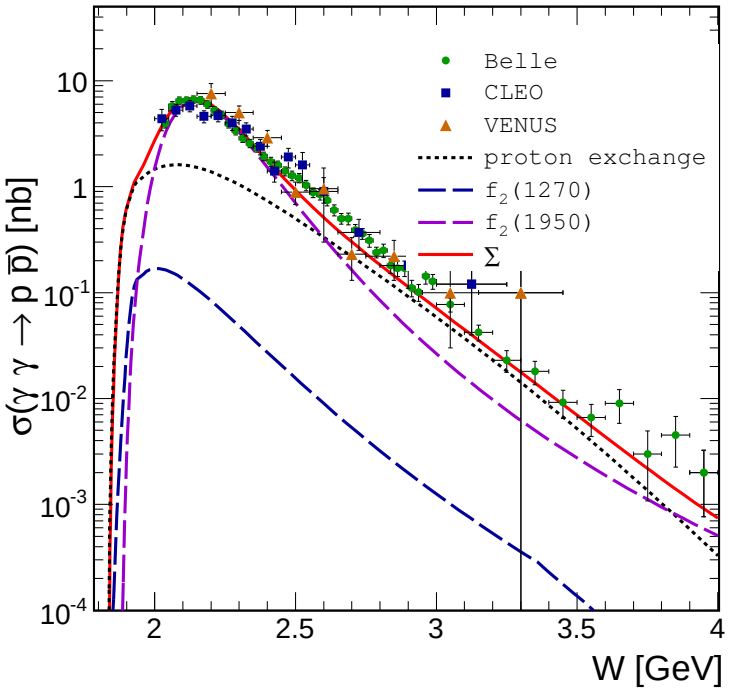
➢ M. Diehl, P. Kroll, and C. Vogt,
Two-photon annihilation into baryon anti-baryon pairs,
Eur. Phys. J. **C26** (2003) 567

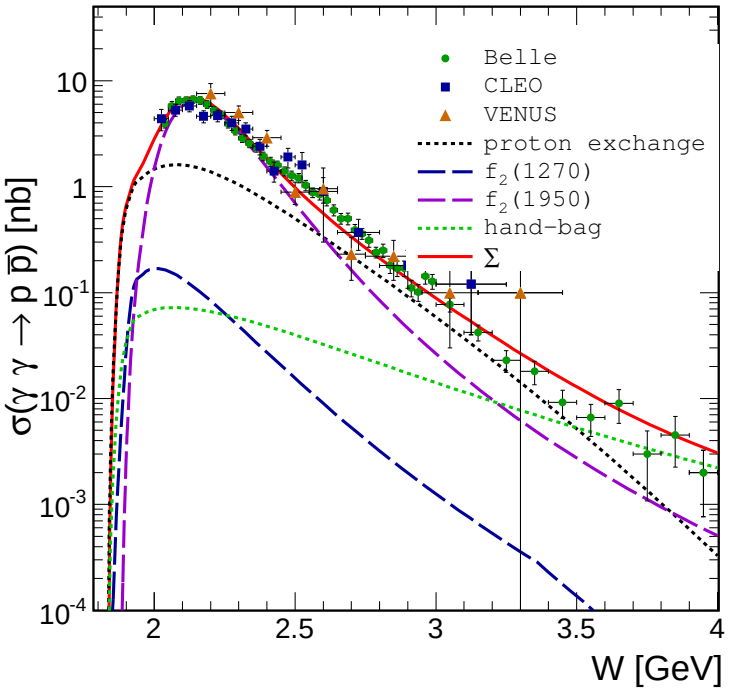
Free parameters: off-shell form factors, the coupling constants.

$\gamma\gamma \to p\bar{p}$ - results vs. data

$|\cos\theta| < 0.6$

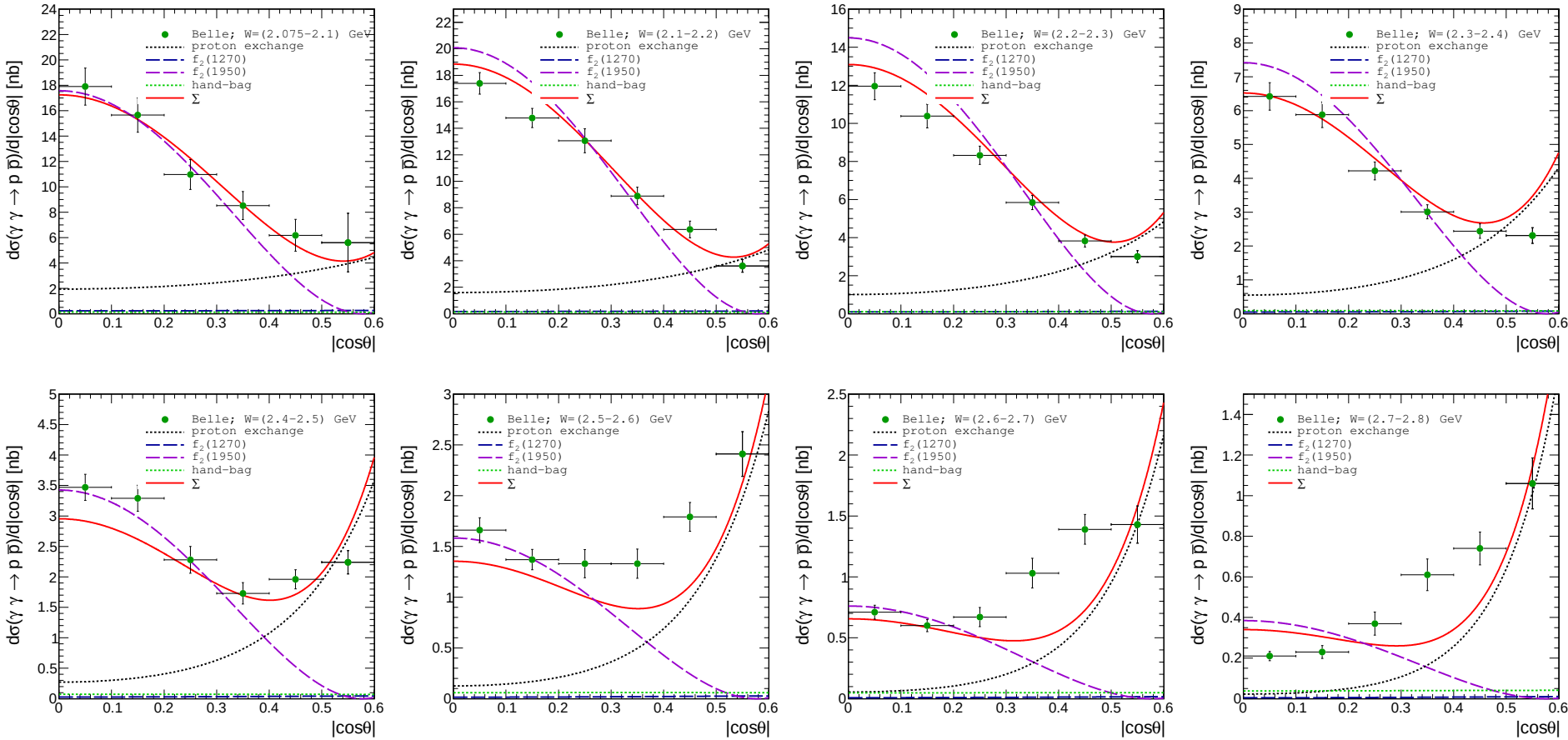
$+$ hand-bag model





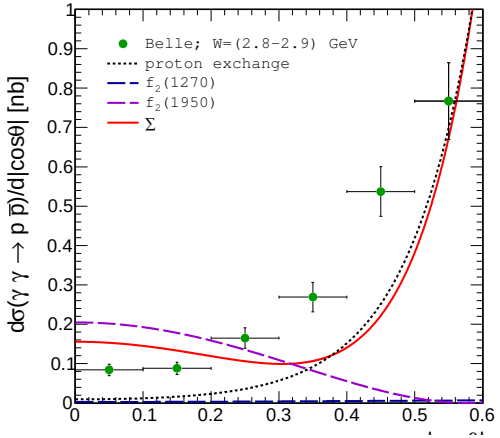
Good description of $\sigma(W)$ data $\Rightarrow \frac{d\sigma}{dz}$?

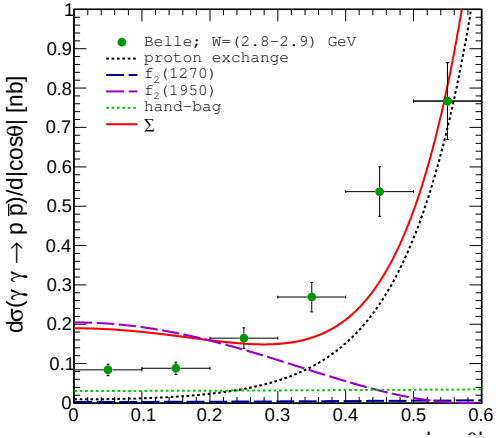
Angular distributions

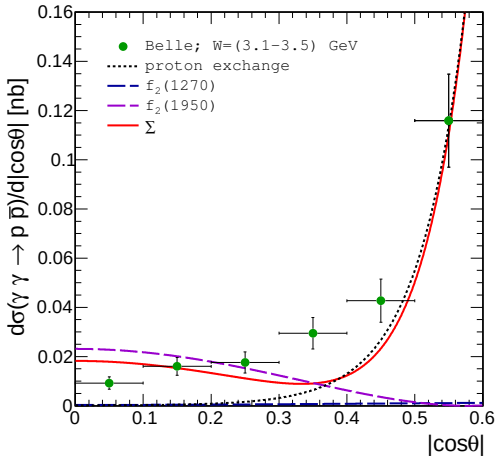


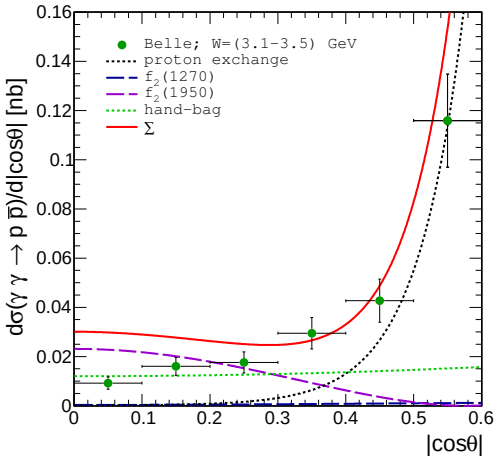
without hand-bag

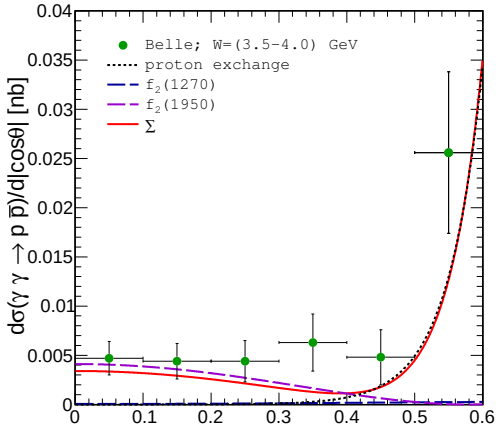
with hand-bag model

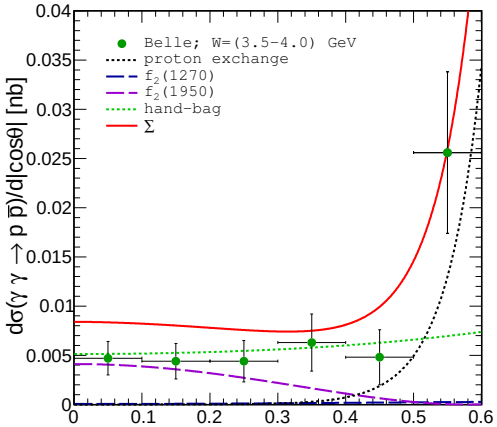






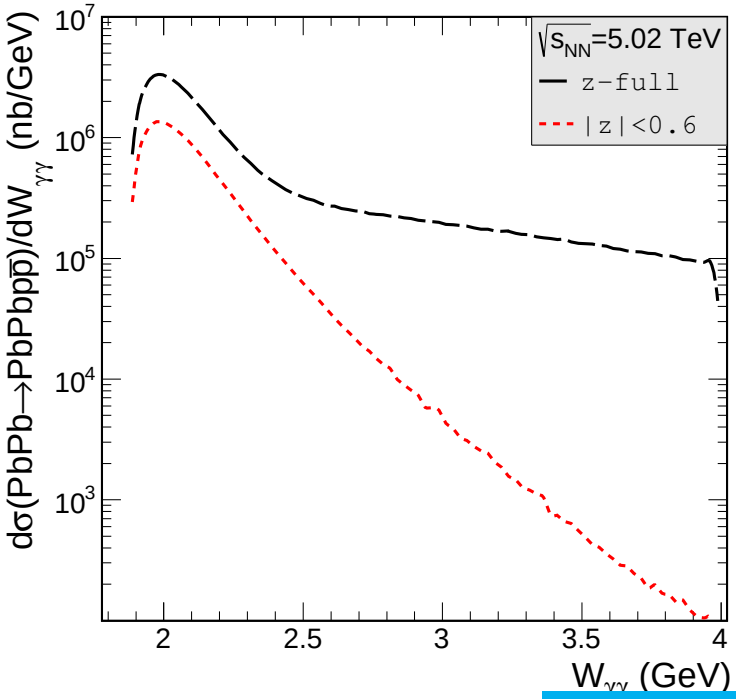




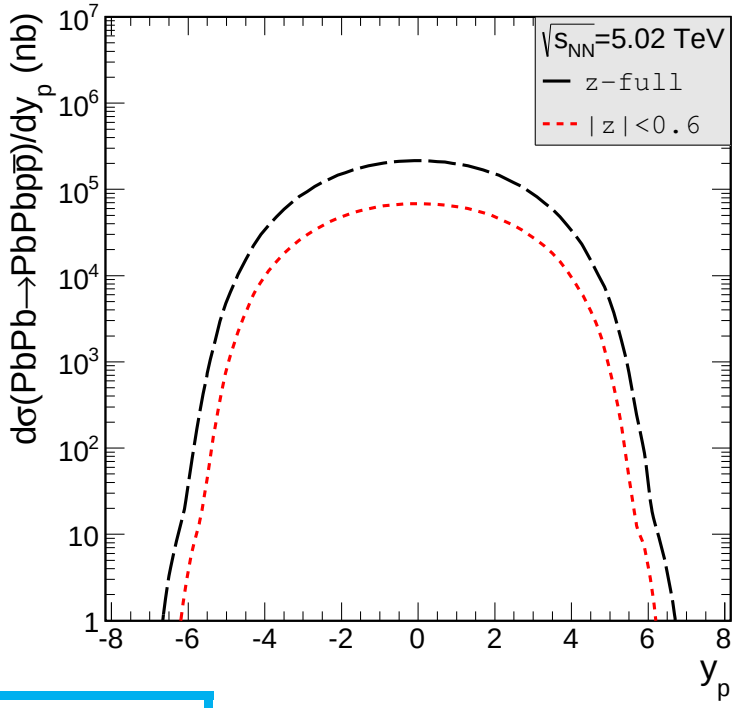


$AA \to AAp\bar{p}$ results

$W_{\gamma\gamma} = M_{p\bar{p}}$



y_p

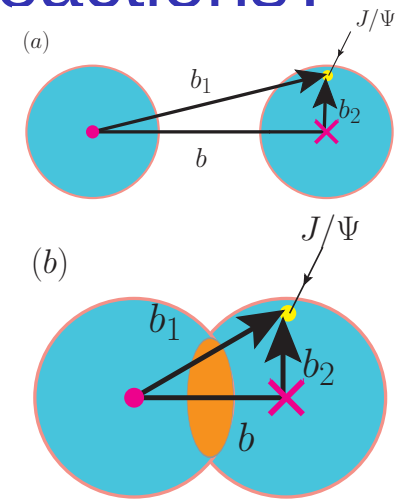


Cross section $\sim$ mb

Can be studied by ALICE, ATLAS, CMS group?

Experiment	Cuts	σ [μb]
ALICE	$p_{t,p} > 0.2$ GeV, $\lvert y_p \rvert < 0.9$	100
ATLAS	$p_{t,p} > 0.5$ GeV, $\lvert y_p \rvert < 2.5$	160
CMS	$p_{t,p} > 0.2$ GeV, $\lvert y_p \rvert < 2.5$	500
LHCb	$p_{t,p} > 0.2$ GeV, $2 < y_p < 4.5$	104

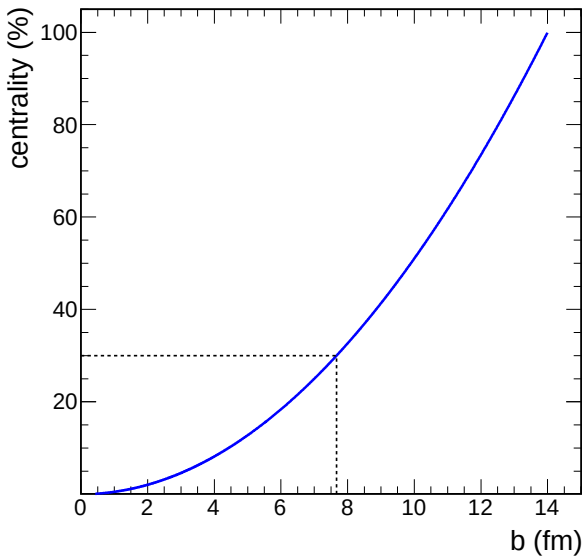
Photon-induced reactions at peripheral or semicentral reactions?

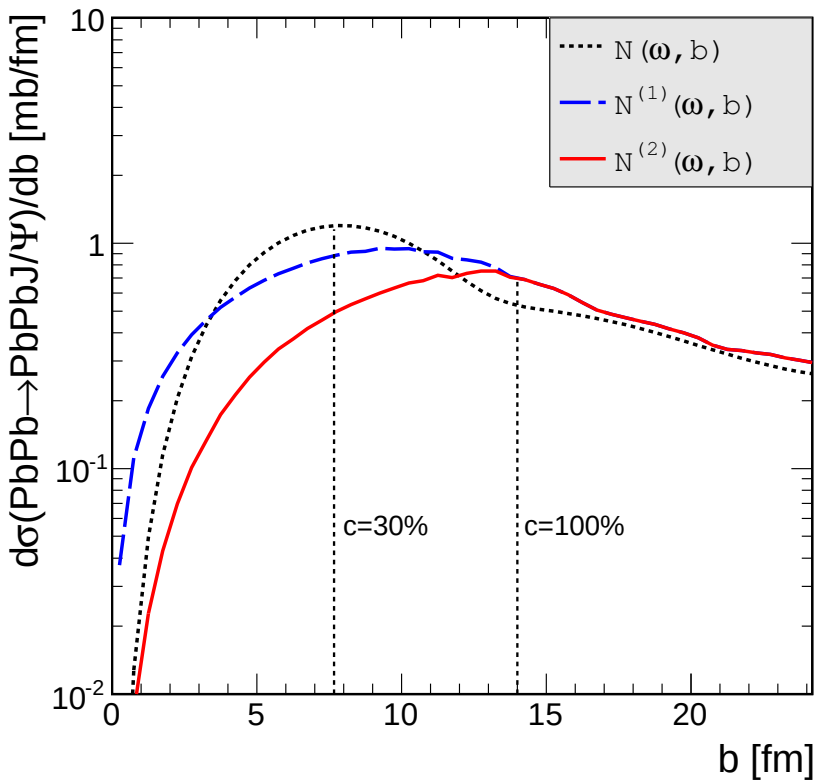


0 $$N(\omega,b) = \frac{Z^2\alpha_{em}}{\pi^2}\left|\int u^2 J_1(u)\,\frac{F\left(\frac{\left(\frac{\omega b}{\gamma}\right)^2+u^2}{b^2}\right)}{\left(\frac{\omega b}{\gamma}\right)^2+u^2}\right|^2 ,$$

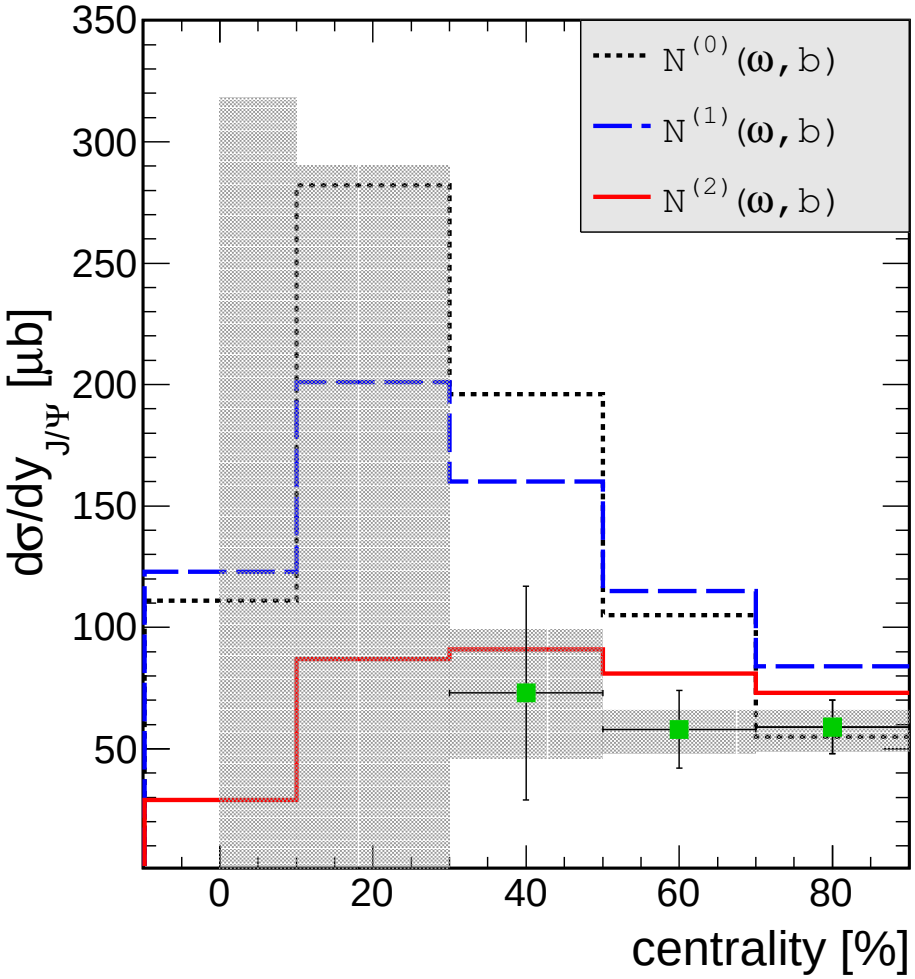
1st $$N(\omega,b) = \int N^{(0)}(\omega,b_1)\,\frac{\theta(R_A-\mathbf{b_2})}{\pi R_A^2}\,\mathrm{d}^2 b_1 ,$$

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





PbPb→PbPbJ/Ψ (semicentral/peripheral)



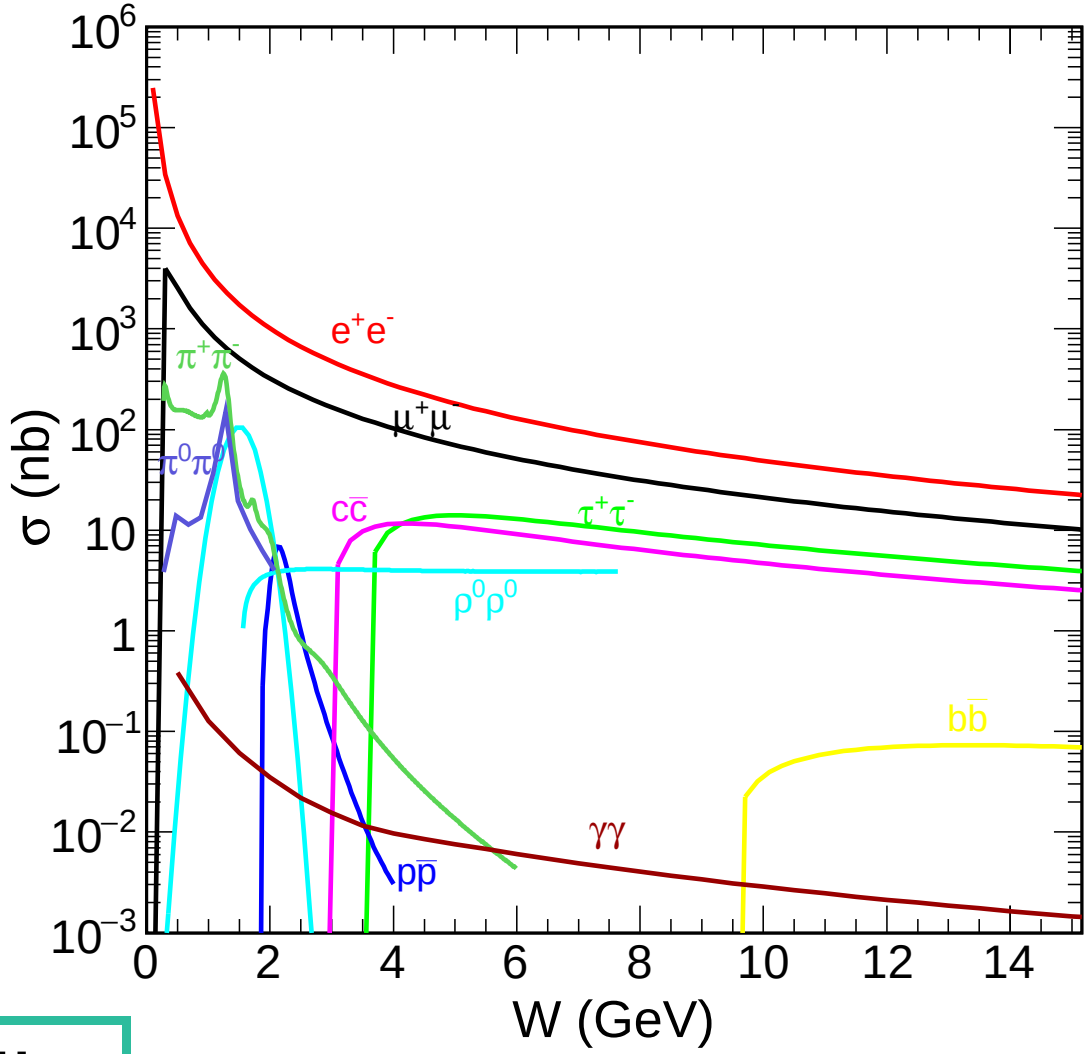
Experimentally one sees a small-p_t enhancement

The situation for J/ψ is unique, photoproduction cross section is of a similar size as for incoherent production

Conclusion

- EPA in the impact parameter space
- $\gamma A \to V$ (multiple scattering) or $\gamma\gamma \to X_1 X_2 (X_3 X_4)$
- Realistic charge distribution
- Predictions for Pb Pb $\to$ Pb Pb $\pi^+\pi^-$ and Pb Pb $\to$ Pb Pb $\pi^0\pi^0$, (fixing model parameters from $\gamma\gamma \to \pi\pi$ Belle data)
- Description of the ATLAS data for Pb Pb $\to$ Pb Pb $\gamma\gamma$ & for ALICE and ATLAS data for Pb Pb $\to$ Pb Pb l^+l^-
- Pb Pb $\to$ Pb Pb $\mu^+\mu^-\mu^+\mu^- \Rightarrow \sigma_{SS}^{NEW} < \sigma_{DS}$
- Difficult to isolate a region where SS dominates
- $\sigma_{AA\to AAl^+l^-} \cong 1000 \times \sigma_{AA\to AAl^+l^-l^+l^-}$
- The cross sections for four-lepton production strongly depend on the $p_{t,min}$ and y_l
- Light-by-light scattering in UPC for $M_{\gamma\gamma} < 5$ GeV - **new project**
- Predictions for Pb Pb $\to$ Pb Pb $p\bar{p}$ (fixing model parameters from $\gamma\gamma \to p\bar{p}$ Belle data)

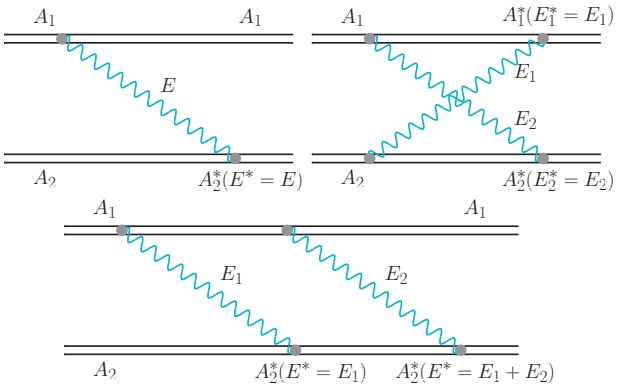
$\gamma\gamma \to X_1 X_2$ - review

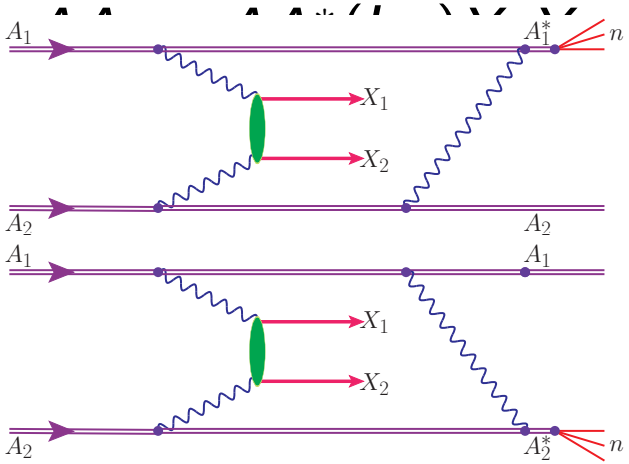


Thank you

Backup Slides

❍ Multiple Coulomb excitations





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"

ρ^0 production in heavy ion UPC with nuclear excitation