ULTRAPERIPHERAL HEAVY-ION COLLISIONS - THEORY CONSIDERATIONS

Mariola Kłusek-Gawenda
The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences

- Equivalent Photon Approximation
- $\gamma\gamma \to \gamma\gamma$
- $\ell^+\ell^-\ell^+\ell^-$ production
- $\pi^+\pi^-\pi^+\pi^-$ production
- Electromagnetic excitation of nuclei and neutron evaporation

2023 CMS heavy ion workshop: bringing together the LHC heavy ion community

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STRONG-2020
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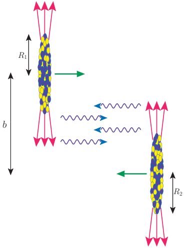
ULTRAPERIPHERAL COLLISION OF HEAVY IONS



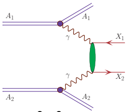
The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions. Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

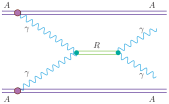
UPC: $b_{min} = R_1 + R_2 \approx 14$ fm

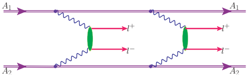
Photon energy: $\omega = \frac{\gamma}{b_{min}} \approx \gamma \times 15$ MeV

Virtuality: $Q^2 = \frac{1}{R^2} \approx 0.0008$ GeV^2

$\gamma\gamma$ fusion



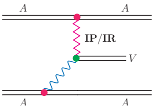


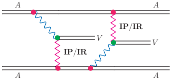


- ✓ $\rho^0\rho^0$, $J/\psi J/\psi$
- ✓ $\pi^+\pi^-$, $\pi^0\pi^0$
- ✓ $c\bar{c}$, $b\bar{b}$
- ✓ e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- ✓ $\gamma\gamma$

- ✓ $p\bar{p}$
- ✓ $\pi^+\pi^-\pi^+\pi^-$
- ✓ $e^+e^-e^+e^-$
- ✓ $\mu^+\mu^-\mu^+\mu^-$

Photoproduction





- ✓ ρ^0, J/ψ
- ✓ $\rho^0\rho^0$, $J/\psi J/\psi$

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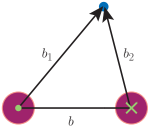
Equivalent Photon Approximation

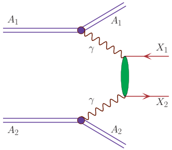
$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2) \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \to \dots n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b) \dots$$

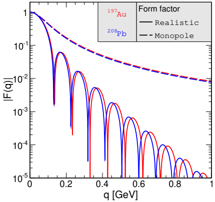
$$= \int \sigma_{\gamma\gamma \to X_1 X_2} \left(W_{\gamma\gamma}\right) N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{X_1 X_2} \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \, \mathrm{d}^2 b$$



$$= \int \frac{\mathrm{d}\sigma_{\gamma\gamma \to X_1 X_2}\left(W_{\gamma\gamma}\right)}{\mathrm{d}\cos\theta} N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) \, S^2_{abs}(\mathbf{b}) \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{X_1 X_2} \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \, \mathrm{d}^2 b$$

$$\times \frac{\mathrm{d}\cos\theta}{\mathrm{d}y_{X_1} \, \mathrm{d}y_{X_2} \, \mathrm{d}p_t} \times dy_{X_1} \, dy_{X_2} \, dp_t \, .$$





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

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

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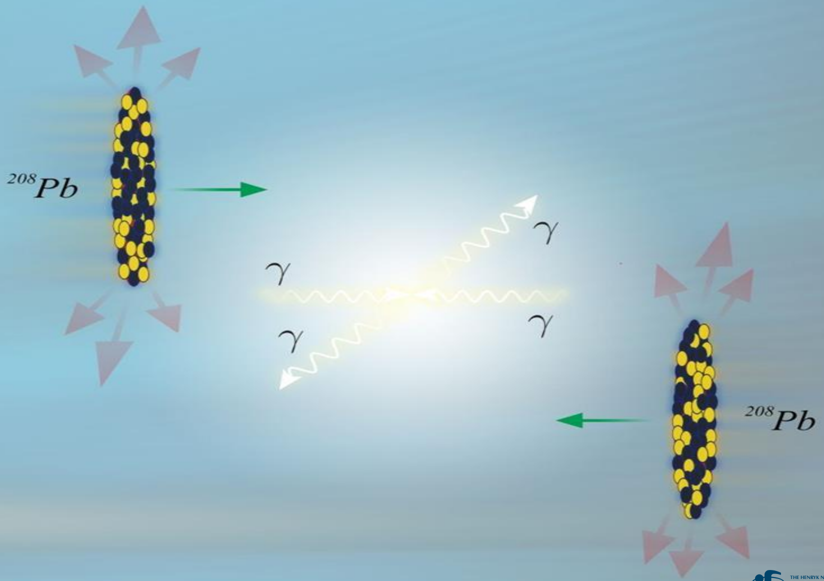
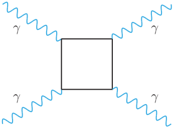
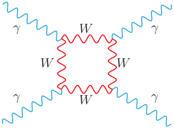
LIGHT-BY-LIGHT SCATTERING



LIGHT-BY-LIGHT SCATTERING

Boxes **WELL-KNOWN**

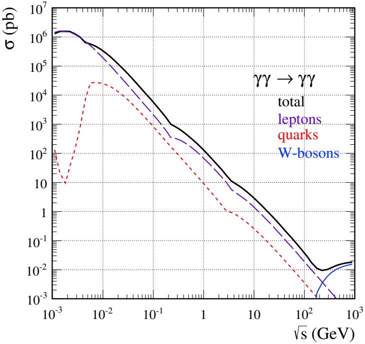




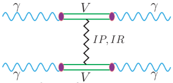
Fermionic boxes (LO QED) — FormCalc.

W Box — LoopTools.

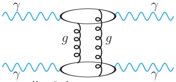
$$\overline{|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}|^2} = \alpha_{em}^4 f(\hat{t}, \hat{u}, \hat{s})$$



VDM-Regge **WE ADD** **2-gluon exch.**



fluctuation of γ into virtual ρ, ω, ϕ



formally 3-loops

We have compared our results with:

- Jikia et al. (1993),
- Bern et al. (2001),
- Bardin et al. (2009).

Bern et al. consider QCD and QED corrections (two-loop Feynman diagrams) to the one-loop fermionic contributions in the ultrarelativistic limit ($\hat{s}, |\hat{t}|, |\hat{u}| \gg m_f^2$). The corrections are quite small numerically.

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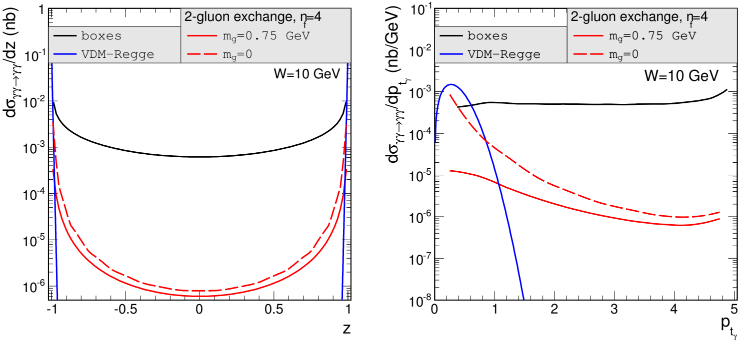
ELEMENTARY CROSS SECTION

- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

$W = 10$ GeV

$z = \cos\theta$

$p_{t_\gamma} = p \sin\theta$



$\theta = \frac{\pi}{2}$ - boxes , large z (low p_{t_γ}) - VDM-Regge.

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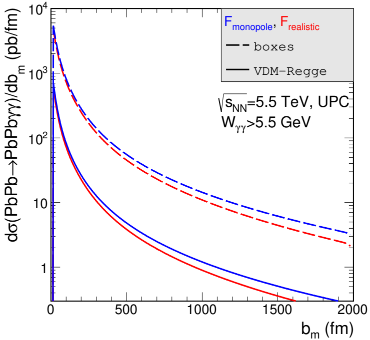
AA→AA$\gamma\gamma$ - FORM FACTOR

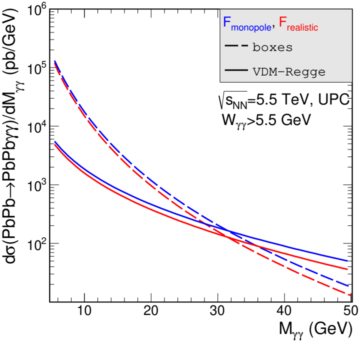
⇨ realistic

⇨ monopole

impact parameter

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





↑ theoretical distribution

VDM-Regge: $W_{\gamma\gamma} > 30$ GeV

$\frac{\sigma_{monopole}}{\sigma_{realistic}} \nearrow$ for larger value of kinematical variables

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AA→AA$\gamma\gamma$ - CMS & ATLAS RESULTS - $M_{\gamma\gamma} > 5$ GEV

- CMS Coll., Phys. Lett. **B797** (2019) 134826
  - ✗ $E_{t_\gamma} > 2$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 5$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
  - ✗ Aco < 0.01

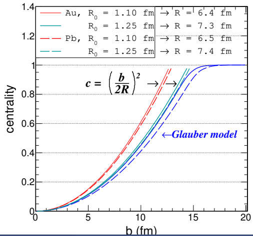
- ATLAS Collaboration, JHEP **03** (2021) 243
  - ✗ $E_{t_\gamma} > 2.5$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 5$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
  - ✗ Aco < 0.01

Experiment		Theory		
		Nuclear radius: $R = R_0 A^{\frac{1}{3}}$		Glauber model
Collaboration	σ nb	$\sigma(b = 13\text{fm})$	$\sigma(b = 14.8\text{fm})$	$\sigma(b = 20\text{fm})$
ATLAS (2018 data)	78 ± 13(stat.)±7(syst.)	52	50	45
ATLAS (2015+2018)	120 ± 17(stat.)±13(syst.)	82	80	71
CMS (2015)	120 ± 46(stat.)±28(syst.)	105	103	92

UPC $\rightarrow b_{min} > 2\times$ R

SO FAR IT WAS 14 FM

centrality [%]	100
nucleus and radius	b (fm)
Pb, R = 6.5 fm	13.0
Pb, R = 7.4 fm	14.8
Pb Pb, Glauber	20.0



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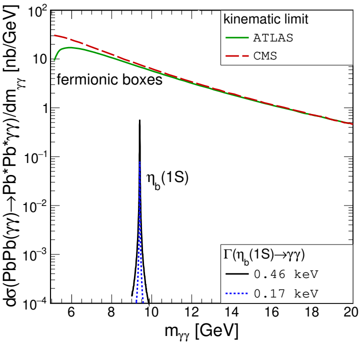
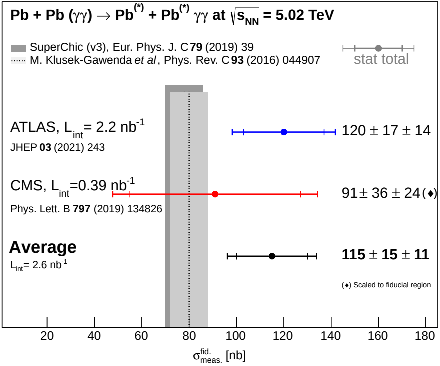
2022 RESULTS

$\eta_b(1S)$

The averaged $\sigma(Pb + Pb \to Pb + Pb\gamma\gamma)$





- The European Union's Horizon 2020 research and innovation program under STRONG-2020, G. K. Krintiras, I. Grabowska-Bołd, M. Kłusek-Gawenda and É. Chapon and R. Chudasama, *Acta Phys.Polon.Supp.* ***16*** *(2023) 1, 123*; Light-by-light scattering cross-section measurements at LHC

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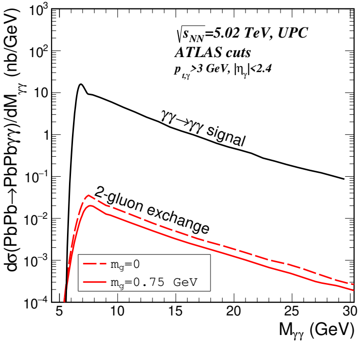
HIGHER ORDER PROCESSES..?

$\gamma\gamma$ invariant mass

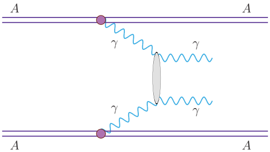


Coherent sum of both processes...?

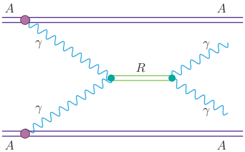
Pionic boxes...?

AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ?

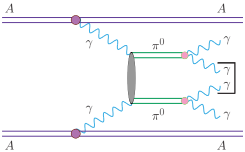
CONTINUUM

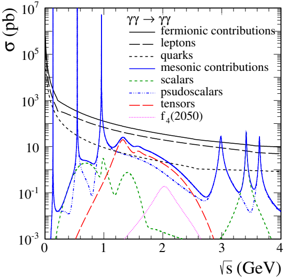


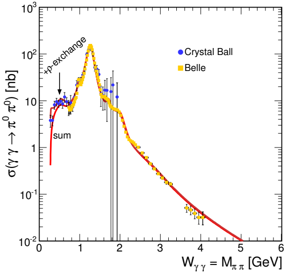
RESONANCES



BACKGROUND





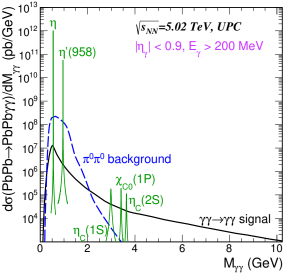


- P. Lebiedowicz, A. Szczurek, *Phys. Lett. **B772** (2017) 330*, The role of meson exchanges in light-by-light scattering
- M. K-G, A. Szczurek, *Phys. Rev. **C87** (2013) 054908*; $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion collisions

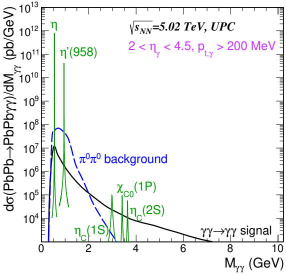
UPC of AA...

- ✔ boxes
- ✔ bkg
- ✔ mesons

ALICE cuts



LHCb cuts



Total nuclear cross section [nb]

Energy	$W_{\gamma\gamma}$ = (0 – 2) GeV		$W_{\gamma\gamma} > 2$ GeV	
Fiducial region	ALICE	LHCb	ALICE	LHCb
Boxes	4 890	3 818	146	79
$\pi^0\pi^0$ bkg	135 300	40 866	46	24
η	722 573	568 499		
$\eta'(958)$	54 241	40 482		
$\eta_c(1S)$			9	5
$\chi_{c0}(1P)$			4	2
$\eta_c(2S)$			2	1

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AA→AA$\gamma\gamma$ @ FORWARD REGION ?

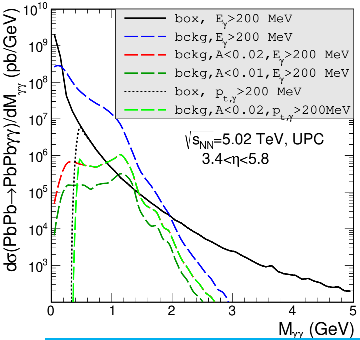
✓ ALICE Collaboration,
Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment,
CERN-LHCC-2020-009

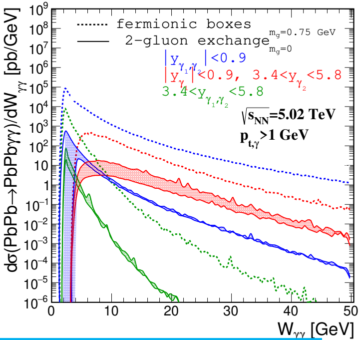
FOCAL $\rightarrow$ 3.4 $< \eta <$ 5.8

The forward electromagnetic and hadronic calorimeter is an upgrade to the ALICE experiment, to be installed during LS3 for data-taking in 2027–2029 at the LHC.

$E_\gamma > 0.2$ GeV

$p_{t,\gamma} > 1$ GeV

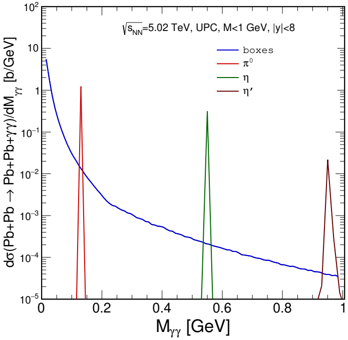




Boxes & Pionic bkgr & 2-gluon exchange (with effective gluon mass)

AA→AA$\gamma\gamma$ @ LOW p_t REGION ?

$M_{\gamma\gamma} < 1$ GeV



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

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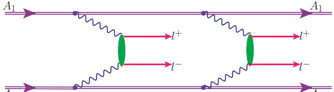
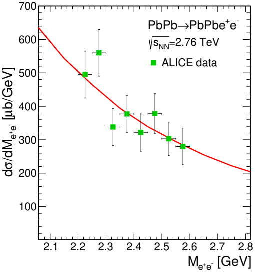
FOUR-LEPTON PRODUCTION

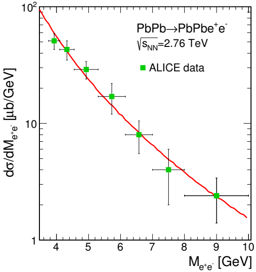


$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 (\ell^+\ell^-)(\ell^+\ell^-)}}{dy^I_{\ell+}\, dy^I_{\ell-}\, dy^{II}_{\ell+}\, dy^{II}_{\ell-}} = \frac{1}{2}\int \left(\frac{dP^I_{\gamma\gamma\to\ell^+\ell^-}\left(b, y^I_{\ell+}, y^I_{\ell-}; p_{t,\ell}\right)}{dy^I_{\ell+}\, dy^I_{\ell-}} \times \frac{dP^{II}_{\gamma\gamma\to\ell^+\ell^-}\left(b, y^{II}_{\ell+}, y^{II}_{\ell-}; p_{t,\ell}\right)}{dy^{II}_{\ell+}\, dy^{II}_{\ell-}} \right) \times 2\pi b\, db$$

$$P_{\gamma\gamma\to\ell^+\ell^-}(b; y_{\ell+}, y_{\ell-}, p_{t,\ell}) = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \times \frac{d\sigma_{\gamma\gamma\to\ell_1\ell_2}\left(W_{\gamma\gamma}\right)}{d\cos\theta}\, d\bar{b}_x\, d\bar{b}_y\, \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{\ell_1\ell_2}$$

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





Good description of single pair production ⇒ two e^+e^- pair production...?

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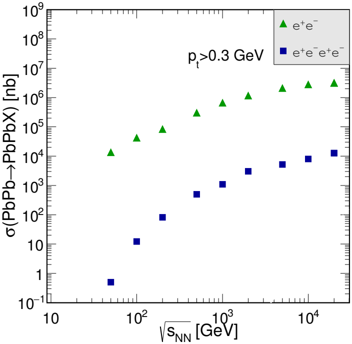
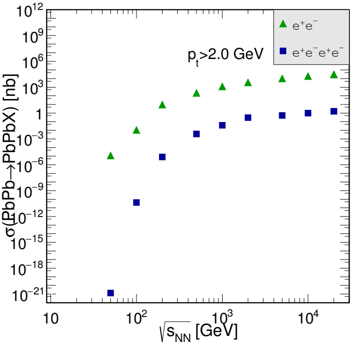
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

Single e^+e^- pair production
vs.
double scattering production of two e^+e^- pairs

$p_t > 0.3$ GeV

$p_t > 2.0$ GeV

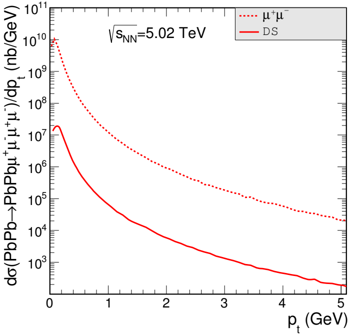




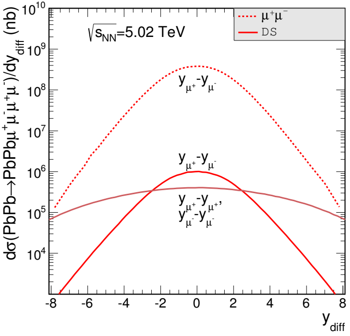
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

Single $\mu^+\mu^-$ pair production v. double scattering production of two $\mu^+\mu^-$ pairs

$p_{t,\mu}$



y_{diff}



$$\sigma_{\ell^+\ell^-} \simeq 1000 \times \sigma_{\ell^+\ell^-\ell^+\ell^-}$$

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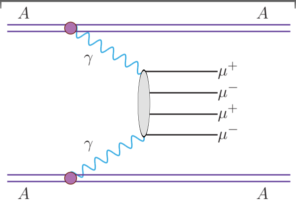
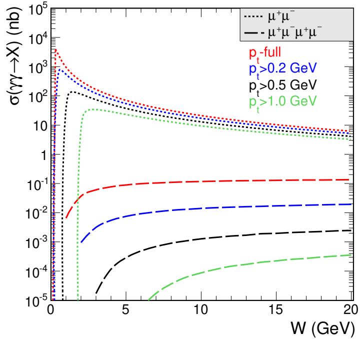
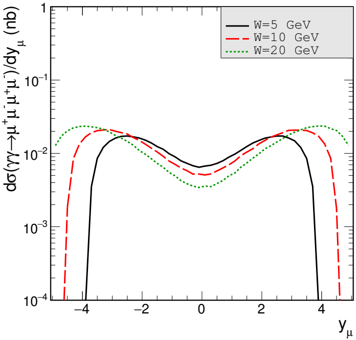
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - SINGLE SCATTERING



⇑

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.





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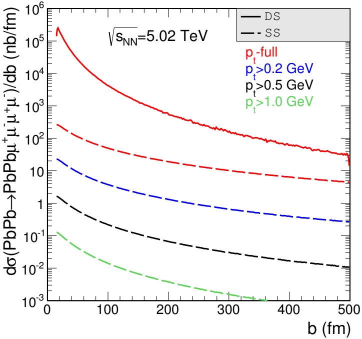
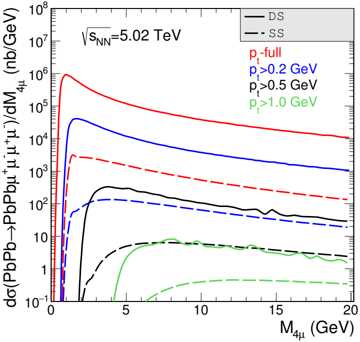
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

impact parameter

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



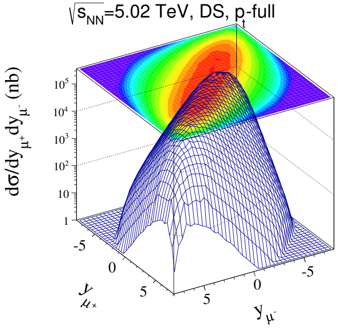


It is difficult to isolate range of SS domination

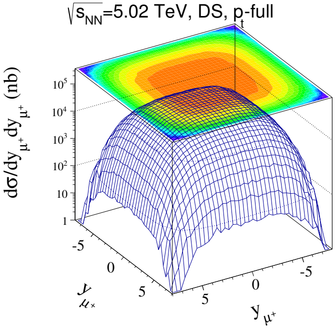
*DS - double-scattering mechanism
*SS - a NEW single-scattering mechanism

AA→AA$\mu^+\mu^-\mu^+\mu^-$

y_{μ^+}, y_{μ^-}

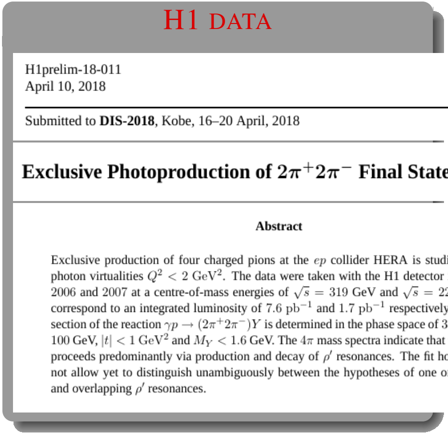


$y_{\mu\pm}, y_{\mu\pm}$



creation of similar distributions by ALICE or CMS?

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



H1 DATA

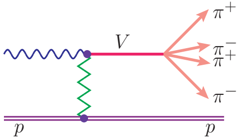
H1prelim-18-011
April 10, 2018

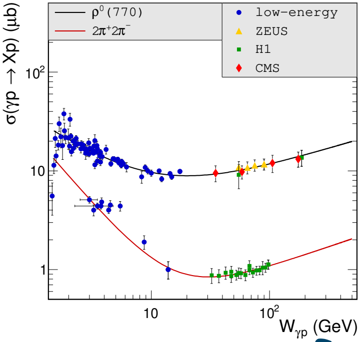
Submitted to **DIS-2018**, Kobe, 16–20 April, 2018

Exclusive Photoproduction of $2\pi^+2\pi^-$ Final State at H

Abstract

Exclusive production of four charged pions at the ep collider HERA is studied at sm photon virtualities $Q^2 < 2$ GeV^2. The data were taken with the H1 detector in the ye 2006 and 2007 at a centre-of-mass energies of $\sqrt{s} = 319$ GeV and $\sqrt{s} = 225$ GeV a correspond to an integrated luminosity of 7.6 pb^{-1} and 1.7 pb^{-1} respectively. The cr section of the reaction $\gamma p \to (2\pi^+2\pi^-)Y$ is determined in the phase space of $35 < W_{\gamma p}$ 100 GeV, $|t| < 1$ GeV^2 and $M_Y < 1.6$ GeV. The 4π mass spectra indicate that the react proceeds predominantly via production and decay of ρ' resonances. The fit however do not allow yet to distinguish unambiguously between the hypotheses of one or two bro and overlapping ρ' resonances.





vector meson ?

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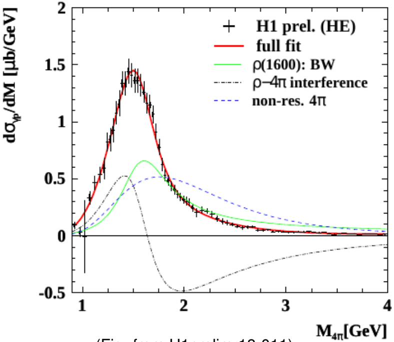
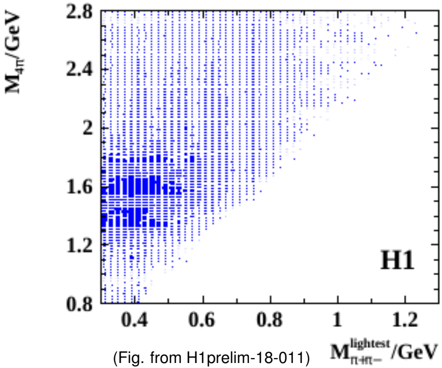


(Fig. from H1prelim-18-011)



(Fig. from H1prelim-18-011)

77. The $\rho(1450)$ and the $\rho(1700)$

Updated November 2015 by S. Eidelman (Novosibirsk), C. Hanhart (Juelich) and G. Venanzoni (Frascati).

In our 1988 edition, we replaced the $\rho(1600)$ entry with two new ones, the $\rho(1450)$ and the $\rho(1700)$, because there was emerging evidence that the 1600-MeV region actually contains two ρ-like resonances. Erkal [1] had pointed out this possibility with a theoretical analysis on the consistency of 2π and 4π electromagnetic form factors and the $\pi\pi$ scattering length. Donnachie [2], with a full analysis of data on the 2π and 4π final states in e^+e^- annihilation and photoproduction reactions, had also argued that in order to obtain a consistent picture, two resonances were necessary. The existence of $\rho(1450)$ was supported by the analysis of $\eta\rho^0$ mass spectra obtained in photoproduction and e^+e^- annihilation [3], as well as that of $e^+e^- \to \omega\pi$ [4].

The analysis of [2] was further extended by [5,6] to include new data on 4π-systems produced in e^+e^- annihilation, and in τ-decays (τ decays to 4π, and e^+e^- annihilation to 4π can be related by the Conserved Vector Current assumption). These systems were successfully analyzed using interfering contributions from two ρ-like states, and from the tail of the $\rho(770)$ decaying into two-body states. While specific conclusions on $\rho(1450) \to 4\pi$ were obtained, little could be said about the $\rho(1700)$.

DECAY MODE

$M_{4\pi}$ = 1.6 GeV

or

$M_{4\pi}$ = 1.45 GeV **&** $M_{4\pi}$ = 1.7 GeV

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RESONANCES SKETCH PDG

$\rho(1570)$ $I^G(J^{PC}) = 1^+(1^{--})$

$\rho(1570)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1570±36±62	54	[1] AUBERT	08S	BABR	10.6 $e^+e^- \to \phi\pi^0\gamma$

$\rho(1570)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
144±75±43	54	[3] AUBERT	08S	BABR	10.6 $e^+e^- \to \phi\pi^0\gamma$

$\rho(1570)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	
Γ_2	$\phi\pi$	not seen
Γ_3	$\omega\pi$	

$\rho(1450)$ [r] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1465 \pm 25$ MeV [l]
Full width $\Gamma = 400 \pm 60$ MeV [l]

$\rho(1450)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	720
$\pi^+\pi^-$	seen	719
4π	seen	669

$\rho(1700)$ [r] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1720 \pm 20$ MeV [l] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)
Full width $\Gamma = 250 \pm 100$ MeV [l] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

$\rho(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$2(\pi^+\pi^-)$	seen	803

$\rho(770)$ [h] $I^G(J^{PC}) = 1^+(1^{--})$

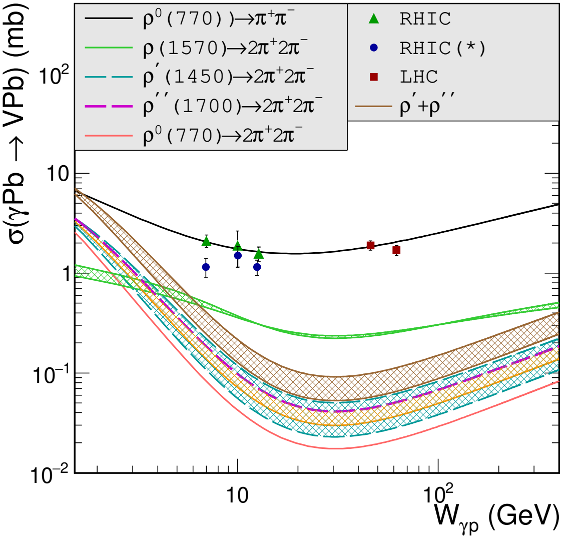
Mass $m = 775.26 \pm 0.25$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

$\rho(770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	$\sim$ 100 %		363
$\pi^+\pi^-\pi^+\pi^-$	$(1.8 \pm 0.9) \times 10^{-5}$		251

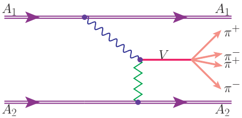
MY CALCULATION

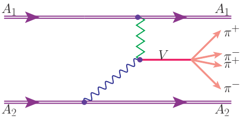
m [GeV]	Γ [GeV]	$\Gamma(e^+e^-)$ [keV]
	$\rho(1570)$	
1.57 ± 0.07	0.144 ± 0.09	$0.35 - 0.5^*$
	$\rho(1450) \equiv \rho'$	
1.465 ± 0.025	0.40 ± 0.05	$4.3 - 6^*$
	$\rho(1700) \equiv \rho''$	
1.72 ± 0.02	0.25 ± 0.01	7.6 ± 1.3

COHERENT VECTOR MESON PHOTOPRODUCTION

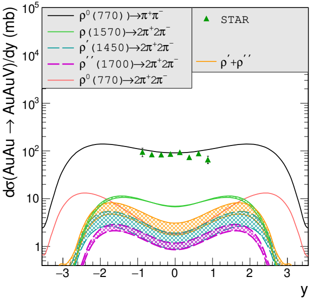


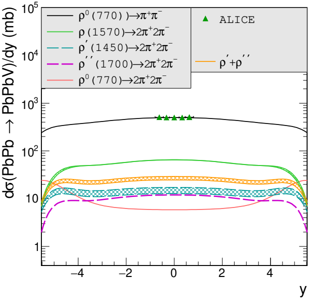
DIFFERENTIAL CROSS SECTION





$$\frac{\sigma(A_1A_2 \to A_1A_2\,2\pi^+2\pi^-)}{dy_V} = d^2b \times \left[\int \omega_1 \frac{dN(\omega_1, b)}{d^2b\,d\omega_1}\,\sigma_{\gamma A_2 \to VA_2}\left(W_{\gamma A_2}\right) + \int \omega_2 \frac{dN(\omega_2, b)}{d^2b\,d\omega_2}\,\sigma_{\gamma A_1 \to VA_1}\left(W_{\gamma A_2}\right)\right]$$





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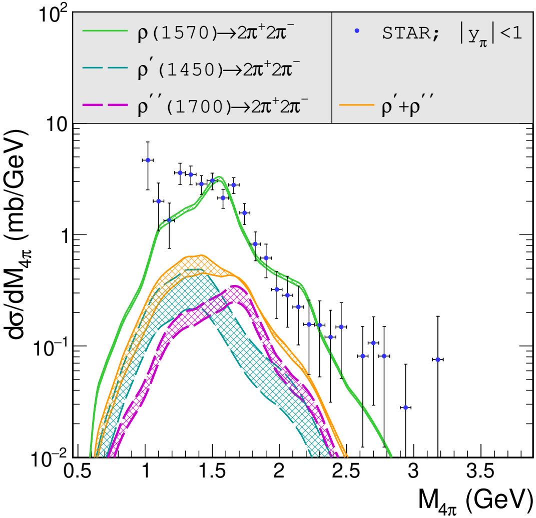

Success of ρ(1570) - Results for the LHC are necessary

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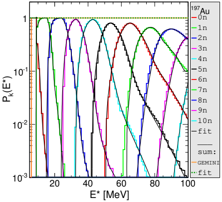
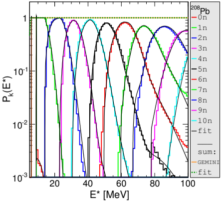
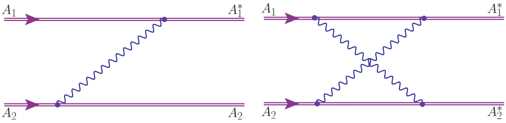
ELECTROMAGNETIC EXCITATION

$P_k(E*)$

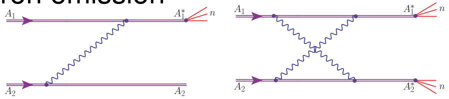




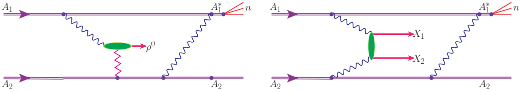
➤ Photon → nucleus excitation



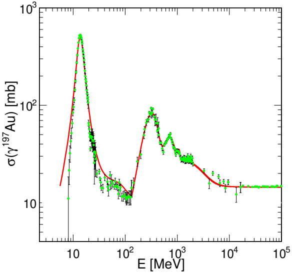
✚ neutron emission



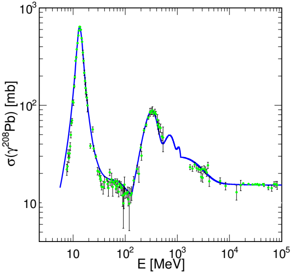
✚ particle production



$\gamma\ ^{197}\mathrm{Au}$

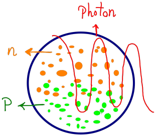


$\gamma\ ^{208}\mathrm{Pb}$

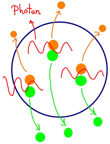


$$\sigma_{\gamma A} = \sigma_{\mathrm{GDR}} + \sigma_{\mathrm{QD}} + \sigma_{\mathrm{nucleon\ res.}} + \sigma_{\mathrm{nucleon\ cont.}}$$

❶ Giant Dipole Resonance
$E_\gamma < 40$ MeV

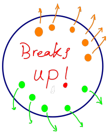


❷ quasi-deuteron contribution
$E_\gamma = (40 - 100)$ MeV



❸ nucleon resonances
$E_\gamma = (0.1 - 1)$ GeV

❹ break-up of nucleons
$E_\gamma > 1 - 8$ GeV



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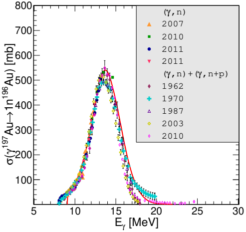
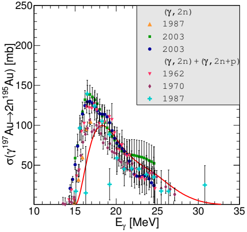
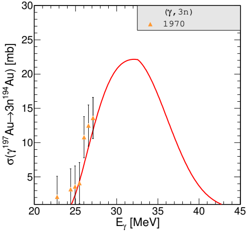
$\gamma\ ^{197}\mathrm{Au} \rightarrow 1\mathrm{n}\ ^{196}\mathrm{Au}$



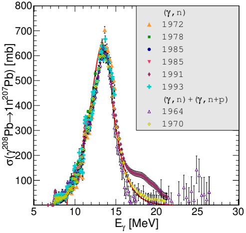
$\gamma\ ^{197}\mathrm{Au} \rightarrow 2\mathrm{n}\ ^{195}\mathrm{Au}$



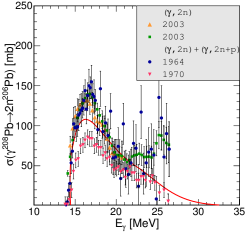
$\gamma\ ^{197}\mathrm{Au} \rightarrow 3\mathrm{n}\ ^{194}\mathrm{Au}$



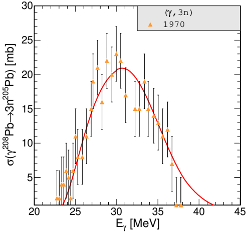
$\gamma\ ^{208}\mathrm{Pb} \rightarrow 1\mathrm{n}\ ^{207}\mathrm{Pb}$



$\gamma\ ^{208}\mathrm{Pb} \rightarrow 2\mathrm{n}\ ^{206}\mathrm{Pb}$



$\gamma\ ^{208}\mathrm{Pb} \rightarrow 3\mathrm{n}\ ^{205}\mathrm{Pb}$



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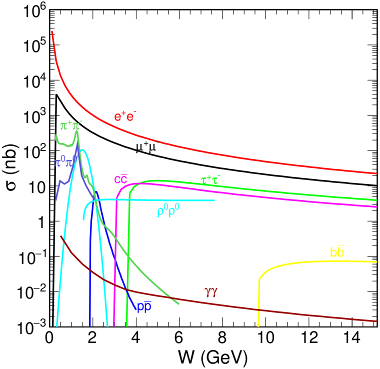
Conclusion

- EPA in the impact parameter space
- Fourier transform of the charge distribution
- Multidimensional integrals $\rightarrow$ differential cross section
- Description of experimental data for UPC
- Predictions include the experimental acceptance
- Electromagnetic excitation - ZDC
- Collaboration - theoreticians and experimenters
- Future:
  - more forward/backward region
  - lower p_t



Thank you