LATEST THEORETICAL DEVELOPMENTS IN UPC PHYSICS

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Polish Academy of Sciences

- Equivalent Photon Approximation
- $\gamma\gamma \to \gamma\gamma$
- $\ell^+\ell^-\ell^+\ell^-$ production
- $c\bar{c}$ & $b\bar{b}$ production
- $\pi^+\pi^-\pi^+\pi^-$ production
- Electromagnetic excitation of nuclei and neutron evaporation

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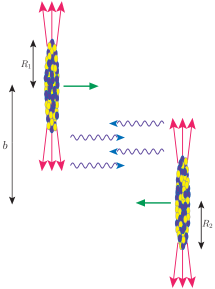
ULTRAPERIPHERAL COLLISION OF HEAVY IONS



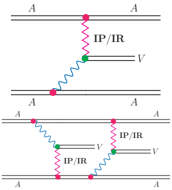
The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions. Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

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

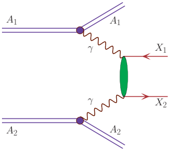
Photon energy: $\omega = \frac{\gamma}{b_{min}} \approx \gamma \times 15$ MeV

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

Photoproduction



$\gamma\gamma$ fusion



GOAL

- testing QED
- probing the structure of the nucleus and nucleons
- exploration of exotic physics
- minimalization of the QGP production
- bridge the gap between high-energy and nuclear physic

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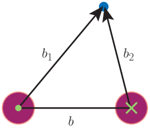
Equivalent Photon Approximation

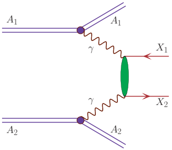
$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2) \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \to \ldots n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b) \ldots$$

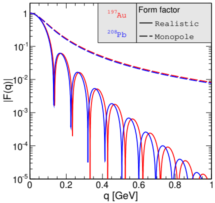
$$= \int \sigma_{\gamma\gamma \to X_1 X_2} \left(W_{\gamma\gamma} \right) N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{X_1 X_2} \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \, \mathrm{d}^2 b$$

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

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







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

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

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MC EVENT GENERATORS

1. STARlight simulates two-photon and γ-IP interactions between relativistic nuclei and protons. It produces a variety of final states. For two-γ, it simulates lepton pairs and a variety of mesons. For photonuclear interactions, it models coherent and incoherent vector mesons production.
   S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth,
   Comp. Phys. Comm. ***212*** *(2017) 258*

2. SuperChic - event generator for exclusive and γ-initiated production in proton and heavy ion collisions. A range of SM final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival factor is given. Arbitrary user-defined histograms and cuts may be made.
   L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, W.J. Stirling,
   Eur. Phys. J. ***C80*** *(2020) 925*

3. UPCgen - simulation program for $\ell^+\ell^-$ pair production implements a refined treatment of the γ flux allowing us to improve the agreement with ATLAS data at large dilepton rapidities. Besides, the new generator offers a possibility to study γ polarization effects and set arbitrary values of the lepton anomalous magnetic moment.
   N. Burmasov, E. Kryshen, P. Buehler, R. Lavicka,
   Comput.Phys.Commun. 277 (2022) 108388

4. gamma-UPC is a library for calculating the photon fluxes in the exclusive γ-γ processes in ultraperipheral proton and nuclear collisions. It is derived from electric dipole or charge form factors, and has incorporated hadronic survival probabilities.
   H.-S. Shao, D. d'Enterria,
   J. High Energ. Phys. ***2022****, 248 (2022)*

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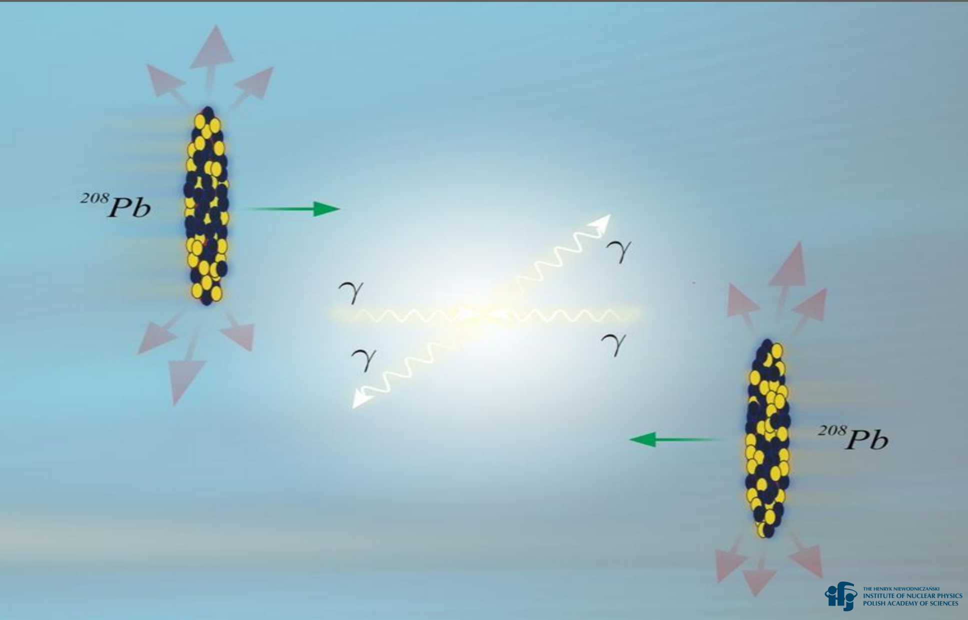
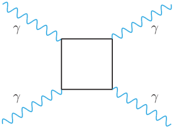
LIGHT-BY-LIGHT SCATTERING

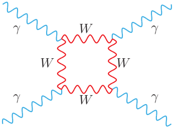


LIGHT-BY-LIGHT SCATTERING

Boxes

WELL-KNOWN





Fermionic boxes (LO QED) — FormCalc.

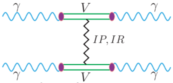
W Box — LoopTools.

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

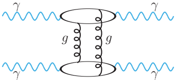
VDM-Regge

WE ADD

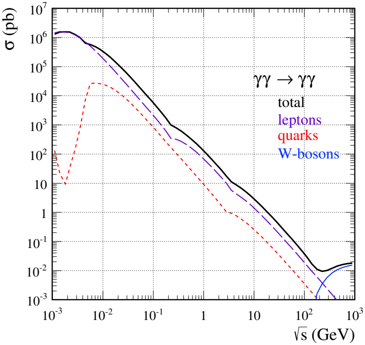
2-gluon exch.



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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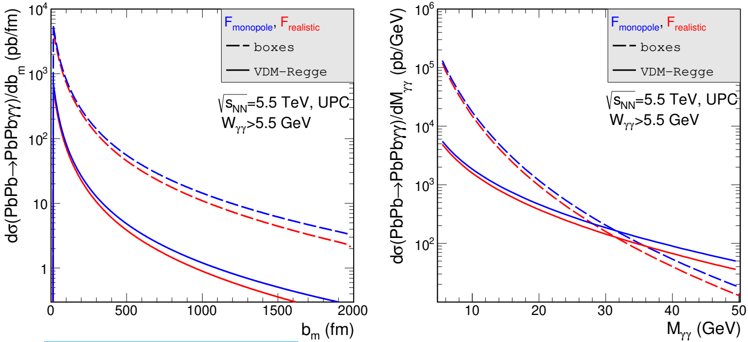
AA→AA$\gamma\gamma$ - form factor

⇨ 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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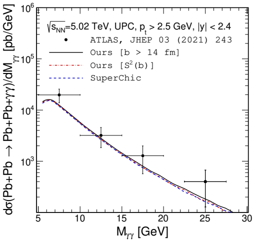
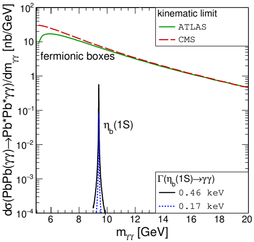
$AA \to AA\gamma\gamma$ - CMS & ATLAS results

- ATLAS Collaboration, PRL **123** (2019) 052001
  - ✗ $p_{t_\gamma} > 3$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 6$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 2$ 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
- CMS Collaboration, PL**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

Experiment		Theory		
Collaboration	σ [nb]	Vegas	SuperChic	gamma-UPC
ATLAS (2018 data)	78 ± 13(stat.)± 7(syst.)	51	50	–
ATLAS (2015+2018)	120 ± 17(stat.)± 13(syst.)	80	77	70
CMS (2015)	120 ± 46(stat.)± 28(syst.)	103	101	–





Underestimation:

- tetraquarks $X(6900)$?
- graviton, axion ?
- coherent sum of higher order processes ?
- pionic boxes ?

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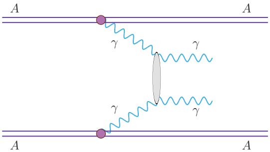
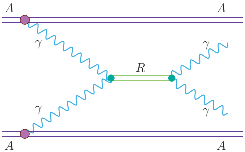
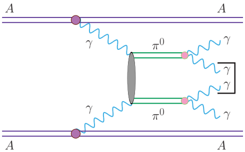
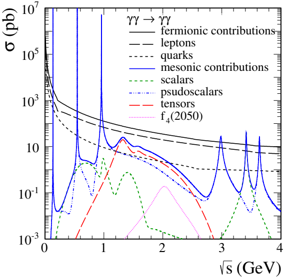
AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ?

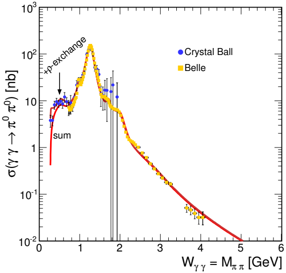
CONTINUUM | **RESONANCES** | **BACKGROUND**











- 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

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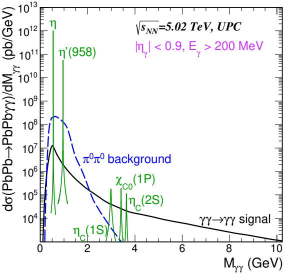
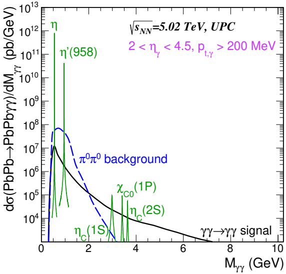
UPC of AA...

ALICE cuts

- ✔ boxes
- ✔ bkg
- ✔ mesons

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 ?

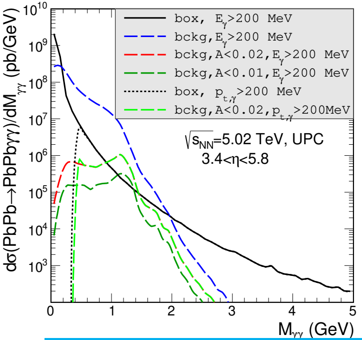
✓ ALICE Collaboration,
Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment,
CERN-LHCC-2020-009

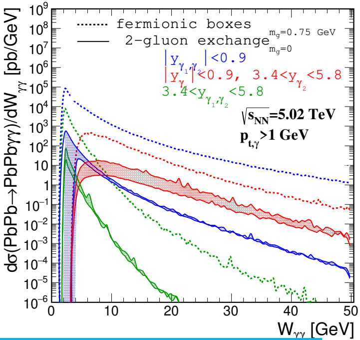
FOCAL $\rightarrow$ $3.4 < \eta < 5.8$

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)

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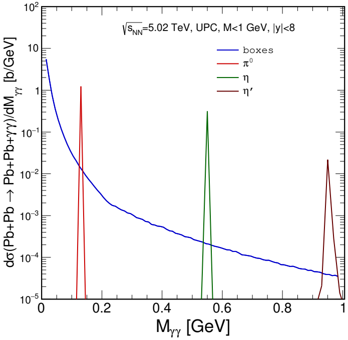
$AA \to AA\gamma\gamma$ @ LOW p_t REGION ?

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



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

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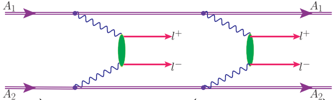
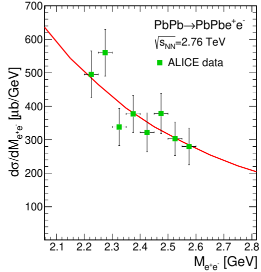
FOUR-LEPTON PRODUCTION

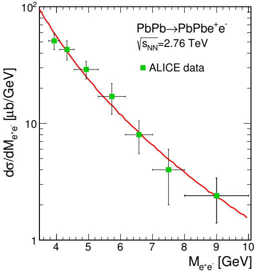


$$\frac{d\sigma_{A_1A_2\to A_1A_2(\ell^+\ell^-)(\ell^+\ell^-)}}{dy^I_{\ell+}\,dy^I_{\ell-}\,dy^{II}_{\ell+}\,dy^{II}_{\ell-}} = \frac{1}{2}\int\left(\frac{dP^I_{\gamma\gamma\to\ell^+\ell^-}\left(b,y^I_{\ell+},y^I_{\ell-};p_{t,\ell}\right)}{dy^I_{\ell+}\,dy^I_{\ell-}}\times\frac{dP^{II}_{\gamma\gamma\to\ell^+\ell^-}\left(b,y^{II}_{\ell+},y^{II}_{\ell-};p_{t,\ell}\right)}{dy^{II}_{\ell+}\,dy^{II}_{\ell-}}\right)$$
$$\times \quad 2\pi b\, db$$

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

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





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

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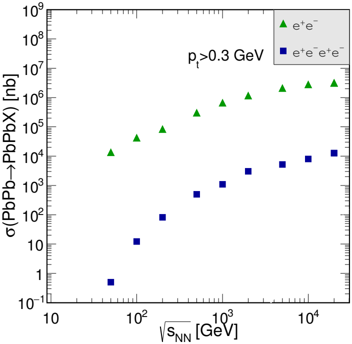
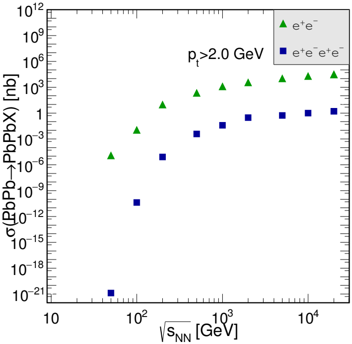
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

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

$p_t > 0.3$ GeV

$p_t > 2.0$ GeV





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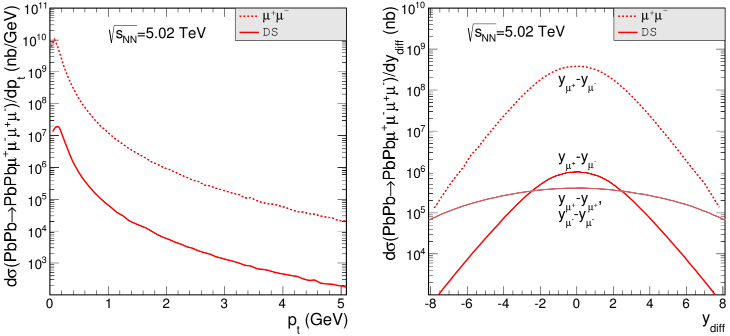
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

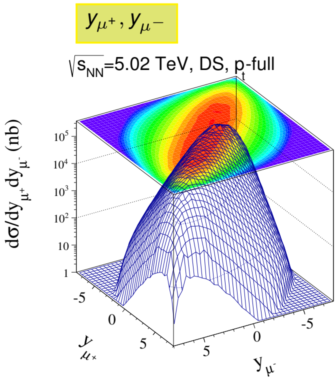
Single $\mu^+\mu^-$ pair production vs. double scattering production of two $\mu^+\mu^-$ pairs

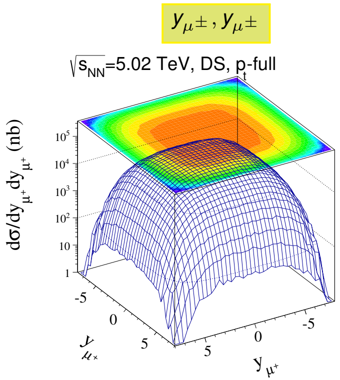
$p_{t,\mu}$ | y_{diff}



$$\sigma_{\ell^+\ell^-} \simeq 1000 \times \sigma_{(\ell^+\ell^-)(\ell^+\ell^-)} \simeq 1000000 \times \sigma_{\ell^+\ell^-\ell^+\ell^-}$$

AA→AA$\mu^+\mu^-\mu^+\mu^-$





creation of similar distributions by ALICE or CMS?

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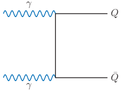
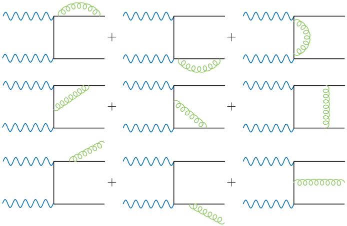
QUARKS PRODUCTION

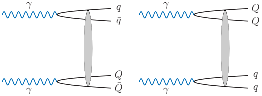
❶ $2 \to 2$ process (Born amplitude)



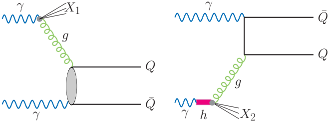
❷ LO QCD corrections



❸ $Q\bar{Q}q\bar{q}$ production

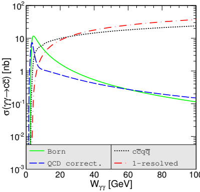


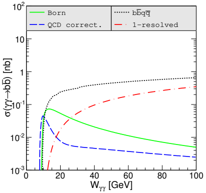
❹ single-resolved mechanism



Nuclear cross secion at $\sqrt{s_{NN}}$ = 5.5 TeV

	σ_{tot}	Ad.1	Ad.2	Ad.3	Ad.4
$c\bar{c}$	2.47 mb	42.5%	14.6%	27.1%	15.8%
$b\bar{b}$	10.83 μb	18.9%	7.7%	64.5%	8.9%





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

H1 DATA

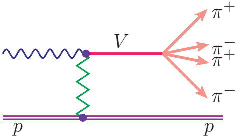
H1prelim-18-011
April 10, 2018

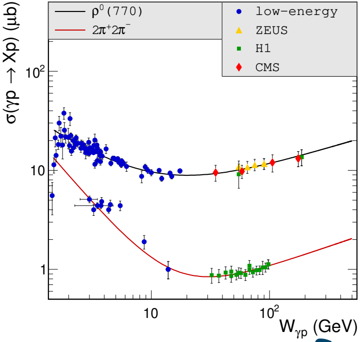
Submitted to **DIS-2018**, Kobe, 16–20 April, 2018

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 d not allow yet to distinguish unambiguously between the hypotheses of one or two bro and overlapping ρ' resonances.





vector meson ?

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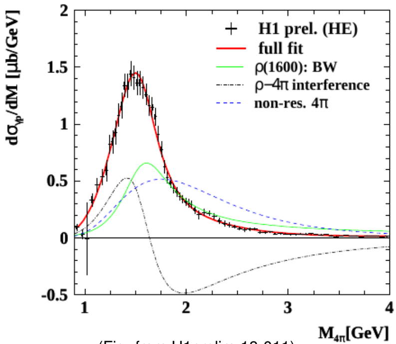
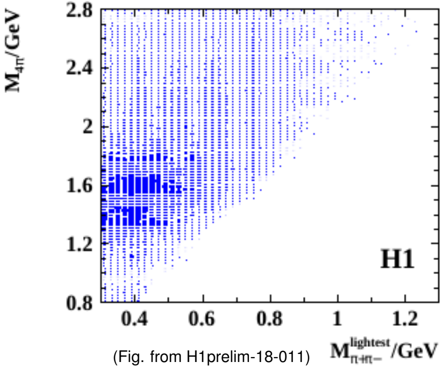


(Fig. from H1prelim-18-011)



(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 ±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

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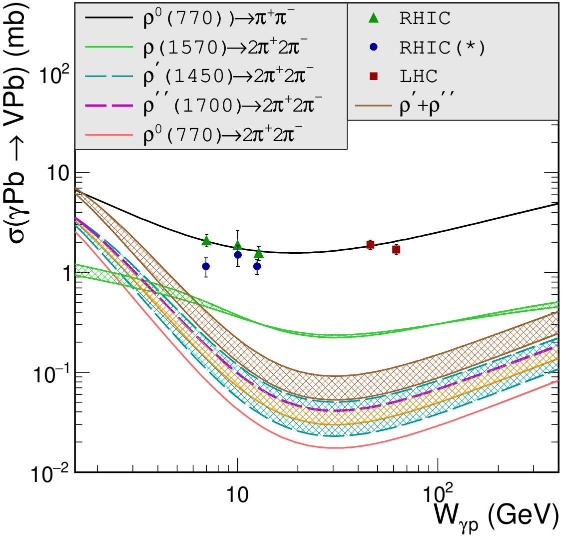
COHERENT VECTOR MESON PHOTOPRODUCTION



$$\sigma_{tot}(VA) = \int \left[1 - \exp\left(-\sigma_{tot}(Vp)\, T_A(\vec{b})\right)\right] \mathrm{d}^2 b$$

$$T_A(\vec{b}) = \int_{-\infty}^{+\infty} \rho(\vec{b}, z)\mathrm{d}z$$

$$\sigma(\gamma A \to VA) = \frac{1}{16\pi} \frac{e^2}{f_V^2} \sigma_{tot}^2(VA) \int |F(t)|^2 \, \mathrm{d}t$$

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

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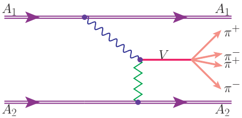
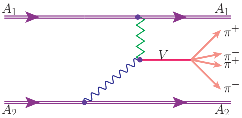
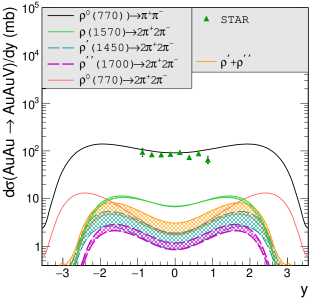
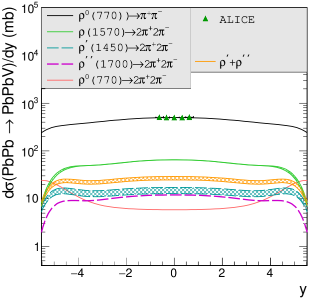
DIFFERENTIAL CROSS SECTION





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





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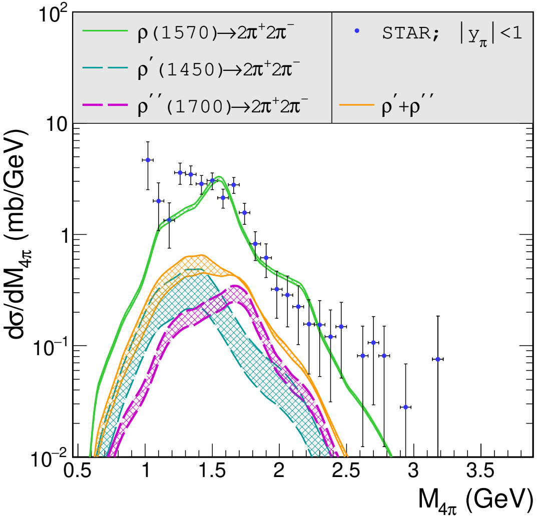
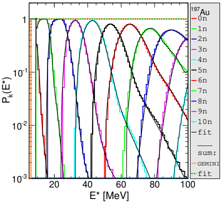
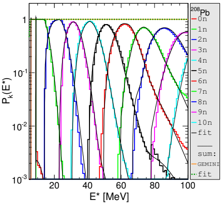


Success of $\rho(1570)$ for STAR. New ALICE-LHC data!

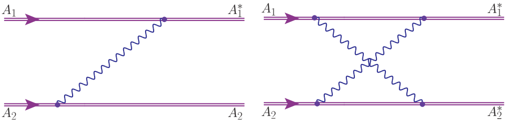
Electromagnetic excitation

$P_k(E*)$

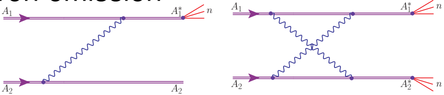




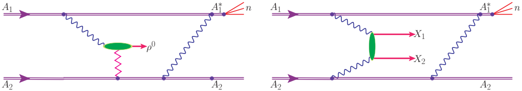
➤ Photon → nucleus excitation



✚ neutron emission



✚ particle production



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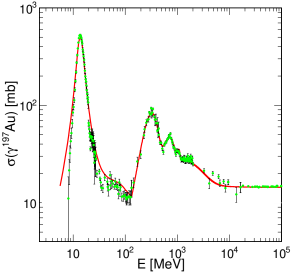
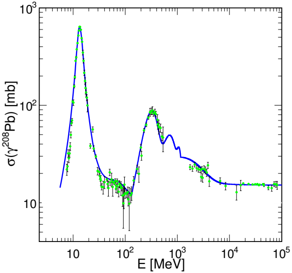
PHOTOABSORPTION

$\gamma\ ^{197}$Au

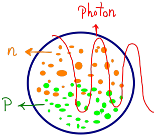


$\gamma\ ^{208}$Pb

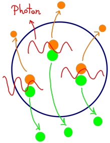


$$\sigma_{\gamma A} = \sigma_{\rm GDR} + \sigma_{\rm QD} + \sigma_{\rm nucleon\ res.} + \sigma_{\rm nucleon\ cont.}$$

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

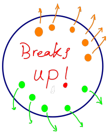


❷ quasi-deuteron contribution
$E_\gamma = (40 - 100)$ MeV



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

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



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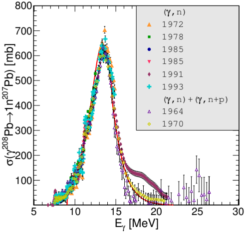
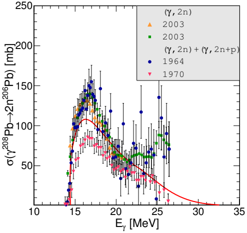
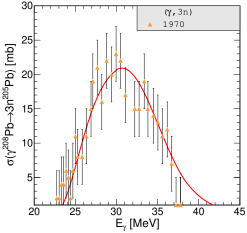
$\gamma\ ^{208}\mathrm{Pb} \to 1n\ ^{207}\mathrm{Pb}$

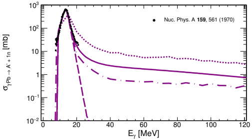


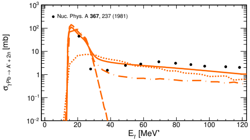
$\gamma\ ^{208}\mathrm{Pb} \to 2n\ ^{206}\mathrm{Pb}$

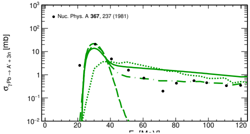


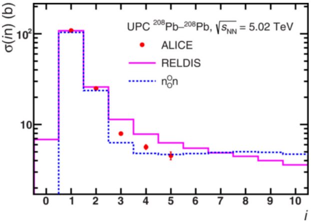
$\gamma\ ^{208}\mathrm{Pb} \to 3n\ ^{205}\mathrm{Pb}$

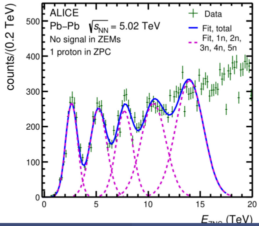




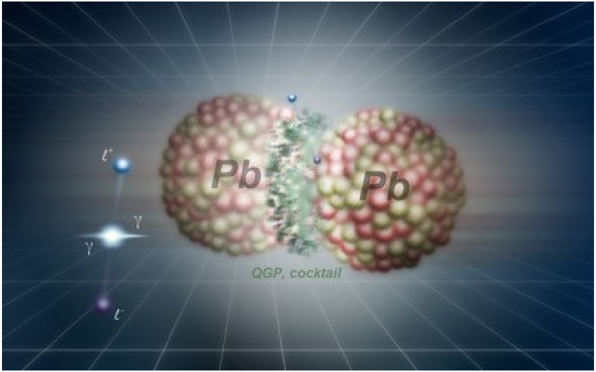








SEMICENTRAL HEAVY-ION COLLISIONS



- From ultraperipheral to semicentral collisions $\rightarrow$ dilepton sources
  - $\gamma\gamma$ fusion mechanism
- Invariant mass
  - SPS (NA60 data)
  - RHIC (STAR data)
  - LHC (ALICE data)
- Low-P_T dilepton spectra
  - RHIC (STAR data)
  - LHC (ALICE data)
- Acoplanarity
  - LHC (ATLAS data)

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DIELECTRON INVARIANT-MASS SPECTRA - RHIC

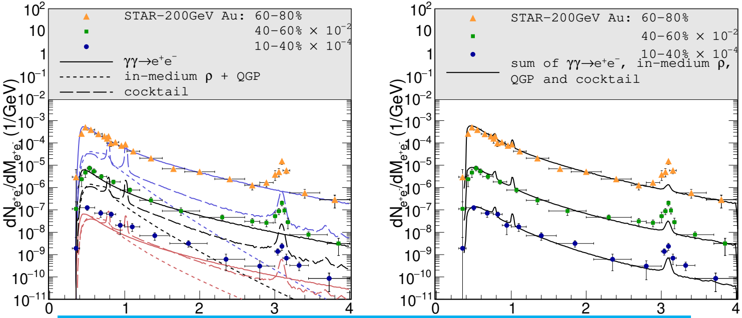
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

$|y_{e^+e^-}| < 1$

- ✔ $\gamma\gamma$-fusion
- ✔ thermal radiation
- ✔ hadronic cocktail

3 centrality classes



The coherent emission dominates for the two peripheral samples

and is comparable to the cocktail and thermal radiation yields in semi-central collisions.

EPA in the impact parameter space - the pair transverse momentum $P_T^{\ell^+\ell^-}$ is neglected

$$\sigma_{A_1A_2\to A_1A_2\ell^+\ell^-} = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2})\, \delta^{(2)}(\mathbf{b}-\mathbf{b}_1-\mathbf{b}_2) \int d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}\, dy_{\ell^+} dy_{\ell^-} dp_{t,\ell}^2 \frac{d\sigma(\gamma\gamma\to\ell^+\ell^-;\hat{s})}{d(-\hat{t})}$$

➯ **k_t-factorization**

$$\frac{dN_{ll}}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2} d^2\boldsymbol{q}_{1t} d^2\boldsymbol{q}_{2t} \frac{dN(\omega_1,q_{1t}^2)}{d^2\boldsymbol{q}_{1t}} \frac{dN(\omega_2,q_{2t}^2)}{d^2\boldsymbol{q}_{2t}} \delta^{(2)}(\boldsymbol{q}_{1t}+\boldsymbol{q}_{2t}-\mathbf{P}_T^{\ell^+\ell^-})\hat{\sigma}(\gamma\gamma\to\ell^+\ell^-)\Big|_{\text{cuts}},$$

➯ **Exact calculation**

$$\frac{d\sigma[\mathcal{C}]}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d^2\boldsymbol{Q}}{2\pi} w(Q;b_{\max},b_{\min}) \int \frac{d^2\boldsymbol{q}_1}{\pi}\frac{d^2\boldsymbol{q}_2}{\pi} \delta^{(2)}(\mathbf{P}_T^{\ell^+\ell^-}-\mathbf{q}_1-\boldsymbol{q}_2) \int \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$

$$\times\; E_i\left(\omega_1,\boldsymbol{q}_1+\frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega_1,\boldsymbol{q}_1-\frac{\boldsymbol{Q}}{2}\right) E_k\left(\omega_2,\boldsymbol{q}_2-\frac{\boldsymbol{Q}}{2}\right) E_l^*\left(\omega_2,\boldsymbol{q}_2+\frac{\boldsymbol{Q}}{2}\right) \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger}\, d\Phi(\ell^+\ell^-)\,.$$

The factorization formula is written in terms of the Wigner function:

$$N_{ij}(\omega,\mathbf{b},\mathbf{q}) = \int \frac{d^2\mathbf{Q}}{(2\pi)^2} \exp[-i\mathbf{bQ}]\, E_i\left(\omega,\mathbf{q}+\frac{\mathbf{Q}}{2}\right) E_j^*\left(\omega,\mathbf{q}-\frac{\mathbf{Q}}{2}\right) = \int d^2\mathbf{s}\, \exp[i\mathbf{qs}]\, E_i\left(\omega,\mathbf{b}+\frac{\mathbf{s}}{2}\right) E_j^*\left(\omega,\mathbf{b}-\frac{bs}{2}\right),$$

$$N(\omega,\mathbf{q}) = \delta_{ij}\int d^2\mathbf{b}\, N_{ij}(\omega,\mathbf{b},\mathbf{q}) = \delta_{ij}\, E_i(\omega,\mathbf{q})E_j^*(\omega,\mathbf{q}) = \left|\boldsymbol{E}(\omega,\mathbf{q})\right|^2,$$

$$N(\omega,\mathbf{b}) = \delta_{ij}\int \frac{d^2\boldsymbol{q}}{(2\pi)^2} N_{ij}(\omega,\mathbf{b},\mathbf{q}) = \delta_{ij}\, E_i(\omega,\mathbf{b})E_j^*(\omega,\mathbf{b}) = \left|\mathbf{E}(\omega,\mathbf{b})\right|^2.$$

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PAIR TRANSVERSE MOMENTUM - RHIC & LHC

$p_t > 0.2$ GeV,

$|\eta_e| < 1$

c=(60-80)%

$|y_{ee}| < 1$

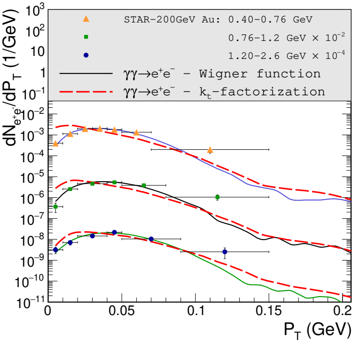
- - - - - - PL**B790** (2019) 339
vs.
—— PL**B814** (2021) 136114

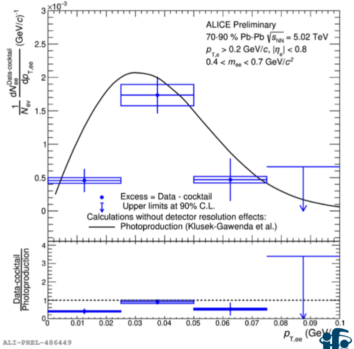
$p_t > 0.2$ GeV,

$|\eta_e| < 0.8$

c=(70-90)%

$M_{e^+e^-}$ =(0.4-0.7) GeV





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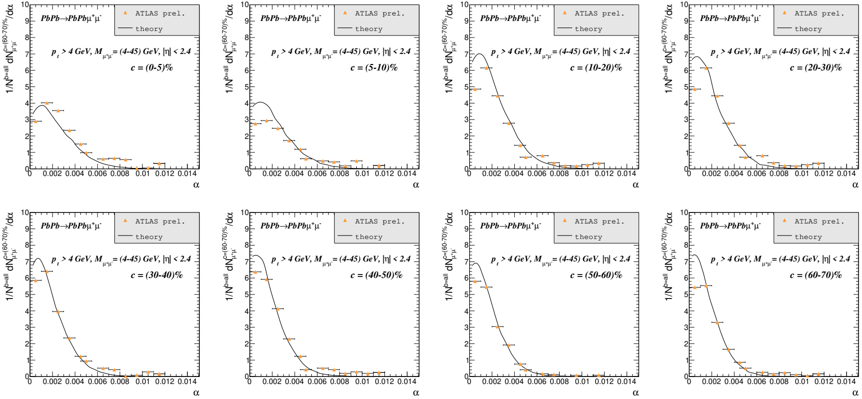
ACOPLANARITY - ATLAS DATA



A successful description of ATLAS data by $\gamma\gamma$-fusion alone

A correct normalization and shape of the distributions

$p_t > 4$ GeV,

$M_{\mu^+\mu^-}$ =(4-45) GeV,

$|\eta_\mu| < 2.4$

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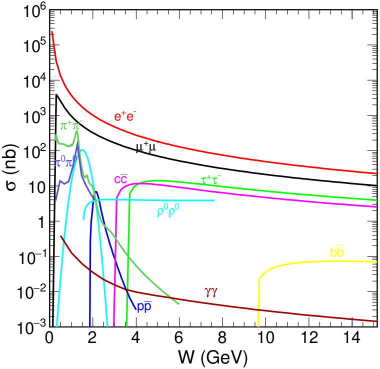
Conclusion

- EPA in the impact parameter space
- Fourier transform of the charge distribution
- Multidimensional integrals → 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