

# THEROTICAL OVERVIEW ON UPC

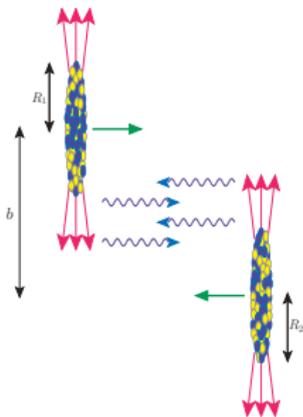
Mariola Klusek-Gawenda

*The Henryk Niewodniczański Institute of Nuclear Physics  
Polish Academy of Sciences*

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



# ULTRAPERIPHERAL COLLISION OF HEAVY IONS



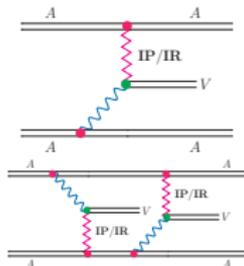
The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions. Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

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

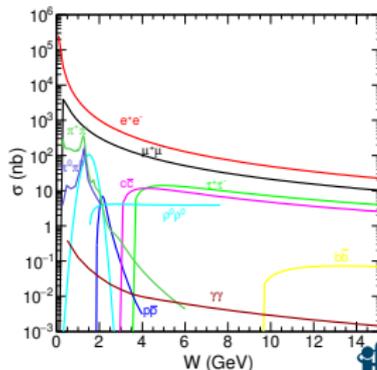
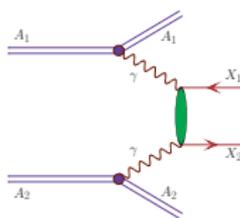
$$\text{Photon energy: } \omega = \frac{\gamma}{b_{min}} \approx \gamma \times 15 \text{ MeV}$$

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

## Photoproduction

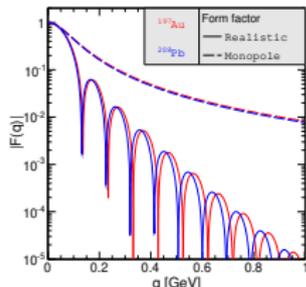
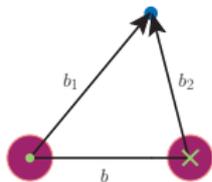


## $\gamma\gamma$ fusion



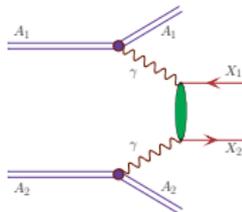
## EQUIVALENT PHOTON APPROXIMATION

$$\begin{aligned}
 \sigma_{A_1 A_2 \rightarrow A_1 A_2 X_1 X_2} &= \int \sigma_{\gamma\gamma \rightarrow X_1 X_2}(\omega_1, \omega_2) d\omega_1 d\omega_2 n(\omega_1) n(\omega_2) \rightarrow \dots n(\omega) = \int_{R_{min}}^{\infty} 2\pi b db N(\omega, b) \dots \\
 &= \int \sigma_{\gamma\gamma \rightarrow X_1 X_2}(W_{\gamma\gamma}) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S_{abs}^2(\mathbf{b}) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1 X_2} d\bar{b}_x d\bar{b}_y d^2 b \\
 &= \int \frac{d\sigma_{\gamma\gamma \rightarrow X_1 X_2}(W_{\gamma\gamma})}{d \cos \theta} N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S_{abs}^2(\mathbf{b}) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1 X_2} d\bar{b}_x d\bar{b}_y d^2 b \\
 &\times \frac{d \cos \theta}{dy_{X_1} dy_{X_2} dp_t} \times dy_{X_1} dy_{X_2} dp_t.
 \end{aligned}$$



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

$$F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \sin(|\mathbf{q}| r) r dr$$



# MC EVENT GENERATORS

- ① **STARlight** simulates two-photon and  $\gamma$ -IP interactions between relativistic nuclei and protons. It produces a variety of final states. For two- $\gamma$ , it simulates lepton pairs and a variety of mesons. For photonuclear interactions, it models coherent and incoherent vector mesons production.

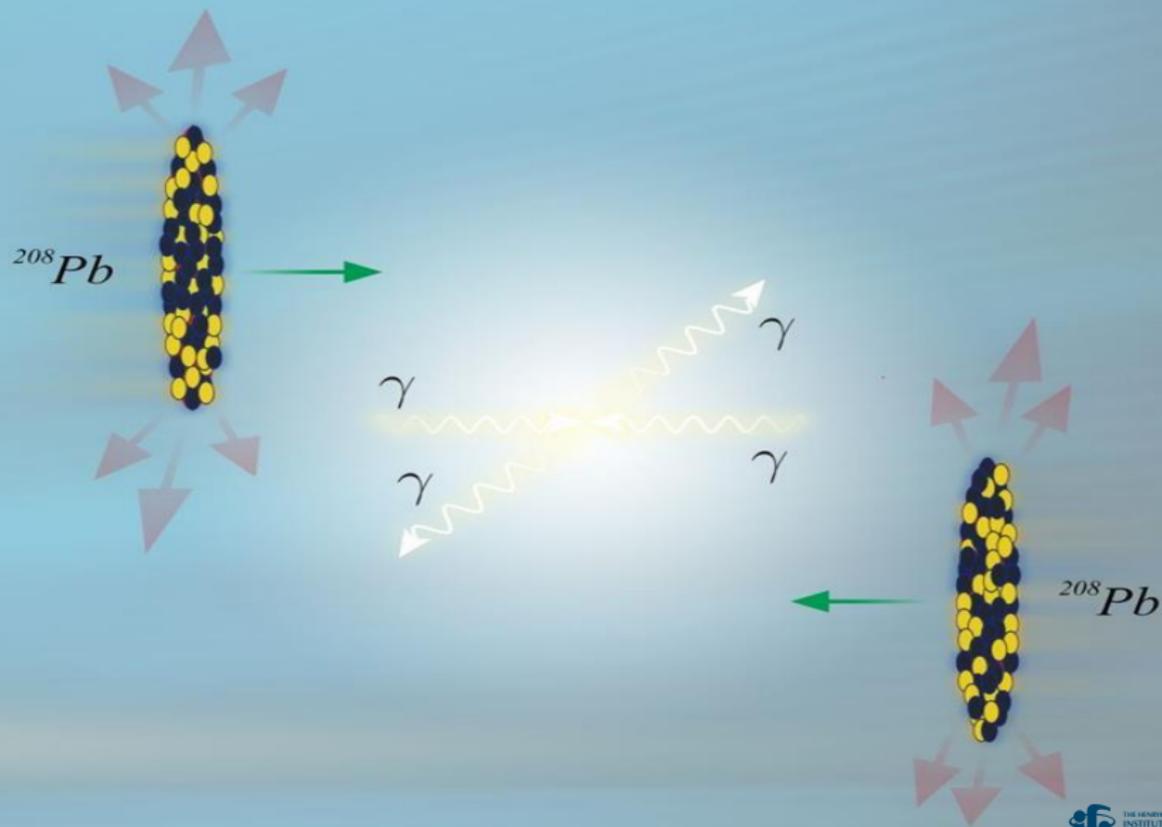
*S.R. Klein, J. Nystrand, J. Seger, Y. Gorunov, J. Butterworth, Comp. Phys. Comm. **212** (2017) 258*
- ② **SuperChic** - event generator for exclusive and  $\gamma$ -initiated production in proton and heavy ion collisions. A range of SM final states are implemented, in most cases with spin correlations 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  $\gamma$  flux allowing us to improve the agreement with ATLAS data at large dilepton rapidities. Besides, the new generator offers a possibility to study  $\gamma$  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  $\gamma$ - $\gamma$  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)*

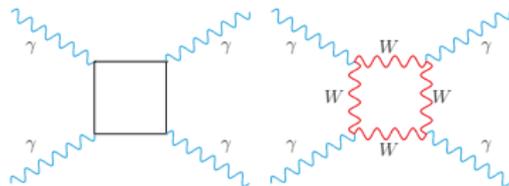
## LIGHT-BY-LIGHT SCATTERING



# LIGHT-BY-LIGHT SCATTERING

**Boxes**

**WELL-KNOWN**



Fermionic boxes (LO QED)

FormCalc.

W Box

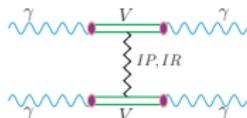
LoopTools.

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

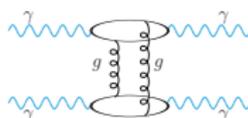
**VDM-Regge**

**WE ADD**

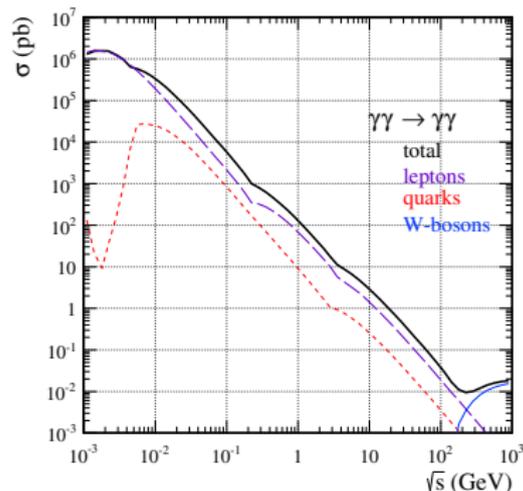
**2-gluon exch.**



fluctuation of  $\gamma$   
into virtual  $\rho, \omega, \phi$



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](#).

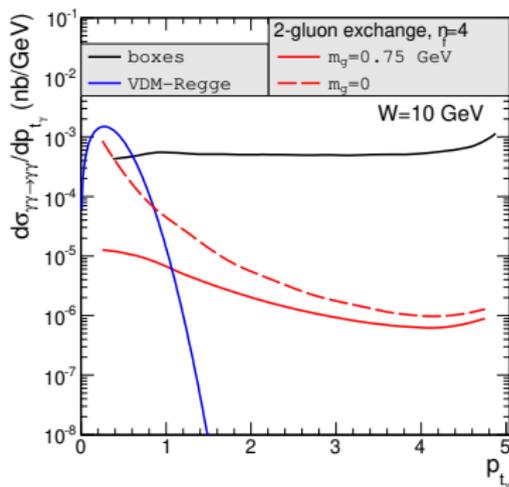
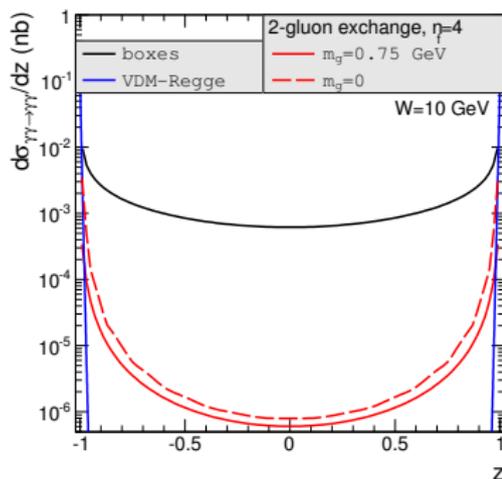
## ELEMENTARY CROSS SECTION

$$z = \cos \theta$$

- ✓ boxes
- ✓ VDM-Regge
- ✓ 2-gluon exchange

$$W = 10 \text{ GeV}$$

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



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

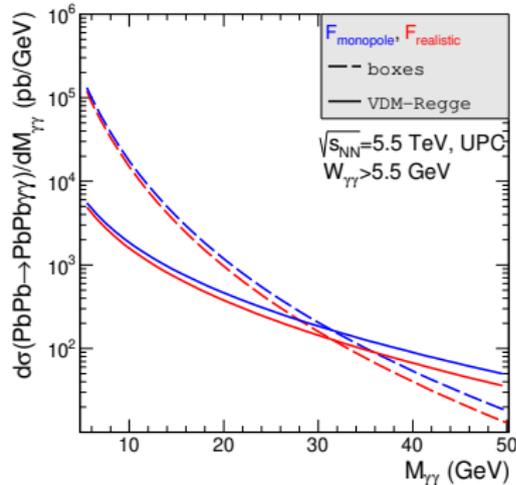
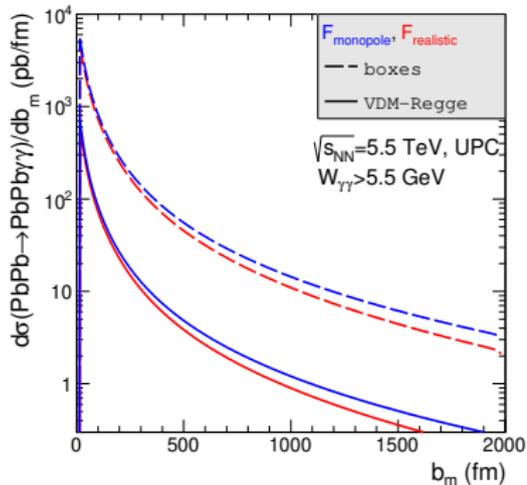
# AA $\rightarrow$ AA $\gamma\gamma$ - FORM FACTOR

$\Rightarrow$  realistic

$\Rightarrow$  monopole

impact parameter

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



$\uparrow$  theoretical distribution

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

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

# AA → AAγγ - CMS & ATLAS RESULTS

⇒ ATLAS Collaboration,  
PRL **123** (2019) 052001

- ×  $p_{t\gamma} > 3 \text{ GeV}$
- ×  $|\eta_\gamma| < 2.4$
- ×  $M_{\gamma\gamma} > 6 \text{ GeV}$
- ×  $p_{t\gamma\gamma} < 2 \text{ GeV}$
- ×  $A_{co} < 0.01$

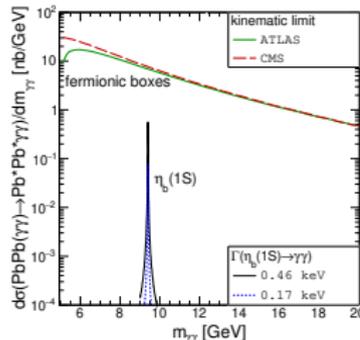
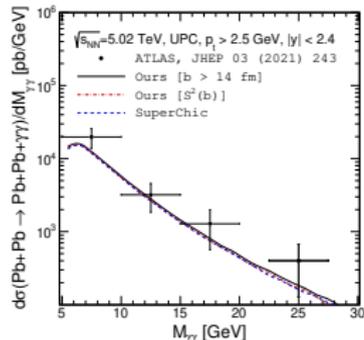
⇒ ATLAS Collaboration,  
JHEP **03** (2021) 243

- ×  $E_{t\gamma} > 2.5 \text{ GeV}$
- ×  $|\eta_\gamma| < 2.4$
- ×  $M_{\gamma\gamma} > 5 \text{ GeV}$
- ×  $p_{t\gamma\gamma} < 1 \text{ GeV}$
- ×  $A_{co} < 0.01$

⇒ CMS Collaboration,  
PLB **797** (2019) 134826

- ×  $E_{t\gamma} > 2 \text{ GeV}$
- ×  $|\eta_\gamma| < 2.4$
- ×  $M_{\gamma\gamma} > 5 \text{ GeV}$
- ×  $p_{t\gamma\gamma} < 1 \text{ GeV}$
- ×  $A_{co} < 0.01$

Experiment		Theory		
Collaboration	$\sigma$ [nb]	Vegas	SuperChic	gamma-UPC
ATLAS (2018 data)	$78 \pm 13(\text{stat.}) \pm 7(\text{syst.})$	51	50	—
ATLAS (2015+2018)	$120 \pm 17(\text{stat.}) \pm 13(\text{syst.})$	80	77	70
CMS (2015)	$120 \pm 46(\text{stat.}) \pm 28(\text{syst.})$	103	101	—

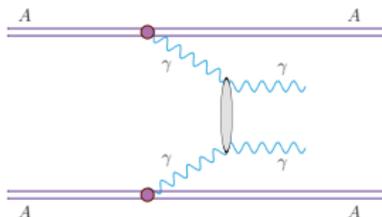


Underestimation:

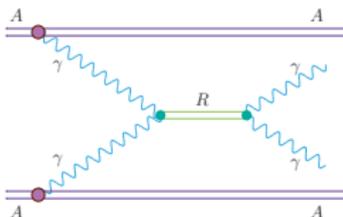
- tetraquarks X(6900) ?
- graviton, axion ?
- coherent sum of higher order processes ?
- pionic boxes ?

# AA → AAγγ FOR $M_{\gamma\gamma} < 5$ GeV ?

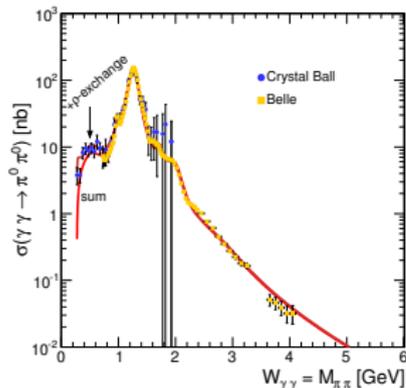
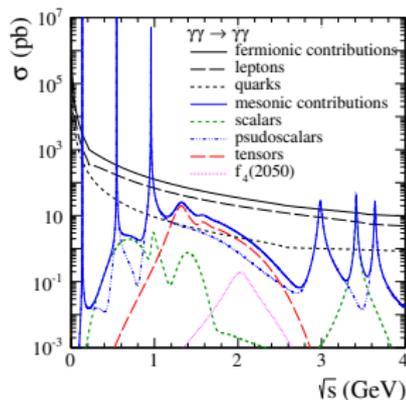
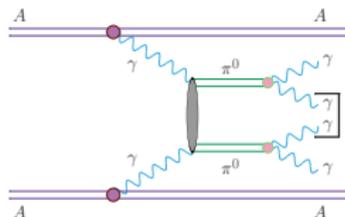
CONTINUUM



RESONANCES



BACKGROUND



⇒ P. Lebedowicz, 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...

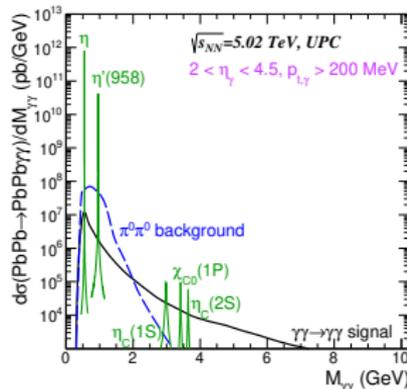
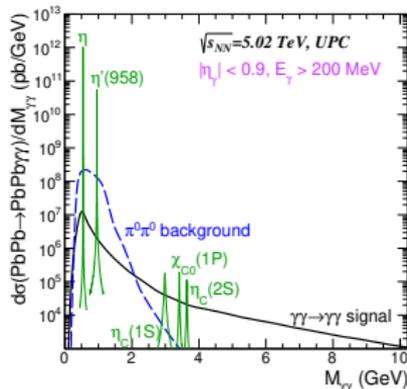
ALICE cuts

✓ boxes

✓ bkg

✓ mesons

LHCb cuts

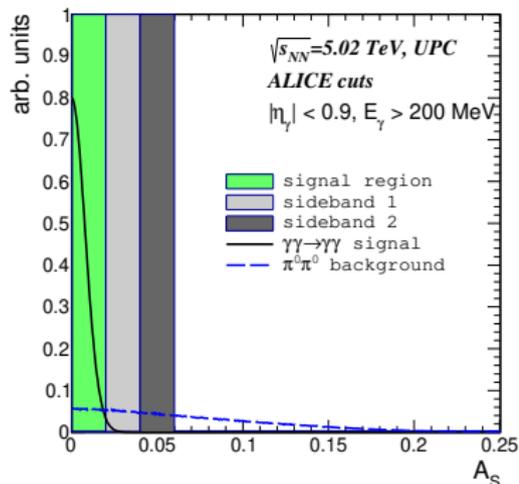
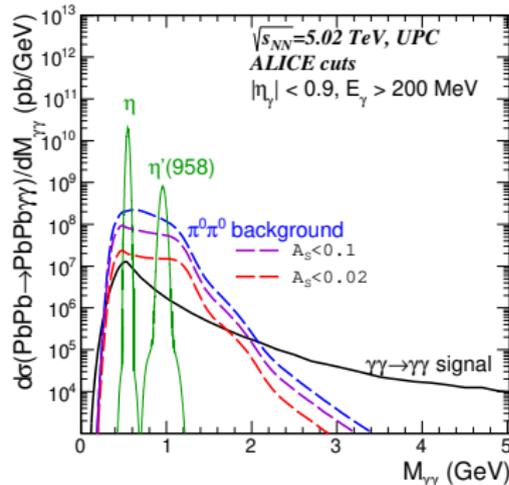


Total nuclear cross section [nb]

Energy	$W_{\gamma\gamma} = (0 - 2) \text{ GeV}$		$W_{\gamma\gamma} > 2 \text{ GeV}$	
	ALICE	LHCb	ALICE	LHCb
Fiducial region				
Boxes	4 890	3 818	146	79
$\pi^0 \pi^0$ bkg	135 300	40 866	46	24
$\eta$	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

## EXPERIMENTAL RESOLUTION &amp; SCALAR ASYMMETRY &amp; PIONIC BKG

$$A_S = \frac{|\vec{p}_T(1)| - |\vec{p}_T(2)|}{|\vec{p}_T(1)| + |\vec{p}_T(2)|}$$

 $A_S$  $M_{\gamma\gamma}$ 80% of the signal events at  $A_S < 0.02$

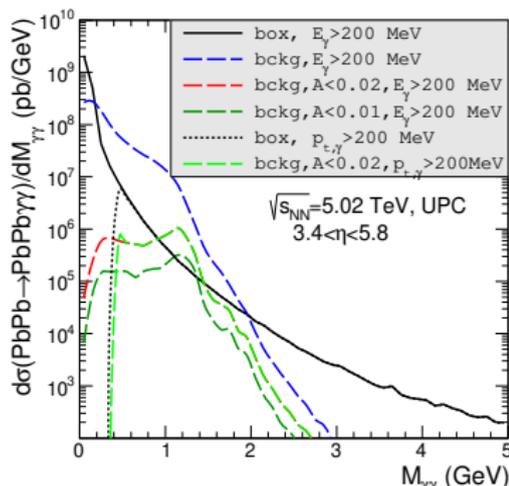
# AA $\rightarrow$ AA $\gamma\gamma$ @ FORWARD REGION ?

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

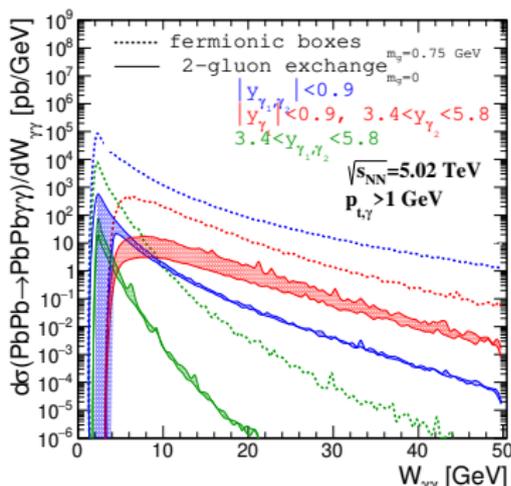
**FoCAL**  $\rightarrow 3.4 < \eta < 5.8$

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



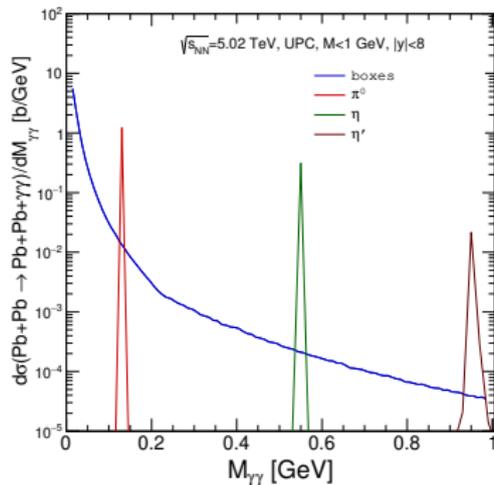
$p_{t,\gamma} > 1$  GeV



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

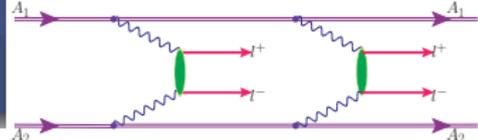
# AA $\rightarrow$ AA $\gamma\gamma$ @ LOW $p_t$ REGION ?

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



$$\gamma\gamma \rightarrow \pi^0 \rightarrow \gamma\gamma$$

# FOUR-LEPTON PRODUCTION



$$\frac{d\sigma_{A_1 A_2 \rightarrow A_1 A_2 (\ell^+ \ell^-) (\ell^+ \ell^-)}}{dy_{\ell^+}^I dy_{\ell^-}^I dy_{\ell^+}^{II} dy_{\ell^-}^{II}} = \frac{1}{2} \int \left( \frac{dP^I}{\gamma\gamma \rightarrow \ell^+ \ell^- (b, y_{\ell^+}^I, y_{\ell^-}^I; p_{t, \ell})} \times \frac{dP^{II}}{\gamma\gamma \rightarrow \ell^+ \ell^- (b, y_{\ell^+}^{II}, y_{\ell^-}^{II}; p_{t, \ell})} \right)$$

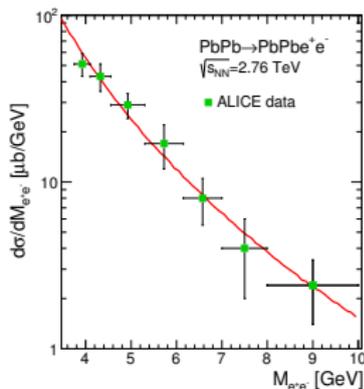
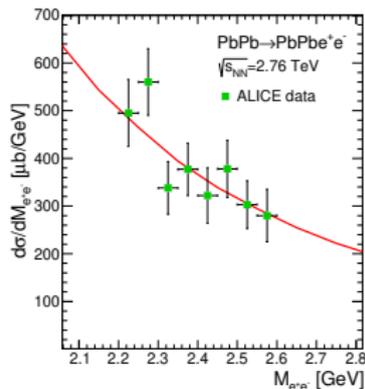
$$\times 2\pi b db$$

$$P_{\gamma\gamma \rightarrow \ell^+ \ell^-} (b; y_{\ell^+}, y_{\ell^-}, p_{t, \ell}) = \int N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S_{abs}^2(\mathbf{b}) \times \frac{d\sigma_{\gamma\gamma \rightarrow \ell_1 \ell_2}(W_{\gamma\gamma})}{d\cos\theta} d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\ell_1 \ell_2}$$

$$2.2 \text{ GeV} < M_{ee} < 2.6 \text{ GeV}$$

$$|y_e| < 0.9$$

$$3.7 \text{ GeV} < M_{ee} < 10 \text{ GeV}$$

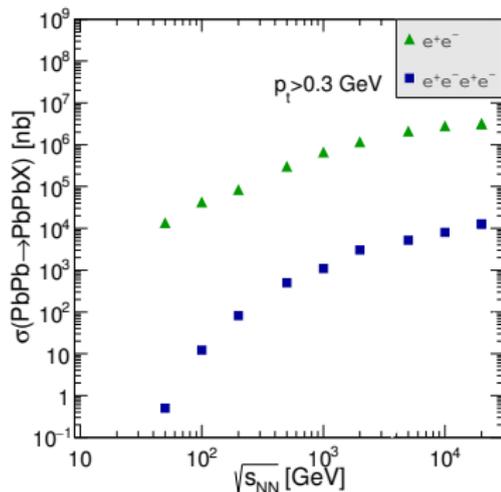


Good description of single pair production  $\Rightarrow$  two  $e^+ e^-$  pair production...?

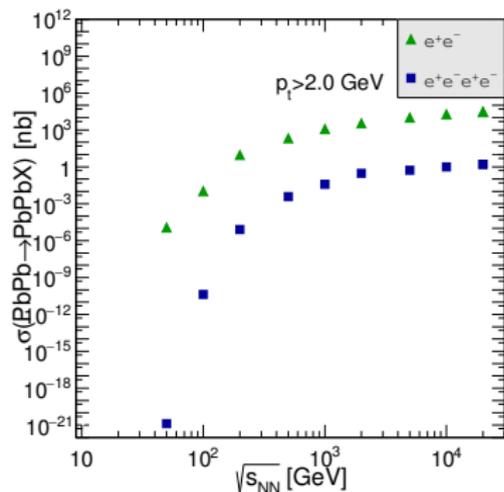
$$AA \rightarrow AAe^+e^- \text{ \& \ } AA \rightarrow AAe^+e^-e^+e^-$$

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

$p_t > 0.3 \text{ GeV}$

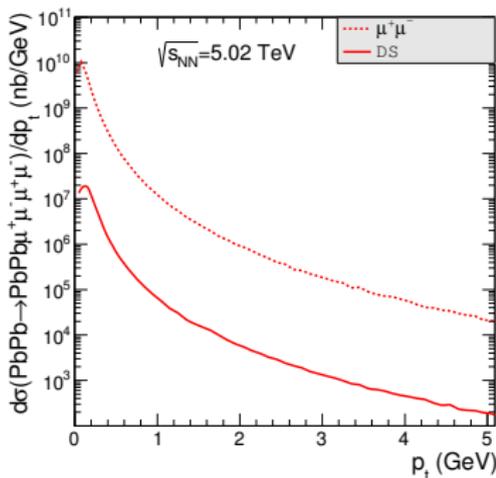
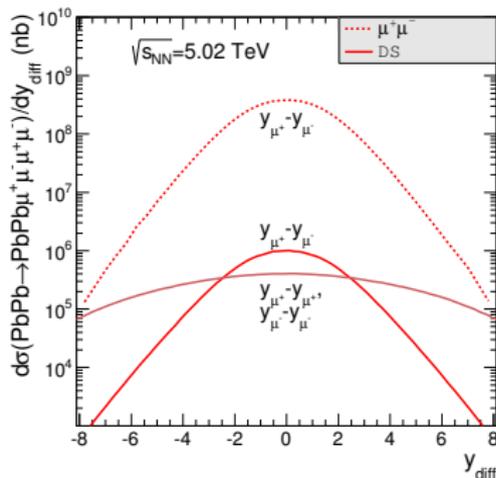


$p_t > 2.0 \text{ GeV}$



$$AA \rightarrow AA\mu^+\mu^- \text{ \& \ } AA \rightarrow AA\mu^+\mu^-\mu^+\mu^-$$

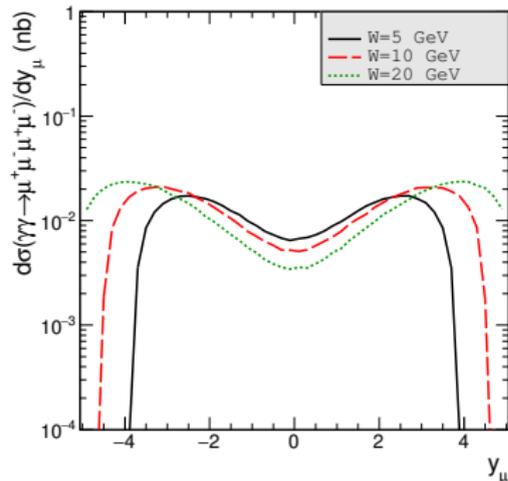
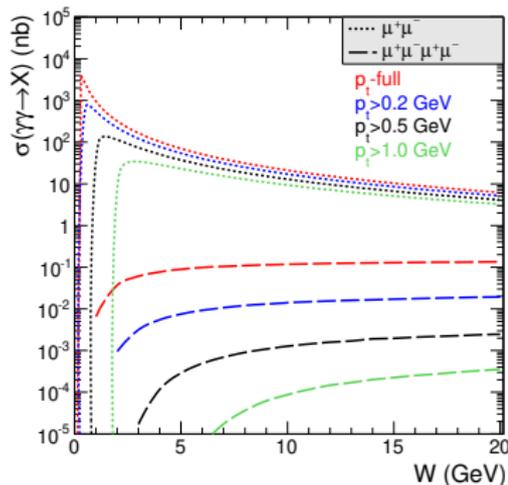
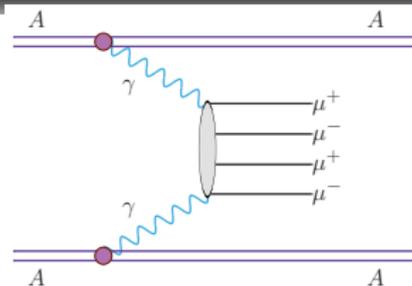
## Single $\mu^+\mu^-$ pair production vs. double scattering production of two $\mu^+\mu^-$ pairs

 $\rho_{t,\mu}$ 

 $y_{diff}$ 


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

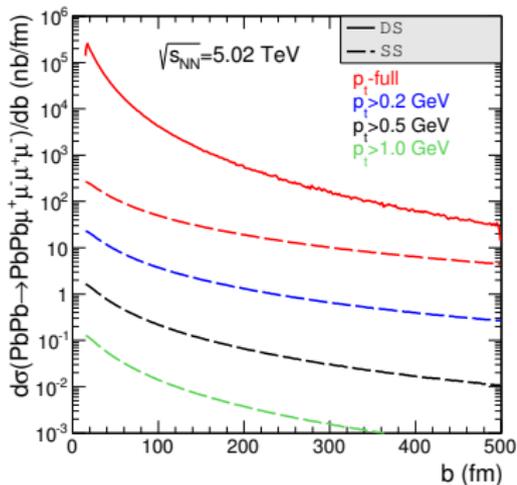
$$\gamma\gamma \rightarrow \mu^+\mu^-\mu^+\mu^- - \text{SINGLE SCATTERING}$$


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.

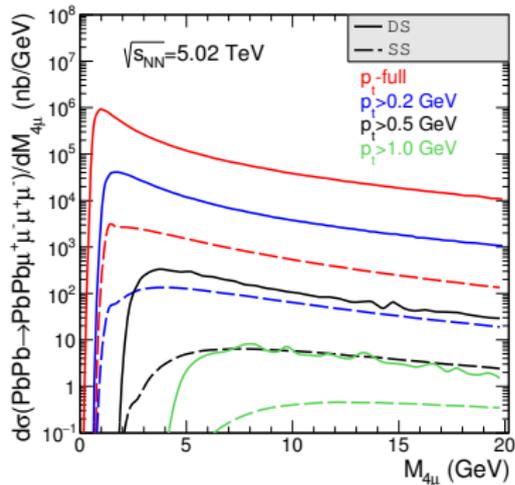


$$AA \rightarrow AA \mu^+ \mu^- \mu^+ \mu^-$$

impact parameter



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

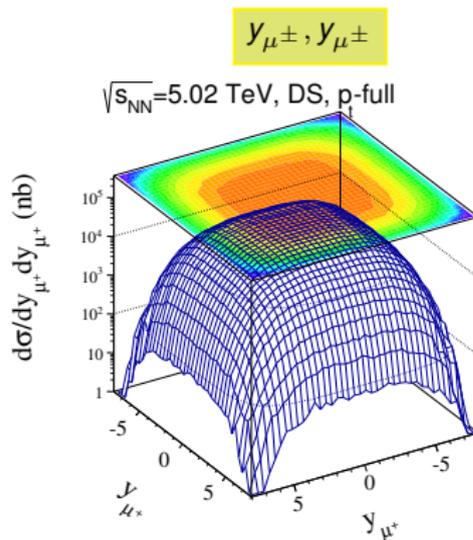
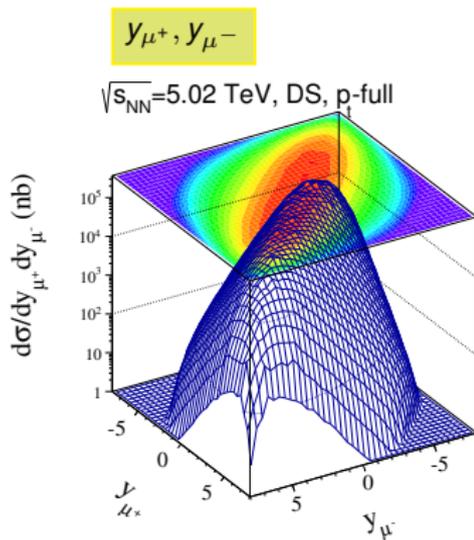


It is difficult to isolate range of SS domination

\*DS - double-scattering mechanism

\*SS - a NEW single-scattering mechanism

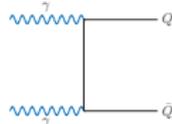
$$AA \rightarrow AA \mu^+ \mu^- \mu^+ \mu^-$$



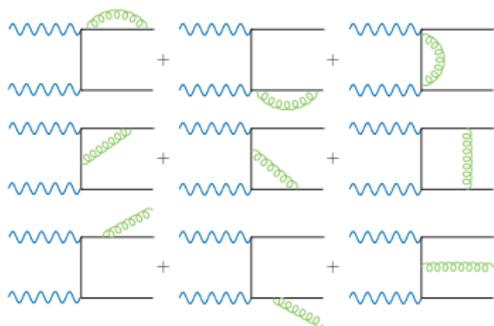
creation of similar distributions by ALICE or CMS?

# QUARKS PRODUCTION

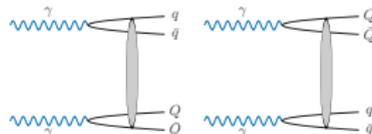
## 1 $2 \rightarrow 2$ process (Born amplitude)



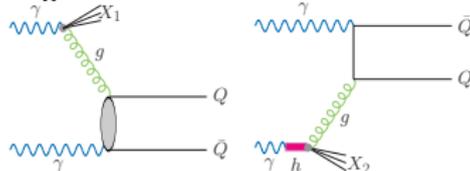
## 2 LO QCD corrections



## 3 $Q\bar{Q}q\bar{q}$ production

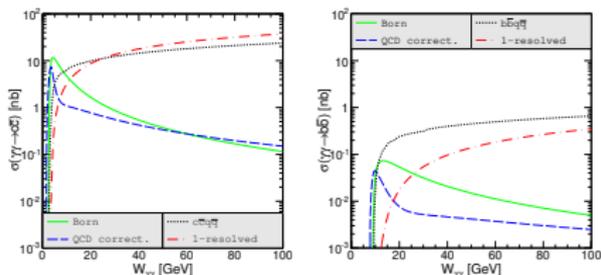


## 4 single-resolved mechanism

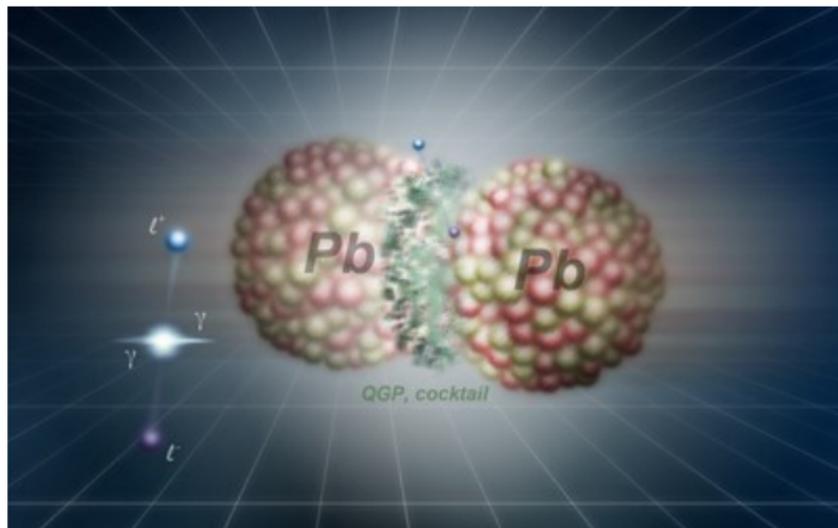


Nuclear cross section at  $\sqrt{s_{NN}} = 5.5$  TeV

	$\sigma_{tot}$	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 $\mu$ b	18.9%	7.7%	64.5%	8.9%



## SEMICENTRAL HEAVY-ION COLLISIONS



- From ultraperipheral to semicentral collisions → 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)

## DIELECTRON INVARIANT-MASS SPECTRA - RHIC

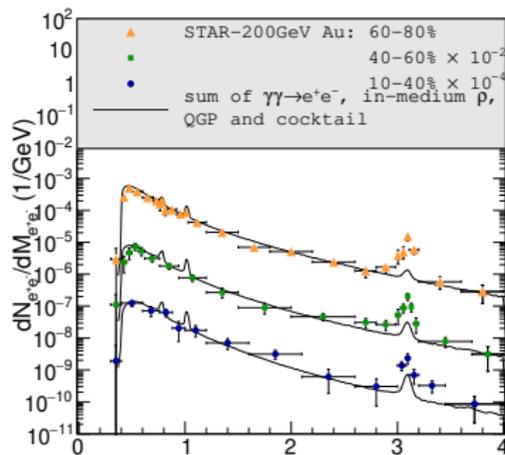
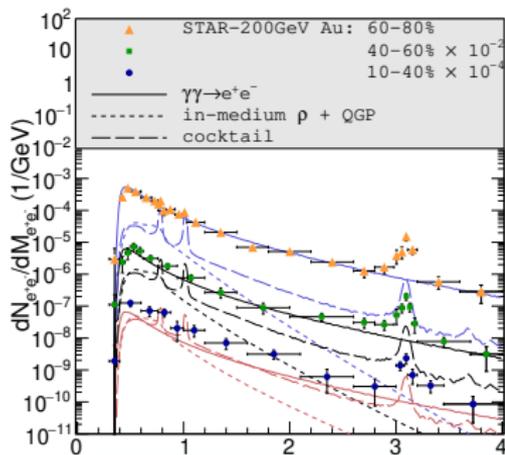
$$p_t > 0.2 \text{ GeV},$$

$$|\eta_e| < 1$$

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

- ✓  $\gamma\gamma$ -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

$$\sigma_{A_1 A_2 \rightarrow A_1 A_2 \ell^+ \ell^-} = \int N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 - \mathbf{b}_2) \int d^2 \mathbf{b}_1 d^2 \mathbf{b}_2 d^2 \mathbf{b} dy_{\ell^+} dy_{\ell^-} d\rho_{T, \ell}^2 \frac{d\sigma(\gamma\gamma \rightarrow \ell^+ \ell^-; \hat{s})}{d(-\hat{t})}$$

⇒  $k_t$ -factorization

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

⇒ Exact calculation

$$\begin{aligned} \frac{d\sigma[C]}{d^2 \mathbf{P}_T^{\ell^+ \ell^-}} &= \int \frac{d^2 \mathbf{Q}}{2\pi} w(\mathbf{Q}; b_{\max}, b_{\min}) \int \frac{d^2 \mathbf{q}_1}{\pi} \frac{d^2 \mathbf{q}_2}{\pi} \delta^{(2)}(\mathbf{P}_T^{\ell^+ \ell^-} - \mathbf{q}_1 - \mathbf{q}_2) \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} \\ &\times E_j\left(\omega_1, \mathbf{q}_1 + \frac{\mathbf{Q}}{2}\right) E_j^*\left(\omega_1, \mathbf{q}_1 - \frac{\mathbf{Q}}{2}\right) E_k\left(\omega_2, \mathbf{q}_2 - \frac{\mathbf{Q}}{2}\right) E_l^*\left(\omega_2, \mathbf{q}_2 + \frac{\mathbf{Q}}{2}\right) \frac{1}{2\hat{s}} \sum_{\lambda \bar{\lambda}} M_{ik}^{\lambda \bar{\lambda}} M_{jl}^{\lambda \bar{\lambda} \dagger} d\Phi(\ell^+ \ell^-). \end{aligned}$$

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

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

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

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

## PAIR TRANSVERSE MOMENTUM - RHIC &amp; LHC

$$p_t > 0.2 \text{ GeV},$$

$$|\eta_e| < 1$$

$$c = (60-80)\%$$

$$|y_{ee}| < 1$$

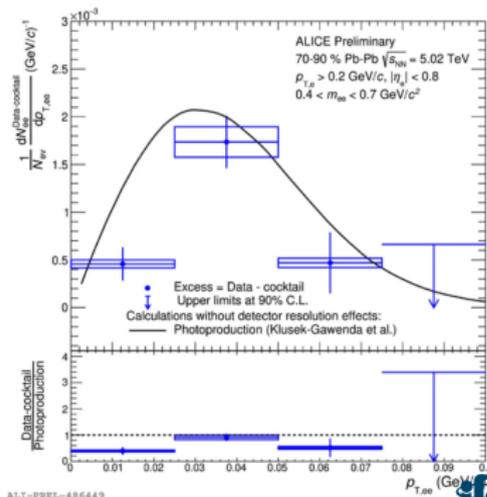
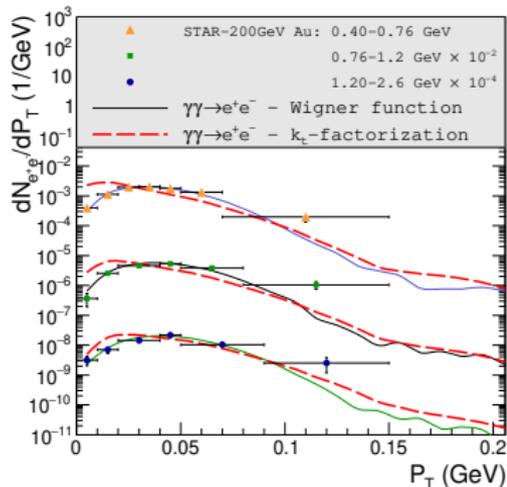
----- PLB790 (2019) 339  
vs.  
—— PLB814 (2021) 136114

$$p_t > 0.2 \text{ GeV},$$

$$|\eta_e| < 0.8$$

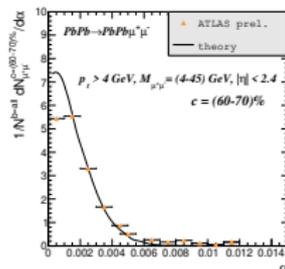
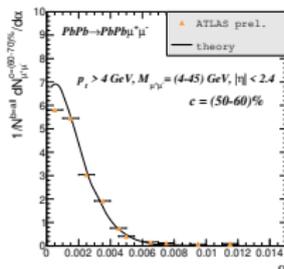
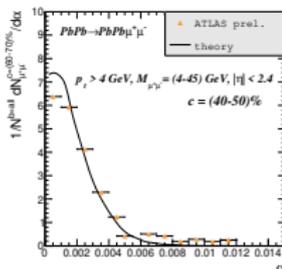
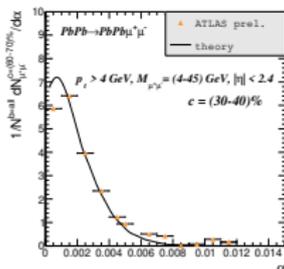
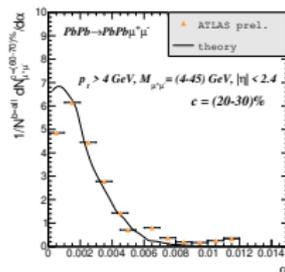
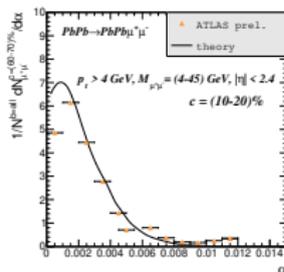
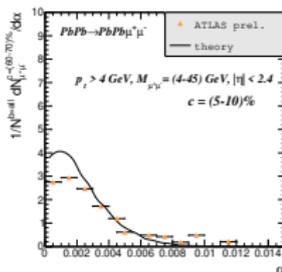
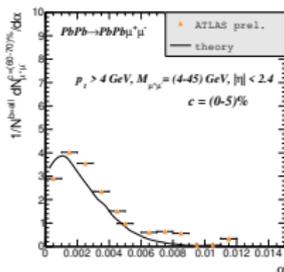
$$c = (70-90)\%$$

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



ALI-PREL-486449

## ACOPLANARITY - ATLAS DATA



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

A correct normalization and shape of the distributions

$$p_t > 4 \text{ GeV},$$

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

$$|\eta_{\mu}| < 2.4$$

$$AA \rightarrow AA \pi^+ \pi^- \pi^+ \pi^-$$

## H1 DATA

H1prelim-18-011

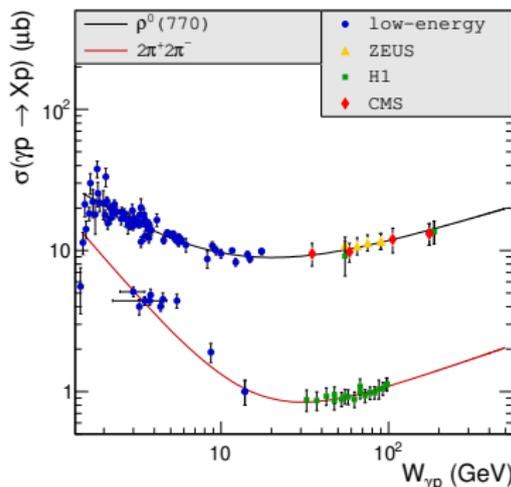
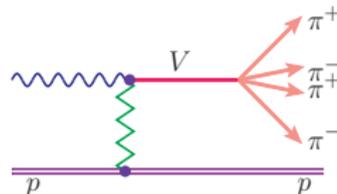
April 10, 2018

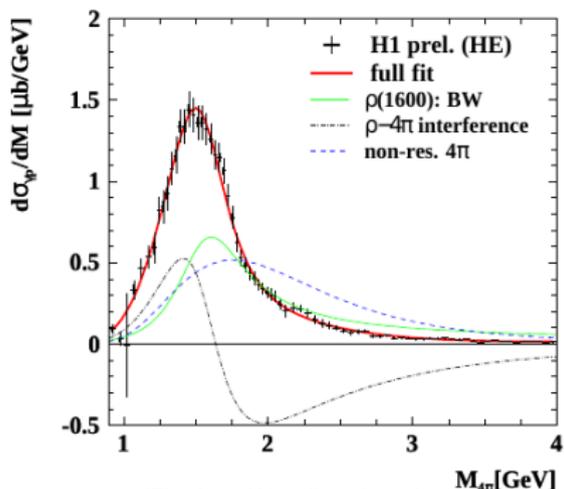
Submitted to **DIS-2018**, Kobe, 16–20 April, 2018

### 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 small photon virtualities  $Q^2 < 2 \text{ GeV}^2$ . The data were taken with the H1 detector in the years 2006 and 2007 at a centre-of-mass energies of  $\sqrt{s} = 319 \text{ GeV}$  and  $\sqrt{s} = 225 \text{ GeV}$ ; correspond to an integrated luminosity of  $7.6 \text{ pb}^{-1}$  and  $1.7 \text{ pb}^{-1}$  respectively. The cross section of the reaction  $\gamma p \rightarrow (2\pi^+2\pi^-)Y$  is determined in the phase space of  $35 < W_{\gamma Y} < 100 \text{ GeV}$ ,  $|t| < 1 \text{ GeV}^2$  and  $M_Y < 1.6 \text{ GeV}$ . The  $4\pi$  mass spectra indicate that the reaction proceeds predominantly via production and decay of  $\rho'$  resonances. The fit however does not allow yet to distinguish unambiguously between the hypotheses of one or two but overlapping  $\rho'$  resonances.

**vector meson ?**



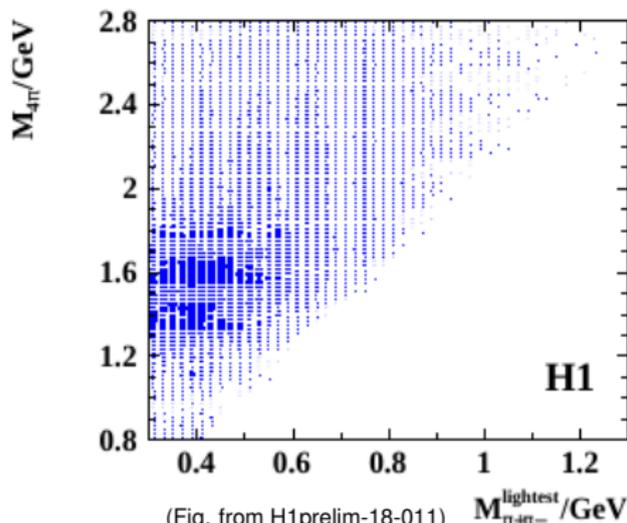
(Fig. from H1prelim-18-011)

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  $\rho$ -like resonances. Erkel [1] had pointed out this possibility with a theoretical analysis on the consistency of  $2\pi$  and  $4\pi$  electromagnetic form factors and the  $\pi\pi$  scattering length. Donnachie [2], with a full analysis of data on the  $2\pi$  and  $4\pi$  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  $e^+e^- \rightarrow \omega\pi$  [4].

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



(Fig. from H1prelim-18-011)

DECAY MODE

$$M_{4\pi} = 1.6 \text{ GeV}$$

or

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

## RESONANCES SKETCH PDG

 $\rho(1570)$ 

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

 $\rho(1570)$  MASS

VALUE (MeV)	EVT5	DOCUMENT ID	TECN	COMMENT
<b>1570 ± 36 ± 62</b>	54	<sup>1</sup> AUBERT	08S BABR	10.6 e <sup>+</sup> e <sup>-</sup> → $\phi\pi^0\gamma$

 $\rho(1570)$  WIDTH

VALUE (MeV)	EVT5	DOCUMENT ID	TECN	COMMENT
<b>144 ± 75 ± 43</b>	54	<sup>3</sup> AUBERT	08S BABR	10.6 e <sup>+</sup> e <sup>-</sup> → $\phi\pi^0\gamma$

 $\rho(1570)$  DECAY MODES

Mode	Fraction ( $\Gamma_i/\Gamma$ )
$\Gamma_1$ e <sup>+</sup> e <sup>-</sup>	
$\Gamma_2$ $\phi\pi$	not seen
$\Gamma_3$ $\omega\pi$	

 $\rho(1450)$  [1]

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

Mass  $m = 1465 \pm 25$  MeV [1]Full width  $\Gamma = 400 \pm 60$  MeV [1]

$\rho(1450)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$\pi\pi$	seen	720
$\pi^+\pi^-$	seen	719
$4\pi$	seen	669

 $\rho(1700)$  [1]

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

Mass  $m = 1720 \pm 20$  MeV [1] ( $\eta\rho^0$  and  $\pi^+\pi^-$  modes)Full width  $\Gamma = 250 \pm 100$  MeV [1] ( $\eta\rho^0$  and  $\pi^+\pi^-$  modes)

$\rho(1700)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$2(\pi^+\pi^-)$	seen	803

 $\rho(770)$  [14]

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

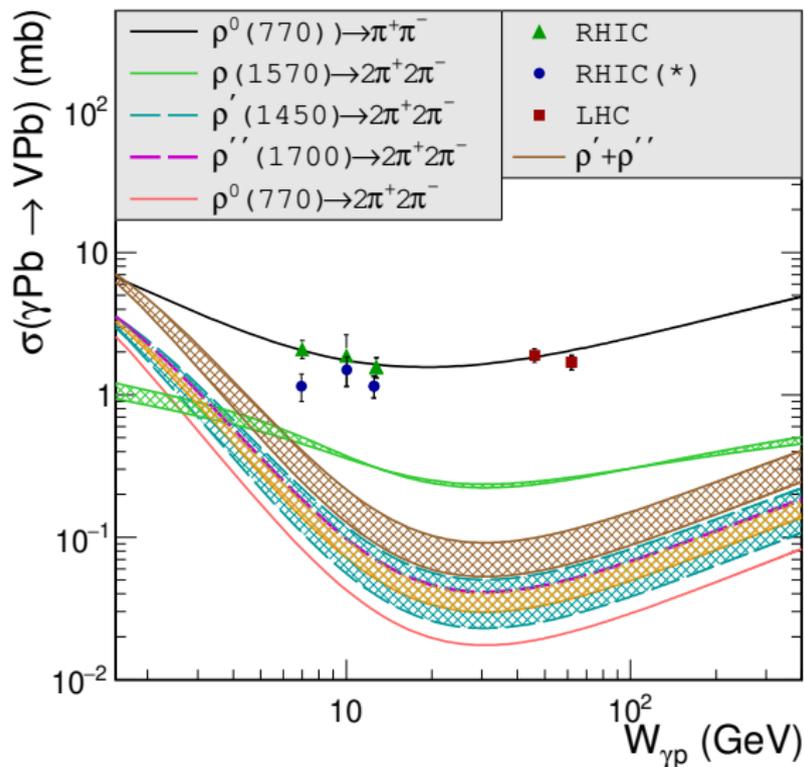
Mass  $m = 775.26 \pm 0.25$  MeVFull width  $\Gamma = 149.1 \pm 0.8$  MeV $\Gamma_{ee} = 7.04 \pm 0.06$  keV

$\rho(770)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$\pi\pi$	~ 100	%	363
$\pi^+\pi^-\pi^+\pi^-$	( 1.8 ± 0.9 ) × 10 <sup>-5</sup>		251

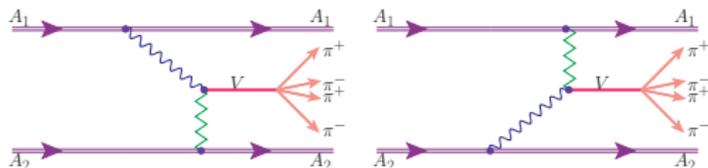
## MY CALCULATION

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

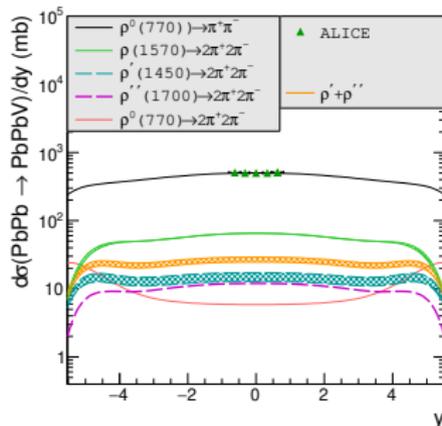
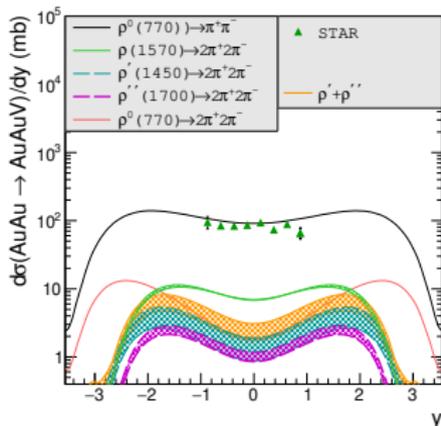
## COHERENT VECTOR MESON PHOTOPRODUCTION

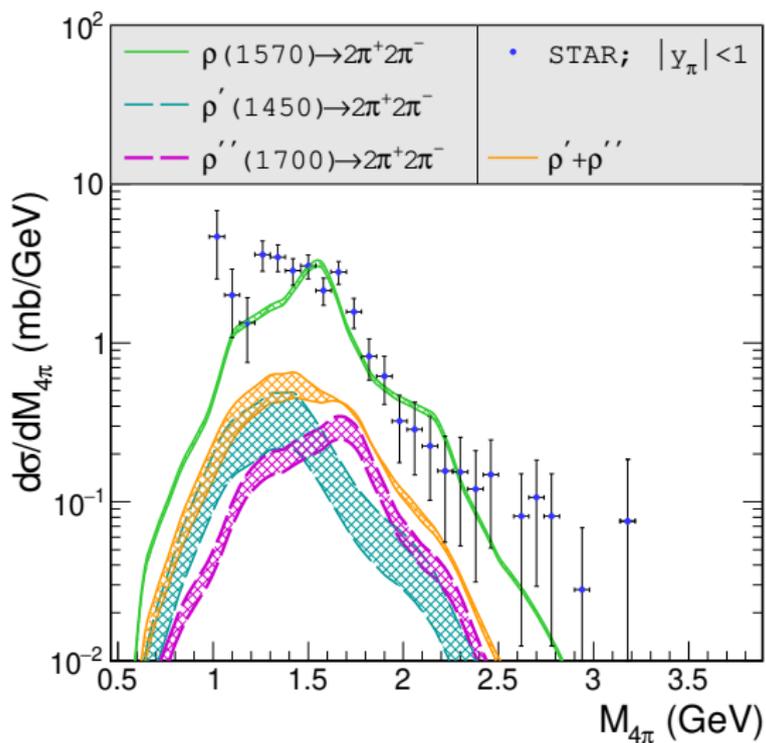


# DIFFERENTIAL CROSS SECTION



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

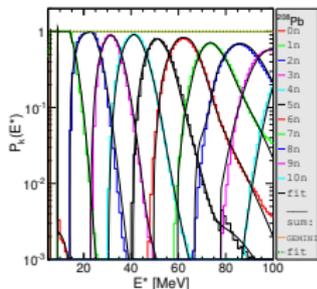
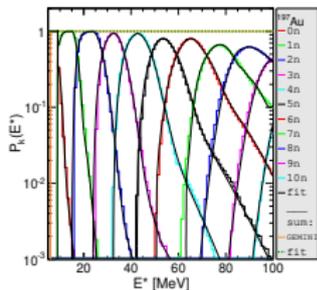




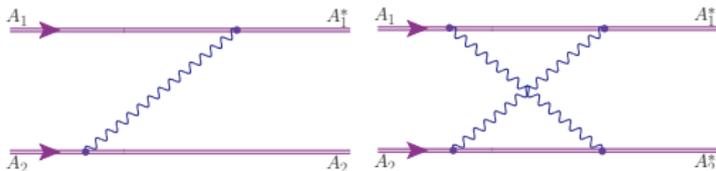
Success of  $\rho(1570)$  - Results for the LHC are necessary

## ELECTROMAGNETIC EXCITATION

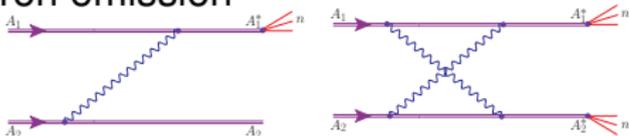
$$P_k(E^*)$$



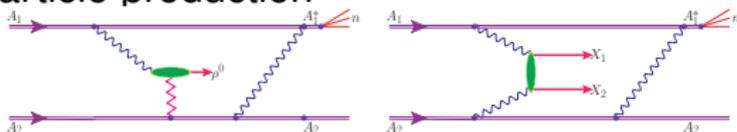
➤ Photon  $\rightarrow$  nucleus excitation

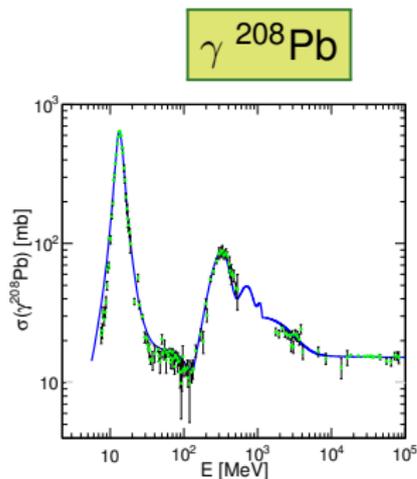
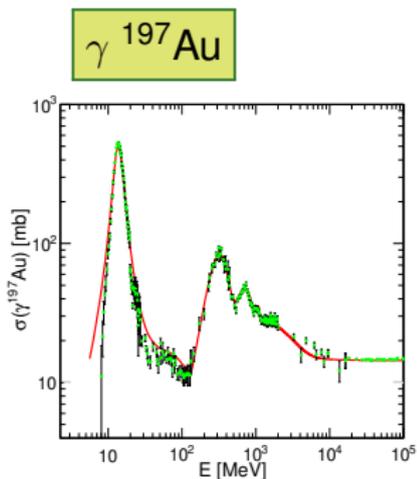


✚ neutron emission



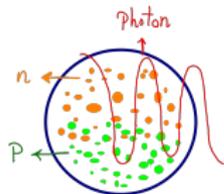
✚ particle production



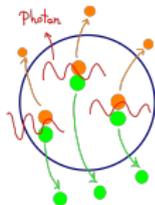


$$\sigma_{\gamma A} = \sigma_{\text{GDR}} + \sigma_{\text{QD}} + \sigma_{\text{nucleon res.}} + \sigma_{\text{nucleon cont.}}$$

- ❶ Giant Dipole Resonance  
 $E_{\gamma} < 40$  MeV



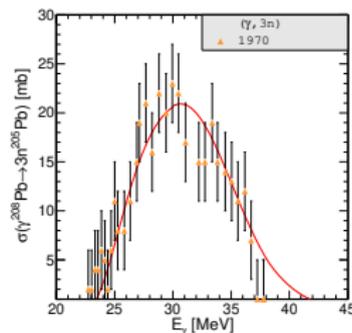
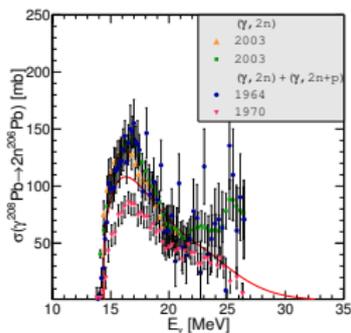
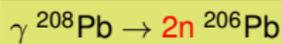
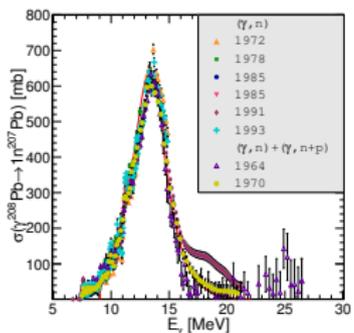
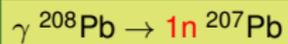
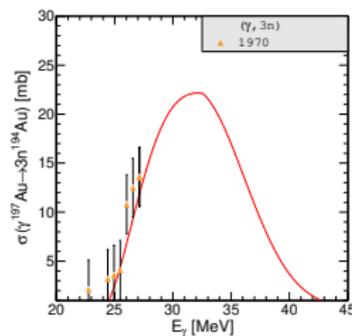
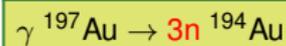
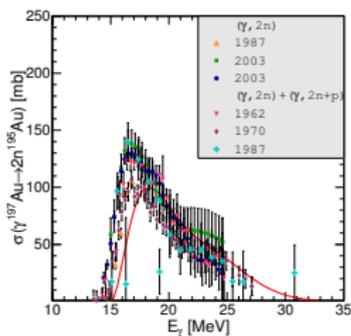
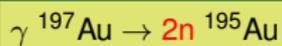
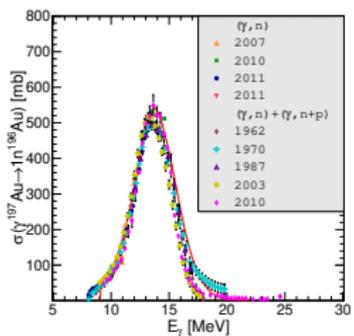
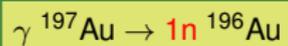
- ❷ quasi-deuteron contribution  
 $E_{\gamma} = (40 - 100)$  MeV



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

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

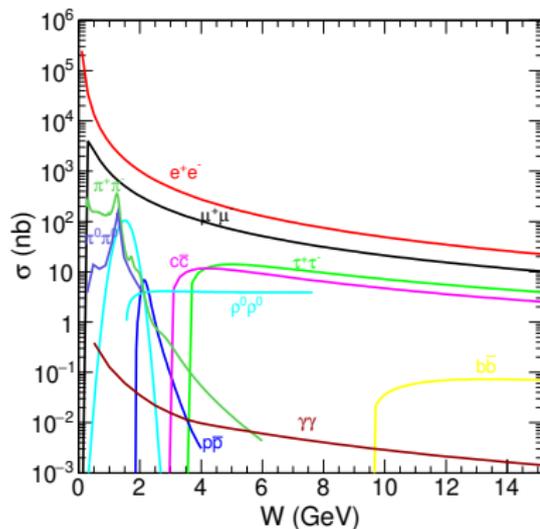




Generator: RELDIS &  $n_0n$

# 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