HEAVY-ION PROCESSES ASSOCIATED WITH MEASUREMENTS OF FORWARD PROTONS AND NEUTRONS

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- Equivalent Photon Approximation
- $\gamma\gamma \to \gamma\gamma$
- Electromagnetic excitation of nuclei. Neutron (and PROTON) evaporation

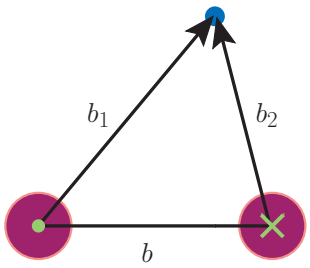
Equivalent Photon Approximation

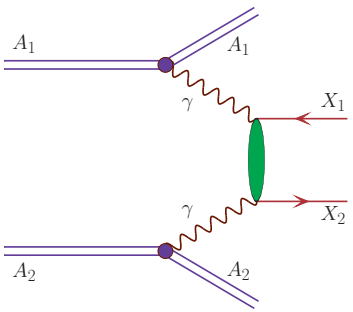
$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2) \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \to \ldots n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b) \ldots$$

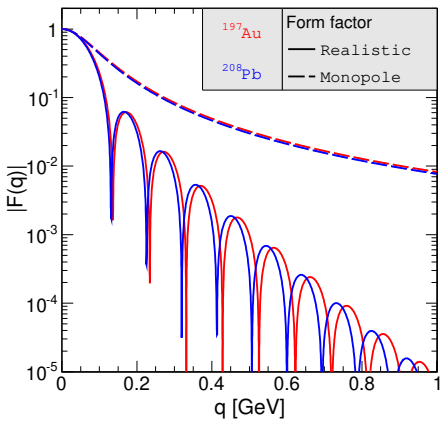
$$= \int \sigma_{\gamma\gamma \to X_1 X_2} \left(W_{\gamma\gamma} \right) N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{X_1 X_2} \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \, \mathrm{d}^2 b$$

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

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







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

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

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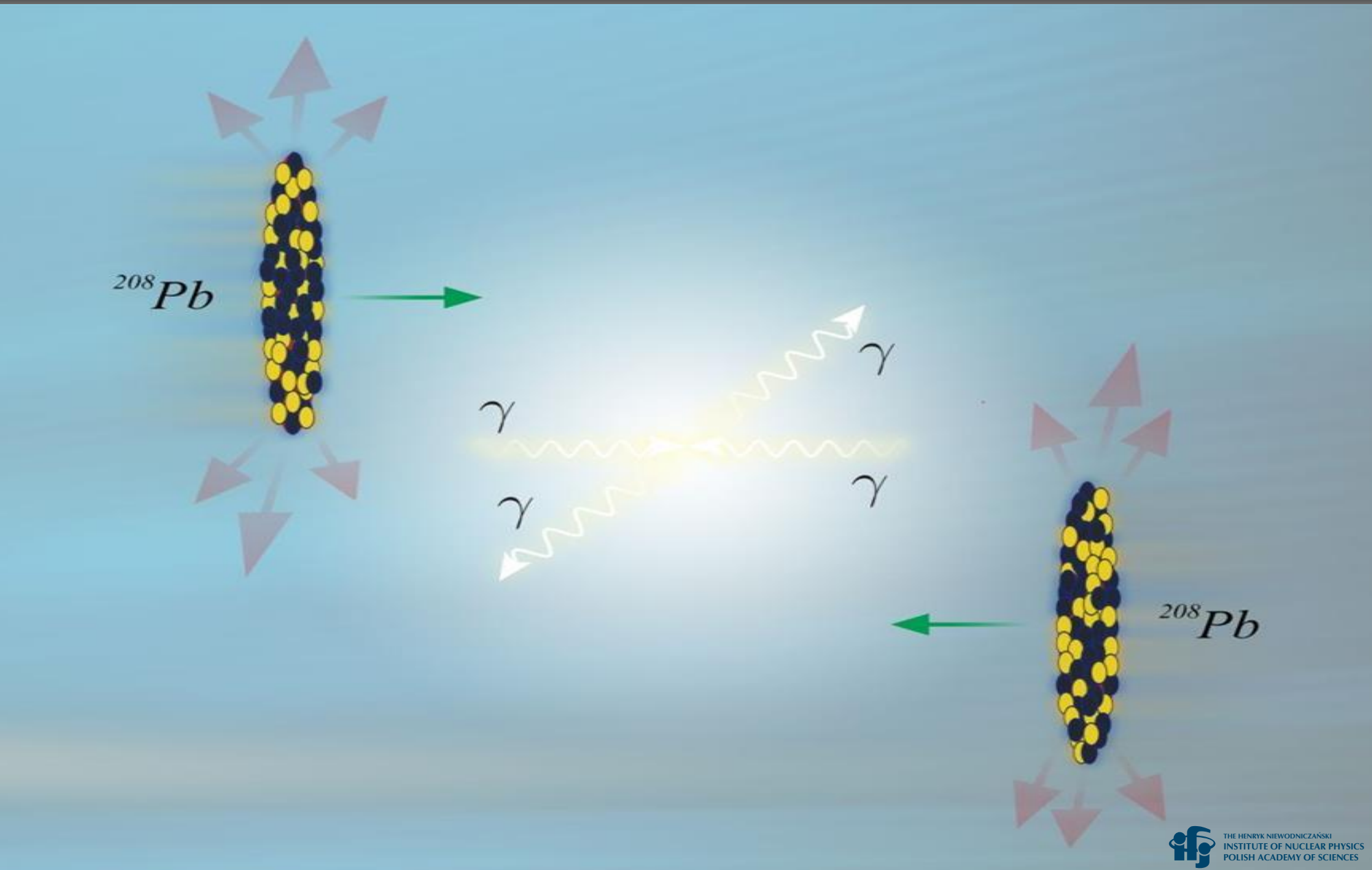
LIGHT-BY-LIGHT SCATTERING



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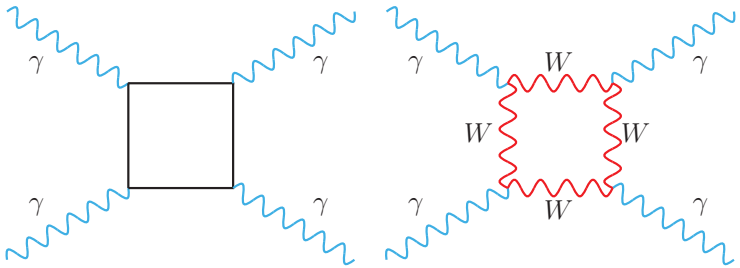
LIGHT-BY-LIGHT SCATTERING

Boxes

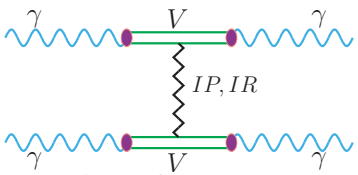
WELL-KNOWN



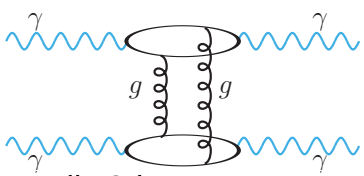
Fermionic boxes (LO QED) — FormCalc. — *W* Box — LoopTools.

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

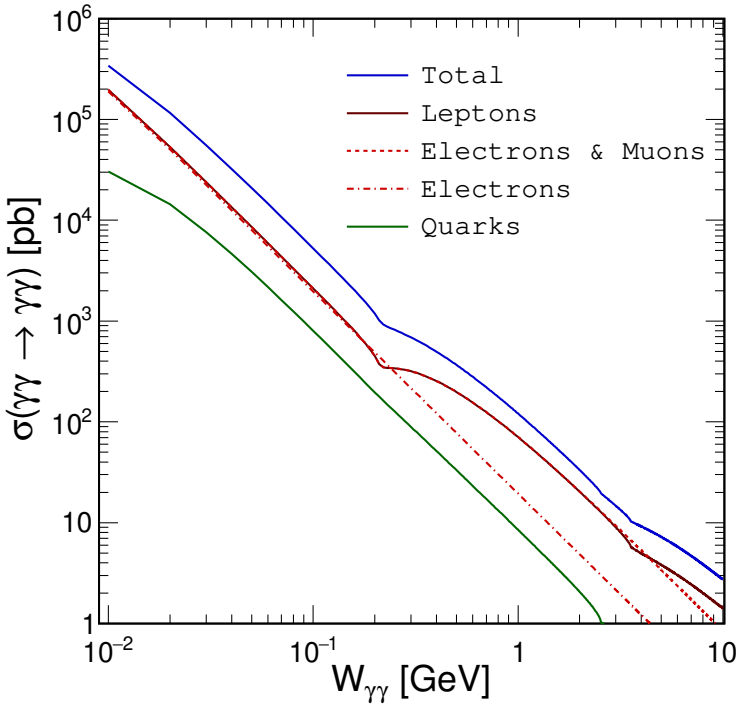
VDM-Regge **WE ADD** **2-gluon exch.**



fluctuation of γ into virtual $\rho, \omega, \phi, J/\psi$



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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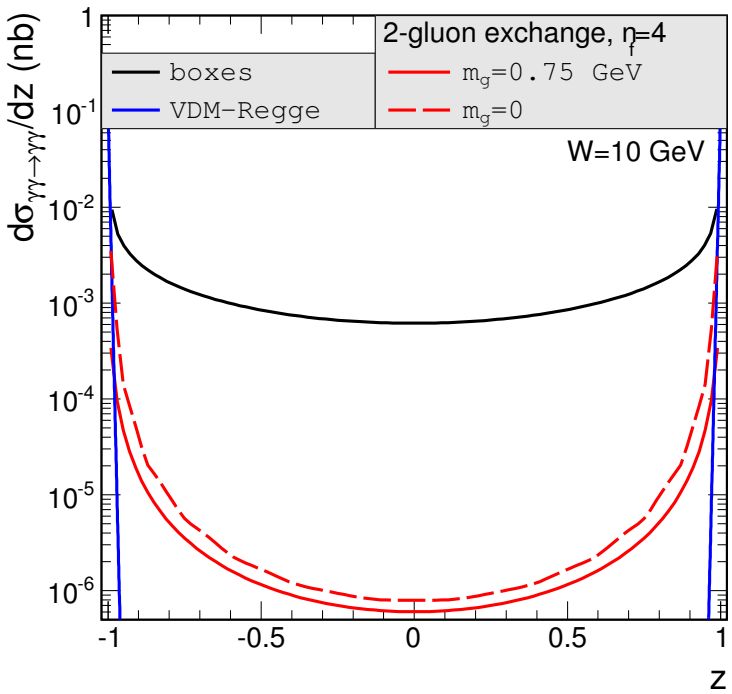
ELEMENTARY CROSS SECTION

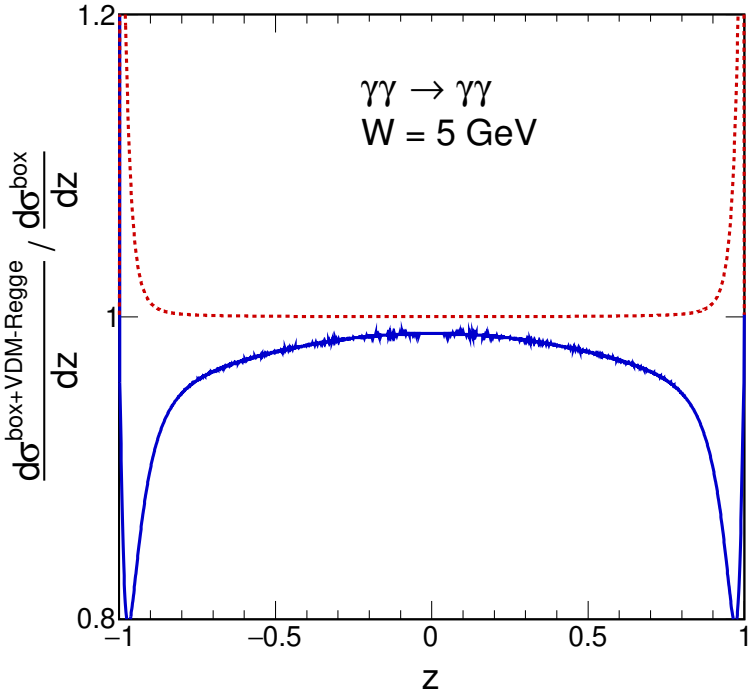
- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

W = 10 GeV

$z = \cos\theta$ GeV

SUM; W = 5 GeV

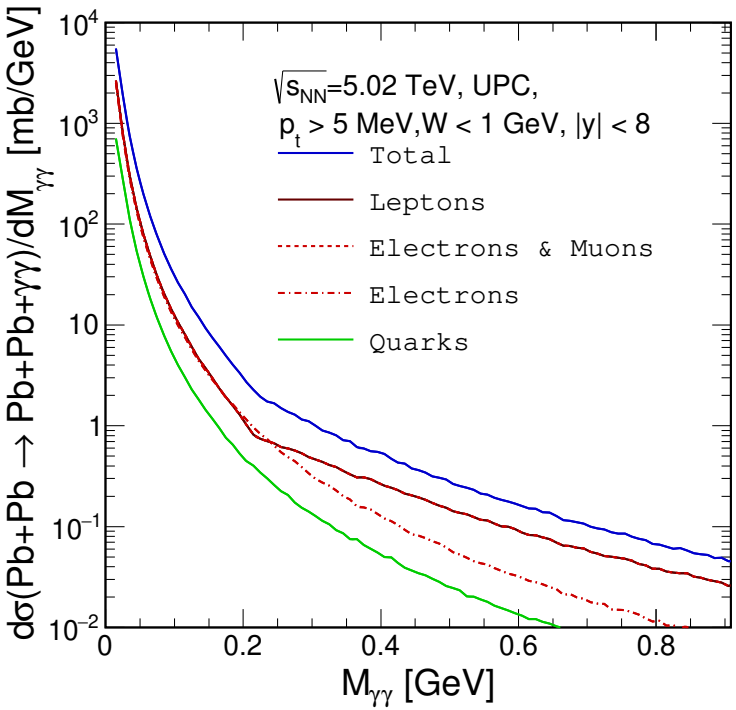




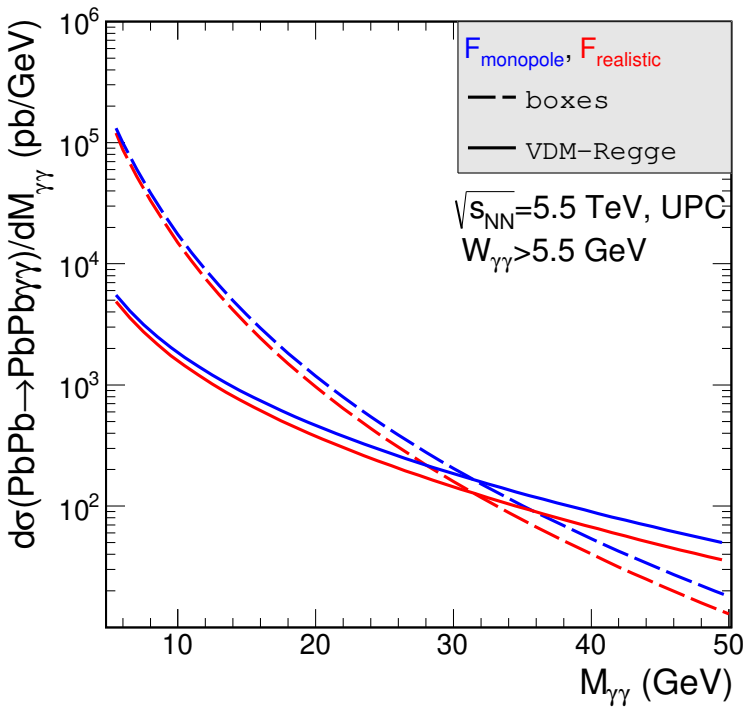
large z (low p_{t_γ}) - VDM-Regge dominates. Incoherent vs. coherent sum

AA→AAγγ - DIPHOTON INVARIANT MASS

$p_{t,\gamma} > 5$ MeV



$p_{t,\gamma} > 2.5$ GeV



	σ_{tot} [mb]
Total	91.675 ± 0.023
electrons+muons	41.597 ± 0.010
electrons	39.163 ± 0.010
quarks	12.483 ± 0.003

$\frac{\sigma_{monopole}}{\sigma_{realistic}}$ ↗

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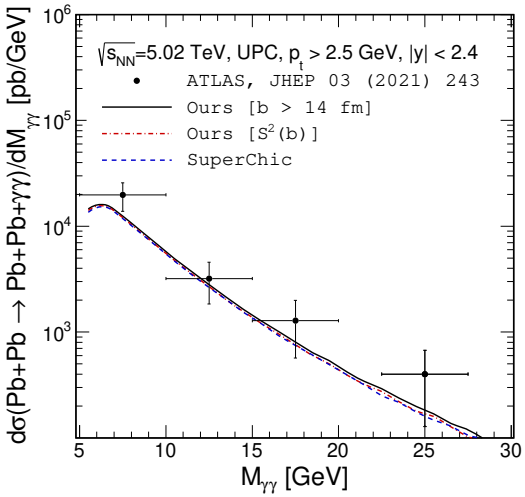
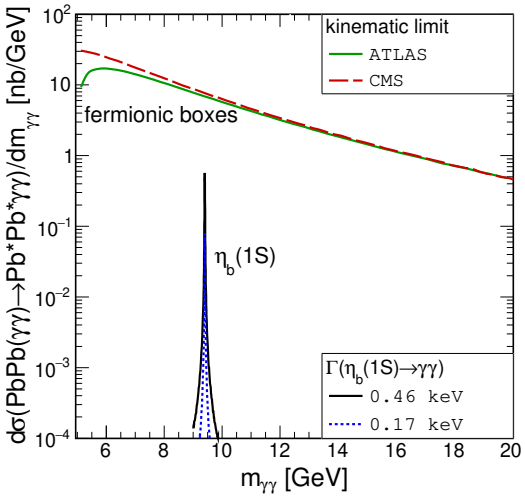
$AA \to AA\gamma\gamma$ - CMS & ATLAS RESULTS

- 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.)	78	77	70
CMS (2015)	120 ± 46(stat.)± 28(syst.)	102	101	–





Underestimation:

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

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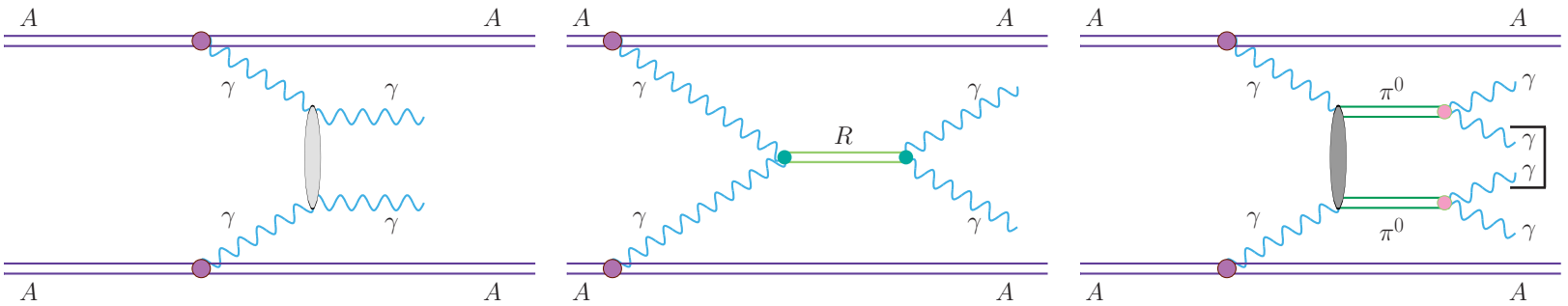
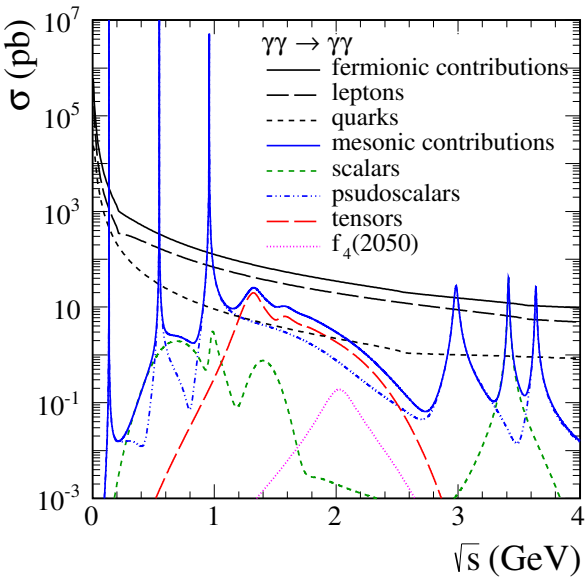
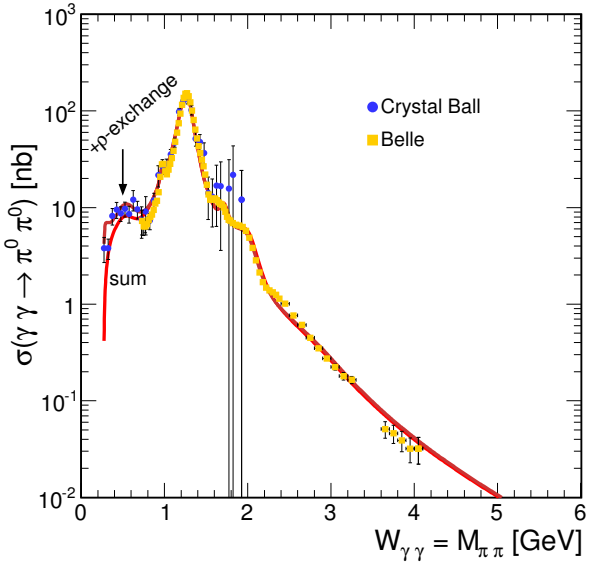
$AA \to AA\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ?

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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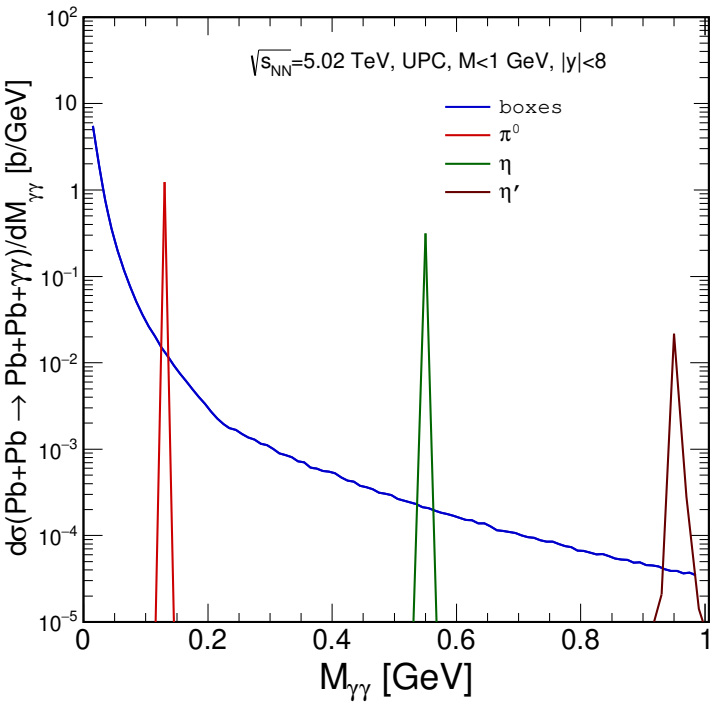
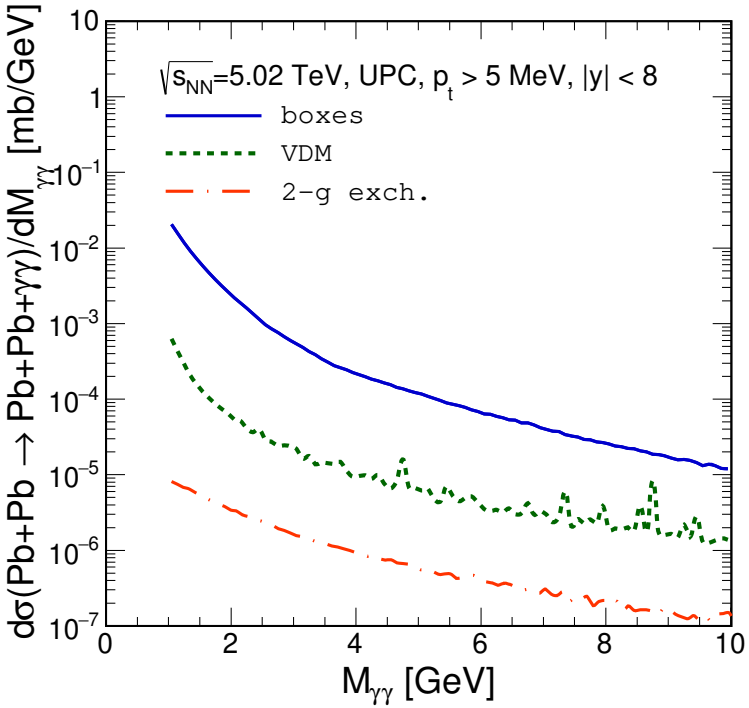
AA→AAγγ @ LOW p_t REGION ?

full rapidity range





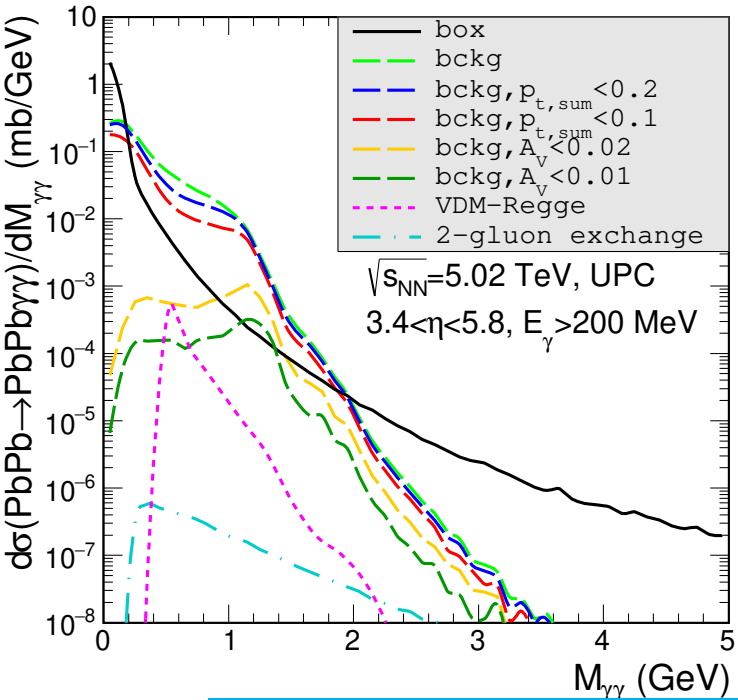
$AA \to AA\gamma\gamma$ @ FORWARD REGION ?

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

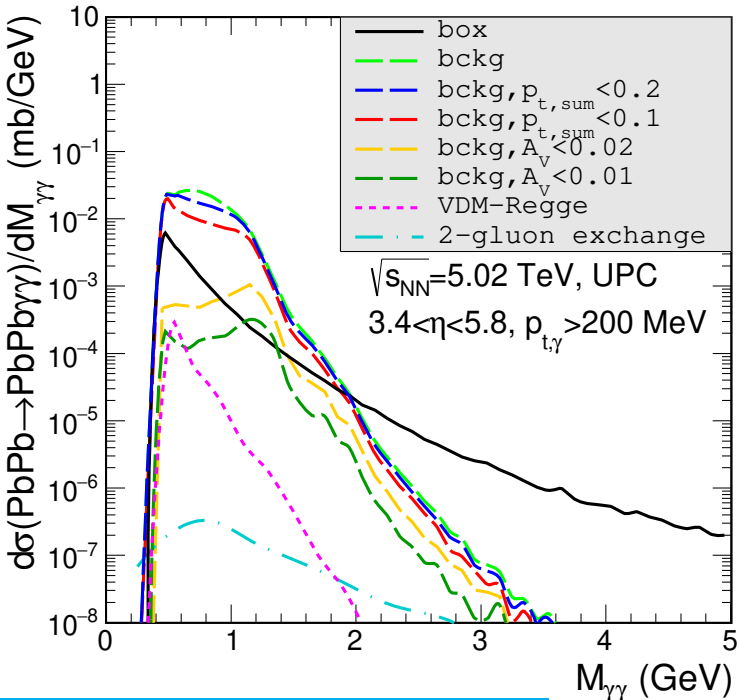
FOCAL $\to 3.4 < \eta < 5.8$

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



$p_{t,\gamma} > 0.2$ GeV



Boxes & Pionic bkgr & VDM-Regge & 2-gluon exchange

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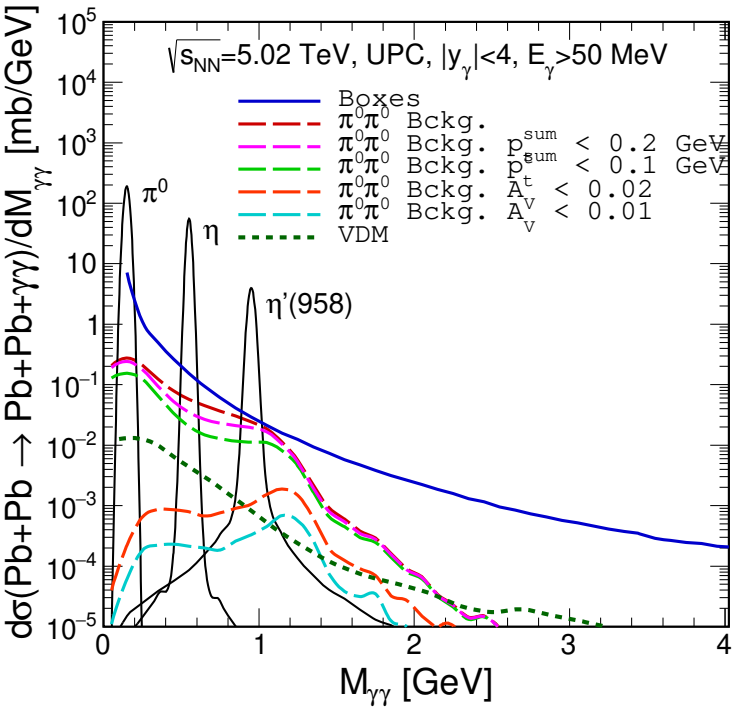
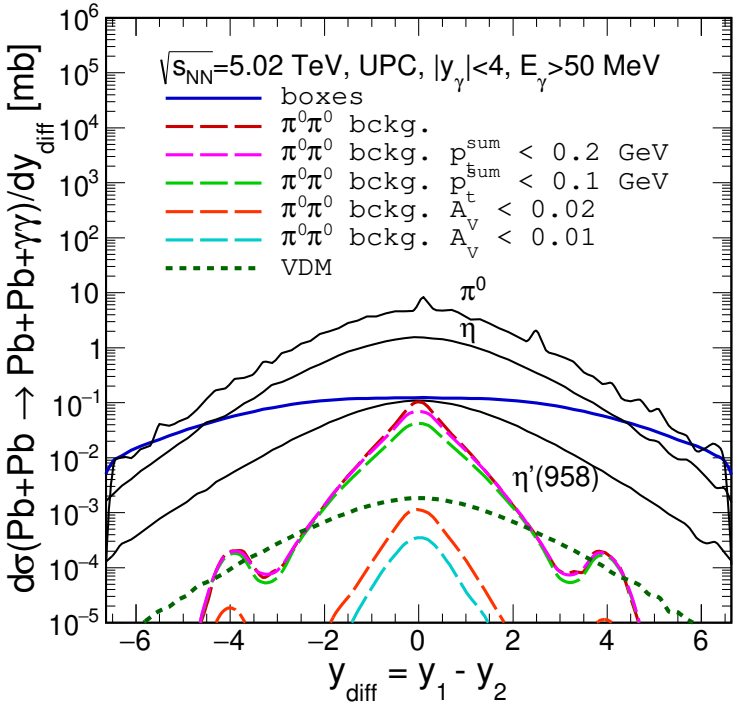
AA→AAγγ @ ALICE 3

$p_{t,\gamma} > 50$ MeV, $|\eta| < 4$

Diphoton invarian mass

$y_{diff} = y_{\gamma_1} - y_{\gamma_2}$

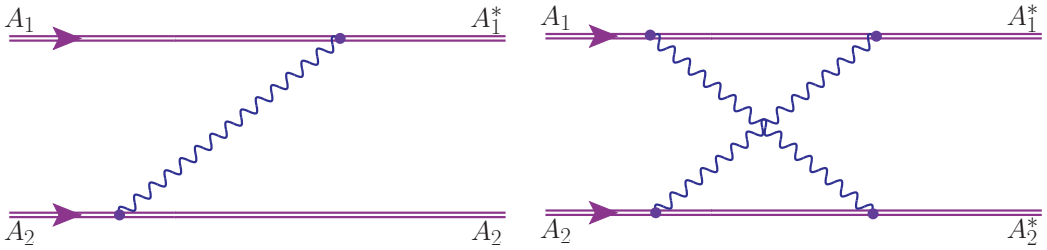




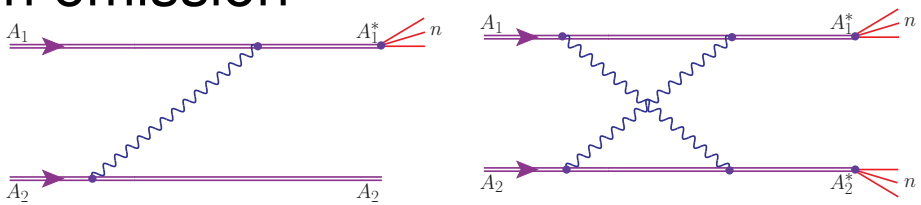
Pure signal

ELECTROMAGNETIC EXCITATION

- Photon $\rightarrow$ nucleus excitation



- neutron/proton emission



Cross section in barns for a given multiplicity of neutrons in single-nucleus, single-photon excitation in ^{208}Pb + ^{208}Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV:

Single excitations [b]		
	Our results	ALICE data
0 neutrons	6.403	
1 neutron	84.301	93.0
2 neutrons	18.608	21.0
3 neutrons	2.858	6.5

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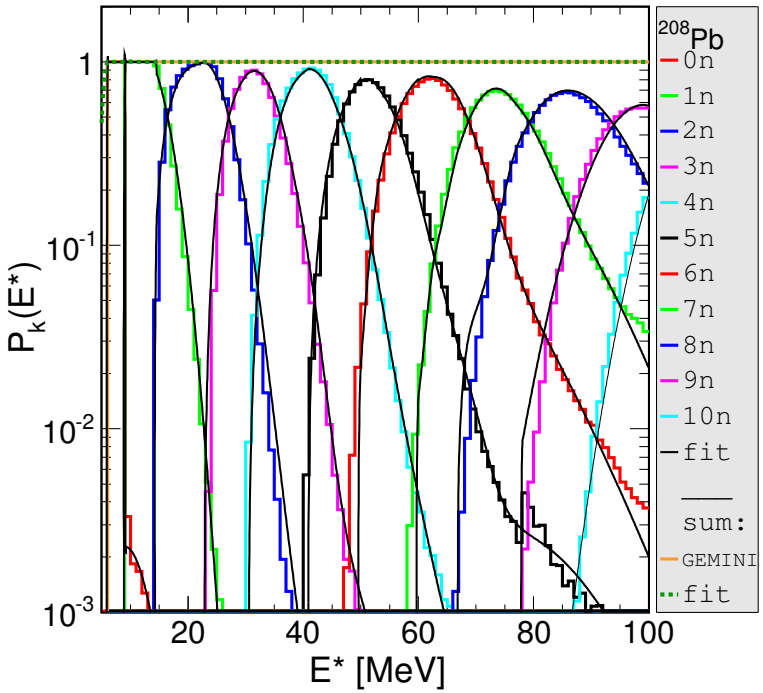
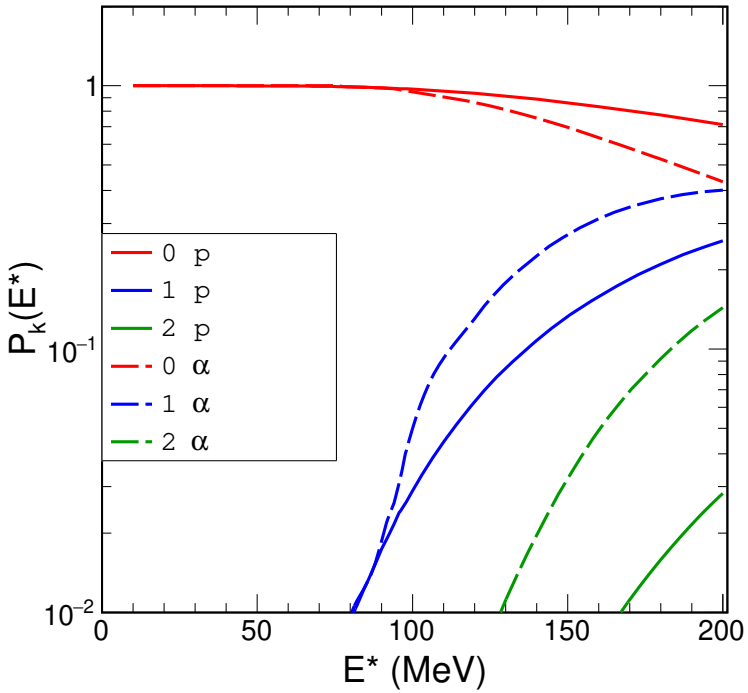
DECAY OF EXCITED NUCLEAR SYSTEM

The calculation of the probability of evaporated neutron & proton multiplicity as a function of ^{197}Au and ^{208}Pb excitation energy was performed with the help of the Monte Carlo code **GEMINI++**

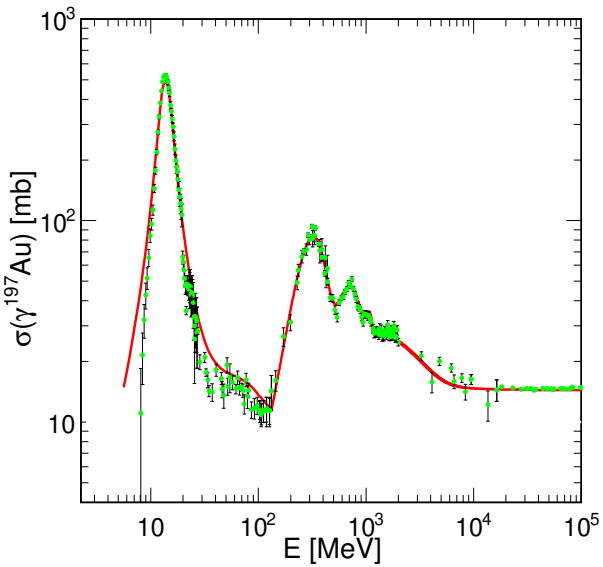


neutron

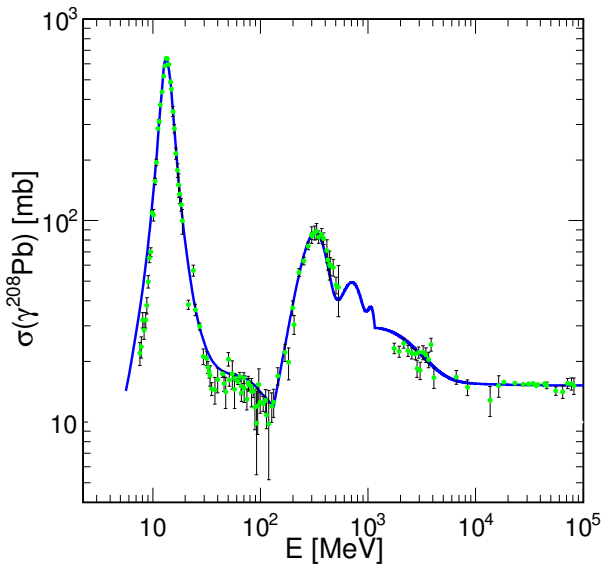


proton !!!

$\gamma\ ^{197}$Au

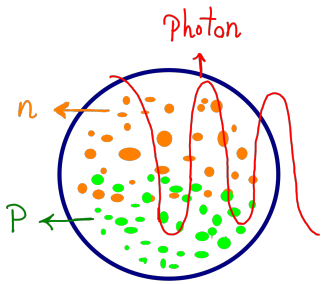


$\gamma\ ^{208}$Pb

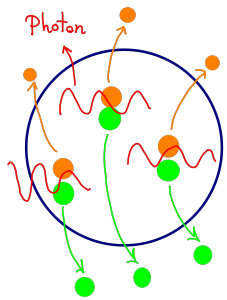


$$\sigma_{\gamma A} = \sigma_{\mathrm{GDR}} + \sigma_{\mathrm{QD}} + \sigma_{\text{nucleon res.}} + \sigma_{\text{nucleon cont.}}$$

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

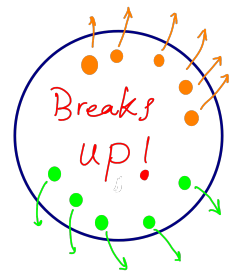


❷ quasi-deuteron contribution
$E_\gamma = (40 - 100)$ MeV

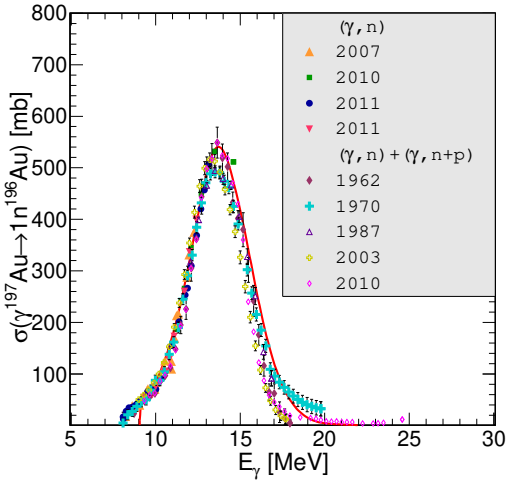


❸ nucleon resonances
$E_\gamma = (0.1 - 1)$ GeV

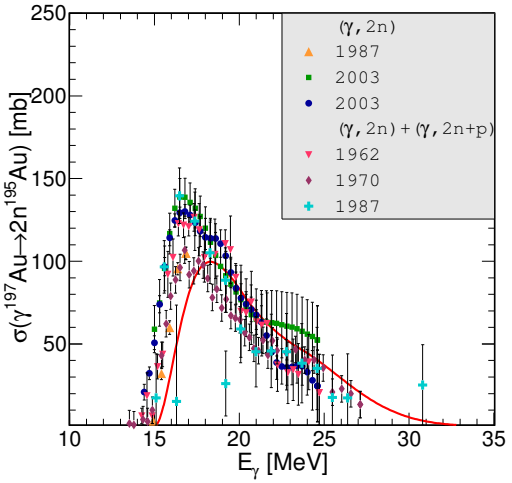
❹ break-up of nucleons
$E_\gamma > 1 - 8$ GeV



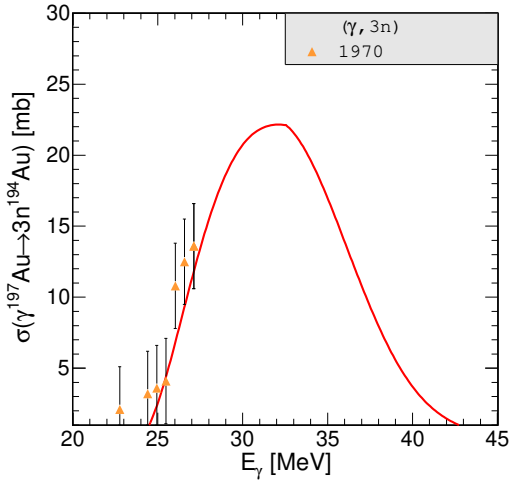
$\gamma\ ^{197}Au \rightarrow 1n\ ^{196}Au$



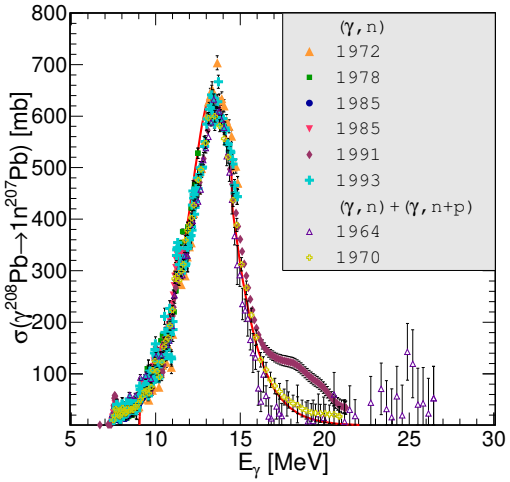
$\gamma\ ^{197}Au \rightarrow 2n\ ^{195}Au$



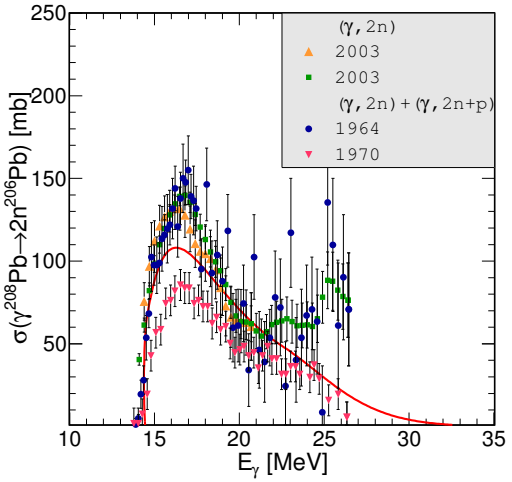
$\gamma\ ^{197}Au \rightarrow 3n\ ^{194}Au$



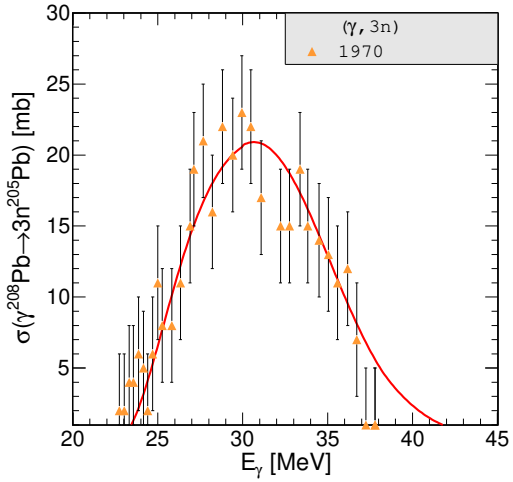
$\gamma\ ^{208}Pb \rightarrow 1n\ ^{207}Pb$



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



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



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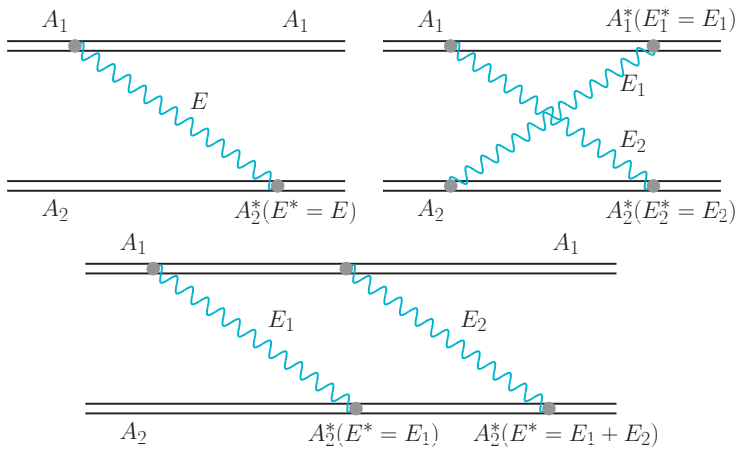
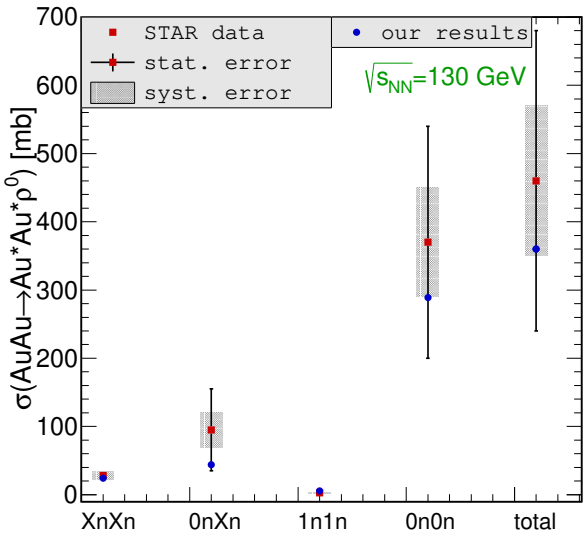
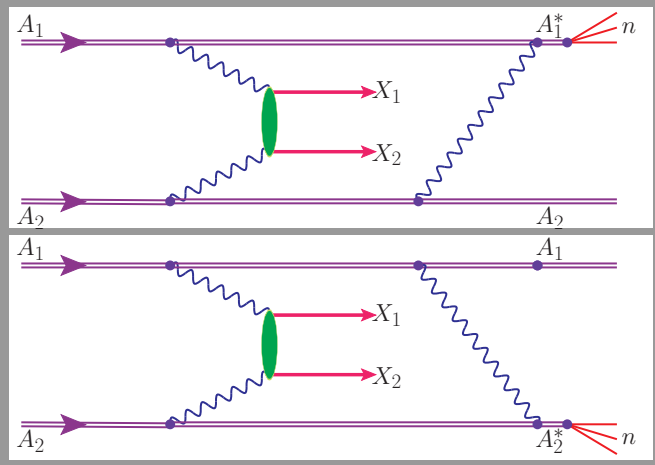


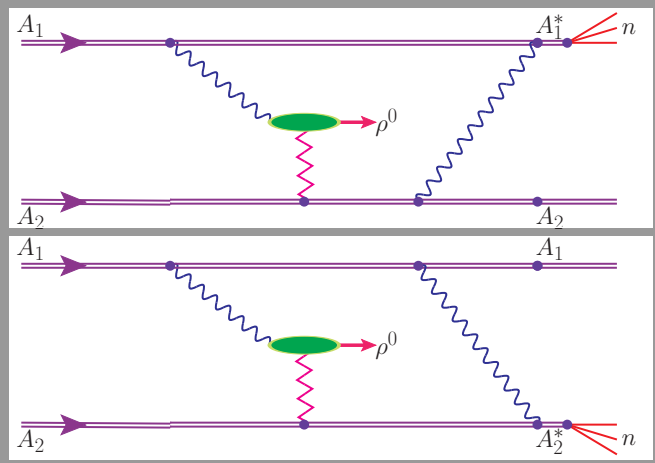
ρ^0 production in heavy ion UPC with nuclear excitation



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



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



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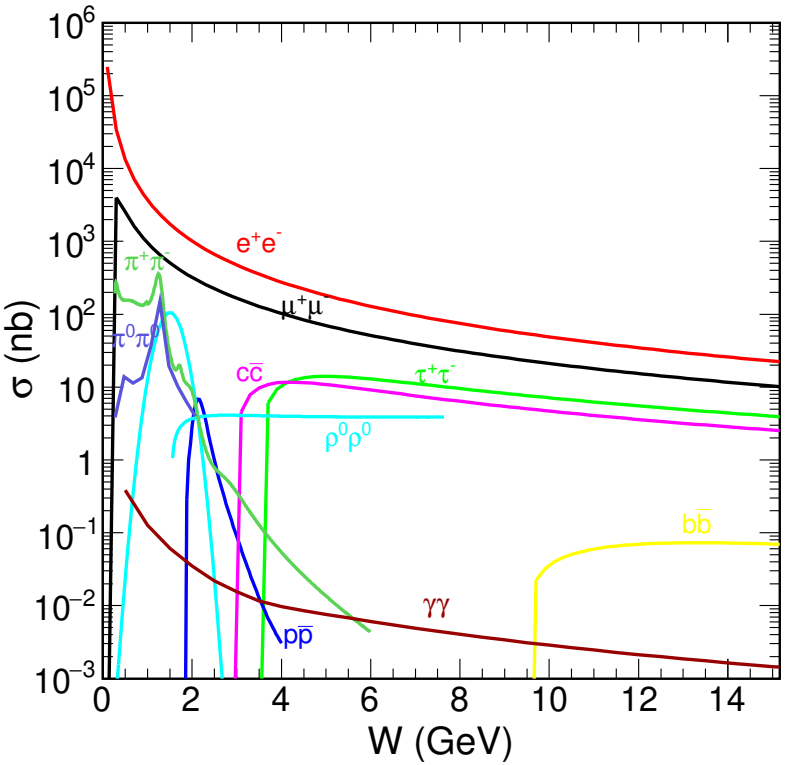
Conclusion

- 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
- Future:
  - more forward/backward region
  - lower p_t
  - Light-by-light scattering + neutron ~~proton~~ emission



Thank you