Studying initial state effects using peripheral and ultra-peripheral collisions

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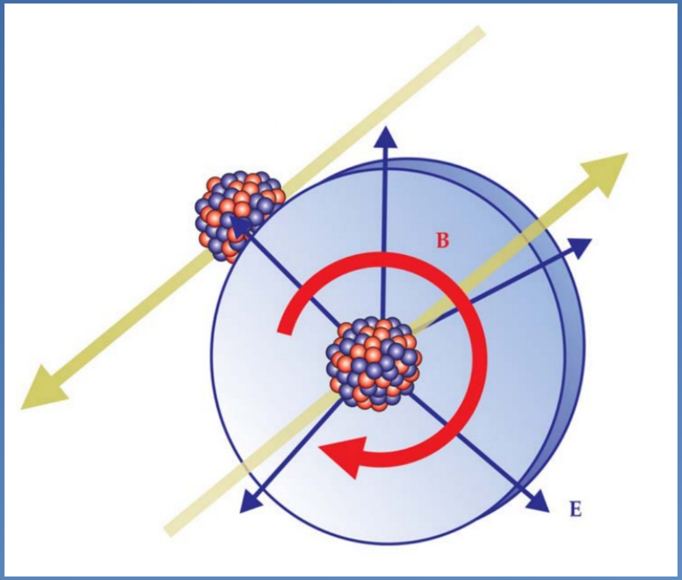
Electromagnetic fields at the LHC

The strong electromagnetic fields associated with heavy-ion beams at the LHC correspond to an equivalent flux of photons (Fermi/Weizsäcker-Williams).

The fields are present in ultra-peripheral ($b>2R$, the nuclei do not interact hadronically) and peripheral ($b<2R$, the nuclei interact hadronically) collisions



Particles can be produced in photonuclear interactions.

Represent the energy frontier for electromagnetic interactions.

Photonuclear interactions in UPC

A variety of photonuclear and two-photon interactions may occur at the LHC.

Vector meson dominance (VMD): Quantum numbers of the photon $J^{PC} = 1^{--}$ High probability for fluctuation to vector meson.

While in the vector meson state, it will interact strongly.

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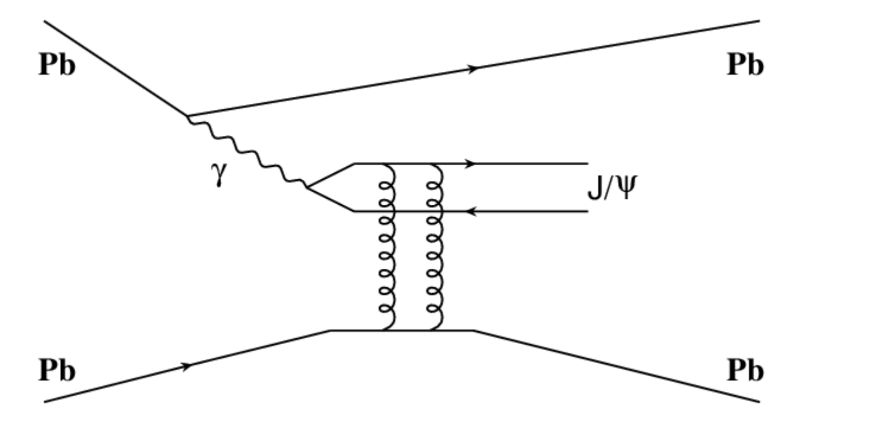
Exclusive production: The VM is knocked on mass shell by scattering off the target nucleus.

Target remains intact ⇒ Color-neutral exchange particle.

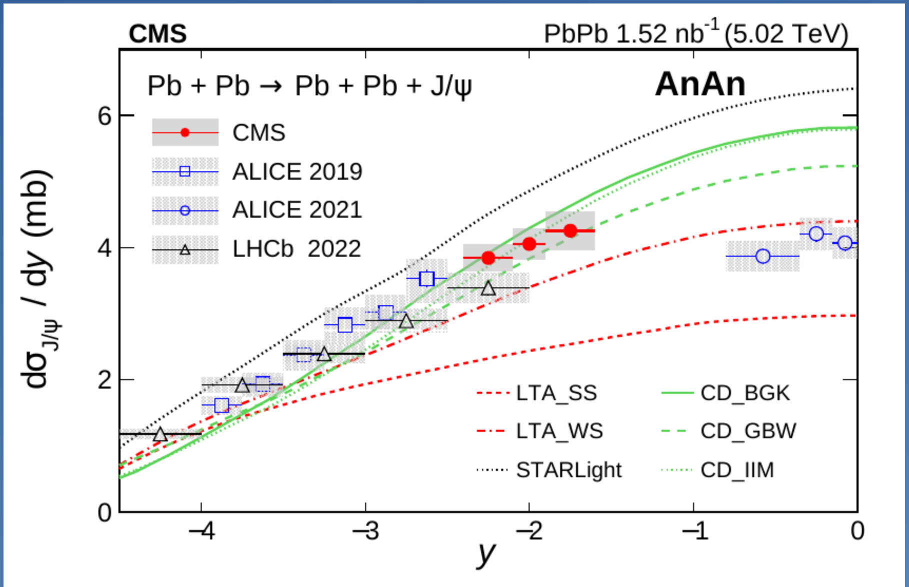
2-gluon or ”Pomeron” exchange.

Cross section sensitive to gluon distribution.



Photonuclear interactions in UPC

Exclusive J/ψ production: Cross section as function of rapidity ⇒ suppression relative to the impulse approximation and hadronic models.



ALICE: EPJC 82 (2021) 712. LHCb: JHEP 06 (2023) 146. CMS: PRL 131 (2023) 262301.

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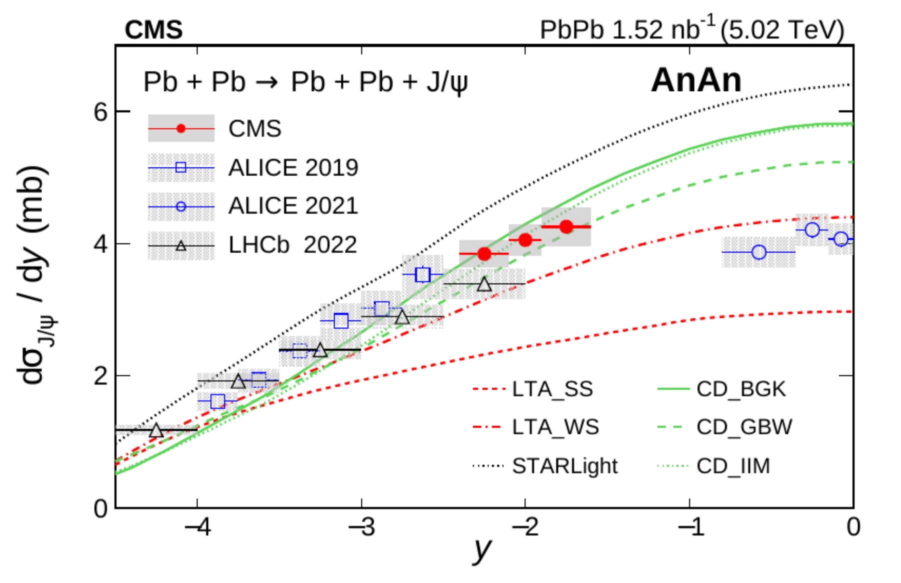

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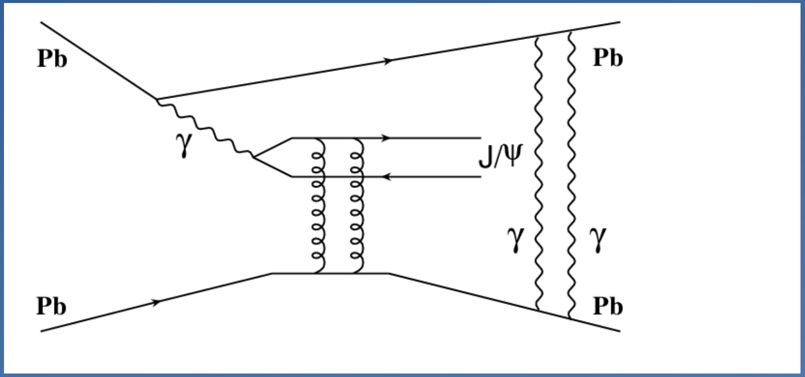
- Away from midrapidity contributions from two photon energies ⇔ two γ-nucleon center of mass energies $W_{\gamma p}$.

$$\frac{d\sigma}{dy} = n(k_1)\sigma_{\gamma A}(W_{\gamma p,1}) + n(k_2)\sigma_{\gamma A}(W_{\gamma p,2})$$

Photonuclear interactions in UPC

How can one separate the low and high energy components to extract $\sigma_{\gamma A}(W_{\gamma p})$?

Exchange of multiple photons!



Can divide events into breakup classes:

0n0n – no neutrons emitted.

0nXn – neutrons emitted in one direction but not in the other.

XnXn – neutrons emitted in both directions.

$$\frac{d\sigma_{0n0n}}{dy} = n_{0n0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{0n0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

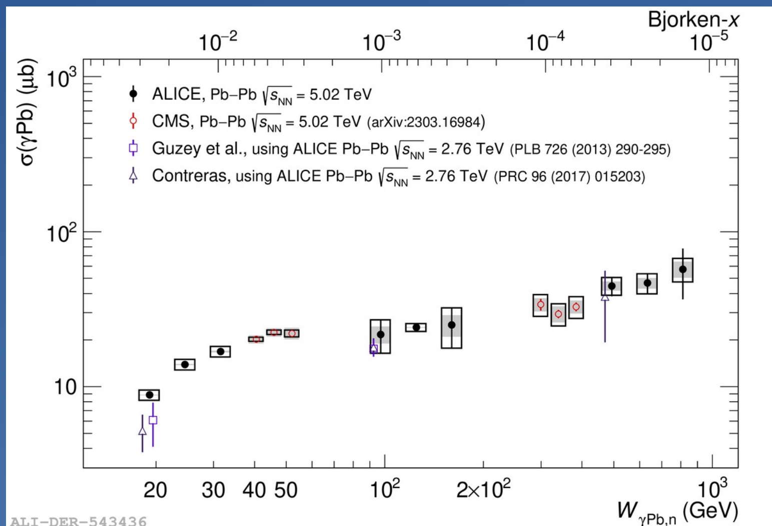
$$\frac{d\sigma_{Xn0n}}{dy} = n_{Xn0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{Xn0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

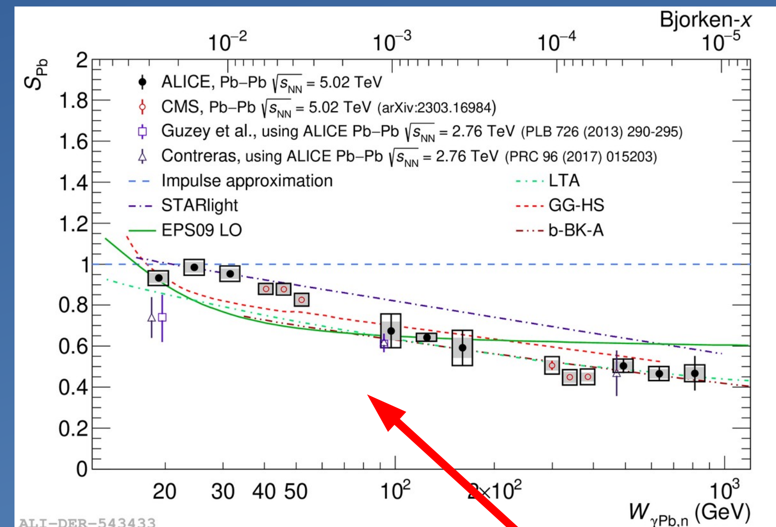
$$\frac{d\sigma_{XnXn}}{dy} = n_{XnXn}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{XnXn}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

Gives a system of equations that can be solved to extract $\sigma_{\gamma A}(W_{\gamma p})$.

Photonuclear interactions in UPC

Enables the reaction γ+Pb→J/ψ+Pb to be studied over the energy range $20 < W_{\gamma p} < 800$ GeV in a single experiment!





ALICE JHEP 10 (2023) 119; CMS PRL 131 (2023) 262301.

- Data in agreement with partonic models which include nuclear shadowing at high energies.
- In agreement with hadronic models at low energies.
- No model can explain data over the full energy range.

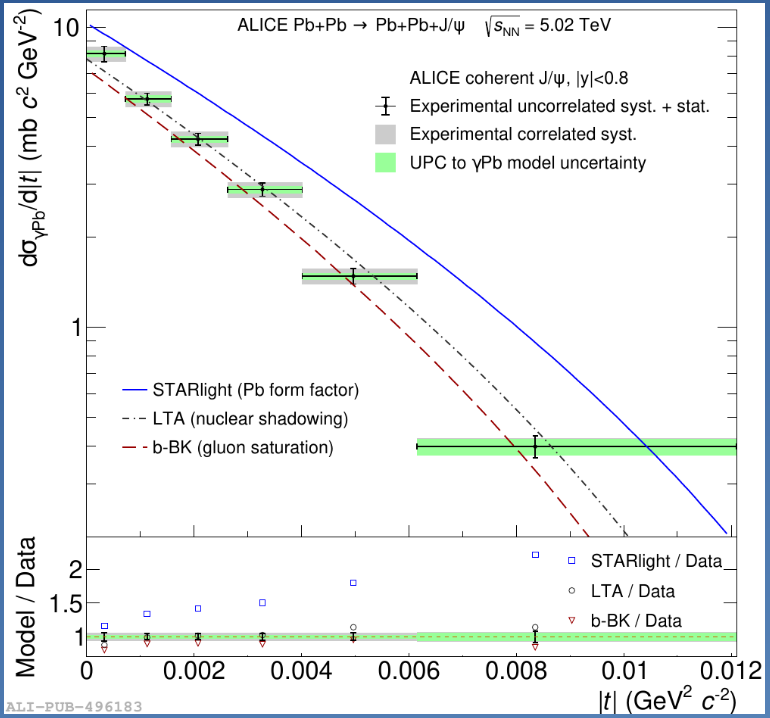
Suppression S_{Pb} relative to impulse approximation (no nuclear effects).

$$S_{Pb}(W_{\gamma Pb,n}) = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma^{IA}_{\gamma Pb}}}$$

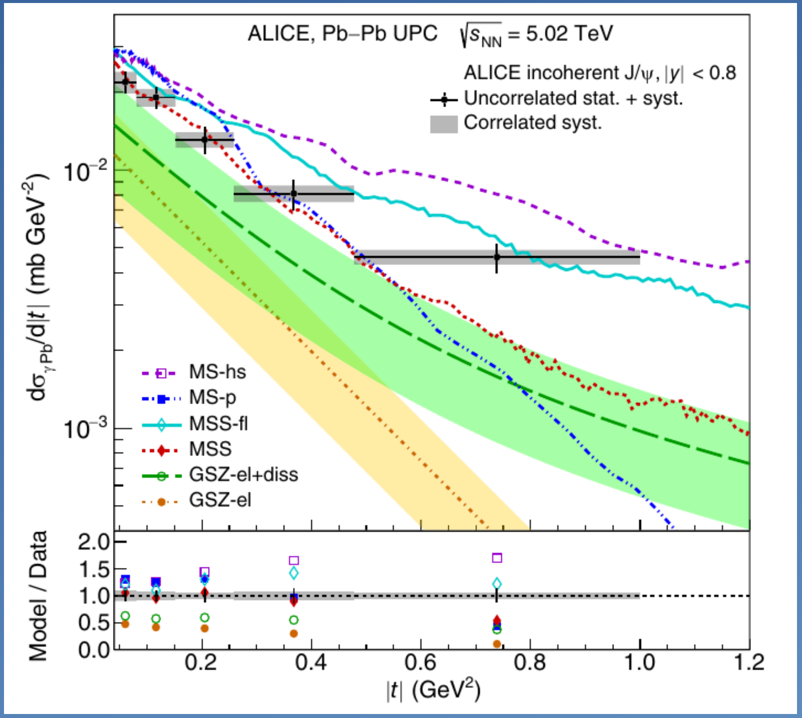
Photonuclear interactions in UPC

More information from differential measurement, $d\sigma/d|t|$ reflects the transverse distribution of matter in the target nucleus.

$t \approx p_T^2$.



ALICE PLB 817 (2021) 136280.



ALICE PRL 132 (2024) 162302.

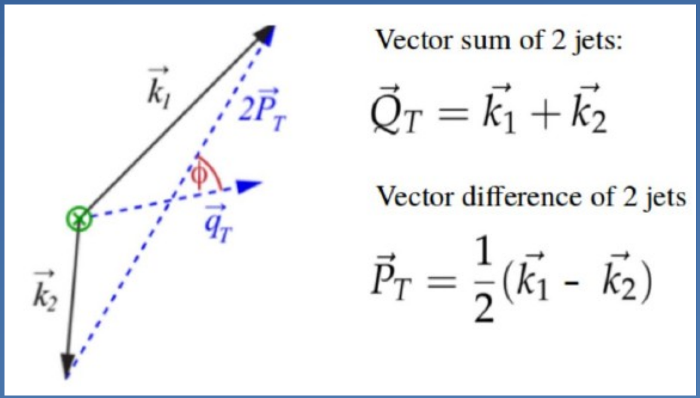
Coherent: best agreement with nuclear shadowing or gluon saturation models.

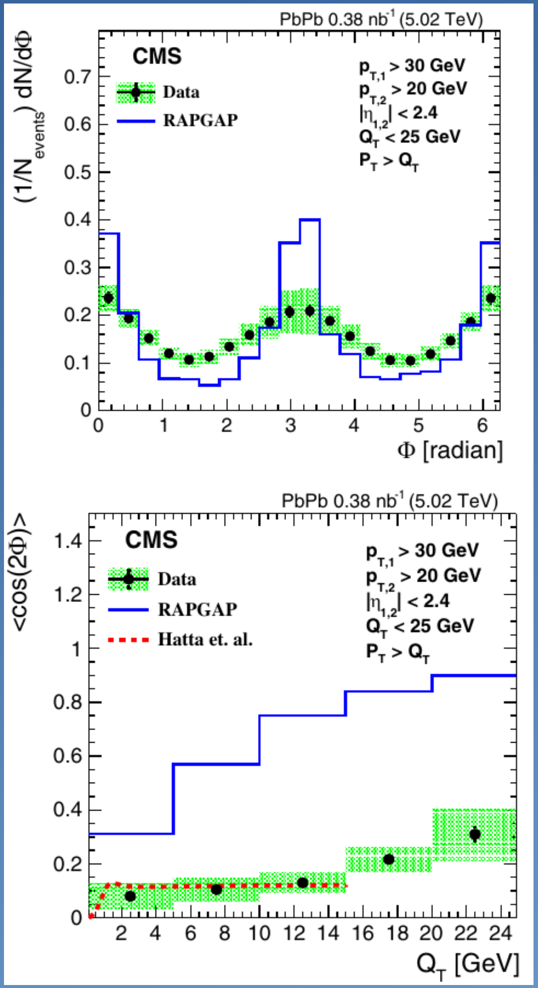
Incoherent: best agreement with models with quantum fluctuations.

Photonuclear interactions in UPC

Further information can be obtained from differential measurements.

Angular correlations in the transverse plane for diffractive dijet production (γ-Pomeron interaction).





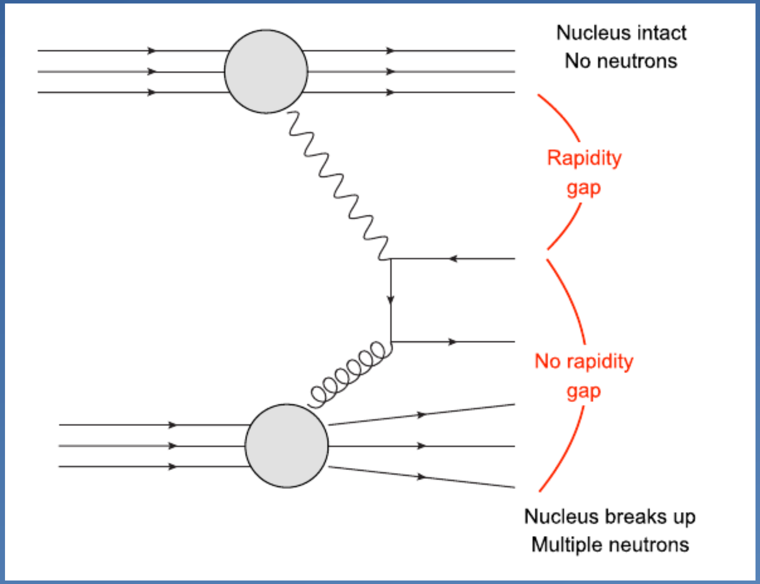
- Hatta et al. soft gluon radiation from final-state jets.

- RAPGAP tuned to HERA data with a DGLAP-based initial state parton shower.

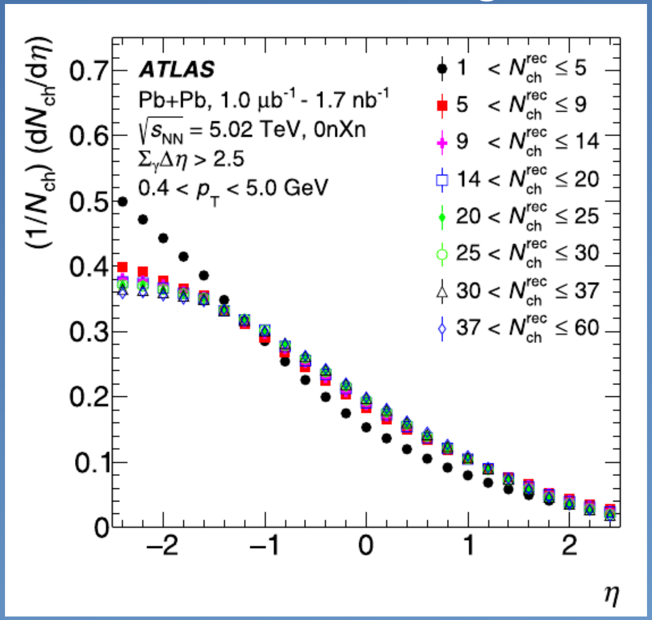
CMS PRL 131 (2023) 051901

Photonuclear interactions in UPC

- The interactions don’t have to be exclusive (nuclei remain intact) but can also be inclusive, $\gamma + A \rightarrow X$.
- Dominated by resolved interactions where the photon fluctuates to a $q\bar{q}$ pair.
- Should resemble pA collisions.



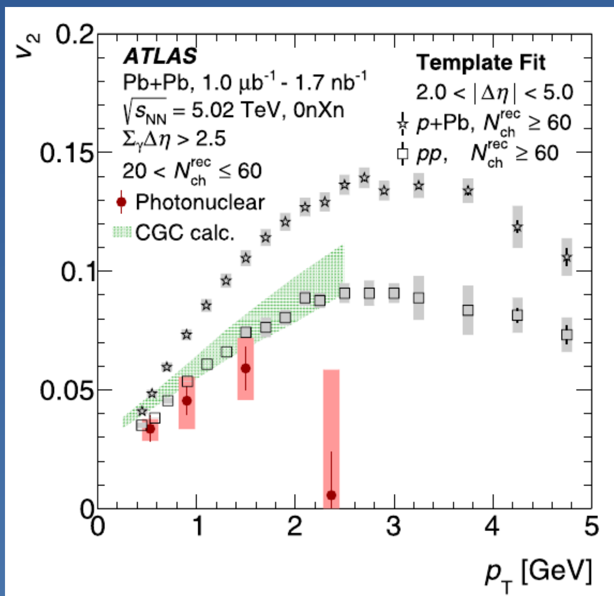
Photon energy << beam energy ⇒ Rapidity distributions shifted in the direction of the target.



ATLAS PRC 104 (2021) 014903.

Photonuclear interactions in UPC

- Measurement of elliptic flow (v_2 parameter) in photon-induced interactions by ATLAS (γPb) and CMS (γp).



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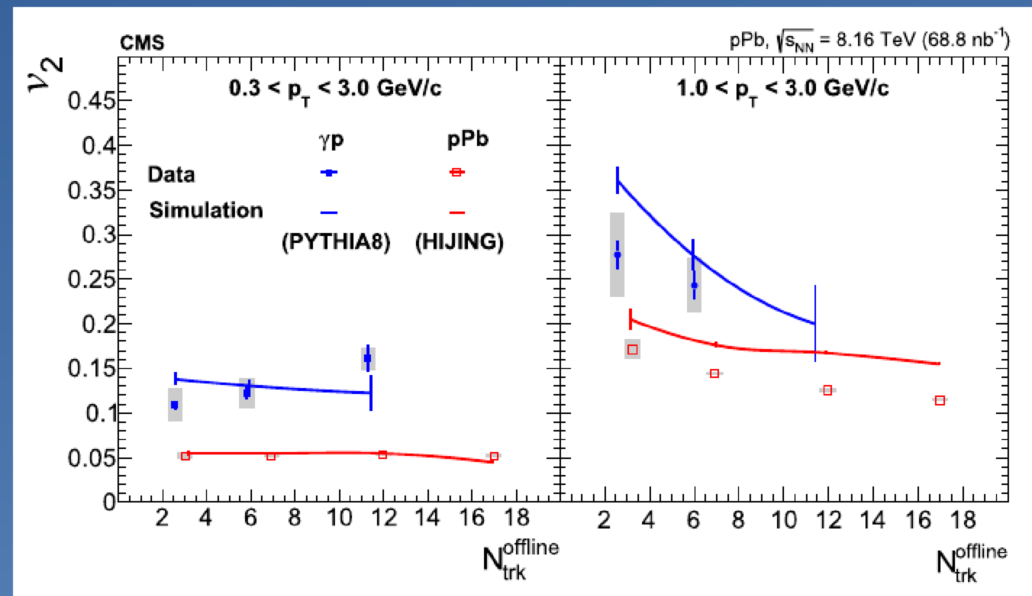
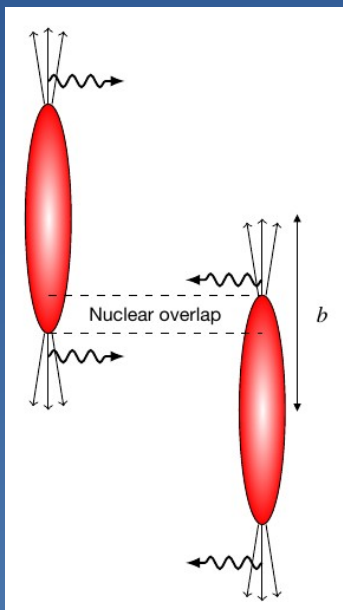


CMS PLB 844 (2023) 137905.

- Enables the study of elliptic flow for a variety of systems of different sizes: γp, pp, γPb, pPb, PbPb.
- Help in separating cold matter effects from quark gluon plasma efffects.
- Opposite trend in γPb vs. pPb (ATLAS) and in γp vs. pPb (CMS).

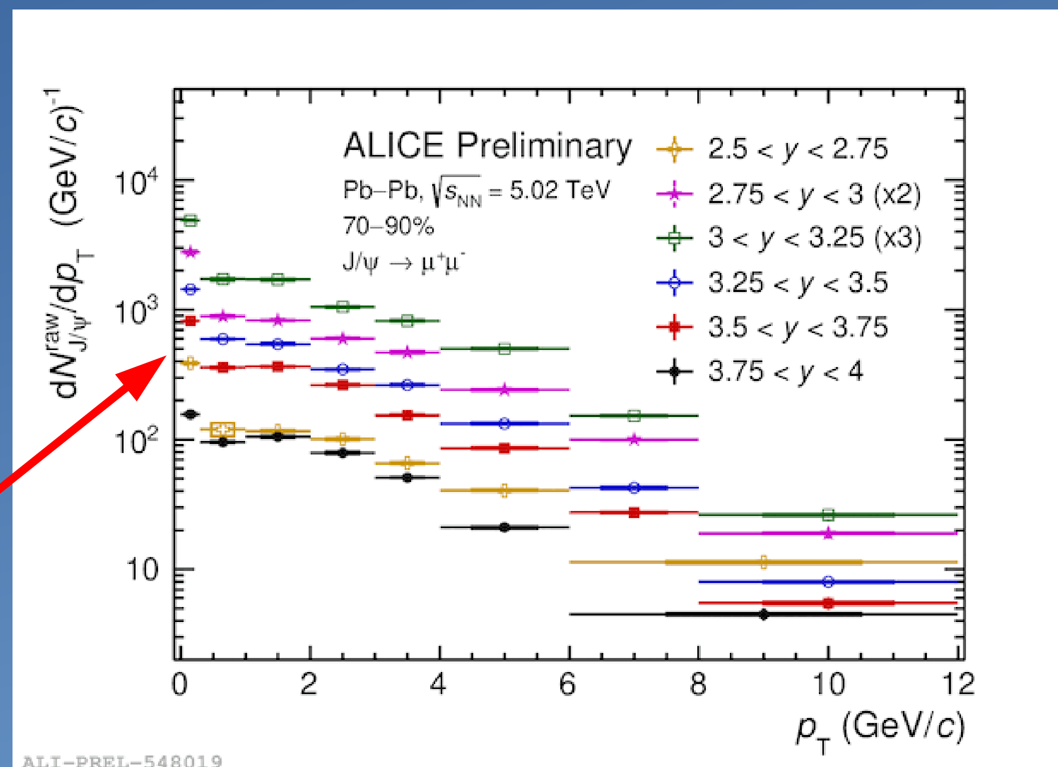
Photonuclear interactions in peripheral collisions

The electromagnetic fields are present also in interactions where the nuclei overlap ==> Photoproduction in hadronic events.



First observation of a coherent J/ψ peak in Run 1.
Peripheral events, 70-90% centrality.

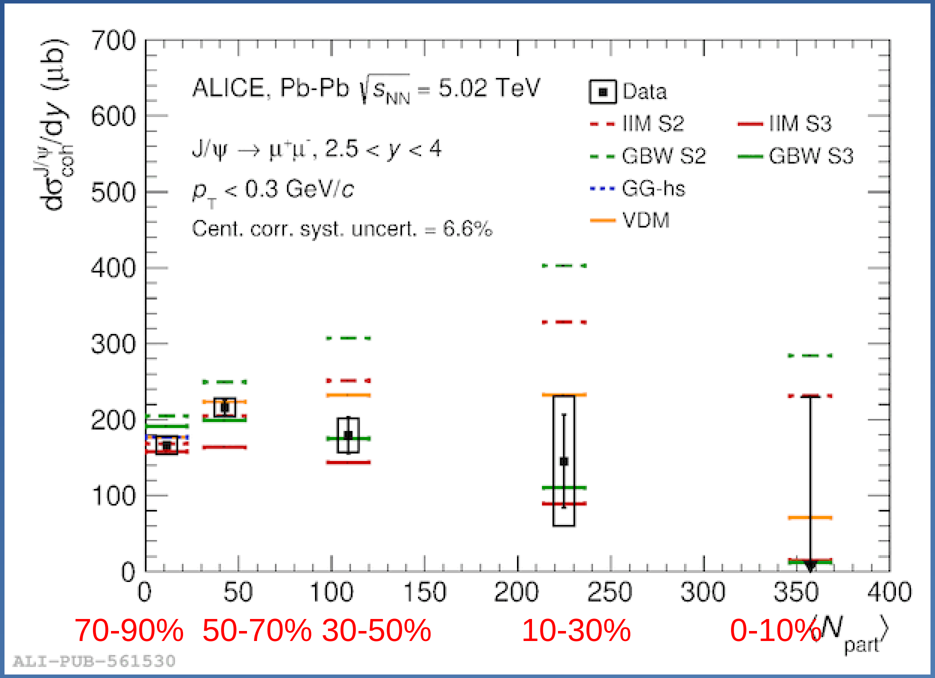
ALICE PRL 116 (2016) 222301

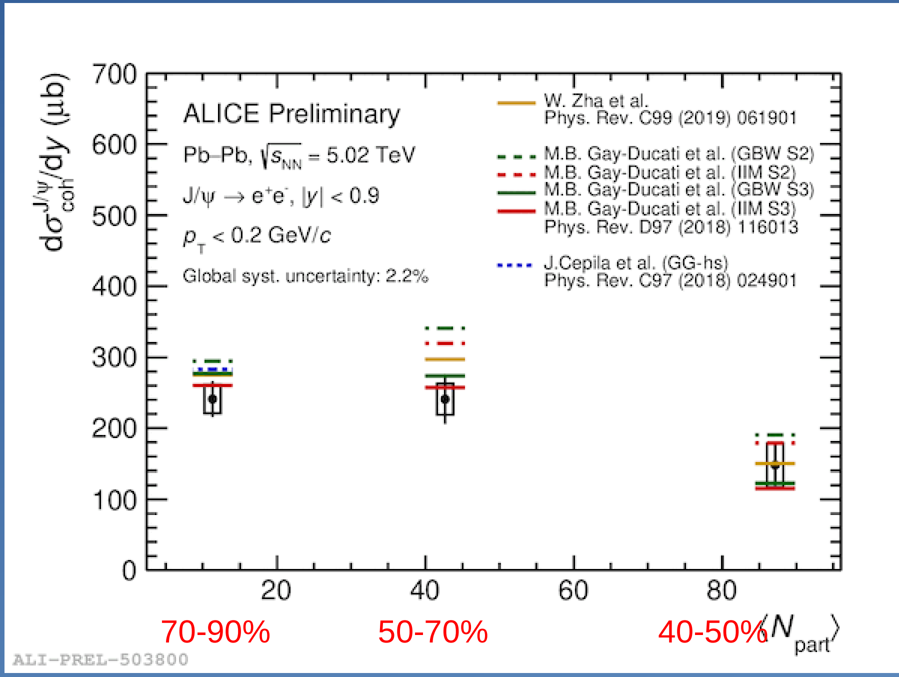


Much higher statistics in Run 2.
Coherent peak observed as function of rapidity.

Photonuclear interactions in peripheral collisions

A signal is observed down to 10% centrality!



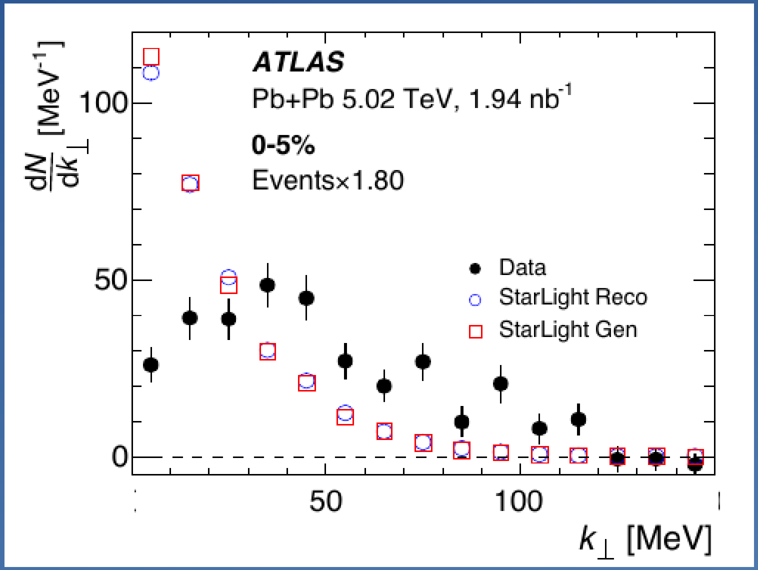


ALICE PLB 846 (2023) 137467

- cross section in agreement with models that assume only the spectators act as target.
- tests the coherence when nucleus breaks up.

Two-photon interactions in peripheral collisions

A signal ($\gamma\gamma \rightarrow \mu\mu$) is observed for the 0-5% most central collisions



ATLAS PRC 107 (2023) 054907, P. Steinberg Quark Matter 2023.

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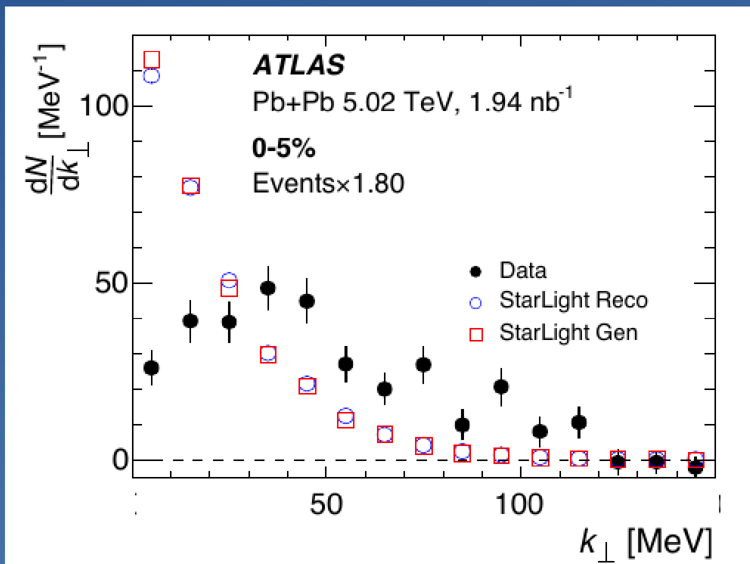

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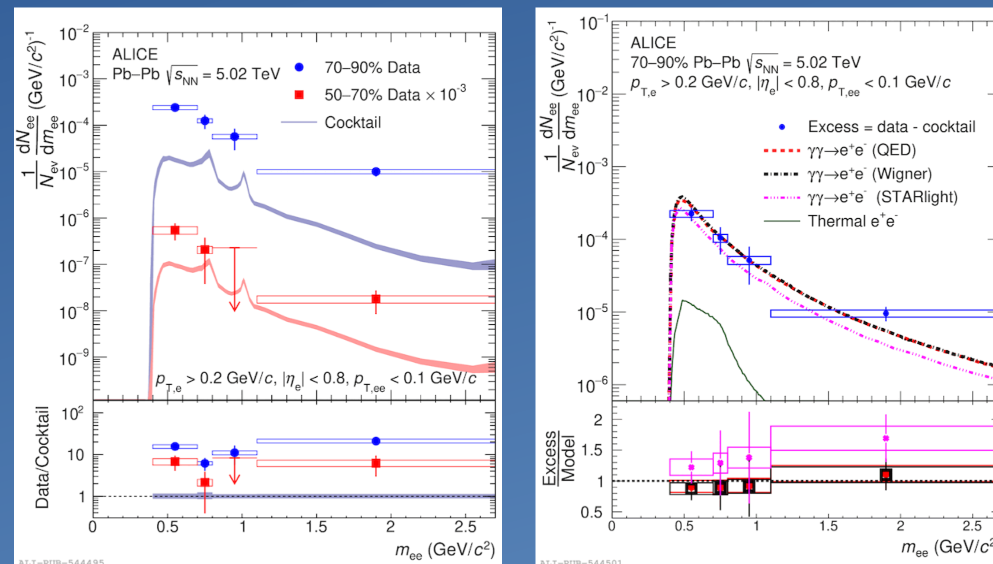
Also ($\gamma\gamma \rightarrow ee$) is observed with a clear excess over the hadronic cocktail.



ALICE JHEP 06 (2023) 024

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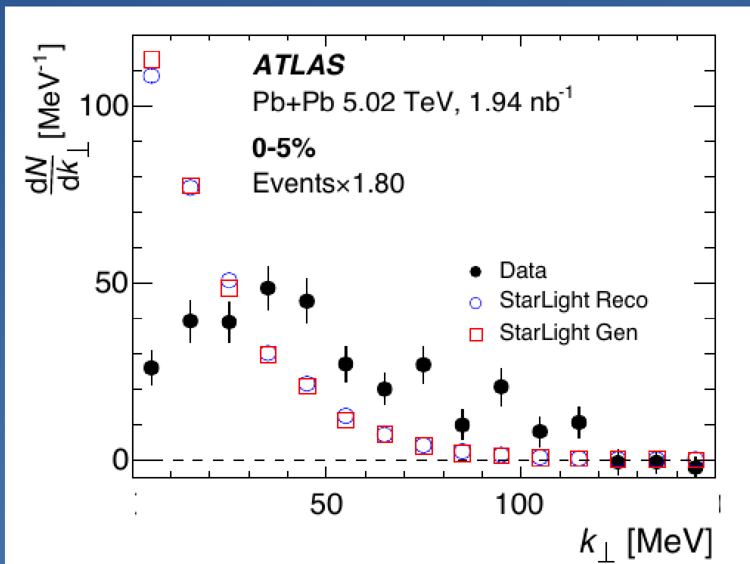

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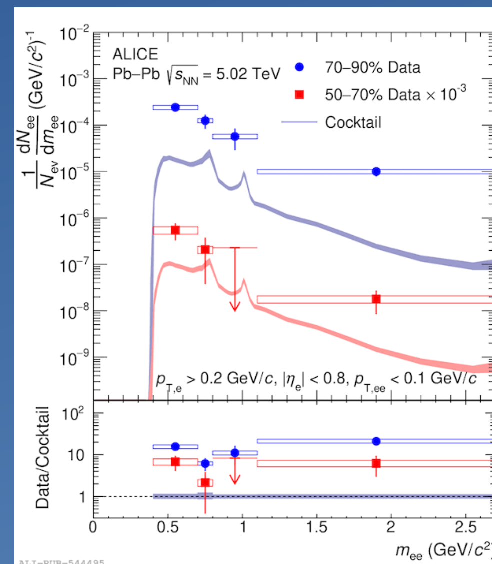

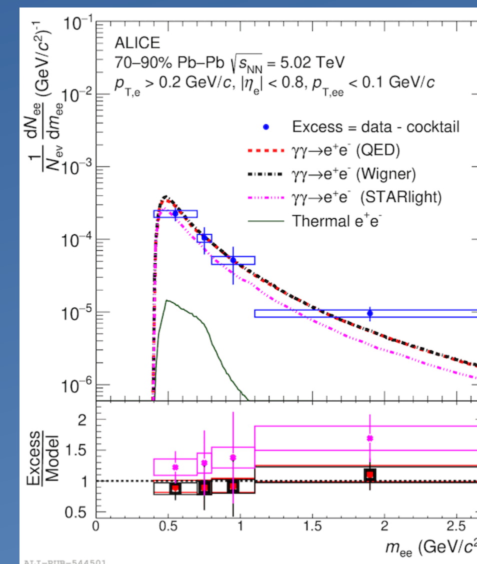

ALICE JHEP 06 (2023) 024

- Do both the spectator and participant contribute to the EM field? The answer seems to be yes.
- Origin of the broadening of the p_T spectrum in central collision?
- Interactions between the photoproduced e^+e^- with the quark gluon plasma?

Summary

- A huge amount of new data on UPCs and photoproduction in peripheral collisions has come out during the last 1-2 years.

- Different results address different topics.

- First measurements of cross sections, $d\sigma/dy$, now complemented by more differential studies owing to higher statistics.

- Further studies should contribute to the understanding of gluon shadowing and saturation, and the possible separation of the two.

- Inelastic photonuclear interactions may help to disentangle cold nuclear matter effects (e.g. v_2).

Backup Slide

Photonuclear interactions in UPC

Early, leading-order calculation related the cross section to the gluon distribution.

$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Ryskin 1993
(Z. Phys. 57 (1993) 89)

Attempts have been made to incorporate NLO effects[1,2]:

EFGLP: Strong sensitivity to choice of scale, surprisingly large contribution from quarks.

[1]Jones, Martin, Ryskin, Teubner, J. Phys. G 43 (2016) 035002;
[2]Eskola, Flett, Guzey, Löytäinen, Paukkunen, Phys. Rev. C 106 (2022) 035202; 107 (2023) 044912.