# Photoproduction in semi-central nuclear collision

Forward QCD: open questions and future directions

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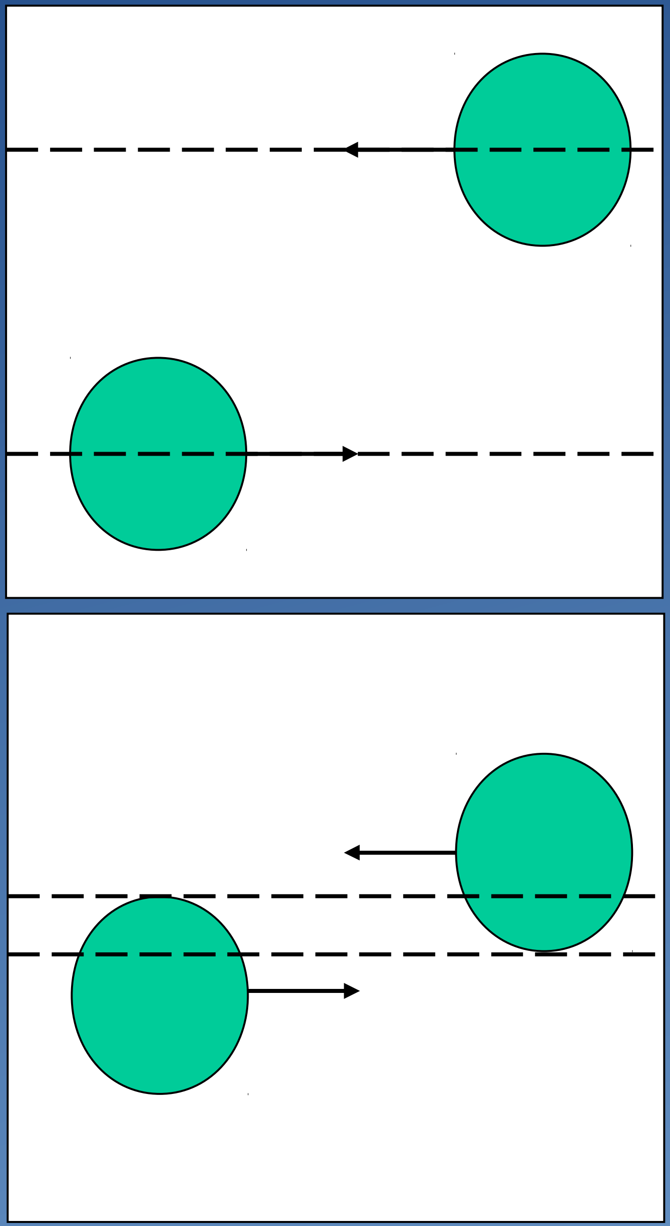
# Outline

- Photoproduction in ultra-peripheral collisions (b>2R) vs. in collisions with overlap.

- Photonuclear production of vector mesons ($J/\psi$) in semi-central collisions.

- Two-photon interactions in semi-central collisions.

# Photoproduction in Collisions with Overlap



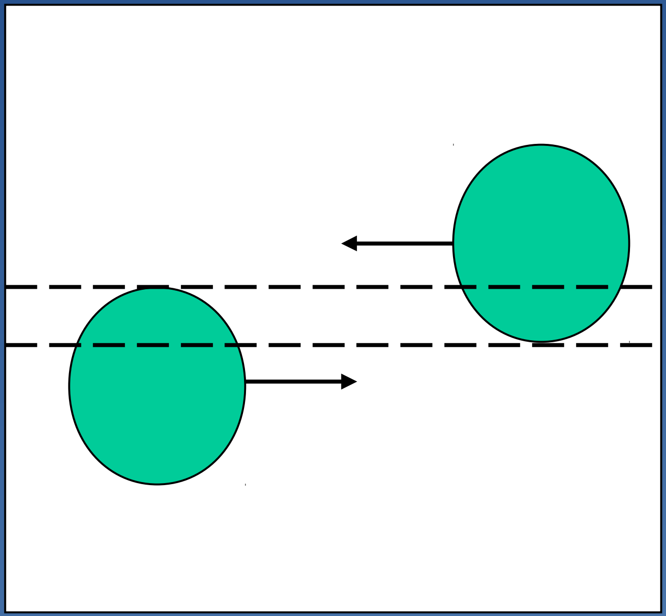
Ultra-peripheral colllisions, b > ≈15 fm.

Electromagnetic interactions possible, photonuclear or two-photon.

Collisions of intermediate centrality (b ≈ 10 - 15 fm or lower in Pb+Pb collisions).

The photons from (at least) the spectator parts may interact with the other spectator part or the participant region.

# Photoproduction in Collisions with Overlap



Collisions of intermediate centrality (b ≈ 10 - 15 fm or lower in Pb+Pb collisions).

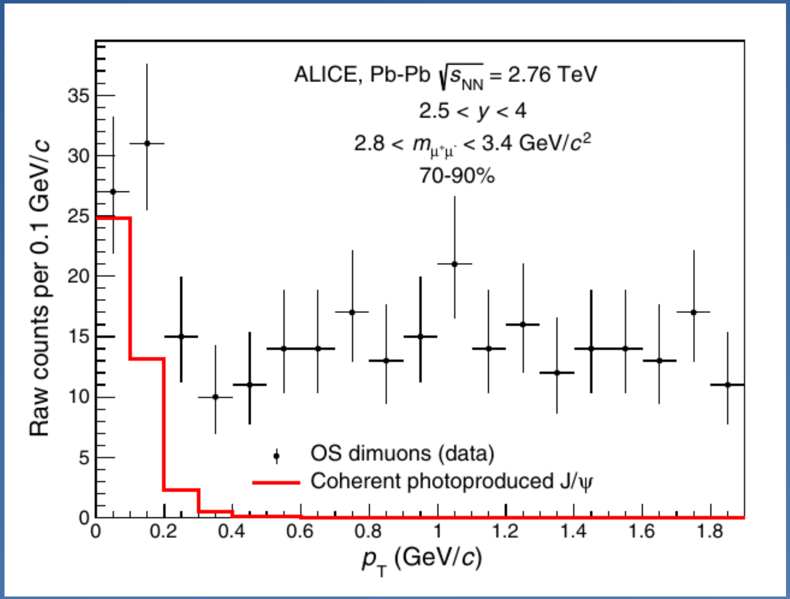
The photons from (at least) the spectator parts may interact with the other spectator part or the participant region.

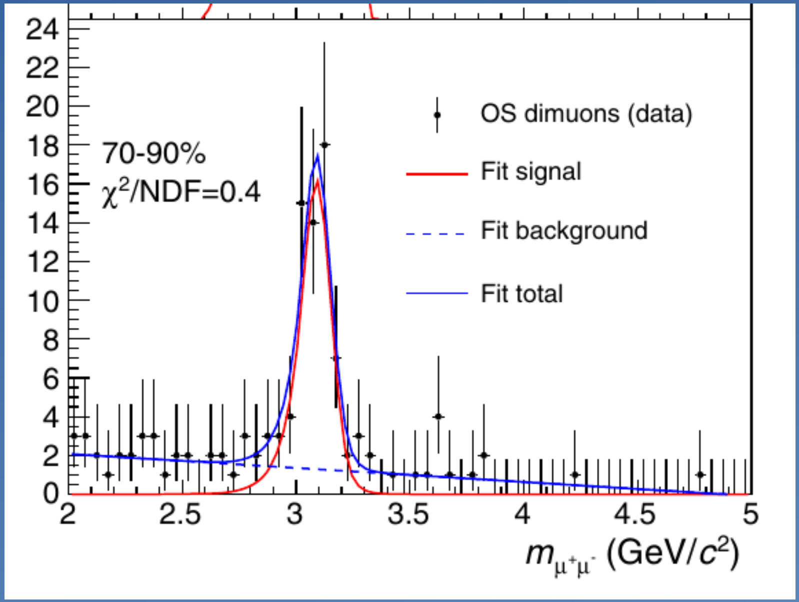
J/Ψs can be produced both hadronically and electro-magnetically.

Two-photon production of dilepton pairs also possible.

# Photoproduction in semi-central collisions - J/ψ

Photoproduction of J/ψ in semi-central collisions first observed by ALICE, Phys. Rev. Lett. 116 (2016) 222301.



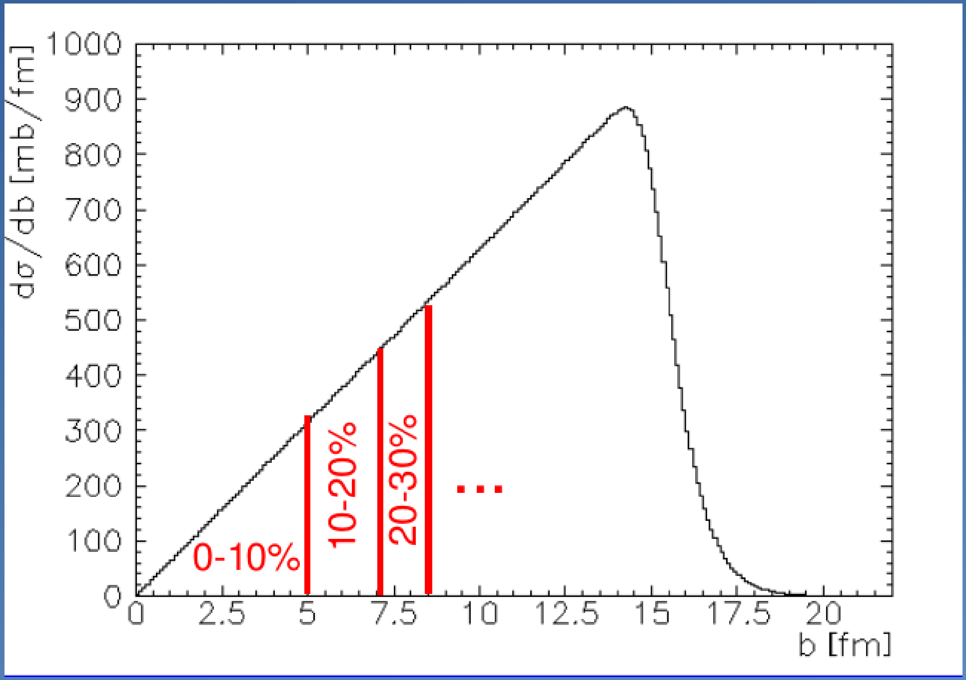




- Clear coherent peak seen in $p_T$ spectrum.
- Nice J/ψ peak with little background.

# Photoproduction in semi-central collisions - J/ψ

## Model calculations

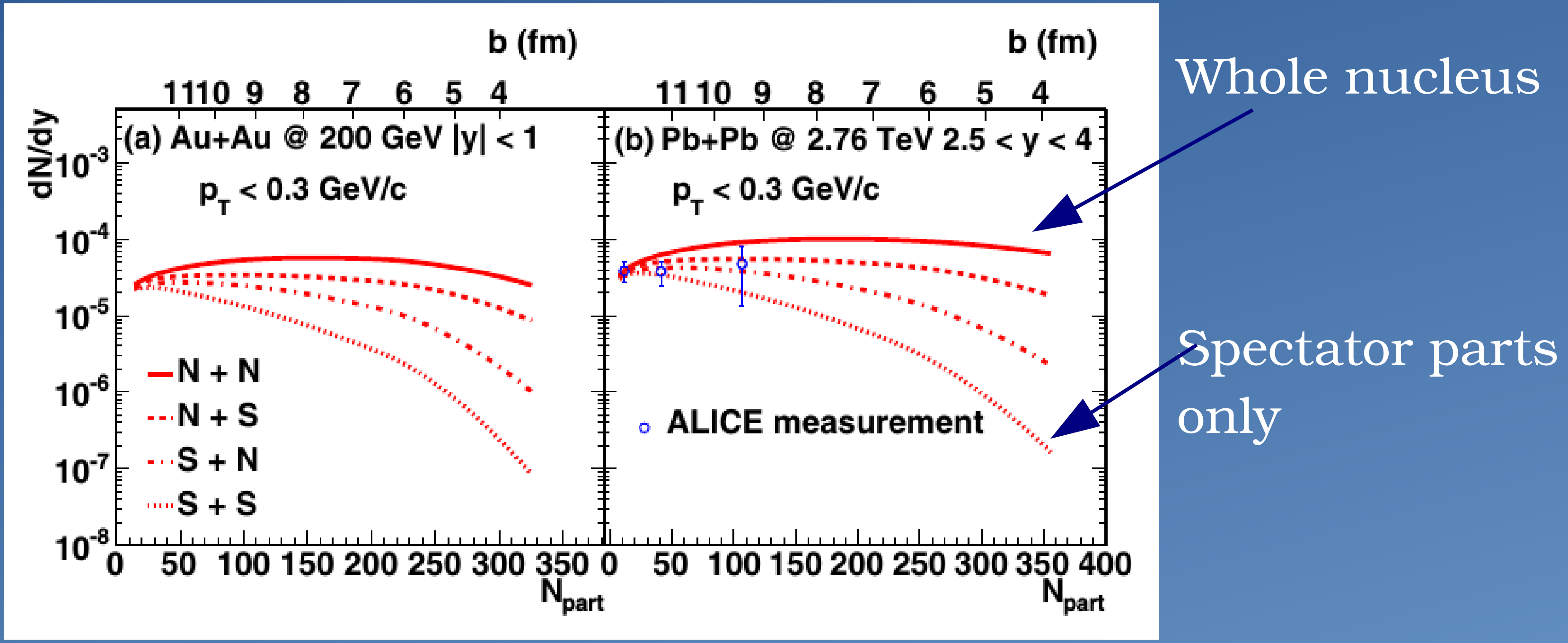
Impact parameter is a good variable. For a given centrality one has a certain range ($b_{min}$, $b_{max}$) [but the limits are of course not sharp].




In UPC, integrate over all b > 2R to calculate the photon spectrum. In semi-central collisions, integrate between $b_{min}$, $b_{max}$ for a given centrality range.

# Photoproduction in semi-central collisions - J/ψ

Coherent J/ψ cross section.
What contributes to the photon flux, what is the target?
The whole nucleus? Just the spectator parts?




M. Zha et al., Phys. Rev. C 97 (2018) 044910.

First ALICE data somewhere in between the two extremes and consistent with both.

# Photoproduction in semi-central collisions - J/$\psi$

A calculation based on the color dipole model, J. Cepila, J.G. Contreras, M. Krelina, Phys. Rev. C 97 (2018)024901.

Uses two approaches to scale the $\sigma(\gamma p)$ to $\sigma(\gamma A)$:
A Gribov-Glauber approach

$$\left(\frac{d\sigma_{dA}}{d\vec{b}}\right)_j = 2\left[1 - \exp\left(-\frac{1}{2}\sigma_{dp}(x,r)T_A^j(\vec{b})\right)\right],$$

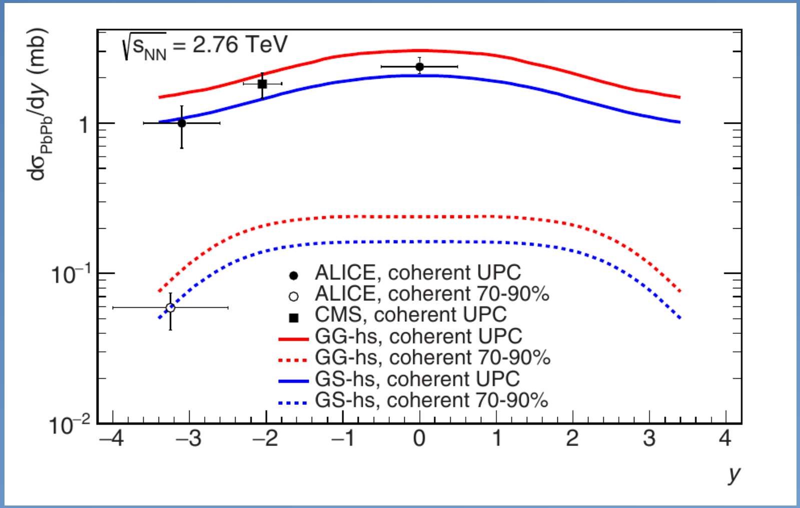
And a saturation model

$$\left(\frac{d\sigma_{dA}}{d\vec{b}}\right)_j = \sigma_0^A\left[1 - \exp\left(-r^2 Q_{A,s}^2(x)/4\right)\right]T_A^j(\vec{b}).$$

Also consider targets made up of nucleons and “hot spots”, but this only affects the incoherent cross section, not the coherent one.

Assumes that the whole nucleus contributes as photon emitter and target, but since the calculation is only for 70-90% centrality most of the nucleus is spectator.

Agreement with ALICE Run 1 result.



# Photoproduction in semi-central collisions - J/ψ

Another calculation also based on the color dipole model, M.B. Gay Ducati, S. Martins, Phys. Rev. D 97 (2018) 116013.

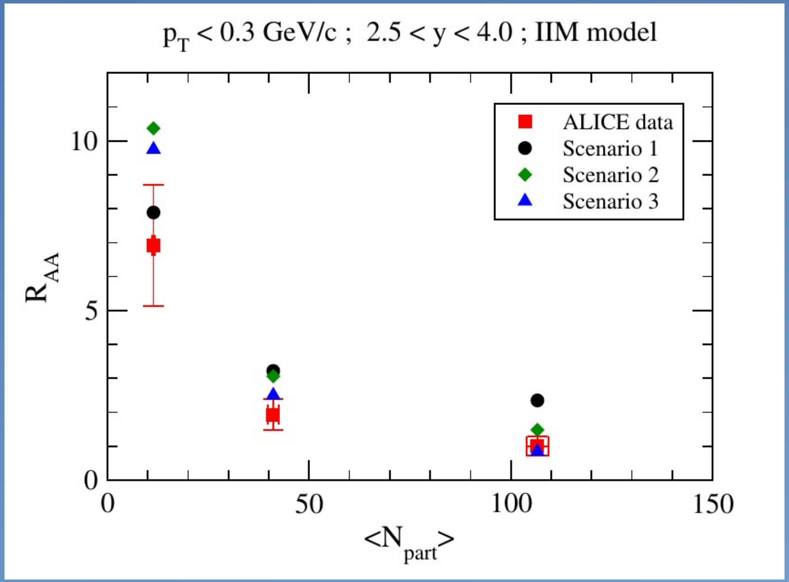
Two models for the dipole+proton cross section.

Three scenarios for the effective photon flux and target size:

1) The whole nucleus contributes to the photon spectrum and as target.

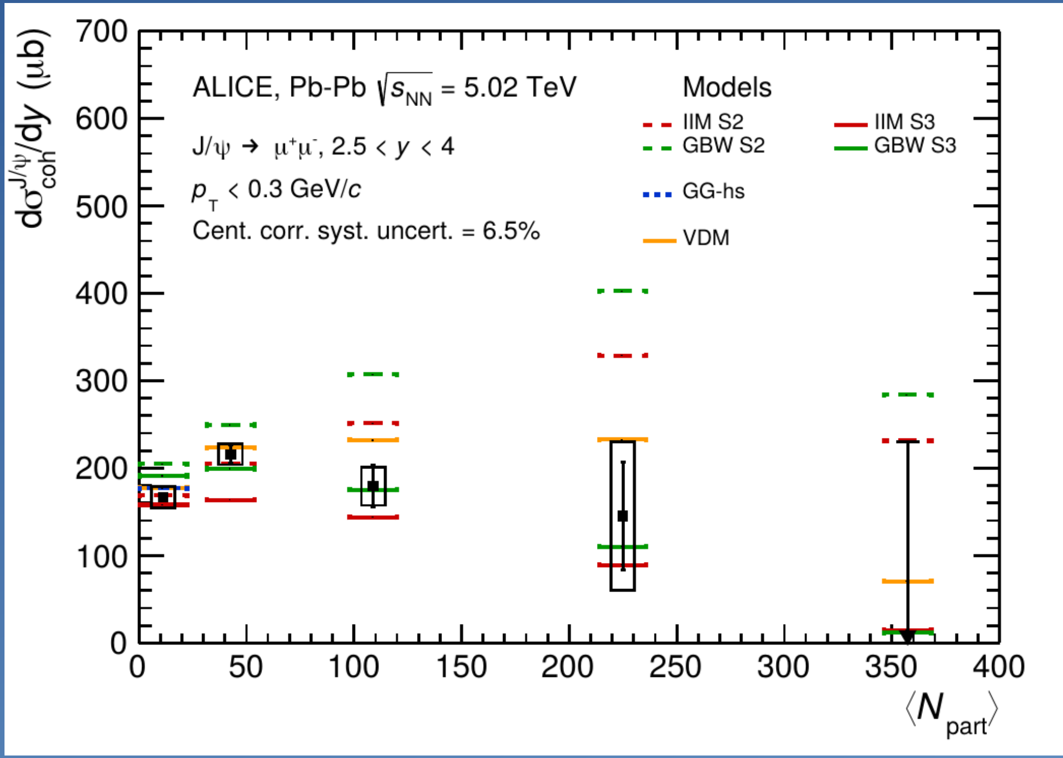
2) Only the spectators contribute to the photon flux.

3) Only the spectators contribute to the photon flux and as target.



# Photoproduction in semi-central collisions - J/ψ

Latest result from ALICE (arxiv:2204.10684) extends the measurement to 10% centrality (with an upper limit for the 0-10% centrality class)

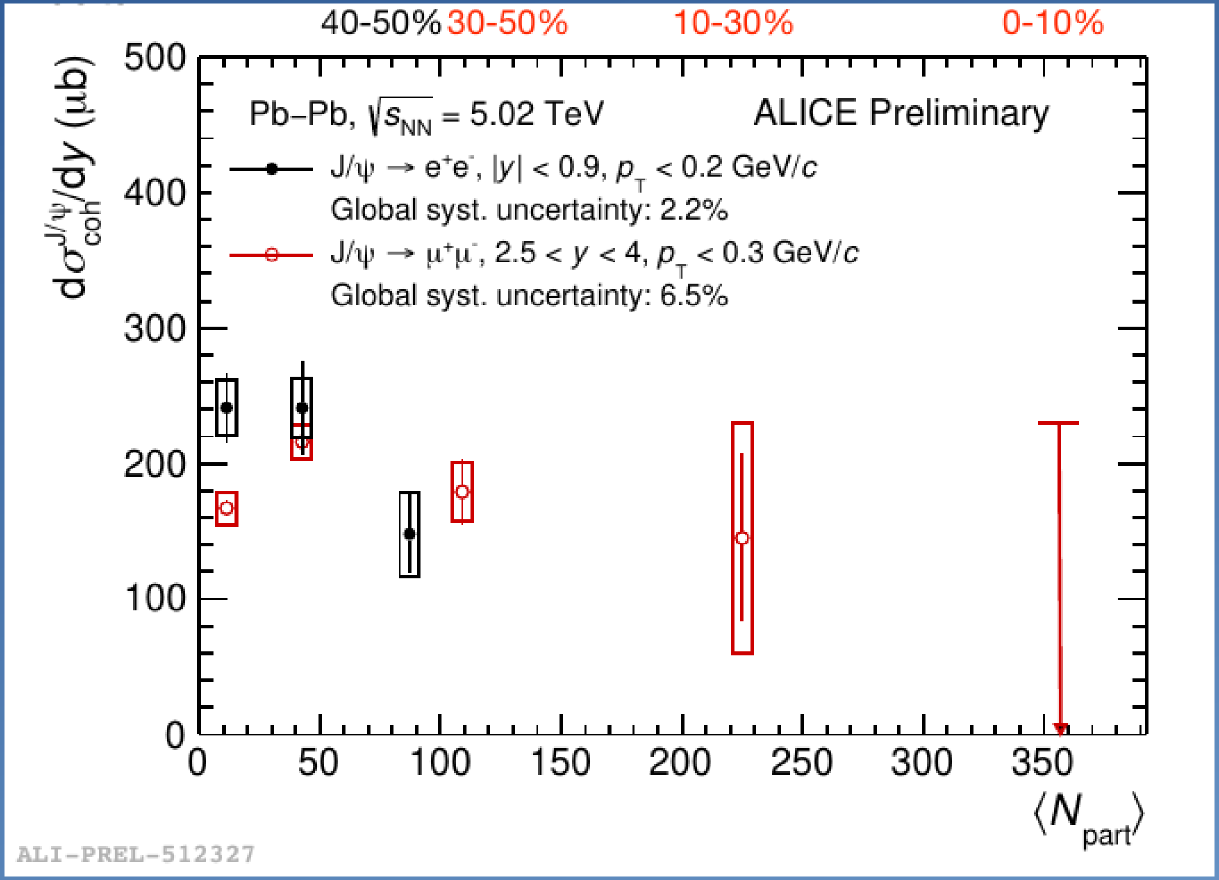



Here, the difference between the scenarios become very obvious.

That the whole nucleus contributes can be clearly ruled out!

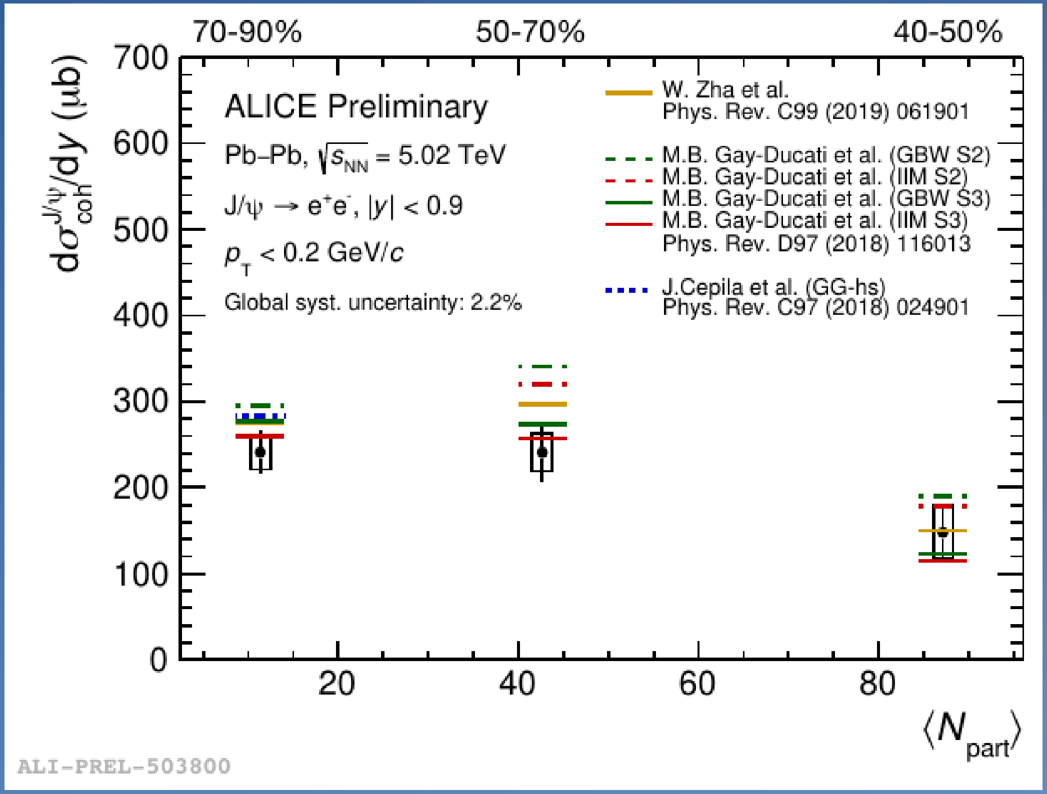
# Photoproduction in semi-central collisions - J/ψ

Preliminary results also from midrapidity in the $e^+e^-$ decay channel (A. Neagu, Quark Matter 2022).



# Photoproduction in semi-central collisions - J/ψ

Consistent picture with results from forward rapidity although the centrality range is still limited (A. Neagu, Quark Matter 2022).



# Photoproduction in semi-central collisions - $\gamma\gamma$

Results from ALICE, Atlas and STAR focussing on $\gamma\gamma \rightarrow e^+e^-$ (ALICE, STAR)and $\gamma\gamma \rightarrow \mu^+\mu^-$ (Atlas).

Kinematic ranges, all measurements at midrapidity

STAR: $0.4 < m_{inv} < 2.6$ GeV

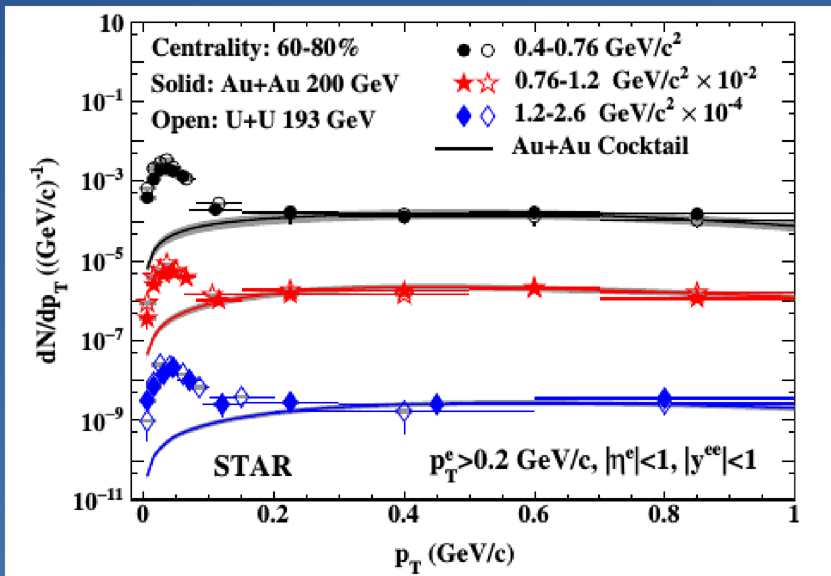
ATLAS: $4 < m_{inv} < 45$ GeV

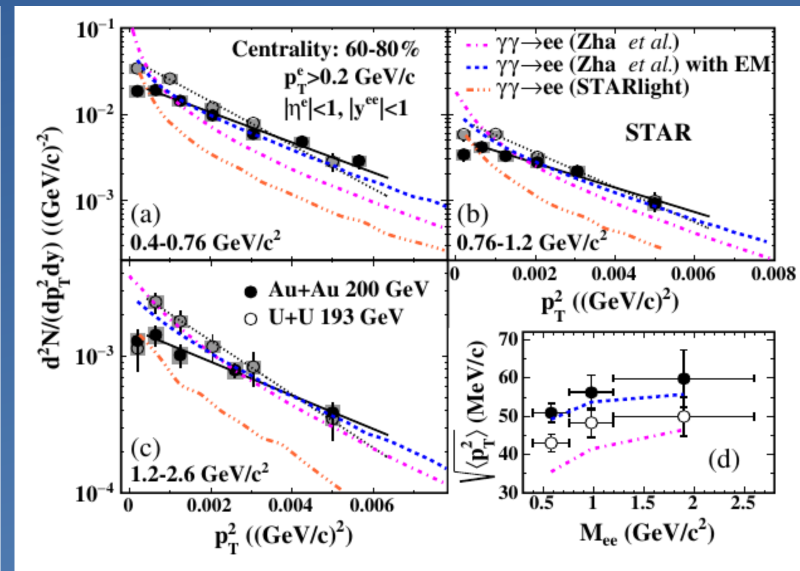
ALICE: $0.4 < m_{inv} < 2.7$ GeV

Much focus has been on the shape of the pair $p_T$ distributions. One observes a broader $p_T$ spectrum than in UPC.

# Photoproduction in semi-central collisions - $\gamma\gamma$

Results from STAR on $\gamma\gamma \rightarrow e^+e^-$.



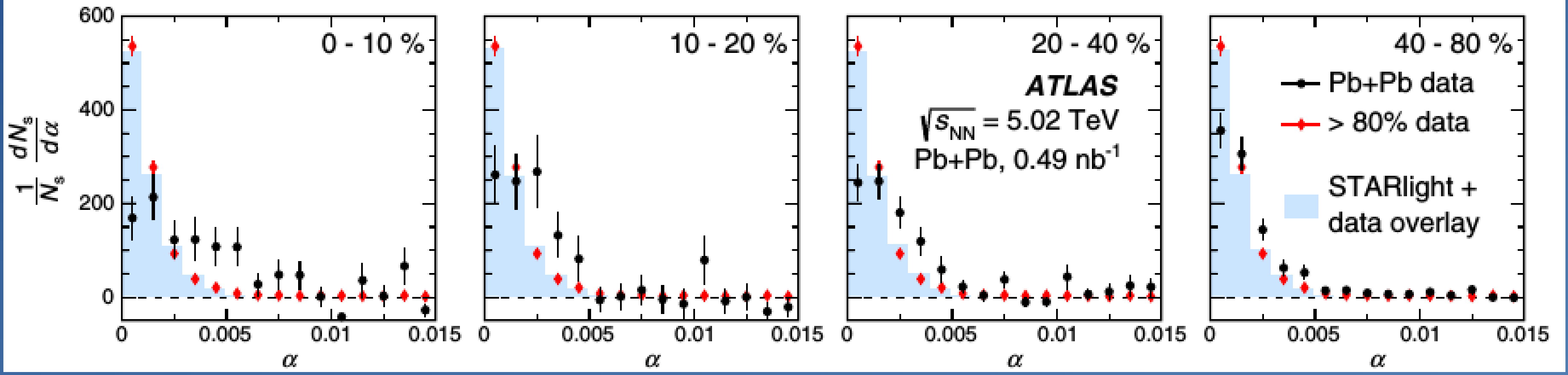




STAR Collaboration, PRL 121 (2018) 132301.
Indications of photoproduction down to 10-40% centrality.

Also observes a modification of the $p_T$ spectrum compared with UPC:
*The level of $p_T$ broadening may indicate the possible existence of a strong magnetic field trapped in a conducting QGP.*

# Photoproduction in semi-central collisions - $\gamma\gamma$

Results from Atlas on $\gamma\gamma \rightarrow \mu^+\mu^-$.



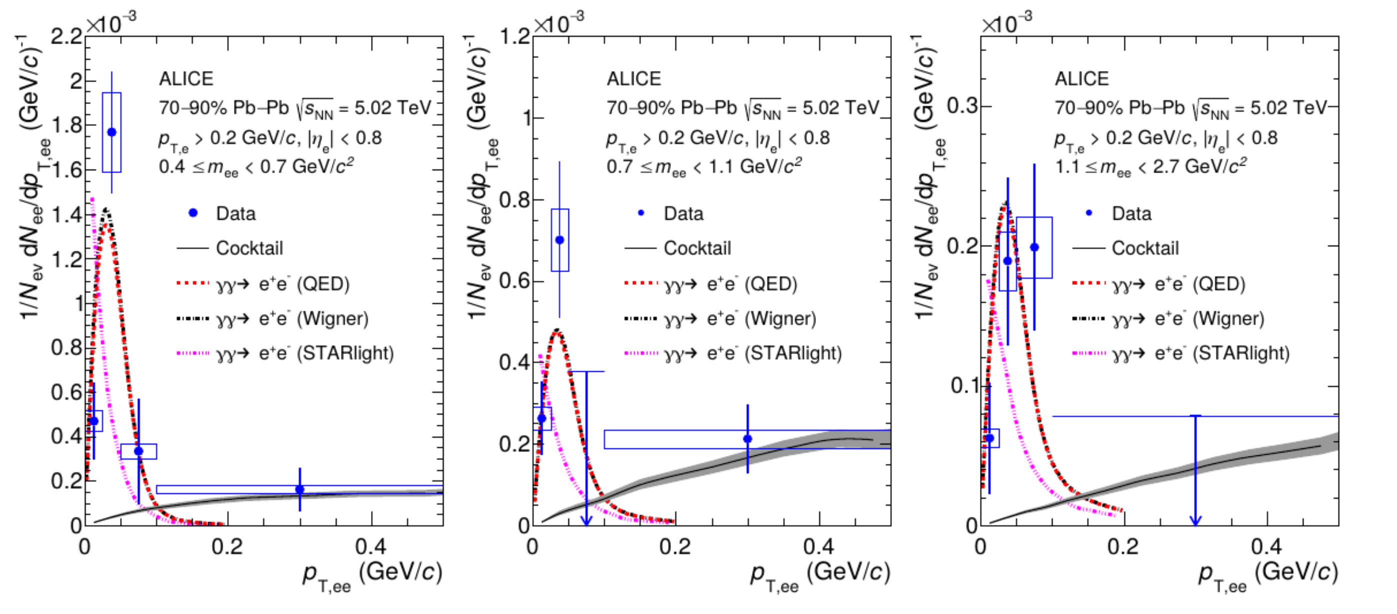

Atlas Collaboration, PRL 121 (2018) 212301.
Indications of photoproduction also in most central collisions.

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

*"It is expected that charged leptons produced in this region interact with the electric charges in the QGP that is formed, which may modify the leptons' momenta … electro-magnetic interactions may result in the broadening of the momentum and angular correlations of the lepton pair, in analogy with the original picture of jet energy loss proposed by Bjorken."*

# Photoproduction in semi-central collisions - $\gamma\gamma$

Results from ALICE on $\gamma\gamma \rightarrow e^+e^-$.




ALICE Collaboration, arxiv:2204.11732

Also observes a significantly broader $p_T$ distribution than in STARLight.

# Photoproduction in semi-central collisions - $\gamma\gamma$

The $p_T$ spectrum from STARLight. There is no explicit impact parameter dependence on the photon transverse momentum spectrum in STARLigt. The spectrum is calculated from ($k_T$-factorisation)

$$\frac{dN}{dk_\perp} = \frac{2Z^2\alpha F^2(k_\perp^2 + k^2/\gamma^2)k_\perp^3}{\pi[k_\perp^2 + k^2/\gamma^2]^2}.$$

The lepton pair $p_T$ spectrum is then calculated as a convolution of the two sources

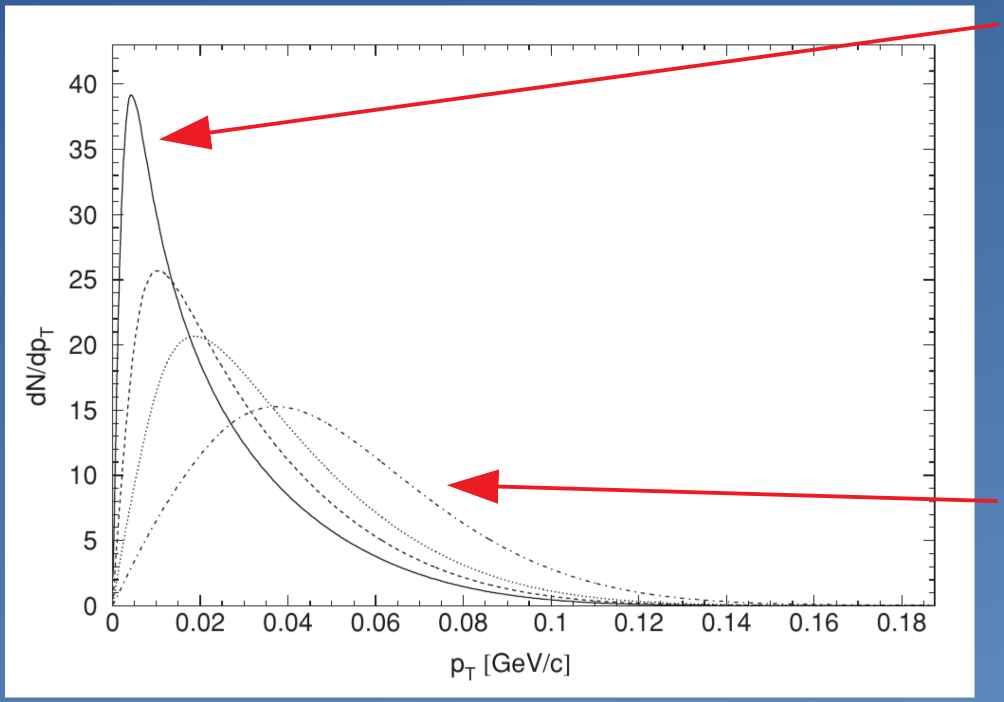
$$\frac{dn}{dp_T} = \int f_1(\vec{p}_T')f_2(\vec{p}_T - \vec{p}_T')d^2\vec{p}_T'.$$

A.J. Baltz, Y. Gorbunov, S.R. Klein, J. Nystrand, PRC 80 (2009) 044902.

# Photoproduction in semi-central collisions - $\gamma\gamma$

This leads to an energy dependent $p_T$ spectrum.

Transverse momentum distribution of dilepton pairs with different invariant masses in UPC in Au+Au collisions at RHIC.




$M_{inv} = 0.2$ GeV

$M_{inv} = 0.5$ GeV

$M_{inv} = 1.0$ GeV

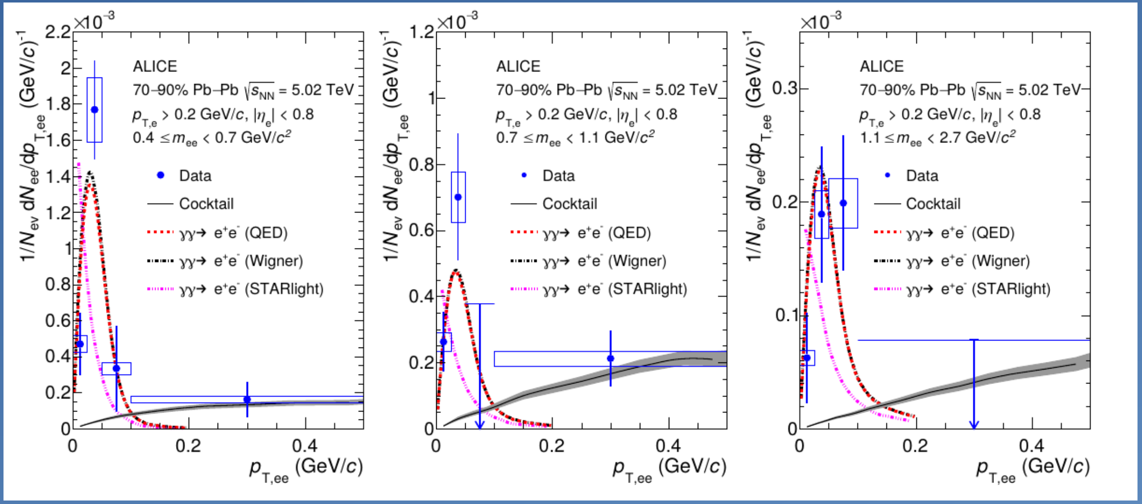
$M_{inv} = 3.0$ GeV

J. Nystrand, arXiv:nucl-th/0112055.

This is for UPC ($b > 2R$), but as $M_{inv}$ increases the mean $\langle b \rangle$ decreases, thereby leading to an indirect dependence of the width on impact parameter. But this is apparently not enough to explain the distributions seen in data.

# Photoproduction in semi-central collisions - $\gamma\gamma$

Several groups have tried to explain the broadening by introducing an impact parameter dependent photon $p_T$ spectrum (e.g. M. Kłusek-Gawenda, R. Rapp, W. Schäfer, A. Szczurek, PLB 790 (2019) 339; PLB 814 (2021) 136114, S. Klein, A.H. Mueller, B.W. Xiao, F. Yuan PRD 102 (2020) 094013, W. Zha, J.D. Brandenburg, Z. Tang, Z. Xu, PLB 800 (2020) 135089) with some success:

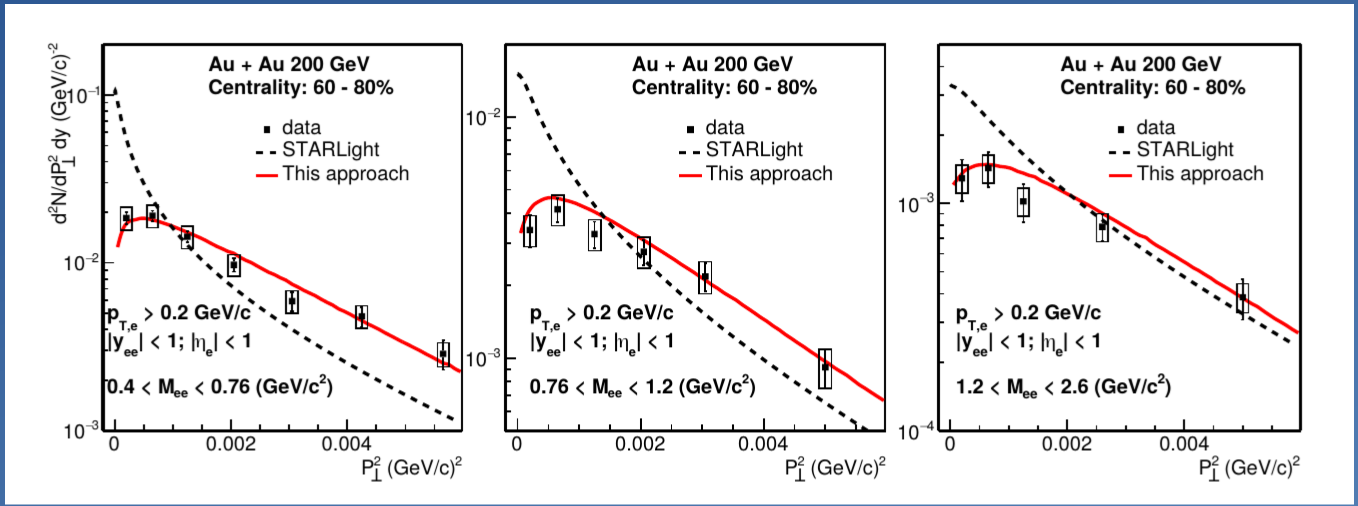



QED: W. Zha, J.D. Brandenburg, Z. Tang, Z. Xu, PLB 800 (2020) 135089, J.D. Brandenburg, W. Zha, Z. Xu, Eur. Phys. J A 57 (2021) 299.

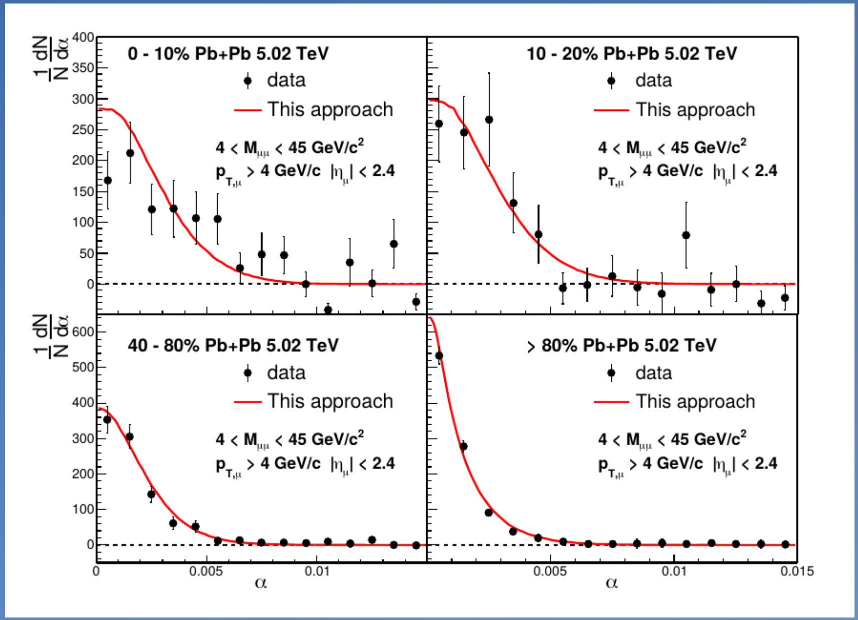
Wigner: M. Kłusek-Gawenda, W. Schäfer, A. Szczurek, PLB 814 (2021) 136114.

# Photoproduction in semi-central collisions - γγ

Also in agreement with STAR and ATLAS data.




STAR




ATLAS

W. Zha, J.D. Brandenburg, Z. Tang, Z. Xu, PLB 800 (2020) 135089.

# Photoproduction in semi-central collisions - $\gamma\gamma$

But there are still some uncertainties involved. One can calculate the impact parameter dependent photon spectrum from

a) The Weizsäcker-Williams method (as described in Jackson) for a point charge

$$\frac{d^3n}{dk\,db^2} = \frac{Z^2\alpha}{\pi^2}\frac{1}{kb^2}x^2K_1^2(x),$$

where $x = bk/\gamma$ and $\gamma \gg 1$ is the Lorentz factor.

b) The nuclear form factor

$$\frac{d^3n(b,k)}{dkd^2b} = \frac{Z^2\alpha}{\pi^2 k}\left|\int_0^\infty dk_\perp \frac{F(k_\perp^2 + k^2/\gamma^2)k_\perp^2}{k_\perp^2 + k^2/\gamma^2} J_1(bk_\perp)\right|^2,$$

In both cases, the spectrum is integrated (explicitly or implicitly) over all transverse momenta.

# Photoproduction in semi-central collisions - $\gamma\gamma$

The point is that $p_T$ and b are conjugate variables and both cannot be measured at the same time.

One can go from one of the spaces ($p_T$ or b) to the other through a Fourier transform.

We wrote back in 2009 (PRC 80 (2009) 044902)

"The $k_\perp$ spectra of the virtual photon fields are complicated because $k_\perp$ and transverse position are conjugate variables and cannot both be defined at the same time. This complicates any determination of the $k_\perp$ spectrum with constraints on transverse position"

So, despite the agreement with data, I don't think this is completely understood.

# Photoproduction in semi-central collisions - $\gamma\gamma$

There are also ideas that the broadening is due to interactions of the lepton pair with the quark-gluon plasma.

S. Klein, A.H. Mueller, B.W. Xiao, F. Yuan PRD 102 (2020) 094013 write

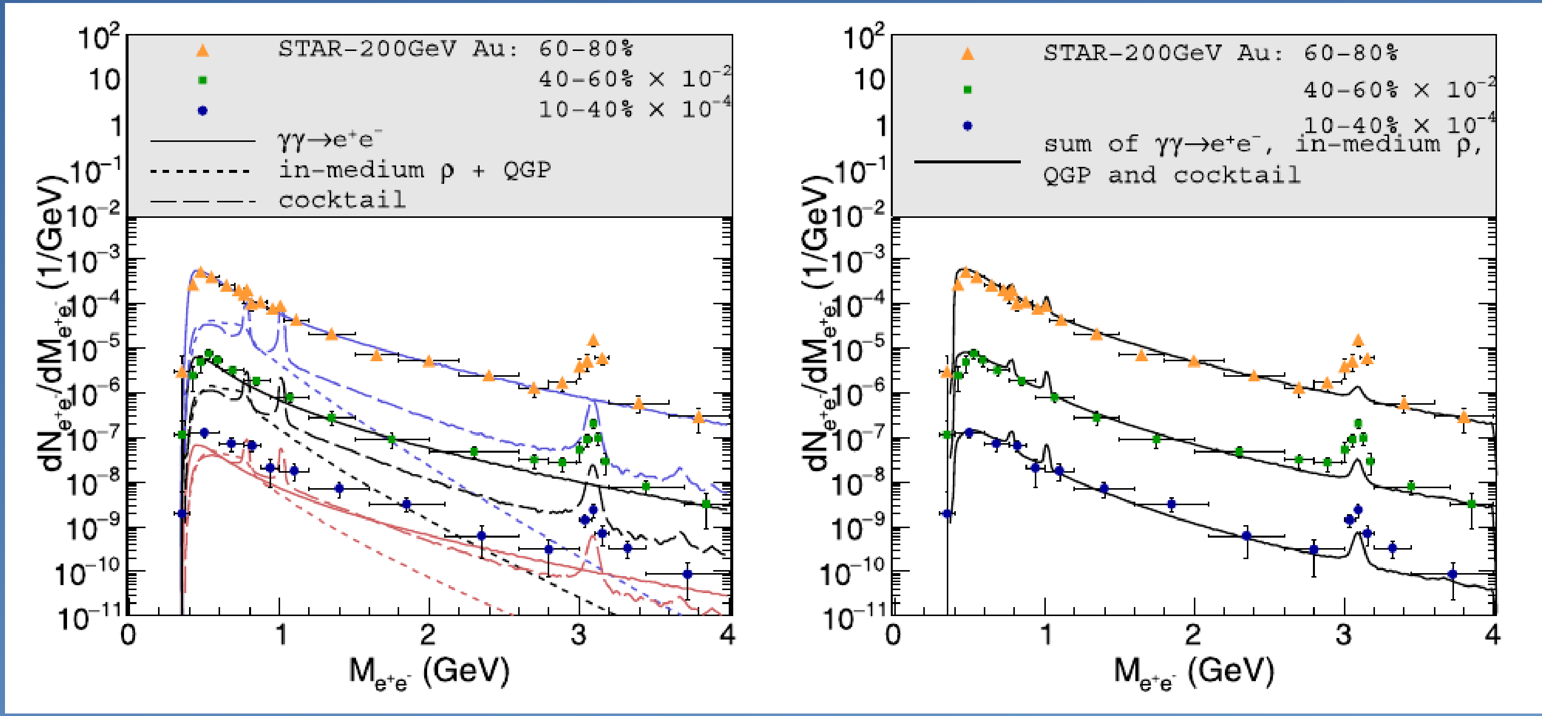
"Last but not least, to interpret the $p_T$-broadening phenomena of dilepton productions observed by STAR and ATLAS collaborations as a result of QED interaction of the lepton pair with the medium crucially depend on how precisely we know that the initial state contributions from the incoming photon fluxes of the colliding nuclei. We emphasize that more theoretical developments and experimental measurements are needed to understand this physics. Only with this being resolved, can we reliably apply this process to study the electromagnetic property of the quark-gluon plasma created in heavy-ion collisions."

And I think this is where things stand now.

# Photoproduction in semi-central collisions - $\gamma\gamma$

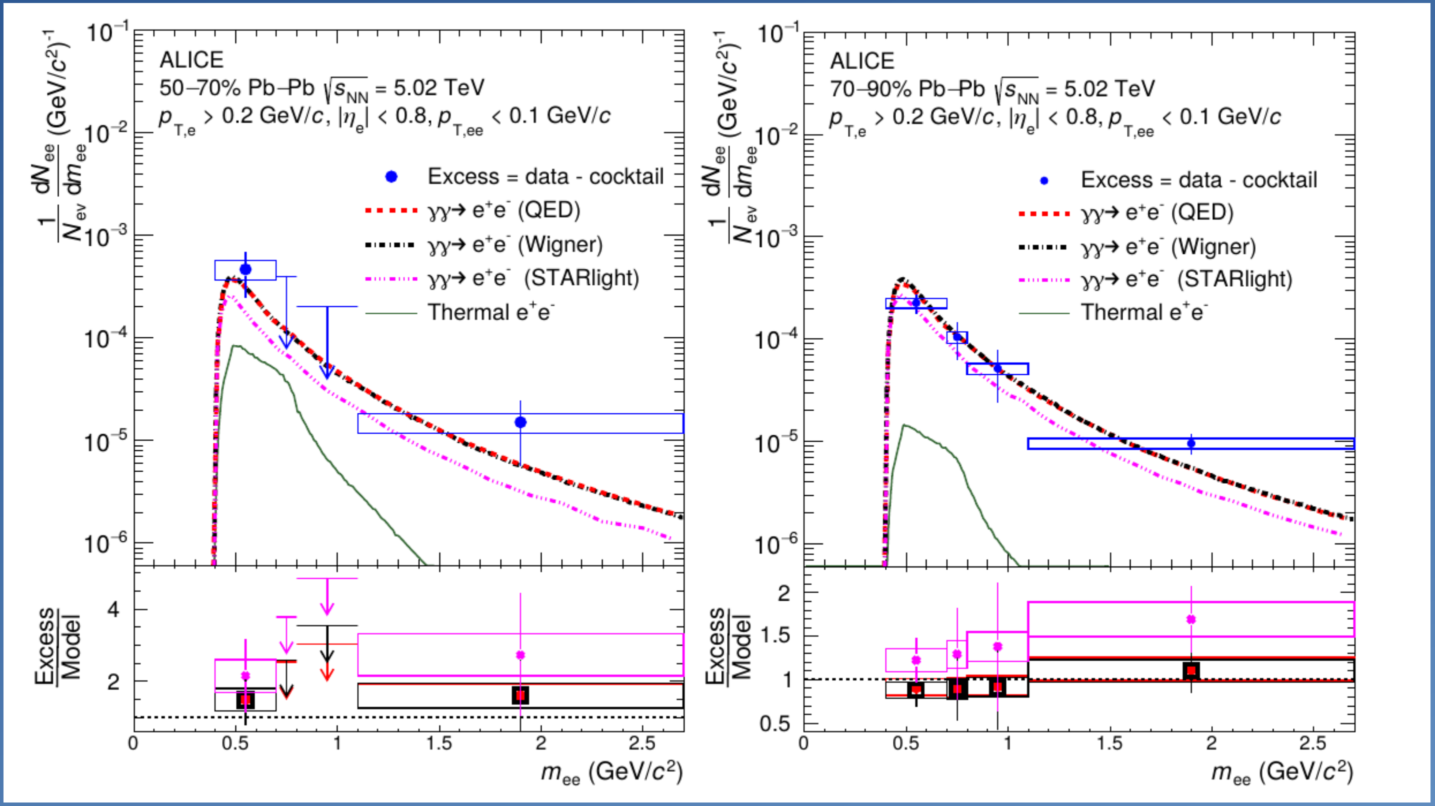
The invariant mass spectrum of the lepton pairs has attracted less attention but seems to be in good agreement with expectations.

Calculation combining two-photon production with thermal dilepton production and cocktail of resonance decays, M. Kłusek-Gawenda, R. Rapp, W. Schäfer, A. Szczurek, Phys. Lett. B 790 (2019) 339.



# Photoproduction in semi-central collisions - $\gamma\gamma$

Agreement also with ALICE data.




ALICE Collaboration, arxiv:2204.11732.

# Summary

- Photoproduction of J/ψ in semi-central collisions shows that not the whole nucleus acts as target. Best agreement if only the spectators contribute.

- For two-photon production of lepton pairs, a broadening of the pair $p_T$ distribution compared with ultra-periheral collisions has been observed in semi-central collisions.

- Not yet determined if this reflects the interaction of the produced leptons with the quark-gluon plasma, or if it is just a question of an incomplete understanding of the photon spectra.