GDR QCD

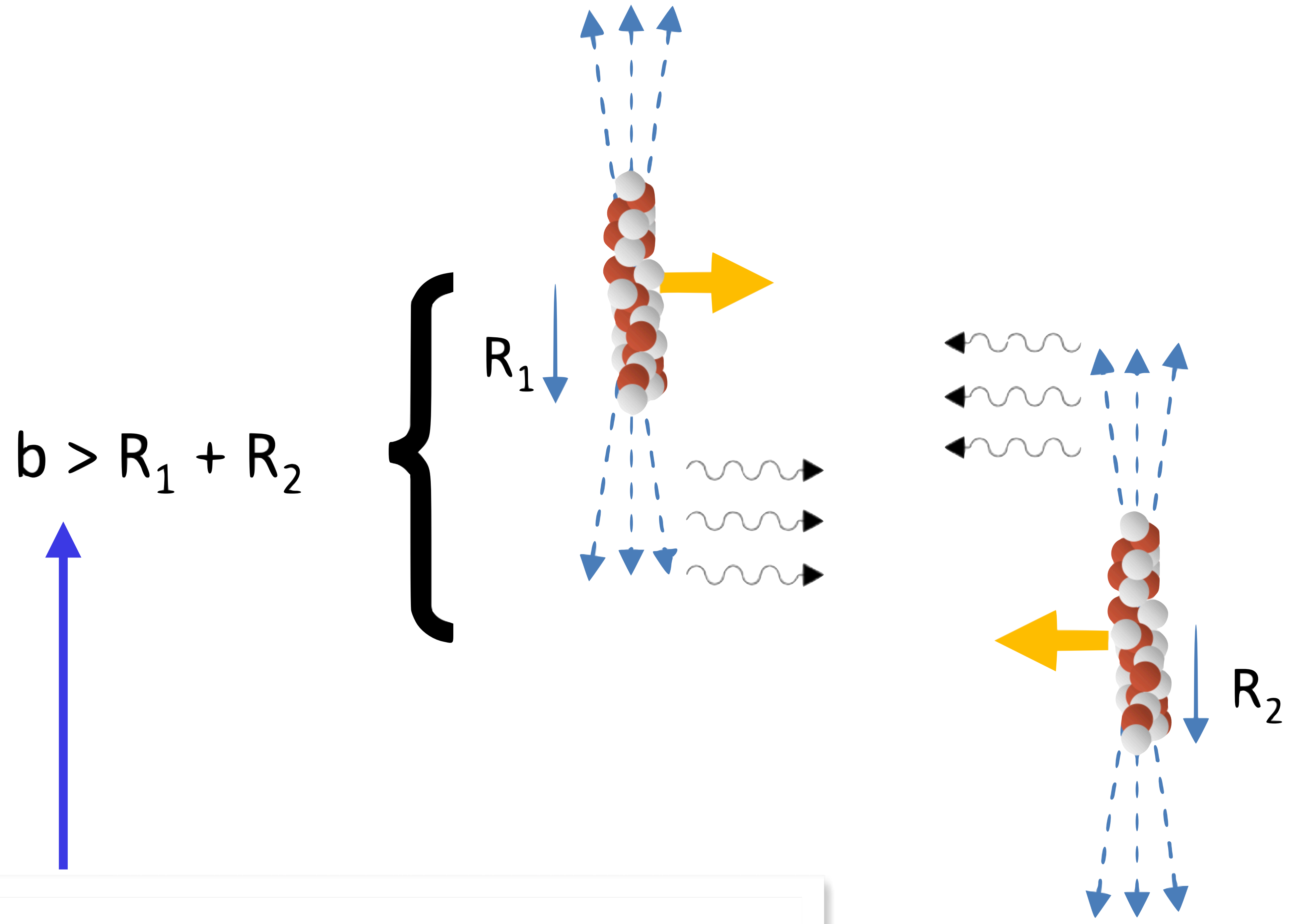
Prospects on various aspects of the dilepton probe in hadronic physics

UPC at the LHC

A. GLAENZER - CEA-SACLAY/IRFU/DPHN - 25/11/2021

Ultra Peripheral Collisions

- Ultra-relativistic heavy ions produce highly Lorentz contracted electromagnetic fields.
- Weizsäcker-Williams or Equivalent Photon Approximation (EPA) approach: these EM fields can be treated as fluxes of photons which are:
  - linearly polarized
  - coherent
  - quasi-real with $Q^2 < (\hbar c/R_A)^2 \approx 10^{-3}$ GeV² (with R_A = 7 fm)

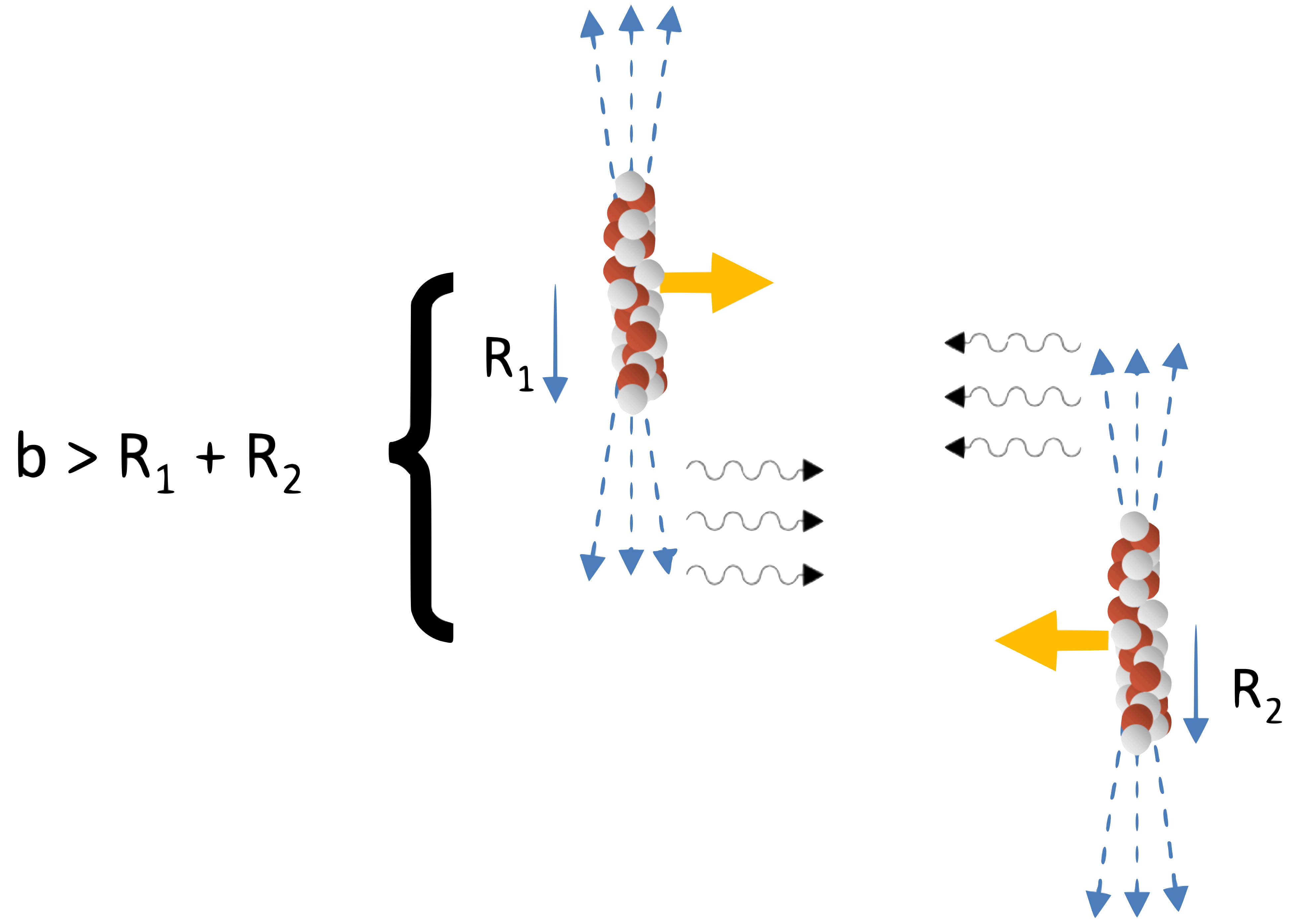


- Large impact parameter ($b > R_1 + R_2$)
  - No nuclear overlap
  - Hadronic interactions are strongly suppressed
  - Intense sources of photons (photon flux $\propto Z^2$)
  - Photon induced reactions dominate

Ultra Peripheral Collisions with Pb-Pb beams

- Small transverse momenta of photons: $k_T \sim O(\hbar c/R_A)$ (= 30 MeV/c in Pb-Pb UPCs)
    - high-energy decay products in exclusive final states are almost perfectly balanced in the transverse direction

- Maximum energy of coherent photons: $E_\gamma = \gamma \hbar c/R_A$ up to 75–100 GeV at the highest-available LHC nuclear beam energies (2.51 TeV per beam, corresponding to a Lorentz boost of γ_L = 2595)
    - study photon–photon and photon–nucleus scattering at unprecedentedly high energies

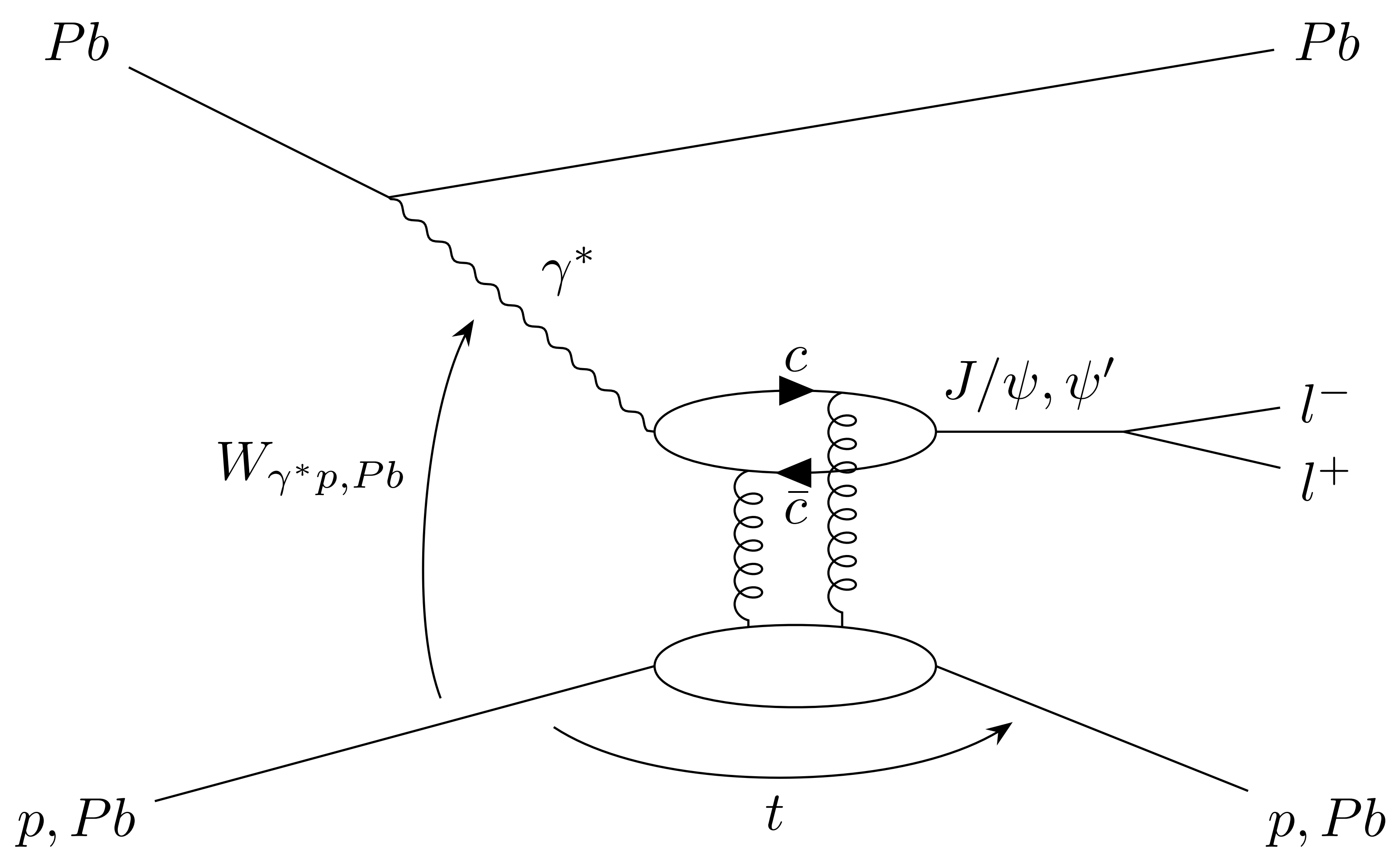


- At such high energies, Pb-Pb UPCs can induce a **wide variety of exclusive final states** - dileptons, dijets, and diphotons being the most commonly measured
    - via photonuclear production
    - or via two-photon interactions

Ultra Peripheral Collisions: photonuclear production

- UPCs of heavy ions: **exclusive photonuclear production** (p+γ or A+γ interactions)
  - exclusive vector meson production → sensitive to the gluon density and to the gluon space distribution inside nuclei (GPDs)
  - diffractive photon-nucleus dijet events → provides information on the proton diffractive PDFs (in p-A) or nuclear diffractive PDFs (in A-A) (JHEP 04 (2016) 158)

In this example:
$\sigma(\gamma A \to J/\psi A)|_{t\to 0} \propto$ [gluon PDF in the proton]^2 at LO in pQCD
→ could probe saturation effects or gluon shadowing



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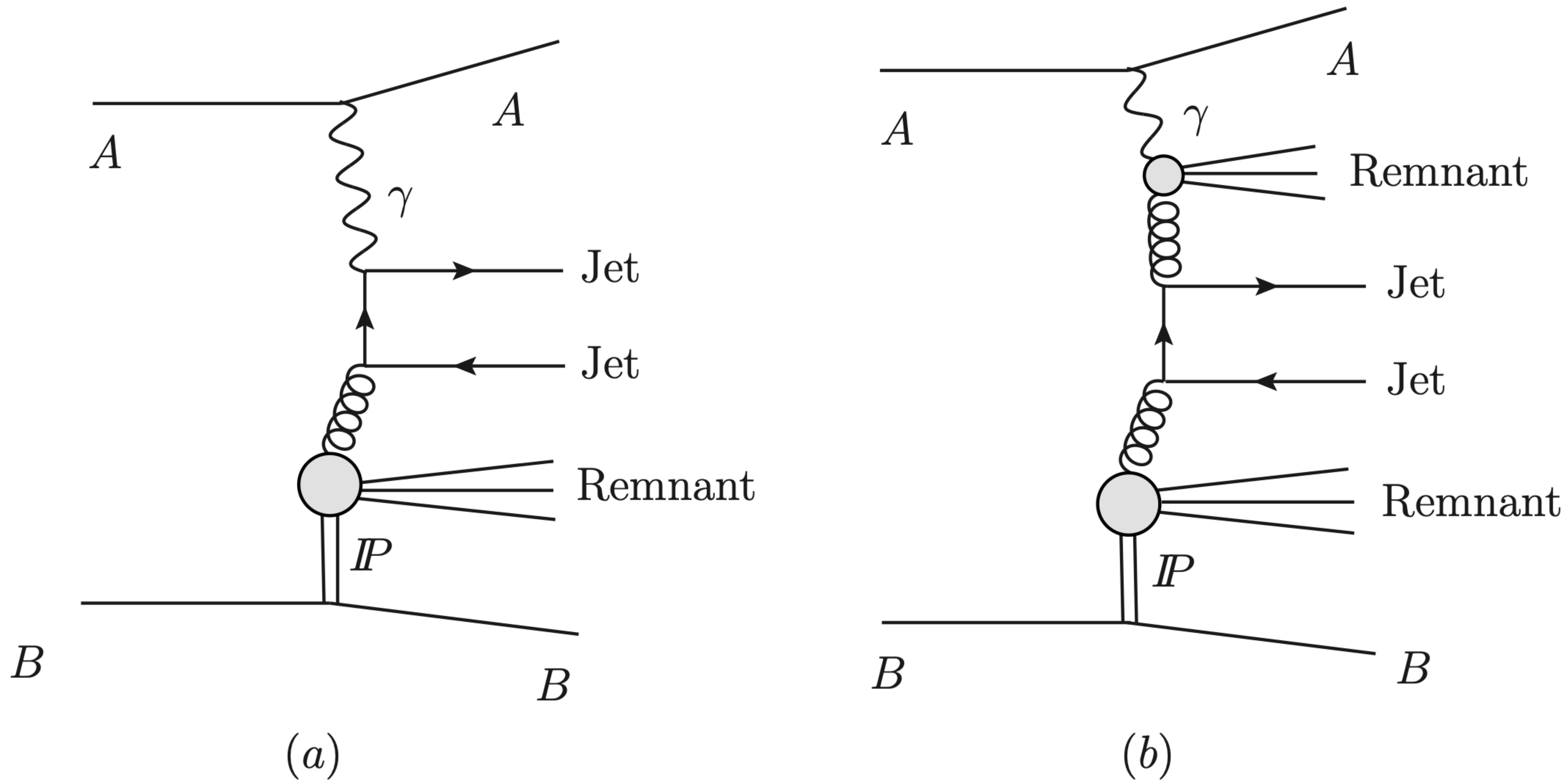
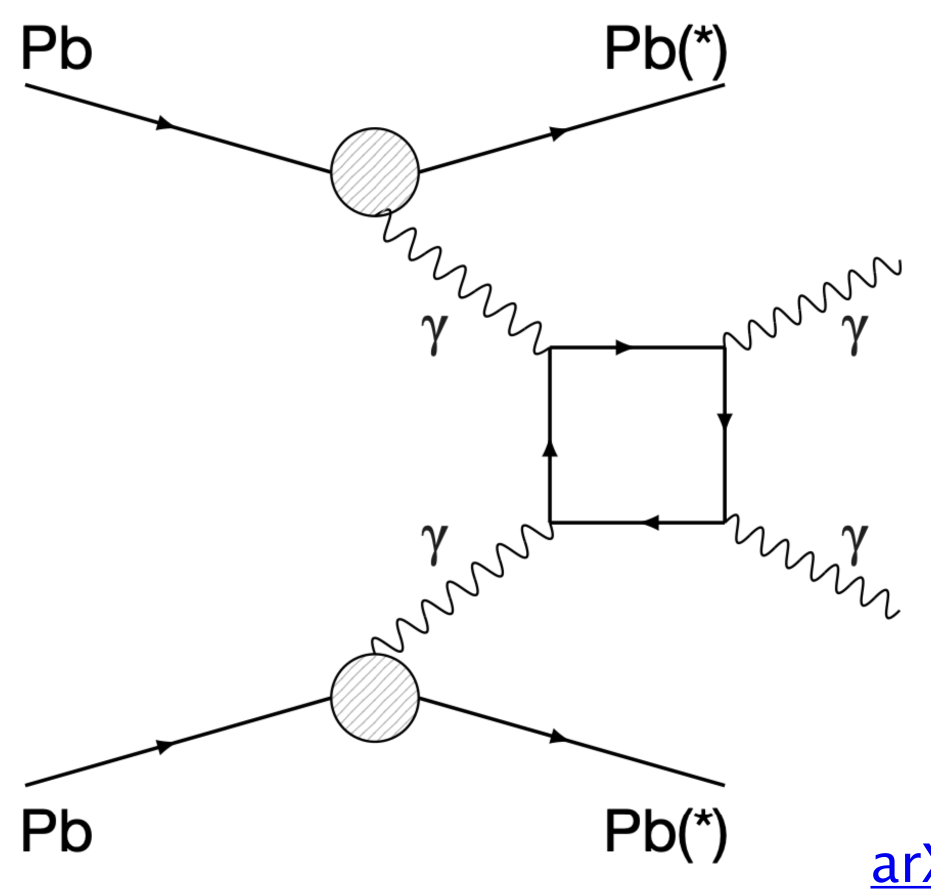
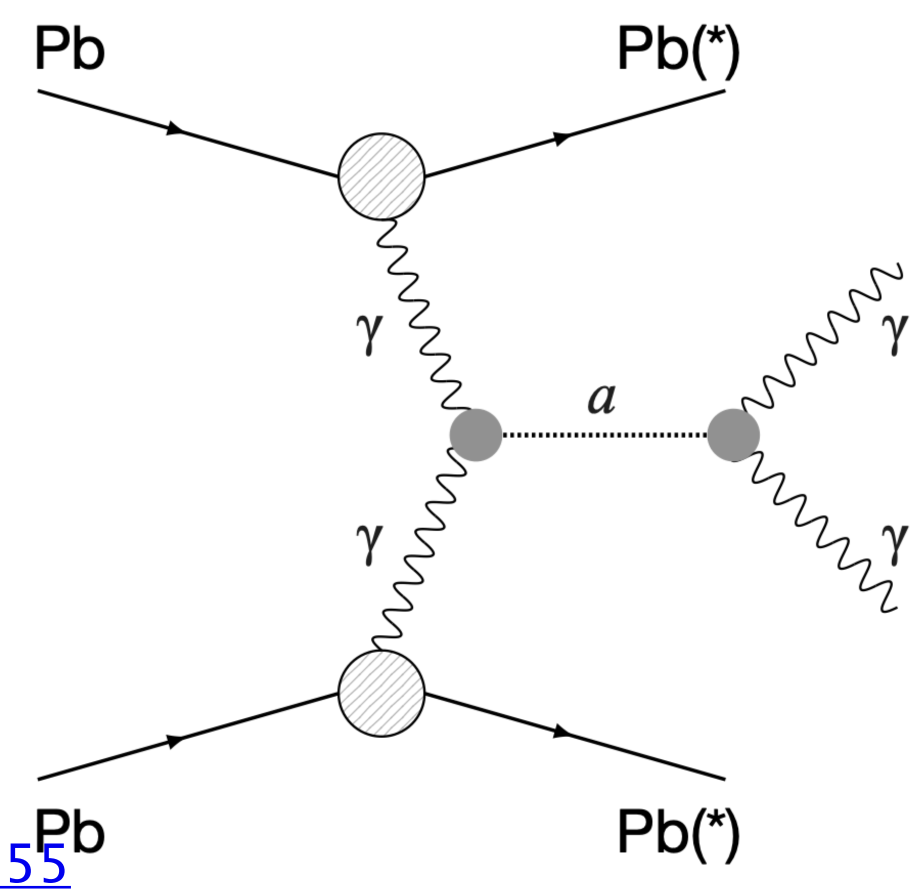


arXiv:1603.06055

Ultra Peripheral Collisions: two-photon interactions

- UPCs of heavy ions: **two-photon interactions (γγ)**
  - two photons (via light-by-light scattering)
    - in the standard model: cross section is sensitive to all charged particles (leptons, quarks, $W^{\pm}$ bosons...)
    - beyond the standard model: cross section might be sensitive to vector fermions, GeV-mass axion-like particles, Lorentz-violating operators in electrodynamics, … (JHEP 03 (2021) 243)
  - single mesons or meson pairs
    - production rates small (feed-down from photoproduction rates are larger than the two-photon production rates) (annurev-nucl-030320-033923)





arXiv:2008.05355

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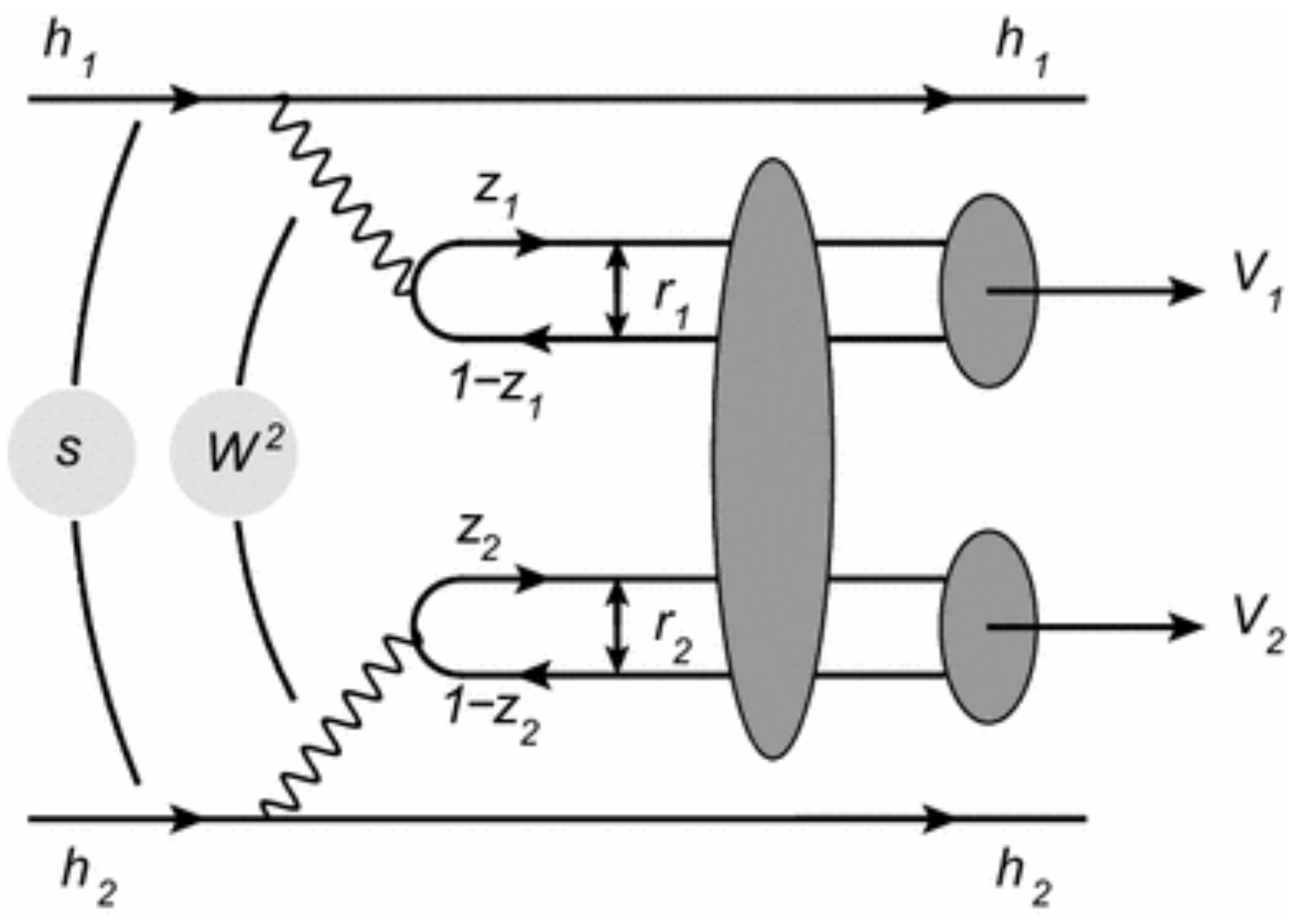
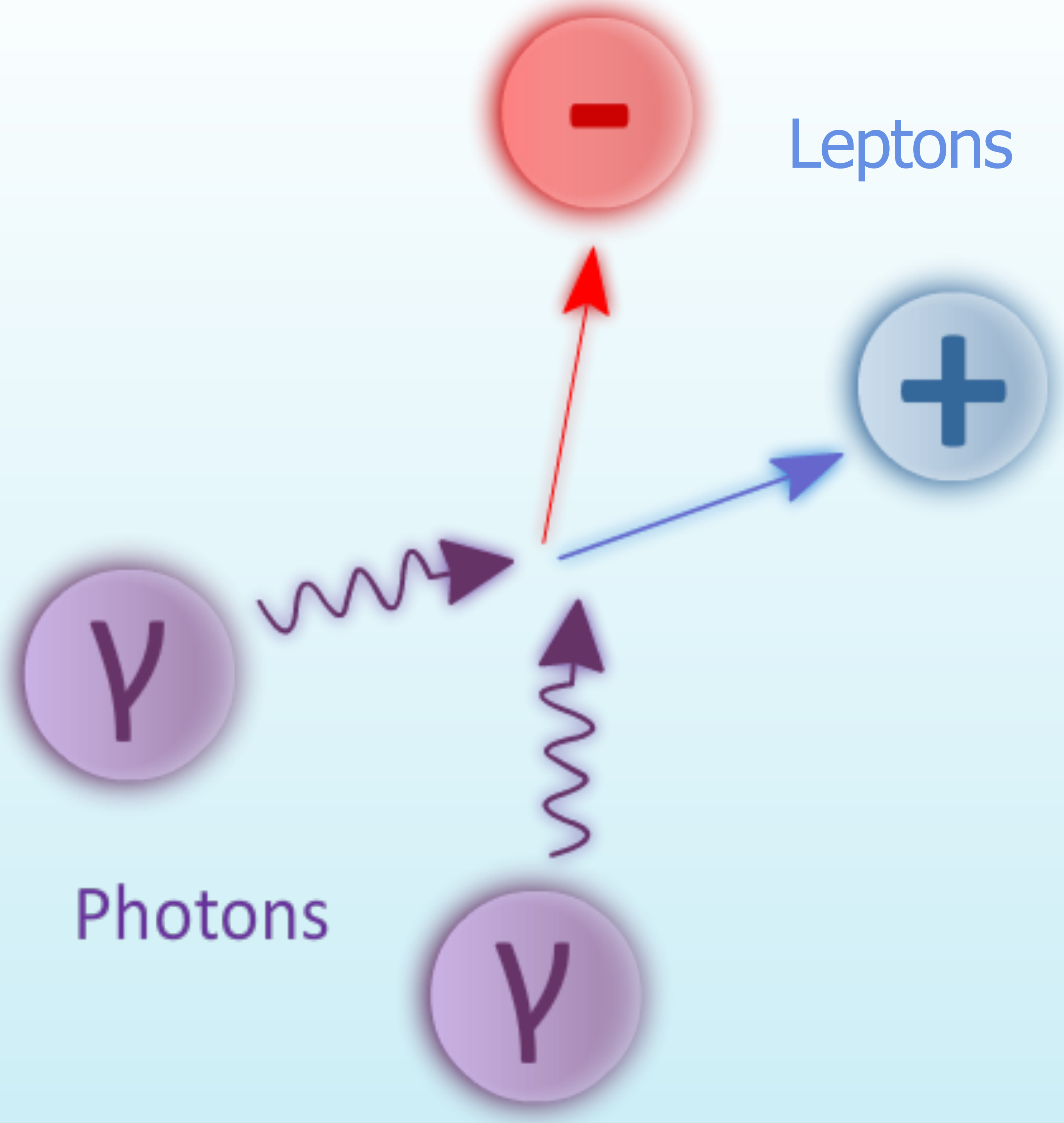


Ultra Peripheral Collisions: two-photon interactions

- UPCs of heavy ions: **two-photon interactions (γγ)**
  - dileptons (also referred to as Breit-Wheeler process ($\gamma\gamma \rightarrow l^+l^-$))
    - ✻ Precise measurements of the incoming photon fluxes → calibrate the rates of other hard processes involving UPC, such as the photonuclear production of hadrons and jets (Phys. Rev. Lett. 96, 082001)
    - ✻ Prediction of a sizable v_4 anisotropic distribution with respect to the reaction plane, which is purely generated by the initial EM field configuration → crucial handle on the production mechanism for dileptons in two photon processes in non-UPC collisions (arXiv:2003.06352 [hep-ph], arXiv:2003.02947 [hep-ph])
    - ✻ Angular modulations of the pair momentum relative to the single electron momenta, reflecting the linear polarization of the initial photons (Adam J, et al. arXiv:1910.12400 [nucl-ex] (2019), Li C, Zhou J, Zhou YJ. Phys. Lett. B795:576 (2019))
    - ✻ Measurement of τ g-2 in $\gamma\gamma \rightarrow \tau^+\tau^-$ only for incoming diphoton invariant masses above 3.5 GeV (arXiv:1908.05180 [hep-ph])

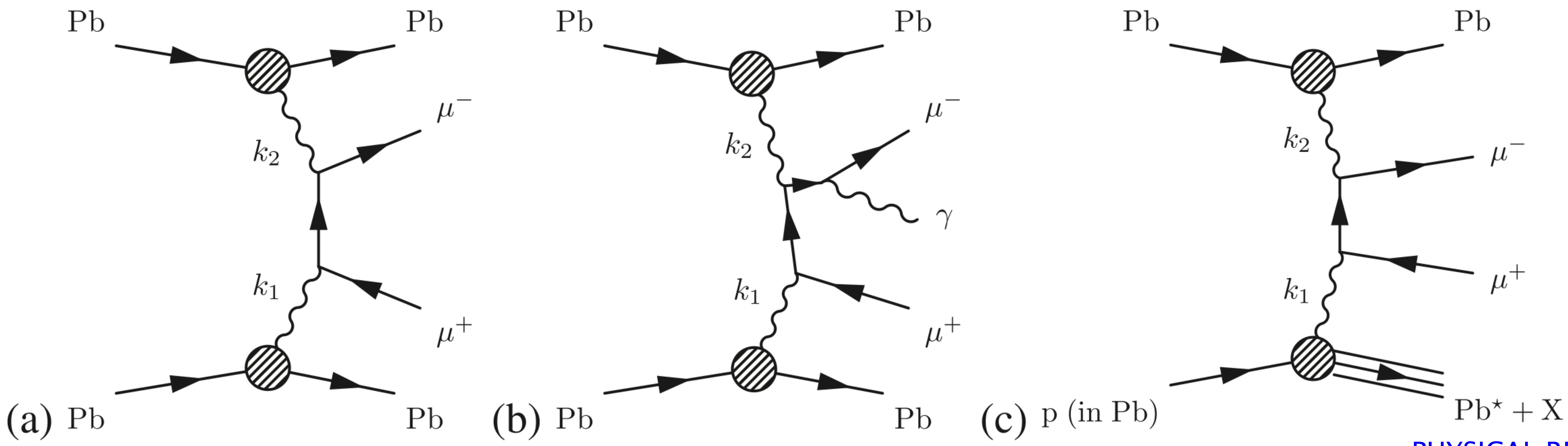


Measurements of Breit-Wheeler processes

Exclusive dimuon pair production in ATLAS

- ATLAS data: Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, $\mathscr{L}_{\text{int}}$ = 480 μb^{-1}
- The two-photon luminosity in UPC enhanced over the nuclear luminosity by Z^4.
- Data selection: $p_{T,\mu}$ > 4 GeV, $|\eta_\mu|$ < 2.4, $m_{\mu\mu}$ > 10 GeV, $p_{T,\mu\mu}$ < 2 GeV, divided in several bins:
  - $m_{\mu\mu} \in$ [10, 20] GeV, [20, 40] GeV, [40, 80] GeV
  - $|y_{\mu\mu}| \in$ [0, 0.8], [0.8, 1.6], [1.6, 2.4]

- 2 contributions is the data:
  - BW process ($\gamma\gamma \rightarrow l^+l^-$) and higher order final state.
  - Dissociative background from $\gamma\gamma \rightarrow l^+l^-$ where one photon comes from Pb (p_T ~ 25 MeV) and other (harder) from a nucleon



a) leading-order PbPb(γγ) → $\mu^+\mu^-$ (PbPb)

b) next-to-leading-order PbPb(γγ) → $\mu^+\mu^-$ +γ(PbPb)

c) the dissociative PbPb(γ γ*) → $\mu^+\mu^-$ + X (Pb*Pb) process

PHYSICAL REVIEW C 104, 024906 (2021)

Exclusive dimuon pair production in ATLAS

- Binned maximum-likelihood fit applied to the dimuon acoplanarity ($\alpha = 1 - |\Delta\phi|/\pi$):

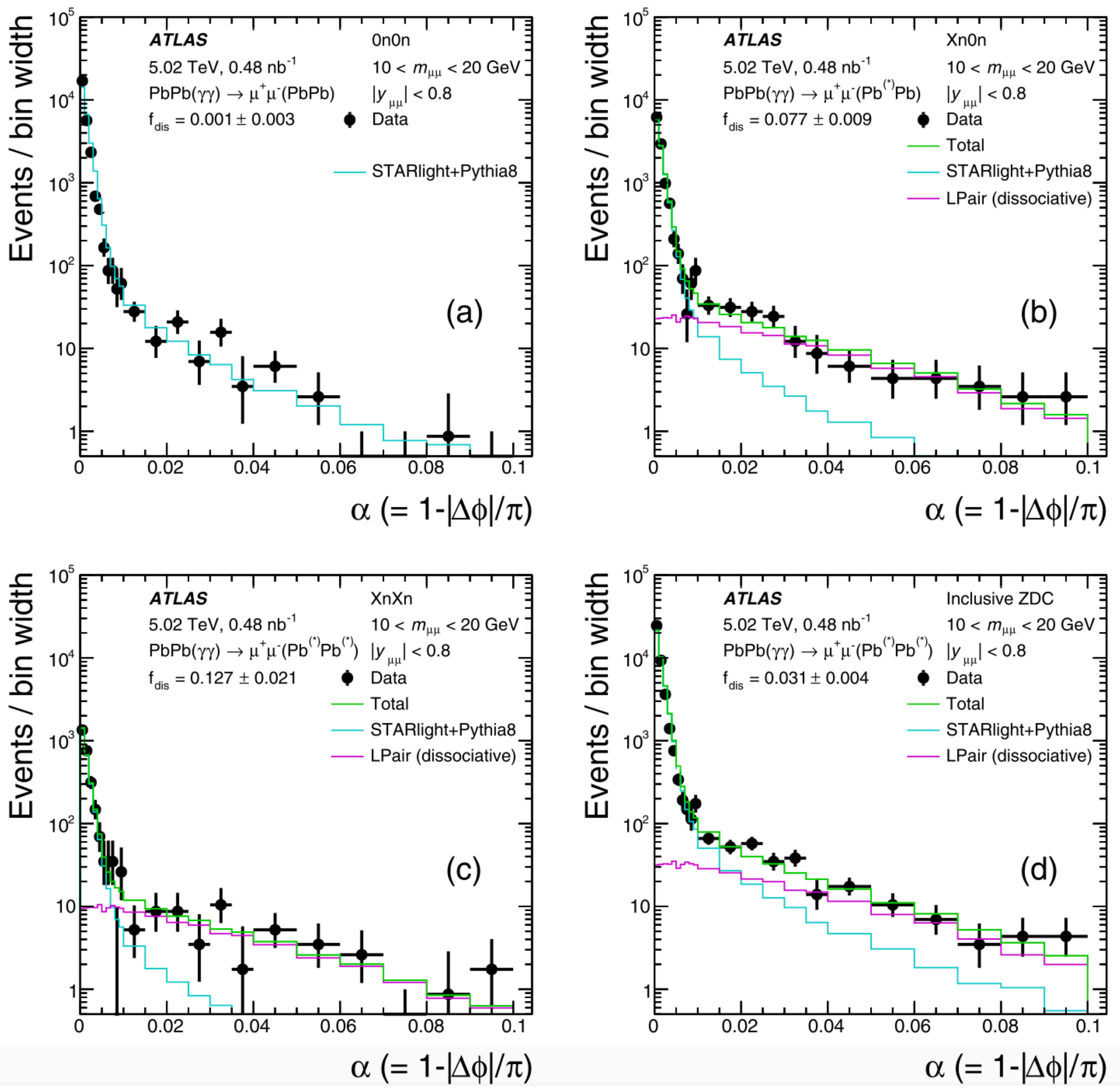
$$P(\alpha, m_{\mu\mu}, y_{\mu\mu}) = (1 - f_{\rm dis})P_{\rm EPA}(\alpha, m_{\mu\mu}, y_{\mu\mu}) + f_{\rm dis}P_{\rm dis}(\alpha, m_{\mu\mu}, y_{\mu\mu})$$

template from STARlight 2.0 + Pythia8

fraction of dissociative events

template from LPair 4.0

- Results:
  - OnOn selection: no significant dissociative background, and the tails in the α distributions derive only from higher-order QED contributions.
  - XnOn and XnXn selections: inclusion of the LPAIR contribution gives a good description in the region beyond $\alpha > 0.02$ → significant dissociative contribution
  - Inclusive selection in forward neutron topology: $f_{\rm dis}$ = 3% for this kinematic selection



PHYSICAL REVIEW C 104, 024906 (2021)

Exclusive dimuon pair production in ATLAS

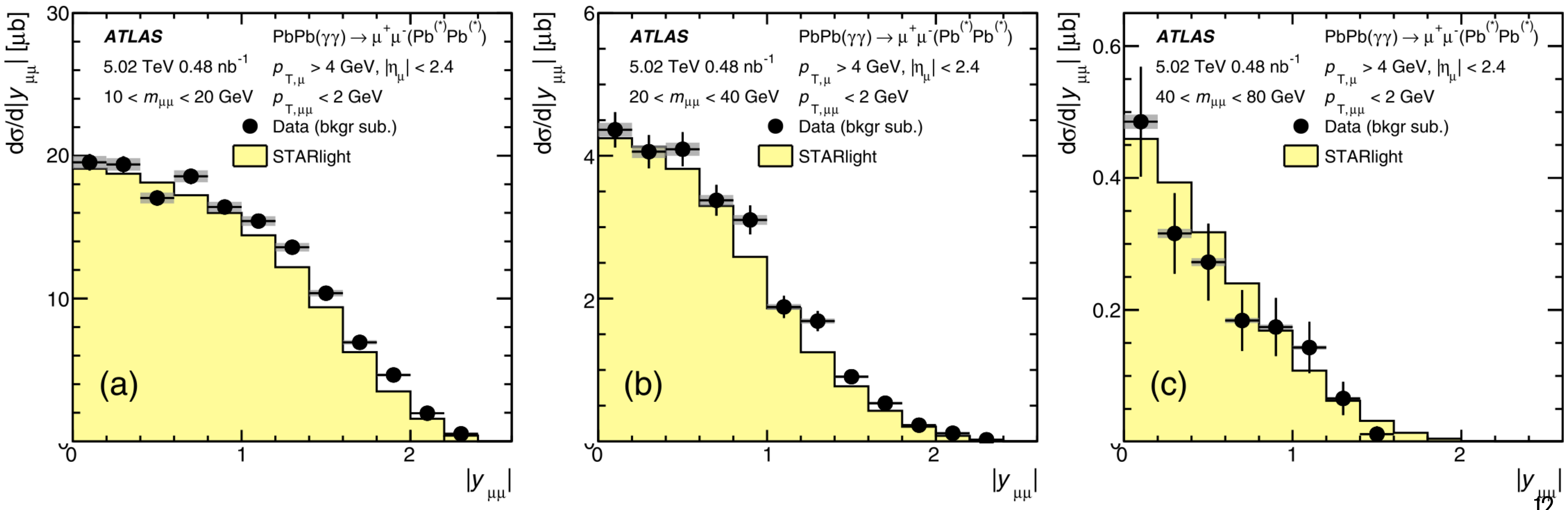
- Differential cross sections measured as functions of: $m_{\mu\mu}$, $y_{\mu\mu}$, $\cos(\theta_{\mu\mu})$, α and $k_{\min,\max}$
- Integration over the full fiducial phase space ($p_{T,\mu}$ > 4GeV, $|\eta_\mu|$ < 2.4, $m_{\mu\mu}$ > 10GeV, $p_{T,\mu\mu}$ < 2GeV):

$$\sigma_{\mu\mu} = 34.1 \pm 0.3(\text{stat}) \pm 0.7(\text{sys})$$

(it is 32.1 μb for STARlight and 30.8 μb for STARlight+PYTHIA8)

- Generally well described by STARlight 2.0

- Important for characterizing the interactions between the 2 photons
- Some increase in data observed at higher $y_{\mu\mu}$.



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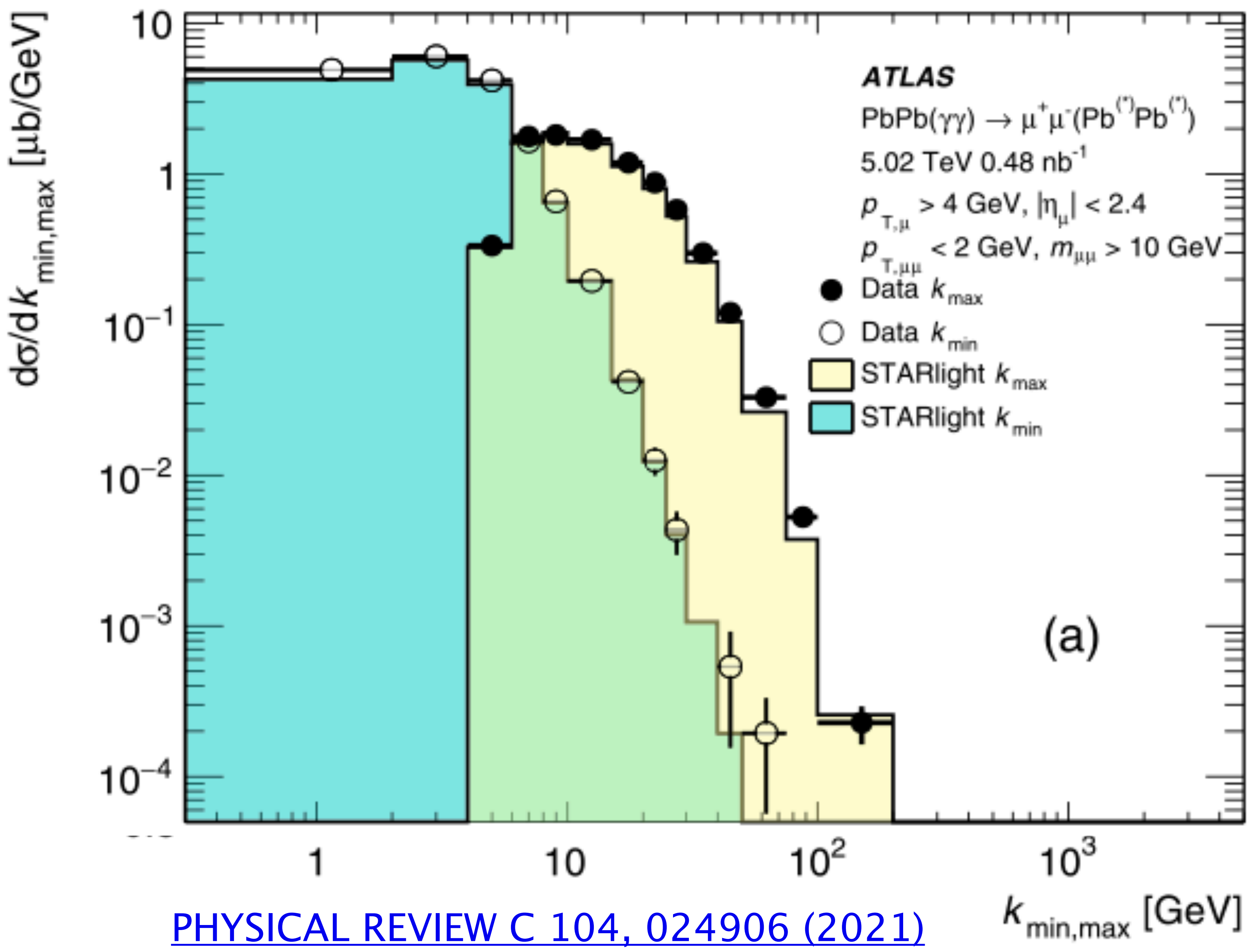
- Initial photon energies estimated for $p_T \sim 0$: $k_{1,2} = (m_{\mu\mu}/2)\exp(\pm y_{\mu\mu})$
- Comparison of STARlight and data:
  - Compatible around 10-20 GeV
  - Disagreement for 75 < $k_{\max}$ < 100 GeV and $k_{\min}$ < 2 GeV
- A systematic modification of the initial energy spectrum needed → decrease the integration limit on the impact parameter by one nuclear skin depth?



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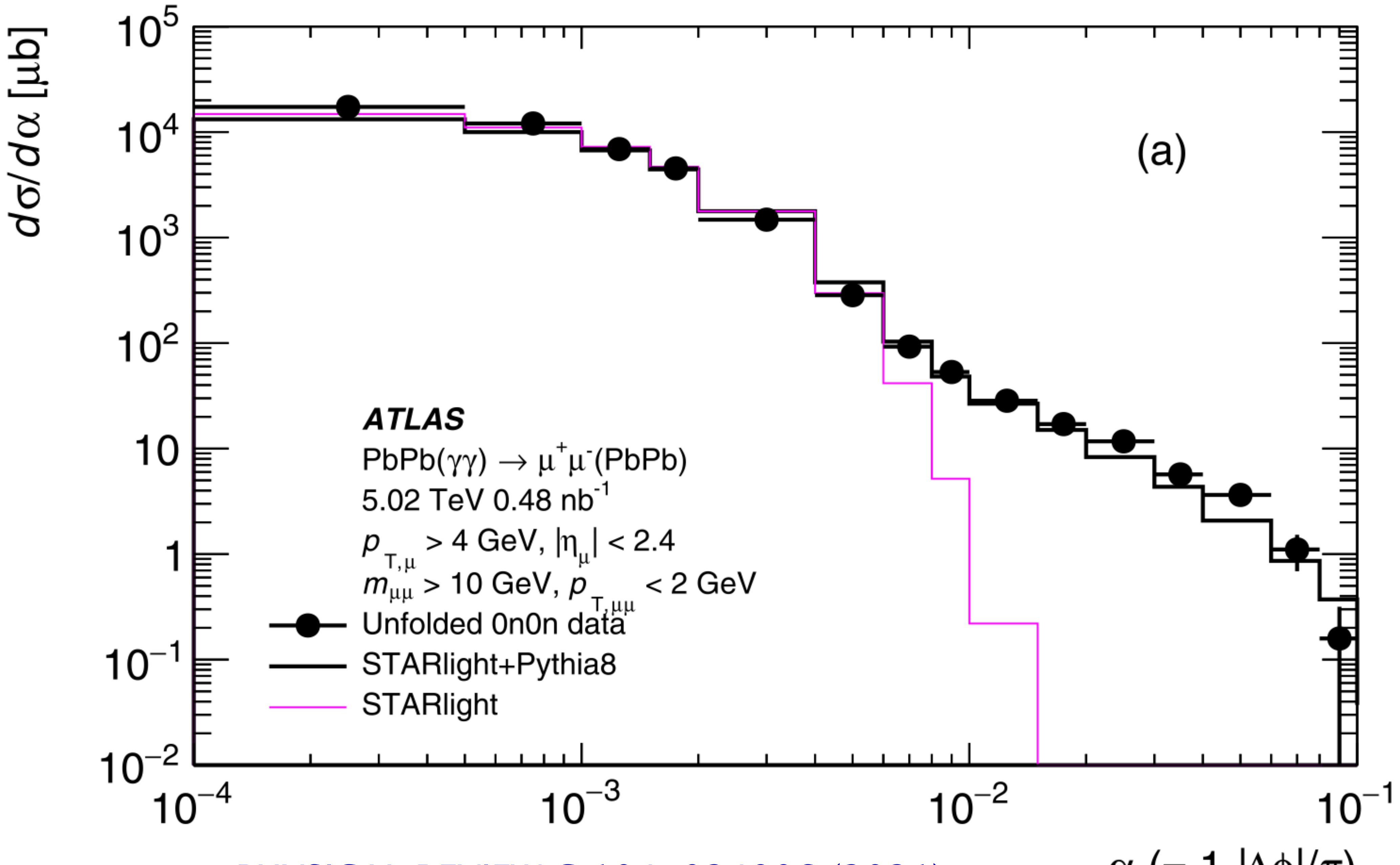
- $0n0n$ topology
- For α > 0.01 (only the QED showering): agrees well with STARlight + Pythia
- For α < 0.01: difference in shape can be explained by a small change in the p_T spectrum in STARlight (the p_T spectrum controls the width of the α distribution)



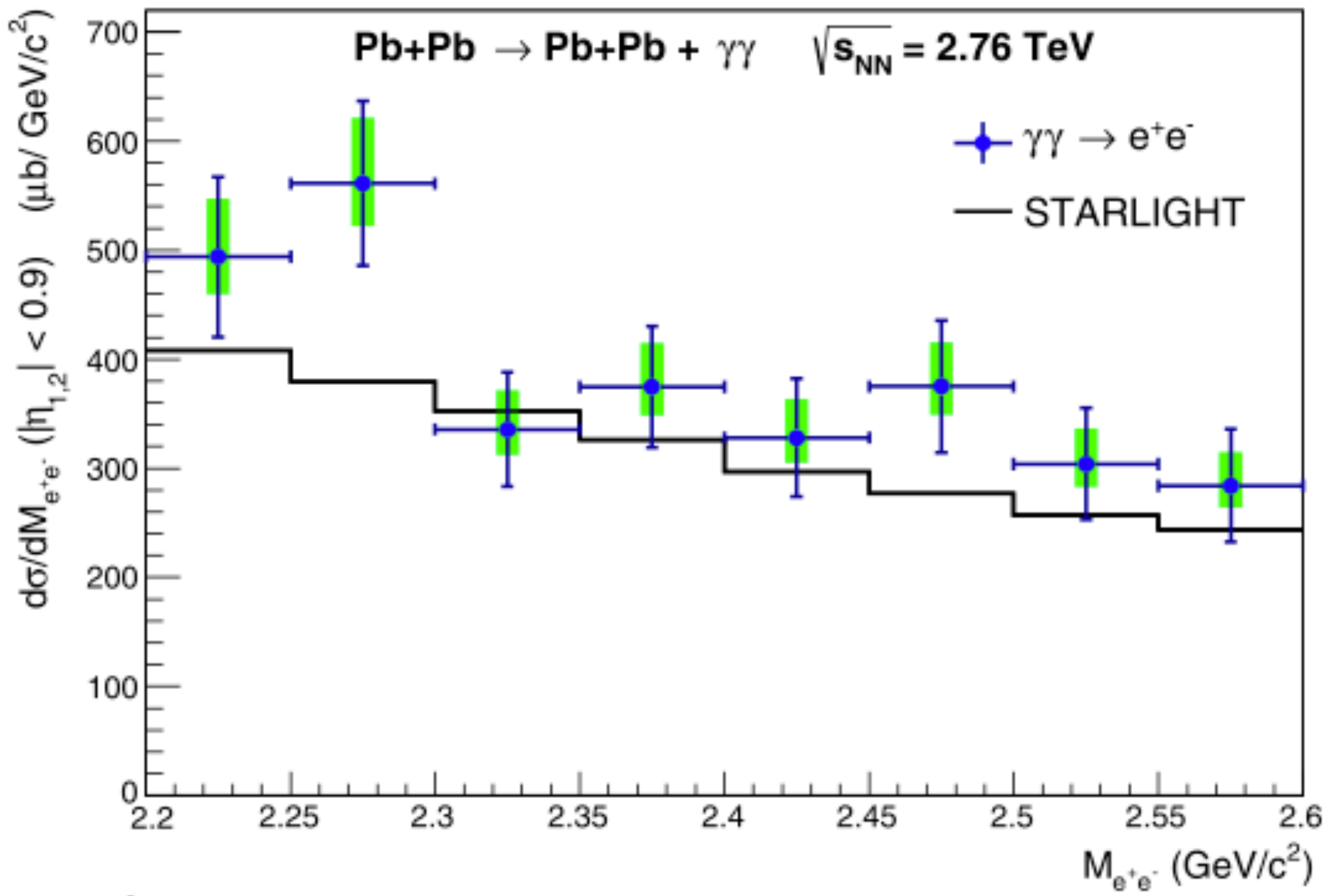
PHYSICAL REVIEW C 104, 024906 (2021)

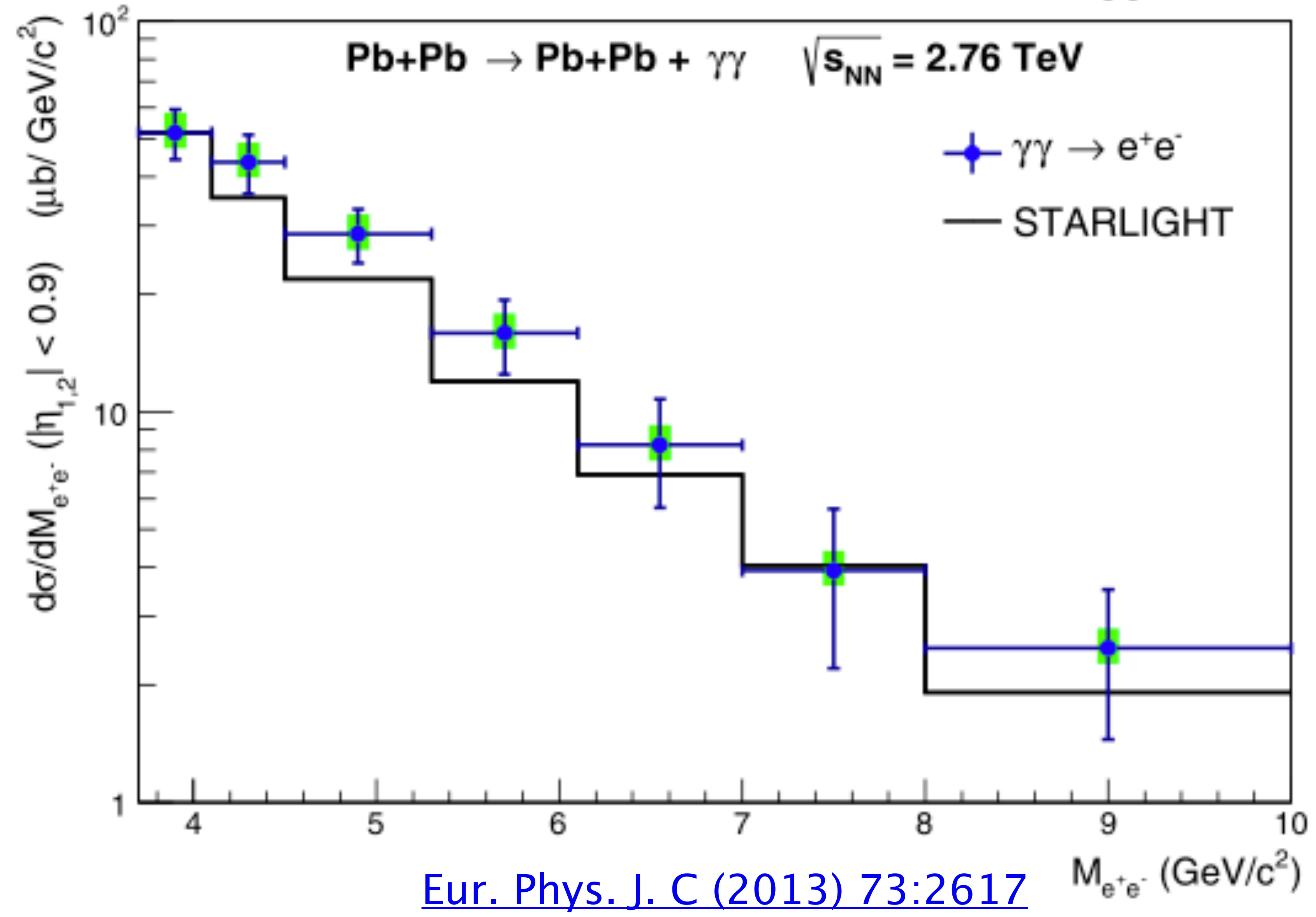
First measurement of $\gamma\gamma \rightarrow e^+e^-$ in Pb–Pb UPCs at $\sqrt{s_{NN}}$ = 2.76 TeV with ALICE

- Continuum fitted in 2.2 < M_{inv} < 2.6 GeV/c² and 3.7 < M_{inv} < 10 GeV/c²
- −0.9 < y < 0.9 and −0.9 < $\eta_{1,2}$ < 0.9
- $\mathscr{L}_{\text{int}} = 21.7^{+0.7}_{-1.1}$ μb⁻¹

Cross section measurements (20 % above STARlight prediction):

- 2.2 < M_{inv} < 2.6 GeV/c²: $\sigma_{\gamma\gamma\rightarrow e^+e^-} = 154 \pm 11$(stat)$^{+17}_{-11}$(syst) μb (STARlight: $\sigma_{\gamma\gamma\rightarrow e^+e^-}$ = 128 μb, compatible within 1.0 σ)
- 3.7 < M_{inv} < 10 GeV/c²: $\sigma_{\gamma\gamma\rightarrow e^+e^-} = 91 \pm 10$(stat)$^{+11}_{-8}$(syst) μb (STARlight: $\sigma_{\gamma\gamma\rightarrow e^+e^-}$ = 77 μb, compatible within 1.5 σ)





Eur. Phys. J. C (2013) 73:2617

- A reduction in $\sigma_{\gamma\gamma}$ of up to 30 % compared with LO calculations were predicted (A.J. Baltz, Phys. Rev. C 80, 034901, A.J. Baltz, Phys. Rev. Lett. 100, 062302)
- Implies that **calculations predicting a strong contribution of higher-order terms** (not included in STARlight) to the cross section are **not favored**.

Other measurements of two-photon interactions at the LHC

- Measurement of non-exclusive dimuon pairs produced via γγ scattering in Pb+Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV with the ATLAS detector (ATLAS-CONF-2019-051)
- Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector (arXiv:2008.05355 [hep-ex])
- Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (CMS Collaboration) (Physics Letter B 797 (2019) 134826)
- Measurement of exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ production in proton–proton collisions at $\sqrt{s_{NN}}$ = 7 TeV with the ATLAS detector (Physics Letter B 749 (2015) 242-261)
- Measurement of the exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ process in proton–proton collisions at $\sqrt{s_{NN}}$ = 13 TeV with the ATLAS detector (Physics Letter B 777 (2018) 303-323)
- Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production in proton-proton collisions at $\sqrt{s_{NN}}$ = 7 TeV in p-p collisions (CMS Collaboration) (J. High Energ. Phys. 2012, 52 (2012))
- Evidence for exclusive $\gamma\gamma \rightarrow W^+W^-$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s_{NN}}$= 7 and 8 TeV (CMS Collaboration) (J. High Energ. Phys. 2016, 119 (2016))

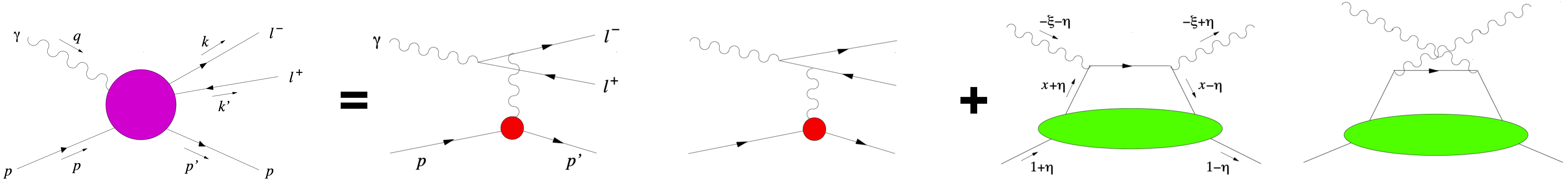
Conclusion

- ATLAS: measurement of the exclusive dimuon pair production in Pb-Pb UPCs
  - in good agreement with STARlight 2.0 + PYTHIA8 (with QED showering)
  - some systematic differences may be explained by deficiencies in the modeling of the incoming photon flux
- ALICE: measurement of the two-photon cross section for di-electron production in Pb-Pb UPCs
  - consistent with the STARLIGHT model
  - models predicting a strong contribution of higher-order terms to the cross section are not favored.
- Many other results from UPC and non-UPC two-photon collisions from RHIC and LHC.
- Ongoing analysis on $\gamma\gamma \rightarrow \mu^+\mu^-$ in ALICE in p-Pb UPCs at low invariant mass (1.0 GeV/c^2 < $M_{\mu\mu}$ < 2.5 GeV/c^2, where J/Ψs are absent)
- Feasibility of time-like-Compton scattering could be investigated as well

THANK YOU FOR YOUR ATTENTION!

Back-up

Feasibility of timelike Compton scattering (TCS) at the LHC



The physical process where to observe TCS is photoproduction of a heavy lepton pair, $\gamma N \to l^+ l^- N$

Bethe-Heitler mechanism subprocess $\gamma(q)\gamma(\Delta) \to l^+ l^-)$

(contributes to amplitude level)

- Amplitude is completely calculable in QED provided one knows the Nucleon form factors at small t

$$\frac{d\sigma_{BH}}{dQ'^2\, dt\, d(\cos\theta)\, d\phi} \propto \frac{1+\cos^2\theta}{\sin^2\theta}$$

→ imposes a cut on θ

Compton process to leading order in α_s

- In the region where the final photon virtuality is large, the amplitude is given by the convolution of hard scattering coefficients, calculable in perturbation theory, and generalized parton distributions, which describe the nonperturbative physics of the process
  - The crucial ingredient to estimate the TCS amplitude at large energies is a realistic model of GPDs at small skewedness