Ultra-peripheral collisions: shining light in hadronic colliders

Jani Penttala
University of California, Los Angeles
SURGE collaboration
February 21 2025
TH Heavy Ion Coffee, CERN

Ultra-peripheral collisions (UPCs)

Nuclear collisions can be divided in to different centralities

- Correspond to the amount of overlap between the nuclei

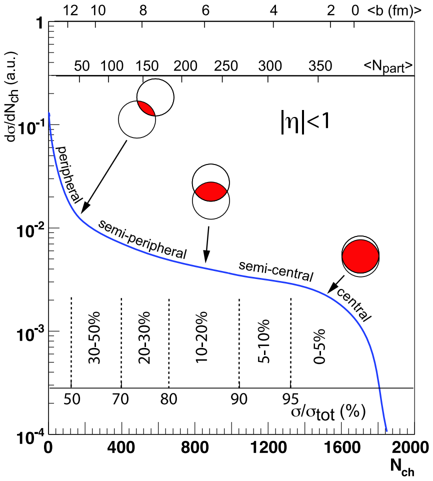
Ultra-peripheral: **No overlap** between the colliding nuclei

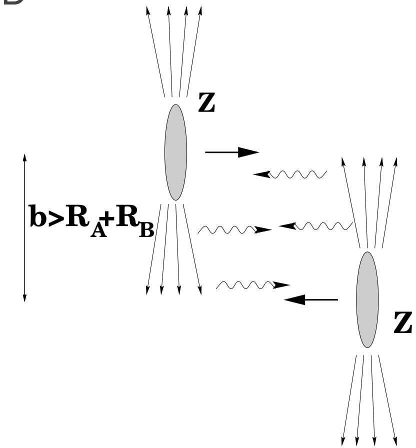
- Nucleons color neutral: No interaction through QCD
- Protons are charged objects:

  Can emit photons even when far away!

- Photon virtuality $Q^2 \sim 1/b^2 \approx 0$

  $\Longrightarrow$ "Quasi-real"





Why UPCs?

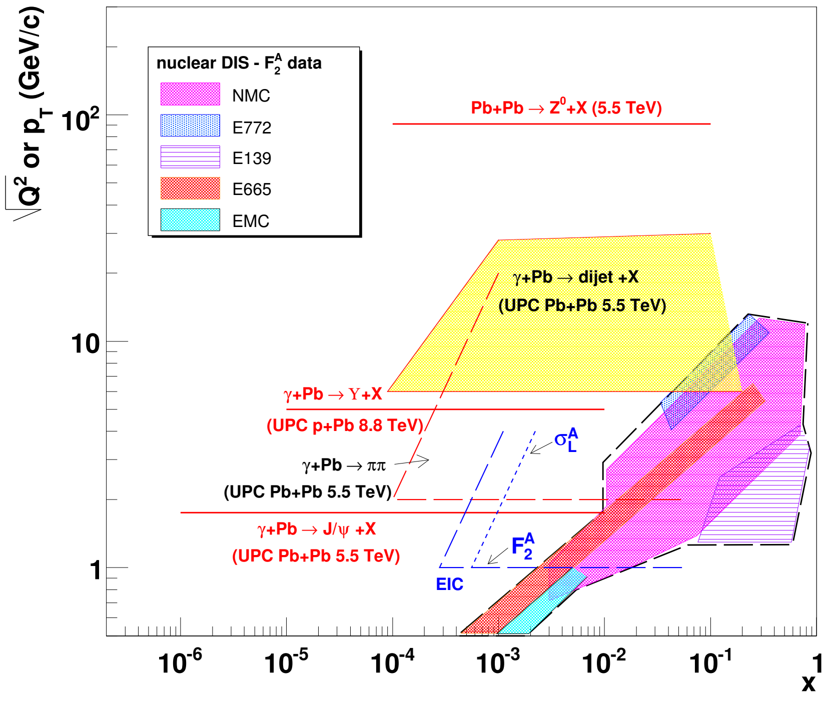
- UPCs allow us to probe photon-initiated processes

Complementary range in (Q^2, x)-plane to electron–ion colliders

- Can access higher energy $\Longleftrightarrow$ smaller x
- $Q^2 \approx 0 \implies$ Momentum scale completely determined by the process

UPCs in heavy-ion collisions:

Access to nuclear targets before EIC



Baltz et al [0706.3356]

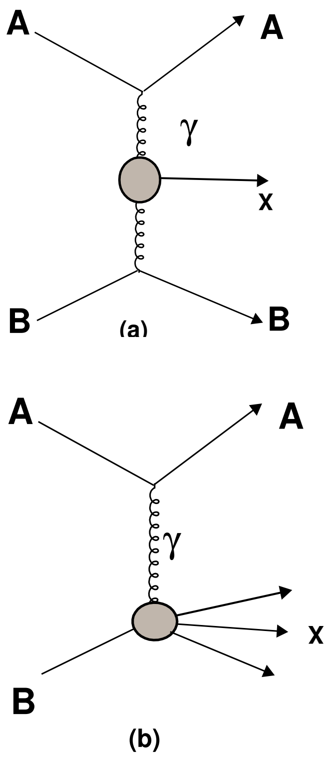
Factorization in UPCs

Due to the large impact parameter, we can factorize the photon emission from the rest of the process:

$$\sigma_{AA}^{2\text{ photons}} = \int d\omega_1 d\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma_{\gamma\gamma}(\omega_1, \omega_2)$$

$$\sigma_{AA}^{1\text{ photon}} = \int d\omega\, n(\omega)\, \sigma_{\gamma A}(\omega)$$

- $n(\omega)$ = photon flux for energy ω



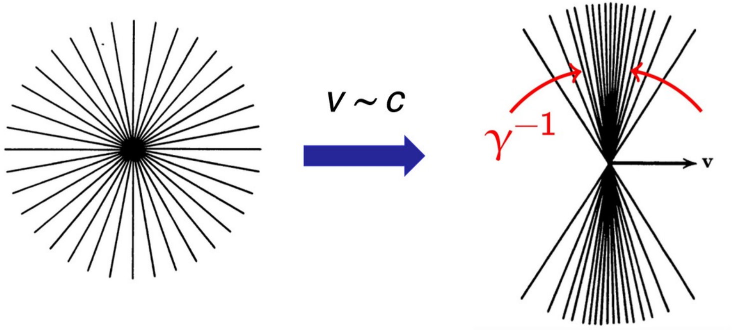
Equivalent photon approximation

Charged nucleus moving with a high energy:

Creates a strong electromagnetic field with transverse polarization

$\Longrightarrow$ Cannot be distinguished from real photons!

Bertulani, UPC2023



Photon flux for a given impact parameter b:

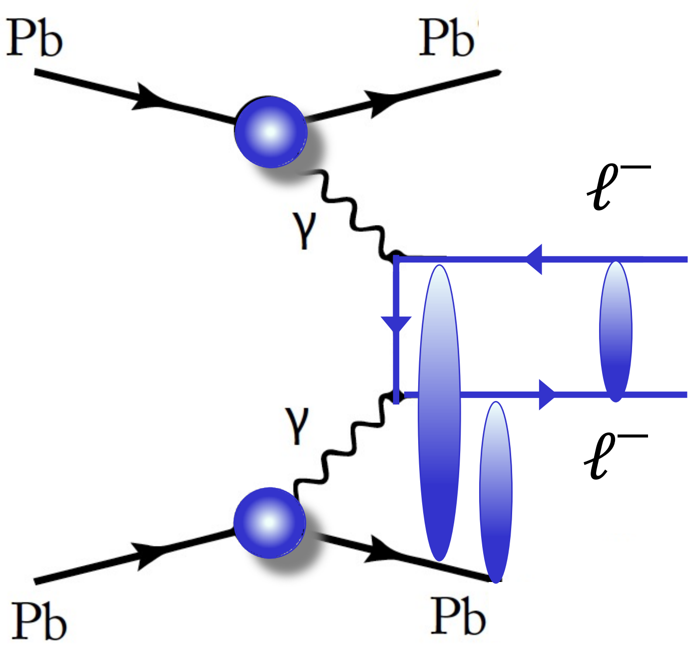
$$n(\omega, b) = \frac{4Z^2\alpha}{\omega} \left| \int \frac{d^2k_T}{(2\pi)^2} \frac{F(k_T^2 + \omega^2/\gamma^2)}{k_T^2 + \omega^2/\gamma^2} e^{-i\vec{b}\cdot\vec{k}_T} \vec{k}_T \right|^2$$

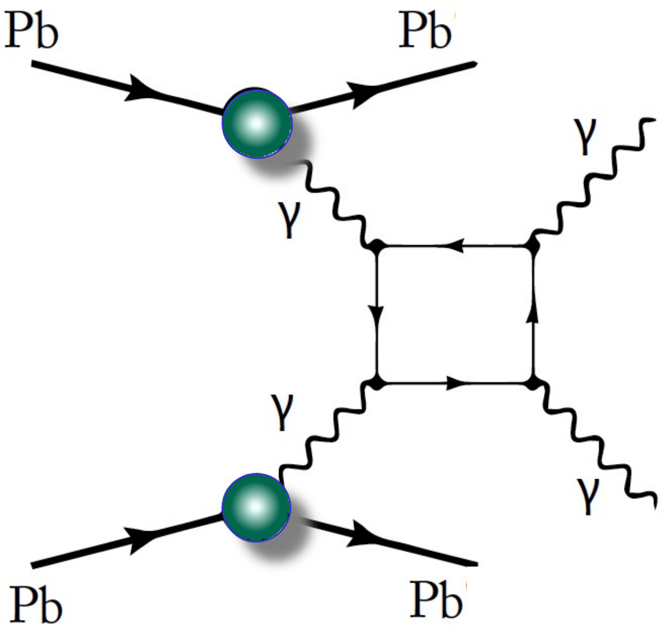
where F is the form factor of the nucleus

- Reduces to Weizsäcker–Williams flux for a point charge

Vidović et al, Phys. Rev. C 47, 2308 (1993)

$\gamma\gamma$ processes





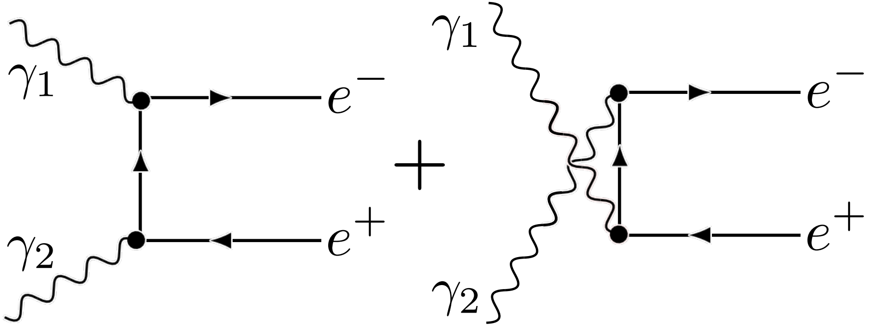
Dilepton production in $\gamma\gamma$

Breit–Wheeler process: $\gamma\gamma \to e^- e^+$

- Forbidden in classical electromagnetism
- “Non-linear” effect of QED
- Proposed in 1934, yet experimentally elusive!
- “First” observed in UPCs at STAR

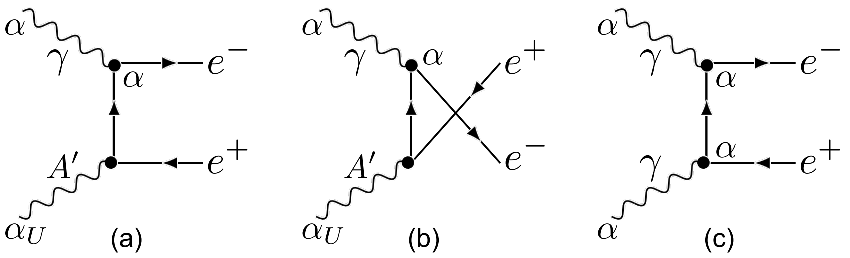
STAR collaboration [1910.12400]

Breit, Wheeler, Phys.Rev. 46 (1934) 12, 1087-1091



Dark photons in the Breit–Wheeler process

Additional contribution from dark photons A'

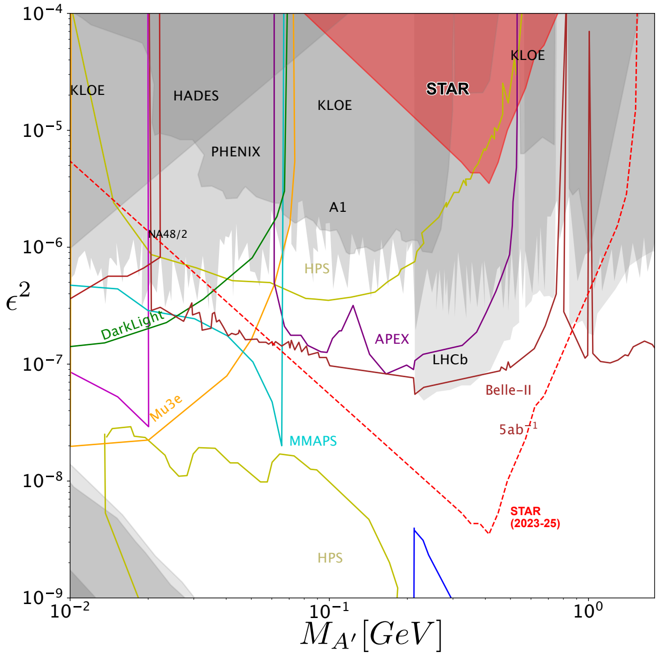


$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\text{dark}}^{\mu\nu}$$

Effective dark photon coupling: $\alpha_U = \epsilon^2 \alpha_{\text{em}}$

Bounds for the mixing strength ϵ and dark

photon mass $M_{A'}$ from UPCs

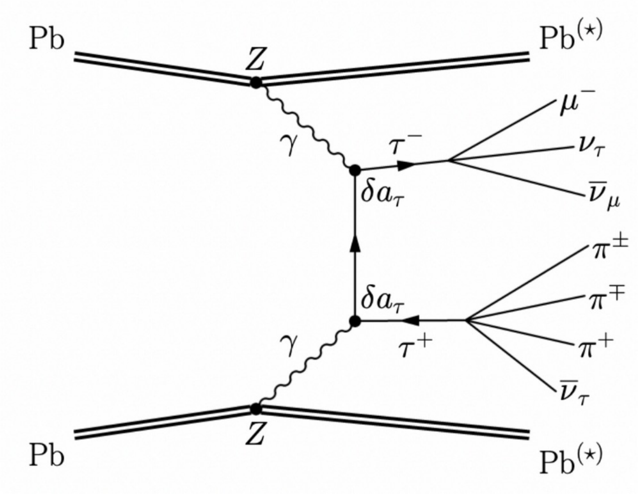


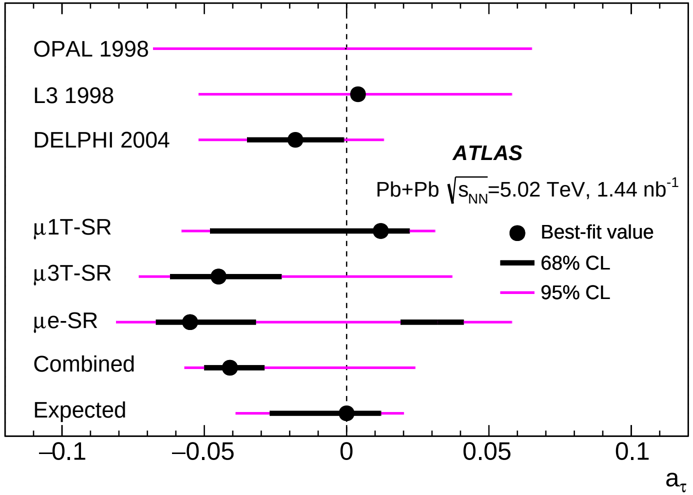
Xu et al [2211.02132]

Dilepton production in $\gamma\gamma$

Di-tau production: $\gamma\gamma \to \tau^+\tau^-$

- Access to the anomalous magnetic moment $a_\tau = (g_\tau - 2)/2$
- First results competitive with other measurements — expected to improve with Run-3 data





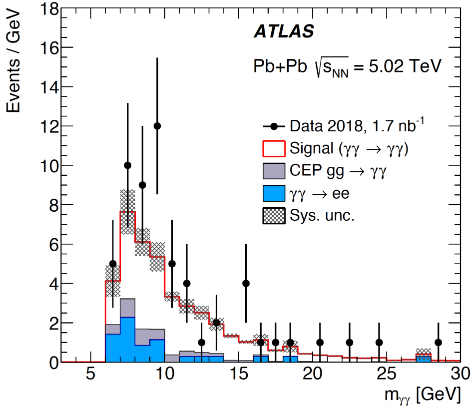
ATLAS collaboration [2204.13478]

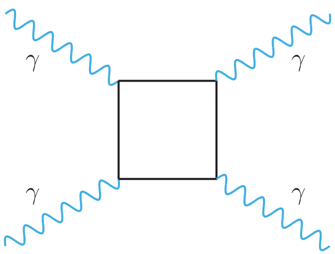
Light-by-light scattering $(\gamma\gamma \to \gamma\gamma)$

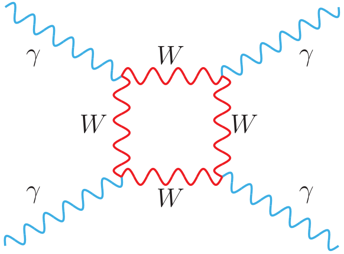
QED in extreme conditions

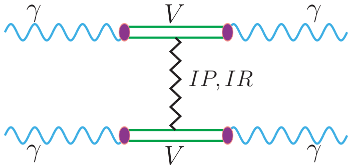
- Violation of the superposition principle in classical electromagnetism
- Can be used to test the standard model and search for BSM physics

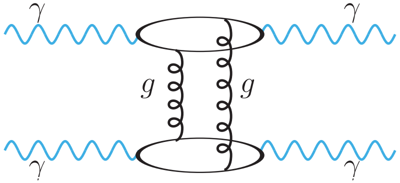
ATLAS collaboration, 1702.01625











Kłusek-Gawenda, Lebiedowicz, and Szczurek [1601.07001]

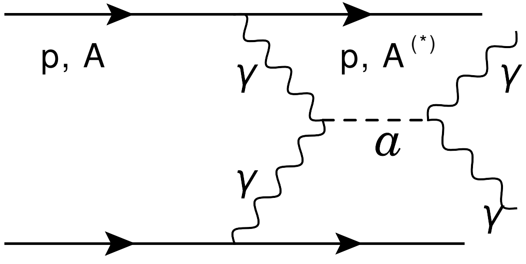
Search for axion-like particles in light-by-light scattering

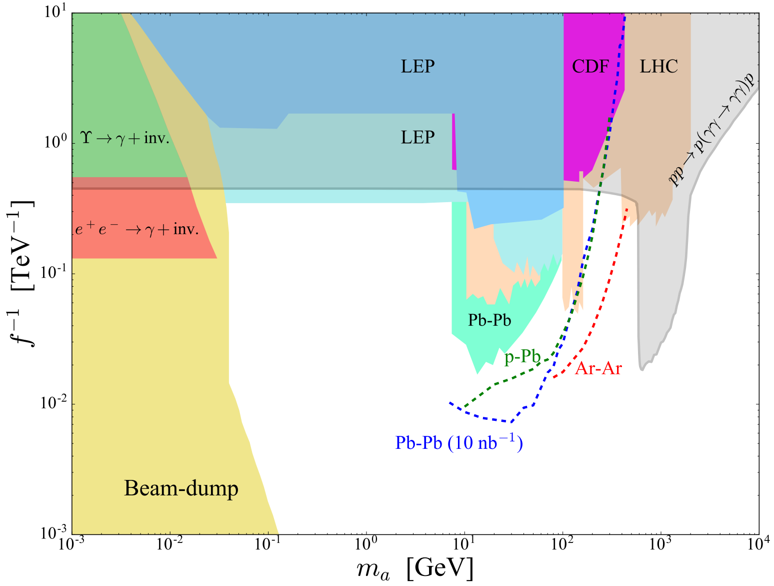
Axion-like particles:

would lead to an increase of the cross section

through an additional Feynman diagram

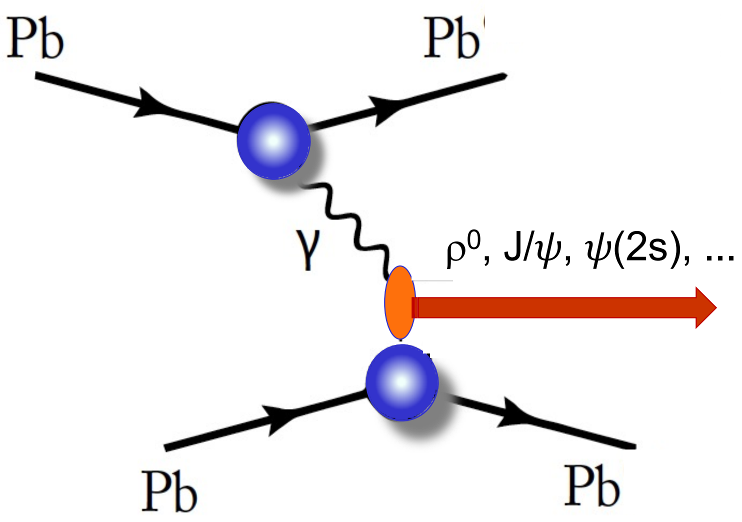
$$\mathcal{L}_{\text{int}} = \frac{1}{f} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

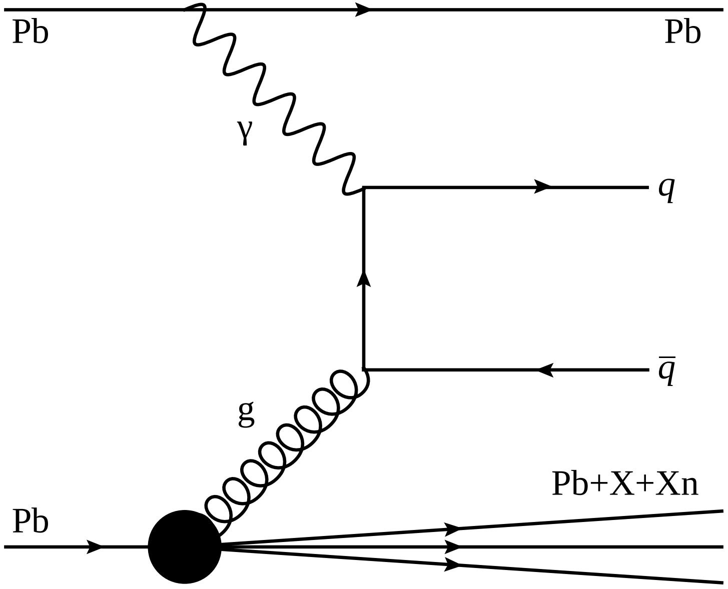




Baldenegro et al [1903.04151]

γp and γA processes



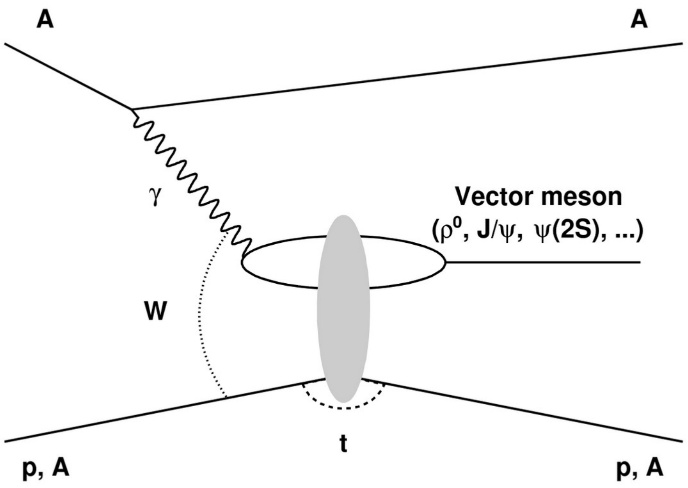


Exclusive vector meson production

- Vector mesons: same quantum as photon $J^{PC}=1^{--}$
- No quantum numbers exchanged with the target:

  a "pomeron"
- Real photon $Q^2=0$:
  - Perturbative scale given by the meson mass M_V
  - In practice:

    Perturbative only for heavy mesons



UCLA

Sensitivity to gluon distribution

- Leading order: couples to gluons in the target
- Depends on the gluon density **squared**

$$\frac{d\sigma^{\gamma+A\to V+A}}{dt} \propto [xg(x,\mu = M_V)]^2$$

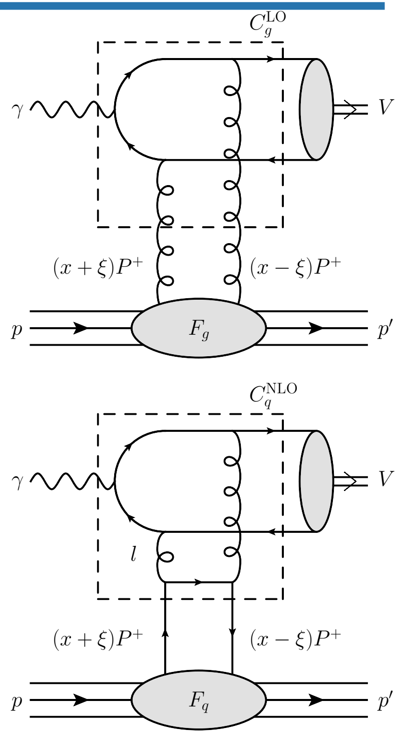
Ryskin, Z.Phys.C 57 (1993) 89-92

Exclusive process: access **generalized** parton distributions

$$g(x,\mu) \to F^g(x,\xi,t,\mu)$$

- Often modeled with PDFs using the **Shuvaev transform**

Shuvaev et al [hep-ph/9902410]



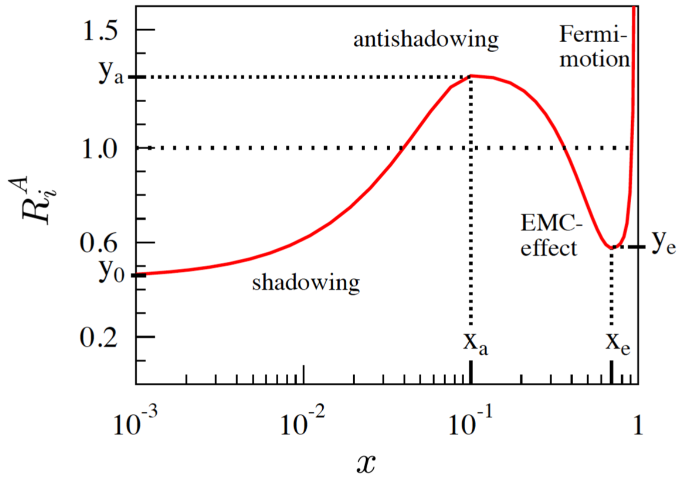
Jones et al [1610.02272]

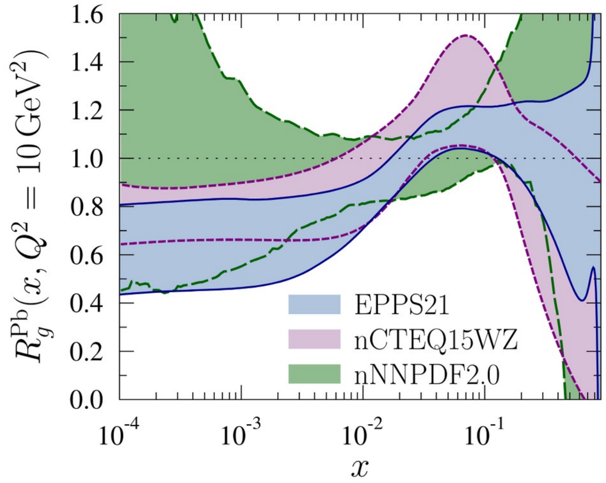
Nuclear shadowing

Modification of PDFs in nuclei: $$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) \times f_i^p(x, Q^2)$$

Small x $(x < 0.01)$: **shadowing region**

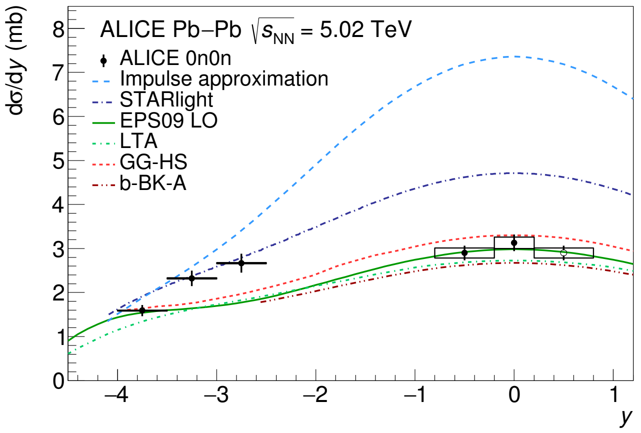
- Suppression of the cross section from multiple scatterings



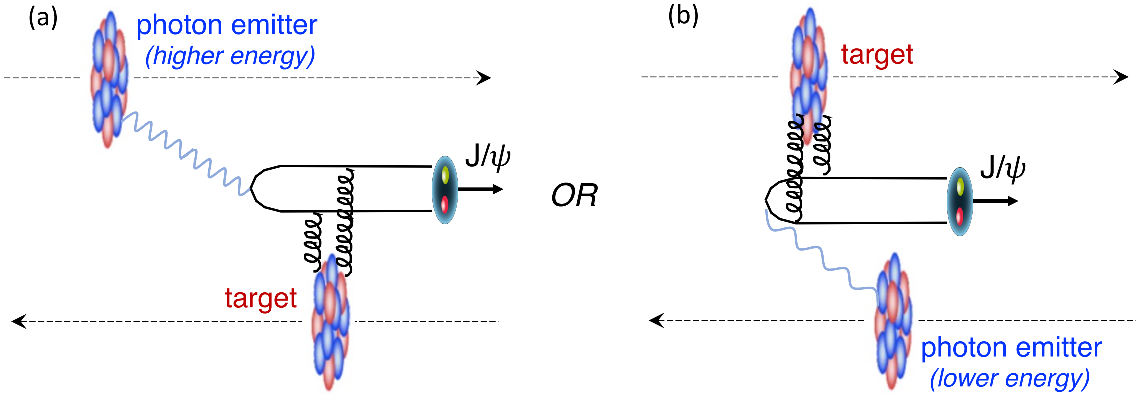


EPPS21 [2112.12462]

Two-way ambiguity



ALICE collaboration [2305.19060]



CMS collaboration [2303.16984]

$$\frac{d\sigma_{J/\psi}}{dy} = n_{\gamma A}(\omega_1)\sigma_{J/\psi}(\omega_1) + n_{\gamma A}(\omega_2)\sigma_{J/\psi}(\omega_2)$$

- ω_i = photon energy from nucleus i
- $n_{\gamma A}$ = photon flux

One cross section, two unknowns

$\Longrightarrow$ cannot distinguish the emitter from the target

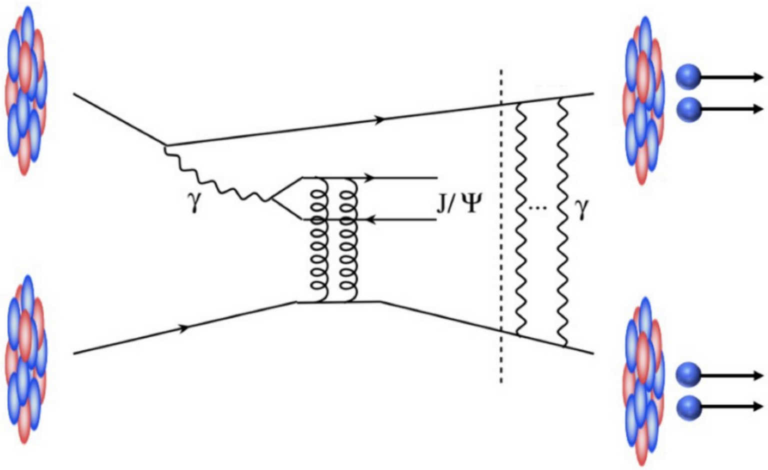
Determining the direction with neutrons

Solution: event tagging using forward neutrons

- Electromagnetic dissociation of a nucleus from independent photon exchanges

System of three equations:

- **0n0n**: no neutrons on either side
- **0nXn + Xn0n**: neutrons on one side only
- **XnXn**: forward neutrons on both sides



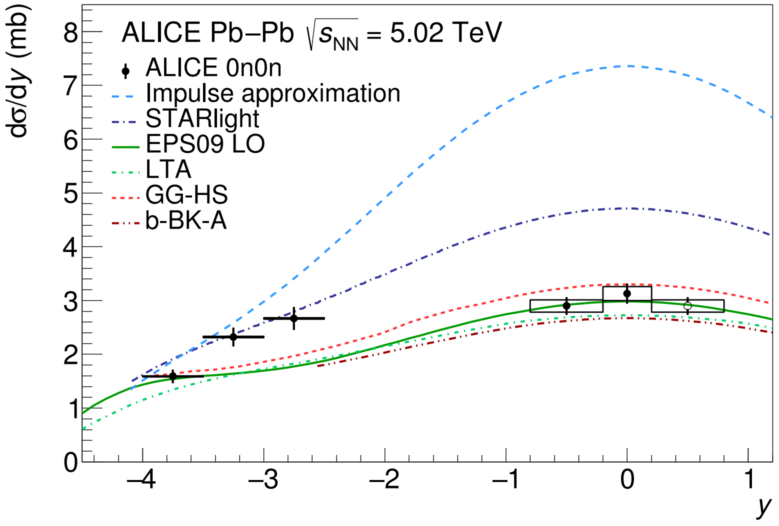
$$\frac{d\sigma_{J/\psi}^{injn}}{dy} = n_{\gamma A}^{injn}(\omega_1)\sigma_{J/\psi}(\omega_1) + n_{\gamma A}^{injn}(\omega_2)\sigma_{J/\psi}(\omega_2)$$

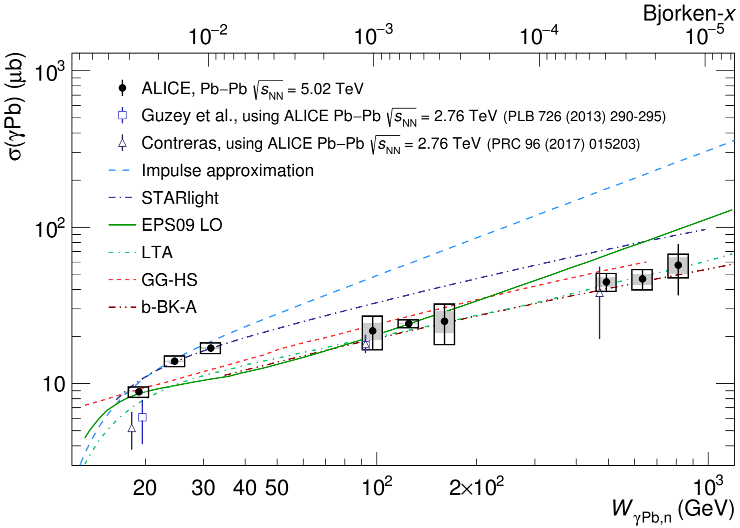
- $n_{\gamma A}^{injn}$ = photon flux with i,j neutrons in the forward and back direction

Energy dependence

Solving the two-way ambiguity: Rapidity spectrum $\Longrightarrow$ Energy dependence

- A clearer physical picture of the process





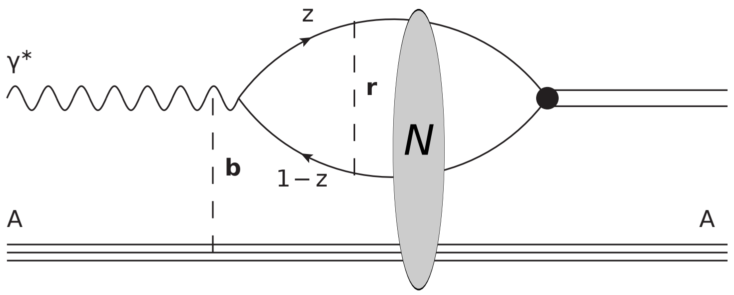
ALICE collaboration [2305.19060]

Small *x*: Dipole picture

High energy:

Interaction with the target is an

instantaneous **shock wave**



Factorization of the process into three parts:

1) Photon fluctuates into a quark–antiquark dipole $\Longrightarrow$ Photon wave function (perturbative)

2) Dipole interacts with the target $\Longrightarrow$ "Dipole amplitude" N (non-perturbative)

3) Formation of the vector meson $\Longrightarrow$ Meson wave function (non-perturbative)

Color-glass condensate (CGC)

Description of the target as a **dense gluonic object**

- Dense $\Longrightarrow$ Neglect quantum effects
- Can think in terms of **classical color fields**
- McLerran–Venugopalan model:

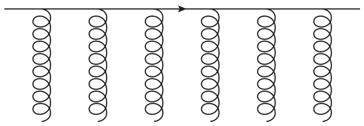
  Color fluctuations with a Gaussian weight

$$\langle \mathcal{O} \rangle_{\rm CGC} = \int \mathcal{D}\rho \, \mathcal{W}[\rho] \, \mathcal{O}$$

$$\mathcal{W}[\rho] = \exp\left(- \int d^2 x_\perp dx^+ \frac{\mathrm{tr}\rho^2}{\mu^2} \right)$$

McLerran, Venugopalan [hep-ph/9309289]

Interaction with the target: resum **eikonal scatterings** to all orders $\Longrightarrow$ a Wilson line!



$$= \mathcal{P} \exp\left(-ig_s \int dx^+ A^-(x_\perp, x^+) \right) = V(x_\perp)$$

Dipole amplitude: most common combination of Wilson lines that appears in physical quantities

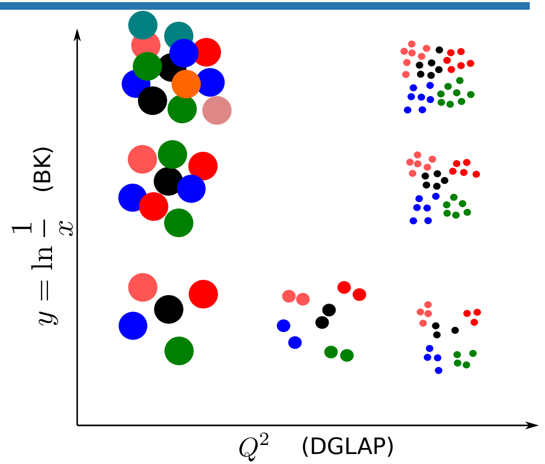
$$N(x_\perp, y_\perp) = 1 - \frac{1}{N_c} \langle V(x_\perp) V^\dagger(y_\perp) \rangle_{\rm CGC}$$

Energy evolution at small x

Perturbative **energy** evolution for the dipole amplitude:

Balitsky–Kovchegov equation

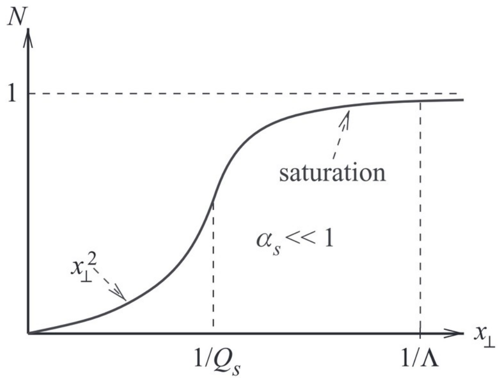
$$\frac{d}{dY}N(x_{q\perp}, x_{\bar{q}\perp}) = \alpha_s \int d^2x_{g\perp} K(x_{q\perp}, x_{\bar{q}\perp}, x_{g\perp})[N(x_{q\perp}, x_{g\perp}) + N(x_{g\perp}, x_{\bar{q}\perp}) - N(x_{q\perp}, x_{\bar{q}\perp}) - N(x_{q\perp}, x_{g\perp})N(x_{g\perp}, x_{\bar{q}\perp})]$$



- Y = rapidity (~ energy)
- Non-linear evolution:

  Leads to **gluon saturation**

  $\Longrightarrow$ Slows down the evolution of the dipole amplitude
- Without non-linear term: BFKL evolution

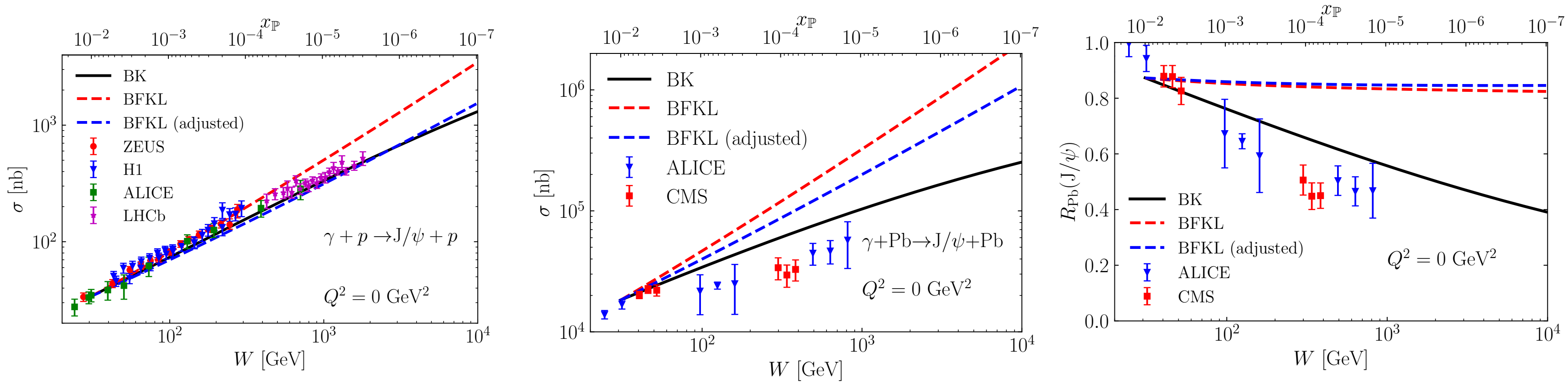


Probe for saturation

Compare **linear** (BFKL) and **non-linear** (BK) evolution: Test for saturation effects!

- Protons: BFKL and BK close $\Longrightarrow$ No sign of saturation (linear behavior in logarithmic plot)
- Lead: Energy dependence very different $\Longrightarrow$ Saturation?
- Especially clear difference in the nuclear modifcation ratio R_{Pb}

JP, Royon [2411.14815]



Coherent and incoherent production

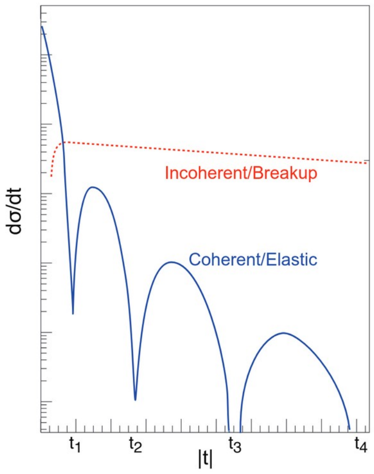
We can further divide diffractive processes into two categories:

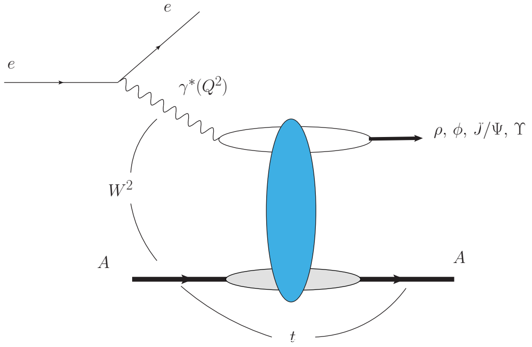
1) Coherent production

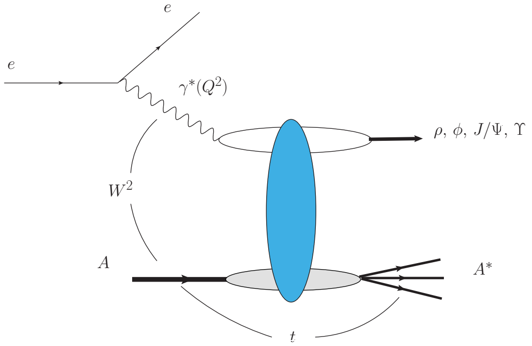
Target stays intact

2) Incoherent production

Target dissociates







Very different dependence on the momentum transfer t!

Krelina, Goncalves, Cepila [1905.06759]

Good–Walker picture

Good, Walker, Phys.Rev. 120 (1960) 1857-1860

How can we describe coherent and incoherent production from the theory?

Approach by Good and Walker: think in terms of quantum states

$$\sigma_{\mathrm{tot}} \propto \sum_X \langle A|\mathcal{O}|X\rangle\langle X|\mathcal{O}|A\rangle = \langle \mathcal{O}^2\rangle_{\mathrm{CGC}}$$

$$\sigma_{\mathrm{coh}} \propto \langle A|\mathcal{O}|A\rangle^2 = \langle \mathcal{O}\rangle^2_{\mathrm{CGC}}$$

$$\sigma_{\mathrm{incoh}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{coh}} \propto \langle \mathcal{O}^2\rangle_{\mathrm{CGC}} - \langle \mathcal{O}\rangle^2_{\mathrm{CGC}}$$

In terms of color-glass condensate:

1) Coherent: probe the “**average**” color-field configuration target

2) Incoherent: probe “**variance**” of the color fields

Nuclear geometry in the transverse plane

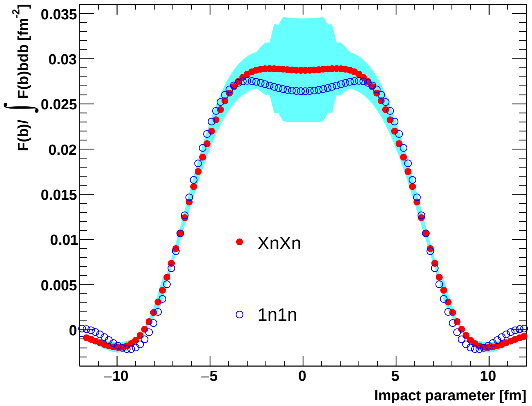
Diffractive process:

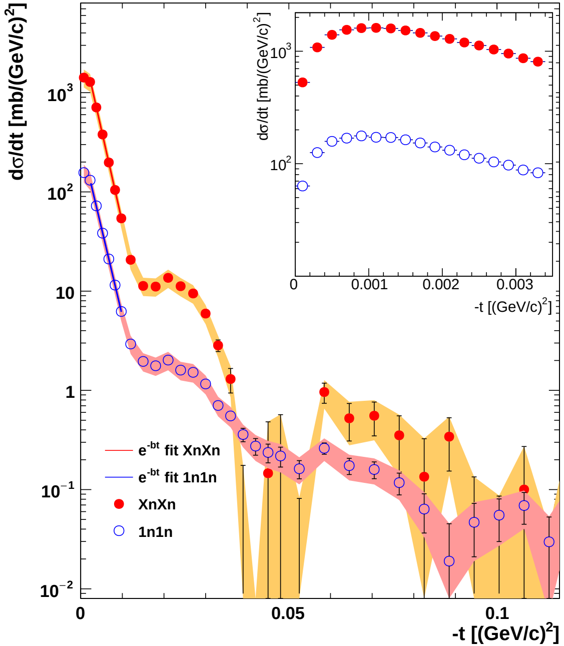
t-spectrum provides information about transverse structure of the target

~ distribution of nucleons inside the heavy nucleus

$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

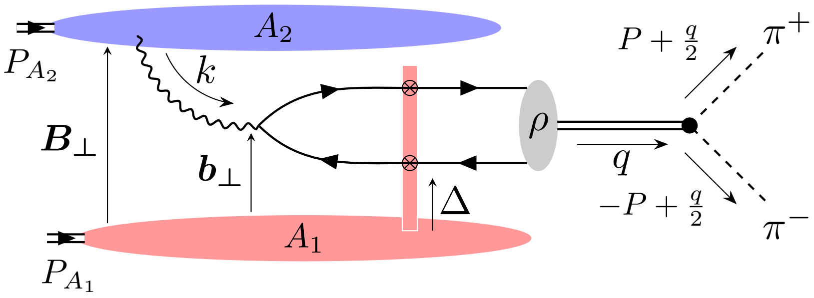
Shape similar to Woods–Saxon

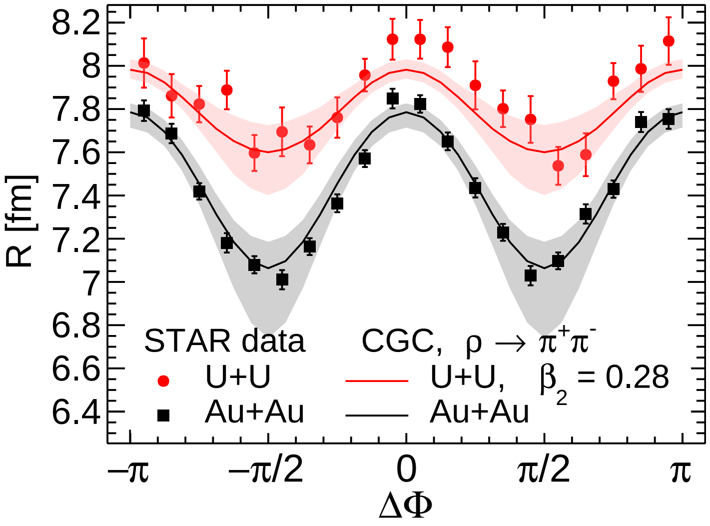




STAR collaboration [1702.07705]

Quantum interference in the decay products





Two-way ambiguity ⟹ Quantum interference effects

- $\Delta\Phi$ = angle between P and q
- Information about the target **deformations**

Mäntysaari et al [2310.15300]

Woods–Saxon with an angle-dependent radius:

$$\rho(r,\theta) = \frac{\rho_0}{1+\exp[(r-R'(\theta))/a_{\rm WS}]}$$

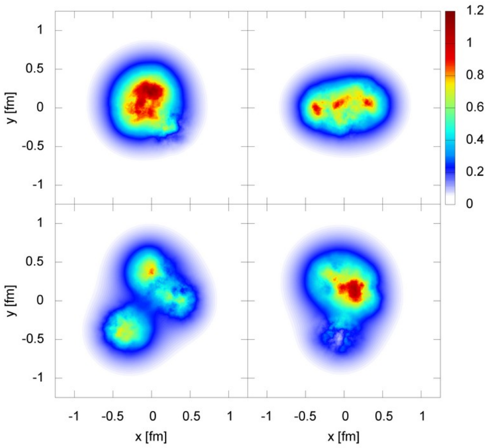
$$R'(\theta) = R_{\rm WS}[1+\beta_2 Y_2^0(\theta)+\beta_3 Y_3^0(\theta)+\beta_4 Y_4^0(\theta)]$$

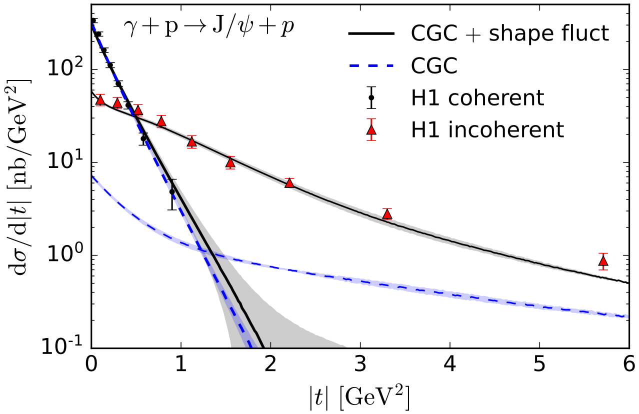
Target fluctuations

- Target geometry fluctuations event-by-event: Important for incoherent production
- Example: "hot spot" model

  Gluonic density concentrated around valence quarks

$$T_p(b) \to \frac{1}{N_q} \sum_{i=1}^{N_q} T_q(b - b_i)$$





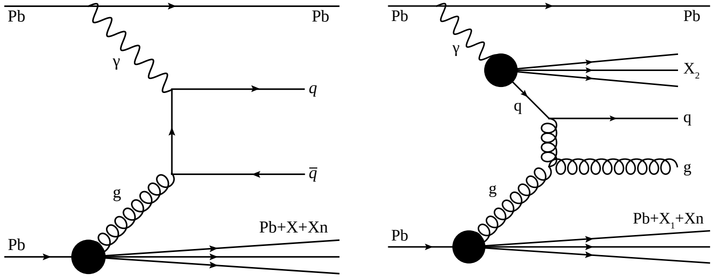
Mäntysaari, Schenke [1603.04349]

Mäntysaari, Salazar, Schenke [2207.03712]

Dijet production in $\gamma + A$

Two contributions:

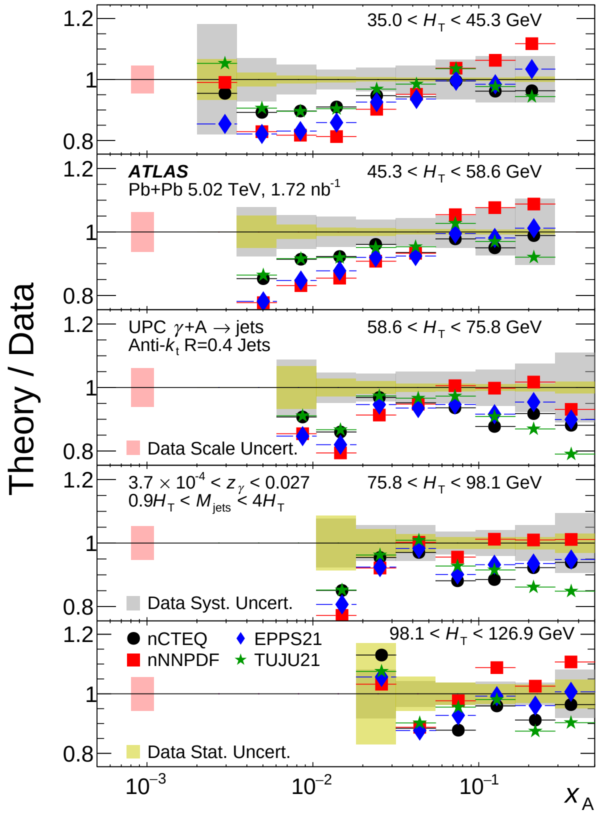
1) Direct
2) Resolved



- Can be used to probe nuclear PDFs

Comparisons at LO:

- Theory underpredicts the cross section in the shadowing region $(x < 0.01)$
- Some nPDFs overpredict anti-shadowing region

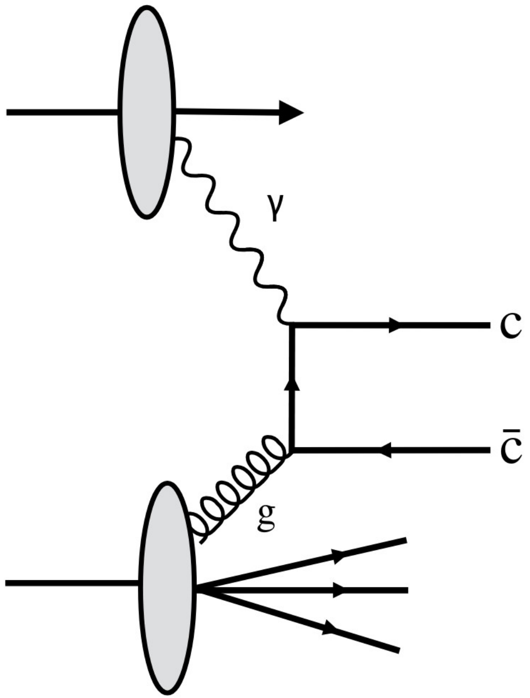


ATLAS collaboration [2409.11060]

Future measurements: Open charm and bottom production

Inclusive $\gamma + A$: structure functions at $Q^2 = 0$

- Need heavy quarks (*c* or *b*) for a perturbative scale
- Access to **nuclear** structure functions before EIC



Data analysis still on-going

- Distinguishing from background non-trivial

Michele Innocenti, Diffraction and gluon saturation at the EIC and the LHC (2024)

UCLA

UPC workshop

UPC 2023: International workshop on the physics of Ultra Peripheral Collisions

Dec 10 – 15, 2023
Playa del Carmen
America/Cancun timezone

Enter your search term

- Overview
- Scientific Program
- Call for Abstracts
- Timetable
- Contribution List
- Book of Abstracts
- Registration
- Important dates
- Conference location and accommodation
- Students/postdoc support
- Students day
- Travel
- Conference rates
- Social event and excursion
- Code of conduct

The first international workshop on the physics of Ultra Peripheral Collisions will be organized at Hotel Iberostart Tucan/Quetzal in Playa del Carmen, Mexico from December 11-15, 2023. **We are on the Tucan side.**

UPC 2023

UPC2025: The second international workshop on the physics of Ultra Peripheral Collisions

Jun 9 – 13, 2025
Saariselkä, Finland
Europe/Helsinki timezone

Enter your search term

- Overview
- Scientific Program
- Call for Abstracts
- Registration
- Participant List
- Important dates
- Financial support
- Travel and accommondation
- Conference fee

The second international workshop on the physics of Ultra Peripheral Collisions will be organized in Finland in June 2025.

This is an in-person only event.

The following research topics will be discussed:

- Exclusive processes and small-x physics
- Monte Carlo event generators for UPCs and photon-mediated processes
- Inclusive and diffractive processes and photon, proton and nuclear structure
- Photon-photon physics, precision tests of SM and BSM
- New directions in UPCs, connection to heavy-ion physics, and synergies with EIC and other facilities

UPC 2025

Summary

- UPCs allow us to measure process with quasi-real photons in the initial state
- Energy range beyond DIS experiments
- Photon–photon processes:
  - Access non-linear region of QED
  - Search for BSM physics
- Photo–nuclear processes:
  - Both proton and heavy nuclei as targets
  - Can measure nuclear shadowing for small x
  - Diffractive processes: access to nuclear geometry in the transverse plane