The energy frontier for electromagnetic interactions - Ultra-peripheral collisions at the LHC

Science Coffee Seminar
University of Lund,
14 November, 2023

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(Scientific Associate 2023-2024)

Not the first time I talk on this topic here

Växelverkande fält i relativistiska kärnkollisioner
- en fråga av perifer natur?

Joakim Nystrand
Fysiska Institutionen, Lunds Universitet

Not the first time I talk on this topic here

Översikt

• Centrala, Perifera, Ultraperifera kollisioner.

• Elektromagnetiska fält alstrade av relativistiska partiklar.

• Partikelproduktion i ultraperifera kollisioner.
  - Reaktioner: $\gamma\gamma$, γ-gluon, γ-Pomeron, …
  - koherent vs. inkoherent växelverkan

• Ultraperifera kollisioner vid *Relativistic Heavy-Ion Collider* (RHIC).

• Utsikter inför LHC.

Joakim Nystrand Docentföreläsning 12 mars 2003

Outline of this talk

- Introduction to ultra-peripheral collisions (UPC).

- Exclusive interactions, vector meson production.

- Inelastic photonuclear interactions.

What are Ultra-peripheral Collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.

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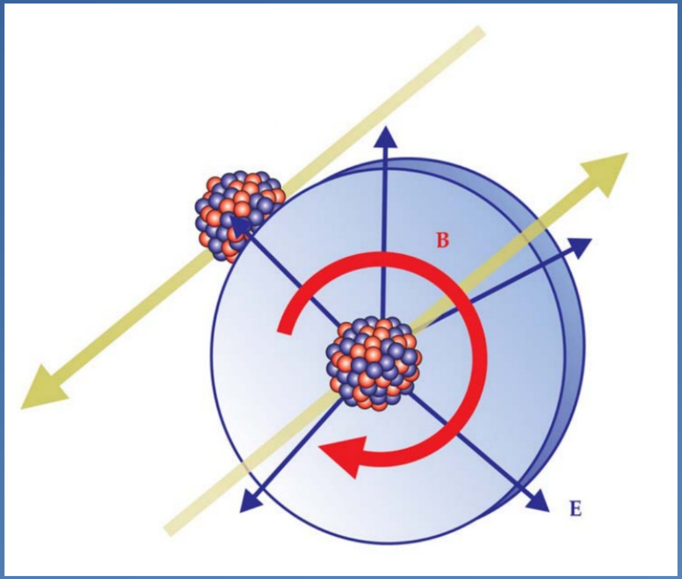
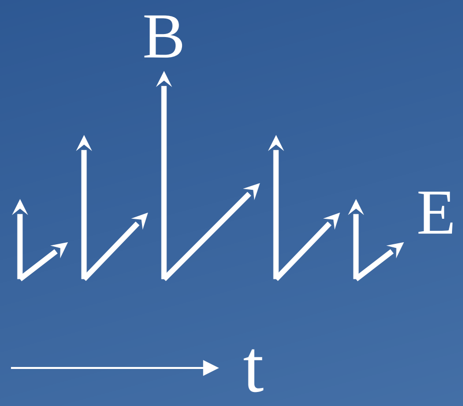


The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

Electromagnetic fields of a moving charged particle



1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$

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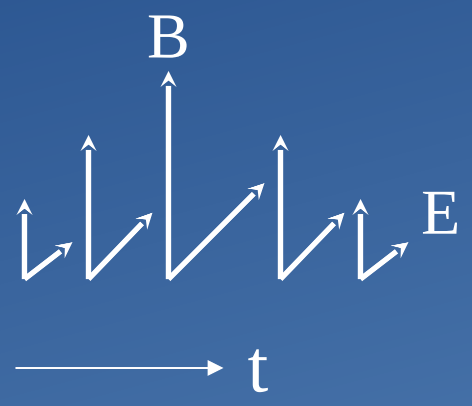

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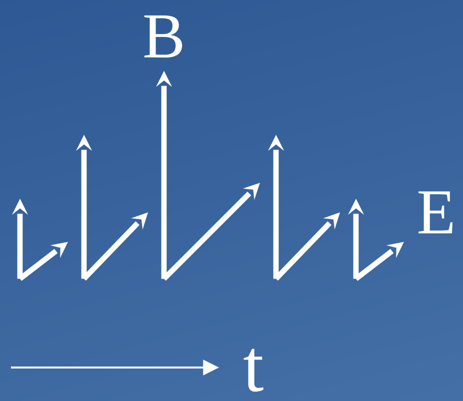
Fermi 1924: The effect of the field is equivalent to a flux of of photons with a continous energy spectrum. (hep-th/0205086)

Electromagnetic fields of a moving charged particle



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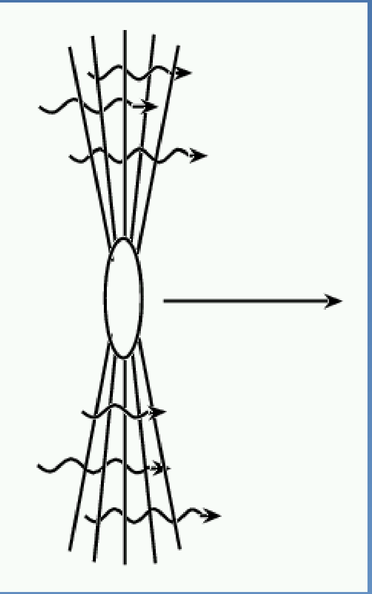


Pulse width $b/\gamma c$ $\leftrightarrow$ the spectrum contains photons w/ $\omega < \gamma c/b$

Quantum Mechanical derivation 1934 by Weizsäcker,Williams. $\Rightarrow$ *Weizsäcker-Williams method*

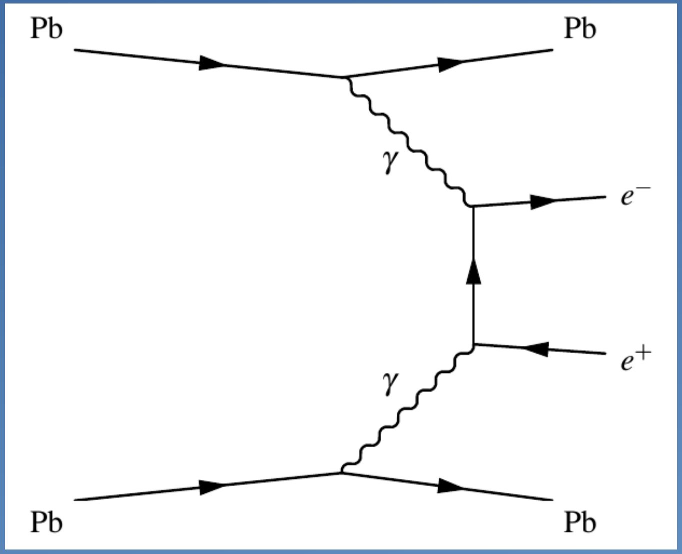
We can calculate $n(\omega)$ through a Fourier transform.

Early developmens in the 1930's

1932: Discovery of the positron (C.D. Anderson).

1934: Calculation of the cross section $\gamma\gamma \rightarrow$ e+e- (Breit-Wheeler).

1933-1937: Calculation of the cross section for two-photon production of e^+e^- pairs in nucleus-nucleus collisions (Furry, Carlson, Landau, Lifshitz, Bhabha, Racah, Nishina,Tomonaga).



Early developmens in the 1930's

The idea to use heavy-ions to study electromagnetic interactions is thus not new:

Charged particles are able to excite nuclei without penetrating into the nucleus by means of the action of the their electric field upon the nucleus when they pass nearby.
V.F. Weisskopf, Physical Review, 1938.

Early developmens in the 1930's

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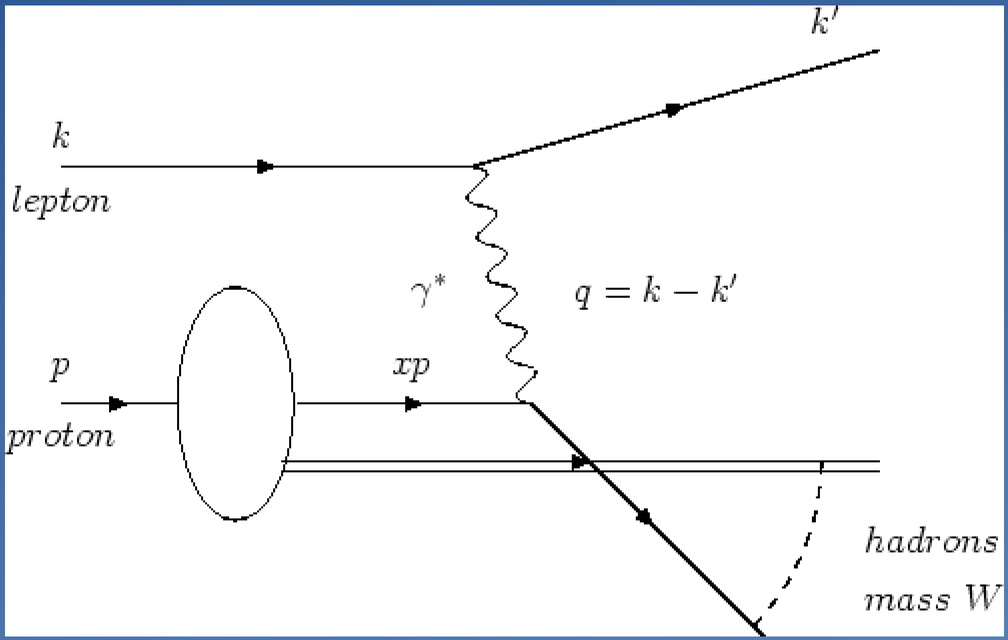
V.F. Weisskopf, Physical Review, 1938.

But for a long time, the energy of hadronic/nuclear beams were not high enough to investigate particle production.

⇨ The energy frontier of electromagnetic (and weak) interactions used to be with lepton beams.

Electromagnetic interactions with lepton beams

First observation of deep inelastic electron-proton scattering at Stanford, late 1960's.



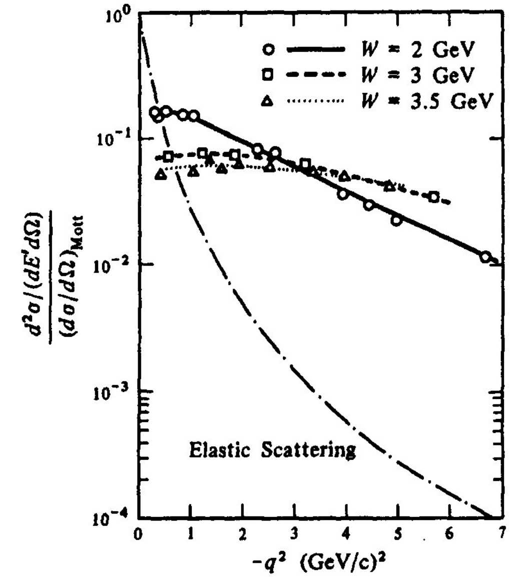


Fig. 6.19. Elastic and double differential cross sections, normalized by division with $\sigma_{\text{Mott}} = (d\sigma/d\Omega)_{\text{Mott}}$. $(d^2\sigma/dE'\,d\Omega)/\sigma_{\text{Mott}}$, in GeV^{-1}, is given for $W = 2$, 3, and 3.5 GeV. [After M. Breidenbach et al., *Phys. Rev. Lett.* **23**, 935 (1969).] Better data now exist, but we show these results because they demonstrate the salient features clearly.

⇨ The basis for the parton model of the proton.

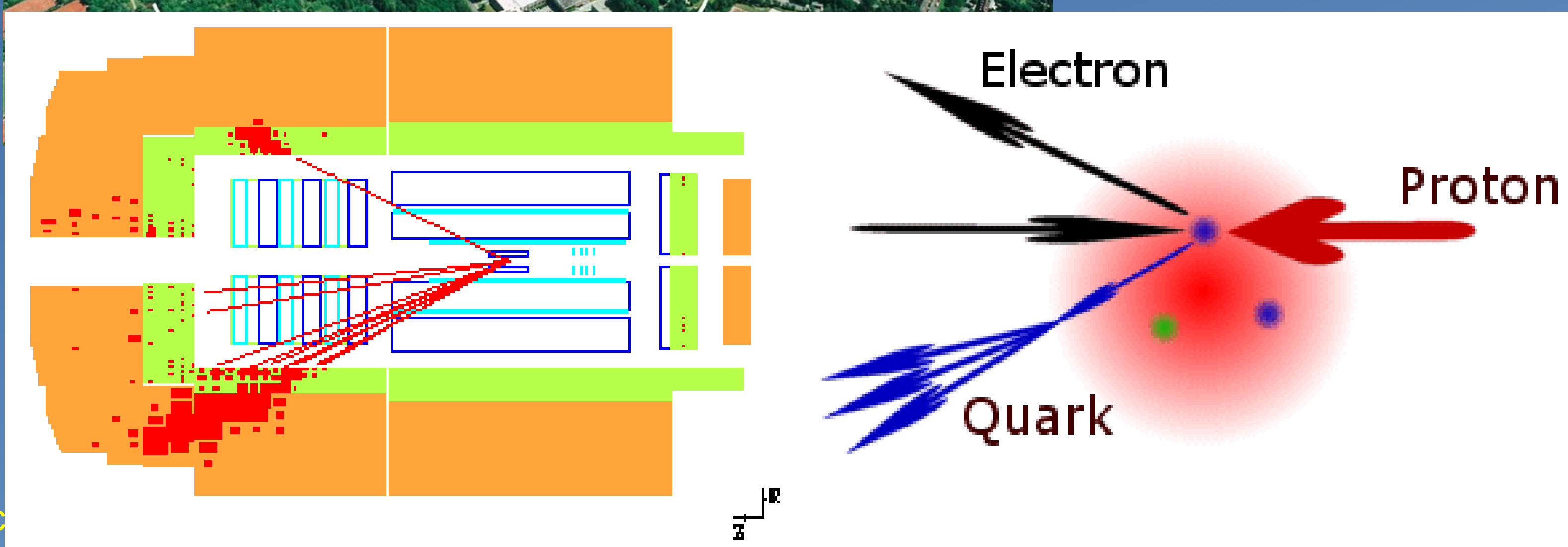
Electromagnetic interactions with lepton beams

The electron-proton collider HERA at DESY in Hamburg, Germany.

- In operation 1992 – 2007.

- electron-proton collisions at CM energy of 320 GeV.

- Mapped out the proton parton distribution functions (PDFs) in detail.



Electromagnetic interactions with hadronic beams

To maintain coherence, the maximum photon energy with a hadronic/nuclear beam will be $\sim\gamma\hbar c/R$

γ – Lorentz factor of the beam

R – Hadron/nuclear radius

⇨ The photon energy will only be a few % of the beam energy.

⇨ The photons will be almost real, $Q^2 \sim (\hbar/R)^2 \sim 0.001$ GeV^2/c^2.

First observation of two-photon production of $\mu^+\mu^-$ pairs ($\gamma\gamma \rightarrow \mu^+\mu^-$) at Intersecting Storage Rings (ISR) at CERN in 1980.

Electromagnetic interactions at the LHC

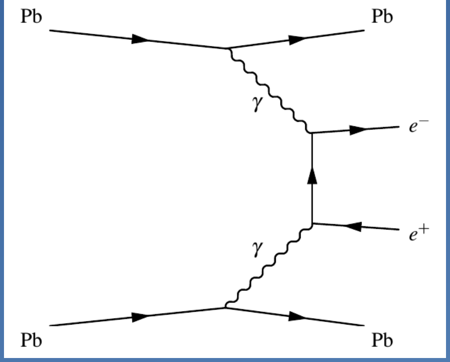
Two sources of photons (one from each beam). Possibilities:

1) Two-photon interaction, $\gamma\gamma \rightarrow$ X.

X: A single meson, η_c;

a dilepton pair $\tau\tau$;

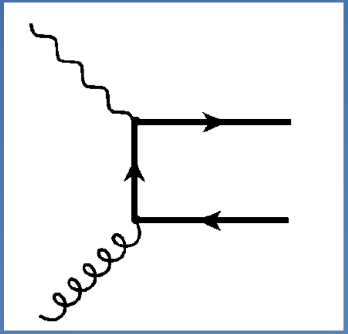
$\gamma\gamma$ ($\gamma\gamma \rightarrow \gamma\gamma$ scattering).

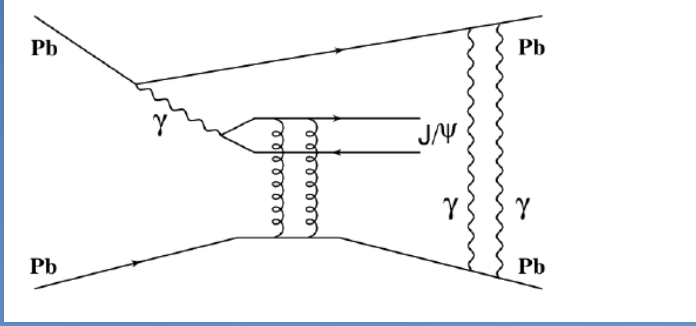


2) Photonuclear interaction, γ+A $\rightarrow$ X

X: Elastic interaction γ+A $\rightarrow$ V+A

V = Vector Meson



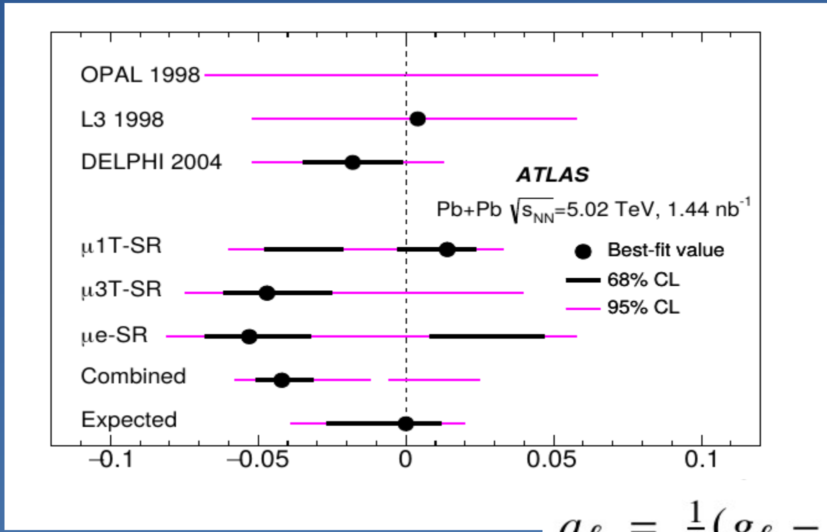


X: Any inelastic interaction, γ+A $\rightarrow$ X ,

for example γ+gluon $\rightarrow$ q+qbar

Two-photon interactions

Just some highlights from two-photon interactions
Recent paper from Atlas on $\gamma\gamma \to \tau\tau$. (PRL 131 (2023) 151802)

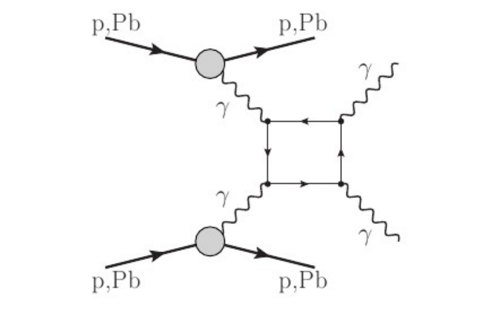


$$a_\ell = \frac{1}{2}(g_\ell - 2)$$

Sets limits on the anomalous magnetic moment of the τ comparable to the LEP measurements from the 1990's.

Observation by the ATLAS and CMS experiments of the process $\gamma\gamma \to \gamma\gamma$ (Atlas: Nat. Phys. 13 (2017) 852, PRL 123 (2019) 052001, JHEP 03 (2021) 243; CMS: PLB 797 (2019) 134826).

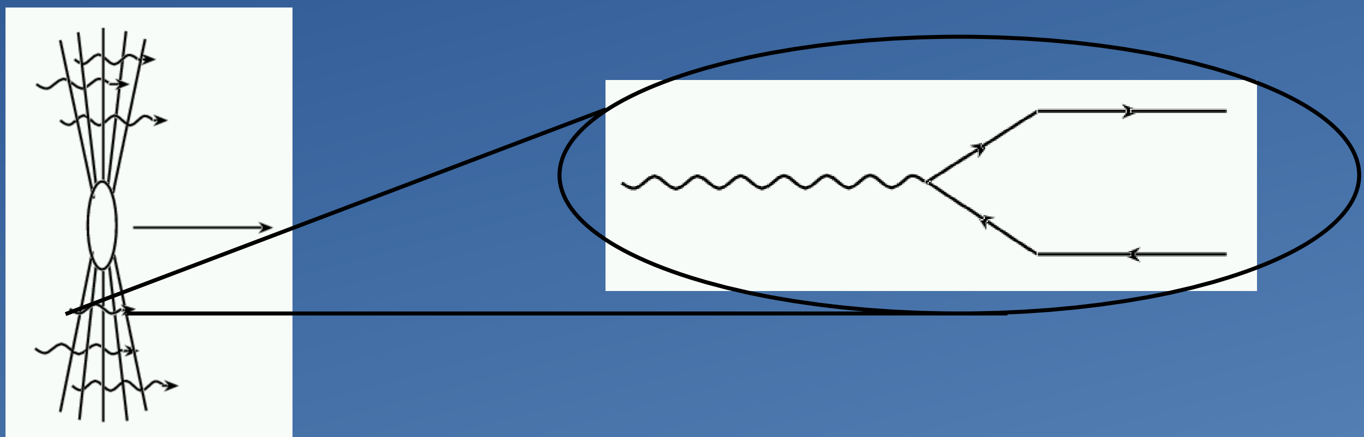
Sets new limits on axions production.



Photonuclear interactions in UPC

A photon is not always a photon ...

It can fluctuate to a quark-antiquark pair.



Quantum numbers $J^{PC} = 1^{--}$ ==> Fluctuations to Vector Mesons dominate. Can write wave function as a Fock state

$$|\gamma\rangle = c_{\mathrm{bare}}|\gamma_{\mathrm{bare}}\rangle + \sum_{V=\rho^0,\omega,\phi,\mathrm{J}/\psi} c_V|V\rangle + \sum_{\mathrm{q}=\mathrm{u,d,s,c,b}} c_{\mathrm{q}}|\mathrm{q\bar{q}}\rangle + \sum_{\ell=\mathrm{e},\mu,\tau} c_\ell|\ell^+\ell^-\rangle$$

G.A. Schuler, T. Sjöstrand, Phys. Lett. B300 (1993) 169; Nucl. Phys. B407 (1993) 539; Z. Phys. Z C 73 (1997) 677.

Photonuclear interactions in UPC

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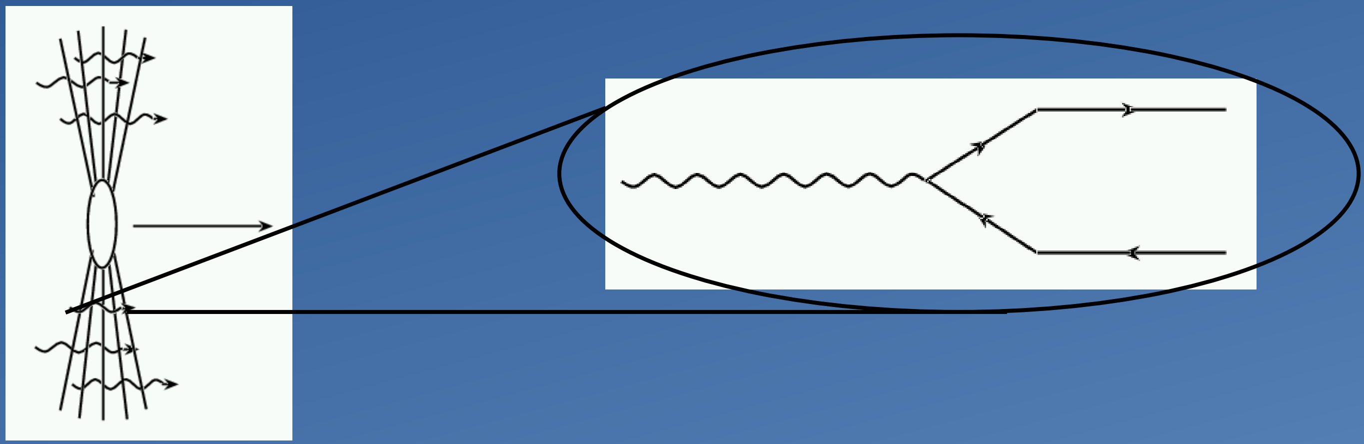


When the photon is in a hadronic state it will interact strongly.

Life time of fluctuation $$\Delta t = \frac{2E_\gamma}{M_V^2 + Q^2}\hbar \approx \frac{2E_\gamma}{M_V^2}\hbar$$

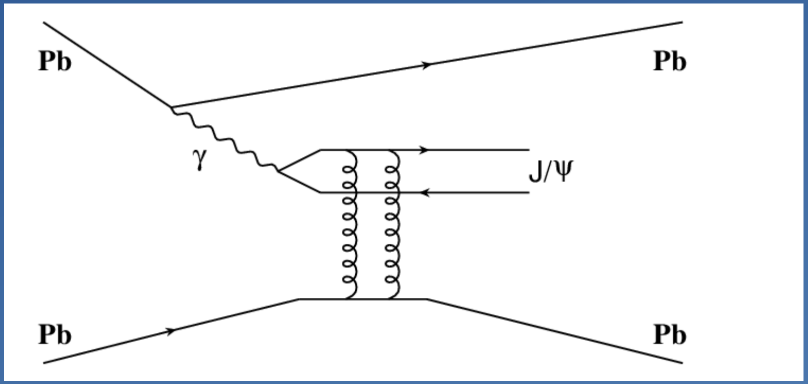
In nucleon rest frame (for a ρ^0)

E_γ = 1000 GeV ($\sqrt{s}$ = 43 GeV) $\Delta\tau$ = 2 800 fm/c

E_γ = 10000 GeV ($\sqrt{s}$ = 137 GeV) $\Delta\tau$ = 28 000 fm/c

Photonuclear interactions in UPC

The vector meson can scatter elastically off the target and emerge as a real VM.



This has so far been the main focus of UPCs.

But the long-lived ρ^0 can of course just bang into the target nucleus as any other (real) hadron.

These interaction are known as resolved interactions and they dominate the photonuclear cross section.

Photonuclear interactions at the LHC

To each source we associate a photon flux (i.e. a certain number of photons per energy interval, $dn_\gamma/d\omega$)

$$\sigma(A + A \rightarrow A + X) = 2 \int n(\omega)\sigma_{\gamma A \rightarrow X}(\omega)d\omega$$

The "2" just takes into account that both nuclei can emit photons.

Integral between some ω_{min} and ω_{max}.

Natural cut-offs:

ω_{min} – threshold for the reaction $\gamma A \rightarrow X$.

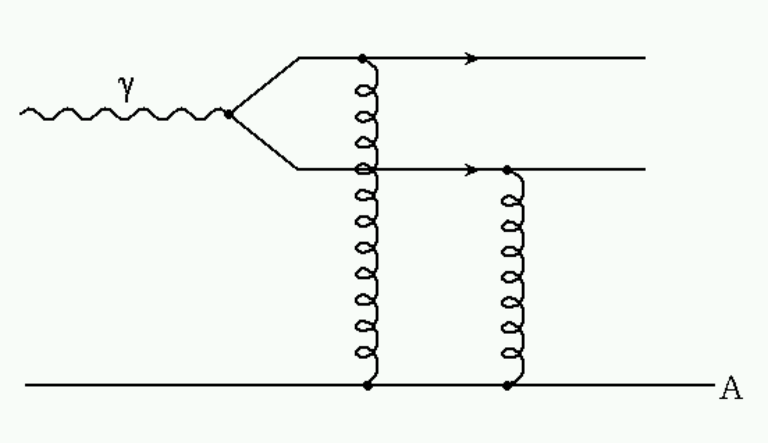
ω_{max} – cut off by the photon spectrum; $\omega_{max} << E_{beam}$ for protons and nuclei.

Exclusive Vector Meson production

Exclusive photoproduction of heavy vector mesons calculable from pQCD

$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$ Ryskin 1993

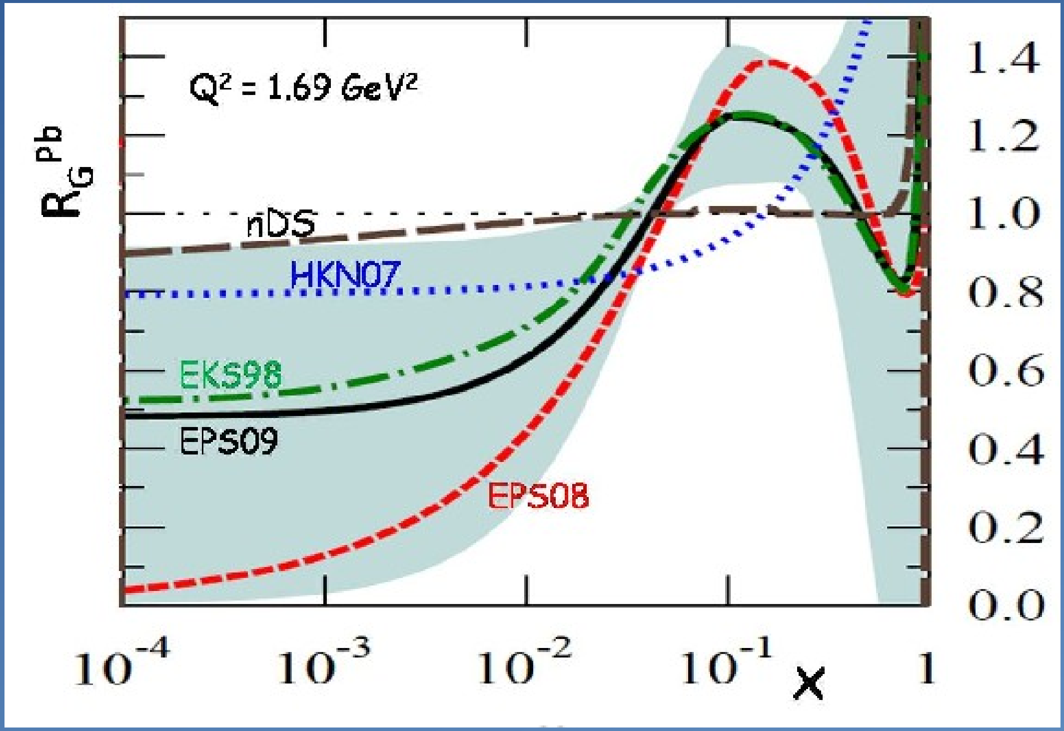
⇒ Sensitive probe of g(x), [(g(x))^2]



Two gluons can be exchanged without color transfer ↔ exchange of a Pomeron

Exclusive Vector Meson production

Big uncertainties in the nuclear gluon distribution. Different parameterizations available.



Measuring exclusive vector meson production at the LHC can Improve this for $Q^2 \sim M_V^2$ and $x \approx 10^{-2} - 10^{-4}$ (x range is rapidity dependent).

Exclusive Vector Meson production

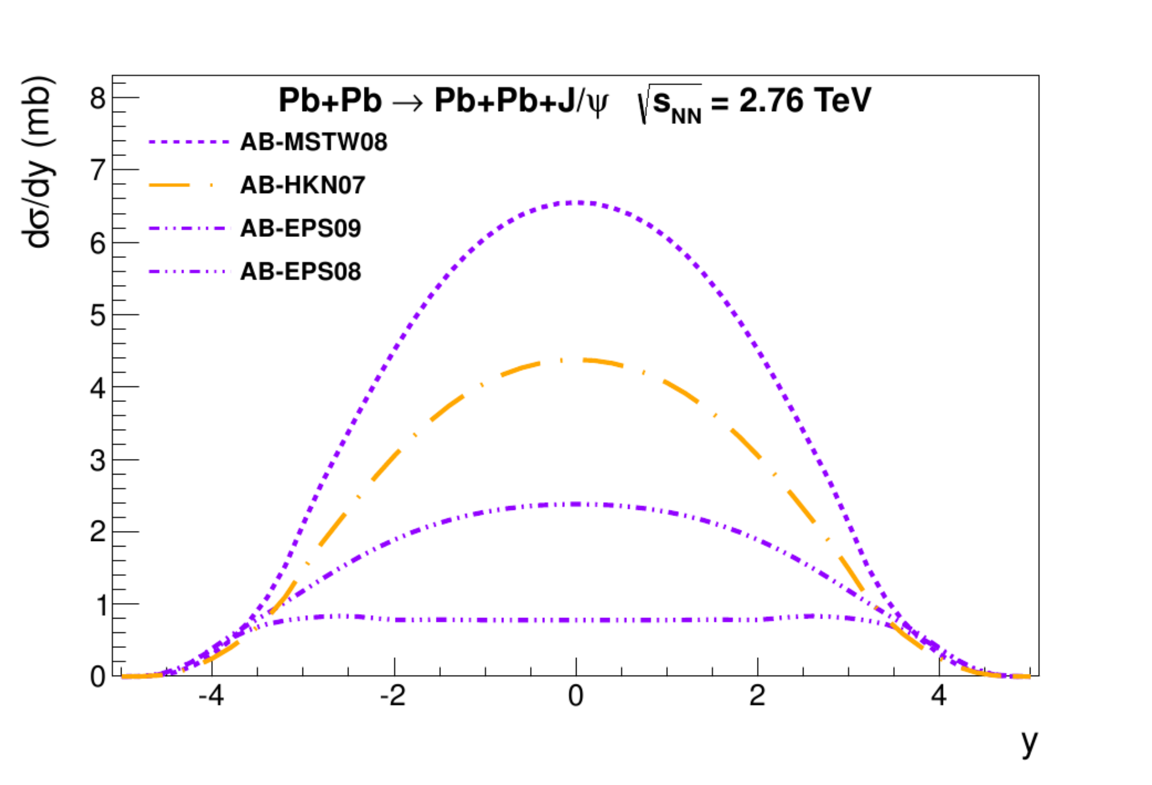
Calculation by Adeluyi and Bertulani assuming $\sigma \propto (g(x))^2$.
(Phys. Rev. C 85 (2012) 044904)

Normalizing to γp data from HERA.

MSTW08 – no nuclear effects (A^2 scaling)

HKN07, EPS09, EPS08 - different nuclear g(x).

Leads to very different cross sections for J/ψ, especially at midrapidity!



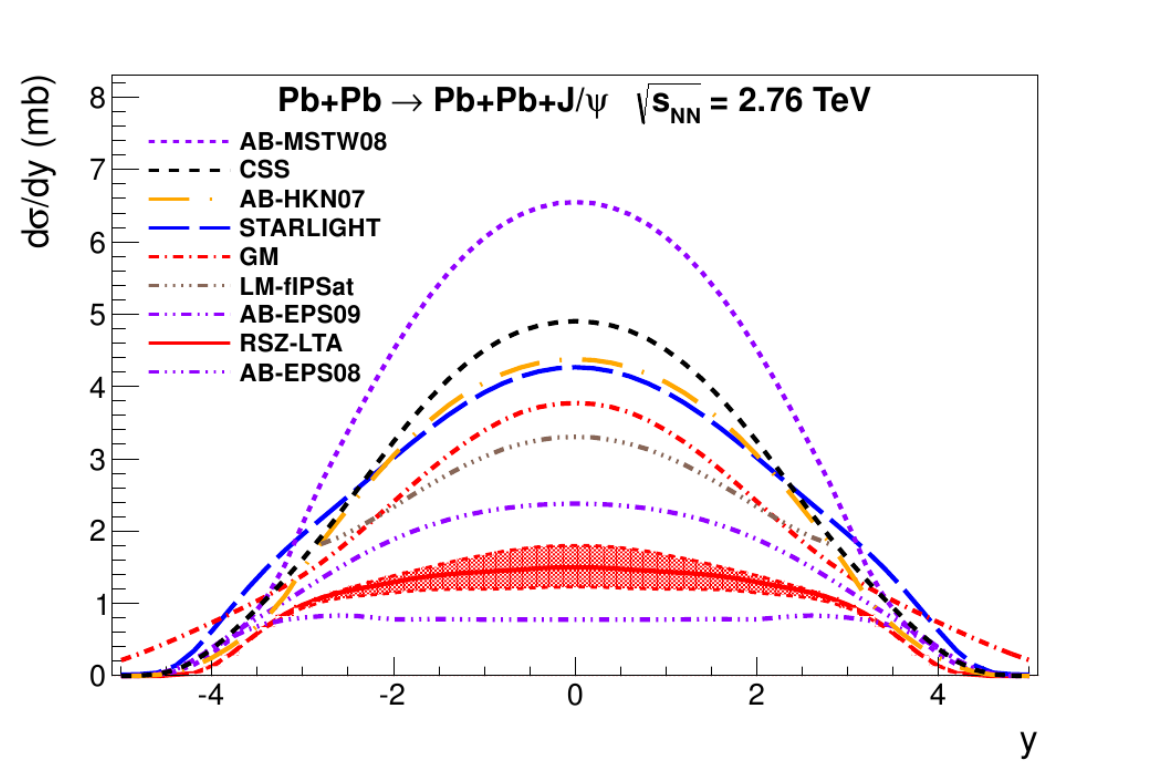
Exclusive Vector Meson production

Also other models on the market

Many based on the Color Dipole Model (CSS, GM, LM-fIPSat).

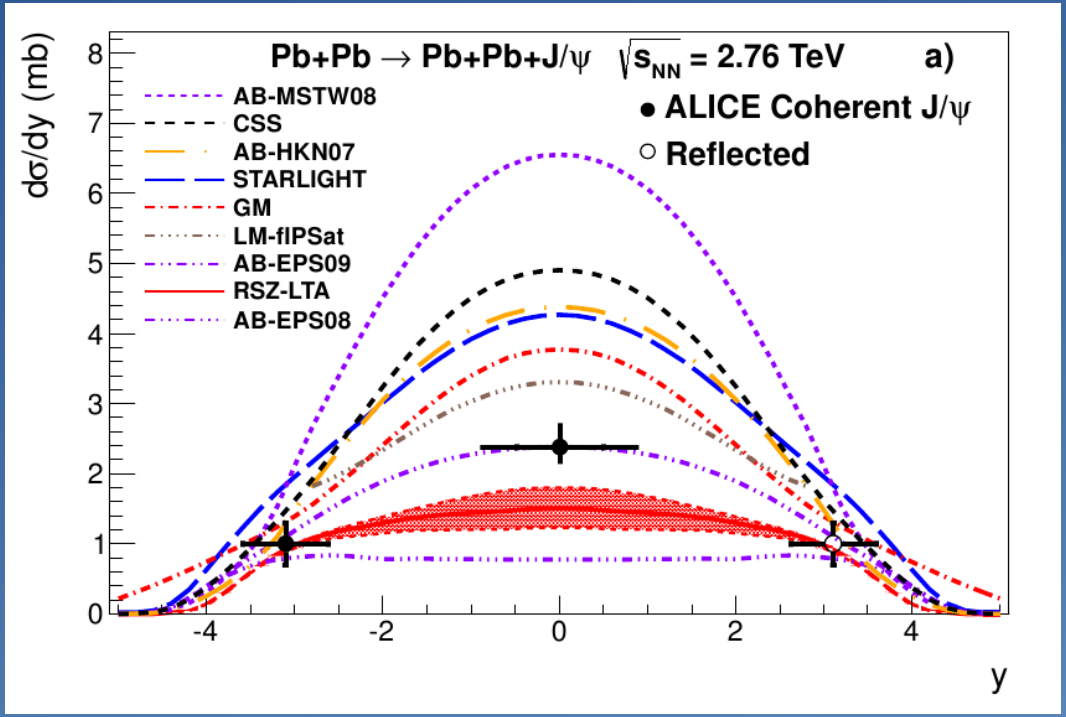
RSZ-LTA – calculates nuclear shadowing from Leading Twist Approximation

STARLIGHT – scales the measured γp cross section using a Glauber Model.



For exact references, see Eur. Phys. J 73 (2013) 2617.

Exclusive J/ψ production in ALICE



ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

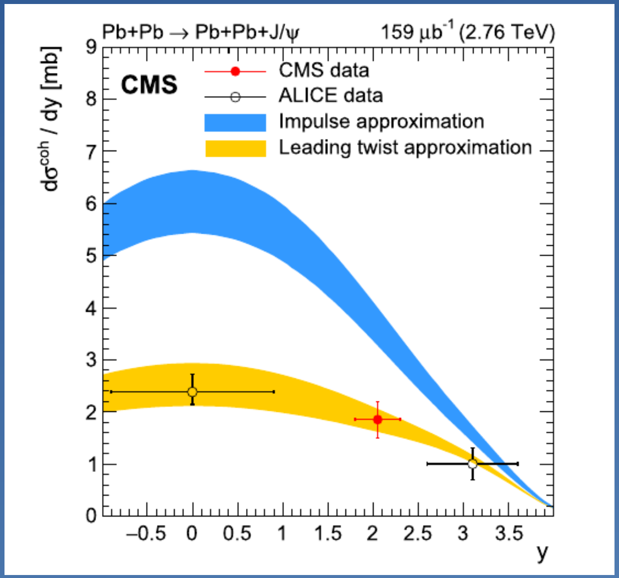
and

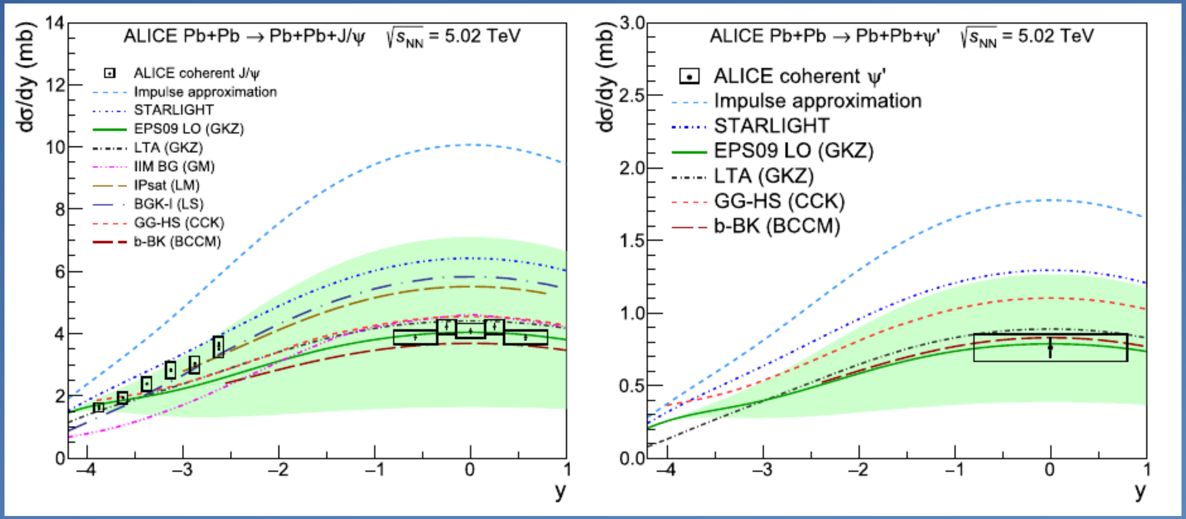
EPJ C 73 (2013) 2617.

This result from ALICE shows that the distribution in the $x \approx 10^{-2} - 10^{-3}$ range is consistent with the EPS09 parameterization.

Exclusive vector meson production

These results have been updated with higher statistics and also CMS has measured the same thing with similar conclusions.





CMS Collaboration Phys. Lett. B 772 (2017) 489.

ALICE Collaboration Eur. Phys. J. C 82 (2021) 712

Exclusive vector meson production

A nice picture of vector meson production!

But is it true?

Exclusive J/ψ photoproduction in ultraperipheral Pb+Pb collisions at the LHC to next-to-leading order perturbative QCD

K. J. Eskola,[1,2] C. A. Flett,[1,2] V. Guzey, T. Löytäinen,[1,2,*] and H. Paukkunen[1,2]
[1] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*
[2] *Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*
(Dated: March 23, 2022)

Phys. Rev. C 106 (2022) 035202

There are big differences between LO and NLO calculations and uncertainties on the relevant scale.

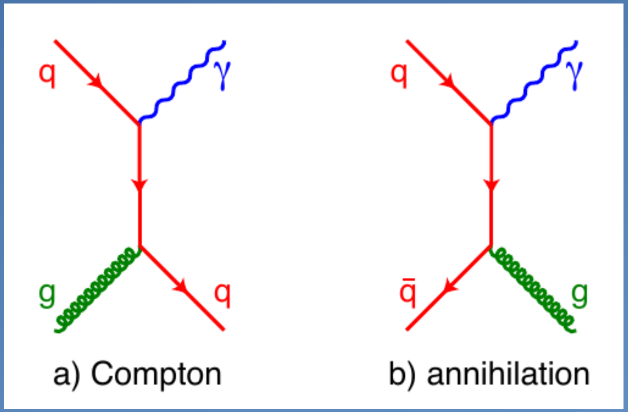
Direct photonuclear interactions in UPC

One can write the photon wave function as a Fock decomposition

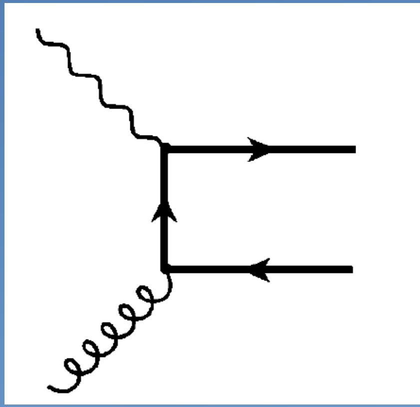
$$|\gamma\rangle = C_{bare}\,|\gamma_{bare}\rangle + C_\rho\,|\rho\rangle + C_\omega\,|\omega\rangle + C_\phi\,|\phi\rangle + \ldots + C_q\,|qq\rangle$$

While the resolved processes dominate the cross section, the photon can also act as a “bare” or “real” photon and interact with a parton in the target.

One can have direct photon production:



But one can of course turn these diagrams around and study e.g. γ+g → q+qbar interactions.



Direct photonuclear interactions in UPC

The cross sections are huge for γ+gluon fusion (S.Klein, J.Nystrand, R.Vogt, Phys. Rev C 66 (2002) 044906)!

Total cross sections in Pb+Pb @ $\sqrt{s}$ = 5.5 TeV.

σ(Pb+Pb $\rightarrow$ Pb + ccbar +X) = 2 b

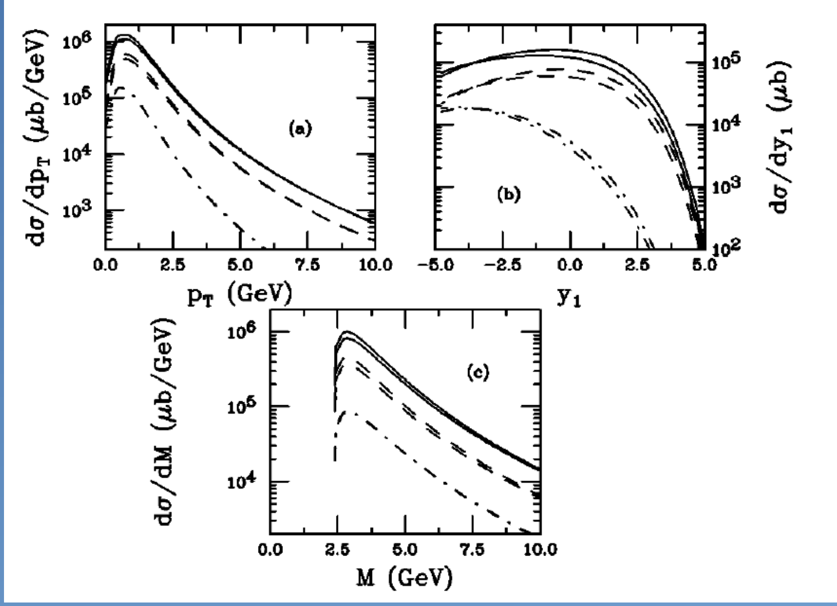
σ(Pb+Pb $\rightarrow$ Pb + bbbar +X) = 830 μb

A small fraction of the hadroproduction cross sections, but still large.

Yield inside the ALICE acceptance (central barrel).

Can be measured by reconstructing D^0.

Single quark p_T and y distributions.
M_{inv} distribution for ccbar pairs.



Direct photonuclear interactions in UPC

A γ+parton interaction could also lead to jet production.

No calculations available for this, as far as I know.

The jets would be different from jets in pp or Pb-Pb in that there shoud be *no underlying event*.

The jet energy would also be lower than in pp or Pb-Pb collisions (because of the lower photon energy).

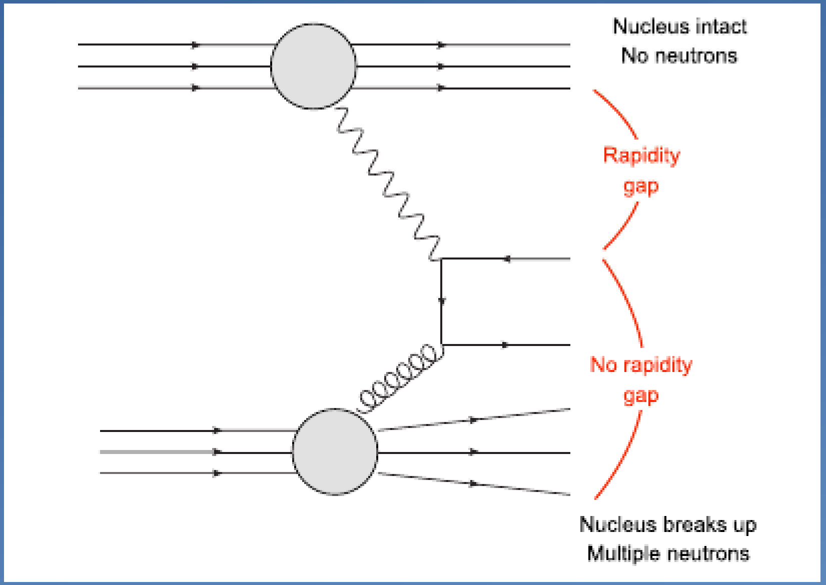
Note: A third type of photonuclear interaction are so called anomalous interactions. Here, the photon fluctuates to a hadronic state, e.g. a vector meson, and a parton from this hadronic state interacts with a parton in the target. The cross section for these interactions are typically much smaller than for direct photon interactions.

Photonuclear interactions in UPC

Experimental signatures for inelastic photonuclear interactions:

1) There is a rapidity gap on the side of the photon-emitting nucleus ==> main experimental signature.

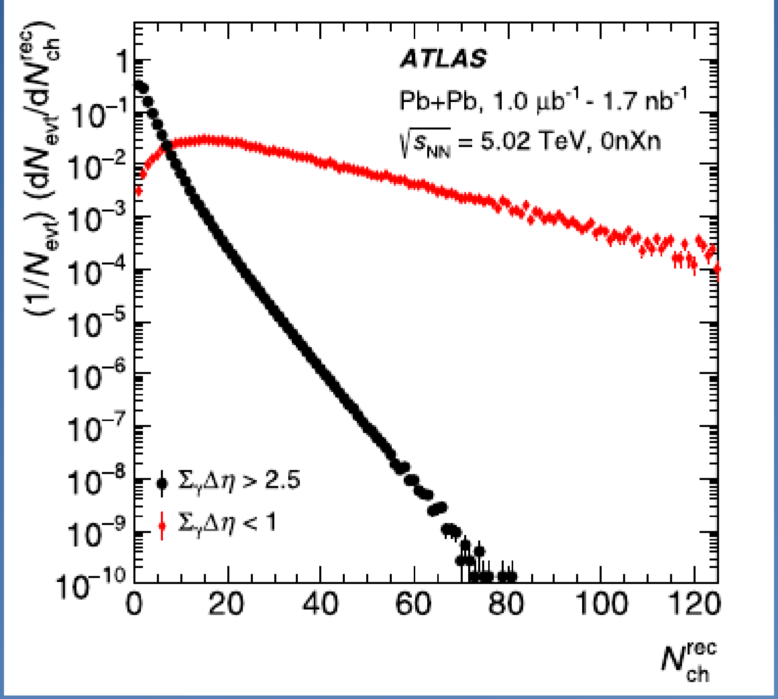
2) The photon energy << beam energy ==> particle production is shifted in rapidity to the side of the target nucleus.

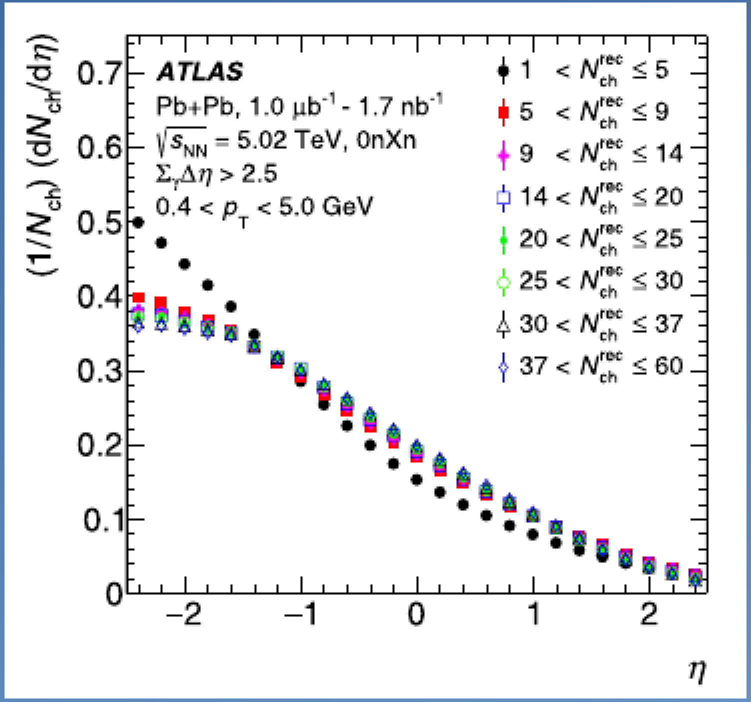


Results on photonuclear interactions in UPC

Inelastic photonuclear interactions studied by ATLAS (PRC 104 (2021) 014903).

Multiplicity and pseudo-rapidity distributions for γ+Pb events.

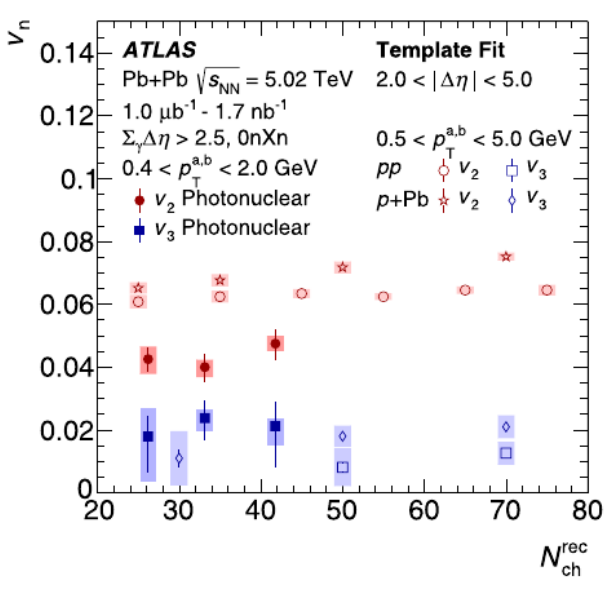


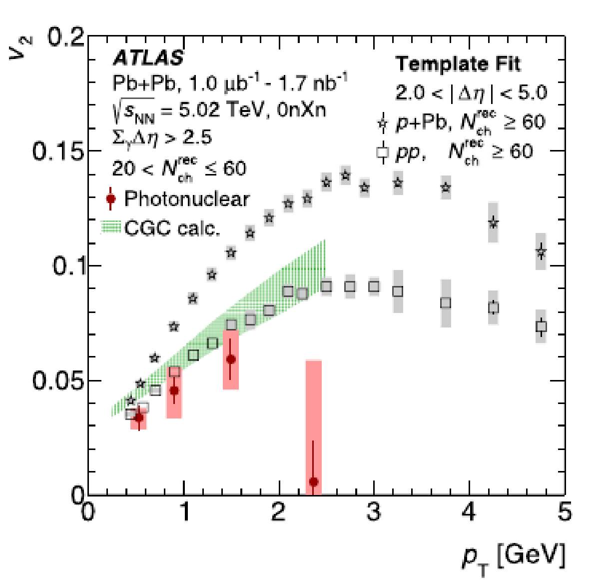


The rapidity distribution of charged particles is shifted away from midrapidity.

Results on photonuclear interactions in UPC

ATLAS observes non-zero v_2 and v_3.





v_3 in agreement with p+Pb, but v_2 lower.

ATLAS showed indications of radial flow at QM 2023.

Various other QGP signatures can be studied as well, complementing the proton-nucleus measurements.

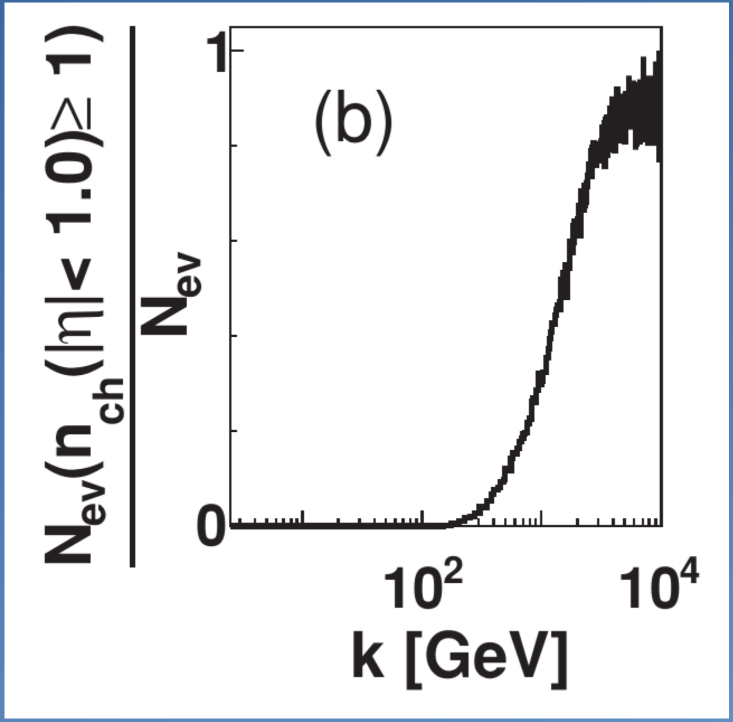
The energy is in the RHIC range or between RHIC and LHC.

Models for photonuclear interactions in UPC

Use the photon spectrum from starlight and convolute it with DPMJET 3.0-5 (Ø. Djuvsland, J. Nystrand, Phys. Rev. C 83 (2011) 041901).

The photon spectrum extends to infinity as the photon energy $\rightarrow 0$.

Has to define a meaningful minimum photon energy.



The probability to have at least one charged particle inside $|\eta| < 1$.

The photon energy is here in the rest frame of the nucleus.

This is in the region k ~ 1000 – 10 000 GeV.

Models for photonuclear interactions in UPC

The total photonuclear cross sections for these photon energies (starlight+DPMJET):

$\sqrt{s}$ = 2.76 TeV

σ(k > 1000 GeV) = 4.9 b

σ(k > 10 000 GeV) = 0.9 b

$\sqrt{s}$ = 5.36 TeV

σ(k > 1000 GeV) = 8.9 b

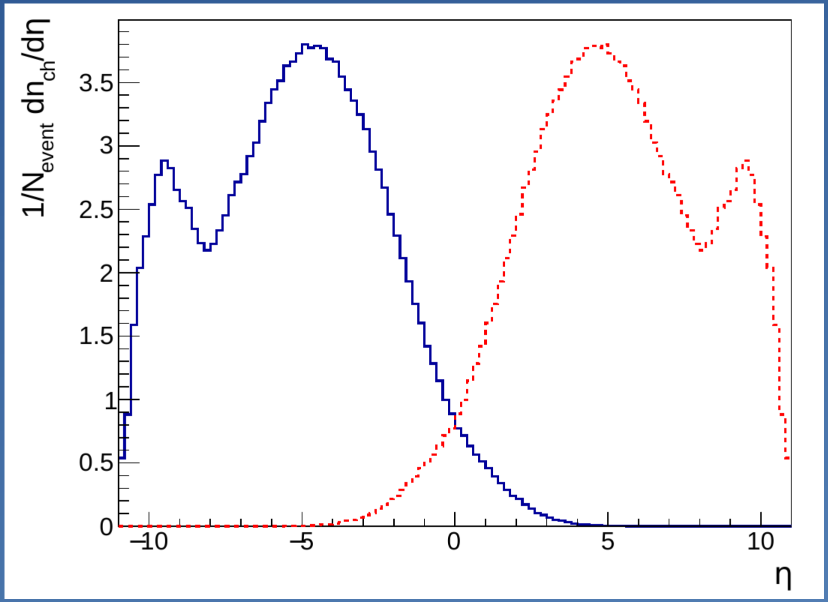
σ(k > 10 000 GeV) = 2.9 b

Increase by a factor of ~2-3 from 2.76 to 5.36 TeV.

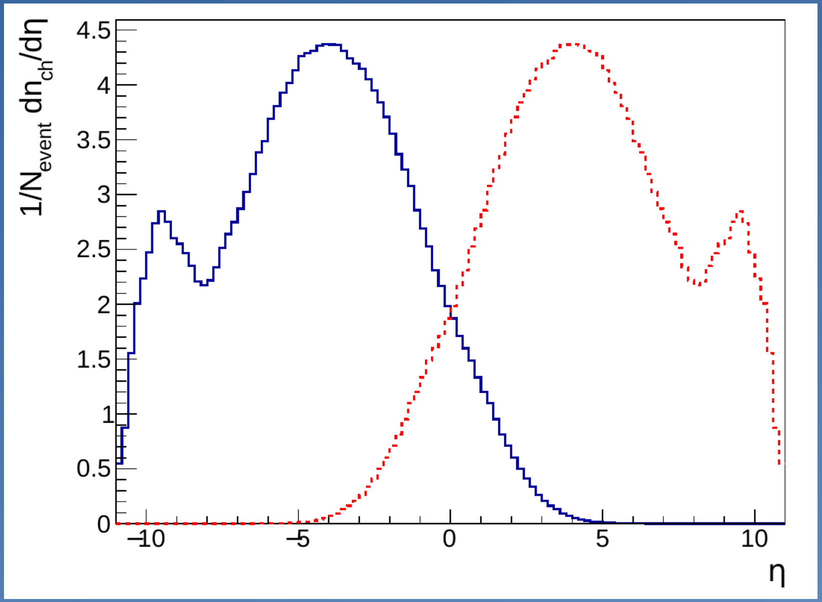
Models for photonuclear interactions in UPC

Pseudorapidity distributions of charged particles (π,K,p):

k > 1000 GeV



k > 10 000 GeV



Spectrum shifted away from y = 0, but each nucleus can emit the photon or act as target, so the total distribution includes the reflection.

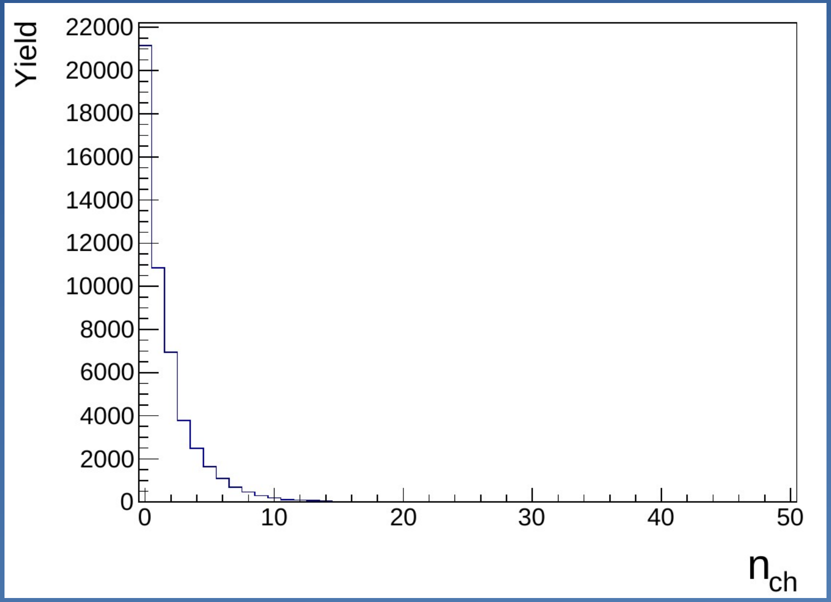
Distribution shifted closer to mid-rapidity for higher k.

Increase in multiplicity with increasing k.

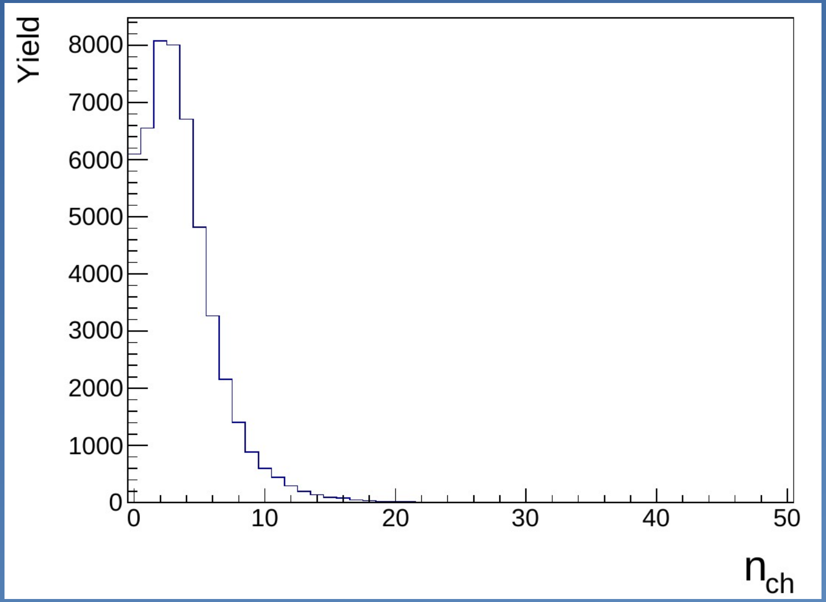
Models for photonuclear interactions in UPC

Multiplicity distributions of charged particles (π,K,p) inside $|\eta| < 0.9$:

k > 1000 GeV



k > 10 000 GeV

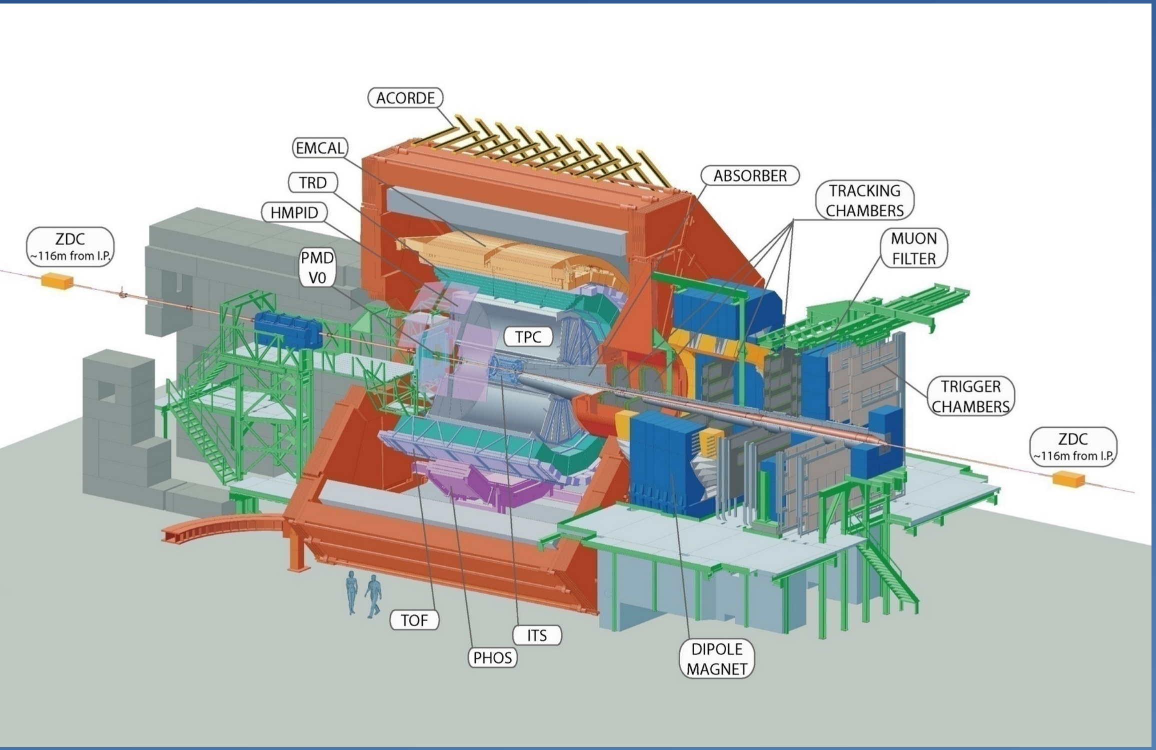


Typical multiplicities ~1-20 charged particles in $|\eta| < 0.9$.

But these simulations are for limited statistics (50 000 events) ↔ low total integrated luminosities (6 mb^{-1}, 17 mb^{-1}).

Can expect to reach higher multiplicities with higher luminosity.

The ALICE Experiment at the LHC



- A central tracking system (ITS + TPC) with particle identification.
- Acceptance $|\eta| \leq 0.9$, $p_T >$ 100 MeV/c
- Continuous read-out in Run 3

- A muon arm at forward rapidities $-4.0 < \eta < -2.5$.
- Triggering, tracking and identification of muons.
- Zero-Degree Calorimeters (ZDC) – 116 m from interaction point.

Summary

- Ultra-peripheral collisions is the energy frontier for electromagnetic and electroweak interactions.

- A variety of interactions and final states can be studied.

- Focus initially on exclusive vector meson production, but now broadening to include other two-photon and photonuclear interactions.


UPC 2023 First international workshop on the physics of Ultra Peripheral Collisions
Scientific Topics
Photon-Proton and Photon-Nucleus Physics
Two Photon Physics
Nonlinear And Gluon Saturation
Parton Distribution Developments
Hadronization In Exclusive Processes
Soft Nucleon And Nucleus Interactions
Photoproduction In Events With Nuclear Overlap
UPCs And Future Electron-Ion Colliders
Playa del Carmen (Riviera Maya), Mexico December 11-15, 2023
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Photonuclear interactions in UPC

The $\gamma\tau\tau$ vertex factor

$$i\Gamma_{\mu}^{(\gamma\ell\ell)}(p', p) = -ie\left[\gamma_{\mu}F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^{\nu}F_2(q^2) + \frac{1}{2m_\ell}\gamma^5\sigma_{\mu\nu}q^{\nu}F_3(q^2)\right],$$

$$\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$$

In the limit $q^2 \rightarrow 0$:

$$F_1(0) = 1,\ F_2(0) = a_\ell$$

Photoproduction in p+Pb Collisions at the LHC

Why is this energy dependence interesting?
Recall Ryskin's formula:

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

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Assuming a power law for the gluon PDF

$$x \cdot g(x, \mu^2) = N x^{-\lambda}$$

$$\lambda = a + b \ln(\frac{\mu^2}{0.45 GeV^2})$$

This implies

$$\frac{d\sigma}{dt} \propto x^{-2\lambda}$$

$$\sigma(\gamma + p \rightarrow J/\psi + p) \propto x^{-2\lambda}$$

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$$\sigma(\gamma + p \to J/\psi + p) \propto x^{-2\lambda}$$

With the expression for Bjorken-x this gives

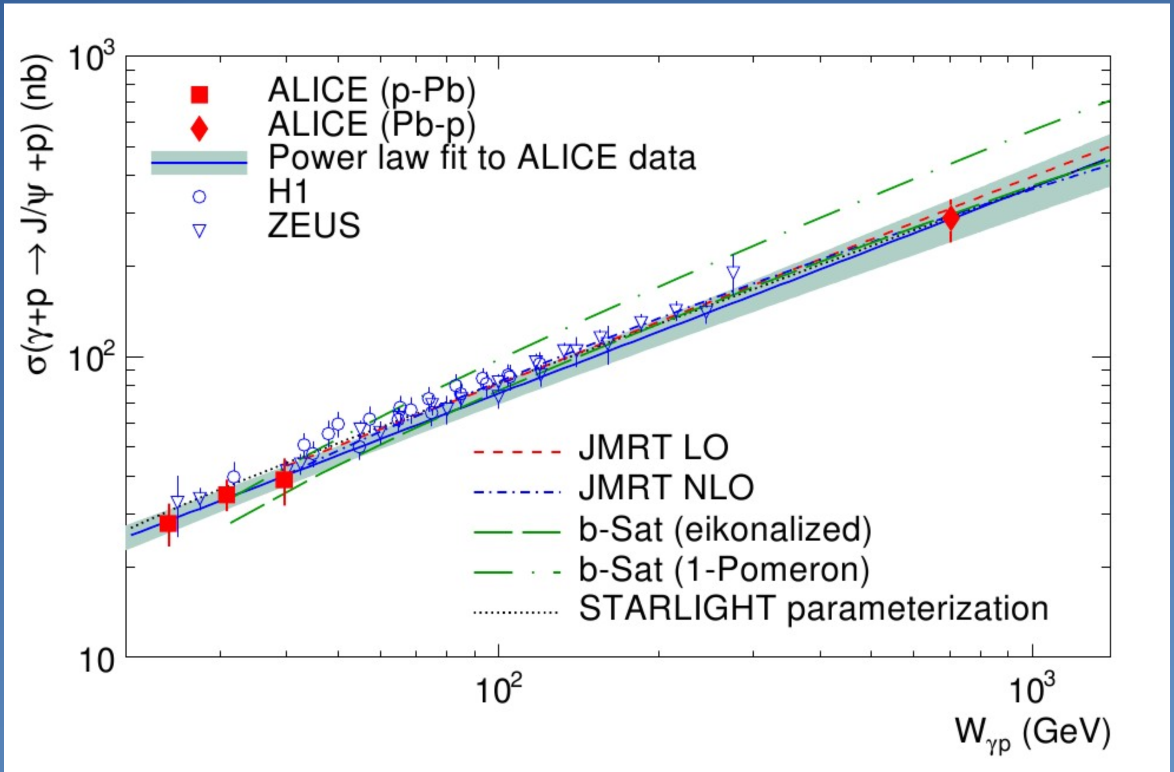
$$x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2}$$

$$\sigma(\gamma + p \to J/\psi + p) \propto W^{4\lambda}$$

Photoproduction in p+Pb Collisions at the LHC

Extracted cross section in $21 \leq W \leq 45$ GeV (p-Pb) range in good agreement with previous measurements.

New measurement in $580 \leq W \leq 950$ GeV (Pb-p) in good agreement with a power law.



From Run 1.
$\sqrt{s}$ = 5 TeV.

"A natural explanation is that no change in the behaviour of the gluon PDF in the proton is observed between HERA and LHC energies" PRL 113 (2014) 232504.