Probing gluons in nuclei using UPC

Guillermo Contreras
Czech Technical University in Prague

On behalf of

ALICE
ATLAS
CMS
Key questions we are interested in

What can we learn about the structure of hadrons at high energies with the LHC?
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Measurements at HERA imply that, when seen with a high-energy probe, nucleons are made mainly of gluons.
Key questions we are interested in

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Key question: have we reached the saturation regime?
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How does this structure change when the nucleon is embedded in a nucleus?

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Key question: what is the origin of shadowing at high energies?

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H1 and ZEUS

H1 and Zeus, EPJC 75 (2015) 580
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Key question: what is the origin of shadowing at high energies?

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How does the gluon structure of nucleons change with energy at high energies?

Key question: have we reached the saturation regime?

Saturation is expected to set at higher x in heavy nuclei.

H1 and Zeus, EPCJ 75 (2015) 580

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Lead ions have an intense EM field $\sim Z^2$
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and interact with the other ion.
Photons at the LHC to understand QCD

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If the impact parameter is large enough, photon induced interactions dominate: ultra-peripheral collisions (UPC)
Jet production in Pb-Pb UPC
Photonuclear jet production: the process

The process:

\[
Pb + Pb \rightarrow X + \text{Jet} + \text{Jet} + \text{Jet}
\]
Photonuclear jet production: the process

The process:

Test knowledge of the photon flux

Pb → Jet → x

Guillermo Contreras, CTU in Prague
Photonuclear jet production: the process

The process:

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Access to nPDFs

\[ \text{Pb} \rightarrow \text{Jet} \rightarrow \text{Jet} \rightarrow X_n \]

Guillermo Contreras, CTU in Prague
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Selection:

- Rapidity gap in one side

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**Kinematics:**
- Photon energy
  \[ z_\gamma \equiv \frac{M_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{+Y_{\text{jets}}} \]

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  \[ z_\gamma \equiv \frac{M_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{+y_{\text{jets}}} \]
- nPDF: 'Bjorken-x'
  \[ x_A \equiv \frac{M_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{-y_{\text{jets}}} \]
- nPDF: Scale
  \[ H_T \equiv \sum_i p_T^i \]

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Photonuclear jet production: photon energy

Triple differential cross section

Photon energy

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Photonuclear jet production: photon energy

Triple differential cross section

Photon energy

Fixed $x_A$
Photonuclear jet production: photon energy

Different hard scales

Fixed $x_A$

Photon energy

ATLAS-CONF-2022-021

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Photonuclear jet production: photon energy

Different hard scales

Fixed $x_A$

Triple differential cross section

Theory

Photon energy

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Photonuclear jet production: photon energy

The photon flux seems to be relatively well understood.

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Photonuclear jet production: $x_A$ dependence

Different hard scales

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Photonuclear jet production: $x_A$ dependence

Increasing photon energy

Different hard scales
Photonuclear jet production: $x_A$ dependence

Increasing photon energy:

Different hard scales:

Evolution in $x_A$ for a fixed hard scale, relatively well understood down to a few times $10^{-3}$

ATLAS-CONF-2022-021

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The process I have discussed until now, is sensitive to the gluon distribution in hadrons. Can we do something different/complementary?
What else can we do?

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Let's look at a process that depends at leading order on the square of the gluon distribution in hadrons.
Coherent $J/\psi$ production in Pb-Pb UPC
Bjorken-$x$ dependence
Diffractive $J/\psi$ photoproduction in UPC
Diffractive J/ψ photoproduction in UPC

At least two gluons here!
Diffractive $J/\psi$ photoproduction in UPC

At least two gluons here!

Does the target breaks or not?

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Diffractive J/ψ photoproduction in UPC

Proton: dissociative or exclusive production

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Proton: dissociative or exclusive production

Nucleus: incoherent or coherent production

Guillermo Contreras, CTU in Prague
Diffractive $J/\psi$ photoproduction in UPC

At least two gluons here!

$\text{p, Pb}$

Does the target breaks or not?

proton: dissociative or exclusive production
nucleus: incoherent or coherent production

$J/\psi$

Kinematics: vector meson rapidity $\Rightarrow$ energy (Bjorken-x) evolution

$\frac{m}{\sqrt{s}} e^{-\gamma} = \frac{m^2}{W^2}$

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**Diffractive J/ψ photoproduction in UPC**

- **Proton:** dissociative or exclusive production
- **Nucleus:** incoherent or coherent production

Does the target breaks or not?

Kinematics: vector meson rapidity $\Rightarrow$ energy (Bjorken-$x$) evolution

$$x = \frac{m}{\sqrt{s}} e^{-\gamma} = \frac{m^2}{W^2}$$

Kinematics: Mandelstam $t$ $\Rightarrow$ transverse structure of the target

At least two gluons here!

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Diffractive $\uppsi$ photoproduction in UPC

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Kinematics: vector meson rapidity $\Rightarrow$ energy (Bjorken-x) evolution

Kinematics: Mandelstam $t \Rightarrow$ transverse structure of the target

Transverse momentum of the vector meson $|t| \approx p_{\perp}^2$

Proton: dissociative or exclusive production

Nucleus: incoherent or coherent production

$Pb$ $Pb$

Does the target break or not?

$x = \frac{m}{\sqrt{s}} e^{-\gamma} = \frac{m^2}{W^2}$
Diffractive J/ψ photoproduction in UPC

For coherent production, different impact parameters (for the photon emission): peripheral, several ultra-peripheral ranges

Kinematics: vector meson rapidity => energy (Bjorken-x) evolution

Kinematics: Mandelstam t => transverse structure of the target

Transverse momentum of the vector meson

$p, \text{Pb}$

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At least two Pb

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proton: dissociative or exclusive production

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Kinematics: vector meson rapidity => energy (Bjorken-x) evolution

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$|t| \approx p_{\perp}^2$

Does the target breaks or not?

$p, \text{Pb}$
Diffractive $J/\psi$ photoproduction in UPC

For coherent production, different impact parameters (for the photon emission): peripheral, several ultra-peripheral ranges

We need to know the rapidity (wrt the direction of the target)

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Rapidity dependence

CMS, PLB772 (2017) 489

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We need to know the rapidity (wrt the direction of the target)

Rapidity dependence

Two photon sources

CMS, PLB 772 (2017) 489

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We need to know the rapidity (wrt the direction of the target).

Two photon sources

What we measure

What we want

Photonuclear cross sections at two rapidities, i.e. Bjorken-x
We need to know the rapidity (wrt the direction of the target)

Two photon sources

What we measure

What we want

What we want

How to extract the photonuclear cross section if the photon fluxes are known?

Photonuclear cross sections at two rapidities, i.e. Bjorken-x
Ambiguity problem: first solutions applied to LHC Run 1 data

At midrapidity both contributions are equal, no problem

\[
\frac{d\sigma_{\text{PbPb}}}{dy} = n_\gamma(y; \{b\})\sigma_{\gamma\text{Pb}}(y) + n_\gamma(-y; \{b\})\sigma_{\gamma\text{Pb}}(-y)
\]

What we measure

What we want

What we want

Photonuclear cross sections at two rapidities, i.e. Bjorken-x

How to extract the photonuclear cross section if the photon fluxes are known?
Ambiguity problem: first solutions applied to LHC Run 1 data

At forward rapidities, dominates (95% of the cross section).

At midrapidity, both contributions are equal, no problem.

What we measure:

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\frac{d\sigma_{PbPb}}{dy} = n_\gamma(y; \{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y; \{b\})\sigma_{\gamma Pb}(-y)
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What we want:

Photonuclear cross sections at two rapidities, i.e. Bjorken-x.

How to extract the photonuclear cross section if the photon fluxes are known?


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Ambiguity problem: first solutions applied to LHC Run 1 data


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What we measure:
$$\frac{d\sigma_{\text{PbPb}}}{dy} = n_\gamma (y; \{b\}) \sigma_{\gamma \text{Pb}} (y) + n_\gamma (-y; \{b\}) \sigma_{\gamma \text{Pb}} (-y)$$

What we want:
$$\left( \frac{d\sigma_{\text{PbPb}}}{dy} \right)_A = n_\gamma (y; \{b\}_A) \sigma_{\gamma \text{Pb}} (y) + n_\gamma (-y; \{b\}_A) \sigma_{\gamma \text{Pb}} (-y)$$
$$\left( \frac{d\sigma_{\text{PbPb}}}{dy} \right)_B = n_\gamma (y; \{b\}_B) \sigma_{\gamma \text{Pb}} (y) + n_\gamma (-y; \{b\}_B) \sigma_{\gamma \text{Pb}} (-y)$$

Perform two independent measurements at the same rapidity, but different impact parameter, then solve the equations.

Photonuclear cross sections at two rapidities, i.e. Bjorken-x

How to extract the photonuclear cross section if the photon fluxes are known?

Guillermo Contreras, CTU in Prague
Ambiguity problem: first solutions applied to LHC Run 1 data

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What we measure

$\frac{d\sigma_{PbPb}}{dy} = n_{\gamma}(y; \{b\})\sigma_{\gamma Pb}(y) + n_{\gamma}(-y; \{b\})\sigma_{\gamma Pb}(-y)$

What we want

Perform two independent measurements at the same rapidity, but different impact parameter, then solve the equations.

$\left( \frac{d\sigma_{PbPb}}{dy} \right)_A = n_{\gamma}(y; \{b\}_A)\sigma_{\gamma Pb}(y) + n_{\gamma}(-y; \{b\}_A)\sigma_{\gamma Pb}(-y)$

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What we want

How to extract the photonuclear cross section if the photon fluxes are known?

Photonuclear cross sections at two rapidities, i.e. Bjorken-x

For example, use peripheral and ultra-peripheral collisions

JGC, PRC 96, 015203 (2017)

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Energy/Bjorken-x dependence of coherent production from Run 1

Analyses using ALICE data from Run 1

- GKSZ, using ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV (PLB 726 (2013) 290-295)
- Contreras, using ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV (PRC 96 (2017) 1, 015203)
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Electromagnetic dissociation of nuclei

Independent interaction

neutrons are emitted along the beamline

Guzey, Strikman, Zhalov, EPJ C74 (2014) 2942

Guillermo Contreras, CTU in Prague
Ambiguity problem: use EMD

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Ambiguity problem: use EMD

Photon fluxes at fwd rapidity:

Independent interaction

Neutrons are emitted along the beamline

nOOn: Photon fluxes at fwd rapidity:

High $\gamma$ energy

Low $\gamma$ energy

0n0n: no EMD neutron (large b)
0nXn: single EMD (medium b)
XnXn: mutual EMD (smaller b)
Photon fluxes at fwd rapidity:

Ambiguity problem: use EMD

Electromagnetic dissociation of nuclei

Independent interaction

neutrons are emitted along the beamline

**nOOn** Photon fluxes at fwd rapidity:

**High γ energy**

**Low γ energy**

Broz et al., CPC 235 (2020) 107181

Guzey, Strikman, Zhalov, EPJ C74 (2014) 2942

Guillermo Contreras, CTU in Prague

0n0n: no EMD neutron (large b)

0nXn: single EMD (medium b)

XnXn: mutual EMD (smaller b)

Three independent measurements at the same rapidity, but different impact parameters
Run 2: rapidity dependence of $J/\psi$ coherent production in EMD classes

Pb + Pb $\rightarrow$ Pb + Pb + $J/\psi$

CMS

$\sigma_{J/\psi}$ (mb)

$dy$ (mb)

CMS, arXiv 2303.16984

Guillermo Contreras, CTU in Prague
Run 2: rapidity dependence of $J/\psi$ coherent production in EMD classes

CMS, arXiv 2303.16984
ALICE, CERN-EP-2023-100

Guillermo Contreras, CTU in Prague
Run 2: rapidity dependence of $J/\psi$ coherent production in EMD classes

Several UPC measurements for each rapidity range → We can extract the photonuclear cross sections!
Energy/Bjorken-x dependence of coherent production from Run 2

New Run 2 data from CMS and ALICE

- ALICE Preliminary, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV
- CMS, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV (arXiv:2303.16984)
- Guzey et al., using ALICE Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (PLB 726 (2013) 290-295)
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CMS, arXiv 2303.16984

ALICE, CERN-EP-2023-100

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3 orders of magnitude in x

810 GeV

810 GeV

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Consistency CMS-ALICE

810 GeV
Energy/Bjorken-x dependence of coherent production from Run 2

New Run 2 data from CMS and ALICE

3 orders of magnitude in x

Bjorken-x

10^{-5}

10^{-4}

10^{-3}

10^{-2}

\sigma(\gamma\text{Pb}) (\mu b)

10^3

10^2

10

20

30

40

50

10^2

2\times10^2

W_{\gamma\text{Pb,n}} (\text{GeV})

3 orders of magnitude in x

Agreement with analyses of Run 1 data

Consistency CMS-ALICE

ALICE Preliminary, Pb–Pb \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}

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810 \text{ GeV}

Agreement

CMS, arXiv 2303.16984

ALICE, CERN-EP-2023-100

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Energy/Bjorken-x dependence of coherent production from Run 2: Models

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Impulse approximation and STARlight work at low energies
Energy/Bjorken-x dependence of coherent production from Run 2: Models

![Graph showing the energy/Bjorken-x dependence of coherent production from Run 2. The graph includes data points from ALICE and CMS for various energies and models such as Impulse approximation, STARlight, EPS09 LO, LTA, GG-HS, b-BK-A. The graph also notes that LTA and colour dipole based models (b-BK-A, GG-HS) work at high energies, while Impulse approximation and STARlight work at low energies.](image)
Energy/Bjorken-x dependence of coherent production from Run 2: Shadowing

\[ S_{Pb} = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma_{IA}}} \]

- ALICE Preliminary, Pb–Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
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- Impulse approximation
- STARlight
- EPS09 LO

ALICE, CERN-EP-2023-100

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Energy/Bjorken-x dependence of coherent production from Run 2: Shadowing

Nuclear suppression factor (shadowing)

\[ S_{Pb} = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma_{IA}}} \]

No suppression at low energies?

ALICE Preliminary, Pb–Pb \( \sqrt{s_{NN}} = 5.02 \) TeV

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- Impulse approximation
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- b-BK-A

ALI-PREL-542299

CMS, arXiv 2303.16984

ALICE, CERN-EP-2023-100

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Energy/Bjorken-x dependence of coherent production from Run 2: Shadowing

Nuclear suppression factor (shadowing)

\[ S_{\text{Pb}} = \sqrt{\frac{\sigma_{\gamma\text{Pb}}}{\sigma_{\gamma\text{IA}}}} \]

No suppression at low energies?

Flattening of suppression at high energies?

ALICE Preliminary, Pb–Pb \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)

CMS, Pb–Pb \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) (arXiv:2303.16984)

Guzey et al., using ALICE Pb–Pb \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) (PLB 726 (2013) 290-295)

Contreras, using ALICE Pb–Pb \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) (PRC 96 (2017) 1, 015203)

Impulse approximation

STARlight

EPS09 LO

LTA

GG-HS

b-BK-A

ALI–PREL–542299

CMS, arXiv 2303.16984

ALICE, CERN-EP-2023-100

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Energy/Bjorken-x dependence of coherent production from Run 2: Shadowing

Nuclear suppression factor (shadowing)

\[ S_{\text{Pb}} = \sqrt{\frac{\sigma_{\gamma \text{Pb}}}{\sigma_{\gamma \text{IA}}}} \]

No suppression at low energies?

Shadowing and saturation based models describe data equally well.

Flattening of suppression at high energies?

ALICE, CERN-EP-2023-100

Guillermo Contreras, CTU in Prague
Energy/Bjorken-x dependence of coherent production from Run 2: Shadowing

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What can we do to disentangle saturation and shadowing models?

No suppression at low energies?

Shadowing and saturation based models describe data equally well.

Flattening of suppression at high energies?
J/ψ photonuclear production in Pb-Pb UPC
Mandelstam-\(t\) dependence
γPb collisions: Mandelstam-t dependence of coherent production

ALICE Pb+Pb → Pb+Pb+J/ψ, |y|<0.8

Very clear signals

HERA-like precision!

ALICE coherent J/ψ, |y|<0.8

Experimental uncorrelated syst. + stat.
Experimental correlated syst.
UPC to γPb model uncertainty

ALICE, Pb+Pb → J/ψ, |y|<0.8

|t| (GeV² / c²)

Counts per 25 (MeV / c)

ALICE, Pb+Pb → J/ψ, |y|<0.8

Very clear signals

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ALICE coherent J/ψ, |y|<0.8

Experimental uncorrelated syst. + stat.
Experimental correlated syst.
UPC to γPb model uncertainty

ALICE, Pb+Pb → J/ψ, |y|<0.8

|t| (GeV² / c²)

Counts per 25 (MeV / c)

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Very clear signals

HERA-like precision!

ALICE coherent J/ψ, |y|<0.8

Experimental uncorrelated syst. + stat.
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Guillermo Contreras, CTU in Prague
γPb collisions: Mandelstam-t dependence of coherent production

Very clear signals

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A model based on the form factor does not describe data
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A shadowing based, and a BK computation with impact-parameter dependence, close to data

A model based on the form factor does not describe data

ALICE coherent J/ψ, |y|<0.8
Experimental uncorrelated syst. + stat.
Experimental correlated syst.
UPC to γPb model uncertainty

ALICE Pb+Pb → Pb+Pb+J/ψ $\sqrt{s_{NN}} = 5.02$ TeV

Model / Data

STARlight (Pb form factor)
LTA (nuclear shadowing)
b-BK (gluon saturation)

Guillermo Contreras, CTU in Prague
γPb collisions: Mandelstam-t dependence of coherent production

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|t| related to the transverse size of the target (b and p_T are Fourier conjugates)

Very clear signals

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γPb collisions: Mandelstam-t dependence of coherent production

A shadowing based, and a BK computation with impact-parameter dependence, close to data

A model based on the form factor does not describe data

Very clear signals

Dynamic QCD effects seem to make the t-distribution steeper ... do nuclei grow with energy?
γPb collisions: Mandelstam-\(t\) dependence of incoherent production

\[ \text{\textit{ALICE, Pb-Pb UPC} } \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ \text{ALICE incoherent } J/\psi, |y| < 0.8 \]

- Uncorrelated stat. + syst.
- Correlated syst.

\[ d\sigma_{\gamma\text{Pb}}/dt (\text{mb GeV}^2) \]

- MS-hs
- MS-p
- GSZ-el+diss
- GSZ-el

Model / Data

It\(l\) related to the size of the target: effect of smaller structures appears at larger It\(l\)
γPb collisions: Mandelstam-t dependence of incoherent production

Production off nucleons (Shadowing+HERA data)

Production off nucleons (CGC approach)

|t| related to the size of the target: effect of smaller structures appears at larger |t|
γPb collisions: Mandelstam-t dependence of incoherent production

Production off nucleons (Shadowing+HERA data)

Production off nucleons including dissociation (Shadowing+HERA data)

Production off nucleons including hot spots (CGC approach)

Itl related to the size of the target: effect of smaller structures appears at larger Itl
γPb collisions: Mandelstam-\(t\) dependence of incoherent production

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Models including hot spots or dissociation agree better with the slope of data
γPb collisions: Mandelstam-t dependence of incoherent production

Production off nucleons (Shadowing+HERA data)

Production off nucleons including hot spots (CGC approach)

Production off nucleons including dissociation (Shadowing+HERA data)

Larger |t| is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales

|t| related to the size of the target: effect of smaller structures appears at larger |t|

Models including hot spots or dissociation agree better with the slope of data

Guillermo Contreras, CTU in Prague
A brief look at the future
Current measurements were done with few thousand of $J/\psi$ candidates from LHC Run 2 data
Current measurements were done with few thousand of J/ψ candidates from LHC Run 2 data

The LHC Run 3 is ongoing and new data are being recorded!
### Expectations for Run 3+4 at the LHC

Current measurements were done with few thousand of J/$\psi$ candidates from LHC Run 2 data

- The LHC Run 3 is ongoing and new data are being recorded!

Pb-Pb UPCs: projections for 13 1/nb in the LHC Run 3 and 4

| Meson                              | $\sigma$ | |y|<0.9 | |y|<2.4 | 2.5<|y|<4 | 2<|y|<5 |
|------------------------------------|----------|--------|-------|-------|--------|-------|
| $\rho \rightarrow \pi^+ \pi^-$     | 5.2b      | 68 B   | 5.5 B | 21B   | 4.9 B  | 13 B  |
| $\rho' \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ | 730 mb   | 9.5 B  | 210 M | 2.5 B | 190 M  | 1.2 B |
| $\phi \rightarrow K^+ K^-$        | 0.22b     | 2.9 B  | 82 M  | 490 M | 15 M   | 330 M |
| $J/\psi \rightarrow \mu^+ \mu^-$  | 1.0 mb    | 14 M   | 1.1 M | 5.7 M | 600 K  | 1.6 M |
| $\psi(2S) \rightarrow \mu^+ \mu^-$ | 30 $\mu$b | 400 K  | 35 K  | 180 K | 19 K   | 47 K  |
| $Y(1S) \rightarrow \mu^+ \mu^-$   | 2.0 $\mu$b | 26 K  | 2.8 K | 14 K  | 880 K  | 2.0 K |

Pb-Pb UPCs: projections for 13 1/nb in the LHC Run 3 and 4

- Millions of J/$\psi$ expected in Run 3+4

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Citron et al, CERN Yellow Rep.Monogr. 7 (2019) 1159-1410

Guillermo Contreras, CTU in Prague
The LHC keeps producing new photoproduction measurements, which allow us to understand better the nuclear structure at high energies (small Bjorken-x)
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Many of the measurements from photon-induced processes not shown today: polarisation, flow, exclusive dijet production, $A$-dependence of $\rho^0$, exclusive and dissociative vector meson production off protons, ...

See partial list of results in the backup

Summary

Guillermo Contreras, CTU in Prague
Summary and outlook

The LHC keeps producing new photoproduction measurements, which allow us to understand better the nuclear structure at high energies (small Bjorken-\(x\)).

Many of the measurements from photon-induced processes not shown today: polarisation, flow, exclusive dijet production, \(A\)-dependence of \(\rho^0\), exclusive and dissociative vector meson production off protons, ...

The LHC Run 3 has started! 
Large Pb-Pb data sample this year
Oxygen-Oxygen and proton-Oxygen collisions for 2024
Later on p-Pb (\(\gamma p\)) collisions

Event from the 2022 data taking period

See partial list of results in the backup

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A bright future for photoproduction studies at the LHC with Run 3+4 data!
Partial list of LHC results on photon-induced interactions


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