Ultra-peripheral collisions in heavy ions at the LHC

Daniel Tapia Takaki

Diffraction:
International Workshop on Diffraction in High-Energy Physics
Catania, Sicily - 7 September 2016
UPC experimental talks at Diffraction

- **ALICE:**
  - J. Adam: two-photon process and VM results in gamma-p
  - G. Contreras: VM results in gamma-Pb

- **ATLAS:**
  - M. Arrieta: two-photon process

- **CMS:**
  - A. Bylinkin: VM result in gamma-p
Using the LHC as a γγ, γPb, γp collider

The most powerful collider not only for pp and Pb-Pb collisions, but also for photon-photon and photon-hadron interactions

UPC physics at LHC
Why Ultra-Peripheral collisions

Enrico FERMI

The electromagnetic field surrounding these protons/ions can be treated as a beam of quasi real photons.

Two ions (or protons) pass by each other with impact parameters \( b > 2R \). **Hadronic interactions are strongly suppressed**

\[ \text{High photon flux} \sim Z^2 \]

→ well described by the Weizsäcker-Williams approximation

Therefore, we consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.
LHC: *the most energetic photon source ever built*

Photon-induced collisions at the Tera-eV scale
UPCs: multiple studies are possible

- Understanding of the initial state produced in high energy nucleus-nucleus collisions
- Understanding gluons and their self-interactions in nucleons/nuclei
- Glueballs, exotic quarkonia …
- QED physics, radiative decays, strong fields
- Electro-weak final states
- Beyond the Standard Model
9 UPC studies with heavy ions at the LHC


- Charmonium and $e^+e^-$ pair photoproduction at mid-rapidity in ultra-peripheral $Pb-Pb$ collisions at $s_{NN}\sqrt{s}=2.76$ TeV Eur.Phys.J. C73 (2013) 11, 2617

- Exclusive $J/\psi$ photoproduction off protons in ultra-peripheral $p-Pb$ collisions at $s_{NN}\sqrt{s}=5.02$ TeV Phys.Rev.Lett. 113 (2014) 23, 232504

- Coherent $\rho^0$ photoproduction in ultra-peripheral $Pb-Pb$ collisions at $s_{NN}=2.76$ TeV JHEP 1509 (2015) 095


- Coherent $J/\psi$ photoproduction in ultra-peripheral $Pb-Pb$ collisions at $s_{NN}=2.76$ TeV with the CMS detector CMS-PAS-HIN-12-009. Submitted to PLB

- Measurement of exclusive Upsilon in $pPb$ collisions at $s_{NN} = 5.02$ TeV CMS-PAS-FSQ-13-009

- Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at $s_{NN} = 5.02$ TeV with the ATLAS detector at the LHC ATLAS-CONF-2016-025
The ALICE experiment at LHC

Central rapidity
Inner Tracking (ITS), Time Projection Chamber (TPC), Time-of-Flight, TRD, EMCAL
$|\eta| < 0.9$

Forward rapidity
Muon Spectrometer
$-4 < \eta < -2.5$

Dedicated triggers for UPC, using VZERO forward detectors for vetoing And MUON, TOF and SPD
ALICE can measure $J/\psi$ mesons down to zero $p_T$

ZDC at 116 m from IP, to study neutron/proton emitted at the very forward region
Forward detectors at CMS

G. Brona

FSC (6 < |η| < 8)

ZDC (|η| > 8.4)

CASTOR (5.2 < |η| < 6.6)

TOTEM T2 (5.2 < |η| < 6.6)

TOTEM T1 (3.1 < |η| < 4.7)

ZDC (|η| > 8.4)

FSC (6 < |η| < 8)

[TOTEM]

Roman Pots

\( y_p = 9.05 \)

\( \sqrt{s} = 5.02 \text{ TeV} \)

\( y_{po} = 8.12 \)
UPC: The most gentle collisions

CMS Experiment at LHC, CERN
Data recorded: Thu Nov 26 00:39:30 2015 CET
Run/Event: 262620 / 11202709
Lumi section: 217
Orbit/Crossing: 56785710 / 3145

Dimuon object
Invariant mass = 3.05 GeV
Ultra-peripheral Pb-Pb collisions
Coherent $\rho_0$

$\sqrt{s_{NN}} = 2.76$ TeV

$0.6 \leq M(\pi^+\pi^-) < 1.1$ GeV/$c^2$

$|y(\pi^+\pi^-)| < 0.5$

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7 September 2016
Both ALICE and STAR find measured cross section ~40% lower than predicted by Glauber, although works fine at fixed-target experiments.

Nuclei does not behave like individual nucleons?
Both ALICE and STAR find measured cross section \(~40\%\) lower than predicted by Quantum Glauber, although works fine at fixed-target experiments.

Nuclei does not behave like individual nucleons?
Nuclear effects
Nuclear gluon density

UPC studies provide the best information the community will get for the next 10 years before, the EIC turns on.
Vector meson photoproduction

\[
\left. \frac{d\sigma_{\gamma A \rightarrow J/\Psi A}}{dt} \right|_{t=0} = \xi_{J/\Psi} \left( \frac{16\pi^3\alpha_s^2\Gamma_{l+l^-}}{3\alpha M_{J/\Psi}^5} \right) [xG_A(x, \mu^2)]^2
\]
Coherent $J/\Psi$ photoproduction

Essentially Model independent. Parametrization of exclusive $J/\Psi$ data in gamma-proton $i.e. No nuclear effects$

Experimental evidence of nuclear gluon effects at low Bjorken-x and low virtuality

$Pb+Pb \rightarrow Pb+Pb+J/\Psi \quad \sqrt{s_{NN}} = 2.76\ TeV$

$L_{int} = 159\ \mu b^{-1}$

CMS
ALICE
Impulse Approximation
Leading Twist Approximation

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Both ALICE and STAR find measured cross section ~40% lower than predicted by Glauber, although works fine at fixed-target experiments.

Nuclei does not behave like individual nucleons?
Nuclear gluon density

For $x \sim 10^{-3}$ and $Q^2 = 3 \text{ GeV}^2$

$$S_A(W_{\gamma p}) = \frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)} = 0.61$$
Nuclear gluon density

For $x \sim 10^{-3}$ and $Q^2 = 3$ GeV$^2$

$$S_A(W_{\gamma p}) = \frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)} = 0.61$$

Recent: CTEQ group is starting to study UPC data for nPDF
See F. Olness, C. Bertulani, et al.
VM photoproduction data

\[ \sigma_{\gamma p} \rightarrow VM p (\mu b) \]

- \( \gamma p \rightarrow \omega p \)
- \( \gamma p \rightarrow \phi p \)
- \( \gamma p \rightarrow J/\psi p \)
- \( \gamma p \rightarrow \psi(2S)p \)
- \( \gamma p \rightarrow \tau(1S)p \)

\[ W (GeV) \]

Legend:
- \( \circ \) fixed target
- \( \times \) HERMES
- \( \square \) H1/ZEUS
- \( \triangle \) LHCb/ALICE

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Exclusive J/psi photoproduction


**UPC VM in pp, p-Pb is a direct tool to measure saturation**

Bjorken $x \sim 10^{-2} - 10^{-5}$

accessible at LHC

$\frac{d\sigma_{\gamma p\rightarrow J/\psi p}(t=0)}{dt} = \frac{16 \Gamma_{ee} \pi^3}{3\alpha_{em} M_{J/\psi}^5} \left[\alpha_s(Q^2)xG_{Pb}(x, Q^2)\right]^2$
Exclusive Upsilon photoproduction in $p$-$Pb$ collisions at 5.02 TeV
Results & Conclusions

Martin Hentschinski (BUAP)

BFKL & the growth of the VM Xsec.

September 4, 2016
t-differential measurements give a gluon tranverse mapping of the hadron/nucleus.
Exclusive J/ψ in p-Pb

Data well described by templates

Energy dependence is clearly visible

Low $W_{gp}$ energy point

$<W_{gp}> \sim 30$ GeV

High $W_{gp}$ energy point

$<W_{gp}> \sim 700$ GeV
Energy dependence of dissociative photoproduction: *signature of gluon saturation*

\[
\frac{d\sigma_{\text{PbPb}}(y)}{dy} = N_{\gamma/\text{Pb}}(y, M)\sigma_{\gamma\text{Pb}}(y) + N_{\gamma/\text{Pb}}(-y, M)\sigma_{\gamma\text{Pb}}(-y)
\]

**Neutron dependence**

\[
d\sigma(\text{total})/dy = d\sigma(0n0n)/dy + 2d\sigma(0nXn)/dy + d\sigma(XnXn)/dy
\]
Coherent J/psi predictions for Run 2

V. Guzey et al.  
*arXiv:1602.01456 [nucl-th]*
The Ridge in small systems

The ridge in UPC collisions?

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**Inclusive v. diffractive two-particle production**

- **Diffractive** dijet photoproduction:
  - Back-to-back correlation gets **enhanced** due to the saturation scale.
  - Balance between: $p_{1T}, p_{2T}, \Delta, Q_s$

- **Inclusive** dijet:
  - Back-to-back correlation gets **suppressed** due to the saturation scale.
  - Balance between: $p_{1T}, p_{2T}, Q_s$
High-$$p_T$$ jets with two leading protons

- At least two jets with $$p_T > 20$$ GeV.
- Forward Shower Counters (FSC) empty.
- Proton tracks (non-elastic) at TOTEM Roman Pots on both sides of IP.

**Very large rapidity coverage!**

**CMS:** $$|\eta| < 5$$  
**T2:** 5.3 < $$|\eta|$$ < 6.5  
**FSC:** 6 < $$|\eta|$$ < 8  
**TOTEM RP**
QED physics, radiative decays, strong fields:

...Two-photon production of lepton pairs
2010: Low luminosity, but trigger allows to cover the low mass region

2011: High luminosity, measurement to higher masses possible

A LO QED calculation (STARLIGHT) describes the data

Strong constraint on NLO contributions
No hits of strong field effects
Beyond the Standard Model
UPCs and Axion-like particles

S. Knapen, et al.
UPCs and Axion-like particles

S. Knapen, et al.
LHC schedule

CERN Yellow Report: \textit{CERN-PH-LPCC-2015-001}

At the very least, UPC physics at the LHC is a good testbed of EIC physics.
Summary and outlook

• Studying QCD with high energy photon-photon, photon-proton and photon-nuclear interactions at the LHC

• Searching for saturation effects in the proton

• Nuclear effects at both low and high Bjorken-x

• So far, most analyses have been carried out for exclusive VM photoproduction but new studies possible for other final states (dijets, double VM, diphoton, etc)

• Inclusive photo-nuclear and photon-proton reactions also possible
• It is now time to

…..discuss and prepare for future LHC runs

…discuss/work on theoretical challenges

…discuss applications for future experimental facilities such as the EIC
Additional slides
Event-by-event fluctuations:

- Coherent diffraction: target remains intact
  \[
  \frac{d\sigma}{dt} \sim |\langle A(x, Q^2, t) \rangle|^2
  \]

- Incoherent, target breaks up: variance
  \[
  \frac{d\sigma}{dt} \sim \langle |A(x, Q^2, t)|^2 \rangle - |\langle A(x, Q^2, t) \rangle|^2
  \]

\[\langle \rangle = \text{Target average.}\]
Constraining proton fluctuations in $\gamma + p \rightarrow J/\Psi + p^*$

- Incoherent data requires large fluctuations
Data and theoretical predictions

Coherent $J/\psi$

Incoherent $J/\psi$

Direct evidence of nuclear gluon shadowing

At mid-rapidity, Bjorken-$x \sim 10^{-3}$

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

Two UPC publications by ALICE


Color fluctuation effects in UPCs

Color fluctuations are much larger than in the case of the proton interactions resulting in a large enhancement of the nuclear shadowing.

L. Frankfurt et al.
Prospects for Run 2

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Do nuclear effects affect differently 1S and 2S states? Need more precise data!

\[ \Psi(2s)/J/\Psi \text{ enhancement in } \text{gamma+Pb collisions} \]
A transverse slice through CMS

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Dashed Green: Neutral Hadron (e.g., Neutron)
- Blue Dashed: Photon

Hadron Calorimeter
Electromagnetic Calorimeter
Silicon Tracker

Iron return yoke interspersed with Muon chambers
Superconducting Solenoid

Transverse slice through CMS
Forward detectors at CMS

Forward Shower Counters
6 < |\eta| < 8

Zero Degree Calorimeter
|\eta| > 8.1

TOTEM T1, 3.1 < |\eta| < 4.7

CASTOR, -6.6 < \eta < -5.2

HF (Hadron Forward)
3 < |\eta| < 5

BSC (MinBias triggers)
3.23 < |\eta| < 4.65

TOTAL Roman Pots
±147m, ±220m

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