 Photon-proton and photon-nucleus measurements in CMS

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On behalf of CMS collaboration

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Outline

- Introduction: Exclusive quarkonia photoproduction is a clean probe of the proton/nucleus gluon density

- Exclusive photoproduction of Upsilon in pPb collisions at $\sqrt{s} = 5.02$ TeV
  - t-differential cross-section
  - total cross-section as a function of c.m. energy

- Coherent photoproduction of J/$\psi$ in PbPb collisions at $\sqrt{s} = 2.76$ TeV
  - cross-section as a function rapidity

- Summary
Photon-proton and photon-nucleus interaction

Peripheral interactions with impact parameter $b$, greater than sum of nuclear radii, $b > 2R$ (or $R_A + R_B$) dominated by electromagnetic/diffractive interactions.

- The flux of photons is $\alpha Z^2$.

- $\gamma$–proton interaction:
  Pb emits photon, gg(singlet) exchange between $q\bar{q}$ pair and target proton (Dominant contribution in pPb collisions).

- $\gamma$–nucleus interaction:
  Proton/Pb emits photon, gg(singlet) exchange between $q\bar{q}$ pair and target Pb nucleus.
The CMS Experiment

- **Total weight**: 14k tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

- **Steel Return Yoke**: 12,500 tonnes
- **Silicon Trackers**: $|\eta| < 2.5$
- **Superconducting Solenoid**: Ni-Ti coil carrying 18,000 A
- **Muon Chambers**
- **Preshower**: $1.65 < |\eta| < 2.6$
- **Hadronic Forward (HF)**: $2.9 < |\eta| < 5.2$
- **Electromagnetic Calorimeter (ECAL)**: $|\eta| < 1.48$ + $1.48 < |\eta| < 3.00$
- **Hadron Calorimeter (HCAL)**: HB + HO: $|\eta| < 1.3$
  HE: $1.3 < |\eta| < 3.0$

- **CASTOR**: $5.2 < |\eta| < 6.6$
- **ZDC**: $|\eta| < 8.1$
Exclusive Y photoproduction in pPb at 5 TeV

- Ions emit quasi-real photon with flux $\alpha Z^2$
- $\gamma p$: Dominant contribution, $\gamma Pb$: Small contribution
- Photoproduction process is sensitive to the square of the gluon density in the proton

$$\frac{d \sigma_{\gamma p, A \rightarrow V p, A}}{dt} \bigg|_{t=0} = \frac{\alpha_s \Gamma_{ee}}{3 \alpha M_V^5} 16 \pi^3 \left[ x G (x, Q^2) \right]^2$$

$t =$transverse momentum exchanged square

$$\sigma_{\gamma p} = \frac{1}{b} \frac{d \sigma_{\gamma p, A \rightarrow V p, A}}{dt} \bigg|_{t=0}$$

$b \sim \text{slope of exp (t)}$

- Probe badly-known gluon distribution in the proton at low $x$ ($10^{-4}$ to $2 \times 10^{-2}$)

$$x = \left( \frac{M_Y}{W_{\gamma p}} \right)^2$$

$W_{\gamma p}$ – photon proton center of mass energy

- Photonuclear cross-section follows power law dependance with $W_{\gamma p}$ (same as gluon PDF evolution)

$$\sigma \propto W_{\gamma p}^\delta$$

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Exclusive Y photoproduction in pPb at 5 TeV

- 2013 pPb data at 5.02 TeV with 32.6 nb$^{-1}$

- Offline exclusive pPb $\rightarrow \Upsilon (\gamma p) \rightarrow \mu^+\mu^-$ signal selection
  - Invariant mass ($\mu\mu$) : 9.12-10.64 GeV
  - Opposite-sign $\mu\mu$ pair (final state) originating from common primary vertex
  - No extra tracks at $\mu\mu$ vertex to suppress non-exclusive background
  - Upsilon $p_T$ : 0.1-1 GeV to suppress QED and non-exclusive background
  - Upsilon rapidity : $|y| < 2.2$ high muon finding efficiency

QED continuum Background
Exclusive Y in pPb at 5 TeV: Data-MC comparison

Data compared to MC simulation including:

- Low $p_T$: QED elastic background (STARLIGHT)
- High $p_T$: Non-exclusive background (estimated from data)

STARLIGHT MC: $\gamma\text{Pb}$(small contribution) and $\gamma p$ contributions reweighted

Good agreement between data and MC
Number of signal events estimated by subtracting all background contributions.
\( d\sigma/dt \) (\( t = \) transverse momentum exchanged square) fitted with an exponential function, provides information on the transverse profile of the proton.

The differential cross section is determined according to

\[
\frac{d\sigma}{dt} = \frac{N_{\text{sig}}^{\text{Unfolded}}}{L \times \Delta t}
\]

\( N_{\text{sig}} \), the background subtracted, unfolded and acceptance corrected number of upsilon events in each \( |t| \) bin.

CMS Results:
\( b = 4.5 \pm 1.7 \) (stat.) \( \pm 0.6 \) (syst.) \( \text{GeV}^{-2} \)

Data is in agreement with ZEUS measurements & consistent with pQCD predictions

ZEUS for \( \Upsilon(1S) \)
\( b = 4.3^{+2.0}_{-1.3} \) (stat)
Total cross-section is estimated by
\[ \sigma_{\gamma p \rightarrow Y(1S)p}(W_{\gamma p}^2) = \frac{1}{\Phi} \frac{d\sigma_{Y(1S)}}{dy} \]

\( \Phi = \) Photon flux

Rapidity distribution of \( Y(1S+2S+3S) \)

\( Y(1S) \) cross-section (multiplied by branching ratio) corrected for feed-down from \( Y(2S) \)

A fit with power-law \( A \times X (W/400)^{\delta} \) to CMS data
\[ \delta = (0.96 \pm 0.43), A = 655 \pm 196 \]

Data compatible with power-law dependence of \( \sigma(W_{\gamma p}) \), disfavours steeper LO pQCD predictions.
Evolution consistent with previous HERA/LHCb results
Exclusive $J/\psi$ photoproduction in PbPb at 2.76 TeV

- Coherent vector meson production:
  - Quasireal photons emitted coherently from whole Pb ion:
    \[ (\omega_{\text{max}} \sim \gamma/R), \langle p_T \rangle \sim 1/R_{\text{Pb}} \sim 60 \text{ MeV/c} \]

- Incoherent vector meson production:
  - Photon couples to single nucleon
  - \( \langle p_T \rangle \sim 1/R_{\text{P}} \sim 200 \text{ MeV/c} \)
  - Target nucleus normally breaks up

- Photoproduction process is sensitive to very badly-known gluon PDF (squared) in Pb

\[
\left. \frac{d\sigma_{\gamma A \rightarrow J/\psi A}}{dt} \right|_{t=0} = \frac{\xi_{J/\psi}}{\Gamma_{J/\psi}} \left( \frac{16\pi^3 \alpha_s^2 \Gamma_{\ell+\bar{\ell}}}{3\alpha M_{J/\psi}^5} \right) [x G_A(x, \mu^2)]^2
\]

- Probe gluon distribution in Pb at low x
  \( x(J/\psi) \sim 10^{-5} \) to \( 2*10^{-2} \)

- Promising probe to study nuclear gluon saturation/shadowing at small Bjorken x

\[
R^D_g(x, Q^2) = \frac{G_A(x, Q^2)}{AG_p(x, Q^2)} - \text{gluon shadowing factor}
\]
Exclusive J/ψ photoproduction in PbPb at 2.76 TeV

- 2011 PbPb data at 2.76 TeV with 159 μb⁻¹

- Offline exclusive PbPb → J/ψ → μ⁺μ⁻ signal selection
  - Muons within 1.2 < |η| < 2.4 & 1.2 < p_T < 1.8
  - No extra tracks at μμ vertex to suppress non-exclusive background
  - Invariant mass (μμ) : 2.6-3.5 GeV
  - J/ψ p_T < 1 GeV and rapidity : 1.8 < |y| < 2.3
  - No HF activity
  - (Xn0n) nuclear break up mode: at least one neutron in one ZDC and other ZDC empty
Coherent J/ψ yield in PbPb at 2.76 TeV

- Yield extraction via maximum likelihood fit to dimuon $p_T$
- Coherent J/ψ dominant for $p_T < 0.15$ GeV
- Fit yields: $207 \pm 18$ (stat) coherent J/ψ candidates,
  $75 \pm 13$ (stat) incoherent J/ψ candidates,
  $75 \pm 13$ (stat) $\gamma\gamma$ QED events with $p_T < 0.15$ GeV
Cross-section estimated via:

$$\frac{d\sigma^{coh}_{X_{n0n}}(J/\psi)}{dy} = \frac{N^{coh}_{X_{n0n}}}{B(J/\psi \rightarrow \mu^+\mu^-) \mathcal{L}_{int} \Delta y (A \varepsilon)_{J/\psi}}$$

corrected for feed-down fraction of J/ψ meson coming from ψ(2S)

Coherent cross-section for $X_{n0n}$ mode

$$\frac{d\sigma}{dy} = 0.36 \pm 0.04 \text{(stat)} \pm 0.04 \text{(syst)} \text{ mb}$$

Extrapolate $X_{n0n}$ mode cross-section to total cross-section:

<table>
<thead>
<tr>
<th>J/ψ with $p_T &lt; 0.15$ GeV/c</th>
<th>$X_nX_{n}/X_{n0n}$</th>
<th>$1_{n0n}/X_{n0n}$</th>
<th>$1_{n1n}/X_{n0n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>0.36±0.04</td>
<td>0.26±0.03</td>
<td>0.03±0.01</td>
</tr>
<tr>
<td>STARLIGHT</td>
<td>0.37</td>
<td>N/A</td>
<td>0.02</td>
</tr>
<tr>
<td>GSZ</td>
<td>0.32</td>
<td>0.30</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Leading-Twist Approximation (GSZ) reproduces better data than Starlight MC
→ Total coherent cross-section for J/ψ
dσ<sub>coh</sub>/dy = 1.82 ± 0.22 (stat) ± 0.20
(syst) ± 0.19 (theo) mb.

→ The data strongly disfavour the impulse approximation model prediction (proton PDF), indicating that nuclear effects are needed to describe coherent J/ψ photoproduction in γ + Pb interactions.

→ The data are found to be consistent with the leading twist approximation, which includes nuclear gluon shadowing.
Summary

Proton data compatible with powerlaw dependence of $\sigma(W_{\gamma p})$ in agreement w/ NLO predictions & HERA/LHCb data

Pb data consistent with the leading twist approximation including nuclear gluon shadowing.

Both measurements provide new constraints on the (badly known) proton/nuclear low-x glue