MEASUREMENT OF EXCLUSIVE DIMUON PRODUCTION IN ULTRA-PERIPHERAL COLLISIONS WITH ATLAS AT THE LHC

Peter Steinberg, for the ATLAS collaboration
25 May 2016
IS2016 Lisbon, Portugal
ULTRA PERIPHERAL COLLISIONS

Boosted nuclei are intense source of quasi-real photons

Typically treated using EPA (Weiszacker-Williams)

Photons with $E \lessgtr (\hbar c/R)\gamma$ are produced coherently ($Z^2$)

Up to $\sim 80$ GeV at 5.02 TeV

Experiments at RHIC & LHC have begun a systematic investigation of UPC, including:

**Photon-pomeron:**
production of vector mesons
(sensitivity to nPDF)

**Photo-nuclear:**
dijet production
(probe nPDF directly)

**Photon-photon:**
dilepton production
(& other exclusive states)
ULTRA PERIPHERAL COLLISIONS

- Boosted nuclei are intense source of quasi-real photons
- Typically treated using EPA (Weiszacker-Williams)
- Photons with $E \lesssim (\hbar c/R)\gamma$ are produced coherently ($Z^2$)
- Up to $\sim 80$ GeV at 5.02 TeV

ATLAS has first results on this one

**Photon-pomeron:**
production of vector mesons
(sensitivity to nPDF)

**Photo-nuclear:**
dijet production
(probe nPDF directly)

**Photon-photon:**
dilepton production
(& other exclusive states)
Measurement performed primarily with ATLAS muon spectrometer ($|\eta| < 2.7$, L1 triggering in $|\eta| < 2.4$) and inner detector ($|\eta| < 2.5$)

Calorimeter system ($|\eta| < 4.9$) used to select events with low transverse energy

MBTS scintillators cover forward region ($2.07 < |\eta| < 3.86$), with inner ring covering $2.76 < |\eta| < 3.86$

ZDC installed for 2015 but not used in this analysis
DATA & MONTE CARLO SAMPLES

- Uses \( L_{\text{int}} = 515 \, \mu b^{-1} \) of data with a special UPC muon trigger
  - Loose muon L1 trigger
  - Limit of total \( E_T < 50 \, \text{GeV} \) at L1
  - Maximum of 1 hit in both MBTS inner rings
  - At least one track with 400 MeV measured by high-level trigger tracking algorithm
  - Efficiency of MBTS part measured in data to be 98+1-2%

- Two different simulated samples used
  - 1.5M Single muons (2-10 GeV, \(|\eta| < 3\), realistic \( v_z \))
    - used to determine reconstruction efficiency
  - 1.5M STARLIGHT 1.1 events simulating \( \text{Pb} + \text{Pb} \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)} + \mu^+ + \mu^- \)
    - Integrated over nuclear excitation states, since no ZDC requirements made
    - Used for studying vertex efficiency, effect of \( \mu \) resolution/smearing
    - Truth level used for comparison cross sections
DILEPTONS FROM PHOTON–PHOTON COLLISIONS: THEORY

STARLIGHT cross sections implement formalism from Baltz, et al (PRC80 044902, 2009)

\[
\frac{d^2 \sigma}{dM_{\mu\mu} dY_{\mu\mu}} = \frac{d^2 \mathcal{L}_{\gamma\gamma}}{dM dY} \times \sigma(\gamma\gamma \rightarrow \mu\mu)
\]

**Lumi.** \[
\frac{d^2 \mathcal{L}}{dM dY} = \mathcal{L}_{\AA} \frac{M}{2} \int_{b_1 > R_A} d^2 b_1 \int_{b_1 > R_A} d^2 b_2 \ n(k_1, b_1)n(k_2, b_2)P(b)[1 - P_H(b)]
\]

\[Z^4 \sim 45 M!\]

**Nuclear photon flux from EPA:**

\[
n(k, b) = \frac{d^3 N}{dk d^2 b} = \frac{Z^2 \alpha}{\pi^2 kb^2} x^2 K_1^2(x)
\]

\[x = bk/\gamma.\]

**QED**

\[
\sigma_{\gamma\gamma} = \frac{4\pi \alpha^2}{W^2} \left[ 2 + \frac{8M^2}{W^2} - \frac{16M^4}{W^4} \right] \ln \frac{W + \sqrt{W^2 - 4M^2}}{2M} - \sqrt{1 - \frac{4M^2}{W^2}} \left( 1 + \frac{4M^2}{W^2} \right)
\]
EVENT SELECTION

For all triggered events (248k), a sequence of selections is applied

- All events must come from runs for which detector was in good condition
- Two good muons are required
  - both of which passing “tight” working point selections, requiring good compatibility between muon spectrometer and inner detector measurements
  - At least one of the muons must match a Level-1 muon (in cone with $\Delta R < 0.5$)
- Muons pass fiducial kinematic acceptance, ensuring good performance of ATLAS muon spectrometer

$\boldsymbol{p_T1, p_T2 > 4 \text{ GeV, } |\eta_1|, |\eta_2| < 2.4, M_{\mu\mu} > 10}$

- There exists a primary vertex in the event
- Both muons match good inner detector tracks, which comprise the primary vertex
- The muons have unlike signs
- No other good tracks in the vertex than the muons
- No other good tracks in the event

- After selections, 12069 events remain
Highest-mass UPC dimuon event in 5.02 TeV data:

$M_{\mu\mu} = 173$ GeV
To compare cross sections with theory calculations, must correct for detector effects

- Muon Trigger efficiency (>80%)
- Muon reconstruction and identification efficiency (>90%)
- Vertex reconstruction efficiency (~97% in MC)
- Contributions from possible backgrounds
- Effects from momentum resolution found to be negligible (within ~1%)

Event weight formed from factorized trigger (T) & reco (R) efficiency correction (each separately as function of $p_T$ and $q \times \eta$)

\[
\frac{1}{w} = \epsilon_R(\mu_1)\epsilon_R(\mu_2)(1 - (1 - \epsilon_T(\mu_1))(1 - \epsilon_T(\mu_2)))
\]
Due to nuclear form factor, UPC dimuon distributions should have pair $p_{T\mu\mu} \sim 0$ and thus small acoplanarity ($Aco = 1 - |\Delta\phi|/\pi$)

Aco distributions shown here in 3 rapidity bins, $10 < M_{\mu\mu} < 100$ GeV

Good agreement with STARLIGHT in the bulk

N.B. STARLIGHT does not incorporate QED final-state radiation (FSR)
ACOPLANARITY & HIGHER-ORDER QED

Radiative corrections $O(\alpha^3)$ involve an additional real photon in the final state

Expected to broaden $\mu^+\mu^-$ acoplanarity distribution, similar to what is seen in $e^+e^-$ (e.g. TASSO, shown here)

- Dotted line positioned at $A_c=0.008$ (corresponding to 1.44 degrees)
ACCOUNTING FOR ACOPLANARITY TAILS

➤ Reported cross sections allow for both scenarios to be true
  ➤ The tails are all backgrounds: thus we select Aco<0.008, and use the fits shown previously to extrapolate the tail into this region.
  ➤ This is a 2-4% correction, depending on Y_{μμ}
  ➤ The tails are all signals: all events are used, regardless of Aco

➤ The average of the results is presented as the central value
  ➤ The systematic uncertainty is half the difference
SYSTEMATIC UNCERTAINTIES

➤ Muon trigger efficiencies
   ➤ Agreement between minimum-bias and T&P methods good to 5%
➤ Reconstruction efficiencies
   ➤ Nominal muon uncertainties, based on systematic assessment of data/MC differences, are 2-4%
   ➤ Using looser (“medium”) identification requirements gives good agreement for $M_{\mu\mu}<30$ GeV, and 10% difference for $M_{\mu\mu}>30$ GeV.
➤ Unfolding uncertainties
   ➤ 1% uncertainty assigned due to fluctuations in bin-by-bin factors
➤ Vertex efficiency
   ➤ Data vs. MC gives 2.2% difference. 3% uncertainty assigned
➤ Background estimation
   ➤ Uncertainty includes assumptions that Aco tails are all background, and all signal
➤ MC closure is good to 2% level
➤ Luminosity uncertainty assigned to be 7%
➤ ~10-12% uncertainty overall
RESULTS: SINGLE MUON DISTRIBUTIONS

- Distributions of single muons, after full dimuon selections
- Data only corrected for dimuon trigger efficiency
PAIR CROSS SECTIONS VS. MASS AND RAPIDITY

- $\frac{d\sigma}{dM_{\mu\mu}}$ shown for $|Y_{\mu\mu}| < 2.4$ and $|Y_{\mu\mu}| > 1.6$
- $\frac{d\sigma}{dY_{\mu\mu}}$ shown for $10 < M_{\mu\mu} < 20$, $20 < M_{\mu\mu} < 40$, $40 < M_{\mu\mu} < 100$ GeV
- Truth STARLIGHT 1.1 (for $\gamma = 2705$) shown in solid histograms
RATIOS RELATIVE TO STARLIGHT

- Ratios relative to STARLIGHT
- Surprisingly good agreement over full range in $M_{\mu\mu}$ and $Y_{\mu\mu}$
- Verifies both overall $Z^4$ scaling of $\gamma\gamma$ luminosity & $\gamma$ spectrum
Different beam energies, but confirms expectations over >2 orders of magnitude in $M_{ll}$
CONCLUSIONS & OUTLOOK

➤ First ATLAS measurement of high-mass muon pairs from ultra-peripheral collisions in lead-lead collisions at 5.02 TeV

➤ Good agreement with STARLIGHT 1.1 calculations
  ➤ Verification of expected photon flux
  ➤ Precision now limited by lack of higher-order QED calculations

➤ These measurements are just the first step in the ATLAS UPC program
  ➤ Adding ZDC selections will probe impact parameter dependence in more detail
  ➤ ZDC-tagged events should have smaller impact parameter, and thus harder colliding photon spectra

➤ Next steps will be to probe nuclear wave function, including
  ➤ Vector mesons (ρ and J/Ψ)
  ➤ Jet production in photonuclear processes
EXTRA SLIDES
In principle, the nuclei can exchange additional photons during the collision, exciting one or both nuclei (e.g. nucl-th/0307031) via the giant dipole resonance (GDR) (referred to as “Pb*”)

- Excited nuclei emit one or more neutrons
- These are more likely for smaller impact parameters between the nuclei
- However, the impact parameter also controls the two-photon luminosity
  - Higher masses are enhanced more at smaller impact parameters
- Thus, expect ZDC-tagged events to have harder spectra than events only triggered on the muons
  - In this measurement we only trigger on the muons, such that the ZDC could be used to independently study this effect
- The next iteration of this measurement will include ZDC selections
➤ Single-muon trigger efficiency measured using 2015 Pb+Pb data
➤ Measured in two ways
  ➤ Single muons in minimum-bias HI data
    ➤ Coincidence of tight offline muon and Level-1 muon in ΔR<0.5
    ➤ Perform in FCal E_T bins (here using <1000 GeV)
  ➤ Tag and probe (T&P) in UPC dimuon events
    ➤ For events with two tight muons, at least one of which coincides with Level-1 muon (to trigger event), if the pair has p_T<500 MeV, then the other muon can be used as a probe

➤ Good (<5%) consistency between the two, limited by statistical precision of T&P:
  ➤ Fits performed to minimum-bias data since it has better statistical precision