with 16:9 format
...here be dragons...
...& there be dragons!
ELECTROMAGNETIC PROCESSES WITH QUASIREAL PHOTONS IN PB+PB COLLISIONS: QED, QCD, AND THE QGP

PETER STEINBERG, BNL FOR THE ATLAS COLLABORATION
INTRODUCTION

QUASI-REAL PHOTONS FROM LEAD-NUCLEI

- Boosted nuclei are intense source of quasi-real photons
- Typically treated using EPA (Weizsacker-Williams)
- Quantize classical field
- Photons with $E \approx \langle hc/R \rangle \gamma$ are produced coherently ($Z^2$)
- Up to ~80 GeV for Pb+Pb @ 5.02 TeV, 1.4 TeV for p+p!

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

- Photon-pomeron: production of vector mesons (sensitivity to nPDF)
- Photo-nuclear: jet photoproduction (probe nPDF directly)
- Photon-photon: dilepton, diphoton! (and other exclusive states)
1. Precise charged-particle tracking in $|\eta|<2.5$
INTRODUCTION

ATLAS DETECTOR

1. Precise charged-particle tracking in $|\eta|<2.5$

2. Hadronic & EM calorimetry in $|\eta|<4.9$

"pseudorapidity"

$\eta = -\ln \tan(\theta/2)$
INTRODUCTION

ATLAS DETECTOR

1. Precise charged-particle tracking in $|\eta|<2.5$

2. Hadronic & EM calorimetry in $|\eta|<4.9$

3. Precise $\mu$ tracking in $|\eta|<2.7$

Exclusive final-states require a fully-hermetic detector!
INTRODUCTION

ZERO DEGREE CALORIMETERS

UPC MEASUREMENTS

M=173 GEV EXCLUSIVE DIMUON EVENT

Run: 287038
Event: 71765109
2015-11-30 23:20:10 CEST

Dimuons UPC Pb+Pb 5.02 TeV
Exclusive dimuon event distributions corrected for trigger, reco & vertex efficiency, systematics cover whether long Aco tails are all signal or all background

STARLIGHT 1.1 provides good description of fully-corrected dimuon distributions, with hint of small excess at high $Y_{\mu\mu}$

(but NB missing physics: e.g. higher-order QED)
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration

σ_fid = 70±24 (stat.) ±17(syst) nb

4.4σ significance observed
3.8σ expected
Two or more jets (anti-$k_T$ $R=0.4$) with $p_T > 15$ GeV, $|\eta|<4.4$
At least one with $p_T > 20$ GeV, $|\Delta \phi|_{12} > 0.2$, $m_{jets} > 35$ GeV
UPC MEASUREMENTS

PHOTONUCLEAR DIJETS

jet variables: \( H_T = \sum_i P_{T,i}, \quad x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-\gamma_{\text{jets}}} \)

Excellent agreement with PYTHIA6 reweighed to STARLIGHT
UPC Dimuons in “Non-UPC” Events

- UPC dimuon rates calculated assuming the nuclei “miss”
  - However, you can still produce them when they don’t!

More details in poster by A. Angerami
Event and muon selection

- **Trigger**
  - *Dimuon trigger, each with 4 GeV at L1, and 4 GeV in HLT*

- **Muon selection**
  - *Tight selection, $p_T > 4 \text{ GeV, } |\eta| < 2.4$
  - *Selections on transverse and longitudinal impact parameter $< 1.5 \text{ mm}*

- **Pair requirement**
  - *Opposite sign pairs with $4 < M_{\mu\mu} < 45 \text{ GeV}*$

- **Trigger & reconstruction efficiencies determined using J/Ψ**
  - *Applied to each muon as $w^{-1} = \epsilon_{\text{trig}}\epsilon_{\text{reco}}$*
ANALYSIS STRATEGY

- Acoplanarity: difference in azimuthal angle (cf. UPC dimuons)

\[ \alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi} \]

- Asymmetry: difference in transverse momentum, divided by sum

\[ A \equiv \frac{|p_T^+ - p_T^-|}{p_T^+ + p_T^-} \]

- Combined impact parameter, larger for HF decays

\[ d_{0\text{pair}} \equiv d_0^+ \oplus d_0^- \]

Decompose measured spectra for \( A \) and \( \alpha \) to isolate contribution from signal \( \mu\mu \)

Heavy flavor dimuons have a clear signature of larger impact parameters
BACKGROUND FRACTION FROM TEMPLATES

For each centrality selection:

- Create HF templates in $d_{0,\text{pair}}$, by selecting $\alpha>0.02$ & $A>0.15$
  - Use PYTHIA8 template for centralities with low statistics
- Signal template by fully simulated STARLIGHT 1.1
- Fit to form:
  \[
  F(d_{0,\text{pair}}) \equiv f S(d_{0,\text{pair}}) + (1-f) B(d_{0,\text{pair}})
  \]
For each centrality selection:

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For each centrality selection:

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- Fit to form:

\[
\mathcal{F}(d_{0,\text{pair}}) \equiv f S(d_{0,\text{pair}}) + (1 - f) B(d_{0,\text{pair}})
\]

Signal fraction ~100% in >80% (mainly UPC)
Decreases for more central events (\( N_{\text{coll}} \) scaling)
Uptick in 0-10% most-center (jet quenching)
BACKGROUND TEMPLATES BY CUT INVERSION

For each centrality selection:

- BG Template for $A$: $\alpha > 0.015$
- BG Template for $\alpha$: $A > 0.06$
- Fit to 2nd order polynomial
- systematics by const. & linear fits

For each centrality selection:

- $\gamma \gamma \rightarrow \mu \mu$ IN Pb+Pb

\[P_{\text{ATLAS}} = 5.02 \text{ TeV} \]
\[s^{-1} \text{Pb+Pb, 0.49 nb} \]

Data background
Heavy flavor: \(1 - P_{\text{ATLAS}}\) 

$\gamma \gamma \rightarrow \mu \mu$ IN Pb+Pb

\[P_{\text{ATLAS}} = 5.02 \text{ TeV} \]
\[s^{-1} \text{Pb+Pb, 0.49 nb} \]

Data background
Heavy flavor

\[\alpha \rightarrow \mu \mu\]
BACKGROUND EXTRACTION

For each centrality selection:

- Now focus on signal region
  - Select $A_{\mu\mu}<0.06$ to study $\alpha$
  - Select $\alpha<0.015$ to study $A$
- Normalize BG templates to signal fraction and subtract
Simulated STARLIGHT events show no centrality-dep. broadening

HF-determined backgrounds saturate tails

No obvious contribution from Drell-Yan, Y, or dissociative processes
Fit width of signal distributions using Gaussian + background template

- Alternate fit convolving over $\sigma(p_T)$
- $\alpha$ width clearly grows with centrality
- No sensitivity to asymmetry distributions
EXTRACTING RMS $k_T$ FROM DIMUON DISTRIBUTIONS

- Assume broadening from small transverse momentum imparted to each muon

- $<k^2_T>$ extracted using
  - $<\alpha^2>$ from centrality-dependent $\sigma$
  - Nominal variance $<\alpha^2>_0$ from fit to >80% centrality (UPC)
  - Nominal $p^2_{T,\text{avg}}$ from fits to measured distributions

\[
<\alpha^2> = <\alpha^2>_0 + \frac{1}{\pi^2} \frac{\langle k^2_T \rangle}{\langle p^2_{T,\text{avg}} \rangle}
\]

<table>
<thead>
<tr>
<th>Centrality [%]</th>
<th>$N_{\text{part}}$</th>
<th>$p^\text{RMS}_{T,\text{avg}}$ [GeV]</th>
<th>Gaussian fit</th>
<th>Convolution fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_A$[\times10^3]</td>
<td>$\sigma_\alpha$[\times10^3]</td>
<td>$k^\text{RMS}_T$ [MeV]</td>
<td>$k^\text{RMS}_T$ [MeV]</td>
</tr>
<tr>
<td>0 – 10</td>
<td>359</td>
<td>$7.0 \pm 0.1$</td>
<td>1.79 $^{+0.10}_{-0.09}$</td>
<td>3.3 $^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>10 – 20</td>
<td>264</td>
<td>$7.7 \pm 0.4$</td>
<td>1.36 $^{+0.12}_{-0.10}$</td>
<td>2.3 $^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>20 – 40</td>
<td>160</td>
<td>$7.4 \pm 0.3$</td>
<td>1.72 $^{+0.04}_{-0.04}$</td>
<td>2.5 $^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>40 – 80</td>
<td>47</td>
<td>$6.8 \pm 0.3$</td>
<td>1.61 $^{+0.01}_{-0.00}$</td>
<td>2.0 $^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>&gt; 80</td>
<td>-</td>
<td>$7.0 \pm 0.3$</td>
<td>1.55 $^{+0.01}_{-0.01}$</td>
<td>1.54 $^{+0.02}_{-0.02}$</td>
</tr>
</tbody>
</table>
FITS TO EXTRACT RMS $k_T$

- Additional per-muon RMS $k_T$ beyond that found for >80% centrality (UPC)
- Small in absolute terms, but grows systematically with centrality
- In most central events $<k_T> \sim 70$ MeV
- Specific “tomographic” interpretation hinges on whether there are additional mechanisms for influencing muons in the context of a heavy ion collision.
EM PROCESSES IN PB+PB COLLISIONS

CONCLUSIONS

- EM-induced processes in Pb+Pb collisions in ATLAS teaches us about:

- 

![Graph](image1)

QED

![Graph](image2)
EM PROCESSES IN Pb+Pb COLLISIONS

CONCLUSIONS

- EM-induced processes in Pb+Pb collisions in ATLAS teaches us about:

- Events / 0.005
  0 2 4 6 8 10 12 14 ATLAS
  = 5.02 TeV
  NN s
  Pb+Pb
  Signal selection
  no Aco requirement

- QED

- QCD

- 42 < \mathrm{H}_T < 50 \text{ GeV}
- 58 < \mathrm{H}_T < 70 \text{ GeV (x 10^{-4})}
- 70 < \mathrm{H}_T < 84 \text{ GeV (x 10^{-4})}
- 84 < \mathrm{H}_T < 100 \text{ GeV (x 10^{-4})}
- 100 < \mathrm{H}_T < 119 \text{ GeV (x 10^{-4})}
- 119 < \mathrm{H}_T < 141 \text{ GeV (x 10^{-4})}
- 141 < \mathrm{H}_T < 168 \text{ GeV (x 10^{-4})}
- 168 < \mathrm{H}_T < 200 \text{ GeV (x 10^{-4})}
EM PROCESSES IN Pb+Pb COLLISIONS

CONCLUSIONS

- EM-induced processes in Pb+Pb collisions in ATLAS teaches us about:

QGP?

QED

QCD
BACKGROUND FITS VS. CENTRALITY

- **ATLAS internal 0 - 10 %**
- **10 - 20 %**
  - $\sqrt{s_{\text{NN}}} = 5.02$ TeV
  - Pb+Pb, 0.49 nb$^{-1}$
- **20 - 30 %**

- **30 - 40 %**
- **40 - 50 %**
- **50 - 60 %**

- **60 - 70 %**
- **70 - 80 %**
- **> 80 %**

**Entries**

**$d_{o\text{ pair}}$ [mm]**

**Data**
- **Fit (S+B)**
- **Signal (S)**
- **Background (B)**
ACOPLANARITY DISTRIBUTIONS VS. CENTRALITY FOR $\alpha < 0.015$

HF background saturates tails
ASYMMETRY DISTRIBUTIONS VS. CENTRALITY FOR $A < 0.06$

HF background saturates tails