Ultra Peripheral Collision
Experimental overview

Yongsun Kim
16 VI 2022
SQM2022, Busan
HADRONIC collisions

Central PbPb collision shown in CMS

Hadronic AA collision

- Large energy deposit at forward calorimeters
- Nuclei must be broken and deposit energy at forward calorimeters
Ultra peripheral collision

Ultra Peripheral Collision (UPC)
- quasi-elastic and diffractive collision
- No energy deposit in forward calorimeters
- Occasionally neutrons are emitted from excited ions
Equivalent Photon Approximation

Trajectory of fast moving charged particle is equivalent to a flux of photons (Fermi, 1924)
Later, this method was extended to relativistic regime by Weizsacker[1] and Williams[2]
At LHC photon energy can reach to 80 GeV, and at RHIC 3 GeV
We can practice high energy $\gamma + (p \text{ or } A)$ and $\gamma + \gamma$ collisions by triggering non-hadronic collisions

[1] Z. Phys. 88, 612 (1934)
Impact parameters of photo-interaction

- Giant dipole resonance knocks out neutrons
- Measured by Zero Degree Calorimeters
UPC depending on Impact parameter

Some UPC process

intact after collision

intact after collision

Close bypass

Far bypass

$P'_n(b)$

UPC

STARLIGHT 3.13
LHC beam energy

$XnXn$

$OnOn$

$XnOn$

b (fm)
UPC depending on Impact parameter

Some UPC process

intact after collision

breakup

Ø Bearing analogy to centrality

\[ b_{XnXn} < b_{0nXn} < b_{0n0n} \]

Some UPC process

\[ P_{in}(b) \]

UPC

STARLIGHT 3.13
LHC beam energy

- XnXn
- 0n0n
- Xn0n

b (fm)

10

10^2

10^3

0

0.5

1

2020

Klein and Steinberg, arXiv: 2005.01872

Shuai Yang, Hard Probes 2020
Neutron emission can be a proxy for the centrality among UPC
• The smallest (or non-) QCD system made by hadronic collision
  • $\gamma + A \simeq$ vector meson + A collision in the vector-meson dominance picture
  • Control measurement for study of quark gluon plasma
  • gluon momentum distribution at very low $x$
  • Low background provides precise test for BSM physics
Light by light scattering
Distinctive features:

- Concentrated at low $p_T$ (back to back)
- Smooth mass spectrum

Photon-photon interaction

$\gamma + \gamma \rightarrow \tau^+ + \tau^-$

$\gamma + \gamma \rightarrow \gamma + \gamma$
UPC for BSM search

$\gamma + \gamma \rightarrow \tau^+ + \tau^-$

*QED*

$\gamma + \gamma \rightarrow \gamma + \gamma$

*QED*

*Anomalous signal*

$\delta a_\tau$

*BSM*

$\gamma \gamma \rightarrow \gamma \gamma$

*BSM*

PLB 797 (2019) 134826, CMS

JHEP 03 (2021) 243, ATLAS


PLB 797 (2019) 134826, CMS

JHEP 03 (2021) 243, ATLAS
\(\gamma + \gamma \rightarrow \gamma + \gamma\)

- QED + CEP backgrounds are also well described by acoplanarity nature.
- No deviation from SM was observed.
- The strongest constraints for the mass ranges 6 < m_a < 100 GeV.
\[ \gamma + \gamma \rightarrow \tau + \tau \]

- Deviation from calculation can be a signal for anomalous magnetic moment \( a_\tau = (g_\tau - 2)/2 \)
- UPC at LHC is great laboratory by virtue of small backgrounds
- Cross section scales by \( Z^4 \sim 40,000,000 \) compared to pp
\[ \gamma + \gamma \rightarrow \tau + \tau \]

- ATLAS measured all three channels above with full Run II data
  - Analyzed the \( p_T \) shape to find the best fit with \( a_\tau \) as a parameter
  - \( a_\tau : (-0.058, -0.012) \cup (-0.006, 0.025) \) in 95% CL
- CMS measured Muon + 3 tracks with partial Run II data (full stat. in preparation)
  - Cross section with efficiency correction: \( \sigma_{\text{fiducial}} = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{sys}) \) \( \mu b \)
  - Compared \( \sigma_{\text{fiducial}} \) with theoretical calculation to extract \( a_\tau \)
\[ \gamma + \gamma \rightarrow \tau + \tau \]

**Results:**

<table>
<thead>
<tr>
<th>OPAL 1998</th>
<th>L3 1998</th>
<th>DELPHI 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a^{\tau} )</td>
<td>( a^{\tau} )</td>
<td>( a^{\tau} )</td>
</tr>
<tr>
<td>(-0.1)</td>
<td>(-0.05)</td>
<td>(0)</td>
</tr>
<tr>
<td>(0.02)</td>
<td>(0.04)</td>
<td>(0.06)</td>
</tr>
<tr>
<td>(0)</td>
<td>(0.02)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>(0.06)</td>
<td>(0.04)</td>
<td>(0.02)</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

Pb+Pb \( \sqrt{s_{NN}} = 5.02 \) TeV, 1.44 nb\(^{-1}\)

- **Best-fit value**
- **68% CL**
- **95% CL**

- **Expected 95% CL limits from combined fit:**
  \(-0.039 < a^{\tau} < 0.020\)

- **Observed 95% CL limits:**
  \((-0.058, -0.012) \cup (-0.006, 0.025)\)

- **Double-interval structure due to interference of SM and BSM amplitude**
- **Constraints on \( a^{\tau} \) similar to those observed by DELPHI**
- **Statistical uncertainties dominant, leading systematic uncertainties:**
  - Trigger efficiency
  - \( \tau \) decay modelling

**Summary**

† **UPC \( \gamma \gamma \) processes: test of QED & search for BSM**

† **Evidence (4 \( \sigma \)) of LbyL scattering in UPC PbPb**

† **< \( \alpha \) \( \odot \) \( \odot \) \( > \) \& < \( \beta \) \( \odot \) \( \odot \) \( > \) depend on \#neutron & b**

† **Observation of the \( \nu \) pair production in HI collisions**

† **Fiducial cross section of \( \gamma \gamma \rightarrow \nu \nu \) & limits on \( \psi \) \( - \) \( \gamma \)**

- Compared to DELPHI, better resolution is expected with Run3 + Run4 data

---

**DELPHI**

ee\( \rightarrow \)e(\( \gamma \gamma \rightarrow \tau \tau \))e


**CMS Preliminary**

PbPb\( \rightarrow \)Pb\( (\gamma \gamma \rightarrow \tau \tau \odot 3_{\text{prong}})\)Pb\( (\gamma \gamma \rightarrow \tau \tau \odot 3_{\text{prong}})\)

68% CL, 0.4 nb\(^{-1}\)

**CMS Phase 2 Projection Preliminary**

PbPb\( \rightarrow \)Pb\( (\gamma \gamma \rightarrow \tau \tau \odot 3_{\text{prong}})\)Pb\( (\gamma \gamma \rightarrow \tau \tau \odot 3_{\text{prong}})\), 68% CL, 13 nb\(^{-1}\)

Based on rate-only-analysis, assuming 4% uncertainty
Validation of Photon flux

- Concentrated at low $p_T$ (back to back)
- Smooth mass spectrum

Photon-photon interaction

Both nuclei intact

- Is our understanding of QED in UPC perfect?
Validation of Photon flux

• Concentrated at low $p_T$ (back to back)
• Smooth mass spectrum

Photon - photon interaction

Shuai Yang, Hard Probes 2020

• Is our understanding of QED in UPC perfect?
• Do we have good estimate for the initial photon flux?
Validation of Photon flux

- Is our understanding of QED in UPC perfect?
- Do we have good estimate for the initial photon flux?

\[ \gamma + \gamma \to \mu^- + \mu^+ \] may answer
Cross section of $\gamma\gamma \rightarrow \mu\mu(\text{ee})$ in PbPb UPC

- Cross section is proportional to the incoming photon flux
- Thus useful for calibration of photon flux
- SuperChic and STARLIGHT calculate inclusive cross section within uncertainties
Cross section of $\gamma\gamma \rightarrow \mu\mu(ee)$ in PbPb UPC

- $f_{Xn0n}/f_{XnXn}$: Deviation deviation between STARlight and data
Dilepton acoplanarity in non-UPC events

\[ \langle p_T^2 \rangle (\text{MeV/c}) \]

\[ M_{ee} (\text{GeV/c}^2) \]

\[ \alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{+l^-} \]

- \( \gamma + \gamma \rightarrow l + l \) excess observed in non-UPC peripheral events by STAR and ATLAS
- Production of magnetic field or effect by \( b \)-dependent effect?

ATLAS, PRL 121 (2018) 212301

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ \text{Pb+Pb}, 0.49 \text{ nb}^{-1} \]

\[ \frac{1}{N_s} \frac{dN_s}{d\alpha} \]

\[ 0 \rightarrow 0.015 \]

\[ 0 \rightarrow 0.015 \]

\[ \gamma_1 \gamma_2 \]

Initial-state effect?

- Initial photon \( \langle p_T \rangle \) increases with \( b \) decreases
Dimuon acoplanarity in UPC

- Photo-produced dimuon pairs had acoplanarity depending on the impact parameter
- Theory compatible with data when the b-dependnt photon $p_T$ is considered [arXiv:2006.07365]
Dimuon acoplanarity in UPC

- ATLAS observed the excess of high acoplanarity events ($\alpha > 0.01$) which is not in STARlight
- Need for NLO calculation
Vector meson in $\gamma + p(\text{Pb})$

- $\rho(770)$, $J/\psi$, $\psi(2S)$, $\Upsilon(\text{nS})$, $\phi$
- Test for pQCD and nuclear structure

[Diagram showing production of vector meson in $\gamma + p$ reaction with nuclear targets.]
\( J/\psi \) probes gluon distribution in Pb

- \( J/\psi \) was suppressed by more than factor of 2 when compared to normalized \( \gamma + p \) calculation with impulse approximation.
- Models with shadowing and saturation effects better describes data.
- Yet, none can reproduce the rapidity distribution in \(-4 < y < 1\)
The suppression of $\psi(2S)$ level is same to $J/\psi$ in UPC

- Confirm the suppression occurs by gluon distributions in A
$J/\psi$ probes gluon distribution in Pb

- First measurement of charmonia spectra vs $p_T$
J/ψ probes gluon distribution in Pb

- LHCb also measured rapidity-differential cross section and single ratio of J/ψ and ψ(2S), providing input for pQCD models
NLO calculation looks promising for $J/\psi$ phenomenology

Löytäinen’s slides in QM22

- Sensitive to the scale, but can find an optimal value that reproduce $\gamma + p$ and $\gamma + Pb$ results simultaneously
NLO calculation looks promising for $J/\psi$ phenomenology

Löytäinen’s slides in QM22

- Sensitive to the scale, but can find an optimal value that reproduce $\gamma + p$ and $\gamma + Pb$ results simultaneously
- At mid rapidity, quark contribution is dominant because gluon’s amplitudes cancel for LO and NLO
Exclusive $\rho(770)$ in pPb collision at 5.02 TeV

- $|t|$ dependence shows proton density profile
- Diff. cross section of $\rho$ in $\gamma + p$ agrees well with HERA data
- Diff. cross section of $J/\psi$ in $\gamma + Pb$ agrees well with nuclear shadowing models
Exclusive $J/\psi$ in pPb collision at 8.16 TeV

- New $J/\psi$ result from ALICE shows agreement with HERA experiments and LHCb
- Also measured dissociative cross section where proton is broken by $\gamma$ interaction
- Agrees with saturation model (CCT)
Exclusive $\Upsilon(1S)$ in pPb collision at 5.02 TeV

- Exclusive $\Upsilon(1S)$ in $\gamma+p$ was measured as a function of rapidity.
- Compared with saturation deployed models CGC model (flPsat), Color dipole formalism (IIM), and pQCD calculation with DGLAP formalism (JMRT).
- $W_{\gamma p}$ dependence, power-law, is compatible with H1 and ZEUS.
\( \gamma + d \rightarrow J/\psi + X \)

- Gluon density in deuteron
- \( x \sim 0.01 \) where shadowing effect to be small
- Neutrons tagged for d-going direction
- The results disfavor LTA
- Better agrees with CGC saturation model, but doesn’t reprocess the \(|t|\)-dependence
Exclusive $\rho(770)$ in XeXe

- Study of target species dependence
- Power law fit $\alpha \sim 0.96 \pm 2$
- Coherent VM cross section is expected to scale by $A^{4/3}$, however, the nPDF cancel this out, as suggested by CKZ (shadowing) and CCKT (saturation)
Exclusive $\rho(770)$ in XeXe

- Study of target species dependence
- Power law fit $\alpha \sim 0.96 \pm 2$
- Coherent VM cross section is expected to scale by $A^{4/3}$, however, the nPDF cancel this out, as suggested by CKZ (shadowing) and CCKT (saturation)
Exclusive $\rho(770)$ in XeXe

- Study of target species dependence
- Power law fit $\alpha \sim 0.96 \pm 2$
- Coherent VM cross section is expected to scale by $A^{4/3}$, however, the nPDF cancel this out, as suggested by CKZ (shadowing) and CCKT (saturation)
Polarization in $\rho \rightarrow \pi^+ \pi^-$

A STAR: Signal $\pi^+ \pi^-$ pairs with $p_T < 60$ MeV

- $\rho \rightarrow \pi^+ \pi^-$ decay in Au+Au and U+U

- Photon polarization vector is aligned radially from the emitting source

- Evidence of the quantum interference between the transverse linear polarization?
Polarization in $\rho \rightarrow \pi^+ \pi^-$

**STAR:** Signal $\pi^+ \pi^-$ pairs with $P_T < 60$ MeV

![Graph showing polarization](image)

- Photon polarization vector is aligned radially from the emitting source
- No such signal in $\gamma+p$ collision
- Evidence of the quantum interference between the transverse linear polarization?
Polarization in $\rho \rightarrow \pi^+\pi^-$

**STAR:** Signal $\pi^+\pi^-$ pairs with $P_T < 60$ MeV

- Photon polarization vector is aligned radially from the emitting source
- No such signal in $\gamma+p$ collision
- Evidence of the quantum interference between the transverse linear polarization?
Photon polarization vector is aligned radially from the emitting source

No such signal in $\gamma+p$ collision

Evidence of the quantum interference between the transverse linear polarization?
Polarization in $\rho \rightarrow \pi^+\pi^-$

**A STAR:** Signal $\pi^+\pi^-$ pairs with $P_T < 60$ MeV

- $f(\phi) = 1 + A \cos(2\phi)$
- Syst. Uncert.
- \(f(\phi)\):
  - Au+Au: $A = (29.1 \pm 0.4 \pm 0.4) \times 10^{-2}$
  - U+U: $A = (23.8 \pm 0.6 \pm 0.4) \times 10^{-2}$
  - p+Au: $A = (-0.5 \pm 1.2 \pm 0.9) \times 10^{-2}$

**CMS**

- Exclusive VM production in UPC, Quark Matter 22
- Vector Meson photoproduction in UPC

\(Pb\) (p) \(p\) (Pb) \(Pb\) (p) \(Pb\)

\(Q^2 = -q^2\)

**Signal**
- Photon-Nuclear Interaction
- Photon-Photon Interaction
- Proton (and/or Lead) dissociation

**Background**

- jet1
- jet2

\(jet1\)
\(jet2\)

**arxiv:2205.00045, CMS**

PbPb 0.38 nb\(^{-1}\) (5.02 TeV)

- $p_{T,1} > 30$ GeV
- $p_{T,2} > 20$ GeV
- $|n_{\perp,1}| < 2.4$
- $Q_2 < 25$ GeV
- $P_T > Q_T$
Dijet probes gluon polarization

**arxiv:2205.00045, CMS**

PbPb 0.38 nb\(^{-1}\) (5.02 TeV)

- Data
- RAPGAP
- Hatta et. al.

\[ p_{T,1} > 30 \text{ GeV} \]
\[ p_{T,2} > 20 \text{ GeV} \]
\[ |\eta_{1,2}| < 2.4 \]
\[ Q_T < 25 \text{ GeV} \]
\[ P_T > Q_T \]

\[ \bar{Q}_T = \vec{k}_1 + \vec{k}_1 \]
\[ \bar{P}_T = \frac{\vec{k}_1 - \vec{k}_1}{2} \]

- A novel method to study Wigner and Husimi gluon distributions (*PRL 116, 202301 (2016)*)
- due to dipole scattering amplitude in the small-\(x\), so called “elliptic gluon” distribution
- Quantified as \(v_2\)

\(Q_T\) is the proxy for recoil momentum of Pb target.
Exclusive dijet probes gluon polarization

- Weaker polarization is observed in data compared to RAPGAP
- Hatta et al reproduces the $v_2$ as a function of $Q_T$ below 15 GeV, but presents a rapid plateau unlike steady increasing trend in data
Exclusive dijet - differential cross section

- Triply differential cross section as a function of $(\mathcal{H}_T, Z_\gamma, x_A)$
- Compared with nCTEQ (nPDF) \(\otimes\) STARlight (photon flux) \(\otimes\) PYTHIA8 (jet)
- Useful input to constrain nPDF
Correlation in UPC

Yeongdo
Two-particle correlation at LHC energy

\[ \gamma + p \text{ at CMS} \]
- Two-particle correlation for \(|\Delta \eta| > 2\)
- Significant \(v_2\), but no ridge
- \(2 < N_{\text{trk}} < 12\)
- Compatible with ALEPH [1], ZEUS [2], BELLE [3]

Azimuthal anisotropies in $\gamma + Au\sqrt{s_{NN}} = 54$ GeV ($\gamma + Au$-rich) 

- No signature of collectivity (near side ridge) in the $\gamma + Au$,
- Higher energy and activity events under exploration with STAR forward upgrades.

**γ + p @ CMS**
- Two-particle correlation for $|\Delta \eta| > 2$
- $2 < N_{\text{trk}} < 12$

**γ + Au @ STAR**
- Two-particle correlation for $|\Delta \eta| > 1$
- $1 < N_{\text{trk}}^{\text{TOF}} < 8$
Two-particle correlation at LHC energy

\[ \gamma + Pb \] @ ATLAS

- 20 < N_{trk} < 60
- Two-particle correlation for |\Delta \eta| > 2.5
- Jet-like contribution is subtracted using template fit using low multiplicity events
- \( v_2 \) is still alive
- A signal for collectivity, or breakup of assumptions in template methods?
Maybe, flow in UPC is not so surprising

Vector Meson dominance

- Ultra peripheral $A + A = \gamma + A = \rho + A$ by equivalent photon approximation and vector meson dominance
- Since it’s a hadronic collision, it may not be strange to make collectivity
Take home messages and questions

UPC, sic parvis magna

• UPC program at LHC was initially motivated for nuclear shadowing in heavy ion
• Proved to be useful for BSM searches
• Exclusive channels for gluon polarization
• Hints for collectivity

Questions to be answered in near future

• How can such a small system make very diverse phenomena?
  -> 2p correlation, high multiplicity event, jets, vector meson dominance, and many
• Can delicate theories, including NLO, shed light on new results?