Photo-production in heavy ion collision
All happening in HADRONIC collisions

Forward Calorimeter (HF) signal
- Used for centrality classification
All happening in HADRONIC collisions

Forward Calorimeter (HF) signal
- No energy deposit at HF
- Very small hadronic activity in whole event
1. UPC and photon scattering

\[ X_n X_n < b_0 n X_n < b_0 n n \]

\[ P_{nn}(b) \]

\[ b > 2R \]

\[ v \sim c \]
Di-jet from photo-production

\[ \gamma + \gamma \text{ process} \quad \gamma + IP \text{ process} \]
Di-muon production in UPC
Di-muon production in UPC

Some UPC process

breakup

intact after collision
Di-muon production in UPC

Some UPC process
ZDC - neutron detector

- Nuclear breakup measured by ZDC
- Number of neutrons = proxy for impact parameter
- CMS can categorize events by 0n0n, 0nXn, XnXn
Di-muon production in UPC

Control "centrality" in UPC

Klein and Steinberg, arXiv: 2005.01872

Shuai Yang, Hard Probes 2020

\[ P_{\text{fn}}(b) \]

UPC

STARLIGHT 3.13
LHC beam energy

- XnXn
- 0n0n
- Xn0n

\[ b \text{ (fm)} \]

0 10 100 1000

0 0.5 1
1. Light-by-light scattering
Photon from where?
Equivalent Photon Approximation (EPA)

E. Fermi suggested that trajectory of fast moving charged particle is equivalent to a flux of photons (1924)

Later, this method was extended to Ultra-relativistic regime by Weizsacker and Williams

Fast moving charged particle

... is equivalent to photon flux

where \( N_\gamma \) proportional to \( Z^2 \)

Nuovo Cim., 2:143-158, 1925

(arXiv:hep-th/0205086 in English)
**LHC, the most powerful photon collider**

\[ \omega_{\text{max}} = \frac{\hbar}{\Delta t} \sim \frac{\gamma \hbar v}{b}, \]

\[ N(\omega, b) = \frac{Z^2 \alpha \omega^2}{\pi^2 \gamma^2 \hbar^2 \beta^2 c^2} \left( K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right) \]


<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Ions</th>
<th>Max. Energy per nucleon pair (CM)</th>
<th>Luminosity</th>
<th>Max. $\gamma p$</th>
<th>Max. $\gamma \gamma$ energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN SPS</td>
<td>Pb+Pb</td>
<td>17 GeV</td>
<td>—</td>
<td>3.1 GeV</td>
<td>0.8 GeV</td>
</tr>
<tr>
<td>RHIC</td>
<td>Au+Au</td>
<td>200 GeV</td>
<td>$4 \times 10^{26}$ cm$^{-2}$ s$^{-1}$</td>
<td>24 GeV</td>
<td>6.0 GeV</td>
</tr>
<tr>
<td>RHIC</td>
<td>p+p</td>
<td>500 GeV</td>
<td>$6 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
<td>79 GeV</td>
<td>50 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>Pb+Pb</td>
<td>5.6 TeV</td>
<td>$10^{27}$ cm$^{-2}$ s$^{-1}$</td>
<td>705 GeV</td>
<td>178 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>p+p</td>
<td>14 TeV</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>3130 GeV</td>
<td>1400 GeV</td>
</tr>
<tr>
<td>Tevatron</td>
<td>p+\bar{p}</td>
<td>20 TeV</td>
<td>$5 \times 10^{31}$ cm$^{-2}$ s$^{-1}$</td>
<td>320 GeV</td>
<td>200 GeV</td>
</tr>
</tbody>
</table>
Light-by-light scattering

[ATLAS, Nature Phys 13, 852–858 (2017)]

- Provides test for axion-like particles, relatively light and gauge-singlet in the form of narrow di-photon resonances
- LHC can search $6 < M_{ALP} < 100 \text{ GeV/c}^2$
Constraints for ALP coupling to photons
2. Di-jet in UPC
Di-jet production in hadronic collisions

Hadron collision
* Uncertainty in proton PDF
* Complicated hard scattering calculation

Ultra-Peripheral Collision (UPC)
* Free from projectile PDF
* Much smaller uncertainties
* Complementary kinematic region
Distributions for the dijet production in pp/pA/AA collisions

dictions for the pseudo-rapidity and transverse momentum and pseudo-rapidity distributions for the differ-
we will perform a comprehensive analysis of the transverse
presented in Fig.
actions in pA and AA collisions. As a consequence, it is pos-
generalize this Monte Carlo to treat
in hadronic collisions and recently improved to also include
the calculations. In order to do that, we will use the Forward
pomeron-induced interactions including experimental cuts in
mate these processes considering the same set of assump-
son between its predictions. Our goal in this paper is to esti-
have been performed considering different approximations
arate these different contributions for the dijet production.
cinciple, it is possible to introduce a selection criterion to sep-
tum distributions, with those associated to pomeron-induced
generate emerging hadrons with different transverse momen-

\begin{align*}
\gamma + \gamma \text{ process} \\
\gamma + IP \text{ process}
\end{align*}
Di-jet from photo-production

\[ \eta \quad -8 \quad 0 \quad 8 \]

rapidity gap

\[ A' \]
\[ \gamma_A \]
\[ j_1 \]
\[ j_2 \]
\[ B' \]
\[ Pb \]

rapidity gap

\[ \eta \quad -8 \quad 0 \quad 8 \]

hadrons

\[ \eta \quad -8 \quad 0 \quad 8 \]

rapidity gap

\[ A' \]
\[ \gamma_A \]
\[ j_1 \]
\[ j_2 \]
\[ B' \]
\[ Pb \]
**Exclusive di-jet correlation**

The only process which can directly access to the Wigner distribution [PRL116, 202301 (2016)]

- Jets were used as the proxy of quarks decayed from the gluon
- Correlation between gluon and impact parameter vector due to dipole scattering amplitude in the small-x, so called "elliptic gluon" distribution
- Observable: $\nu_2 = \langle \cos(2\phi) \rangle$

Vector sum of 2 jets:
$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

Vector difference of 2 jets:
$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$
Exclusive di-jet correlation

- UPC events are selected by
  - Veto activity in the forward and backward regions $2.8 < |\eta| < 5.2$
  - Existence of only two jets:
    - $|\eta_{lab}| < 2.4$, $p_{T,1} > 30 GeV$, $p_{T,2} > 20 GeV$
- Jets are reconstructed by anti-$k_T$ algo with $R=0.4$
- ParticleFlow algo was used to provide input particles for jet finder
Exclusive di-jet correlation

- Rapidity gap = $\Delta \eta$ between the forward calorimeter boundary and the closest track in the event.
- Signature of exclusive di-jet process.
Exclusive di-jet correlation

- Result shows a back-to-back correlation in both data and RAPGAP MC
- Positive $\nu_2$ ($=<\cos(2\phi)>$) values for all PT and QT bins
Exclusive di-jet correlation

- Result is compared with the RAPGAP simulation and toyMC models
- $<\cos(2\phi)>$ in data is lower than in RAPGAP prediction by 20-30%, which provides input to the theory community
Feedback from theory society

- Theoretical developments are being made for our data
- In the following model, $v_2$ turns to be constant for $Q_T > 5$ GeV
- For better benchmarking, the unfolded data would be appreciated


FIG. 2. Anisotropy in diffractive dijet production $\gamma + A \rightarrow q\bar{q} + A$ in ultra peripheral heavy ion collisions at the LHC. The kinematics correspond to the CMS measurements [34] with the leading jet $P_{\perp} = 35$GeV and the two jets are at the same rapidity $\Delta y_{12} = 0$. The figure shows $\langle \cos(2\phi) \rangle$ as a function of $q_{\perp}$, where $\phi$ is the azimuthal angle between $q_{\perp}$ and $P_{\perp}$. 
3. Characterization of Pomeron interaction
Diffraction phenomenology

Non-Diffractive

Single Diffraction

Central Diffraction

Double Diffraction
Diffraction phenomenology in pPb

- Diffraction can be characterized by the rapidity gap
- Contribution from photon and Pomeron can be separated by comparing p-Pb and Pb-p collision
- CMS, as a hermetic & symmetric detector, is the best place for this test
Diffraction in pPb UPC

**IP-Pb interaction**
- Cross section in theoretical models are lower than data by factor of 2-4, but with similar shape as a function of $\Delta \eta$.
- HIJING model shows large deficit for high $\Delta \eta$ due to the lack of low mass diffraction.

**IP-p interaction**
- Neither normalization nor shape agree with data.
- Significant contribution from $\gamma$ +p is missing in MC simulations.
4. Di-lepton in UPC
Production of magnetic field (B = $10^{15}$ T) in the medium?

*PRL 121 (2018) 132301 by STAR
*PRL 121 (2018) 212301 by ATLAS
*PRL 127, 122001 (2021) by CMS
Di-lepton correlation

- $\gamma\gamma \rightarrow e^+e^-$ measured by STAR collaboration
  - Au+Au collision at $\sqrt{s_{NN}} = 200\,\text{GeV}$
  - U+U collision at $\sqrt{s_{NN}} = 193\,\text{GeV}$

- Data fits well with model with $B = 10^{14}\,\text{T}$
  - Evidence of formation of B field in heavy ion collision?

$\text{STAR PRL 121 (2018) 132301}$
Angular correlation measured at the LHC

- ATLAS collaboration
  - Pb+Pb collision at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
- Measured the azimuthal angular correlation of di-muon pairs
  $$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$$

ATLAS, PRL 121 (2018) 212301

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$
Pb+Pb, 0.49 nb$^{-1}$

$\alpha = 0.1$
Interpretation of di-muon acoplanarity

Final state effect?

Initial state effect?

Pair $\langle p_T \rangle$ increases with $b$ decreases

- Initial photon $\langle p_T \rangle$ increases with $b$ decreases

or, transverse momentum of initial photons?

Formation of magnetic field?

UPC experiment can judge because there is no QCD medium produced in UPC

$e^+ e^- \otimes \Phi$

$\left\langle p_T \right\rangle$ increases with $b$ decreases

$0.4 < M_{ee} < 0.76 \text{ GeV}/c^2$

$0.76 < M_{ee} < 1.2 \text{ GeV}/c^2$

$1.2 < M_{ee} < 2.6 \text{ GeV}/c^2$

Au+Au 200 GeV

$p_{T,e} > 0.2 \text{ GeV}/c$

$|y_{ee}| < 1; |\eta_e| < 1$
$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}$, $\alpha \propto p_T^{l^+l^-}$

$\alpha = 0$

$\mu^+$, $\mu^-$

$\alpha = 0.1$

$\mu^+$, $\mu^-$
Core (red dashed line) structure is attributed to the leading order interaction, and the tail to the next to leading order.
• Strong dependence of the di-muon acoplanarity on the impact parameter among UPC collisions
• Significant acoplanarity observed without production of QCD medium
Take home messages

- **UPC** in heavy ion experiments is useful to study photo-induced dynamics with very small noise.
- Photon-photon scattering was recently measured by ATLAS and CMS and provided strong constraints for ALP production mechanism.
- CMS made the first step to extract the Wigner/Husimi distribution of nucleus using di-jet correlation.
- More interesting results are in the queue, including precision measurement of di-jet, $\tau$ g-2, etc, so please stay tuned.
BACKUP