Particle production in photon – photon interactions at hadronic colliders: Recent results and prospects

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Motivation

Photon – Induced Interactions:

Center of mass energies

LHC = Photon collider

1. $\gamma h$ Processes: $\sigma(h_1 h_2 \rightarrow X) = n_h(\omega) \otimes \sigma^{\gamma h \rightarrow X} (W_{\gamma h})$

2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \rightarrow X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \rightarrow X} (W_{\gamma\gamma})$
Motivation

Photon – Induced Interactions:

Center of mass energies

<table>
<thead>
<tr>
<th>LHC</th>
<th>Interaction</th>
<th>Energy Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>$W_{\gamma p}$ (\lesssim 8390) GeV</td>
<td>$W_{\gamma p} \lesssim 4504) GeV</td>
</tr>
<tr>
<td>pPb(Ar)</td>
<td>$W_{\gamma A}$ (\lesssim 1500) GeV</td>
<td>$W_{\gamma A} \lesssim 260) GeV</td>
</tr>
<tr>
<td>PbPb</td>
<td>$W_{\gamma A}$ (\lesssim 950) GeV</td>
<td>$W_{\gamma A} \lesssim 160) GeV</td>
</tr>
<tr>
<td>ep</td>
<td>$W_{\gamma p}$ (\lesssim 200) GeV</td>
<td>-</td>
</tr>
</tbody>
</table>

LHC allow us to probe the particle production by photon – photon interactions in a energy range unexplored by LEP and higher than that proposed for the ILC.
LHC = Photon collider

\[ \sigma (h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2 ; s) = \int \hat{\sigma} (\gamma \gamma \rightarrow R ; W) N (\omega_1, b_1) N (\omega_2, b_2) S_{\text{abs}}^2 (b) d^2 b_1 d^2 b_2 d\omega_1 d\omega_2 \]
Motivation

Photon – Induced Interactions:

Center of mass energies

LHC = Photon collider

\[ \sigma (h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2; s) = \int \delta (\gamma \gamma \rightarrow R; W) N (\omega_1, b_1) N (\omega_2, b_2) S_{abs}^2 (b) d^2 b_1 d^2 b_2 d\omega_1 d\omega_2 \]

\[ \sigma^{PbPb} (\gamma \gamma) \approx Z^2 \sigma^{pp} (\gamma \gamma) \approx Z^4 \sigma^{pp} (\gamma \gamma) \]
Resonance production

\[ \sigma (h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2; s) = \int \delta (\gamma \gamma \rightarrow R; W) \, N (\omega_1, b_1) \, N (\omega_2, b_2) \, S_{abs}^2 (b) \, d^2 b_1 \, d^2 b_2 \, d\omega_1 \, d\omega_2 \]

\[ \sigma_{\gamma \gamma \rightarrow R}(\omega_1, \omega_2) = 8\pi^2 (2J + 1) \frac{\Gamma_{R \rightarrow \gamma \gamma}}{M_R} \delta (4\omega_1 \omega_2 - M_R^2) \]
Photon – Induced Interactions:

Motivation

Resonance production

\[
\sigma (h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2; s) = \int \hat{\sigma} (\gamma \gamma \rightarrow R; W) N (\omega_1, b_1) N (\omega_2, b_2) S_{abs}^2 (b) d_2 b_1 d_2 b_2 d \omega_1 d \omega_2
\]

\[
\sigma_{\gamma \gamma \rightarrow R}(\omega_1, \omega_2) = 8 \pi^2 (2 J + 1) \frac{\Gamma_{R \gamma \gamma}}{M_R} \delta (4 \omega_1 \omega_2 - M_R^2)
\]
Photon – Induced Interactions:

Resonance production

\[ \sigma(h_1 h_2 \to h_1 \otimes R \otimes h_2; s) = \int \hat{\sigma} (\gamma \gamma \to R; W) N(\omega_1, b_1) N(\omega_2, b_2) S^2_{\text{abs}}(b) d^2b_1 d^2b_2 d\omega_1 d\omega_2 \]

\[ \sigma_{\gamma \gamma \to R}(\omega_1, \omega_2) = 8\pi^2(2J + 1) \left( \frac{\Gamma_{R \gamma \gamma}}{M_R} \right) \delta(4\omega_1 \omega_2 - M_R^2) \]
Resonance production

\[ \sigma (h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2; s) = \int \delta (\gamma \gamma \rightarrow R; W) N (\omega_1, b_1) N (\omega_2, b_2) S_{abs}^2 (b) d^2 b_1 d^2 b_2 d\omega_1 d\omega_2 \]

\[ \sigma_{\gamma\gamma \rightarrow R}(\omega_1, \omega_2) = 8\pi^2 (2J + 1) \frac{\Gamma_{R \rightarrow \gamma\gamma}}{M_R} \delta(4\omega_1 \omega_2 - M_R^2) \]
Photoproduction of X(4350):

Constrained by Belle Collaboration.
Probing Exotic Charmoniumlike states in photon – photon interactions

Photoproduction of $X(4350)$:

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Probing Exotic Charmoniumlike states in photon – photon interactions

Photoproduction of $X(4350)$:

Constrained by Belle Collaboration.

<table>
<thead>
<tr>
<th>Collision</th>
<th>Resonance</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$ ($\sqrt{s} = 13$ TeV)</td>
<td>$X(4350)$, $0^{++}$</td>
<td>$2.47 - 6.13$ fb</td>
</tr>
<tr>
<td></td>
<td>$X(4350)$, $2^{++}$</td>
<td>$2.52 - 6.88$ fb</td>
</tr>
<tr>
<td>$pPb$ ($\sqrt{s} = 8.1$ TeV)</td>
<td>$X(4350)$, $0^{++}$</td>
<td>$(10.20 - 25.30)$ pb</td>
</tr>
<tr>
<td></td>
<td>$X(4350)$, $2^{++}$</td>
<td>$(10.30 - 28.30)$ pb</td>
</tr>
<tr>
<td>$PbPb$ ($\sqrt{s} = 5.02$ TeV)</td>
<td>$X(4350)$, $0^{++}$</td>
<td>$(14.60 - 36.20)$ nb</td>
</tr>
<tr>
<td></td>
<td>$X(4350)$, $2^{++}$</td>
<td>$(14.90 - 40.60)$ nb</td>
</tr>
</tbody>
</table>

Such channel can be used to confirm (or not) the existence of resonances observed in $e^+e^-$ colliders.
Motivation

Photon – Induced Interactions:

Probing Exotic Charmoniumlike states in photon – photon interactions

\[
\sigma(h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2; s) = \int \sigma(\gamma\gamma \rightarrow R; W) N(\omega_1, b_1) N(\omega_2, b_2) S_{abs}^2(b_1) d^2b_1 d^2b_2 d\omega_1 d\omega_2
\]

\[
\sigma_{\gamma\gamma \rightarrow R}(\omega_1, \omega_2) = 8\pi^2(2J + 1)\frac{\Gamma_{R \rightarrow \gamma\gamma}}{M_R} \delta(4\omega_1\omega_2 - M_R^2)
\]

Probing Exotic Charmoniumlike states in photon – photon interactions

**Table I:** Cross sections for exotic meson production in Pb-Pb collisions using the theoretical decay rates presented in Refs. [34–36].

<table>
<thead>
<tr>
<th>State</th>
<th>Mass</th>
<th>$\Gamma_{\gamma\gamma}^{\text{theor}}$ (keV)</th>
<th>$\sigma_{b_{\min}}$ (μb)</th>
<th>$\sigma_F$ (μb)</th>
<th>$\sigma_R$ (μb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.76 TeV</td>
<td>5.5 TeV</td>
<td>39 TeV</td>
<td>2.76 TeV</td>
</tr>
<tr>
<td>$X(3940), 0^{++}$</td>
<td>3943</td>
<td>0.33</td>
<td>4.2</td>
<td>8.2</td>
<td>31.6</td>
</tr>
<tr>
<td>$X(3940), 2^{++}$</td>
<td>3943</td>
<td>0.27</td>
<td>17.2</td>
<td>33.6</td>
<td>129.2</td>
</tr>
<tr>
<td>$X(4140), 0^{++}$</td>
<td>4143</td>
<td>0.63</td>
<td>6.5</td>
<td>12.9</td>
<td>51.2</td>
</tr>
<tr>
<td>$X(4140), 2^{++}$</td>
<td>4143</td>
<td>0.50</td>
<td>26.0</td>
<td>51.2</td>
<td>201.0</td>
</tr>
<tr>
<td>$Z(3930), 2^{++}$</td>
<td>3922</td>
<td>0.083</td>
<td>5.4</td>
<td>10.5</td>
<td>40.9</td>
</tr>
<tr>
<td>$X(4160), 2^{++}$</td>
<td>4169</td>
<td>0.363</td>
<td>18.4</td>
<td>36.4</td>
<td>144.2</td>
</tr>
<tr>
<td>$Y_p(3912), 2^{++}$</td>
<td>3919</td>
<td>0.774</td>
<td>50.5</td>
<td>98.6</td>
<td>382.4</td>
</tr>
<tr>
<td>$X(3915), 0^{++}$</td>
<td>3919</td>
<td>0.20</td>
<td>2.6</td>
<td>5.1</td>
<td>19.8</td>
</tr>
</tbody>
</table>

**Table III:** Cross sections for exotic meson production in pp collisions using the theoretical decay rates presented in Refs. [34–36].

<table>
<thead>
<tr>
<th>State</th>
<th>Mass</th>
<th>$\Gamma_{\gamma\gamma}^{\text{theor}}$ (keV)</th>
<th>$\sigma_{b_{\min}}$ (pb)</th>
<th>$\sigma_F$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 TeV</td>
<td>14 TeV</td>
<td>100 TeV</td>
</tr>
<tr>
<td>$X(3940), 0^{++}$</td>
<td>3943</td>
<td>0.33</td>
<td>0.98</td>
<td>1.3</td>
</tr>
<tr>
<td>$X(3940), 2^{++}$</td>
<td>3943</td>
<td>0.27</td>
<td>4.0</td>
<td>5.6</td>
</tr>
<tr>
<td>$X(4140), 0^{++}$</td>
<td>4143</td>
<td>0.63</td>
<td>1.6</td>
<td>2.2</td>
</tr>
<tr>
<td>$X(4140), 2^{++}$</td>
<td>4143</td>
<td>0.50</td>
<td>6.2</td>
<td>8.7</td>
</tr>
<tr>
<td>$Z(3930), 2^{++}$</td>
<td>3922</td>
<td>0.083</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>$X(4160), 2^{++}$</td>
<td>4169</td>
<td>0.363</td>
<td>4.4</td>
<td>6.1</td>
</tr>
<tr>
<td>$Y_p(3912), 2^{++}$</td>
<td>3919</td>
<td>0.774</td>
<td>11.7</td>
<td>16.3</td>
</tr>
<tr>
<td>$X(3915), 0^{++}$</td>
<td>3919</td>
<td>0.20</td>
<td>0.60</td>
<td>0.84</td>
</tr>
</tbody>
</table>

(*) Bertulani, VPG, Moreira, Navarra, PRD 94, 094024 (2016)
Dilepton production

\[ \sigma(PbPb \rightarrow Pb \otimes l^+l^- \otimes Pb; s) = \int d^2b_1d^2b_2d\omega_1d\omega_2 \; \hat{\sigma}(\gamma\gamma \rightarrow l^+l^-; W) \; N(\omega_1, b_1) \; N(\omega_2, b_2) \; S^2_{\text{abs}}(b) \]
Motivation

Photon - Induced Interactions:

Center of mass energies

Dilepton production - pp collisions

DOUBLE DIFFRACTION

SINGLE DIFFRACTION

(*) VPG, Jaime, Martins, Rangel, PRD97, 074024 (2018)
Dilepton production – pp collisions –

\[
\sigma(h_1 h_2 \rightarrow h_1 \otimes X \mu^+ \mu^- X' \otimes h_2) = \int dx_1 \int dx_2 \left[ q_1^D(x_1, Q^2) \cdot \bar{q}_2^D(x_2, Q^2) + \bar{q}_1^D(x_1, Q^2) \cdot q_2^D(x_2, Q^2) \right] \cdot \hat{\sigma}(q\bar{q} \rightarrow \mu^+ \mu^-)
\]

(*) VPG, Jaime, Martins, Rangel, PRD97, 074024 (2018)
Dilepton production
- pp collisions -

\[ \sigma(h_1 h_2 \rightarrow Y \mu^+ \mu^- X \otimes h_1) = \int dx_1 \int dx_2 [q_1^D(x_1, Q^2) \cdot \bar{q}_2(x_2, Q^2) + q_1(x_1, Q^2) \cdot \bar{q}_2^D(x_2, Q^2) + (q \leftrightarrow \bar{q})] \cdot \hat{\sigma}(q\bar{q} \rightarrow \mu^+ \mu^-) \]

(*) VPG, Jaime, Martins, Rangel, PRD97, 074024 (2018)
Dilepton production
- pp collisions -

W/o cuts:

(*) VPG, Jaime, Martins, Rangel, PRD97, 074024 (2018)

<table>
<thead>
<tr>
<th>Process</th>
<th>PP</th>
<th>PR + RP</th>
<th>RR</th>
<th>DD</th>
<th>$p$</th>
<th>$Pp$</th>
<th>Rp</th>
<th>SD</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cross Section [ pb ]</td>
<td>31.0</td>
<td>27.0</td>
<td>6.1</td>
<td>64.1</td>
<td>694.0</td>
<td>425.0</td>
<td>1119.0</td>
<td>7101.1</td>
<td></td>
</tr>
</tbody>
</table>
Motivation

Photon – Induced Interactions:

- Center of mass energies
- Dilepton production - pp collisions

Including cuts:

<table>
<thead>
<tr>
<th>Cut \ Process</th>
<th>PP</th>
<th>PR + RP</th>
<th>RR</th>
<th>DD</th>
<th>Pp</th>
<th>Rp</th>
<th>SD</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>31.0</td>
<td>27.0</td>
<td>6.1</td>
<td>64.1</td>
<td>694.0</td>
<td>425.0</td>
<td>1119.0</td>
<td>7101.1</td>
</tr>
<tr>
<td>$1. p_T (\mu^\pm) &gt; 0.4 \text{ GeV}$</td>
<td>28.6</td>
<td>23.9</td>
<td>4.5</td>
<td>57.3</td>
<td>616.4</td>
<td>310.3</td>
<td>926.7</td>
<td>2601.3</td>
</tr>
<tr>
<td>$2. \text{ Inv. mass range } 1.0 \leq M_{\mu^+\mu^-} \leq 20 \text{ GeV}$</td>
<td>23.3</td>
<td>19.3</td>
<td>2.6</td>
<td>45.2</td>
<td>499.6</td>
<td>189.5</td>
<td>689.1</td>
<td>1531.1</td>
</tr>
<tr>
<td>$3. p_T^2 (\mu^+\mu^-) &lt; 2 \text{ GeV}^2$</td>
<td>16.5</td>
<td>13.0</td>
<td>1.5</td>
<td>31.0</td>
<td>236.1</td>
<td>82.2</td>
<td>318.2</td>
<td>1529.5</td>
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<tr>
<td>$4. \eta \text{ in the CMS acceptance}$</td>
<td>5.7</td>
<td>3.4</td>
<td>0.8</td>
<td>9.8</td>
<td>66.6</td>
<td>46.9</td>
<td>113.5</td>
<td>775.3</td>
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<tr>
<td>$\eta \text{ in the LHCb acceptance}$</td>
<td>1.7</td>
<td>1.4</td>
<td>0.1</td>
<td>3.2</td>
<td>20.8</td>
<td>6.2</td>
<td>27.0</td>
<td>46.6</td>
</tr>
<tr>
<td>$5. \text{ Exclusivity: CMS}$</td>
<td>1.3</td>
<td>1.2</td>
<td>0.5</td>
<td>3.0</td>
<td>16.4</td>
<td>12.3</td>
<td>28.7</td>
<td>775.3</td>
</tr>
<tr>
<td>$\text{Exclusivity: Backward and forward LHCb}$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.01</td>
<td>0.2</td>
<td>0.9</td>
<td>0.6</td>
<td>1.4</td>
<td>46.6</td>
</tr>
</tbody>
</table>

Dominated by photon – photon interactions!
**Motivation**

Photon – Induced Interactions:

- Center of mass energies
- Dilepton production - pp collisions

Including cuts:

<table>
<thead>
<tr>
<th>Cut</th>
<th>Process</th>
<th>PP</th>
<th>PR + RP</th>
<th>RR</th>
<th>DD</th>
<th>Pp</th>
<th>Rp</th>
<th>SD</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td></td>
<td>31.0</td>
<td>27.0</td>
<td>6.1</td>
<td>64.1</td>
<td>694.0</td>
<td>425.0</td>
<td><strong>1119.0</strong></td>
<td>7101.1</td>
</tr>
<tr>
<td>1. $p_T (\mu^\pm) &gt; 0.4 \text{GeV}$</td>
<td></td>
<td>28.6</td>
<td>23.9</td>
<td>4.5</td>
<td>57.0</td>
<td>616.4</td>
<td>310.3</td>
<td><strong>926.7</strong></td>
<td>2601.3</td>
</tr>
<tr>
<td>2. Inv. mass range $1.0 \leq M_{\mu^+\mu^-} \leq 20 \text{ GeV}$</td>
<td></td>
<td>23.3</td>
<td>19.3</td>
<td>2.6</td>
<td>45.2</td>
<td>499.6</td>
<td>189.5</td>
<td>689.1</td>
<td>1531.1</td>
</tr>
<tr>
<td>3. $p_T^2 (\mu^+\mu^-) &gt; 2 \text{ GeV}^2$</td>
<td></td>
<td>4.7</td>
<td>4.2</td>
<td>0.6</td>
<td><strong>9.6</strong></td>
<td>166.8</td>
<td>63.3</td>
<td><strong>230.1</strong></td>
<td>0.1</td>
</tr>
<tr>
<td>4. $\eta$ in the CMS acceptance</td>
<td></td>
<td>2.2</td>
<td>1.7</td>
<td>0.3</td>
<td><strong>4.3</strong></td>
<td>70.4</td>
<td>38.5</td>
<td><strong>108.9</strong></td>
<td>0.04</td>
</tr>
<tr>
<td>$\eta$ in the LHCb acceptance</td>
<td></td>
<td>0.6</td>
<td>0.6</td>
<td>0.1</td>
<td><strong>1.2</strong></td>
<td>17.6</td>
<td>5.8</td>
<td><strong>23.4</strong></td>
<td>0.005</td>
</tr>
<tr>
<td>5. Exclusivity: CMS</td>
<td></td>
<td><strong>0.04</strong></td>
<td>0.2</td>
<td>0.08</td>
<td><strong>0.3</strong></td>
<td>1.5</td>
<td>2.1</td>
<td><strong>3.6</strong></td>
<td>0.04</td>
</tr>
<tr>
<td>Exclusivity: Backward and forward LHCb</td>
<td>8 $\times$ 10$^{-4}$</td>
<td>0.002</td>
<td>5 $\times$ 10$^{-4}$</td>
<td><strong>0.004</strong></td>
<td>0.01</td>
<td>0.01</td>
<td><strong>0.02</strong></td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

**Dominated by diffractive interactions!**
Dilepton production in PbPb collisions

\[ \sigma (PbPb \to Pb \otimes l^+ l^- \otimes Pb; s) = \int d^2b_1 d^2b_2 d\omega_1 d\omega_2 \hat{\sigma} (\gamma \gamma \to l^+ l^-; W) N (\omega_1, b_1) N (\omega_2, b_2) S_{abs}^2 (b) \]
Dilepton production

- PbPb collisions

\[ \sigma (PbPb \to Pb \otimes l^+ l^- \otimes Pb; s) = \int d^2b_1 d^2b_2 d\omega_1 d\omega_2 \, \hat{\sigma} (\gamma \gamma \to l^+ l^-; W) \, N(\omega_1, b_1) \, N(\omega_2, b_2) \, S_{abs}^2 (b) \]

(*) Azevedo, VPG, Moreira, EPJC79, 432 (2019)
Dilepton production

- PbPb collisions

\[ \sigma (\text{PbPb} \rightarrow \text{Pb} \otimes l^+ l^- \otimes \text{Pb}; s) = \int d^2b_1 d^2b_2 d\omega_1 d\omega_2 \hat{\sigma} (\gamma \gamma \rightarrow l^+ l^- ; W) N(\omega_1, b_1) N(\omega_2, b_2) S_{\text{abs}}^2(b) \]

(*) Azevedo, VPG, Moreira, EPJC79, 432 (2019)
Dilepton production

\[ \sigma (\text{PbPb} \rightarrow \text{Pb} \otimes l^+l^- \otimes \text{Pb}; s) = \int d^2b_1 d^2b_2 d\omega_1 d\omega_2 \hat{\sigma} (\gamma\gamma \rightarrow l^+l^-; W) N(\omega_1, b_1) N(\omega_2, b_2) S_{abs}^2 (b) \]

(*) Azevedo, VPG, Moreira, EPJC79, 432 (2019)
Dilepton production
- PbPb collisions -

\[
\sigma \left( \text{PbPb} \rightarrow \text{Pb} \otimes l^+l^- \otimes \text{Pb} ; s \right) = \int d^2 b_1 d^2 b_2 d\omega_1 d\omega_2 \hat{\sigma} \left( \gamma\gamma \rightarrow l^+l^- ; W \right) N(\omega_1, b_1) N(\omega_2, b_2) S_{abs}^2(b)
\]

(*) Azevedo, VPG, Moreira, EPJC79, 432 (2019)
Motivation

Photon–Induced Interactions:

Center of mass energies

Dilepton production - PbPb collisions

Including experimental cuts:
Dilepton production - PbPb collisions - 

Including experimental cuts:
Prospects
Probing Exotic Charmoniumlike states in
photon - hadron interactions

Photoproduction of $Z_c(3900)^+$:

$\sigma(pp \rightarrow pJ/\Psi\pi)$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Resonance</th>
<th>Contribution</th>
<th>$\sigma$ [nb] ($\sqrt{s} = 0.2$ TeV)</th>
<th>$\sigma$ [nb] ($\sqrt{s} = 7$ TeV)</th>
<th>$\sigma$ [nb] ($\sqrt{s} = 14$ TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(pp \rightarrow pJ/\Psi\pi)$</td>
<td>$Z_c(3900)$</td>
<td>$IP$</td>
<td>1.15</td>
<td>8.18 – 9.64</td>
<td>10.33 – 12.65</td>
</tr>
</tbody>
</table>

Cross sections are enhanced by a factor $Z^2$ in pPb collisions.

The enhancement occurs at very large rapidities (small photon – proton center – of – mass energies)!
Exclusive VM photoproduction in fixed target collisions at the LHC

* Beam – gas collisions have been studied by the LHCb Collaboration and a similar programme can be developed by the AFTER@LHC experiment;

* Such collisions allows to study the vector meson photoproduction at low energies.

(*) VPG, Medina EPJC78, 693 (2018)
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Thank you for your attention!