Exclusive production of muon pairs in the CMS experiment

Albert-Ludwigs-Universität Freiburg
LHC & CMS
central & forward detectors
Exclusive muon pairs
gamma-gamma fusion
theory & motivations
selection
applications
Upsilon photoproduction
theory & measurement

This work was done during my Ph.D. in the Université Catholique de Louvain (Belgium)
The LHC accelerator
LHC : Large Hadron Collider

Goal: study the structure of matter with particles colliding at very high energies

CERN – Genève (Suisse)
Large Hadron Collider

- 100 m underground
- 27 km circumference
- 2 proton beams
- 7 TeV per beam

4 interaction points = 4 large experiments

ATLAS

ALICE

CMS

LHCb

Xavier Rouby - IPNLyon
Large Hadron Collider

- 2835 x 2835 bunches
- $10^{11}$ protons per bunch
- 40 000 000 beam crossings per second
The CMS experiment
The CMS experiment

Central detector

21 m long
15 m high
12 500 t

Generic experiment for the study of Physics within and beyond the Standard Model (Higgs, SUSY, ...).
The CMS experiment

The central detector is composed by several layers, for the identification and the measurement of the particles.
Some final state particles are emitted or are scattered with a very small angle with respect to the beam direction. These can escape from CMS by the beampipe without being detected.

Tracking: $-2.5 < \eta < 2.5$
Calorimeters: $-5 < \eta < 5$
Some final state particles are emitted or are scattered with a very small angle with respect to the beam direction. These can escape from CMS by the beampipe without being detected.

D. d'Enterria, [hep-ex/0708.0551]
Some distant detectors have been added in order to increase the coverage of the experiment. Moreover, a common physics programme has been settled with the TOTEM experiment.

\[
\eta = -\ln\left(\tan\frac{\theta}{2}\right)
\]

CASTOR, ZDC: Calorimeters
T1, T2, RP, FP420: tracking
CMS: forward detectors

**CALORIMETRY**
- Totem T1
- Totem T2
- CASTOR (*)

**TRACKING**
- FP420
- ZDC

**CALORIMETRY neutrals**
- CMS + T1
- LHC inner ring
- LHC outer ring

**TOTEM Coll [CERN/LHCC 2004-002]**
X. Rouby, CMS CR-2008/020

21/11/2008
Xavier Rouby - IPN Lyon
Photon-induced processes
Collisions at the LHC

Protons are not elementary particles and they will mainly interact with the strong force. This leads to a lot of particle observed in the final state.

However, if protons interact through the exchange of one or several photons, there is a significant probability that they stay intact and survive from the collision.
Photon exchanges

Direct consequence:

- The observed final state contains far less particles.

Cleaner final state!

- At least one protons is scattered in the forward region with a very small angle.

The detection of the forward proton(s) allows to tag the photon interactions from the usual proton-proton collision.
Production of exclusive pairs of muons
Exclusive muon pairs

The incoming protons interact via two photons. The photon-photon fusion yields a $\mu^+\mu^-$ pair.

Due to the photon emission, the protons are *elastically* scattered, with a tiny angle with respect to the beam direction.

- **Muons**: measured by CMS.
- **Protons**: seen in the forward detectors.
Exclusive muon pairs

Motivations:

- Theoretically well known process. (<1% on $\sigma$)
- Easy selection; few processes have a similar signature.
- CMS is made for muon measurement
- Observing such muon pairs allow to measure the integrated luminosity ($L$) provided by the LHC to CMS, which is crucial to compare predictions ($\sigma$) to data ($N$):

$$N = L \sigma$$
The incoming proton beam can be seen as an flux of photon

LHC as a photon collider!

EPA: Equivalent Photon Approximation

Collision \((pp) = \text{collision } (\gamma \gamma) \times \text{flux}_1(\gamma) \times \text{flux}_2(\gamma)\)

\[
d\sigma_{pp} = \sigma_{\gamma\gamma}(x_1, x_2, s) \ dN(x_1, Q_1^2) \ dN(x_2, Q_2^2)
\]


The EPA approximation allows to factorize the photon emission from the collision process
Total cross section (LPAIR):
- $1.47 \times 10^8$ fb – no cut
- $74.7 \times 10^3$ fb – $p_T > 2.5$ GeV: elastic case:
  - the protons remain intact
- $76.2 \times 10^3$ fb – $p_T > 2.5$ GeV: inelastic case:
  - one proton dissociates

Large cross section
Very well known: QED

Very clean final state (if pile-up neglected: $L < 10^{33}$ cm$^{-2}$ s$^{-1}$)
Exclusive pair of muons
(Almost) no proton remnant in CMS
Exclusive muon pairs: backgrounds

• Signal and main backgrounds

**photon-photon (LPAIR)**
- no cut:
  \[ 1.47 \times 10^8 \text{ fb} \] (elastic)

- \( p_T > 2.5 \text{ GeV} \)
  \[ 74.7 \times 10^3 \text{ fb} \] (elastic)

- \( p_T > 2.5 \text{ GeV} \)
  \[ 76.2 \times 10^3 \text{ fb} \] (inelastic)

Reducible background events include:
- Drell-Yann processes
- W pairs
- Heavy quark decays
  (Upsilon exclusive photoproduction)
The selection of these events by CMS is possible thanks to the following characteristics:

1° Exclusivity requirement: only two muons in CMS

2° Kinematical requirements: Very good balance of the direction and the momentum of each muon, in the transverse plane.
Exclusive muon pairs: selection

Trigger (online selection):
$p_T > 3$ GeV (default CMS di-muon trigger) at low luminosity
Central pseudorapidity  ($|\eta|<2.4$)
Exclusive muon pairs: selection

- Offline selection
  - Kinematical requirements

Back-to-back muons in the transverse plane
Exclusive muon pairs: selection

- Offline selection
  - Exclusivity requirements

Only 2 muons are expected
Exclusive muon pairs: results

Selection efficiency

| $|\Delta \phi| > 2.9$ | $|\Delta p_T| < 2.0 \text{ GeV}$ | $N(\text{towers}) < 5$ | $N(\text{tracks}) < 3$ |
|-------------------|-----------------|----------------|----------------|
| $\mu\mu$ | inel | DY$_1$ | DY$_2$ | DY$_3$ |
| 99.9 | 57.8 | 10.1 | 23.9 | 53.5 |
| 99.8 | 49.4 | 7.9 | 10.9 | 10.6 |
| 99.8 | 47.6 | < 7.0 | < 0.26 | < 0.14 |
| 95.4 | 45.8 | < 3.5 | < 0.16 | < 0.14 |

Without the “Forward detector veto”

Selection summary

<table>
<thead>
<tr>
<th>$\sigma$ (pb)</th>
<th>$\mu\mu$</th>
<th>inel</th>
<th>DY$_1$</th>
<th>DY$_2$</th>
<th>DY$_3$</th>
<th>$\Upsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$ (events)</td>
<td>100k</td>
<td>20k</td>
<td>96.6k</td>
<td>3M</td>
<td>3M</td>
<td>16k</td>
</tr>
<tr>
<td>$\epsilon_{\text{trig}}$ (%)</td>
<td>10.0</td>
<td>18.3</td>
<td>0.1</td>
<td>4.8</td>
<td>9.7</td>
<td>8.5</td>
</tr>
<tr>
<td>$\epsilon_{\text{sel}}$ (%)</td>
<td>95.4</td>
<td>45.8</td>
<td>&lt; 3.5</td>
<td>&lt; 0.16</td>
<td>&lt; 0.14</td>
<td>95.0</td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ (pb)</td>
<td>7.09</td>
<td>6.38</td>
<td>&lt; 0.59</td>
<td>&lt; 0.003</td>
<td>&lt; 0.001</td>
<td>5.02</td>
</tr>
</tbody>
</table>

Without the “Forward detector veto”
Rejection of inelastic events

The remnant of the broken proton can be seen in the forward detectors (T2+CASTOR, ZDC)

"Forward detector veto"
Exclusive muon pairs: results

Selection results, after $L=100\text{pb}^{-1}$

\[ N_{\text{elastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 709 \pm 27\,(\text{stat}) \]
\[ N_{\text{inelastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 636 \pm 25\,(\text{stat}) \pm 121\,(\text{model}) \]
\[ N_{\text{inelastic}}^{w/veto}(\gamma\gamma \rightarrow \mu^+\mu^-) = 223 \pm 15\,(\text{stat}) \pm 42\,(\text{model}) \]
Applications
The global selection efficiency is known from the MC analysis.

\[ \gamma - \text{veto} : \quad M_{\mu\mu} < 9 \text{ GeV} \text{ OR } M_{\mu\mu} > 11 \text{ GeV} \]

\[ L = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\epsilon \sigma} \]

The cross-section $\sigma$ is very well known theoretically (<1%)

\[ N_{\text{elastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 426 \pm 21(\text{stat}) \pm 4(\text{th}) \]

\[ N_{\text{w/o veto inelastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 407 \pm 20(\text{stat}) \pm 77(\text{model}) \]

\[ N_{\text{w/ veto inelastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 141 \pm 12(\text{stat}) \pm 27(\text{model}) \]
Luminosity measurement

\[ L = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\epsilon \sigma} \]

Systematic uncertainties are kept under control

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>1.5%</td>
<td>Calibration using inclusive low ( p_T ) muon</td>
</tr>
<tr>
<td>Muon ( p_T ) scale</td>
<td>&lt; 0.3%</td>
<td>Use ( \gamma p \rightarrow \gamma p \rightarrow \mu^+ \mu^- p )</td>
</tr>
<tr>
<td>Calorimetric excl.</td>
<td>2%</td>
<td>Monitoring and masking the noisy calotowers and/or forward rap gap without calorimeter excl.</td>
</tr>
<tr>
<td>Tracking excl.</td>
<td>–</td>
<td>Use tracking algorithm dedicated to low ( p_T ) track reconstruction</td>
</tr>
<tr>
<td>Acoplanarity fit</td>
<td>1.5%</td>
<td>More data and/or other types of fit.</td>
</tr>
</tbody>
</table>

Syst. errors < 3%

At \( L=100 \text{ pb}^{-1} \), the statistical error dominates.
Luminosity measurement

X. Rouby, K. Piotrzkowski, CMS AN 2008/061

\[ L = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\epsilon \sigma} \]

Overall uncertainty < 7%

Scenario (i): \( L_{\text{true}} = 100 \text{ pb}^{-1} \)
\[ L_{\text{meas}} = 96.8 \pm 6.1(\text{stat}) \pm 1.0(\text{th}) \pm 2.9(\text{syst}) \text{ pb}^{-1} \]

Scenario (ii): \( L_{\text{true}} = 100 \text{ pb}^{-1} \) with forward calorimeter veto
\[ L_{\text{meas}} = 99.4 \pm 5.3(\text{stat}) \pm 1.0(\text{th}) \pm 2.9(\text{syst}) \text{ pb}^{-1}. \]

At low luminosity (low pile-up) this method looks the best one for the absolute luminosity measurement in CMS
Alignment of the forward detectors

- Luminosity normalization: offline calibration of lumi monitors
- Forward detector calibration + alignment

Rouby, de Favereau, Piotrzkowski
[JINST 2 P09005]
Upsilon photoproduction
Mass and branching ratio

(1S) \( m = 9.46 \text{ GeV} \quad \text{BR}(\mu\mu) = 2.48\% \)

(2S) \( m = 10.02 \text{ GeV} \quad \text{BR}(\mu\mu) = 1.93\% \)

(3S) \( m = 10.36 \text{ GeV} \quad \text{BR}(\mu\mu) = 2.18\% \)

The upsilon masses are very precisely measured
(narrow resonances)

This can serve as a calibration tool for the experiment
Upsilon meson production

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma_{\text{prod}} ) (pb)</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma IP \rightarrow \Upsilon \rightarrow \mu^+\mu^- )</td>
<td>12 (1S)</td>
<td>PHITI</td>
</tr>
<tr>
<td>( \gamma IP \rightarrow \Upsilon \rightarrow \mu^+\mu^- )</td>
<td>39 (1S), 13 (2S), 10 (3S)</td>
<td>STARLIGHT</td>
</tr>
</tbody>
</table>

**HERA measurements**

**Exclusive production**

Same dimuon final state as in the previous analysis!
Selection of the dimuon pairs as before

Observation of the three resonances!
- low $p_T$ track calibration
- detector alignment $p_T$
- sensitivity to very low-x distributions
Conclusions

• Photon physics at the LHC:
  – Using LHC as a photon collider! Nice final states, with a lot of physics within and beyond the Standard Model.

• $\gamma \gamma \rightarrow \mu^+ \mu^-$:
  – Very interesting final state: easy selection, early physics, well known theoretically
  – Absolute luminosity measurement
  – Forward detector alignment

• $\gamma p \rightarrow Y \mu^+ \mu^-$:
  – Improving HERA measurements. Cross-section measurement. Calibration tool for the detector

Informations complémentaires
Forward detectors for ATLAS

**LUMI**

**LUCID**

Cerenkov

**ZDC**

**RP220**

**ALFA**

**FP420**

Si + Cerenkov

**TRACK & TIMING**

~2009

~2010

**CALORIMETRY**

neutrals

**TRACKING**

Scintillating fibers

**TAN**

**ZDC modules**
Détections des protons émis à très petits angles

Un proton émis à très petit angle peut s'échapper de CMS par le tube du faisceau, sans être détecté.

S'il a perdu de l'énergie, sa trajectoire sera différente de celle des protons du faisceau.

Il est possible de l'observer en utilisant les détecteurs situés le long de la ligne de faisceau.
Détecteurs de protons diffusés

Les protons *diffusés vers l'avant* ont une énergie proche de celle du faisceau, mais légèrement inférieure. Leur trajectoire suit, plus ou moins, celle du faisceau.

Il est donc possible de détecter ces protons à l'aide de senseurs placés à quelques millimètres du faisceau.
Plus le détecteur est proche du faisceau, plus grande est la gamme des énergies qu'il couvre.

Nécessité de minimiser la distance entre le bord physique et la zone sensible du détecteur. Cette distance doit être de quelques dizaines de microns.

On parle alors de détecteur sans bord.
Contrainte supplémentaire :
les détecteurs doivent également

\[ O(10^{14} - 10^{15}) \text{ protons/an/cm}^2 \]

Solution : détecteurs sans bord au silicium

→ Développement de détecteurs coupés.