Measurement of the differential isolated diphoton production cross section at CMS

and other research activities during my PhD studies

Marco Peruzzi
Institute for Particle Physics, ETH Zurich

CHIPP Prize talk
SPS Annual Meeting and CHIPP Plenary Meeting 2014
July 1st, 2014
Main goal of my PhD thesis: measurement of diphoton differential cross sections with the CMS detector

- challenging from the experimental point of view
- stringent test of QCD higher-order calculations
- tight connection between analysis performance and understanding of detector and reconstruction algorithm details

Several other activities in the context of the electromagnetic calorimeter (ECAL) group:

- pileup effect studies on ECAL reconstruction
- improved energy corrections scheme providing better resolution
- sampling calorimeter prototype construction and first test-beam measurements
Diphoton production probes perturbative QCD @ NNLO

- theoretical calculation arXiv:1110.2375
  (Catani, Cieri, De Florian, Ferrera, Grazzini)

At LO (photons back to back), this region is not populated: we can probe NNLO with excellent sensitivity

- Developments on $\gamma\gamma + 2$ jets at NLO
  arXiv:1308.3660 (Gehrmann, Greiner, Heinrich)
Photon reconstruction

- PbWO₄ crystal electromagnetic calorimeter
- Excellent energy resolution and granularity

- Calorimeter cells clustered to reconstruct energy deposit
- **Particle-Flow** reconstruction algorithm combines information from all sub-detectors

Clusters and tracks ↔ Particles

Marco Peruzzi (ETH Zurich)
Background subtraction

- Background from boosted neutral mesons collimated diphoton decays, reconstructed as single photons

Key concepts:
- shape of em shower
- isolation energy
- Variables de-correlated
  - sideband method
- Background fraction from a template fit
Analysis strategy

➢ **Goal: extract the fraction of prompt diphoton events**

\[
\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}^U}{\varepsilon \cdot L \cdot \Delta X}
\]

❖ **Asymmetric selection on photon p_T**
(40/25 GeV) enhancing contribution from higher-order corrections

❖ **Fully data-driven templates**
for prompt photons and background

❖ **Fit the PF isolation distribution**
in data, extracting purity of prompt diphotons

❖ **Unfold** to generator-level quantities, correct for selection efficiency

❖ **Compare the results to theory**
Particle-Flow photon isolation

- **Particle-Flow (PF) event reconstruction**
  - combines information from all subdetectors
  - exploits full detector granularity
  - unambiguous event interpretation in terms of particle candidates

- **Novel algorithm developed to use PF isolation in photon measurements**

- **Paves the way for using PF in all CMS precision measurements with photons**

- **Has become the reference variable for photon purity estimation in CMS**

- **Improvements propagated to global reconstruction code, being commissioned for LHC Run 2 data taking**

- Prompt photon → only pileup, UE in the isolation cone

- Photon footprint excluded from isolation sum
Signal template: random cone

 Procedure (event-by-event):

✦ rotate the isolation cone in \( \varphi \) by a random angle
✦ check that no other photon or jet is nearby
✦ underlying activity does not change (same \( \eta \))
✦ build the template from this isolation sum away from the photon candidate

Prompt photon template built in data with random cone:
gauge pileup in an “empty” region of the detector
Signal template: random cone

❖ Excellent performance thanks to the new technique
❖ Removing photon footprint from the isolation cone very effectively
Fake photon template built in data with sideband technique: exploit small correlation between shower width and isolation sum

Very good performance after effective photon footprint removal
Event mixing at particle level

- **Low statistics** for building two-dimensional background template: would need two sideband photons in the same event
- Product of one-dimensional templates would not describe the *correlation between isolation sums*
- Solution is to use an **event mixing strategy**
Event mixing at particle level

- Template events chosen with $\rho_1 + \rho_2 = \rho$ measured in the event to be fitted
- Fully exploiting the rationale of the Particle-Flow reconstruction approach
- A leap forward in the use of Particle-Flow: Mixing had never been used before in this way for SM precision measurements
- Dramatic increase in template statistics in the most interesting region of the phase space
Purity extraction

- Prompt diphoton fraction extracted through two-dimensional template fit, measuring $\gamma\gamma$, $\gamma$+jet, di-jet components
- Differential measurement as a function of $m_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, $\cos \theta^*$, $\Delta \phi_{\gamma\gamma}$
The measured diphoton yield is corrected for selection efficiency.

Efficiency measured in data from $Z\rightarrow ee$ and $Z\rightarrow \mu\mu\gamma$ events, with tag-and-probe methods:

$$\epsilon_{\gamma\gamma} = \epsilon_{\text{trigger}} \times \epsilon_{\text{reco&sel}} \times C_{\gamma_1}^{Z\rightarrow e^+e^-} \times C_{\gamma_2}^{Z\rightarrow e^+e^-} \times C_{\gamma_2}^{Z\rightarrow \mu^+\mu^-\gamma} \times C_{\gamma_1}^{Z\rightarrow \mu^+\mu^-\gamma}$$

The differential cross section is given by:

$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}^U}{\epsilon \cdot L \cdot \Delta X}$$
Theoretical predictions

- Diphoton production diagrams:

- Properties of the theoretical calculations:

<table>
<thead>
<tr>
<th>Generator</th>
<th>ME/PS</th>
<th>Resumation</th>
<th>Born</th>
<th>1-frag</th>
<th>2-frag</th>
<th>Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\gamma NNLO$</td>
<td>ME</td>
<td>-</td>
<td>NNLO</td>
<td>-</td>
<td>-</td>
<td>LO</td>
</tr>
<tr>
<td>DIPHOX + GAMMA2MC</td>
<td>ME</td>
<td>-</td>
<td>NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>(LO)</td>
</tr>
<tr>
<td>RESBOS</td>
<td>ME</td>
<td>NNLL</td>
<td>NLO</td>
<td>LO</td>
<td>-</td>
<td>NLO</td>
</tr>
<tr>
<td>Sherpa</td>
<td>ME+PS</td>
<td>LL</td>
<td>LO + up to 3 jets</td>
<td>-</td>
<td>-</td>
<td>LO</td>
</tr>
</tbody>
</table>

Figure 1: Generators for the processes $\gamma\gamma$. 

Comparison with theory predictions

- Properties of the theory calculations:

- Diphoton production diagrams:


Cross section results

- NNLO prediction improves the data/theory agreement in the low mass region
- SHERPA also shows good agreement

➢ Very low systematic uncertainties ~ 10%, despite challenging conditions (pileup)

Marco Peruzzi (ETH Zurich)
Measurement of the differential isolated diphoton production cross section at CMS
Cross section results

arXiv:1405.7225, submitted to EPJC

NNLO-enhanced region

➢ Low $\Delta \phi_{\gamma\gamma}$ region corresponds to low mass, after the kinematic selection
Cross section results

Data/DIPHOX

Data/SHERPA

Data/RESBOS

Data/2γ NNLO

"Shoulder" around $p_{T1} + p_{T2}$ described by SHERPA and NNLO predictions

NNLO-enhanced region

arXiv:1405.7225, submitted to EPJC
Integrated cross section

- The measured integrated diphoton cross section is:

\[ \sigma = 17.2 \pm 0.2 \text{ (stat.)} \pm 1.9 \text{ (syst.)} \pm 0.4 \text{ (lum.) pb}, \]

- to be compared to:

\[ \sigma_{\text{NNLO}}(2\gamma_{\text{NNLO}}) = 16.2^{+1.5}_{-1.3} \text{ (scale) pb}, \]
\[ \sigma_{\text{NLO}}(\text{DIPHOX + GAMMA2MC}) = 12.8^{+1.6}_{-1.5} \text{ (scale)}^{+0.6}_{-0.8} \text{ (pdf+}\alpha_S) \text{ pb}, \]
\[ \sigma_{\text{NLO}}(\text{RESBOS}) = 14.9^{+2.2}_{-1.7} \text{ (scale)} \pm 0.6 \text{ (pdf+}\alpha_S) \text{ pb}, \]
\[ \sigma_{\text{LO}}(\text{SHERPA}) = 15.2^{+3.2}_{-1.9} \text{ (scale) pb}. \]

- **Best agreement with the NNLO calculation**

- ~10% final uncertainty is the result of a **strong effort** towards detailed **detector understanding and algorithm optimization**
Out-of-time pileup in ECAL

- Energy deposition in ECAL crystals measured with a pulse shape fit
- **Dynamic pedestal subtraction used to subtract the noise**
- Level of pedestal influenced by previous energy depositions:
  - pulse shape much longer than spacing between LHC bunches
  - effect scales with pileup (detector occupancy increases)
Discrepancies between data and simulation observed in ECAL quantities:

- The main reason was the OOT pileup
- Simulation improved:
  - benefit to all analyses using photons
  - crucial to understand this effect in view of the next data taking (high pileup)
Photon energy corrections

- Photon energy corrections development:
  - Photons can convert in the tracker material in front of ECAL
  - Correlation between azimuthal energy spread and position in the detector
- New factorization of cluster energy corrections: \( f(\sigma_\phi/\sigma_\eta, \eta) \times F(ET) \)
- Improvement in resolution, very robust method used as default both in trigger and offline reconstruction
ECAL upgrade studies

- Studies in the framework of the CMS ECAL Phase II upgrade project
  - radiation-induced damage of PbWO₄ crystals, leading to loss of transparency and worsening performance
  - need to upgrade the endcap region of ECAL for operation at HL-LHC

- Joint ETHZ / INFN effort to build a sampling calorimeter prototype channel:
  - CeF₃ scintillating crystals, tungsten absorber plates
  - wavelength-shifting fibers on channel corners to extract light to PMT readout
  - BGO crystals for lateral shower energy containment

Dimensions:

- 10 x (3 mm W + 1 cm CeF₃) = 17 X₀ as suitable for the 750 MeV e⁻ beam

Studies in the framework of the CMS ECAL Phase II upgrade project

- radiation-induced damage of PbWO₄ crystals, leading to loss of transparency and worsening performance
- need to upgrade the endcap region of ECAL for operation at HL-LHC

- Joint ETHZ / INFN effort to build a sampling calorimeter prototype channel:
  - CeF₃ scintillating crystals, tungsten absorber plates
  - wavelength-shifting fibers on channel corners to extract light to PMT readout
  - BGO crystals for lateral shower energy containment

Dimensions:

- 10 x (3 mm W + 1 cm CeF₃) = 17 X₀ as suitable for the 750 MeV e⁻ beam
Test-beam activity

- **Involvement throughout design, construction and commissioning** phases
- **Very successful (and exciting) test-beam!**
  Excellent experience gathered in Frascati
- First look at data looks really promising
Conclusions and outlook

- **Diphoton cross sections measurements probe QCD at NNLO**
- **Data-driven techniques** specially developed to make the analysis robust and **reduce the systematic uncertainties**
- This work has paved the way for using PF isolation in precision SM measurements involving photons at CMS
- **More to come: inclusion of jet information** in the analysis, expected to be finalized in summer

- Contributions in **understanding ECAL reconstruction** behaviour in high-pileup conditions
- Involvement in **R&D studies for CMS ECAL upgrade**, from design of a sampling calorimeter prototype channel to successful tests in an e⁻ beam