Will focus mostly on LHC results

- Introduction: [Why]
- Photon reconstruction and Identification: [How]
- Photons and: [What]
  - Tests of pQCD & Tunning of PDFs
  - “Completion” of the SM
  - Test of EW SM sector and perform
    **SM Measurements for the discovery of new physics**
- Summary and Future

A small selection of results, cannot show everything!!
Introduction

Measurements with photons in the final state are of great importance in order to:

- Test pQCD in ever-growing and new energy regime
- Test the EW sector of the SM
- Provide constraints on PDFs, whose uncertainties often dominate both Standard Model (SM) measurements, and beyond the SM searches
- Tune Monte Carlo generators in order to better describe the data.
- Measure and understand the main background to a variety of new physics searches, or get a chance to have a first glimpse of something new and unexpected.
ATLAS and CMS Experiments

3.8 T

Pixels
\[ \sigma_{pT} \sim 1.5 \cdot 10^{-4} pT(GeV) \oplus 0.005 \]

Electromagnetic Calorimeter
\[ \sigma_{E/E} \approx 2.9\%/\sqrt{E(GeV)} \oplus 0.5\% \oplus 0.13 GeV/E \]

Hadronic Calorimeter
\[ \sigma_{E/E} \approx 120\%/\sqrt{E(GeV)} \oplus 6.9\% \]

Muon Spectrometer
\[ \sigma_{pT/pT} \approx 1\% \text{ for low } pT \text{ muons} \]
\[ \sigma_{pT/pT} \approx 5\% \text{ for } 1 \text{ TeV muons} \]

2.0 T

Pixels, Si strips & Straw tubes
\[ \sigma_{pT} \sim 3.8 \cdot 10^{-4} pT(GeV) \oplus 0.015 \]

Electromagnetic Calorimeter
\[ \sigma_{E/E} \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\% \oplus 0.2 GeV/E \]

Hadronic Calorimeter
\[ \sigma_{E/E} \approx 60-100\%/\sqrt{E(GeV)} \oplus 3\% \]

Muon Spectrometer
\[ \sigma_{pT/pT} < 10\% \text{ up to } 1 \text{ TeV muons} \]

N. Saoulidou, Univ. of Athens, Greece
Data Collection

All of the ATLAS and CMS results shown can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

N. Saoulidou, Univ. of Athens, Greece
Prompt Photons and Backgrounds

- **Prompt photons** are isolated energy deposits in the experiments electromagnetic calorimeter (ECAL), with no charged track pointing to them, and with a **shape compatible with a photon electromagnetic shower**: they can be converted or unconverted.

- **Non prompt photons** (main background) are $\pi^0$ from hadronic jets, discrimination in this case based on isolation and different shower shape characteristics.

![Diagram](https://via.placeholder.com/150)

**Prompt Photons**
- Annihilation & Compton Scattering
- Fragmentation

**Non-prompt Photons**
- $\pi^0 \eta$ in jets

N. Saoulidou, Univ. of Athens, Greece
Photon Identification in CMS

• Several shower shape and isolation variables, used as sequential cuts, or combined in a multivariate analyzer (BDT).

• Selection efficiencies estimated in a data-driven way using $Z \rightarrow ll\gamma$ and $Z \rightarrow ee$ data-drive methods.

JINST 10 (2015) no.08, P08010
Photon Identification in ATLAS

- Several shower shape and isolation variables utilized and combined with sequential cuts.

- Detailed data-driven methods deployed to measure efficiencies in data and simulation, using $Z \rightarrow \mu\mu\gamma$, $Z \rightarrow ee$ and isolation measurements using the tracker in an inclusive photon sample.

Isolated prompt Photon and Photon + jets measurements

- Direct photons are a direct (colorouless) probe of the hard scattering
- Sensitive in the gluon PDF
- Can be used to tune MC Models
• Utilizing ratios of photon cross section measurements at 8 TeV and 13 TeV achieve, through cancelation, smaller experimental and theoretical systematics!

• Main theoretical uncertainty coming from scale, and PDFs and main experimental uncertainty from photon energy scale.

Theoretical uncertainties now smaller than experimental ones

N. Saoulidou, Univ. of Athens, Greece
Photon isolation in a cone of $\Delta R = 0.4$ is
\[ I < 4.8 + 4.2 \cdot 10^{-3} \cdot E_T^\gamma \ [\text{GeV}] \]

- The **significant reduction** of the experimental and theoretical uncertainties allows for a **more stringent test** of NLO QCD.
- NLO pQCD predictions and data agree given uncertainties. This validates the description of the evolution of isolated-photon production in pp collisions with the centre-of-mass energy.
Inclusive photon and Photon plus jet cross section at 13 TeV : CMS

EPJC 79 (2019) 20

- Measurements compared with theoretical predictions produced using JETPHOX NLO calculations and several different PDF sets, and found to be in agreement.

- For low to middle range in photon energies, where the experimental uncertainties are smaller or comparable to theoretical uncertainties, these measurements provide the potential to further constrain the proton gluon PDFs.
Ratio of photon + jet / Z+jet cross differential sections at 8 TeV : CMS (1)


• At high vector boson pT and at LO effects due to the mass of the Z boson are small: cross section ratio of Z + jets to γ + jets as a function of pT is expected to become constant, reaching a plateau.

• A precise measurement of the (pp→Z+jets)/(pp→ γ + jets) cross section ratio provides important information about the higher-order effects of large logarithmic corrections [ln( pT_Z /m_Z )] at higher pT.

• Searches for NP characterized by the presence of large missing ET and hard jets, use the γ + jets process to model the invisible Z decays, Z → vv. Measurements of the (pp→Z+jets)/(pp→ γ + jets) can help reduce uncertainties related to the Z → vv background estimation in these searches.
Ratio of photon + jet / Z+jet cross differential sections at 8 TeV : CMS (2)


- Four phase space regions used: \( n_{\text{jets}} \geq 1, 2, 3, \) and \( H_T > 300 \text{ GeV} \).

- MADGRAPH+PYTHIA6 (LO+PS) and BALCKHAT (NLO) overestimates the data by a factor \(~1.2\), but with the same shape.

- These results show that properties of the \( Z \rightarrow \nu\nu \) process can be predicted by the measured \( \gamma + \text{jets} \) and the simulated ratio between \( Z \rightarrow \nu\nu + \text{jets} \) and \( \gamma + \text{jets} \).

N. Saoulidou, Univ. of Athens, Greece
gluon PDFs with photons
Prompt photon production used in PDF fits (1)

Authors conclude “...we have shown that the available isolated-photon data provides constraints on the gluon PDFs and thus on many relevant LHC processes, most importantly Higgs production in gluon-gluon fusion. Given that even more precise data as well as theoretical improvements will be available in the next future, we see no objection why isolated-photon data should not become integral part of future global QCD analyses.”
Prompt photon production used in PDF fits (2)

• Authors conclude “...that there is no reason, neither in principle nor in practice, for excluding collider direct photon data from a global PDF analysis. Indeed, the most precise LHC measurements available agree well with state-of-the-art theoretical predictions, and the latter can be included in global PDF analyses using fast interpolation tables..... For these reasons, collider direct photon production should be rightfully restored to its well-deserved position as a full member of the global PDF analysis toolbox.”
Inclusive diphoton measurements
Diphoton non-resonant Production

- Diphoton production important test of pQCD and non-perturbative QCD: Rich phenomenology, making theoretical predictions challenging.

- Experimental challenge: distinguish it from non-prompt jet background.

- Irreducible background to Higgs diphoton decay channel

- Irreducible background to Non-resonant diphoton production from BSM physics.
The 2γNNLO and SHERPA predictions show an improved agreement in shape with the data for the kinematic distributions with respect to the DIPHOX + GAMMA2MC and RESBOS predictions, especially in the low \(m_{\gamma\gamma}\), low \(\Delta\phi_{\gamma\gamma}\) regions, which are the most sensitive to higher-order corrections.
The predictions of DIPHOX and RESBOS show significant deviations from the data for all variables under consideration.
The predictions of a parton-level calculation of varying jet multiplicity up to NLO matched to a parton-shower algorithm in SHERPA 2.2.1 provide an improved description of the data.
Resonant Diphoton Production: CMS

CMS PAS HIG-18-029

Photon “SM” measurement yielding major discoveries

N. Saoulidou, Univ. of Athens, Greece
Resonant Diphoton Production: ATLAS

ATLAS-CONF-2018-028

Photon “SM” measurement yielding major discoveries

N. Saoulidou, Univ. of Athens, Greece
Diboson Production: \( V\gamma, VV\gamma, V\gamma\gamma \)

- Test the electroweak sector of the SM with high accuracy.
- Probe the \( \text{SU}(2)_L \times \text{U}(1)_Y \) gauge symmetry that determines the structure and self-couplings of the vector bosons.
- Search for signs of new physics through anomalous triple and quartic gauge-boson coupling (aTGC and aQGC).
- Tune MCs for main backgrounds in SM and BSM analyses.

N. Saoulidou, Univ. of Athens, Greece
**Zγ @ 8 TeV : CMS**

- At high pTs measurement well described by the NNLO calculation and by the SHERPA prediction including up to two additional partons at matrix element level,

- A clear excess is observed with respect to the MCFM (NLO) calculation. This emphasizes the importance of NNLO QCD corrections for this measurement.

- Place limits on NP (aTGC)

---

N. Saoulioudou, Univ. of Athens, Greece
Wγγ - Zγγ @ 8 TeV : CMS

JHEP10(2017)072

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured fiducial cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wγγ → e±νeγγ</td>
<td>4.2 ± 2.0 (stat) ± 1.6 (syst) ± 0.1 (lumi) fb</td>
</tr>
<tr>
<td>Wγγ → µ±νµγγ</td>
<td>6.0 ± 1.8 (stat) ± 2.3 (syst) ± 0.2 (lumi) fb</td>
</tr>
<tr>
<td>Wγγ → ℓ±νℓγγ</td>
<td>4.9 ± 1.4 (stat) ± 1.6 (syst) ± 0.1 (lumi) fb</td>
</tr>
<tr>
<td>Zγγ → e⁺e⁻γγ</td>
<td>12.5 ± 2.1 (stat) ± 2.1 (syst) ± 0.3 (lumi) fb</td>
</tr>
<tr>
<td>Zγγ → µ⁺µ⁻γγ</td>
<td>12.8 ± 1.8 (stat) ± 1.7 (syst) ± 0.3 (lumi) fb</td>
</tr>
<tr>
<td>Zγγ → ℓ⁺ℓ⁻γγ</td>
<td>12.7 ± 1.4 (stat) ± 1.8 (syst) ± 0.3 (lumi) fb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wγγ → ℓ±νℓγγ</td>
<td>4.8 ± 0.5 fb</td>
</tr>
<tr>
<td>Zγγ → ℓ⁺ℓ⁻γγ</td>
<td>13.0 ± 1.5 fb</td>
</tr>
</tbody>
</table>

- NLO calculations and observations agree.
- **Stringent limits on NP (aQGC)**
• Very **consistent** results with the ones obtained **with CMS**, both in terms of the SM measurements, and in terms of searches for NP

N. Saoulioudou, Univ. of Athens, Greece
Z(vv)γ @13 TeV : ATLAS

JHEP12 (2018) 010

- Z(vv)γ process is less contaminated with hadrons by a large multijet background.
- A higher branching ratio of Z→vv yields higher sensitivity to bosonic couplings.
- This channel is sensitive to anomalous neutrino dipole moments, although a higher integrated luminosity would be required to improve over previous LEP results.

Results in agreement with the leptonic channels

N. Saoulidou, Univ. of Athens, Greece
Exclusive light-by-light scattering occurs at impact parameters larger than about twice the radius of the ions. **The strong interaction becomes less significant and the electromagnetic (EM) interaction becomes more important in these ultraperipheral collision (UPC) events.**

- **Light-by-light scattering**, $\gamma \gamma \rightarrow \gamma \gamma$ proceeds via virtual box diagrams involving electrically charged fermions (leptons and quarks) or W bosons, **at order $\alpha^4_{\text{EM}}$**

- In various BSM models extra contributions are possible, making the measurement of $\gamma \gamma \rightarrow \gamma \gamma$ scattering **sensitive to new physics**

N. Saoulidou, Univ. of Athens, Greece
In various BSM models extra contributions are possible, making the measurement of $\gamma\gamma \rightarrow \gamma\gamma$ scattering sensitive to new physics.

CMS sets best limits on the production of a pseudoscalar-axion like particle.
The high luminosity LHC is an approved upgrade of the LHC accelerator complex and the experiments.

The HE-LHC is an option under discussion, going up to energies of 27 TeV at centre of mass.

There are many options for the future, including linear colliders, muon colliders …
 Photons and the Future : HL-LHC, HE-LHC

ATL-PHYS-PUB-2018-051

- Significantly increase statistics and probe much higher energies!

arXiv:1902.04070v2

N. Saoulidou, Univ. of Athens, Greece
• Inclusive photon and photon+jet measurements aid in decreasing gluon PDF uncertainties.

• Diphoton production at higher energies significantly benefits from reduced PDF uncertainties.
• Photons are excellent probes of the EW and QCD sector of the SM.

• Photon measurements reduce main theoretical uncertainties for precision SM measurements and BSM searches.

• Photon measurements yielded a monumental discovery at the LHC, that of the Higgs Boson

• Photon measurements are also clean probes of BSM physics.

  Phos = Φως in Greek means “light” and “bright” and the Photon Physics near and longer term future is Bright!
BACKUP
Photon Shower Shape

Signal shape: Pythia MC

Background Shape: Track Isolation Sideband

Saoulidou, Univ. of Athens, Greece
JetPhox Predictions

• NLO pQCD
  – JETPHOX1.1, CT10 PDFs, BFG II FF
  – Renormalization, fragmentation, and factorization scales set to ET
  – Require “isolated” definition: $\Sigma \text{ET} < 5$ GeV within $R < 0.4$

• Scale uncertainty
  – 30 to 11% with ET, change all scales to ET/2 and 2ET

• PDF uncertainty
  - 6% over full ET range

• Envelope of CT10, MSTW08 and NNPDF2.0 (PDF4LHC recommendation)

• CTEQ6M instead of CT10: 3%
• BFG I instead of BFG II: <1%

N. Saoulidou, Univ. of Athens, Greece
Non Perturbative Corrections

• Non-perturbative effects increase energy in isolation cone

• Correction is obtained by comparing the efficiency of isolation cut of 5GeV in a cone of radius 0.4 with and without:
  – Multi-parton interaction
  – Hadronization

• Final correction is the mean of the four different tunes considered
  – D6T
  – Z2
  – DWT
  – P0

• ~3% overall correction applied to the NLO calculation

N. Saoulidou, Univ. of Athens, Greece
Photon Reconstruction

Photons are key objects for both calibration and major discoveries. (H-→γγ and BMS searches)

• Photons are isolated energy deposits in the ECAL, with no charged track pointing to them, and with a shape compatible with a photon electromagnetic Shower.

\[ \mathcal{L} = -\ln L = -(N_S + N_B) + \sum N_i \ln(N_S S_i + N_B B_i) \]

\[
\sigma^2_{\eta_i} = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{w_i}, \quad \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}
\]

\[ w_i = \max(0, 4.7 + \log(\frac{E_i}{E_{\gamma\gamma}})) \]
# Photon reconstruction & identification

<table>
<thead>
<tr>
<th>$E_T$ [GeV]</th>
<th>$\epsilon_{ID} \pm (\Sigma (1/\sqrt{E_T}))^{-\frac{1}{2}}$</th>
<th>$\epsilon_{ID}^{MC} \pm stat$</th>
<th>$\epsilon_{ID}^{\text{correctedMC}} \pm stat$</th>
<th>$\epsilon_{ID} \pm (\Sigma (1/\sqrt{E_T}))^{-\frac{1}{2}}$</th>
<th>$\epsilon_{ID}^{MC} \pm stat$</th>
<th>$\epsilon_{ID}^{\text{correctedMC}} \pm stat$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-25</td>
<td>0.597 ± 0.021</td>
<td>0.621 ± 0.001</td>
<td>0.613 ± 0.001</td>
<td>0.648 ± 0.024</td>
<td>0.667 ± 0.002</td>
<td>0.679 ± 0.002</td>
</tr>
<tr>
<td>25-30</td>
<td>0.689 ± 0.025</td>
<td>0.697 ± 0.002</td>
<td>0.686 ± 0.002</td>
<td>0.733 ± 0.035</td>
<td>0.761 ± 0.003</td>
<td>0.759 ± 0.003</td>
</tr>
<tr>
<td>30-35</td>
<td>0.769 ± 0.024</td>
<td>0.756 ± 0.002</td>
<td>0.746 ± 0.002</td>
<td>0.777 ± 0.033</td>
<td>0.821 ± 0.004</td>
<td>0.818 ± 0.004</td>
</tr>
<tr>
<td>35-40</td>
<td>0.792 ± 0.023</td>
<td>0.793 ± 0.003</td>
<td>0.784 ± 0.003</td>
<td>0.820 ± 0.025</td>
<td>0.851 ± 0.005</td>
<td>0.849 ± 0.005</td>
</tr>
<tr>
<td>40-45</td>
<td>0.816 ± 0.026</td>
<td>0.822 ± 0.004</td>
<td>0.806 ± 0.004</td>
<td>0.893 ± 0.049</td>
<td>0.886 ± 0.006</td>
<td>0.882 ± 0.006</td>
</tr>
<tr>
<td>45-50</td>
<td>0.847 ± 0.022</td>
<td>0.846 ± 0.001</td>
<td>0.835 ± 0.001</td>
<td>0.911 ± 0.036</td>
<td>0.899 ± 0.002</td>
<td>0.896 ± 0.002</td>
</tr>
<tr>
<td>50-60</td>
<td>0.874 ± 0.018</td>
<td>0.864 ± 0.001</td>
<td>0.856 ± 0.001</td>
<td>0.930 ± 0.029</td>
<td>0.923 ± 0.002</td>
<td>0.919 ± 0.002</td>
</tr>
<tr>
<td>60-80</td>
<td>0.902 ± 0.013</td>
<td>0.889 ± 0.001</td>
<td>0.883 ± 0.001</td>
<td>0.956 ± 0.027</td>
<td>0.939 ± 0.002</td>
<td>0.936 ± 0.002</td>
</tr>
<tr>
<td>80-100</td>
<td>0.918 ± 0.008</td>
<td>0.908 ± 0.001</td>
<td>0.905 ± 0.001</td>
<td>0.962 ± 0.030</td>
<td>0.956 ± 0.001</td>
<td>0.955 ± 0.001</td>
</tr>
<tr>
<td>100-125</td>
<td>0.926 ± 0.005</td>
<td>0.914 ± 0.001</td>
<td>0.912 ± 0.001</td>
<td>0.969 ± 0.023</td>
<td>0.962 ± 0.001</td>
<td>0.961 ± 0.001</td>
</tr>
<tr>
<td>125-150</td>
<td>0.934 ± 0.006</td>
<td>0.918 ± 0.001</td>
<td>0.917 ± 0.002</td>
<td>0.977 ± 0.023</td>
<td>0.969 ± 0.001</td>
<td>0.968 ± 0.002</td>
</tr>
<tr>
<td>150-175</td>
<td>0.930 ± 0.008</td>
<td>0.920 ± 0.001</td>
<td>0.918 ± 0.001</td>
<td>0.985 ± 0.017</td>
<td>0.971 ± 0.001</td>
<td>0.970 ± 0.001</td>
</tr>
<tr>
<td>175-250</td>
<td>0.933 ± 0.008</td>
<td>0.918 ± 0.001</td>
<td>0.917 ± 0.001</td>
<td>0.987 ± 0.016</td>
<td>0.971 ± 0.001</td>
<td>0.971 ± 0.001</td>
</tr>
</tbody>
</table>

**ECAL Barrel** ($|\eta| < 1.4442$)

<table>
<thead>
<tr>
<th>ET</th>
<th>MC</th>
<th>DATA</th>
<th>MC Ratio $\gamma/e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 - 35</td>
<td>84.18 ± 0.20%</td>
<td>86.73 ± 1.69%</td>
<td>1.032 ± 0.003</td>
</tr>
<tr>
<td>35 - 45</td>
<td>87.27 ± 0.19%</td>
<td>89.28 ± 1.27%</td>
<td>1.025 ± 0.004</td>
</tr>
<tr>
<td>45 - inf</td>
<td>88.50 ± 0.23%</td>
<td>89.04 ± 1.83%</td>
<td>1.005 ± 0.005</td>
</tr>
<tr>
<td>TOT</td>
<td>86.30 ± 0.12%</td>
<td>88.41 ± 0.89%</td>
<td>1.012 ± 0.002</td>
</tr>
</tbody>
</table>

**ECAL Endcap** ($1.566 < |\eta| < 2.5$)

<table>
<thead>
<tr>
<th>ET</th>
<th>MC</th>
<th>DATA</th>
<th>MC Ratio $\gamma/e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 - 35</td>
<td>87.40 ± 0.25%</td>
<td>92.24 ± 2.70%</td>
<td>1.035 ± 0.003</td>
</tr>
<tr>
<td>35 - 45</td>
<td>91.33 ± 0.22%</td>
<td>91.43 ± 2.43%</td>
<td>1.008 ± 0.005</td>
</tr>
<tr>
<td>45 - inf</td>
<td>92.55 ± 0.26%</td>
<td>91.06 ± 3.23%</td>
<td>1.013 ± 0.005</td>
</tr>
<tr>
<td>TOT</td>
<td>90.05 ± 0.14%</td>
<td>91.59 ± 1.60%</td>
<td>1.009 ± 0.002</td>
</tr>
</tbody>
</table>

**CMS Preliminary 2010**

![CMS Preliminary 2010](image1)

N. Saoulidou, Univ. of Athens, Greece