The top threshold effect in the $\gamma\gamma$ production at LHC

Prasenjit Sanyal

Indian Institute of Technology Kanpur
Department of Physics

in collaboration with

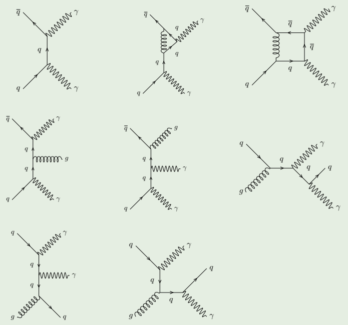
Pankaj Jain[1], Shashi R. Dugad[2], Subhadip Mitra[3] and Ravindra K. Verma[1,2]

[1]IIT Kanpur,[2]TIFR Mumbai,[3]IIIT Hyderabad

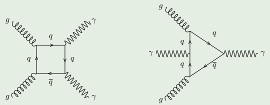
- The $\gamma\gamma$ pair production at LHC plays an important role in search of new physics.
- We look into the top quark threshold effect which appears about diphoton invariant mass, $M_{\gamma\gamma} \sim 340$ GeV.
- Once $M_{\gamma\gamma}$ reaches two times the mass of top quark, a dip is expected in the $gg \to \gamma\gamma$ cross section.
- Gluon fusion is the subdominant contribution to the total $pp \to \gamma\gamma$ production at LHC.
- We look into different kinematic cuts to capture this feature in the $pp \to \gamma\gamma$ channel at 13 TeV.

$pp \to \gamma\gamma$ production channels

$qX \to \gamma\gamma$ at NLO



$gg \to \gamma\gamma$ at LO

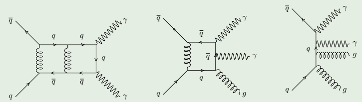


- LO $q\bar{q} \to \gamma\gamma$ at $\mathcal{O}(\alpha_{ew}^2)$
- Virtual diagrams at $\mathcal{O}(\alpha_{ew}^2\alpha_s)$
- Real diagrams at $\mathcal{O}(\alpha_{ew}^2\alpha_s)$

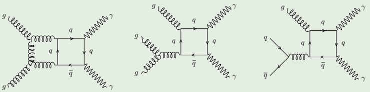
- LO Quark loop process at $\mathcal{O}(\alpha_{ew}^2\alpha_s^2)$

$pp \to \gamma\gamma$ production channels

$qX \to \gamma\gamma$ at NNLO



$gg \to \gamma\gamma$ at NLO



- The NNLO $qX \to \gamma\gamma$ and NLO $gg \to \gamma\gamma$ can be computed using MCFM.

- $k^{qX}_{NNLO} = \frac{\sigma_{qX\to\gamma\gamma} \text{ at } \mathcal{O}(\alpha^2_{ew}\alpha^2_s)}{\sigma_{qX\to\gamma\gamma} \text{ at } \mathcal{O}(\alpha^2_{ew}\alpha_s)} = 1.46$

- $k^{gg}_{NLO} = \frac{\sigma_{gg\to\gamma\gamma} \text{ at } \mathcal{O}(\alpha^2_{ew}\alpha^3_s)}{\sigma_{gg\to\gamma\gamma} \text{ at } \mathcal{O}(\alpha^2_{ew}\alpha^2_s)} = 1.20$

Event Generation in MADGRAPH5_AMC@NLO

- NLO $qX \to \gamma\gamma$ process and LO $gg \to \gamma\gamma$ process are generated in MADGRAPH5_AMC@NLO.

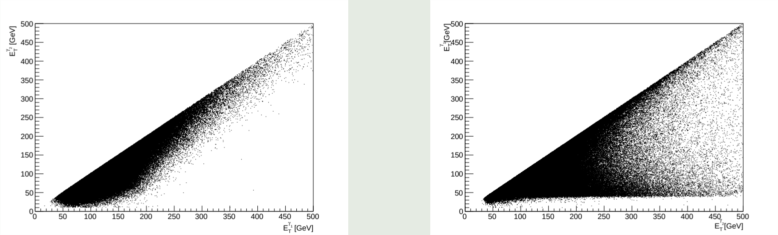
- The run card of $qX \to \gamma\gamma$ generated is modified to:
  1. Number of events $\longrightarrow$ 8,000,000
  2. Beam energy $\longrightarrow$ 6500 GeV.
  3. PDF $\longrightarrow$ nn23nlo
  4. Parton Shower $\longrightarrow$ PYTHIA6Q
  5. Renormaization Scale $\longrightarrow$ 91.118 GeV
  5. Factorization Scale $\longrightarrow$ 91.118 GeV
  6. Minimum photon transverse momentum $\longrightarrow$ 40 GeV.

Event Generation in MADGRAPH5_AMC@NLO

- The run card of $gg \to \gamma\gamma$ is modified to:
    1. Number of events $\longrightarrow$ 6,00,000
    2. Beam energy $\longrightarrow$ 6500 GeV.
    3. PDF $\longrightarrow$ nn23lo1
    4. Parton Shower $\longrightarrow$ PYTHIA8.
    5. Renormalization Scale$\longrightarrow$ 91.118 GeV
    5. Factorization Scale $\longrightarrow$ 91.118 GeV
    6. Minimum photon transverse momentum $\longrightarrow$ 40 GeV.
    7. minimum invariant mass of photon pair $\longrightarrow$ 200 GeV.

- To get realistic distribution the events are passed through DELPHES3.3.1 with default ATLAS card.

2D Correlation Plot Left: *gg* events Right:*qX* events

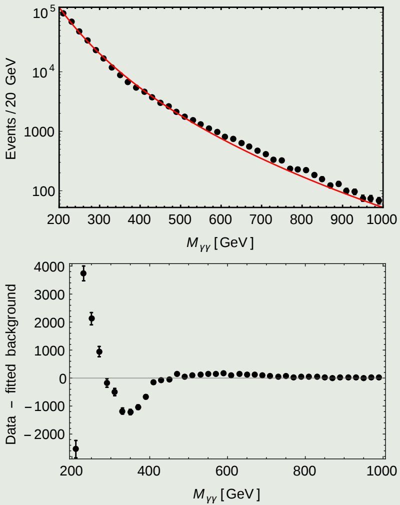


- Cut1: The leading and subleading photon should satisfy $E_T^{\gamma_1} > 0.4 M_{\gamma\gamma}$, $E_T^{\gamma_2} > 0.3 M_{\gamma\gamma}$ and $M_{\gamma\gamma} \geq 200$GeV (ATLAS collaboration, 2016).

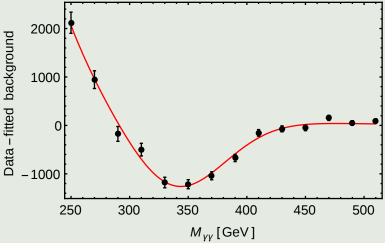
- Cut2: $E_T^{\gamma_1} > 0.25 M_{\gamma\gamma}$, $E_T^{\gamma_2} > 0.25 M_{\gamma\gamma}$ and $M_{\gamma\gamma} \geq 200$GeV.

- For $E_T^\gamma \geq 40$ GeV, $\sigma_{gg\to\gamma\gamma} = 308$ fb.
- For Cut2, $\sigma_{gg\to\gamma\gamma} = 180$ fb.
- ATLAS Fitting Function: $f_0(x) = (1 - x^{1/3})^b x^{a_0}$, $x = M_{\gamma\gamma}/\sqrt{s}$.
- The dip appears from the destructive interference between top loop diagrams containing on-shell top quarks and other diagrams containing light quark loops.

$gg \to \gamma\gamma$ distribution



$gg \to \gamma\gamma$ distribution

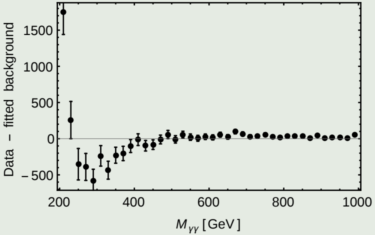


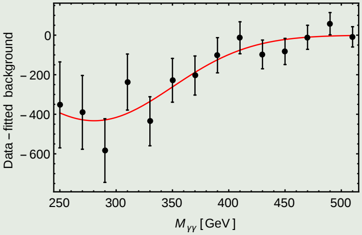
- In $250 \le M_{\gamma\gamma} \le 510$ GeV, we fit the dip with the following function

$$g_0(x) = -A \exp\left[-\frac{(x-x_0)^2}{2\sigma_g^2}\right] - B\left[\exp\left(-\frac{x}{\sigma}\right) - \left(\frac{\sigma}{x}\right)^6\right]$$

- $x_0 = 0.026 \longrightarrow M_{\gamma\gamma} = 337$ GeV (position of the dip).
- $\sigma_g = 3.28 \times 10^{-3} \longrightarrow$ width of 42.6 GeV.
- Relative normalization $\longrightarrow B/A = 3.73 \times 10^{-5}$.
- $\chi^2/dof \sim 2$.

$qX \to \gamma\gamma$ distribution





- With Cut2 $\sigma_{qX\to\gamma\gamma} = 1652$ fb.
- ATLAS fitting function is not good in $250 \leq M_{\gamma\gamma} \leq 510$ GeV, creating a shallow dip at about $M_{\gamma\gamma} \approx 300$ GeV.
- We fit the difference by

$$q_0(x) = -C \exp\left[-\frac{(x-x_{01})^2}{2\sigma_q^2}\right]$$

- $C = 433$ (amplitude)
- $x_{01} = 0.02 \longrightarrow M_{\gamma\gamma} = 280$ GeV.
- $\sigma_q = 5.34 \times 10^{-3} \longrightarrow 69.4$ GeV.
- $\chi^2/dof = 0.58$.

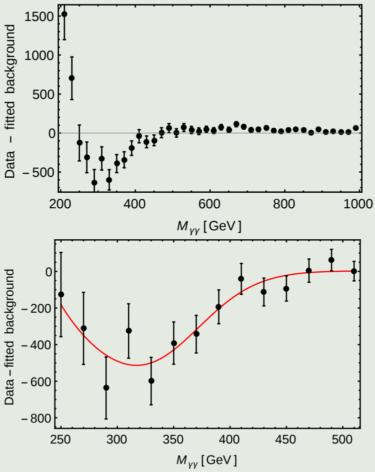
Combined Process $gg \to \gamma\gamma + qX \to \gamma\gamma$

- $pp \to \gamma\gamma$ at Luminosity 230 fb^{-1}
- Gluon fusion events get overshadowed by large $qX \to \gamma\gamma$ events.
- In $250 \le M_{\gamma\gamma} \le 510$ GeV we fit the difference with

$$c_0(x) = -\mathcal{Q}\, C \exp\left[-\frac{(x-x_{01})^2}{2\sigma_q^2}\right] - A\,\mathcal{G}\left[\exp\left\{-\frac{(x-x_0)^2}{2\sigma_g^2}\right\} + \frac{B}{A}\left\{\exp\left(-\frac{x}{\sigma}\right) - \left(\frac{\sigma}{x}\right)^6\right\}\right]$$

- $A = 189$ (normalization factor)
- $\mathcal{Q} = 1.08$ and $\mathcal{G} = 1.0 \pm 0.3$ hence 3σ detection of the dip.
- $\chi^2/dof = 0.6$.

$pp \to \gamma\gamma$ distribution



Combined Process $gg \to \gamma\gamma + qX \to \gamma\gamma$

- The above procedure of fitting the difference is equivalent to fitting $pp \to \gamma\gamma$ combined events with

$$f_0'(x) = \begin{cases} f_0(x) + c_0(x) & \text{if } 250 \leq M_{\gamma\gamma} \leq 510 \text{ GeV} \\ f_0(x) & \text{otherwise} \end{cases}$$

- In the full range $200 \leq M_{\gamma\gamma} \leq 1000$ GeV,

$$\chi^2_{global} = 198 \qquad \text{for } f_0(x)$$

$$\chi^2_{global} = 129 \qquad \text{for } f_0'(x)$$

- $\Delta\chi^2 = 69 \longrightarrow f_0'(x)$ is a better fitting function compared to $f_0(x)$ (ATLAS fitting function).

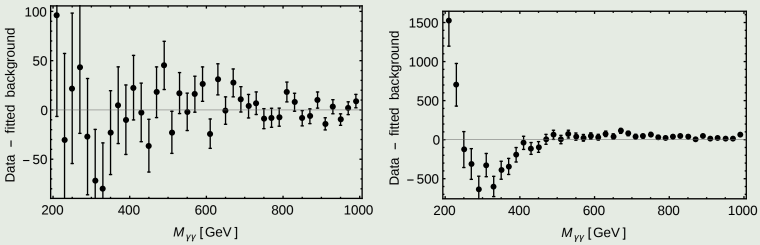
Possible Improvement

Selection Criteria	$\sigma_{gg}(fb)$	$\sigma_{qX}(fb)$	σ_{gg}/σ_{qX}
$\mathcal{C}_1$	180	1652	0.11
$\mathcal{C}_2$	64	217	0.29

- Recent literature provide statistical discrimination of quark jet and gluon jet.
- A good fraction of *qX* events have leading quark jet because of the process $qg \to \gamma\gamma q$.
- Gluon-jet Cut: We demand that the leading jet is a gluon jet (in addition to the modified ATLAS cut).
- $\mathcal{C}_1$ is Cut2 and $\mathcal{C}_2$ is the Gluon-jet cut.

Possible Improvement

Gluon-jet cut. Left: *qX* events. Right: *qX* and *gg* combined events.



- In the right panel, the dip is clearer and significant and the event at 350 GeV bin lies 3σ away from the smooth fit.
- We considered the gluon jet tagging efficiency $\epsilon = 1$
- In practice because of miss-tagging, efficiency $\epsilon \approx 0.4$
- Assuming efficiency to be same for *qX* and *gg* channel, the effect can be seen at a higher luminosity $(230/\epsilon = 575)$ fb^{-1}.

Conclusion

- Destructive interference of top quark loop with other light quark loops in the gluon fusion process produces a dip in the invariant mass distribution at the threshold of top quark production.
- For a luminosity of 230 fb^{-1}, we obtain a dip at $\approx$ 340 GeV diphoton invariant mass at 3σ by relaxing the cut followed by ATLAS collaboration.
- Introducing a cut where the leading jet is a gluon jet increses the effect considerably, but the required luminosity also increases.
- Through statistical analysis we aim to establish that though dificult, it is possible to observe this effect at LHC in near future.
- Besides the study of the SM background of photon pair production, it can provide another way of probing heavy colored fermion or colored scalar running in the $gg \to \gamma\gamma$ loop.

Important Formulas

- Invariant Mass: $M^2_{\gamma\gamma} = 2p_T^{\gamma_1} p_T^{\gamma_2} \cosh(\eta_{\gamma_1} - \eta_{\gamma_2}) \cosh(\phi_{\gamma_1} - \phi_{\gamma_2})$

  $\eta \rightarrow$ pseudorapidity and $\phi \rightarrow$ azimuthal angle.

- Cross-section: $\sigma_{CUT} = \sigma_{MG} \times \frac{\text{Number of events surviving the CUT}}{\text{Number of events generated at MG}}$

- Combining $qX \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ events:

$$N_{comb} = N_{qX} + N_{gg} \times \frac{\sigma_{gg \rightarrow \gamma\gamma}}{\text{Number of events survivng the cut}} \times \frac{\text{Number of events survivng the cut}}{\sigma_{qX \rightarrow \gamma\gamma}}$$

- Error bar: $\sqrt{\text{Number of events in each bin}}$

References

1. ATLAS collaboration, search for resonance in diphoton events with the ATLAS detector at $\sqrt{s} = 13$ TeV, ATLAS-CONF-2016-018(2016).
2. T.Binoth, J.P. Guillet,E.Pilon and M.Warlen, A full next-to-leading order study of direct photon pair production in hadronic collisions, Eur.Phys.J. C16(2000)311-330, [hep-ph/9911340].
3. J.M Campbell, R.K.Ellis, Y.Li and C.Williams,Predictions for diphoton Production at the LHC through NNLO in QCD, 1603.02663.
4. D.Chway,R.Dermek,T.H.Jung and H.D.Kim, Gluons to Diphotons via new Particles with Half the Signals Invariant Mass, Phys.Rev.Lett. 117(2016)061801, [1512.08221].

Thank You