Tri-vector boson production at NLO with parton shower

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September 24, 2013
IMSc, Chennai

Tri-vector boson production in NLO with parton shower,
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(in preparation)

PLAN OF THE TALK:

- Introduction
- Basics and Importance of NLO
- Why NLO+PS?
- Calculation of virtual part
- Preparation of aMC@NLO Sample
    - Calculation of real part.
    - Cancellation of IR poles.
    - Removal of double counting.
- Results for Tri-gamma production at the LHC
- Conclusion

INTRODUCTION

- Large Hadron Collider provides opportunity not only to test the Standard Model (SM) but also to constrain most of the physics beyond the Standard Model (BSM) scenarios.
- BSM scenarios often give signals very similar to those coming from SM.

$$P + P \to G + X \qquad\qquad G - BSM \quad particle$$

- SM processes are the potential background to BSM studies at the LHC.

SM-BSM INTERFERENCE

- SM processes can also interfere when BSM processes through virtual effects.

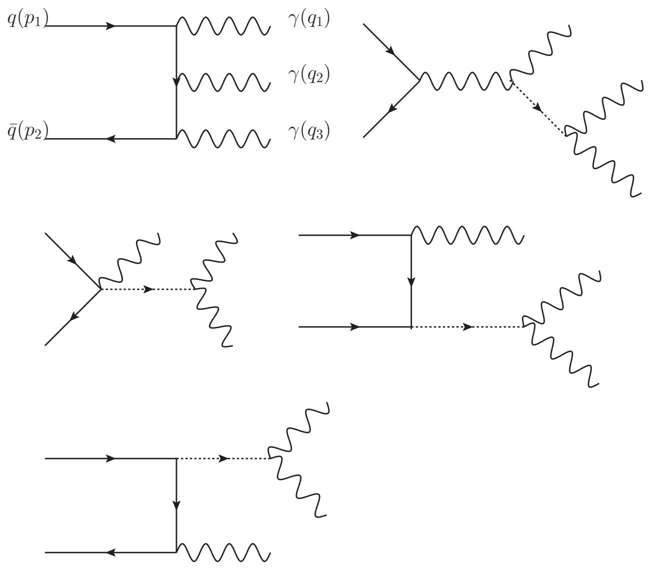
$$P + P \to G^* \to l^+ + l^-/\gamma\gamma + X \qquad G^* - virtual \quad BSM \quad particle$$

- In order to constrain the parameters of the BSM models, both background contributions as well as interference efffect from SM need to be understood to a very good accuracy.
- Drell-Yan, di-photon, di-Z, di-W in SM are the well known processes where BSM physics contributes. They are already known to NLO and NLO+parton shower accuracy and few at NNLO level.

SM-BSM INTERFERENCE

- Tri-photon production is a potential background to techni-pion + photon production where the techni-pion decays into a photon pair.
- BSM particles can also contribute to Tri-photon production through virtual particles in models with large extra-dimensions.
- Full NLO in SM is available from the work by Zeppenfield et al.
- Predictions with parton shower (PS) at NLO level will be presented in this talk.
- The computation to include contribution from the interference effects is underway.

TRI-VECTOR BOSON PRODUCTION



GENERAL STRUCTURE OF NLO CALCULATION

NLO Cross section:

$$2S\ d\sigma^{P_1 P_2}_{NLO}\left(\tau, Q^2\right) = \sum_{ab} \int_{\tau}^{1} \frac{dx}{x} \Phi_{ab}\left(x, \mu_F\right) 2\hat{s}\ d\hat{\sigma}^{ab}_{NLO}\left(\frac{\tau}{x}, Q^2, \mu_F\right)$$

$$\begin{aligned} d\hat{\sigma}^{ab}_{NLO} &= d\hat{\sigma}^{ab}_{LO} + \frac{\alpha_s}{4\pi}\ \delta d\hat{\sigma}^{ab}_{NLO} \\ \delta d\hat{\sigma}^{ab}_{NLO} &= d\hat{\sigma}^{ab}_{virt} + d\hat{\sigma}^{ab}_{real} + d\hat{\sigma}^{ab}_{ct} \end{aligned}$$

- $d\hat{\sigma}^{ab}_{LO}$: Born contribution, all final state particles resolved.
- $d\hat{\sigma}^{ab}_{virt}$: One loop renormalised virtual corrections, having the same external particles as the Born, but with an extra power of the coupling constant α_s.
- $d\hat{\sigma}^{ab}_{real}$: One gluon/quark real emission from the Born processes.
- $d\hat{\sigma}^{ab}_{ct}$: Collinear counter terms (Mass factorisation counter terms).

Role of NLO

- Observables are "free" of
  - UV Renormalisation scale (μ_R)
  - Factorisation scale (μ_F)
  - Choice Parton Distribution Functions (PDF)
- But "fixed order" perturbative predictions do depend on them
- Role of NLO corrections
  - Reduce the scale dependence and choice of PDFs inherent to the tree level predictions.
  - Opening up of production channels.
  - Affect the shape of distributions significantly.
- Accurate theoretical predictions are necessary for the search of new physics.

ROLE OF NLO+PARTON SHOWER

- NLO and parton shower Monte Carlos (MC's) are complementary approaches, the former is good for hard emissions, the latter for soft / collinear ones
- Retain the virtues of the two while discarding the weaknesses: give a prediction which is MC in the soft / collinear region and NLO for hard radiation
- Avoid double counting because fixed order NLO contains soft contributions as well.
- Achieve a smooth transition between the two regimes
- Matched computations are some of the most accurate / realistic predictions currently available

QGRAF

- Our process contains a large no. of Feynamn diagrams and each expression is very legnthy due to spin-2 coupling (vertices are often rank-4 tensors).
  - LO Diagrams
    - SM → 6 diagrams
    - BSM → 12 diagrams
  - One Loop Diagrams
    - SM → 48 diagrams
    - BSM → 57 diagrams

So we have used the package QGRAF to generate all the feynman diagrams.

QGRAF TO FORM

- Processed the QGRAF output using FORM routines to get the expression for the matrix elements.
- First, the interference of the leading (LO) and next-to-leading order (NLO) matrix elements is decomposed into the individual contributions of loop diagrams Γ.
- The sum over spins and colors are performed for each loop diagram separately

$$\sum_{\text{col}}\sum_{\text{spin}}\mathcal{M}^{(\text{NLO})}\left(\mathcal{M}^{(\text{LO})}\right)^{*}=\sum_{\Gamma}\left[\sum_{\text{col}}\sum_{\text{spin}}\mathcal{M}^{(\Gamma)}\left(\mathcal{M}^{(\text{LO})}\right)^{*}\right]$$

Tensor reduction

The Tensor integrals that appear at one loop level are of the form:

$$I_n^{\mu_1 \cdots \mu_m} = \int \frac{d^n l}{(2\pi)^n} \frac{l^{\mu_1} \ldots l^{\mu_m}}{((l - q_1)^2 + i\epsilon) \cdots ((l - q_n)^2 + i\epsilon)}$$

- Here $q_1 = p_1, \; q_2 = p_1 + p_2, \quad \cdots, \quad q_n = \sum_{i=1}^{n} p_i$
- $d = 4 + \epsilon$ is the spacetime dimension and ϵ is the dimension regulator.
- The finite term of this expansion contain physical information, while $\frac{1}{\epsilon}$ and $\frac{1}{\epsilon^2}$ provide additional cross checks as they have to cancel against similar terms from real emission.

TENSOR REDUCTION

- We have written a FORM code which does this tensor reduction in terms of these coeffcients.
- These coefficients of one-loop tensor integrals are directly related to scalar integrals in higher dimensions.
- These higher dimensional integrals can be expressed in terms of integrals in n dimensions via certain dimensional recurrence relations.
- The gram determinants need to be handled with care.
- These have been already implemented in the PJFry package.

VALIDATION OF OUR CODE

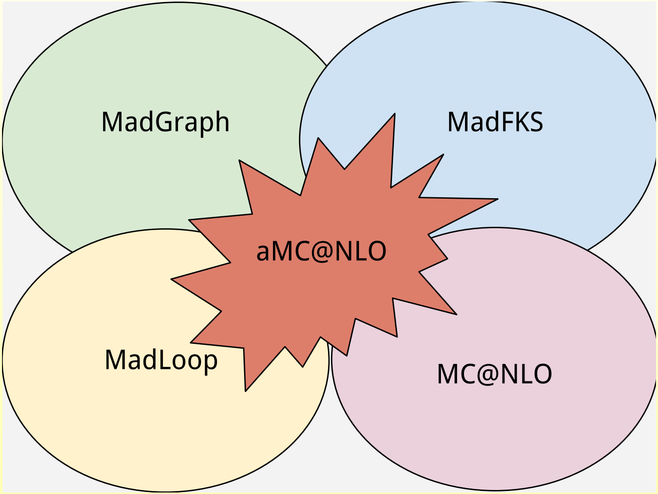
- PJFry uses QCDLoop/OneLOop for n-dim scalar integrals.
- For validation of our FORM codes and also to validate FORTRAN routines, which evaluates virtual contributions numerically using PJFry:
  - We have recalculated the vitual corrections to di-photon production to order α_s and compared against the analytical results presented in our earlier article.
  - We found very good agreement upto nine decimals at a wide range of phase space points.

STATUS

- Our results on fixed order Standard Model contribution to tri-photon at NLO level is in complete agreement with those of Zeppenfeld et al.
- Fixed order + Parton shower in Standard Model is now complete and they provide realistic predictions for various observables.
- BSM effects coming from spin-2 graviton in the ADD model is underway taking into direct BSM and SM-BSM contributions at NLO level.
- Rest of the talk will have only SM effects at NLO+PS accuracy for the LHC.

aMC@NLO

The aMC@NLO framework automates the matching of PS with NLO accurate matrix-element calculations based upon the MC@NLO formalism.



aMC@NLO

aMC@NLO Framework:

- The underlying tree-level computations are performed with MadGraph.
- One-loop amplitudes are evaluated via MadLoop, via the OPP integrand reduction method.
- MADFKS takes care of the real emission contributions and the corresponding phase-space subtractions.
    - Cancellation of the IR poles and the subsequent integration is done in MADFKS.
    - The MC@NLO matching is done at the time of generating the events
    - Afterwards it is showered to get the physical results.

aMC@NLO Sample

- The input parameters used for the whole computation.

$$
\begin{aligned}
M_W &= 80.419\ \mathrm{GeV}, & \sin^2\theta_W &= 0.222, \\
M_Z &= 91.188\ \mathrm{GeV}, & \alpha_{em}^{-1} &= 132.507, \\
G_F &= 1.16639 \cdot 10^{-5}\ \mathrm{GeV}^{-2}\ .
\end{aligned}
$$

- This value of α_{em} ensures that the mass of the W-boson remains closer to the experimental value.
- We have considered massless quarks with five flavours($n_f = 5$) and in the process we have not considered any effect from the top quark.

aMC@NLO Sample

- The (N)LO events are generated using MSTW2008(N)LO parton distribution functions with errors estimated at 68% for the (N)LO and it also sets the value of the strong coupling $\alpha_s(M_Z)$ at LO and NLO in QCD.
- The factorisation scale (μ_F) and the renormalisation scale (μ_R) are set equal to the invariant mass of the three photon final state. $\mu_F = \mu_R = \mu_0 = M_{\gamma\gamma\gamma} \equiv \sqrt{(P_{\gamma_1} + P_{\gamma_2} + P_{\gamma_3})^2}$.

Frixione Isolation:

- Photons in the final state are produced not only at the partonic level but also through fragmentation of partons into a photon and a jet of hadrons, often collinear to it. This introduces the non-perturbative fragmentation functions.
- In the case of real emission, the collinear emission of a photon from a massless quark also leads to additional infrared divergences.
- While a naive separation cut between these two particles can remove the dependence on fragmentaion function, it will spoil the cancellation of soft divergences between virtual and real parts in a infra red safe way.

Frixione Isolation:

- Define a cone around each photon with cone radius R in $\eta - \phi$ plane and introduce the following cut on the energy of the hadrons:

$$E_{had,max} \leq \epsilon_\gamma p_{T_\gamma} \left(\frac{1-\cos r}{1-\cos R_\gamma} \right)^n$$

  - $E_{had,max}$ is the maximum hadronic energy permitted inside the cone.
  - r is the separtion between the photon and the extra parton in the $\eta - \phi$ plane.
  - p_{T_γ} has been taken on event by event basis.
  - This ensures the removal of fragmentaion function dependence by allowing the parton to be arbitrarily close to the photon, as long as its momentum vanishes simultaneously, thereby ensuring IR safty.

aMC@NLO Sample

- For the fixed order calculation we have taken 2 choices of cuts.
  - CUTI: $P_T^\gamma > 20$ GeV, $|Y^{(\gamma)}| < 2.5$, $\Delta R^{\gamma\gamma} > 0.4$ and Frixione isolation with $R_\gamma = 0.7$, $\epsilon_\gamma = 1$ and $n = 2$
  - CUTII: $P_T^\gamma > 30$ GeV, $|Y^{(\gamma)}| < 2.5$, $\Delta R^{\gamma\gamma} > 0.4$ and Frixione isolation with $R_\gamma = 0.7$, $\epsilon_\gamma = 1$ and $n = 2$
- The parton level events are generated with the following loose cuts:
  - $P_T^{(\gamma)} > 15$ GeV,
  - $|Y^{(\gamma)}| < 2.7$,
  - Frixione isolation with $R_\gamma = 0.6$, $\epsilon_\gamma = 1$ and $n = 2$
  - $\Delta R^{\gamma\gamma} > 0.3$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ denotes the separation of the two particles in the rapidity-azimuthal plane.

aMC@NLO Sample

- We have explicitly checked that the events produced with these cuts remain unbiased in total rates and differential distributions. (Keeping the analysis cuts fixed and varying the generation cuts)

- The generated events are showered with HERWIG6.

- After the shower and hadronisation, a set of stringent cuts on transverse momenetum and rapidity to take into account of the requirements of the experimental detectors and also frixione isolation and a separtion between the photons itself to remove fragmentation function and collinear divergences in a IR safe way is imposed.

- We have taken CUTII: $P_T^\gamma > 30$ GeV, $|Y^{(\gamma)}| < 2.5$, $\Delta R^{\gamma\gamma} > 0.4$ and Frixione isolation with $R_\gamma = 0.7$, $\epsilon_\gamma = 1$ and $n = 2$ as our choice here.

FO PLOT FOR THE HARDEST PHOTON

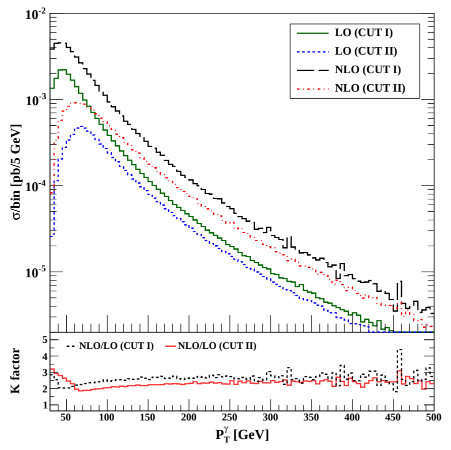


Figure : Transverse momentum distribution of the hardest photon p_T^γ among the three photon for the fixed order NLO and LO for 2 different cuts.

FO PLOT FOR THE INVARIANT MASS

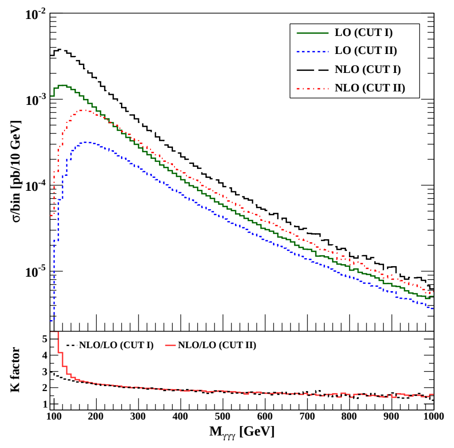
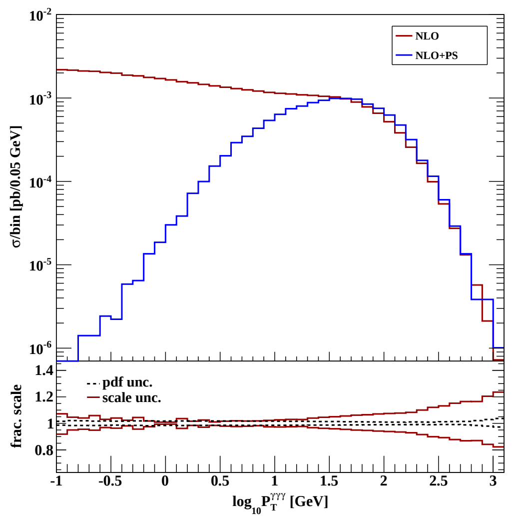


Figure : Invariant mass ditribution $M_{\gamma\gamma\gamma}$ of the three photon for the fixed order NLO and LO for 2 different cuts.

aMC@NLO Sample

- The lower inset shows the bin-by-bin distribution of the K-factor for the respective observables.
- For low transverse momenta the K-factor is large as it is due to the fact that the recoil against the extra parton helps to fulfil the tranverse momentum cut which was not possible at LO.

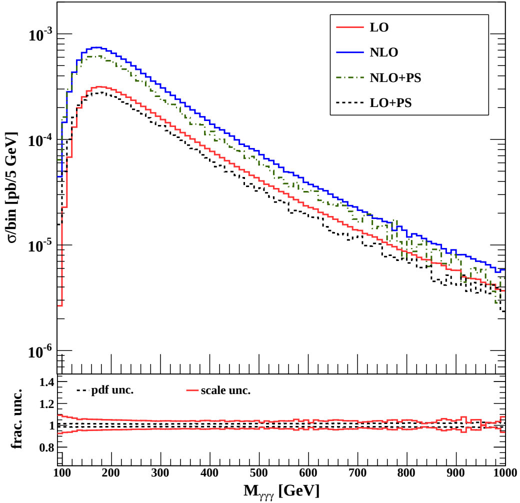
aMC@NLO


10^-2
10^-3
10^-4
10^-5
10^-6
σ/bin [pb/0.05 GeV]
NLO
NLO+PS
1.4
1.2
1
0.8
frac. scale
pdf unc.
scale unc.
-1
-0.5
0
0.5
1
1.5
2
2.5
3
log10 P_T^γγγ [GeV]

aMC@NLO Sample

- The fixed order NLO results diverges for $p_T^{\gamma\gamma\gamma} \to 0$.
- It is clear that at low $p_T^{\gamma\gamma\gamma}$ values, NLO+PS correctly resums the Sudakov logarithms, leading to a suppression of the cross section.
- At high $p_T^{\gamma\gamma\gamma}$, the NLO fixed order and NLO+PS results are in agreement.
- In the lower inset, the scale and PDF variation is shown.

aMC@NLO


LO
NLO
NLO+PS
LO+PS
10^{-3}
10^{-4}
10^{-5}
10^{-6}
σ/bin [pb/5 GeV]
frac. unc.
pdf unc.
scale unc.
1.4
1.2
1
0.8
100
200
300
400
500
600
700
800
900
1000
$M_{\gamma\gamma\gamma}$ [GeV]

SEPERATION BETWEEN THE PHOTONS IN $\eta - \phi$ PLANE

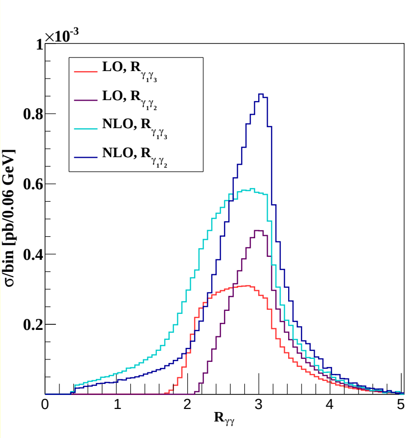


Figure : The differenetial distribution between the Hardest photon (γ_1) and the softer photons(γ_2, γ_3) at LO and NLO

SEPERATION BETWEEN THE PHOTONS IN $\eta - \phi$ PLANE

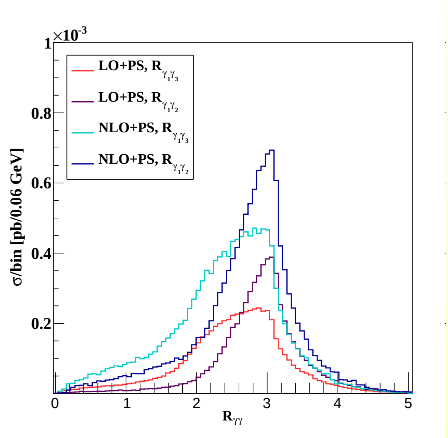


Figure : The differenetial distribution between the Hardest photon (γ_1) and the softer photons(γ_2, γ_3) at LO+PS and NLO+PS accuracy

R DISTRIBUTION

- We have ordered the photons according to their transverse momentum. The hardest one is γ_1 and the softer is γ_3 and γ_2 being in the middle of them.
- We have plotted the differntial distribution in the distance $R_{\gamma\gamma} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ with a selection cut at $R^{\gamma\gamma} > 0.4$
- The rapidity seperation between the harder photon and the softer photons are small.
- Therefore , the peak in this distribution suggests that the distribution peaks where the harder photon and the softer ones are mostly back-to-back and central in rapidity.
- The harder photon is seperated form the softest phtons by at least $R_{\gamma\gamma} = 1.6$ at LO, whereas at NLO they can be as close as permitted by the selection cut due to the extra radiation at NLO.

CONCLUSIONS

- Tri-boson production is one of the processes at the LHC that can be used for studying the BSM physics.
- Constraining the parameters of BSM requires better understanding signals, backgrounds and the interferences coming from the SM.
- NLO and NLO+PS are important to constrain these models as the uncertainties are better controlled.
- At present we have completed NLO+PS contributions for Tri-photon production in the SM.
- Parton shower reduces the rates in most of the distributions.
- Work on NLO+PS for BSM (with SM interference) is underway.