MAX-PLANCK-GESELLSCHAFT

Diphoton + jet(s) at NLO

Nicolas Greiner
Max-Planck-Institute for Physics, Munich

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Based on arxiv:1303.0824,1308.3660 [Gehrmann,NG,Heinrich]

RADCOR 2013, 22.-27.9. 2013

Outline

- Diphoton + jets - Motivation
- Diphoton + one jet @ NLO
  - Photon Fragmentation effects
  - Impact of isolation criteria
- Diphoton + two jets @ NLO

  → See also Adriano Lo Presti's talk
- Summary and Outlook

MAX-PLANCK-GESELLSCHAFT

Motivation

- Next step after discovery of the Higgs: Precise determination of couplings, branching ratios, quantum numbers etc.
  $\rightarrow$ Deviations from SM ?

- H $\rightarrow \gamma\gamma$ one of the most important channels, clean signature, (small BR).

- Diphoton plus jets: Background process, needs to be determined precisely.
- Precision of sideband subtraction might not be sufficient for precision studies.
  $\rightarrow$ Need theoretical predictions at NLO in QCD.
- Diphoton plus two jets background to VBF signature.

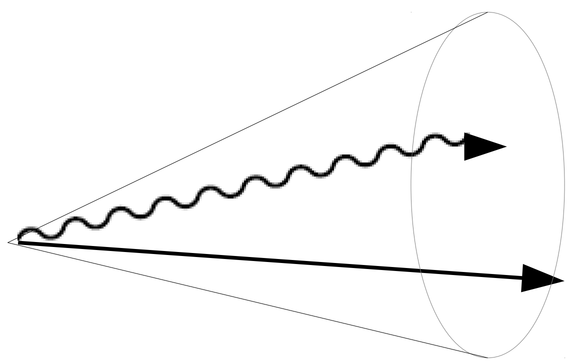
Diphoton + Jet @ NLO

Presence of a photon in a NLO QCD calculation makes the situation more complicated...

Diphoton + Jet @ NLO

Presence of a photon in a NLO QCD calculation makes the situation more complicated...

- Experiment: Photon accompanied by QCD stuff
- Collinear Limit between Photon and Quark resolved



Theory:
Quark and Photon collinear: Singularity!
- QED singularity → no cancellation with QCD virtuals

- No problem at LO, but additional singularity present in real emission at NLO, needs to be regulated.

Diphoton + Jet @ NLO

MAX-PLANCK-GESELLSCHAFT

Photon Fragmentation / Cone isolation

- Photon can have two origins:
  I. Direct radiation off quark/antiquark
  II. Fragmentation of hadronic jets into photons
    - Non-perturbative, described by photon fragmentation function (measured)
- Collinear singularity absorbed into photon fragmentation function

→ In cone around photon

$$z = \frac{p_{T,hadr}}{p_T(p_{hadr} + p_\gamma)} \leq z_{cut}$$

✔ Compatible with experiment
✗ Theoretically complicated

Frixione Isolation criterion [Frixione '98]

- The closer to the collinear limit, the less hadronic energy is allowed.

→ Inside cone around photon with radius R

$$E_{\mathrm{had,max}}(r_\gamma) = \epsilon\, p_T^\gamma \left(\frac{1-\cos r_\gamma}{1-\cos R}\right)^n$$

➡ In the limit, no hadronic energy is allowed
➡ **Finite!**

✔ Theoretically nice, no extra contributions needed
✗ Experimentally no smooth cut-off possible

Diphoton + Jet @ NLO

Status: pp->$\gamma\,\gamma$: Diphox [Binoth et al. '99] cone/Frixione, MCFM [Campbel et al.]

pp $\rightarrow \gamma$ j : Jetphox [Catani et al. '02], [Aurenche et al. '06], [Belghobsi et al. '09]
cone isolation / Frixione isolation

pp $\rightarrow \gamma\,\gamma$ j : NLOJet++ [DelDuca,Maltoni,Nagy,Trocsanyi '03] Frixione isolation
Resbos: resummation contr. [Balazs et al.]
Gamma2MC: includes gg initial at NLO [Bern,Dixon,Schmidt, '02]
2GammaNNLO: NNLO corrections to diphoton [Catani et al. '12]

New: Comparison between the two methods (cone vs. Frixione)

Setup: Virtuals with GoSam
Tree level /real radiation with MadGraph 4 [Stelzer,Long '94]
Subtraction terms for QCD with MadDipole [Frederix,Gehrmann,NG '08,'10]
Phase space integration with MadEvent [Maltoni,Stelzer '02]

Additional subtraction terms for QED singularities with MadDipole
Include LO fragmentation from BFGW [Bourhis,Fontannaz,Guillet,Werlen '00] set.

Calculation Setup

- **GoSam: Automated generation of one loop amplitudes**

[Cullen,van Deurzen,NG,Heinrich,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,Reichel,Reiter,Schlenk,von Soden-Fraunhofen, Tramontano]

→ See Pierpaolo Mastrolias's talk for details on GoSam.

- For diphoton plus one jet,virtuals can be reduced to $q\bar{q} \to \gamma\gamma g$
- Virtual amplitude interfaced with **MadGraph/MadDipole/MadEvent**

→ See Gionata Luisoni's talk for details on interfaces with MC.

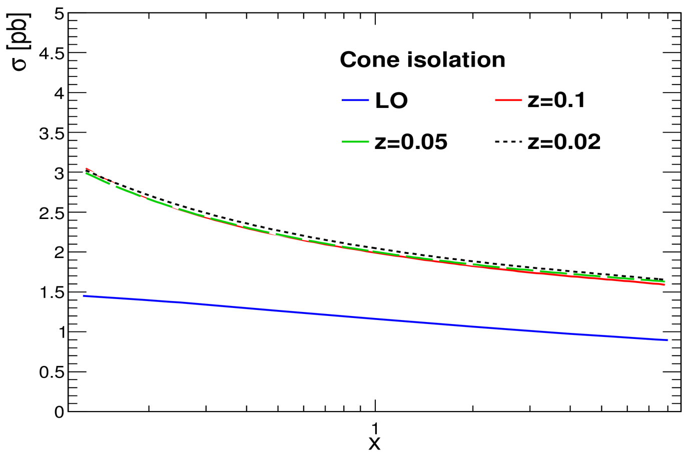
- Use of cone isolation leads to QED singularities in real emission contribution.
  - Treatment of non-collinear safe observables in QED known [Dittmaier,Kabelschacht,Kasprzik '07]
  - Implemented in QED version of MadDipole [Gehrmann,NG '10] , also provides interface to photon fragmentation function.

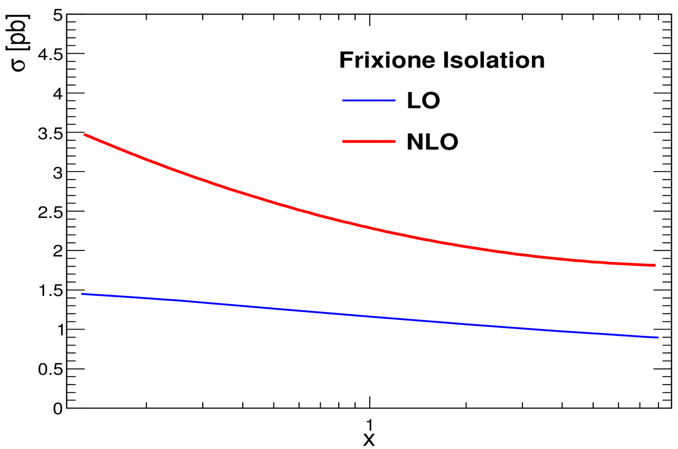
Diphoton + Jet @ NLO

Scale variation: $\mu_0^2 = \frac{1}{4}\left(m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2\right)$ $\mu_r = \mu_f = \mu_F$ $\sqrt{s} = 8$ TeV

$p_T^{\text{jet}} > 40\,\text{GeV},\, p_T^{\gamma} > 20,\, |\eta^\gamma, \eta^j| \leq 2.5,$ $R \geq 0.4$ $100\,\text{GeV} \leq m_{\gamma\gamma} \leq 140\,\text{GeV}.$

Inclusive cuts:



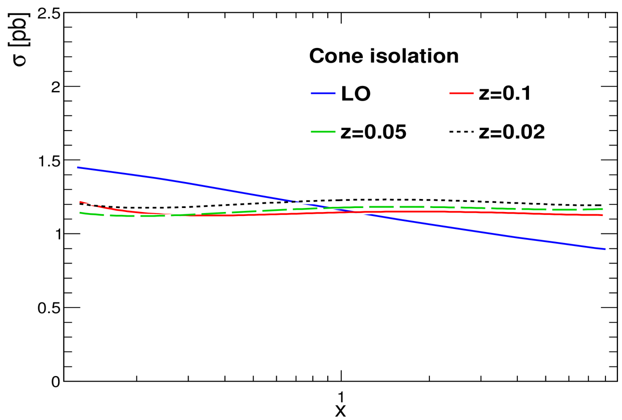


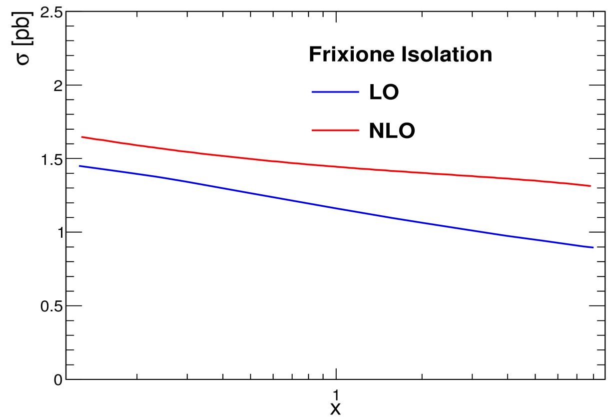
$\epsilon = 0.5,\ n = 1$

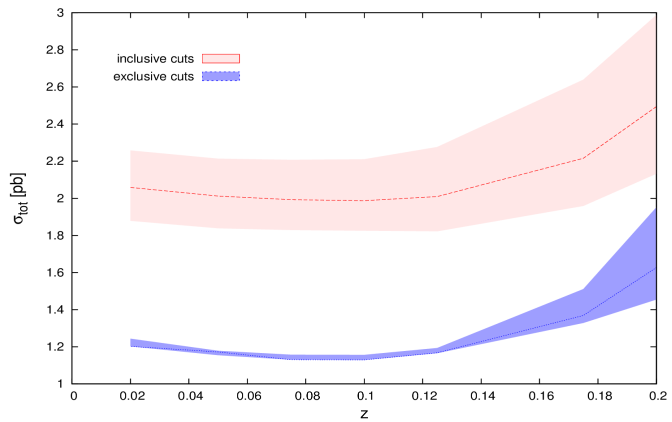
- Large K-factor ~2
- No reduction of scale uncertainty

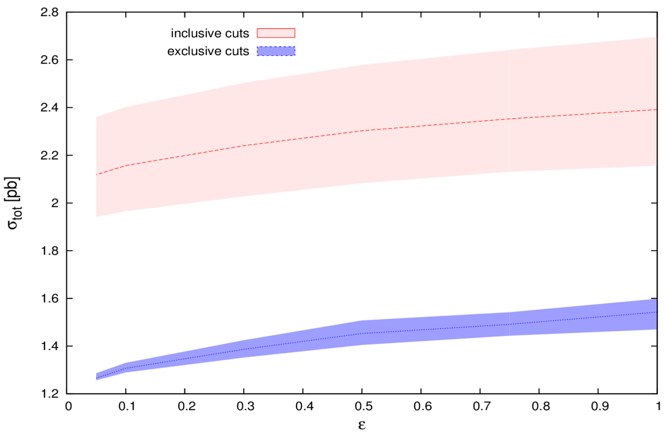
Diphoton + Jet @ NLO

Impose veto on second jet (exclusive cuts): $p_{T,j2} \leq 30$ GeV









- Reduction of scale uncertainty compared to LO.
- Strong reduction of K-factor compared to inclusive cuts.
- Cone isolation more stable under scale variation

Diphoton + Jet @ NLO

What is not (yet) included:

- Gluon to Photon fragmentation: Regarded as higher order contribution
- NLO fragmentation: Only LO fragmentation included. Sizeable ?
- Virtuals for gluon-gluon initial state: One-loop squared, higher order, but gluon-pdf enhanced. Sizeable ?
- Fixed hadronic energy inside cone for cone isolation.

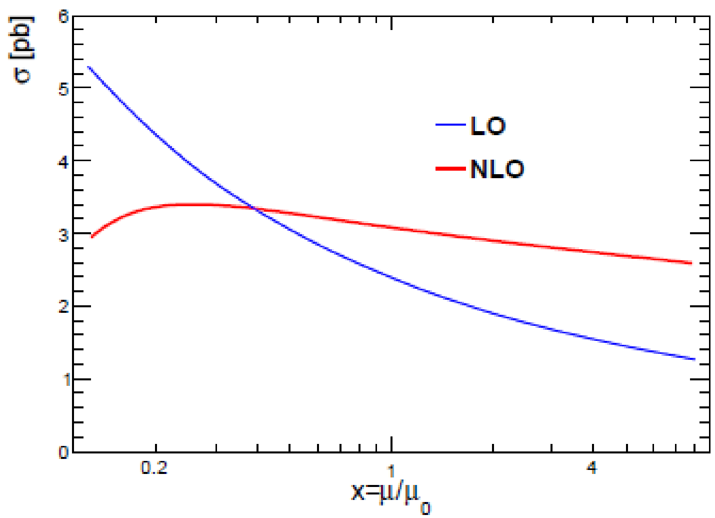
The whole package is made public as a complete stand alone code

http://gosam.hepforge.org/diphoton

- Installation with ./setup.py install
- Generation of results with ./integrate.py
- Short README with more information.

Diphoton + 2 Jets

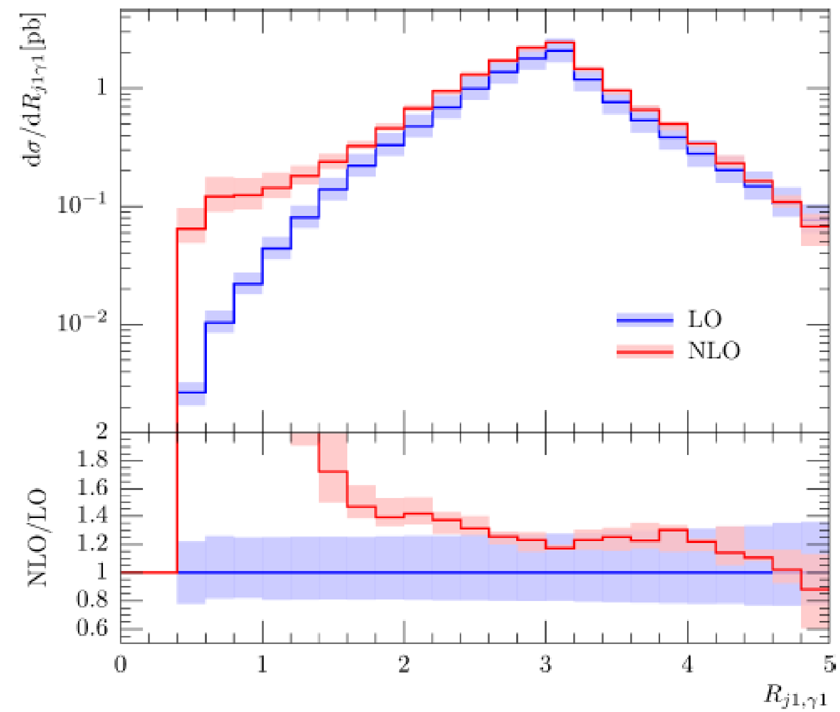
- Diphoton plus two jets important for VBF signature
- Same setup as for diphoton plus one jet
  Virtual corrections needed for $q\bar{q} \to \gamma\gamma q\bar{q}, \quad q\bar{q} \to \gamma\gamma q'\bar{q}', \quad gg \to \gamma\gamma q\bar{q}$
- Parameters: $p_T^{\mathrm{jet}} > 30\ \mathrm{GeV}, \quad p_T^{\gamma,1} > 40\ \mathrm{GeV}, \quad p_T^{\gamma,2} > 25\ \mathrm{GeV},$
  $|\eta^\gamma| \leq 2.5, \quad |\eta^j| \leq 4.7, \quad R_{\gamma,j} > 0.5, \quad R_{\gamma,\gamma} > 0.45$
- Frixione isolation with $R = 0.4, n = 1$ and $\epsilon = 0.05$



- Clear reduction of scale uncertainty
- Sizeable NLO contributions for central scale (K-factor ~1.3)
- Dependence on isolation type / parameter ??

Diphoton + 2 Jets

NLO corrections in general more pronounced in differential distributions, in particular if certain regions are kinematically not allowed at LO, e.g. R(jet1,gamma1)



TO DO:

- Implementation of photon frag. function.
- Detailed study of photon isolation effects.
- Inclusion of one-loop squared contributions.
- Effects of alternative clustering algorithms (democratic clustering).
- Code will be made public as standalone package.
- ….

MAX-PLANCK-GESELLSCHAFT

Summary and Outlook

- Diphoton + jets important background to H + jets.
- Diphoton + one jet:
  - Photon Fragmentation vs. Frixione isolation: Differences decrease when the allowed hadronic energy around the photon is reduced.
  - Process made public as fully stand alone package ready to use.
- Diphoton plus two jets:
  - Implementation with Frixione isolation finished.
  - Sizeable NLO corrections, in particular in differential distributions.
- Outlook
  - Photon fragmentation effects in diphoton plus two jets.
  - Additional features: One-loop squared contributions, different clustering, fixed hadronic energy in cone.
  - Make everything public.