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Automation of NLO Calculations
-
Precise Predictions for LHC Processes

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Motivation

Why is this necessary / useful ?

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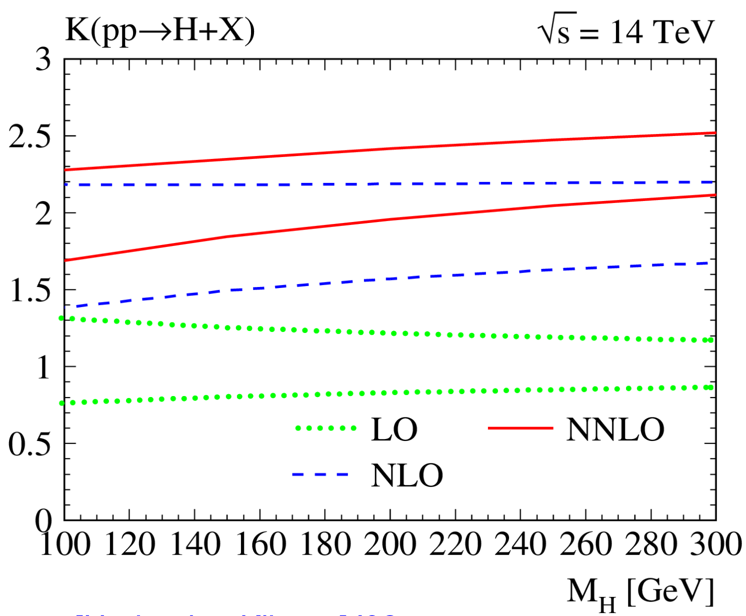
Why is this necessary / useful ?

→ LHC relevant processes need precise predictions

Example: Higgs production:



[Harlander, Kilgore] '02

- Large corrections from higher orders
- Strong dependence on ren./fac. scale

→ LO predictions unreliable, need at least NLO

NLO calculations are hard, complicated and time consuming!

Motivation

Why is this necessary / useful ?

"I designed a program that allows me to run the entire plant from my computer. By the way, how's the weather back there?"

Automation is important because

- ✔ it saves time
- ✔ avoids human mistakes
- ✔ allows to reuse building blocks
- ✔ easier to handle for the user
- ✔ not necessary to understand all details
- ✔ multipurpose

But

- ✗ For a specific task, often one can design a dedicated tool which is better suited

Motivation

How can I benefit from automation ?

- It enables the user to perform complex NLO calculations.
- No need to reinvent things from scratch.
- Can be used as a black box, no need to know the internal details.
- Can also be used by experimentalists (not just a toy for theorists).
- Different tools can be combined (modular structure).

Structure of NLO

$$\sigma_{NLO} = \int_n \left(d\sigma^B + d\sigma^V + \int_1 d\sigma^A \right) + \int_{n+1} \left(d\sigma^R - d\sigma^A \right)$$

Tree level

Virtual corrections - one loop

Real emission (infrared divergent)

Subtraction terms: Needed to cancel infrared singularities numerically.
Idea: Add zero in suitable way to cancel infrared singularities from real emission

Several methods available:

- Residue subtraction [Frixione, Kunszt, Signer]
- Dipole formalism [Catani, Seymour],[Catani, Dittmaier, Seymour, Trocsanyi]
- Antenna formalism [Kosower], [Campbell,Cullen,Glover],[Gehrmann-De Ridder,Gehrmann,Glover],[Daleo,Gehrmann,Maitre],[Gehrmann-De Ridder,Ritzmann]

NLO (R)evolution

Enormous progress in recent years:

Automation of subtraction methods

- SHERPA [Gleisberg,Krauss]
- TeVJet [Seymour,Tevlin]
- MadDipole [Frederix,Gehrmann,NG]
- AutoDipole [Hasegawa,Moch,Uwer]
- HELAC-NLO [Czakon,Papadopulos,Worek]
- MadFKS [Frederix,Frixione,Maltoni,Stelzer]

Automation of virtual corrections

- BlackHat [Berger et al.]
- Collier [Denner, Dittmaier]
- FeynArts/Formcalc/Looptools [Hahn et al.]
- GoSam [Cullen et al.]
- HELCA-NLO [Bevilacqua et al.]
- MadGolem [Goncalves Netto et al.]
- MadLoop [Hirschi et al.]
- MCFM [Campbell et al.]
- Ngluon/Njet [Badger et al.]
- OpenLoops [Cascioli et al.]
- PJFry [Fleischer et al.]
- POWHEG [Alioli et al.]
- Prospino [Beenakker et al.]
- Recola [Actis et al.]
- Rocket [Ellis et al.]
- VBFNLO [Arnold et al.]

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MadDipole

Public package to generate subtraction terms in the Dipole formalism

- For general process in **QCD** [Frederix, Gehrmann,NG '08, '10] and **QED** [Gehrmann,NG, '10]
- Specify real emission process, e.g. **p p → j j j**

  → Generates **Fortran** code for all necessary subtraction terms for all possible tree level processes.

  → Generates the corresponding integrated subtraction terms.

- Although MadGraph framework, completely independent and **standalone.**

  → Can be linked with other tools.

http://madgraph.uiuc.edu

Golem+ Samurai = GoSam

General One Loop Evaluator of Matrix elements +

Scattering Amplitudes from Unitarity based Reduction At Integrand level

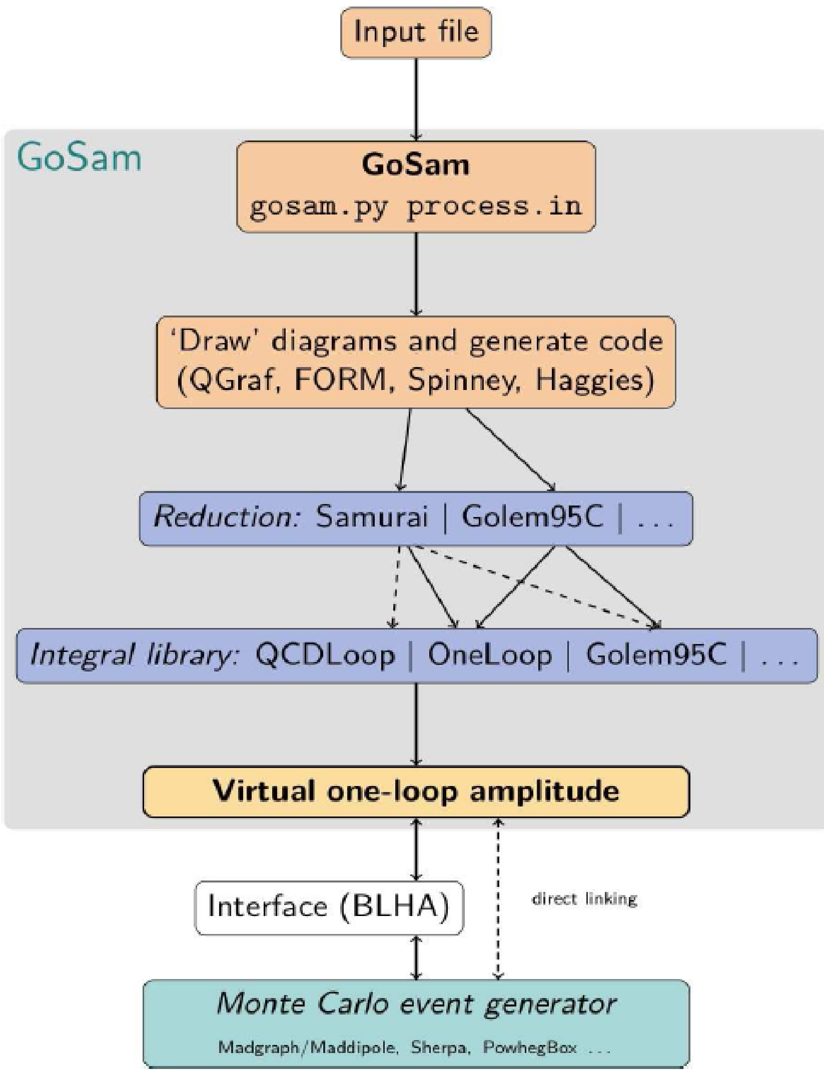
= **Automated generation of virtual amplitude.**

arXiv: 1111.2034 [hep-ph] (EPJC 72, 2012)
[Cullen,NG,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]

- Based on **Feynman diagrams**
- Generates **Fortran95** code
- Can be used for **QCD**, **EW, effective Higgs coupling** and **BSM**
- Interface with existing tools for real radiation and integration (MadGraph, Sherpa, Powheg)

http://gosam.hepforge.org

GoSam



I. **Input card:** Specify process dependent information

II. **Code generation:**
- Uses QGraf [Nogueira] and
- FORM [Vermaseren]
- Writes Fortran code

III. **At runtime:**
Reduction of diagrams
- Integrand level (OPP) with Samurai [Mastrolia,Ossola,Reiter,Tramontano]
- Passarino-Veltman with Golem95C [Cullen et al.]
- Can be chosen at runtime
- Several integral libraries available
  OneLoop [van Hameren]
  QCDLoop [Ellis,Zanderighi]
  Golem95C
- Can be linked to Monte Carlo via standardized interface (BLHA)

→ G. Luisoni T10.4

GoSam

ttH : bash

File Edit View Bookmarks Settings Help

```
greiner@pcl340b:~/GoSam/gosam-1.0/ttH> ls
codegen    diagrams-0.hh  diagrams-1.log  helicity1   helicity13  helicity4  helicity8  Makefile.conf    model.hh
common     diagrams-0.log doc             helicity11  helicity15  helicity5  helicity9  Makefile.source
config.sh  diagrams-1.hh  helicity0       helicity12  helicity3   helicity7  Makefile   matrix
greiner@pcl340b:~/GoSam/gosam-1.0/ttH>
```

parameters and setup in config.f90 / model.f90

Index	1	2	3	4	5
0	−	−	0	−	−
1	+	−	0	−	−
2 → 1	−	+	0	−	−
3	+	+	0	−	−
4	−	−	0	+	−
5	+	−	0	+	−
6 → 5	−	+	0	+	−
7	+	+	0	+	−
8	−	−	0	−	+
9	+	−	0	−	+
10 → 9	−	+	0	−	+
11	+	+	0	−	+
12	−	−	0	+	+
13	+	−	0	+	+
14 → 13	−	+	0	+	+
15	+	+	0	+	+

GoSam 1.0: $gg \to Ht\bar{t}$

greiner

2013-02-27 (17:37:36)

Abstract

This process consists of 8 tree-level diagrams and 160 NLO diagrams. Golem has identified 15 groups of NLO diagrams by analyzing their one-loop integrals.

Detailed documention in process.ps

main file matrix.f90

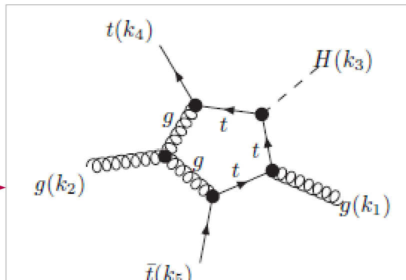


Diagram 158

$S' = S_{Q \to -q-(-k3-k4)}$, rk = 4

Interfacing GoSam

- GoSam + MadDipole + MadGraph/MadEvent [Stelzer,Long, '94],[Maltoni,Stelzer, '02]
  - NLO QCD corrections to pp $\rightarrow b\bar{b}b\bar{b}$

    [Binoth, NG, Guffanti, Guillet, Reiter, Reuter '10, '11]
  - NLO QCD corrections to pp $\rightarrow$ W+ W- + 2 jets

    including massive top loops

    [NG, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
  - SUSY QCD corrections to neutralino pair + jet in MSSM

    [Cullen, NG, Heinrich '12]
- GoSam + Sherpa
  - H + 2 jets in gluon fusion

    H. van Deurzen, T10.6

    [van Deurzen,NG,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,von Soden-Fraunhofen,Tramontano '13]
  - More ready-to-go packages at **http://gosam.hepforge.org/proc**

    [Luisoni, Tramontano]

Diphoton + Jet @ NLO

Diphoton + jet – Photon Fragmentation [Gehrmann,NG,Heinrich, '13]

- Background to H +jet, $H \rightarrow \gamma\gamma$ $\rightarrow$ need NLO QCD corrections!

More than just a normal NLO calculation...

Diphoton + Jet @ NLO

Diphoton + jet – Photon Fragmentation [Gehrmann,NG,Heinrich, '13]

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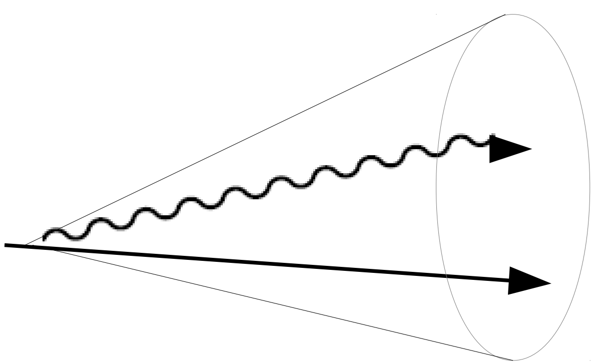
More than just a normal NLO calculation...

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



Theory:
Quark and Photon collinear: Singularity!

- QED singularity → no cancellation with virtuals

Diphoton + Jet @ NLO

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_γ

$$E_{\text{had,max}}(r_\gamma) = \epsilon_\gamma p_{T,\gamma} \left(\frac{1-\cos r_\gamma}{1-\cos R_\gamma} \right)^{n\gamma}$$

➡ 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 $\to \gamma\,\gamma$: Diphox [Binoth,Guillet,Pilon,Werlen '99] cone isolation / Frixione isolation

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

pp $\to \gamma\,\gamma$ j : NLOJet++ [DelDuca,Maltoni,Nagy,Trocsanyi '03] Frixione isolation

New: Comparison between the two methods

Setup: Virtuals with GoSam
Tree level /real radiation with MadGraph
Subtraction terms for QCD with MadDipole ➡ "normal" QCD
Phase space integration with MadEvent

Additional subtraction terms for QED singularities with MadDipole
Include LO fragmentation from BFGW set.

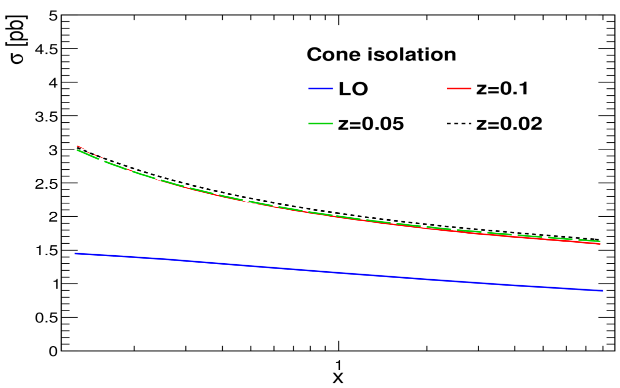
Modular structure of automated building blocks allows easy combination.

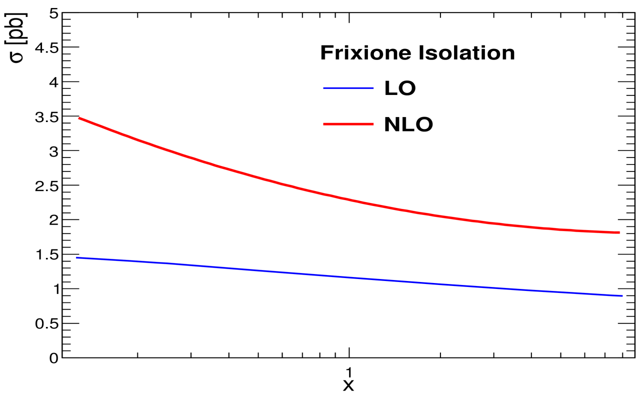
Diphoton + Jet @ NLO

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

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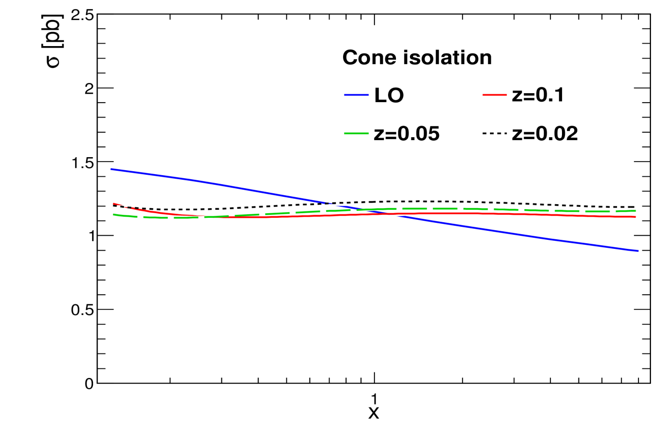
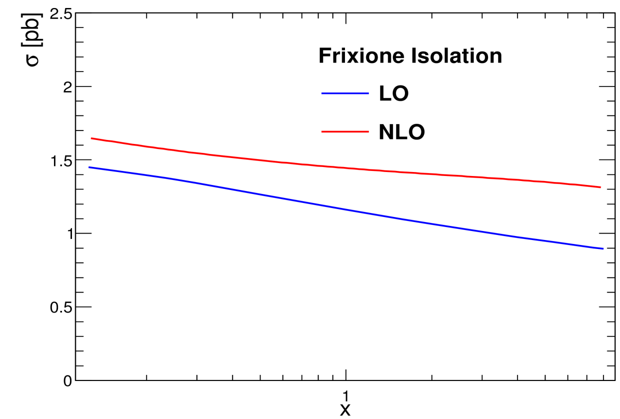
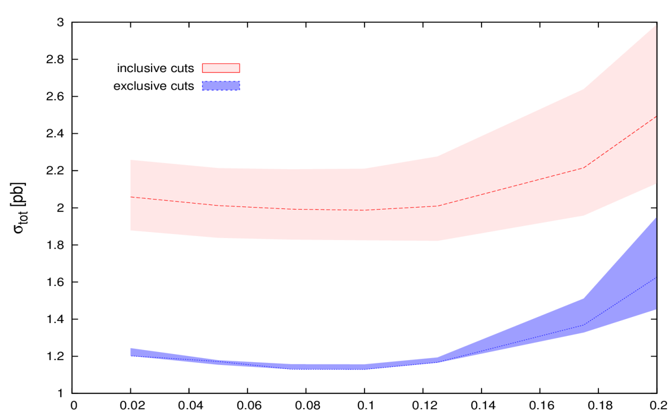
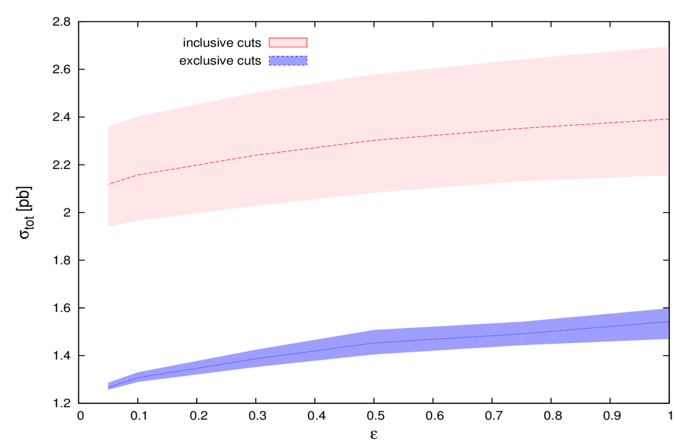
Impose veto on second jet (exclusive cuts): $p_{T,j2} \leq 30\ \mathrm{GeV}$









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

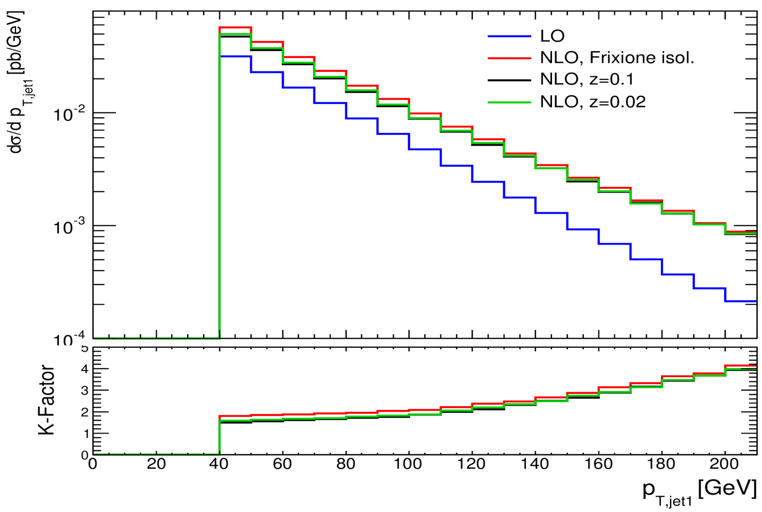
Summary and Outlook

- Automation of NLO calculations important step for LHC processes.
- Still ongoing process, lots of room for improvements.
- Diversity of excellent tools for various purposes.
- **MadDipole:** Public standalone tool for subtraction terms in QCD and QED using dipole formalism.
- **GoSam:** Public tool for calculating virtual corrections in SM and BSM.
- **Example:** QCD corrections to Diphoton + jet including fragmentation effects.
    - Comparison between Frixione isolation and cone isolation
    - Large corrections, rescaling with global K-factor imprecise
    - Reduction of scale uncertainty requires jet veto
    - **Outlook:** Fully automated package will be made public!

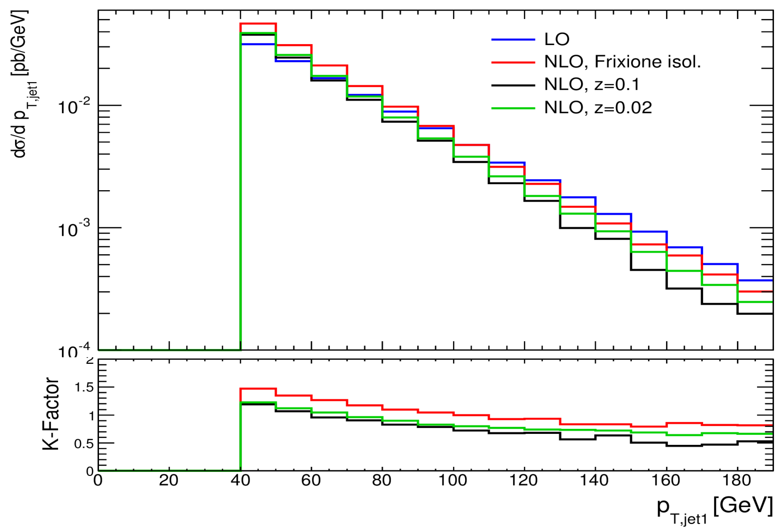
Backup slides

Diphoton + Jet @ NLO

In general no constant K-factors:



inclusive



exclusive

- Rescaling with global K-factor not sufficient.
- Differential K-factor sensitive on cuts.
- Counterexample: invariant mass distribution of photons