MAX-PLANCK-GESELLSCHAFT

Automated NLO calculations with GoSam
-
Higgs production at the LHC

Nicolas Greiner
Max-Planck-Institut für Physik, München

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

Theory Seminar, DESY Hamburg, 20.01.2014

Motivation

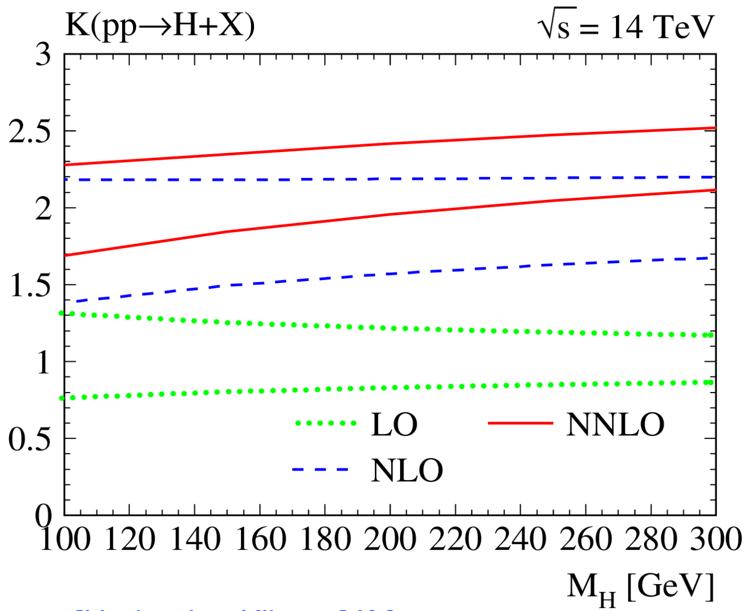
Why is this necessary / useful ?

Motivation

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

MAX-PLANCK-GESELLSCHAFT

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]

Golem+ Samurai = GoSam

General **O**ne **L**oop **E**valuator of **M**atrix elements +

Scattering **Am**plitudes from **U**nitarity based **R**eduction **A**t **I**ntegrand level

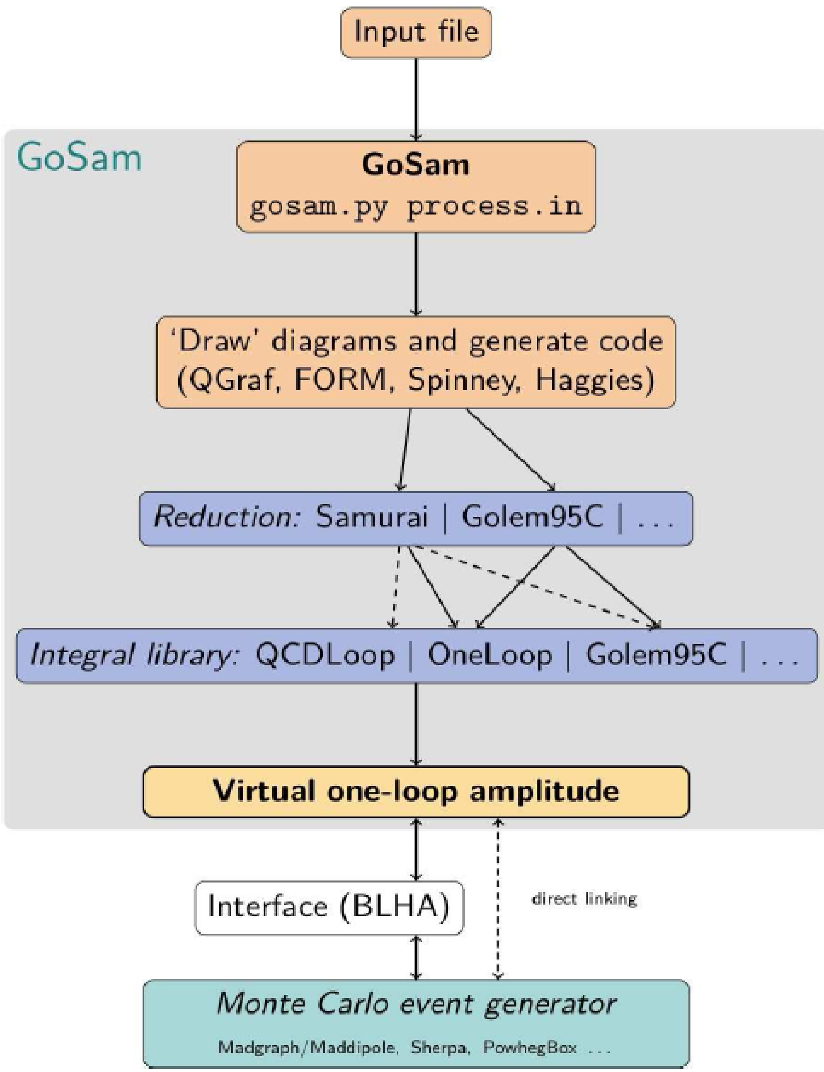
= **Automated generation of virtual amplitude.**

arXiv: 1111.2034 [hep-ph] (EPJC 72, 2012)
[Cullen,NG,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
+H.vanDeurzen,J.F.v.Soden-Fraunhofen,E.Mirabella,T.Peraro,J.Reichel,J.Schlenk

- 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, aMC@NLO, Herwig)

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)

MAX-PLANCK-GESELLSCHAFT

How to use GoSam

Preparation of Input Card I

```
#!/bin/env /home/pcl340b/greiner/GoSam/gosam.py

process_name=ttH
process_path=./ttH_virtual

#### physics options  #####

in=g,g                    # accepts also PDG codes
out=H,t,t~
order=gs, 2, 4

model=smdiag
model.options= masses: mT mH, width: none, \
     alpha: 0.0072973525376, mZ: 91.1876, mW:
80.385, \
     mT: 172.4, mH: 125.0, Nf:5, Nfgen:1

zero=mU,mD,mC,mS,mB,wT,wB,wW,wZ,wH
one=gs,e
symmetries=family,generation
helicities=[+-][+-]0[+-][+-]

qgraf.options=onshell,notadpole,nosnail
qgraf.verbatim=true=iprop[D,S,C,B, 0, 0]
```

Example:
Higgs + Top quark pair

New models can be imported from FeynRules or LanHEP

Specify which parameters should be set ALGEBRAICALLY to zero or one

Options on helicity and loop diagrams

How to use GoSam

Preparation of Input Card II

```
#### program options ####

extensions=samurai, golem95, dred

# abbrev.level=helicity  # group , diagram
# abbrev.limit=0

form.bin=tform
form.tempdir=/tmp
fc.bin=gfortran -O2

samurai.fcflags=-I${HOME}/include/samurai
samurai.ldflags=-L${HOME}/lib/ -lqcdloop -lavh_olo \
        –lsamurai
samurai.version=2.1.1

golem95.fcflags=-I${HOME}/include/golem95
golem95.ldflags=-L${HOME}/lib/ -lgolem
```

Further options, more available

Compiler options

How to use 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

main file matrix.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

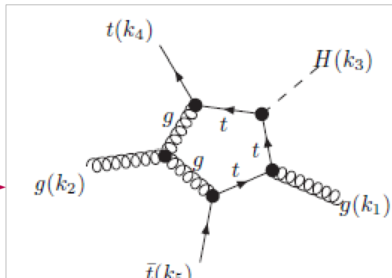


Diagram 158

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

How to use GoSam

- /matrix directory contains test program for calculation of single phase space points.

```
$ cd matrix
$ make test.exe
$ ./test.exe
```

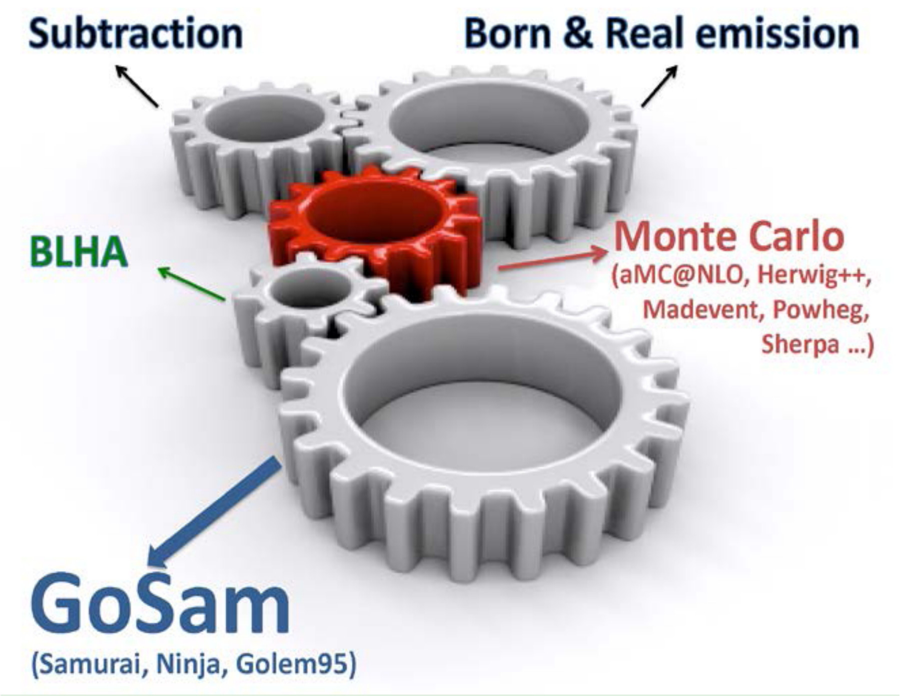
```
#                  LO:   0.1013146112820217E-03
# NLO, finite part:    17.31560363490869
# NLO, single pole:   -9.235244935244870
# NLO, double pole:   -6.000000000000000
# IR,  single pole:   -9.235244935222976
# IR,  double pole:   -6.000000000000001
#  Time/Event [ms]:                201.969
greiner@pcl340b:~/GoSam/gosam-1.0/ttH/matrix>
```

- Implementation of infrared poles allows for checking pole cancellation 'on the fly'.
  → Can be used to reject points during runtime. (PSP_check)

$$
\begin{aligned}
|\mathcal{M}|^2_{\text{1-loop}} &= 2\,\Re\left(\mathcal{M}_B^\dagger \cdot \mathcal{M}_{Virt}\right) \\
&= \frac{\alpha_{(s)}(\mu)}{2\pi}\,\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \cdot (g_{(s)})^{2b} \cdot \left[c_0 + \frac{c_{-1}}{\epsilon} + \frac{c_{-2}}{\epsilon^2} + \mathcal{O}(\epsilon)\right]
\end{aligned}
$$

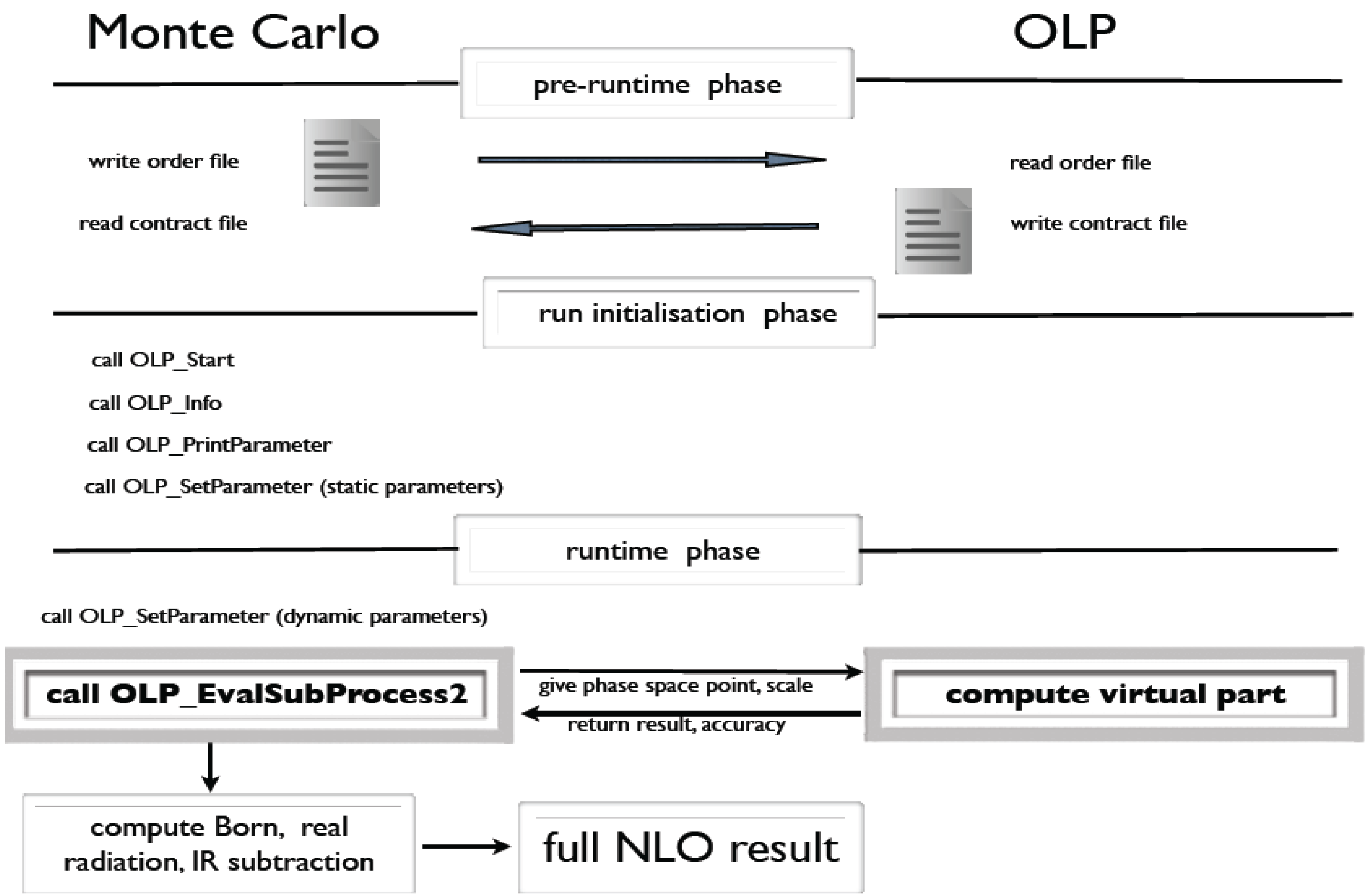
Binoth Les Houches Interface (BLHA)

- **Standard** for communication between MC and OLP
- Recently updated to increase automation and flexibility [Alioli et al '12]
  - Support for dynamical parameters (couplings, masses etc.)
  - Synchronization of EW schemes.
  - Standards for treatment of unstable points
  - Standard for merging different jet multiplicities.



- Extension to provide color correlated (CC) and spin correlated (SC) tree amplitudes.

Binoth Les Houches Interface (BLHA)



Interfacing GoSam

- GoSam + MadDipole/MadGraph/MadEvent
  - $pp \to b\bar{b}b\bar{b}$ [Binoth, NG, Guffanti, Guillet, Reiter, Reuter '10, '11]
  - $pp \to W^+W^-jj$ [NG, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
  - $pp \to \tilde{\chi}\tilde{\chi}j$ in MSSM [Cullen, NG, Heinrich '12]
  - $pp \to \gamma\gamma j(j)$ [Gehrmann,NG,Heinrich '13]
  - $pp \to G(\to \gamma\gamma)j$ in ADD [NG,Heinrich,Reichel,vSoden-Fraunhofen '13]
- GoSam + Sherpa
  - $pp \to Hjj$ [v.Deurzen,NG,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,vSoden-Fraunhofen,Tramontano '13]
  - $pp \to t\bar{t}(j)$ [Hoeche,Huang,Luisoni,Schoenherr,Winter '13]
  - $pp \to Ht\bar{t}(j)$ [v.Deurzen.Luisoni,Mastrolia,Mirabella,Ossola,Peraro '13]
  - $pp \to W^+W^-b\bar{b}$ [Heinrich,Maier,Nisius,Schlenk,Winter '13]

Interfacing GoSam

- GoSam + MadDipole/MadGraph/MadEvent +Sherpa
  - $pp \rightarrow Hjjj$ [v.Deurzen,NG,Luisoni,Matrolia,Mirabella,Ossola,Peraro,Tramontano '13]
- GoSam + Powheg
  - $pp \rightarrow HWj/HZj$ [Luisoni,Nason,Oleari,Tramontano '13]
- GoSam + aMC@NLO
  - Successfully tested for several benchmark processes.
- GoSam + Herwig++
  - First application of BLHA2 standards for color-correlated and spin-correlated amplitudes.
  - Successfully tested for several processes.

Towards GoSam 2.0

- Continous developments in code generation and reduction have led to significant improvements. → Will be made public in **GoSam 2.0**

Code generation

- New optimization strategy (use new features of FORM >4.0 to optimize algebraic expressions).
→ Leads to faster generation, smaller code, and better run-time!
- Numerical polarization vectors reduce code size.
- Parallelization of diagram generation: Each diagram can be generated independently. → Enormous reduction of generation time.
- Diagsum option: Diagrams with identical denominators are summed on FORM level algebraically.

MAX-PLANCK-GESELLSCHAFT

Towards GoSam 2.0

Improvements on the reduction side

- Implementation of higher rank integrals in Samurai [van Deurzen, Mastrolia] and in Golem95 [Guillet, Heinrich, v.Soden-Fraunhofen '13].
  → Needed for effective Higgs couplings, BSM scenarios.
- Alternative reduction with NINJA (C++ library) [Mastrolia,Mirabella,Peraro '12]
  Idea: Combining Integrand reduction and Laurent expansion, implemented through polynomial division for triple, double and single cuts, allows to determine coefficients without the sampling as in OPP
  → Faster and more stable reduction.
- Interface for NINJA implemented in GoSam.
  [van Deurzen,Luisoni,Mastrolia,Mirabella,Ossola,Peraro '13]

Phenomenology

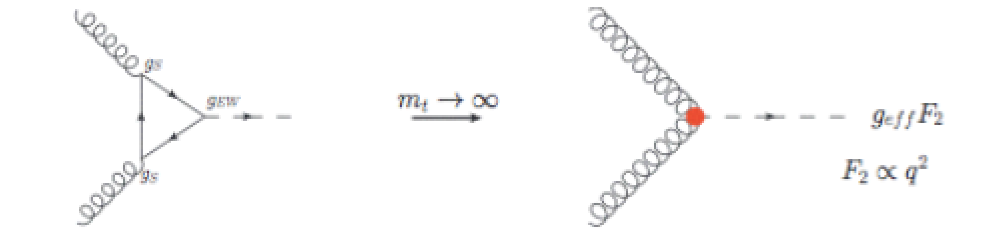
Selected Results for

Higgs + jets

Signal and Background ...

Higgs + jets in gluon fusion

H+0j	**1 NLO**
$gg \to H$	1 NLO
H+1j	**62 NLO**
$qq \to Hqq$	14 NLO
$qg \to Hqg$	48 NLO
H+2j	**926 NLO**
$qq' \to Hqq'$	32 NLO
$qq \to Hqq$	64 NLO
$qg \to Hqg$	179 NLO
$gg \to Hgg$	651 NLO
H+3j	**13179 NLO**
$qq' \to Hqq'g$	467 NLO
$qq \to Hqqg$	868 NLO
$qg \to Hqgg$	2519 NLO
$gg \to Hggg$	9325 NLO



- Dominant channel for Higgs production
- Large background makes it prohibitive to directly study the Higgs
- However, precise knowledge of ggf-channel is important:
  - When applying jet vetoes
    → Higgs + jets cross section needed to estimate uncertainties in efficiencies
  - When studying VBF production channel:
    → Estimate contamination in VBF sample coming from GGF events.

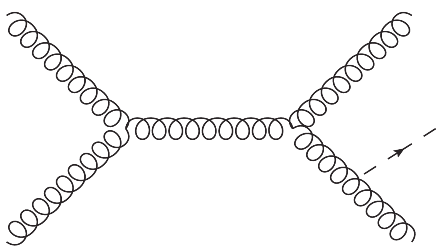
Higgs + 2j

- Possibility to test the framework by comparing with existing results
  → MCFM (v6.4) [Campbell,Ellis,Williams]

Setup:

LHC 8 TeV
Jet algorithm: anti-kt: R=0.5 p_T>20 GeV |η| < 4.0
PDFs: cteq6L1 @ LO cteq6mE @ NLO

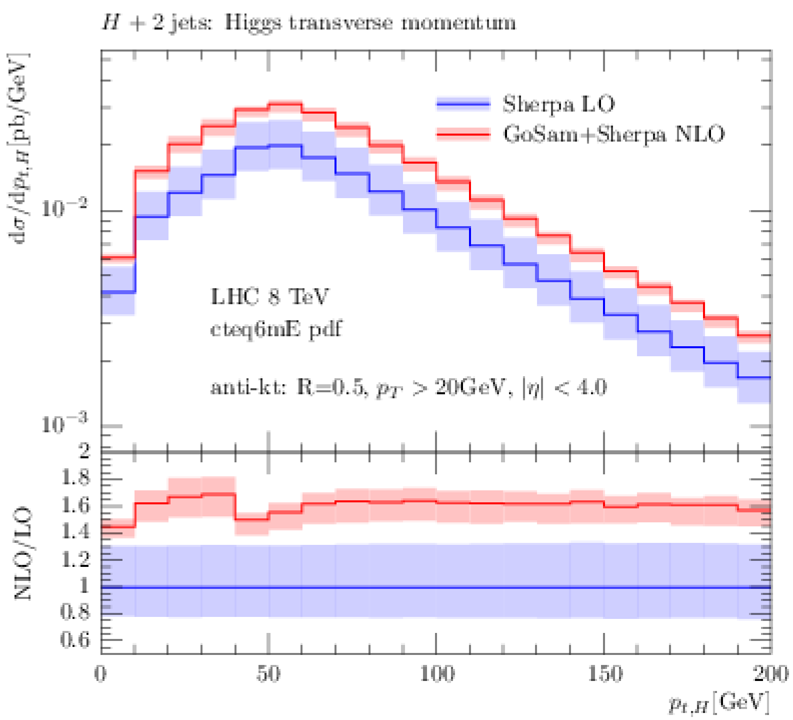
Scales: $\mu_r = \mu_f = \hat{H}_t = \sqrt{M_H^2 + p_{t,H}^2} + \sum_j p_{T,j}$

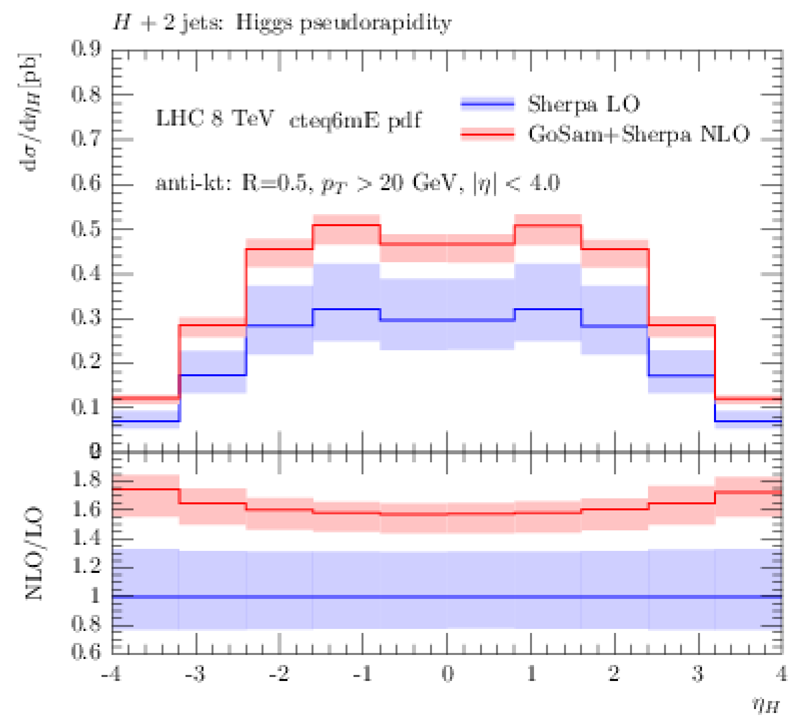


$\alpha_s^4 \to \alpha_s^2(m_H)\alpha_s^2(\hat{H}_T)$

$$\sigma_{LO}(\hat{H}_T) = 1.88^{+0.59}_{-0.43}[pb]$$
$$\sigma_{NLO}(\hat{H}_T) = 3.02^{+0.16}_{-0.27}[pb]$$

Higgs + 2j

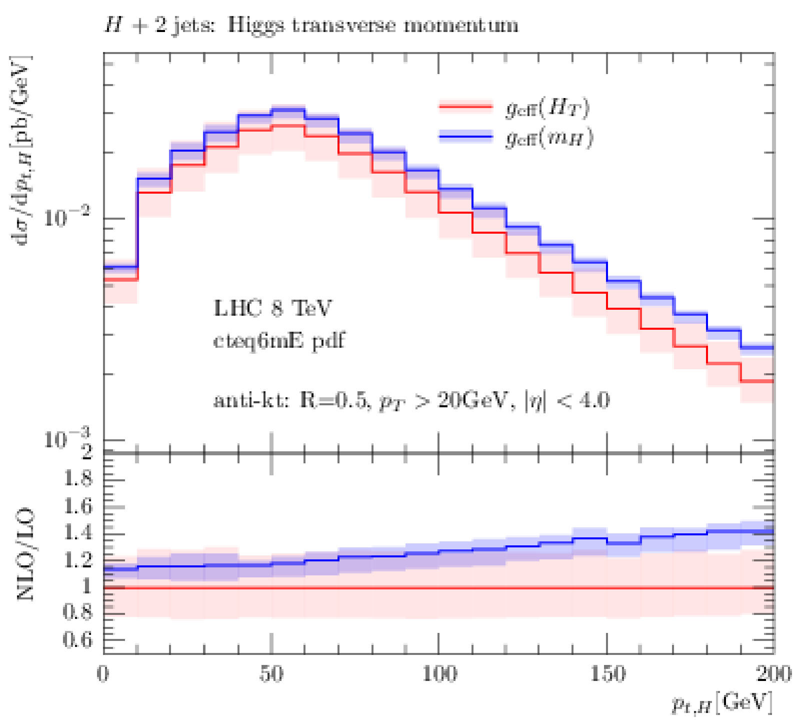


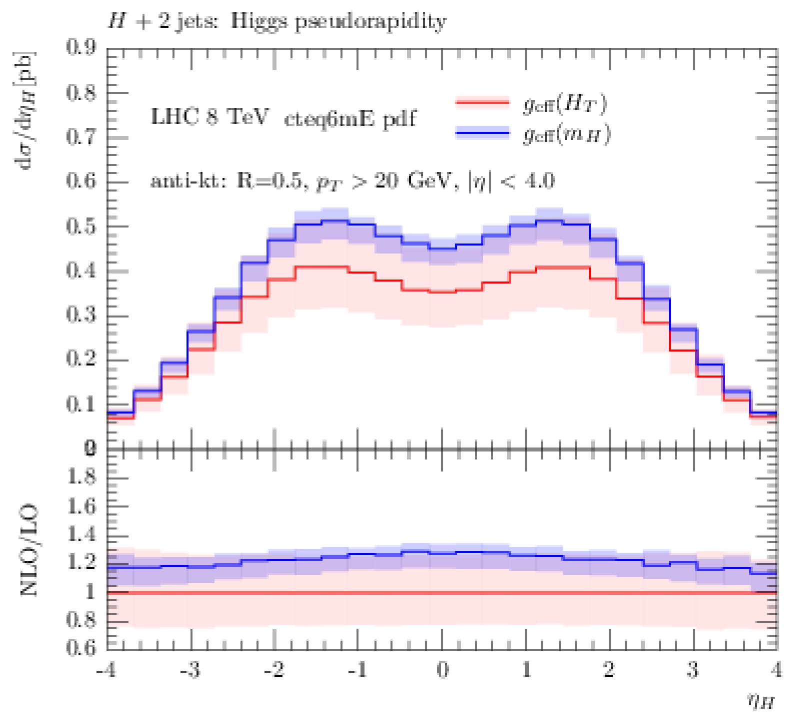


- Non-constant K-factor
- Clear reduction of scale uncertainty

Higgs + 2j

- Fixed scale vs dynamical scale in effective vertex:



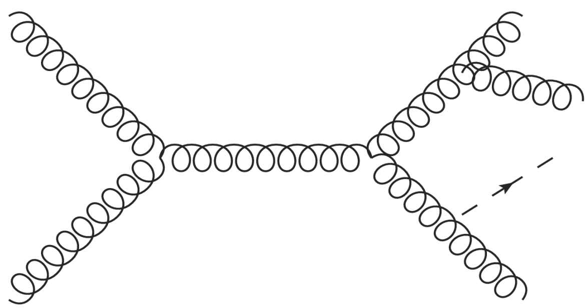


Important impact of scale choice in effective vertex!

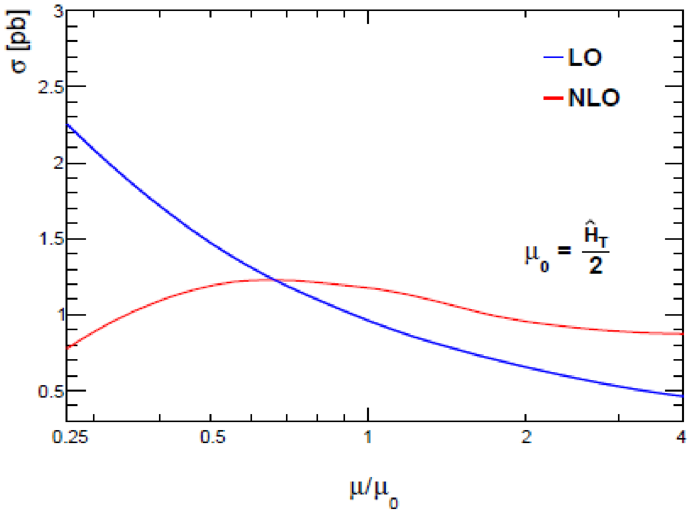
Higgs + 3j

- Calculational setup: GoSam + MadGraph/MadDipole/MadEvent + Sherpa
- Same setup/cuts as for H+2 but use for scales $\mu_r = \mu_f = \frac{\hat{H}_t}{2} = \frac{1}{2}\sqrt{M_H^2 + p_{t,H}^2} + \sum_j p_{T,j}$

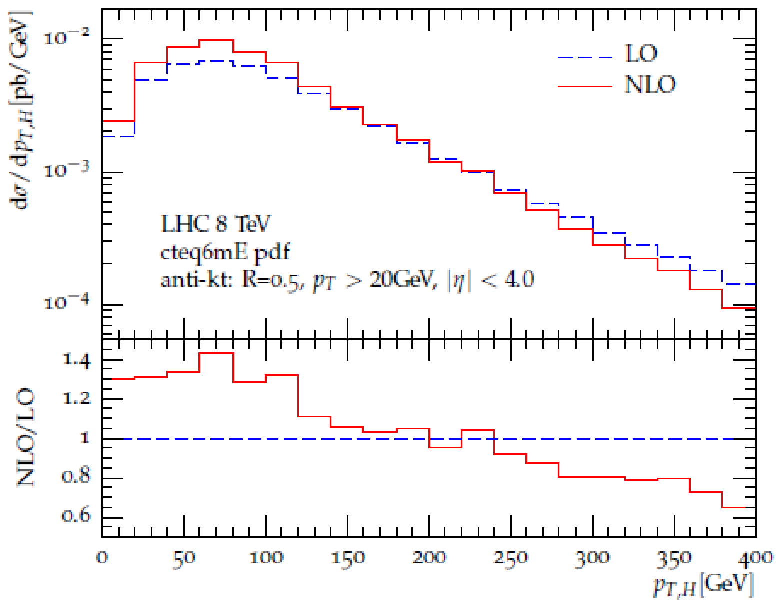
$$\sigma_{LO}(\hat{H}_T/2) = 0.96^{+0.51}_{-0.31}[pb]$$
$$\sigma_{NLO}(\hat{H}_T/2) = 1.18^{+0.01}_{-0.22}[pb]$$

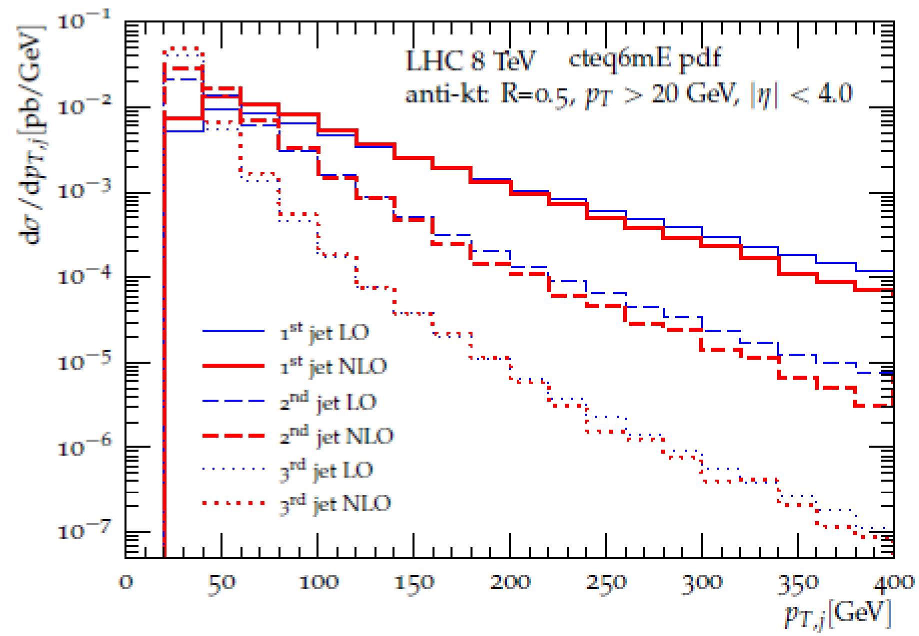


$$\alpha_s^5 \rightarrow \alpha_s^2(m_H)\alpha_s^3(\hat{H}_T/2)$$



Higgs + 3j





- Moderate but non-constant K-factor
- Change in shapes due to NLO corrections
- More phenomenology to follow (observables, decay, shower,....)

Diphoton + Jet @ NLO

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

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

More than just a normal NLO calculation...

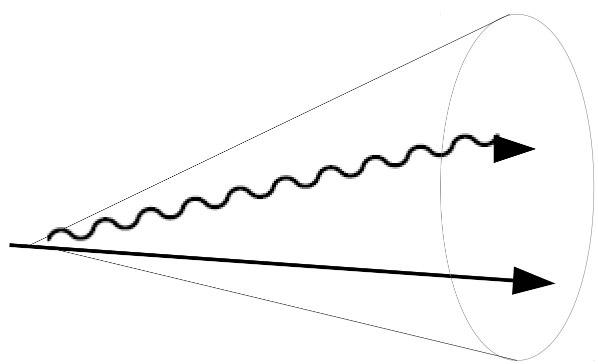
Diphoton + Jet @ NLO

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

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

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 $\to$ no cancellation with QCD virtuals

Diphoton + Jet @ NLO

Photon Fragmentation / Cone isolation	Frixione Isolation criterion [Frixione '98]
• 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	• The closer to the collinear limit, the less hadronic energy is allowed. → Inside cone around photon with radius R $E_{\text{had,max}}(r_\gamma) = \epsilon\, p_T^\gamma \left(\frac{1-\cos r_\gamma}{1-\cos R}\right)^n$ ➡ 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]
pp $\rightarrow \gamma\ \gamma$ jj:[Gehrmann,NG,Heinrich '13],[Badger,Guffanti,Yundin],[Bern et al] Frixione isolation
pp $\rightarrow \gamma\ \gamma$ jjj:[Badger,Guffanti,Yundin] Frixione isolation

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

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

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

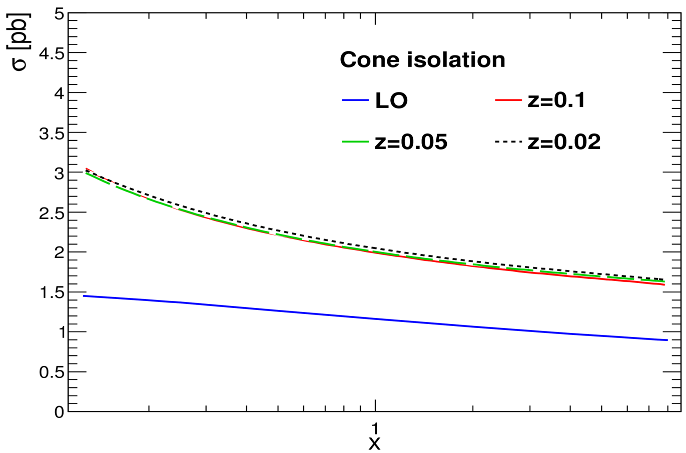
Modular structure of automated building blocks allows easy combination.

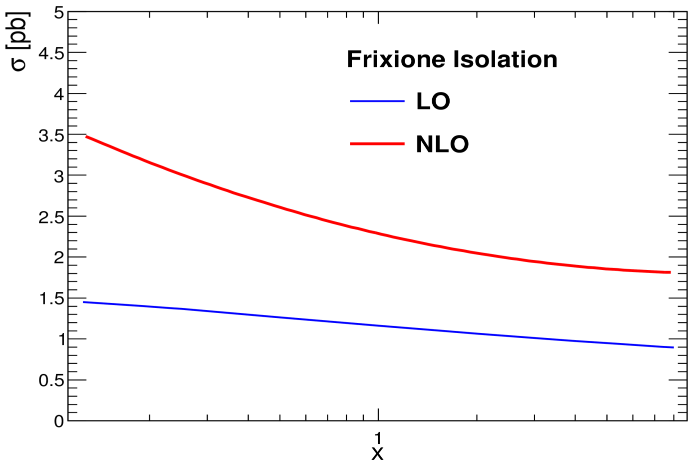
Diphoton + Jet @ NLO

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

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

Inclusive cuts:



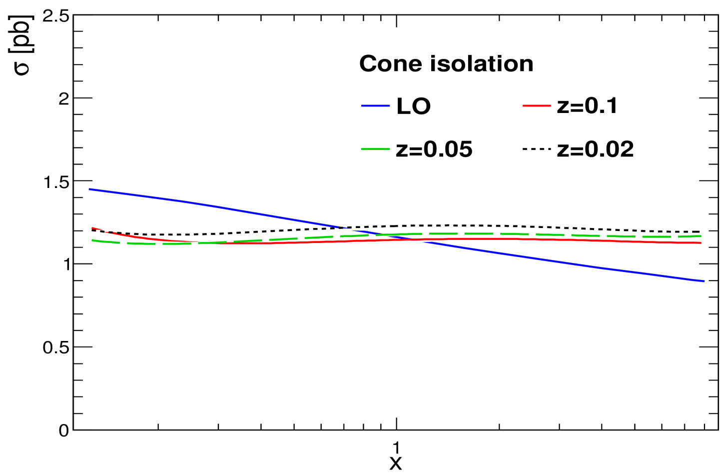


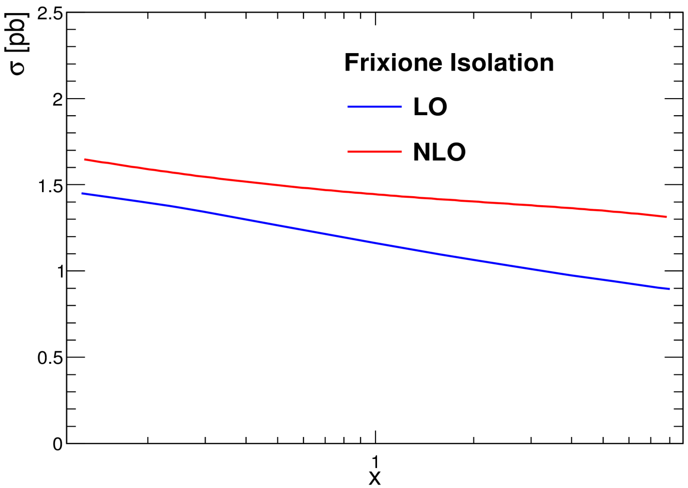
$\epsilon = 0.5,\ n = 1$

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

Diphoton + Jet @ NLO

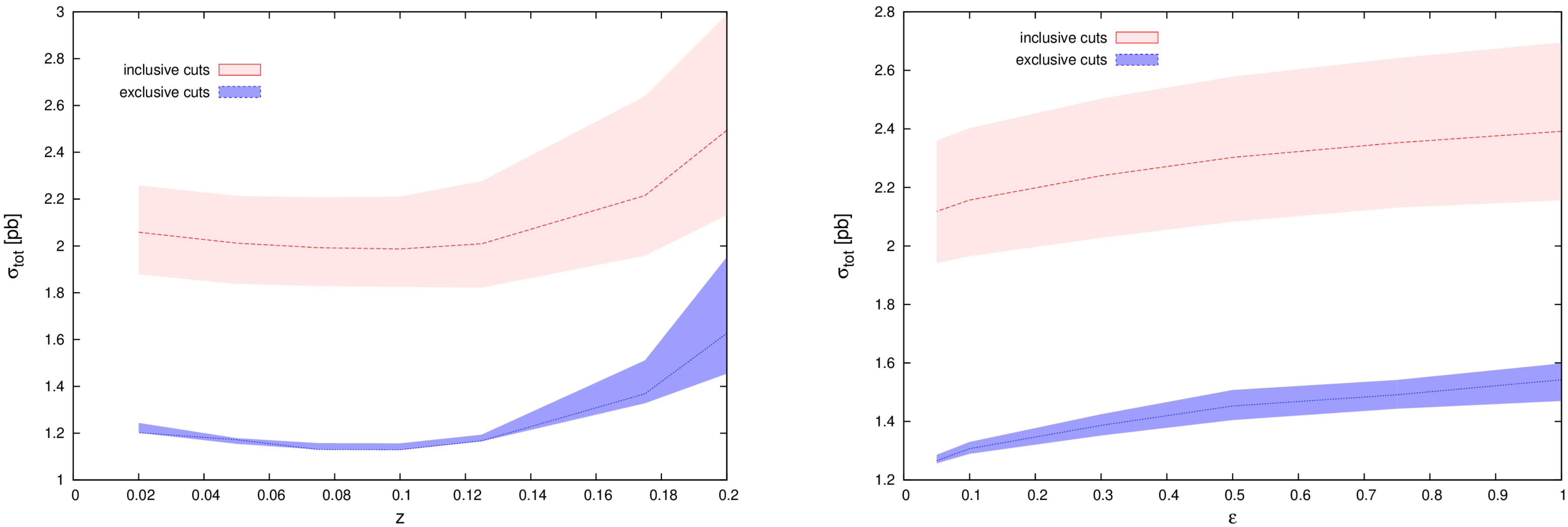
Impose veto on second jet (exclusive cuts): $p_{T,j2} \leq 30$ GeV





- 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



- Cone isolation and Frixione isolation similar for small hadronic energy.
- Substantial deviations for increasing hadronic energy.

➡ The whole package is made public as a complete standalone code.

http://gosam.hepforge.org/diphoton

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.
- **GoSam:** Public tool for calculating virtual corrections in SM and BSM.
- **GoSam 2.0** contains multiple improvements, will be made public later this year.
- **Examples:**
  - H+2j/ H+3j in gluon fusion
  - Diphoton + jet(s) important background to H + jet(s)