



# Interfacing GoSam with Monte Carlo event generators

Gionata Luisoni

luisonig@mpp.mpg.de

Max Planck Institute for Physics  
Munich

In collaboration with:

G.Cullen, H. Van Deurzen, N. Greiner, G.Heinrich, P.Mastrolia, E.Mirabella, G.Ossola, T.Peraro,  
J. Reichel, J. Schlenk, J.F.G. von Soden-Fraunhofen, F. Tramontano  
and  
P. Nason, C. Oleari ; S.Höche, J. Huang, M.Schönherr, J.Winter



# Outline

- GoSam framework
- NLO calculations
  - The Binoth-Les Houches-Accord (BLHA)
- Recent NLO results with GoSam
- Selected results:
  - HVJ with GoSam + Powheg
  - $t\bar{t}(j)$  NLO analysis of forward-backward asymmetry
  - BSM physics with GoSam
- Conclusions & Outlook



# GoSam meeting, January 2013



G. Cullen, T. Peraro, J. Schlenk, F. Tramontano, J. F. v. Soden-Fraunhofen, N. Greiner, P. Mastrolia  
G. Ossola, J. Reichel, H. v. Deurzen, G. Heinrich, GL, E. Mirabella



# The GoSam framework

- GoSam: a tool to compute virtual 1-loop amplitudes:



[Mastrolia, Ossola, Reiter, Tramontano]

[Binoth, Cullen, Guillet, Heinrich, Pilon, Reiter]

- Generation of numerators based on Feynman diagrams
- Algebraic manipulation in D-dimensions before reduction  
[FORM: Kuipers, Ueda, Vermaseren]
- Optimization: cashing/grouping/summing

More details in P.Mastrolia's talk tomorrow



# The GoSam framework

Integrand  
reduction  
methods

Samurai

[Mastrolia, Ossola, Reiter, Tramontano]

GoSam

Golem95

[Binoth, Cullen, Guillet, Heinrich, Pilon, Reiter]

- Several reduction strategies/tools at running time



# The GoSam framework

Integrand reduction methods

Samurai

[Mastrolia, Ossola, Reiter, Tramontano]



Ninja

[Mastrolia, Mirabella, Peraro]

GoSam

Tensor-integral methods

Golem95

[Binoth, Cullen, Guillet, Heinrich, Pilon, Reiter]

- Several reduction strategies/tools at running time
- Framework very modular
  - New developments easy to embed
  - Ninja: new reduction library based on Laurent expansion

More details in P.Mastrolia's talk tomorrow



• • •

# NLO calculations

- For a full NLO calculation other ingredients are needed:

$$\sigma_{\text{NLO}} = \int d\Phi_m d\sigma_{\text{Born}} + \int d\Phi_{m+1} (d\sigma_{\text{NLO}}^R - d\sigma_{\text{NLO}}^S) + \int d\Phi_m \left[ \int d\Phi_1 d\sigma_{\text{NLO}}^S + d\sigma_{\text{NLO}}^V \right]$$



•••

# NLO calculations

- For a full NLO calculation other ingredients are needed:

$$\sigma_{\text{NLO}} = \int_{d\Phi_m} d\sigma_{\text{Born}} + \int_{d\Phi_{m+1}} (d\sigma_{\text{NLO}}^{\text{R}} - d\sigma_{\text{NLO}}^{\text{S}}) + \int_{d\Phi_m} \left[ \int_{d\Phi_1} d\sigma_{\text{NLO}}^{\text{S}} + d\sigma_{\text{NLO}}^{\text{V}} \right]$$

- Virtual corrections: for long time bottleneck in a NLO calculation



•••

# NLO calculations

- For a full NLO calculation other ingredients are needed:

$$\sigma_{\text{NLO}} = \int_{d\Phi_m} d\sigma_{\text{Born}} + \int_{d\Phi_{m+1}} (d\sigma_{\text{NLO}}^R - d\sigma_{\text{NLO}}^S) + \int_{d\Phi_m} \left[ \int_{d\Phi_1} d\sigma_{\text{NLO}}^S + d\sigma_{\text{NLO}}^V \right]$$

- Virtual corrections: for long time bottleneck in a NLO calculation
- Tree amplitudes: Born and real matrix elements
- Subtraction: different schemes available
- Phase space integral: challenging when many particles in final state  
(intermediate resonances / singularities)



# ... NLO calculations

- For a full NLO calculation other ingredients are needed:

$$\sigma_{\text{NLO}} = \int_{d\Phi_m} d\sigma_{\text{Born}} + \int_{d\Phi_{m+1}} (d\sigma_{\text{NLO}}^R - d\sigma_{\text{NLO}}^S) + \int_{d\Phi_m} \left[ \int_{d\Phi_1} d\sigma_{\text{NLO}}^S + d\sigma_{\text{NLO}}^V \right]$$

- Virtual corrections: for long time bottleneck in a NLO calculation

One Loop Program

BLHA

Monte Carlo

- Tree amplitudes: Born and real matrix elements
- Subtraction: different schemes available
- Phase space integral: challenging when many particles in final state  
(intermediate resonances / singularities)



# Binot Les Houches Interface (BLHA)

[Binot et al.]

- Standards for communication between **MC** and **OLP**

- recently updated to increase automation and flexibility:

[Alioli et al.]



- Support for dynamical parameters (coupling, masses, ...)
- Synchronization of EW schemes
- Standards for treatment of unstable phase space points
- Standards for merging different jet multiplicities
- Extension to provide also colour correlated (CC) and helicity correlated (HC) tree amplitudes



•••

# NLO results using GoSam

- Recently several NLO computation involving **GoSam** interfaced to an external **MC**:



• • •

# NLO results using GoSam

- Recently several NLO computation involving **GoSam** interfaced to an external **MC**:

- GoSam + MadGraph/MadDipole/MadEvent**

[Greiner]

- $pp \rightarrow b\bar{b}b\bar{b}$

[Greiner, Guffanti, Reiter, Reuter; '11]

- $pp \rightarrow W^+ W^- jj$

[Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano; '12]

- $pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 j$

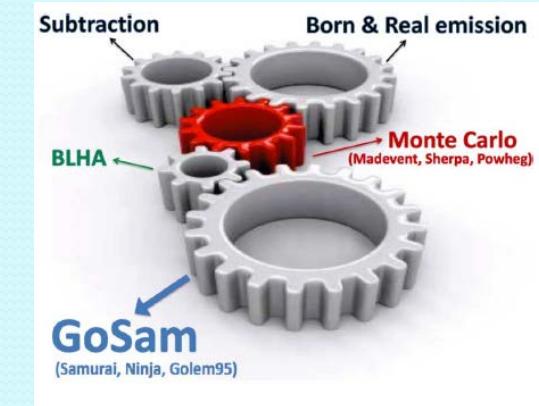
[Cullen, Greiner, Heinrich; '12]

- $pp \rightarrow \gamma \gamma j / \gamma \gamma jj$

[Gehrmann, Greiner, Heinrich; '13]

- $pp \rightarrow G (-\rightarrow \gamma \gamma) j$

[Greiner, Heinrich, Reichel, v. Soden-Fraunhofer; '13]



More details in N.Greiner's talk later



• • •

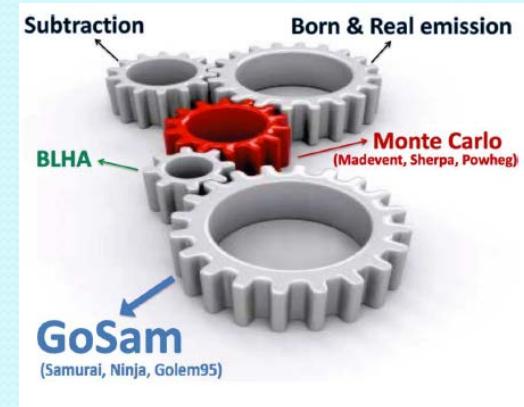
# NLO results using GoSam

- Recently several NLO computation involving **GoSam** interfaced to an external **MC**:
  - GoSam + MadGraph/MadDipole/MadEvent**
  - GoSam + Powheg** [Luisoni, Nason, Oleari, Tramontano]
    - pp -> HW j / HZ j [Luisoni, Nason, Oleari, Tramontano; '13]



# ••• NLO results using GoSam

- Recently several NLO computation involving **GoSam** interfaced to an external **MC**:
  - GoSam + MadGraph/MadDipole/MadEvent**
  - GoSam + Powheg**
  - GoSam + Sherpa**
    - $\text{pp} \rightarrow H jj$  [in ggf]
    - $\text{pp} \rightarrow t\bar{t}(j)$
    - $\text{pp} \rightarrow H t\bar{t}(j)$
    - $\text{pp} \rightarrow W^+ W^- b\bar{b}$
    - Several other process packages available online at: <http://gosam.hepforge.org/proc/>



More details in P.Mastrolia's talk tomorrow

More details in P.Mastrolia's talk tomorrow

More details in J.Schlenk's talk on Thursday



• • •

# NLO results using GoSam

- Recently several NLO computation involving **GoSam** interfaced to an external **MC**:
  - GoSam + MadGraph/MadDipole/MadEvent**
  - GoSam + Powheg**
  - GoSam + Sherpa**
  - GoSam + MadGraph/MadDipole/MadEvent + Sherpa**
    - $\text{pp} \rightarrow H jjj$  [in ggf] [Cullen, v. Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano; '13]



→ More details in P.Mastrolia's talk tomorrow



# ••• NLO results using GoSam

- Recently several NLO computation involving **GoSam** interfaced to an external **MC**:
  - GoSam + MadGraph/MadDipole/MadEvent**
  - GoSam + Powheg**
  - GoSam + Sherpa**
  - GoSam + MadGraph/MadDipole/MadEvent +Sherpa**
- Furthermore:
  - GoSam + aMC@NLO** [v.Deurzen, Frederix, Frixione, Hirschi, Luisoni, Mastrolia, Ossola, Peraro]
  - GoSam + Herwig** [Bellm, Gieseke, Greiner, Heinrich, Plätzer, Reuschle, v.Soden-Fraunhofer]





# Interfaces in progress

- **GoSam + aMC@NLO:** [v.Deurzen, Frederix, Frixione, Hirschi, Luisoni, Mastrolia, Ossola, Peraro]

- Successfully tested for several benchmark processes:

Process	$\sigma_{\text{tot}}$ [pb] (Madloop)	$\sigma_{\text{tot}}$ [pb] (GoSam)
pp->t $\bar{t}$	162.08 +/- 0.12	162.3 +/- 0.4
pp->W	6146.2 +/- 9.8	6139 +/- 2.4
pp->W j	1065.3 +/- 1.8	1063 +/- 2.5
pp->HW	0.4455 +/- 0.0003	0.443 +/- 0.0010
pp->HZ	0.3659 +/- 0.0002	0.3661 +/- 0.0006

- **GoSam + Herwig:** [Bellm, Gieseke, Greiner, Heinrich, Plätzer, Reuschle, v.Soden-Fraunhofer]

- First application of BLHA2 standards for CC/HC tree amplitudes
- Preliminary tests ongoing



...

# Phenomenology

Selected recent results...



# HVJ with Powheg+GoSam

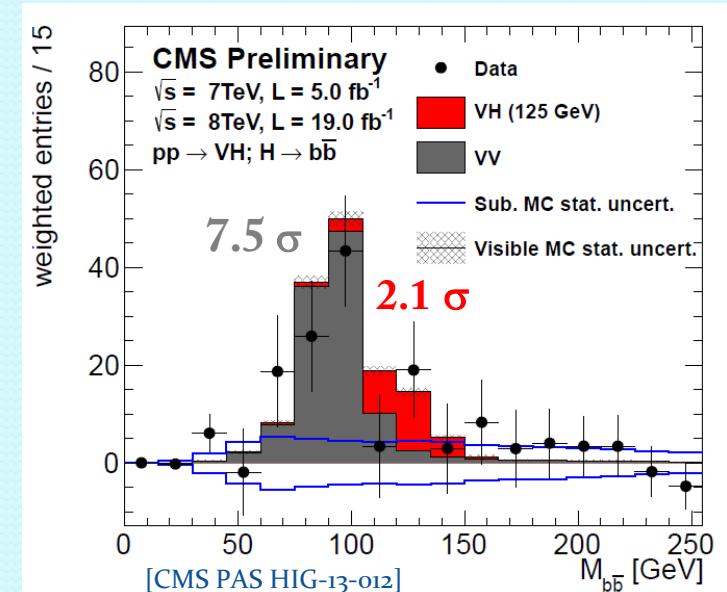
[Luisoni, Nason, Oleari, Tramontano]

- Allow to measure  $H \rightarrow b\bar{b}$  or set limit to **invisible** decay

- Tevatron:  $\sim 3\sigma$  significance
- ATLAS: no significant excess
- CMS:  $2.1\sigma$  excess over  $7.5\sigma$

significance for VZ signal

[Status at EPS 2013]



# HVJ with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

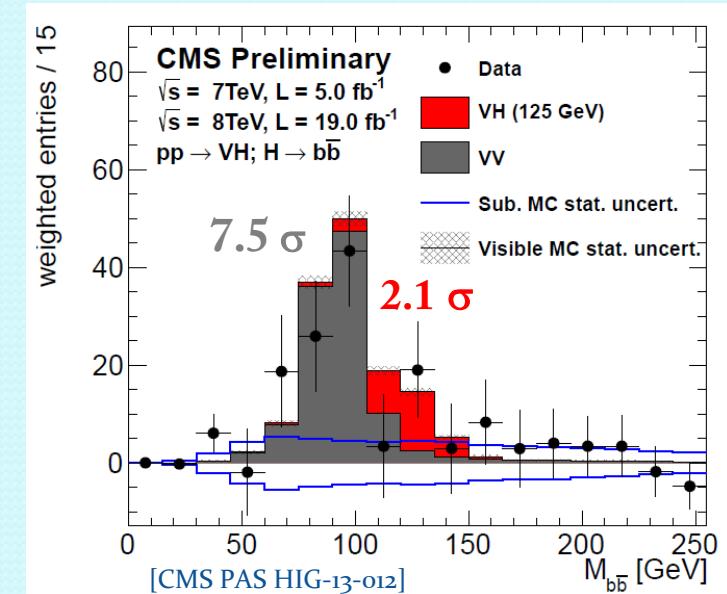
- Allow to measure  $H \rightarrow b\bar{b}$  or set limit to **invisible** decay

- Tevatron:  $\sim 3\sigma$  significance
- ATLAS: no significant excess
- CMS:  $2.1\sigma$  excess over  $7.5\sigma$  significance for VZ signal

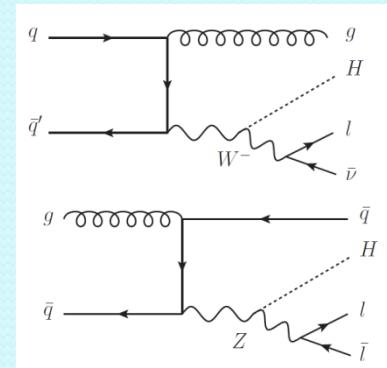
[Status at EPS 2013]

- Interesting application of *MiNLO* procedure with a white final state at lowest multiplicity

[Hamilton, Nason, Oleari, Zanderighi]



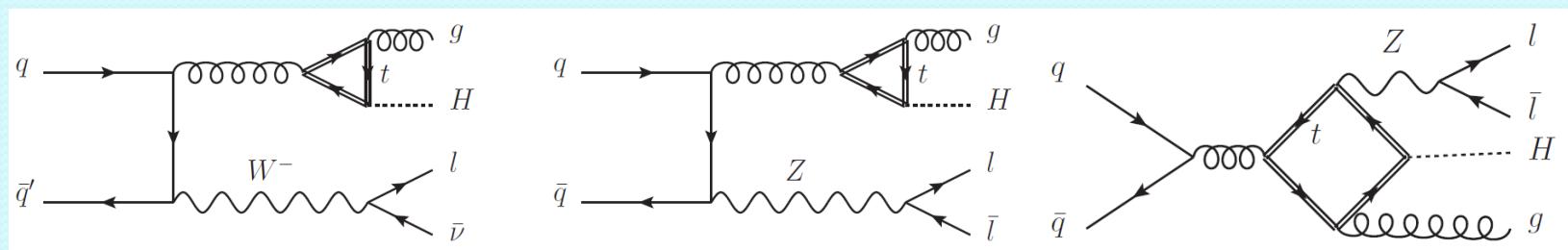
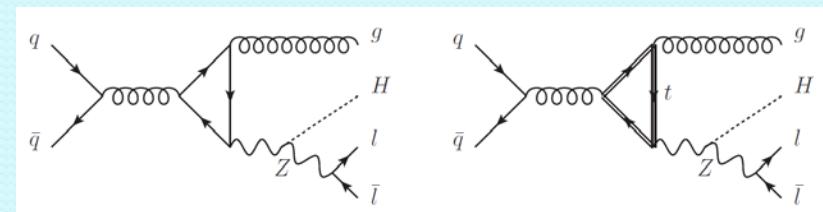
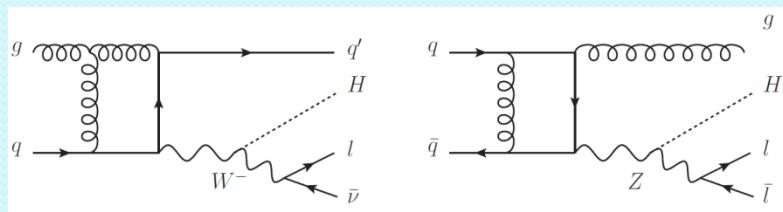
- Development of BLHA interface within Powheg
  - Now automatic generation of tree/1-loop amplitudes



# HVJ with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

- 3 classes of loop diagrams: top contributions retained



- MiNLO procedure analogous to previous applications if only Higgs-Strahlung diagrams are kept (no top):

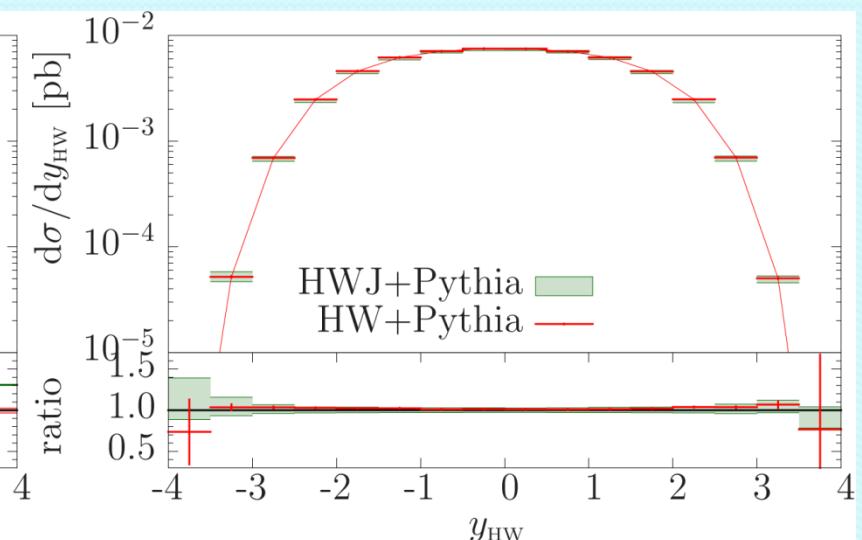
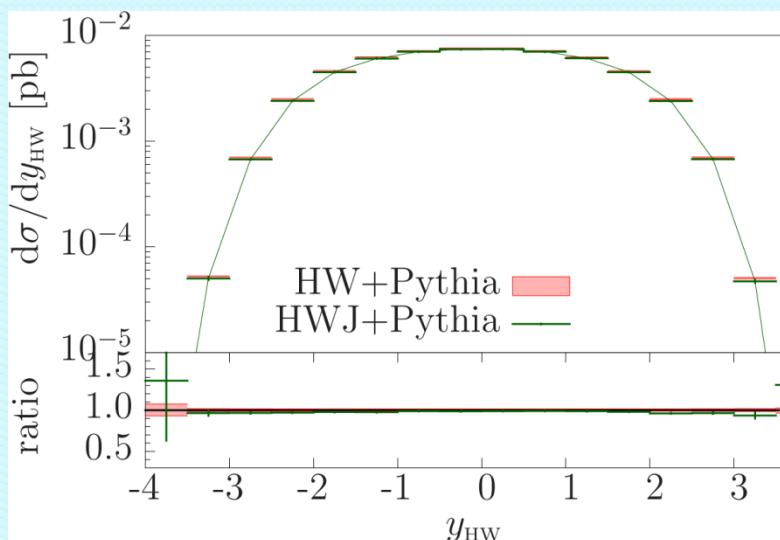
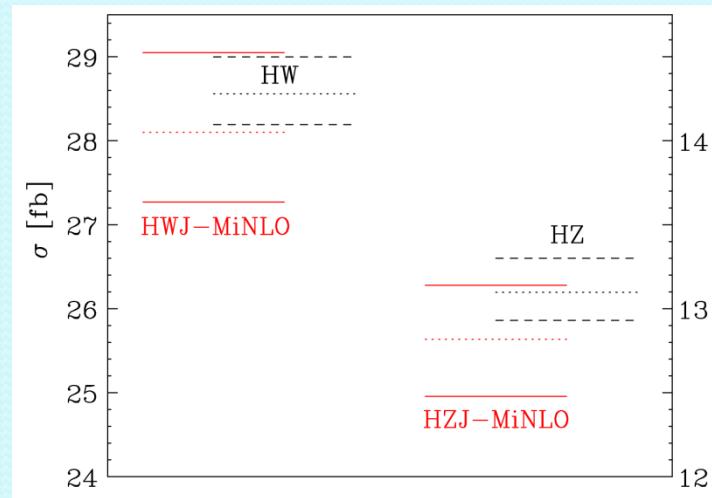
$$pp \rightarrow V^*(-\rightarrow H l_1 l_2) j$$



# HVJ with Powheg+GoSam

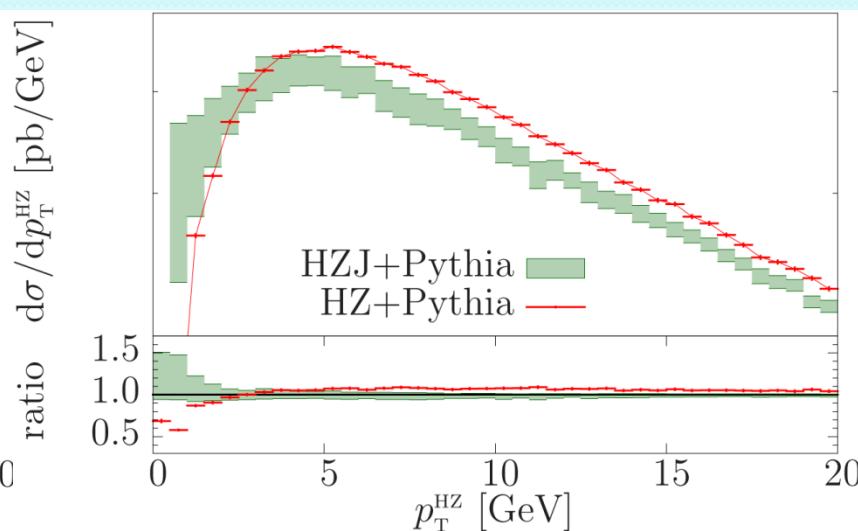
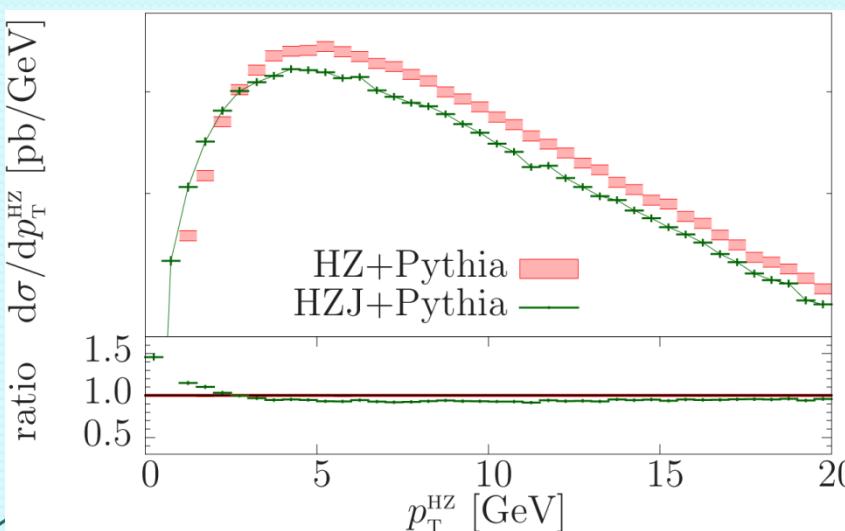
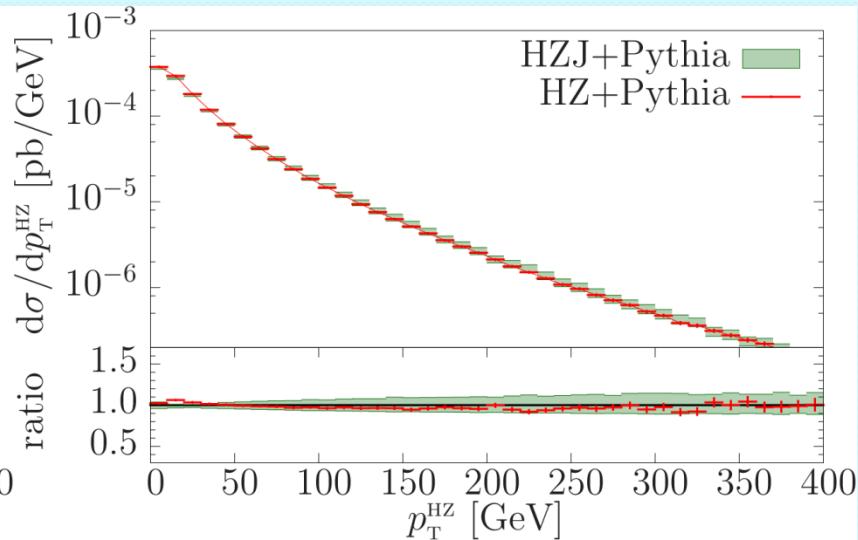
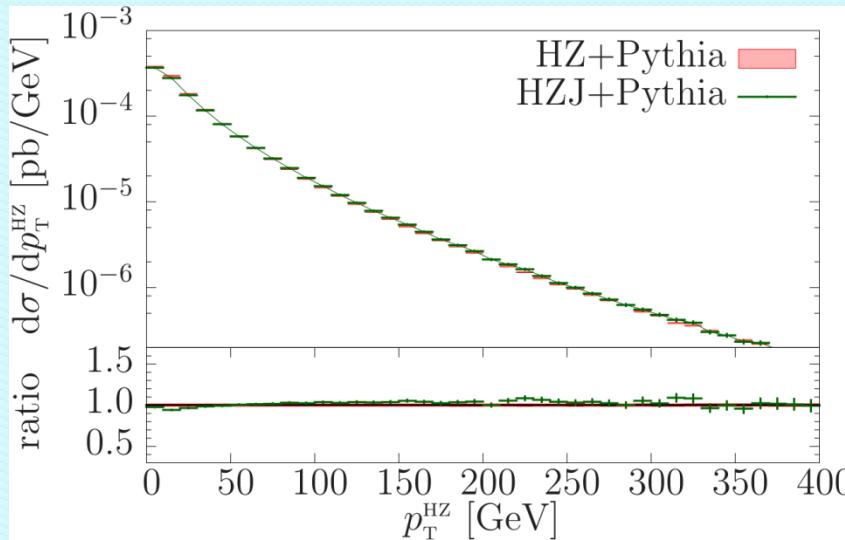
[Luisoni, Nason, Oleari, Tramontano]

- Results for LHC @ 8 TeV:
  - 5Mio events ;  $p_{T,\min} = 260$  MeV
  - achieve NLO accuracy for observables inclusive in HV
  - uncertainty band by varying independently  $K_R, K_F$  by factors of 0.5 and 2.



# HVJ with Powheg+GoSam

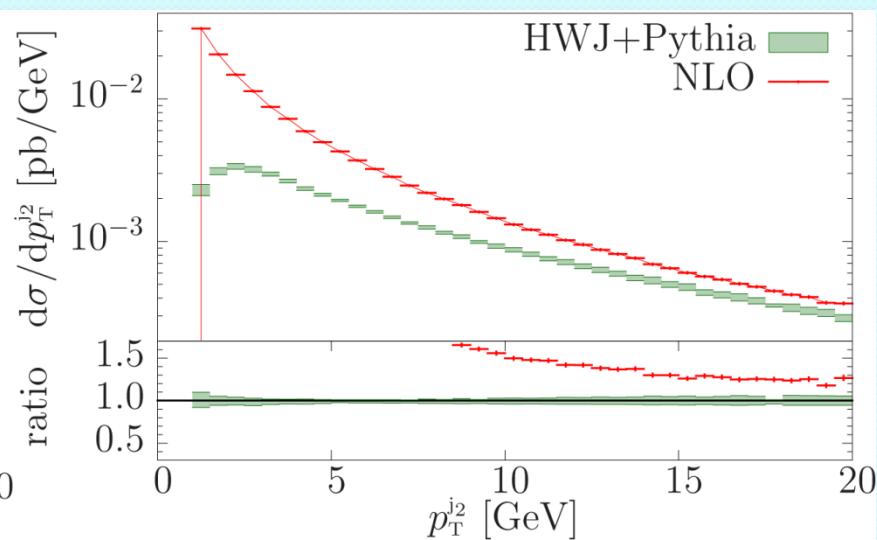
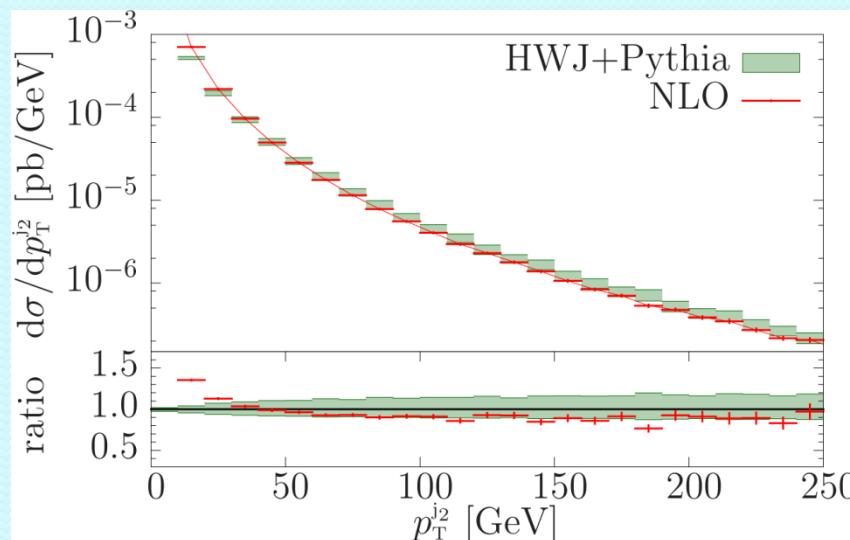
[Luisoni, Nason, Oleari, Tramontano]



# HVJ with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

- Effect of the Powheg formalism visible on the 2. jet:



- Possibility to construct an NNLO+PS generator by reweighting with NNLO results

[Hamilton, Nason, Oleari, Re, Zanderighi]

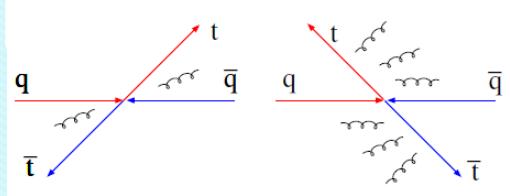


# • $t\bar{t}+0,1$ jet $A_{FB}$ with Sherpa+GoSam

[Höche, Huang, Luisoni, Schönherr, Winter]

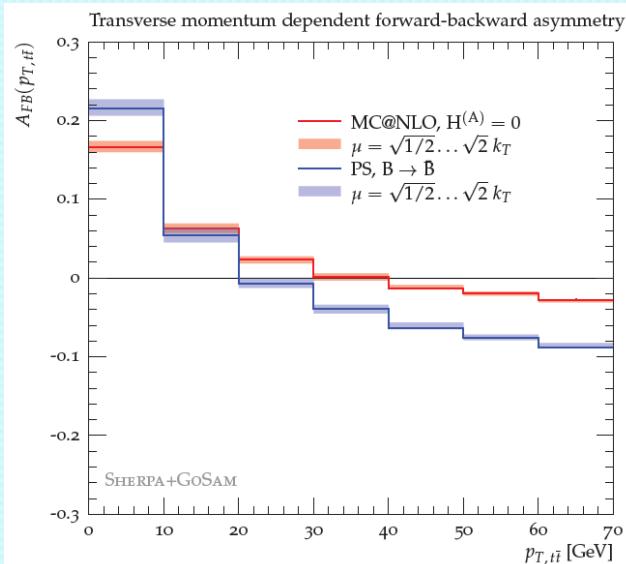
- Motivation: PS with colour-coherence creates asymmetry

[Skands, Webber, Winter]



- investigate effect of merging ME+PS @ NLO for  $t\bar{t}$  and  $t\bar{t}j$  on  $A_{FB}$  at Tevatron:

$$A_{FB}(O) = \frac{d\sigma_{t\bar{t}}/dO|_{\Delta y>0} - d\sigma_{t\bar{t}}/dO|_{\Delta y<0}}{d\sigma_{t\bar{t}}/dO|_{\Delta y>0} + d\sigma_{t\bar{t}}/dO|_{\Delta y<0}}$$



- Substantial impact from inclusion of color coherence in MC@NLO (full color treatment of first emission)

[Höche, Krauss, Schönherr, Siegert]

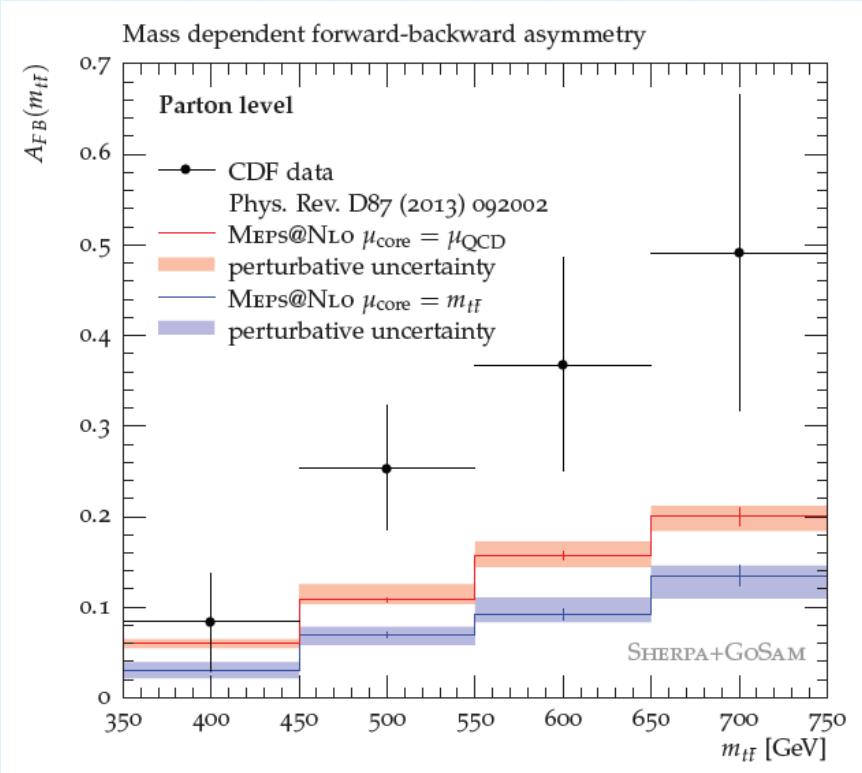
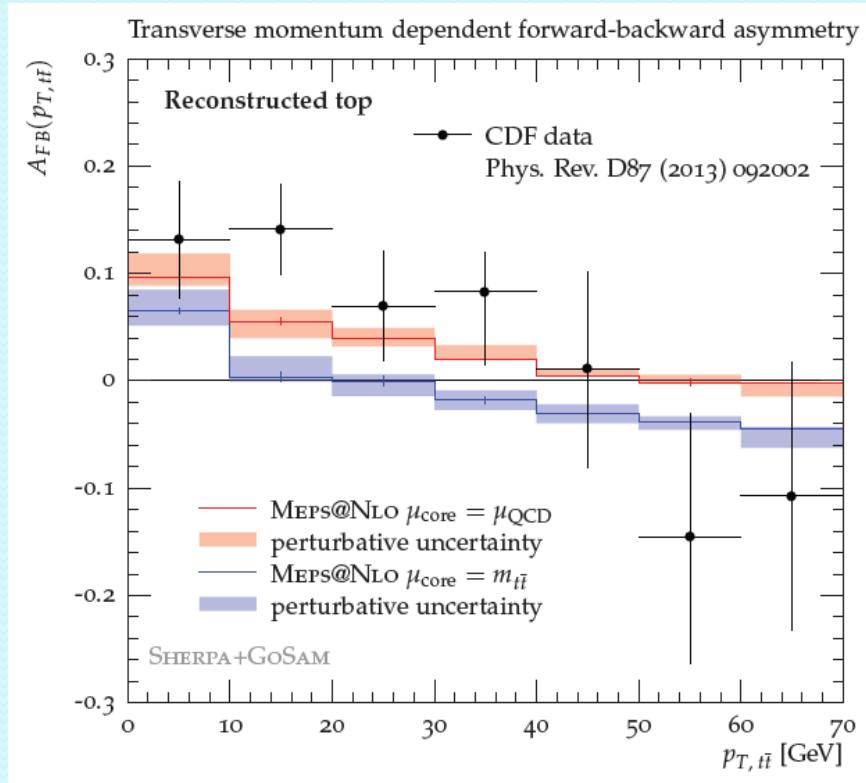
- Combined NLO multiplicities with merging scale :

$$Q_{cut} = 7 \text{ GeV}$$



# $t\bar{t}+0,1$ jet $A_{FB}$ with Sherpa+GoSam

[Höche, Huang, Luisoni, Schönherr, Winter]

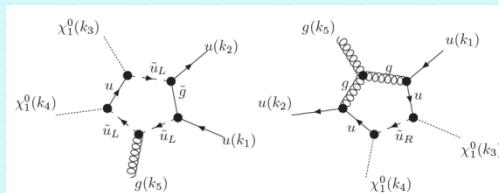


- NLO accurate except for first bin
- Consistent description over the full  $p_{T,t\bar{t}}$  spectrum

- Noticeable dependence on choice of the central core scale

# ••• BSM physics with GoSam

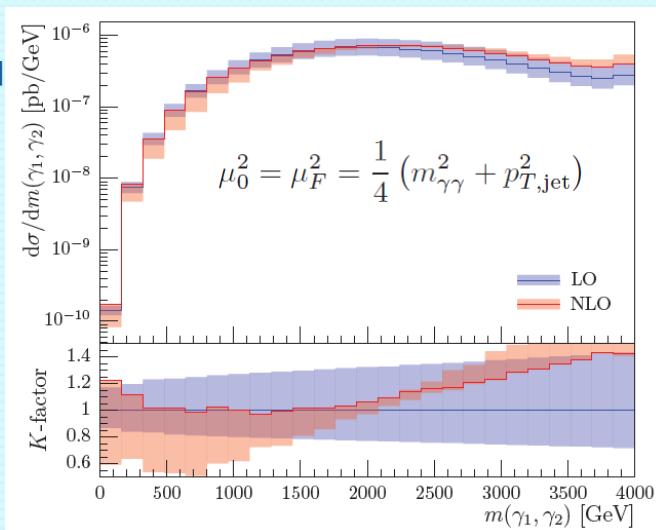
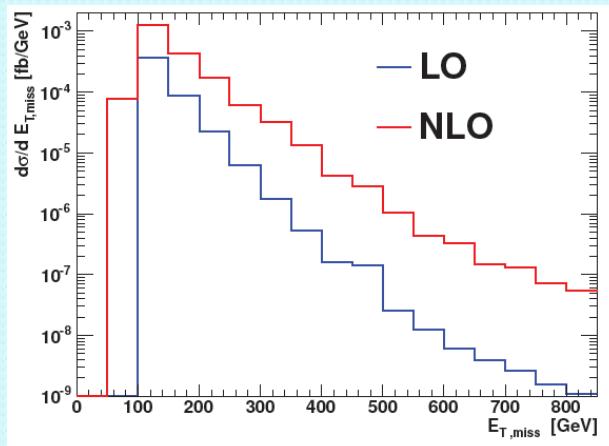
- $pp \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 jj$ : [Cullen, Greiner, Heinrich]
  - Susy-QCD corrections
  - **FeynRules** → UFO model file → GoSam
  - ~1400 diag.: rank-3 pentagons, up to 4 internal masses
  - Full inclusion of all non-resonant diagrams



- $pp \rightarrow G \rightarrow \gamma\gamma jj$ : [Greiner, Heinrich, Reichel, v. Soden-Fraunhofer]
  - NLO QCD in ADD with  $\delta=4$  large extra dimensions
  - spin-2 particle / non-standard propagator of G due to sum over KK modes

$$D(s) = \sum_{\vec{n}} \frac{i}{s - m_{\vec{n}}^2 + i\epsilon}$$

- approx. spectrum with continuous density function



# Conclusions & Outlook

<http://gosam.hepforge.org>

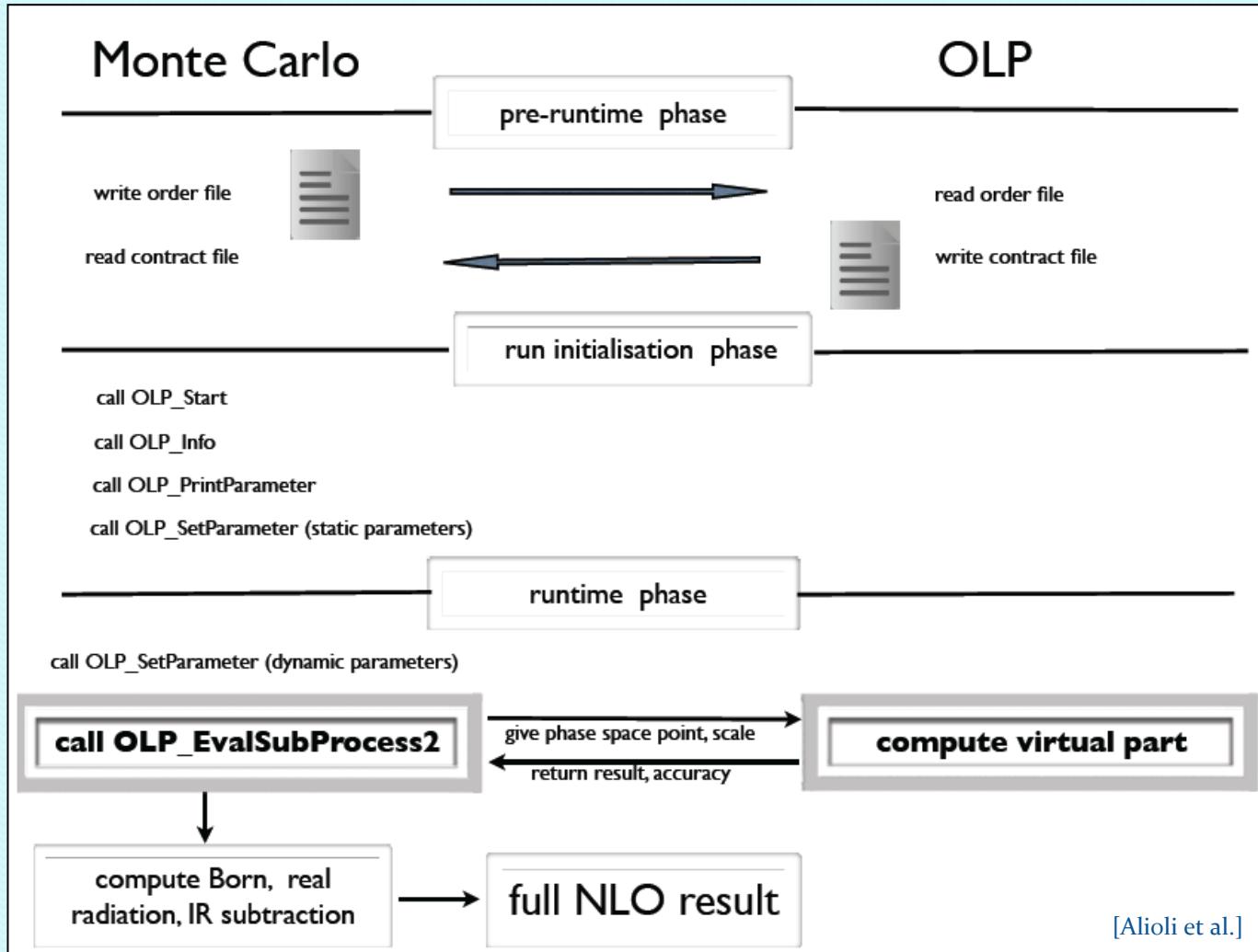
- **GoSam**: tool for automatic computation of 1-loop amplitudes
  - interfaced with several MC event generators via BLHA
    - allows applications exploiting strength of different tools:  
**MadGraph-MadDipole-MadEvent/Powheg/Sherpa/aMC@NLO/Herwig++**
- Selected results:
  - HVJ with Powheg and MiNLO
  - $t\bar{t}(j)$  with Sherpa for  $A_{FB}$  at Tevatron
  - BSM physics:  $\tilde{\chi}^0 \tilde{\chi}^0 j / G (-> \gamma \gamma) j$
  - And more... → **in N. Greiner's, P. Mastrolia's and J. Schlenk's talks**
- **Outlook**: towards GoSam-2.0
  - prepare new release with recently developed features
  - further improvements and applications



# Bineth Les Houches Interface (BLHA)

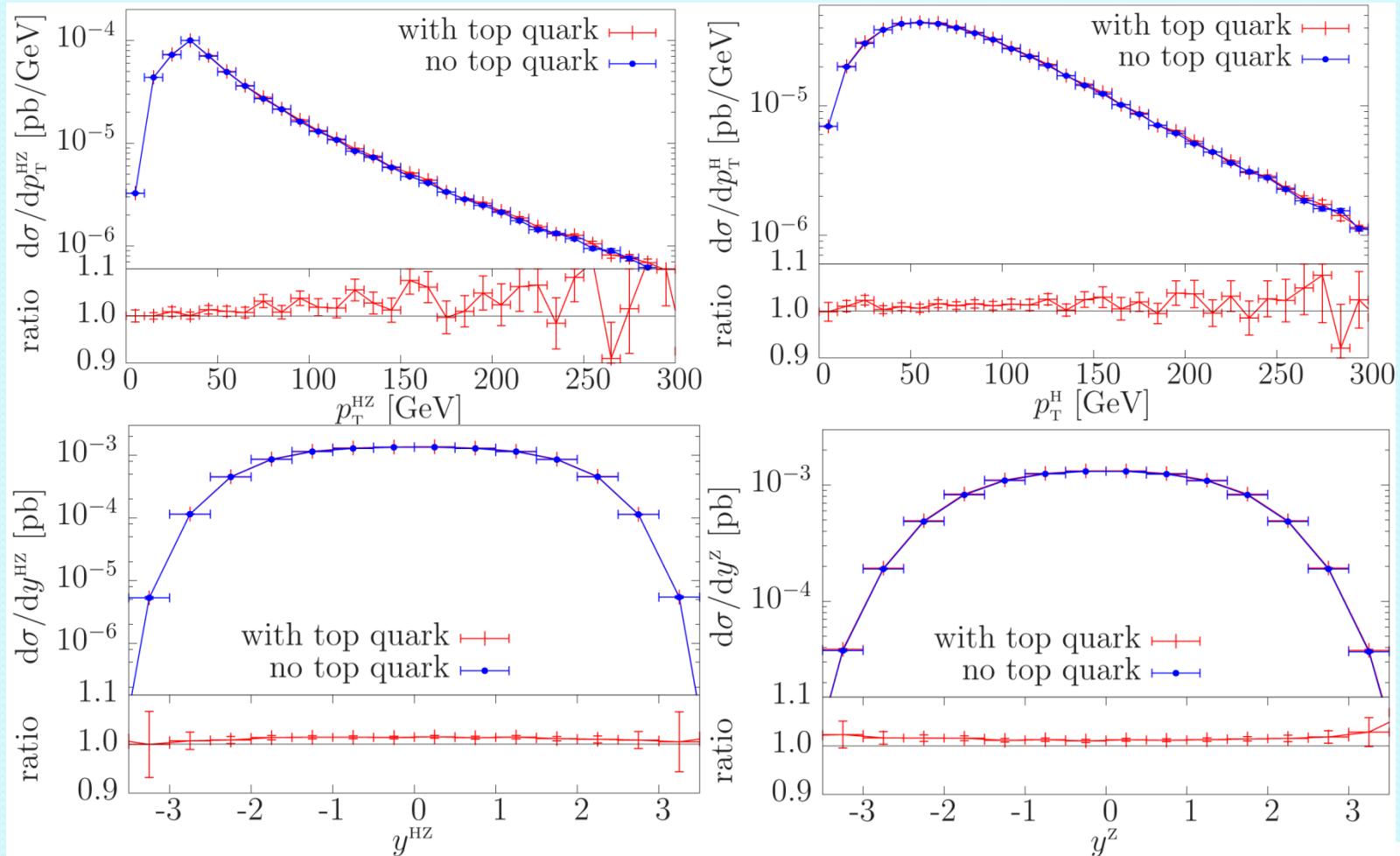
[Binoth et al.]

- Standards for communication between **MC** and **OLP**



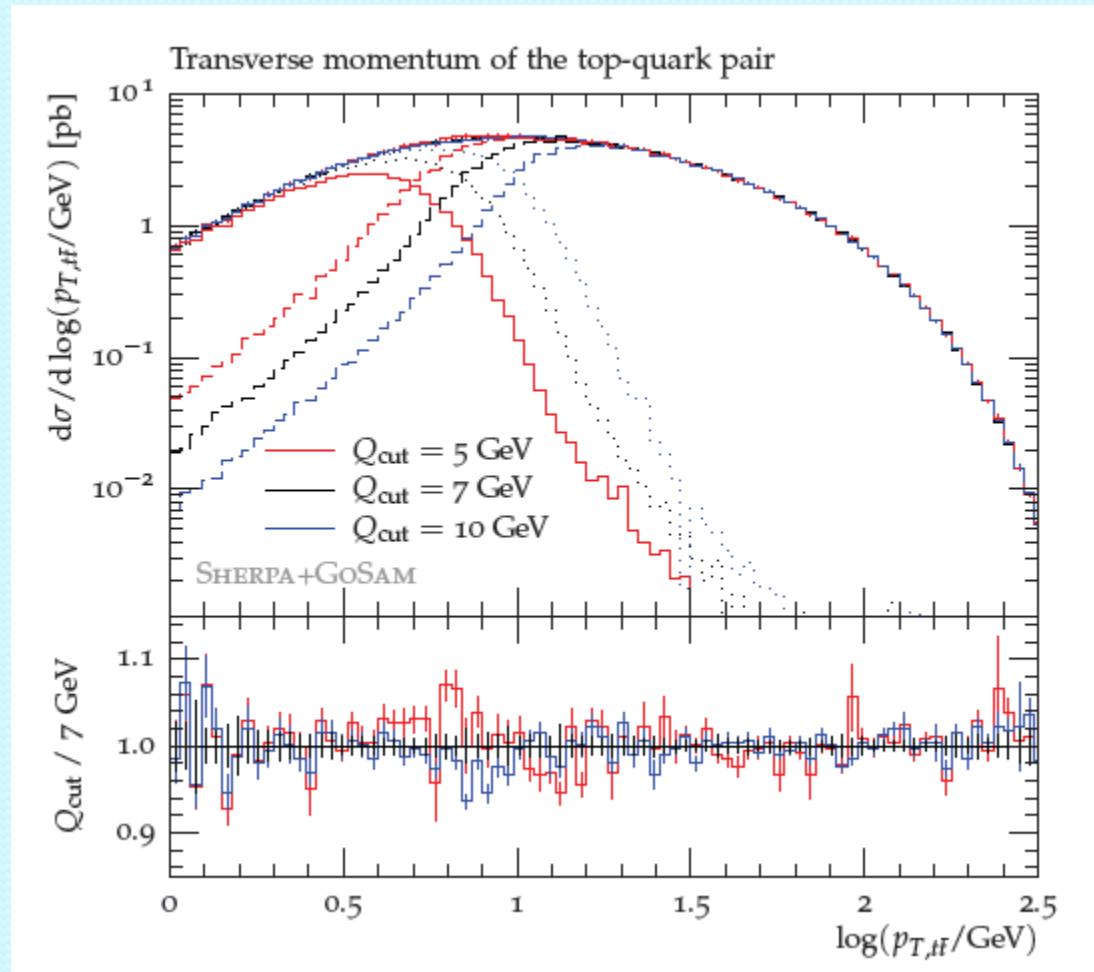
# HVJ with Powheg+GoSam

- Effect of inclusion of top-quark 1-loop diagrams:



# • $t\bar{t}+0,1$ jet $A_{FB}$ with Sherpa+GoSam

- Merging scale dependence:



# ••• References

## • GoSam 2012-2013:

- T. Gehrmann, N. Greiner & G. Heinrich, “*Precise QCD predictions for the production of a photon pair in association with two jets,*” arXiv:1308.3660.
- N. Greiner, G. Heinrich, J. Reichel & J. F. von Soden-Fraunhofen, “*NLO QCD corrections to diphoton plus jet production through graviton exchange,*” arXiv:1308.2194.
- H. van Deurzen, G. Luisoni, P. Mastrolia, EM, G. Ossola & T. Peraro, “*NLO QCD corrections to Higgs boson production in association with a top quark pair and a jet,*” arXiv:1307.8437.
- G. Cullen, H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, EM, G. Ossola, T. Peraro & F. Tramontano, “*NLO QCD corrections to Higgs boson production plus three jets in gluon fusion,*” arXiv:1307.4737 .
- S. Hoeche, J. Huang, G. Luisoni, M. Schoenherr & J. Winter, “*Zero and one jet combined NLO analysis of the top quark forward-backward asymmetry,*” Phys.Rev. D88 (2013) 014040, arXiv:1306.2703.
- G. Luisoni, P. Nason, C. Oleari & F. Tramontano, “*HW/HZ + o and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO,*” arXiv:1306.2542.
- M. Chiesa, G. Montagna, L. Barze‘, M. Moretti, O. Nicrosini, F. Piccinini & F. Tramontano, “*Electroweak Sudakov Corrections to New Physics Searches at the CERN LHC,*” arXiv:1305.6837.
- T. Gehrmann, N. Greiner & G. Heinrich, “*Photon isolation effects at NLO in gamma gamma + jet final states in hadronic collisions,*” JHEP 1306, 058 (2013).
- H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, EM, G. Ossola, T. Peraro, J. F. von Soden-Fraunhofen & F. Tramontano, “*NLO QCD corrections to the production of Higgs plus two jets at the LHC,*” Phys. Lett. B 721, 74 (2013).
- G. Cullen, N. Greiner & G. Heinrich, “*Susy-QCD corrections to neutralino pair production in association with a jet,*” Eur. Phys. J. C 73, 2388 (2013).

