Spin polarization in top pair production in association with two photons at NLO+PS

Gionata Luisoni

gionata.luisoni@cern.ch

CERN

25th International Workshop on Deep Inelastic Scattering and Related Topics

Birmingham, UK

04.04.2017

In collaboration with:

Hans Van Deurzen, Rikkert Frederix, Valentin Hirschi, Pierpaolo Mastrolia, Giovanni Ossola

CERN

Outline

- GoSam

- Interfacing GoSam to MadGraph5_aMC@NLO

- Spin polarization analysis in $t\bar{t}\gamma\gamma$:

  - setup
  - $t\bar{t}$ - charge asymmetry
  - spin polarization observables

- Conclusions

GoSam and MG5_aMC@NLO

Interface and Validation

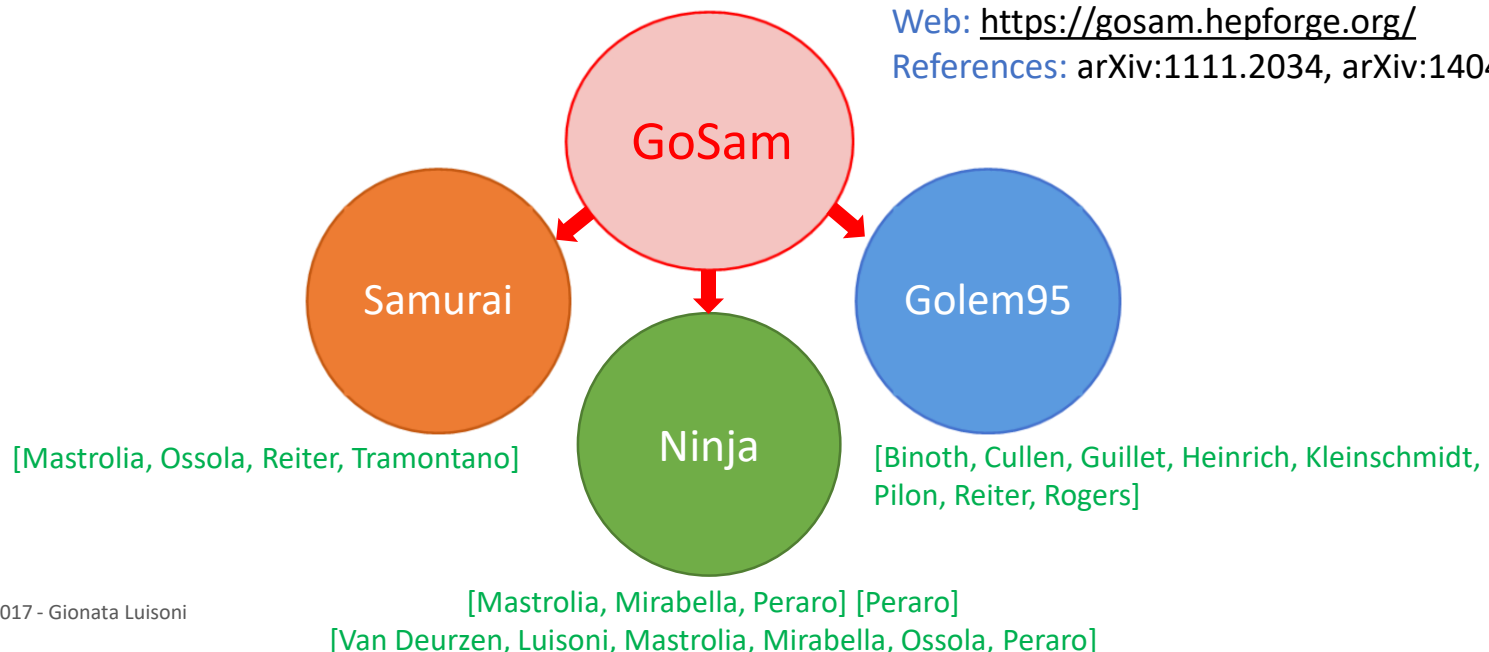# GoSam

[The GoSam collaboration:
Nicolas Greiner, Gudrun Heinrich, Stephan Jahn, Stephen Jones, Gionata Luisoni, Pierpaolo Mastrolia,
Giovanni Ossola, Tiziano Peraro, Johannes Schlenk, Francesco Tramontano and also
Gavin Cullen, Hans van Deurzen, Edoardo Mirabella, Joscha Reichel, Thomas Reiter, Johann Felix von Soden-Fraunhofen]

- Code for the automatic computation of 1-loop amplitudes

- Philosophy and main characteristics:
  - Compute amplitudes from algebraic generation of D-dimensional integrands via Feynman diagrams
  - Reduction at the integrand level via D-dimensional OPP method (Samurai), via Laurent expansion (Ninja) or tensor integral calculation (Golem)

Web: https://gosam.hepforge.org/
References: arXiv:1111.2034, arXiv:1404.7096

GoSam

Samurai

Ninja

Golem95

[Mastrolia, Ossola, Reiter, Tramontano]

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

[Mastrolia, Mirabella, Peraro] [Peraro]
[Van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro]

NLO calculations

- For a full NLO calculation other ingredients are needed:

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

Monte Carlo

- Tree amplitude
- Subtraction scheme
- Phase space integral

BLHA

One Loop Program

- Virtual corrections

POWHEG-BOX

[Alioli, Hamilton, Jezo, Nason, Oleari, Re, Zanderighi]

Sherpa

[Höche, Krauss, Kuttimalai, Schönherr, Schumann, Siegert, Thompson, Winter, Zapp]

GoSam

HERWIG

[Bellm, Gieseke, Grellscheid, Plätzer, Rauch, Reuschle, Richardson, Schichtel, Seymour, Siódmok, Wilcock]

MG5_aMC@NLO

[Alwall, Artoisenet, Degrande, Frederix, Frixione, Fuks, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro]

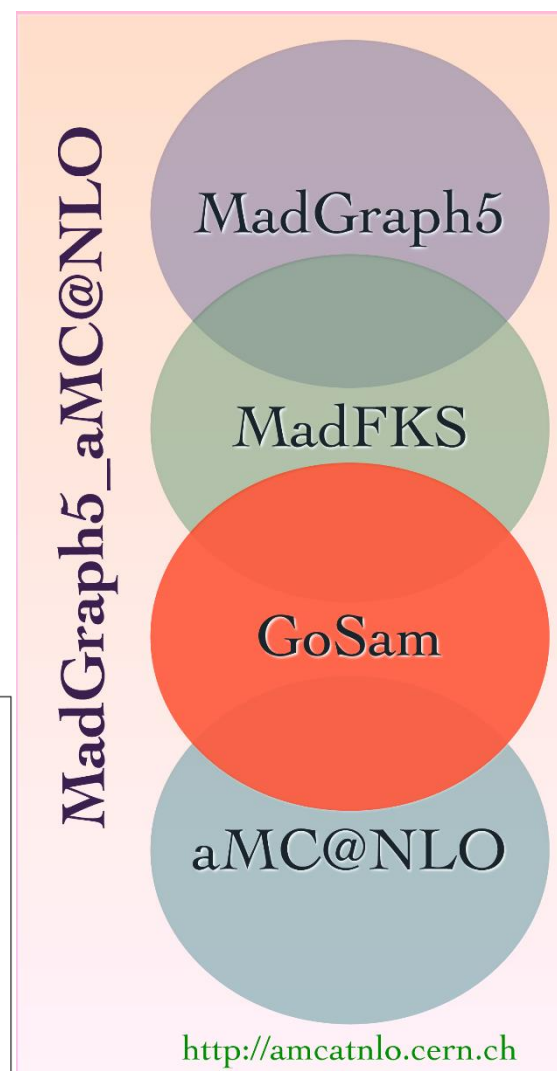# GoSam + MadGraph5_aMC@NLO

- Interface GoSam to MadGraph5_aMC@NLO:

  - Possibility to switch between build-in loop generator Madloop to GoSam

    ➤ Flexibility is good for benchmarking, stability, backup

  - GoSam: algebraic expressions for integrands
  - Madloop: purely numerical integrands

  - Two codes communicate via Binoth Les Houches Accord (BLHA):   [arXiv 1203.6803, arXiv 1308.3462]

```
#OLE_order written by MadGraph5_aMC@NLO

MatrixElementSquareType CHaveraged
CorrectionType          QCD
IRregularisation        CDR
AlphasPower             2
AlphaPower              2
NJetSymmetrizeFinal     Yes
ModelFile               ./param_card.dat
Parameters              alpha_s


# process
21 21 -> 22 22 6 -6
2 -2 -> 22 22 6 -6
1 -1 -> 22 22 6 -6
-2 2 -> 22 22 6 -6
-1 1 -> 22 22 6 -6
```
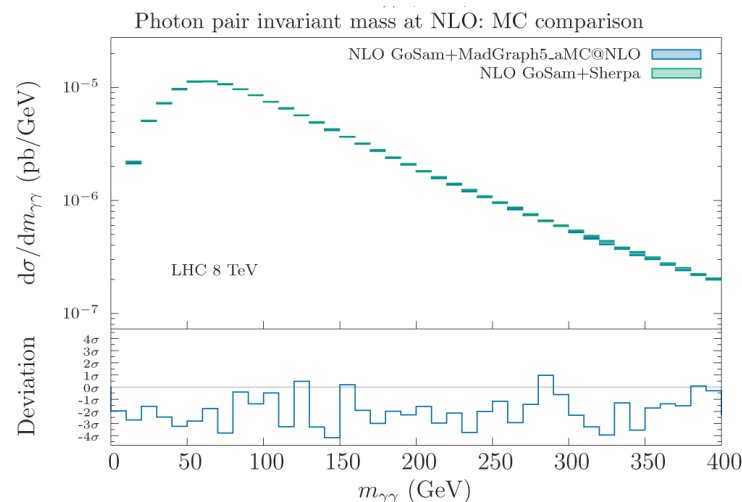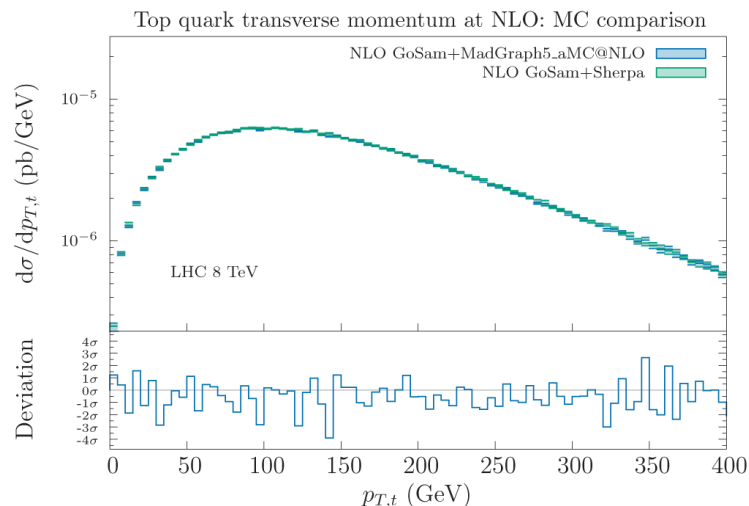
```
# vim: syntax=olp
#@OLP GoSam 2.0.0
#@IgnoreUnknown True
#@IgnoreCase False
#@SyntaxExtensions
MatrixElementSquareType CHaveraged | OK
CorrectionType QCD | OK
IRregularisation CDR | OK
AlphasPower 2 | OK
AlphaPower 2 | OK
NJetSymmetrizeFinal Yes | OK #Ignored by OLP
ModelFile ./param_card.dat | OK
Parameters alpha_s | OK
21 21 -> 22 22 6 -6 | 1 2
2 -2 -> 22 22 6 -6 | 1 0
1 -1 -> 22 22 6 -6 | 1 3
-2 2 -> 22 22 6 -6 | 1 1
-1 1 -> 22 22 6 -6 | 1 4
```


MadGraph5_aMC@NLO

MadGraph5

MadFKS

GoSam

aMC@NLO

http://amcatnlo.cern.ch

Validation of interface

- Several processes computed and checked at various levels:
  - Single phase space point
  - Inclusive cross sections
  - Differential distributions

- Example: NLO calculation of $t\bar{t}\gamma\gamma$ with two MCs and two OLPs:

$\sigma_{t\bar{t}\gamma\gamma}$, $\sqrt{s} = 8$ TeV	MG5_AMC + MADLOOP	MG5_AMC + GoSAM	SHERPA+GoSAM
LO [pb]	$1.0241 \pm 5.50 \cdot 10^{-4}$		$1.0246 \pm 3.51 \cdot 10^{-4}$
NLO [pb]	$1.3507 \pm 5.85 \cdot 10^{-3}$	$1.3432 \pm 5.16 \cdot 10^{-3}$	$1.3593 \pm 1.80 \cdot 10^{-3}$

Top quark transverse momentum at NLO: MC comparison
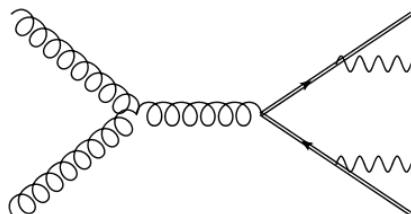

Photon pair invariant mass at NLO: MC comparison

Phenomenological application to spin polarization effects in $t\bar{t}\gamma\gamma$ production

Similar analysis carried out before at LO in **arXiv:1403.1790**   [Biswas, Frederix, Gabrielli, Mele]
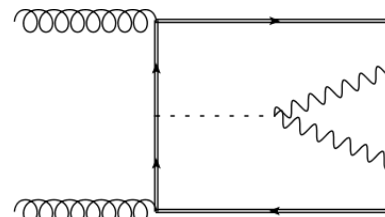
Physical setup

- Study top-pair production in association with di-photon pair
- Can originate from:

continuum background   or   Higgs signal

- Include top-decay and leptonic W-decay with MadSpin (keeps spin correlation)
  [Artoisenet, Frederix, Mattelaer, Rietkerk]

- Shower events with Pythia 8   [Sjöstrand, Christiansen, Desai, Ilten, Mrenna, Prestel, Skands]

- Scale and PDFs: $\mu_0 = \dfrac{\hat{H}_T}{2} = \dfrac{1}{2} \left(\displaystyle\sum_{\text{final state i}} m_{T,i} \right),$ CTEQ6L1 @ LO and CT10 @ NLO

- <u>Selection cuts:</u>

  - 2 isolated photons: $p_{T,\gamma} > 20 \text{ GeV}, \quad |\eta_\gamma| < 2.5, \quad 123 \text{ GeV} < m_{\gamma\gamma} < 129 \text{ GeV}$
    - Furthermore Fixione isolation: $R_\gamma < 0.4$ and distance between photons $R_{\gamma\gamma} = 0.4$

  - 2 charged leptons: $p_{T,l^\pm} > 10 \text{ GeV}, \quad |\eta_{l^\pm}| < 2.7$

  - 2 bottom-jets (assume 100% tagging efficiency): $\Delta R = 0.4, \quad p_{T,j} > 20 \text{ GeV}, \quad |\eta_j| < 4.7$

  - We used MC truth to reconstruct top-quarks with "right" leptons/b-jets

Results: fiducial cross sections

- Total fiducial cross sections:

$\sqrt{s} = 13$ TeV	$pp \to t\bar{t}H,\ H \to \gamma\gamma$	$pp \to t\bar{t}\gamma\gamma$
LO [pb]	$8.84(2) \cdot 10^{-7}\ {}^{+27\%}_{-20\%}\ {}^{+10\%}_{-11\%}$	$1.442(2) \cdot 10^{-7}\ {}^{+25\%}_{-18\%}\ {}^{+10\%}_{-12\%}$
NLO [pb]	$11.77(5) \cdot 10^{-7}\ {}^{+6\%}_{-8\%}\ {}^{+11\%}_{-12\%}$	$2.175(7) \cdot 10^{-7}\ {}^{+10\%}_{-10\%}\ {}^{+10\%}_{-11\%}$
K-factor	$1.33(1)$	$1.51(1)$

- Very tiny cross sections – very challenging for LHC
- Simple selection cuts allow to enhance signal over background

- NB: neglected effect of photon bremsstrahlung from charged top decay products (can be partially reduced by proper kinematical cuts – contribution can however be sizable)
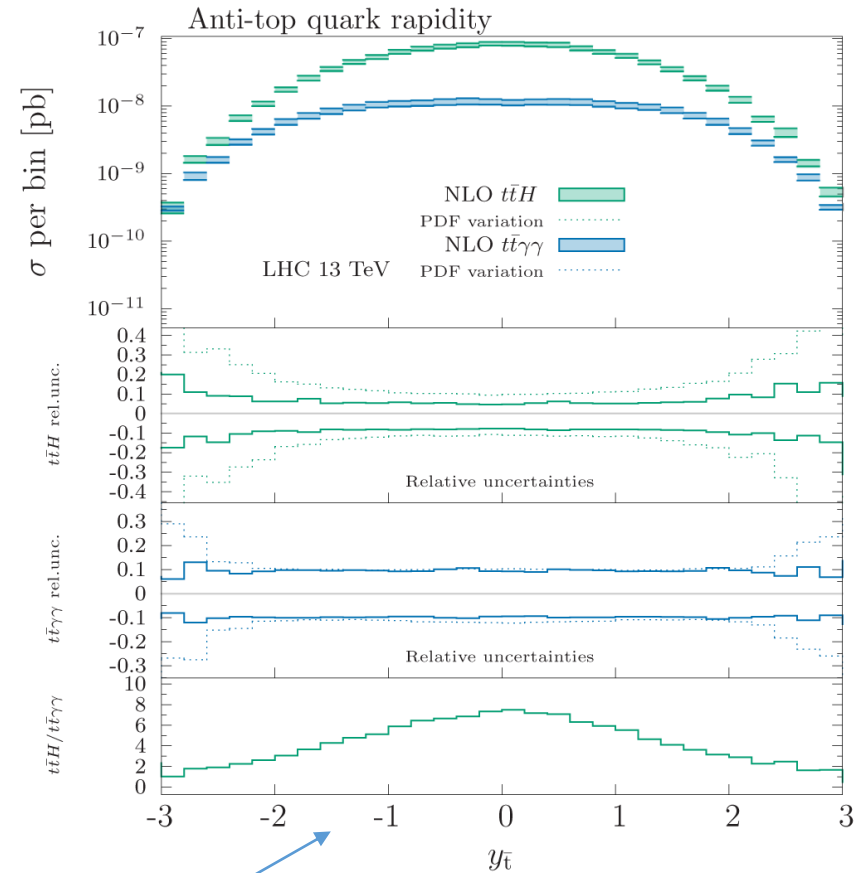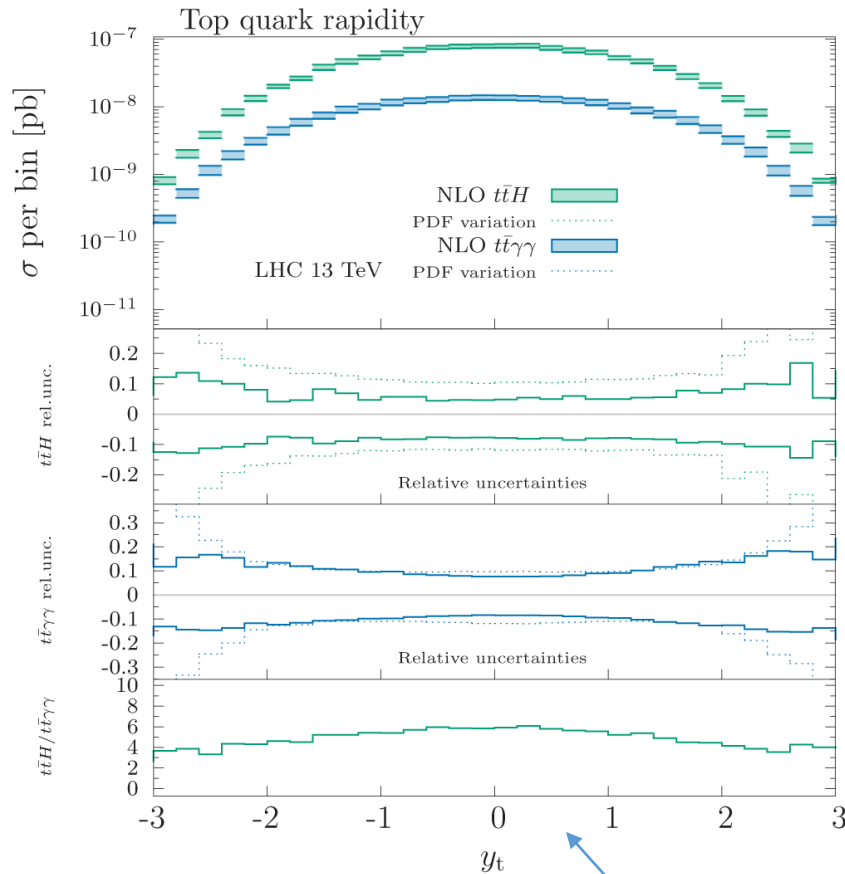
Results: transverse momentum spectra

- P$_T$ distributions for top and anti-top:
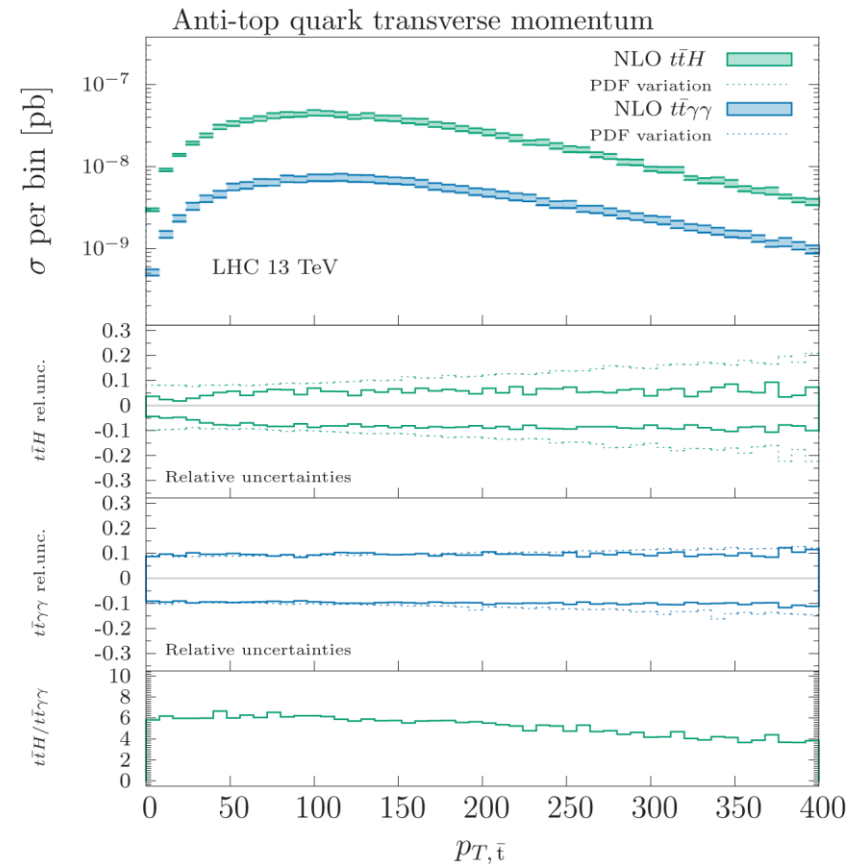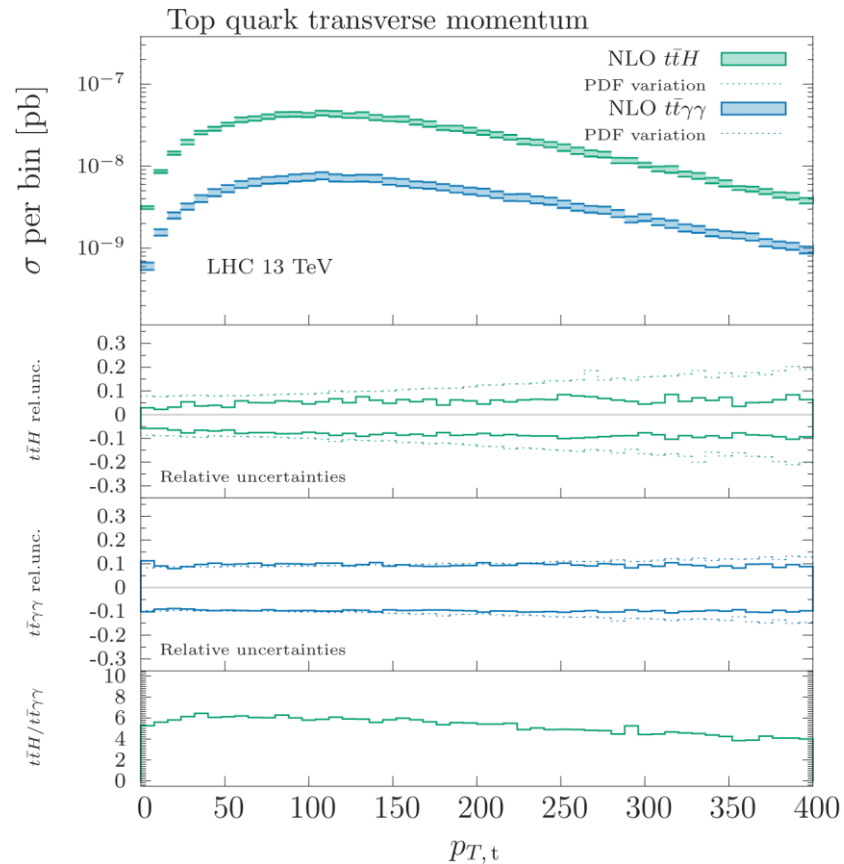
- Signal has larger PDF uncertainties due to dominant gluon-channel production

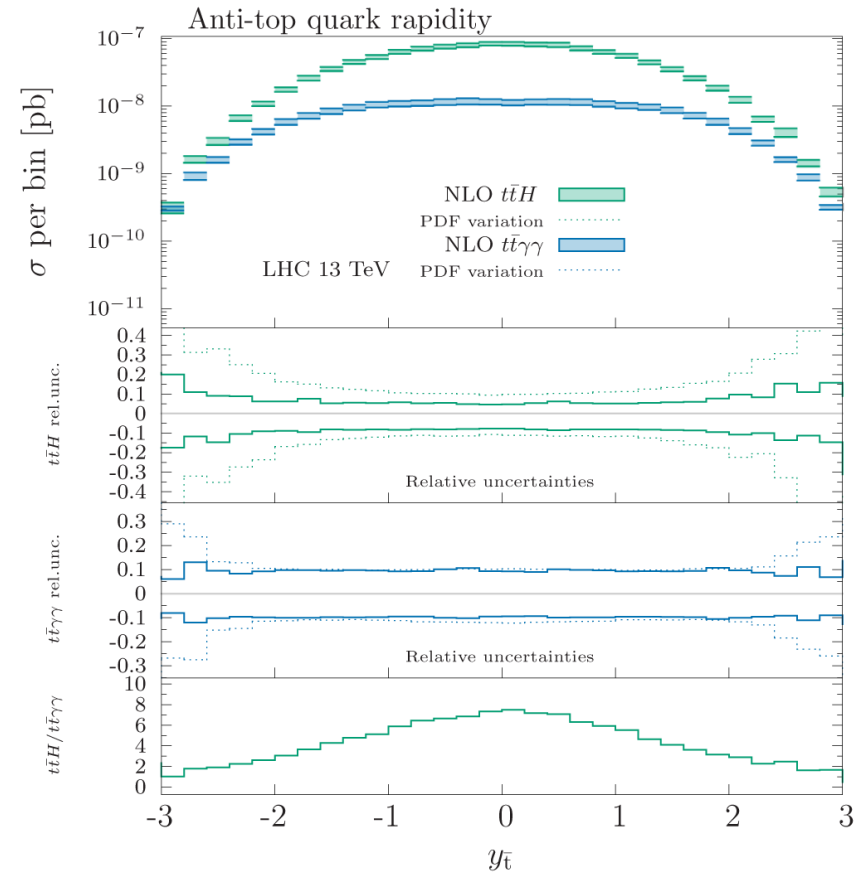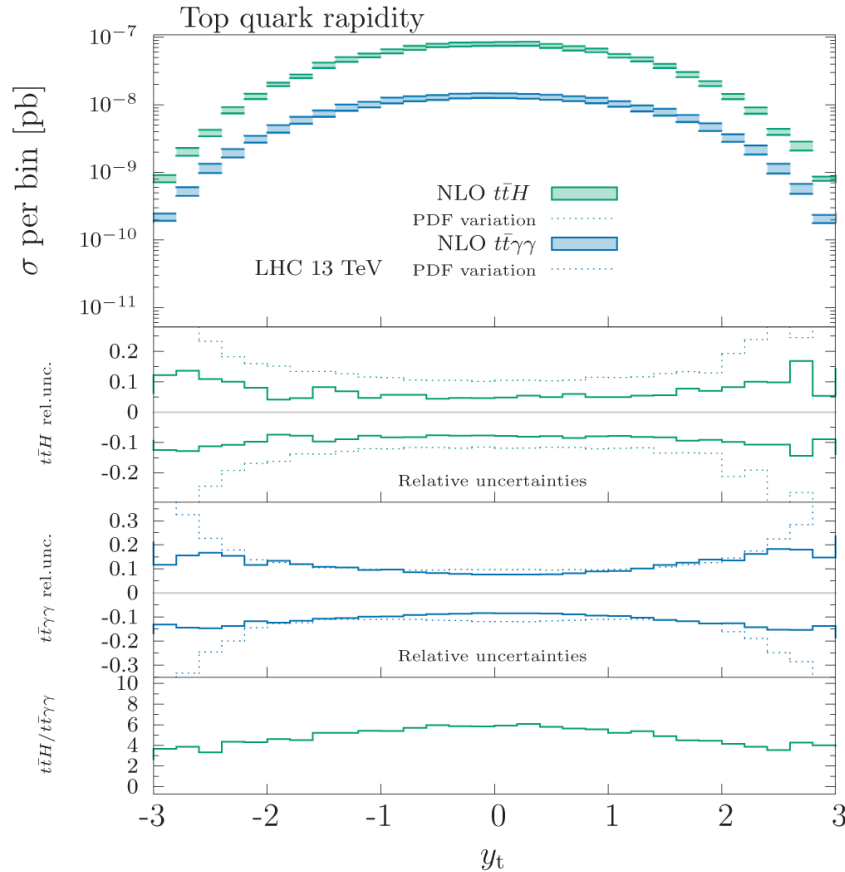# Results: $t\bar{t}$ - charge asymmetry

- Rapidity distributions of top and anti-top:

Visible difference between signal and background

Results: $t\bar{t}$ - charge asymmetry

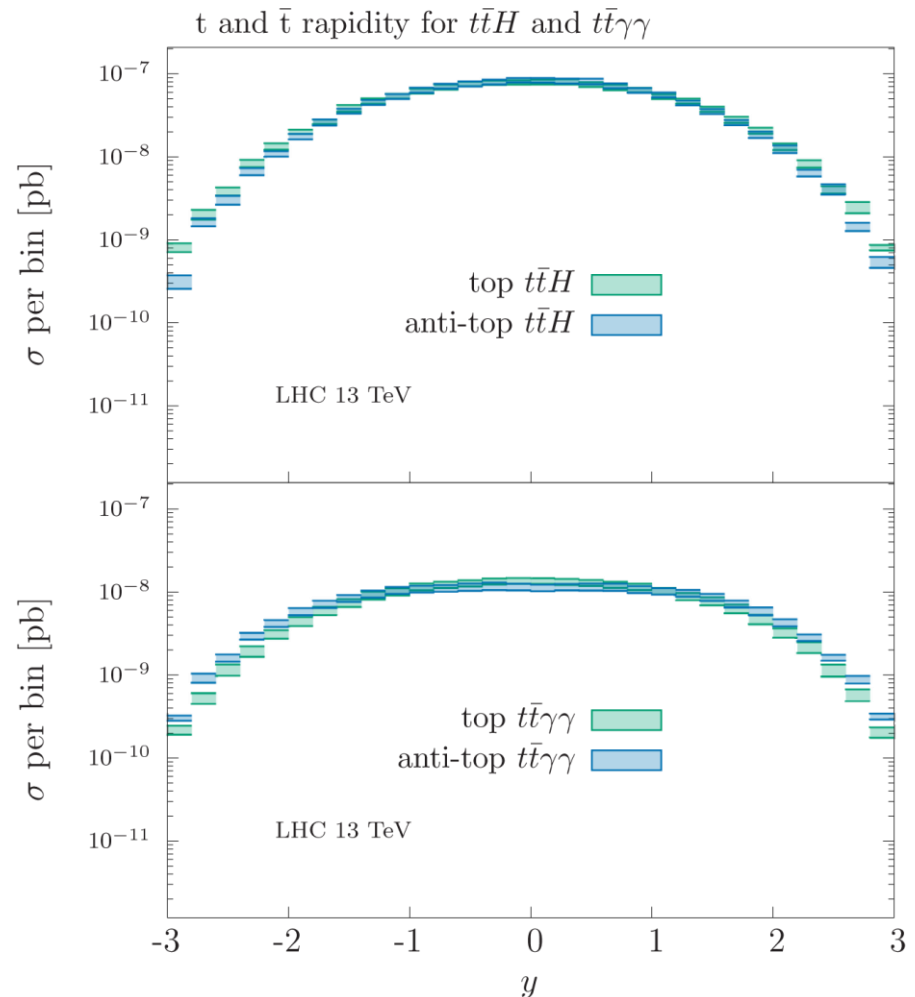- Rapidity distributions of top and anti-top:

- Difference quantified by charge-asymmetry: $A_{t\bar{t}}^{C} = \dfrac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| < 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| < 0\right)}$, $\Delta|y| = |y_t| - |y_{\bar{t}}|$

- For $t\bar{t}$ or $t\bar{t}H$ production: $A_{t\bar{t}}^{C} > 0$ (top at larger rapidities compared to anti-top)

- Radiation of photon(s) reverses sign of $A_{t\bar{t}}^{C}$

Results: $t\bar{t}$ - charge asymmetry

- Rapidity distributions of top and anti-top:

➤ In $t\bar{t}H$ tops produced at larger rapidities than anti-tops

➤ In $t\bar{t}\gamma\gamma$ tops produced more central than anti-tops

t and $\bar{t}$ rapidity for $t\bar{t}H$ and $t\bar{t}\gamma\gamma$

Results: $t\bar{t}$ - charge asymmetry

- Rapidity distributions of top and anti-top:

  - ➢ To appreciate shape differences between signal and background, normalize distributions to total $t\bar{t}H$ cross section

  - ➢ Top very similar
    - ➢ despite tops being produced at higher rapidities than anti-tops in $t\bar{t}H$ overall they are still slightly more central than in $t\bar{t}\gamma\gamma$
  - ➢ Anti-top larger differences
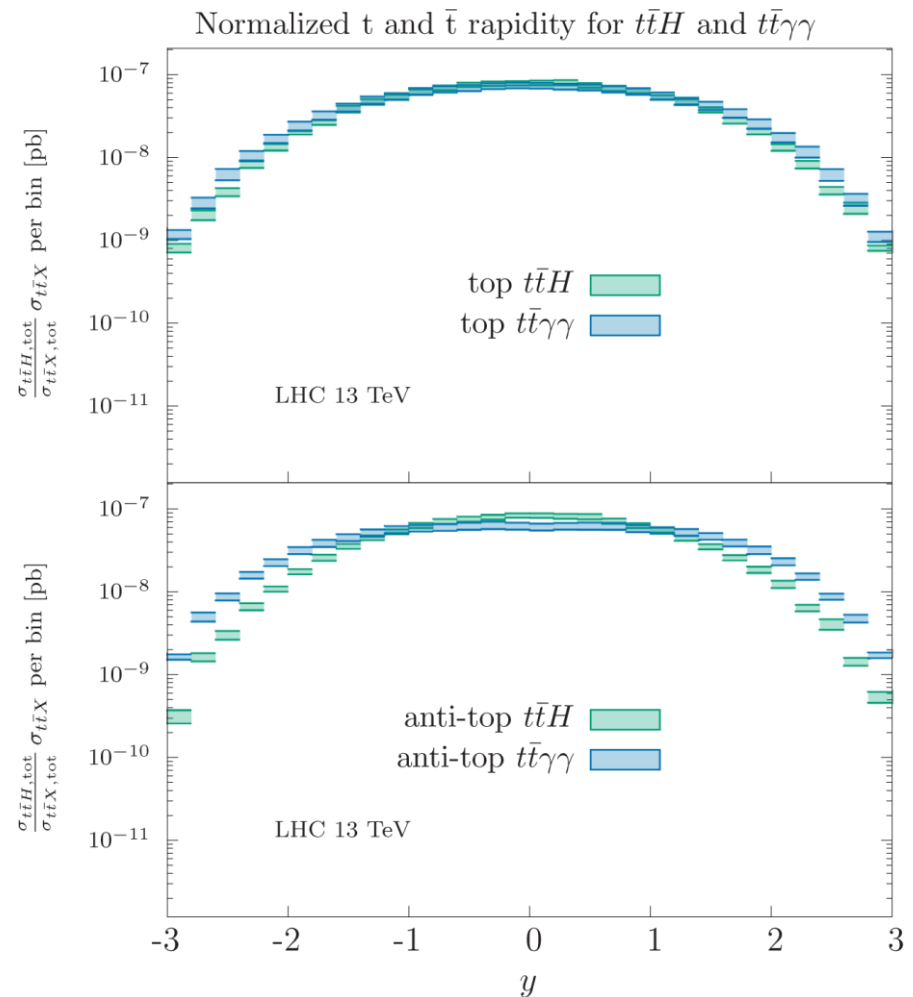
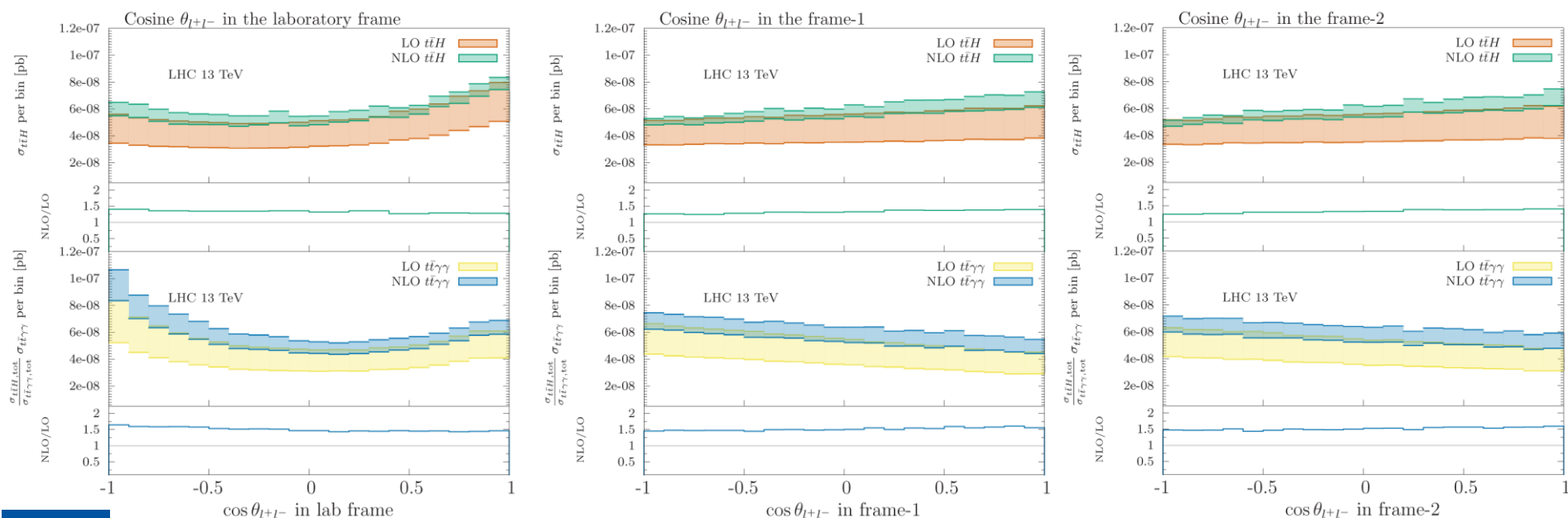Normalized t and $\bar{t}$ rapidity for $t\bar{t}H$ and $t\bar{t}\gamma\gamma$

Results: spin polarization

- Make spin analysis based on leptons: define 3 different frames
  - Angle between leptonic decay of top (l⁺) and antitop (l⁻)

- *lab frame*: momenta in the laboratory frame

- *frame-1*: the Lorentz boosts to bring t and $\bar{t}$ separately at rest are defined with respect to the $t\bar{t}$-pair center-of-mass frame,

- *frame-2*: the Lorentz boosts to bring t and $\bar{t}$ separately at rest are defined with respect to the lab-frame.

Angle between l⁺ in the top rest frame and l⁻ in anti-top rest frame

Results: spin polarization

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Angle between l⁺ in the top rest frame and l⁻ in anti-top rest frame
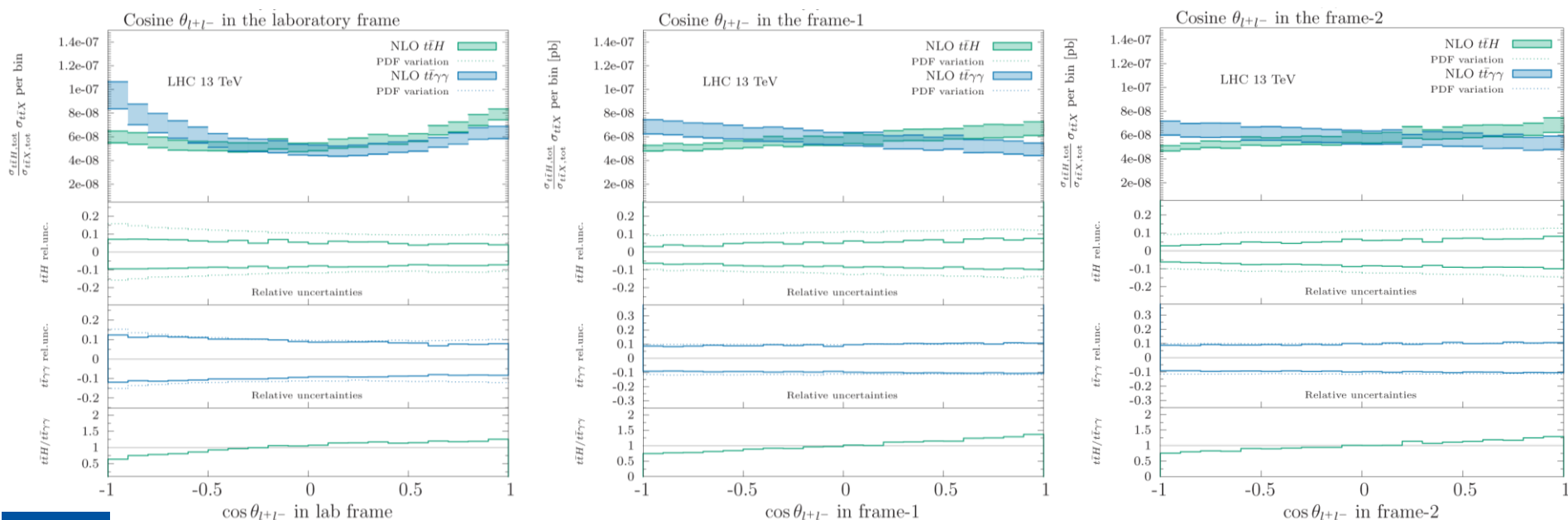
Conclusions

- Presented new interface between GoSam and MG5_aMC@NLO

  - Possibility to change loop provider for more flexibility in

    availability   -   speed   -   stability   -   form of amplitudes

- Application to simple signal vs. background study for $t\bar{t}H$ vs. $t\bar{t}\gamma\gamma$

  - Tiny cross sections

  - Interesting rapidity differences for top and especially anti-top between signal and background

  - Spin correlation observables:
    - impact of NLO limited to K-factor
    - Signal vs. background largely independent from the frame