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LHC Physics with GoSam 2.0

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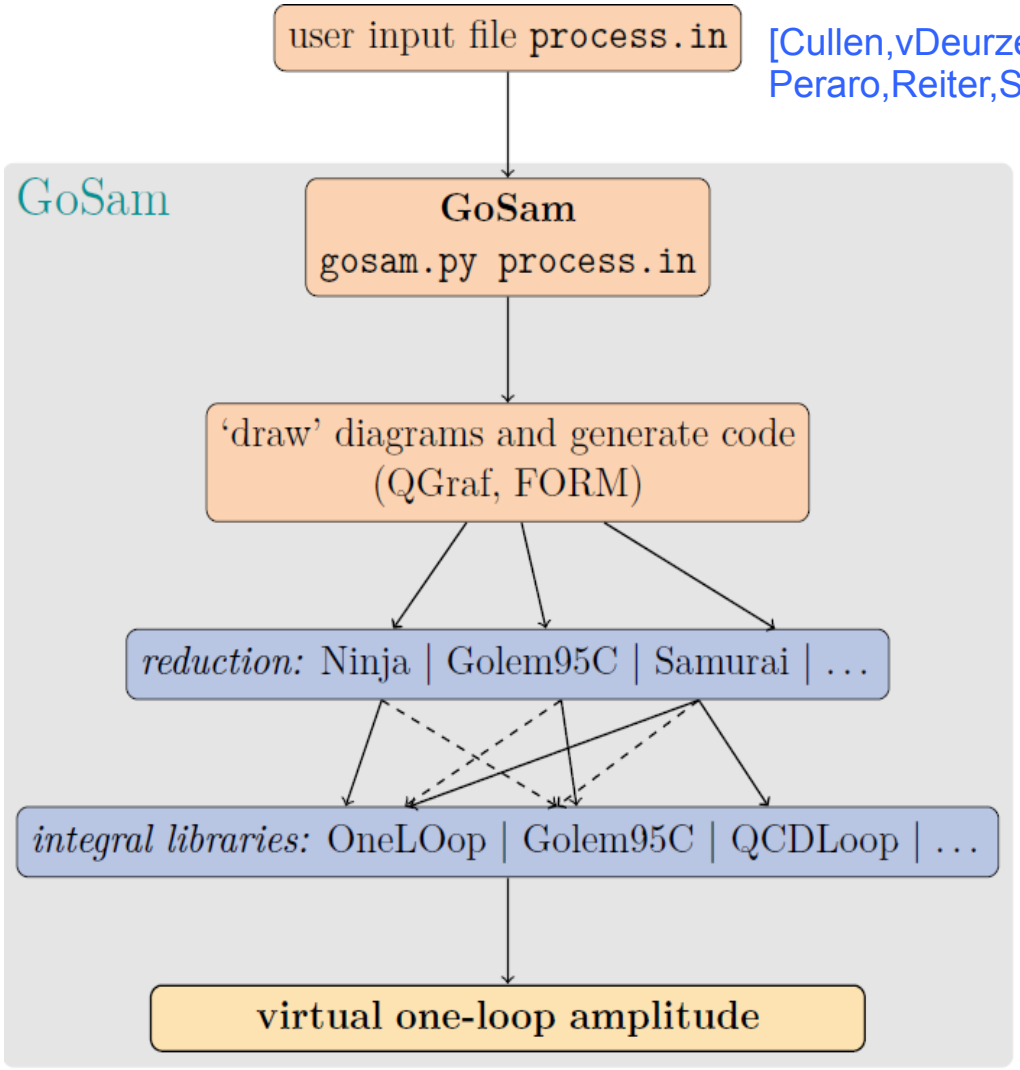
Outline

- Very brief introduction to **GoSam**

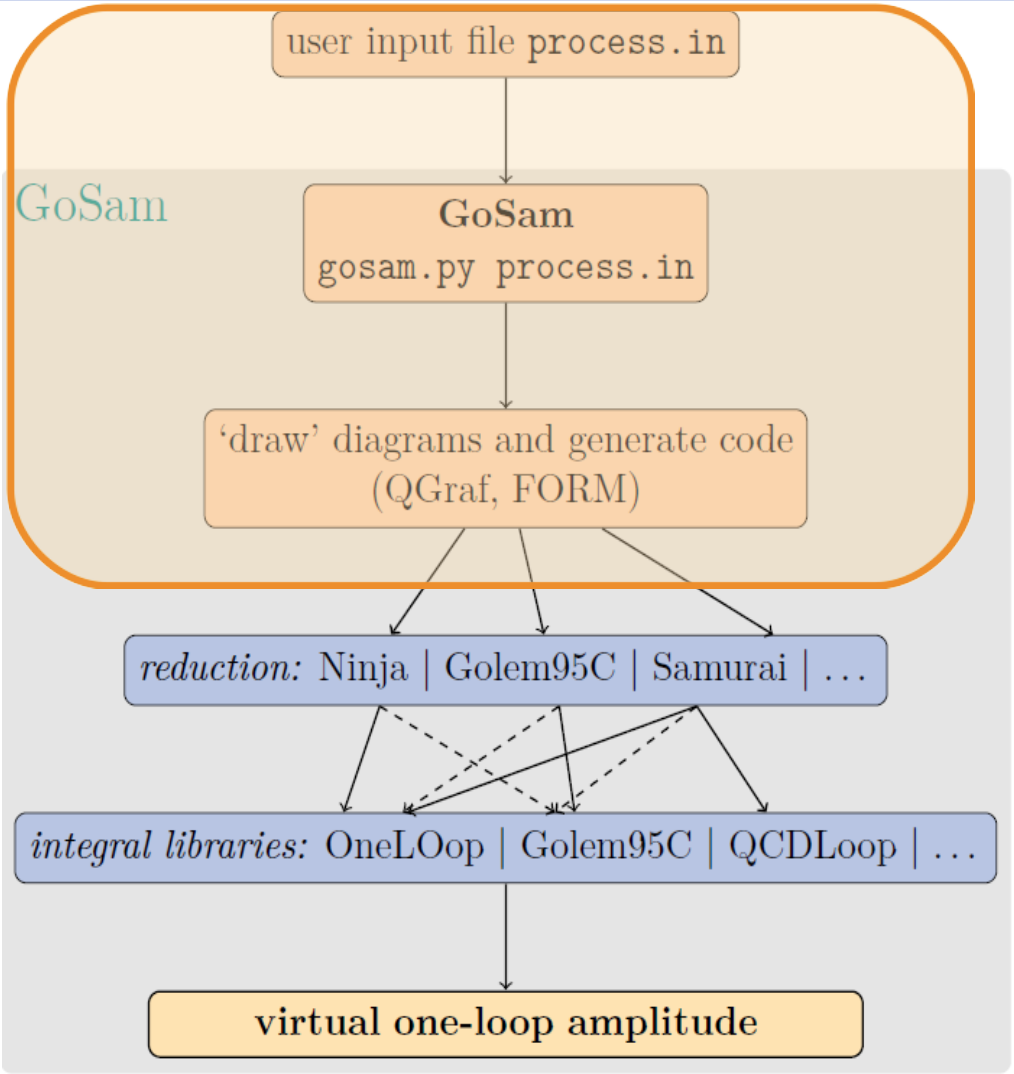
- Phenomenological results for **Higgs+jets @ NLO QCD** in Gluon Fusion

GoSam 2.0 – A Quick Overview

[Cullen,vDeurzen,NG,Heinrich,Luisoni,Mastrolia,Mirabella,Ossola, Peraro,Reiter,Schlenk,vSoden-Fraunhofen,Tramontano]



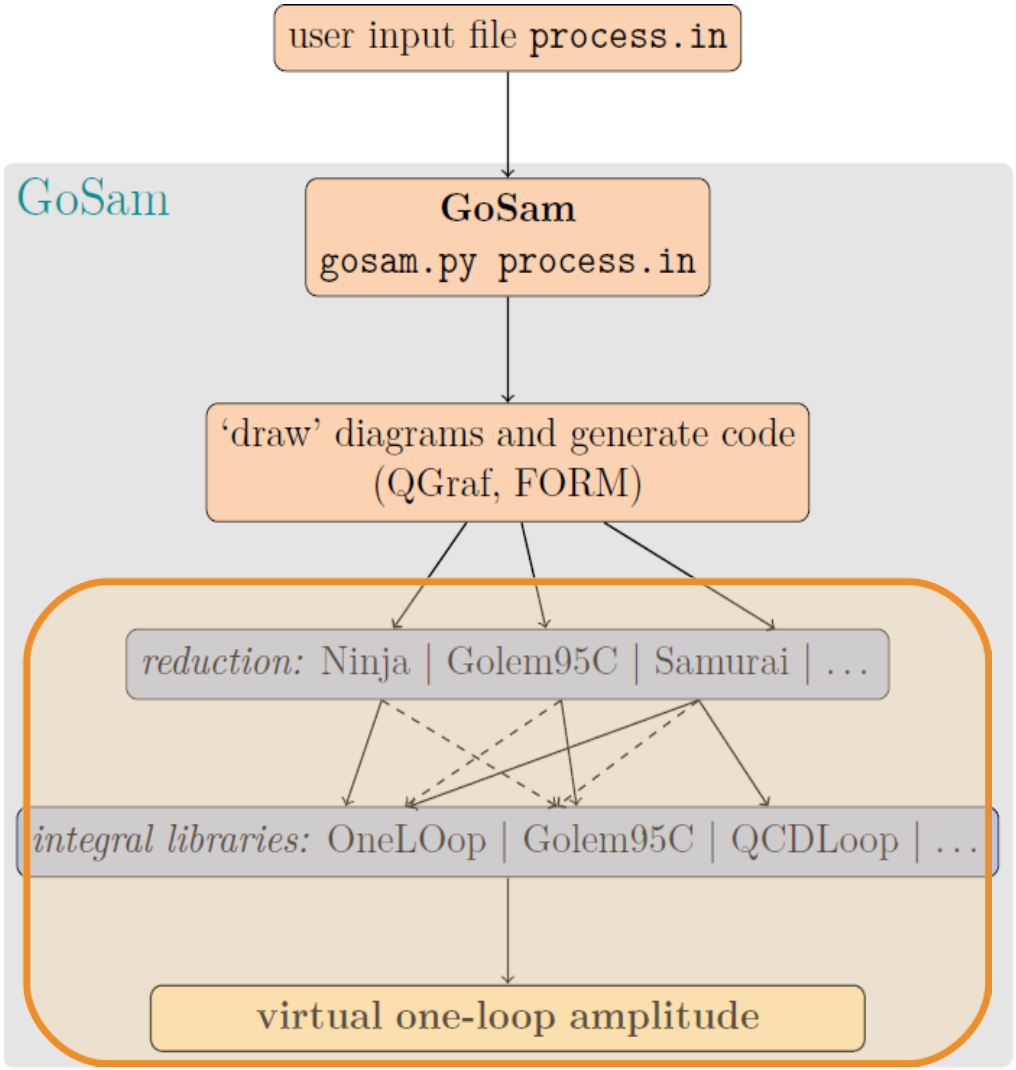
GoSam 2.0 – A Quick Overview



GENERATION

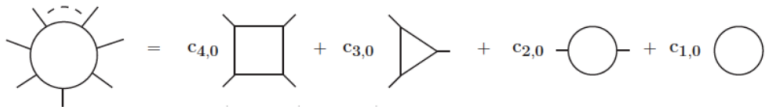
- Specify process (process.in):
  in=g,g
  out=H,t,t~
  order=QCD,2,4
  model=smdiag
  (new models can be imported)
- Many additional options
  (Parameter settings, Filter)
- 'Draw' Feynman diagrams
  with Qgraf [Nogueira]
- Apply Feynman rules and
  optimize expression with
  FORM
  [Vermaseren,Kuipers,Ueda,Vollinga]
- Fortran code

GoSam 2.0 – A Quick Overview



REDUCTION

- Any one loop amplitude can be written as combination of scalar integrals:

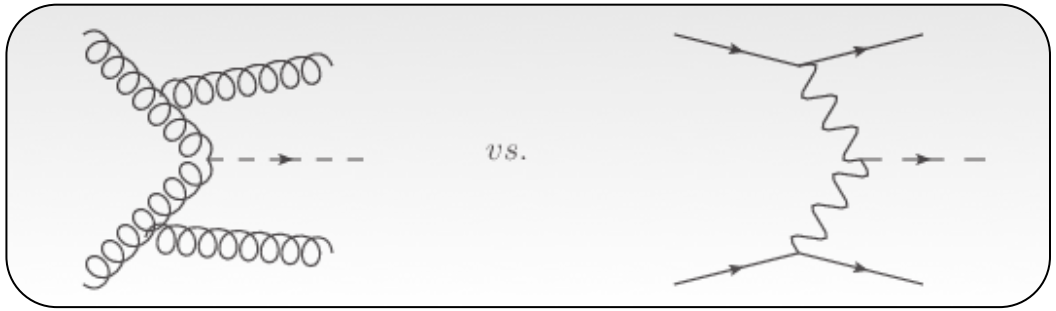


- Determine coefficients numerically, using either unitarity based methods Ninja [Mastrolia,Mirabella,Peraro] , Samurai [Mastrolia,Ossola,Reiter,Tramontano] or modified Passarino-Veltman reduction of Golem95 [Cullen et al.]
- Scalar integral libraries OneLoop [v.Hameren] ,QCDLoop [Ellis,Zanderighi] , Golem95

Higgs + jets in Gluon Fusion

NG, Hoeche, Luisoni, Schonherr, Winter, Yundin
arxiv:1506.01016

Higgs + jets in gluon fusion



- Gluon fusion dominant production mechanism
- Irreducible background to VBF production
- Precise understanding important for distinction between GF and VBF contribution.
- Need at least two jets for VBF, H+2 describes further radiation only at LO accuracy .
  → Inclusion of H+3 at NLO desirable
  → Effects of additional radiation ?
- Existing calculations for **H+j** [deFlorian,Grazzini,Kunszt '99],
  H+2j [Campbell,Ellis,Zanderighi '06] [Campbell,Ellis,Williams '10] [vDeurzen et al. '13] ,
  H+3j [Cullen et al. '13]

Calculational Setup

GoSam + **Sherpa (Comix)** : pp → H + 1,2,3

Output: Weighted Events as **Root Ntuples**

H+1 : 1.5 billion events → 290 GB
H+2 : 1.0 billion events → 250 GB
H+3 : 3.5 billion events → 1.25 TB

Individually for **8 TeV** and **13 TeV**

~ 4 TB data
Will be made public!

- Ntuples allow for fast analysis, change of **scale, pdf, cuts, jet radius**
  → 50 CPU hours for H+3 per analysis
- Running from scratch every time:
  (3 scale variations) x (4 scales) x (5 jet radii) x (2 cuts) = 120
  → ~ 4 million CPU hours (~ 4.6 year on 100 cores)
- **ApplGrid** for fast PDF convolution and scale variation [1312.4460]

Calculational Setup

Basic Setup:

anti-k_T $R = 0.4$

$p_T > 30$ GeV, $|\eta| < 4.4$

VBF:

$m(j_1, j_2) > 400$ GeV, $|\Delta y_{j_1,j_2}| > 2.8$

Tagging jets j_1, j_2 either pt-ordered (pt-tagging) or rapidity-ordered (y-tagging)

$$\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$$

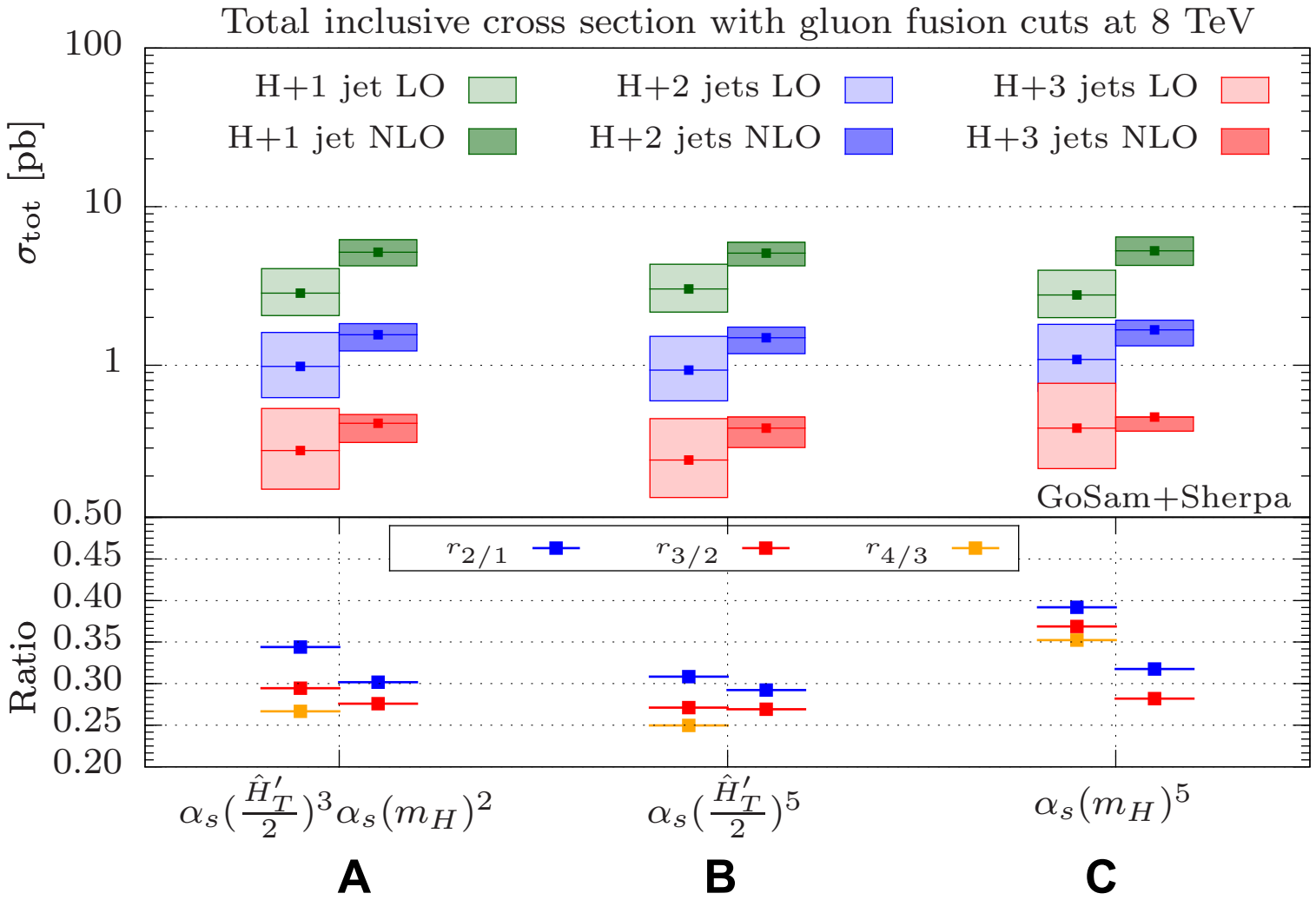
$$A: \quad \alpha_s\left(x \cdot \frac{\hat{H}'_T}{2}\right)^3 \alpha_s\left(x \cdot m_H\right)^2$$

$$B: \quad \alpha_s\left(x \cdot \frac{\hat{H}'_T}{2}\right)^5$$

$$C: \quad \alpha_s\left(x \cdot m_H\right)^5.$$

Scale choices

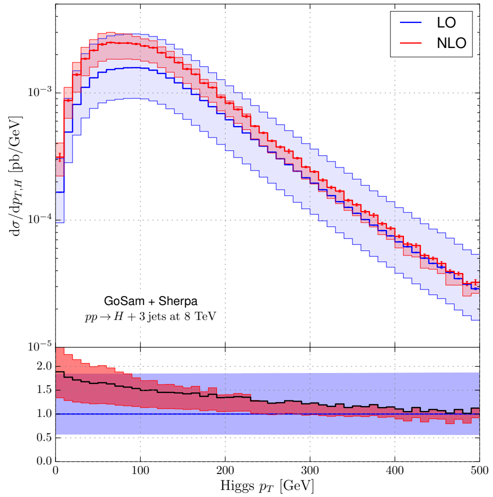
- Total cross sections for three different scale choices

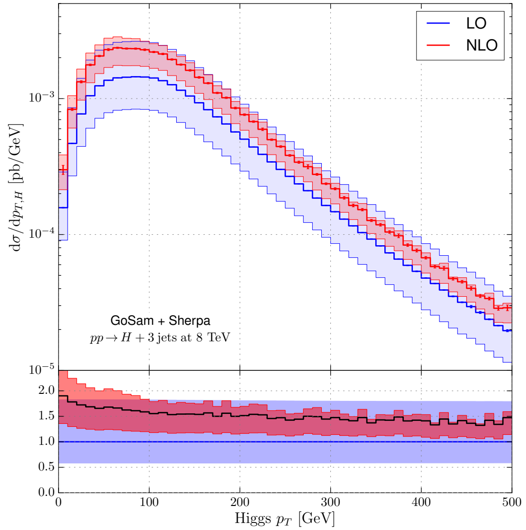


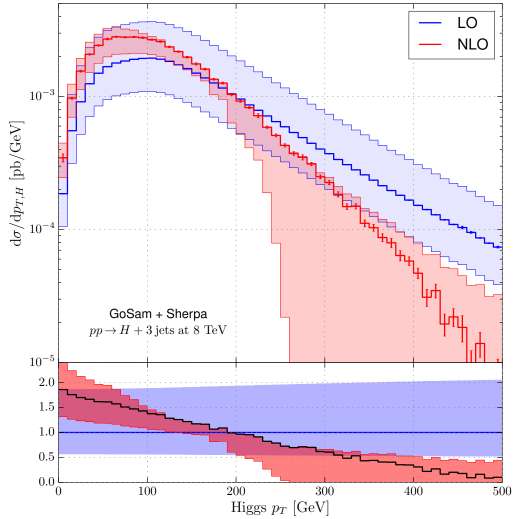
Scale choices

- pT distribution of Higgs for the three scale choices A,B,C from upper left to lower right
- Fixed scale not a good choice (C)
- Best results for scale B, moderate corrections, flat K-factor

Use scale B as default scale





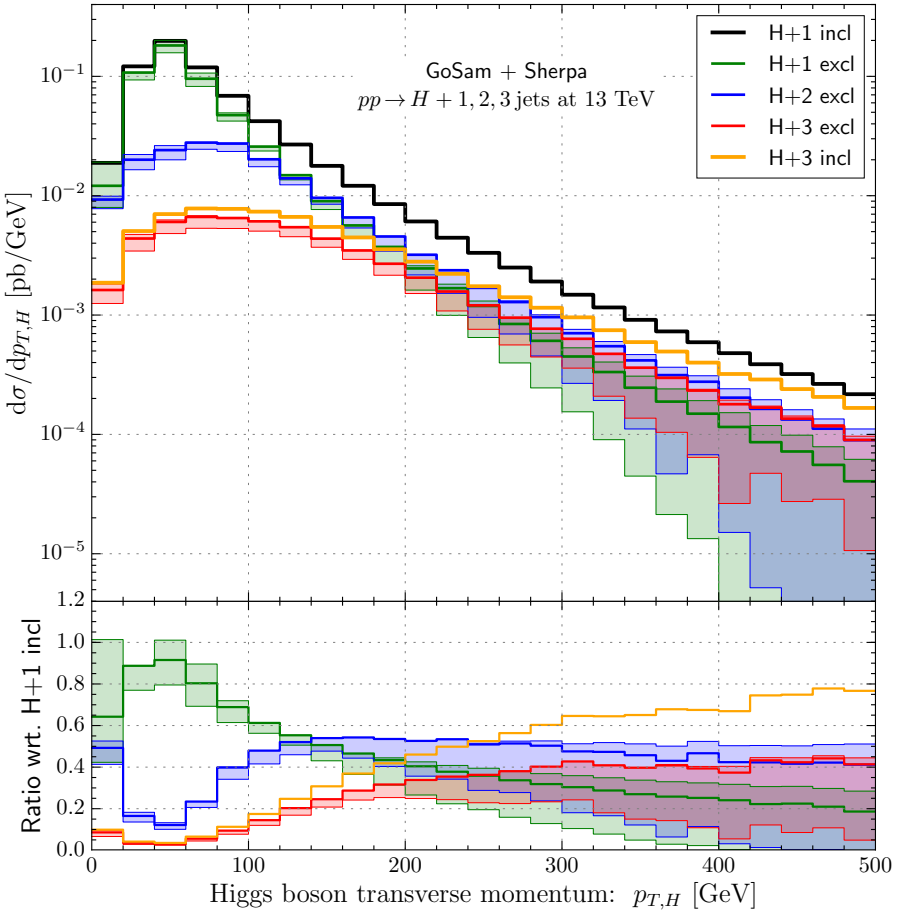


Multi-jet ratios

- Investigate impact of additional jets to specific observables

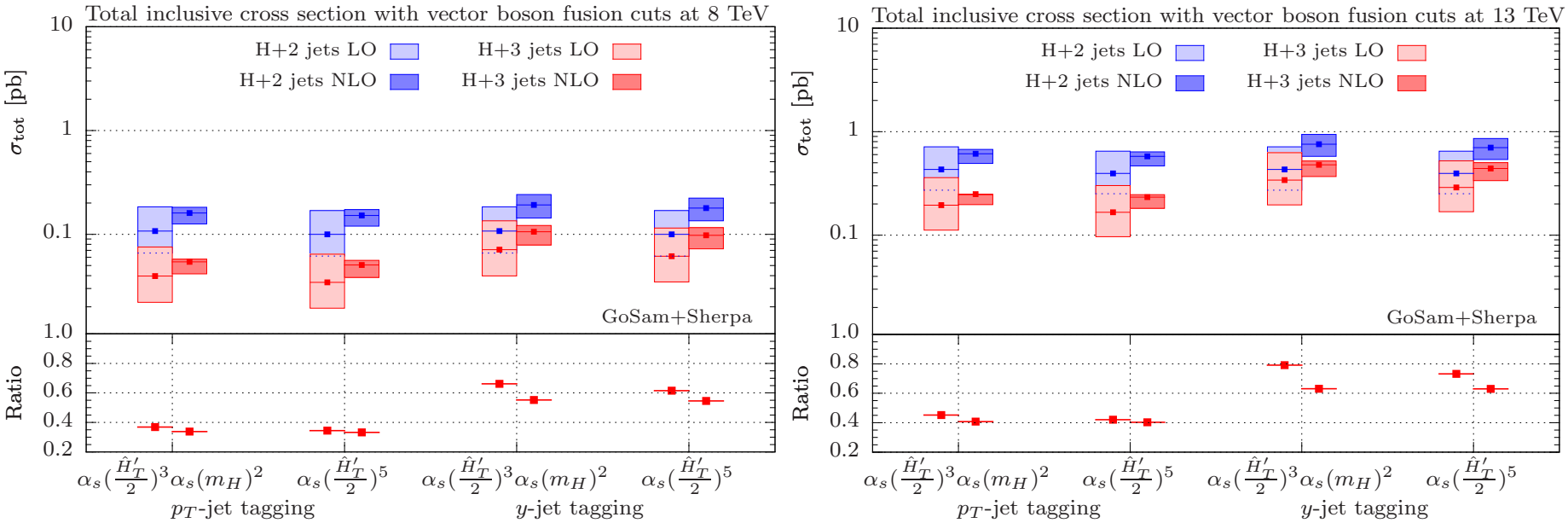
- **Example: Higgs pT**
  Plots normalized to the H+1 inclusive result (i.e. full NLO including possibility of second jet)

- Jet multiplicity has considerable impact on distribution.
  At ~120 GeV second jet contribution more important than first jet,
  at ~200 third jet more important than first.



Vector-Boson-Fusion cuts

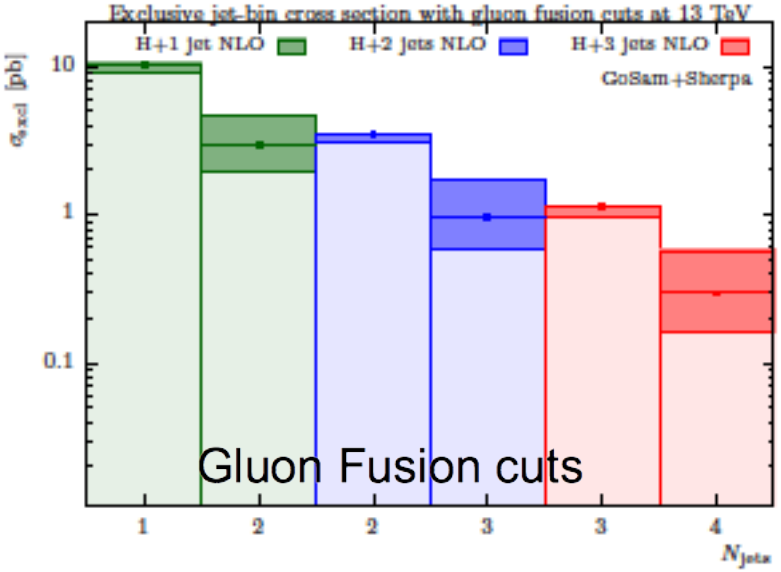
- Effects of **scale choice**, **energy** and **tagging selection**

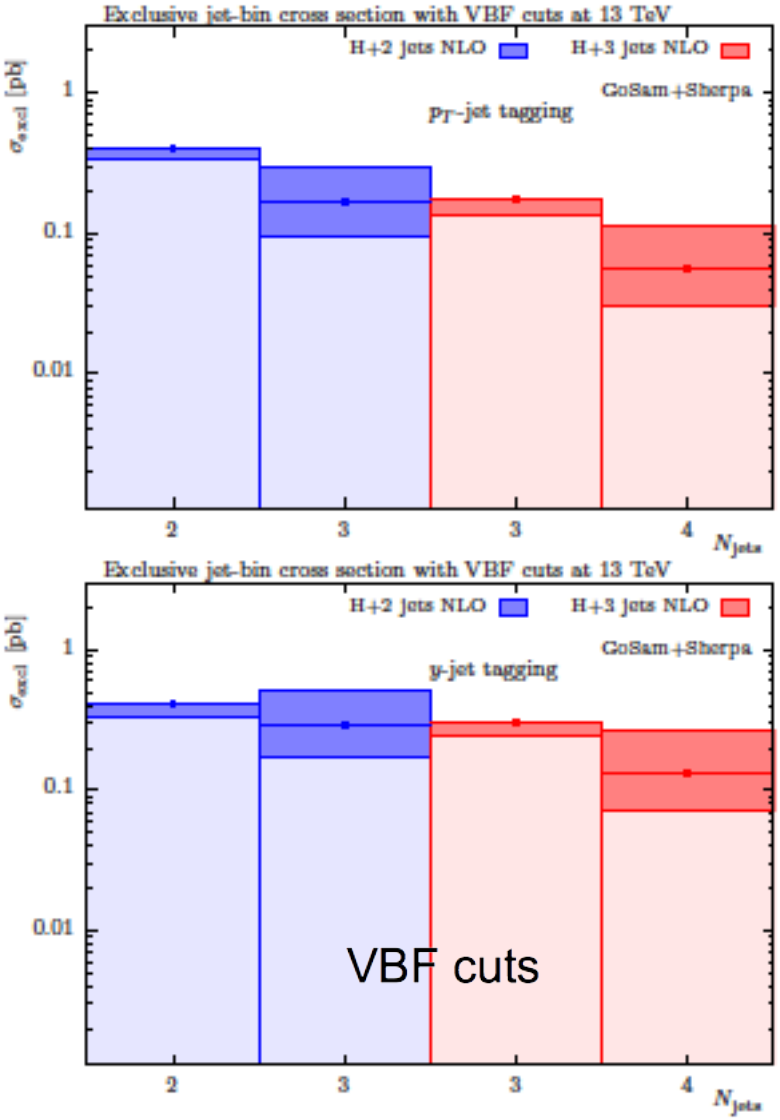


- Ratios slightly enhanced compared to GF cuts
- H+3 / H+2 ratio still very similar for both LO and NLO for pT- tagging
- y-tagging increases H+3 contribution

Exclusive n-jet cross section with VBF cuts

- VBF cuts lead to relative enhancement of real emission jet
- Large fraction of cross section only LO accuracy
- Jet-veto reintroduces theoretical uncertainty





Conclusions and Outlook

- GoSam: Automated calculation of generic one-loop amplitudes within and beyond SM.
- H+jet: Sizeable NLO corrections for up to three jets
- Besides phenomenology for H+3 investigate influence of jet-multiplicity and gluon fusion contribution after applying VBF cuts.
- Open questions / Improvements / To do:
  - Inclusion of parton shower
  - Jet merging
  - Impact of mass effects (finite top-mass)

BACKUP SLIDES

Previous calculations

Higgs +2,3 jets with GoSam: [vDeurzen et al. '13][Cullen et al. '13]

Important developments / prerequisites:

- Inclusion of effective **gluon-Higgs** coupling
- **Higher rank integrals** r >= N +1: $I_N^{n,\mu_1\dots\mu_r}(S) = \int \mathrm{d}^n k \frac{k^{\mu_1}\dots k^{\mu_r}}{\prod_{i=1}^{N}\left((k+r_i)^2 - m_i^2 + i\delta\right)}$

  Extended versions of **Samurai** [Mastrolia,Ossola,Reiter,Tramontano '10] [van Deurzen et al. '12] and **Golem95** [Binoth et al.][Guillet,Heinrich,vSoden-Fraunhofen '13]
- **Improvements in reduction**: Extract coefficients of the residues of a loop integral by performing a Laurent expansion of the integrand[Mastrolia,Mirabella,Peraro '12]

  → **Ninja** [vDeurzen,Luisoni,Mastrolia,Mirabella, Ossola,Peraro '13] [Peraro '14]

Impact of jet multiplicities on observables

- Azimuthal separation between **Higgs** and **leading jet:**

1-jet: NLO accuracy only at

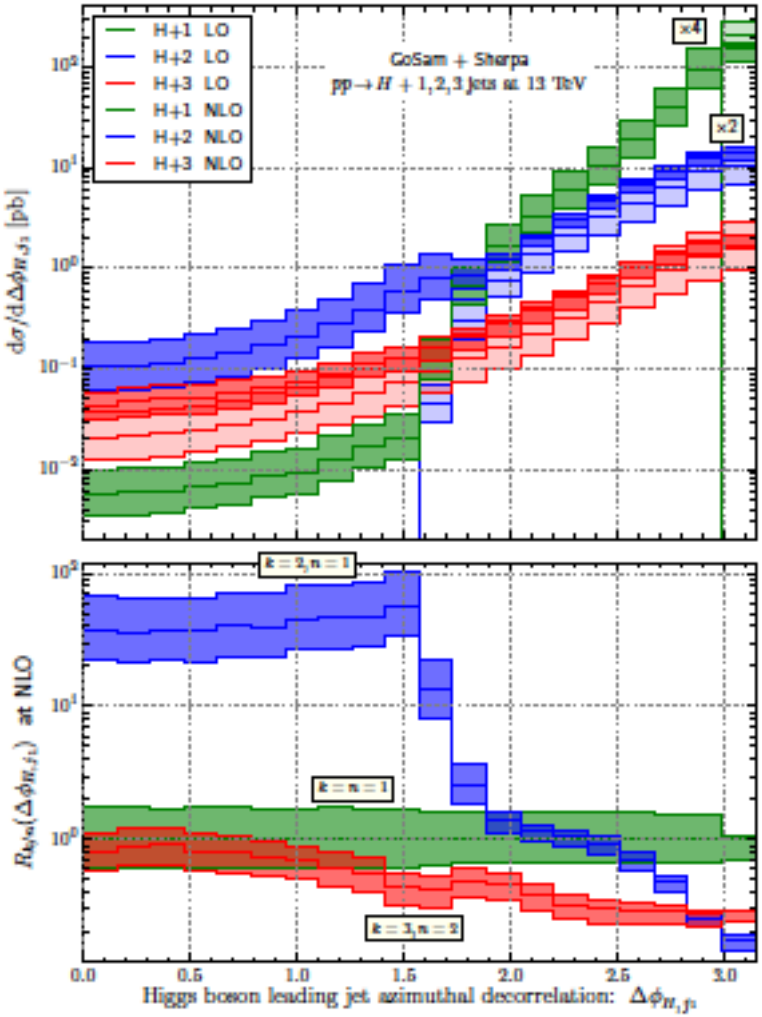
$$\Delta\phi = \pi$$

2-jet: NLO accuracy only at

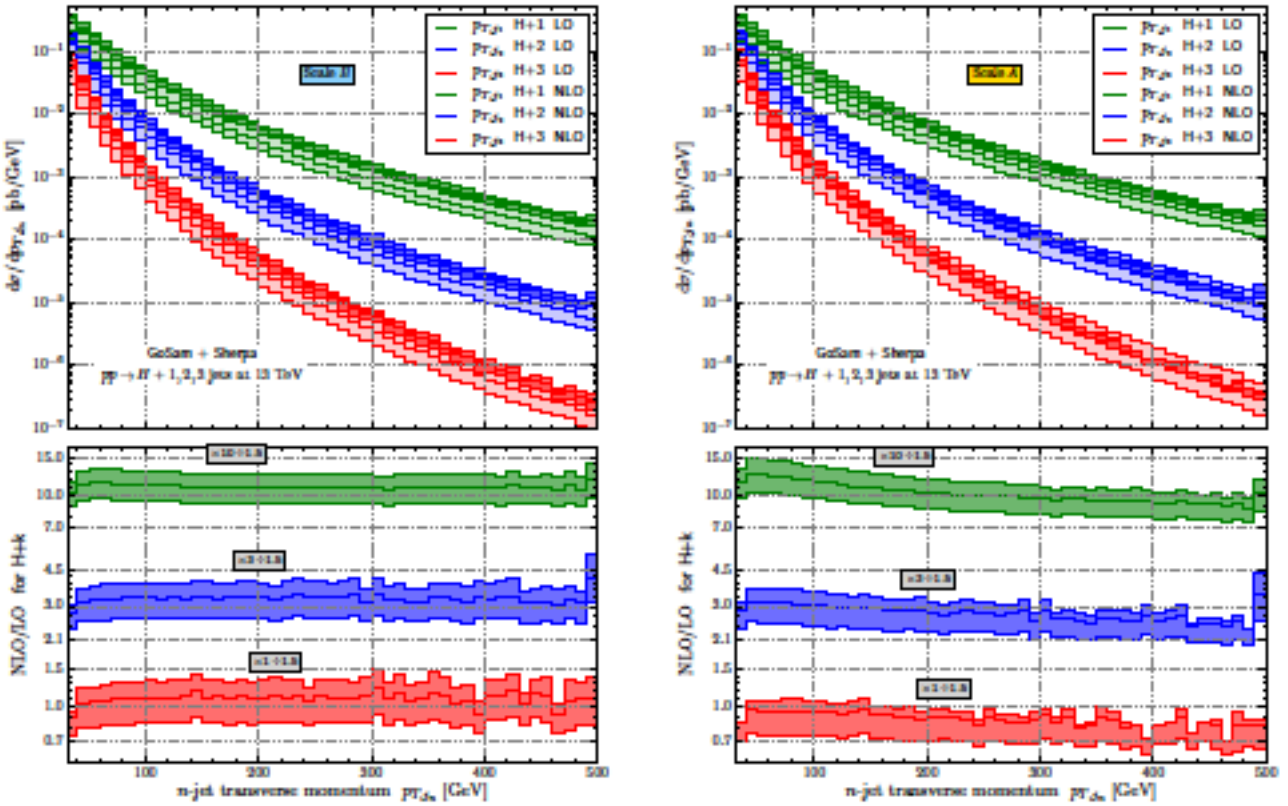
$$\frac{\pi}{2} \leq \Delta\phi \leq \pi$$

3-jet: NLO accuracy in full range

$$0 \leq \Delta\phi \leq \pi$$



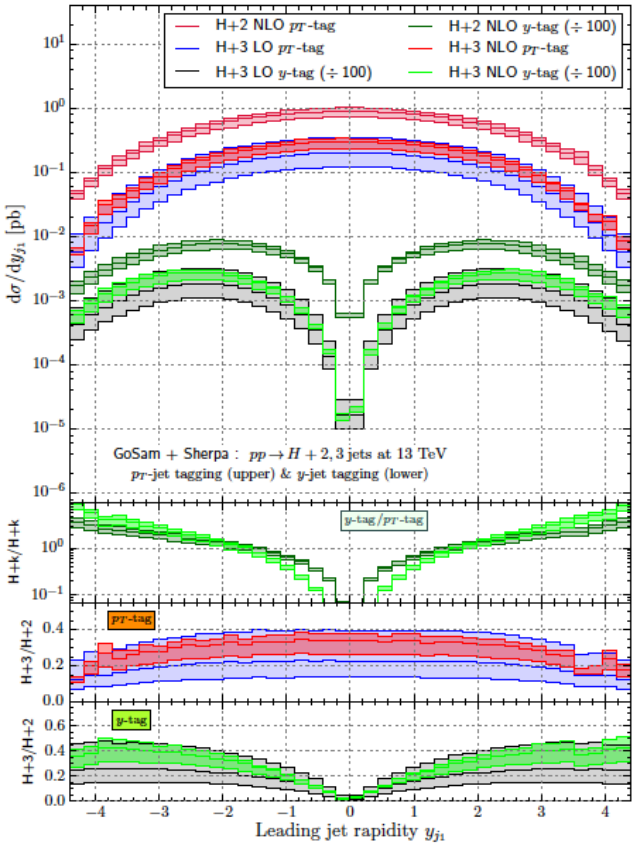
Scale choices II

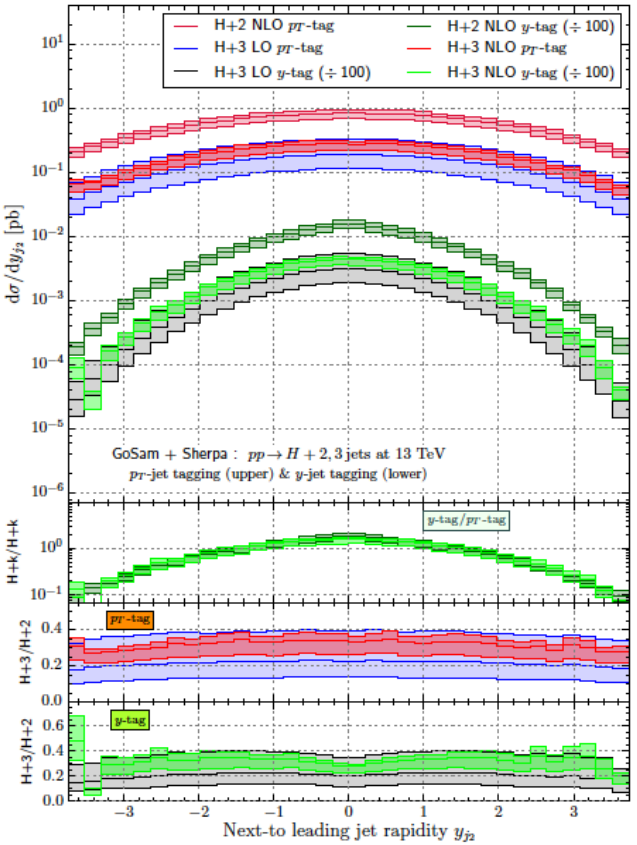


- K-Factor of **wimpiest** jet is flat only for dynamical scale **B**
  → In agreement with observations from W/Z + jets

Tagging jet selection

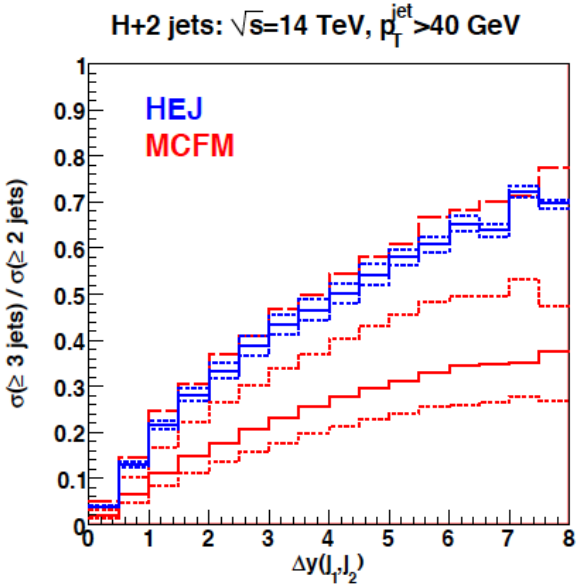
- Compare two different definitions of tagging jet selection:
  (1) : pT ordered (**pT-tagging**)
  (2) : Tagging jets defined as most forward/backward, order according to |y| (**y-tagging**).





Tagging jet selection

- **y-tagging** leads to non-flat K-factors for certain observables, e.g. rapidity-difference between tagging jets
- Discrepancy between **HEJ** [Andersen,Smillie '09, '11] and **MCFM** [Campbell,Ellis,Williams '10] can largely be resolved by adding NLO corrections



[Snowmass Working group report QCD: 1310.5189]