# Higgs + Multi-jets in Gluon Fusion


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**DESY**

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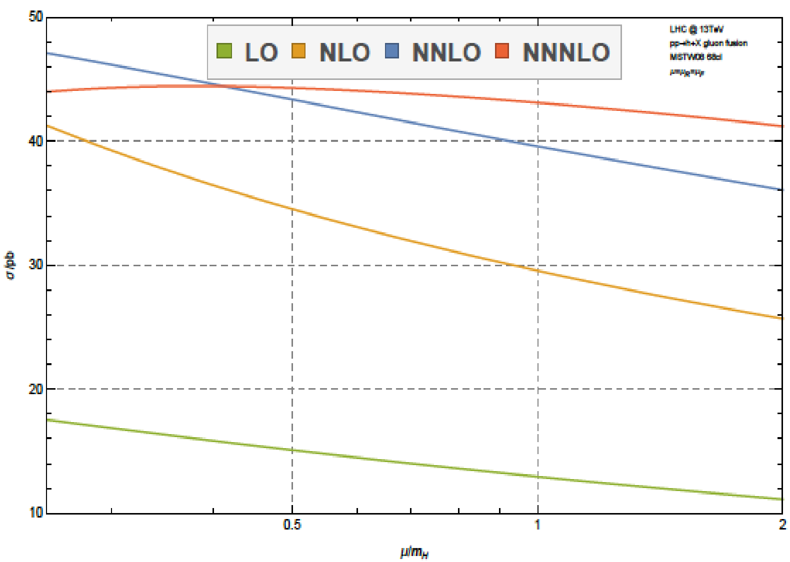
HELMHOLTZ
GEMEINSCHAFT

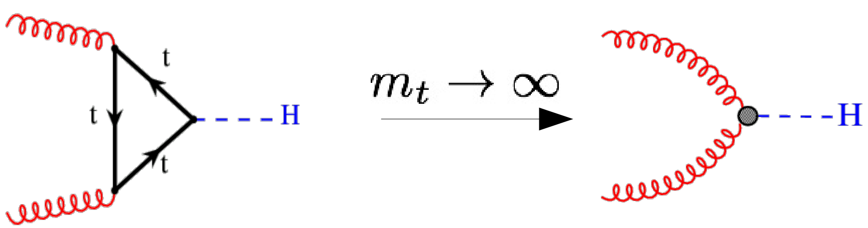
DESY

# Higher order corrections in Higgs physics

- Higher order corrections mandatory for reliable corrections
- **Example:** Higgs production in gluon fusion



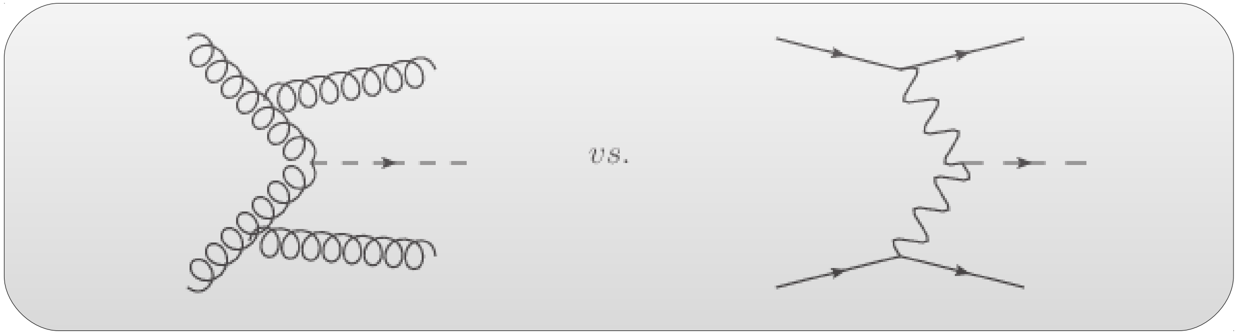

[Anastasiou,Duhr,Dulat,Herzog,Mistlberger '15]




- Large corrections from higher orders
- Strong dependence on ren./fac. Scale
- Unreliable estimation of theoretical uncertainties

**Also for H+jets considerable NLO corrections ~30%**

# 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 .
  $\rightarrow$ Inclusion of H+3 at NLO desirable
  $\rightarrow$ 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]

# 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: $I_N^{n,\mu_1\ldots\mu_r}(S) = \int d^n k \frac{k^{\mu_1}\ldots k^{\mu_r}}{\prod_{i=1}^N \left((k+r_i)^2 - m_i^2 + i\delta\right)}$

  Extended versions of **Samurai** [Mastrolia,Ossola,Reiter,Tramontano '10] [van Deurzen et al. '12] and **Golem95** [Binoth et al.][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]

- → **GoSam 2.0** [Cullen,vDeurzen,NG,Heinrich,Luisoni,Mastrolia,Mirabella,Ossola,Peraro, Schlenk,vSoden-Fraunhofen,Tramontano '13]

→ **Giovanni Ossola's talk**

# 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

## > Checks of the calculation:

- H+2 compared to MCFM (xsec and virtual amp, previous pub.)
- H+3 virtual amplitude : Ward Idendities (previous pub.)
- **New:** Effective Higgs-gluon vertex in Comix
  → Compare tree-level xsec between Comix and Amegic
  → Compare real emission xsec between Comix and previous calculation (**MadGraph/MadDipole/MadEvent**)
  → **Excellent agreement !**

## > Basic Setup:

$$\text{anti-}k_T \quad R = 0.4$$

$$p_T > 30 \text{ GeV}, \quad |\eta| < 4.4$$

VBF:

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

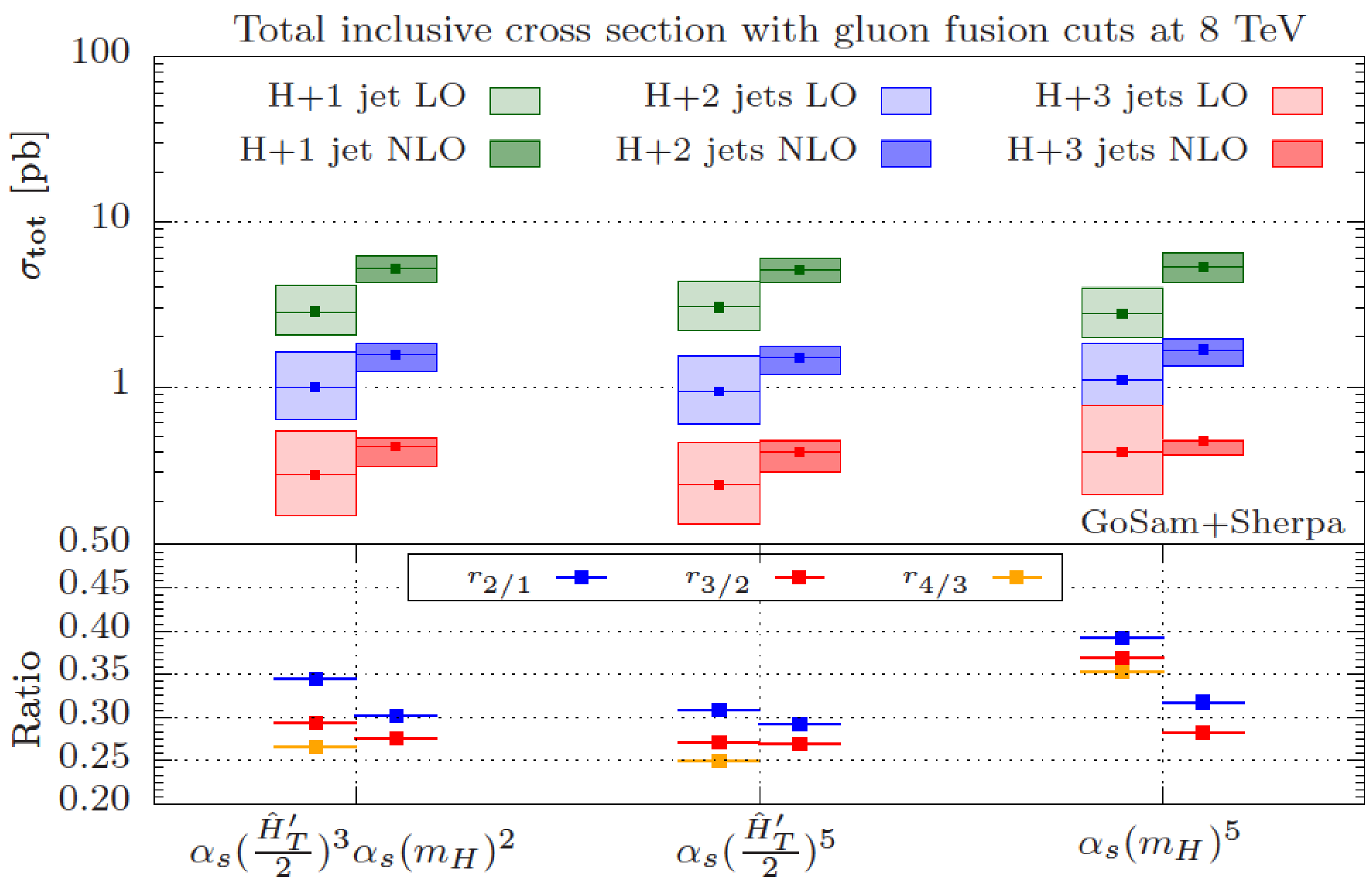
$$\mu_F = \mu_R = \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$$

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

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

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

> Total cross sections for three different scale choices

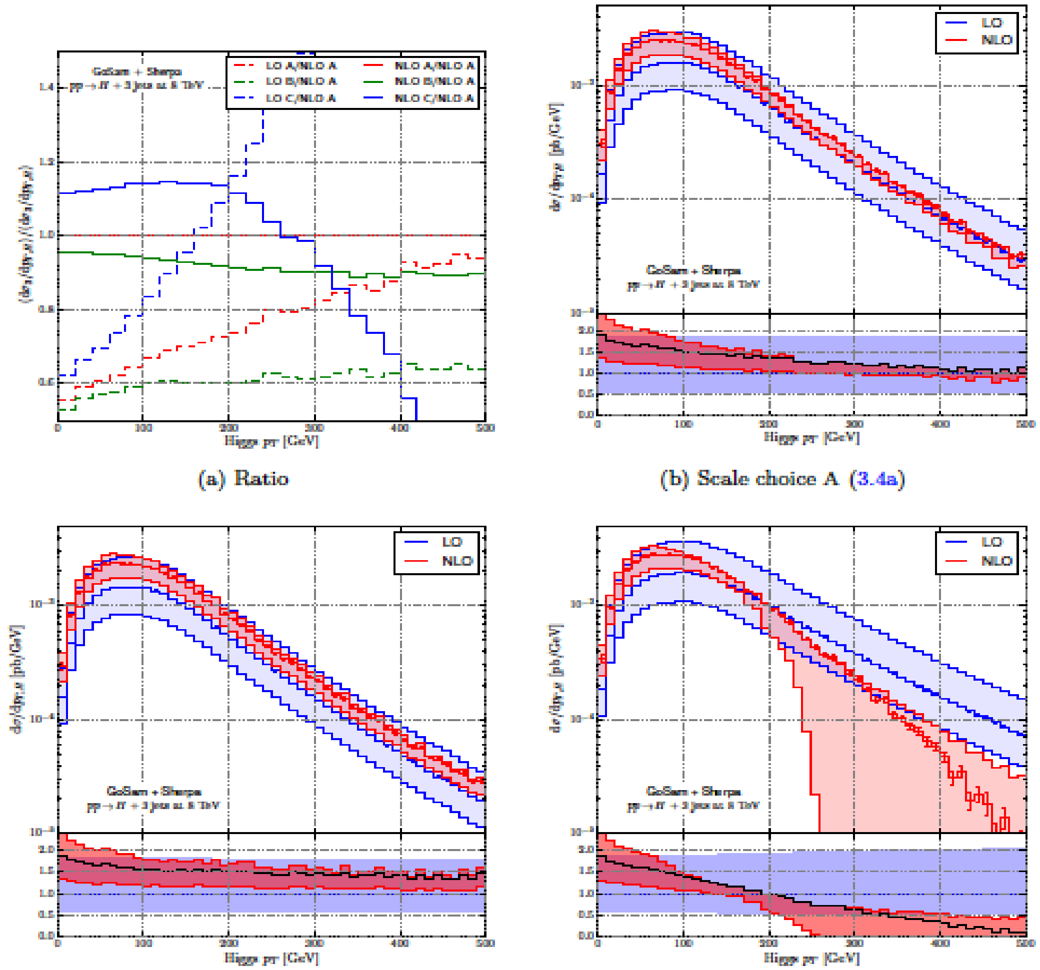



**A** **B** **C**

# 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**



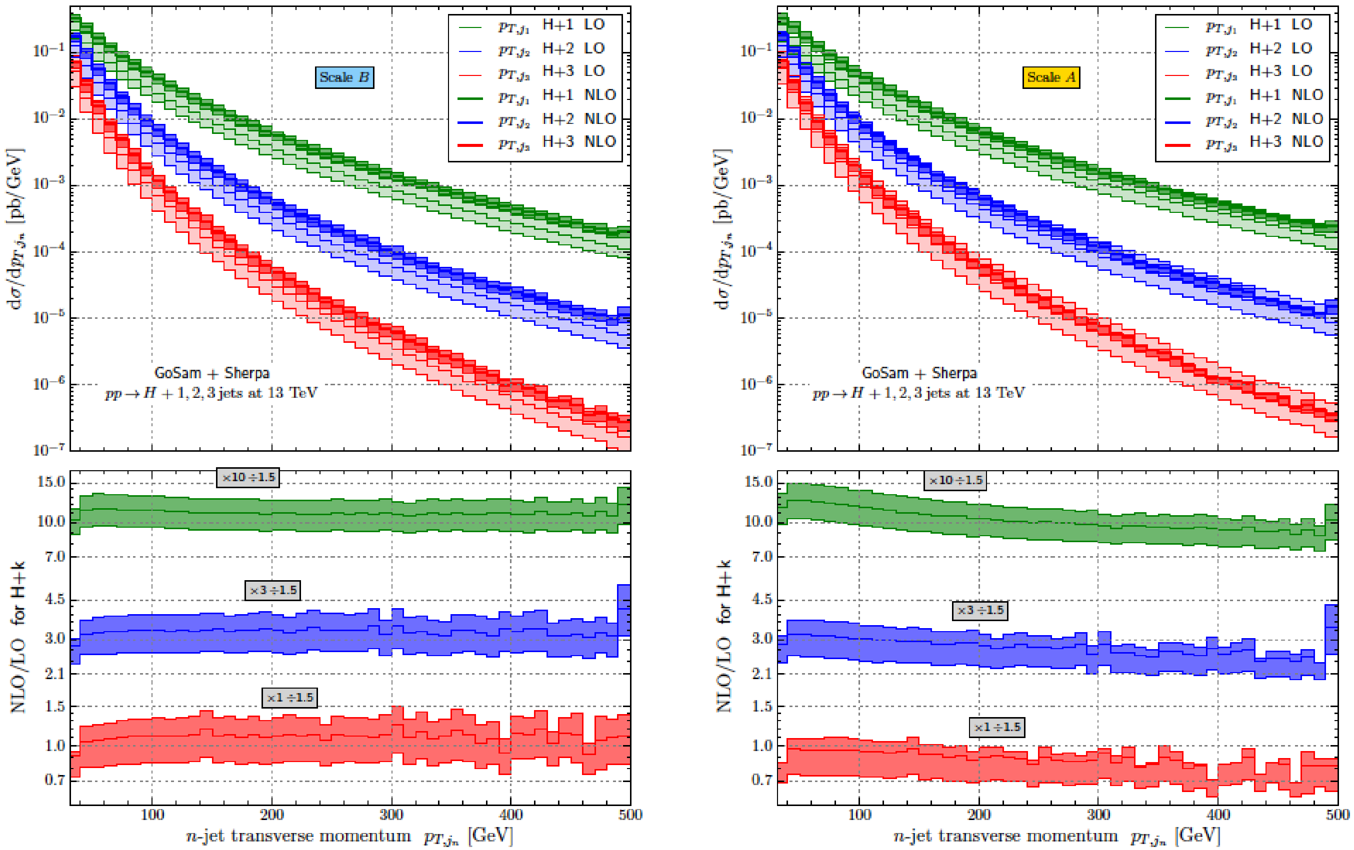

(a) Ratio

(b) Scale choice A (3.4a)

(c) Scale choice B (3.4b)

(d) Scale choice C (3.4c)

# Scale choices II



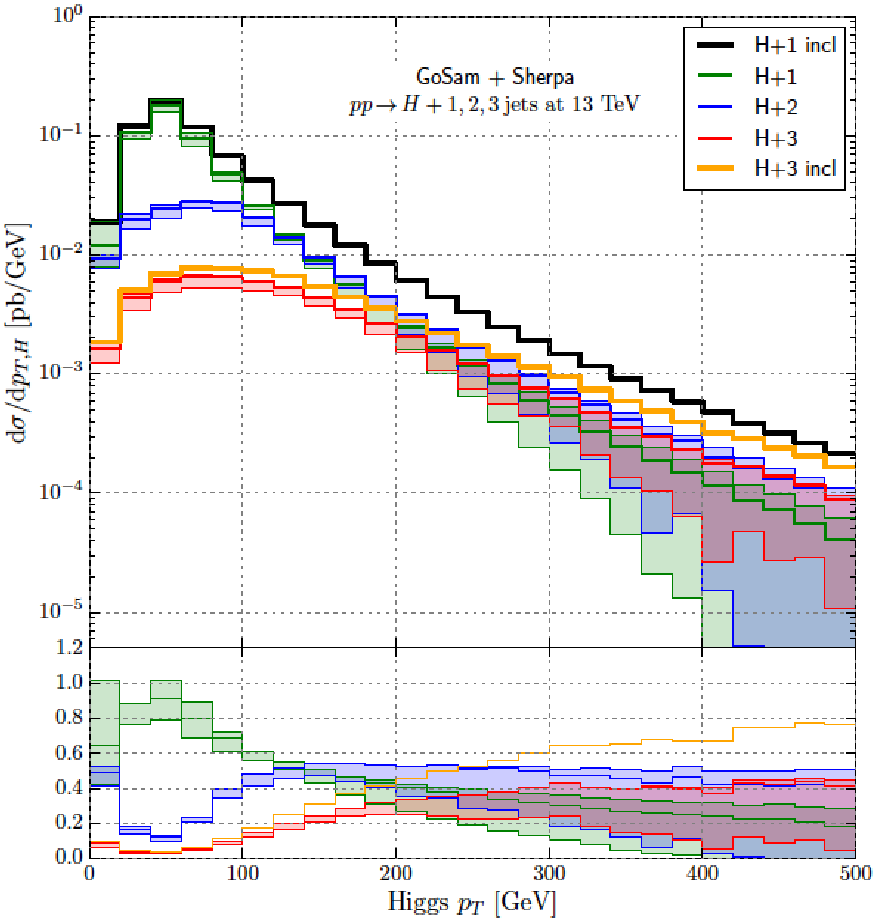

- K-Factor of **wimpiest** jet is flat only for dynamical scale **B**
  → In agreement with observations from W/Z + jets

# 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.



# Impact of jet multiplicities on observables

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

**1-jet:** NLO accuracy only at

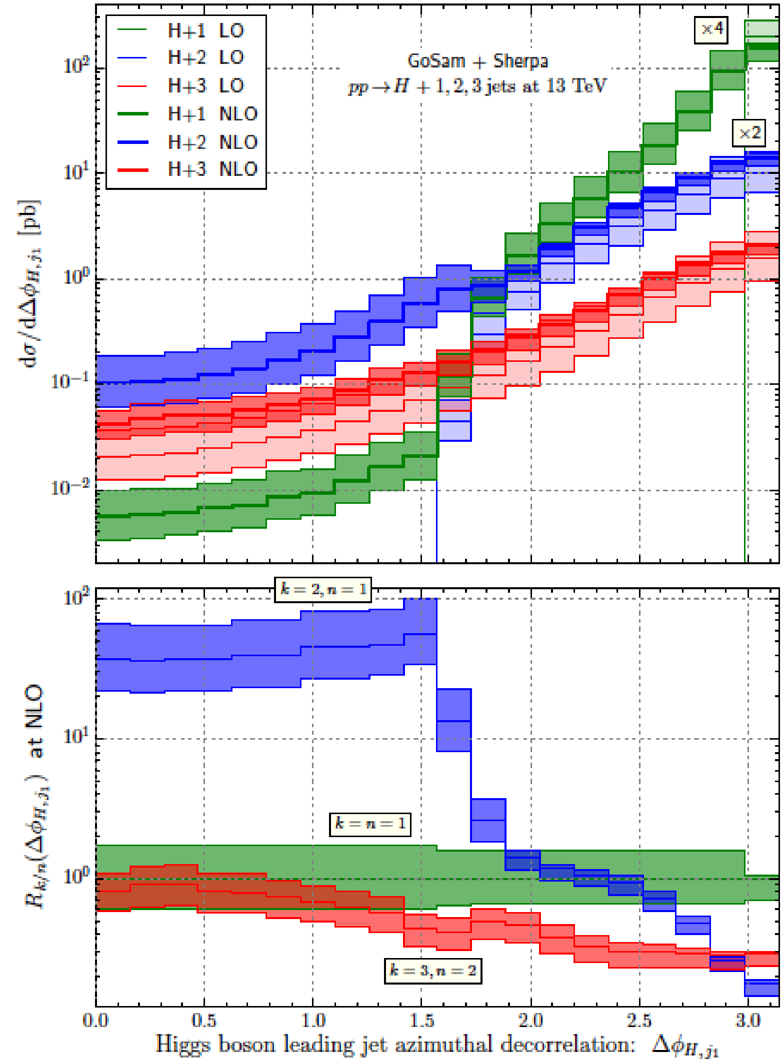
$$\Delta\phi = \pi$$

**2-jet:** NLO accuracy only at

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

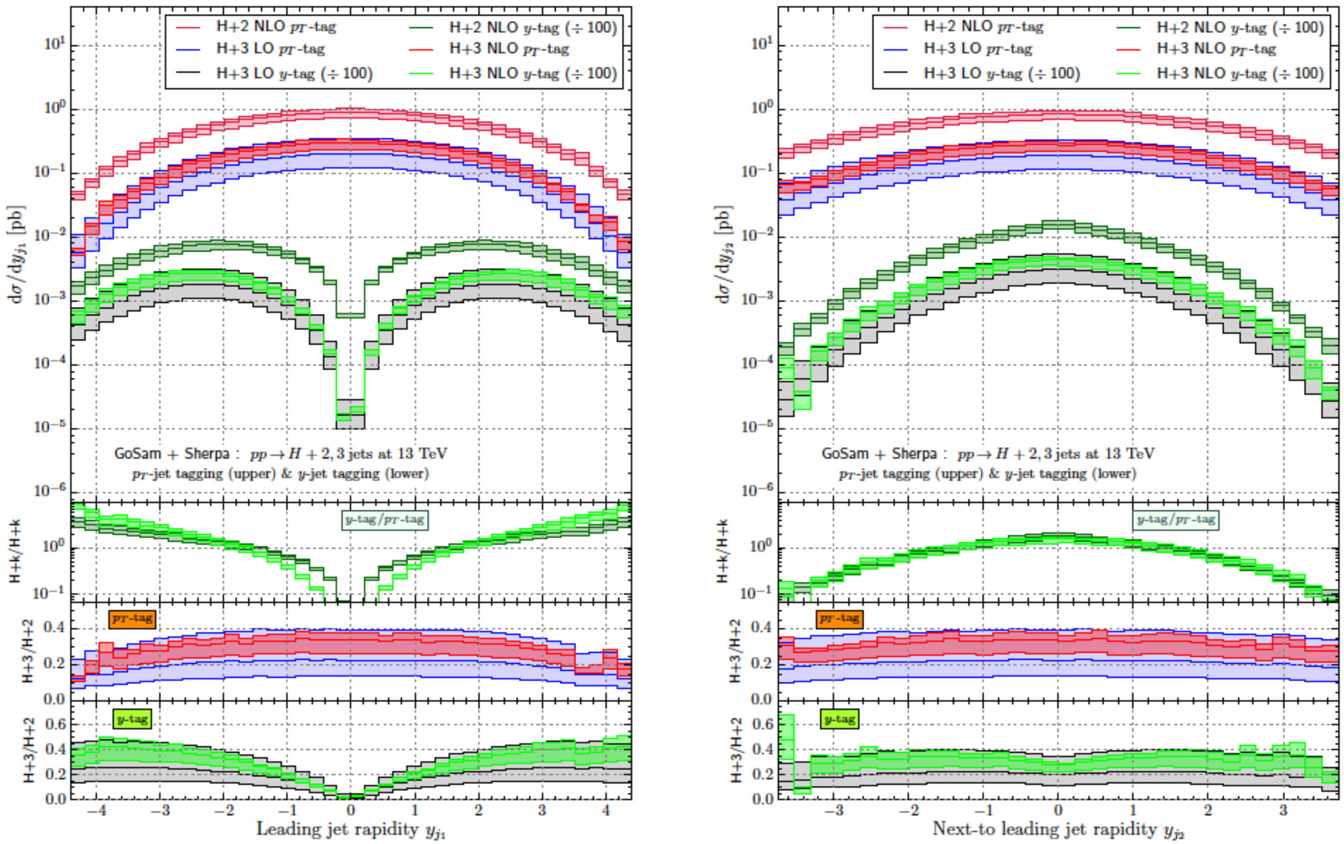
**3-jet:** NLO accuracy in full range

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



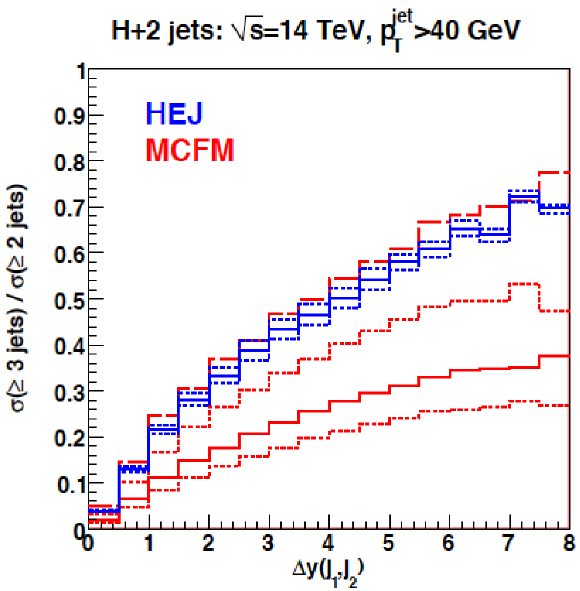
# Tagging jet selection

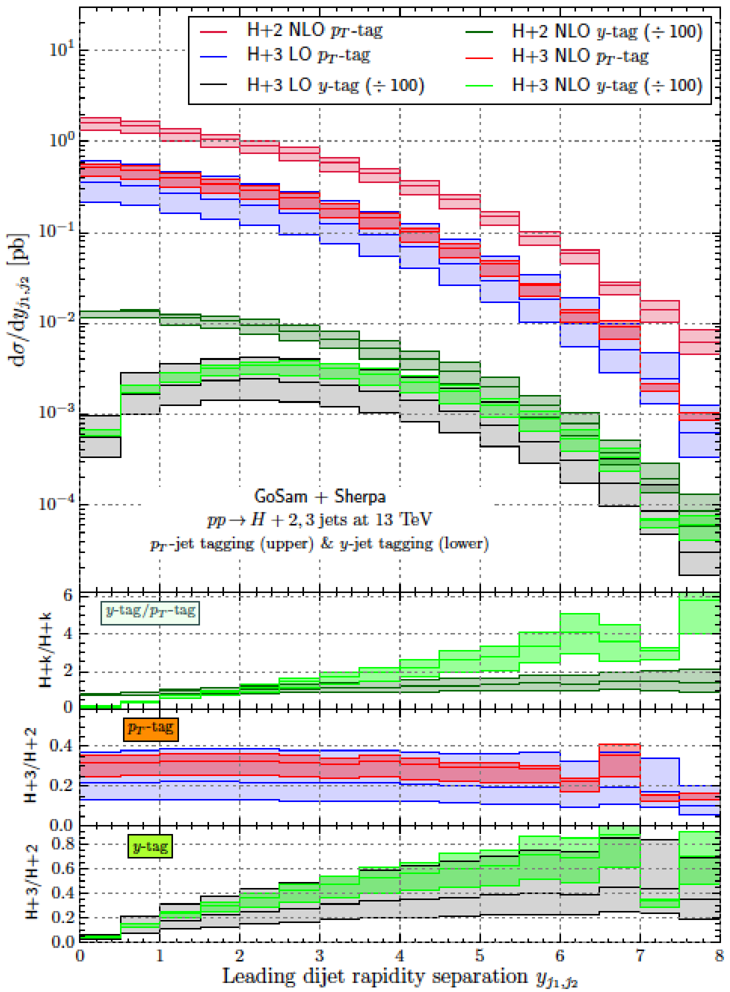
- Compare two different definitions of tagging jet selection:
  (1) : pT ordered (**pT-tagging**)
  (2) : Tagging jets defined as most forward/backward, order according to |y| (**y-tagging**).



# 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

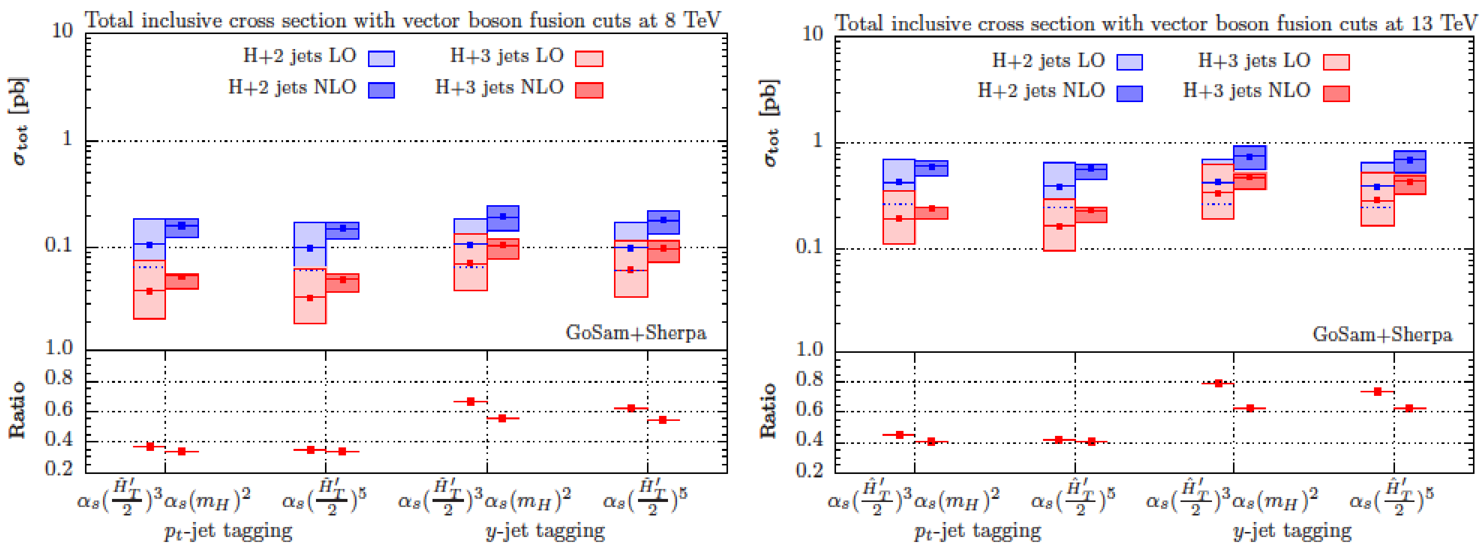



[Snowmass Working group report QCD: 1310.5189]

# Vector-Boson-Fusion cuts

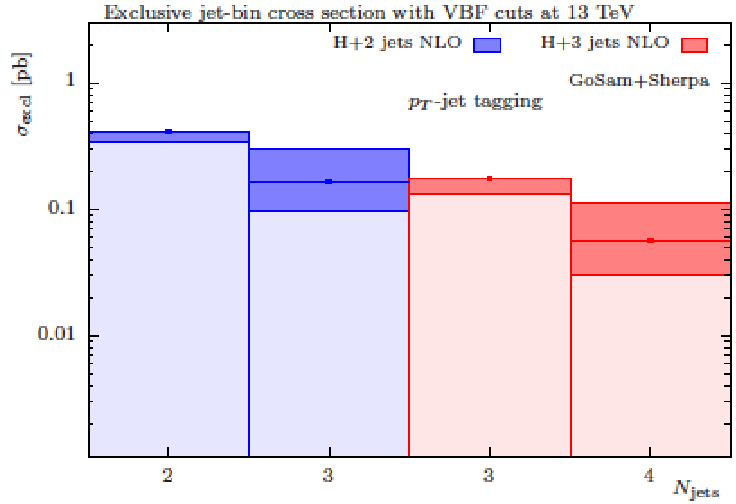
> Effects of **scale choice**, **energy** and **tagging selection**

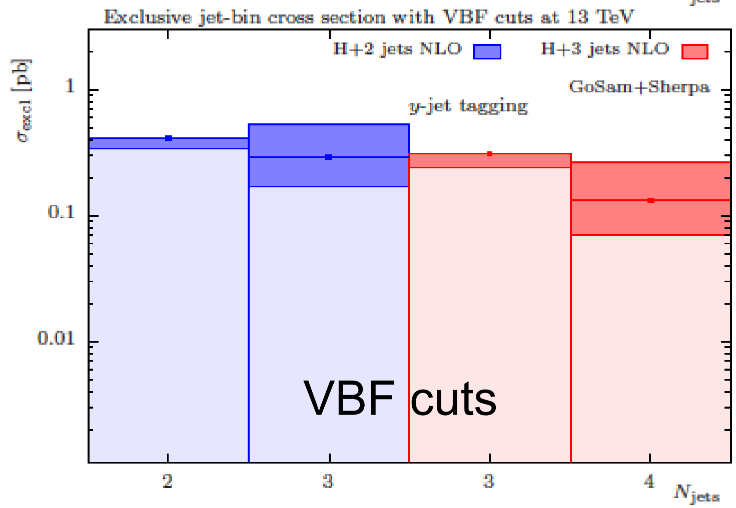


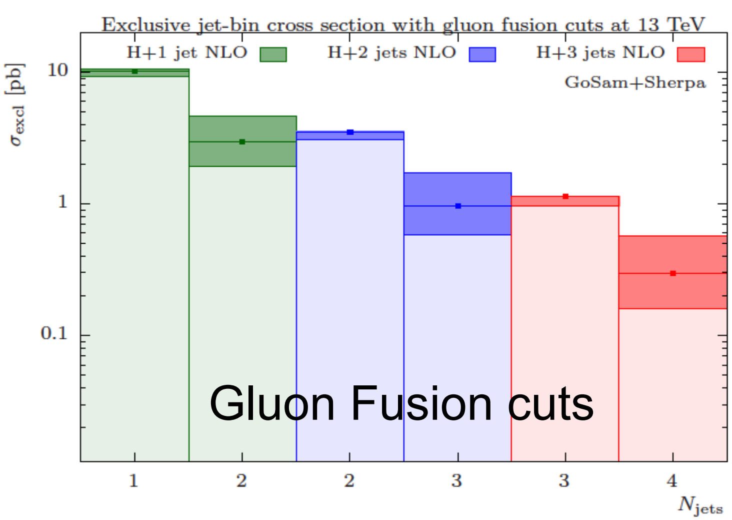

- Ratios slightly enhanced compared to GF cuts
- H+3 / H+2 ratio still very similar for both LO and NLO for pT- tagging
- y-tagging increases H+3 contribution

# 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
- H+3 NLO can be used to obtain exclusive H+2 result



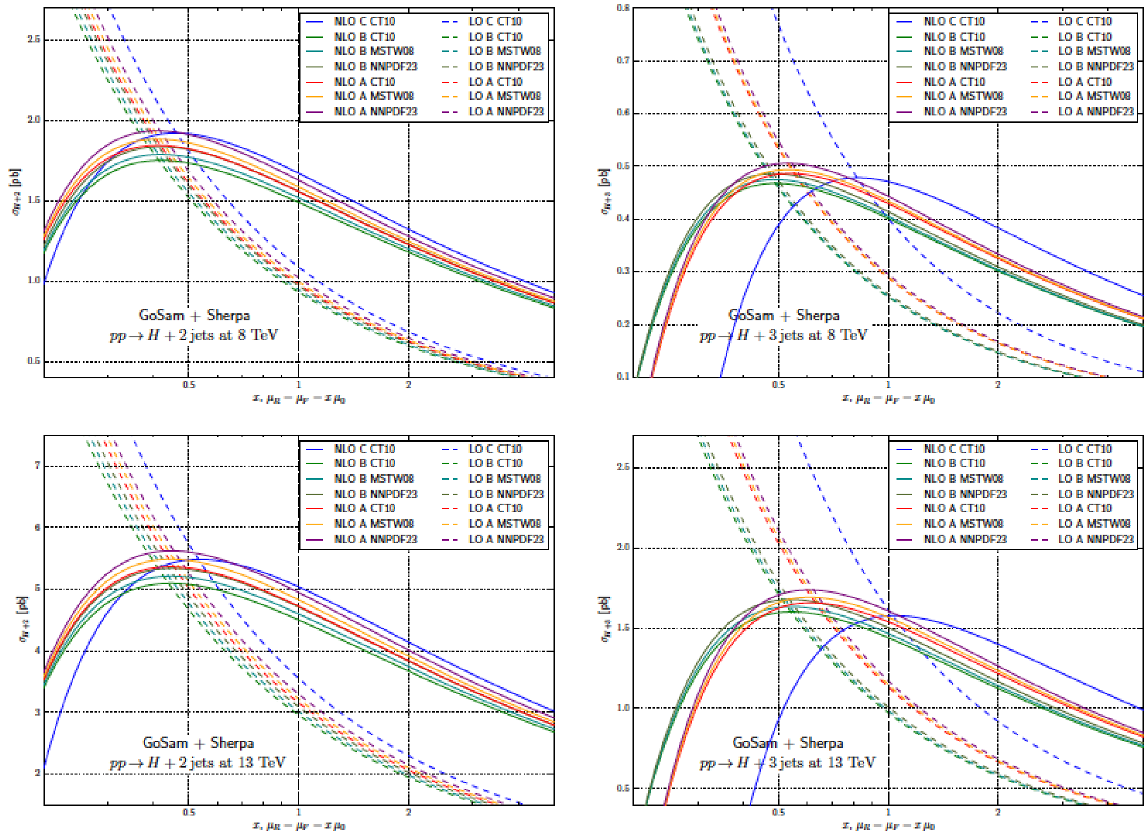
# Conclusions and Outlook

- Higgs plus jets in gluon fusion important for a better understanding of Higgs physics at the LHC
- 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

# Total cross sections and scale variations

> Total cross sections for H+2 and H+3



# VBF – Differential Distributions

> Azimuthal separation of the two tagging jets