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Higgs Production in Gluon Fusion in Association with Jets

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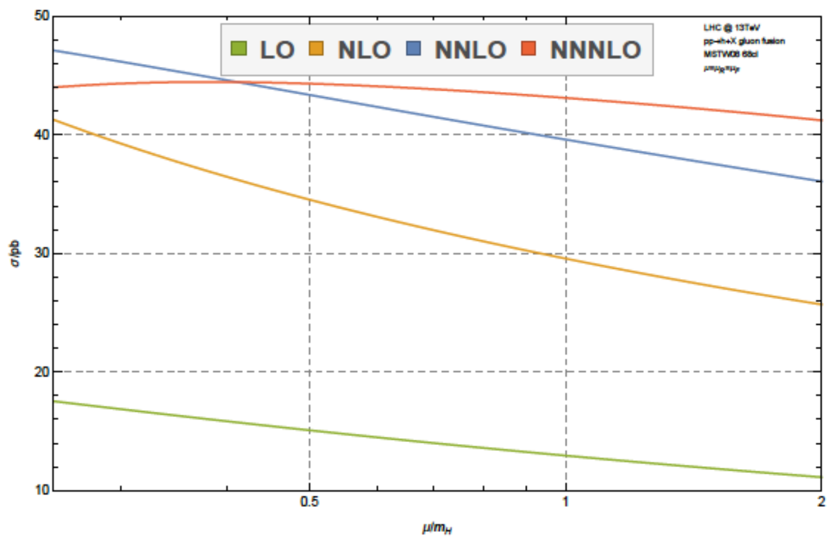
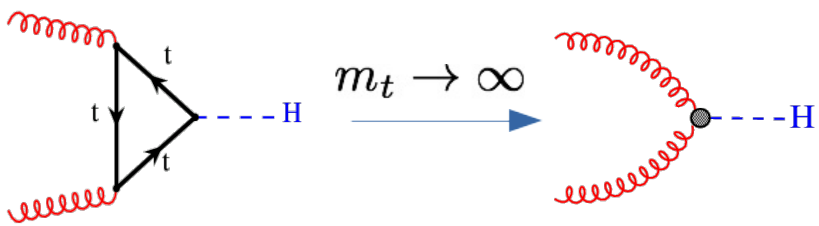
Higher order corrections in Higgs physics

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



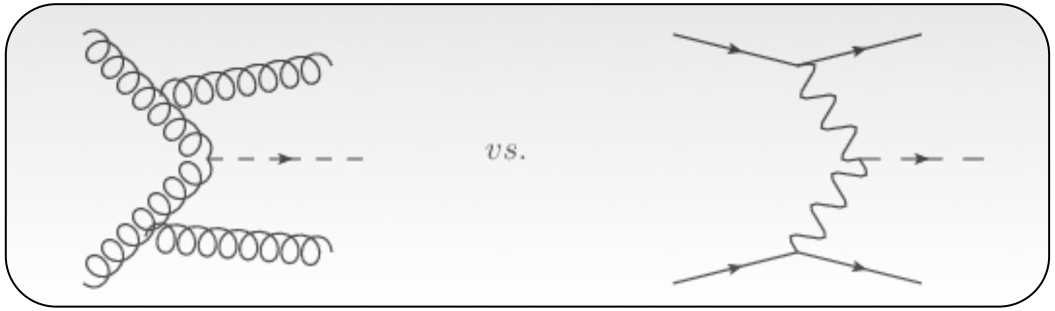
[Anastasiou,Duhr,Dulat,Herzog,Mistlberger '15]



- 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 .
  → 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]

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

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

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:

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

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

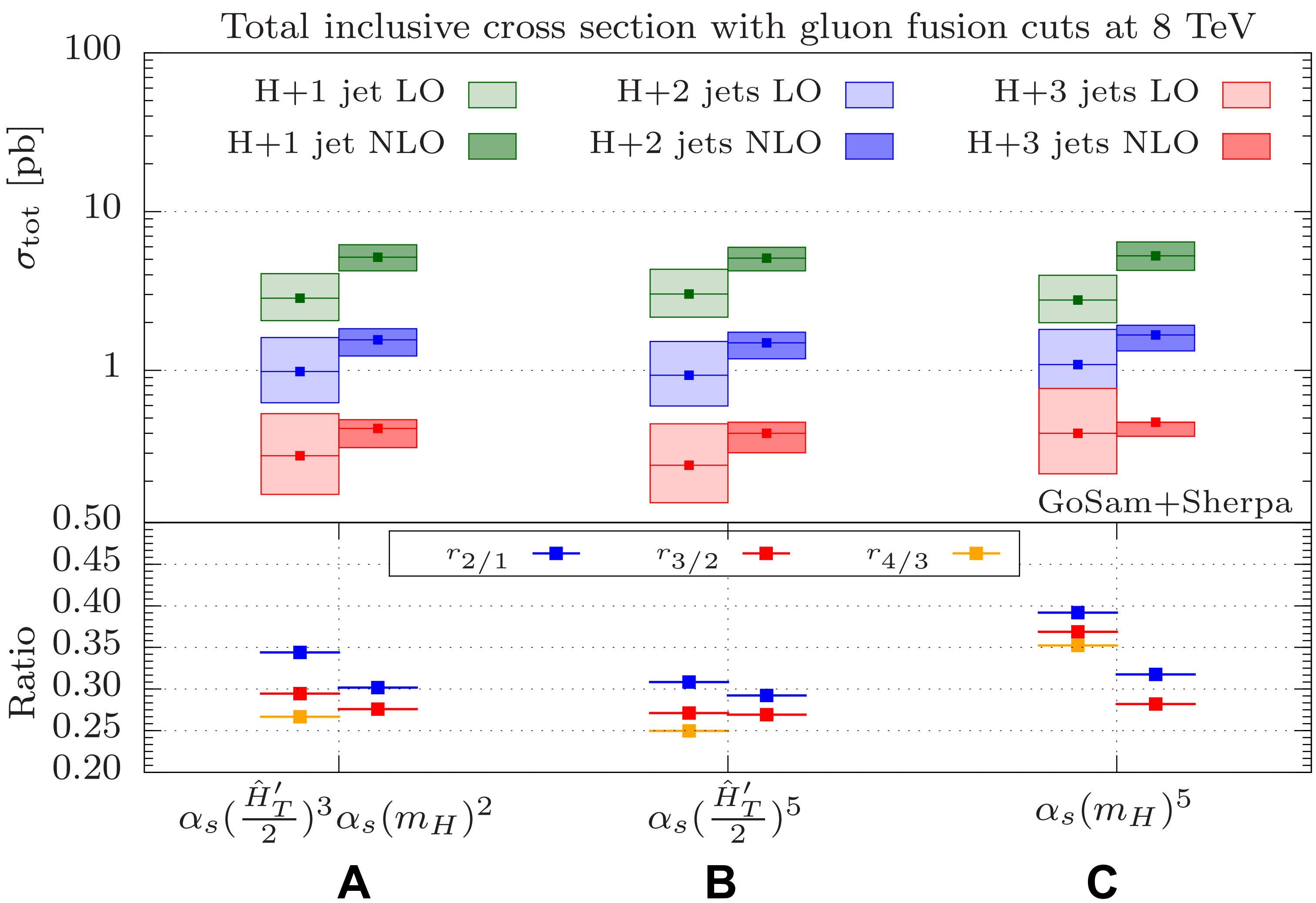
$$A: \quad \alpha_s\left(x \cdot \frac{\hat{H}'_T}{2}\right)^3 \alpha_s\left(x \cdot m_H\right)^2$$

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

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

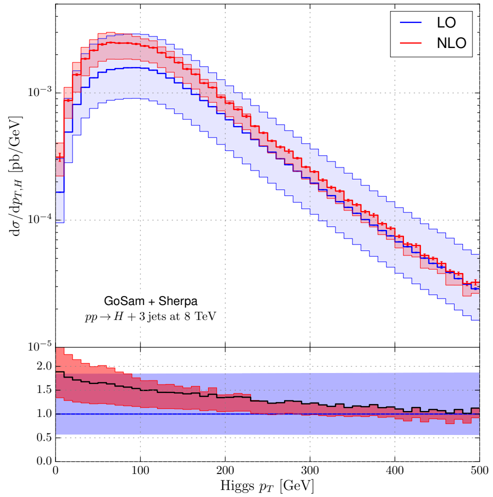
Scale choices

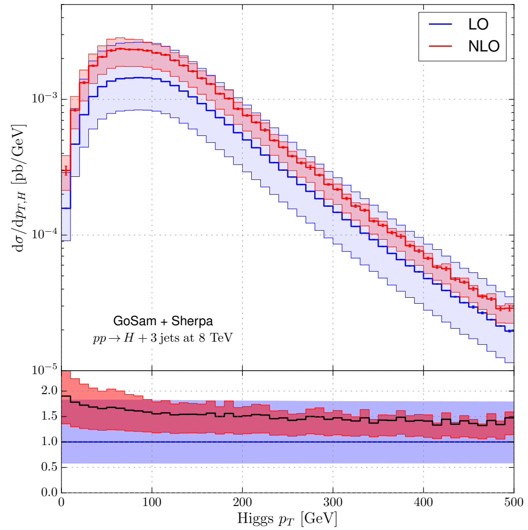
- Total cross sections for three different scale choices

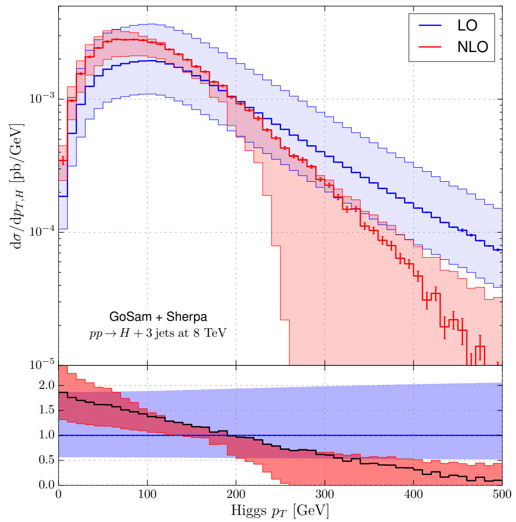


Scale choices

- 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







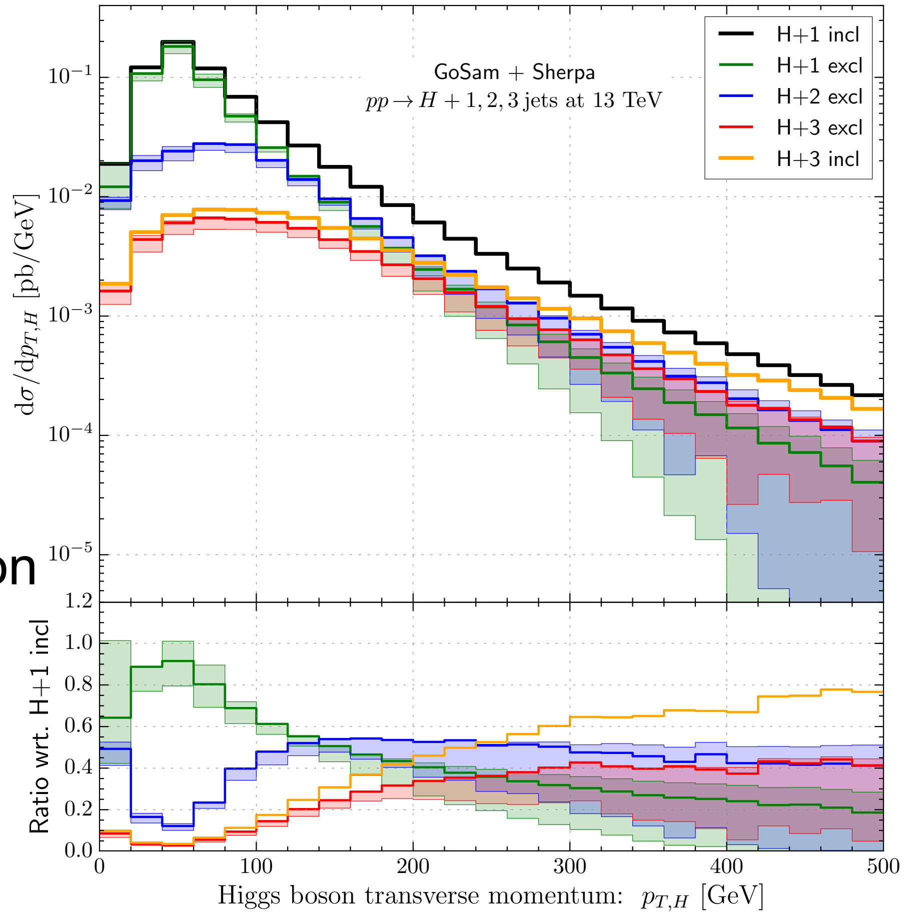
→ **Use scale B as default scale**

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.



Impact of jet multiplicities on observables

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

  1-jet: NLO accuracy only at

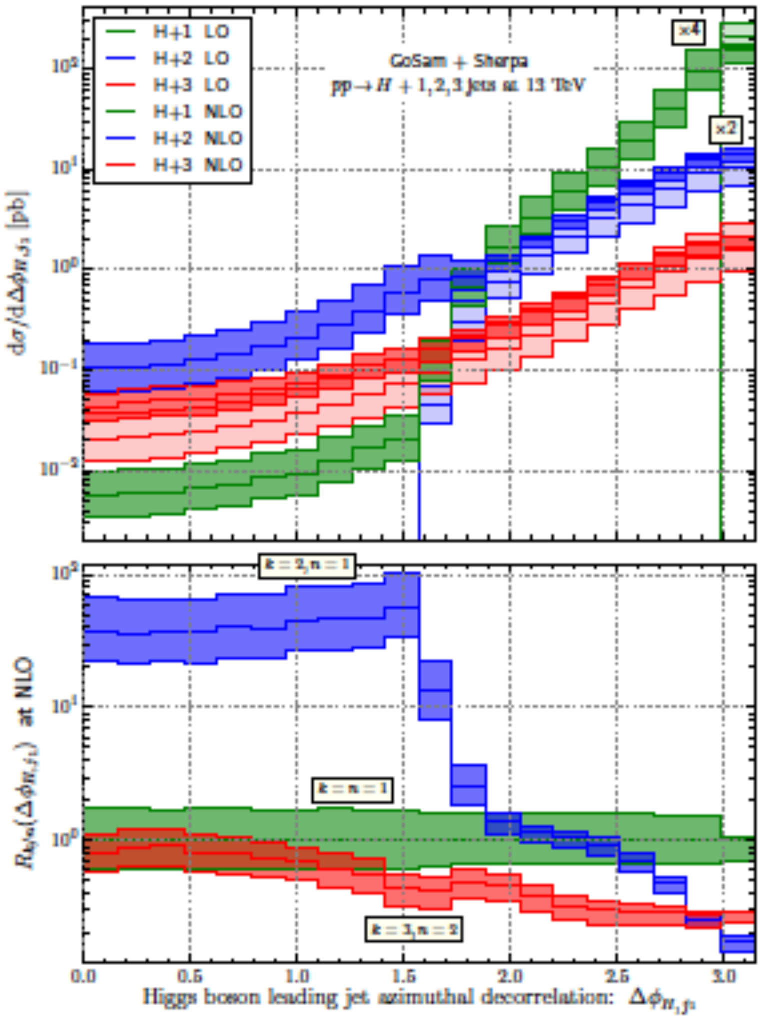
  $$\Delta\phi = \pi$$

  2-jet: NLO accuracy only at

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

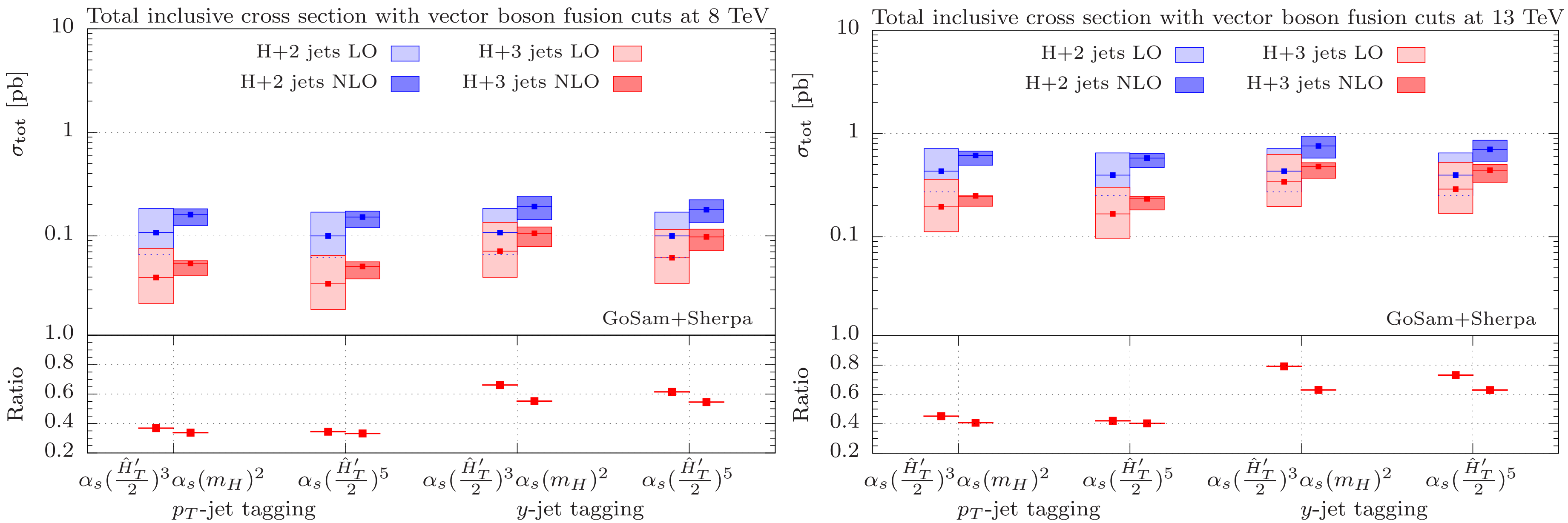
  3-jet: NLO accuracy in full range

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



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

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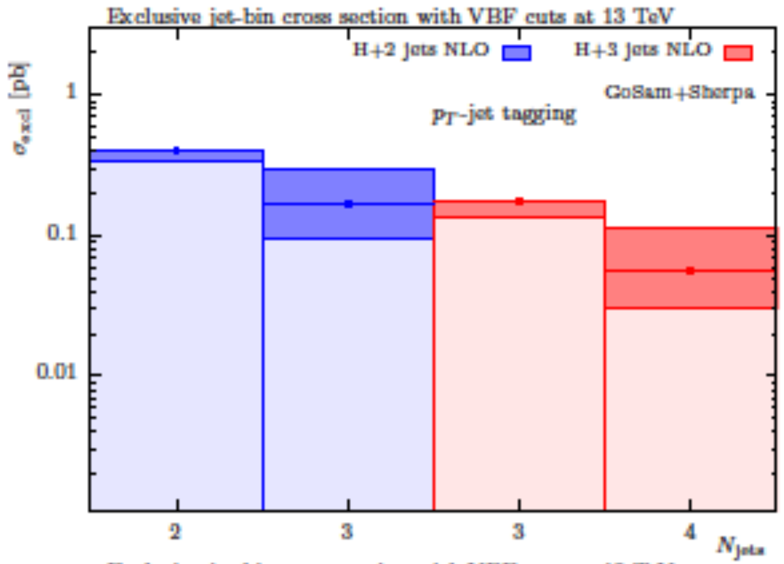
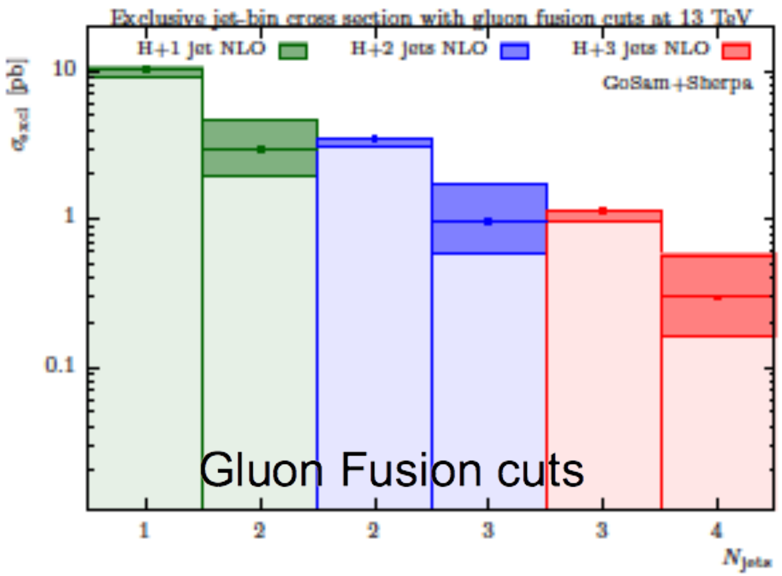
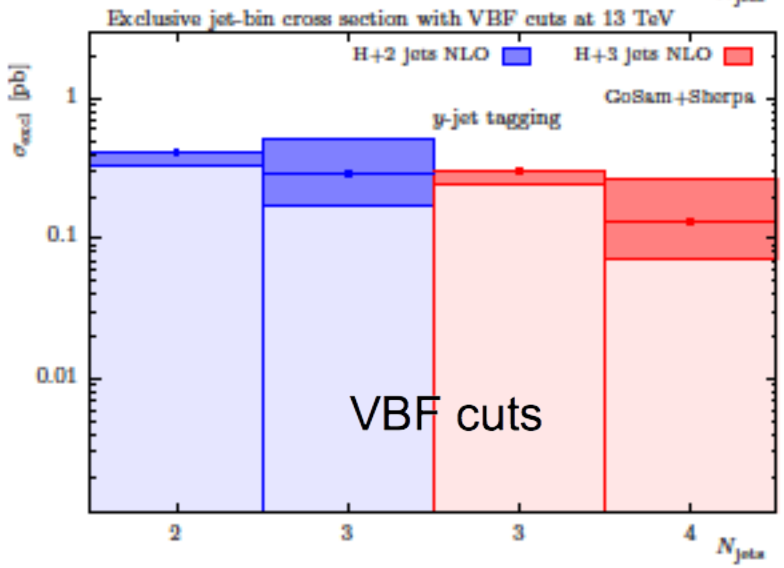
Exclusive n-jet cross section with VBF cuts

- 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

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

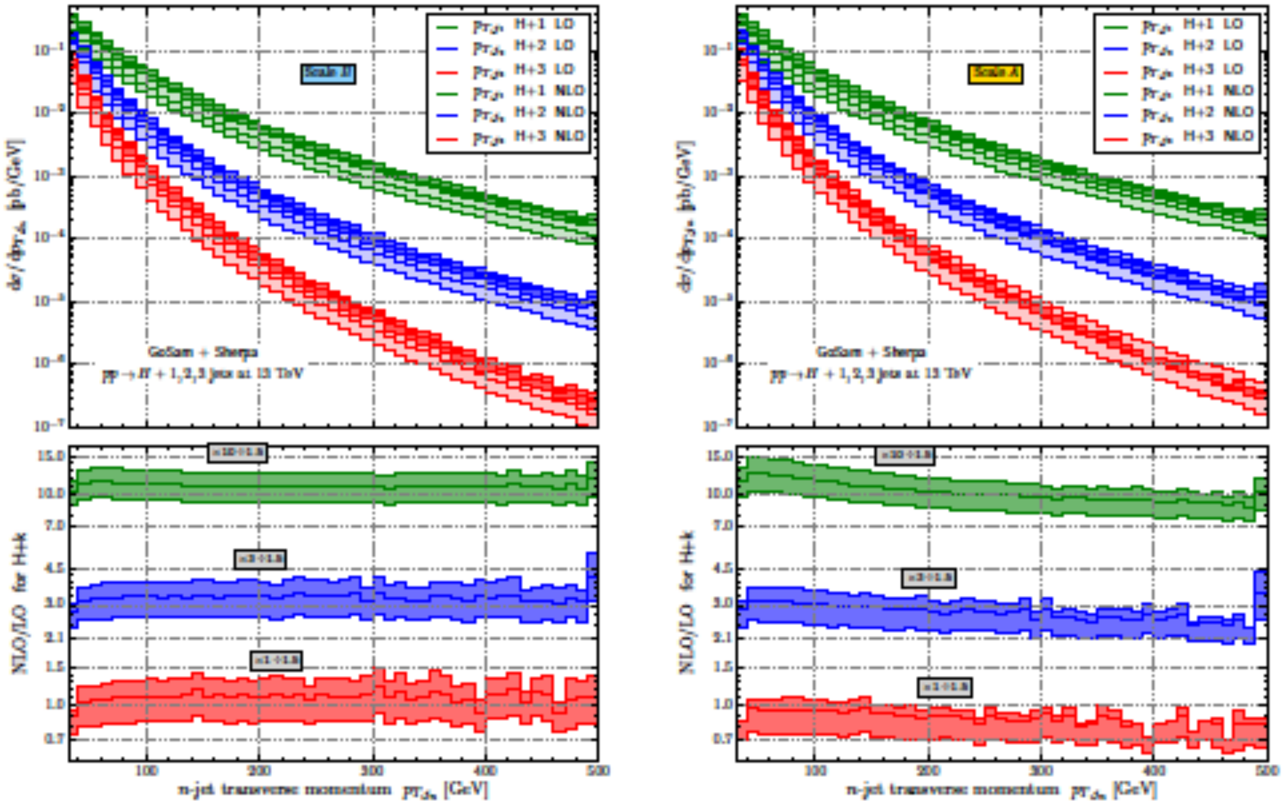
- Sizeable NLO corrections for up to three jets

- 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

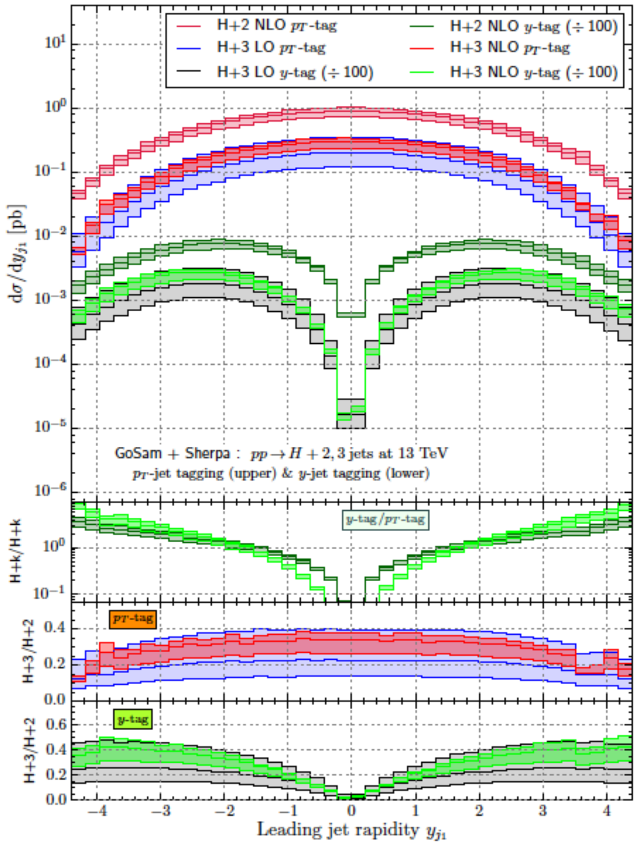
Scale choices II

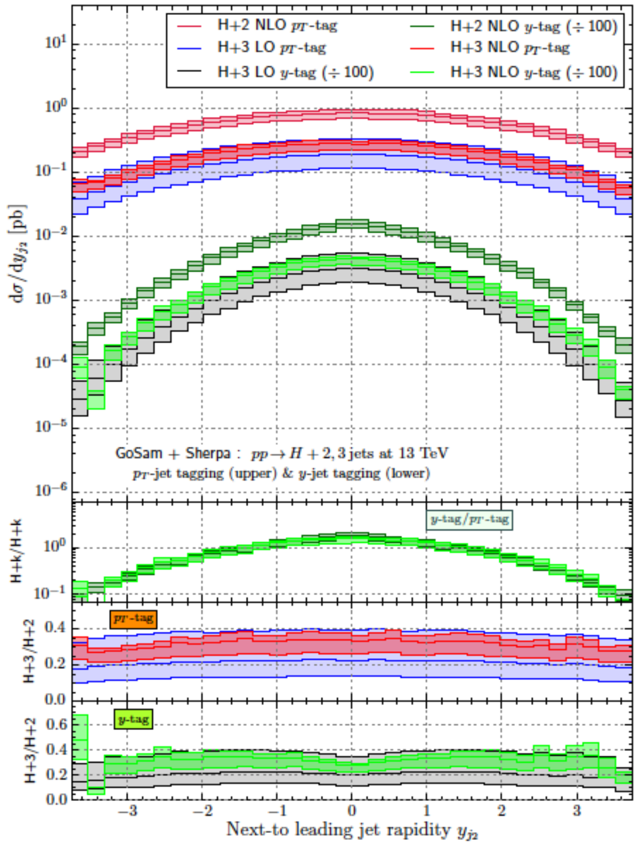


- K-Factor of **wimpiest** jet is flat only for dynamical scale **B**
  → In agreement with observations from W/Z + jets

Tagging jet selection

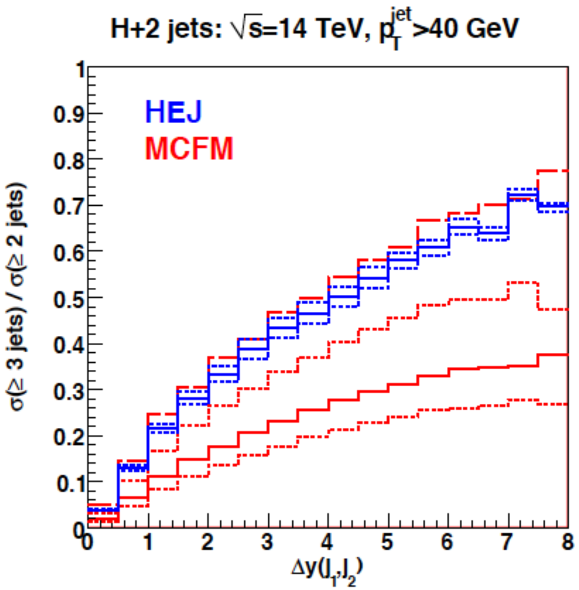
- Compare two different definitions of tagging jet selection:
  (1) :   pT ordered (**pT-tagging**)
  (2) : Tagging jets defined as most forward/backward, order according to |y| (**y-tagging**).





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]