Higgs + multi-jets at NLO

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DESY

In collaboration with
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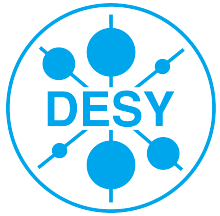
HELMHOLTZ GEMEINSCHAFT

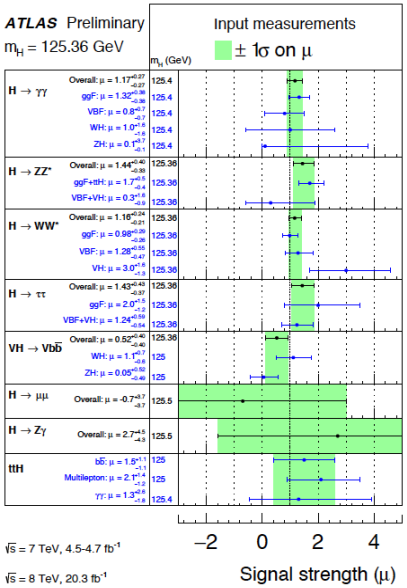


What have we learned about the Higgs so far ?

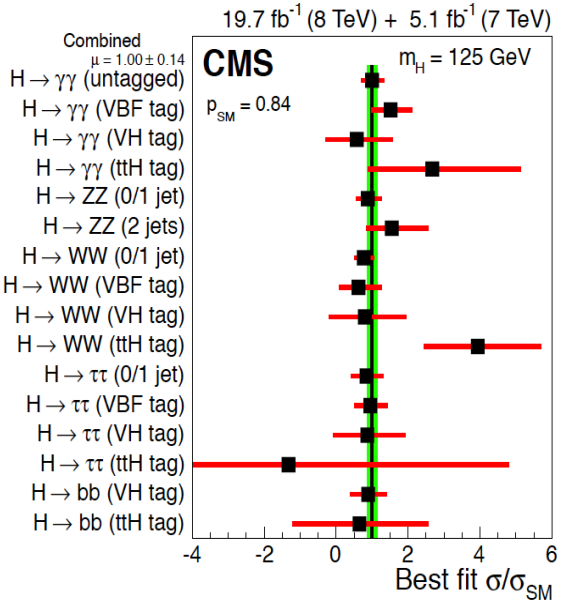
- Found a scalar boson at ~125 GeV !
- Seems to be in good agreement with SM predictions

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\text{observed}}}{(\sigma \cdot \mathrm{BR})_{\text{expected}}}$$

Data / Standard Model



[Atlas-Conf-2015-007]



[1412.8662]

- No signs of new physics!
- Standard Model contribution essential ingredient, conclusions only as good as experiment and theory.

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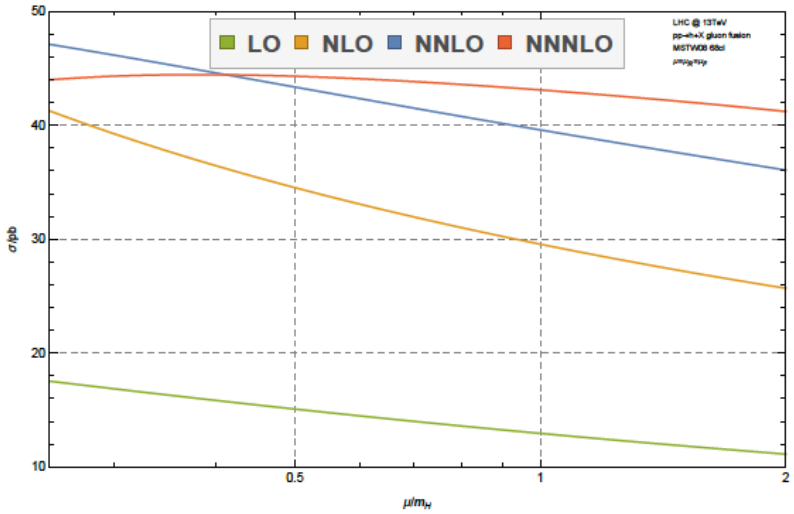
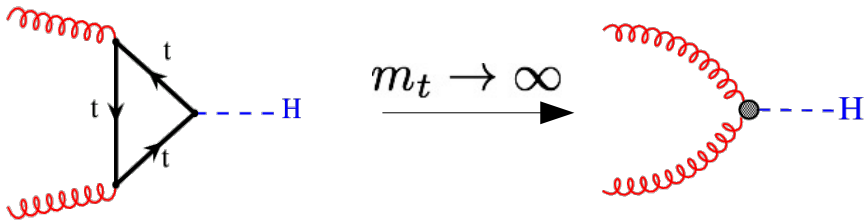
Higher order corrections in Higgs physics

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



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

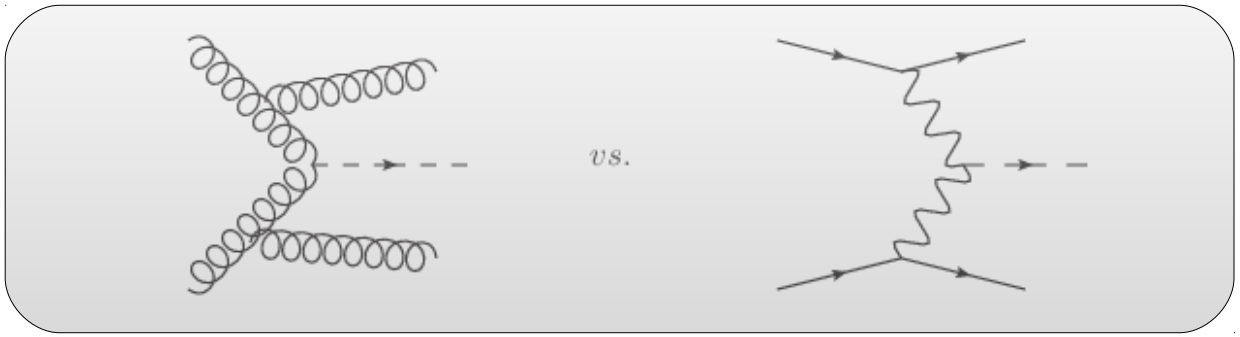
➡ Talk by F.Dulat



- 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] , **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

> 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:

anti-k_T $\quad R = 0.4$

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

VBF:

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

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

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

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

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

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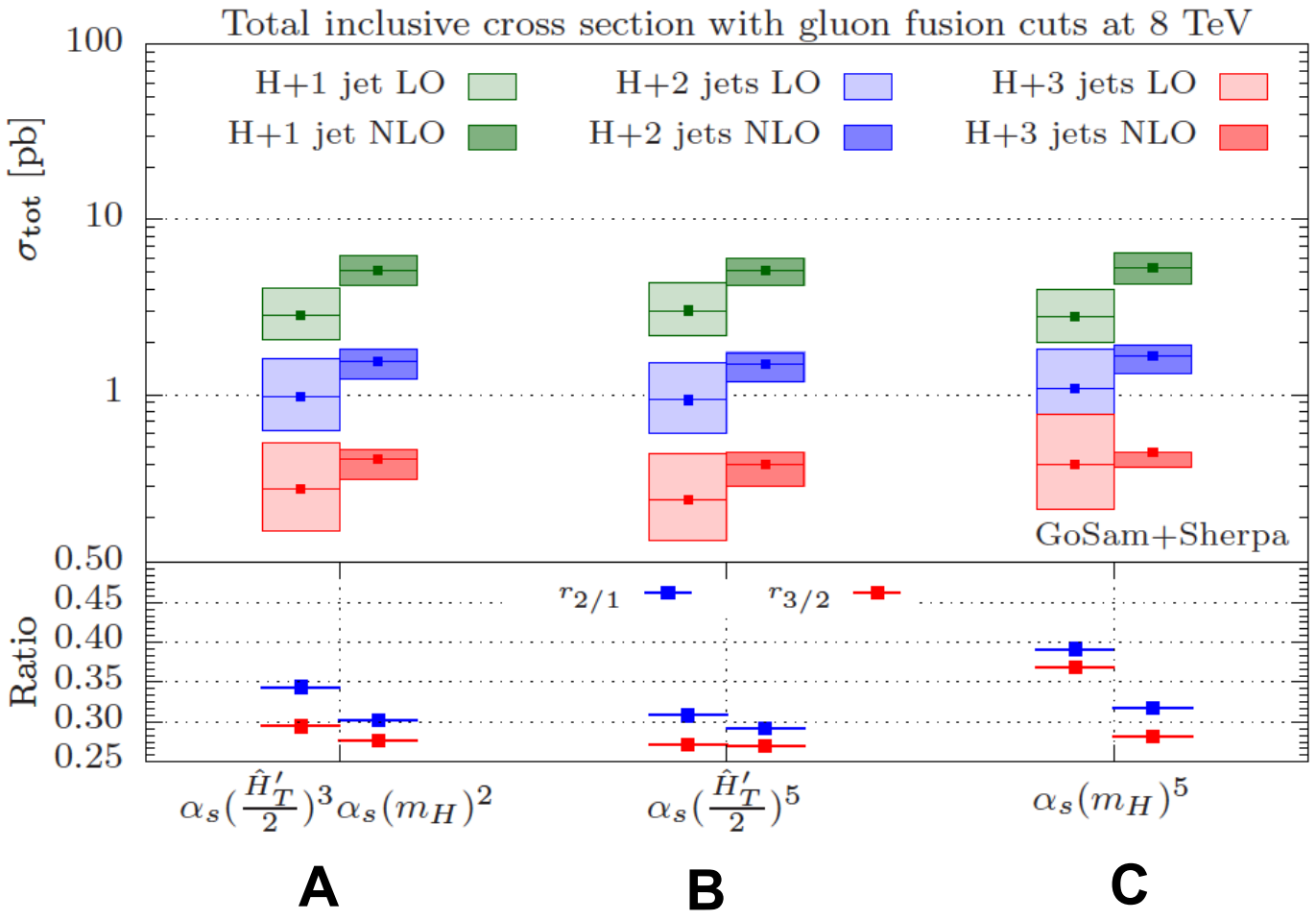
Scale choices

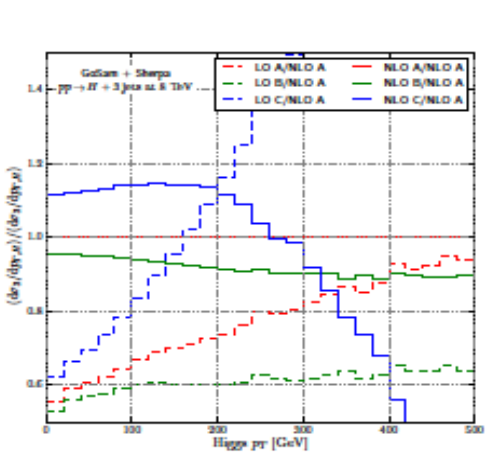
- Total cross sections for three different scale choices



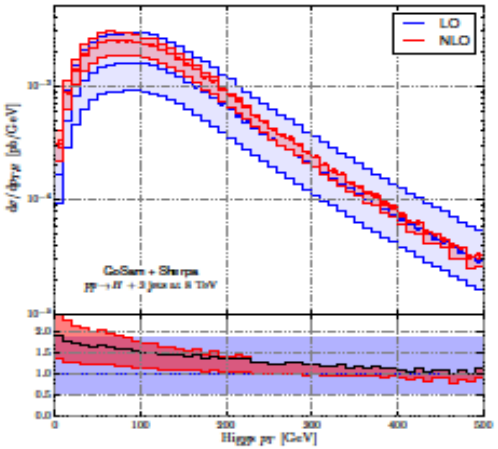
Scale choices

- 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

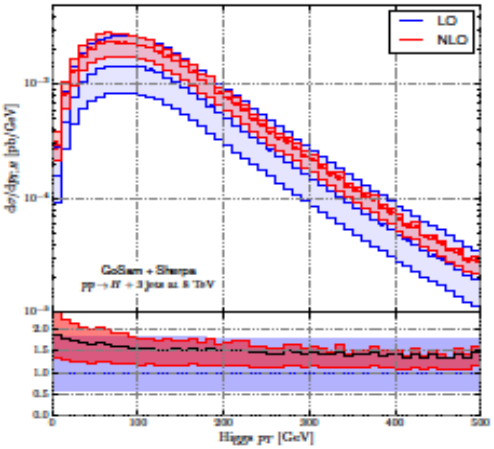
Use scale B as default scale



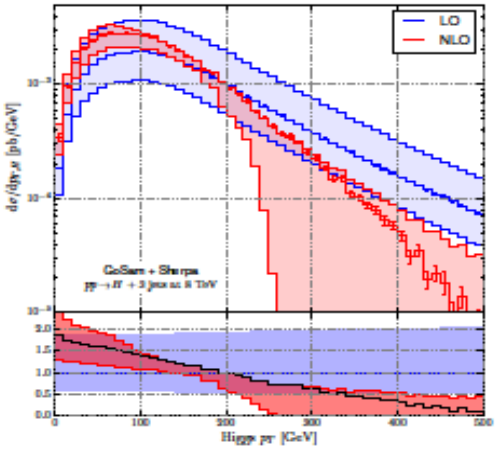
(a) Ratio



(b) Scale choice A (3.4a)



(c) Scale choice B (3.4b)

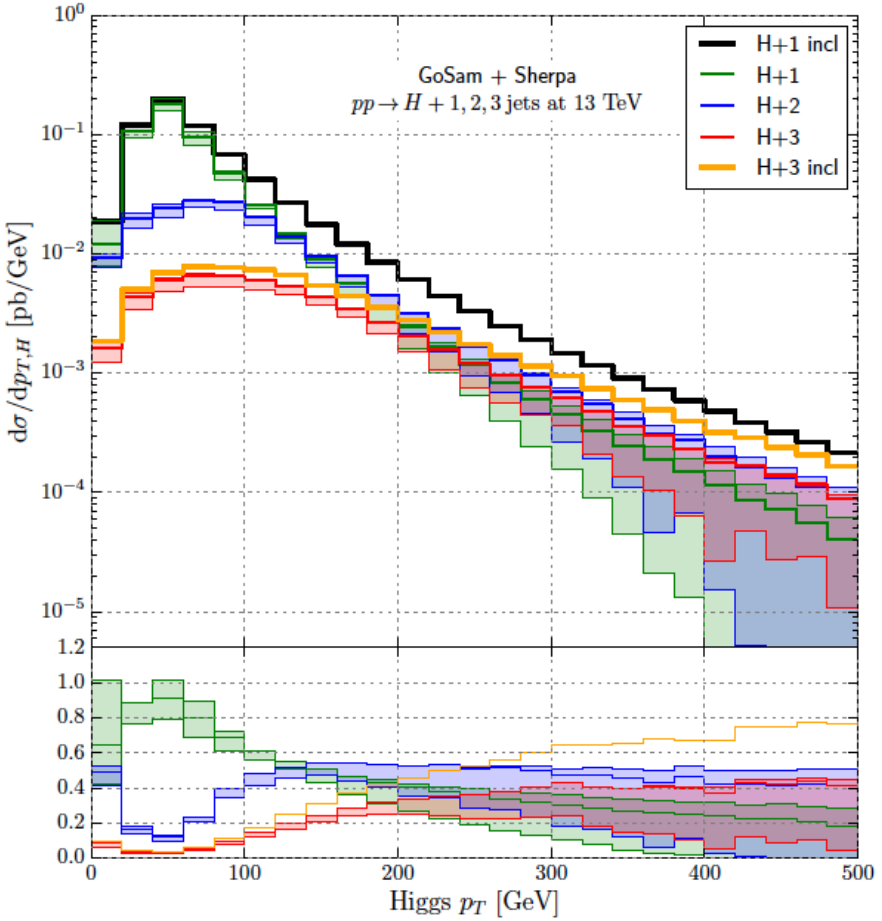


(d) Scale choice C (3.4c)

Multi-jet ratios

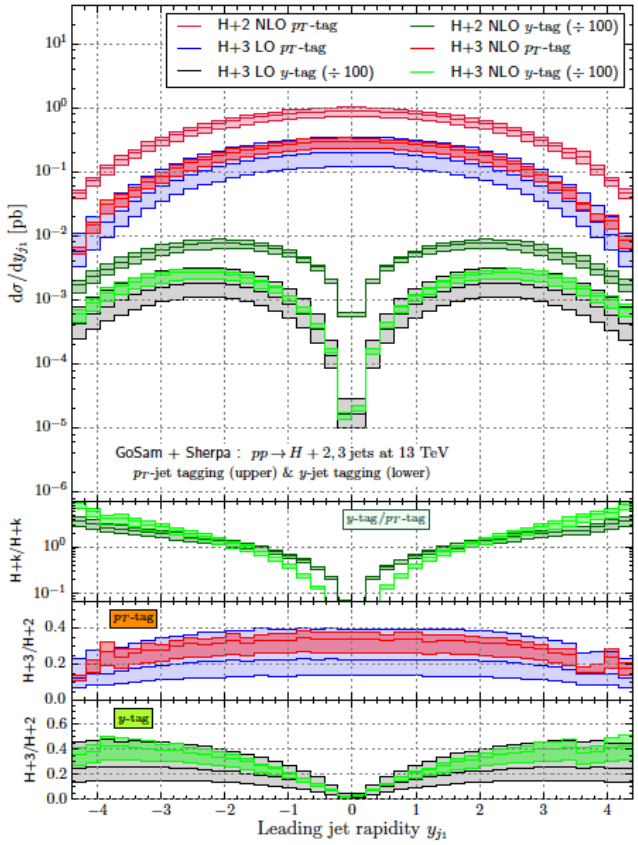
- Investigate impact of additional jets to specific observables.

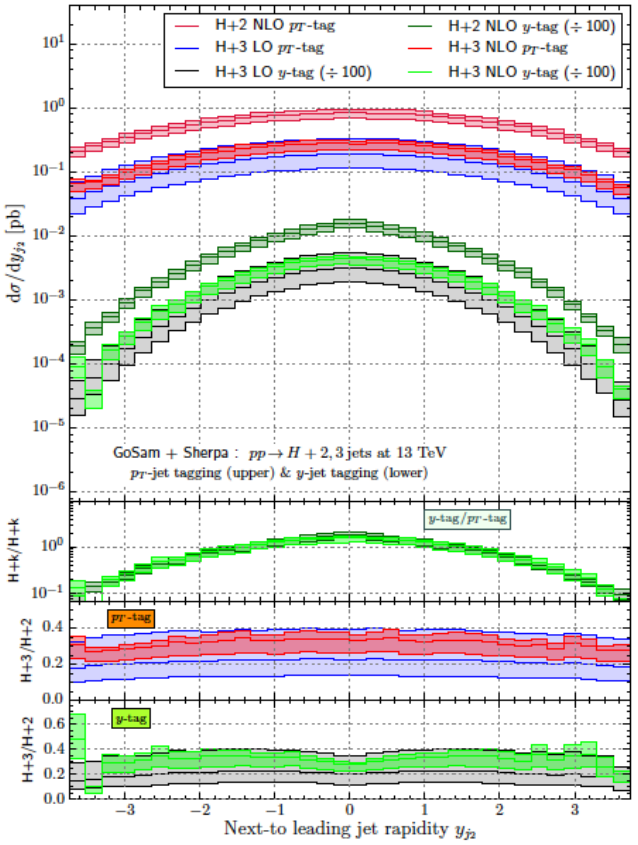
- **Example: Higgs pT**
  Plots normalized to the H+1 inclusive result (i.e. full NLO including possibility of second jet)
- Jet multiplicity has considerable impact on distribution. At ~120 GeV second jet contribution more important than first jet, at ~200 third jet more important than first.



Tagging jet selection

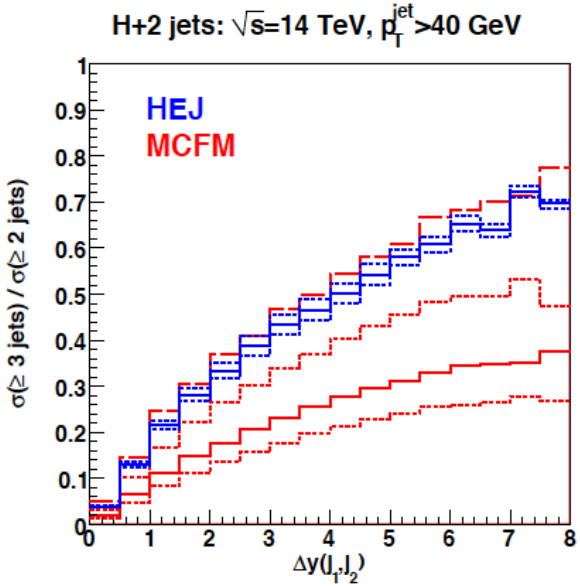
- Compare two different definitions of tagging jet selection:
  (1) : pT ordered (**pT-tagging**)
  (2) : Tagging jets defined as most forward/backward, order according to |y| (**y-tagging**).



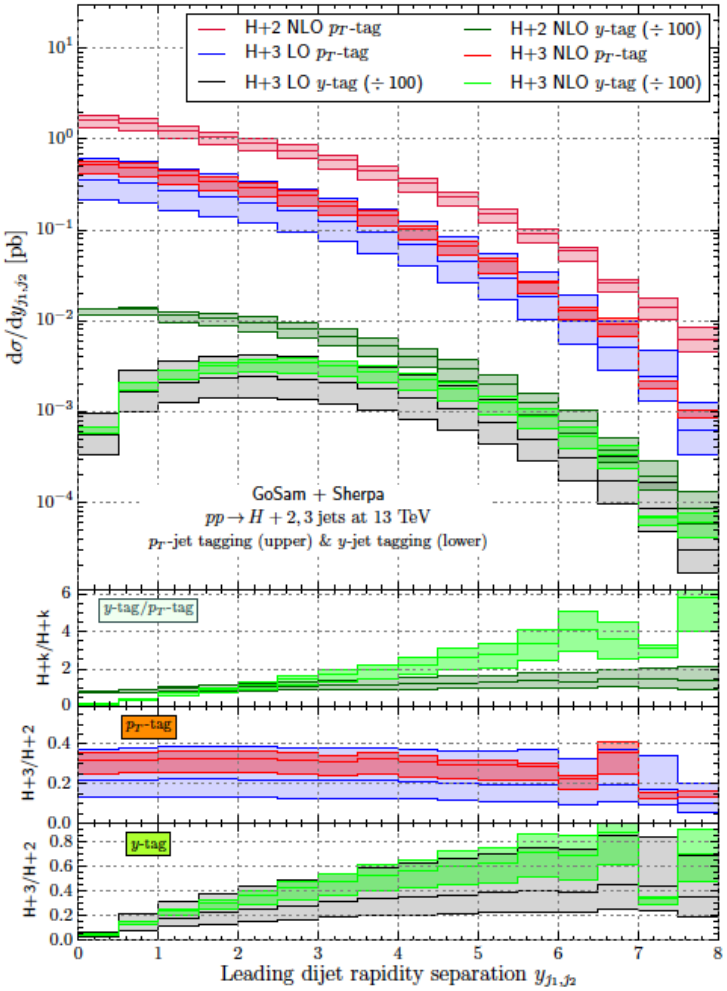


Tagging jet selection

- **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

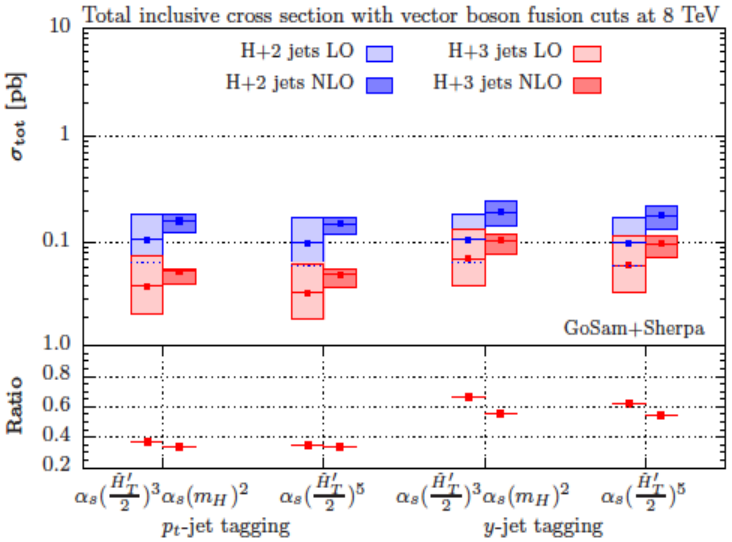


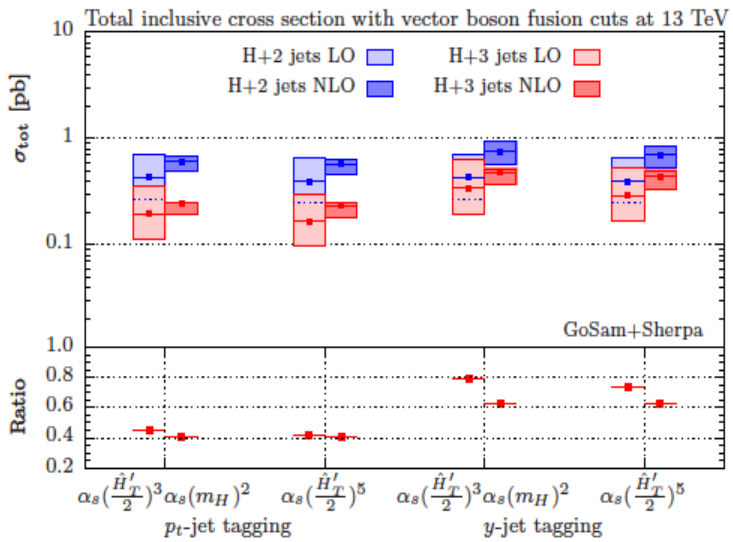
[Snowmass Working group report QCD: 1310.5189]



Vector-Boson-Fusion cuts

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

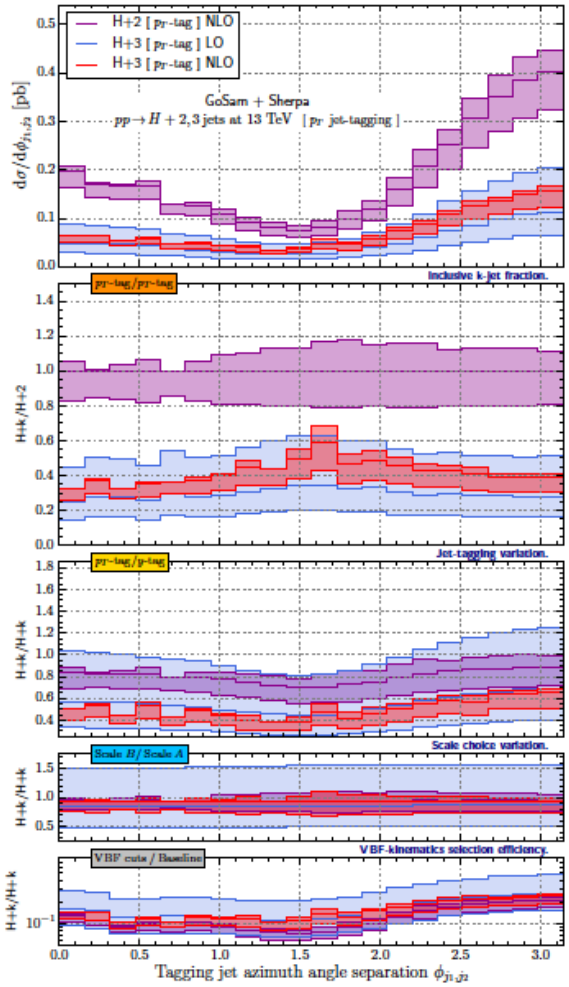


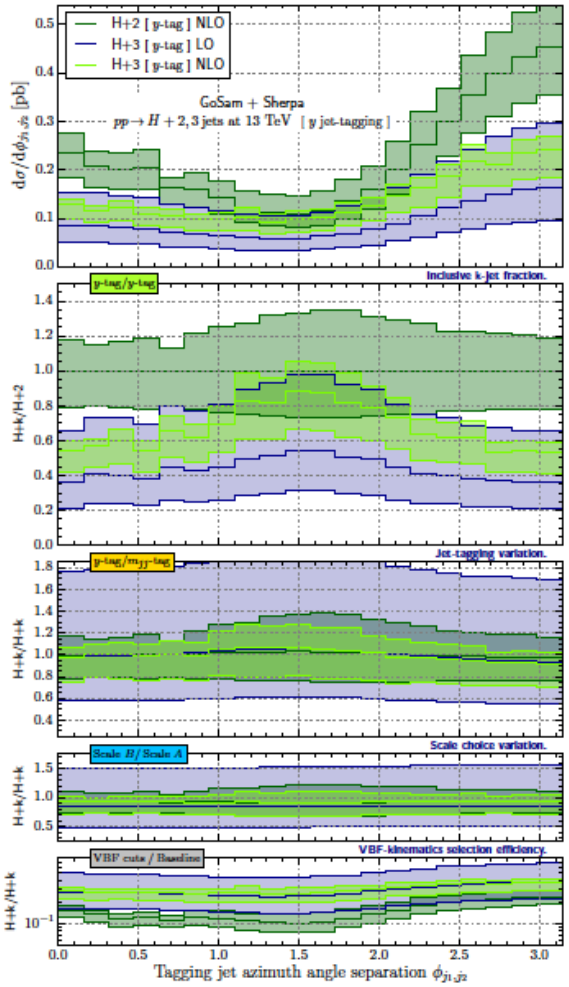


- Ratios slightly enhanced compared to GF cuts
- H+3 / H+2 ratio still very similar for both LO and NLO for pT-tagging
- y-tagging increases H+3 contribution

VBF – Differential Distributions

- Azimuthal separation of the two tagging jets





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
- Detailed phenomenology for Higgs plus up to three jets at NLO coming soon
- Besides phenomenology for H+3 investigate influence of jet-multiplicity and gluon fusion contribution after applying VBF cuts.
- Open questions / To do:
  - Inclusion of parton shower
  - Impact of mass effects (finite top-mass)

BACKUP SLIDES

Total cross sections and scale variations

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