

# ELECTROWEAK HIGGS BOSON PRODUCTION IN ASSOCIATION WITH THREE JETS (A.K.A. VBF + 1 JET) AT NLO QCD

IN COLLABORATION WITH  
S. PLATZER, F. CAMPANERIO, AND M. SJODAHL

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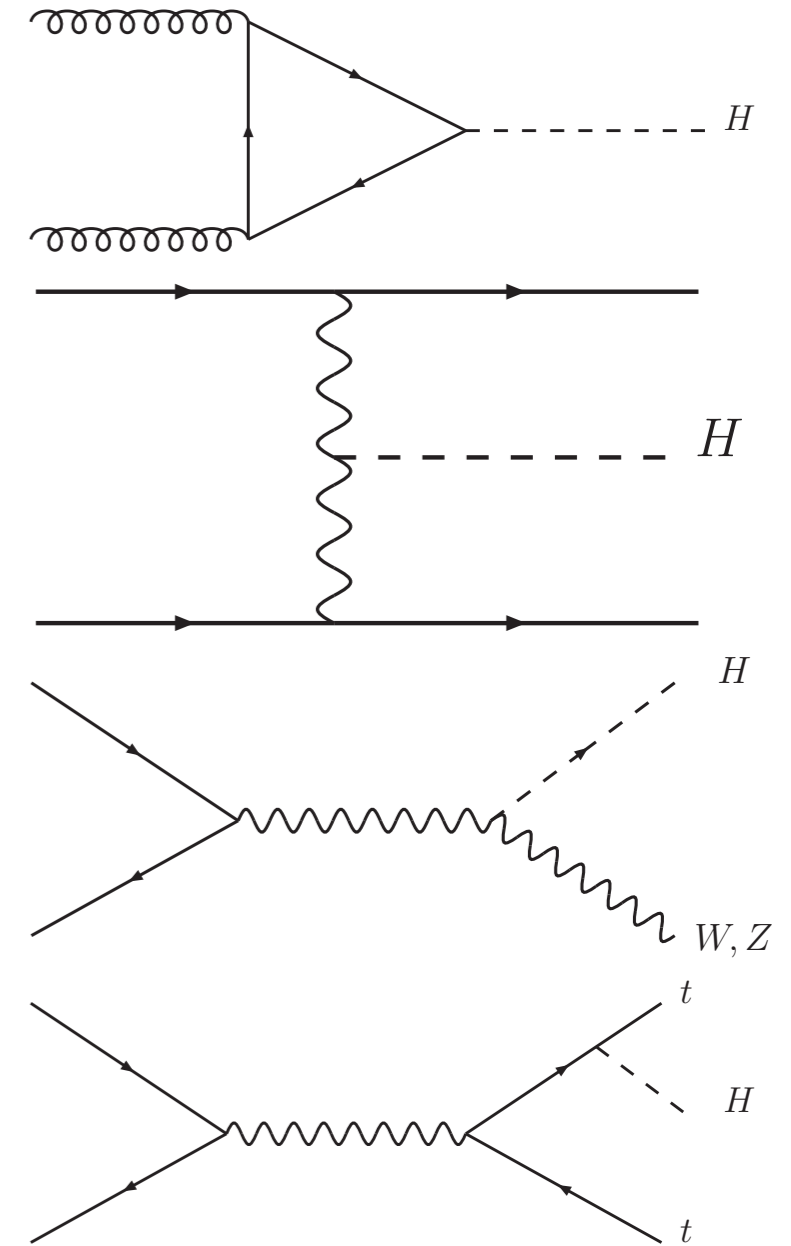
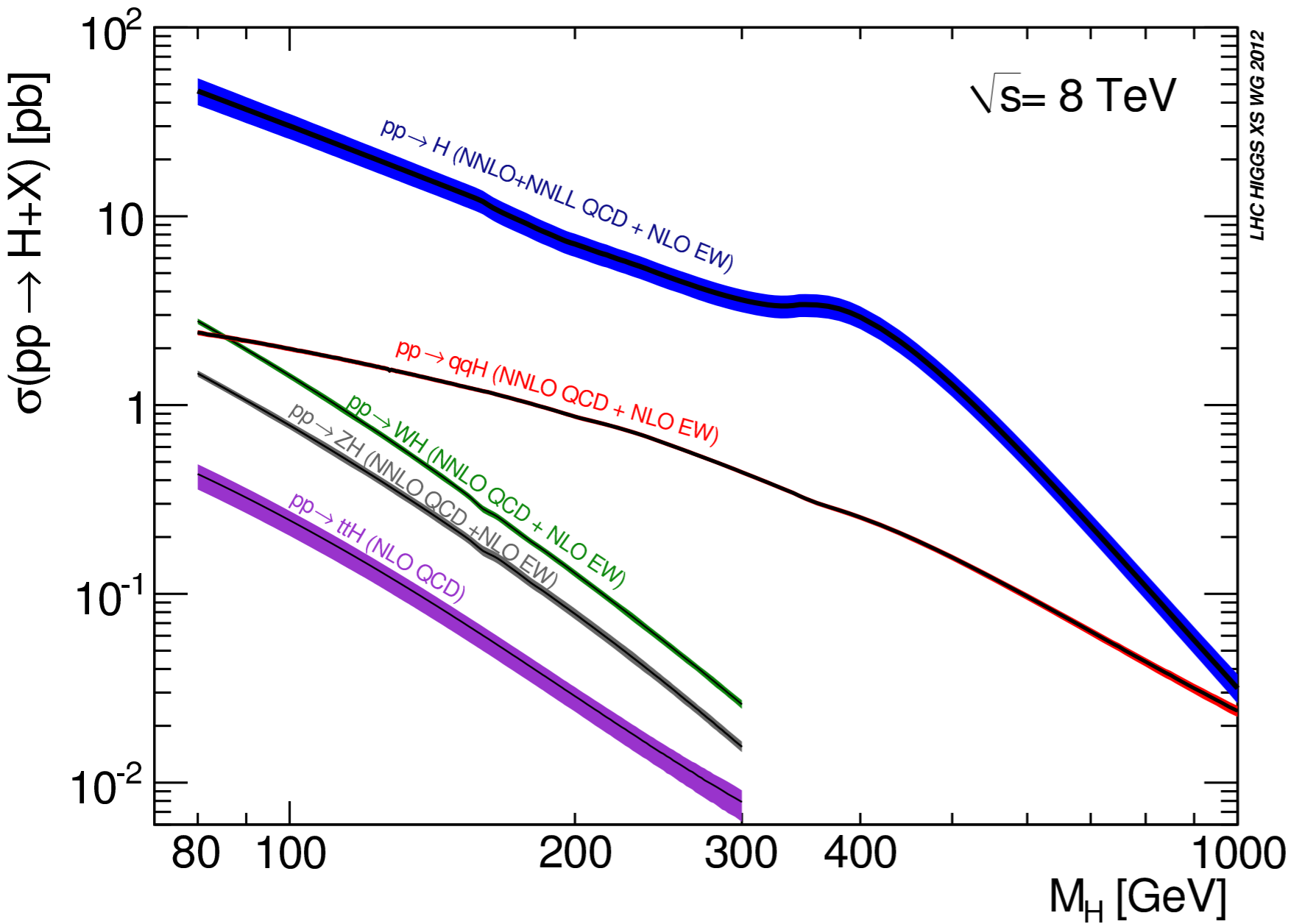
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25 July, 2014  
SUSY 2014  
The University of Manchester

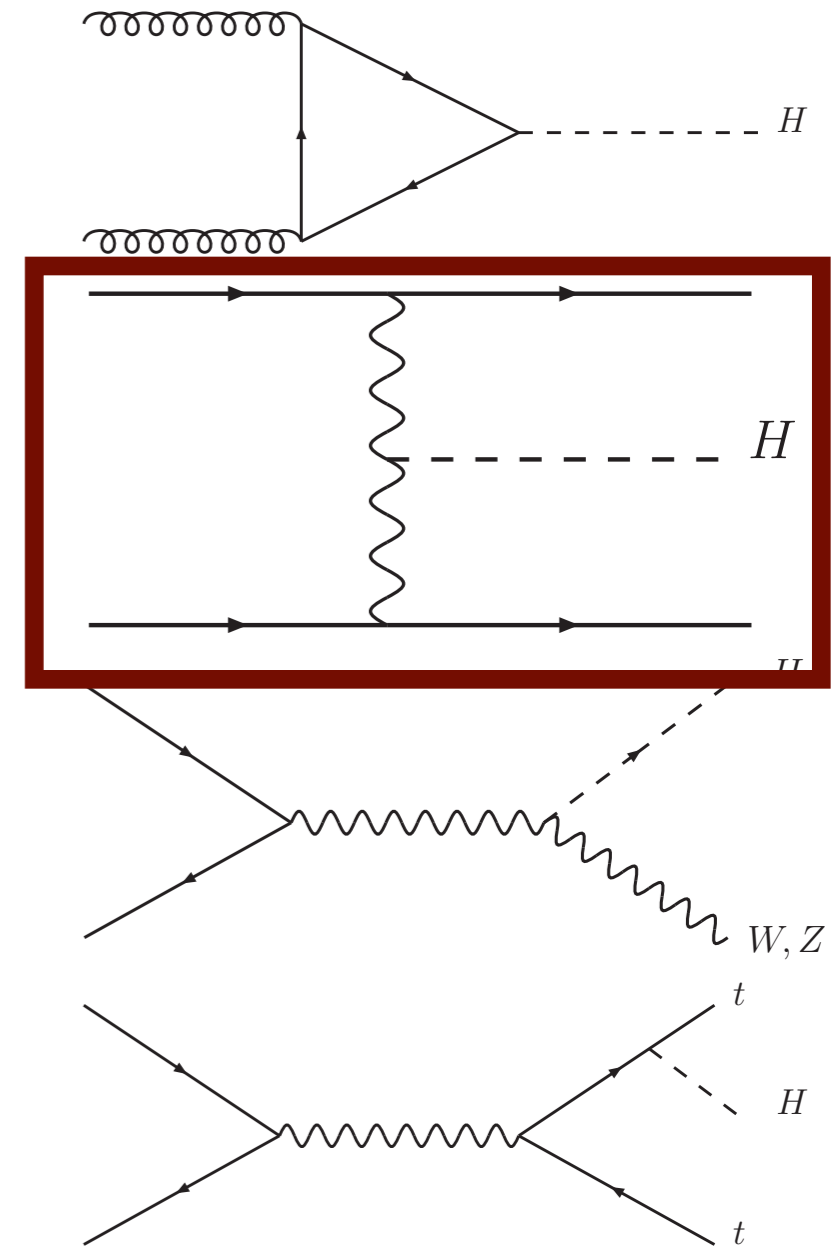
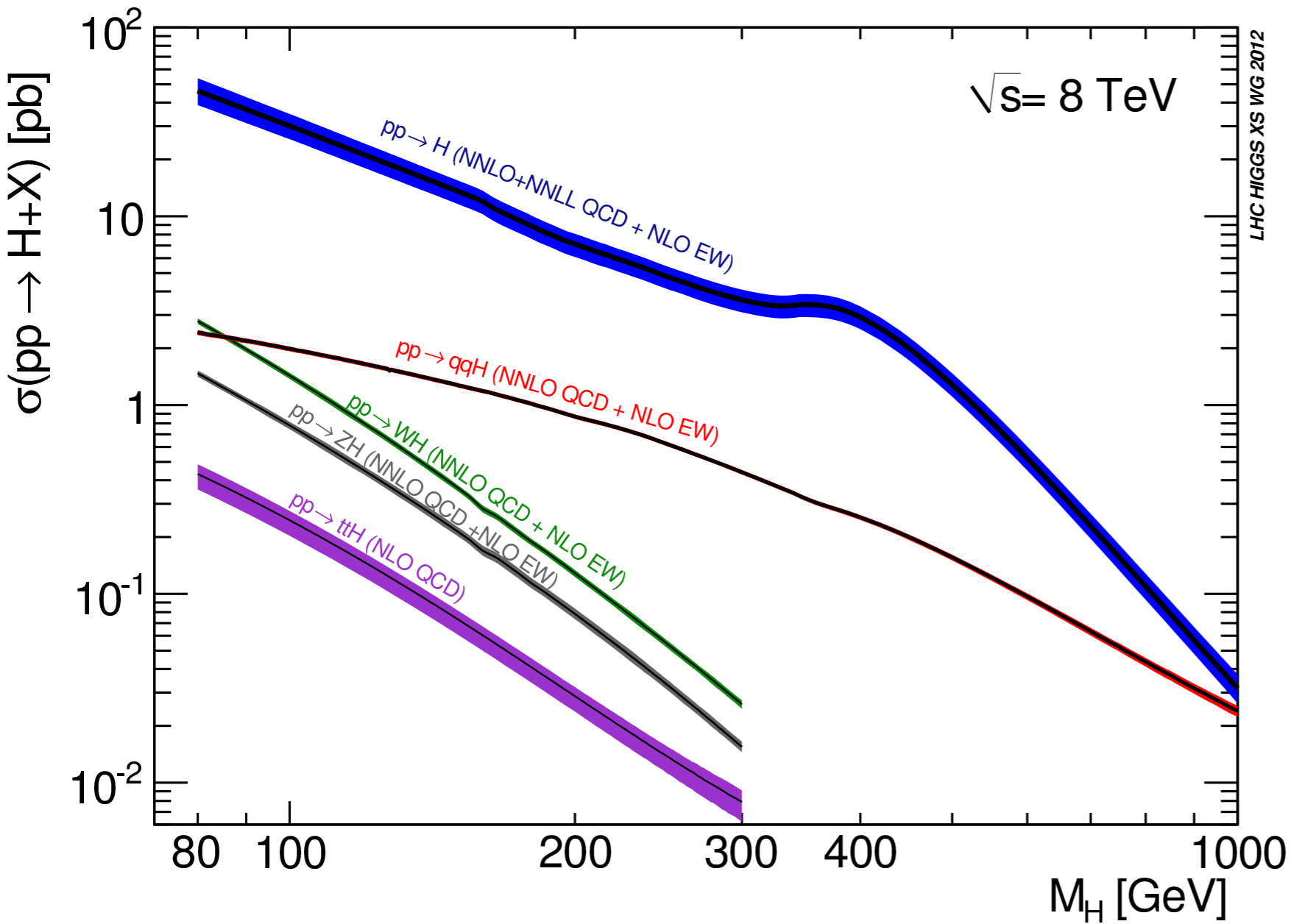
# OUTLINE

- Introduction
- Details of calculation
- Results
- Outlook

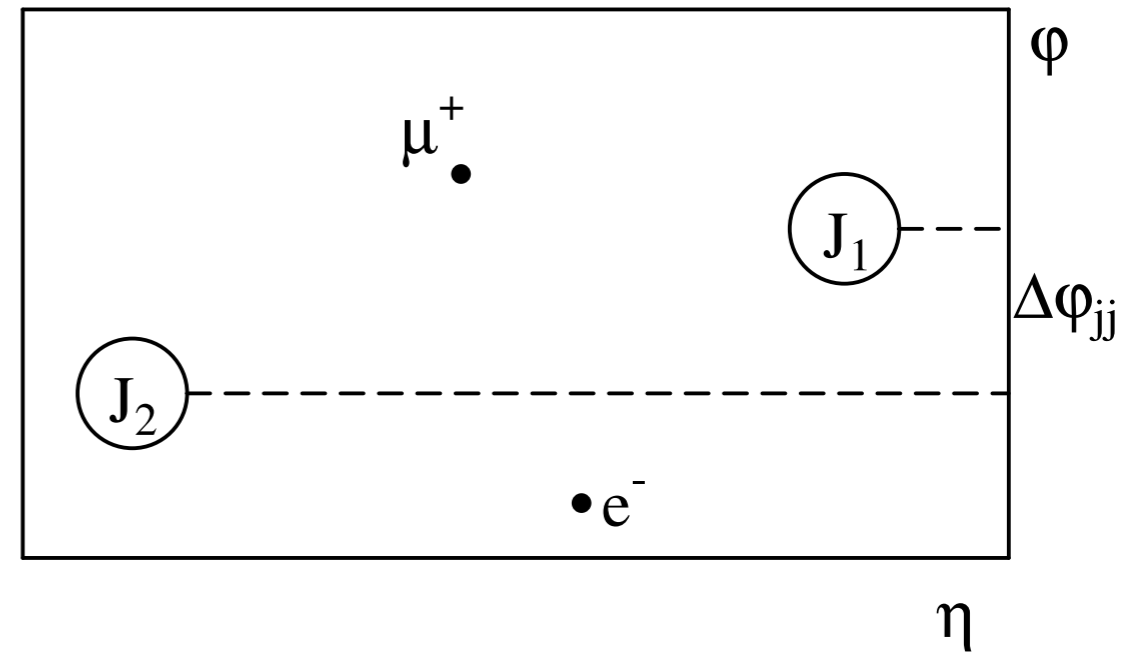
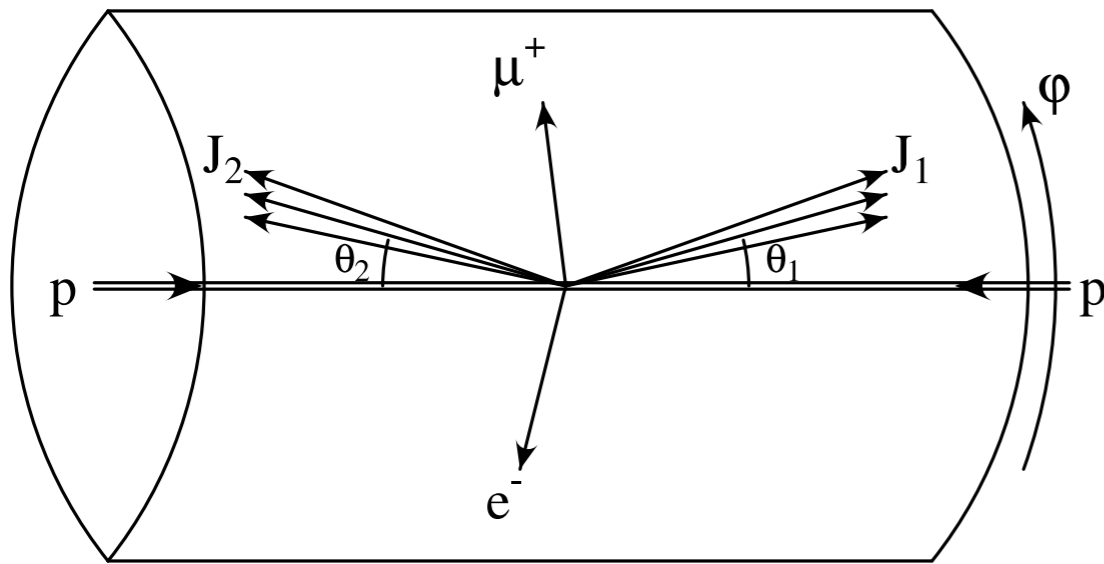
# Total SM Higgs cross sections at the LHC



# Total SM Higgs cross sections at the LHC



# Vector Boson Fusion



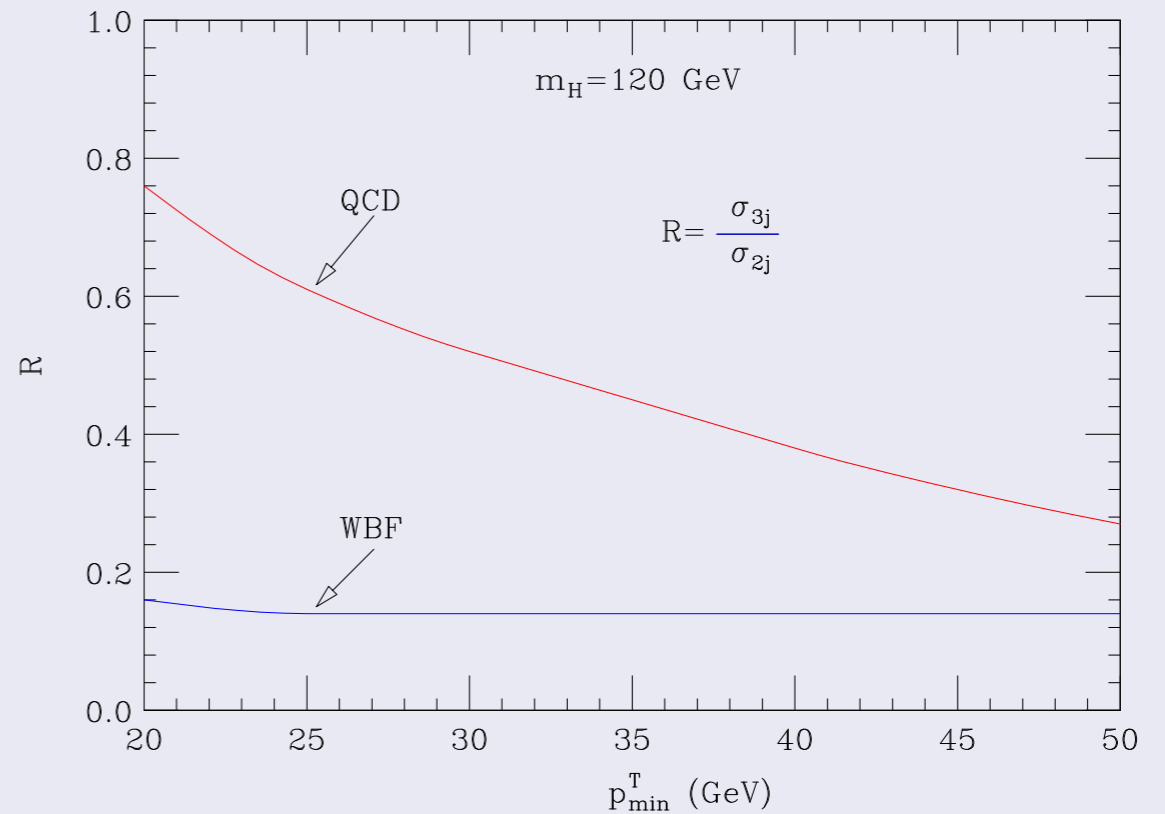
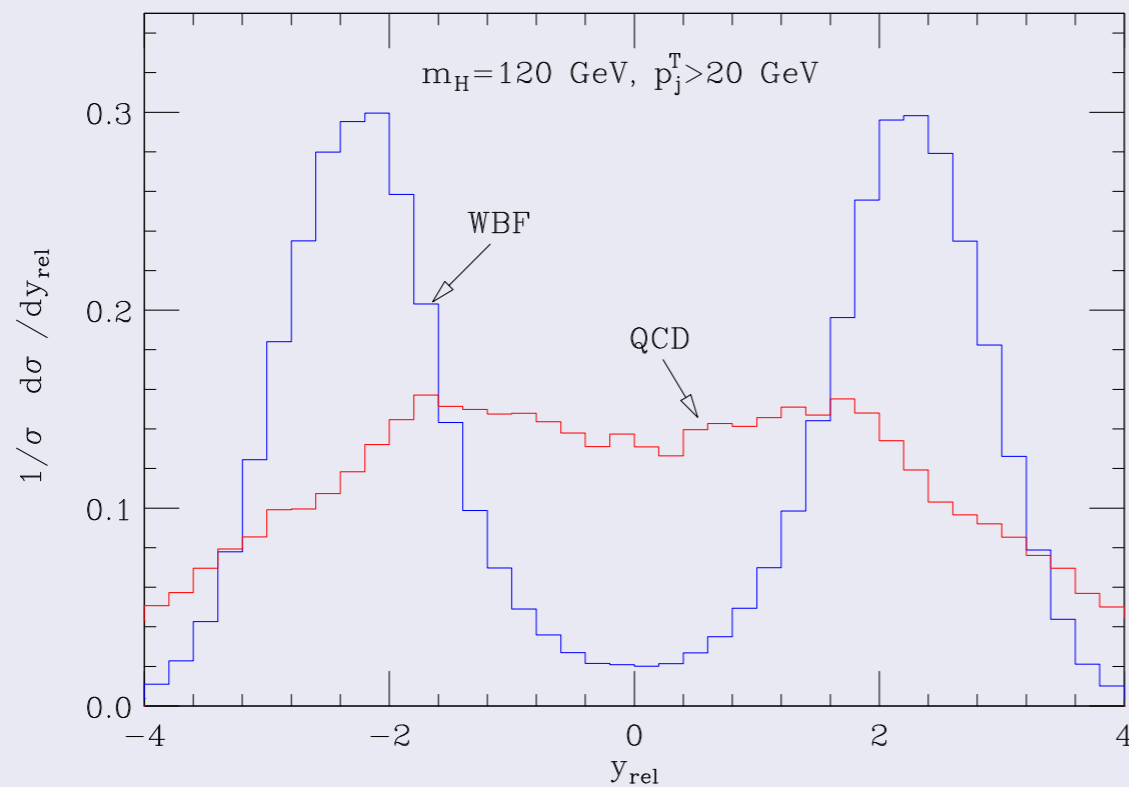
## Event Characteristics

- Energetic jets in the forward and backward directions ( $p_T > 20$  GeV)
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless  $W/Z$  exchange (central jet veto: no extra jets with  $p_T > 20$  GeV and  $|\eta| < 2.5$ )

# Vector Boson Fusion

## Central Jet Veto

### Example: Gluon fusion vs vector boson fusion

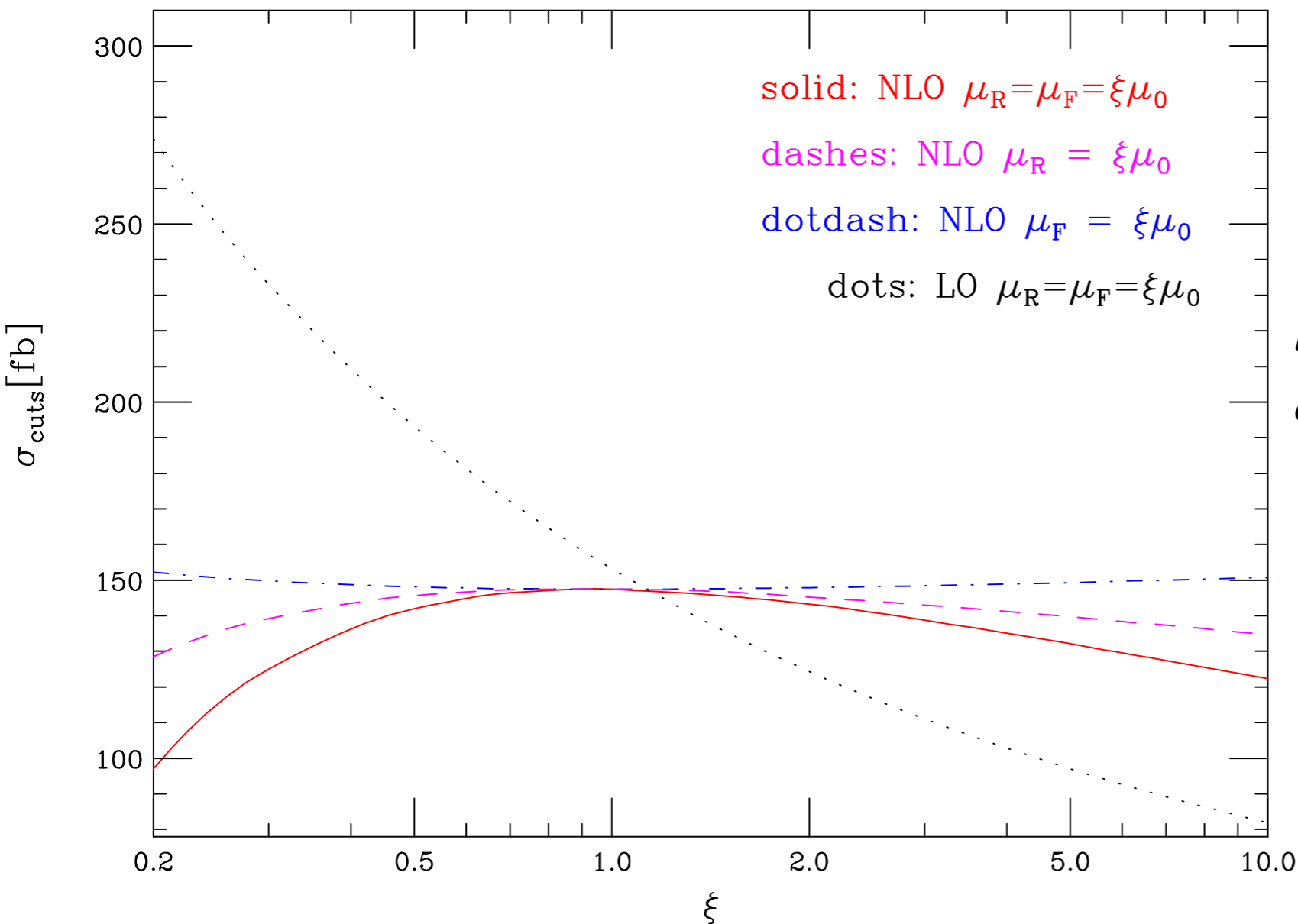


JHEP 05 (2004) 064

$$y_{\text{rel}} = y_j^{\text{veto}} - (y_j^{\text{tag } 1} + y_j^{\text{tag } 2})/2$$

# $Hjjj$ via VBF at NLO (only $t$ -channels)

Total Cross section



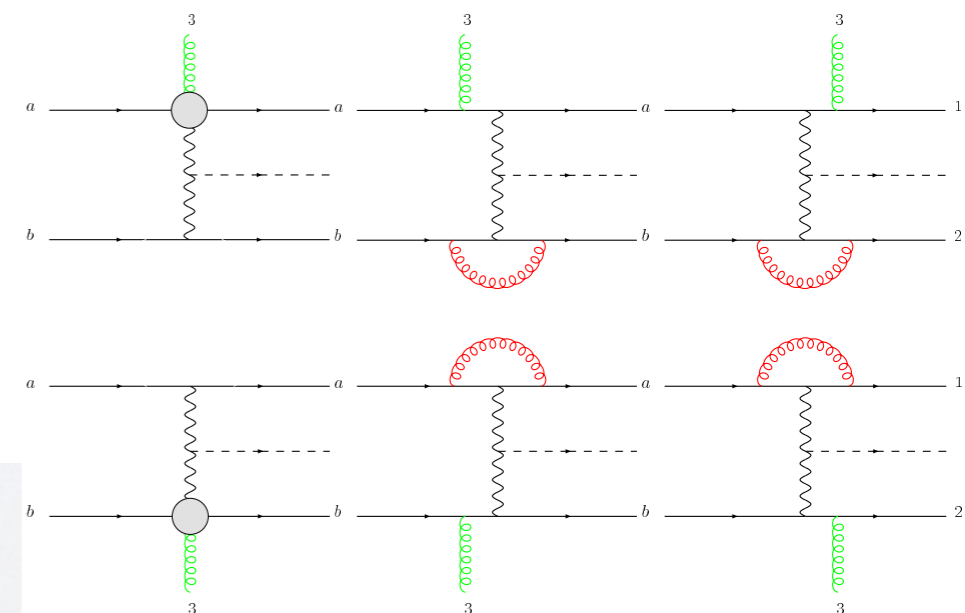
JHEP 0802 (2008) 076 [arXiv:0710.5621]

No pentagon or hexagon diagrams included.  
Approximate as two DIS reactions.

$\mu_0 = 40$  GeV

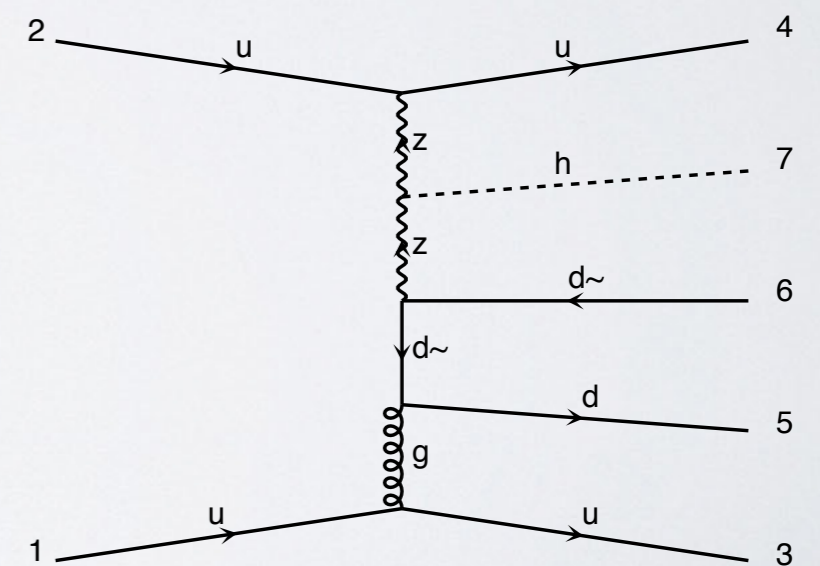
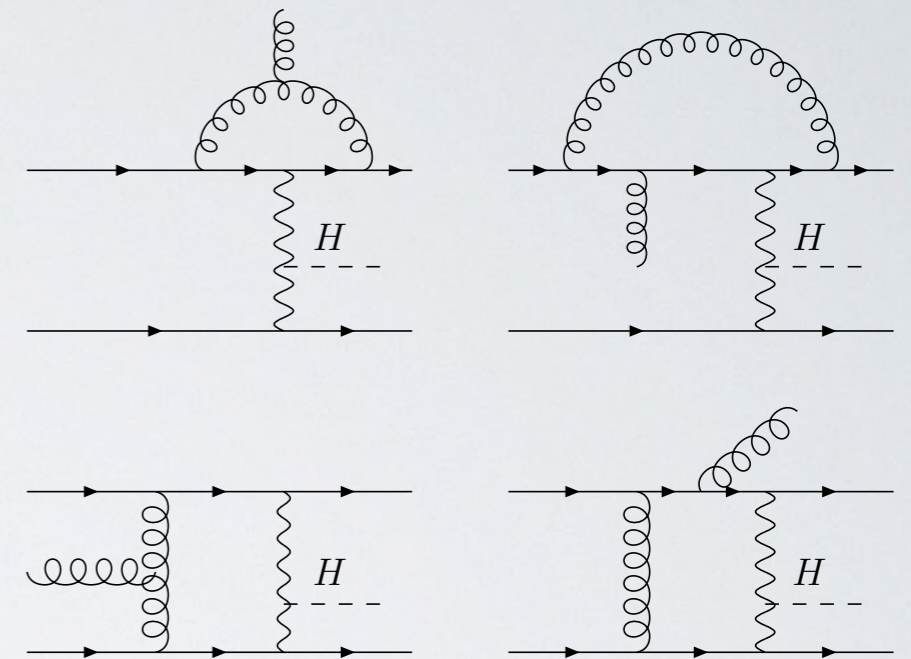
$\xi = 2^{\mp 1}$  scale variations:

- LO: +26% to -19%
- NLO: less than 5%



# HJETS++

- Our aim was to compute the missing pieces (s, t, and u-channel one-loop amplitudes) in H+3 Jets production where the Higgs boson is produced via the HVV coupling (a.k.a VBF+Jet).
- Virtuals: Hexagons, Pentagons, Boxes, and Triangles
- Reals: H+6 parton amplitudes (6 quark + H, 4 quark + 2 gluons + H)





# DIPOLE SUBTRACTION

Catani and Seymour, hep-ph/9605323

$$\begin{aligned} \sigma_{ab}^{NLO}(p, \bar{p}) &= \sigma_{ab}^{NLO\{4\}}(p, \bar{p}) + \sigma_{ab}^{NLO\{3\}}(p, \bar{p}) \\ &+ \int_0^1 dx [\hat{\sigma}_{ab}^{NLO\{3\}}(x, xp, \bar{p}) + \hat{\sigma}_{ab}^{NLO\{3\}}(x, p, x\bar{p})] \end{aligned}$$

$$\sigma_{ab}^{NLO\{3\}}(p, \bar{p}) = \int_3 [d\sigma_{ab}^V(p, \bar{p}) + d\sigma_{ab}^B(p, \bar{p}) \otimes \mathbf{1}]_{\epsilon=0}$$

$$\begin{aligned} \int_0^1 dx \hat{\sigma}_{ab}^{NLO\{3\}}(x, xp, \bar{p}) &= \sum_{a'} \int_0^1 dx \int_3 \{d\sigma_{a'b}^B(xp, \bar{p}) \\ &\otimes [\mathbf{P}(x) + \mathbf{K}(x)]^{aa'}\}_{\epsilon=0} \end{aligned}$$

$$\sigma_{ab}^{NLO\{4\}}(p, \bar{p}) = \int_4 [d\sigma_{ab}^R(p, \bar{p})_{\epsilon=0} - d\sigma_{ab}^A(p, \bar{p})_{\epsilon=0}]$$

For the H+2,3, and 4 jet amplitudes we use the in-house spinor library of Matchbox.

# HJETS++

- Matchbox [S. Platzer and S. Gieseke, arXiv:1109.6256]
  - Catani-Seymour Dipole subtraction [hep-ph/9605323]
  - Subtractive and POWHEG style matching to parton shower
- ColorFull [M. Sjodahl, arXiv:1211.2099, <http://home.thep.lu.se/~malin/ColorMath.htm#ColorMath>, ColorFull will soon be public.]
- Tensorial Reduction [F. Capanario, arXiv:1105.0920]
- Scalar Loop Integrals: OneLooop [A. van Hameren arXiv:1007.4716]

# THE RESULTS

- Input parameters and selection cuts.
- Scale variations for total cross section.
- Kinematic distributions.

# INPUT PARAMETERS

- $E_{cm} = 14 \text{ TeV}$  (proton - proton LHC)
- At least three anti-KT  $D=0.4$  (E-scheme recombination) of  $20 \text{ GeV}$  and rapidity within  $-4.5$  and  $4.5$  using FastJet [arXiv:0802.1189, arXiv:1111.6097]
- PDF choices: CT10 for NLO and CTEQ 6L1 for LO [arXiv:hep-ph/0201195, arXiv:1007.2241]
- Scales:  $W$ -boson mass ( $M_W$ ) and sum of transverse momentum of reconstructed jets (HT)

$y_i$ : rapidity

$\phi_i$ : azimuthal angle

$p_i$ : four momentum vector of  $i$

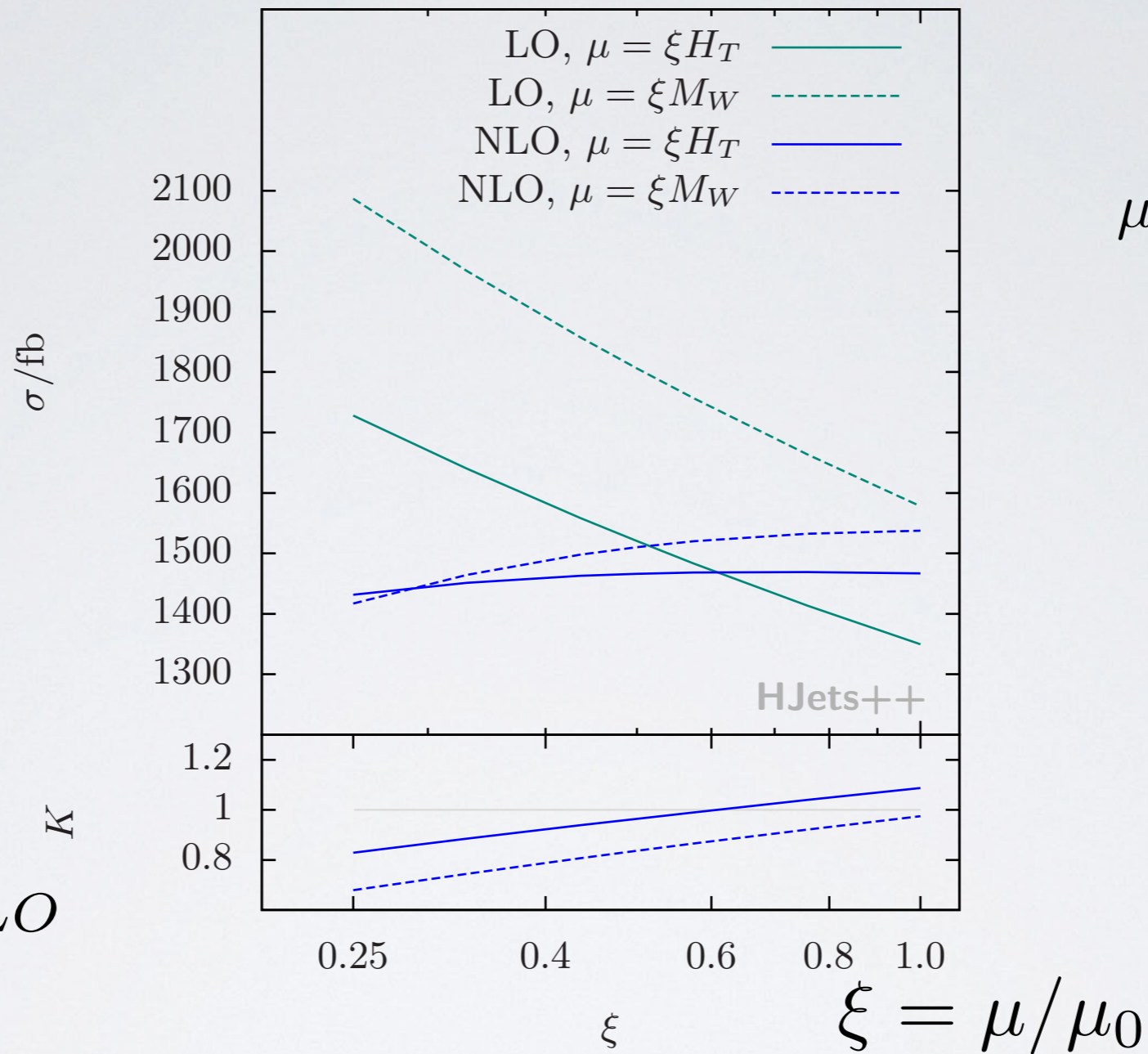
$\Delta y_{ij} = |y_i - y_j|$ : absolute rapidity difference between  $i$  and  $j$

$\Delta \phi_{ij} = |\phi_i - \phi_j|$ : absolute azimuthal angle difference between  $i$  and  $j$

$m_{ij} = \sqrt{(p_i + p_j)^2}$ : invariant mass of  $i$  and  $j$

# Scale Variations on Integrated Cross-sections

$$K = \sigma_{NLO} / \sigma_{LO}$$



$$\mu_0 = H_T (M_W)$$

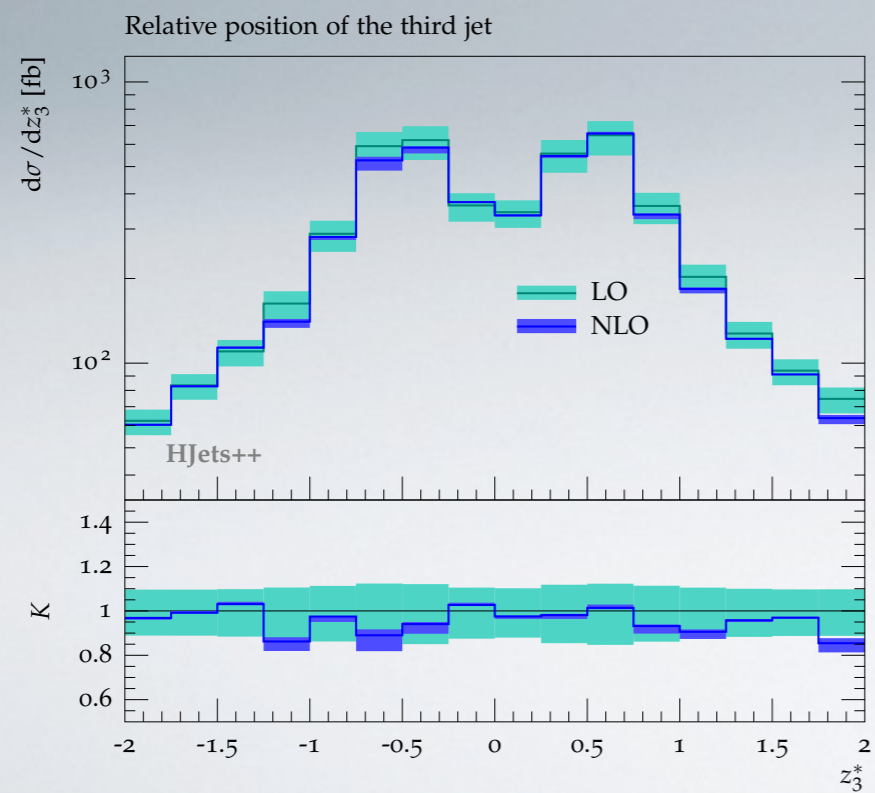
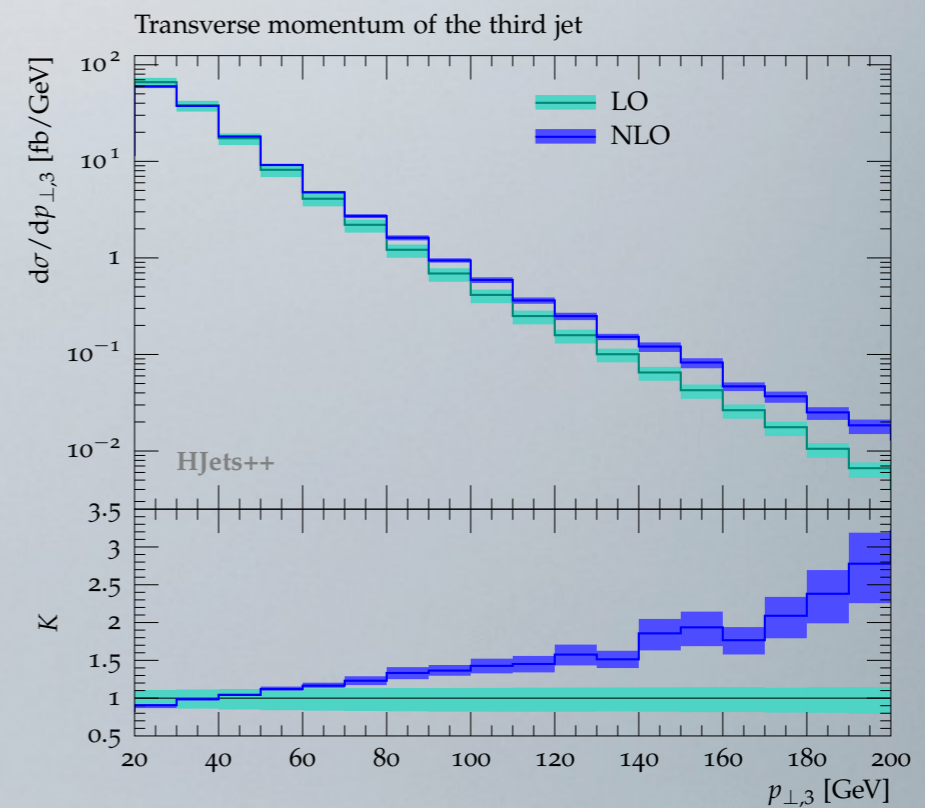
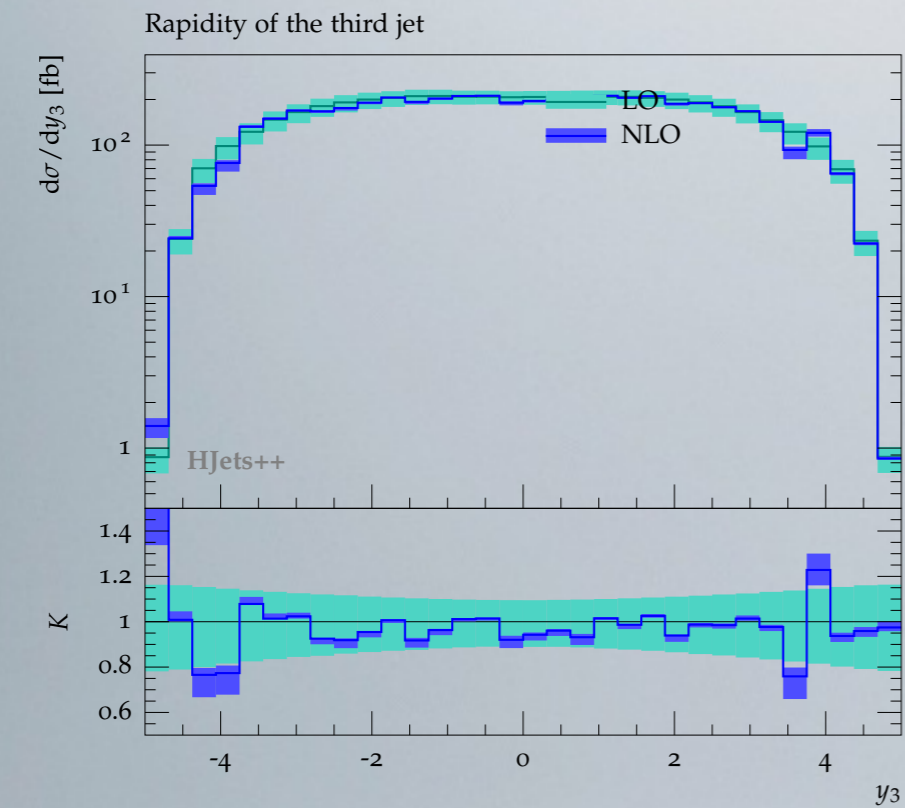
$$H_T = \sum_j p_{T,j}$$

$\mu_R = \mu_F = H_T/2 (M_W/2)$ :  
 30% (24%) at LO and 2% (8%) at NLO

$$\sigma_{LO} = 1520(8)_{-171}^{+208} \text{ fb}$$

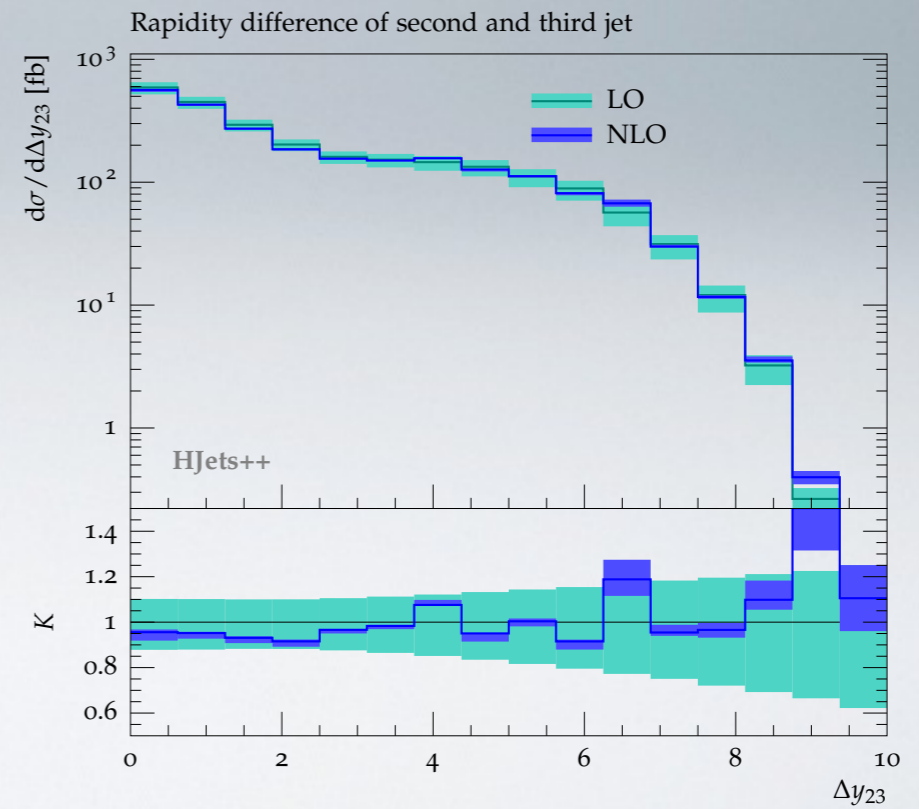
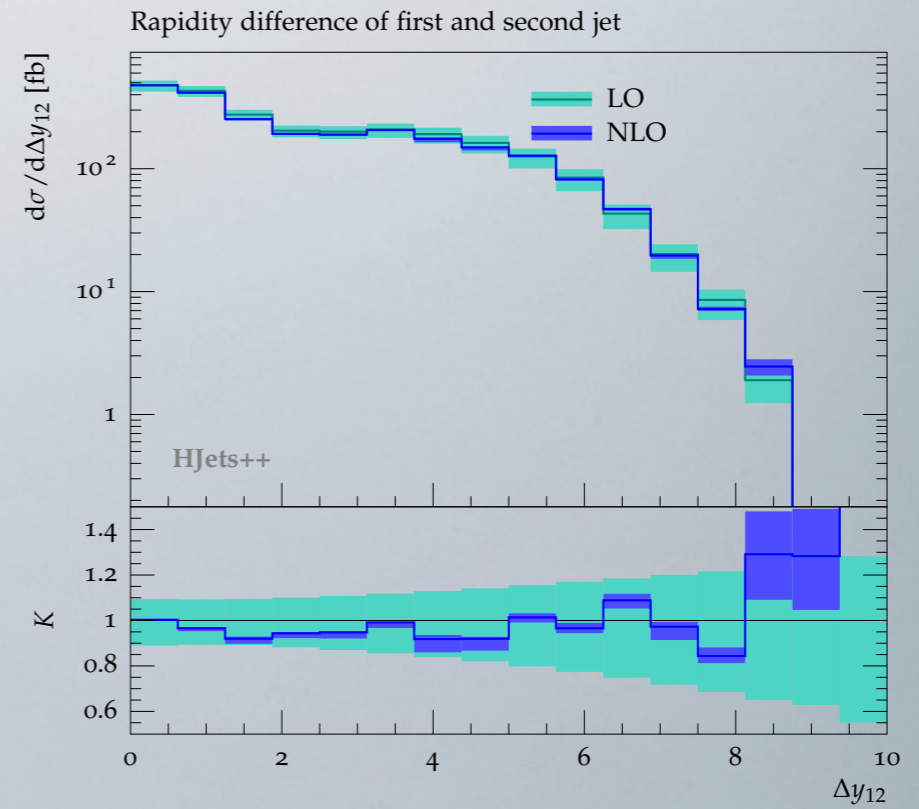
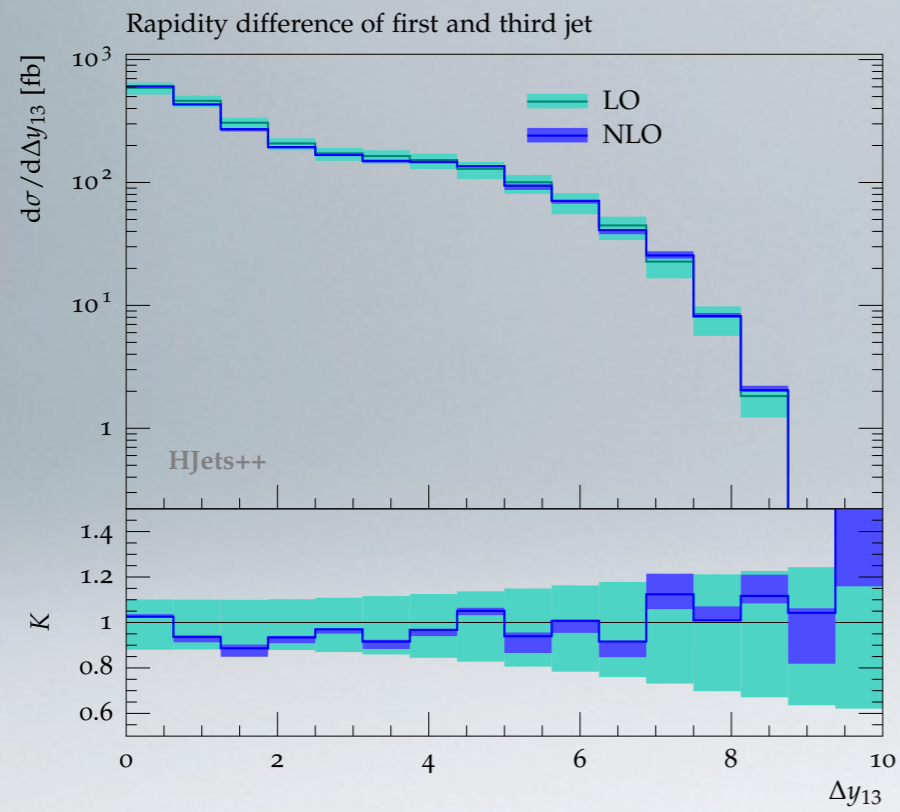
$$\sigma_{NLO} = 1466(17)_{-35}^{+1} \text{ fb}$$

# JET DISTRIBUTIONS



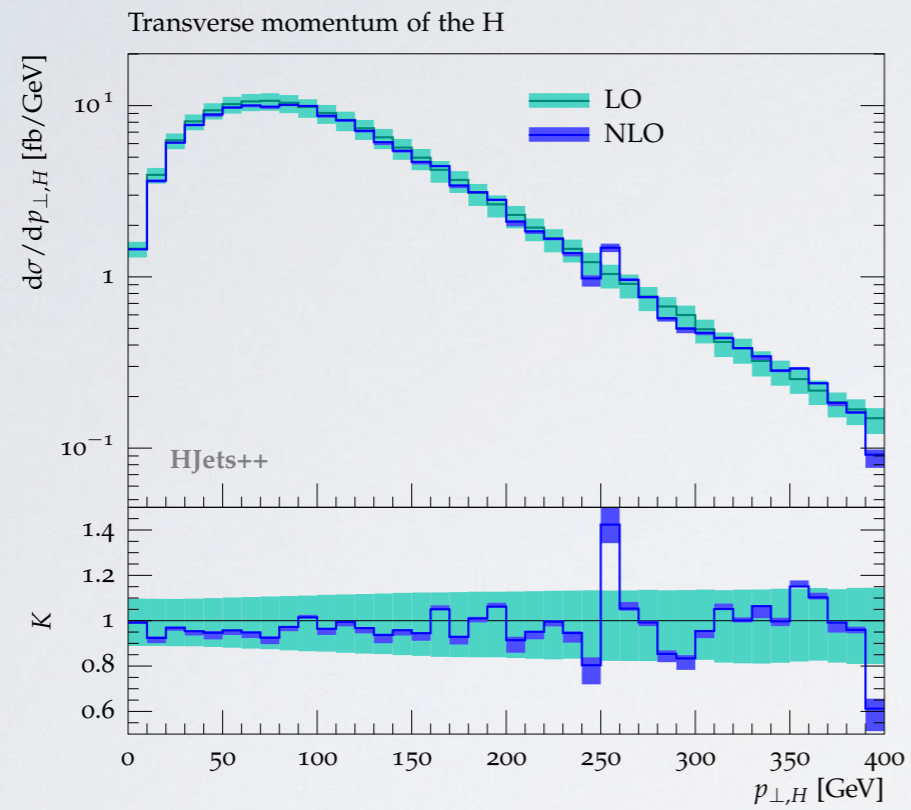
$$z_3^* = (y_3 - \frac{1}{2}(y_1 + y_2)) / (y_1 - y_2)$$

# Rapidity separation

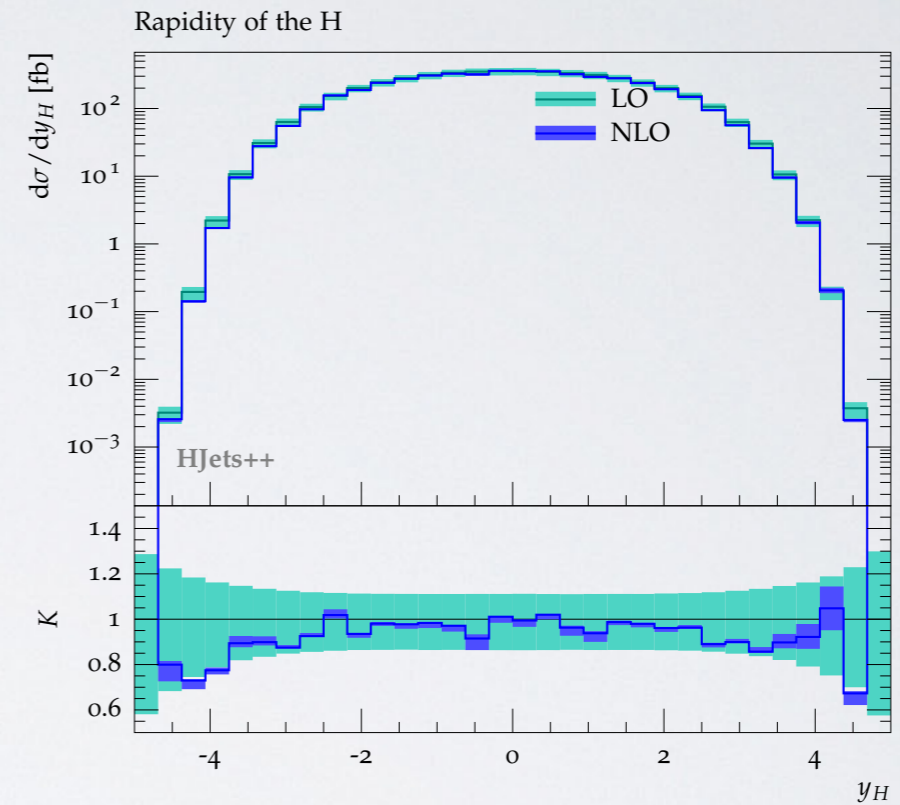




# Higgs Boson Distributions

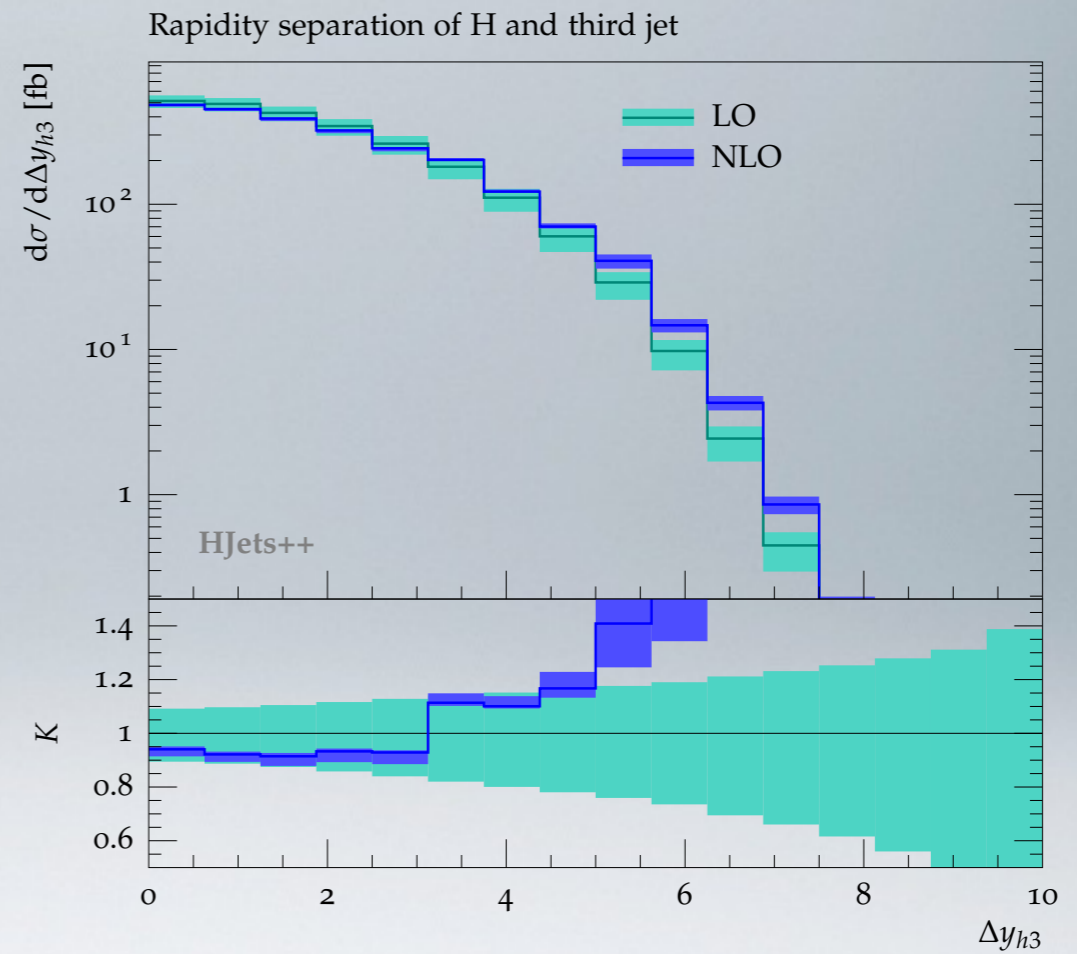
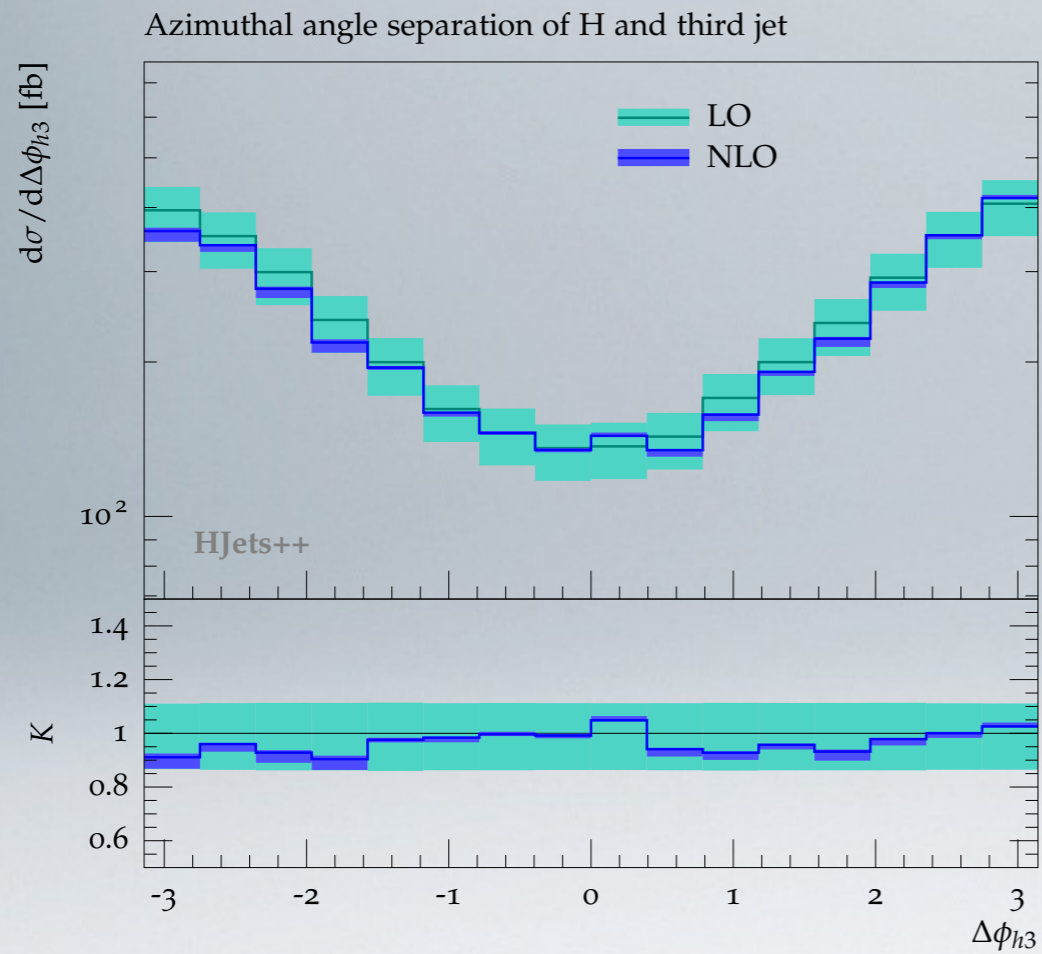


Transverse momentum

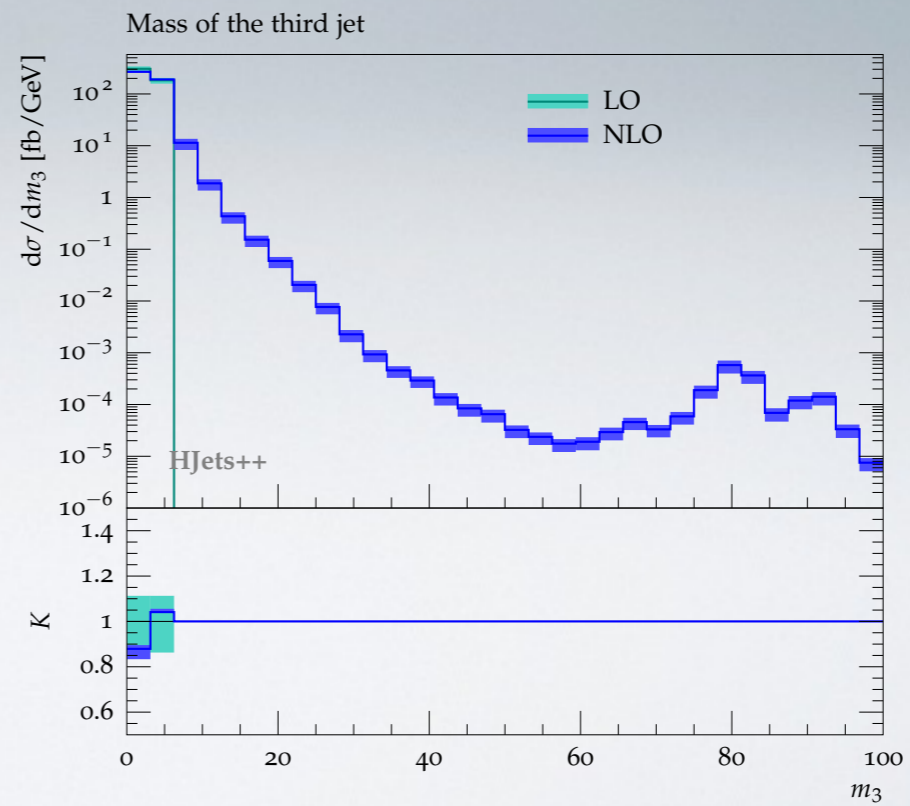
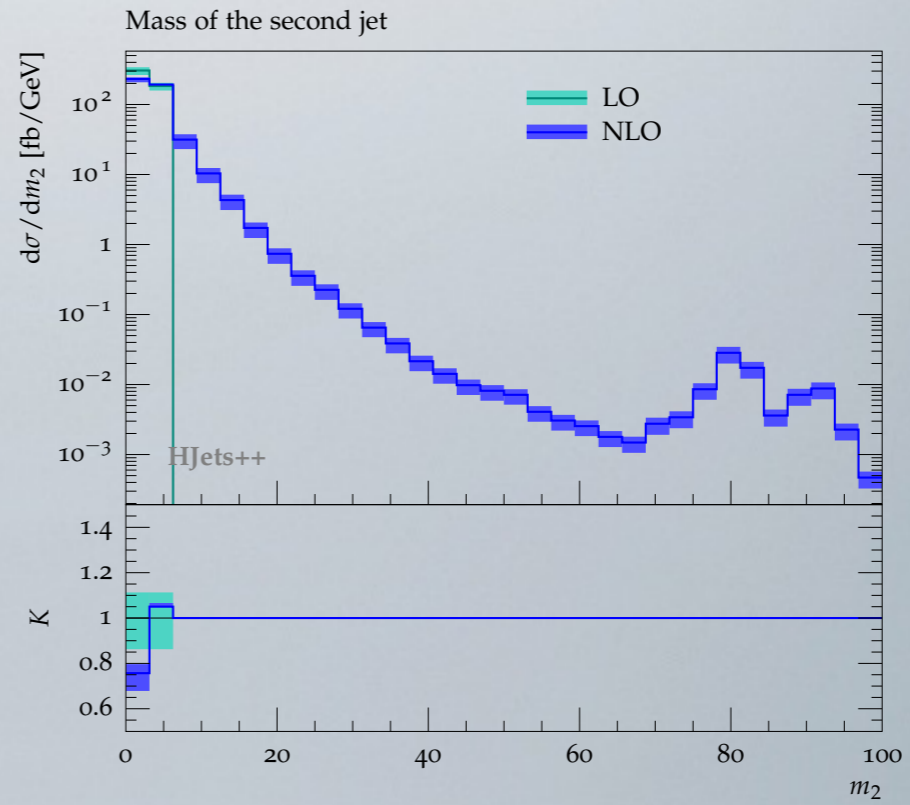
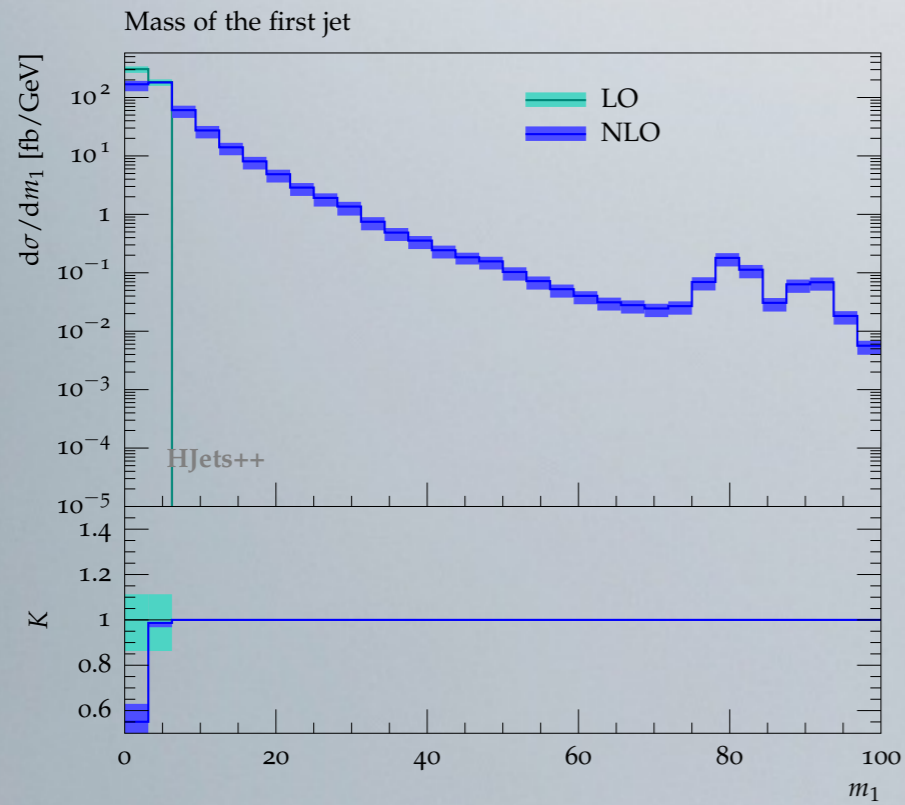


Rapidity

# Higgs Boson Distributions

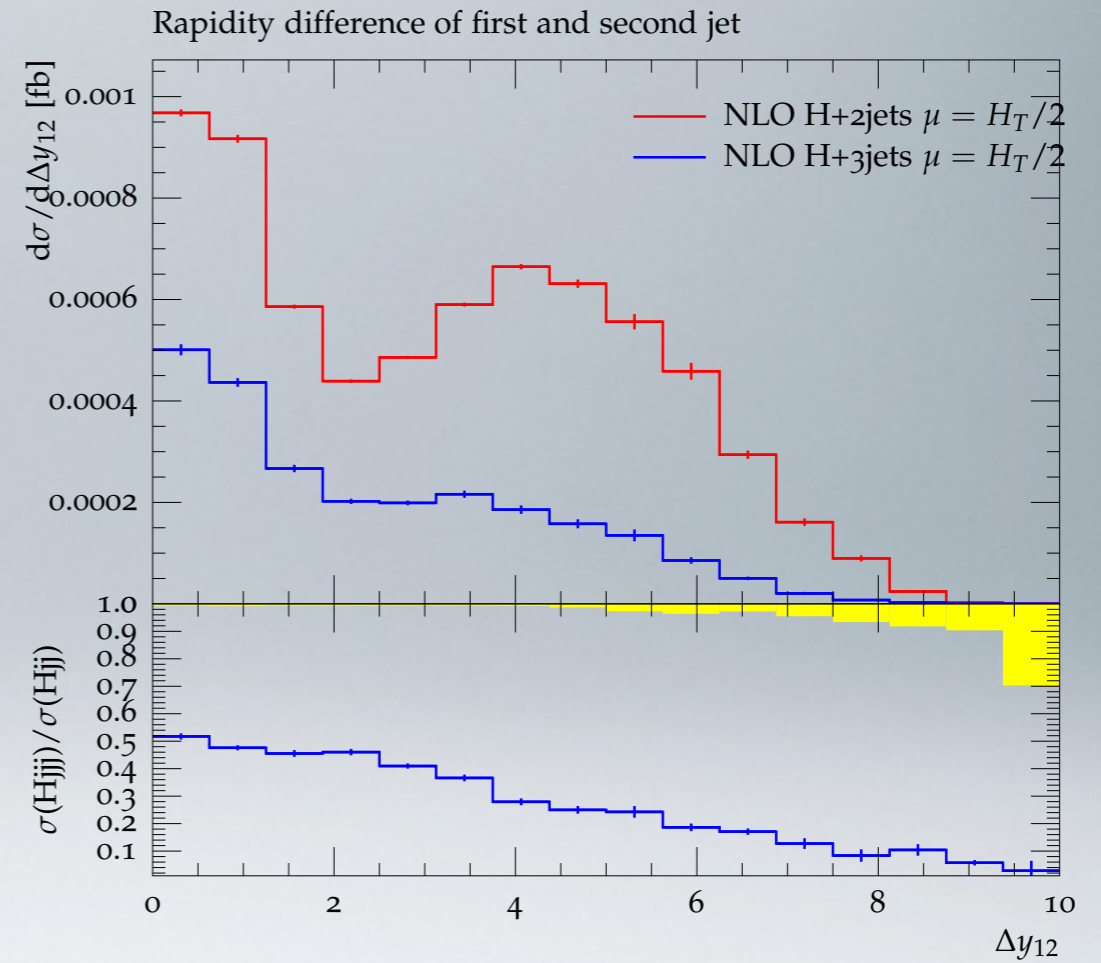
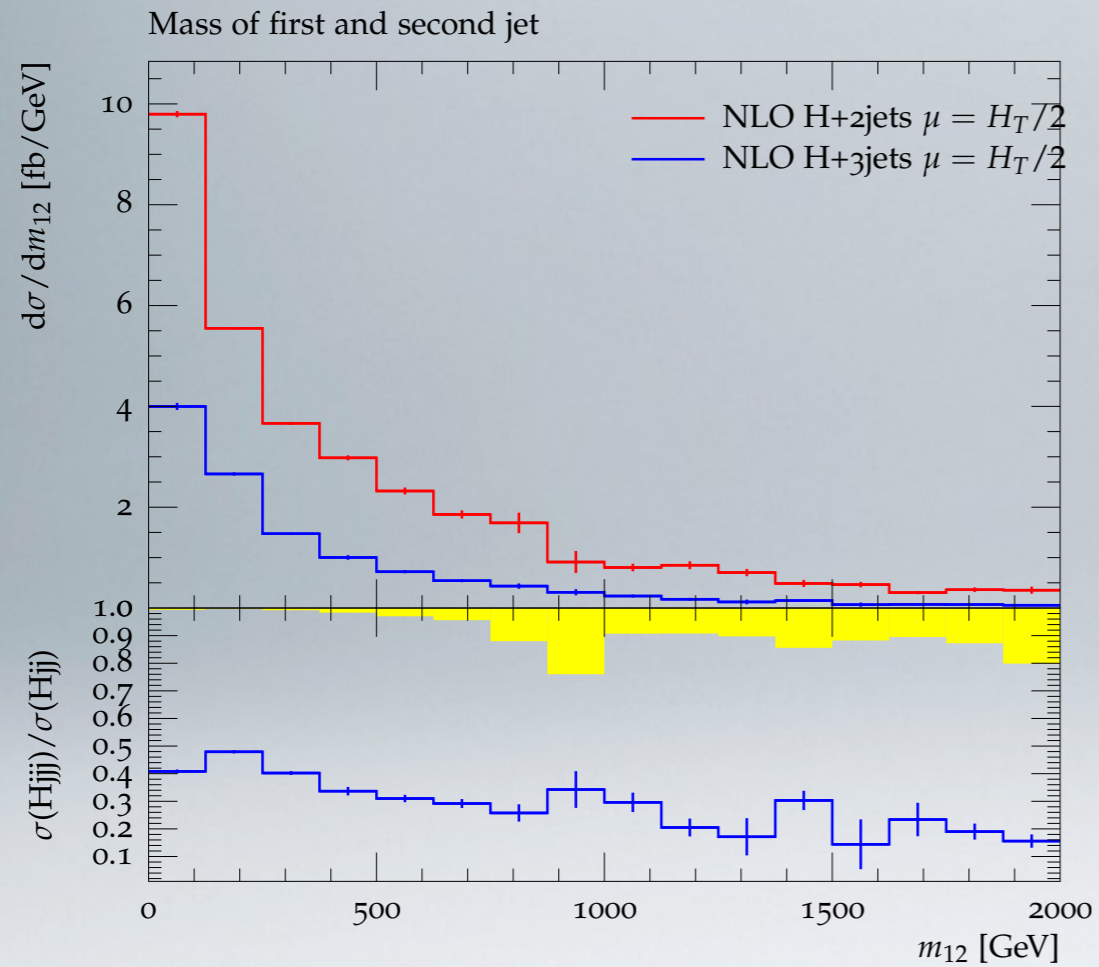


# Jet Masses

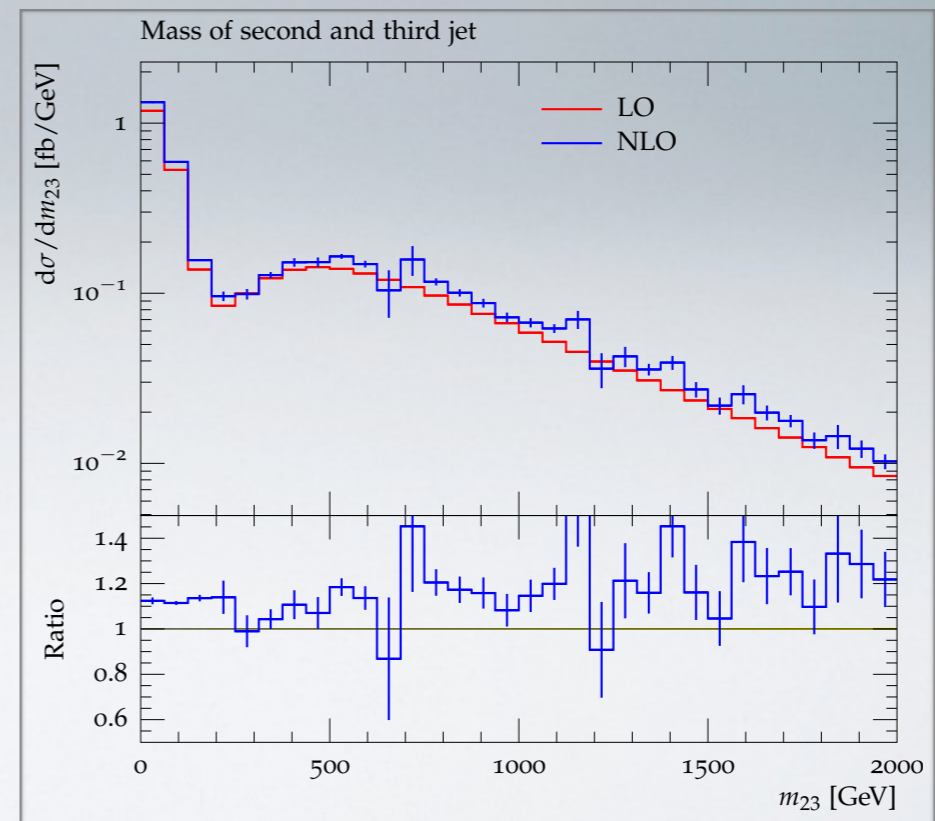
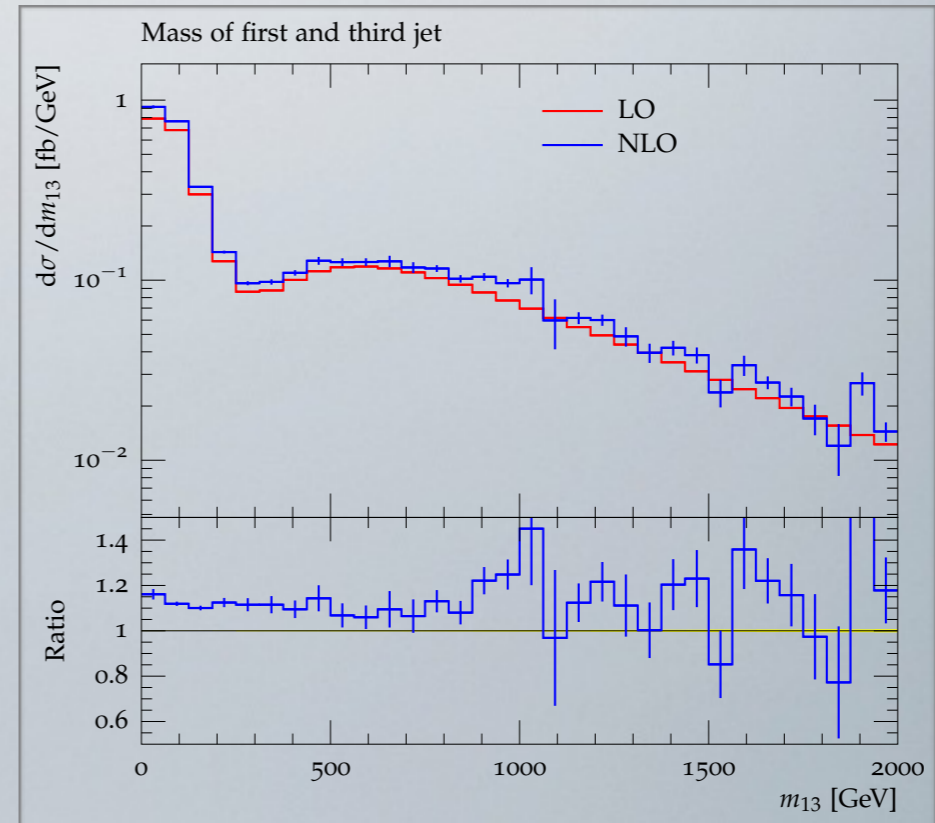
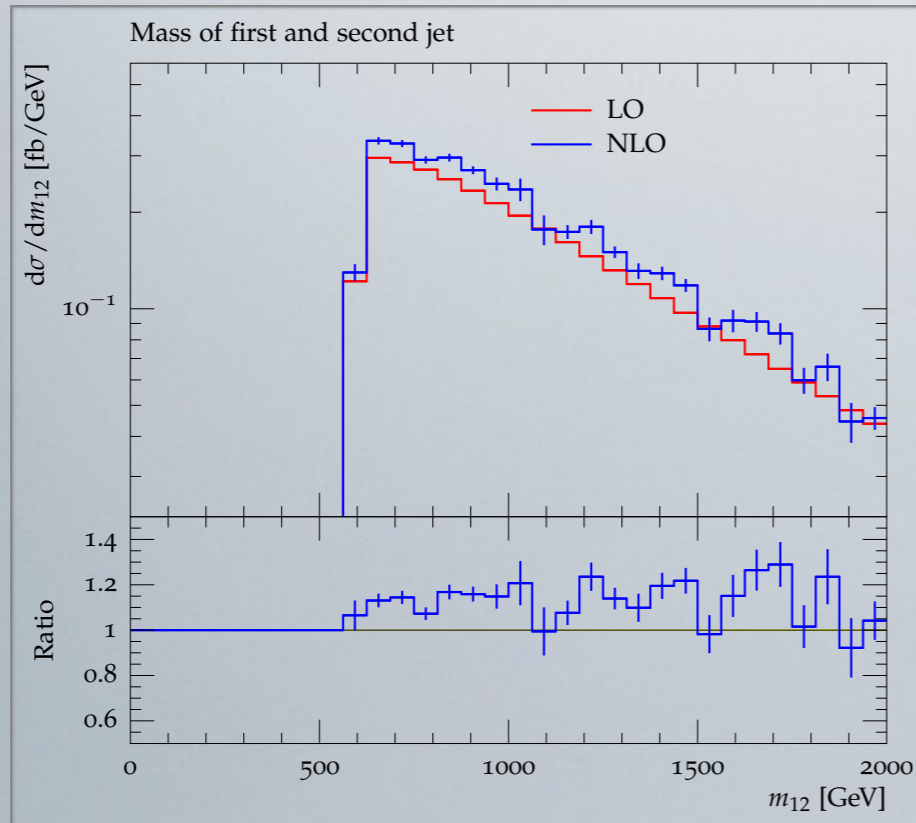


Here we see fat jets.

# H+3 JETS AND H+2 JETS

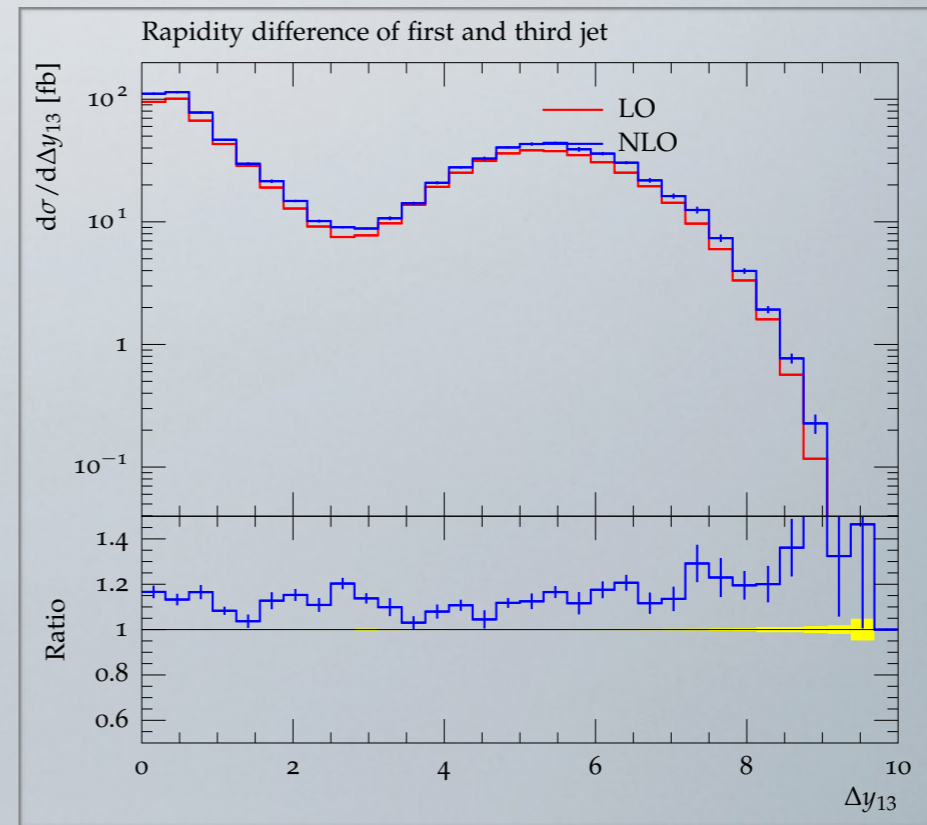
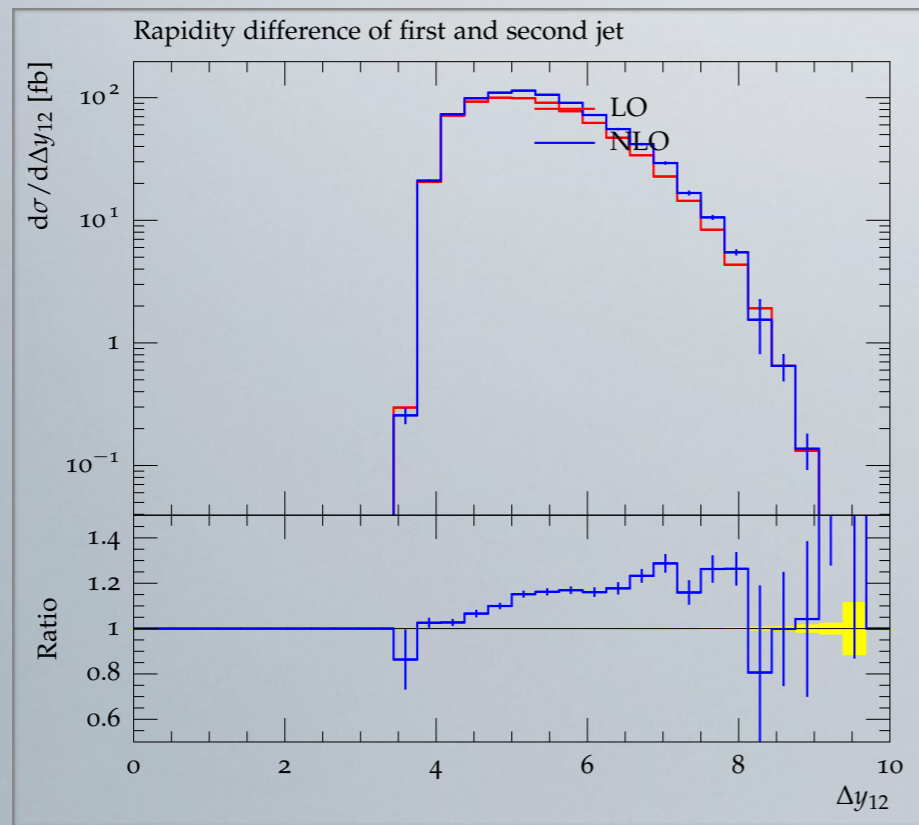


# Distributions with VBF cuts

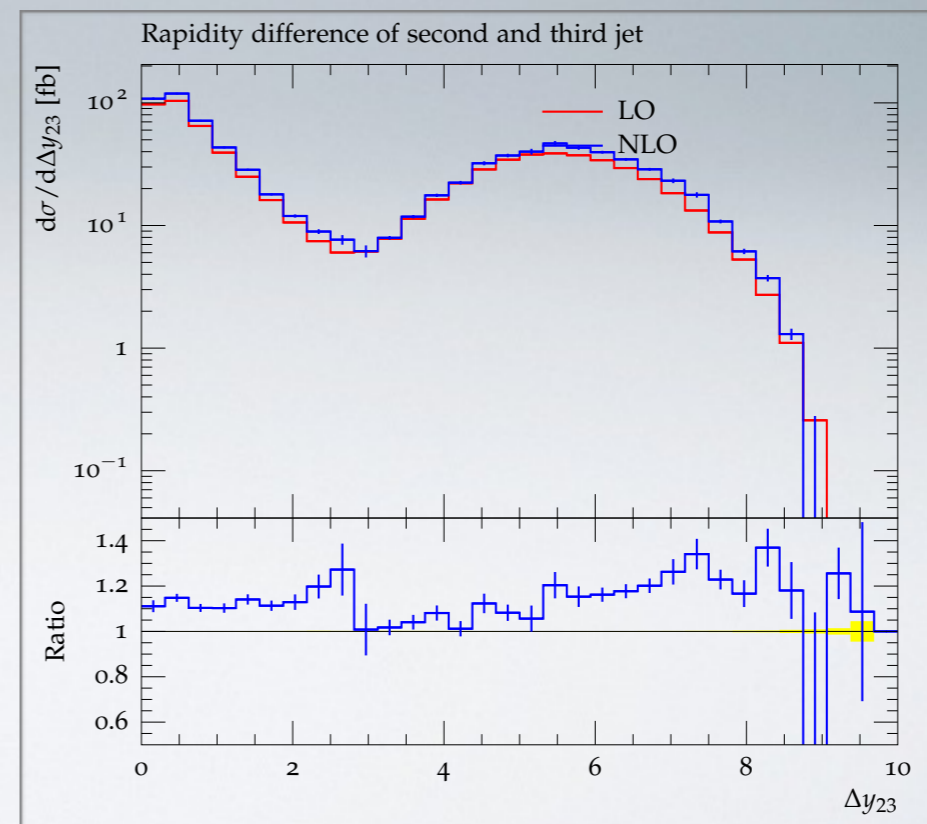


- $m_{j_1 j_2} > 600 \text{ GeV}$
- $\Delta y_{j_1 j_2} > 4.0$

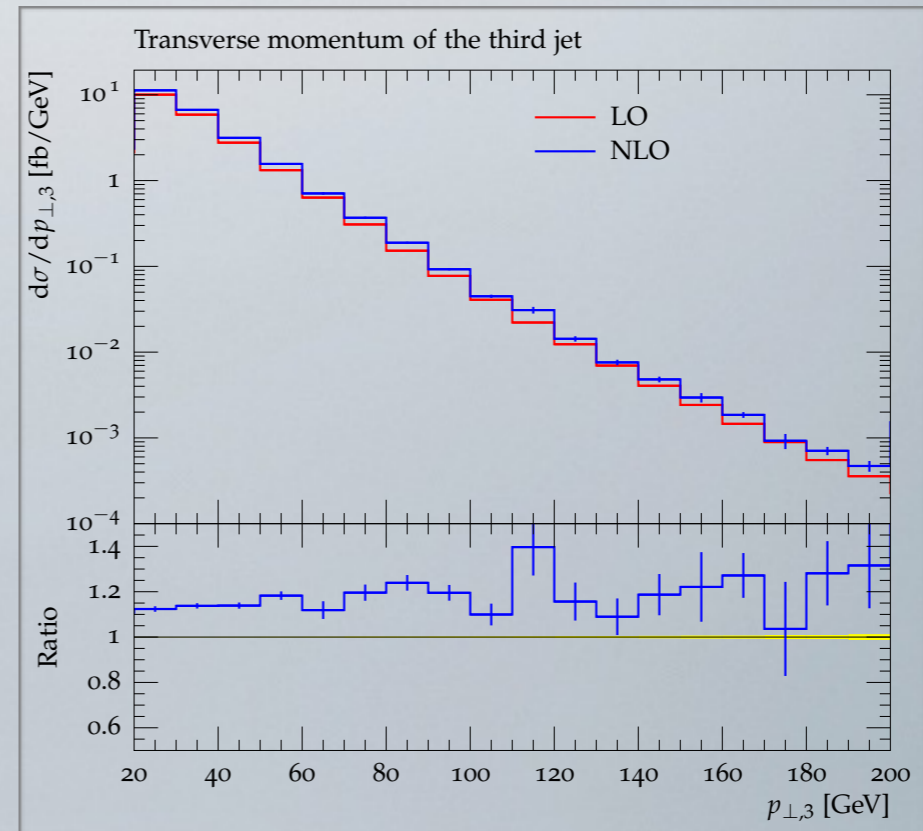
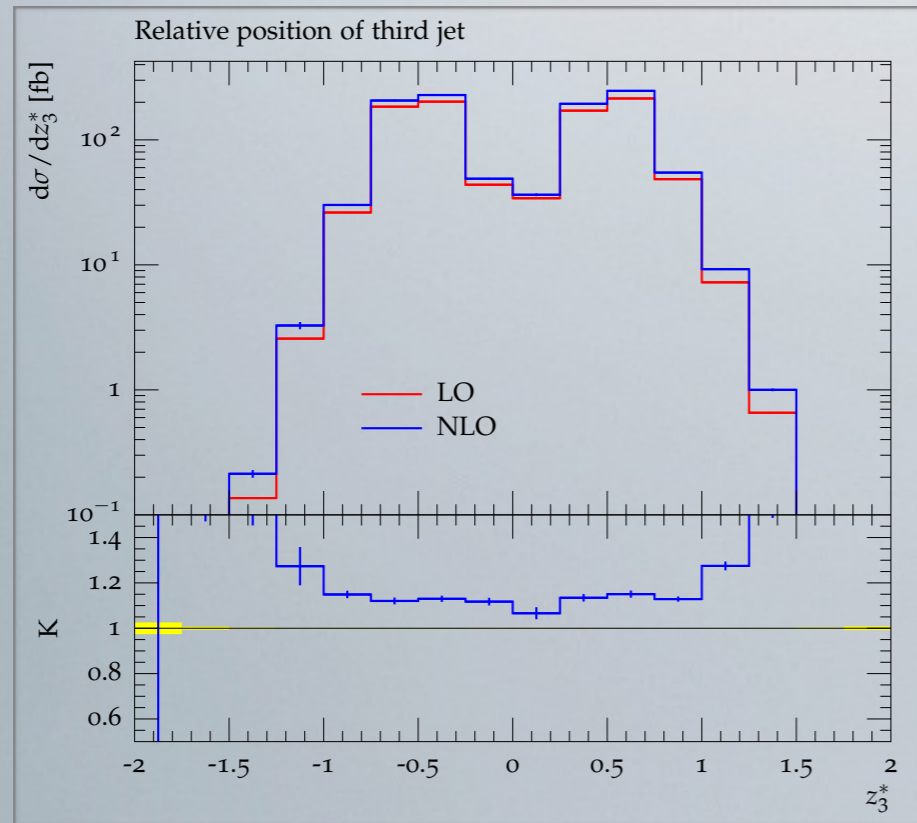
# Distributions with VBF cuts



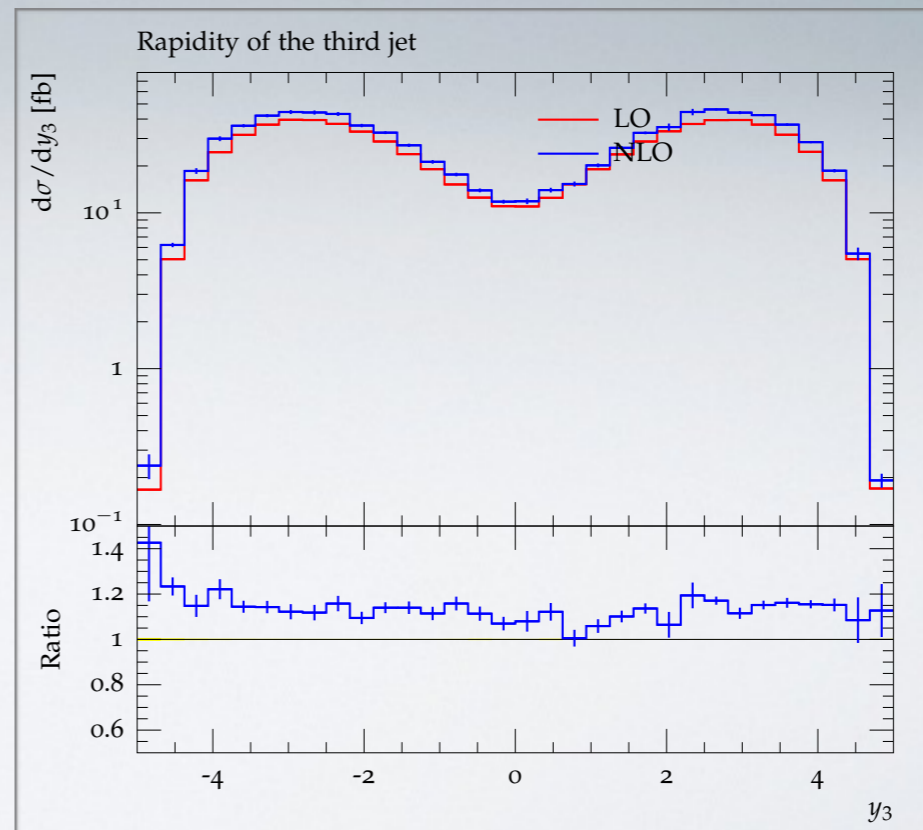
- $m_{j_1 j_2} > 600$  GeV
- $\Delta y_{j_1 j_2} > 4.0$

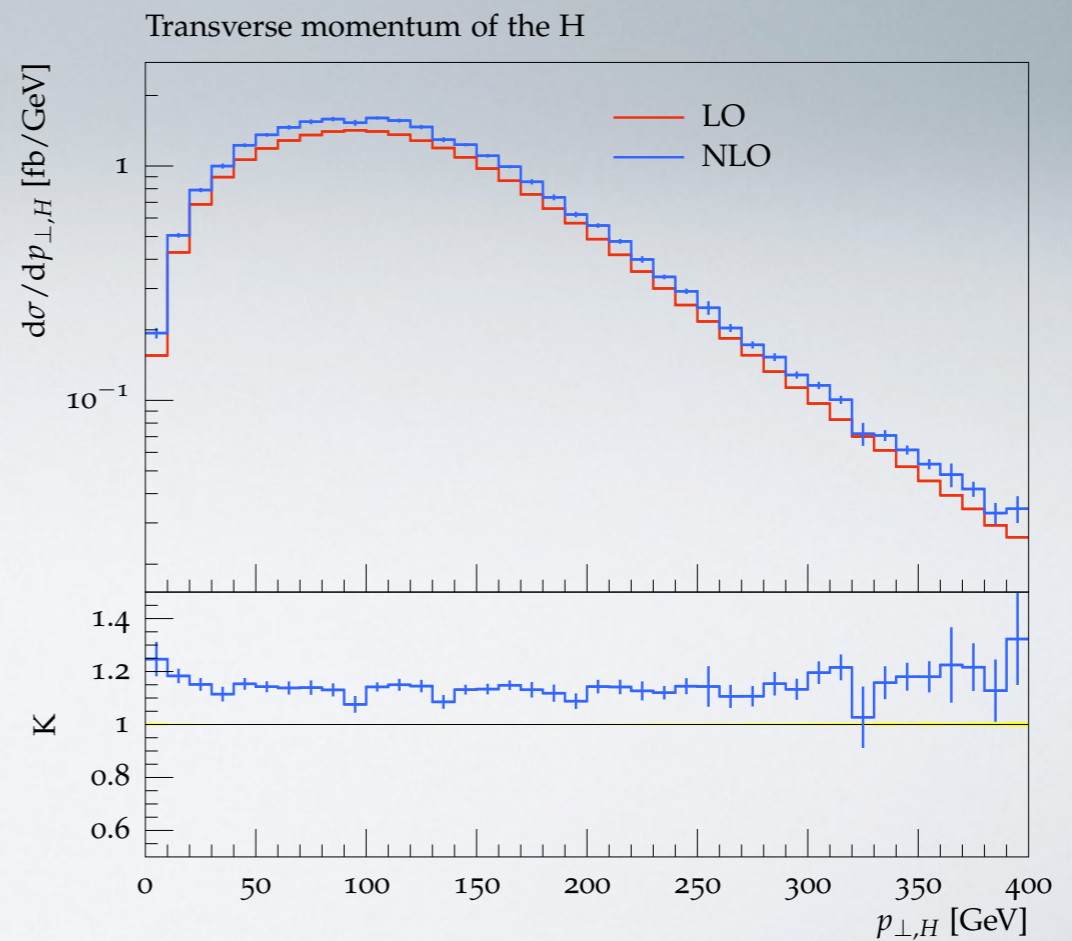
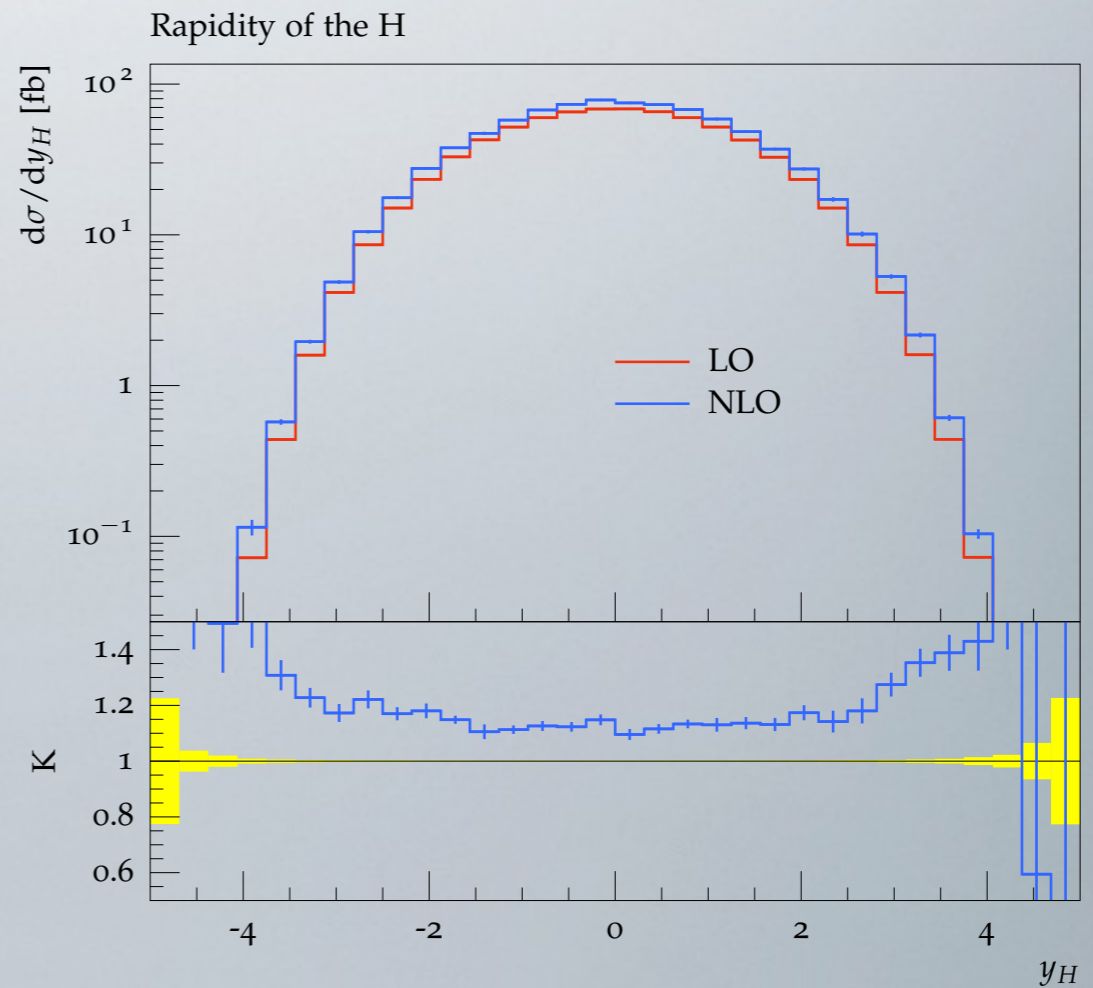
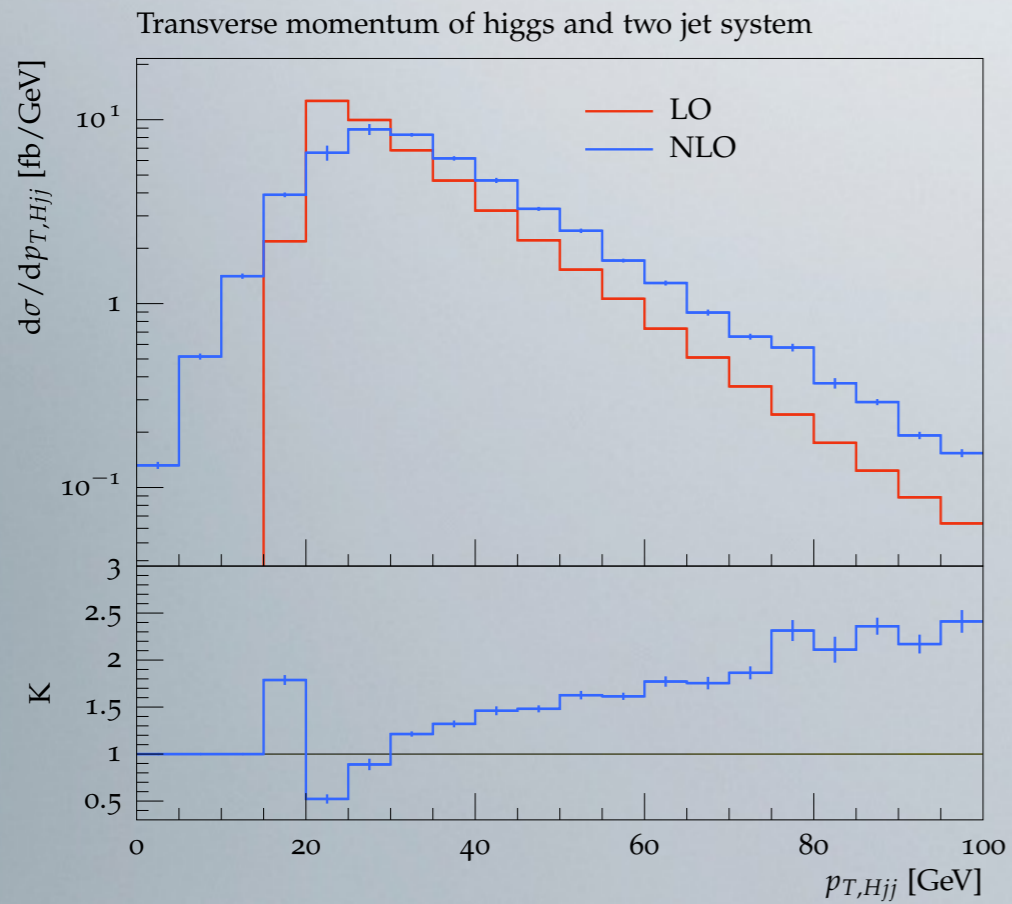


# Distributions with VBF cuts



- $m_{j_1 j_2} > 600$  GeV
- $\Delta y_{j_1 j_2} > 4.0$

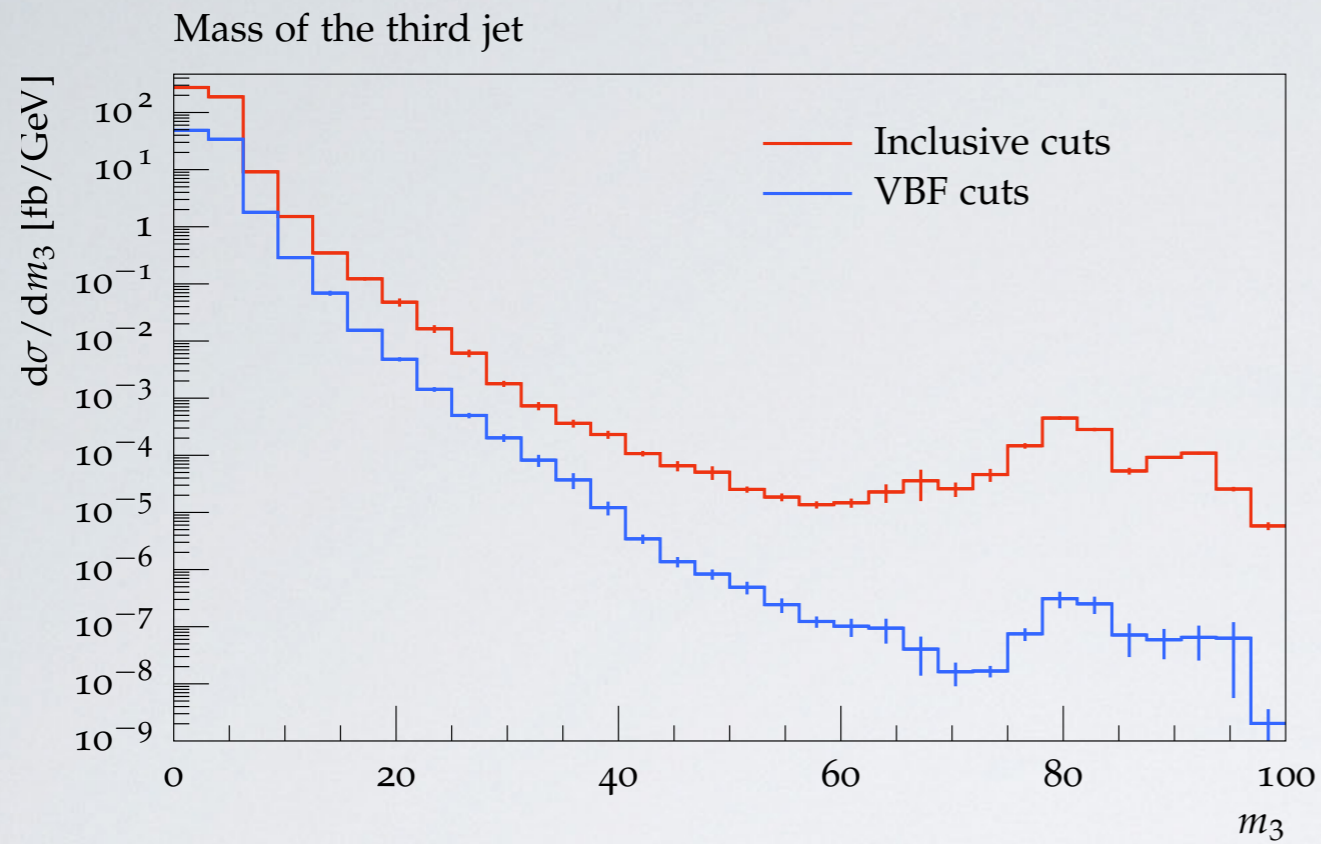




- $m_{j_1 j_2} > 600 \text{ GeV}$

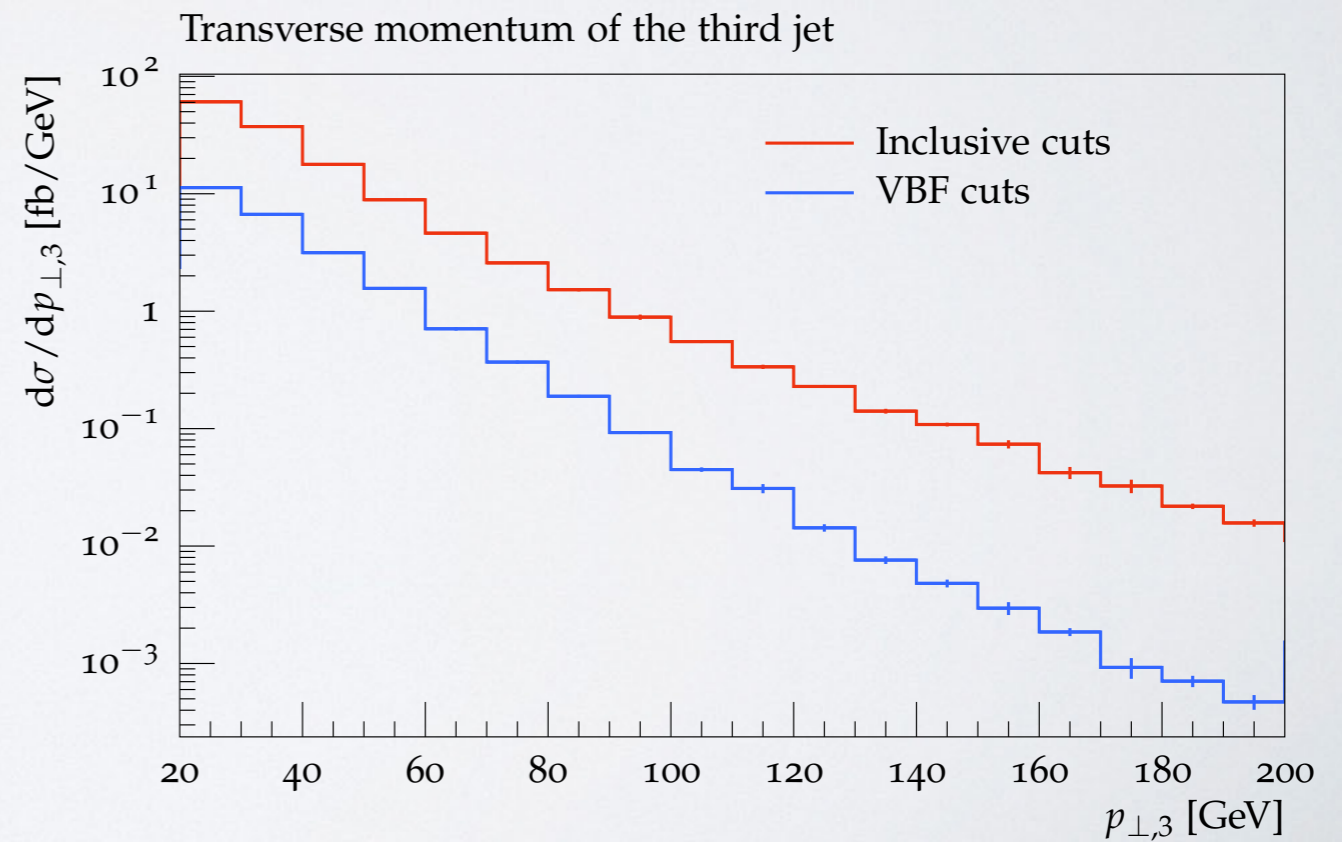
- $\Delta y_{j_1 j_2} > 4.0$





Third Jet Mass

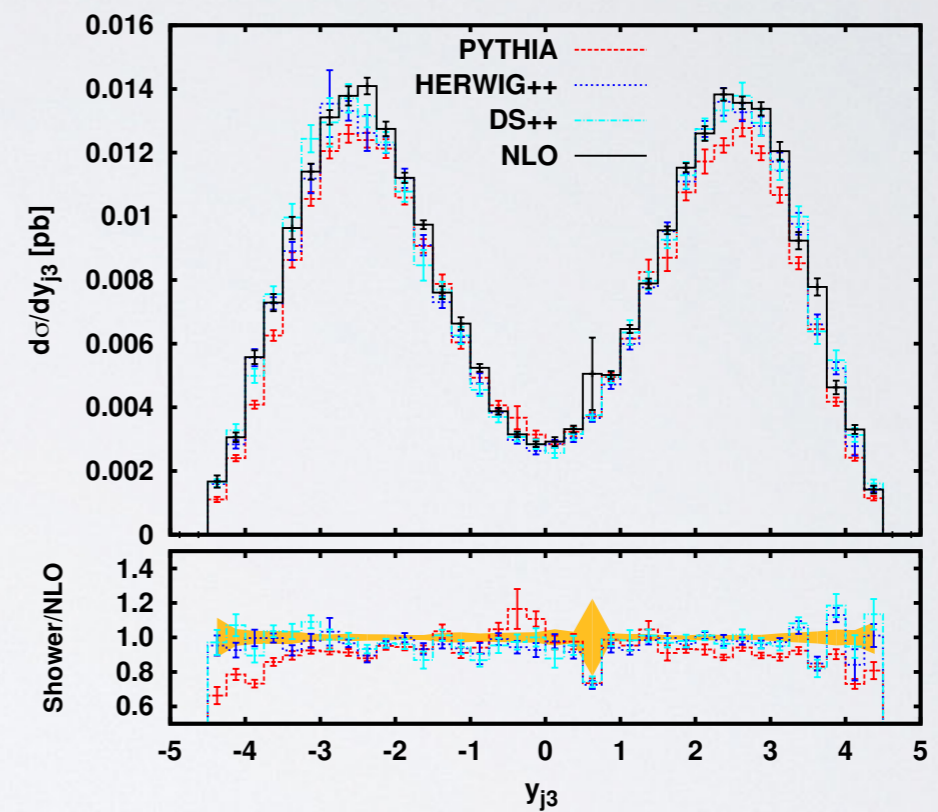
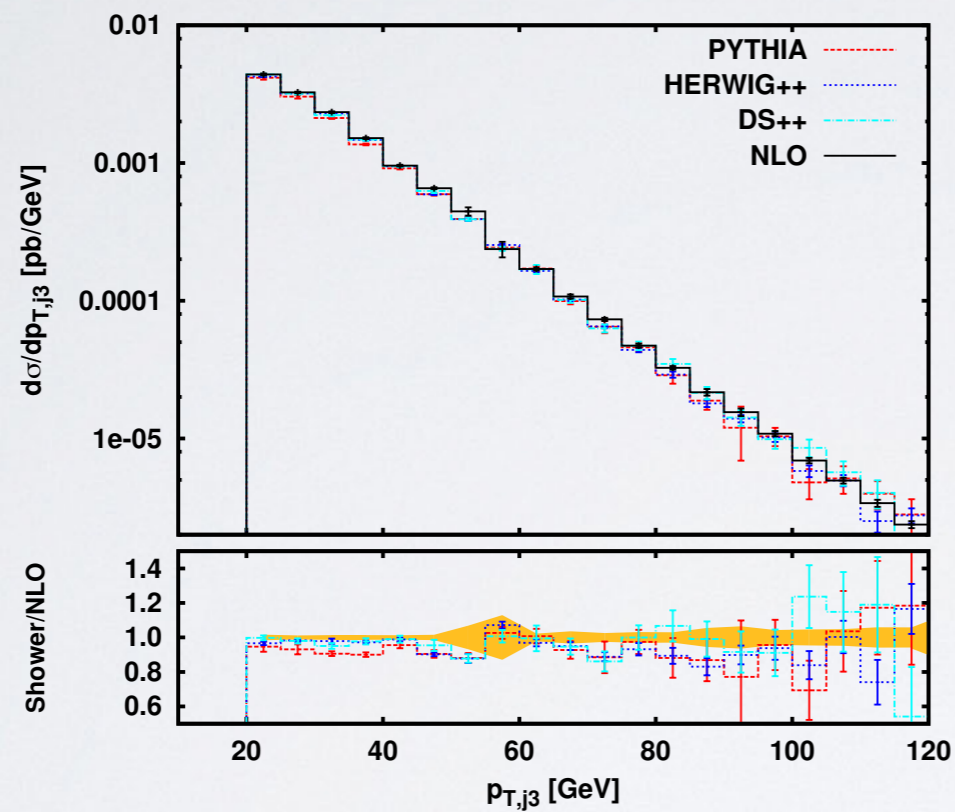
PT of Third Jet



# OUTLOOK

- NLO + Parton Shower matching
- Perform comprehensive phenomenology for Run 2
- Matching H+2 jets and H+3 jets to parton shower

# Parton-shower effects on Higgs boson plus 3 jets (arXiv:1405.6950) [Jager, Schissler, Zeppenfeld]



# Comparison to VBFNLO

