NLO QCD CORRECTIONS TO ELECTROWEAK HIGGS BOSON PLUS THREE JET PRODUCTION AT THE LHC

IN COLLABORATION WITH
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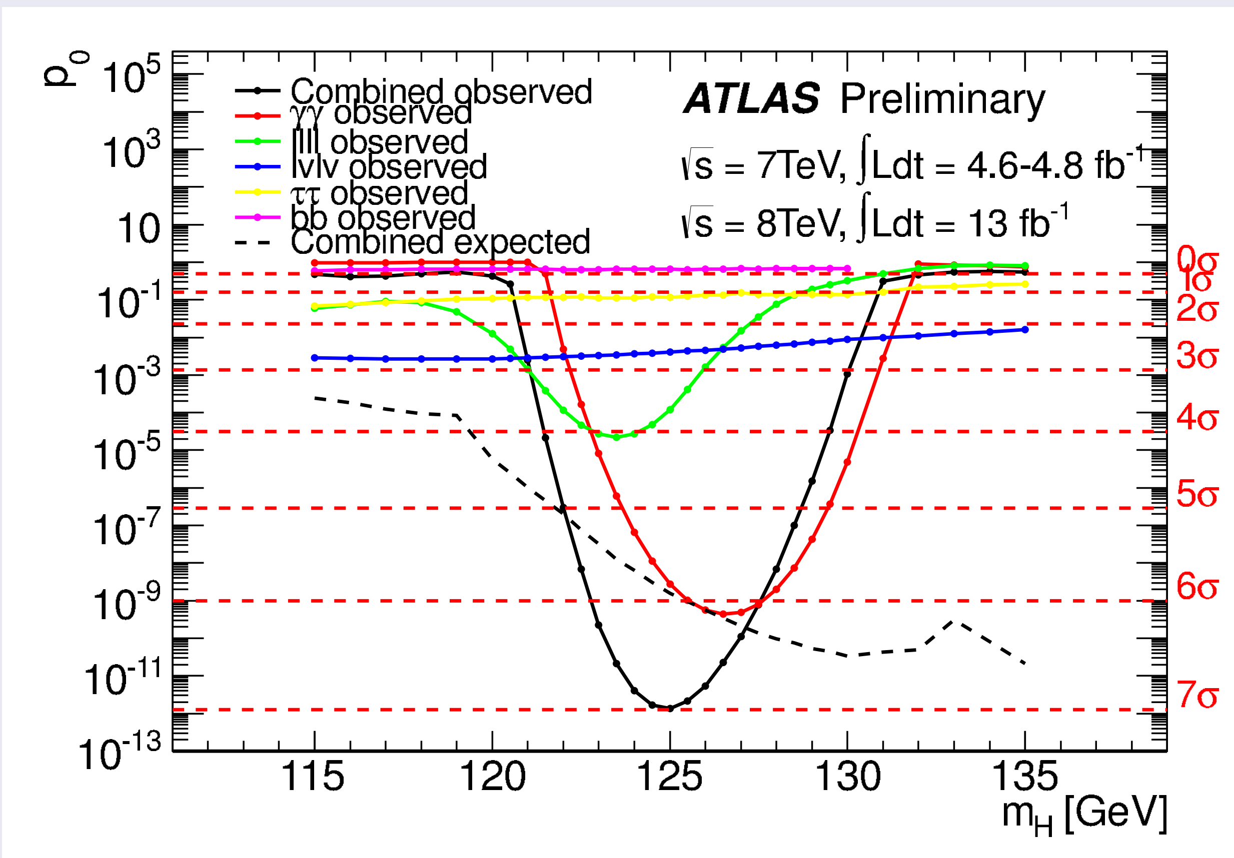
OUTLINE

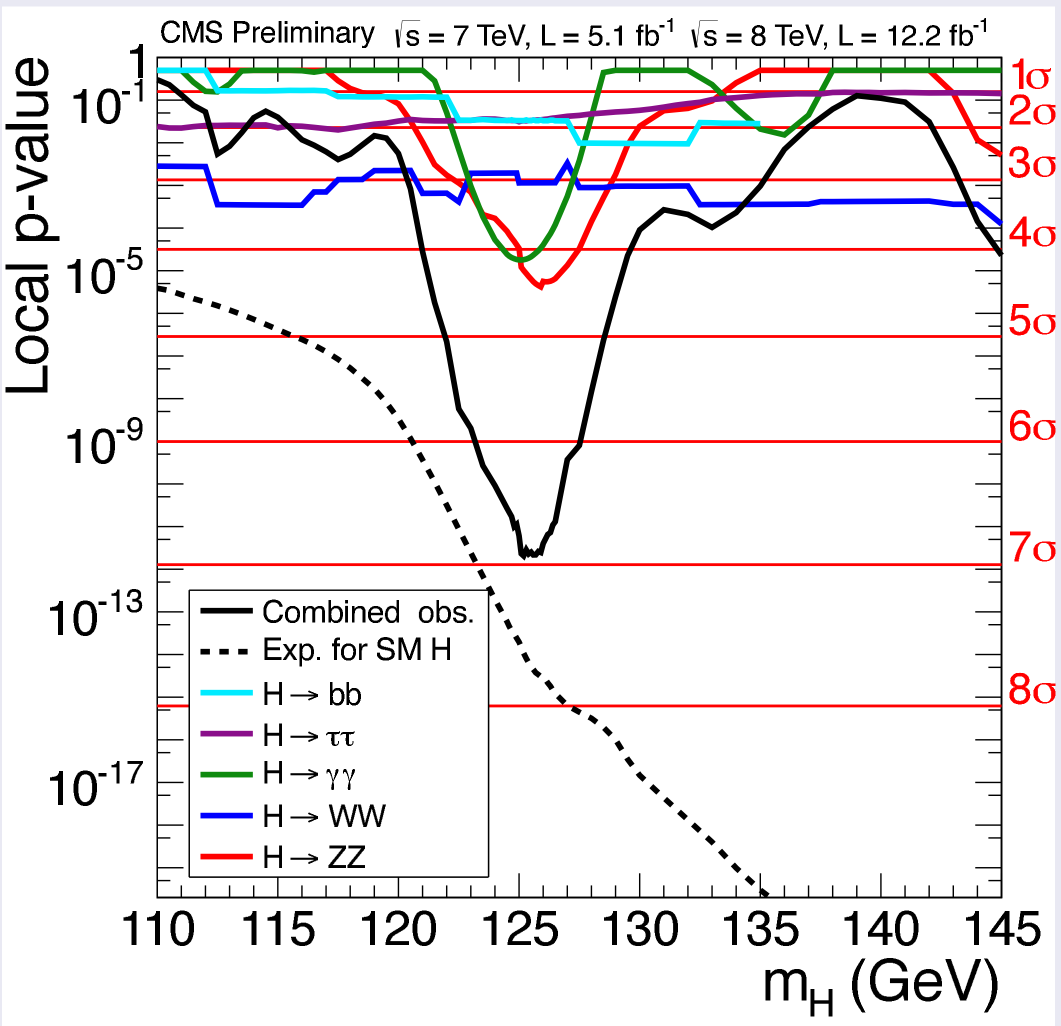
- Introduction
- Some Details
- The Results
- Outlook

Happy Higgsdependence Day!

"I think we have it" -Rolf-Dieter Heuer, 4 July 2012



ATLAS-CONF-2012-170



CMS-PAS-HIG-12-045

SM Higgs boson

Spontaneous Symmetry Breaking: $SU(2)_L \times U(1)_Y \to U(1)_{em}$

SM Higgs Doublet

$$\Phi = U(x)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

The remormalizable Lagrangian

$$\mathcal{L} = |D_\mu \Phi|^2 + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

leads to the vacuum expectation value $v = \sqrt{\frac{\mu^2}{\lambda}}$ for the Higgs field H.

SM Higgs boson

Higgs couplings to fermions

Fermion masses arise from Yukawa couplings via $\Phi^\dagger \rightarrow \left(0, \frac{v+H}{\sqrt{2}}\right)$.

$$\mathcal{L}_{\text{Yukawa}} = -\sum_f m_f \bar{f} f \left(1 + \frac{H}{v}\right)$$

- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_f / v$
- Observation of $H f \bar{f}$ Yukawa coupling is no proof that a v.e.v exists

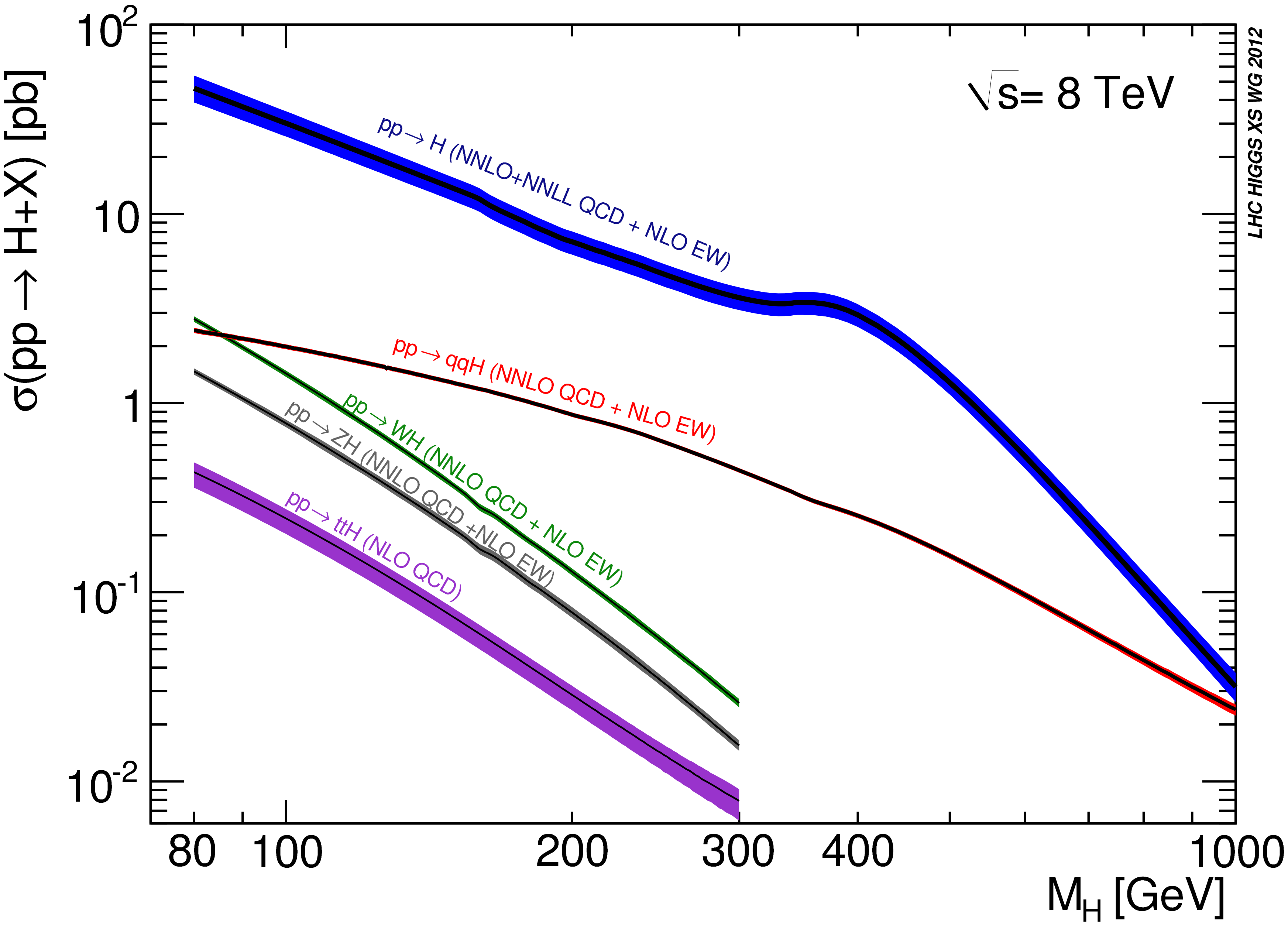
SM Higgs boson
Higgs couplings to gauge bosons

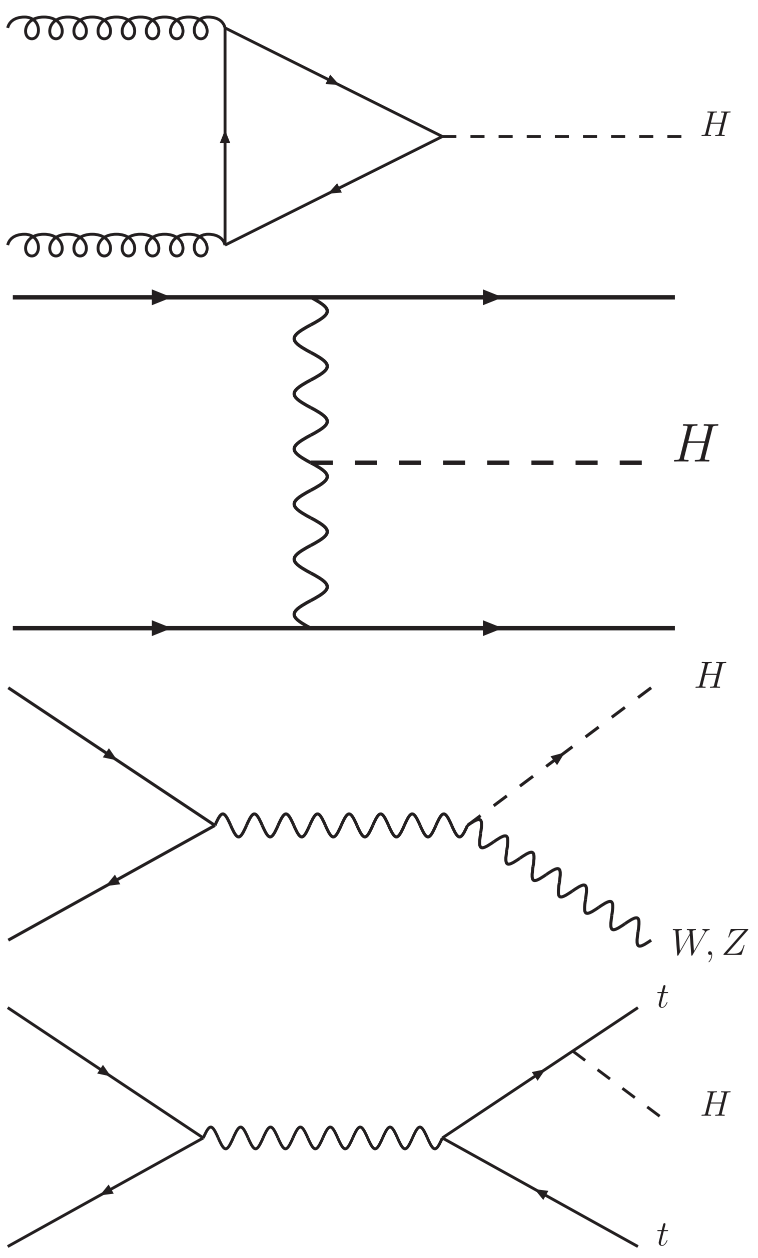
Kinetic energy term of the Higgs doublet field:

$$(D^\mu \Phi)^\dagger (D_\mu \Phi) = \frac{1}{2}\partial^\mu H \partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu +} W^-_\mu + \frac{1}{2}\frac{(g^2+g'^2)v^2}{4} Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

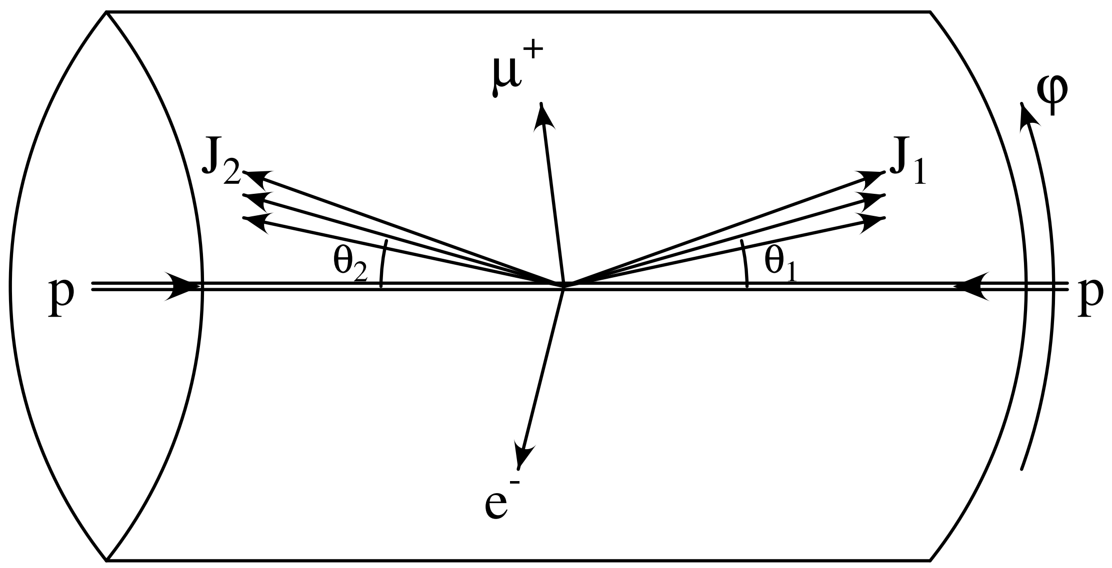
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{\left(g^2+g'^2\right)v^2}{4}$
- WWH and ZZH couplings are generated:coupling strength $= 2m_V^2/v \approx g^2 v$ within SM

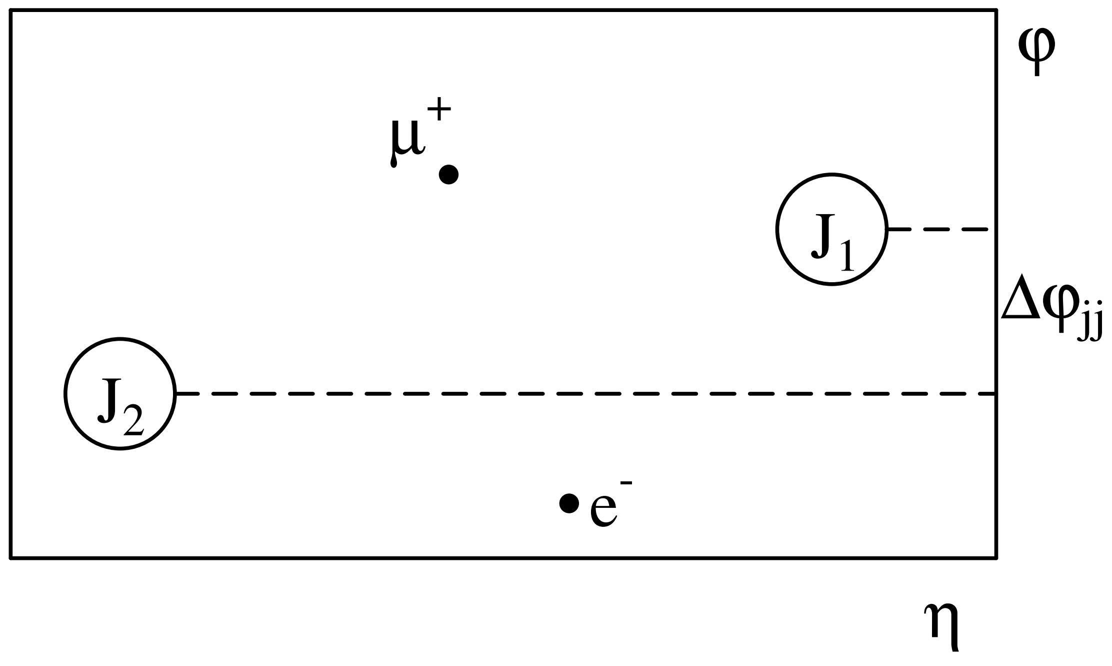
Total SM Higgs cross sections at the LHC





Vector Boson Fusion



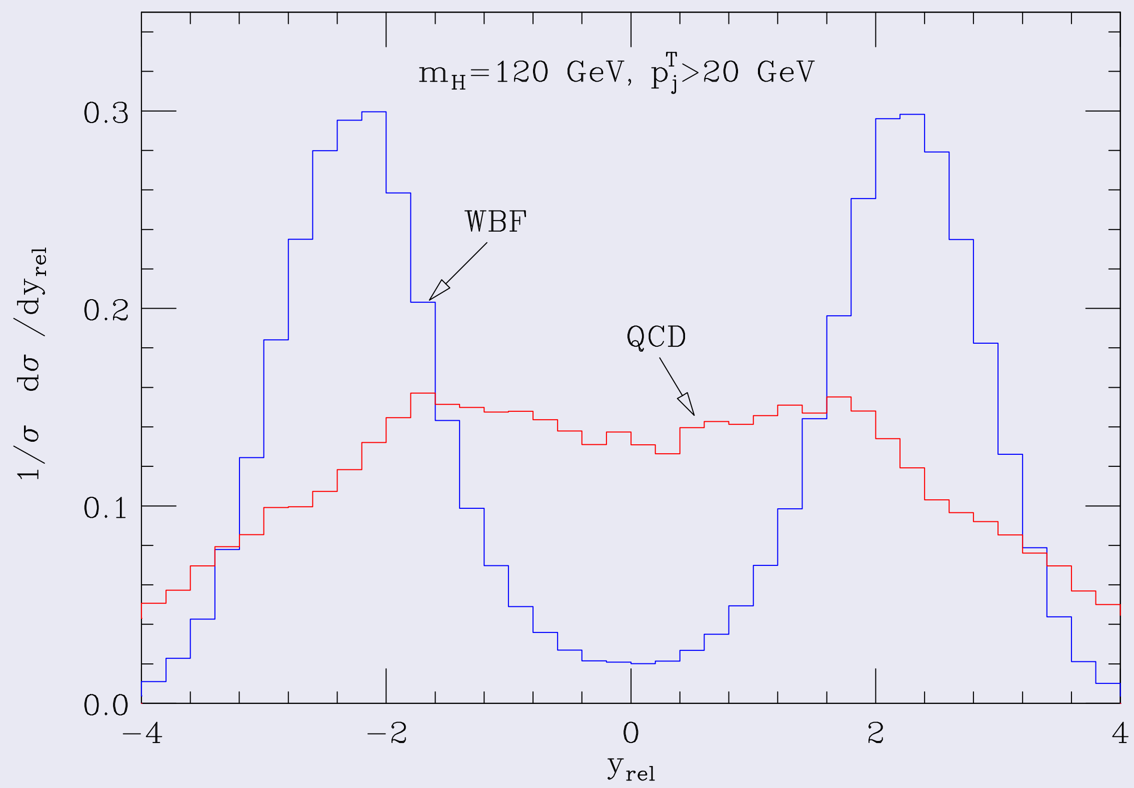


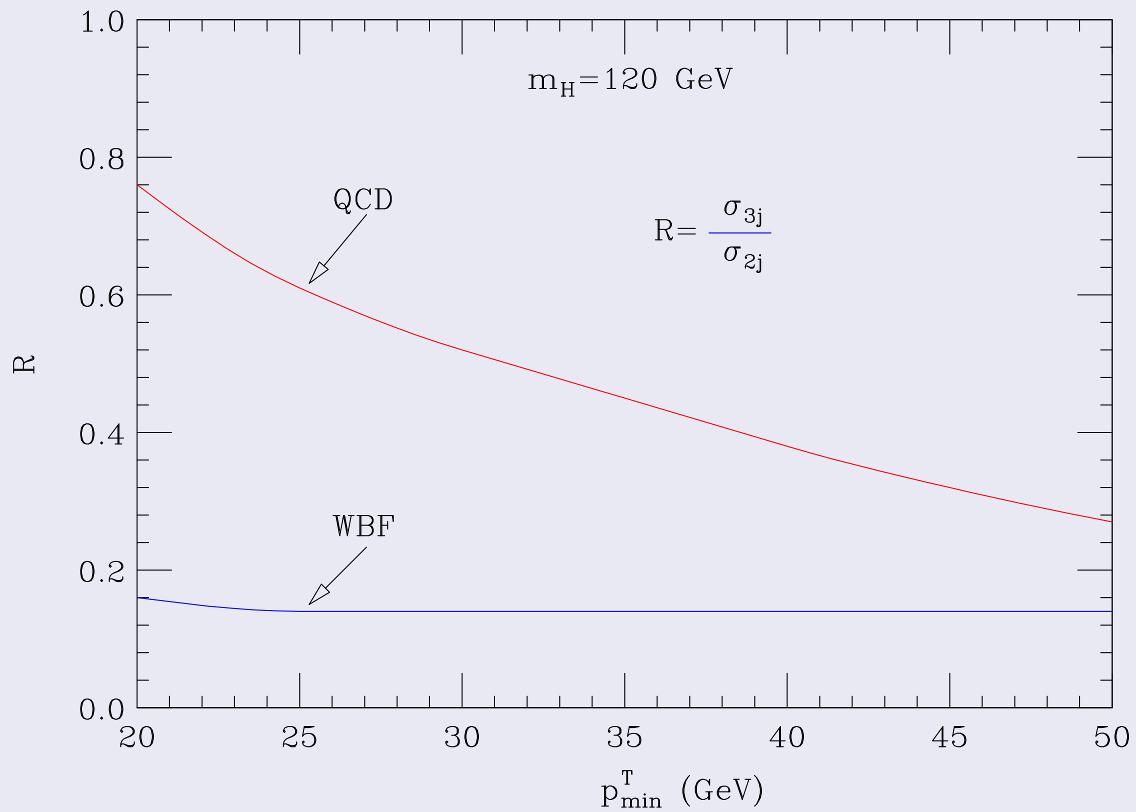
Event Characteristics

- 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



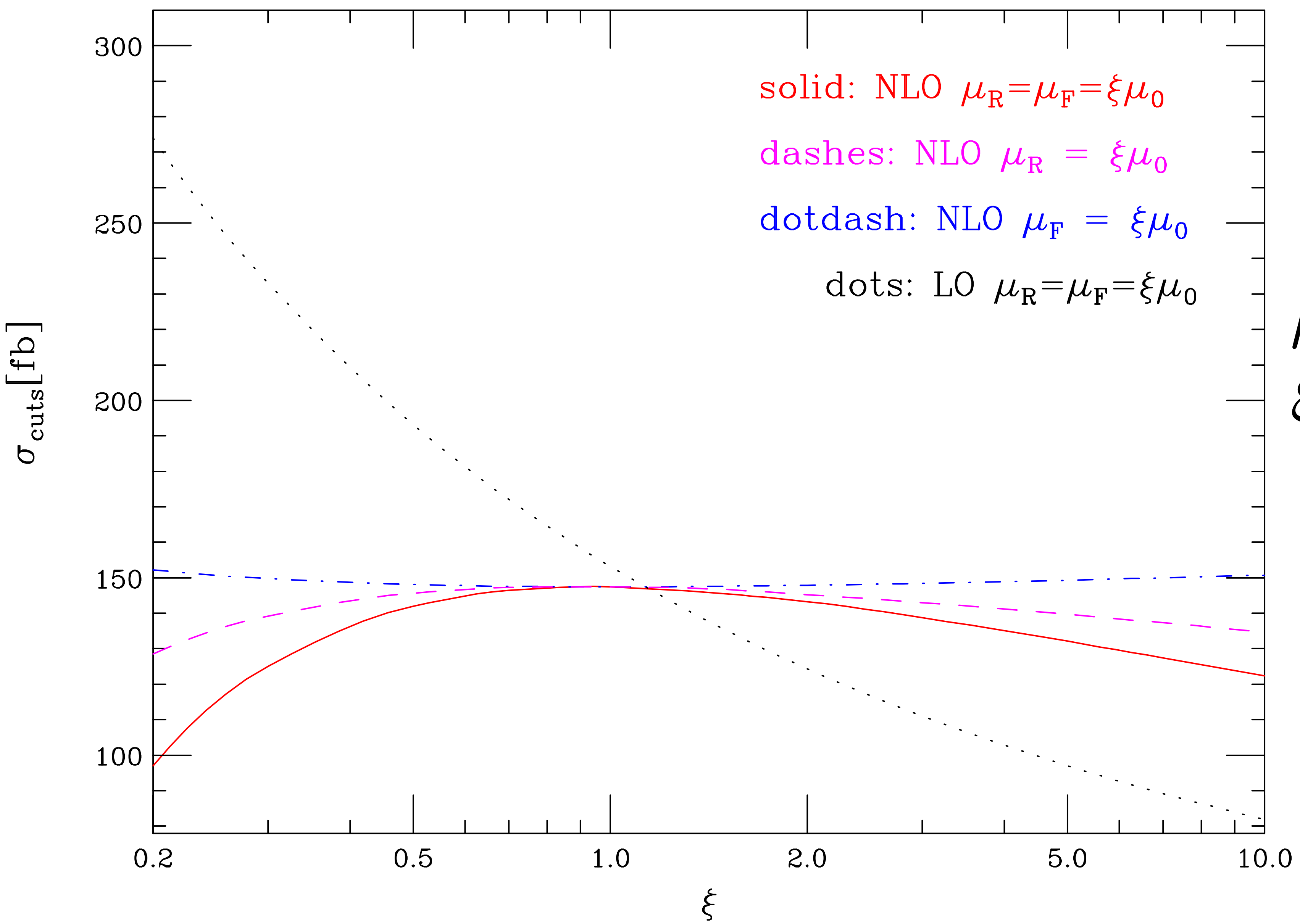


JHEP 05 (2004) 064

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

Hjjj via VBF at NLO (only *t*-channels)

Total Cross section



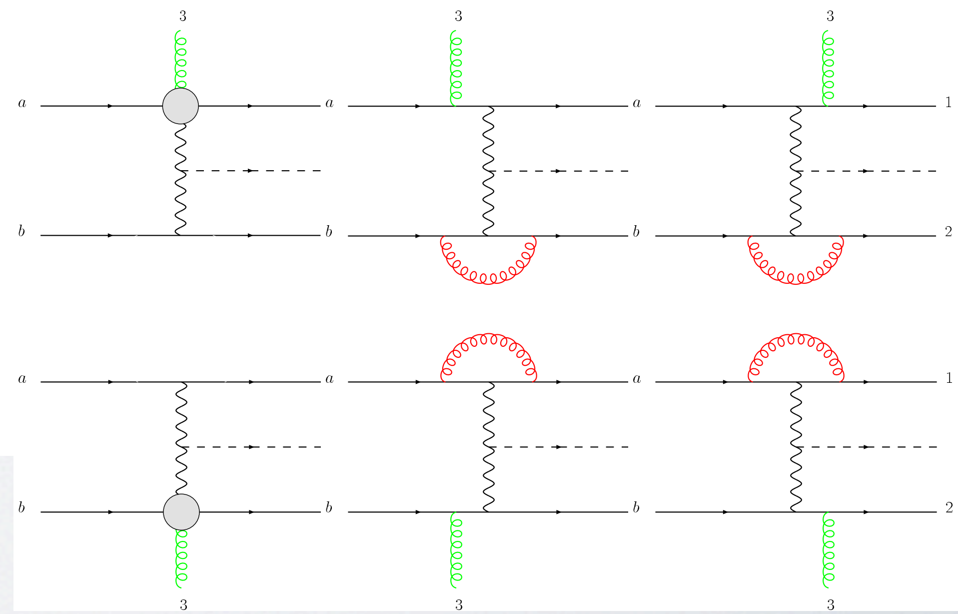
JHEP **0802** (2008) 076 [arXiv:0710.5621]

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

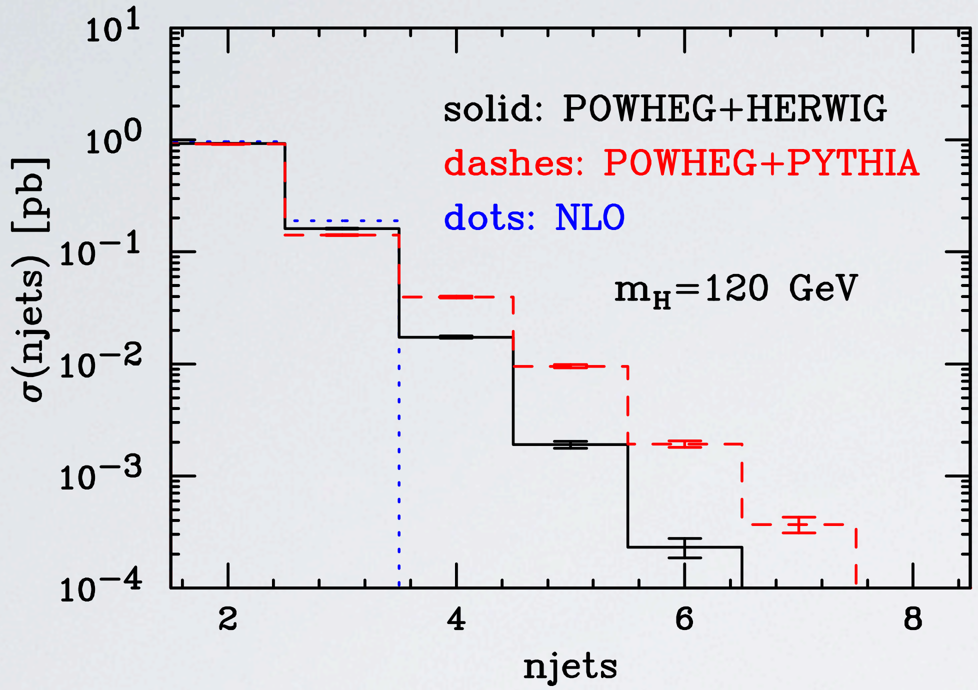
$\mu_0 = 40$ GeV

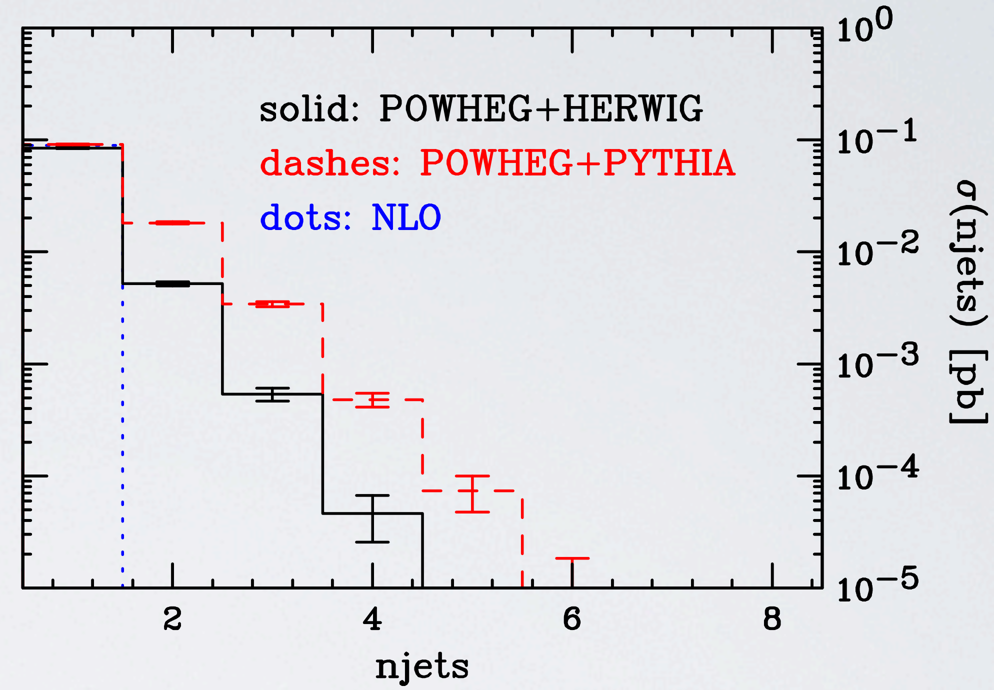
$\xi = 2^{\mp 1}$ scale variations:

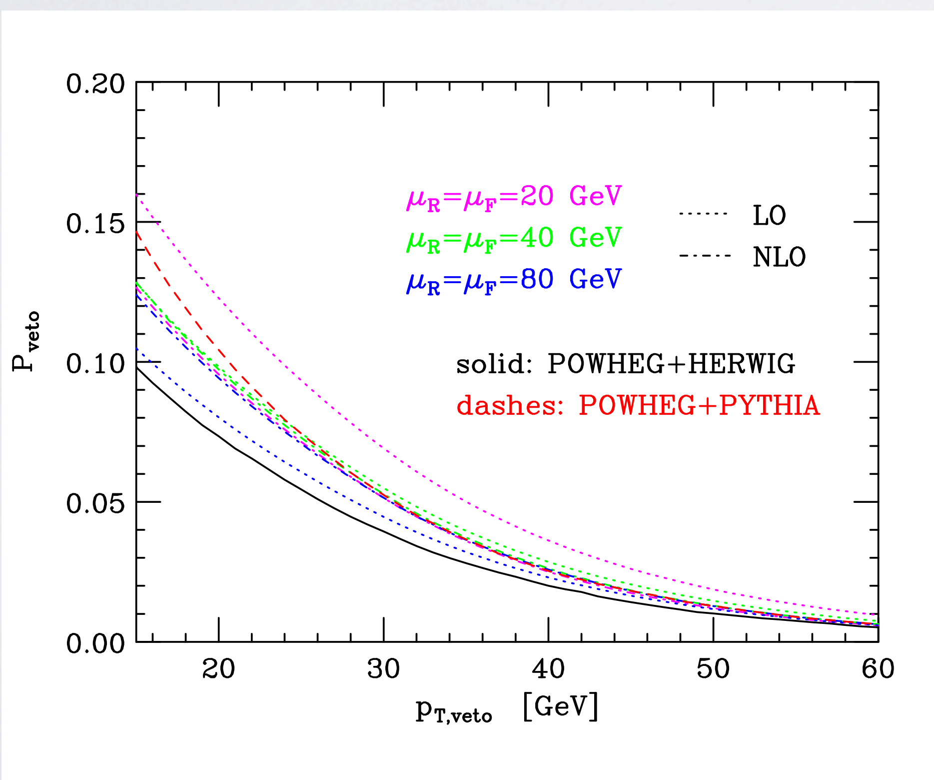
- LO: +26% to −19%
- NLO: less than 5%

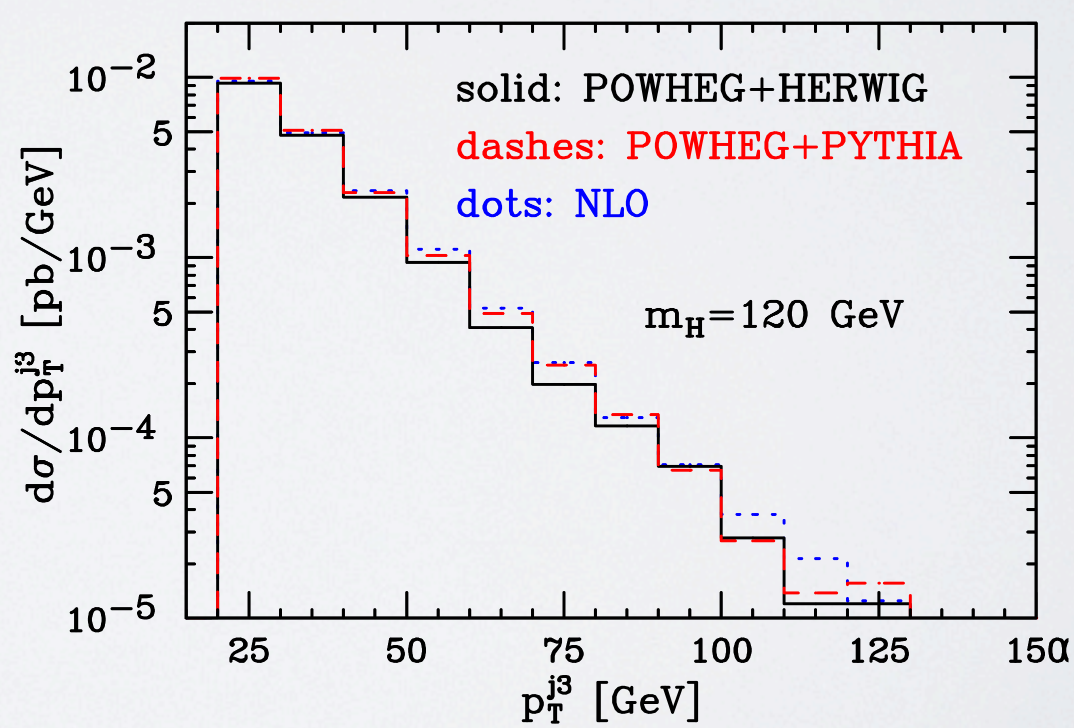


COMMENTS ON VBF POWHEGBOX [ARXIV:0911.5299]





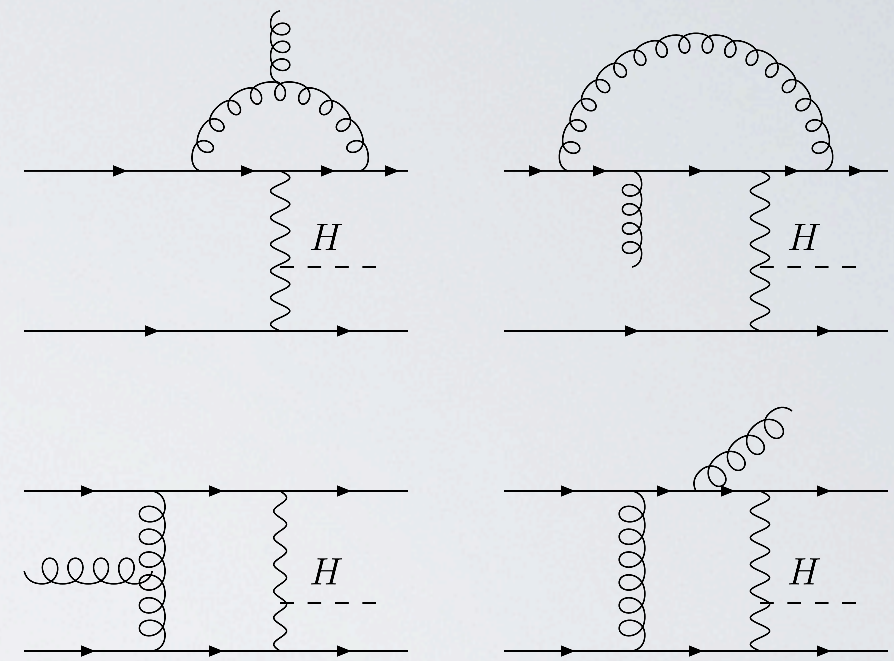




$$\sqrt{S} = 14 \text{ TeV } m_h = 120 \text{ GeV}$$

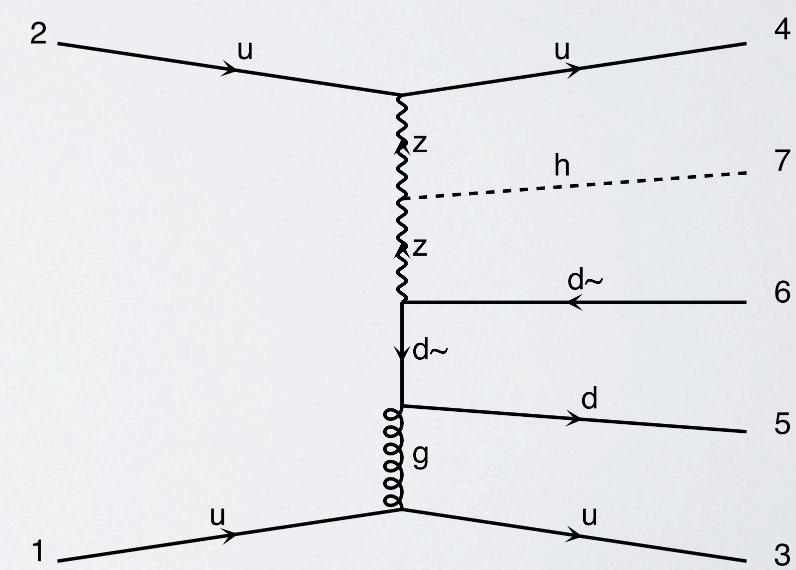
THIS WORK (HJETS++)

- 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)



SOME DETAILS

- 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: OneLOop [A. van Hameren arXiv:1007.4716]

DIPOLE SUBTRACTION

Catani and Seymour, hep-ph/9605323

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

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

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

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

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

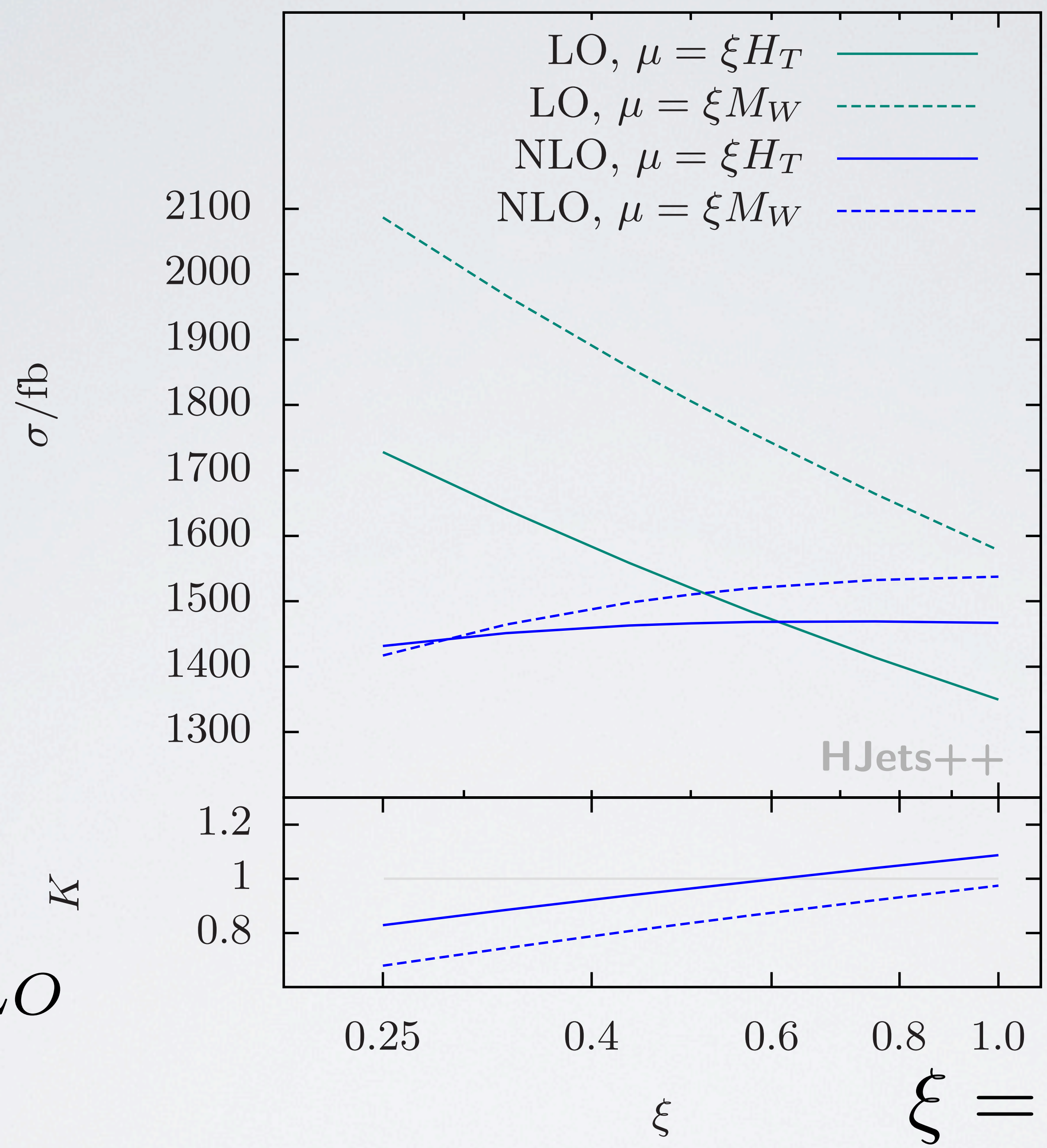
THE RESULTS

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

INPUT PARAMETERS

- Ecm=14 TeV (proton - proton LHC)
- At least three anti-KT D=0.4 (E-scheme recombination) of 20 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 (MW) and sum of transverse momentum of reconstructed jets (HT)

Scale Variations on Integrated Cross-sections



$$\mu_0 = H_T \ (M_W)$$
$$H_T = \sum_j p_{T,j}$$

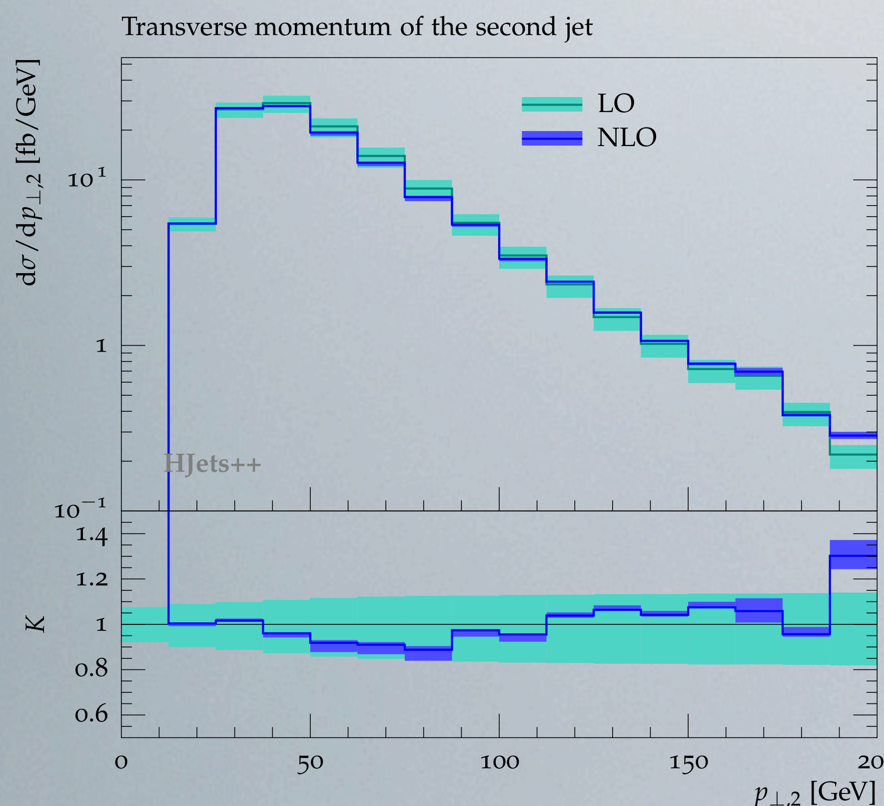
$$K = \sigma_{NLO}/\sigma_{LO}$$

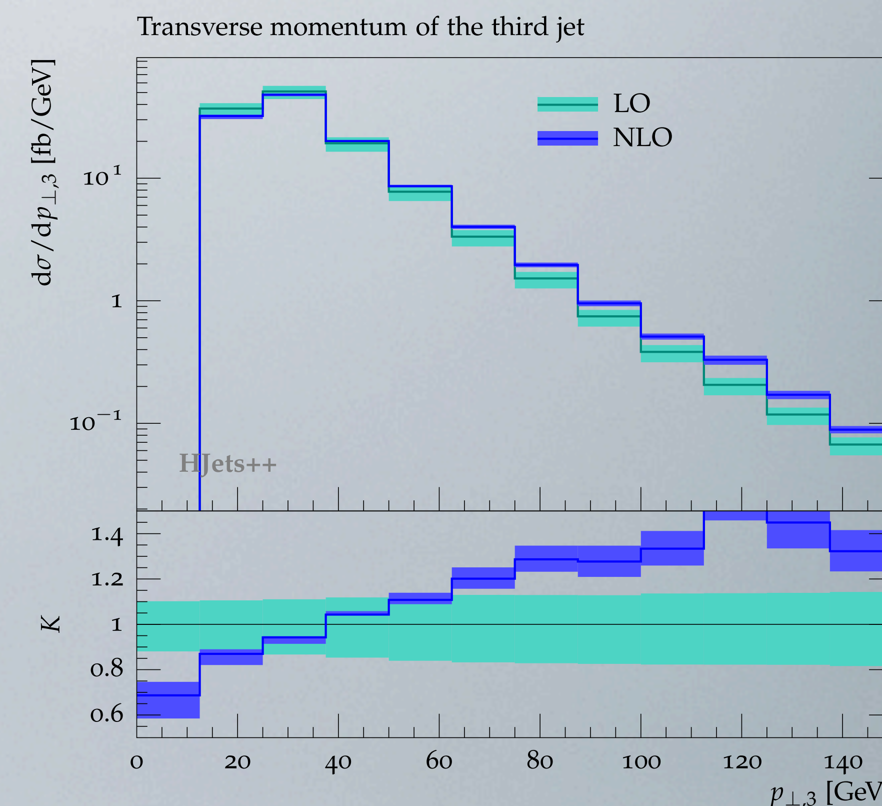
$$\xi = \mu/\mu_0$$

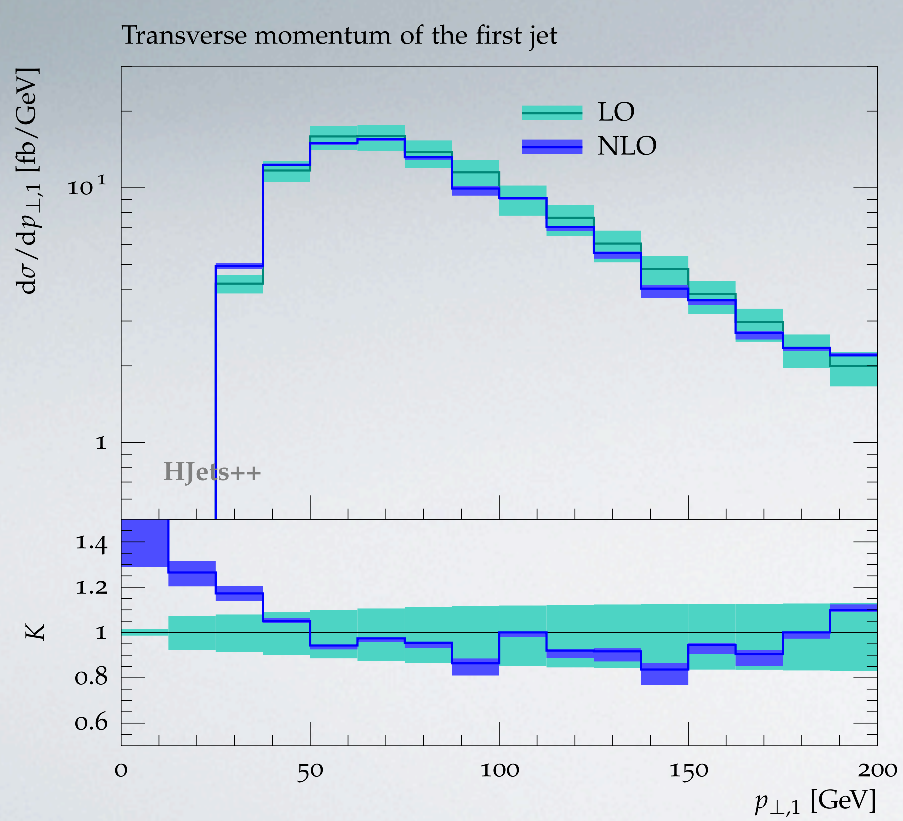
$\mu_R = \mu_F = H_T/2 \ (M_W/2)$:
30% (24%) at LO and 2% (8%) at NLO

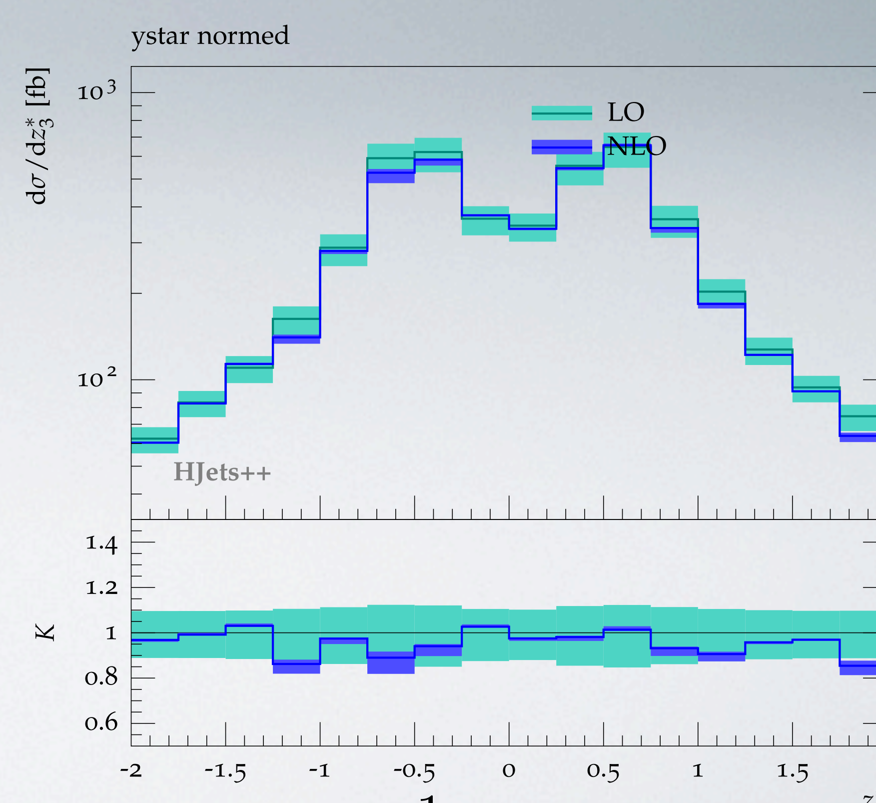
$$\sigma_{LO} = 1520(8)^{+208}_{-171} \text{ fb} \qquad \sigma_{NLO} = 1466(17)^{+1}_{-35} \text{ fb}$$

JET DISTRIBUTIONS



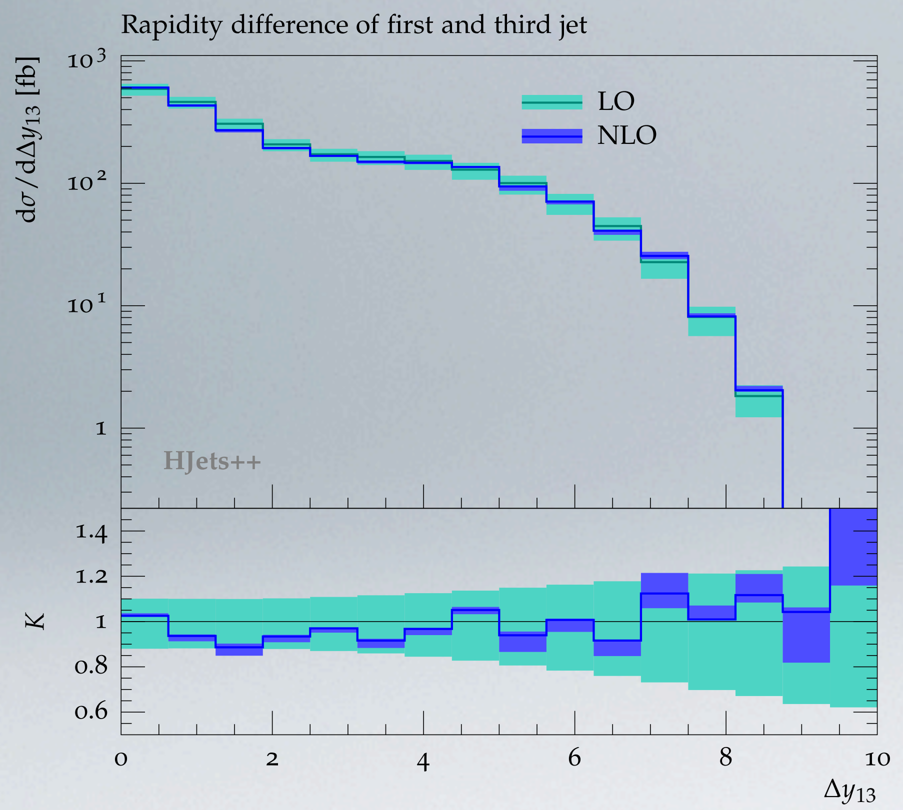


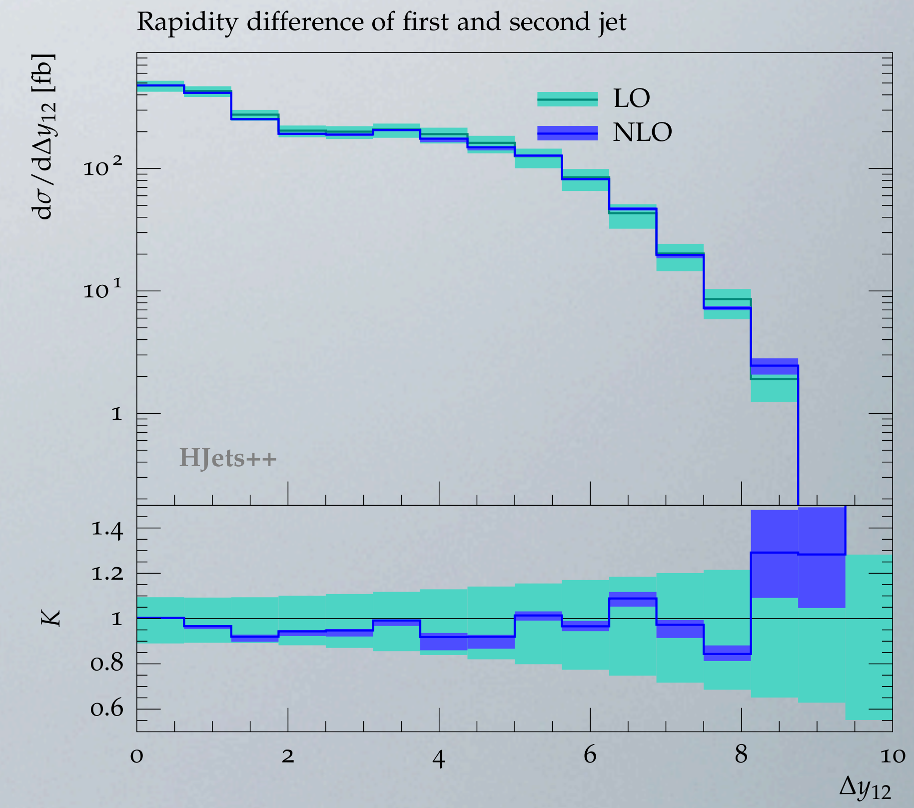


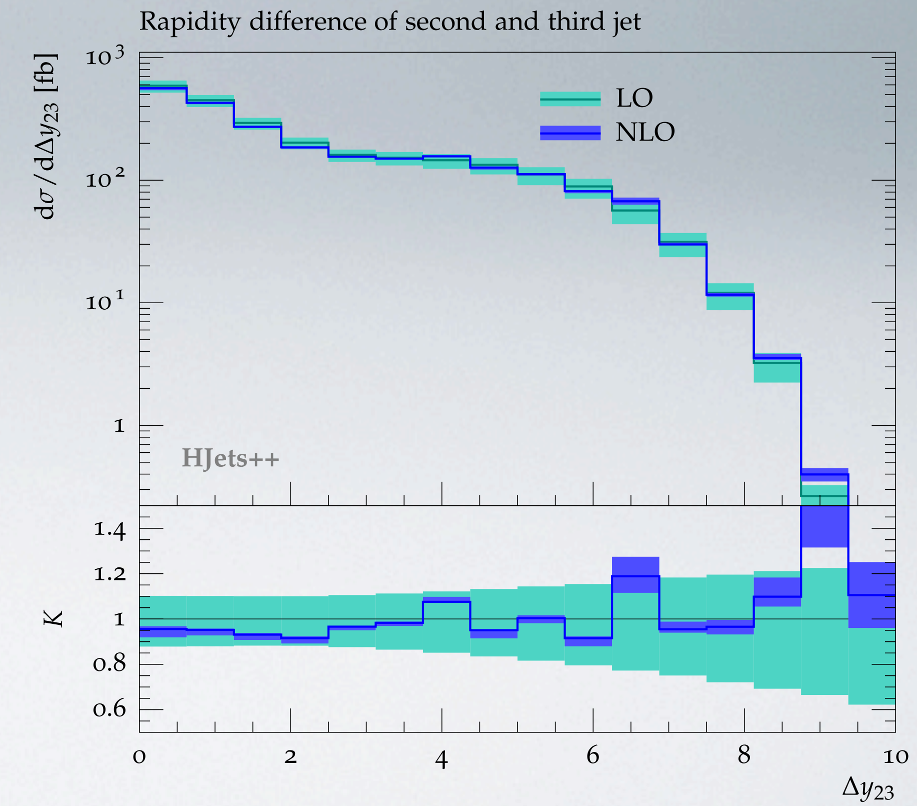


$$z_3^\star = (y_3 - \frac{1}{2}(y_1 + y_2))/(y_1 - y_2)$$

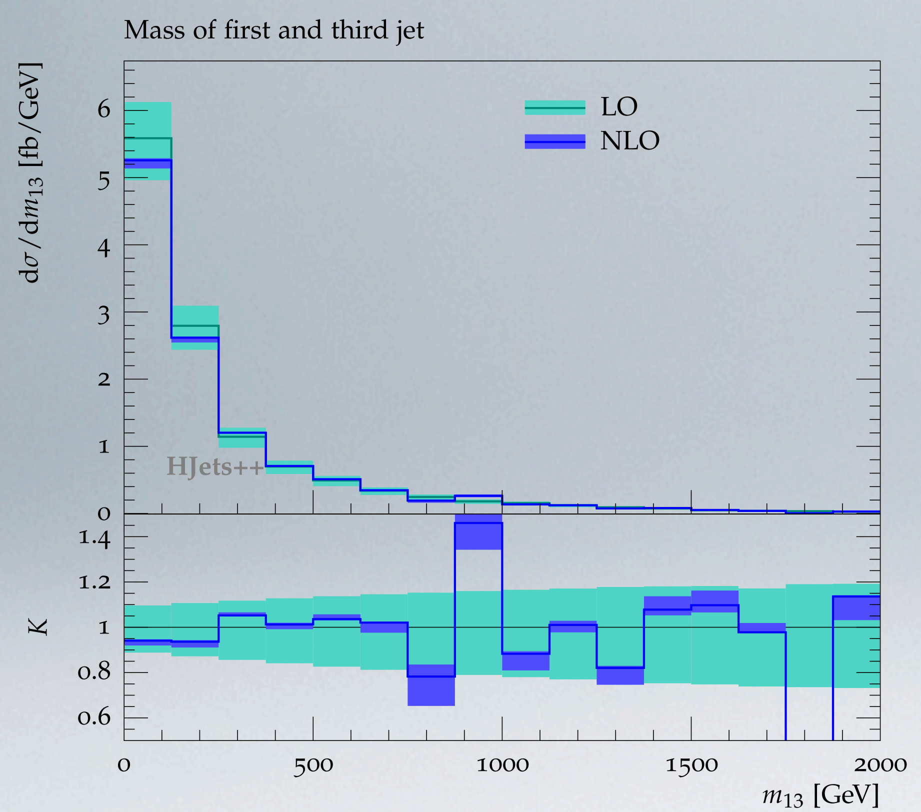
Rapidity separation

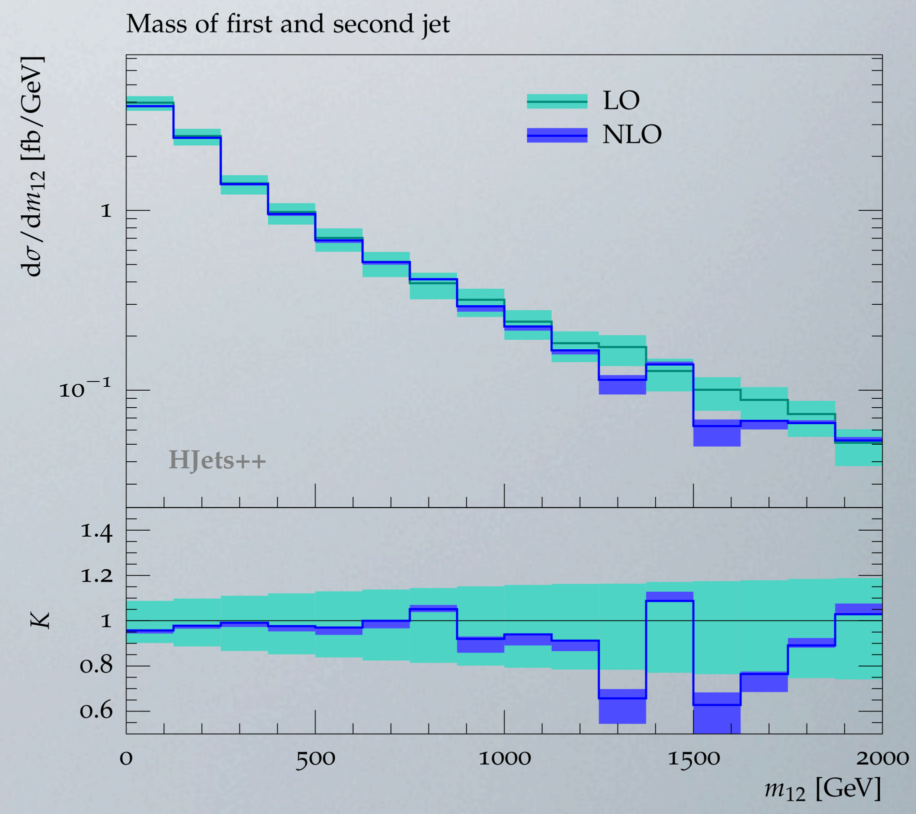


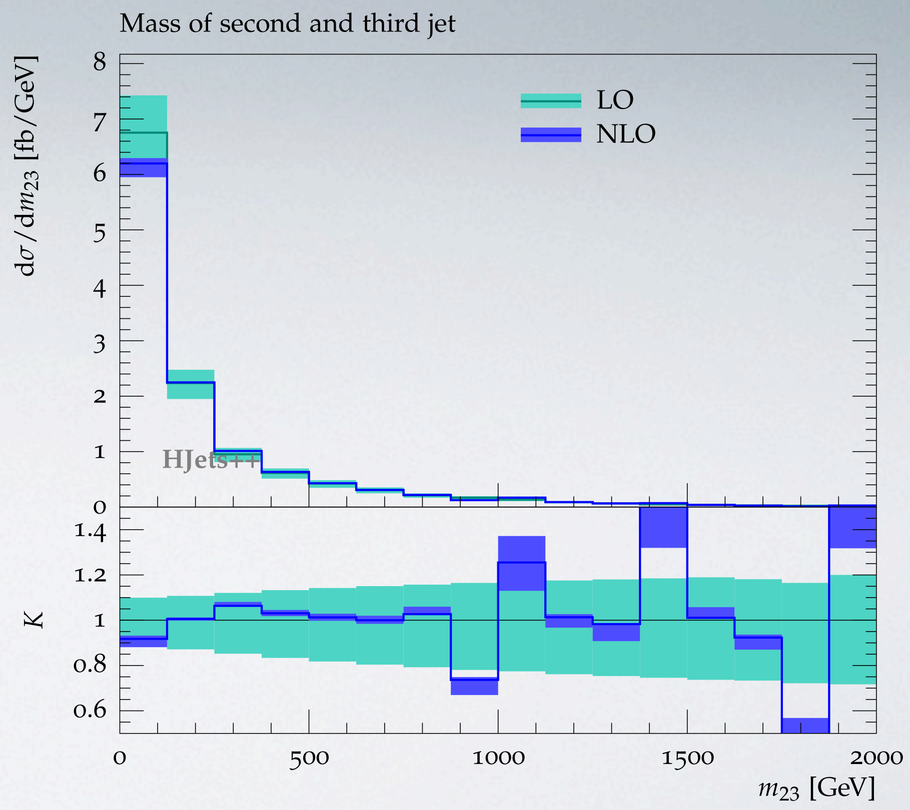




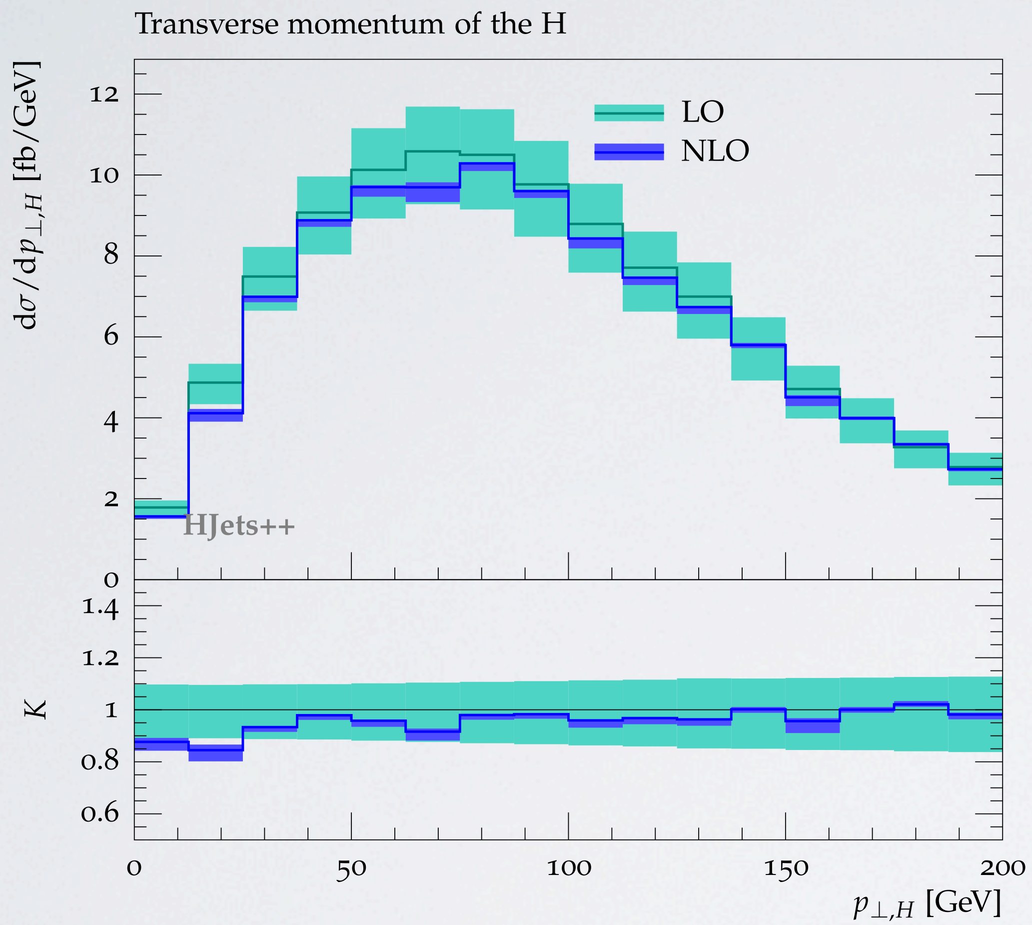
Di-jet Invariant Mass



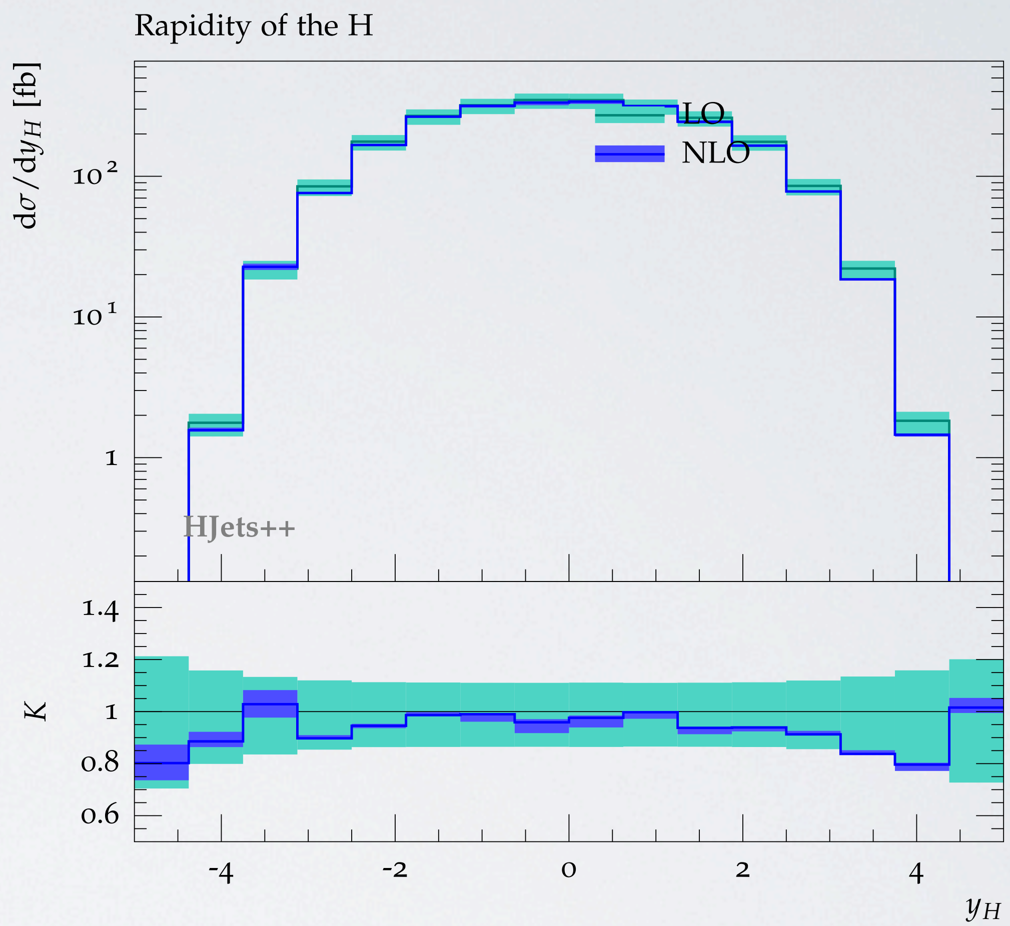




Higgs Boson Distributions

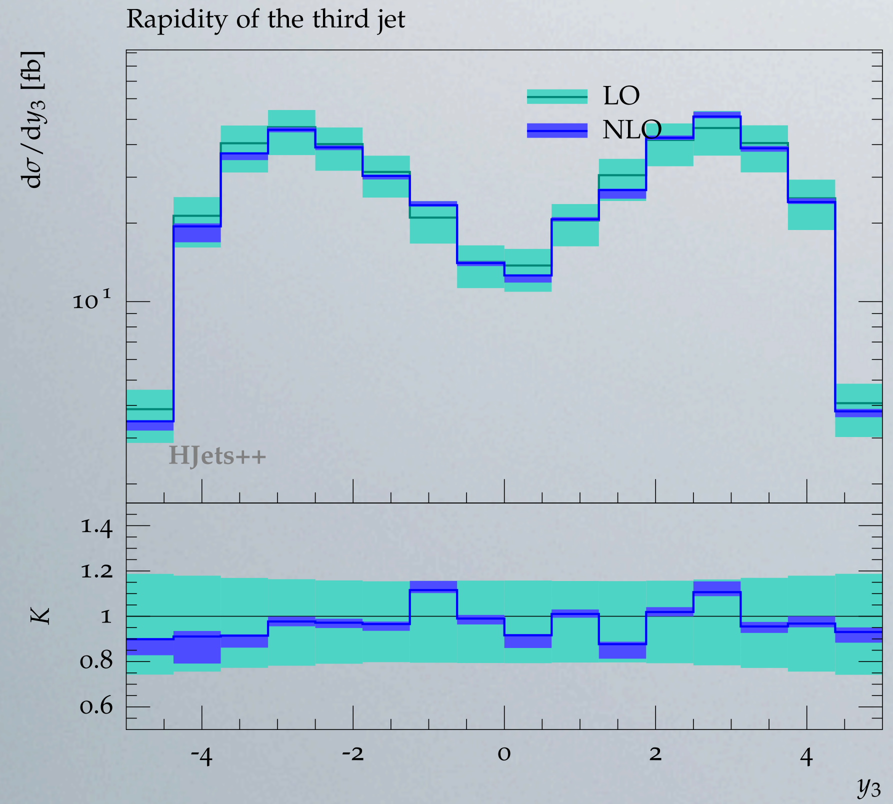


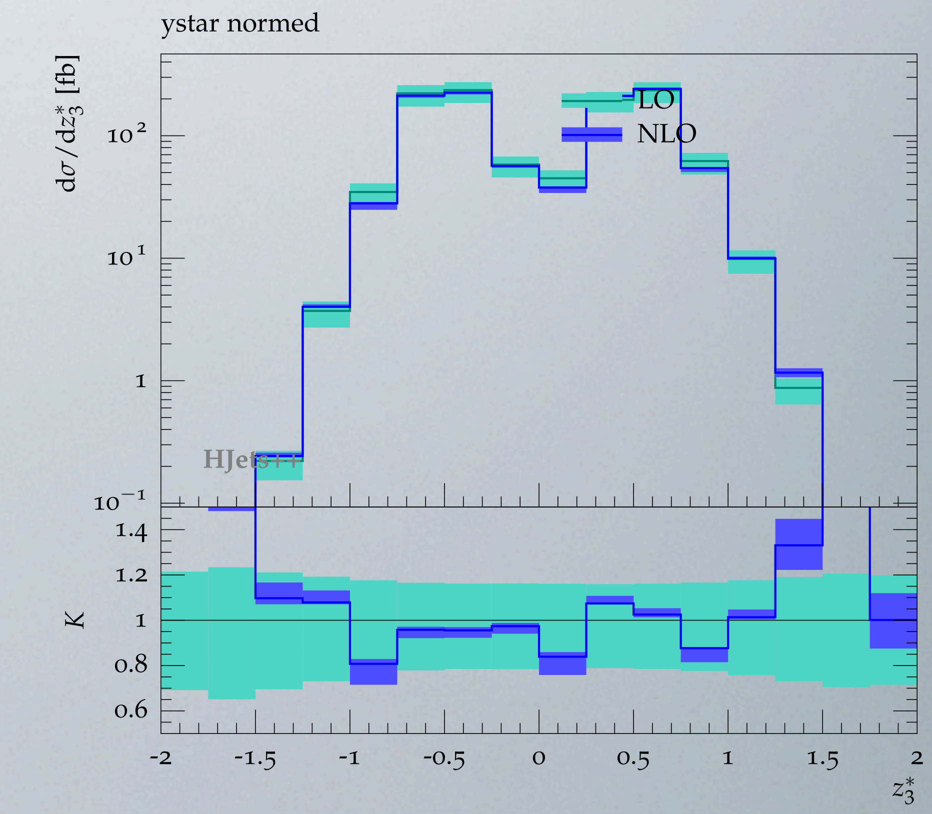
Transverse momentum



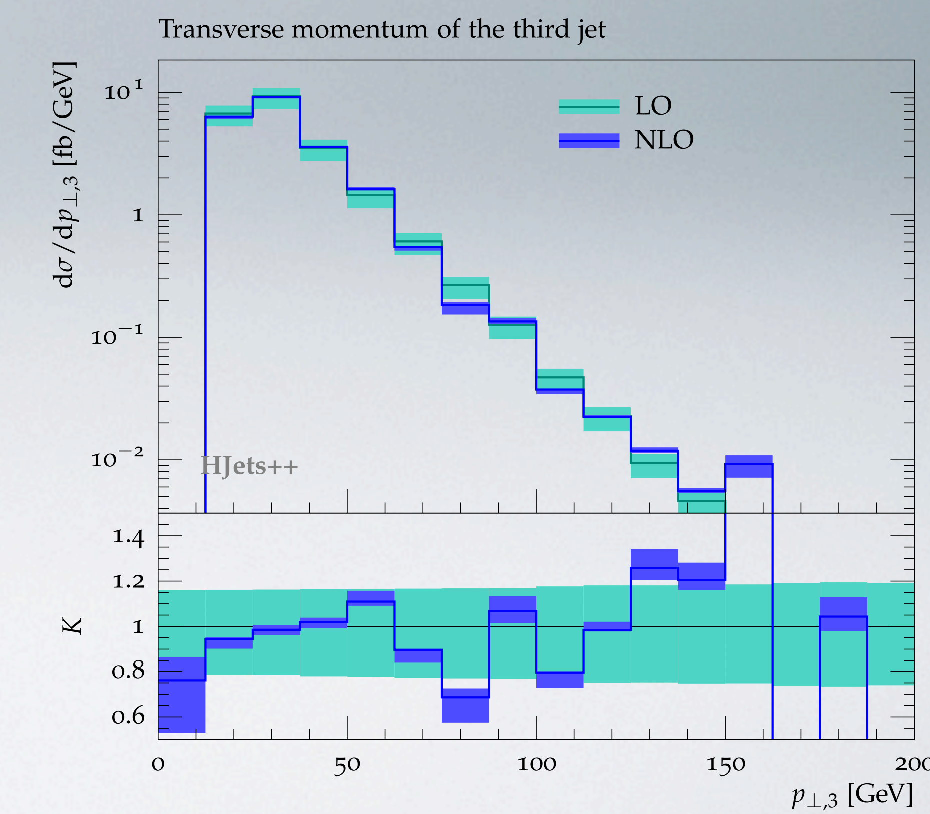
Rapidity

Distributions with VBF cuts

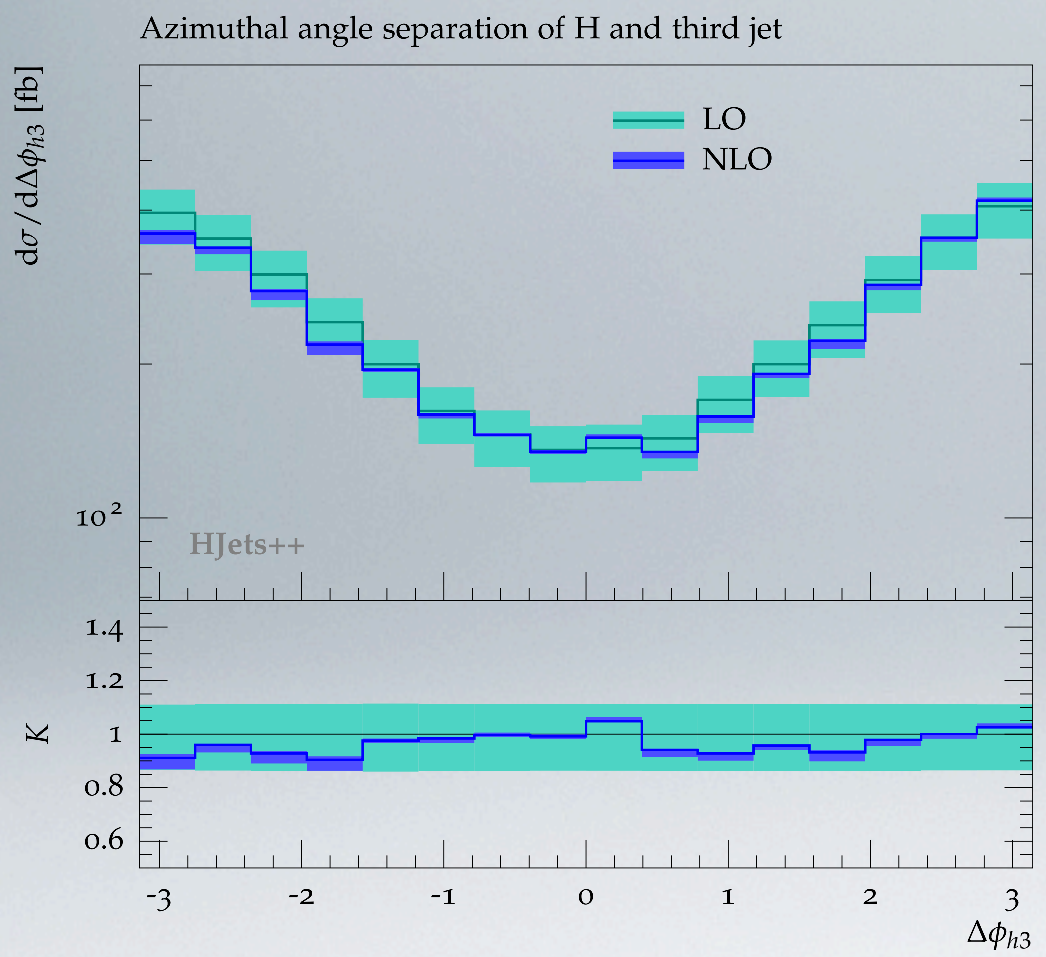


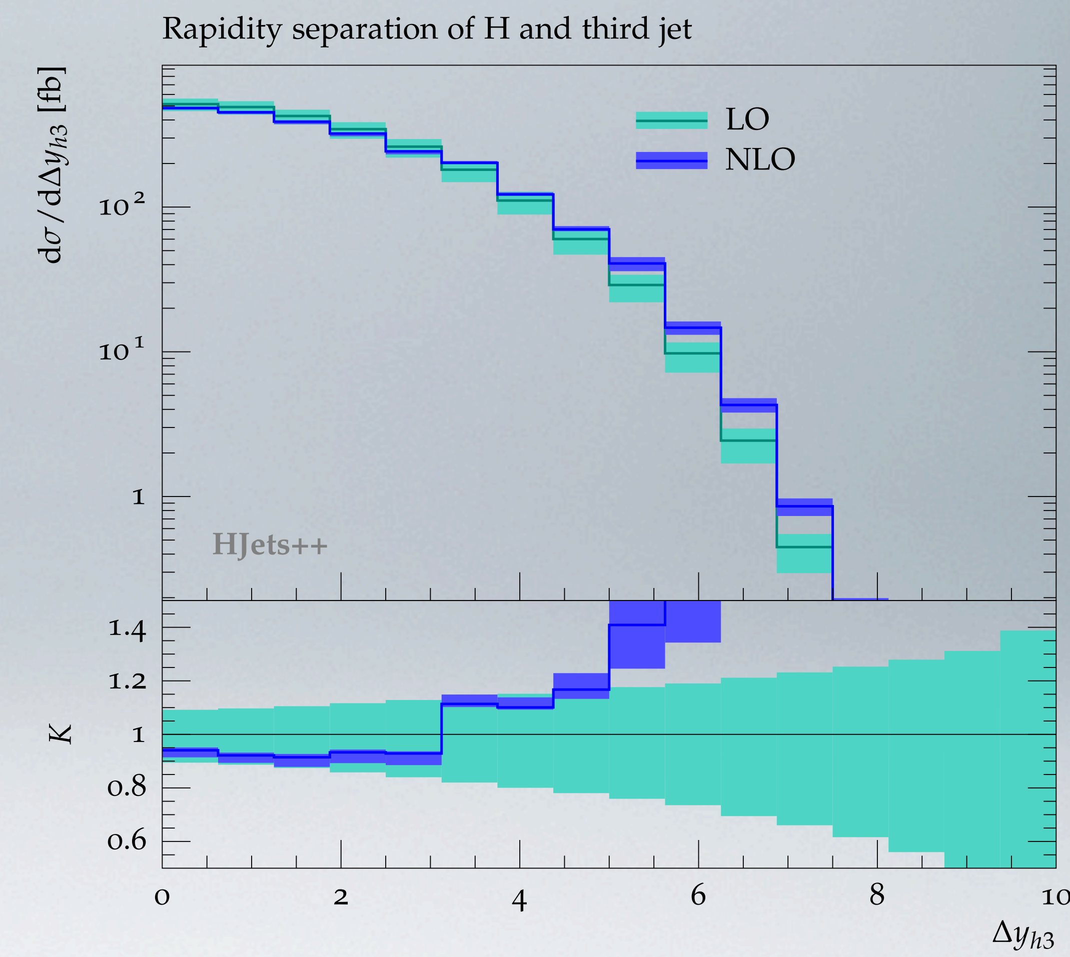


- $m_{j_1 j_2} > 600$ GeV
- $\Delta y_{j_1 j_2} > 4.0$
- $y_{j_1} \cdot y_{j_2} < 0$

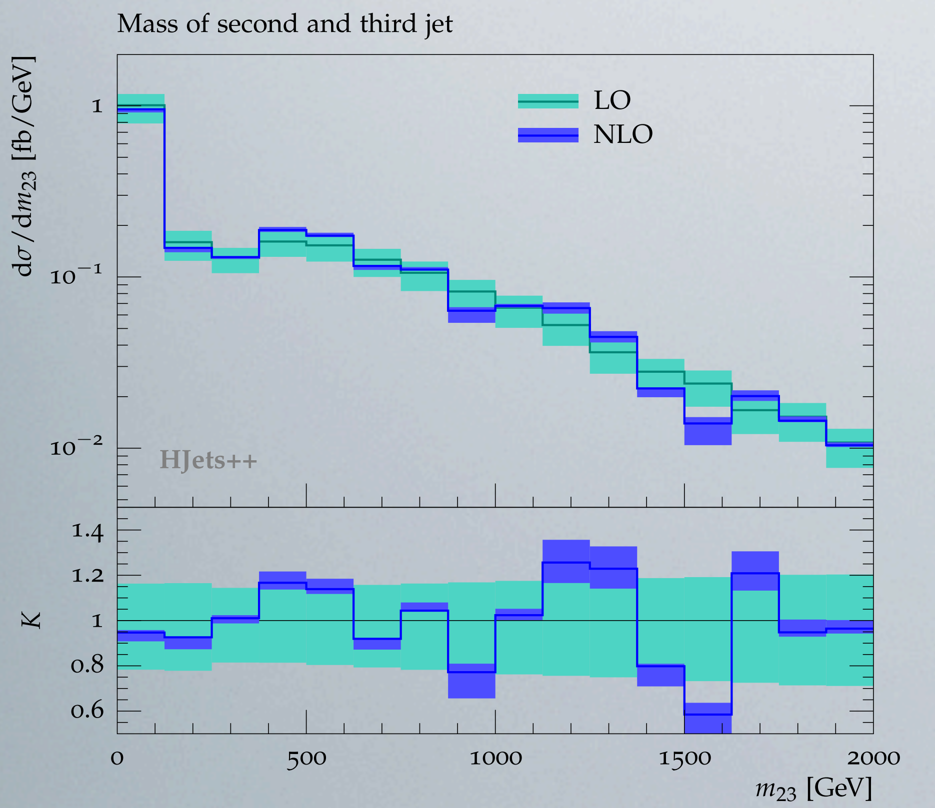


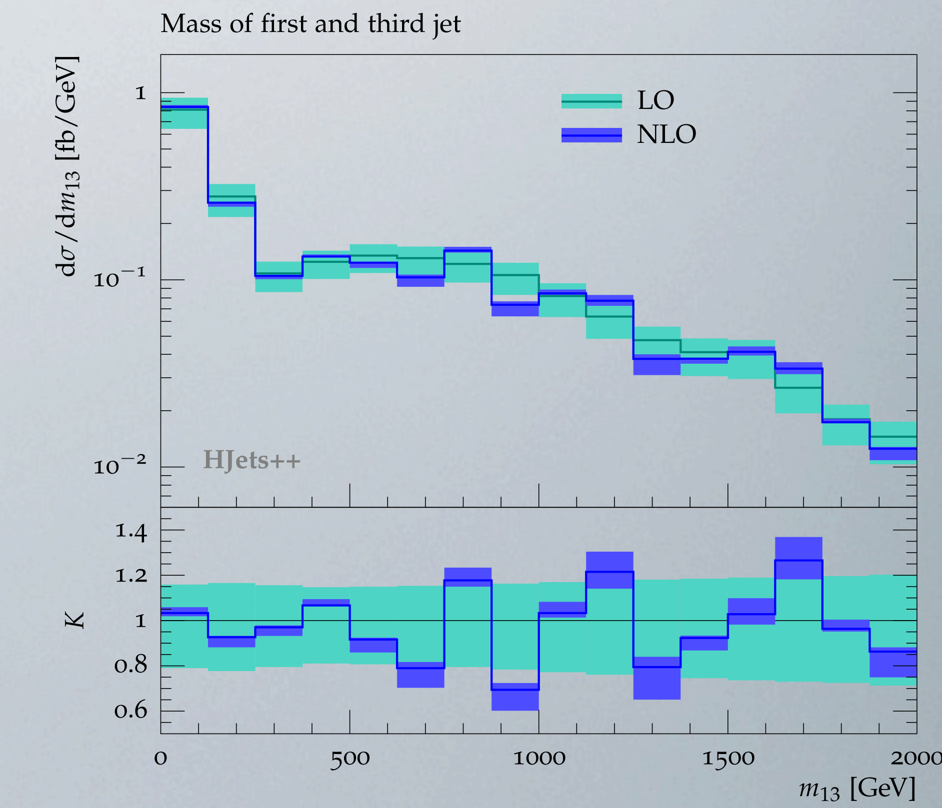
Higgs Boson Distributions





Distributions with VBF cuts





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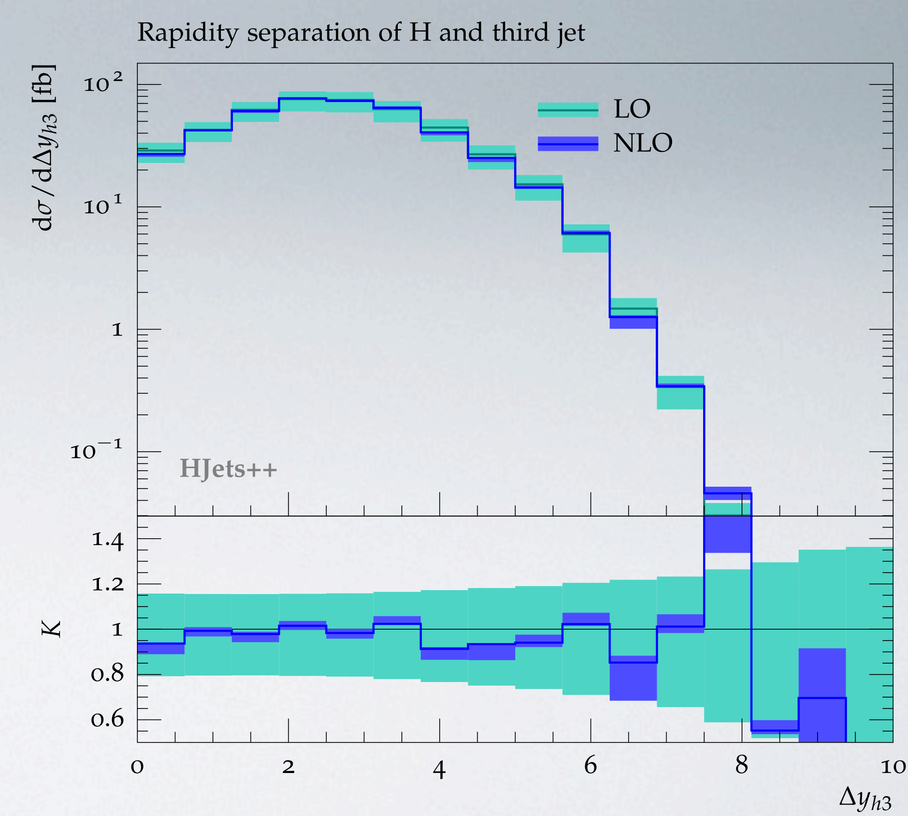

OUTLOOK

- Write a longer paper with more details (study VBF cuts, etc.)
- Matching to parton shower (angular ordered and dipole shower in Herwig++)

Comparison to VBFNLO