NEXT-TO-LEADING ORDER QCD CORRECTIONS TO ELECTROWEAK HIGGS BOSON PRODUCTION IN ASSOCIATION WITH THREE JETS AT THE LHC

IN COLLABORATION WITH
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29 April 2014
Loops and Legs in Quantum Field Theory
Weimar, Germany

OUTLINE

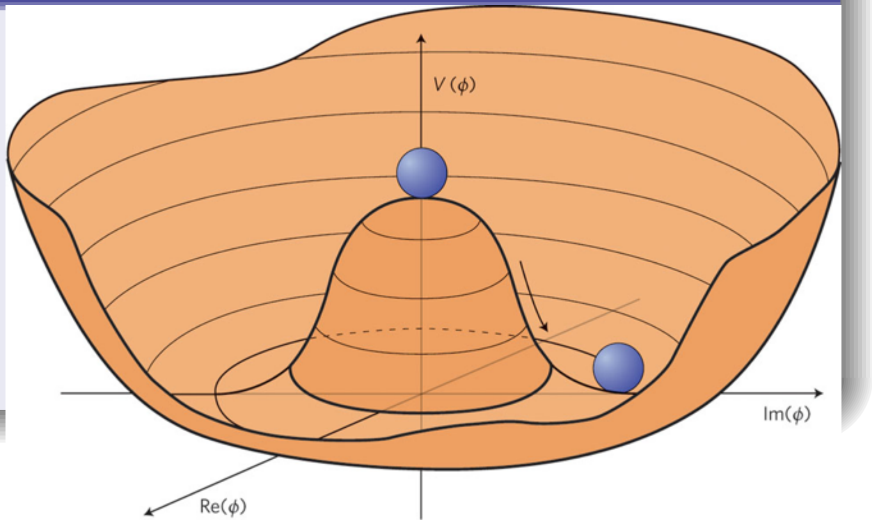
- Introduction
- Details of calculation
- Results
- Outlook

SM Higgs boson

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

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.

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

SM Higgs boson

Higgs couplings to fermions

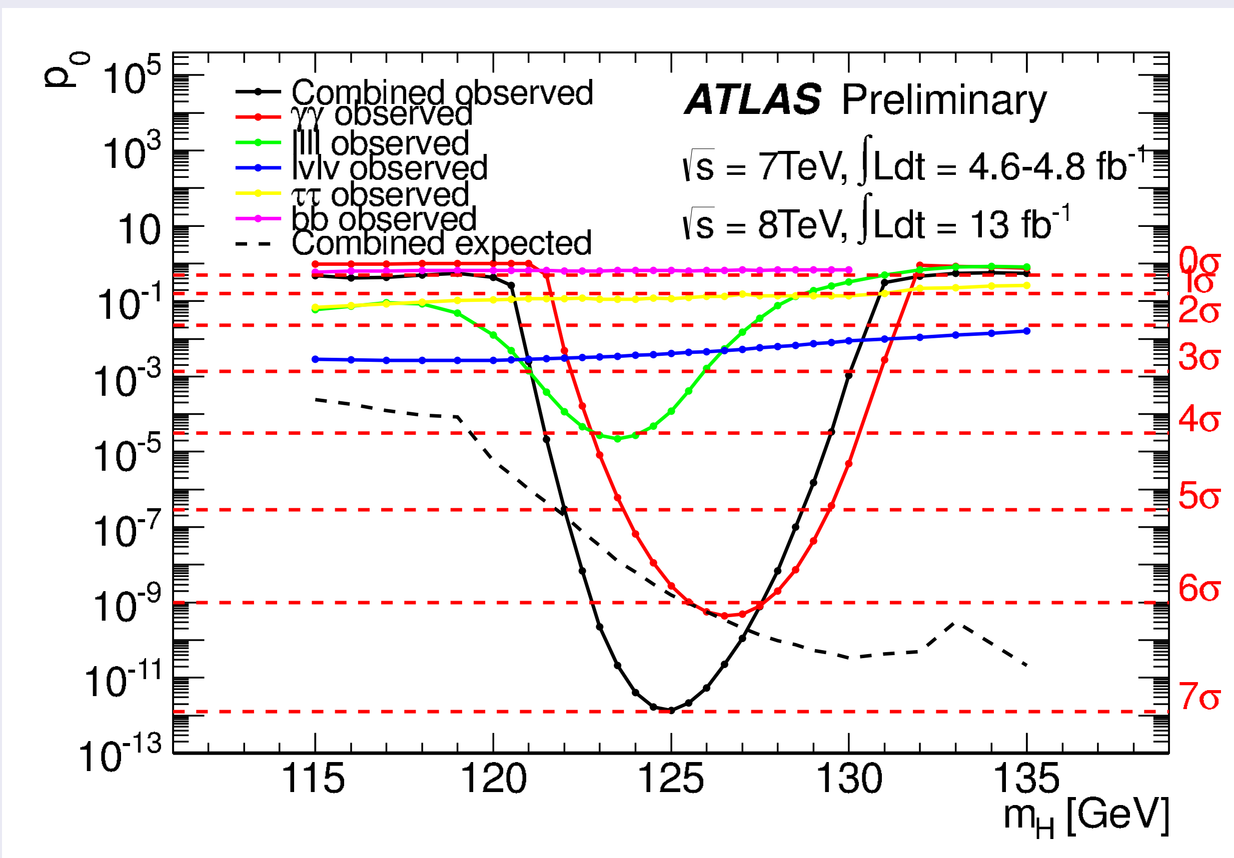
Fermion masses arise from Yukawa couplings via $\Phi^\dagger \to \left(0, \frac{v+H}{\sqrt{2}}\right)$.

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

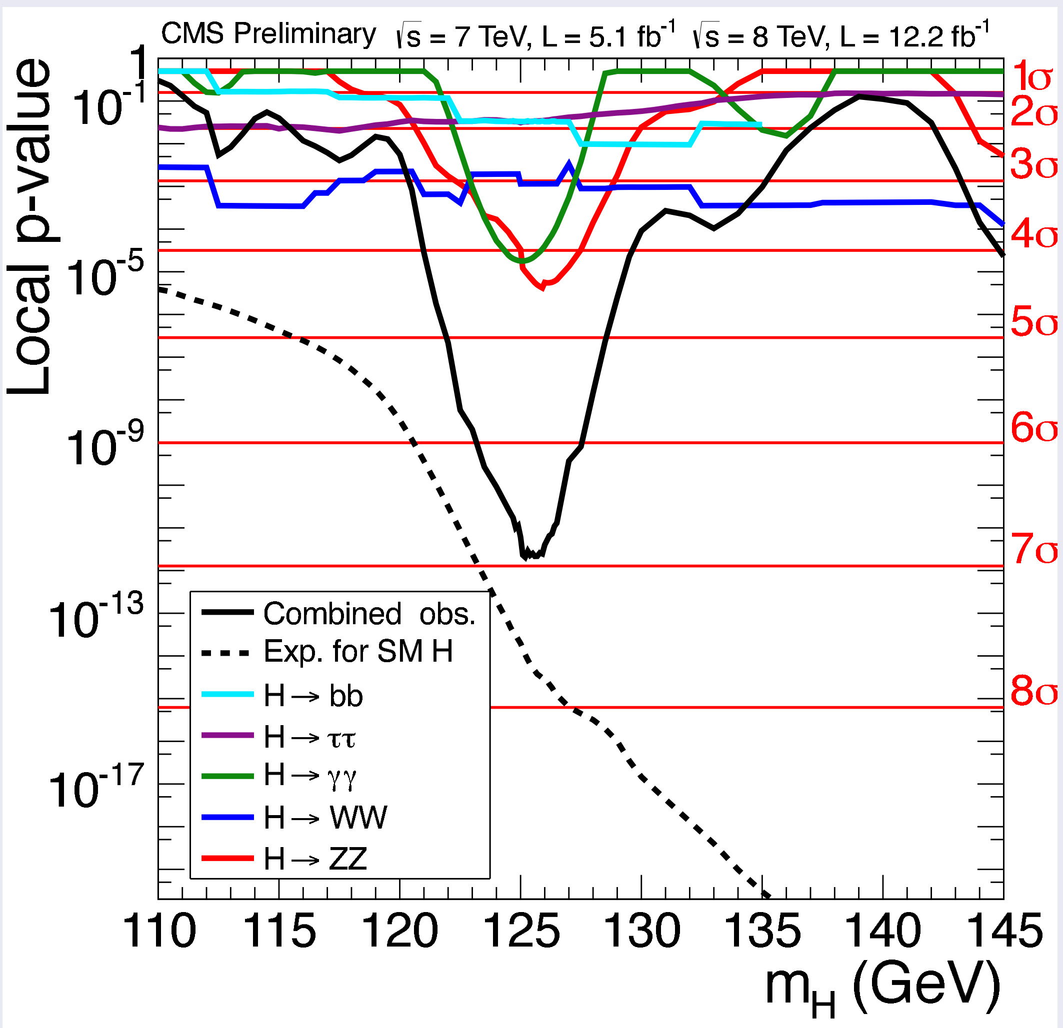
- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_f / v$
- Observation of $H f \bar{f}$ Yukawa coupling is no proof that a v.e.v exists

Happy Higgsdependence Day!

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



ATLAS-CONF-2012-170



CMS-PAS-HIG-12-045

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to **François Englert** and **Peter W. Higgs** "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

The Nobel Prize 2013 **in Physics**

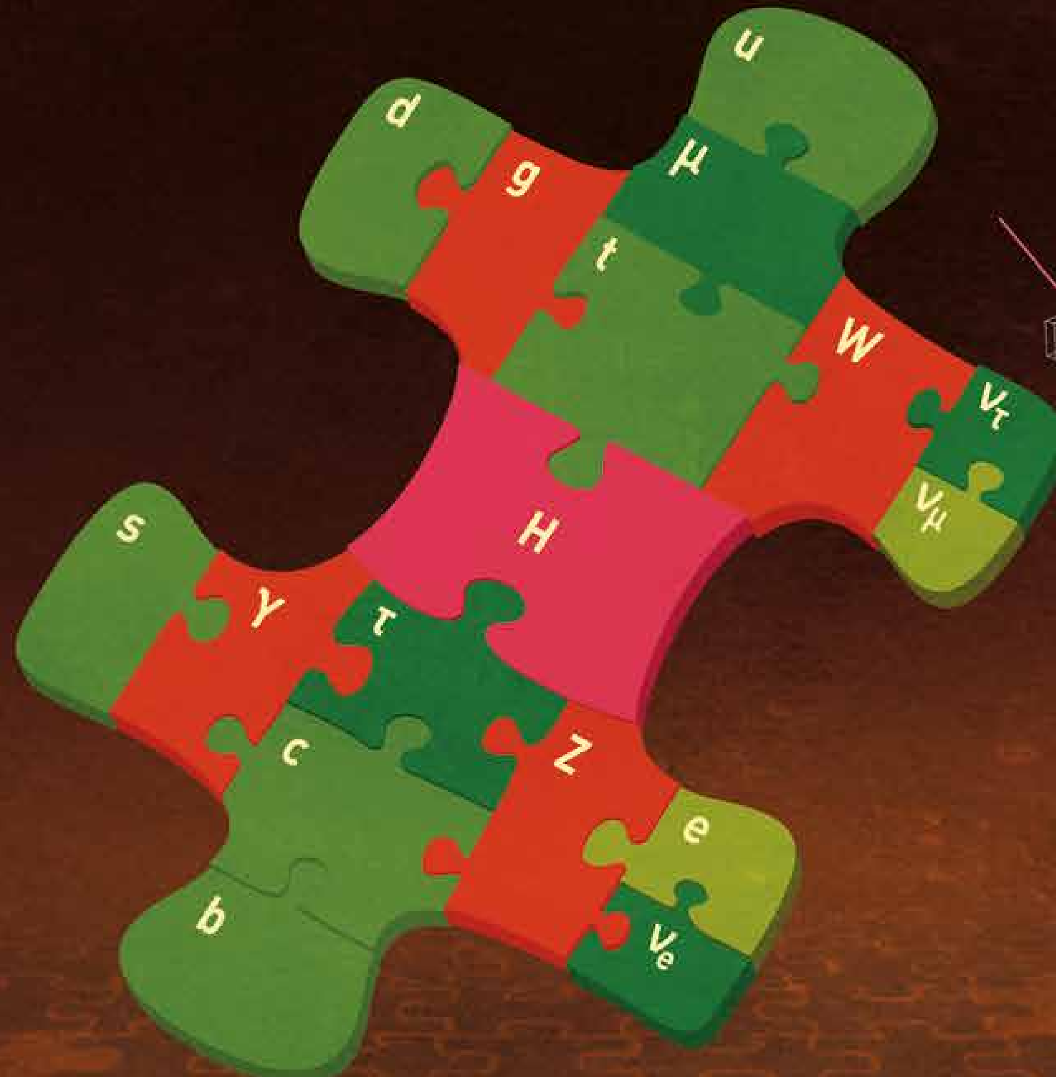
Here, at last!

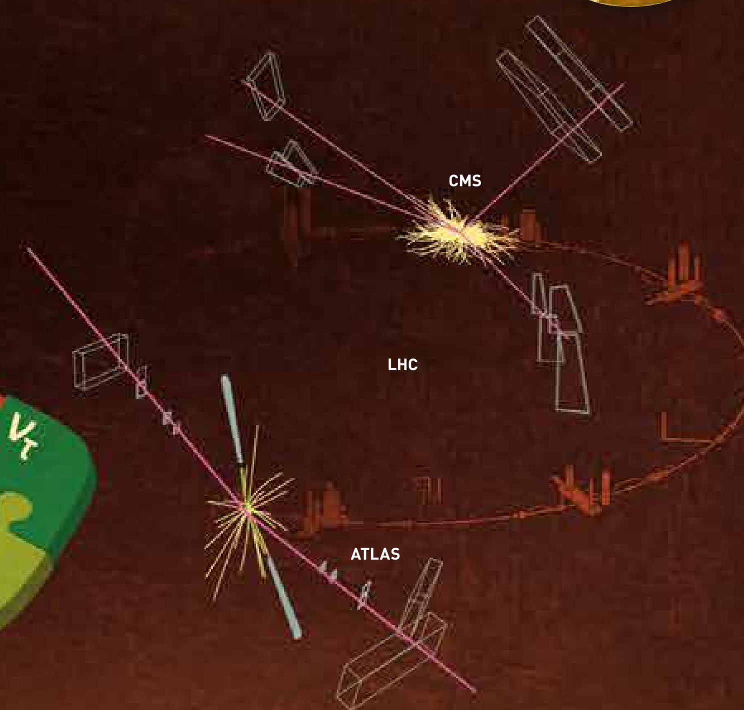
François Englert and Peter W. Higgs are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other (Englert did so together with his now-deceased colleague Robert Brout). In 2012, their ideas were confirmed by the discovery of a so-called Higgs particle, at the CERN laboratory outside Geneva in Switzerland.

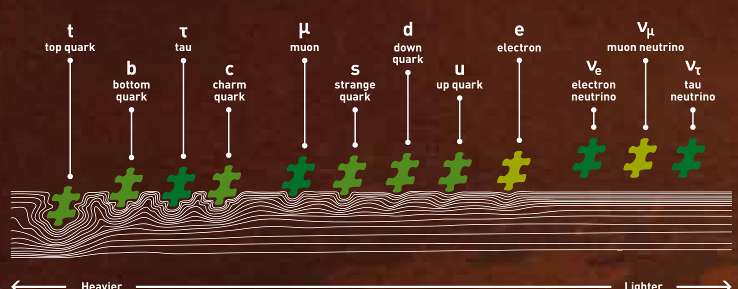
The awarded mechanism is a central part of the Standard Model of particle physics that describes how the world is constructed. According to the Standard Model, everything – from flowers and people to stars and planets – consists of just a few building blocks: *matter particles* which are governed by forces mediated by *force particles*. And the entire Standard Model also rests on the existence of a special kind of particle: *the Higgs particle*.

The Higgs particle is a vibration of an invisible field that fills up all space. Even when our universe seems empty, this field is there. Had it not been there, nothing of what we know would exist because particles acquire mass only in contact with the Higgs field. Englert and Higgs proposed the existence of the field on purely mathematical grounds, and the only way to discover it was to find the Higgs particle.

The Nobel Laureates probably did not imagine that they would get to see the theory confirmed in their lifetimes. To do so required an enormous effort by physicists from all over the world. Almost half a century after the proposal was made, on July 4, 2012, the theoretical prediction could celebrate its biggest triumph, when the discovery of the Higgs particle was announced.







ATLAS
In the collision, a short-lived Higgs particle is created, which decays into two muons (tracks in red) and two electrons (tracks in green).

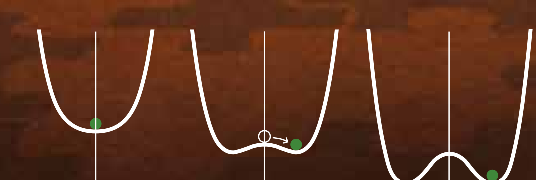
CMS
A short-lived Higgs particle is created in the collision and decays into four muons (tracks in red).

The Particle Collider LHC
Protons – hydrogen nuclei – travel at almost the speed of light in opposite directions inside the circular tunnel, 27 kilometres long. The LHC (Large Hadron Collider) is the largest and most complex machine ever constructed by humans. In order to find a trace of the Higgs particle, two huge detectors, ATLAS and CMS, are capable of seeing the protons collide over and over again, 40 million times a second.

↑
The Field
Matter particles acquire mass in contact with the invisible field that fills the whole universe. Particles that are not affected by the Higgs field do not acquire mass, those that interact weakly become light, and those that interact strongly become heavy. For example, electrons acquire mass from the field, and if it suddenly disappeared, all matter would collapse as the suddenly massless electrons dispersed at the speed of light. The weak force carriers, W and Z particles, get their masses directly through the Higgs mechanism, while the origin of the neutrino masses still remains unclear.

→
Broken Symmetry
The Higgs mechanism relies on the concept of spontaneous symmetry breaking. Our universe was probably born symmetrical (1), with a zero value for the Higgs field in the lowest energy state – the vacuum. But less than one billionth of a second after the Big Bang, the symmetry was broken spontaneously as the lowest energy state moved away (2) from the symmetrical zero-point. Since then, the value of the Higgs field in the vacuum state has been non-zero (3).

Potential energy of the Higgs field



1. 2. 3.

The Puzzle
The Higgs particle (H) was the last missing piece in the Standard Model puzzle. But the Standard Model is not the final piece in the cosmic puzzle. One of the reasons for this is that the Standard Model only describes visible matter, accounting for one sixth of all matter in the universe. To find the rest – the mysterious so-called dark matter – is one of the reasons why scientists continue to chase unknown particles at CERN.

← ←
François Englert
Belgian citizen. Born 1932 in Etterbeek, Belgium. Professor emeritus at Université Libre de Bruxelles, Brussels, Belgium.

←
Peter W. Higgs
British citizen. Born 1929 in Newcastle upon Tyne, United Kingdom. Professor emeritus at University of Edinburgh, United Kingdom.

Photo: portrait of François Englert: Jean Dominique Burton; portrait of Peter Higgs: Callum Bennetts.

FURTHER READING! More information on the Nobel Prize in Physics 2013: http://kva.se/nobelprizephysics2013 and http://nobelprize.org **REVIEW ARTICLES:** ● **Rose, J.** (2013) *I mörkret bortom Higgs*, Forskning & Framsteg, nr 6 (Swedish). ● **Llewellyn-Smith, C.** (2000) *The Large Hadron Collider*, Scientific American, July. ● **Weinberg, S.** (1999) *A Unified Physics by 2050?*, Scientific American, December.
BOOKS: ● **Randall, L.** (2013) *Higgs Discovery: The Power of Empty Space*, Bodley Head. ● **Sample, I.** (2013) *Massive: The Higgs Boson and the Greatest Hunt in Science*, Virgin Books. ● **Carroll, S.** (2012) *The Particle at the End of the Universe*, Dutton. ● **Close, F.** (2011) *The Infinity Puzzle*, Oxford University Press. ● **Wilczek, F.** (2008) *The Lightness of Being: Mass, Ether, and the Unification of Forces*, Basic Books.
LINKS: ● **Link TV** (2012) *CERN Scientists Announce Higgs Boson: The Moment:* http://www.youtube.com/watch?v=0CugLD9HF94 ● **CERN** (2010) *CERN LHC Brochure:* http://cds.cern.ch/record/1278169?ln=en ● **Cham, J.** (2012) *The Higgs Boson Explained.* (animation): http://www.phdcomics.com/comics/archive.php?comicid=1489 ● **Higgs, Peter W.** (2010) *My Life as a Boson.* (transcribed speech): http://www.kcl.ac.uk/nms/depts/physics/news/events/MyLifeasaBoson.pdf ● **More references can be found in the Scientific Background:** http: //kva.se/nobelprizephysics2013

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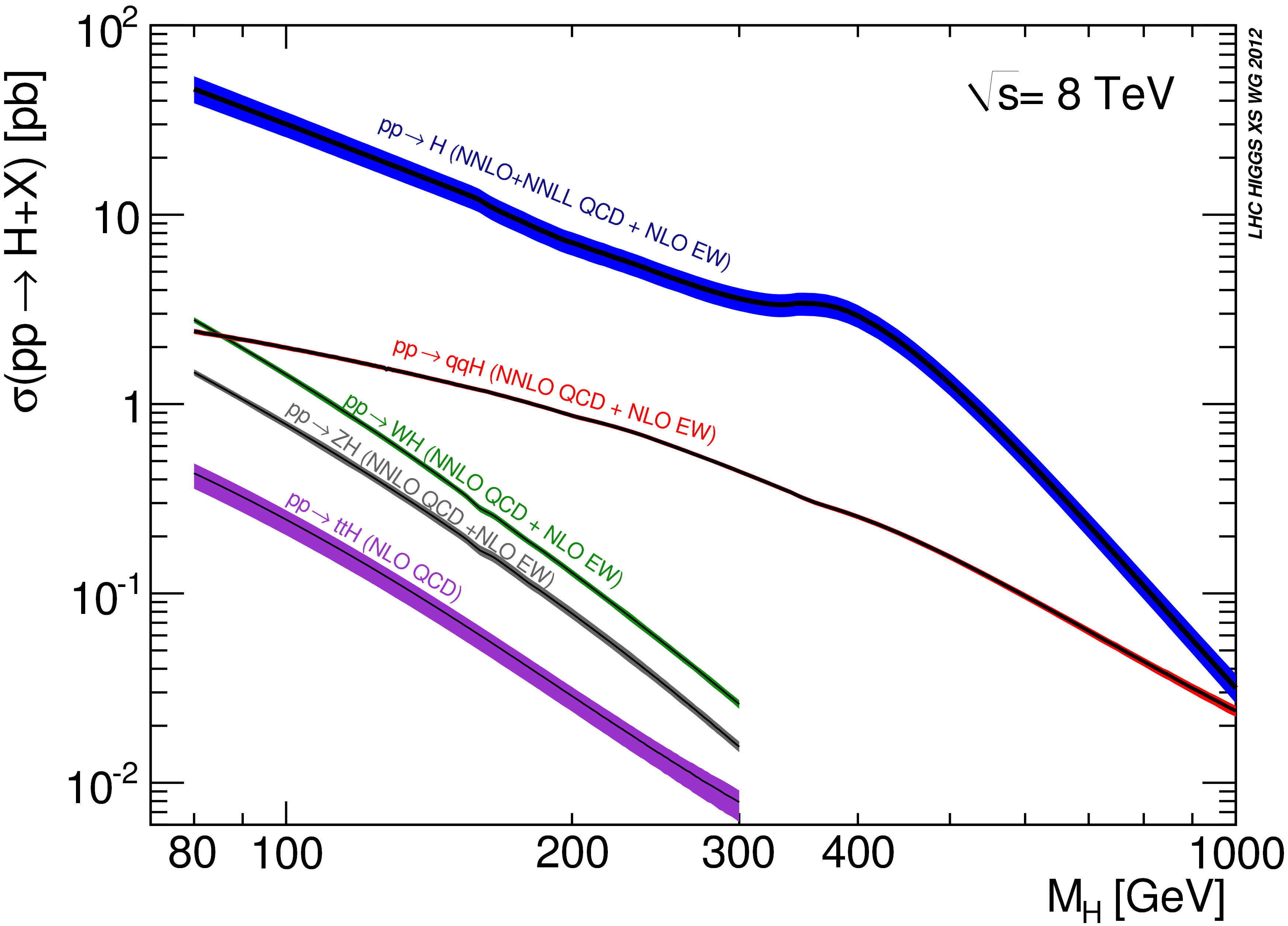
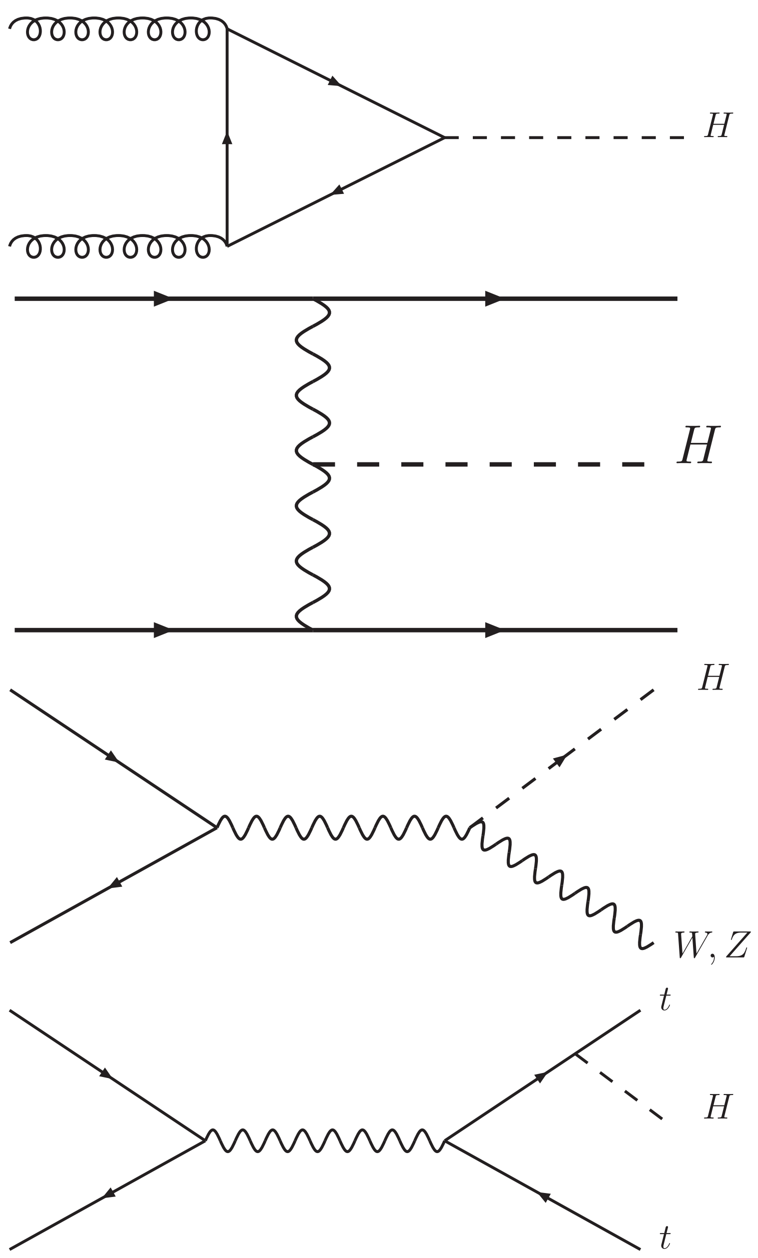
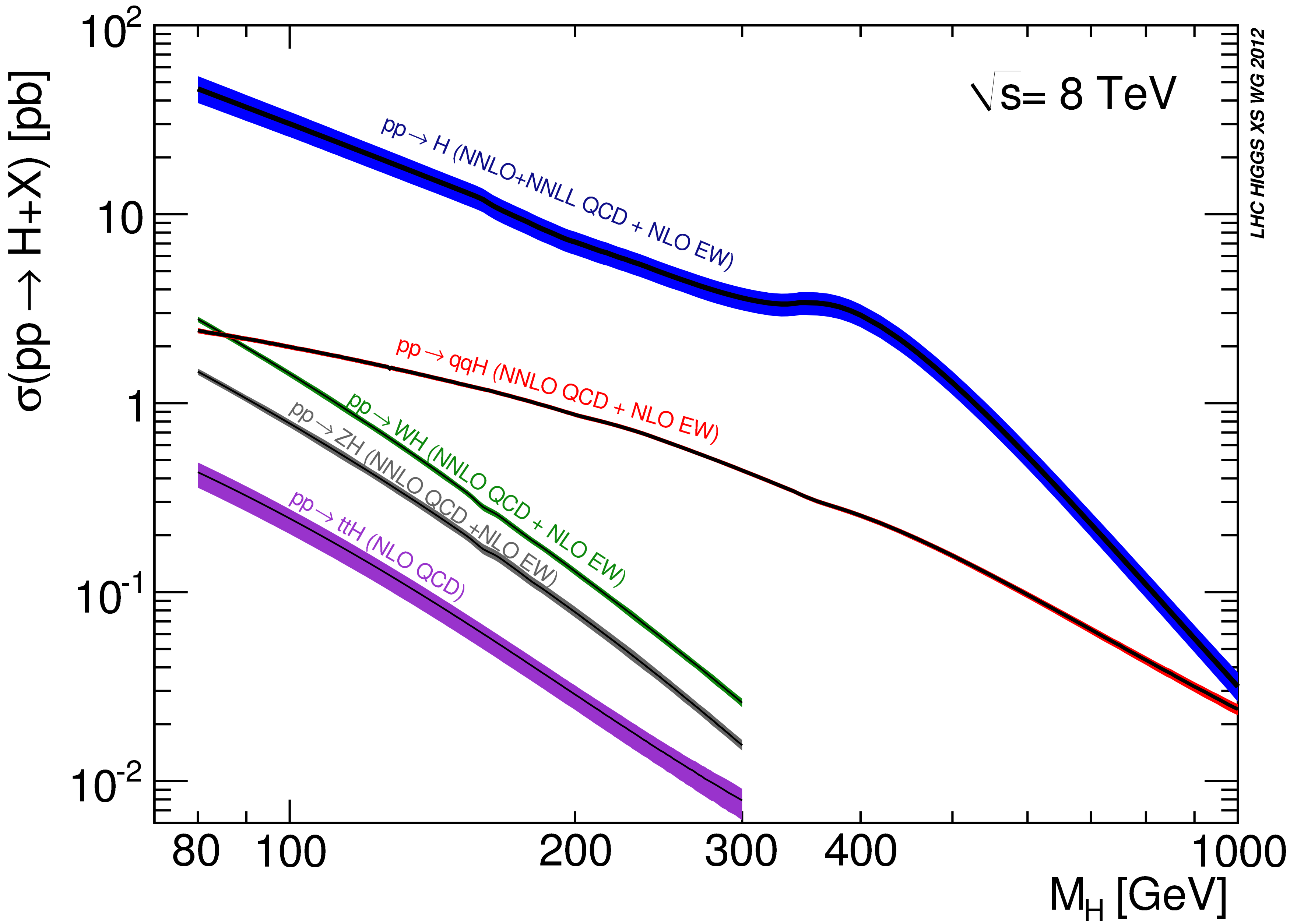
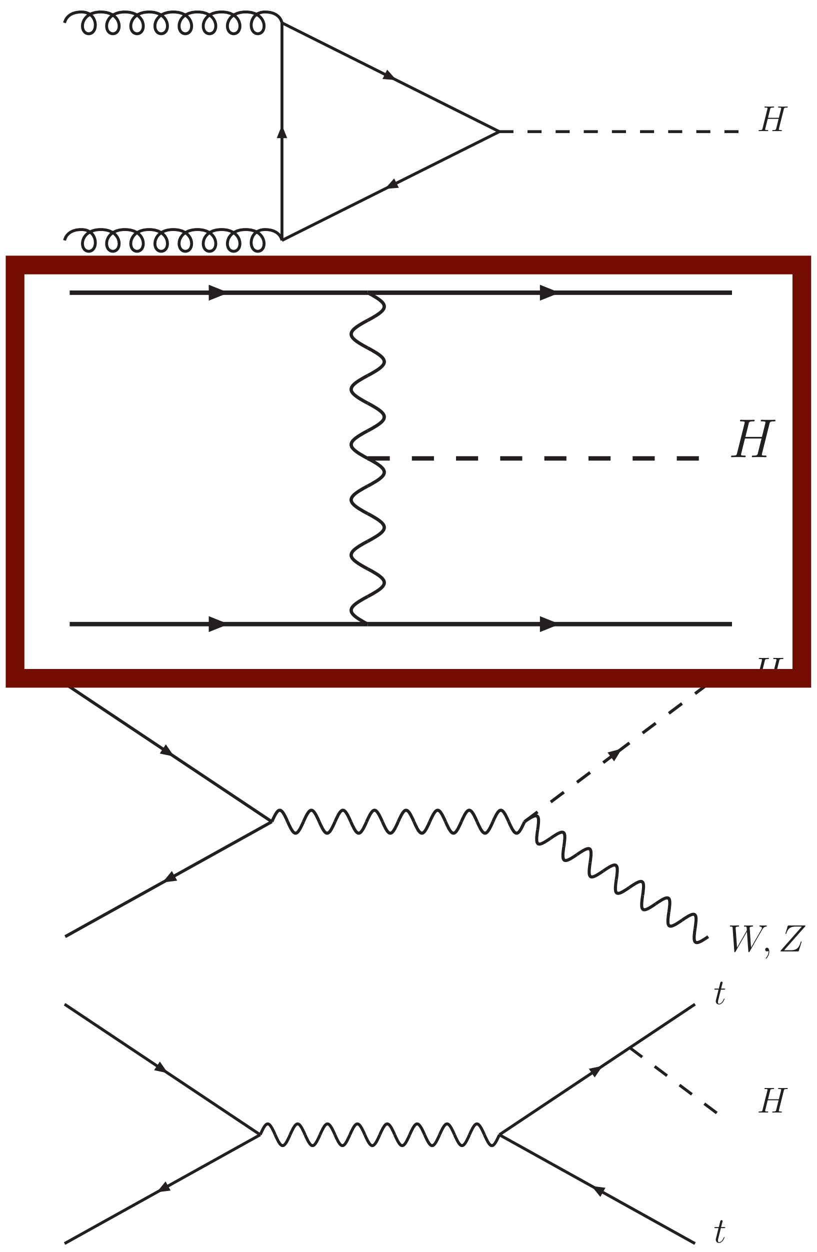
Total SM Higgs cross sections at the LHC



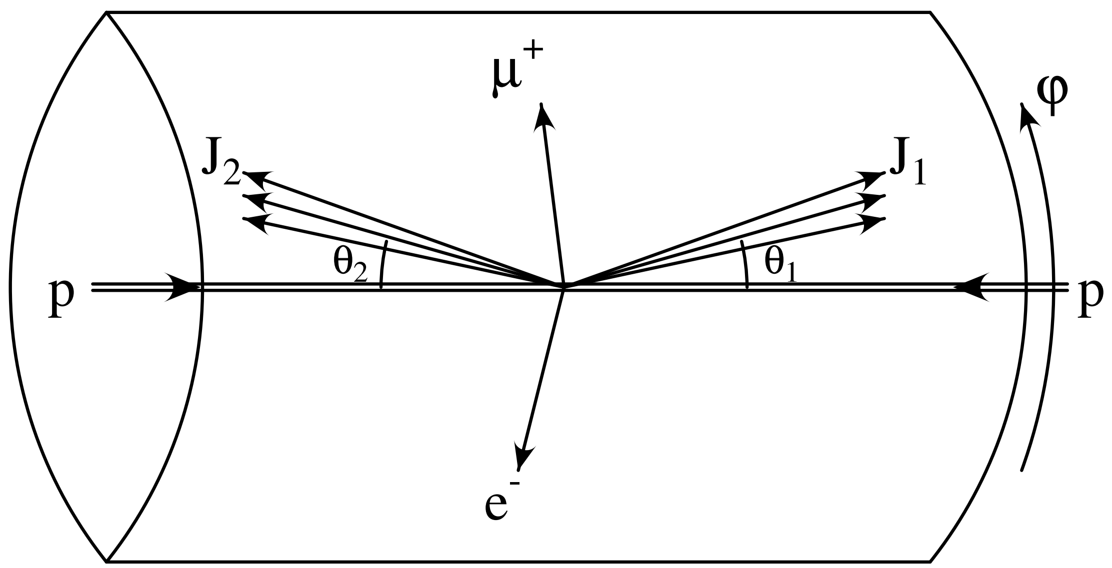


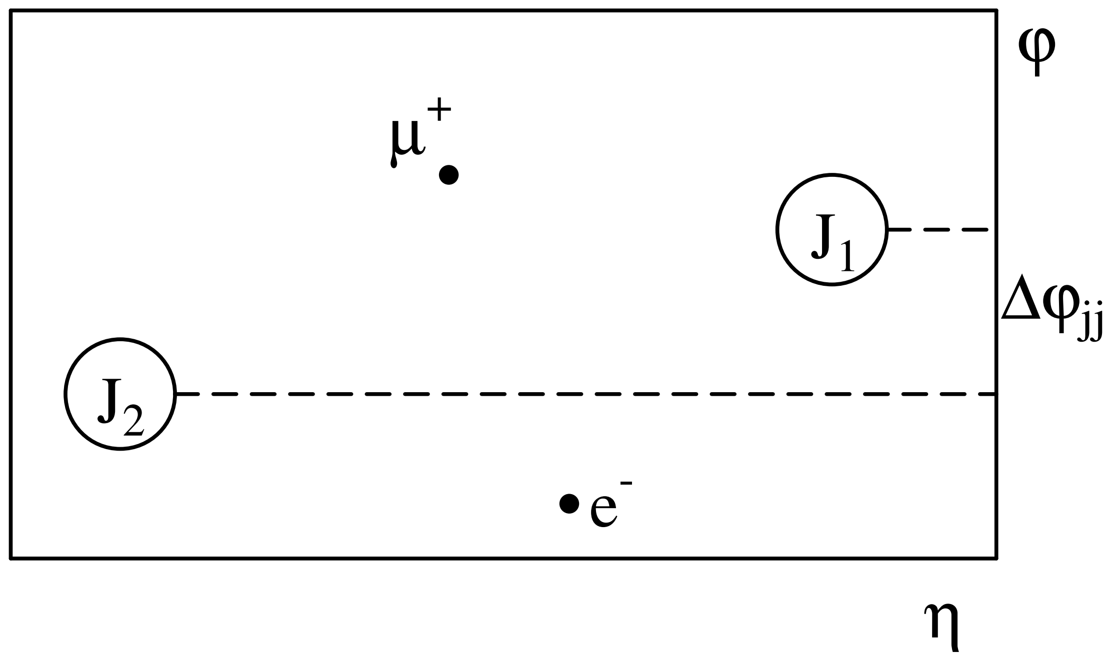
Total SM Higgs cross sections at the LHC





Vector Boson Fusion



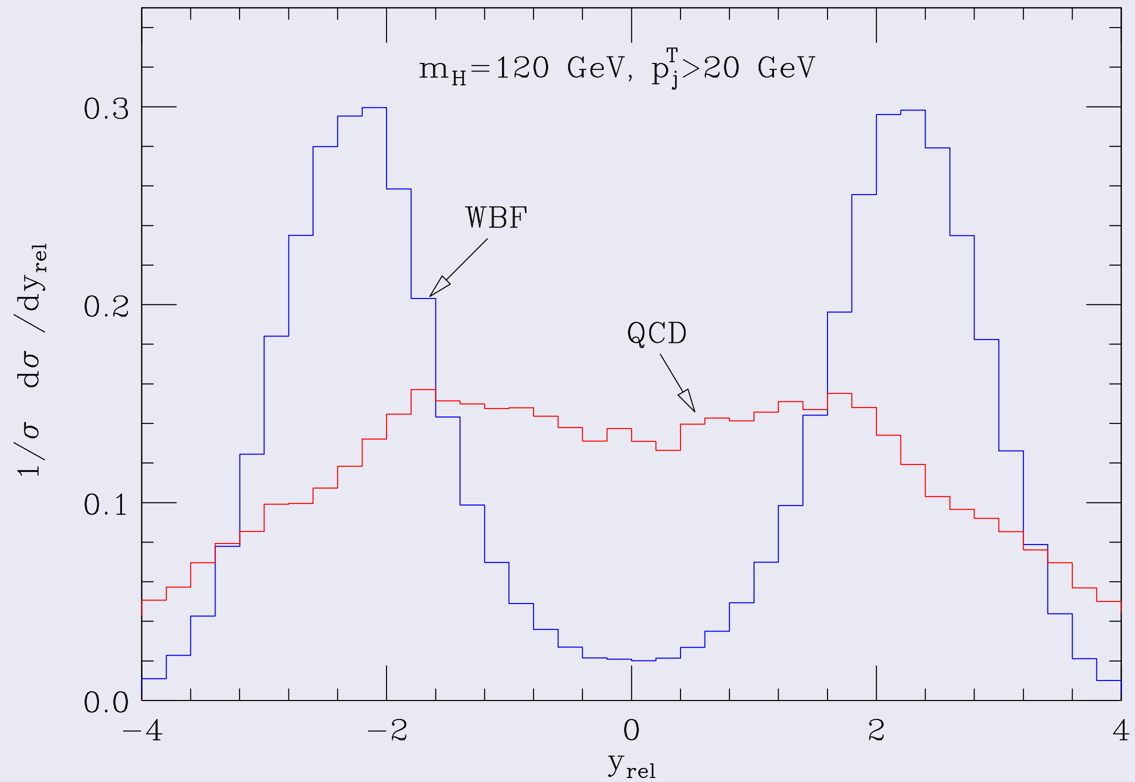


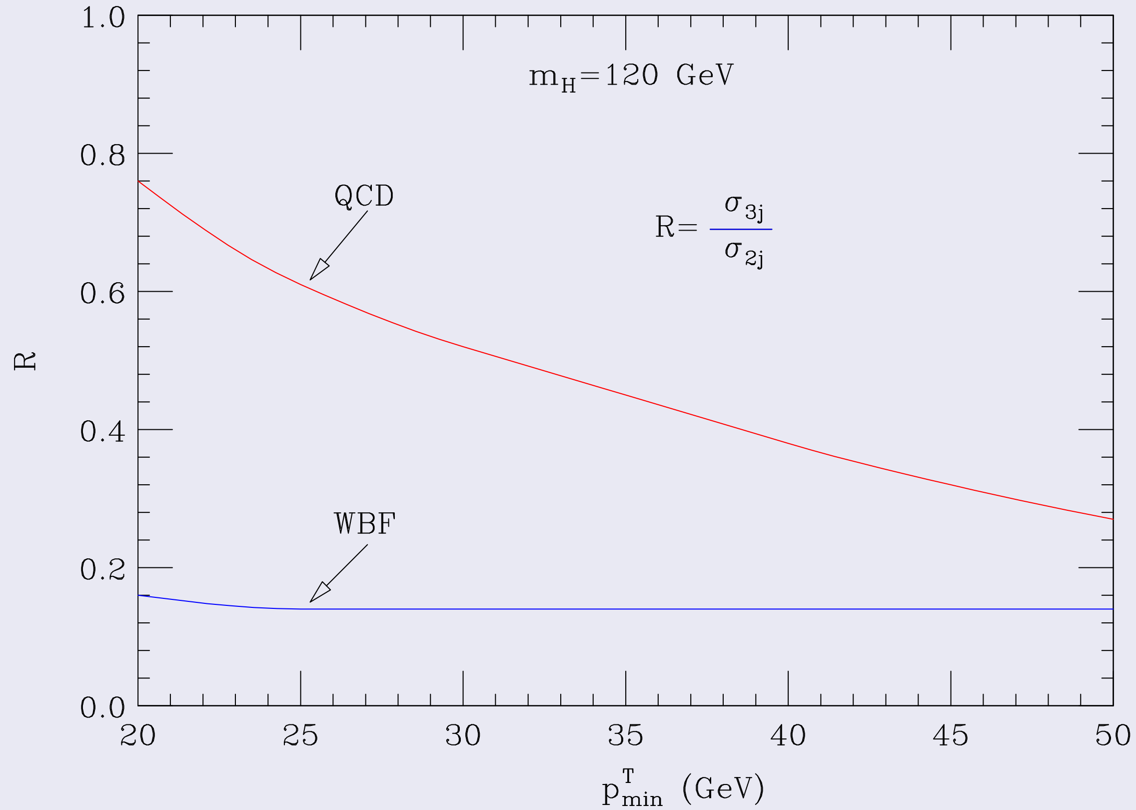
Event Characteristics

- 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



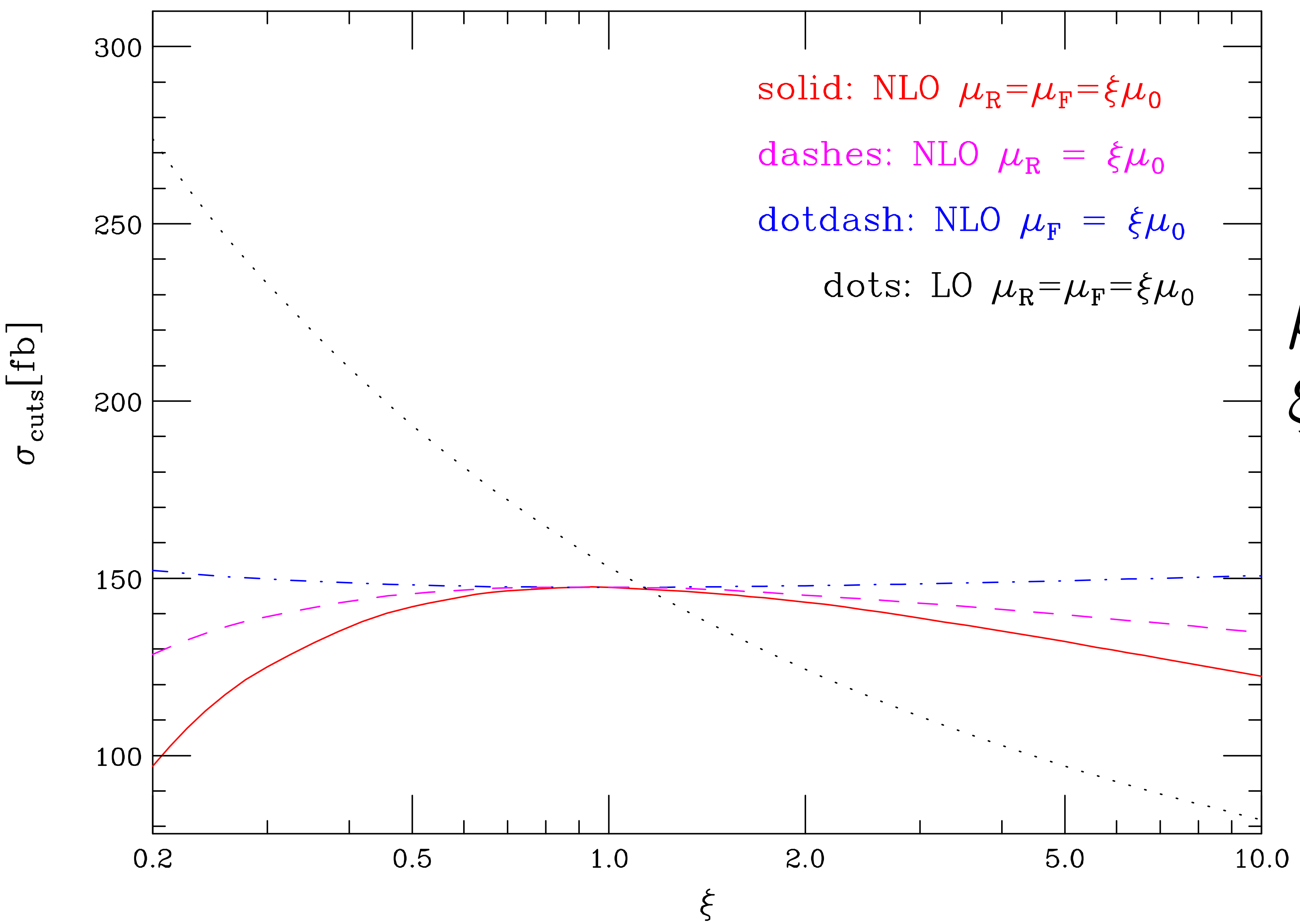


JHEP 05 (2004) 064

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

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

Total Cross section



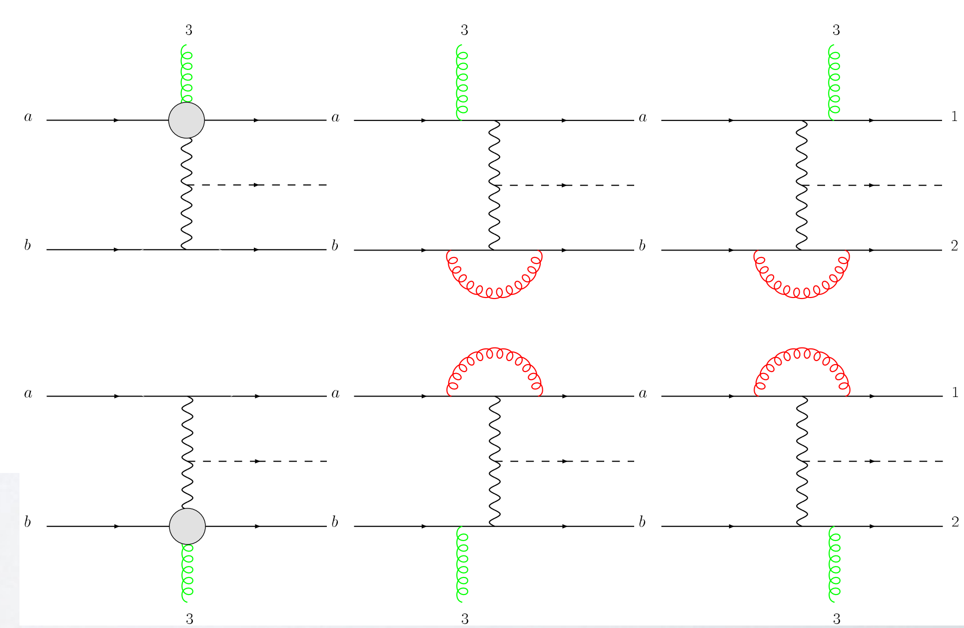
JHEP **0802** (2008) 076 [arXiv:0710.5621]

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

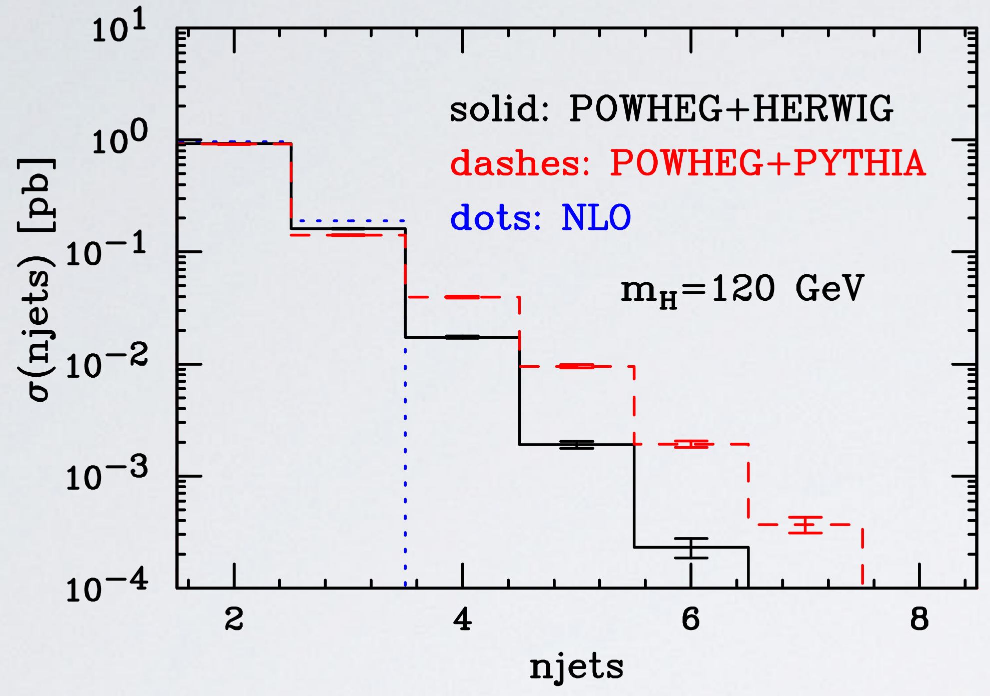
$\mu_0 = 40$ GeV

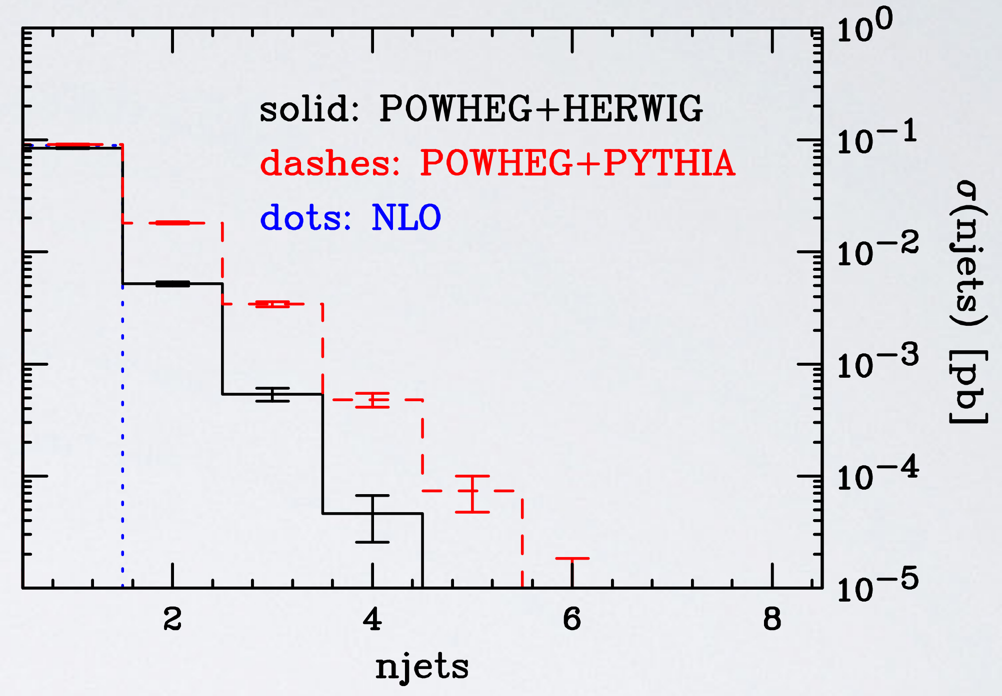
$\xi = 2^{\mp 1}$ scale variations:

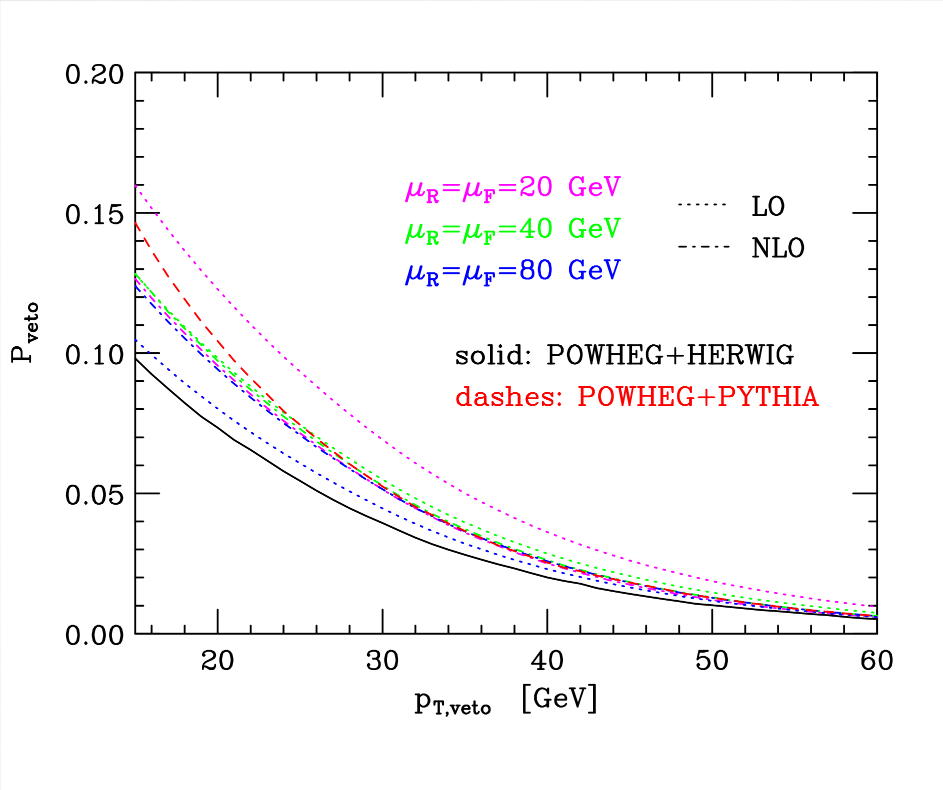
- LO: +26% to −19%
- NLO: less than 5%

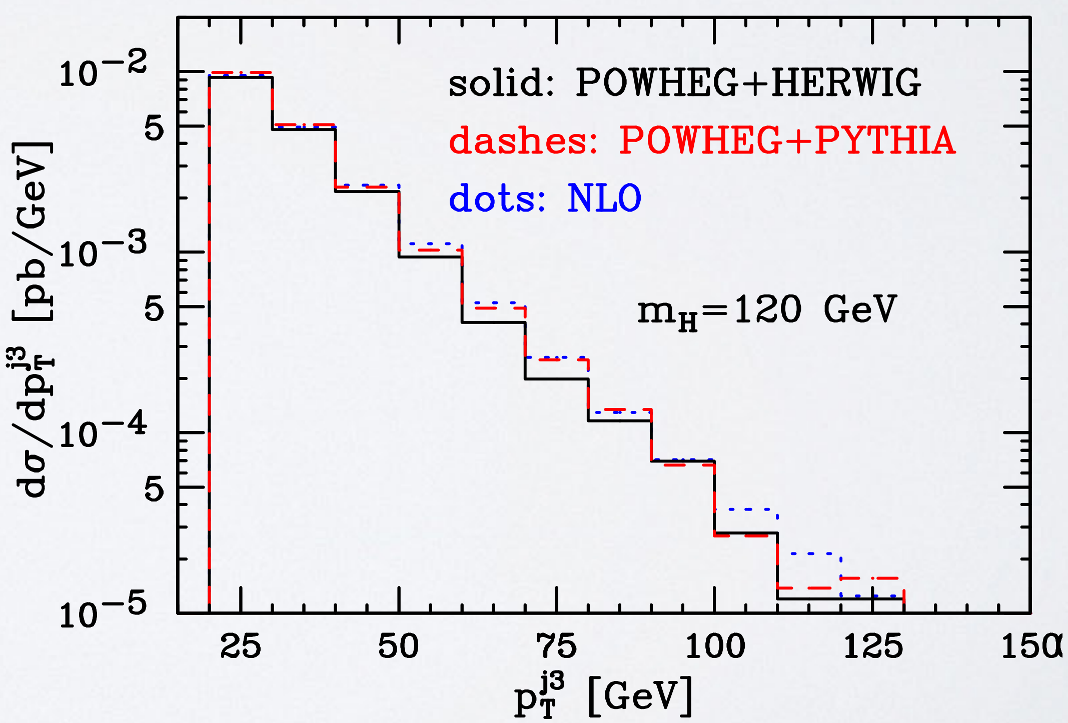


COMMENTS ON VBF POWHEGBOX [ARXIV:0911.5299]





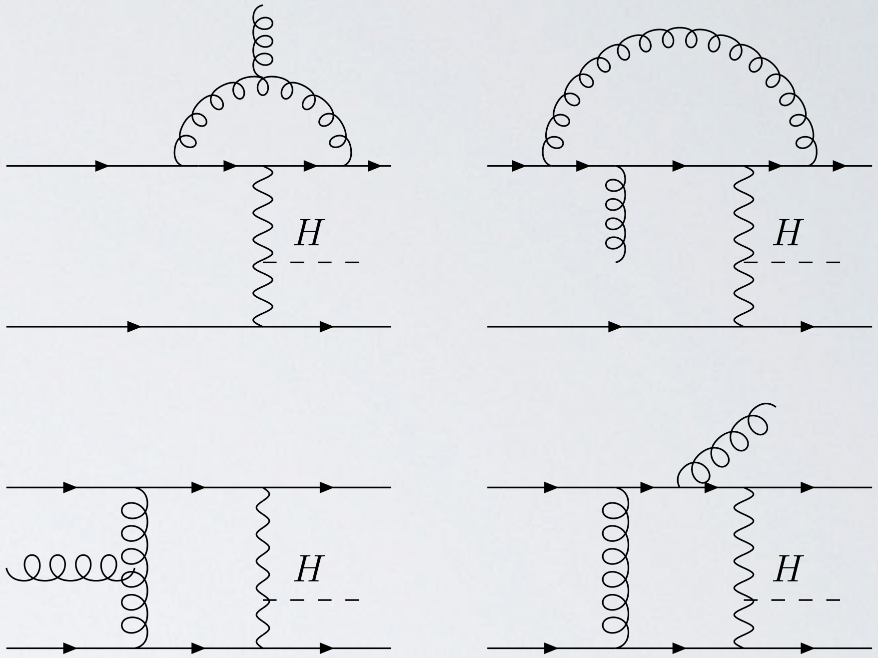




$$\sqrt{S} = 14\ \text{TeV}\ \ m_h = 120\ \text{GeV}$$

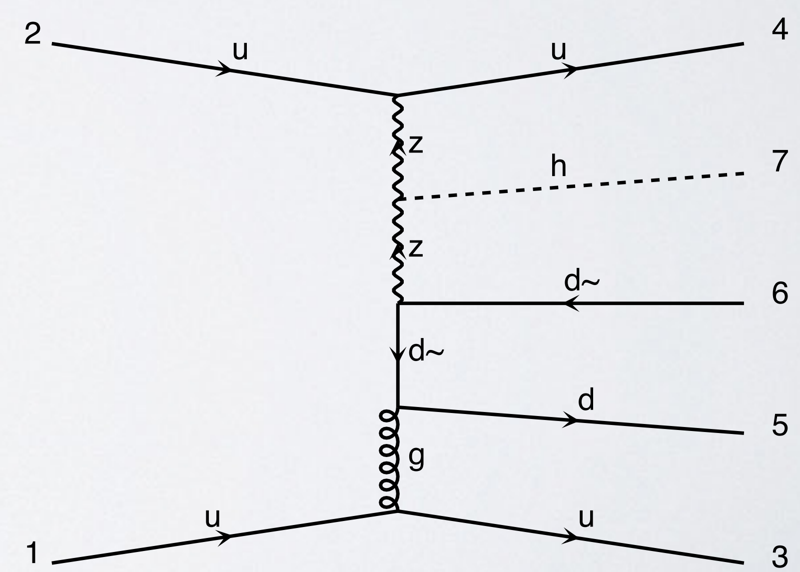
HJETS++

- 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

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

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

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

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

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

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: OneLOop [A. van Hameren arXiv:1007.4716]

THE RESULTS

- Input parameters and selection 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)

y_i: rapidity

ϕ_i: azimuthal angle

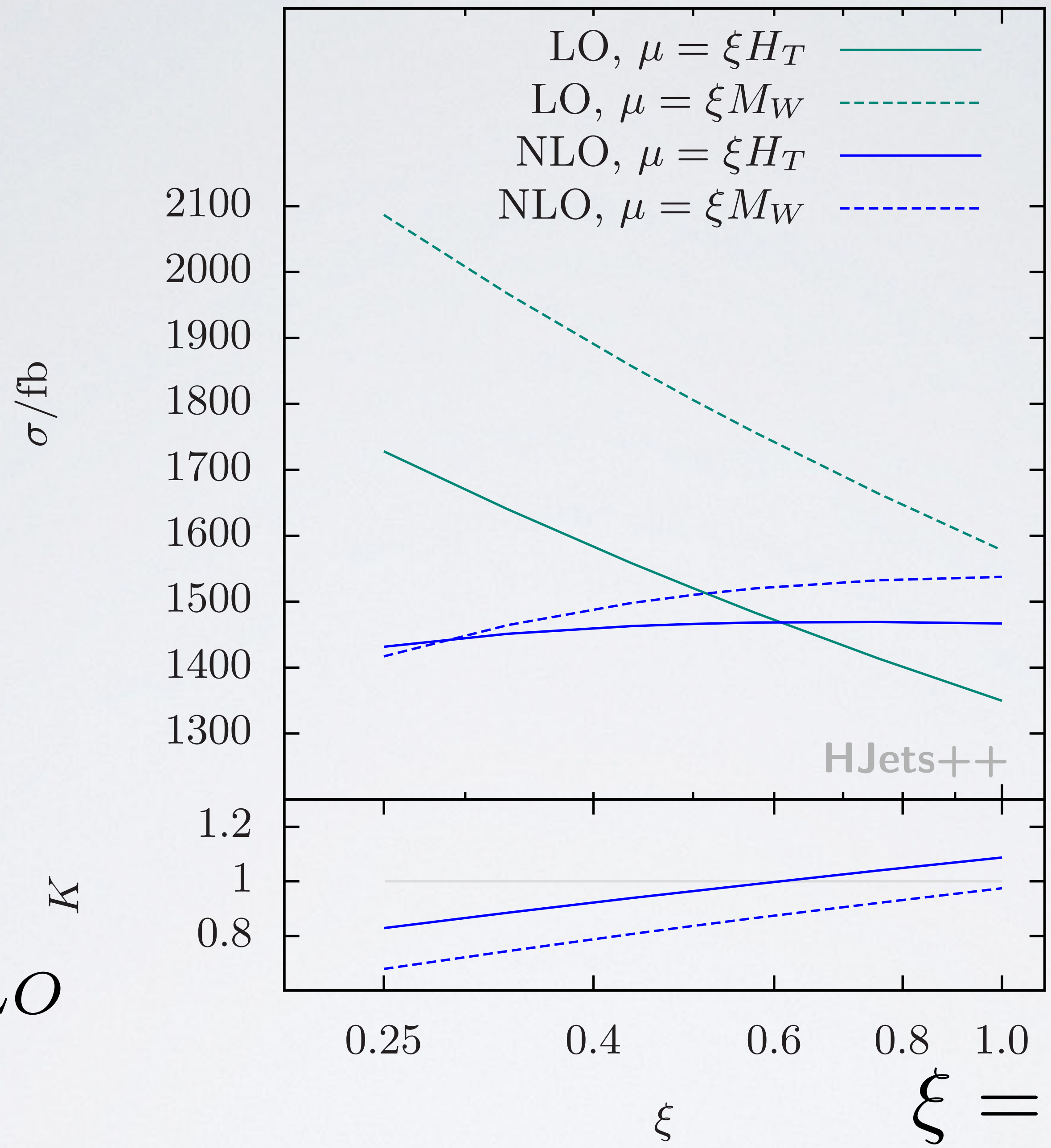
p_i: four momentum vector of i

$\Delta y_{ij} = |y_i - y_j|$: 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



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

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

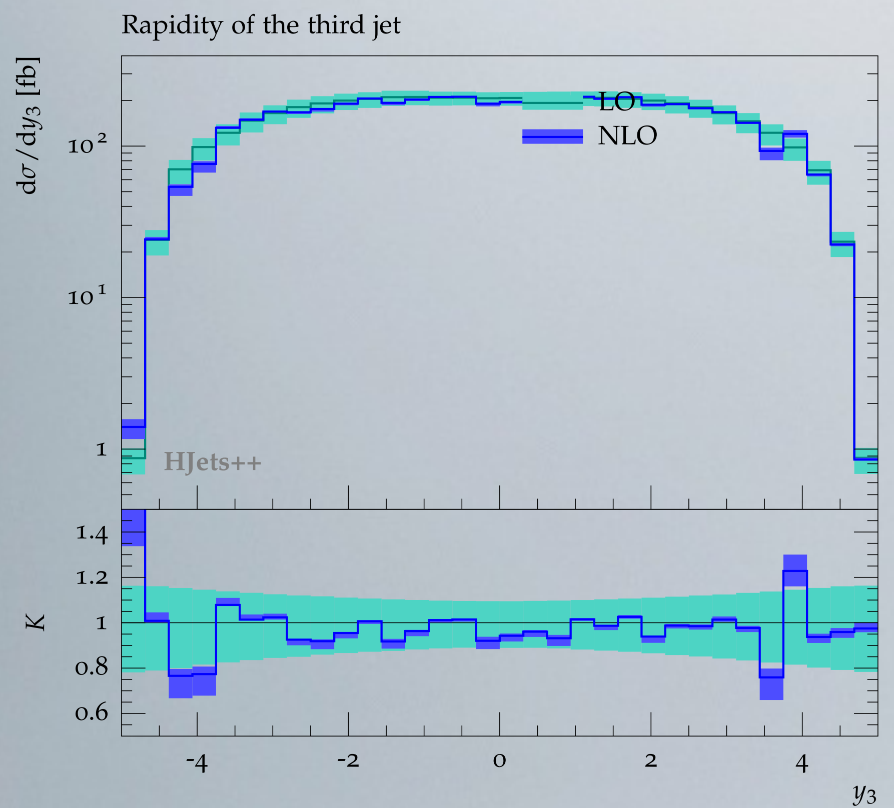
$$\xi = \mu/\mu_0$$

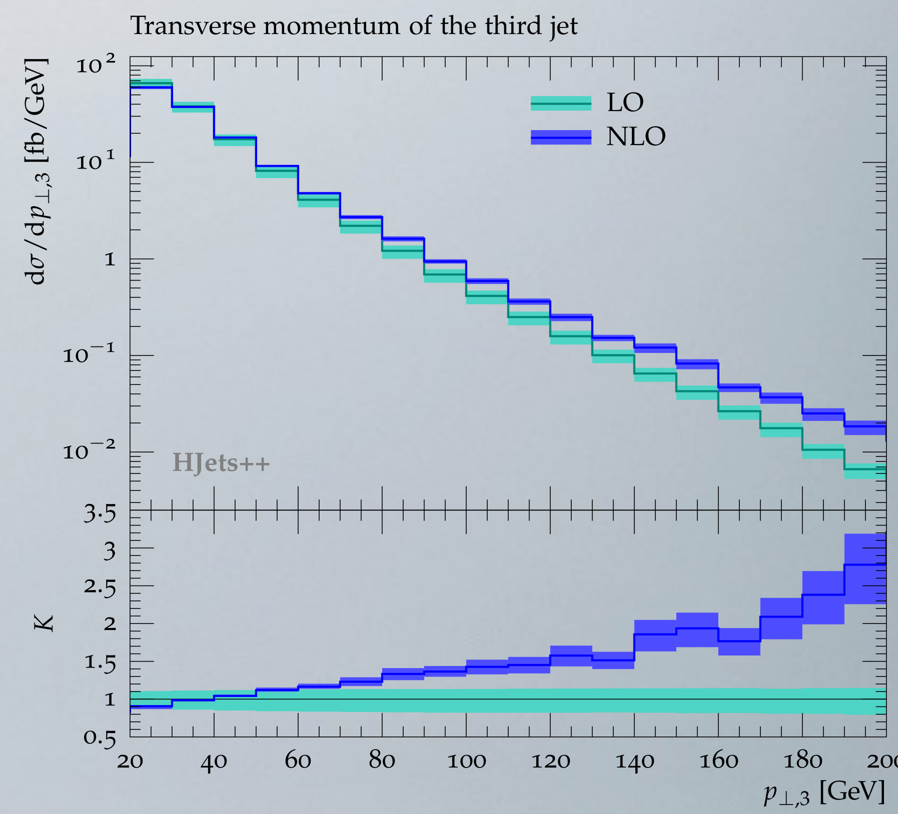
$\mu_R = \mu_F = H_T/2 \ (M_W/2)$:
30% (24%) at LO and 2% (8%) at NLO

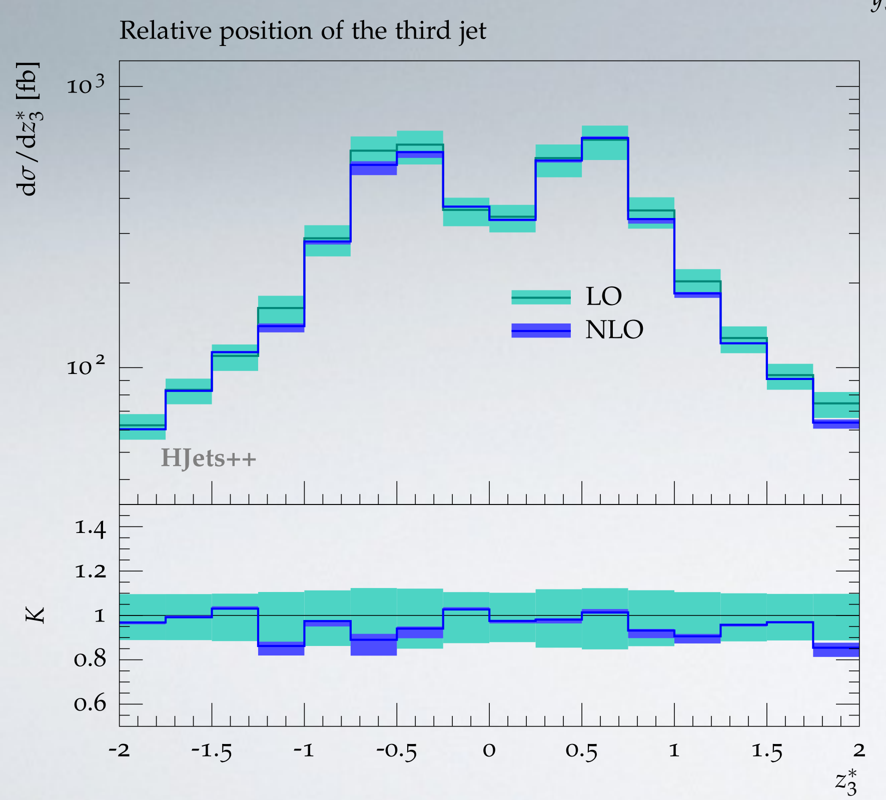
$\sigma_{LO} = 1520(8)^{+208}_{-171}$ fb

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

JET DISTRIBUTIONS

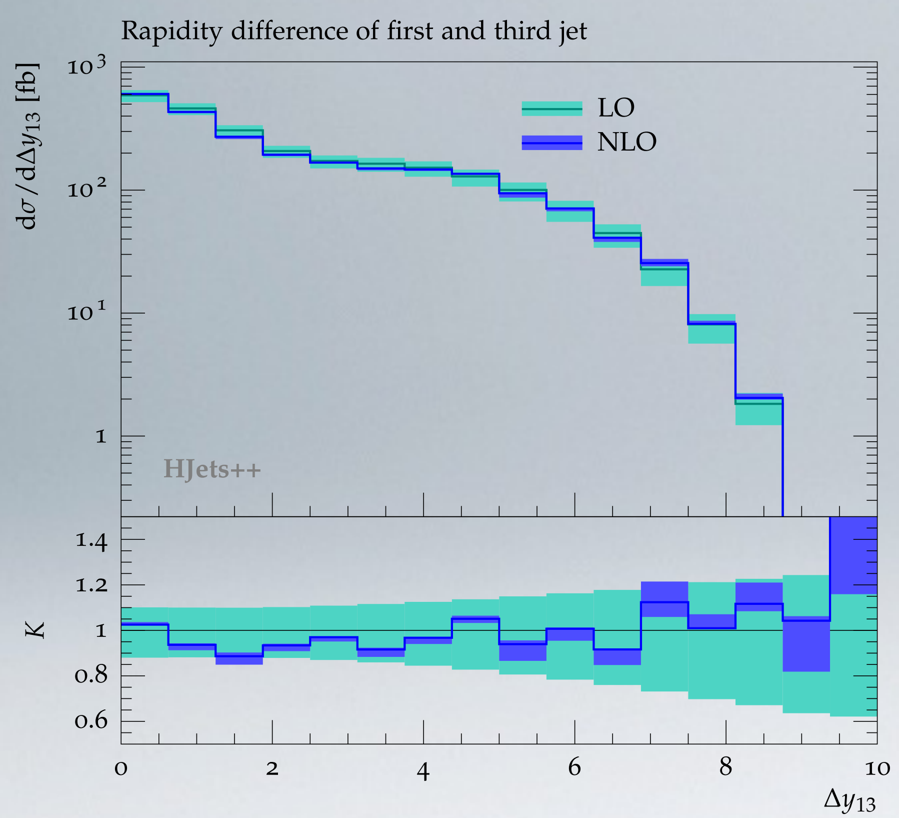


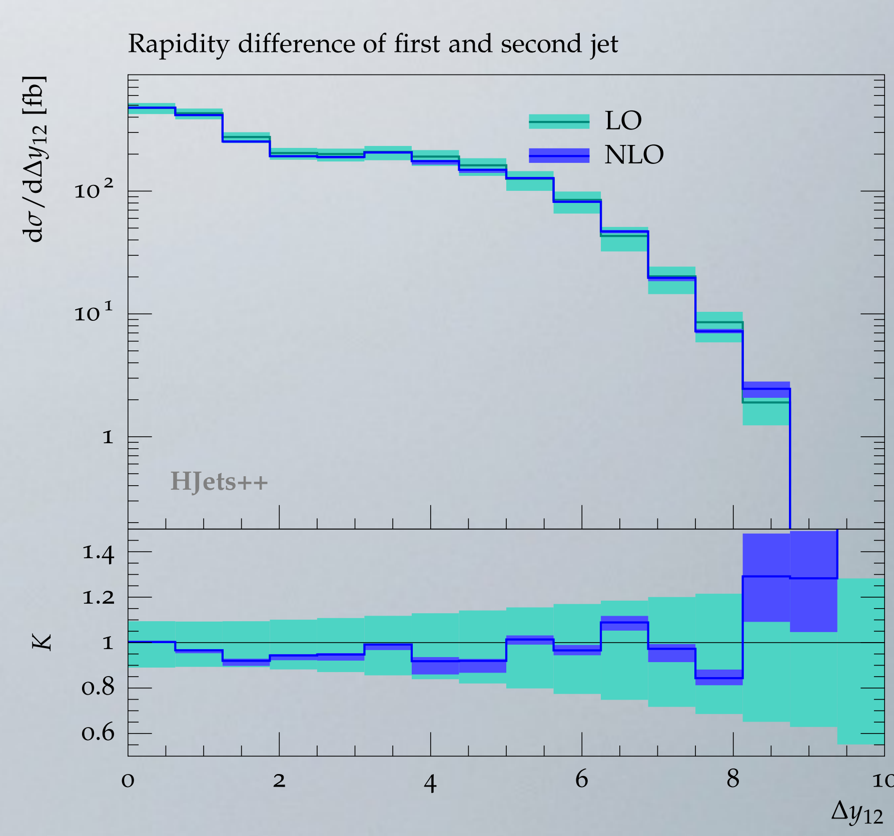


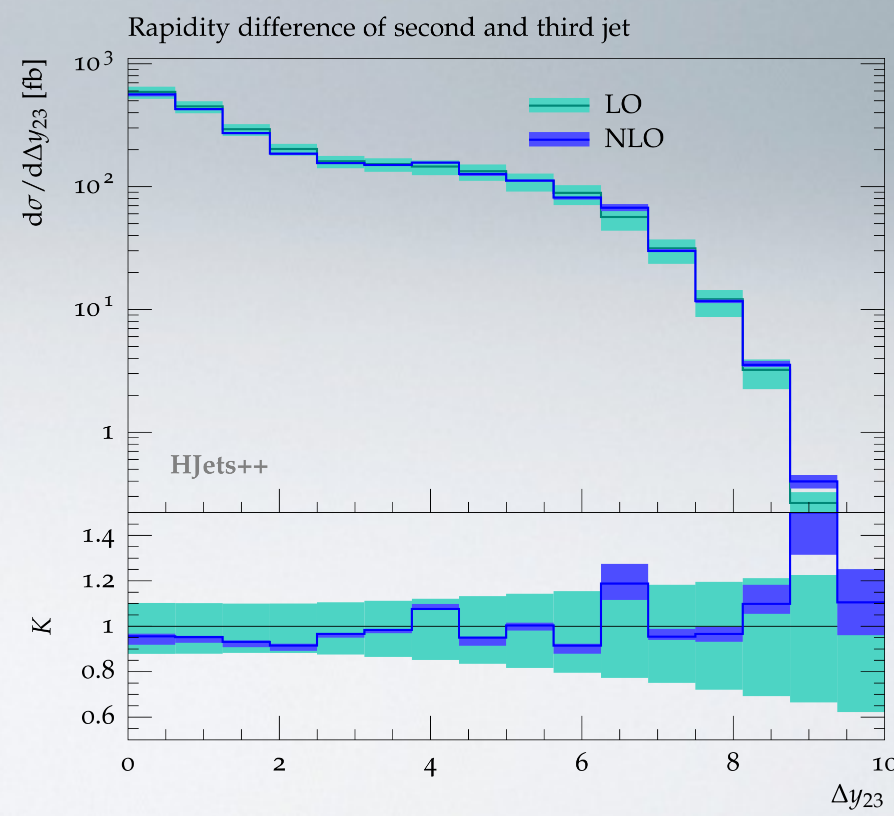


$$z_3^\star = (y_3 - \frac{1}{2}(y_1 + y_2))/(y_1 - y_2)$$

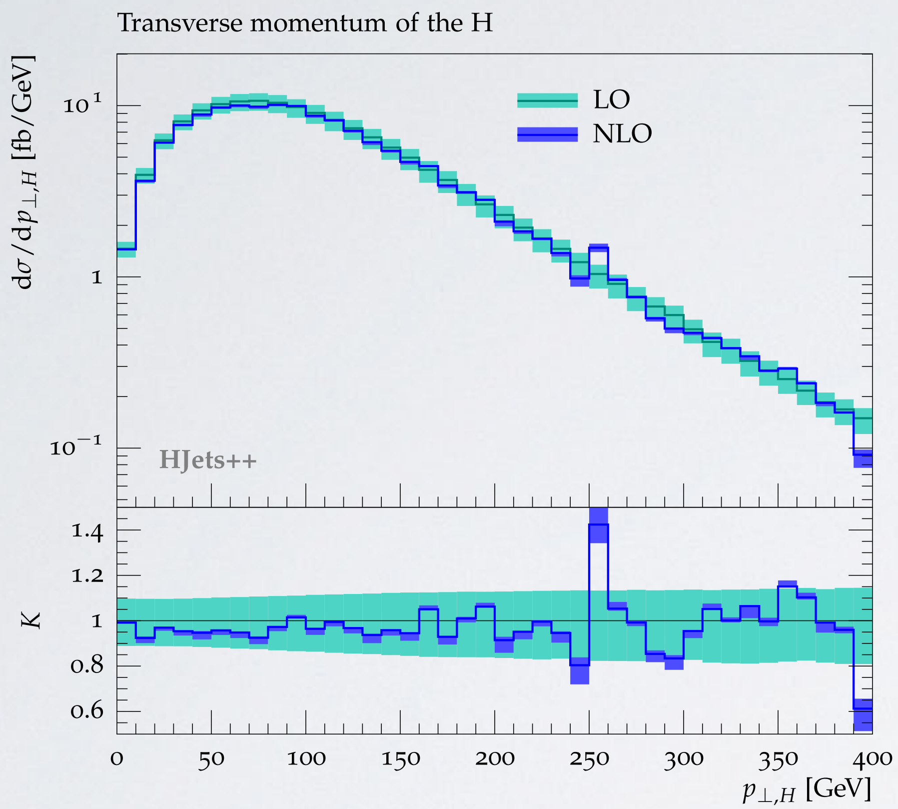
Rapidity separation



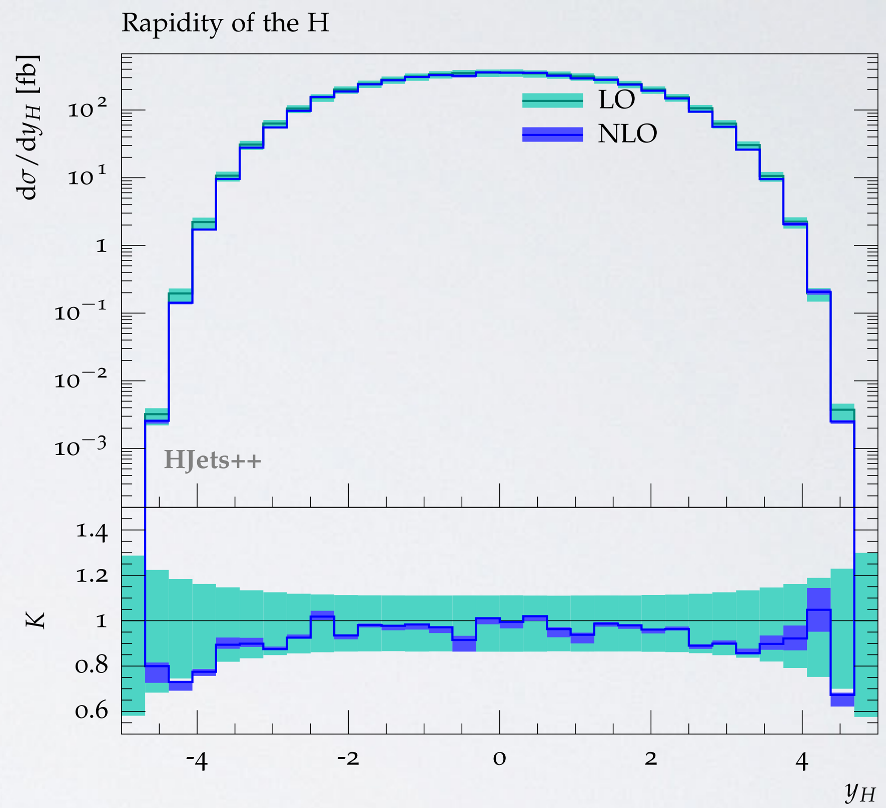




Higgs Boson Distributions

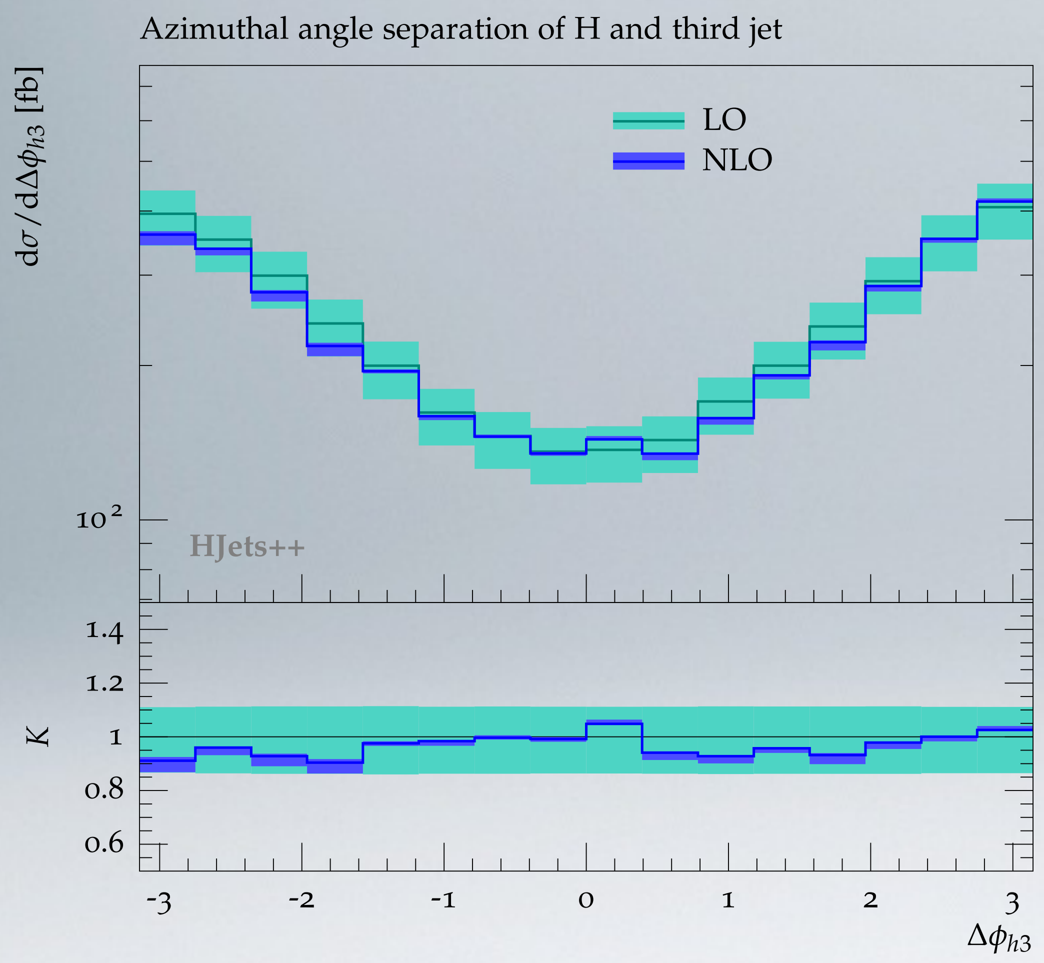


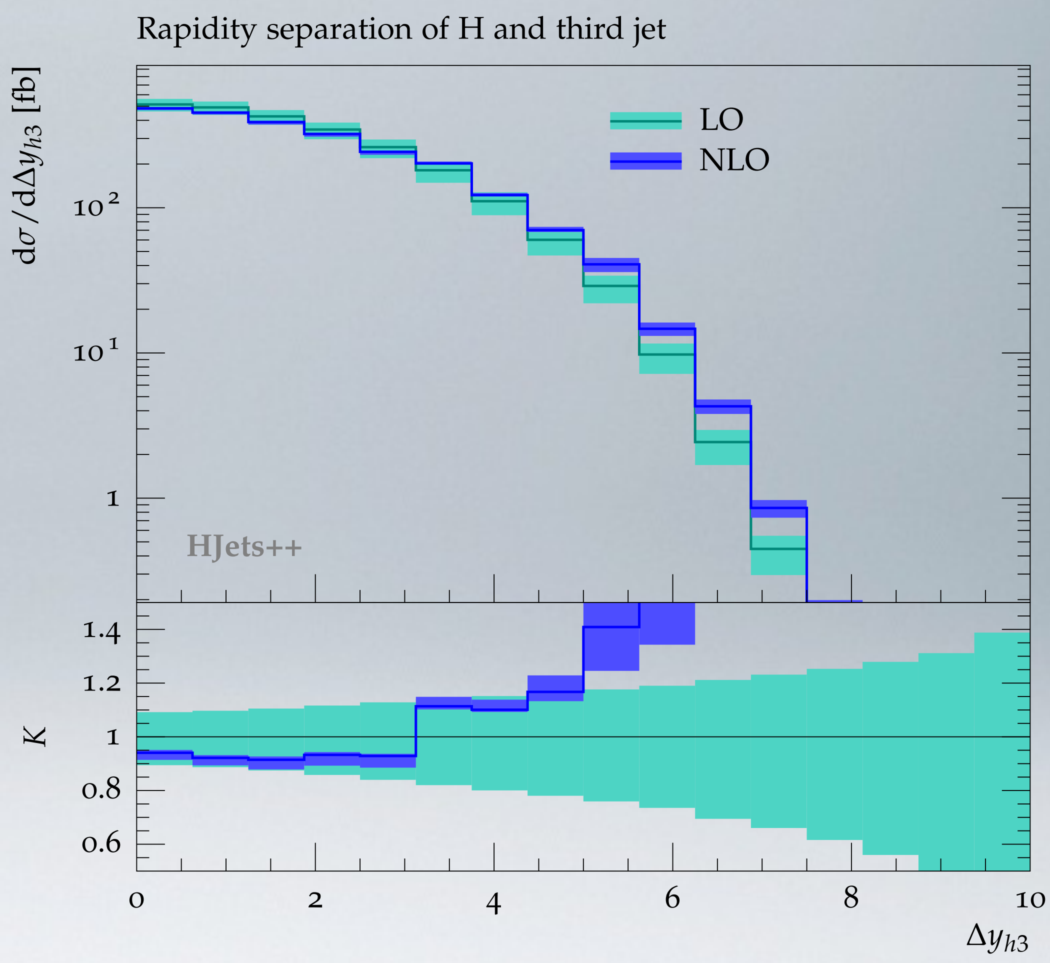
Transverse momentum



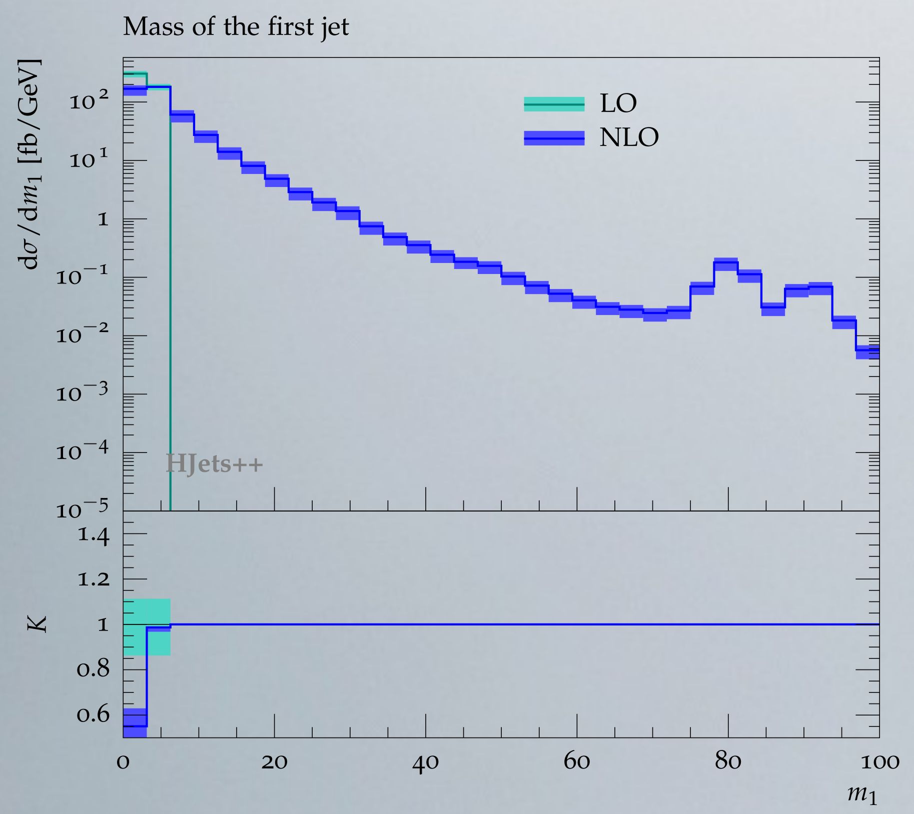
Rapidity

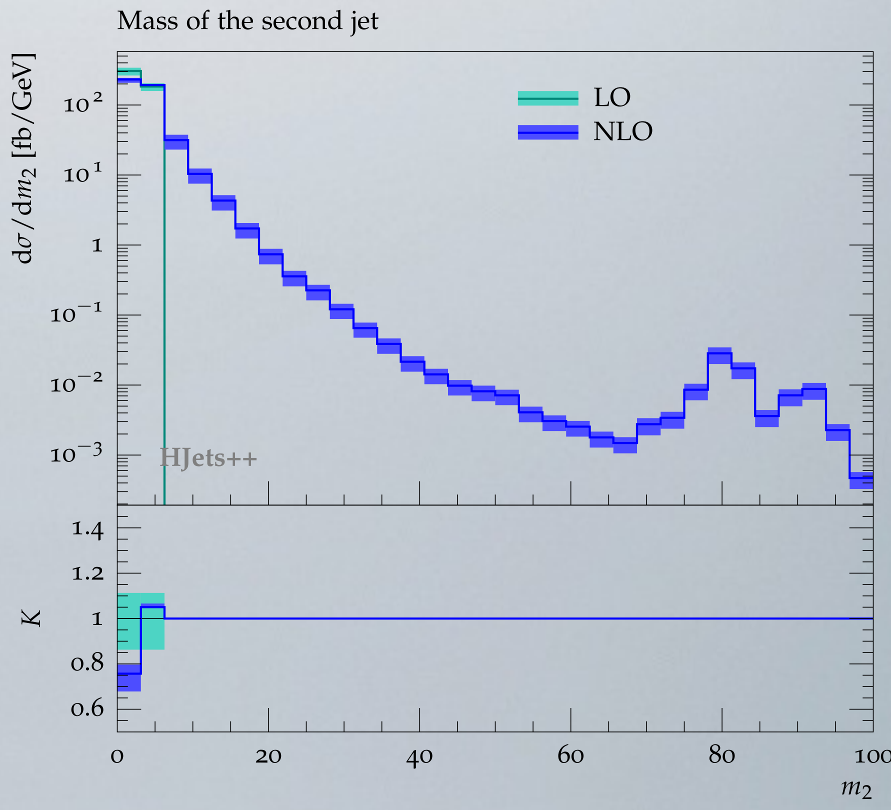
Higgs Boson Distributions



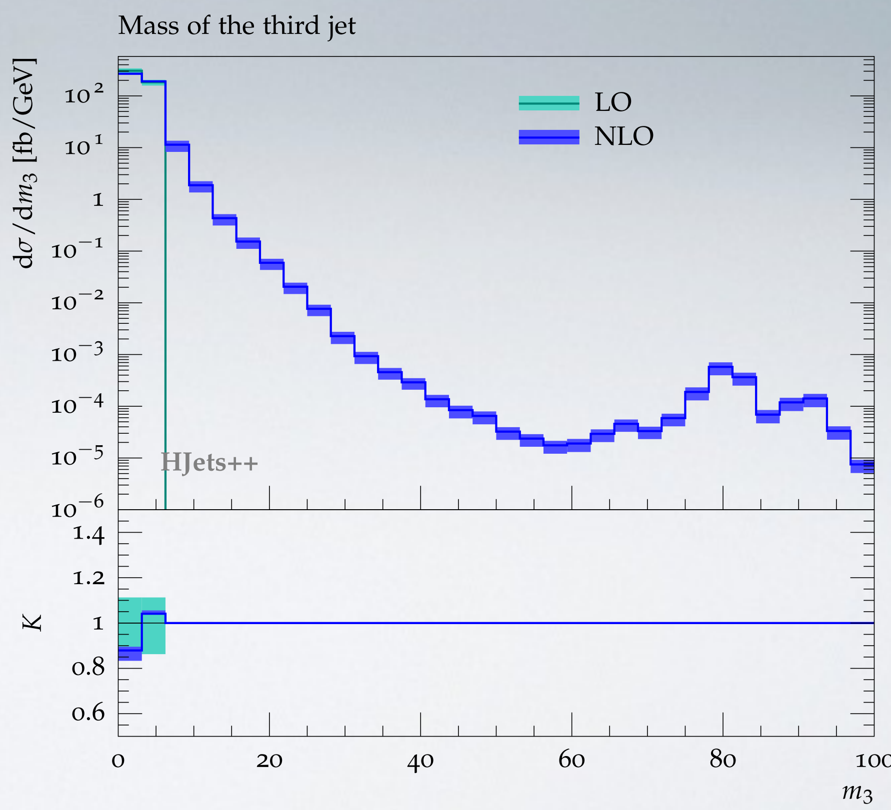


Jet Masses

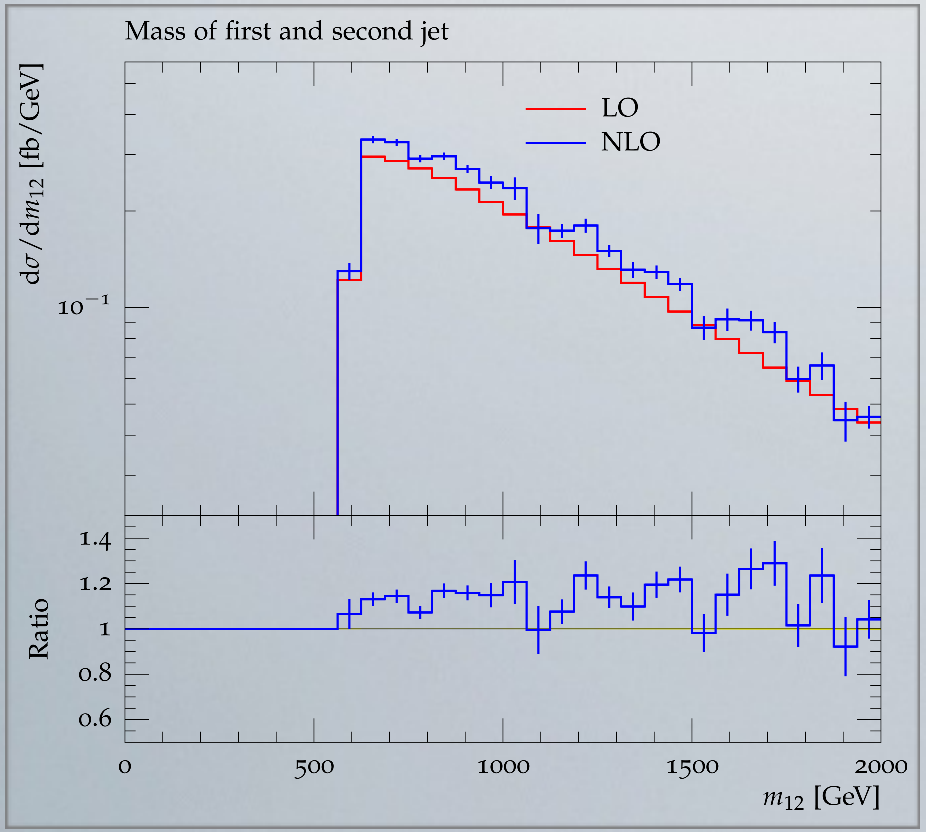


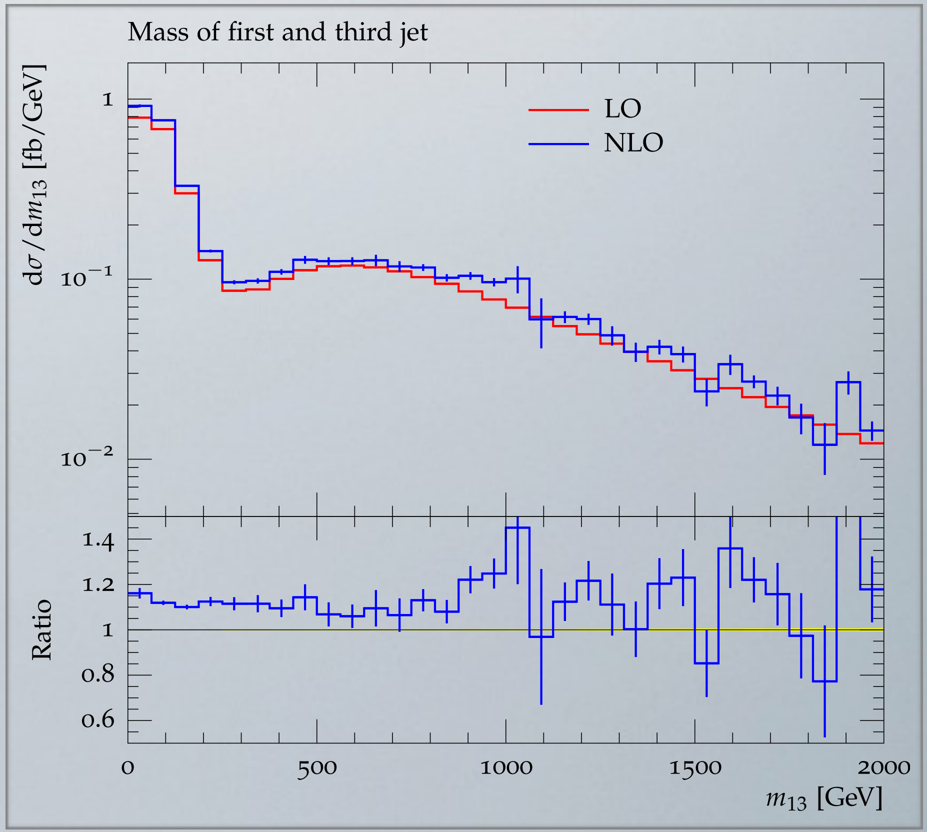


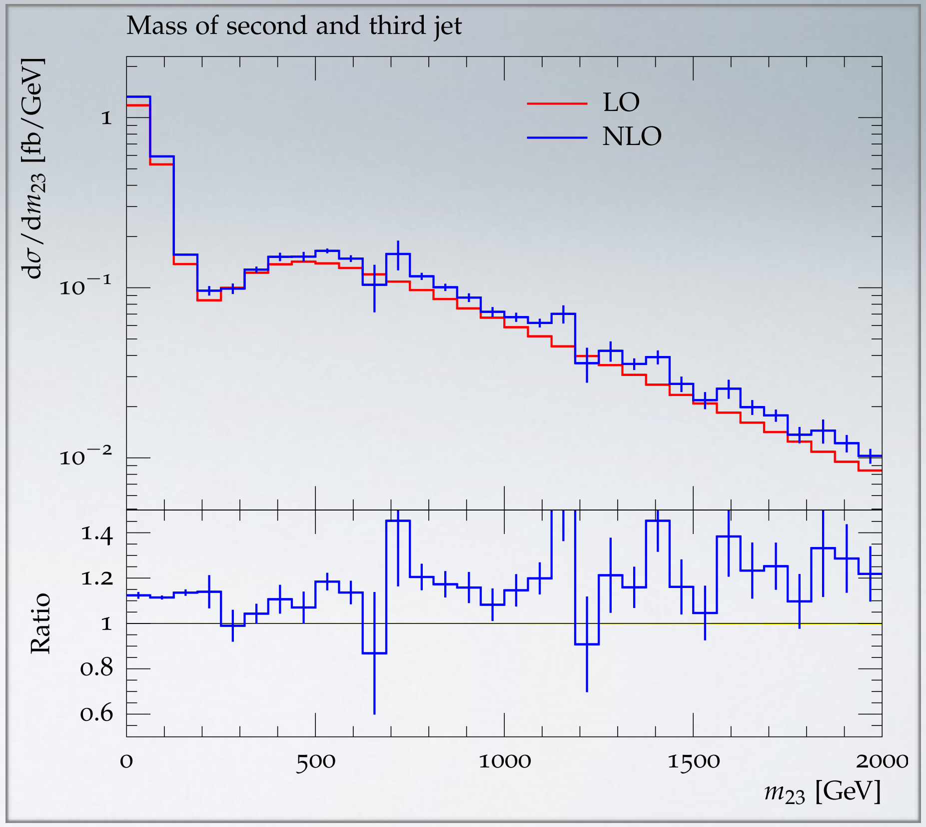
Here we see fat jets.



Distributions with VBF cuts

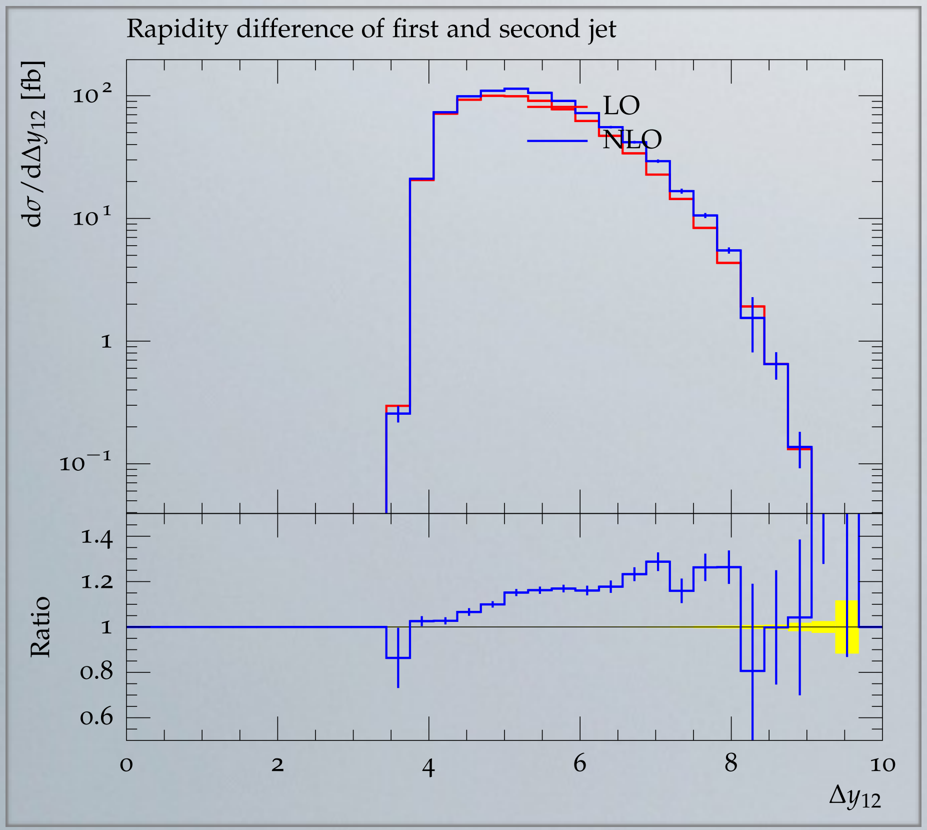


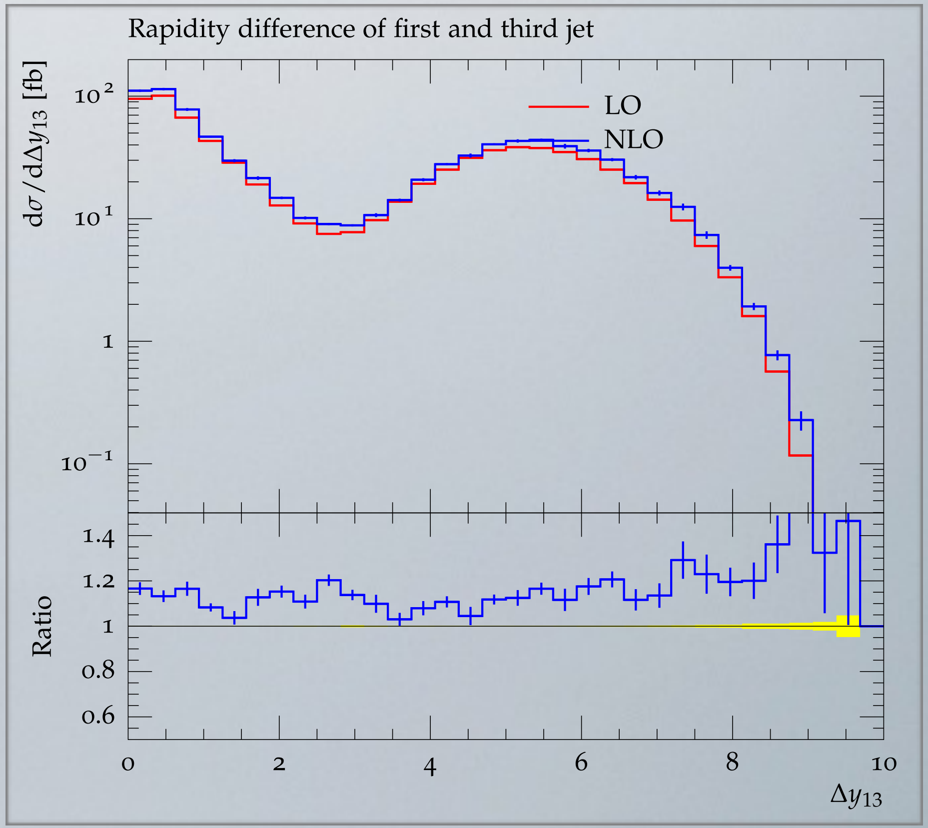


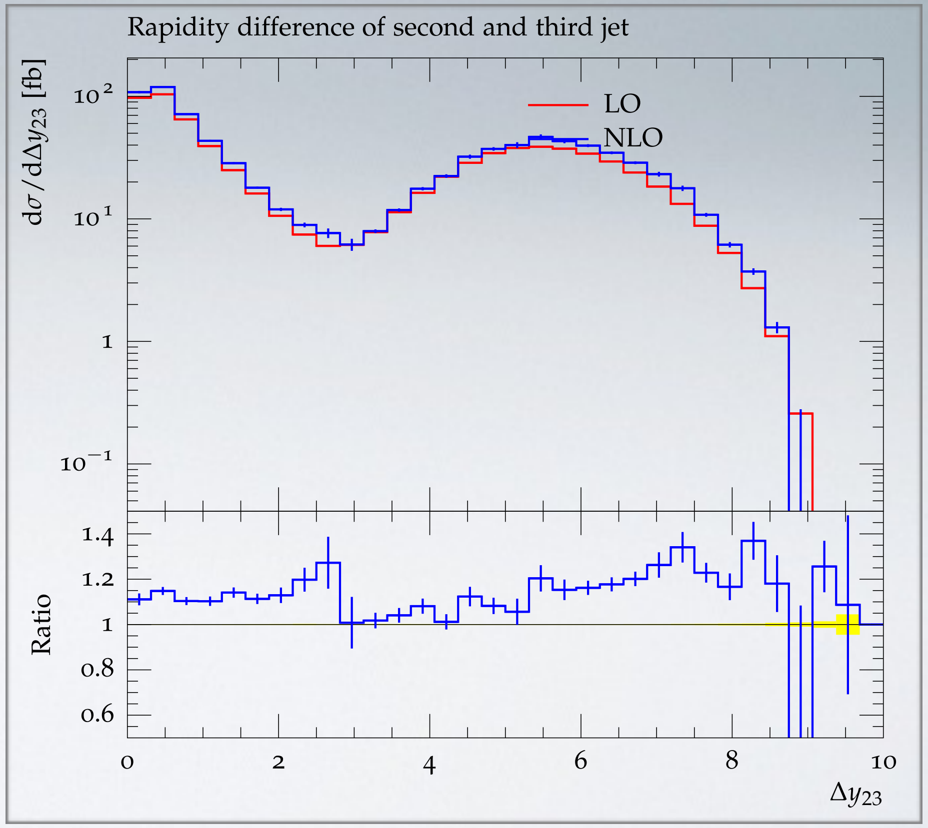


- $m_{j_1 j_2} > 600$ GeV
- $\Delta y_{j_1 j_2} > 4.0$

Distributions with VBF cuts

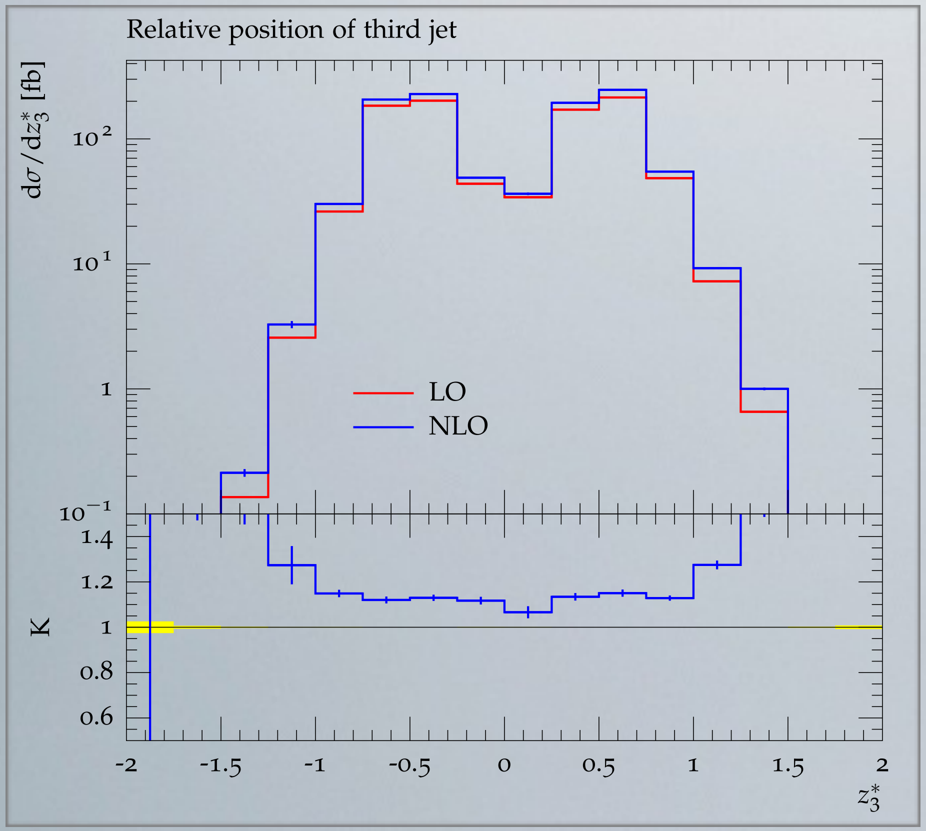


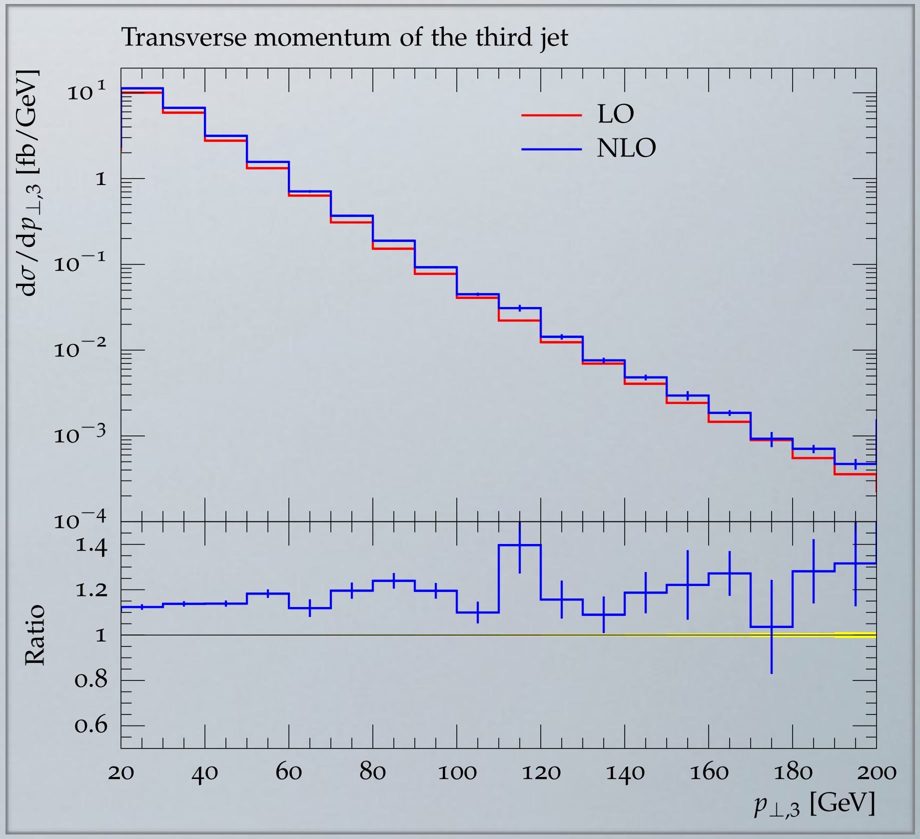


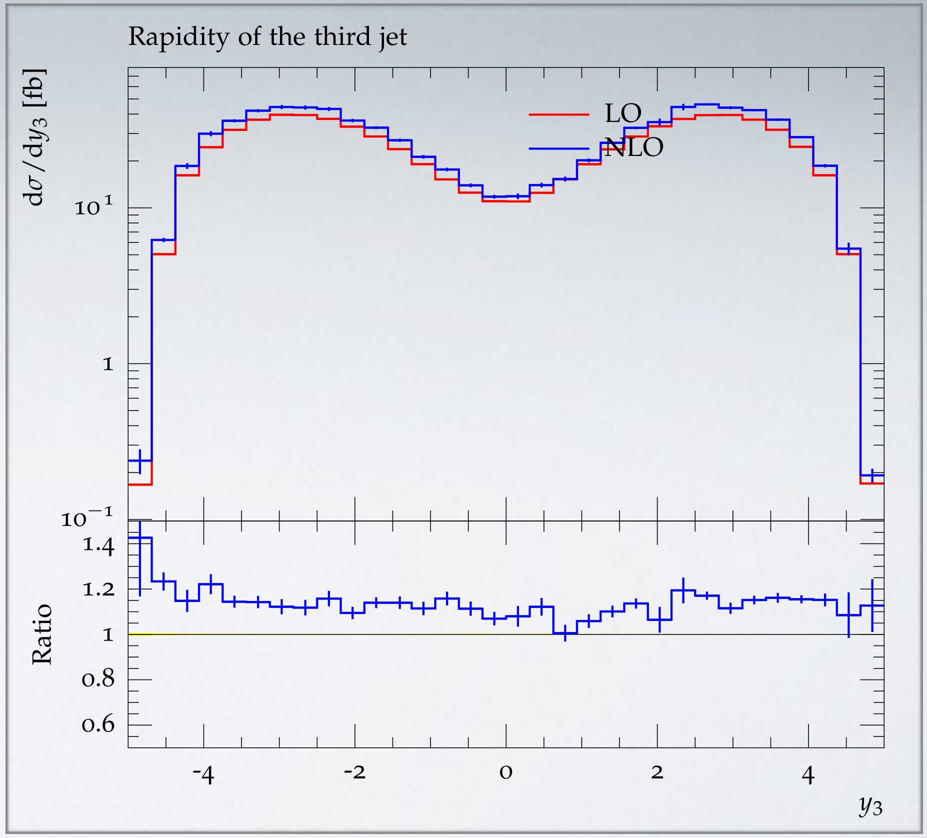


- $m_{j_1 j_2} > 600\ \mathrm{GeV}$
- $\Delta y_{j_1 j_2} > 4.0$

Distributions with VBF cuts







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

OUTLOOK

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

Comparison to VBFNLO