A Comparative Study of Electroweak Higgs Boson Production at Future Hadron Colliders

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Overview

Motivation

- The High-Luminosity Large Hadron Collider (HL-LHC) project is an upgrade of LHC and develops to increase luminosity by a factor of 10 beyond the LHC's design value.
- The HL-LHC will have many innovative technologies: a cutting-edge 11-12 Tesla superconducting magnets, compact superconducting crab cavities with ultra-precise phase control for beam rotation, new technology for beam collimation, etc. (HL-LHC website: http://hilumilhc.web.cern.ch/)
- The HL-LHC will produce at least 15 million Higgs bosons per year. In 2017, the LHC produced about three million Higgs bosons.
- The project is led by CERN with the support of an international collaboration of 29 institutions in 13 countries. The materials budget for the accelerator is set at 950 million Swiss francs between 2015 and 2026. (https://home.cern/topics/high-luminosity-lhc)

HL-LHC

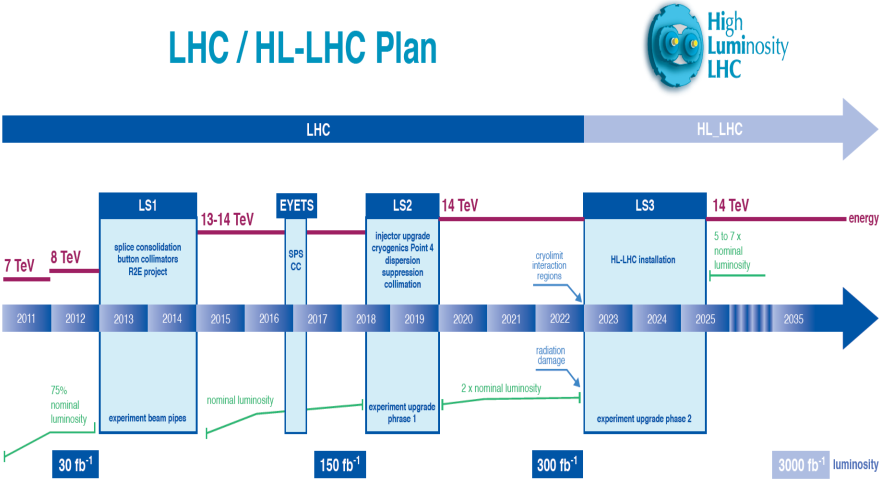


Figure: *The new HL-LHC timeline.*
Credit: CERN.
https://cds.cern.ch/record/2062983/files/LHC-2015-eng-1$_1$¡mage.jpg?subformat =

FCC

- The Future Circular Collider (FCC) is developing designs for a higher performance particle collider. The FCC will reach collision energies of 100 TeV.

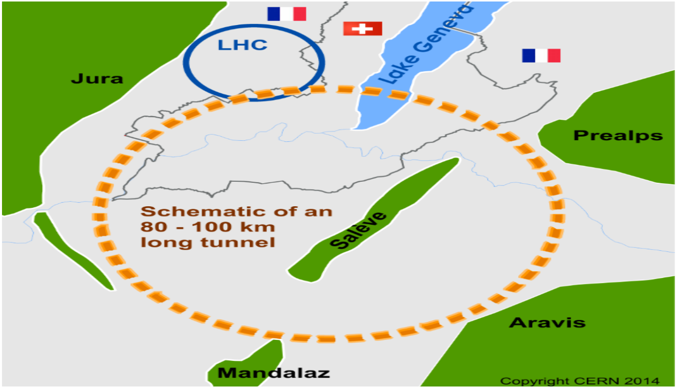


Figure: *A schematic map showing where the Future Circular Collider tunnel is proposed to be located.*
Credit: CERN. https://home.cern/about/accelerators/future-circular-collider

Higgs Production

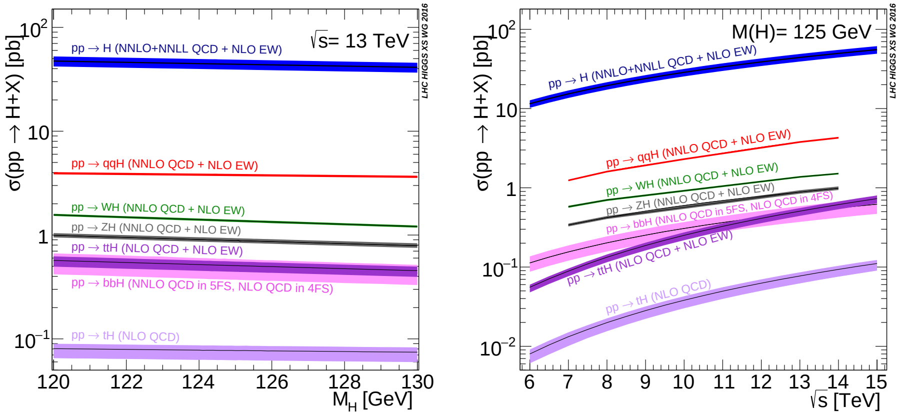


Figure: *Total Higgs production cross section. The left figure shows Higgs production cross section at* $\sqrt{s} = 13$ *TeV. The right figure shows Higgs production cross section at* $m_H = 125 GeV. Credit : arXiv : 1101.0593[hep - ph]$.

Vector Boson Fusion and Higgs-strahlung

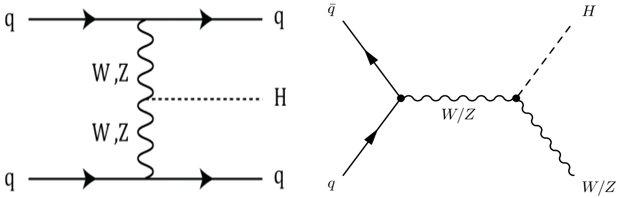


Figure: *Contribution to Higgs boson production from associated vector boson fusion (LHS) $qq \to qqV^*V^* \to qqH$ and $q\bar{q} \to V^* \to VH$ production (RHS) at lowest order. Credit: Spira, Michael. "Higgs boson production and decay at hadron colliders." Progress in Particle and Nuclear Physics 95 (2017): 98-159.*

NLO Calculation

$$
\begin{aligned}
\sigma_{\mathsf{NLO}}^{\mathsf{matched}} &= \int_n \left(\mathrm{d}\sigma_{\mathsf{LO}} + \mathrm{d}\sigma_{\mathsf{virt}}\right) \\
&+ \int_n \int_1 \left(\mathrm{d}\sigma_{\mathsf{PS}} - \mathrm{d}\sigma_{\mathsf{sub}}\right) \\
&+ \int_{n+1} \left(\mathrm{d}\sigma_{\mathsf{R}} - \mathrm{d}\sigma_{\mathsf{PS}}\right) \ ,
\end{aligned}
\tag{1}
$$

where the "LO" is the leading order cross section; "virt" is the contribution by one-loop diagrams, integrated subtraction terms and collinear counter-terms; "sub" is the un-integrated subtraction terms; "R" is the real emission and "PS" is the parton-shower approximation to the real-emission cross section [1].

Objectives and Techniques

Herwig 7 event generator

Herwig 7 is a multi-purpose particle physics event generator [2]. The current version is Herwig 7.1.4. It provides all the different simulation steps such as hard process generation, parton shower, hadronization and multiple parton interactions. Detail information and tutorials can be obtained from the website `https://herwig.hepforge.org/` or the user manual [2].

HJets++

HJets++ is a plugin for Matchbox providing amplitudes for the calculation of electroweak Higgs boson plus jets production at NLO(next-to-leading order) QCD [3]. All relevant topologies of either VBF or Higgs-Strahlung type are taken into account along with all interferences. It is built in the *LHC-Matchbox.in* file.

VBFNLO

VBFNLO is a fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production in hadronic collisions at NLO QCD [4]. Further information can be found in the user manual of the VBFNLO.

Rivet

Rivet (Robust Independent Validation of Experiment and Theory) is a toolkit that allows for the comparison of Monte Carlo simulations and experimental data. It is also a widely used analysis code from the LHC and other high energy particle experiments. Further information can be obtained from the Rivet user manual [5].

XSEDE and Open Science Grid

XSEDE (Extreme Science and Engineering Development Environment) is a virtual cyberinfrastructure that scientist use to share computing resources and data. It has many allocated resources can be used include Stampede2, Open Science Grid (OSG) [6], [7], etc.

Notations

Five observables are chosen to present:

- Higgs centrality, defined as

$$y_h^* = \frac{y_h - (y_1 - y_2)/2}{\mid y_1 - y_2 \mid} \tag{2}$$

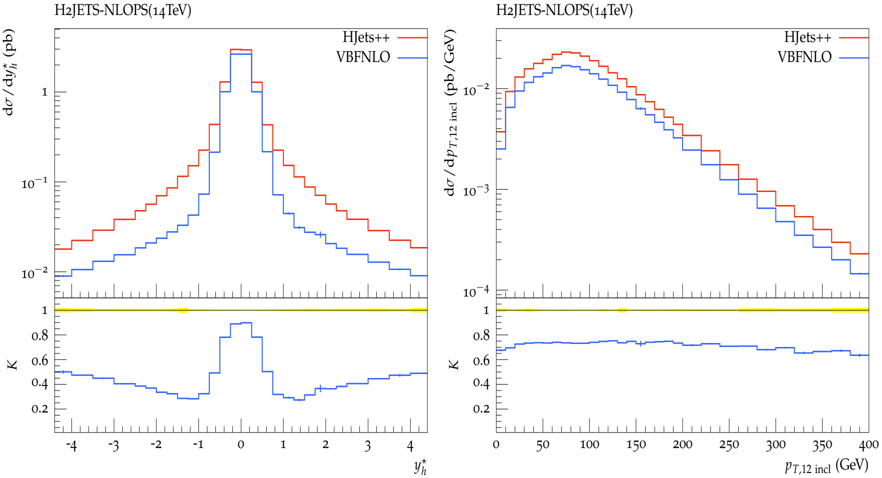
  where y is denoted as rapidity,

$$y = \frac{1}{2} \ln\left(\frac{E + p_z c}{E - p_z c}\right) \tag{3}$$

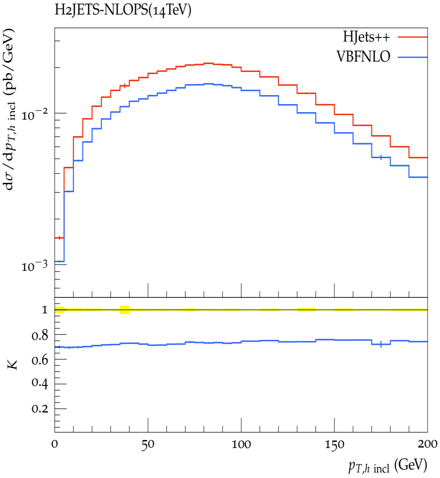
- Transverse momentum of jets, $p_{T,12}$
- Transverse momentum of Higgs boson, $p_{T,h}$
- Rapidity gap of jets, defined as $\Delta y_{12} = |y_1 - y_2|$
- Invariant mass of jets, m_{12}

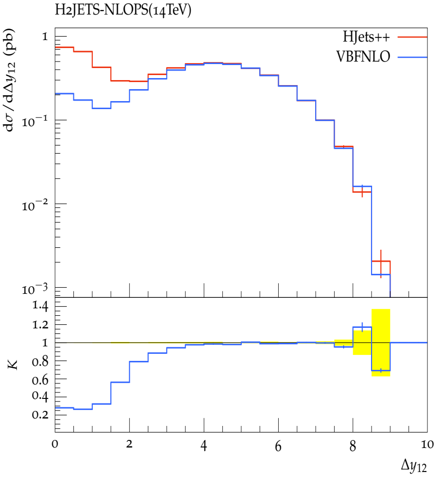
Inclusive Cuts Comparison at 14 TeV

- applied inclusive cuts $p_{T,j} > 30$ GeV, $|y_j| < 4.5$

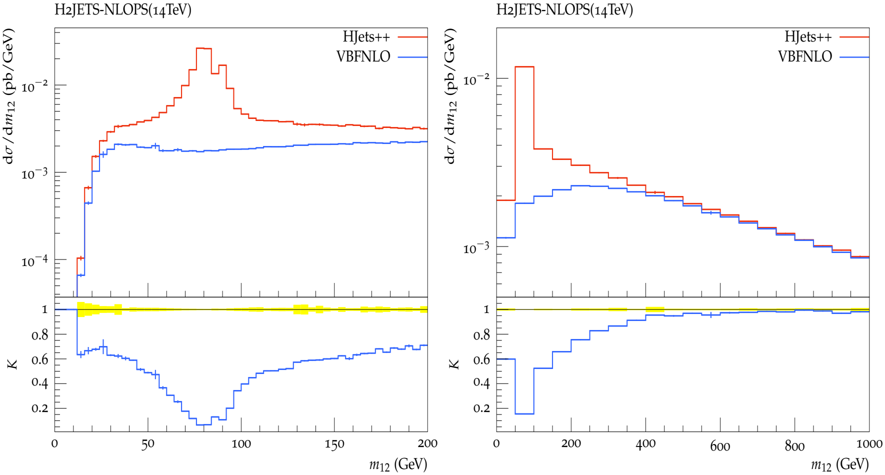


Inclusive Cuts Comparison at 14 TeV





Inclusive Cuts Comparison at 14 TeV



VBF Cuts

- Cut applied to 14 TeV: $m_{12} > 400$ GeV and $\Delta y_{12} > 3$
- Cut applied to 33 TeV and 100 TeV: $m_{12} > 600$ GeV and $\Delta y_{12} > 3$

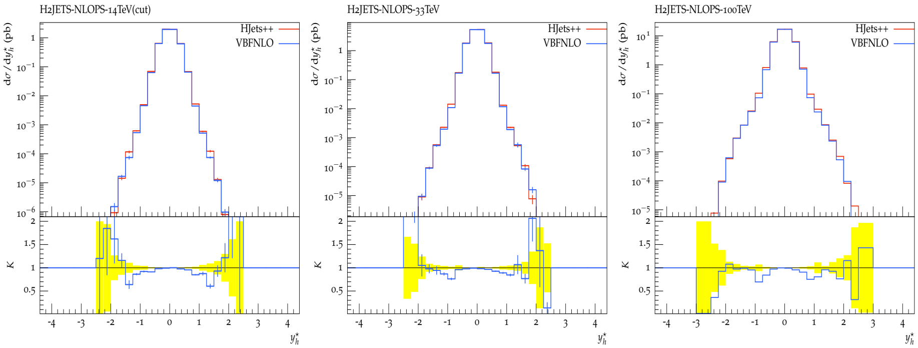


Figure: *Higgs centrality of NLOPS calculation at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

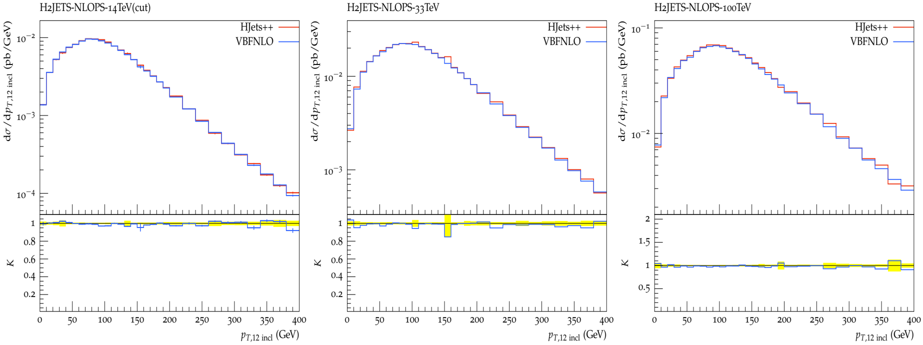


Figure: *Transverse momentum of jets of NLO+PS calculation at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV*

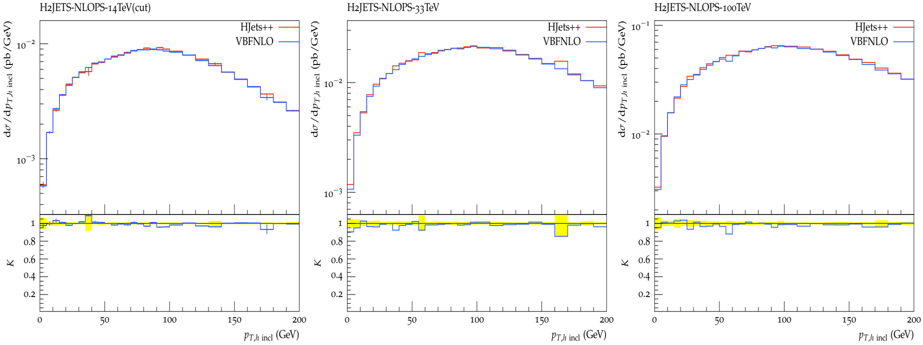


Figure: *Transverse momentum of Higgs boson of NLO+PS calculation at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

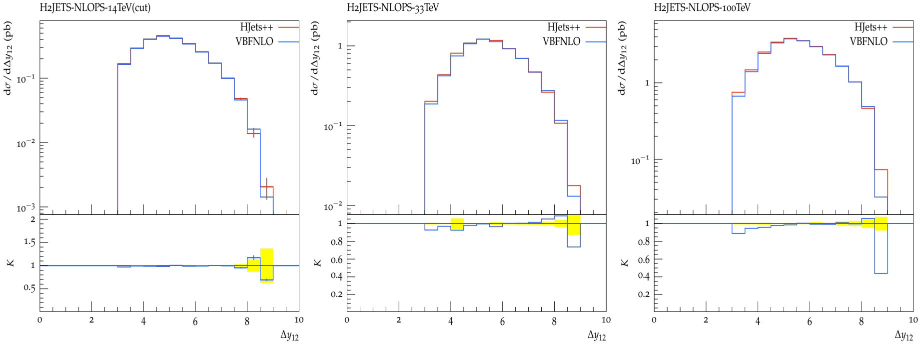


Figure: *Rapidity gap between jets of NLOPS calculation at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

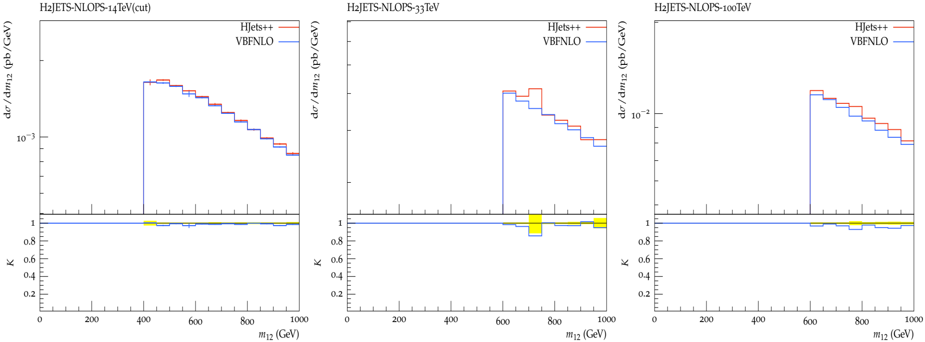
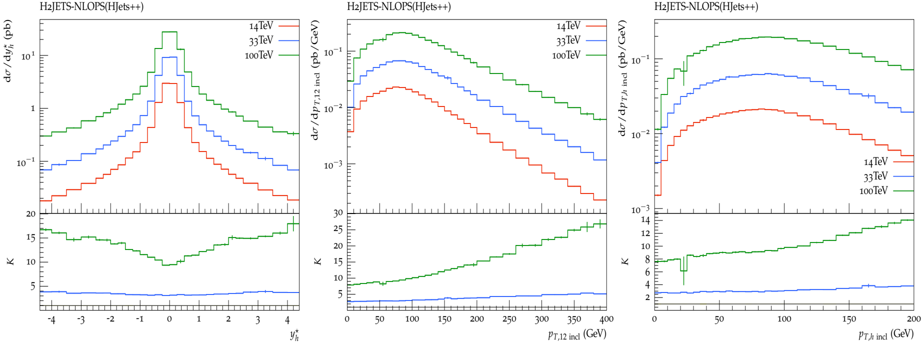
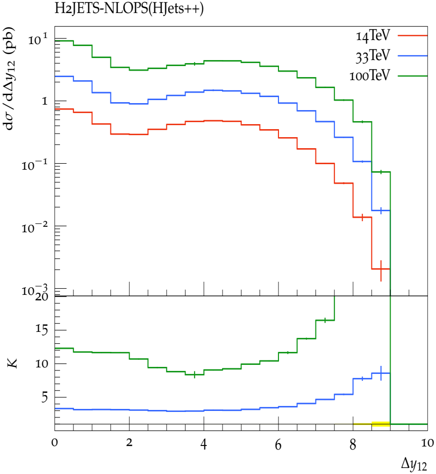


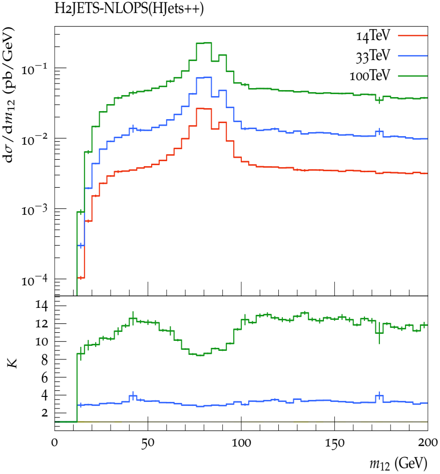
Figure: *The distribution of invariant mass of two jets at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

HJets++ Comparison between different CM energy

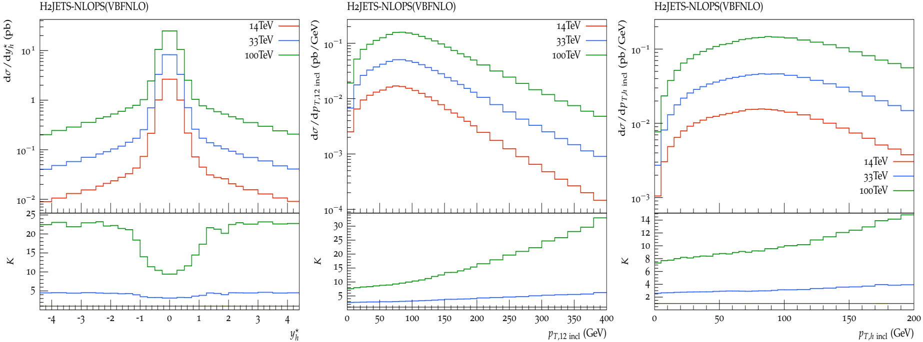


HJets++ Comparison between different CM energy

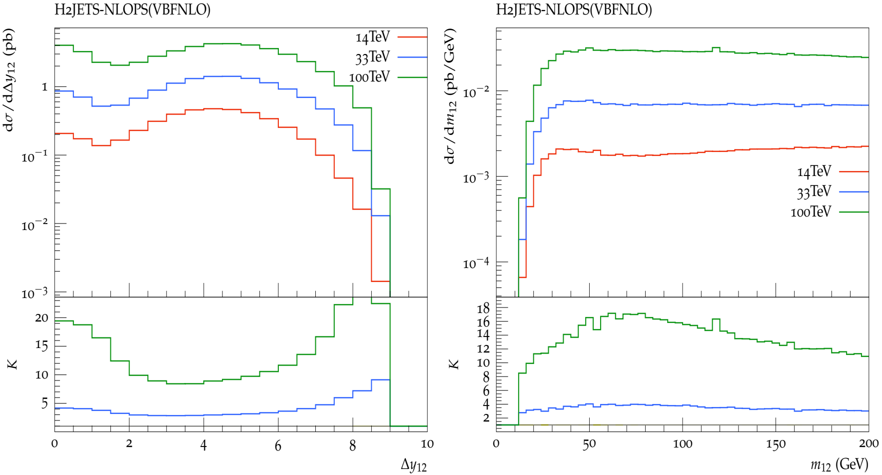




VBFNLO Comparison between different CM energy



VBFNLO Comparison between different CM energy



Summary

- Both HJets and VBFNLO matrix elements have agreements in select kinematic variables after applied VBF cuts. Comparison plots show a slightly difference after applied cut.
- The distribution of kinematic variables have been presented in the NLO plus parton shower at different CM energy.

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Thank You

Comparisons among the NLO and LO with Parton Shower

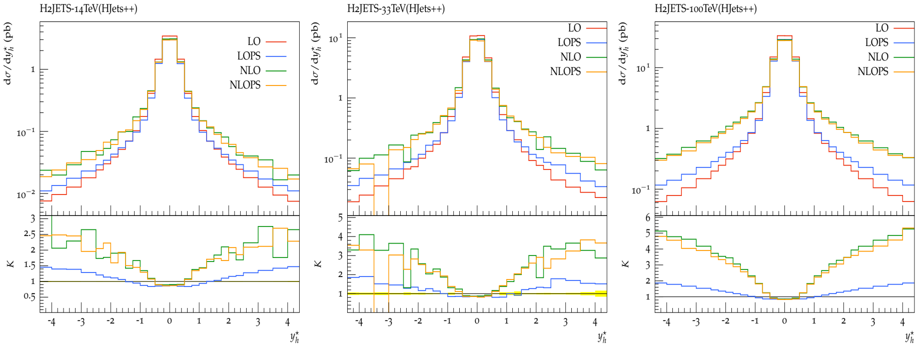


Figure: *Higgs centrality distribution at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

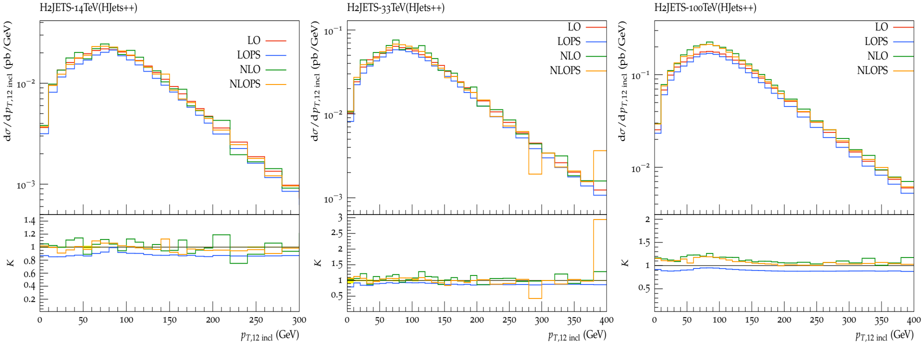


Figure: *Distribution of transverse momentum for jets at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

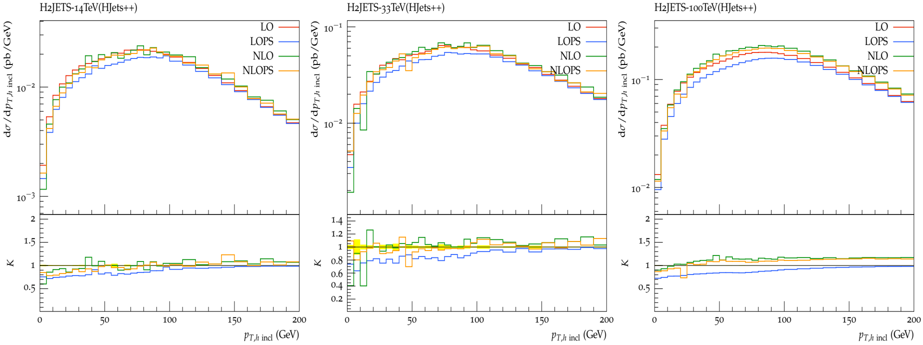


Figure: *Distribution of transverse momentum for Higgs boson at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

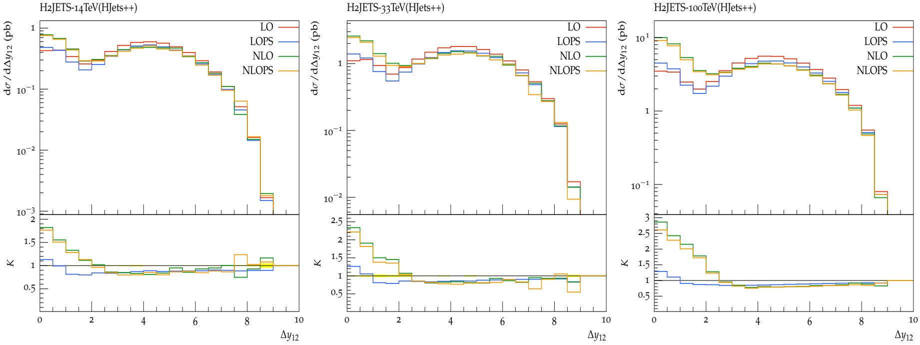


Figure: *Separation of rapidity between jets at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

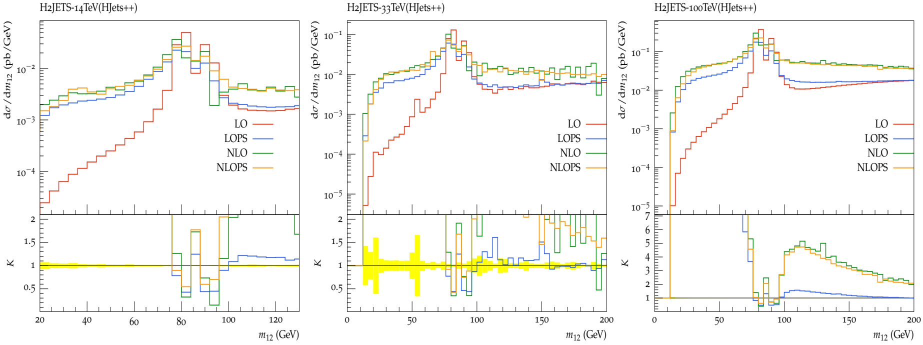
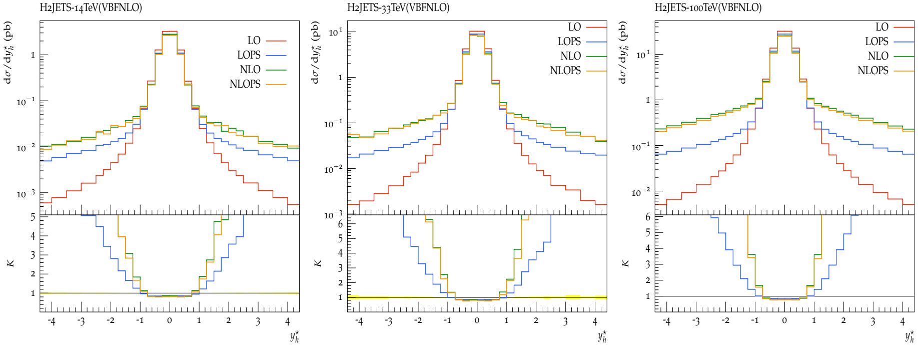


Figure: *Invariant mass of jets distribution at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV*

Comparison Plots for VBFNLO



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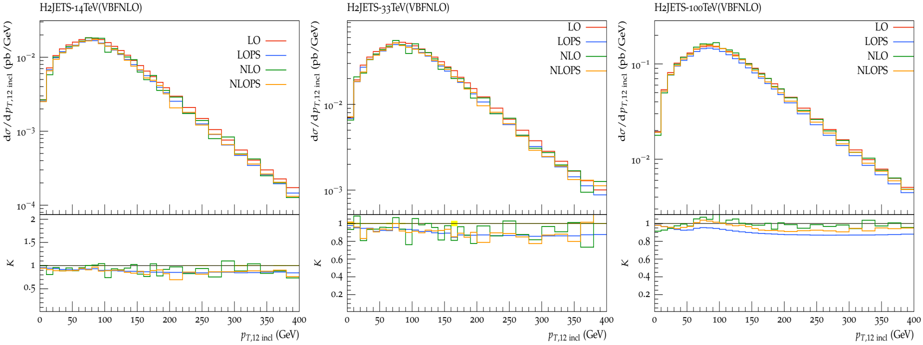

Figure: *Distribution of transverse momentum for jets at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

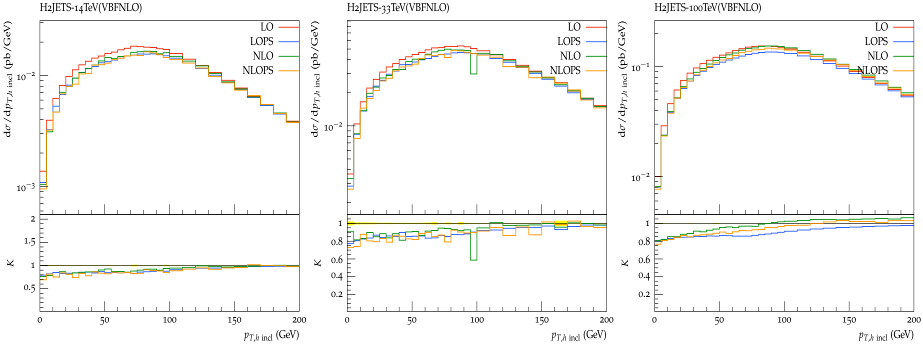

Figure: *Distribution of transverse momentum for Higgs boson at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

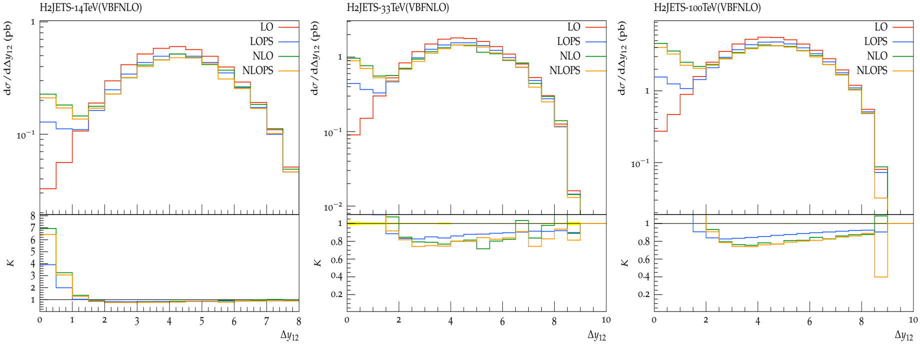

Figure: *Separation of rapidity between jets at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV.*

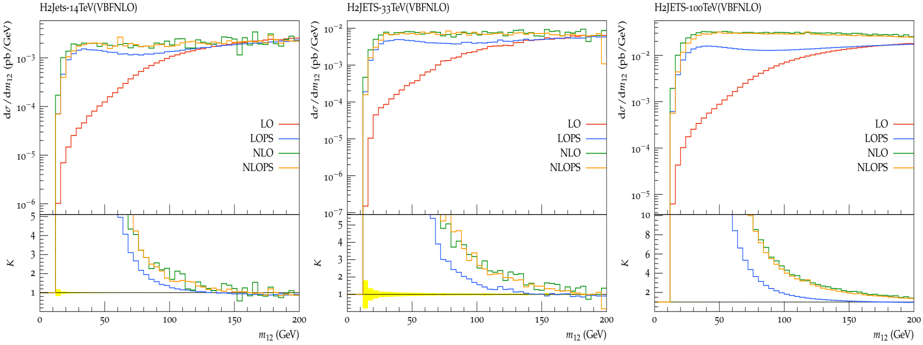

Figure: *Invariant mass of jets distribution at* $\sqrt{s} = 14$ *TeV, 33 TeV, 100 TeV*