Monte-Carlo simulation and uncertainties

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Introduction and disclaimer

There are high precision calculations available for all production modes.

Fully exclusive particle level calculations are available for every channel at least at NLO accuracy employing at least two diff. matching algorithms.

Most channels have well tested multijet merged calculations available.

Question: How do these calculations compare against dedicated calculations at higher accuracy?
Perfect agreement is not expected, as different scale choices, resummation variables, non-perturbative corrections, etc.

Can the differences be understood?

For *ggF* such a study was conducted within LH'15.
Ideal testbed because of the size of the effects and the availability of many different specialised calculations.

Performance of Monte-Carlo event generators

LH'15 arXiv:1605.04692

Aim & focus

- study description of QCD activity in $pp \to h +$ jets
- use state-of-the-art fixed-order and/or resummed calculations, modern precision parton shower matched & multijet merged calcs
- inclusive wrt. to Higgs kinematics and decay channels to accommodate as many calculations as possible
- purely perturbative calculation, no non-perturbative physics $\to$ no MPI, hadronisation, intrisic $k_\perp$, etc.
- study (idealised) observables of theoretical interest/importance
- assess difference in description of these observables between MCs and fixed-order and/or resummed calculations
- provide RIVET analysis for common analysis with $O(100)$ observables $\to$ used by MCs and NLO calculations

Setup

- $pp \to h +$ jets in gluon fusion @ LHC 13 TeV
- HEFT in $m_t \to \infty$ limit, $m_b = 0$
- $m_h = 125\,\text{GeV}$, $\Gamma_h = 4.07\,\text{MeV}$
- PDF: `MMHT2014nlo68clas118` (LHAPDF id: 25200)
  `MMHT2014nnlo68cl` (LHAPDF id: 25300)
  $\rightarrow$ modern PDF set, $\alpha_S(m_Z) = 0.118$, 5 flavour running
- scales: use scale that reduces to $\frac{1}{2}\, m_h$ in zero jet limit
- uncertainties: renormalisation and factorisation scale
  resummation scale, shower starting scale, etc.
  merging scale
- jets: anti-$k_\perp$ with $R = 0.4$ and $p_\perp > 30\,\text{GeV}$ in $|\eta| < 4.5$

https://phystev.cnrs.fr/wiki/2015:groups:tools:hjets#contributions

Contributions

Fixed-order calculations

- SHERPA $pp \to h$ @ NNLO

  Höche, Li, Prestel Phys. Rev. D90 (2014) 054011

  $\mu_R = \mu_F = \frac{1}{2}\, m_h$
  uncertainties: 7-pt variation by factor two

- BFGLP $pp \to hj$ @ NNLO

  Boughezal et.al. Phys. Lett. B748 (2015) 5

  $\mu_R = \mu_F = \frac{1}{2}\sqrt{m_h^2 + \sum p_{\perp,j_i}^2}$
  uncertainties: 7-pt variation by factor two

Contributions

Fixed-order calculations

- GoSam+Sherpa $pp \to h + 1, 2, 3j$ @ NLO
  Greiner et.al. JHEP01(2016)169
  $\mu_R = \mu_F = \frac{1}{2}\sqrt{m_h^2 + \sum p_{\perp,j_i}^2}$
  uncertainties: 7-pt variation by factor two
- GoSam+Sherpa $pp \to h + 1, 2, 3j$ @ MiNLO
  LH'15 arXiv:1605.04692
  local emission scales, Sudakov form factors, $\mu_{\text{core}} = \frac{1}{2}\,H_T'$
  uncertainties: 7-pt variation by factor two
- GoSam+Sherpa $pp \to h + (1, 2)j$, $pp \to h + (2, 3)j$ @ nNLO
  LH'15 arXiv:1605.04692
  LoopSim with $\mu_R = \mu_F = \frac{1}{2}\sqrt{m_h^2 + \sum p_{\perp,j_i}^2}$
  uncertainties: 7-pt variation by factor two

Contributions

Analytic resummations

- HQT: $p_\perp(h)$ in $pp \to h$ @ NNLL+NNLO
  Bozzi et.al. Nucl. Phys. B737 (2006) 73, de Florian et.al. JHEP11(2011)064
  $\mu_R = \mu_F = Q = \frac{1}{2}\, m_h$
  uncertainties: constrainted by $\frac{1}{2} < \mu_R/\mu_F < 2$ and $\frac{1}{2} < \mu_R/Q < 2$
- ResBos 2: $p_\perp(h)$ in $pp \to h$ @ NNLL+NNLO,
  $p_\perp(hj)$ in $pp \to hj$ @ NLL+NLO
  Wang et.al. Phys. Rev. D86 (2012) 094026, Sun et.al. ...
  $\mu_R = \mu_F = Q = \frac{1}{2}\, m_h$, non-perturbative parameters
  uncertainties: factor 2 var. of $\mu_{R,F}$, Q
- STWZ: $p_\perp^{\text{veto}}$ in $pp \to h$ @ NNLL'+NNLO
  Stewart et.al. Phys. Rev. D89 (2014) 054001
  $\mu_H = -i\, m_h$ reproduces $\mu_R = \mu_F = \frac{1}{2}\, m_h$, profile scales
  uncertainties: 3-pt $|\mu_H|$, profile scales, phase of μ_H

Contributions

Parton-shower matched & multijet merged

- POWHEG-BOX+PYTHIA8 $pp \to h$ NNLOPS

  Hamilton et.al. JHEP10(2013)222

  $\frac{1}{2}\,m_h$ for core, $k_\perp$ for emissions (CKKW/MiNLO)
  uncertainties: 21-pt (7-pt in POWHEG, 3-pt in HNNLO) for $\mu_{R/F}$
  no resummation uncertainty evaluatable

- SHERPA $pp \to h$ NNLOPS

  Höche, Li, Prestel Phys. Rev. D90 (2014) 054011

  $\mu_R = \mu_F = \mu_Q = \frac{1}{2}\,m_h$
  uncertainties: 7-pt for $\mu_{R/F}$, 3-pt for μ_Q

Multiperipheral limit resummation (BFKL)

- HEJ $pp \to h + \text{jets}$

  Andersen, Smillie JHEP06(2011)010

  $\mu_R = \mu_F = \frac{1}{2}\,H_T'$
  uncertainties: 7-pt for $\mu_{R/F}$

Contributions

Parton-shower matched & multijet merged

- MG5_aMC+PYTHIA8 $pp \to h + 0, 1, 2j$@NLO

  Frixione, Frederix JHEP12(2012)061

  `MMHT2014nlo68` with $\alpha_S(m_Z) = 0.12$
  FxFx merging, $\mu_R = \mu_F = m_\perp(h)$ on hj clustered config
  uncertainties: 7-pt for μ_R, μ_F, merging scale $\{25, 35, 50\}$

- HERWIG7+MADGRAPH5+OPENLOOPS
  $pp \to h + 0, 1, 2j$@NLO $+ 3, 4j$@LO

  Bellm et.al. Eur. Phys. J. C76 (2016) 196

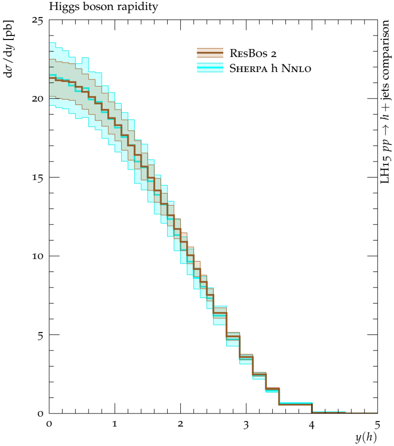
  UNLOPS merging, $\frac{1}{2}\, m_h$ for core config, t for reconstructed emissions
  uncertainties: 7-pt for $\mu_{R/F}$, merging and shower scale variations

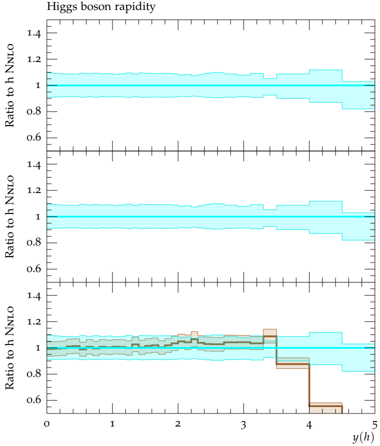
- SHERPA+GOSAM $pp \to h + 0, 1, 2, 3j$@NLO, $4, 5j$@LO

  Höche, Krauss, MS Phys. Rev. D90 (2014) 014012

  MEPS@NLO, $\frac{1}{2}\, m_h$ for core config, t for reconstructed emissions
  uncertainties: 7-pt for $\mu_{R/F}$, 3-pt for μ_Q, $Q_{\text{cut}} = \{15, 20, 30\}$

Inclusive Higgs boson rapidity





- exellent agreement between NNLO and NNLOPS
- multijet merged with NLO normalisation, PDF effects

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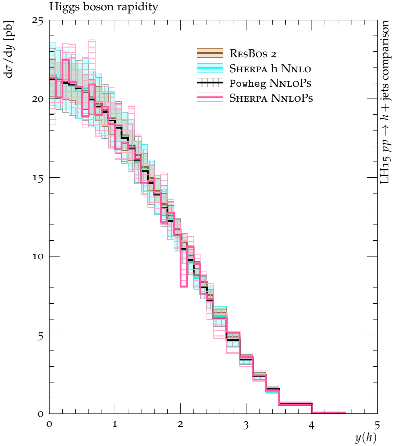

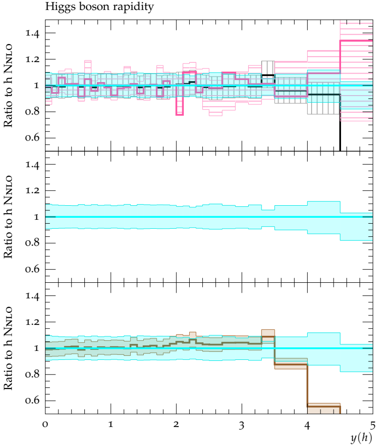

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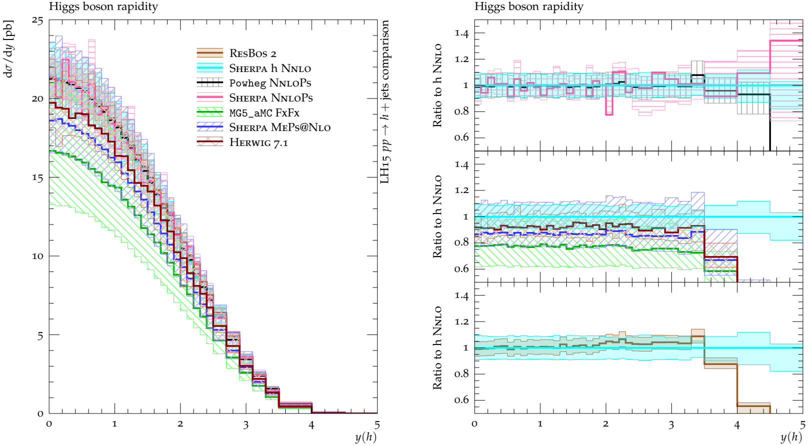

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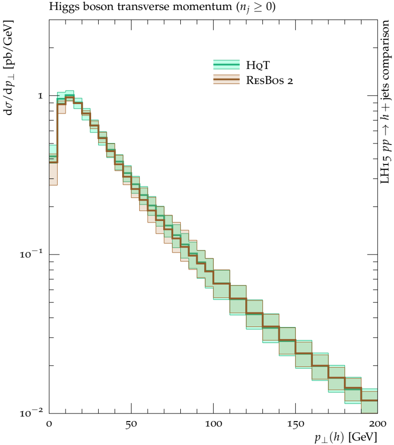
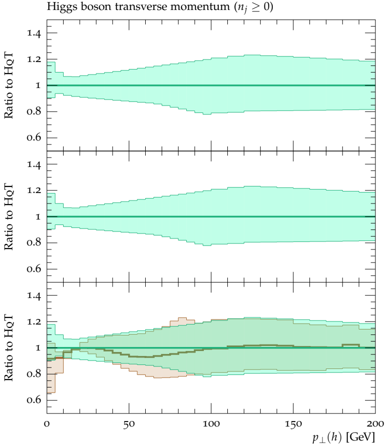
Higgs boson transverse momentum ($n_j \geq 0$)





- good agreement between HQT and NNLOPS, scale choice at high $p_\perp$
- multijet merged with NLO normalisation, very different at low $p_\perp$

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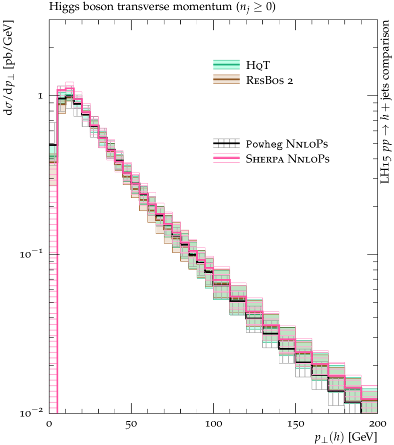

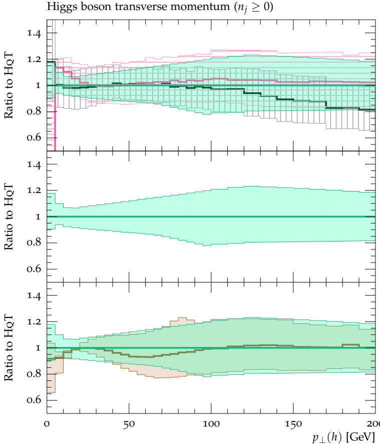

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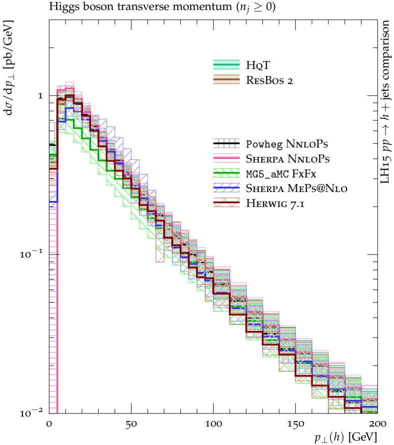

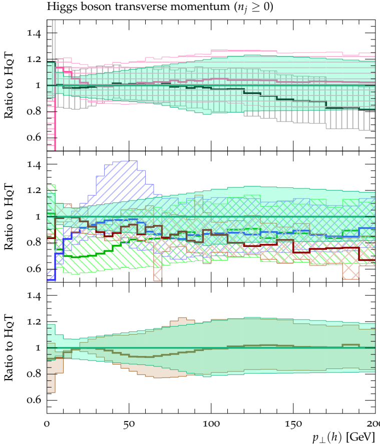

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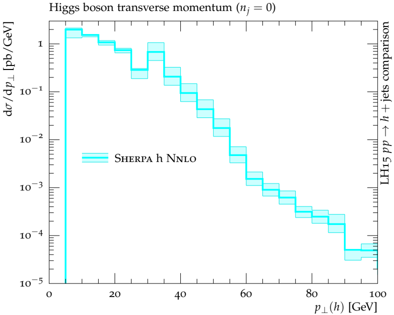
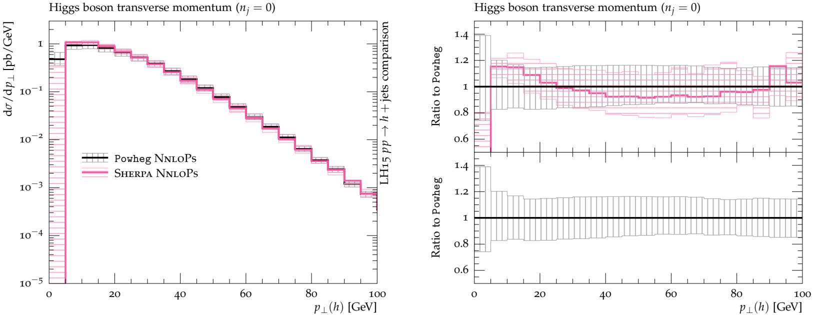
Higgs boson transverse momentum ($n_j = 0$)



- fixed-order has various unphysical features
- good agreement between the NNLOPS
- multijet merged with NLO normalisation, HERWIG7 has much less soft radiation

Higgs boson transverse momentum ($n_j = 0$)



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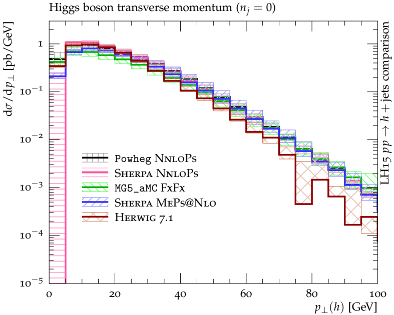

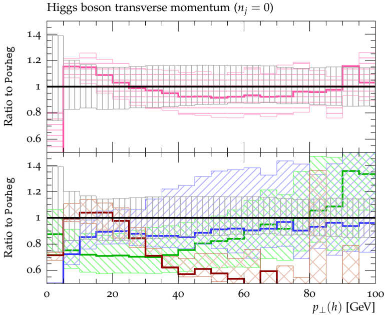

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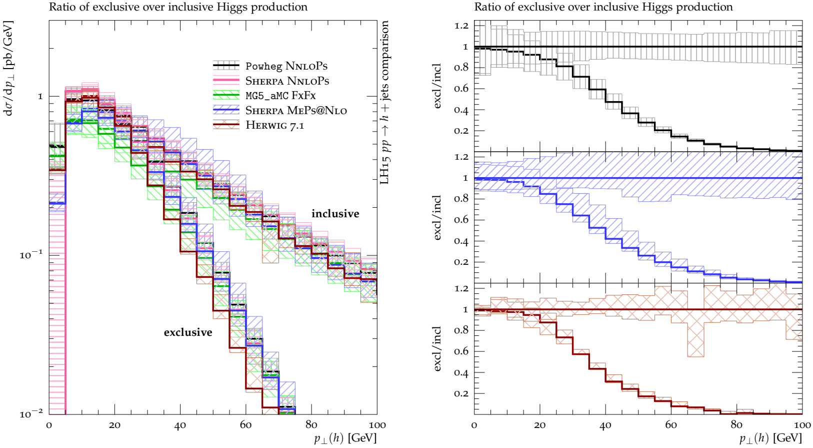
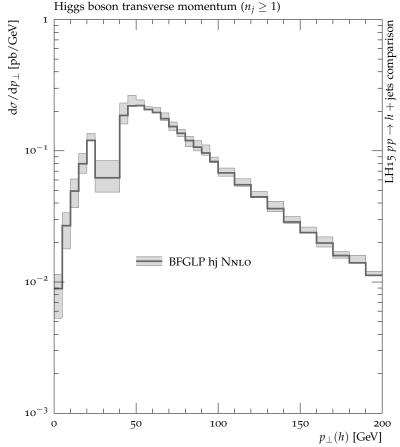
Aside: Exclusive over inclusive rate



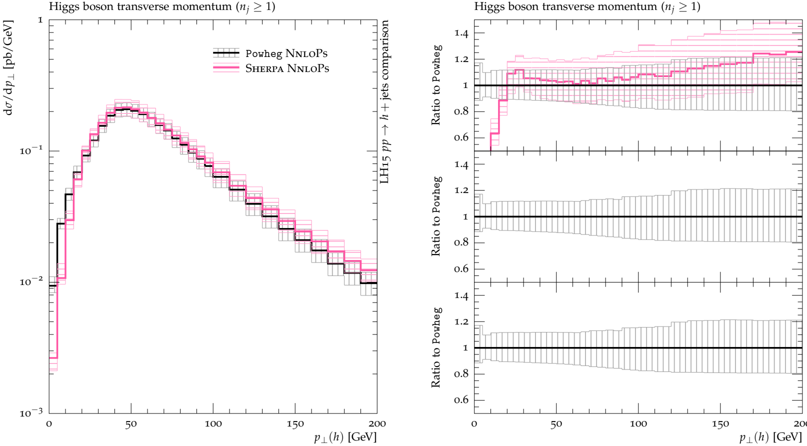
- $\approx 20\%$ of Higgs with $p_\perp = 60\,\text{GeV}$ are not accompanied by a jet

Higgs boson transverse momentum ($n_j \geq 1$)



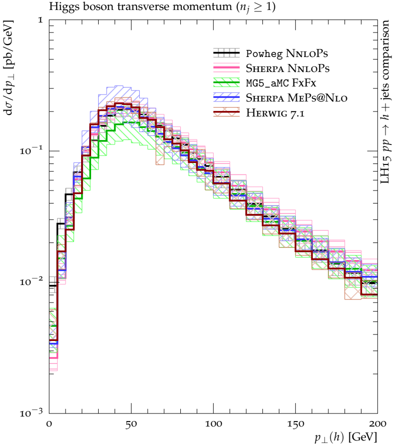
- fixed-order has Sudakov shoulder at $p_\perp^h = 30\,\text{GeV}$ due to jet cut
  here: bins left and right set to avarage

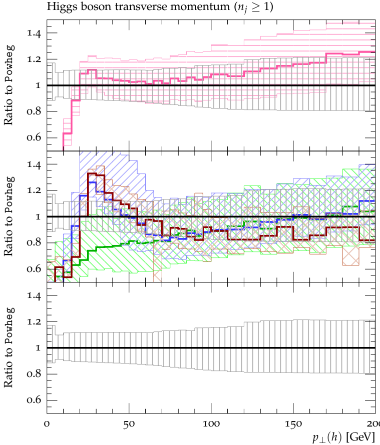
Higgs boson transverse momentum ($n_j \geq 1$)



- good agreement between NNLOPs, different scales at large $p_\perp$
- excess of POWHEG as $p_\perp \to 0$ (Higgs strahlung off dijet)

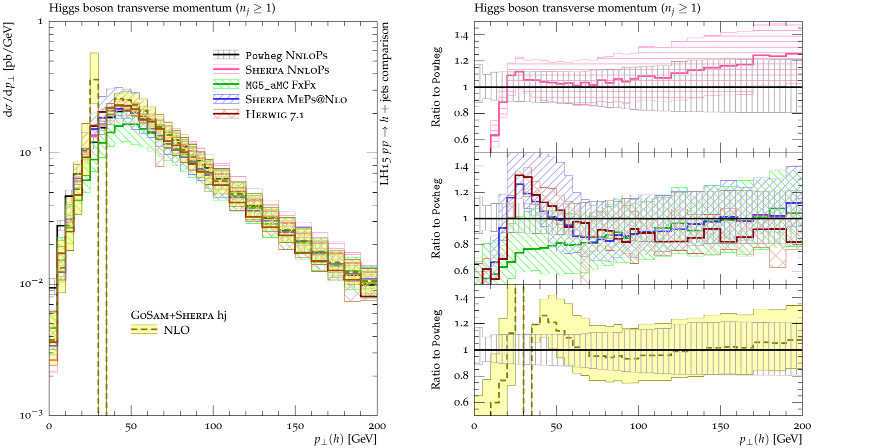
Higgs boson transverse momentum ($n_j \geq 1$)





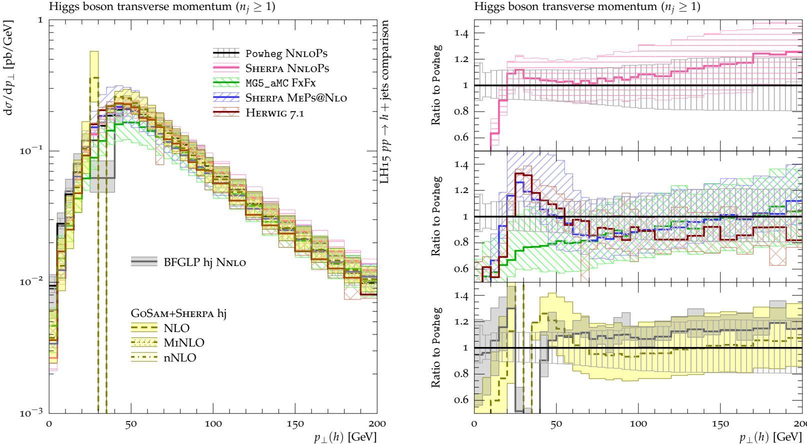
- multijet merged different shape at $p_\perp \lesssim 60$ GeV
- except MG5_aMC (due to different scales?)

Higgs boson transverse momentum ($n_j \geq 1$)



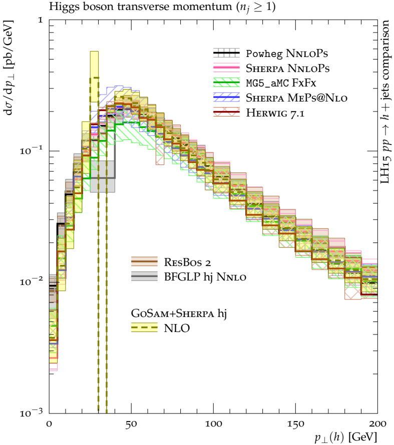
- multijet merged different shape at $p_\perp \lesssim 60$ GeV
- same as at fixed-order NLO

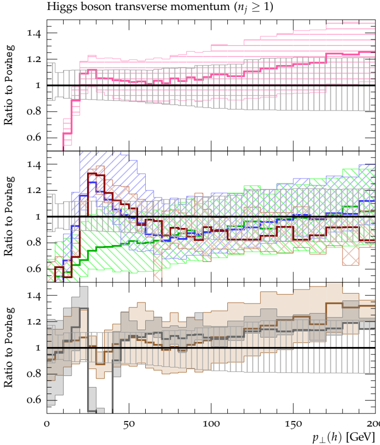
Higgs boson transverse momentum ($n_j \geq 1$)



- NNLO impacts on shape at $p_\perp \lesssim 60\,\text{GeV}$
- NLL+NLO resummation gets close to NNLO result

Higgs boson transverse momentum ($n_j \geq 1$)





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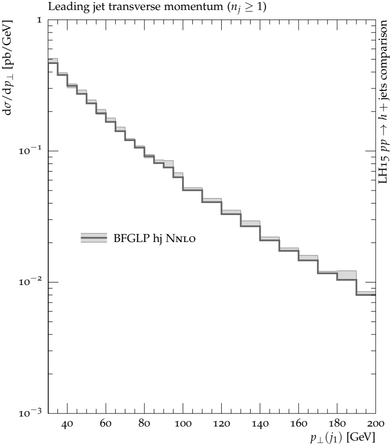
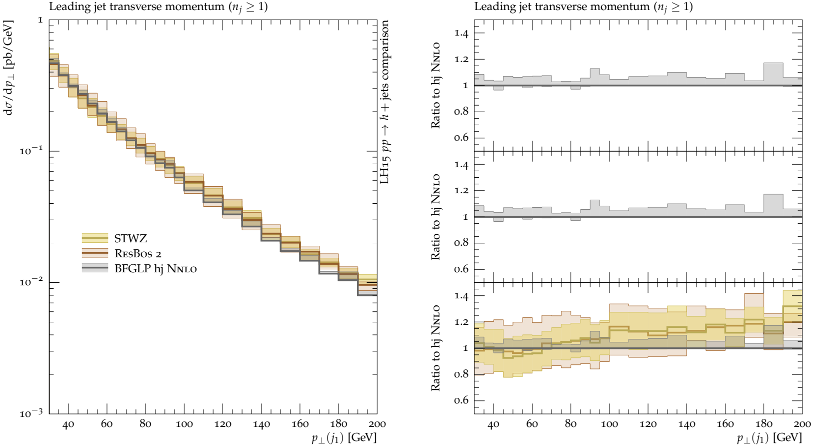
Leading jet transverse momentum ($n_j \geq 1$)



- NNLO and NLO show very good convergence for this scale choice
- multijet merged *sim* 20% lower in high-$p_\perp$ (due to showering)

Leading jet transverse momentum ($n_j \geq 1$)



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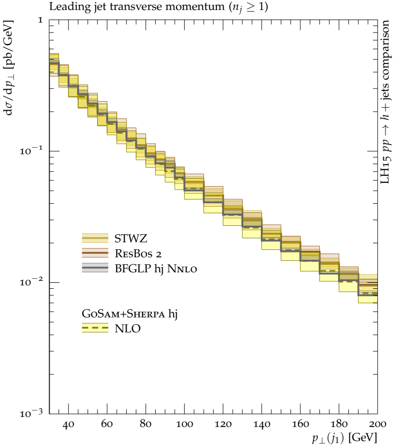

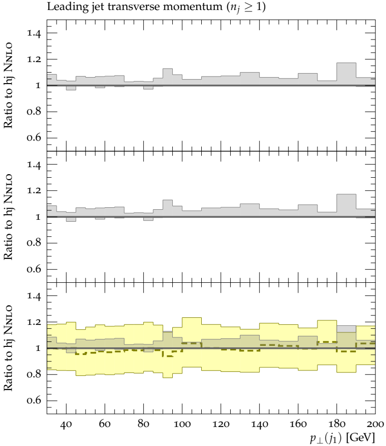

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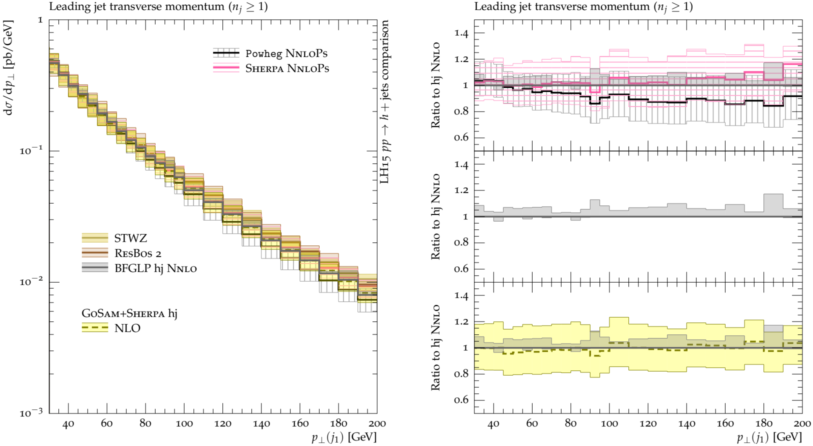

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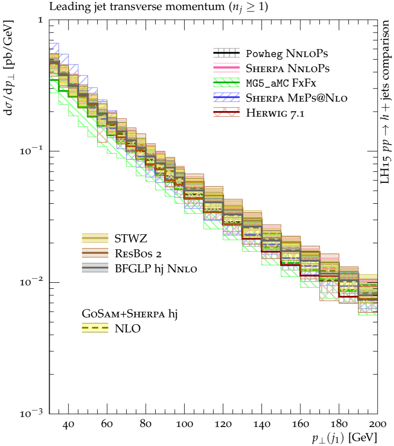

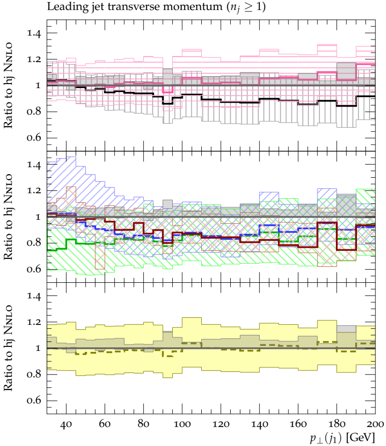

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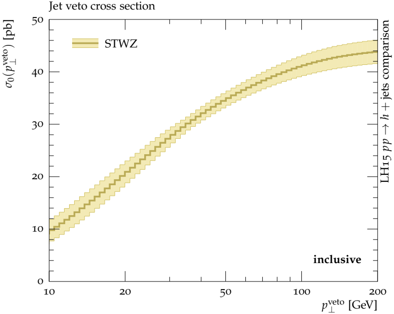
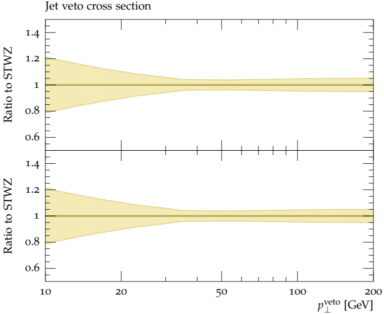
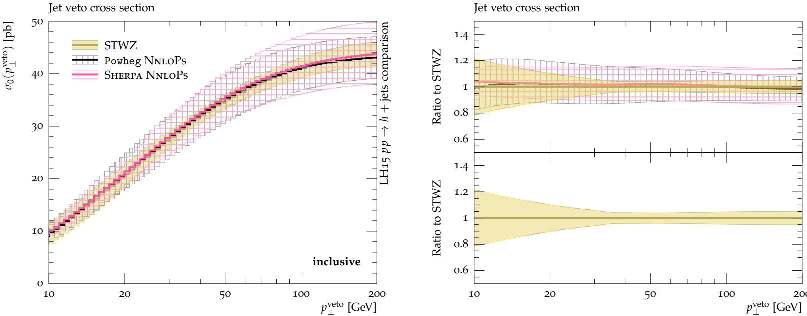
Jet vetoed cross sections – inclusive





- very good agreement between NNLOPS and STWZ
- multijet merged with larger spread in shape, but within uncertainties once NLO normalisations accounted for
- PS resummation uncertainties nowhere fully assessed

Jet vetoed cross sections – inclusive



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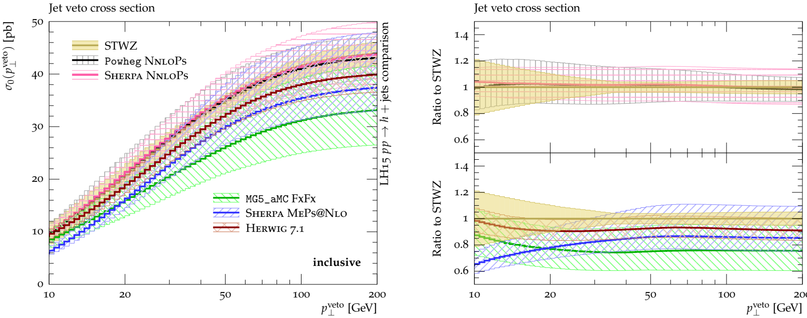

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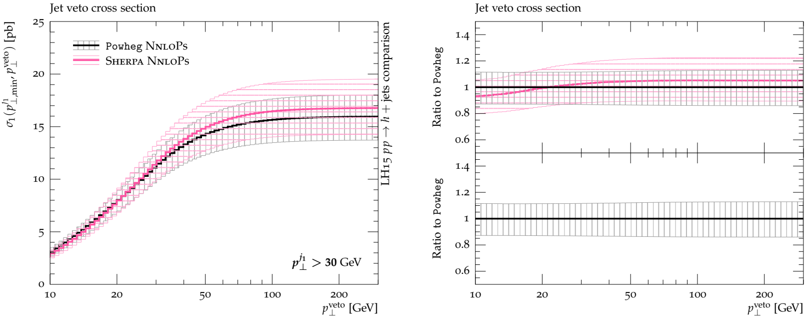
Jet vetoed cross sections – $p_\perp^{\text{lead}} > 30\,\text{GeV}$



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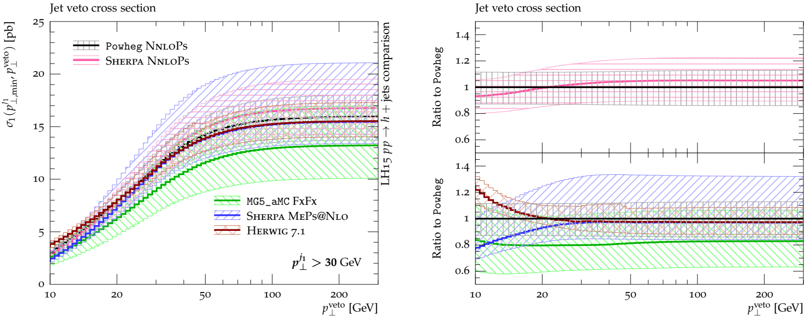

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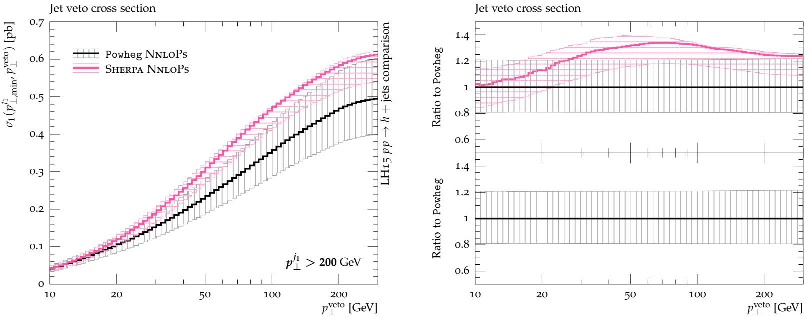
Jet vetoed cross sections – $p_\perp^{\text{lead}} > 200\,\text{GeV}$



- larger differences between NNLOPs, also in normalisation
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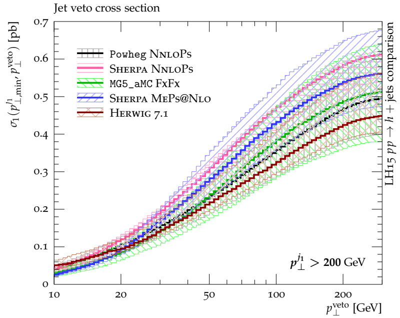
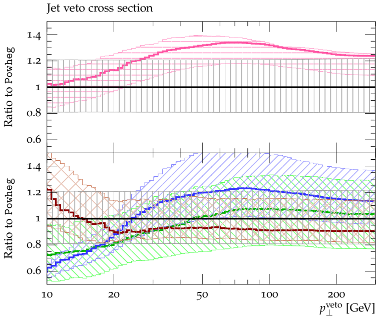
Jet vetoed cross sections – $p_\perp^{\text{lead}} > 200\,\text{GeV}$





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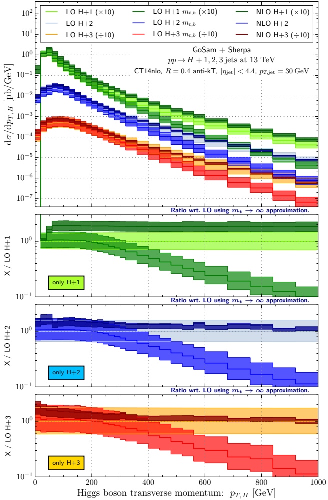
Mass corrections in Monte-Carlo event generators

Greiner et.al. arXiv:1608.01195

For the previous comparison all mass corrections were diabled to facilitate cross-tool comparsion.

However, mass corrections are extremely important as they quickly grow larger than the (substantial) higher order corrections.

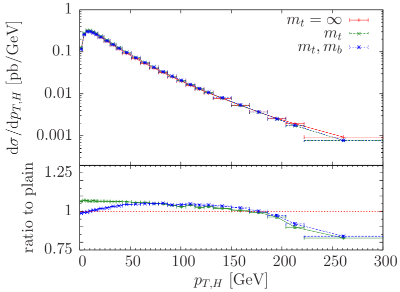
Most event generators allow for finite mass corrections in some approximation. Generally, m_t important at large $p_\perp$, m_b at small $p_\perp$.



Mass corrections in Monte-Carlo event generators

POWHEG NNLOPS

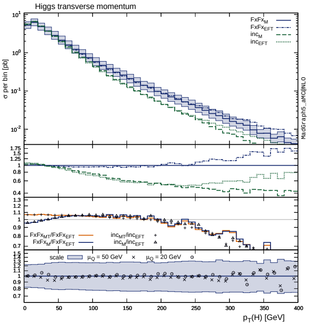
Hamilton, Nason, Zanderighi JHEP05(2015)140



- m_t, m_b corrections up to NLO
- with different options for resummation of m_b corrections

MG5_aMC FxFx

Frederix et.al. JHEP08(2016)006



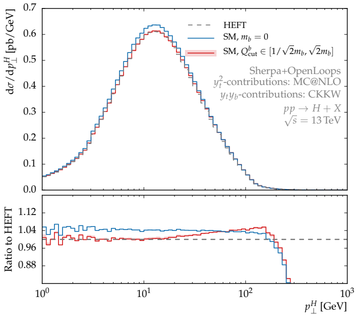
- m_t corrections in all multiplicities at NLO
- m_b corrections only in lowest multiplicity

Mass corrections in Monte-Carlo event generators

SHERPA NNLOPS

Höche et.al. Phys. Rev. D90 (2014) 054011

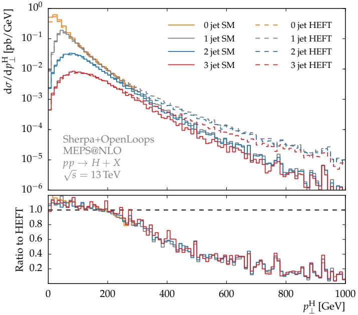
- m_t, m_b corrections in Wilson coefficients to NLO



SHERPA MEPS@NLO

Buschmann et.al. JHEP02(2015)038

- m_t corrections in all multiplicities at NLO
- m_b corrections in all multiplicities at LO



Conclusions

Higgs production in gluon fusion

- generally good agreement between Monte-Carlo event generators, but the more differential, the greater the differences
- generally good agreement with dedicated fixed-order calculations or resummations, but the more differential, the greater the differences
- differences enlarged when moving away from tuned comparison to individual default settings

$\Rightarrow$ differences most likely larger in boosted region

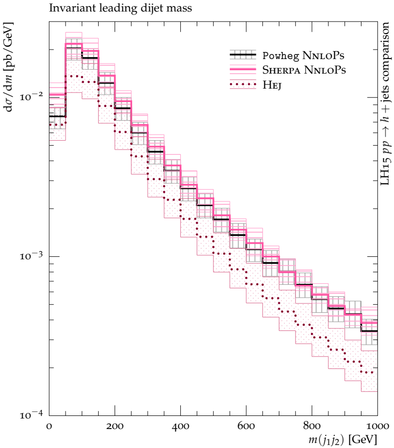
Other production channels

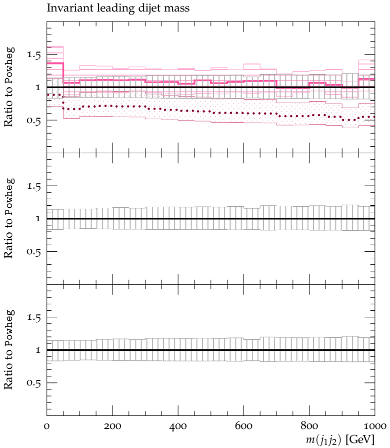
- not investigated in particular
- all channels available in NLO matched calculations, most in NLO merging if necessary

Thank you for your attention!

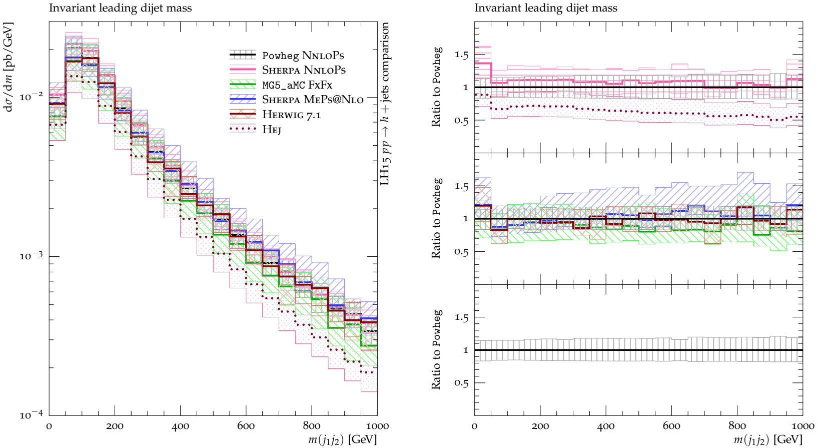
Backup

Dijet invariant mass

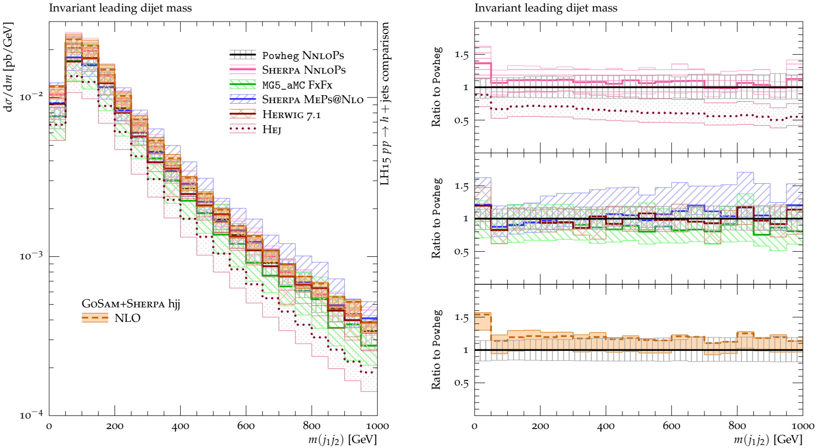




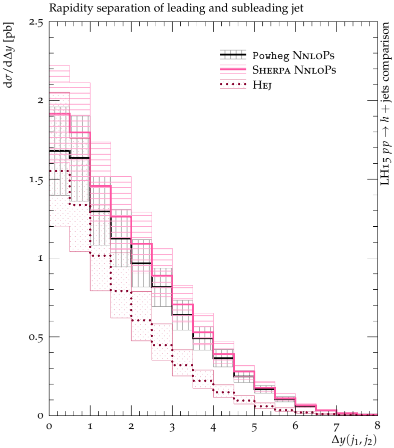
Dijet invariant mass

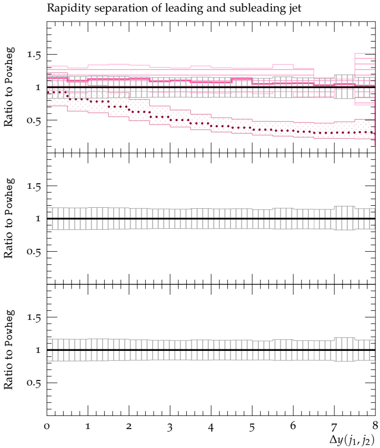


Dijet invariant mass

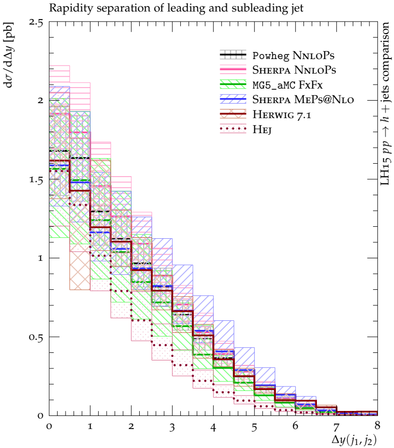


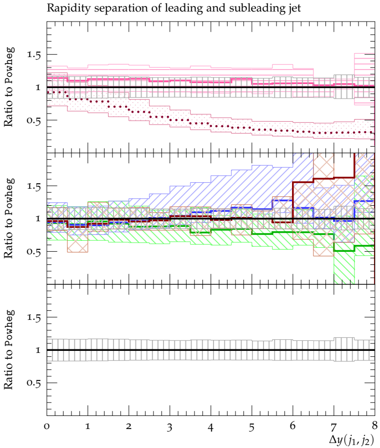
Dijet rapidity difference





Dijet rapidity difference





Dijet rapidity difference