$t\bar{t}$+X hadroproduction at NLO+SMC

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based on arXiv:1101.2672, 1108.0387 and unpublished

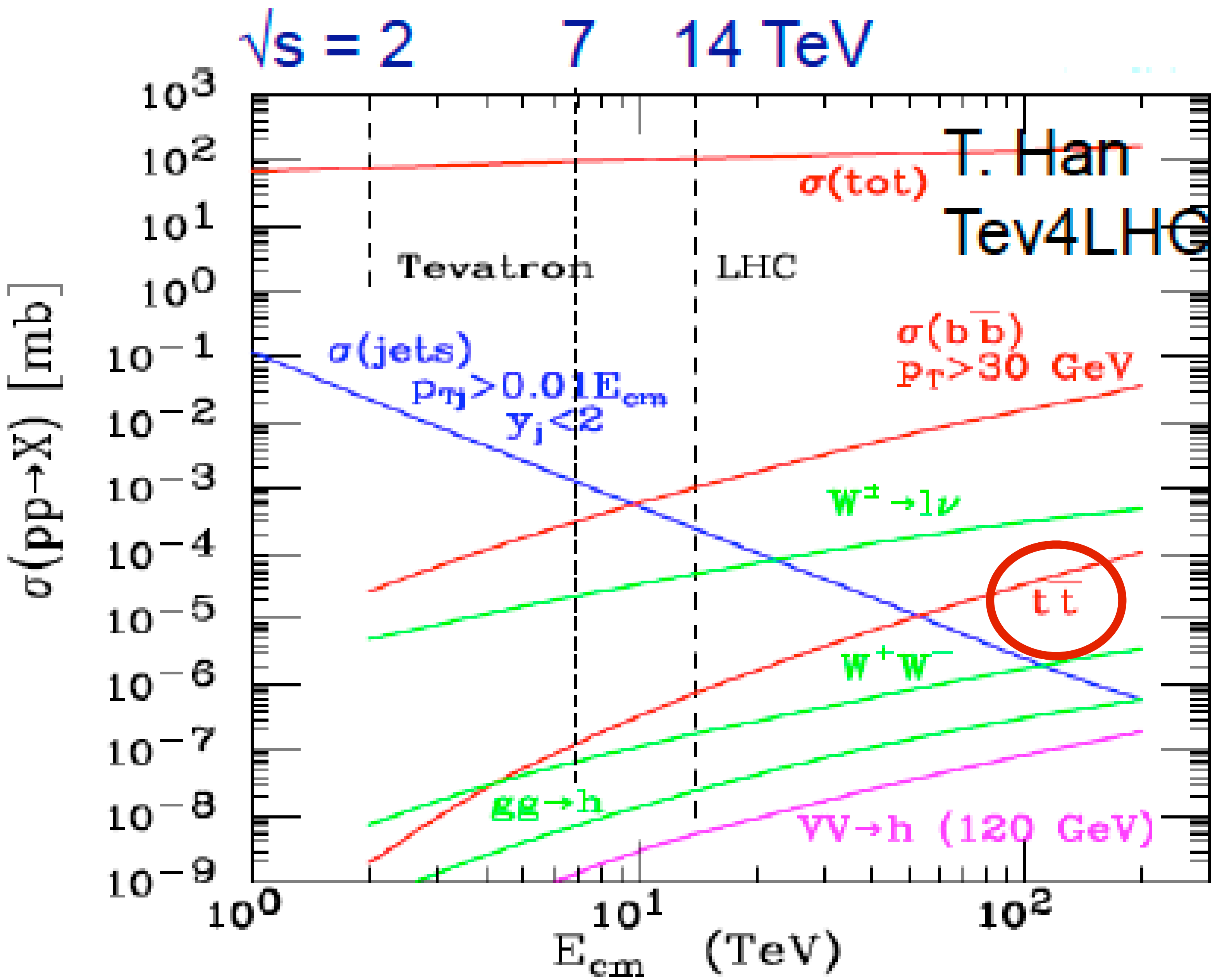
Outline

- Motivation
- Method
- Predictions
- Conclusions and Plans

Motivation

The importance of being top

1. The higher collider energy, the larger weight in total cross section



The importance of being top

1. The higher collider energy, the larger weight in total cross section
2. The t-quark is heavy, Yukawa coupling ~1

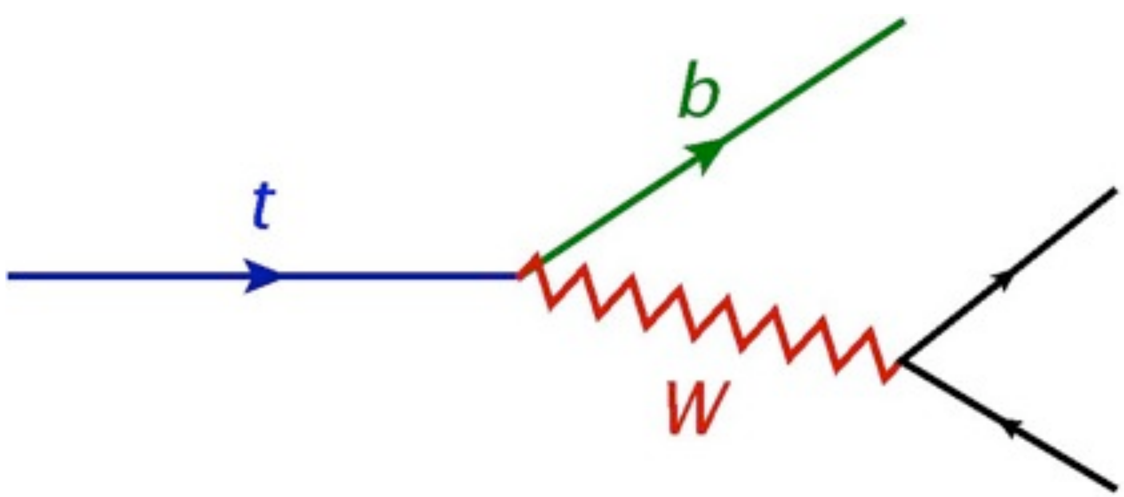
$$m_t = 172.0 \pm 0.9 \pm 1.3 \text{ (PDG) } 173.3 \pm 1.1 \text{ (TeVatron)}$$

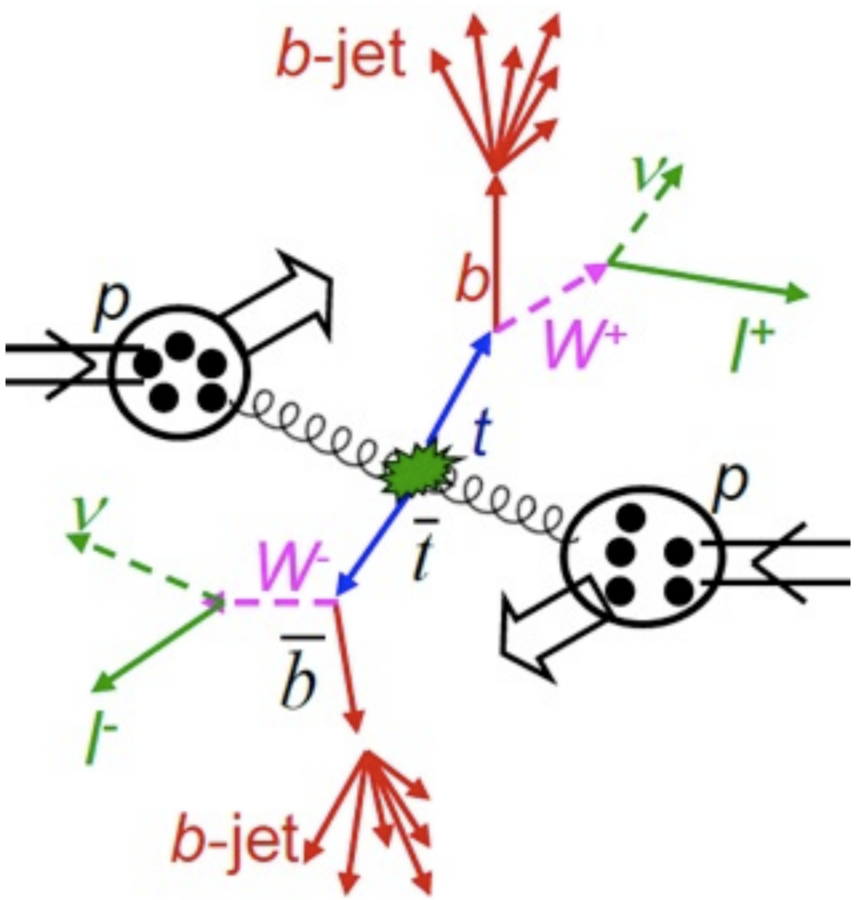
$\Rightarrow$ plays important role in Higgs physics

The importance of being top

1. The higher collider energy, the larger weight in total cross section
2. The t-quark is heavy, Yukawa coupling ~1
3. The t-quark decays before hadronization
   ⇒ quantum numbers more accessible than in case of other quarks

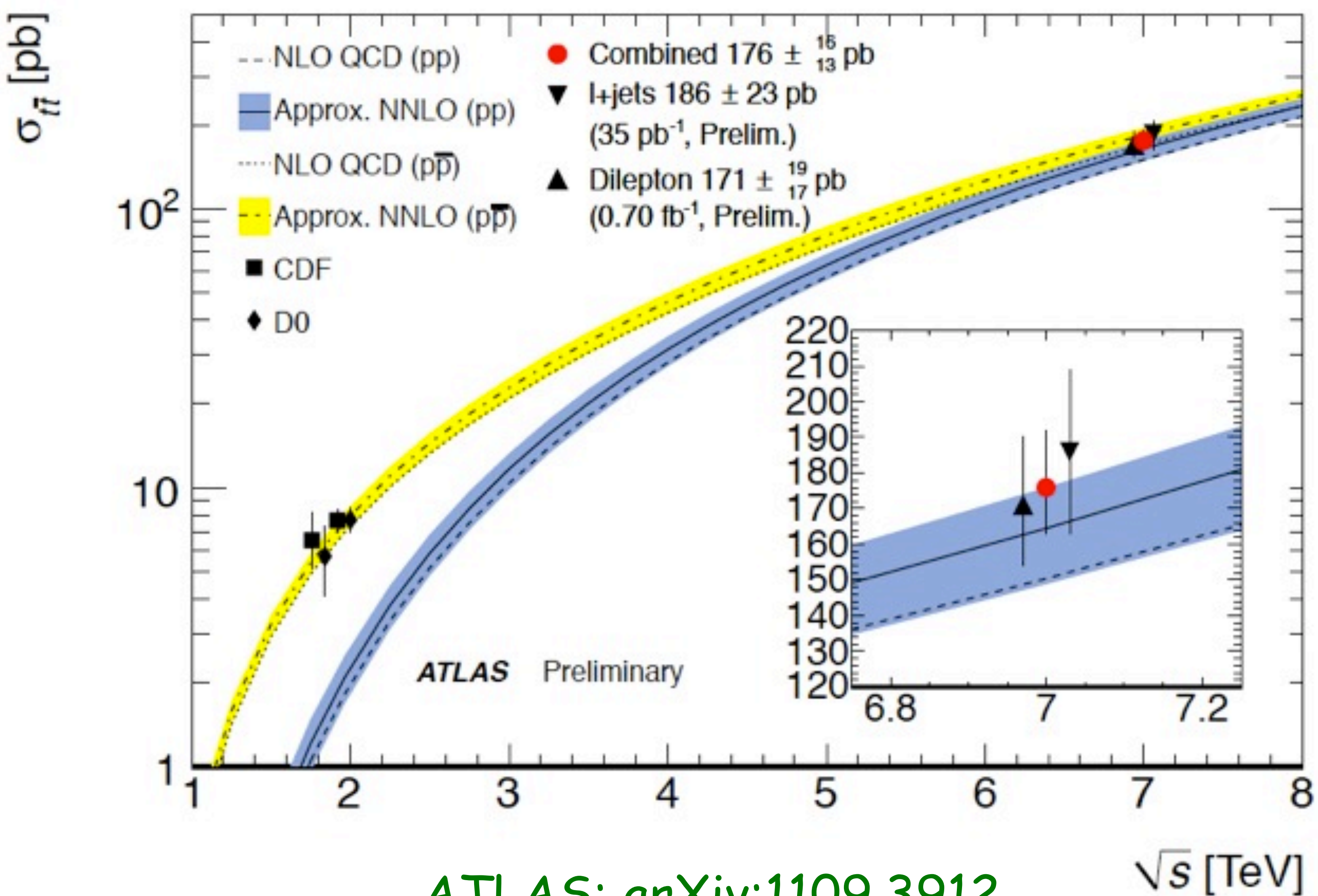
$$|V_{tb}|^2 \gg |V_{ts}|^2,\ |V_{td}|^2$$





Top at the LHC

1. Present: precision measurement of production cross section, mass



ATLAS: arXiv:1109.3912

Top at the LHC

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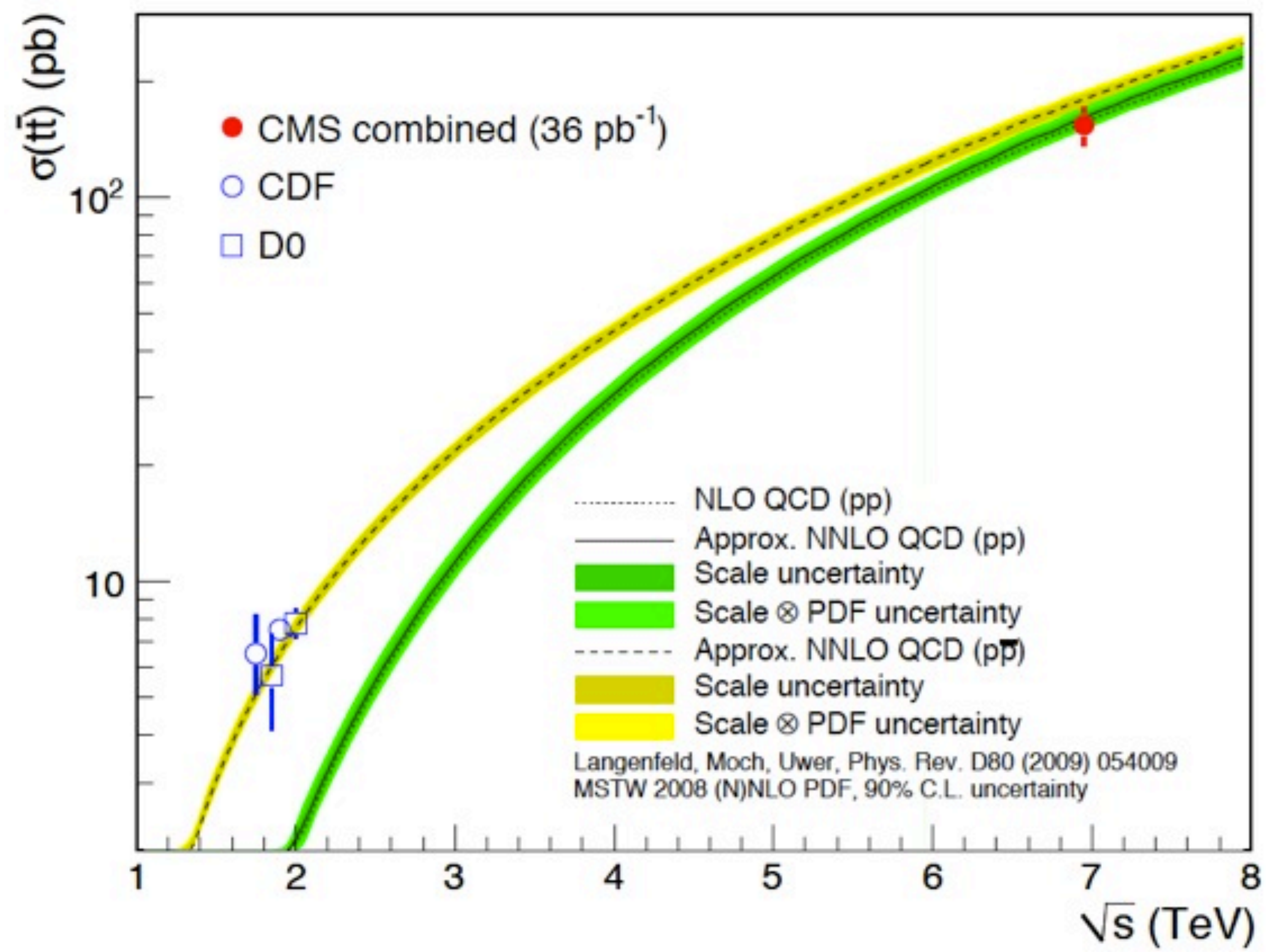
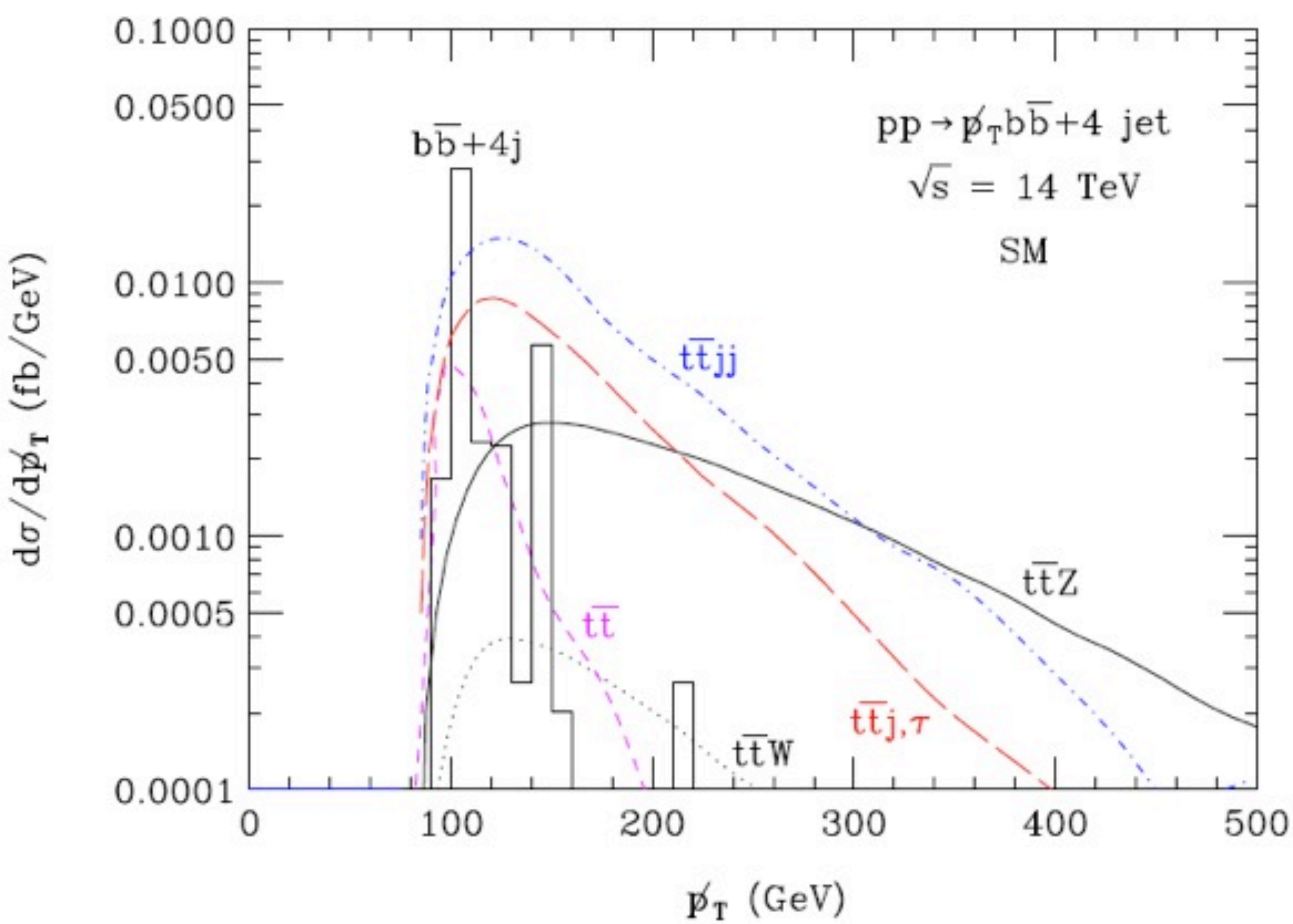


CMS: arXiv:1108.3773

Top at the LHC

1. Present: precision measurement of σ_{tot}, m_t quantum numbers, decay rates
2. Future: measurement of couplings



Baur et al, hep-ph/0412021, 0512262

Top at the LHC

1. Present: precision measurement of σ_{tot}, m_t quantum numbers, decay rates
2. Future: plenty of radiation in association with t-pair

$$\sigma_{\rm NLO}(pp \to {\rm t}\,\bar{\rm t}) = 806\,{\rm pb}$$

$$\sigma_{\rm NLO}(pp \to {\rm t}\,\bar{\rm t}{+}{\rm jet};\ p_\perp^j > 50\,{\rm GeV}) = 376\,{\rm pb}$$

3. Important backgrounds to coupling measurements, Higgs searches:

$$pp \to t\bar{t}j,\ t\bar{t}b\bar{b},\ t\bar{t}jj$$

These require precise predictions for distributions at hadron level

(with decays, top is not detected)

Method

NLO subtractions

- Idea: exact calculation in the first two orders of pQCD
- Subtraction method (FKS in POWHEG-Box)

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \left[B(\Phi_n) + \mathcal{V}(\Phi_n) + R(\Phi_{n+1})\mathrm{d}\Phi_{\mathrm{rad}}\right]\mathrm{d}\Phi_n$$
$$= \left[B(\Phi_n) + V(\Phi_n) + \left(R(\Phi_{n+1}) - A(\Phi_{n+1})\right)\mathrm{d}\Phi_{\mathrm{rad}}\right]\mathrm{d}\Phi_n$$

$$B(\Phi_n) = \int \mathrm{d}\sigma^{\mathrm{LO}}\,, \qquad V(\Phi_n) = \mathcal{V}(\Phi_n) + \int \mathrm{d}\Phi_{\mathrm{rad}} A(\Phi_{n+1})$$

$$\mathrm{d}\Phi_{n+1} = \mathrm{d}\Phi_n\,\mathrm{d}\Phi_{\mathrm{rad}}\,, \qquad \mathrm{d}\Phi_{\mathrm{rad}} \propto \mathrm{d}t\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}$$

From NLO to NLO+PS

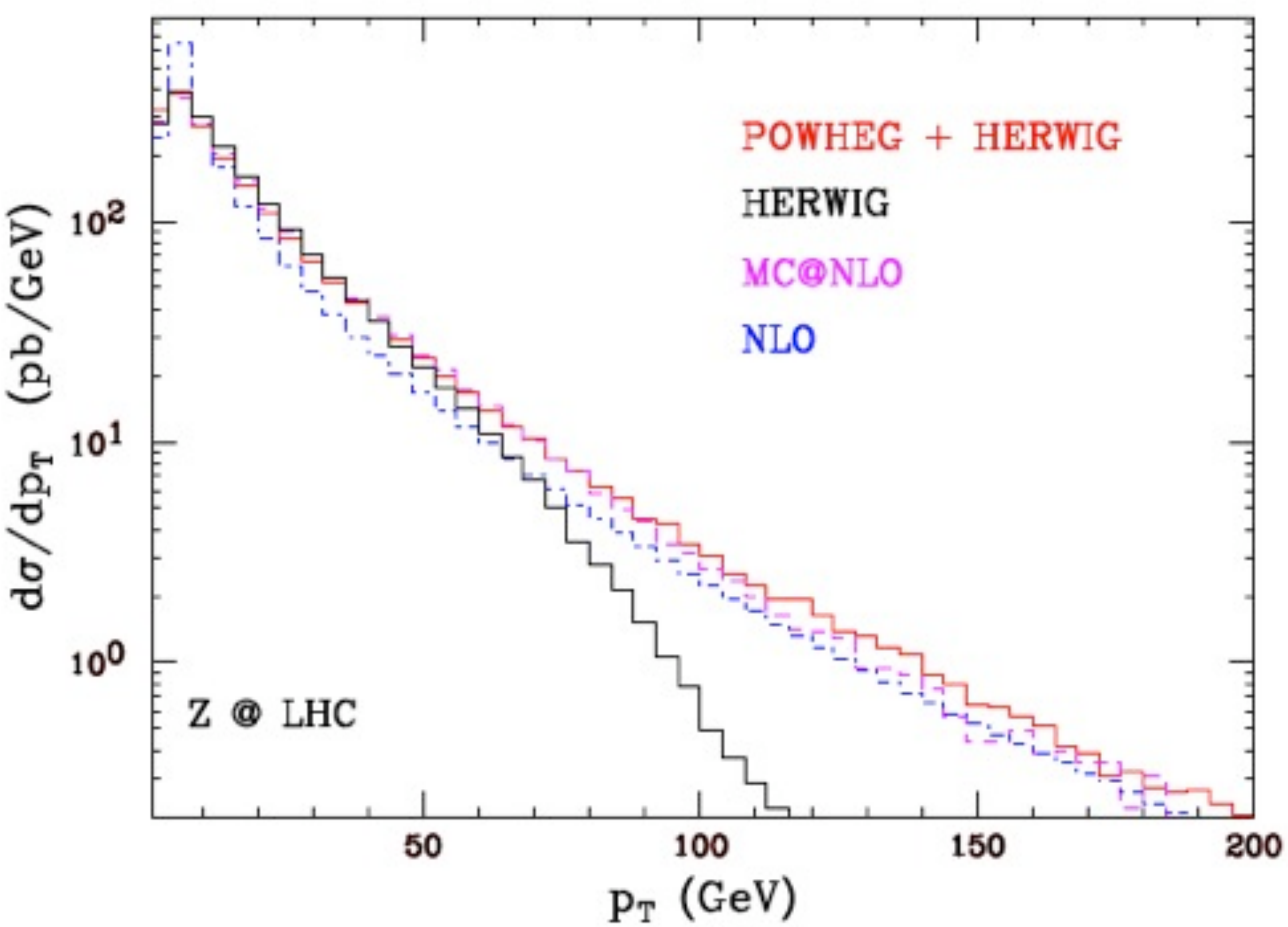
Idea: use NLO calculation as hard process as input for the SMC

Bottleneck: how to avoid double counting of first radiation w.r.to Born process (present both in R and in the PS)

Solutions:

- MCatNLO [Frixione, Webber hep-ph/0204244]
- POWHEG [Nason hep-ph/0409146, Frixione, Nason, Oleari arXiv:0709.2092]

Result: PS events giving distributions exact to NLO in pQCD



Nason, Ridolfi hep-ph/0606275

From standard SMC to POWHEG MC

SMC idea: use probabilistic picture of parton splitting in the collinear approximation, iterate splitting to high orders

- Standard MC first emission:

$$d\sigma_{\mathrm{SMC}} = B(\Phi_n) d\Phi_n \left[\Delta_{\mathrm{SMC}}(t_0) + \Delta_{\mathrm{SMC}}(t) \underbrace{\frac{\alpha_s(t)}{2\pi} \frac{1}{t} P(z)}_{= \lim_{k_\perp \to 0} R(\Phi_{n+1})/B(\Phi_n)} \Theta(t - t_0) \, d\Phi_{\mathrm{rad}}^{\mathrm{SMC}} \right]$$

- POWHEG MC first emission:

$$d\sigma = \bar{B}(\Phi_n) d\Phi_n \left[\Delta(\Phi_n, p_\perp^{\min}) + \Delta(\Phi_n, k_\perp) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Theta(k_\perp - p_\perp^{\min}) \, d\Phi_{\mathrm{rad}} \right]$$

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \Big[R(\Phi_{n+1}) - A(\Phi_{n+1}) \Big] d\Phi_{\mathrm{rad}}$$

From standard SMC to POWHEG MC

- SMC Sudakov (probability of no emission with virtuality above t)

$$\Delta_{\rm SMC}(t) = \exp\left[-\int_t \mathrm{d}\Phi'_{\rm rad} \frac{\alpha_{\rm s}(t')}{2\pi} \frac{1}{t'} P(z') \right]$$

- PMC Sudakov (probability of no emission with transverse momentum above $p_\perp$)

$$\Delta(\Phi_n, p_\perp) = \exp\left[-\int \mathrm{d}\Phi'_{\rm rad} \frac{R(\Phi_n, \Phi'_{\rm rad})}{B(\Phi_n)} \Theta(k_\perp(\Phi_n, \Phi'_{\rm rad}) - p_\perp) \right]$$

Accuracy of POWHEG MC

- The cross section is:

$$\int d\sigma = \int \bar{B} d\Phi_n \left[\Delta(\Phi_n, p_\perp^{\min}) + \int d\Phi_{\rm rad} \Delta(\Phi_n, k_\perp) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Theta(k_\perp - p_\perp^{\min})\right]$$

- PMC Sudakov (probability of no emission with transverse momentum above $p_\perp$)

$$\Delta(\Phi_n, p_\perp) = \exp\left[-\int d\Phi'_{\rm rad} \frac{R(\Phi_n, \Phi'_{\rm rad})}{B(\Phi_n)} \Theta(k_\perp(\Phi_n, \Phi'_{\rm rad}) - p_\perp)\right]$$

Accuracy of POWHEG MC

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$$\int \mathrm{d}\sigma = \int \bar{B}\mathrm{d}\Phi_n \left[\Delta(\Phi_n, p_\perp^{\min}) + \underbrace{\int \mathrm{d}\Phi_{\mathrm{rad}} \Delta(\Phi_n, k_\perp) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Theta(k_\perp - p_\perp^{\min})}_{1-\Delta(\Phi_n, p_\perp^{\min})}\right]$$

$$\int \mathrm{d}\sigma = \int \mathrm{d}\Phi_n \bar{B} = \sigma_{\mathrm{NLO}}$$

- We obtained the NLO cross section

This can be shown for observables as well, see Frixione, Nason, Oleari arXiv:0709.2092

Three frameworks

- POWHEG-BOX [Alioli et al, 1002.2581] is used to perform the related calculations to generate equal weight events for further showering (black box)
- HELAC-NLO [Bevilacqua et al 1007.4918] codes are used to provide squared matrix elements
- Standard Shower Monte Carlo [Sjostrand et al, hep-ph/0603175, Corcella et al hep-ph/0210213] (SMC) is used to shower the events

RESULT of PowHel (=POWHEG-BOX+HELAC-NLO):

Les Houches file of Born and Born+1st radiation events (LHE) ready for processing with SMC followed by almost arbitrary experimental analysis http://grid.kfki.hu/twiki/bin/view/DbTheory/WebHome#Events_with_NLO_accuracy_for_par

TWiki > DbTheory Web > TtjProd (2011-07-15, AdamKardos)

Top quark pair production in association with a jet

This page contains those event files which concern top quark pair production with a jet. The used code can be found here: ttj.tgz.

TeVatron @ 1.96 TeV

1. m_t = 172 GeV , \mu = \mu_R = \mu_F = m_t, CTEQ6M PDF, 2-loop running \alpha_s, p_{\bot,\mathrm{min}} = 5 GeV . This set was taken for comparison with Melnikov and Schulze(arXiv:1004.3284). ttj-tev-01.tgz (315 Mb)
2. m_t = 174 GeV , \mu = \mu_R = \mu_F = m_t, CTEQ6M PDF, 2-loop running \alpha_s, p_{\bot,\mathrm{min}} = 5 GeV . This set was taken for comparison with Dittmaier, Uwer and Weinzierl(arXiv:0810.0452). ttj-tev-02.tgz (152 Mb)

LHC @ 7 TeV

1. m_t = 172 GeV , \mu = \mu_R = \mu_F = m_t, CTEQ6M PDF, 2-loop running \alpha_s, p_{\bot,\mathrm{min}} = 5 GeV . To reproduce the predictions of arXiv:1101.2672. ttj-lhc-01.tgz (410 Mb)
2. m_t = 172 GeV , \mu = \mu_R = \mu_F = m_\bot (for a precise definition please see arXiv:1101.2672), CTEQ6M PDF, 2-loop running \alpha_s, p_{\bot,\mathrm{min}} = 5 GeV . To reproduce the predictions of arXiv:1101.2672. ttj-lhc-02.tgz (397 Mb)

SMC's with veto

- In POWHEG-Box the first emission is the hardest one measured by transverse momentum
- If the ordering variable in the shower is different from the transverse momentum of the parton splitting, such as the angular ordering in HERWIG, then the hardest emission is not necessarily the first one
- In such cases the HERWIG discards shower evolutions (vetoed shower) with larger transverse momentum in all splittings occurring after the first emission
- In principle, a truncated shower simulating wide-angle soft emission before the first emission is also needed
- There is no implementation of truncated shower in HERWIG using external LHE event files, the effect of the truncated showers is absent from our predictions

Input to POWHEG-BOX

- Flavour structures, Born phase space
- From Helac-OneLoop (in the process of automatization):
  - Tree-level helicity amplitudes for the Born and real radiation processes (crossed into physical channels from all incoming kinematics)
  - One-loop corrections to the helicity amplitudes of Born processes (unitarity based numerical evaluation of one-loop amplitudes)
  - Use polarization vectors to project tree-level helicity-correlated matrix elements to Lorentz basis to get the spin-correlated squared matrix elements
- From HELAC-Dipoles: two subroutines for colour-correlated squared matrix elements of the Born processes

Checks

- ✓ Check (implementation of) real emission squared matrix elements in POWHEG-BOX to those from HELAC-PHEGAS in randomly chosen phase space points
- ✓ Check (implementation of) virtual correction in POWHEG-BOX to those from HELAC-OneLoop in randomly chosen phase space points
- ✓ Check the ratio of soft and collinear limits to real emission matrix elements tends to 1 in randomly chosen kinematically degenerate phase space points

Comparison to NLO

✓ Compare LO and NLO cross sections to published predictions

➡ ttZ: Lazopoulos et al, arXiv:0709.4044

➡ ttγ: Melnikov et al, arXiv:1102.1967

➡ ttH: Beenakker et al, hep-ph/0107081, 0211352

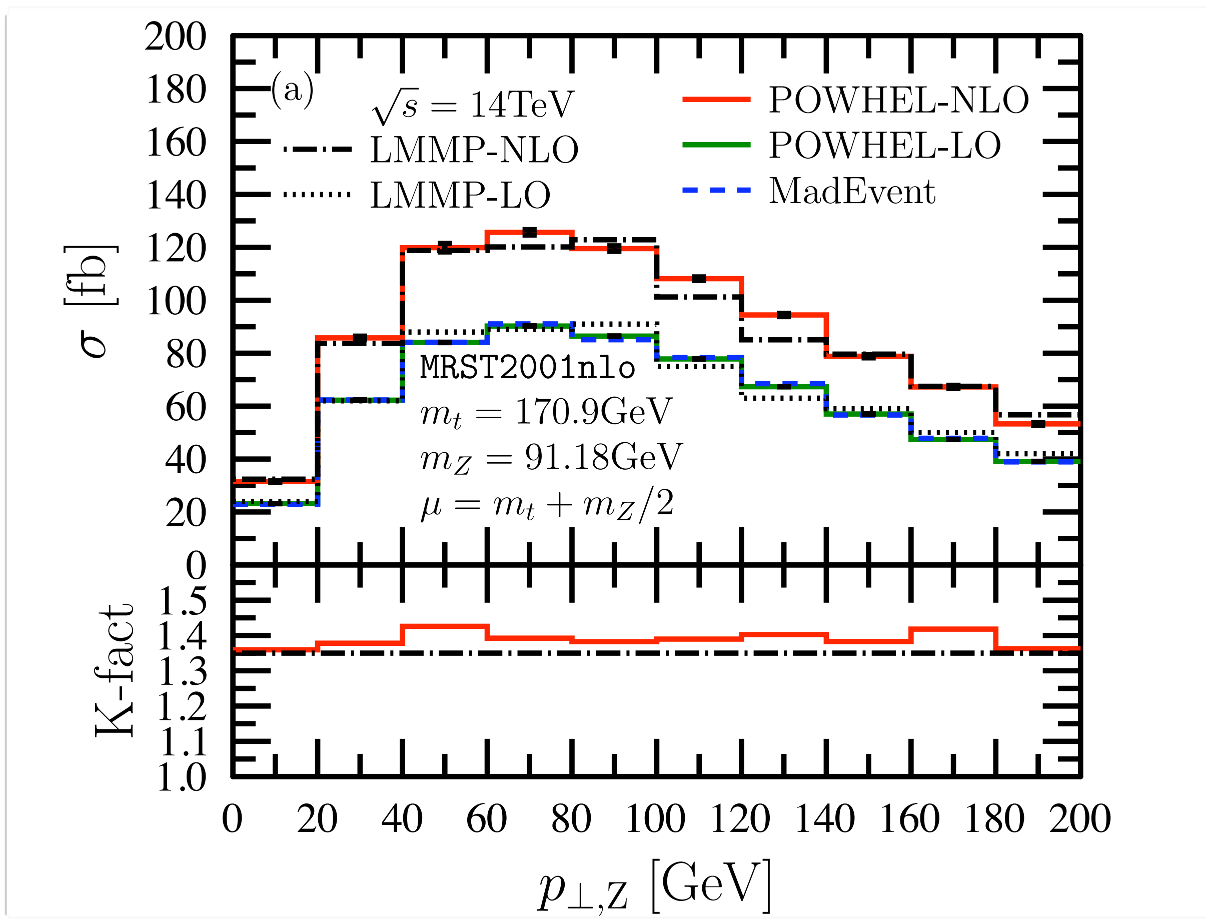
Reina et al, hep-ph/0107101, 0109066, 0305087

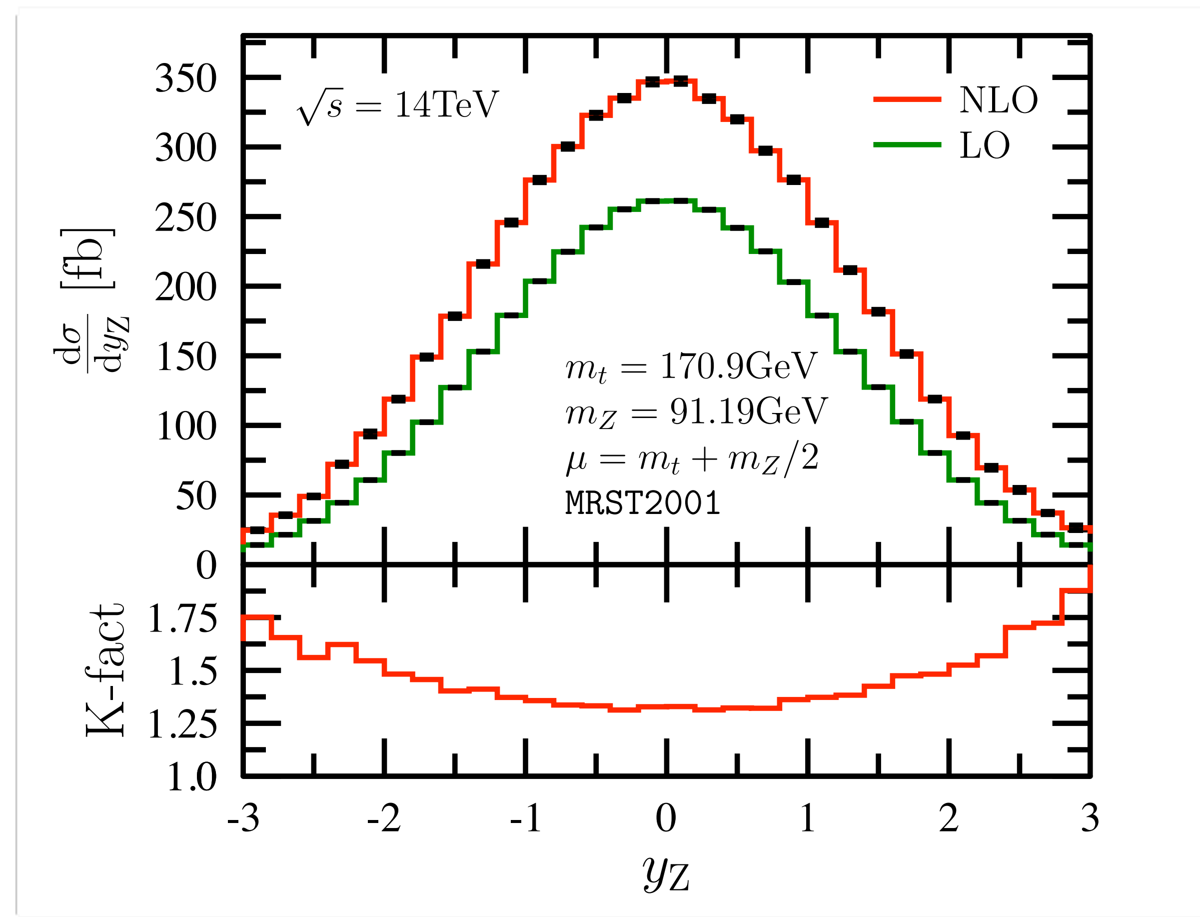
➡ ttjet: Dittmaier et al, hep-ph/0703120, 0810.0452

➡ ttbb: Bredenstein et al, arXiv: 0905.0110, 1001.4006

Bevilacqua et al, arXiv:0907.4723

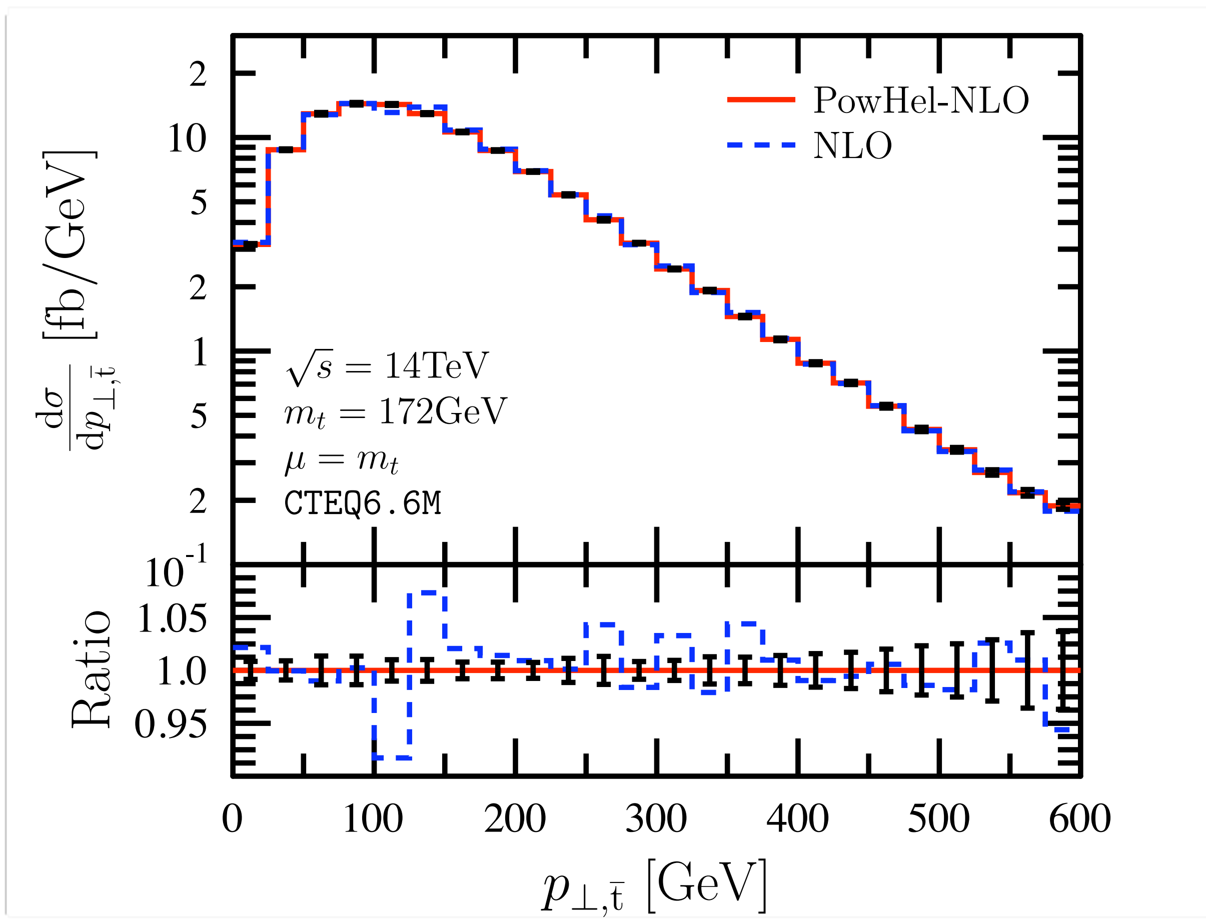
PowHel-NLO vs. NLO

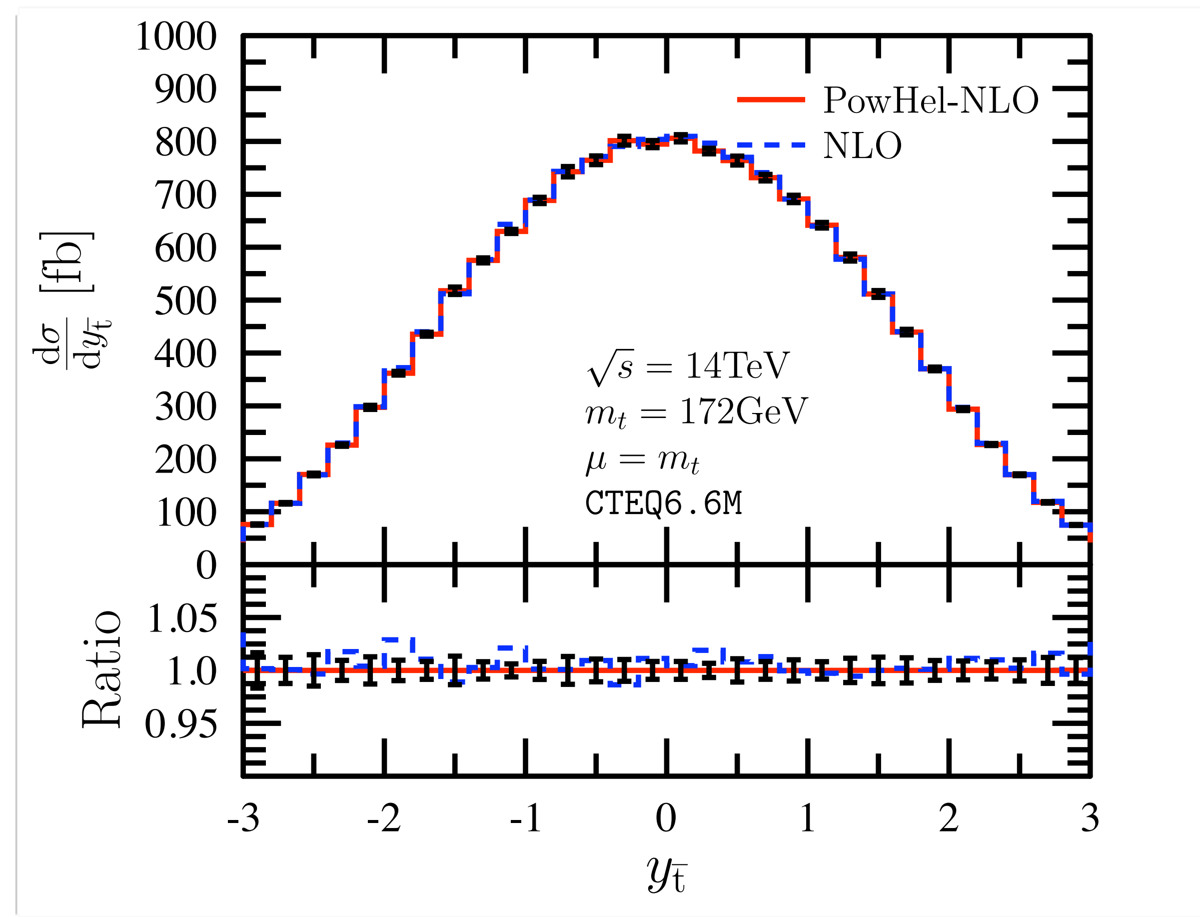




Transverse momentum & rapidity distributions of the Z^0-boson in pp $\rightarrow$ $t\bar{t}$ Z at the LHC

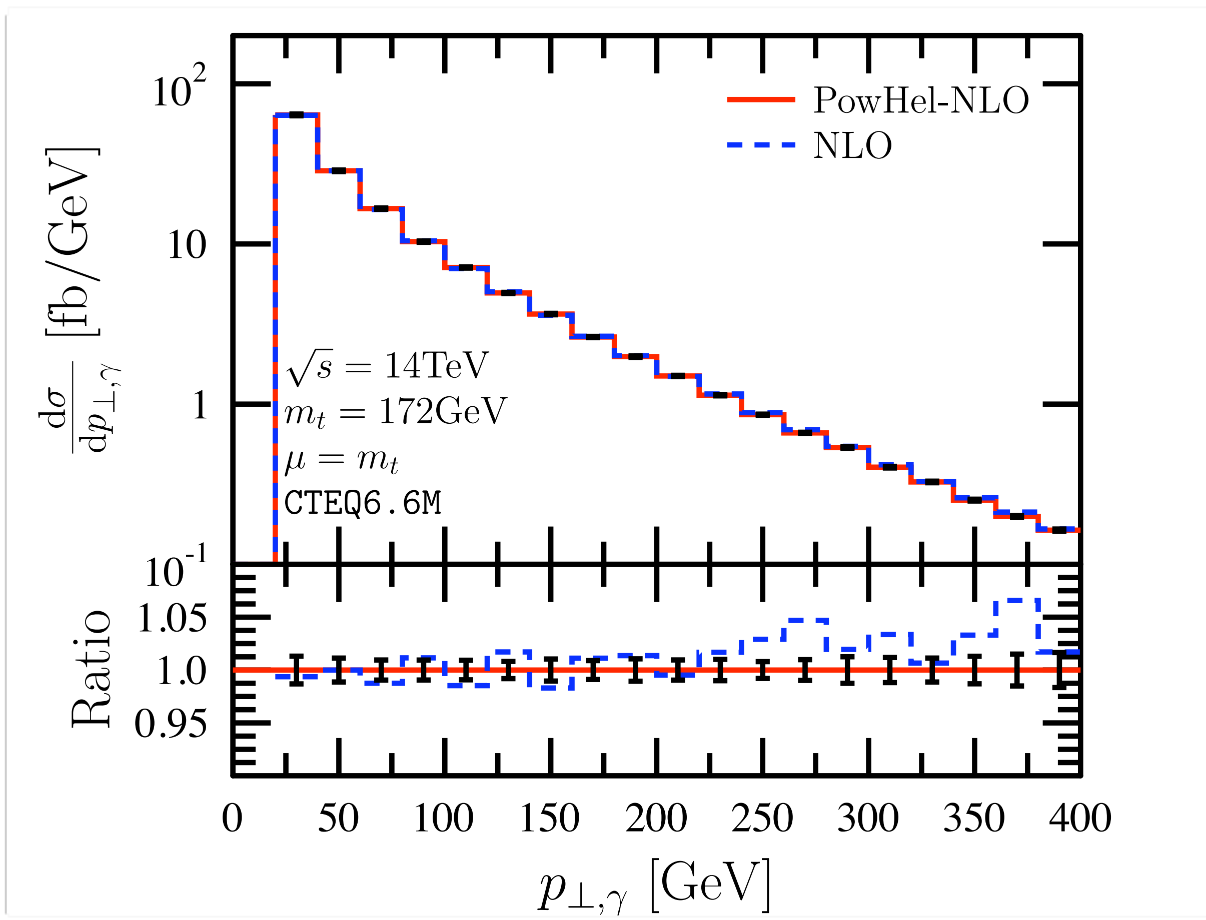
PowHel-NLO vs. NLO

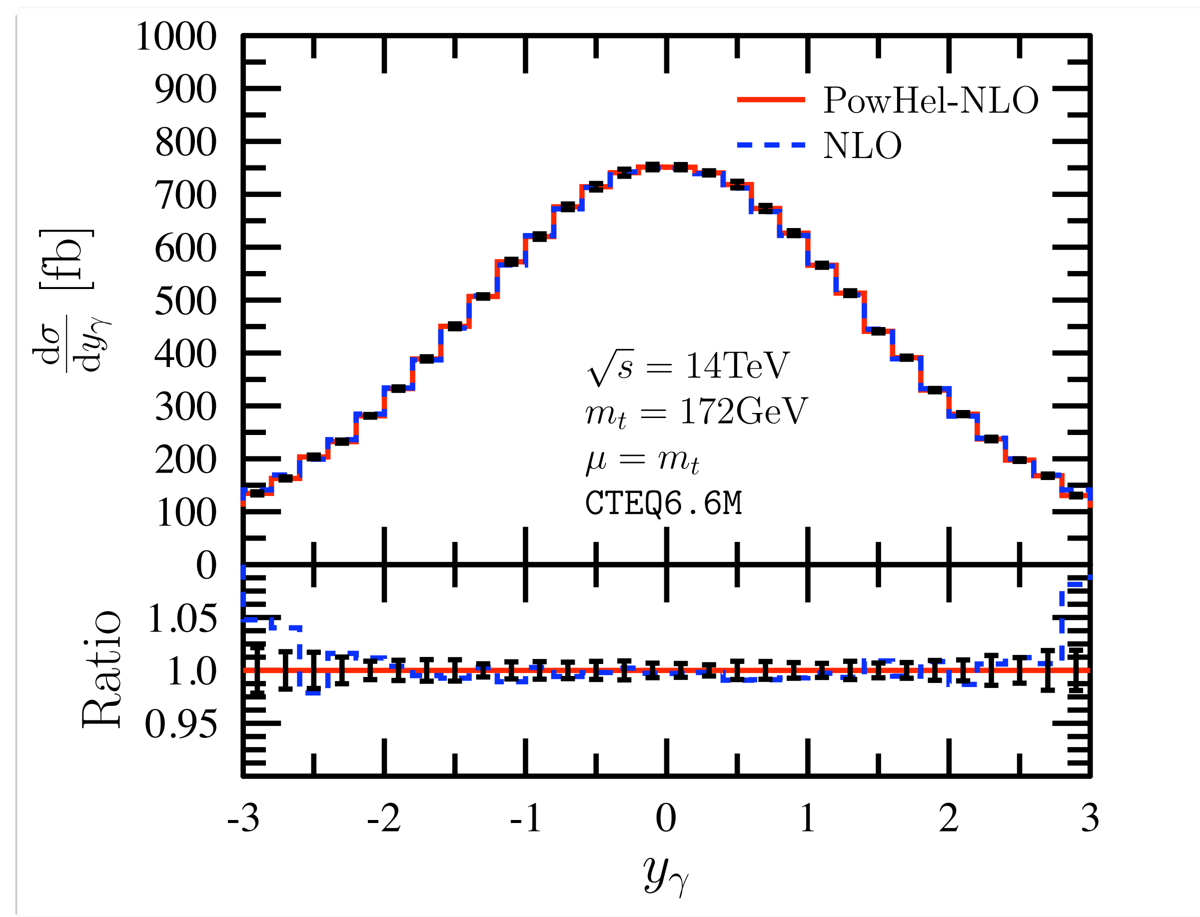




Transverse momentum and rapidity distributions of the t-quark in pp → $t\bar{t}\gamma$ at the LHC (with Frixione-isolation)

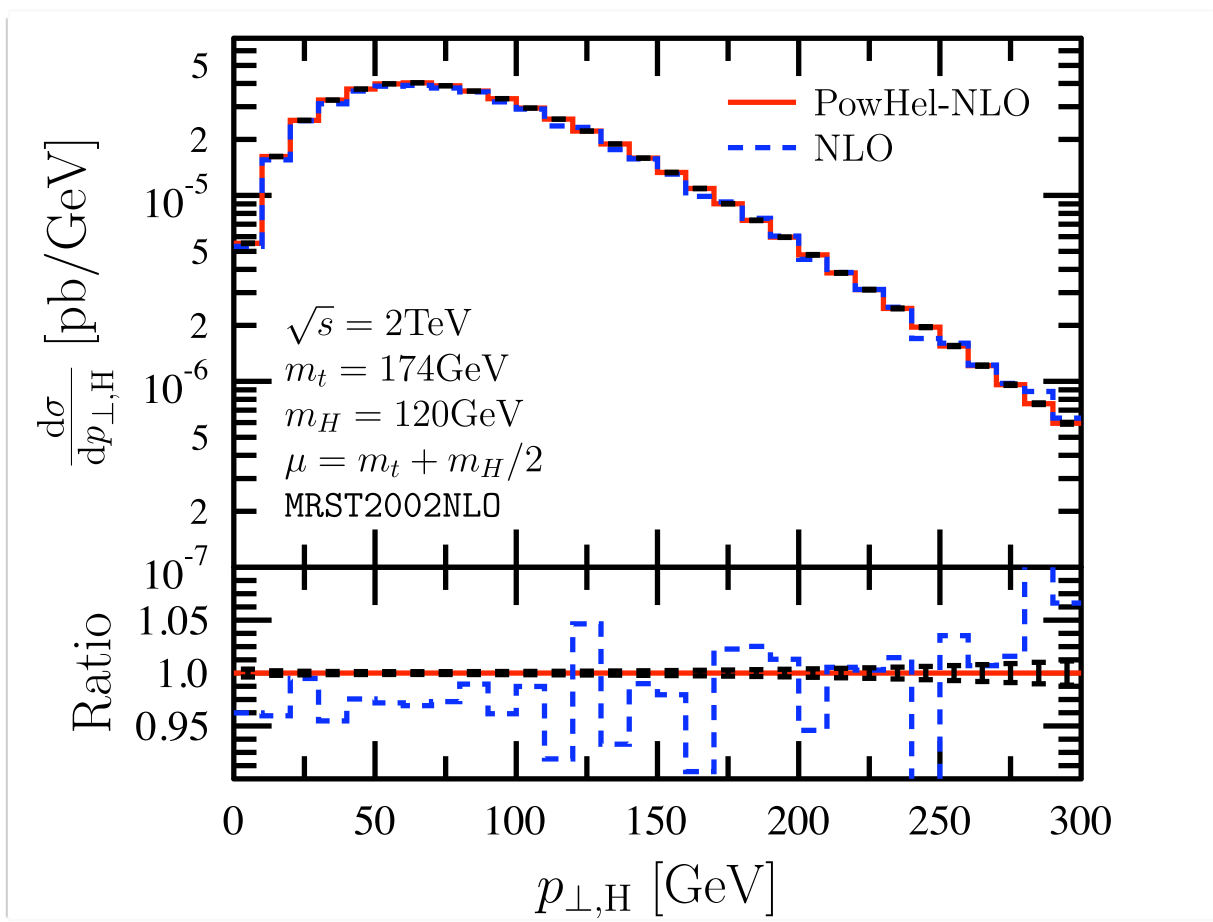
PowHel-NLO vs. NLO

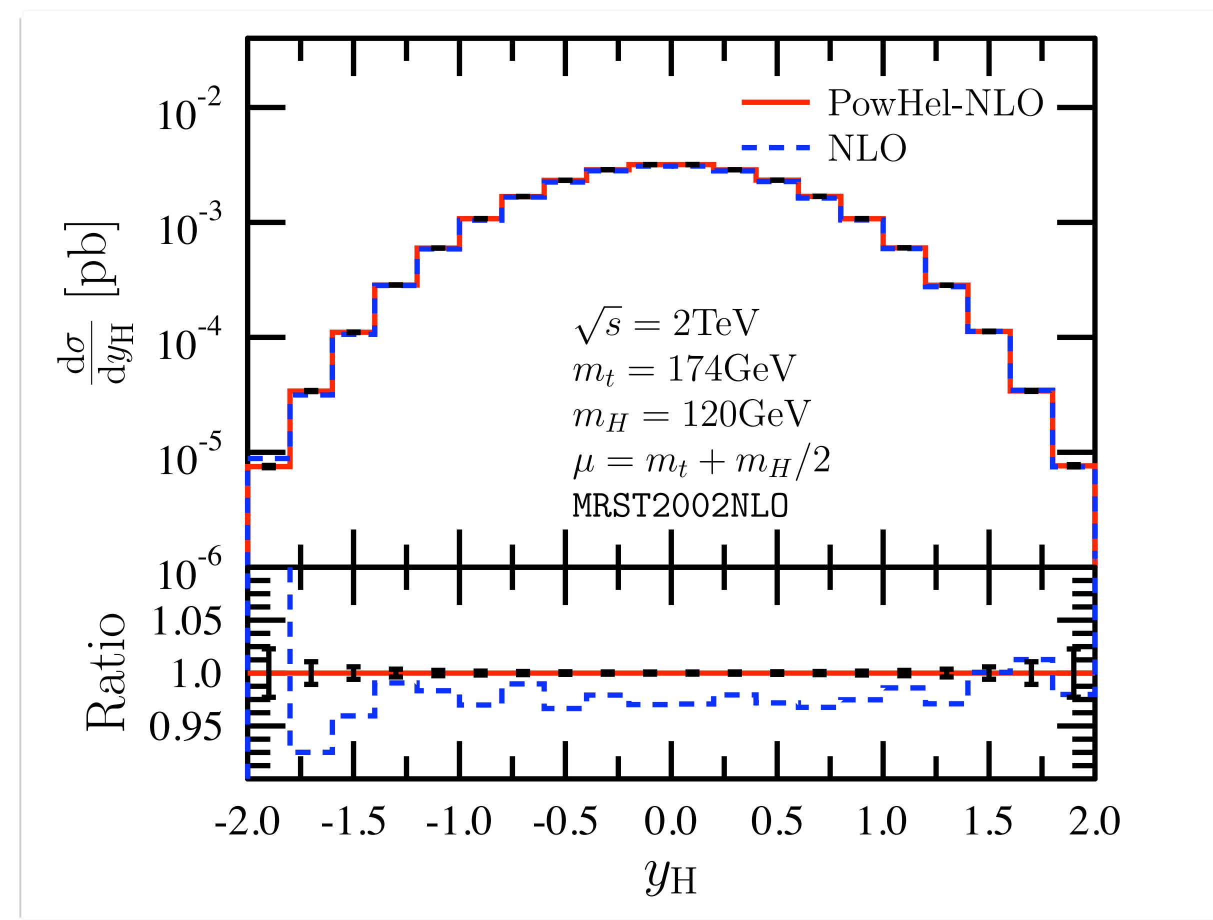




Transverse momentum & rapidity distributions of the photon in $pp \to t\bar{t}\gamma$ at the LHC (with Frixione-isolation)

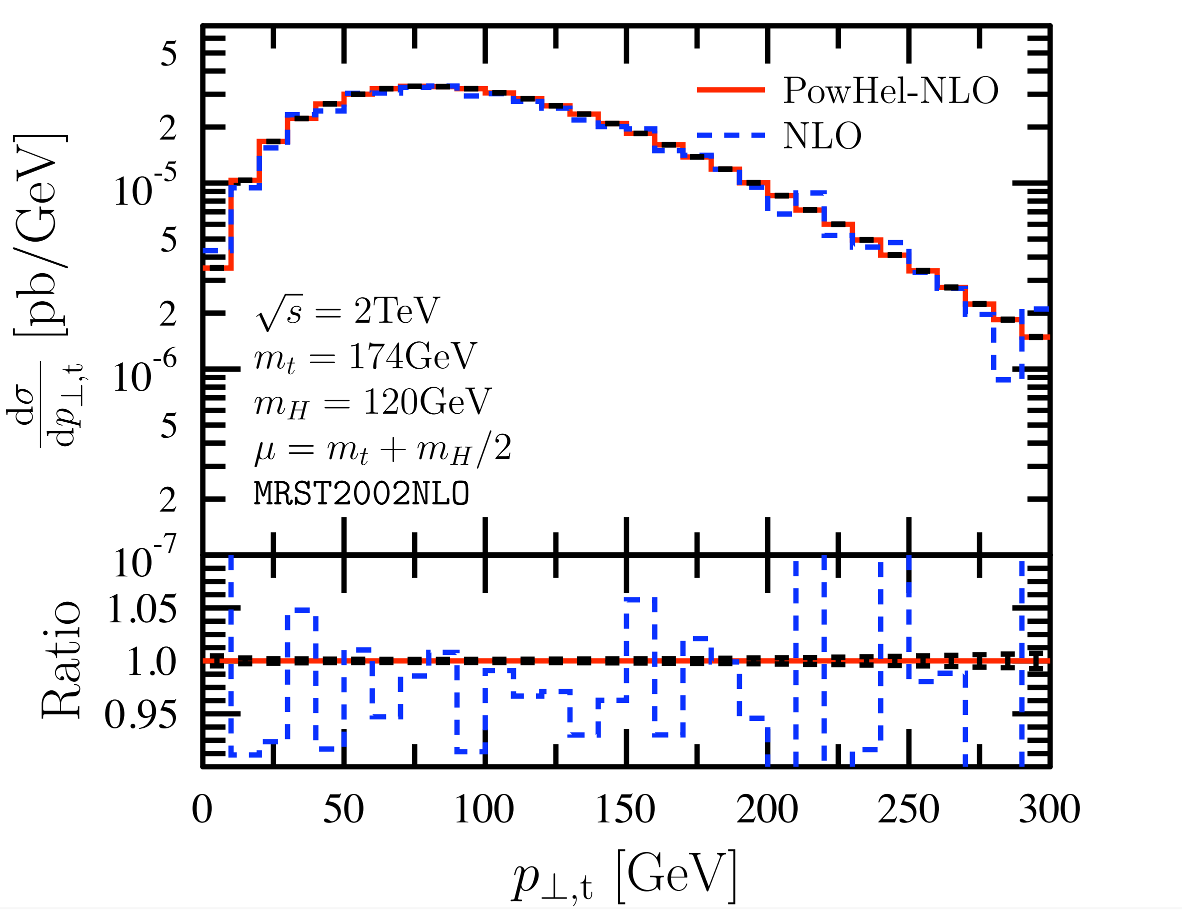
PowHel-NLO vs. NLO

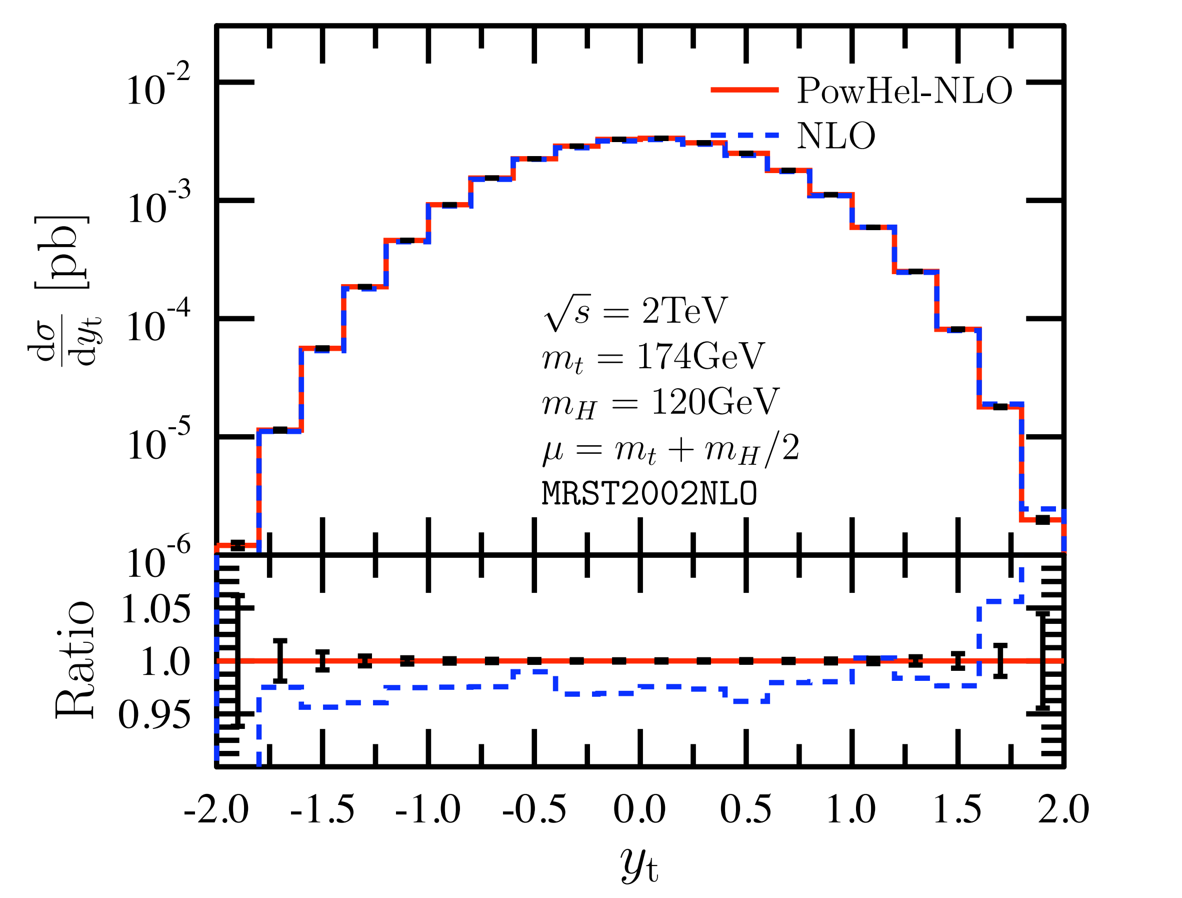




Transverse momentum and rapidity distributions of the Higgs boson in $p\bar{p} \to t\bar{t}\,H$ at the TeVatron

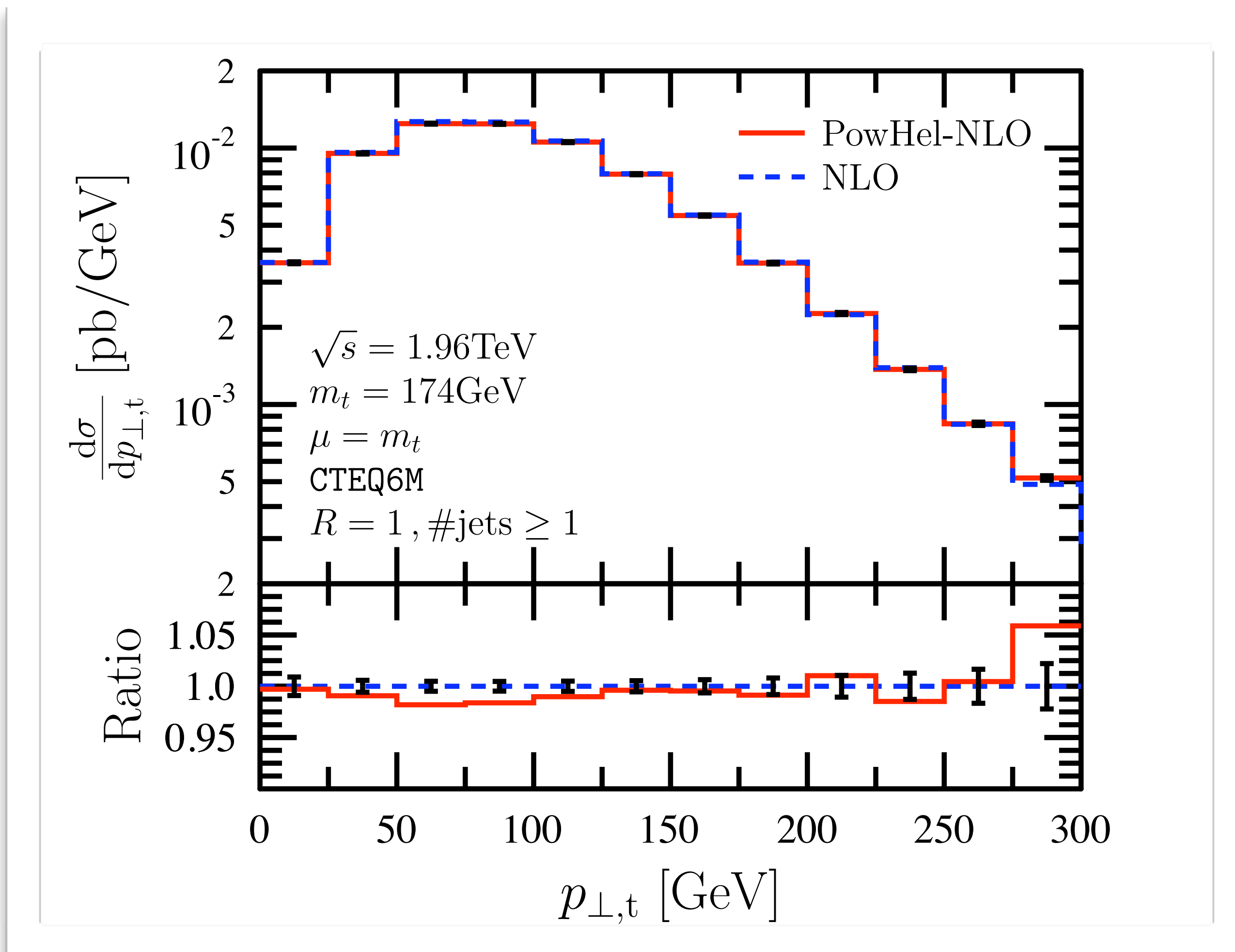
PowHel-NLO vs. NLO

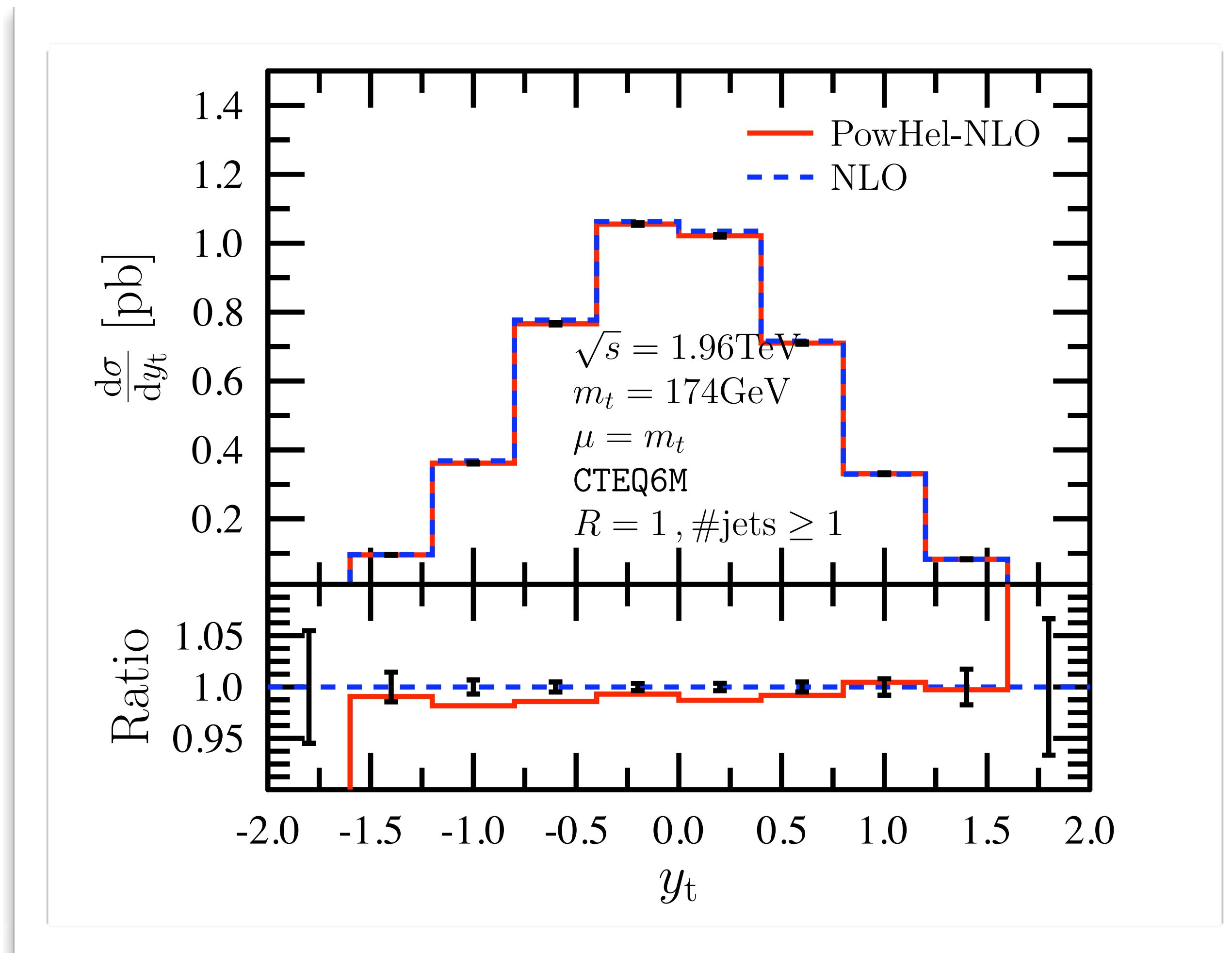




Transverse momentum and rapidity distributions of the t-quark in $p\bar{p} \rightarrow t\bar{t}\,H$ at the TeVatron

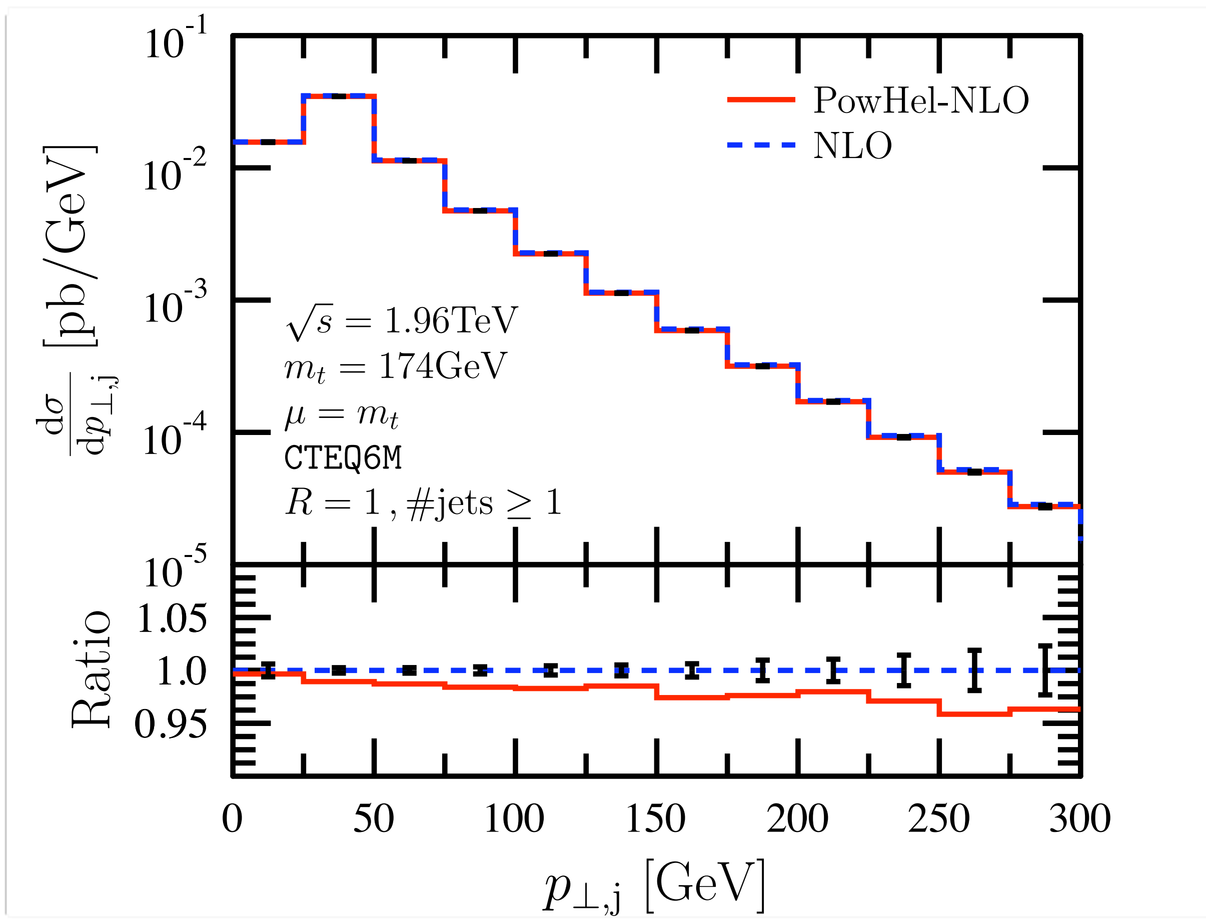
PowHel-NLO vs. NLO

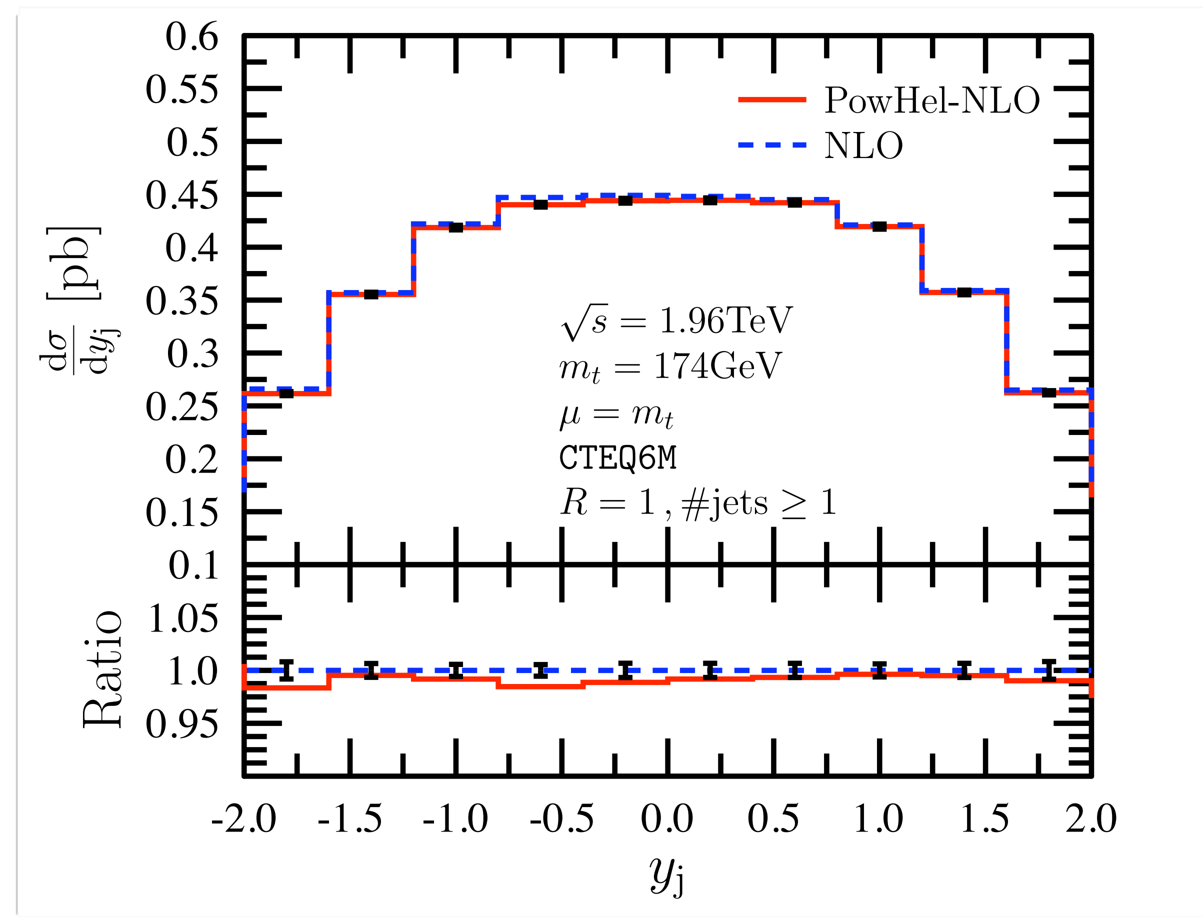




Transverse momentum and rapidity distributions of the t-quark in $p\bar{p} \to t\bar{t}$ jet at the TeVatron

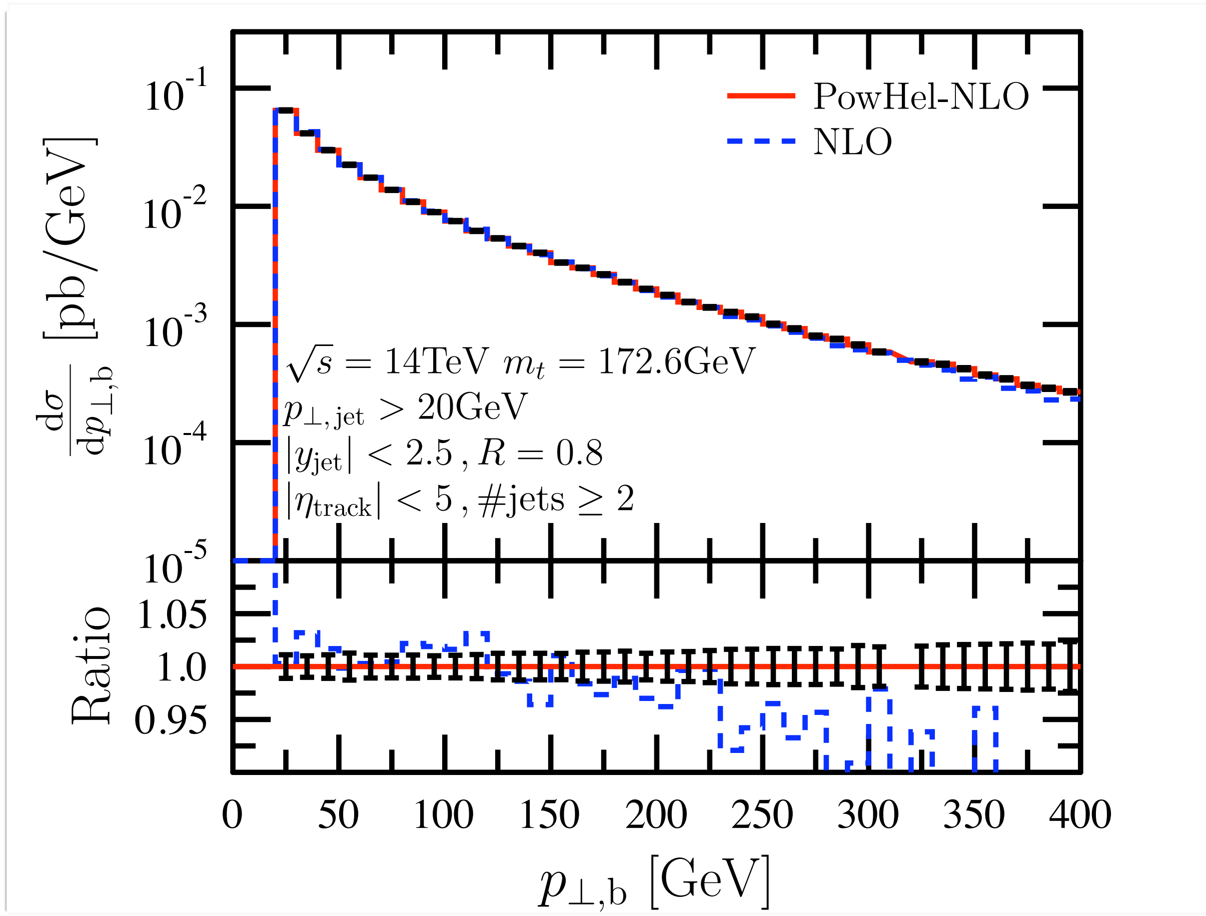
PowHel-NLO vs. NLO

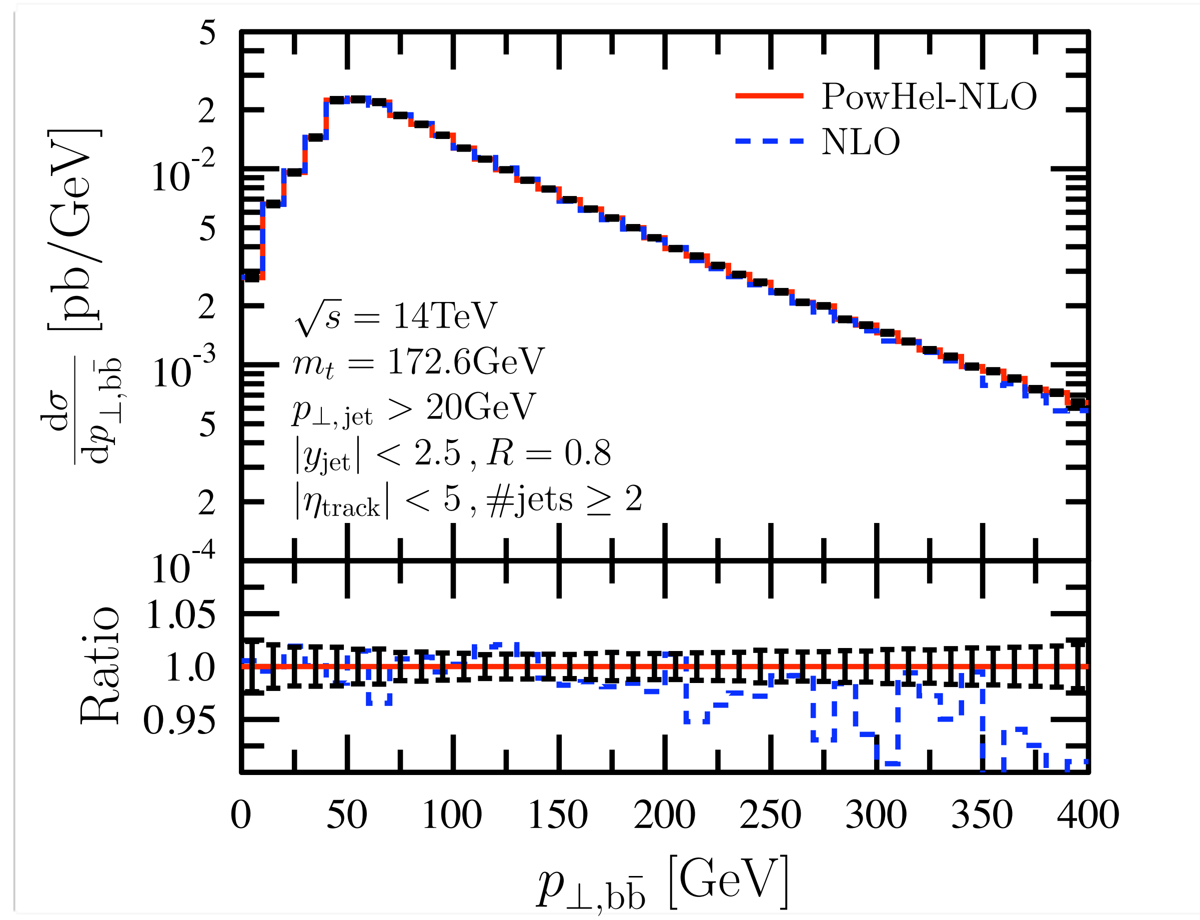




Transverse momentum & rapidity distributions of the hardest jet in $p\bar{p} \to t\bar{t}$ jet at the TeVatron

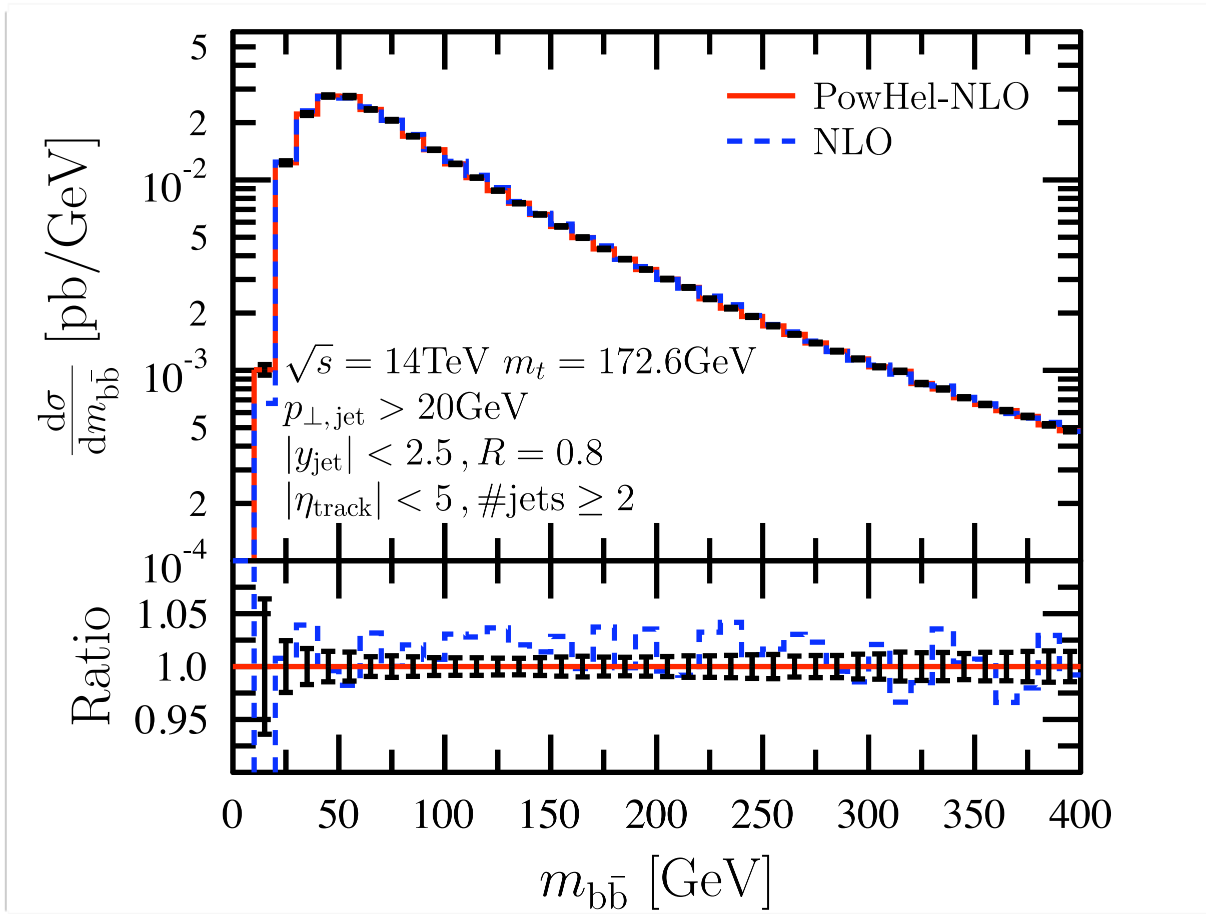
PowHel-NLO vs. NLO

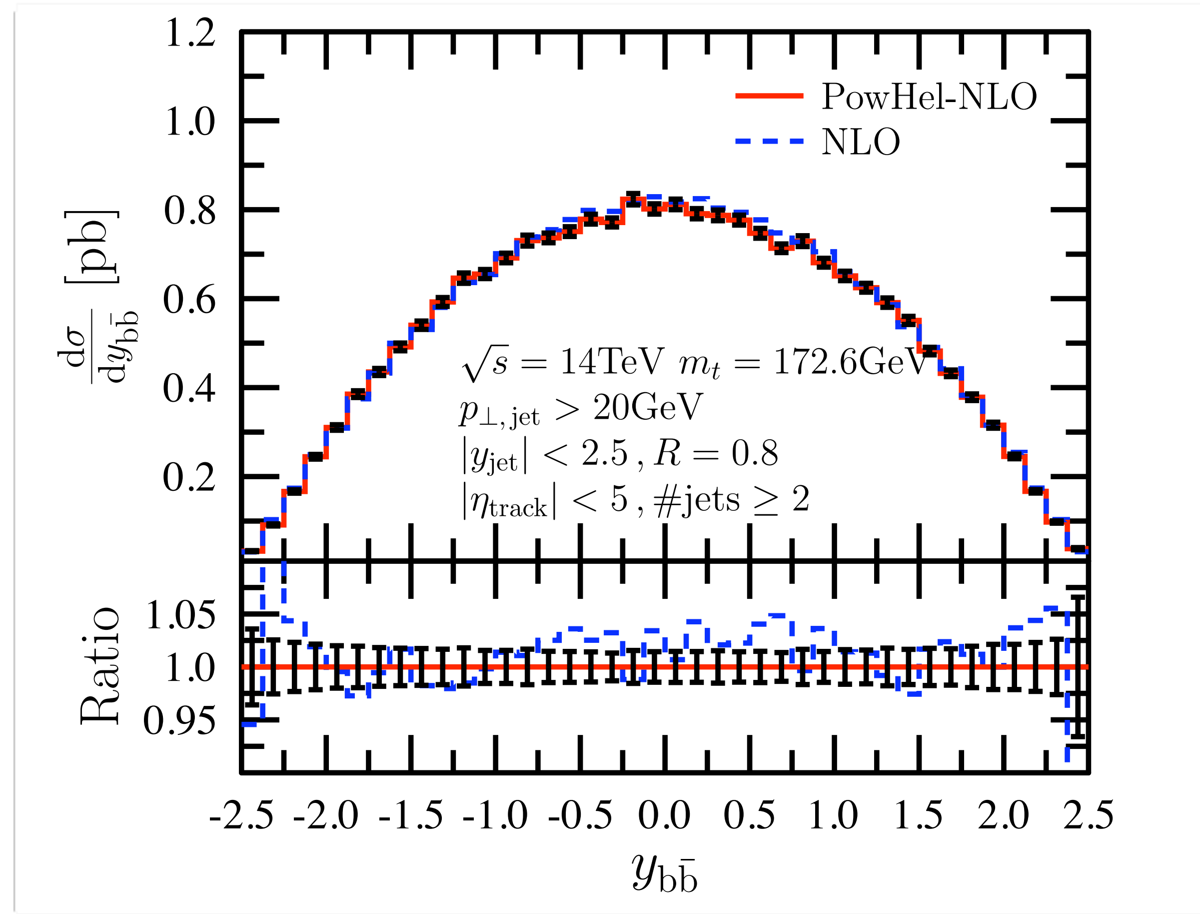




Transverse momentum distributions of the b-quark and the $b\bar{b}$-pair in $pp \to t\bar{t}\,b\bar{b}$ at the LHC

PowHel-NLO vs. NLO





Invariant-mass and rapidity distributions of the $b\bar{b}$-pair in $pp \to t\bar{t}\,b\bar{b}$ at the LHC

PowHel-NLO vs. NLO

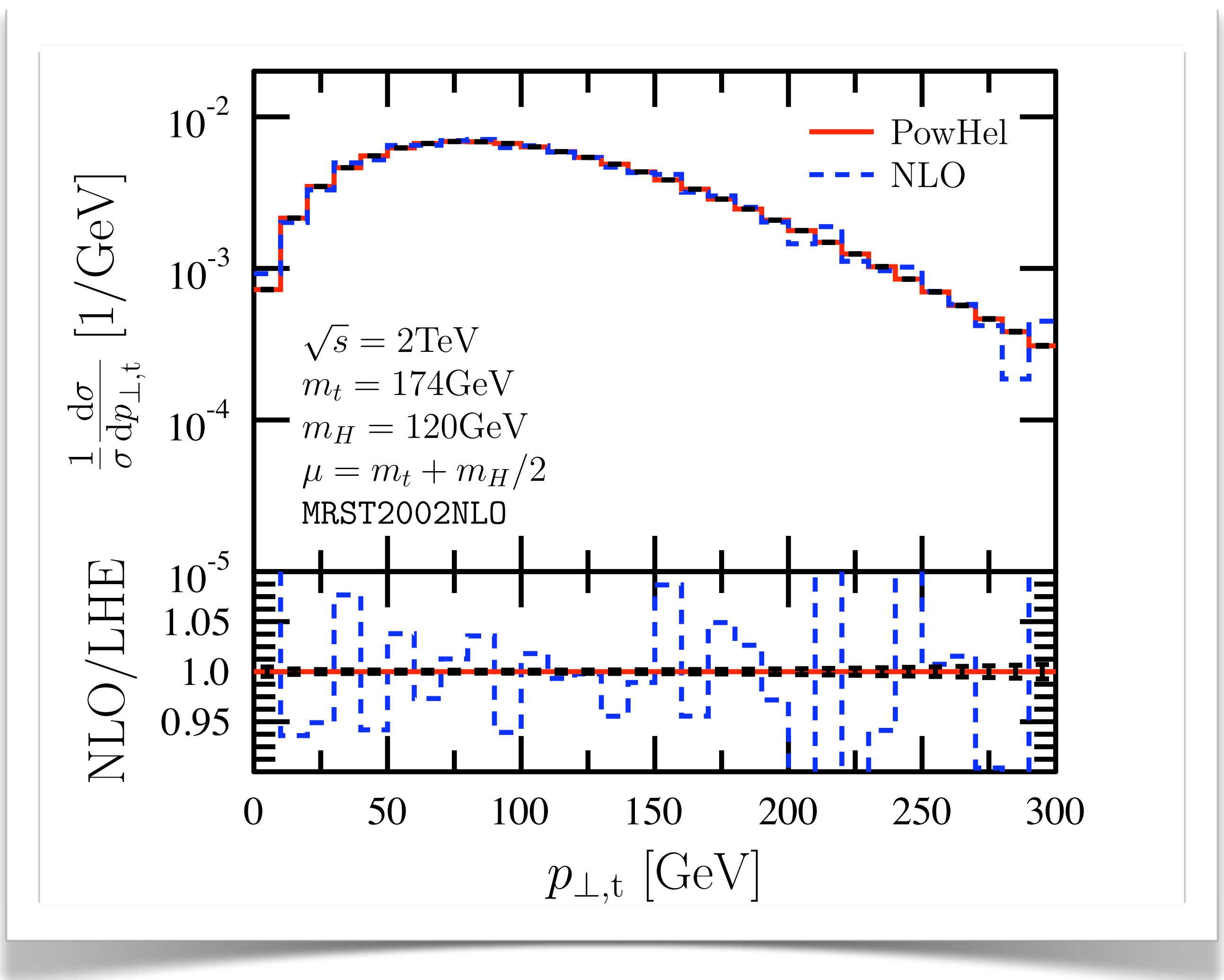
Message: PowHel-NLO is reliable

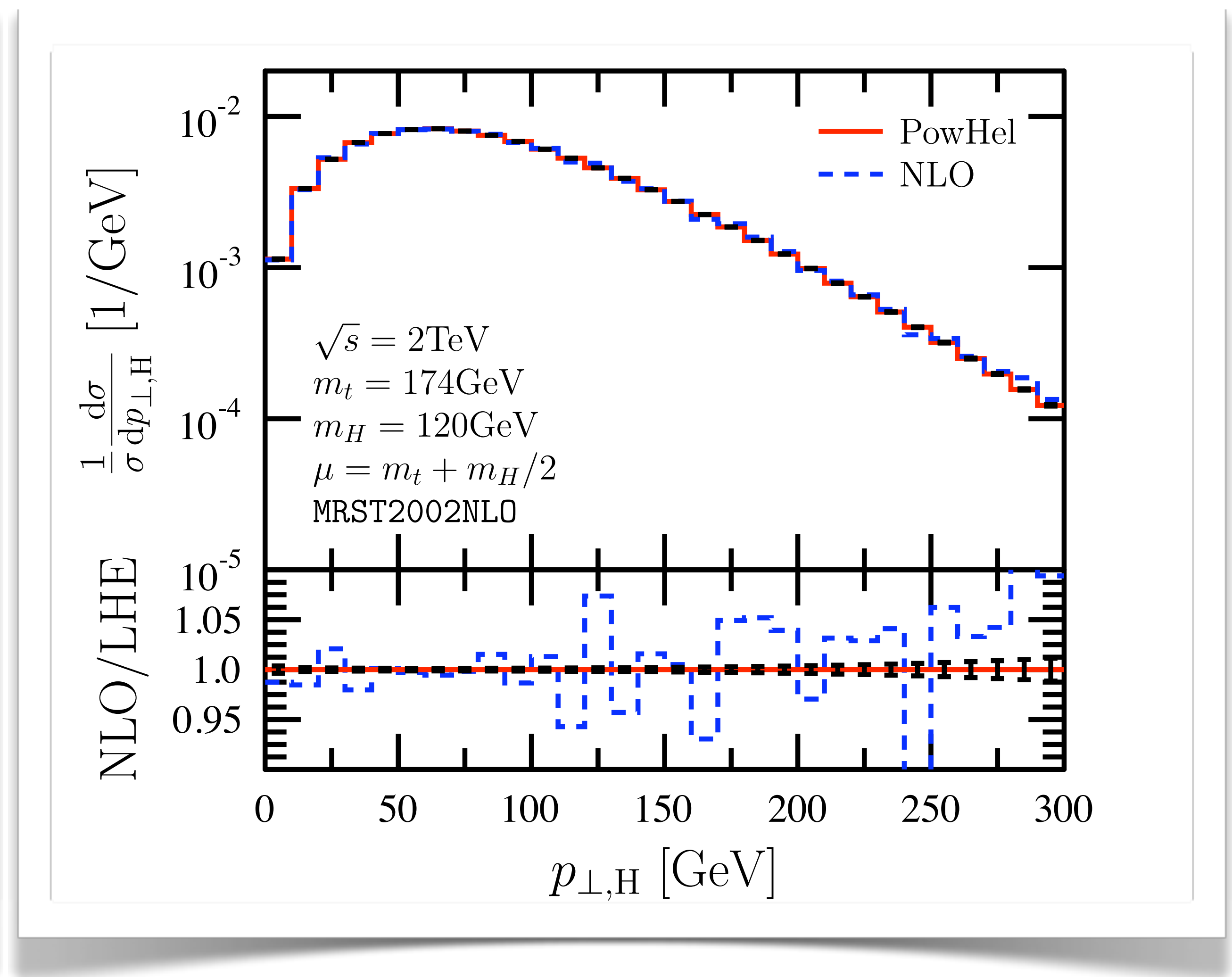
Comparison to NLO

✓ Compare distributions based on events at Born+1st radiation level (LHE) to those at NLO accuracy

Remember: $\sigma_{LHE} = \sigma_{NLO}\,(1+O(\alpha_s))$

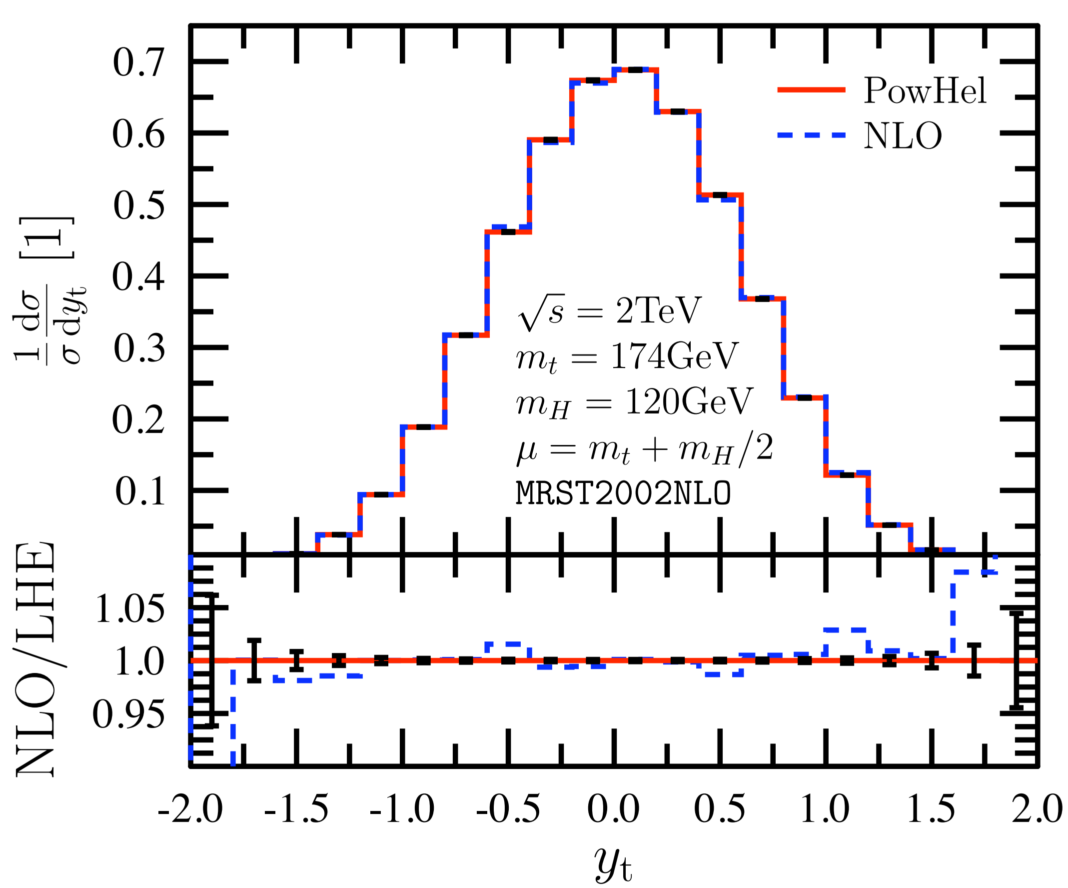
LHE vs. NLO

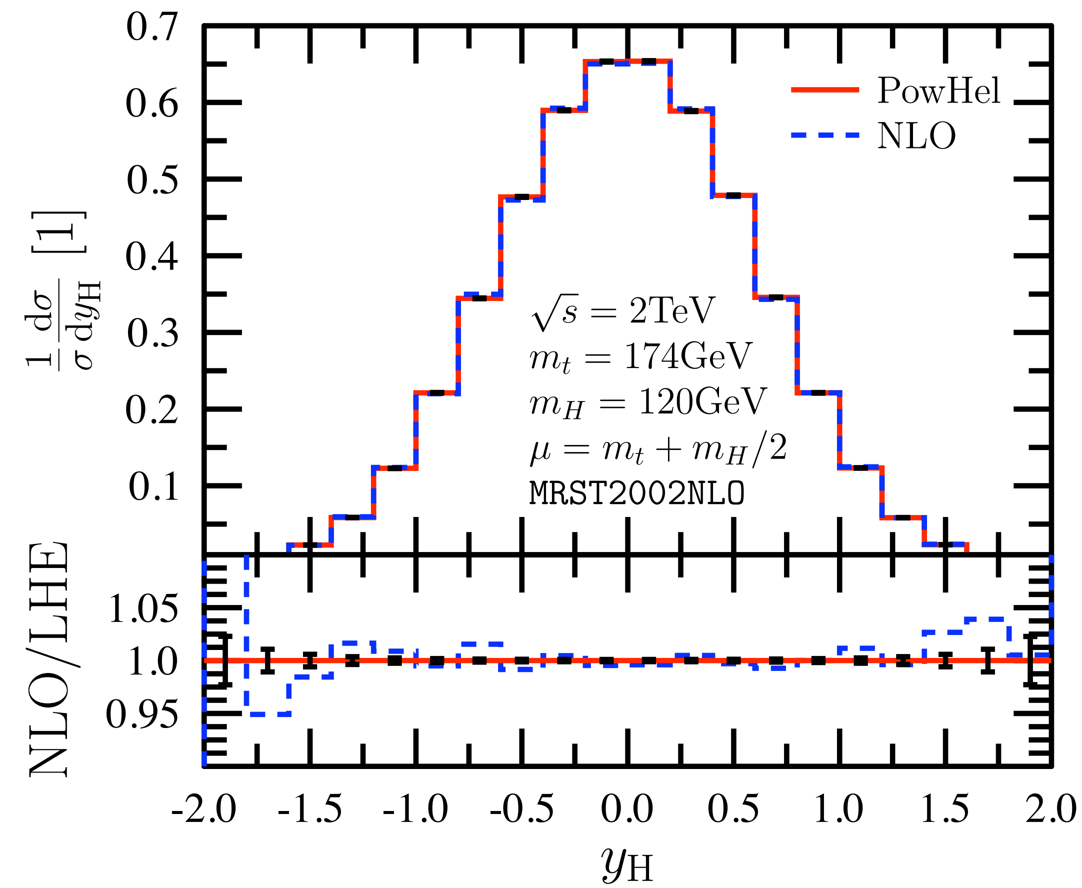




Transverse momentum distributions of the t-quark and the Higgs in $p\bar{p} \to t\bar{t}\,H$ at the TeVatron

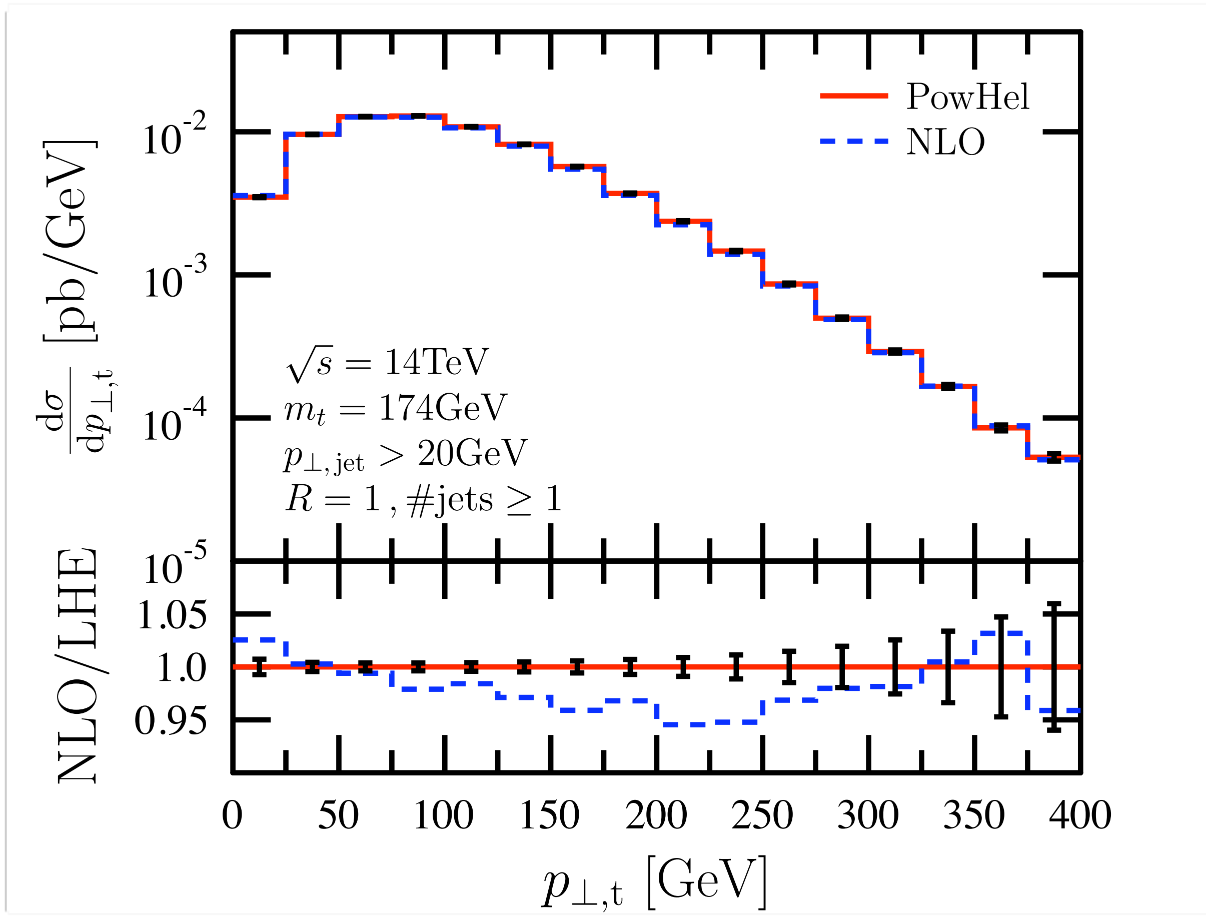
LHE vs. NLO

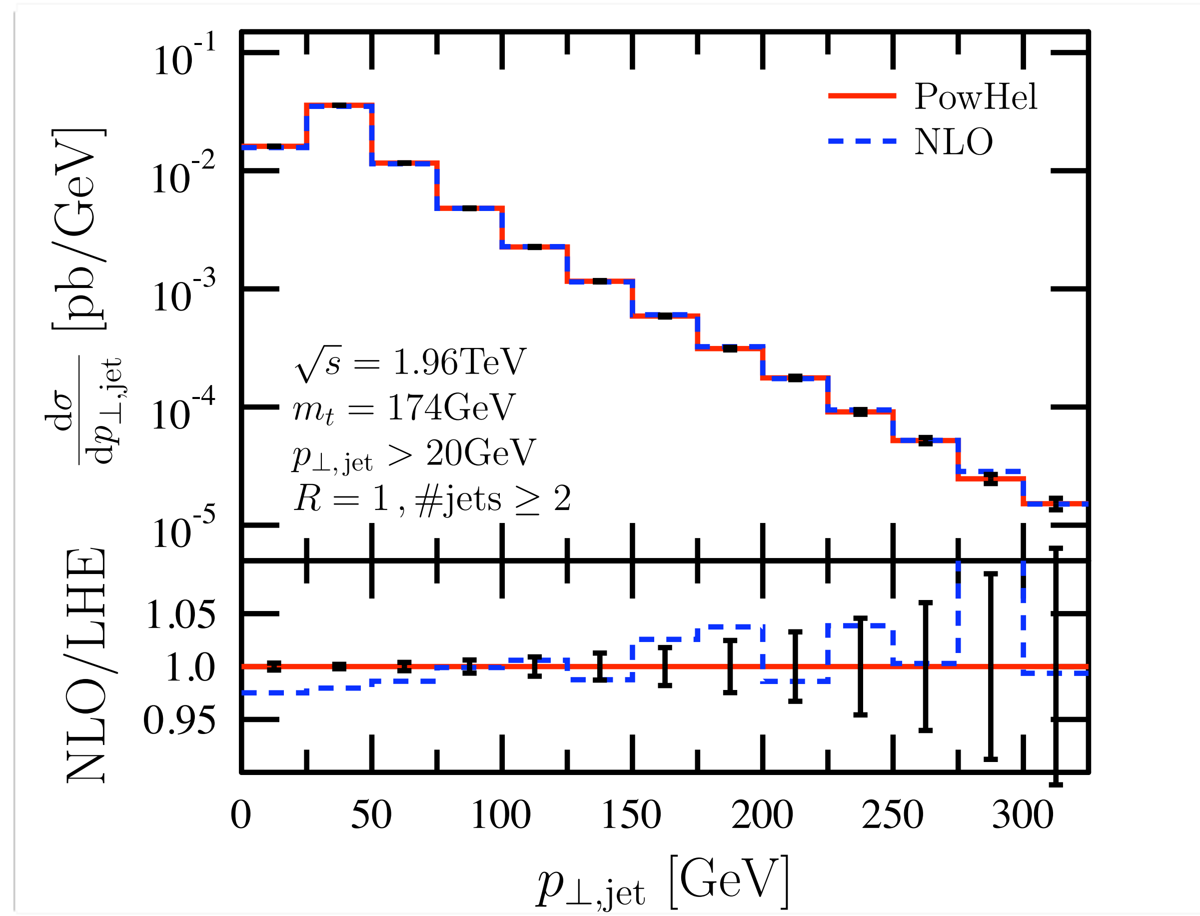




Rapidity distributions of the t-quark and the Higgs boson in $p\bar{p} \to t\bar{t}\,H$ at the TeVatron

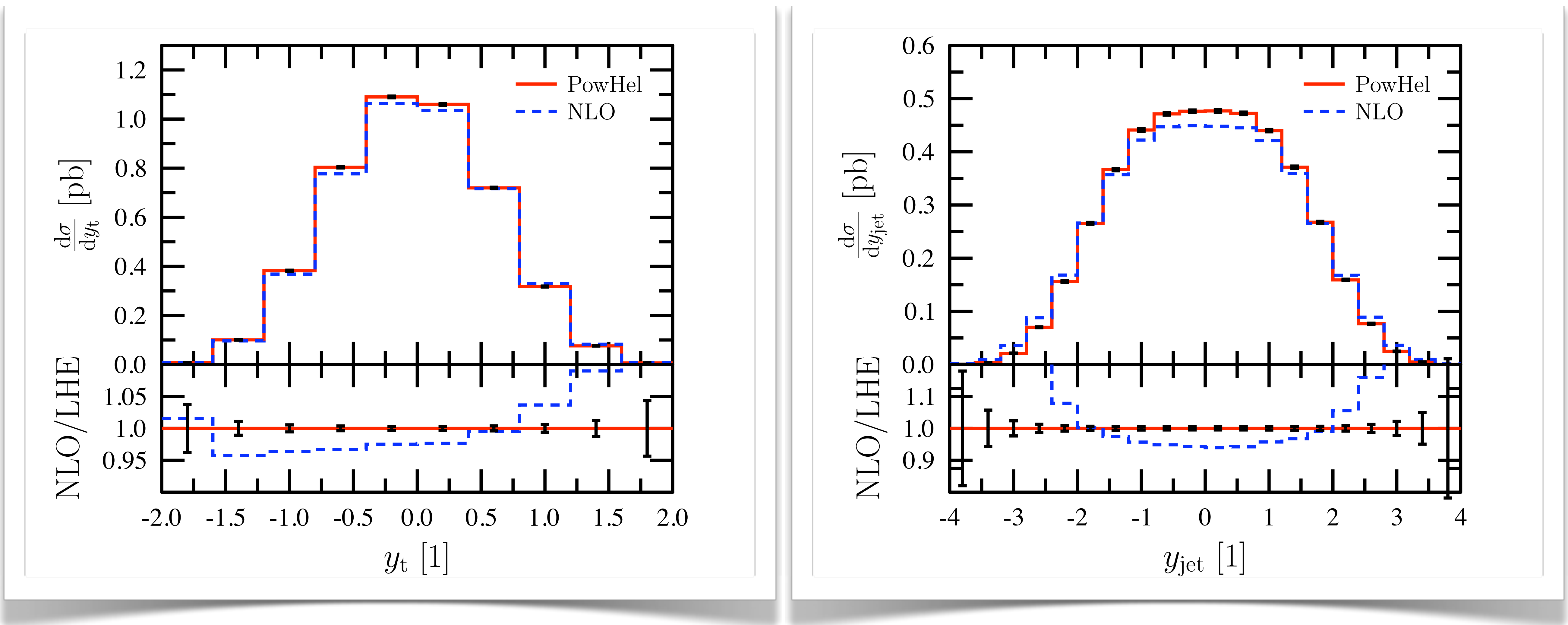
LHE vs. NLO





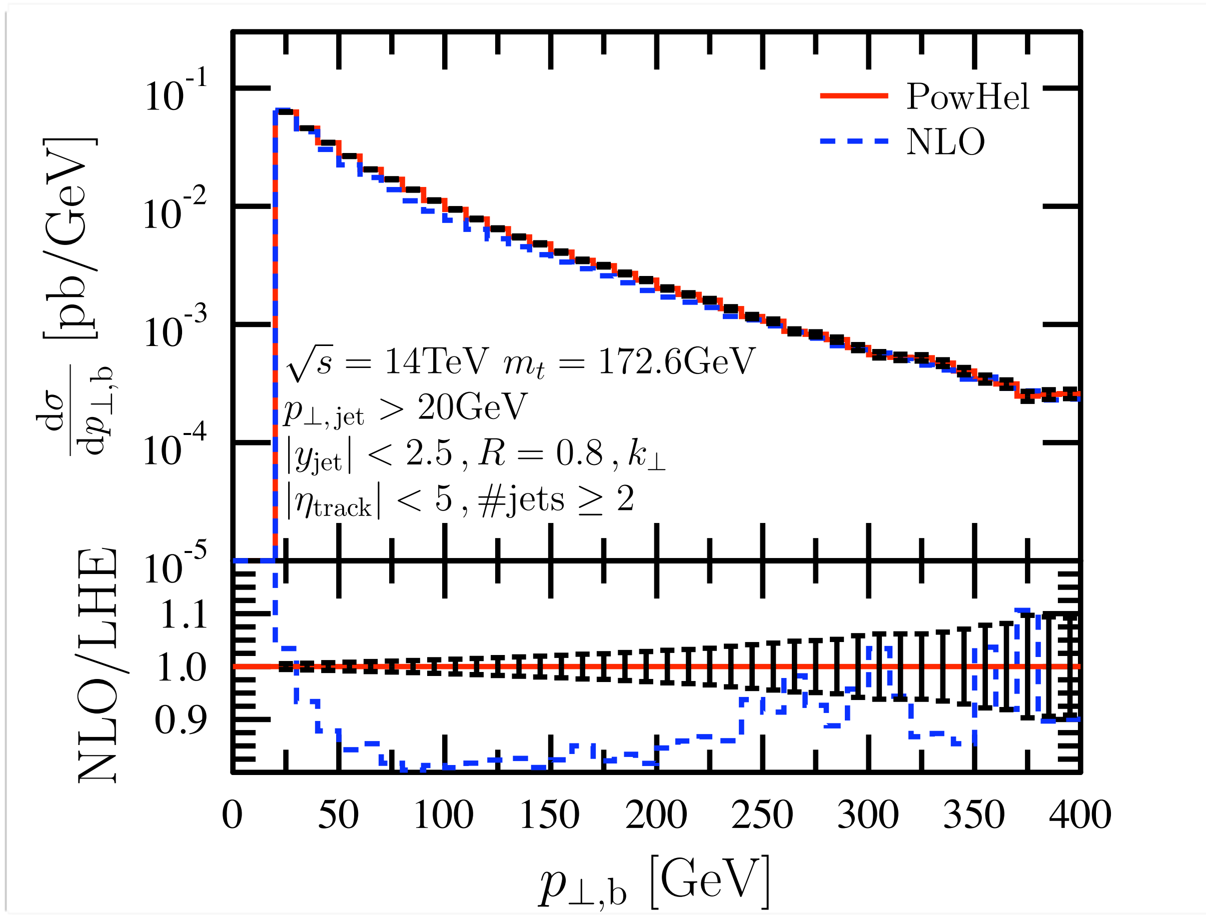
Transverse momentum distributions of the t-quark and the jet in $p\bar{p} \rightarrow t\bar{t}$ jet at the TeVatron

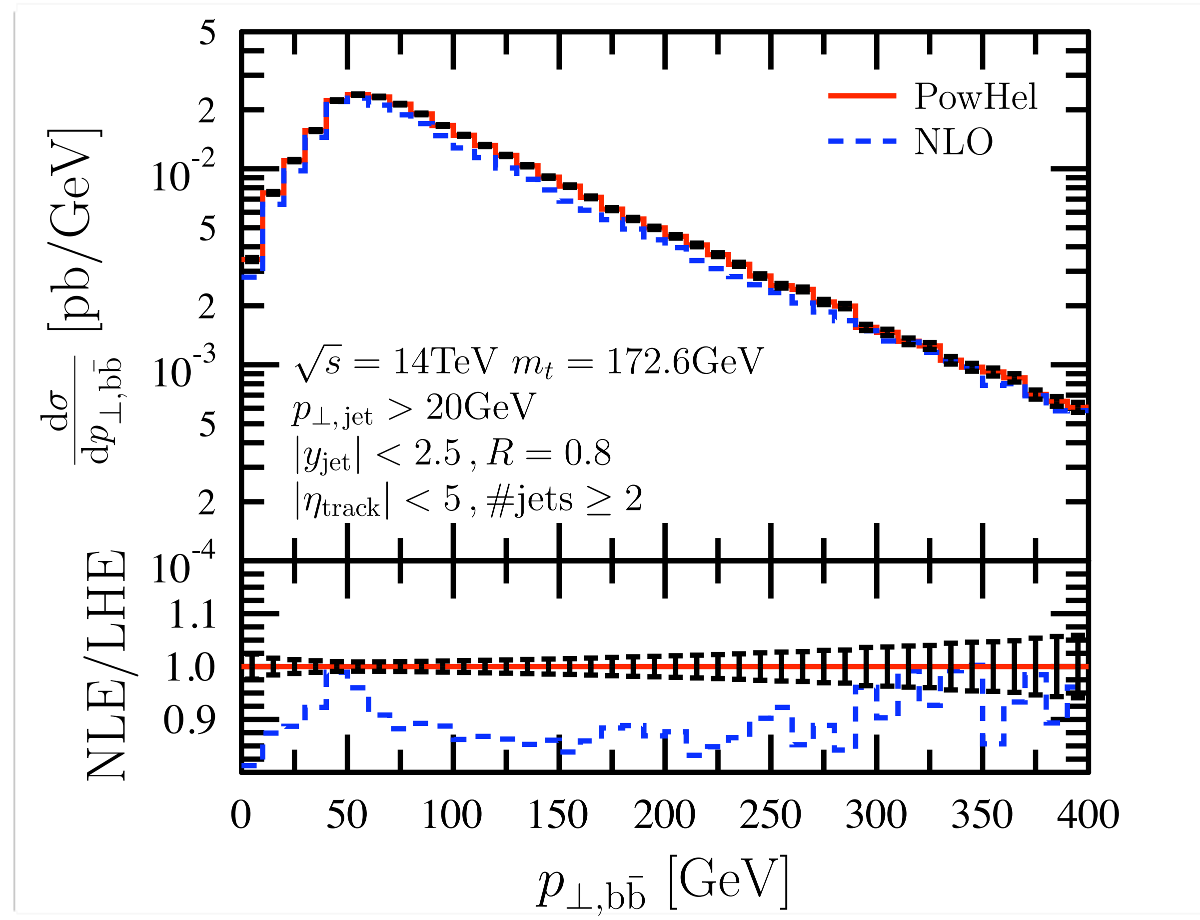
LHE vs. NLO



Rapidity distributions of the t-quark and the jet in $p\bar{p} \to t\bar{t}$ jet at the TeVatron

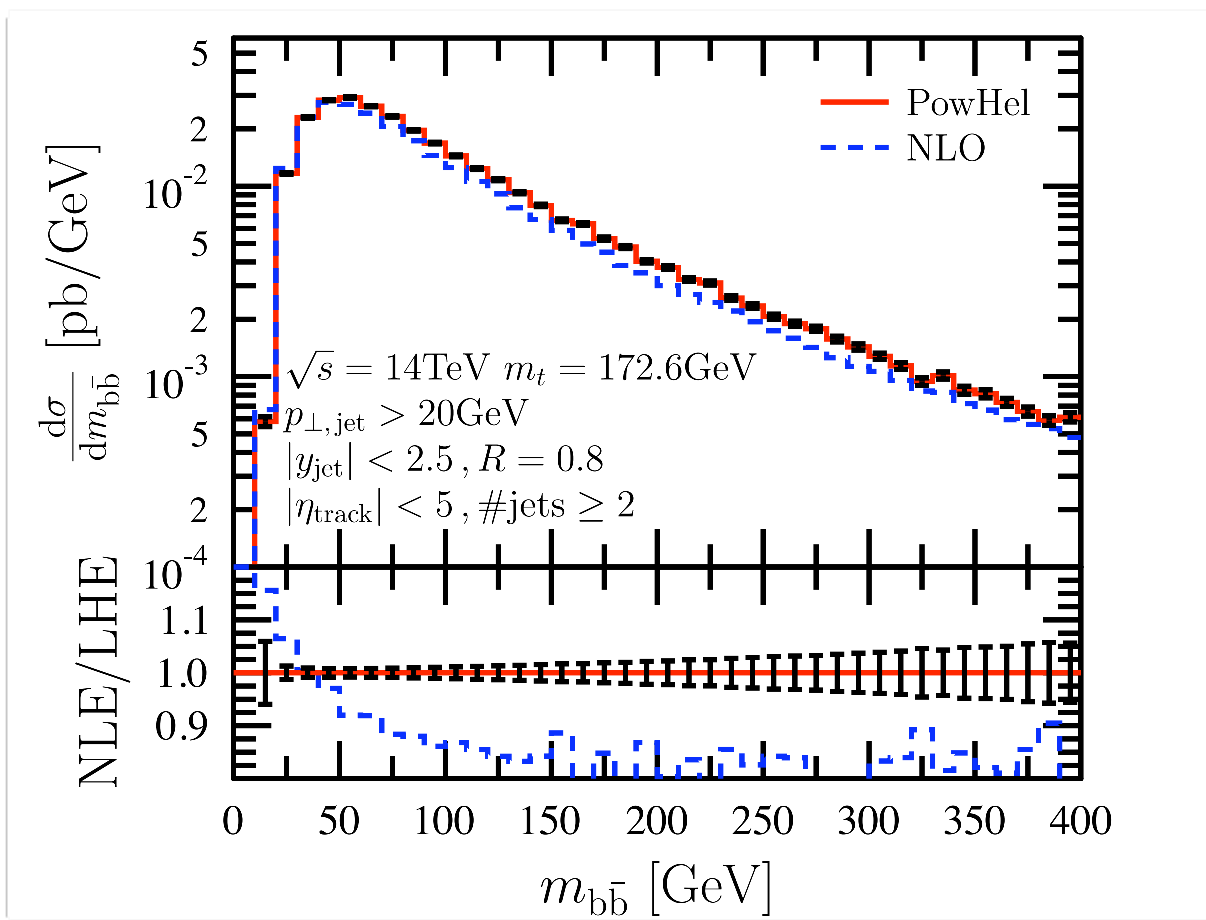
LHE vs. NLO

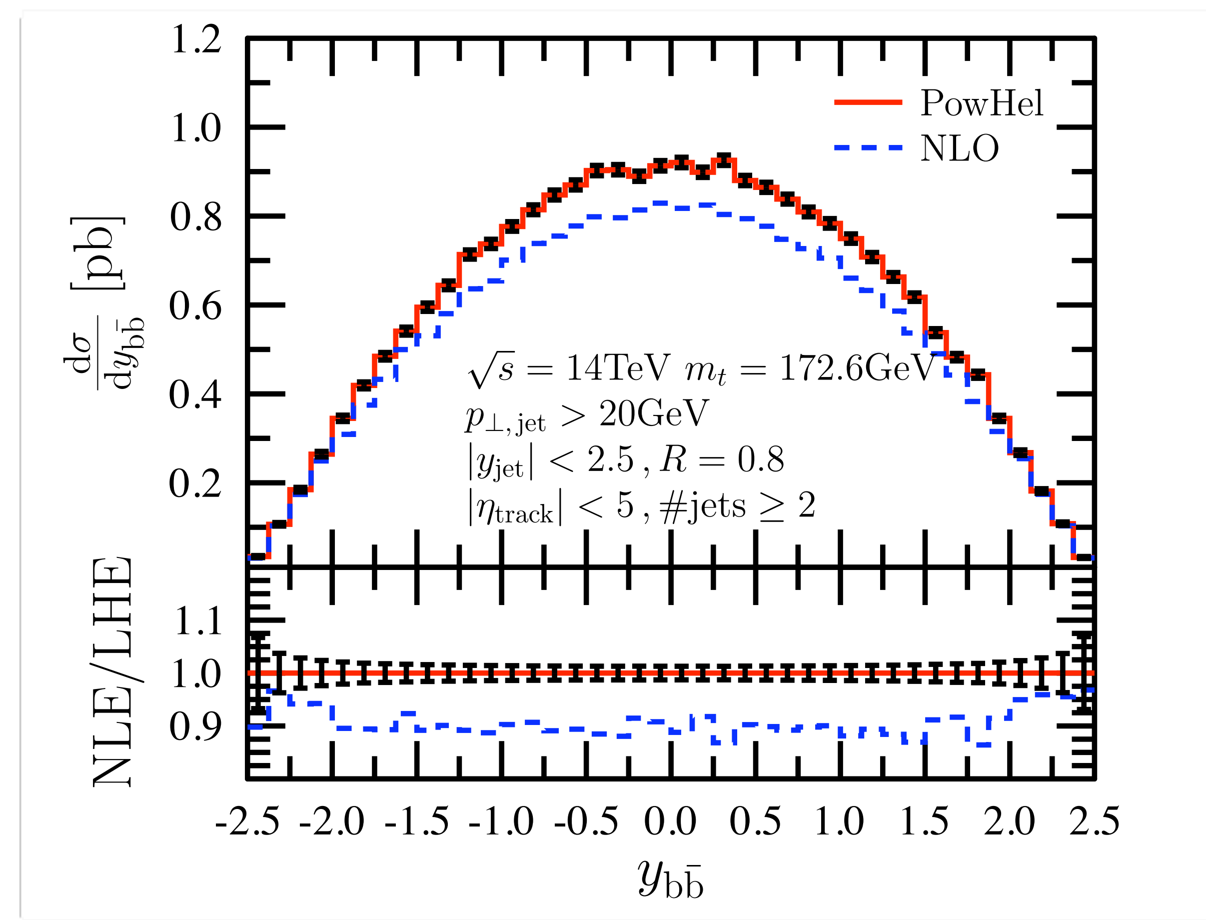




Transverse momentum distributions of the b-quark and $b\bar{b}$-pair in $p\bar{p} \rightarrow t\bar{t}\, b\bar{b}$ at the TeVatron

LHE vs. NLO





Invariant-mass and rapidity distributions of the $b\bar{b}$-pair in $p\bar{p} \to t\bar{t}\, b\bar{b}$ at the TeVatron

PowHel-LHE vs. NLO

Message: PowHel-LHE's are reliable

(but tell me your doubts)

Three levels of predictions

PowHel: we use the events at BORN+1st radiation

PowHel+Decay: we just include on-shell decays of t-quarks and the heavy bosons, decay of tau's emerging from heavy boson-decay as implemented in PYTHIA, turning off any shower and hadronization effects

PowHel+SMC: decays, showering and hadronization have been included, using both PYTHIA and HERWIG

Number and type of particles are very different =>
the possible selection cuts are restricted in comparisons

Three levels of cuts

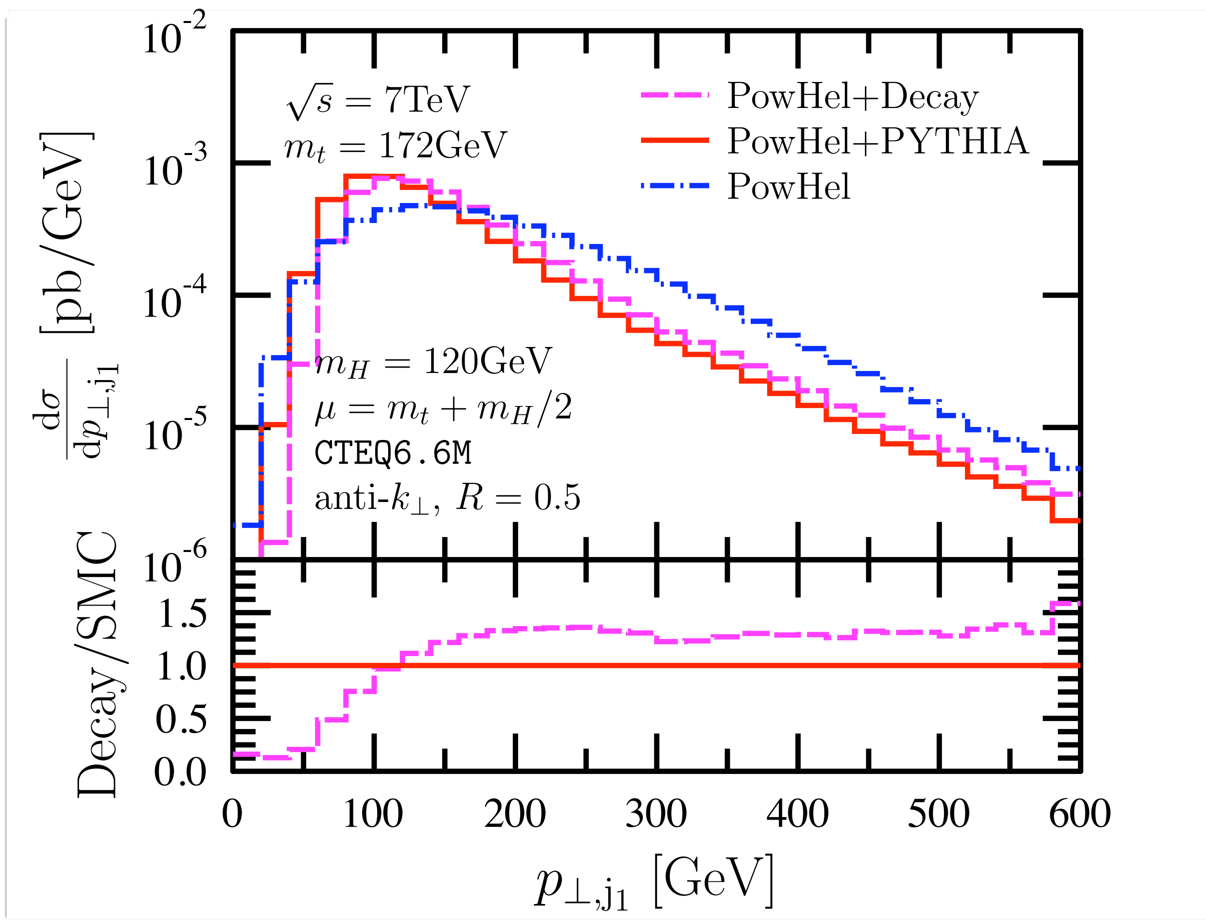
No cuts: to compare all three predictions (no leptons, and only one extra jet, beyond Born in POWHEG predictions)

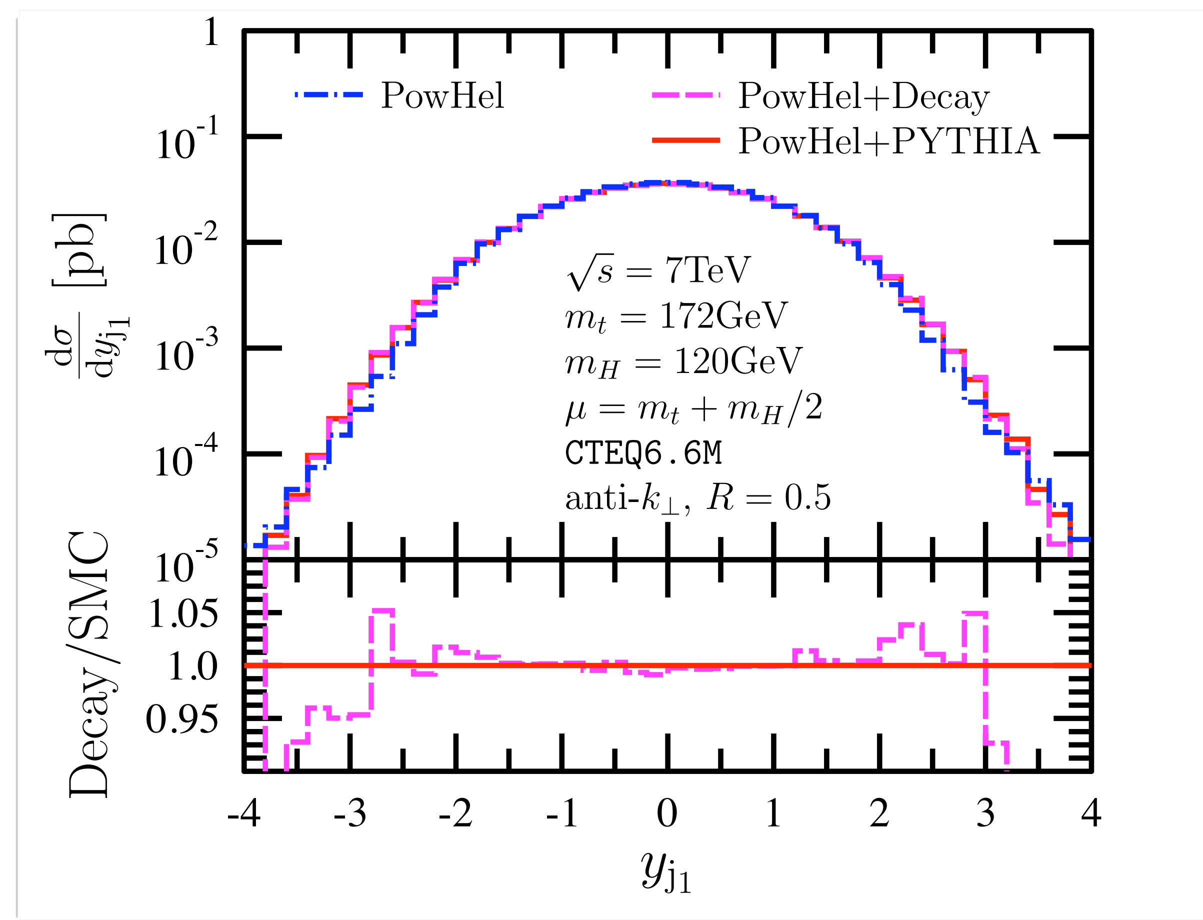
Jet cuts: to compare decay and full SMC predictions with physical cuts to the extent it is meaningful (leptons are very different at the two levels)

Physical cuts: to compare physical predictions from PYTHIA and HERWIG

Cuts are shown in figures

LHE vs. decay vs. full SMC, no cuts

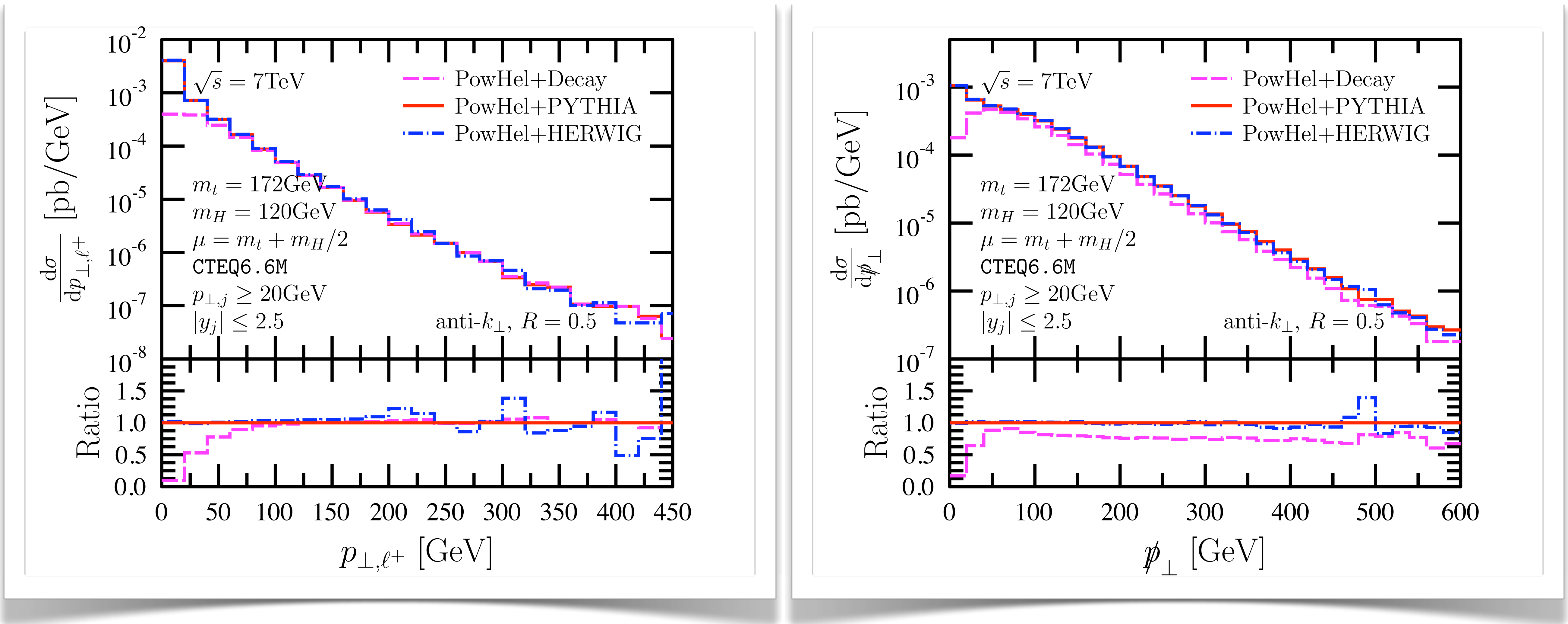




Transverse momentum and rapidity distributions of the hardest jet in $pp \to t\bar{t}H$ at the LHC

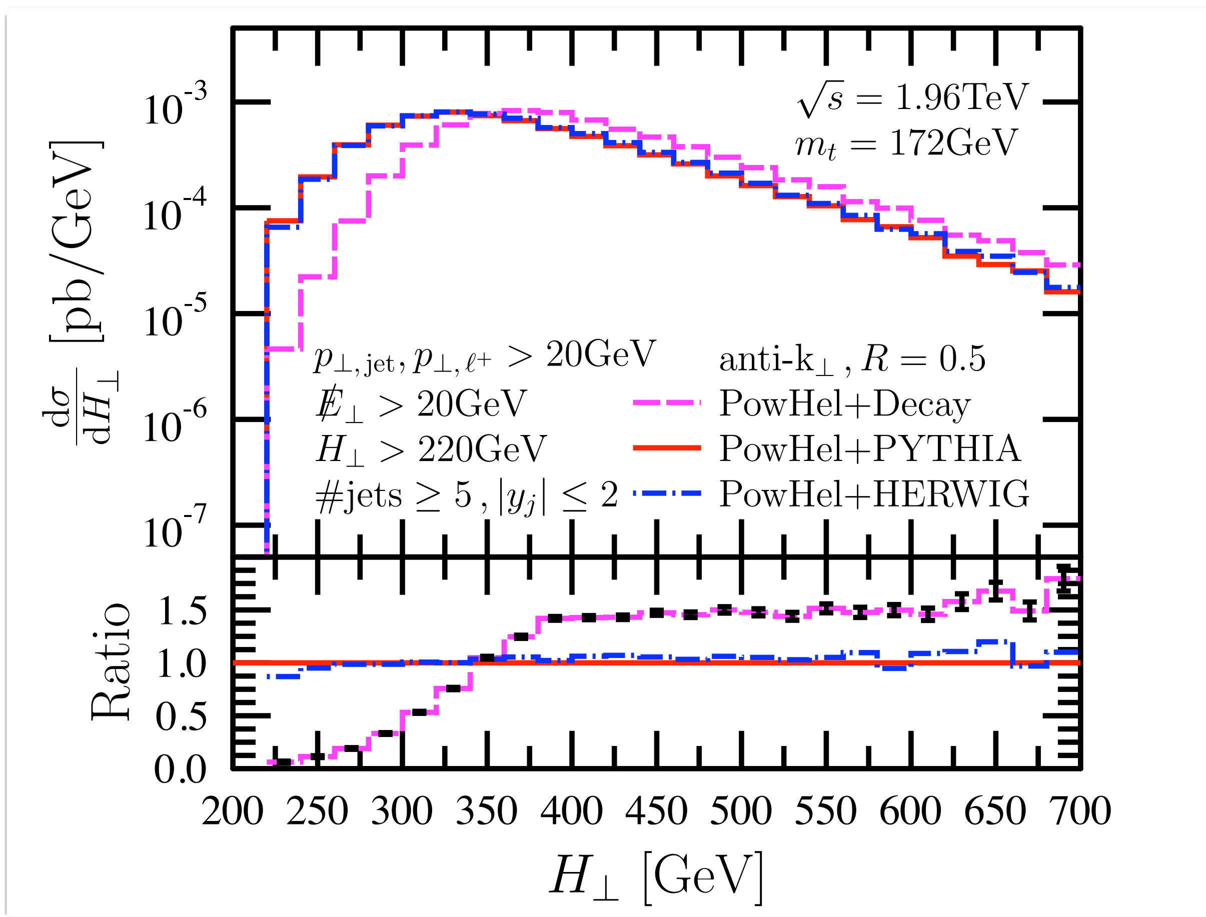
(n.b.: top-jet is included in LHE but not after decay)

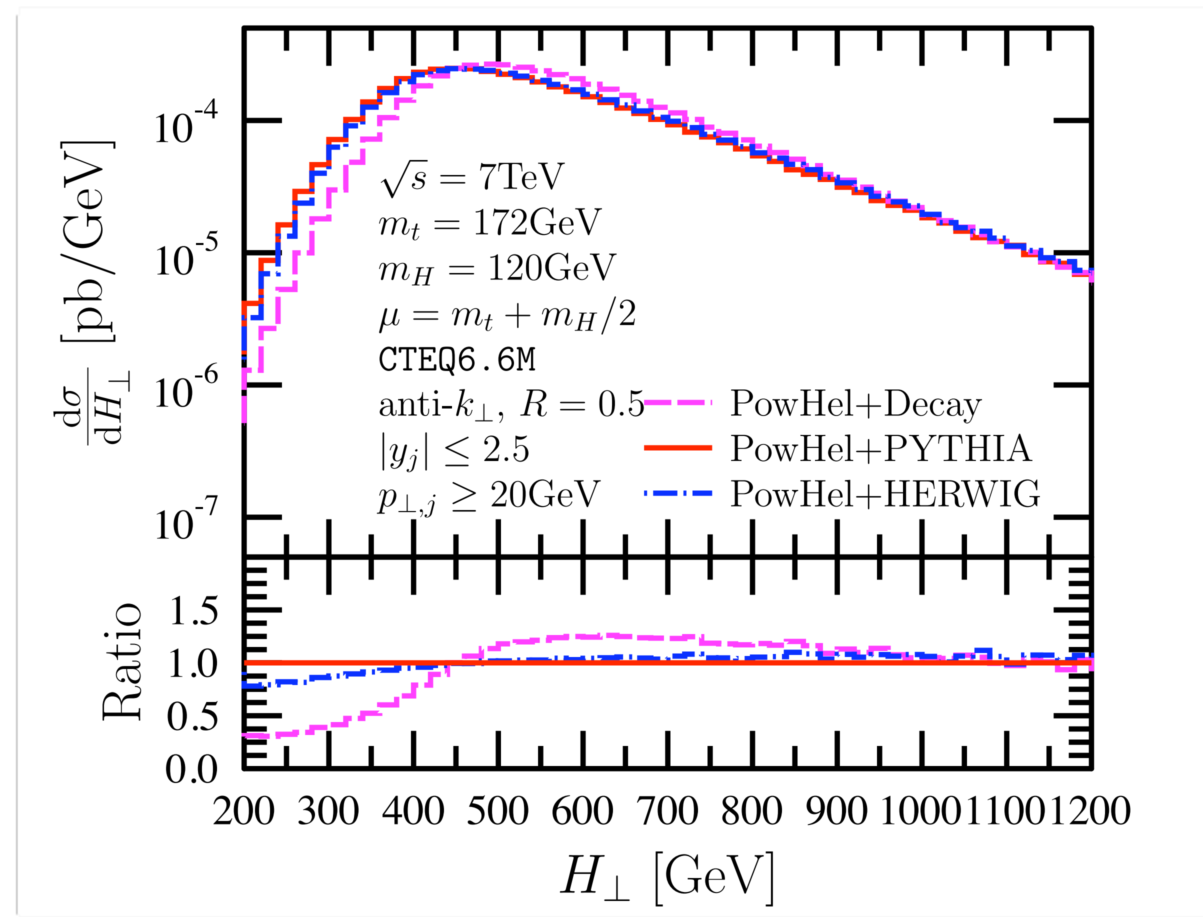
Decay vs. full SMC, jet cuts



Lepton and missing p_T distributions in pp → $t\bar{t}$ H at the LHC

Decay vs. full SMC, jet cuts





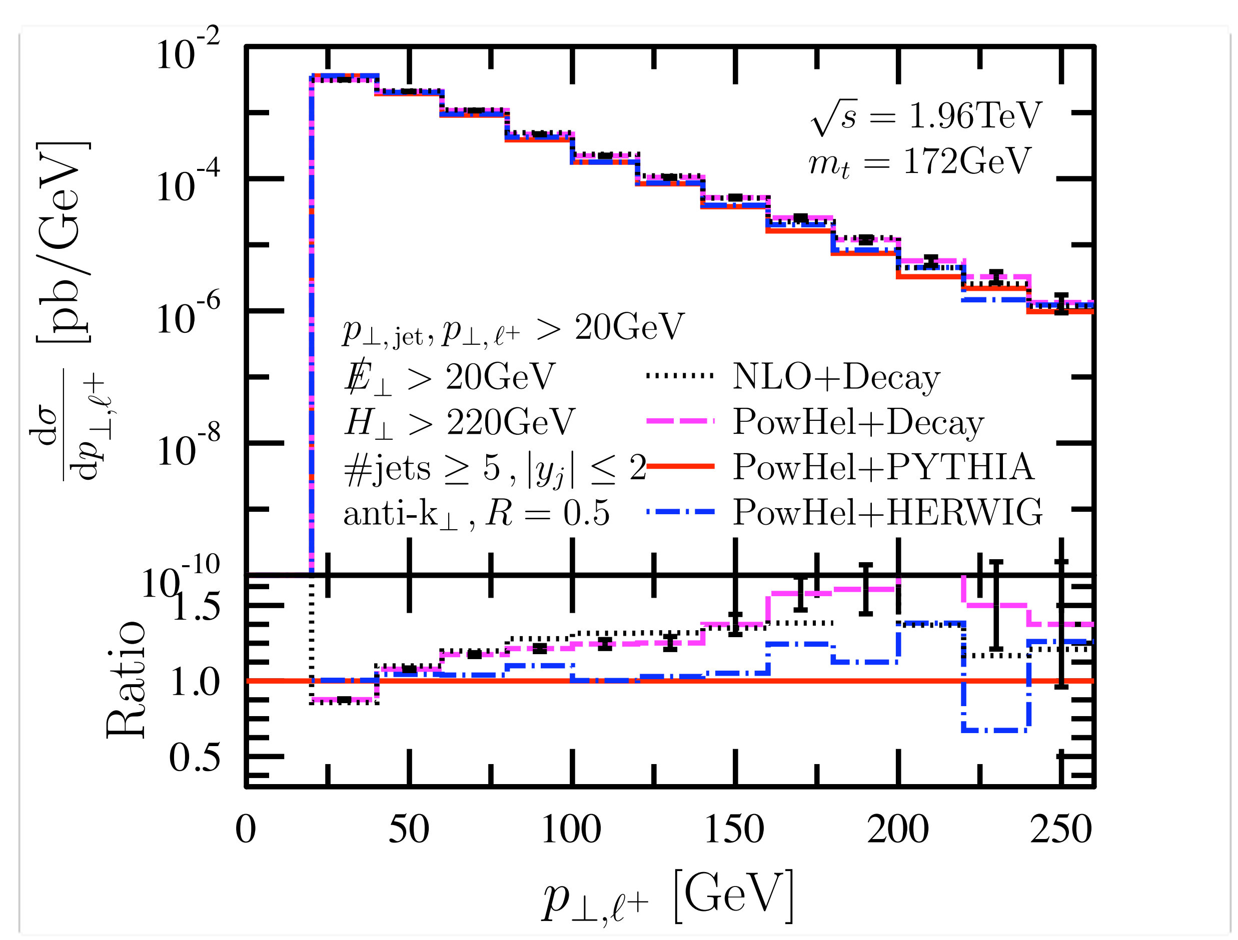
H_T distributions in $p\bar{p} \to t\bar{t}$ jet at the TeVatron and $pp \to t\bar{t}\,H$ at the LHC (scalar sum of all transverse momenta)

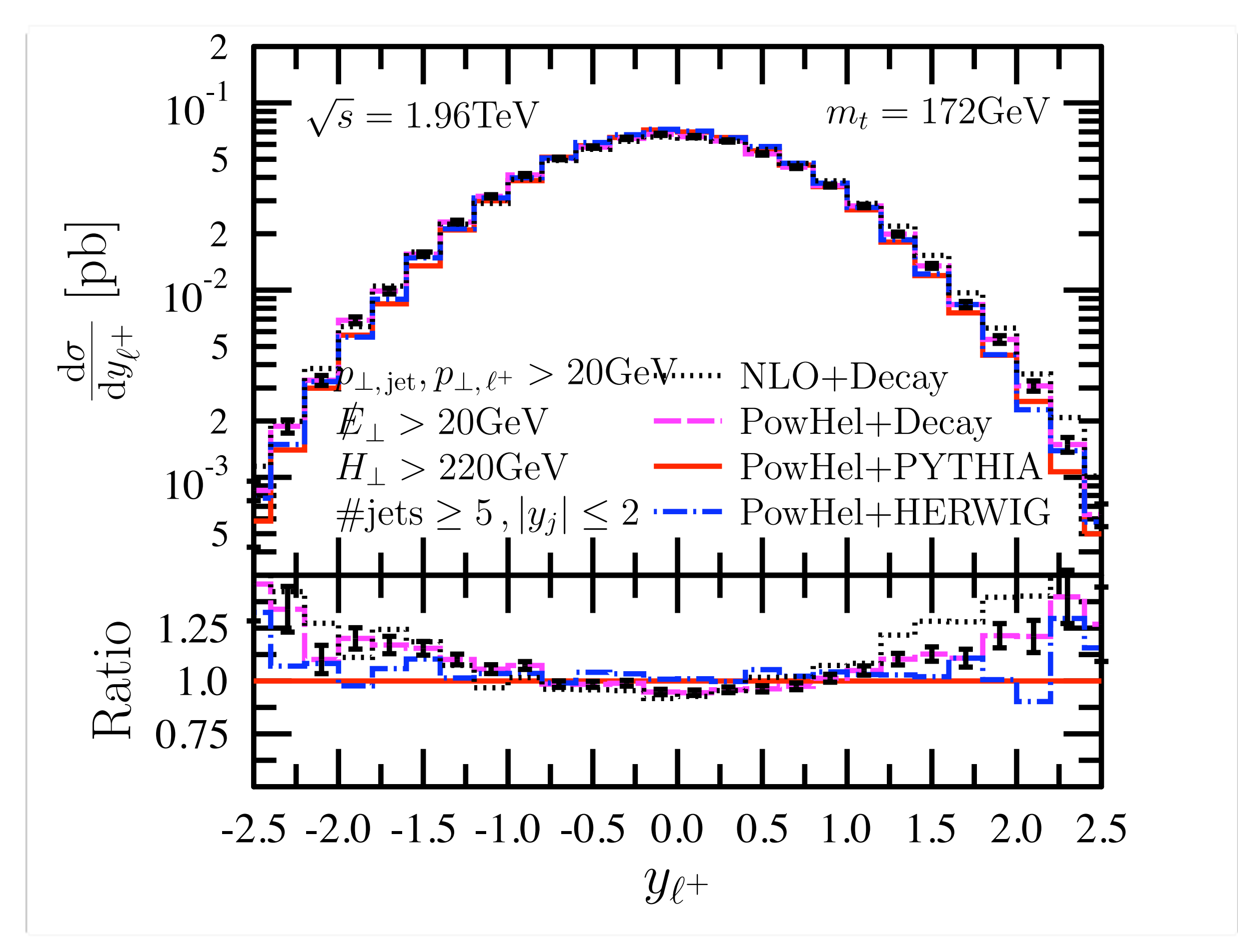
LHE vs. decay vs. full SMC

Message: decay, shower and hadronization can have significant effect, depending strongly on the process, observable, shower setup and selection

Predictions

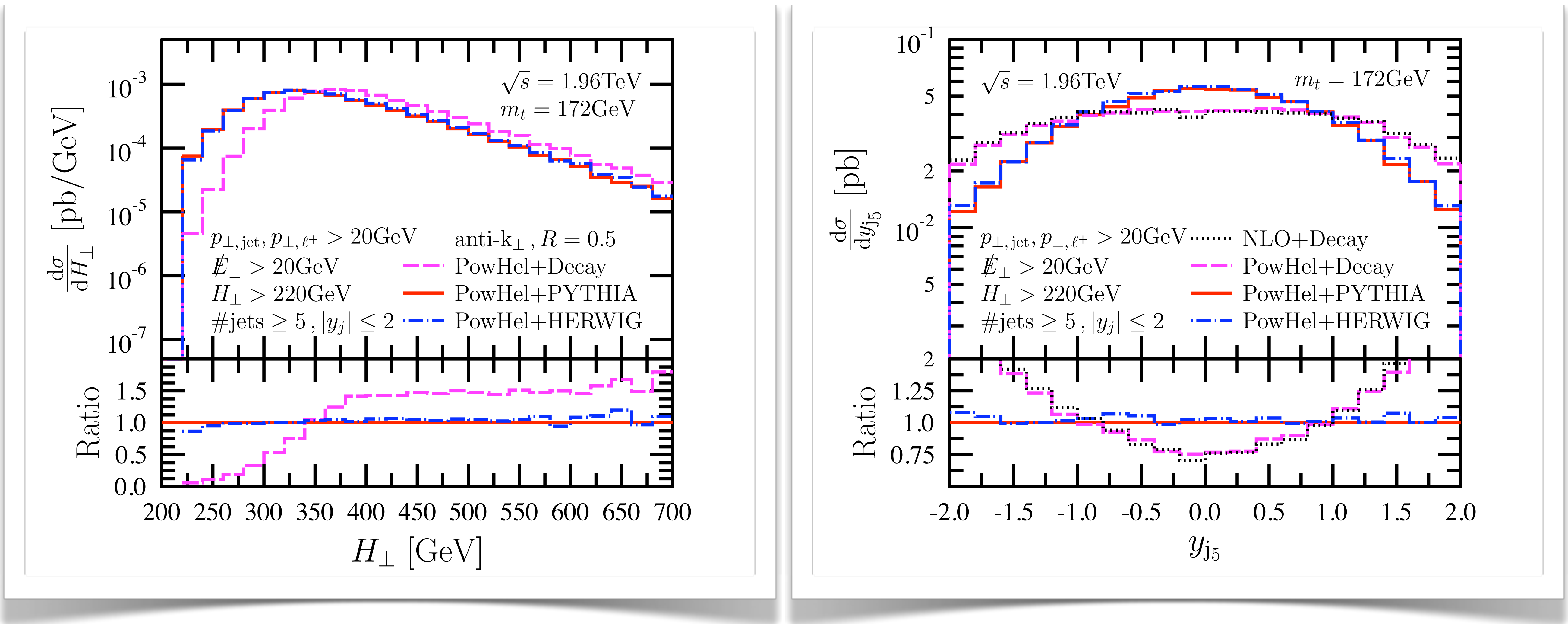
Decay vs. full SMC, physical cuts





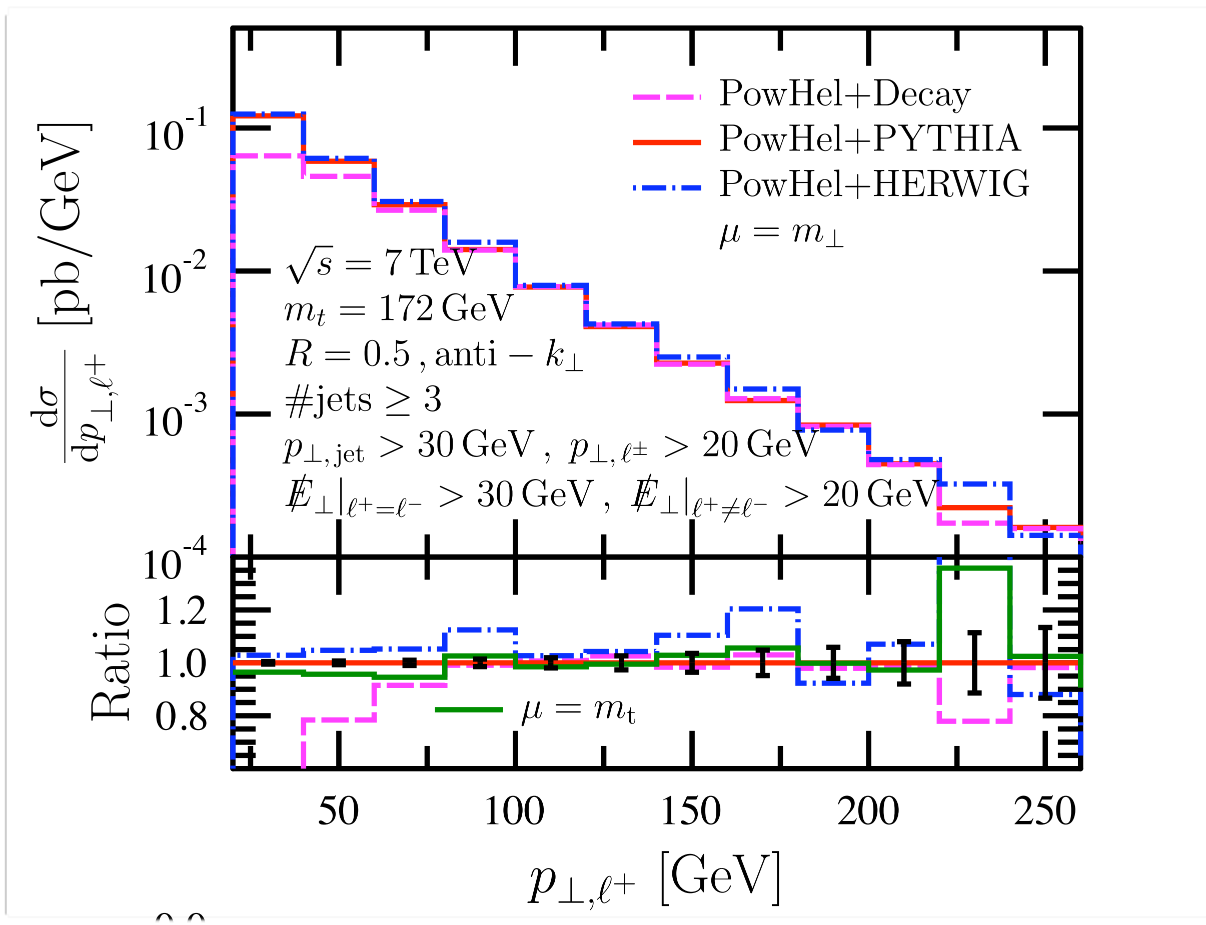
Lepton transverse momentum and rapidity distributions in $p\bar{p} \rightarrow t\bar{t}$ jet at the TeVatron (NLO+Decay: Melnikov and Schulze, arXiv:1004.3284)

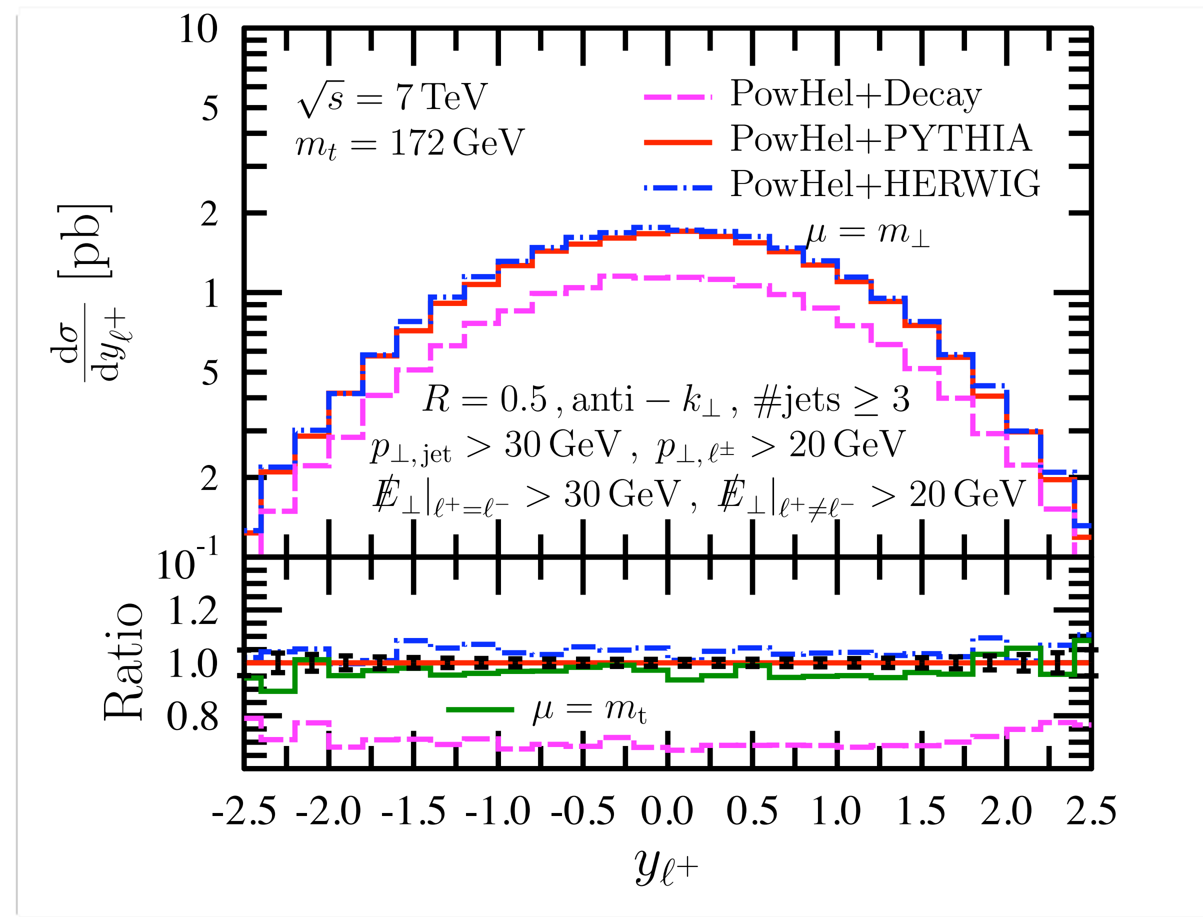
Decay vs. full SMC, physical cuts



Distributions of H_T and rapidity of the fifth jet in $p\bar{p} \to t\bar{t}$ jet at the TeVatron (NLO+Decay: Melnikov and Schulze, arXiv:1004.3284)

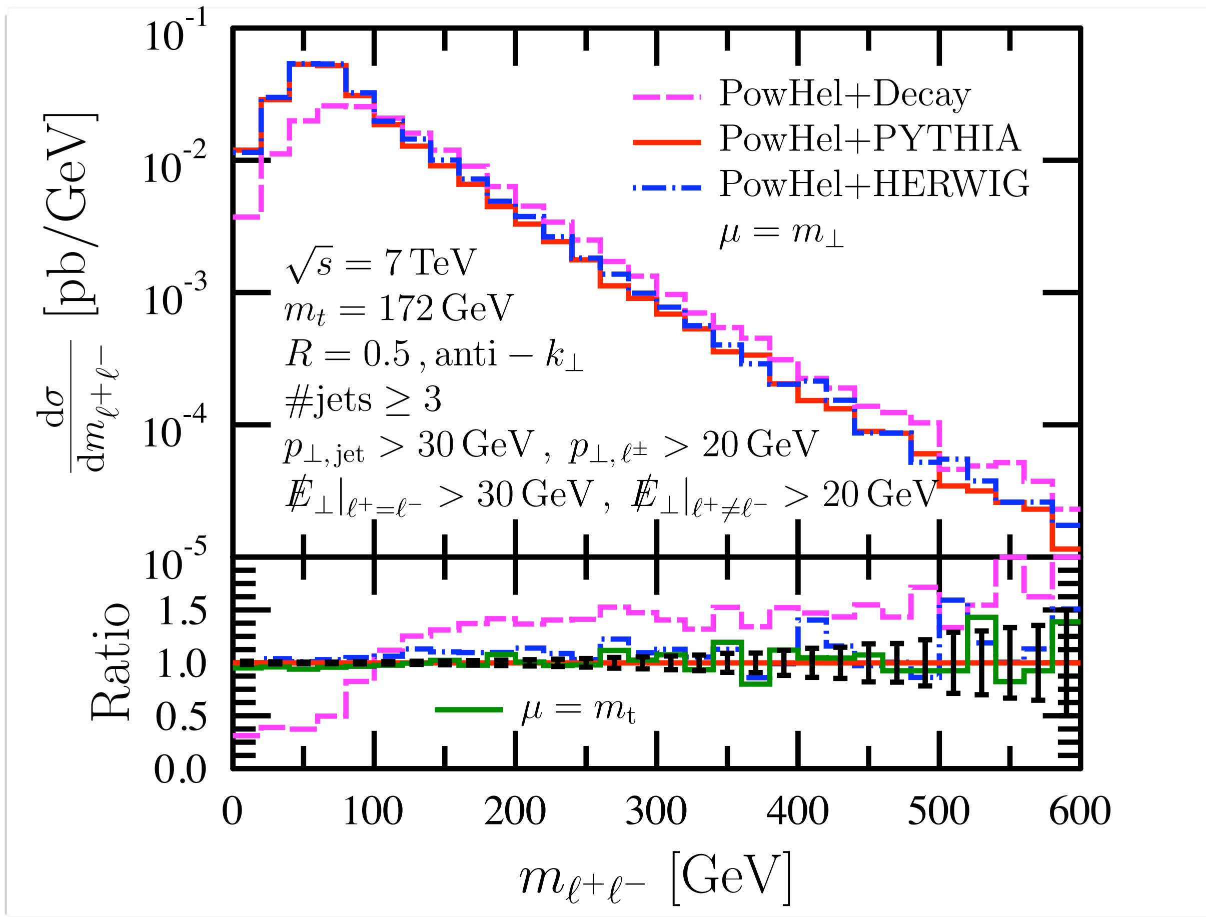
Full SMC, physical cuts

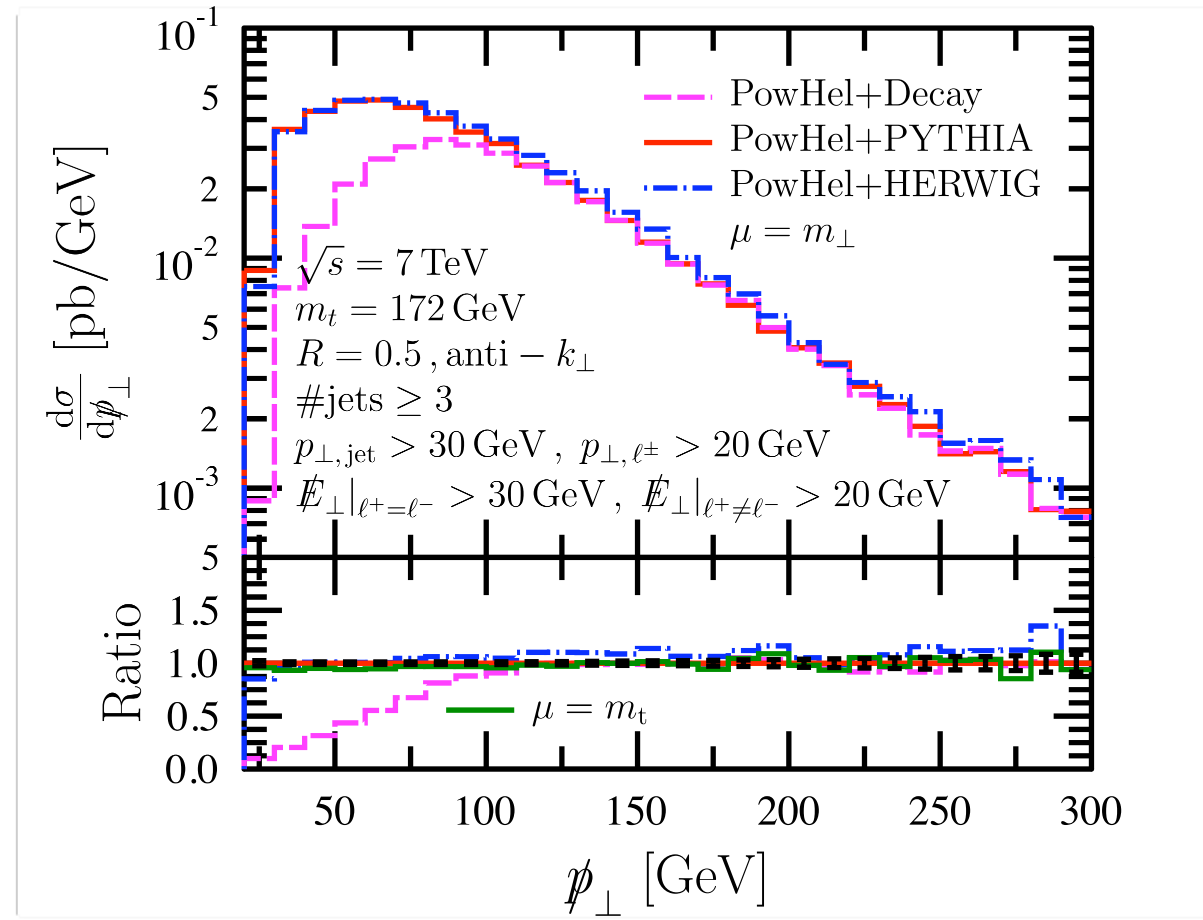




Distributions of lepton transverse momentum & rapidity in $pp \to t\bar{t}$ jet at the LHC

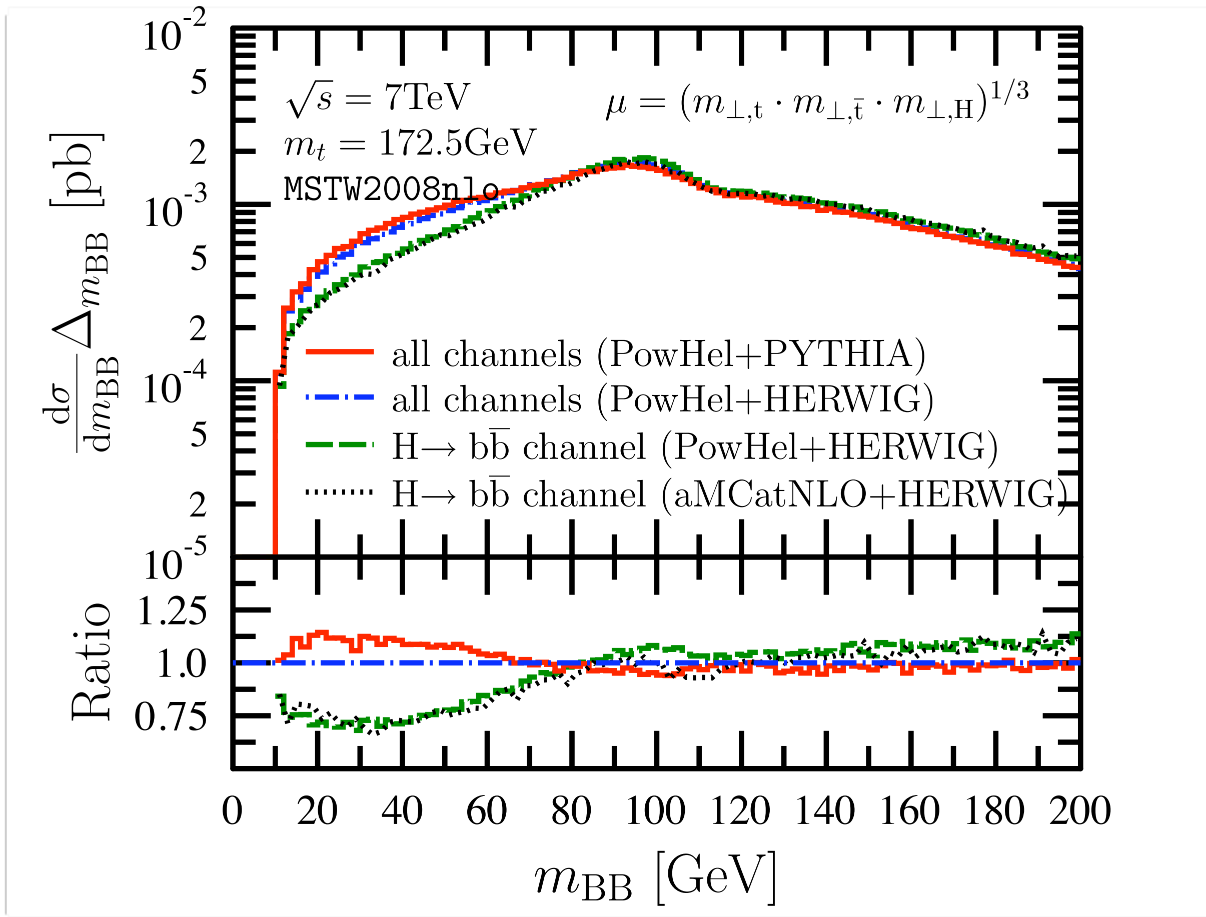
Full SMC, physical cuts

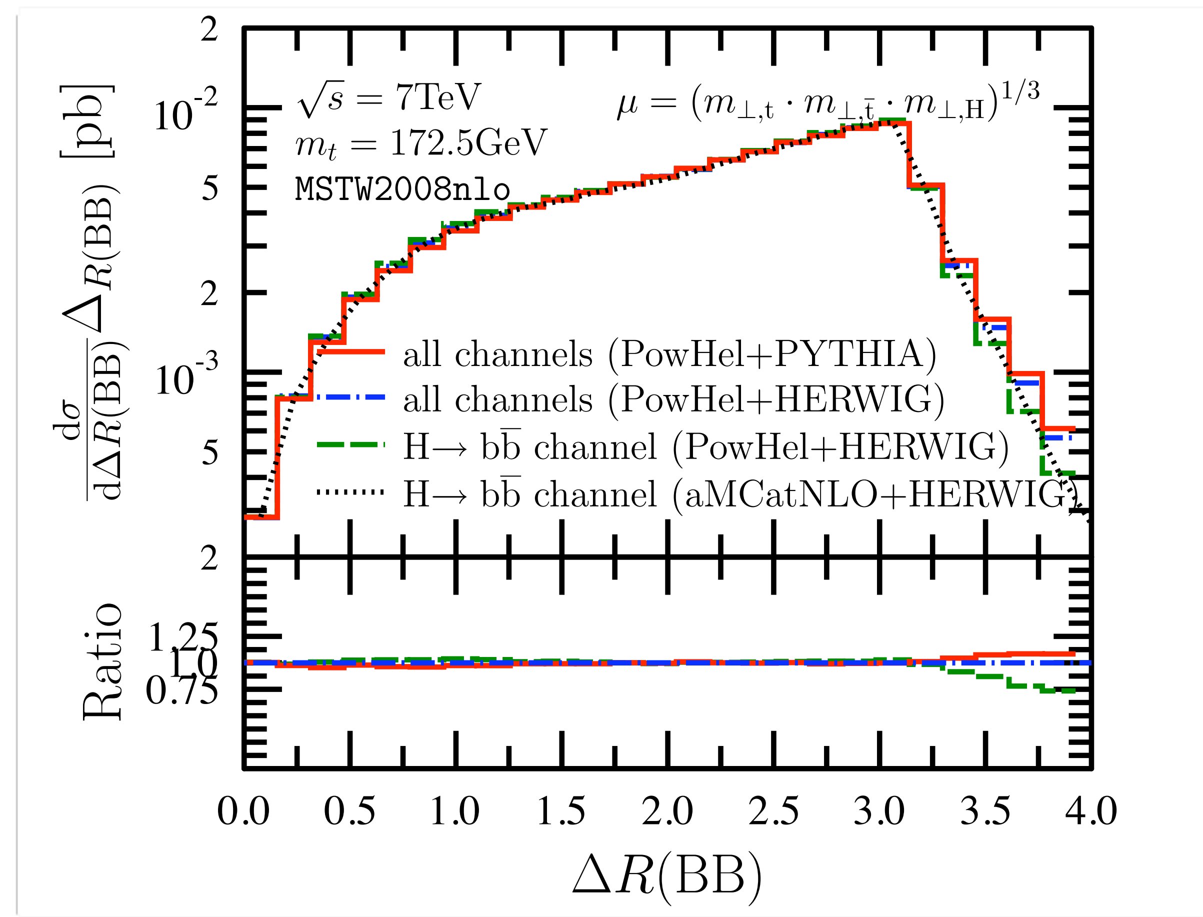




Distributions of l^+l^- invariant mass and missing transeverse momentum in pp $\rightarrow$ $t\bar{t}$ jet at the LHC

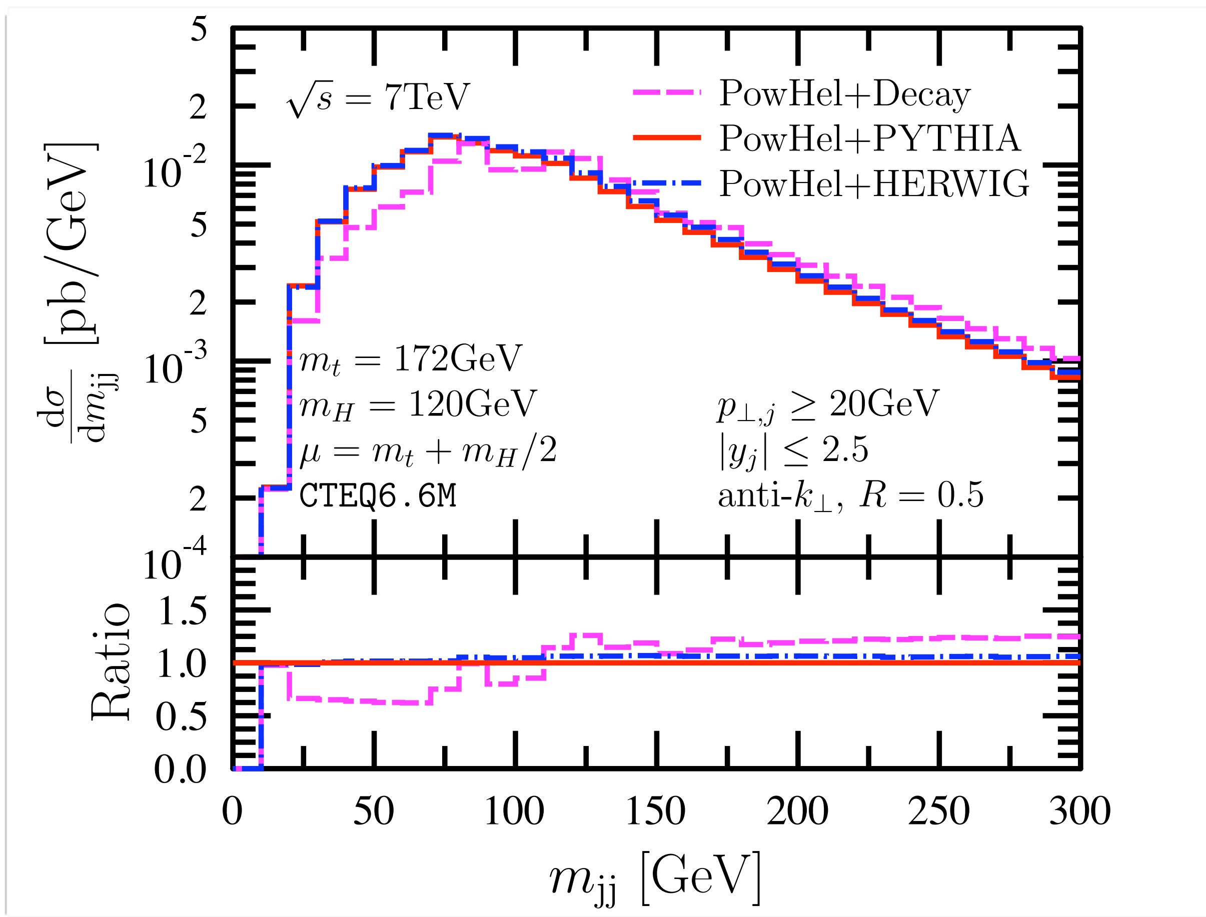
Decay vs. full SMC, physical cuts

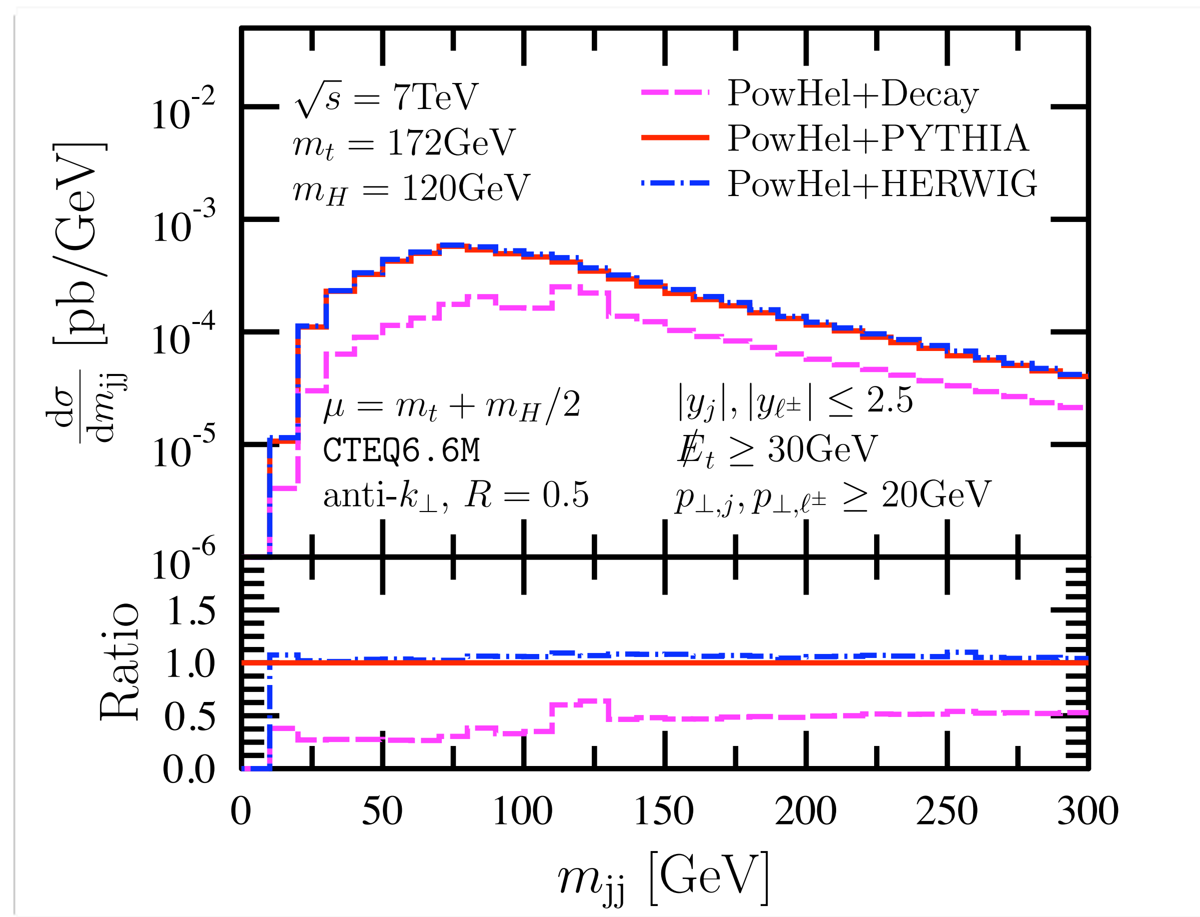




B-meson pair invariant mass and ΔR distributions in pp → $t\bar{t}$ H at the LHC (aMCatNLO: Hirschi et al, arXiv: 1104.5613)

Decay vs. full SMC, jet and physical cuts





jet-jet invariant mass distribution in $pp \to t\bar{t}H$ at the LHC

left: only jet cuts

right: physical cuts

Conclusions and outlook

Conclusions

- ✓ First applications of POWHEG-Box to pp→$t\bar{t}$X processes
- ✓ SME's obtained easily from HELAC-NLO
- ✓ NLO cross sections are reliable
- ✓ PowHel LHE are reliable
- ➡ Effects of decays and showers are often important, depending on process, observable, shower setup and selection
- ✓ LHE event files for pp →$t\bar{t}$, $t\bar{t}$H, $t\bar{t}$jet processes available
- ➡ Easy predictions for LHC with NLO+PS accuracy

Plans

➡ Study scale choices and dependences

➡ Generation of events on request

➡ Comparison to data (in progress)

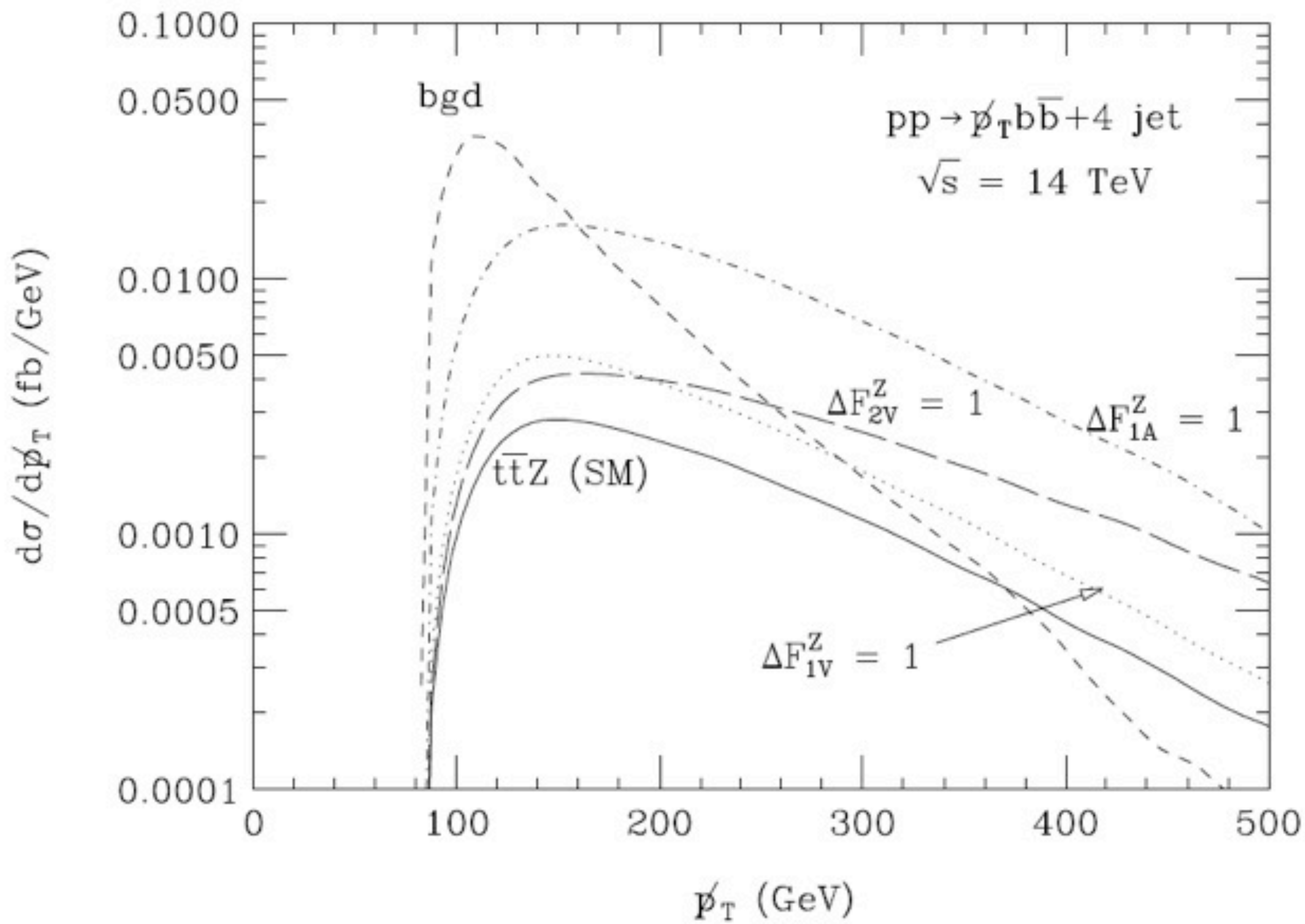
➡ Make codes public

➡ Extension to further processes...

The end

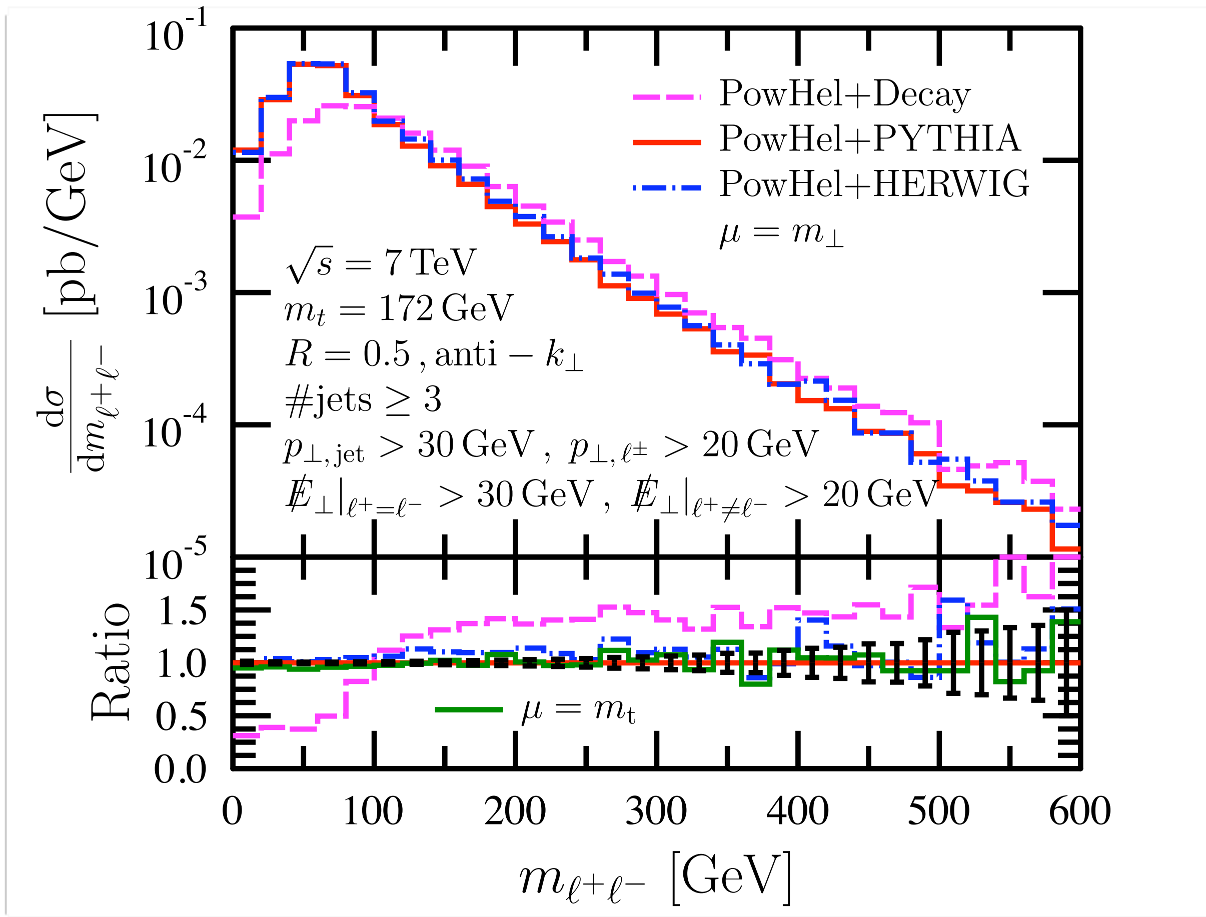
Top at the LHC

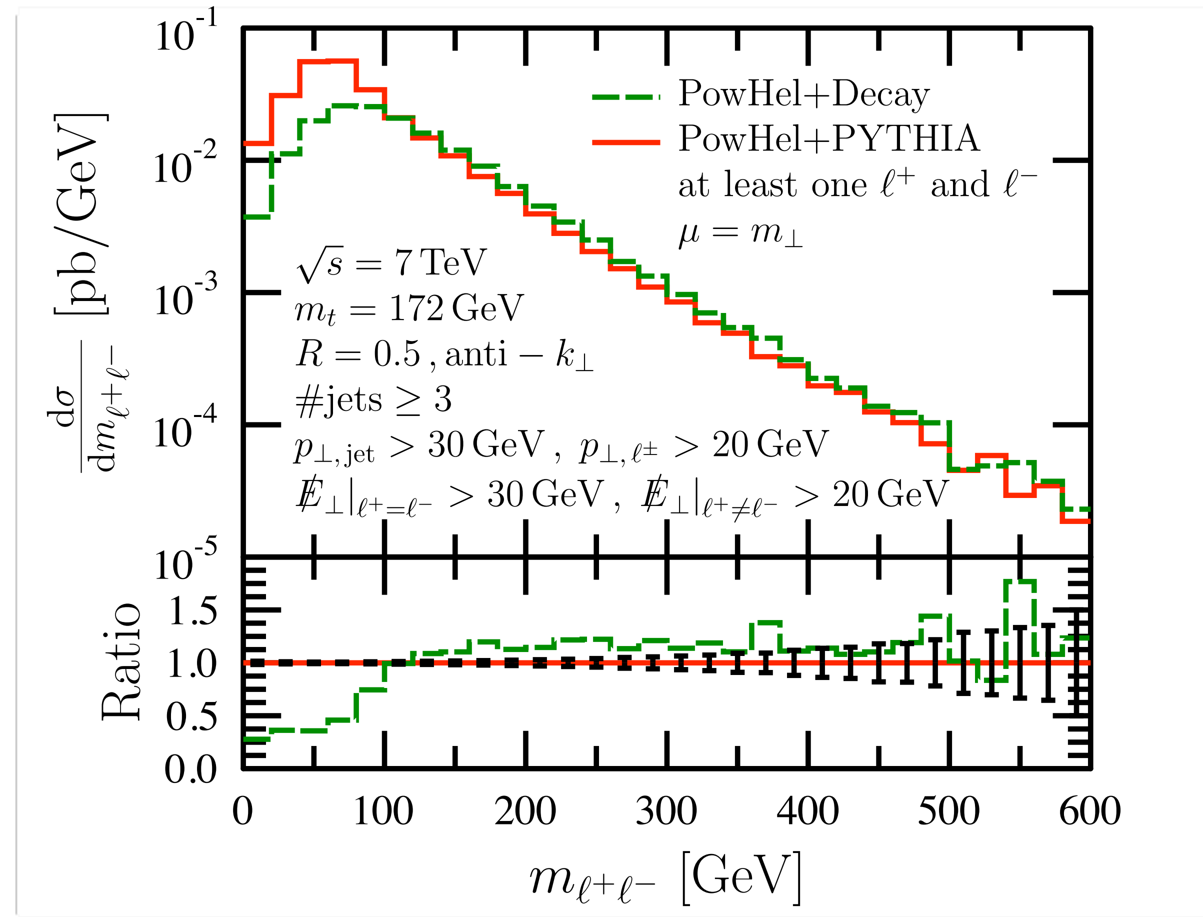
1. Present: precision measurement of σ_{tot}, m_t quantum numbers, decay rates
2. Future: measurement of couplings



Baur et al, hep-ph/0412021, 0512262

Full SMC, physical cuts





Distributions of l^+l^- invariant mass in pp $\rightarrow$ $t\bar{t}$ jet at the LHC

left: exactly one right: at least one

lepton and one antilepton