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RG-improved fully differential cross sections for $t\bar{t}$ at hadron colliders

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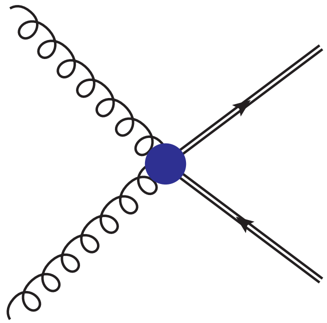
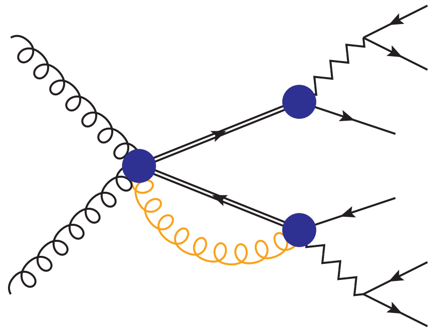
top pair production at hadron colliders

stable tops



- $\sigma_{\rm tot}$ known at NNLO [Bärnreuther, Czakon, Fiedler, Mitov]
- $\sigma_{\rm tot}$ known at NNLL in threshold expansion [Beneke et al.]
- NNLL known for (PIM and 1PI)
  $\dfrac{d\sigma}{dM_{t\bar{t}} d\cos\theta}$ and $\dfrac{d\sigma}{dp_T\, dy}$
  [Kidonakis et al; Ahrens et al.]

unstable tops



- closer to experiment
- NLO known (production and decay) for fully differential distributions [Bernreuther et al; Melnikov, Schulze; . . .]
- off shell effects known [Bevilacqua et al; Denner et al; Falgari et al; . . .]

outline

- NNLL renormalization-group improved calculations for $d\sigma/(dM_{t\bar{t}}\, d\cos\theta)$ (PIM) and $d\sigma/(dp_T\, dy)$ (1PI) available [Kidonakis et al., Ahrens et al. . . .]
- resummation can reproduce dominant (??) terms of fixed-order approach
- generalize resummed cross section to include decay of top quarks
- obtain approximate NNLO corrections to the production part of $q\bar{q}/gg \to t\bar{t} \to W^+ b\, W^- \bar{b}$ through expansion of resummed results
- implement these and match to fixed-order NLO to obtain 'improved' weight for parton-level Monte Carlo
- investigate 'universality' of method
  - can we compute arbitrary observables?
  - what happens if we say compute the p_T distribution with the "wrong" PIM kinematics?
- attempt to include most important features of fully differential NNLO corrections
- here this is done for $t\bar{t}$, but could think of other processes

approx NNLO

pair-invariant mass (PIM) kinematics

- $h_1(P_1)\, h_2(P_2) \to (t+\bar{t})(p_3+p_4) + X(p_X)$
- soft limit $z = (p_3+p_4)^2/\hat{s} \to 1$
- factorization of cross section

$$\frac{d\sigma}{dM_{t\bar{t}}\, d\cos\theta} \simeq \sum_{ij} \int \frac{dz}{z} \int \frac{dx}{x} f_{i/h_1}(x) f_{j/h_2}(\tau/(zx)) \left(\mathrm{Tr}\left[\mathbf{H_{ij}} \cdot \mathbf{S}^{\mathrm{PIM}}_{\mathbf{ij}}\right] + \mathcal{O}(1-z)\right)$$

- plus distribution $P_n(z) = \left[\frac{\ln^n(1-z)}{1-z}\right]_+$

one-particle inclusive (1PI) kinematics

- $h_1(P_1)\, h_2(P_2) \to t(p_3) + (\bar{t}+X)(p_4+p_X)$
- soft limit $s_4 = (p_4+p_X)^2 - m_t^2 \to 0$
- factorization of cross section

$$\frac{d\sigma}{dp_T\, dy} \simeq \sum_{ij} \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} f_{i/h_1}(x_1) f_{j/h_2}(x_2) \left(\mathrm{Tr}\left[\mathbf{H_{ij}} \cdot \mathbf{S}^{\mathrm{1PI}}_{\mathbf{ij}}\right] + \mathcal{O}(s_4)\right)$$

- plus distribution $P_n(s_4) = \left[\frac{1}{s_4} \ln^n\left(\frac{s_4}{m_t^2}\right)\right]_+$

parton-level Monte Carlo

- compute modified hard function: glue together one-loop helicity amplitudes for production [Badger, Sattler, Yundin] and decay (narrow-width approximation)
- soft functions and structure of RGE [Ferroglia et al; Ahrens et al.] not affected
- obtain approximate NLO (for consistency checks only) and NNLO corrections by expansion in α_s $\longrightarrow$ coefficients of plus distributions
- e.g. for PIM @ NNLL $\longrightarrow$ NNLO:

$$\mathrm{Tr}\left[\mathbf{H_{ij}}\cdot\mathbf{S_{ij}}\right] \sim D_3\, P_3(z) + D_2\, P_2(z) + D_1\, P_1(z) + D_0\, P_0(z) + C_0\, \delta(1-z) + R(z)$$

- restore dependence on final-state particles $\longrightarrow$ weight of events in Monte Carlo

$$D_i(M_{t\bar{t}}, \cos\theta) \longrightarrow D_i(\{p_i\})$$

- different resummation, PIM and 1PI (and different approximations in phase space)
- we include

$\mathrm{Tr}\left[\mathbf{H}^{(1)}_{\mathbf{ij}}\cdot\mathbf{S}^{(1)}_{\mathbf{ij}}\right]$	fully	get P_1, P_0 and δ terms
$\mathrm{Tr}\left[\mathbf{H}^{(0)}_{\mathbf{ij}}\cdot\mathbf{S}^{(2)}_{\mathbf{ij}}\right]$	partially	get P_3, P_2, P_1 and P_0 terms, δ terms missing
$\mathrm{Tr}\left[\mathbf{H}^{(2)}_{\mathbf{ij}}\cdot\mathbf{S}^{(0)}_{\mathbf{ij}}\right]$	not at all	δ terms missing

approx NNLO

successive improvements: approximate NLO (nLO) $\longrightarrow$ NLO $\longrightarrow$ approximate NNLO (nNLO)

only in production part, decay always fixed NLO

$$d\sigma^{\text{nLO}}_{\text{full}} = (\Gamma_t^{\text{NLO}})^{-2}\Big\{ \Big(d\sigma^{(0)}_{t\bar t} + d\tilde\sigma^{(1)}_{t\bar t}\Big) \otimes d\Gamma^{(0)}_{t\to l^+\nu_l b} \otimes d\Gamma^{(0)}_{\bar t\to l^-\bar\nu_l \bar b}$$
$$+ d\sigma^{(0)}_{t\bar t} \otimes d\Gamma^{(1)}_{t\to l^+\nu_l b} \otimes d\Gamma^{(0)}_{\bar t\to l^-\bar\nu_l \bar b}$$
$$+ d\sigma^{(0)}_{t\bar t} \otimes d\Gamma^{(0)}_{t\to l^+\nu_l b} \otimes d\Gamma^{(1)}_{\bar t\to l^-\bar\nu_l \bar b}\Big\}$$

$$d\sigma^{\text{NLO}}_{\text{full}} = (\Gamma_t^{\text{NLO}})^{-2}\Big\{ \Big(d\sigma^{(0)}_{t\bar t} + d\sigma^{(1)}_{t\bar t}\Big) \otimes d\Gamma^{(0)}_{t\to l^+\nu_l b} \otimes d\Gamma^{(0)}_{\bar t\to l^-\bar\nu_l \bar b}$$
$$+ \ldots \text{ decay corrections as for } d\sigma^{\text{nLO}}_{\text{full}} \Big\}$$

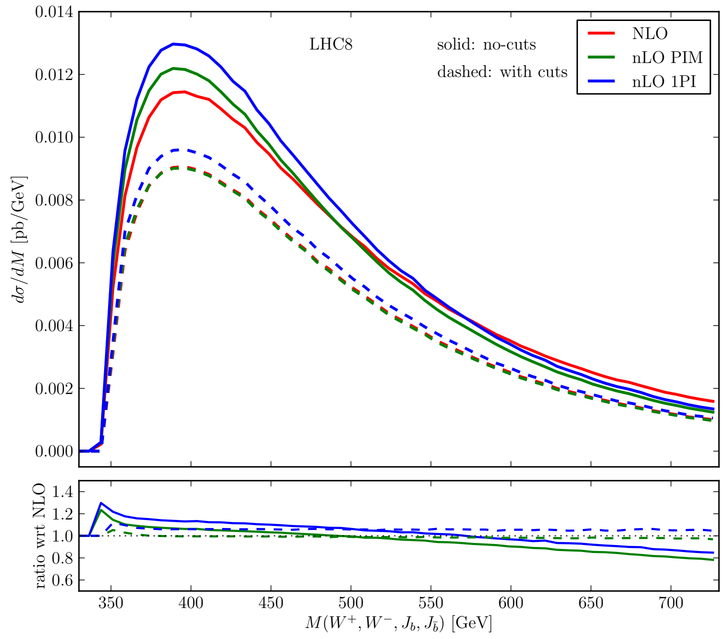
$$d\sigma^{\text{nNLO}}_{\text{full}} = (\Gamma_t^{\text{NLO}})^{-2}\Big\{ \Big(d\sigma^{(0)}_{t\bar t} + d\sigma^{(1)}_{t\bar t} + d\tilde\sigma^{(2)}_{t\bar t}\Big) \otimes d\Gamma^{(0)}_{t\to l^+\nu_l b} \otimes d\Gamma^{(0)}_{\bar t\to l^-\bar\nu_l \bar b}$$
$$+ \ldots \text{ decay corrections as for } d\sigma^{\text{nLO}}_{\text{full}} \Big\}$$

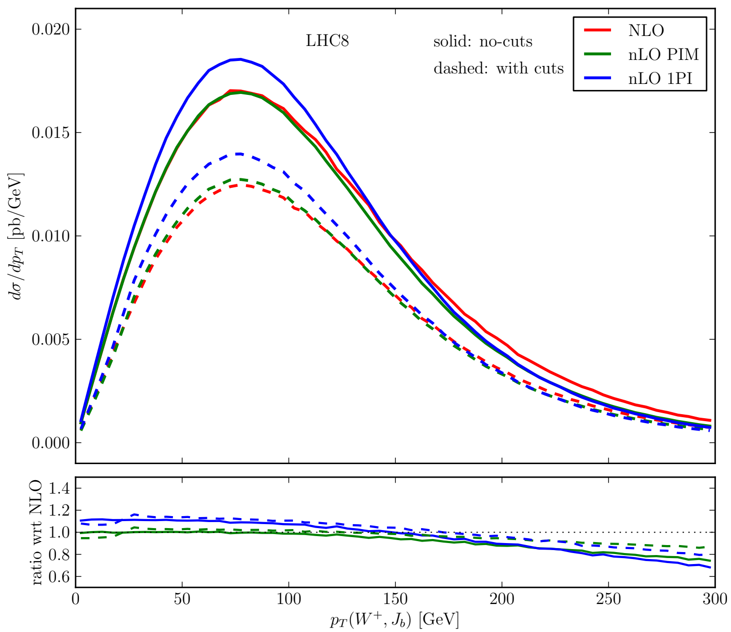
For validation of nLO and nNLO approximation 'switch off' decay corrections

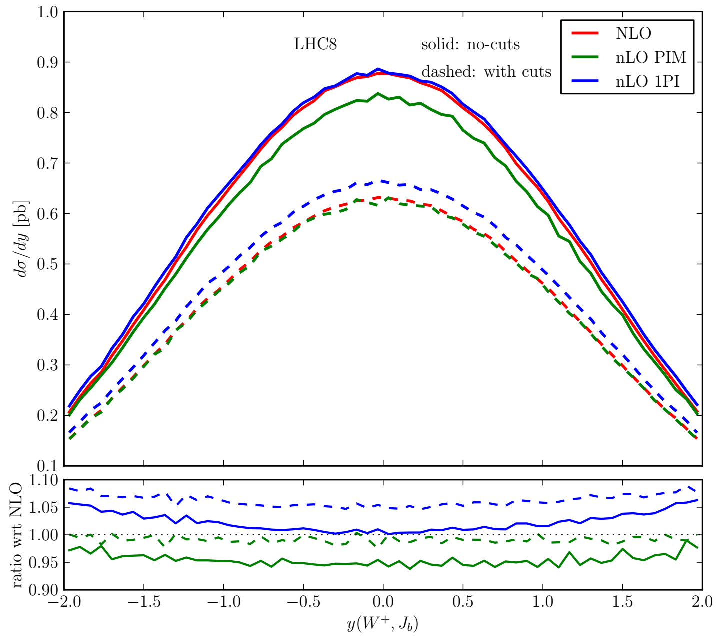
validation nLO vs NLO

check (in)dependence on kinematics

- compute $M_{t\bar{t}}$ (right), $p_T(t)$ (bottom left) and $y(t)$ (bottom right) for LHC 8
- compute NLO, nLO PIM, nLO 1PI
- compute with (dashed) and without (solid) cuts
- even "wrong" resummation gives reasonable results
- PIM seems to do better than 1PI !?

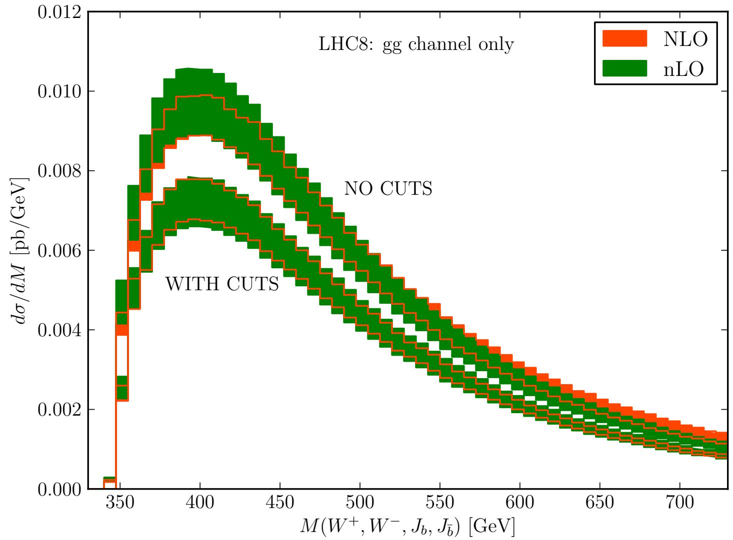


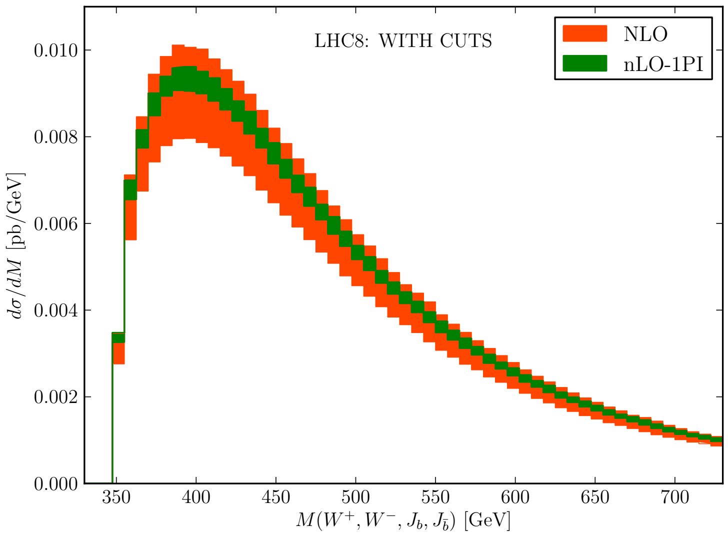


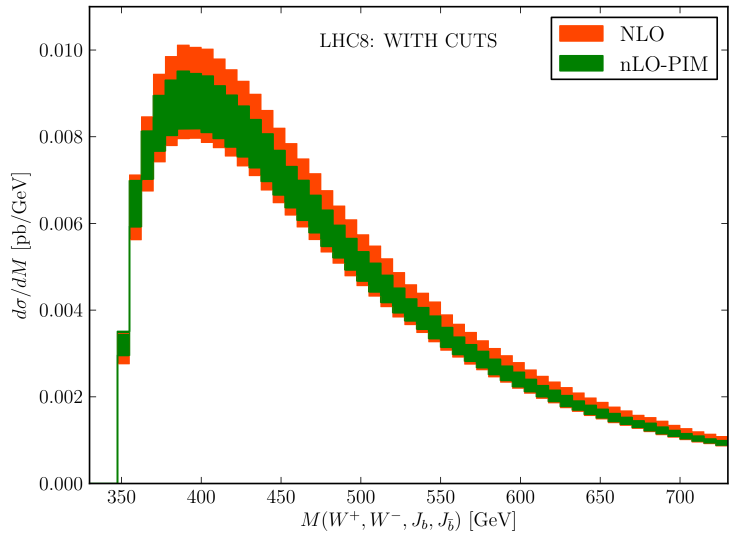


uncertainty bands (for $M_{t\bar{t}}$ at LHC 8)

- take envelope of scale dependence $m_t/2 \le \mu \le 2\, m_t$ and {PIM, 1PI}
- overestimates uncertainty for single channel (gg right) $\longrightarrow$ to compensate 'missing' other channels (qg)
- 1PI and PIM separately (bottom) give consistent results (scale dependence of 1PI alone "too small")



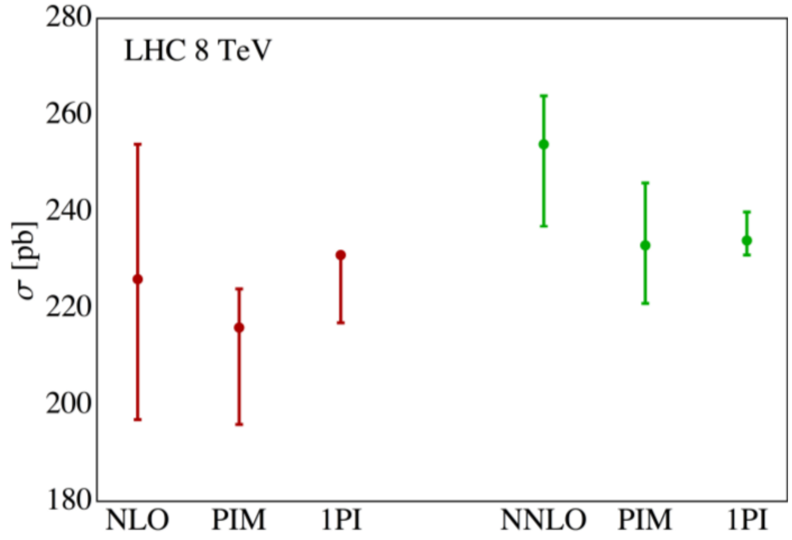


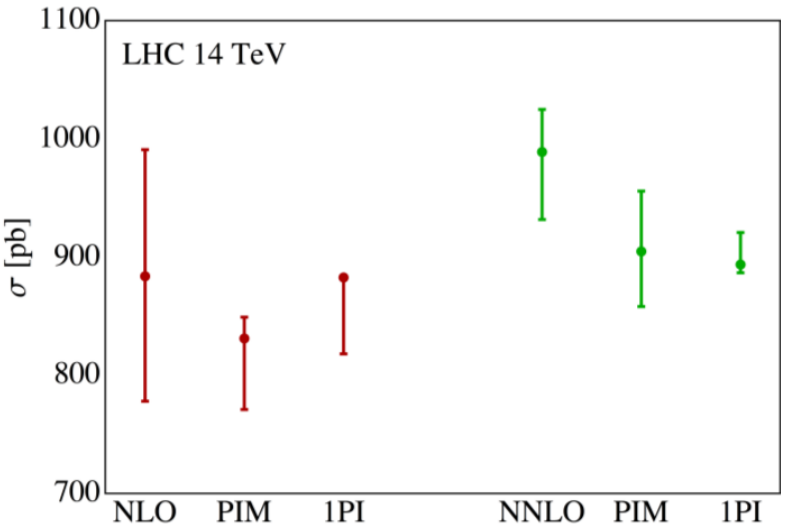


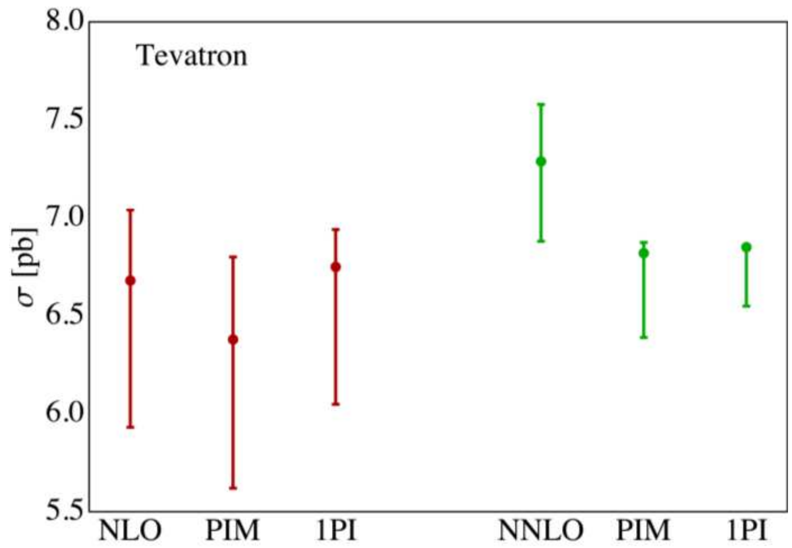
validation nNLO vs NNLO

check quality of nNLO approximation

- compare total cross section nNLO (PIM and 1PI) to NNLO [Top++]
- scale variation $m_t/2 \leq \mu \leq 2\, m_t$
- for LHC 8 and LHC 14 nLO and nNLO give reasonable approximations (a bit low)
- for Tevatron nNLO has only marginal overlap with NNLO

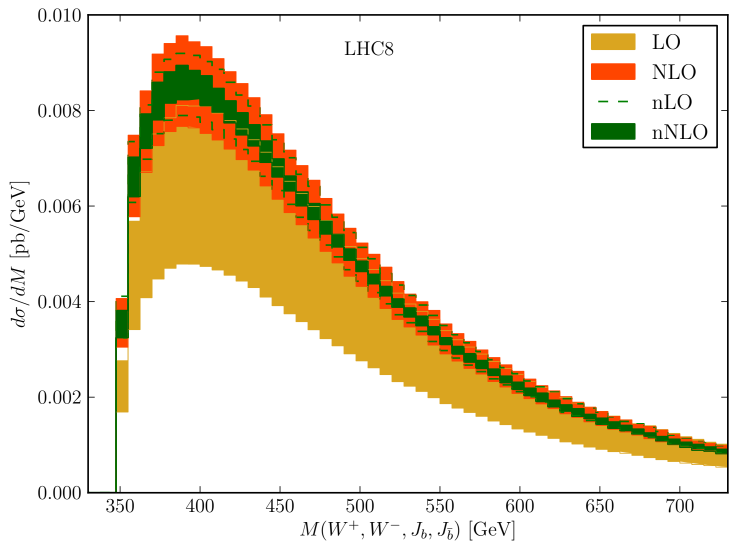






distributions

- cluster final state partons into jets
- reconstruct top $t \doteq J_b + \ell + \nu$
- MSTW2008 NLO/NNLO pdf
- cuts: $p_T(J_{b/\bar{b}}) > 15$ GeV
  $E_T(\ell^\pm) > 15$ GeV
  $\not{E}_T > 20$ GeV
  $M(W^+, W^-, J_b, J_{\bar{b}}) > 350$ GeV

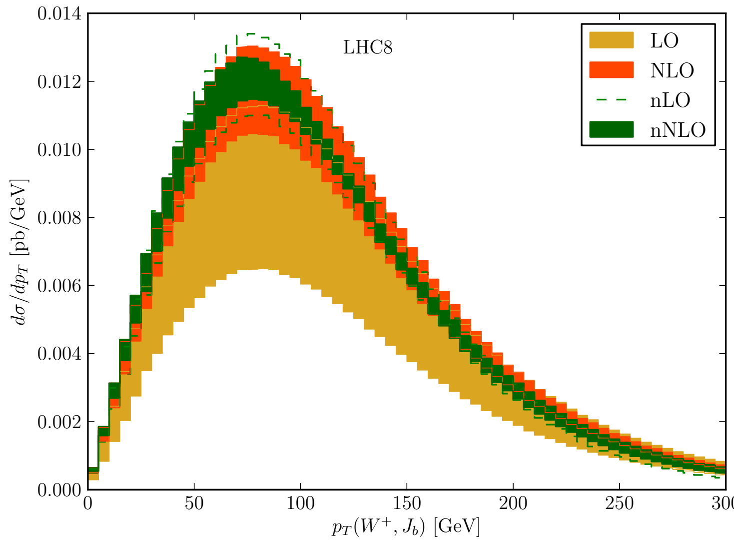


consider $M_{tt} \doteq M(W^+, W^-, J_b, J_{\bar{b}})$

consider $p_T(t) \doteq p_T(J_b, W^+)$

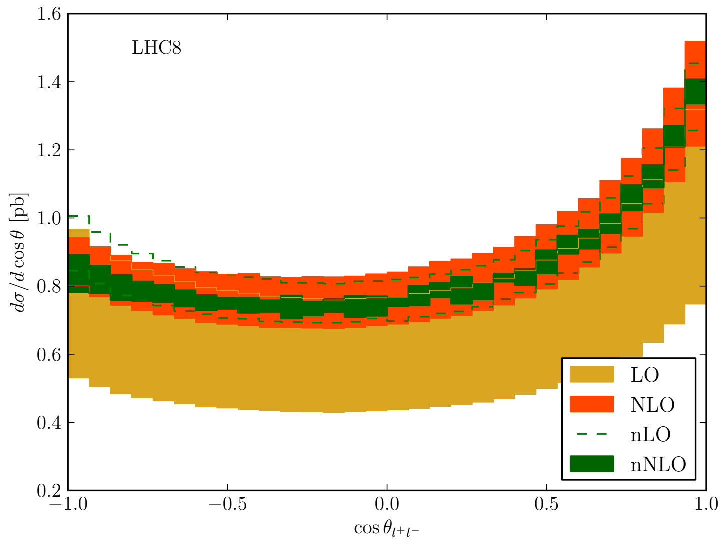
stable perturbative behaviour

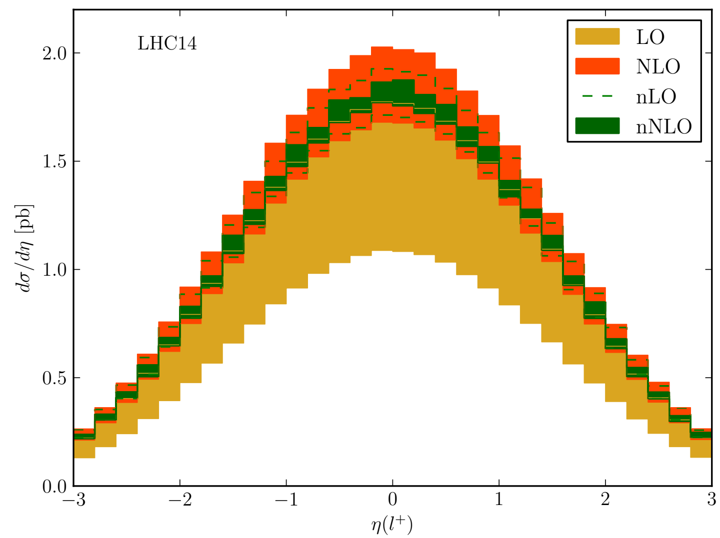
theory error band: envelope of scale variation and {PIM, 1PI} implementations

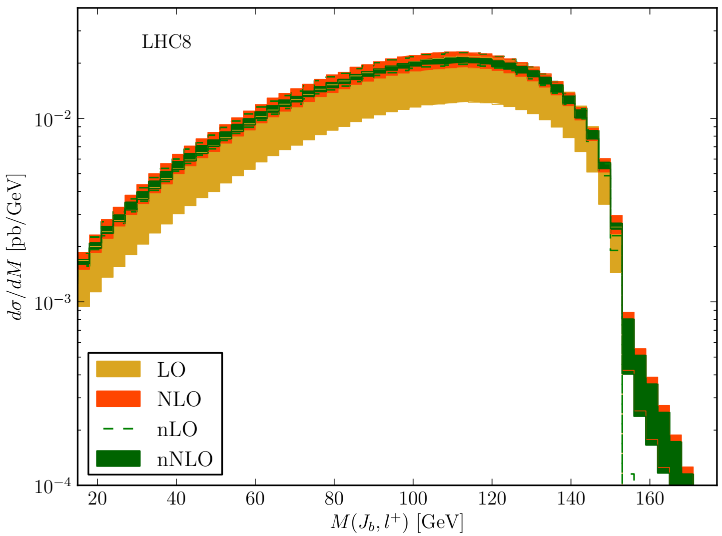


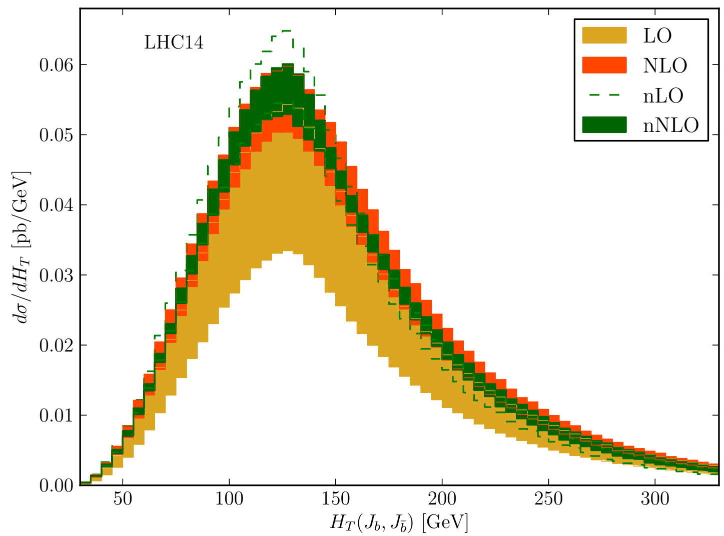
distributions

arbitrary distributions for LHC 8 and LHC 14









summary

- we have generalized PIM and 1PI NNLL resummation to include top (and W) decay in narrow width approximation
- we obtain a parton level Monte Carlo with approximate NNLO corrections for production of $t\bar{t}$ and decay included at NLO
- generic features of resummation remarkably robust under change PIM $\leftrightarrow$ 1PI
  $\Rightarrow$ empirical evidence that results can be used for other observables than M_{tt}, $p_T(t)$ and $y(t)$ and allow for cuts to be applied
- theoretical error must include PIM $\leftrightarrow$ 1PI variation (as well as scale variation)
- further improvements
  - note: nLO approximation to NLO is better than nNLO to NNLO (δ terms missing, would need 2-loop soft function and 2-loop virtual correction with spin information)
  - mismatch between production and decay
    $\Rightarrow$ include decay at NNLO [Gao, Li, Zhu; Brucherseifer, Caola, Melnikov]
  - study impact of relaxing approximations ($z = 1$, $s_4 = 0$) made in phase space integration
  - other processes