Uncertainties in predicting ttbb by PowHel

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Introduction

modeling tt+HF jets at NLO+PS

possible theoretical predictions:

- tt at NLO + b(b)-jet by SMC (POWHEG or `MadGraph5_aMC@NLO`)
- tt + jet (can be b-jet) at NLO + b(b) by SMC (`PowHel`)
- tt + 2jets (one can be b-jet) at NLO + b(b) by SMC (`SHERPA+OpenLoops`)
- tt + bb at NLO + SMC: in this talk

Uncertainties in NLO predictions

- missing higher orders:
  QCD: largest, but NNLO is not feasible during run 2
  ⇒ estimated by variation of renormalization and factorization scales, $\mu_R = \mu_F = \mu_0$ in $[\mu_0/2, 2\,\mu_0]$
  EW: NLO not known, but expected to be small except perhaps for large transverse momenta of t-quarks or jets
- PDF: take envelope of predictions made using various PDF sets
- neglected b-quark mass: <3% at LO [1001.4006]
- treatment of $t \to b\,\ell\,\nu_\ell$ decay if included, NLO for $pp \to b\,\ell\,\nu_\ell + b\,\ell\,\nu_\ell + bb$ is not available at present

Matching NLO to PS

- two methods of matching:
  MC@NLO: SHERPA+OpenLoops (phenomenology in arXiv:1309.5912 and next talk)
  MadGraph5_aMC@NLO (phenomenology in third talk)
  POWHEG: PowHel (phenomenology in J. Phys. G 41 (2014) 075005 [arXiv:1303.6291], arXiv:1307.1347 and 1408.0266, also in this talk)

Uncertainties in PowHel

- matching uncertainty
- choice of SMC and its tune
- neglected truncated showers: likely negligible, but not checked
- approximate treatment of $t \to b\, \ell\, \nu_\ell$ decay (our option: DECAYER)

here we study

- scale uncertainty at NLO
- matching uncertainty
- SMC uncertainty
- PDF and scale uncertainties in NLO+PS

focusing on hardest b-jets

scale uncertainties at NLO

Choice of scales

- QCD corrections are
  - large with scales $\mu_0 = m_t$ or $m_t + m_{b\bar{b}}/2$ (about 80%)
  - moderate with dynamical scale $\mu_0 = (m_t^2\, p_{T,b}\, p_{T,\bar{b}})^{1/4}$ (about 25%) (proposed in arXiv:1001.4006), implying better convergence by emulating higher order effects through CKKW-type scale choice

Choice of scales

- QCD corrections are
  - large with scales $\mu_{fix} = m_t$ or $m_t + m_{b\bar{b}}/2$ (about 70%)
  - moderate with dynamical scale $\mu_{dyn} = (m_t^2 \, p_{T,b} p_{T,\bar{b}})^{1/4}$ (about 25%) (proposed in arXiv:1001.4006), implying better convergence by emulating higher order effects through CKKW-type scale choice,

but

  - we want to simulate higher order effects through the PS: μ_{dyn} is too small near threshold where cross section is largest, even for a b with p_T = 100 GeV and another b with p_T = 20 GeV μ_{dyn} = 90 GeV $\ll m_t$ resulting in an artificially large xsection at LO

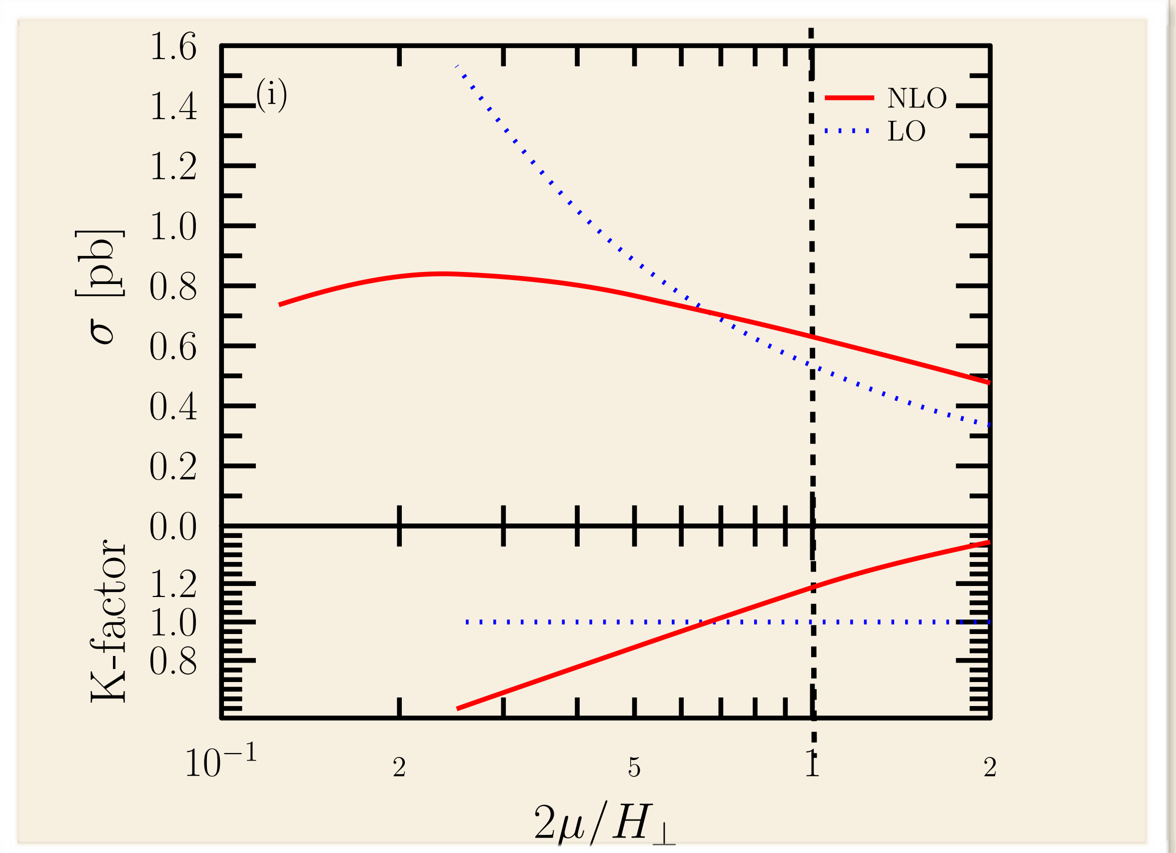
Choice of scales

We use the dynamical scale $\mu_{dyn} = H_T/2$, where H_T is the scalar sum of transverse masses of final-state particles that is a good scale also near threshold

With this scale

✓ the K factor is even smaller, implying good convergence

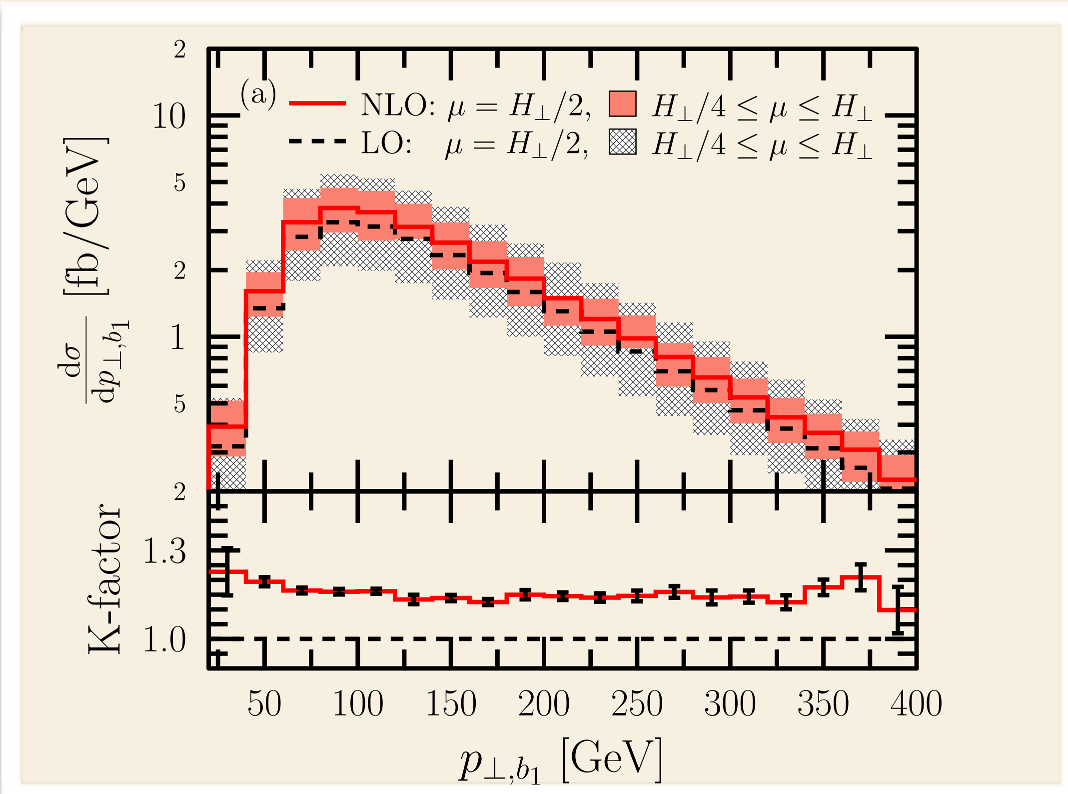
✓ the cross sections are smaller (w/ cuts of 1001.4006):

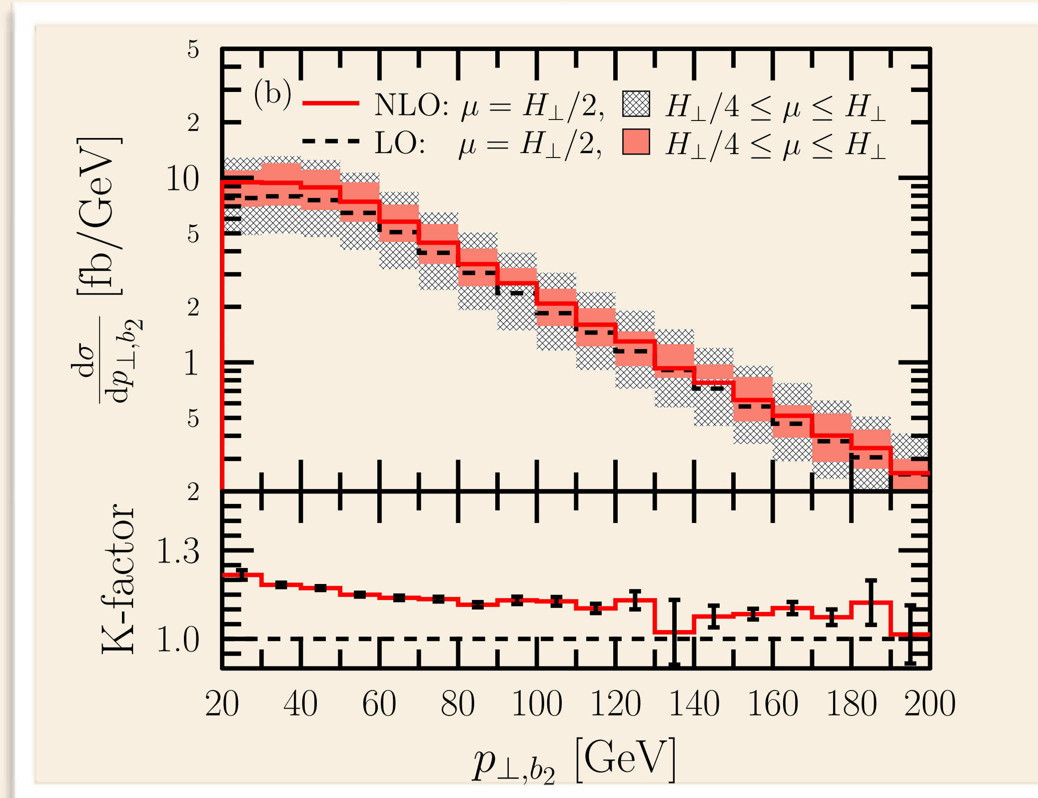


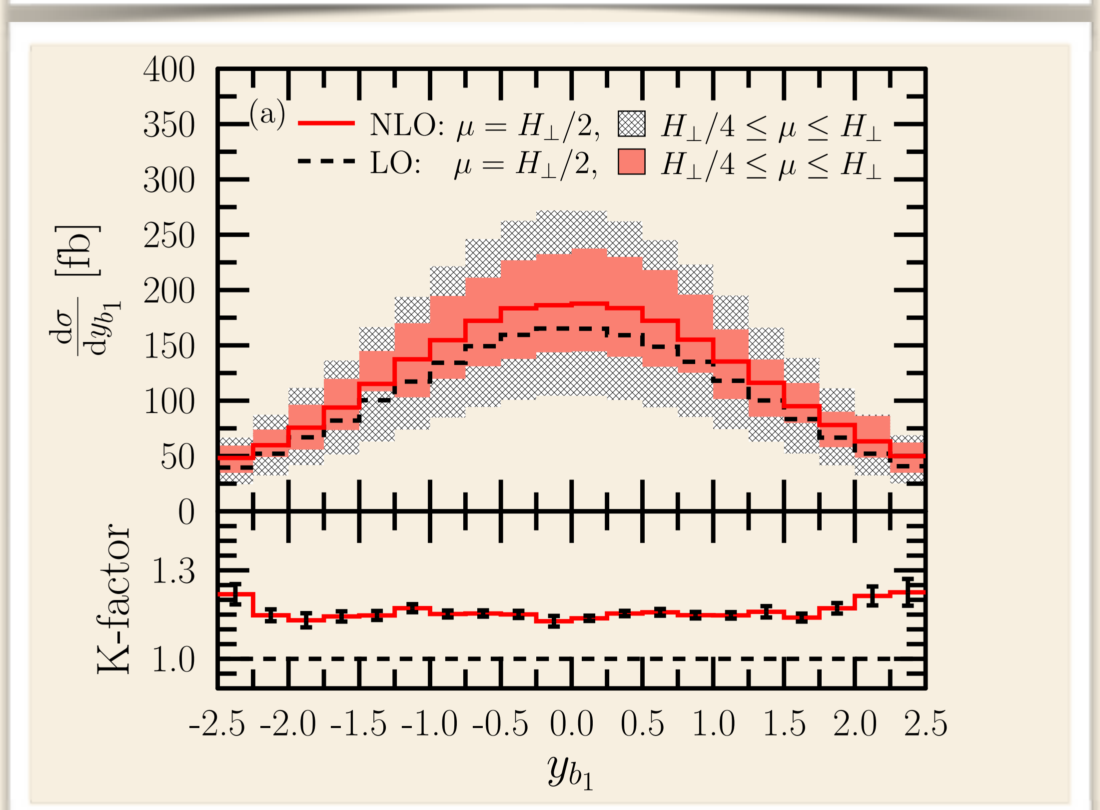
σ_{LO} = 534 fb, σ_{NLO} = 630 fb, K = 1.18

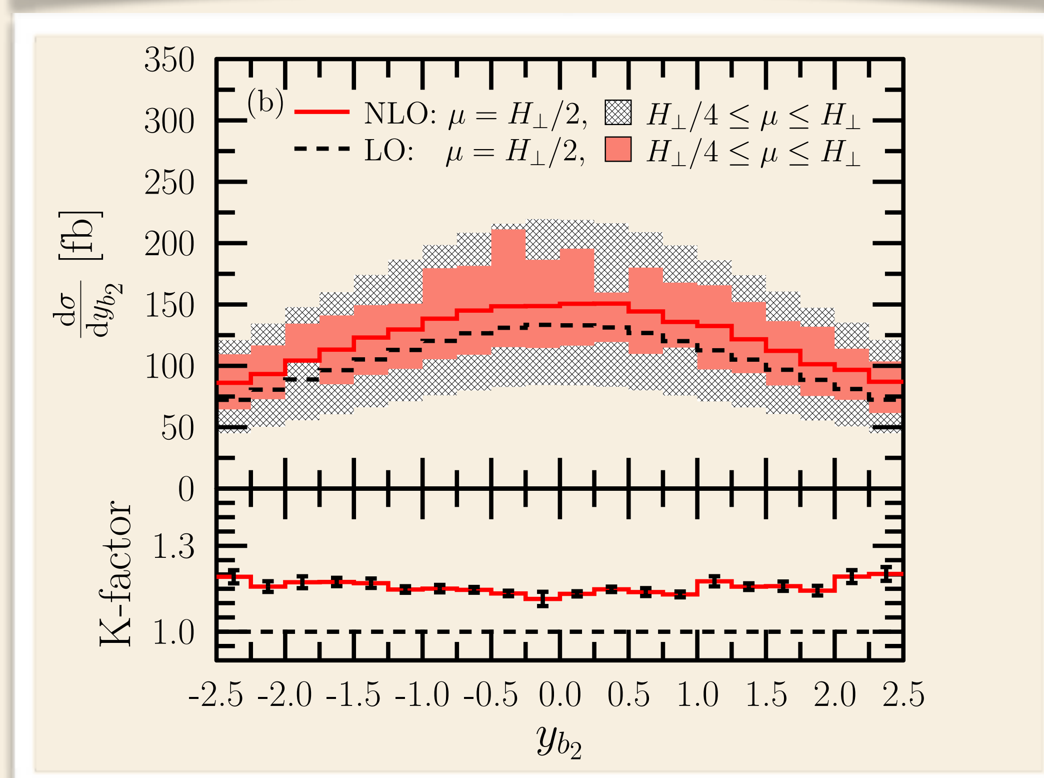
scale dependence: $^{+32\%}_{-22\%}$, largest if $\mu_R = \mu_F = \mu_{dyn}$

Small changes in shapes of distributions

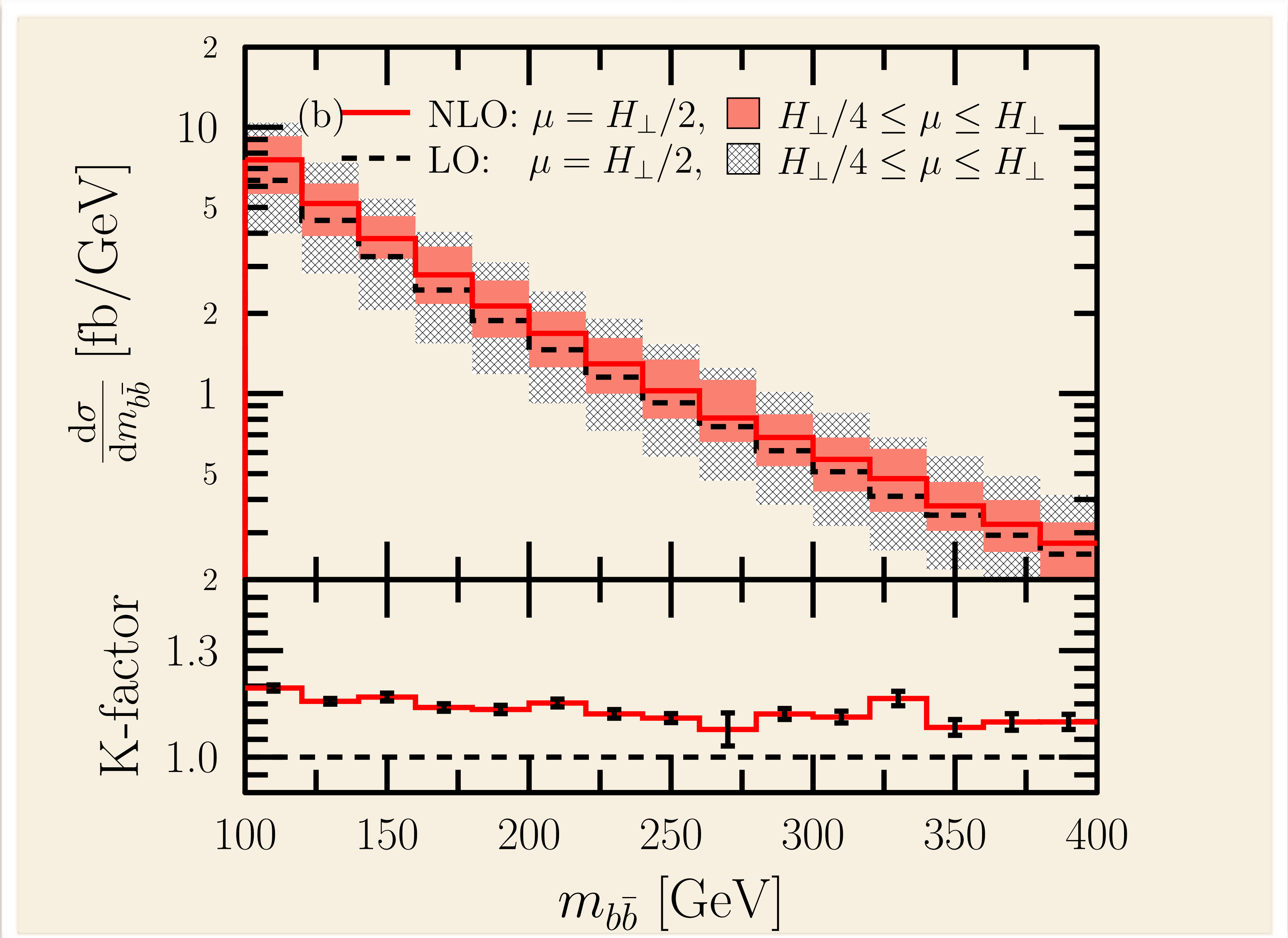








Small changes in shapes of distributions



matching uncertainty

Formal accuracy of the POWHEG MC

$$\langle O \rangle = \int d\Phi_B \widetilde{B} \left[\Delta(p_{\perp,\min}) O(\Phi_B) + \int d\Phi_{\rm rad} \Delta(p_\perp) \frac{R}{B} O(\Phi_R) \right] =$$

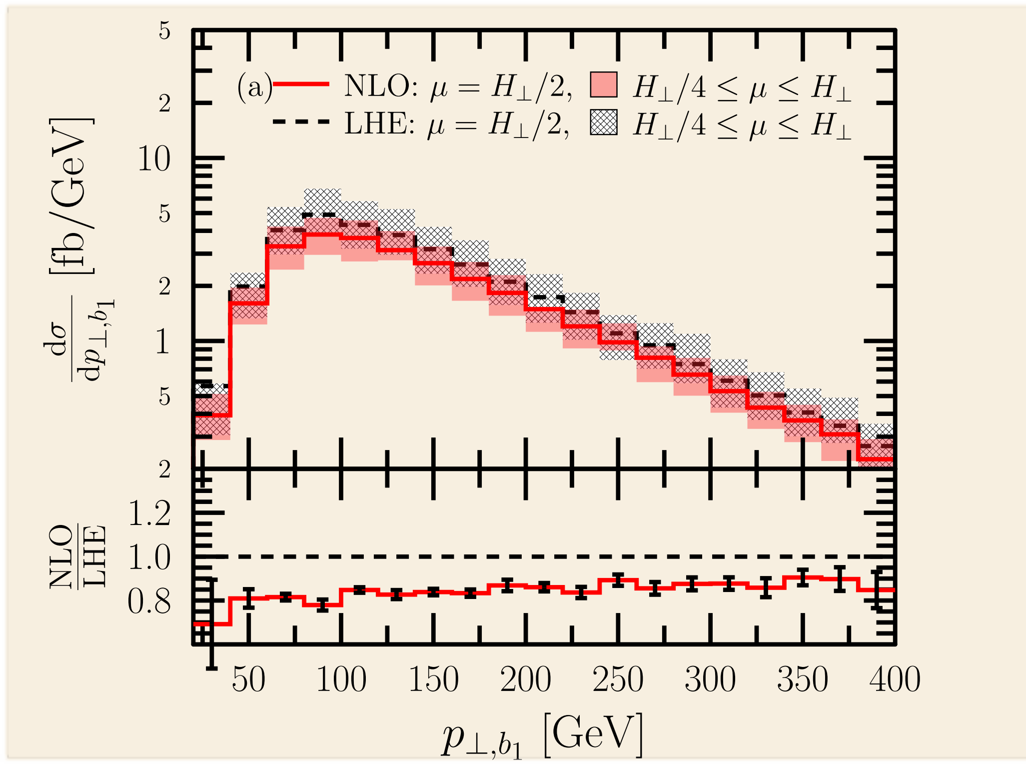
...

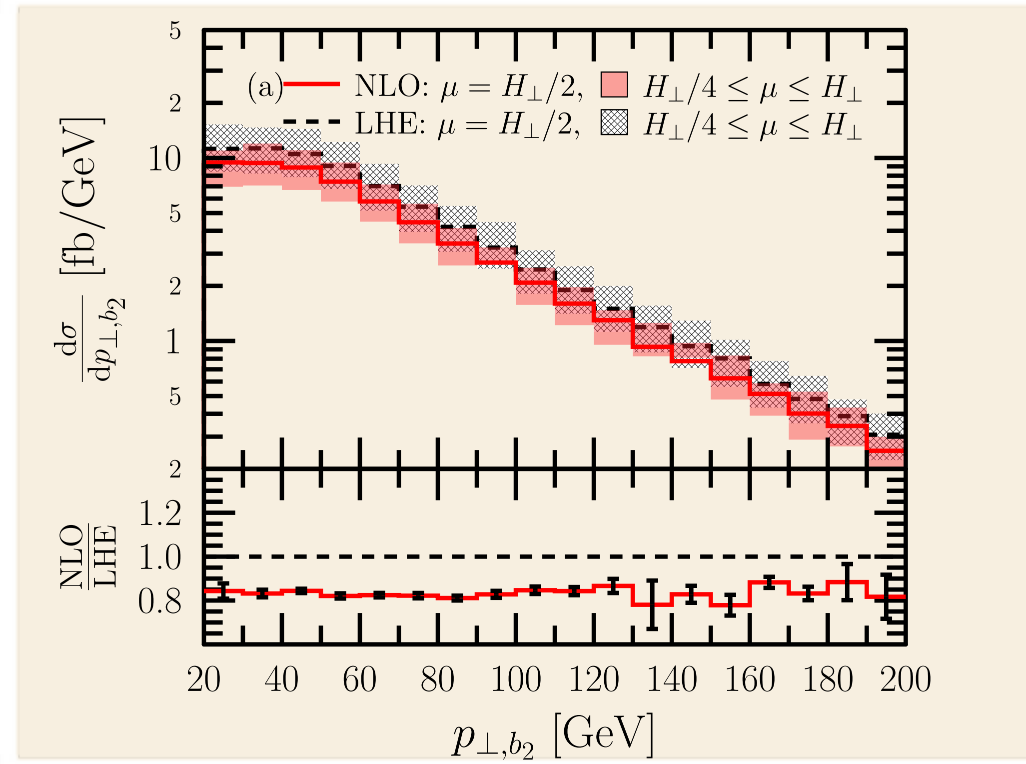
$$= \left\{ \int d\Phi_B \, [B + V] \, O(\Phi_B) + \int d\Phi_R R O(\Phi_R) \right\} (1 + \mathcal{O}(\alpha_S))$$

$\langle O \rangle_{\rm NLO}$

Useful for checking

LHE vs. NLO


(a) NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dp_{\perp,b_1}}$ [fb/GeV]
$\frac{NLO}{LHE}$
$p_{\perp,b_1}$ [GeV]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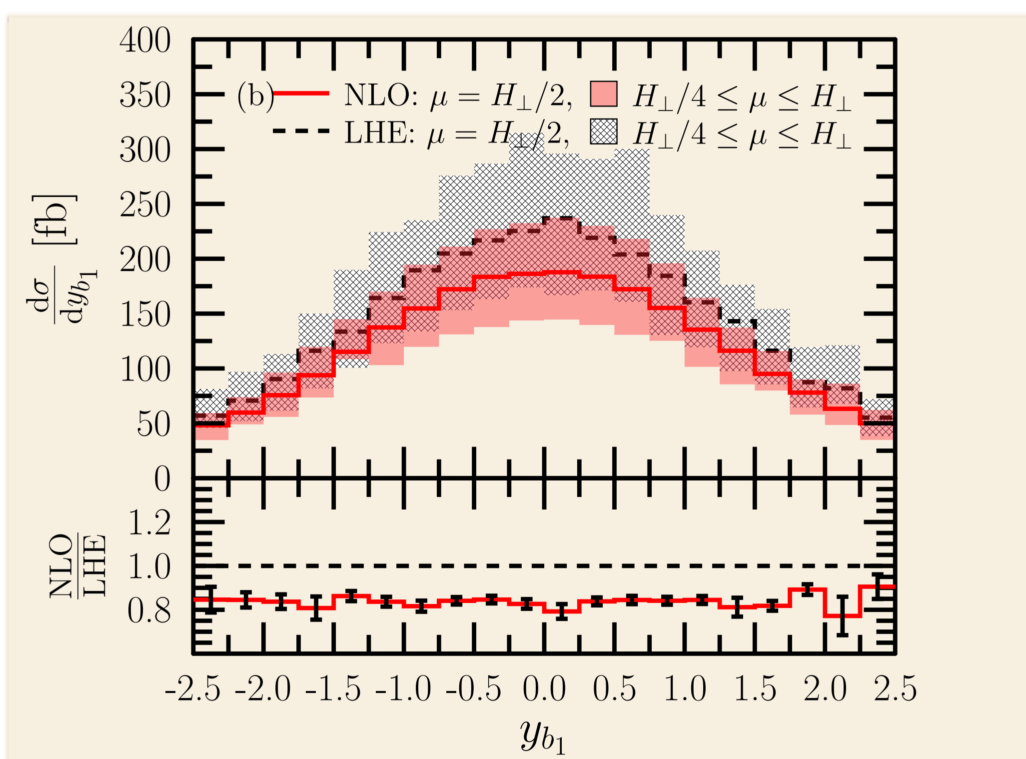
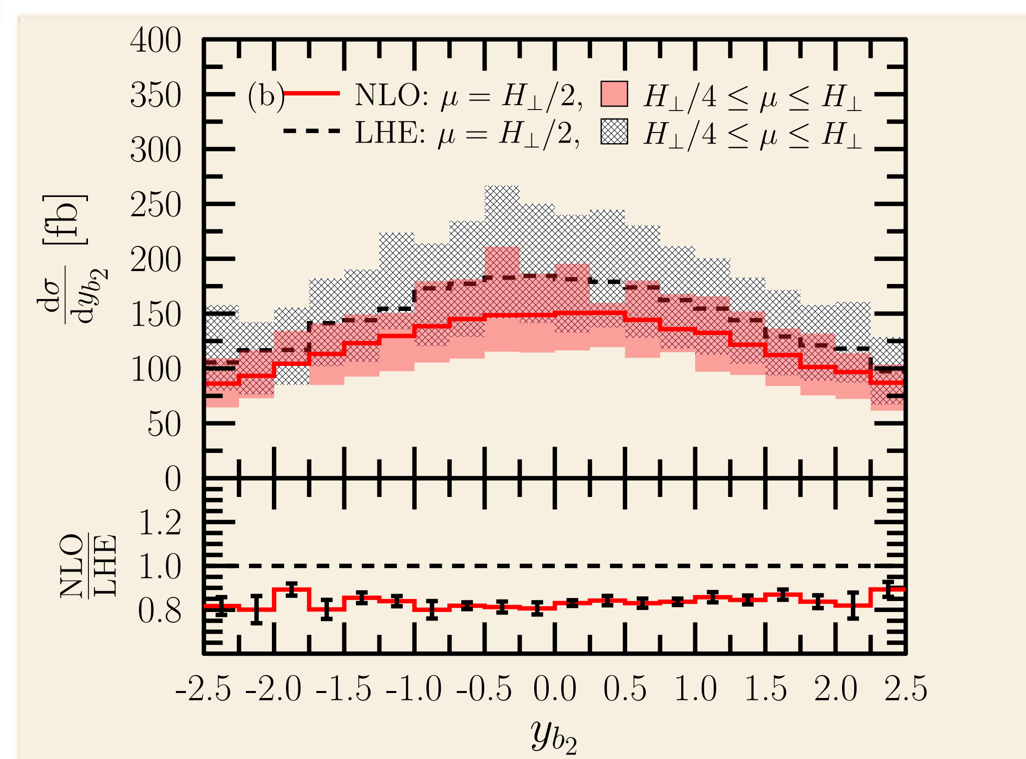
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dp_{\perp,b_2}}$ [fb/GeV]
$\frac{NLO}{LHE}$
$p_{\perp,b_2}$ [GeV]


(b) NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dy_{b_1}}$ [fb]
$\frac{NLO}{LHE}$
y_{b_1}


(b) NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dy_{b_2}}$ [fb]
$\frac{NLO}{LHE}$
y_{b_2}

Four possible forms of predictions

LHE: distributions from events at Born+1st radiation

Decay: on-shell decays of heavy particles (t-quarks), shower and hadronization effects turned off

PS: parton showering (PYTHIA or HERWIG) included (t-quarks kept stable)

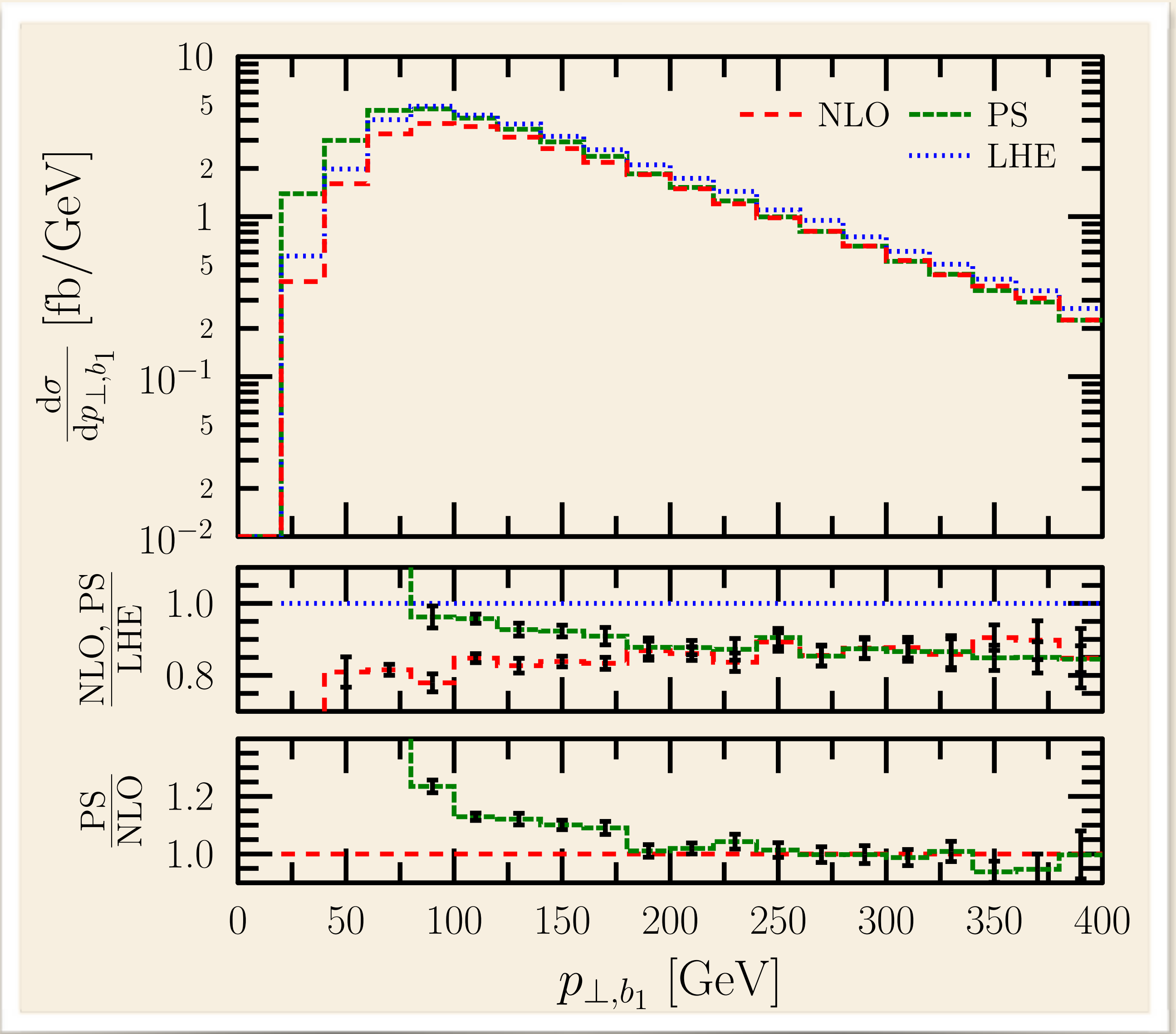
Full SMC: decays, parton showering and hadronization are included by using PYTHIA or HERWIG

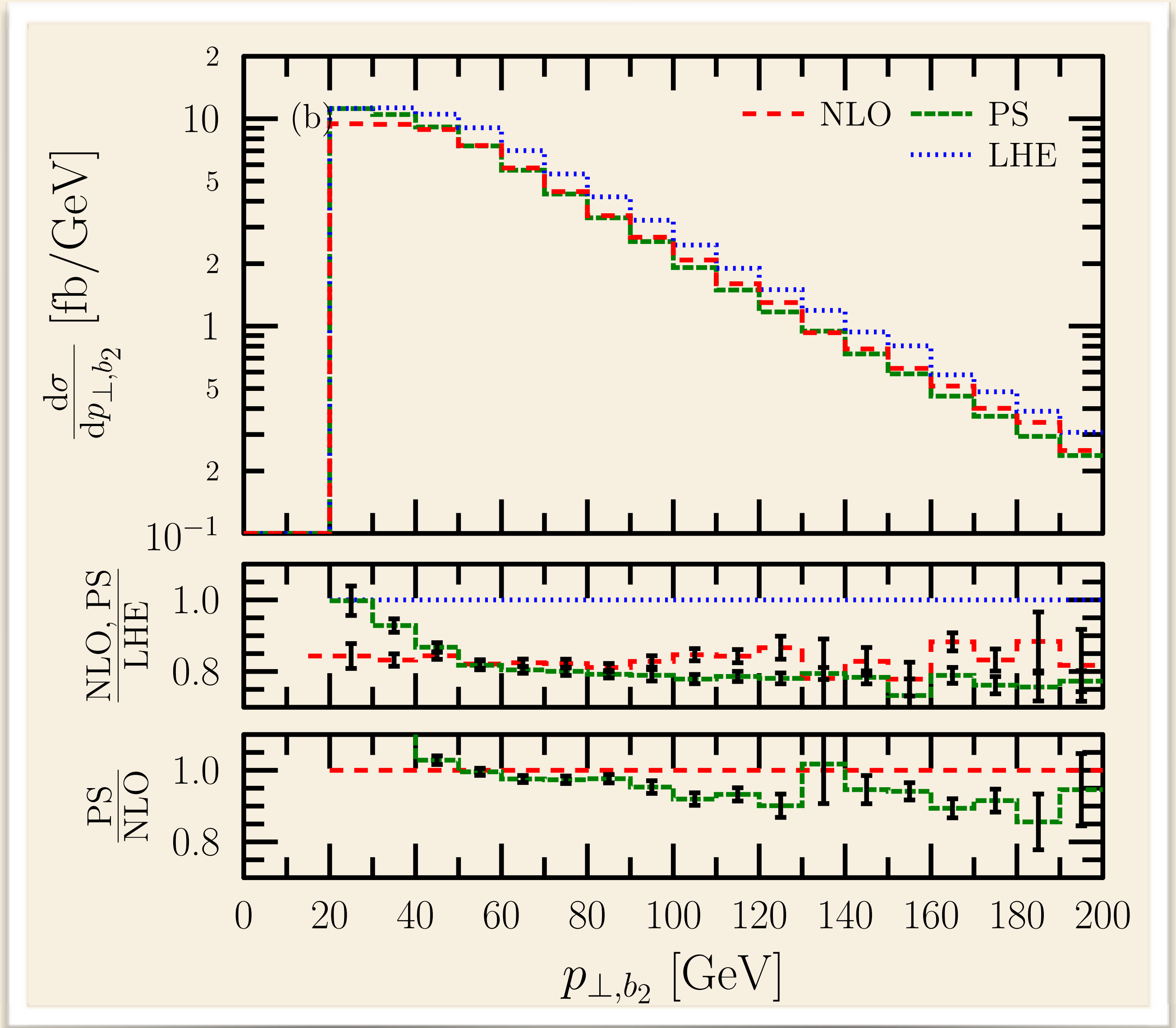
Number and type of particles are very different => to check that SMC does what we expect, we employ selection cuts to keep the cross section fixed

Selection cuts for decay vs. SMC

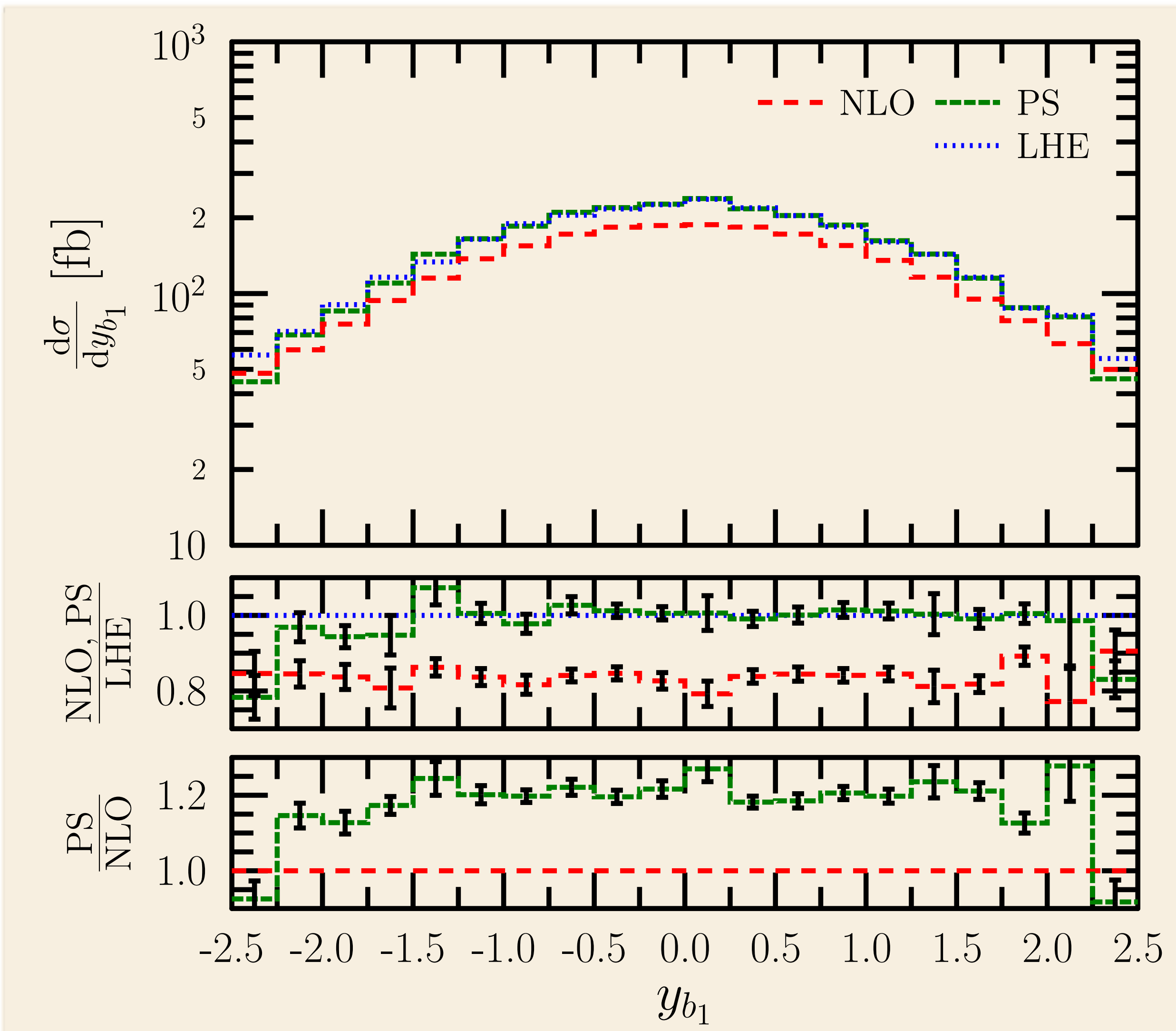
- Applied on the LHE's:
  - A track was considered as a possible jet constituent if $|\eta^{track}|<5$, t-quarks were excluded from the set of possible tracks. Jets were reconstructed with the anti-k_T algorithm using R=0.4.
  - Events with invariant mass of the $b\bar{b}$-jet pair below $m^{min}_{b\bar{b}}$ = 100 GeV were discarded.
- Applied on LHE's and checked also on the existing particles at different stages of evolution:
  - we require $p_{Tmin,j}$ = 25 GeV and
  - at least two, one b- & one $\bar{b}$-jet with $|\eta_{b(\bar{b})}|<2.5$.

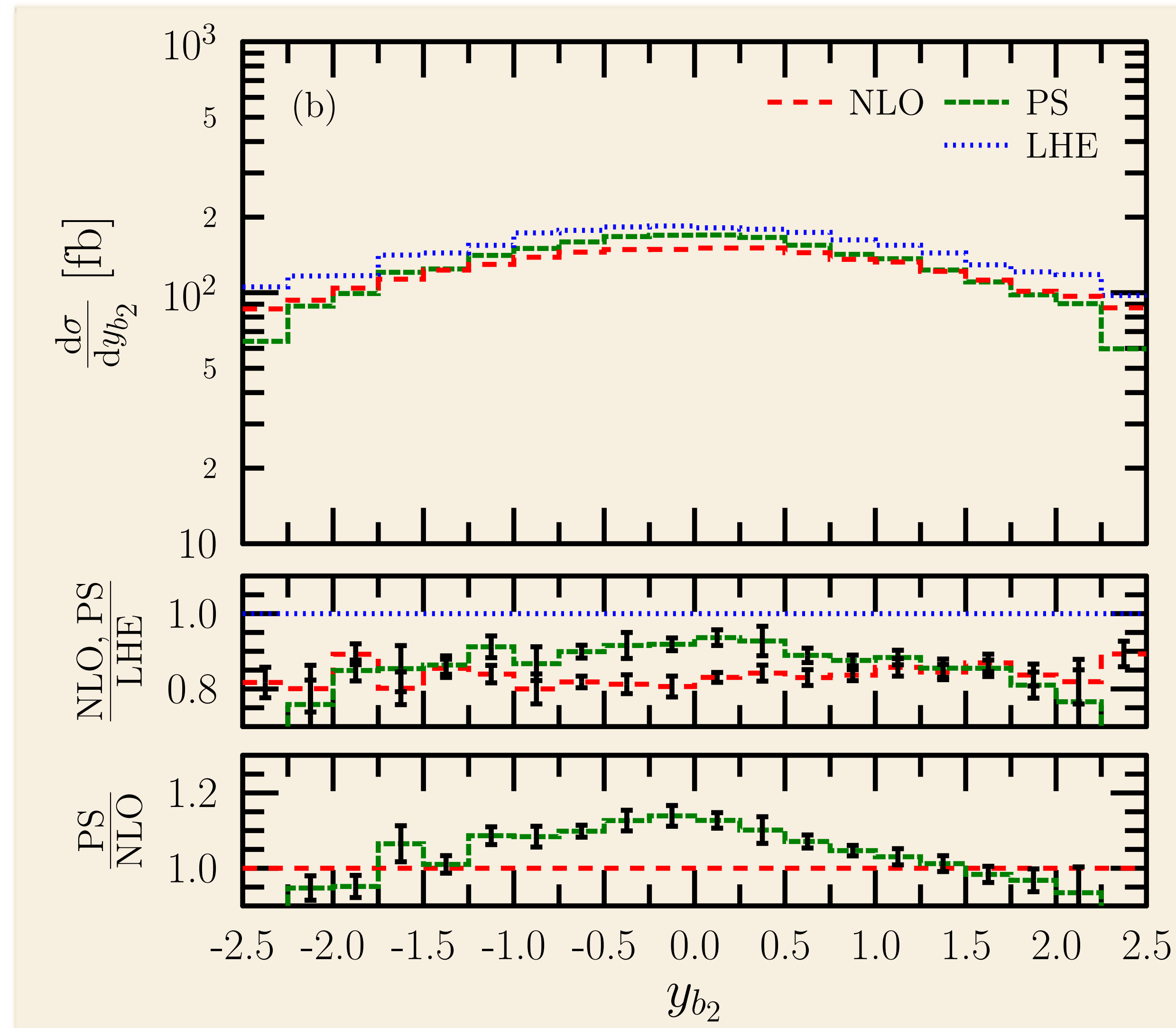
NLO vs. PS vs. LHE at 14TeV, μ = HT/2



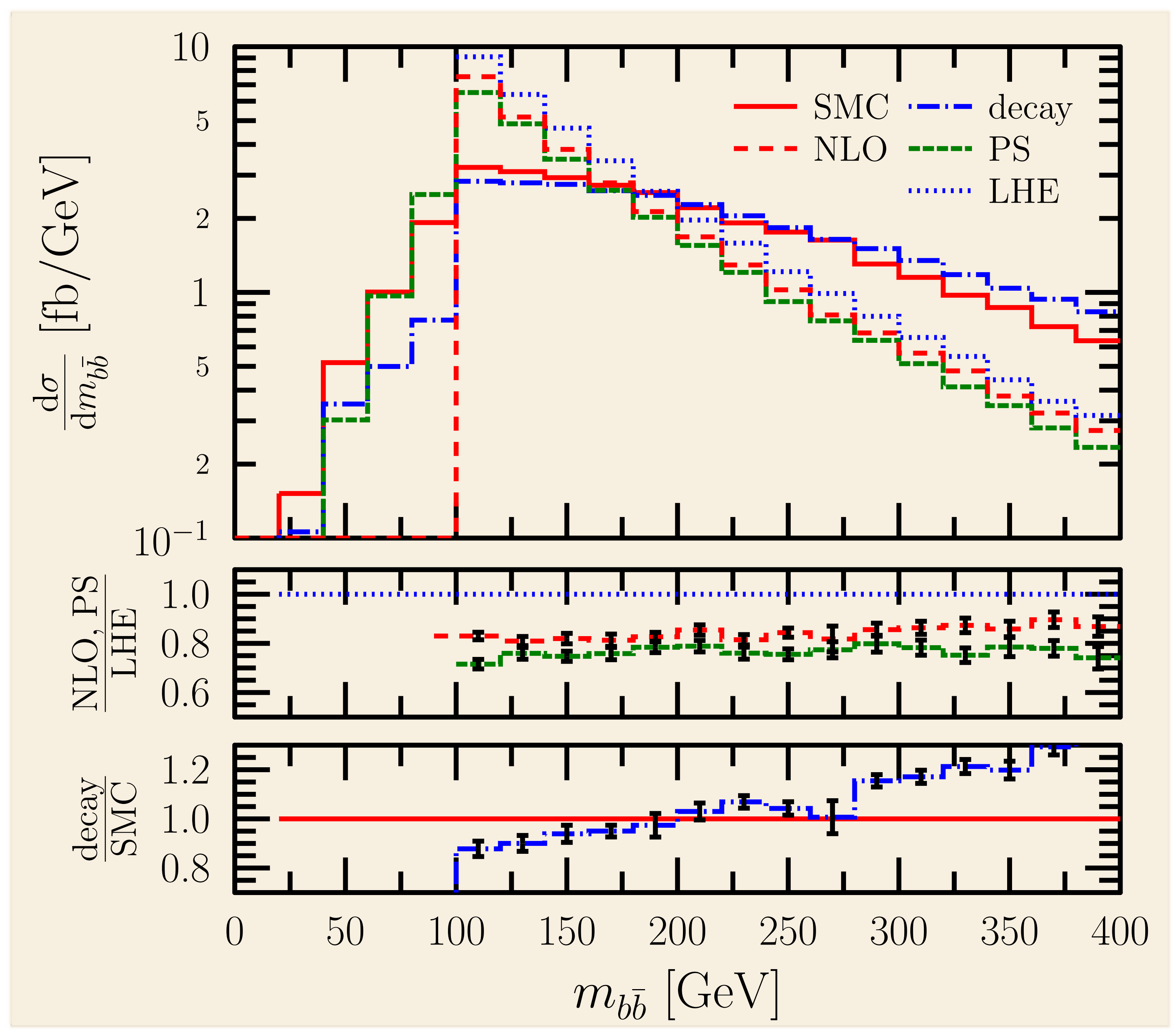


NLO vs. PS vs. LHE at 14TeV, μ = $H_T/2$





NLO vs. PS and decay vs. full SMC at 14TeV, μ = $H_T/2$



Message:

matching and SMC is under control

decay of t-quarks can have big impact

Cuts for estimating the effect of the PS

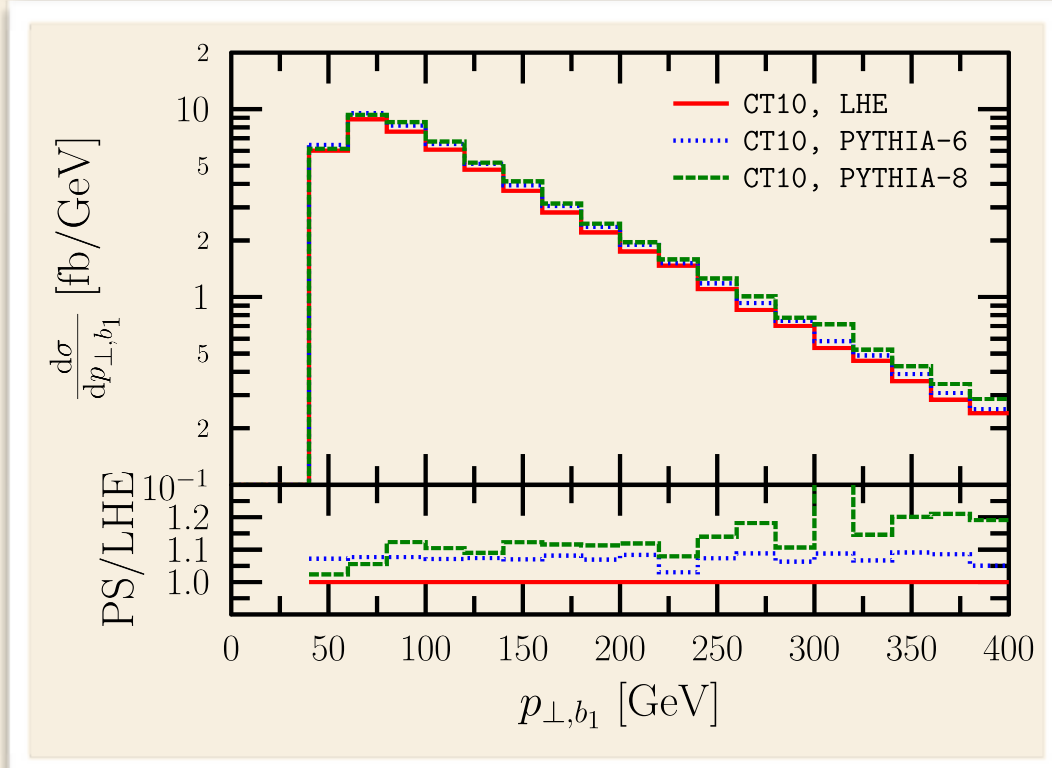
applied separately on LHEs and after PS

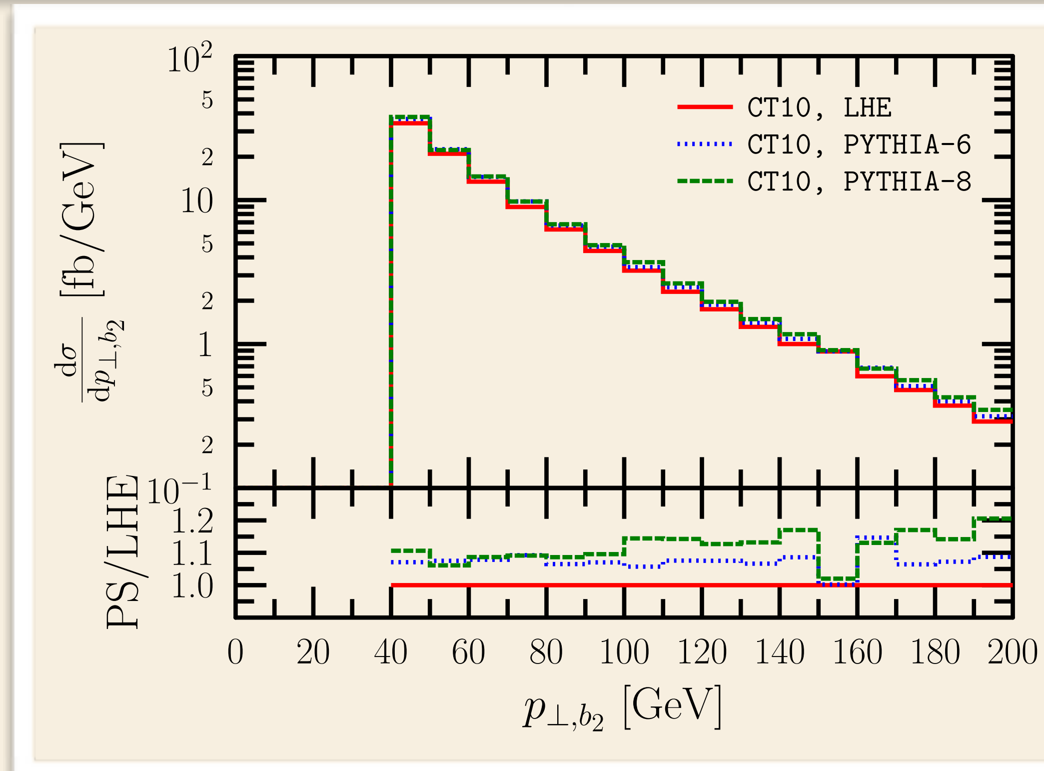
- jets reconstructed with the anti-k_T algorithm using R=0.5, with at least two well-separated b-jets ($\Delta R > 0.5$), $p_{Tmin,bjet}$ = 40 GeV and $|\eta_j|<2.5$

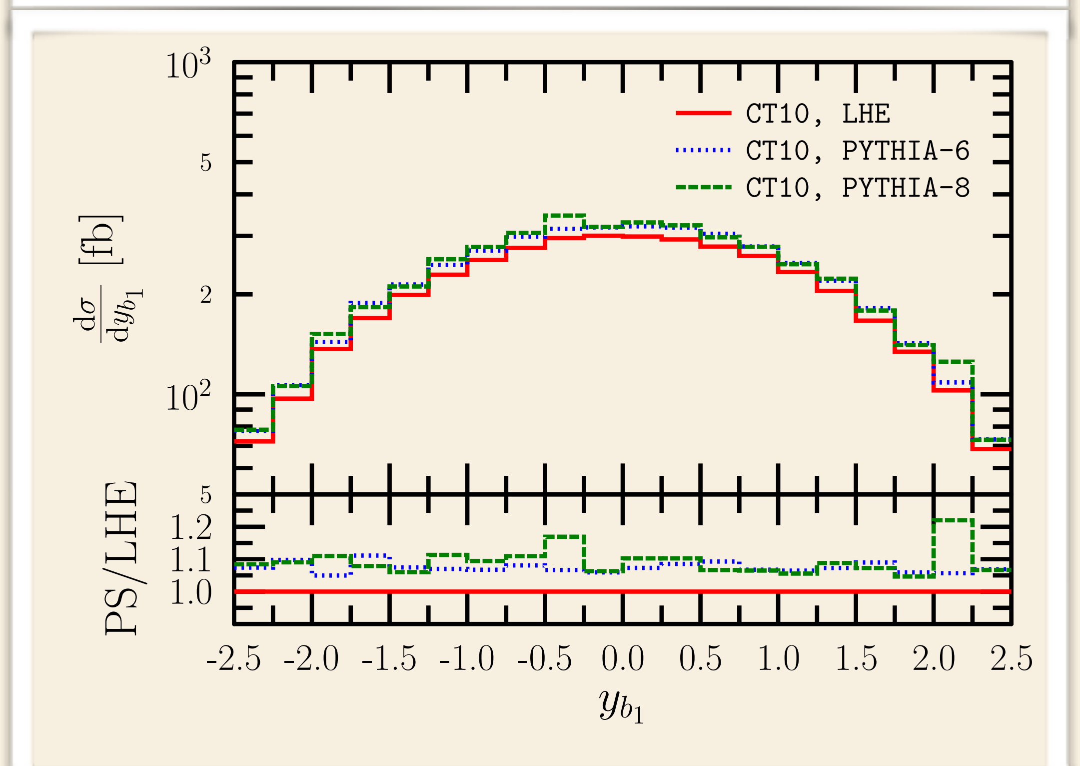
but with

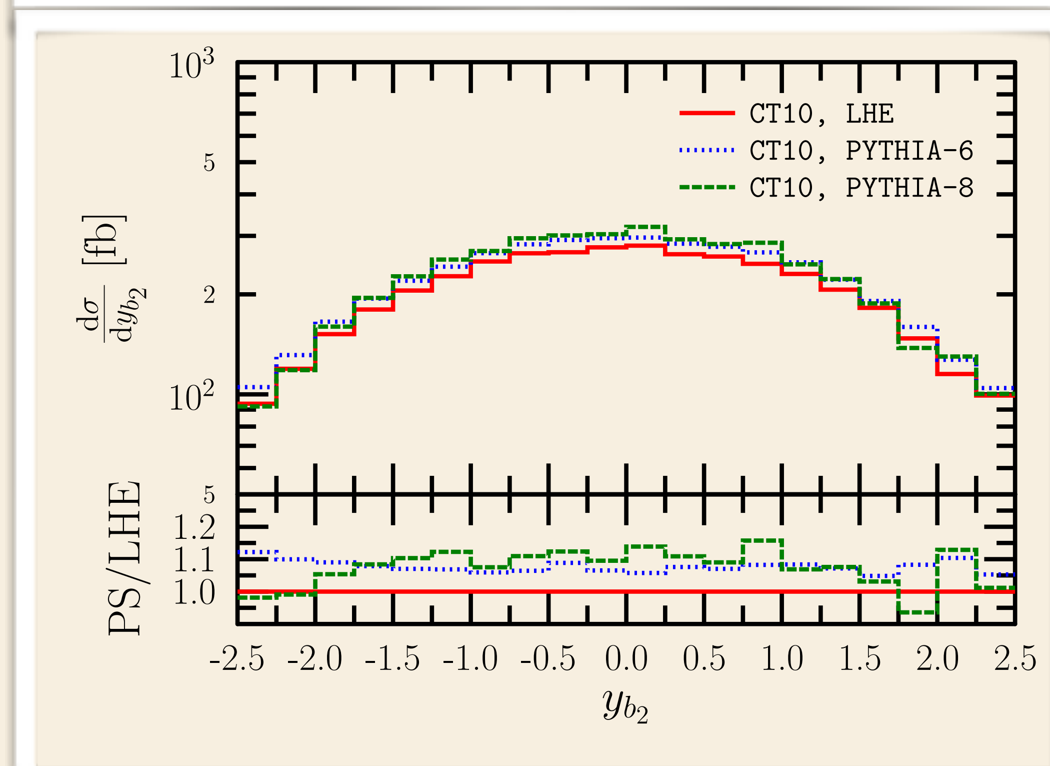
- t-quarks kept stable

PS vs. LHE
at 14TeV, μ = $H_T/2$

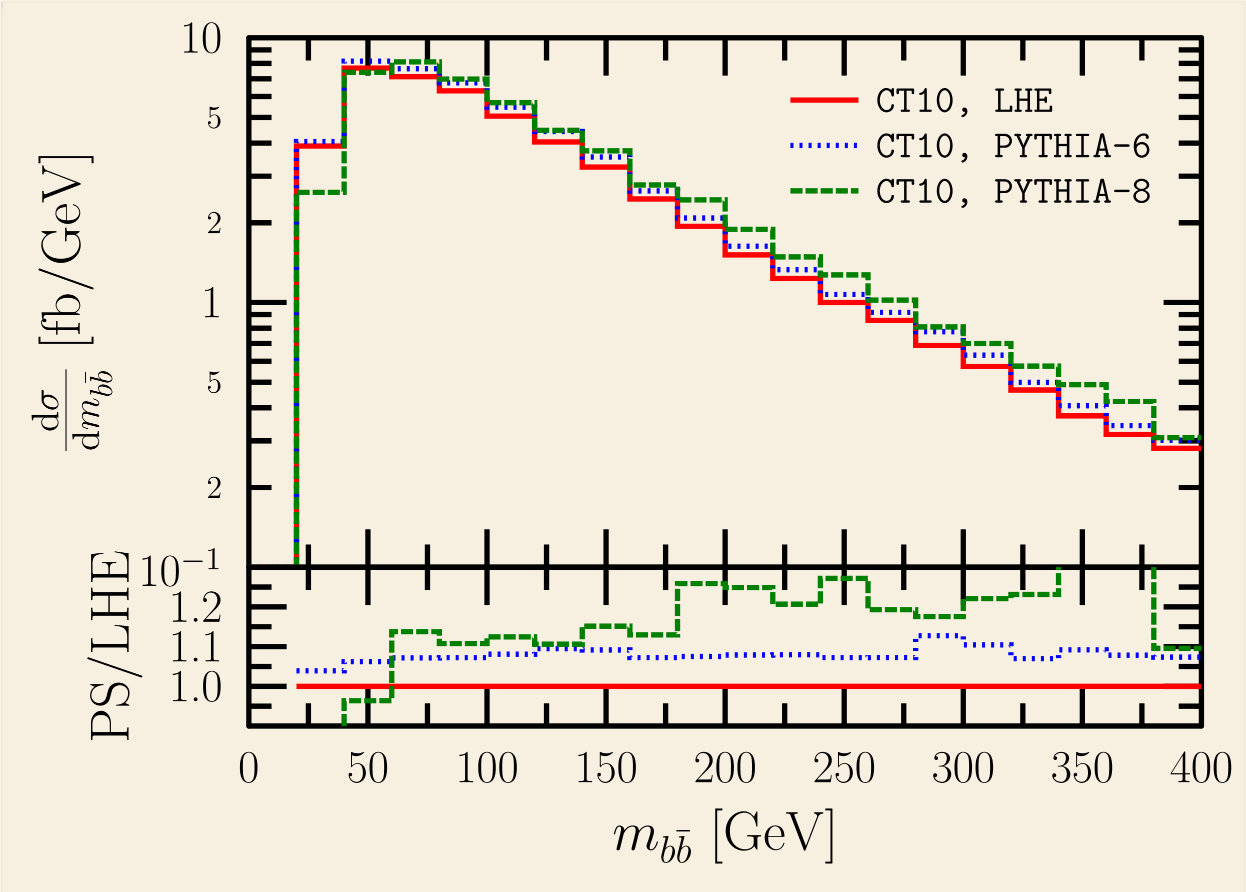


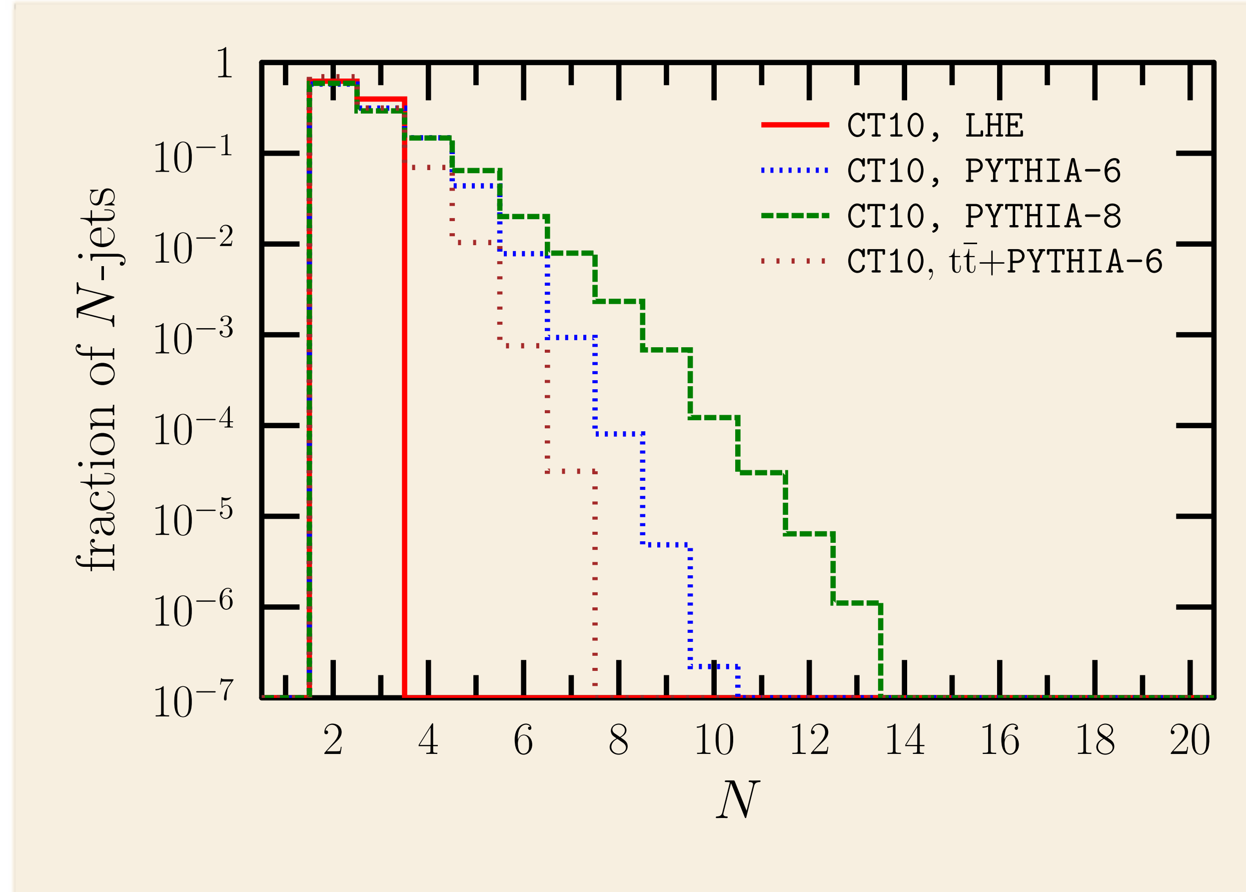






PS vs. LHE
at 14TeV, μ = H_T/2





Message:

PYTHIA-6 and PYTHIA-8 give similar predictions but this may depend on selection cuts (see below)

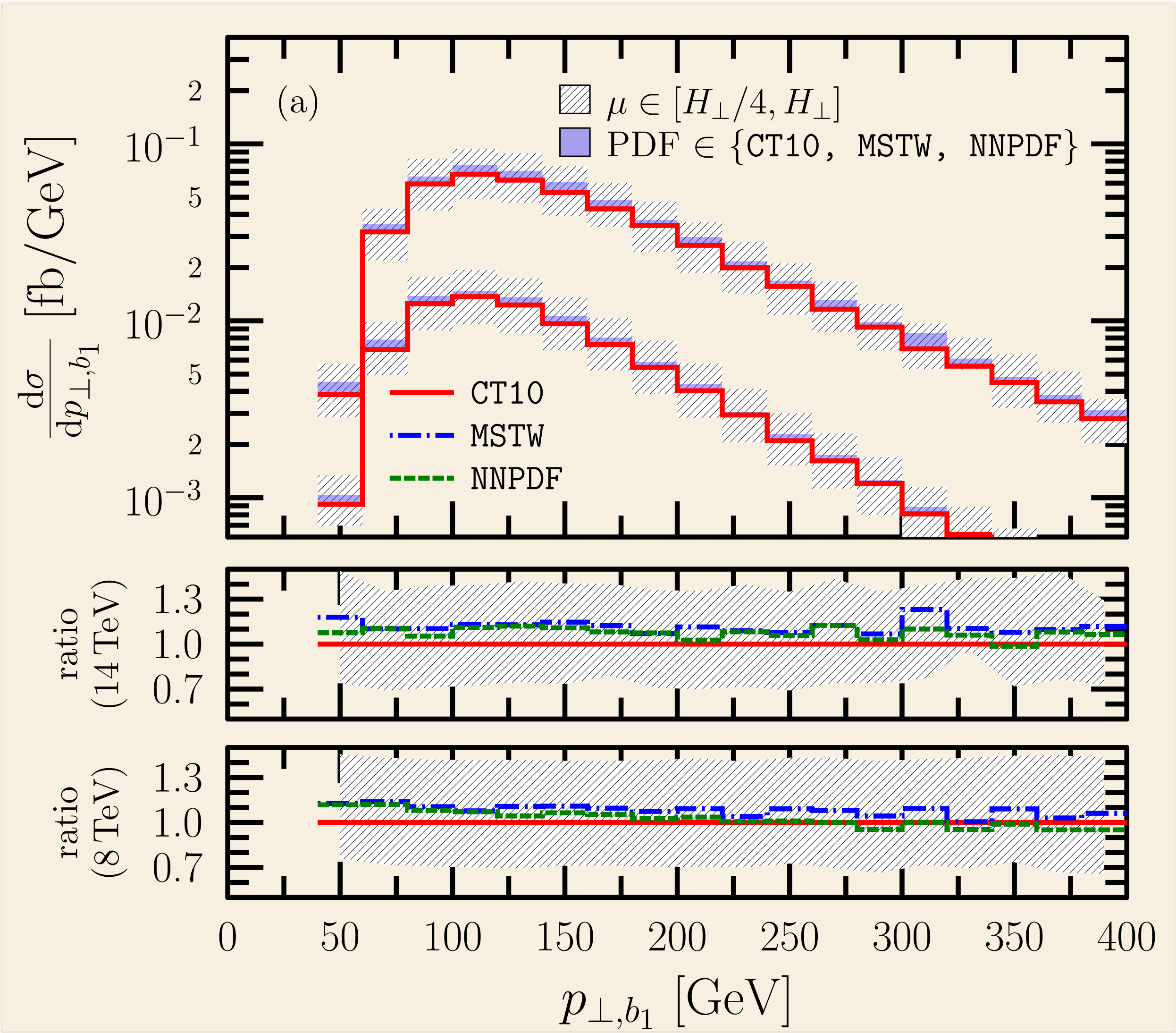
PDF and scale uncertainties of NLO+PS predictions

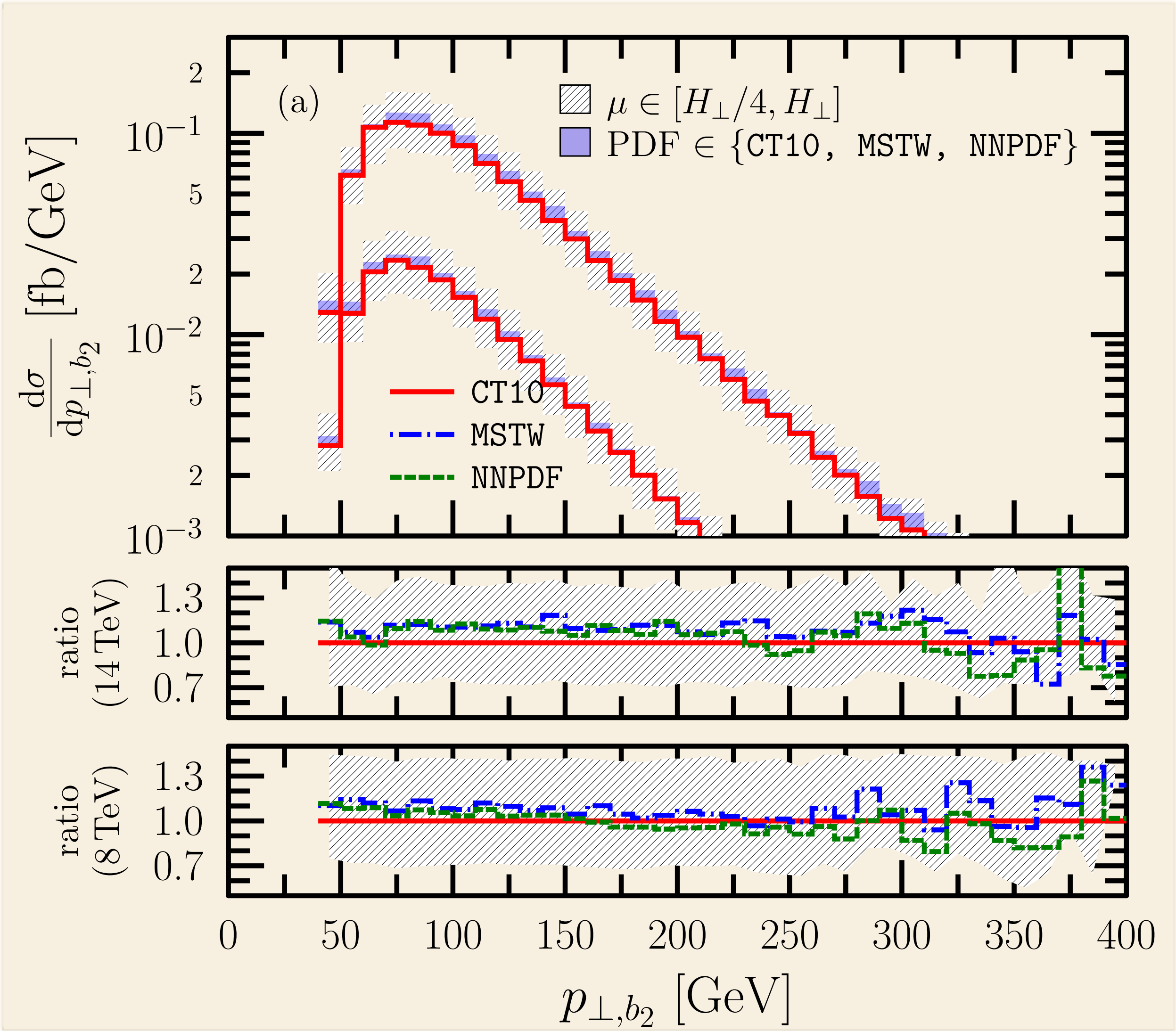
Cuts for scale, PDF and SMC uncertainties

from CMS PAS TOP-13-010

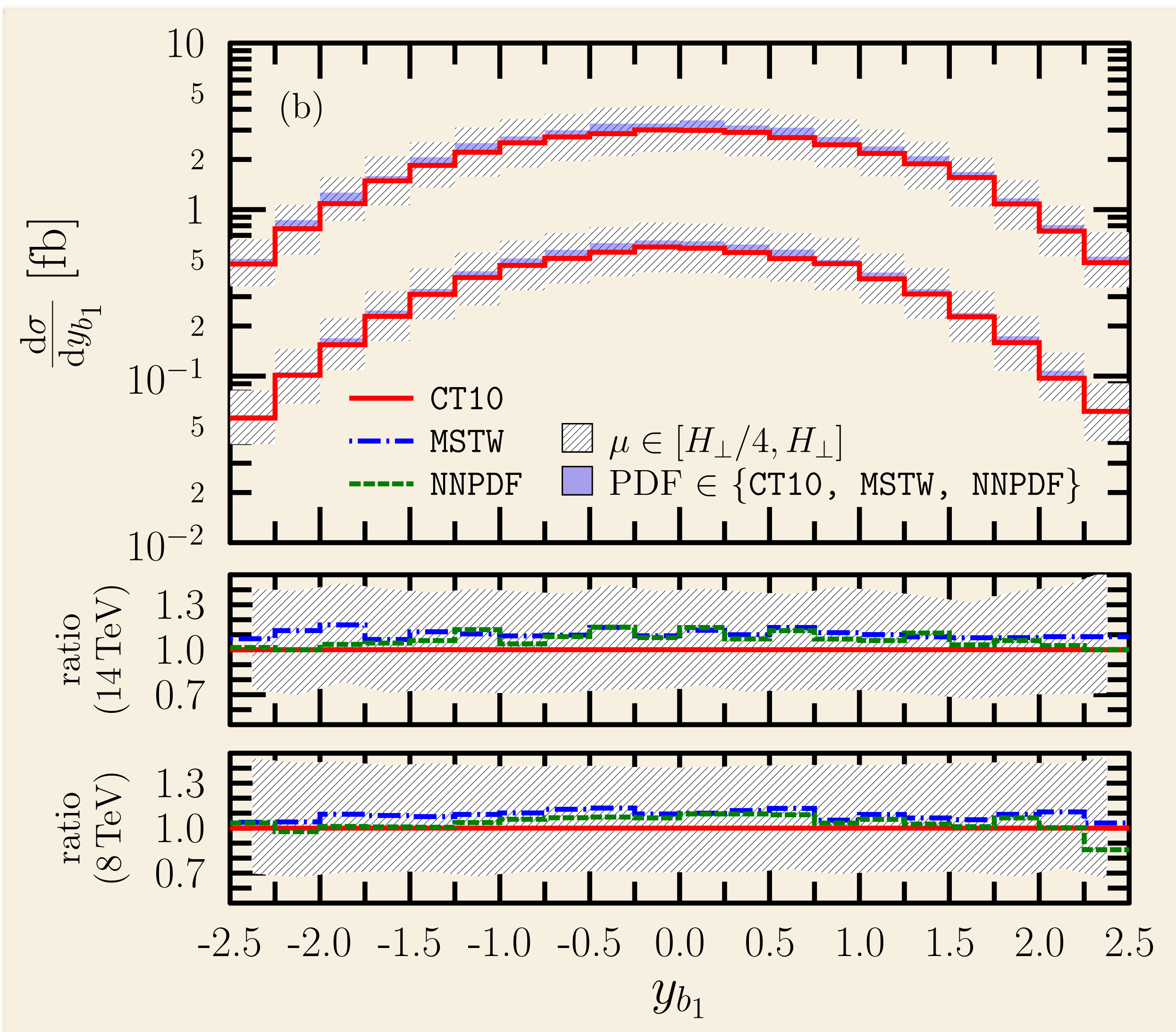
- jets reconstructed with the anti-k_T algorithm using R=0.5, with $p_{Tmin,j}$ = 40 GeV and $|\eta_j|<2.5$
- at least one pair of isolated (with R=0.3, I_{rel} = 0.15) opposite sign leptons with $p_{Tmin,\ell}$ = 20 GeV/c, $|\eta_\ell|<2.4$, 12 GeV < $m_{\ell\ell}c^2$ ($\notin$[77, 107] GeV if ee or μμ)
- p_T^{miss} = 30 GeV/c if ee or μμ
- at least four well separated b-jets with ΔR > 0.5 both from leptons and jets

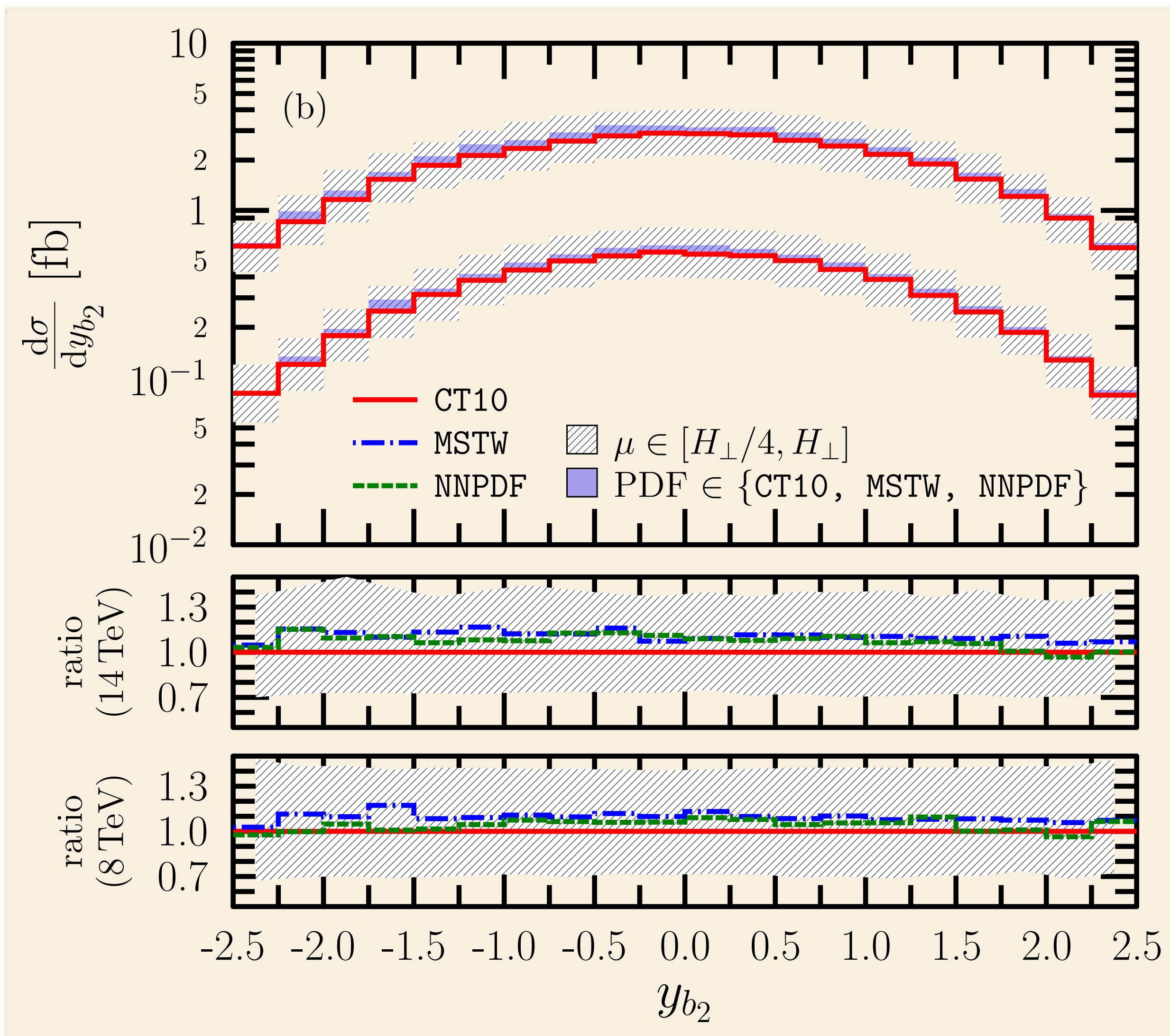
PDF and scale uncertainties





PDF and scale uncertainties





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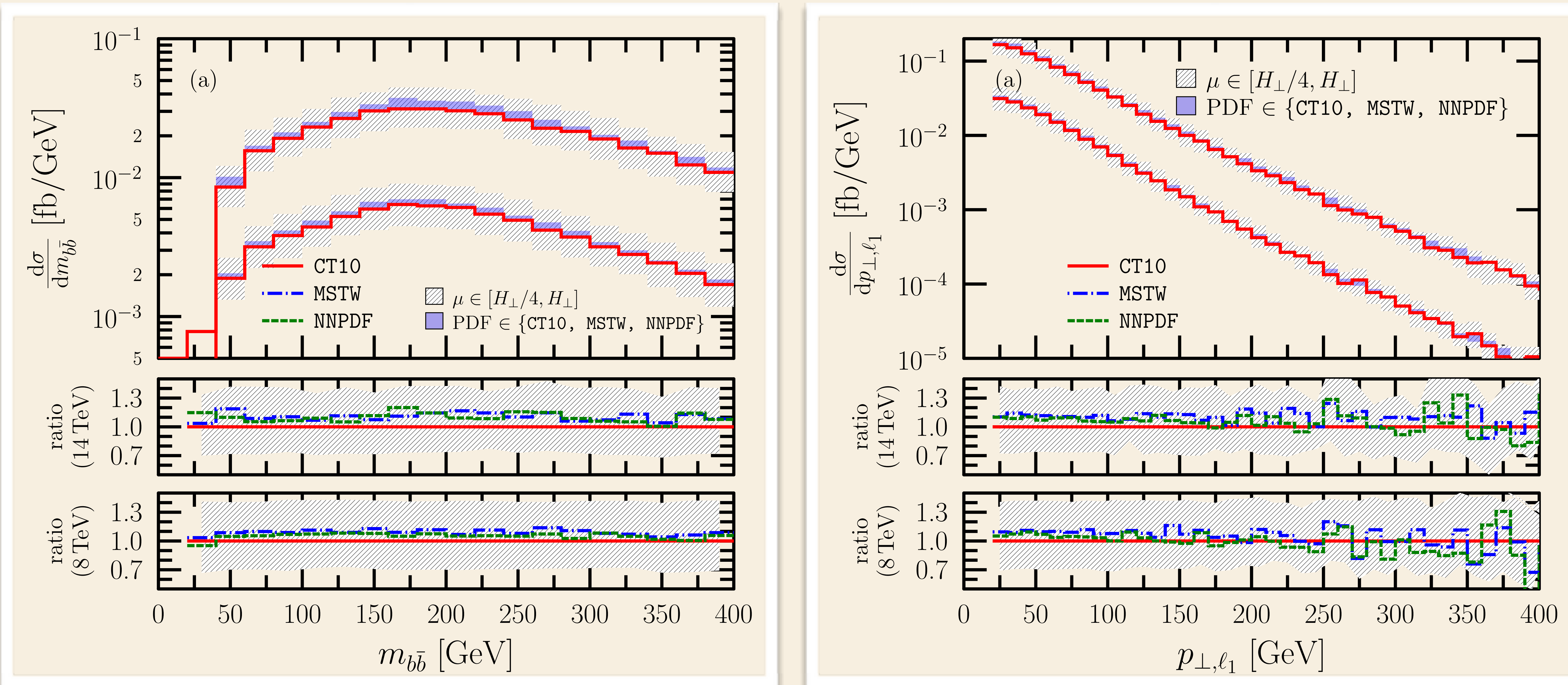
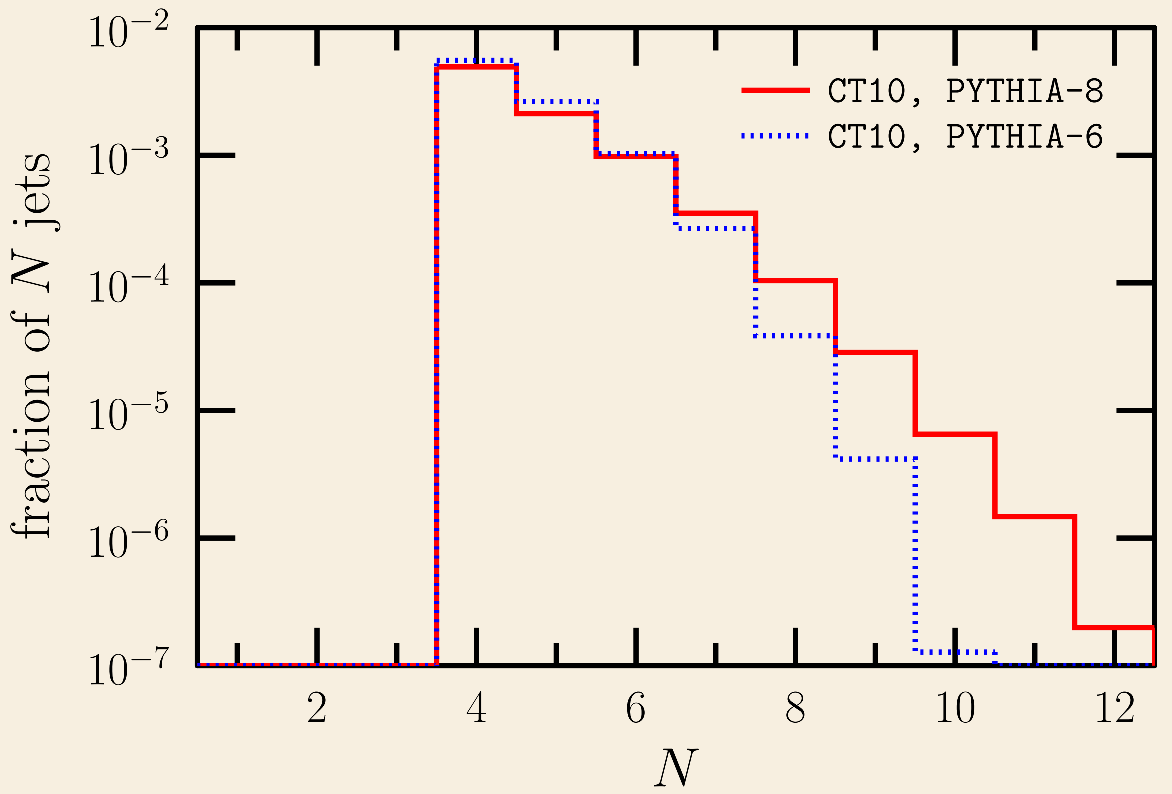
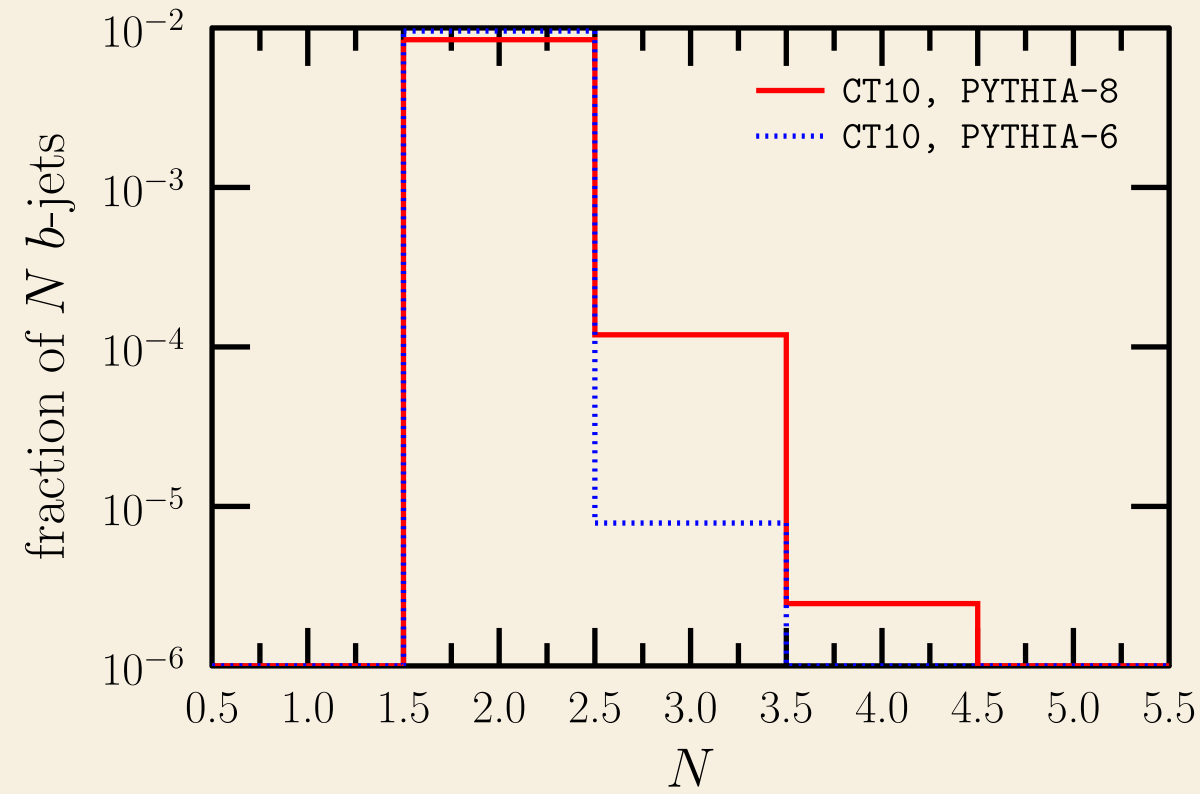


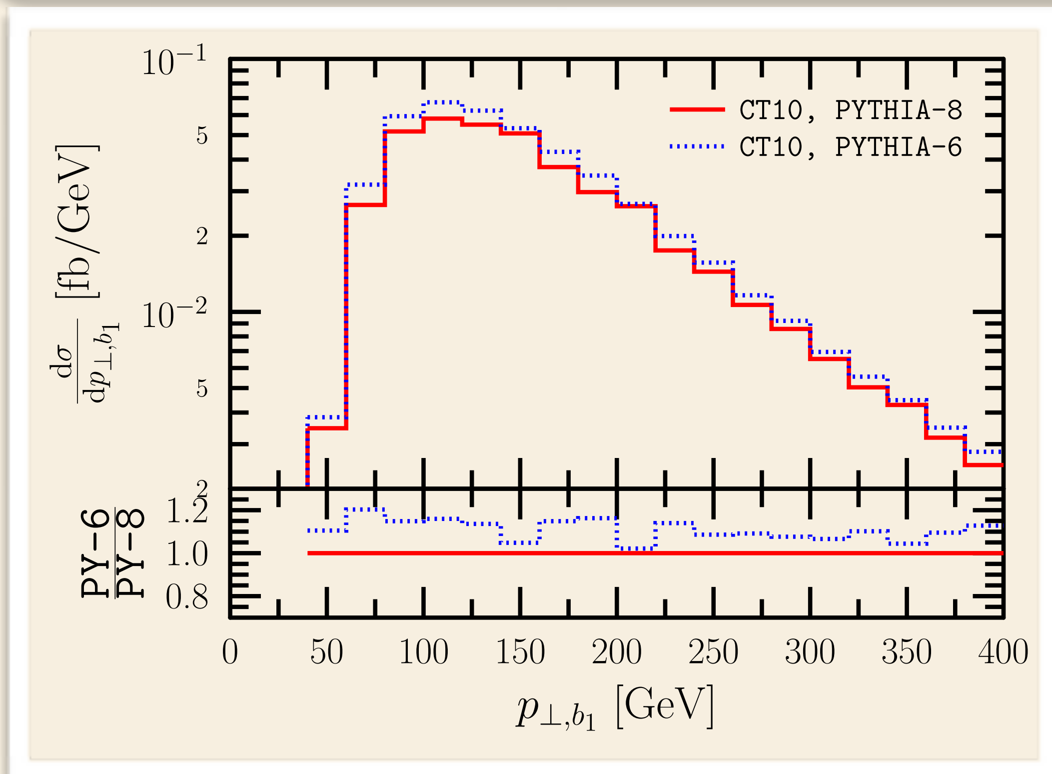
SMC uncertainties

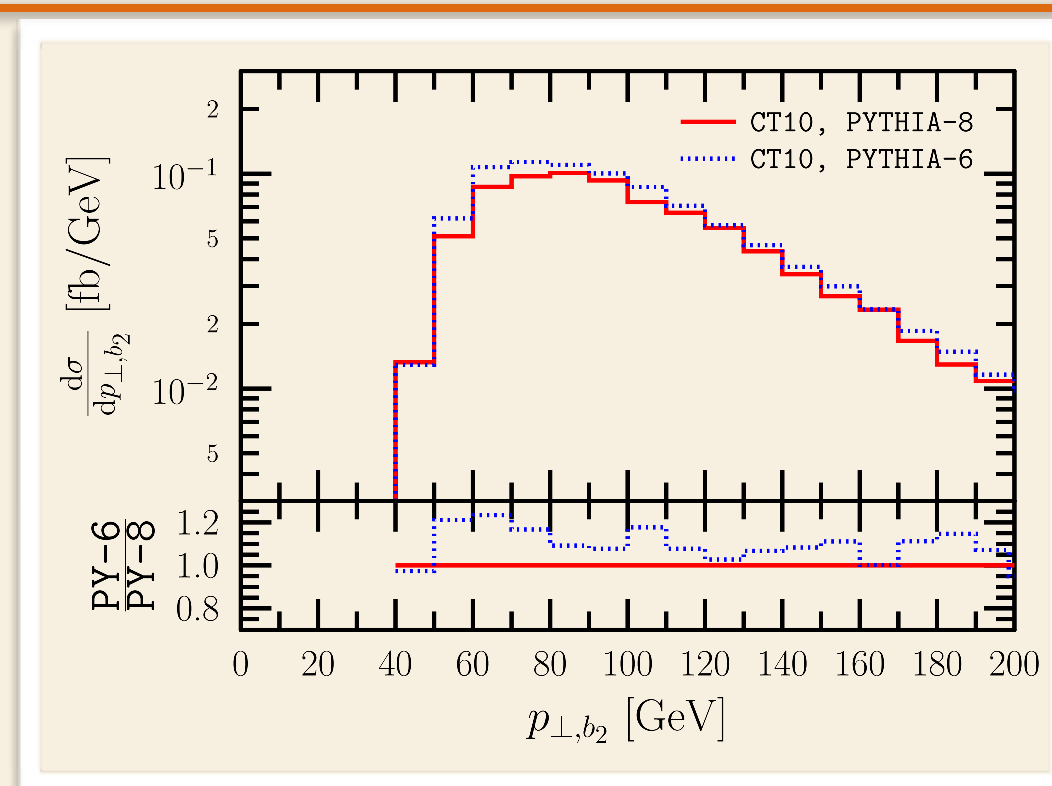
PYTHIA-6 vs. PYTHIA-8 at 14TeV, μ = $H_T/2$

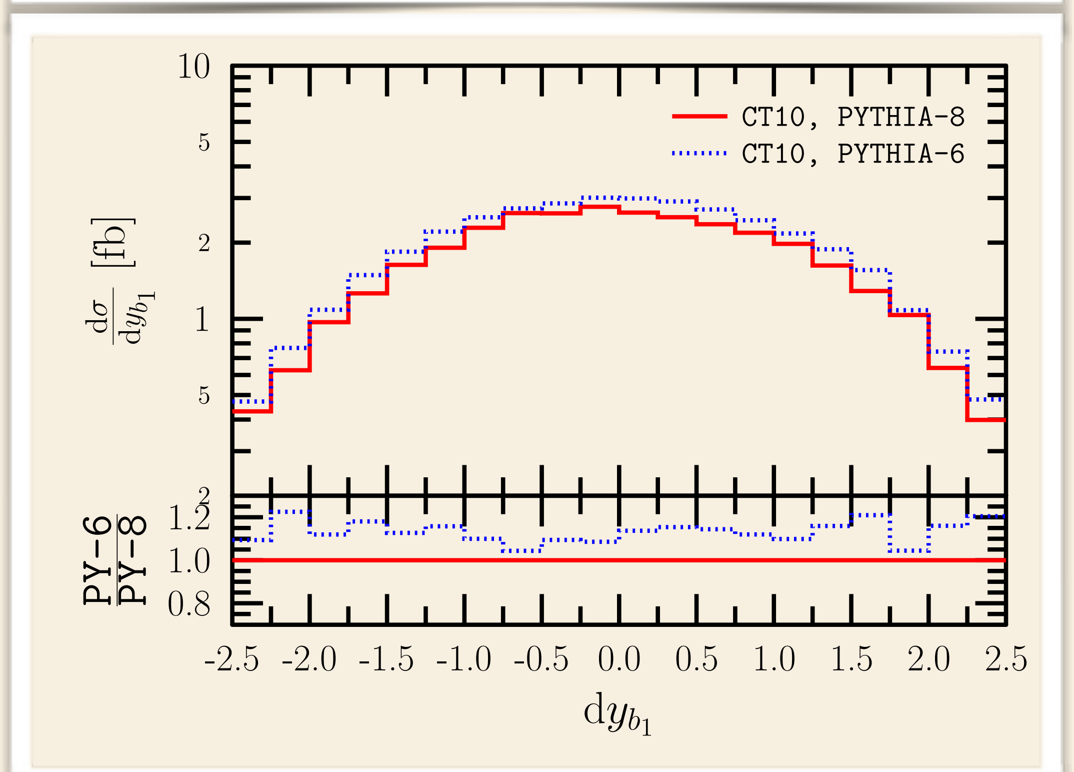


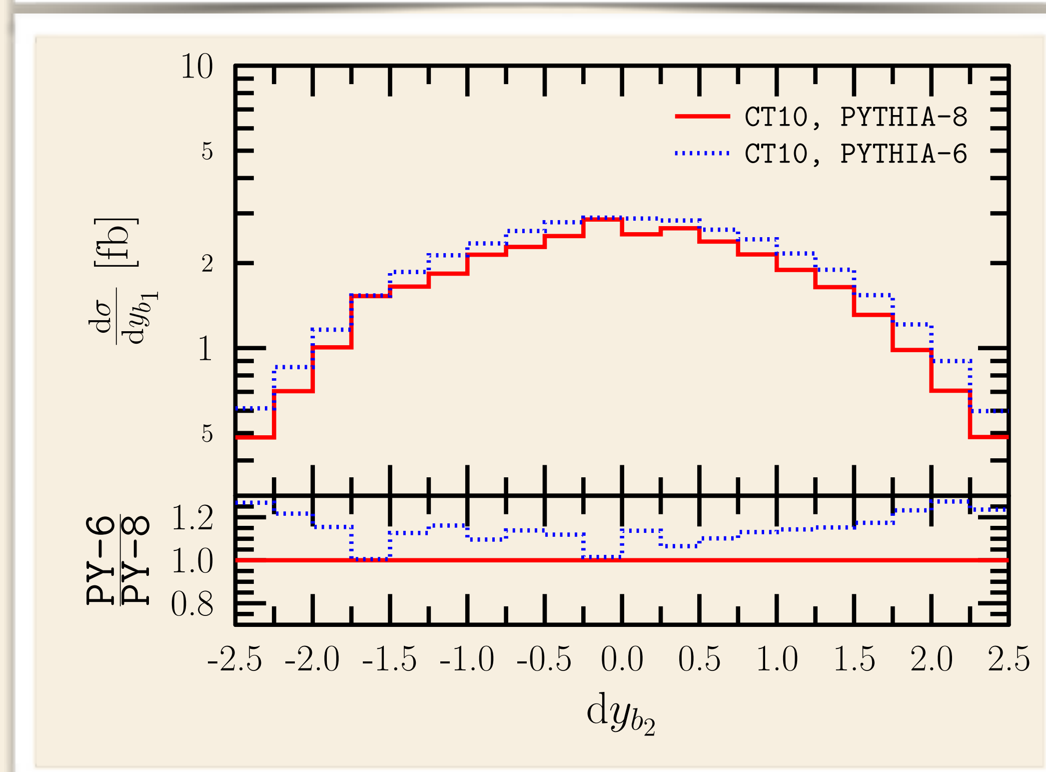


PYTHIA-6 vs. PYTHIA-8
at 14TeV, $\mu = H_T/2$









Conclusions and outlook

Conclusions

- K-factor and scale uncertainty of NLO prediction is moderate with dynamical scales, but choice of central scale matters (we prefer $H_T/2$ for NLO+PS)
- Matching is under control within scale uncertainty
- For NLO predictions matched with SMC
  - scale uncertainties are +35%-30%
  - PDF uncertainties are ~ 10%
  - SMC uncertainties are ~< 10%

…but

- all conclusions are sensitive to selection cuts
- effects of decay of t-quarks could be important

Outlook

We are open to comparison of predictions from
`PowHel, SHERPA+OpenLoops & MadGraph5_aMC@NLO`
with same set of parameters and cuts

(to be agreed together with experimentalists)

Appendix

Selection cuts for NLO predictions

Cuts employed by Bevilacqua et al in arXiv:0907.4723

- A track was considered as a possible jet constituent if $|\eta^{track}|<5$, t-quarks were excluded from the set of possible tracks, jets were reconstructed with the k_T-algorithm using R=0.4
- Events with invariant mass of the $b\bar{b}$-jet pair below $m^{min}_{b\bar{b}}$ = 20 GeV were discarded
- We require $p_{Tmin,j}$ = 20 GeV and
- at least two, one b- and one $\bar{b}$-jet, with $|y_{b(\bar{b})}|<2.5$

Cuts for background study for tTH

Applied after full SMC

- a track was considered as a possible jet constituent if $|\eta^{track}|<5$, jets were reconstructed with the anti-k_T algorithm using R=0.4

we require

- at least six jets with $p_{Tmin,j} = 20$ GeV and $|\eta_j|<5$
- at least two b-jets & two $\bar{b}$-jets with $|\eta_{b(\bar{b})}|<2.7$, with MCTRUTH tagging
- at least one isolated (with R=0.4) lepton with $p_{Tmin,\ell} = 20$ GeV and $|\eta_\ell|<2.5$
- $p_T^{miss} = 15$ GeV

to disentangle background in the semileptonic $t\bar{t}$ decay

$t\bar{t}H$ signal on $t\bar{t}b\bar{b}$ background