tT+hard X hadroproduction with PowHel

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in collaboration with
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and
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Tools for precision and discovery physics with top quarks, CERN
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NEW SZÉCHENYI PLAN

LHCphenonet

Outline

- Motivation
- Method
- Predictions
- Conclusions

Motivation

"The t-quark is special"

Top at the LHC

Present:

production cross section, mass, width, t-T mass difference, spin correlations, W helicity/ polarization, Vtb, charge, charge asymmetry, anomalous couplings, FCNC, jet veto in tT

Future: discovery tool, coupling measurements

These require precise predictions of distributions at hadron level for

pp $\rightarrow$tT+hard X, X = H, A, W, Z, γ , j, bB, 2j...

(with decays, top is not detected)

Why should we care about NLO + PS?

- Hadrons in final state
- Closer to experiments, realistic analysis becomes feasible
- Decayed tops
- Parton shower can have significant effect (in Sudakov regions, at kinematic boundaries)
- For the user:

event generation is, faster than an NLO computation

(once the code is ready!)

...but we deliver the events on request

...to distributions, full of pitfalls & difficulties

There is a long way from loops and legs...

NLO subtractions

- Idea: exact calculation in the first two orders of pQCD
- Subtraction method

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

$$\int \mathrm{d}\Phi_n B(\Phi_n) = \sigma_{\mathrm{LO}}$$

$$V(\Phi_n) = \mathcal{V}(\Phi_n) + \int \mathrm{d}\Phi_{\mathrm{rad}} A(\Phi_{n+1})$$

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

From NLO to NLO+PS

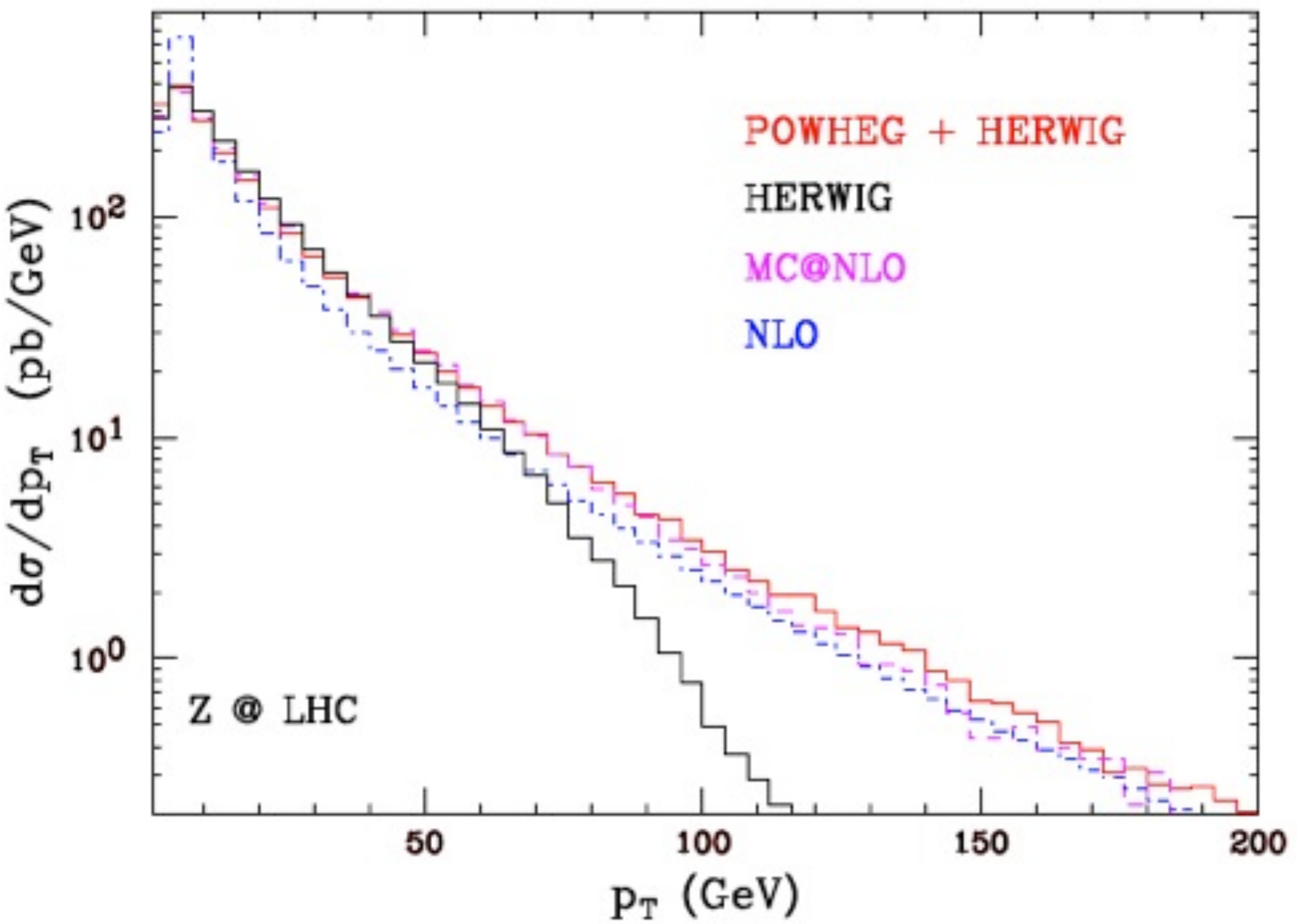
Idea: use NLO calculation as hard process as input for the SMC

Bottleneck: how to avoid double counting of first radiation w.r.to Born process

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]

Our choice: POWHEG-BOX with HELAC-NLO for tT+hard X

PowHel

http://www.grid.kfki.hu/twiki/bin/view/DbTheory/WebHome

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)

Our choice: POWHEG-BOX with HELAC-NLO for tT+hard X

- The POWHEG-BOX implements
  - FKS subtraction scheme
  - POWHEG method for matching

[Alioli, Nason, Oleari, Re arXiv: 1002.2581]

- HELAC-NLO provides tree and 1loop ME

[Bevilaqua et al, arXiv: 1110.1499]

- Processes in PowHel: New!
  - ✓tT and W^+W^-bB
  - ✓tT+H/A
  - ✓tT+Z
  - ✓tT+jet

  Published

  - tT+X_1, X_2, X_3 not yet public

[Garzelli, Kardos, Papadopoulos, ZT arXiv: 1108.0387 arXiv: 1111.0610 arXiv: 1111.1444 arXiv: 1101.2672]

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:

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

$\int B(\Phi_n)d\Phi_n = \sigma_{\rm LO}$

- POWHEG MC first emission:

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

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

$\int \bar{B}(\Phi_n)d\Phi_n = \sigma_{\rm NLO}$

If $\sigma_{\rm LO}$ finite!

Accuracy of the POWHEG cross section

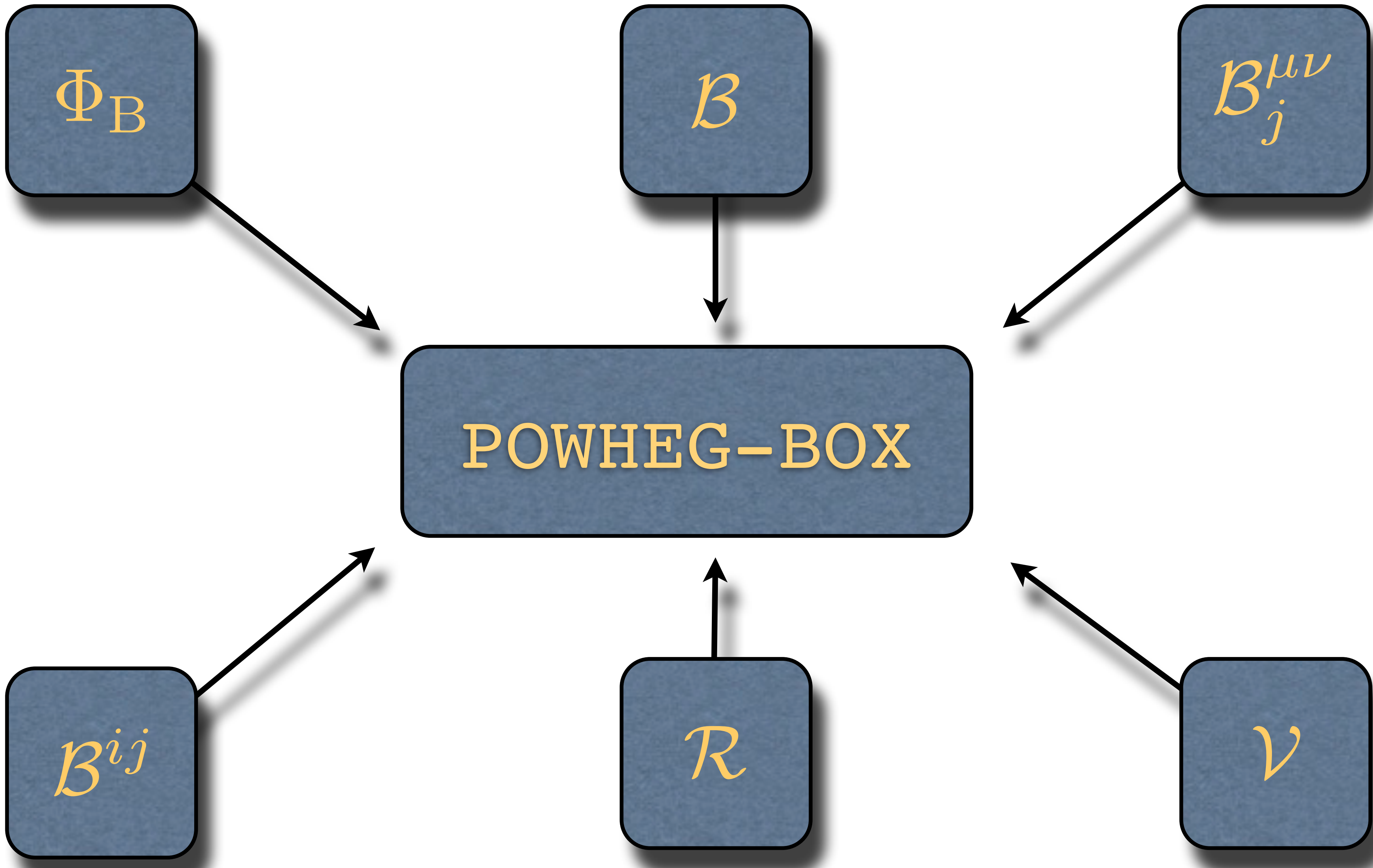
$$\frac{d\sigma_{\rm LHE}}{dO} = \frac{d\sigma_{\rm NLO}}{dO} + {\rm O}(\alpha_{\rm s}) \int d\Phi_R R(\Phi_R) \Big[\delta(O(\Phi_R) - O) - \delta(O(\Phi_B) - O)\Big]$$

Used:

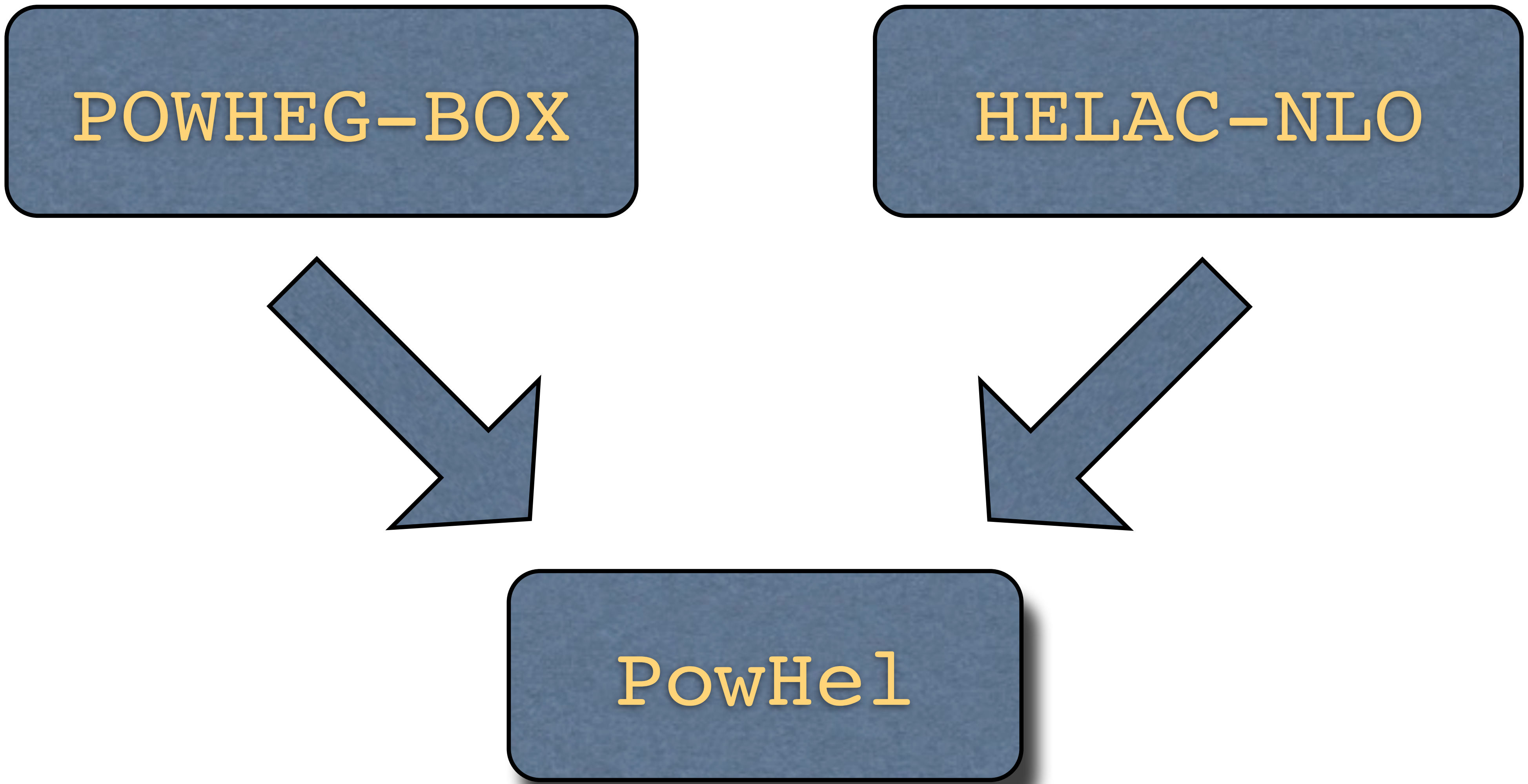
$$\Delta\Big(\Phi_B, k_\perp(\Phi_R)\Big) \frac{\tilde{B}(\Phi_B)}{B(\Phi_B)} = 1 + {\rm O}(\alpha_s)$$

Difference scales with the NLO K-factor

POWHEG-BOX framework



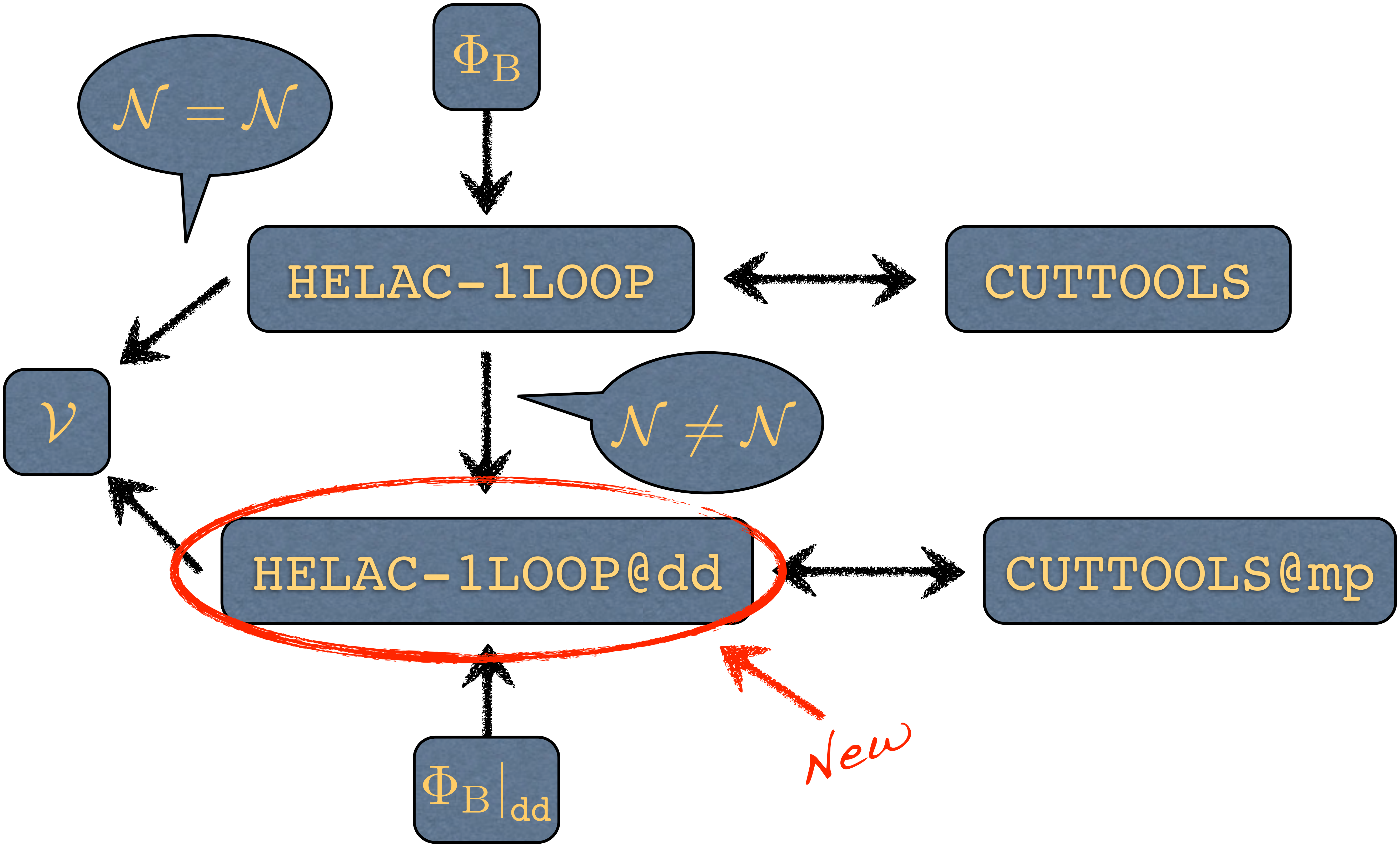
PowHel framework



RESULT of PowHel:

Les Houches file of Born and Born+1st radiation events (LHE) ready for processing with SMC followed by almost arbitrary experimental analysis

HELAC-1LOOP@dd framework



Checks of the NLO computation

- ✓ Check (implementation of) real emission squared matrix elements in POWHEG-BOX to those from HELAC-PHEGAS/MADGRAPH in randomly chosen phase space points
- ✓ Check (implementation of) virtual correction in POWHEG-BOX to those from HELAC-1Loop/GOSAM/MADLOOP 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

Each PowHel computation is an independent one of other NLO predictions for the process

(see e.g. arXiv: 1111.0610 for $t\bar{T}$ Z production)

What about spin-correlations?

Three approaches:

1. Complete at given order in PT: both resonant and non-resonant diagrams
2. Narrow-width approximation (NWA): only resonant contributions (spin correlations kept)
3. Decay-chain approximation (DCA): on-shell production times decay (off-shell and spin-correlation effects are lost)

increasing complexity

decreasing precision

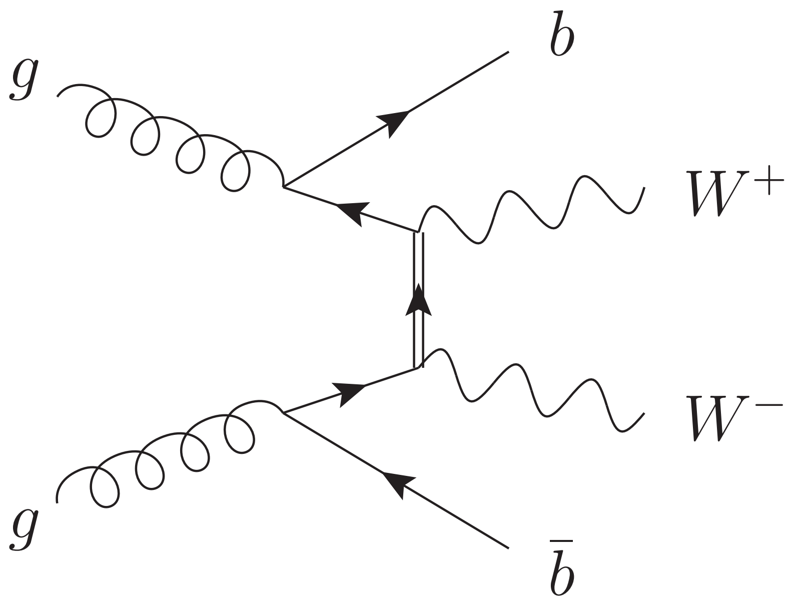
"3" implemented naturally in NLO+SMC

How to decay heavy particles?

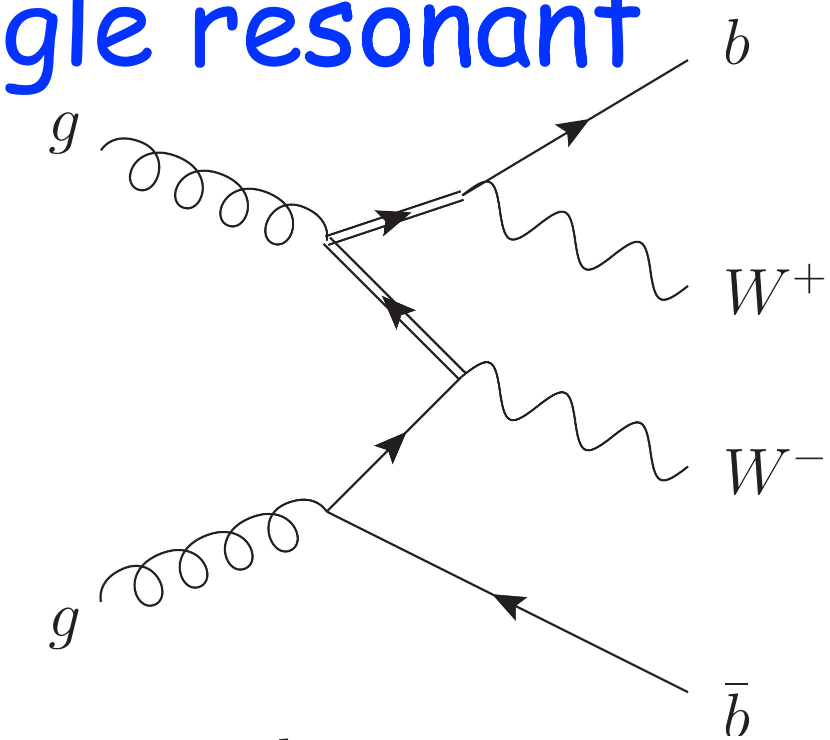
1. Decay at ME level:
   - Resonant, non-resonant graphs with spin correlations
   - CPU time increased
   - Possible different (extra) runs
2. Decay in SMC (DCA):
   - On-shell heavy objects
   - Easy to evaluate
   - No spin correlations, no off-shell effects
3. Decay with DECAYER (NWA): New!
   - Post event-generation run
   - With spin correlations and off-shell effects, but decays at LO accuracy
   - CPU efficient

$W^+ W^- b\bar{b}$ production

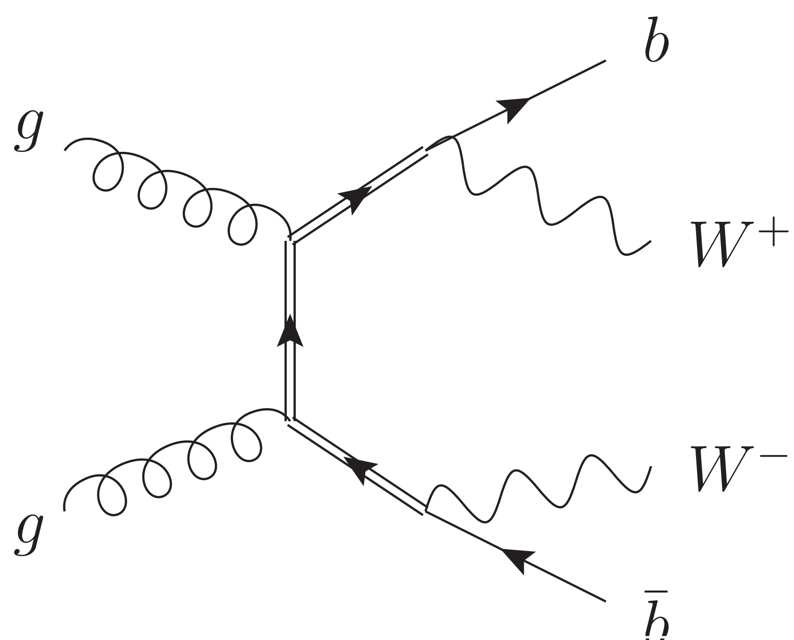
52 Born graphs



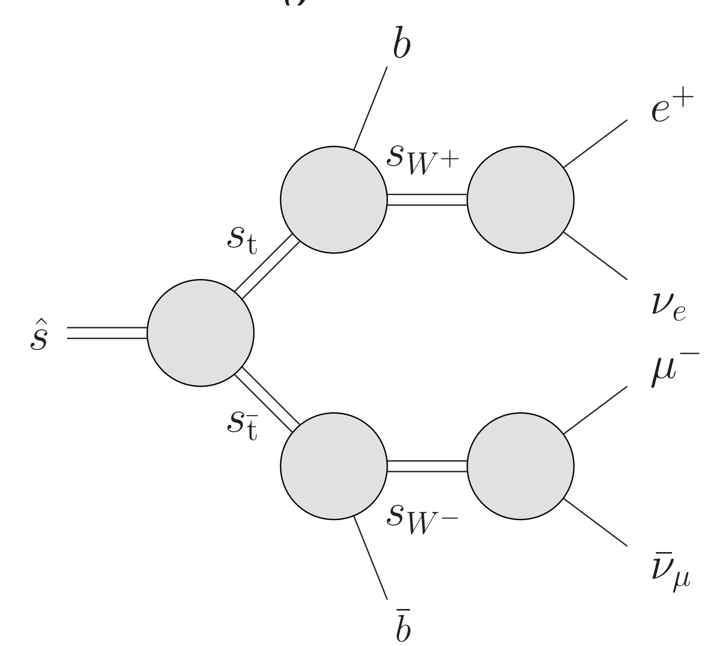
single resonant



non-resonant

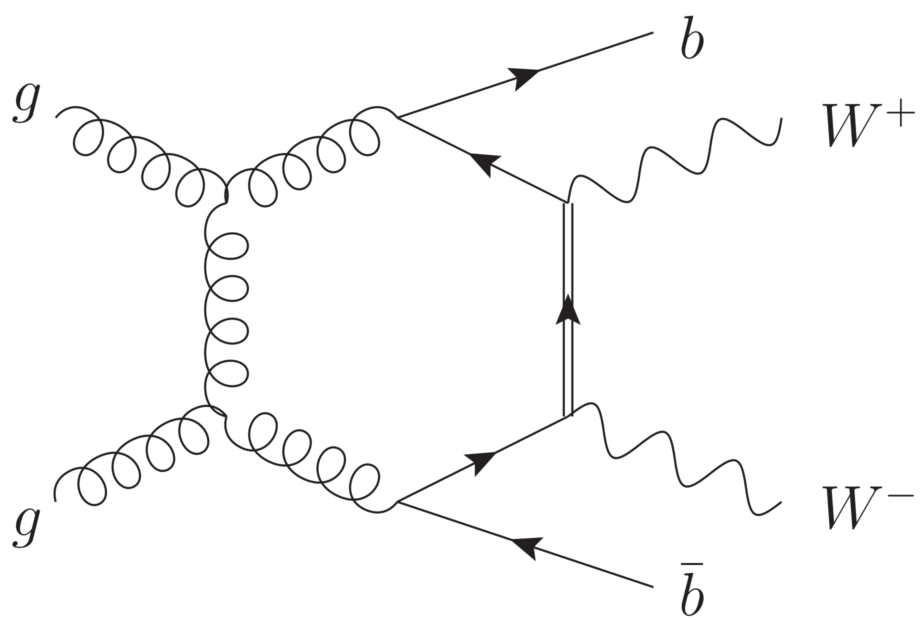


double resonant

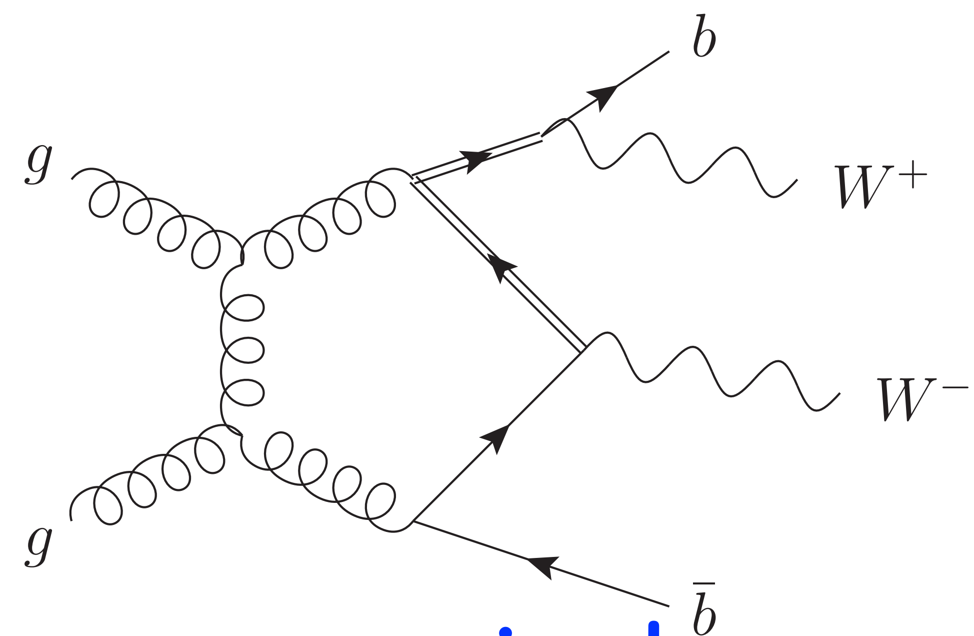


Born phase space

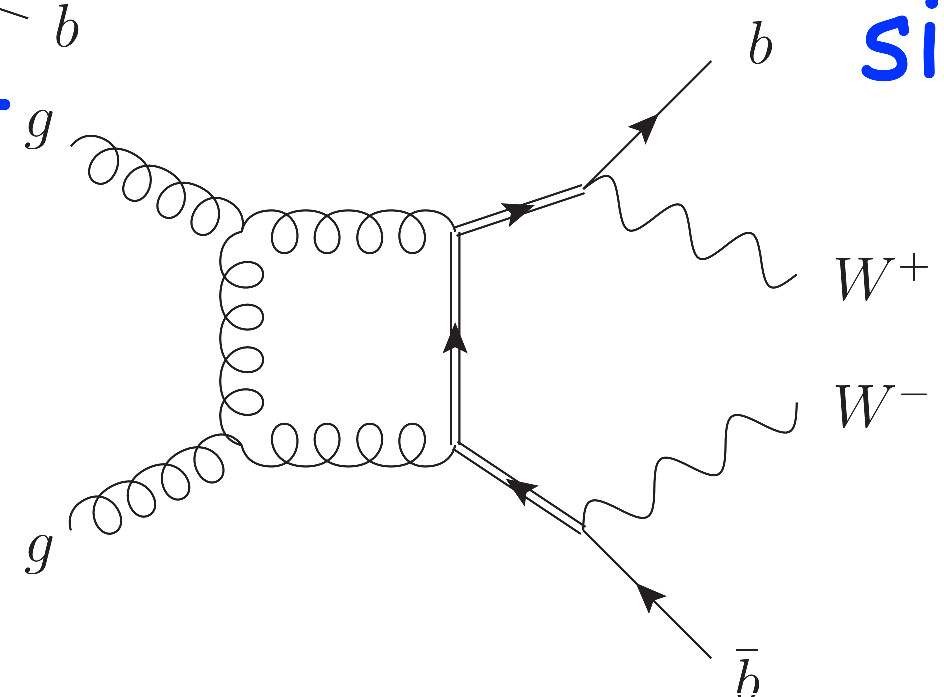
~1k one-loop graphs



non-resonant hexagon

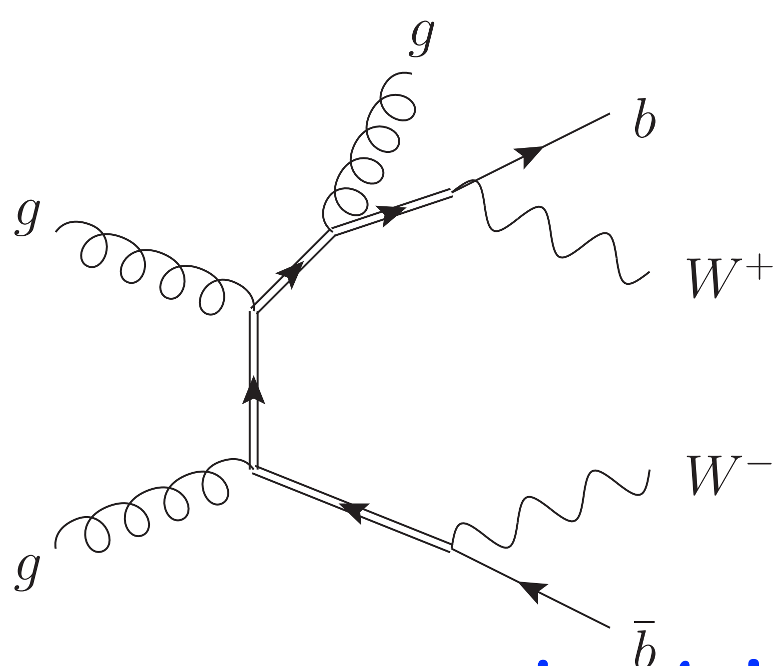


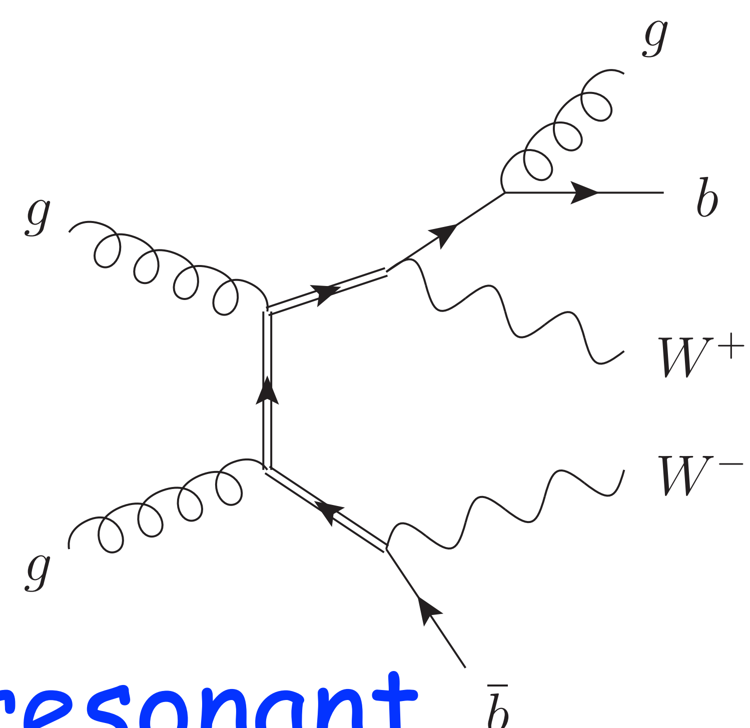
single resonant



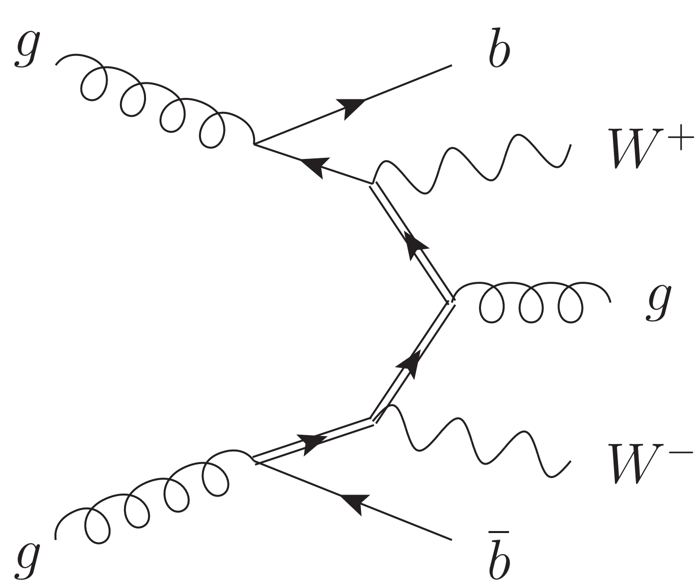
double resonant

Real emissions also from b-quarks

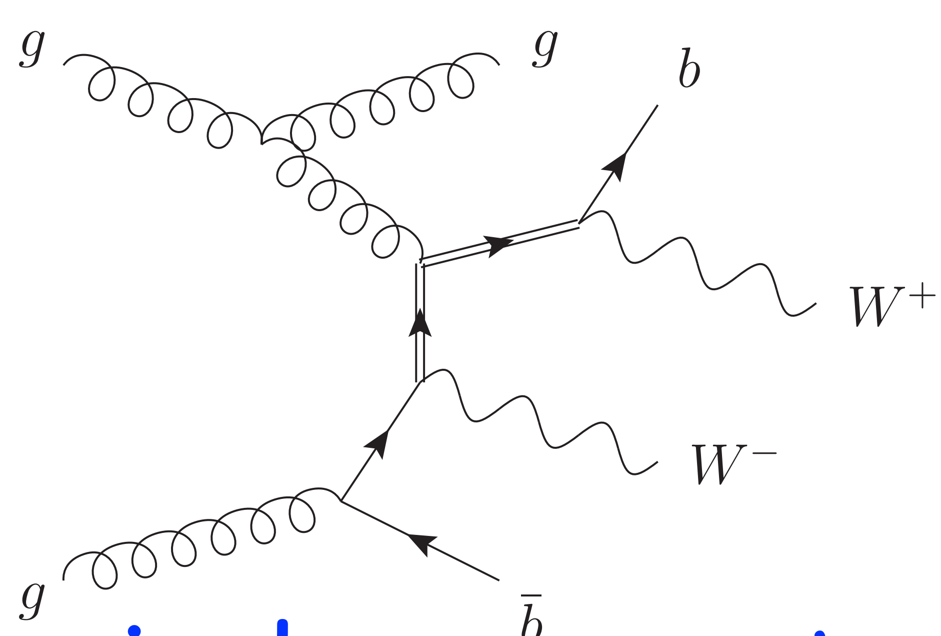




double resonant



non-resonant



single resonant

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$

- Based on the full NLO calculation of the $W^+ W^- b \bar{b}$ [Bevilacqua et. al. arXiv:1012.4230], but new
- Uses
  - complex mass scheme (everywhere)
  - generation cut: $p_{\perp b} > 2GeV$, $m_{bB} > 1GeV$
  - suppression factors of the Born singular region
- Comparison of LHEF to NLO made for the 7 TeV LHC, with a setup listed in arXiv:1012.4230:
  - fixed scale $\mu = m_t$ and PDG parameters, CTEQ6M

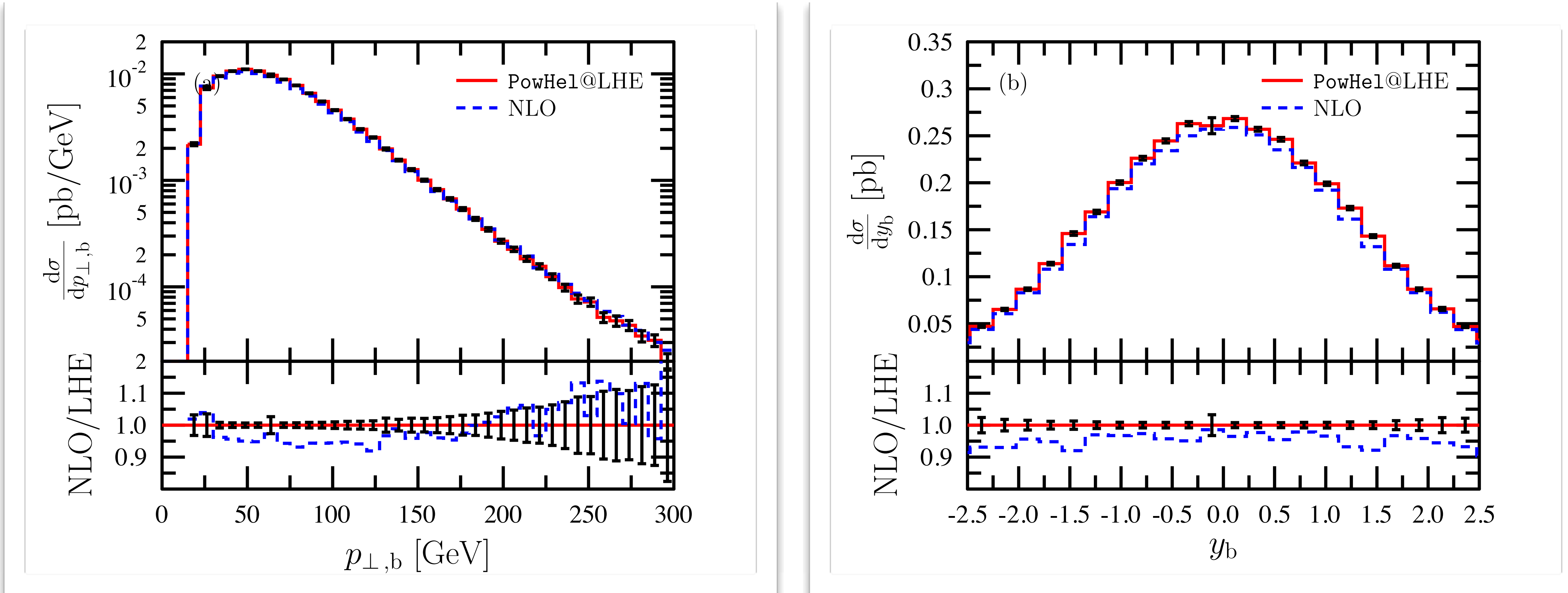
Accuracy of the POWHEG cross section

$$\frac{d\sigma_{\mathrm{LHE}}}{dO} = \frac{d\sigma_{\mathrm{NLO}}}{dO} + \mathrm{O}(\alpha_{\mathrm{s}}) \int d\Phi_R R(\Phi_R) \Big[\delta(O(\Phi_R) - O) - \delta(O(\Phi_B) - O)\Big]$$

Useful for checking

Difference scales with the NLO K-factor

$pp \to e^{+} \nu_{e} \mu^{-} \bar{\nu}_{\mu} b\bar{b} + X$

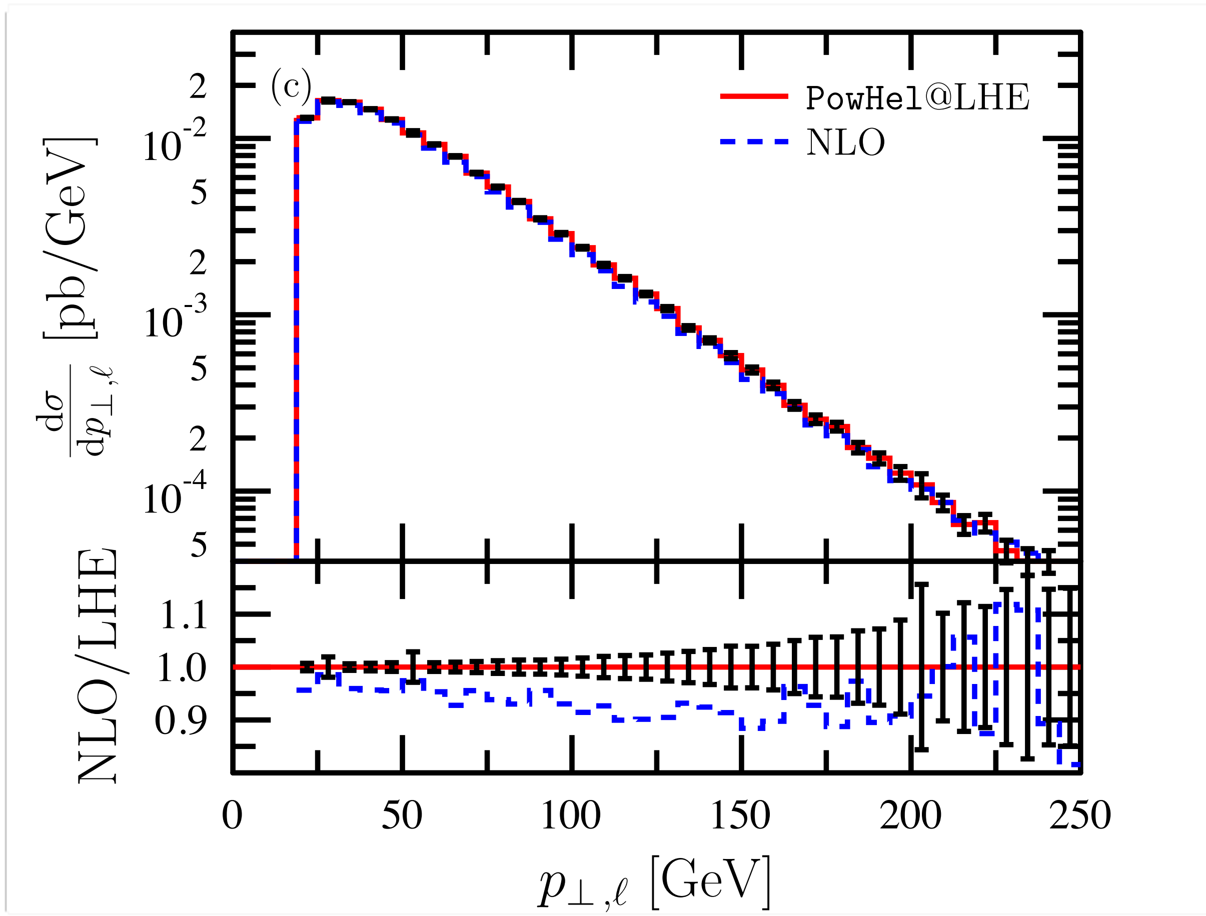


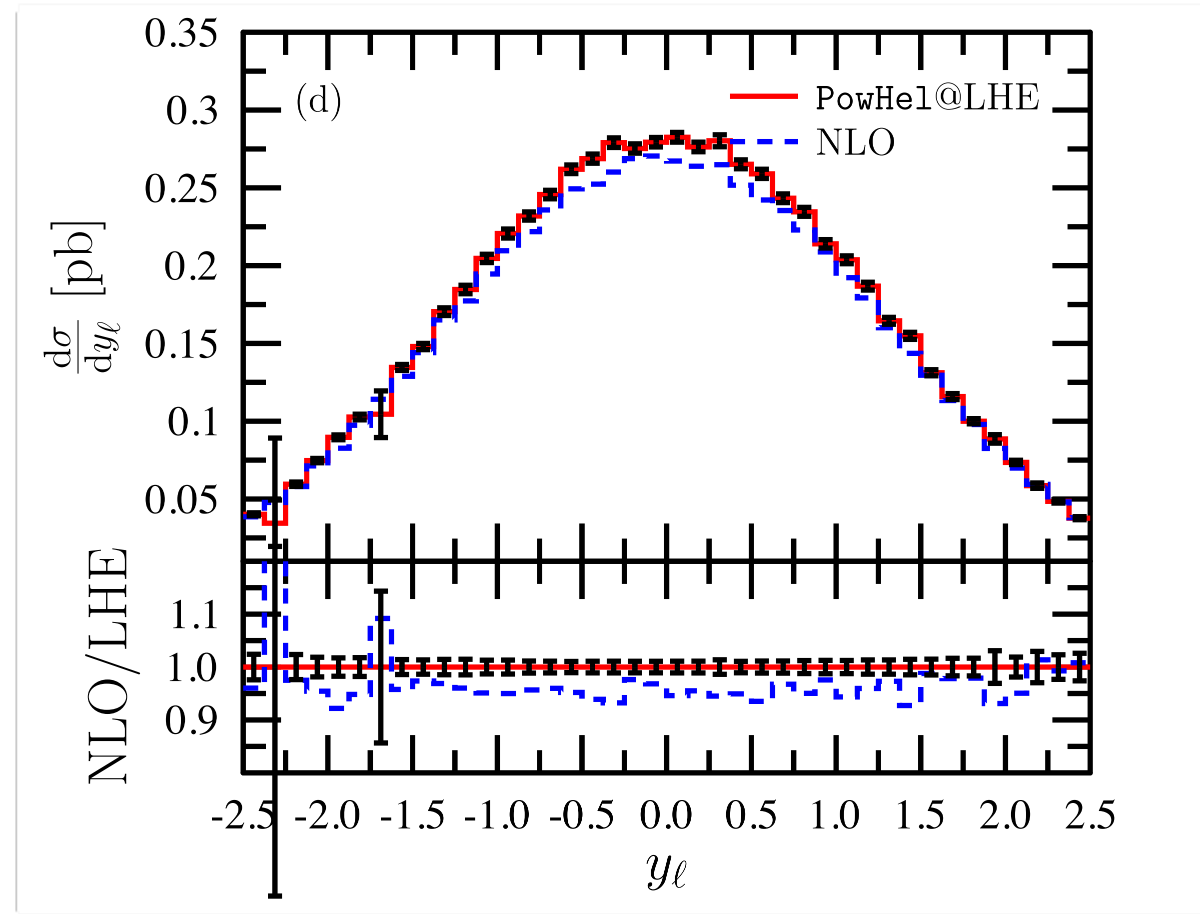
Transverse momentum and rapidity distribution for the b at 7TeV LHC

agreement is within 5%, Remember: $\sigma_{LHE} = \sigma_{NLO} + O(\alpha_s)$ Finite

[inclusive NLO K-factor is large (~1.5)]

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



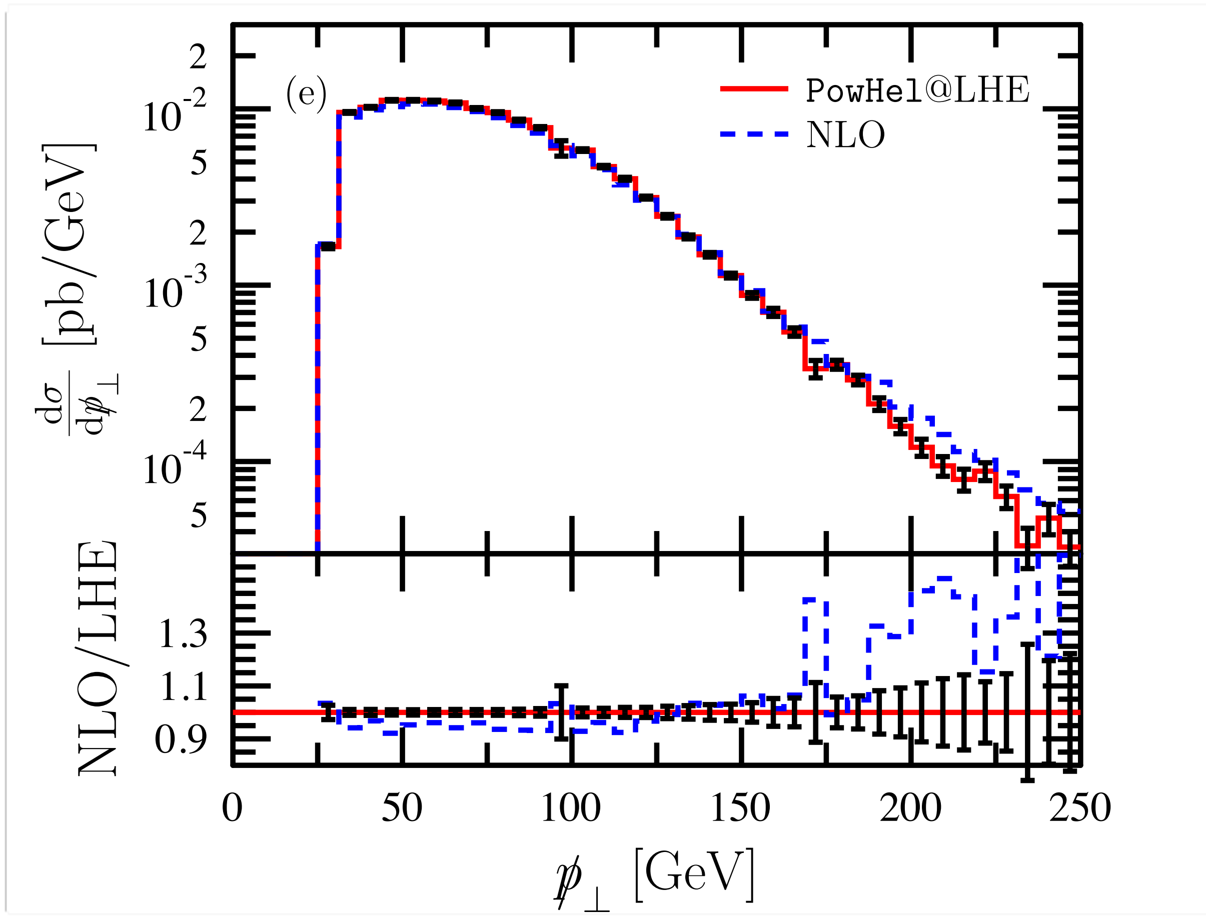


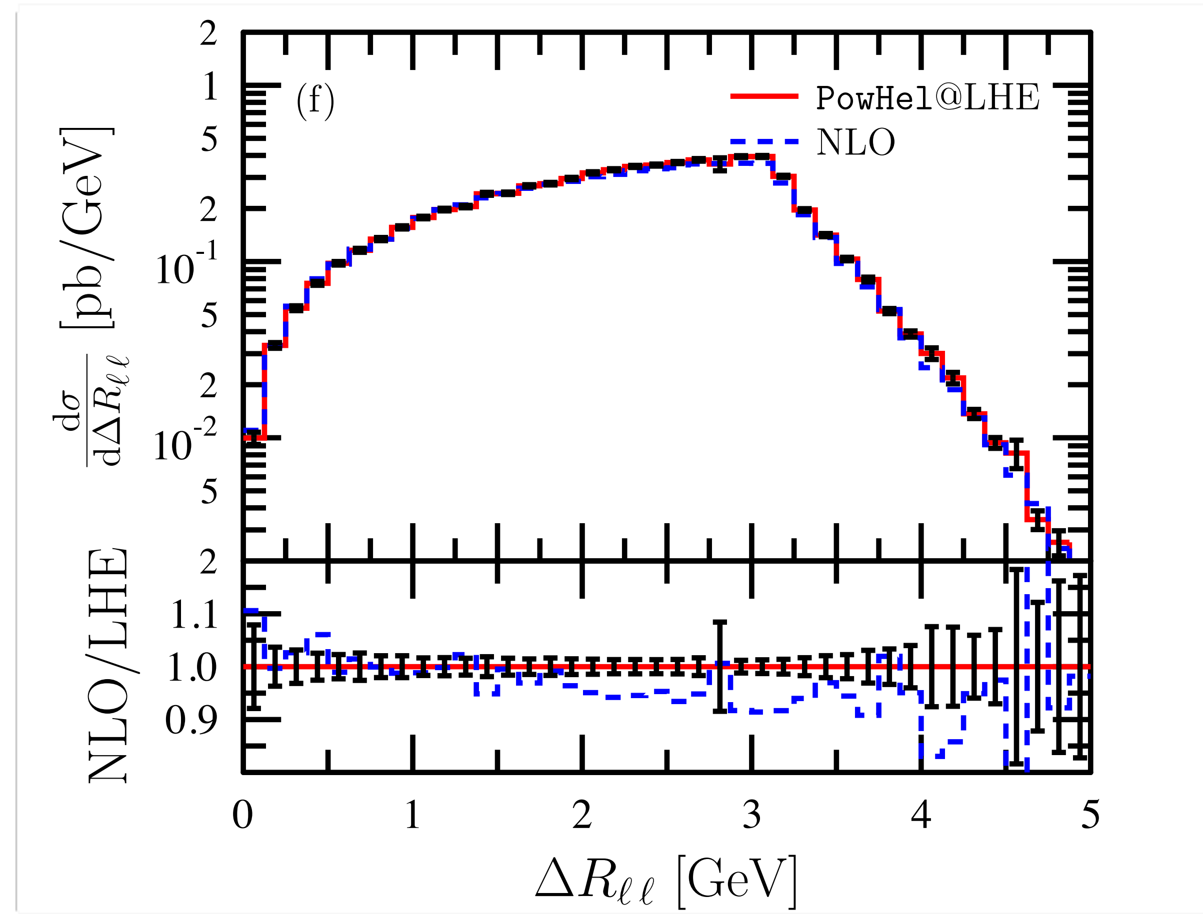
Transverse momentum, rapidity of the positron at 7TeV LHC

agreement is within 10%, Remember: $\sigma_{LHE} = \sigma_{NLO} + O(\alpha_s)$ Finite

[inclusive NLO K-factor is large (~1.5)]

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$





Missing transverse momentum, R-separation of the charged leptons at 7TeV LHC

missing pT differ above 150 GeV, $\sigma_{LHE} = \sigma_{NLO} + O(\alpha_s)$ Finite

differential NLO K-factor > 2 (3) above 150 (200) GeV

$pp \to t\,\bar{t}$ + Z, H, A, jet

Similar, or better agreement between NLO and LHE

(discussed elsewhere)

Predictions

$$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$$

Predictions for LHC at 7 TeV

Goal:

to check effect of various approximations to decays and provide reliable predictions at hadron level

Cuts:

- anti-$k_\perp$, R=0.4
- $|\eta_{trk}|$, $|\eta_j| < 5$, $|\eta_{b\text{-}jet}| < 3$, $|\eta_l| < 2.5$
- $p_\perp^j$, $p_\perp^l > 20$ GeV, $\not{p}_\perp > 30$ GeV,
- $\Delta R_{jl} > 0.4$
- at least one anti-b, b-jet, one isolated l^+ and l^-

Inclusive cross sections

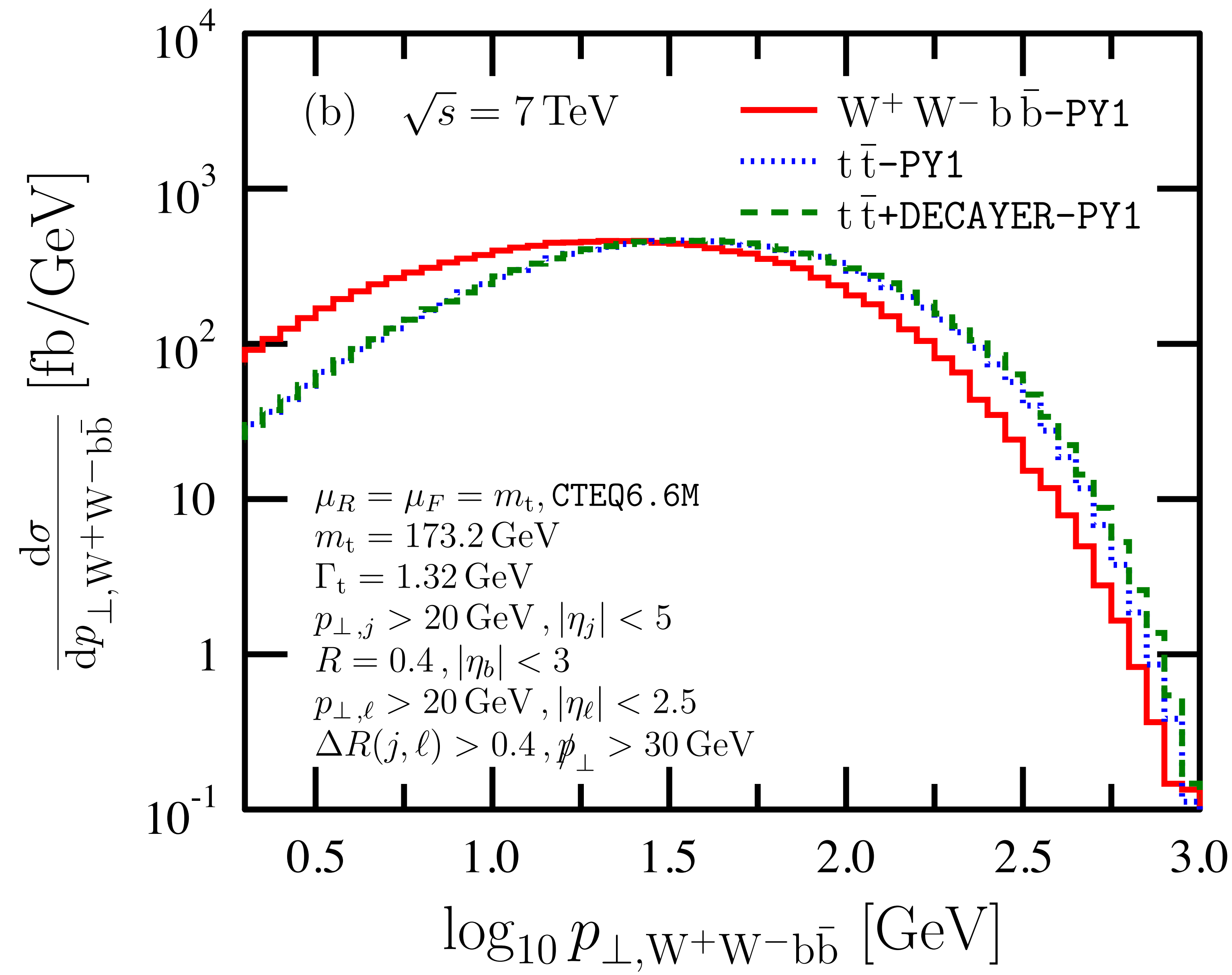
Effect of the PS/SMC:

	cuts (1–6)	cuts (1–6) + jet veto
σ_{LHE} (fb)	844 ± 3	460 ± 2
σ_{PS} (fb)	689 ± 3	416 ± 2
σ_{SMC} (fb)	633 ± 3	406 ± 2

Effect of the different decays:

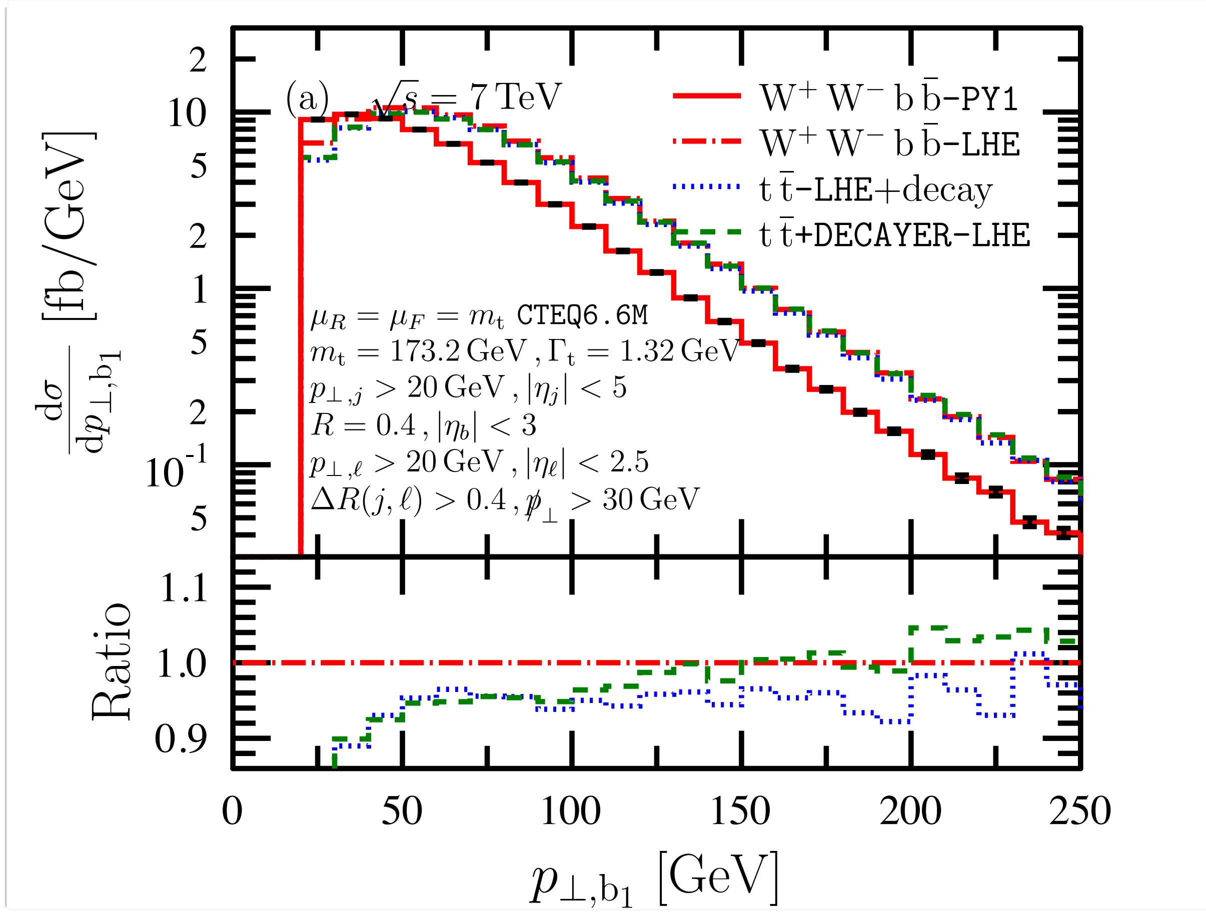
R/case	case 1	case 2	case 3
$\sigma(R = 0.4)$ (fb)	651.1 ± 2.8	572.5 ± 0.3	574.8 ± 0.5
$\sigma(R = 1.2)$ (fb)	685.9 ± 3.3	623.7 ± 0.3	623.1 ± 0.5

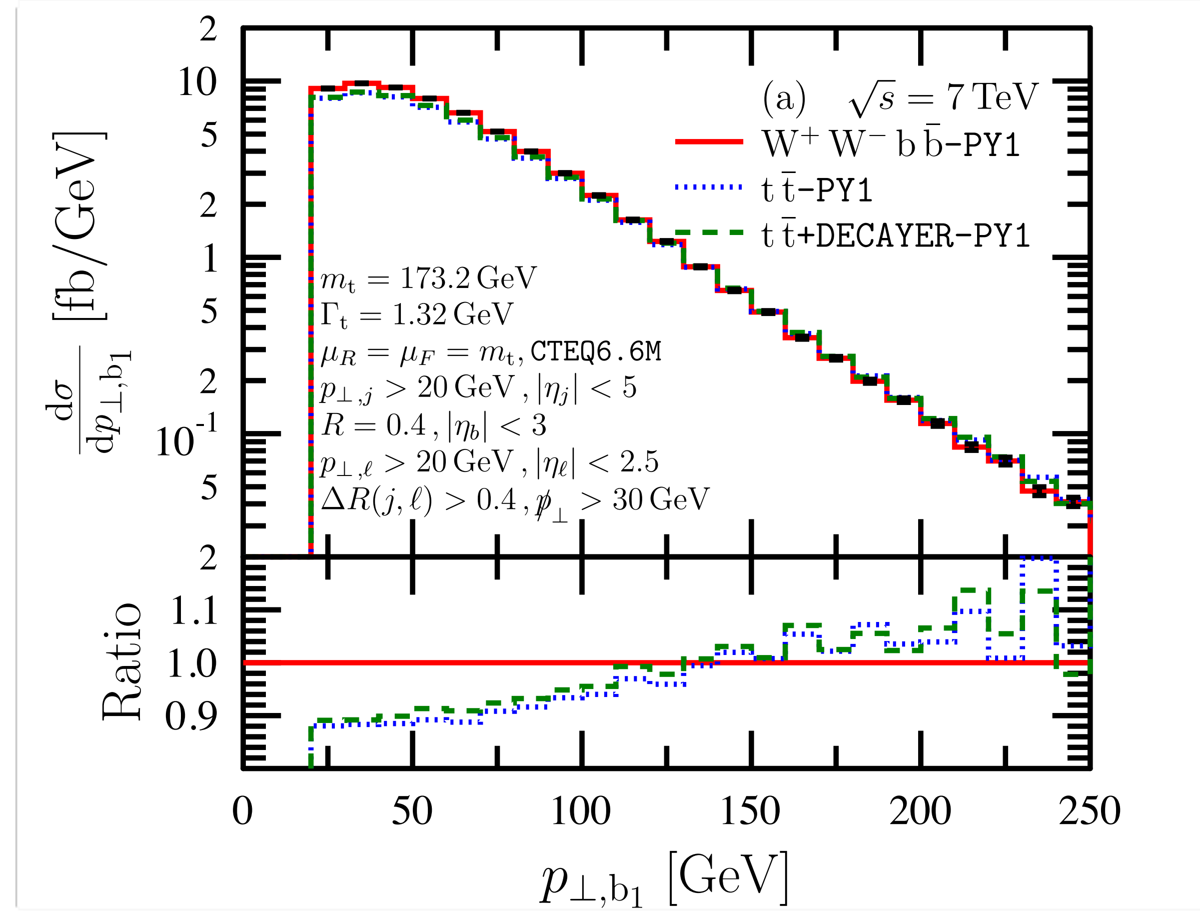
$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



Sudakov suppression at small $p_\perp$, main source of difference is origin of first radiation: from b in WWbB, from t in tT

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}+X$



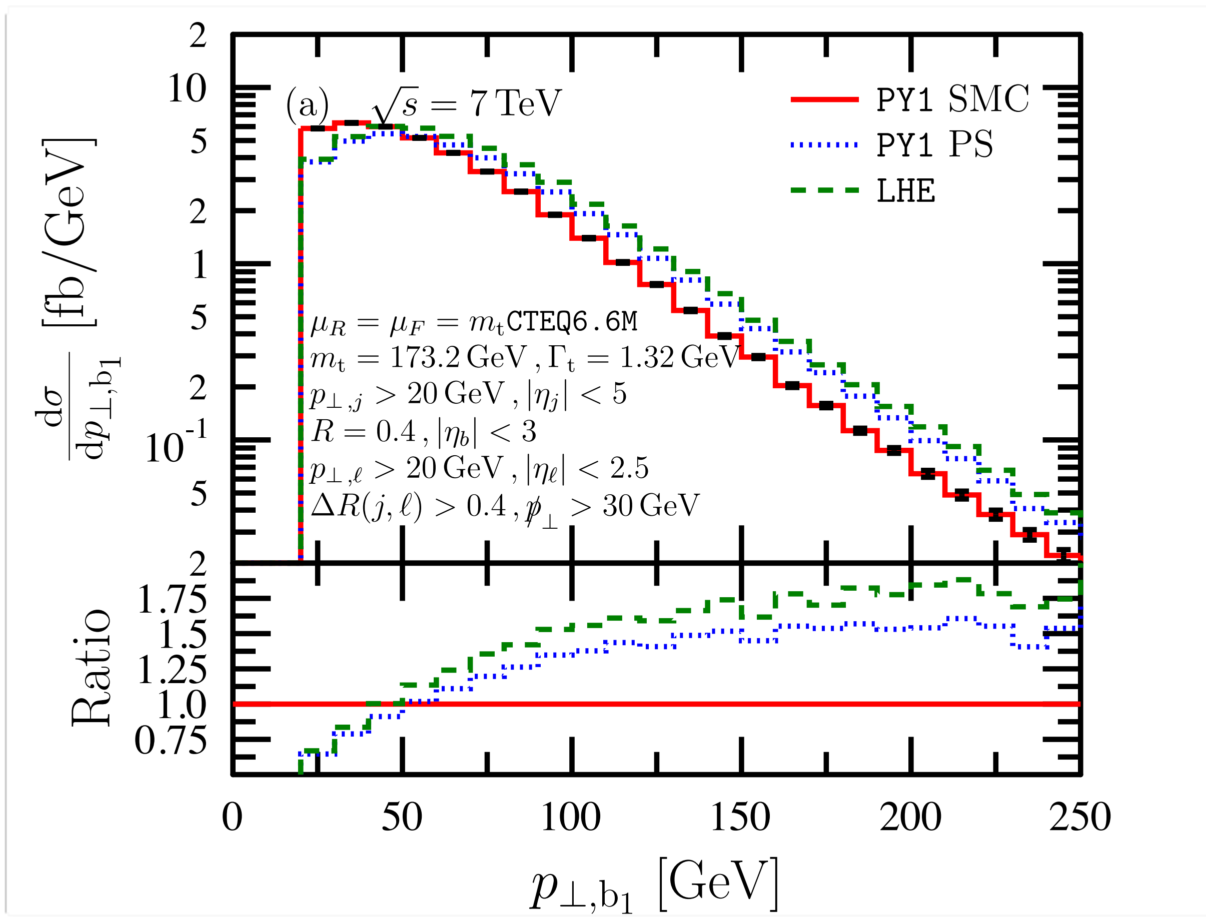


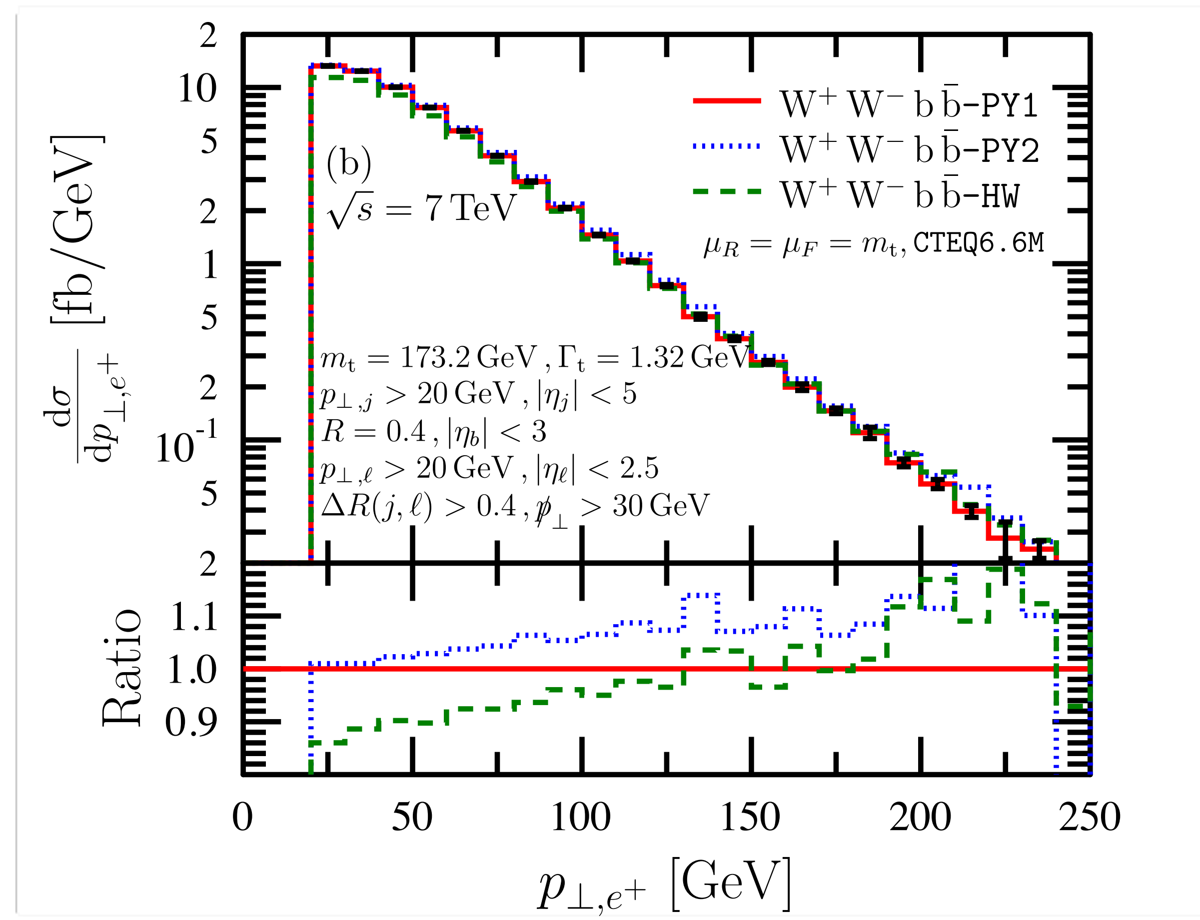
Transverse momentum of b-jet before/after SMC at 7TeV LHC

Effect of NWA vs DCA negligible

full vs NWA small

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



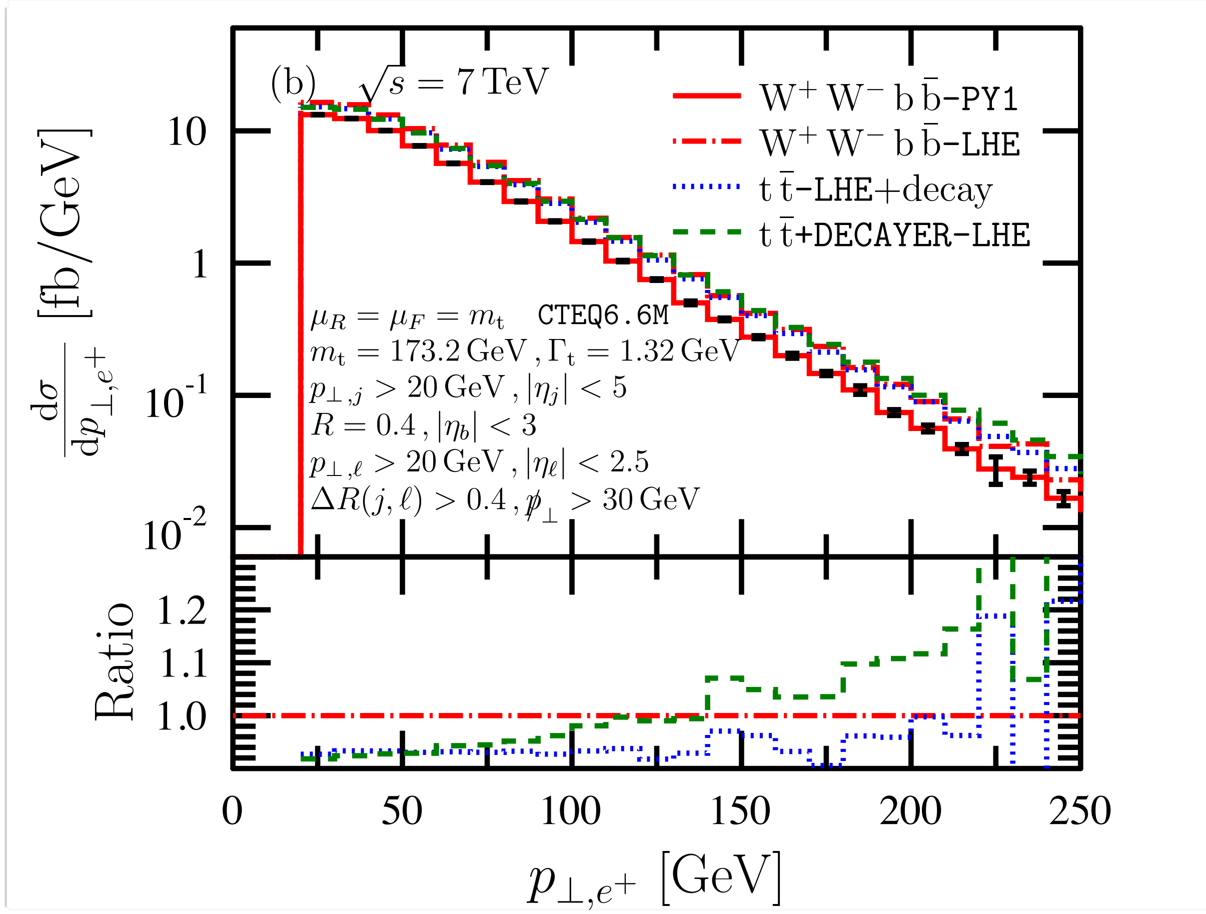


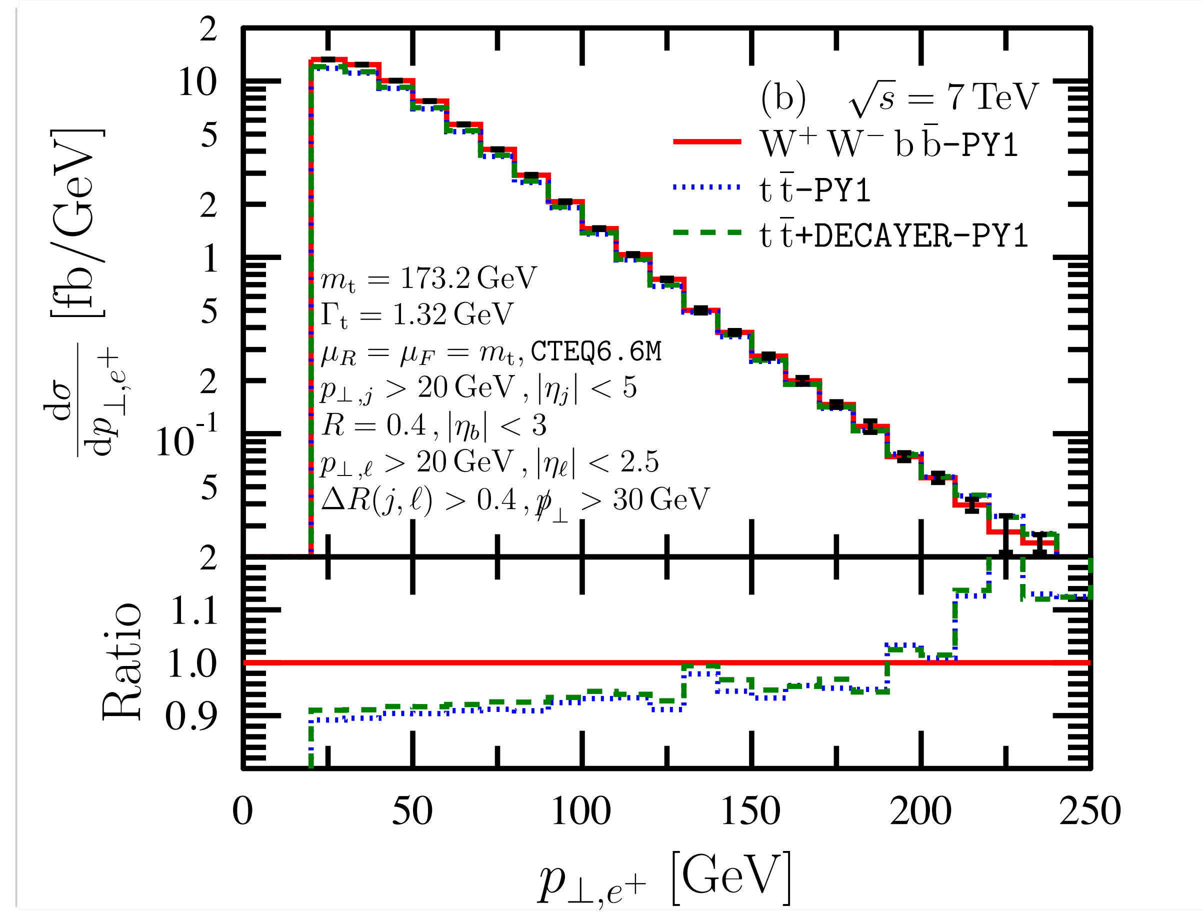
Transverse momentum of b-jet before/after PS/SMC at 7TeV LHC

Effect of PS 0-20%,

hadronization large

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



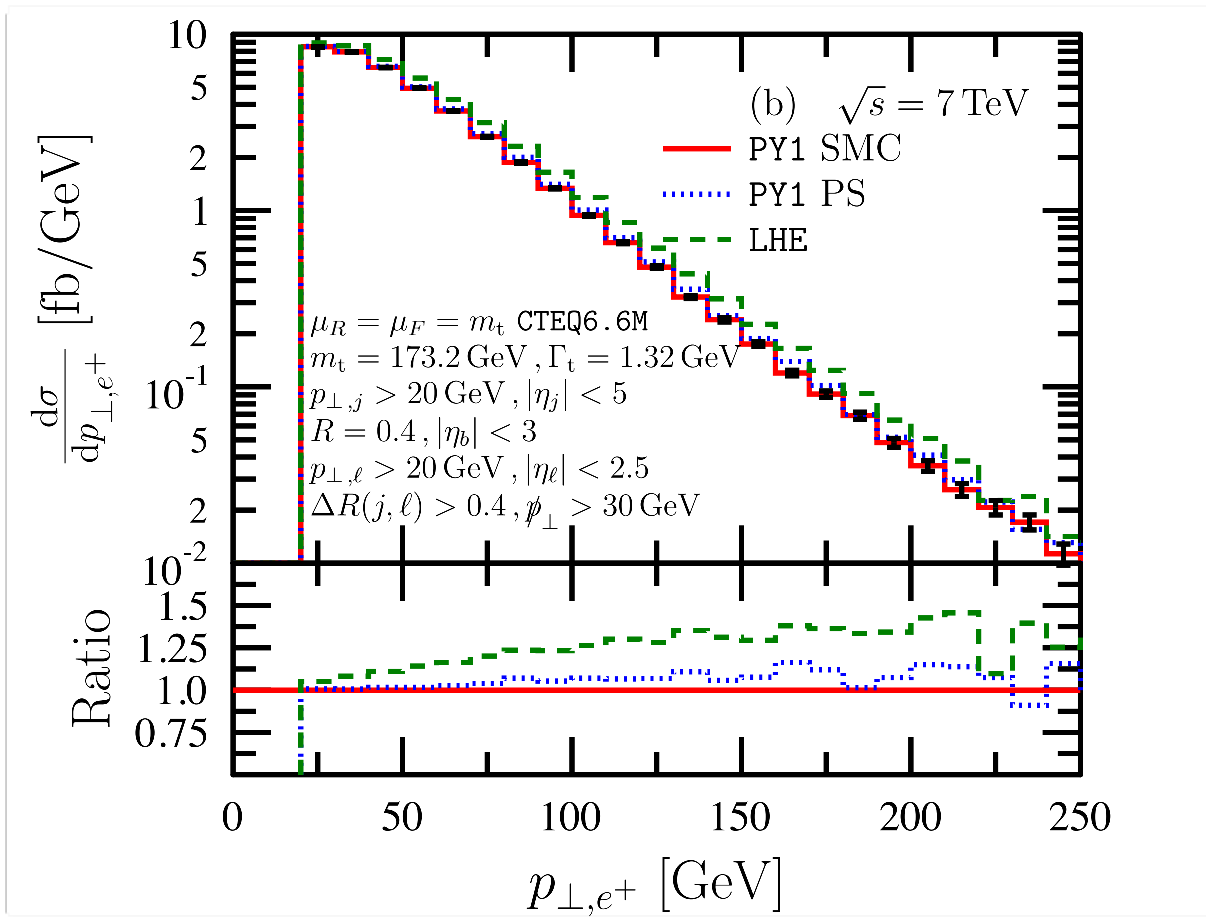


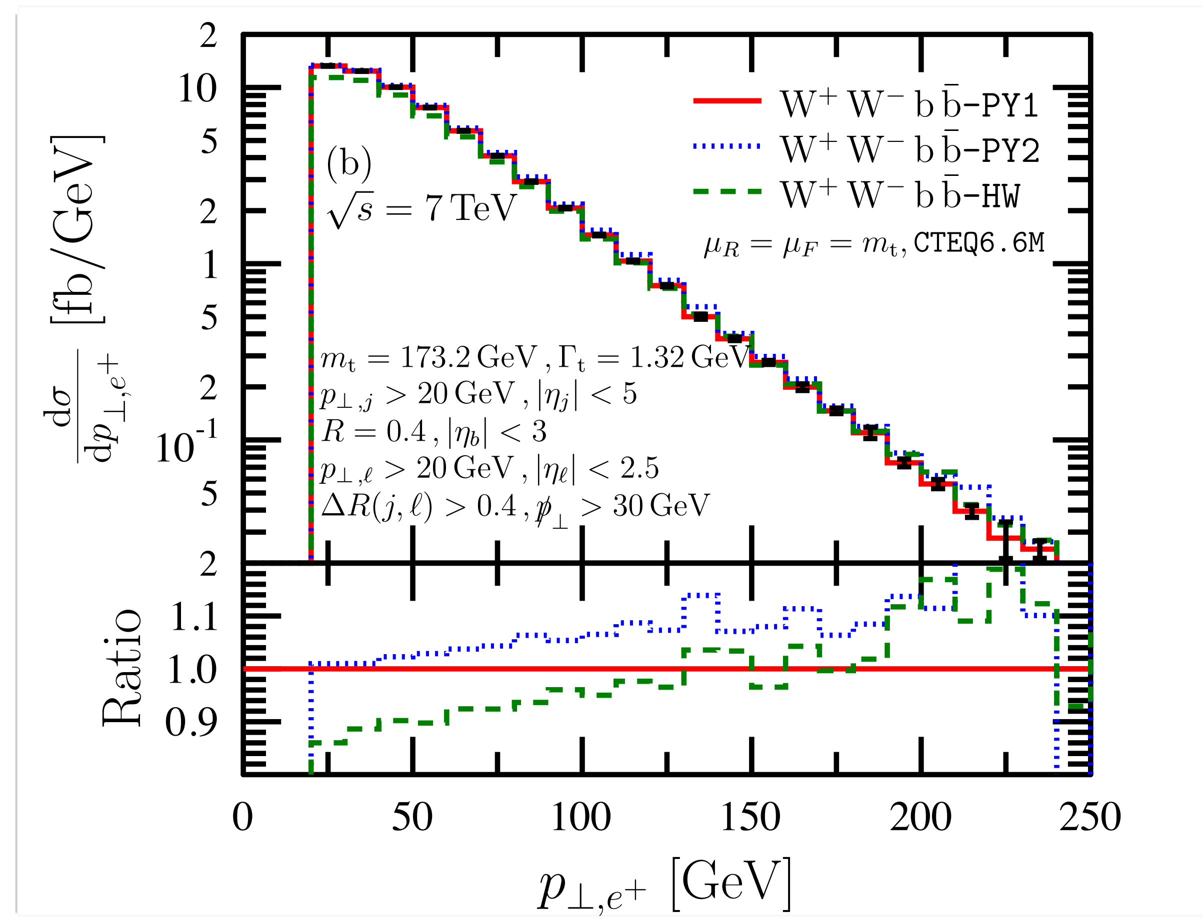
Transverse momentum of positron before/after SMC at 7TeV LHC

Effect of NWA vs DCA negligible

full vs NWA small

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



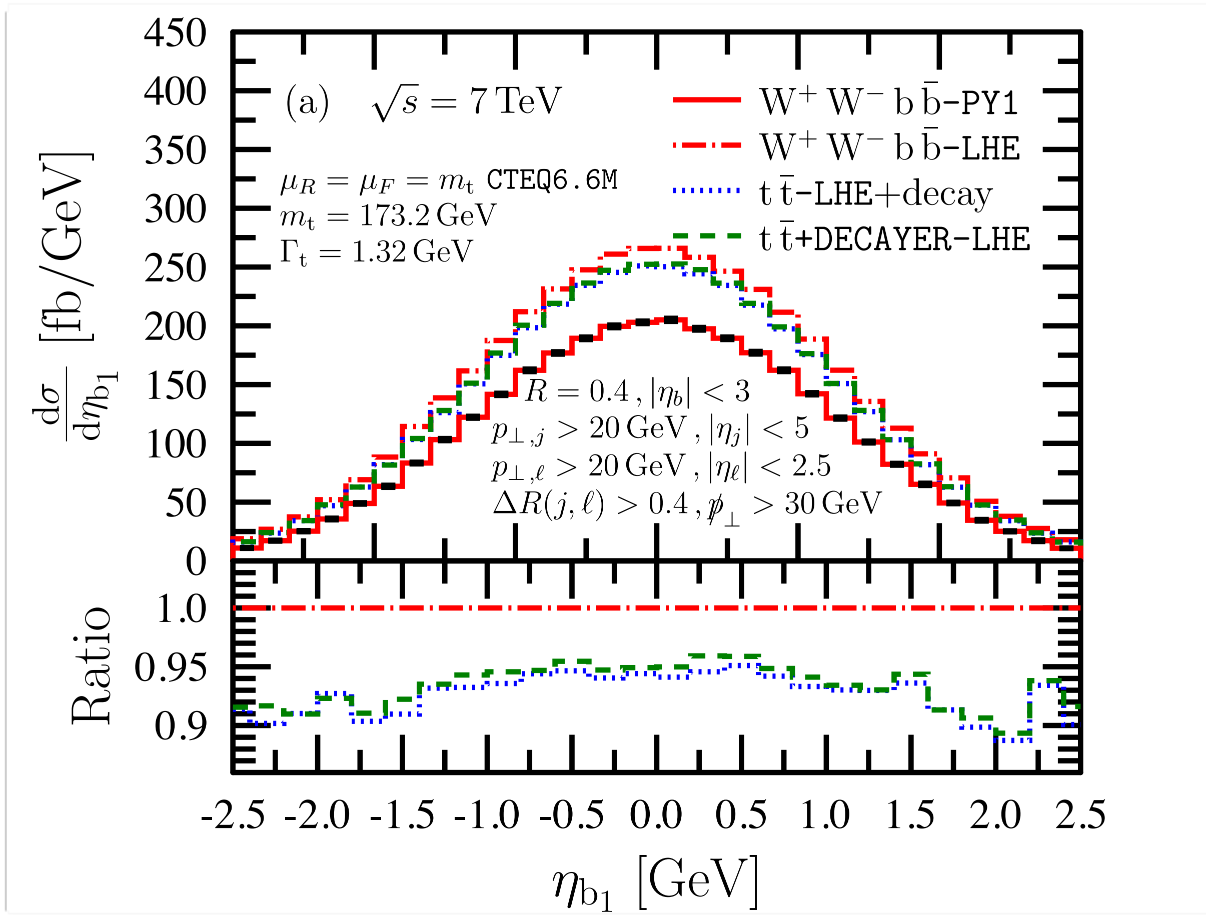


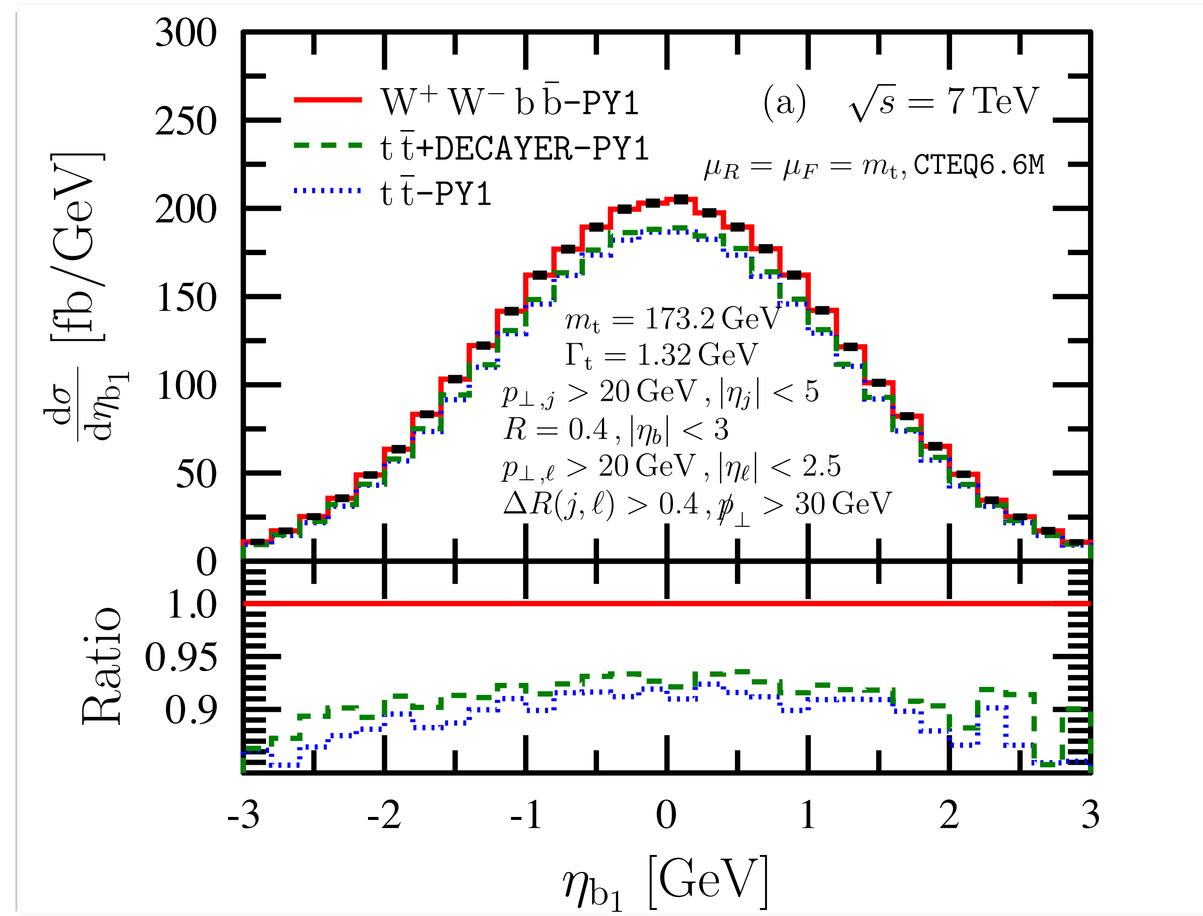
Transverse momentum of positron before/after PS/SMC at 7TeV LHC

Effect of PS 0-20%,

hadronization small

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



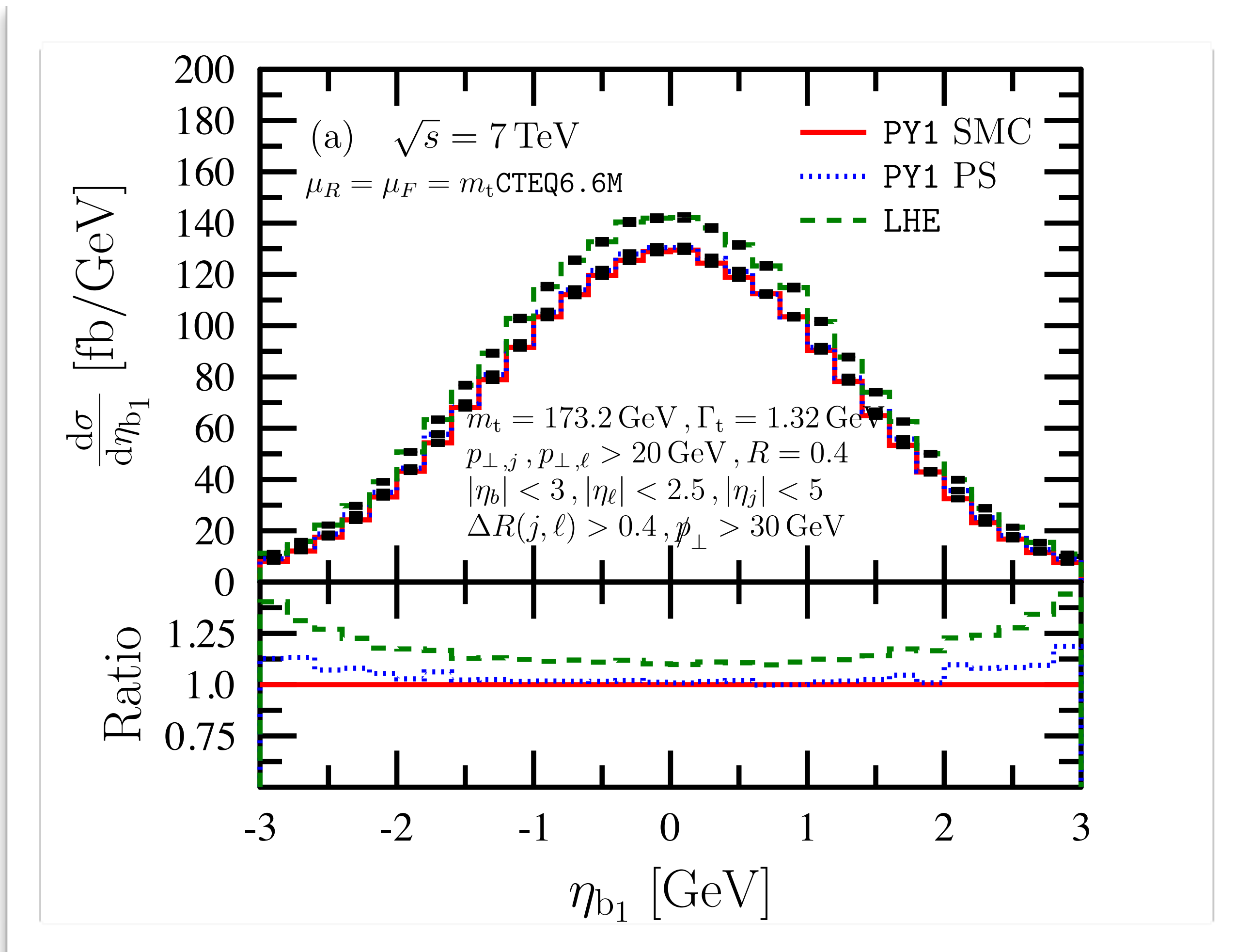


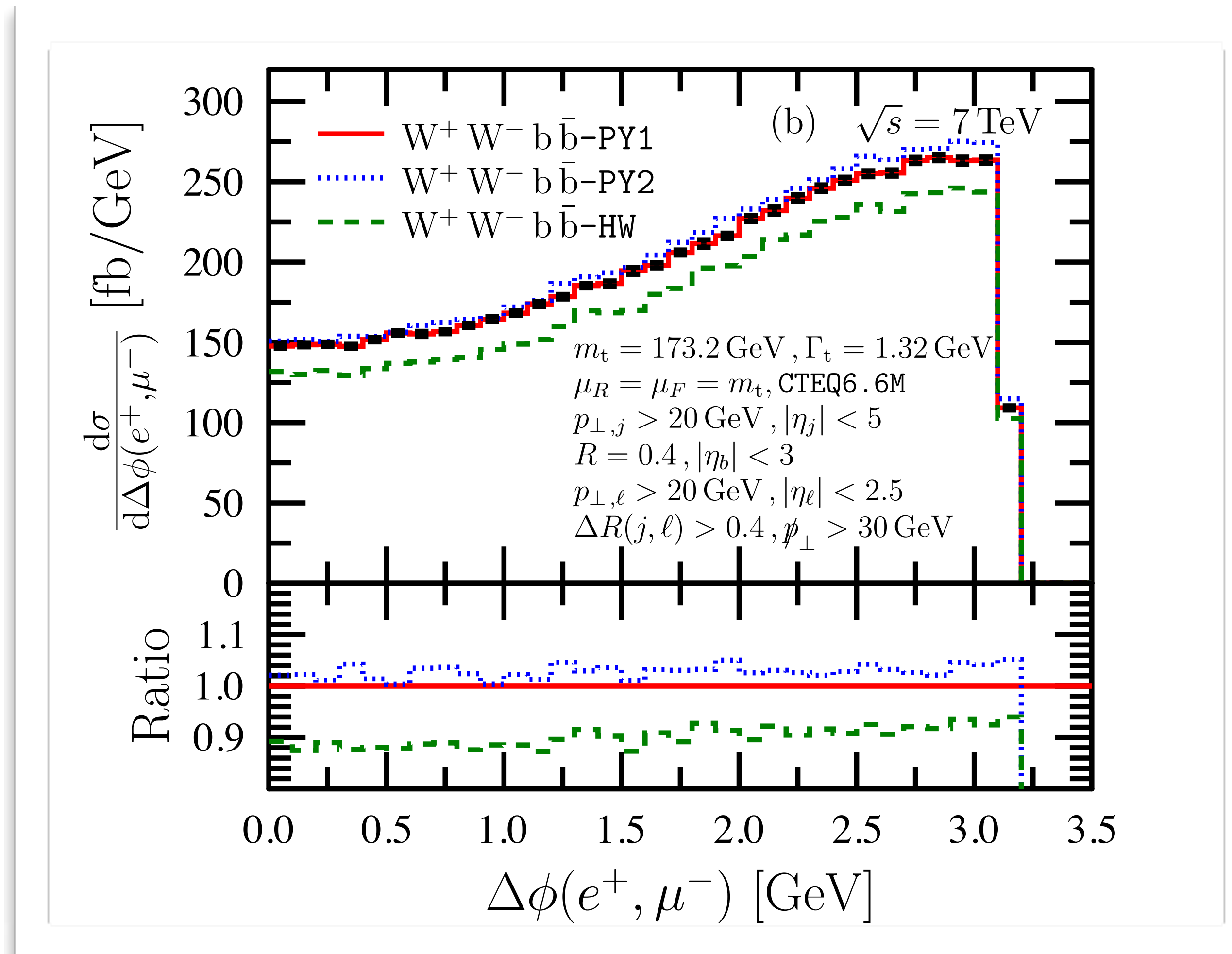
Pseudorapidity of b-jet before/after SMC
at 7TeV LHC

Effect of NWA vs DCA negligible

full vs NWA differ mainly in normalization, slightly in shape

$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



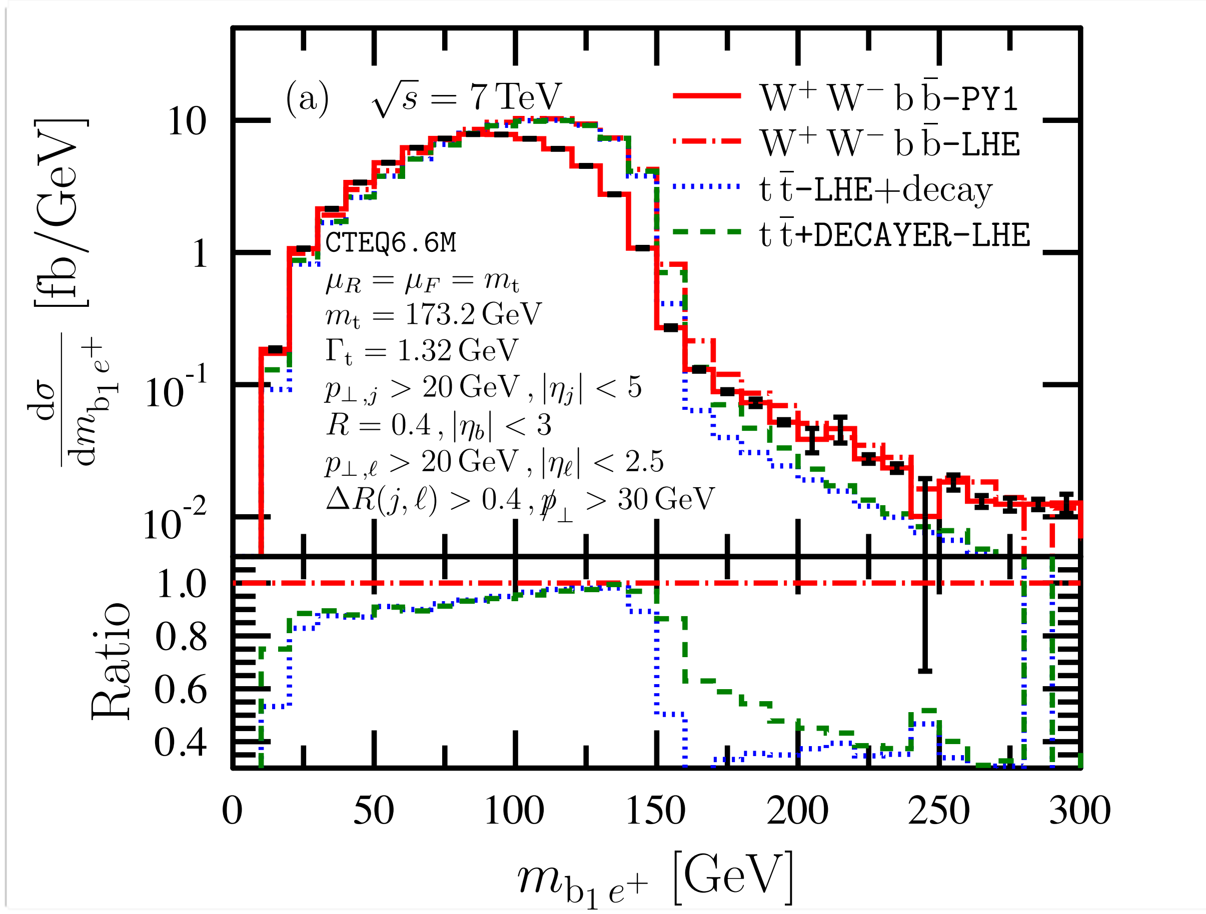


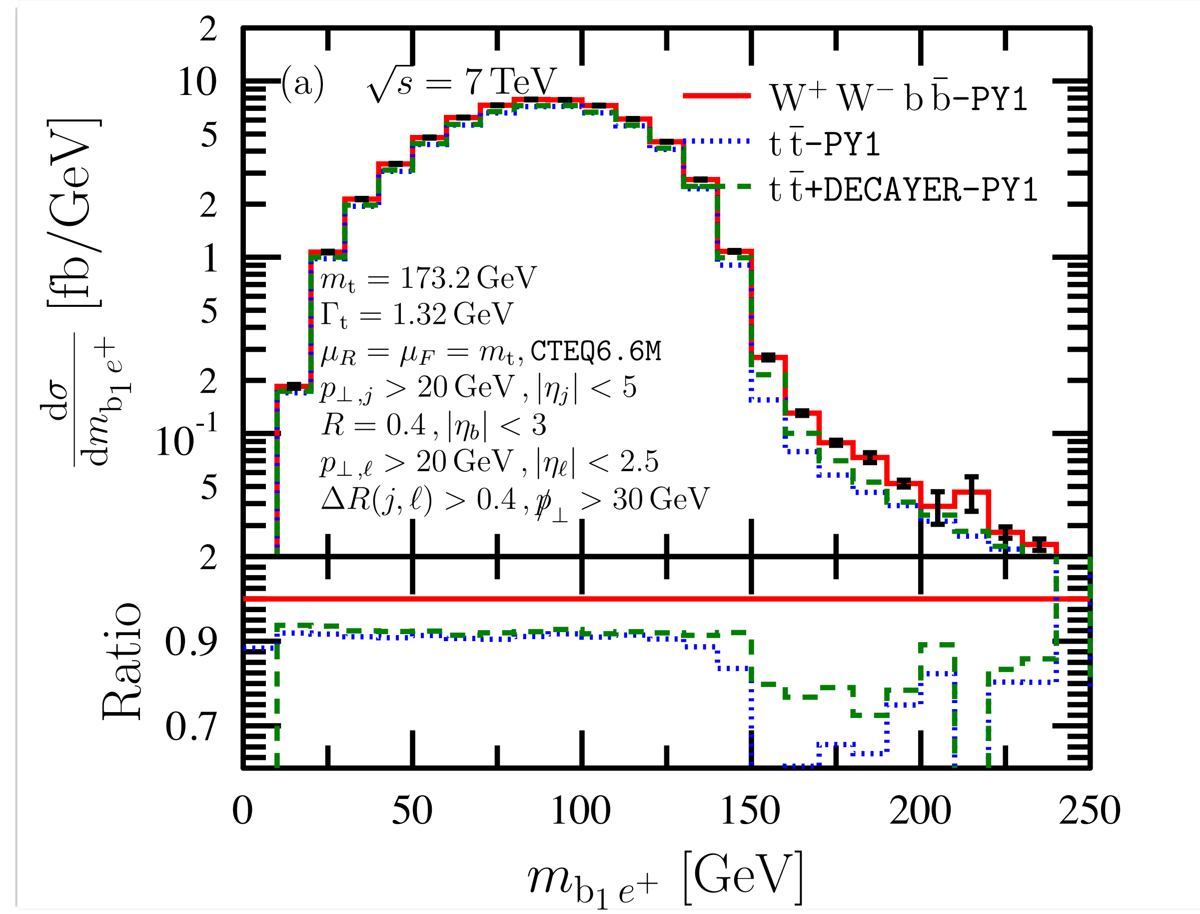
Pseudorapidity of b-jet before/after PS/SMC at 7TeV LHC

Effect of PS 15-20%,

hadronization small

$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



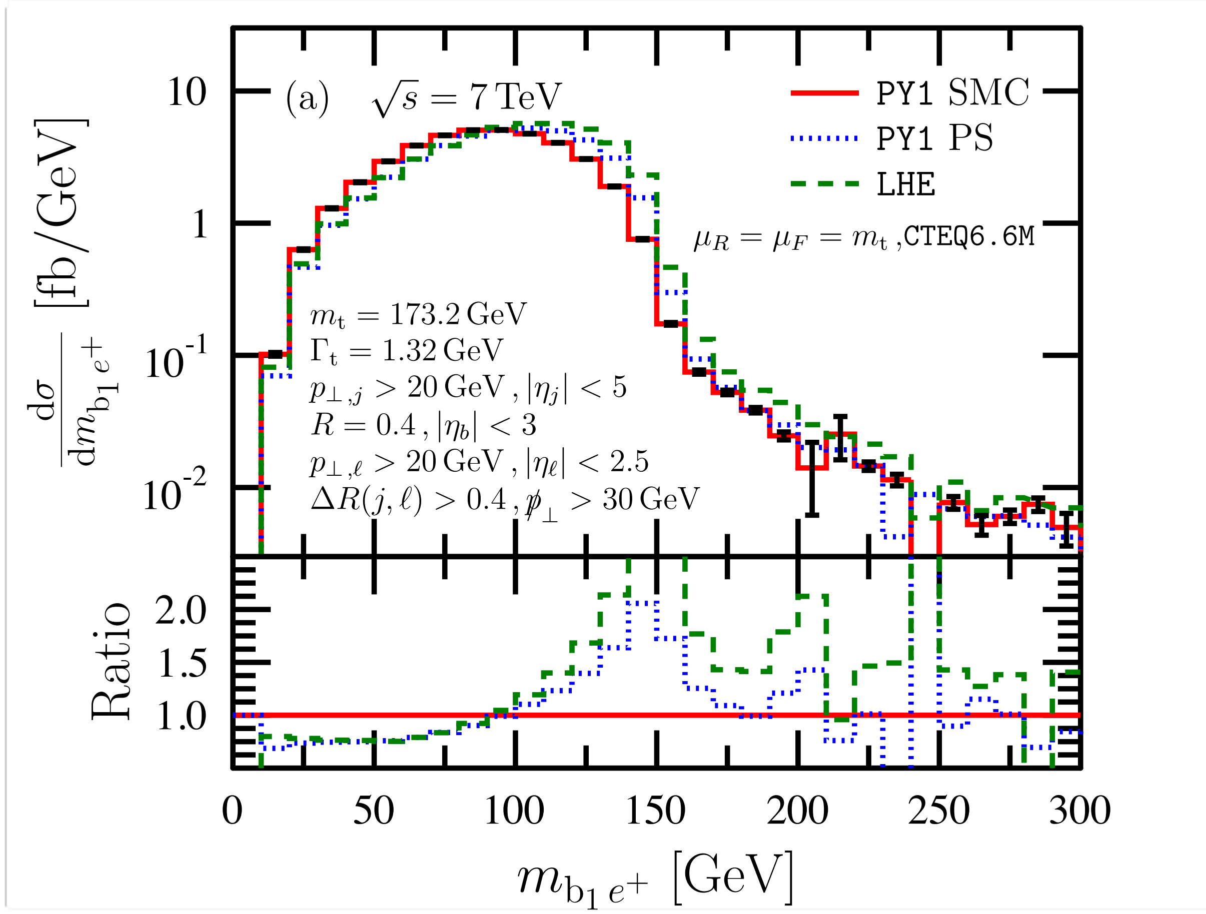


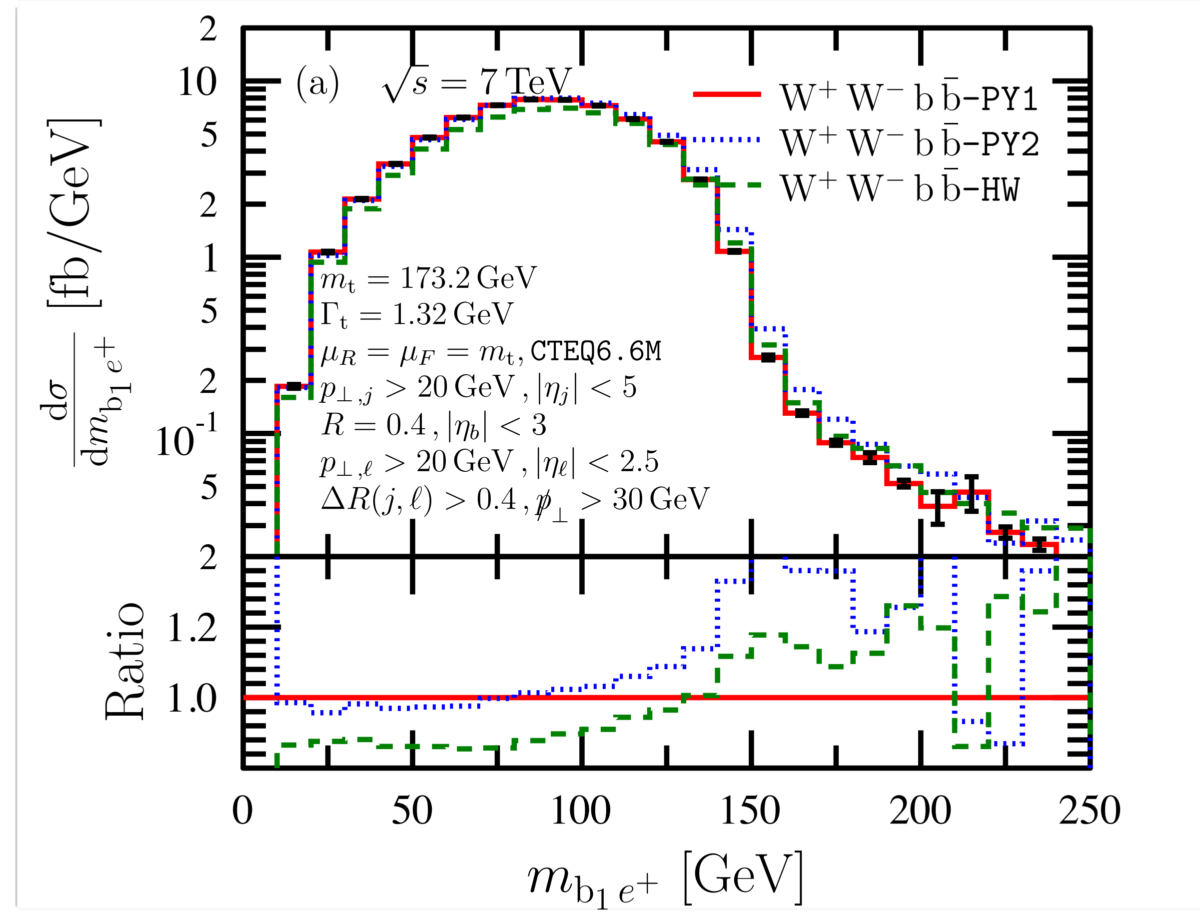
Invariant mass of positron and b-jet before/after SMC at 7TeV LHC

Effect of NWA vs DCA small

full vs NWA ~10% below, ~30% above 150 GeV

pp→ $e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}$+X



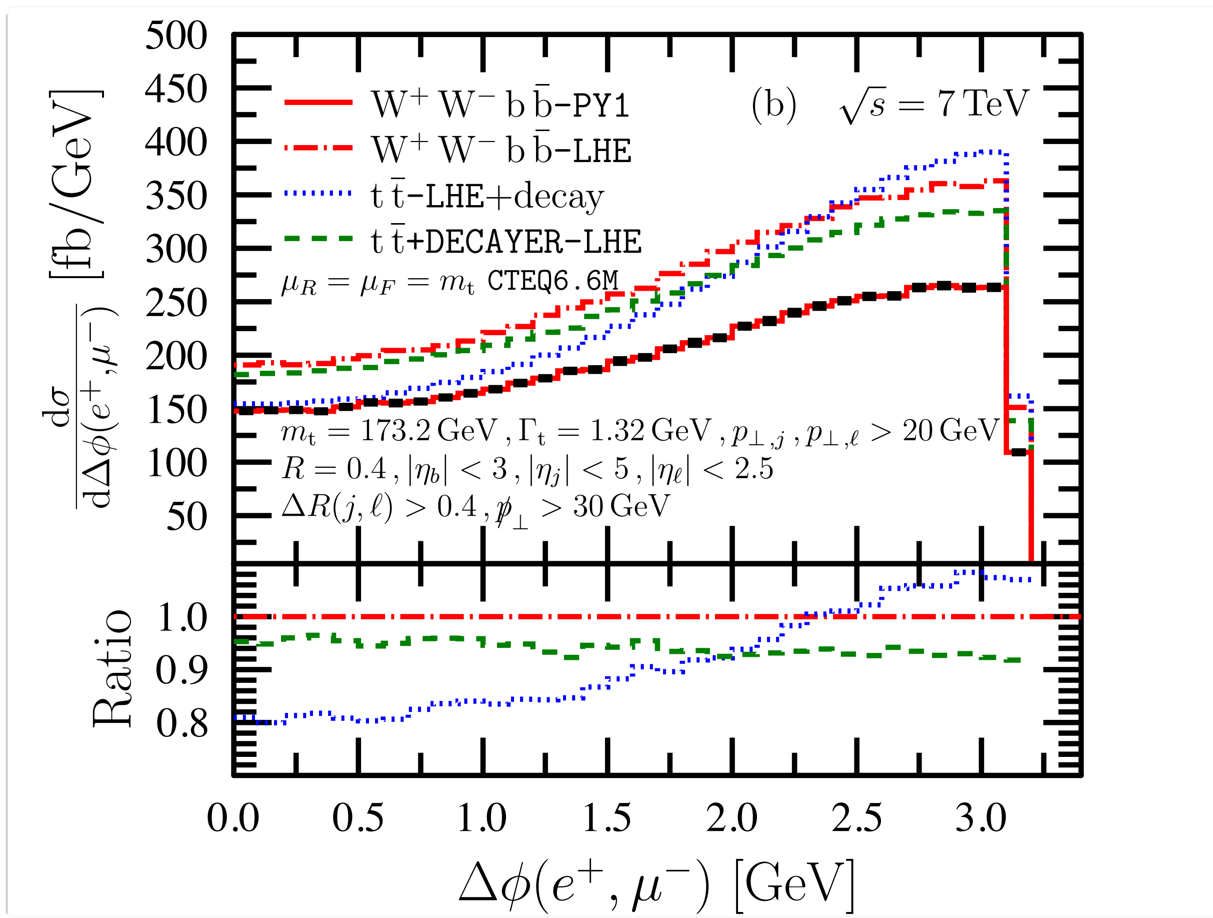


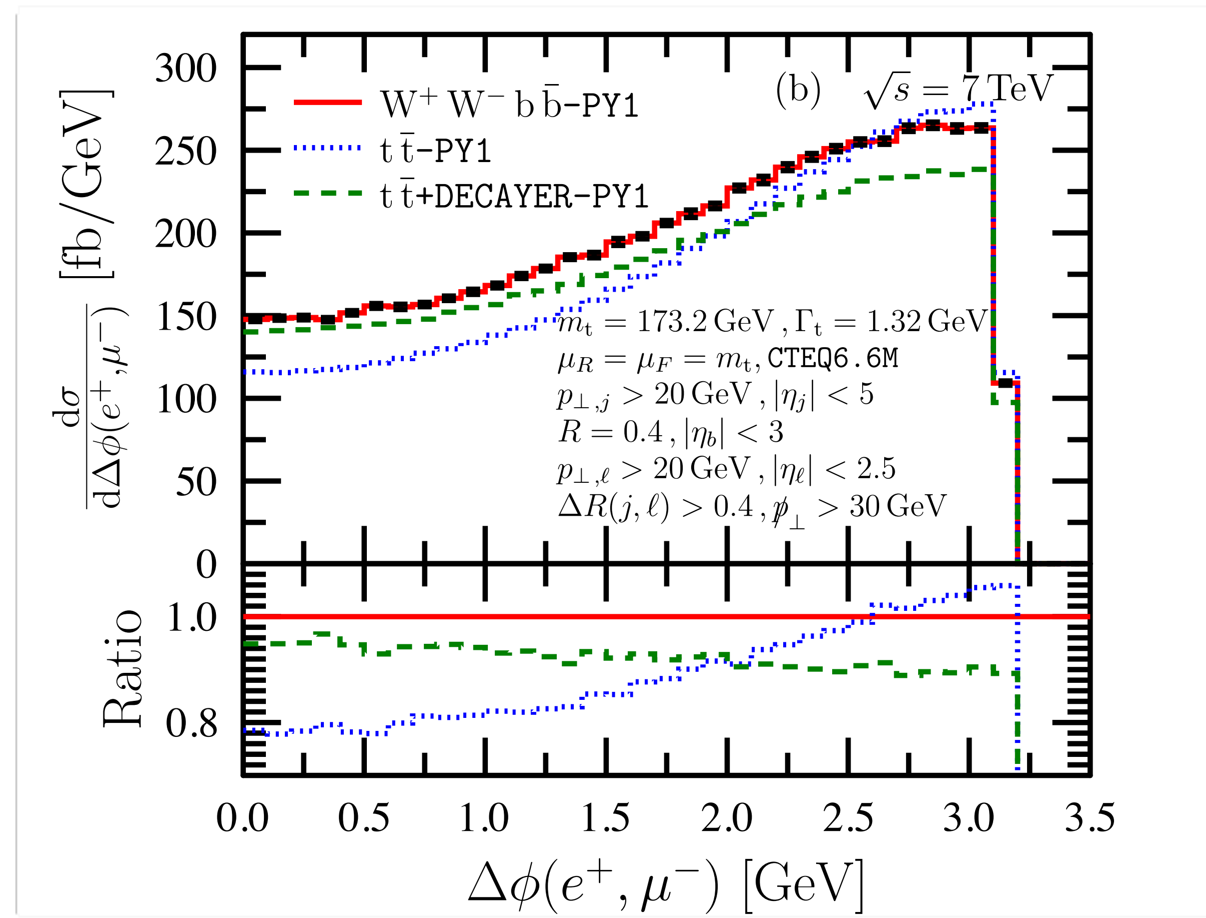
Invariant mass of positron and b-jet before/after PS/SMC at 7TeV LHC

Effect of PS 0-20%,

hadronization in general small, but large at kinematic boundary

$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$



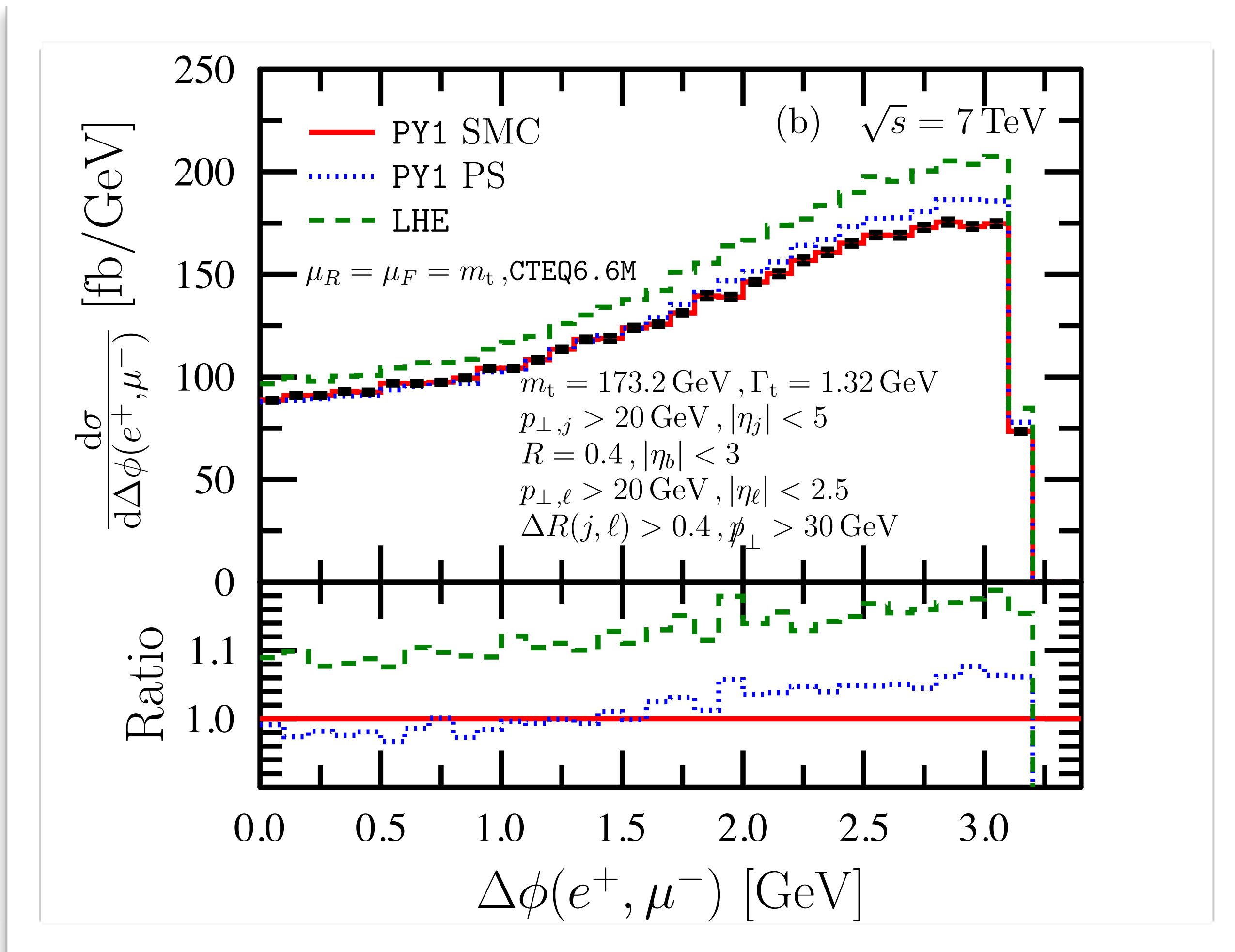


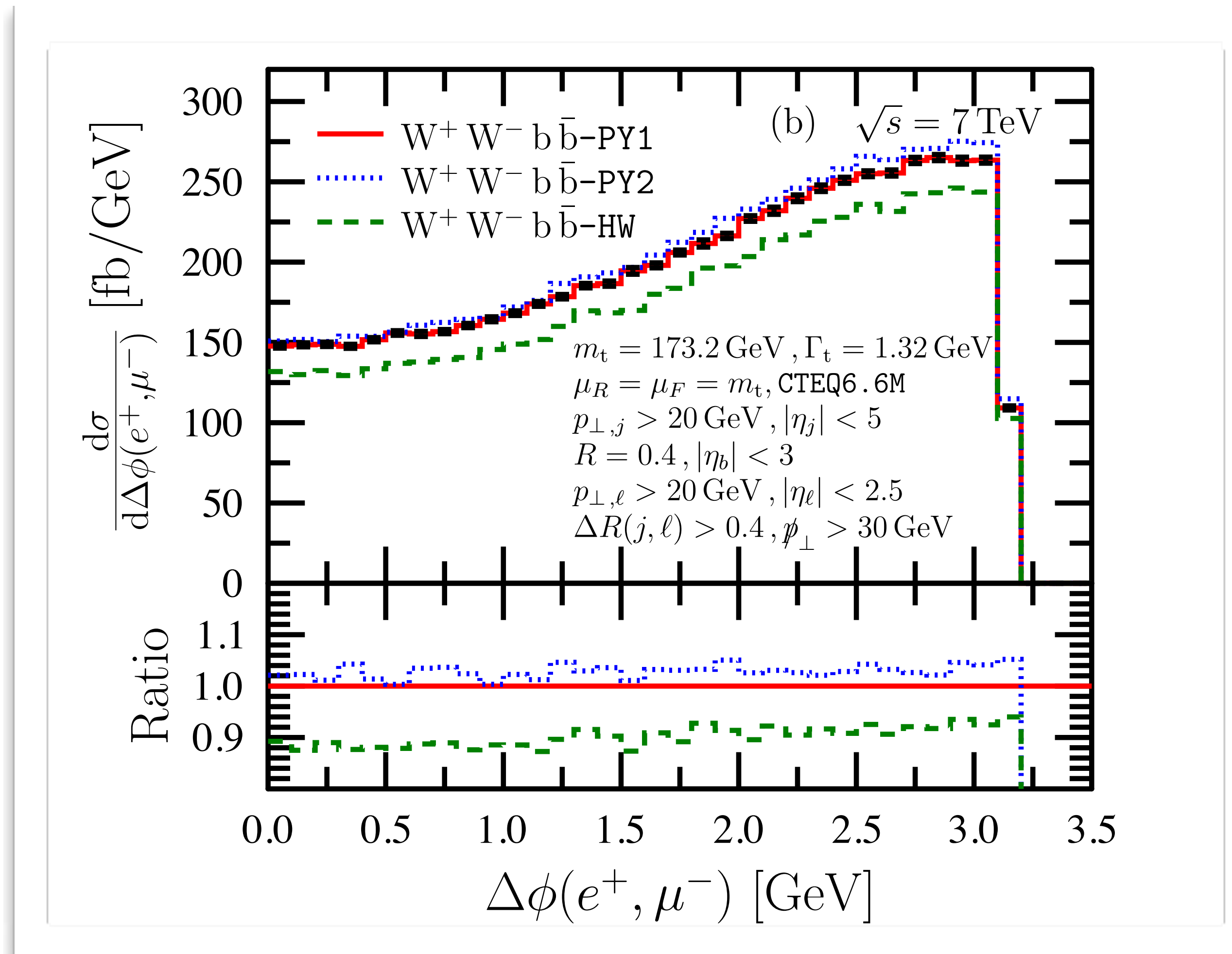
Azimuthal separation of positron and muon before/after SMC at 7TeV LHC

Only distribution where NWA vs DCA differ (among 32)

full - NWA similar in shape

$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$





Azimuthal separation of positron and muon before/after PS/SMC at 7TeV LHC

Effect of PS 10%,

hadronization small

$pp \rightarrow t\,\bar{t} + Z, H, A, jet$

(discussed elsewhere)

Conclusions and outlook

Conclusions

- ✓ First applications of POWHEG-Box to pp→$t\bar{t}$ + hard X processes
- ✓ SME's obtained from HELAC-NLO
- ✓ NLO cross sections are reproduced
- ✓ PowHel LH events 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/A, $t\bar{t}$jet, $t\bar{t}$Z, $W^+W^-b\bar{b}$ processes available
- ➡ Predictions for LHC with NLO+PS accuracy

Room for improvement

- Study scale choices and dependences
- Study dependence on PDF
- NLO decays in `DECAYER`
- Make accuracy quantitative
- Improve efficiency of event generation if remnant large
- Extension to further processes...

Implemented Processes

✓t T

✓t T + Z

✓t T + H/A

✓t T + j

✓WWbB

✳t T + ... (not yet public)

The end