tT+hard X hadroproduction with PowHel

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and
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Loops and Legs in Quantum Field Theory, Wernigerode
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NEW SZÉCHENYI PLAN

LHCphenOnet

Outline

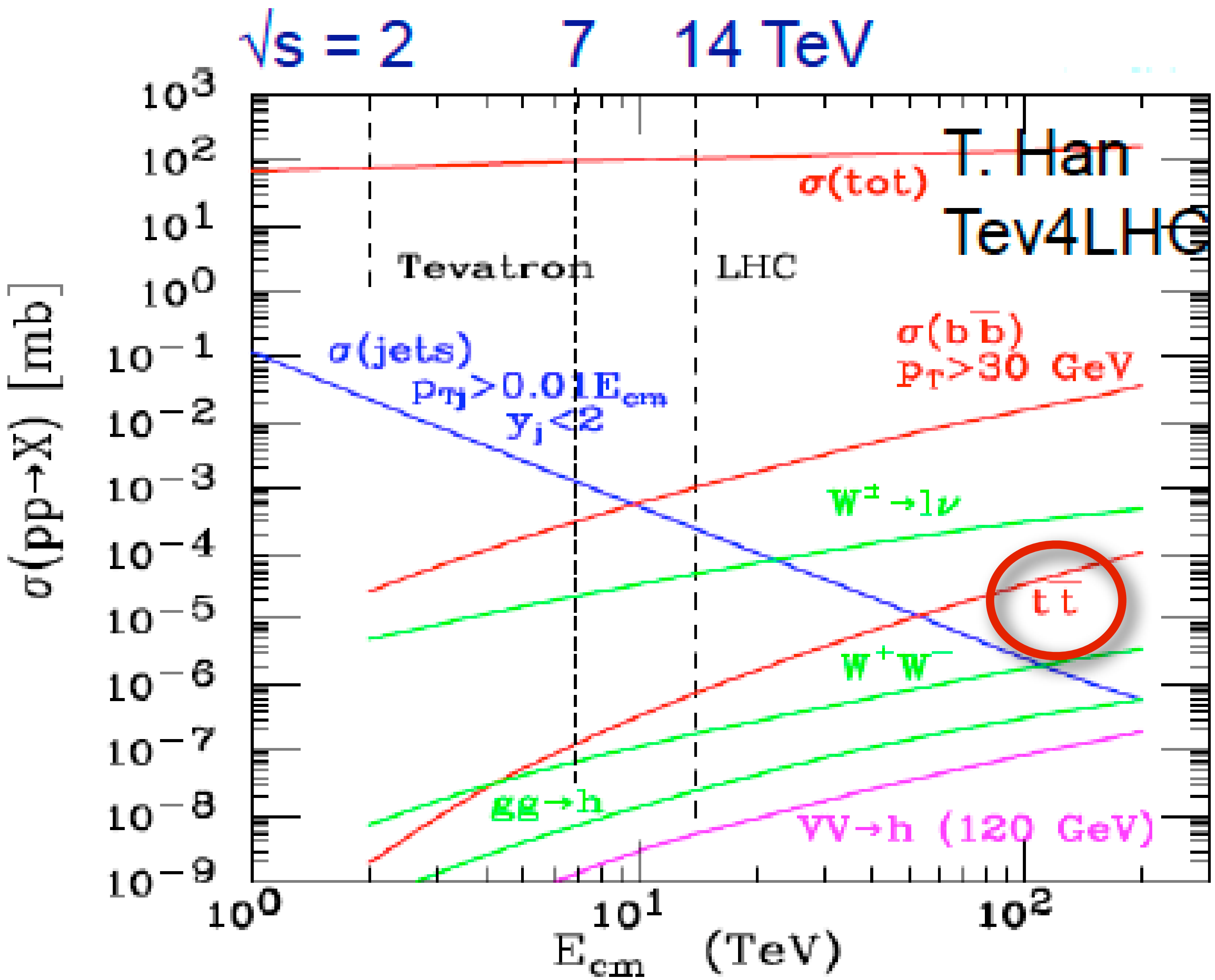
- Motivation
- Method
- Predictions
- Conclusions and Plans

Motivation

"The t-quark is special"

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 [GeV]= $172.9 \pm 0.6_{stat} \pm 0.9_{syst}$ (PDG),

$173.2 \pm 0.6_{stat} \pm 0.8_{syst}$ (TeVatron)

$172.6 \pm 0.6_{stat} \pm 1.2_{syst}$ (CMS)

$174.5 \pm 0.6_{stat} \pm 2.3_{syst}$ (ATLAS)

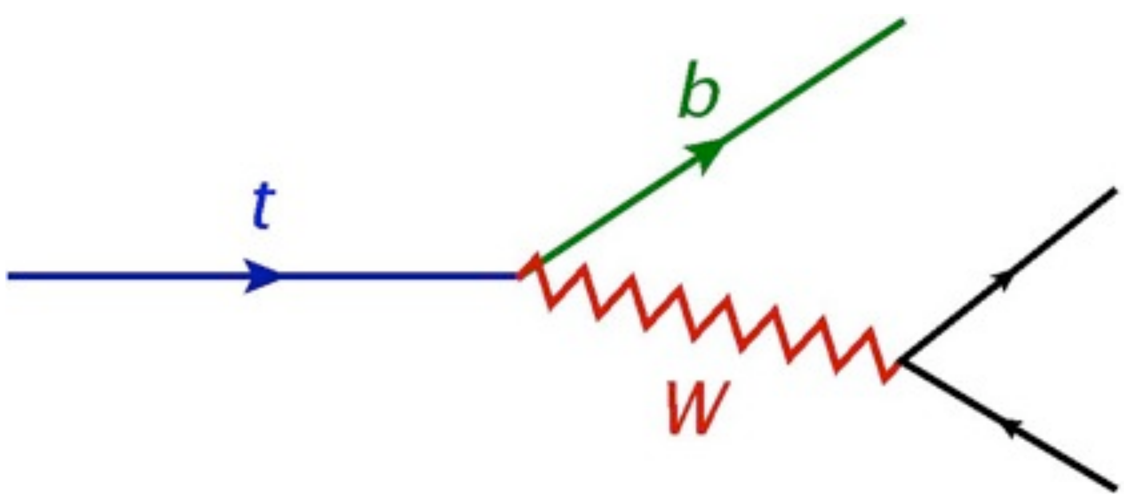
($y_t = 1 \Rightarrow 173.9$)

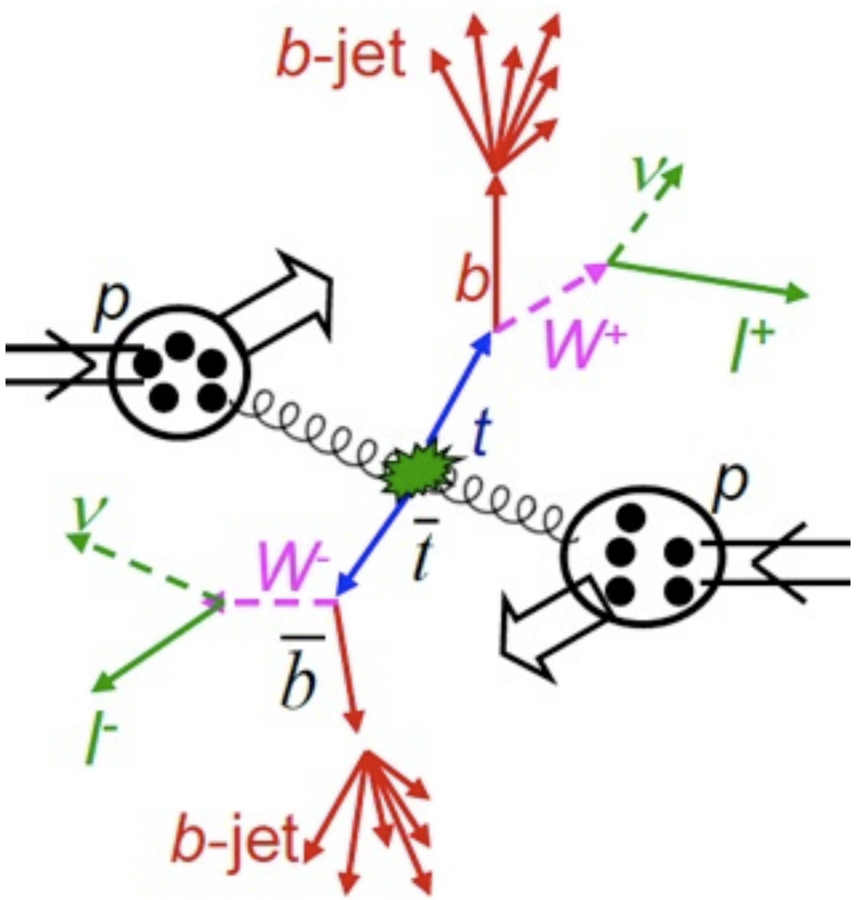
$\Rightarrow$ plays important role in Higgs physics

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
   $\Rightarrow$ quantum numbers more accessible than in case of other quarks

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





Top at the LHC

Present: see talk by Dissertori

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 →tT+hard X, X = H,A,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 (e.g. in Sudakov regions)
- 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

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

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

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

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

From NLO to NLO+PS

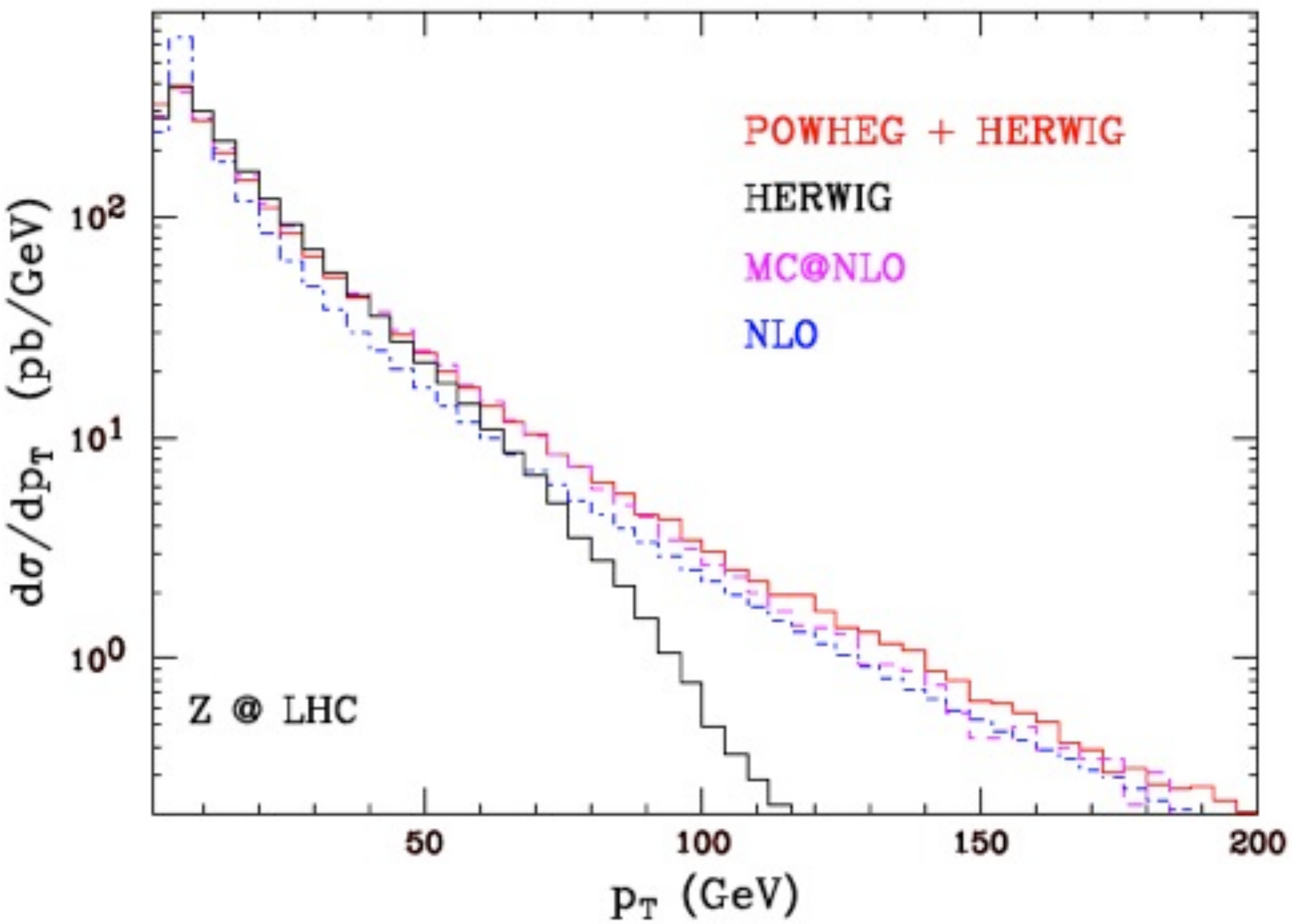
Idea: use NLO calculation as hard process as input for the SMC

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

- The POWHEG-BOX implements
  - FKS subtraction scheme
  - POWHEG method for matching
- HELAC-NLO provides tree and 1loop ME
- Processes in PowHel: *New!*
  - ✓ tT and W^+W^-bB
  - ✓ tT+H/A
  - ✓ tT+Z
  - ✓ tT+jet
  - tT+...

Implemented

in progress

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

[Bevilaqua et al, arXiv: 1110.1499]

[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:

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

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

- POWHEG MC first emission:

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

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

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

Formal accuracy of the POWHEG MC

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

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

$$+\int d\Phi_R \Delta(p_\perp)\frac{\widetilde{B}}{B}R\,(O(\Phi_R) - O(\Phi_B)) =$$

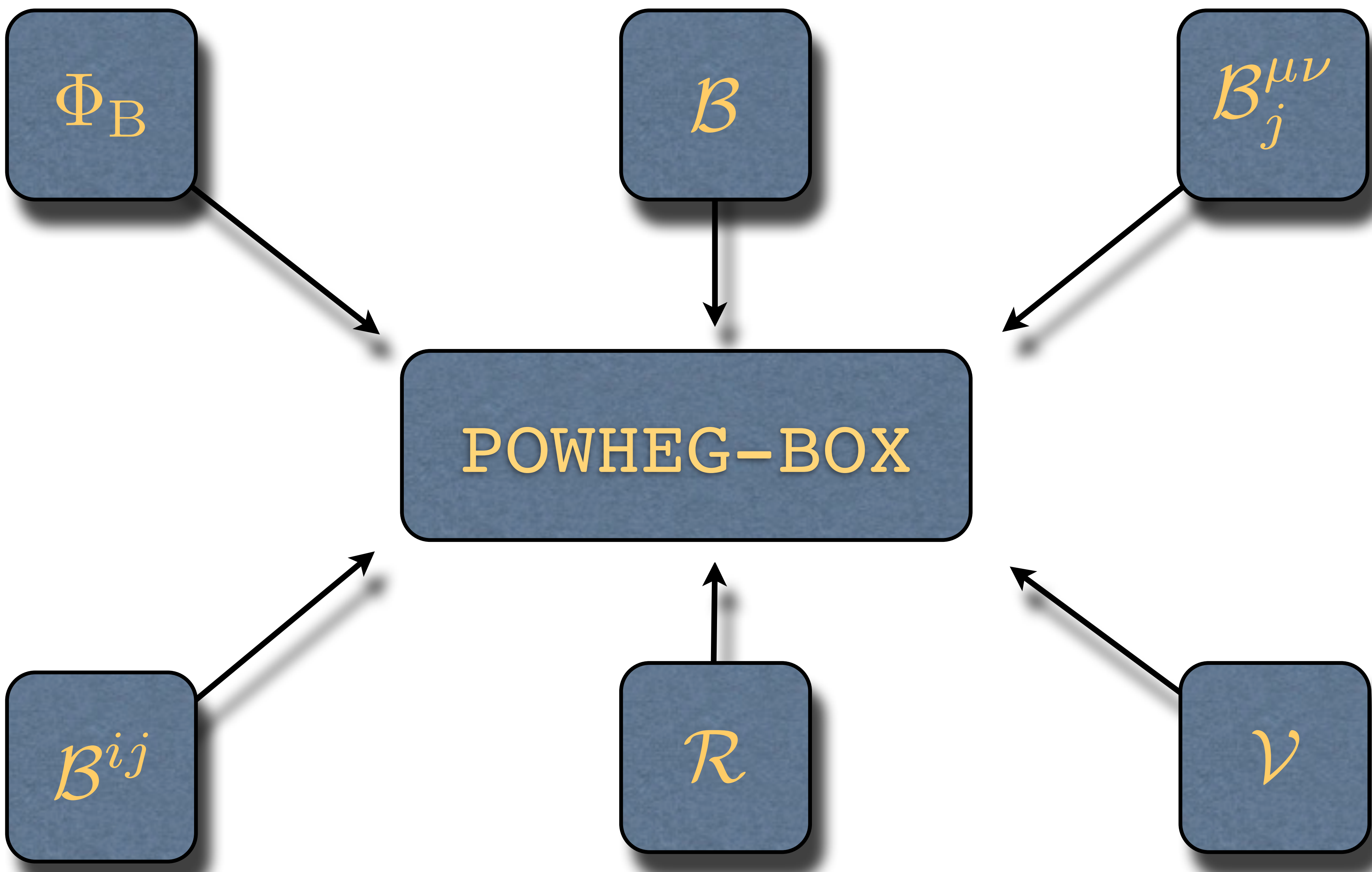
$$= \left\{\int d\Phi_B \widetilde{B} O(\Phi_B) + \int d\Phi_R R\,(O(\Phi_R) - O(\Phi_B))\right\}(1+\mathcal{O}(\alpha_S)) =$$

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

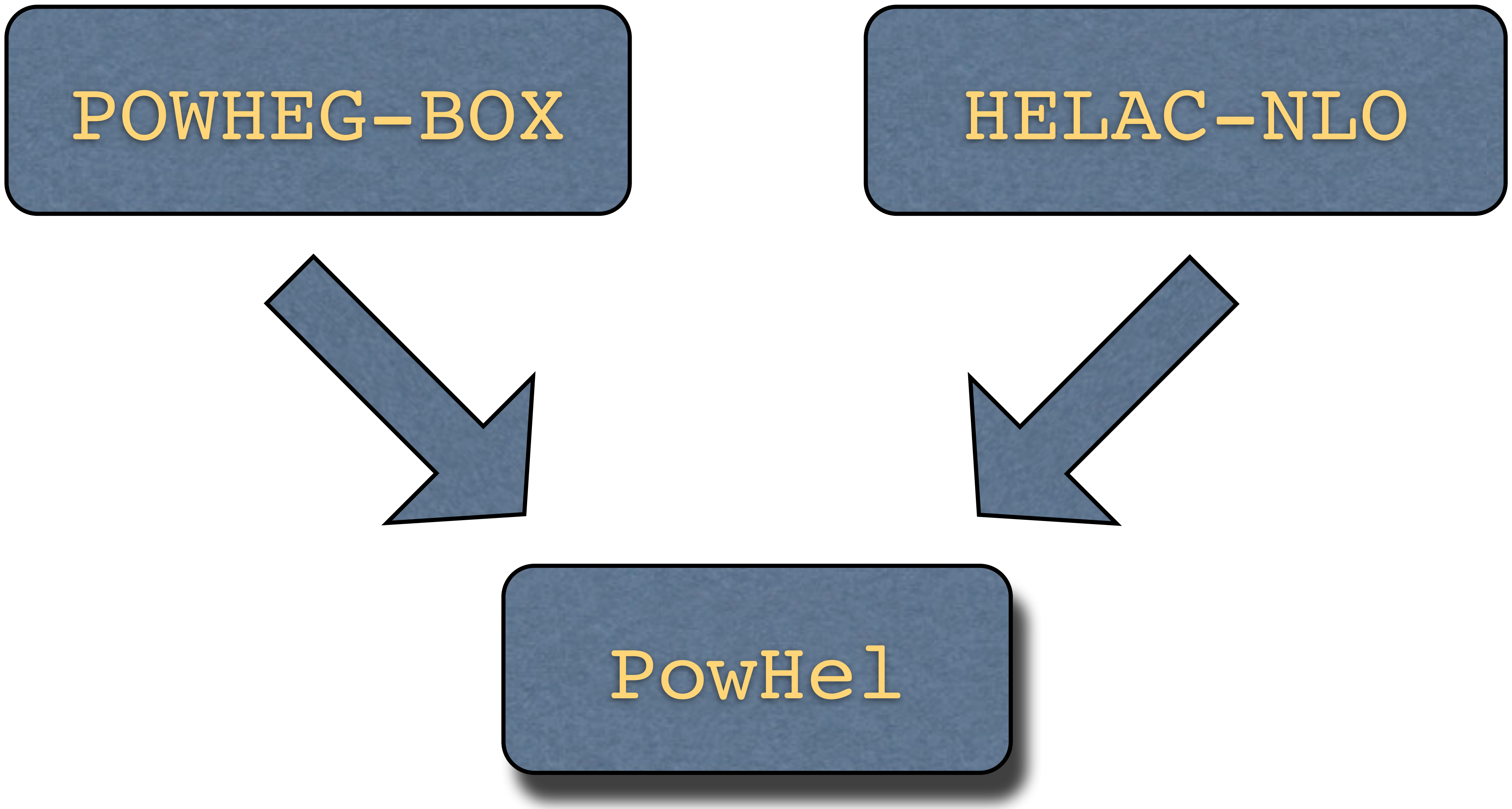
$\langle O\rangle_{NLO}$

Substitute $\Delta(p_\perp)\frac{\widetilde{B}}{B} = 1 + O(\alpha_S)$

POWHEG-BOX framework



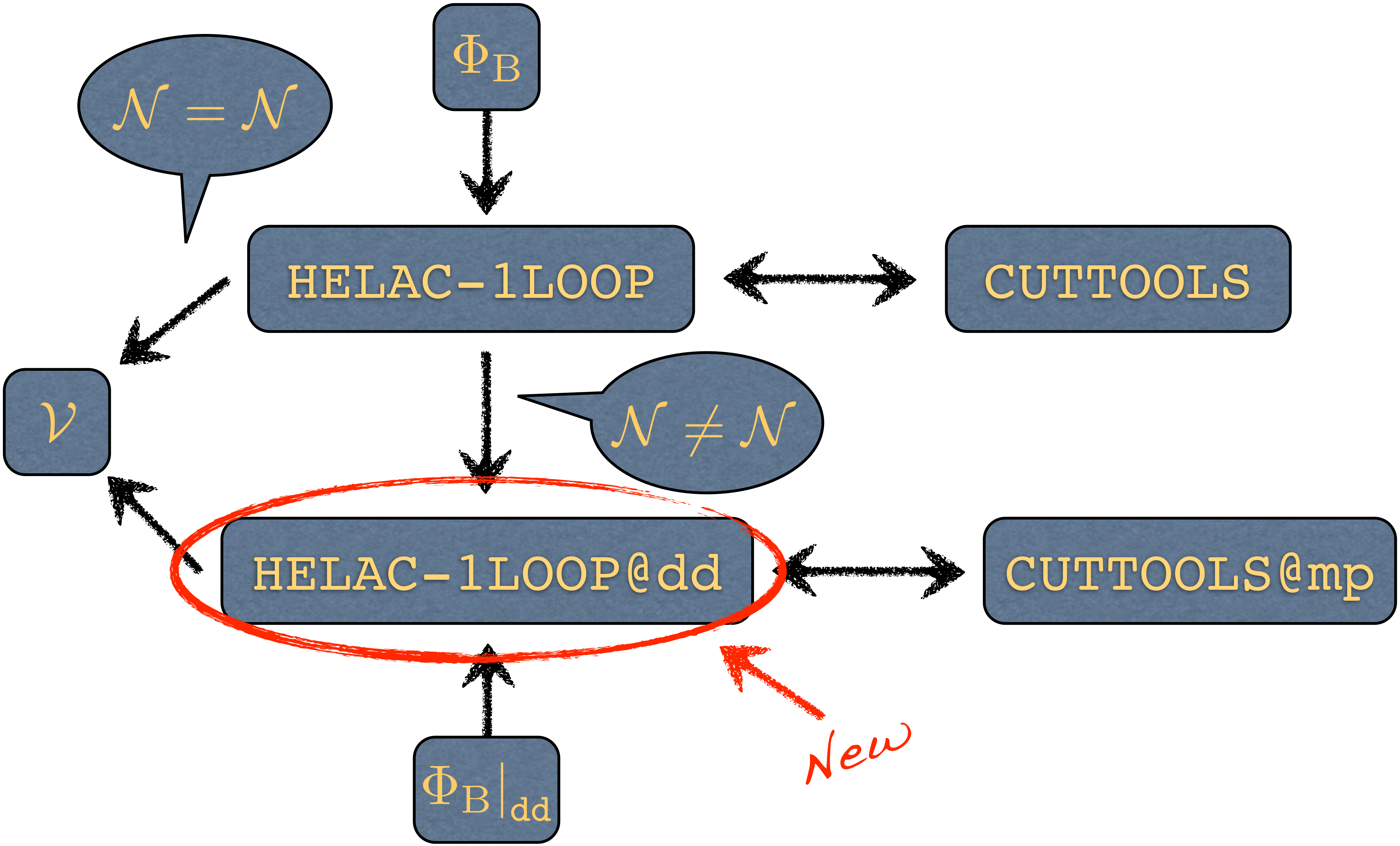
PowHel framework



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 check of other NLO predictions for the process

(see e.g. arXiv: 1111.0610 for tT Z production)

What about spin-correlations?

Three approaches:

increasing complexity

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)

decreasing precision

"3" implemented naturally in NLO+SMC

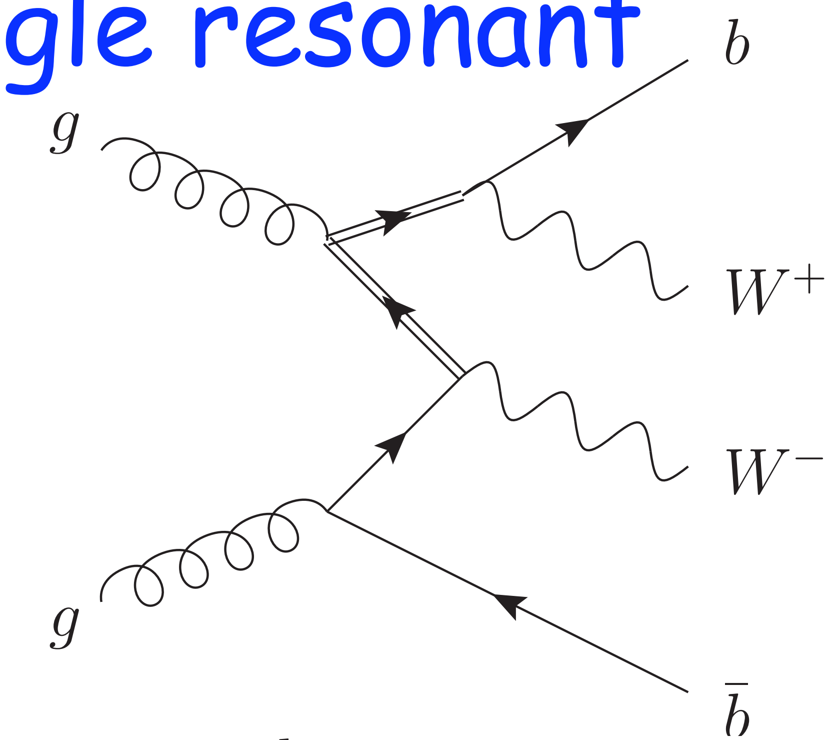
How to decay heavy particles?

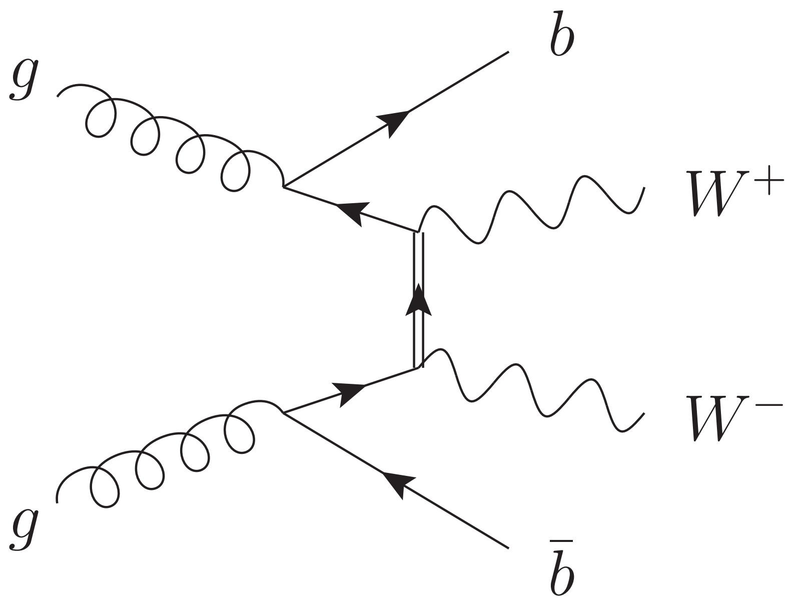
- Decay at ME level:
  - Resonant, non-resonant graphs with spin correlations
  - CPU time increased
  - Possible different (extra) runs
- Decay in SMC (DCA):
  - On-shell heavy objects
  - Easy to evaluate
  - No spin correlations, no off-shell effects
- Decay with DECAYER (NWA): ← New!
  - Post event-generation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

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

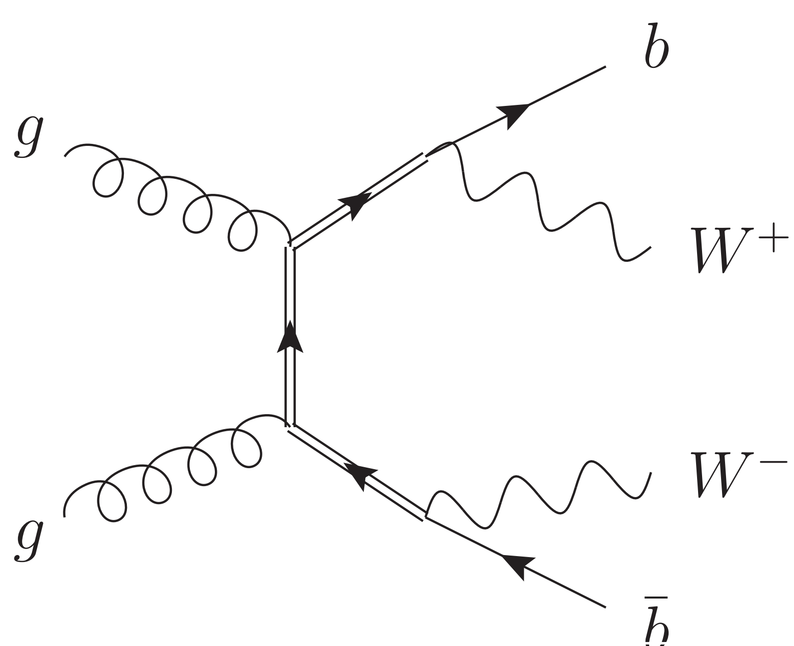
Legs

single resonant

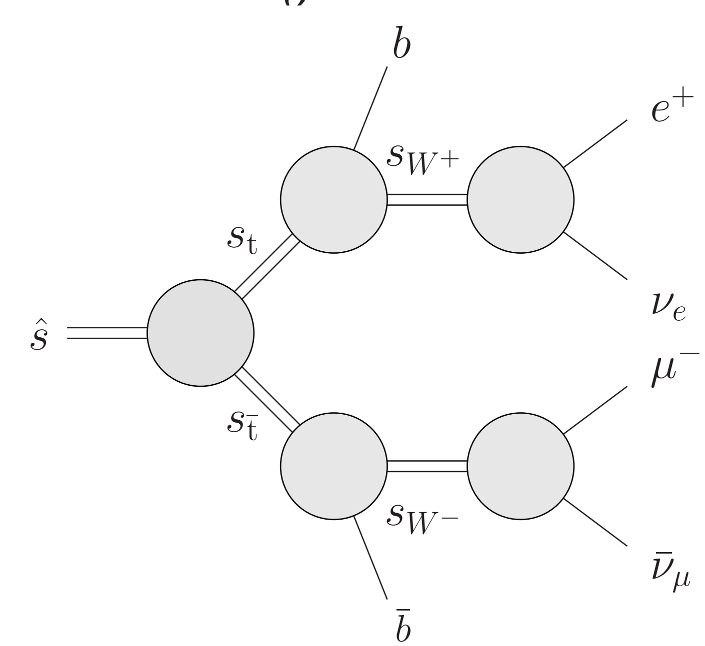




non-resonant

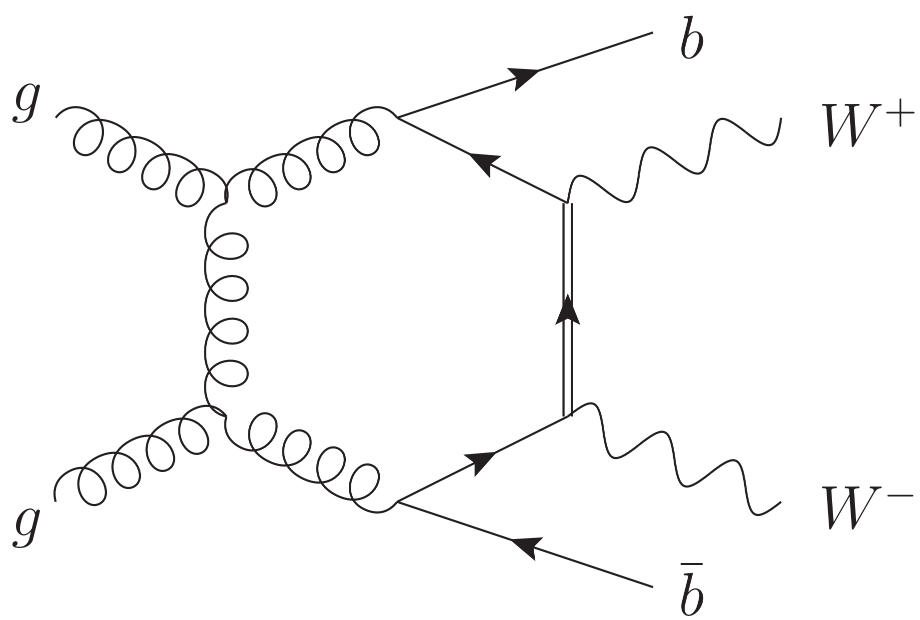


double resonant

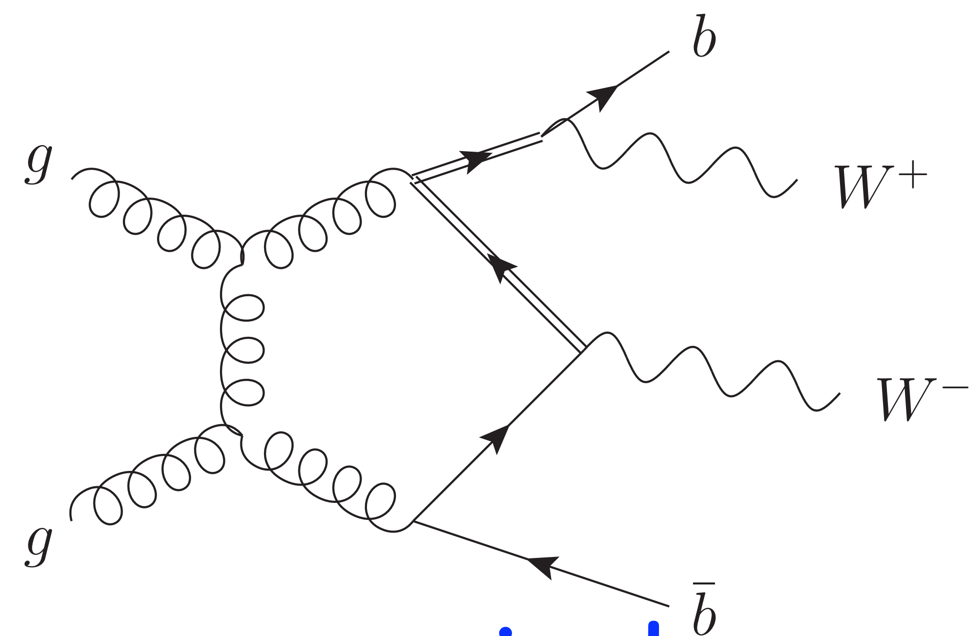


Born phase space

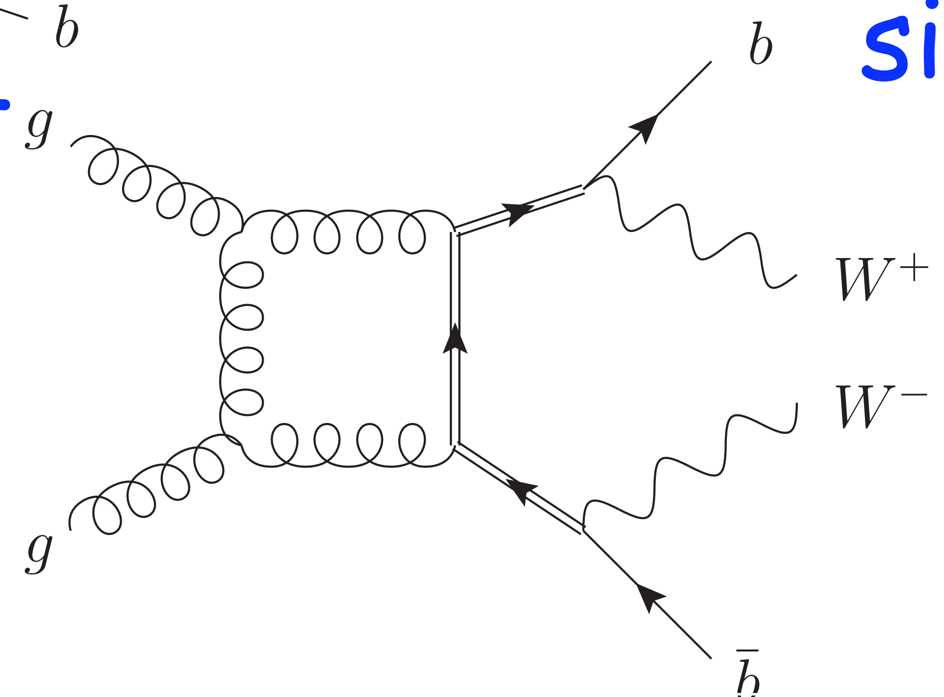
One loop and legs



non-resonant hexagon

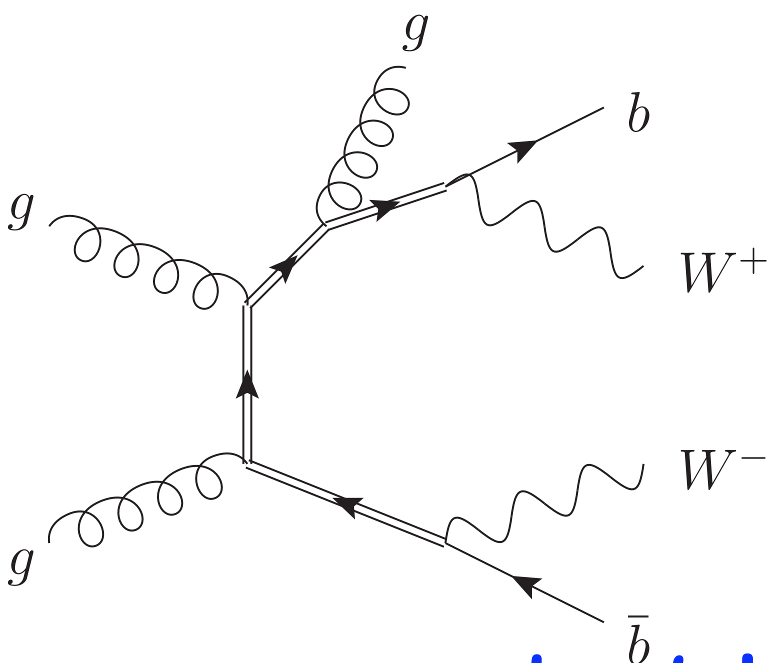


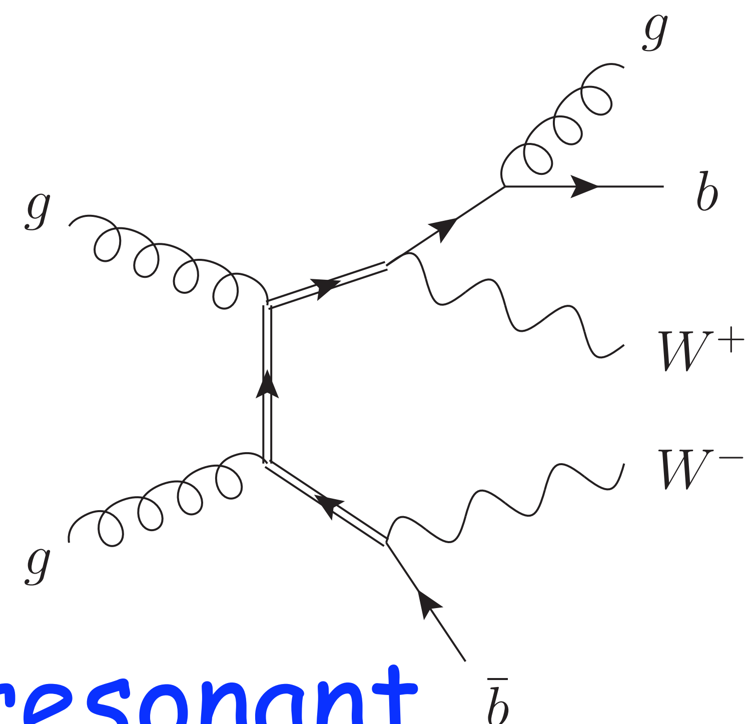
single resonant



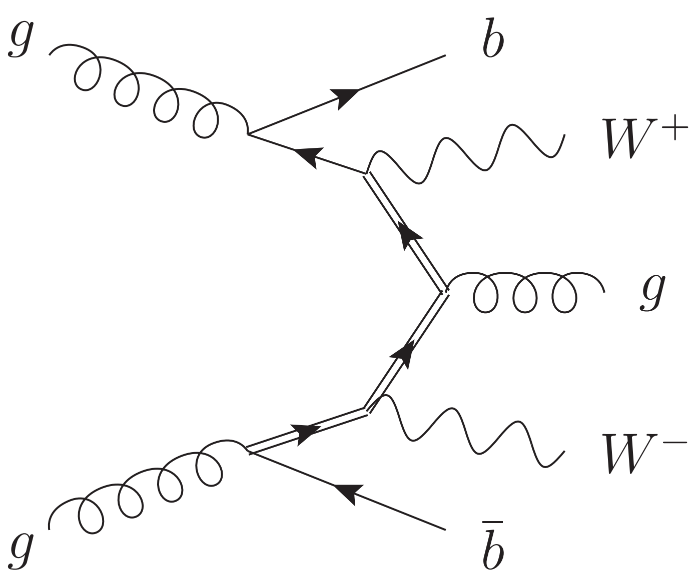
double resonant

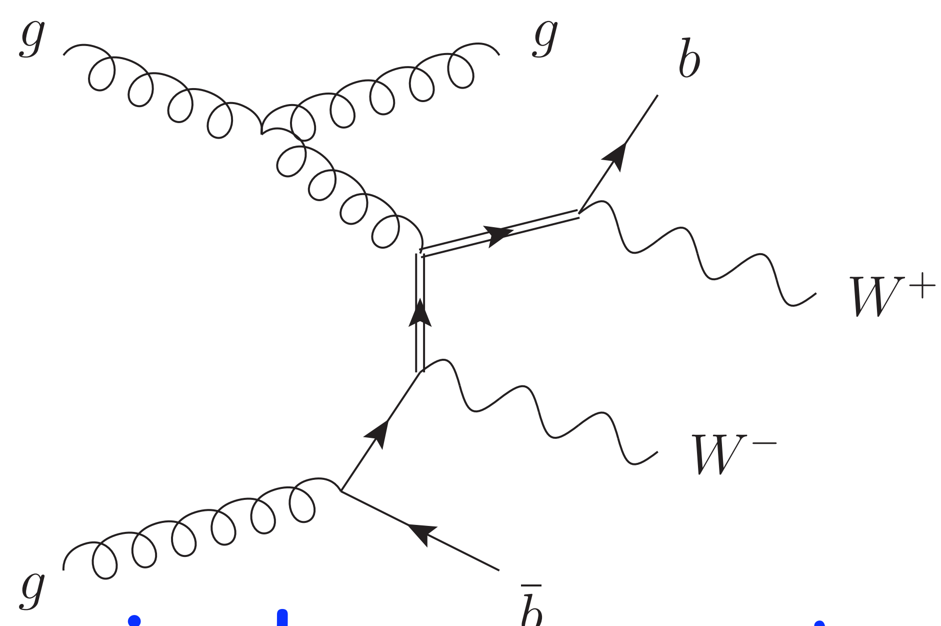
Legs + one more leg





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
  - generation cut: $p_{\perp b} > 2 GeV$
  - 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

Formal accuracy of the POWHEG MC

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

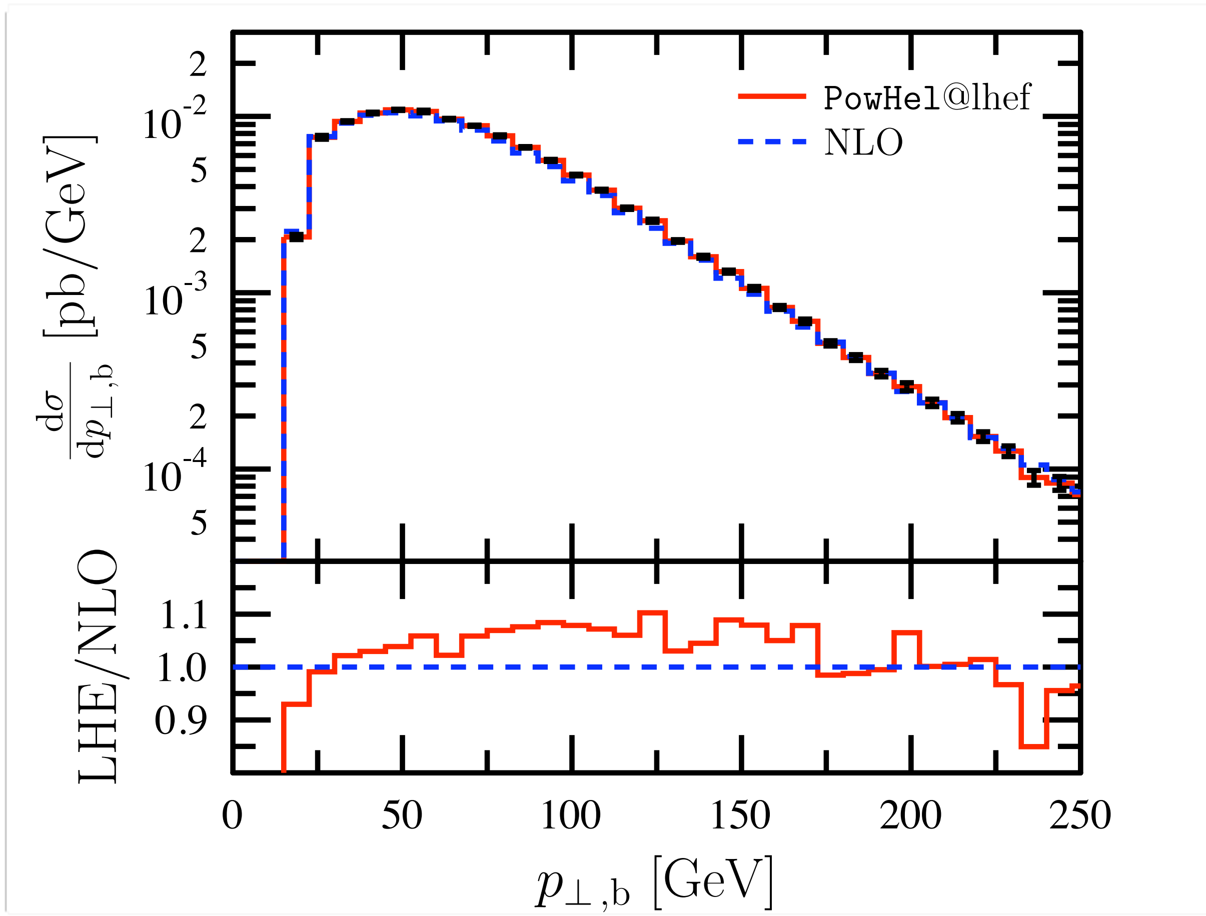
...

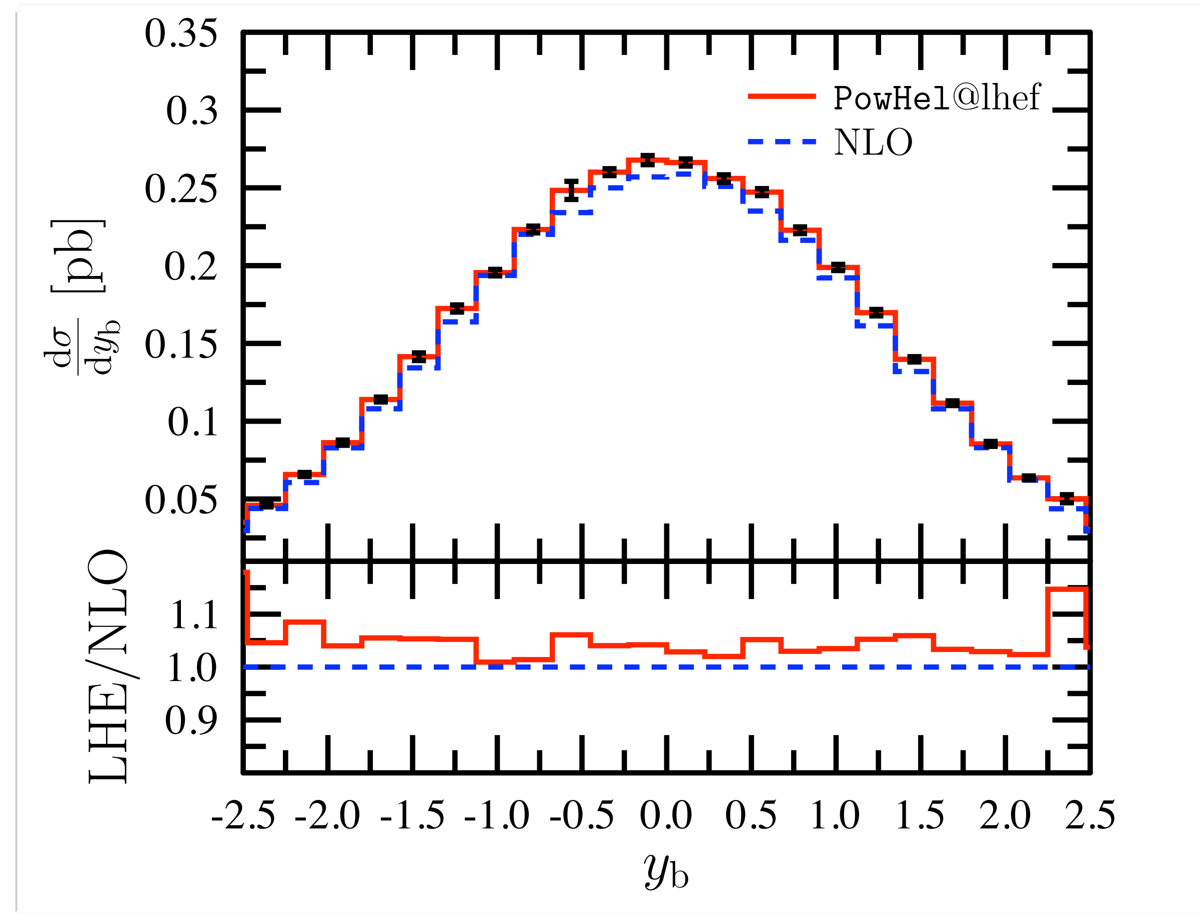
$$= \left\{ \int d\Phi_{\rm B} \left[B + V \right] O(\Phi_{\rm B}) + \int d\Phi_{\rm R} R O(\Phi_{\rm R}) \right\} (1 + \mathcal{O}(\alpha_{\rm S}))$$

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

Useful for checking

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



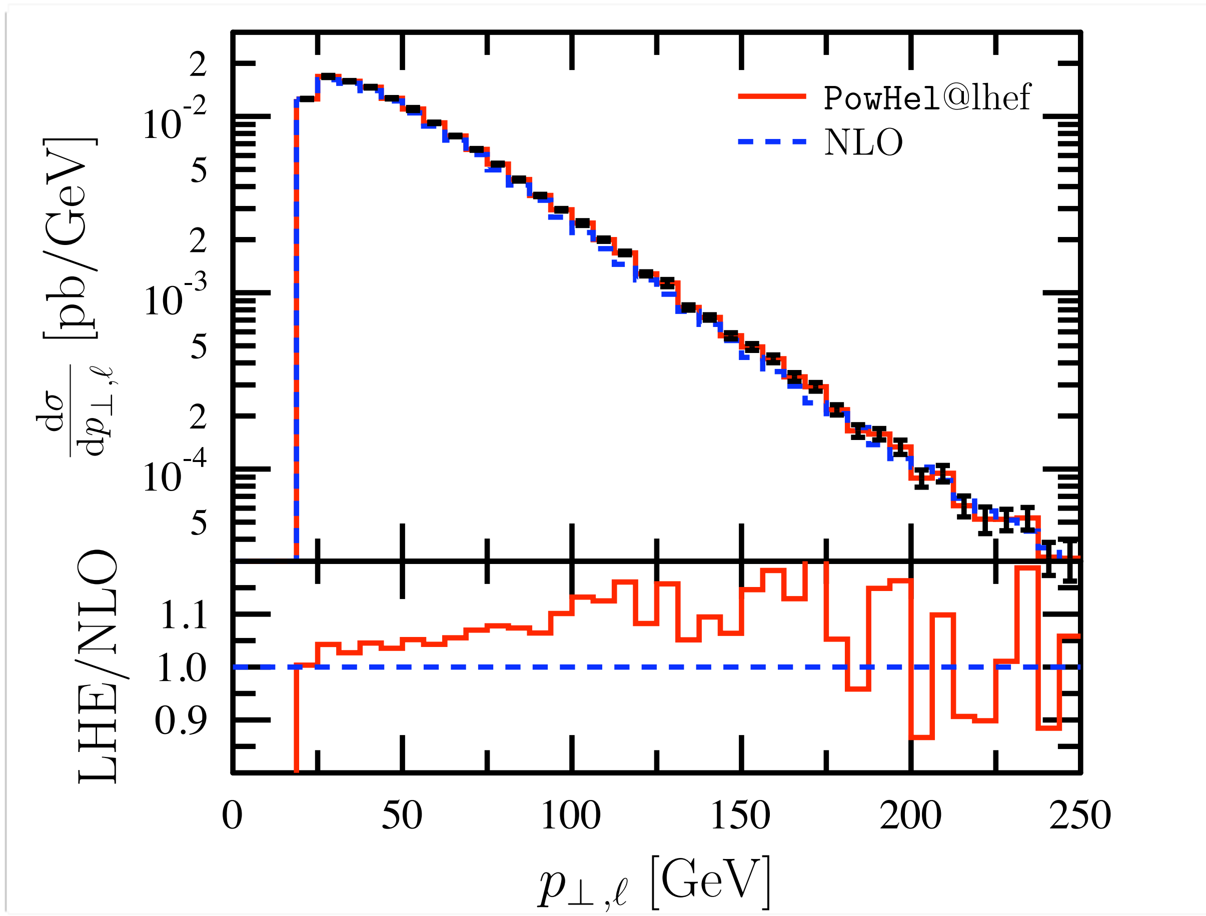


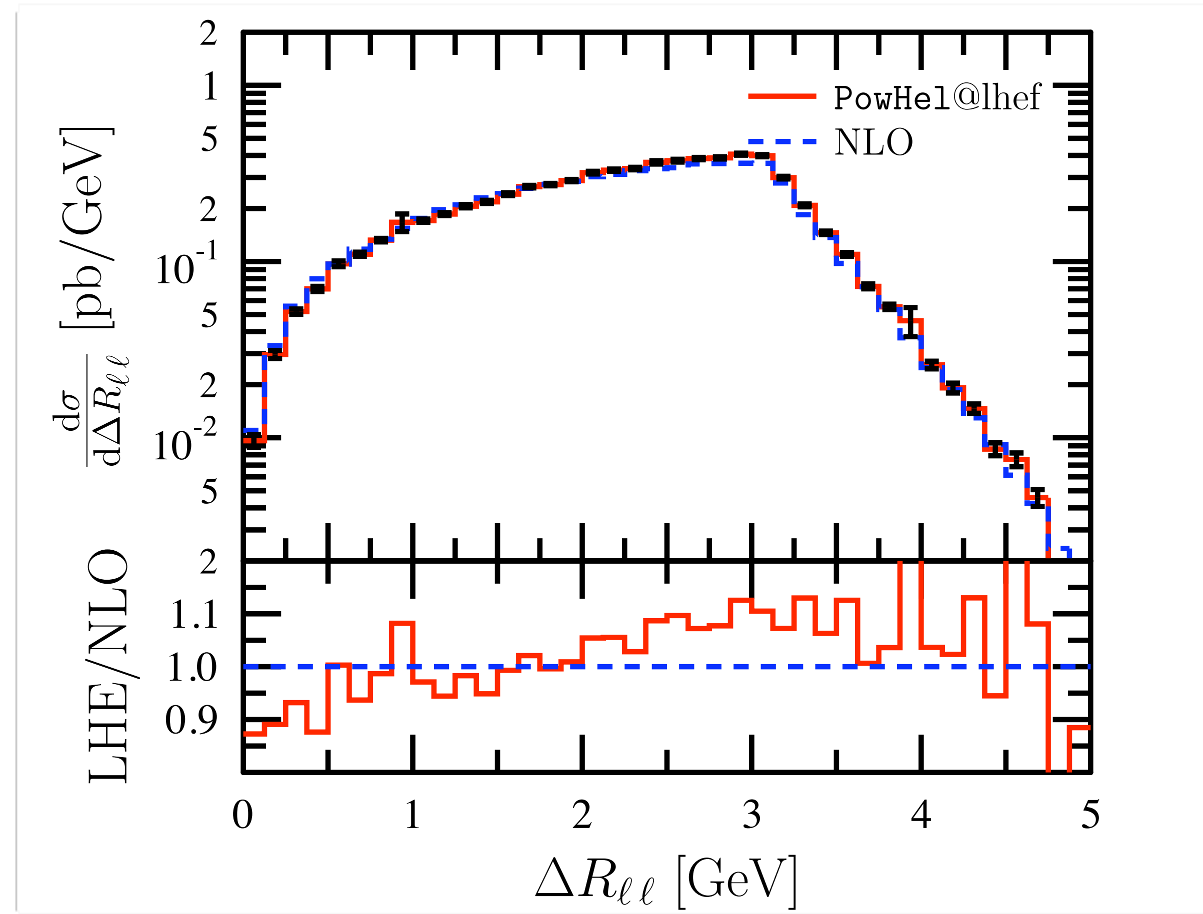
Transverse momentum and rapidity distribution for the b at 7TeV LHC

agreement is within 5%, Remember: $\sigma_{LHE} = \sigma_{NLO} (1+O(\alpha_s))$

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

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





Transverse momentum of positron, R-separation of the charged leptons at 7TeV LHC

agreement is within 10%, Remember: $\sigma_{LHE} = \sigma_{NLO} (1+O(\alpha_s))$

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

Predictions

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

Predictions for LHC at 7 TeV

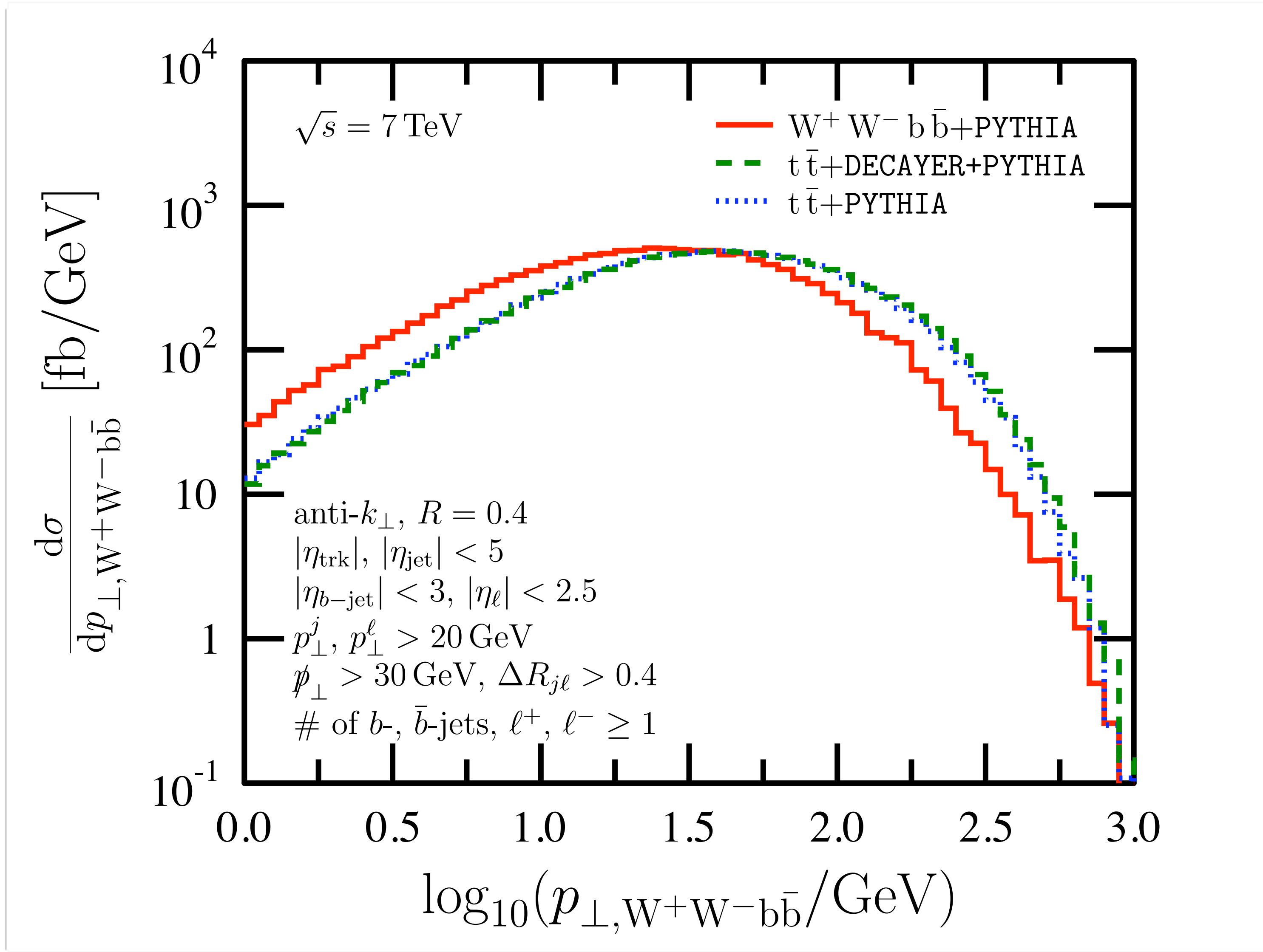
Goal:

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, l^+, l^-

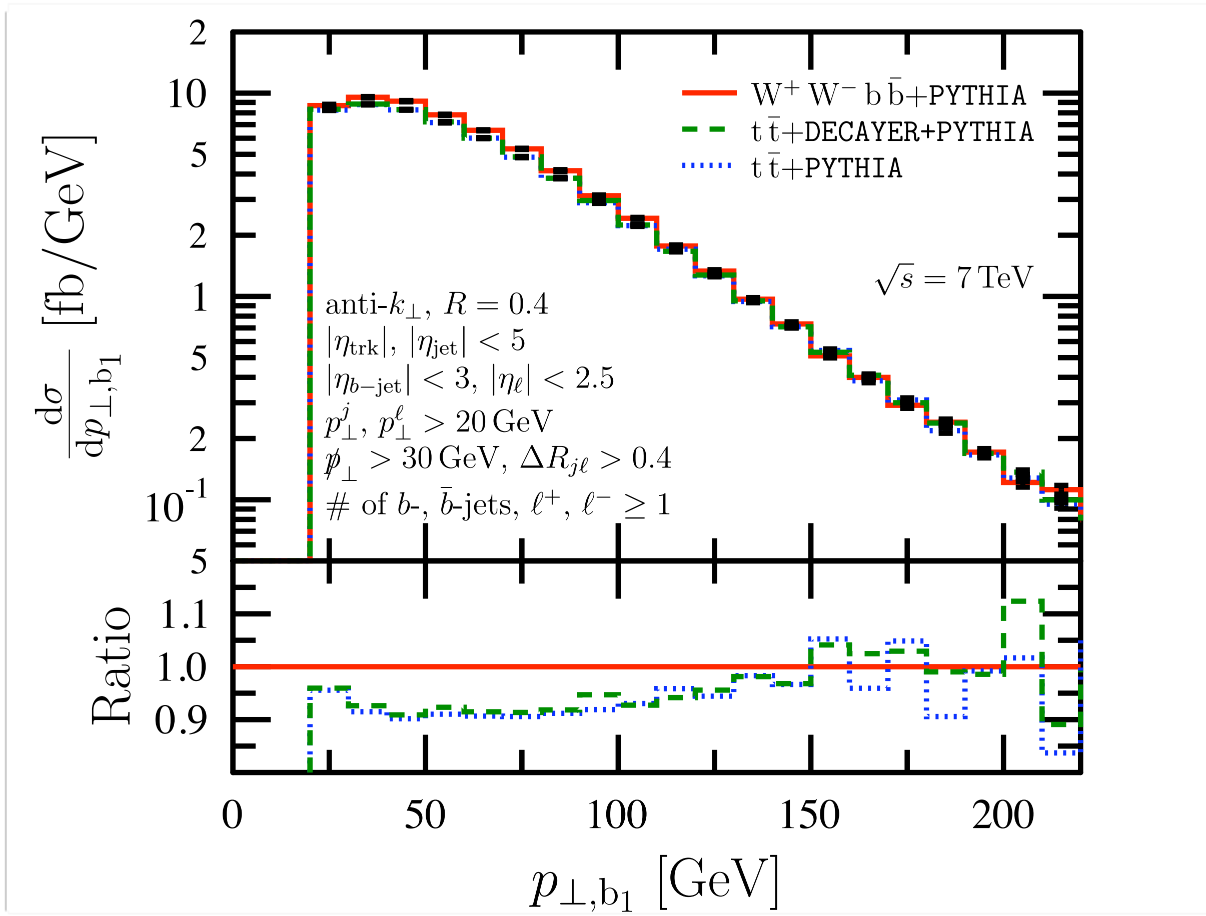
$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} + X$

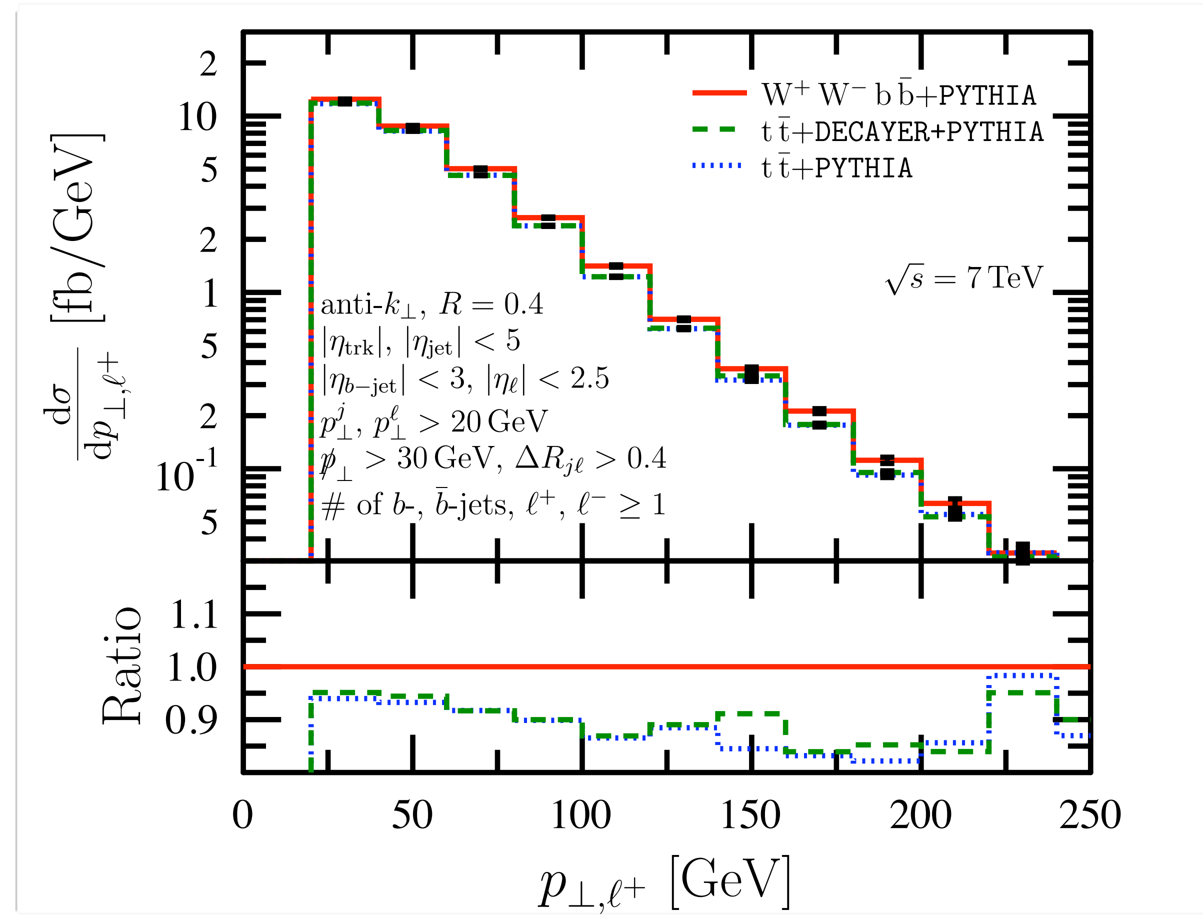


Nice Sudakov suppression at small $p_\perp$, main source of difference is origin of first radiation (in further plots also)

The effect of the shower is ~30% (not shown in these plots)

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



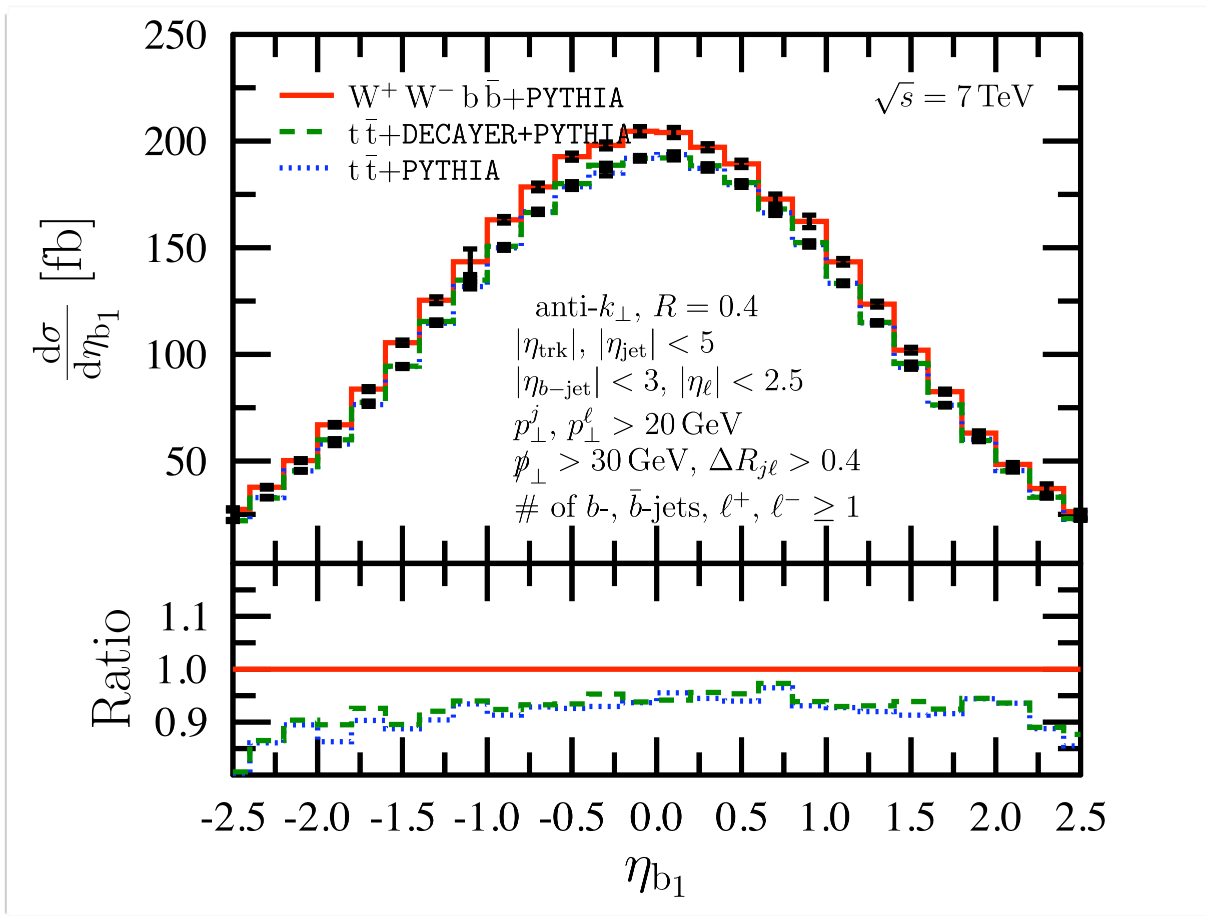


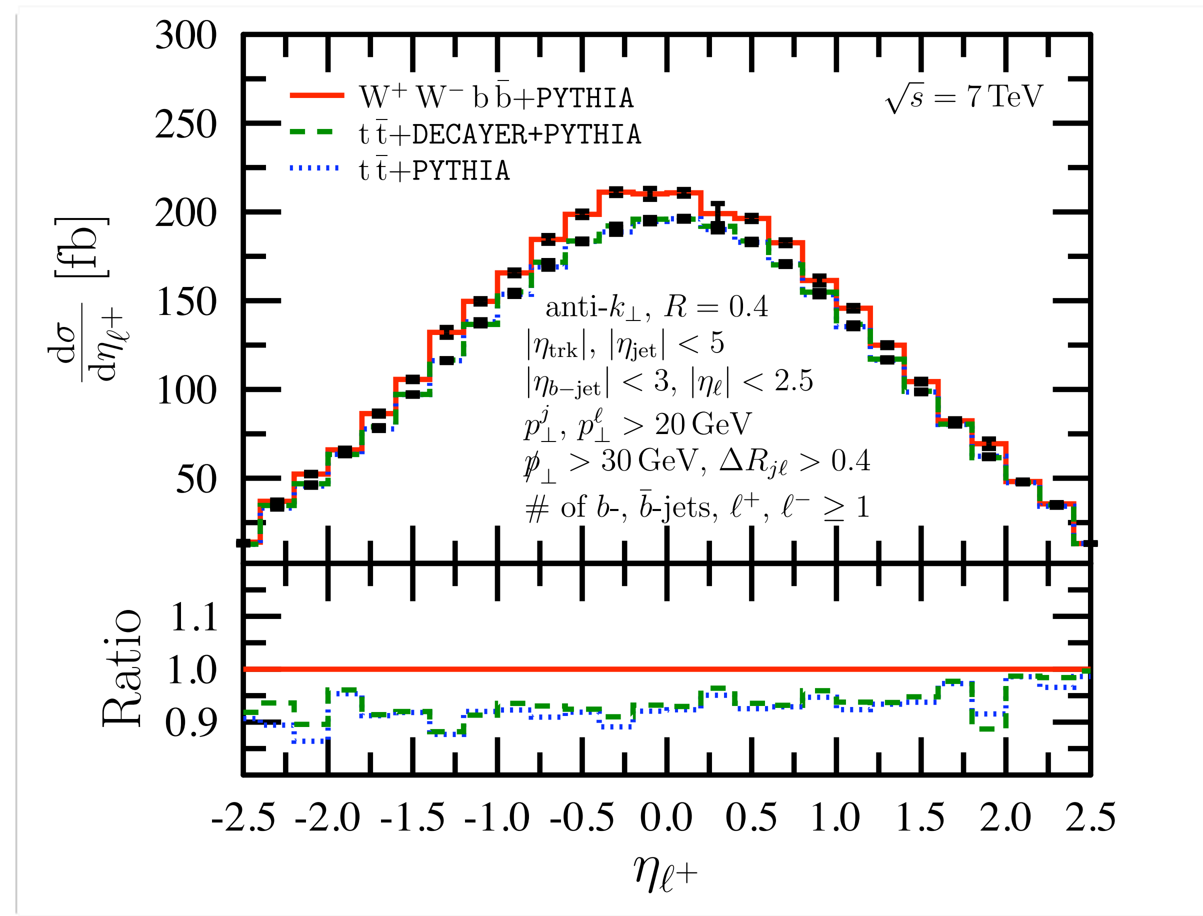
Transverse momentum of b-jet and positron at 7TeV LHC

Effect of NWA vs DCA negligible

full vs NWA small

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



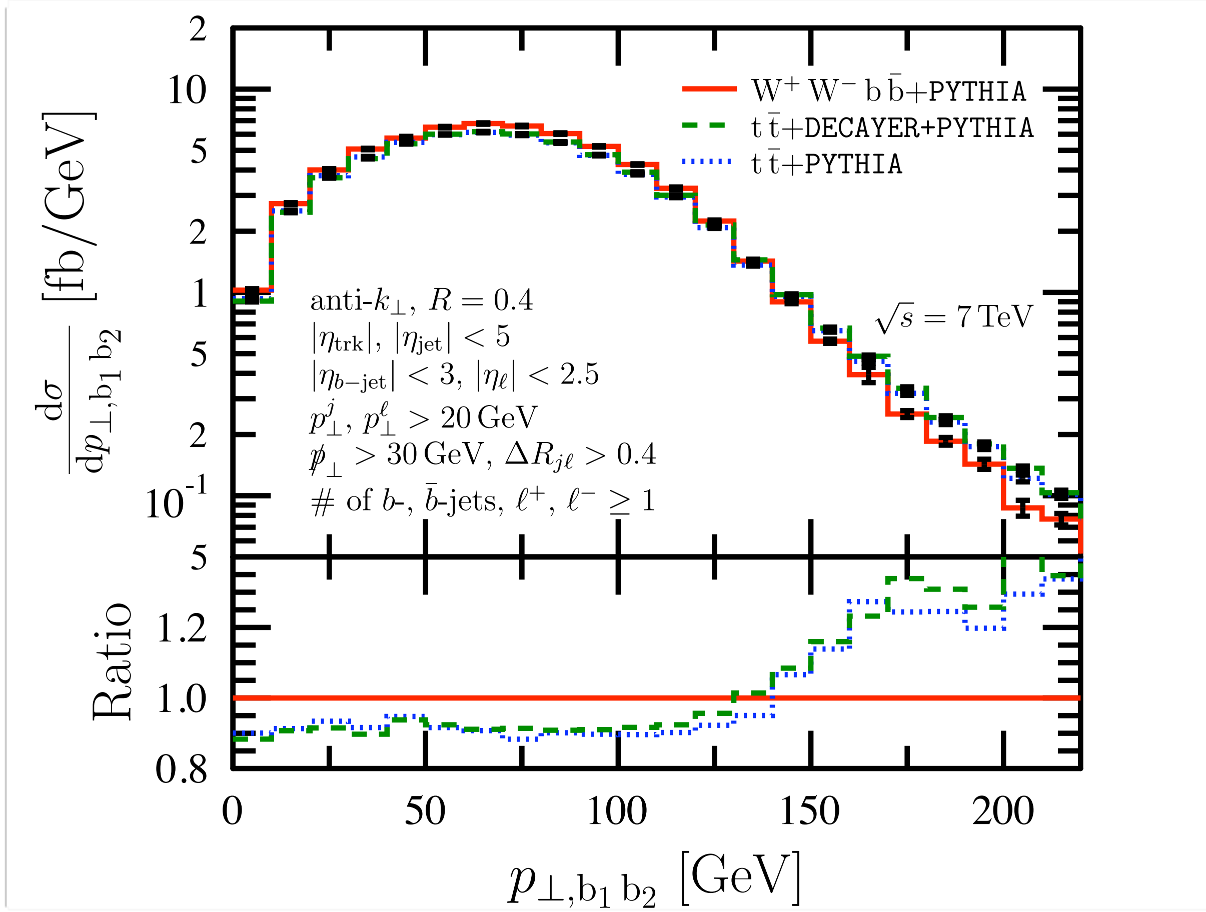


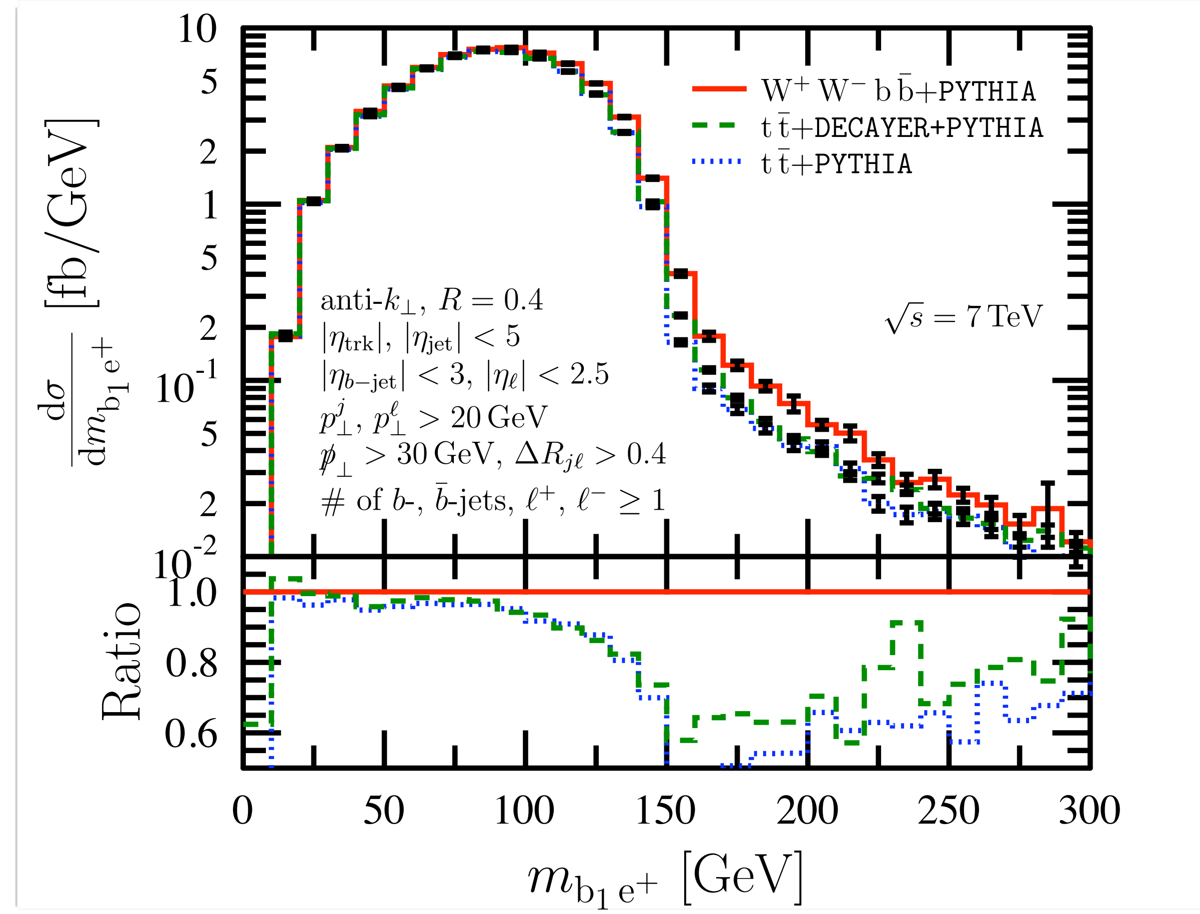
Rapidity of b-jet and positively charged lepton at 7TeV LHC

Effect of NWA vs DCA negligible

full vs NWA small

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



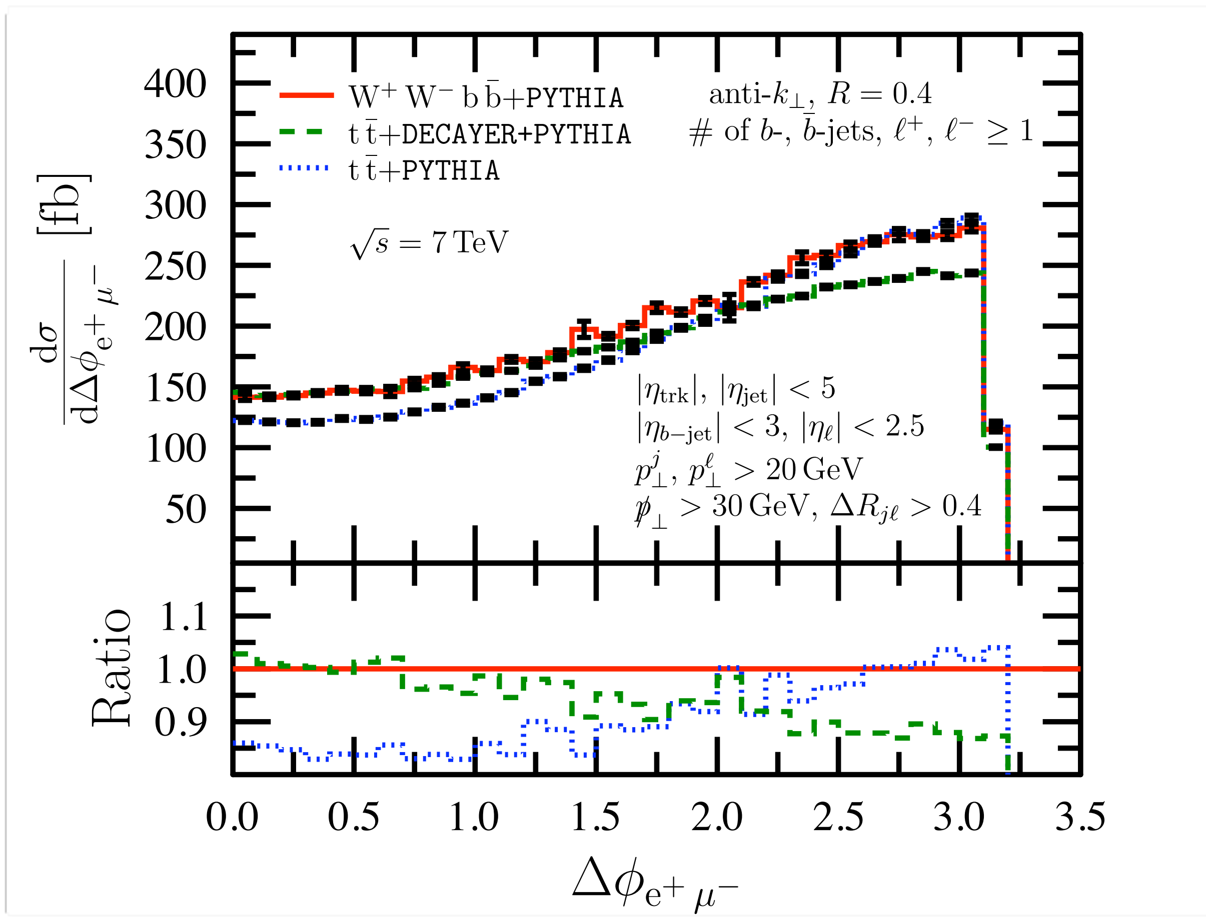


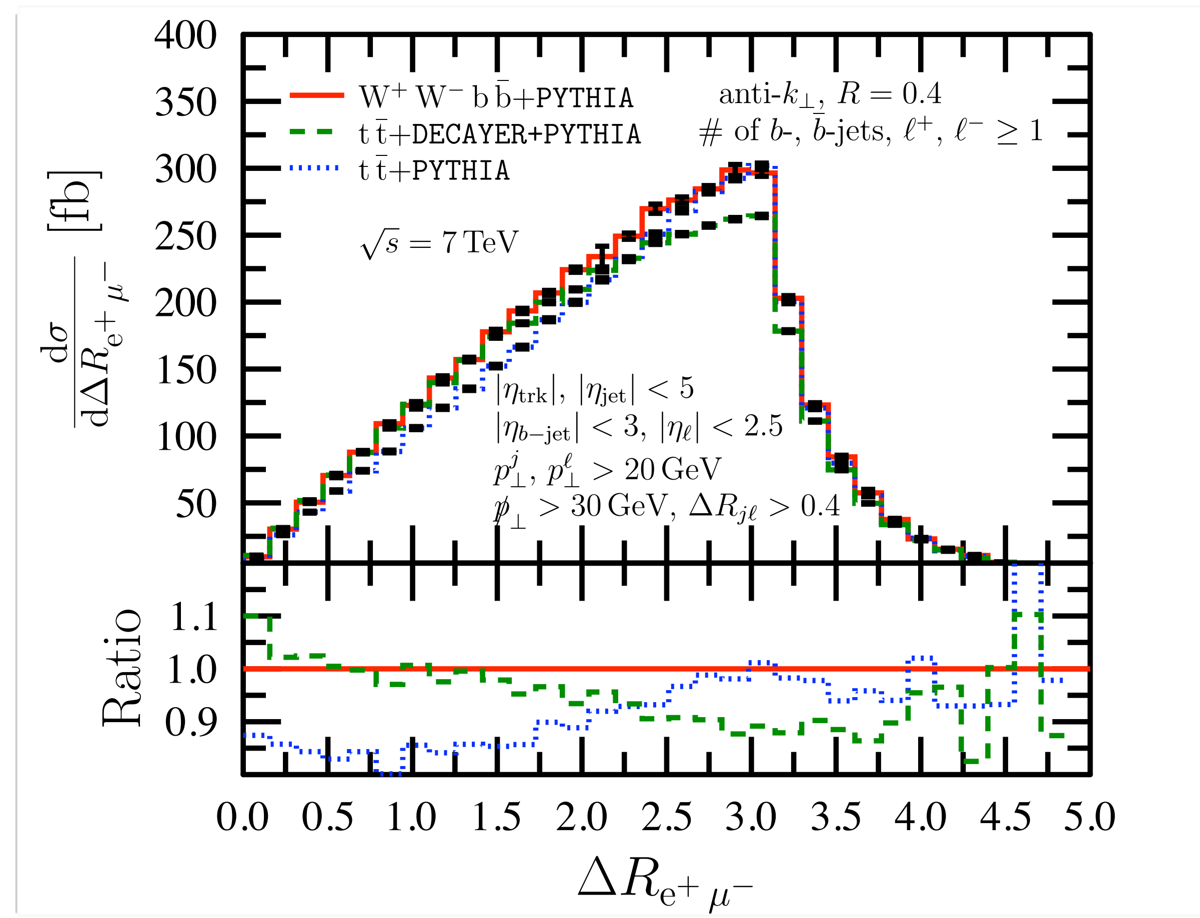
$p_\perp$ of the two b-jets, invariant mass of positron and b-jet at 7TeV LHC

Effect of NWA vs DCA negligible

full vs NWA ~40% above 150 GeV

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





$p_\perp$ of the two b-jets, invariant mass of positron and b-jet at 7TeV LHC

Only distribution where NWA vs DCA differ (among 32)

full - NWA agree below 1.5

Conclusions and outlook

Conclusions

- ✓ First applications of POWHEG-Box to $pp \to t\bar{t}$ + 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 $pp \to t\bar{t}$, $t\bar{t}H/A$, $t\bar{t}$jet, $t\bar{t}Z$, $W^+W^-b\bar{b}$ processes available
- ➡ Predictions for LHC with NLO+PS accuracy

Plans

- ➡ Study scale choices and dependences
- ➡ Generation of events on request
- ➡ Comparison to data (in progress)
- ➡ Make codes public
- ➡ Extension to further processes...

Implemented Processes

- ✓ t T
- ✓ t T + Z
- ✓ t T + H/A
- ✓ t T + j
- ✓ WWbB

Implemented Processes

Stay tuned,
More to come!

✓ $t\bar{T}$

✓ $t\bar{T}+Z$

✓ $t\bar{T}+H/A$

✓ $t\bar{T}+j$

✓ WWbB

The end

Extra

Charge asymmetry at TeVatron

Definition: $$A_C^\eta = \frac{N(\eta_{e^+} > \eta_{\mu^-}) - N(\eta_{e^+} < \eta_{\mu^-})}{N(\eta_{e^+} > \eta_{\mu^-}) + N(\eta_{e^+} < \eta_{\mu^-})}$$

$(\eta_e+\eta_\mu)/2 > \eta_C$	PYTHIA ($p_\perp$-ordered) %	PYTHIA (q-ordered) %	HERWIG (angular-ordered) %
0	4.34±0.15	4.24±0.13	4.47±0.16
0.7	3.14±0.34	3.02±0.35	0.49±0.43
1.4	2.16±0.12	1.86±0.12	-1.89±1.46

Preliminary

FB asymmetry at TeVatron

Definition:

$$A^{\eta}_{FB} = \frac{N(\eta_{part} > 0) - N(\eta_{part} < 0)}{N(\eta_{part} > 0) + N(\eta_{part} < 0)}$$

particle	PYTHIA ($p_\perp$-ordered) %	PYTHIA (q-ordered) %	HERWIG (angular-ordered) %
e^+	3.05±0.15	3.05±0.13	3.10±0.16
μ^-	-3.56±0.34	-3.47±0.35	-3.70±0.16

Preliminary