$t\bar{t}b\bar{b}$ hadroproduction at NLO accuracy matched with parton shower

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in collaboration with
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MAGYARORSZÁG MEGÚJUL

A projekt az Európai Unió támogatásával, az Európai Szociális Alap társfinanszírozásával valósul meg.

ÚJ SZÉCHENYI TERV

Outline

- Motivation
- Method
- Predictions at fixed order
- Comparison LHEF to NLO
- Predictions with SMC
- Conclusions

Motivation

Need for $t\bar{t}b\bar{b}$ at the hadron level

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    - $\sigma(t\bar{t}H) = 0.130$ pb for $m_H = 125$ GeV
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    - experimentally: systematics, JES, b-tagging
    - theoretically: scale uncertainties, effect of PS and hadronization
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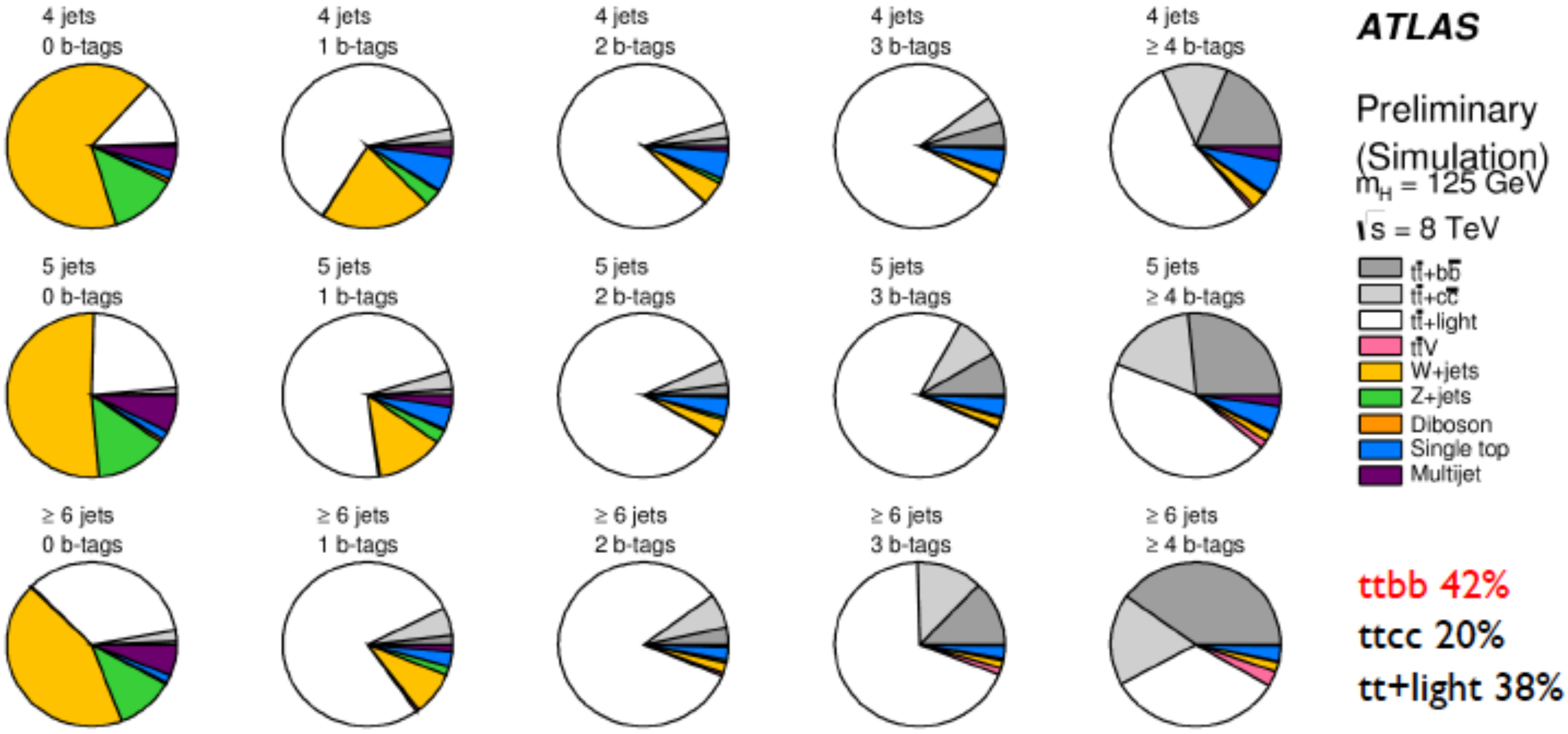
- In this work we use massless b-quarks (3% error@LO)

slide from talk by J. Montejo at ttH workshop 2013

Background composition

- Background composition for lepton+jets analysis
  - After requiring 2 b-tag the background is > 90% ttbar+jets/HF
  - **We need a model giving a good prediction in a wide range of jets and tags multiplicities**



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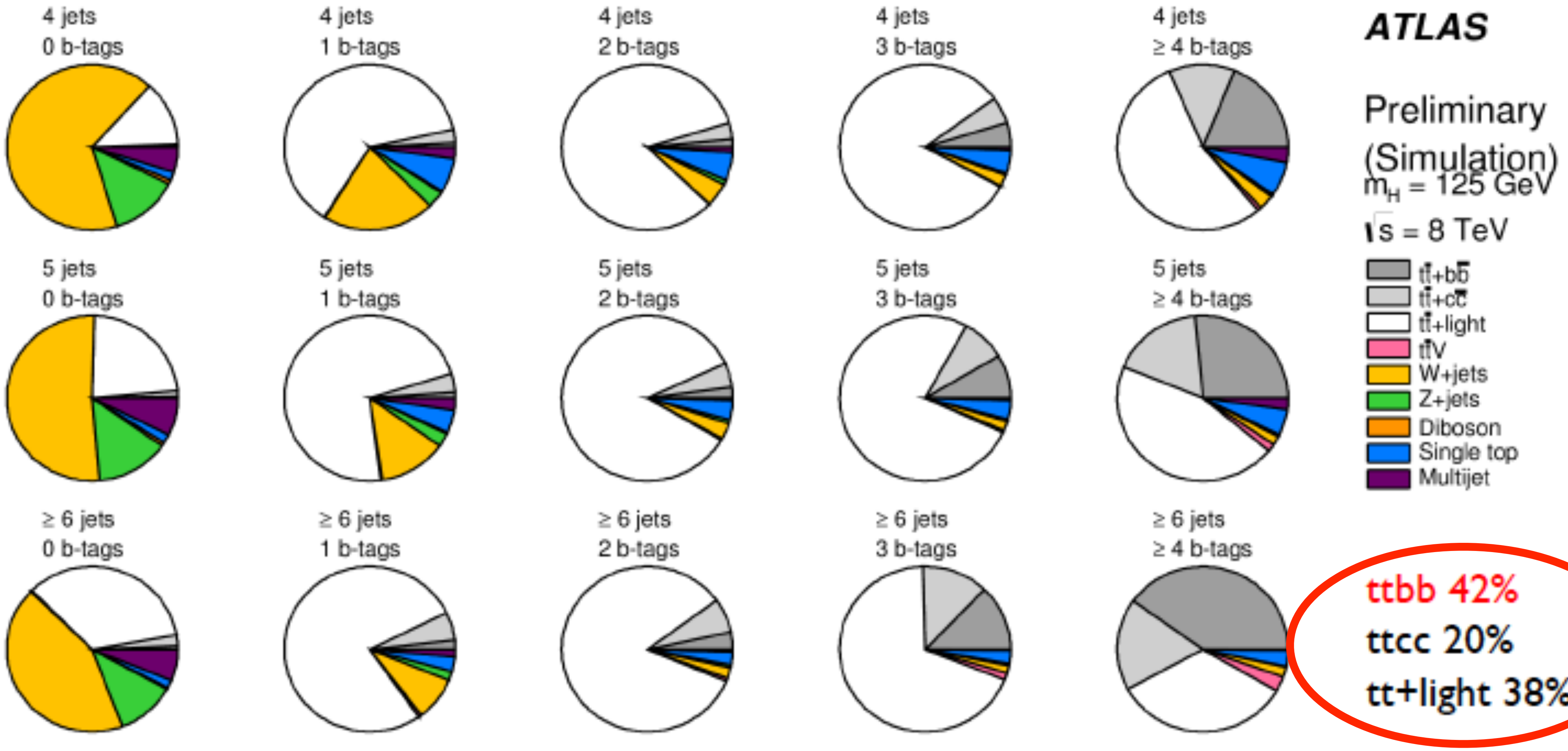

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- Cascioli et al [arXiv:1309.5912]:
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Method

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- Standard MC first emission:

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

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:

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

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

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- POWHEG MC first emission:

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

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

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Formal accuracy of the POWHEG MC

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

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

$$+ \int d\Phi_{\rm R} \Delta(p_\perp) \frac{\widetilde{B}}{B} R \left(O(\Phi_{\rm R}) - O(\Phi_{\rm B}) \right) =$$

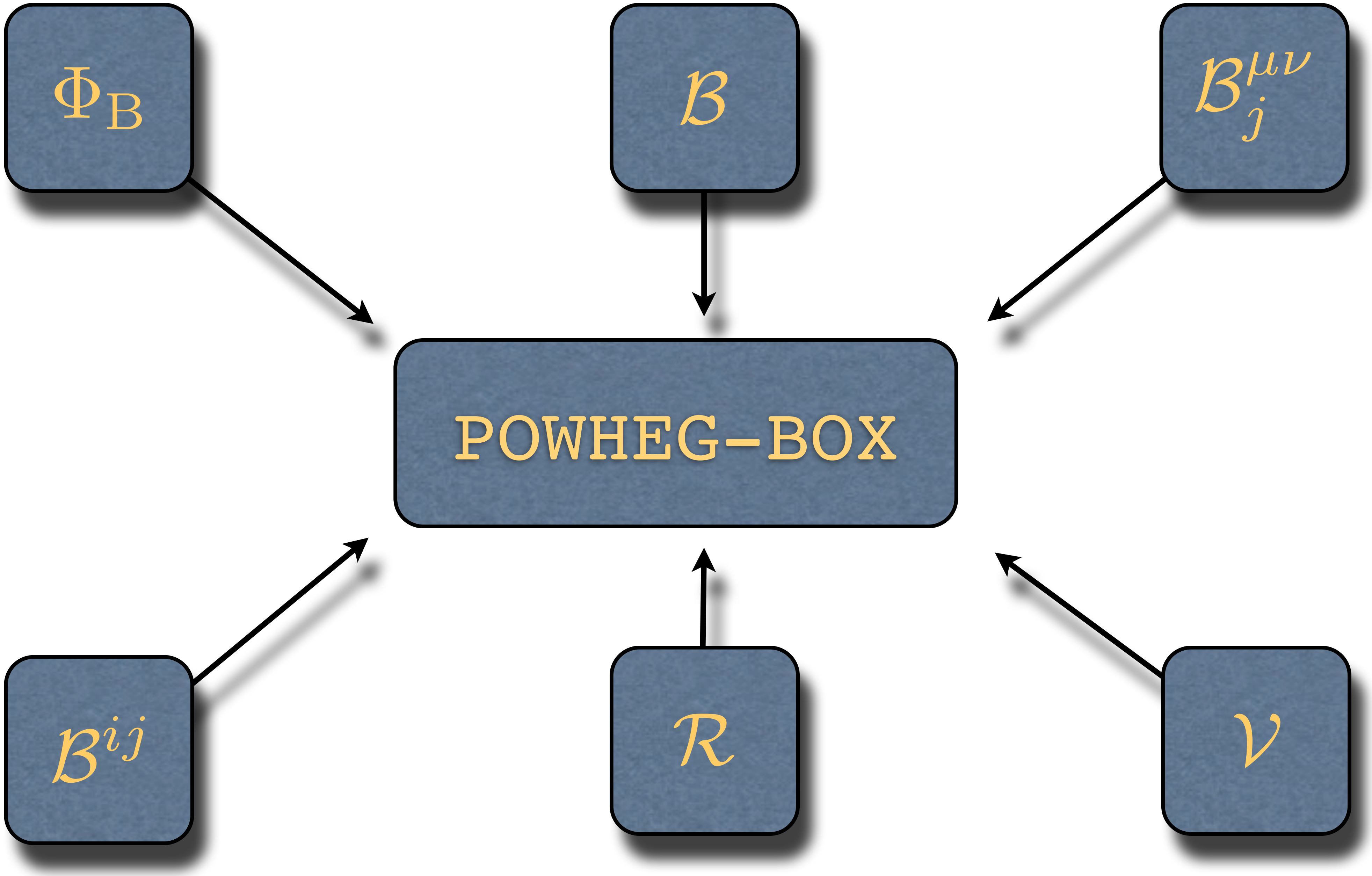
$$= \left\{ \int d\Phi_{\rm B} \widetilde{B} O(\Phi_{\rm B}) + \int d\Phi_{\rm R} R \left(O(\Phi_{\rm R}) - O(\Phi_{\rm B}) \right) \right\} (1 + \mathcal{O}(\alpha_{\rm S})) =$$

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

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

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

POWHEG-BOX framework



Φ_{B}

$\mathcal{B}$

$\mathcal{B}_j^{\mu\nu}$

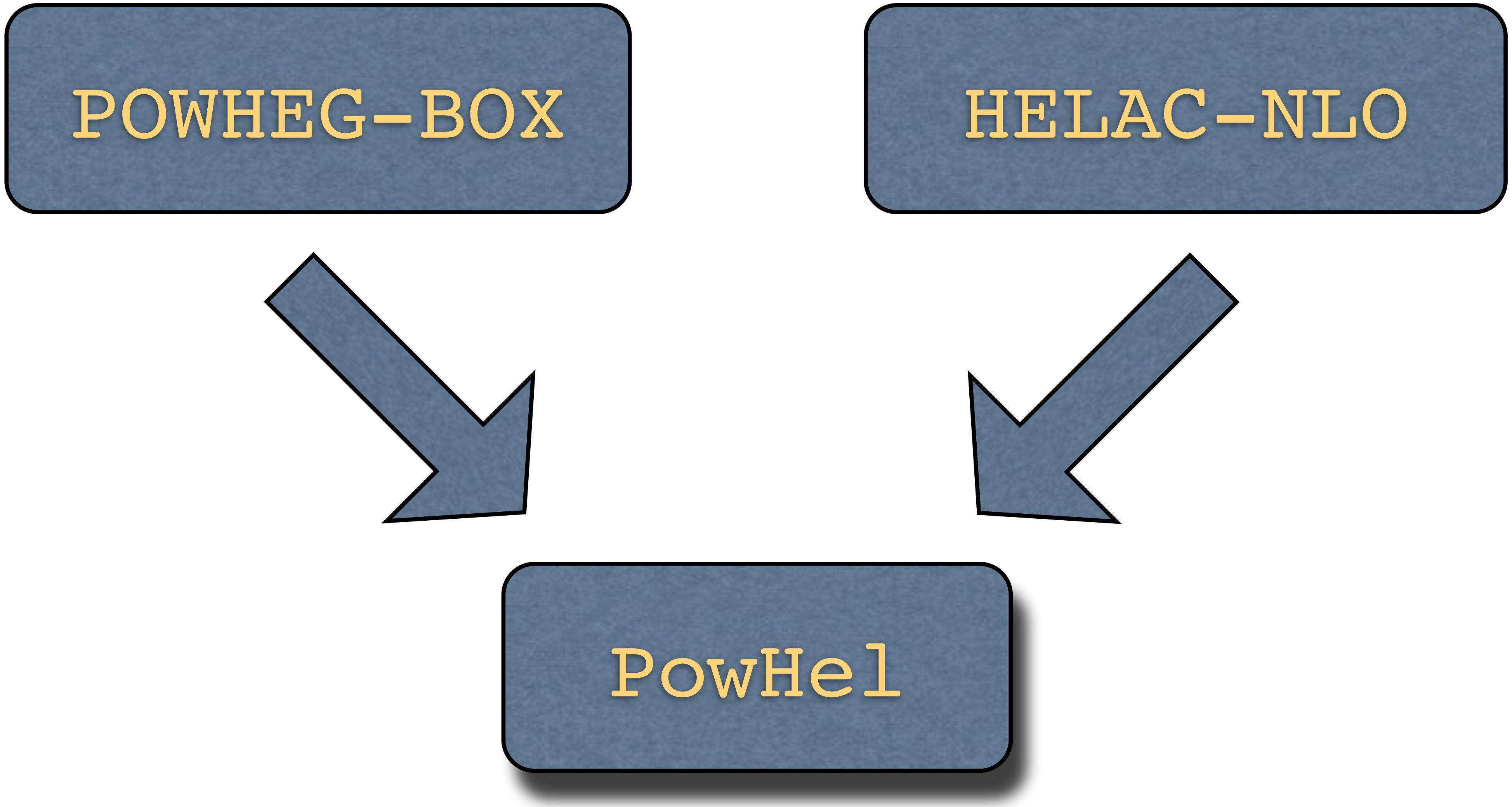
POWHEG-BOX

$\mathcal{B}^{ij}$

$\mathcal{R}$

$\mathcal{V}$

PowHel framework



POWHEG-BOX

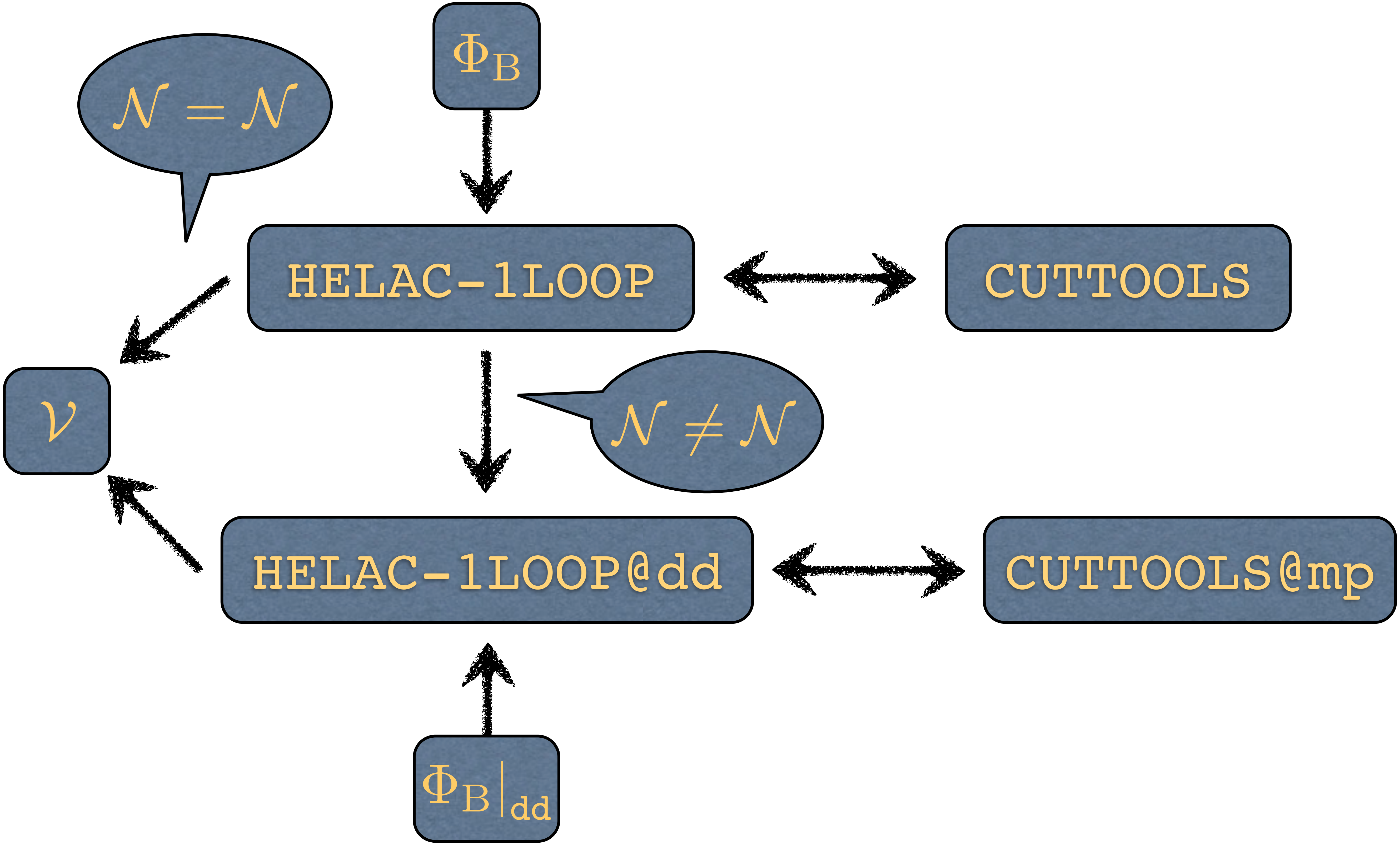
HELAC-NLO

PowHel

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



Φ_B

$\mathcal{N} = \mathcal{N}$

HELAC-1LOOP

CUTTOOLS

$\mathcal{V}$

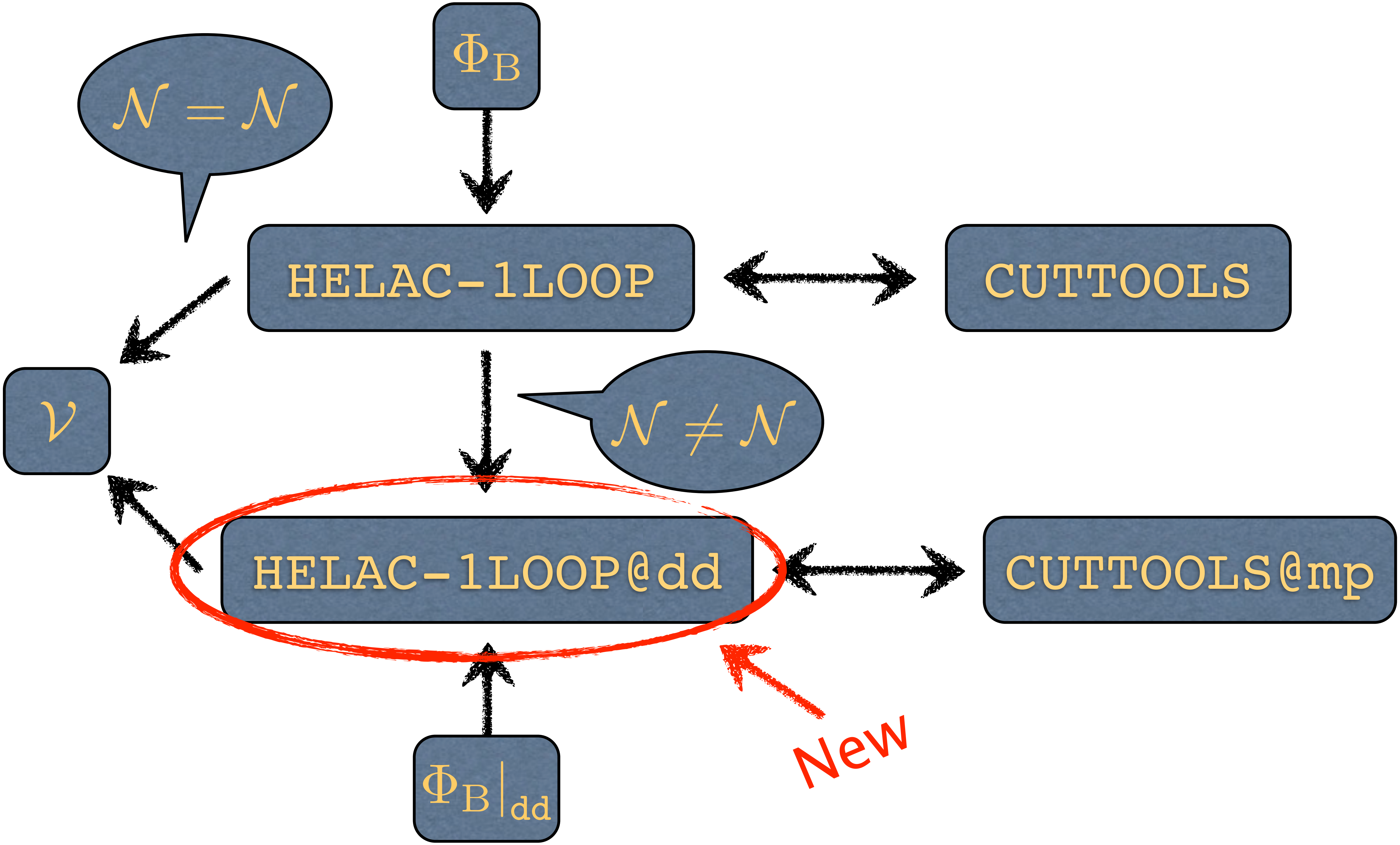
$\mathcal{N} \neq \mathcal{N}$

HELAC-1LOOP@dd

CUTTOOLS@mp

$\Phi_\mathrm{B}|_{\mathrm{dd}}$

HELAC-1LOOP@dd framework



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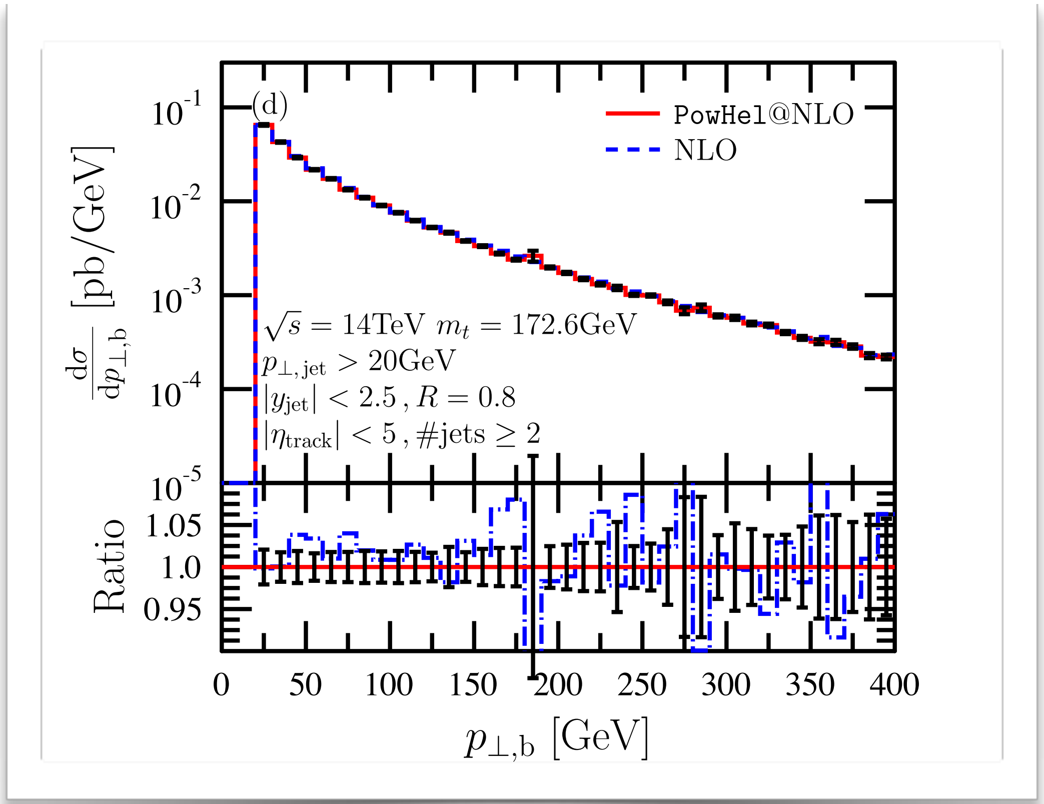
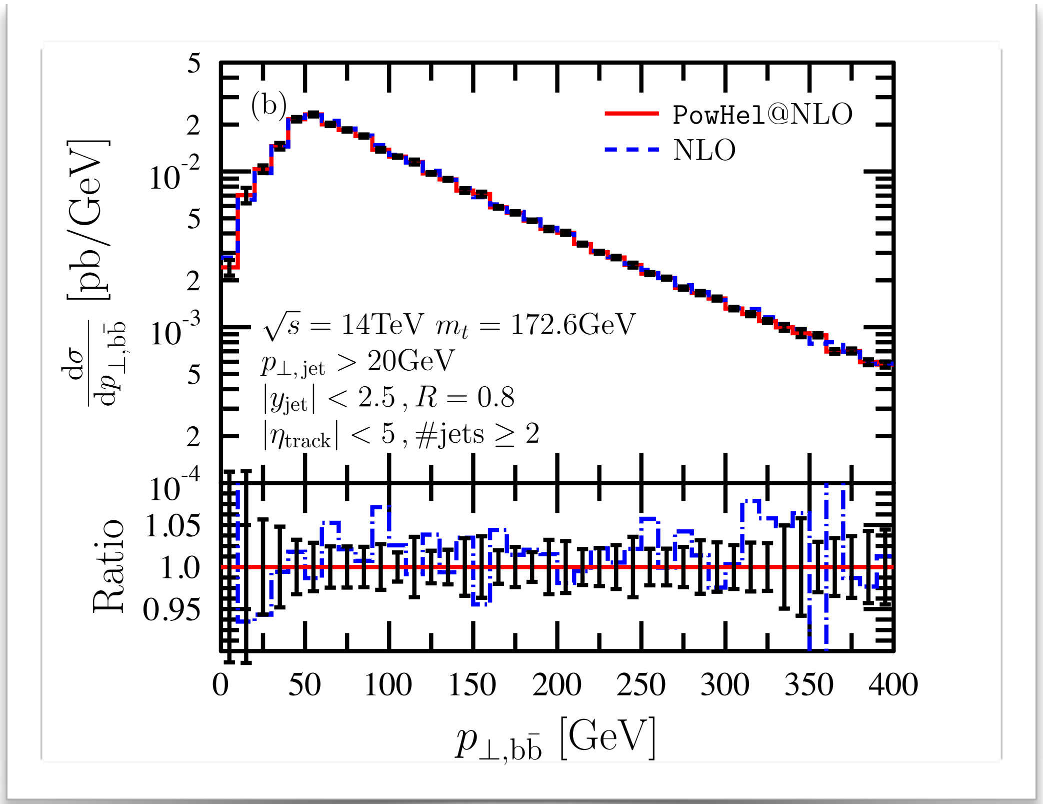
New

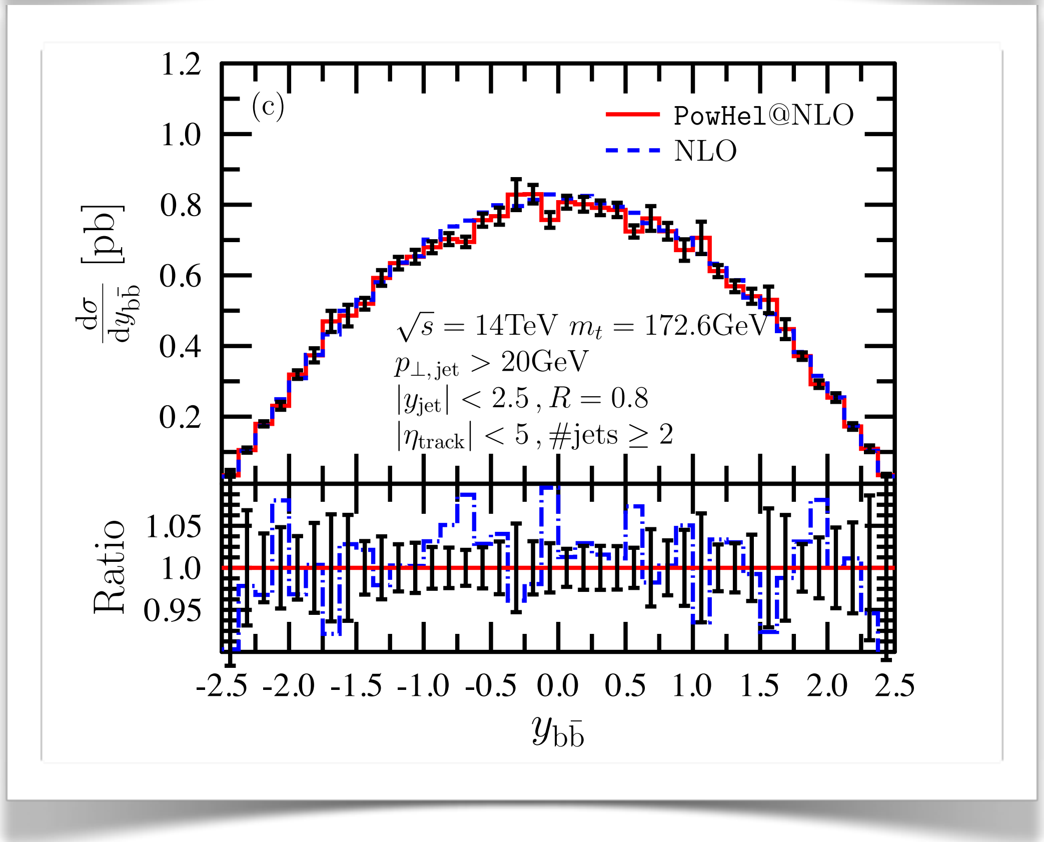
$\Phi_{\mathrm{B}}|_{\mathrm{dd}}$

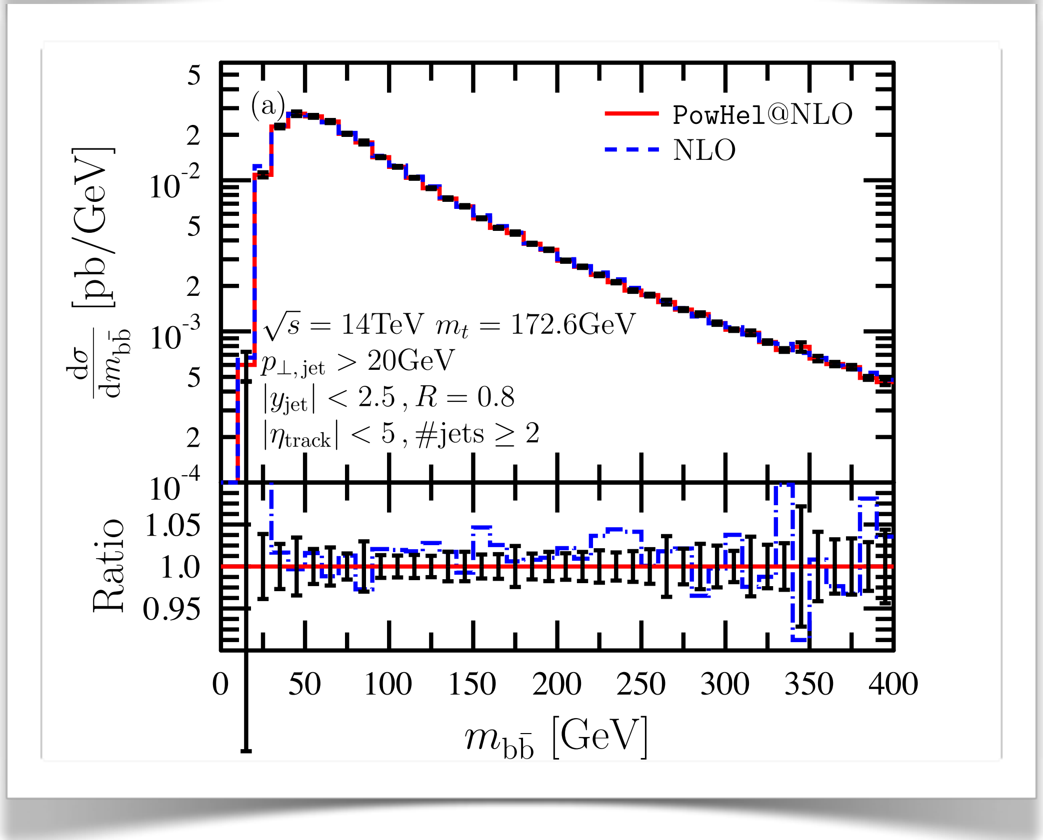
Predictions at fixed order

Comparison to Bevilacqua et al: 0907.4723









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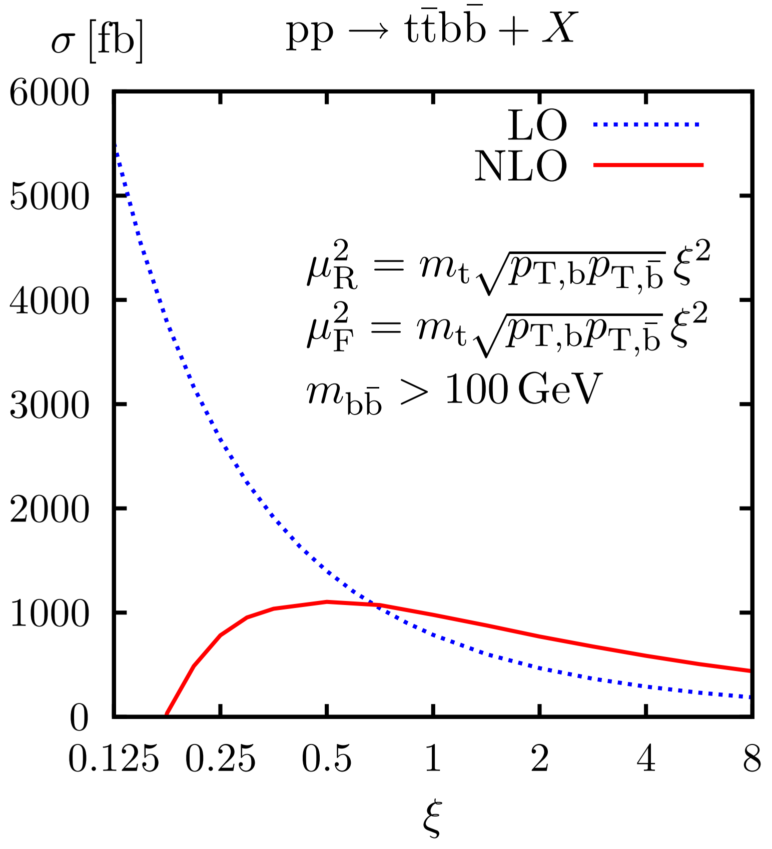
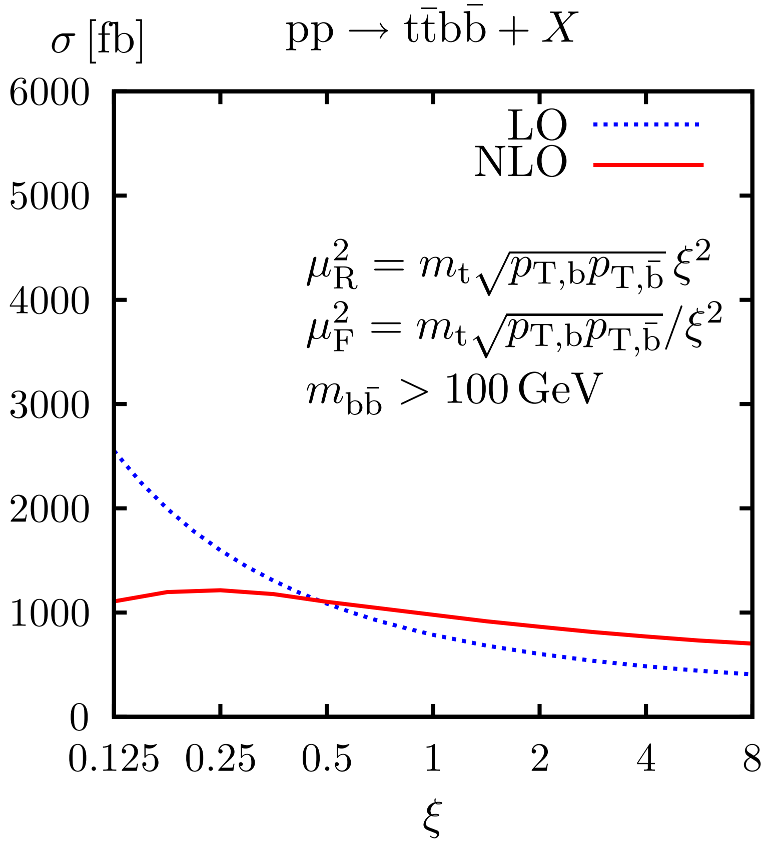
  - moderate with dynamical scale $\mu_0 = (m_t^2\, p_{T,b} p_{T,\bar{b}})^{1/4}$ (about 25%) (proposed by Bredenstein et al in arXiv:1001.4006), implying better convergence

slide from talk by S.Pozzorini at HO10





LO and NLO scale dependence of $\sigma_{t\bar{t}b\bar{b}}$

Variations around new central scale

$$\mu_0^2 = m_t\sqrt{p_{T,b}p_{T,\bar{b}}}$$

Good news for theory: improved convergence

- small correction & uncertainty ($K = 1.25 \pm 21\%$)
- shape of NLO curves: μ_0 close to maximum

Bad news for experiment: $\sigma_{t\bar{t}b\bar{b}}$ enhanced by factor 2.2[a] wrt LO ATLAS simulations

$\sigma_{t\bar{t}b\bar{b}}$	LO	NLO	NLO/LO
$\mu_{R,F} = E_{thr}/2$	449 fb	751 fb	1.67
$\mu_{R,F}^2 = m_t\sqrt{p_{T,b}p_{T,\bar{b}}}$	786 fb	978 fb	1.24

---

[a] (Partially) taken into account in Fat-Jet analysis!

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 by Bredenstein et al in arXiv:1001.4006), implying better convergence

but

- 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 $\mu_{dyn} = 90\ \text{GeV} \ll m_t$ resulting in an artificially large xsection at LO

Choice of scales

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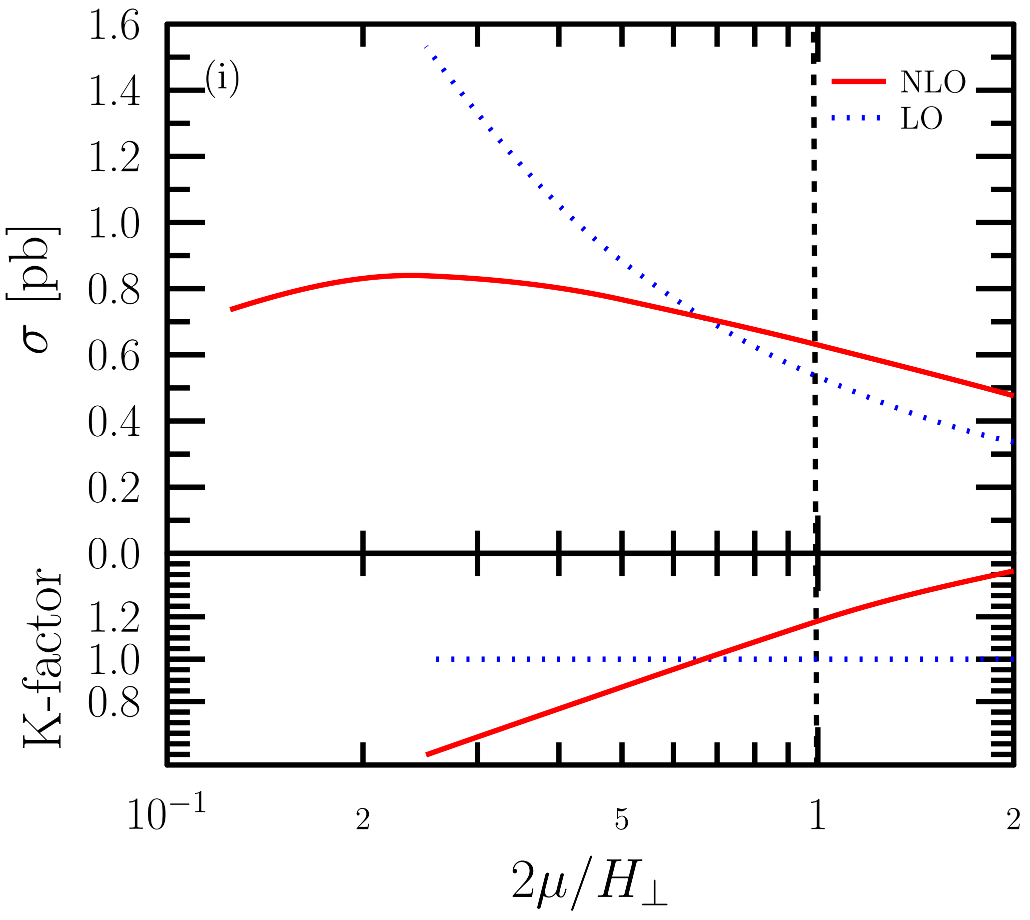

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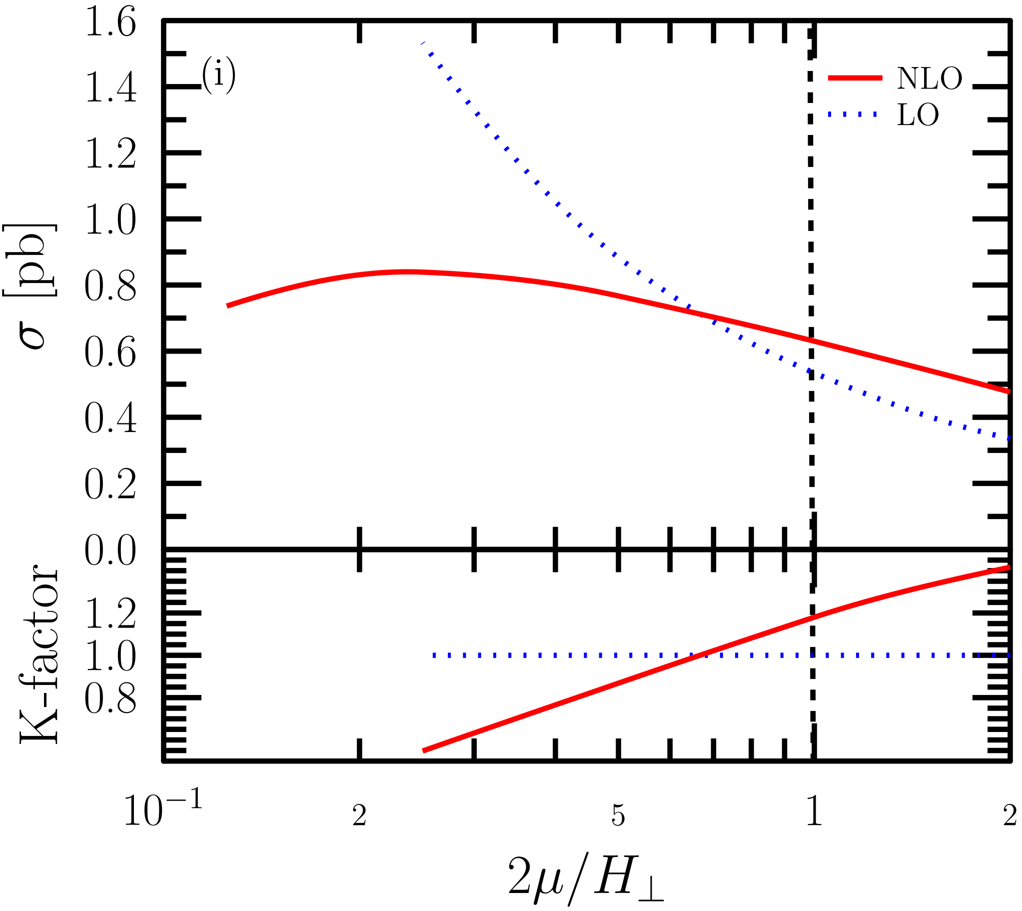

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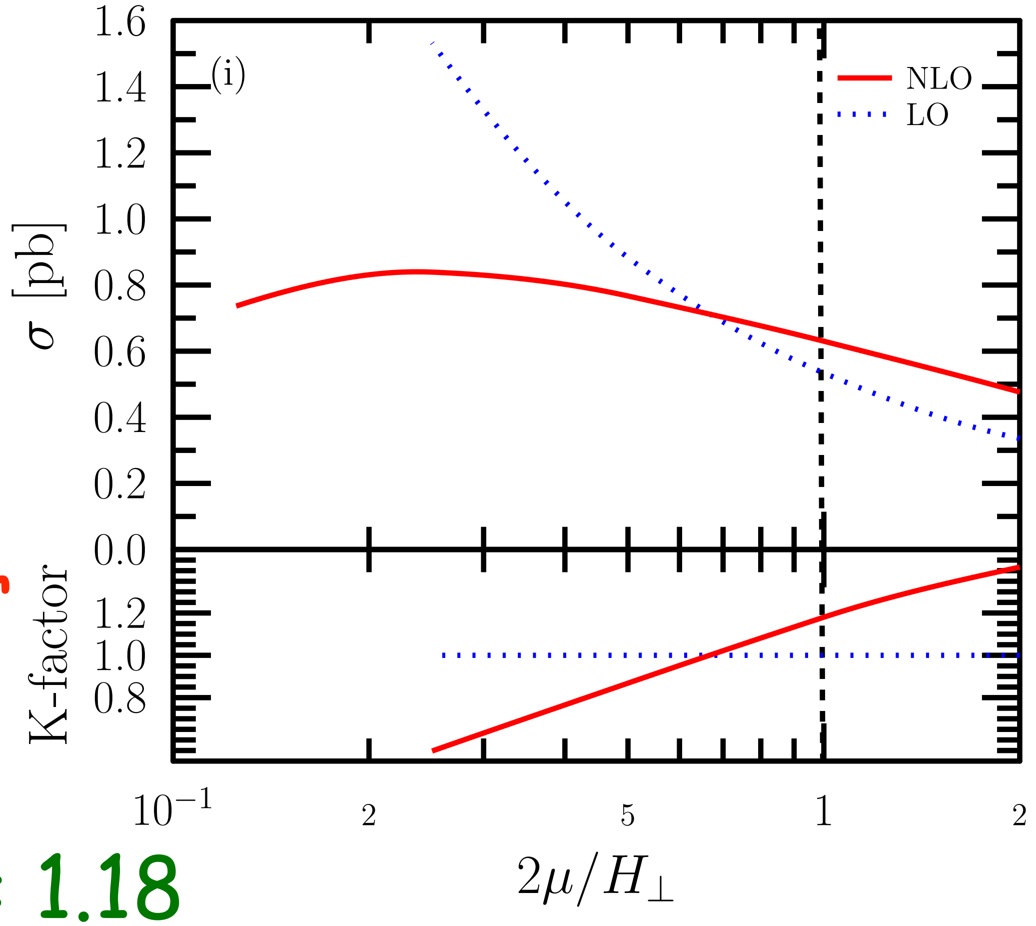

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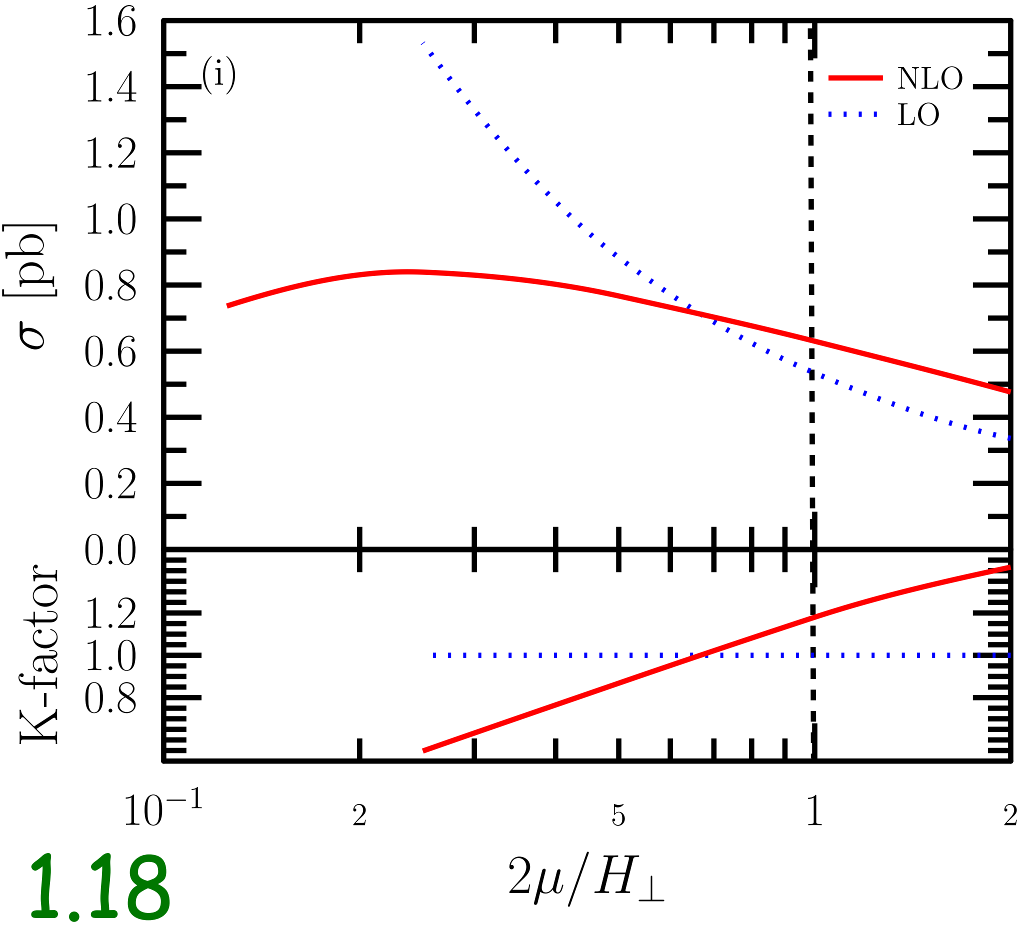
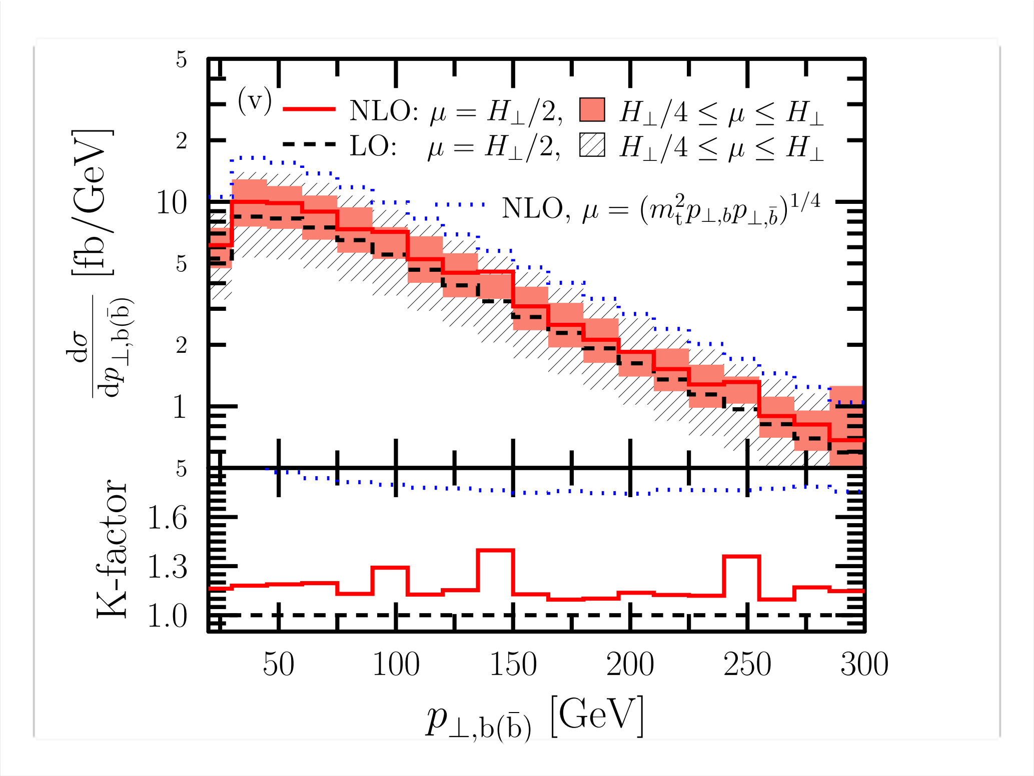
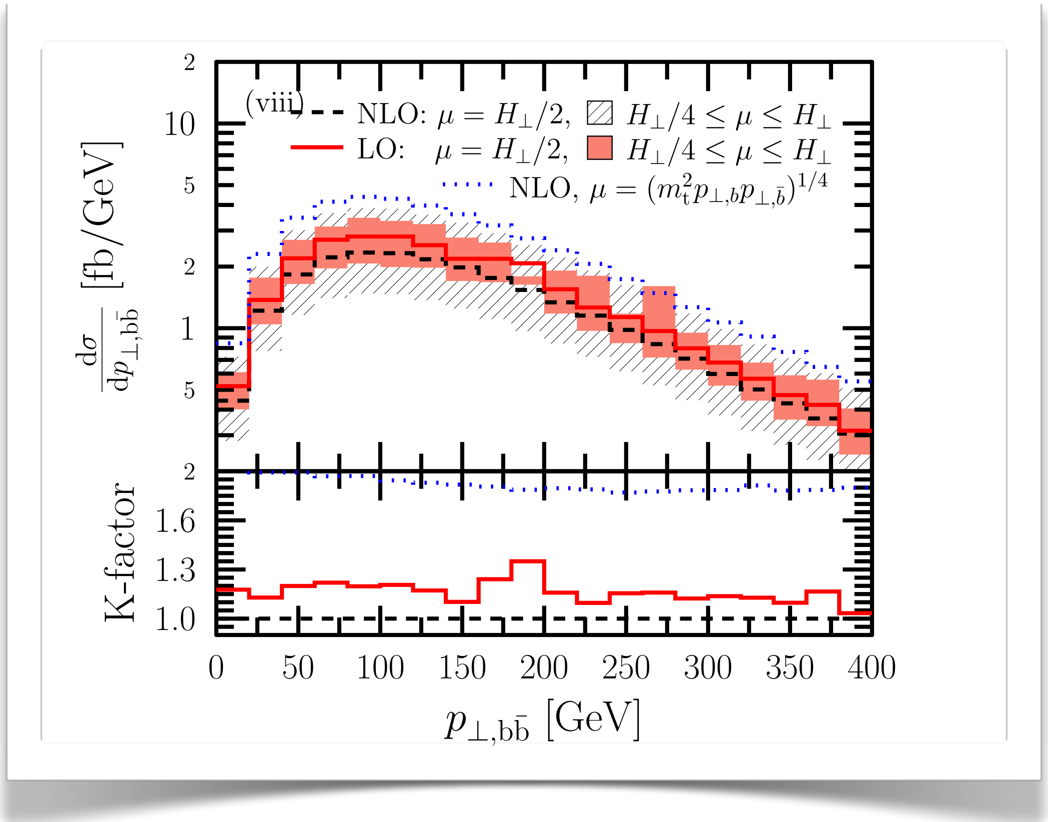


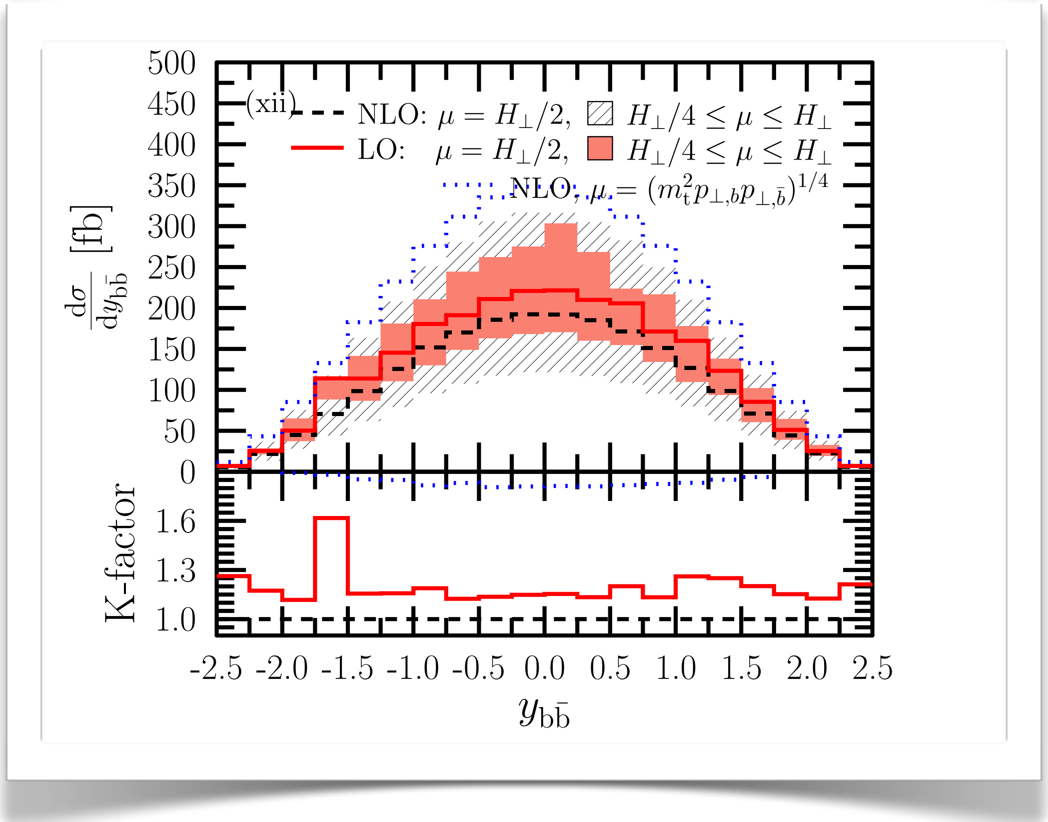
σ_{LO} = 534 fb, σ_{NLO} = 630 fb, K = 1.18

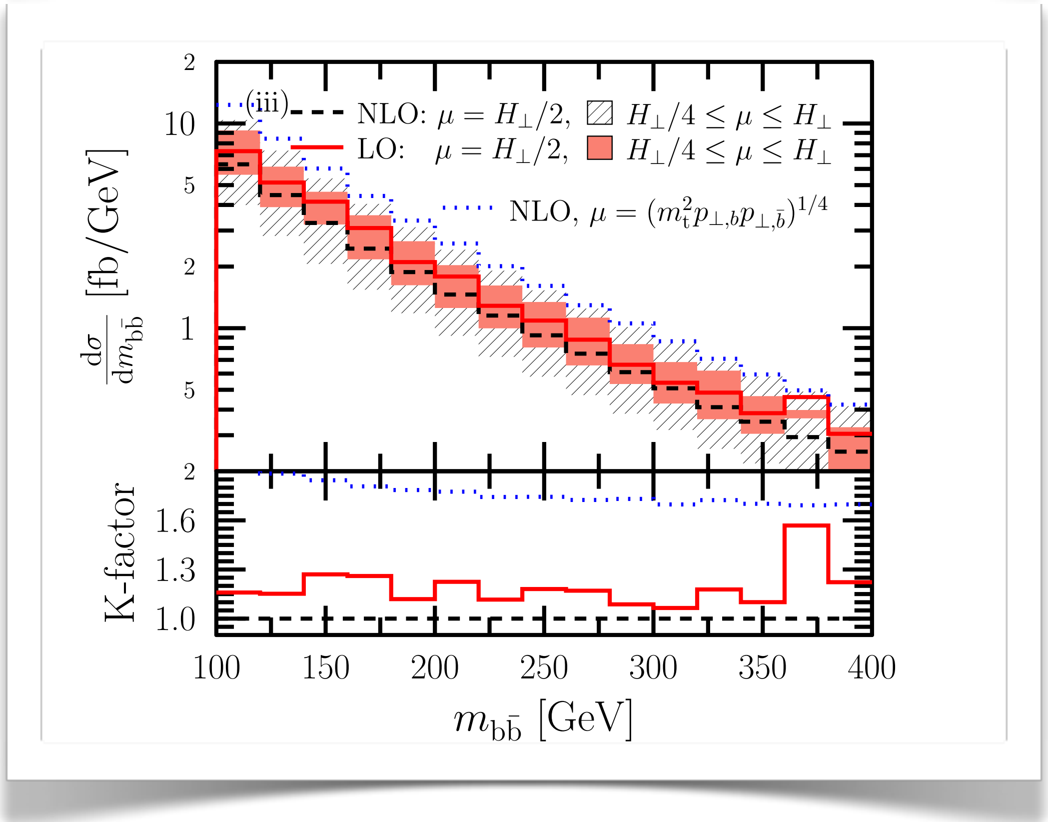
scale dependence: ${}^{+32\%}_{-22\%}$, largest if $\mu_R = \mu_F = \mu_{dyn}$

Small changes in shapes of distributions



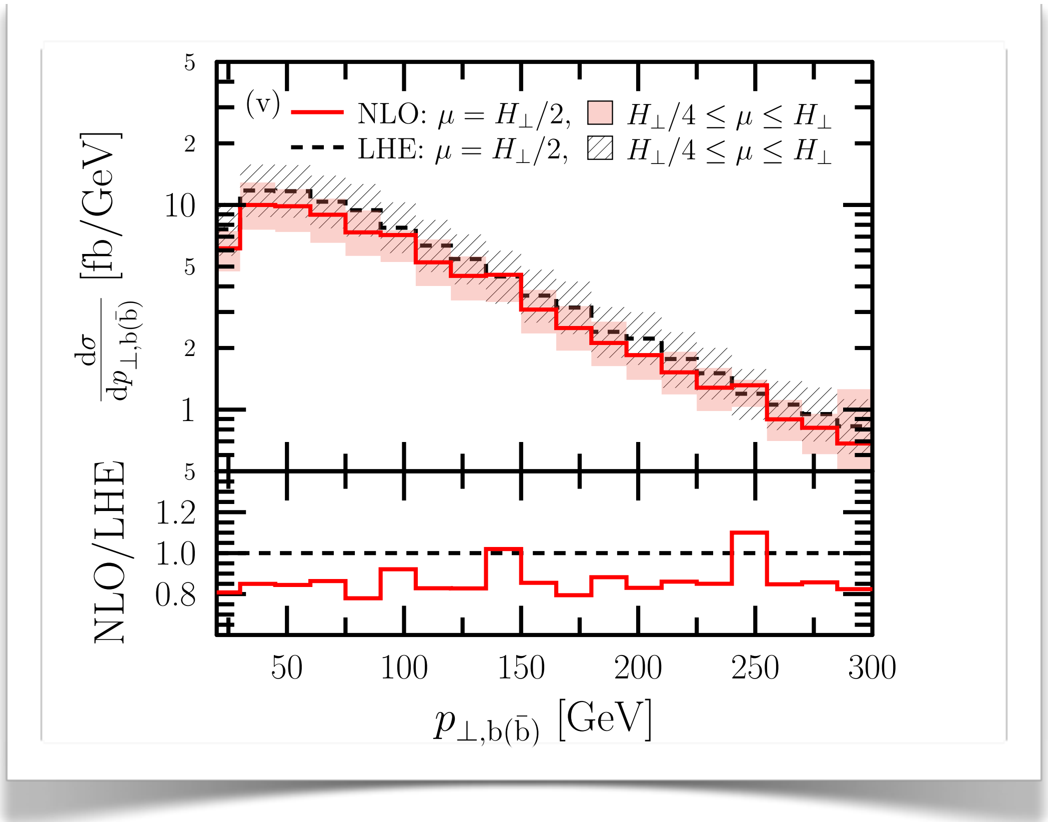


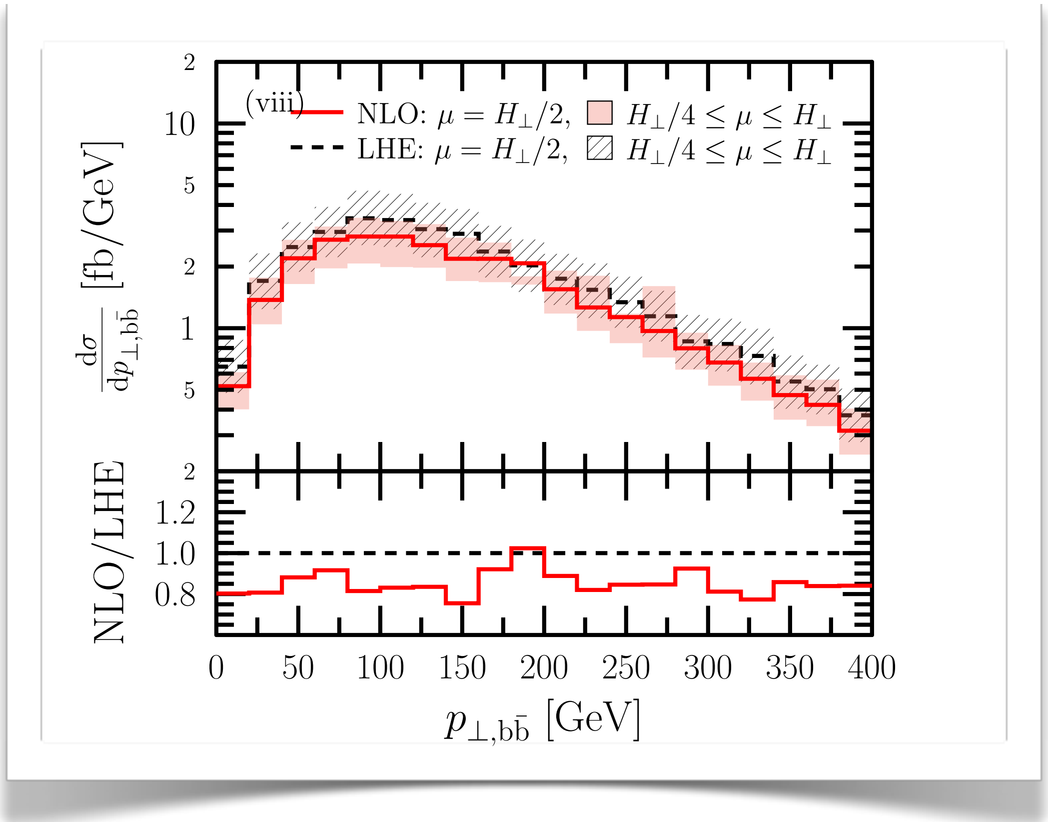




Comparison of LHEF to NLO

LHE vs. NLO


(v)
NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dp_{\perp,b(\bar{b})}}$ [fb/GeV]
5
2
10
5
2
1
5
NLO/LHE
1.2
1.0
0.8
50
100
150
200
250
300
$p_{\perp,b(\bar{b})}$ [GeV]


(viii)
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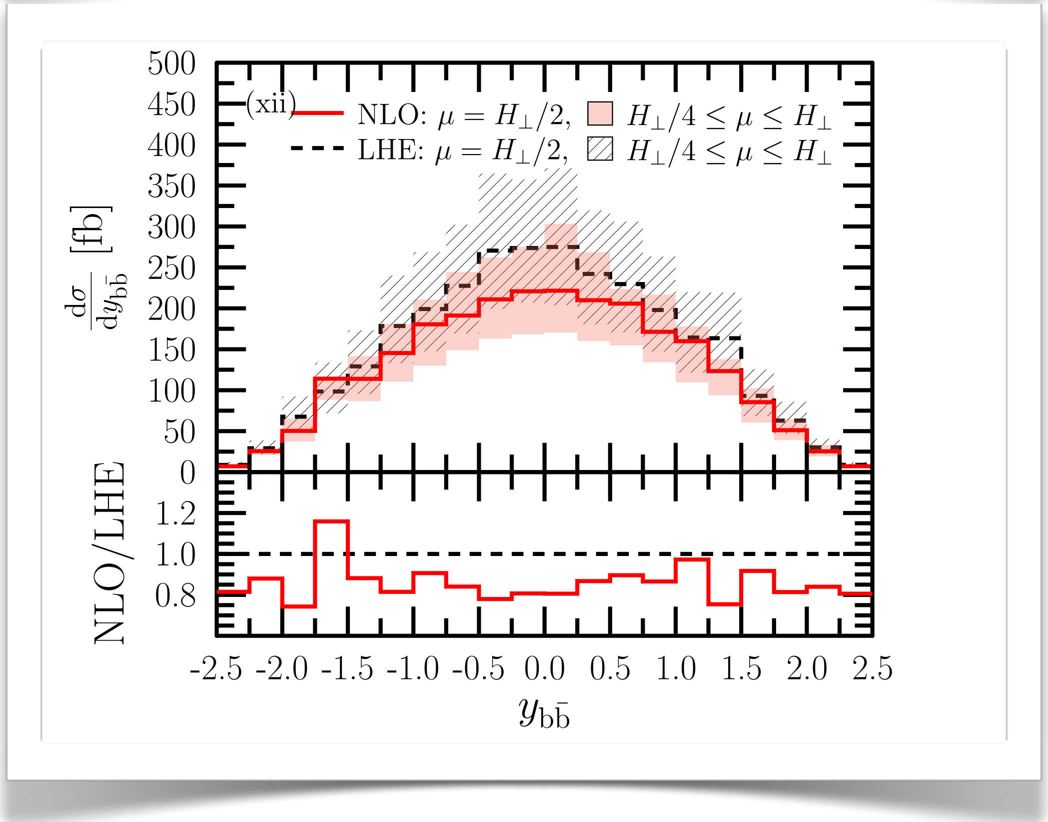
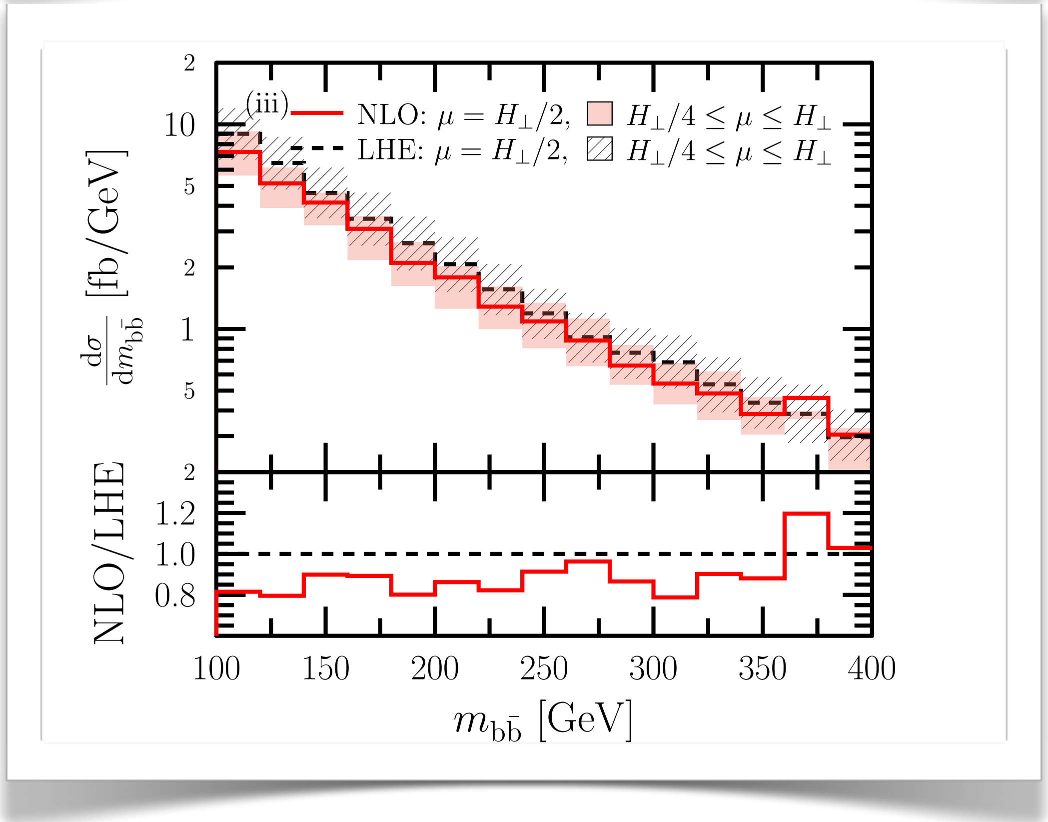
$\frac{d\sigma}{dp_{\perp,b\bar{b}}}$ [fb/GeV]
2
10
5
2
1
5
2
NLO/LHE
1.2
1.0
0.8
0
50
100
150
200
250
300
350
400
$p_{\perp,b\bar{b}}$ [GeV]


(xii)
NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dy_{b\bar{b}}}$ [fb]
500
450
400
350
300
250
200
150
100
50
0
NLO/LHE
1.2
1.0
0.8
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
$y_{b\bar{b}}$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NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dm_{b\bar{b}}}$ [fb/GeV]
2
10
5
2
1
5
2
NLO/LHE
1.2
1.0
0.8
100
150
200
250
300
350
400
$m_{b\bar{b}}$ [GeV]

Message:

we can trust the LHE's, so can make

Predictions

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: decays, parton showering (PYTHIA or HERWIG) included

Four possible forms of predictions

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Number and type of particles are very different =>
to study the effect of SMC 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.

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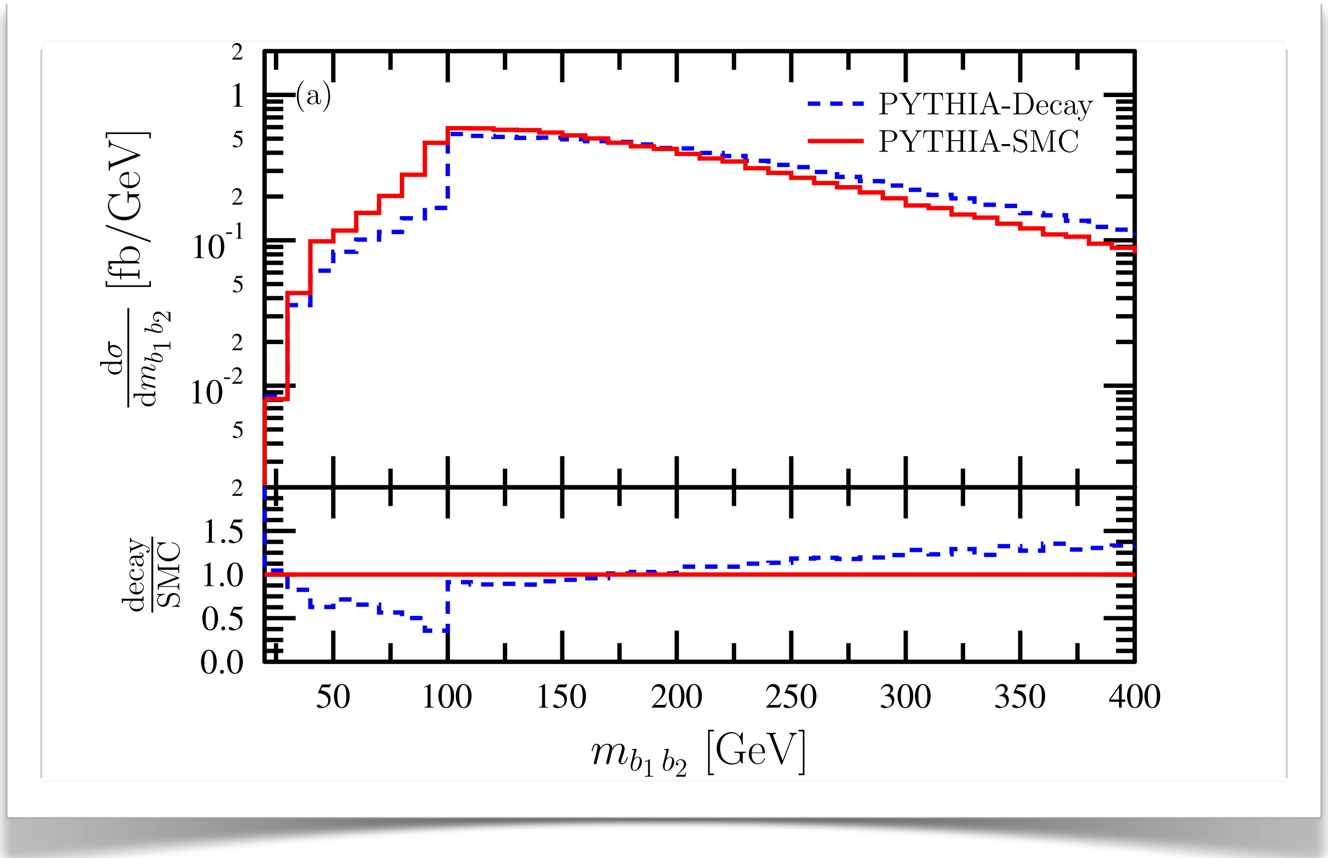
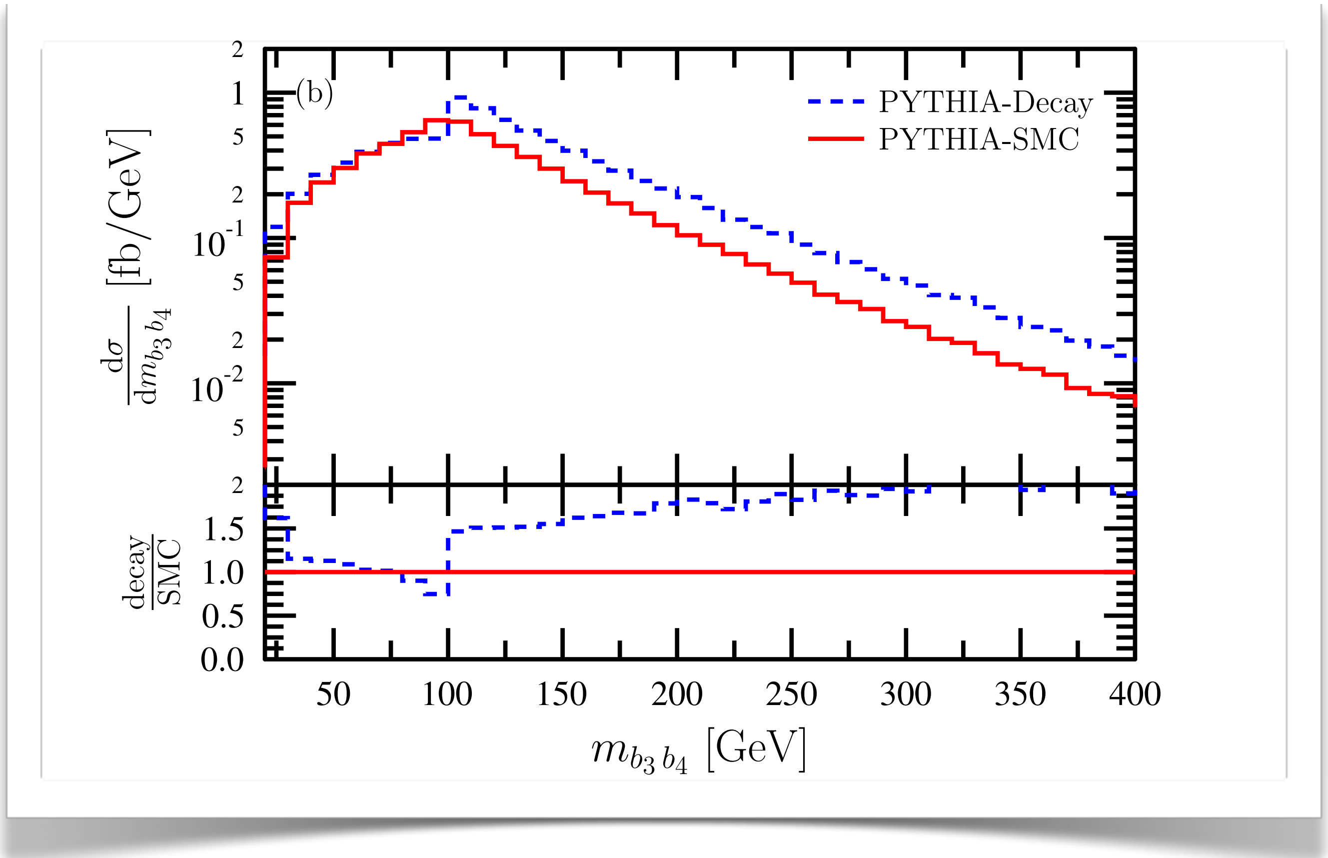
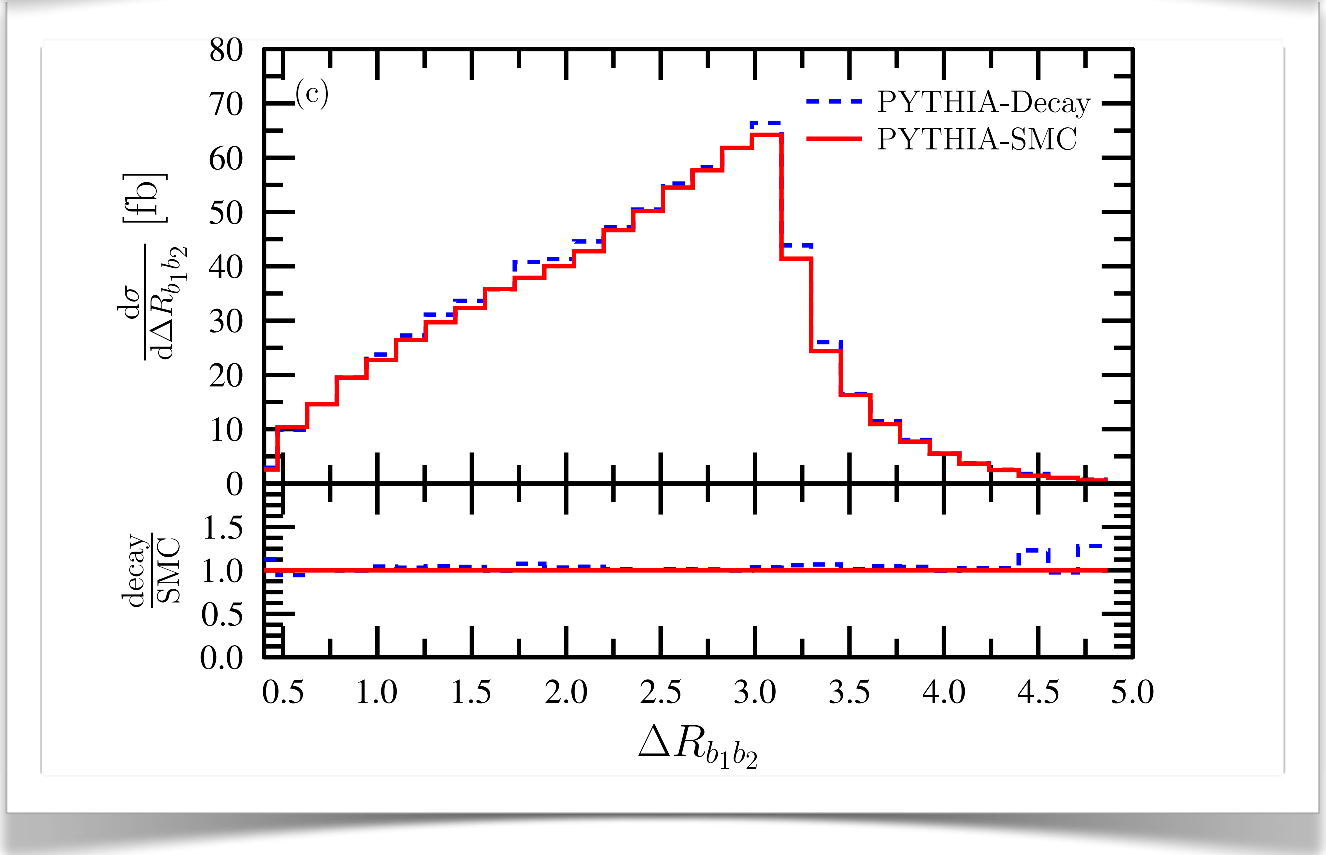
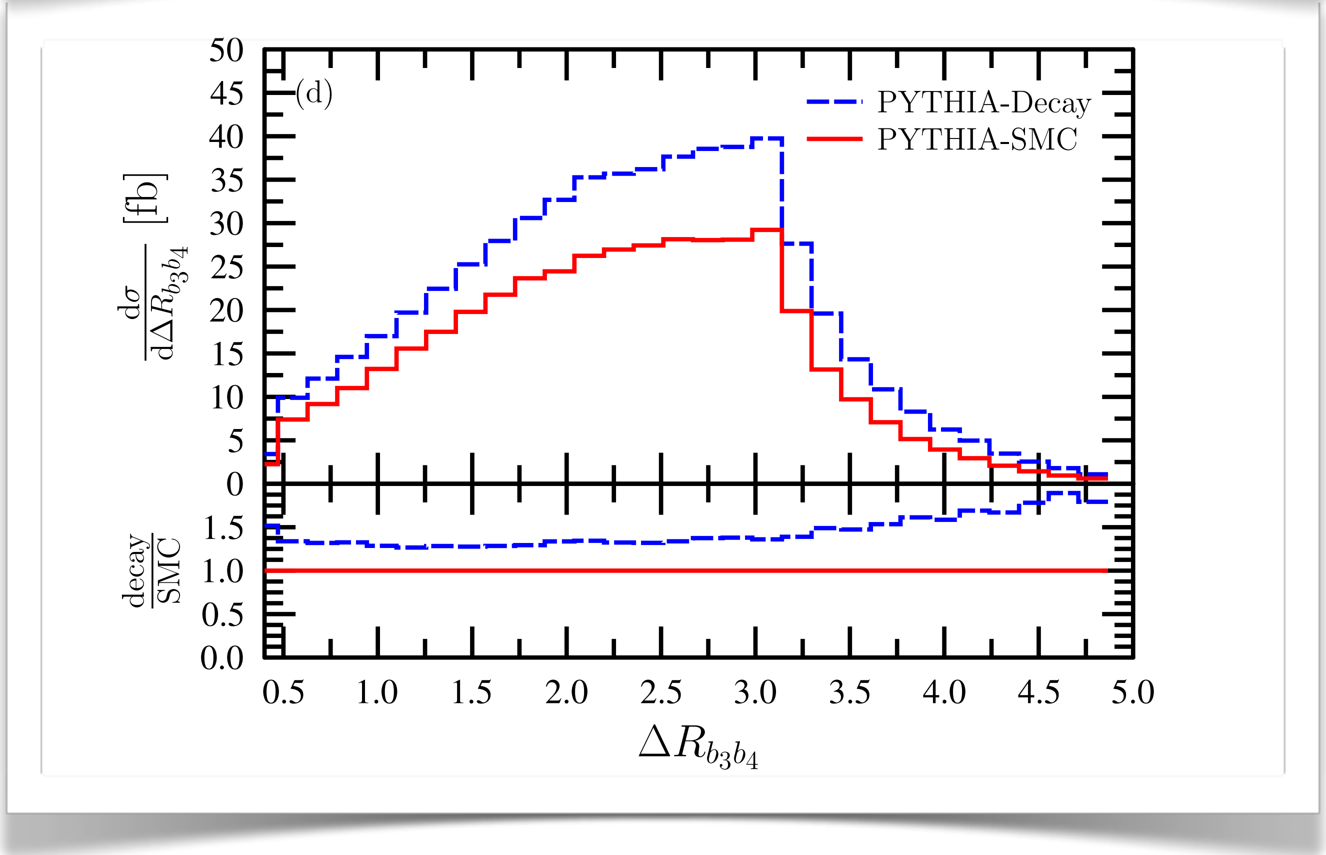
  - Events with invariant mass of the $b\bar{b}$-jet pair below $m^{min}{}_{b\bar{b}} = 100$ GeV were discarded.
- Applied on LHE's and checked also on the existing particles at different stages of evolution:
  - we require $p_{Tmin,j} = 25$ GeV and
  - at least two, one b- & one $\bar{b}$-jet with $|\eta_{b(\bar{b})}|<2.5$.

Decay vs. full SMC at 8TeV, μ = H$_T$/4

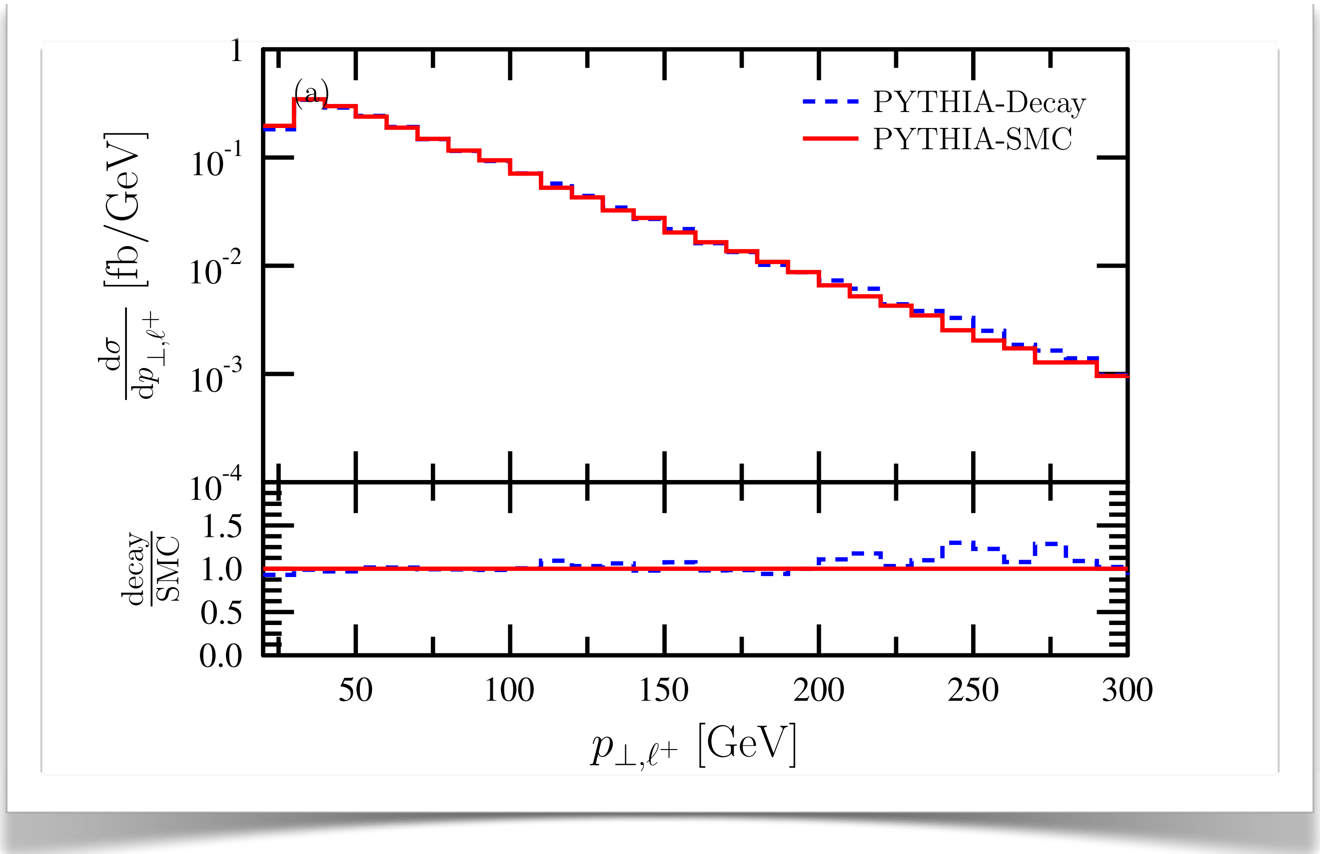


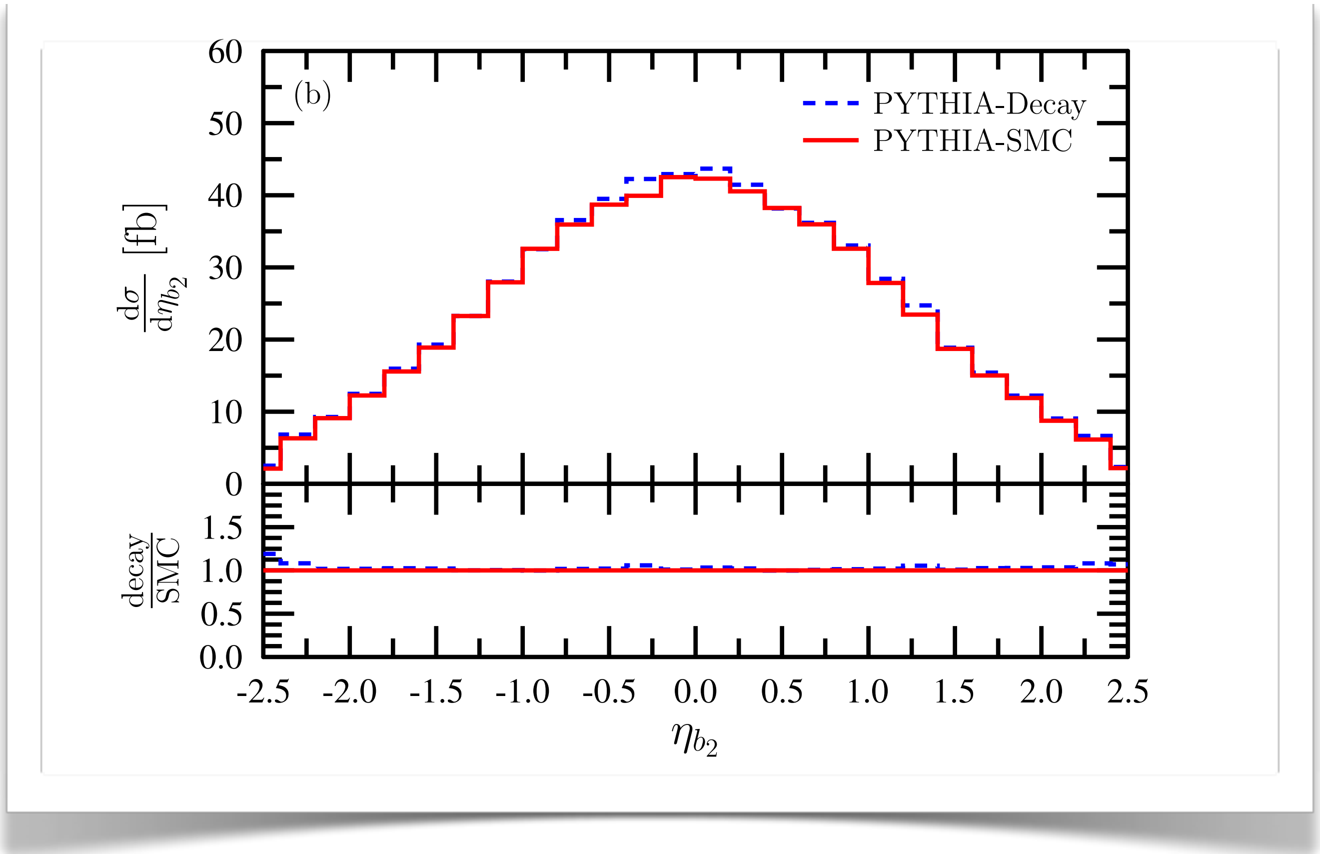






Decay vs. full SMC at 8TeV, $\mu = H_T/4$





Effects of SMC are important for hadronic variables,
except rapidities, small on hardest leptonic ones

Cuts for background study for ttH

Applied after full SMC

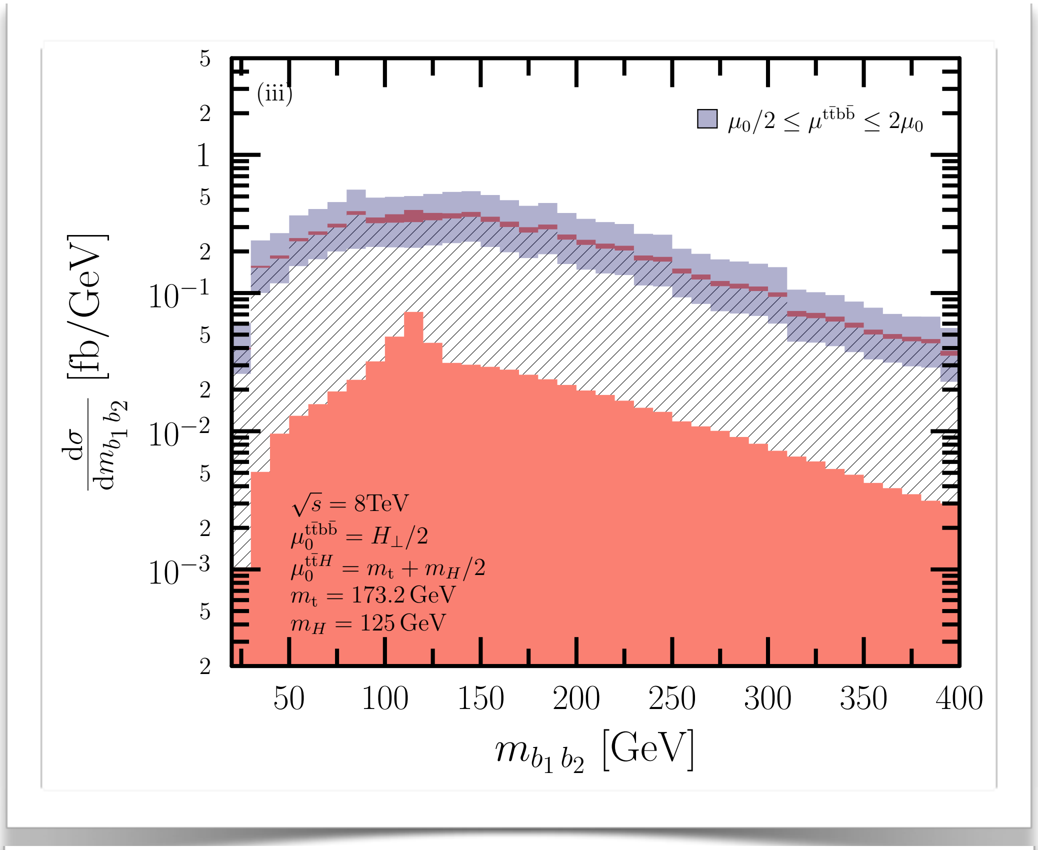
- a track was considered as a possible jet constituent if $|\eta^{track}|<5$, jets were reconstructed with the anti-k_T algorithm using R=0.4

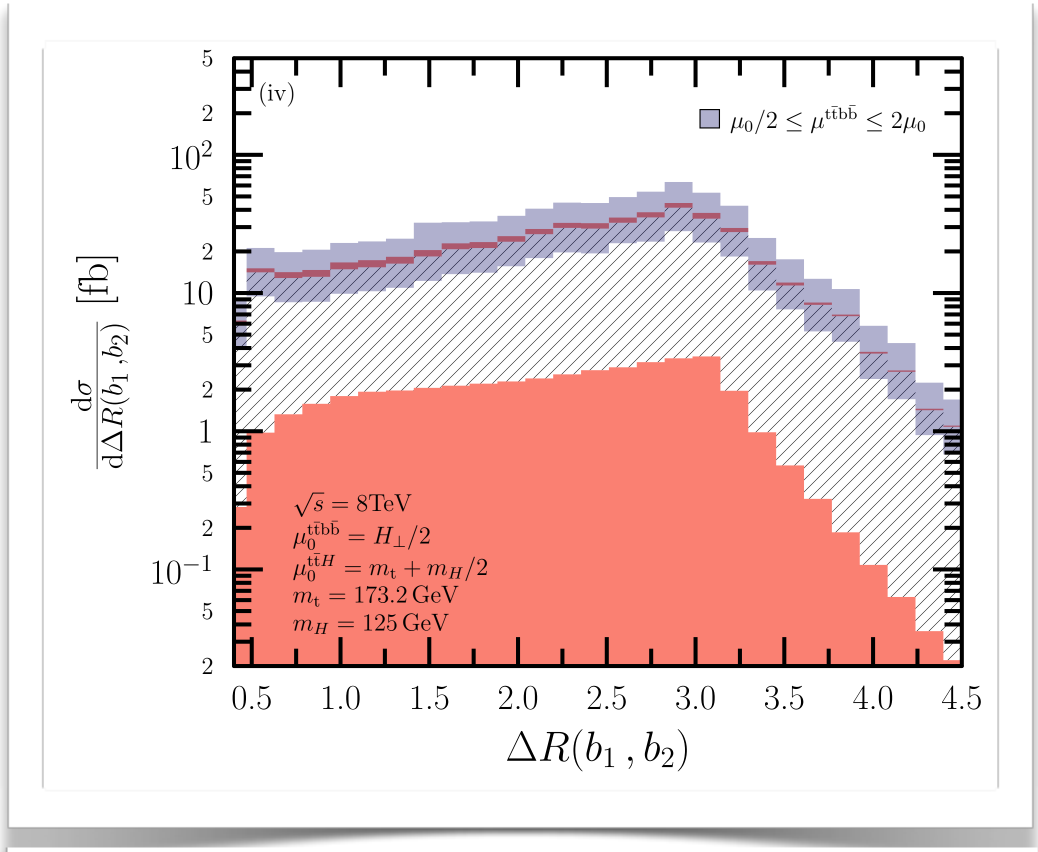
we require

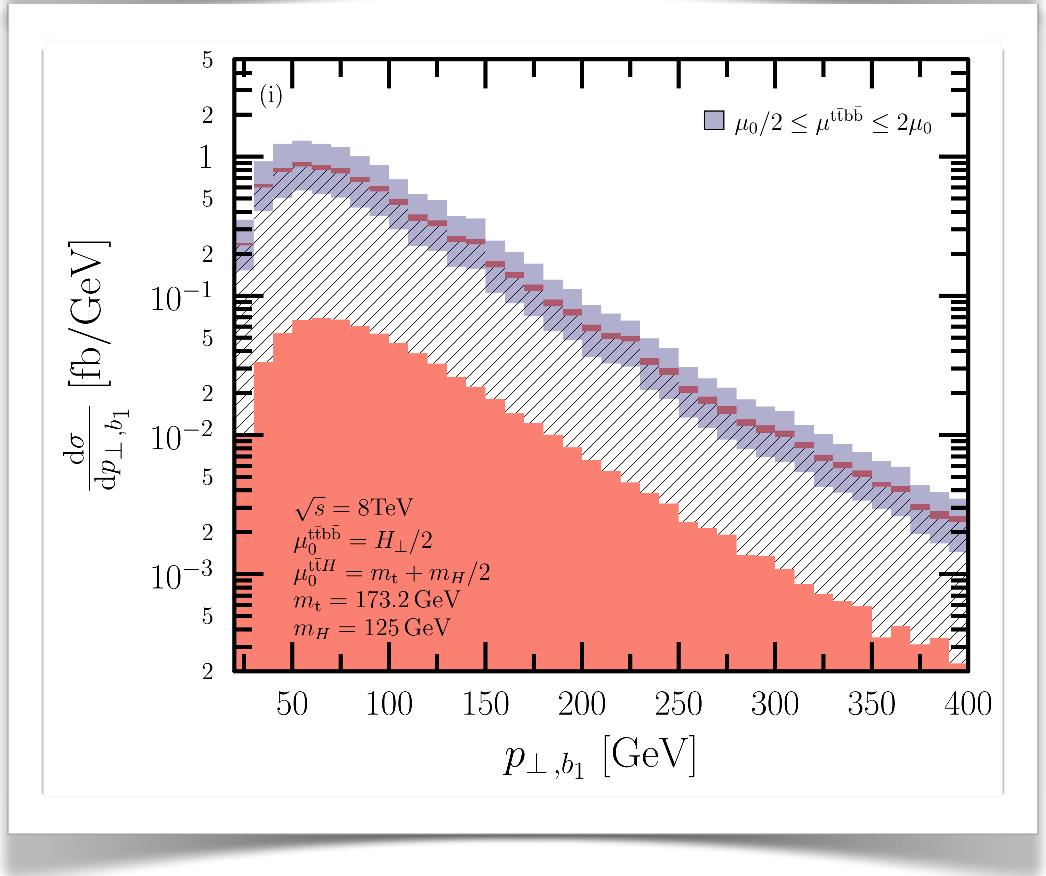
- at least six jets with $p_{Tmin,j}$ = 20 GeV and $|\eta_j|<5$
- at least two b-jets & two $\bar{b}$-jets with $|\eta_{b(\bar{b})}|<2.7$, with MCTRUTH tagging
- at least one isolated (with R=0.4) lepton with $p_{Tmin,\ell}$ = 20 GeV and $|\eta_\ell|<2.5$
- p_T^{miss} = 15 GeV

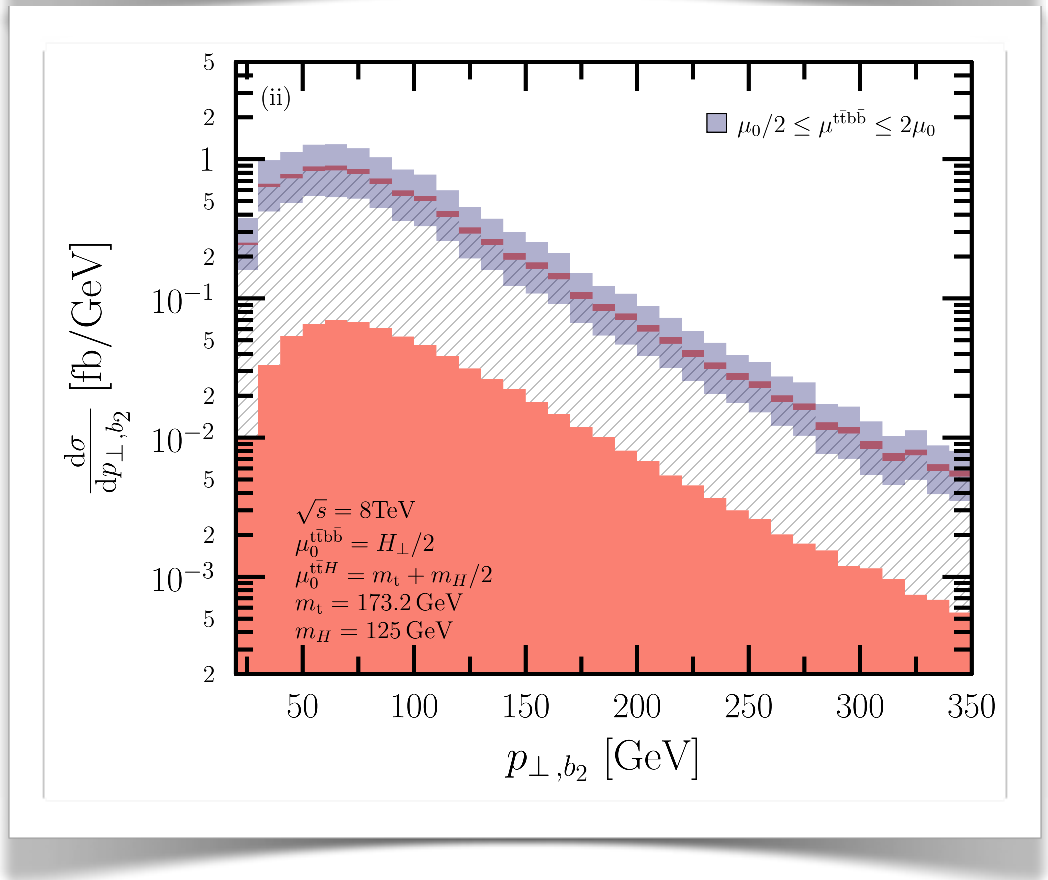
to disentangle background in the semileptonic $t\bar{t}$ decay

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









Conclusions

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- ✓ First computation of pp → $t\bar{t}b\bar{b}$ at NLO + SMC accuracy [A. Kardos and Z.T. arXiv:1303.6291 contained a bug in the code computing the jet function, lead to false predictions - now corrected]
- ✓ NLO cross sections agree with published predictions
- ✓ Effects of SMC are often important, depending on shower setup, variables and cuts strongly
- ✓ LHE event files for pp → $t\bar{t}$, $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$jet, $t\bar{t}b\bar{b}$ processes available, to put into SMC and perform experimental analyses on events with hadrons (all produced within the LHCPhenonet project)

the end