NLO QCD Predictions for $Wb\bar{b}$ Production in Association with Jets at the LHC

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Based on [arXiv:1712.05721]

Outline

Introduction

Motivation for radiative corrections

Precise understanding of Standard Model (SM) predictions is crucial for both SM measurements and for BSM searches!

Motivation for radiative corrections

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Why higher orders?

- Naive power counting in coupling constants (in particular QCD) frequently fails
- Reduce the error from truncation of perturbative expansion, higher order contributions can be large
- Test quantum nature of QFT through loops

Why higher multiplicity?

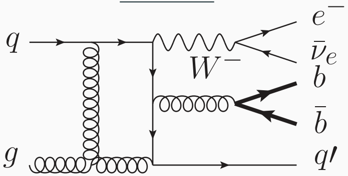
- Lift kinematical constrains and degenerate phase space forced by a fixed order computation
- Take into an account all production channels already at leading order
- BSM searches typically require large multiplicities

Phenomenological relevance

Signature:

One or two tagged b-jets, multiple light jets, missing transverse energy, and a lepton.

$Wb\bar{b}$+jets



(an example of contributing diagram)

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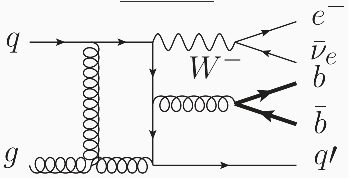
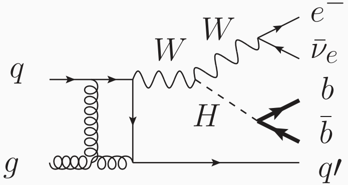
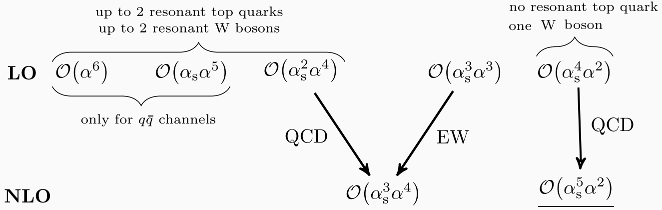


(an example of contributing diagram)

- Test ground for precise measurements of complex signatures at LHC
- Important background for many BSM searches
- Irreducible background for difficult measurements of $H \to b\bar{b}$ decay channel [ATLAS, arXiv:1708.03299],[CMS, arXiv:1709.07497] Many searches use associated $(W/Z)H$ production.



Contributions to $pp \to \mu\nu_\mu b\bar{b}jj$



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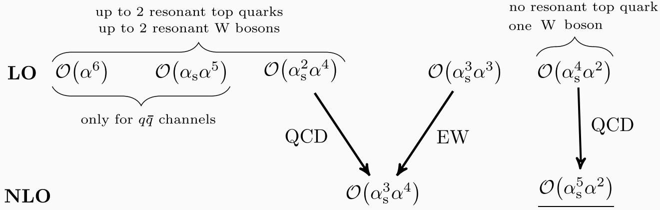
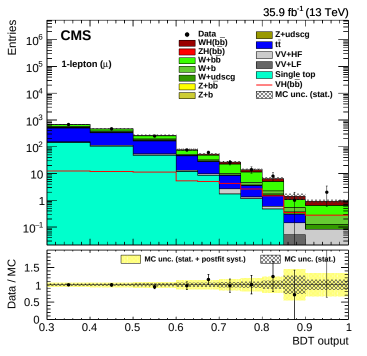


- EW production dominates near top resonances. Considered in a complementary study [arXiv:1711.10359]
- For a setup associated to $H(b\bar{b})W$ studies non-resonant QCD productions is of similar size as off-shell top contributions (not included in this study)



source: [arXiv:1709.07497]

Status

Theory predictions at NLO QCD

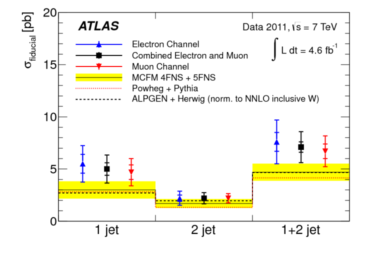
- $Wb\bar{b}$, $m_b = 0$ [arXiv:Ellis and Veseli, 1998]
- $Wb\bar{b}$, $m_b \neq 0$ [Febres Cordero et al, 2006; Badger et al, 2010; Frederix et al, 2011]
- $Wb\bar{b} + 1$ jet, $m_b \neq 0$, using GoSam [Luisoni et al, 2015]
- $Wb\bar{b} + n$ jets $(n \leq 3)$, BlackHat [arXiv:1712.05721]
- Matrix elements available in generators, e.g. OpenLoops, RecOLA

Experimental measurements @ 7 TeV

- $W + \geq 1/2b$, [ATLAS, arXiv:1302.2929]
- $W + \geq 1/2b$, [CMS, arXiv:1312.6608]

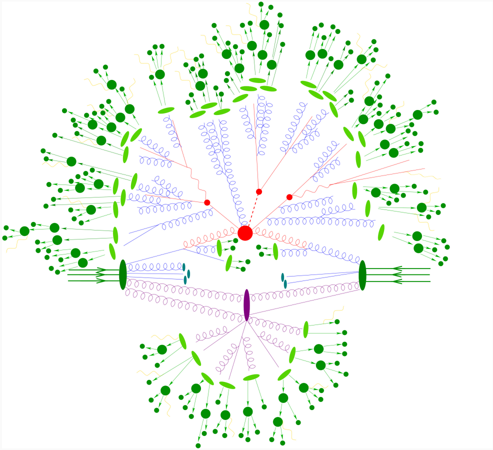
Experimental measurements @ 8 TeV

- $W + \geq 1/2b$, [CMS, arXiv:1608.07561]
- $W + b\bar{b}$, $W + c\bar{c}$, [LHCb, arXiv:1610.08142]



Technology

NLO Cross Section



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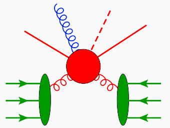
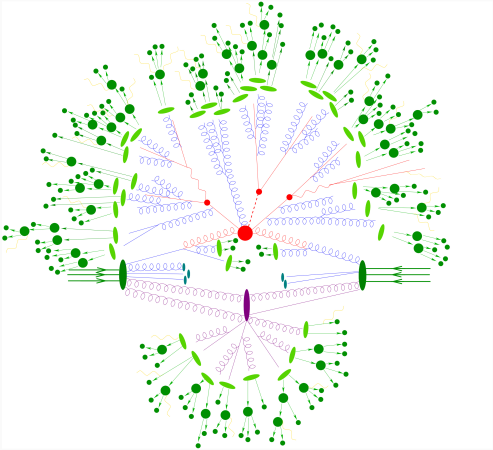
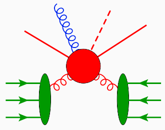


Hard scattering

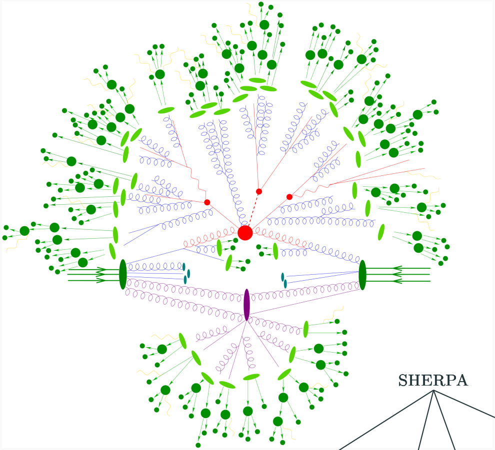
NLO Cross Section



$\longrightarrow$



$$\sigma^{NLO} = \int_n d\sigma^B + \int_{n+1} (d\sigma^R - d\sigma^S) + \int_n (d\sigma^V + \int_1 d\sigma^S)$$



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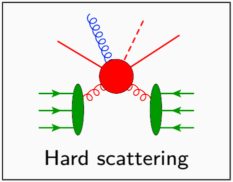


SHERPA

BlackHat

$$\sigma^{NLO} = \int_n d\sigma^B + \int_{n+1} (d\sigma^R - d\sigma^S) + \int_n (d\sigma^V + \int_1 d\sigma^S)$$

Building blocks for QCD amplitudes

Full (*color* and *helicity* summed) matrix elements

↓ Split into contributions from helicity eigenstates

Helicity amplitudes

↓ Collect all pieces contributing to the same *color structure*

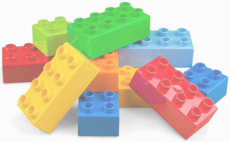
Partial helicity amplitudes

↓ Decompose into a minimal set of gauge-invariant blocks (e.g. [arXiv:1111.4193])

Primitive (color-ordered) helicity amplitudes

Goal

Reduce numerical complexity as much as possible



The Generalized Unitarity method

Bottom-up

Think of the integrand of the full amplitude as already reduced to master integrals.

[Ossola, Papadopoulos, Pittau '07] [Ellis, Giele, Kunszt '08]

$$\mathcal{A}(\ell) = \sum_{\{i\}} \frac{\bar{d}_{i_1 i_2 i_3 i_4}(\ell)}{d_{i_1} d_{i_2} d_{i_3} d_{i_4}} + \sum_{\{i\}} \frac{\bar{c}_{i_1 i_2 i_3}(\ell)}{d_{i_1} d_{i_2} d_{i_3}} + \sum_{\{i\}} \frac{\bar{b}_{i_1 i_2}(\ell)}{d_{i_1} d_{i_2}} + \sum_{\{i\}} \frac{\bar{a}_{i_1}(\ell)}{d_{i_1}}$$

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Numerators are *polynomials* in loop momentum. Can be decomposed into

- Surface terms — vanish upon integration
- Master terms — master integral coefficients

Scalar integrals are known, only need to find coefficients.

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Unitarity

- Access coefficients directly from on-shell tree amplitudes
- Tree amplitudes can be computed numerically via efficient off-shell recursion [Berends, Giele '87]
- Implicit reduction of tensor integrals and $N > 5$ integrals

Massive particles and numerical unitarity

Key developments for the BlackHat upgrade

- ✓ Loop momentum parametrizations to solve on-shell conditions for cuts with masses
- ✓ Solve problems connected with dimensional regularisation of helicity amplitudes with external massive quarks
  F.Anger, VS [arXiv:1803.11127]
- ✓ Coefficients for tadpole integrals and bubble integrals with a single on-shell leg in the corner (scaleless when massless)
- ✓ Clean double cuts from self-energy insertions on external legs
- ✓ Integrals with internal masses

Total cross sections and differential distributions

BlackHat + SHERPA $Wb\bar{b} + n$-jets $(n = 0, 1, 2, 3)$

Model Specification

- Four flavor scheme $(N_f = 4)$ with top and bottom loops included
- On-shell b-quarks; leptonic W decay in matrix elements
- G_μ scheme for EW parameters
- Diagonal CKM matrix
- Dynamical scale: $\mu_0 = \mu_r = \mu_f = \hat{H}'_{\mathrm{T}}/2$,

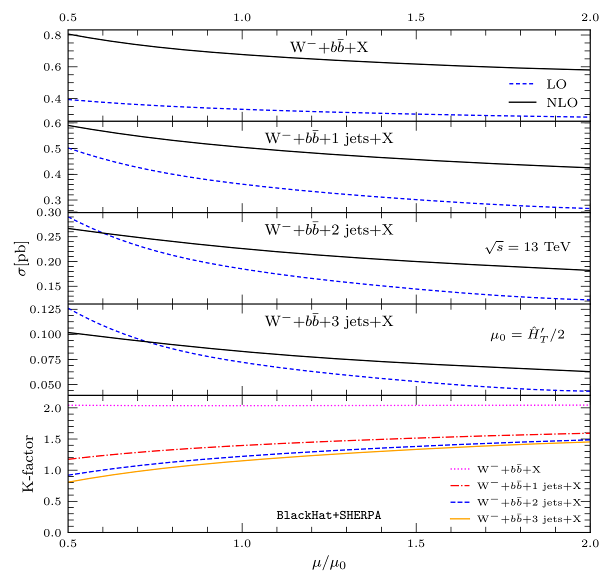
$$\hat{H}'_{\mathrm{T}} \equiv \sum_i p^i_T + E^V_{\mathrm{T}}, \qquad E^V_{\mathrm{T}} \equiv \sqrt{M_V^2 + (p_T^{e\nu})^2}$$

Setup for analysis @ $\sqrt{s} = 13$ TeV

- `CT14` LO (`CT14llo`) and NLO (`CT14nlo`) PDFs
- Two tagged b-jets
- Same cuts on light jets and b-jets: $p_{\mathrm{T}}^{\mathrm{jet}} > 25$ GeV, $|\eta^{jet}| < 2.4$

  lepton cuts: $p_{\mathrm{T}}^e > 25$ GeV, $|\eta^e| < 2.5$, $p_{\mathrm{T}}^\nu > 20$ GeV, $M_T^{W^\pm} > 20$ GeV
- anti-k_{T} jet algorithm with $R = 0.4$

Total Cross Sections And Scale Dependence

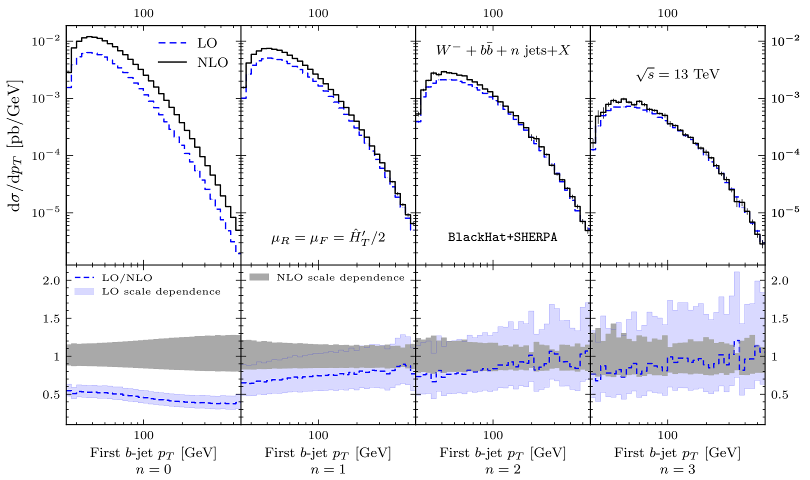


$\#j$	LO	NLO	K
0	$^{+19\%}_{-15\%}$	$^{+19\%}_{-15\%}$	2.03
1	$^{+39\%}_{-26\%}$	$^{+17\%}_{-16\%}$	1.40
2	$^{+57\%}_{-34\%}$	$^{+18\%}_{-18\%}$	1.22
3	$^{+75\%}_{-40\%}$	$^{+23\%}_{-24\%}$	1.15

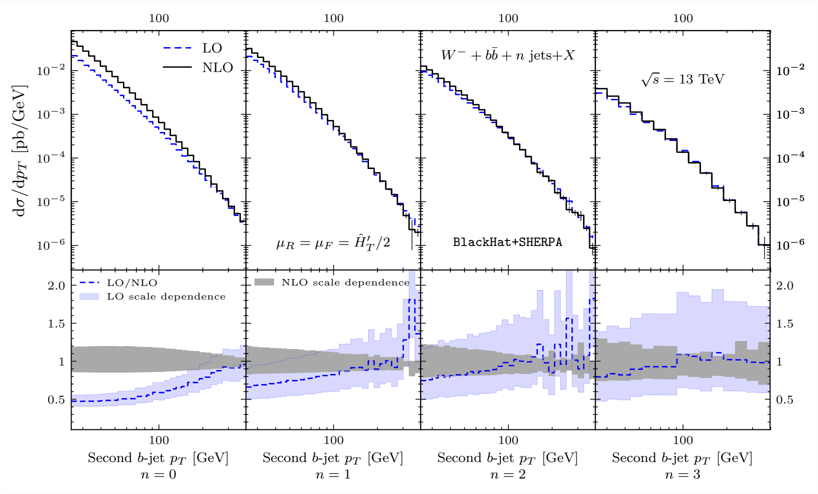
Note scale dependence stabilization for

$\#j \geq 1$

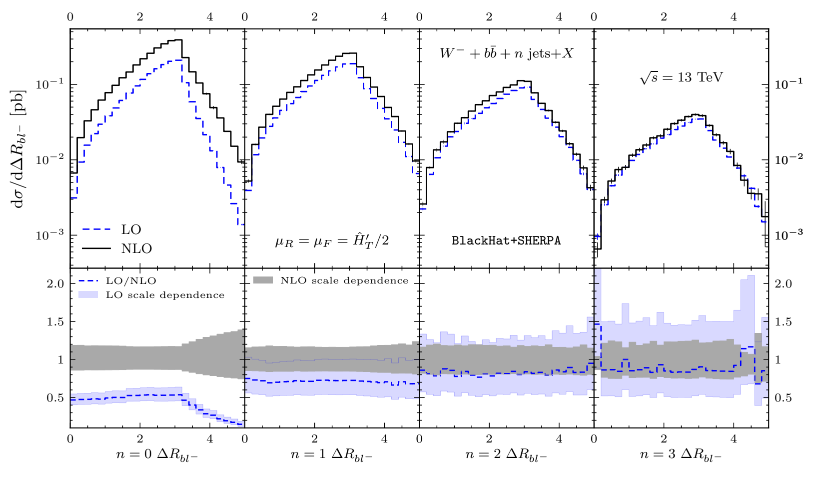
p_T of the leading (hardest) b jet



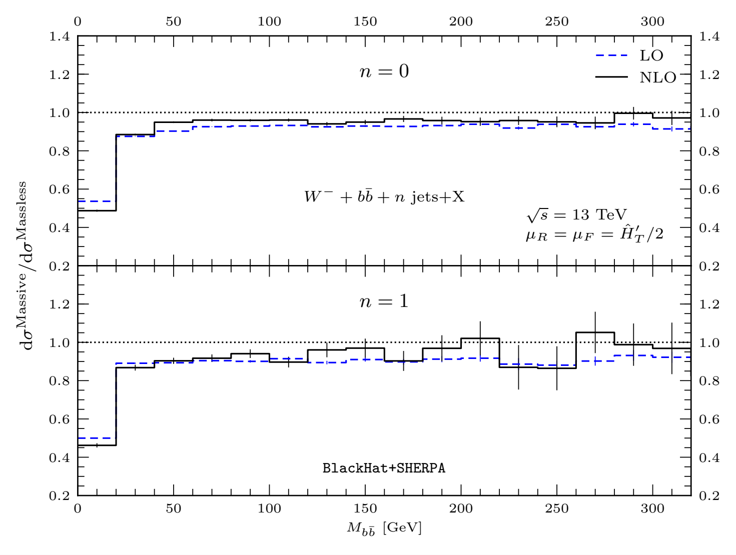
p_T of the subleading (second hardest) b jet



ΔR_{bl^-} between the leading b jet and the charged lepton



4FNS vs 5FNS



n = 0
n = 1
LO
NLO
W⁻ + bb̄ + n jets+X
√s = 13 TeV
μR = μF = Ĥ′T/2
BlackHat+SHERPA
dσ^Massive/dσ^Massless
M_bb̄ [GeV]
0
50
100
150
200
250
300
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Background to HW production

Exclusive sums

Problems with $Wb\bar{b}$ predictions

- Large NLO corrections due to the opening of a new channel with gluons in the initial state $\Rightarrow$ inclusive predictions unreliable
- Exclusive results are very sensitive to jet veto p_T^{veto}

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Exclusive sums

Use available predictions for higher jet multiplicities instead of jet veto:

$$\sigma_0^{\text{NLO+}} = \sigma_0^{\text{exc}} + \sigma_1^{\text{inc}}, \qquad \sigma_0^{\text{NLO++}} = \sigma_0^{\text{exc}} + \sigma_1^{\text{exc}} + \sigma_2^{\text{inc}}$$

Stabilization of NLO predictions is achieved:

- Reduced p_T^{veto} sensitivity to $\approx 5 - 10\%$ from $\approx 40\%$ for exclusive predictions
- Slightly reduced scale dependence

$p_T^{b\bar{b}}$

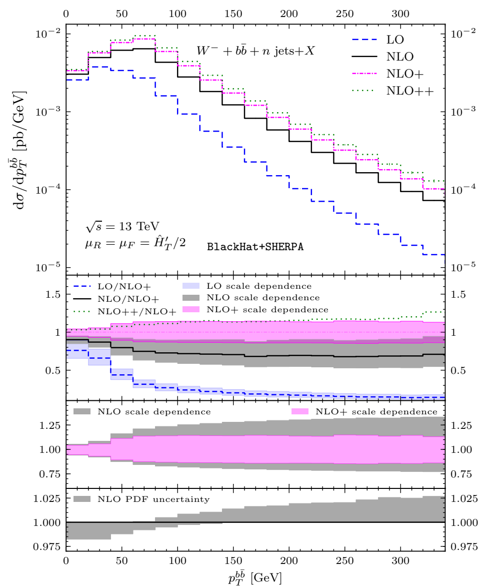
$p_T^{\text{excl}} = 25$ GeV

- LO gives no adequate prediction
- Giant K-factor from real radiation
- Scale-depndence of NLO+ and NLO++ ($\sim$ 13%) reduced compared to NLO ($\sim$26%)
- PDF uncetainties below 2%

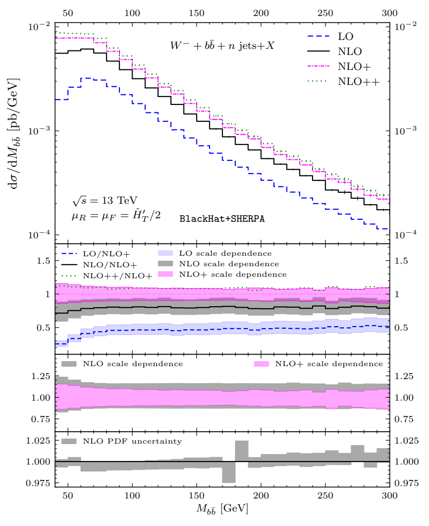
Normalized by NLO+ $\longrightarrow$

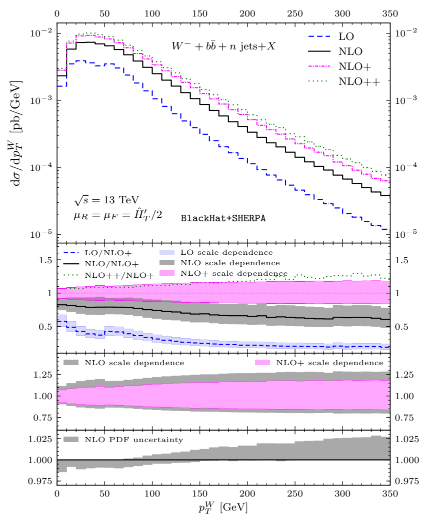
Normalized by central values $\longrightarrow$

Normalized by NLO values $\longrightarrow$



$M_{b\bar{b}}$ and p_T^W





BlackHat NTuples: full flexibility for NLO

NTuples — event-file format for NLO analysis [arXiv:1310.7439]

Contained information

- Kinematics
- Coefficients for factorization and renormalization scale variation
- PDF weights
- Multiple jet algorithms (type, R values, f parametes, ...)

Publicly available (LHC Grid)

- Full support in SHERPA
- A standalone c++ library for manipulating NTuples is provided
  `https://blackhat.hepforge.org/trac/wiki/NtupleReaderInstallation`

Available processes

- $2, 3, 4$ jets
- $W + 0, 1, 2, 3, 4, 5$ jets
- $Z + 0, 1, 2, 3, 4$ jets
- $\gamma\gamma + 2$ jets
- $W^+W^- + 0, 1, 2, 3$ jets
- $Wb\bar{b} + 0, 1, 2, 3$ jets

  (can be made available on the Grid on demand)

Outlook

Outlook

Summary

1. Computation of NLO virtual matrix elements with massive quarks is implemented in a new version of BlackHat
2. We have presented NLO QCD corrections to the processes $Wb\bar{b} + n$-jet ($n = 0, 1, 2, 3$) at the LHC
3. We observe considerable reduction of renormalization- and factorization-scale dependence with the inclusion of the NLO for the large multiplicity cases.
4. We find that exclusive sums stabilize predictions for observables associated to $H(b\bar{b})W$ searches

What's next?

- If called for, more pheno is possible, e.g. $Zb\bar{b}$+jets predictions
- Extension of the developed technology to two loops is in progress. Proof-of-concept results are available:
  - 4 gluon amplitudes @ 2 loops [arXiv:1703.05273]
  - 5 gluon amplitudes @ 2 loops [arXiv:1712.03946]

Backup Slides

Validation

Internal

- Reconstruction of vanishing numerator coefficients
- UV and IR poles
- Full divergence cancellation with SHERPA

Matrix elements

✓ Reproduced all massless QCD processes from the old version

✓ $pp \to t\bar{t} + (\leq 2)j$, $pp \to b\bar{b} + (\leq 2)j$ with RecOLA and OpenLoops

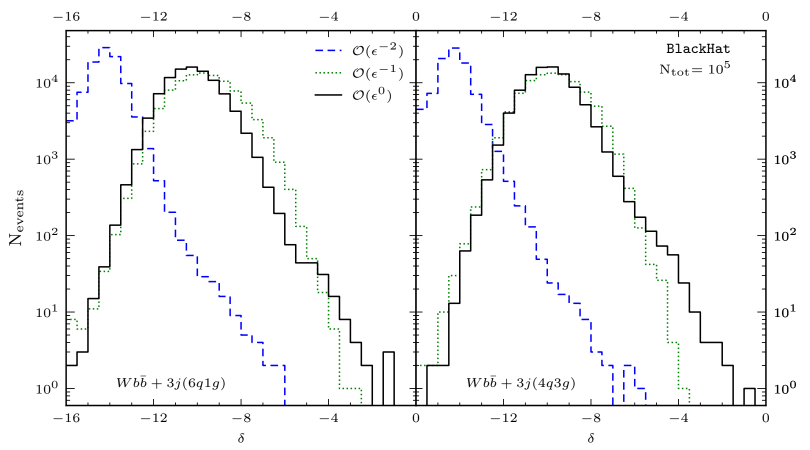
✓ $pp \to Wb\bar{b} + (\leq 3)j$ with RecOLA

✓ $pp \to t\bar{t}b\bar{b}$ with RecOLA

Integrated cross-section

✓ $pp \to Wb\bar{b}$ against `MCFM` to 10^{-3} accuracy

Numerical Stability

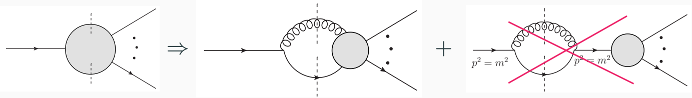


$$\delta = \log_{10}\left(\frac{\left|d\sigma^{\text{prod}} - d\sigma^{\text{HP}}\right|}{\left|d\sigma^{\text{HP}}\right|}\right)$$

$\left|d\sigma^{\text{prod}}\right|$ — normal (production) mode

$\left|d\sigma^{\text{HP}}\right|$ — quadruple precision targets

Self-Energy on External Legs



⇑	⇑	⇑
All double cut contributions	Finite normal contributions	Divergent, included into wave-function and mass renormalization

- Removing a diagram from tree amplitude makes it gauge dependent
- Restored by adding mass counter-terms

Renormalization

Renormalization	Scheme	Counterterm
Heavy quark wave function	on-shell	$\delta_{2,i} = \frac{N_c^2-1}{2N_c}\left(\frac{1}{3\epsilon}+5+3\ln\frac{\mu^2}{m_i^2}\right)$
Light quark wave function	on-shell	0 (UV+IR cancellation)
Quark mass	on-shell	$\delta_{m_i} = \delta_{2,i}$
Gluon wave function	on-shell	$\delta_3 = \frac{3}{\epsilon}+\sum_i \frac{1}{3}\ln\frac{\mu^2}{m_i^2}$
QCD coupling	$\overline{MS}$	$\delta_{\alpha_s} = \frac{1}{\epsilon}\left(\frac{11}{3}N_c-\frac{2}{3}(N_f+N_h)\right)-\frac{N_c}{3}$
Decoupling shift	—	$\Delta_i = -\frac{2}{3}\ln\frac{\mu^2}{m_i^2}$

- Internally computation including renormalization is performed in FDH, then converted to 'tHV

$$\mathcal{A}^{(\text{ren})}_{\text{HV}} - \mathcal{A}^{(\text{ren})}_{\text{FDH}} = -g_s c_\Gamma \left(N_g\ \frac{N_c}{6} + \frac{N_q}{4}\left(N_c - \frac{1}{N_c}\right)\right)\mathcal{A}^{(\text{born})},$$

- The quark mass is renormalized on-shell *at the level of primitive* to restore gauge invariance

$p_T^{\mathbf{excl}}$ variations