Full NLO corrections to 3-jet production and $\mathbf{R_{32}}$ at the LHC

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Outline

Motivation

jet production:

- most abundant process at LHC
  - $\Rightarrow$ allows multi-differential measurements into high-p_{T} regions
  - $\Rightarrow$ benchmark for theoretical predictions
- important SM background to many analyses
- pure jet final state is BSM search ground
  - $\Rightarrow$ enhancements in high p_{T}-tails
- determination of PDFs and α_s at high Q^2
  - $\Rightarrow$ consistency check of RGE evolution over large range of scales

EW corrections:

- naîve relative magnitude of $\alpha \sim 1\%$ to inclusive XS
- weak Sudakov logarithms $\Rightarrow$ $\mathcal{O}(10\%)$ corr in TeV range
  - $\Rightarrow$ inclusion necessitated by high p_{T} reach
- many subprocesses, all dipole kinematics and types involed
  - $\Rightarrow$ strong test case for automized NLO tools

Previous Studies of Jet Production

- NLO QCD up to 5 final state jets
  - [Ellis *et al.*, 1992] [Bern *et al.*, 2012]
  - [Giele *et al.*, 1993] [Badger *et al.*, 2014]
  - [Nagy, 2003]
- NLO QCD combined with parton showers
  - [Alioli *et al.*, 2011] [Höche *et al.*, 2012]
- NNLO QCD dijet completed
  - [Currie *et al.*, 2016] [Ridder *et al.*, 2019]
  - [Currie *et al.*, 2017] [Czakon *et al.*, 2019] (full color)
- pure weak corrections for dijet (no γ; $\mathcal{O}\left(\alpha_s^2\alpha\right)$, $\mathcal{O}\left(\alpha_s\alpha\right)$, $\mathcal{O}\left(\alpha^2\right)$)
  - [Dittmaier *et al.*, 2012]
- full SM NLO for dijet
  - [Frederix *et al.*, 2017]
- full SM NLO for 3jet, inclusive cross section
  - [Frederix *et al.*, 2018]

here: full SM NLO for 3/2jet, (double) differential in Sherpa

Features of EW NLO

Massless photons γ:

- IR divergences necessitate subtraction
  - $\Rightarrow$ descends from QCD via

$$\hat{T}_{(ij)}\hat{T}_k \to Q_{(ij)}Q_k$$

- add γ to jet clustering

Massive $W^\pm$ and Z:

- real emission distinct process class
- IR finite loop contributions:

$$\sim \alpha \log^2\left(\frac{Q^2}{m^2}\right),$$

$\Rightarrow$ *Sudakov logs* $\sim$ 10% @ 1TeV

- unambiguous definition of NLO correction by perturbative order:

$$\alpha_s^{n-1}\,\alpha^m \xleftarrow{\text{QCD NLO}} \alpha_s^n\alpha^m \xrightarrow{\text{EW NLO}} \alpha_s^n\,\alpha^{m-1}$$

$\Rightarrow$ simultaneous QCD and QED subtraction with distinct underlying Borns

$$X+g \xleftarrow{\text{QED subtr.}} X+g+\gamma \xrightarrow{\text{QCD subtr.}} X+\gamma$$

final state

$\Rightarrow$ forces γ in process definition

- photon jet removal desired, requires e.g. fragmentation functions

Automation of EW NLO

- public full SM one-loop provider are becoming available
  - RECOLA
  - OPENLOOPS2
  - GOSAM

⇒ paving road for automatic SM NLO event generator

⇒ already public: MADGRAPH5_AMC@NLO [Frederix *et al.*, 2018]

⇒ still-private version of SHERPA [Schönherr, 2018]
  - bookkeeping in mixed coupling scenario
  - tree level ME
  - simultaneous QCD&QED subtraction: dipole terms, I-operators, ...
  - (approximate) procedures for combination with PS

Validated in growing set of processes

SHERPA + OPENLOOPS

- $V + jets$ [Kallweit *et al.*, 2015]
  [Kallweit *et al.*, 2016]
- $2\ell 2\nu$ [Kallweit *et al.*, 2017]
- $t\bar{t} + jets$ [Gütschow *et al.*, 2018]
  (approximate multijet merging)

SHERPA + GOSAM

- $\gamma\gamma W$ and $\gamma\gamma Z$ [Greiner *et al.*]
- $\gamma\gamma j$ [Chiesa *et al.*]

SHERPA + RECOLA

- $V + j$, $t\bar{t}H$, $e^+e^-\mu^+\mu^-$
  [Biedermann *et al.*, 2017]
- off-shell WWW [Schönherr, 2018]

Calculation Setup - Process Definition

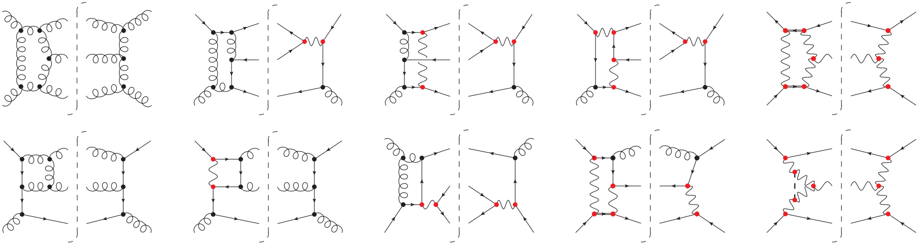
- partonic processes [$ewj \in \{q, g, \gamma, l, \nu\} \rightarrow$ no external W, Z!]

$$3jet: \quad ewj + ewj \rightarrow ewj + ewj + ewj \; (+ewj),$$
$$2jet: \quad ewj + ewj \rightarrow ewj + ewj \qquad (+ewj),$$

- perturb. orders $\alpha_s^n \alpha^m$

$$3jet: \quad m + n = 3, 4$$
$$2jet: \quad m + n = 2, 3,$$

- sensitive to full SM spectrum (tops, Higgs, ...)



$\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^3\alpha)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s\alpha^3)$ $\mathcal{O}(\alpha^4)$

Calculation Setup - Input and Observable

- SHERPA interfaced to RECOLA
- pp @ 13 TeV,   PDF: `NNPDF31_nlo_as_0118_luxqed`
- scale choice $\mu_R = \mu_F = \frac{1}{2}\,\hat{H}_\mathrm{T}$

  $\Rightarrow$ missing higher orders estimated by 7 point scale variation
- G_μ scheme

  $\Rightarrow$ mass logs from $\gamma \to f\bar{f}$ splittings absorbed
- complex mass scheme

jet def and fiducial phase space cuts:

- 3 resp. 2 democratic anti-k_T jets with $R = 0.4$ and   [no ν!]

$$|\eta| < 2.8; \qquad p_T^1 \geq 80\text{GeV}, \qquad p_T^{i\geq 2} \geq 60\text{GeV}$$

- reject 'lepton jets': $|\eta_j| < 2.5$ and net lepton number

  $\Rightarrow$ collinear same-flavor lepton pairs survive (IR safety!)

  $\Rightarrow$ leptons outside tracker survive

XS Nomenclature

- nomenclature for n-jet XS:

$$\mathcal{O}\left(\sigma_{nj}^{\mathrm{LO}_i}\right) = \alpha_s^{n-i}\alpha^i, \qquad \mathcal{O}\left(\sigma_{nj}^{\Delta\mathrm{NLO}_i}\right) = \alpha_s^{n+1-i}\alpha^i,$$

- combination of QCD and EW NLO:

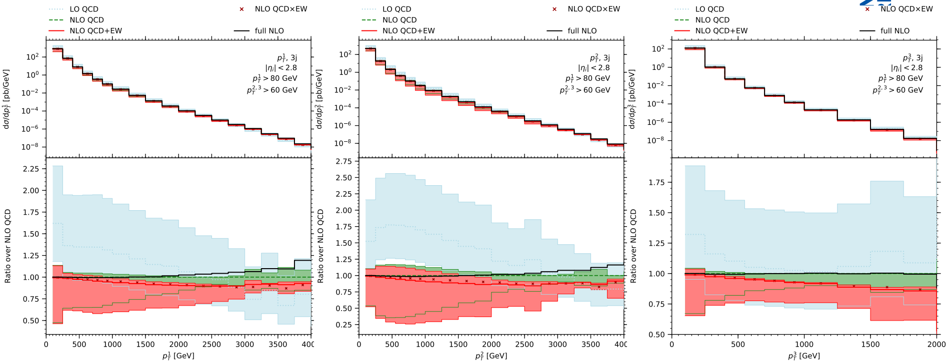
additive: $$\sigma_{nj}^{\mathrm{NLO\ QCD+EW}} = \sigma_{nj}^{\mathrm{LO}_0} + \sigma_{nj}^{\Delta\mathrm{NLO}_0} + \sigma_{nj}^{\Delta\mathrm{NLO}_1}$$

multiplicative: $$\sigma_{nj}^{\mathrm{NLO\ QCD\times EW}} = \sigma_{nj}^{\mathrm{LO}_0}\left(1 + \frac{\sigma_{nj}^{\Delta\mathrm{NLO}_0}}{\sigma_{nj}^{\mathrm{LO}_0}}\right)\left(1 + \frac{\sigma_{nj}^{\Delta\mathrm{NLO}_1}}{\sigma_{nj}^{\mathrm{LO}_0}}\right)$$

- estimate of unknown $\mathcal{O}(\alpha_s\alpha)$ NNLO corrections:

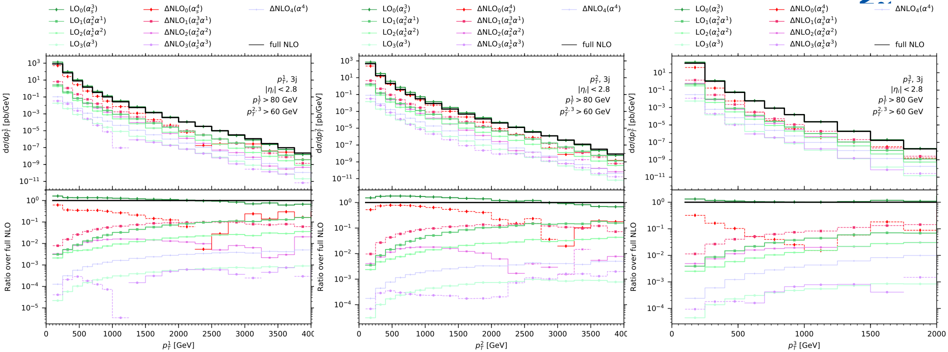
$$\sigma_{\mathrm{QCD\times EW}}^{\mathrm{NLO}} - \sigma_{\mathrm{QCD+EW}}^{\mathrm{NLO}} = \frac{\delta\sigma_{\mathrm{QCD}}^{\mathrm{NLO}} \times \delta\sigma_{\mathrm{EW}}^{\mathrm{NLO}}}{\sigma^{\mathrm{LO}}}$$

p_{T}-Spectra



- large negative Sudakov-type EW NLO corrections
  - $\Rightarrow$ grow with i in p_{T}^{i} ($-10\%, -15\%, -15\%$ at 2TeV)
- scale uncertainties asymmetric, grow from QCD to QCD+EW
- accidental cancellation with subleading LO and NLO contributions
  - mainly $\Delta\mathrm{NLO}_2$, LO_1, LO_2
  - grow larger than $\Delta\mathrm{NLO}_1$ for $p_{\mathrm{T}} > 2.5$TeV
  - $\Rightarrow$ highly dependent on observable & fiducial phase space

p_{T}-Spectra



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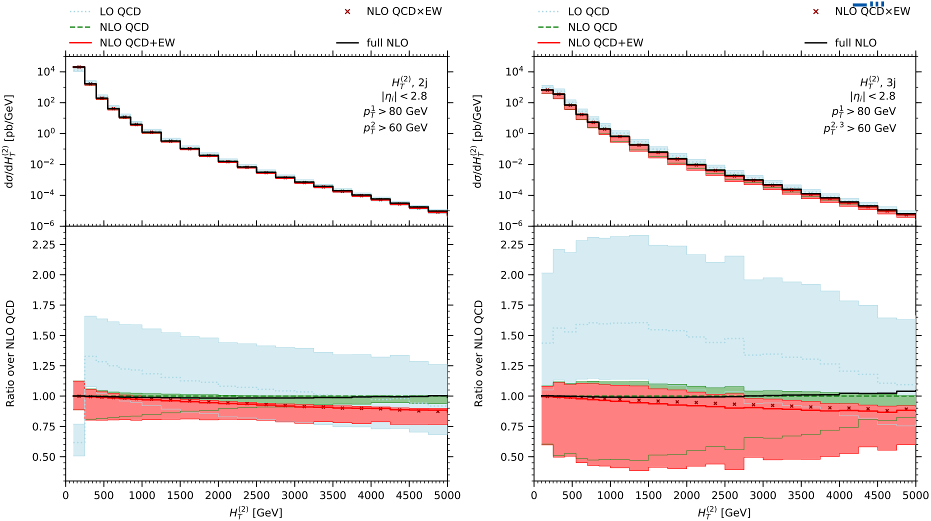
R_{32} Observable

$$R_{32}(H_{\mathrm{T}}^{(2)}) = \frac{\mathrm{d}\sigma_{3j}/\mathrm{d}H_{\mathrm{T}}^{(2)}}{\mathrm{d}\sigma_{2j}/\mathrm{d}H_{\mathrm{T}}^{(2)}}$$

- reduced experimental uncertainties
  - ⇒ e.g. luminosity, jet energy scale
- factorizing contributions in theory predictions cancel

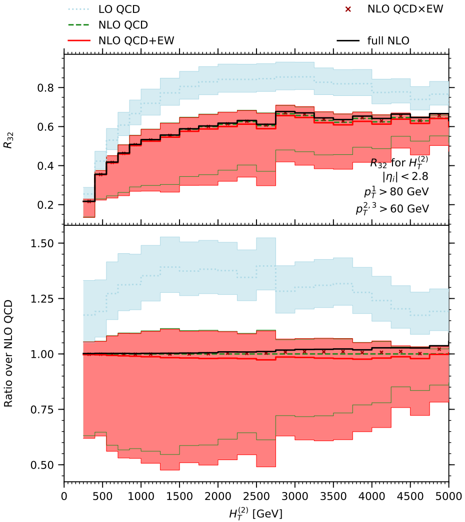
- strongly dependent on $\alpha_s(H_{\mathrm{T}}^{(2)})$
  - ⇒ allows for measurement [Chatrchyan *et al.*, 2013] (fit of theory predictions to data)
  - ⇒ consistency check of RGE evolution at high scales
  - ⇒ possibly sensitive to BSM physics [Becciolini *et al.*]
- sensitive to gluon PDF

Input Distributions to R_{32}



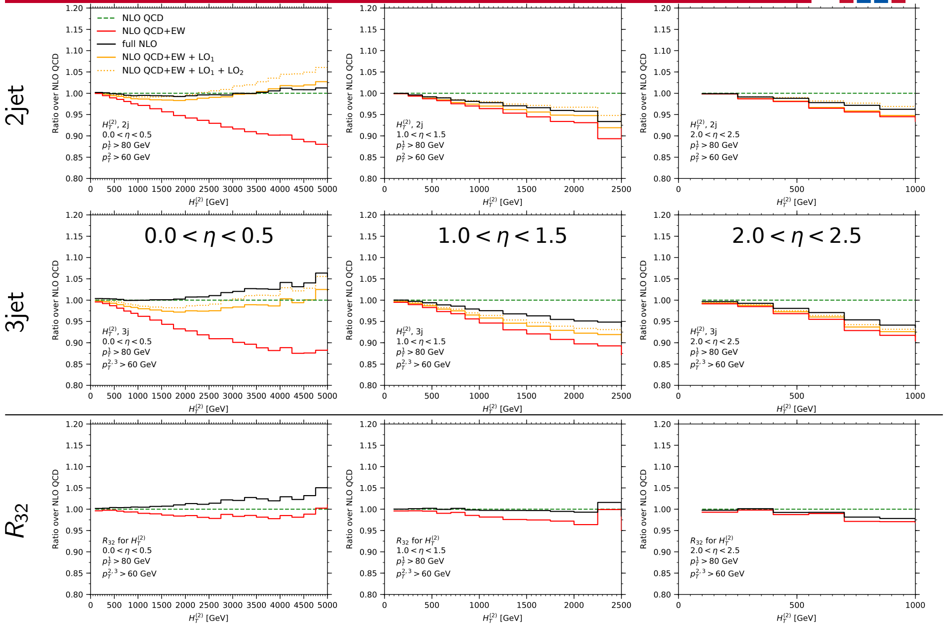
- in 3jet sample: at high $H_T^{(2)}$ 3rd jet predominantly soft
  - $\Rightarrow$ factorizing higher order corrections
  - $\Rightarrow$ similar EW corrections in 2jet and 3jet sample

R_{32} Result



- small EW NLO and subleading order corrections
- factorization of EW corrections in input distributions
  - ⇒ beyond accidental cancellation
  - ⇒ stable w.r.t add cuts on $\eta := |\eta_1 - \eta_2|/2$
- correlated scale variation in ratio
  - ⇒ much larger bands in 3jet
  - ⇒ no cancellation of scale uncert.

Dependence on $\eta := |\eta_1 - \eta_2|/2$



Summary

- EW NLO corrections at high p_T competitive with QCD NLO
- Automated EW NLO MC generators are becoming available
- SHERPA + RECOLA/OPENLOOPS/GOSAM validated for many processes
- accidental cancellations in $H_{\mathrm{T}}^{(2)}$-distributions
- EW NLO corrections largely cancel in R_{32} of $H_{\mathrm{T}}^{(2)}$

Outlook:

- Multijet merging in $\mathrm{EW}_{\mathrm{virt}}$-approximation: [Kallweit *et al.*, 2016]

$$d\sigma_{\mathrm{NLO\,EW_{virt}}} = \left[B(\Phi_n) + V_{\mathrm{EW}}(\Phi_n) + I_{\mathrm{EW}}(\Phi_n)\right] d\Phi_n$$

  $\Rightarrow$ No double counting issue

  $\Rightarrow$ EW-NLO accurate multijet merging w/ LO complexity
- Studies of photon jet removal and fragmentation functions $D_{q\to\gamma}$, $D_{\gamma\to had}$
- Impact of initial state γ

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Thank you!

BACKUP: Masses

- masses set to

$$
\begin{aligned}
G_\mu &= 1.16639 \times 10^{-5}\ \text{GeV}^{-2} & & \\
m_W &= 80.385\ \text{GeV} & \Gamma_W &= 2.085\ \text{GeV} \\
m_Z &= 91.1876\ \text{GeV} & \Gamma_Z &= 2.4952\ \text{GeV} \\
m_h &= 125.0\ \text{GeV} & \Gamma_h &= 0.00407\ \text{GeV} \\
m_t &= 173.21\ \text{GeV} & \Gamma_t &= 1.3394\ \ \text{GeV}\,.
\end{aligned}
$$

- complex mass scheme:

$$\mu_i^2 = m_i^2 - \mathrm{i} m_i \Gamma_i \qquad \text{and} \qquad \sin^2\theta_\mathrm{w} = 1 - \frac{\mu_W^2}{\mu_Z^2}\,,$$

- all other particles massless

BACKUP: Fiducial XS Tables

	NLO [nb]	$\frac{LO_0}{NLO}$ [%]	$\frac{LO_1}{NLO}$ [%]	$\frac{LO_2}{NLO}$ [%]	$\frac{LO_3}{NLO}$ [%]	
σ_{2j}	3385(3)	67.34(6)	0.0713(1)	0.03915(4)	–	
σ_{3j}	169(1)	148(1)	0.293(2)	0.196(2)	0.00217(2)	

		$\frac{\Delta NLO_0}{NLO}$ [%]	$\frac{\Delta NLO_1}{NLO}$ [%]	$\frac{\Delta NLO_2}{NLO}$ [%]	$\frac{\Delta NLO_3}{NLO}$ [%]	$\frac{\Delta NLO_4}{NLO}$ [%]
σ_{2j}		32.59(8)	−0.118(7)	0.0759(3)	0.00022(1)	–
σ_{3j}		−48.4(8)	−0.74(1)	0.344(7)	−0.00433(6)	0.0135(2)

Full fiducial XS

	NLO [fb]	$\frac{LO_0}{NLO}$ [%]	$\frac{LO_1}{NLO}$ [%]	$\frac{LO_2}{NLO}$ [%]	$\frac{LO_3}{NLO}$ [%]	
σ_{2j}	51.9(6)	60(1)	7.07(8)	1.82(2)	–	
σ_{3j}	40.0(4)	99(1)	8.6(1)	2.05(4)	0.061(1)	

		$\frac{\Delta NLO_0}{NLO}$ [%]	$\frac{\Delta NLO_1}{NLO}$ [%]	$\frac{\Delta NLO_2}{NLO}$ [%]	$\frac{\Delta NLO_3}{NLO}$ [%]	$\frac{\Delta NLO_4}{NLO}$ [%]
σ_{2j}		36.9(8)	−4.5(1)	−1.02(2)	−0.552(7)	–
σ_{3j}		−0.9(9)	−9.8(4)	1.09(7)	0.057(4)	0.314(5)

Fiducial XS after additional leading jet cut $p_T^1 > 2\text{TeV}$

BACKUP: Fiducial XS Tables

	NLO [nb]	LO QCD [nb]	NLO QCD [nb]	NLO EW [nb]	NLO QCD + EW [nb]
σ_{2j}	$3385(3)^{+334}_{-338}$	$2279.4(6)^{+553.7}_{-404.4}$	$3383(3)^{+335}_{-338}$	$2275.4(6)^{+552.4}_{-403.5}$	$3379(3)^{+333}_{-338}$
σ_{3j}	$169(1)^{+16}_{-73}$	$249.86(6)^{+102.28}_{-67.89}$	$168(1)^{+16}_{-73}$	$248.62(6)^{+101.62}_{-67.46}$	$167(1)^{+17}_{-73}$

Full fiducial XS

	NLO [fb]	LO QCD [fb]	NLO QCD [fb]	NLO EW [fb]	NLO QCD + EW [fb]
σ_{2j}	$51.9(6)^{+5.9}_{-6.7}$	$31.2(5)^{+11.4}_{-7.9}$	$50.4(6)^{+7.1}_{-7.3}$	$28.9(5)^{+9.6}_{-6.7}$	$48.1(6)^{+5.2}_{-6.1}$
σ_{3j}	$40.0(4)^{+0.4}_{-6.9}$	$39.4(2)^{+19.0}_{-12.1}$	$39.0(4)^{+0.0}_{-5.0}$	$35.5(2)^{+15.7}_{-10.2}$	$35.1(4)^{+0.9}_{-8.2}$

Fiducial XS after additional leading jet cut $p_{\mathrm{T}}^{1} > 2\mathrm{TeV}$