Complete off-shell effects for $t\bar{t}$ + jet production with leptonic decays at the LHC

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Outline

Motivations for $t\bar{t}j$ at the LHC

- $t\bar{t}j$ as a *signal*
- $t\bar{t}j$ as a *background*

Anatomy of NLO off-shell effects in $t\bar{t}j$ production

- Narrow Width Approximation vs Off-Shell: differences and challenges

Results for LHC @ 8 TeV

- total cross sections, differential distributions

Summary and Outlook

$t\bar{t}j$ as a signal

Alternative method for the extraction of m_{top} $\rightarrow$ look at $t\bar{t}j$ invariant mass

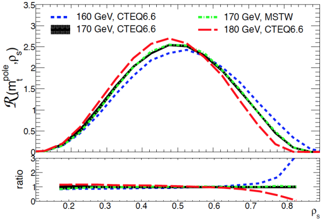
Alioli *et al.* ('13)

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\,\sigma_{t\bar{t}j}}{d\,\rho_s}(m_t^{pole}, \rho_s)$$

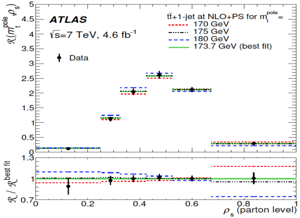
$$\rho_s = \frac{2\,m_0}{\sqrt{s_{t\bar{t}j}}}$$

- ρ_s shape is sensitive to top mass
- $t\bar{t}j$ has higher sensitivity than $t\bar{t}$
- ATLAS: $m_t = 173.7 \pm 1.5 \pm 1.4$ GeV

Alioli *et al.*., arXiv:1303.6415 [hep-ph]



ATLAS Collab., arXiv:1507.01769 [hep-ex]



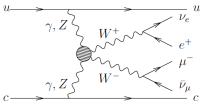
Theoretical and PDF uncertainties affect the extraction of m_{top}

$t\bar{t}j$ as a background

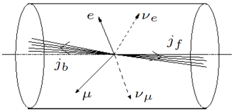
VV scattering: a model-independent probe of EW Symmetry Breaking

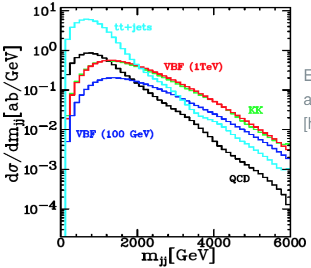
$\hookrightarrow$ Includes SM Higgs production in VBF as a special case $qq \to Hqq \to WWqq$

signal:



signature:





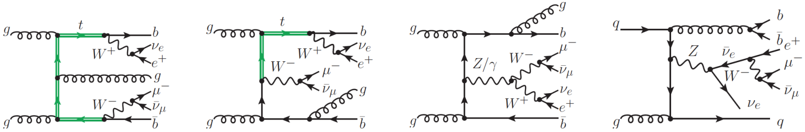
Englert *et al.*, arXiv:0810.4861 [hep-ph]

Level of cuts	$t\bar{t}$ + jets	QCD	VBF $m_H = 100$ GeV	VBF $m_H = 1$ TeV	KK
INCLUSIVE	28710	504.5	16.76	18.55	19.80
INC. + VBF	228.667	5.918	5.063	6.165	6.536
INC. + LEP.	27.4090	6.72	0.828	1.620	1.702
INC. + VBF + b−VETO	64.055	5.473	4.77	5.86	6.22
INC. + VBF + CJV	43.197	–	–	–	–
... + b−VETO	24.025	5.47	4.772	5.856	6.217
... + LEPTONIC	0.381644	0.202	0.1969	0.7011	0.588

Residual background from off-shell $t\bar{t}$ + jets after selection cuts is relevant

Anatomy of off-shellness: $gg \to t\bar{t}g \to b\bar{b}W^+W^-g$

Representative contributions to the LO amplitude at $\mathcal{O}(\alpha_{EW}^4 \alpha_S^3)$:



Narrow Width Approximation: $\frac{1}{(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \overset{\Gamma_t \to 0}{\sim} \frac{\pi}{m_t\Gamma_t}\, \delta(p_t^2 - m^2) + \mathcal{O}(\frac{\Gamma_t}{m_t})$

- in the $\Gamma_t \to 0$ limit, only double-resonant contributions survive
- non-factorizable contributions suppressed by powers Γ_t/m_t
- cross section factorizes into "$t\bar{t}g$ production $\otimes$ decay"

Contributions neglected in the NWA (aka off-shell effects) are suppressed by powers of $\Gamma_t/m_t \approx 1\%$

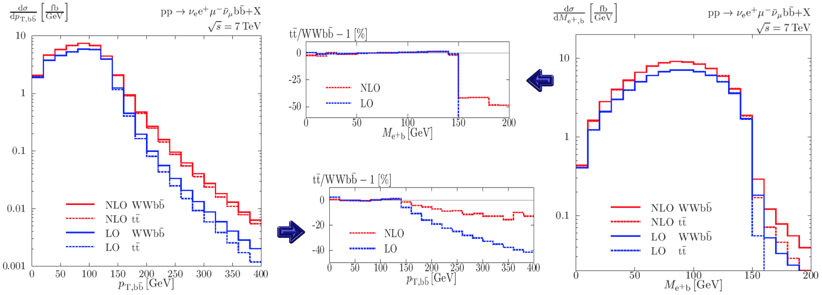
True for inclusive observables. What for the differential level?

The legacy of $pp \to t\bar{t}$: NWA vs Off-Shell

Many studies of off-shell $t\bar{t}$ production, both at NLO QCD and NLO+PS

Denner *et al.* ('11,'12), GB *et al.* ('11), Cascioli *et al.* ('14), Frederix ('14), Heinrich *et al.* ('14)

Kardos *et al.* ('14), Campbell *et al.* ('15)



Denner, Dittmaier, Kallweit, Pozzorini and Schulze, arXiv:1203.6803 [hep-ph]

NLO off-shell effects reach tens of percents in tails

Theoretical predictions for $t\bar{t}j$

NLO QCD accuracy

Fixed Order

- on-shell $t\bar{t}j$ production, stable tops — Dittmaier, Uwer and Weinzierl '07,'09
- on-shell $t\bar{t}j$ production, LO top decays — Melnikov and Schulze '10
- on-shell $t\bar{t}j$ production, full NWA — Melnikov, Scharf and Schulze '11
- off-shell $t\bar{t}j$ production, leptonic decays — GB, Hartanto, Kraus and Worek '16

Matched with Parton Shower

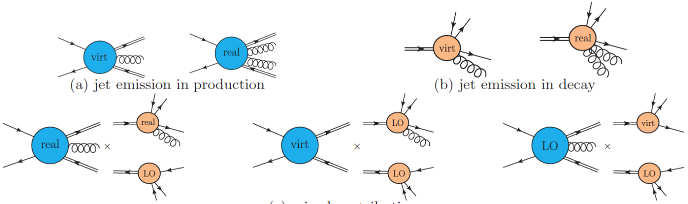
- POWHEG + PYTHIA, no spin corr. — Kardos, Papadopoulos and Trocsanyi '11
- POWHEG + PYTHIA, with LO spin corr. — Alioli, Moch and Uwer '12
- MC@NLO + DEDUCTOR, no top decays — Czakon, Hartanto, Kraus and Worek '15

$t\bar{t}j$: Narrow Width Approximation

Consistent NWA at NLO requires to incorporate jet radiation into top decays

Needs to combine several kinds of *factorizable* contributions

Melnikov, Scharf and Schulze, arXiv:1111.4991 [hep-ph]



(a) jet emission in production

(b) jet emission in decay

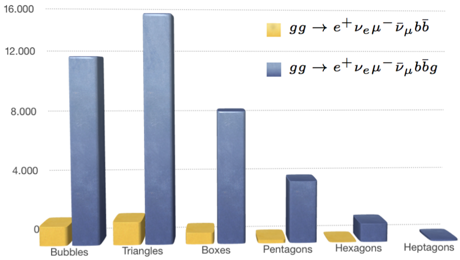
(c) mixed contribution

$$\mathrm{d}\sigma^{\mathrm{NLO}}_{t\bar{t}+1j} = \Gamma^{-2}_{t,\mathrm{tot}}\Big(\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} + \overbrace{\big(\mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+2j}\big)\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}}}^{(a)}$$
$$+ \underbrace{\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\big(\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+2j}\big)}_{(b)} + \underbrace{\mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}}}_{(c)}\Big)$$

Calculation of the *factorizable* contributions involves up to pentagon loops

Beyond NWA: a glimpse into complexity

N. of one-loop Feynman diagrams split by topology: off-shell $t\bar{t}$ vs off-shell $t\bar{t}j$



source: QGRAF (P. Nogueira '93). Special thanks to A. Kardos

$$\mathbf{gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}g}$$

LO: 508

$\hookrightarrow$ Real: 4447

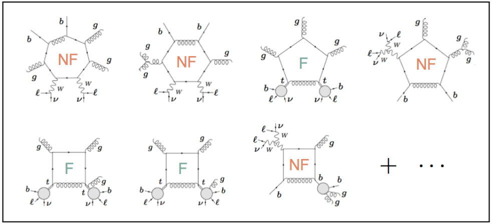
$\hookrightarrow$ Virtual: 39180

Representative loop diagrams

F = factorizable

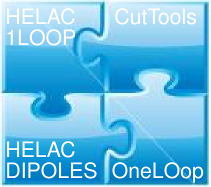
NF = non-factorizable

New functionalities in HELAC−NLO triggered by problem solving



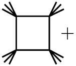
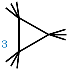
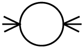
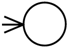
The HELAC−NLO framework

http://helac-phegas.web.cern.ch/helac-phegas



Virtual corrections: reduction at the integrand level (OPP method)

$$\mathcal{A} = \sum_{I\subset\{0,1,\cdots,m-1\}} \int \frac{\mu^{(4-d)}d^dq}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i\in I}\bar{D}_i(\bar{q})}$$

$= \sum d_{i_1i_2i_3i_4}$  $+ \sum c_{i_1i_2i_3}$  $+ \sum b_{i_1i_2}$  $+ \sum a_{i_1}$  $+ R_1 + R_2$

HELAC−1LOOP GB *et al.*, Comput.Phys.Commun. 184 (2013) 986-997

- automatic evaluation of loop numerators $N(q)$ and rational terms R_2

CutTools Ossola, Papadopoulos and Pittau, JHEP 0803 (2008) 042

- reduction of tensor integrals, determination of OPP coefficients and R_1

OneLOop A. van Hameren, Comput.Phys.Commun. 182 (2011) 2427-2438

- evaluation of scalar integrals

The HELAC−NLO framework

http://helac-phegas.web.cern.ch/helac-phegas

Real corrections: subtraction method

$$\sigma^{NLO} = \int_m d\sigma^B + \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

$$\hookrightarrow \quad \int d\sigma^B + \int_{m+1} \left[d\sigma^R - d\sigma^D \right] + \int_m \left[d\sigma^V + d\sigma^I + d\sigma^{KP} \right]$$

HELAC−DIPOLES

Czakon, Papadopoulos and Worek, JHEP 0908 (2009) 085

GB, Czakon, Kubocz and Worek, arXiv:1308.5605 [hep-ph]

- two schemes implemented: Catani-Seymour and Nagy-Soper
- works with massless and massive partons

Comparable efficiency ↔ More robust cross checks

New developments in HELAC-NLO (2016)

Managing complexity

- automatic selection of desired order in strong and EW couplings
- optimization of the algorithms for generating loop topologies

Improving stability & checks

- KALEU multichannel optimized for Nagy-Soper dipoles A. van Hameren ('15)
- phase space restriction ("α_{max}") for Nagy-Soper subtraction

New functionalities

- complete NLO b-quark mass effects
- N-tuple generation + re-weigthing for different scales and PDF's (under testing)

Off-shell $t\bar{t}j$: setup for numerical results

Basics

- $\mathcal{O}(\alpha_{EW}^4 \alpha_S^4)$ contributions , $\sqrt{s} = 8$ TeV , $m_t = 173.3$ GeV , $m_b = 0$
- Complex Mass Scheme for unstable tops: $m_t^2 \to m_t^2 - i\, m_t\, \Gamma_t$

Denner *et al.* '99, Denner *et al.* '05

- Top width for unstable W bosons evaluated at LO and NLO:
  $\Gamma_t^{\text{LO}} = 1.48132$ GeV , $\Gamma_t^{\text{NLO}} = 1.3542$ GeV

Jesabek and Kuhn '89, Denner *et al.* '12

Kinematics

- exactly 2 b-jets , at least one light-jet , 2 charged leptons , missing p_T
- anti-k_T jet algorithm with $R = 0.5$
- cuts:

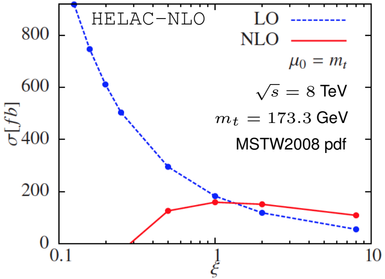
$p_{T\ell} > 30$ GeV	$p_{Tj} > 40$ GeV
$p_T^{\text{miss}} > 40$ GeV	$\Delta R_{jj} > 0.5$
$\Delta R_{\ell\ell} > 0.4$	$\Delta R_{\ell j} > 0.4$
$\lvert y_\ell \rvert < 2.5$	$\lvert y_j \rvert < 2.5$

Stability checks

- *real*: cross-check between Nagy-Soper and Catani-Seymour subtraction
- *virtual*: Ward Identity check

Scale dependence

Total cross section, *fixed-scale* choice: $\mu_R = \mu_F = \xi\, m_t$



GB, Hartanto, Kraus and Worek, arXiv:1509.09242 [hep-ph]

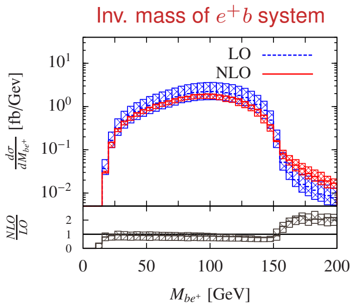
- K-factor is 0.87 at central scale ($\xi = 1$)
- Varying the scale up and down by a factor 2:

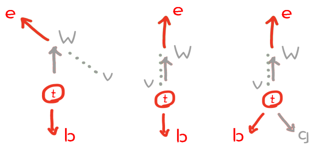
  LO: $\sigma = 183.1\,^{+61\%}_{-35\%}$ fb $\quad\rightarrow\quad$ **NLO**: $\sigma = 159.7\,^{-21\%}_{-5\%}$ fb

- Impact of off-shell effects estimated with the $\Gamma_t \rightarrow 0$ limit: $1\%(2\%)$ at LO (NLO)

Differential distributions

Where are the off-shell contributions more relevant?





(Figure credit: R. Franceschini)

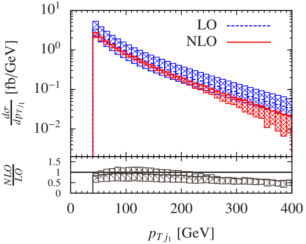
No jet radiation $\Rightarrow$ sharp end-point at $M_{be+} \approx \sqrt{m_t^2 - m_W^2} \approx 153$ GeV

$\hookrightarrow$ Extra-jet radiation $\oplus$ off-shell effects $\Rightarrow$ smearing of M_{be+} end-point

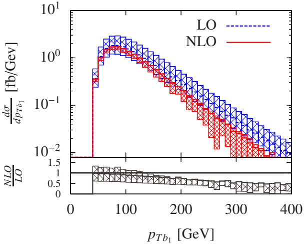
Differential distributions

Light-jet vs b-jet kinematics

p_T of hardest light-jet



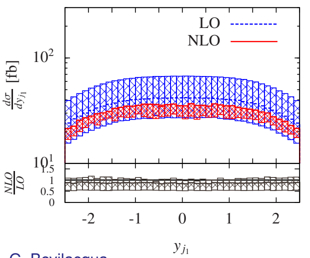
p_T of hardest b-jet



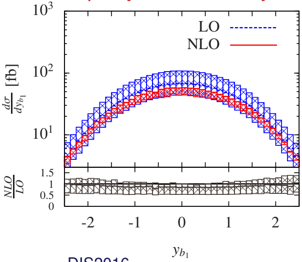
- Non-uniform K-factors
- Distortions up to 50% (with $\mu = m_t$)

$\hookrightarrow$ Better use dyn. scale

rapidity of hardest light-jet



rapidity of hardest b-jet



- More stable NLO/LO ratio

G.B, Hartanto, Kraus and Worek (2016)

Summary and Outlook

NLO QCD corrections to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\, +$ jet are now available

- full description of $t\bar{t}j$ with leptonic decays *beyond NWA*
- complete off-shell effects for tops and W's

Phenomenological applications

- extraction of m_{top}: off-shell effects in ρ_s
- improved accuracy for $t\bar{t}j$ SM background

Further analyses required

- estimate PDF uncertainties
- look for judicious dynamical scales
- impact of finite b-quark mass
- differential-level comparison with NWA