Off-shell $t\bar{t}j$ production and top quark mass studies at the LHC

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Work in collaboration with H. B. Hartanto, M. Kraus, M. Schulze and M. Worek

Phys. Rev. Lett. **116** (2016) 5, 052003

JHEP **1611** (2016) 098

+ new unpublished results

Introduction

LHC is a *top factory*: $t\bar{t}$ pairs are abundantly produced allowing to study top quark properties with high precision

The study of (associated) $t\bar{t}$ production has a wide range of applications...

- SM benchmarks (*e.g.* $t\bar{t}$ cross section)
- precision measurent of SM parameters (*e.g.* m_t)
- probing Higgs-Yukawa sector (*e.g.* $t\bar{t}H$)
- constraining PDFs (particularly at large x)
- searching for BSM effects (*e.g.* heavy resonances decaying to tops)

... and many more

This talk will focus on the production of $t\bar{t}$ in association with one hard jet ($pp \to t\bar{t}j$) and its connection with precision measurements of m_t at the LHC

Why studying $pp \to t\bar{t}j$ with high precision?

1. A relevant fraction of the inclusive $t\bar{t}$ sample shows hard jet activity

Take NNLO $t\bar{t}$ cross section as a benchmark: [LHC-13, CT14 pdf, $m_t = 173.2$ GeV]

$$\boxed{\sigma_{t\bar{t}} = 807 \text{ pb}}$$

Top++ Czakon, Mitov '14

Compare with NLO $t\bar{t}j$ cross section:

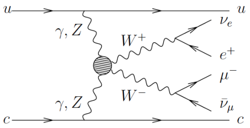
Jet p_T cut [GeV]	$\sigma_{t\bar{t}j}$ $[pb]$	$\sigma_{t\bar{t}j}/\sigma_{t\bar{t}}$ [%]
40	296.97 $\pm$ 0.29	37
60	207.88 $\pm$ 0.19	26
80	152.89 $\pm$ 0.13	19
100	115.60 $\pm$ 0.14	14
120	89.05 $\pm$ 0.10	11

HELAC-NLO G.B. *et al* '13

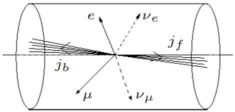
Why studying $pp \to t\bar{t}j$ with high precision?

2. $t\bar{t}j$ is a background for Vector Boson Fusion: $qq \to W^+W^-qq$

VBF *signal*:



VBF *signature*:



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

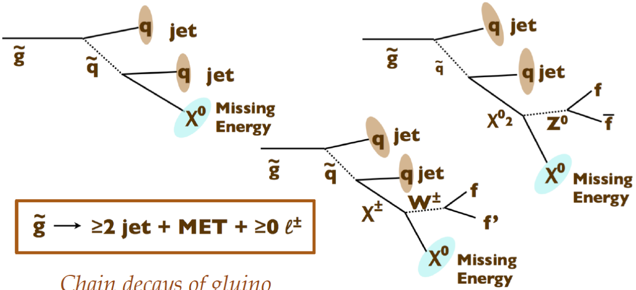
Englert *et al.*, Phys.Rev. D80 (2009) 035027

Residual background from (off-shell) $t\bar{t}$ + jets after VBF cuts is still relevant

$\hookrightarrow$ needs NLO accuracy

Why studying $pp \to t\bar{t}j$ with high precision?

3. $t\bar{t}j$ is a background for SUSY particle searches



Chain decays of gluino

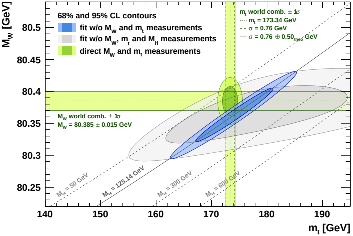
M. L. Mangano '09

Typical signatures of cascade SUSY particle decays:

hadronic jets $+$ charged leptons $+$ missing p_T

Top quark mass: precision matters

Gfitter Collab., Eur.Phys.J. C74 (2014) 3046

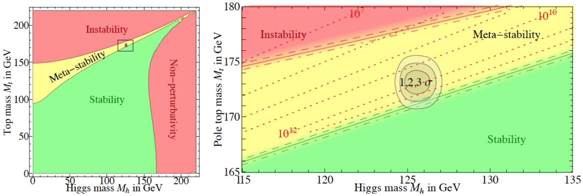


Precision tests of the Standard Model:

global EW fit   Riemann *et al.*, Baak *et al.*, ...

$\hookrightarrow$ check self-consistency through m_t, m_W, m_H correlations

Degrassi *et al*, JHEP 1208 (2012) 098



Stability of EW vacuum:

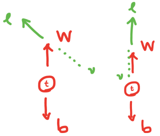
stable or meta-stable?

Different sources of uncertainties in m_t extraction via MC: accuracy of ME's, parton shower + hadronization, color reconnection, b-quark fragmentation ...

$pp \to t\bar{t}j$: sensitivity to top mass

Case study 1: min. invariant mass distribution of lepton and b-jets ($M_{b\ell}$)

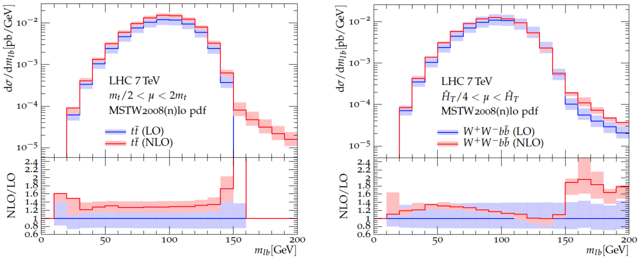
- Assuming *on-shell* top and W decays, $M_{b\ell}$ has a sharp kinematical endpoint:



$$M_{b\ell}^{\text{max}} \approx \sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}$$

- *Off-shell* and *radiative* effects smear the kinematical endpoint ($\Rightarrow$ tail).

  Extensively studied for $t\bar{t}$ Denner *et al.* '12, Heinrich *et al.* '13 ...



Heinrich *et al.* arXiv:1312.659 [hep-ph]

$pp \to t\bar{t}j$: sensitivity to top mass

Case study 2: normalized inverse $t\bar{t}j$ invariant mass ($\mathcal{R}(m_t^{pole}, \rho_s)$)

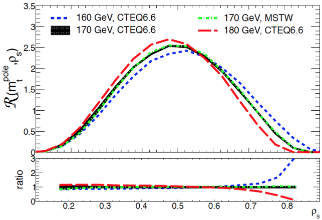
Alioli, Fernandez, Fuster, Irles, Moch, Uwer and Vos ('13)

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

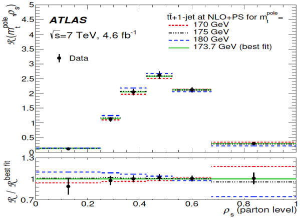
$$\rho_s = \frac{2\,m_0}{\sqrt{s_{t\bar{t}j}}}$$

- ρ_s shape is sensitive to top mass
- $\rho_s \approx 1 \;\Rightarrow\;$ near $t\bar{t}$ threshold
- $t\bar{t}j$ has higher sensitivity than $t\bar{t}$

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



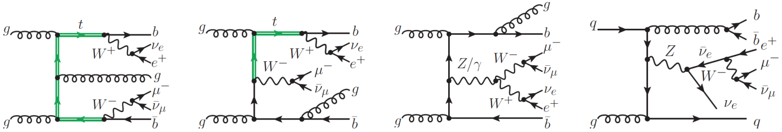
ATLAS Collab., arXiv:1507.01769 [hep-ex]



How sizable is the impact of the off-shell effects in $M_{b\ell}$ and ρ_s?

Off-shell in a nutshell

Example: $gg \to t\bar{t}g$ with leptonic decays, $\mathcal{O}(\alpha^4 \alpha_S^3)$:



double-resonant | single-resonant | non-resonant | non-resonant

$$\text{NWA: } \frac{1}{(p_t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} \overset{\Gamma_t \to 0}{\sim} \frac{\pi}{m_t \Gamma_t} \delta(p_t^2 - m^2) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

In the limit $\Gamma_t \to 0$:

- only *double-resonant* contributions survive
- cross section factorizes into "$t\bar{t}j$ production $\otimes$ top decays"
- contributions neglected by NWA ("off-shell effects") are suppressed by powers of $\Gamma_t / m_t \approx 1\%$

NWA is best suited for inclusive observables. However, at the differential level, off-shell effects can reach several tens of percent

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

NLO QCD

- On-shell $t\bar{t}j$ (stable tops)
  Dittmaier, Uwer and Weinzierl '07,'09
- NWA $t\bar{t}j$ (LO decays)
  Melnikov and Schulze '10
- NWA $t\bar{t}j$, (NLO decays)
  Melnikov, Scharf and Schulze '11
- Off-shell $t\bar{t}j$
  GB, Hartanto, Kraus and Worek '15,'16

NLO QCD + Parton Shower

- NWA $t\bar{t}j$ (LO decays, no spin corr.)
  Kardos, Papadopoulos and Trocsanyi '11
- NWA $t\bar{t}j$ (LO decays, with spin corr.)
  Alioli *et al* '13, Fuster *et al* '17
- On-shell $t\bar{t}j$ + DEDUCTOR (stable tops)
  Czakon, Hartanto, Kraus and Worek '15

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

NLO QCD

- On-shell $t\bar{t}j$ (stable tops)
  Dittmaier, Uwer and Weinzierl '07,'09
- NWA $t\bar{t}j$ (LO decays) $\rightarrow$ "NWA Prod"
  Melnikov and Schulze '10
- NWA $t\bar{t}j$, (NLO decays) $\rightarrow$ "NWA"
  Melnikov, Scharf and Schulze '11
- Off-shell $t\bar{t}j$ $\rightarrow$ "Full"
  GB, Hartanto, Kraus and Worek '15,'16

Focus of our study:

- full analysis of NLO off-shell $t\bar{t}j$ production with `HELAC-NLO` G.B. *et al* '13
- systematic comparison with predictions obtained in NWA M. Schulze
- study of the impact of off-shellness in top mass extraction (template method)

Analysis carried out at fixed order, no parton shower involved at this stage

Numerical results for $t\bar{t}j$ at LHC

Setup for LHC 13 TeV

Final state and parameters

- Fully leptonic decay channel: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$
- All leptons and light quarks (including bottom) are massless $\to$ 5FS
- Top quark (pole mass): $m_t = 173.2$ GeV
- Complex Mass Scheme: $m_t^2 \to m_t^2 - i\, m_t\, \Gamma_t$ Denner *et al.* '99, Denner *et al.* '05

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
$p_T^{\rm miss} > 40$ 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

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

Inclusive cross sections

PDF: CT14

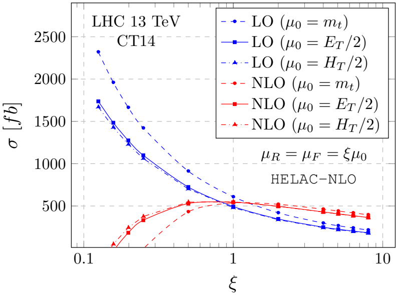
Fixed scale: $\mu_0 = m_t$

Dynamical scales: $\mu_0 = E_T/2$ and $H_T/2$

$$E_T \equiv \sqrt{m_t^2 + p_T^2(t)} + \sqrt{m_t^2 + p_T^2(\bar{t})}$$

$$H_T \equiv \sum_i p_T(i) + p_T^{\text{miss}}, \quad i = e^+, \mu^-, b, \bar{b}, j_1$$

G.B., Hartanto, Kraus and Worek '16

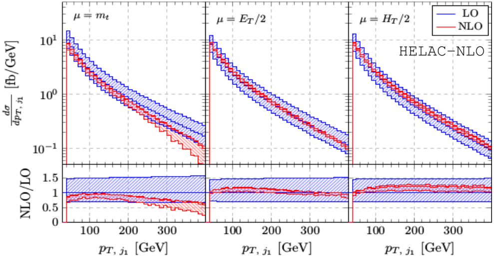


μ_0	$\sigma_{LO}[fb]$	$\sigma_{NLO}[fb]$	$\mathcal{K}$
m_t	$608.09\,^{+50\%}_{-31\%}$(scale)	$537.24\,^{+2\%}_{-20\%}$(scale) $^{+3\%}_{-3\%}$(pdf)	0.88
$E_T/2$	$493.54\,^{+47\%}_{-30\%}$(scale)	$544.64\,^{+1\%}_{-9\%}$(scale) $^{+3\%}_{-3\%}$(pdf)	1.10
$H_T/2$	$479.38\,^{+46\%}_{-30\%}$(scale)	$538.66\,^{+1\%}_{-9\%}$(scale) $^{+3\%}_{-3\%}$(pdf)	1.12

Differential cross sections

Uncertainty bands and K-factors for different scale choices

G.B., Hartanto, Kraus and Worek '16

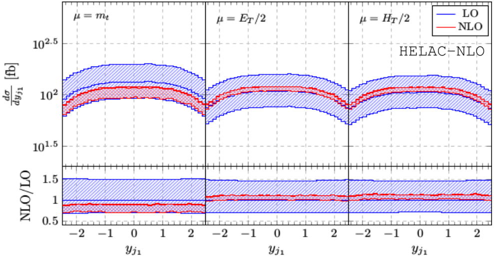


Scale uncertainties:

$$\frac{1}{2} \leq \left(\frac{\mu_R}{\mu_F}\right) \leq 2\,, \quad \frac{1}{2} \leq \mu_R, \mu_F \leq 2$$

p_T of the hardest light jet

rapidity of the hardest light jet



Dynamical scales improve perturbative stability and reduce shape distortions

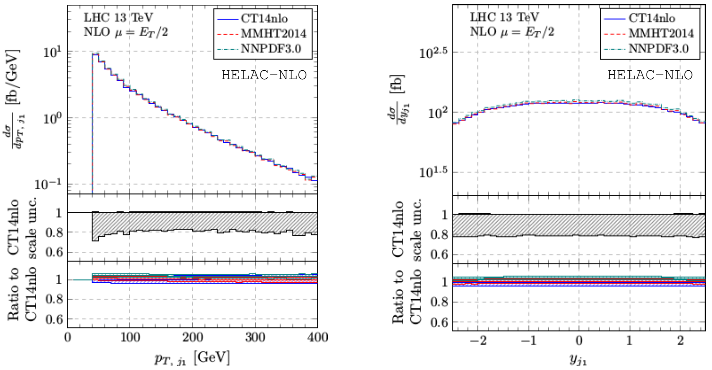
$\hookrightarrow$ "best" prediction:

$\mu = H_T/2$

Differential cross sections

Scale vs PDF uncertainties

G.B., Hartanto, Kraus and Worek '16



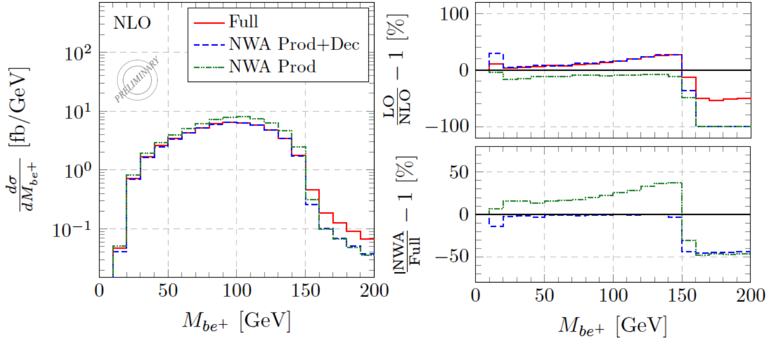
Scales $\sim 20\%$, PDF $\sim 5\%$

Differential cross sections

NEW – Comparison with NWA: M_{be+} $[\mu_R = \mu_F = m_t,$ CT14 PDF]

$$\sigma^{\text{Full}}_{\text{NLO}} = 537 \text{ fb}, \quad \sigma^{\text{Prod+Dec}}_{\text{NLO}} = 527 \text{ fb}, \quad \sigma^{\text{Prod}}_{\text{NLO}} = 656 \text{ fb}$$

G.B., Hartanto, Kraus, Schulze and Worek, in preparation

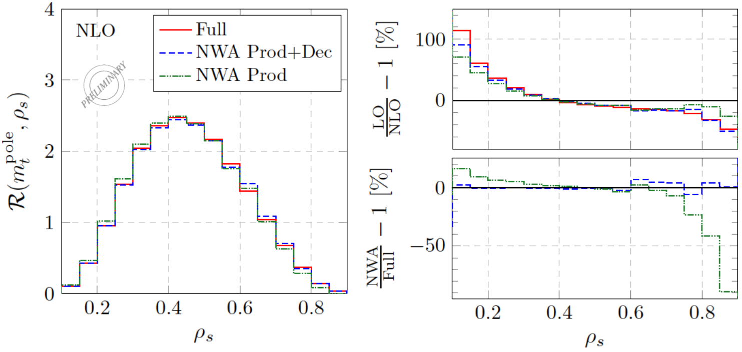


NLO corrections to top decay in NWA important – Large off-shell effects in tail

Differential cross sections

NEW – Comparison with NWA: $\mathcal{R}(m_t^{pole}, \rho_s)$ $[\mu_R = \mu_F = m_t,$ CT14 PDF]

G.B., Hartanto, Kraus, Schulze and Worek, in preparation

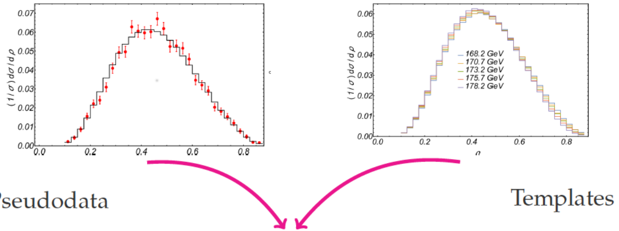


Top quark mass studies with $t\bar{t}j$ at LHC

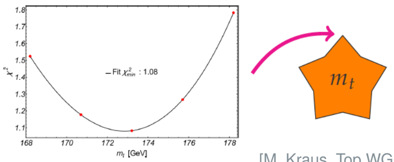
Fitting top quark mass

Basic idea

- generate *pseudo-data* for a given luminosity, randomly distributed according to the most accurate prediction ($\rightarrow$ "full" = NLO with off-shell effects)
- fit pseudo-data with template histograms
- compare results obtained with templates of different accuracy (full vs NWA)

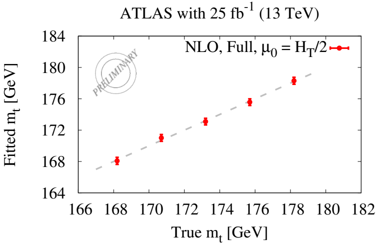


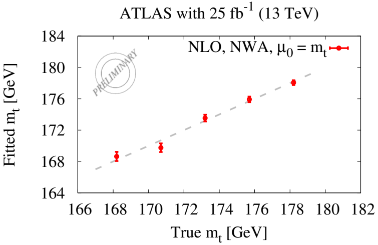
$$\chi^2(m_t) = \sum_i \frac{(x_i^d - x_i^{th})^2}{\sigma_i^2}$$

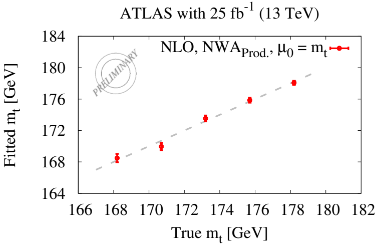


[M. Kraus, Top WG Meeting '17]

Consistency checks







Let's consider $\mathcal{R}(m_t^{pole}, \rho_s)$ (using binning of ATLAS analysis, arXiv:1507.01769 [hep-ex])

Use same theoretical predictions for both templates and pseudo-data generation

True and fitted m_t agree with errors
$\hookrightarrow$ no bias observed

[G.B., Hartanto, Kraus, Schulze and Worek, in preparation]

Results of the fit

Analysing M_{be^+}

G.B., Hartanto, Kraus, Schulze and Worek, in preparation

PRELIMINARY

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [GeV]
		2.5 fb^{-1}		
Full, $\mu_0 = H_T/2$	173.09 ± 0.48	1.05	0.38 (0.9σ)	$+0.11$
Full, $\mu_0 = E_T/2$	173.01 ± 0.50	1.06	0.37 (0.9σ)	$+0.19$
Full, $\mu_0 = m_t$	173.07 ± 0.49	1.22	0.18 (1.3σ)	$+0.13$
NWA, $\mu_0 = m_t$	173.90 ± 0.50	1.11	0.30 (1.0σ)	-0.70
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	172.56 ± 0.54	1.64	0.01 (2.6σ)	$+0.64$
		25 fb^{-1}		
Full, $\mu_0 = H_T/2$	173.18 ± 0.15	1.02	0.42 (0.8σ)	$+0.02$
Full, $\mu_0 = E_T/2$	173.23 ± 0.15	1.03	0.41 (0.8σ)	-0.03
Full, $\mu_0 = m_t$	173.22 ± 0.16	1.78	0.005 (2.8σ)	-0.02
NWA, $\mu_0 = m_t$	173.98 ± 0.16	2.56	$5 \cdot 10^{-6}$ (4.6σ)	-0.78
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	172.62 ± 0.17	8.23	0 ($\gg 5\sigma$)	$+0.58$

- NWA vs Off-shell: shift of $\mathcal{O}(800)$ MeV
- PDF uncertainties: $\mathcal{O}(30)$ MeV
- Scale uncertainties: dyn. $\rightarrow \mathcal{O}(50)$ MeV, fix. $\rightarrow \mathcal{O}(1)$ GeV

Results of the fit

Analysing $\mathcal{R}(m_t^{pole}, \rho_s)$

G.B., Hartanto, Kraus, Schulze and Worek, in preparation

PRELIMINARY

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [GeV]
		$2.5\ \text{fb}^{-1}$		
Full, $\mu_0 = H_T/2$	173.05 ± 1.31	0.99	$0.42\ (0.8\sigma)$	$+0.15$
Full, $\mu_0 = E_T/2$	172.19 ± 1.34	1.05	$0.39\ (0.9\sigma)$	$+1.01$
Full, $\mu_0 = m_t$	173.86 ± 1.39	1.42	$0.21\ (1.2\sigma)$	-0.66
NWA, $\mu_0 = m_t$	175.22 ± 1.15	1.38	$0.23\ (1.2\sigma)$	-2.02
$NWA_{\text{Prod.}}$, $\mu_0 = m_t$	169.39 ± 1.46	1.12	$0.35\ (0.9\sigma)$	$+3.81$
		$25\ \text{fb}^{-1}$		
Full, $\mu_0 = H_T/2$	173.06 ± 0.44	0.97	$0.44\ (0.8\sigma)$	$+0.14$
Full, $\mu_0 = E_T/2$	172.36 ± 0.44	1.38	$0.23\ (1.2\sigma)$	$+0.84$
Full, $\mu_0 = m_t$	173.84 ± 0.42	5.12	$1 \cdot 10^{-4}\ (3.9\sigma)$	-0.64
NWA, $\mu_0 = m_t$	175.23 ± 0.37	5.28	$7 \cdot 10^{-5}\ (4.0\sigma)$	-2.03
$NWA_{\text{Prod.}}$, $\mu_0 = m_t$	169.43 ± 0.50	2.61	$0.02\ (2.3\sigma)$	$+3.77$

- NWA vs Off-shell: shift of $\mathcal{O}(1.4)$ GeV
- PDF uncertainties: $0.4 - 0.7$ GeV
- Scale uncertainties: dyn. $\rightarrow 0.6 - 1.2$ GeV, fix. $\rightarrow 2.1 - 2.8$ GeV

Summary and conclusions

Full calculation of $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}j$ at NLO QCD

- complete description of $t\bar{t}j$ with all resonant and non-resonant contributions
- predictions for the LHC Run II with scale and PDF uncertainties
- interesting phenomenological applications

Comparison with NWA (”on-shell *production* $\otimes$ *decay*”)

- off-shell effects: $\sim$ 2% for the total cross section, much larger differentially
- NLO corrections to top decays are important

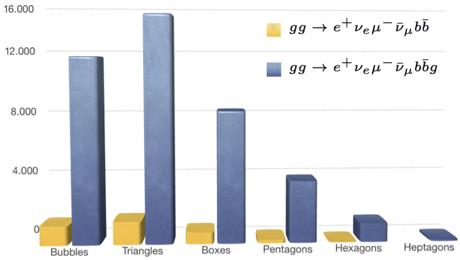
First applications to top mass extraction

- preliminary results: analysis of M_{be^+} and $\mathcal{R}(m_t^{pole}, \rho_s)$ observables
- fixed scale $\mu = m_t$ not suitable for m_t extraction, better use dynamical scales
- complete study to appear soon: M_{be^+}, $\mathcal{R}(m_t^{pole}, \rho_s)$, $M_{t\bar{t}}$, $M_{e^+\mu^-}$, H_T

Backup slides

$t\bar{t}j$ beyond NWA at NLO

of one-loop diagrams classified by topology: **off-shell $t\bar{t}$** vs **off-shell $t\bar{t}j$**



source: QGRAF (Nogueira '93)

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

LO: 508

$\hookrightarrow$ Real: 4447

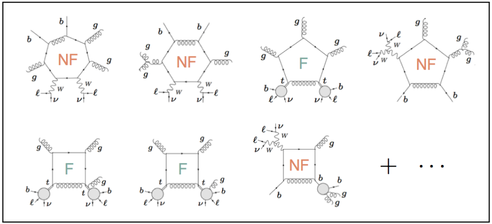
$\hookrightarrow$ Virtual: 39180

Representative loop diagrams

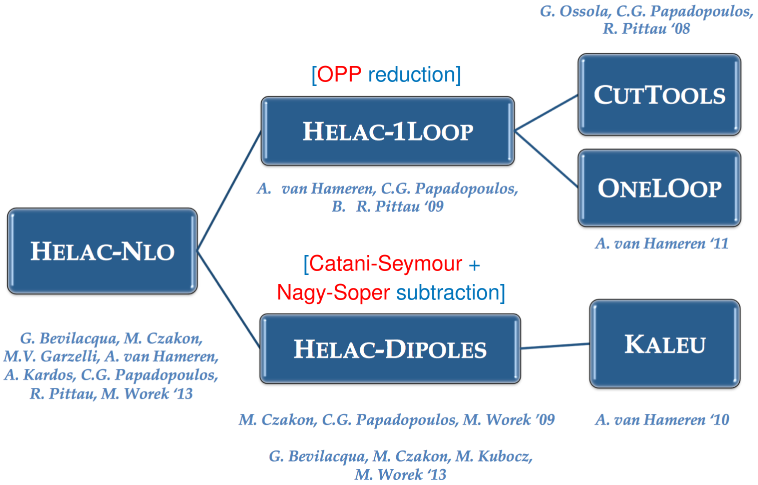
F = factorizable

NF = non-factorizable

New functionalities in HELAC-NLO triggered by problem solving



The HELAC-NLO framework



Functionality extended to produce NTuples of events $\rightarrow$ scale variations, PDF errors ...

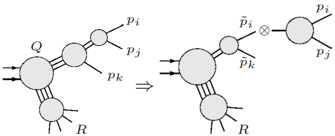
Recomputing for different scales/PDFs is not practical: use event re-weighting

Catani-Seymour vs Nagy-Soper subtraction

Number of subtraction terms for representative processes

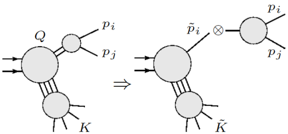
Partonic Subprocess	N. of Diagrams	N. of CS Dipoles	N. of NS Dipoles
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}gg$	4447	56	14
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$	3904	48	12
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q\bar{q}$	1952	40	10
$qq \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}qq$	930	20	5
$qq' \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}qq'$	501	12	3

Catani-Seymour



$$\{p\}_{m+1} \to \{\tilde{p}\}_m^{(ijk)}$$

Nagy-Soper



$$\{p\}_{m+1} \to \{\tilde{p}\}_m^{(ij)}$$