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NLO QCD corrections to off-shell ttj production at the LHC

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Plan

- Motivation for *ttj* production at the LHC
- Motivation for top-quark off-shell effects based on *tt* production
- Status of theoretical predictions for *ttj*
- Complete off-shell effects with **HELAC–NLO** for *ttj*
- Results for LHC @ 8 TeV
- Summary & Outlook

Collaborators:
G. Bevilacqua (University of Debrecen)
H. B. Hartanto (RWTH Aachen University)
M. Kraus (RWTH Aachen University)

Motivation for ttj

- @ LHC tops are produced with large energies & high transverse momenta
- Increase probability for additional (hard) radiation of gluons → *ttj* final state
- How big is the contribution of *ttj* in the inclusive *tt* sample ?

- NNLO *tt* cross section for m_t = 173.2 GeV @ LHC$_{13\ \mathrm{TeV}}$ with CT14 PDF set:

σ(tt) = 807 pb

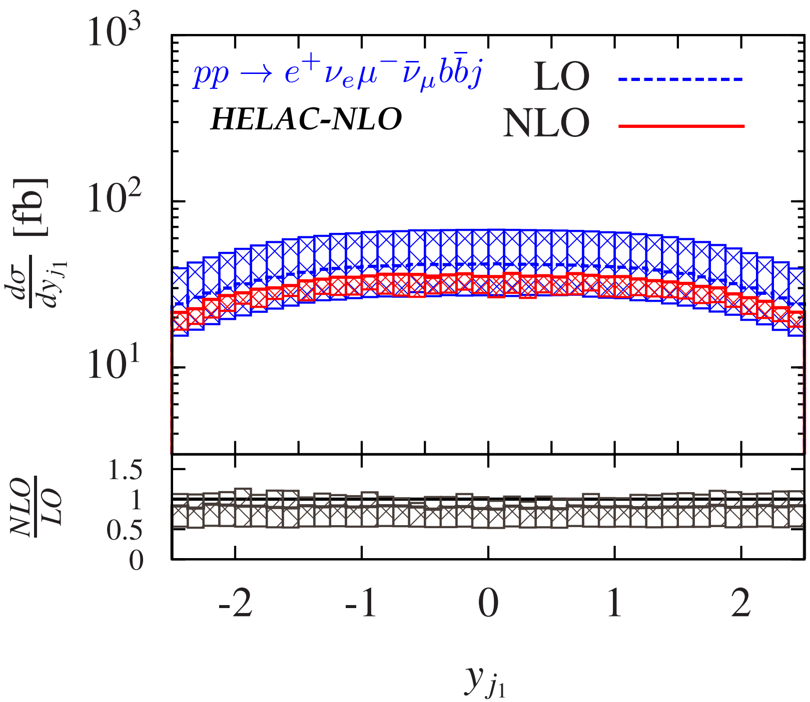
TOP++, Czakon, Mitov '14

Jet p_T cut [GeV]	**σ(ttj) [pb]**	**σ(ttj)/σ(tt) [%]**
40	296.97 ± 0.29	37
60	207.88 ± 0.19	26
80	152.89 ± 0.13	19
100	115.60 ± 0.14	14
120	89.05 ± 0.10	11

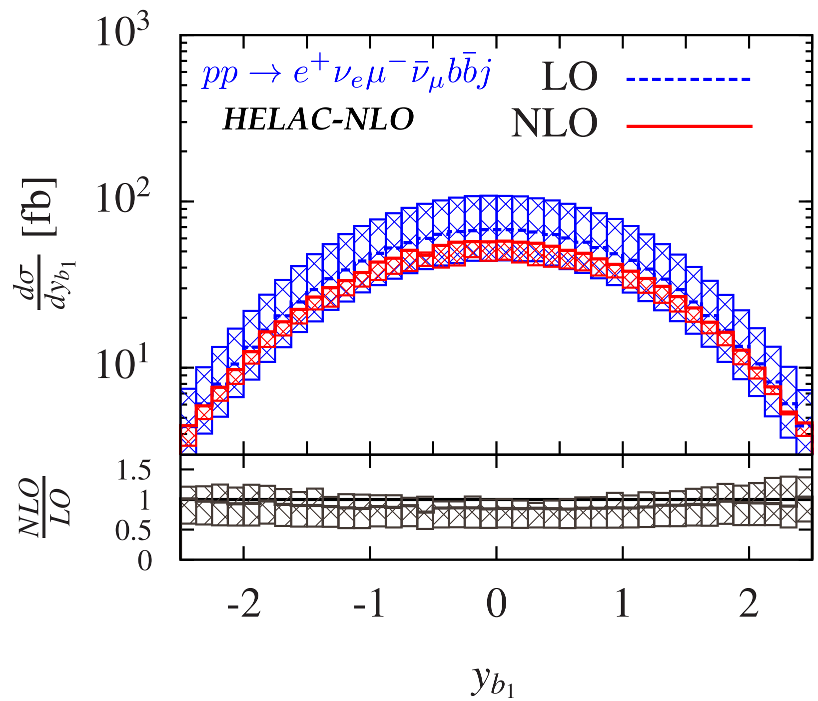
HELAC-NLO, G. Bevilacqua et al., '13

Motivation for ttj

- Background to SM Higgs production in VBF: $qq \to Hqq \to WWqq$
- 2 tagging jets: $\Delta y_{jj} = |y_{j1} - y_{j2}| > 4 \;\; \& \;\; y_{j1} \times y_{j2} < 0$
- ↓ tt background: tt → WWbb & ↑ ttj background: ttj → WWbbj



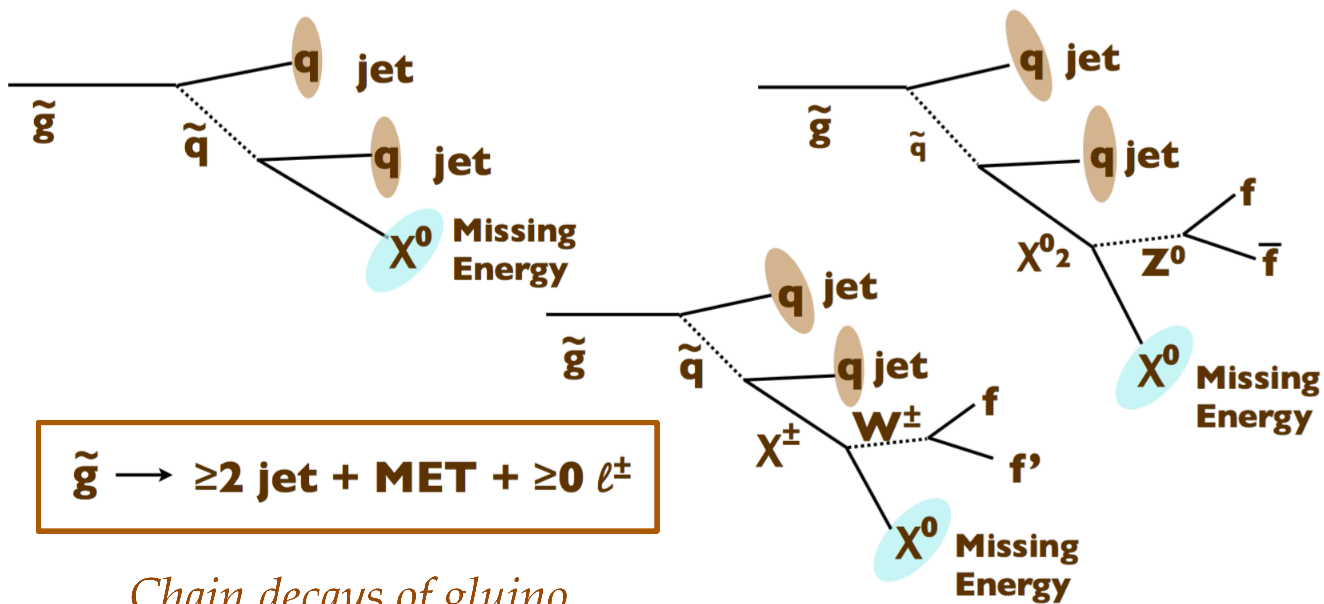
forward/backward light-jets



b-jets from tops are central

Motivation for ttj

- Background to supersymmetric particle production
- Top decays into W and b-quark → SM : $t \to Wb \approx 100\%$
- *Decay channels:* di-leptons ($\mathcal{B}r$ =4%), lepton+jet ($\mathcal{B}r$ =30%), all-jets ($\mathcal{B}r$ =46%)
  - ★ *ttj signature:* jets, charged leptons & p_T^{miss} from invisible neutrinos
  - ★ *Typical signals:* jets, charged leptons & p_T^{miss} due to escaping lightest supersymmetric particle (neutralino)



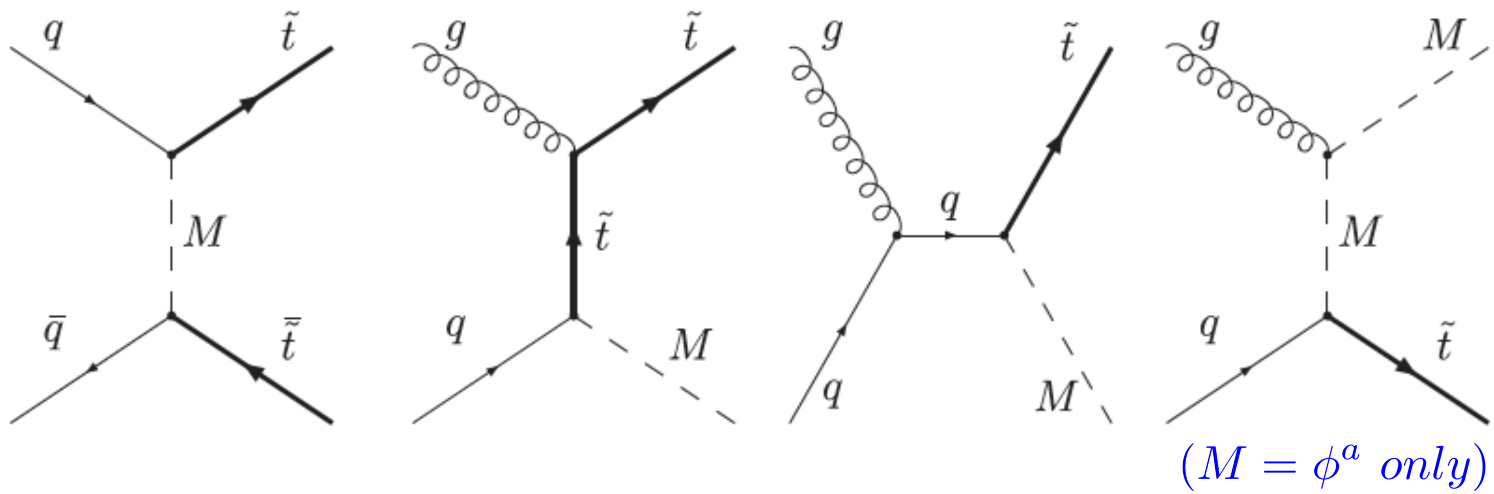
Chain decays of gluino

M. L. Mangano '09

Motivation for ttj

- Background to production of top flavor violating resonances $pp \to Mt \to t\bar{t}j$

M. I. Gresham, I.-W. Kim, K. M. Zurek '11



$$\tilde{t} = t \text{ for } M = W', Z'_H \text{ and } \tilde{t} = \bar{t} \text{ when } M = \phi^a \text{ (color triplet or sextet)}$$

- W' signal: $W' \to \bar{t}q$
- Production processes: $pp \to W't \to t\bar{t}j$

$$m_{W'} \in \{200, \ldots, 600\} \text{ GeV}$$

$$\sigma_{7\text{TeV}} \in \{40, \ldots, 4\} \text{ pb}$$

$$\mathcal{L}_{W'} = \frac{1}{\sqrt{2}} \bar{d} \gamma^\mu g_R P_R t W'_\mu + \text{H.c.},$$

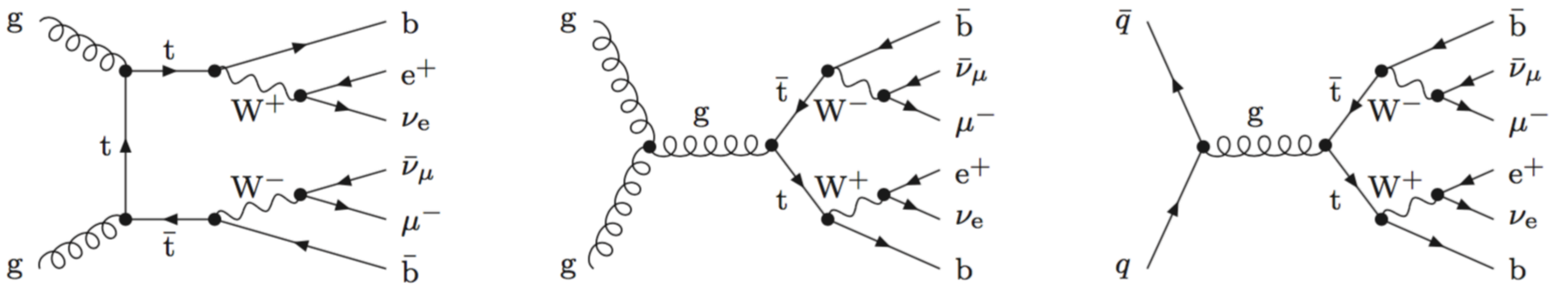
$$\mathcal{L}_{Z'_H} = \frac{1}{\sqrt{2}} \bar{u} \gamma^\mu g_R P_R t Z'_{H\mu} + \text{H.c.},$$

$$\mathcal{L}_\phi = \bar{t}^c T^a_r (g_L P_L + g_R P_R) u \phi^a + \text{H.c.},$$

- ***ATLAS:*** $m_{W'} > 430$ ***GeV*** arXiv:1209.6593

NWA Vs. Off-shell Effects

- NWA → Tops are restricted to on-shell states
- Approximation is controlled by the ratio: $\Gamma_t/m_t \approx 10^{-2}$
- Contributions from diagrams involving two top-quark resonances



- Should be accurate for sufficiently inclusive observables
- Indeed → *top-quark off-shell effects for* $\boldsymbol{\sigma}$ *at few % level for:*

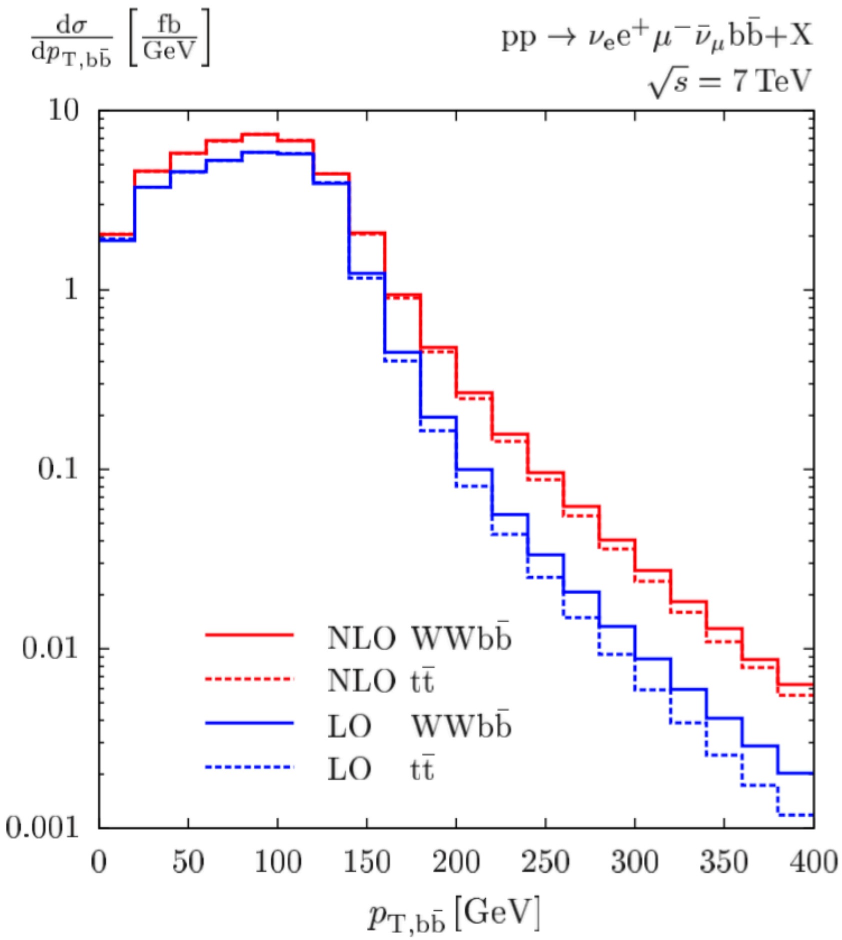
★ *pp → tt* — *A. Denner et al. '11, G. Bevilacqua et al. '11, A. Denner et al. '12, R. Frederix '14, F. Cascioli et al. '14, G. Heinrich et al '14*

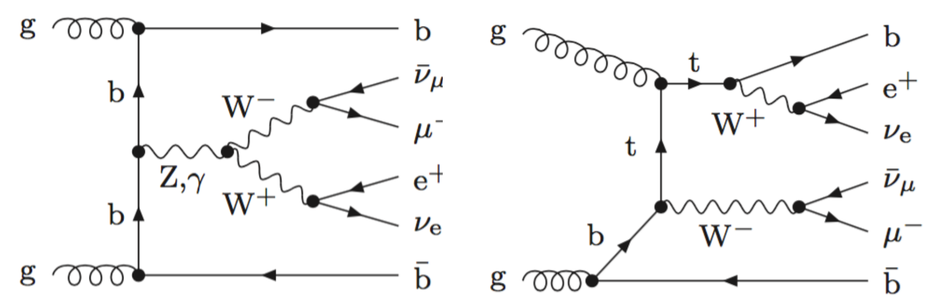
★ *pp → ttH* — *A. Denner, R. Feger '15*

★ *pp → ttj* — *G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16*

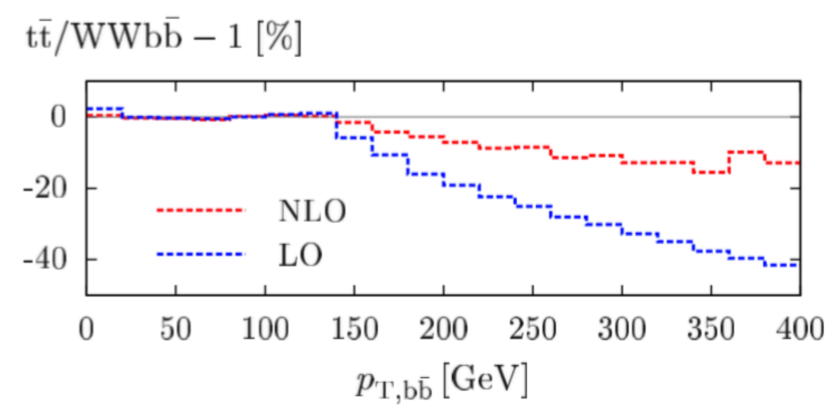
NWA Vs. Off-Shell Effects

- Larger impact on differential distributions
- Full NWA (tt) versus full calculation (WWbb) for $p_T(bb)$





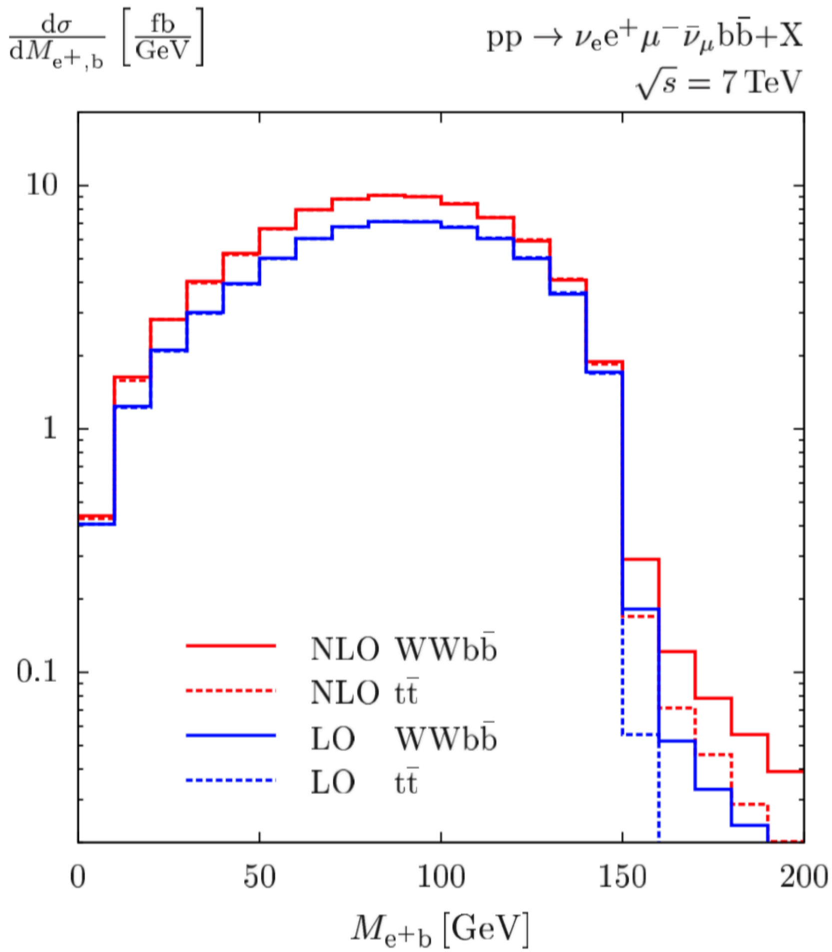
…also diagrams with one or no top-quark resonances



A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12

NWA Vs. Off-Shell Effects

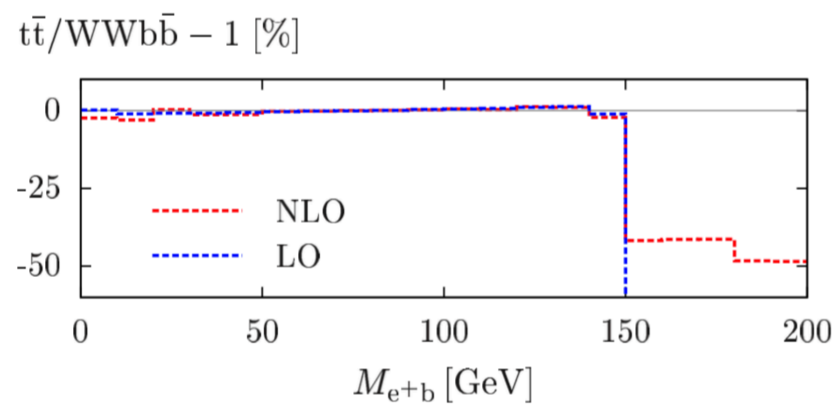
- Full NWA (tt) versus full calculation (WWbb) for M_{e+b}



- If both top and W decay on-shell
  → end-point given by sharp cut

$$M_{\ell b} = \sqrt{m_t^2 - m_W^2} \approx 152 \text{ GeV}$$

- Additional radiation & off-shell effects introduce smearing



A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12

Theoretical Predictions for ttj

- NLO QCD corrections to on-shell *ttj* production

  S. Dittmaier, P. Uwer, S. Weinzierl '07 '09

- NLO QCD correction to on-shell *ttj* production with LO decays

  K. Melnikov, M. Schulze '10

- NLO QCD corrections to *ttj* in NWA (with jet radiation in top-quark decays)

  K. Melnikov, M. Schulze '12

- **NLO QCD corrections to *ttj* with full top-quark and W off-shell effects**

  G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

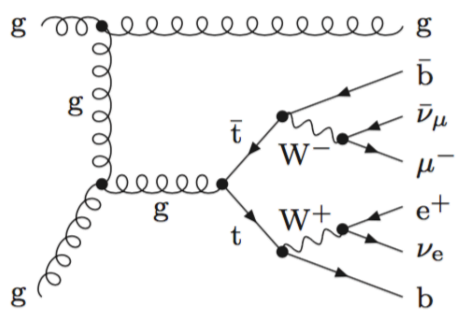
- NLO QCD correction to on-shell *ttj* production + PS
  - ★ **POWHEG + PYTHIA**, no spin correlations

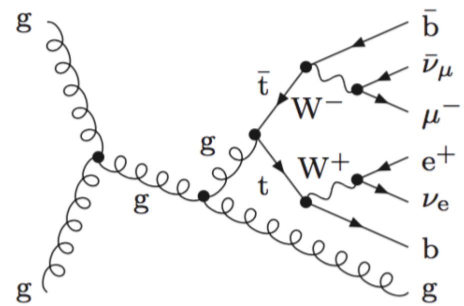
    A. Kardos, C. G. Papadopoulosa, Z. Trocsanyi '11
  - ★ **POWHEG + PYTHIA/HERWIG** with spin-correlations @ LO

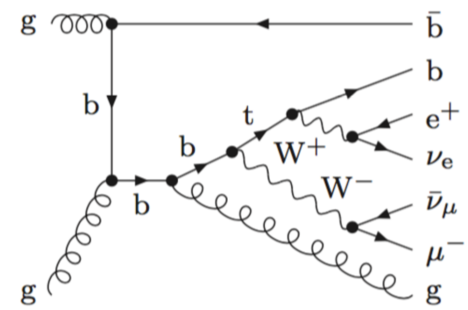
    S. Alioli, S.Moch, P. Uwer '12
  - ★ **MC@NLO + DEDUCTOR**, without top-quark decays

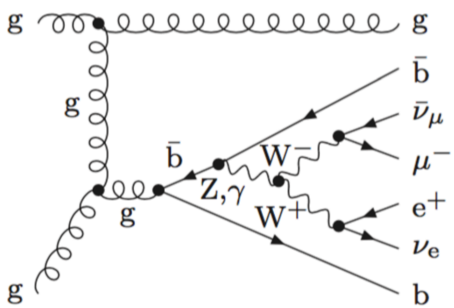
    M. Czakon, H. B. Hartanto, M. Kraus, M. Worek '15

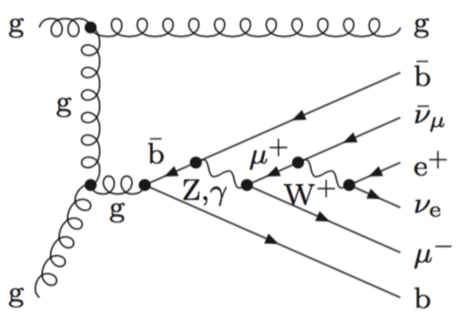
Off-Shell Effects for ttj











$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

- *ttj* with leptonic decays at $\mathcal{O}(\alpha_s^4\alpha^4)$
- 2 → 5 process from the QCD point of view
- Diagrams with complete off-shell effects for top & W gauge boson for gg initial state:
  - ★ *LO: 508*
  - ★ *Real emission: 4447*

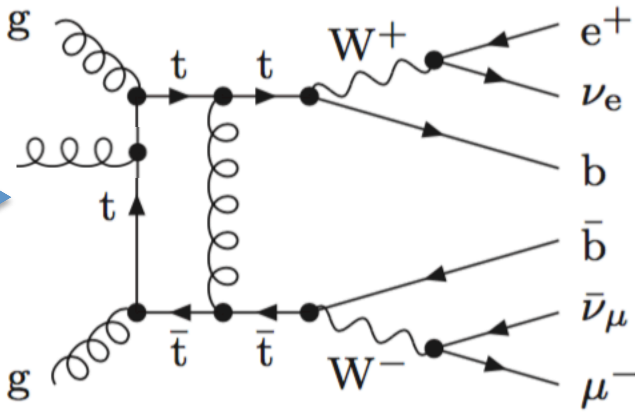
Off-Shell Effects for ttj

- *gg* channel comprises *39 180 one-loop diagrams* → according to **QGRAF**

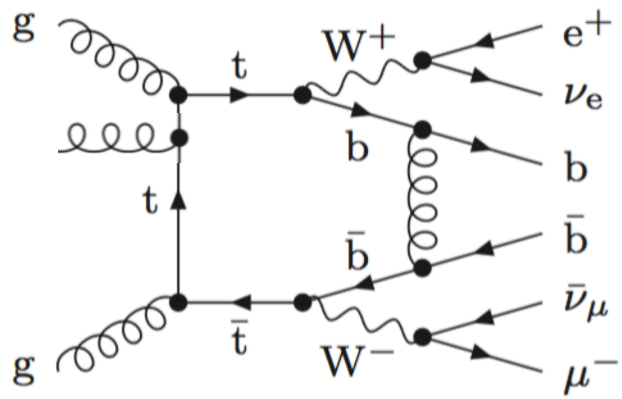
P. Nogueira '93

- The most complicated ones are *1155 hexagons & 120 heptagons*
- Tensor integrals up to rank six

NWA for ttj (on-shell top-quark production) – up to pentagons !



Full calculations for ttj – up to heptagons !



Intermediate Top Resonances

- Putting simply $\Gamma_t \neq 0$ violates gauge invariance
- Gauge-invariant treatment → complex-mass scheme
- Γ_t incorporated into top mass via:

$$\mu_t^2 = m_t^2 - i\, m_t \Gamma_t$$

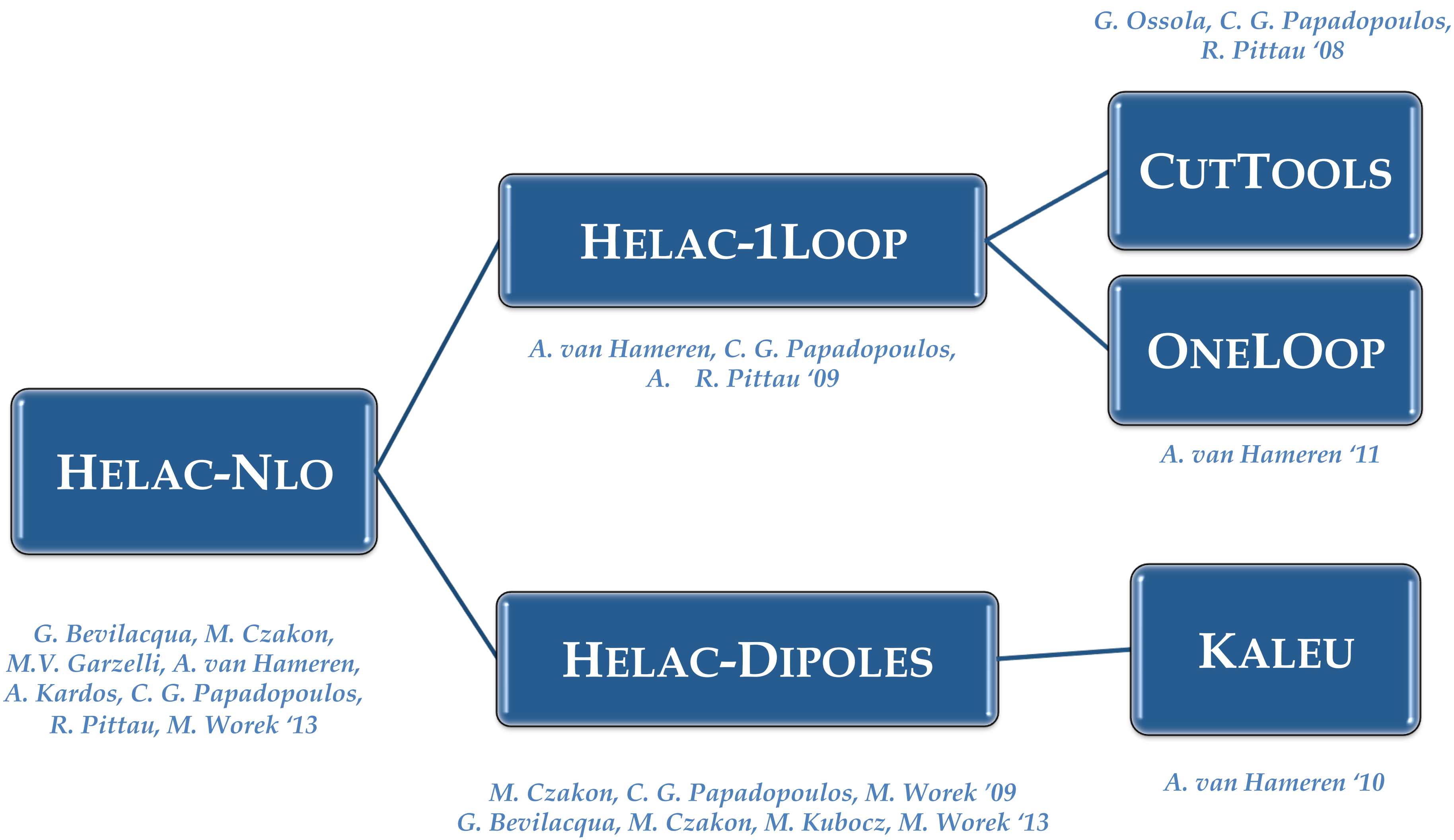
A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99
A. Denner, S. Dittmaier, M. Roth, L. H. Wieders '05

- All matrix elements evaluated using complex masses
- μ_t^2 identified with the position of pole of top-quark propagator
- Top-mass counter-term $\delta\mu_t$ related to top-quark self-energy at: $p_t^2 = \mu_t^2$

- *Another non trivial aspect:* evaluation of one-loop scalar integrals in presence of complex masses !
- Scalar integrals with complex masses → supported e.g. by **ONELOOP**

A. van Hameren '11

HELAC-NLO


G. Ossola, C. G. Papadopoulos,
R. Pittau ‘08
CUTTOOLS
HELAC-1LOOP
ONELOOP
A. van Hameren, C. G. Papadopoulos,
A. R. Pittau ‘09
A. van Hameren ‘11
HELAC-NLO
HELAC-DIPOLES
KALEU
G. Bevilacqua, M. Czakon,
M.V. Garzelli, A. van Hameren,
A. Kardos, C. G. Papadopoulos,
R. Pittau, M. Worek ‘13
M. Czakon, C. G. Papadopoulos, M. Worek ’09
G. Bevilacqua, M. Czakon, M. Kubocz, M. Worek ‘13
A. van Hameren ‘10

HELAC-NLO

- **HELAC-1LOOP** → Virtual corrections in 't Hooft-Veltman version of dimensional regularization
- **CUTTOOLS** → Ossola-Papadopoulos-Pittau (OPP) reduction technique
- **ONELOOP** → Evaluation of scalar integrals with complex masses

- **HELAC-DIPOLES** → The singularities from soft or collinear parton emissions isolated via subtraction methods for NLO QCD:
  - ★ Catani-Seymour dipole subtraction
  - ★ Nagy-Soper subtraction scheme
  - ★ Both for massive and massless cases
  - ★ Restriction on the phase space of the subtraction → α_{max}

- Reweighting & unweighting techniques, helicity, and color sampling methods for optimization

- **KALEU** → Phase-space integration
  - ★ Multi-channel Monte Carlo techniques
  - ★ Adaptive weight optimization
  - ★ Dedicated additional channels for each subtraction term for both subtractions

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

Results for ttj

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

- Different lepton generations → Effects at the level of 0.5% → checked *@ LO*
- Diagrams for gg initial state @ LO: 508 for $e^+\mu^-$ → 1240 for e^+e^-
- SM Parameters in G_μ scheme:

$$G_F = 1.16637 \cdot 10^{-5}\ \mathrm{GeV}^{-2}, \quad m_t = 173.3\ \mathrm{GeV},$$
$$m_W = 80.399\ \mathrm{GeV}, \quad \Gamma_W = 2.09974\ \mathrm{GeV},$$
$$m_Z = 91.1876\ \mathrm{GeV}, \quad \Gamma_Z = 2.50966\ \mathrm{GeV},$$
$$\Gamma_t^{LO} = 1.48132\ \mathrm{GeV}, \quad \Gamma_t^{NLO} = 1.3542\ \mathrm{GeV}.$$

- MSTW2008 set of PDF & $\mu_R = \mu_F = \mu_0 = m_t$
- All light quarks including *b-quarks* and leptons *are massless*
- Suppressed *contribution from b quarks* in the initial state *neglected*
- Amounts to *0.8% @ LO*

Top Width

- Finite W width contributions included in matrix elements & in Γ_t
- *Top width for unstable W bosons, neglecting bottom quark mass @ LO & NLO*

$$\Gamma_{\mathrm{t}}^{\mathrm{LO}} = \frac{G_\mu m_{\mathrm{t}}^5}{16\sqrt{2}\pi^2 M_{\mathrm{W}}^2} \int_0^1 \frac{\mathrm{d}y\, \gamma_{\mathrm{W}}}{(1-y/\bar{y})^2 + \gamma_{\mathrm{W}}^2} F_0(y)$$

M. Jezabek, J. H. Kühn '89
A. Denner, et al. '12

$$\gamma_{\mathrm{W}} = \Gamma_{\mathrm{W}}/M_{\mathrm{W}}, \; \bar{y} = (M_{\mathrm{W}}/m_{\mathrm{t}})^2 \qquad F_0(y) = 2(1-y)^2(1+2y)$$

$$\Gamma_{\mathrm{t}}^{\mathrm{NLO}} = \frac{G_\mu m_{\mathrm{t}}^5}{16\sqrt{2}\pi^2 M_{\mathrm{W}}^2} \int_0^1 \frac{\mathrm{d}y\, \gamma_{\mathrm{W}}}{(1-y/\bar{y})^2 + \gamma_{\mathrm{W}}^2} \left[F_0(y) - \frac{2\alpha_{\mathrm{s}}}{3\pi} F_1(y) \right]$$

$$\begin{aligned} F_1(y) = {} & 2(1-y)^2(1+2y)\left[\pi^2 + 2\,\mathrm{Li}_2(y) - 2\,\mathrm{Li}_2(1-y)\right] \\ & + 4y(1-y-2y^2)\ln(y) + 2(1-y)^2(5+4y)\ln(1-y) \\ & - (1-y)(5+9y-6y^2). \end{aligned}$$

- In the limit $\gamma_W \longrightarrow 0$

$$\frac{\gamma_{\mathrm{W}}}{(1-y/\bar{y})^2 + \gamma_{\mathrm{W}}^2} \to \pi \bar{y}\, \delta(y-\bar{y}).$$

Cuts

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

- *Jets:*
  - ★ Final-state quarks and gluons with pseudo-rapidity $|y| < 5$ converted into infrared-safe jets using *anti-k_T jet* algorithm with $R=0.5$
- *Requirement:*
  - ★ exactly 2 b-jets, at least one light-jet, 2 charged leptons, and missing p_T
- *Final states:*
  - ★ have to fulfill the following kinematical requirements (fairly inclusive cuts)

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

Scale Dependence

- Total cross section *@ LHC* with *8 TeV* (MSTW2008 PDF)

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

$$\sigma^{\text{LO}}_{\text{HELAC-NLO}} = 183.1^{+112.2(61\%)}_{-64.2(35\%)}\ \text{fb},$$

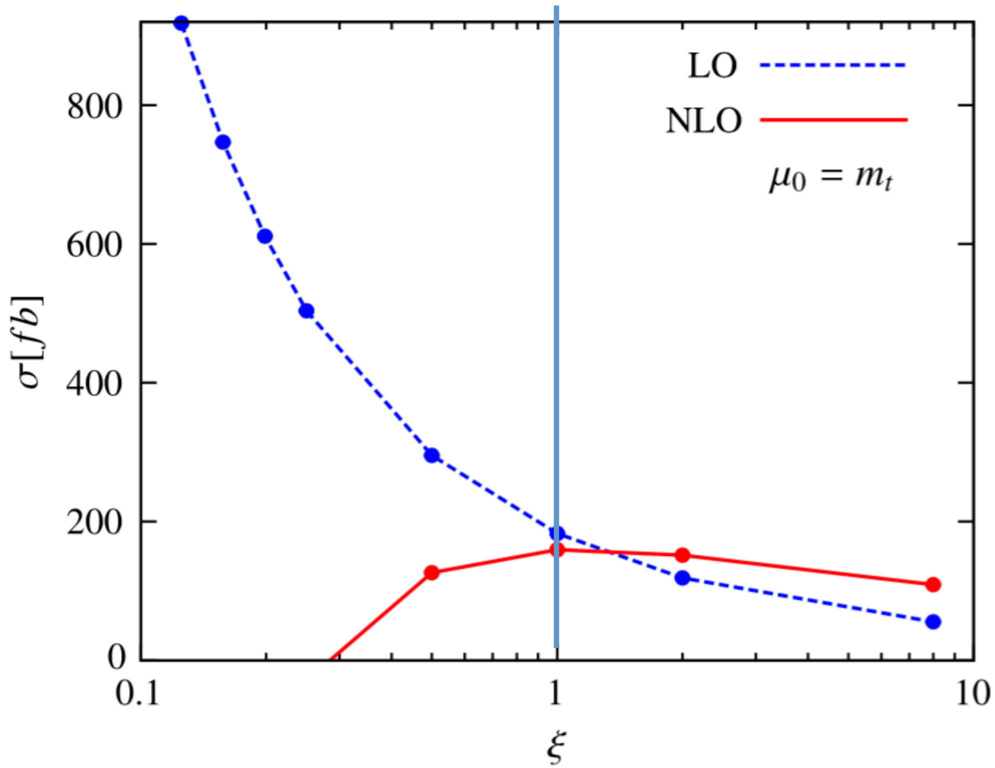
$$\sigma^{\text{NLO}}_{\text{HELAC-NLO}} = 159.7^{-33.1(21\%)}_{-7.9(5\%)}\ \text{fb}.$$

- *NLO* corrections: *-13%*

- Theoretical uncertainties:

  ★ *61% (48%) @ LO*
  ★ *21% (13%) @ NLO*

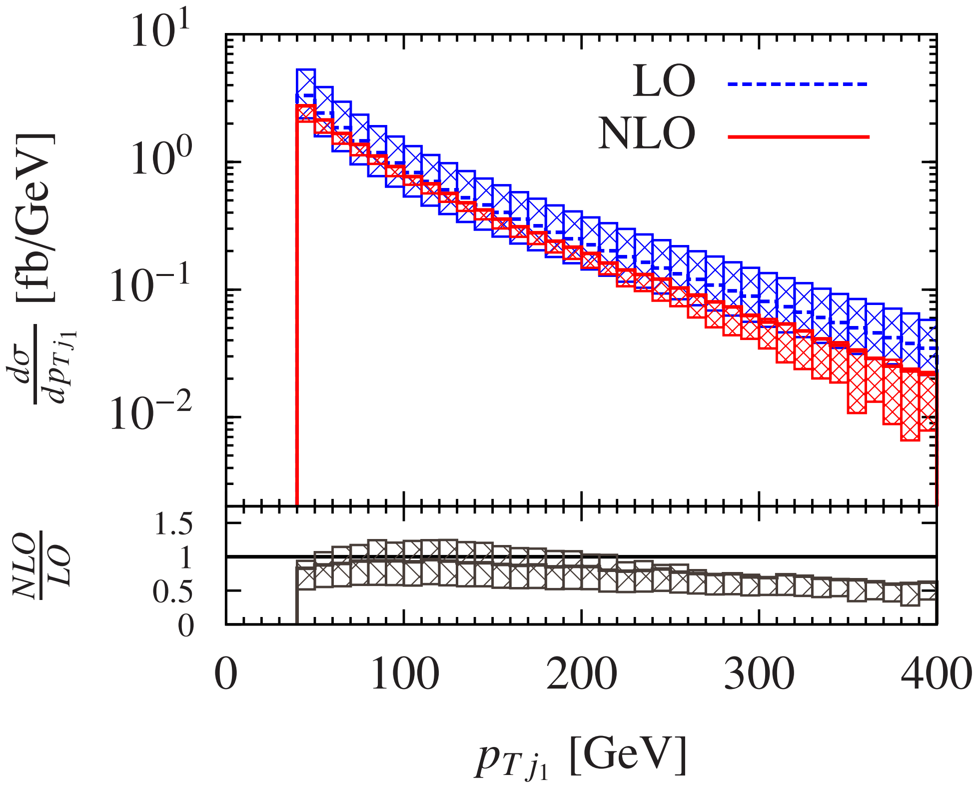
$$\mu_R = \mu_F = \mu_0 = m_t$$



G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

Hardest Light-Jet

- Upper panel: distributions and scale dependence bands: $\{0.5m_t, m_t, 2m_t\}$
- Lower panel: differential *K*-factor



- NLO do not rescale shape of LO
- Distortions up to 50% with $\mu_0 = m_t$
- Properly described only via NLO
- Negative NLO in p_T tails
  → LO higher than NLO

- The *dynamic scale should depend on hardest jet* p_T ↑
- *Asymptotic freedom →* α_s ↓ *in tails*
- *Dependence on* α_s *@ LO >> @ NLO*
- Would drive positive NLO/LO ratio in this region

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

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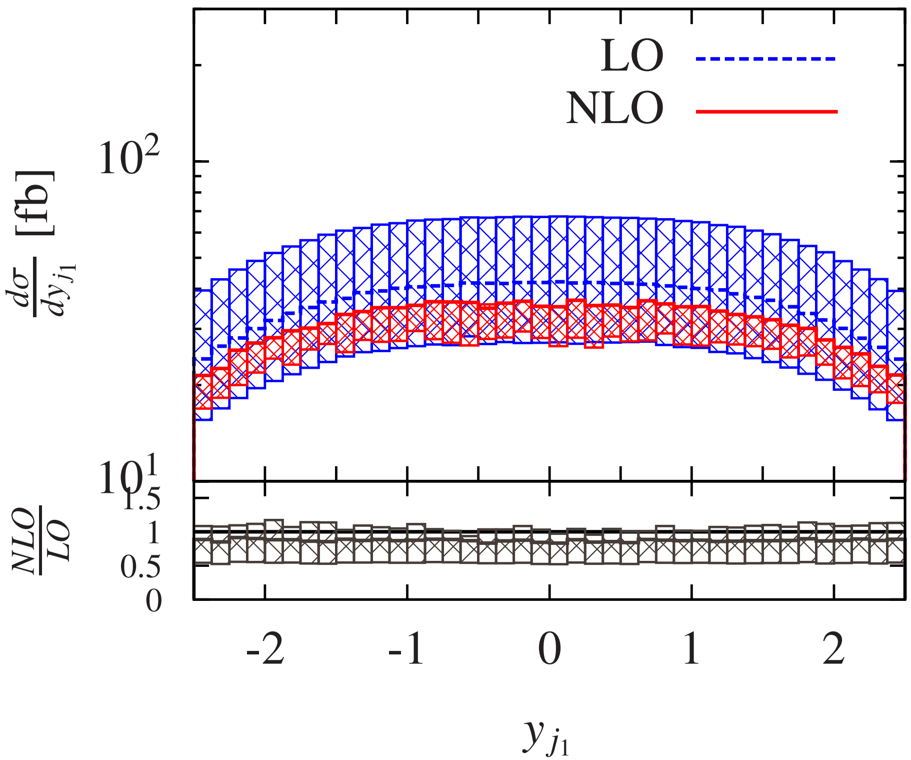
Hardest Light-Jet

- Upper panel: distributions and scale dependence bands
- Lower panel: differential *K*-factor



- Negative, moderate but … quite stable NLO corrections
- Dimensionless nature of y_j
- Receives contributions from various scales → also from these sensitive to threshold for *ttj* production
- For $\mu_0 = m_t$ effects of phase-space regions close to *ttj* threshold dominate

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

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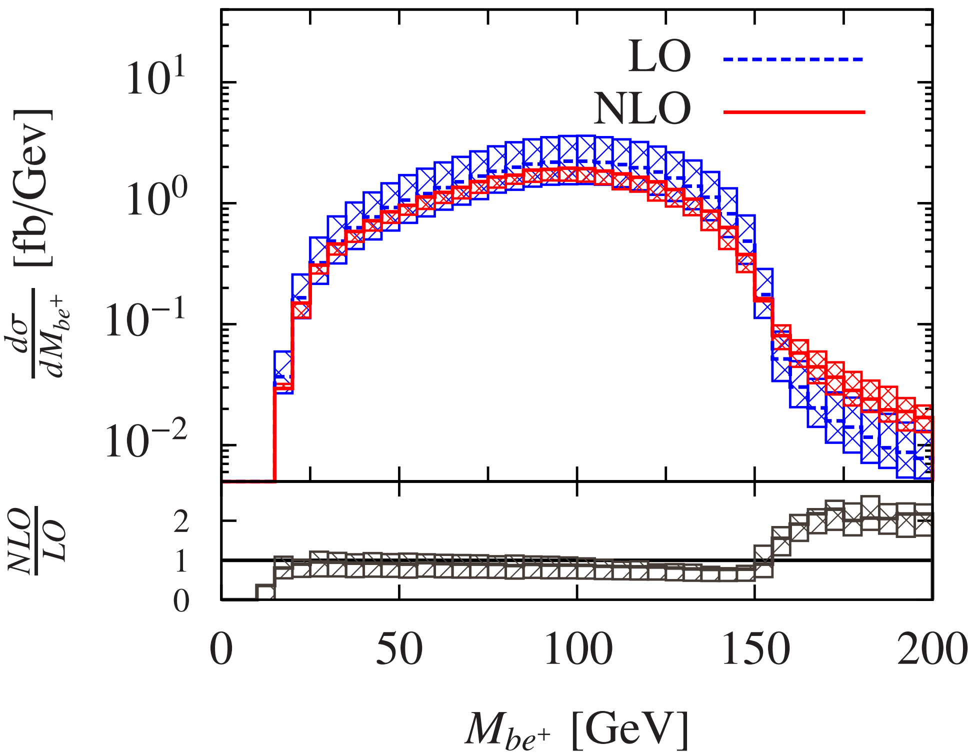
Lepton and b-Jet

- Upper panel: distribution and scale dependence bands
- Lower panel: differential *K*-factor
- be^+ pair that returns the smallest invariant mass



$$M_{be^+} = \sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}$$

- If both top and W decay on-shell
  → end-point given by sharp cut
- Additional radiation & off-shell effects introduce smearing
- Highly sensitive to the details of the description of the process

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

Summary

- Complete description for *ttj* process with “resonant” and “non-resonant” contributions at NLO QCD
- First calculation of 2 → 5 process with HELAC-NLO
- Further studies are needed:
  - ★ Look for judicious choice of a dynamical scale
  - ★ PDF uncertainties
  - ★ Bottom-mass effects
  - ★ Off-shell effects for differential distributions (comparison to NWA)
- Phenomenological applications → m_t extraction
- Shape-based m_t measurement relies on precise modeling of differential distributions
- m_t extraction < 1 GeV → Predictions should go beyond simple approximation of factorizing top production & decays

Outlook

- Alternative method for m_t
- m_t from normalized differential cross section for *ttj*

S. Alioli, et al. '13

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

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}},$$

- $\mathcal{R}$ has been calculated using *ttj* @ NLO + **POWHEG** matched with **PYTHIA**
  → top-quark decays via PS only with spin correlations @ LO

- Theoretical uncertainties & PDF uncertainties should affect m_t extraction < 1 GeV

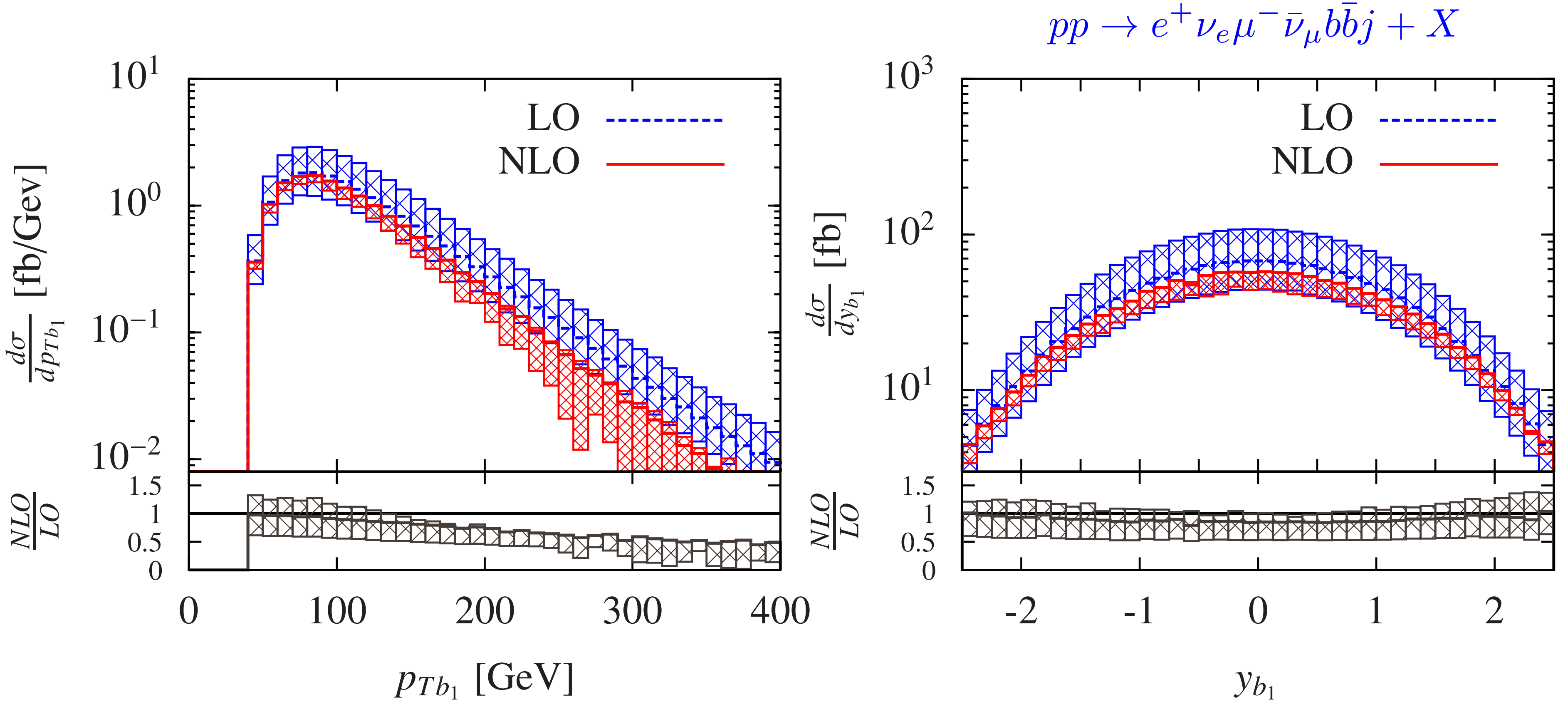
- ***For now: ATLAS @ 7 TeV: m_t = 173.7 ± 2.2 GeV*** *ATLAS, arXiv:1507.01769*

- Worth looking at with complete off-shell effects included…

Backup slides…

b-Jet

- Upper panels: distributions and scale dependence bands
- Lower panels: differential *K*-factors

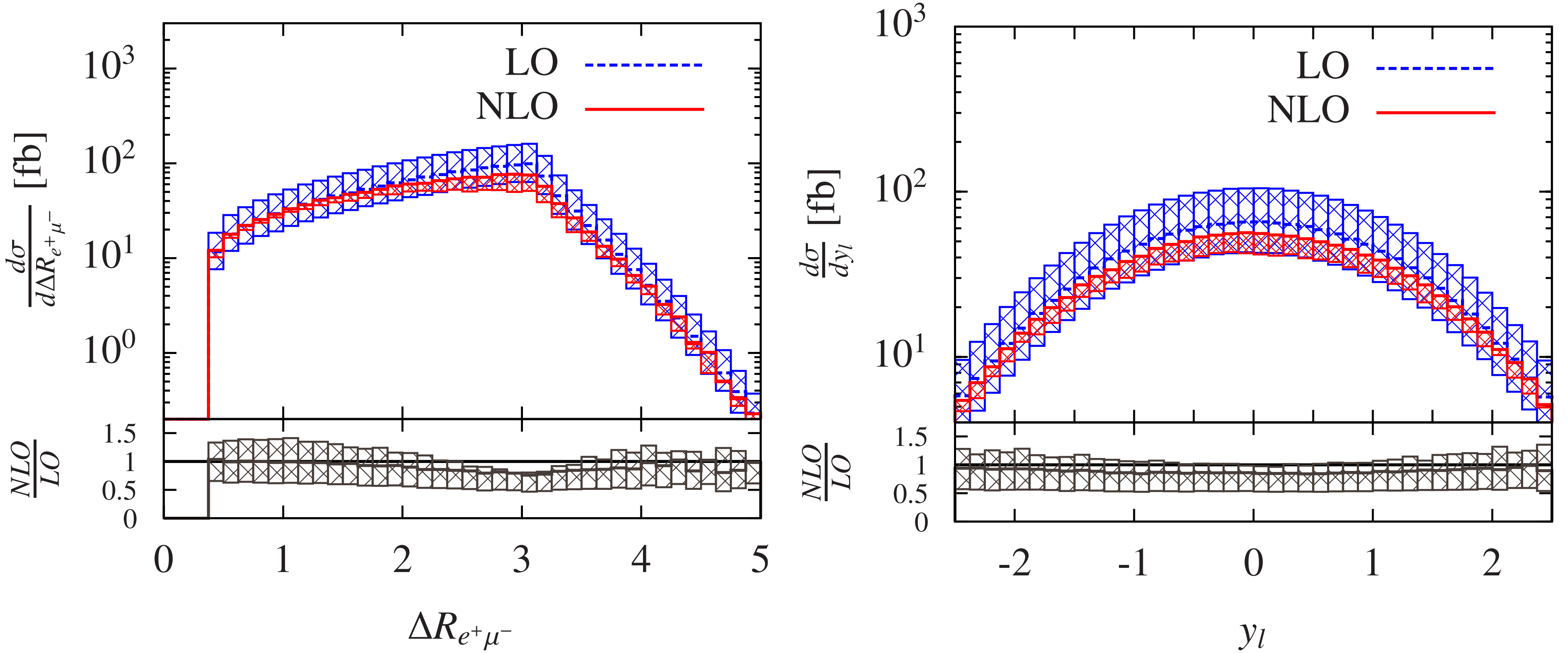


G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

Leptons

- Upper panels: distributions and the scale dependence bands
- Lower panels: differential *K*-factors

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$



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NWA for ttj

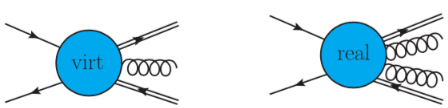
- *Inclusive NLO σ(ttj) in NWA convolution of production σ(tt+nj) & Γ(tt+nj) n ≤ 2*

$$d\sigma_{\rm incl} = \Gamma_{t,\rm tot}^{-2}(d\sigma_{t\bar{t}+0j} + d\sigma_{t\bar{t}+1j} + d\sigma_{t\bar{t}+2j} + \cdots) \otimes (d\Gamma_{t\bar{t}+0j} + d\Gamma_{t\bar{t}+1j} + d\Gamma_{t\bar{t}+2j} + \cdots).$$

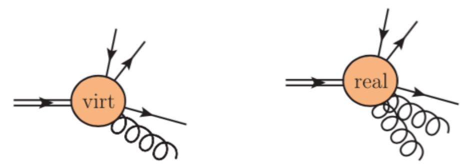
K. Melnikov, M. Schulze '12

- Expanded version with terms up to α_s^4 only

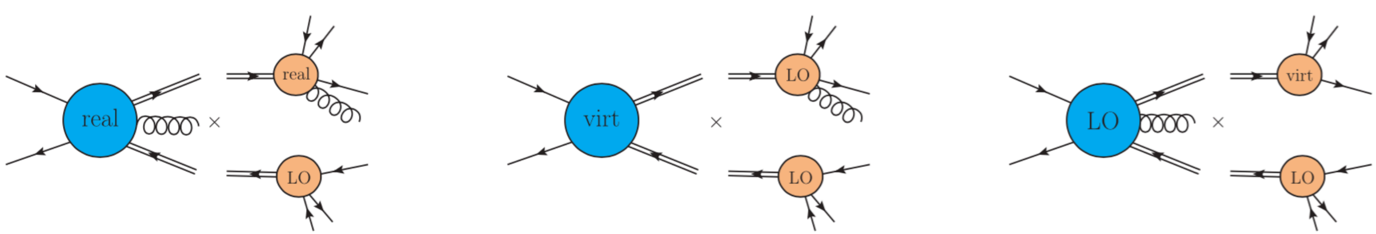
$$d\sigma^{\rm NLO}_{t\bar{t}+1j} = \Gamma_{t,\rm tot}^{-2}\Big(d\sigma^{\rm LO}_{t\bar{t}+1j}d\Gamma^{\rm LO}_{t\bar{t}} + d\sigma^{\rm LO}_{t\bar{t}}d\Gamma^{\rm LO}_{t\bar{t}+1j} + \overbrace{(d\sigma^{\rm virt}_{t\bar{t}+1j} + d\sigma^{\rm real}_{t\bar{t}+2j})d\Gamma^{\rm LO}_{t\bar{t}}}^{\rm (a)}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



(a) jet emission in production

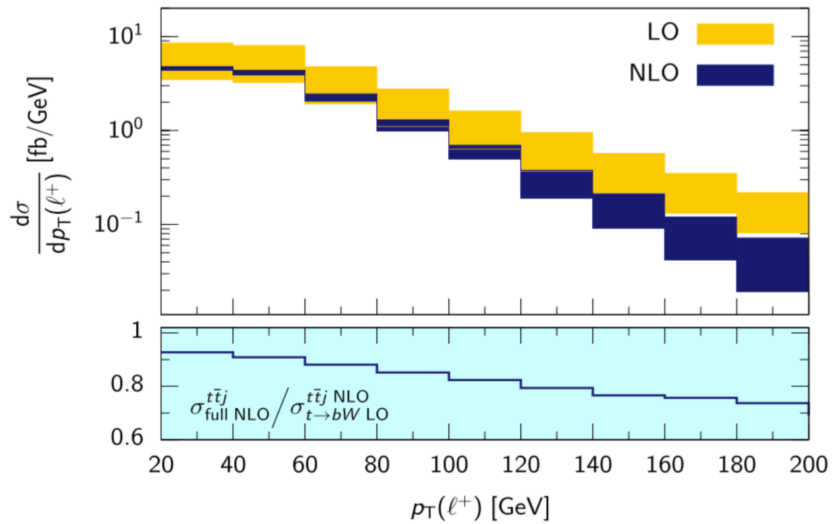


(b) jet emission in decay



(c) mixed contribution

NWA for ttj



LHC @ 7 TeV with inclusive cuts

$$\sigma_{LO} = 316.9\,(\text{Pr}) + 33.4\,(\text{Dec}) = 350.3\ \text{fb},$$
$$\sigma_{NLO} = 323\,(\text{Pr}) + 40.5\,(\text{Dec}) - 75.5\,(\text{Mix}) = 288\ \text{fb}.$$

14% **26%**

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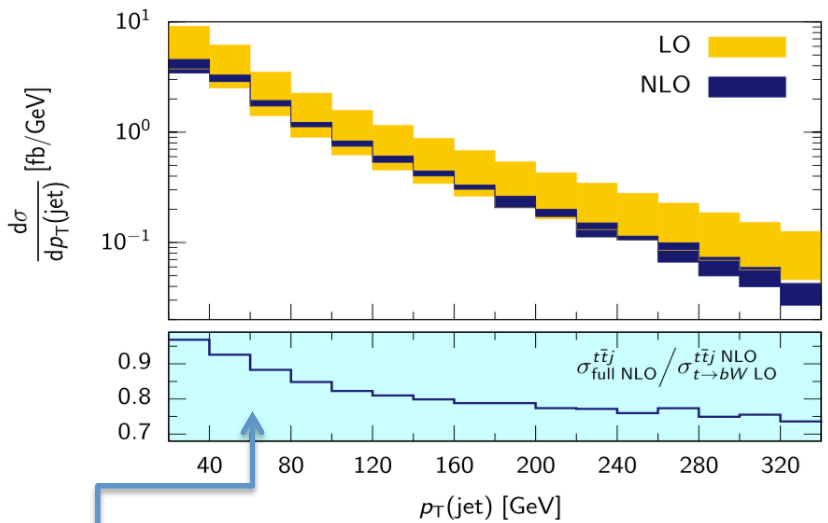

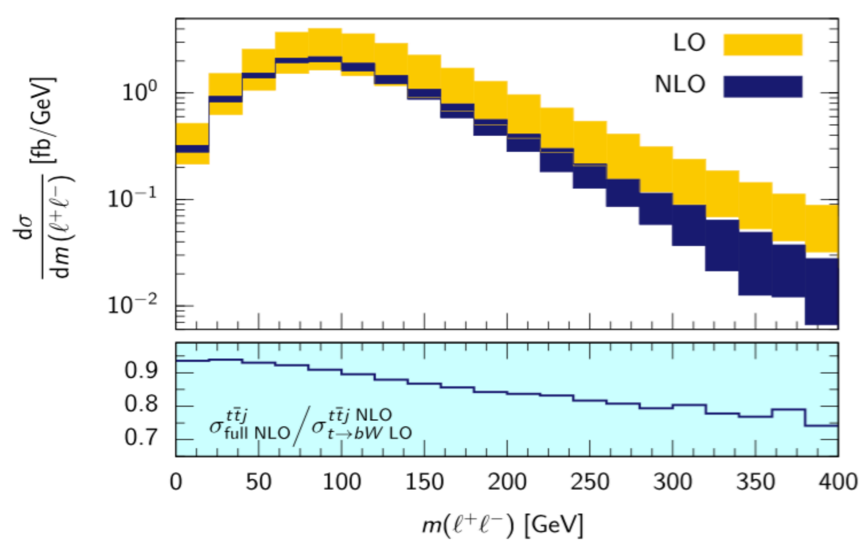

Full NWA versus NWA with LO decays