Deutsche Forschungsgemeinschaft

$t\bar{t}j$ with NLO QCD Off-Shell Effects @ LHC

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Plan

- Motivation for *ttj* production at the LHC
- Motivation for top-quark off-shell effects based on *tt* production
- Importance of NLO QCD corrections to top-quark decays
- Theoretical predictions for *ttj* – Status
- 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)

Top Anti-Top + Jet

ttj Process

- @ LHC tops are produced with large energies & high transverse momenta
- Increase probability for tops to radiate gluons
- How big is the contribution of *ttj* in the inclusive *tt* sample ?

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

σ(tt) = 807 pb

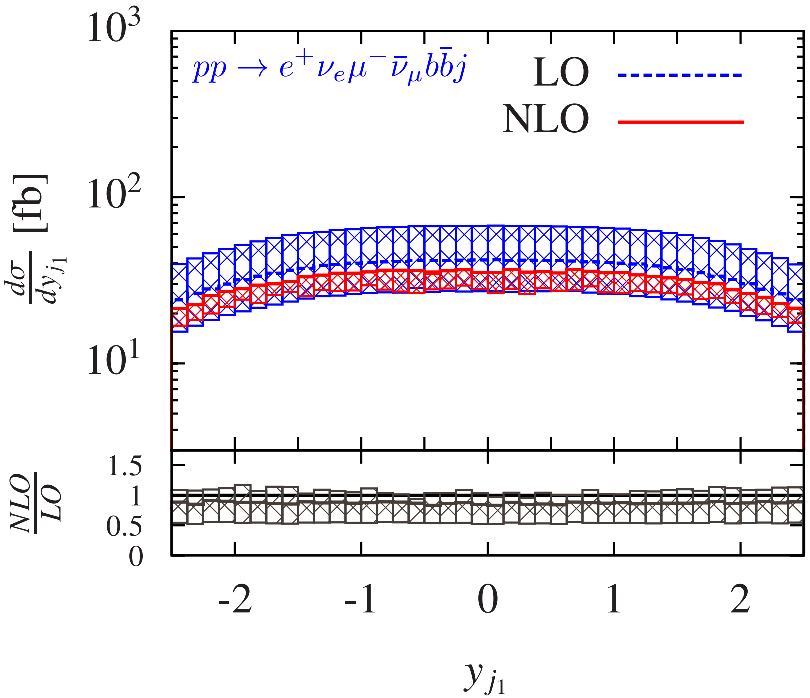
TOP++, Czakon, Mitov '14

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

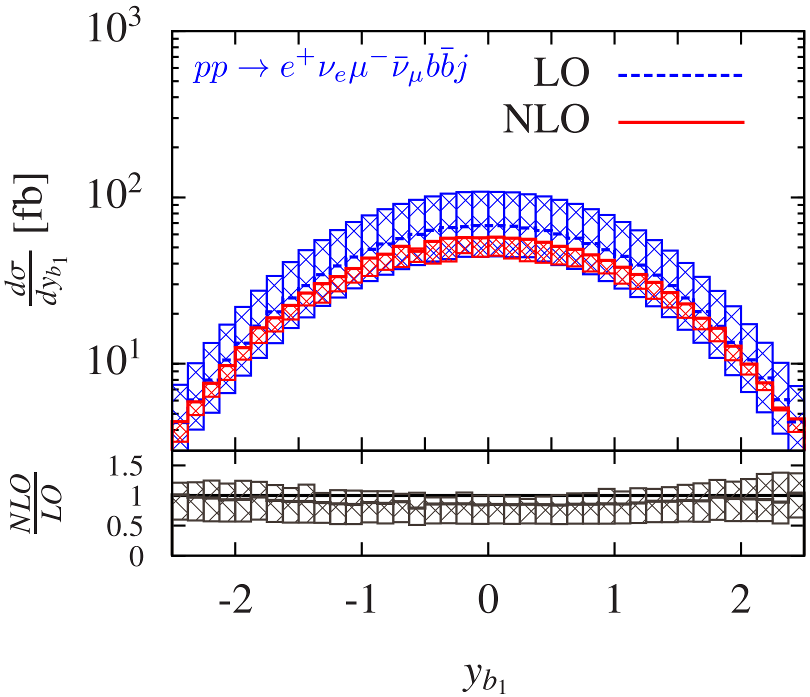
HELAC-NLO, G. Bevilacqua et al., '13

ttj Process

- Background for 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



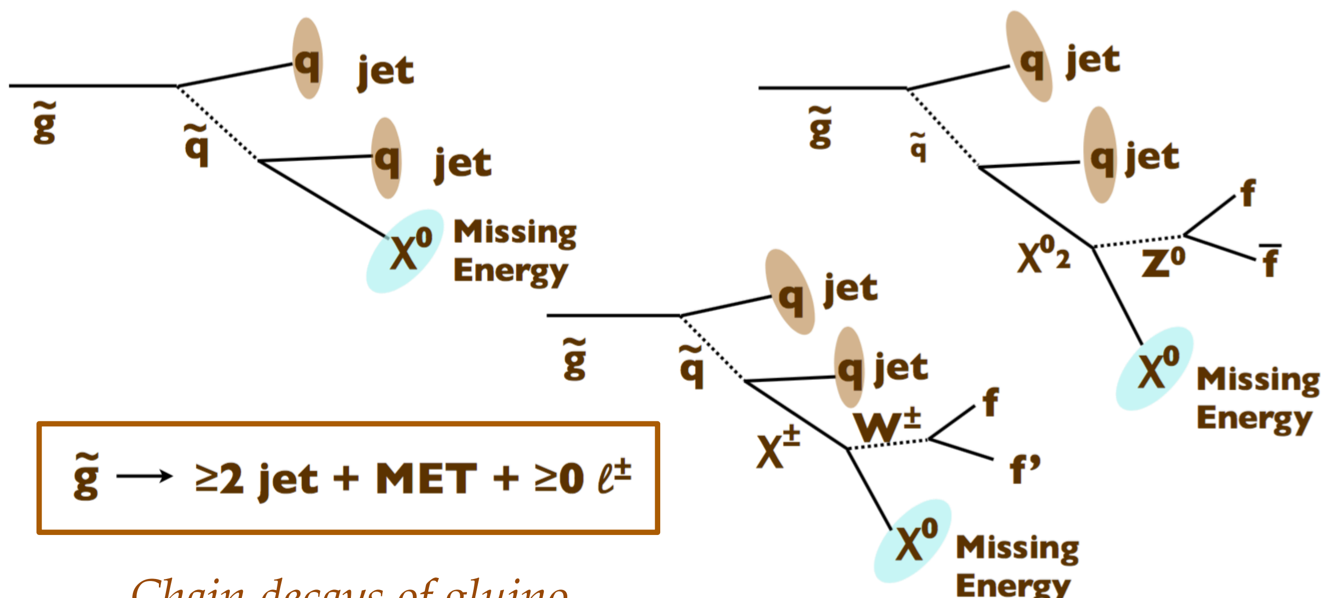
forward/backward light-jets



b-jets from tops are central

ttj Process

- Background to supersymmetric particle production
- Top decays into W and b-quark → SM : $t \rightarrow Wb \approx 100\%$
- *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)



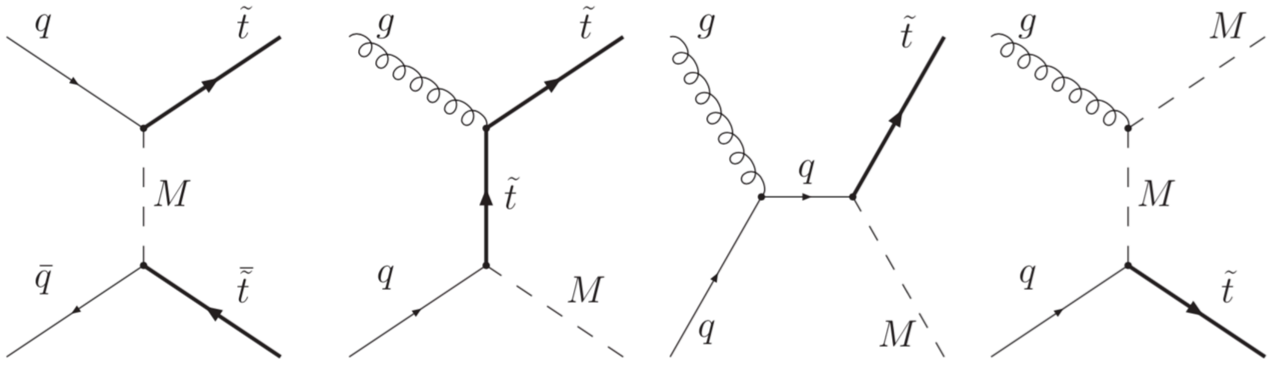
Chain decays of gluino

M. L. Mangano '09

ttj Process

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

- Top flavor violating resonances, singly produced in association with top @ LHC



(a) $t\bar{t}$ production (b) t-channel (c) s-channel (d) u-channel

(M=ϕ^a only)

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

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

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

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

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

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

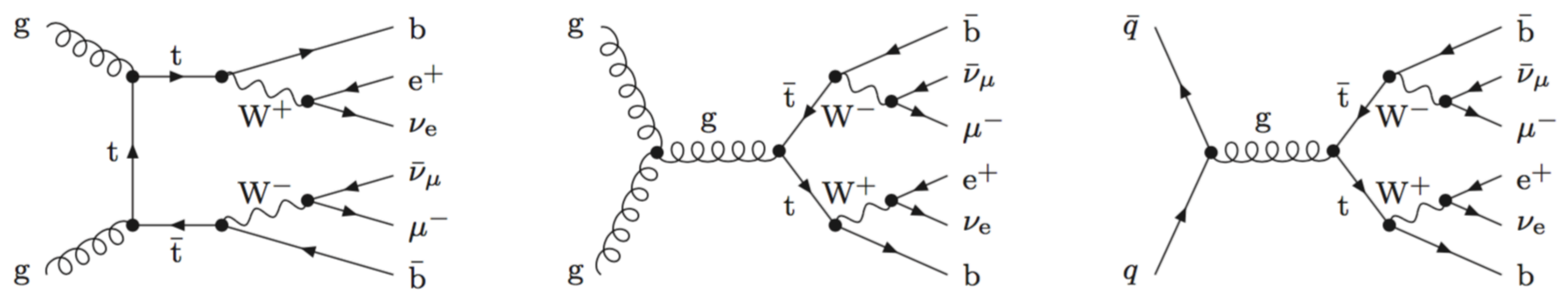
$$\mathcal{L}_\phi = \bar{t}^c T^a_r (g_L P_L + g_R P_R) u \phi^a + \text{H.c.},$$

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

Off-Shell Effects

NWA for *tt*

- Tops are restricted to on-shell states
- Approximation is controlled by the ratio: $\Gamma_t/m_t \approx 10^{-2}$
- Includes double-resonant Feynman diagrams



- Should be accurate for sufficiently inclusive observables
- Indeed → *top-quark off-shell effects for* σ *at few % level*

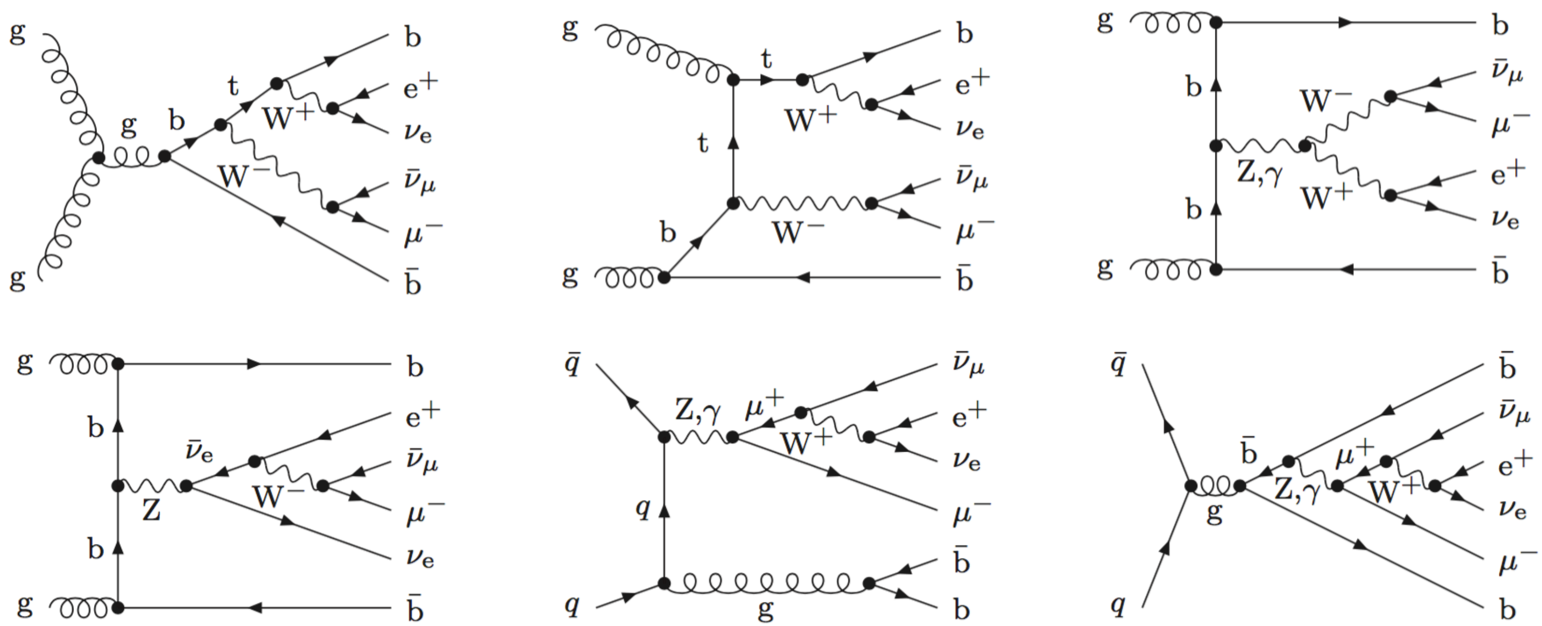
★ *pp → tt* — *A. Denner et al. '11, G. Bevilacqua et al. '11, A. Denner et al. '12 R. Frederix '14, F. Cascioli et al. '14, G. Heinrich et al '14*

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

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

Off-Shell Effects for *tt*

- Single-resonant and non-resonant contributions
- Interferences between double-, single-, and non-resonant diagrams



- Diagrams in NWA versus Full calculation with on-shell and off-shell W for the *gg initial state:*
  - ★ *LO: 3 → 31 → 79*
  - ★ *Real Emission: 28 → 208 → 508*

Off-Shell Effects for *tt*

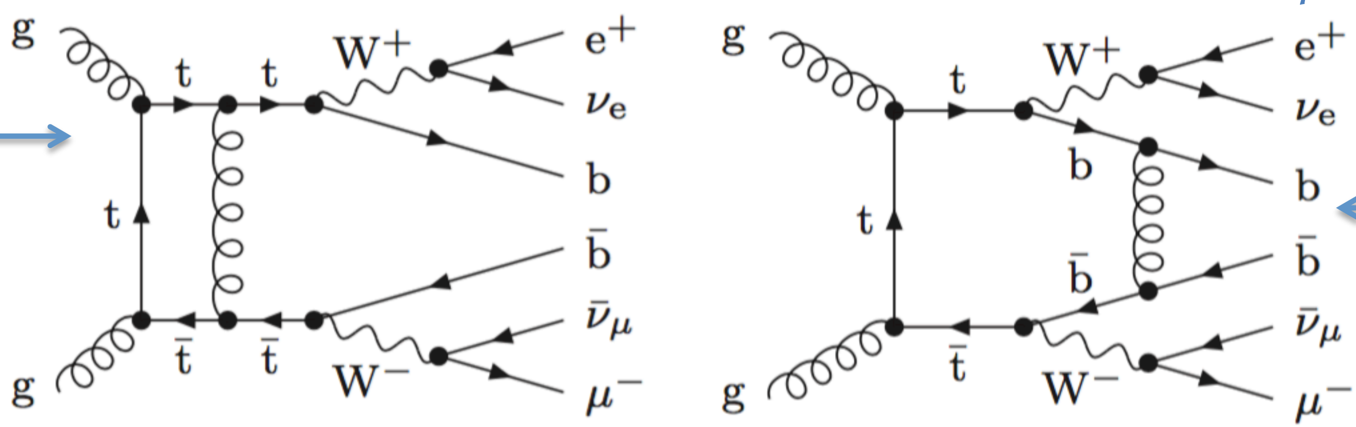
- *gg* channel comprises *3554 one-loop diagrams* → according to **QGRAF**

P. Nogueira '93

- The most complicated ones: *213 pentagons & 20 hexagons*
- Tensor integrals up to rank five

NWA for tt – up to boxes only !

Full calculations for tt – up to hexagons !



Intermediate Top Resonances

- Putting simply $\Gamma_t \neq 0$ violates gauge invariance
- Gauge-invariant treatment → complex-mass scheme (unitarity is violated)
- 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

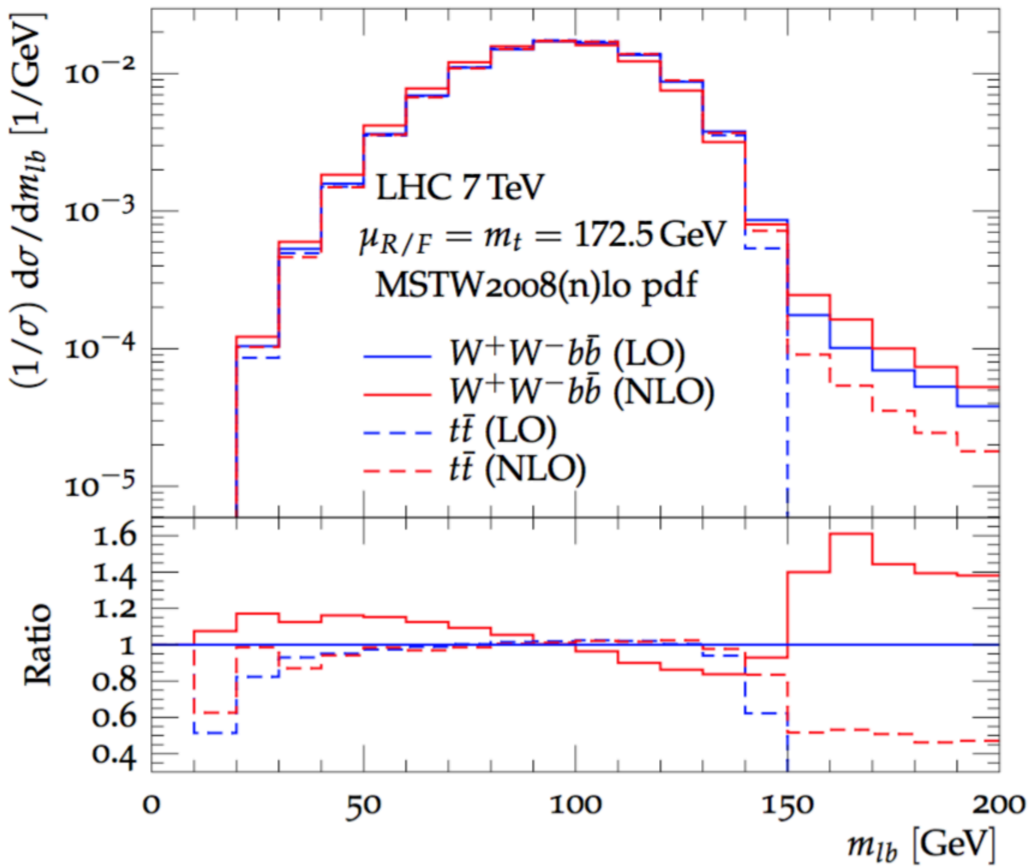
- All matrix elements evaluated using complex masses
- μ_t^2 identified with the position of pole of top-quark propagator
- Top-mass counter-term $\delta\mu_t$ related to top-quark self-energy at: $p_t^2 = \mu_t^2$

- *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

Off-Shell Effects for *tt*

- Off-shell effects could be much larger for differential distributions
- m_t extraction based on M_{lb} observable → sharp upper bound in NWA @ LO
- *NWA* (with LO decays) versus *full calculations* (with on-shell W)



$$M_{\ell b} = \sqrt{m_t^2 - m_W^2} \approx 152.6 \text{ GeV}$$

- Various normalized LO & NLO predictions
- Shape changes of the order of 20%
- Significant impact on m_t

G. Heinrich, A. Maier, R. Nisius, J. Schlenk, J. Winter '14

Off-Shell Effects for *tt*

- *NWA* (with LO decays) versus *full calculations* (with on-shell W)

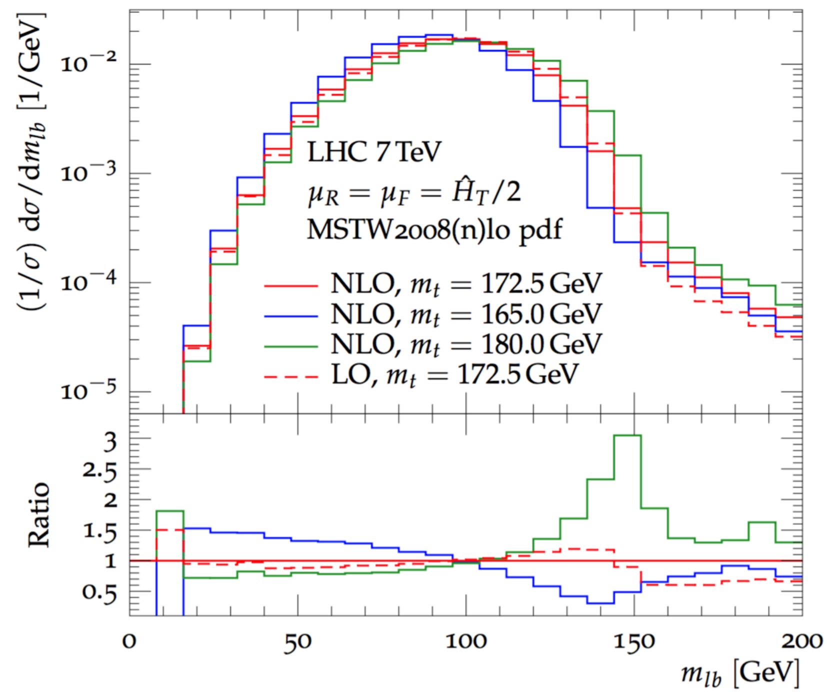
- Method to identify pair of charged lepton and b-jet from the same top

- Combination that minimizes M_{lb}

- Templates method: distributions for different value of m_t^{in}

- Measurements of m_t affected by changes in the bulk

- m_t^{out} & δm_t^{out} ← fit to (pseudo-) data



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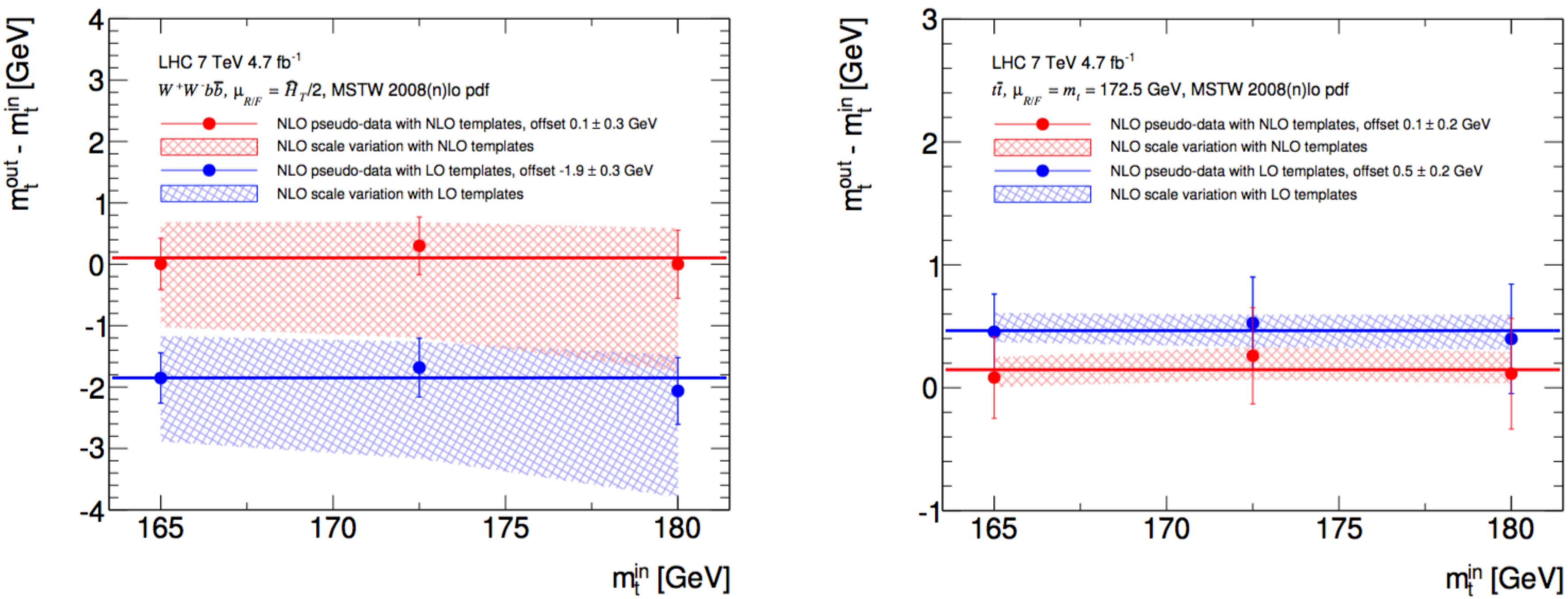


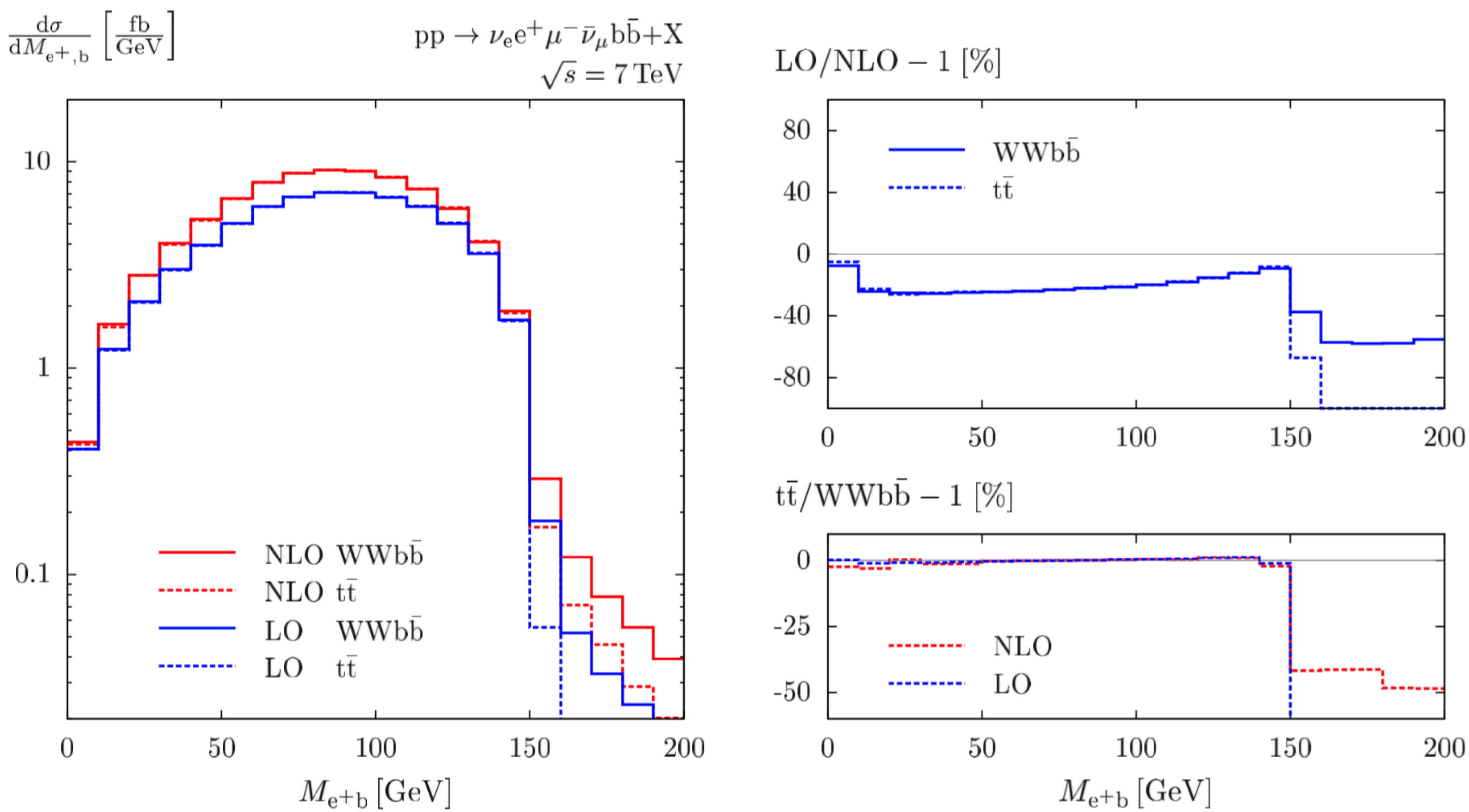
- Size of mass shifts: *full approach: 1.9 GeV* & *NWA: 0.5 GeV*
- Uncertainty on m_t from standard NLO scale variations:
  - ★ *Full approach: 1 GeV* & *NWA: 0.2 GeV*
- NWA not realistic for M_{lb} observable (?) → underestimated error on m_t (?)

G. Heinrich, A. Maier, R. Nisius, J. Schlenk, J. Winter '14

Off-Shell Effects for *tt*

- Most probably not ! → decays @ NLO need to be added in NWA
- *Full NWA (tt) versus full calculation (WWbb)* for M_{e+b}

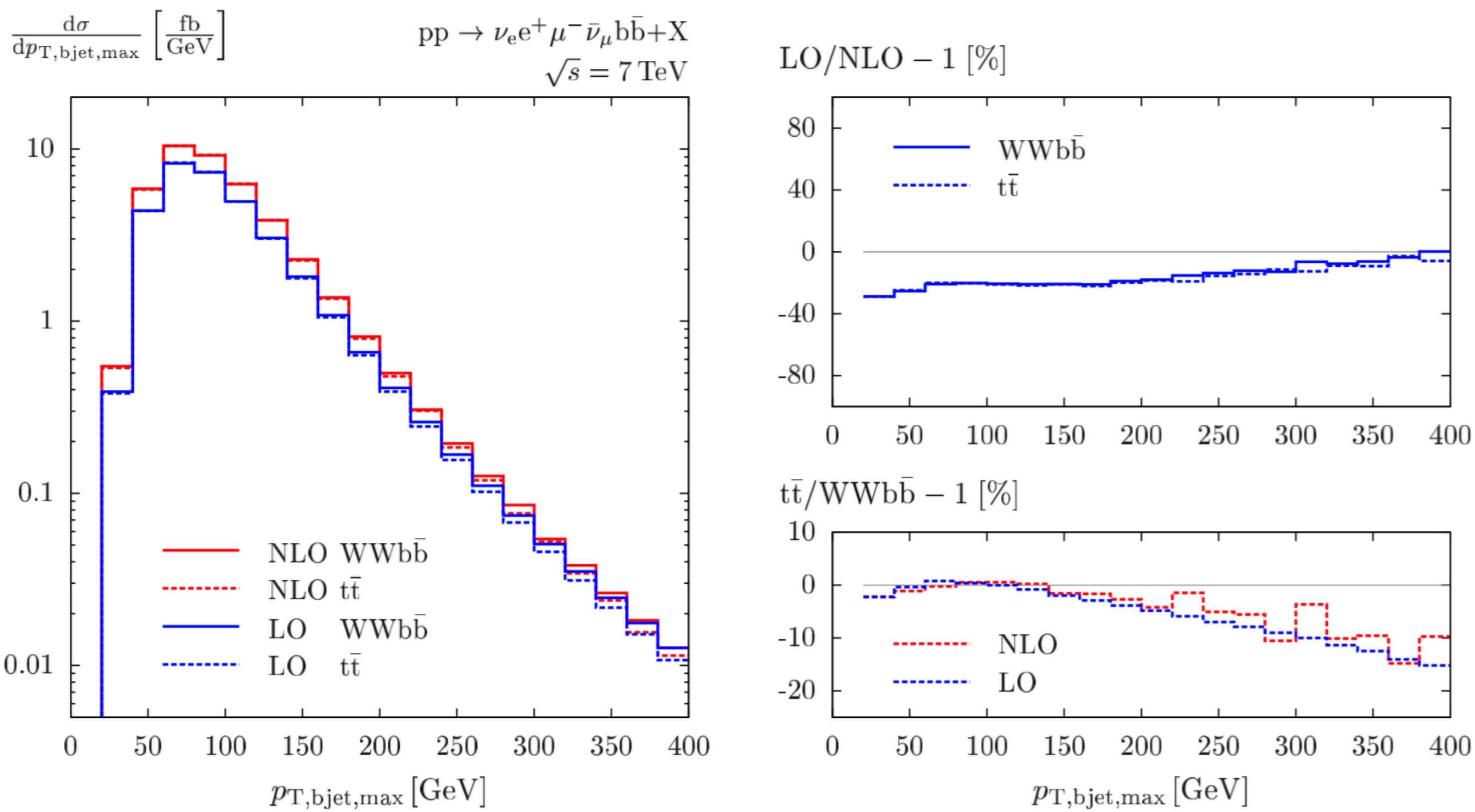
THE SM AND NLO MULTILEG AND SM MC WORKING GROUPS



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

Off-Shell Effects for *tt*

- Off-shell effects could be much larger for differential distributions
- *Full NWA (tt) versus full calculation (WWbb)* for *p_T(b)* *(the hardest b-jet)*



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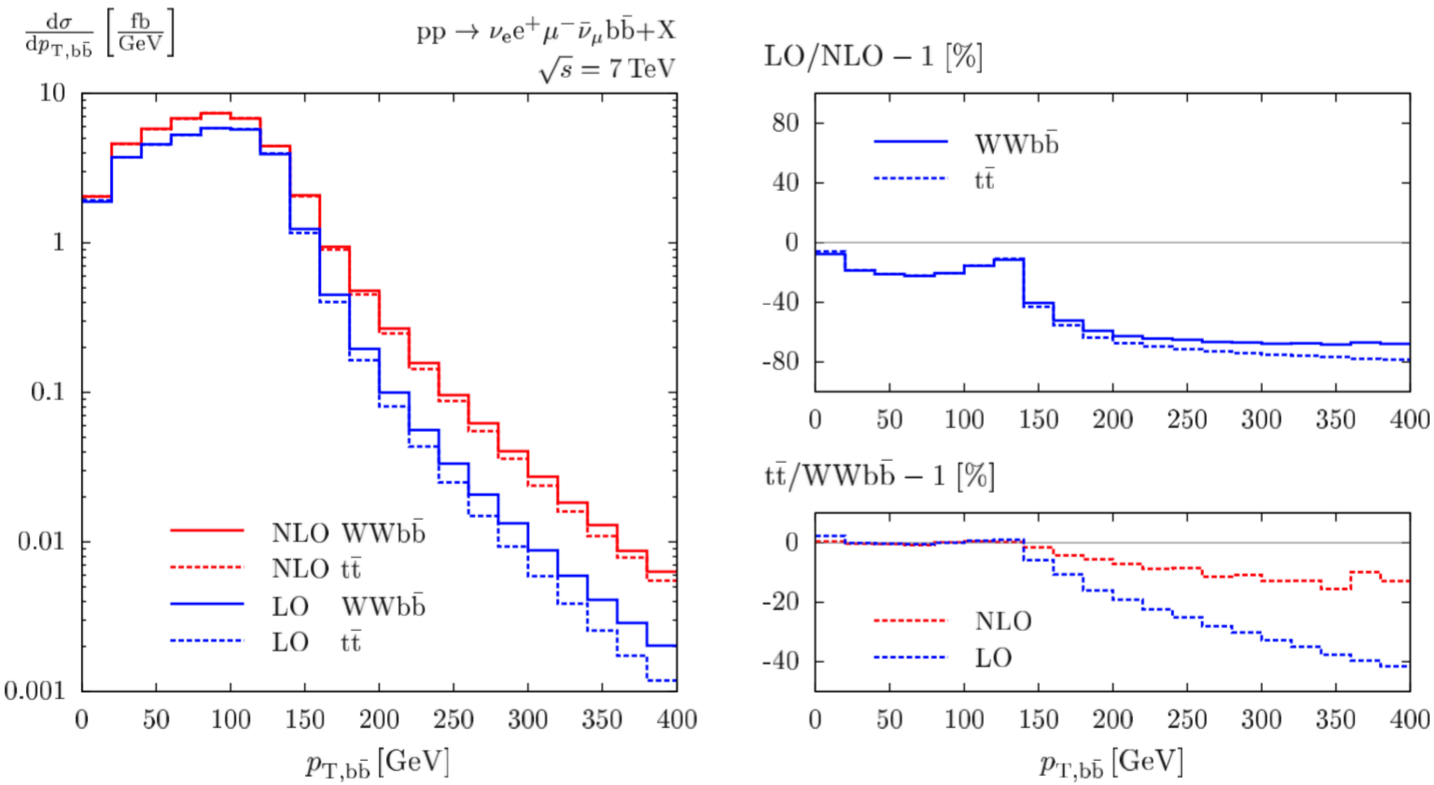

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Prediction For ttj

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

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NWA for *ttj*

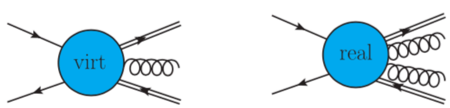
- *Inclusive NLO σ(ttj) in NWA convolution of production σ(tt+nj) & Γ(tt+nj) n ≤ 2*

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

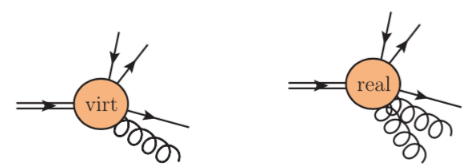
K. Melnikov, M. Schulze '12

- Expanded version with terms up to α_s^4 only

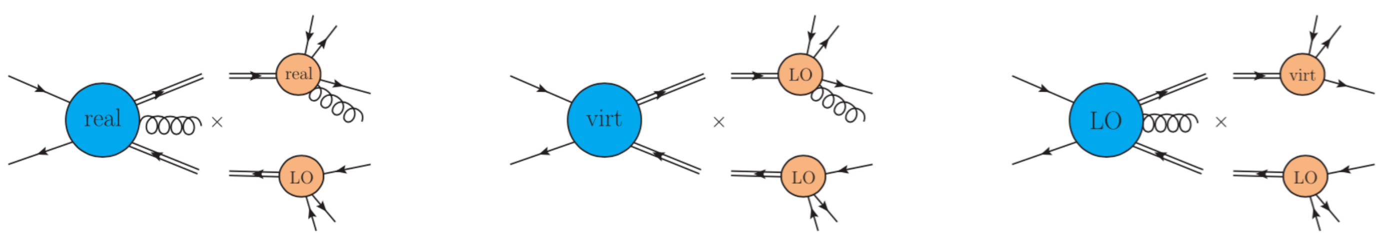
$$d\sigma^{\rm NLO}_{t\bar{t}+1j} = \Gamma_{t,\rm tot}^{-2}\Big(d\sigma^{\rm LO}_{t\bar{t}+1j}d\Gamma^{\rm LO}_{t\bar{t}} + d\sigma^{\rm LO}_{t\bar{t}}d\Gamma^{\rm LO}_{t\bar{t}+1j} + \overbrace{(d\sigma^{\rm virt}_{t\bar{t}+1j} + d\sigma^{\rm real}_{t\bar{t}+2j})d\Gamma^{\rm LO}_{t\bar{t}}}^{\rm (a)}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



(a) jet emission in production

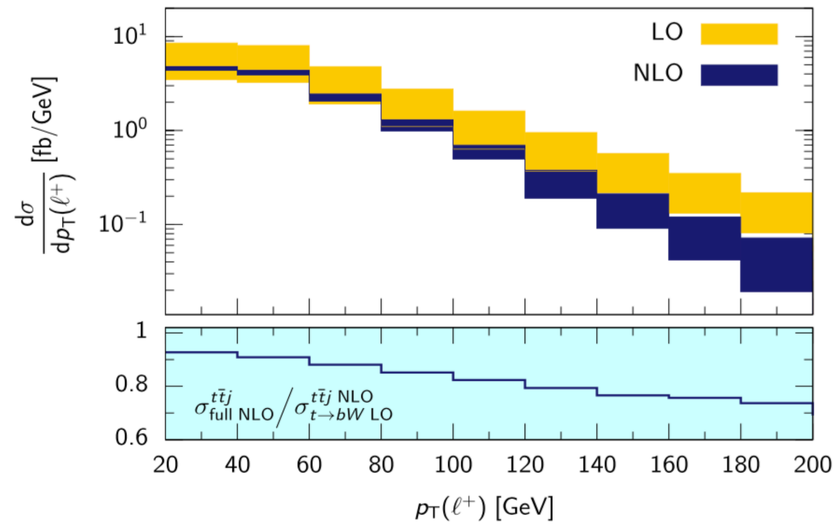


(b) jet emission in decay



(c) mixed contribution

NWA for *ttj*



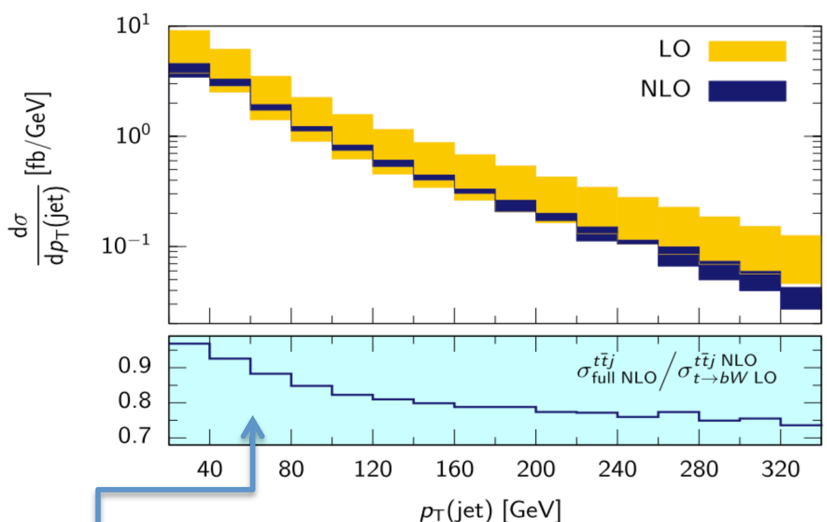
LHC @ 7 TeV with inclusive cuts

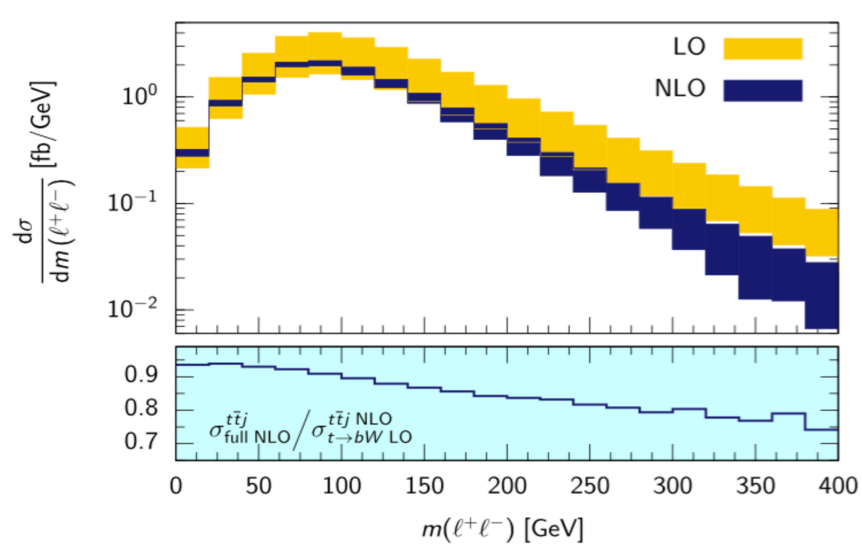
$$\sigma_{\text{LO}} = 316.9\,(\text{Pr}) + 33.4\,(\text{Dec}) = 350.3 \text{ fb},$$

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

14%   26%

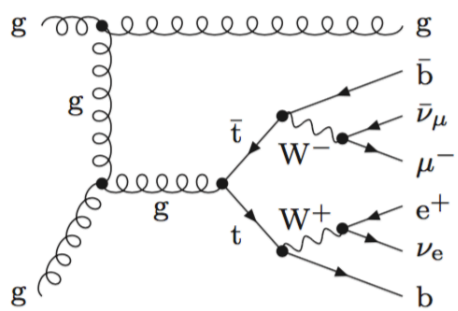
K. Melnikov, M. Schulze '12

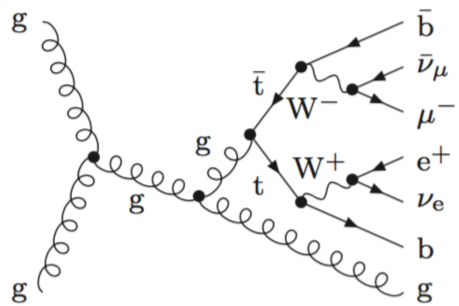


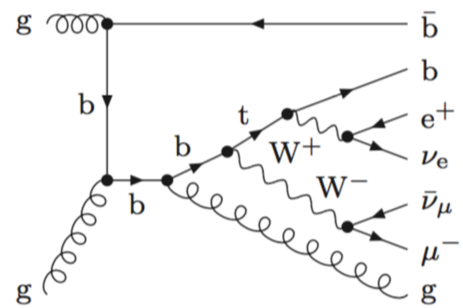


Full NWA versus NWA with LO decays

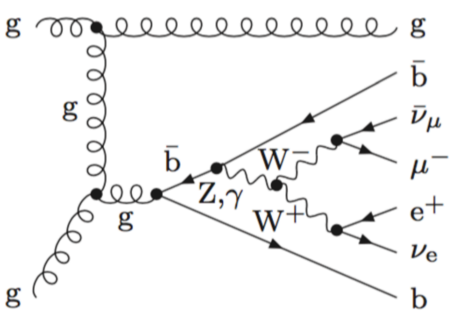
Off-Shell Effects for *ttj*



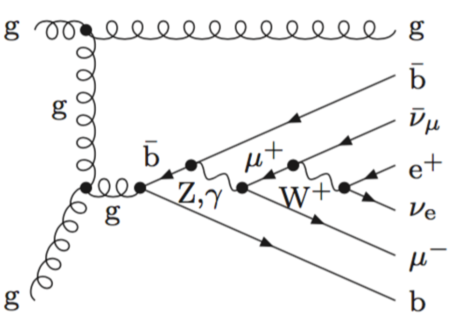




$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$



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



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

Off-Shell Effects for *ttj*

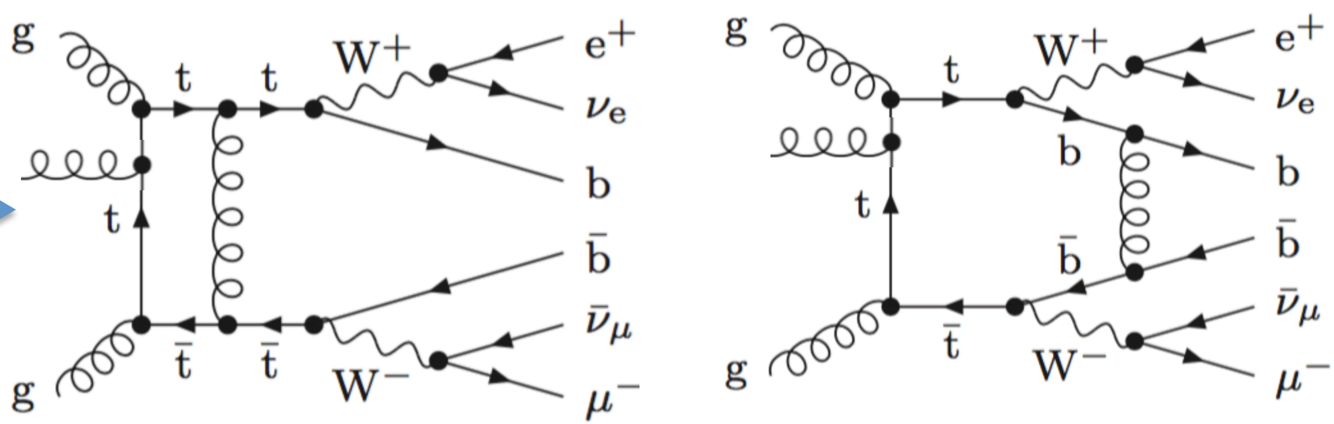
- *gg* channel comprises *39 180 one-loop diagrams* → according to **QGRAF**

P. Nogueira '93

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

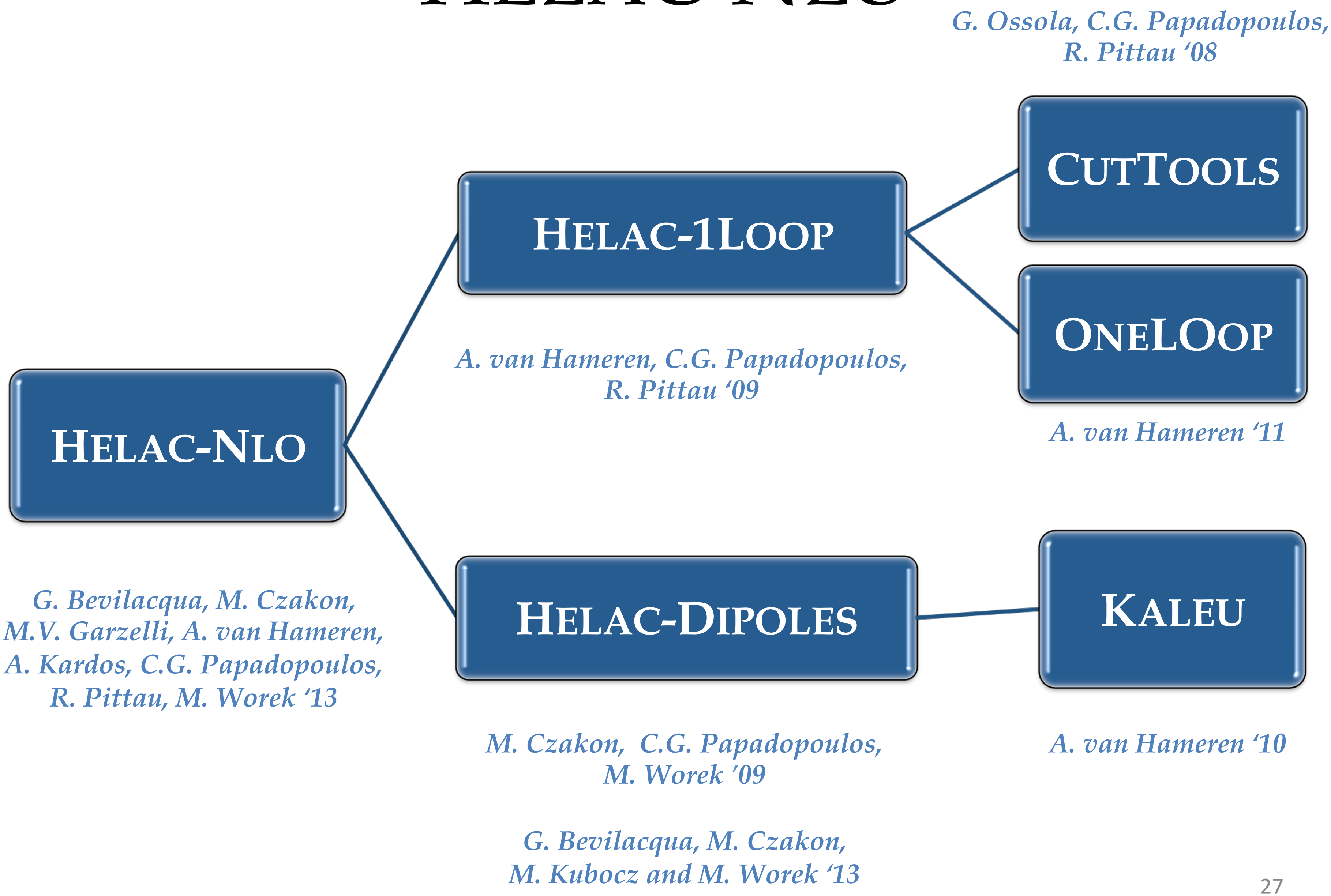
NWA for ttj
– up to pentagons !

Full calculations for ttj
– up to heptagons !



Helac-Nlo

HELAC-NLO


G. Ossola, C.G. Papadopoulos, R. Pittau '08
CUTTOOLS
HELAC-1LOOP
ONELOOP
A. van Hameren, C.G. Papadopoulos, 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
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G. Bevilacqua, M. Czakon, M. Kubocz and M. Worek '13

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

  Reweighting 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/

HELAC-NLO

Jan Mayen
(NORWAY)
Norwegian
Sea
Murmansk
NORWAY
SWEDEN
FINLAND
ICELAND
Reykjavík
Faroe
Islands
(DEN.)
Tórshavn
Arkhangel'sk
White Sea
Gulf
of
Bothnia
Helsinki
Bergen
Oslo
Stockholm
St. Petersburg
Tallinn
EST.
Rockall
(U.K.)
UNITED
KINGDOM
Glasgow
Belfast
North
Sea
DENMARK
Copenhagen
Baltic
Sea
Riga
LAT.
Yaroslavl'
Nizhniy
Novgorod
Moscow
RUSSIA
LITH.
Vilnius
Minsk
BELARUS
Dublin
IRELAND
Isle of
Man
Manchester
Amsterdam
NETH.
Hamburg
Berlin
POLAND
Warsaw
Łódź
Kraków
Voronezh
Saratov
London
Brussels
Cologne
GERMANY
Prague
CZECH REP.
L'viv
Kiev
UKRAINE
Kharkiv
Celtic
Sea
Guernsey (U.K.)
Jersey (U.K.)
Lille
BELGIUM
LUX.
Luxembourg
SLOVAKIA
Paris
Munich
LIECH.
Vienna
Bratislava
AUSTRIA
Budapest
HUNGARY
MOLDOVA
Chisinau
Donets'k
Volgograd
Rostov
FRANCE
SWITZ.
Bern
Ljubljana
SLOVENIA
ROMANIA
Odesa
Bay of
Biscay
Lyon
Milan
Zagreb
CROATIA
Belgrade
Bucharest
Sea of
Azov
Bordeaux
Turin
SAN
MARINO
MONACO
BOS. & HER.
SER.& MONT.
Sarajevo
Black Sea
Bilbao
ANDORRA
Marseille
Corsica
(FR.)
ITALY
VATICAN
CITY
Sofia
BULGARIA
GEORGIA
Tbilisi
Rome
ALB.
Tirana
Skopje
MACEDONIA
İstanbul
PORTUGAL
Madrid
SPAIN
Barcelona
Valencia
Naples
Bursa
Ankara
ARMENIA
Yerevan
Lisbon
BALEARIC
ISLANDS
(SP.)
Sardinia
(IT.)
GREECE
İzmir
TURKEY
Sevilla
Palermo
Athens
Konya
Adana
Sicily
(IT.)
Gibraltar (U.K.)
Algiers
Tunis
MALTA
Valletta
Aleppo
Mosul
Kirkuk
Ceuta (SP.)
Oran
Melilla
(SP.)
TUNISIA
Nicosia
SYRIA
CYPRUS
Crete
LEB.
Mediterranean Sea

HELAC-NLO

Top & bottom quark physics:

- $pp \to t\bar{t}b\bar{b} + X$ *G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09*
  M. Worek '12
- $pp \to t\bar{t}jj + X$ *G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek '10 '11*
- $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$ *G. Bevilacqua, M. Czakon, A. van Hameren C. G. Papadopoulos,*
  M. Worek '11
- $pp \to t\bar{t}t\bar{t} + X$ *G. Bevilacqua, M. Worek '12*
- $pp \to b\bar{b}b\bar{b} + X$ *G. Bevilacqua, M. Czakon, M. Krämer, M. Kubocz and M. Worek '13*
- $pp \to t\bar{t}j + \mathrm{PS}$ *M. Czakon, H. B. Hartanto, M. Kraus, M. Worek '15*
- $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$ *G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16*

Results

Off-Shell Effects for *ttj*

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

- Different lepton generations → to avoid virtual photon singularities $\gamma \to \ell\ell$
- Effects at the level of 0.5% → checked *@ LO*
- *gg* initial state @ LO: *508 different leptons → 1240 same leptons*
- SM Parameters in G_μ scheme:

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

- 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 for Unstable W Bosons

- Finite W width contributions included in matrix elements & in top-quark width (input parameter)

- *Top width for unstable W bosons, neglecting bottom quark mass @ LO*

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

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

- *Top width @ NLO*

M. Jezabek, J. H. Kühn '89
A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini '12

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

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

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 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)

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

Scale Dependence

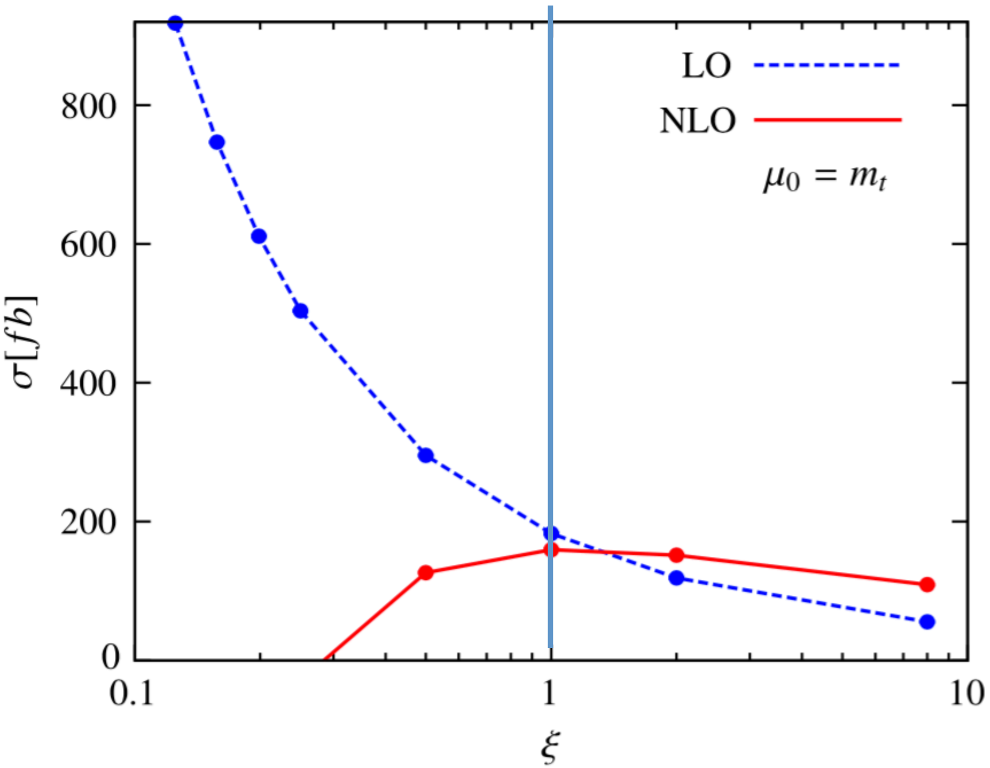
- Total cross section *@ LHC* with *8 TeV* (MSTW2008 PDF)

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

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

- *NLO* corrections: *-13%*
- Theoretical uncertainties:
  - ★ *61% (48%) @ LO*
  - ★ *21% (13%) @ NLO*

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



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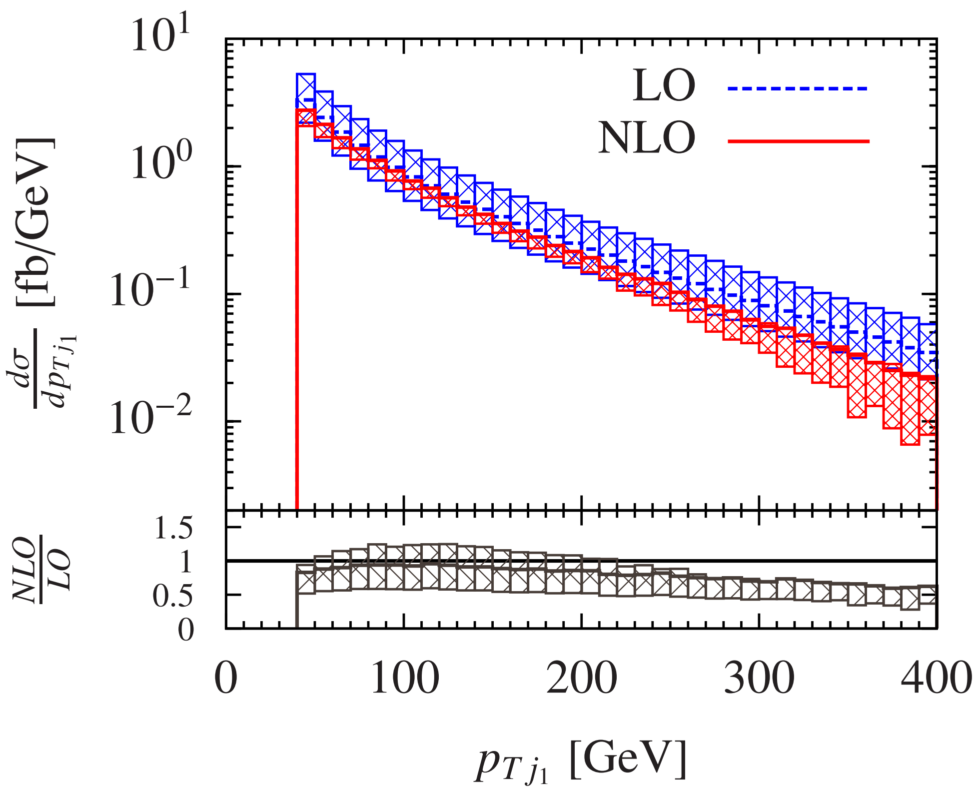
Hardest Light-Jet

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



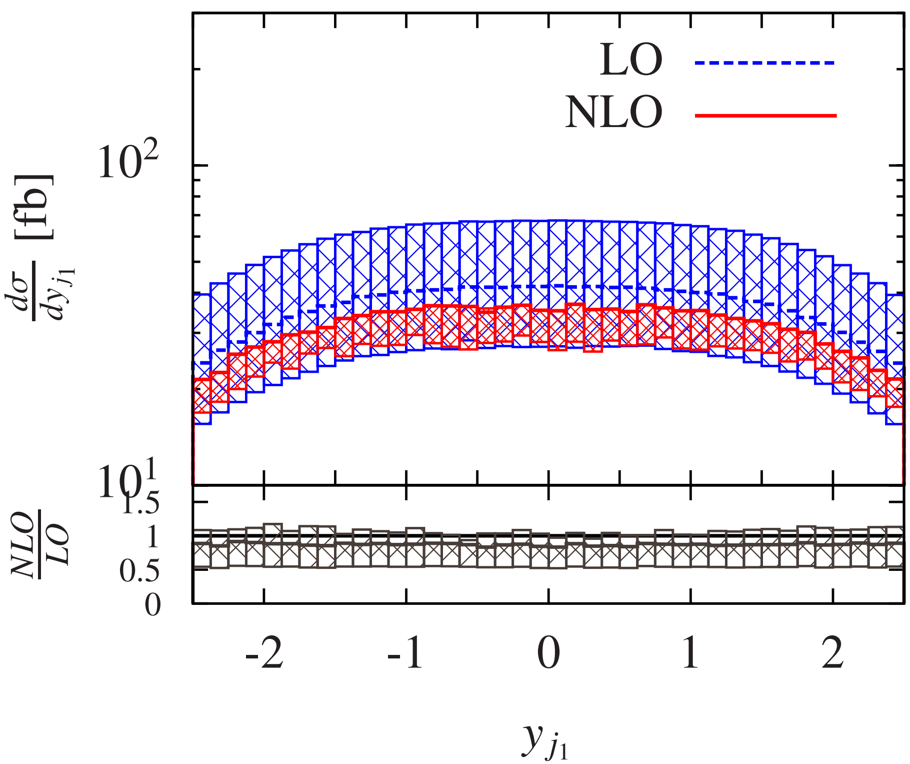
- NLO do not rescale shape of LO
- Distortions up to 50% with $\mu_0 = m_t$
- Properly described only via NLO
- Negative NLO in p_T tails
  → LO higher than NLO

- 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

LO together with some global K-factor is not enough to describe p_{Tj}

Hardest Light-Jet

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

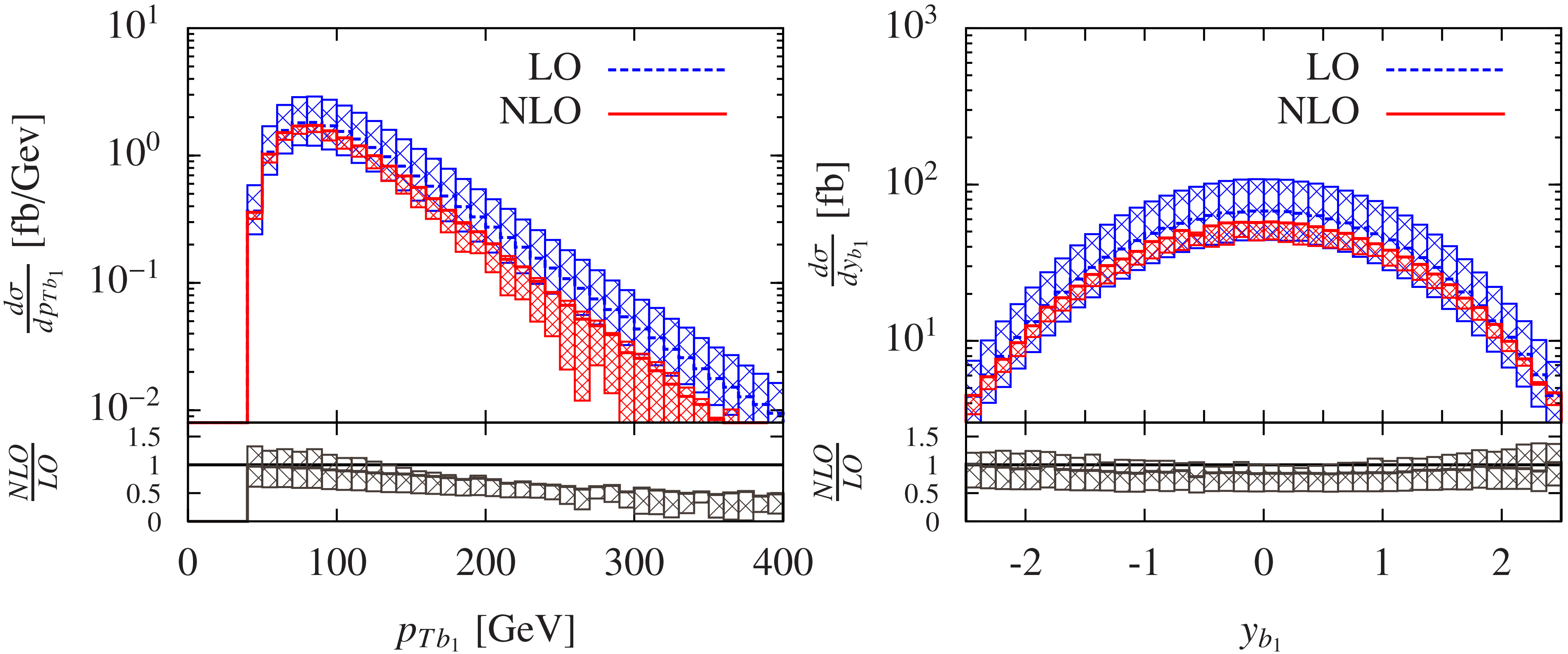


- Negative, moderate but … quite stable NLO corrections
- Dimensionless nature of y_j
- Receives contributions from various scales → also from these sensitive to threshold for *ttj* production
- For $\mu_0 = m_t$ effects of phase-space regions close to *ttj* threshold dominate
- Dynamic scale will not alter this behavior

LO together with some global K-factor is good enough to describe y_j

b-Jet

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



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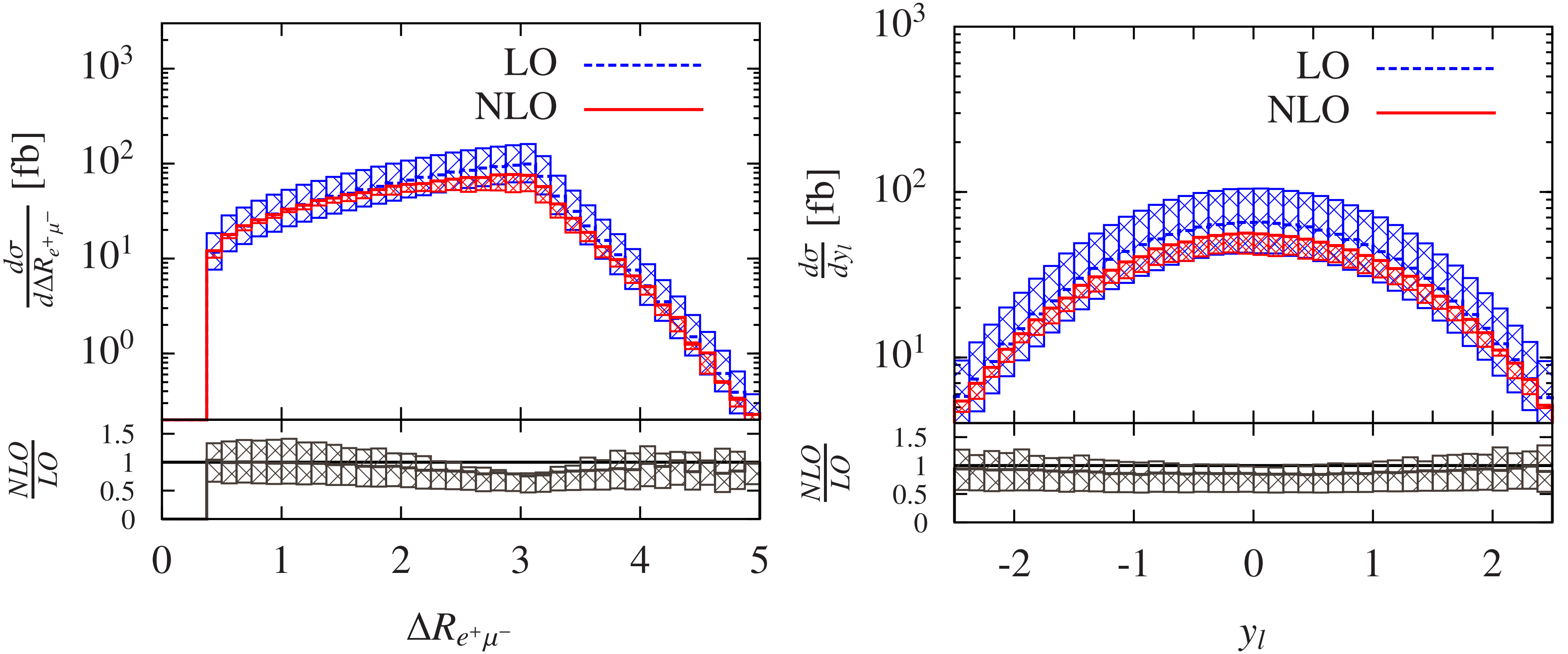
Leptons

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



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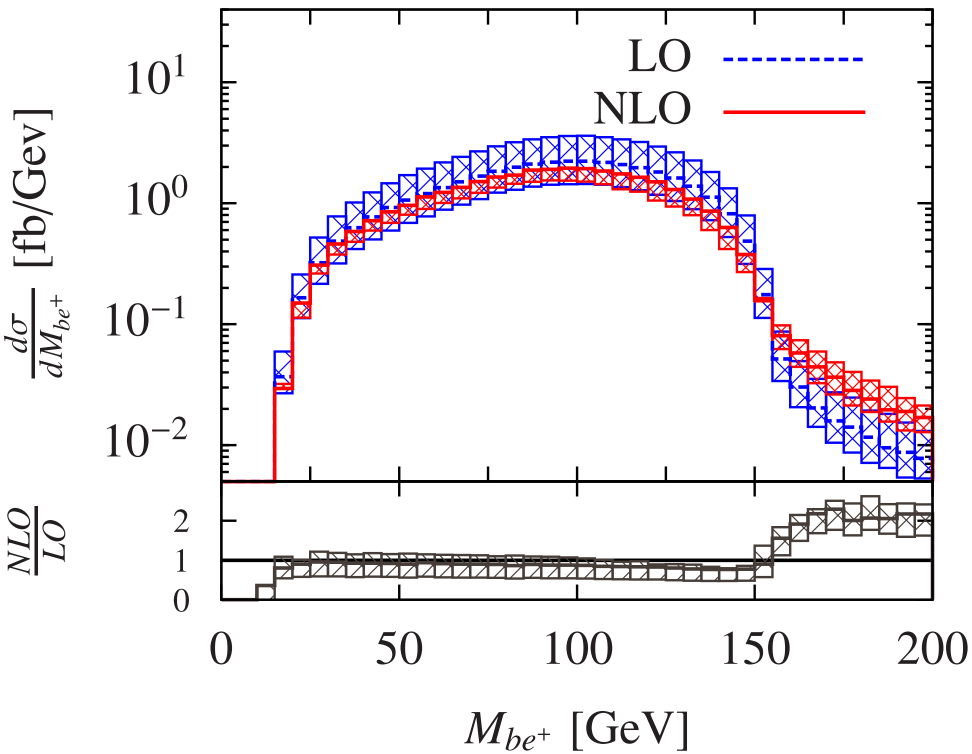
Lepton and b-Jet

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



$$M_{be^+} = \sqrt{m_t^2 - m_W^2} \approx 153.5 \text{ GeV}$$

- 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

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Summary

- Complete description for *ttj* process with "resonant" and "non-resonant" contributions at NLO QCD

- Further studies are needed:

  ★ Look for judicious choice of a dynamical scale
  ★ Study PDF uncertainties
  ★ Study 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
  ★ Corrections to decays important
  ★ Predictions might need to 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 with spin correlations @ LO

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

- ***ATLAS @ 7 TeV: m_t = 173.7 ± 2.2 GeV***

ATLAS, arXiv:1507.01769

- Worth looking at