Top & Co. @ NLO

CERN, May 2012

Keith Ellis, Fermilab

“Top quark processes at NLO in production and decay”, arXiv: 1204.1513 [hep-ph]
“ttbarW production and decay at NLO”, arXiv:1204.5678 [hep-ph]
John Campbell and RKE

Why top now?

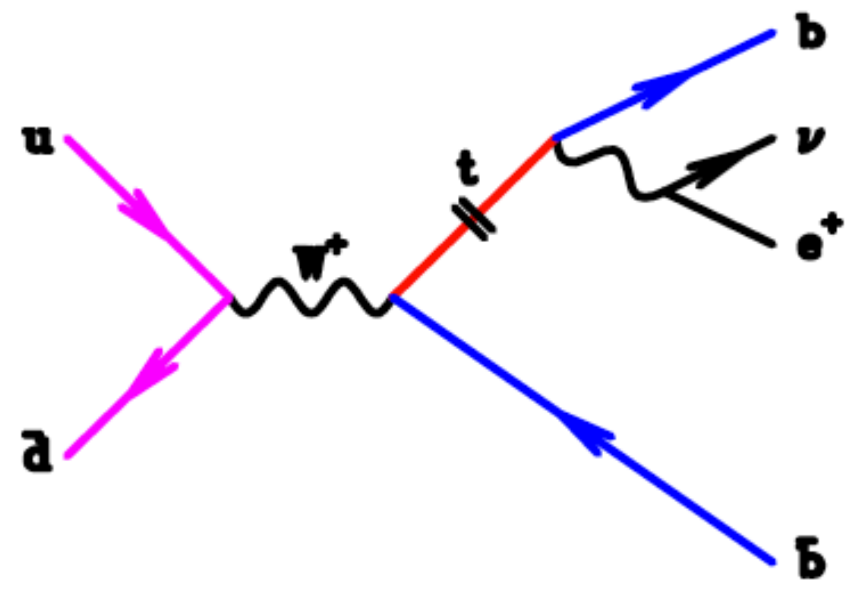
- Top is unstudied
  - Tevatron studies of the top quark have limited statistical precision.
- Top is special
  - $1/m_t$ < $1/\Gamma_t$ < $1/\Lambda$ < m_t/Λ^2

    Production time < Lifetime < Hadronization time < Spin decorrelation time
  - Top quark has large coupling to Higgs, and may play a special role in Electroweak symmetry breaking and other BSM physics
- Top is ubiquitous.
  - Top cross section is large at LHC because of large gluon flux
  - Top-related processes are significant backgrounds for new physics.

(Double) Resonance Approximation

- In leading order (LO) we can treat top quark production exactly including off-resonance contributions and top quark decays.
- This is (currently) not feasible at NLO, NNLO...., so in MCFM we treat top production in the pole approximation.

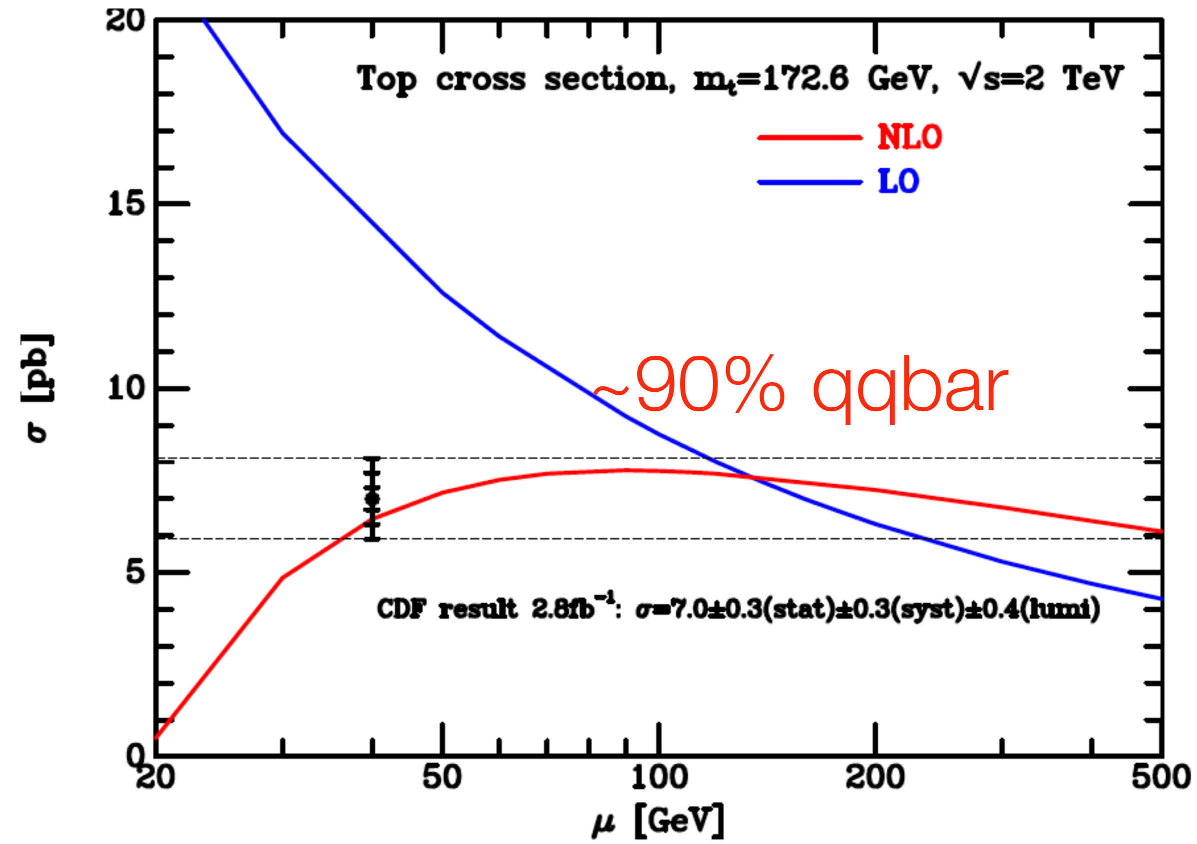
Example for s-channel single top at LO

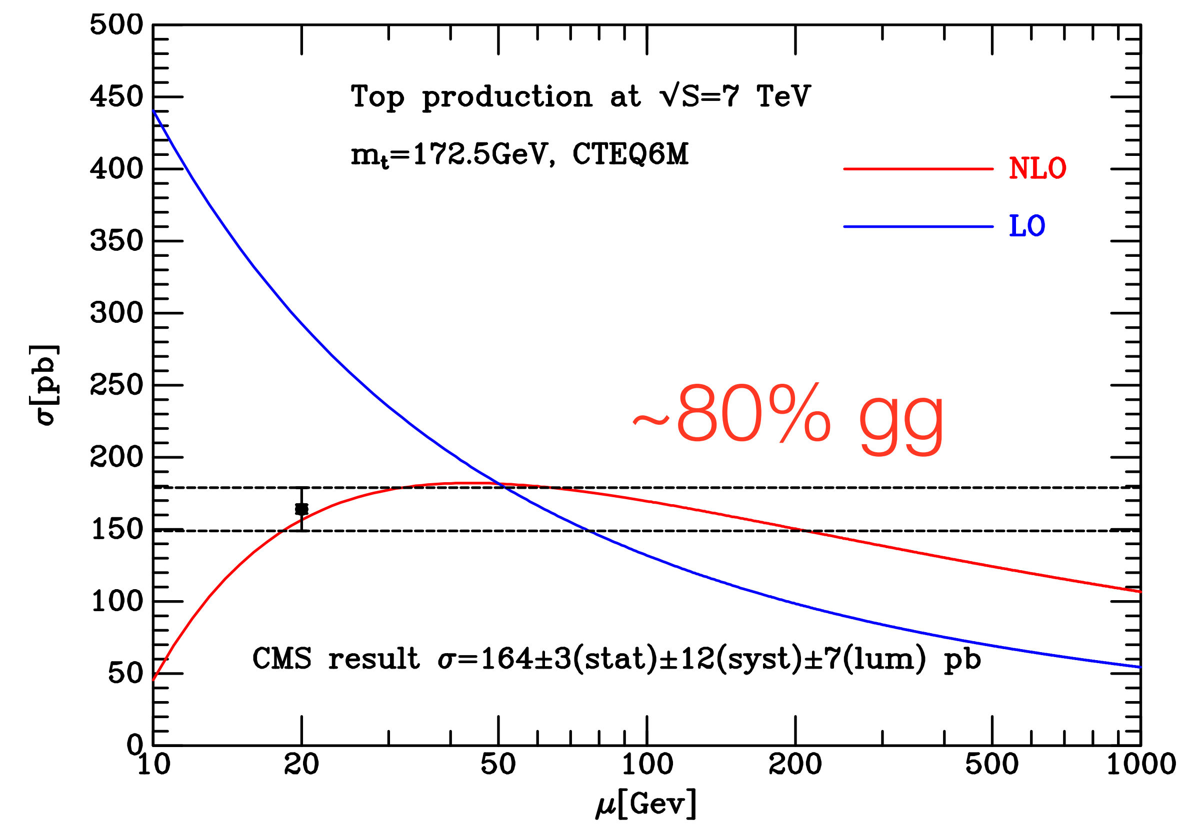


- Top quarks are produced on shell and then decay giving access to the kinematics of the decay products.
- All spin correlations are kept.
- A systematic approximation extensible to NLO, NNLO,..
- Production and decay are separately gauge invariant.

Why NLO?

- Less sensitivity to unphysical input scales, (eg. renormalization and factorization scales) at least formally.
- LO uncertainty becomes larger for multijet production, where Born approximation starts at high power of α_s^n
- NLO first approximation in QCD which gives an idea of suitable choice for μ.
- NLO has more physics, parton merging to give structure in jets, initial state radiation, more species of incoming partons enter at NLO.
- A necessary prerequisite for more sophisticated techniques which match NLO with parton showering.





MCFM

- MCFM is a unified approach to NLO corrections, both to cross sections and differential distributions: http://mcfm.fnal.gov (v6.2, April 2012)
- Publically available code, offers possibilities for recycling, (cf Powheg, diboson pairs, De Florian et al, HRES .....).

  J. M. Campbell, R. K. Ellis, C. Williams (main authors)
  R. Frederix, F. Maltoni, F. Tramontano, S. Willenbrock, G. Zanderighi....

- Standard Model processes for diboson pairs, vector boson+jets, heavy quarks, Higgs...
- Decays of unstable particles are included, maintaining spin correlations.
- Amplitudes (especially the one-loop contributions) calculated *ab initio* or taken from the literature.

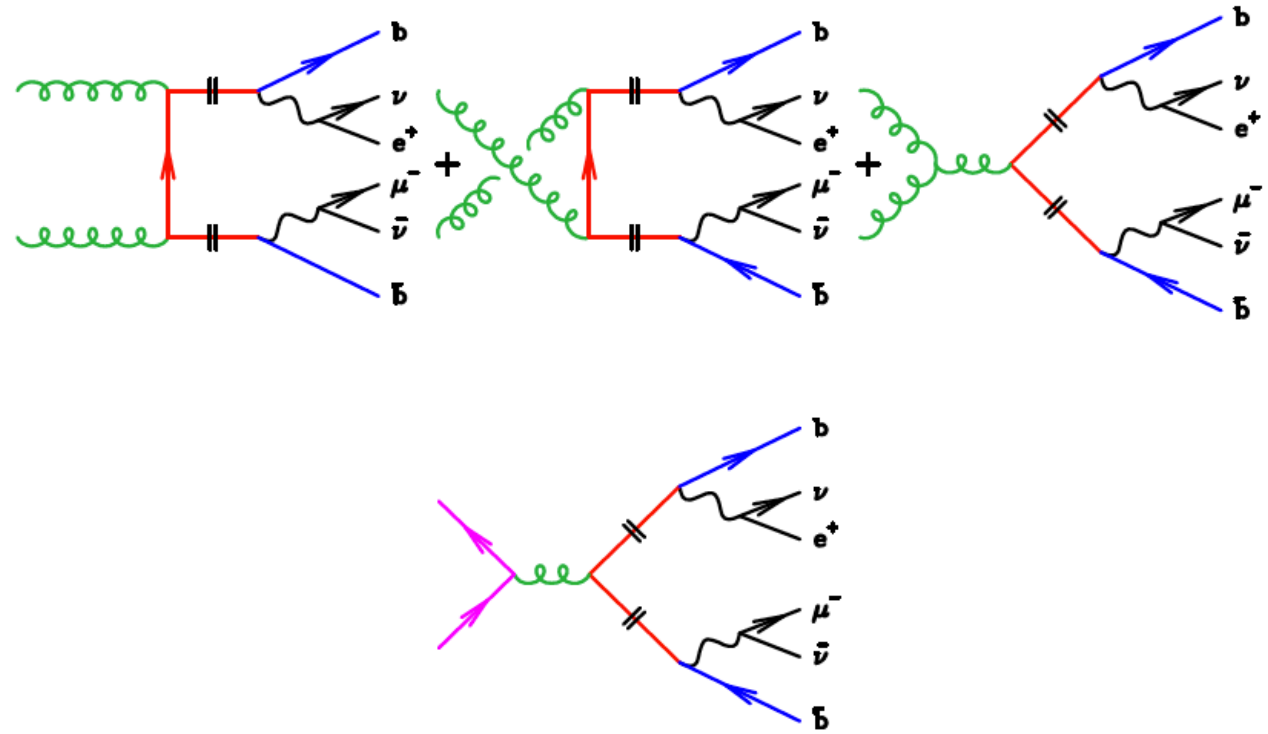
New features in v6.2

- A complete update of top-pair production, t-channel single-top production, s-channel single-top production in the full top-pole approximation
  - Top quark is produced on shell but with complete spin correlations through NLO. (For the case of top pair production inclusion of the one-loop analytic amplitudes of Badger, Sattler and Yundin, (arXiv:1101.5947) leading to a factor of 3 improvement in the speed of the code).
  - Inclusion of radiation in decay.
  - Inclusion of off-shell W effects.
  - Full dependence on the mass of the b-quark in top production and decay.
  - Our treatment builds on our earlier work Campbell, Ellis, Tramontano (hep-ph/0408158) and Melnikov and Schulze, (arXiv:0907.3090, arXiv:1004.3284)

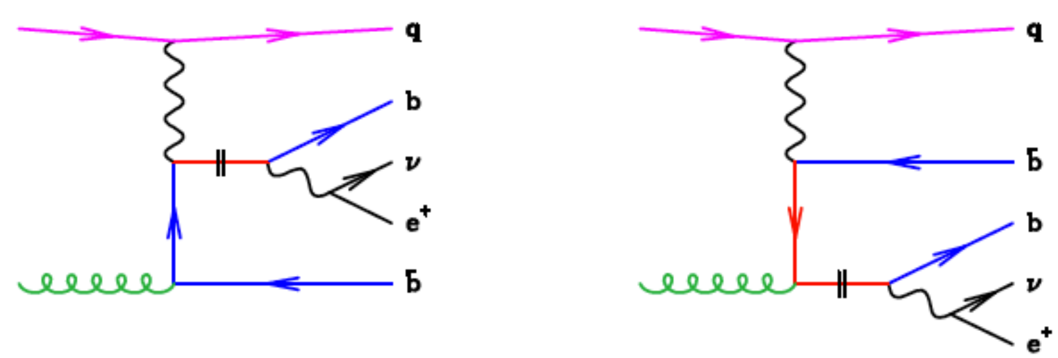
Commonly used programs such as MC@NLO and POWHEG do not currently have a *full* NLO implementation of the top pole approximation.

Lowest order diagrams for currently included processes

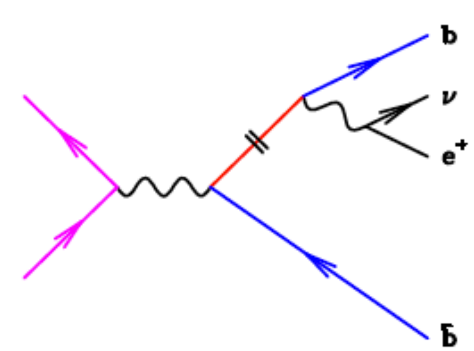
* top-pair production



* t-channel single top



* s-channel single top



Inclusion of spin correlations with on shell top

- Since characteristic time for production of the top quark is $1/m_t$ whereas characteristic time for decay is $1/\Gamma_t$, interference between production and decay is of order $\alpha_s\, \Gamma_t\, /m_t$ and can be neglected.

- Factorization of the calculation into amplitude for production and amplitudes for decay.

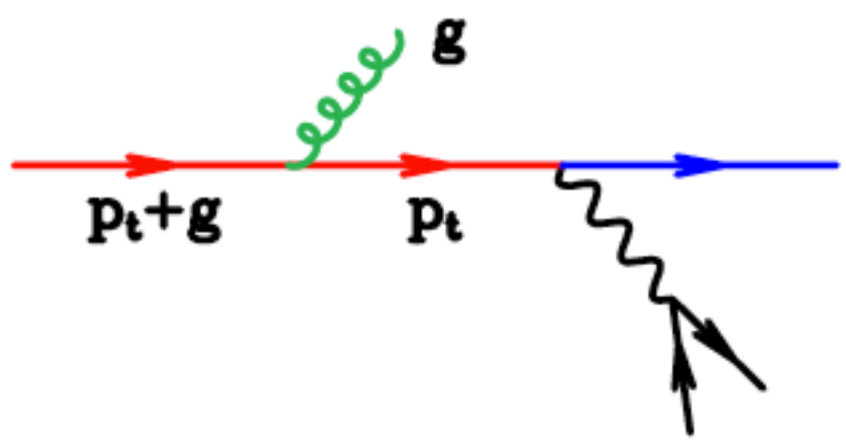
$$\frac{\not{p}_t + m_t}{p_t^2 - m_t^2 + i m_t \Gamma_t} \to \frac{\sum_\lambda u_\lambda(p_t)\bar{u}_\lambda(p_t)}{i m_t \Gamma_t}$$

- Massive spinors written as combinations of massless spinors

$$u_-(p_t) = (\not{p}_t + m_t)|\eta_t\rangle \frac{1}{\langle t \eta_t \rangle}, \quad u_+(p_t) = (\not{p}_t + m_t)|\eta_t] \frac{1}{[t \eta_t]}$$

- such that $p_t = t^\mu + \alpha \eta, \;\; t.t = \eta.\eta = 0$ and $\sum_{\lambda=\pm} u_\lambda(p_t)\bar{u}_\lambda(p_t) = \not{p}_t + m_t$

Separation of radiation in production and decay



$$\frac{1}{[(p_t+g)^2-m_t^2+im_t\Gamma_t)]\,[p_t^2-m_t^2+im_t\Gamma_t)]}=\frac{1}{2p_t\cdot g}\left\{\frac{1}{[p_t^2-m_t^2+im_t\Gamma_t)]}-\frac{1}{[(p_t+g)^2-m_t^2+im_t\Gamma_t)]}\right\}$$

Radiation in production on this pole

Radiation in decay on this pole

- Artificial separation by partial fractioning makes it clear that radiation in production and decay belong together.

Width of the top quark

* Since we treat the top quark as being on shell, the width of the top quark is an overall scale parameter.
* NLO corrections to the width are relevant to ensure that we only keep terms of order $O(\alpha_s)$.
* We have (re-)performed the NLO calculation of the width including finite mass effects and off-shell corrections for the W. Czarnecki, Jezabek and Kuhn
* The correction gives $\frac{\alpha_S \Gamma_1}{\Gamma_0} \approx -0.8\alpha_S$ lowering the leading order result by about 10%.

	$m_W = 80.398$ GeV,$m_b = 4.7$ GeV	$m_W = 80.398$ GeV,$m_b = 0$
Γ_0^{BW} [GeV]	1.453518	1.457412
$\Gamma_1^{BW}/\Gamma_0^{BW}$	-0.7878491	-0.7972087
Γ_0^{NW} [GeV]	1.476596	1.480522
$\Gamma_1^{NW}/\Gamma_0^{NW}$	-0.7878090	-0.7971276

Consistent treatment of top decay

- Full cross section integrated over the decay products of the top is given by production cross section X branching fraction to appropriate channel.
- eg. for single top production

$$\sigma^{NLO}(pp \to t(\to \nu e^+ b) + X) = (\sigma_0 + \alpha_S \sigma_1) \times \frac{d\Gamma_0^{(l)} + \alpha_S d\Gamma_1^{(l)}}{\Gamma_0 + \alpha_S \Gamma_1}$$

- Removing superfluous $O(\alpha_s^2)$ corrections we have that

$$\sigma^{NLO} = (\sigma_0 + \alpha_S \sigma_1) \times Br(W \to \nu e^+) + \alpha_S \sigma_0 Br(W \to \nu e^+) \left[\frac{\Gamma_1^{(l)}}{\Gamma_0^{(l)}} - \frac{\Gamma_1}{\Gamma_0} \right]$$
$$\equiv (\sigma_0 + \alpha_S \sigma_1) \times Br(W \to \nu e^+)$$

Melnikov and Schulze, arXiv:0907.3090

- Thus integrating over all decay products, radiation in decay does not change total cross section; but in the presence of cuts it can change cross sections.

Application to s-channel single top at the Tevatron

- s-channel single top without cuts

Treatment of W-boson and b-quark	σ_{LO} [fb]	σ_{NLO} (prod.) [fb]	σ_{NLO} (prod.+decay) [fb]
Narrow width, $m_b = 0$	30.98(2)	48.84(3)	48.82(3)
Narrow width, $m_b = 4.7$ GeV	30.78(2)	48.61(3)	48.60(3)
Breit-Wigner, $m_b = 4.7$ GeV	30.77(2)	48.61(3)	48.59(3)

  - Note agreement between columns 2&3 and small b-mass effect.

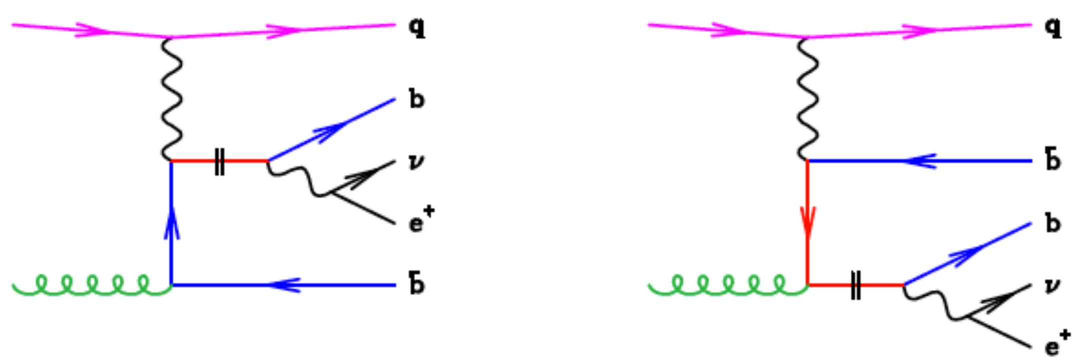
- s-channel single top with Higgs style cuts.

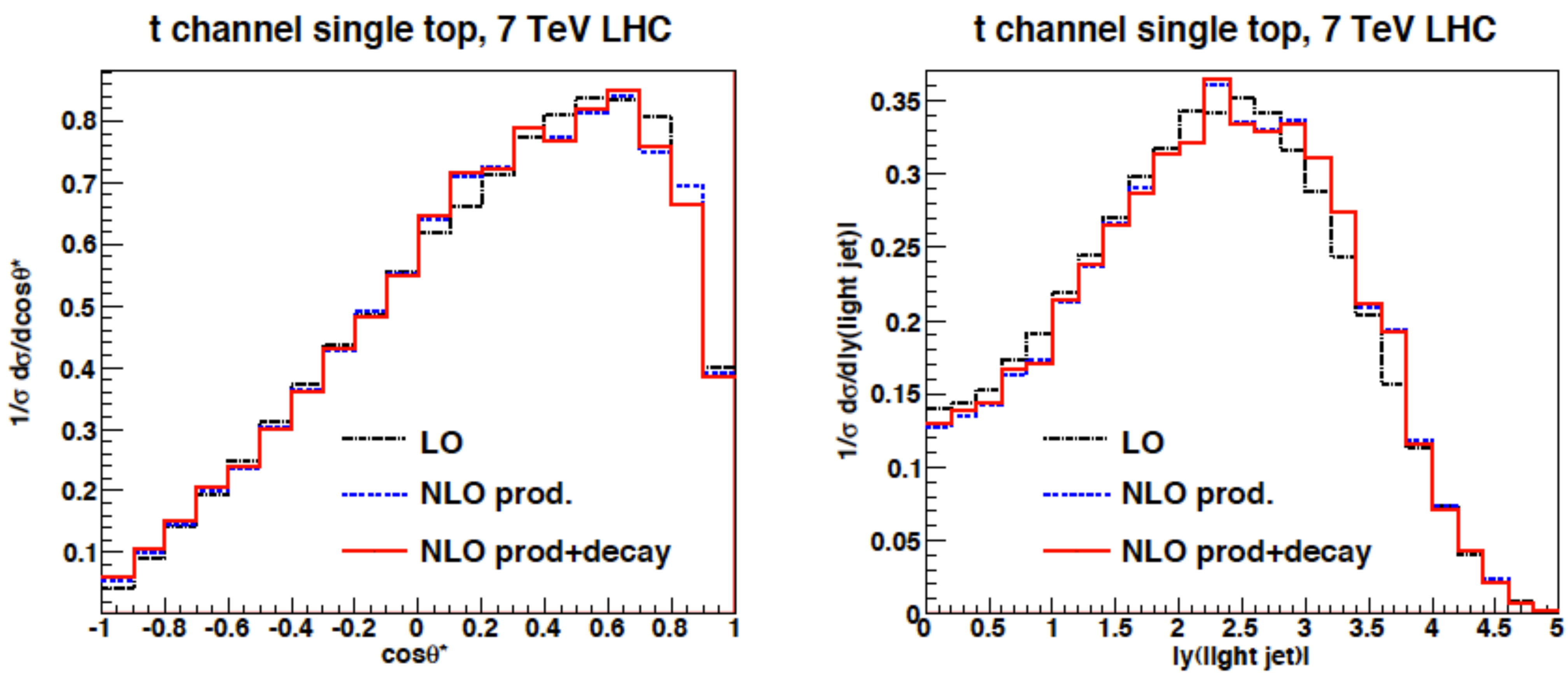
Treatment of W-boson and b-quark	σ_{LO} [fb]	σ_{NLO} (prod.) [fb]	σ_{NLO} (prod.+decay) [fb]
Narrow width, $m_b = 0$	12.14(2)	19.96(2)	20.03(2)
Narrow width, $m_b = 4.7$ GeV	12.12(2)	19.96(2)	20.01(2)
Breit-Wigner, $m_b = 4.7$ GeV	12.08(2)	19.88(2)	19.95(2)

  - Note small difference between columns 2&3 and negligible b-mass effect.

t-channel single top at LHC7

- Important variables are:-
  - rapidity of light jet and
  - angle between lepton and light jet in rest frame of reconstructed top quark

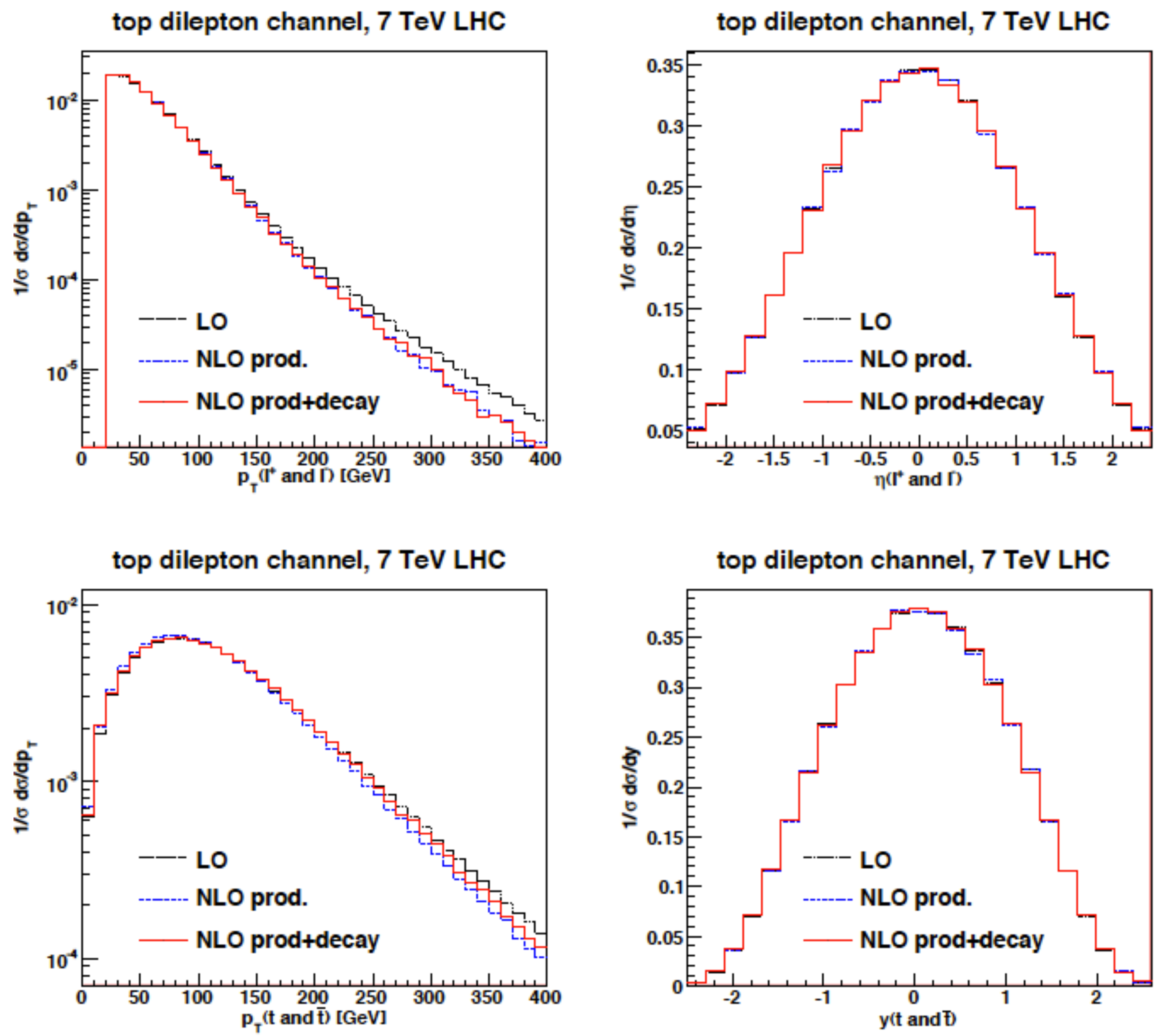




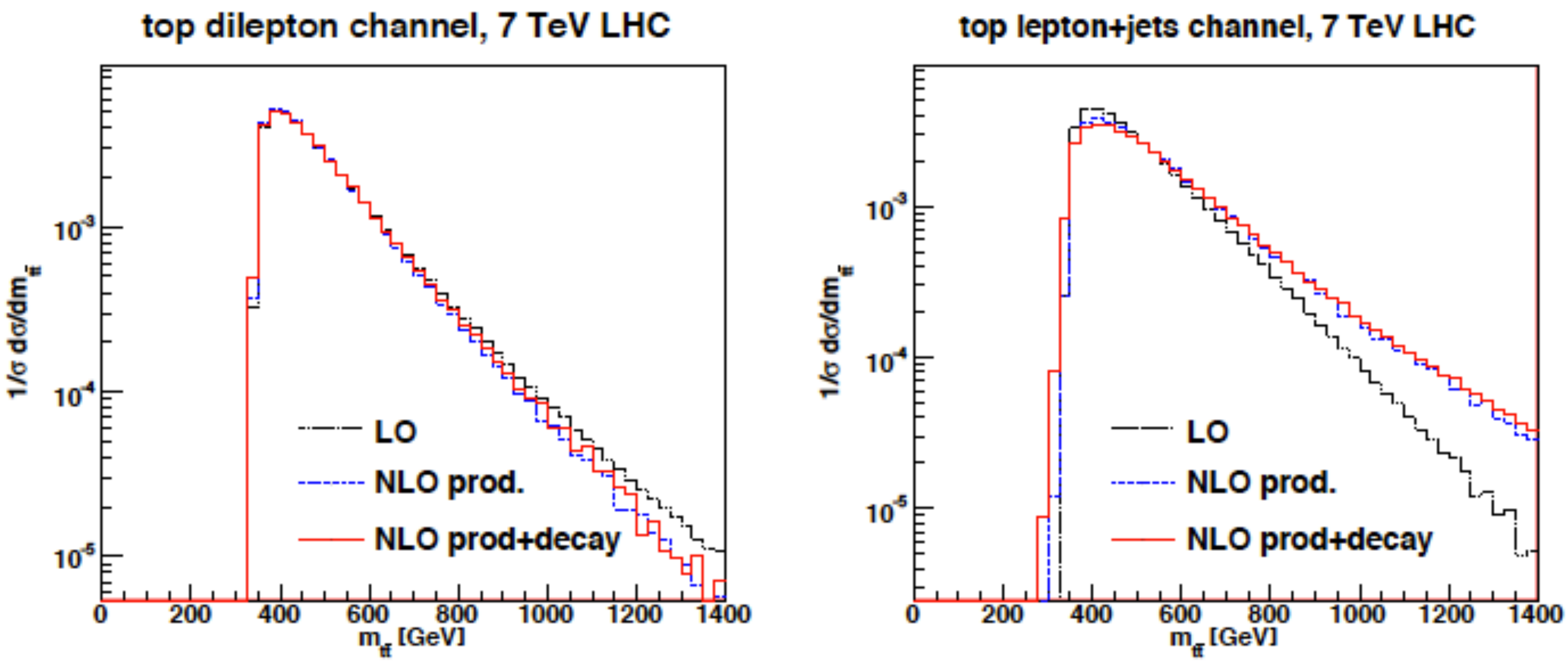
- NLO - slight change in shape, additional corrections due to radiation in decay small.

Top pair production: semileptonic decays

- Our reconstruction of top sample differs in a substantial way from the experimental one.
- Assume leptonically decaying W is perfectly reconstructed; assign remaining light jets with mass closest to W, W +tagged jet with mass closest to top gives top, etc.
- At large P_T there are significant corrections with the NLO prod +decay curve lying between LO and NLO prod.

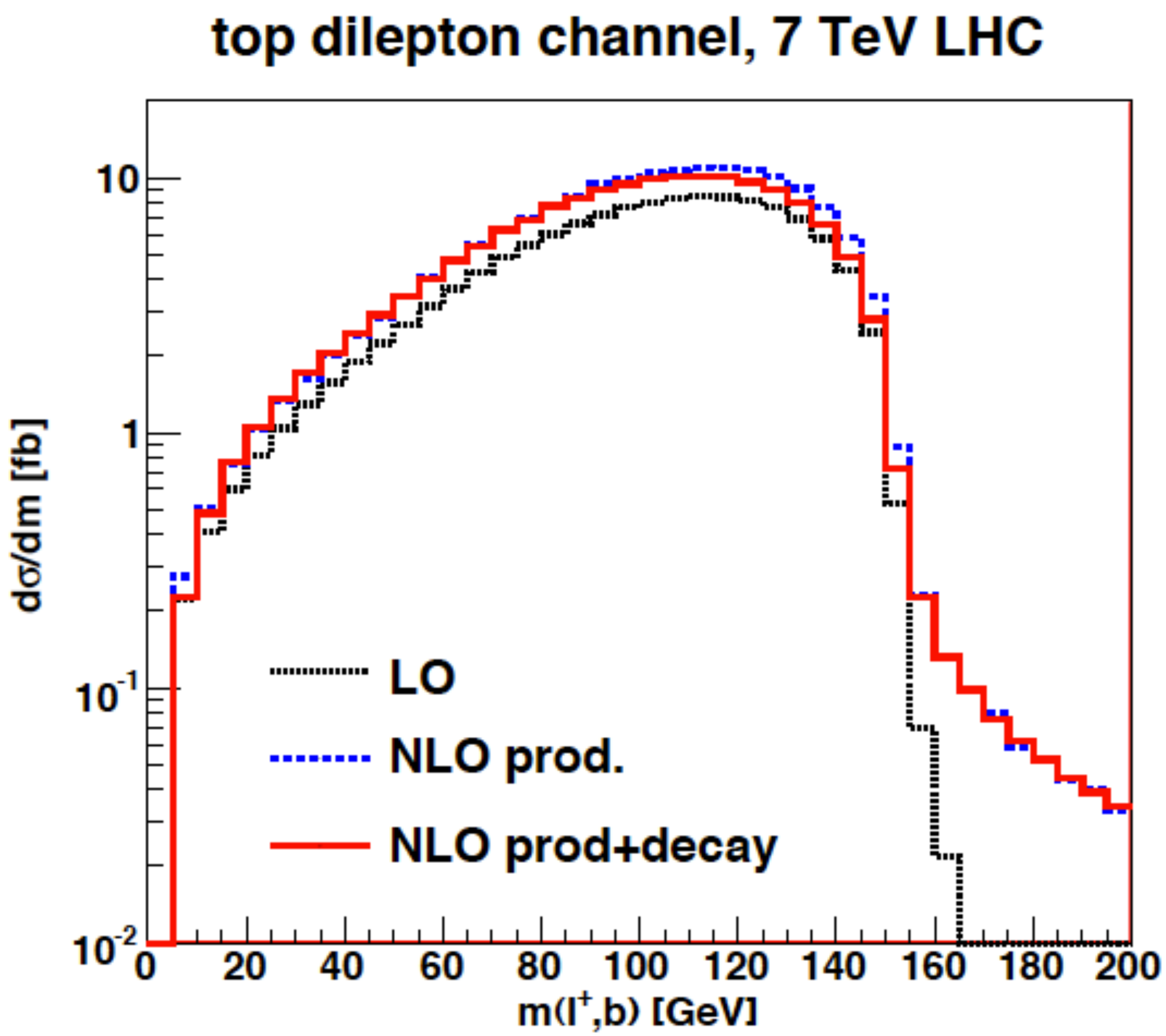


Top pair production: ttbar pair mass



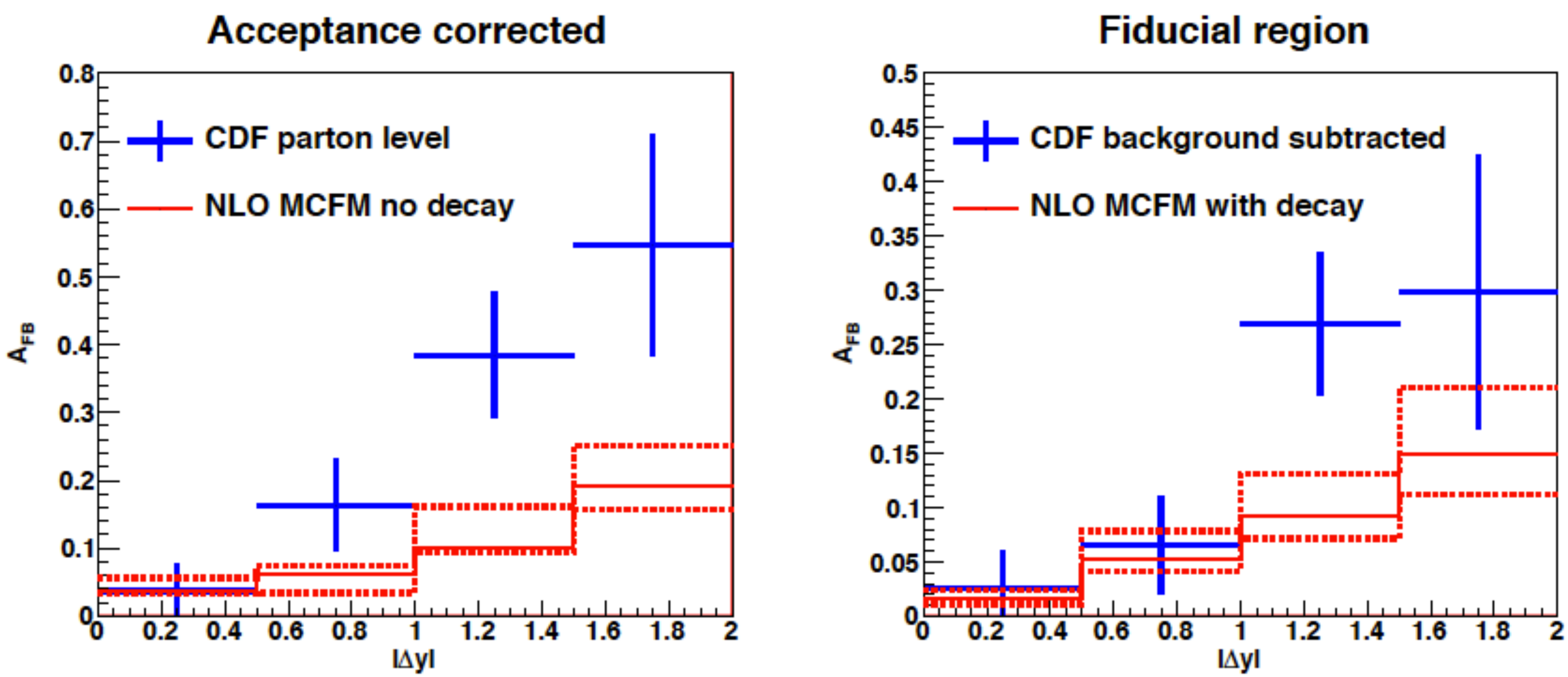
- NLO effects can change the shape of the Mtt distribution, but this is due to radiative effects in production not in decay. Large difference between LO and NLO is due to the choice of scale $\mu = m_t$.
- No evidence of big change due to radiation in decay.

Top pair production: Invariant mass of lepton+b



- Significant effect of radiation in decay as first noted by Melnikov and Schulze
- Could have some influence of extraction of tbW couplings, since the lepton helicity angle is $\cos\theta_e \sim \frac{4p_b.p_e}{m_t^2 - M_W^2}$

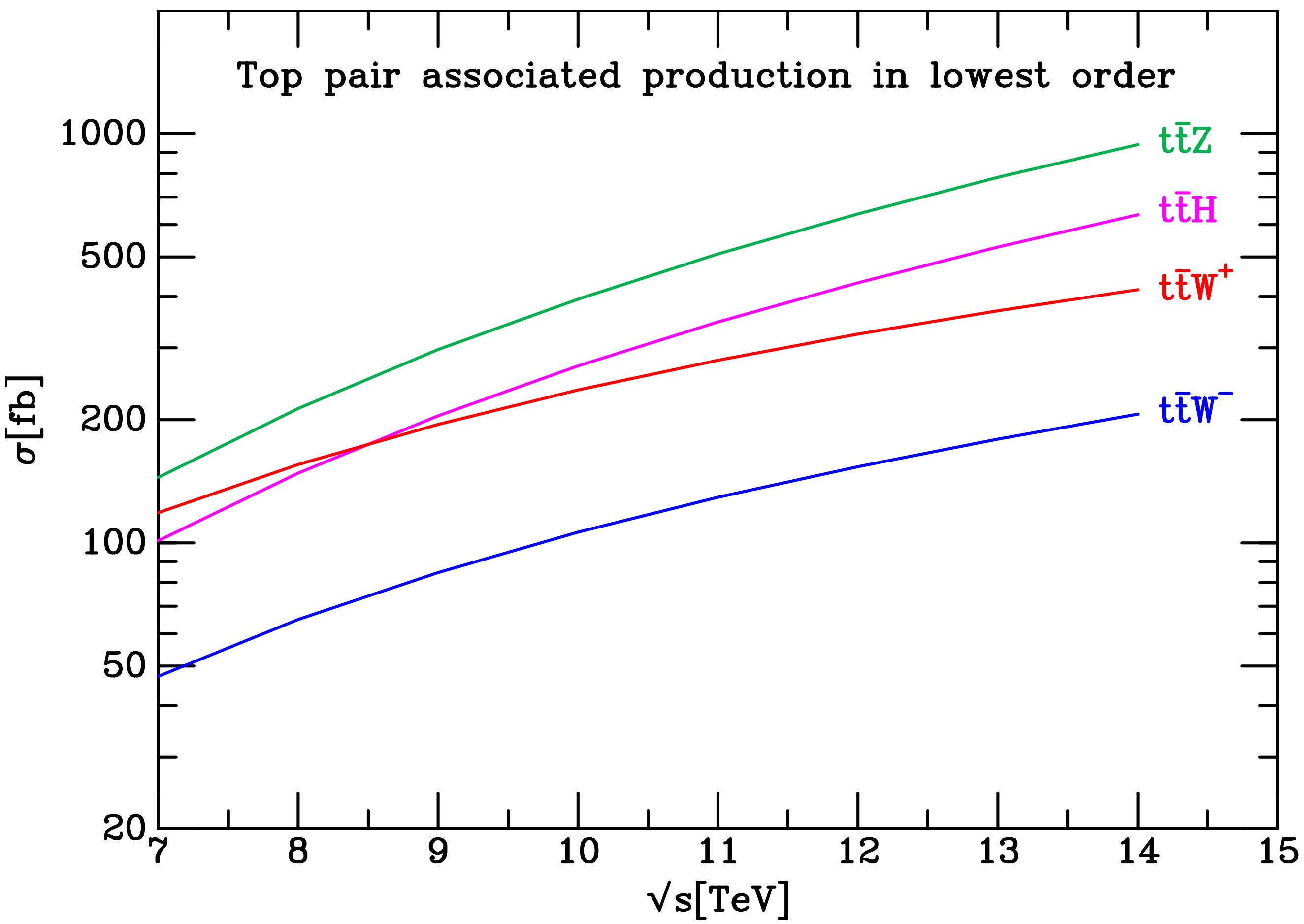
Top pair production: Forward-backward asymmetry



* Left hand plot shows the asymmetry for the reconstructed quarks a la NDE.
* Right hand plot includes radiation in both production and decay and is the result in the fiducial region.

Top & Co:Associated production of massive bosons

- Cross sections for associated production are quite small ~100fb at current energies, before inclusion of efficiencies and branching ratios.
- ttH and ttZ have been considered theoretically. Here we consider ttW that has so far received little attention.



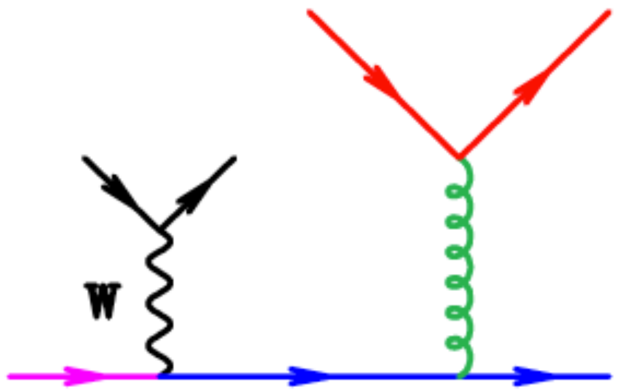
Associated production: current status

Final state	Top decay	NLO in Top decay	Full Virtual spin correlatio ns	Matching with parton shower	Reference
ttH	✗	n/a	n/a	✗	Beenakker et al, hep-ph/ 0107081
ttH	✗	n/a	n/a	✗	Reina et al, hep-ph/ 0109066,hep-ph/0305087
ttH	✓	✗	✗	✓	Kardos et al. , arXiv: 1108.0387
ttZ	✗	n/a	n/a	✗	Lazopoulos et al. , arXiv: 0804.2220
ttZ	✓	✗	✗	✓	Kardos et al. , arXiv: 1111.0610,1111.1444
ttW	✓	+	✓	✗	Campbell ,Ellis, arXiV: 1204.5678

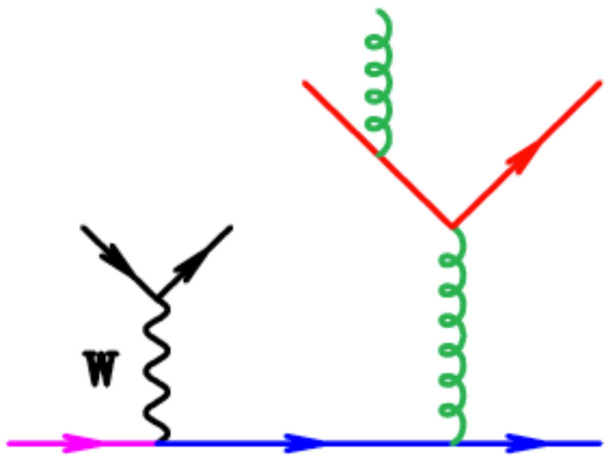
Legend
✓=done
✗=not done
+=in progress

NLO calculation of ttW±

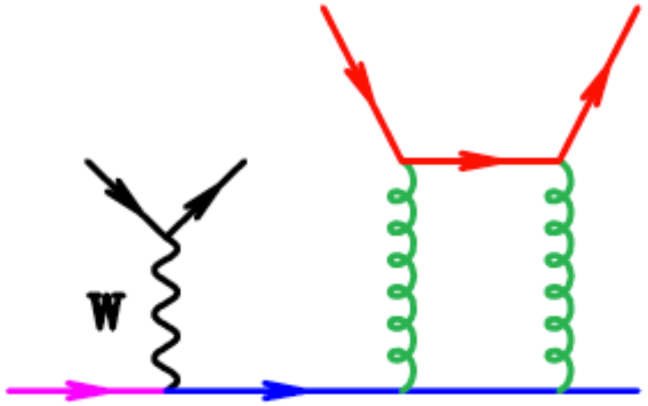
- As usual NLO calculation requires the LO amplitude.



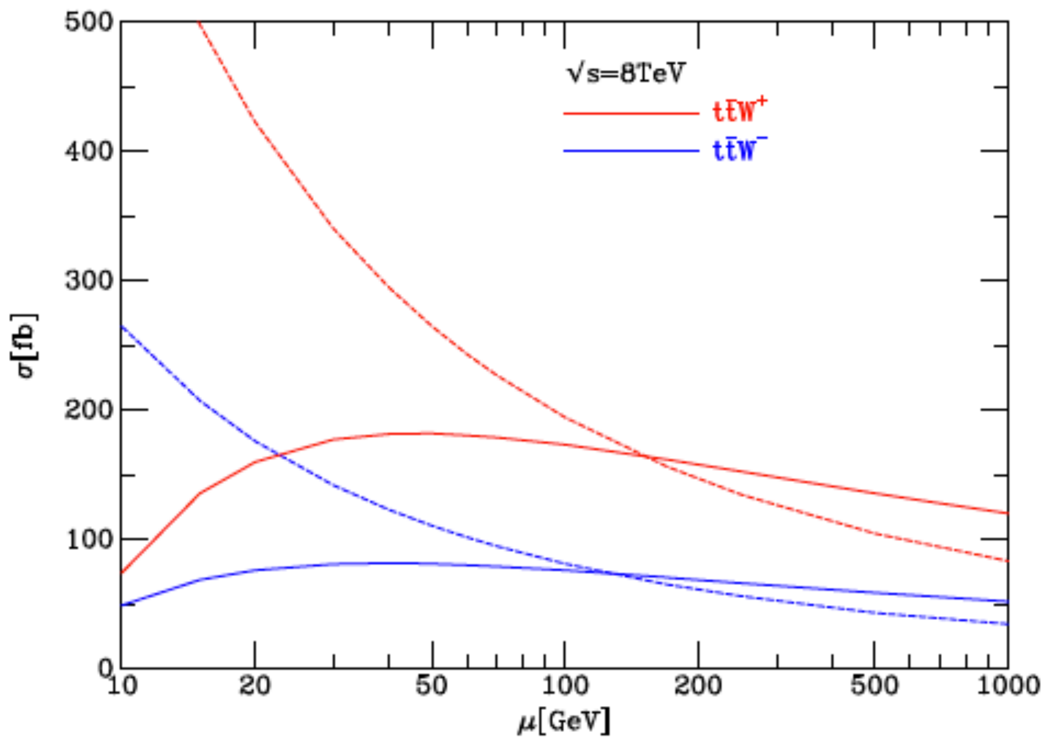
- the amplitude for real emission.

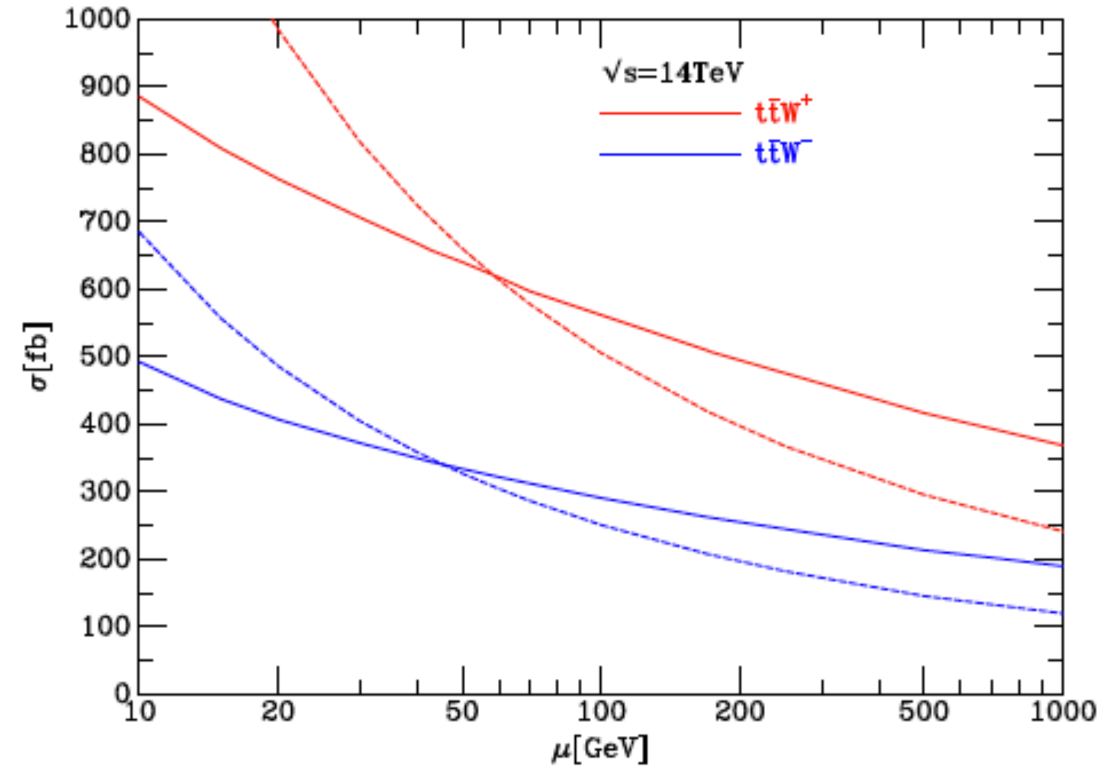


- the one-loop amplitude with masses for heavy quarks,
  - recycled from Wbb~ calculation, Badger et al, arXiv:1011.6647, in turn recycled in part from Bern et al, hep-ph/9708239).



Theoretical error for ttW±





- Scale dependence is better behaved at 7~8TeV. NLO errors above 30%

Best predictions → NLO

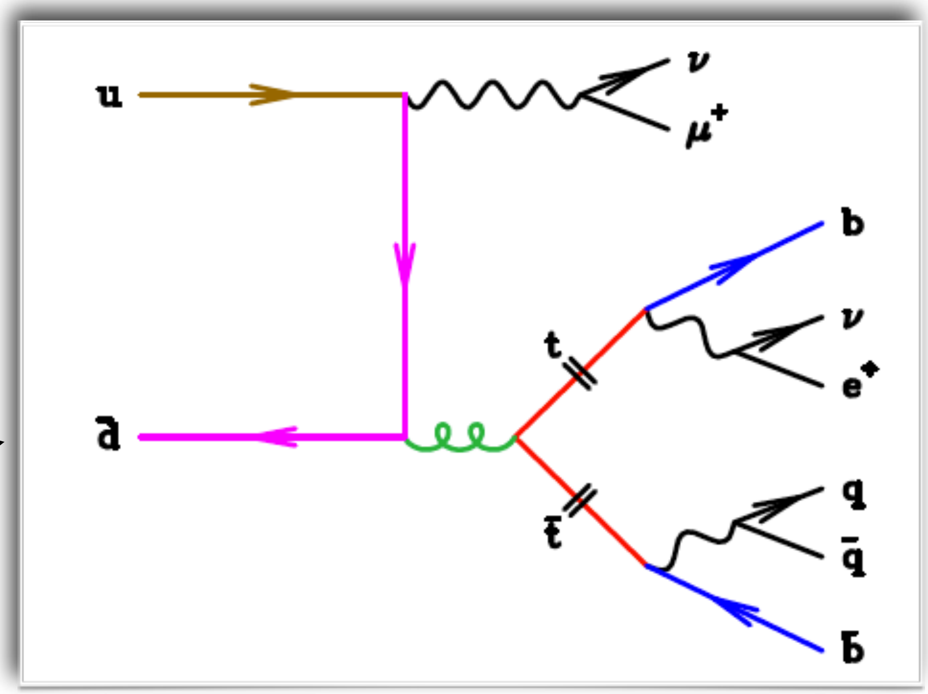
$t\bar{t}W^+$	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=14$ TeV
LO	$118^{+87\%}_{-40\%}$(scale)$^{+6\%}_{-6\%}$(pdf)	$156^{+83\%}_{-39\%}$(scale)$^{+6\%}_{-5\%}$(pdf)	$416^{+68\%}_{-36\%}$(scale)$^{+4\%}_{-4\%}$(pdf)
NLO	$119^{+8\%}_{-20\%}$(scale)$^{+7\%}_{-8\%}$(pdf+α_s)	$161^{+12\%}_{-20\%}$(scale)$^{+7\%}_{-8\%}$(pdf+α_s)	$507^{+29\%}_{-22\%}$(scale)$^{+7\%}_{-8\%}$(pdf+α_s)
$t\bar{t}W^-$	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=14$ TeV
LO	$47^{+87\%}_{-41\%}$(scale)$^{+6\%}_{-6\%}$(pdf)	$65^{+84\%}_{-40\%}$(scale)$^{+5\%}_{-6\%}$(pdf)	$206^{+68\%}_{-36\%}$(scale)$^{+4\%}_{-5\%}$(pdf)
NLO	$50^{+12\%}_{-21\%}$(scale)$^{+6\%}_{-8\%}$(pdf+α_s)	$71^{+16\%}_{-21\%}$(scale)$^{+6\%}_{-8\%}$(pdf+α_s)	$262^{+31\%}_{-23\%}$(scale)$^{+7\%}_{-8\%}$(pdf+α_s)

Same-sign lepton events

* Experimental sources are fakes and q-flips

Backgrounds fixed using data-driven methods

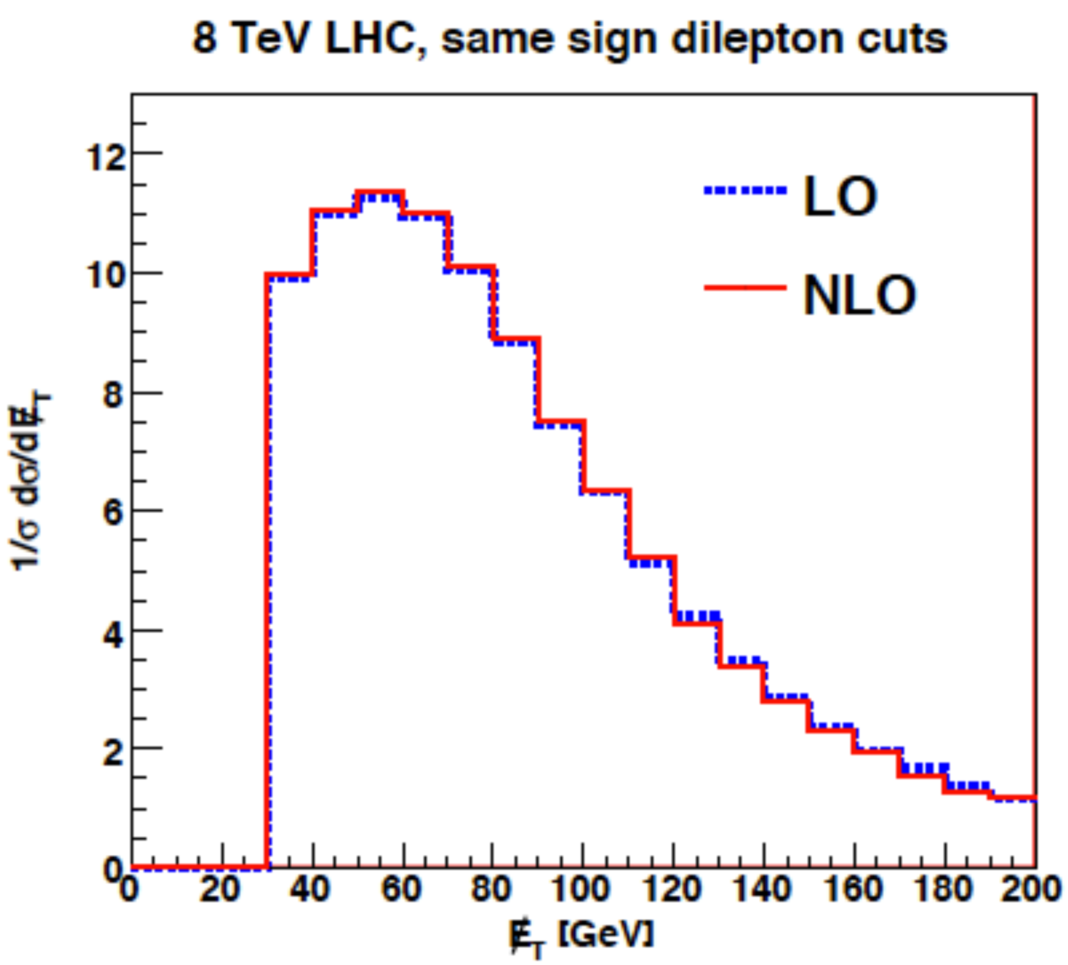
* Other theoretical background sources are:-
  * WZ,ZZ production
  * $W^{\pm}W^{\pm}$ +dijets
  * $W^{\pm}W^{\pm}$ in Vector Boson Fusion
  * WWW,WWZ,ZZZ production
  * t-tbar Z production
  * t-tbar W production

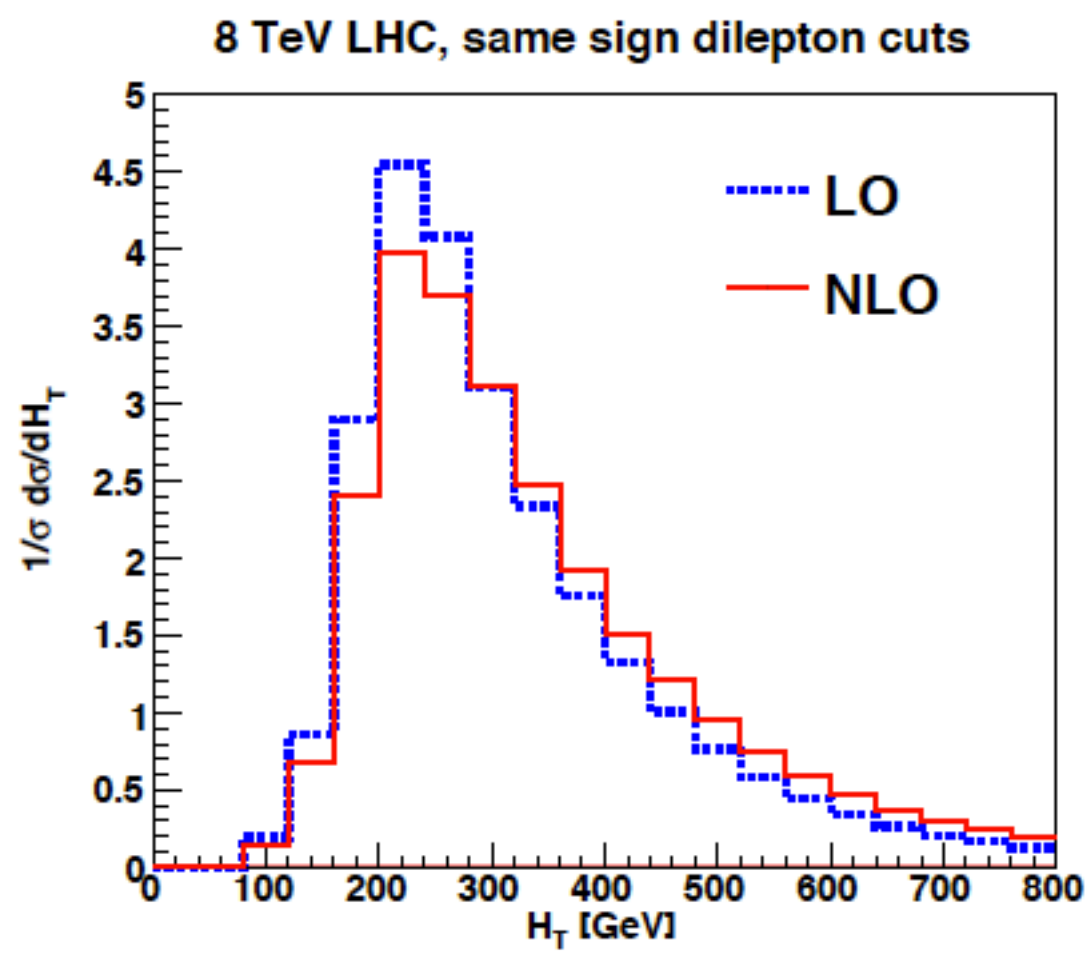


* Relative size of backgrounds controlled by further cuts applied to search

Example: influence of NLO on recent CMS analysis

- Search for new physics in events with same-sign dileptons, b-tagged jets and missing energy http://cdsweb.cern.ch/record/1434376

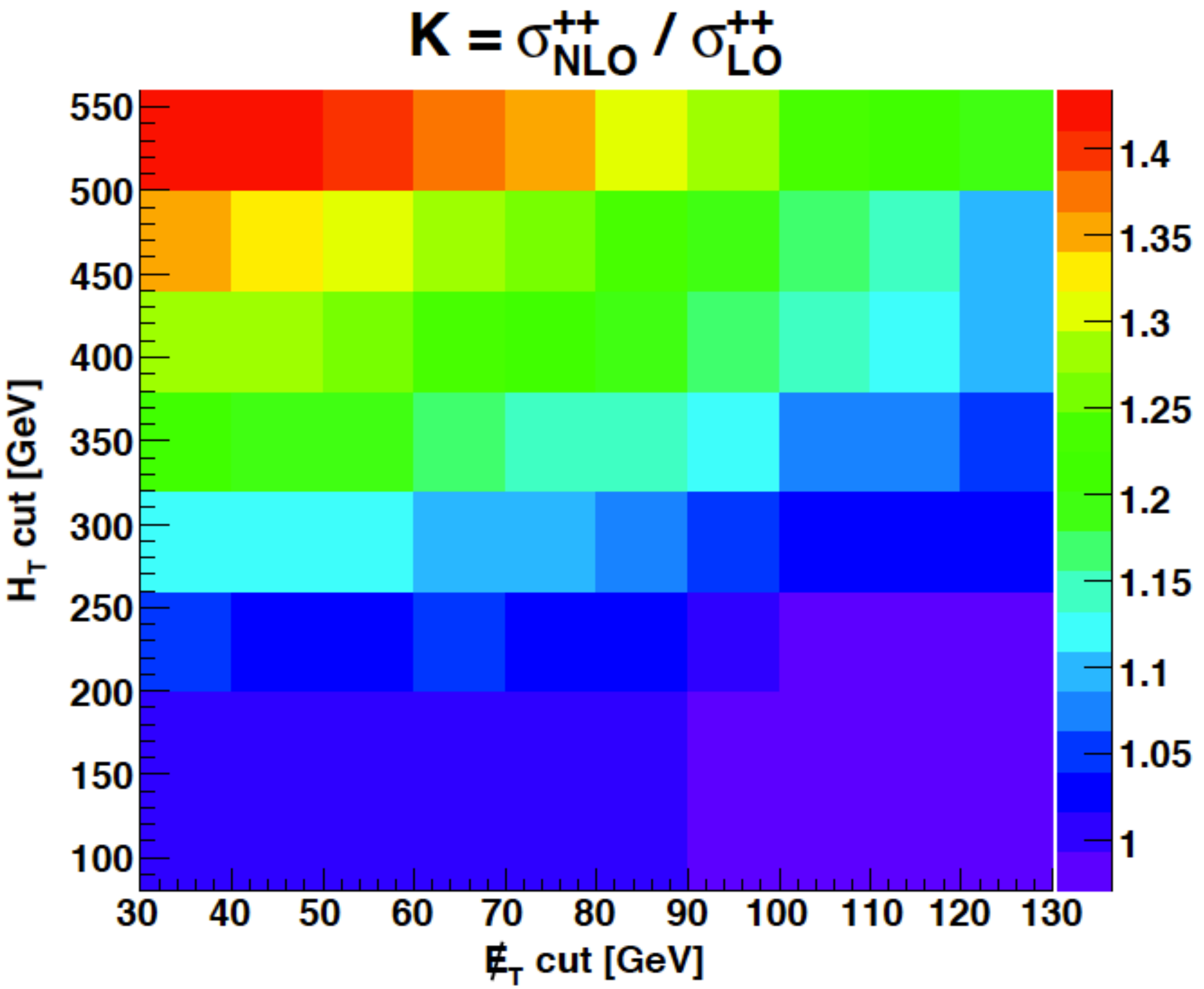




- E_T-missing distribution is little changed at NLO.
- H_T-distribution is changed at NLO.

Dependence of K-factor on E_T and H_T cuts

* In line with the results on the previous slide, the K-factor is less dependent on the E_T missing cut and more dependent on the H_T cut.



Conclusions

- MCFM now includes ttbar, t-channel single top, s-channel single top with decay and radiation in the decay. It provides the most sophisticated possible NLO treatment of these processes within the context of the top pole approximation.
- We can now assess the importance of NLO radiative effects, the effect of an off-shell W, the effect of the b quark mass. For many distributions we have examined these effects turn out to be quite small.
- These processes are included in an amplitude formalism allowing easy extension to other processes, Wt, ttH, ttZ ....
- Associated production of bosons with top is a new frontier that is beginning to be opened up experimentally. Recent results on ttW have implications for same-sign lepton events.