Kinematic distributions in top quark pair production

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Based on work done in collaboration with
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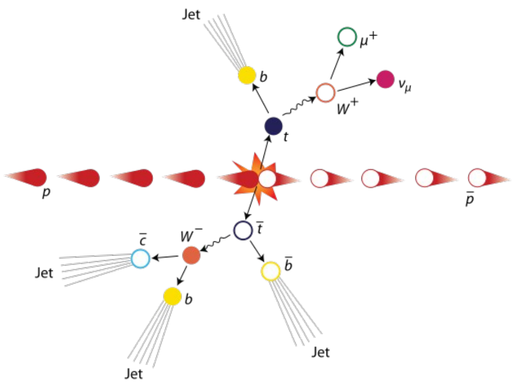
Top quarks at a hadron collider

- Top quark physics is interesting on its own right . Also, it shares many features of expected BSM signals; for this reason – a great playground
  - top quarks are heavy
  - top quarks are unstable; they are observed through a variety of decay products
  - top quark production/decay chain exhibits spin correlations thanks to short life-times of top quarks
  - top quark production exhibits forward-backward asymmetry (Tevatron) and charge asymmetry (LHC)
  - top quark mass is attempted to be extracted from data with highest precision possible
  - top quark ``couplings'' ($V_{\rm tb}$, anomalous couplings, exotic decay modes) are of great interest and need to be studied in detail
  - other couplings and properties are accessible through associated production processes (ttZ, ttW, ttH, tt+photon, tt+jet)



To do this physics in the right way, top quark theory must combine precision with realism ; this proved to be harder than one could have expected but we are on the right track

The summary

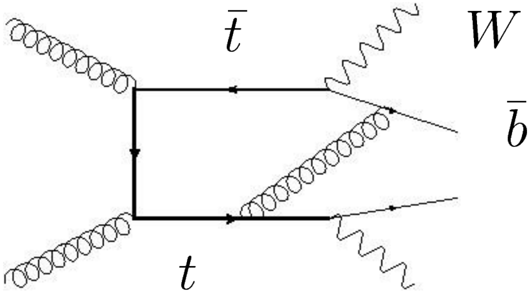
- Here are a few points that I want you to take away from this talk
  - narrow width approximation with spin correlations is a reliable framework to describe top quark processes at hadron colliders; it can be used at different orders in perturbative QCD and for different processes, including associated production
  - it is useful to include radiative corrections to top quark decays; their importance depends on a physics question that one is trying to address
  - use of K-factors computed for stable top quarks, to estimate NLO QCD effects to full (including decays) processes should be discouraged
  - physics conclusions look more convincing if they follow from kinematic distributions of final state particles that can be understood within pQCD rather than from reconstructed distributions of top quarks
  - knowledge of kinematic distributions in higher orders of pQCD allows us to do more physics

The references

- Top quark physics is a popular topic and a lot is available by now
- First NLO QCD top pair production cross-section Dawson et al.; Beenakker et al.
- Inclusion of QCD corrections to both production and decay of top quarks pairs was pioneered by Bernreuther, Si and P. Uwer
- Computations that accounts for QCD effects in top quark pair production and decay, allow for realistic jet algorithms and provide arbitrary differential distributions are available M. Schulze, K.M. ; Bernreuther and Si, Ellis and Campbell (MCFM)
- Calculation of WWbb production through NLO QCD: Denner, Dittmaier, Kallweit, Pozzorini ; Bevilacqua, Czakon, Papadopoulos, Worek
- NLO QCD calculation of tt+j cross-section for stable top quarks: Dittmaier, Uwer, Weinzierl; Bevilacqua, Czakon, Papadopoulos, Worek
- tt+jet with decays including NLO QCD corrections M. Schulze, A. Scharf, K.M.

Top quark pair production

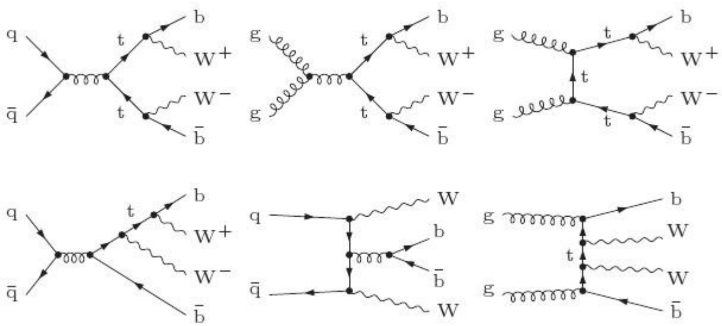
- Interesting physics can often be accessed only by working with kinematic distributions of top quark decay products; therefore need reasonable description of those
- This can be done in the narrow width approximation:
  - polarized top quarks are produced on the mass shell
  - polarized on-shell top quarks decay
- Higher order corrections can be included, in both production and decay stages
- Neglected effects are suppressed by Γ_t/m_t or by $\alpha_s\Gamma_t/m_t$ in sufficiently inclusive distribution; non-factorizable corrections are further suppressed at higher energies
- The narrow width approximation is useful because it is parametric, it captures important physics and it is applicable to processes of arbitrary complexity



Example of non-factorizable corrections to top quark pair production

Top quark pair production

- We can assess the quality of the narrow width approximation by comparing ``narrow width'' kinematic distributions for top quark pair production with the recent computation of pp $\rightarrow$ WWbb through NLO QCD
- The full computation includes double resonance, single resonance and non-resonance diagrams; it can deviate from ``top pair production'' cross-section but the effect is expected to be small for realistic selection criteria



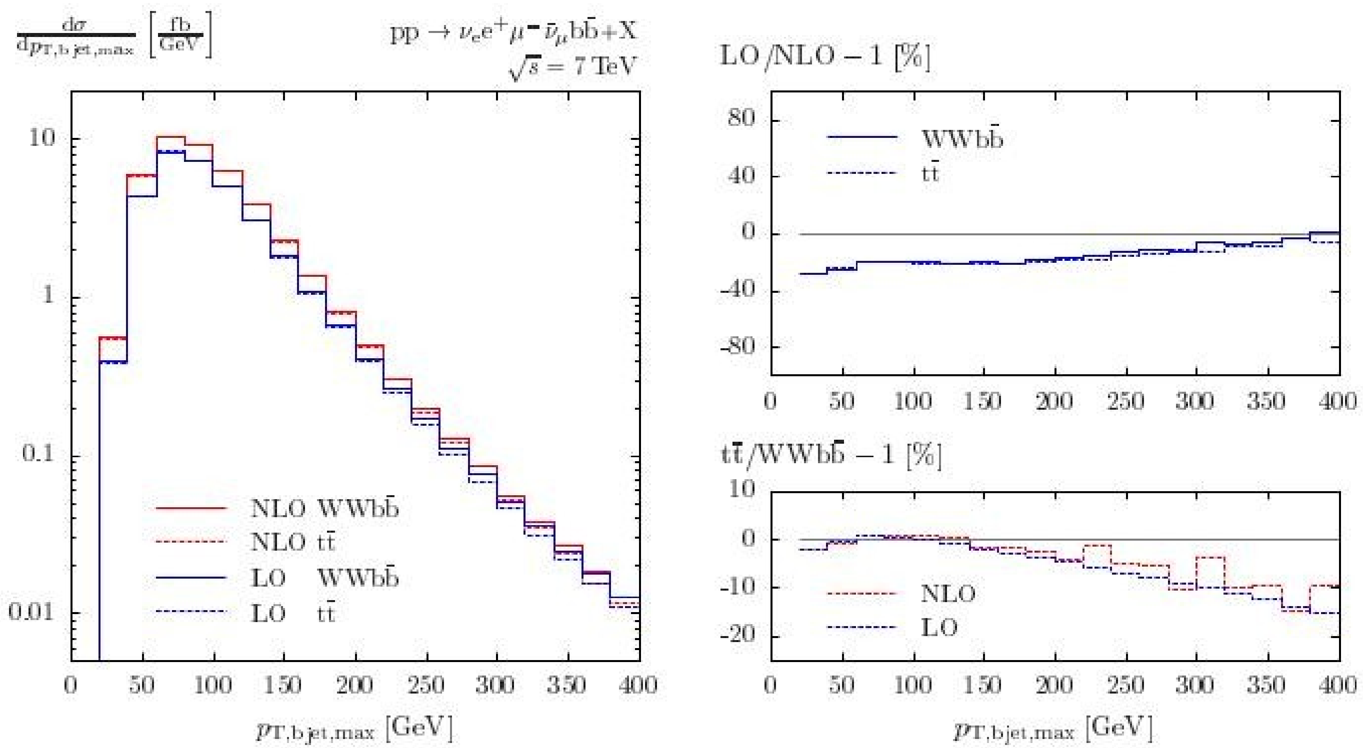
Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{WWb\bar{b}}$ [fb]	$\sigma_{t\bar{t}}/\sigma_{WWb\bar{b}} - 1$	Ref. [25]
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$	$+0.8\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$	$+0.9\%$
LHC	7	LO	$659.5(1)^{+261.8}_{-173.1}$	$662.35(4)^{+263.4}_{-174.1}$	$-0.431(16)\%$	-0.4%
		NLO	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-0.41(31)\%$	-0.2%
LHC	14	LO	$3306.3(1)^{+1086.8}_{-763.6}$	$3334.6(2)^{+1098.5}_{-771.2}$	$-0.849(7)\%$	$- - -$
		NLO	$4253(3)^{+282}_{-404}$	$4286(7)^{+283}_{-407}$	$-0.77(19)\%$	$- - -$

Top production cross-section in the di-lepton final state; no cuts on top invariant mass; typical cuts on transverse momenta, missing energies, rapidities etc.

Denner, Dittmaier, Kallweit, Pozzorini, Schulze

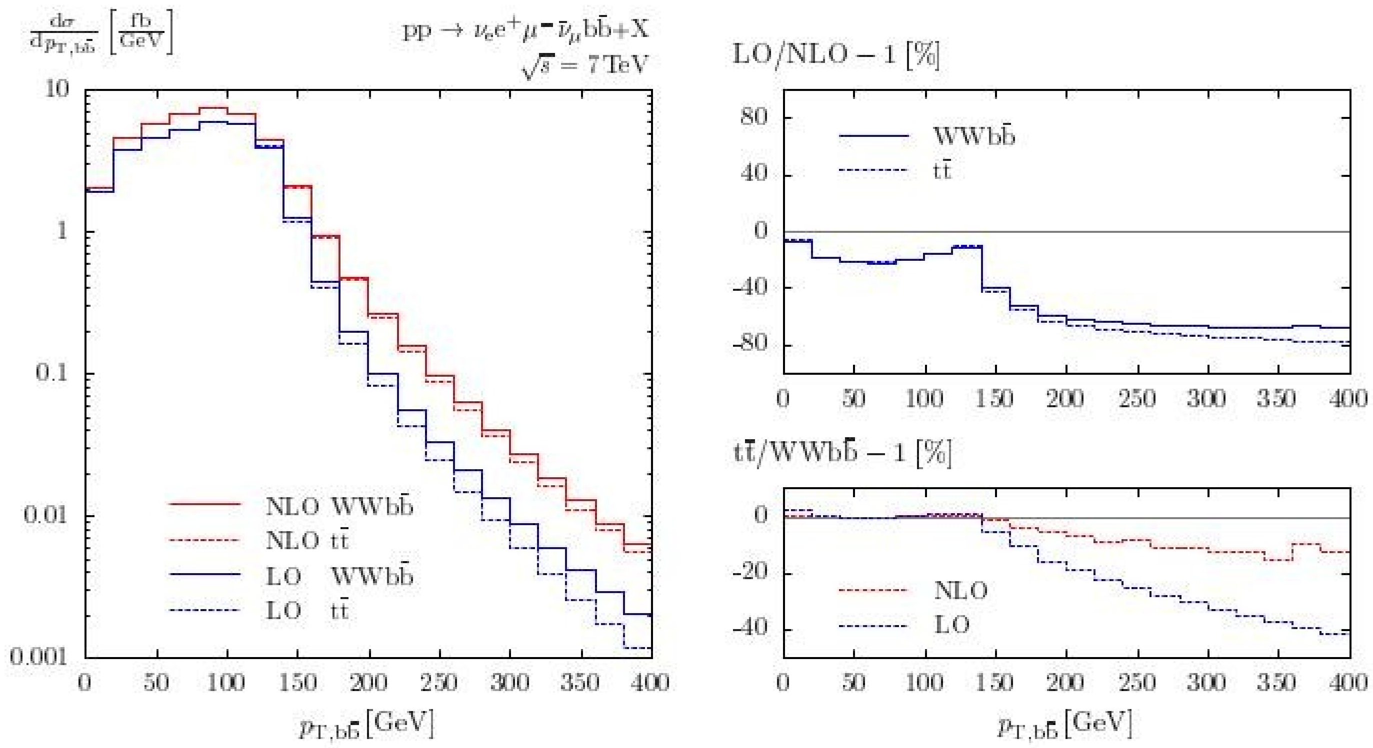
Top quark pair production

- The transverse momentum distribution of the harder b-jet is well described by the narrow widths approximation up to 150 GeV, a ten percent deviation occurs at around 250 GeV. K-factors are similar up to 400 GeV.



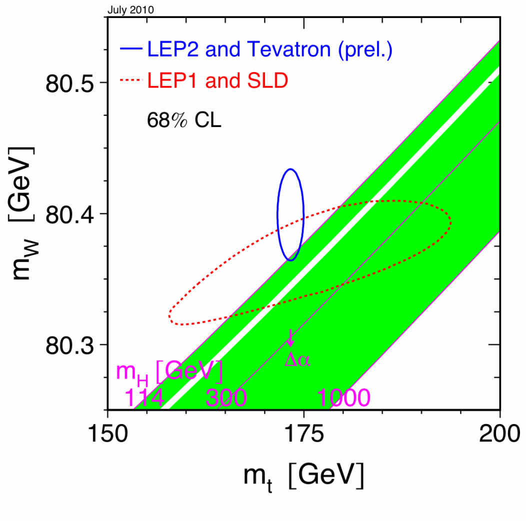
Top quark pair production

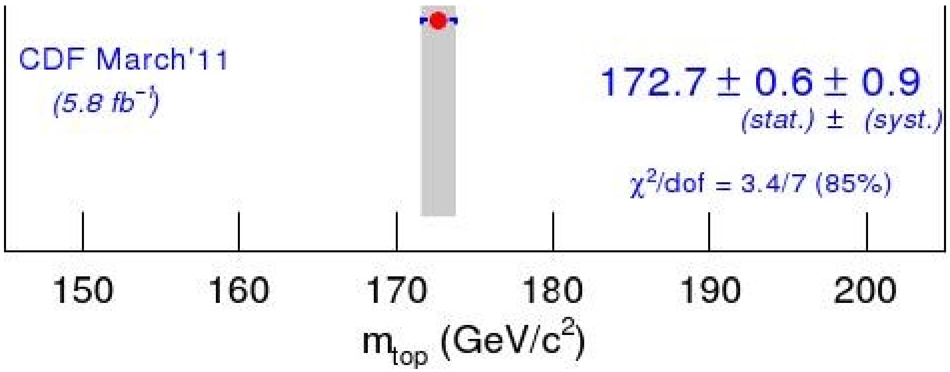
- The transverse momentum distribution of the two b-jets is well described by the narrow widths approximation up to 150 GeV; after that significant deviations occur
- We observe larger differences at LO than at NLO (off-resonance effects vs. additional radiation). K-factors remain very similar up to very high momenta..



The top quark mass

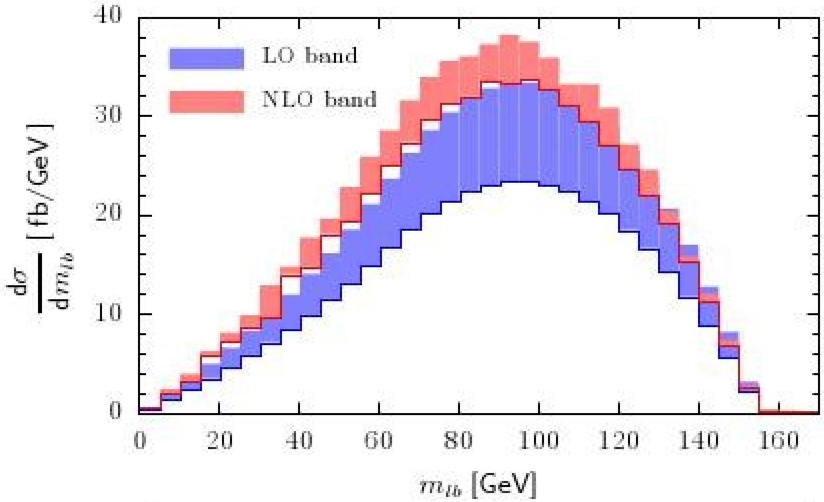
- Accurate and reliable determination of the top quark mass is important.
- CDF, D0, CMS and ATLAS have measured the top quark mass precisely but we do not know what this mass parameter is
- It is important to have extraction of the top quark masses from observables that can be described by perturbative QCD (short-distance) because in such cases we can switch between different renormalization schemes for the top quark mass
- An ideal observable for the top quark mass determination should be insensitive to top production; it should be determined by top quark decay

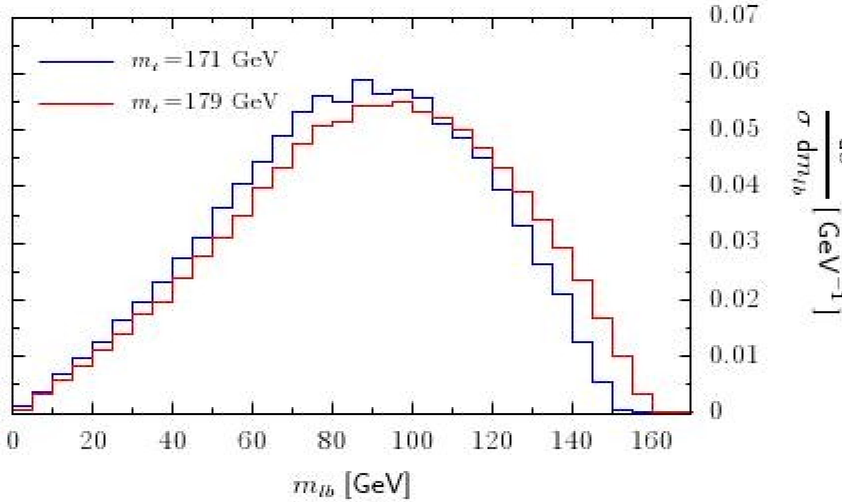


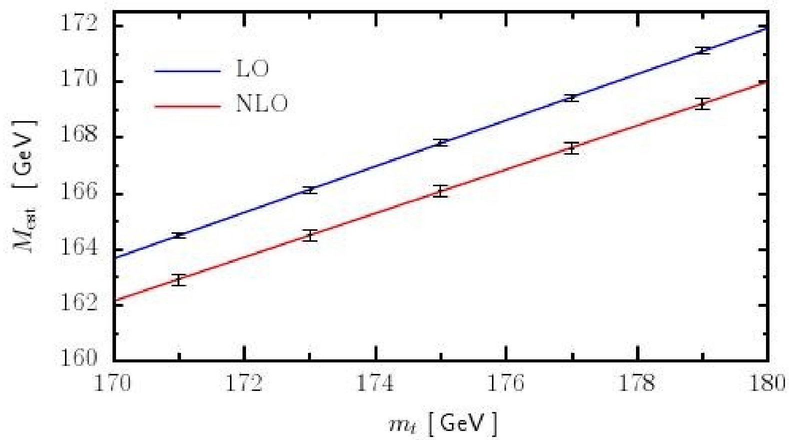


Top quark mass measurements and kinematic distributions

- The top quark mass can be measured from the invariant mass distribution of a lepton and a b-jet. I ignore experimental issues and focus on genuine NLO QCD effects







$$M_{\rm est}^2 = m_W^2 + \frac{2\langle m_{lb}^2\rangle}{1-\langle\cos\theta_{lb}\rangle}$$

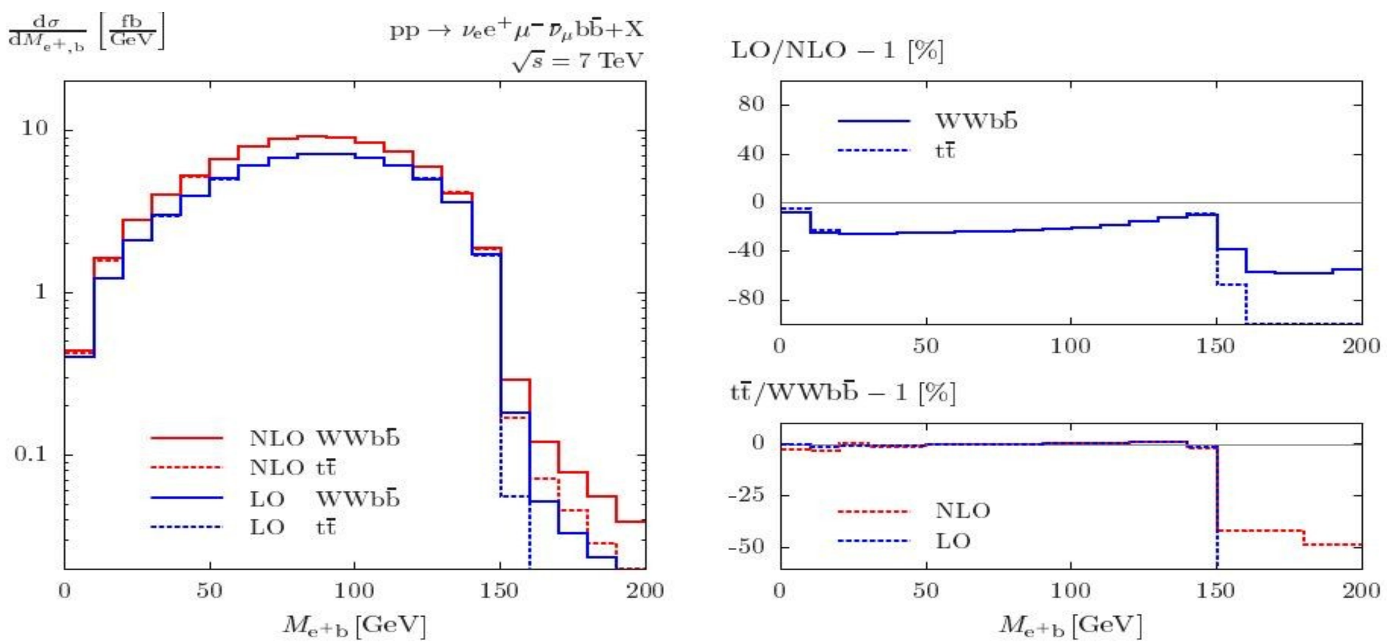
$$M_{\rm est}^{\rm LO} = 0.8262 m_t + 23.22 \text{ GeV}$$

$$M_{\rm est}^{\rm NLO} = 0.7850\, m_t - 28.70 \text{ GeV}$$

Many other short-distance distributions that may show sensitivity to the top quark mass are available through NLO QCD

Top quark mass measurements and kinematic distributions

- Are off-mass-shell effects important for the top quark mass determination?
- They should not be, although they do remove the sharp kinematic boundary that is present at leading order ; beyond the boundary off-shell effects and radiative corrections to them are quite significant
- However, most of the sensitivity to the top mass comes from the position of the peak, not from kinematic boundary



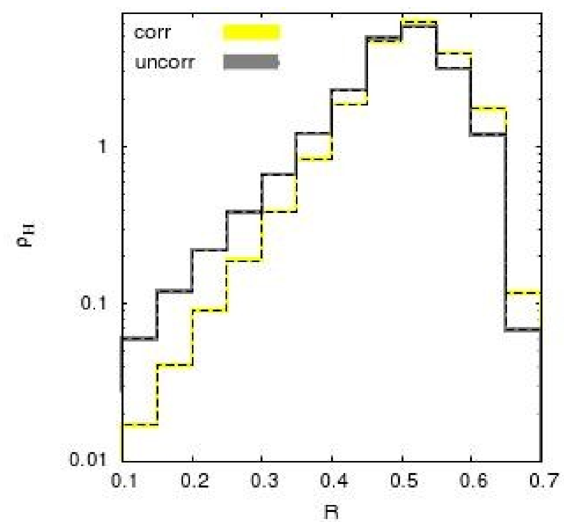
Denner, Dittmaier, Kallweit, Pozzorini, Schulze

Spin correlations and light stops

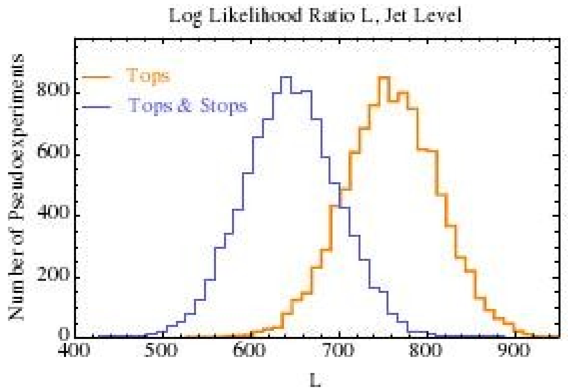
- Existence of top quark spin correlations was first established (3 sigma) by D0 collaboration using the likelihood variable R . Note small QCD corrections !

$$\mathcal{R}(\{x\}) = \frac{|M|^2_{\rm corr}(\{x\})}{|M^2|_{\rm uncorr}(\{x\}) + |M|^2_{\rm corr}(\{x\})}$$

- Light stops can hide underneath the ``top background'' but their presence can be revealed by studying the likelihood variable; smallness of radiative corrections is important



Likelihood variable distribution at the Tevatron



Likelihood at the 8TeV LHC after 20 inverse fb . 95% CL separation of a pure top events from a mix (12/1) of top/stop events. Stop mass is 200 GeV.

Han, Katz, Krohn and Reece

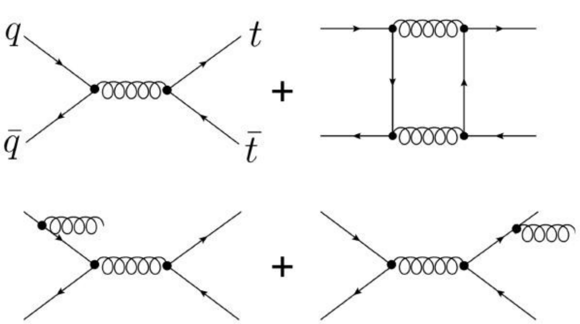
Top quark forward-backward asymmetry

- In proton anti-proton collisions, top quarks are produced with forward-backward asymmetry

$$A_{\rm lab}(t\bar{t}) = \frac{N_t(y>0) - N_t(y<0)}{N(y_t>0) + N_{(}y_t<0)} \qquad A_{\rm rest}(t\bar{t}) = \frac{N_t(\Delta y>0) - N_t(\Delta y<0)}{N(\Delta y>0) + N_{(}\Delta<0)}$$

- The asymmetry only appears at one-loop in QCD

Kuhn, Rodrigo



$$A^{\rm theory}_{\rm rest} = 0.07 \pm 0.006$$

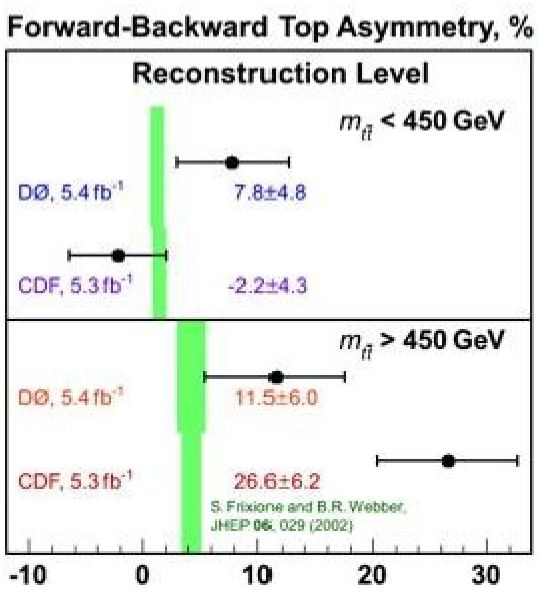
$$A_{\rm rest} = 0.15 \pm 0.05 \quad {\rm CDF}$$

$$A_{\rm rest} = 0.196 \pm 0.065, \quad {\rm D0}$$

The discrepancy with the SM prediction is about two standard deviations.

CDF finds larger asymmetries/discrepancy at large invariant masses and large rapidities. D0 does not confirm that finding. CMS and ATLAS do not see any indication of deviations from the Standard Model in the (related) charge asymmetry.

Many BSM interpretations of this result, some already ruled out by the LHC



Top quark asymmetries: lepton distributions

- The top quark asymmetry becomes much more convincing if we talk about quantities that can be measured directly
- Indeed, top asymmetry differs by a factor of two between the ``reconstruction level'' and the ``production level''; this itself causes doubts in the reliability of this result.
- On the other hand, leptons from the top quark sample should exhibit the forward-backward asymmetry which should show no difference between the ``production level'' and the ``reconstruction level'' !

TABLE VI. Lepton-based asymmetries.

	A^{l}_{FB} (%) Reconstruction level	Production level
Data	14.2 ± 3.8	15.2 ± 4.0
MC@NLO	0.8 ± 0.6	2.1 ± 0.1

Lepton-jets channel – large 3 sigma differencies between SM prediction and the measured asymmetry

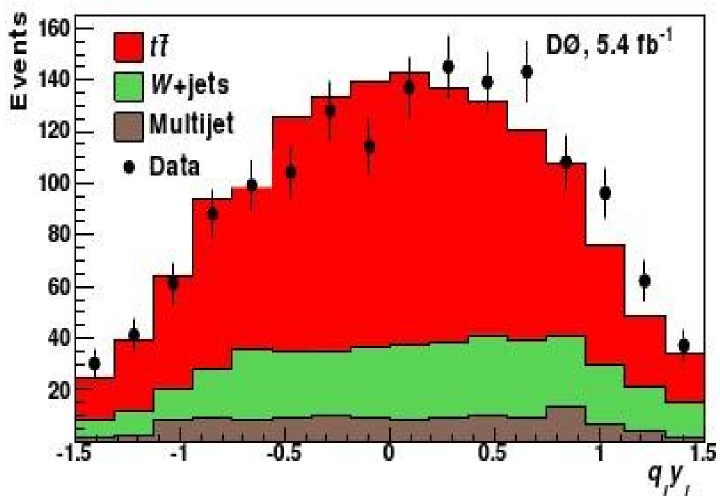
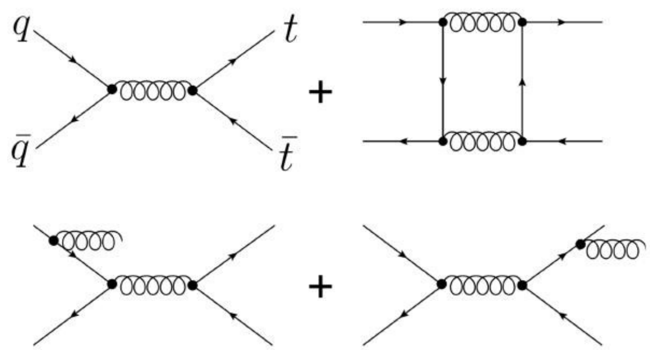


FIG. 4. The reconstructed charge-signed lepton rapidity.

However, a recent D0 measurement in the di-lepton channel finds a value $A_{\mathrm{FB}} = 5.8 \pm 5.1(\mathrm{stat}) \pm 1.3(\mathrm{syst})\%$ that is consistent with the Standard Model prediction $A_{\mathrm{FB}} = 4.7 \pm 0.1\%$

Asymmetries and QCD radiation

- The dependence of the SM asymmetry on QCD radiation is strong: QCD prediction for the asymmetry is positive – for the inclusive tt and negative – for the tt+jet.



Positive asymmetry

Negative asymmetry

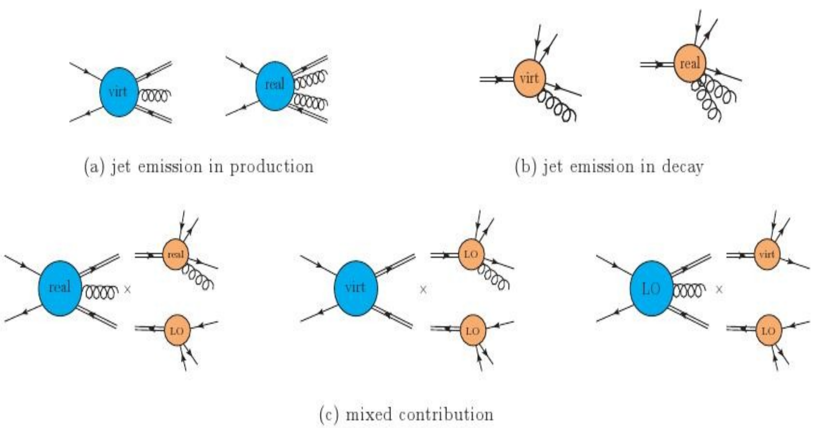
But, in reality both are infinite and can not be treated independently from each other

- Although it does not make sense to talk about the two contributions separately, the asymmetry may change , if significant cuts on additional radiation are applied. In fact, this is already seen in D0 data since they separate their events into the 0-jet bin and the 1-jet bin.

	$l+\geq 4$ jets	$e+\geq 4$ jets	$\mu+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
Raw N_F	849	455	394	717	132
Raw N_B	732	397	335	597	135
$N_{t\bar{t}}$	1126 ± 39	622 ± 28	502 ± 28	902 ± 36	218 ± 16
$N_{W+\text{jets}}$	376 ± 39	173 ± 28	219 ± 27	346 ± 36	35 ± 16
N_{MJ}	79 ± 5	56 ± 3	8 ± 2	66 ± 4	13 ± 2
A_{FB}(%)	9.2 ± 3.7	8.9 ± 5.0	9.1 ± 5.8	12.2 ± 4.3	-3.0 ± 7.9
MC@NLO A_{FB} (%)	2.4 ± 0.7	2.4 ± 0.7	2.5 ± 0.9	3.9 ± 0.8	-2.9 ± 1.1

Additional QCD radiation in top production

- There are many reasons to be interested in top quark pair production in association with a jet $pp \to t\bar{t} + j$
- The most reliable description of this process requires computation of $pp \to W^+W^-b\bar{b} + j$ but this is unrealistic.
- The best predictions – similar to top pair production case, should be based on the narow width approximation with the NLO QCD corrections to both production and decay
- Such a calculation is available; it extends previous computations of this process that were performed for stable top quarks
- I want to discuss briefly the significance of radiation in the decay and how to describe it



(a) jet emission in production (b) jet emission in decay

(c) mixed contribution

$$\mathrm{d}\sigma^{\mathrm{NLO}}_{t\bar{t}+j} \sim \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{t\bar{t}}}\mathrm{d}\Gamma^{\mathrm{LO}}_{\mathrm{t\bar{t}+1j}}$$

$$+\left(\mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+2j}\right)\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}}$$

$$+\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\left(\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+2j}\right)$$

$$+\mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}}$$

Mixed contribution; not sign-definite

Cross-sections for top pair and jet production at the Tevatron

- The cross-section for the Tevatron in lepton + jets channel

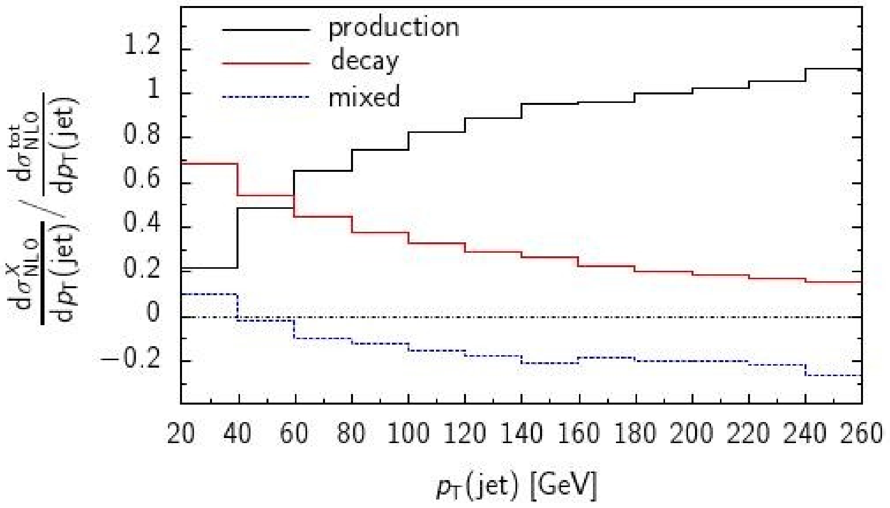
$$p_{\perp,l} = 20\ \mathrm{GeV},\ \ E_\perp^{\mathrm{miss}} > 20\ \mathrm{GeV},\ \ \Delta R = 0.5,\ \ p_{\perp,j} > 20\ \mathrm{GeV},\ \ H_\perp > 220\ \mathrm{GeV}$$

$$\sigma_{\mathrm{LO}} = 75.29^{\pm 49.2}_{-27.4}\ \mathrm{fb},\ ; \qquad \sigma_{\mathrm{NLO}} = 78.9^{+5.6}_{-5.6}\ \mathrm{fb}$$

$$\sigma_{\mathrm{LO}} = 75.29\ \mathrm{fb} = 46.33(\mathrm{Prod}) + 28.59(\mathrm{Dec})\ \mathrm{fb}$$

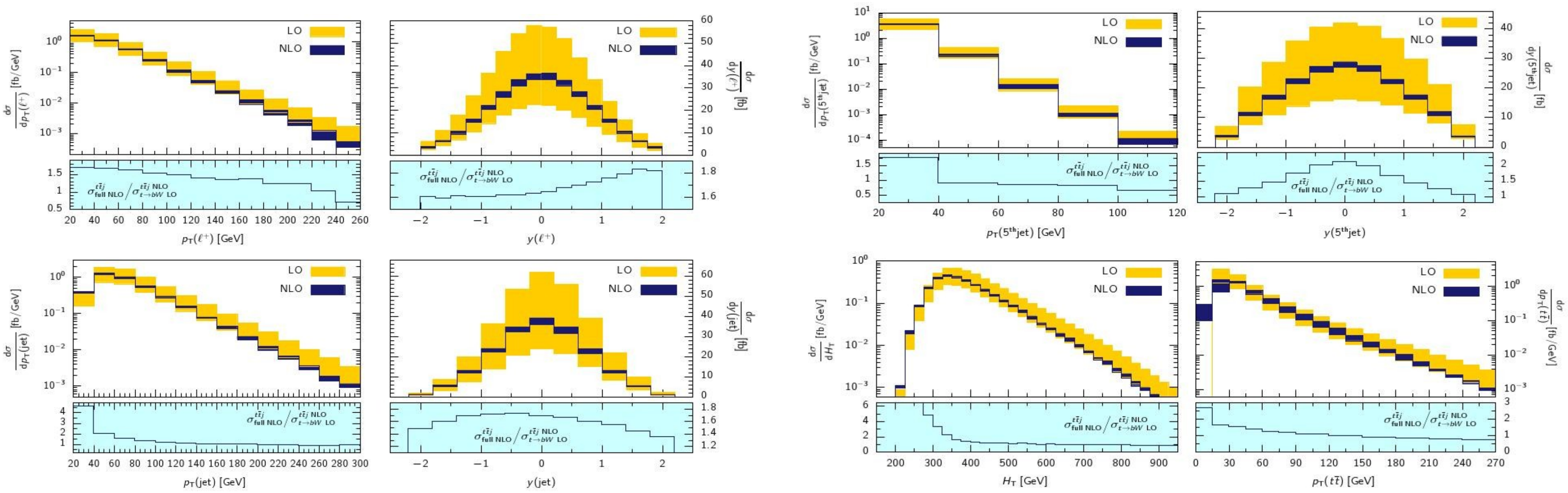
$$\sigma_{\mathrm{NLO}} = 78.9\ \mathrm{fb} = 47.7(\mathrm{Prod}) + 36.7(\mathrm{Dec}) - 5.5(\mathrm{Mix})$$

Note a small K-factor to the production, large K-factor to the decay and negative mixed contribution which compensates large correction to the decay. This is a complicated enough pattern so that estimates of QCD corrections to the full process based on K-factors to production for stable tops are not meaningful



Cross-sections for top pair and jet production

- Kinematic distributions for ttj in lepton + jets channel, at the Tevatron
- Note very large corrections to certain kinematic quantities due to radiation in the decay
- Note that the lepton rapidity distribution becomes symmetric and shows very small asymmetry (radiation in the decay is important for washing it out so strongly)



Cross-sections for top pair and jet production at the 7 TeV LHC

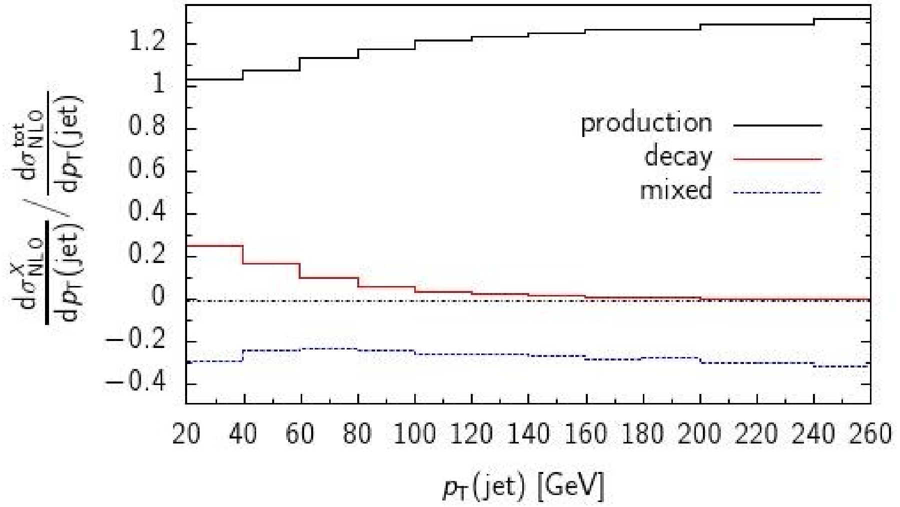
- The cross-section for the 7 TeV LHC in dileptons

$$p_{\perp,l} = 25\ \mathrm{GeV},\quad E_\perp^{\mathrm{miss}} > 50\ \mathrm{GeV},\quad \Delta R = 0.4,\quad p_{\perp,j} > 25\ \mathrm{GeV},$$

$$\sigma_{\mathrm{LO}} = 350.3\ \mathrm{fb} = 316.9(\mathrm{Prod}) + 33.4(\mathrm{Dec})\ \mathrm{fb}$$

$$\sigma_{\mathrm{NLO}} = 288\ \mathrm{fb} = 323(\mathrm{Prod}) + 40.5(\mathrm{Dec}) - 75.5(\mathrm{Mix})$$

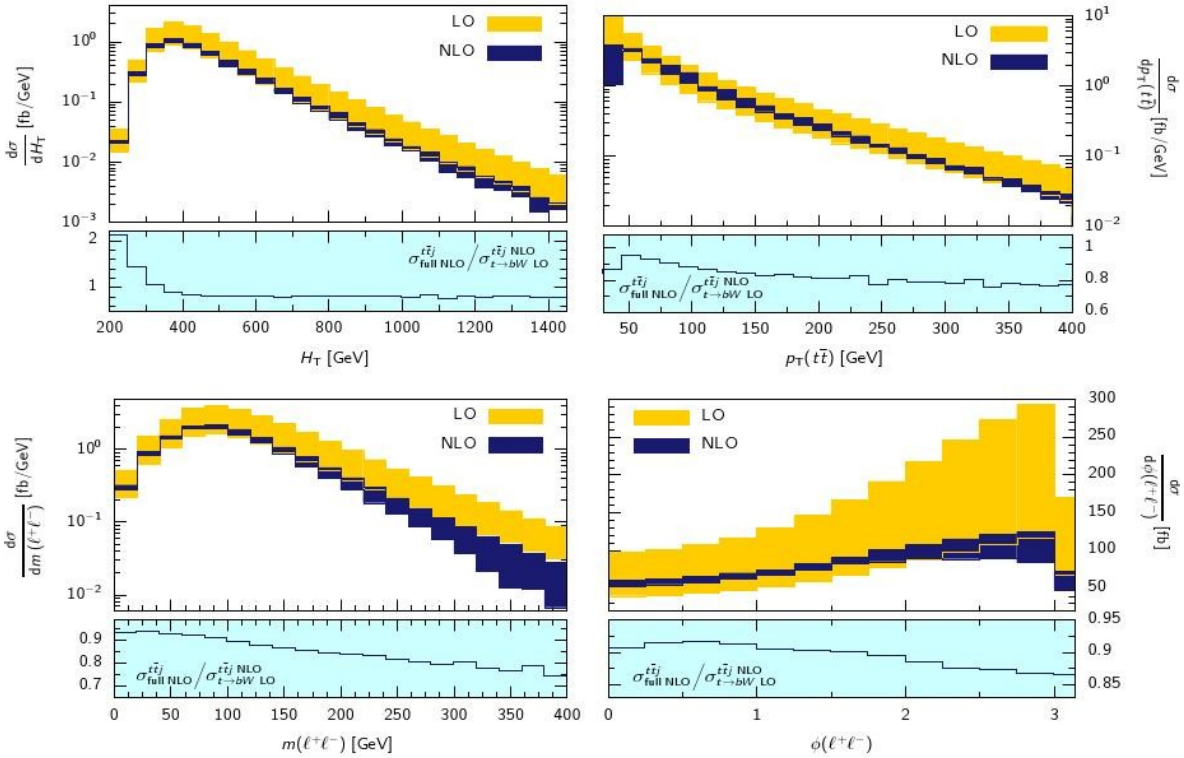
Radiation in the decay is less important but the interplay between different contributions to the NLO cross-section is different; if the K-factor for the production is used, the estimate of the full NLO cross-section will be quite off



Radiation in the decay shuts off but negative mixed contribution survives; it will be balanced by the overall LO → NLO change in the top width

Cross-sections for top pair and jet production

- Kinematic distributions for ttj in lepton + jets channel, at the 7 TeV LHC
- Radiation in the decay is less important than at the Tevatron but the mixed contribution appears to be important even at high transverse momentum (this is essentially normalization)



Conclusions

- In the past 3-4 years calculations appeared that provide true NLO QCD accuracy for kinematic distributions of top quark decay products and jets in pp → tt and pp → ttj
- The most advanced results are in the form of parton level ``integrators'' – unweighted events can not be generated but any infra-red-safe kinematic distribution can be obtained
- These computations rely on the narrow width approximation whose validity was convincingly verified for top pair production
- There is no parametric suppression of NLO QCD effects in top quark decays; whether or not they are important depends on the physics question that is studied
- The availability of kinematic distributions at NLO QCD should allow us to do better physics; I gave you some examples including the top quark mass determination, lepton asymmetries, stop searches, but of course other things can be done