Top quark physics at hadron colliders with QCD corrections to production and decay

Kirill Melnikov

Johns Hopkins University

Workshop ``Heavy Particles at the LHC''

ETH Zurich, January 5-8, 2011

Outline

- Introduction
- Mass measurements
- Spin correlations
- Top quark pair production in association with a jet
- Top quark pair production in association with a photon
- Summary

Introduction

- Top quarks differ from other known quarks
- Experimental program for studying top quarks is in high gear at the Tevatron and is already up to speed at the LHC
- Production cross-sections of top quark pairs are significant
  - 7 pb at the Tevatron
  - 150 pb at the 7 TeV LHC
- Some Tevatron measurements are still limited by statistical uncertainties, but this is not an issue for the LHC where statistics is overwhelming
- We are well-positioned to begin high-precision studies of the top quark properties at the LHC next year

Top quarks are not stable

- For experimentalists there is no such thing as ``a stable top quark'' but theorists often use this concept as a simplifying assumption
- This simplification has a price since -- if top quarks are stable -- their production and decays are totally independent
- To learn anything about top quarks -- or to get rid of backgrounds related to them -- we must deal with their decay products
- A unique feature of top quarks are their short lifetimes, about one quarter of a Fermi/c. This means that top quarks decay before they have time to hadronize

Top quarks are not stable

- For real top quarks, production and decay stages are tied together
- Top quark instability influences physics in several ways
  - kinematic features of top and anti-top decay products are correlated
  - QCD radiation can occur in top quark decays
  - kinematic cuts are applied to top quark decay products
  - top quarks are produced off-shell
- In what follows I will discuss these features and describe their relative importance for top quark physics

Top quarks do not get depolarized

- Once produced, top quarks interact with vacuum QCD fields. Those fields are soft - $\mathcal{O}(\Lambda_{\rm QCD}^2)$ - and they do not change top quark polarization significantly

$$\frac{|\Delta \vec{S}|}{|\vec{S}|} \sim \frac{\Lambda_{\rm QCD}}{m_t} \quad \frac{\Lambda_{\rm QCD}}{\Gamma_t}$$

- As the result, top quarks keep their polarizations from production to decay
- Because top quark polarization influences kinematic distributions of its decay products, we need to consider top pair production and their decays at the same time (spin correlations)
- This is straightforward at leading order in QCD, but less so at next-to-leading order

Total cross-sections are unobservable

- The simplest quantity in top quark physics is the top pair production cross-section. We say that it is known at NLO QCD and that the NNLO QCD is the next frontier
- But total cross-section is not measurable. It is derived from the number of observed events and the theoretical acceptance which is the fraction of events that passes selection cuts
- It is not consistent to use leading order acceptances in experimental analysis, to obtain top quark pair production cross-sections that are later compared to (N)NLO theory predictions
- The quantity that the theory should provide and that should be compared to experiment is e.g. the top quark pair production cross-section after cuts on top quark decay products

Top quark mass from kinematic distributions

- High precision top quark mass measurements are performed at the Tevatron and are planned at the LHC. The target precision is about 1 GeV; systematic uncertainties are the limiting factor
- Clean measurements of the top quark mass must involve top decay products and explore correlations between their kinematics and the top quark mass
- QCD radiation in top quark decays becomes important
- Uncertainties of those measurements are often estimated with parton shower event generators which is a very questionable procedure

Non-factorizable corrections

- Corrections that do not mix production and decay stages are called factorizable; the ones that do mix them -- non-factorizable
- Non-factorizable QCD corrections and their close relatives -- color reconnection effects - are non-trivial but it is believed that their general features are well understood
- Non-factorizable corrections do not decouple, in spite of the fact that production and decay are separated by a ``macroscopic'' time intervals

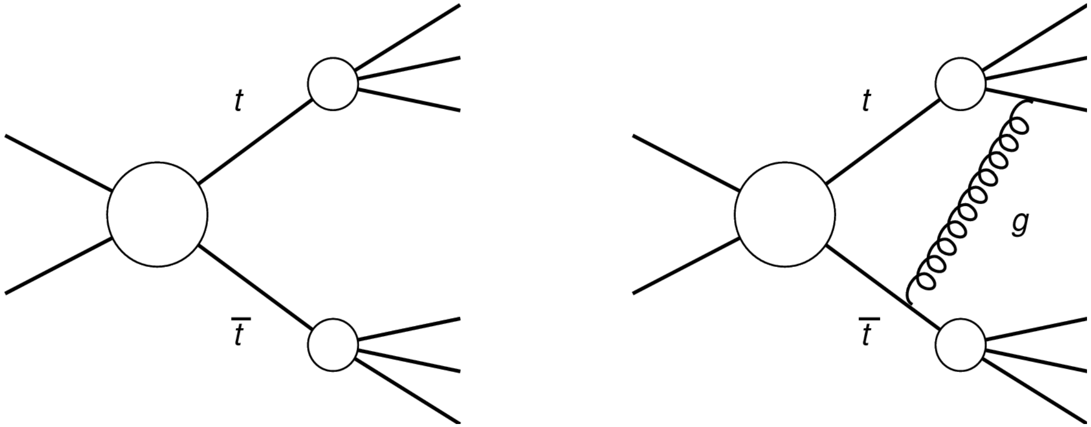


Figure taken from a review by Bernreuther

Fadin, Khoze, Martin
K.M., Yakovlev
Berends, Beenakker,
Chapovsky, Pittau

Non-factorizable corrections

- Many features of non-factorizable corrections are understood:
  - they may induce $\mathcal{O}(\alpha_s)$ corrections in invariant mass distributions
  - they are determined by gluons with momenta comparable to the top quark width (implies larger value of the strong coupling constant)
  - they are enhanced at the threshold, but they get screened at high-energies due to ``charged current conservation''
  - once the integration over invariant masses is performed, those corrections become small $\mathcal{O}(\alpha_s) \Rightarrow \mathcal{O}(\alpha_s \Gamma_t / m_t)$
- Typical observables in top quark pair production involve integration over broad ranges of invariant masses and are not threshold dominated. Hence, it is to be expected that non-factorizable corrections to top quark pair production at hadron colliders are tiny

The goal

- Given these remarks, we would like to have a description of the top quark pair production, possibly in association with jets, photons, Z-bosons or Higgs boson, and top quark decays, subject to the following conditions
  - accurate through NLO QCD
  - top quarks are on the mass shell (error $\mathcal{O}(\Gamma_t/m_t)$)
  - top decays (t → Wb) are included, ideally with radiative corrections
  - all spin correlations are accounted for
  - arbitrary restrictions on the kinematics of final state particles, originating from top decays, can be applied.

Top pair production: state of the art

- Classic calculations of NLO QCD corrections to top pair production process were performed almost twenty years ago

  Dawson, Ellis, Nason, Beenaker, Mertig, van Neerven,, Schuler, Smith, Mangano, Ridolfi

- QCD and EW corrections to spin correlations in top pair production defined in a particular way are known since 2000

  Bernreuther, Brandenburg, Si, Uwer

- In the past two years results for QCD corrections to top quark pair production and decay were obtained , including spin correlations and allowing for arbitrary selection cuts

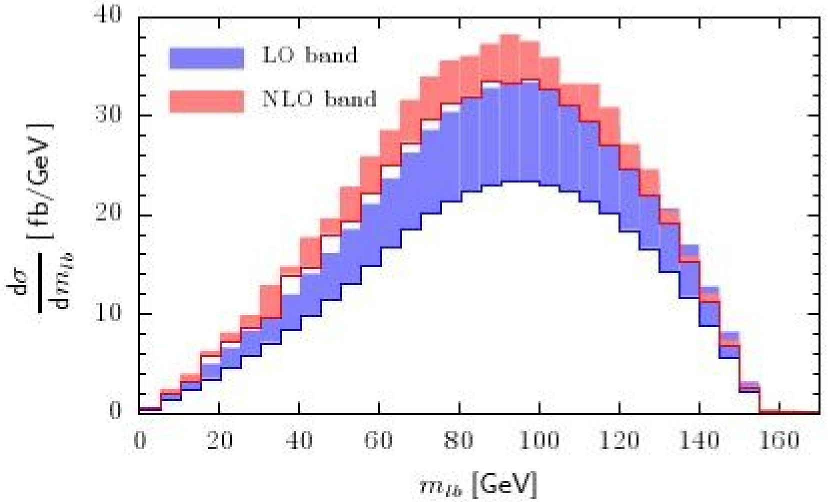
  Schulze, K.M.,
  Bernreuther, Si, Ellis, Campbell

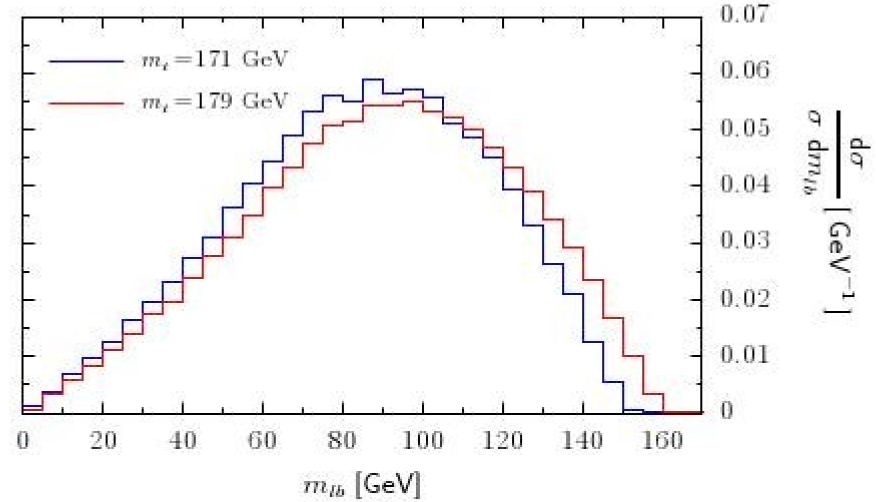
- Very recently NLO QCD corrections to top quark pair production, including off-shell effects (WWbb final state) were computed, confirming that such effects are small

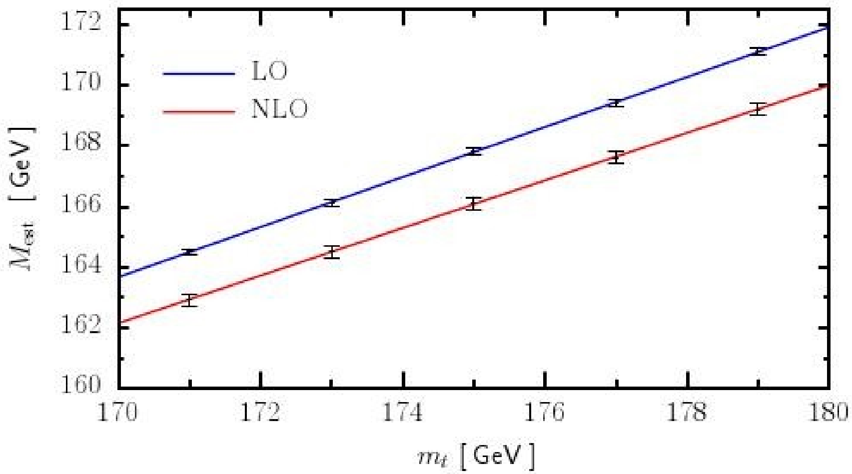
  Denner, Dittmaier, Kawlert, Pozzorini
  Bevilacqua, Czakon, von Hameren, Papadopoulos, Worek

Top quark mass measurements

- An invariant mass distribution of a lepton and a b-jet is correlated with the top quark mass. It can be computed through NLO QCD







Biswas, Schulze, K.M.

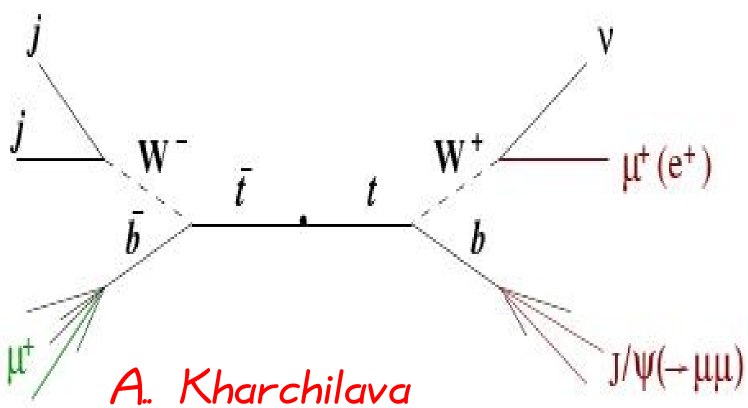
$$M^2_{\rm est} = m^2_W + \frac{2\langle m^2_{lb}\rangle}{1-\langle\cos\theta_{lb}\rangle}$$

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

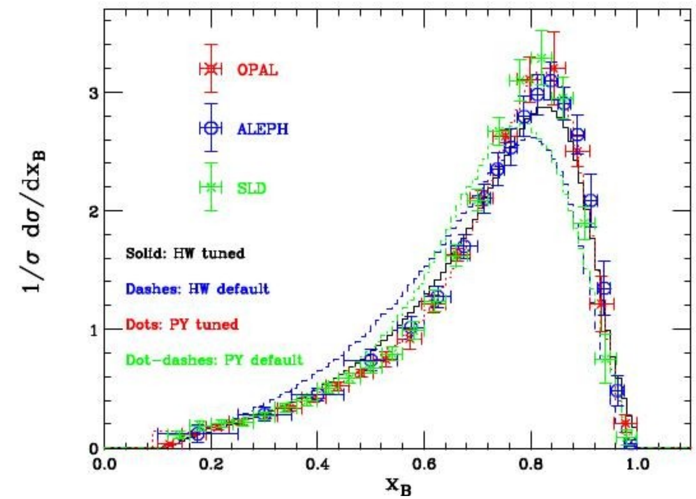
$$M^{\rm NLO}_{\rm est} = 0.7850 m_t + 28.70 \text{ GeV}$$

Top quark mass measurements

- One of the smallest error on the top quark mass can be obtained from the measurement of the invariant mass distribution of a J/ψ meson and a lepton from top quark decay



A.. Kharchilava
R. Chierici, A. Dierlamm



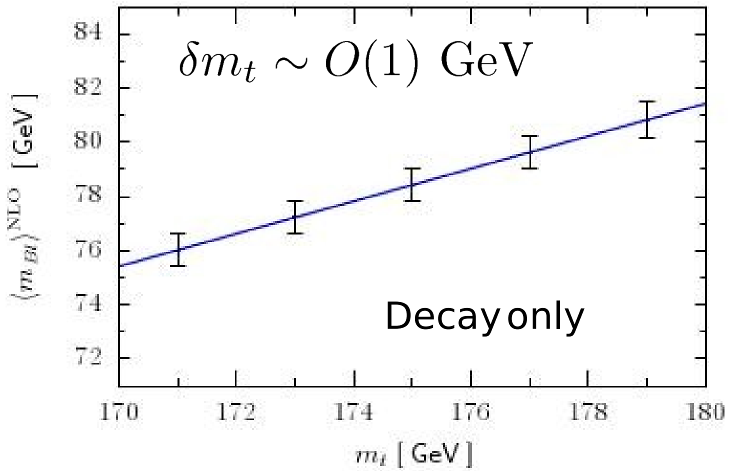
- Many studies over the years to assess the systematic uncertainty; rely on parton showers (restricted to b → B fragmentation)

$$\langle m_{Bl} \rangle_{\text{Pythia}} = 0.59\ m_t - 24.11\ \text{GeV}$$
$$\langle m_{Bl} \rangle_{\text{Herwig}} = 0.61\ m_t - 25.31\ \text{GeV}$$

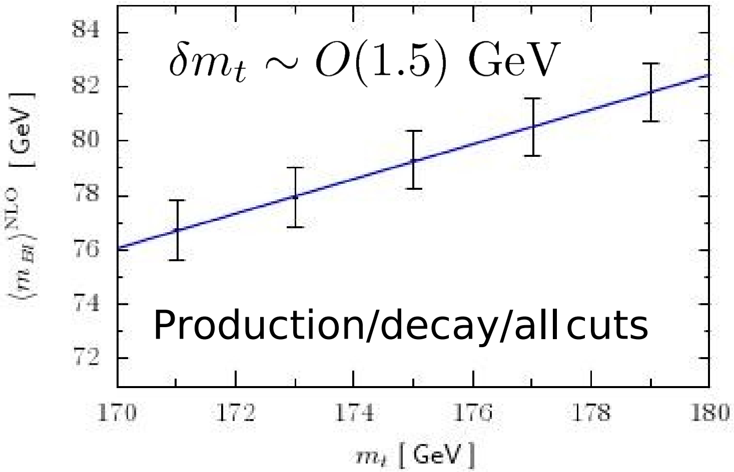
Mangano, Seymour, Corcella, Mescia

Top quark mass measurements

- But we don't need to use parton showers, we can compute the required quantity in QCD perturbation theory..
- We need NLO QCD corrections to top production and decay and we need b → B fragmentation function; it is known from LEP *Cacciari, Corcella, Mitov*
- We can estimate the uncertainty by considering different fragmentation functions, different parton distribution functions, check the scale stability of the result, etc.



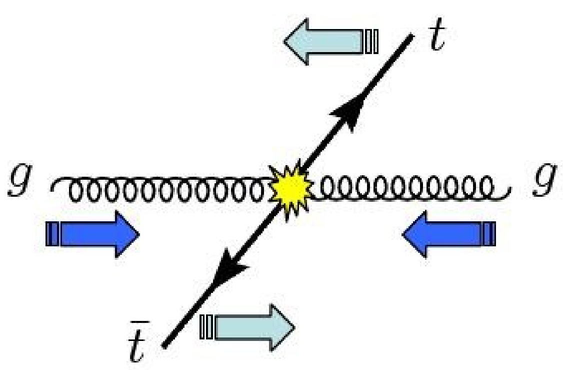
$$m_t = 0.601 m_t - 26.7 \text{ GeV}$$



$$m_t = 0.635 m_t - 32.12 \text{ GeV}$$

Spin correlations

- If top quarks are produced in a polarized state, they decay in a correlated fashion
- Polarization of top quarks differ at the Tevatron and the LHC because of different production mechanisms
  - Tevatron: qq → g → tt J(tt) = 1 ↔ L=0, S=1 → allinged spins of two tops;
  - LHC: gg->tt (color octet) J(tt) = 0 ↔ L=0, S=0, spins of two tops are anti-parallel
- Since positron follows the top quark spin direction and electron prefers to go in the direction opposite to the spin of the anti-top, leptons like to have parallel (anti-parallel) momenta at the LHC (Tevatron)



Spin correlations

- Spin correlations are often discussed in the context of lepton angular correlations in specially chosen reference frames such as the rest frames of top quarks or their zero momentum frame

  Mahlon, Parke, Stelzer, Willenbrock, Brandenburg, Bernreuther et. al

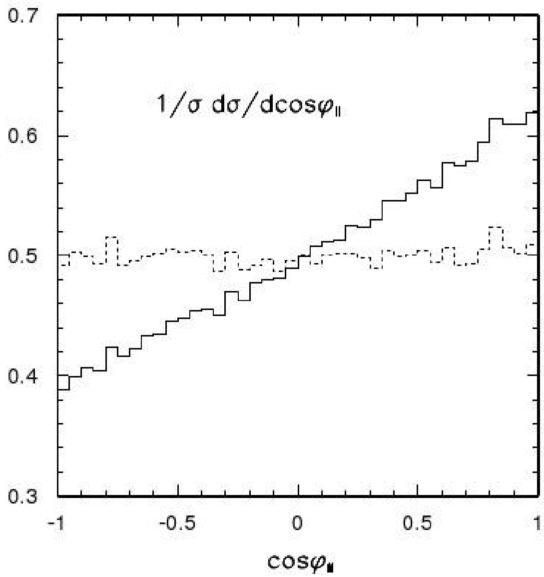
- The effect of spin correlations on these distributions is pronounced but it is not easy to measure them

$$\frac{\mathrm{d}\sigma}{\sigma \mathrm{d}\cos\varphi} = \frac{1}{2} - \frac{D}{2}\cos\varphi$$

$$\frac{\mathrm{d}^2\sigma}{\sigma \mathrm{d}\cos\theta_+ \mathrm{d}\cos\theta_-} = \frac{1-\kappa\cos\theta_+\cos\theta_-}{4}$$

$$\kappa = 0.60 \pm 0.50(\mathrm{stat}) + 0.16(\mathrm{syst})$$

CDF measurement, 2010

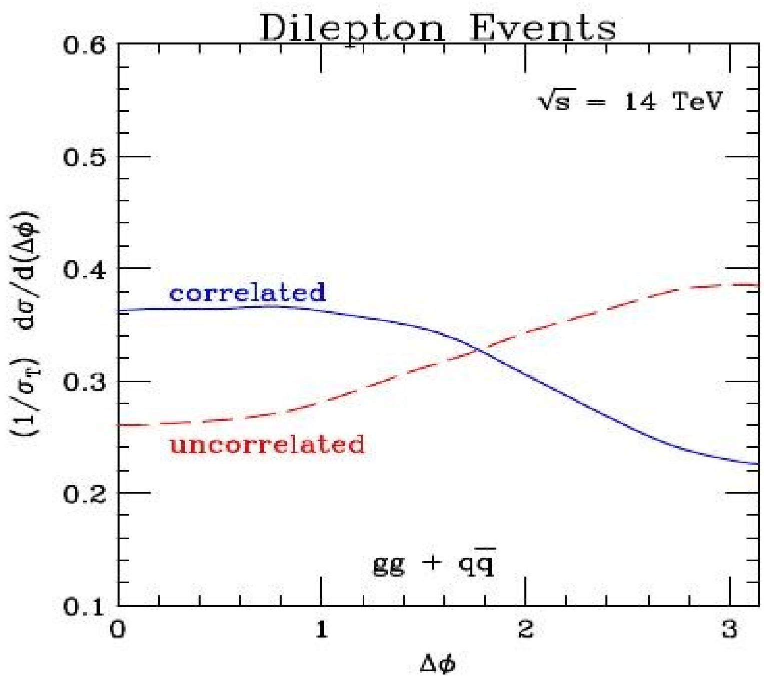


Bernreuther and Si

Spin correlations in the lab frame

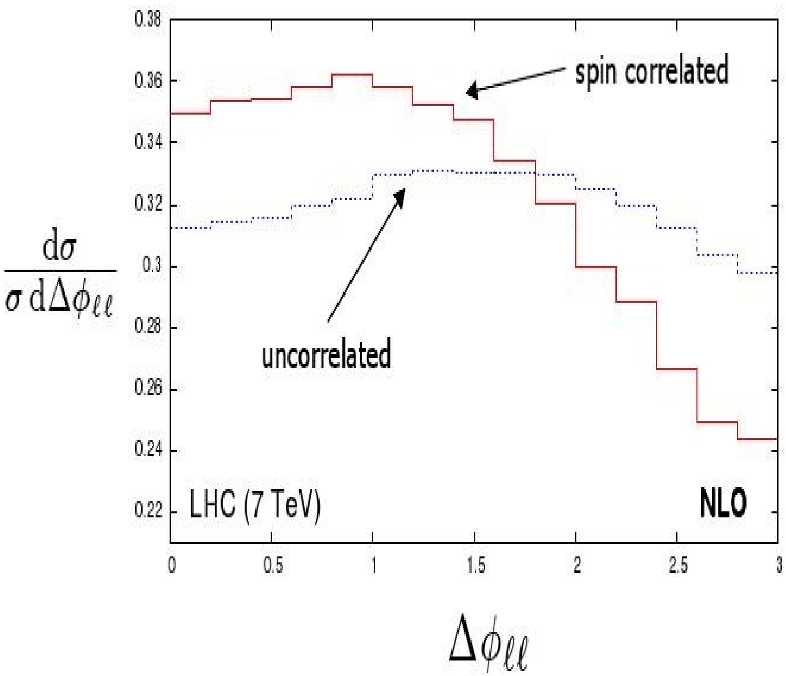
- It is possible to use the opening angle of the two leptons in the lab frame, as a way to prove the existence of spin correlations provided that kinematics is restricted to threshold

Mahlon, Parke



$M_{t\bar{t}} < 400$ GeV

Mahlon and Parke



$p_{\perp,l} < 50$ GeV

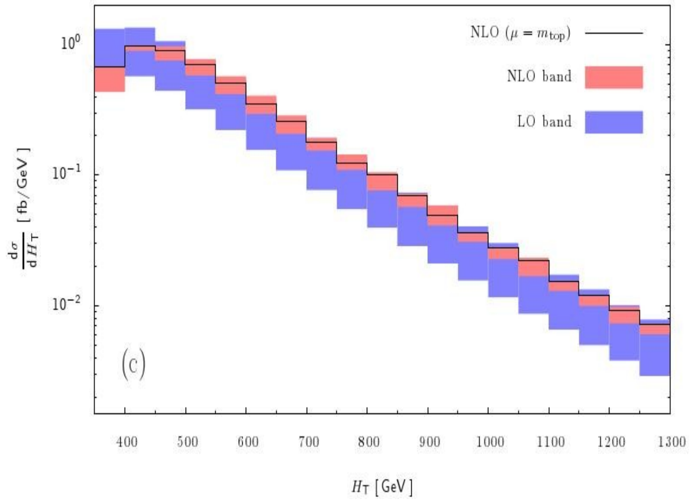
$m_{l^+l^-} < 100$ GeV

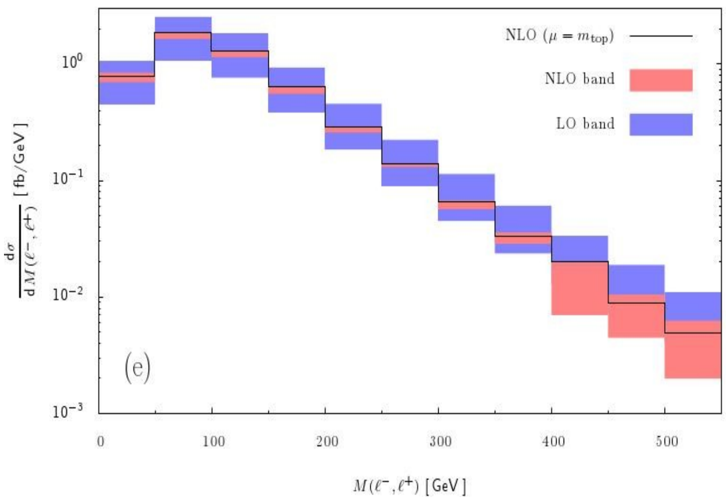
Schulze, K.M.

Top quark pair with one jet

- Top quarks are often produced in association with hard jets. NLO QCD corrections recently computed Dittmaier, Uwer, Weinzierl
- For proper background rejection/acceptance calculations, need to include decays of top quarks
- For the 7 TeV LHC, we require 3 or more jets, two leptons and missing energy (no QCD-radiative top decay included)

$p_{\perp,l} > 20$ GeV, $p_{\perp,\text{miss}} > 40$ GeV. $p_{\perp,j} > 50$ GeV; $p_{\perp,b} > 20$ GeV;





Schulze, K.M.

Understanding the charge asymmetry

- There is an interesting story in $p\bar{p} \to t\bar{t} + j$ production, related to forward-backward asymmetry of top quarks

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

- In $p\bar{p} \to t\bar{t}$, the asymmetry appears at next-to-leading order only $A_{\rm FB}(t\bar{t}) = 0.05$; it is small compared to CDF and D0 measurements
- In $p\bar{p} \to t\bar{t} + j$, the asymmetry appears at LO already; NLO prediction for $p\bar{p} \to t\bar{t} + j$ gives NLO asymmetry
- The result is peculiar -- asymmetry receives large positive correction

$$A_{\rm FB}(t\bar{t} + j)^{\rm LO} \approx -8\ \% \ \ \Rightarrow A_{\rm FB}(t\bar{t} + j)^{\rm NLO} \approx -2.3\ \%.$$

Does this result imply that a similar shift in the asymmetry occurs in the top quark pair production ?

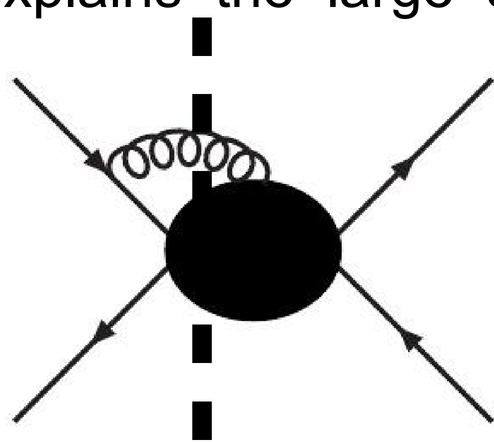
Understanding the charge asymmetry

- How does the leading order asymmetry depend on the jet $p_\perp$ cut?

$$\sigma_{\mathrm{t\bar{t}j}} \sim \frac{2C_F\alpha_s}{\pi}\ln^2\frac{m_t}{p_{\perp,j}}\,\sigma_{t\bar{t}}. \quad \sigma(y_t>0)-\sigma(y_t<0) \sim \frac{C_F\alpha_s}{\pi}\ln\frac{m_t}{p_{\perp,j}}\sigma_{t\bar{t}}$$

$$A_{\mathrm{FB}} = \frac{\sigma(y_t>0)-\sigma(y_t<0)}{\sigma_{t\bar{t}j}} \sim \left[\ln\frac{m_t}{p_{\perp,j}}\right]^{-1}$$

- The asymmetry is generated by the soft jet at leading order, but at NLO it can be generated by the hard exchange while the soft jet produces double logarithmic enhancement.. This explains the large shift at NLO.



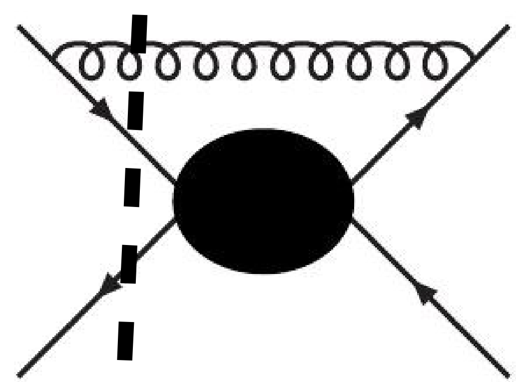
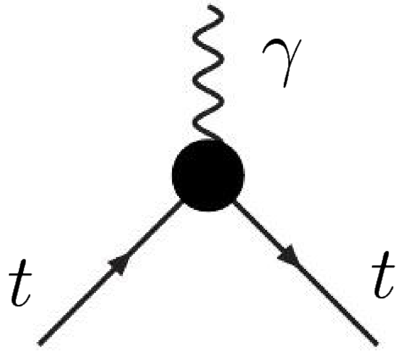


Diagram that shifts the asymmetry by +5 % at NLO

Top quark pair in association with a photon

- Production of a top quark pair in association with a photon allows us to directly probe electromagnetic properties of top quarks
  Baur, Buice, Orr
- A (rather weak) constraint on the top quark charge from D0
- CDF observation of the $p\bar{p} \longrightarrow t\bar{t}\gamma$ production
- Measurement of the coupling is, largely, a counting experiment; so that radiative corrections may be important



$$= -iQ_t e \, \epsilon_\mu \, \bar{u}_t \, \hat{\Gamma}^\mu \, u_t$$

$$\hat{\Gamma}^\mu = -\gamma_\mu + a_t \frac{i\sigma_{\mu\nu} q_\nu}{2m_t}$$

Top quark pair in association with a photon

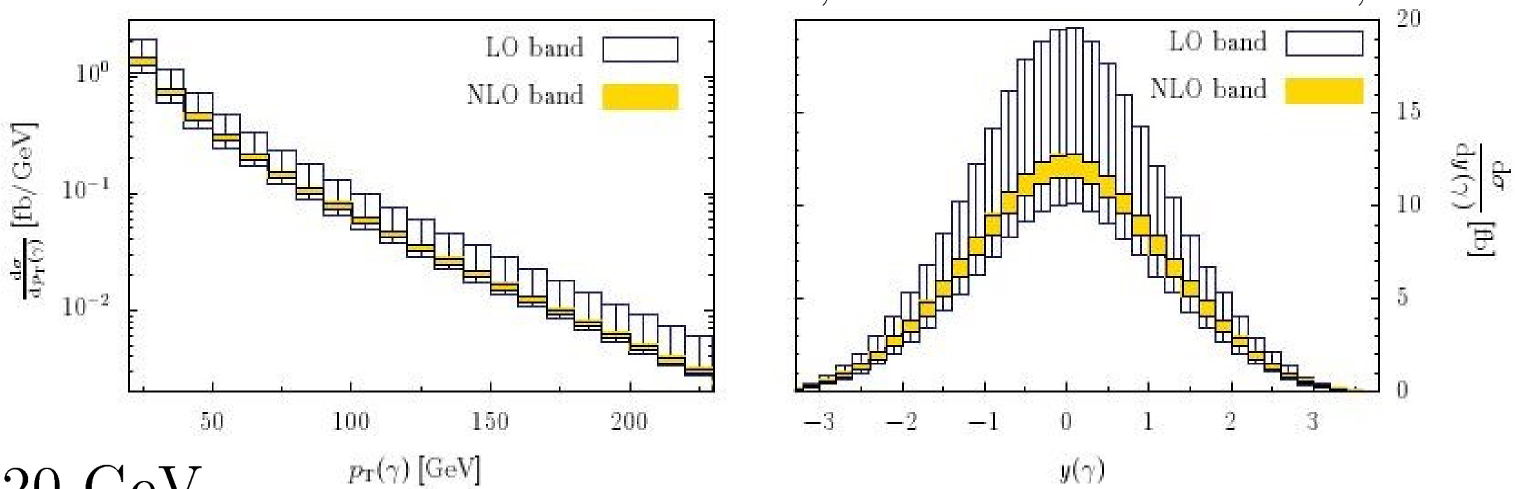
- Stable top quarks; NLO QCD prediction for the cross-sections

Schulze, Scharf, K.M.

Tevatron: $\sigma_{\rm LO} = 39.97^{+16.77}_{-10.91}$ fb $\Rightarrow \sigma_{\rm NLO} = 37.6^{+0.9}_{-3.7}$ fb

LHC (14 TeV): $\sigma_{\rm LO} = 1.957^{+0.642}_{-0.446}$ pb $\Rightarrow \sigma_{\rm NLO} = 3.034^{+0.469}_{-0.4}$ pb

- K-factors at the Tevatron and the LHC are similar to top quark pair production
- The forward-backward asymmetry of top quarks is reduced at NLO by about five percent: $A_{t,\rm LO} = -17.2~\% \Rightarrow A_{t,\rm NLO} = -11.9~\%$



$p_{\perp,\gamma} > 20$ GeV

Similar calculation was recently done by Wen-Gan Ma et. al

Top quark pair in association with a photon

- Is it sufficient to work with stable top quarks? It is not clear because photon radiation can occur in decays of the top quarks. Since light particles tend to radiative more, it may have non-trivial consequences

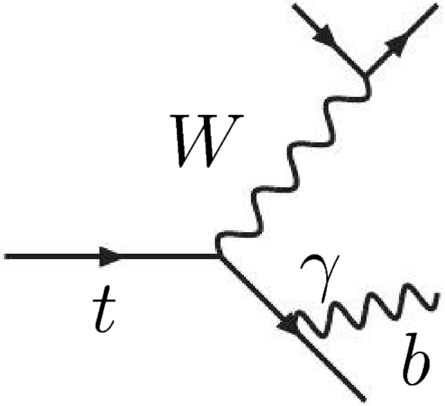
- For example, the CDF collaboration uses the following cuts

$$p_\perp^{\rm lep} > 20~{\rm GeV},~~p_\perp^{\gamma} > 10~{\rm GeV}, p_{\perp,j} > 15~{\rm GeV}$$

$$\eta_{\rm lep} < 1.1,~~|\eta_\gamma| < 1.1,~~|\eta_j| < 2. \qquad \Delta R_{j\gamma} > 0.4, \quad \Delta R_{l\gamma} > 0.4.$$

$$H_{\rm perp} > 200~{\rm GeV},~~E_\perp^{\rm miss} > 20~{\rm GeV}.$$

$$K = \frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}} = \begin{cases} 0.94 & \text{stable tops} \\ 0.92 & \text{CDF cuts} \end{cases}$$



The K-factor applied in the original CDF analysis was 1.1

$$\sigma_{\rm exp} = 0.15 \pm 0.08~{\rm pb} \qquad \sigma_{\rm th} = 0.068 \pm 0.01~{\rm pb}$$

Conclusions

- I discussed top quark pair production and decay that includes spin correlations and radiative corrections.
- This is an accurate framework to describe top quark physics; it generalizes to more complex processes; non-factorizable corrections are not important
- Top quark pair production and decay is important for
  - acceptances / background rejections
  - top quark mass measurements
  - spin correlations
- Large radiative correction to forward-backward asymmetry in $p\bar{p} \to t\bar{t} + j$ does not imply large positive corrections to the asymmetry in $p\bar{p} \to t\bar{t}$
- NLO QCD effects in $p\bar{p} \to t\bar{t}\gamma$ including top quark decays and radiation in the decays are computed