Topics in top quark theory

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Aspen Winter workshop
``Data from New Energy Frontier''

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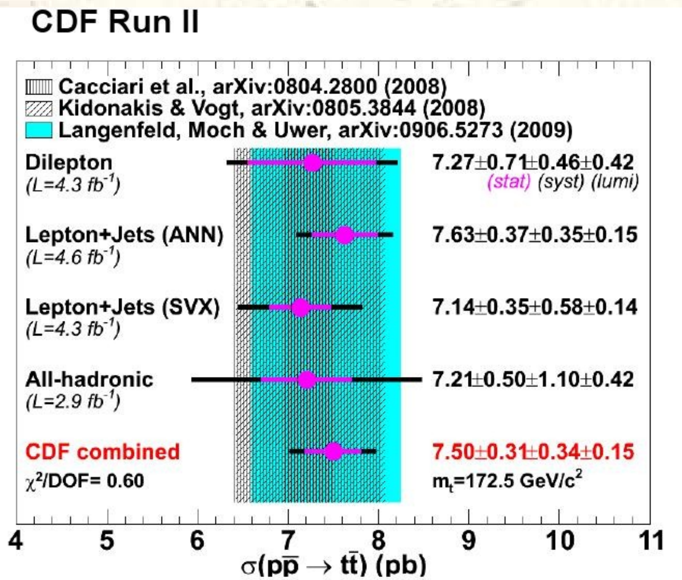
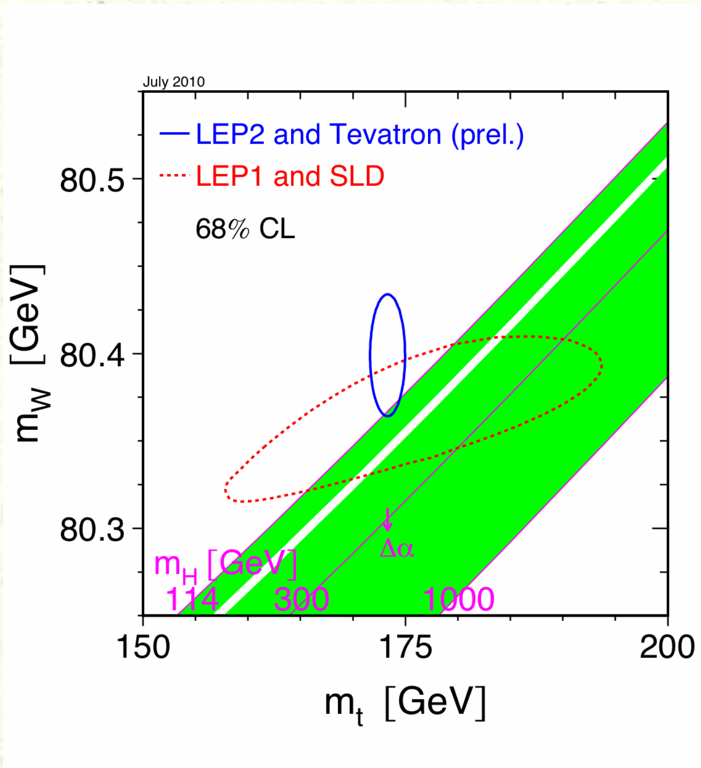
Outline

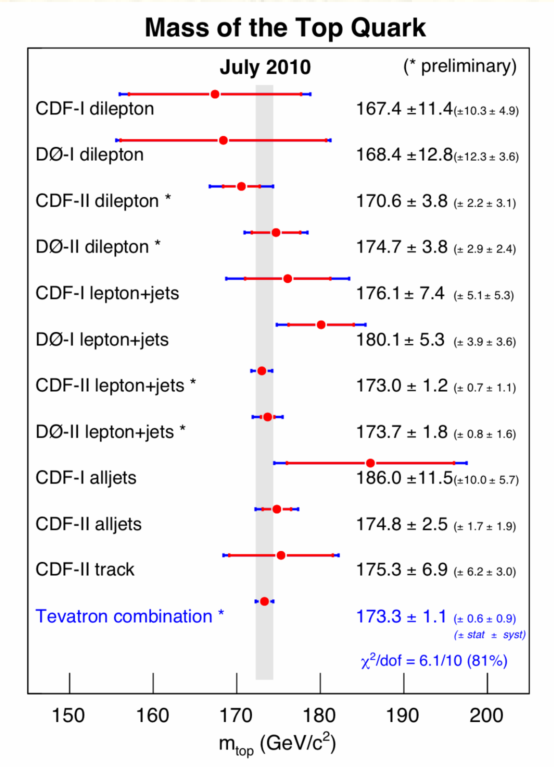
- Introduction
- The role of top quark instability
- Mass measurements
- Spin correlations
- Asymmetries
- Electromagnetic couplings
- Conclusions

Introduction

- Thanks to the Tevatron experiments top quark physics is associated with high precision







Introduction

- We often say that things can be only better a the LHC and they will be eventually, but perhaps not immediately

	σ (pb)	$\delta\sigma$ (pb)	comment
ABKM09	139.55	7.96	combined PDF and α_s
CTEQ6.6	156.2	8.06	combined PDF and α_s *
GJR08	169	6	PDF only
HERAPDF1.0	147.31	+5.18 -13.76	combined PDF and α_s**
MSTW08	168.1	+7.2-6.0	combined PDF and α_s***
NNPDF2.0	169	7	combined PDF and α_s ****

Gluon annihilation becomes a dominant channel; gluon PDFs are poorly known

Report of the PDF4LHC, talk by J. Stirling

Top quarks are not stable

- High precision top quark physics means higher orders, at least QCD
- Top quarks are unstable → we must deal with their decay products
- Top quark instability is often ignored especially in theoretically advanced (NLO, NNLO) computations where spin-average cross-sections are calculated
- Starting from these result, we can put top quark decays back in, in the narrow width approximation
- However, we will miss quantum mechanical coherence of top quark wave functions in the production and the decays (spin correlations)

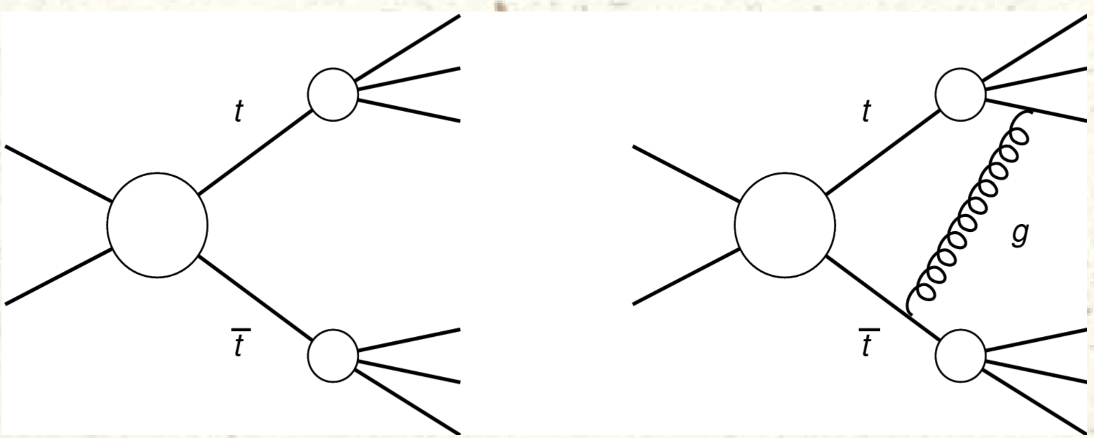
Top quarks are not stable

- Top quark production and decays are tied together
  - kinematic features of top and anti-top decay products are correlated
  - QCD radiation can occur in top quark decays and in top production
  - kinematic cuts are applied to top quark decay products
  - top quarks can be produced off the mass shell
  - non-factorizable corrections
- How do these effects influence top quark observables?

Top quarks live long enough to justify the narrow width approximation but not so long as to enable indepenent description of the production and decay stages

Non-factorizable corrections

- QCD corrections that do not connect production and decay stages of top quarks are called factorizable; the ones that do, are called non-factorizable
- Non-factorizable effects (and their relatives – color reconnection effects) are non-trivial but believed to be well-understood
- Non-factorizable corrections do not vanish in the limit when the lifetime of an unstable particle increases – highly unusual feature!



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

Non-factorizable corrections

- Non-factorizable corrections
  - induce $\mathcal{O}(\alpha_s)$ to invariant mass distributions
  - are determined by gluons with momenta comparable to the top quark width
  - are enhanced at the threshold and they get screened at high energy, essentially due to color current conservation
  - after integrating over the invariant masses, become small

$$\mathcal{O}(\alpha_s) \Rightarrow \mathcal{O}(\alpha_s \Gamma_t / m_t)$$

- We should expect non-factorizable contributions to top quark pair production processes at a hadron collider to be small

The framework

- At leading order, there is no issue with including top quark decays, but this approach is not feasible for NLO and NNLO QCD computations
- Realistic, accurate and feasible framework for top quark physics
  - top quarks are produced on the mass shell but then decay
  - all spin correlations are accounted for
  - description of the production process through N(N)LO QCD
  - description of the decay process through N(N)LO QCD
  - access to kinematics of final state particle

Theory of top quark pair production

- Twenty five years ago – classic computations of NLO QCD corrections to stable top quarks
  Dawson, Ellis, Nason, Beenaker, Mertig, van Neerven,, Schuler, Smith, Mangano, Ridolfi
- Ten years ago NLO QCD/EW corrections to spin correlations in top quark pair production defined in a particular way
  Bernreuther, Brandenburg, Si, Uwer
- Two years ago -- top quark pair production through NLO QCD with spin correlations and arbitrary selection cuts on the final states
  Schulze, K.M., Bernreuther, Si, Ellis, Campbell
- Two months ago – NLO QCD corrections to top quark pair production including all off-shell and non-factorizable effects
  Bevilacqua, Czakon, von Hameren, Papadopoulos, Worek
  Denner, Dittmaier, Kawlert, Pozzorini
- Many associated production processes – ttj, ttjj, ttbb, ttH, ttZ – are still only known in the approximation of stable top quarks
  Dawson, Reina, Wackeroth, Jackson, Dittmaier, Kramer, Petriello, Lazopoulis, McElmurry,Pozzorini, Czakon, Worek, Papadopoulos, Denner, Kawlert. Uwer, Weinzierl

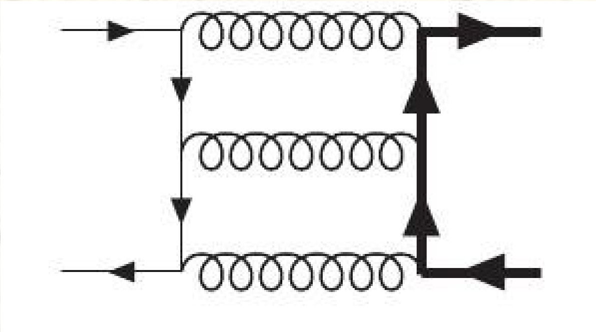
Theory of top quark pair production

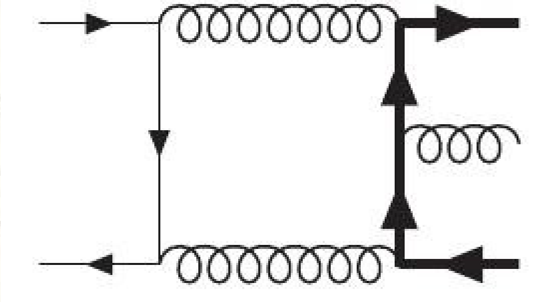
- In addition to progress with NLO computations, there is a serious effort to compute top quark pair production through NNLO QCD

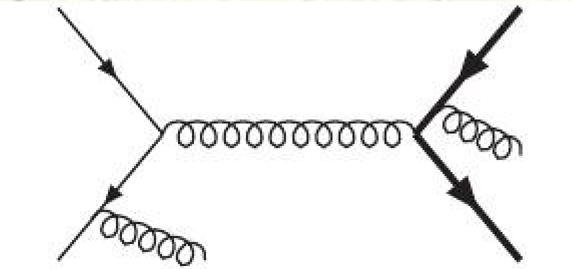
Czakon, Gehrmann, Ferroglia, Bonciani

- Complimentary approach – resummation of enhanced perturbative effects (soft, threshold, etc.)

Kidonakis, Langenfeld, Moch, Uwer
Beneke, Czakon, Mitov, Sterman
Ahrens, Ferroglia, Neubert, Pecjak, Yang



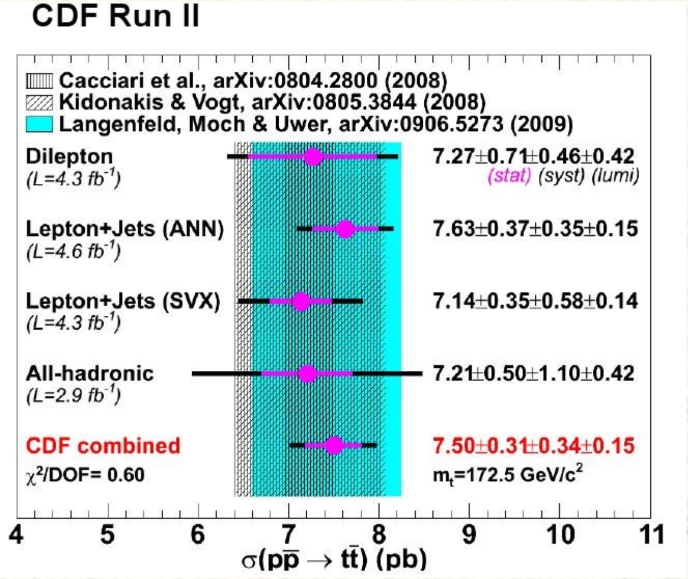




Quite remarkable progress occurred with understanding almost all of these contributions recently; so NNLO QCD prediction for top quark pair production is, perhaps within reach

Finite acceptances

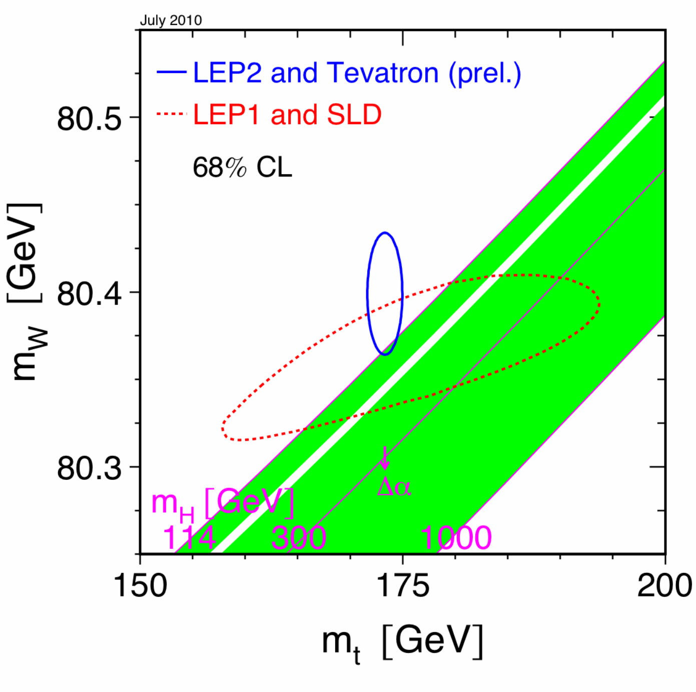
- Acceptances are required to translate measured number of events to total cross-sections
$$N_{\rm exp} = \sigma^{(i)}_{\rm tot} A^{(i)} L \epsilon$$
- Acceptances are subject to perturbative corrections which, until rather recently were not quite known
- As we keep comparing total cross-sections, computed to higher and higher orders in pQCD, to experimental measurement, it is important to remember that

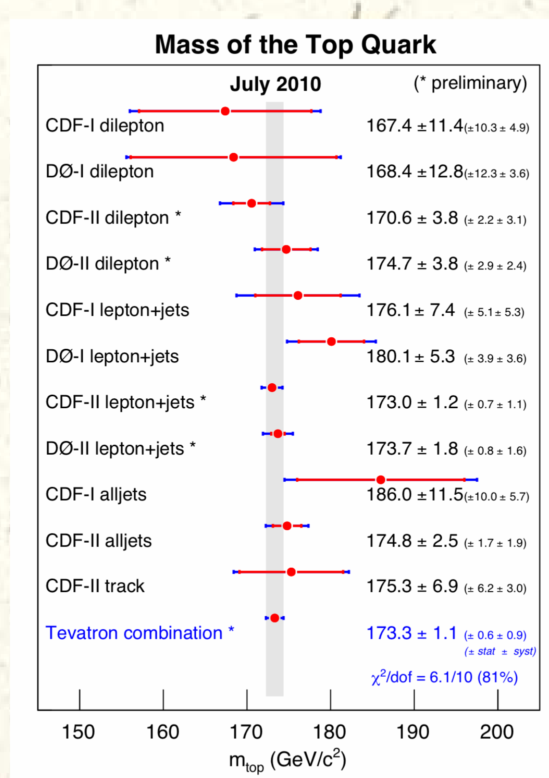


The top quark mass

- The top quark mass is important for constraining the Higgs boson mass. It is very precisely measured by the CDF and D0 collaborations, but .. what exactly is it?

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$





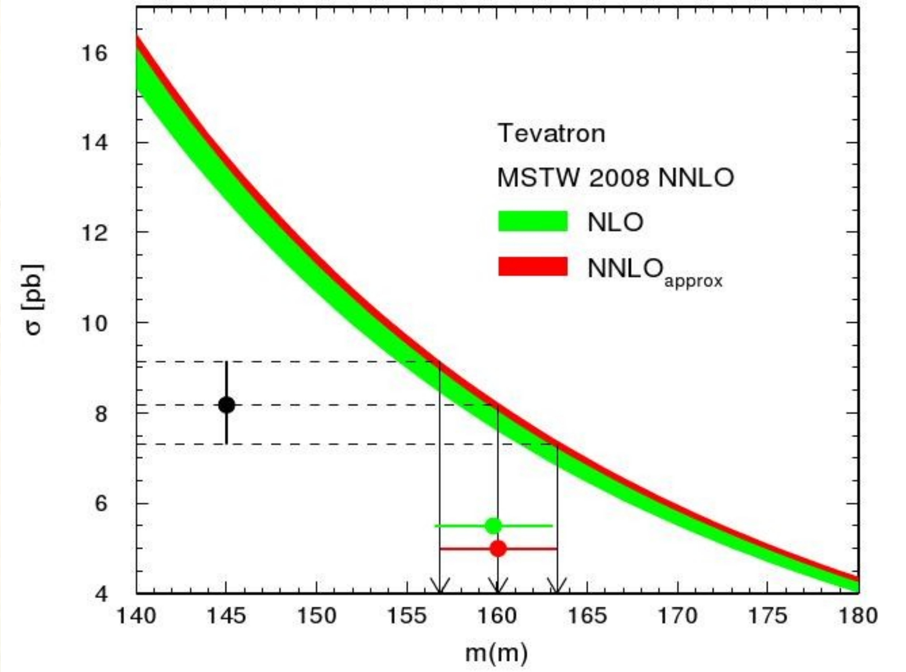
$$m_t^{\text{pole}} = \bar{m}_t(\bar{m}_t)\left(1 + \frac{4\alpha_s}{3\pi} + ..\right) \approx (170 + 7 + ..) \text{ GeV}$$

The top quark mass

- Top quark mass measurements should deal with short-distance quantities, computable in perturbative QCD
- Matrix element methods – that yield most precise values of the top quark mass – are hardly pQCD-compatible
- Suitable quantities can be constructed by exploring kinematic features of the top quark decay products and their correlation with the top quark mass
- Gluon radiation in top quark decays becomes important
- Theory uncertainties on the top quark mass measurements are often estimated using parton showers; given the required precision, this is a very questionable procedure

Top quark mass measurement

- The simplest observable for the top quark mass determination is the total cross-section.
- Traditionally used to extract the pole mass of the top quark but extraction of the MS-mass gives very stable results



Langenfeld, Moch, Uwer

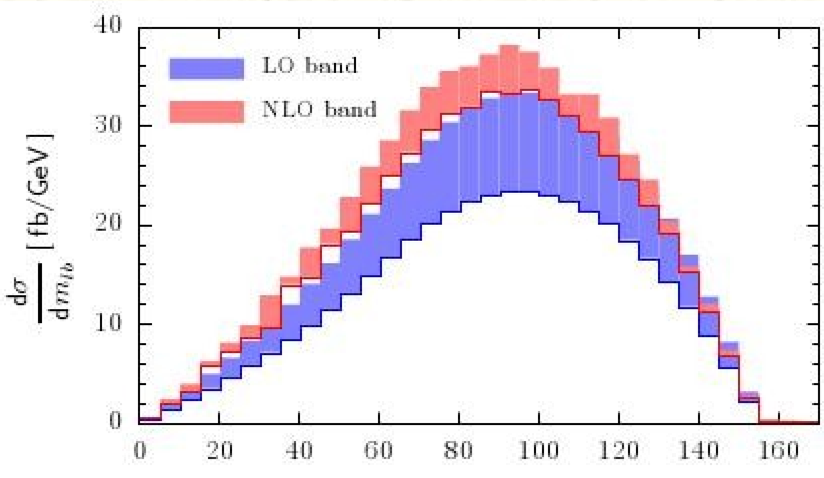
	$m(m)$ [GeV$/c^2$]	m_t [GeV$/c^2$]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

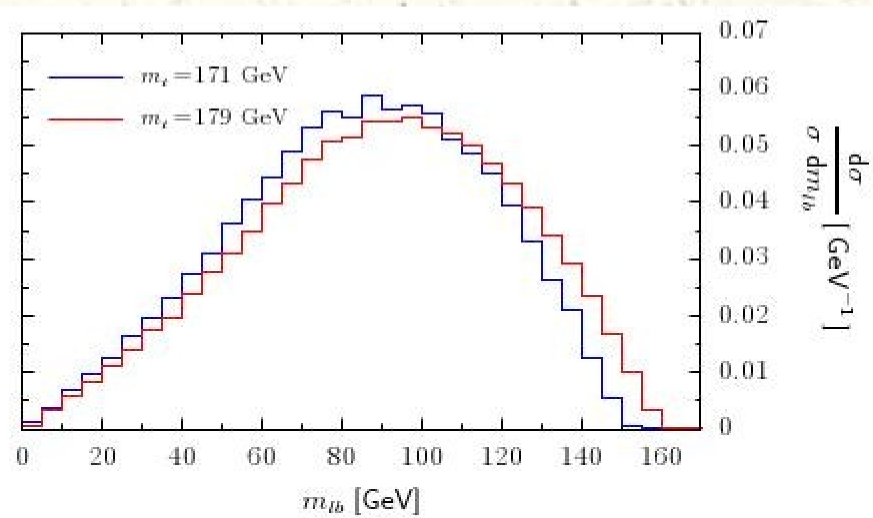
The MS-mass from precision electroweak fit is 161.3 GeV

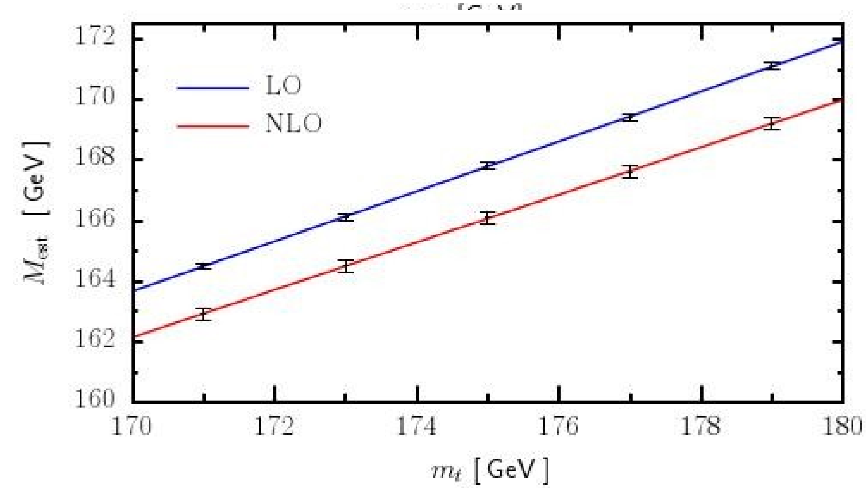
No obvious consistency between theoretically clean and ``all possible" measurements $m_t = 173.3 \pm 1.1$ GeV

Top quark mass measurements

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







Biswas, Schulze, K.M.

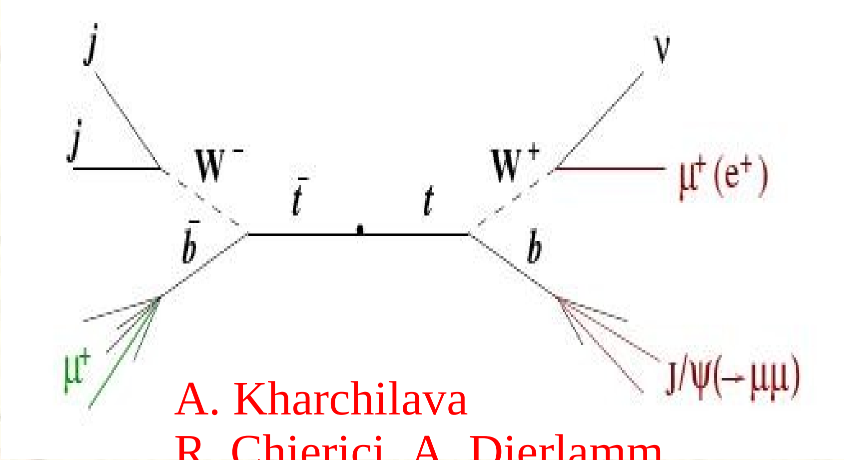
$$M_{\rm est}^2 = m_W^2 + \frac{2\langle m_{lb}^2\rangle}{1-\langle\cos\theta_{lb}\rangle}$$

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

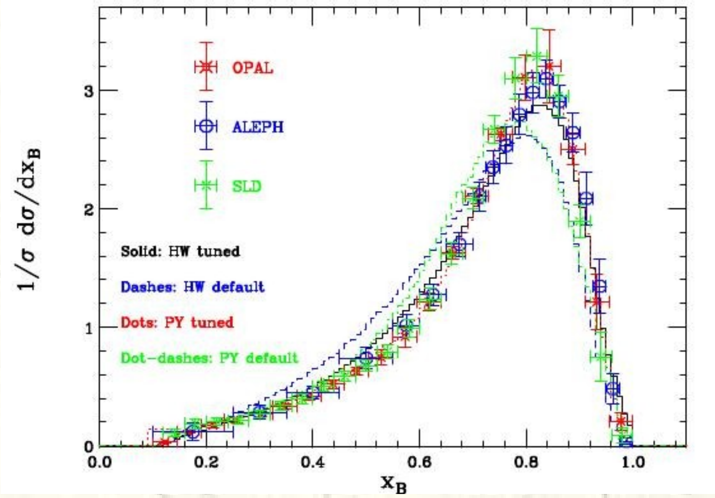
$$M_{\rm est}^{\rm NLO} = 0.7850 m_t + 28.70 \text{ GeV}$$

Top quark mass measurement

- One of the most precise measurements of the top quark mass at the LHC can be obtained from the study of the invariant mass of the J/ψ and a lepton from top quark decays



A. Kharchilava
R. Chierici, A. Dierlamm



- Many studies over the years, to understand systematic uncertainties; rely on parton showers

Mangano, Seymour, Corcella, Mescia

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

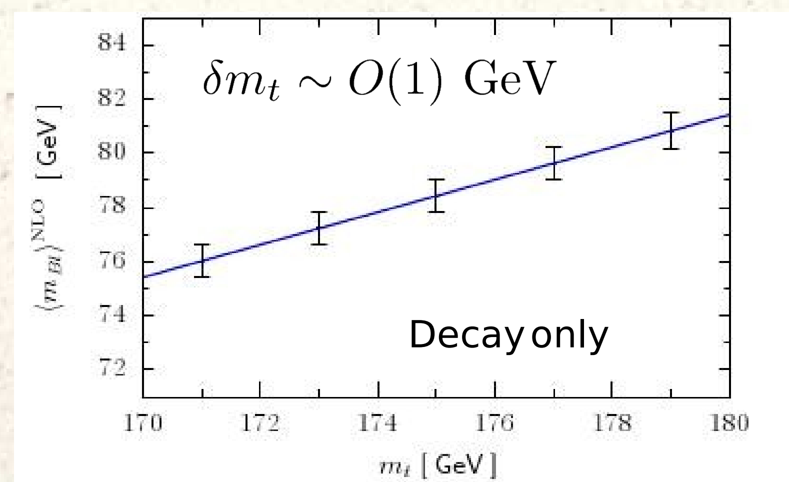
$$\langle m_{Bl} \rangle_{\text{Herwig}} = 0.61\ m_t - 25.31\ \text{GeV}$$

Top quark mass measurement

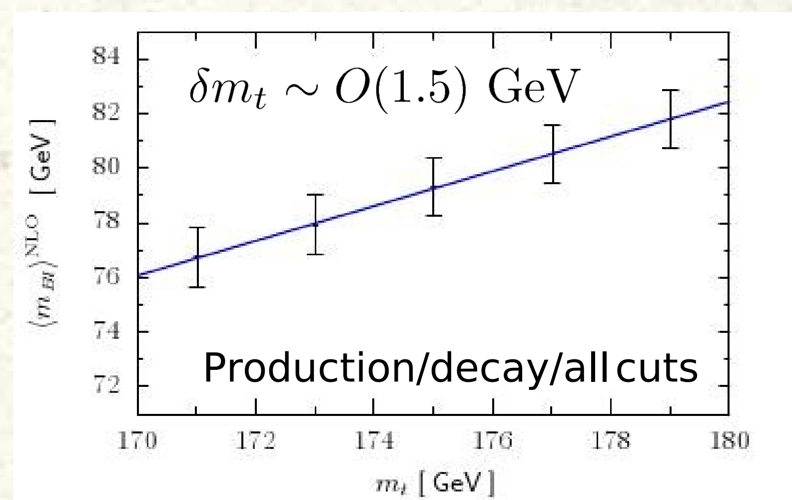
- One does not need the parton shower; the required quantity can be computed in QCD perturbation theory
- We need the NLO QCD correction to top production and decay and we require a fragmentation function for b → B

Cacciari, Corcella, Mitov

- Estimate uncertainty by considering different fragrmentation functions, change renormalization/factorization scales etc.



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



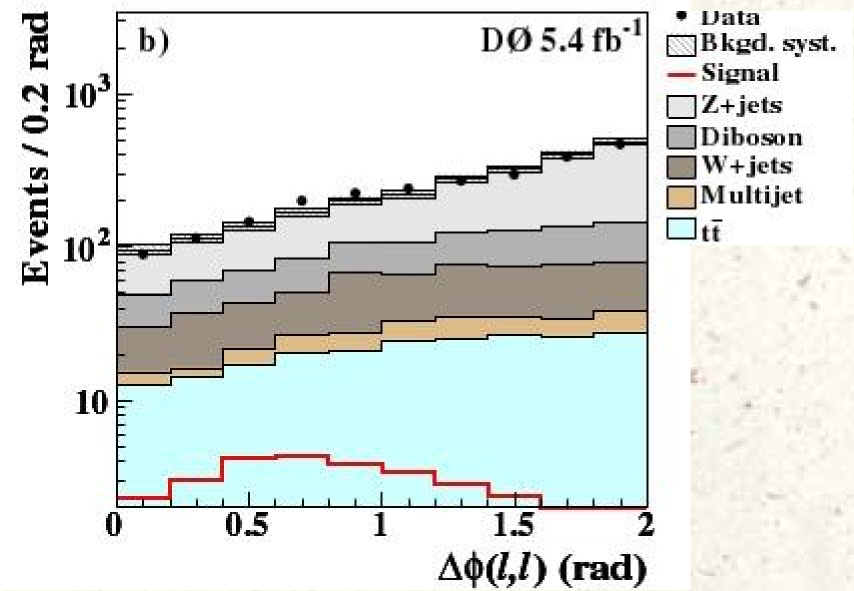
$$m_t = 0.635 m_t - 32.12 \text{ GeV}$$

Spin correlations

- Top quarks interact with QCD vacuum fields that are too weak to change top and anti-top polarizations

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

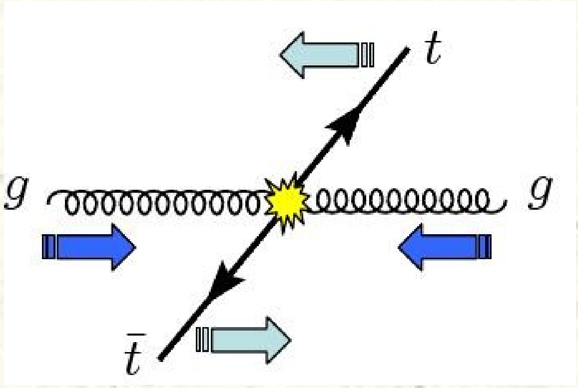
- Kinematics of top quark decay products depends on the top quark polarization; spin correlations
- To describe spin correlations, we must consider $t\bar{t}$ production and $t\,(\bar{t})$ decay at once.
- This is straightforward in leading order QCD but harder in higher orders



Di-lepton opening angle; heavy Higgs search at the Tevatron

Spin correlations

- If top quarks are produced in a polarized state, they decay in a correlated fashion
- Polarization of top quarks at the Tevatron and the LHC differ, because of different production mechanisms
  - Tevatron: qq → g → tt, J=1, S=1, L=0 (spins parallel)
  - LHC : gg → tt, J=0, L=0,S=0 (spins antiparallel)
- Since positron likes to follow the spin direction of the top quark and electron prefers to go into the direction opposite to that of the anti-top spin, leptons like to have parallel (anti-parallel) momenta at the LHC/Tevatron



Spin correlations

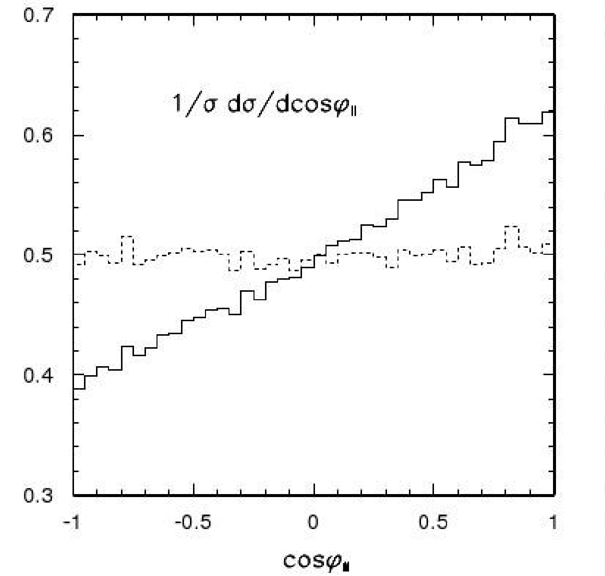
- Traditionally, top quark spin correlations are discussed in the context of lepton angular correlations in special reference frames
- The effect of spin correlations on these distributions is pronounced but it is hard to reconstruct those frames; as the result no conclusive measurement of spin correlations exists

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

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

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

CDF measurement, 2010

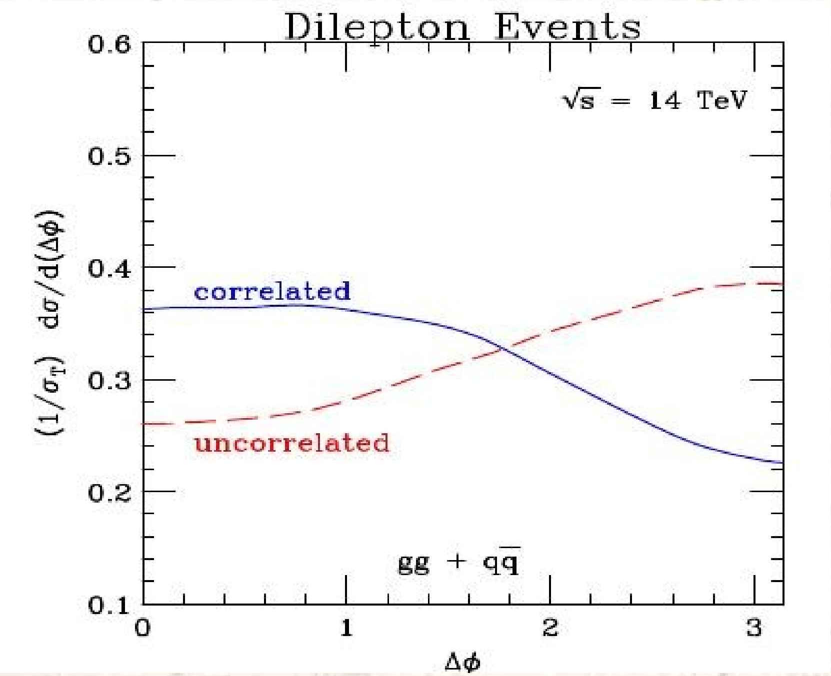


Bernreuther, Si

Spin correlations

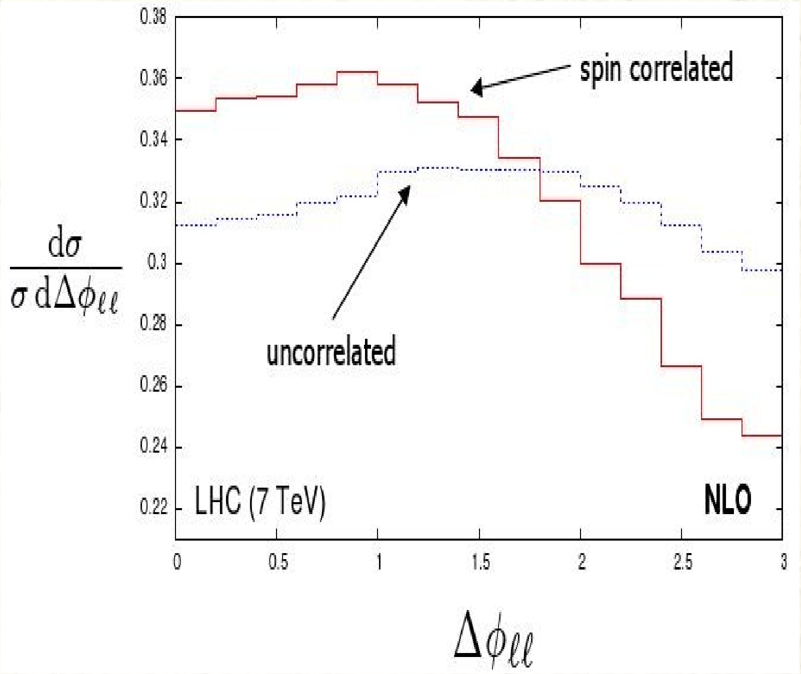
- It is possible to study spin correlations at the LHC by looking at the opening angle of the two leptons in the laboratory frame, provided that kinematics is restricted to top threshold

Mahlon, Parke



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

Mahlon and Parke



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

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

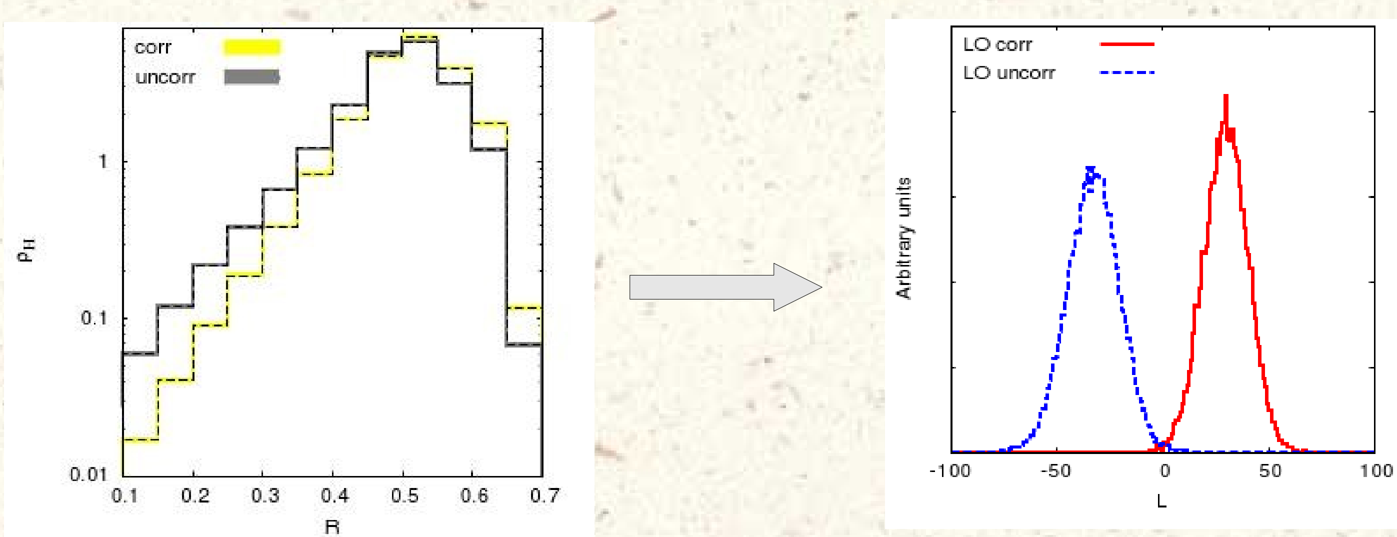
Schulze, K.M.

Spin correlations

- It is possible to construct an observable to study spin correlations without reference to the opening angle of the lepton pair

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

- In reality – more complicated, since momentum of neutrinos can not be measured; integration can be done explicitly



Schulze, K.M.

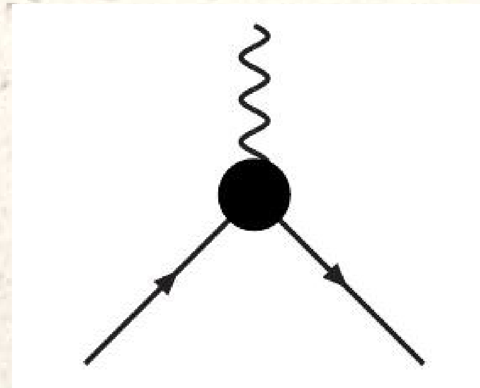
Just about five hundred dilepton events at the Tevatron are needed to prove the existence of top quark spin correlations

Top quarks and the photon

- Production of a top pair in association with the photon gives access to the top quark charge and the anomalous magnetic moment

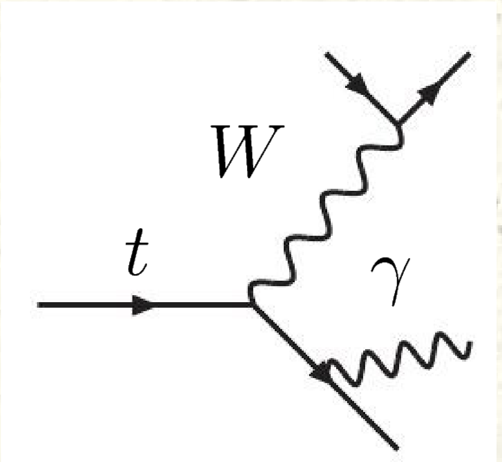
Baur, Buice, Orr, Rainwater

- Recent measurement by the CDF collaboration
- Photon can be radiated in the production and in the decay; both mechanisms significantly contribute to the cross-section
- Top quark charge/magnetic moment can be studied at the LHC in detail



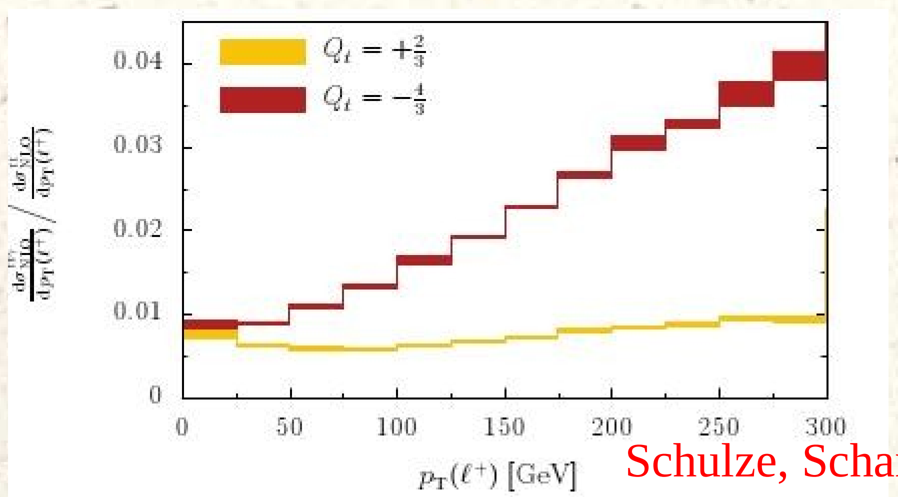
$$= -iQ_t e \, \epsilon_\mu \, \bar{u}_t \, \hat{\Gamma}^\mu \, u_t$$

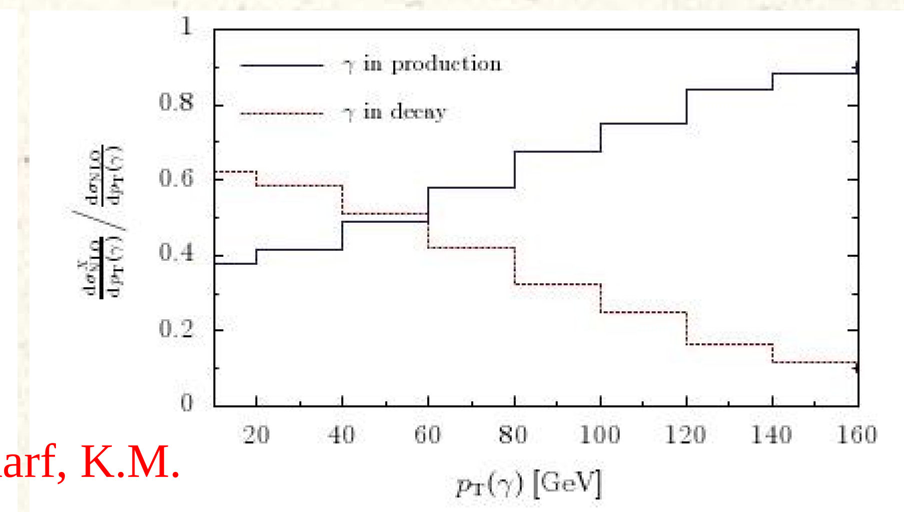
$$\hat{\Gamma}^\mu = -\gamma_\mu + a_t \frac{i\sigma_{\mu\nu} q_\nu}{2m_t}$$



Top quarks and the photon

- For the CDF-like analysis, fifty percent of all photons come from radiation in top quark decays; radiation in the decay dominates for photons with transverse momenta up to 60 GeV
- QCD corrections to $t\bar{t}\gamma$ production and QCD corrections to radiative decays of top quarks are unrelated – both need to be considered
- For inclusive enough cuts, QCD corrections to $t\bar{t}\gamma$ are similar to QCD corrections to $t\bar{t}$ production





Schulze, Scharf, K.M.

Top quarks and the photon

- The CDF collaboration measured the $t\bar{t}\gamma$ production rate
- They found 9 events in 1.9/fb sample and 17 events in 6/fb sample (I don't show error bars, they are significant)
- Our results for the cross-sections (lepton and jet, single charge/flavor lepton) for the CDF-like cuts are

$$\sigma_{t\bar{t}\gamma} = \begin{cases} 2.85^{+1.14}_{-0.75}\ \text{fb}, & \text{LO} \\ 2.64^{+0.21}_{-0.03}\ \text{fb}, & \text{NLO} \end{cases}$$

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

$$\eta_{\rm lep} < 1.1,\ \ |\eta_\gamma| < 1.1,\ \ |\eta_j| < 2.$$

$$\Delta R_{j\gamma} > 0.4,\quad \Delta R_{l\gamma} > 0.4.$$

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

- Assuming 22 percent efficiency (b-tagging, leptons, photons etc). we estimate that 4 events should have been observed in 1.9/fb and 14 events in 6/fb
- Everything looks consistent; further increase in statistics will help

Asymmetries

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

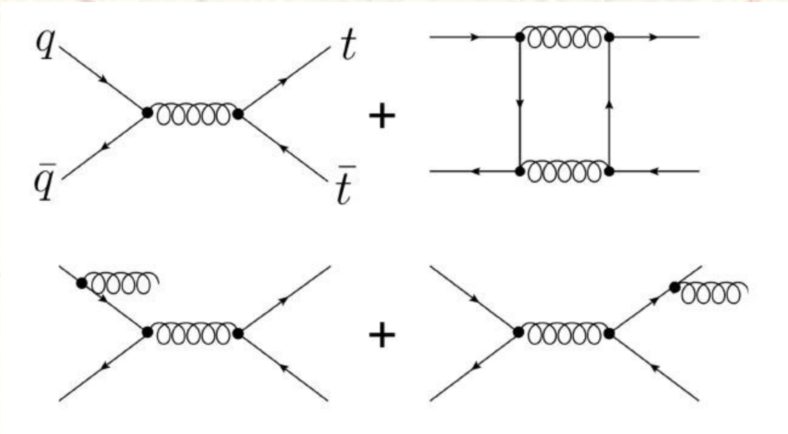
$$A_{\rm FB}(t\bar{t}) = \frac{N_t(y>0) - N_t(y<0)}{N(y_t>0) + N_(y_t<0)}$$

- The asymmetry only appears at one-loop in QCD

Kuhn, Rodrigo

$$A_{\rm FB}^{\rm th} = 0.05 \pm 0.006$$

$$A_{\rm FB}^{\rm exp} = 0.15 \pm 0.05 \quad {\rm CDF}$$



The discrepancy is about two standard deviations. It is stronger at large invariant masses and large rapidities

Many BSM interpretations of this result

Asymmetries

- Theoretical prediction for the asymmetry appears robust
  - it is stable against inclusion of (approximate) higher order corrections to top quark pair production

    Almeida, Sterman, Vogelsang
    Ahrens, Ferroglia, Neubert, Pecjak, Yang
  - it is stable against allowing top quarks to decay and calculating asymmetries for realistic acceptances

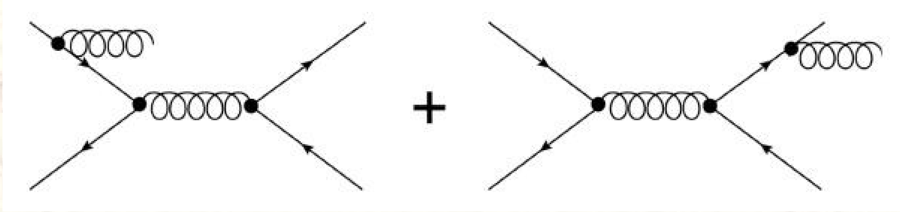
    K.M., Schulze, Bernreuther, Si, Bevilacqua, Czakon, van Hammeren, Papadopoulos, Worek
  - it appears stable against off-shell effects and the interference with non-resonance backgrounds

    Bevilacqua, Czakon, van Hammeren, Papadopoulos, Worek

Asymmetries

- Asymmetry in $p\bar{p} \to t\bar{t} + j$ provides a counter-example
- In contrast to $p\bar{p} \to t\bar{t}$ the asymmetry in $p\bar{p} \to t\bar{t} + j$ appears already at leading order ; so NLO QCD calculation for $p\bar{p} \to t\bar{t} + j$ will also give first-order correction to the asymmetry
- The result is peculiar: there is large positive correction to the asymmetry

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



Dittmaier, Uwer, Weinzierl
K.M., Schulze

Should we take this result as an indication that large POSITIVE correction are to be expected in $p\bar{p} \to t\bar{t}$ asymmetries?

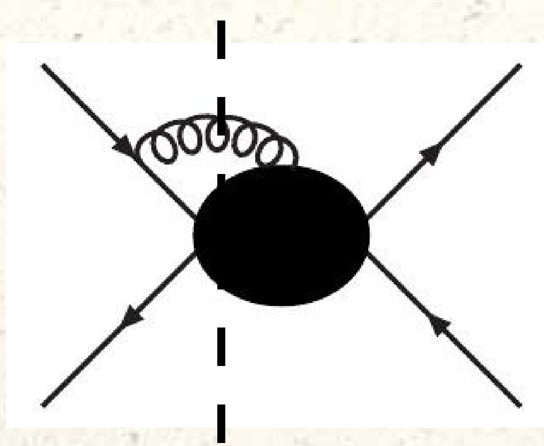
Asymmetries

- At leading order the asymmetry is generated by soft, non-collinear exchange between initial and final state

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

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

- At NLO, can generate asymmetry by hard exchanges and use soft initial-initial interference to provide regular double logarithmic enhancement of the cross-section



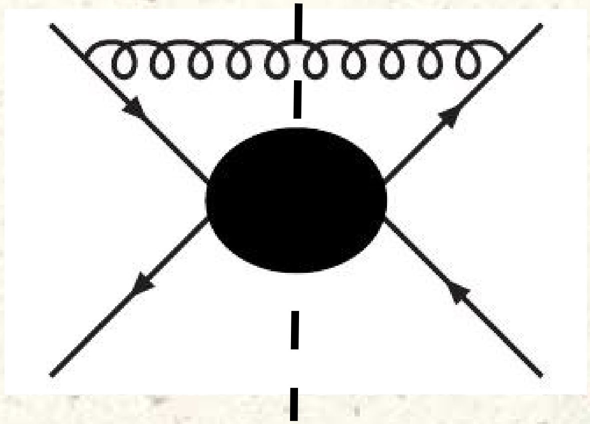


Diagram that shifts the asymmetry by +5 % at NLO

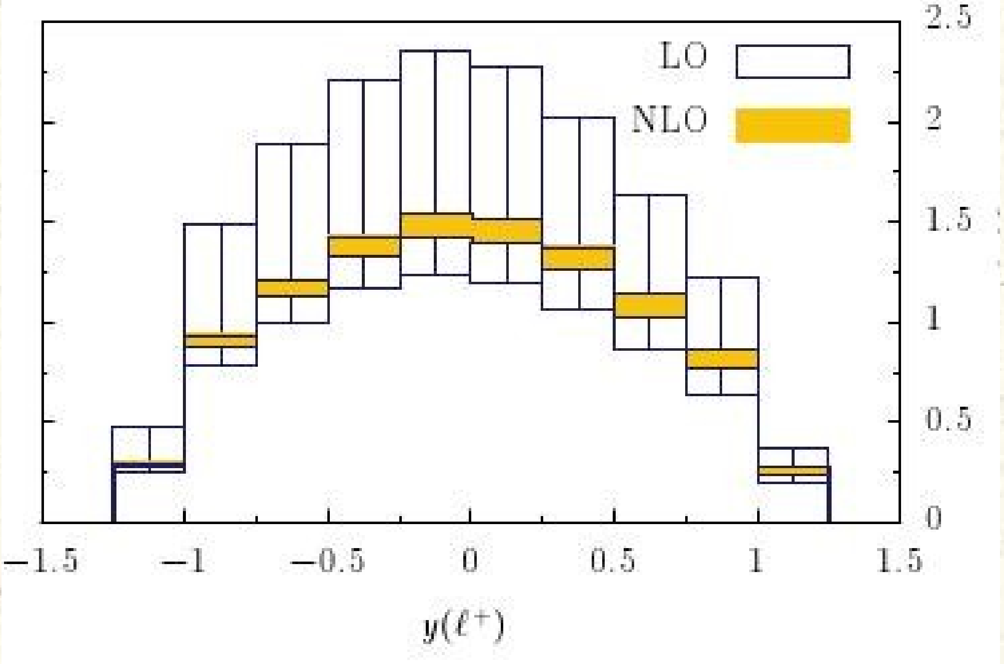
Asymmetries

- If this is a mechanism for generating large asymmetries, it should also show up in the NLO QCD description of $p\bar{p} \longrightarrow t\bar{t}\gamma$
- Indeed, a very similar effect is found

Schulze, Scharf, K.M.; earlier work by Duang, Ma, Zhang, etc.

$$A_{\rm FB}(t\bar{t}+\gamma)^{\rm LO} \approx -17.2\ \%$$

$$A_{\rm FB}(t\bar{t}+\gamma)^{\rm NLO} \approx -11.9\ \%$$



However, in this case allowing top quarks to decay, washes out the asymmetry, almost completely

Conclusion

- Current state of the top quark physics is very interesting
- On one hand – extraordinary results from the Tevatron
  - precision $\sigma_{t\bar{t}}, \quad m_t$
  - tiny cross-sections measured $p\bar{p} \to t\bar{t}j, \quad p\bar{p} \to t\bar{t}\gamma$
  - unexpected phenomenon $A_{\rm FB}$
- On the other hand – some theoretical issues need to be sorted out (pole mass of the top, top is unstable, radiation in the decay, spin correlations etc.) to have precise and realistic description
- At the LHC, we will not have an excuse of having low statistics to not care about such details
- Thanks to recent progress in combining higher-order QCD effects with the top quark instability, we have a good foundation to move forward

Conclusions

- Top quark mass measurements should be done with the short-distance observables, computable within perturbative QCD
- There is a possibility to establish the existence of top quark spin correlations with limited statistics
- Measurements of top production cross-sections in association with other particles (jet, photon) have been performed at the Tevatron and appear to be consistent with the SM prediction
- Resolution of the asymmetry puzzle will require NNLO QCD computation but there is no indication that large perturbative corrections are to be expected
- It will be good to have experimental results for leptonic asymmetries, to compare with theoretical computations directly