Kinematics of Top Quark Final States &

Top Quark Charge Asymmetry

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Outline

- Study of theoretical error estimates on basic kinematic distributions
- Study of theoretical error estimates for boosted kinematics
- Top quark spin correlations
- Top quark charge asymmetry

Basic kinematic distributions

- We use MCFM to study theoretical uncertainties at NLO QCD for

$$p_{\mathrm{T}}^{t},\ y_t,\ |y_t| - |y_{\bar{t}}|$$

  at the 14 TeV and 33 TeV LHC.

- Errors are estimated from varying renormalization and factorization scales, and from using different pdf sets (MSTW,NN) with their error sets.

- The results hopefully give some guidance for error estimates on more complicated observables that involve the top quark decay products.

Basic kinematic distributions

- The total NLO QCD cross section at the 14 TeV LHC

$$\sigma_{t\bar{t}}^{\rm NLO} = 845 \text{ pb} \;\; \pm 12\% \text{ (scale)} \;\; \begin{array}{l} \pm 2\% \text{ (MSTW)} \\ \pm 8\% \text{ (NNPDFS)} \end{array}$$

Scales are varied by a factor of two around mtop.
Pdf errors are obtained from MSTW/NN by varying 40/100 eigenvector sets

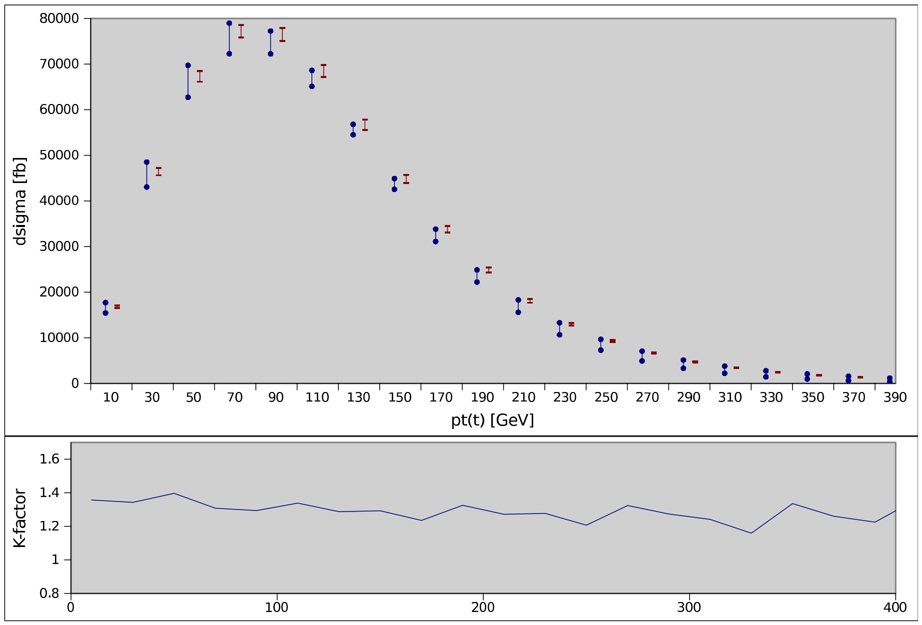
- Scale uncertainty is reduced by a factor of two wrt. the LO.

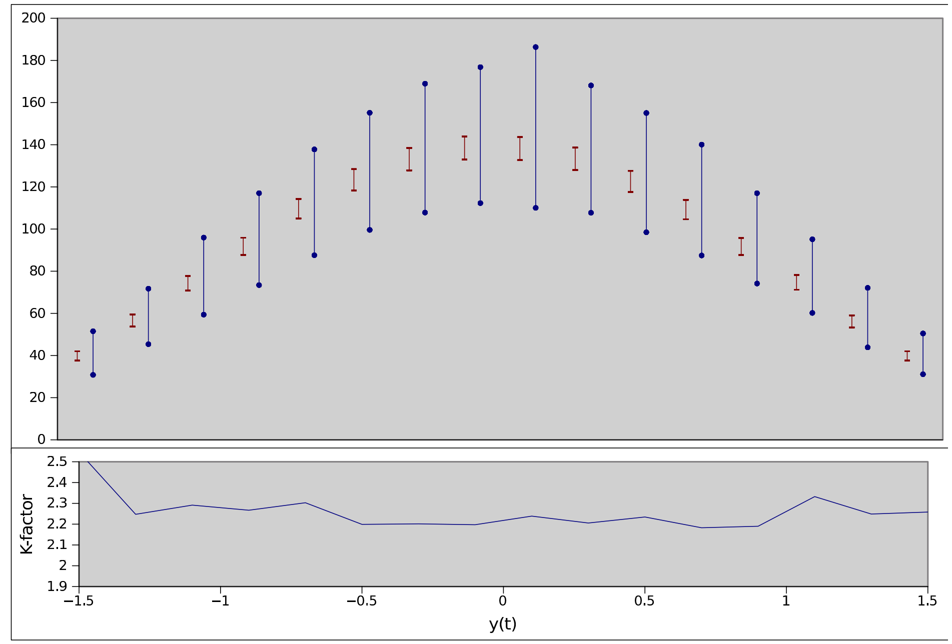
- NLO QCD corrections enhance the total cross section by 30%

- The total NLO QCD cross section at the 33 TeV LHC

$$\sigma_{t\bar{t}}^{\rm NLO} = 5 \text{ nb} \;\; \pm 11\% \text{ (scale)}, \qquad K{=}1.23$$

Basic kinematic distributions

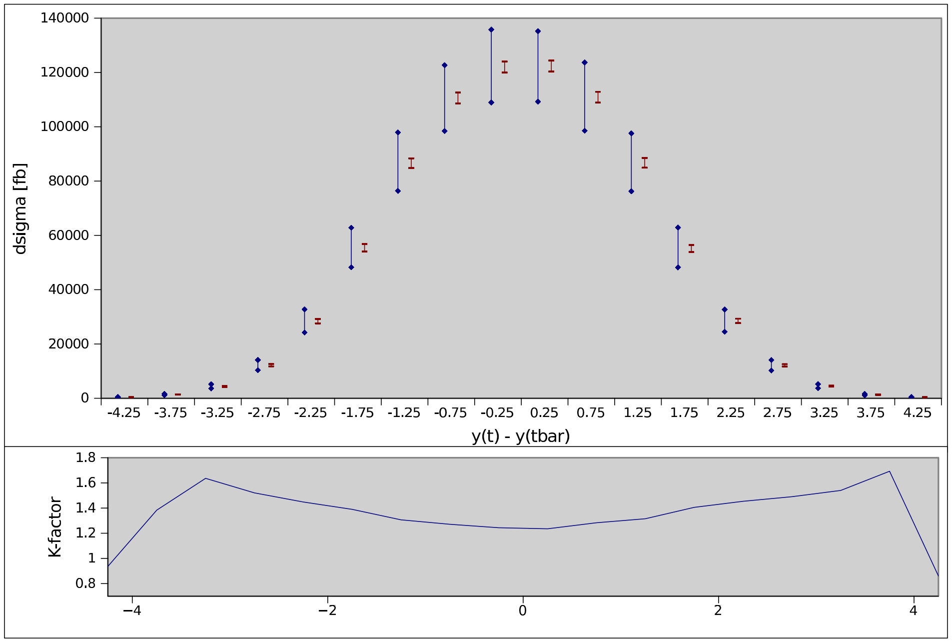




- The transverse momentum distribution can be predicted with 15-20% precision at NLO QCD.
  The *K*-factor is almost constant over a wide range of pT.

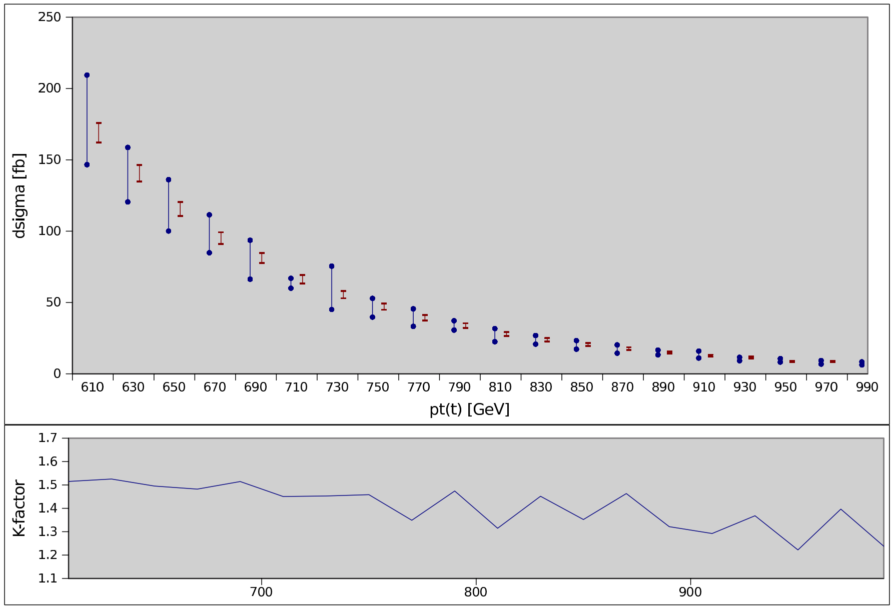
- The rapidity distribution has a scale uncertainty of up to 20% in the central region. A comparison of MSTW and NN pdf errors shows the significantly different erorr estimates. However, central values agree well.

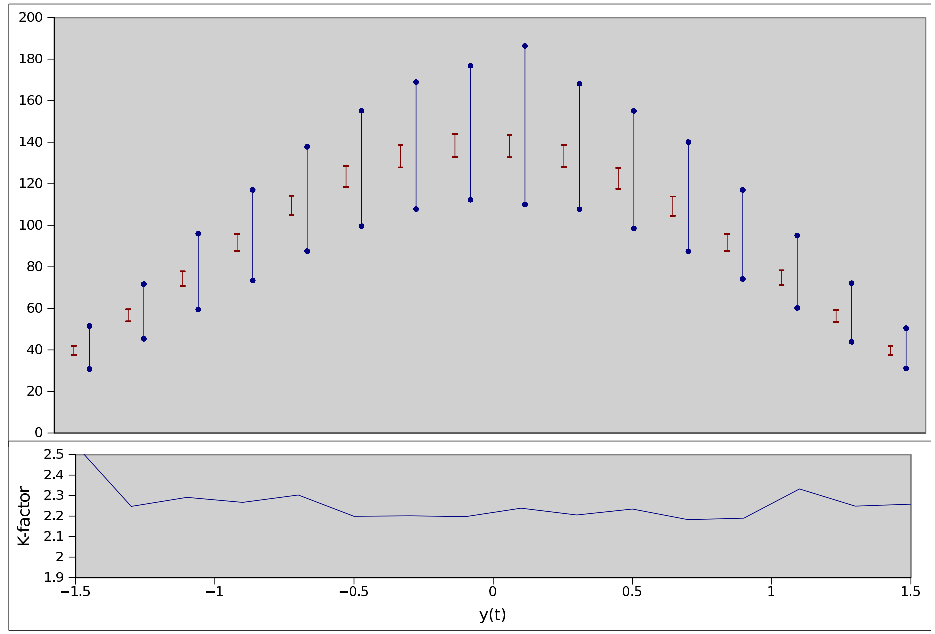
Basic kinematic distributions



- Rapidity difference is sensitive to the charge asymmetry at the LHC.
- Similar errors as for rapidity distribution.
  (Expect smaller errors on A because it is a ratio of cross sections)
- NLO QCD introduces a significant shape shift that introduces the asymmetry.

Boosted kinematics





- Require $p_{\rm T}^{t}$ or $p_{\rm T}^{\bar t} \geq 600\ {\rm GeV}$ and set $\mu_{\rm R} = \mu_{\rm F} = 600\ {\rm GeV}$

- The cross section at 14 TeV is

$$\sigma_{t\bar t}^{\rm NLO} = 1.05\ {\rm pb}\ \pm 15\ \%\ ({\rm scale})\ \pm 10\ \%\ ({\rm MSTW})$$

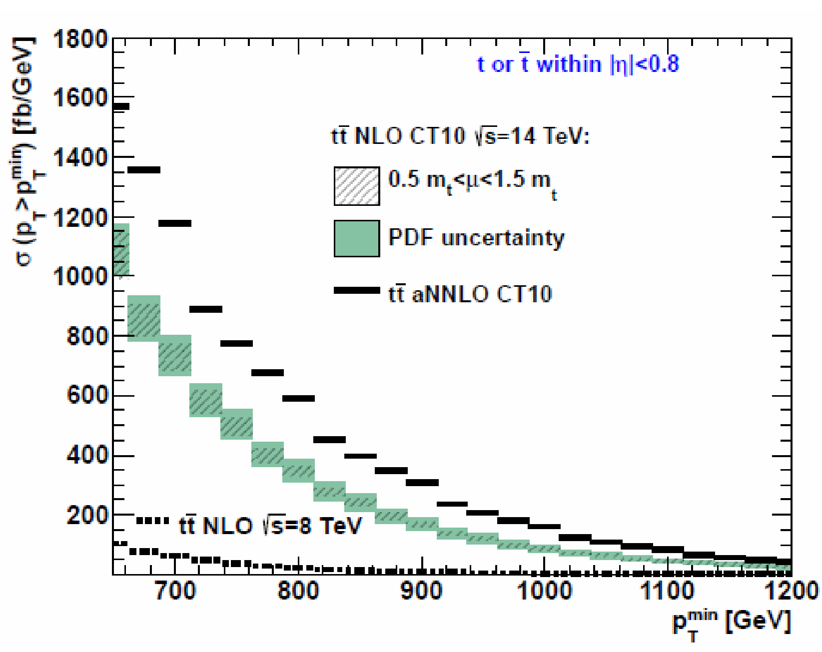
- Uncertainties on single $p_{\rm T}$,y bins range up to 20-30%

- NLO QCD corrections induce moderate shape changes but the overall K-factor, K=1.45, is 10% larger than for the total cross section

Boosted kinematics

- Calculations of approximate NNLO QCD corrections suggest that soft-gluon resummation is mandatory for boosted kinematics:
  Corrections range up to 100% wrt. to NLO predictions for $m_{t\bar{t}} \geq 1$ TeV

[Auerbach,Chekanov,Kidonakis]
[Ferroglia,Pecjak,Yang]



[Auerbach,Chekanov,Kidonakis]

	$M = 500$ GeV	$M = 1500$ GeV	$M = 3000$ GeV
LO	1.11	3.50×10^{-3}	2.04×10^{-5}
NLO corr. ($z \to 1$)	8.58×10^{-1}	3.74×10^{-3}	2.51×10^{-5}
NNLO corr. (approx. A)	2.64×10^{-1}	2.00×10^{-3}	1.77×10^{-5}
NNLO corr. (approx. B)	3.05×10^{-1}	2.40×10^{-3}	2.11×10^{-5}
NNLO corr. (approx. C)	3.65×10^{-1}	2.67×10^{-3}	2.31×10^{-5}
NNLL corr.	3.72×10^{-1}	3.79×10^{-3}	4.42×10^{-5}

Table 2: Same as Table 1, but with $\sqrt{s} = 14$ TeV.

[Ferroglia,Pecjak,Yang]

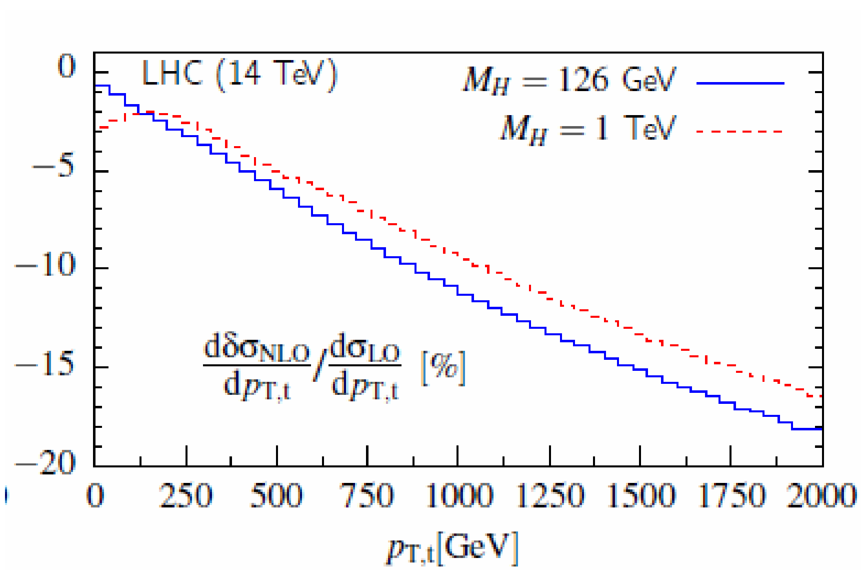
Boosted kinematics

- At high energies, when $M_Z, M_W \ll \sqrt{s}$, (electro)weak corrections can become relevant.

- Effects on the total ttbar cross section ~ -2% at 14 TeV and 33 TeV

- Significantly larger corrections for energy-related distributions, e.g.

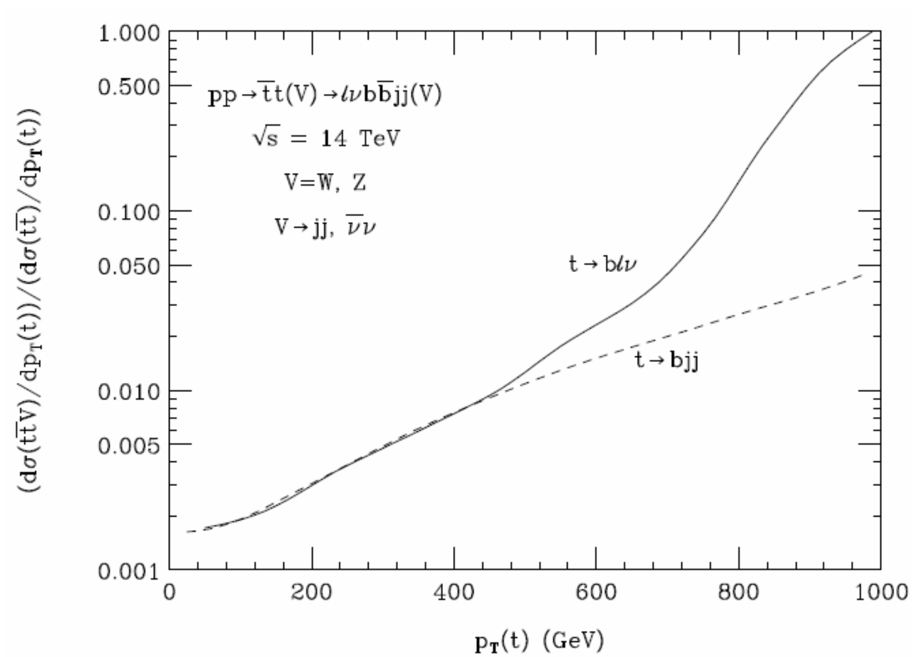
  [Kühn,Scharf,Uwer]: -10% at pT=1 TeV and -18% at pT=2 TeV.



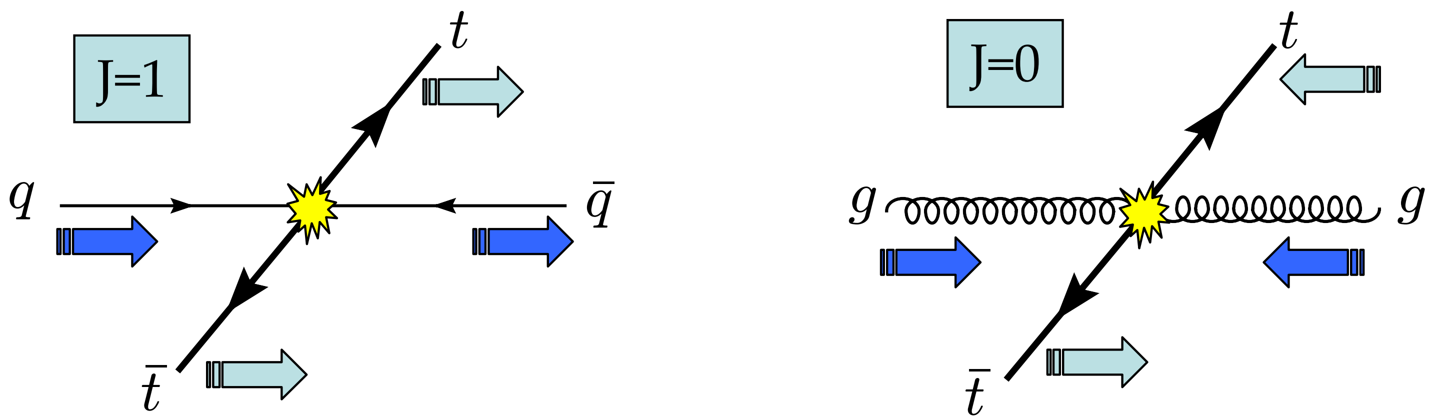
Boosted kinematics

- Partial cancellations with real emission of W,Z bosons are possible.

[Baur]: 1-2% cancellation at pT=500 GeV,
much larger at pT=1 TeV, but very dependent on selection cuts

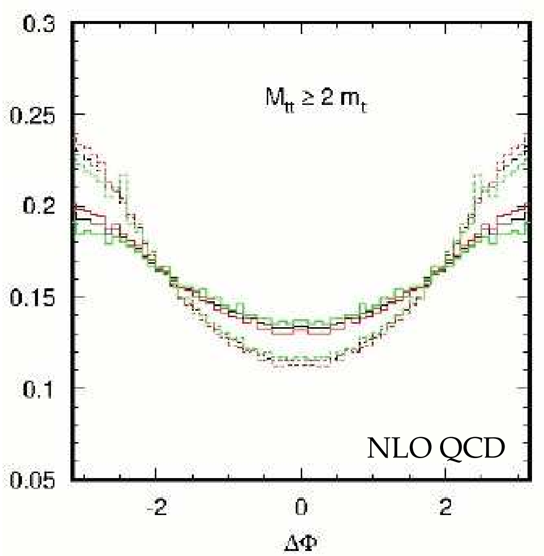


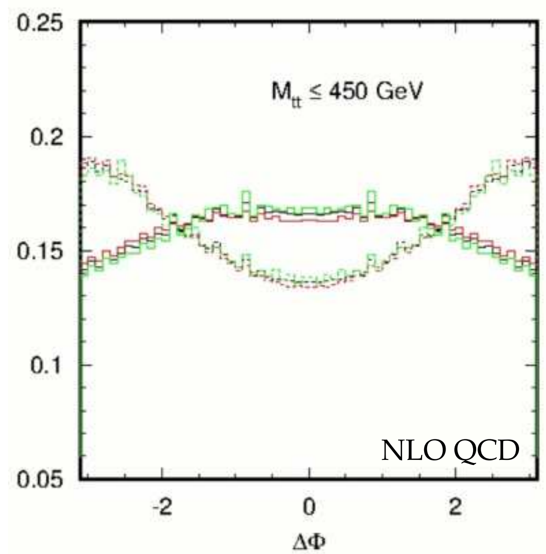
Top quark spin correlations



- Top quark spin correlations are a unique tool for studying the interplay of electroweak and strong physics in the top quark sector.
- Spin correlations are also sensitive to effects of physics beyond the SM

Top quark spin correlations

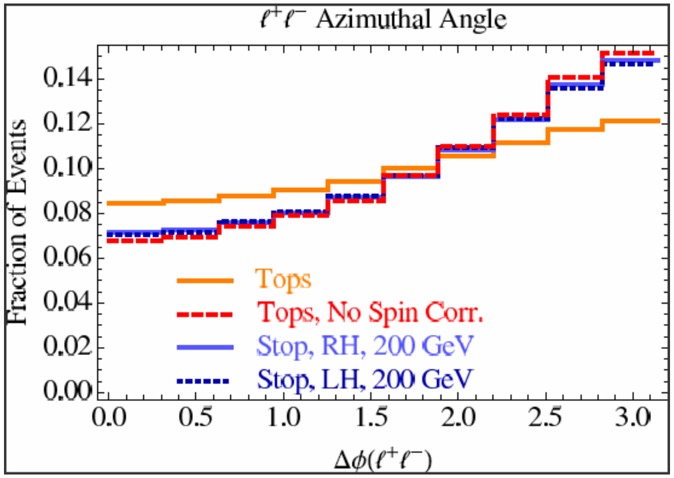




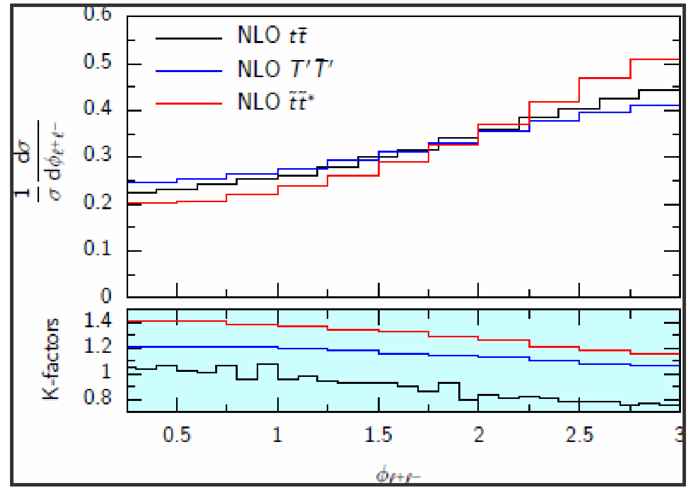
[Bernreuther,Si]

- The azimuth opening angle of the two leptons in the di-lepton channel is one of the cleanest probes of spin correlations.
- This observable has been shown to be most robust under higher order corrections and parton shower effects.
- Dependence on unphysical scales cancels almost completely in normalized distributions.

Top quark spin correlations



[Han,Katz,Krohn,Reece]



[Boughezal,Schulze]

- For standard acceptance cuts, NLO QCD introduces shape changes of at most 20%
- In scenarios where total cross sections are degenerate, spin correlations help separating SM tops, scalar partners and fermionic partners.
- Using 20 fb^{-1} at 8 TeV spin corrlations can exclude 200 GeV stop quark pair production at the 95% C.L.

Top quark spin correlations

[Bernreuther,Si]: $$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

- Top quark spin correlations can be used to constrain anomalous chromo-magnetic and -electric dipole moments.

- The di-leptonic top quark sample can be used to constrain $\mathrm{Re}\hat{\mu}_t,\ \mathrm{Re}\hat{d}_t$ at the few percent level with 20 fb^{-1} at 8 TeV

- Asymmetries of lepton top helicity angles in the lepton+jet channel can be used to constrain $\mathrm{Im}\hat{\mu}_t,\ \mathrm{Im}\hat{d}_t$ at the 10-20 percent level with 20 fb^{-1} at 8 TeV

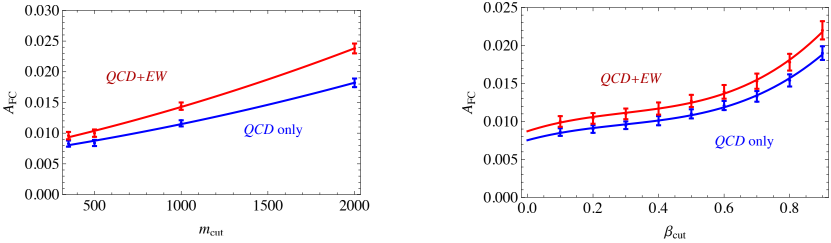
[Baumgart,Tweedie]:

- With 100fb^{-1} and 13 TeV constraints of below 1% are possible

A_{FC} at LHC14

- Challenging signal for LHC14: intrinsic signal size smaller than at LHC7 and LHC8
- Observability a question of systematic errors
- Study in progress for Snowmass Minnesota
- Here: some quick estimations (input welcome)

Predictions as a function of cuts



SM predictions for A_{FB} at LHC14 as a function of cuts on $M_{t\bar{t}}$ (left) and $\eta_{t\bar{t}}$ (right), from Bernreuther and Si, 2012.

(Semileptonic) Measurements at LHC7

- ATLAS, 1 fb^{-1}:

$$A_{FC} = -0.019 \pm 0.028 \pm 0.024$$

- CMS, 5 fb^{-1}:

$$A_{FC} = 0.004 \pm 0.010 \pm 0.011$$

- systematically limited

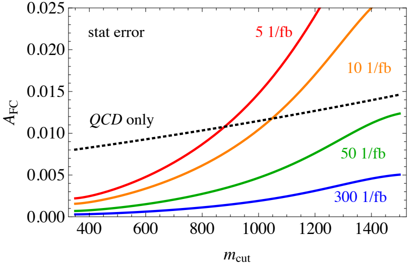
Do systematic errors scale with $\mathcal{L}$?

- Leading sources of systematic uncertainty:
    - Modelling of backgrounds (W+jets, multijets)
    - lepton selection efficiency
    - model dependence of unfolding
    - $t\bar{t}$ modeling
    - jet energy scale

Quick feasibility estimate

Assumptions

- rough efficiency for reconstructing semileptonic tops $\epsilon \approx 1/5$
- systematic error is $\Delta \approx 0.0011$ at 5 fb^{-1}.



Statistical uncertainty as a function of cut on $M_{t\bar{t}}$

Quick feasibility estimate

Assumptions

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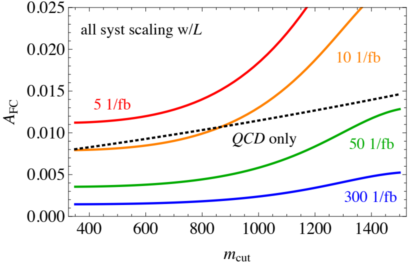
- systematic error is $\Delta \approx 0.0011$ at 5 fb^{-1}.

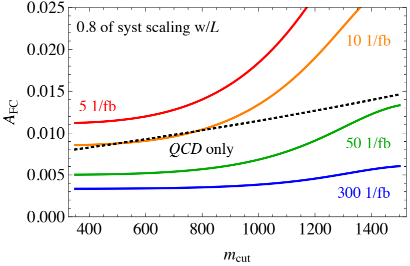


Statistical plus systematic uncertainty as a function of cut on $M_{t\bar{t}}$, assuming all systematic uncertainty scales with luminosity

Quick feasibility estimate

Assumptions

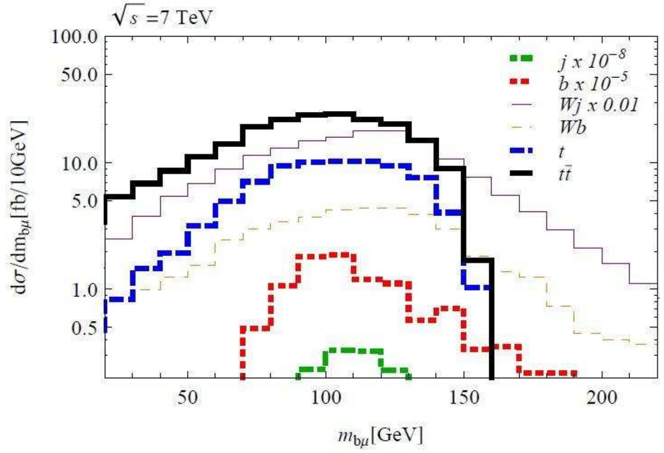
- rough efficiency for reconstructing semileptonic tops $\epsilon \approx 1/5$
- systematic error is $\Delta \approx 0.0011$ at $5\ \mathrm{fb}^{-1}$.



Statistical plus systematic uncertainty as a function of cut on $M_{t\bar{t}}$, assuming 0.8 of the systematic uncertainty scales with luminosity

Top forward-backward at LHCb

- Large forward-backward asymmetry at the Tevatron, increases if going to rapidity differences of > 1
- "LHCb may be able to measure a tt production rate asymmetry, and thus indirectly probe an anomalous forward-backward tt asymmetry in the forward region" PRL 107, 082003 (2011) [arxiv:1103.3747]
  - Not a detailed experimental study



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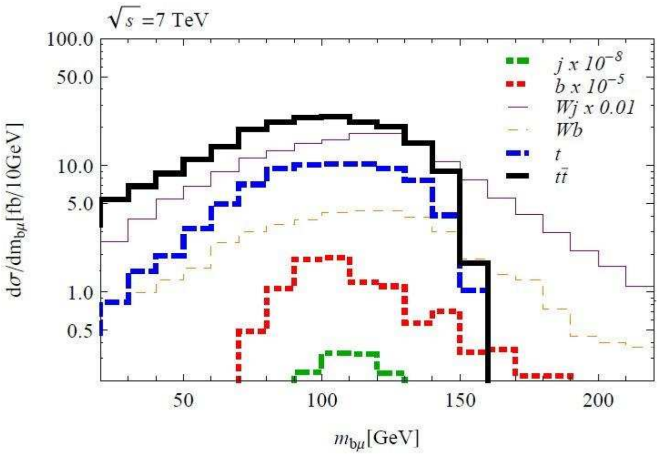


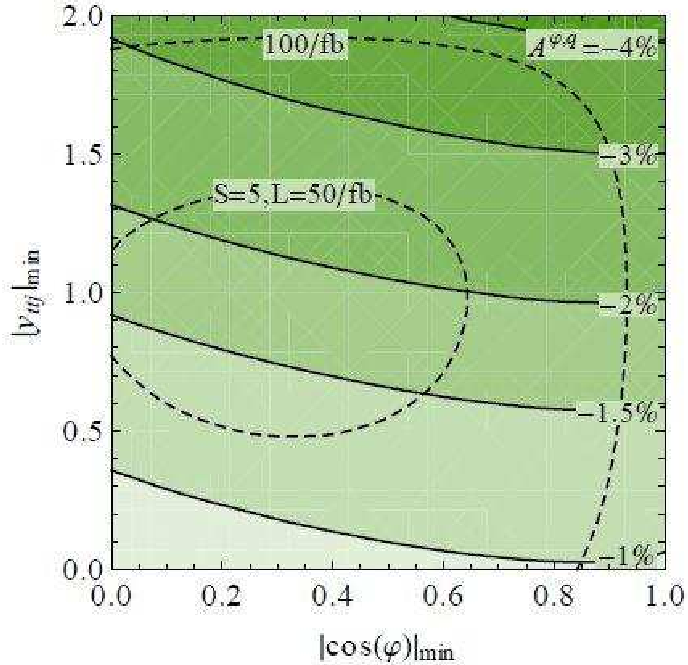
- Currently ongoing:
  - Detailed study by LHCb to give expected asymmetry
  - Include uncertainties, effect of b-tagging and bg uncertainties
  - Include expected yields for tops (towards a cross section measurement)
  - Detailed experimental study, expect result for Minnesota !

(Study needs approval by LHCb)

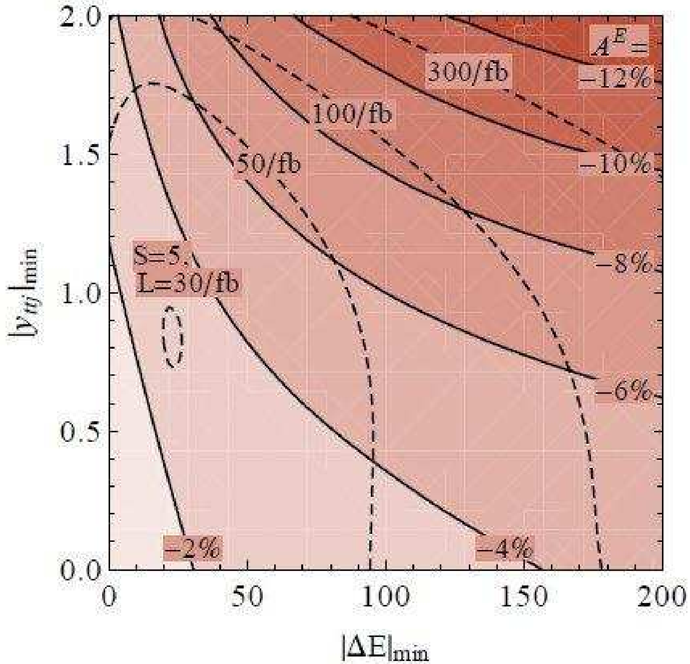
Top forward-backward asymmetry in ttbar + jet final state

- New observables to understand top asymmetries A: [arxiv: 1305.3272]
  - *Incline asymmetry* - sensitive to A from q-qbar initial state
  - *Energy asymmetry* - sensitive to A from q-g channel
- Good potential to observe these at LHC14 (300 /fb)-1

LHC14 Incline asymmetry:



LHC14 Energy asymmetry:



Top forward-backward asymmetry in ttbar + jet final state

- Top asymmetry at 100 TeV, very preliminary numbers by Berge, Westhoff:
  - Higher energies means more gg "background", --> hard cuts to enhance top asymmetry
  - Requires large amounts of integrated luminosities
  - energy asymmetry of ~ 8% require jets |y| < 5 (its 3.5% for |y|<2.5)
  - work in progress...very preliminary: not much advantage

Backup

Top Polarization

- Potential Snowmass study for top polarization at LHC14
  - No deviation from SM top polarization in LHC7, limited by systematic uncertainties
  - Constrain e.g. axi-gluon models (can explain the forward-backward asymmetry at the Tevatron)