Top Quark Physics
part 2

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Topics in This Talk

- Forward-backward /charge asymmetry
- Top spin effects (Top-antitop spin correlations)
- Flavor Changing Neutral Currents
- Anomalous couplings, CP violation, rare decays (not covered – waiting higher statistics)

Forward-backward / charge asymmetry in tt-bar production

Forward-backward / charge asymmetry in tt-bar

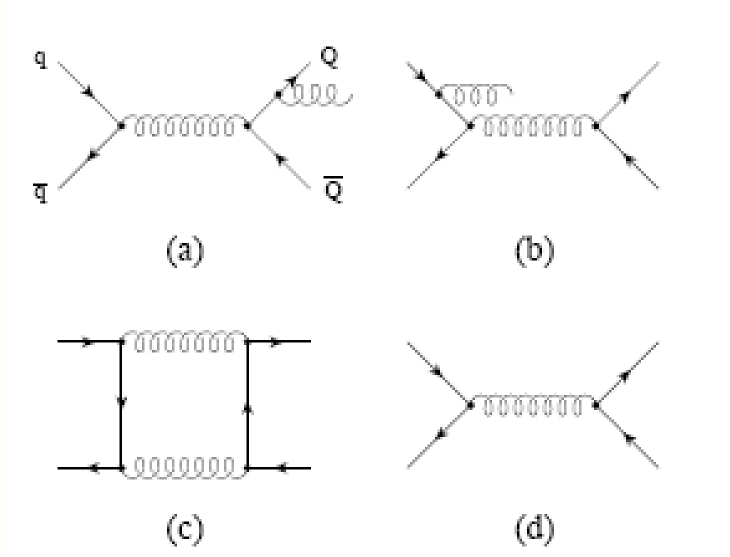
$p\bar{p}$ collisions (Tevatron experiments):

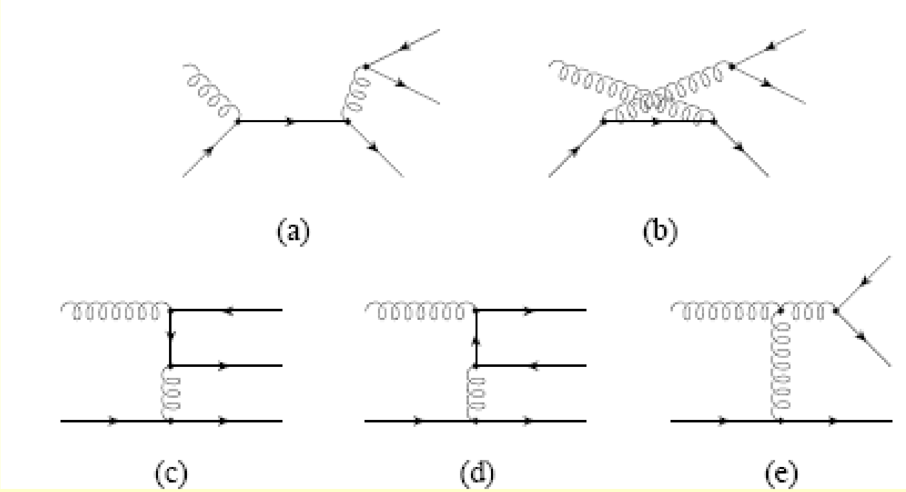
FB asymmetry: $N(t \to p)$: t in p direction vs $N(t \to \bar{p})$: t in $\bar{p}$ direction

Charge asymmetry: $N(t \to p)$ vs $N(\bar{t} \to p)$

LO strong interaction processes $q+\bar{q} \to Q+\bar{Q}$ and $g+g \to Q+\bar{Q}$: no AFB!

AFB: interference of amplitudes with the same initial final state particles.



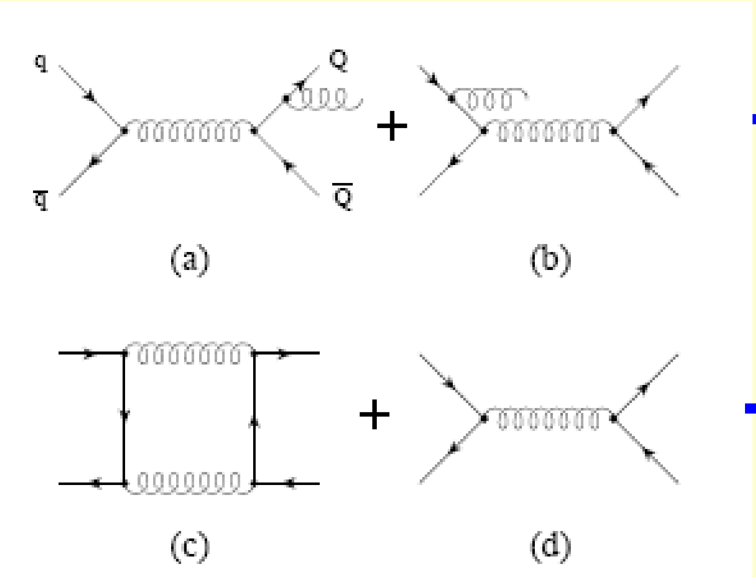


- ✓ Interference of final-state (a) with initial-state (b) gluon radiation amplitude
- ✓ Interference of the box (c) with Born diagram (d)

Charge asymmetry through flavor excitation in quark-gluon interaction (small contribution)

Forward-backward asymmetry in tt-bar production

The dependence of the SM asymmetry on QCD radiation is strong:



(a) + (b) → Negative asymmetry

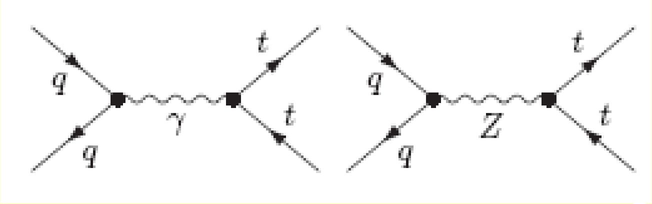
Contribution $\sim\alpha_s^3$

In reality both are infinite and cannot be treated independently

(c) + (d) → Positive asymmetry

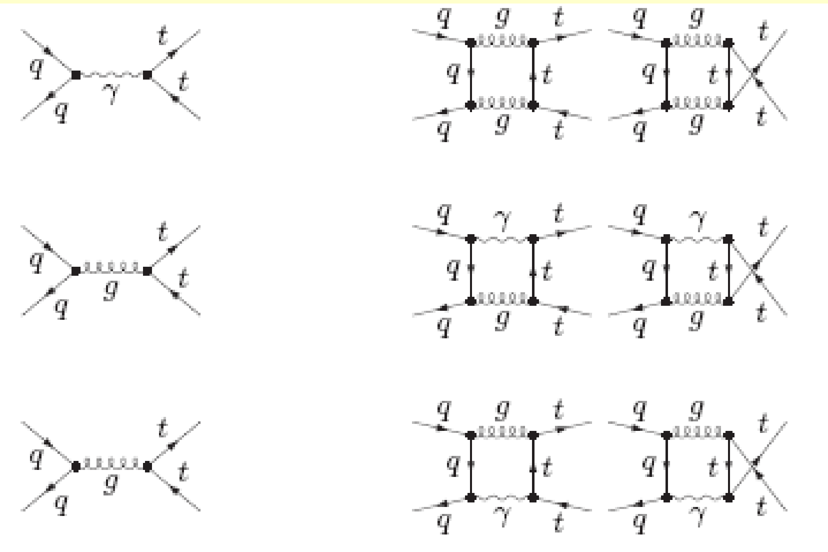
Non negligible contribution from to tT AFB comes from EW processes (~20% of QCD, Hollik and Pagani, arXiv.1107.2606v1):

Purely electroweak processes →

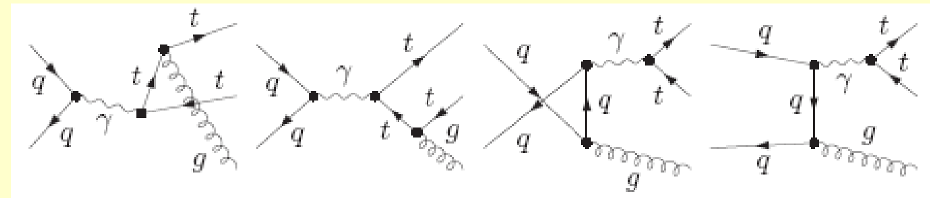


AFB in tt-bar production: QED-QCD interference

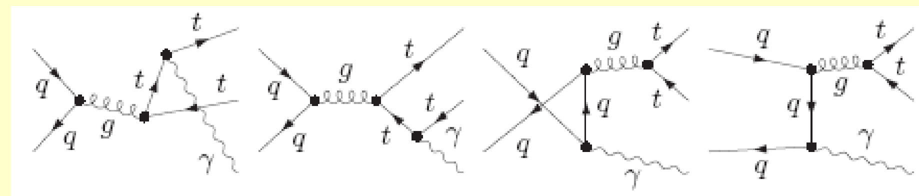
QED – QCD interference at $O\left(\alpha_S^2\alpha\right)$: from $q\bar{q}\rightarrow t\bar{t}$, $q\bar{q}\rightarrow t\bar{t}g$, $q\bar{q}\rightarrow t\bar{t}\gamma$



Interference tree-level and box diag.



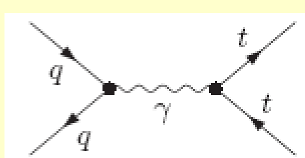
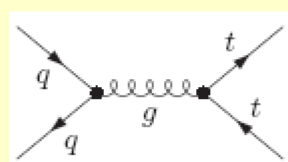
Real gluon emission from photon exchange



Real photon emission from gluon exchange

A$_{FB}$ =N/D

Hollik, Pagani: $R^{t\bar{t}}_{O\left(\alpha_S^2\alpha\right)+O\left(\alpha^2\right)} = \dfrac{N^{t\bar{t}}_{O\left(\alpha_S^2\alpha\right)+O\left(\alpha^2\right)}}{N^{t\bar{t}}_{O\left(\alpha_S^3\right)}} = \left(0.190,\ 0.220,\ 0.254\right)$ for μ = (*m/2,m,2m*)

Question: can  and  interfere?

AFB formulae, qq-bar rest frame

At partonic level: charge asymmetry | forward-backward asymmetry

$$\hat{A}_{Ch}\left(\cos\hat{\theta}\right)=\frac{N_Q(\cos\hat{\theta})-N_{\bar{Q}}(\cos\hat{\theta})}{N_Q(\cos\hat{\theta})+N_{\bar{Q}}(\cos\hat{\theta})}\qquad \hat{A}_{FB}\left(\cos\hat{\theta}\right)=\frac{N_Q(\cos\hat{\theta})-N_Q(-\cos\hat{\theta})}{N_Q(\cos\hat{\theta})+N_Q(-\cos\hat{\theta})}$$

$\hat{\theta}\equiv$ Angle of Q (=t,b) quark production angle in $q\bar{q}$ rest frame

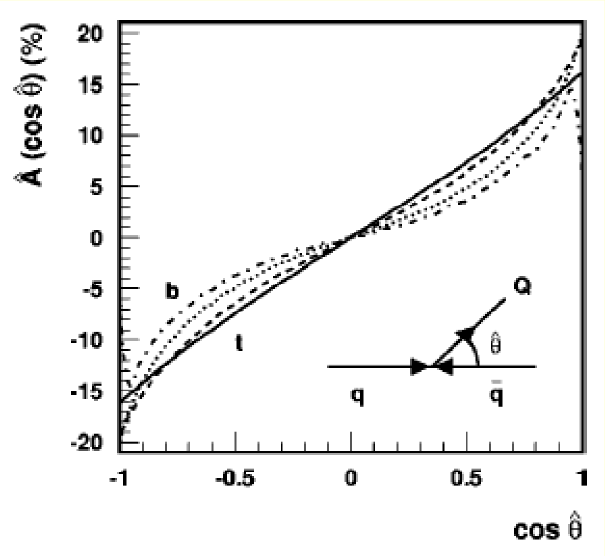
$$N(\cos\hat{\theta})=d\sigma/d\Omega(\cos\hat{\theta})$$

Assuming CP conservation:

$$N_{\bar{Q}}(\cos\hat{\theta})=N_Q(-\cos\hat{\theta})\quad\Rightarrow\quad \hat{A}_{Ch}=\hat{A}_{FB}$$

Integrated charge/FB asymmetry:

$$\bar{\hat{A}}=\frac{N_Q(\cos\hat{\theta}\geq 0)-N_{\bar{Q}}(\cos\hat{\theta}\geq 0)}{N_Q(\cos\hat{\theta}\geq 0)+N_{\bar{Q}}(\cos\hat{\theta}\geq 0)}$$

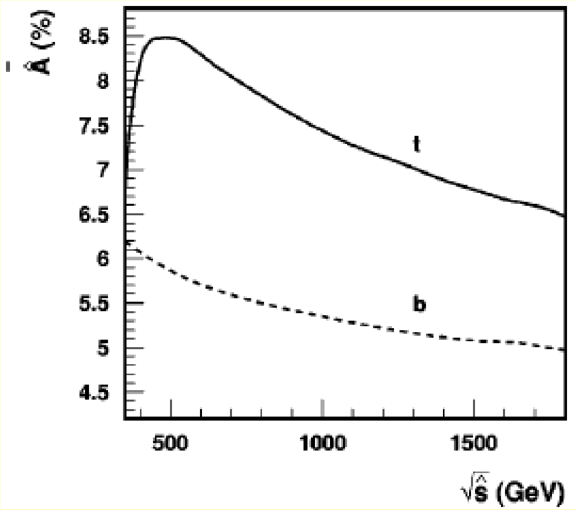


SM prediction for $t\bar{t}$ AFB ($q\bar{q}$ rest frame):

✓Integrated $A_{FB}\approx$ 6-8.5%

✓Differential A_{FB}: maximum at cosθ = ±1

PhysRev D59 054017(1999)



AFB in bb-bar at Tevatron

Using rapidity instead of $\cos\theta$ for AFB (diff. and integral) in $p\bar{p}$ rest frame one gets:

$$A_{FB}(y_t) = \frac{N(y_t) - N(-y_t)}{N(y_t) + N(-y_t)} \qquad A_{FB} = \frac{N(y_t > 0) - N(y_t < 0)}{N(y_t > 0) + N(y_t < 0)}$$

Charge asymmetry is got by: $N(-y_t) \to N(y_{\bar{t}})$ (CP conservation: $N(-y_t) = N(y_{\bar{t}})$)

Assuming CPC the AFB can be expressed through variable $\Delta y_t = y_t - y_{\bar{t}}$ (is the same in both $p\bar{p}$ and $t\bar{t}$ rest frame.

t-quark production angle, θ, in $t\bar{t}$ rest frame vs. Δy_t :

$$\Delta y_t = 2\tanh^{-1}(\beta\cos\theta), \quad \beta = \sqrt{1 - 4m_{top}^2 / \hat{s}}$$

The asymmetry (integral and differential):

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y_t > 0) - N(\Delta y_t < 0)}{N(\Delta y_t > 0) + N(\Delta y_t < 0)}, \qquad A_{FB}^{t\bar{t}}(\Delta y_t) = \frac{N(\Delta y_t) - N(-\Delta y_t)}{N(\Delta y_t) + N(-\Delta y_t)}$$

Experimental results on top AFB

A_{FB} reconstructed in lepton+jets and dilepton channel

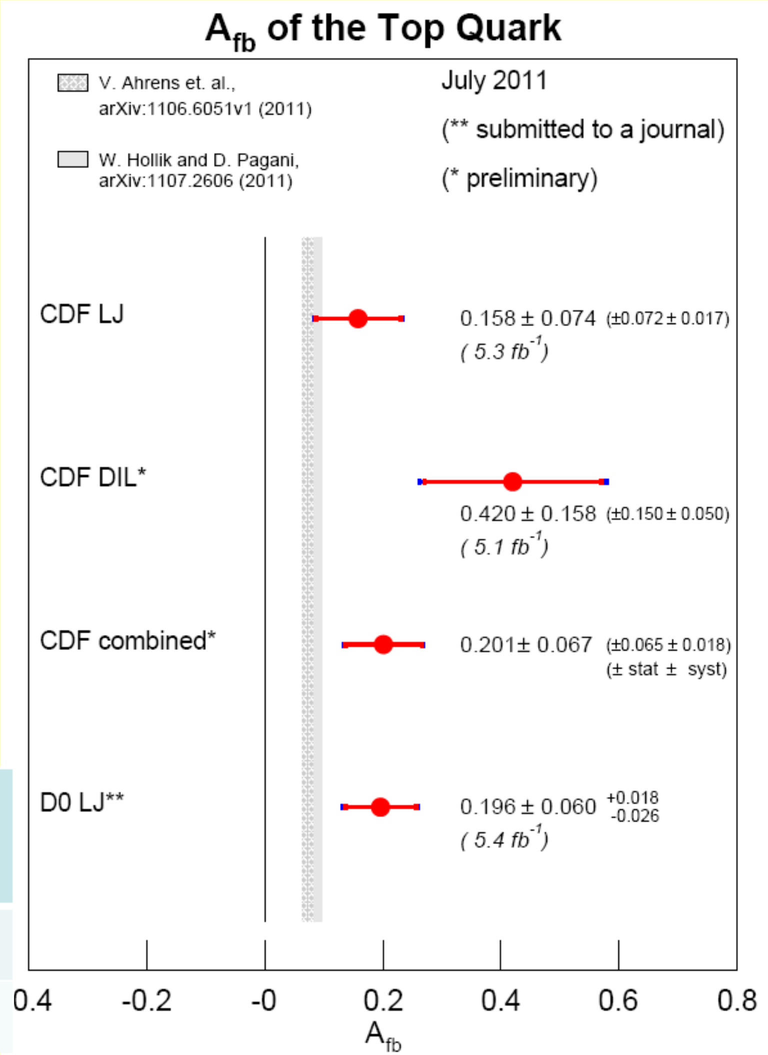
$$l + \not{E}_T + 4j \geq + \geq 1btag \rightarrow t\bar{t}$$

- jet parton match and $p_z(\nu)$ solution – using simple constraints and χ^2
- Sign of lepton → charge of top

✓ measured a M_{tt} and Δy dependent A_{fb} in tt system

✓ Corrected the M_{tt} and Δy spectra to derive parton level A_{FB}, $A_{FB}(\Delta y)$, $A_{FB}(M_{tt})$

✓ Strong dependence on M_{tt}



Background-Subtracted A_{FB} (%)	D0 Lep+Jet, 5.4 fb^{-1}	CDF Lep+Jet, 5.3 fb^{-1}	CDF Lep+Jet, 8.7 fb^{-1}
$M_{tt} < 450$ GeV/c^2	7.6 ± 4.8	−2.2 ± 4.3	2.5 ± 3.1
$M_{tt} \geq 450$ GeV/c^2	11.5 ± 6.0	26.6 ± 6.2	19.8 ± 4.3

Charge Asymmetry

- ✓ LHC: $t\bar{t}$ produced mainly in $gg \to t\bar{t}$ events and an asymmetry can be seen only in $q\bar{q} \to t\bar{t}$ and $qg \to t\bar{t}q \Rightarrow$ A_{FB} is strongly diluted!
- ✓ Charge asymmetry: tops preferentially emitted in quark direction.
- ✓ Quarks generally carry a larger momentum fraction of the proton than antiquarks, tops tend to be more forward than antitops in the lab frame

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y>0|) + N(\Delta|y|<0)}, \quad \text{where } \Delta|y| = |y_t| - |y_{\bar{t}}|$$

ATLAS: 7 TeV, L = 1.04fb^{-1}, lepton+jet channel, 2 bins of $m_{t\bar{t}}$

MC@NLO used to model $t\bar{t}$ events – prediction: $\boldsymbol{A_C = 0.06 \pm 0.02}$

Standard L+jets selection: 1 high p_T iso.lepton (e/μ), ≥4 jets +1b-tagged,
e: $\not{E}_T > 35\text{GeV}$ and $m_T(W) > 25\text{GeV}$, μ: $\not{E}_T > 20\text{GeV}$ and $\not{E}_T + m_T(W) > 60\text{GeV}$

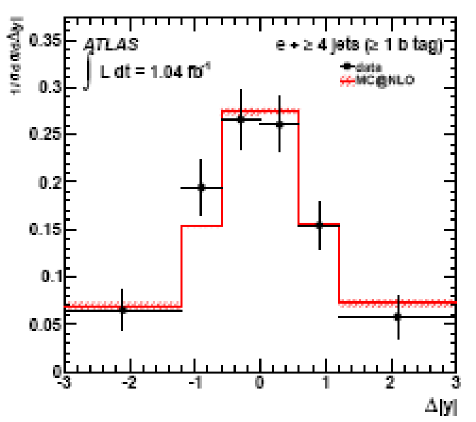
Δ|y| distribution is unfolded: MC is used to correct this distribution to parton level

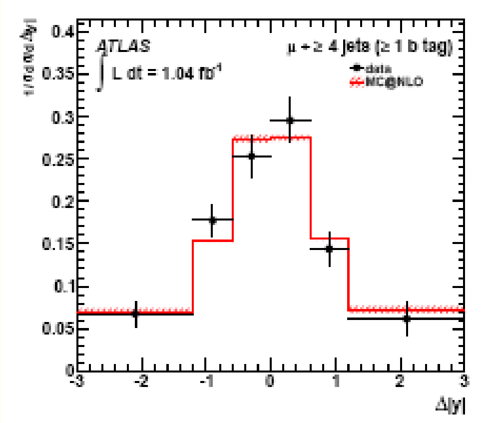
Unfolded Δ|y| distribution

Charge asymmetry results

A_C	reconstructed	detector and acceptance unfolded
e	-0.034 ± 0.019 (stat.) ± 0.010 (syst.)	-0.047 ± 0.045 (stat.) ± 0.028 (syst.)
μ	-0.010 ± 0.015 (stat.) ± 0.008 (syst.)	-0.002 ± 0.036 (stat.) ± 0.023 (syst.)

Background subtracted unfolded distribution for ***e*** and ***μ*** channel





Uncertainties:
Statistical +
Systematic

Combined e+μ result: $A_C = -0.018 \pm 0.028(\text{stat.}) \pm 0.023(\text{syst.})$

for $m_{t\bar{t}} < 450\,\text{GeV}$ for $m_{t\bar{t}} > 450\,\text{GeV}$

$A_C = -0.053 \pm 0.070 \pm 0.054$ $A_C = -0.008 \pm 0.035 \pm 0.032$

Conclusion: a good agreement with MC@NLO, higher statistics needed..

Top pair spin correlations, CP violation, FCNC

$t\bar{t}$ spin correlations

Top decays before hadronization $\Rightarrow$ Imprint of $t\bar{t}$ production spin:

- Spin of top is not diluted
- Gluon emission unlike to do $\Delta S \neq 0$

Angular distributions of top decay products

Considered parton reactions: $gg, q\bar{q} \to t\bar{t} + X \to b\bar{b} + 4f + X\ , \quad f = q, l, \nu$

Decay of polarized t quark

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + \kappa_f \xi_t \cdot \hat{q}_f\right)$$

$\theta_f \equiv \sphericalangle\left(f \text{ direction } (\hat{q}_f), \text{ top polarisat. vec. } \xi_t \right)$

$\kappa_f \equiv$ spin-analzyer qualitz of product f

$$\kappa_{l^+} = \kappa_{\bar{d}} = \cdots = 1,\ \kappa_b = -0.41, \cdots$$

for anti-t decay: $\kappa_f \to -\kappa_f$

Most promising: Dilepton l^+l^- angular distribution

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + C\kappa_{l^+}\kappa_{l^-}\cos\theta_+\cos\theta_-}{4},$$

$\theta_+ \equiv \sphericalangle\left(n_t \text{ in } t\bar{t} \text{ c.m.s. },\ n_{l^+} \text{ in } t \text{ rest frame} \right)$

Where in helicity basis (quantization axis $\equiv$ top direction)

$$C = \frac{\left[N(t_R\bar{t}_R) + N(t_L\bar{t}_L)\right] - \left[N(t_R\bar{t}_L) + N(t_R\bar{t}_L)\right]}{\left[N(t_R\bar{t}_R) + N(t_L\bar{t}_L)\right] + \left[N(t_R\bar{t}_L) + N(t_R\bar{t}_L)\right]}$$

A few comments...

- A set of spin-correlation variables (observables) can be defined:

A) $\left(\hat{k}_t \cdot s_t\right)\left(\hat{k}_{\bar{t}} \cdot s_{\bar{t}}\right)$,

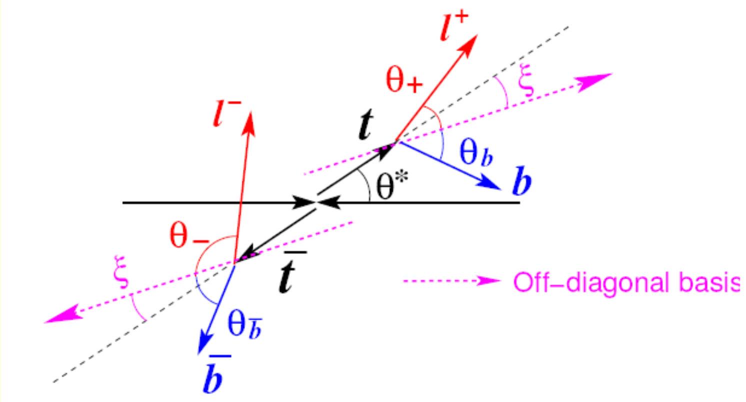
B) $(\hat{p} \cdot s_t)(\hat{p} \cdot s_{\bar{t}})$, $(s_t \cdot s_{\bar{t}})$, $(\hat{p} \cdot s_t)\left(\hat{k}_{\bar{t}} \cdot s_{\bar{t}}\right) + (\hat{p} \cdot s_{\bar{t}})\left(\hat{k}_t \cdot s_t\right)$

$\hat{p}\left(\hat{k}_t\right) \equiv$ proton (top quark) moment.

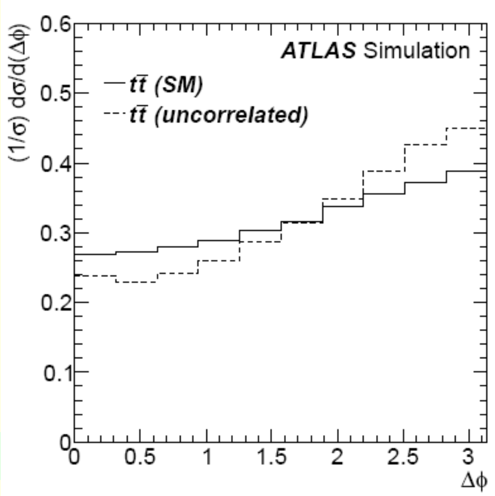
- In addition to „helicity basis“ observable (A) is used „beam line basis“ a combination of observables (B) or „off-diagonal basis“ :

  tan*$\xi \equiv$ *sqrt(1-*β^2*) tan* θ**.

  In ttbar frame: $\beta \equiv$ top velocity and $\theta^* \equiv$ top flight direction w.r.t. proton direction.



- In dilepton case:
  angular difference, $\Delta\phi$, in azimuthal plane between l^+ and l^- is used



CMS: tt-bar spin correlations

Measurement for pp collisions at $\sqrt{s}$ =7 TeV, L=5fb^{-1}

Dilepton events $t\bar{t} \to l^+ \nu_l \, l^- \bar{\nu}_l \, b\bar{b}$ used (2***l***, 2 b-jets and $\not{E}_T$ are required)

Background: W/Z+jets (V decays leptonically) and single top quark.

Imprint of spin correlation using:

- ✓ angular difference in azimuthal plane between ***l***$^+$ and ***l***$^-$ ($\Delta\phi_{l+l-} = |\phi_{l+} - \phi_{l-}|$)
- ✓ Angles θ_l^+ and θ_l^- of ***l***$^+$ and ***l***$^-$ w.r.t. t and $\bar{t}$ directions in $t\bar{t}$ rest frame

Spin correlation coefficient:

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\downarrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\downarrow\uparrow) + N(\uparrow\downarrow)}$$

Arrows refer to the spin orientation of t and $\bar{t}$ w.r.t. the quantisation axis.

Other observables:

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{l+l-} > \pi/2) - N(\Delta\phi_{l+l-} < \pi/2)}{N(\Delta\phi_{l+l-} > \pi/2) + N(\Delta\phi_{l+l-} < \pi/2)}$$

$$A_{c1c2} = \frac{N\left(\cos(\theta_l^+) \times \cos(\theta_l^-) > 0\right) - N\left(\cos(\theta_l^+) \times \cos(\theta_l^-) < 0\right)}{N\left(\cos(\theta_l^+) \times \cos(\theta_l^-) > 0\right) + N\left(\cos(\theta_l^+) \times \cos(\theta_l^-) < 0\right)}$$

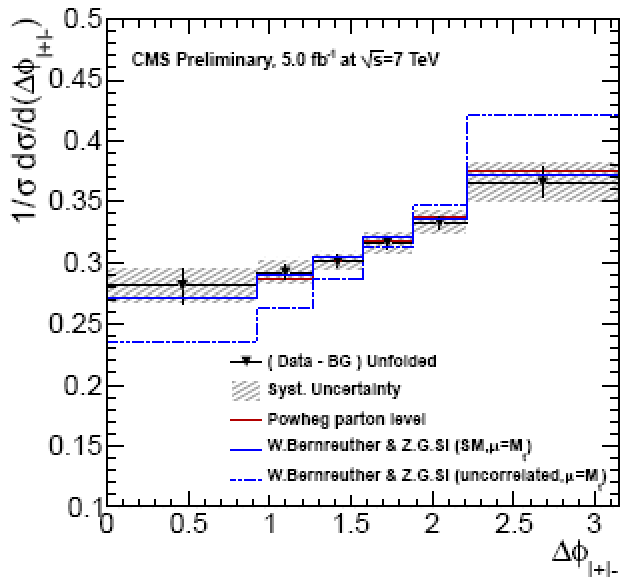
CMS: spin correlations results

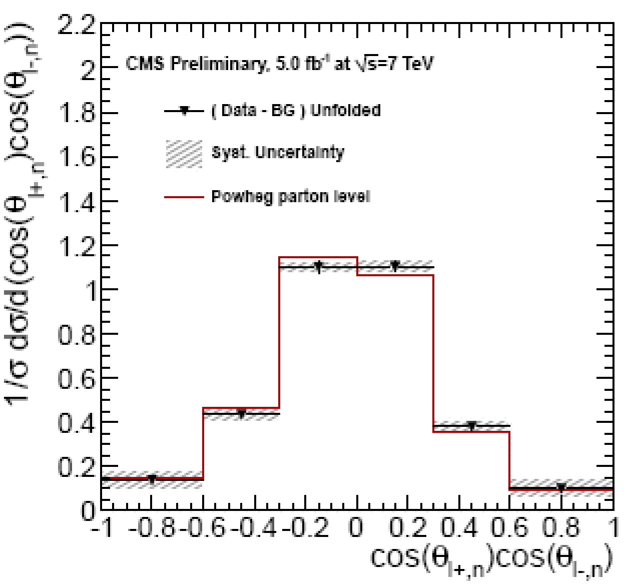
Main results (helicity basis – quantization axis ≡ top direction):

$$A_{hel}^{meas} = 0.24 \pm 0.02(\text{stat}) \pm 0.08(\text{syst}) \text{ vs SM expected } A_{hel}^{meas} = 0.31$$

Asymmetry coefficients:
$A_{\Delta\phi}$ and A_{c1c2} for 2 M_{tt} bins

Reconstructed asymmetries	Data	Simulation
$A_{\Delta\phi}$, inclusive region	-0.158 ± 0.010	-0.171 ± 0.002
A_{c1c2}, inclusive region	-0.062 ± 0.011	-0.087 ± 0.002
$A_{\Delta\phi}$, $M_{t\bar{t}} > 450$ GeV	-0.378 ± 0.019	-0.384 ± 0.003
A_{c1c2}, $M_{t\bar{t}} > 450$ GeV	-0.019 ± 0.016	-0.044 ± 0.003



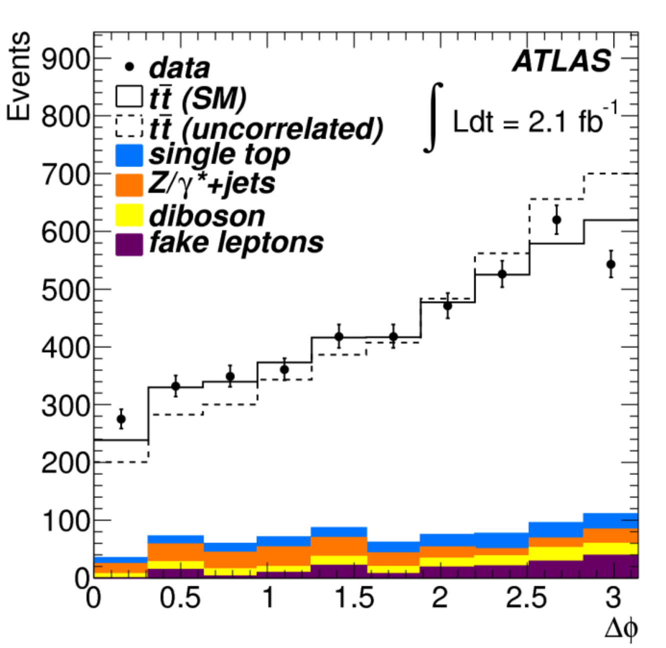


Bkg-subtracted and unfolded diff. Xsec for $\Delta\phi_{l+l-}$ and $\cos(\theta_l^+) \times \cos(\theta_l^-)$

ATLAS: top spin correlations

- Measurement for pp collisions at $\sqrt{s}$ =7 TeV, L=2.1fb^{-1} , Dilepton events
- Standard DIL cuts (2l, ≥2jets (≥1b) and $\not{E}_T$) + $m_{l^+l^-} > 15\,\mathrm{GeV},\ \notin M_Z \pm 10\,\mathrm{GeV}$
- Spin correlation coef. ***A*** found *via* templates applied to Δϕ distribution
- Coeficient ***A*** is calculated in two bases:
  - ✓ the helicity basis
  - ✓ the maximal basis which is optimized for $t\bar{t}$ production from *gg* fusion (P. Uwer, Phys. Lett. B 609, 271 (2005))
- SM prediction: $A_{hel}^{SM} = 0.31, \quad A_{\max}^{SM} = 0.44$, 1% err
- Background Z/γ+jets, W+jets, S.Top, Dibosons

Total (non-$t\bar{t}$)	740^{+150}_{-80}
$t\bar{t}$ (MC)	3530^{+280}_{-340}
Total expected	4270^{+320}_{-350}
Observed	4313



ATLAS: spin correlations results

- Measured quantities: $A_{helicity}$, $A_{maximal}$ and f^{SM}

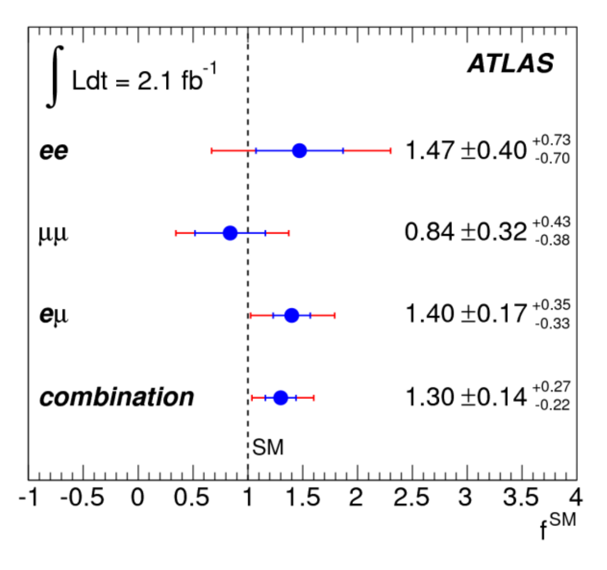
Fit of data $\Delta\phi$ distribution fitted also to $f^{SM} \cdot \Delta\phi^{corr}_{SM} + \left(1 - f^{SM}\right)\Delta\phi^{uncorr}_{MC}$

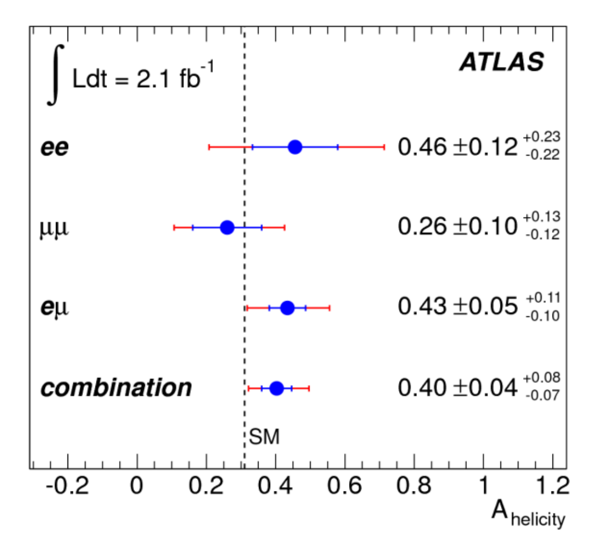
$$A_{helicity} = 0.40 \pm 0.14\left(\text{stat}\right)^{+0.08}_{-0.07}\left(\text{syst}\right)$$

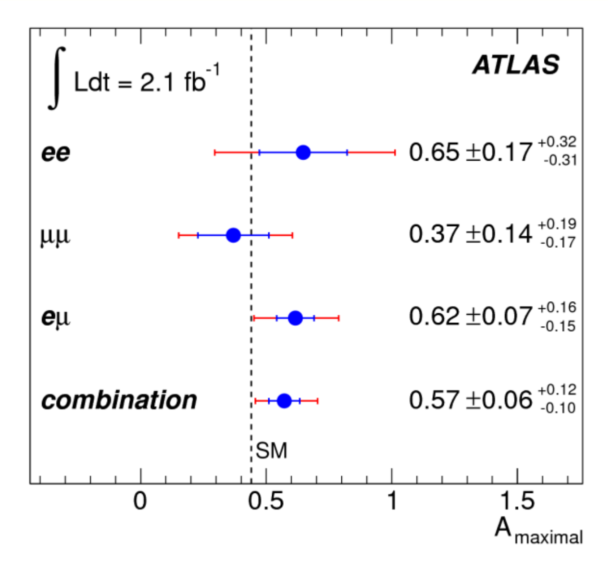
$$f^{SM} = 1.30 \pm 0.14\left(\text{stat}\right)^{+0.27}_{-0.22}\left(\text{syst}\right)$$

$$A_{maximal} = 0.57 \pm 0.06\left(\text{stat}\right)^{+0.12}_{-0.10}\left(\text{syst}\right)$$

SM expectations: $A^{SM}_{hel} = 0.31,\quad A^{SM}_{max} = 0.44,\quad f^{SM} = 1.0$





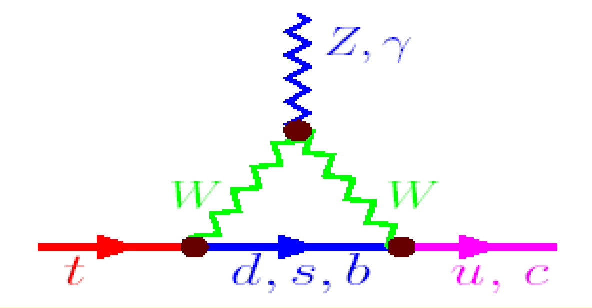


Details – see: arXiv.1203.4081, Phys.Rev.Lett 108.212001(2012)

Flavor Changing Neutral Currents

FCNC in Top Quark Physics

FCNC couplings tVc and tVu; V = g, γ, Z



- Absent at tree-level and highly suppressed in SM: direct proceses: $t \to Z + c$, $\to \gamma + c$ $\to g + c$ forbiden in SM
- in SM present only through loop contributions

- Observation of top quark FCNC processes $\Rightarrow$ New Physics!

$t \to$	SM	two-Higgs	SUSY
$g\,q$	5×10^{-11}	10^{-6}	10^{-3}
$\gamma\,q$	5×10^{-13}	10^{-6}	10^{-5}
$Z\,q$	$\sim 10^{-13}$	10^{-9}	10^{-4}

CDF & LEP2
Present Limits

BR < 17%

BR < 3.2%

BR < 18%

ATLAS FCNC measurement

Study performed at √s = 7 TeV L = 2.1 fb−1, for tt-production events with 1 top quark decaying through $t \to Zq$ FCNC ($q = u, c$) channel

Selected events required to be consistent with $t\bar{t} \to Wb\,Zq$ where $W \to l\nu$

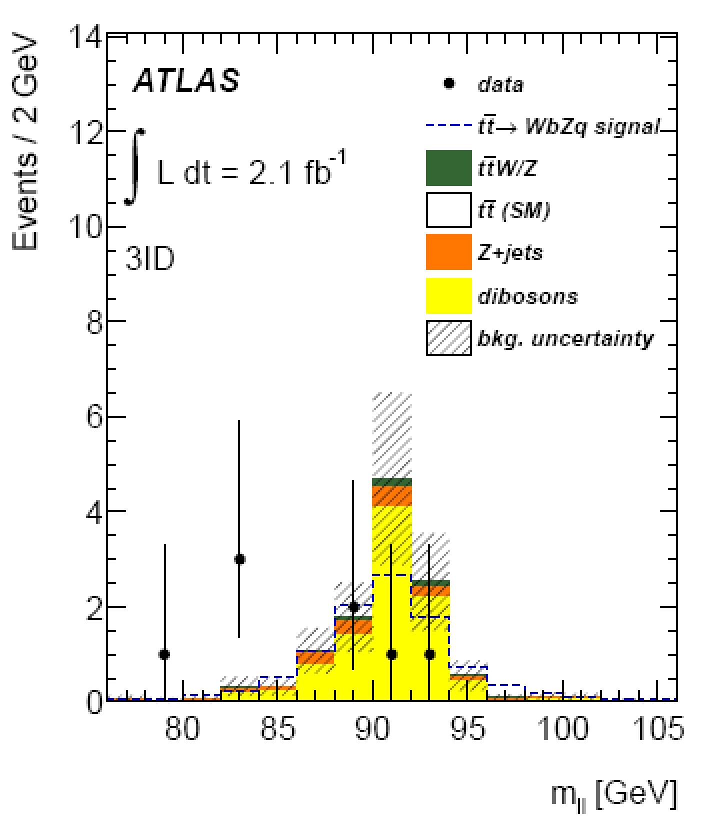
Final-state topology: 3 isolated leptons, ≥2 jets and $\not{p}_T$ (due to ν)

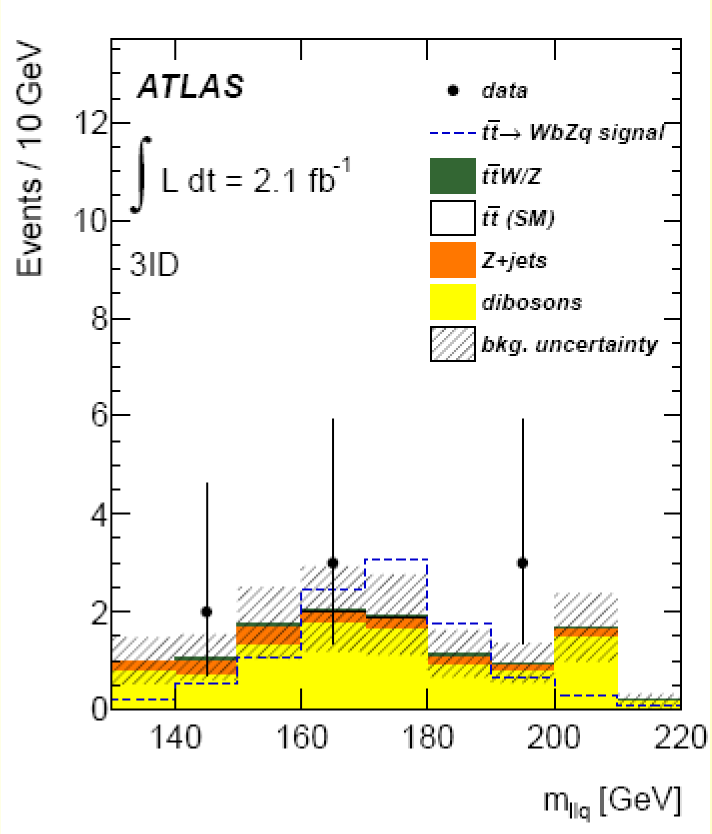
Background

	3ID	2ID+TL
ZZ and WZ	9.5 ± 4.4	$1.0 \pm^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	7.6 ± 2.2
Z+jets	1.7 ± 0.7	
Single top	0.01 ± 0.01	
2+3 fake leptons	$0.0 \pm^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	$(0.205 \pm 0.024)\%$	$(0.045 \pm 0.007)\%$

ATLAS FCNC results

Expected and observed Z-boson and top-quark mass distributions for the FCNC decay hypothesis in the 3ID topology





Upper limit on $t \rightarrow Zq$ branching ratio of $BR(t \rightarrow Zq) < 0.73\%$ (95% C. L.)

Details – see: arXiv.1206.0257, subm. to JHEP)

Conclusions

- LHC is a top quark factory with very rich and interesting top quark physics
- It enables very stringent tests of SM – QCD tests, indirect study of Higgs mass, etc.
- Provides a lot of channels for search of a new physics
- Precise knowledge of top quark processes is inevitable for other studies (e.g. Higgs boson studies)
- Stay tunned and look forward to more than 20 fb^{-1} at 8 TeV

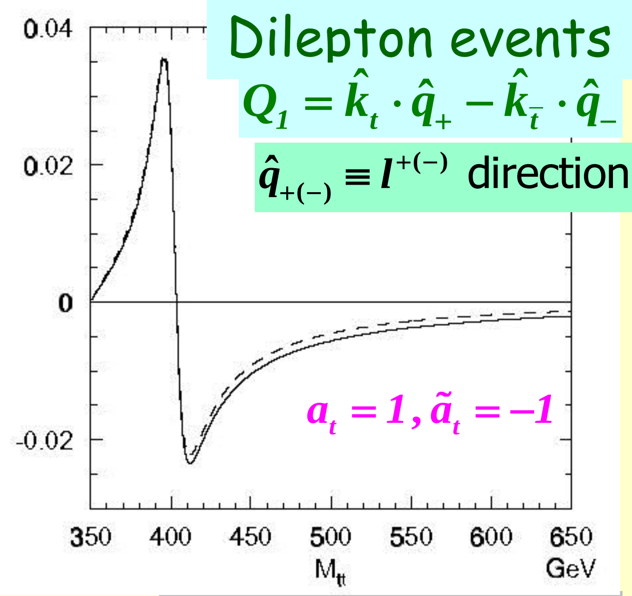
Thank you!

Top and CP violation

- CKM phase → only tiny effect on t-pair production and decay
- Non SM CP-violating interactions → in prod. density matrix (R) 2 types CP-odd spin-momentum correlations:

$$\hat{k}_t \cdot (s_t - s_{\bar{t}}), \quad \hat{k}_t \cdot (s_t \times s_{\bar{t}}), \qquad \hat{k}_t \to \hat{p}$$

$\hat{k}_t \equiv$ top direction, $\hat{p} \equiv$ init. quark direction



Dilepton events

$Q_1 = \hat{k}_t \cdot \hat{q}_+ - \hat{k}_{\bar{t}} \cdot \hat{q}_-$

$\hat{q}_{+(-)} \equiv l^{+(-)}$ direction

Bernreuther et al, hep-ph/9812387

Examples:

- In MSSM fermion-sfermion-neutralino interactions → CP violating phases from SUSY breaking terms
- Extended scalar sector → via non-degenerate neutral Higgs bosons with undefined CP parity.

Coupling of Higgs (φ) with top: $\sim m_t \left(a_t \bar{t}\, t + i\tilde{a}_t \bar{t}\, \gamma_5 t \right) \varphi$

(in SM $a_t = 1, \tilde{a}_t = 0$)

becomes resonant at $m_\varphi \sim 2\, m_t$ or above $gg \to \varphi \to t\bar{t}$

Can be also employed:

Asymmetry:

$$A(Q_1) = \frac{N_{ll}(Q_1 > 0) - N_{ll}(Q_1 < 0)}{N_{ll}}$$

Top quark anomalous interactions

- Top Xsection known with ~5-7% accuracy
- No top hadrons
- Top decay via pure V-A weak interaction
- Only one significant decay channel: $t \rightarrow Wb$

} Top quark a unique place for a new physics behind SM

New physics from symmetry breaking at scale Λ (~1TeV)?

Anomalous $gt\bar{t}$ couplings: Cross section of $q\bar{q} \rightarrow t\bar{t}$ will have terms for
- anomalous chromomagnetic and chromoelectric dipole moments
- Retrieved from l^+l^- (top pair decay) observables:

Choi et al, PhysLettB415(1997)67

Anomalous Wtb couplings

- Can be probed in top pair and single top production.
- 4 form factors describe Wtb – two are ½ (from SM) and 2 to be analyzed:

$$F_{L(R)2} = \frac{2M_W}{\Lambda} \kappa_{tb}^{W} \left(- f_{tb}^{W*} - (+) i h_{tb}^{W*} \right)$$

⇒Boos et al,EFJC11(1999)473