Some remarks on top

Werner Bernreuther
RWTH Aachen

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Where do we stand

Significant progress in exploration of top physics since Top2008 ws @ La Biodola/Elba

CDF @ D0 experiments @ Tevatron:

Impressive number of new results, including

improved measurements of $\sigma_{t\bar{t}}$ in the main channels
single top production: evidence $\longrightarrow$ observation
improved ms. of top mass (value "converges")
knowledge about t decay – i.e. its flavour-interactions – refined:
  $t \to bW$ still the only decay-mode observed
  strength & structure of tWb vertex known to $\mathcal{O}(10\%)$
top width recently measured: direct ms. (CDF), indirect ms. (D0)
$t\bar{t}$ events: ms. of distributions, including
  charge asymmetry
  $t\bar{t}$ spin correlations
  $M_{t\bar{t}}$ spectrum and search for resonances $m_X \lesssim 1$ TeV

Recent progress in theory/phenomenology (≥ 2008), including

- updates of $\sigma_{t\bar{t}}$ (NLO QCD + threshold resumm. (NLL))
  (Moch, Uwer; Cacciari et al.; Kidonakis, Vogt, 2008)
- NNLL extensions (Czakon et al., Beneke et al., Ahrens et al.)

production threshold $\beta = \sqrt{1 - 4m_t^2/\hat{s}} \to 0$ vs. thresh. in P.I.M. kinematics $z = M_{t\bar{t}}^2/\hat{s} \to 1$ (no phase space for hard gluon emiss.)
$\longrightarrow$ talk by S. Moch

- $\sigma_{t\bar{t}}$ very near prod. threshold (Hagiwara et al., Kiyo et al.) $\longrightarrow$ talk by H. Yokoya

A_{FB} from threshold resummed cross section (Almeida et al., Ahrens et al.) $\longrightarrow$ talk by G. Rodrigo

- partial results towards $\sigma_{t\bar{t}}$ @ NNLO QCD (Czakon, Bonciani et al., ...)
- $t\bar{t} + \text{jets}$ & NLO; top as important background to Higgs searches: weak boson fusion $W^+W^- \to H$, and $t\bar{t}H$:
  - $t\bar{t}+$ jet (Dittmaier, Uwer, Weinzierl; Melnikov, Schulze)
  - $pp \to t\bar{t} + b\bar{b}$ (Bredenstein et al., Bevilacqua et al.)
  - $pp \to t\bar{t} + 2$ jets (Bevilacqua et al.)

  $\longrightarrow$ talk by M. Worek
- $t\bar{t}$ spin correlations revisited (Mahlon, Parke; W.B., Si) $\longrightarrow$ talk by G. Mahlon
- PDF $\longrightarrow$ talk by A. Guffanti
- new features in NLO MC generators MC@NLO, POWHEG, MCFM $\longrightarrow$ talk by P. Nason
- special programs for $t\bar{t}$ production & decay @ NLO QCD (Melnikov, Schulze), + weak-int. corr. (W.B., Si)
- single top t channel production @ NLO QCD within 4 and 5 flavour scheme (Campbell et al.) $\longrightarrow$ talk by R. Frederix
- Wt production @ NLO QCD within MC@NLO (Frixione et al.) $\longrightarrow$ talk by C. White
- many pheno studies, including
  - boosted tops (Almeida et al., Kaplan et al., ...) $\longrightarrow$ talk by E. Chabert
  - comprehensive det. of anomalous couplings in single t production and t decay (simulation code) (Aguilar-Saavedra et al.)
- many pheno investigations on BSM effects in top production @ decay, including
  - BSM contributions to A_{FB}^t ($\sim$ 30 papers) $\longrightarrow$ talk by G. Rodrigo
  - effects of a 4th generation or of heavy exotic quarks $\longrightarrow$ talk by G. Hou
  - resonance studies, $X_J \to t\bar{t}$, BSM Higgs, colored resonances, KK states, ...
  - BSM CP violation $\longrightarrow$ talk by G. Valencia

Thus, state of the art:

CDF and D0: $\longrightarrow$ so far, top behaves pretty much standard
(A^t_{FB} may point to an exception)

Theory: main ttX and single t processes computed to NLO in SM gauge couplings,
many options for BSM effects studied

Present & future issues:

- sharpen top profile further: mass, charge, spin, decay modes $\&$ width
- more detailed ms./investig. of cross sections & distributions

- Hope to gain potentially new insights into **flavour physics**
  New decay modes ? $t \longrightarrow \tilde{t}$ ..., FCNC decays $t \longrightarrow c$?
  or detectable FCNC in top production: $pp \rightarrow t\bar{c}\,X$?
  Hints for existence of a new quark generation or exotic heavy quarks?

- Eventually explore:
  top's capability to probe **mechanism of electroweak gauge-symmetry breaking**

Remarks on some topics (subjective choice):

- mass
- strength and structure of tWb vertex, new decay modes
- Charge asymmetry @ Tevatron
- $t\bar{t}$ spin correlations
- Single top production
- new heavy resonances $X_J \longrightarrow t\bar{t}$ in “early” LHC phase?

Top quark mass

Precisely measured by exploitation of $t\bar{t}$ event kinematics
using matrix element method, template method, ...

CDF & D0 average (2009): $m_t^{exp} = 173.1 \pm 1.3$ GeV

m_t^{exp} has an error of 0.75 % – but which mass is measured?

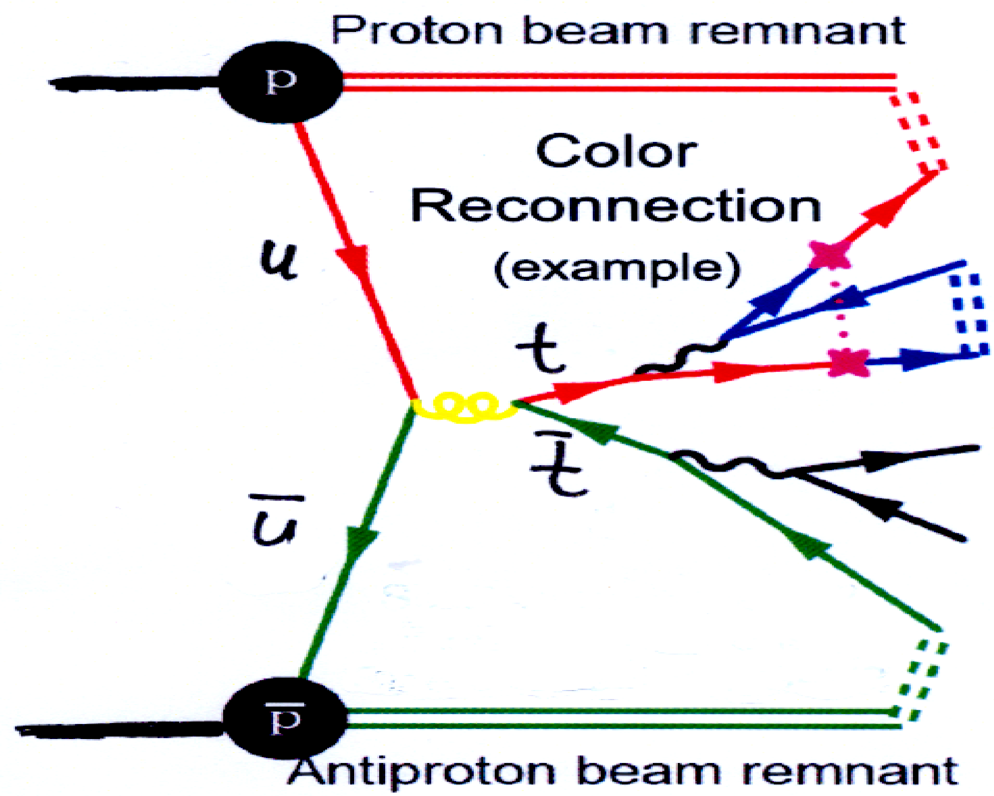
Discussion already @ top2008/Elba: (A. Hoang, ...)

Relation to a (well-defined) quark mass parameter?

$m_t^{exp} \leftrightarrow m_t^{pole}$ is reasonable, but cannot be completely correct.

Exp. determination hard to map onto a QCD calculation

m_{top} from peak of invariant mass distribution and from fits to Born ME:



from D. Wicke

Color reconnection, i.p. color exchange between t, $\bar{t}$ decay products (i.p. b and $\bar{b}$) and proton remnants non-perturbative QCD effect

heuristic Monte-Carlo model (Skands, Wicke 2008):
$\rightarrow$ $\delta m_t \approx 0.5$ GeV (color reconnection), taken into account by D0 and CDF
Challenge: Ab initio calc. of color reconnection effects in hadronic $t\bar{t}$ production & decay

Exploiting that $\frac{\Delta\sigma}{\sigma} \simeq -5\frac{\Delta m_t}{m_t}$ both for Tevatron & LHC cross section

Computation of $\sigma_{t\bar{t}}$ in terms of a short-distance mass, e.g. $m_t^{\overline{\rm MS}}$:

$$\sigma_{t\bar{t}}^{exp} \leftrightarrow \sigma_{t\bar{t}}^{th}(m_t^{\overline{\rm MS}})$$

Determination of $\overline{\rm MS}$ mass $\overline{m}_t$ from $\sigma_{t\bar{t}}$ @ Tevatron (Langenfeld, Moch, Uwer):

$$\overline{m}_t(\mu = \bar{m}_t) = 160.0 \pm 3.3 \text{ GeV} \quad \leftrightarrow \quad m_t^{pole} = 168.9 \pm 3.5 \text{ GeV}$$

However, SM production dynamics is assumed!

Other kinematical methods (in high lumi phase of LHC):

• $t\bar{t} \to b\,(\to J/\Psi \to \mu\mu)\, + \ell\nu_\ell\; + \;\text{jets}$
m_t correlated with inv. mass $M_{J/\Psi\ell}$ (Kharchilava)

similar variable: $M_{\ell+j_b}$. At LO: max $M^2_{\ell+j_b} = m_t^2 - m_W^2$,
NLO dist. by Melnikov, Schulze .... (sensitivity to m_t studied?)

• m_t from b hadron decay length (Incandela)

• $\langle M_{t\bar{t}} \rangle$ and higher moments sensitive to m_t (assuming SM) (Frederix, Maltoni)

These methods have different theoretical and exp. uncertainties – new studies/ideas?

$\longrightarrow$ talks by G. Corcella, O. Brandt, ...

$t \longrightarrow bW$ & universality of weak interactions

in 3-gen. SM: $B(t \to bW) \simeq 99.9\%$ D0: $B(t \to bW) = 0.97^{+0.09}_{-0.08}$

Lorentz structure from W-boson helicity fractions:

precisely known in SM (Do et al., Piclum et al.)

$$f_0(h_W = 0) \simeq 70\%, \qquad f_-(h_W = -1) \simeq 30\%, \qquad f_+(h_W = +1) \simeq 0.1\%$$

depend on m_t

Measurements by $\cos\theta^*_\ell$, $M^2_{\ell b}$, p^ℓ_T distributions

CDF, D0: 1- and 2-parameter fits $\longrightarrow \delta f_{0,\mp} \sim 10\%$

$\longrightarrow$ talks by D. Mousumi, A. Harel

Interpretation in terms of form factors/anomalous couplings:

Lorentz covariance $\Rightarrow$

$$\frac{g_W}{\sqrt{2}}\{\ \bar{b}\gamma^{\mu}(f_L P_L + f_R P_R)tW_{\mu} + \bar{b}i\sigma^{\mu\nu}\frac{q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}\ \}$$

- SM with 3 quark generations: $f_L = V_{tb}$, i.e. $|f_L| = 1$, $f_R, g_L, g_R = 0$

(small) admixture of $V + A$ coupling $t_R \to b_R$?
chirality flipping couplings $t_R \to b_L$ or $t_L \to b_R$?

- strong indirect constraints on f_R and g_L from decays $B \to X_s\gamma$:
$\longrightarrow |f_R|, |g_L| \lesssim$ few $\times 10^{-3}$, but not fool-proof

Studies for LHC, 14 TeV, 10 fb^{-1}: Hubaut et al.; Aguilar-Saavedra et al., ...

- $|\delta f_R| \gtrsim 0.06$, $|\delta g_L| \gtrsim 0.05$, $|\delta g_R| \gtrsim 0.03$

- **strength of vertex, i.e. f_L: $\leftrightarrow$ single top production**

D0: 1.07 ± 0.12 CDF: $0.91 \pm 0.11 \pm 0.07$

(long term) goal for LHC: $|\delta f_L| \sim 0.05$

Sensitivity to these couplings @ LHC (7 TeV) with < 1 fb^{-1} ?

Theoretical expectations for form factors f_L, f_R, g_L, g_R:

- SM extensions with 3 quark generations:

multi-Higgs extensions, SUSY extensions, TC2 models ...

1-loop corrections $\longrightarrow f_R, g_L, g_R \neq 0$, **but very small,** $\lesssim 0.01$

i.p. phases due to FSI or non-standard CP violation are small

deviation of f_L from $V_{tb}^{SM} = 0.999..$: $\lesssim$ a few %

- deviation $\delta f_L \sim 0.1$ possible if new, heavy $Q = 2/3$ quarks exist that mix with top.

4th sequential quark generation t', b':

$\rightarrow 4 \times 4$ mixing matrix $\rightarrow |f_L| = |V_{tb}| < 1$

scans using imput from B, D, K decays, electroweak precision measurements (S, T):

$\rightarrow |f_L| = |V_{tb}| > 0.93$ Eberhardt et al. (2010)

more exotic possibility: new heavy vector-like T quark

Little Higgs models; models with extra dim., ... $|f_L| \gtrsim 0.9$

Other top decay modes?

- CKM-suppressed modes in SM:

$$\mathrm{B}(t \longrightarrow W^+ s) = 1.9 \times 10^{-3}, \quad \mathrm{B}(t \longrightarrow W^+ d) = 10^{-4}$$

- New decay modes, e.g. $t \longrightarrow b\, H^+$ or $t \longrightarrow \tilde{t}\, \tilde{\chi}^0$?

Searches by CDF and D0 (negative so far) still leave some room for light $H^{\pm}$ or light $\tilde{t}$

- FCNC decays $t \longrightarrow c$? CDF (2009): $B(t \longrightarrow Zq) < 0.037$

most SM extensions predict very small Br (Bar-Shalom et al.,....)

$\mathrm{B}(t \longrightarrow cg)$	$\mathrm{B}(t \longrightarrow cZ)$	$\mathrm{B}(t \longrightarrow c\gamma)$	
10^{-11}	10^{-13}	10^{-13}	SM
$\sim 10^{-4}$	$\sim 10^{-6}$	$\sim 10^{-6}$	$\not{R}$ SUSY

$Br \gtrsim 10^{-3}$ would point to mixing of t with exotic (vector-like) quark(s)

(Del Aguila et al.,....)

The charge/forward-backward asymmetry @ Tevatron

differential top charge asym. ($y=$ rapidity of t and or $\bar{t}$ in lab. frame) integrated charge asy.

$$A(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}\,, \qquad A = \frac{\int\limits_{y>0} N_t(y) - \int\limits_{y>0} N_{\bar{t}}(y)}{\int\limits_{y>0} N_t(y) + \int\limits_{y>0} N_{\bar{t}}(y)}$$

$$\text{pair asym.} \quad A^{t\bar{t}} = \frac{\int N(\Delta y > 0) - \int N(\Delta y < 0)}{\int N(\Delta y > 0) + \int N(\Delta y < 0)}\,, \quad \Delta y = y_t - y_{\bar{t}}$$

Halzen et al. (1998), ..., Kühn, Rodrigo (1999), Bowen et al. (2006), Antunano et al. (2008), Almeida et al. (2008)

generated by asym. terms $t \leftrightarrow \bar{t}$ in $\mathcal{O}(\alpha_s^3)$ M.E. of $q\bar{q} \longrightarrow t\bar{t}(g)$
and (much smaller) $gq\,(\bar{q}) \longrightarrow t\bar{t}q\,(\bar{q})$.
NLO computation by Kühn, Rodrigo (1999) – actually LO, because asys are $\mathcal{O}(\alpha_s)$
updated by Antunano, Kühn, Rodrigo (2008):

$$A = 0.051(6), \qquad A^{t\bar{t}} = 0.078(9) \qquad \text{with LO PDF}$$

contains factor 1.09 for contrib. of weak-int. corrections to $q\bar{q} \longrightarrow t\bar{t}$

QCD computations of A from threshold resummed cross sections:
Almeida et al.(2008) (NLL), Ahrens et al.(2010) (NNLL) $A = 7.3^{+1.1}_{-0.7}\%$
i.e. theory uncertainty $\sim 15 - 20\%$

Experimental results ($\ell + j$ final states):
D0 (2008): $A^{t\bar{t}} = 0.12 \pm 0.08 \pm 0.01$ (not unfolded)
CDF (2008): $A^{t\bar{t}} = 0.24 \pm 0.14$ (unfolded)
CDF (2009): $A^{t}_{FB} = 0.193 \pm 0.065 \pm 0.024$ (unfolded)

Although no stat. significant discrepancy between SM pred. and exp.
room for speculations on new physics contributions
$\sim$ 30 papers in last 2 years $\longrightarrow$ talk by G. Rodrigo

- new physics must provide positive contribution
- why no hint of new physics in other distributions?

Lepton charge asymmetries @ Tevatron, $\ell + j$, $\ell\ell'$ final states:

Lepton asymmetry:

$$A^{\ell} = \frac{\int\limits_{y>0} N_{\ell+}(y) \; - \; \int\limits_{y>0} N_{\ell-}(y)}{\int\limits_{y>0} N_{\ell+}(y) \; + \; \int\limits_{y>0} N_{\ell-}(y)},$$

pair asymmetry:

$$A^{\ell\ell} = \frac{\int N(\Delta y_{\ell} > 0) - \int N(\Delta y_{\ell} < 0)}{\int N(\Delta y_{\ell} > 0) + \int N(\Delta y_{\ell} < 0)}$$

where $\Delta y_{\ell} = y_{\ell+} - y_{\ell-}$ in lab. frame

A^{ℓ} and $A^{\ell\ell}$ should be easier to measure than A and $A^{t\bar{t}}$,
but so far not measured (?)

W.B., Si (2010): calc. for $\ell\ell'$ final states @ Tevatron with standard acceptance cuts:
fixed order NLO (production & decay) with mixed weak-QCD corrections included

	Tevatron ($t\bar{t}$ correlated)			Tevatron ($t\bar{t}$ uncorrelated)		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m_t	$2m_t$
A^ℓ (NLO')	0.038	0.033	0.031	0.037	0.033	0.030
A^ℓ (NLOW')	0.039	**0.034**	0.032	0.038	0.035	0.032
$A^{\ell\ell}$ (NLO')	0.047	0.042	0.038	0.050	0.045	0.041
$A^{\ell\ell}$ (NLOW')	0.048	**0.044**	0.040	0.052	0.047	0.043

scale uncertainties underestimate th. error.
More realistic etimate: threshold calc. $\longrightarrow \delta A \sim 30\%$

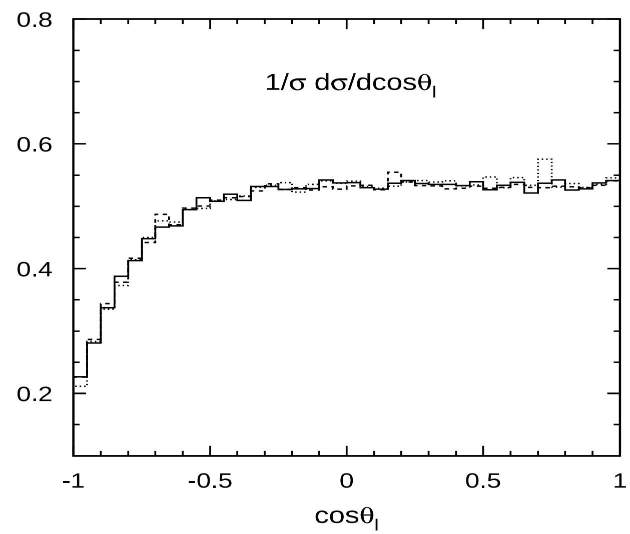
may eventually lead to more conclusive comparison between SM and exp.

$$p\bar{p}, pp \to t\bar{t} \to \ell^+ + \text{jets} + E_T^{miss}$$

non-SM PV interactions $\Rightarrow$ long. pol. $< \mathbf{s_t} \cdot \hat{\mathbf{k}}_\mathbf{t} >$ $\Rightarrow$ nontrivial dist. $\sigma^{-1} d\sigma/d\cos\theta_{\ell+}$

W.B., Si: SM prediction: NLO QCD + mixed weak-QCD corr.

with acceptance cuts for LHC (14 TeV):



- distribution would be flat without cuts & weak int. switched off
- dist. $\sigma^{-1} d\sigma/d\cos\theta_{\ell-}$ identical to this order
- dist. for Tevatron $\ell + \text{jets}$ events same shape

If top charge asy. receive contrib. from new PV interactions $\Rightarrow$ longitudinal top pol.
$\Rightarrow$ expect non-flat dist. for $\cos\theta_\ell > 0$.

$t\bar{t}$ spin correlations

measured @ Tevatron (2009, 2010):

$\ell\ell'$ events ($\sim$ 200): D0: beam basis, CDF: off-diagonal basis
CDF: helicity basis, $\ell + j$ events ($\sim$ 1000)

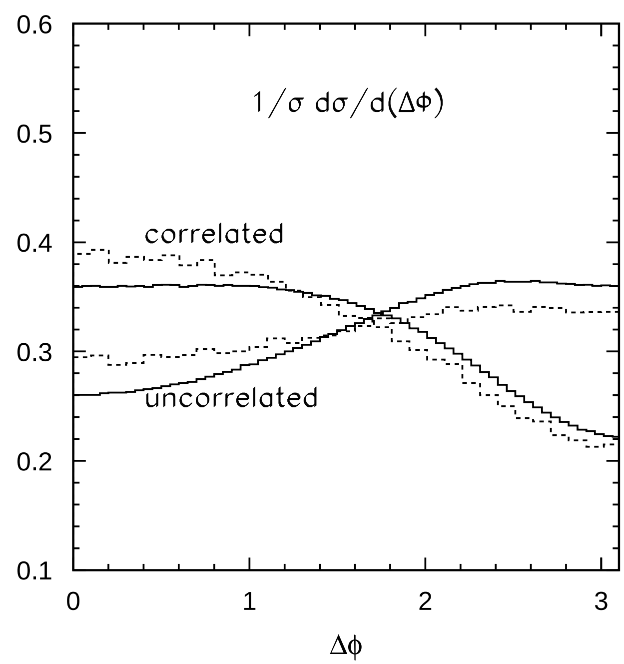
agree within still large exp. errors with SM NLO QCD predictions
W.B. et al. (2004), W.B., Si (2010)

$\longrightarrow$ see talk by G. Head

As SM dynamics @ LHC is dominated by $gg \to t\bar{t}$
sensitive correlations: helicity correl. and opening angle distrib.

Observables are designed such that they discriminate betw. correlated @ uncorrelated $t\bar{t}$ events
require reconstruction of t and $\bar{t}$ rest frames
difficult for $\ell\ell'$ events, which have highest sensitivity

Mahlon, Parke (2009,2010):
Dilepton azimuthal angle correlation $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ **@ LHC (14 TeV), where** $\Delta\phi = \phi^+ - \phi^-$ **measured in lab frame**
discriminates between correlated & uncorrelated $t\bar{t}$ events for $\ell\ell'$ events with low $M_{t\bar{t}}$.
useful cut for LHC (14 TeV): $M_{t\bar{t}} < 400$ GeV



W.B. , Si (2010) calc. @ NLO QCD (incl. weak int.) with acceptance cuts

event nr. @ LHC (14 TeV): $\sigma_{\ell\ell'}(M_{t\bar{t}} < 400\,\mathrm{GeV})/\sigma_{\ell\ell'} \simeq 18.6\%$ $\Rightarrow$ $\sim$ 3200 dilepton events with 1 fb^{-1}

- shapes depend sensitively on how precisely ${M_{t\bar{t}}}^{\rm cut}$ can be determined by exp.
- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ looses dicriminating power rapidly for ${M_{t\bar{t}}}^{\rm cut} >$ 400 GeV
- more robust cut variable ? transverse mass ?

$\longrightarrow$ talk by G. Mahlon

While $\sigma^{-1}d\sigma/d\Delta\phi$ probes $t\bar{t}$ spin dynamics only in low-energy tail of $M_{t\bar{t}}$ spectrum, for high energy tail - possible (non)resonant new physics effects – helicity and opening angle correlation $\sigma^{-1}d\sigma/d\cos\varphi = (1 - D\cos\varphi)/2$ can be used

In addition: measure CP-odd angular correlations/asymmetries
(due to CP-odd $t\bar{t}$ spin correlations) $\longleftarrow$ generated by non-SM CPV interactions

$\longrightarrow$ talk by G. Valencia

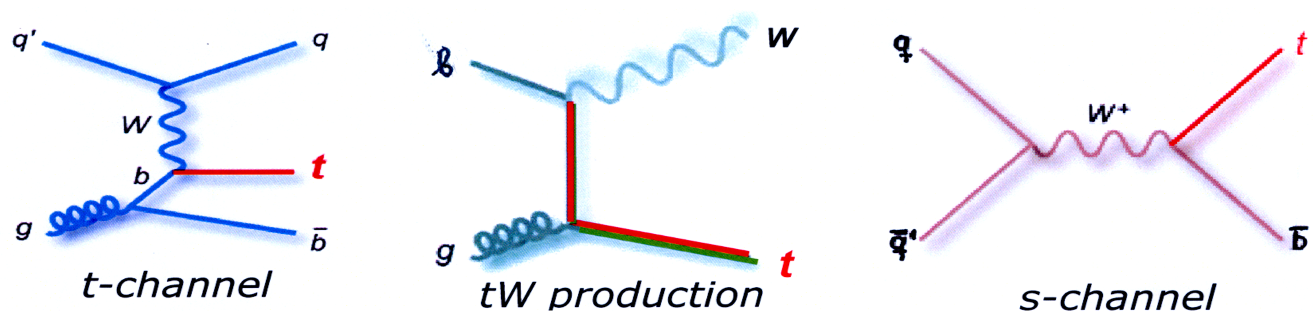
Expectations for measuring spin correlations @ LHC (7 TeV) with $< \mathbf{1}\ \mathrm{fb}^{-1}$?

a few hundred to 10^3 $\ell\ell'$ events selected (?)
obviously: $\ell + j$ events should also be used: sensitivity smaller by factor $\sim$ 2,
but 6 $\times$ more statistics

Single top production:

- **weak interactions** involved in production; in SM: $\sigma_t \propto |V_{tb}|^2$
- source of **polarized** tops
- possible **new physics effects** (charged resonances, FCNC) different from $t\bar{t}$
- may eventually allow determination of b-**quark distribution**

3 production channels in SM:



D0 & CDF (2009): evidence $\longrightarrow$ observation
SM cross sect. known to NLO + weak corr.
(Harris et al., Campbell et al., Cao et al., Kidonakis (resumm.), ..., Beccaria et al.)

Expectations for LHC @ 7 TeV?
uncert. of cross-sect. predictions? 4- vs. 5-flavour scheme $\longrightarrow$ talk by R. Frederix
expectations for improving on ms. of f_L ? $\longrightarrow$ talk by D. Hirschbuel
polarization ms. ?
......

Search for heavy resonances that strongly couple to $t\bar{t}$

Extensions of SM and/or alternatives to Higgs mechanism
e.g. supersymmetric extensions, top-condensation, extra dim. models ...
$\longrightarrow$ heavy resonances that couple (strongly) to top quarks
could be a non-SM Higgs boson, a bound state, a KK excitation...
or a heavy top T, ...
Many investigations ....

$q_e = 0$ bosonic resonances φ_J that couple to $t\bar{t}$:

$\varphi_\mathbf{J}$: a non-SM Higgs boson (2HDM, SUSY,..), leptophobic Z' (top-color models), massive $J = 1$ color-octet state (KK gluon, axigluon), massive $J = 2$ KK state, ...

Exclusion limits from Tevatron: Search for $p\bar{p} \longrightarrow \varphi_J \longrightarrow t\bar{t}$:

D0, CDF: leptophobic Z' with $M_{Z'} < 820$ GeV (assumption: $\Gamma_{Z'} = 0.012 M_{Z'}$)
massive KK gluon with $M_G \lesssim 1$ TeV, ... $\longrightarrow$ talk by P. Sinervo

will take a while to be superseded @ LHC perhaps most conservative speculation: **φ = heavy Higgs boson**

H $(J^{PC} = 0^{++})$ or A $(J^{PC} = 0^{-+})$, $M \gtrsim 2m_t$
(2HDM, MSSM, ...)

Specific feature of pseudoscalar A: $A \not\rightarrow W^+W^-, ZZ$ in lowest order,
but A can strongly couple to top quarks

$$\mathrm{gg} \longrightarrow \varphi \longrightarrow \mathrm{t\bar{t}} \longrightarrow \ell + \mathrm{j}$$
$$\mathrm{gg} \longrightarrow \mathrm{t\bar{t}} \longrightarrow \ell + \mathrm{j}$$

interference of amplitudes leads to typical peak-dip resonance structure in $M_{t\bar{t}}$ spectrum
Dicus, Stange, Willenbrock (1994); W.B., Flesch, Haberl (1998), Frederix, Maltoni (2009), ...

If φ exists, with 300 GeV $\lesssim m_\varphi \lesssim \mathcal{O}(600\,\mathrm{GeV})$ & strong coupling to top

$\rightarrow$ $t\bar{t}$ **resonance bump conceivable @ LHC, but not at Tevatron !**

Of course, exp. resolution and understanding of non-resonant background crucial

How well can $M_{t\bar{t}}$ spectrum be measured after 1st LHC (7 TeV) running period?

However, we – especially many theorists among us – have to face reality:

We have the LHC @ 7 TeV and perhaps an int. lumi ~ 200 pb^{-1} .... ? at the end of 2011

Needless to say: ATLAS @ CMS first have to calibrate their detectors & software tools, etc.

What kind of top physics can we expect? (with ~ 200 pb^{-1})

$\sigma_{t\bar{t}} \simeq 150$ pb $\rightarrow$ 30 k $t\bar{t}$ before sel. $\quad \sigma_t \simeq 65$ pb $\rightarrow$ 13 k t

after sel. $\sim 200\ell\ell'$, 2k $\ell\, j$

cross sections, $\delta\sigma_{t\bar{t}}$?

distributions ?

......

......

When will the first single Euro tops be detected? **the TEUROs**

What will come more from CDF @ D0 ?

Backup slides

Top quark width

In the SM: t quark decays almost 100 % into

$$t \longrightarrow b + W^+$$

Top decay width: precisely known in SM ($\mathcal{O}(\alpha_s^2)$):

$$\Gamma_t^{SM} = 1.3 \text{ GeV} \longrightarrow \text{lifetime } \tau_t \simeq 4 \times 10^{-25} \text{ sec}$$

Exploration of top interactions so far: $\longrightarrow$ Γ_t can't differ much from Γ_t^{SM} !

D0 2010: $\Gamma_t = 2.1 \pm 0.6$ GeV CDF 2010: $0.3 \text{ GeV} < \Gamma_t < 4.4$ GeV

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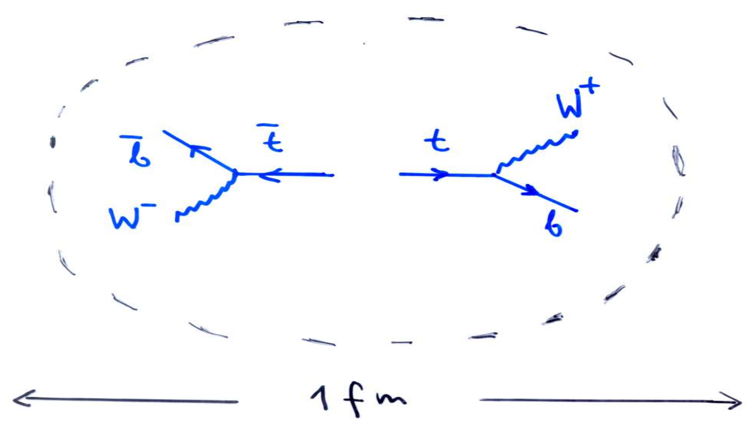
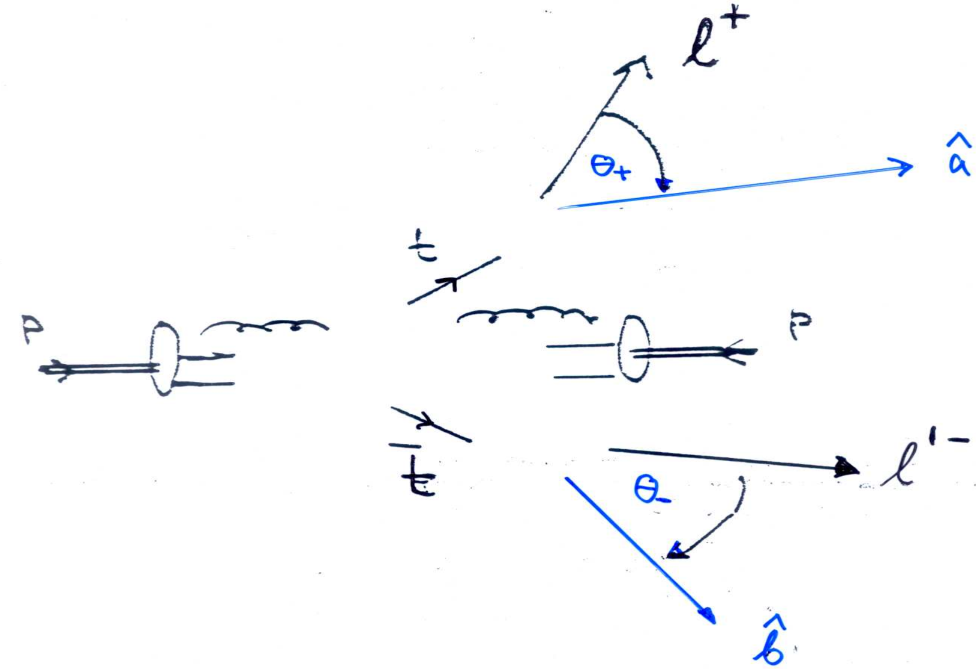
t and $\bar{t}$ decay before they can form hadronic bound states $(t\bar{q})$, (tqq')



top quark $\sim$ quasi-free, instable particle

$\longrightarrow$ top-quark spin effects are calculable and measurable – remains to be fully explored.



ℓ^+
θ_+
$\hat{a}$
t
p
p
$\bar{t}$
ℓ'^-
θ_-
$\hat{b}$

$t\bar{t}$ spin correl. in $\ell\ell'$ and $\ell + j$ final states :

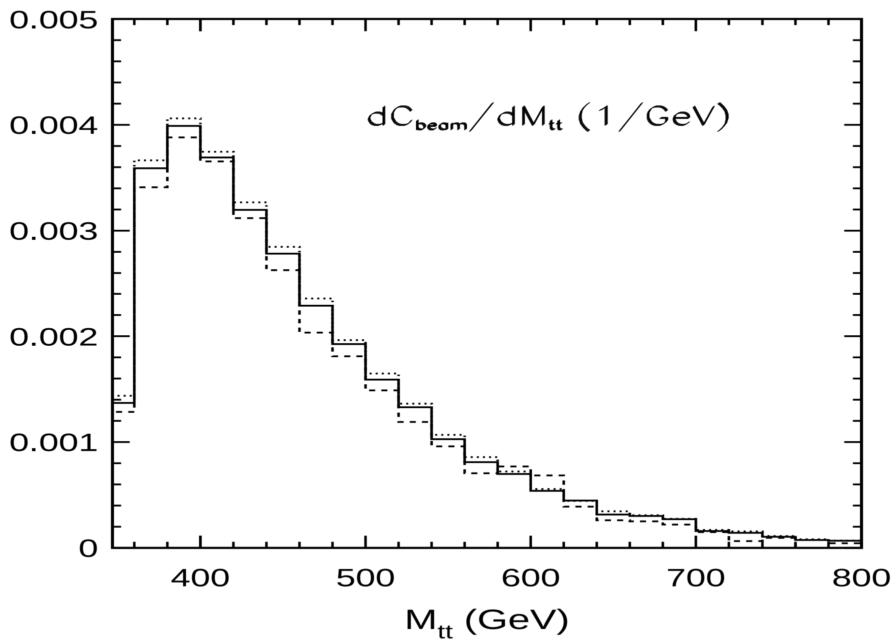
With acceptance cuts, use instead the estimators (esp. for double dist.):

$$\hat{C} = -9\langle\cos\theta_1 \cos\theta_2\rangle$$

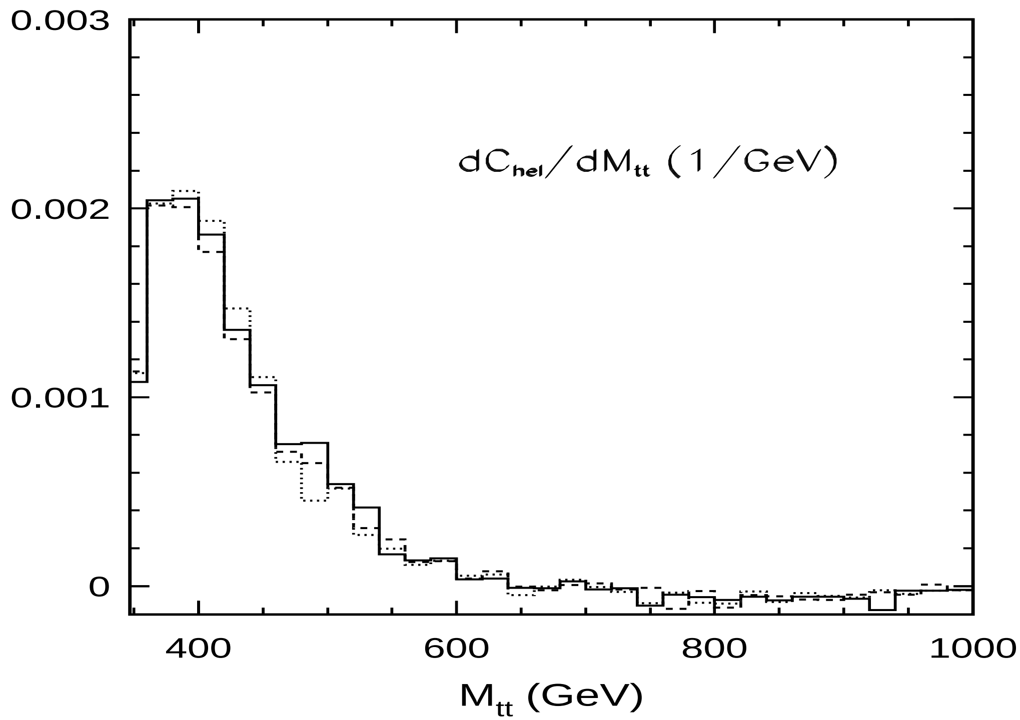
$$\hat{D} = -3\langle\cos\varphi\rangle$$

$\hat{C} = C$, $\hat{D} = D$ when no cuts are applied

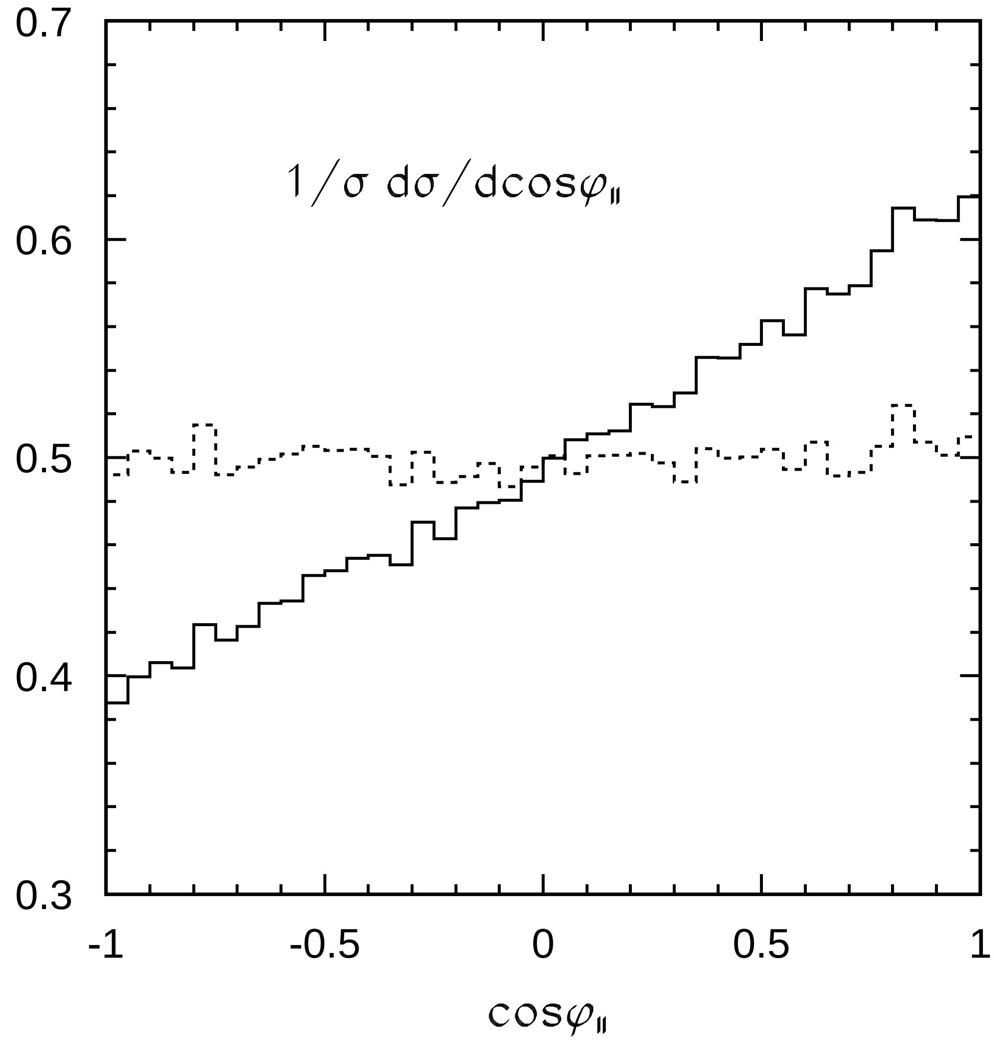
(W.B., Brandenburg, Si, Uwer 2004; W.B., Si 2010) correlation with resp. to beam axis @ Tevatron



$\mu = m_t$ (solid), $m_t/2$ (dashed), $2m_t$ (dotted) helicity correl. @ LHC (14 TeV)

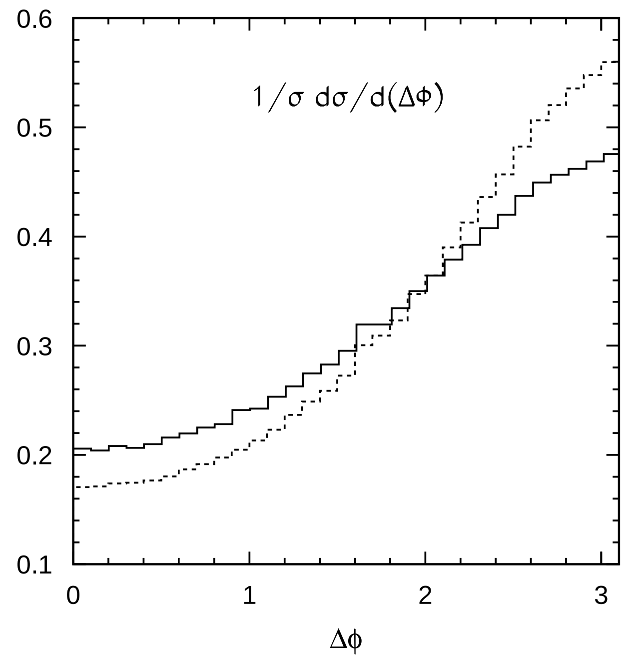


Opening angle distribution @ LHC (14 TeV)



solid = $t\bar{t}$ correlated, dashed = $t\bar{t}$ uncorrelated

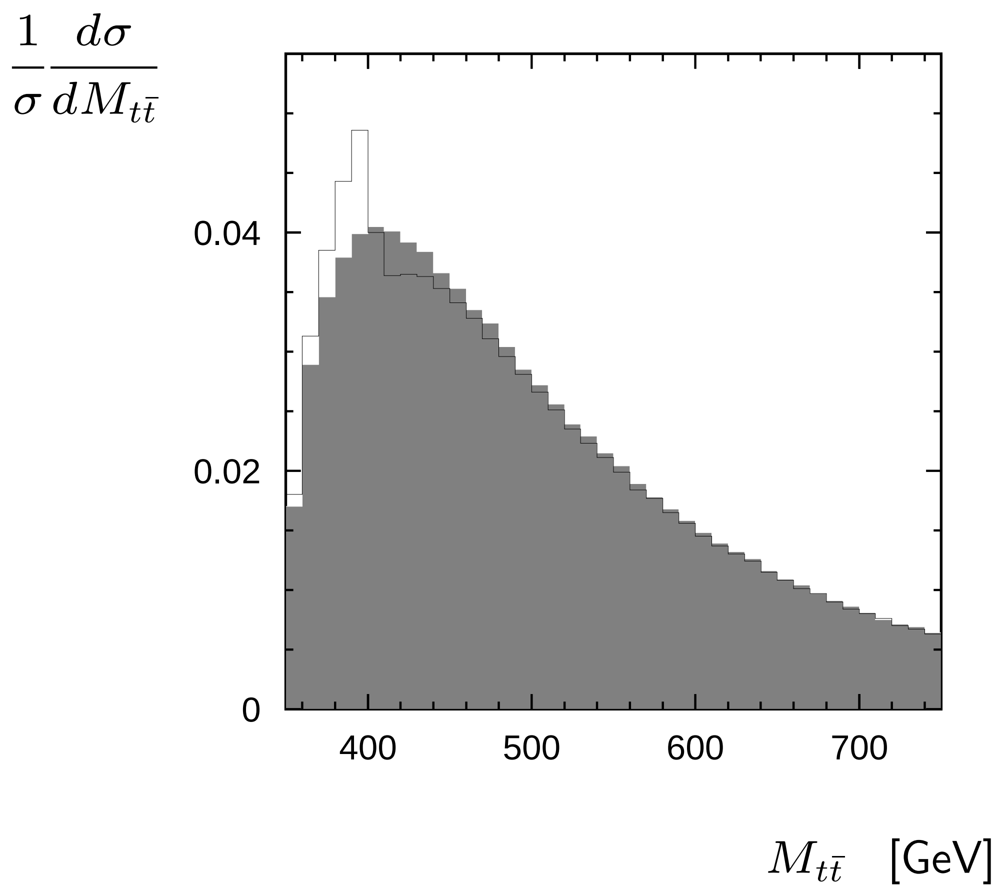
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ with no cut on $M_{t\bar{t}}$: LHC (14 TeV)



LHC (14 TeV) solid = correlated, dashed = uncorrelated

LHC: $pp \to A + X \to t\bar{t} + X \to \ell +$ Jets

Example: $m_A = 400$ GeV, $\Gamma_A = 12$ GeV, $\tan\beta = 3$



(W.B., Flesch, Haberl)

exp. resolution and understanding of non-resonant background crucial

If resonance φ will be found, $\longrightarrow$ spin from polar angle dist.,

CP parity/properties from spin correlations W. B., Brandenburg, Schmidt, Peskin, ...