BSM physics with the Top Quark

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Outline

- Introduction (Why top is interesting?)
- Role of the top quark
- BSM models related to the top quark
- Collider phenomenology. Prospects to search for new particles and anomalous top interactions
- Concluding remarks

Reviews: Willenbrock; Han; Hill and Simmons; Bernreuther; Rainwater;
Morrissey, Plehn, and Tait; Incandela, Quadt, Wagner, and Wicke; Boos, Dudko, and Slabospitsky; ….

Top Quark in SM

$Q^t_{em} = +\frac{2}{3} \mid e \mid$

Weak isospin partner of b quark: $T^t_3 = \frac{1}{2}$

Color triplet

spin-$\frac{1}{2}$

$$
\begin{array}{lcccccc}
 & & & & \underline{SU(3)} & \underline{SU(2)} & \underline{U(1)_Y} \\
Q^i_L = & \begin{pmatrix} u_L \\ d_L \end{pmatrix} & \begin{pmatrix} c_L \\ s_L \end{pmatrix} & \begin{pmatrix} t_L \\ b_L \end{pmatrix} & 3 & 2 & \frac{1}{6} \\
u^i_R = & u_R & c_R & t_R & 3 & 1 & \frac{2}{3} \\
d^i_R = & d_R & s_R & b_R & 3 & 1 & -\frac{1}{3}
\end{array}
$$

Why top is special? What is the difference?

Mass

Mtop = 173.1±0.6 (stat.)± 1.1(syst.)

CKM elements

$$V_{CKM} = (U_L^u)^\dagger \, U_L^d$$

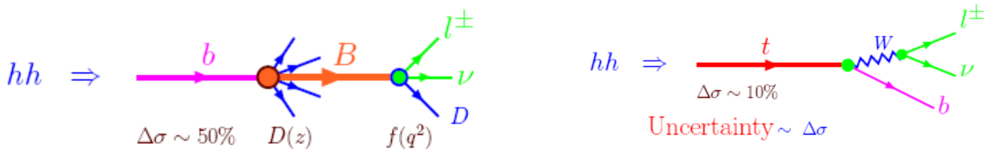
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.2257^{+0.0009}_{-0.0010}\,, \qquad A = 0.814^{+0.021}_{-0.022}$$

$$\bar{\rho} = 0.135^{+0.031}_{-0.016}\,, \qquad \bar{\eta} = 0.349^{+0.015}_{-0.017}$$

Top quark is the heaviest elementary particle found so far with a mass slightly less than the mass of the gold nucleus

• **Top decays ($\tau_t \sim 5 \times 10^{-25}\ sec$) much faster than a typical time-scale for a formation of the strong bound states ($\tau_{QCD} \sim 3 \times 10^{-24}\ sec$).**
No top hadrons. A very clean source for a fundamental information.

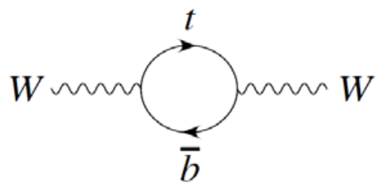


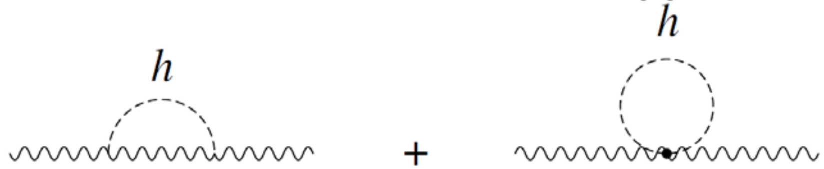
• **Top is so heavy and point like at the same time.**
• **Top Yukawa coupling ($\lambda_t = 2^{3/4} G_F^{1/2} m_t$) is very close to unit. Studies of top may shed a light on an origin of the mechanism of the EW symmetry breaking.**

What is a role of the Top quark?

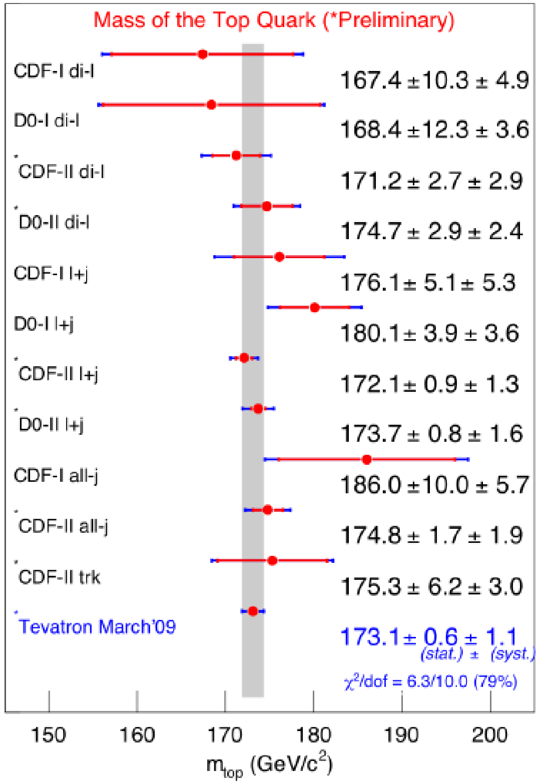
-chiral anomaly cancellation in SM
-top mass measurements and loop corrections to its mass => upper limit on the Higgs mass
-largest Yukawa coupling, main contribution to the Higgs mass parameter => hierarhy problem
-key object in various BSM models
-top quark is a “laboratory” for many experimental or simulational aspects in searches for new physics

Top precision mass measurement => upper limit on the Higgs mass

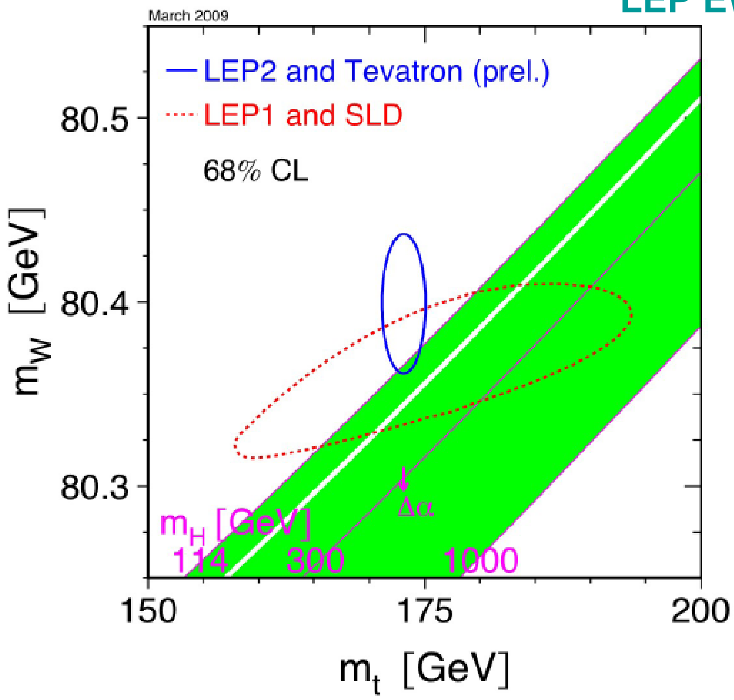


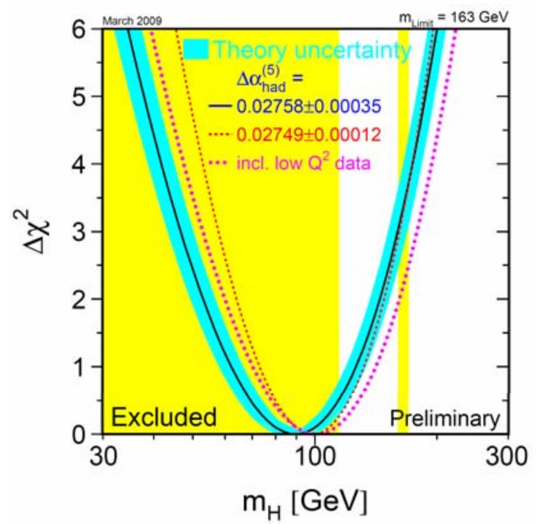


$$(\Delta r)_{\mathrm{top}} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{t_W^2} \qquad (\Delta r)_{\mathrm{Higgs}} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}$$



LEP EW working group



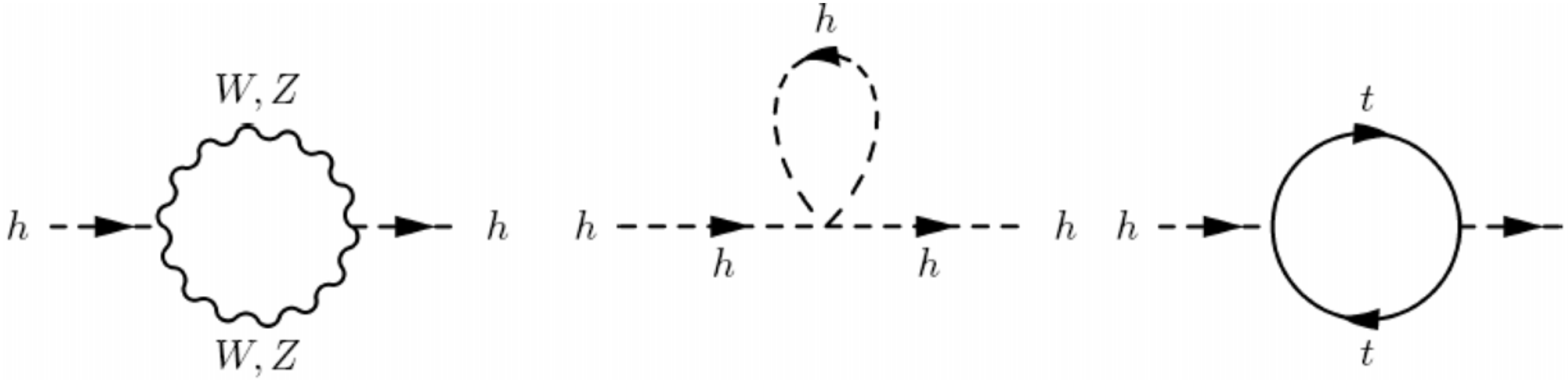


$$M_H = 85^{+39}_{-28}\ \text{GeV}$$

M_H < 160 GeV, 95% C.L.

The simplest Higgs mechanism SM is not stable with respect to quantum corrections (naturalness problem)

Loop corrections to the Higgs mass



$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\ \Lambda)^2$$

δm_H < 160 GeV (95% CL limit on SM Higgs) $\Lambda \sim 1$ TeV

In SM there is no symmetry which protects a strong dependence of Higgs mass on a possible new scale

Something is needed in addition to the SM top… => Rather light top partner is one of the most robust prediction to resolve the hierarchy problem

One might expect deviations from the SM predictions in the top sector.

Mostly discussed BSM models pretend to provide

(at least partly)

- a stable with respect to quantum corrections EWSB mechanism
- a candidate for Dark Matter
- a source for amount of CP violation to be large enough
- inclusion of gravity

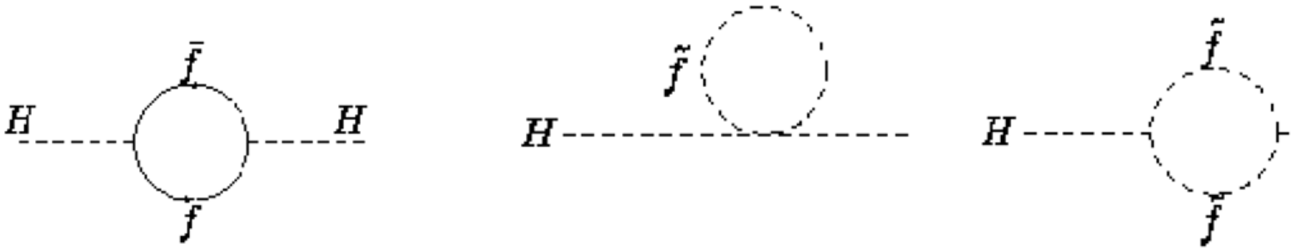
Supersymmetric models
(MSSM, NMSSM…)

Models with extra space dimensions
(ADD, RS, UED …)

Models with new strong dynamics
(latest technicolor variants, Little Higgs…)

Top plays a special role in most of BSM models

1. In MSSM stop (top partner) helps to cancel Λ^2 dependence



=>

$$\Delta M_H^2|^{tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right]$$

M_H is protected!

In MSSM large top (stop) loop corrections shift after renormalization the upper bound for the light Higgs mass (< 135-140 GeV) to be consistent to the LEP2 limits

$$\Delta m_h^2 = \frac{12}{(4\pi)^2}\sin^2\beta\, y_t^2 m_t^2 \log\frac{m_{\tilde{t}_L} m_{\tilde{t}_R}}{m_t^2}$$

On the other hand large loop corrections to m_{Hu}^2 lead to fine-tuning problem if $m_{Hu}^2 >> m_Z^2$

$$m_Z^2 = -2\,|\mu|^2 - \frac{2\,m_{H_u}^2\tan^2\beta - 2\,m_{H_d}^2}{\tan^2\beta - 1} \simeq -2\,|\mu|^2 - 2\,m_{H_u}^2$$

$$\Delta m_{H_u}^2 \simeq -\frac{12\,y_t^2}{(4\pi)^2}\, m_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}}$$

S.P. Martin

2. Compositeness models

(topcolor assisted technicolor, topcolor seesaw, various variants of Little Higgs… are based on effective operators containing the top)

In topcolor assisted technicolor topgluon exchange leads to the effective operator:

W. A. Bardeen, C. T. Hill, M. Lindner

$$-\frac{g^2}{M^2}\left[\bar{t}_R\gamma^\mu T^a t_R\right]\left[\bar{Q}_L\gamma_\mu T^a Q_L\right] = -\frac{g^2}{M^2}\left[\bar{t}_R Q_L\right]\left[\bar{Q}_L t_R\right]$$

Might be written in a form:

$$\mathcal{L}(\Lambda) = \frac{1}{2}g_t\bar{Q}_L t_R\Phi + g_t^*\bar{t}_R Q_L\Phi^* - \Lambda^2|\Phi|^2$$

Kinetic term appears at loop level leading nicely to effective Higgs potensial:

$$\mathcal{L}(\mu) = Z(\mu)\left(D^\mu\Phi\right)^2 - m^2(\mu)|\Phi|^2 - \lambda(\mu)|\Phi|^4 + \frac{1}{2}g_t(\mu)\left(\bar{Q}_L t_R\Phi + \text{h.c.}\right)$$

$$Z(\mu) = N_c\frac{g_t^2}{16\pi^2}\log\left(\frac{\Lambda}{\mu}\right) + \ldots \quad Z(\Lambda) = 0$$

(However, too large top mass ~ 700 GeV)

In the top-seesaw the problem is resolved by adding an additional vector-like quark, its right and left components are charged under two different SU(3) color

$$\left(\bar{t}_L \quad \bar{\chi}_L\right)\begin{pmatrix} 0 & g_t v \\ M_{t\chi} & M_{\chi\chi}\end{pmatrix}\begin{pmatrix} t_R \\ \chi_R\end{pmatrix} + \text{h.c.}$$

B. A. Dobrescu, C. T. Hill, R. S. Chivukula, H. Georgi, H. J. He, T. M. P. Tait, C. P. Yuan, …

(However, some problems with precision data)

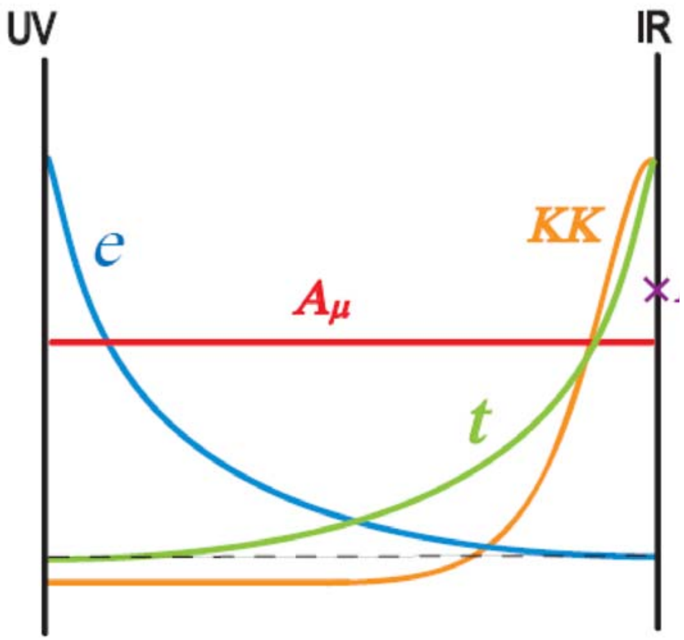
New vectorial top-partner T fermion appears in Little Higgs model.

N. Arkani-Hamed, A. G. Cohen, H. Georgi, E. Katz, A. E. Nelson…

3. **Models with extra warped dimensions**

Top-seesaw type of model occurs naturally in extra dimensional models, the role of the topgluon plays the KK gluons, and T-fermion - the KK mode of t_R

H. C. Cheng, B. A. Dobrescu, C. T. Hill, N. Arkani-Hamed, L. J. Hall, G. Burdman, L. Da Rold, Y. Bai, M. Carena, E. Ponton…



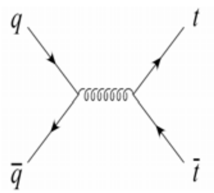
Interactions are determined by wave function overlap;
the top quark: close to Higgs profile,
KK modes of W,Z,g with masses O(1 TeV)are localized near the IR brane with preferential couplings to top quarks

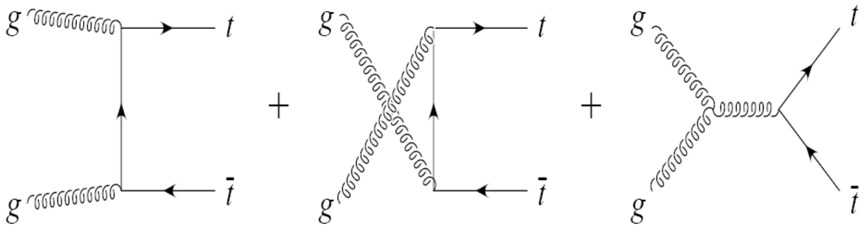
Randall, Sundrum, Dicus, McMullen, Nandi, Agashe, Wagner, …

At hadron colliders top quarks are produced in pair or singly

SM leading order diagarms

Two mechanisms of top pair production:

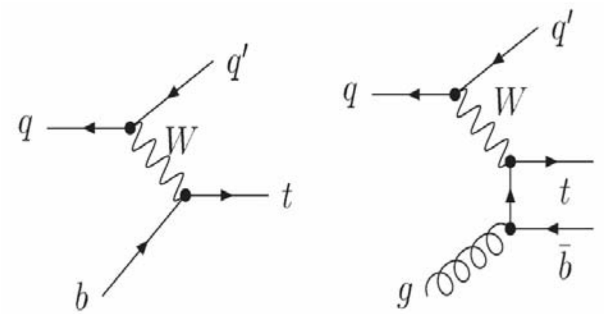




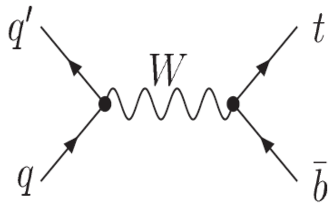
Top pair — strong top–gloun coupling in production and top-W-b coupling in decay

Single top — electroweak top-W-b coupling in production

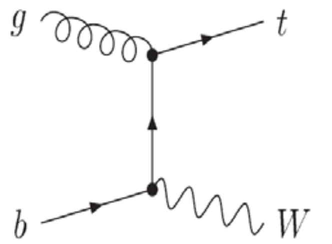
Three mechanisms of single top production:



t-channel



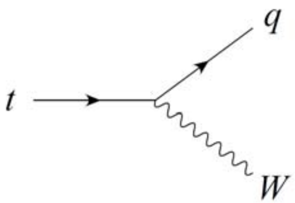
s-channel



Wt associated production

t-channel $(Q_W^2 < 0)$ s-channel $(Q_W^2 > 0)$ associated tW $(Q_W^2 = M_W^2)$

Q_W^2 - W-boson virtuality



In SM top decays to W-boson and b-quark practically with 100% probability

$$\Gamma(t \to bW)_{LO} \simeq 1.53 \text{ GeV}, \quad \Gamma(t \to bW)_{correc} = 1.42 \text{ GeV}$$

Basic top pair production cross sections in SM

	$\sigma_{\rm NLO}$ (pb)	$q\bar{q} \to t\bar{t}$	$gg \to t\bar{t}$
Tevatron ($\sqrt{s} = 1.8$ TeV $p\bar{p}$)	$4.87 \pm 10\%$	90%	10%
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$6.70 \pm 10\%$	85%	15%
LHC ($\sqrt{s} = 14$ TeV pp)	$833 \pm 15\%$	10%	90%

14TeV: $\sigma(t\bar{t}) = 908 \pm 83(\text{scale}) \pm 30(\text{PDF})$ pb NLO + NLL resummation **S. Kidonakis**

10TeV: $\sigma(t\bar{t}) = 414 \pm 40(\text{scale}) \pm 20(\text{PDF})$ pb

Basic single top production cross sections in SM

	s channel	t channel	Wt	
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$0.90 \pm 5\%$	$2.0 \pm 5\%$	$0.1 \pm 10\%$	3 pb
LHC ($\sqrt{s} = 14$ TeV pp)	$10.6 \pm 5\%$	$250 \pm 5\%$	$75 \pm 10\%$	335 pb

Cross sections at $\sqrt{s} = 1.96 TeV$ **Z. Sullivan et. al**

s-channel (tb) σ_{NLO} **= 0.88 ± 0.11 pb** t-channel (tqb) σ_{NLO} **= 1.98 ± 0.25 pb**

The single top rate is about 40% of the top pair rate

LHC is a top factory: 9×10^5 top pairs and 3.4×10^5 single tops

Two possibilities in general

Collision energy E > production thresholds

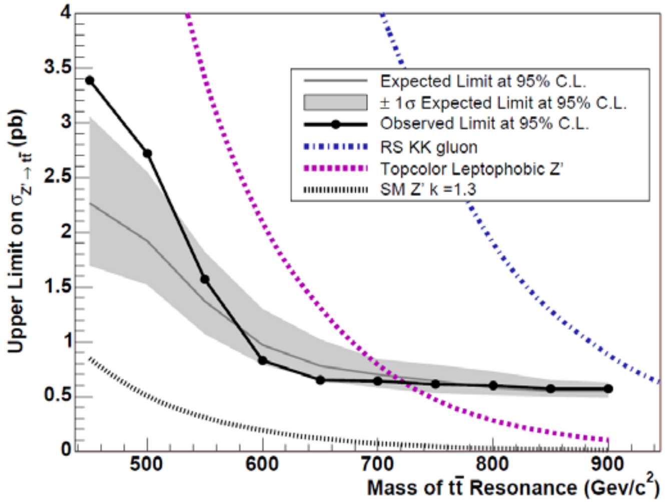
$\Rightarrow$New resonances decaying to tops
$\Rightarrow$New states produced in association with the top

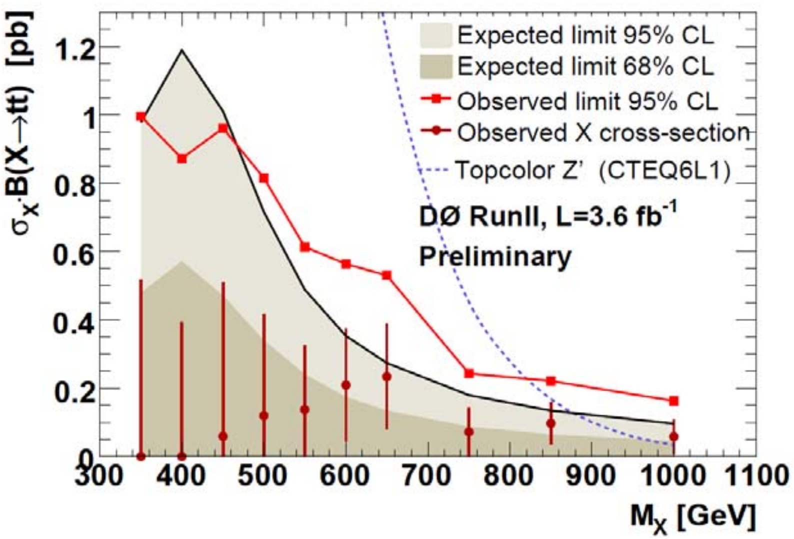
Collision energy E < production thresholds

$\Rightarrow$New effective anomalous interactions of the top with other SM particles
(modification of top decay and production properties)

s-channel resonances decaying to tops

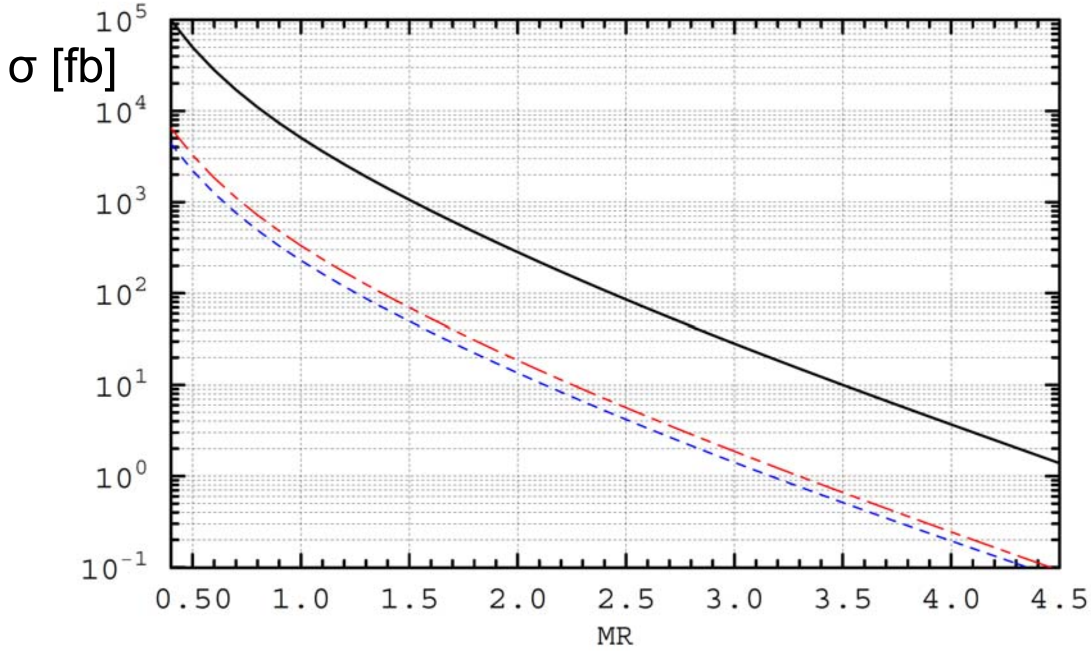
Higgses in SUSY models, 2HDM…
KK gluons, KK gravitons , KK Z, KK W … in models with extra dimensions
π_T, ρ_T, topgluons, topcolor Z',W' … in with new strong dynamics





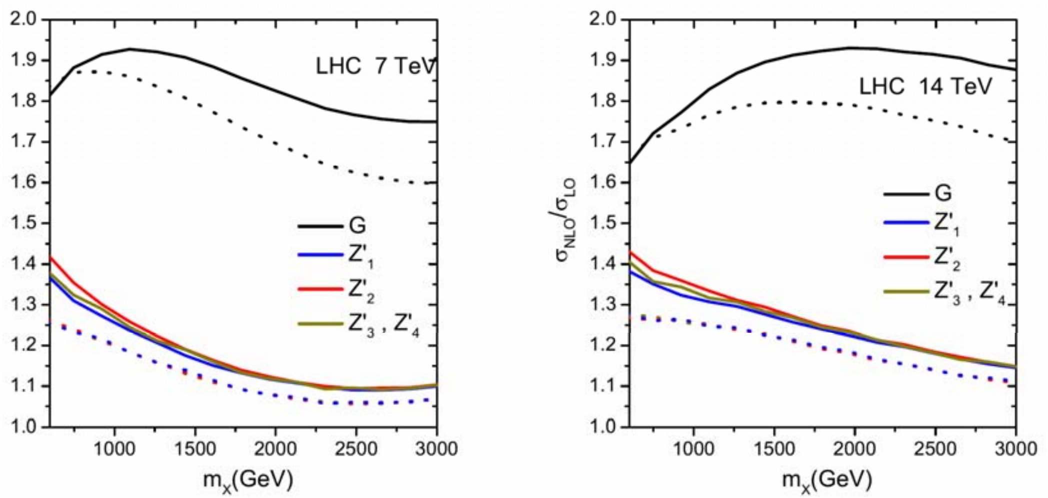
D0 limits based on 3.6 fb^{-1}: (topcolor Z') $M_{Z'}$ > 860 GeV at 95 % CL

G. Burdman, B. A. Dobrescu, E. Ponton

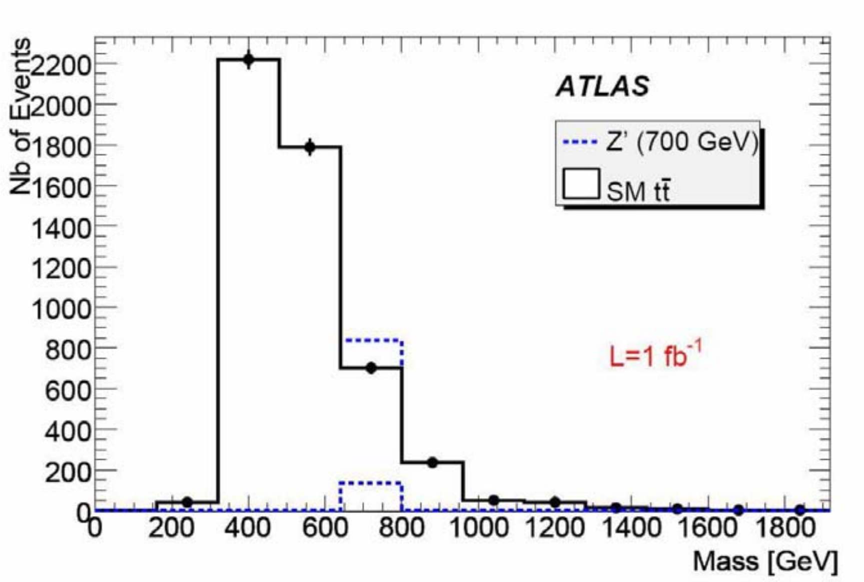


Production cross section at the LHC (14 TeV) for KK G^1, KK W_3^1, KK B^1

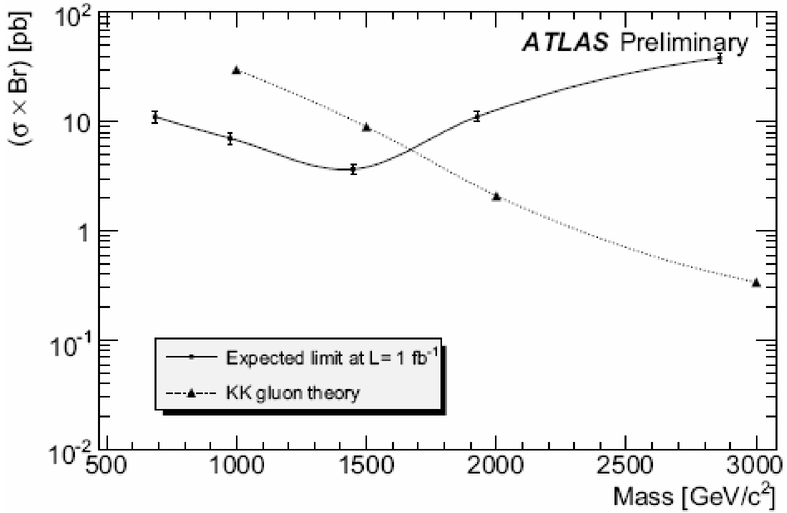
J. Gao, C.S. Li, B.H Li, H.X. Zhu, C.-P.Yuan



NLO K-factors for RS graviton and Z’



Top pair invariant mass distribution for Z' signal ($m_{Z'}$ = 700 GeV, σ∗BR = 11 pb) and SM background (ATLAS 1 fb^{-1}).

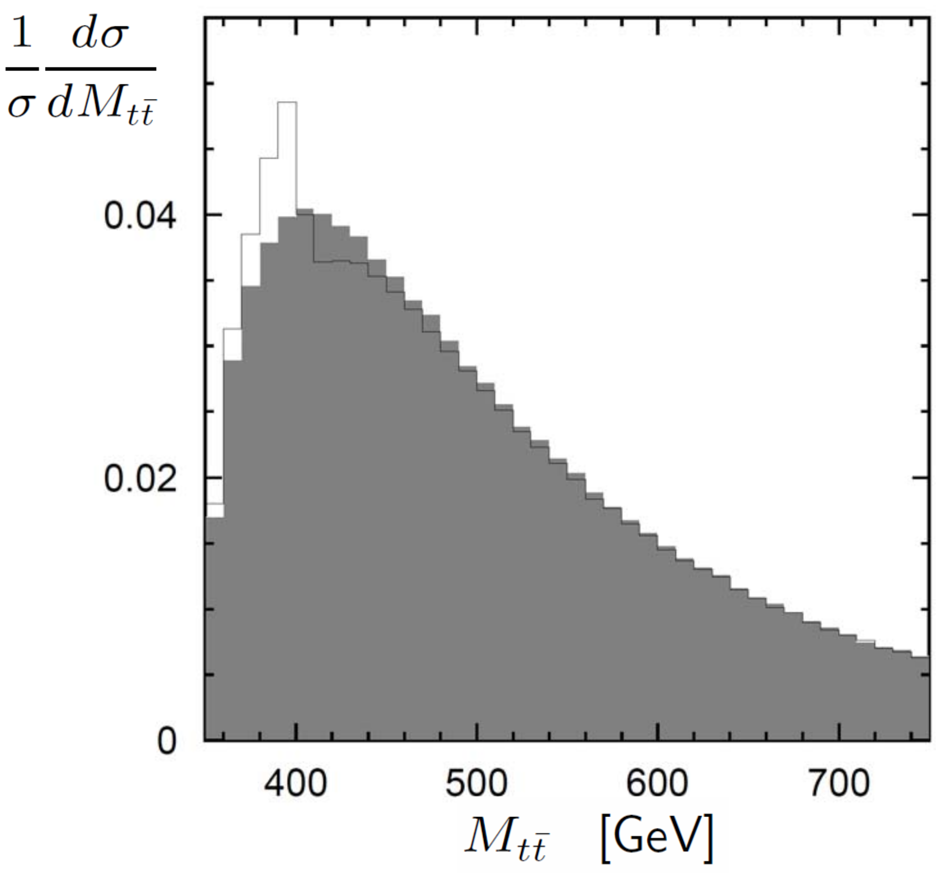


Kaluza-Klein gluon resonances can be excluded up to 1.5 TeV with 1 fb^{-1}

s-channel CP-odd Higgs boson production decaying to the top pair at the LHC

$$pp \longrightarrow A + X \longrightarrow t\bar{t} + X \longrightarrow \ell + \text{Jets}$$

W. Bernreuther, M. Flesch and P. Haberl

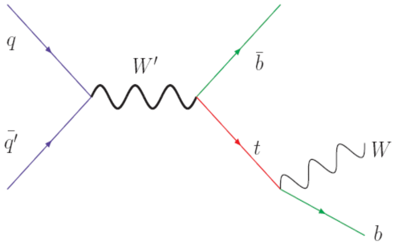


Signal of a heavy CP-odd Higgs boson *A* in top-antitop invariant mass normalized distribution (m_A =400 GeV, G_A= 10*GeV*)

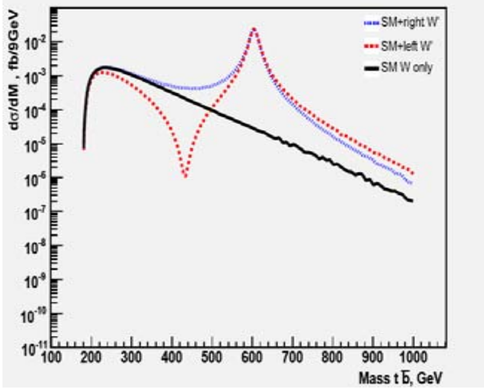
spin determination from polar angle dist., CP parity - from spin correlations

Bernreuther, Brandenburg, Schmidt, Peskin, ...

searches for W' resonance in single top

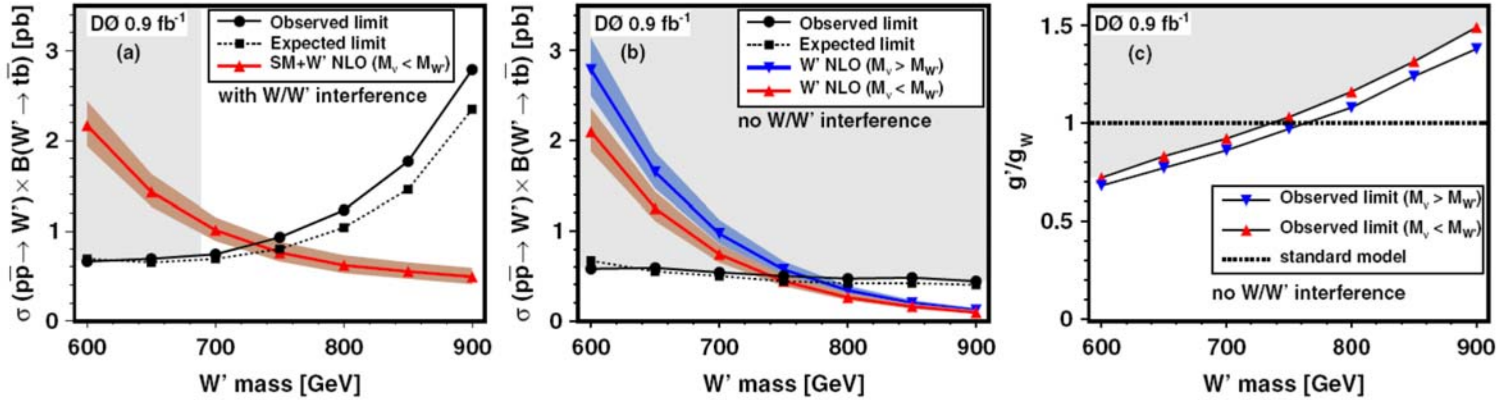


Boos, Bunichev, Dudko, Perfilov



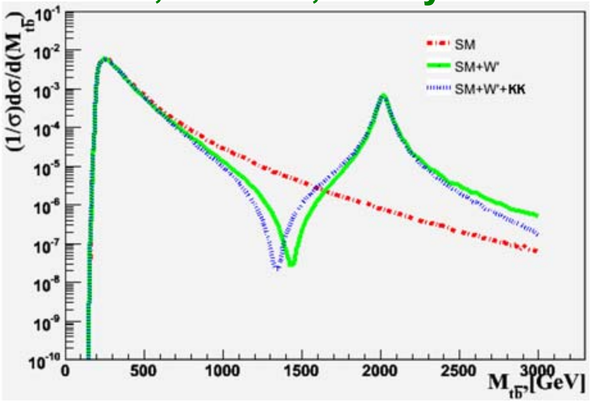
Negative interference

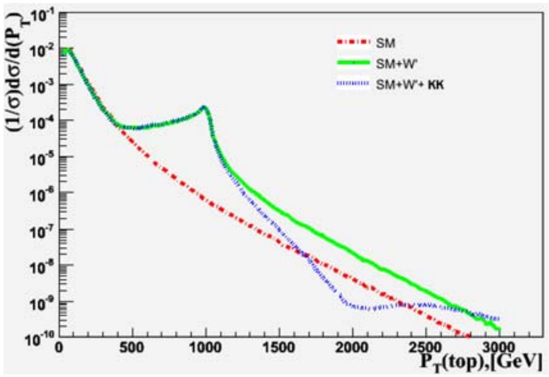
Tevatron Limits on W' boson mass (900 pb^{-1}): MW' > 710 (730-770) GeV   L(R)



Boos, Perfilov, Smolyakov Volobuev

KK W' at the LHC

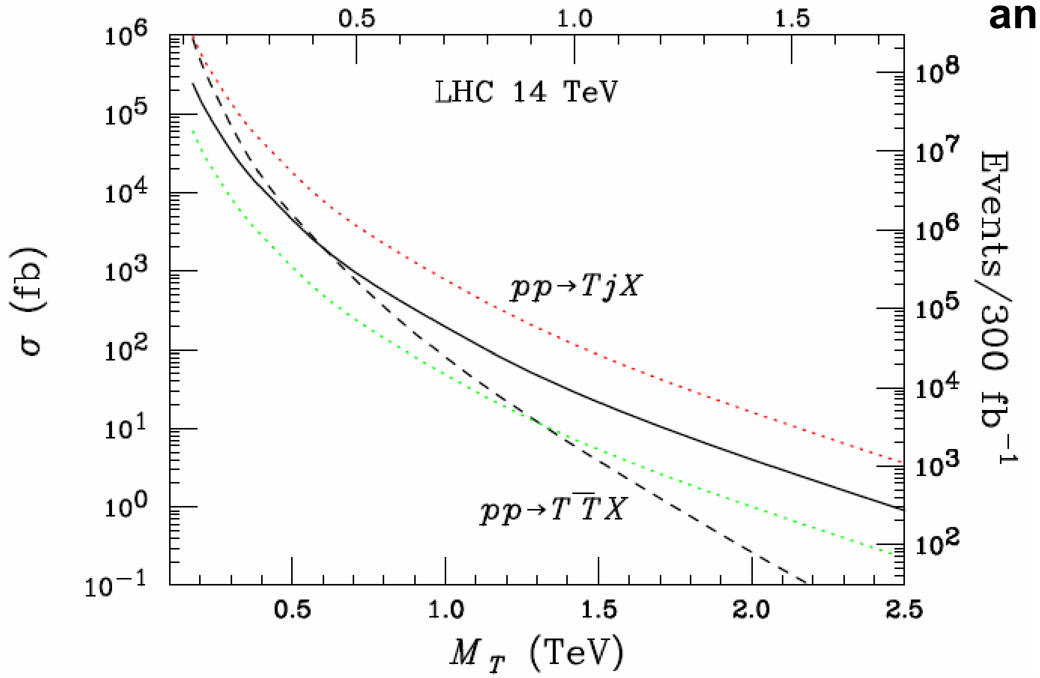




Expected LHC limits:
2-3 TeV
(Detail CMS study
in progress)

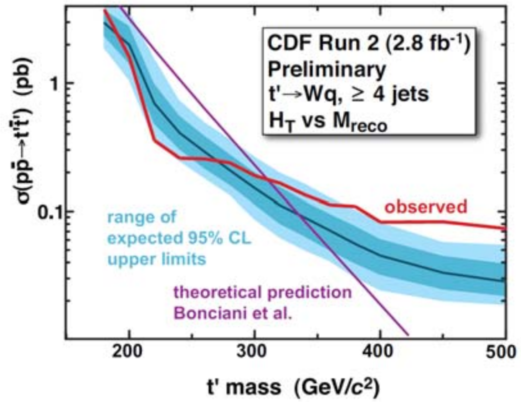
Production of top quark partner T predicted in many BSM in accord with "naturalness" argument to cancel quadratic scale dependence in loops (stop, Little Higgs Top, KK top mode…)

T. Han, H. E. Logan, B. McElrath, L. T. Wang

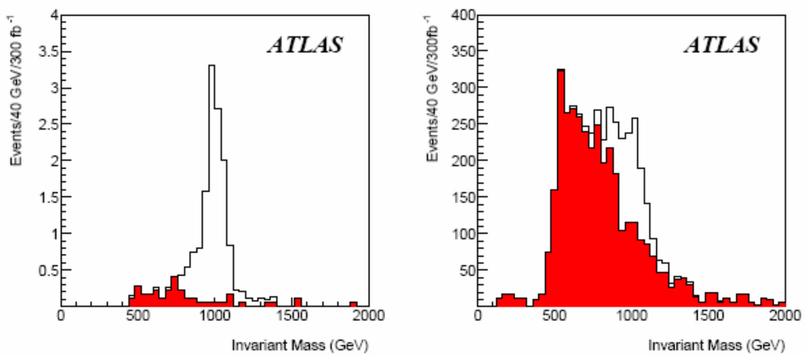


Single state T for various couplings (dominates for heavy T) and TT pair

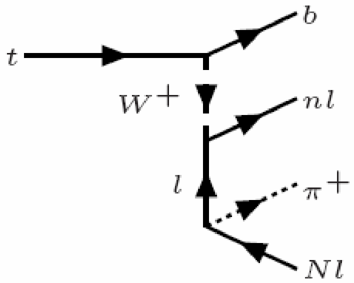
CDF limit:
$M_{t'}$ > 311GeVat the 95% C.L.



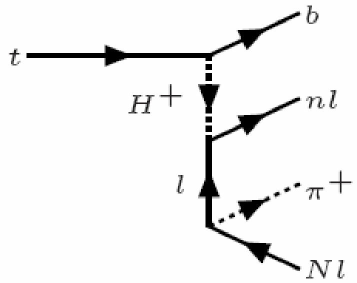
ATLAS simulation for T->tZ and T->Wb decay modes



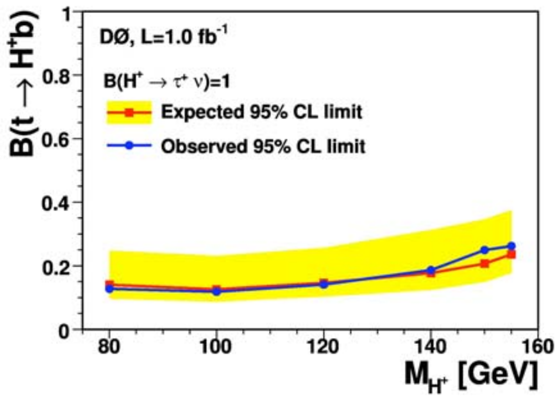
Charged Higgs in Top Decay (impact of tau polarization)



diagr.1



diagr.2



In the rest frame of top $t \to bR \to b\tau\nu_\tau \to b\nu_\tau\bar{\nu}_\tau\pi$

where a resonance R is W boson or charged H

$$\frac{1}{\Gamma}\frac{d\Gamma}{dy_\pi} = \frac{1}{x_{max} - x_{min}}$$

$$\begin{cases} (1-P_\tau)log\frac{x_{max}}{x_{min}} + 2P_\tau y_\pi(\frac{1}{x_{min}} - \frac{1}{x_{max}}), & 0 < y_\pi < x_{min} \\ (1-P_\tau)log\frac{x_{max}}{y_\pi} + 2P_\tau(1 - \frac{y_\pi}{x_{max}}), & x_{min} < y_\pi \end{cases}$$

where $y_\pi = \frac{E_\pi^{top}}{M_{top}}, \quad x_{min} = \frac{E_\tau^{min}}{M_{top}}, \quad x_{max} = \frac{E_\tau^{max}}{M_{top}}, \quad E_\tau^{min} = \frac{M_R^2}{2M_{top}}, \quad E_\tau^{max} = \frac{M_{top}}{2}$

$P_\tau = -1$ for W boson and $P_\tau = 1$ for charged Higgs

(M.Nojiri; E.B.,G.Moortgat-Pick, M.Sachwitz, A.Sherstnev, P.Zerwas; E.B., S.Bunichev, M.Carena, C.Wagner)

$e^+e^- \rightarrow t\bar{t} \rightarrow \tau\nu_\tau b\bar{b} + 2jets$

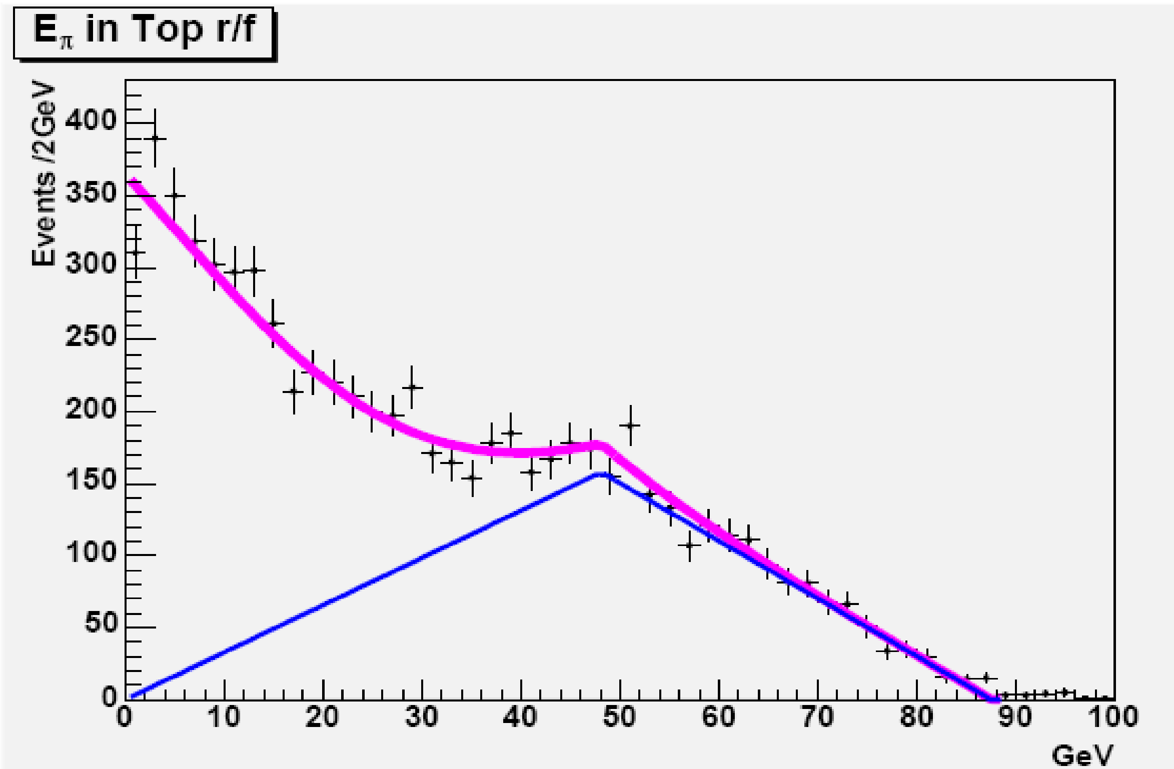
Simulations are performed for e^+e^- collisions at 500 GeV cms and for 500 fb^{-1} integrated luminosity

π-meson energy spectrum for the MSSM point $\tan\beta = 50$, $\mu = 500$, $M_{H^\pm} = 130\ GeV$ with $Br(t \rightarrow H^+ b) = 9.1\%$

E.B., S.Bunichev, M.Carena, C.Wagner

One of the most precise way to measure charged Higgs mass:

$M_{H^\pm}$ = 129.4 +/- 0.9 GeV



Anomalous Top Couplings

The top quark interactions of dimension 4:

$$\begin{aligned}\mathcal{L}_4 &= -g_s \bar{t}\gamma^\mu T^a t G^a_\mu - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu (v^W_{tq} - a^W_{tq}\gamma_5) q W^+_\mu \\ &\quad -\frac{2}{3} e \bar{t}\gamma^\mu t A_\mu - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu (v^Z_{tq} - a^Z_{tq}\gamma_5) q Z_\mu\end{aligned}$$

The dimension 5 couplings have the generic form:

$$\begin{aligned}\mathcal{L}_5 &= -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f^g_{tq} + i h^g_{tq}\gamma_5) q G^a_{\mu\nu} - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^W_{tq} + i h^W_{tq}\gamma_5) q W^+_{\mu\nu} \\ &\quad -e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^\gamma_{tq} + i h^\gamma_{tq}\gamma_5) q A_{\mu\nu} - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^Z_{tq} + i h^Z_{tq}\gamma_5) q Z_{\mu\nu}\end{aligned}$$

Present constrains come from

- Low energy data via loop contributions
  $K_L \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $b \to l^+ l^- X$, $b \to s\gamma$
- LEP2
- Tevatron Run1,2
- HERA
- Unitarity violation bounds

Anomalous Wtb Couplings

- Lagrangian

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{tb} \left[W_\nu^- \bar{b} \gamma_\mu P_- t - \frac{1}{2M_W} W_{\mu\nu}^- \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+) t \right] + h.c.$$

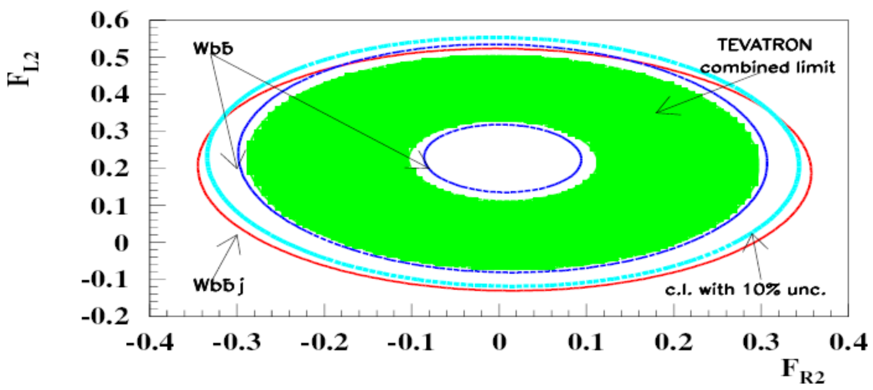
  with $W_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm$, $D_\mu = \partial_\mu - ieA_\mu$,
  $\sigma^{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$ and $P_\pm = (1 \pm \gamma_5)/2$. The couplings F_2^L and F_2^R are proportional to the coefficients of the effective Lagrangian
  $F_{L2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W - ih_{tb}^W)$,
  $F_{R2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W + ih_{tb}^W)$, $|F_{L2,R2}| < 0.6$ from unitary bounds

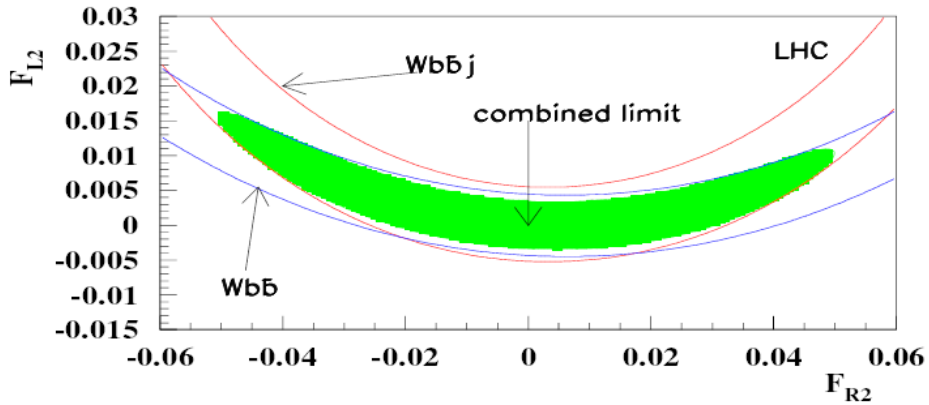
- $|V_{tb}|$ is very close to 1 in SM with 3 generations. ($|V_{tb}|$ is very weakly constrained in case of 4 generations, e.g.)

- A possible $V + A$ form factor is severely constrained by the CLEO $b \to s\gamma$ data to 3×10^{-3} level

Expectations for Wtb anomalous couplings for the Tevatron and LHC

E.B., L.Dudko, T.Ohl





D0 limits based on 900 pb^{-1} data

Scenario	Cross Section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\|V_{tb} f_1^L\|^2 = 1.4^{+0.6}_{-0.5}$
		$\|V_{tb} f_2^L\|^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\|V_{tb} f_1^L\|^2 = 1.8^{+1.0}_{-1.3}$
		$\|V_{tb} f_1^R\|^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\|V_{tb} f_1^L\|^2 = 1.4^{+0.9}_{-0.8}$
		$\|V_{tb} f_2^R\|^2 < 0.3$ at 95% C.L.

FCNC couplings

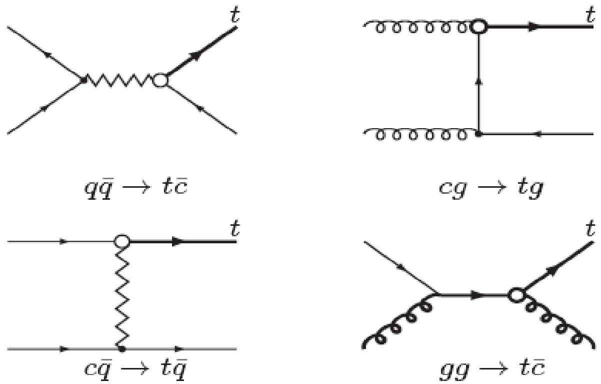
- Couplings: $tqg,\ tq\gamma,\ tqZ$, where $q = u, c$

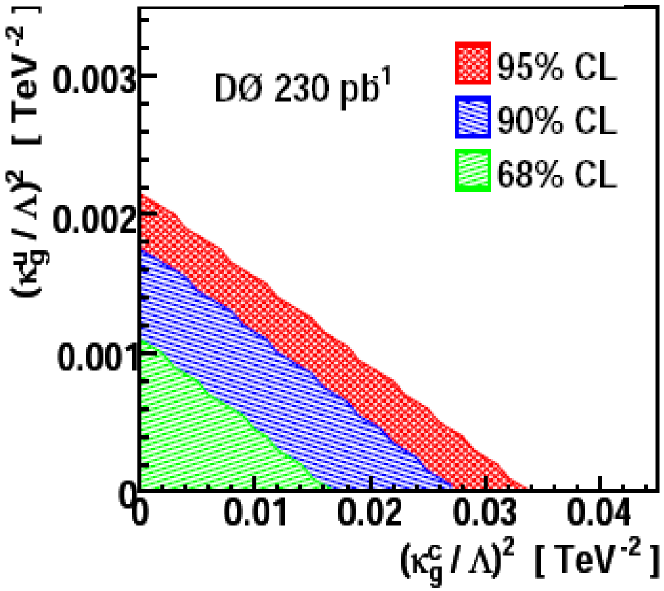
$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\left[\kappa_{tq}^{\gamma,Z} e\bar{t}\sigma_{\mu\nu} q F_{\gamma,Z}^{\mu\nu} + \kappa_{tq}^{g} g_s \bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2} q G^{i\mu\nu}\right] + h.c.$$

D0 Limits on FCNC couplings 230 pb^{-1}:

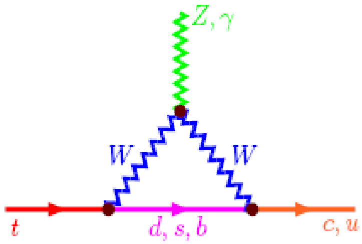
$$\kappa_g^u/\Lambda < 0.037\ \mathrm{TeV}^{-1}$$

$$\kappa_g^c/\Lambda < 0.15\ \mathrm{TeV}^{-1}$$





W' boson and FCNC MC event samples from SingleTop (CompHEP) generator



	SM	two-Higgs	SUSY
$\mathrm{BR}(t \to cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$\mathrm{BR}(t \to c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$\mathrm{BR}(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

FCNC decays are highly suppressed in SM $t \to qg,\quad t \to q\gamma,\quad t \to qZ$

To compare FCNC limits from top decays and top production one can express limits on FCNC couplings in term of Br fractions

$$\Gamma(t \to qg) = \left(\frac{\kappa^g_{tq}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t \to q\gamma) = \left(\frac{\kappa^\gamma_{tq}}{\Lambda}\right)^2 2\alpha m_t^3,$$

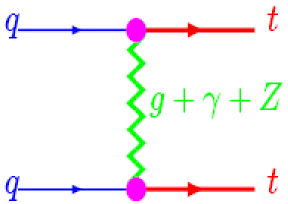
$$\Gamma(t \to qZ)_\gamma = \left(|v^Z_{tq}|^2 + |a^Z_{tq}|^2\right) \alpha\, m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right),$$

$$\Gamma(t \to qZ)_\sigma = \left(\frac{\kappa^Z_{tq}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)$$

$t \to$	Tevatron Run II	LHC decay	LHC production	ILC
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}	–
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}	4×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}	2×10^{-4}

Interesting process to be studied:

like top (tt or $\bar{t}\,\bar{t}$) pair production: $pp \to t\,t\,X \quad pp \to \bar{t}\,\bar{t}\,X$



$\sigma(tt) \propto (\kappa_g)^4$

no background from $t\bar{t}$ or from single-top

$$A_{fb} = \frac{N(-Q_l \cdot y_{\rm had} > 0) - N(-Q_l \cdot y_{\rm had} < 0)}{N(-Q_l \cdot y_{\rm had} > 0) + N(-Q_l \cdot y_{\rm had} < 0)}$$

CDF (2 sigma away from SM):

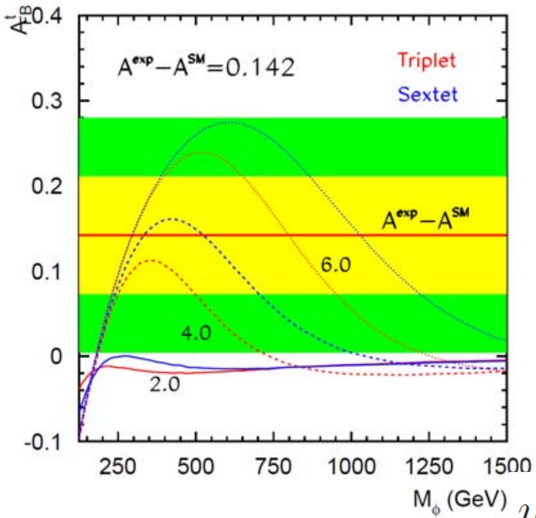
$$A^t_{FB} \ = \ 0.193 \pm 0.065_{\,\rm stat.} \pm 0.024_{\,\rm syst.}$$

$$A^{t\ (SM)}_{FB} \ = \ 0.051$$ **J.H.Kuhn, G.Rodrigo**

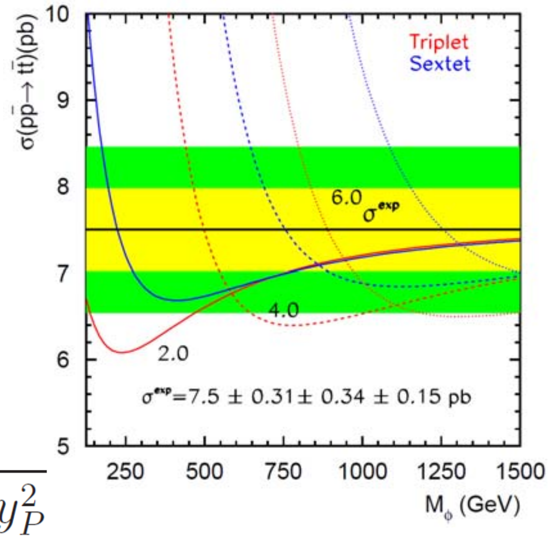
$$A^{p\bar{p}}_{t\bar{t}+jet} = -0.07 \xrightarrow{NLO} -0.015(15)$$ **Dittmaier, Uwer, Weinzierl; Melnikov, Schulze**

Many different variants of new physics may lead to the asymmetry **Review: Wagner et .al**

$$\mathcal{L}_\phi \ = \ D_\mu \phi^\dagger D^\mu \phi - M^2_\phi |\phi|^2 + \phi^a \bar{\hat{t}} T^a_r (y_S + y_P \gamma_5) u + h.c.$$ **T.Tait et al.**



$$y \equiv \sqrt{y_S^2 + y_P^2}$$



Concluding remarks

Top quark plays a very special role in SM and many BSM extensions

Taking EW naturalness problem seriously a presence of the top quark partners is a robust prediction of many BSM models

SM top quark production and decay is an important background for many BSM searches

BSM models may manifest in top searches differently depending on relations between characteristic collision energy and thresholds of new states

$E > E_{Th}$: New resonances decaying to tops;
New states produced in association with the top

$E > E_{Th}$: New effective anomalous interactions

Top physics is an important part of all collider projects.
The LHC will be a real top quark factory

Tevatron, LHC, ILC, CLIC ???

Victor Boos (1999)

Top quark probably helps…

Back up slides