Heavy resonances in the top quark sector: from hadron colliders to the ILC

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The top quark: motivation

Top quark is the heaviest known elementary particle ⇨ it plays a fundamental role in many extensions of the Standard Model (SM) / alternative mechanisms of EWSB.

⇩

Production and decay channels are promising probes of new physics.

The total cross section of top-antitop quark production at LHC is about 100 times (@14 TeV) larger than at Tevatron ⇨ Millions of top quark pairs per year would be produced even at the designed low luminosity of $L = 10^{33} cm^{-2} s^{-1}$ (equivalent to 10 fb^{-1}/year integrated luminosity)*.

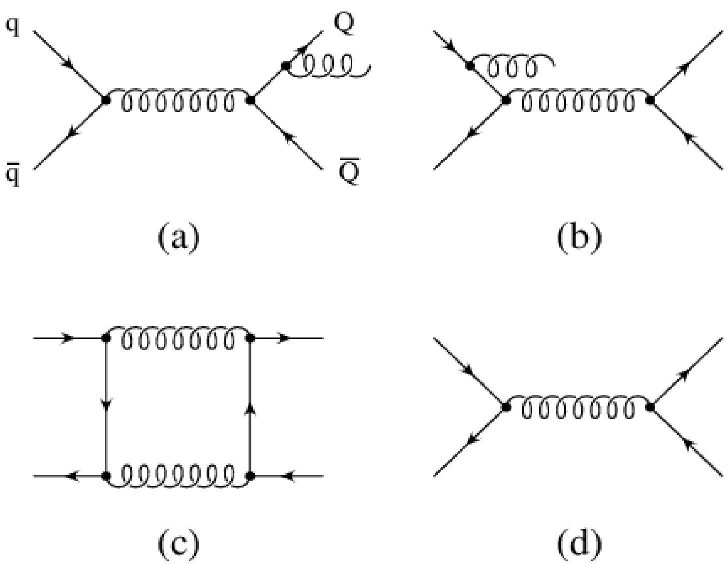
at the ILC σ = 0.6 pb (500 GeV) and 0.16 pb (1 TeV),
10^5 top quark pairs per ab^{-1}

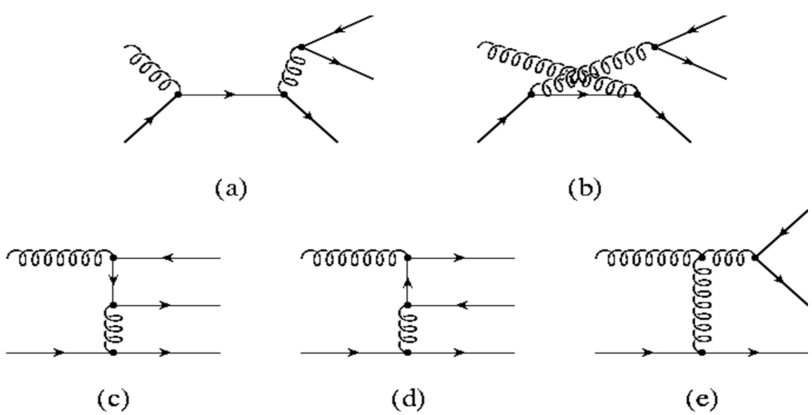
* 200 pb^{-1} (1fb^{-1}) @ 7 TeV by the end of 2010 (2011) (10^5 top quark pairs)

Charge asymmetry in QCD

At $O(\alpha_S^2)$: top and antitop quarks have identical angular distributions

[Kühn, GR,1998]





A charge asymmetry arises at $O(\alpha_S^3)$

- Interference of ISR with FSR
  LO for ttbar+jet
  negative contribution

- Interference of box diagrams with Born
  positive contribution

color factor d_{abc}^2 : **pair in color singlet**

Loop contribution larger than tree level
top quarks are preferentially emitted in the direction of the incoming quark

- Flavor excitation much smaller

Inclusive asymmetry at Tevatron

Charge conjugation symmetry

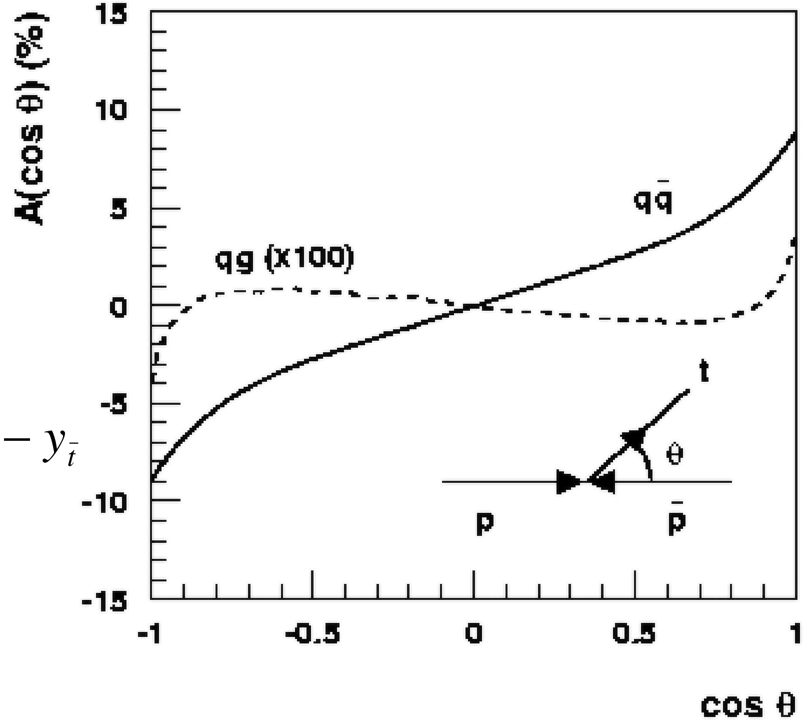
($N_{\bar{t}}(y) = N_t(-y)$)

Forward-backward

[Kühn, GR,1998; Antuñano, Kühn, GR, 2008]

$$A^{p\bar{p}} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

$$A^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$



mixed QCD-EW interference: factor 1.09 included

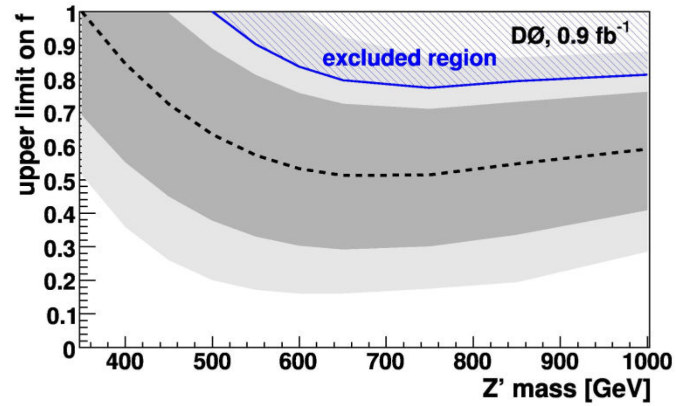
stable to threshold resummations (one per mille) [Almeida,Sterman,Vogelsang, 2008]

Asymmetry measurements at Tevatron

- **D0** [PRL101(2008)202001]   uncorrected

A_{FB}^{ppbar} = 0.12   0.08 (stat)   0.01 (syst)   0.9 fb^{-1}

Limits as a function of the fraction (f) of ttbar events produced via a topcolor leptophobic Z′ resonance



- **CDF** [Conf. Note 9724, PRL101(2008)202001]

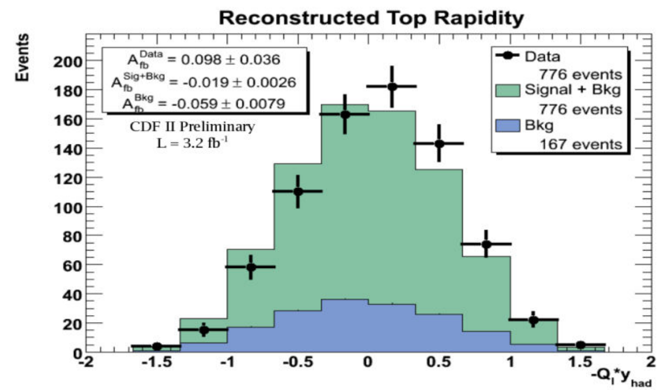
ppbar rest frame [new measurement soon, Rob Roser]

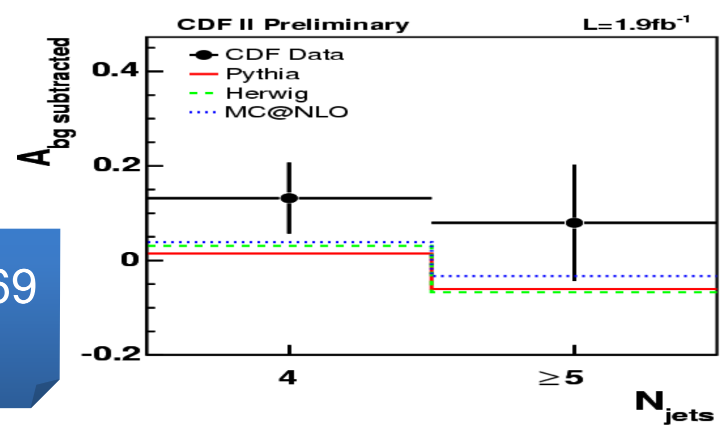
A_{FB}^{ppbar} = 0.193   0.065 (stat)   0.024 (syst)   3.2 fb^{-1}
A_{FB}^{ppbar} = 0.17   0.07 (stat)   0.04 (syst)   1.9 fb^{-1}

ttbar rest frame

A_{FB}^{ttbar} = 0.24   0.13 (stat)   0.04 (syst)   1.9 fb^{-1}

At least 4 jets: A_{FB}^{ttbar} = 0.119   0.064 (stat)
Exact 4 jets: A_{FB}^{ttbar} = 0.132   0.075 (stat)
At least 5 jets: A_{FB}^{ttbar} = 0.079   0.123 (stat)





2.8σ from zero, $(A^{exp} - A^{SM})_{ppbar}$ =0.142   0.069

room for BSM within 2σ

Which model BSM

Chiral Color Models

[Pati , Salam, PLB58(1975)333; Hall,Nelson, PLB153(1985)430; Frampton, Glashow, PLB190(1987)157; PRL58(1987)2168]

Extend the standard color gauge group to

$$\mathbf{SU(3)_L \times SU(3)_R \rightarrow SU(3)_C}$$

different implementations with new particles in varying representations (anomaly cancellation requires extra fermions), but

model-independent prediction: existence of a massive color-octet axial-vector gauge boson: **axigluon**

- couples to quarks with an **axial-vector** structure and the same strong interaction coupling strength as QCD
- the **charge asymmetry** that can be generated is maximal.

because of parity a single axigluon do not couple to gg

Asymmetric Chiral Color [Cuypers, ZPC48(1990)639]: chiral color with different couplings ξ_1, ξ_2: $g_V = g_S \cot 2\theta$, $g_A = g_S / \sin 2\theta$

Colorons

[Hill, PLB266(1991)419; Hill, Parke, PRD 49(1994)4454;
Chivukula, Cohen, Simmons, PLB380(1996)92]

Extend the standard color gauge group to

$$SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$$

- with gauge couplings ξ_1, ξ_2 and $\xi_1 << \xi_2$
- massive gluons / color-octet vector boson (colorons)
- coupling to quarks $g_S \cot \theta = g_S (\xi_2 / \xi_1) > g_S$
- no **charge asymmetry**

GUT theories

- Grand Unified Theories (GUT) based on larger gauge groups, e.g., E6 and SO(10), or left-right symmetric models often introduce additional gauge bosons, such as W′ and Z′, which decay to f fbar and f fbar, respectively.

The E6 GUT model also predicts the presence of a diquark (colored scalars) which decays to qq or qbar qbar.

colored scalars (singlet, triplet, sextet and octet) in SU(5) GUT

$5_H = H_1 + T = (\mathbf{1},\mathbf{2},1/2) + (\mathbf{3},\mathbf{1},-1/3)$

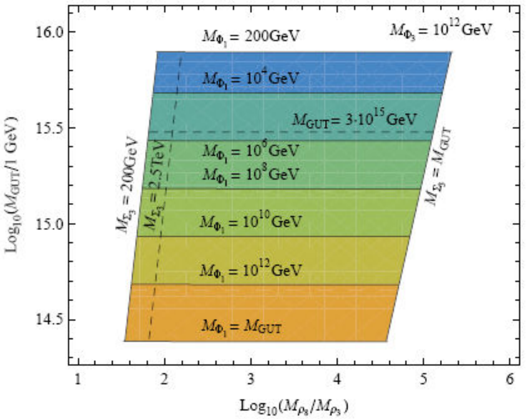
$24_H = \Sigma_i = (\mathbf{8},\mathbf{1},0) + (\mathbf{1},\mathbf{3},0) + (\mathbf{3},\mathbf{2},-5/6) + (\mathbf{\bar{3}},\mathbf{2},5/6) + (\mathbf{1},\mathbf{1},0)$

$45_H = (\mathbf{8},\mathbf{2},1/2) + (\mathbf{\bar{6}},\mathbf{1},-1/3) + (\mathbf{3},\mathbf{3},-1/3) + (\mathbf{\bar{3}},\mathbf{2},-7/6) + (\mathbf{3},\mathbf{1},-1/3) + (\mathbf{\bar{3}},\mathbf{1},4/3) + (\mathbf{1},\mathbf{2},1/2)$

scalar color-octet in Adjoint SU(5) [Fileviez et al.,2008]

$\mathbf{\Phi}_1 = (\mathbf{8},\mathbf{2},1/2) \subset 45_H$

Unification and proton decay $M_{\Phi 1} < 440$ TeV



Top color assisted technicolor (TC2)

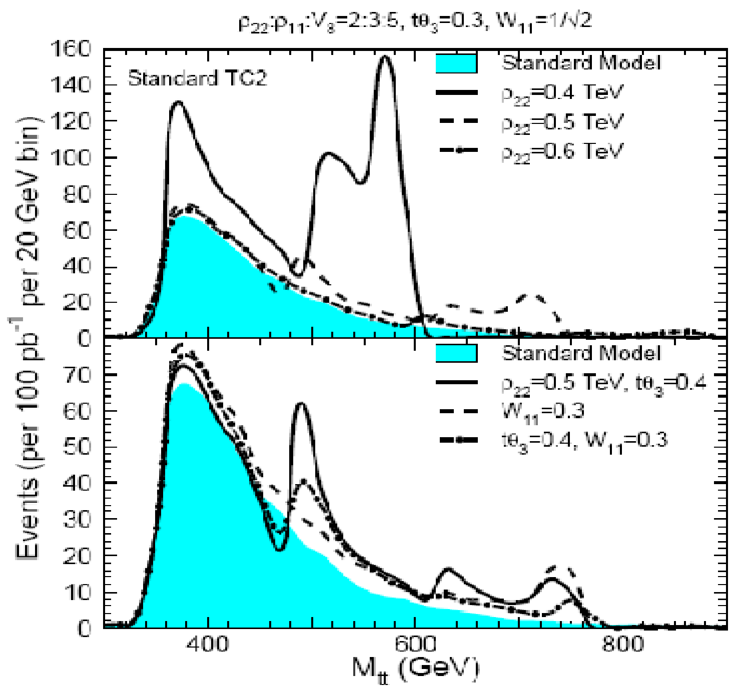
[Hill, PLB345(1995)483; Lane, Ramana, PRD 44 (1991) 2678;
Lane, Mrenna, PRD67(2003) 115011]

Combine extended technicolor and topcolor assisted technicolor

$$G_{ETC} \times [SU(3)_1 \times U(1)_1] \times [SU(3)_2 \times U(1)_2] \times SU(2)_L \rightarrow SU(3)_C \times U(1)_{EM}$$

where $SU(3)_1 \times U(1)_1$ couples preferentially to the third generation, and the weaker $SU(3)_2 \times U(1)_2$ to the first and second

Z (leptophobic or not), 8 colorons and 4 color-octet technirho vector mesons (ρ_{T8}) which decays to qqbar or gg

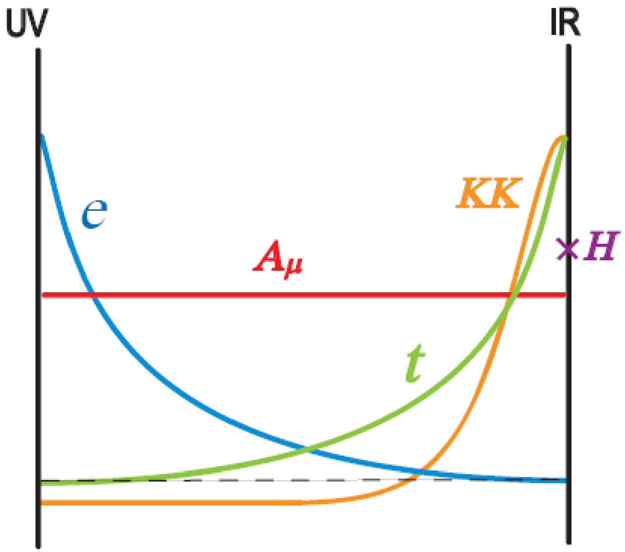


Warped extra dimensions

[Randall, Sundrum, PRL 83, 3370 (1999);
Dicus, McMullen, Nandi, PRD65 (2002) 076007]

The RS model of a warped extra dimension offers a solution for the hierarchy between the electroweak scale and Planck scale M_{Pl} by introducing an extra spacial dimension. Predicts a Kaluza-Klein tower of graviton states (RS gravitons) which decay to ffbar or gg.

RS Kaluza-Klein gauge bosons (KK g*, Z ,W): explains mass hierarchy between top and light quarks, with preferential couplings to top quarks, no couplings to gg (odd number of g*), suppression of FCNC



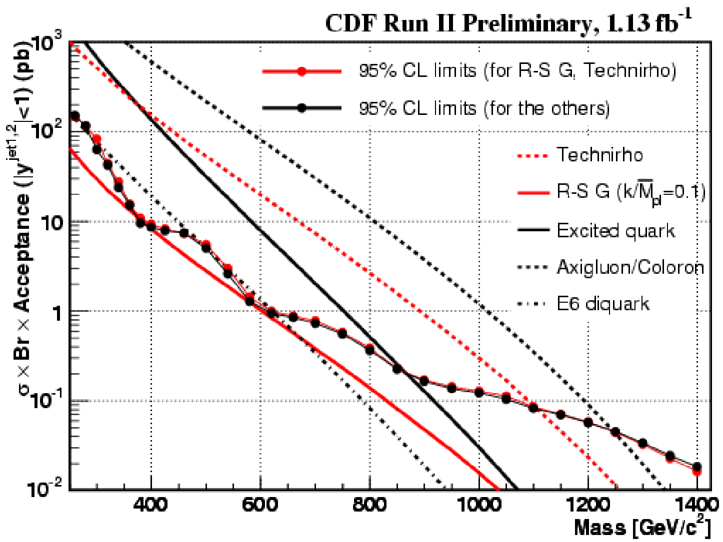
Interactions are given by wave function overlap

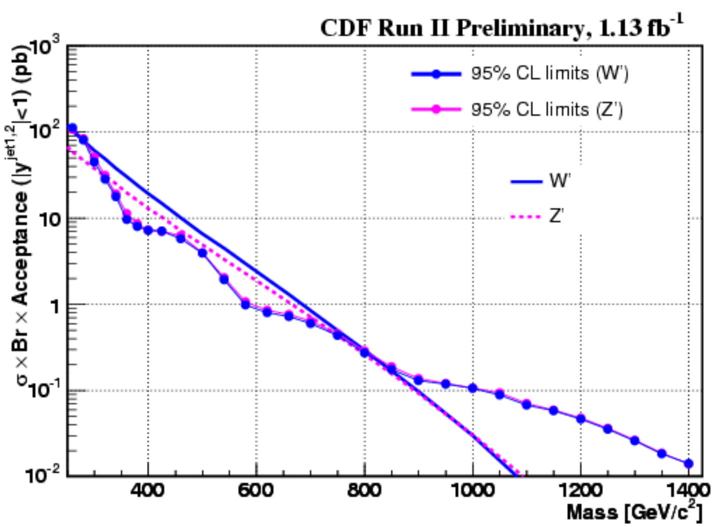
The top quark: close to Higgs profile

KK modes have masses O(1 TeV): localized near the IR brane too: preferential couplings to top quarks

EW precision measurements: M_Z >3TeV [Agashe et al. 2003]

Mass exclusion from Tevatron





Dijet channel CDF arXiv:0812.4036

260-870 GeV/c^2	Excited quark (f=f'=fs=1)
260-1100 GeV/c^2	Color-octet technirho [top-color-assisted technicolor (TC2) couplings, M'_8=0, M($pi_{22}{}^8$)=5M(rho)/6, M($pi_{22}{}^1$)=M($pi_{22}{}^8$)/2, M_8=5M(rho)/6]
260-1250 GeV/c^2	Axigluon and flavor-universal coloron (mixing of two SU(3)'s, cot(theta)=1)
290-630 GeV/c^2	E_6 diquark
280-840 GeV/c^2	W' (SM couplings)
320-740 GeV/c^2	Z' (SM couplings)

* Low mass window for axigluons also excluded [Doncheski,Robinet, 97] from hadronic Z-decays

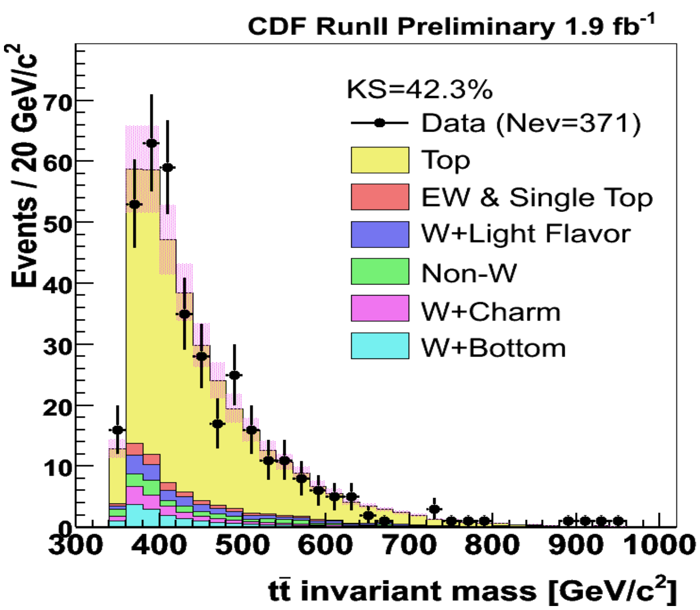
Other channels CDF

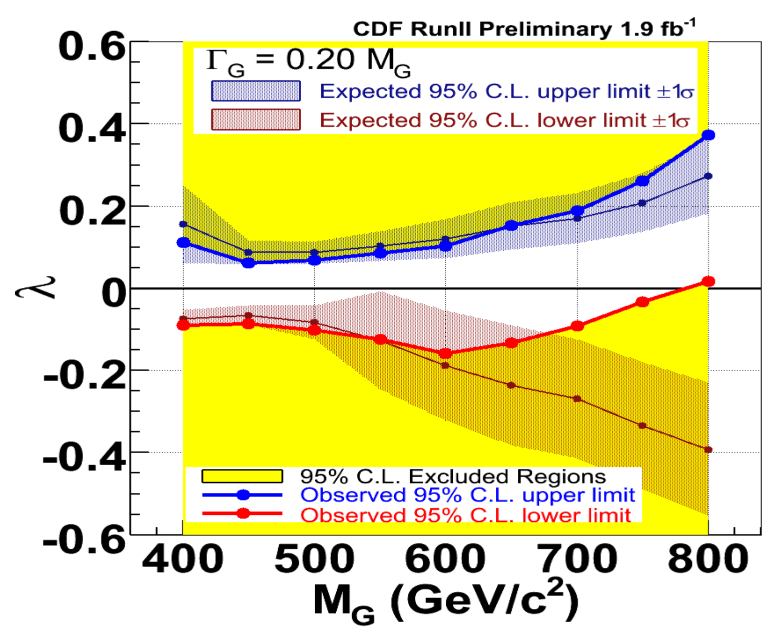
WW/WZ (eνjj)	$m_{Z'}$ > 545 GeV $m_{W'}$ > 515 GeV $m_{graviton}$ > 606 GeV	2.9 fb^{-1}
ZZ	$m_{graviton}$ > 491 GeV (k/M_{Pl} = 0.1)	3.0 fb^{-1}
tb	$m_{W'}$ > 800 GeV for $m_{W'} > m_{\nu R}$ $m_{W'}$ > 825 GeV for $m_{W'} < m_{\nu R}$	1.9 fb^{-1}

ttbar channel at Tevatron

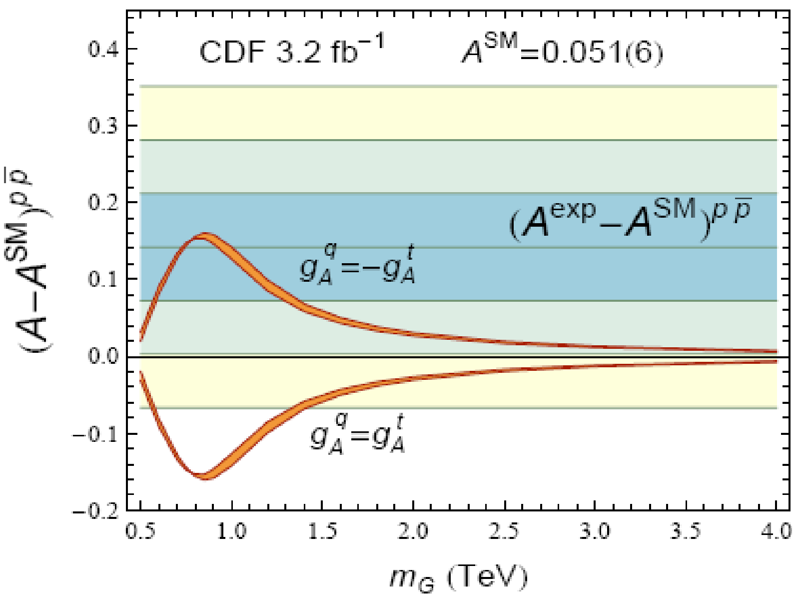
* Some new results were made public these days: CDF and D0 Winter results (not included)

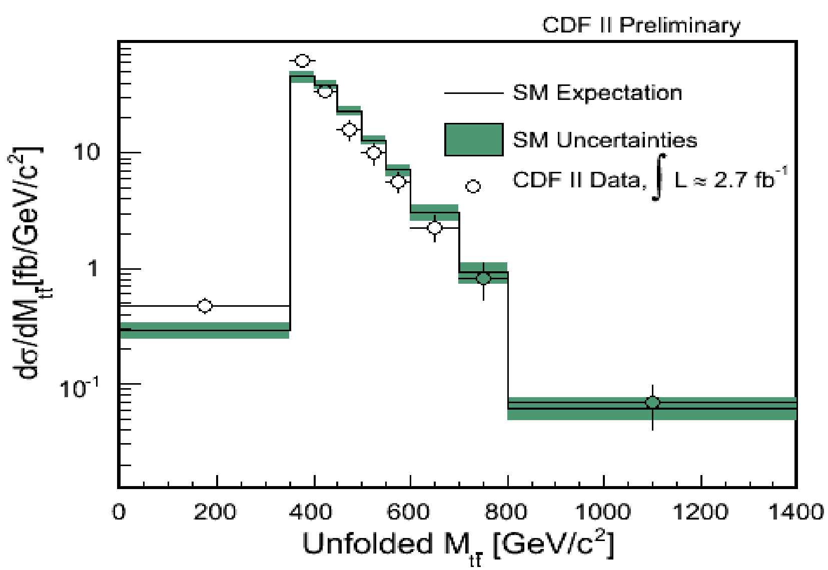
D0	Lepton+jet	topcolor-assisted technicolor, leptophobic $m_{Z'} > 820$ GeV	3.6 fb^{-1}
CDF	All hadronic	$m_{Z'} > 805$ GeV (SM couplings)	2.8 fb^{-1}
CDF	Lepton+jet	Topcolor leptophobic $m_{Z'} > 720$ GeV Out of range of sensitivity to SM Z´	1 fb^{-1}
CDF	Lepton+jet	Limits on massive gluon coupling $\lambda = g_V^q g_V^t$ as a function of width	1.9 fb^{-1}





save the axigluon





The FB asymmetry disfavour at 2σ vanishing or negative contributions (axigluons or colorons)

m_G > 1.6 TeV at 99%C.L. (g_V=0,g_A=1)

Larger exclusion limit than dijet channel.

It is still possible to generate a positive asymmetry for large values of the vector couplings, or if sign($g_A{}^q$)= -sign($g_A{}^t$)

[Ferrario, GR, arXiv:0906.5541]
[Frampton,Shu,Wang, arXiv:0911.2955]

while keeping dσ/dM$_{ttbar}$ small
[CDF note 9602 (Nov 2008)]

$$d\sigma / dM_{t\bar{t}}(0.8-1.4\text{TeV}) =$$

$$0.07 \pm 0.032_{stat} \pm 0.015_{sys} \pm 0.004_{lumi}(\text{fb GeV}^{-1})$$

The last bin is the most sensible to masses of O(1TeV): sets lower bound

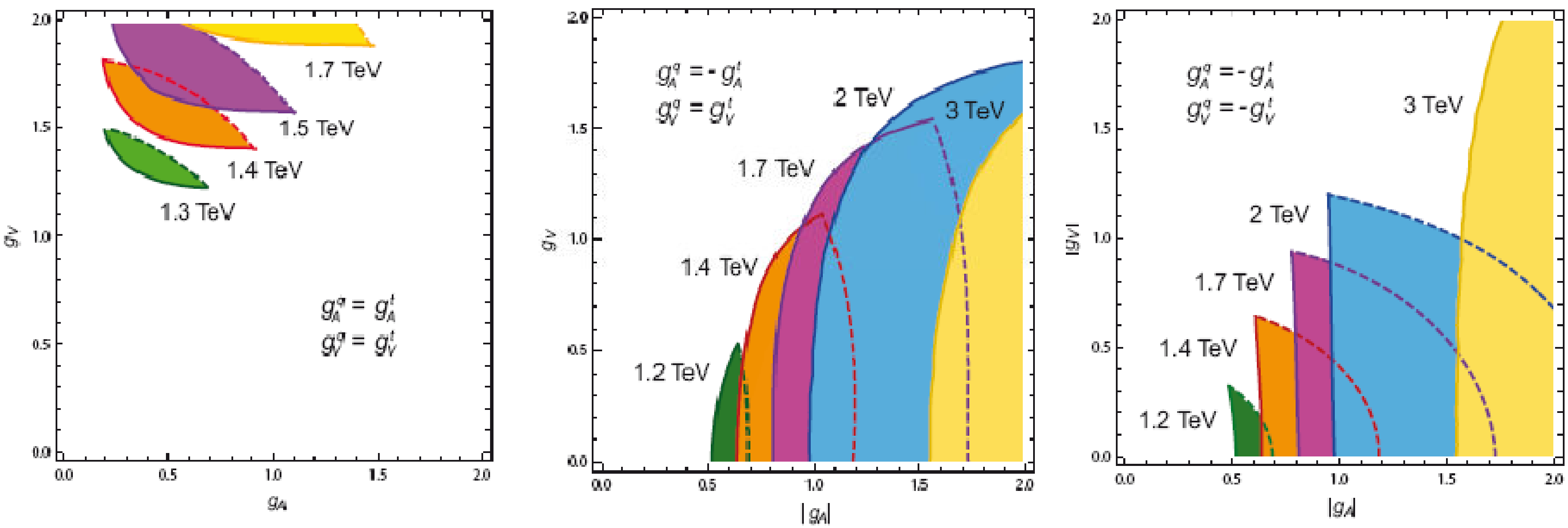
* RS graviton M=600 GeV, κ/M$_{Pl}$ > 0.16 at 95%C.L.

Flavour universal and non-universal axigluon

[Ferrario, GR, arXiv:0906.5541]

Combining limits on the charge asymmetry (solid lines) and the invariant mass distribution (dashed)

$$L = g_S T^a \overline{q}_i \gamma^\mu (g_V^{qi} + g_A^{qi} \gamma_5) G'_\mu q_i$$



Flavour Universal

no overlapping region @ 90 % C.L.
m_G>1.2 TeV @ 95 % C.L.

$$|g_A| = 1 \quad \left\{ \begin{array}{l} m_G > 1.44\text{TeV} \\ g_V > 1.45 \end{array} \right.$$

Flavour non-Universal

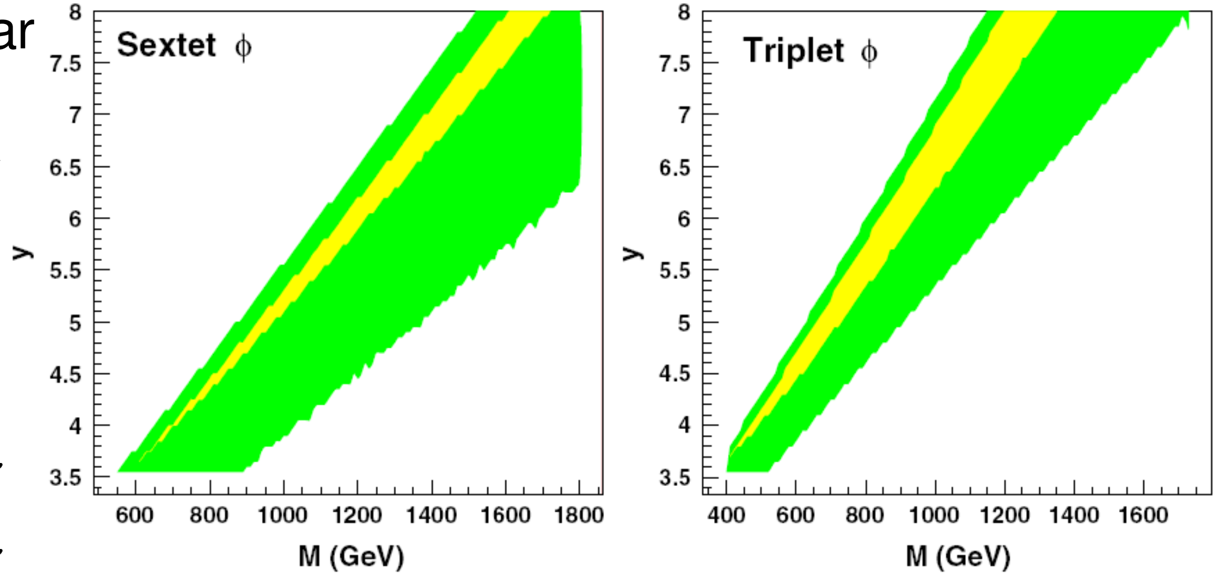
Fixing the couplings sets lower and upper bounds on the mass

$$|g_A| = 1 \qquad 1.33\text{TeV} < m_G < 2\text{TeV} \qquad @\,90\%\,C.L.$$

Scalars in the t-channel

Flavour violating scalars in the t-channel: uubar→ ttbar

[Shu,Tait,Wang, arXiv:0911.3237]



$$L = \phi^a \bar{t} T^a (g_S + g_P \gamma_5) u$$

$$y = \sqrt{g_S^{\ 2} + g_P^{\ 2}}$$

- Singlet (**1**,**2**,-1/2) ✗
- Triplet (**3bar**,**1**,4/3) ✓
- Sextet (**6**,**1**,4/3) ✓
- Octet (**8**,**2**,-1/2) ✗

* (**6**,**3**,1/3) and (**3bar**,**3**,1) more constrained from flavour observables

Requires large flavour violating couplings
Potential uu→ tt (same sign dileptons): singlet and octet; sextet in the s-channel

R-parity violating MSSM: sleptons (singlet) ✗, and squarks (triplet) ✓, in ddbar→ ttbar

[Cao,Heng,Wu,Yang, arXiv:0912.1447]

GUT: triplet (**3bar**,**1**,4/3) ✓ ($M_{ttbar} \to m_\Phi <$ O(TeV)), octet (**8**,**2**,-1/2) ✗ [Dorsner et.al. arXiv:0912.0972]

Triplet ✓ and sextet ✗ [Arhrib,Benbrik,Chen,arXiv:0911.4875]

EFT: singlet ✓, triplet ✗, sextet ✗, octet ✓ [Jung,Ko,Lee,Nam,arXiv:0912.1105]

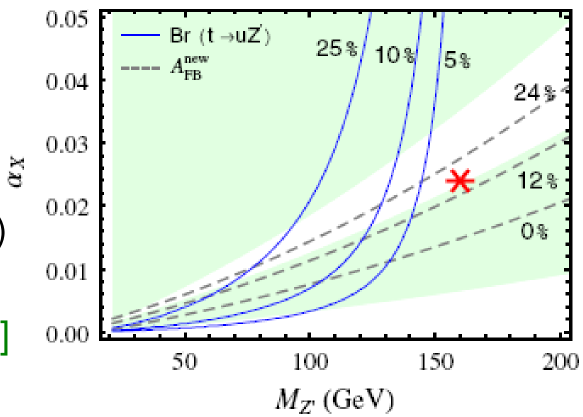
Z' and W' in the t-channel

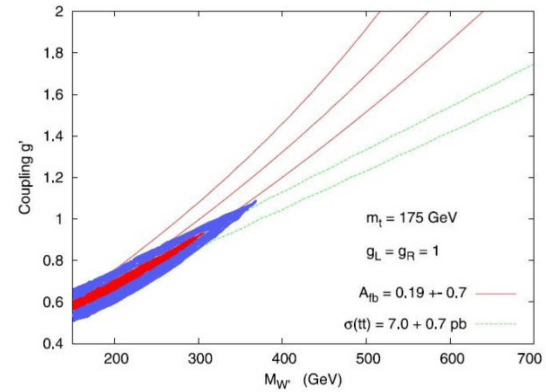
Flavour violating weak vector bosons in the t-channel (mostly):

[Jung,Murayama,Pierce,Wells, arXiv:0907.4112]

$$L = g_X Z'_\mu (\overline{u}\gamma^\mu P_R t + \varepsilon_X \overline{u_i}\gamma^\mu P_R u_i)$$

best fit: m_Z = 160 GeV , α_X=0.024
light to avoid uu→ tt (same sign dileptons)
ε_X≠0 to suppress uubar→ Z Z (like sign tt)





[Cheung,Keung,Yuan, arXiv:0908.2589]

$$L = -g' W'_\mu \overline{t}\gamma^\mu (g_V + g_A\gamma_5) d$$

Third generation enhanced LR model SU(2)$_L$ x SU(2)$_R$ x U(1)$_{B-L}$: uubar → Z →ttbar
[Cao,Heng,Wu,Yang, arXiv:0912.1447] No u_R-t_R mixing (s-channel) ✗ , with mixing (t-channel) ✓

Asymmetric LR model SU(2)$_L$ x (SU(2) x U(1) →U(1)$_Y$): Z (s-channel) and W (t-channel)
[Barger,Keung,Yu, arXiv:1002.1040]: m_Z = 190 GeV , m_W = 175 GeV

[Cao,McKeen,Rosner,Saughnessy, Wagner, arXiv:1003.3461]: W large couplings and large amount of fine tuning

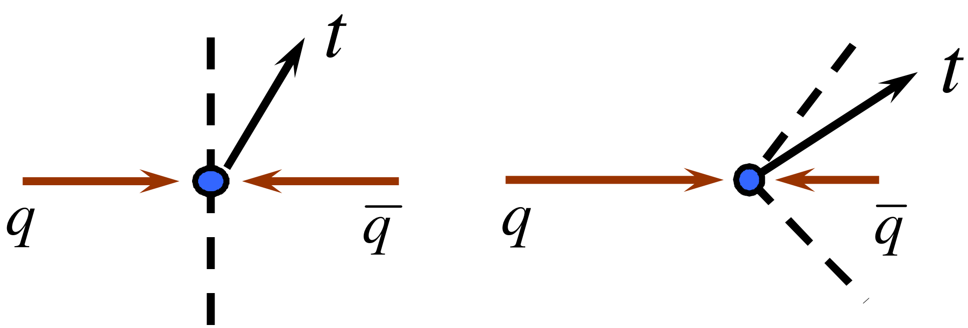
Requires light Z and W : O(200 GeV) or large flavour violating couplings, although more efficient than scalars

Charge asymmetry at LHC

LHC is symmetric ➡ no forward-backward

But suppose that there is a charge asymmetry at parton level
(QCD predicts that tops are preferentially emitted in the direction of the incoming quark, resonance asymmetry depends on ($s-m_G$) and relative sign of couplings)

quarks carry more momenta than antiquarks



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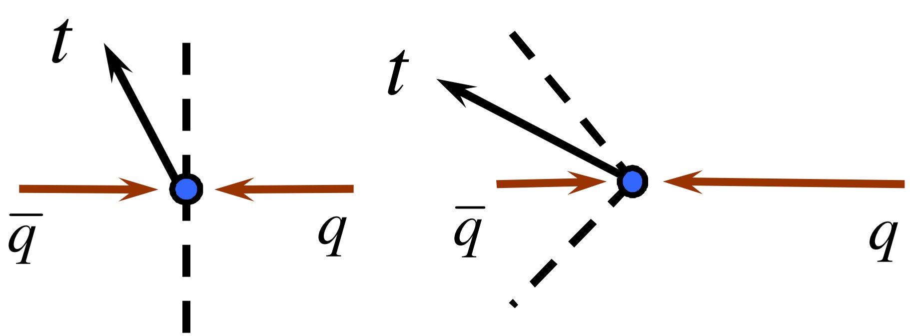


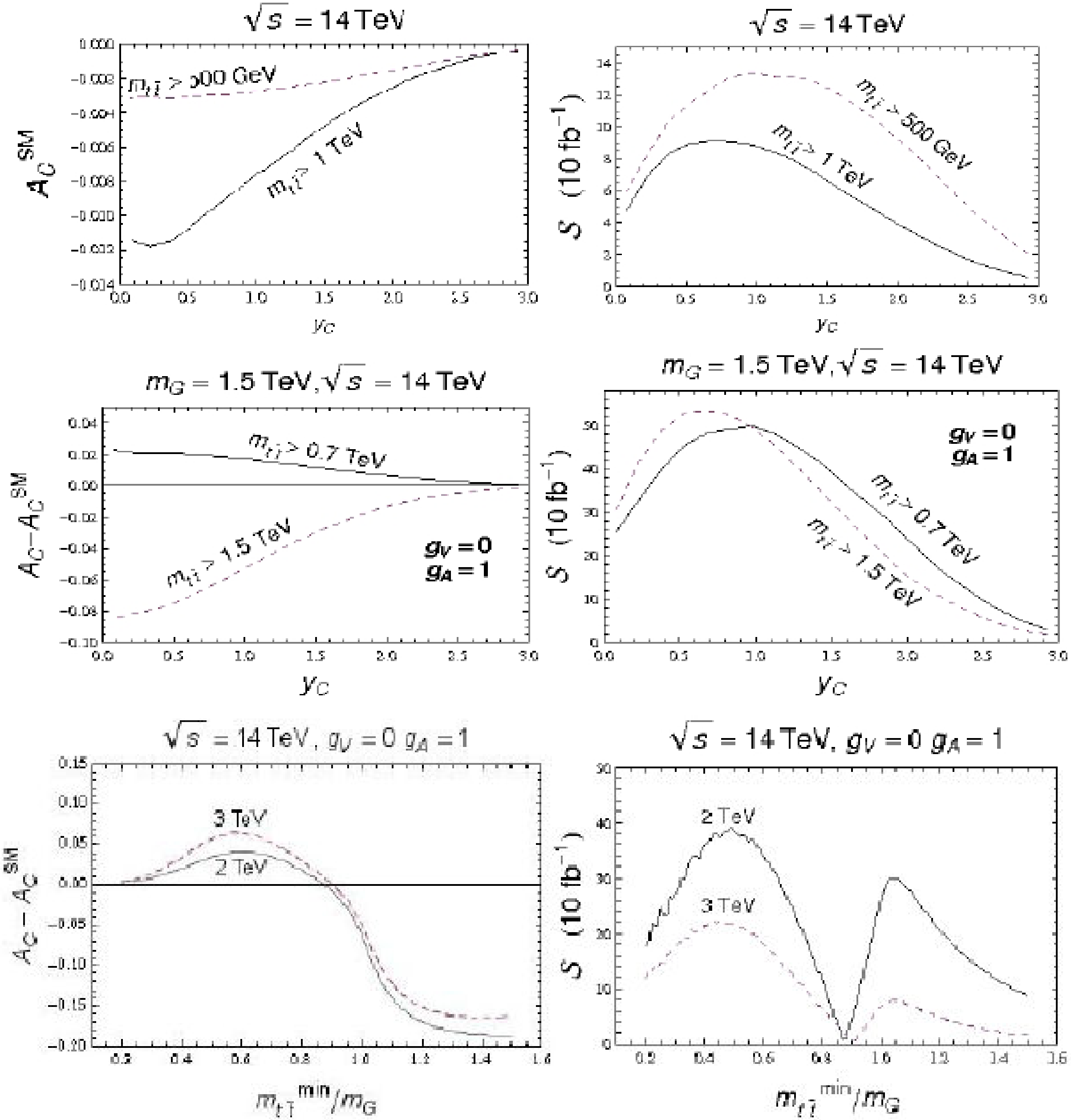
Excess of tops (or antitops) in the forward and backward regions

$$A_C(y_C) = \frac{N_t(|y| < y_C) - N_{\bar{t}}(|y| < y_C)}{N_t(|y| < y_C) + N_{\bar{t}}(|y| < y_C)}$$

$$A_C(y_C >> 1) = 0$$

Opposite in sign to the parton asymmetry

However, top cross section is gg dominated, which is symmetric; but gg can be suppressed by selecting pairs with large invariant mass



[Ferrario, GR, arXiv:0809.3354]
[Ferrario, GR, arXiv:0912.0687]

Charge asymmetry suppressed by gg-fusion (90% @14TeV) but statistical significance can be maximized by tuning y_C and m_{tt}^{min}

smallness of QCD asymmetry compensated by statistics at low m_{tt}^{min}

Color-octet resonance: maximum statistical significance at about $m_G/2$ (less boosted tops)

f_{abc}^2 contributions (color octet state) too in ttbar+jet

From LHC to ILC

- **ILC** no direct production of coloured resonances in the ttbar s-channel

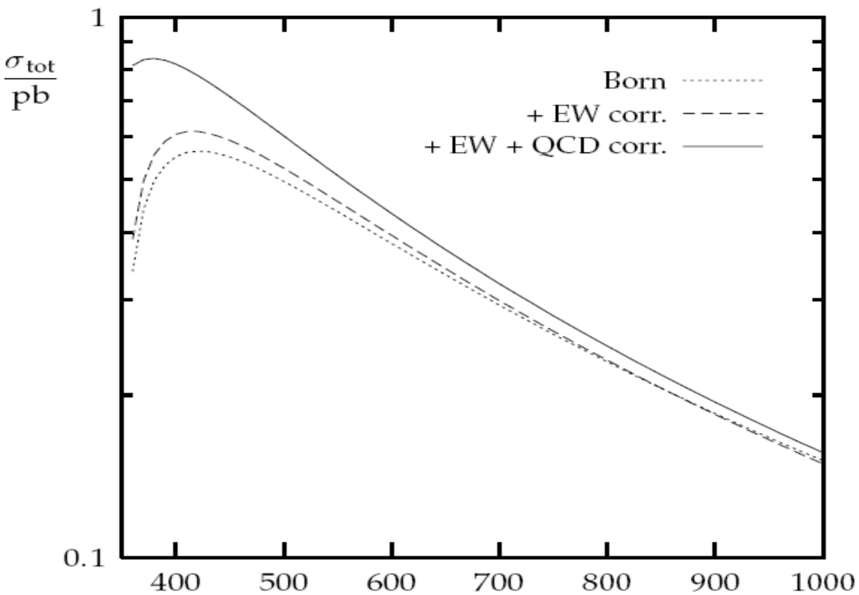
colored gauge bosons
through loops, or in ttbar+2jets (small contributions to A_{FB}), not yet studied

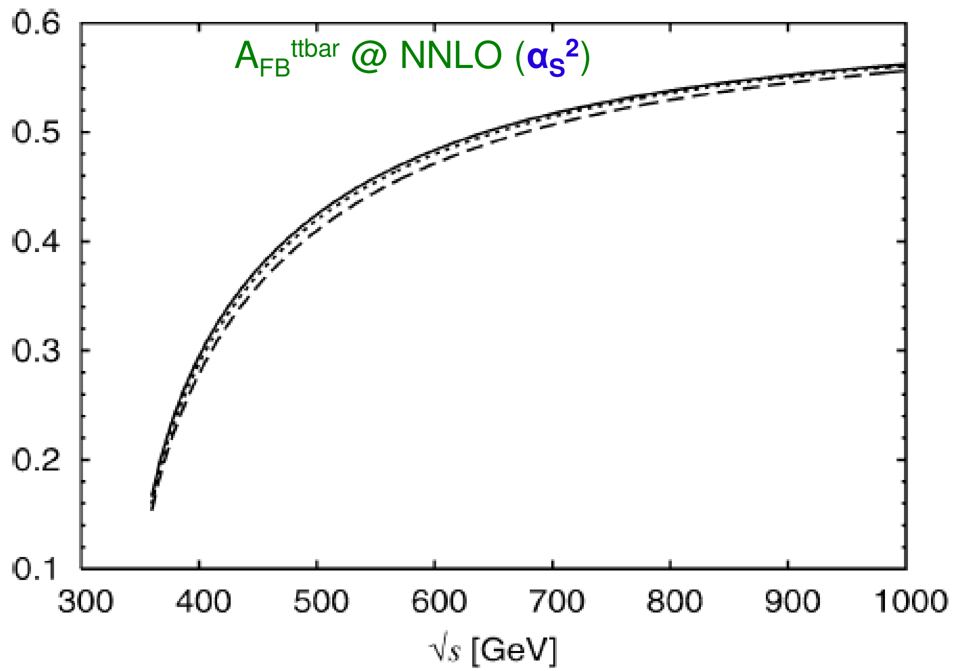
colored scalars in t-channel
spin-0 lepto-quarks, little studied for tops

Z in the s-channel, not suppressed as in hadron colliders ✔, planned for Physics Report [talk by K. Fuji]

In the t-channel: spin-1 lepto-quarks

[Bernreuther et al., 2006]





Conclusions

room for BSM within 2σ at the Tevatron from the measurement of the top quark charge asymmetry (forward-backward), early to claim new physics, but, together with $d\sigma/dM_{ttbar}$, allows to set constrains in the top quark sector

- ✔ Flavour Universal axigluons with large vector couplings
- ✔ Flavour non-Universal axigluons: sign(g_A^q)= -sign(g_A^t)
- ✔ Flavour violating scalars in the t-channel: triplet or sextet
- ✔ Flavour violating Z and W relatively light O(200 GeV)

with very positive and exciting evolution

The charge asymmetry can be measured at the LHC too, and is a good observable to discriminate among different models

If BSM colored physics is discovered at hadron colliders, the ILC will study loop-effects or multijet events, LQ are still an option

Backup

Massive gluon diff cross section

Resonances might produce
Charge asymmetry at LO

- **Quark-antiquark annihilation**

Gluon-resonance interference
generates charge asymmetry → FB
vanishes upon integration over charge symmetric regions of phase space
changes sign (s-m_G^2)
probes axial couplings

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \left(1 + c^2 + 4m^2 + \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} \left[g_V^q g_V^t (1+c^2+4m^2) + g_A^q g_A^t (2c) \right] \right.$$
$$+ \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} \left[\left((g_V^q)^2 + (g_A^q)^2 \right) \left((g_V^t)^2 (1+c^2+4m^2) + (g_A^t)^2 (1+c^2-4m^2) \right) \right.$$
$$\left. \left. + g_V^q g_A^q g_V^t g_A^t (8c) \right] \right)$$

where

resonance-resonance amplitude
generates charge asymmetry too

$$m = \frac{m_t}{\sqrt{\hat{s}}} \qquad c = \beta\cos\theta = \sqrt{1-4m^2}\cos\theta \qquad \frac{\Gamma_G}{m_G} \approx \frac{\alpha_S}{6} \sum_{i=q,t} \left(\left(g_V^i\right)^2 + \left(g_A^i\right)^2 \right)$$

gluon-gluon fusion at tree-level the same as in the SM