Resonances in the top quark sector

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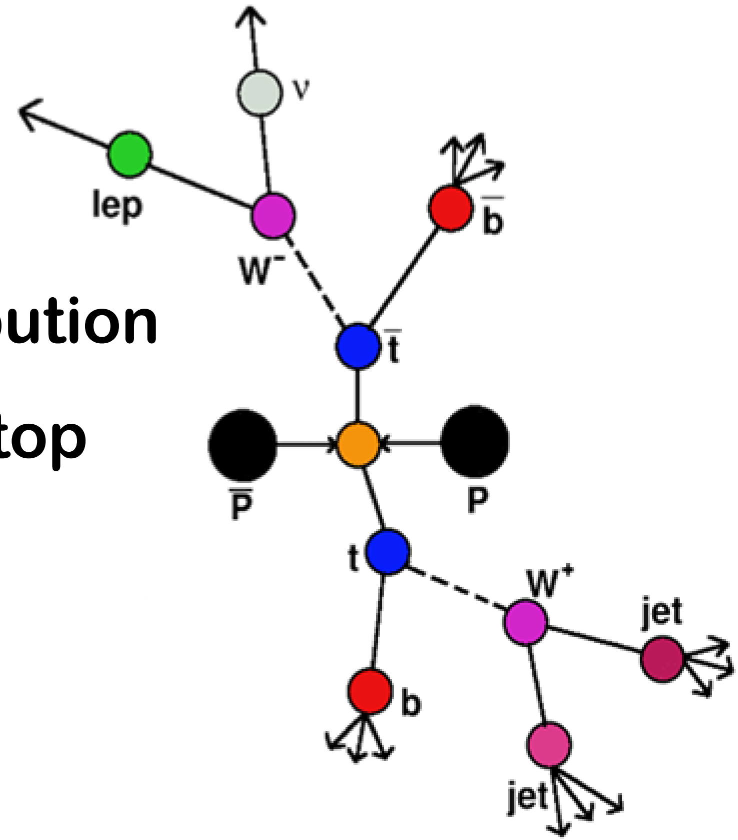
- Top quark is the heaviest known elementary particle ⇨ it plays a fundamental role in many extensions of the Standard Model (SM) / alternative mechanisms of EWSB.

- 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 will be produced even at the initial low luminosity of $L = 10^{33} cm^{-2} s^{-1}$ (equivalent to 10 fb^{-1}/year integrated luminosity)*.

- Production and decay channels are promising probes of new physics.

* 200-300 pb^{-1} @ 10 TeV by the end of 2010 ???

- **Top quark at production:**
  - ⇨ $d\sigma/M_{ttbar}$ invariant mass distribution
  - ⇨ charge asymmetry: top vs antitop
- **And decay**
  - ⇨ angular distribution of decaying lepton/s correlated with the spin of the top quark [talks by Parke, Godbole]
  - ⇨ sensitive to anomalous Wtb too [talk by Aguilar-Saavedra]



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

$$SU(3)_L \times SU(3)_R \rightarrow SU(3)_C$$

- different implementations with new particles in varying representations, 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

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**

Top color asisted technicolor (TC2)

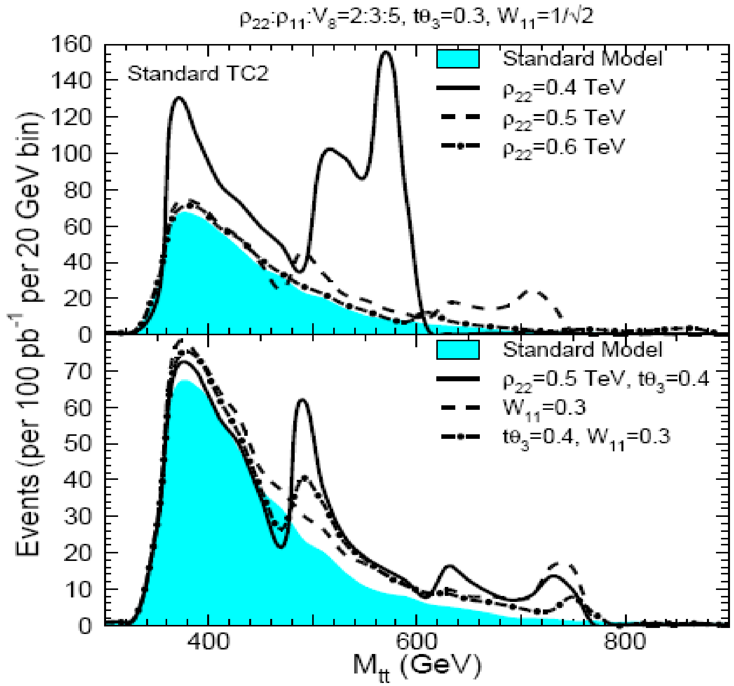
[Hill, PLB345(1995)483; Lane, Ramana, PRD 44 (1991) 2678; Lane, Mrenna, PRD67(2003) 115011]

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



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 q qbar´ and qqbar, respectively .

- The E6 GUT model also predicts the
presence of a diquark which decays to qq or qbar qbar.

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

$$\Phi_1 = (8,2,1/2) \subset 45_H$$

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

Warped extra dimensions

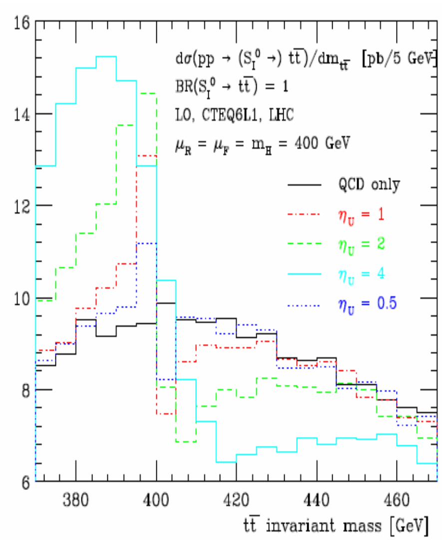
[Randall, Sundrum, PRL 83, 3370 (1999);
Dicus, McMullen, Nandi, PRD65 (2002) 076007]

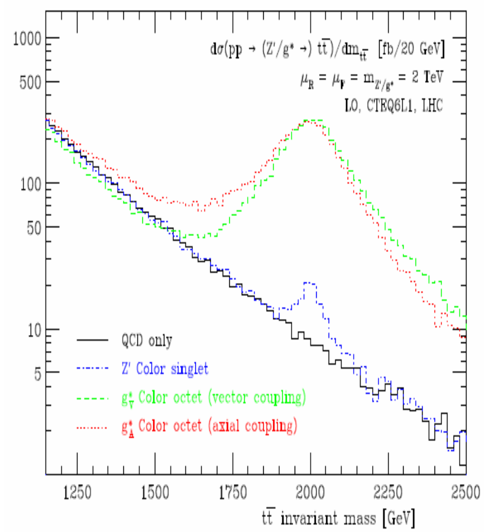
- The RS model of a warped extra dimension offers a solution for the hierarchy between the electroweak scale and Planck scale M_{Pl} by introducing an extra spacial dimension. Predicts a Kaluza-Klein tower of graviton states (RS gravitons) which decay to qqbar or gg.

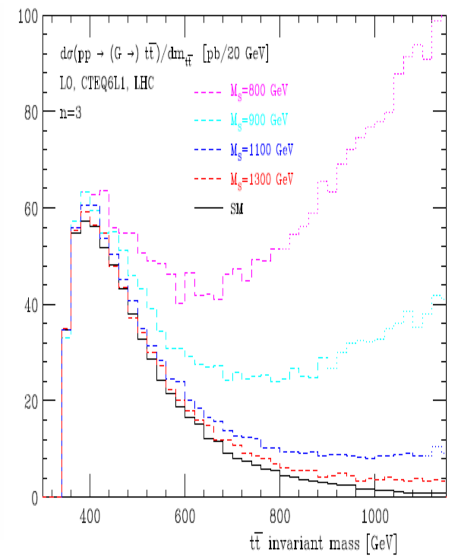
- RS Kaluza-Klein gluons: explains mass hierarchy between top and light quarks, with preferential couplings to top quarks, no couplings to gg (odd number of g*)

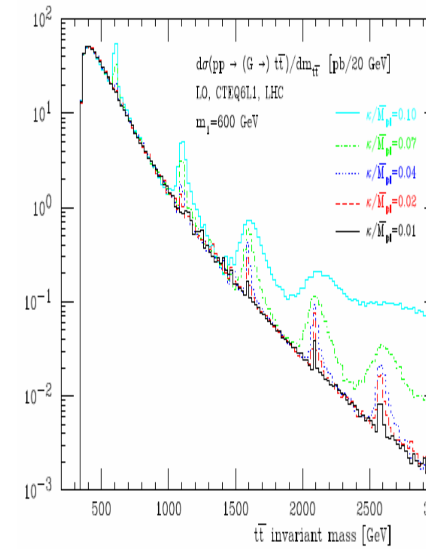
Resonances in M_{ttbar}

[Frederix, Maltoni, JHEP 0901:047,2009]





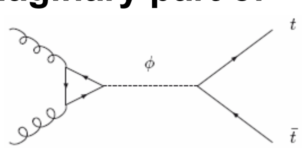




Color-singlet or color-octet (pseudo)-scalar

Coupling to quarks proportional to mass

Peak-dip due to imaginary part of



Z´ or massive gluon

Single peak

Z´ narrow:

$\Gamma_{Z'}/m_{Z'} = O(\alpha_{EW})$

Color-octet broad:

$\Gamma_G/m_G = O(\alpha_S) \approx 10\%$

Graviton (ADD)

No peak

Large number of almost degenerated KK gravitons

Huge enhancement at high M_{ttbar}

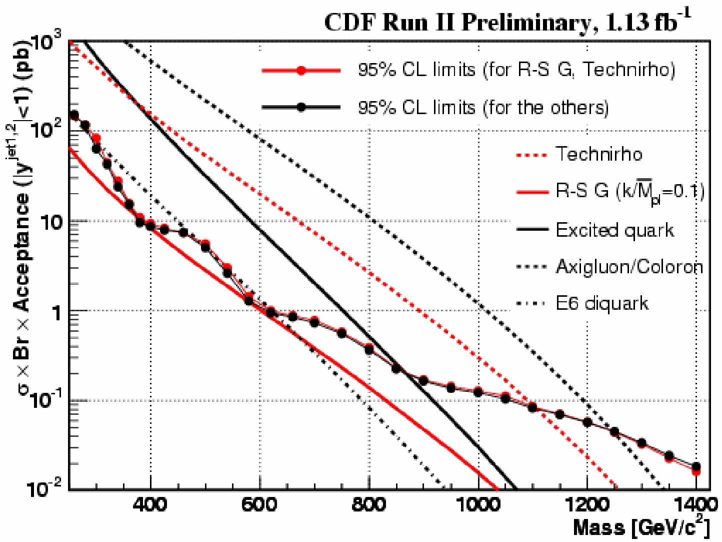
Graviton (RS)

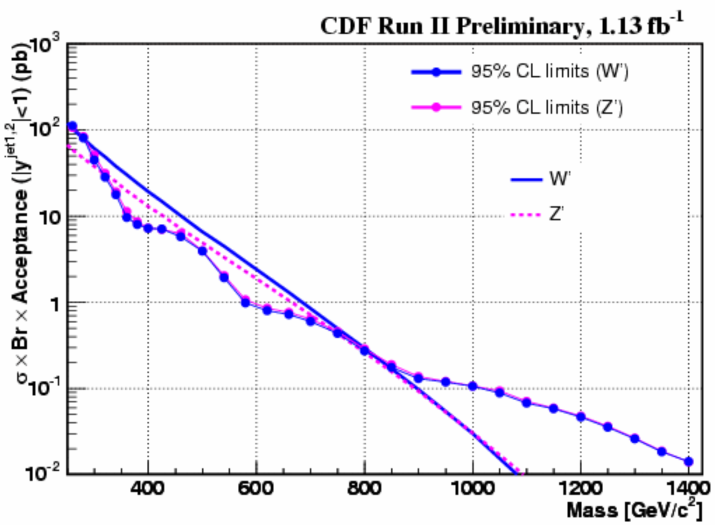
Series of peaks approx equally spaced

(tower of Kaluza-Klein states)

Dijet channel at Tevatron

CDF arXiv:0812.4036v1 [hep-ex]





Mass exclusion:

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

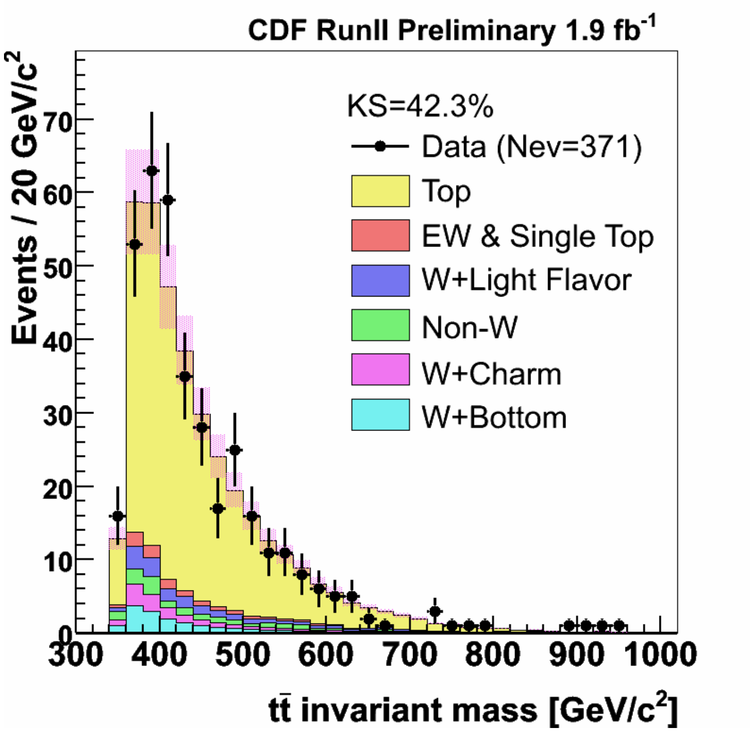
other channels

CDF

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

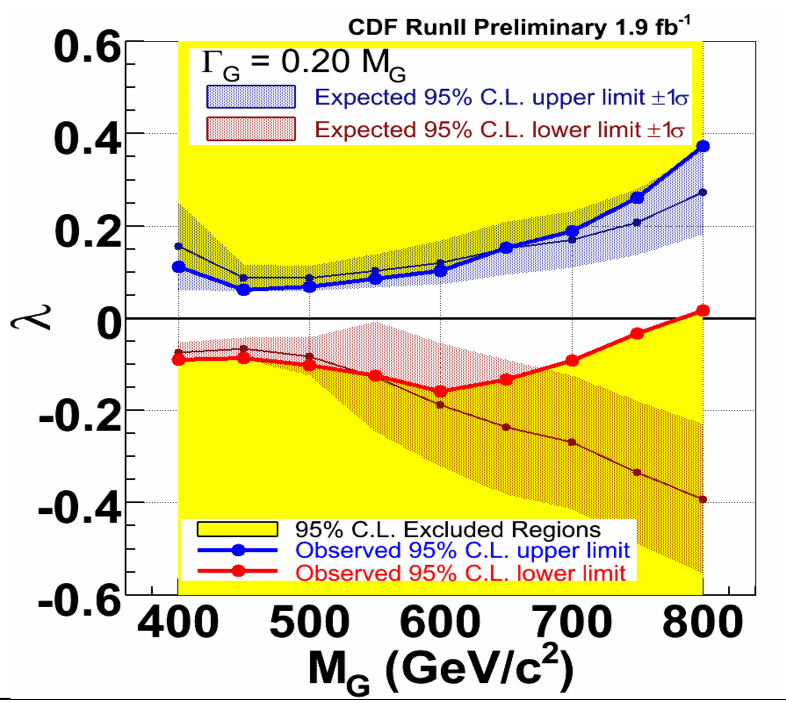
ttbar channel at Tevatron

D0	topcolor-assisted technicolor, leptophobic $m_{Z'} > 820$ GeV		$3.6\ fb^{-1}$



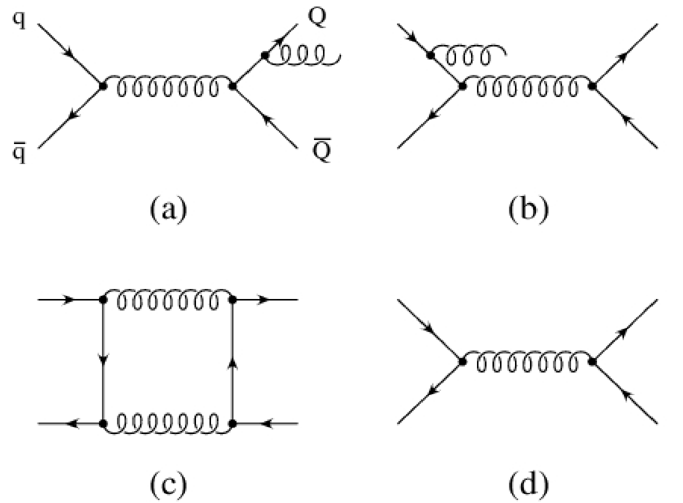
CDF: $1.9\ fb^{-1}$

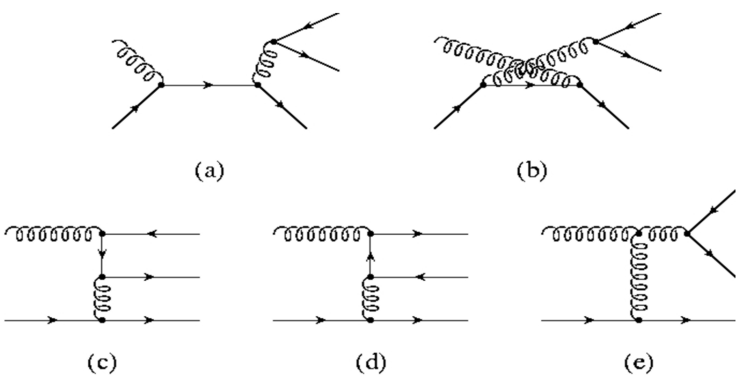
Limits on massive gluon coupling $\lambda = g_V^q\, g_V^t$ as a function of width



charge asymmetry in QCD

[Kuhn, GR, PRL81:49,1998/PRD59:054017,1999]





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

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

⇦ Flavor excitation much smaller

Massive gluon diff cross section

Resonances might produce Charge asymmetry at LO

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

- **Quark-antiquark annihilation**

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

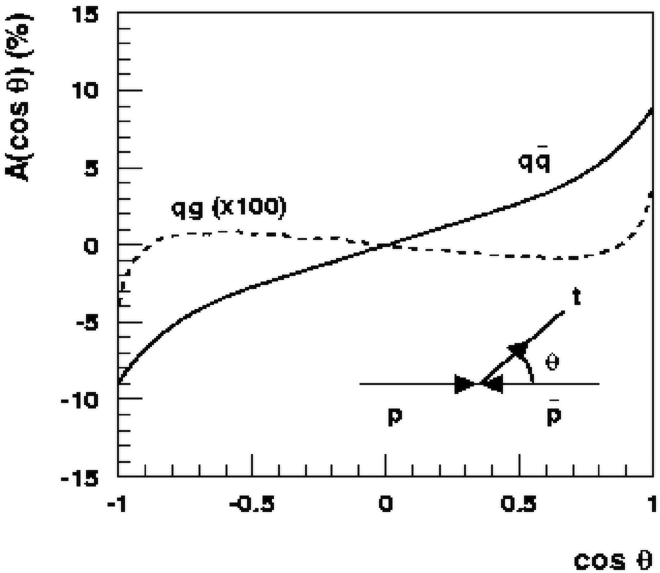
resonance-resonance amplitude
- generates charge asymmetry too

where

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

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

Inclusive asymmetry at Tevatron



[Kuhn, GR, PRL/PRD (1998), Antuñano,Kuhn, GR, PRD(2008)]

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

⇨ Forward-backward

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

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

- mixed QCD-EW interference: factor 1.09 included
- stable to threshold resummations (1 per mille)

[Almeida,Sterman,Vogelsang, PRD(2008)]

Conservative: K factor = 1.3 then A^{pp}=0.036(4) ≈ MC@NLO

$$A^{p\bar p} = 0.045(12) \qquad A^{t\bar t} = 0.070(17)$$

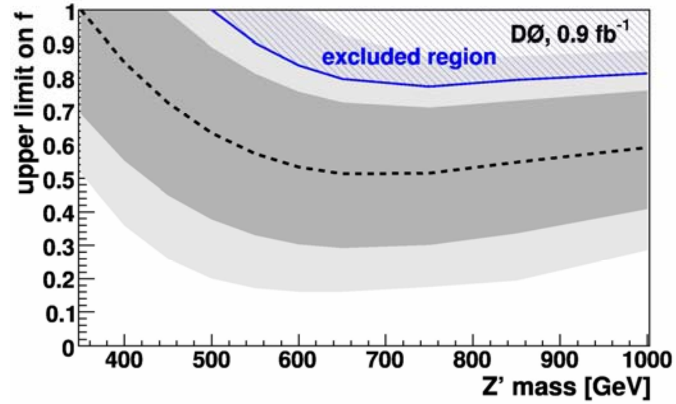
Pessimistic: asymmetry washed out in ttbar+jet @ NLO [Dittmaier, Uwer, Weinzierl, PRL(2007)]

$$A^{p\bar p}_{t\bar t + jet} = -0.07 \xrightarrow{NLO} -0.015(15) \quad ⇨ \quad A_{NLO} \approx 0.015(15) \quad ???$$

Asymmetry measurements at Tevatron

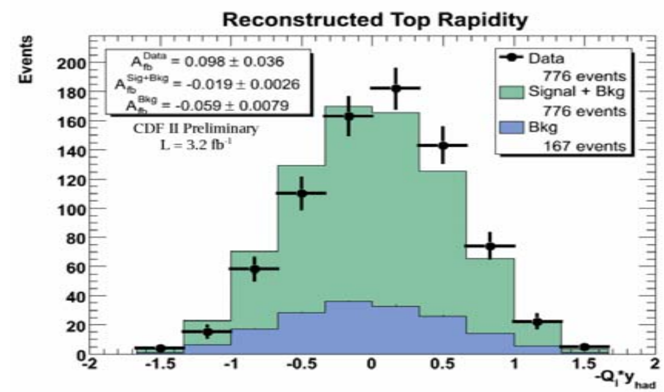
- **D0** [PRL101(2008)202001] uncorrected

  $A_{FB}^{ppbar} = 0.12 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)}$ 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]



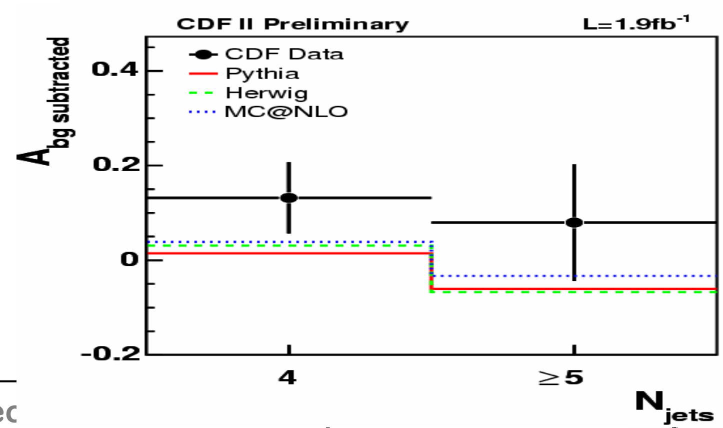
  ppbar rest frame

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

  ttbar rest frame

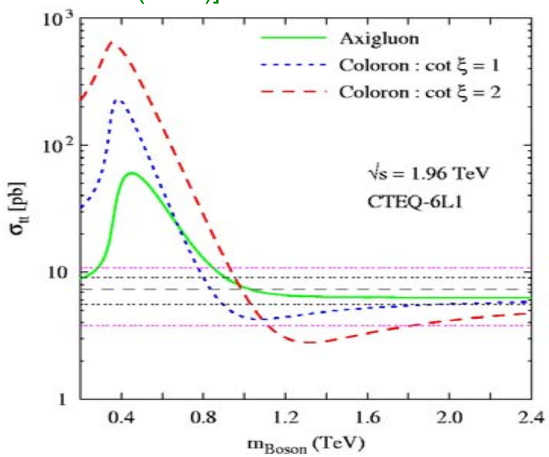
  $A_{FB}^{ttbar} = 0.24 \pm 0.13 \text{ (stat)} \pm 0.04 \text{ (syst)}$ 1.9 fb^{-1}

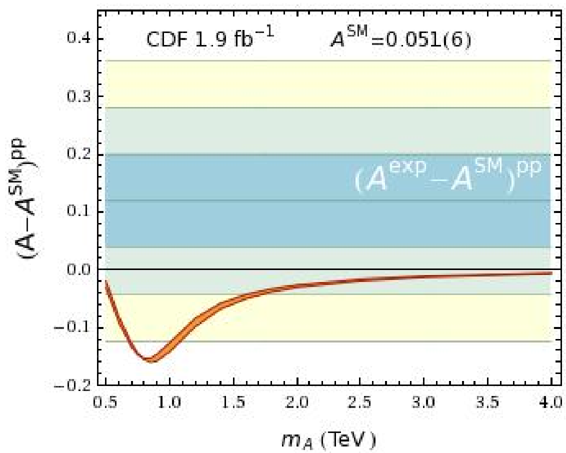
  At least 4 jets: $A_{FB}^{ttbar} = 0.119 \pm 0.064 \text{ (stat)}$
  Exact 4 jets: $A_{FB}^{ttbar} = 0.132 \pm 0.075 \text{ (stat)}$
  At least 5 jets: $A_{FB}^{ttbar} = 0.079 \pm 0.123 \text{ (stat)}$

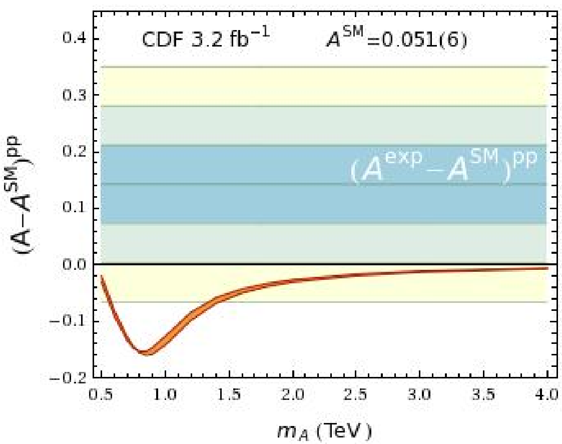


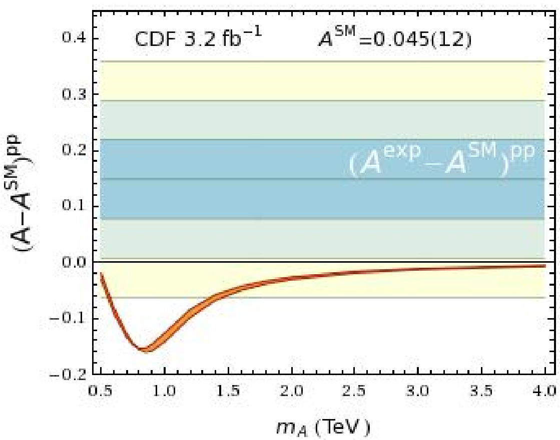
Bounds on the axigluon mass

[Choudhury,Godbole,Singh,Wagh, PLB(2007)]









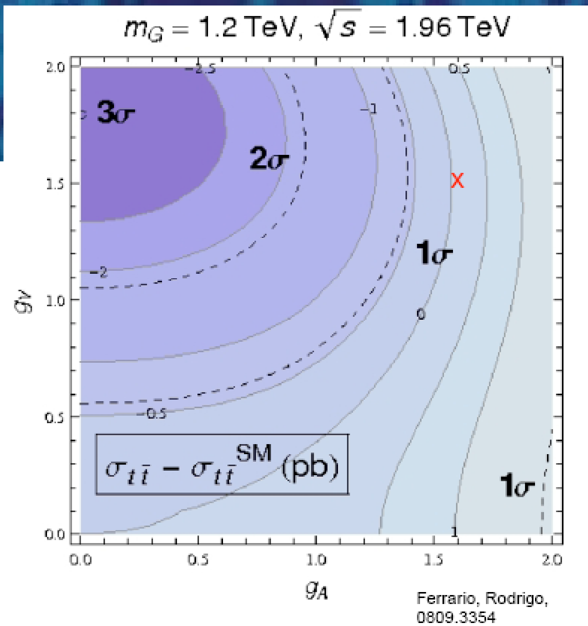
Better measurement / prediction of the top quark cross-section will not lead to a significant improvement in the bound on the axigluon mass

$$m_A > 1\text{TeV} \qquad 95\%\text{C.L.}$$

↓

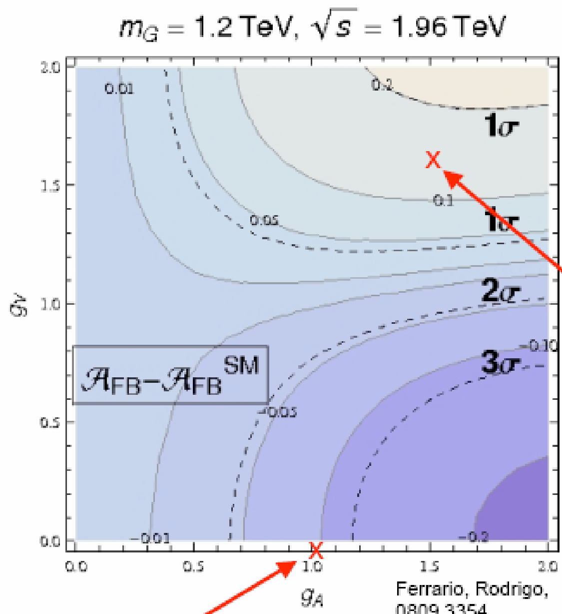
$$m_A > 1.4\text{TeV} \qquad 95\%\text{C.L.}$$

Uncertainty statistically dominated ⇨ ½ with 10 fb^{-1}



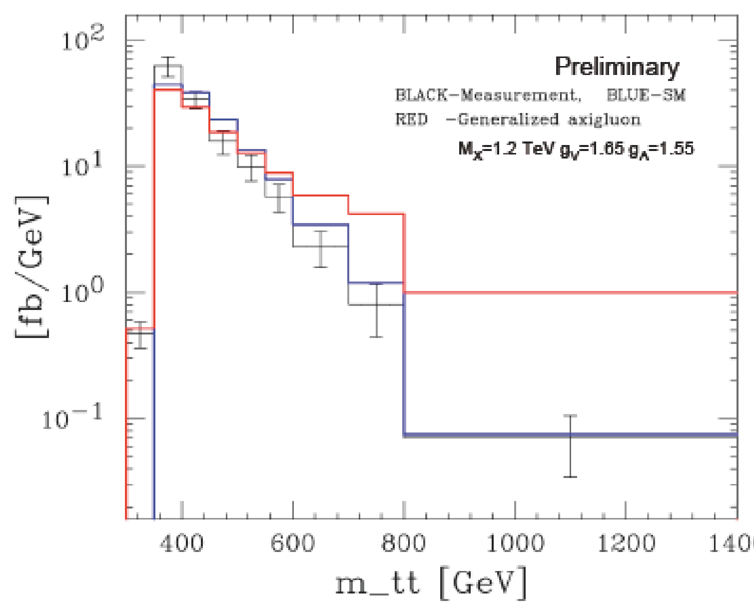
[talk by Wells]

But in conflict with $d\sigma/dM_{ttbar}$ from CDF [CDF note 9602 (Nov 2008)]



Couplings are with respect to the QCD gauge coupling.

This point looks good!



Pure axigluon coupling (large negative contribution to A_{FB})

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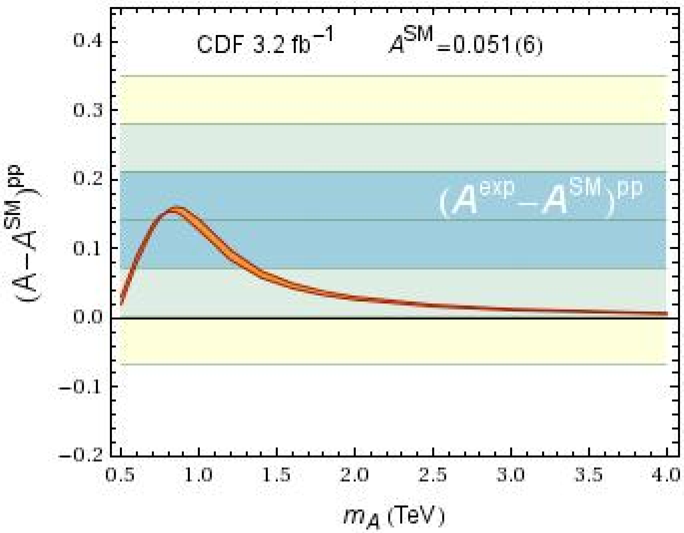
save the axigluon



CDF

$$d\sigma / dM_{t\bar{t}}(800-1400\text{GeV}) = 0.07 \pm 0.04(\text{fbGeV}^{-1})$$

The sign of the asymmetry can be changed if $g_A^q = - g_A^t$ while keeping $d\sigma/dM_{ttbar}$ small

$$\left.\frac{d\sigma}{d\sigma^{SM}} - 1\right|_{M_{t\bar{t}}>800\text{GeV}} = 3.4 \qquad M_G = 1200\text{GeV}$$

$$\left.\frac{d\sigma}{d\sigma^{SM}} - 1\right|_{M_{t\bar{t}}>800\text{GeV}} = 1.5 \qquad M_G = 1400\text{GeV}$$

Can set an upper bound on the mass

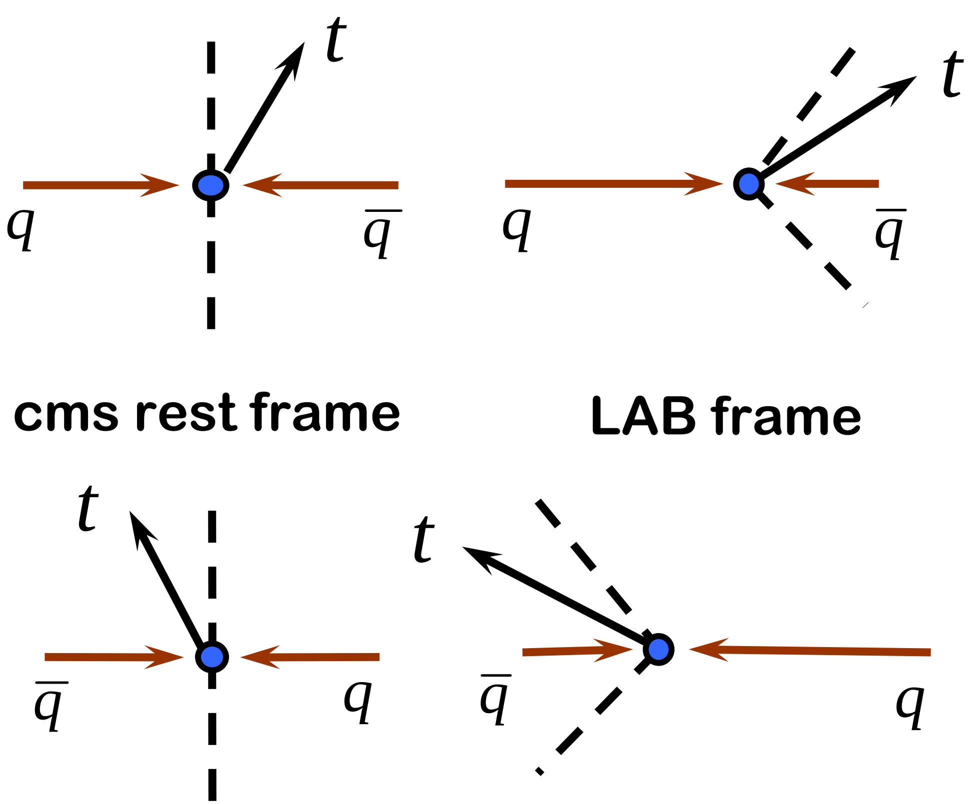
Very preliminary

Charge asymmetry at LHC

QCD predicts that tops are preferentially emitted in the direction of the incoming quark

Resonance asymmetry depending on $(s-m_G^2)$

LHC is symmetric: **but quarks carry more momenta than antiquarks**



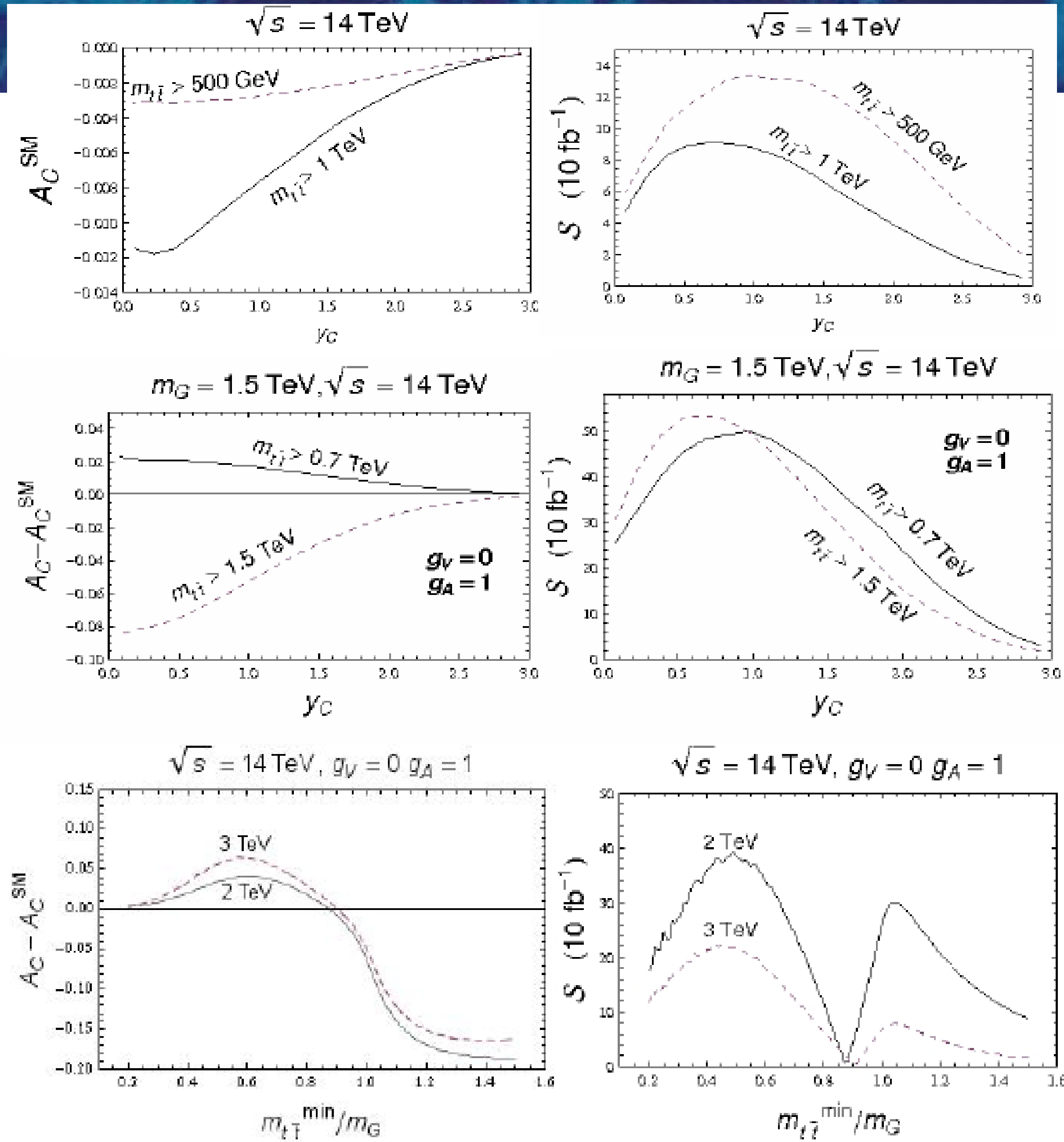
Excess of tops (or antitops) in the forward and backward regions

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

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

@ LHC

[Ferrario, GR, PRD78:094018,2008]



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

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

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

Conclusions

- $d\sigma/M_{ttbar}$ and the charge asymmetry at Tevatron and LHC complementary to discover/exclude new resonances in the top quark sector.
- Probe different combinations of vector and axial-vector couplings.
- Charge asymmetry might be more sensitive to higher masses and less boosted tops

The game is becoming very interesting: still room for improvements / further studies