Parity violation constraints on top A_{FB}

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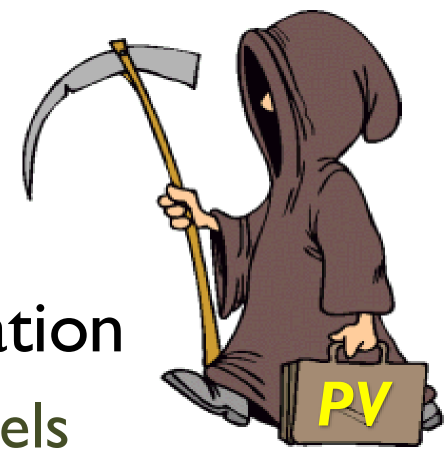
Overview

1. Top forward-backward asymmetry
   - Measured by CDF and D0 at Tevatron
   - 2–3σ disagreement with prediction from Standard Model

2. A hint for new physics in top sector?



3. Low-energy precision tests of parity violation
   - Strong constraints on many new physics models
   - Especially "collider-safe" models

A hint for new physics?

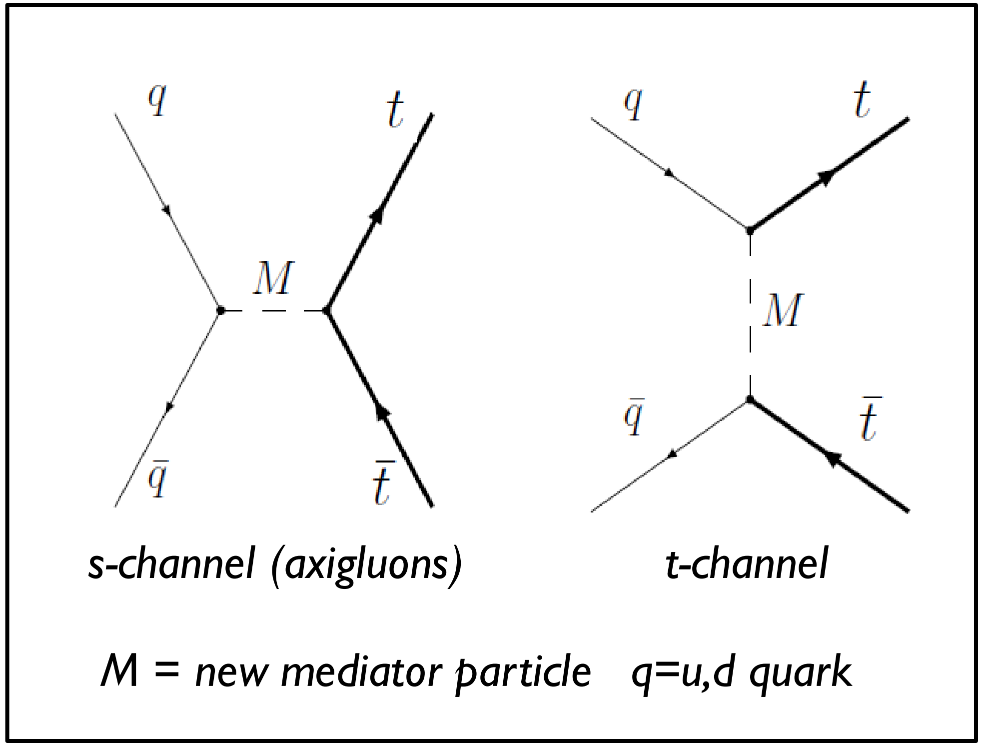
New physics models:

- s-channel models

  Sehgal, Wanninger (1988), Bagger, Schmidt, King (1988), Ferrario, Rodrigo (2009), Frampton, Shu, Wang (2009), Chivukula, Simmons, Yuan (2010), …

- t-channel models

  Jung, Murayama, Pierce, Wells (2009), Cheung, Keung, Yuan (2009), Shu, Tait, Wang (2010), …



- Other scenarios

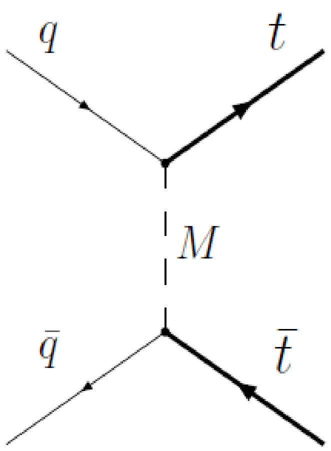
  New top-like partners (stops) *Isidori & Kemanik (2011)*

  Modification to top interactions from new physics at one-loop

  Davoudiasl, McElmurry, Soni (2011), Gabrielli & Raidal (2011)

t-channel models: brief summary

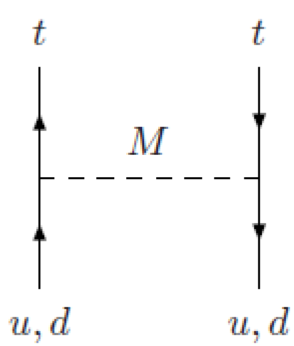
- New mediators with u-t or d-t flavor-violating coupling
  - Color singlet, weak doublet scalar
    Shu et al (2009), Blum et al (2011), Nelson et al (2011), …
  - Color triplet scalar diquark
    Dorsner et al (2009), Shu et al (2009), Ligeti et al (2011), …
  - Color sextet scalar diquark
    Shu et al (2009), Stone et al (2011), …
  - Color singlet vector Z'
    Jung et al (2009), …
  - Color singlet vector W'
    Cheung et al (2009), Barger et al (2010), Shelton & Zurek (2011), Duffty et al (2012)
  - Massive spin-2 flavor-changing "graviton" *Grinstein et al (2012)*

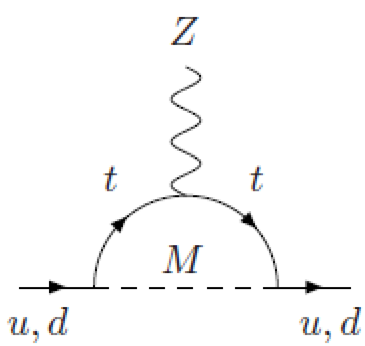


Constraints on top A_{FB}

- Direct constraints: ttbar cross section, invariant mass distribution, top spin polarization, charge asymmetry
  - Light mediators ($m_M < m_t$) are more "collider-safe" (inv. mass distr.)

- Indirect constraints: precision tests of parity violation
  - Anomalous coupling of Z boson to first generation quarks at 1-loop





New physics correction
$\sim (\lambda^2/(4\pi)^2)\,(m_t^2/m_M^2)$

  - Light mediators give $O(10^{-2})$ correction (complementary to colliders)

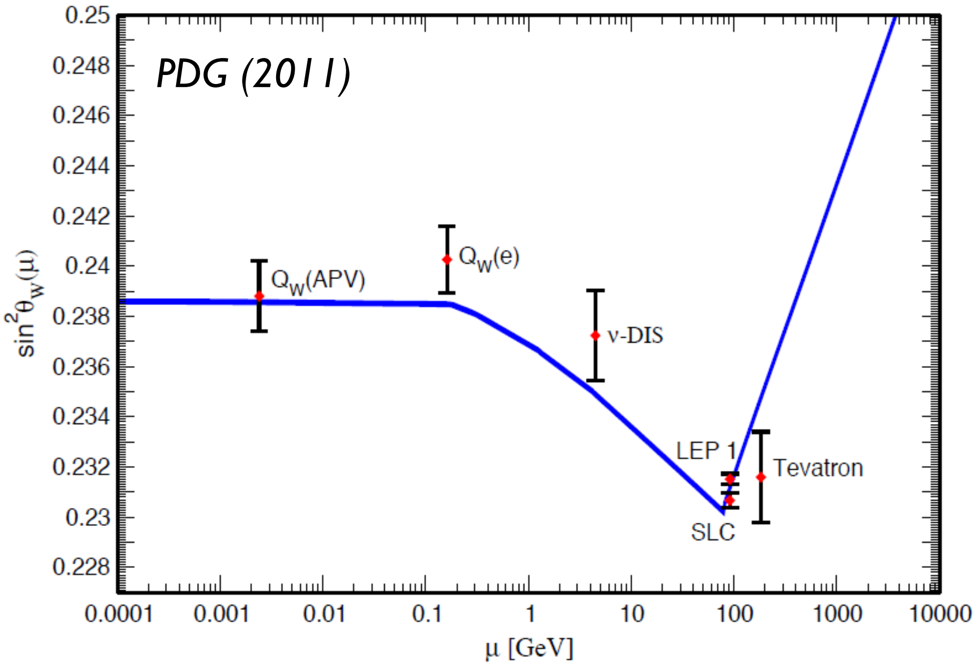
Weak nuclear charge

$$\mathscr{L}_{eq}^{PV} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left(C_{1q} \bar{e}\gamma^\mu \gamma_5 e\, \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e\, \bar{q}\gamma_\mu \gamma_5 q \right)$$

$$Q_W(Z,N) \equiv -2\left[(2Z+N)C_{1u} + (2N+Z)C_{1d}\right]$$

$$\approx -N + (1 - \sin^2\theta_W)Z$$

(+ SM radiative corrections)



Marciano, Sirlin (1983),
Erler, Ramsey-Musolf (2005)

Measurements of Q_W sensitive to:

- Running of $\sin^2\theta_W$
- New physics for fixed $\sin^2\theta_W$ extracted at Z-pole

Lepton, bottom, charm couplings to Z

Inclusive hadronic couplings diluted by $1/N_F$

Weak nuclear charge

$$\mathscr{L}_{eq}^{PV} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left(C_{1q} \bar{e}\gamma^{\mu}\gamma_5 e\, \bar{q}\gamma_{\mu} q + C_{2q} \bar{e}\gamma^{\mu} e\, \bar{q}\gamma_{\mu}\gamma_5 q \right)$$

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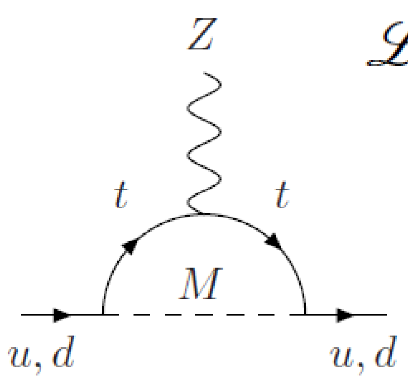
$$\approx -N + (1-\sin^2\theta_W)Z$$ (+ SM radiative corrections)

Erler, Ramsey-Musolf (2005)

New physics contribution:



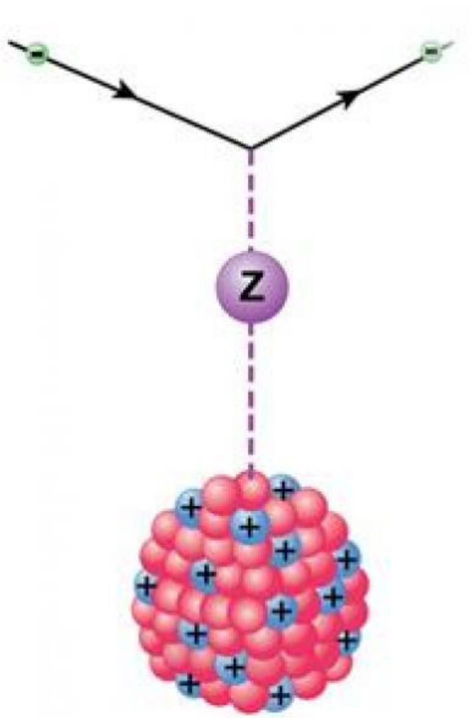
$$\mathscr{L}_{\rm eff} = -\frac{g_2}{c_W} Z^{\mu} \left(a_R^{\rm NP}(q)\, \bar{q}_R \gamma_{\mu} q_R + a_L^{\rm NP}(q)\, \bar{q}_L \gamma_{\mu} q_L \right)$$

$$C_{1q}^{\rm NP} = a_L^{\rm NP}(q) + a_R^{\rm NP}(q)$$

$$\sim \left(\lambda^2/(4\pi)^2\right)\left(m_t^2/m_M^2\right)$$

Parity violation constraints on top A_{FB}

- Atomic parity violation measurements in cesium provide strongest constraints on Q_W



Parity-violating atomic transitions due to inference between Z (due to Q_W) and γ (due to external E field)

Bouchiat and Bouchiat (1974)

Current bounds:

$$Q_W(\mathrm{Cs}) = -73.20 \pm 0.35$$ *Wood et al. (1997), Guena et al. (2005)*

$$Q_W^{\mathrm{SM}}(\mathrm{Cs}) = -73.15 \pm 0.02$$ *PDG*

Sensitive to C_{1q} at 0.3% level!

Parity violation constraints on top A_{FB}

- Proton weak charge $Q_W(p) = -4\,C_{1u} - 2\,C_{1d}$

$$Q_W^{\mathrm{SM}}(p) = 0.0713(8)$$ SM value

$$Q_W(p) = 0.054(17)$$ Current exp value *Young et al (2007)*

Polarized e-p elastic scattering data

- $Q_W(p)$ measurement at 4% level by Q-Weak experiment at JLab (in progress)

Sensitive to C_{1q} at ~0.1% level!

Parity violation constraints on top $A_{\rm FB}$

- Neutrino deep inelastic scattering

$$\mathscr{L}_{\nu q}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \bar{\nu}\gamma^{\mu}(1-\gamma_5)\nu$$
$$\times \left(\epsilon_L(q)\,\bar{q}\gamma_{\mu}(1-\gamma_5)q + \epsilon_R(q)\,\bar{q}\gamma_{\mu}(1+\gamma_5)q\right)$$

New physics contribution: $\epsilon_{L,R}^{\rm NP}(q) = -a_{L,R}^{\rm NP}(q)$

Measured values (PDG)

$$g_L^2 \equiv \sum_q \epsilon_L^2(q) = 0.3025(14)$$
$$g_R^2 \equiv \sum_q \epsilon_R^2(q) = 0.0309(10)$$

SM prediction

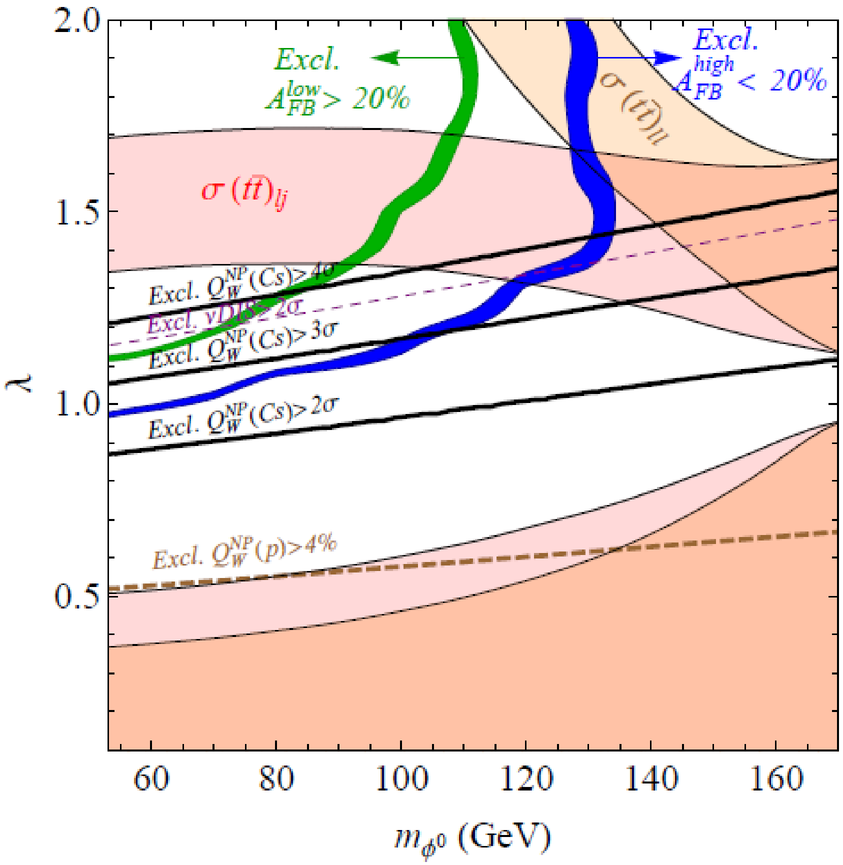
$$(g_L^2)_{\rm SM} = 0.30499(17)$$
$$(g_R^2)_{\rm SM} = 0.03001(2)$$

Weak scalar doublet model

Interaction: $\lambda\,(\bar{u}_R V_{ib} u_L^i \phi^0 - \bar{u}_R b_L \phi^+) + \text{h.c.}$

Blum, Hochberg, Nir (2011), Hochberg, Nir (2011)

Provides good fit for A_{FB} for $m_{\phi 0} < 130$ GeV



Collider constraints:

A_{FB} (parton level, NP only):

$$A_{FB}^{\text{high}} > 20\%\,, \quad A_{FB}^{\text{low}} < 20\%$$

Total cross section:

$$\sigma(t\bar{t})_{\ell j}/\sigma(t\bar{t})_{\ell j}^{\text{SM}}\big|_{\text{LO}} = 1 \pm 30\%$$

$$\sigma(t\bar{t})_{\ell\ell}/\sigma(t\bar{t})_{\ell\ell}^{\text{SM}}\big|_{\text{LO}} = 1 \pm 30\%$$

Parity violation at one-loop:

$$a_R^{\text{NP}}(u) = \frac{\lambda^2 |V_{tb}|^2 m_t^2}{32\pi^2\, m_M^2} F(m_t^2/m_M^2)$$

Ruled out by atomic parity violation at $>4\sigma$

Color singlet vector model

Horizontal $SU(2)_X$ symmetry acting on $(u,t)_R$. *Jung, Pierce, Wells (2011).*

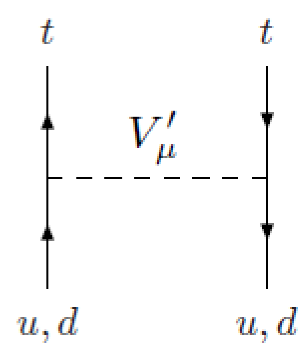
$$\mathscr{L} = \frac{g_X}{\sqrt{2}} V'_\mu [\bar{u}_R \gamma^\mu t_R + \varepsilon(\bar{u}_R \gamma^\mu u_R - t_R \gamma^\mu t_R)] + \text{h.c.}$$

Flavor-changing *V'* (like W boson)

$$+ \frac{g_X}{2} Z'_\mu [\bar{t}_R \gamma^\mu t_R - \bar{u}_R \gamma^\mu u_R + 2\varepsilon(\bar{u}_R \gamma^\mu t_R + \bar{t}_R \gamma^\mu u_R)]$$

Flavor-diagonal *Z'* (like Z boson)

A_{FB} from V'



To avoid large anomalous contribution to ttbar invariant mass distribution:

- *Light $m_{V'}$ ($m_{V'} < m_t$)*
- *Flavor-diagonal V' coupling ε*

V' → jet jet , not V' → t + jet

What about Z'?

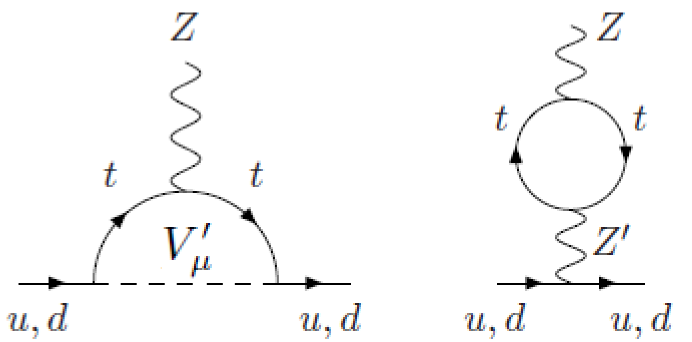
Intermediate mass Z' (130 GeV < $m_{Z'}$ < TeV) ruled out by dijet bounds

Heavy mass Z' is not pretty: requires O(100)-dimensional $SU(2)_X$-breaking Higgs rep to have TeV-scale splitting with V'

Low mass Z'? Hides under large QCD background

Color singlet vector model

Parity violation at one-loop:



Massive vector theories are nonrenormalizable unless we embed them within a consistent gauge theory

Naïve estimate: regulate divergences with fixed cut-off Λ

$$a_R^{\rm NP}(u) = -\frac{\lambda^2}{16\pi^2}\frac{m_t^2}{m_{V'}^2}\left(F\left(\frac{m_t^2}{m_{V'}^2}\right) + \frac{1}{4}\log\left(\frac{\Lambda^2}{m_t^2}\right)\right) + \frac{N_C\lambda^2}{32\pi^2}\frac{m_t^2}{m_{Z'}^2}\log\left(\frac{\Lambda^2}{m_t^2}\right), \quad g_X \equiv \sqrt{2}\lambda$$

Color singlet vector model

Specify UV completion for SU(2)$_X$ model.

1) *Introduce vector quark* $t' \sim (3, 1, 2/3)$
2) *Yukawa interactions* $\mathscr{L} = y_1(\bar{u}_R, \bar{t}_R)t'_L S - y_2 \bar{t}'_R (t_L, b_L)\epsilon H + \text{h.c.}$

   to generate top mass $m_t = y_1 y_2 v_S v / m_{t'}$
3) *Introduce SU(2)$_X$-breaking via doublet S and triplet Σ*

   $\langle S \rangle = (0, v_S) \qquad \langle \Sigma \rangle = v_\Sigma(-2\varepsilon, 0, 1)/\sqrt{2}$
4) *Gauge boson masses*

$$m_{V'}^2 = g_X^2(v_S^2 + v_\Sigma^2)/2 \text{ and } m_{Z'}^2 = g_X^2 v_S^2/2$$

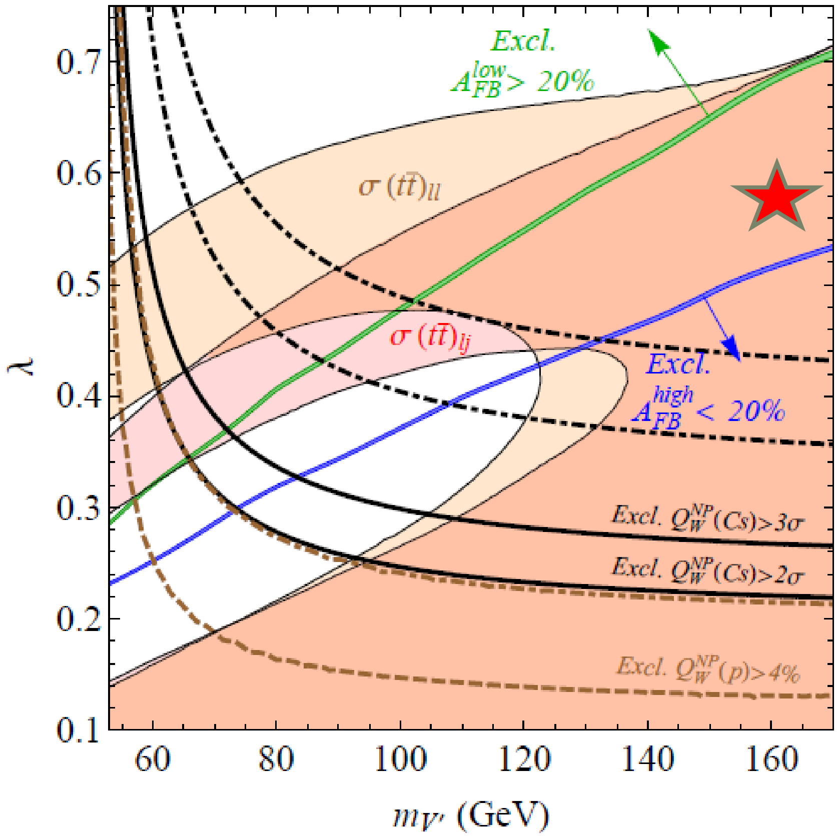
Loop calculation:

$$a_R^{\rm NP}(u) = -\frac{\lambda^2}{16\pi^2}\frac{m_t^2}{m_{V'}^2}F_1\left(\frac{m_t^2}{m_{V'}^2}, \frac{m_{t'}^2}{m_{V'}^2}\right) + \frac{N_C\lambda^2}{32\pi^2}\frac{m_t^2}{m_{Z'}^2}F_2\left(\frac{m_t^2}{m_{t'}^2}\right),$$

$$F_1(x,y) \equiv -\frac{1}{4}\Big(2 + \frac{2-x-y}{(1-x)(1-y)} + \frac{(x^2-2x+4)\log x}{(1-x)^2} + \frac{(2x^2-8x)\log x}{(1-x)(x-y)} + \frac{(y^2-2y+4)\log y}{(1-y)^2} + \frac{(2y^2-8y)\log y}{(1-y)(y-x)}\Big) \quad (14a)$$

$$F_2(x) \equiv \frac{2(x-1)-(1+x)\log x}{1-x}. \quad (14b)$$

Color singlet vector model



"Best model point" of Jung, Pierce, Wells

"Complete" calculation

"Naïve" calculation

Parity violation constraints are model-dependent, but still they are very strong

Fixed $m_{Z'}$ = 120 GeV

$\Lambda = m_{t'}$ = 600 GeV (Constraints stronger for higher mass)

Conclusions

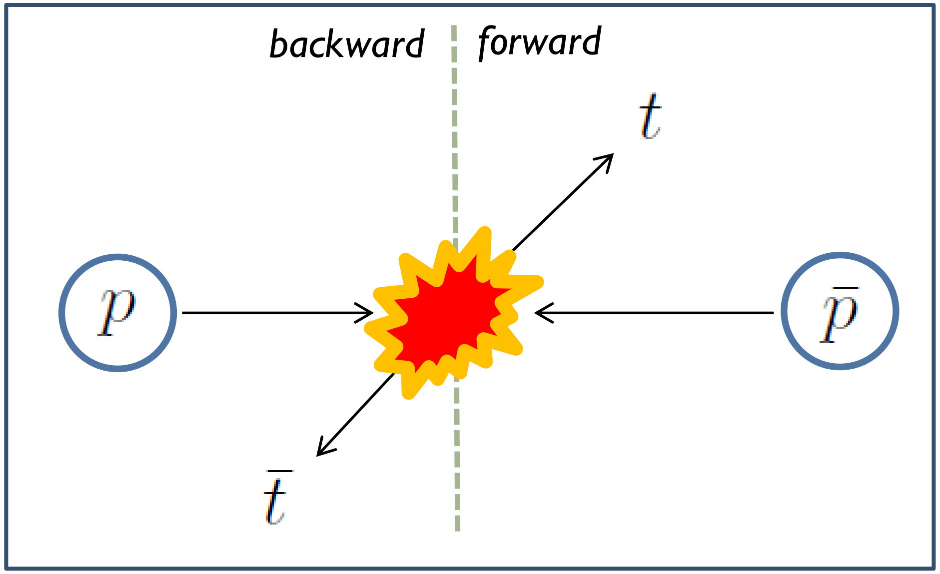
- Possible new physics in top A_{FB} must satisfy constraints from colliders *and* low-energy precision tests

- t-channel models contribute to nuclear weak charge
  - Atomic parity violation (cesium)
  - Neutrino DIS
  - Proton weak charge
    - Qweak experiment: conclude data taking May 2012

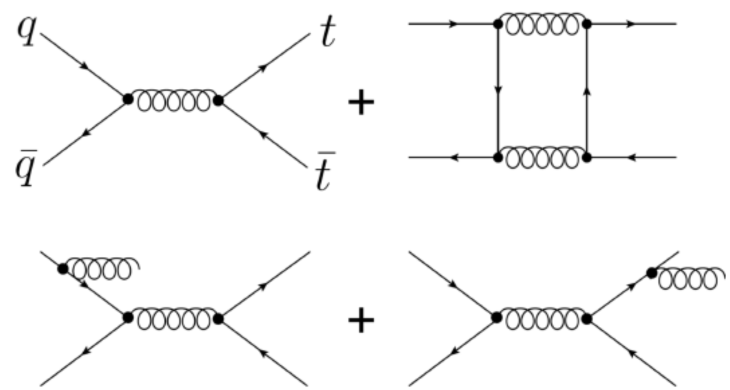
- Simplified models:
  - Light color-singlet, weak doublet scalar disfavored
  - Light Z' [horizontal $SU(2)_X$] disfavored
  - Color triplet scalar diquark disfavored
  - Strong constaints on W' and color sextet scalar also

Backup slides

Top forward-backward asymmetry



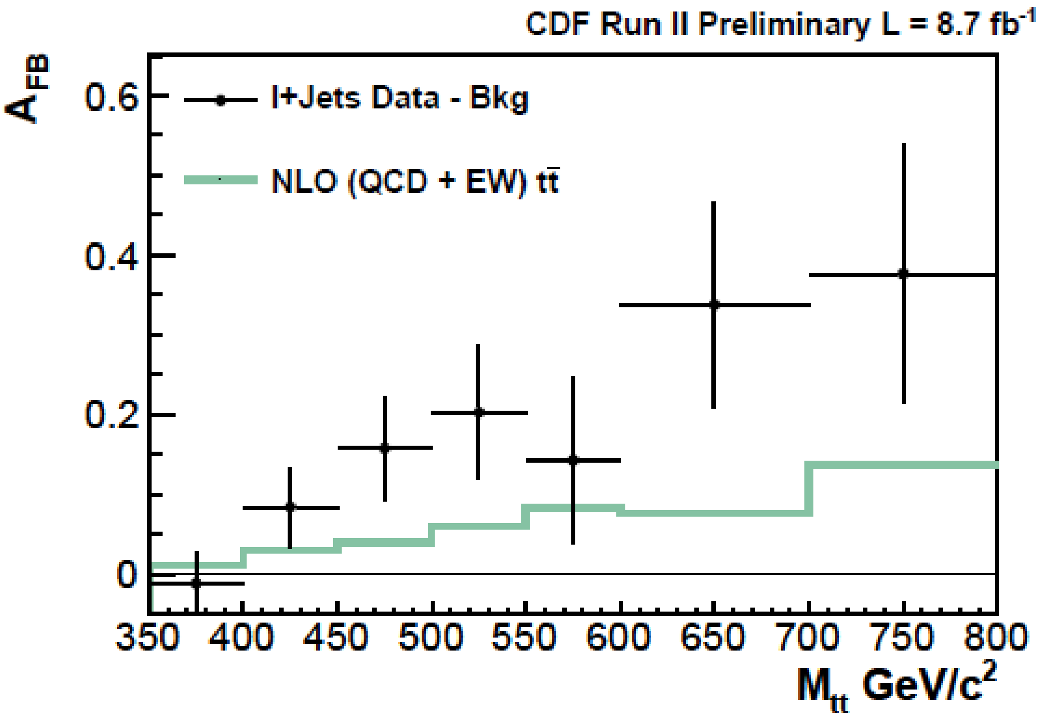
Generated by QCD in Standard Model:



Kuhn & Rodrigo (1998)

$$A_{FB} = \frac{\text{number of forward tops} - \text{backward tops}}{\text{number of forward tops} + \text{backward tops}}$$

Top forward-backward asymmetry



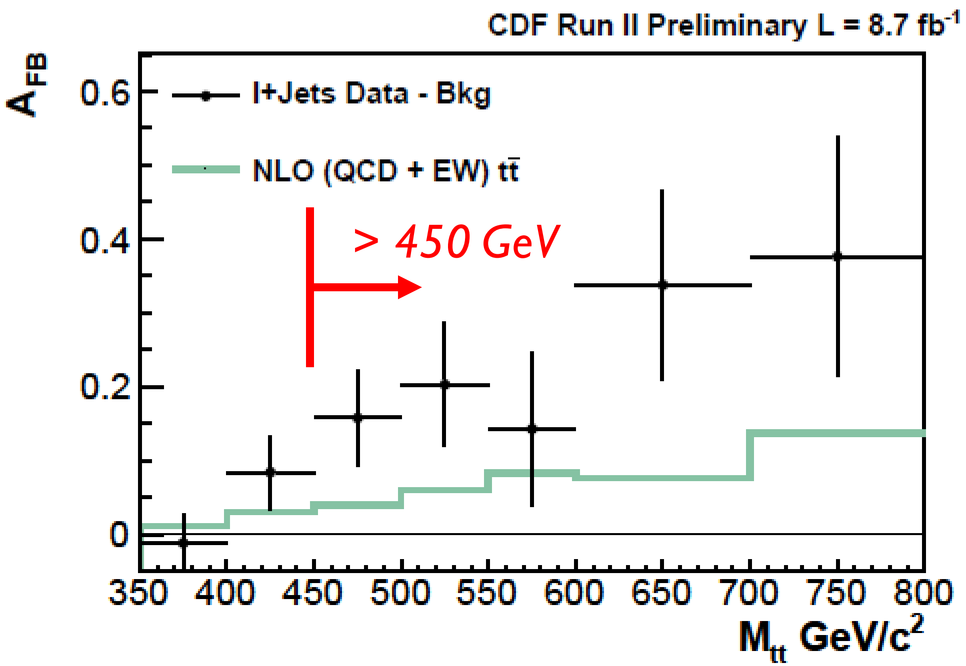
Recent CDF result

Lepton + ≥4 jets (semileptonic)

Parton-level A_{FB} ("unfolded") – accounts for detector resolution & acceptances

t-tbar rest frame (top momenta reconstructed from 4 leading jets)

Top forward-backward asymmetry



Most significant deviation for high invariant mass (> 450 GeV)

No large deviation for low invariant mass

Parton Level $M_{t\bar{t}}$	NLO (QCD+EW) $t\bar{t}$ A_{FB}	5.3 fb^{-1} A_{FB} ($\pm$[stat.+syst.])	8.7 fb^{-1} A_{FB} ($\pm$[stat.+syst.])
$< 450 \mathrm{GeV}/c^2$	0.047	-0.116 $\pm$ 0.153	0.078 $\pm$ 0.054
$\geq 450 \mathrm{GeV}/c^2$	0.100	0.475 $\pm$ 0.112	0.296 $\pm$ 0.067

Top forward-backward asymmetry

Consistent with D0 5.4 fb^{-1}

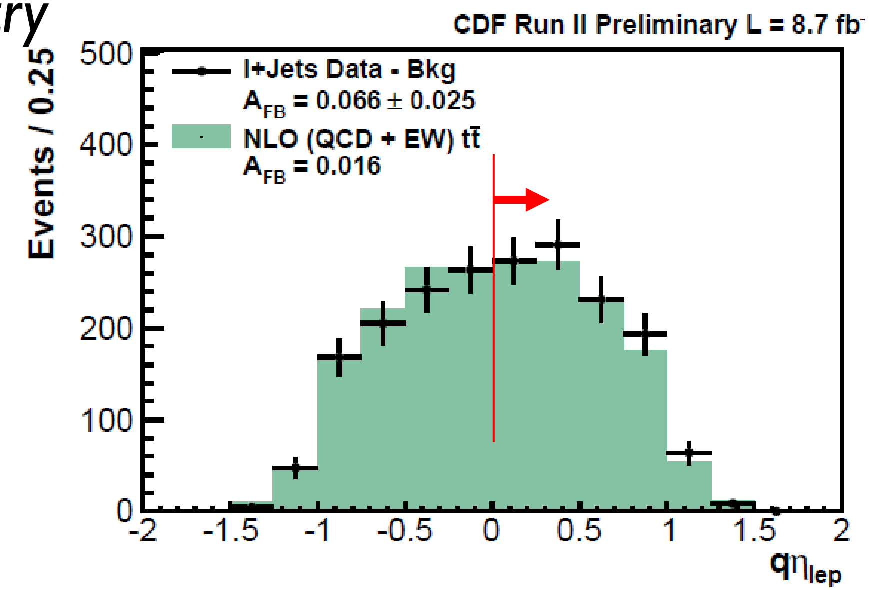
Subsample	A_{FB} (%) Data	MC@NLO
$m_{t\bar{t}} < 450$ GeV	7.8 ± 4.8	1.3 ± 0.6
$m_{t\bar{t}} > 450$ GeV	11.5 ± 6.0	4.3 ± 1.3

Data-level (not unfolded) *QCD*

Confirmed in lepton charge asymmetry

More forward-going e^+,μ^+ and backward-going e^-,μ^-

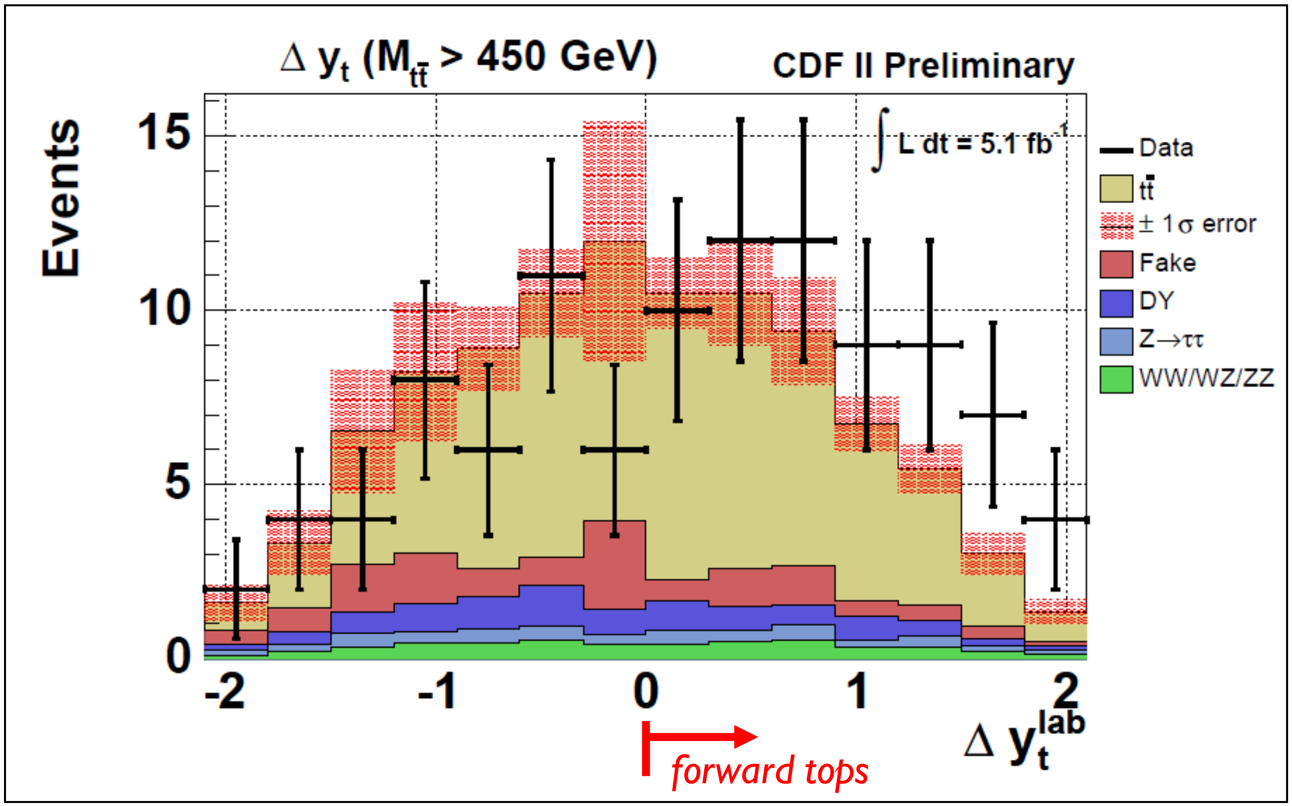
$M_{t\bar{t}}$	Data A_{FB} ($\pm$ [stat.+syst.])	NLO (QCD+EW) $t\bar{t}$ A_{FB}
Inclusive	0.066 ± 0.025	0.016
$< 450\mathrm{GeV}/c^2$	0.037 ± 0.031	0.007
$\geq 450\mathrm{GeV}/c^2$	0.116 ± 0.042	0.032



Top forward-backward asymmetry

Confirmed in dilepton channels

CDF 5.1 fb-1 (Conf. Note 10436)

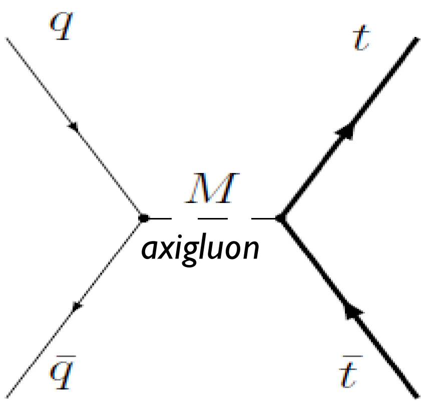


Rapidity difference between top and antitop

Axigluon models: brief summary

Axigluon mass: 50 GeV – few TeV

Frampton et al (2009), Chivukula et al (2010), Bauer et al (2010), Cao et al (2010), Bai et al (2011), Wang et al (2011), Zerwakh et al (2011), Barcelo et al (2011), Alvarez et al (2011), Tavarez et al (2011), Gresham et al (2011), Aguilar-Saavedra et al (2011), Krnjaic (2011), …



Phenomenological issues:

Dijet bounds, ttbar invariant mass distribution, flavor constraints, searches for additional light colored states, EW precision tests, ….

Still OK but not pretty

t-channel models

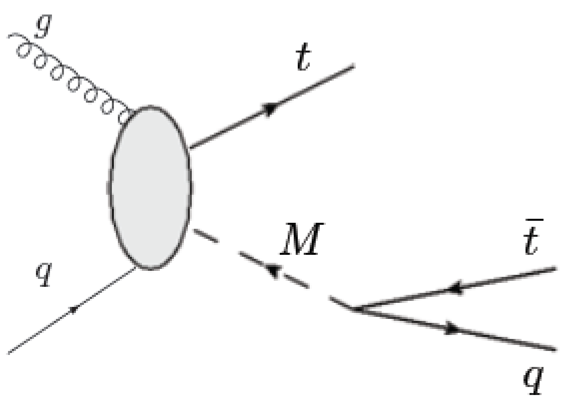
- Phenomenological issues:
  - Direct constraints: ttbar cross section, invariant mass distribution, top spin polarization, charge asymmetry
  - Indirect constraints: **precision tests of parity violation**

Gresham, Kim, Zurek, ST (2012)

- Two general classes:
  - Light mediators ($m_M < m_t$)
    - Color-singlet, weak doublet scalar (additional Higgs)
    - Flavor-changing vector (Z', W')
  - Heavy mediators ($m_t < m_M$)
    - Flavor-changing vector (Z' , W')
    - Scalar diquarks

t-channel models: brief summary

- What does the LHC have to say?
  - Heavy meditors (m_M > m_t) contribute to $t\bar{t}$ production



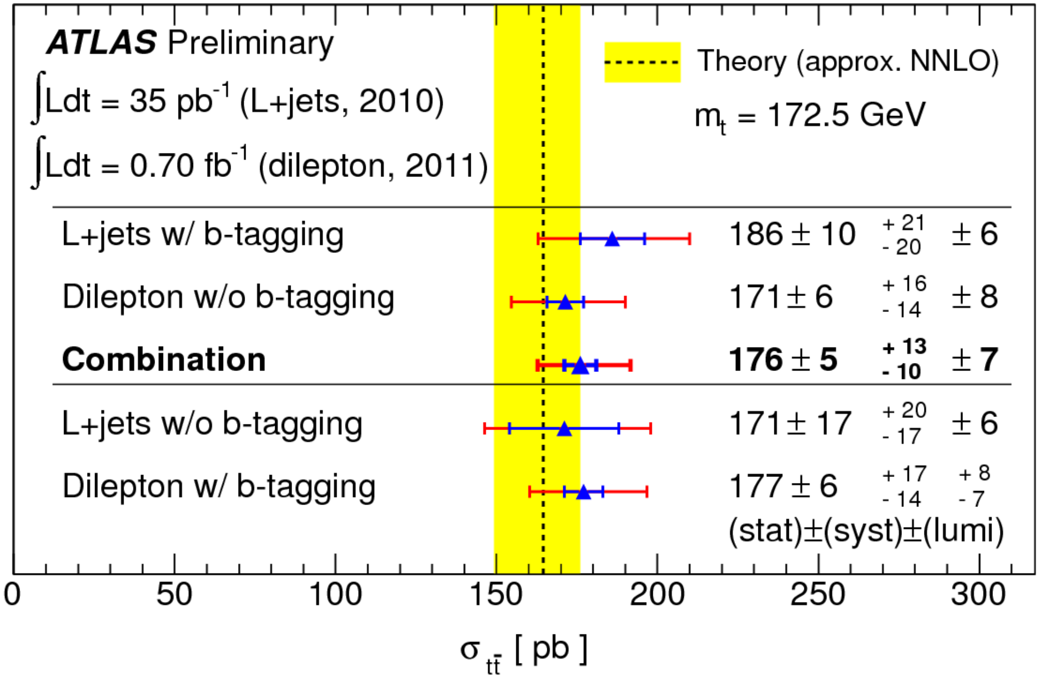
On-shell mediator decays to t+jet

Affects total cross section, invariant mass distribution, number of associated jets

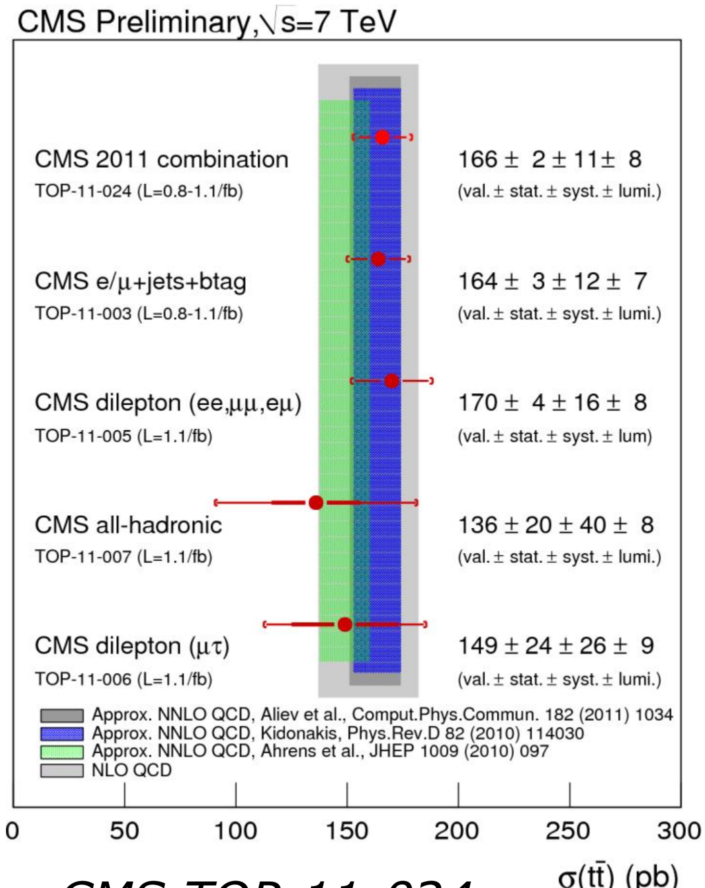
LHC results at ~ 1 fb^{-1} see no hint for new physics in top

t-channel models for top A_{FB}

- $t\bar{t}$ production cross section at LHC



ATLAS CONF 2011-108

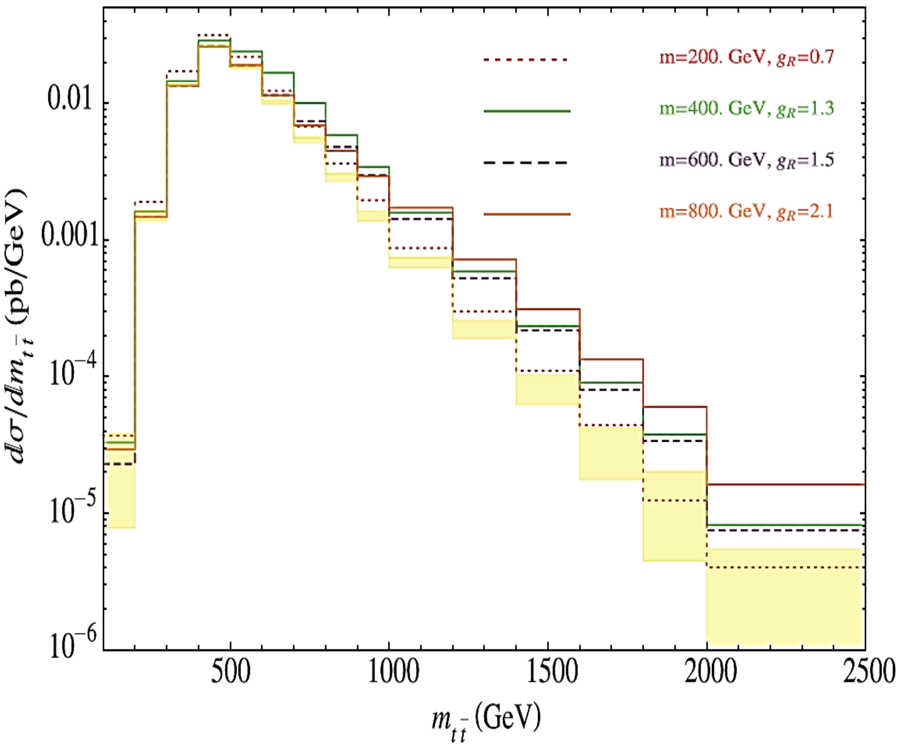


CMS TOP-11-024

t-channel models for top A_{FB}

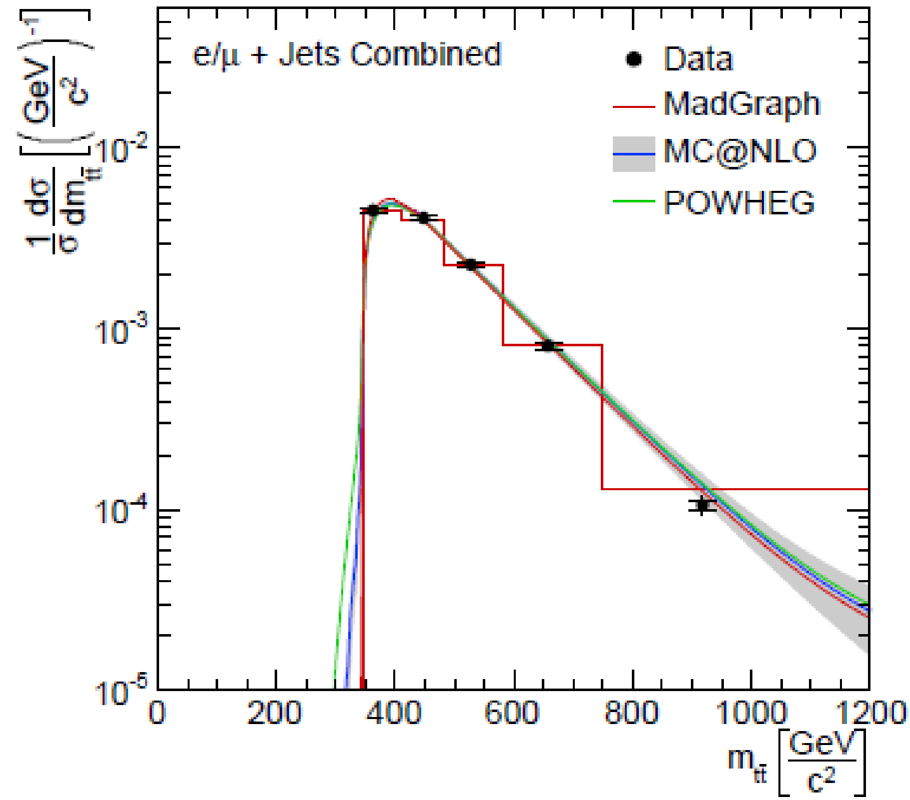
- Example: new vector V' with interaction $\lambda\, \bar{t}_R \gamma^\mu u_R V'_\mu + \text{h.c.}$

Invariant mass distribution (LO)



Gresham, Kim, Zurek (2011)

CMS Preliminary, 1.14 fb^{-1} at $\sqrt{s}$=7 TeV



CMS PAS TOP-11-013

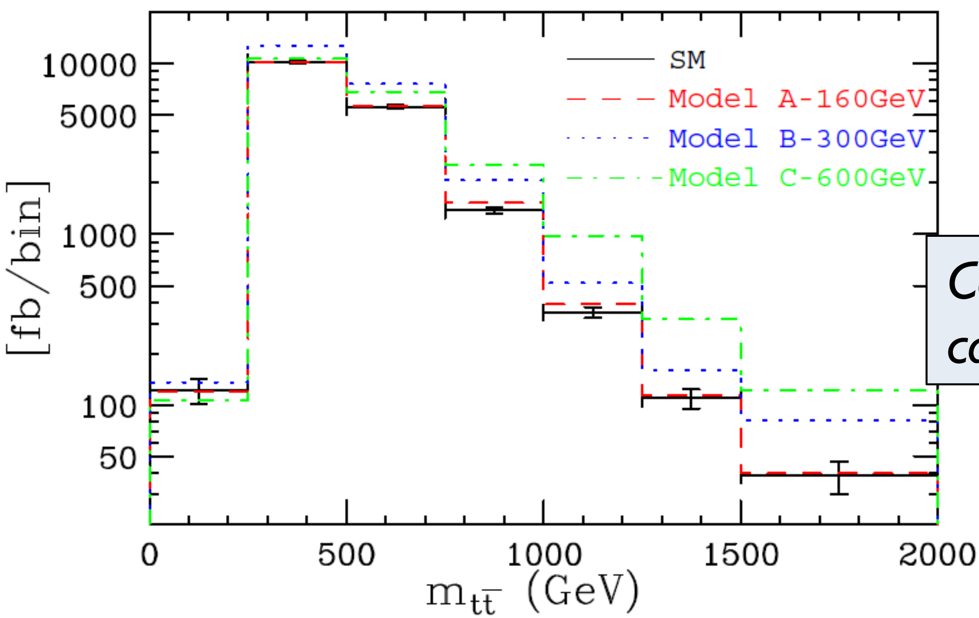
t-channel models for top A_{FB}

Light meditors ($m_M < m_t$) can evade LHC constraints!

Assume M has (small) flavor-diagonal coupling to light quarks

M → jet + jet dominates over M → t* + jet

No contribution to $t\bar{t}$ + *jet* production



Vector V' model

Jung, Pierce, Wells (2011)

Conclusion: Light t-channel mediators can be hidden from collider constraints