

TOP 2012

# New Physics in Top (Pair) Production

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20/09/2012, Winchester

# Outline

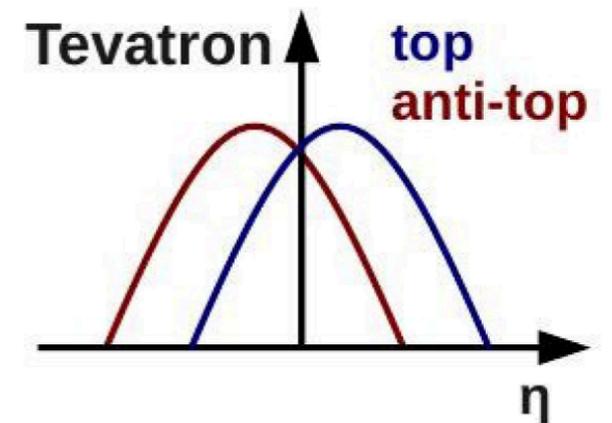
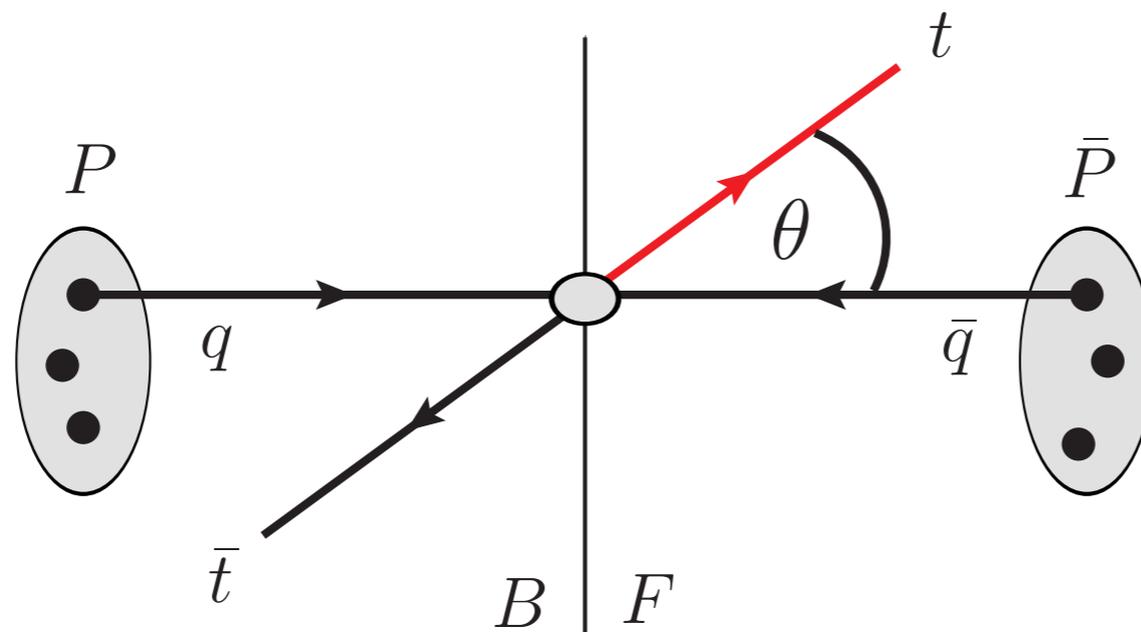
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- Persistent hints of anomalous FBA in  $t\bar{t}$  production at Tevatron
  - NP proposals (phenomenological approach)
- Impact of existing LHC measurements
- Possible future directions
  - Discriminating power of  $t\bar{t}$  observables
- *No time to discuss:* NP in single (& mono) top production

# FB & Charge asymmetries in $t\bar{t}$ production

- Charge (a)symmetric cross-section

$$\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta, \quad \sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta.$$



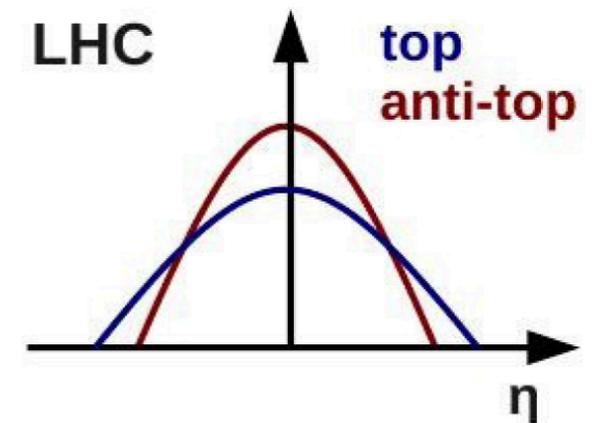
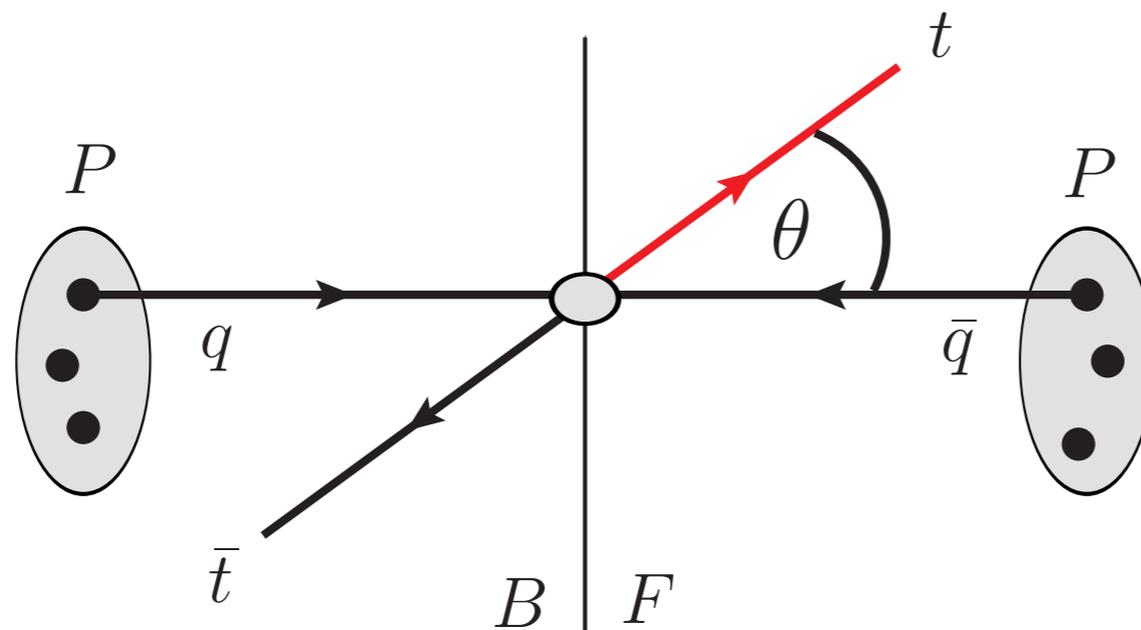
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

# FB & Charge asymmetries in $t\bar{t}$ production

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$$\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta, \quad \sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta.$$



$$A_C = \text{sign}(Y) \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N(\Delta y^2 > 0) - N(\Delta y^2 < 0)}{N(\Delta y^2 > 0) + N(\Delta y^2 < 0)}$$

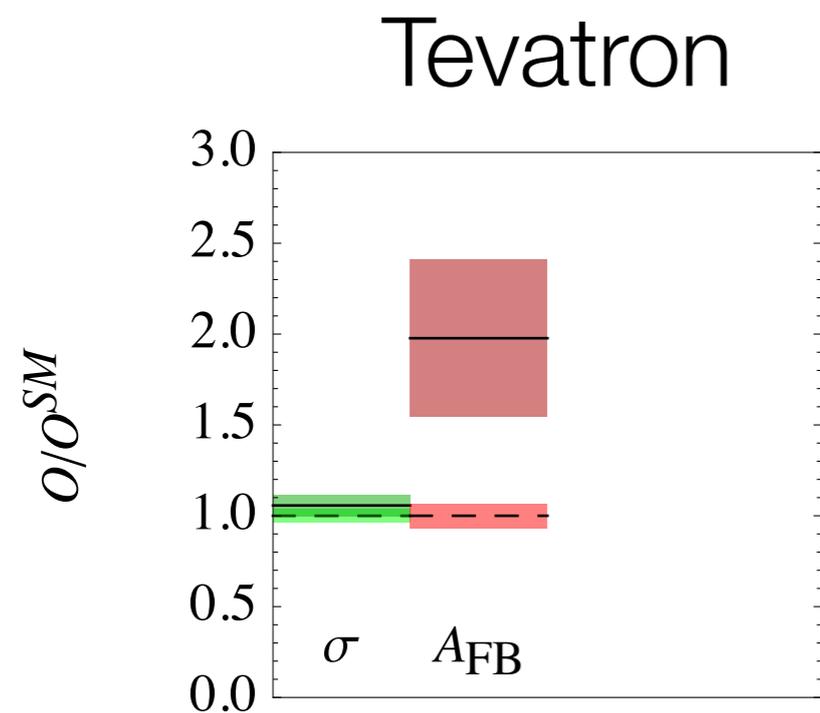
$$Y = y_t + y_{\bar{t}}$$

$$\Delta y^2 = y_t^2 - y_{\bar{t}}^2$$

# Measurements of $t\bar{t}$ production at Tevatron & LHC

see talks by Czako, Parke  
Petrillo, Andrea, Dorland, Amidei, Kim

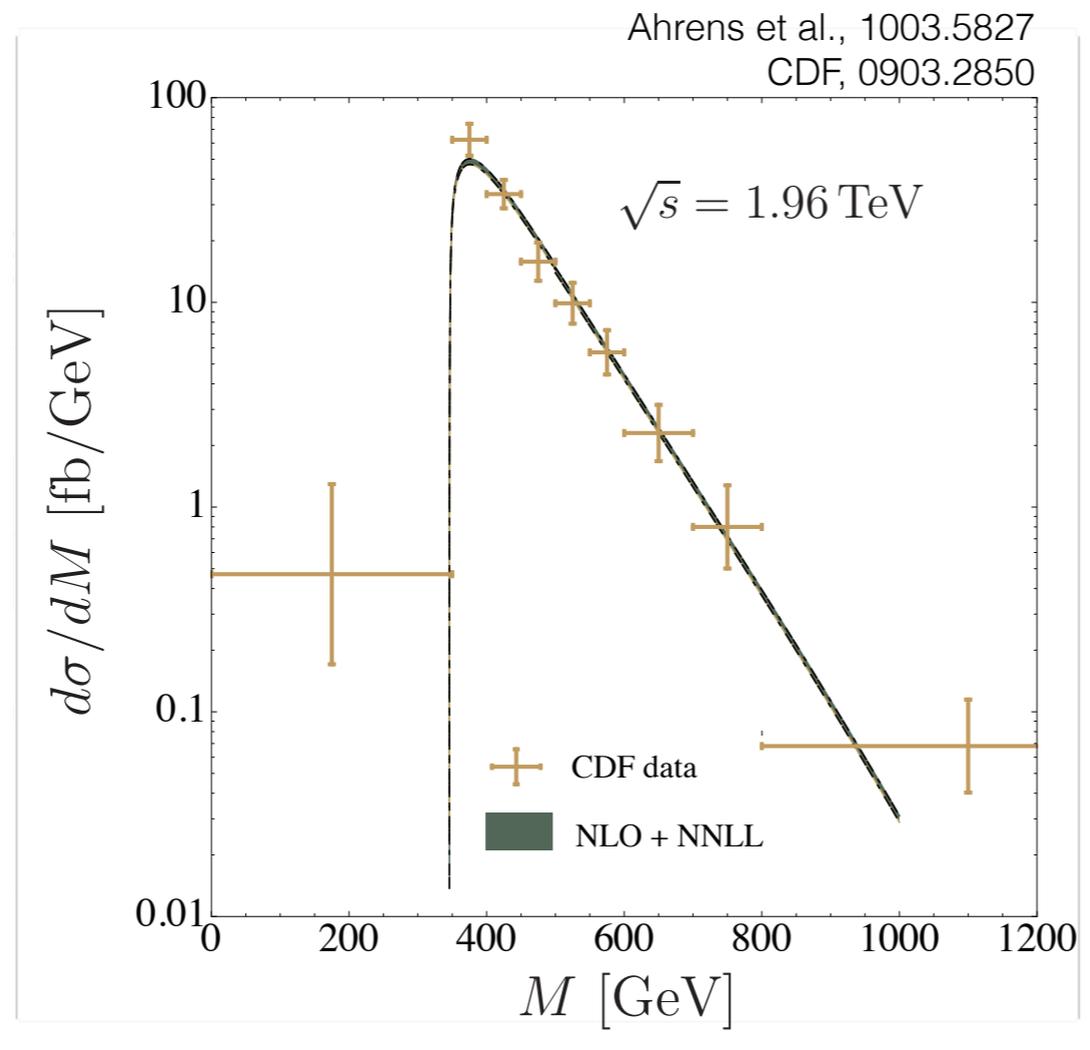
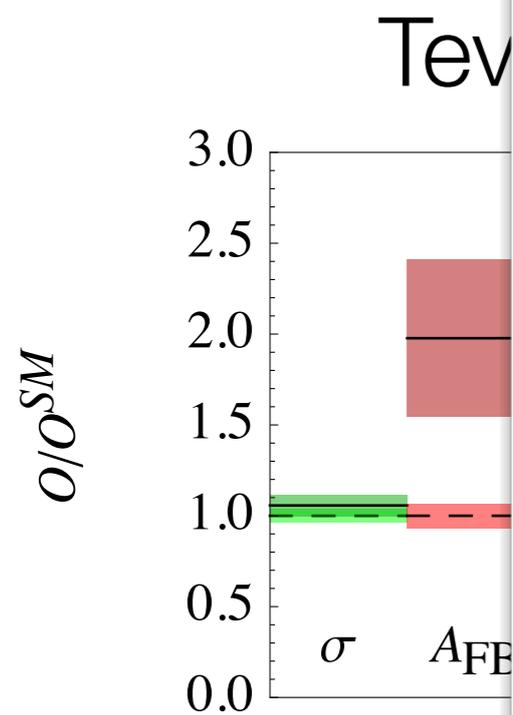
- Precisely measured inclusive observables



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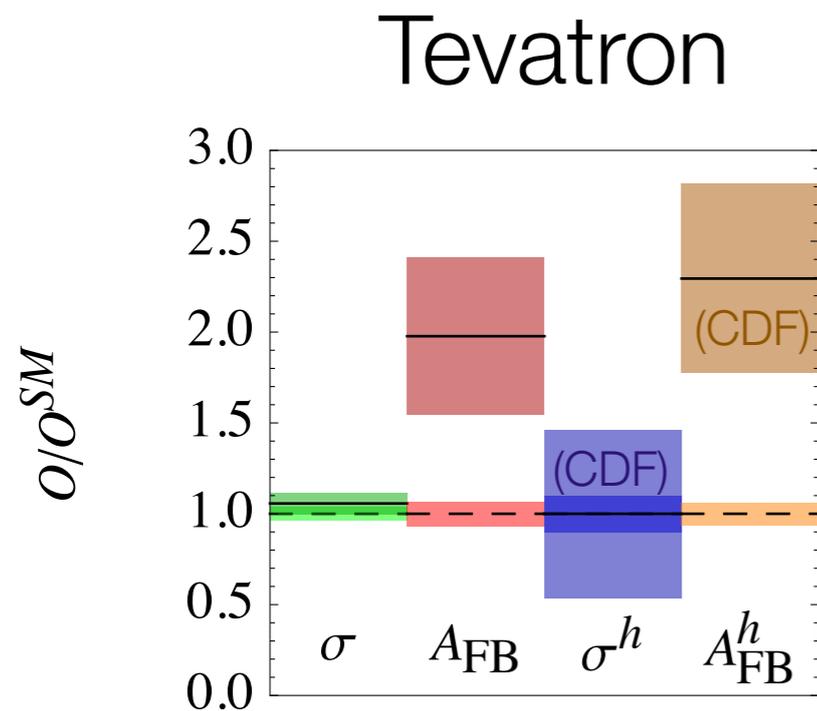


- UV sensitive distributions

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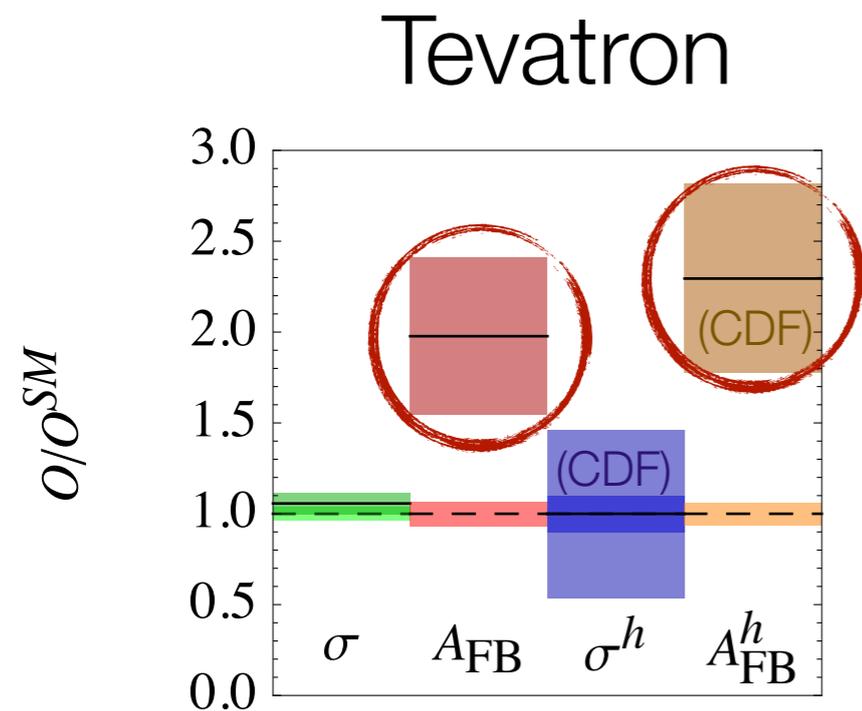
- UV sensitive distributions

$$\sigma^h = \sigma(700\text{GeV} < m_{t\bar{t}} < 800\text{GeV}) \quad A_{FB}^h = A_{FB}(m_{t\bar{t}} > 450\text{GeV})$$

# Measurements of $t\bar{t}$ production at Tevatron & LHC

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- Precisely measured inclusive observables



Sizable deviations in  $A_{FB}$   
good agreement in  $\sigma$ !

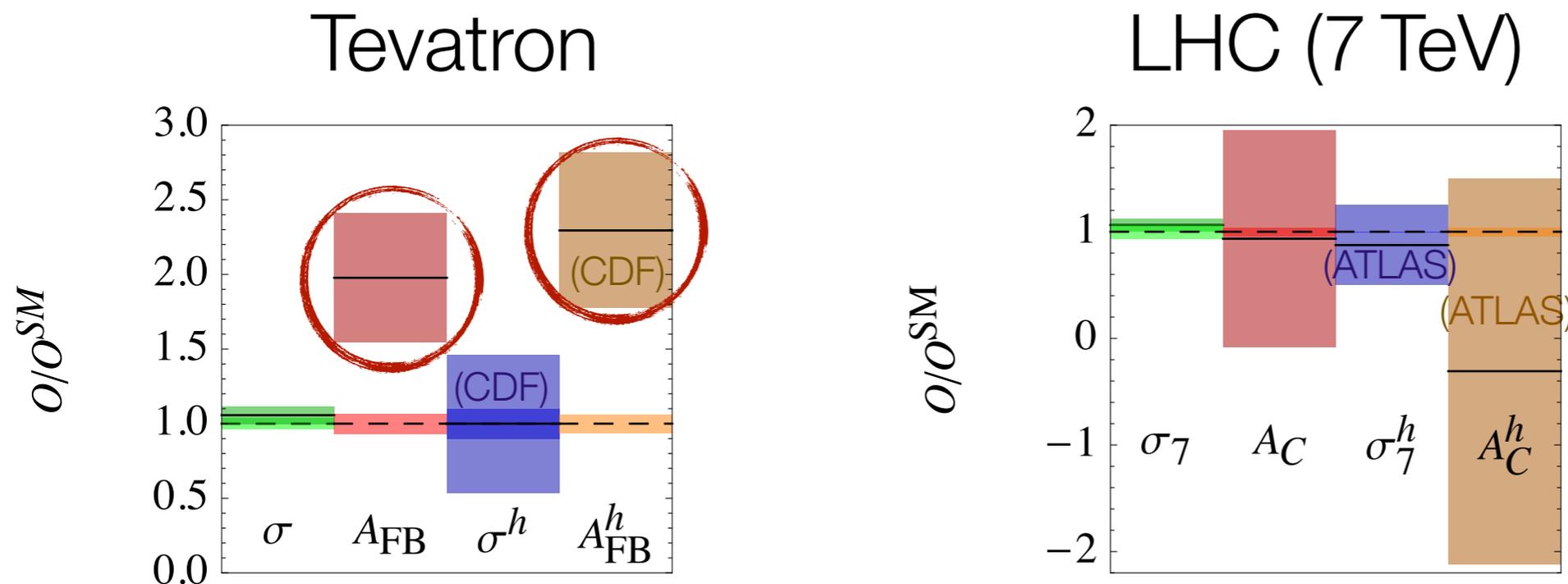
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# Measurements of $t\bar{t}$ production at Tevatron & LHC

see talks by Czakon, Parke  
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- Precisely measured inclusive observables



**No deviations seen at the LHC!**

- UV sensitive distributions

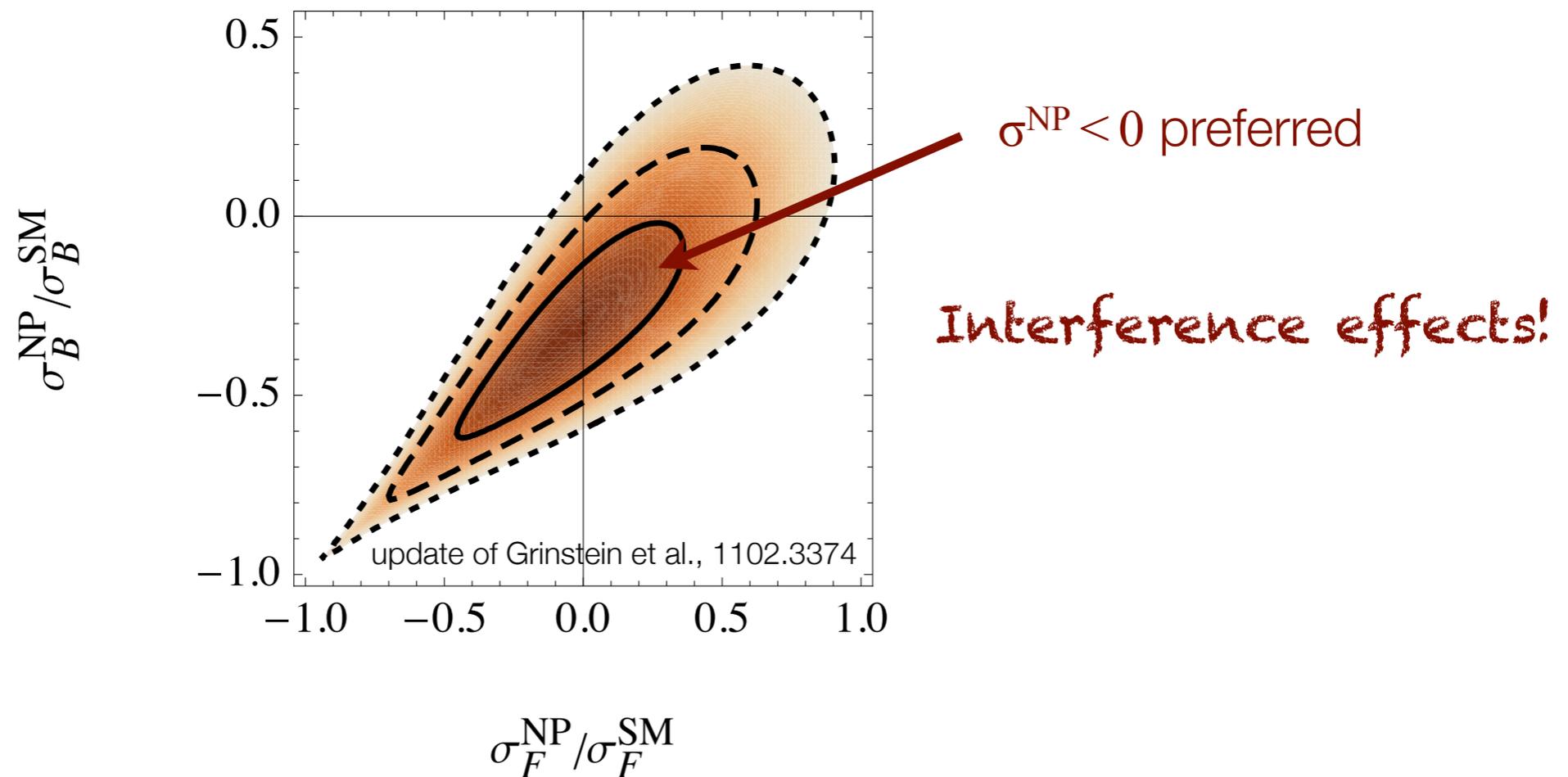
$$\sigma^h = \sigma(700\text{GeV} < m_{t\bar{t}} < 800\text{GeV}) \quad A_{FB,C}^h = A_{FB,C}(m_{t\bar{t}} > 450\text{GeV})$$

$$\sigma_7^h = \sigma(950\text{GeV} < m_{t\bar{t}} < 2700\text{GeV})$$

# New Physics Interpretation(s)

- What are the data suggesting (if NP)?  $\sigma_{F,B} = \sigma_{F,B}^{\text{SM}} + \sigma_{F,B}^{\text{NP}}$

Tevatron ( $m_{tt} > 450 \text{ GeV}$ )



# New Physics Interpretation(s)

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- What are the data suggesting (if NP)?

- First with EFT:  $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^{d_i-4}} Q_i$  [valid below NP thresholds,  $\sim$ expansion in  $(E/\Lambda)^n$ ]

- At dim 5 encounter only QCD dipole ops

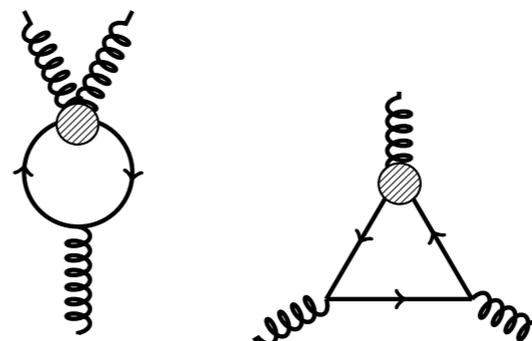
c.f. Hioki & Ohkuma, 1011.2655,  
J.F.K, Papucci & Weiler, 1107.3143,  
Degrande et al., 1205.1065

$$c_{LR,g} \bar{Q} H \sigma^{\mu\nu} T^a U G_{\mu\nu}^a \rightarrow \bar{t} \sigma^{\mu\nu} T^a G_{\mu\nu}^a (\tilde{\mu}_t + i\gamma_5 \tilde{d}_t) t$$

  
 CMDM

  
 CEDM (CPV)

cannot influence  $A_{\text{FB}}$  at  $\mathcal{O}(\alpha_s/\Lambda^{-2})$   
indirect constraints from CEDM of neutron



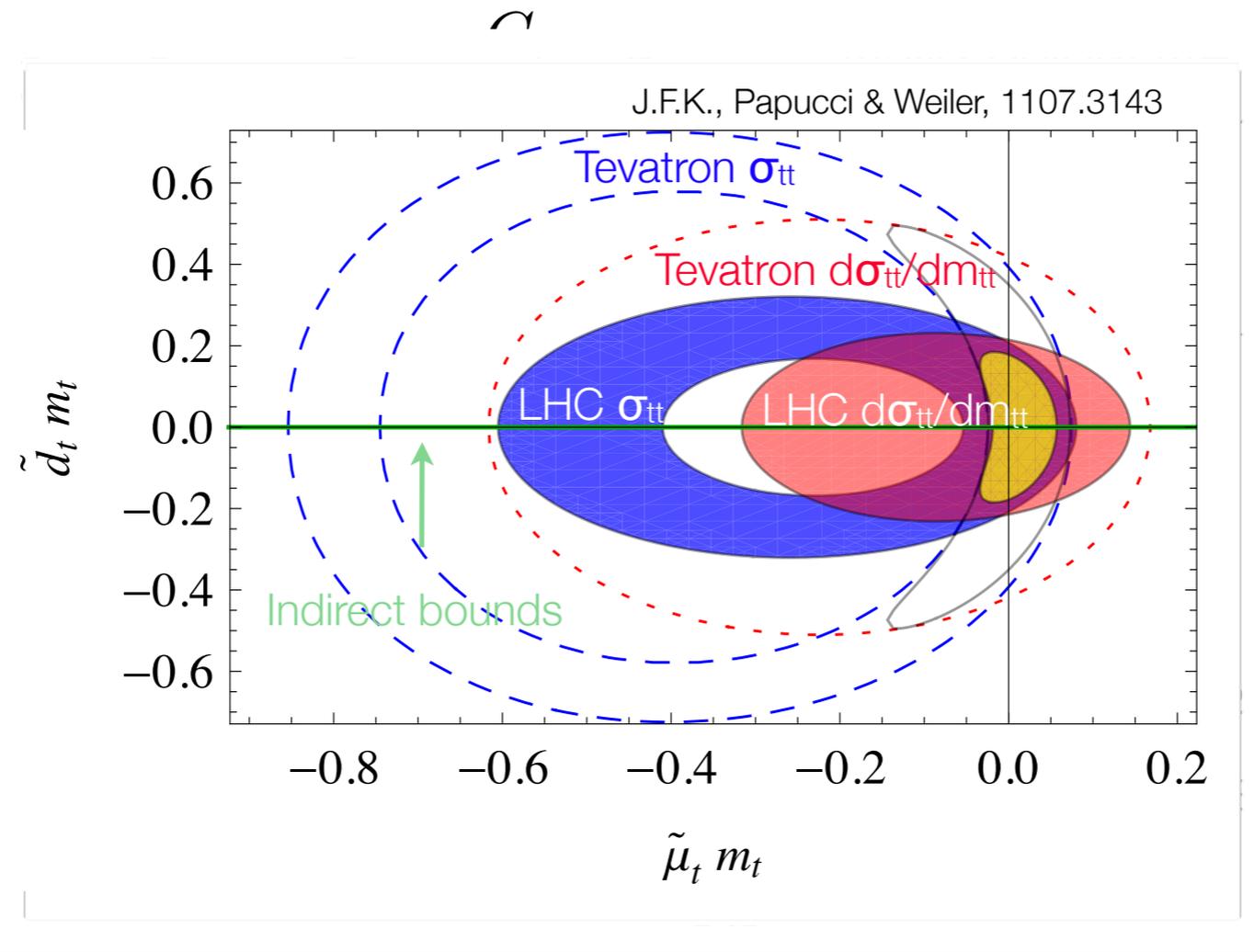
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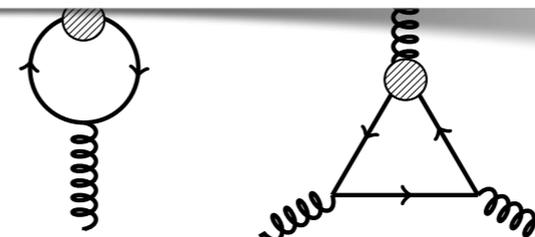
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$$c_{LR,g} \bar{Q} H \sigma^{\mu\nu}$$



thresholds,  
 $(E/\Lambda)^n$  ]

c.f. Hioki & Ohkuma, 1011.2655,  
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- Only two 4q dim 6 ops. interfere with LO QCD [contribute at  $\mathcal{O}(\alpha_s/\Lambda^{-2})$ ]

$$Q_{V,q}^8 = (\bar{q}\gamma_\mu T^a q)(\bar{t}\gamma^\mu T^a t) \quad \text{only contributes to } \sigma\text{'s}$$

$$Q_{A,q}^8 = (\bar{q}\gamma_\mu \gamma_5 T^a q)(\bar{t}\gamma^\mu \gamma_5 T^a t) \quad \text{only contributes to } A_{FB} \text{ and } A_C \text{ (for } q=u,d)$$

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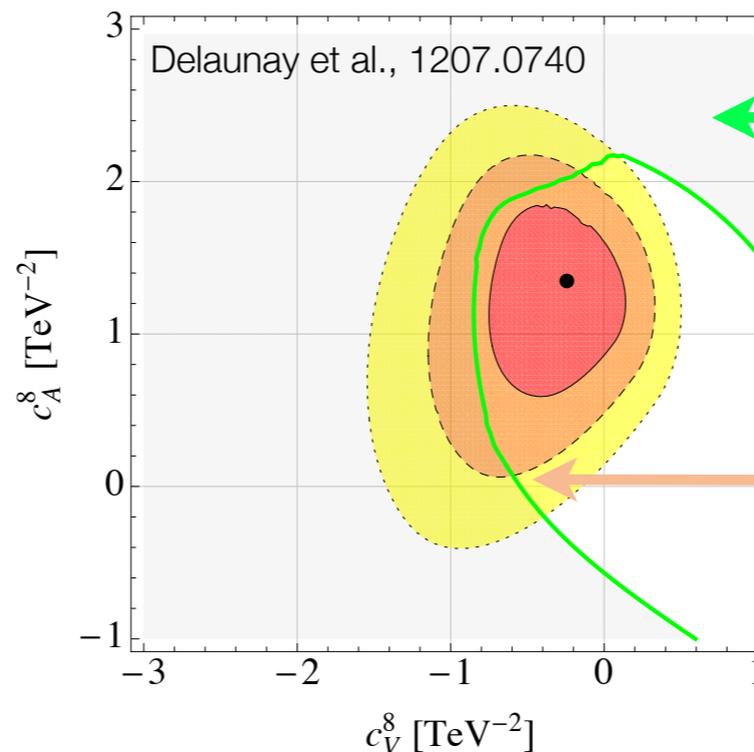
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1. consider only  $q=u$

**However:  
tension with  $A_C$ !**



excluded by  $\sigma_7^h$   
[more ops. at  $\mathcal{O}(1/\Lambda^4)$ ]

requires nonzero  $c_A^8$

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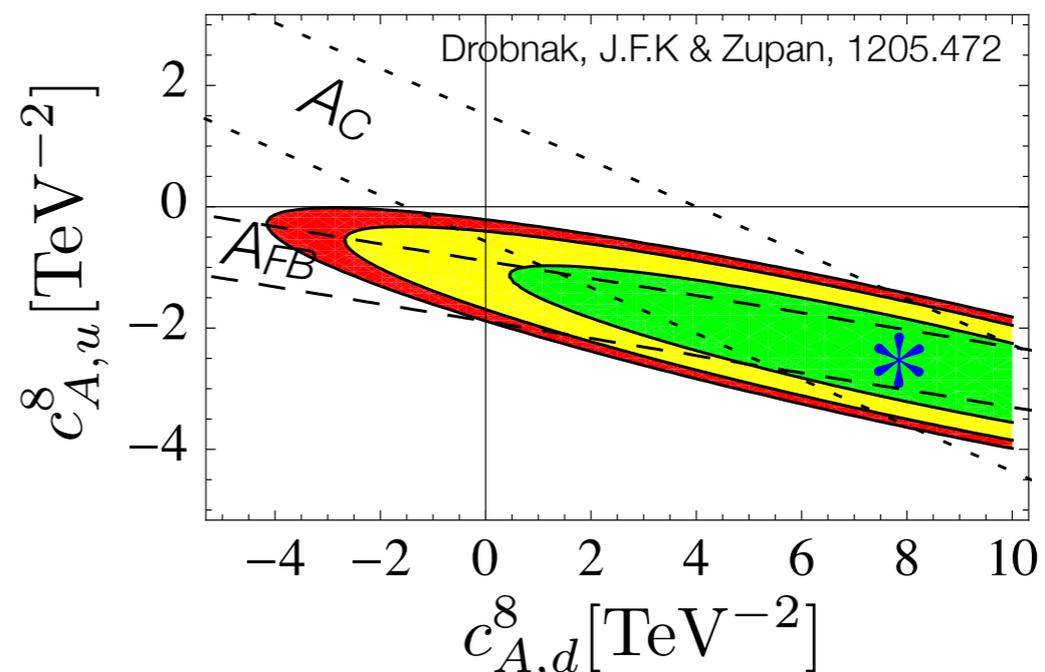
1. consider only  $q=u$

2. consider both  $q=u,d$

see also

Aguilar-Saavedra & Juste, 1205.1898

talk by Pérez-Victoria



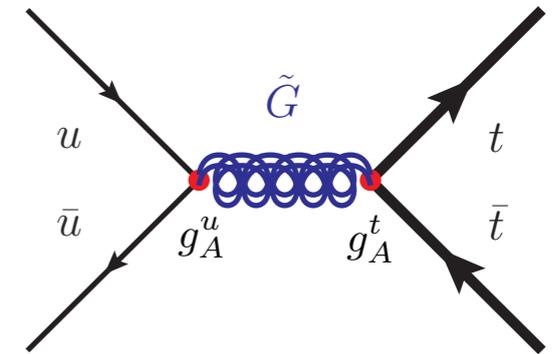
Explicit model realization?

# New Physics Interpretation(s)

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- s-channel color octet spin-1 resonance - “Axigluon”
- If heavy, need opposite sign  $uu$  and  $tt$  couplings

$$A_{FB} \propto \frac{g_A^u g_A^t}{\hat{s} - m_{\tilde{G}}^2}$$

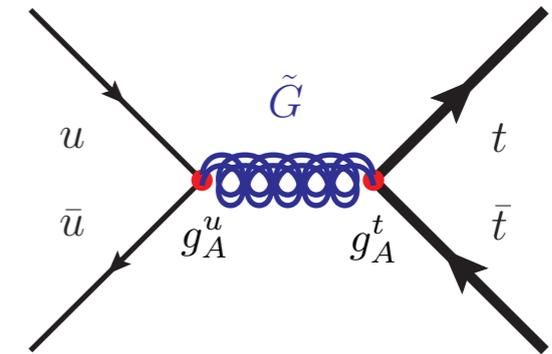


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  - Constrained by LHC **di-jet** searches (also flavor, EWPT - model dependent)

Chivukula et al.,  
1007.0260.  
Haisch & Westhoff,  
1106.0529

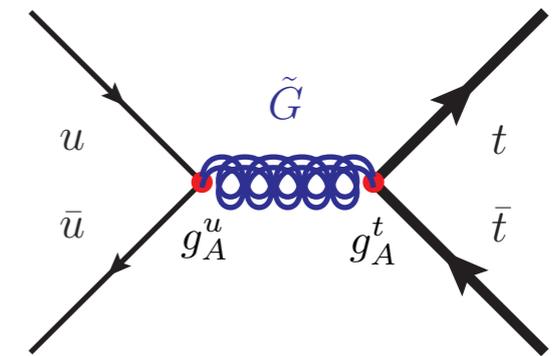
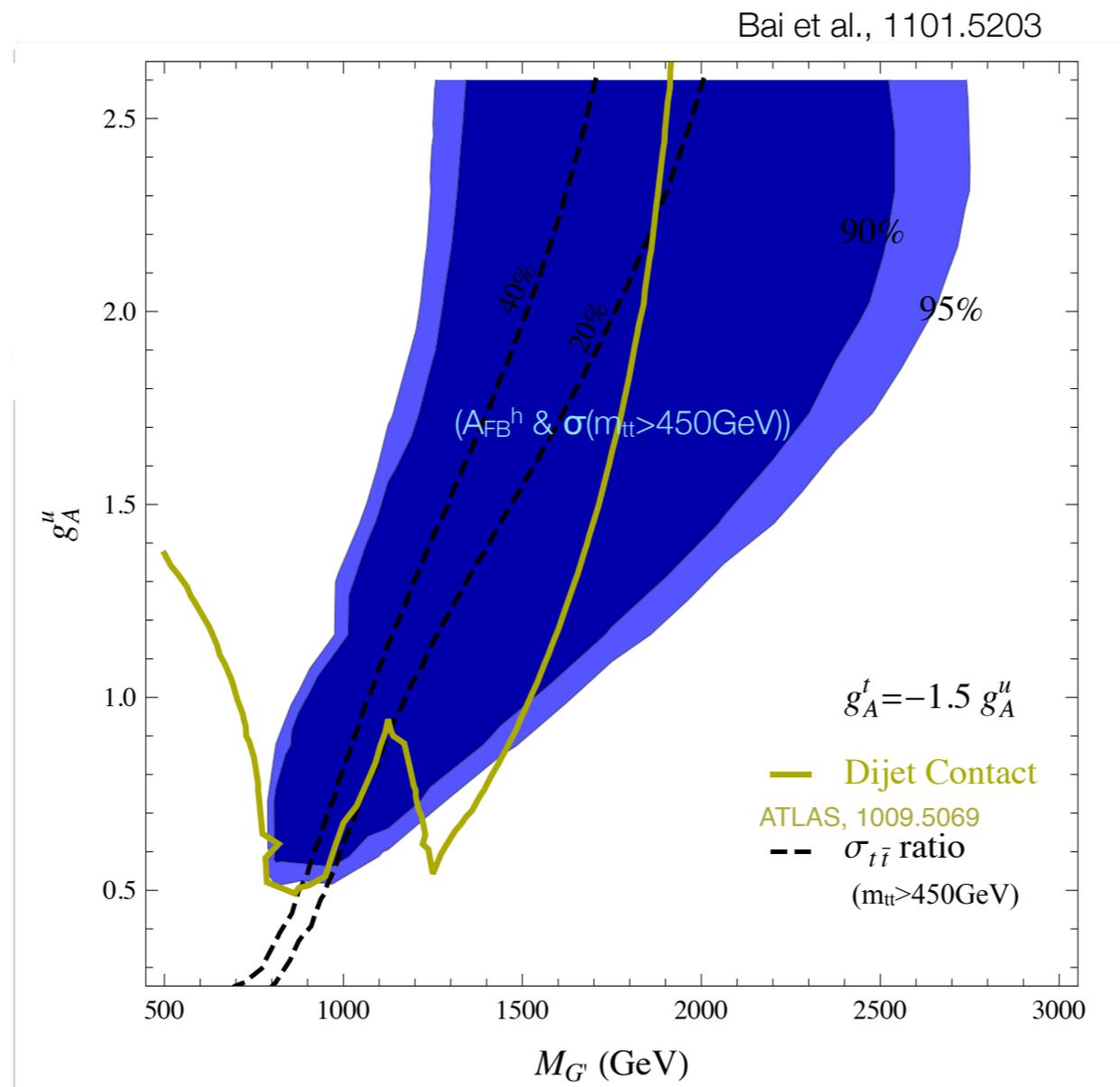


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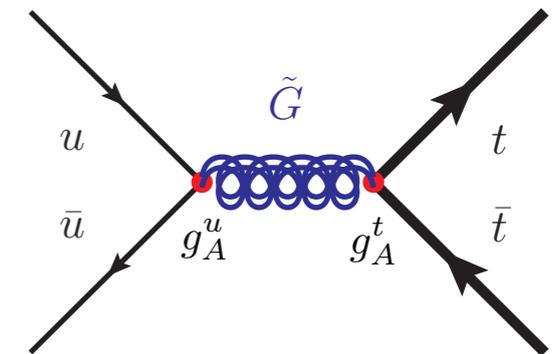
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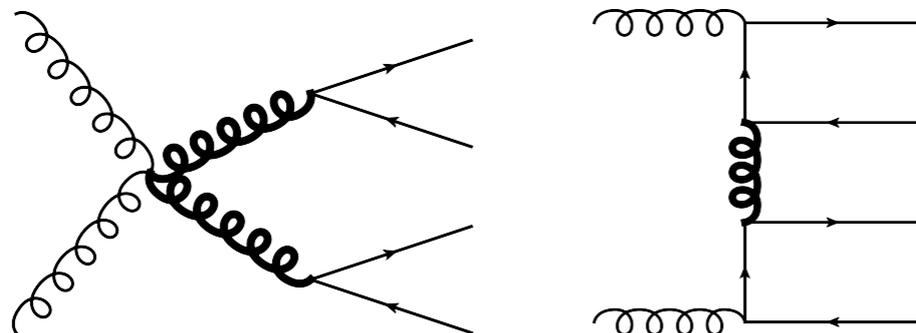
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Haisch & Westhoff,  
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- If light must evade  **$tt$  resonance searches** see talk by Pérez-Victoria

- also (resonant) **4-top** production

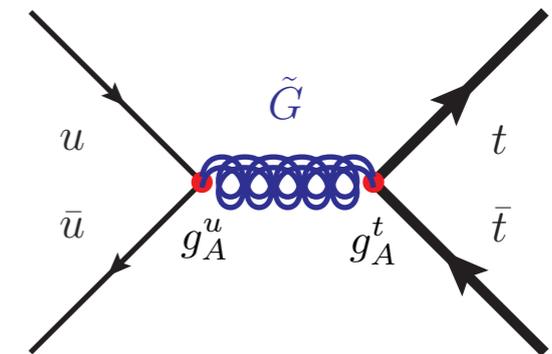
Zhou et al., 1203.5862  
Aguilar-Saavedra & Santiago  
1112.3778



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Chivukula et al.,  
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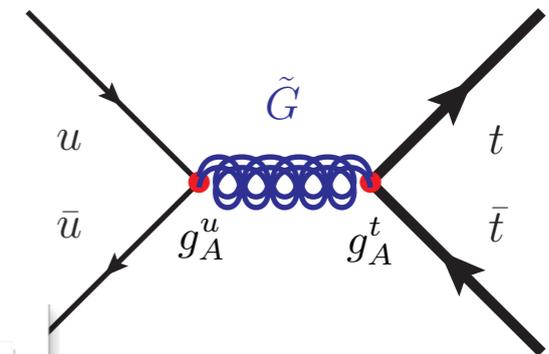
- reconciling  $A_{\text{FB}}$  and  $A_C$  requires large  $dd$  couplings

- can enhance total width
- possible effects on  $b\bar{b}$   $A_{\text{FB}}$

Drobnak, J.F.K & Zupan, 1205.472

# New Physics Interpretation(s)

- s-channel color octet spin-1 resonance - “Axigluon”
- If heavy, need opposite sign  $uu$  and  $tt$  couplings



- Constrained by  $DD$  AFB (also flavor, EM)

- If light must even

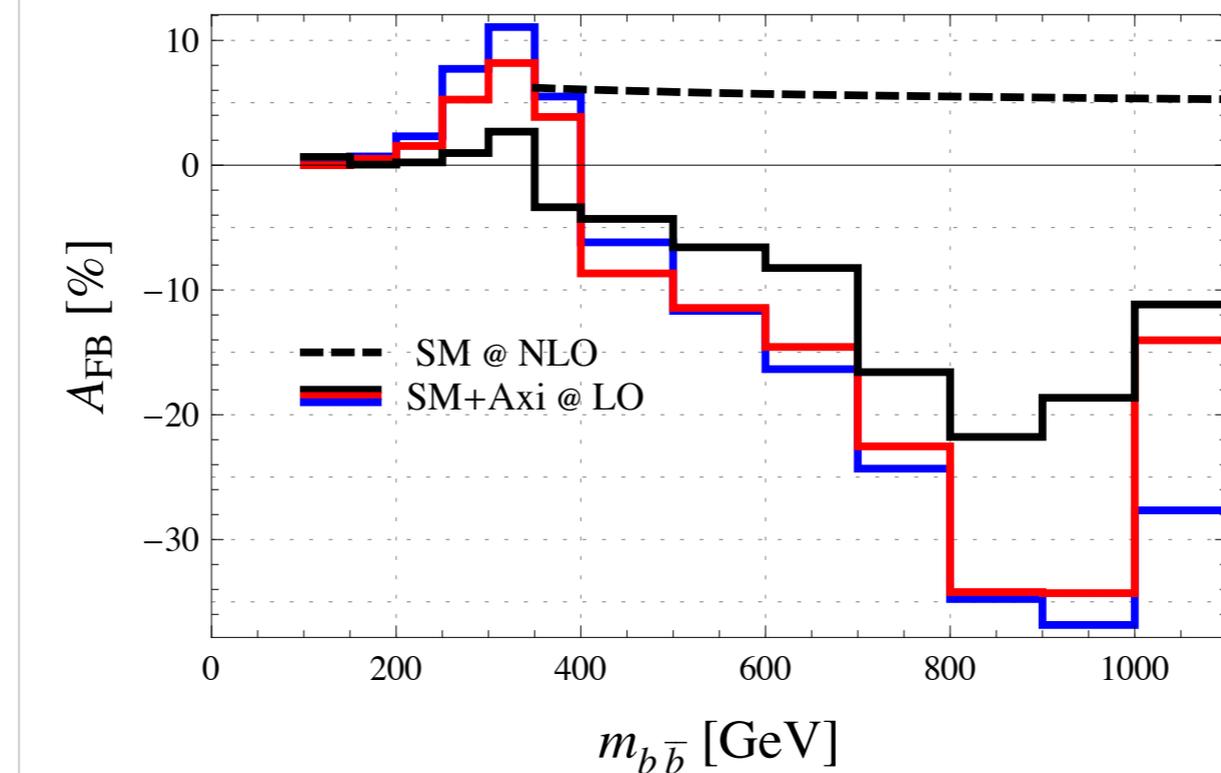
- also (resonance)

- reconciling  $DD$  AFB

- can enhance

- possible effects on  $DD$  AFB

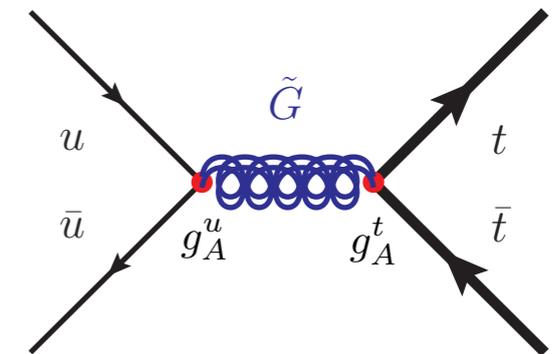
Drobnak, J.F.K & Zupan, 1205.472



predict zero in  $A_{FB}$  spectrum

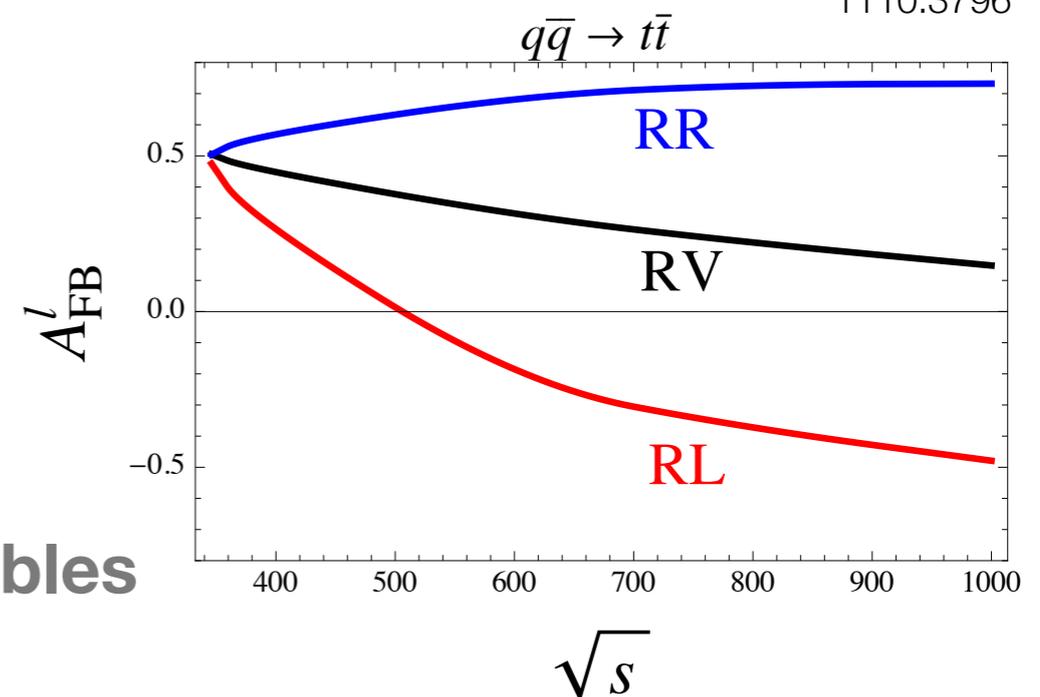
# New Physics Interpretation(s)

- s-channel color octet spin-1 resonance - “Axigluon”
- **asymmetries driven by spin interference effects**
  - top spins at threshold probe initial state chiralities
  - can use **leptonic asymmetries** as probes



$$A_{\text{FB}}^{\ell} = \frac{N_l(q_l \cos \theta_l > 0) - N_l(q_l \cos \theta_l < 0)}{N_l(q_l \cos \theta_l > 0) + N_l(q_l \cos \theta_l < 0)}$$

Falkowski, Perez & Schmaltz  
1110.3796



- at large  $m_{tt}$  interesting top **spin observables**

# Top spin observables

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- Angular distributions of top decay products in  $t\bar{t}$  production

see talk by Parke

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_f d\cos\theta_{\bar{f}}} = \frac{1}{4} \left( 1 + \underset{\substack{\uparrow \\ \text{(anti)top polarization} \\ \text{(tiny in SM)}}}{B_t} \cos\theta_f + \underset{\substack{\uparrow \\ \text{(anti)top polarization} \\ \text{(tiny in SM)}}}{B_{\bar{t}}} \cos\theta_{\bar{f}} - \underset{\substack{\uparrow \\ \text{\(\bar{t}\bar{t}\) spin correlations} \\ \text{(well predicted in SM)}}}{C} \cos\theta_f \cos\theta_{\bar{f}} \right)$$

- QCD vector-like - new chiral interactions can induce large deviations

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- QCD vector-like - new chiral interactions can induce large deviations

- Many optimized observables suggested...

Hewett et al., 1103.4618

Krohn et al., 1105.3743

Bai et al., 1106.5071

Berger et al., 1201.1790

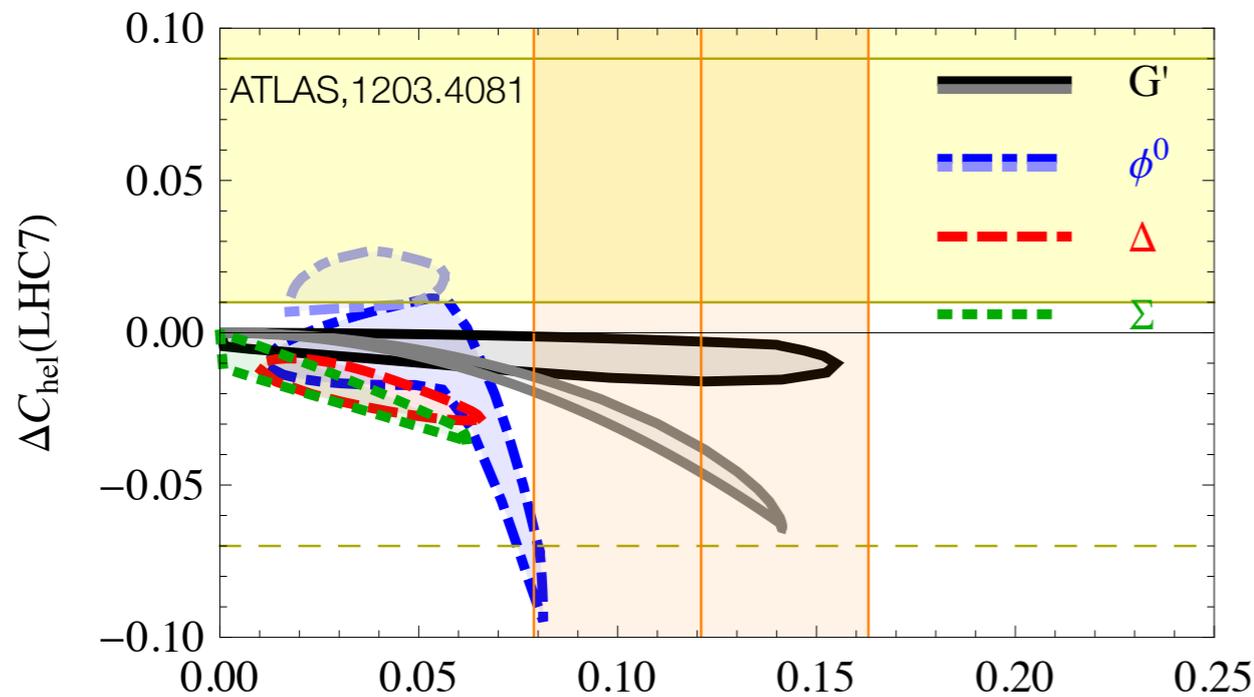
...

# Top spin observables

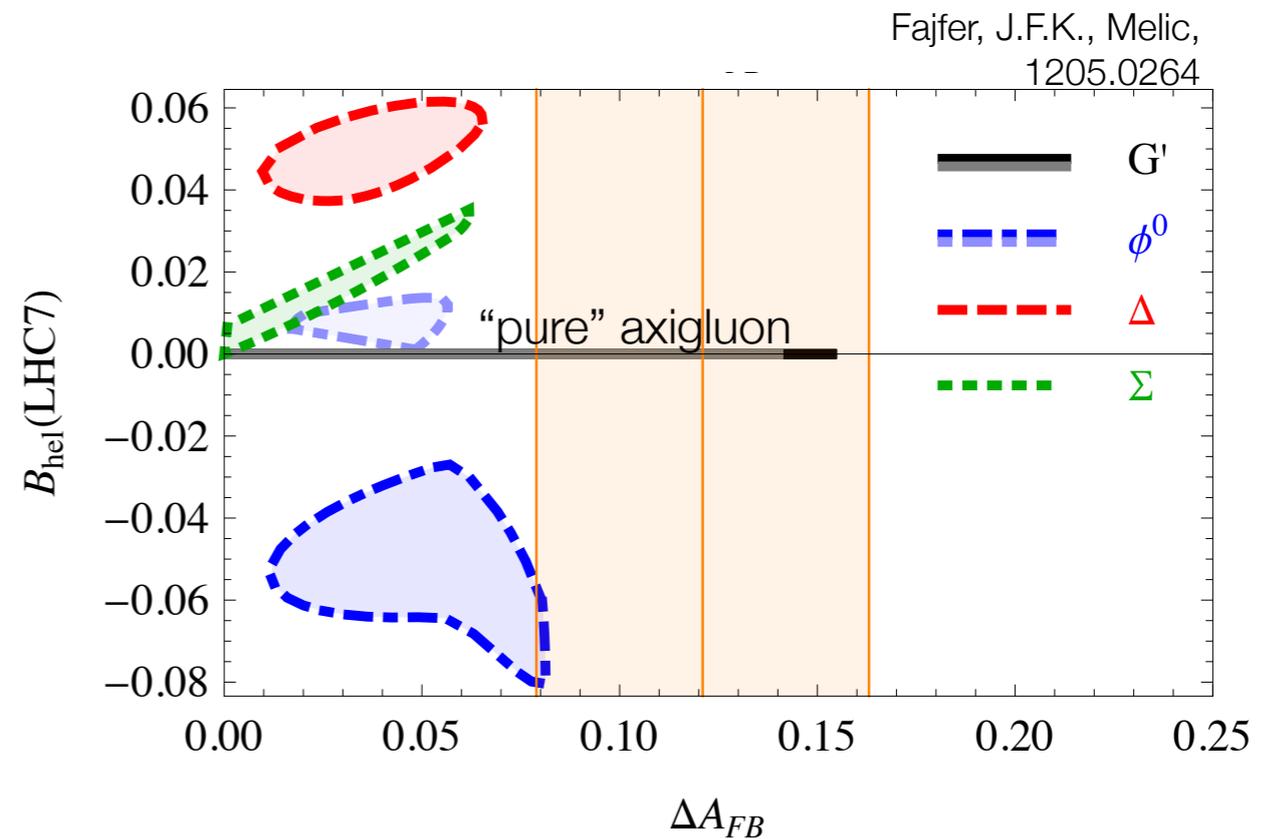
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existing nontrivial constraints



discriminating power of top polarization

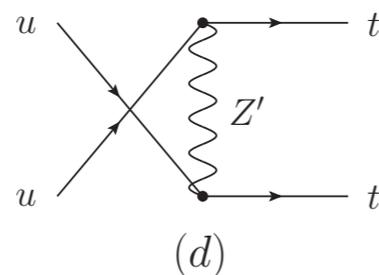
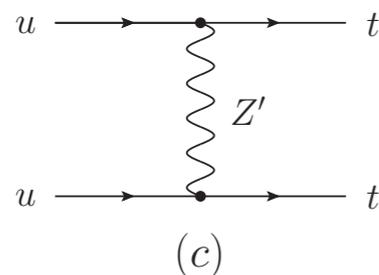
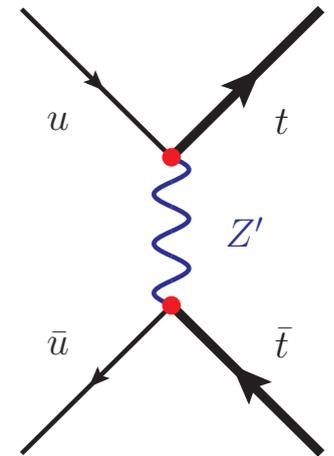
# New Physics Interpretation(s)

- t- (u-) channel exchange (many possibilities)

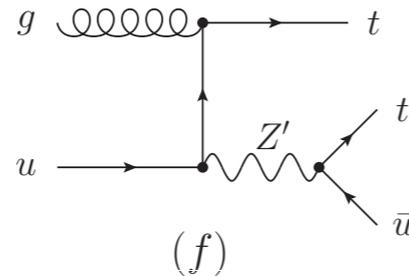
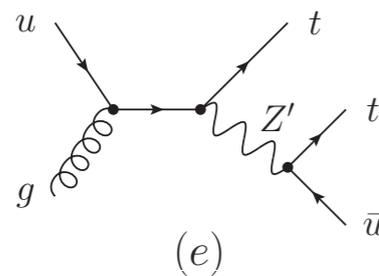
see talk by Pérez-Victoria  
Kamenik, Shu, Zupan,  
1107.5257

- requires large flavor-off-diagonal couplings

- flavor, di-jet, **same-sign top**, ... constraints!



Aguilar-Saavedra & Perez-Victoria,  
1104.1385  
Degrande et al., 1104.1798  
Gresham et al., 1203.1320  
...



- nontrivial model building

Dorsner, Fajfer, J.F.K. & Kosnik, 0912.0972  
Grinstein et al., 1102.3374, 1108.4027  
Jung, Pierce & Wells, 1103.4835  
Ligeti, Tavares & Schmaltz, 1103.2757  
Giudice et al., 1105.3161  
...

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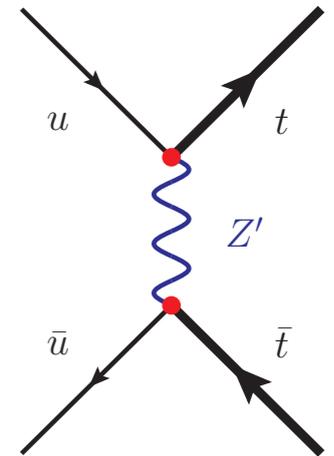
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see talk by Pérez-Victoria  
Kamenik, Shu, Zupan,  
1107.5257

- requires large flavor-off-diagonal couplings

- asymmetries driven by kinematics (Rutherford scattering)



- expect sizable  $\sigma$  excess in the forward region: **top quarks at LHCb?**

Kagan, J.F.K., Perez & Stone, 1103.3747

- alternatively extend rapidity coverage of semileptonic  $t\bar{t}$  events at ATLAS & CMS - **y dependent charge asymmetries**

Arguin et al., 1107.4090

Antunano et al., 0709.1652

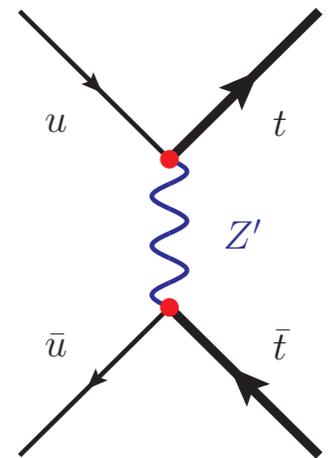
Hewett et al., 1103.4618

# New Physics Interpretation(s)

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- t- (u-) channel exchange (many possibilities)
- requires large flavor-off-diagonal couplings
- asymmetries driven by kinematics (Rutherford scattering)
- rigid correlation between  $A_{FB}$  and  $A_C$

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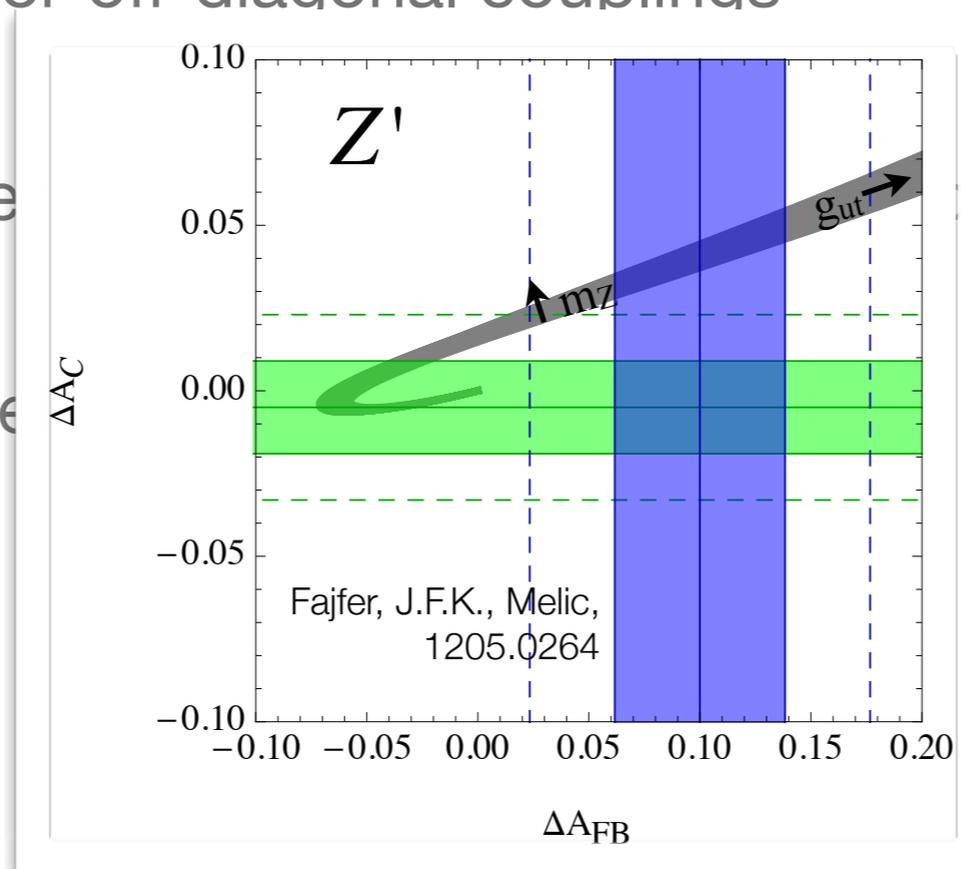
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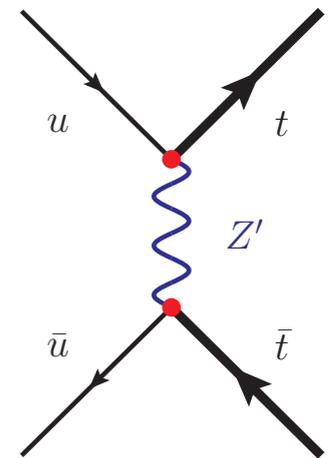
- requires large flavor-off-diagonal couplings

- asymmetries drive

- rigid correlation between



(scattering)

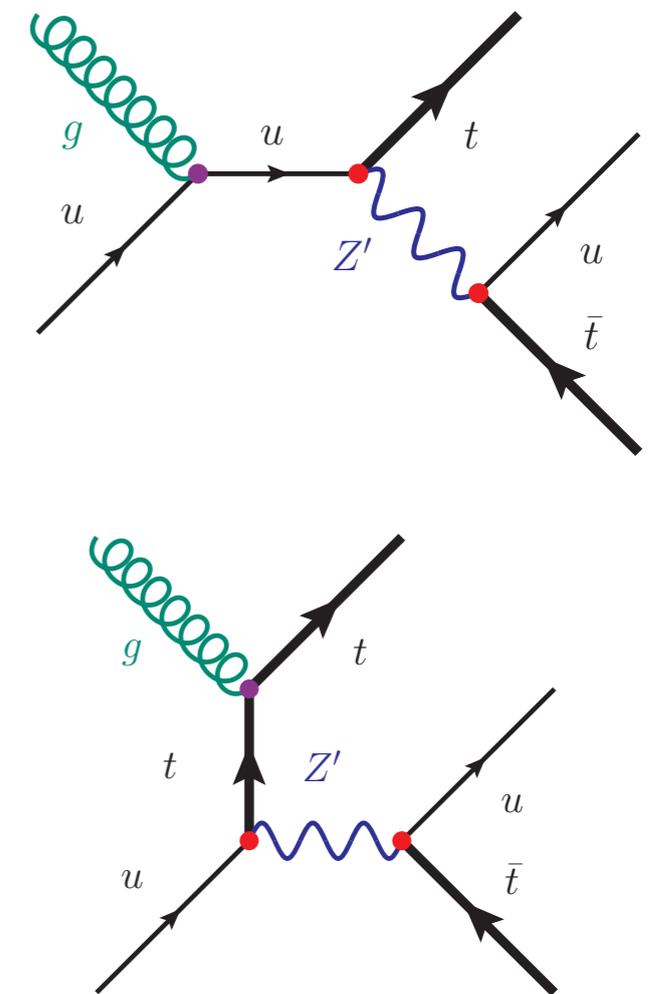
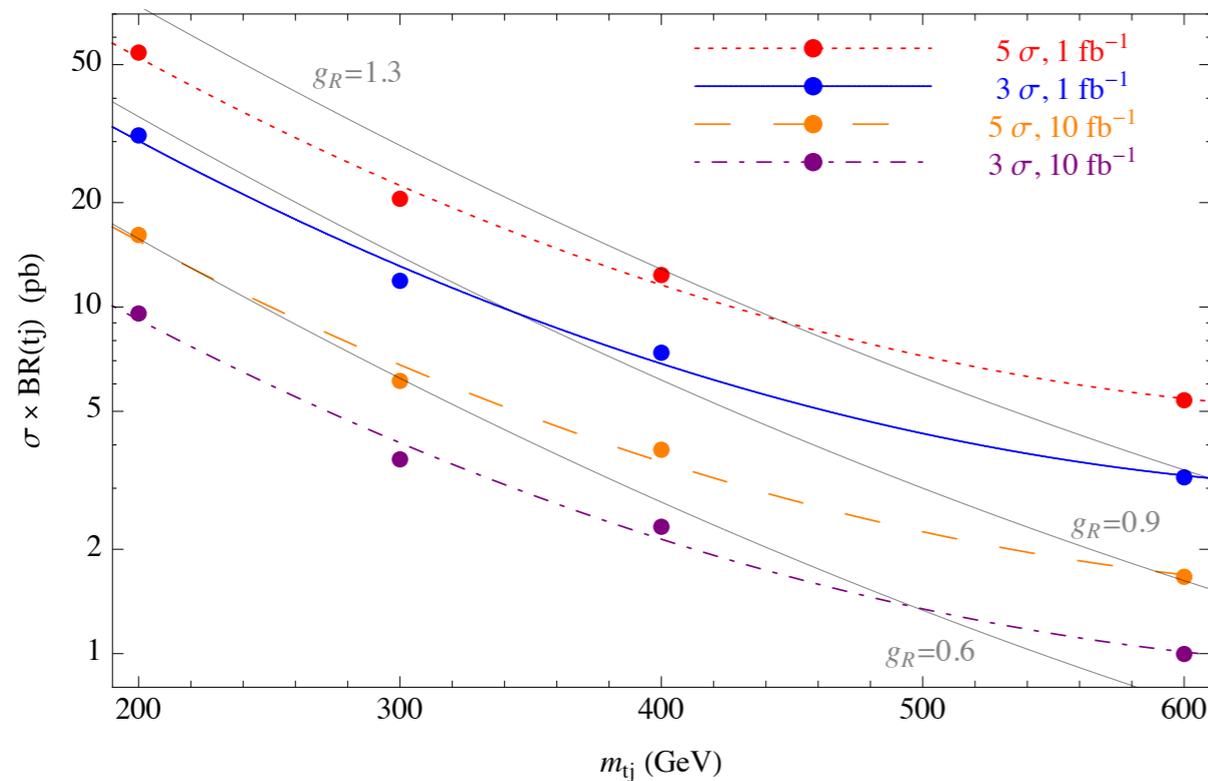


simplest models excluded by  $A_C$ ?

# Importance of associated production

- t- (u-) channel models predict flavor violating (t-j) resonances in t-associated production Gresham et al., 1102.0018

- Promising search channel at the LHC



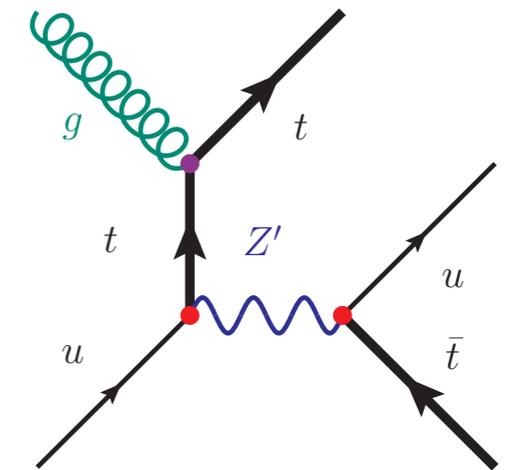
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- Important influence on inclusive  $t\bar{t}$  production ( $Z'$  example)

Drobnak, Kagan, J.F.K., Perez & Zupan, to appear soon.

- $\bar{t}$  from  $Z'$  decay boosted in direction of incoming  $u$

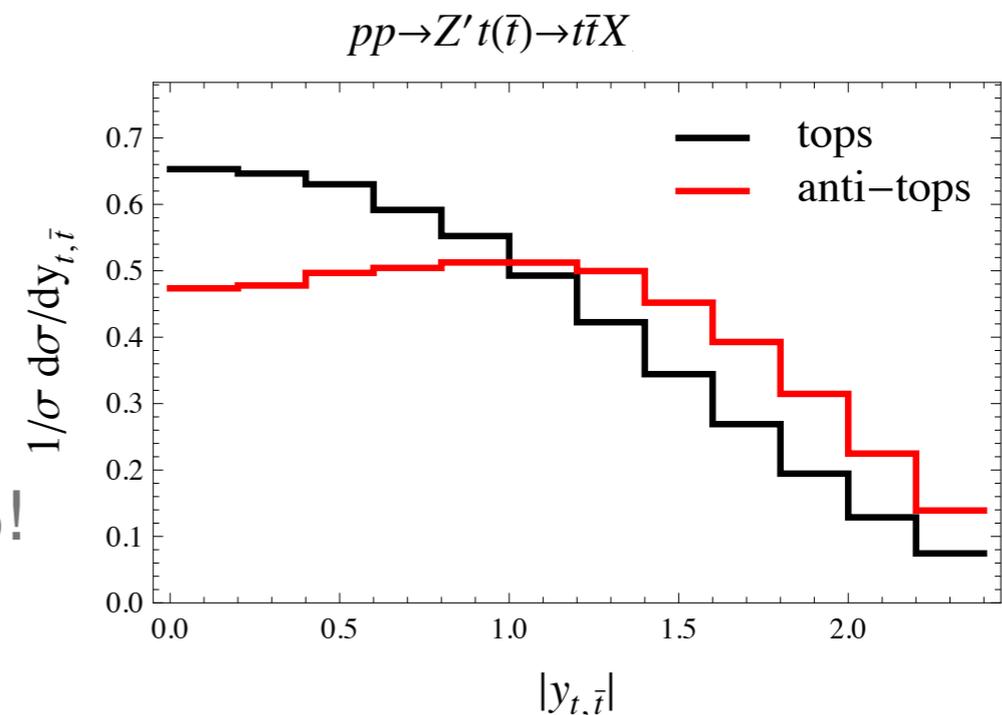


- at LHC  $u$  (but not  $\bar{u}$ ) harder than  $g$

- at Tevatron  $g$  PDF suppressed

- Required incoherent contribution ~few %!

previously explored for  $A_{FB}$ , see Isidori & J.F.K. 1103.0016

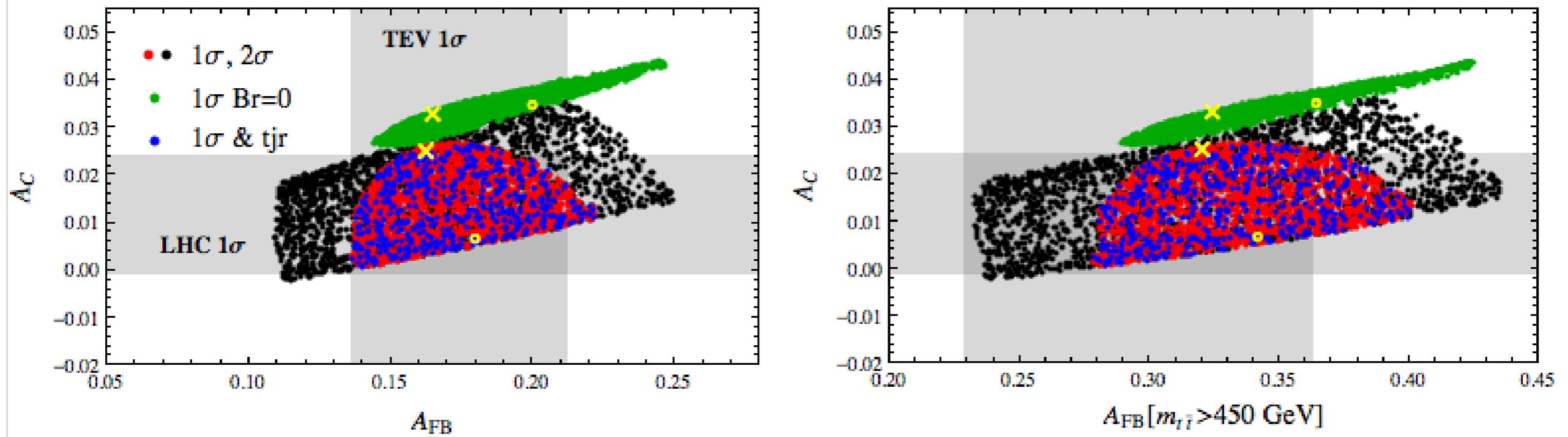


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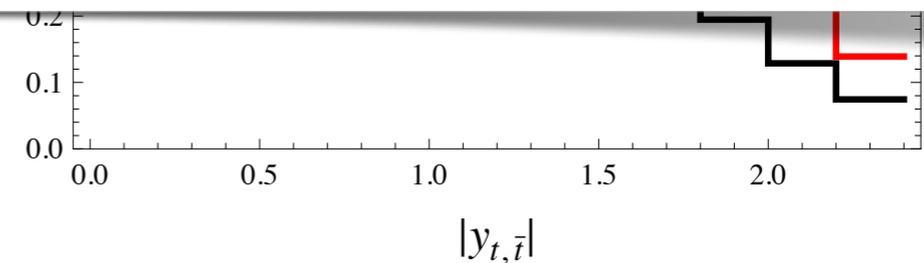
seen

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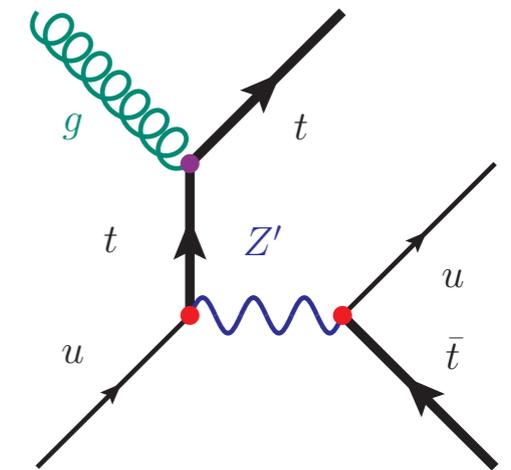


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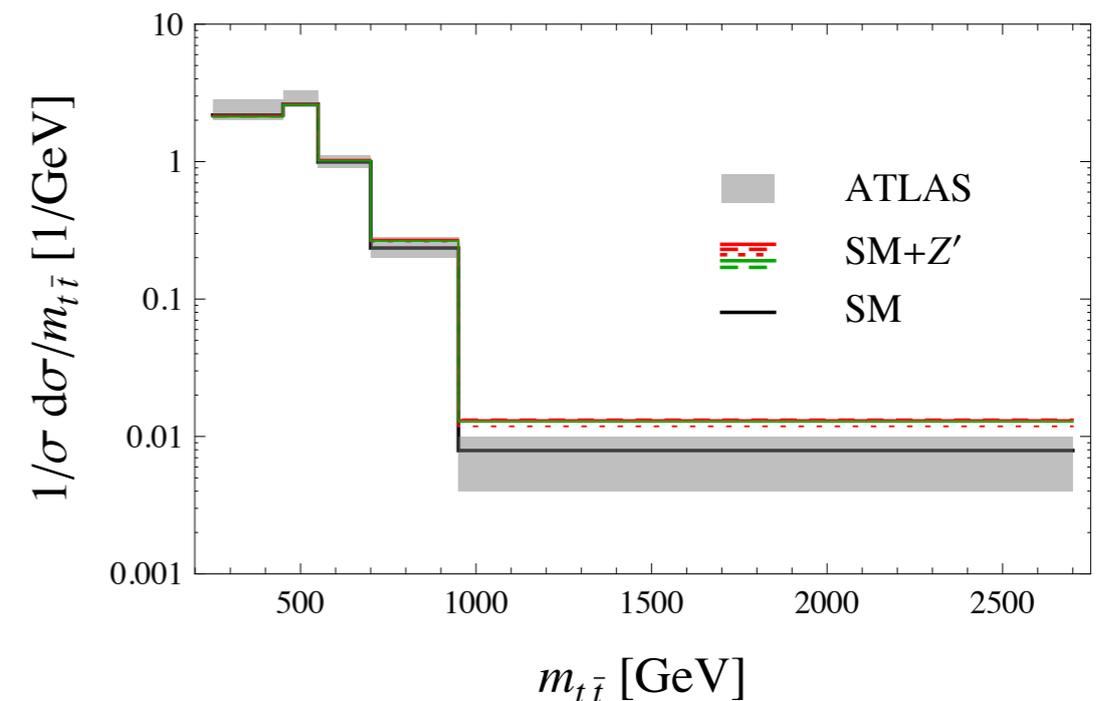


- constraints from top-jet resonance searches ✓

- measured jet multiplicity distributions in  $t\bar{t}$  sample ✓

- $m_{t\bar{t}}$  distributions

Expect observable deviations soon!



# Conclusions

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- The large  $A_{\text{FB}}$  observed at Tevatron could still be due to QCD or systematics
- Viable NP interpretations are being narrowed down by LHC
  - contributions in s-channel
    - O(few TeV) resonances - constrained by di-jet and  $t\bar{t}$  spectra
    - interesting possibility of light (wide) color octets
    - accommodating  $A_C$  requires sizable couplings to down quarks ( $b\bar{b}$   $A_{\text{FB}}$ )
  - NP in t- (u-) channel exchange
    - important effect of associate production on inclusive  $t\bar{t}$  measurements

*$A_C$  consistent with SM does not invalidate anomalous  $A_{\text{FB}}$ !*

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  - NP in t- (u-) channel exchange
    - important effect of associate production on inclusive  $t\bar{t}$  measurements
- New experimental handles crucial:
  - important effects of NP on top polarization in pair production
  - more exclusive (binned) observables

Backup

# FB & Charge asymmetries in $t\bar{t}$ production

- Non-zero  $A_{FB,C}$  require  $\hat{t}$ - $\hat{u}$  odd contributions to  $\sigma$

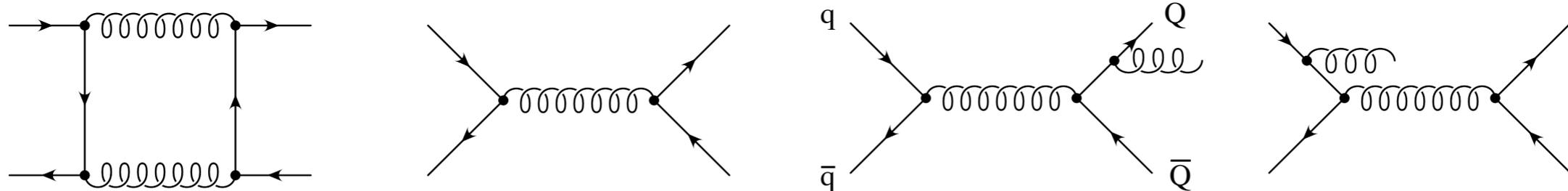
$$\beta_t = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

$$\hat{t} = (p_q - p_t)^2$$

$$\hat{s} = (p_t + p_{\bar{t}})^2$$

$$\hat{t}, \hat{u} = m_t^2 - \frac{\hat{s}}{2} [1 \mp \beta_t \cos \theta]$$

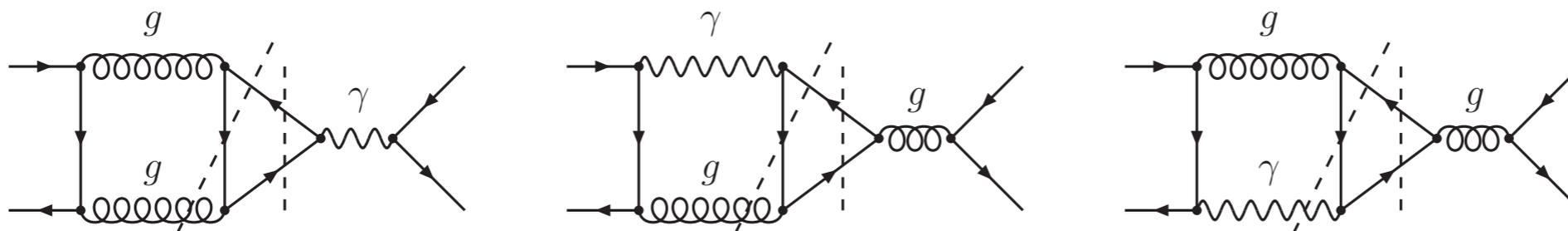
- In QCD induced at order  $\alpha_s^3$



Kuhn & Rodrigo,  
hep-ph/9802268,  
hep-ph/9807420

Ahrens et al.,  
1106.6051  
...

- Additional EW contributions



Hollik & Pagani, 1107.2606  
Kuhn & Rodrigo, 1109.6830

see talk by Parke

- SM predictions for Tevatron:  $A_{FB}^{SM} \sim 9\%$  (q $\bar{q}$  initial states dominate)
- LHC:  $A_C^{SM} \sim 1\%$  (gg initial state dominates)

- Top quarks at LHCb identified via **single muon** and **b-tagged high- $p_T$  jet**

- Backgrounds for  $t\bar{t}$ :

- Real muons, jets:  $W+b\bar{b}$ ,  $W+jets$

- Fake muons, jets:  $b\bar{b}$ ,  $jj$

- Prospects for top charge asymmetry measurement

- top rest-frame cannot be reconstructed

- use  $\mu$ , b pseudorapidity distribution instead

