Fourth Workshop on Theory, Phenomenology and Experiments in Flavour Physics

Hunting for New Physics with Top Quarks

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13/06/2012, Capri

Intervention: Lepton flavor universality in B decays

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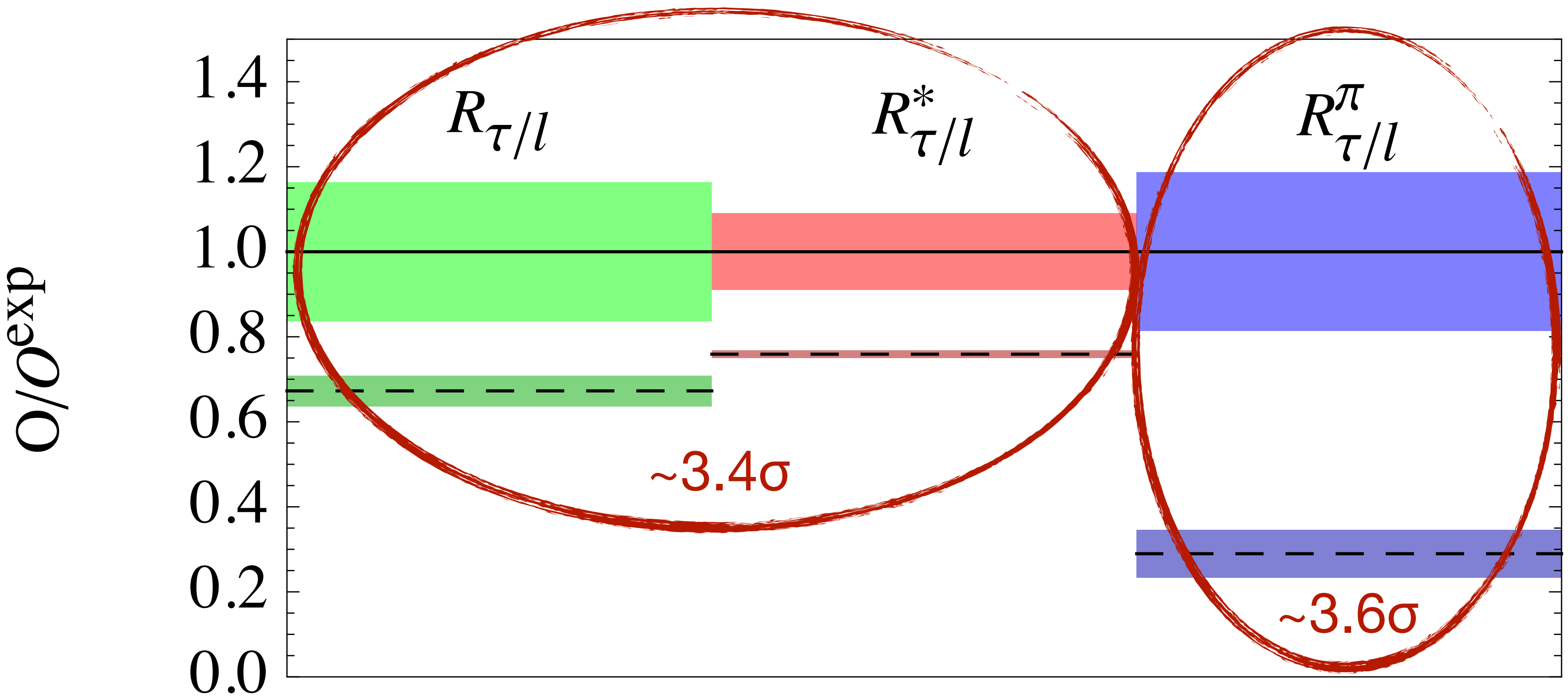
LFU in (semi)leptonic B decays

- Experimental situation



SM predictions

Fajfer, J.F.K., Nisandzic
1203.2654

J.F.K. & Mescia
0802.3790

Nierste, Trine & Westhoff
0801.4938

Tanaka & Watanabe
1005.4306

Laiho, Lunghi & Van de Water
0910.2928

see talk by Ferrarotto

$$\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\ell\nu)} = 0.332 \pm 0.030$$

$$\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D\tau\nu)}{\mathcal{B}(B\to D\ell\nu)} = 0.440 \pm 0.072$$

$$\Big\} \quad b \to c\tau\nu$$

$$\mathcal{R}^\pi_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu})}{\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu})} = 1.07 \pm 0.20 \qquad b \to u\tau\nu$$

LFU in (semi)leptonic B decays

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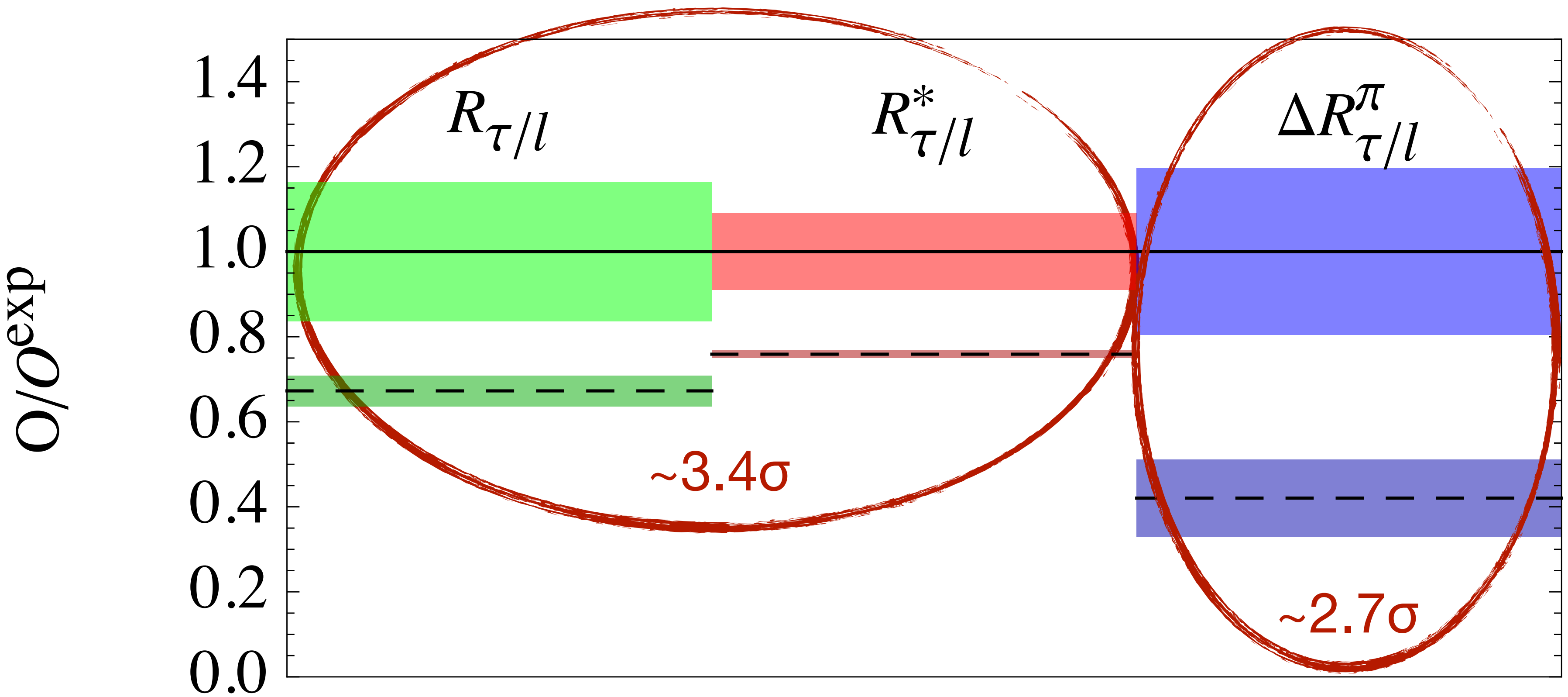

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Khodjamirian et al.
1103.2655

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$$\Delta\mathcal{R}^\pi_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)}\frac{\mathcal{B}(B^-\to\tau^-\bar\nu)}{\Delta\mathcal{B}(\bar B^0\to\pi^+\ell^-\bar\nu)} = 5.17 \pm 1.01 \qquad 16\ {\rm GeV}^2 < q^2 < 26.4\ {\rm GeV}^2$$

New physics interpretation

Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

- General requirements in EFT: $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_a \frac{z_a}{\Lambda^{d_a-4}} \mathcal{Q}_i + \text{h.c.}$
  - no tree-level down quark / charged lepton FCNCs
  - no LFU violations in pion, kaon sectors c.f. HFAG, 1010.1589

} require flavor alignment

$$\mathcal{Q}_L = (\bar{q}_3 \gamma_\mu \tau^a q_3) \mathcal{J}^\mu_{3,a}\,, \qquad \mathcal{J}^\mu_{j,a} = (\bar{l}_j \gamma^\mu \tau_a l_j)$$

$$\mathcal{Q}^i_R = (\bar{u}_{R,i} \gamma_\mu b_R)(H^\dagger \tau^a \tilde{H}) \mathcal{J}^\mu_{3,a}\,,$$

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predict

$c \to u \nu \bar{\nu}$ obscured by tree-level SM

J.F.K. & Smith, 0908.1174

$t \to c(u) \nu \bar{\nu}$ monotops at LHC

Andrea et al., 1106.6199

J.F.K. & Zupan, 1107.0623

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Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

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LFU violation through helicity suppression

$$\mathcal{Q}^i_\psi = (\bar{q}_i b_R)(\bar{l}_3 \psi_R)$$

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⟵ tau lepton number violation + new neutral fermion (ν_R)

c.f. J.F.K. & Smith, 1111.6402

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quark flavor structure not fully determined

Fixing the flavor structure I: MFV

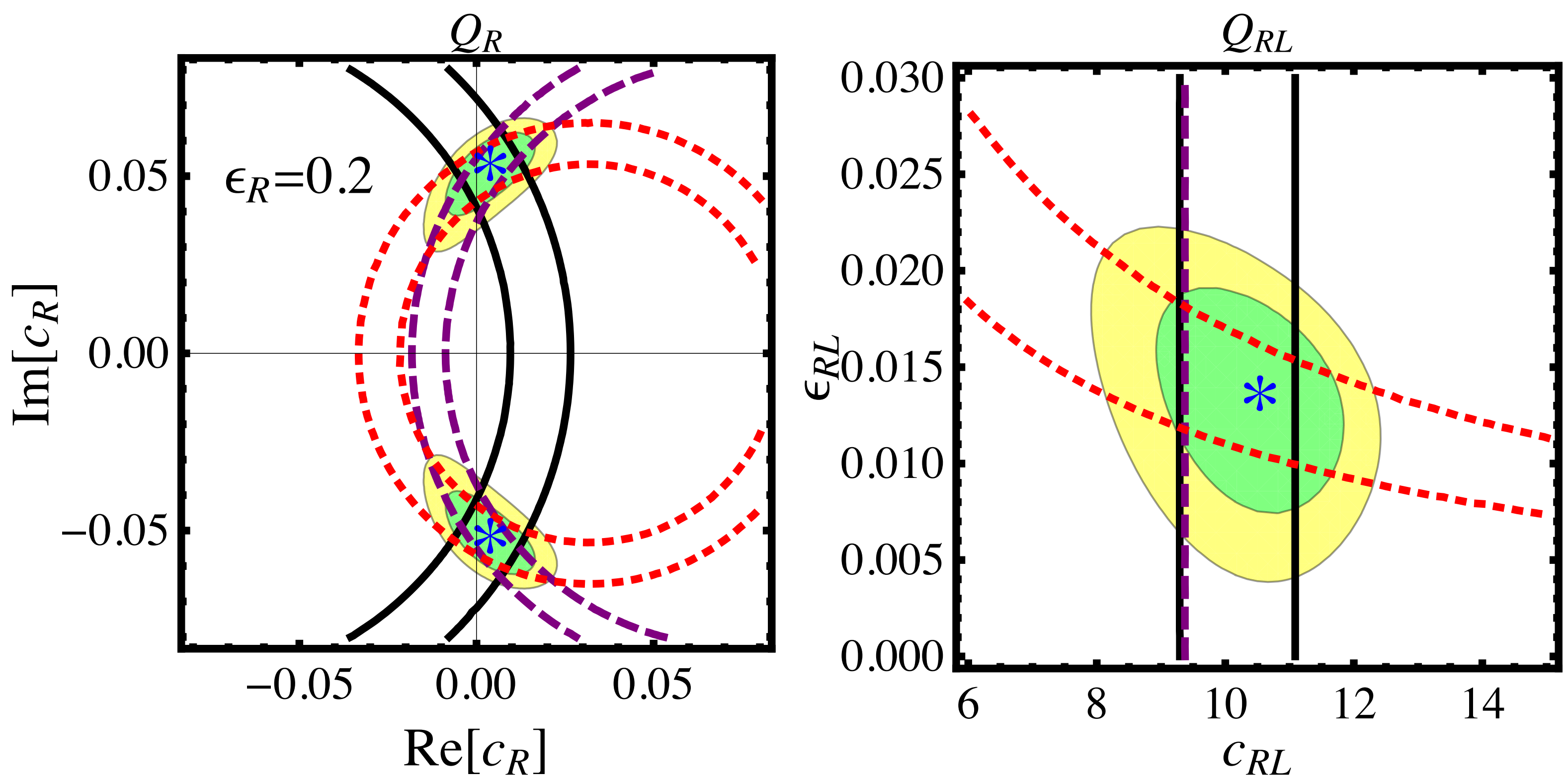
- MFV obeyed by construction for Q_L and Q_{LR}
  - Q_L predicts universal shift to all R - tension between $\mathcal{R}^{(*)}_{\tau/\ell}$, $\mathcal{R}^{\pi}_{\tau/\ell}$
  - Q_{LR} contributions helicity suppressed - tension between $\mathcal{R}_{\tau/\ell}$ and $\mathcal{R}^{*}_{\tau/\ell}$
- imposing MFV on $Q_{R,RL,\psi}$
  - $z^i_{R,RL} \propto m_{u_i}$ - negligible contributions
  - Q_ψ does not interfere with SM, is helicity suppressed - tensions remain

The observed pattern of LFU violations points towards non MFV NP

Fixing the flavor structure II: generic flavor pattern

- Need to parametrize relation between $b \to c$ and $b \to u$ currents

$$z^c_{\psi,R,RL} = c_{\psi,R,RL}(\Lambda/v)^2 \qquad z^u_{\psi,R,RL} = \epsilon_{\psi,R,RL} z^c_{\psi,R,RL}$$



- generic flavor structure does not save Q_ψ

Example NP models: 2HDM

- MFV or “flavor protected” 2HDMs

$$c_{LR} \propto 2m_b v/m_{H^+}^2 \quad c_{RL}^i \propto 2m_{u_i} v/m_{H^+}^2$$

- Generic 2HDM (inert doublet limit)

$$\mathcal{L} \supset \kappa_{RL}^i \bar{q}_3 u_R^i \bar{H} + \kappa_{LR}^i \bar{b}_R \bar{H}^\dagger q_i + \kappa^\tau \bar{\tau}_R l_3 \bar{H} + \text{h.c.}$$

  - can be matched to $i\partial_\mu(\bar{u}_i \tilde{H}^\dagger \tau^a q_3)\mathcal{J}_{3,a}^\mu$ and $i\partial_\mu(\bar{q}_i \tau^a H b_R)\mathcal{J}_{3,a}^\mu$

  - dangerous contributions to *D, B, B*$_s$ mixing

see also, Crivellin, Greub & Kokulu 1206.2634

Example NP models: Leptoquarks

- Many possibilities:
  - scalars in $\boxed{(\mathbf{3}, \mathbf{3}, -1/3),}$ $(\bar{\mathbf{3}}, \mathbf{2}, -7/6)$ and $(\mathbf{3}, \mathbf{1}, -1/3)$
  - vectors in $(\mathbf{3}, \mathbf{3}, 2/3)$, $(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ and $(\mathbf{3}, \mathbf{1}, 2/3)$
- Scalar EW triplet example $\mathcal{L}^{\text{int}}_{S_3} = Y_{S_3} \overline{q_3^c} i\sigma_2 \tau^a S_3^{a*} l_3 + \text{h.c.}\,.$
  - matches onto Q_L - cannot simultaneously explain $\mathcal{R}^{(*)}_{\tau/\ell}$, $\mathcal{R}^{\pi}_{\tau/\ell}$
  - $|Y_{S_3}|/m_{S_3} \simeq 1/150$ GeV in tension with EWPTs

Mizukoshi, Eboli & Gonzalez- Garcia, hep-ph/9411392
Bhattacharyya, Ellis & Sridhar, hep-ph/9406354

  - direct LHC searches already probing interesting mass range

CMS PAS EXO-11-030

Example NP models: Partial compositeness

- Common feature of strong EWSB & composite Higgs models

D. B. Kaplan, Nucl. Phys. B 365, 259 (1991)

- Assume SM fermions obtain masses through kinetic mixing with massive Dirac fermion resonances (Q,L,U,D,E) of the composite sector

- Composite EW vector resonance exchange induces

$$\frac{z_L}{\Lambda^2} \sim \frac{g_\rho^2}{m_\rho^2}[f_3^q]^2[f_3^l]^2\,, \quad \frac{z_R^{u(c)}}{\Lambda^4} \sim \frac{g_\rho^2}{m_\rho^2}\frac{y_3^{Qd}y_{1(2)}^{Qu}}{m_Q^2}[f_3^l]^2$$

  - assume 3rd gen. q, l compositeness $\quad f_3^l = f_3^q = 1$

  - observed LFU violations can be accommodated for

$$g_\rho = \sqrt{4\pi} \qquad m_\rho \simeq 1 \text{ TeV} \qquad \epsilon_{31} \equiv y_3^{Qd}y_1^{Qu}v^2/m_Q^2 \simeq -0.01$$

Prospects

- Experimental verification of observed LFU violations crucial
  - examples: $[\mathcal{B}(B \to \pi\tau\nu)/\mathcal{B}(B \to \pi\ell\nu)]$ $B_c \to \tau\nu$
- ***If confirmed, points towards non MFV NP below TeV***
- Generic LHC predictions

$h + \tau + \mathrm{MET}$ (for $Q_{R,LR,RL}$)

$t{+}\mathrm{MET}$ "monotop" (for $Q_{L,RL}$)

$(t+)\tau + \mathrm{MET}$ (for all Q_i)

  - + on-shell NP d.o.f. production in explicit models

End of intervention

}

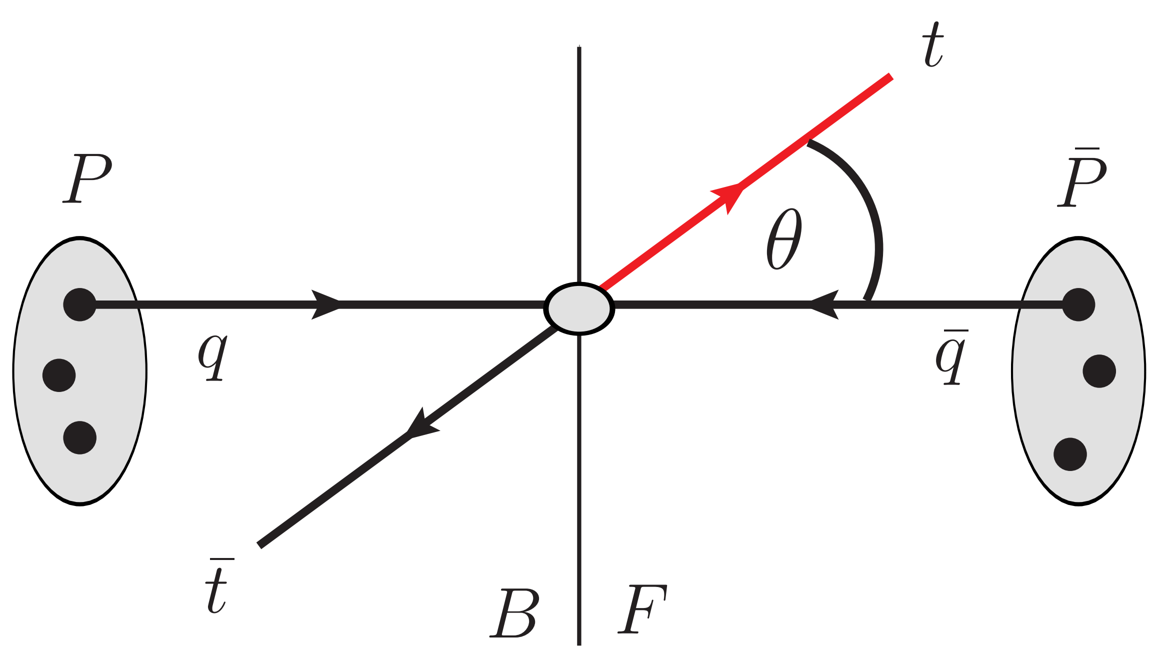
Outline

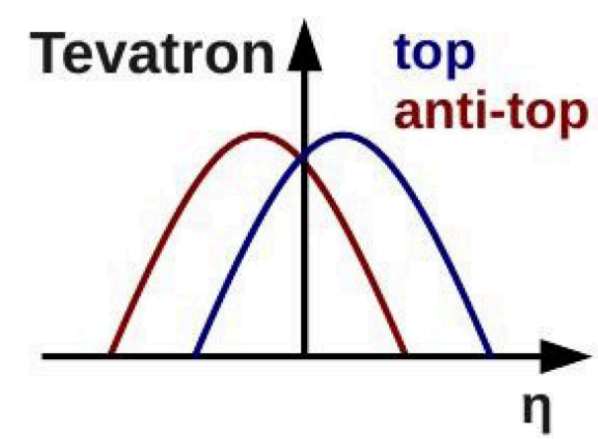
- Persistent hints of anomalies in $t\bar{t}$ production at Tevatron
- Impact of LHC measurements on NP explanations
  - charge asymmetries
  - top spin observables

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

- Charge (a)symmetric cross-section

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





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

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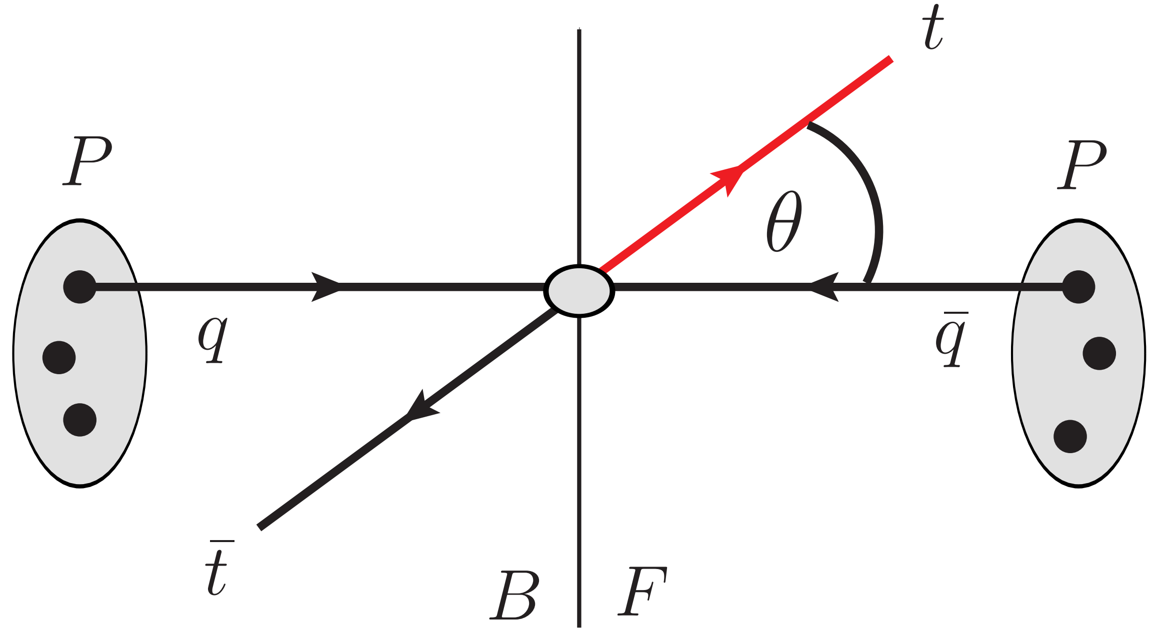
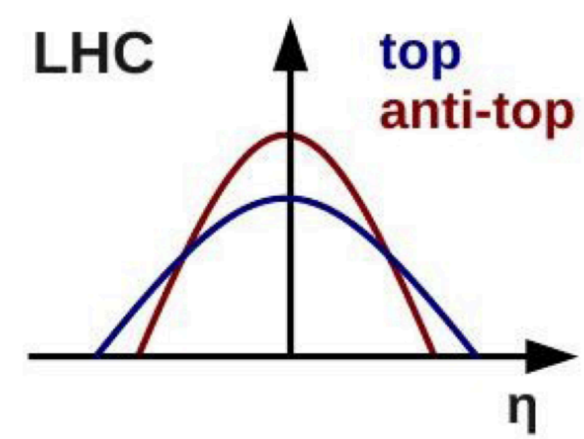




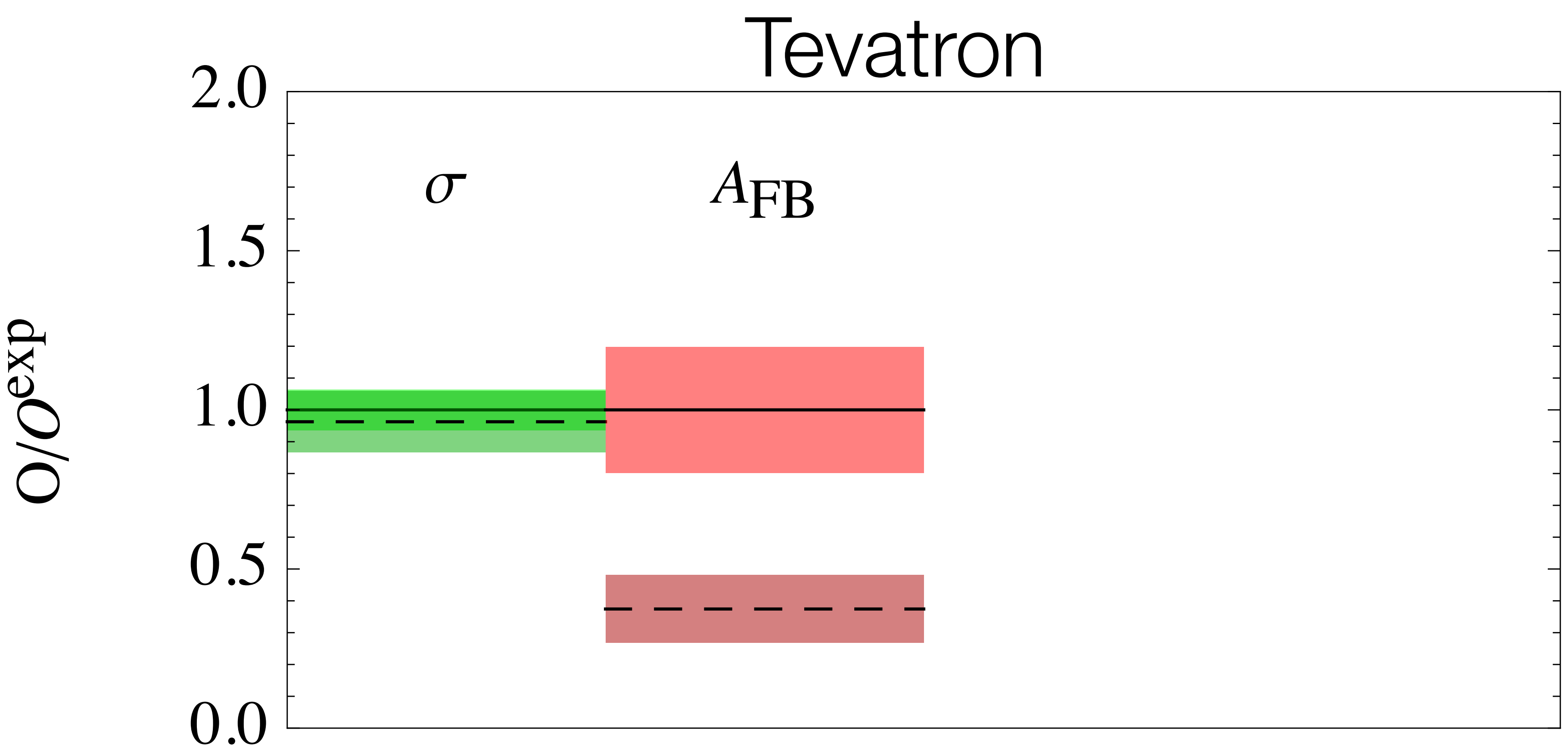
$$A_C = \mathrm{sign}(Y)\frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N(\Delta y^2 > 0) - N(\Delta y^2 < 0)}{N(\Delta y^2 > 0) + N(\Delta y^2 < 0)}$$

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

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

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

- Precisely measured inclusive observables



$\sigma = (7.50 \pm 0.48)\,\text{pb}$ $\qquad$ $A_{FB} = 0.187 \pm 0.037^*$

Baernreuther, Czakon & Mitov, 1204.5201

Kuhn & Rodrigo hep-ph/9802268 hep-ph/9807420 1109.6830

Frixione & Webber hep-ph/0204244

Kidonakis 1105.5167 Ahrens et al. 1106.6051

Hollik & Pagani 1107.2606 Manohar & Trott 1201.3926

CDF, Public Notes 9913, 10398, 10807

D0, 1107.4995

*naive average of CDF & DO measurements

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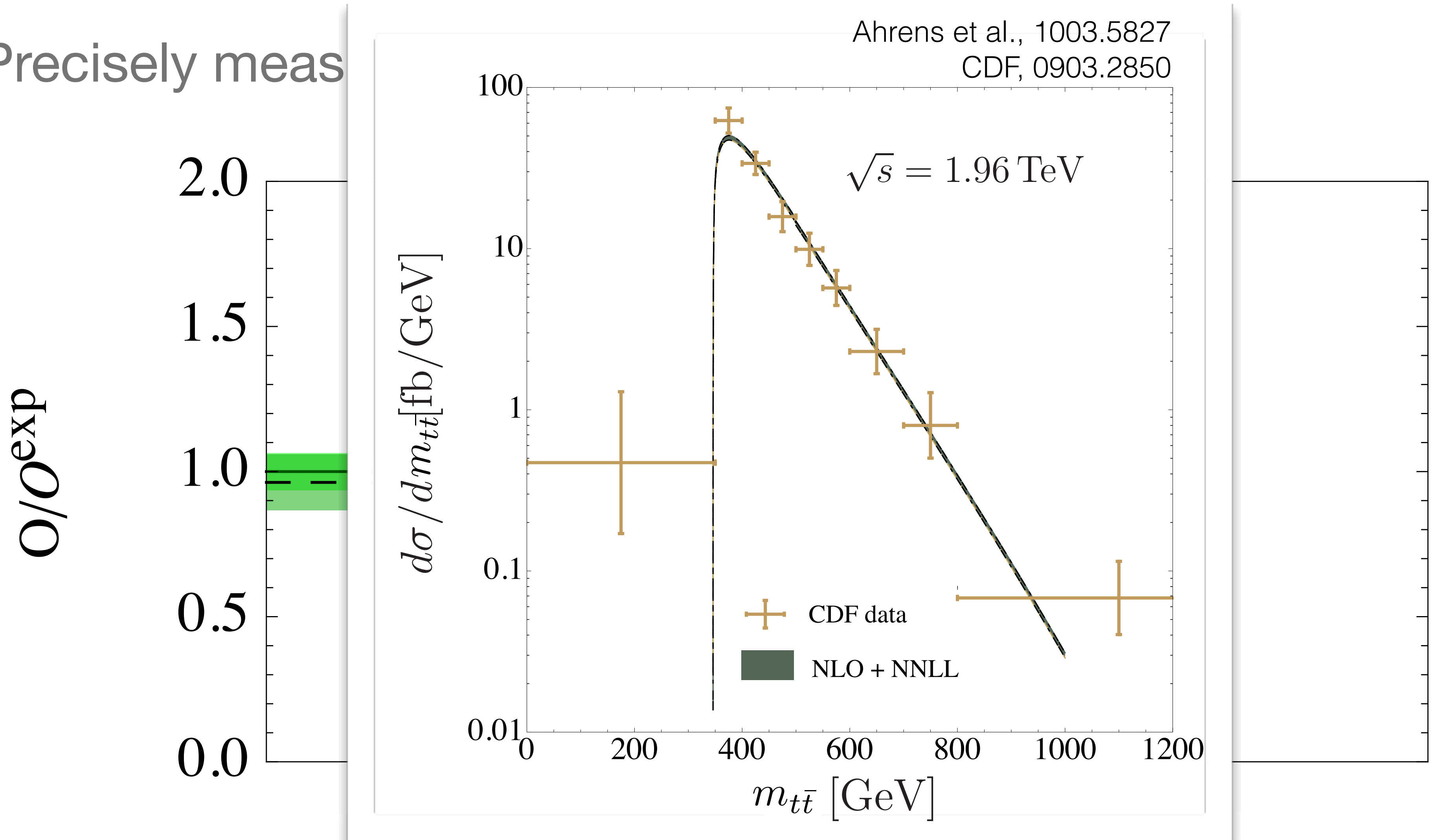

- Sensitive m_{tt} exclusive observables

Baernreuther, Czakon & Mitov,
1204.5201

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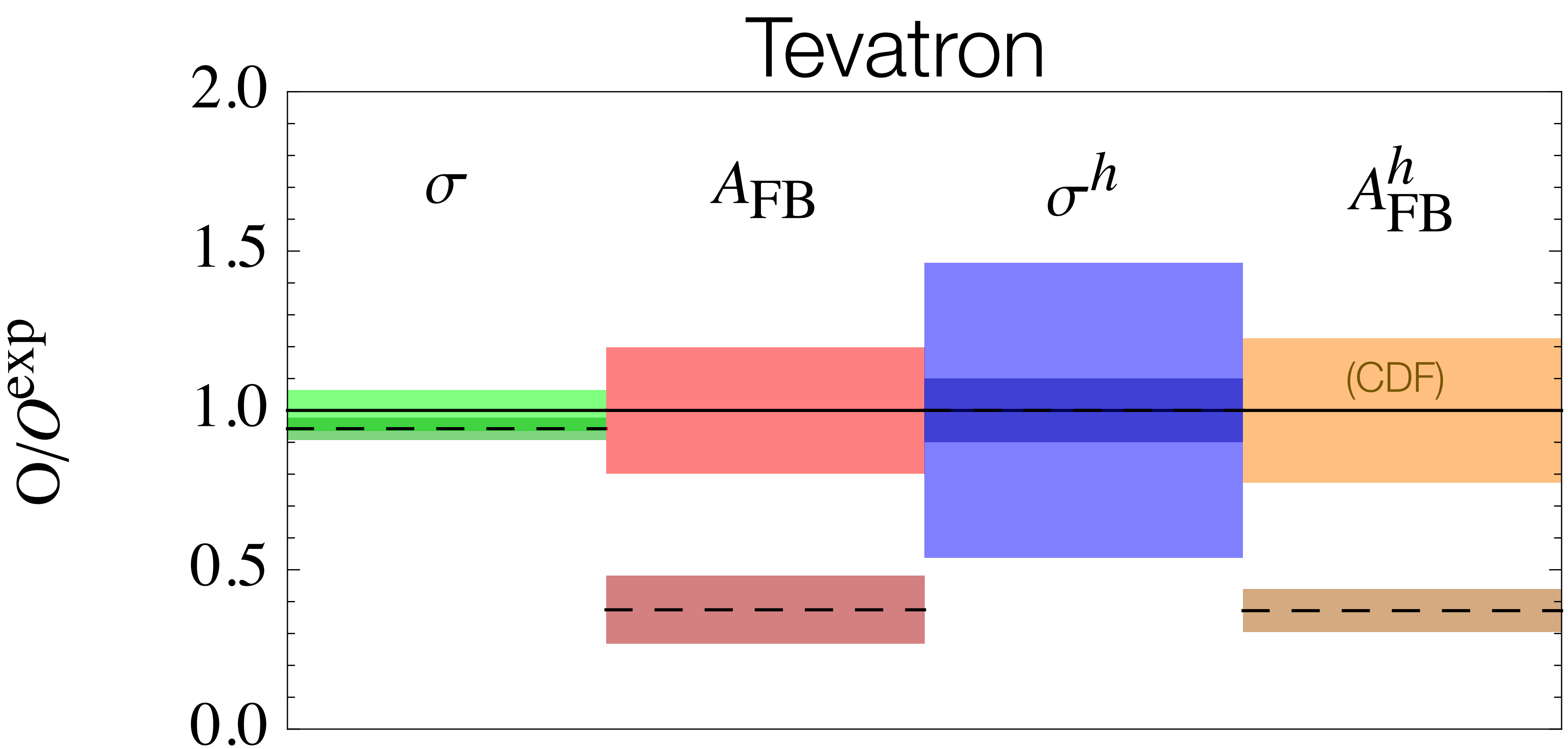

- Sensitive m_{tt} exclusive observables

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

Ahrens et al., 1003.5827
...
Baernreuther, Czakon & Mitov, 1204.5201

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CDF, 0903.2850

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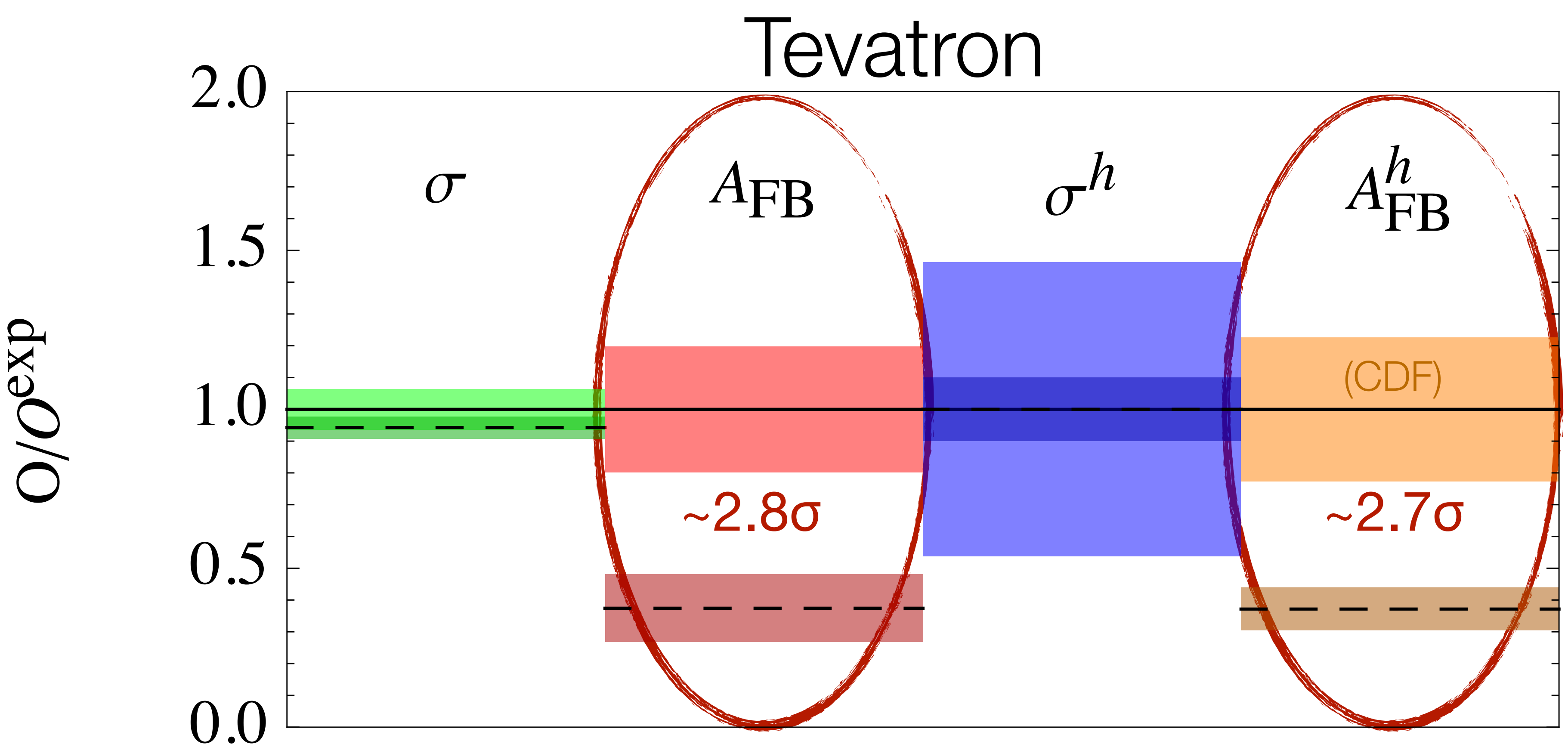

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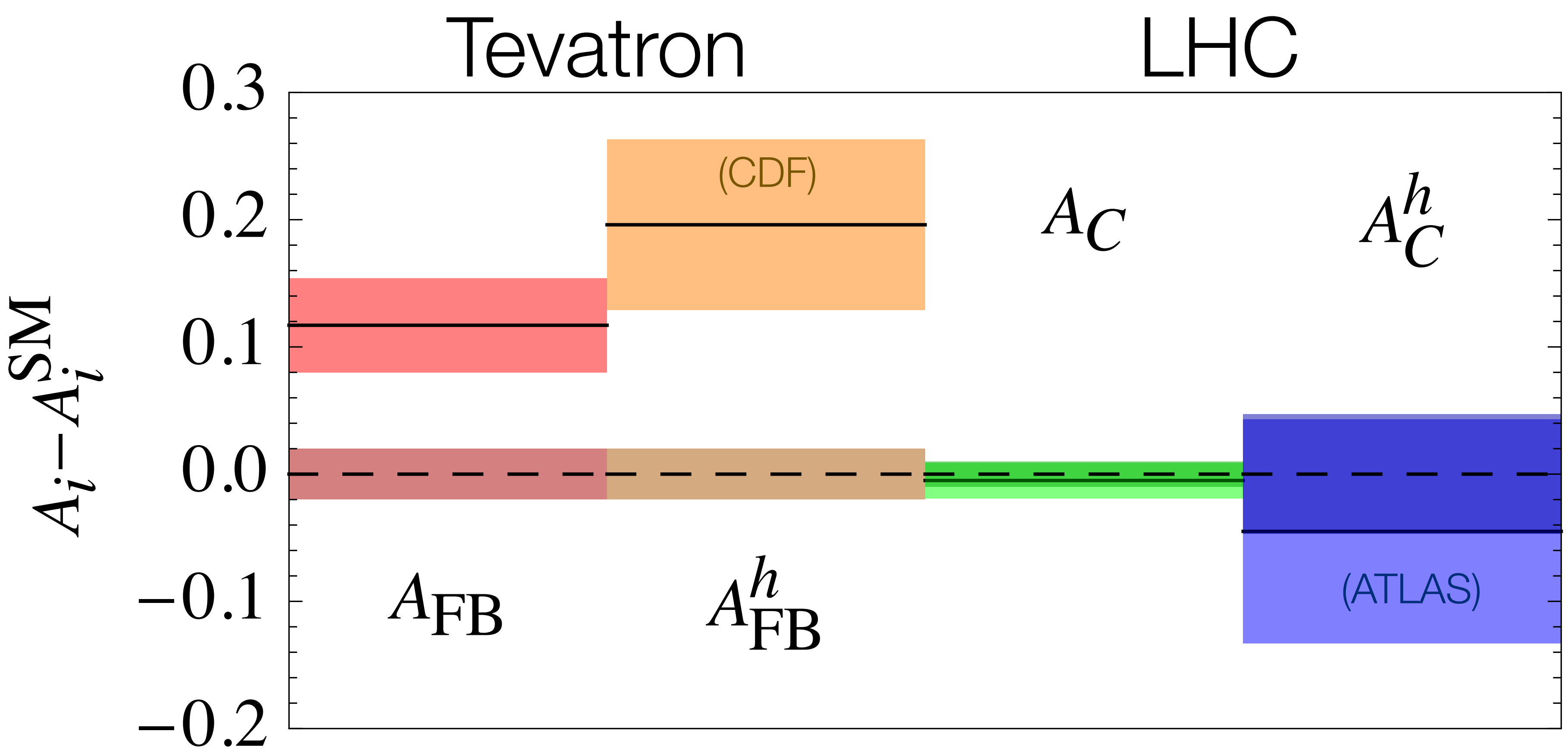
CDF, 0903.2850

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

- Confronting Tevatron A_{FB} & LHC A_C measurements



$$A_C = 0.001 \pm 0.014\ ^*$$

$$A_C^h = -0.008 \pm 0.047 \quad \text{(ATLAS)}$$

No deviations seen at the LHC!

Ahrens et al., 1003.5827
...
Baernreuther, Czakon & Mitov, 1204.5201

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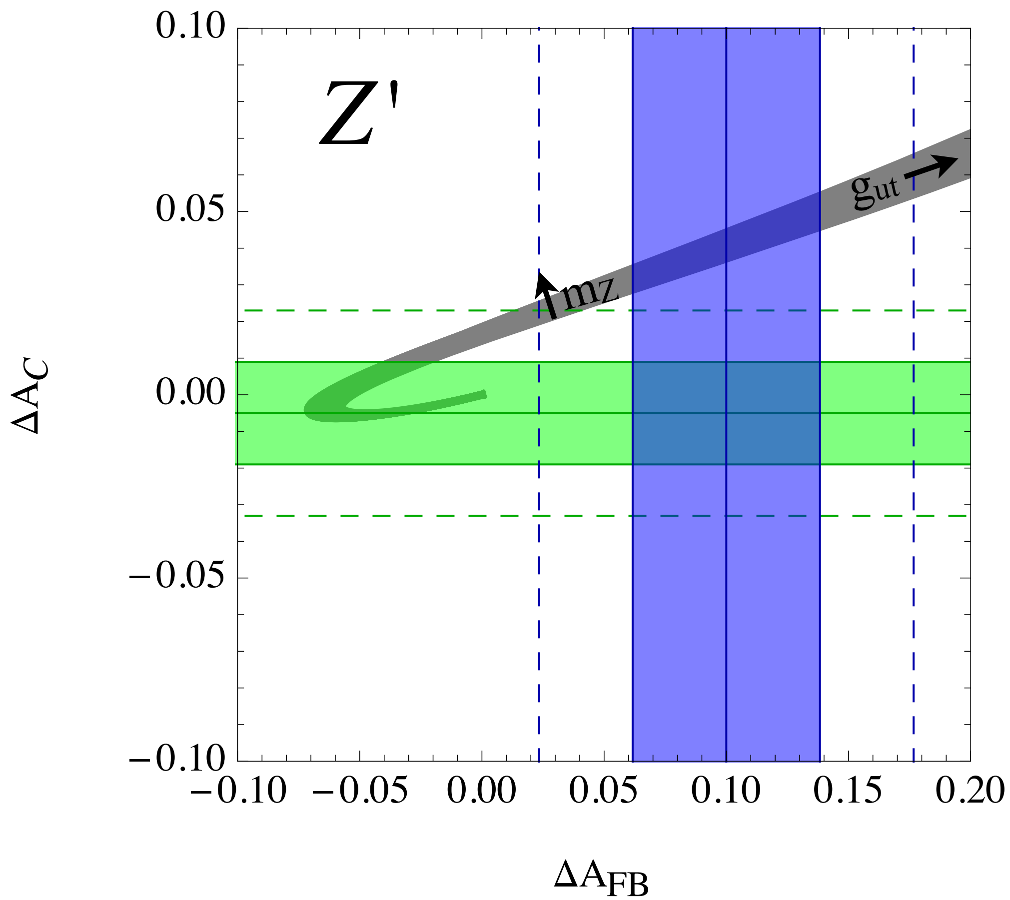
Manohar & Trott
1201.3926

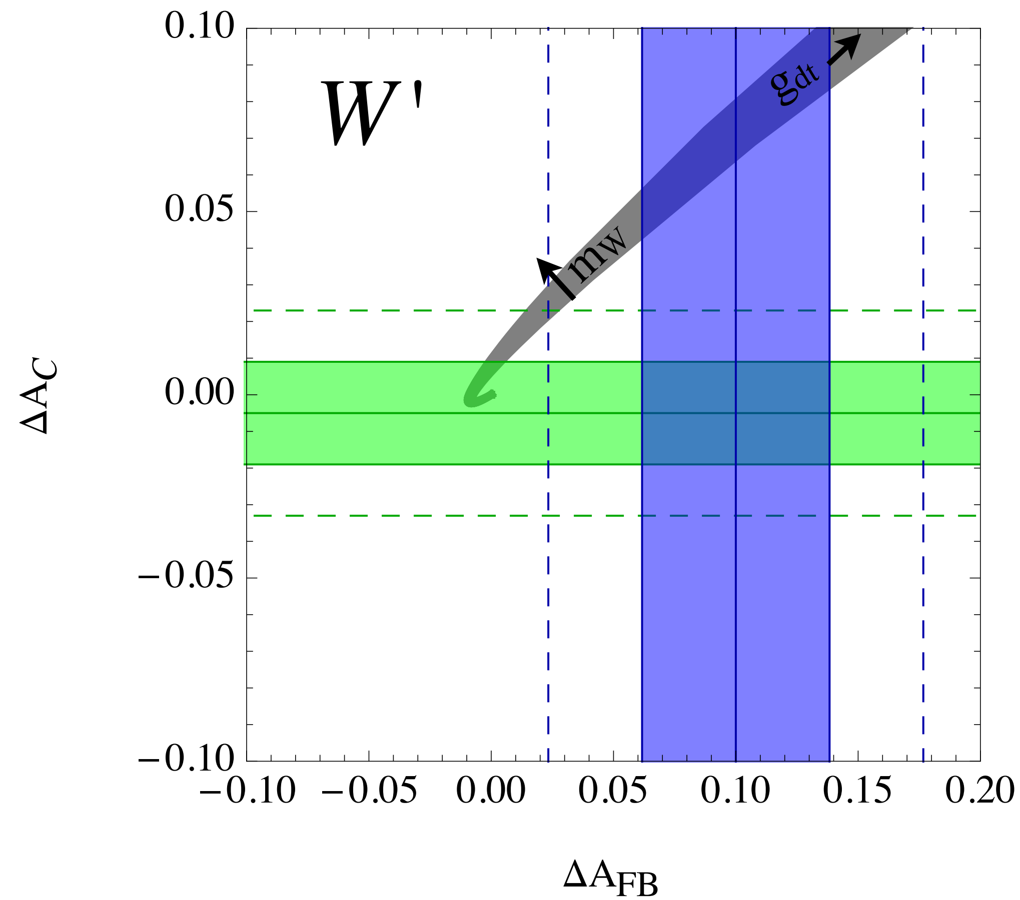
ATLAS, 1203.4211
CMS, PAS-TOP-11-306
ATLAS-CONF-2011-106

*naive average of ATLAS & CMS measurements

Confronting AFB & AC measurements with NP

- Present impact of LHC: Z', W' incompatible with combined A_{FB} & A_C values





Fajfer, J.F.K., Melic, 1205.0264

- Tensions present in all NP interpretations on the market

c.f. Kamenik, Shu, Zupan, 1107.5257

How generic is the observation?

Confronting AFB & AC measurements with NP

- AFB & AC probe different dynamics (uū & dđ luminosities in pp̄ vs. pp)

see also Aguilar-Saavedra & Juste 1205.1898

- EFT illustration $$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{q=u,d} \frac{C_A^{qt}}{\Lambda^2} (\bar{q}\gamma^\mu \gamma_5 q)(\bar{t}\gamma_\mu\gamma_5 t)\,,$$

Drobnak, J.F.K., Zupan, 1205.4721

$$\Delta A_{FB} = -10\% \times \big(0.84 C_A^{ut} + 0.12 C_A^{dt}\big)\big(1{\rm TeV}/\Lambda\big)^2,$$
$$\Delta A_C = -1\% \times \big(1.4 C_A^{ut} + 0.52 C_A^{dt}\big)\big(1{\rm TeV}/\Lambda\big)^2.$$

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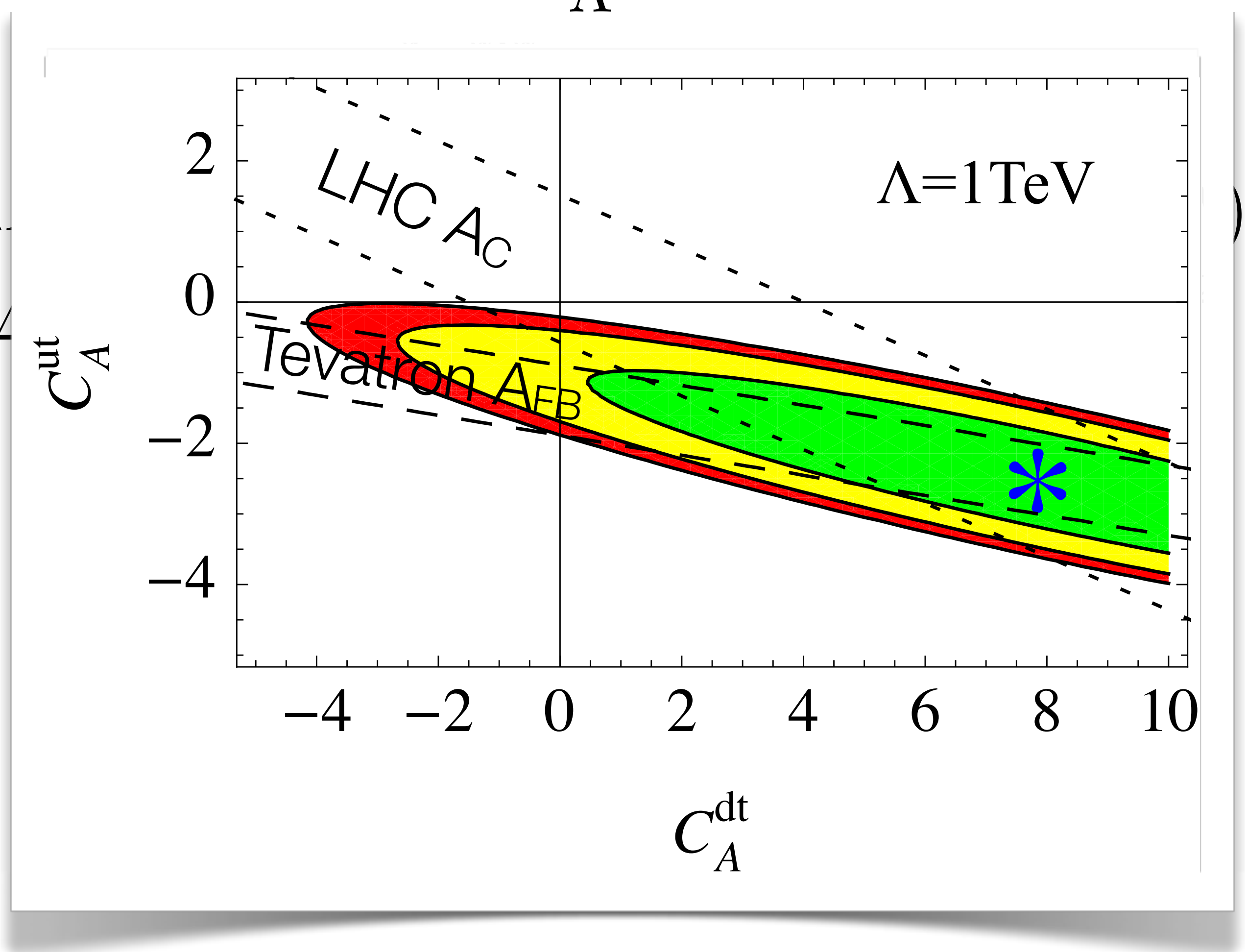
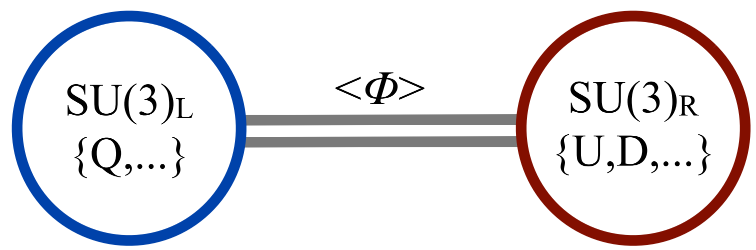
Drobnak, J.F.K., Zupan, 1205.4721



Asymmetric Axigluon

- Explicit model example: two site $SU(3)_L$ x $SU(3)_R$ → $SU(3)_c$

Tavares & Schmaltz
1107.0978



$$\mathcal{L} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{4}(\tilde{G}^a_{\mu\nu})^2 + \frac{\tilde{m}^2}{2}\tilde{A}^2_\mu + \bar{Q}(i\not{D} - \tilde{g}_Q \not{\tilde{A}})Q + \bar{U}(i\not{D} + \tilde{g}_U \not{\tilde{A}})U + \bar{D}(i\not{D} + \tilde{g}_D \not{\tilde{A}})D + \ldots\,,$$

- parity breaking in the new fermionic sector: $\tilde{g}_Q \neq \tilde{g}_U \neq \tilde{g}_D$

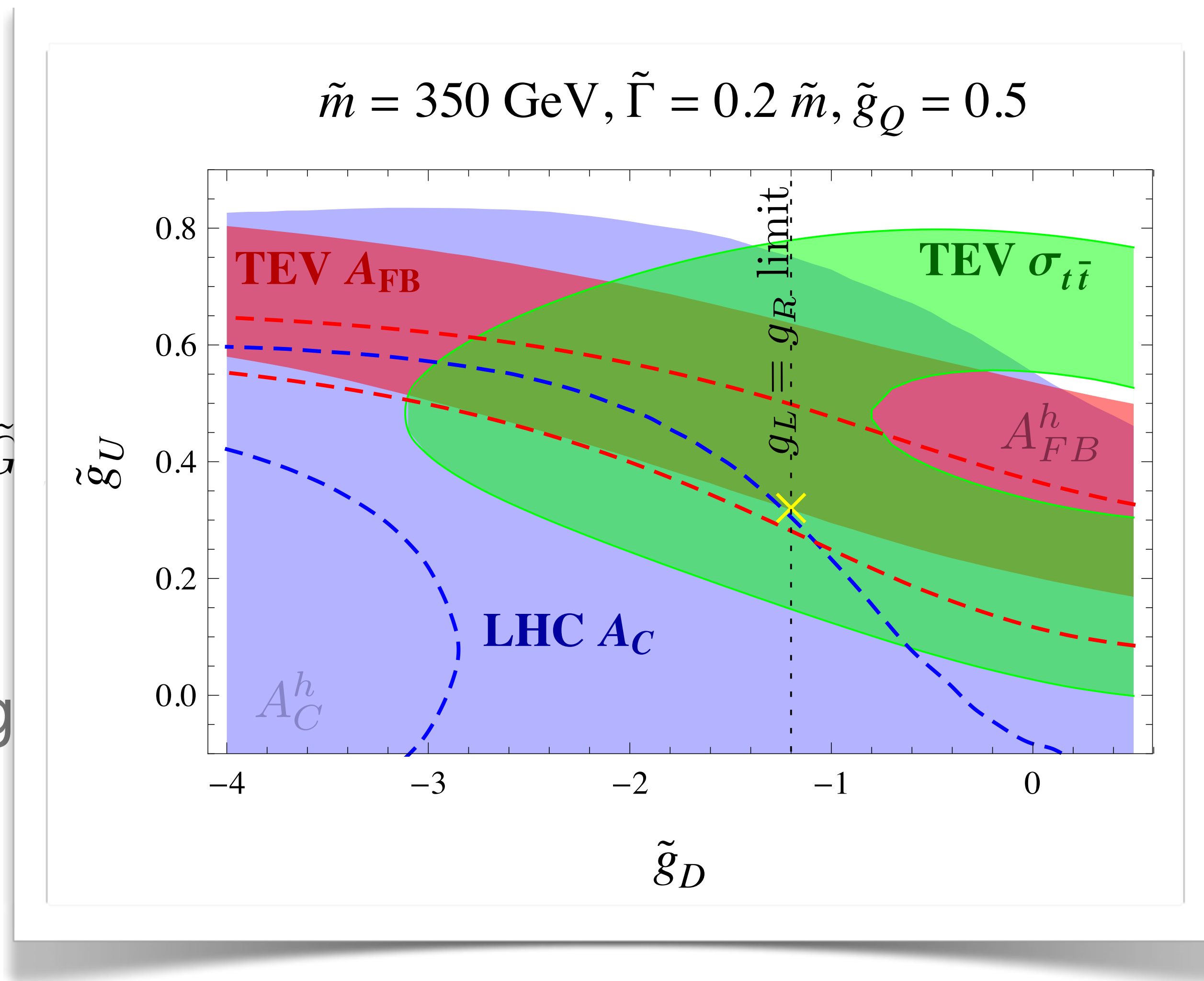
Drobnak, J.F.K., Zupan,
1205.4721

Asymmetric Axigluon

- Explicit model example: two site $SU(3)_L$ x $SU(3)_R$ → $SU(3)_c$

Tavares & Schmaltz
1107.0978

$$\mathcal{L} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{4}(\tilde{G} \quad \bar{D}(i\not{D} + \tilde{g}_D \tilde{\not{A}})D + \dots ,$$



- parity breaking $\quad \tilde{g}_D$

Drobnak, J.F.K., Zupan,
1205.4721

Asymmetric Axigluon

- parity breaking: $\tilde{g}_Q \neq \tilde{g}_U \neq \tilde{g}_D$ - vector contributions - “pseudo axigluon”
    - constraints from $t\bar{t}$, dijet resonance searches
  - flavor universality breaking: large (pseudo) axigluon width possible

$$\Gamma \simeq \frac{\tilde{m}}{48\pi}\left[5\tilde{g}_Q^2 + 2\tilde{g}_U^2 + 3\tilde{g}_D^2\right] \qquad (\tilde{m} < 2m_t)$$

Asymmetric Axigluon

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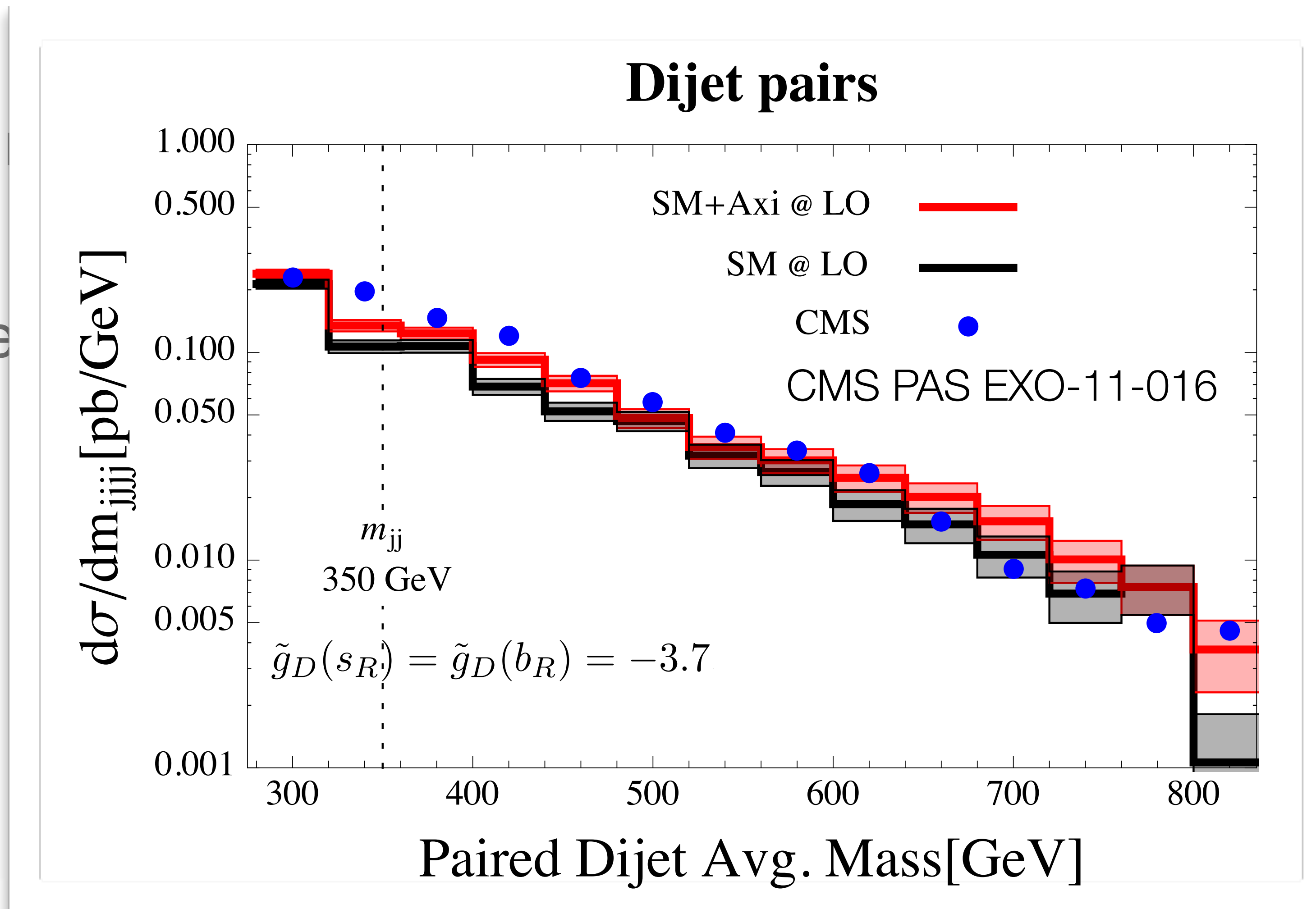
    - constrai

  - flavor unive ossible



Asymmetric Axigluon

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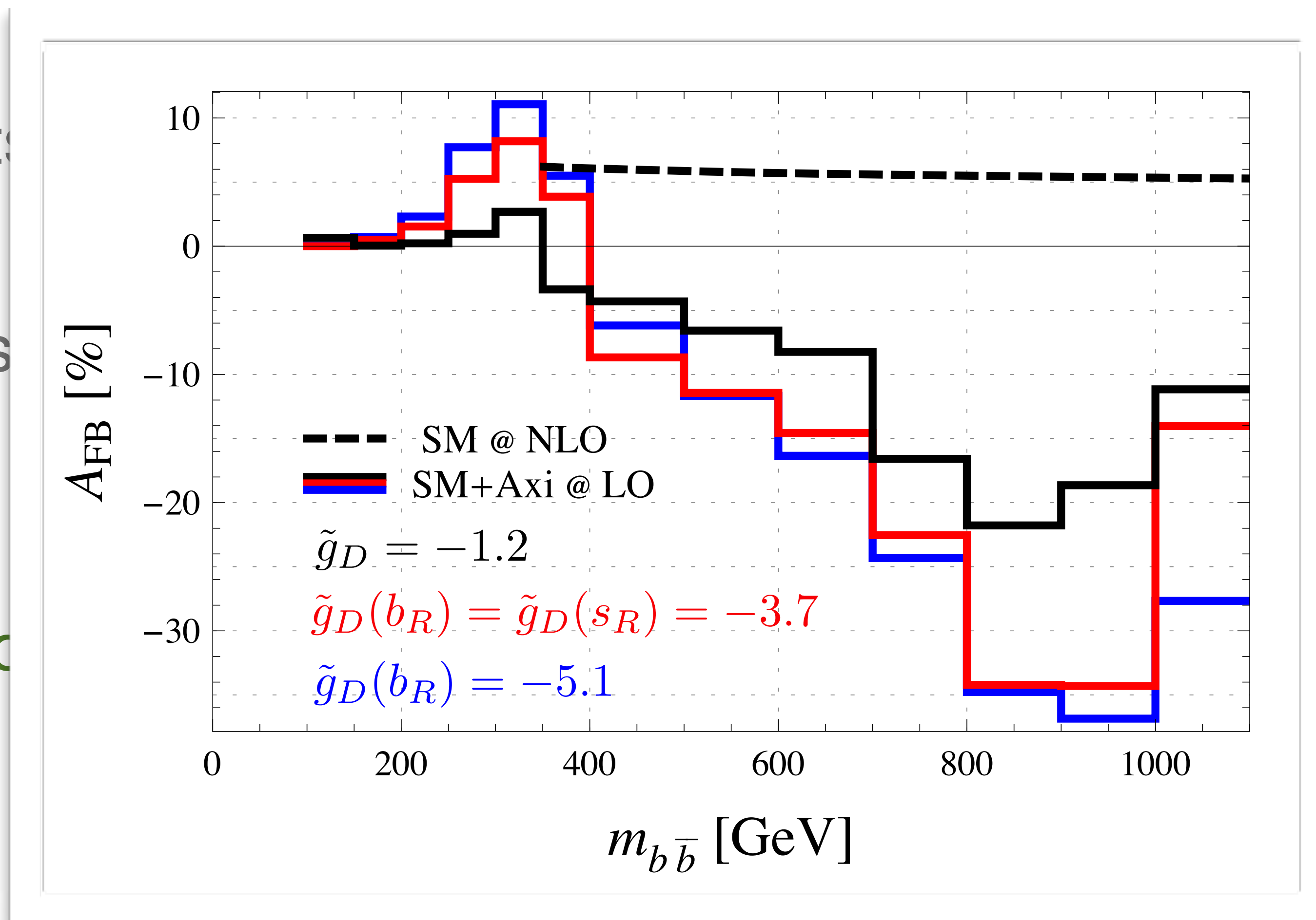
    - contributions to FBA in bb̄ production!

Asymmetric Axigluon

- parity breaking: $\tilde{g}_Q \neq \tilde{g}_U \neq \tilde{g}_D$ - vector contributions - "pseudo axigluon"
    - constraint
- flavor univers ... possible
    - contributio



predict zero in FBA spectrum

Asymmetric Axigluon

- parity breaking: $\tilde{g}_Q \neq \tilde{g}_U \neq \tilde{g}_D$ - vector contributions - “pseudo axigluon”
    - constraints from $t\bar{t}$, dijet resonance searches
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$$\Gamma \simeq \frac{\tilde{m}}{48\pi}\left[5\tilde{g}_Q^2 + 2\tilde{g}_U^2 + 3\tilde{g}_D^2\right] \qquad (\tilde{m} < 2m_t)$$

- contributions to FBA in $b\bar{b}$ production!
- polarized top pair production

Top polarization observables

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

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_f d\cos\theta_{\bar{f}}} = \frac{1}{4}\left(1 + B_t\cos\theta_f + B_{\bar{t}}\cos\theta_{\bar{f}} - C\cos\theta_f\cos\theta_{\bar{f}}\right)$$

(anti)top polarization
(tiny in SM)

$t\bar{t}$ spin correlations
(well predicted in SM)

Bernreuther et al.,
hep-ph/0403035

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

Top polarization observables

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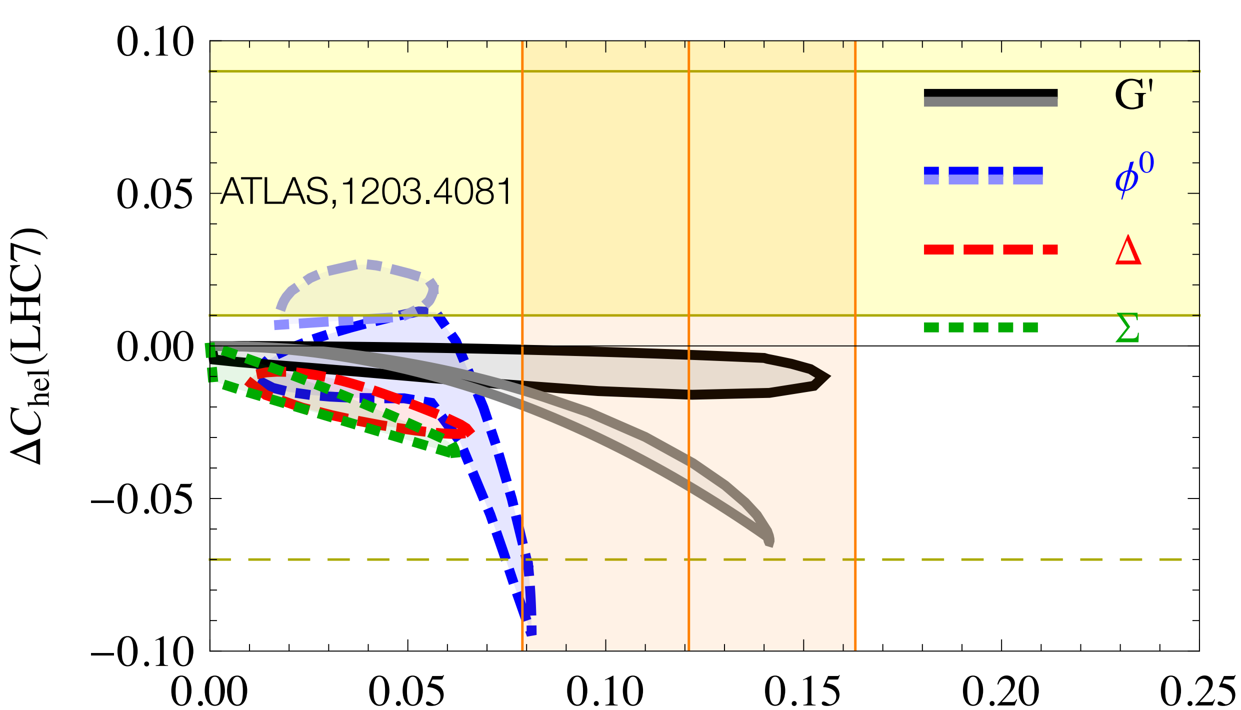
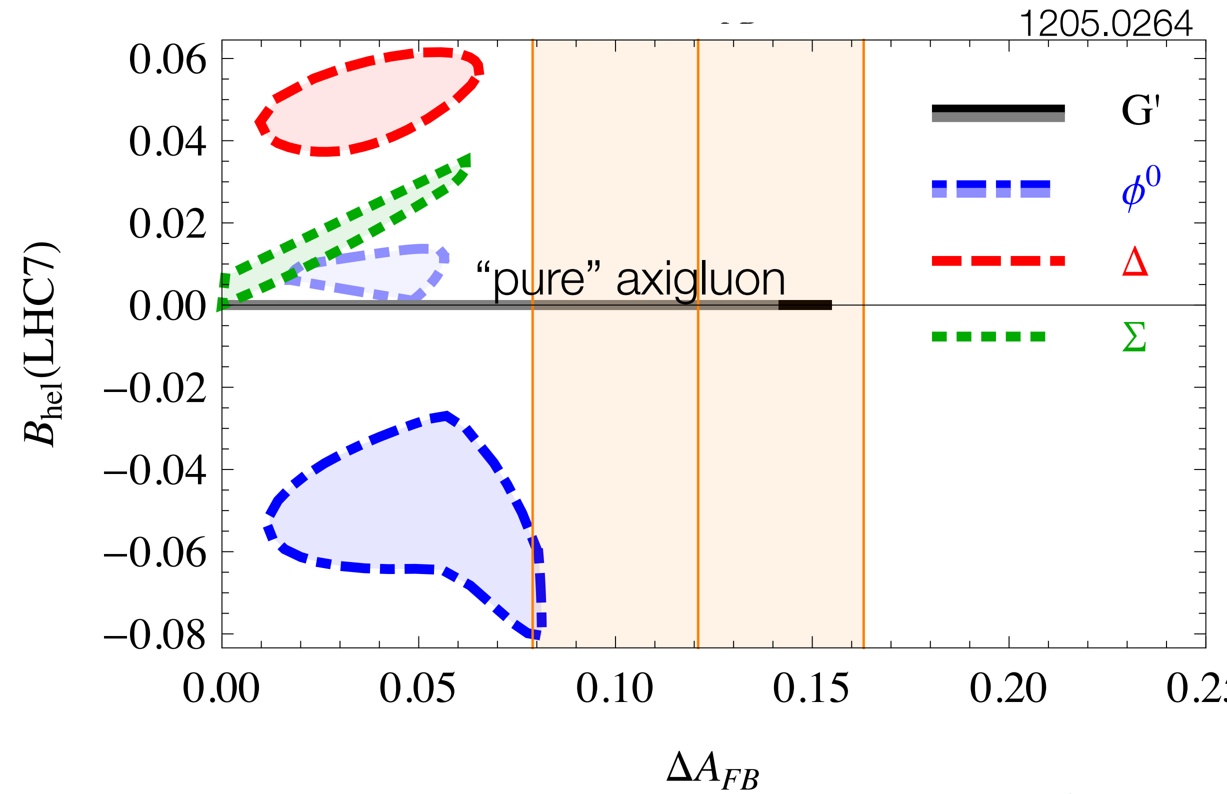
(anti)top polarization $t\bar{t}$ spin correlations

Fajfer, J.F.K., Melic, 1205.0264





existing nontrivial constraint!

discriminating power of top polarization

Top polarization observables

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

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_f d\cos\theta_{\bar{f}}} = \frac{1}{4}\left(1 + B_t \cos\theta_f + B_{\bar{t}}\cos\theta_{\bar{f}} - C\cos\theta_f\cos\theta_{\bar{f}}\right)$$

(anti)top polarization
(tiny in SM)

$t\bar{t}$ spin correlations
(well predicted in SM)

Bernreuther et al.,
hep-ph/0403035

- asymmetric axigluon predictions: $B^{\mathrm{TEV}}_{\mathrm{beam}} \simeq B^{\mathrm{TEV}}_{\mathrm{off-diagonal}} \simeq 13\%$
$B^{\mathrm{LHC7}}_{\mathrm{helicity}} \simeq 2\%$

Drobnak, J.F.K., Zupan,
1205.4721

Prospects

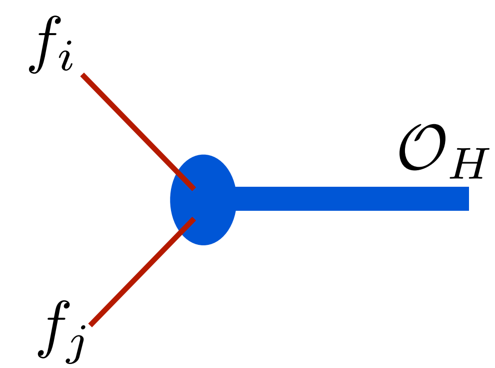
- Anomalies observed in $t\bar{t}$ production at Tevatron will have to be resolved by LHC experiments
  - top charge asymmetry & spin correlation measurements already constrain possible NP interpretations of Tevatron FBA puzzle
  - $t\bar{t}$ spectrum measurements effective for heavy s-channel resonant effects
  - interesting role of high rapidity region - top quarks at the LHCb Kagan, J.F.K., Perez & Stone, 1103.3747
- FBA & CA correlation can be broken in general enough NP models
  - implies interesting effects in top polarization, dijet spectra, $b\bar{b}$ production
  - significant (~10%) room for incoherent ($t\bar{t}$+jet, $t\bar{t}$+MET) contributions barely explored so far, CA @ LHC especially sensitive

    Isidori & J.F.K., 1103.0016
    Zurek et al., 1107.4364

Backup

Partial Compositeness

- Two ways of giving mass to chiral fermions
  - Bi-linear (SM-like): $\mathcal{L} \ni y f_L \mathcal{O}_H f_R\,, \quad \mathcal{O}_H \sim (1,2)_{1/2}$
    - problematic if dim(O_H) > 1 (in strong EWSB models)

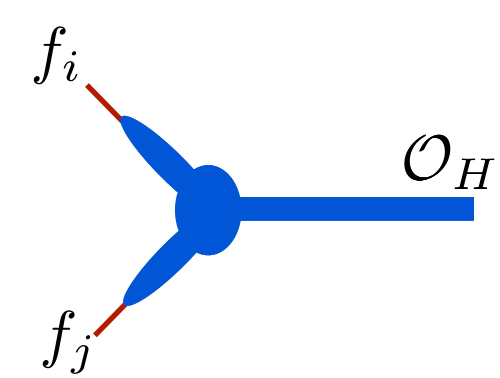


  - Linear: $\mathcal{L} \ni m_L f_L \mathcal{O}_R + m_R f_R \mathcal{O}_L + \lambda \mathcal{O}_L \mathcal{O}_H \mathcal{O}_R\,, \quad \mathcal{O}_L \sim (3,2)_{1/6}\,, \ldots$

Kaplan, Nucl.Phys. B365 (1991) 259-278

    - elementary quarks & leptons mix with a strong sector

$$|SM\rangle = \cos\phi |elem.\rangle + \sin\phi |comp.\rangle\,,$$
$$|heavy\rangle = -\sin\phi |elem.\rangle + \cos\phi |comp.\rangle$$



    - mass ∝ compositeness

3rd gen. SM fermions expected to have largest composite component

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

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

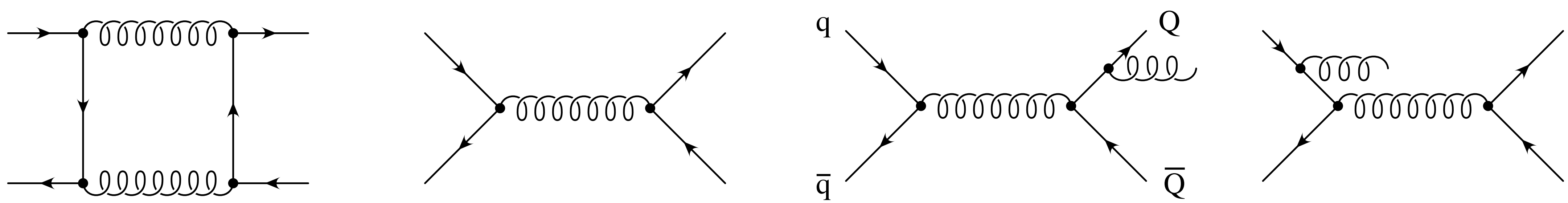
$$\beta_t = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

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

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

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

- In QCD induced at order α_s^3

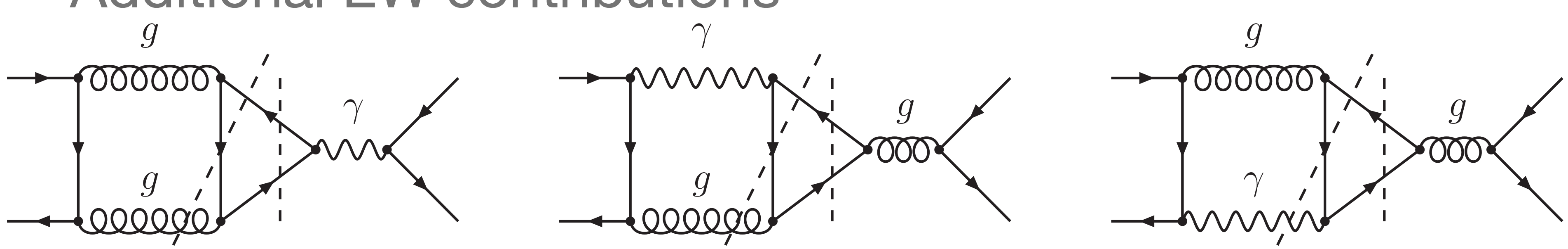


Kuhn & Rodrigo, hep-ph/9802268, hep-ph/9807420

Ahrens et al., 1106.6051

...

- Additional EW contributions



Hollik & Pagani, 1107.2606
Kuhn & Rodrigo, 1109.6830

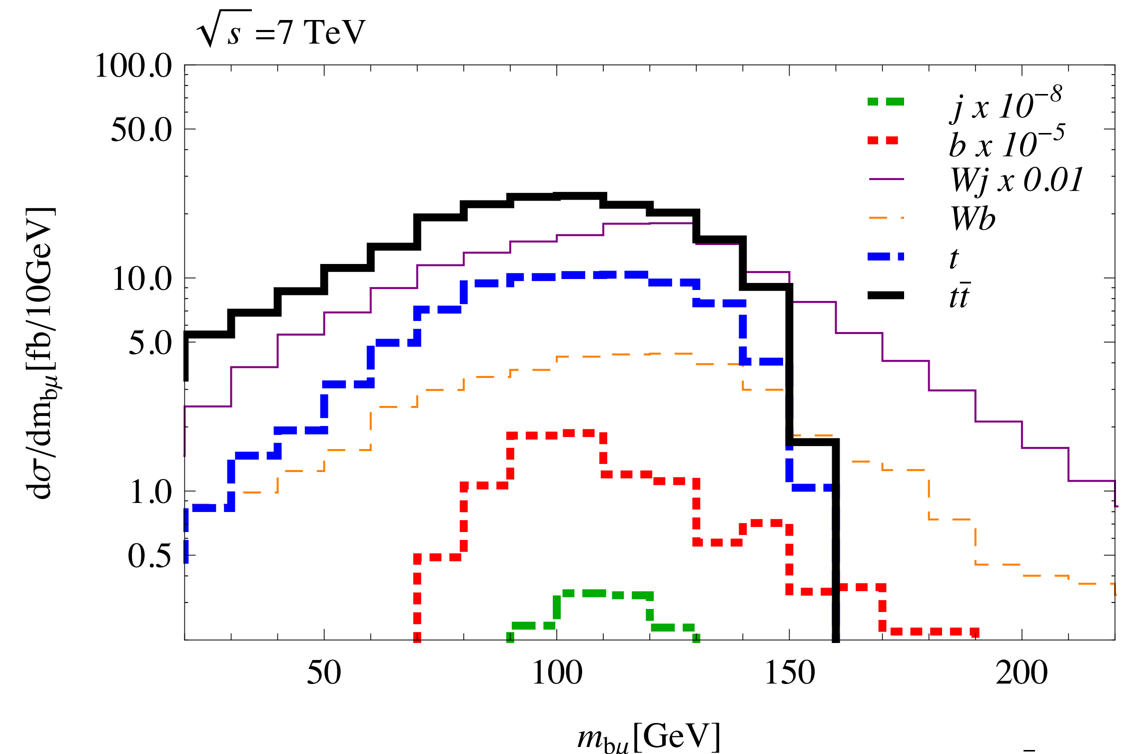
- SM predictions for Tevatron: $A_{FB}^{\mathrm{SM}} \sim 7 - 9\%$ ($q\bar{q}$ initial states dominate)

LHC: $A_C^{\mathrm{SM}} \sim 1\%$ (gg initial state dominates)

LHC~~b~~t

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

- 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 μ, b pseudorapidity distribution instead

$$A_\eta^{t\bar{t}} = \left(\frac{d\sigma^t/d\eta - d\sigma^{\bar{t}}/d\eta}{d\sigma^t/d\eta + d\sigma^{\bar{t}}/d\eta}\right)$$