Flavor Physics and CP Violation 2011

New physics and top

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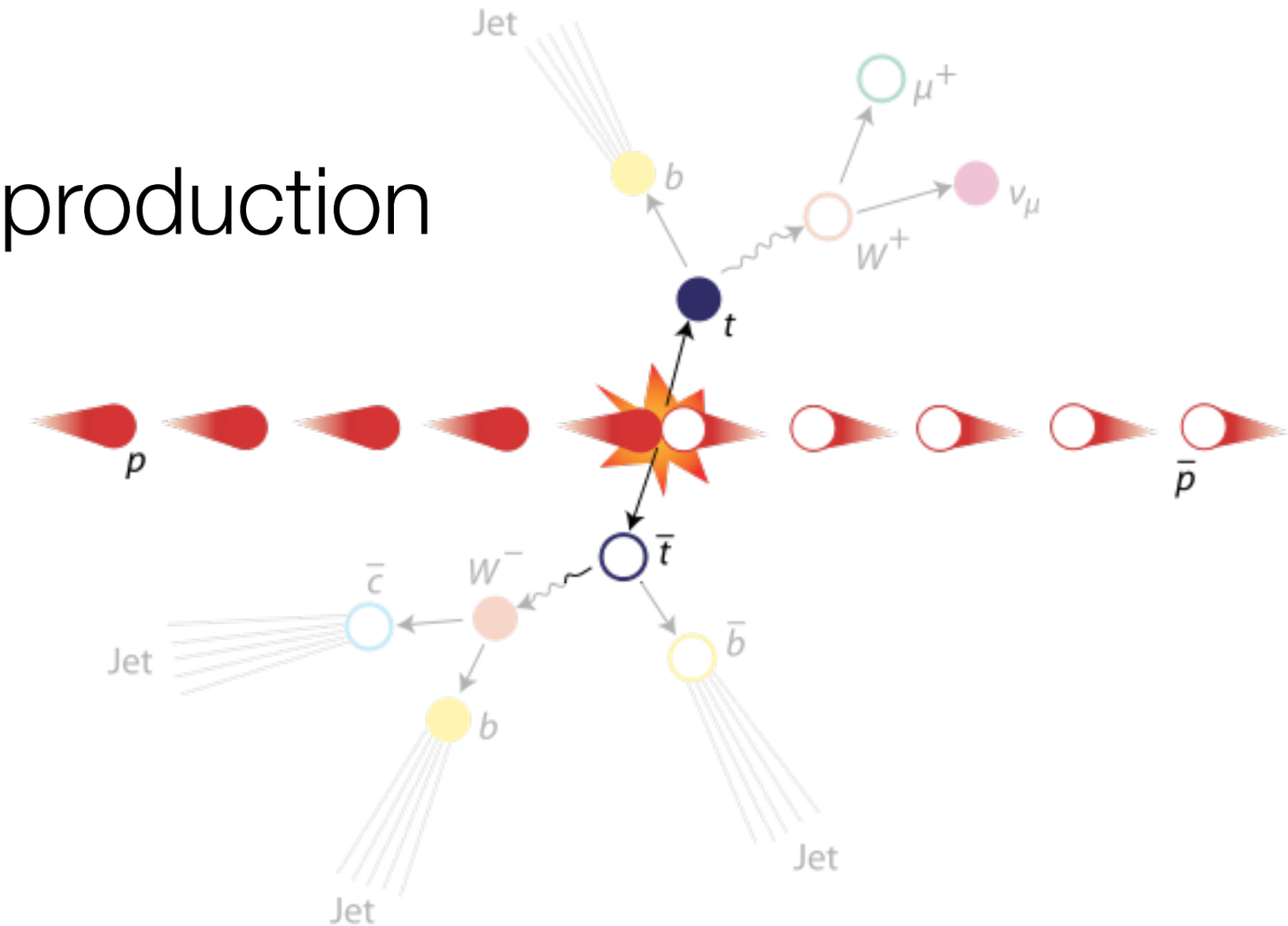
Outline*

- New physics in top production
    - Explanations of FBA @ Tevatron ➜ Observables for LHC
- New physics in top decay
    - Polarization observables in $t \to bW$ ➜ New angles on CPV in B system

*Personally biased choice of topics
Apologies for incomplete referencing

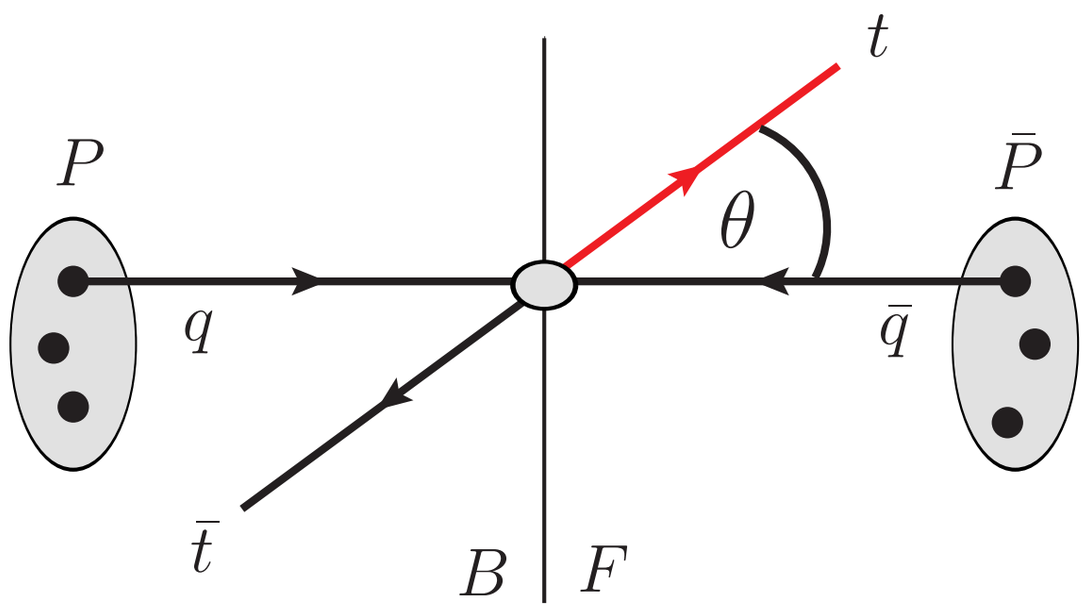
New physics in top production



Forward-backward asymmetry in $t\bar{t}$ production

- Charge (a)symmetric cross-section

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



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

Forward-backward asymmetry in $t\bar{t}$ production

- Non-zero A_{FB} requires u- or t-odd contributions to σ

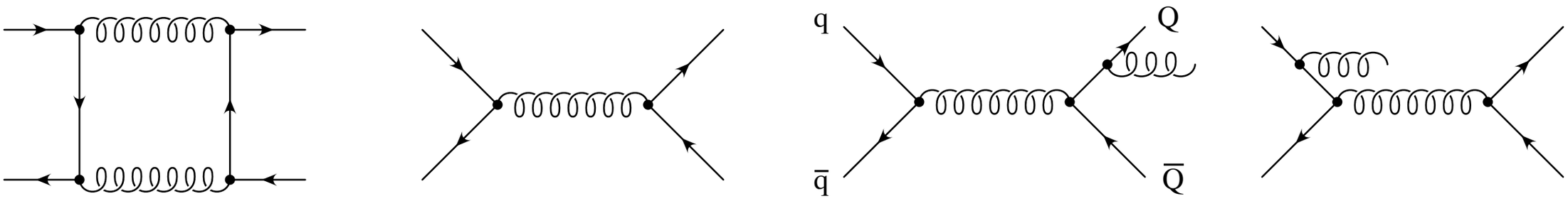
$$\hat{t} = m_t^2 - \frac{\hat{s}}{2}[1 - \beta_t \cos\theta]$$

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

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

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

- In QCD induced at order α_s^3



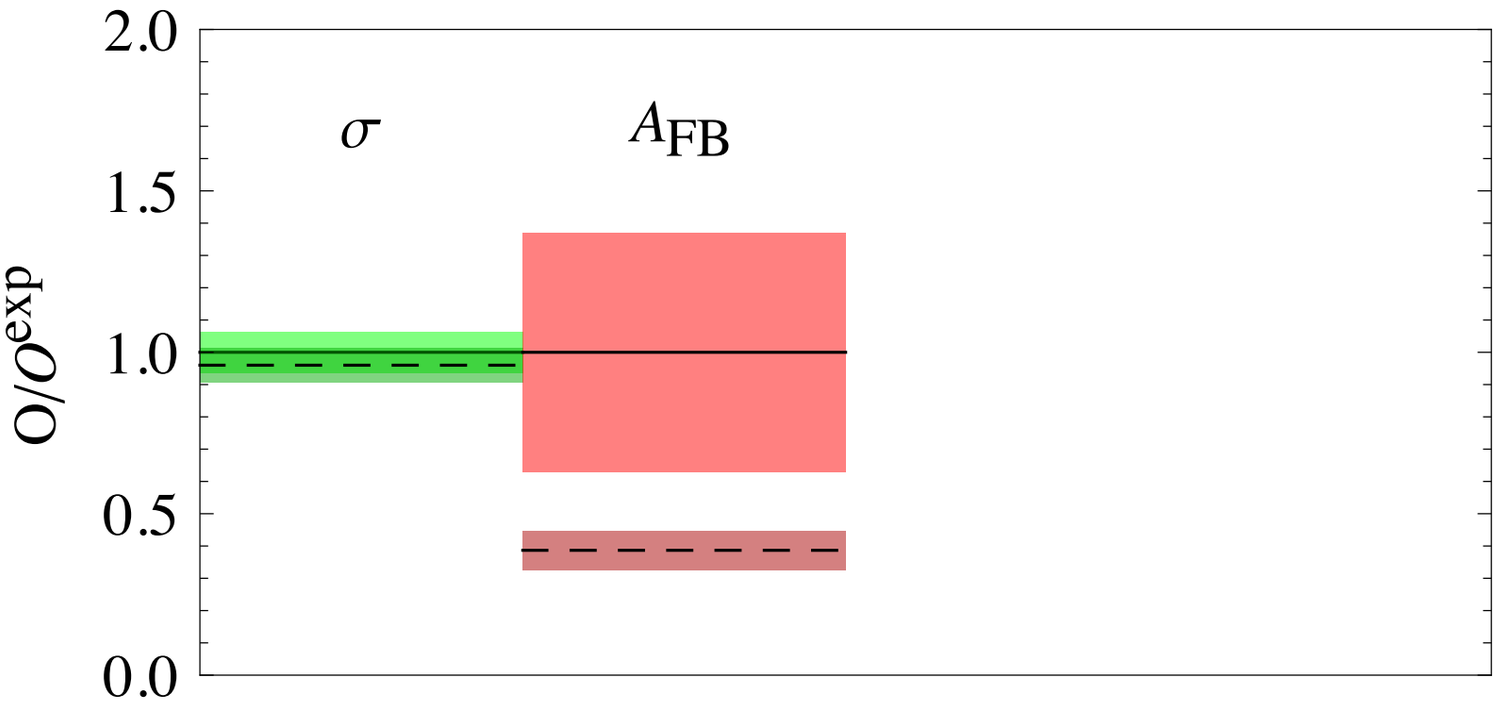
$$A_{FB}^{\mathrm{SM}} = 0.058 \pm 0.009$$

Almeida et al., 0805.1885

Forward-backward asymmetry in $t\bar{t}$ production

- Measurements at the Tevatron

see also talk by Schwarz



Kidonakis, 1009.4935, 1105.3481

$$\sigma = (7.50 \pm 0.48)\,\text{pb} \qquad A_{FB} = 0.158 \pm 0.074$$

CDF, 0903.2850

Schwanenberger [CDF], 1012.2319

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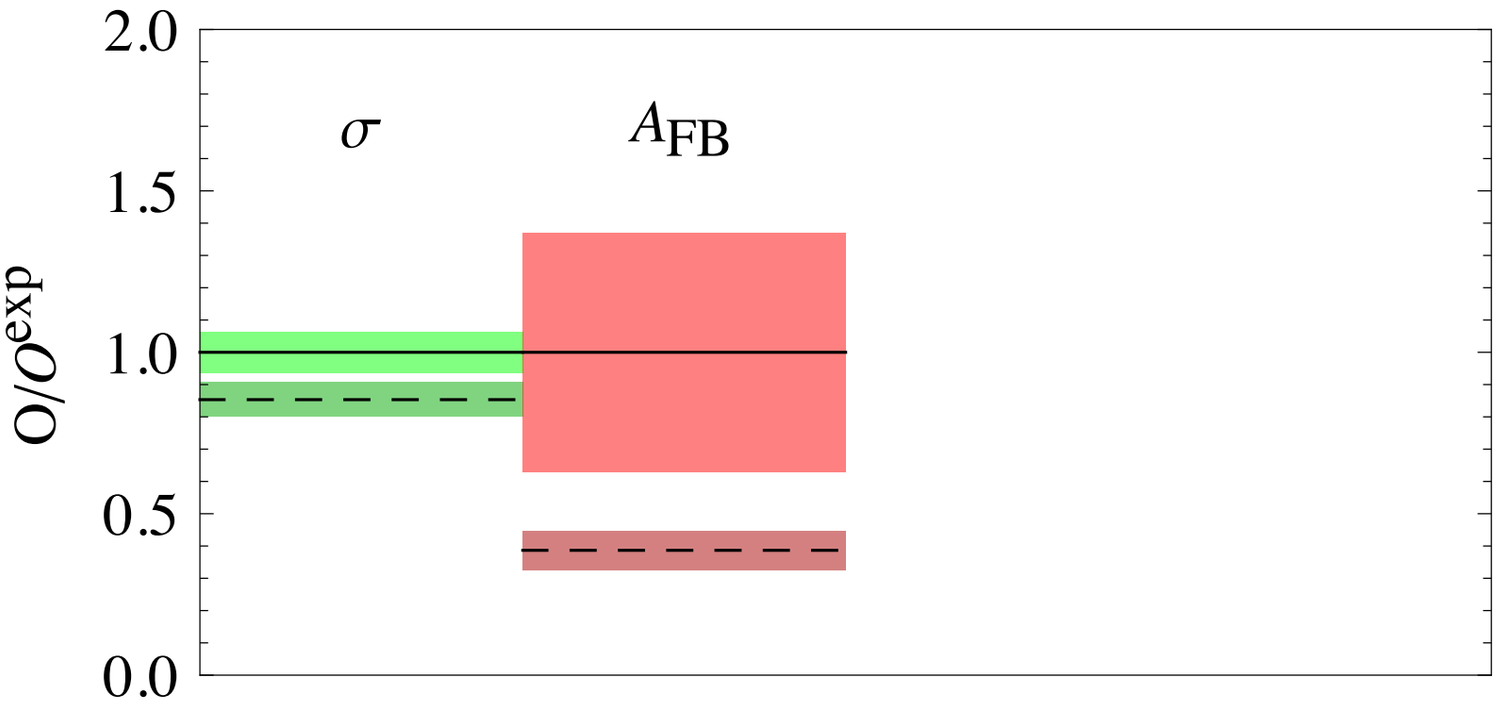

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Ahrens et al., 1003.5827

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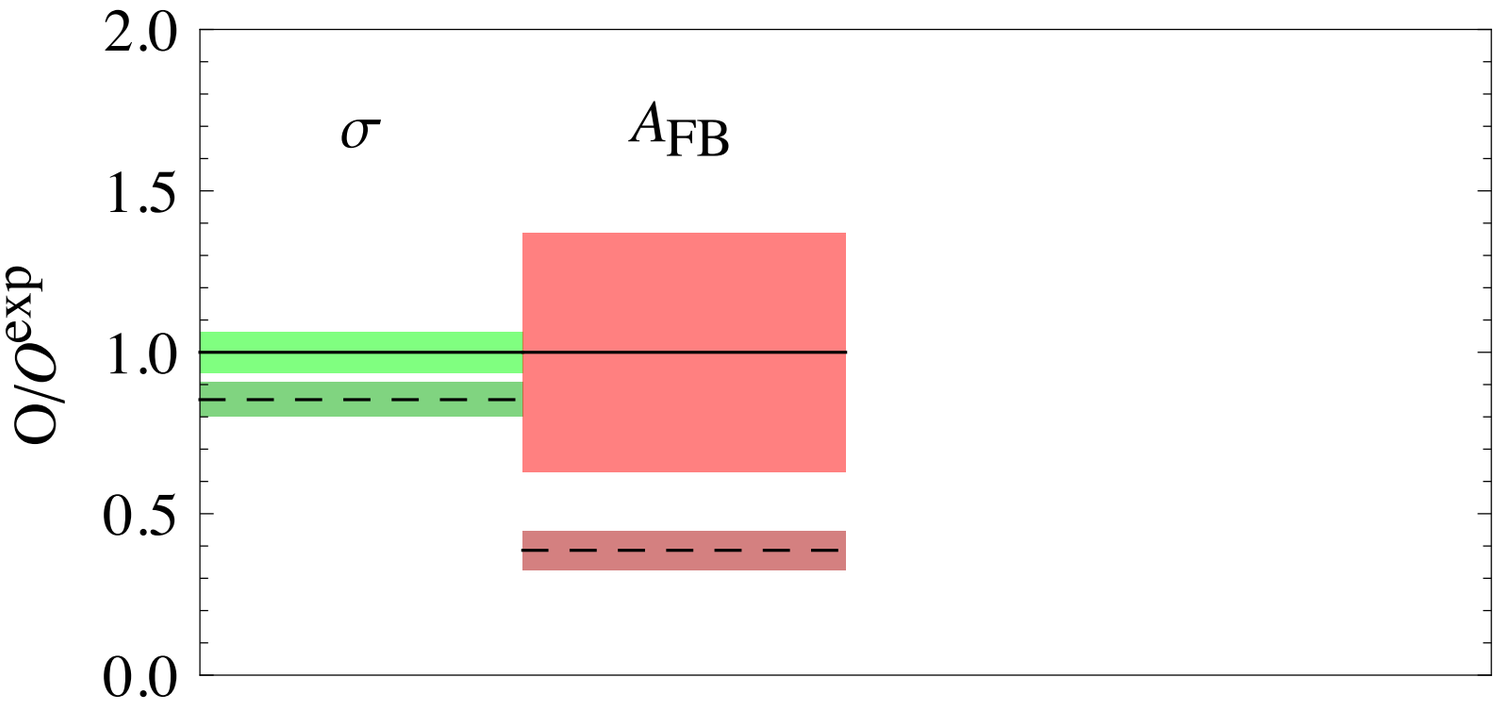

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$$\sigma = (7.50 \pm 0.48)\,\text{pb} \qquad A_{FB} = 0.158 \pm 0.074$$

- High m_{tt} region less sensitive to threshold effects

CDF, 0903.2850

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

Schwanenberger [CDF], 1012.2319

Forward-backward asymmetry in $t\bar{t}$ production

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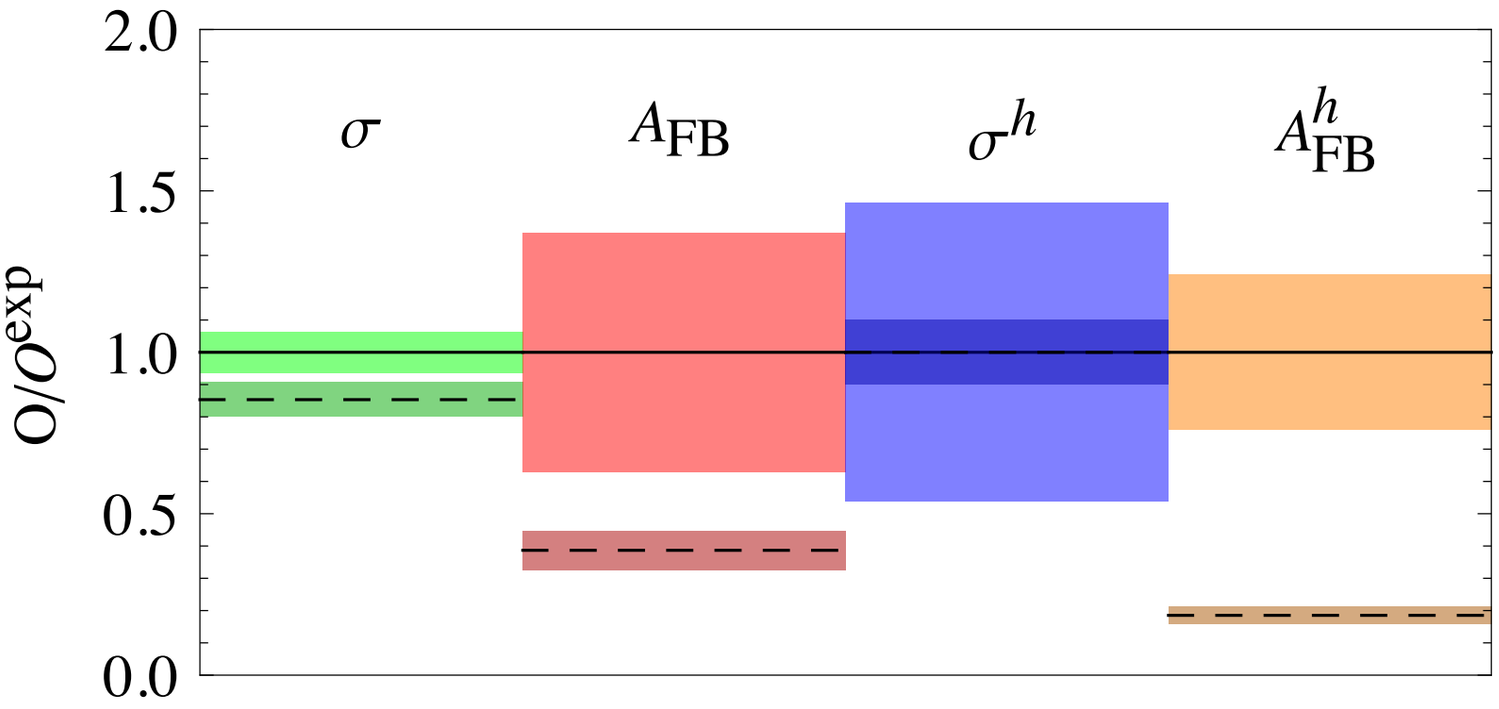


Kidonakis, 1009.4935, 1105.3481

Ahrens et al., 1003.5827

$$\sigma = (7.50 \pm 0.48)\,\text{pb} \qquad A_{FB} = 0.158 \pm 0.074$$
$$\sigma^h = (80 \pm 37)\,\text{fb} \qquad A^h_{FB} = 0.475 \pm 0.114$$

Other measurements:
CDF Note 10436
DØ Note 6062-CONF

CDF, 0903.2850

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

CDF, 1101.0034

Schwanenberger [CDF], 1012.2319

New Physics Interpretation(s)

- ***NP interfering with the SM***

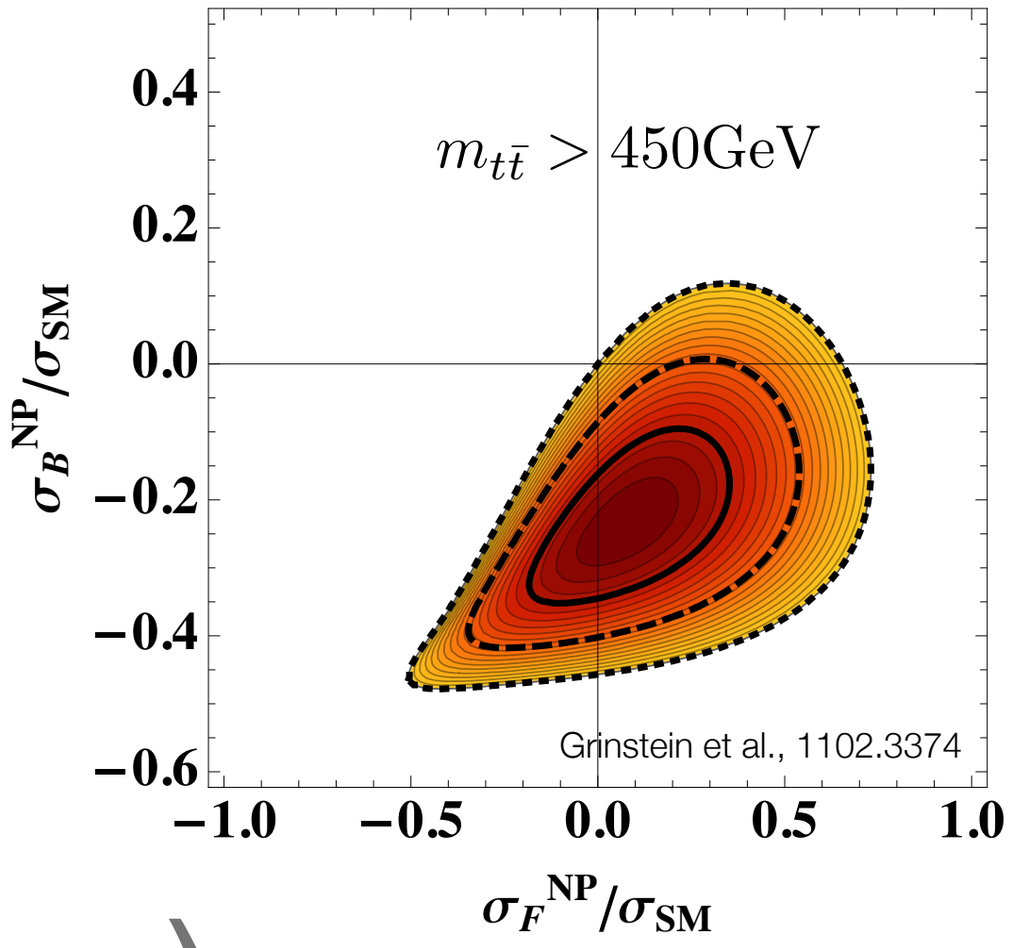
$$A_{FB}^{tot} = \frac{\sigma_F^{SM} - \sigma_B^{SM} + \sigma_F^{NP} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_B^{SM} + \sigma_F^{NP} + \sigma_B^{NP}}$$

  - positive contributions to A_{FB}

$$\sigma_B^{\rm NP} < \sigma_F^{\rm NP}$$

  - interference in σ negative or vanishing

$$\sigma_B^{\rm NP} \lesssim 0$$



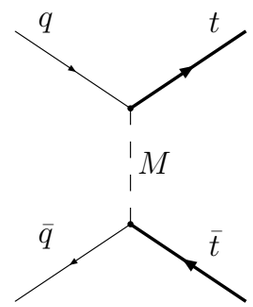
- ***NP not interfering with SM?***

  (
  - saturate uncertainties in σ
  - need very asymmetric incoherent contribution
)

Isidori & J.F.K. 1103.0016

New Physics Interpretation(s)

- ***Light to moderate mass t(u)-channel resonances***
  - Z’, W’, scalar color triplets, sextets



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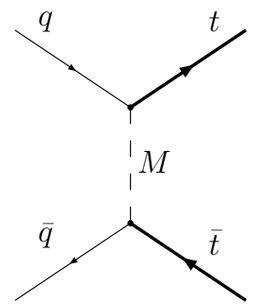


  - Z', W', scalar color triplets, sextets
  - Need large FC (u-t, d-t) couplings
    - potentially severe constraints from ΔF=2 and dijet searches
    - requires non-trivial flavor structure of the underlying theory
      - gauge symmetries $-\frac{\lambda^{\psi}_{ij}}{2}\epsilon^{abc}\phi_a\psi^{iT}_{Rb}C\psi^{j}_{Rc}$

I. Dorsner, S. Fajfer, J.F.K., N. Kosnik, 0912.0972, 1007.2604
Giudice et al., 1105.3161

      - flavor symmetries

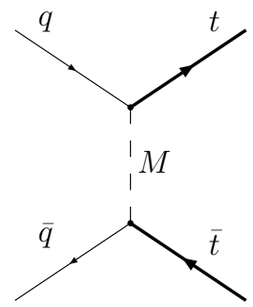
$$(\bar{U}_R T^A \gamma^\mu U_R) V^A_\mu = \left(V^4_\mu - iV^5_\mu\right)\left(\bar{t}_R\gamma^\mu u_R\right) + \cdots$$

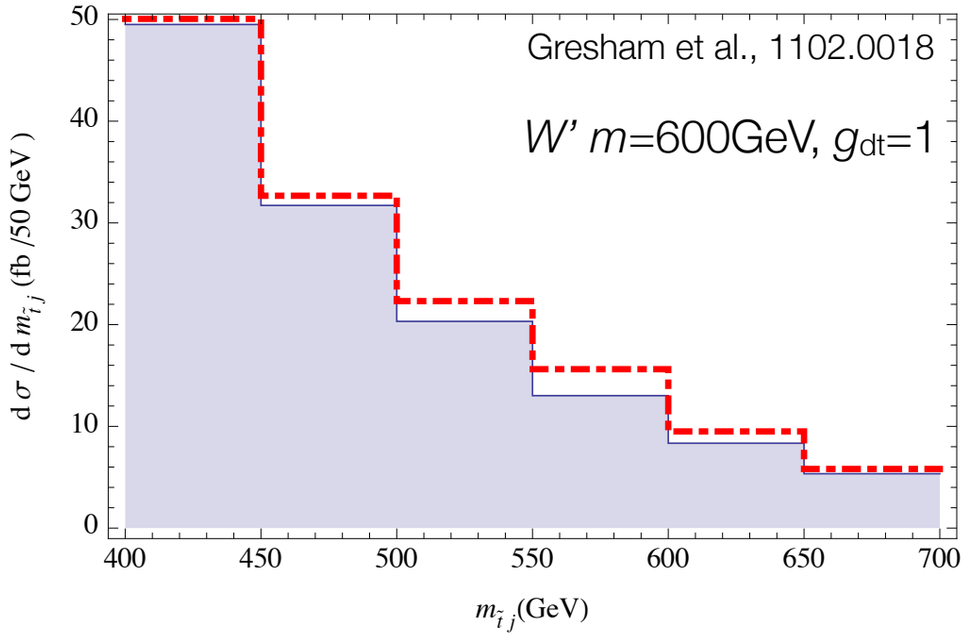
Grinstein et al., 1102.3374
Ligeti et al., 1103.2757
Jung et al., 1103.4835

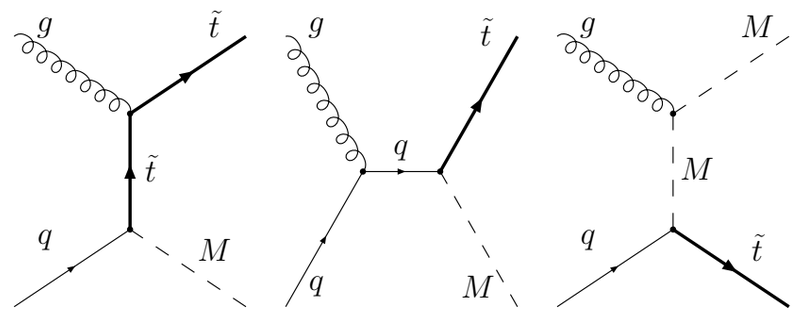
see also
J. Shelton & K. M. Zurek, 1101.5392

New Physics Interpretation(s)

- ***Light to moderate mass t(u)-channel resonances***
  - Z', W', scalar color triplets, sextets
  - Need large FC (u-t, d-t) couplings
    - potentially severe constraints from ΔF=2 and dijet searches
    - requires non-trivial flavor structure of the underlying theory
    - **predict flavor violating (t-j) resonances in t-associated production**



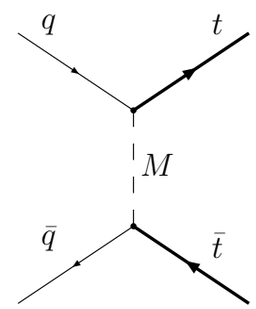




Discoverable with 2011 LHC data!

New Physics Interpretation(s)

- ***Light to moderate mass t(u)-channel resonances***
  - Z', W', scalar color triplets, sextets
  - Need large FC (u-t, d-t) couplings
  - Generically predict slow rise in m_{tt} spectrum*



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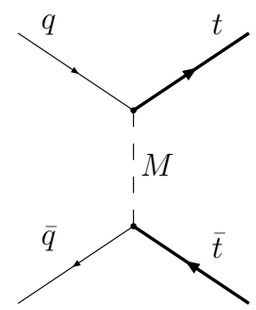
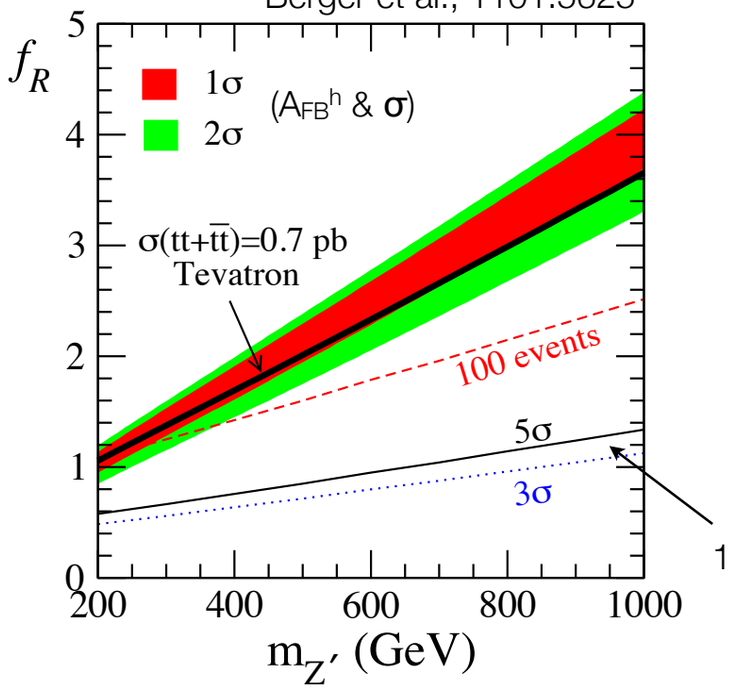


- Same-sign top top production can be a problem - model-dependent

Berger et al., 1101.5625



J. A. Aguilar-Saavedra & M. Perez-Victoria, 1104.1385
Degrande et al.,1104.1798

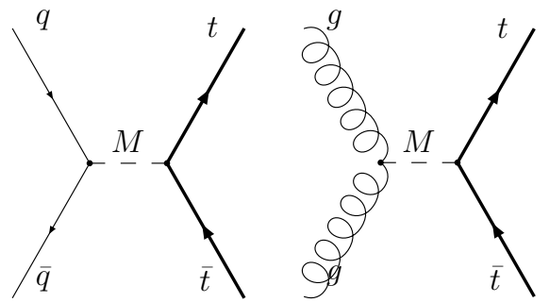
Can be probed efficiently at the LHC

Rajaraman et al., 1104.0947

$$\mathcal{A}_{1\ell} \equiv \frac{N(\text{top pair} \to 1\ell^+) - N(\text{top pair} \to 1\ell^-)}{N(\text{top pair} \to 1\ell^+) + N(\text{top pair} \to 1\ell^-)}$$

New Physics Interpretation(s)

- *Light to moderate mass t(u)-channel resonances*
- ***Heavy (s-channel) resonances or EFT****
  - KK or “Axigluon” - need color octet axial contributions



New Physics Interpretation(s)

- *Light to moderate mass t(u)-channel resonances*
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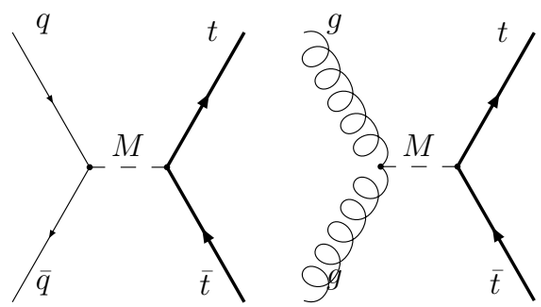
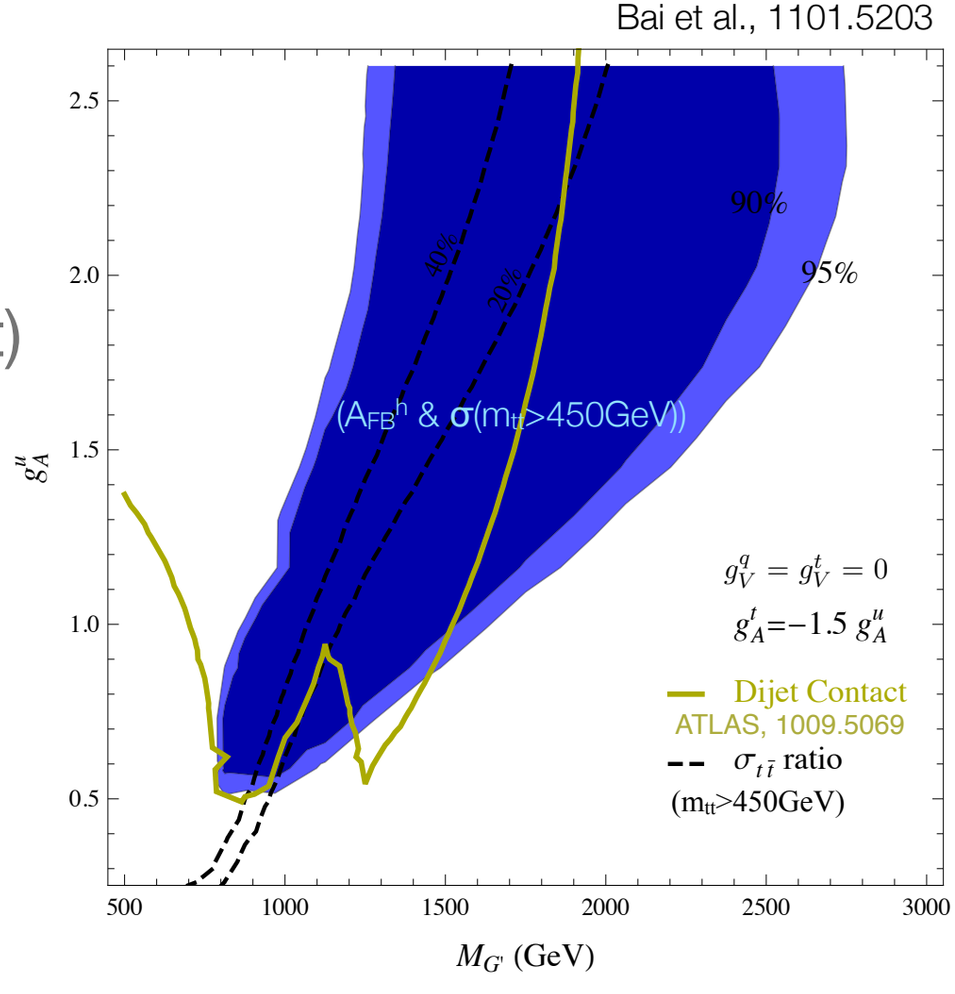
  - KK or “Axigluon” - need color octet axial contributions
    - Need opposite sign uū and tt̄ couplings
  - Constrained by LHC di-jet searches

Chivukula et al., 1007.0260.
Delaunay et al., 1101.2902

(also flavor, EWPT - model dependent)





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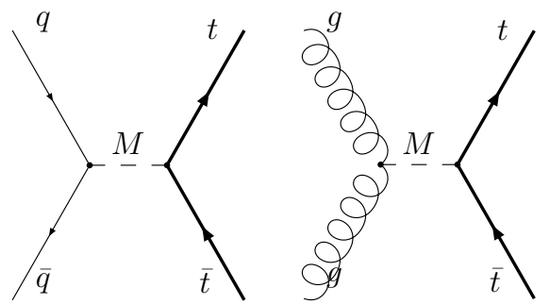
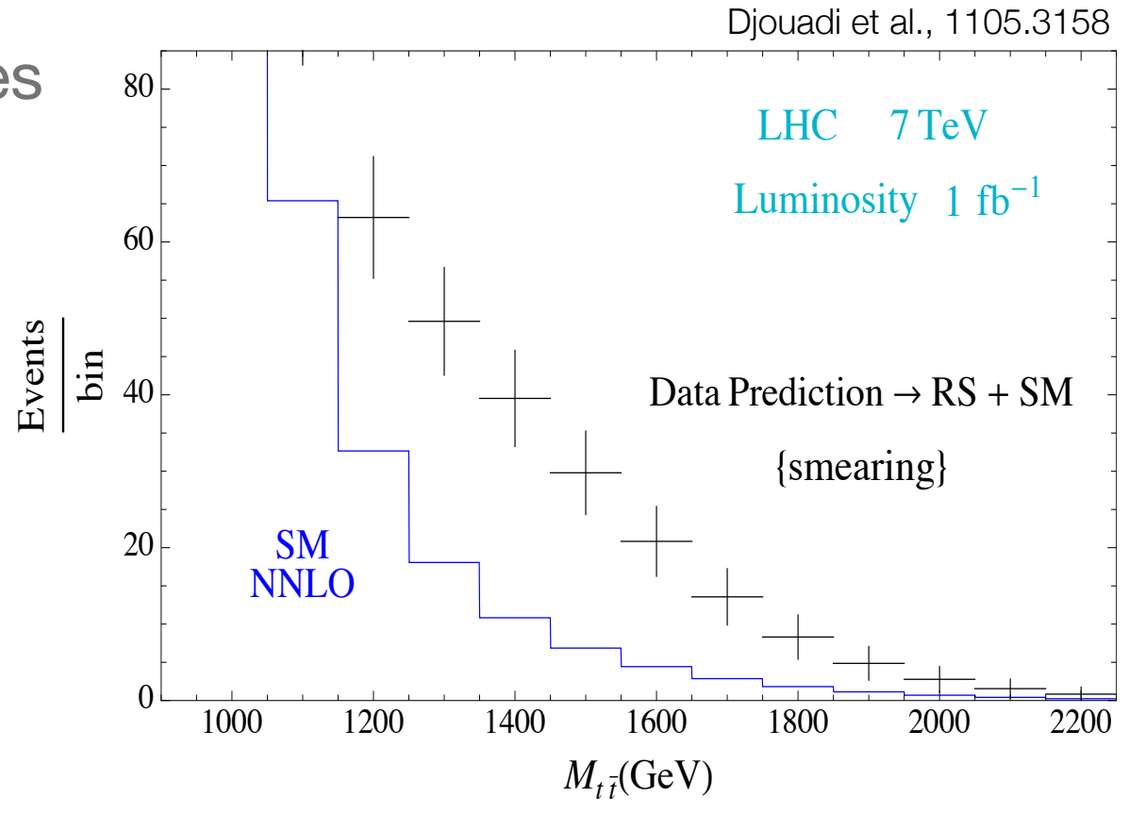
  - KK or “Axigluon” - need color octet axial contributions
  - Need opposite sign uū and tt̄ couplings
    - Constrained by LHC di-jet searches
    - Predict resonance in m_{tt}
      - may be very broad!



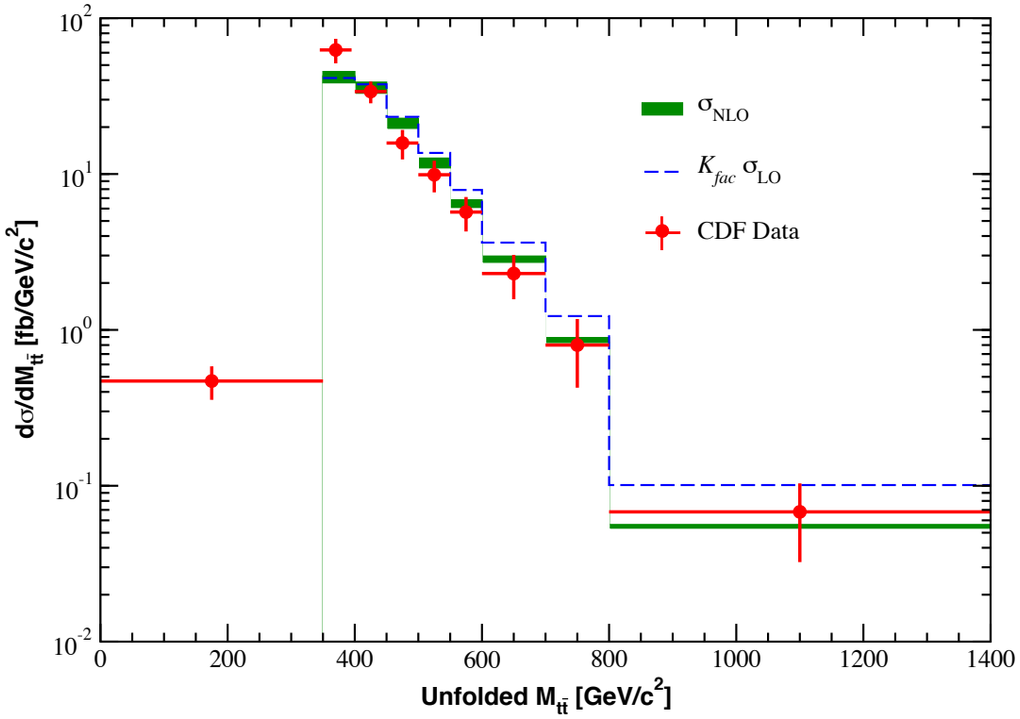
Djouadi et al., 1105.3158



New Physics Interpretation(s) - Caveats

- $|\sigma_i^{\rm NP}/\sigma_i^{\rm SM}| \lesssim \mathcal{O}(1)$: QCD corrections to NP contributions important
  - Especially relevant at high m_{tt}

Cao et al., 1003.3461



New Physics Interpretation(s) - Caveats

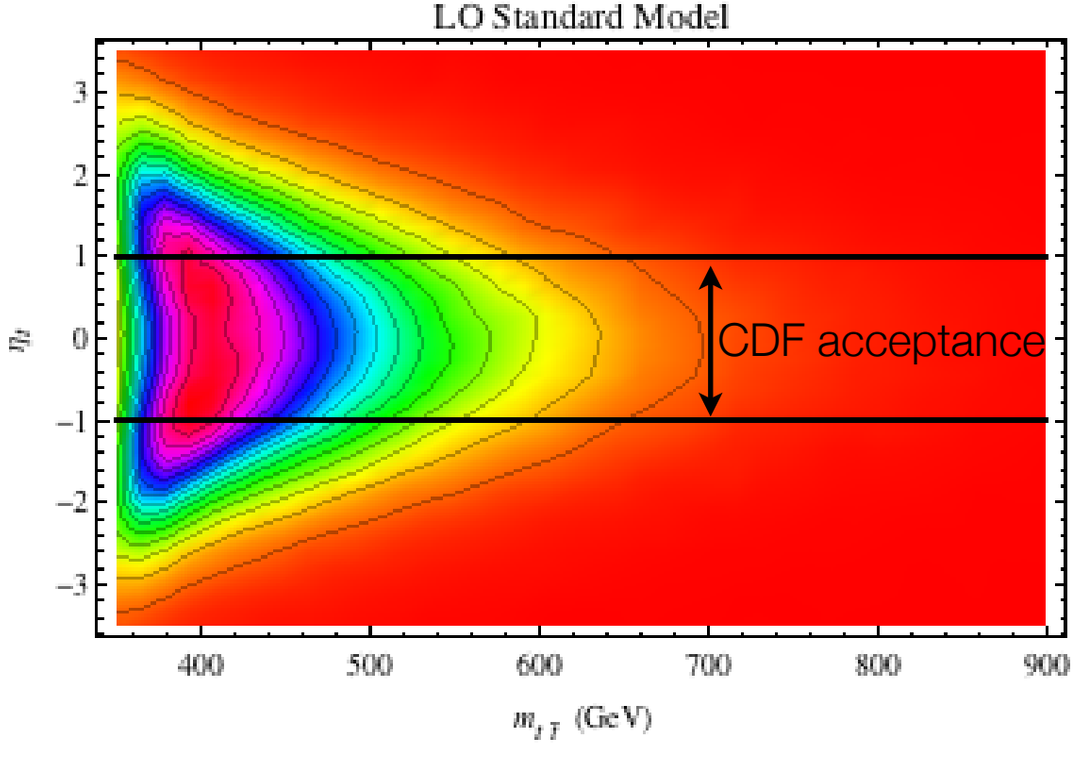
- $|\sigma_i^{\mathrm{NP}}/\sigma_i^{\mathrm{SM}}| \lesssim \mathcal{O}(1)$: QCD corrections to NP contributions important
  - Especially relevant at high m_{tt}
  - May (or not) improve agreement with data (Examples: Z', RS) Xiao et al., 1006.2510 Bauer et al., 1008.0742

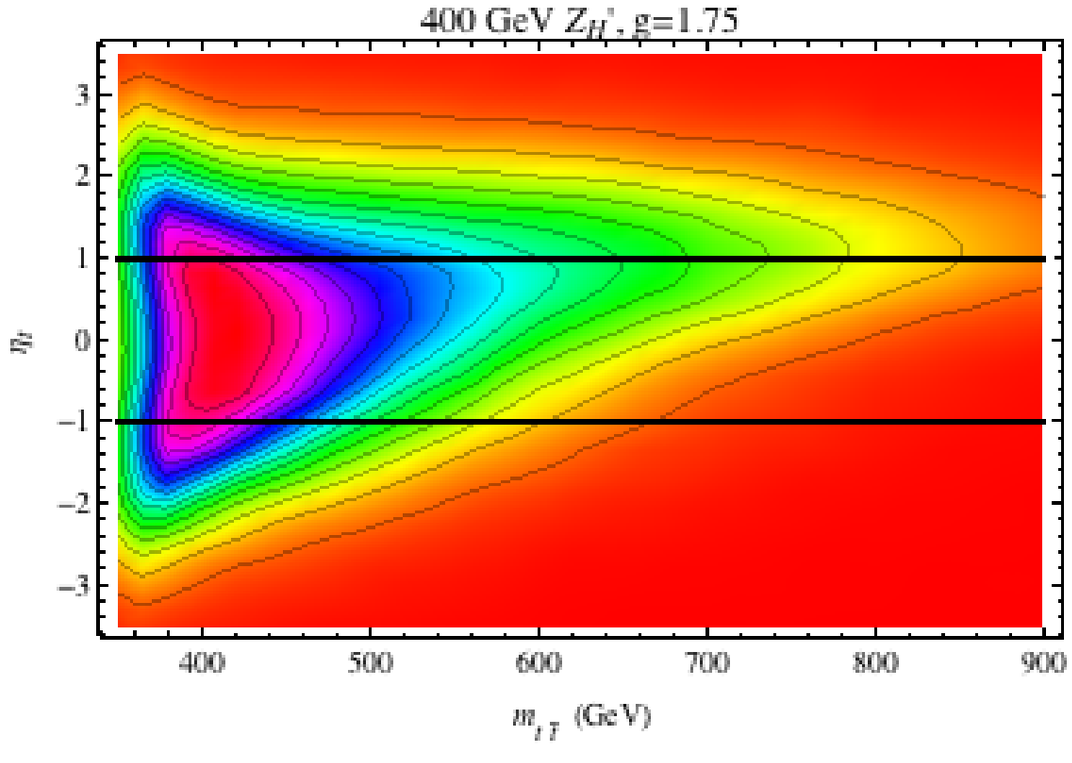
New Physics Interpretation(s) - Caveats

- $|\sigma_i^{\rm NP}/\sigma_i^{\rm SM}| \lesssim \mathcal{O}(1)$: QCD corrections to NP contributions important

- Experimental acceptances may be model dependent

Gresham et al., 1103.3501





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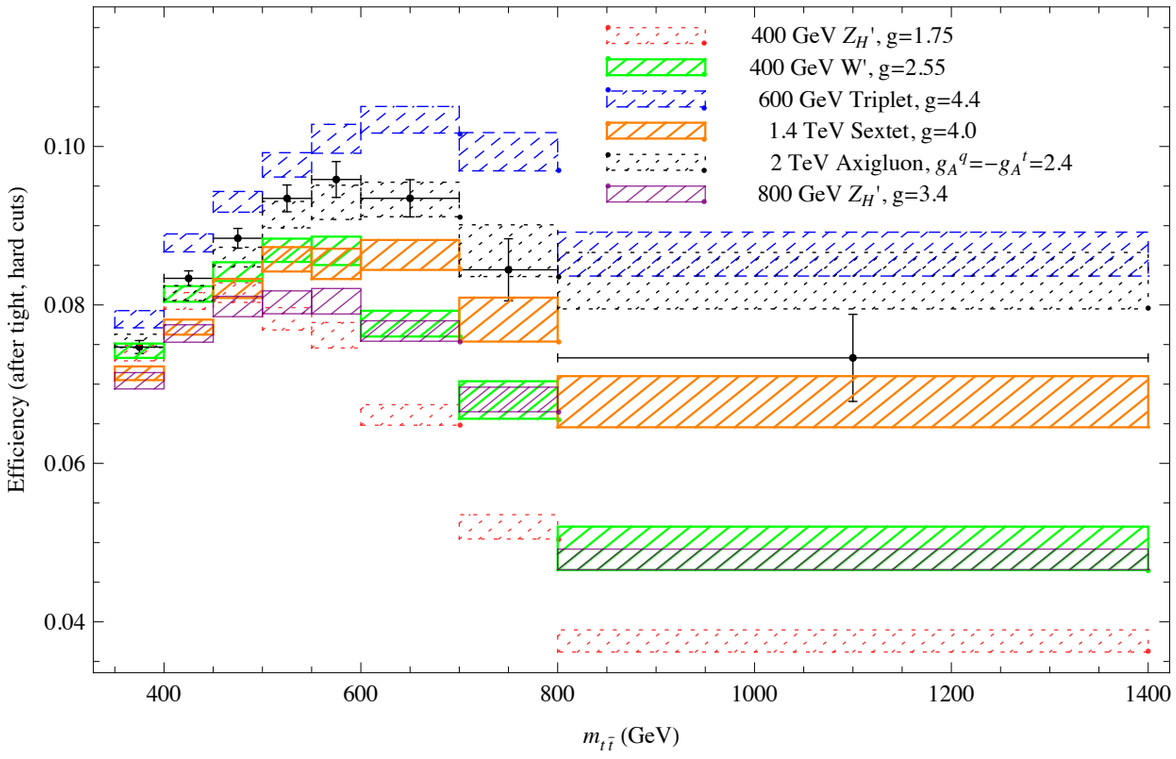

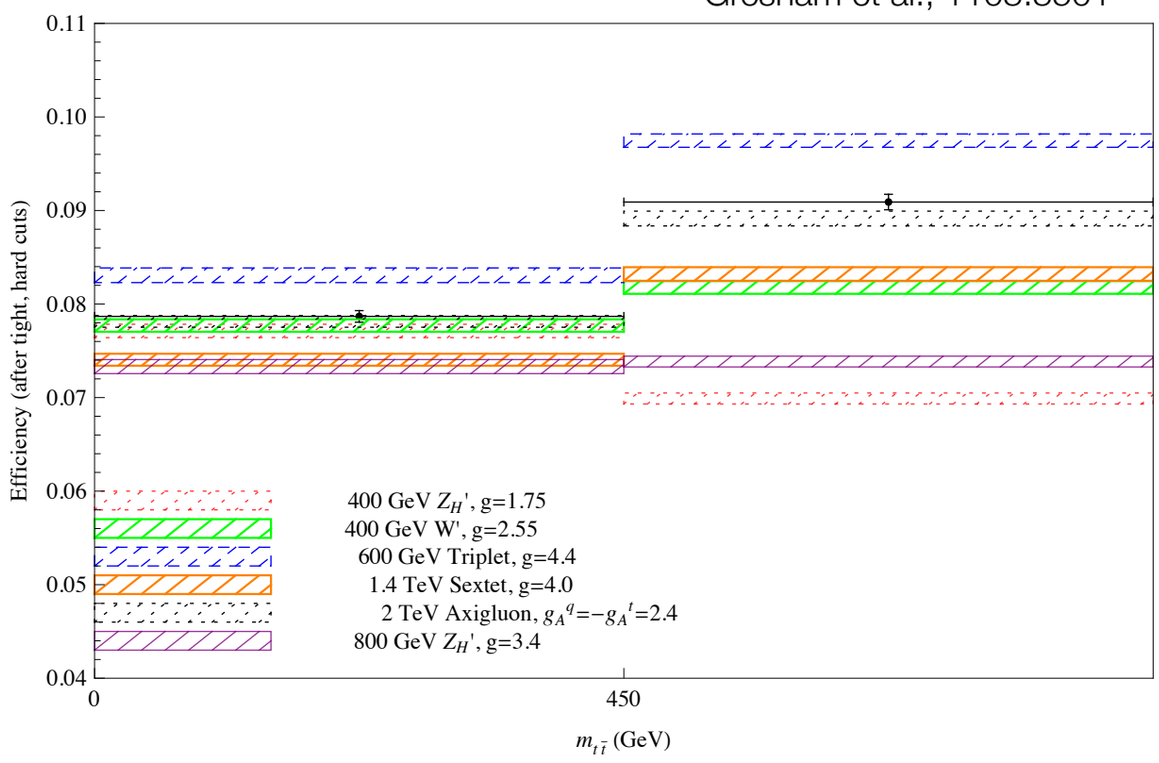

- May suppress light t-channel NP contributions to the high m_{tt} tail!

New Physics Interpretation(s) - Caveats

- $|\sigma_i^{\rm NP}/\sigma_i^{\rm SM}| \lesssim \mathcal{O}(1)$: QCD corrections to NP contributions important
- Experimental acceptances may be model dependent
- Limitations of EFT analyses $\mathcal{L}_{t\bar{t}}(\Lambda^{-2}) = \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i$

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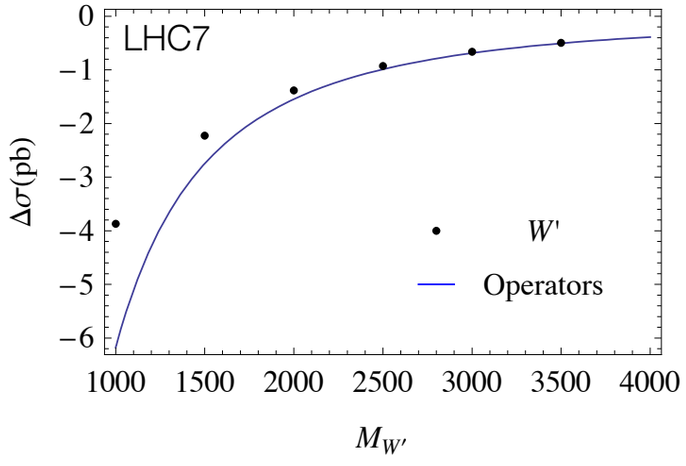
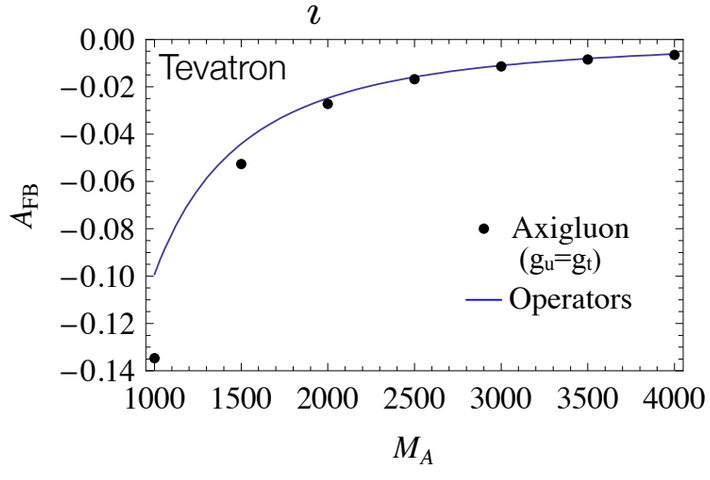


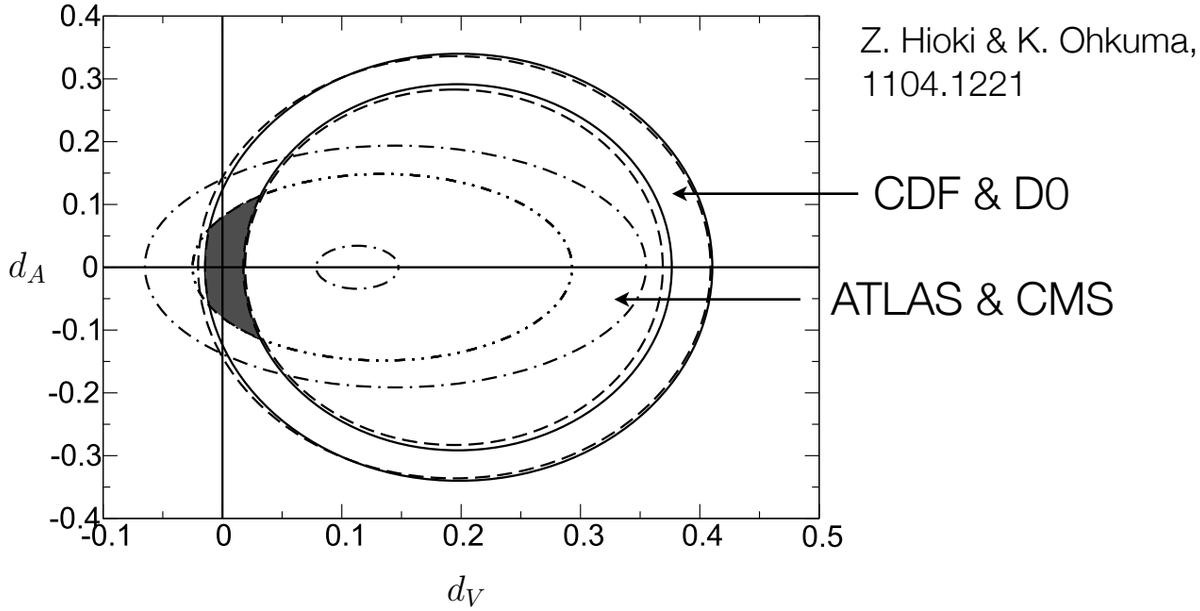


Degrande et al., 1010.6304

- Several models addressing FBA require mediator masses $M_X \lesssim 1\text{TeV}$
- Role of Λ^{-4} terms in explaining A_{FB}^h Delaunay et al., 1103.2297
  - contributions of higher dimensional operators? J. A. Aguilar-Saavedra, 1008.3562

Generic A_{FB} implications for NP searches at LHC

- Complementarity of Tevatron and LHC measurements
  - top pair production dominated by gg initial state at the LHC



Z. Hioki & K. Ohkuma, 1104.1221

$$\bar{\psi}_t(x)\lambda^a\frac{\sigma^{\mu\nu}}{m_t}(d_V + id_A\gamma_5)\psi_t(x)G^a_{\mu\nu}(x)$$

Generic A_{FB} implications for NP searches at LHC

- Complementarity of Tevatron and LHC measurements
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- Spin correlations and polarization

G. Mahlon and S. J. Parke
hep-ph/9512264
Bernreuther et al., hep-ph/0403035

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + C\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$

(reference axis & spin analyzer dependent)

- C≠0 signals top-pair spin correlations
- b_i≠0 would signal new chiral interactions in top pair production!

see also
Godbole et al., 1010.1458
Jung et al., 1011.5976
Choudhury et al., 1012.4750

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(reference axis & spin analyzer dependent)

- 3σ NP effects possible already at Tevatron or ~5fb^{-1} LHC data

Krohn et al., 1105.3743

Generic A_{FB} implications for NP searches at LHC

- Cross-check of Tevatron A_{FB} measurements at a pp collider?
  - initial state valence quarks dominate large x

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

  - result in rapidity dependent charge asymmetry

Antunano et al., 0709.1652

Hewett et al., 1103.4618

$$\mathcal{A}_F(y_0) = \frac{N_t(y_0 < |y| < 2.5) - N_{\bar{t}}(y_0 < |y| < 2.5)}{N_t(y_0 < |y| < 2.5) + N_{\bar{t}}(y_0 < |y| < 2.5)} \qquad \mathcal{A}_C(y_0) = \frac{N_t(|y| < y_0) - N_{\bar{t}}(|y| < y_0)}{N_t(|y| < y_0) + N_{\bar{t}}(|y| < y_0)}$$

Forward Central

$$\mathcal{A}_C = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)} \qquad \Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$$

For other sensitive observables see also
Wang et al., 1008.2685, 1011.1428
Xiao et al., 1101.2507
Craig et al., 1103.2127

Inclusive (first results by CMS! see talk by Tosi)

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Forward Central

- t-channel contributions exhibit a forward (Rutherford) scattering peak in σ
  - expect sizable σ excess in the forward region: **top quarks at LHCb?**

LHCb t

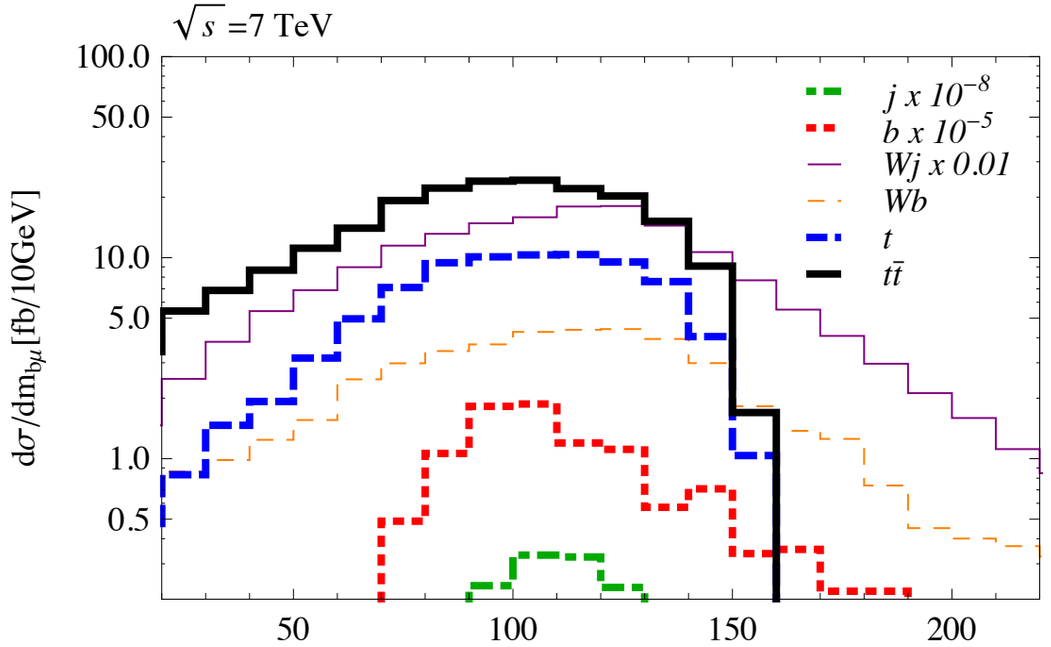
Kagan, J.F.K., Perez & Stone, 1103.3747

- 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

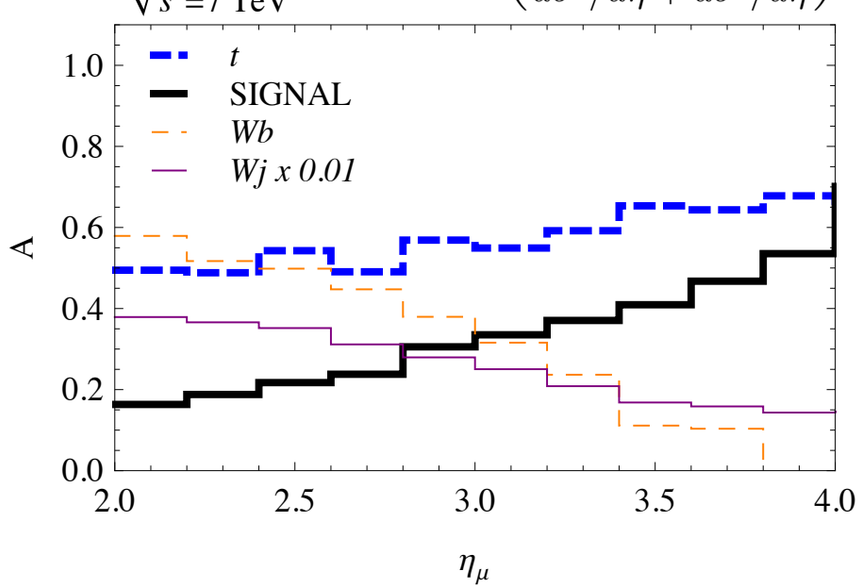


- Prospects for top charge asymmetry measurement

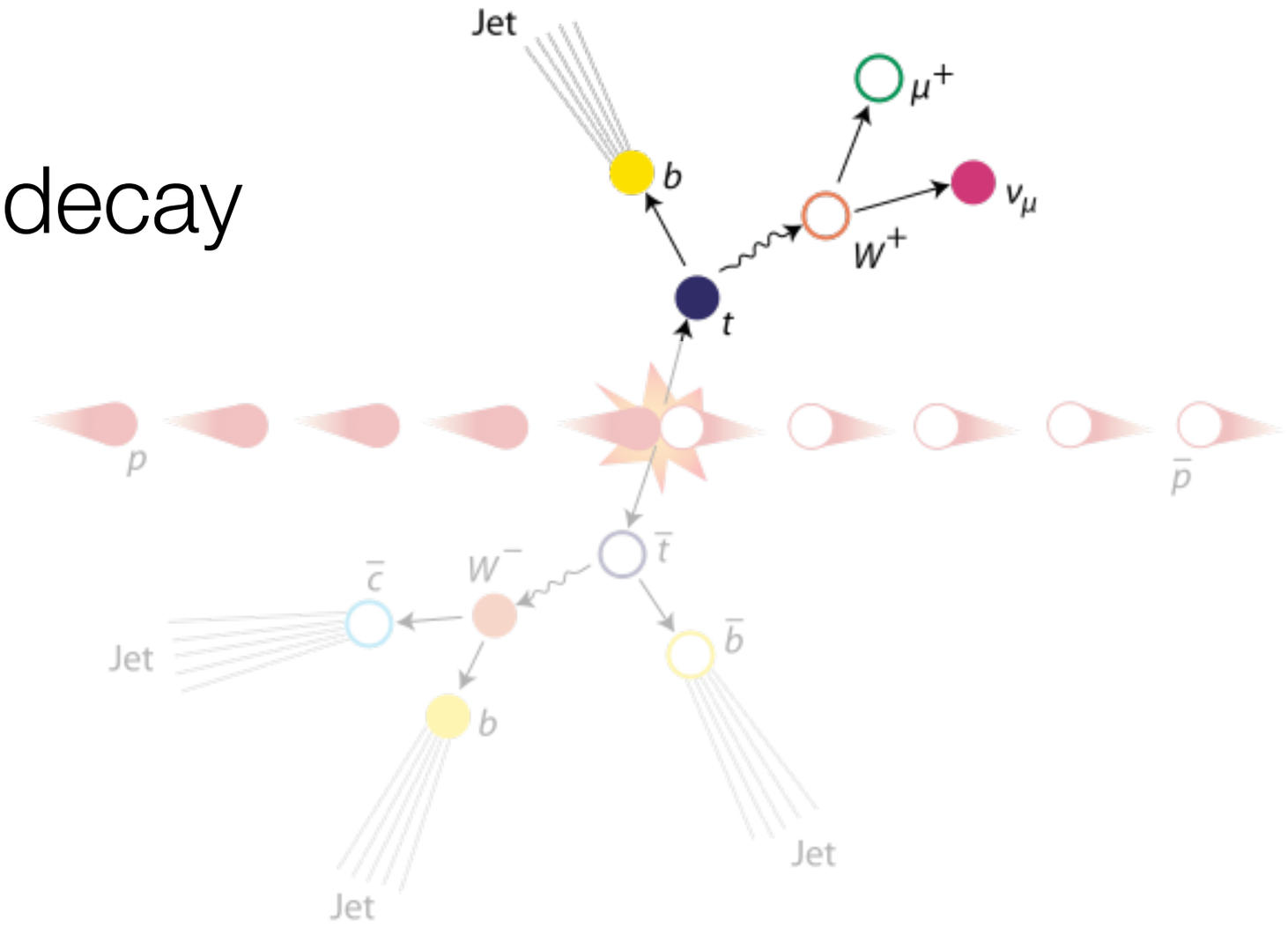
  - top rest-frame cannot be reconstructed

  - use μ, b pseudorapidity distribution instead

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



New physics in top decay



New physics in t→bW?

- The branching ratio is sensitive to the values of V_{tx} CKM elements

$$\Gamma(t \to bW) \approx \frac{\alpha |V_{tb}|^2}{16 s_W^2} \frac{m_t^3}{m_W^2} \qquad \mathcal{B}^{SM} \simeq \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

J. Alwall et al.
hep-ph/0607115

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- Helicity fractions of the final state *W* provide additional information on the structure of the *tWb* coupling

$$\Gamma_{t \to Wb} = \frac{m_t}{16\pi} \frac{g^2}{2} \sum_i \Gamma^i \qquad \begin{aligned} \mathcal{F}_L &\equiv \Gamma^L/\Gamma \\ \mathcal{F}_\pm &\equiv \Gamma^\pm/\Gamma \end{aligned} \qquad \sum_i \mathcal{F}_i = 1$$

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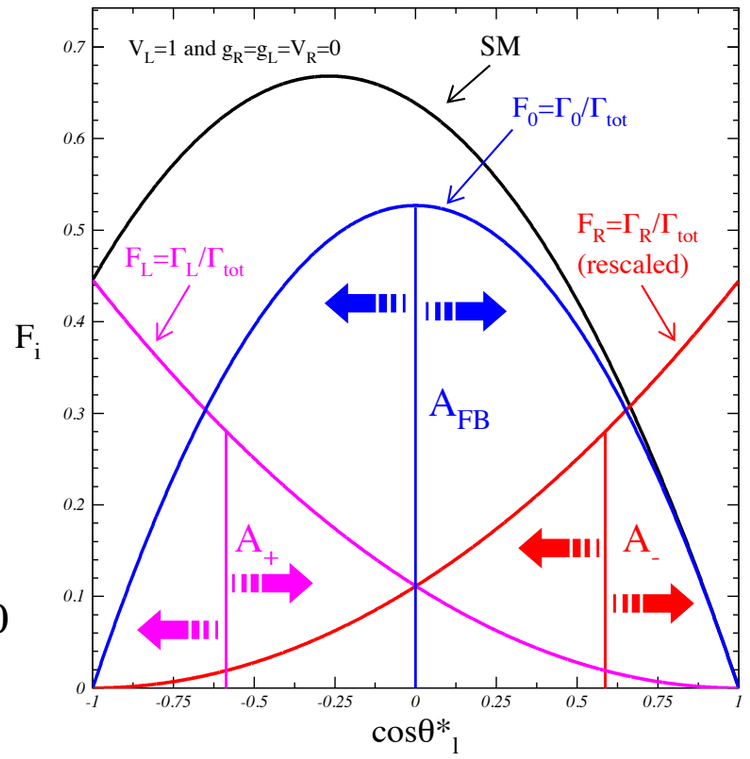
- Can be determined using angular distribution of charged leptons in *W* decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1+\cos\theta_\ell^*)^2 F_R + \frac{3}{8}(1-\cos\theta_\ell^*)^2 F_L + \frac{3}{4}\sin^2\theta_\ell^* F_0$$

N. de Castro, CERN-THESIS-2008-083



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- Recently measured at the Tevatron (also by ATLAS! see talk by Helsens)

$$\begin{aligned} \mathcal{F}_L &= 0.88(13) \\ \mathcal{F}_+ &= -0.15(9) \end{aligned}$$ CDF [1003.0224]

$$\begin{aligned} \mathcal{F}_L &= 0.67(10) \\ \mathcal{F}_+ &= 0.023(53) \end{aligned}$$ D0 [1011.6549]

- SM predictions at NNLO in QCD & NLO in EW

$$\begin{aligned} \mathcal{F}_L^{\rm SM} &= 0.687(5)\,, \\ \mathcal{F}_+^{\rm SM} &= 0.0017(1)\,. \end{aligned}$$

H.S. Do et al., hep-ph/0209185
M. Fischer et al., hep-ph/0011075, hep-ph/0101322
A. Czarnecki et al., 1005.2625

t-b-W interaction beyond the SM

- Analyze using EFT: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{Q}_i + \text{h.c.} + \mathcal{O}(1/\Lambda^3)$
  - Operators invariant under SM gauge group, free of tree-level FCNCs
  - Flavor structure can be controlled within MFV

J. Drobnak, S. Fajfer & J.F.K., 1102.4347

- Restricted set of 7 dominant charged current operators beyond SM

(a)

$$\mathcal{Q}_{RR} = V_{tb}[\bar{t}_R\gamma^\mu b_R]\left(\phi_u^\dagger \mathrm{i}D_\mu\phi_d\right),$$
$$\mathcal{Q}_{LL} = [\bar{Q}'_3\tau^a\gamma^\mu Q'_3]\left(\phi_d^\dagger\tau^a \mathrm{i}D_\mu\phi_d\right) - [\bar{Q}'_3\gamma^\mu Q'_3]\left(\phi_d^\dagger \mathrm{i}D_\mu\phi_d\right),$$
$$\mathcal{Q}_{LRt} = [\bar{Q}'_3\sigma^{\mu\nu}\tau^a t_R]\phi_u W^a_{\mu\nu},$$
$$\mathcal{Q}_{LRb} = [\bar{Q}_3\sigma^{\mu\nu}\tau^a b_R]\phi_d W^a_{\mu\nu},$$
$$\ldots$$

$$\bar{Q}'_3 = \bar{Q}_i V^*_{ti}$$

(b)

$$\mathcal{Q}'_{LL} = [\bar{Q}_3\tau^a\gamma^\mu Q_3]\left(\phi_d^\dagger\tau^a \mathrm{i}D_\mu\phi_d\right) - [\bar{Q}_3\gamma^\mu Q_3]\left(\phi_d^\dagger \mathrm{i}D_\mu\phi_d\right),$$
$$\mathcal{Q}''_{LL} = [\bar{Q}'_3\tau^a\gamma^\mu Q_3]\left(\phi_d^\dagger\tau^a \mathrm{i}D_\mu\phi_d\right) - [\bar{Q}'_3\gamma^\mu Q_3]\left(\phi_d^\dagger \mathrm{i}D_\mu\phi_d\right),$$
$$\mathcal{Q}'_{LRt} = [\bar{Q}_3\sigma^{\mu\nu}\tau^a t_R]\phi_u W^a_{\mu\nu}.$$

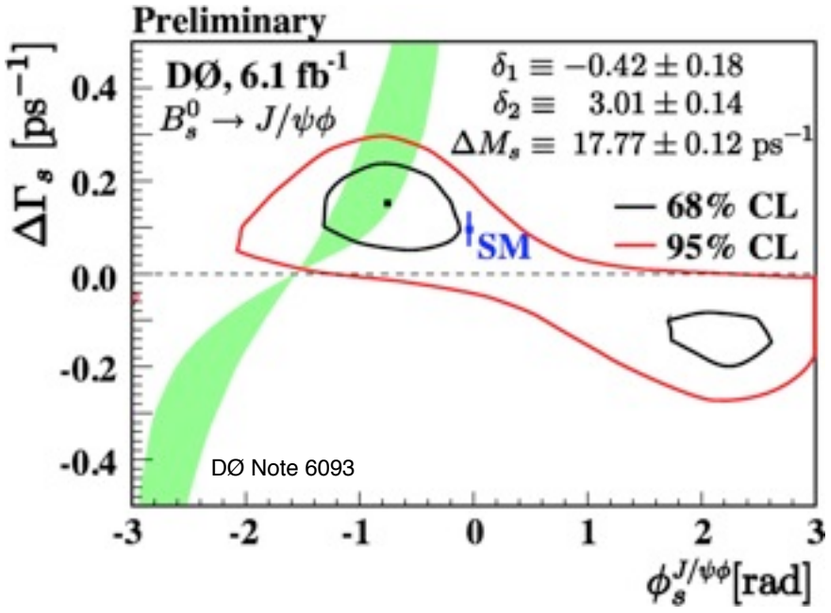
} present in models with large bottom Yukawa

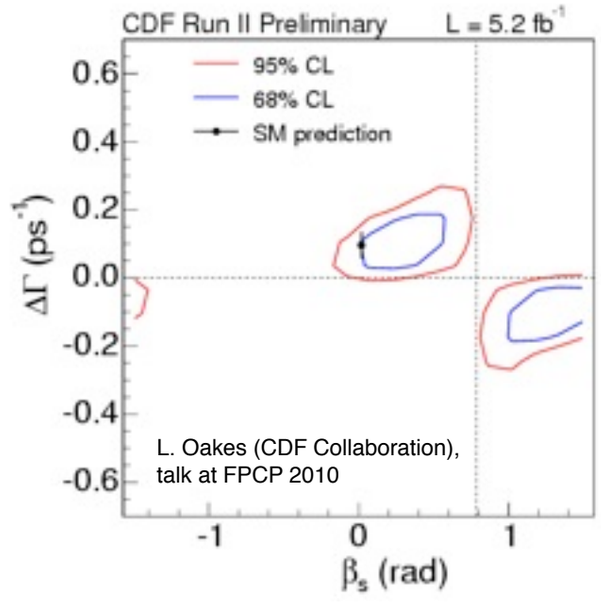
Recent developments in the B sector

- During the last three years increasing experimental hints of sizable CPV in B_s sector

UTFit
0803.0659

- Hints of large (mixing-induced) CP Violation in $B_s \to J/\psi\,\phi$ decays





$$\beta_s = \frac{1}{2}\mathrm{Arg}\lambda_{f_{CP}}$$
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

- Evidence for an anomalous like-sign dimuon charge asymmetry (*b*-inclusive)

DØ, 1005.2757

$$a_{\mathrm{SL}}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \qquad b\bar{b} \to \mu^+\mu^+ X$$

$$a_{\mathrm{SL}}^b = (0.506 \pm 0.043)\, a_{\mathrm{SL}}^d + (0.494 \pm 0.043)\, a_{\mathrm{SL}}^s$$

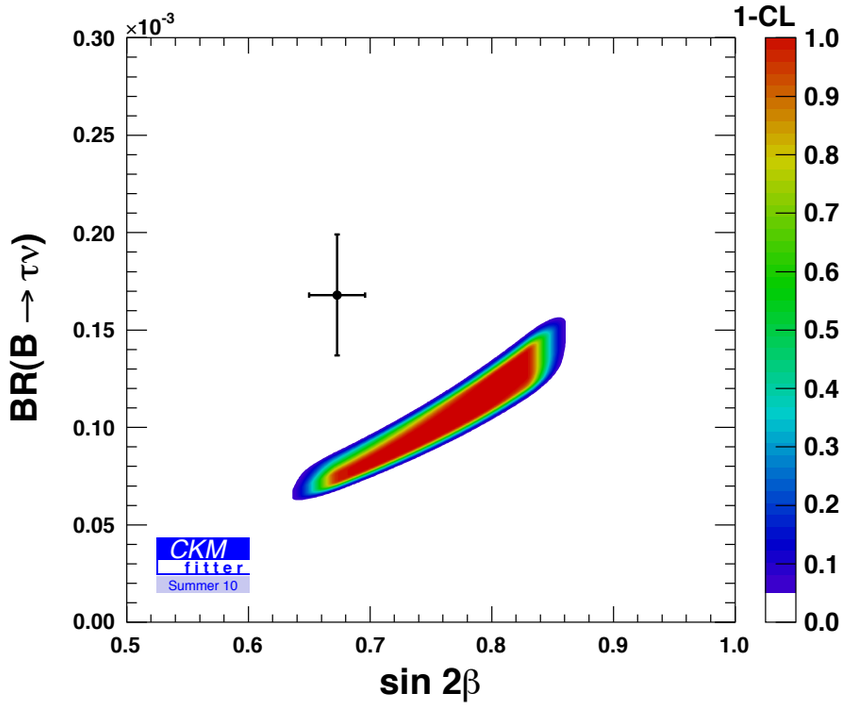
See talks by Abbot & Williams

Recent developments in the B sector

- During the last three years increasing experimental hints of sizable CPV in B_s sector
  - Hints of large (mixing-induced) CP Violation in $B_s \to J/\psi\,\phi$ decays
  - Evidence for an anomalous like-sign dimuon charge asymmetry (b-inclusive)
- At the same time, tensions developed within the CKM UT fit in the B_d sector
  - Leptonic B decay
  - CPV in B_d mixing
  - B_d mass difference

CKMFitter 0810.3139

Lunghi & Soni 0803.4340

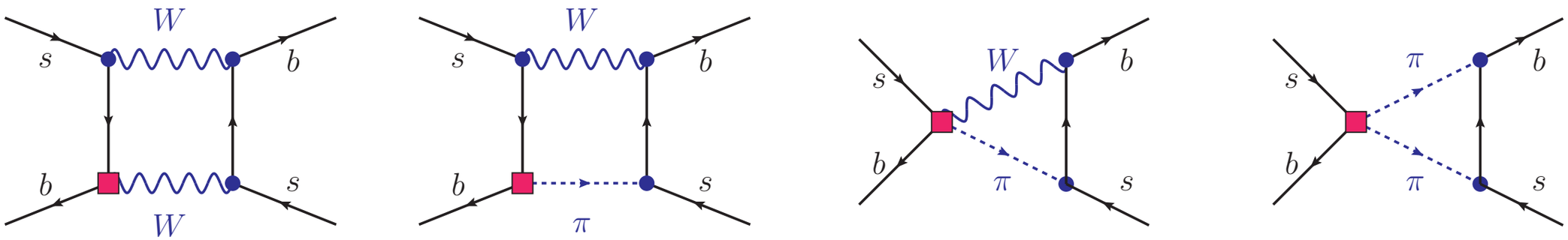


See talk by Lenz

Anomalous t-b-W interactions and B oscillations

J. Drobnak, S. Fajfer & J.F.K., 1102.4347

- Effective operators coupling *t-W-b* enter $B\bar{B}$ mixing observables at one-loop



see also Ligeti et al. 1006.0432 Lenz et al. 1008.1593

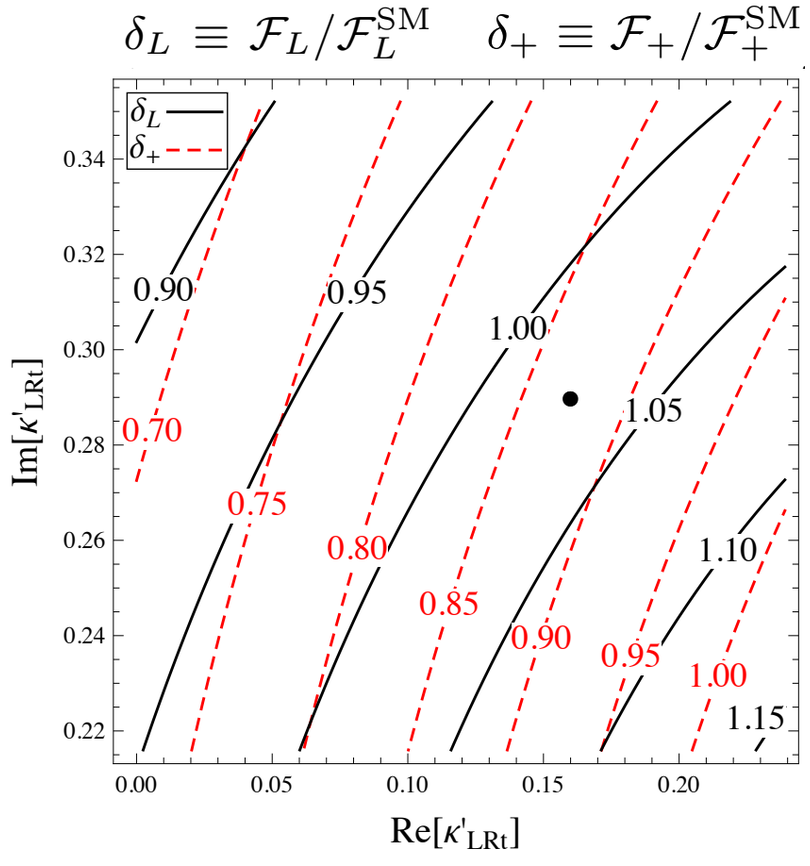
- Result in universal contributions to B_d and B_s oscillations
  - Class (b) $\left(\kappa'^{(\prime\prime)}_{LL} = \frac{C'^{(\prime\prime)}_{LL}}{\Lambda^2 \sqrt{2} G_F}\,, \qquad \kappa'_{LRt} = \frac{C'_{LRt}}{\Lambda^2 G_F} \right)$
    - not overly constrained by $b \to s\gamma$

B. Grzadkowski and M. Misiak, 0802.1413

    - contributions to $B\bar{B}$ at LO can be complex
      can accommodate CPV anomalies

J. Drobnak, S. Fajfer & J.F.K., 1010.2402

    - κ'_{LRt} will affect F_i measurements



CPV in top decay?

J. A. Aguilar–Saavedra & J. Bernabéu, 1005.5382

- In decays of polarized top quarks, define normal, transverse directions

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^{T,N}} = \frac{3}{8}(1+\cos\theta_\ell^{T,N})^2\, F_+^{T,N} + \frac{3}{8}(1-\cos\theta_\ell^{T,N})^2\, F_-^{T,N} + \frac{3}{4}\sin^2\theta_\ell^{T,N}\, F_0^{T,N}$$

  - Asymmetries, sensitive to imaginary part of anomalous *tWb* vertex

$$A_{\rm FB}^{T,N} = \frac{3}{4}P[F_+^{T,N} - F_-^{T,N}]$$

(Information equivalent to the triple product $\vec{s}_t \cdot (\vec{p}_b \times \vec{p}_\ell)$)

Kane et al., Phys. Rev. D 45 (1992)

  - Sum over t and $\bar{\rm t}$ is CPV, i.e. $A_{\rm FB}^{\rm CP} = A_{\rm FB}^{N}(t) + A_{\rm FB}^{N}(\bar{t})$

- Accessible in single top production, complementary to spin correlations

see also
O. Antipin & G. Valencia, 0807.1295
Gupta et al., 0905.1074
S.K.Gupta & G. Valencia, 0912.0707

Conclusions

- ***The most significant hints of BSM physics at the Tevatron in top sector***
  - Large measured A_{FB} could still be due to O(TeV) (s-channel) resonances
    - at LHC predict excess in di-jet & $t\bar{t}$ invariant mass spectra
  - Interesting possibilities of sub TeV contributions in u- or t-channel
    - predicted LHC signatures in $t\bar{t}$+jets
  - At LHC, A_{FB} manifestation as rapidity dependent charge asymmetry
    - Enhanced σ_t in forward region - *opportunity for LHCb*
    - Also top polarization, spin correlations affected by NP addressing A_{FB}
- ***W* helicity fractions in *t*→*bW* decay probe the structure of *tWb* couplings**
  - anomalous contributions might be related to new CPV in B sector
  - can be probed more directly in single top production