DISCERNING NEW PHYSICS IN tt-PRODUCTION FROM THE TOP SPIN OBSERVABLES

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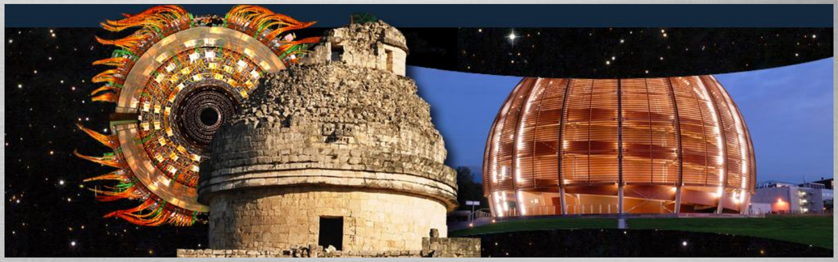


in coll. with J. Kamenik & S. Fajfer

arXiv:1205.0264

WHY IS TOP SO INTERESTING?

- the heaviest of the quarks – it does not hadronize
- the coupling to the Higgs O(1) - special role in the EW symmetry breaking?

TOP QUARK PAIR PRODUCTION

- **TEVATRON** – proton-antiproton collisions at $\sqrt{s} = 1.96\mathrm{TeV}$

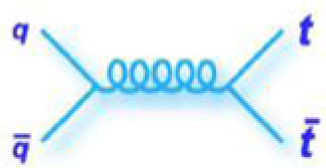
$$q\bar{q} \rightarrow t\bar{t} : 90\%$$

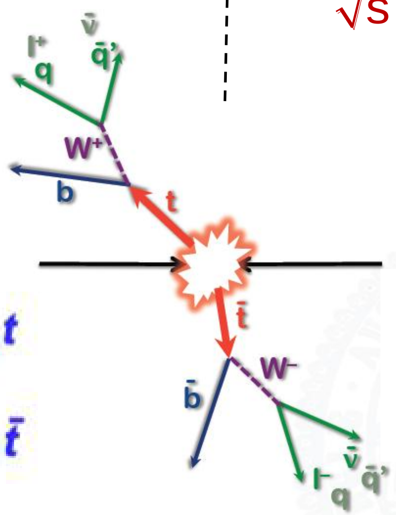
$$gg \rightarrow t\bar{t} : 10\%$$

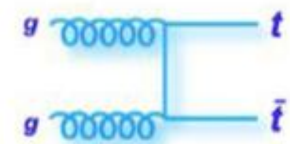
- **LHC** – proton-proton collisions at $\sqrt{s} = 7(14)\mathrm{TeV}$

$$qq \rightarrow t\bar{t} : 15\%$$

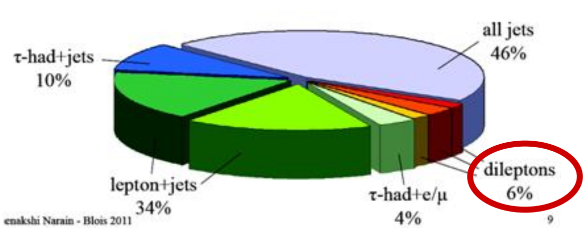
$$gg \rightarrow t\bar{t} : 85\%$$

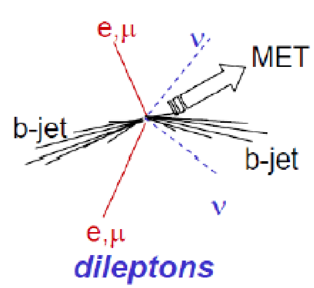


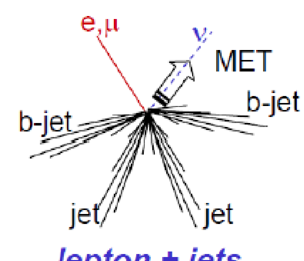


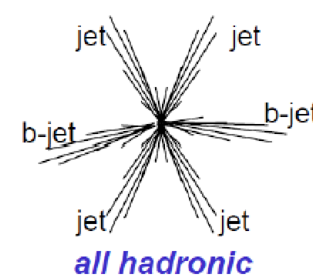


classification by the final W-decays:









$\sigma_{t\bar{t}}$ measurements vs SM theory

TEVATRON (average)

$$\sigma^{tot}_{TEV} = (7.5 \pm 0.48)\ \text{pb}$$

$$\sigma^{tot-SM}_{TEV,NNLO+NNLL} = (7.07 \pm 0.26)\ \text{pb}$$

$m_{t\bar{t}} \in$ 700,800 GeV

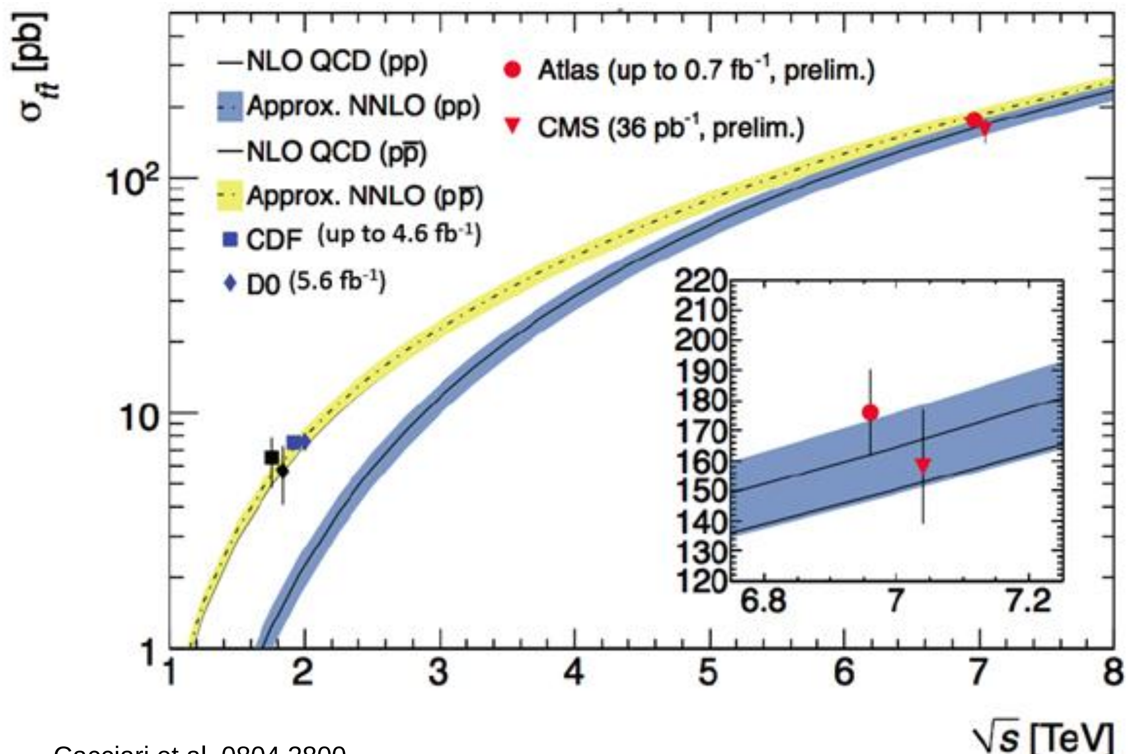
$$\sigma^{had}_{TEV} = (80 \pm 37)\ \text{fb}$$

$$\sigma^{had-SM}_{TEV} = (80 \pm 08)\ \text{fb}$$

LHC at 7 TeV (average)

$$\sigma^{tot}_{LHC} = (172 \pm 10)\ \text{pb}$$

$$\sigma^{tot-SM}_{LHC} = (163^{+11}_{-10})\ \text{pb}$$



Cacciari et al, 0804.2800
Kidonakis & Vogt, 0805.3844
Moch & Uwer, 0807.2794
Ahrens et al, 1105.6824

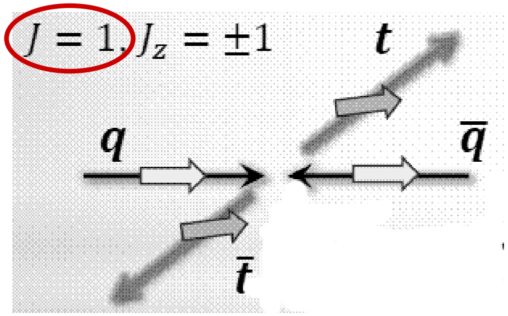
GOOD AGREEMENT WITH THE SM

SPIN CORRELATIONS I

- depending on the production mechanism top quarks are produced in the different spin configuration

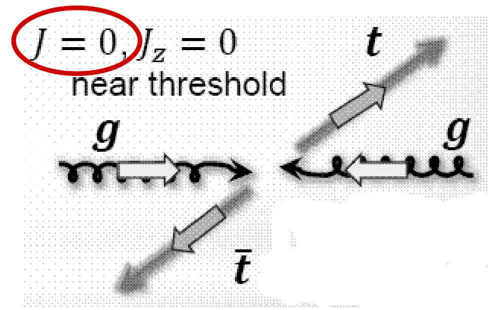
$^3S_1$

$t_L \bar{t}_R, t_R \bar{t}_L$



$^1S_0$

$t_L \bar{t}_L, t_R \bar{t}_R$



- top decays before hadronizing ⇨ decay products contain information about the top spin
- **SPIN CORRELATIONS** – in the angular distributions of the decays products:

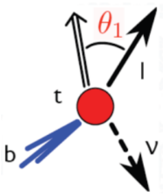
$$\frac{d\sigma}{d\cos\theta_t \, d\cos\theta_{\bar{t}}} = \frac{\sigma}{4}\left(1 + \kappa_t B_t \cos\theta_t + \kappa_{\bar{t}} B_{\bar{t}} \cos\theta_{\bar{t}} - \kappa_t \kappa_{\bar{t}} C \cos\theta_t \cos\theta_{\bar{t}} \right)$$

top-quark polarization

top-antitop quark correlation

κ_t top spin analysing power factors of the top decaying products

i	$l^+, \bar{d}, \bar{s}$	ν_l, u, c	b	W^+	$j_<$
κ	1	-0,31	-0,41	0,41	0,51



SPIN CORRELATIONS II

SPIN OBSERVABLES:

$$\mathcal{O}_1 = S_t \cdot S_{\bar{t}}$$

$$\mathcal{O}_2 = S_t \cdot \hat{a} \ , \ \mathcal{O}_{\bar{2}} = S_{\bar{t}} \cdot \hat{b}$$

$$\mathcal{O}_3 = 4(S_t \cdot \hat{a})(S_{\bar{t}} \cdot \hat{b})$$

-quantization axis

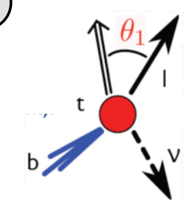
$\hat{a} = -\hat{b} = \hat{k}_t$ **helicity basis (top dir.)**

$\hat{a} = \hat{b} = \hat{p}$ **beamline basis**

$\hat{a} = \hat{b} = \hat{d}_X$ **off-diagonal** (specific for each model X)

$$\frac{d\sigma}{d\cos\theta_t \, d\cos\theta_{\bar{t}}} = \frac{\sigma}{4}\left(1 + \kappa_t B_t \cos\theta_t + \kappa_{\bar{t}} B_{\bar{t}} \cos\theta_{\bar{t}} - \kappa_t \kappa_{\bar{t}} C \cos\theta_t \cos\theta_{\bar{t}} \right)$$

$$\langle \mathcal{O}_2 \rangle = B_t \qquad \langle \mathcal{O}_3 \rangle = C$$



Opening angle distribution among two spin analaysers:

$$\frac{d\sigma}{d\cos\varphi_{l^+l^-}} = \frac{\sigma}{2}\left(1 - \kappa_t D \cos\varphi_{l^+l^-} \right)$$

$$\langle \mathcal{O}_1 \rangle = D$$

almost 100% correlation at Tevatron

[Mahlon and Parke, hep-ph/9512264
Bernreuther et al., hep-ph/0403035]

$$\hat{\mathbf{d}}_{q\bar{q},\mathrm{SM}} = \frac{-\hat{\mathbf{p}} + (1-\gamma)z\,\hat{\mathbf{k}}_1}{\sqrt{1-(1-\gamma^2)z^2}}$$

$$\left[\ \hat{\mathbf{d}}_A = \frac{-\hat{\mathbf{p}} + \left((1-\gamma)z - g_A^2\sqrt{\gamma^2-1}\frac{s}{s-m_A^2}\right)\hat{\mathbf{k}}_1}{\sqrt{1-(1-\gamma^2)z^2+2\gamma\sqrt{\gamma^2-1}g_A^2 s/(s-m_A^2)z-(1-\gamma^2)g_A^4 s^2/(s-m_A^2)^2}}\ \right]$$

C measurements vs SM theory

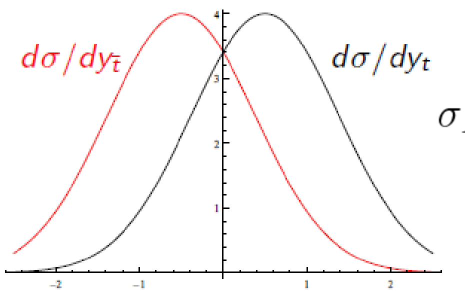
$$\frac{d\sigma}{d\cos\theta_t \, d\cos\theta_{\bar{t}}} = \frac{\sigma}{4}\left(1 + \kappa_t B_t \cos\theta_t + \kappa_{\bar{t}} B_{\bar{t}} \cos\theta_{\bar{t}} - \kappa_t \kappa_{\bar{t}} C \cos\theta_t \cos\theta_{\bar{t}} \right)$$

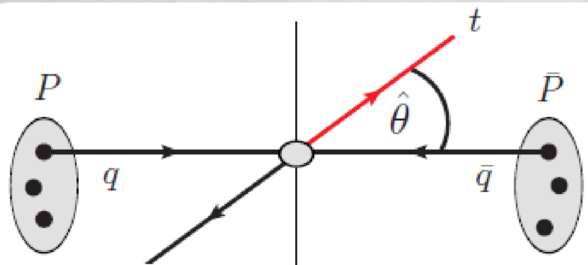
	EXP	SM [Bernreuther et al., hep-ph/0403035]
D0	$C^{TEV}_{beam} = 0.66 \pm 0.23$	$C^{TEV}_{beam,SM} = 0.78^{+0.03}_{-0.04}$
	$C^{TEV}_{hel} = -0.60 \pm 0.52$	$C^{TEV}_{hel,SM} \simeq 0.35$
CDF	$C^{TEV}_{off} = 0.32^{+0.55}_{-0.78}$	$C^{TEV}_{off,SM} = 0.32^{+0.55}_{-0.78}$
ATLAS	$C^{LHC}_{hel} = 0.40^{+0.09}_{-0.08}$	$C^{LHC}_{hel,SM} \simeq 0.31$

GOOD AGREEMENT WITH THE SM

ASYMMETRIES I

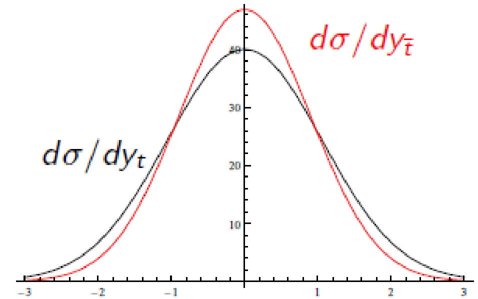
- Tevatron





$$\sigma_B \equiv \int_{-1}^{0} \frac{d\sigma}{d\cos\theta} d\cos\theta \quad B \,|\, F \quad \sigma_F \equiv \int_{0}^{1} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

- LHC



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

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

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

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

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

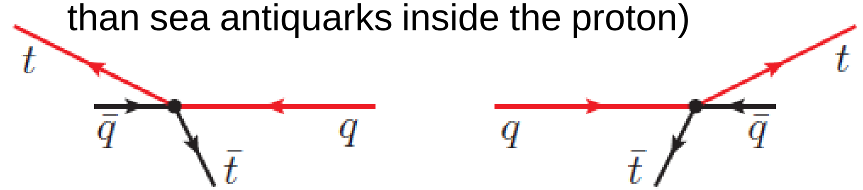
$A_{FB} = A_C$

for a theory with the CP-conserving couplings

$A_{FB} = 0$ A_C(total) = 0

($pp \rightarrow t\bar{t}$ symmetric, no global direction)

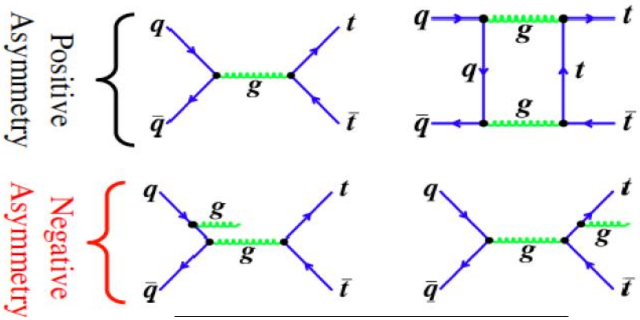
but: tops are more forward than antitops
(because more boosted valence quarks
than sea antiquarks inside the proton)



Excess of boosted top quarks along the beam axis !

ASYMMETRIES II

In SM asymmetry arises at NLO [Kuhn, Rodrigo 1998]



- robust under higher-order QCD corrections [Ahrens et al. 1106.6051 ; Melnikov & Schulze]
- EW corrections about + 20% [Hollik & Pagani, 1107.2606]

A_C measurements:

$$A_C = 0.001 \pm 0.014 \text{ (average)}$$

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

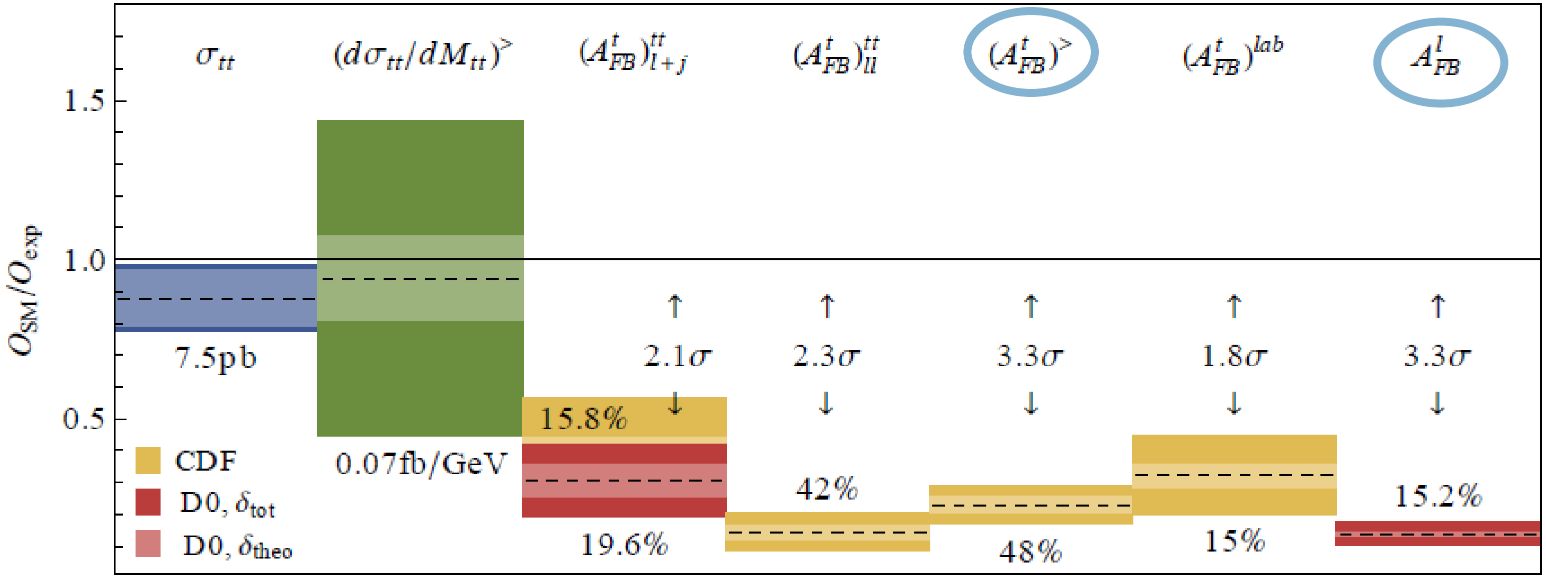
$$A_C^{SM} = 0.006(1)$$

Kidonakis, 1009.4935
1105.3481
Beneke et al, 1109.1536
Ahrens et el, 1003.5827
Bernreuther & Si, 1205.6580

CONSISTENT WITH THE SM

ASYMMETRIES II

TENSIONS between SM & TEVATRON data on asymmetries:



S. Westhoff

$$A_{FB}^{exp} = 0.187 \pm 0.037$$

$$A_{SM}^{Tev} = 0.05 \pm 0.015 \text{ (Antuñano, Kühn, Rodrigo)},$$
$$= 0.066 \pm 0.015 \text{ (Almeida, Sterman, Vogelsang)}$$

NEW PHYSICS ?!

NEW PHYSICS MODELS TO EXPLAIN A_{FB} ?

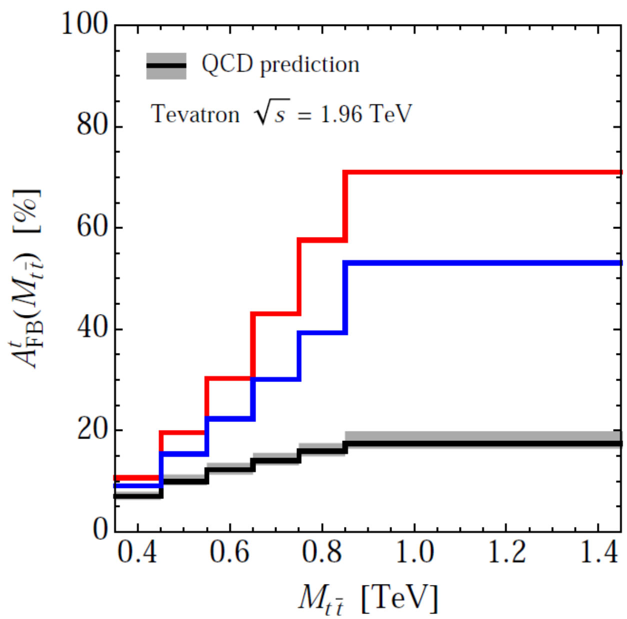
- NP models must explain large A_{FB} without significantly changing the cross section

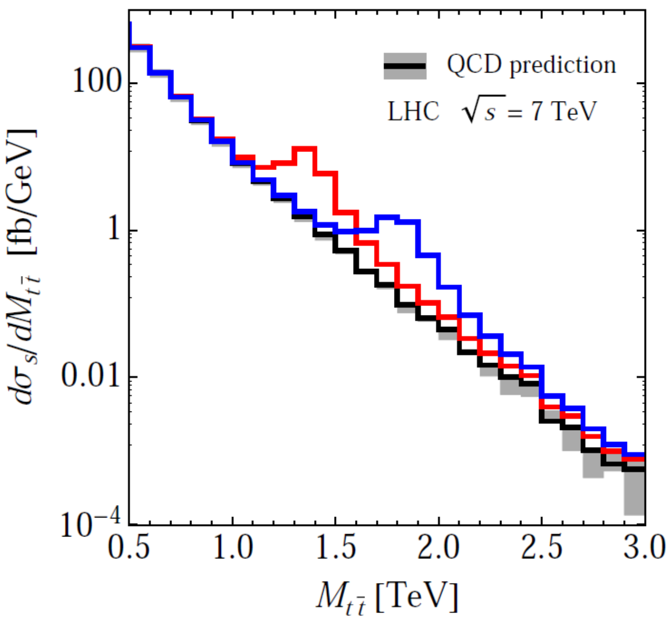
- **MODEL DISTINCTION**

  - from **the shape of $A_{FB}(M_{tt})$**
    [Aguilar-Saavedra & Perez-Victoria, arXiv: 1107.2120]

  - from **resonances in $\sigma(M_{tt})$**
    [Hewett et al, arXiv: 1103.4618]

-an example: axigluon (s-channel) [Haisch & Westhoff , arXiv: 1106.0529]





- from **SPIN CORRELATIONS** [this work]

NEW PHYSICS MODELS TO EXPLAIN A_{FB} ?

MODEL SELECTION:

Colour:

$3 \otimes \bar{3} = 8 \oplus 1$

$3 \otimes 3 = 6 \oplus \bar{3}$

Isospin:

$2 \otimes 2 = 3 \oplus 1$

$2 \otimes 1 = 2$

$1 \otimes 1 = 1$

Hypercharge:

$\sum Y = 0$

	Vectors Label	Vectors Rep.	Scalars Label	Scalars Rep.	
Z'	$\mathcal{B}_\mu$	$(1,1)_0$	ϕ	$(1,2)_{-\frac{1}{2}}$	isodublet
	$\mathcal{W}_\mu$	$(1,3)_0$	Φ	$(8,2)_{-\frac{1}{2}}$	
W'	$\mathcal{B}^1_\mu$	$(1,1)_1$	ω^1	$(3,1)_{-\frac{1}{3}}$	
axigluon	$\mathcal{G}_\mu$	$(8,1)_0$	Ω^1	$(\bar{6},1)_{-\frac{1}{3}}$	
	$\mathcal{H}_\mu$	$(8,3)_0$	ω^4	$(3,1)_{-\frac{4}{3}}$	colour triplet
	$\mathcal{G}^1_\mu$	$(8,1)_1$	Ω^4	$(\bar{6},1)_{-\frac{4}{3}}$	colour sextet
	$\mathcal{Q}^1_\mu$	$(3,2)_{\frac{1}{6}}$	σ	$(3,3)_{-\frac{1}{3}}$	
	$\mathcal{Q}^5_\mu$	$(3,2)_{-\frac{5}{6}}$	Σ	$(\bar{6},3)_{-\frac{1}{3}}$	
	$\mathcal{Y}^1_\mu$	$(\bar{6},2)_{\frac{1}{6}}$			
	$\mathcal{Y}^5_\mu$	$(\bar{6},2)_{-\frac{5}{6}}$			

Aguilar-Saavedra, Perez-Victoria

MODEL FIT TO THE AVAILABLE DATA:

global χ^2 fit - **scenario A** $(A_{FB}, A_C, \sigma^{high}_{TEV}, \sigma_{LHC})$

- **scenario B** $(A^{low}_{FB}, A^{high}_{FB}, d\sigma_{TEV}/m_{tt}, \sigma_{LHC})$

we consider NP model as acceptable if it improves upon χ^2_{SM}

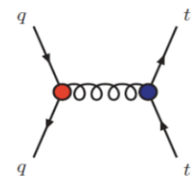
$$\chi^2_{SM}(A) = 2.3 / \text{d.o.f.}$$

$$\chi^2_{SM}(B) = 1.8 / \text{d.o.f.}$$

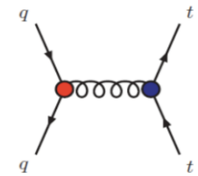
MODELS s-channel exchange :

- **axigluon G'**

$$\mathcal{L}^{\mathrm{int.}}_{G'} = -\bar{q}(g_V^q - g_A^q\gamma_5)\not{G}'q - \bar{t}(g_V^t - g_A^t\gamma_5)\not{G}'t$$



+ SM



parameters: $g_A^u g_A^t$, m_G, $\Gamma_G / m_G \sim 0.2$

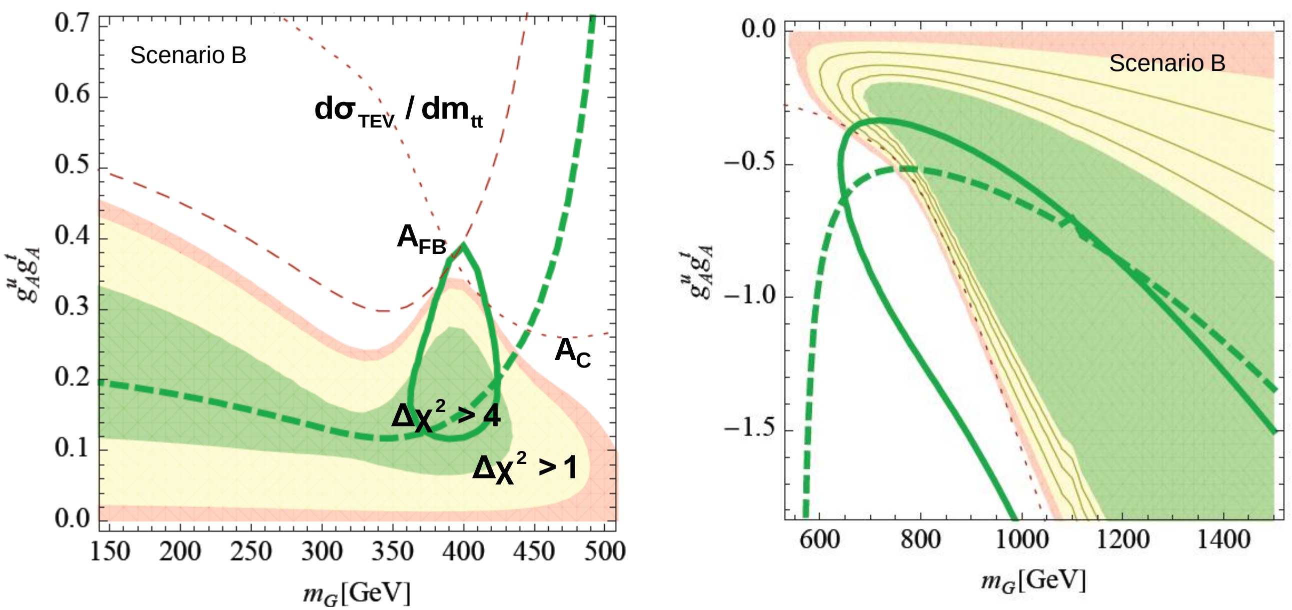


Figure 1: $t\bar{t}$ production constraints on the axigluon model: binned FBA at 1σ in thick full green line, inclusive CA at 1σ (2σ) in thick dashed green line (thin dashed red line), $m_{t\bar{t}}$ spectrum at 2σ in thin red dotted line. Parameter regions where the model can improve the SM χ^2 by $-\Delta\chi^2 > 0, 1, 4$ are shaded in red, yellow and green respectively.

Model fit :

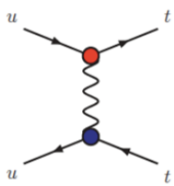
low mass region: m_G < 450 GeV	high mass region: m_G > 700 GeV
$g_A^u g_A^t \sim 0.2$	$g_A^u g_A^t \sim -0.5$

NEW PHYSICS MODELS – MODEL SELECTION II

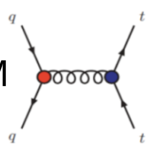
MODELS t-channel exchange:

- **Z', W'**

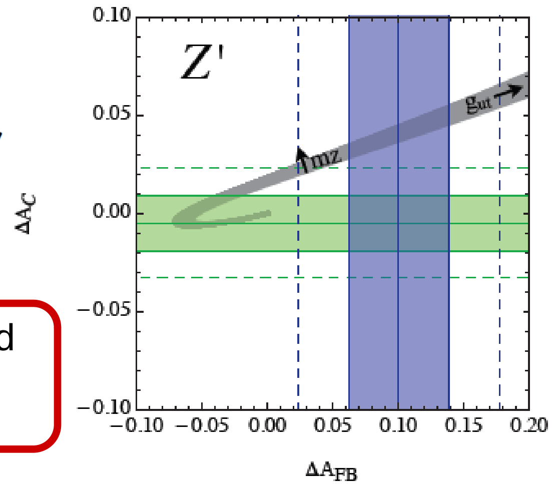
$$\mathcal{L}^{\text{int.}}_{Z'} = -\bar{u}\gamma_\mu(f_L^{Z'} P_L + f_R^{Z'} P_R) t Z'$$
$$\mathcal{L}^{\text{int.}}_{W'} = -\bar{d}\gamma_\mu(f_L^{W'} P_L + f_R^{W'} P_R) t W'$$

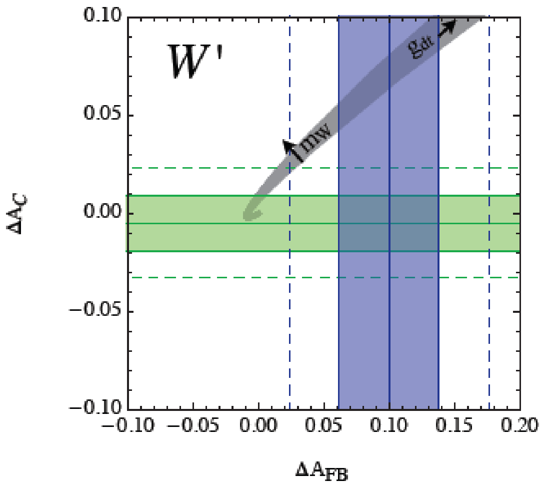


+ SM



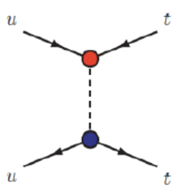
tension between A_{FB} and A_C cannot be reduced below 2 σ level



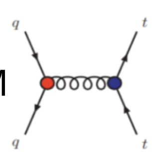


- **scalar doublet Φ**

$$\mathcal{L}^{\text{int.}}_{\Phi} = -y^u_{ij}\bar{q}_{Li}u_{Rj}\Phi - y^d_{ij}\bar{q}_{Li}d_{Rj}\tilde{\Phi}\,.$$

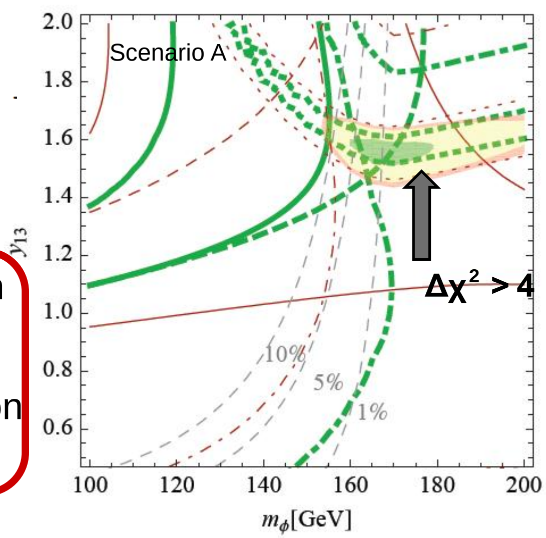


+ SM

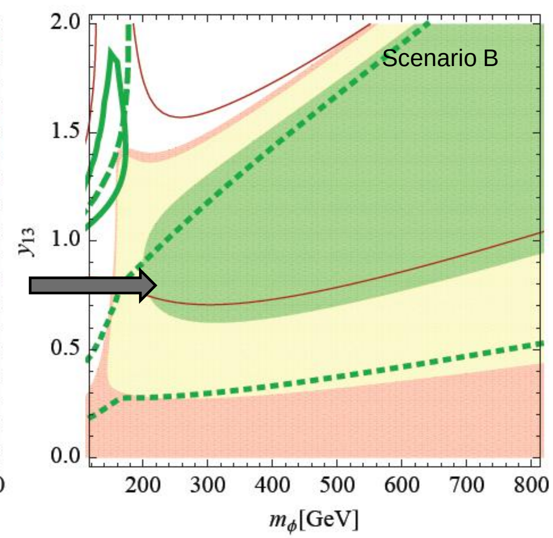


scenario A – low mass region $m(\Phi) < m_t$ - preferred

scenario B – high mass region $m(\Phi) > 200$



$\Delta\chi^2 > 4$

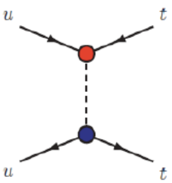


NEW PHYSICS MODELS – MODEL SELECTION III

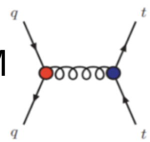
MODELS u-channel exchange:

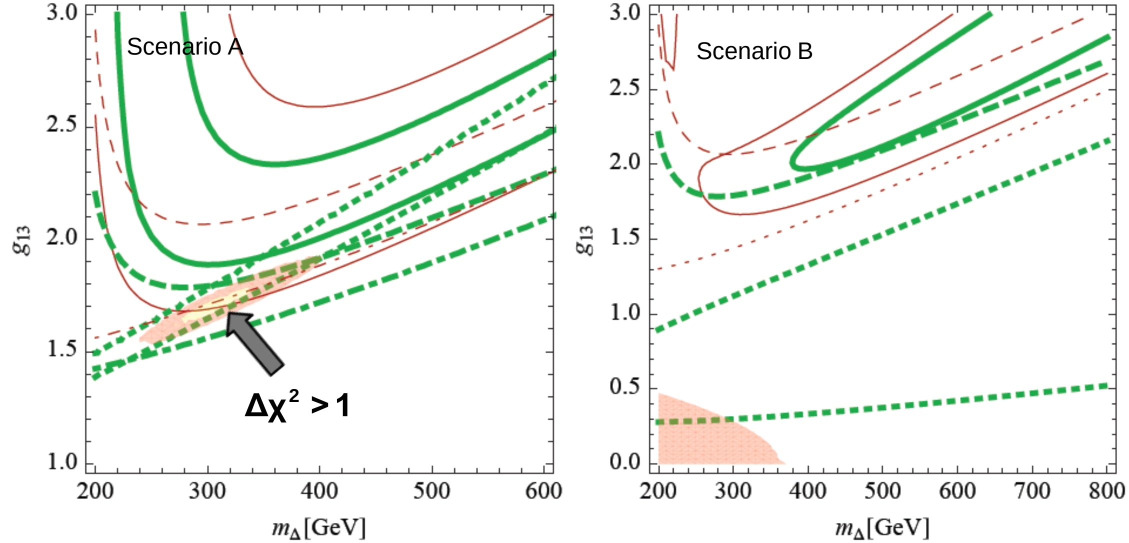
▪ scalar colour triplet Δ

$$\mathcal{L}^{\text{int.}}_{\Delta} = -\boxed{g_{(\Delta)ij}}\,\epsilon_{abc}\bar{u}^{a}_{R,i}(u^{b}_{R,j})^{C}\Delta^{C}$$



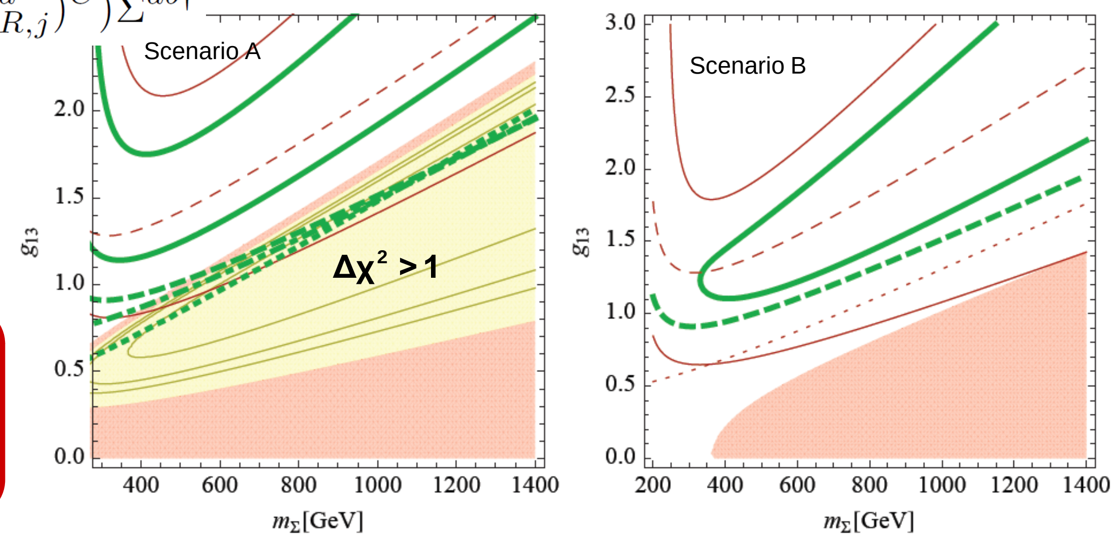
+ SM





▪ scalar colour sextet Σ

$$\mathcal{L}^{\text{int.}}_{\Sigma} = -\boxed{g_{(\Sigma)ij}}\,(\bar{u}^{a}_{R,i}(u^{b}_{R,j})^{C} + \bar{u}^{b}_{R,i}(u^{a}_{R,j})^{C})\Sigma^{ab\dagger}$$



tensions between A_{FB} and ttbar spectrum measurements

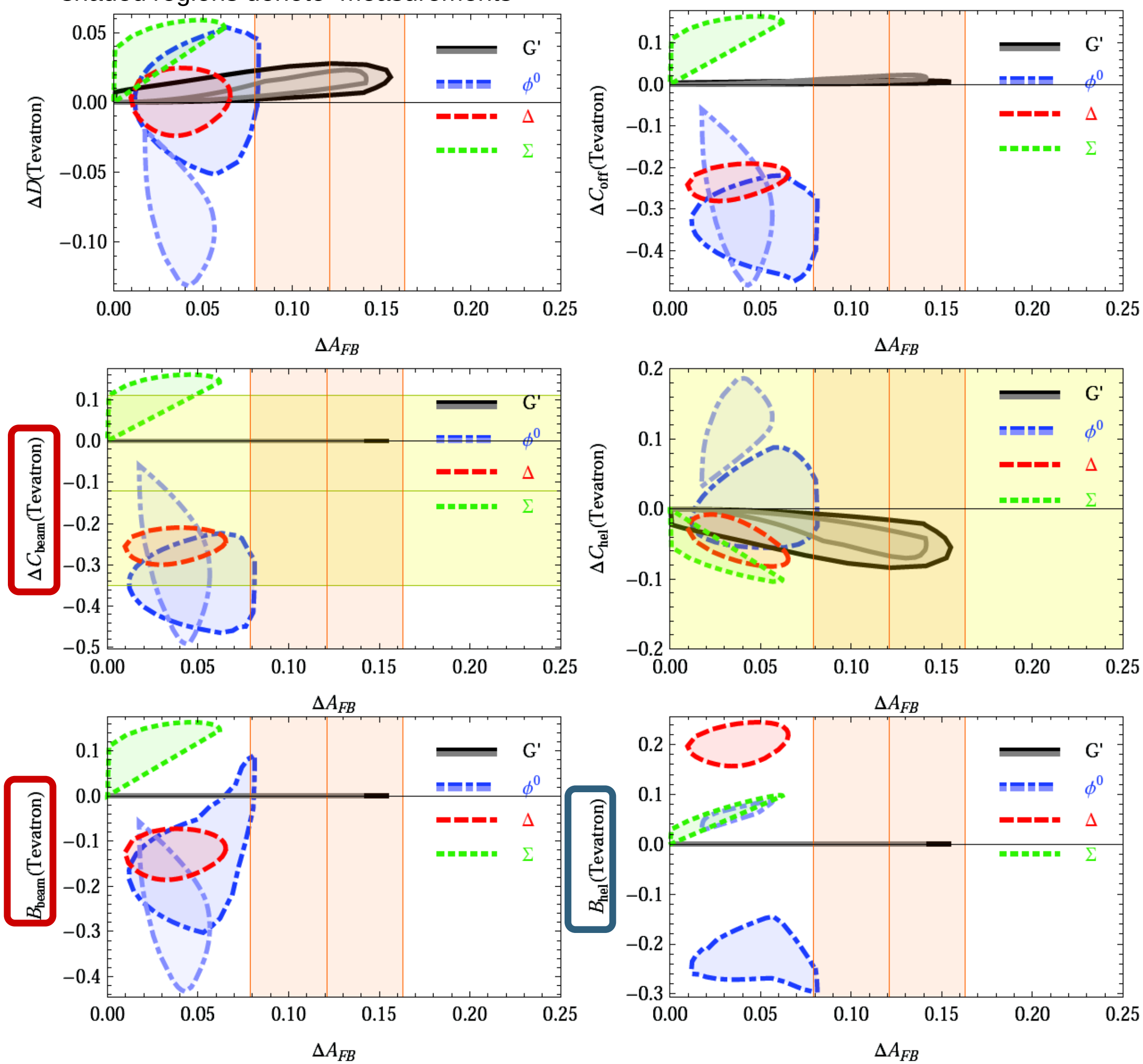
scenario A – preferred parameter regions

NEW PHYSICS MODELS – TOP SPIN OBERVABLES

- **TEVATRON** predictions ($\Delta O = O - O_{SM}$)

off-diagonal axis ≈ beamlike axis

shaded regions denote measurements



Beamline axis – potential for discrimination between Σ and Φ, Δ using correlations ΔC

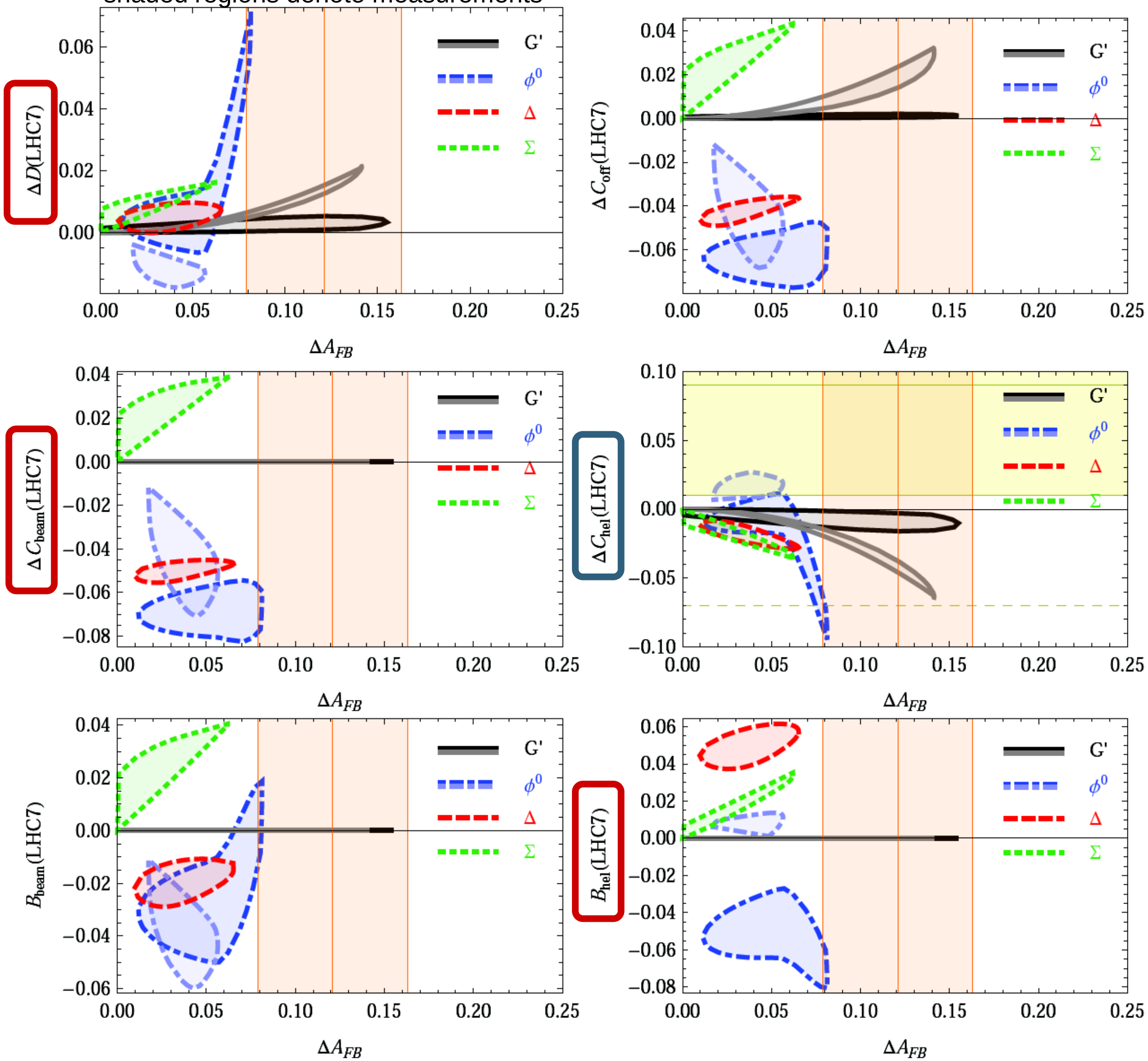
Helicity axis – potential for discrimination between Φ and Δ at O(20%) level using top spin B_{hel}

G' – needs O(2%) precision measurements

NEW PHYSICS MODELS – TOP SPIN OBERVABLES

- **LHC (7 TeV)** predictions ($\Delta O = O - O_{SM}$)

shaded regions denote measurements



D, C_{beam}, B_{hel} at O(5%) could discern among scalars

Helicity axis – ΔC_{hel}^{ex} – already nontrivial constraint for Φ and G' models

G' – very difficult to probe (especially light G')

CONCLUSIONS

we have performed a comprehensive analysis of tt-production at Tevatron and LHC within the NP resonance models addressing the A_{FB} puzzle

- tension between the large positive A_{FB} measurement at the Tevatron and precise A_C at the LHC exclude Z' and W' models as explanation for the AFB anomaly
- among considered models only axigluon state (of mass $m_G \approx 400$ GeV or $m_G \geq 1$ TeV) can reproduce A_{FB} and $A_{FB}{}^{high}$
- Φ^{light} ($m_\Phi < m_t$) is severely constrained by measurements
- Δ , Σ are constrained by σ and $d\sigma/dm_{tt}$ at Tevatron - however given the caveats with the properly reconstructed dm_{tt} spectra, this issue has to be settled by future measurements

we have derived predictions of top spin polarization and tt-correlations at the Tevatron and the LHC

- at the TEVATRON - B_{hel} for the scalar models can deviate more than 20% from B_{hel}^{SM} - discrimination between Φ and Δ is possible
- at the LHC – B_{hel} and ΔC_{hel} at 5-10% can yield competitive constraints (as exemplified by the recent ATLAS measurements)
- axigluon models will be difficult to constrain using top spin observables

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