Physics of selected Top Quark Properties

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Large Yukawa: sensitive to EWSB (and new physics?)

Decays before hadronizing

- Mass
- Spin
- Couplings

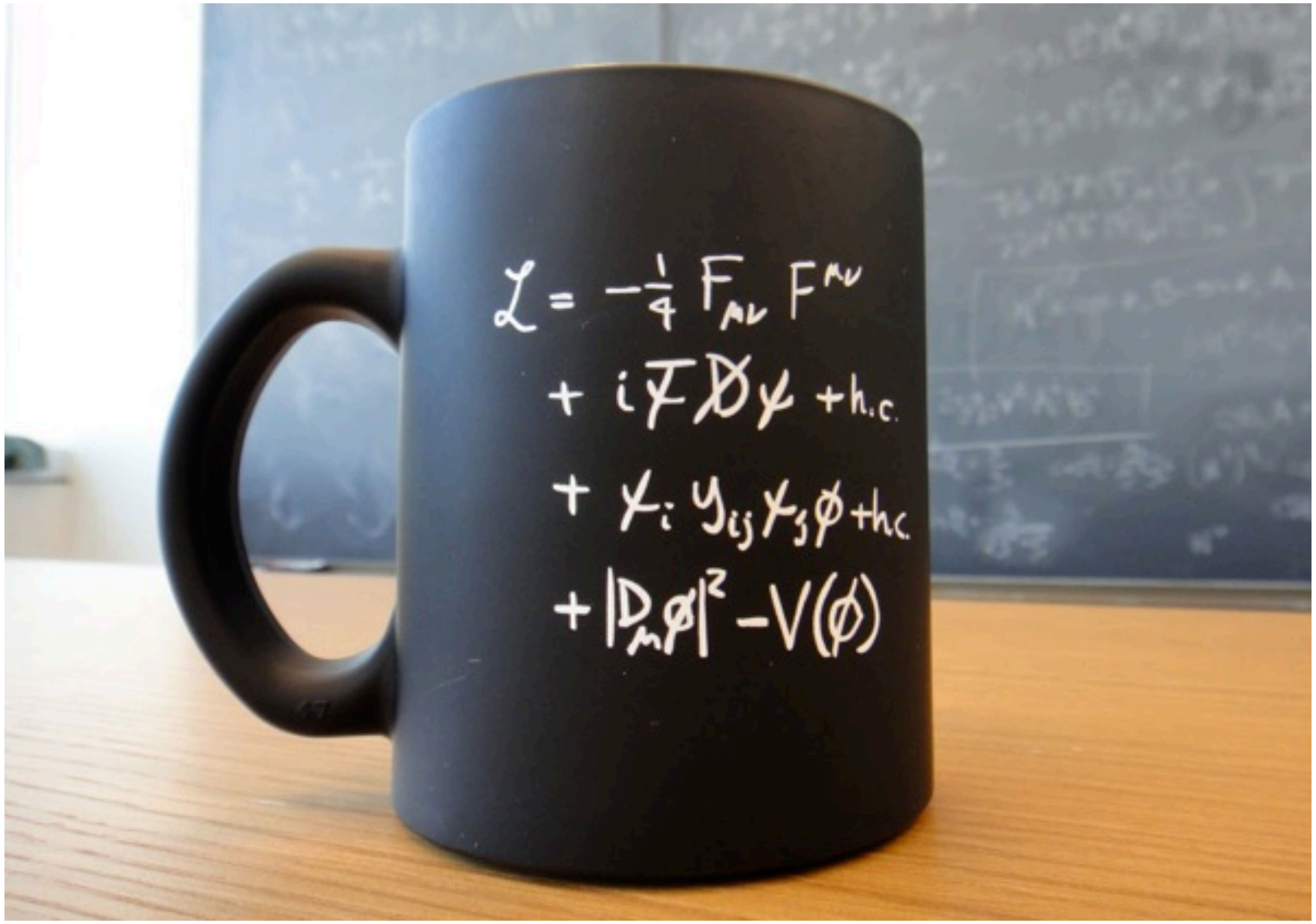
Outline

- General top couplings (model independent)
- Modified couplings from extra quarks
- Charge asymmetries (model independent)
- Charge asymmetries from extra bosons
- Conclusions

Top couplings

$$\mathcal{L} = \mathcal{L}^{(4)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \ldots$$

Dimension 4


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Top Couplings

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[W_{tb}^L \, \bar{t}_L \gamma^\mu b_L + W_{tb}^R \, \bar{t}_R \gamma^\mu b_R \right] W_\mu^+ + \text{h.c.} + \dots$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[X_t^L \, \bar{t}_L \gamma^\mu t_L + X_t^R \, \bar{t}_R \gamma^\mu t_R - X_b^L \, \bar{b}_L \gamma^\mu b_L - X_b^R \, \bar{b}_R \gamma^\mu b_R \right.$$
$$\left. - 2 s_W^2 \left(\frac{2}{3} \bar{t} \gamma^\mu t - \frac{1}{3} \bar{b} \gamma^\mu b \right) \right] Z_\mu + \dots$$

$$\mathcal{L}_H = -\frac{g}{2M_W} \left[m_t Y_t \, \bar{t}t + m_b Y_b \, \bar{b}b \right] H$$

Dimension 4

$O(\Lambda^0)$

$$W_{tb}^L = V_{tb} \simeq 1 \qquad W_{tb}^R = 0$$
$$\dots \simeq 0$$

$$X_t^L = X_b^L = 1 \qquad X_t^R = X_b^R = 0$$

$$Y_t = Y_b = 1 \qquad \dots = 0$$

Dimension 6

I assume new physics only affects the third family

$$\mathcal{L}^{(6)} = \alpha_1(\phi^\dagger i D_\mu \phi)(\bar{q}_L \gamma^\mu q_L) + \alpha_3(\phi^\dagger \tau^I i D_\mu \phi)(\bar{q}_L \gamma^\mu \tau^I q_L)$$
$$+ \alpha_t(\phi^\dagger i D_\mu \phi)(\bar{t}_R \gamma^\mu t_R) + \alpha_b(\phi^\dagger i D_\mu \phi)(\bar{b}_R \gamma^\mu b_R)$$
$$+ \alpha_{tb}(\phi^T \epsilon i D_\mu \phi)(\bar{t}_R \gamma^\mu b_R) + \alpha_{t\phi}(\phi^\dagger \phi)(\bar{q}_L \tilde{\phi} t_R) + \alpha_{b\phi}(\phi^\dagger \phi)(\bar{q}_L \phi b_R)$$

$$+$$

Magnetic/derivative couplings ← Loop suppressed

$$+$$

Four-quark operators ← Later

Top Couplings

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[W_{tb}^L \, \bar{t}_L \gamma^\mu b_L + W_{tb}^R \, \bar{t}_R \gamma^\mu b_R \right] W_\mu^+ + \text{h.c.} + \ldots$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left[X_t^L \, \bar{t}_L \gamma^\mu t_L + X_t^R \, \bar{t}_R \gamma^\mu t_R - X_b^L \, \bar{b}_L \gamma^\mu b_L - X_b^R \, \bar{b}_R \gamma^\mu b_R \right.$$
$$\left. - 2 s_W^2 \left(\frac{2}{3} \bar{t} \gamma^\mu t - \frac{1}{3} \bar{b} \gamma^\mu b \right) \right] Z_\mu + \ldots$$

$$\mathcal{L}_H = -\frac{g}{2M_W} \left[m_t Y_t \, \bar{t} t + m_b Y_b \, \bar{b} b \right] H$$

Dimension 4 & 6

del Aguila, MPV, Santiago '00

$O(\Lambda^{-2})$

$W_{tb}^L \neq V_{tb} \; (\not\simeq 1)$ $\quad$ $W_{tb}^R \neq 0$

$\ldots \not\simeq 0$

$X_t^L \neq 1, \; X_b^L \neq 1$ $\quad$ $X_t^R \neq 0, \; X_b^R \neq 0$

$Y_t \neq 1, \; Y_b \neq 1$ $\quad$ $\ldots \neq 0$

Observation #1

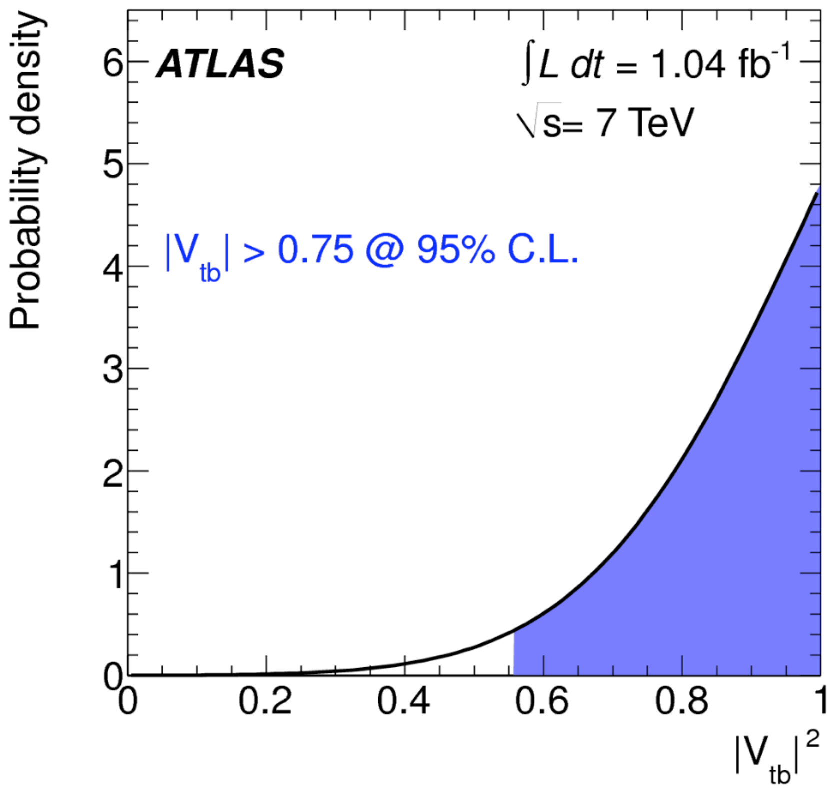
$W^{L,R}$ non unitary in general

$$W^L = \left(1 + \frac{v^2}{\Lambda^2}\Omega\right) V$$

hermitian matrix

W^L_{tb} can be smaller, equal or greater than 1

No theoretical reason for prior $W^L_{tb} \leq 1$ except in specific models



Observation #1

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Ω: hermitian matrix

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ATLAS

$$|V_{tb}| = 1.13^{+0.14}_{-0.13}$$

No experimental reason, either

Observation #2

Gauge invariance relates t_L and b_L

$$X_t^L = 1 + \frac{v^2}{\Lambda^2}(\alpha_3 - \alpha_1)$$

$$X_b^L = 1 + \frac{v^2}{\Lambda^2}(\alpha_3 + \alpha_1)$$

$$W_{tb}^L = 1 + \frac{v^2}{\Lambda^2}\alpha_3$$

$$\Rightarrow \quad 2\,W_{tb}^L = X_t^L + X_b^L$$

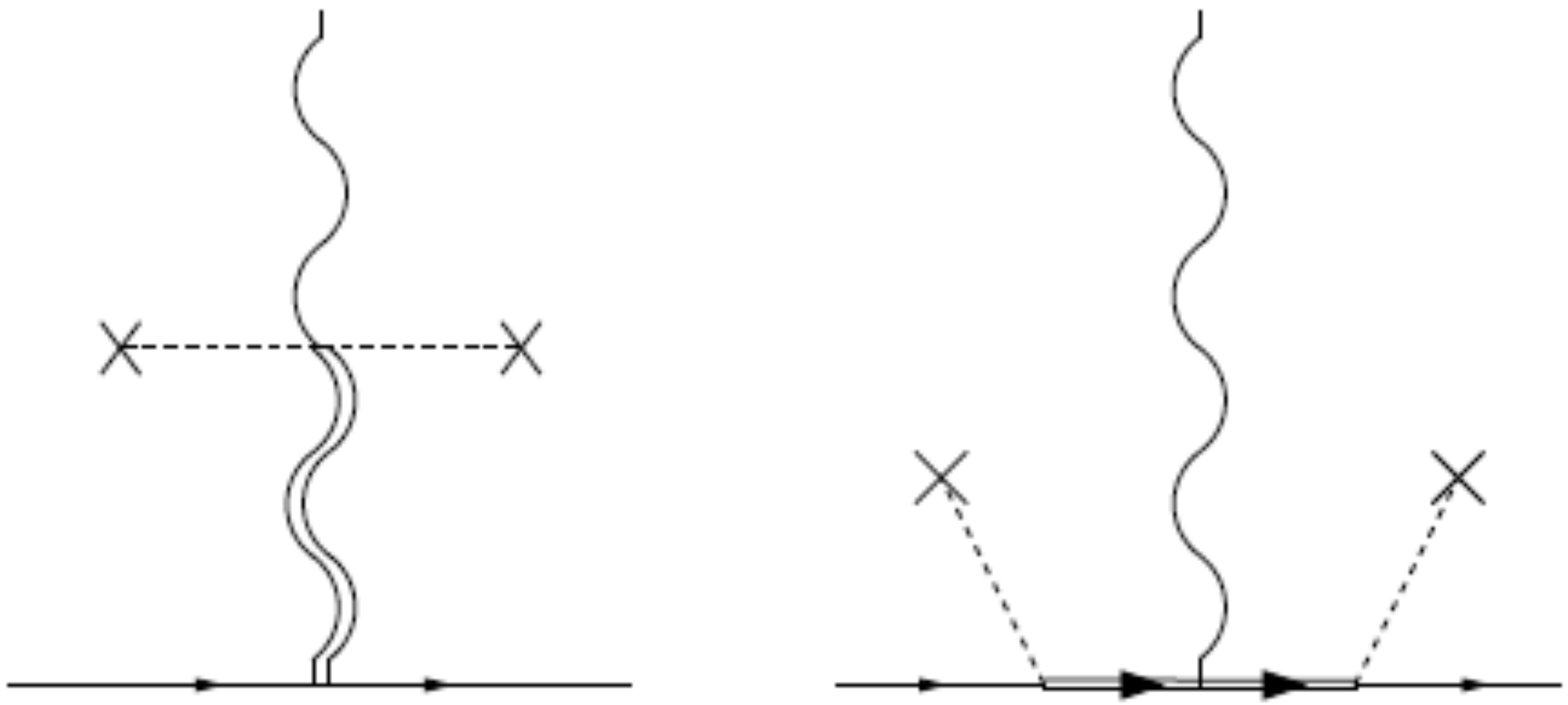
Constraint from R_b at LEP:

$$X_b^L \simeq 1 \longrightarrow 2\,\delta W_{tb}^L \simeq \delta X_t^L$$

Only one parameter in left sector

E.g. models with custodial protection of R_b

Modified couplings to W and Z from New Physics at tree level:



New vector bosons mixing with the Z, W

New quarks mixing with the SM quarks

Extra quarks

Chiral 4th generation

In bad shape until recently...

- No theoretical motivation
- Problems with EWPT (but survive with heavy Higgs)
- Direct limits imply large (~ 3) Yukawa couplings → perturbativity in danger

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- Direct limits imply large (~ 3) Yukawa couplings ➔ perturbativity in danger

Almost excluded after Higgs discovery

- Large enhancement of $gg \to H$ not observed
- Strongly disfavoured by EWPT (Higgs is light!)

Heavy vector-like quarks

- Appear in many motivated extensions of SM
- Do not change gg→H in simplest cases
- Constraint but not excluded by EWPT
- Direct limits do not require large Yukawa couplings

Only 7 relevant multiplets:

$$T \quad B \quad \begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} X \\ T \end{pmatrix} \begin{pmatrix} B \\ Y \end{pmatrix} \begin{pmatrix} X \\ T \\ B \end{pmatrix} \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$$

Easy to be exhaustive!

$T \rightarrow$ charge $2/3$ $\quad X \rightarrow$ charge $5/3$

$B \rightarrow$ charge $-1/3$ $\quad Y \rightarrow$ charge $-4/3$

Extra quarks

Modified couplings

del Aguila, MPV, Santiago '00

	# par	δW_{tb}^L	δW_{tb}^R	δX_t^L	δX_b^L	δX_t^R	δX_b^R	δY_t	δY_b
T	1	↓	—	↓	—	—	—	↓	—
B	1	↓	—	—	↓	—	—	—	↓
$\begin{pmatrix} T \\ B \end{pmatrix}$	2	—	↑	—	—	↑	↑	↓	↓
$\begin{pmatrix} X \\ T \end{pmatrix}$	1	—	—	—	—	↑	—	↓	—
$\begin{pmatrix} B \\ Y \end{pmatrix}$	1	—	—	—	—	—	↑	—	↓
$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	1	↑	—	↓	↑	—	—	↓	↓
$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$	1	↑	—	↑	↓	—	—	↓	↓

Extra quarks

Modified top couplings

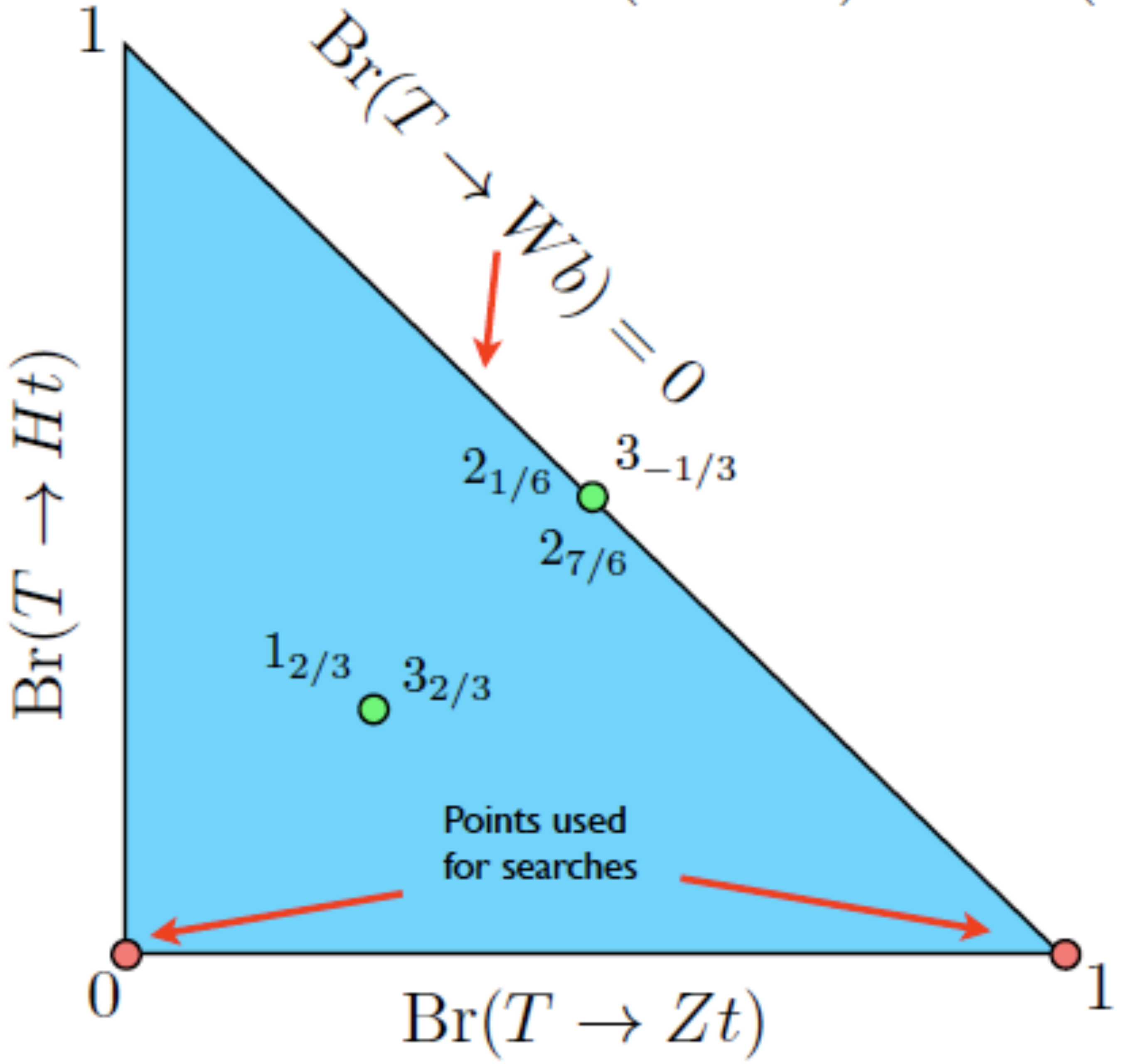
↕

Heavy quark direct searches

Aguilar-Saavedra, Benbrik, Heinemeyer, MPV, in preparation

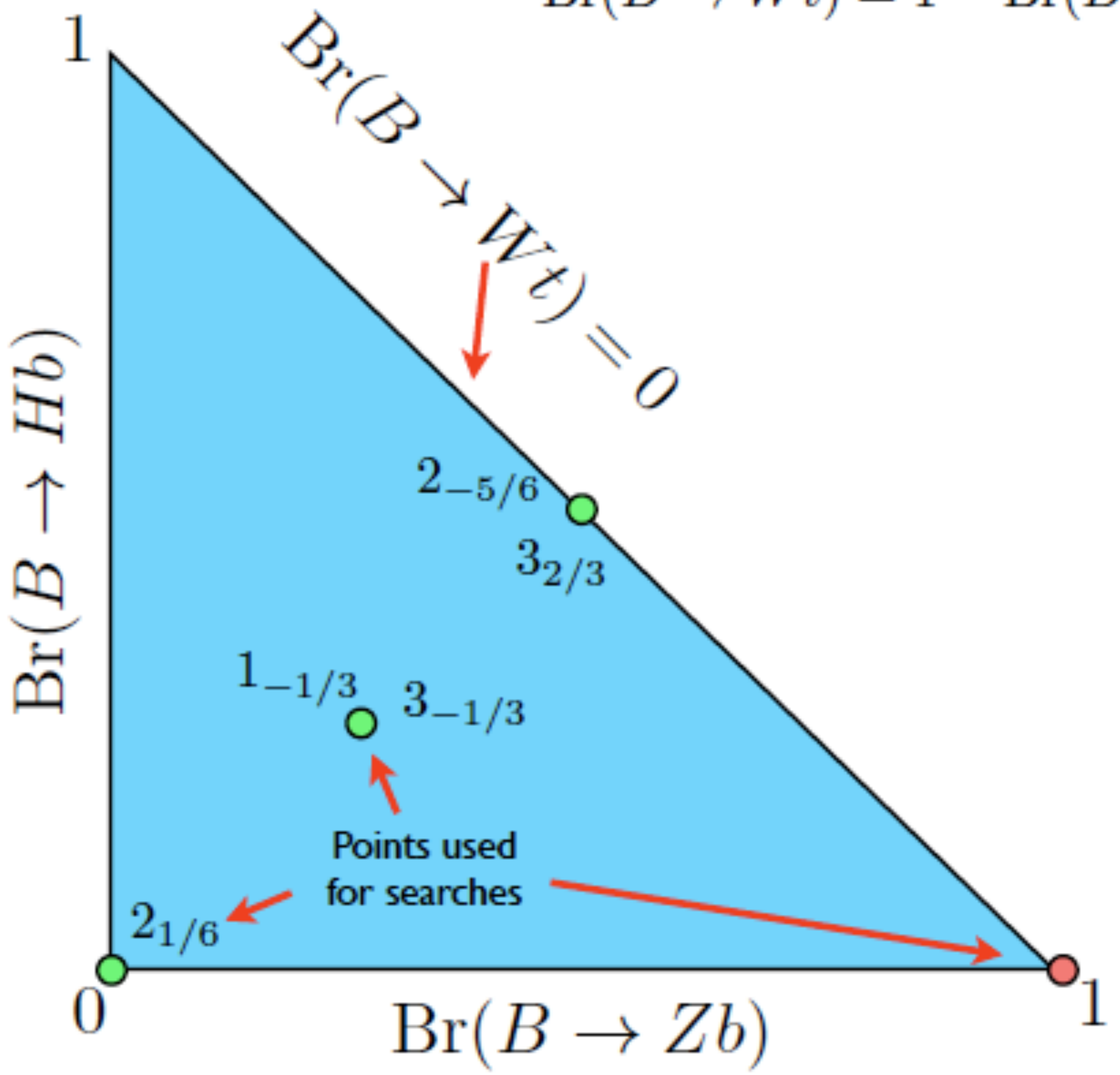
Decays of T (charge 2/3)

$$\mathrm{Br}(T \to Wb) = 1 - \mathrm{Br}(T \to Zt) - \mathrm{Br}(T \to Ht)$$



Decays of B (charge -1/3)

$$\mathrm{Br}(B \to Wt) = 1 - \mathrm{Br}(B \to Zb) - \mathrm{Br}(B \to Hb)$$



Direct limits on vector-like quarks

for T

- $\sim$ 420 GeV $1_{2/3}$, $3_{2/3}$
- ??? $2_{1/6}$, $2_{7/6}$, $3_{-1/3}$

Corrections to top couplings observable at ILC

Aguilar-Saavedra, Fiolhais, Onofre '12

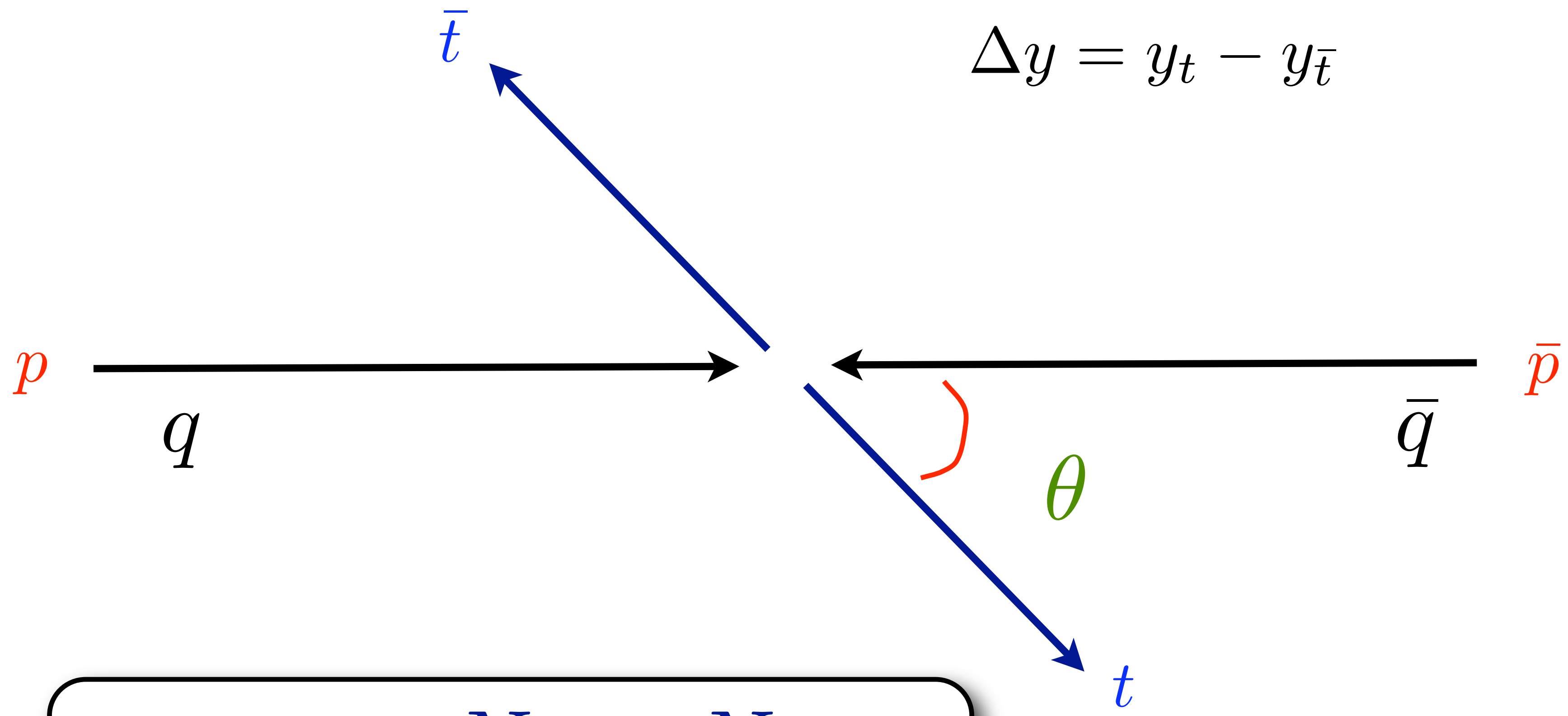
for B

- 611 GeV $2_{1/6}$
- 358 GeV $1_{-1/3}$, $3_{-1/3}$
- ??? $2_{-5/6}$, $3_{2/3}$

still room for discoveries & indirect effects!

Top charge asymmetries

Top forward-backward asymmetry @ Tevatron

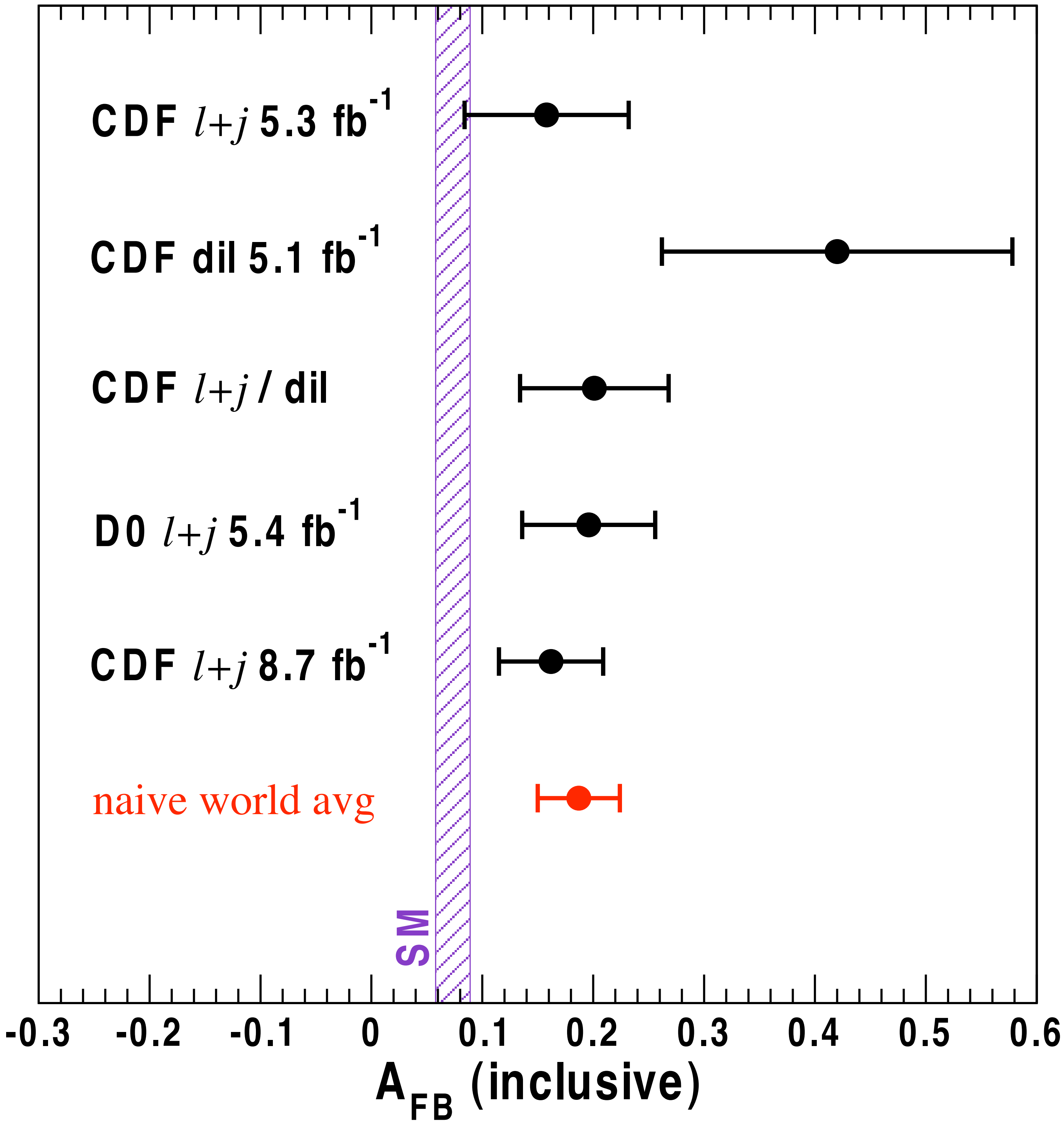


$$\Delta y = y_t - y_{\bar{t}}$$

$$A_{\mathrm{FB}} = \frac{N_F - N_B}{N_F + N_B}$$

Inclusive FB asymmetry

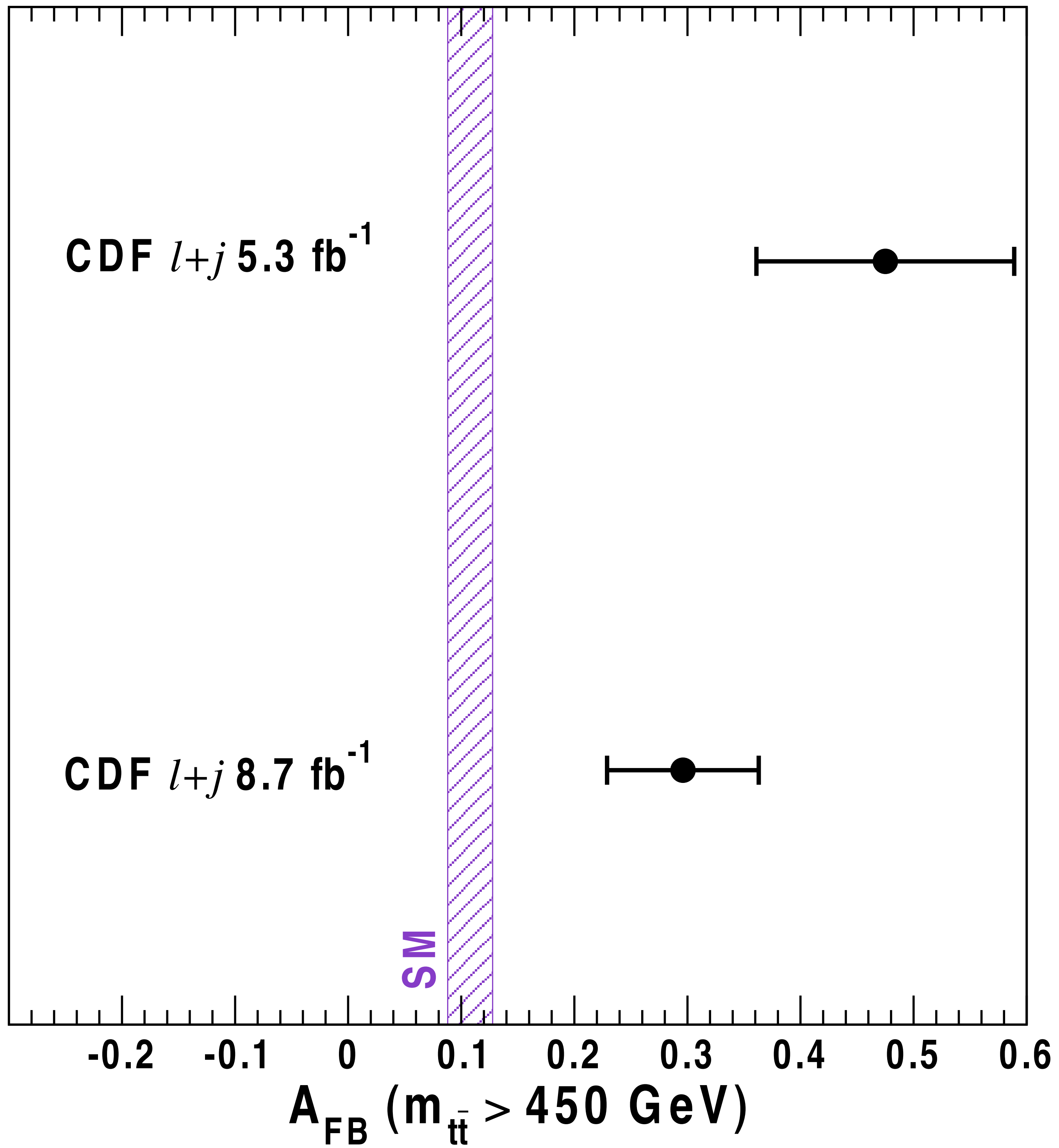
Parton level



Cross section agrees with SM

High-invariant-mass FB asymmetry

Parton level



BSM explanations

$$\sigma_t = \sigma^F + \sigma^B \qquad = \sigma_t^{SM}$$

$$A_{FB} = \frac{\sigma^F - \sigma^B}{\sigma^F + \sigma^B} \qquad \neq A_{FB}^{SM}$$

$$\sigma^{F,B} = \sigma_{\rm SM}^{F,B} + \sigma_{\rm int}^{F,B} + \sigma_{\rm new}^{F,B}$$

$\sigma_{\rm new}^{F,B}$: > 0

$\sigma_{\rm int}^{F,B}$: $\sim \dfrac{g_{\rm new}^2}{M_{new}^2}$

$\sigma_{\rm new}^{F,B}$: $\sim \dfrac{g_{\rm new}^4}{M_{new}^4}$

Need negative interference: $\sigma_{\rm int}^B < 0$

Grinstein, Kagan, Trott, '11

BSM explanations

$$\sigma_t = \sigma^F + \sigma^B \qquad = \sigma_t^{SM}$$

$$A_{FB} = \frac{\sigma^F - \sigma^B}{\sigma^F + \sigma^B} \qquad \neq A_{FB}^{SM}$$

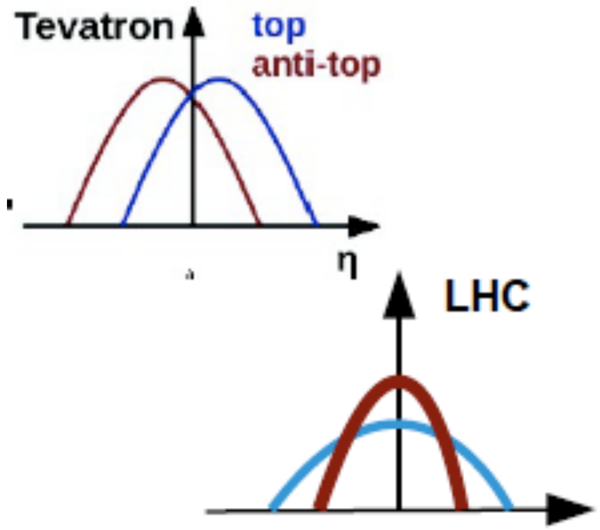
New physics must satisfy one of the following eqs.

- ★ $\sigma^F_{\text{int}} + \sigma^B_{\text{int}} = 0 \quad , \quad \sigma^B_{\text{new}}$ negligible — linear
- ★ $\sigma^F_{\text{int}} + \sigma^B_{\text{int}} = -(\sigma^F_{\text{new}} + \sigma^B_{\text{new}})$ — quadratic

Charge asymmetry @ LHC

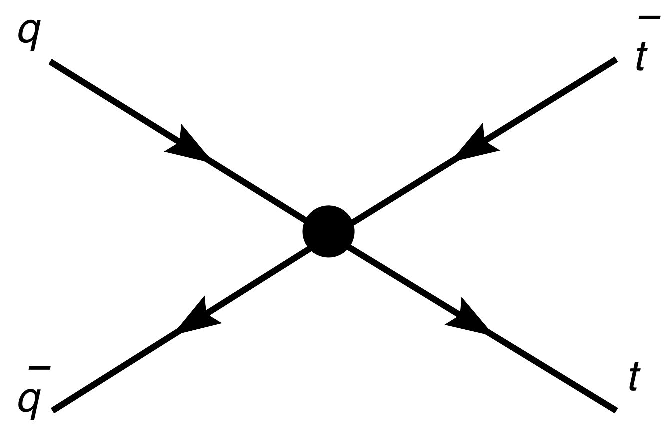
pp symmetric... but p mostly made out of valence quarks

- On average q carries larger x than $\bar{q}$
- This defines, event by event, a preferred direction
- Positive FW asymmetry translates into antiquarks being more central than quarks



$$A_c = \frac{N\left(|y_t| > |y_{\bar{t}}|\right) - N\left(|y_{\bar{t}}| > |y_t|\right)}{N\left(|y_t| > |y_{\bar{t}}|\right) + N\left(|y_{\bar{t}}| > |y_t|\right)}$$

Heavy new physics



Four-fermion operators (dim 6)

$$\mathcal{O}_{Qq}^{(8,1)} = \left(\bar{Q}\gamma^{\mu}T^{A}Q\right)\left(\bar{q}\gamma_{\mu}T^{A}q\right),$$
$$\mathcal{O}_{Qq}^{(8,3)} = \left(\bar{Q}\gamma^{\mu}T^{A}\sigma^{I}Q\right)\left(\bar{q}\gamma_{\mu}T^{A}\sigma^{I}q\right),$$

$$\mathcal{O}_{tu}^{(8)} = \left(\bar{t}\gamma^{\mu}T^{A}t\right)\left(\bar{u}\gamma_{\mu}T^{A}u\right),$$
$$\mathcal{O}_{td}^{(8)} = \left(\bar{t}\gamma^{\mu}T^{A}t\right)\left(\bar{d}\gamma_{\mu}T^{A}d\right),$$

Delaunay et al. '11
Aguilar-Saavedra, MPV '11

quadratic corrections

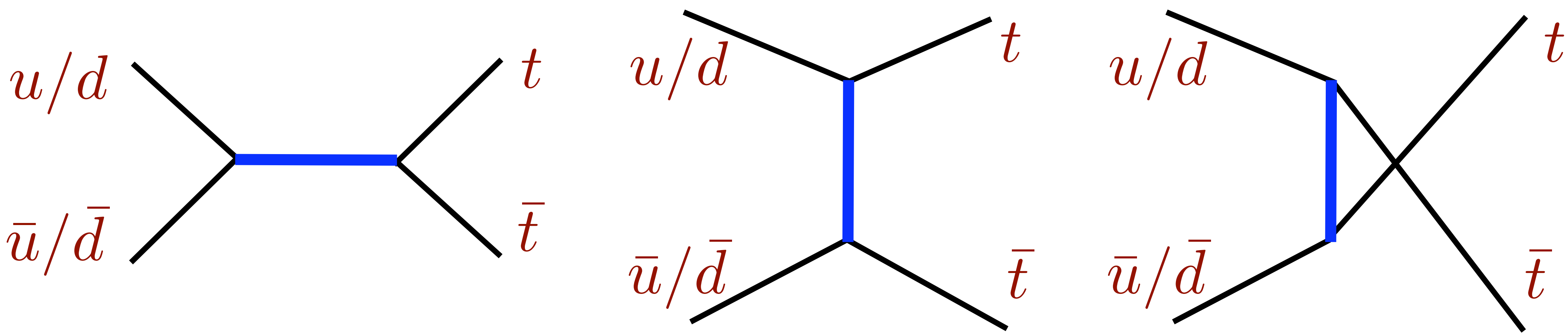
interfering with SM

Degrande et al. '10

$$\mathcal{O}_{Qu}^{(8)} = \left(\bar{Q}\gamma^{\mu}T^{A}Q\right)\left(\bar{u}\gamma_{\mu}T^{A}u\right),$$
$$\mathcal{O}_{Qd}^{(8)} = \left(\bar{Q}\gamma^{\mu}T^{A}Q\right)\left(\bar{d}\gamma_{\mu}T^{A}d\right),$$
$$\mathcal{O}_{tq}^{(8)} = \left(\bar{q}\gamma^{\mu}T^{A}q\right)\left(\bar{t}\gamma_{\mu}T^{A}t\right),$$

Tree-level exchange of new bosons

	s channel	t channel	u channel



electric charge	0	0, ±1	±1/3, ±4/3

All possibilities:

Colour:

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

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

Isospin:

$2 \otimes 2 = 3 \oplus 1$

$2 \otimes 1 = 2$

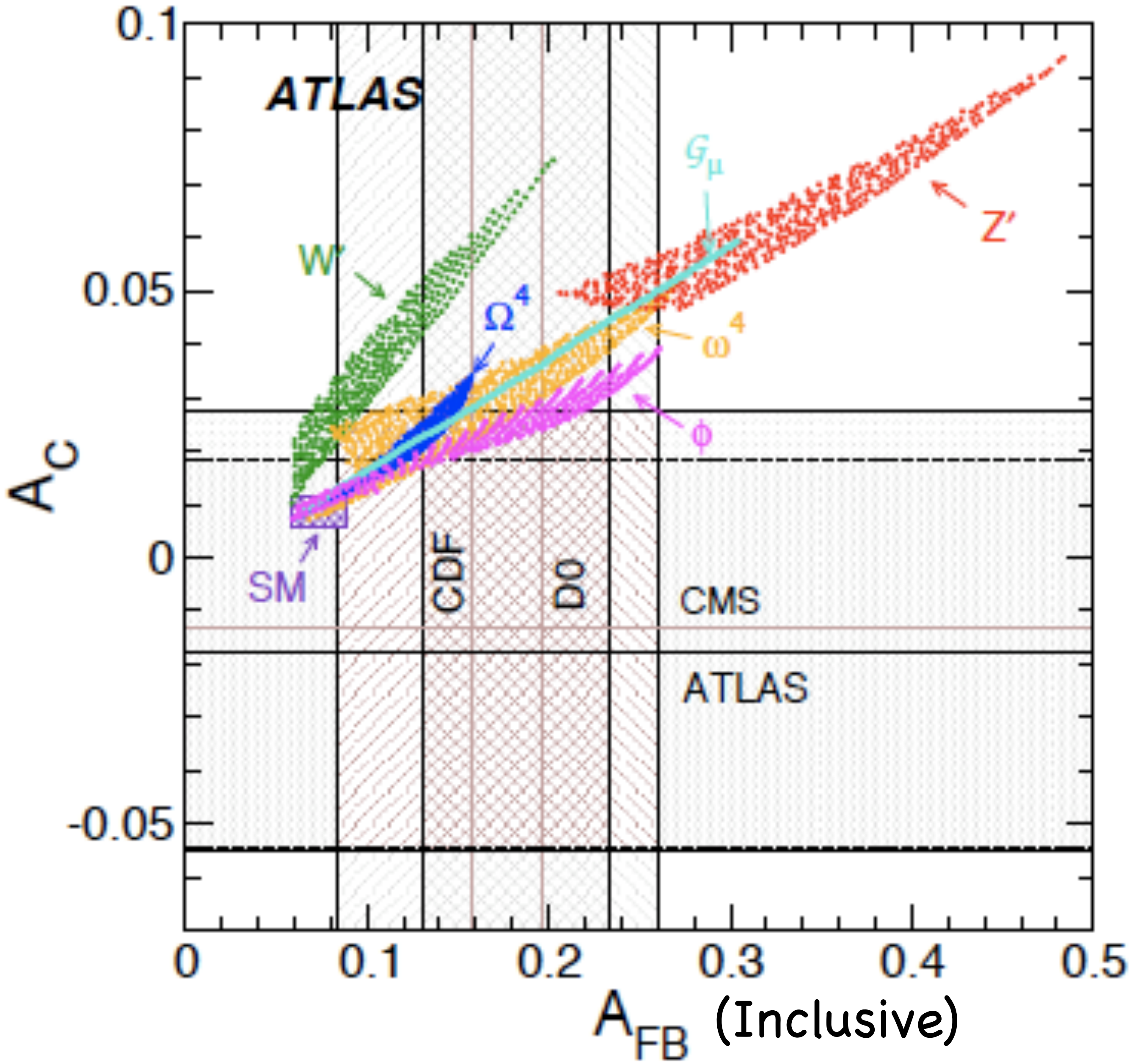
$1 \otimes 1 = 1$

Hypercharge:

$\sum Y = 0$

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

AFB vs Ac: simple models



Model predictions from

Aguilar-Saavedra, MPV '11

Collider-independent charge asymmetries

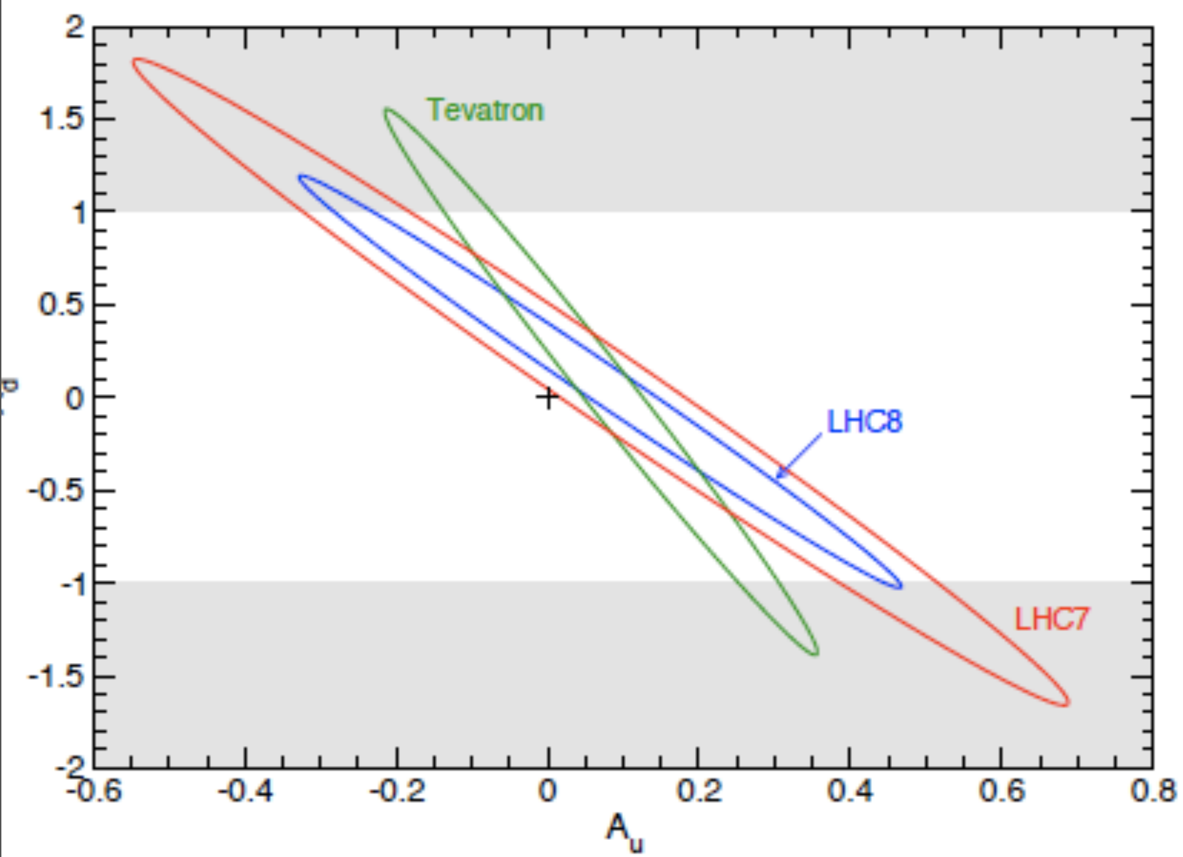
Aguilar-Saavedra, Juste '12

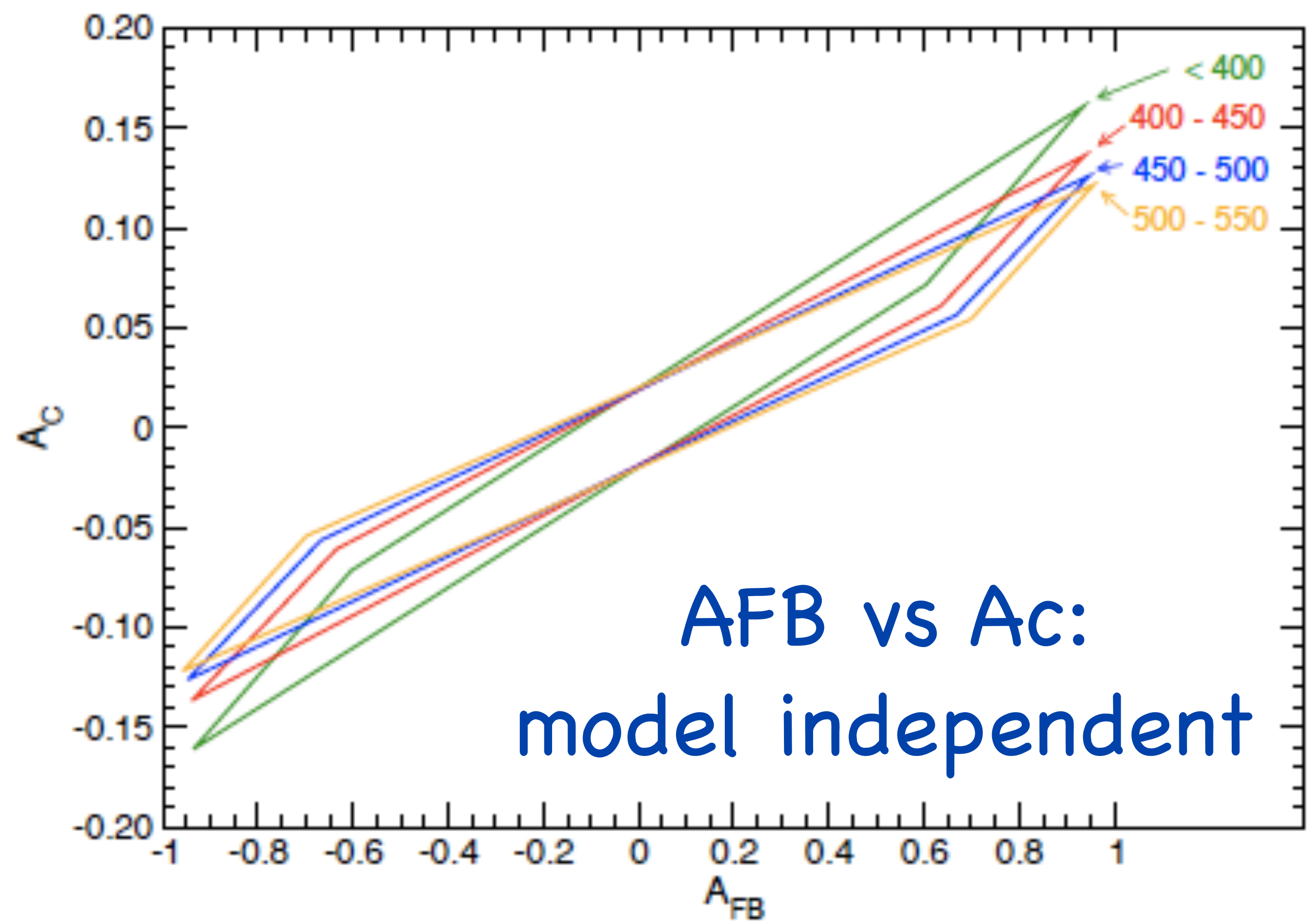
$$A_{FB} = A_u F_u + A_d F_d$$

$$A_C = A_u F_u D_u + A_d F_d D_d$$

$A_u \rightarrow$ asymmetry in $\bar{u}u \rightarrow \bar{t}t$

$A_d \rightarrow$ asymmetry in $\bar{d}d \rightarrow \bar{t}t$





AFB vs Ac: model independent

Collider-independent charge asymmetries

SM predictions

Aguilar-Saavedra, Bernreuther, Si
in preparation

Tevatron

	$\mu = m_t$		$\mu = 2m_t$		$\mu = m_t/2$	
$m_{t\bar{t}}$	A_u	A_d	A_u	A_d	A_u	A_d
< 400	0.0575	0.0393	0.0542	0.0357	0.0612	0.0435
$400 - 450$	0.0957	0.0662	0.0906	0.0603	0.1023	0.0732
$450 - 500$	0.1230	0.0858	0.1160	0.0787	0.1311	0.0947
$500 - 550$	0.1447	0.1018	0.1368	0.0922	0.1538	0.1129
$550 - 600$	0.1645	0.1154	0.1557	0.1055	0.1760	0.1276

LHC 7

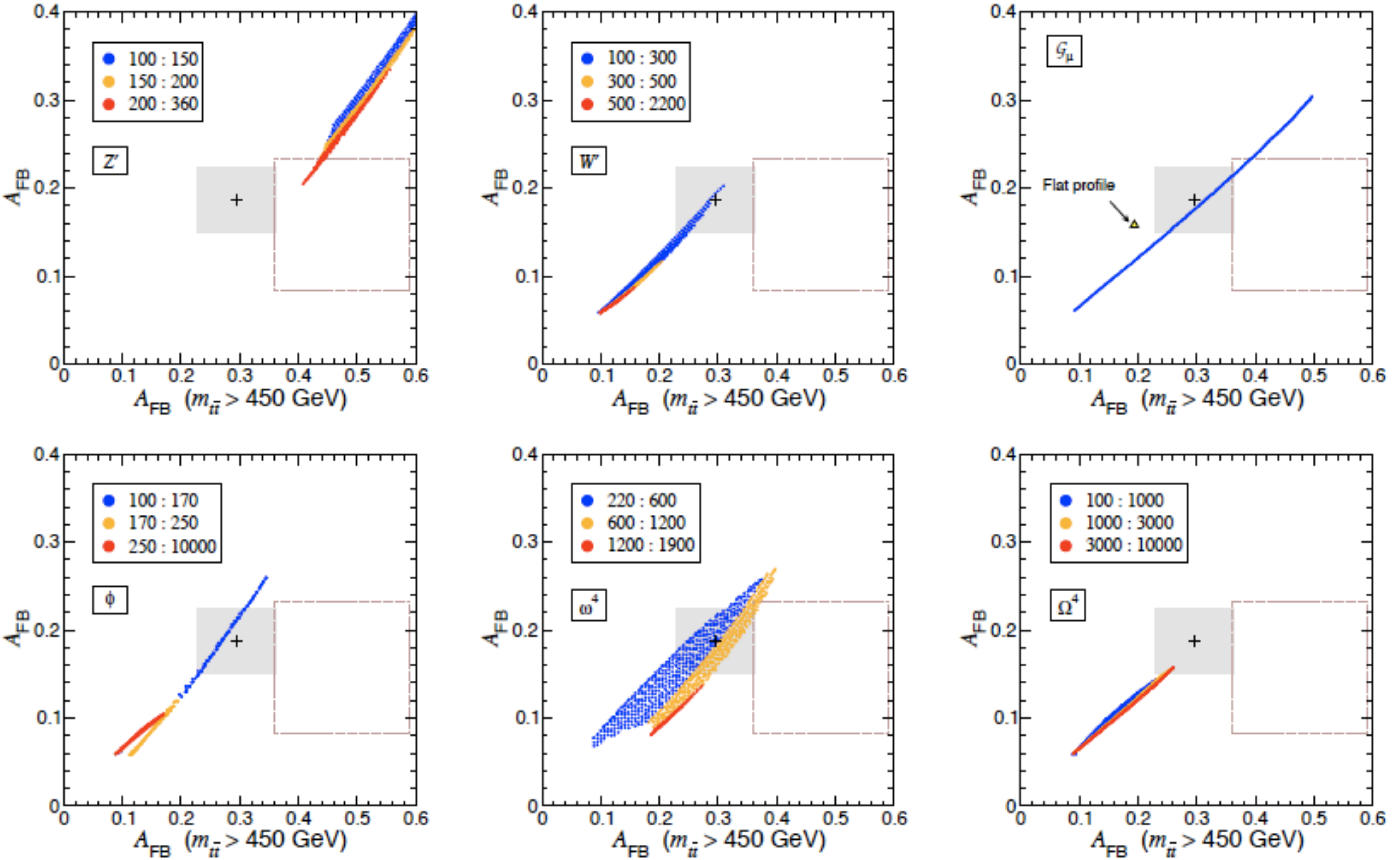
	$\mu = m_t$		$\mu = 2m_t$		$\mu = m_t/2$	
$m_{t\bar{t}}$	A_u	A_d	A_u	A_d	A_u	A_d
< 400	0.0625	0.0611	0.0579	0.0563	0.0667	0.0682
$400 - 450$	0.0845	0.0591	0.0809	0.0530	0.0929	0.0633
$450 - 500$	0.1165	0.0636	0.1098	0.0613	0.1201	0.0779
$500 - 550$	0.1158	0.0556	0.1094	0.0421	0.1212	0.0595
$550 - 600$	0.1459	0.1009	0.1379	0.1017	0.1577	0.1076
$600 - 650$	0.1534	0.1041	0.1488	0.0938	0.1617	0.1165
$650 - 700$	0.1646	0.1030	0.1531	0.0850	0.1668	0.1143
$700 - 750$	0.1706	0.1246	0.1664	0.1198	0.1799	0.1162
$750 - 800$	0.1818	0.1247	0.1772	0.1169	0.2074	0.1451

Consistent

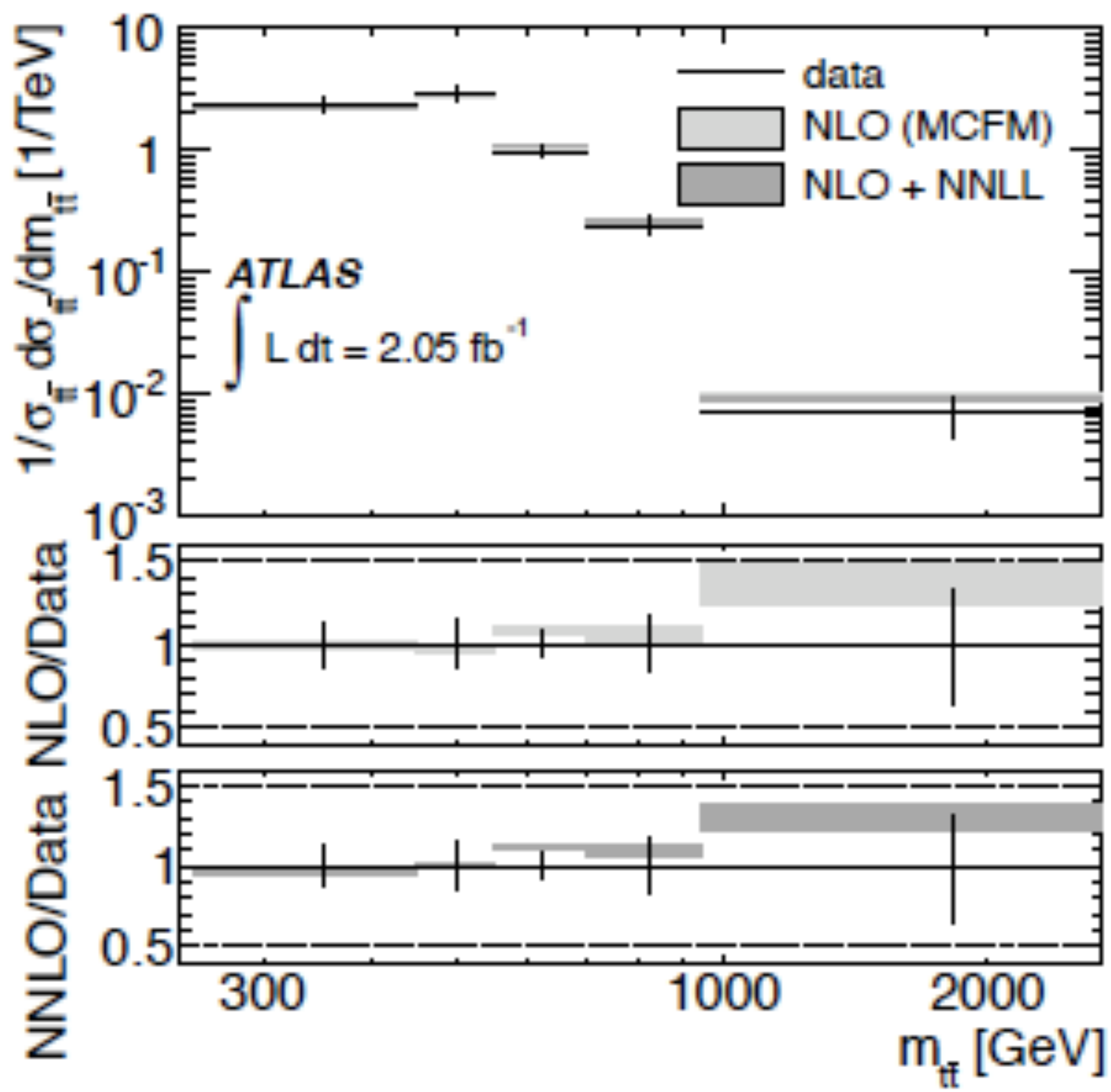
Top charge asymmetries

Impact of tail constraint (< 3 x SM)

Aguilar-Saavedra, MPV '11



New measurement of tail



$$\sigma_{\text{exp}} \lesssim 1.5\ \sigma_{\text{SM}}$$

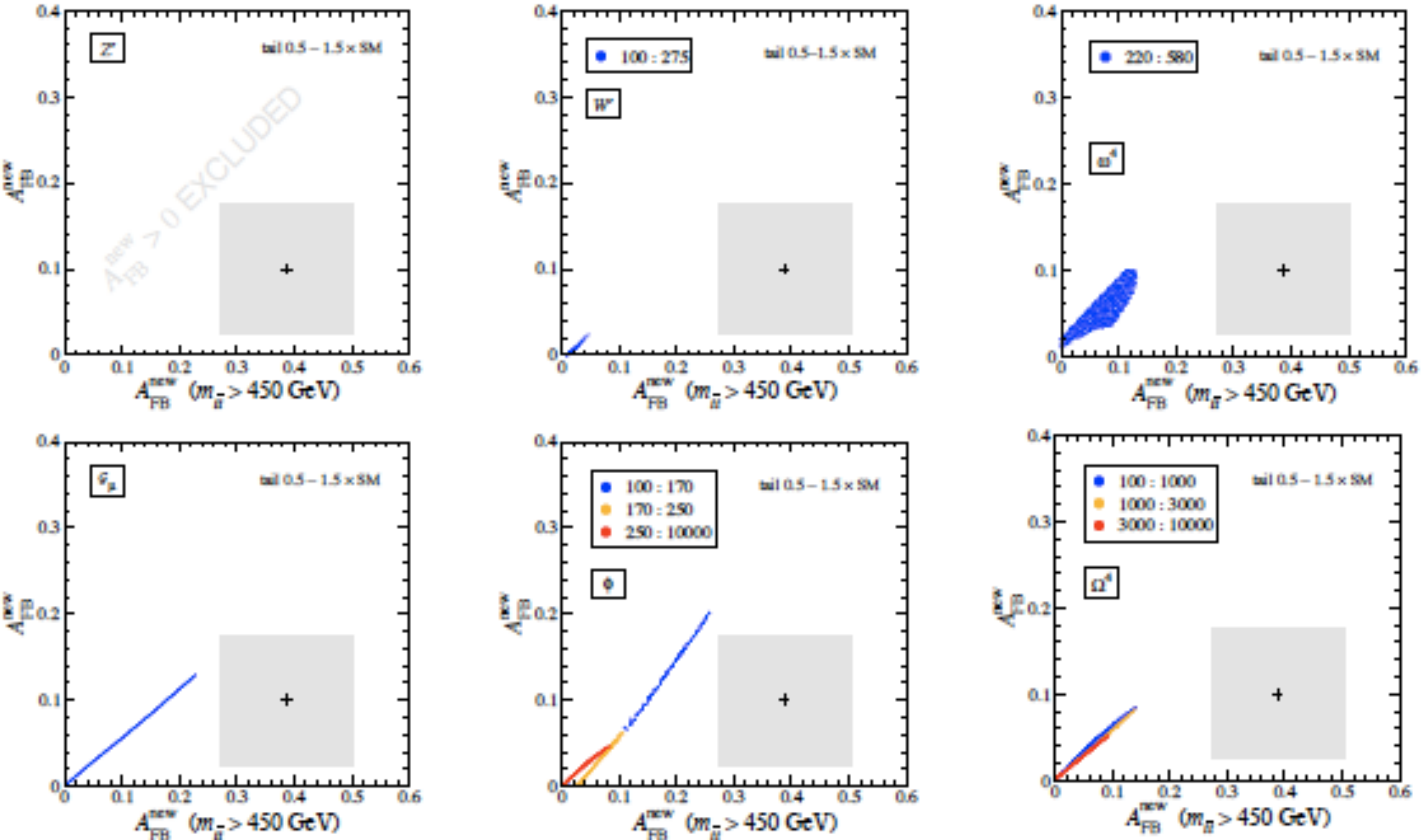
(central value smaller than SM)

Relative differential cross section vs invariant mass

Top charge asymmetries

Impact of tight tail constraint (< 1.5 x SM)

Aguilar-Saavedra, MPV '11
(estimate; new dedicated analysis necessary)



My favourite surviving explanation: light octets

- s channel, but hidden if resonance broad Barceló et al. '11 or below $t\bar{t}$ threshold Aguilar-Saavedra, MPV '11

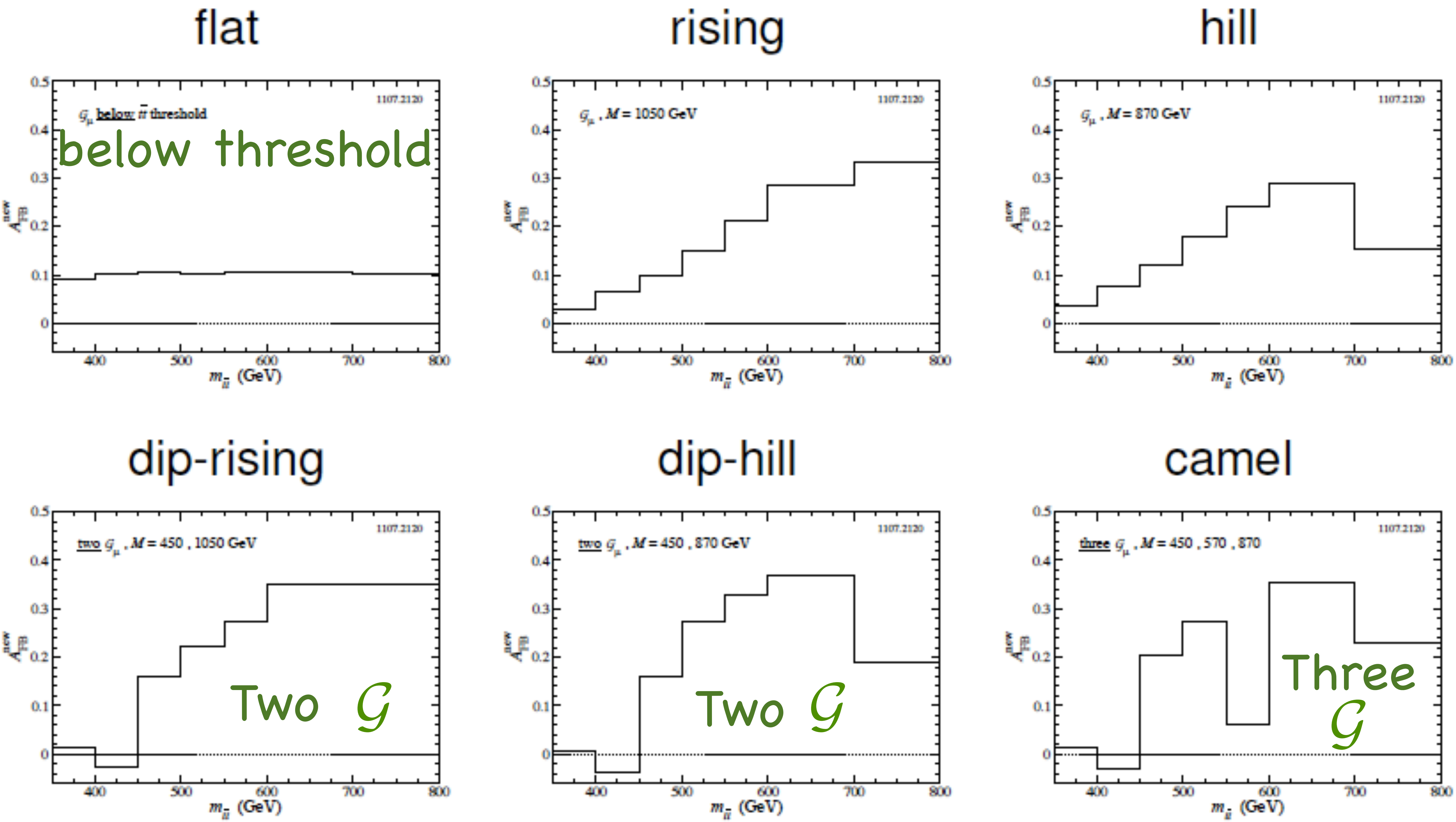
- If very light, small couplings Tavares, Schmaltz '11

- If very light, can have universal couplings and avoid flavour problems Tavares, Schmaltz '11

- Can accomodate $A_{FB} > 0, \quad A_C \lesssim 0$ Drobnak, Kamenik, Zupan '12

Light octets may give rise to peculiar profiles

Aguilar-Saavedra, MPV '11



Conclusions

- Top quark might have non-standard couplings
- Deviations in couplings related to direct searches of new particles
- Model-independent correlation of Ztt and Wtb
- Model-dependent correlation with Htt as well
- Tevatron FB asymmetry still alive, but very constrained by LHC
- New tools can be used to distinguish new physics from experimental issues