$t\bar{t}$ charge asymmetry and family

J. A. Aguilar-Saavedra
University of Granada & University of Coimbra & IFCA

in collaboration with W. Bernreuther, A. Juste, M. Pérez-Victoria, F. Rubbo, J. Santiago, Z.-G. Si

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Outline of the talk

- The Tevatron charge / FB asymmetry
- The younger sister: the LHC charge asymmetry
- The parents: the collider-independent asymmetries
- ~~The friends: $t\bar{t}$ differential distribution, top polarisation~~ ← skipped due to lack of time
- Discussion

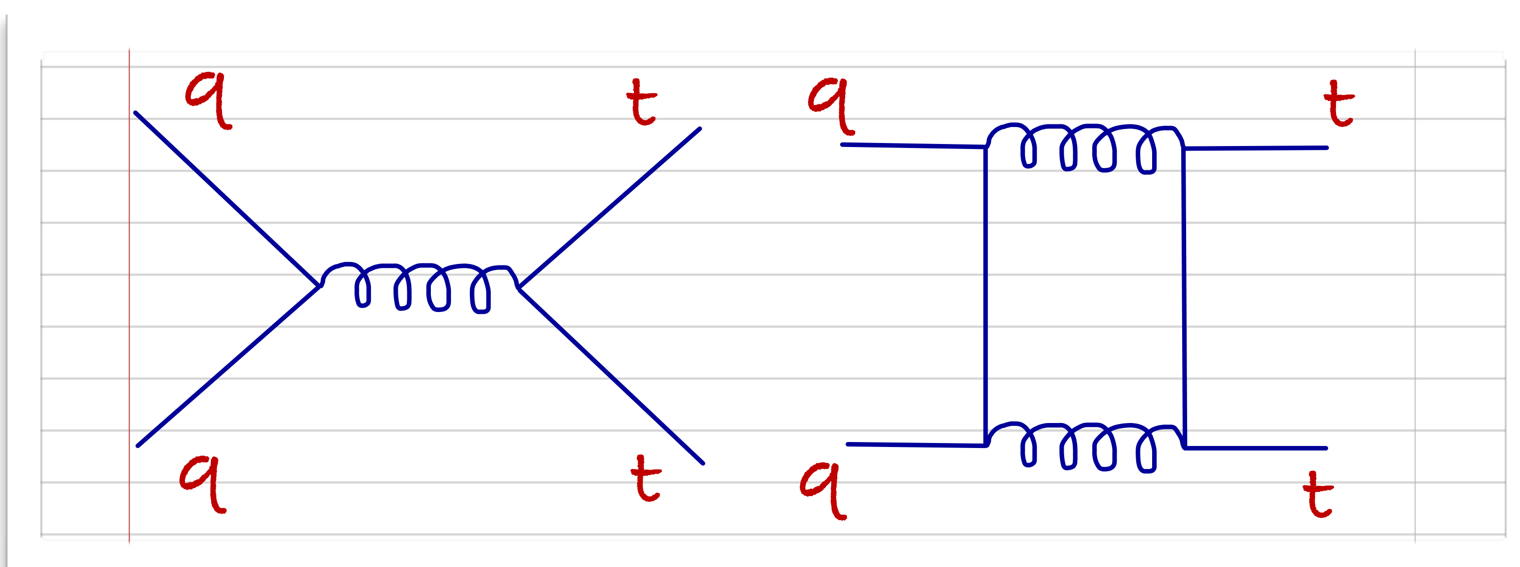
The charge / FB asymmetry at Tevatron

$q\bar{q} \to t\bar{t}$ is not symmetric under interchange of t and $\bar{t}$ momenta; the most commonly used observable at Tevatron is the FB asymmetry

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

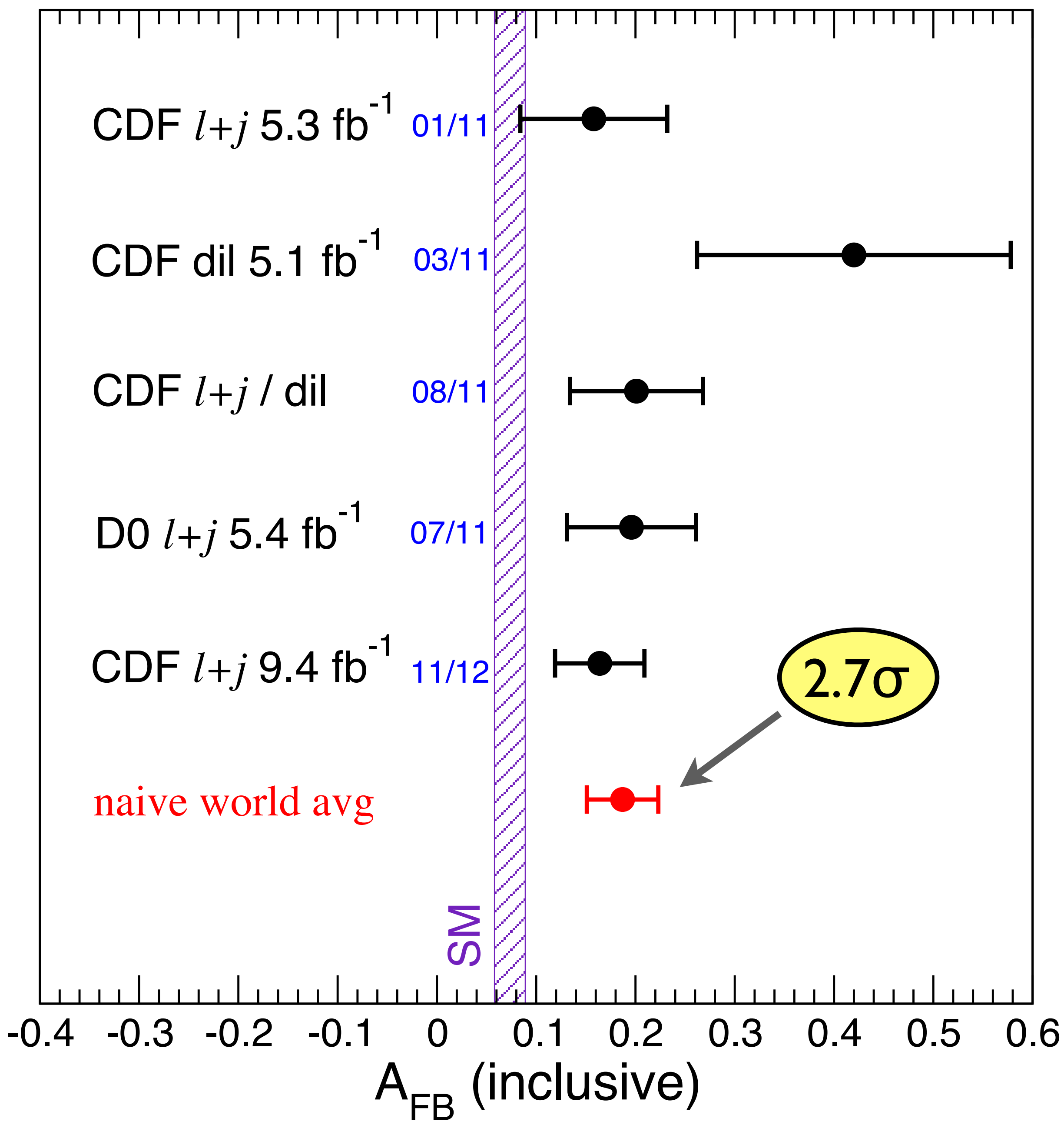
equivalent to an asymmetry in cosine of CM polar angle θ

with $\Delta y = y_t - y_{\bar{t}}$, exploiting that in $p\bar{p}$ collisions we know where q and $\bar{q}$ come from. In the SM this asymmetry arises from interference between LO and NLO diagrams, e.g.



As it is well known, Tevatron measures a *positive* asymmetry exceeding the SM expectation...

Status of Tevatron measurements



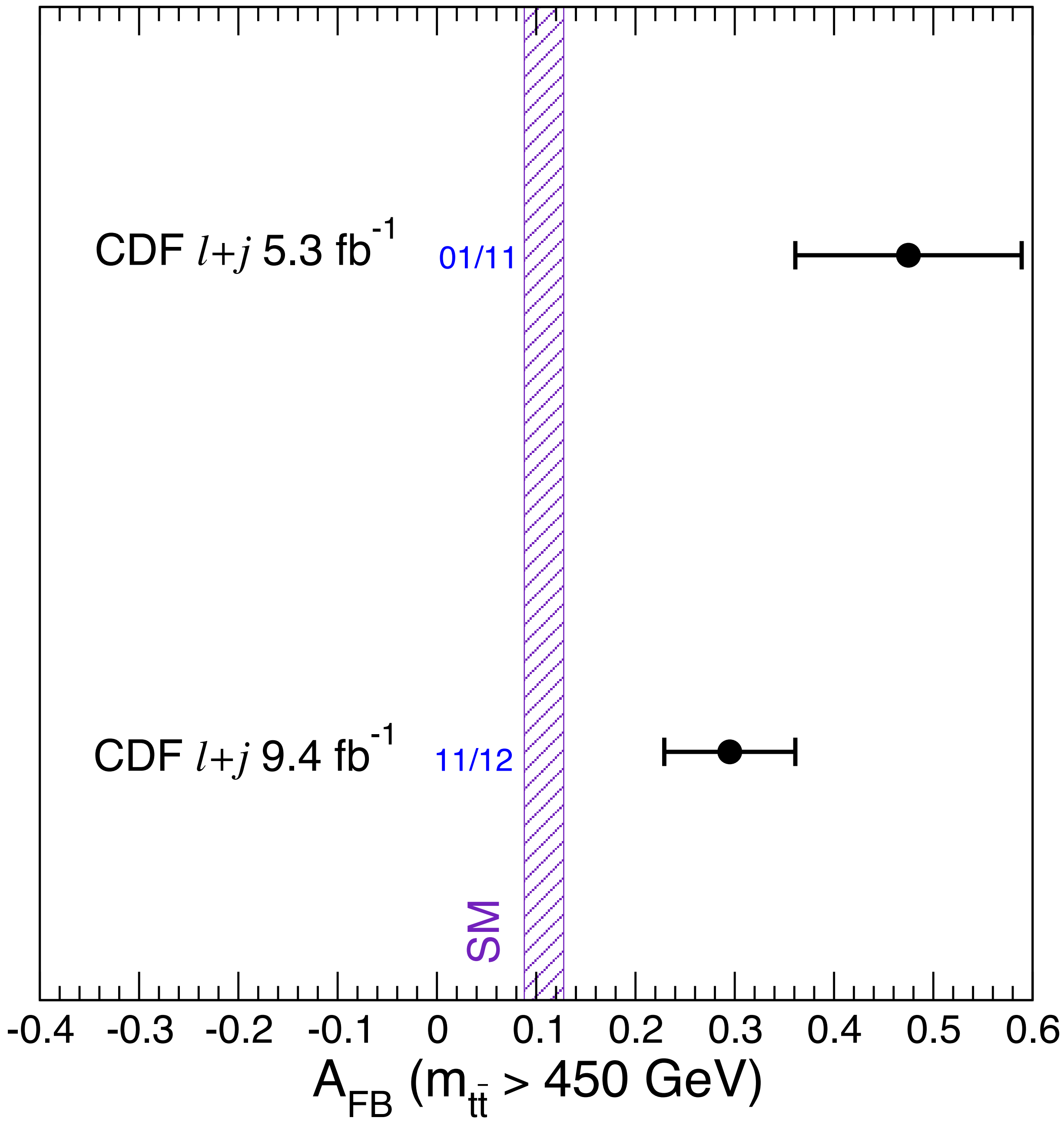
inclusive measurements

<u>not</u> converging to SM

avg 2.7σ from closest prediction

	0.058	MCFM
	0.0724	Ahrens et al.
SM =	0.087	Kuhn & Rodrigo
	0.088	Bernreuther & Si
	0.089	Hollik & Pagani

Status of Tevatron measurements



high-mass measurement that triggered interest is closer to SM but still 2.5σ away

These consistent discrepancies have motivated a plethora of papers proposing new physics explanations

A_{FB} is an effect competing with QCD

- most likely, new physics in $q\bar{q} \to t\bar{t}$
- and expected at tree level

what could this new physics be? Group theory helps here

→ Lagrangian must be singlet under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
type of bosons determined by quantum numbers of quarks

Colour

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

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

Isospin

$$2 \otimes 2 = 3 \oplus 1$$

$$2 \otimes 1 = 2$$

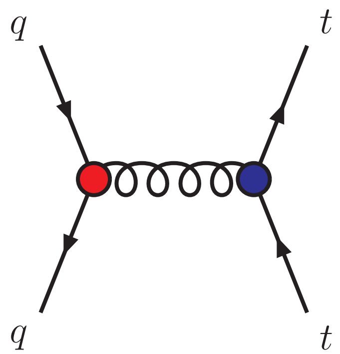
$$1 \otimes 1 = 1$$

Hypercharge

$$\sum Y = 0$$

Vector bosons		Scalars	
label	rep	label	rep
$\mathcal{B}$	$(1,1)_{0}$	φ	$(1,2)_{-1/2}$
$\mathcal{W}$	$(1,3)_{0}$	Φ	$(8,2)_{-1/2}$
$\mathcal{B}^{1}$	$(1,1)_{1}$	ω^{1}	$(3,1)_{-1/3}$
$\mathcal{G}$	$(8,1)_{0}$	Ω^{1}	$(6,1)_{-1/3}$
$\mathcal{H}$	$(8,3)_{0}$	ω^{4}	$(3,1)_{-4/3}$
$\mathcal{G}^{1}$	$(8,1)_{1}$	Ω^{4}	$(6,1)_{-4/3}$
$\mathcal{Q}^{1}$	$(3,2)_{1/6}$	σ	$(3,3)_{-1/3}$
$\mathcal{Q}^{5}$	$(3,2)_{-5/6}$	Σ	$(6,3)_{-1/3}$
Υ^{1}	$(6,2)_{1/6}$		
Υ^{5}	$(6,2)_{-5/6}$		

Most popular models

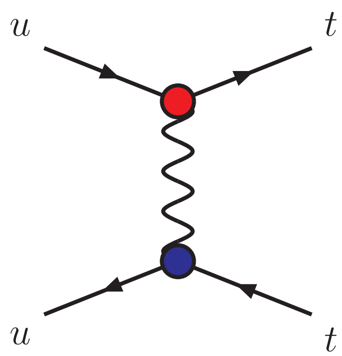


s channel

$\mathcal{G} \sim (8,1)_0$

0809.3354 , 0906.0604 , 0911.2955 , 1007.0243 , 1011.6380 , 1011.6557 , 1101.2902 , 1101.5203 , 1103.0956 , 1104.1917 , 1105.3158 , 1105.3333 , 1106.0529 , 1106.4054 , 1107.0978 , 1107.1473 , 1107.2120 , 1107.5769 , 1109.0648 , 1205.4721 , 1209.2741 , 1209.3636 , 1209.6375 , 1212.1718 , 1301.3990 , 1302.5316

t channel



$Z' \sim (1,1)_0$

0907.4112 , 1101.4456 , 1101.5625 , 1102.0545 , 1103.1266 1103.4835 , 1104.1385 , 1104.3139 , 1106.5982 , 1108.0350 , 1108.1802 , 1205.0407 , 1207.0643 , 1209.4354 , 1209.4872

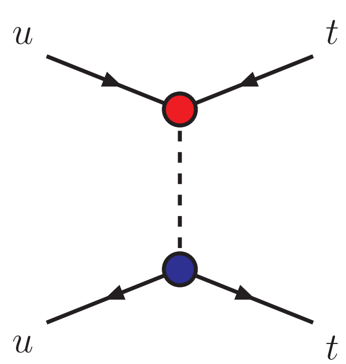
$W' \sim (1,1)_1$

0908.2589 , 1002.1048 , 1003.3461 , 1101.1445 , 1101.5392 , 1104.0083 , 1105.4606 , 1203.4489 , 1205.3311 ,

$\varphi \sim (1,2)_{-1/2}$

1104.4782 , 1107.0841 , 1107.4350 , 1108.4005 , 1203.4477

u channel



$\omega^4 \sim (3,1)_{-4/3}$

$\Omega^4 \sim (6,1)_{-4/3}$

0911.3237 , 0911.4875 , 0912.0972 , 1007.2604 , 1102.3374 , 1102.4736 , 1103.2757 , 1108.4027 , 1205.5005

These models are mostly "phenomenological"

(which means: do not ask for all bells & whistles)

but good to test:

1. can one enhance A_{FB} without spoiling the good agreement of the total cross section?

2. can one reproduce the Tevatron inclusive and high-mass A_{FB}?

3. is this compatible with other measurements, in particular at LHC?

⇒ If all these conditions are met, one can go further and try to build a new physics theory explaining A_{FB}

Test #1

Can the asymmetry be generated keeping $\sigma_{\rm exp} \sim \sigma_{\rm SM}$ at Tevatron?

$\sigma_{\rm exp} = 7.68 \pm 0.41\ {\rm pb}$ — CDF & D0 average

$\sigma_{\rm SM} = 7.5 \pm 0.5\ {\rm pb}$ — HATHOR, Aliev et al `11

$\sigma(t\bar{t}) = \sigma_{\rm SM} + \delta\sigma_{\rm int} + \delta\sigma_{\rm quad} \sim \sigma_{\rm SM}$ implemented in two ways

$$\begin{cases} \delta\sigma_{\rm int} + \delta\sigma_{\rm quad} \sim 0 & \text{fine-tuned cancellation} \\ \delta\sigma_{\rm int} \sim 0 & \delta\sigma^{\rm F}_{\rm int} = -\delta\sigma^{\rm B}_{\rm int} \ \text{from symmetry} \end{cases}$$

These possibilities are radically different:

- $\delta\sigma_{\rm int} + \delta\sigma_{\rm quad} \sim 0$ occurs at a given CM energy for a given coupling
- $\delta\sigma^{\rm F}_{\rm int} = -\delta\sigma^{\rm B}_{\rm int}$ arises from vertex structure (axial), at all energies

Results of test #1

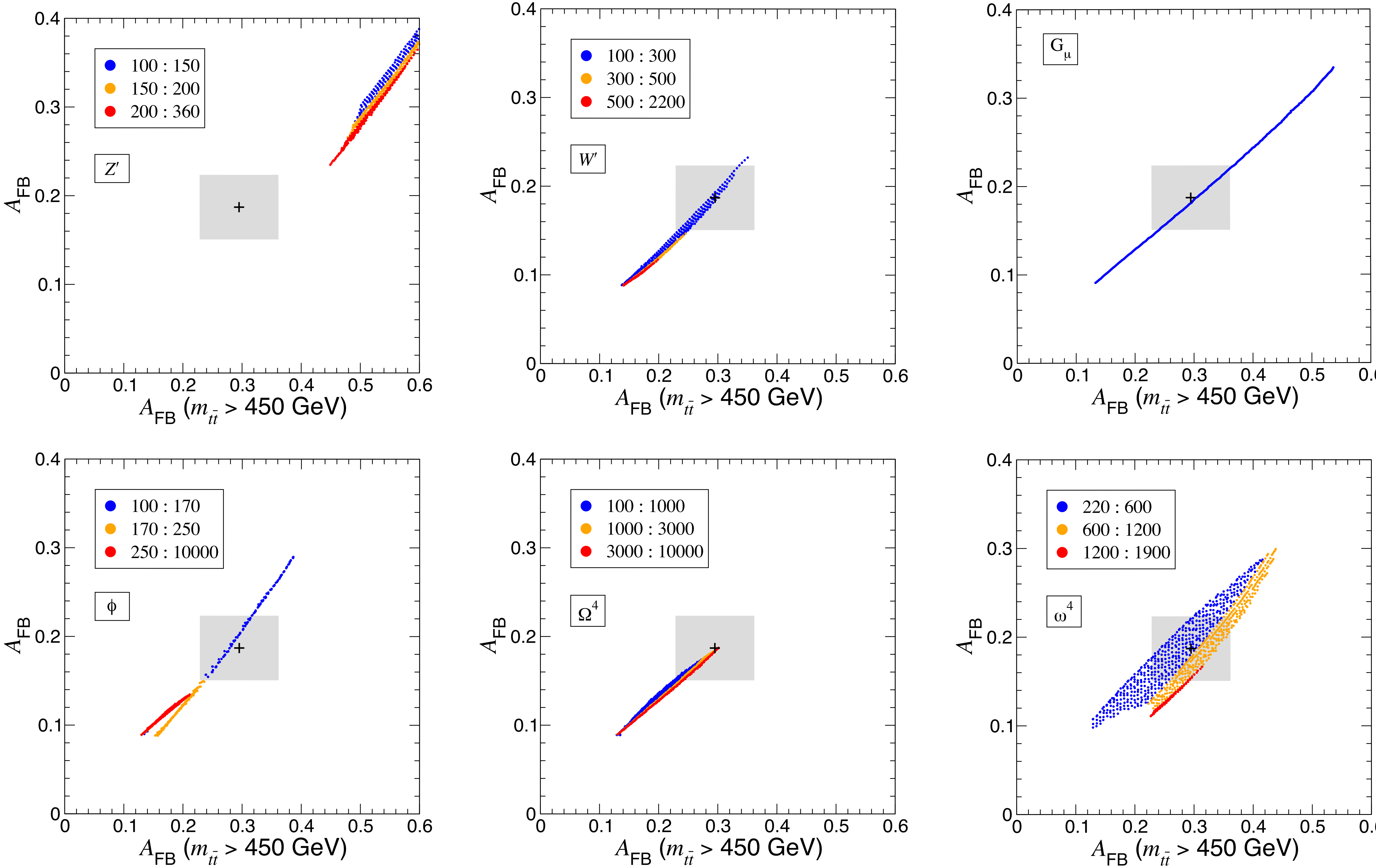
There are many models with new particles exchanged at tree level in s, t or u channel that can generate large A_{FB} while keeping the total σ

Other more exotic models:

- one loop: effective gtt couplings 1106.4553, 1108.1173, 1112.5885
- spin-2 particles 1203.2183
- combinations of particles 1102.0279, 1208.4675

Test #2

Is the Tevatron picture consistent?



Results of test #2

Most models can reproduce the central values

$A_{\mathrm{FB}} = 0.187 \pm 0.036$ inclusive (naive world avg)

$A_{\mathrm{FB}} = 0.295 \pm 0.066$ CDF high-mass (new)

Only Z´ fails the test and will be ignored from now on

The Tevatron picture is more consistent than in January 2011when the 3.6σ discrepancy appeared.

This is good news!

The younger sister: the LHC charge asymmetry

At the LHC, a suitable observable to test "asymmetric" $t\bar{t}$ production is

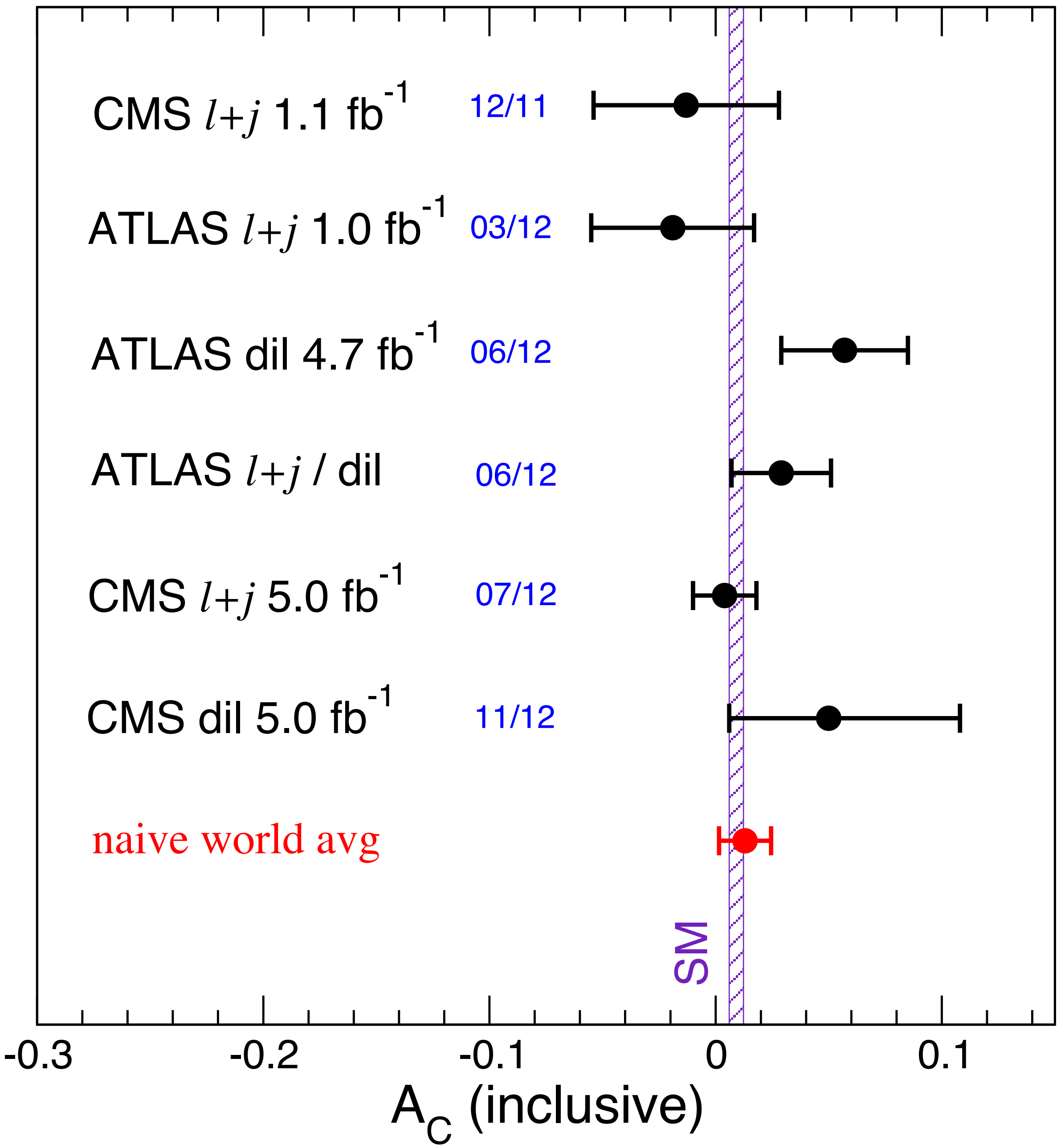
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$, that exploits the fact that we have pp instead of $p\bar{p}$ collisions.

Clearly, this is not the same observable as at Tevatron, and a result consistent with the SM does not say anything about the Tevatron excess.

But comparing predictions for A_{FB} and A_C does say a lot about models addressing the Tevatron excess.

Status of LHC measurements

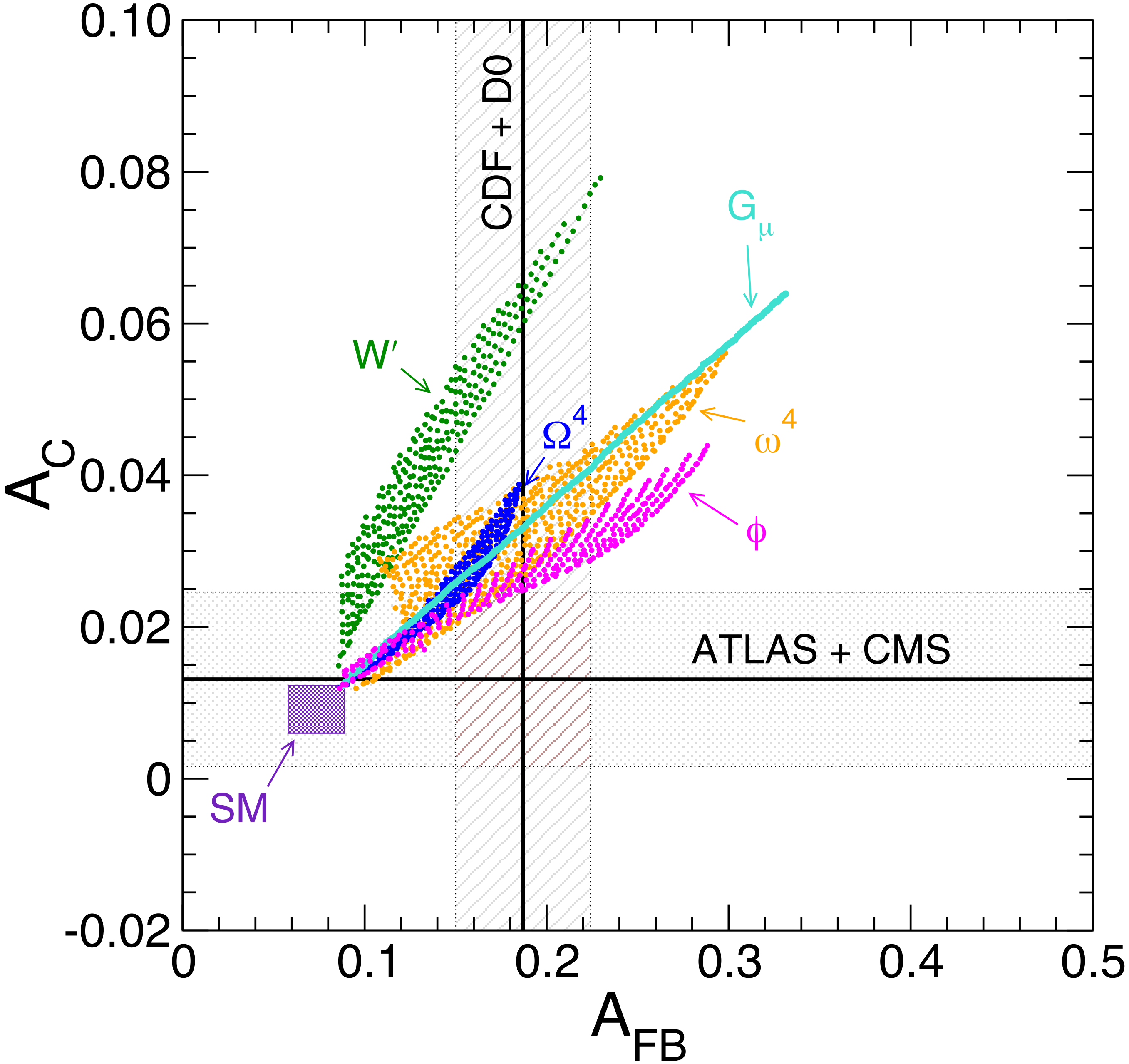


good agreement with SM

	0.006	MC@NLO
SM =	0.0115	Kuhn & Rodrigo
	0.0123	Bernreuther & Si

Test #3

Is the Tevatron - LHC picture consistent?



W´disfavoured/excluded

(choose preferred wording)

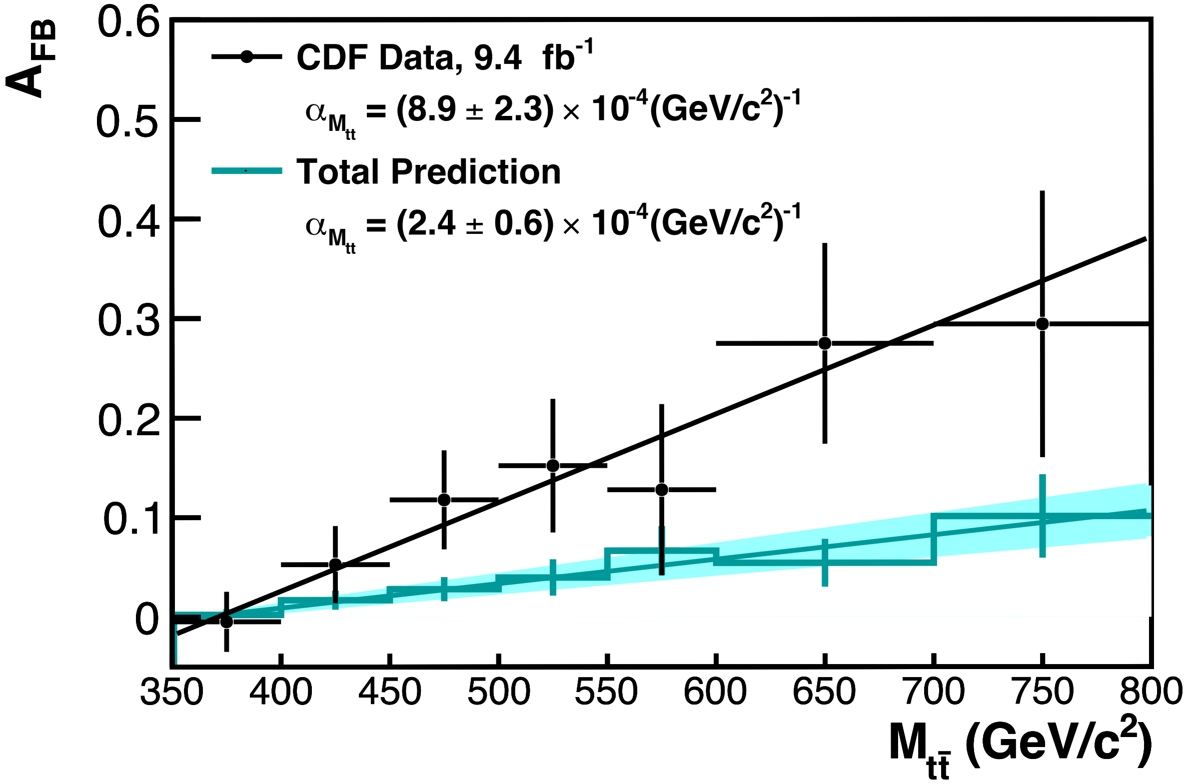
for the rest of simple models

the future is unclear

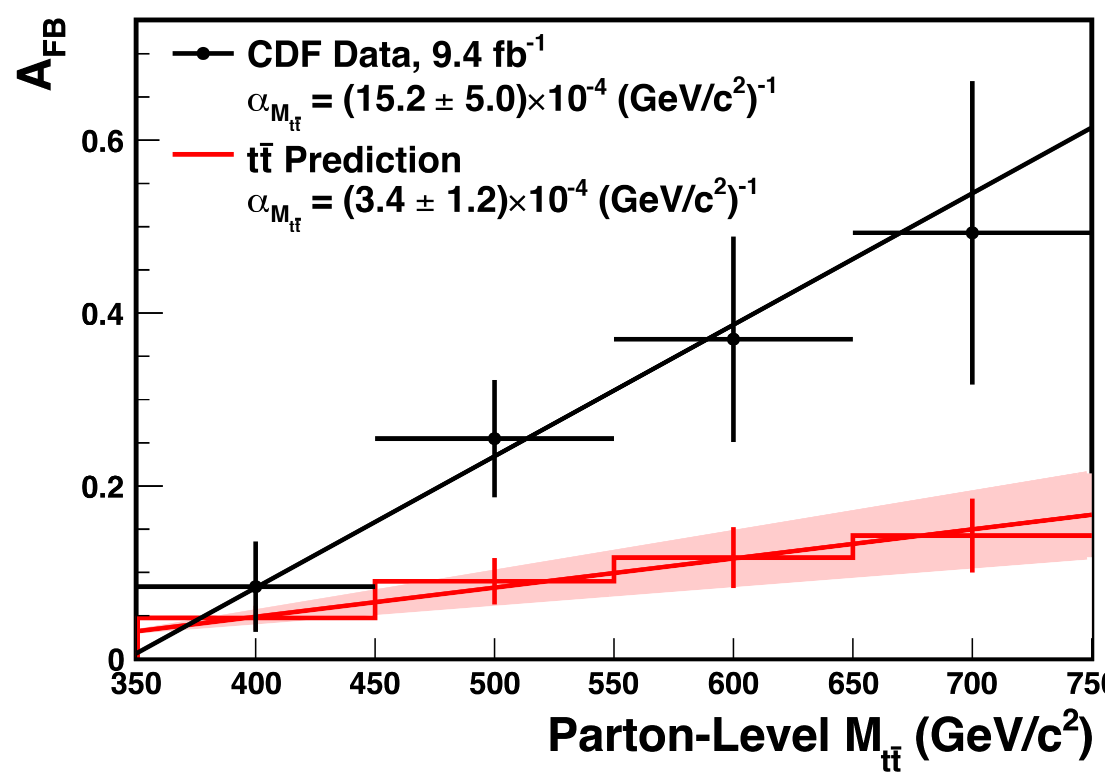
A note for SM skeptics

Full CDF data set shows a smooth, convincing excess…

Raw data



Unfolded



… that is hard to regard as a statistical fluctuation!

→ p-value of slope: 7.4×10^{-3} (2.4σ)

… and the anomaly keeps being consistent!

Write differential cross section in terms of Legendre polynomials

$$\sigma(\theta) = \sum_l a_l P_l(\cos\theta)$$

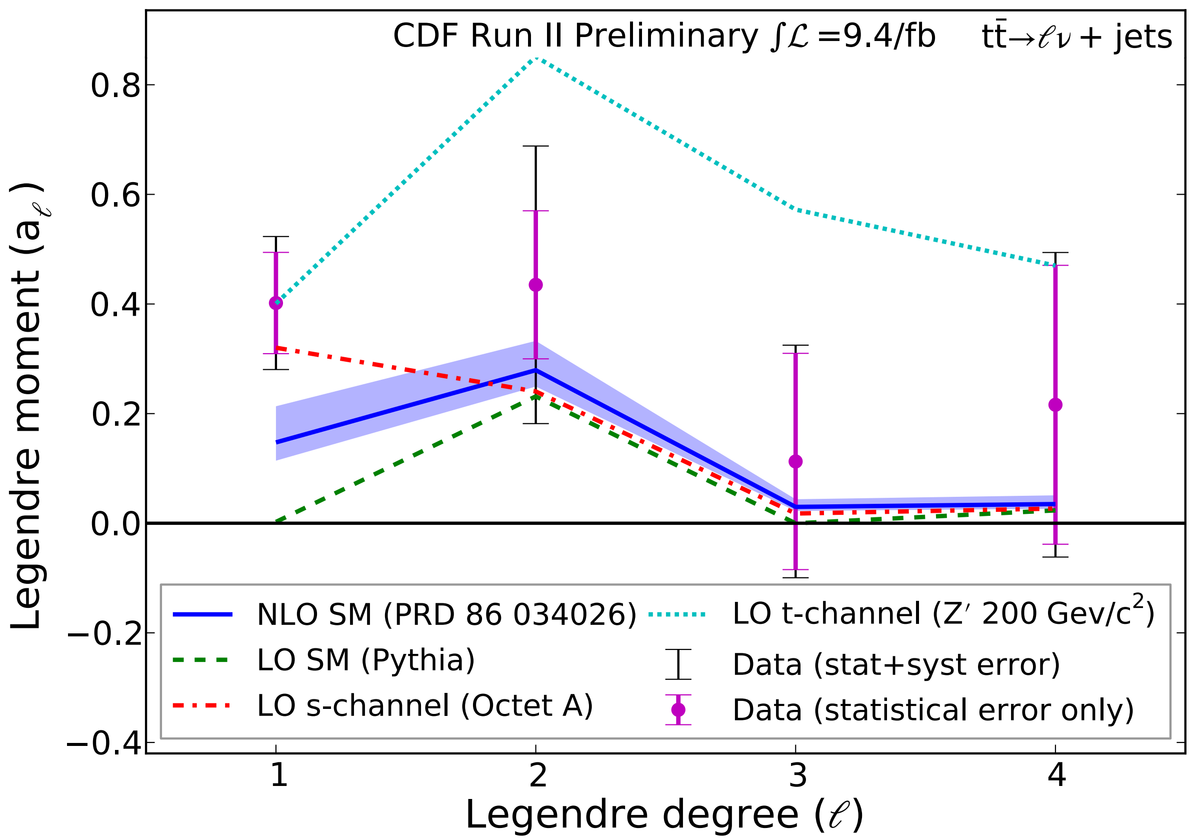
$P_0(x) = 1$

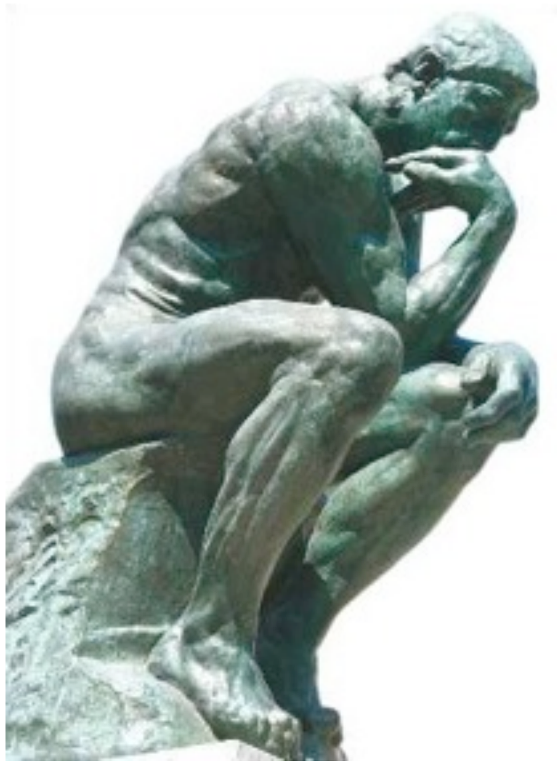
$P_1(x) = x$

$P_2(x) = \frac{1}{2}(3x^2 - 1)$

$\dots$

and measure coefficients from data





- are Tevatron & LHC data compatible?
- how to solve this puzzle?
- is there something we can measure at both colliders and compare?

The parents: the collider-independent asymmetries

The Tevatron and LHC asymmetries originate from the "intrinsic" partonic asymmetries A_u , A_d in $u\bar{u} \to t\bar{t}$ and $d\bar{d} \to t\bar{t}$ respectively. A_{FB} and A_C are different "combinations" of A_u , A_d:

$$A_{\rm FB}(\beta) = A_u F_u(\beta) + A_d F_d(\beta)$$
$$A_C(\beta) = A_u F_u(\beta) D_u(\beta) + A_d F_d(\beta) D_d(\beta)$$

- Different sizes of $u\bar{u} \to t\bar{t}$ and $d\bar{d} \to t\bar{t}$ relative to total production
- Asymmetry "dilution" at LHC due to $q, \bar{q}$ coming from either proton

but, for fixed $\hat{s}$, A_u and A_d are (~) the same at Tevatron and LHC (!!!)

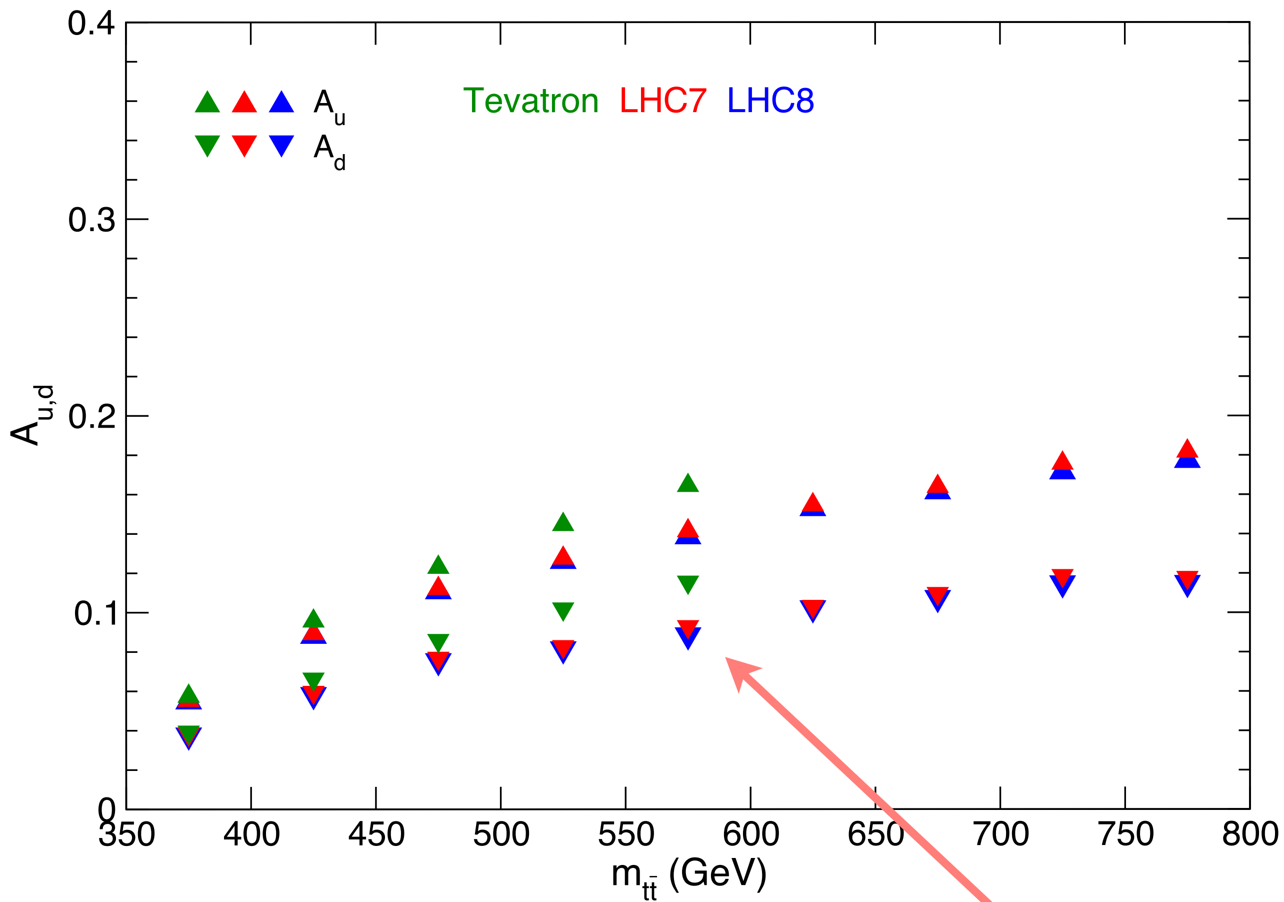
Precisions & caveats:

- in practice, replacing fixed $\hat{s}$ by finite $m_{t\bar{t}}$ intervals introduces small deviations
- deviations smaller at low $p_T^{t\bar{t}}$
- SM asymmetries in $gq \to t\bar{t}j$ irrelevant

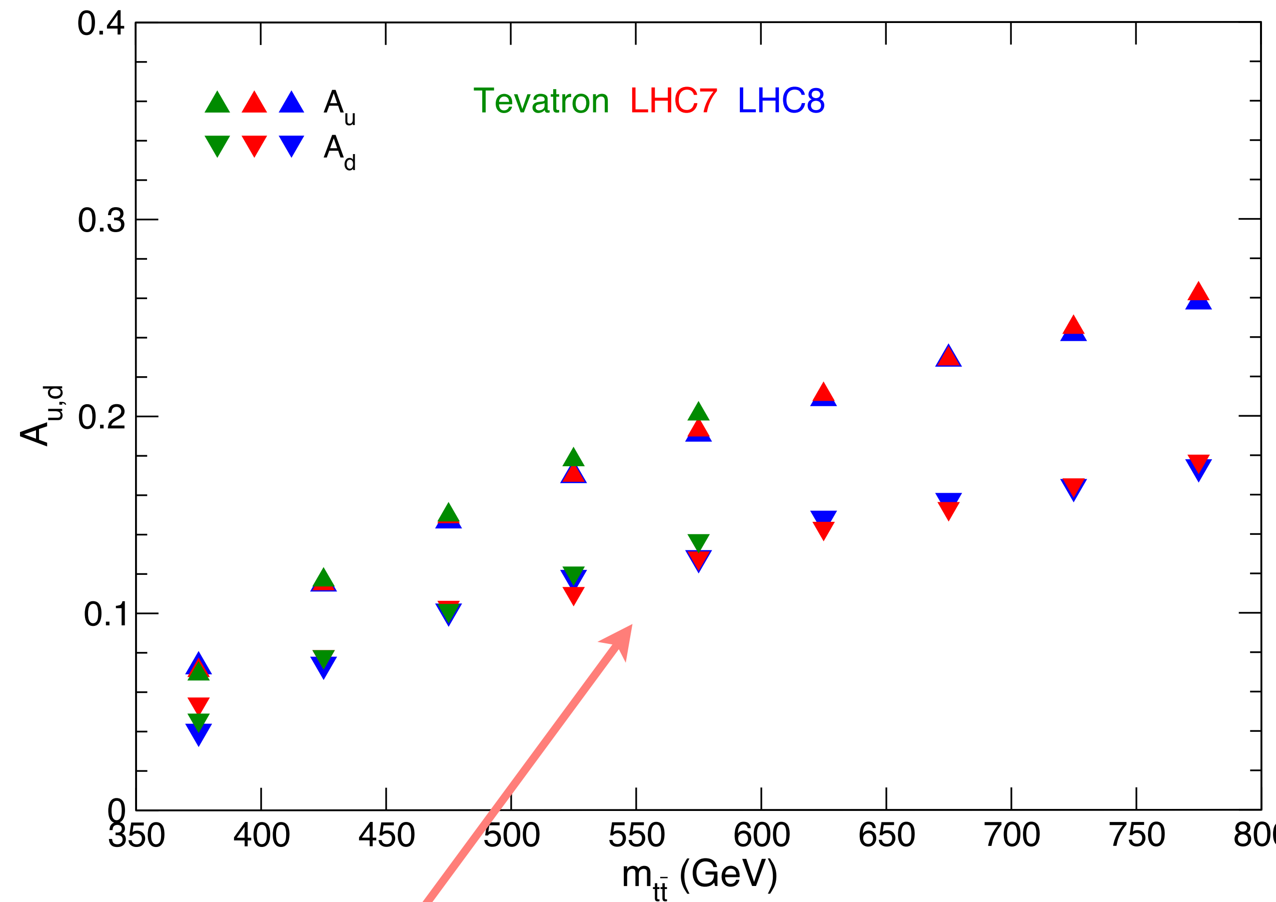
a possible test of the asymmetry puzzle is to measure A_u , A_d at Tevatron and LHC and compare

A_u and A_d in the SM

no cut on $p_T^{t\bar{t}}$



$p_T^{t\bar{t}} < 30$ GeV

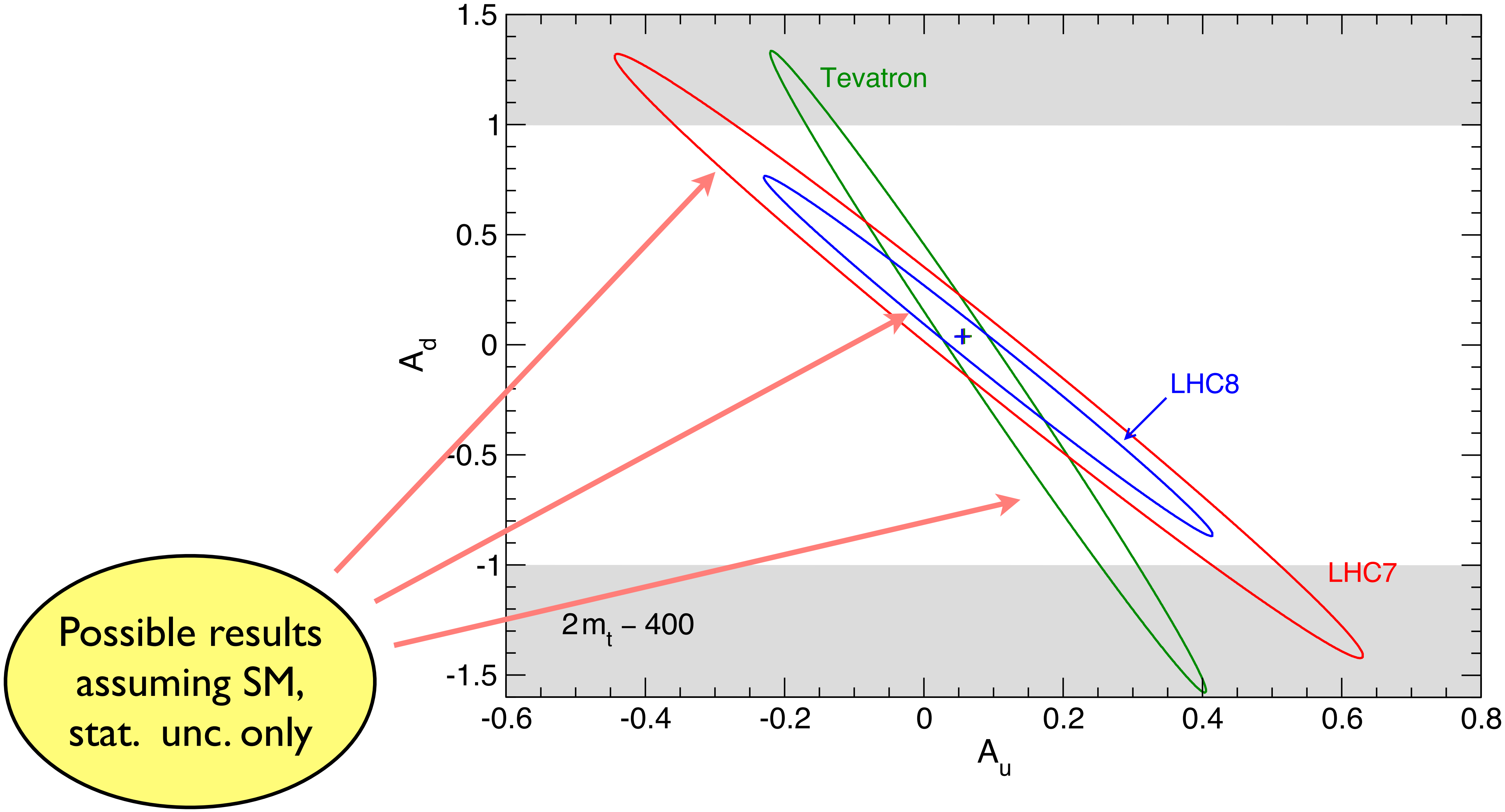


Tevatron / LHC
differences much smaller
than exp. uncertainty

Goal: to measure A_u and A_d. What if?

That might tell us

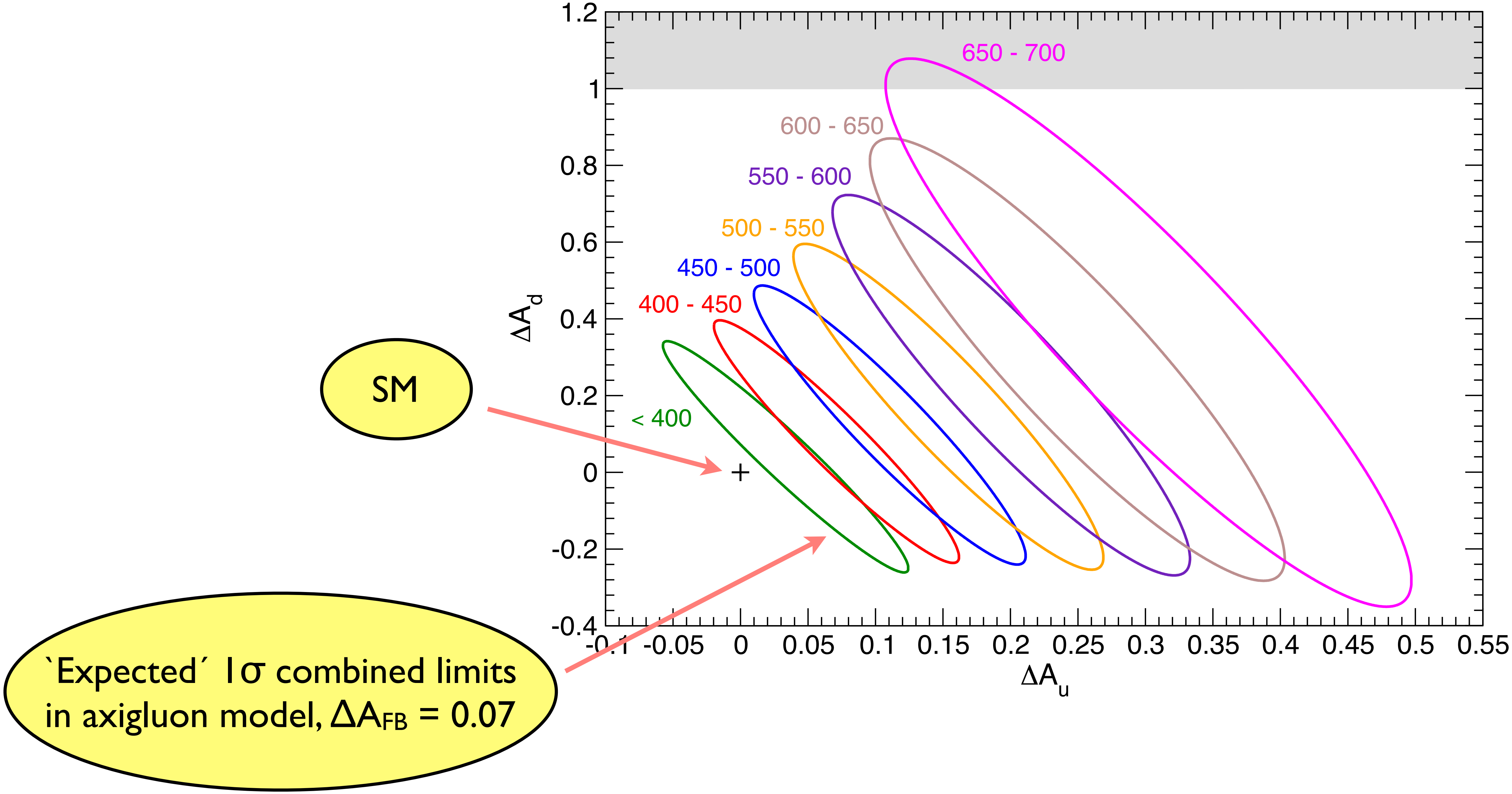
- whether Tevatron and LHC results are compatible or not



Goal: to measure A_u and A_d. What if?

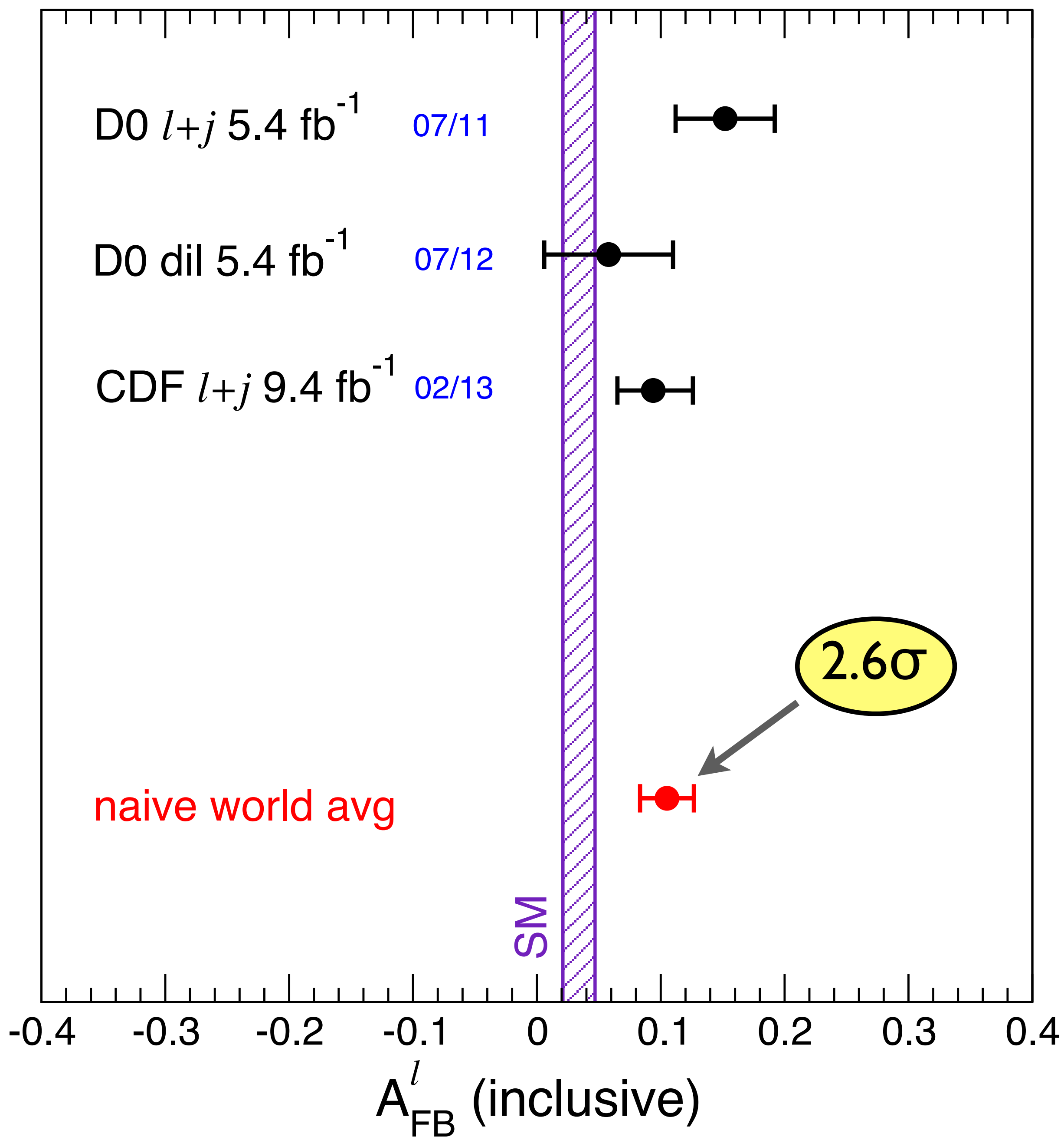
That might tell us

- whether their combination is compatible with SM



Skipping asymmetry friends…

… but cannot help showing results for lepton-based asymmetries



Discussion

After various measurements at the Tevatron and LHC

various updated SM asymmetry predictions

plenty of proposals for new physics explanations

at this point the question is:

Is this a hint of new physics? Or we will have another 3σ disappointment?

Possible answers are:

- it is new physics!
- it is a higher-order QCD effect
- it is an unknown systematic

Can the excess be new physics?

From our six initial simple models, four have been discarded:

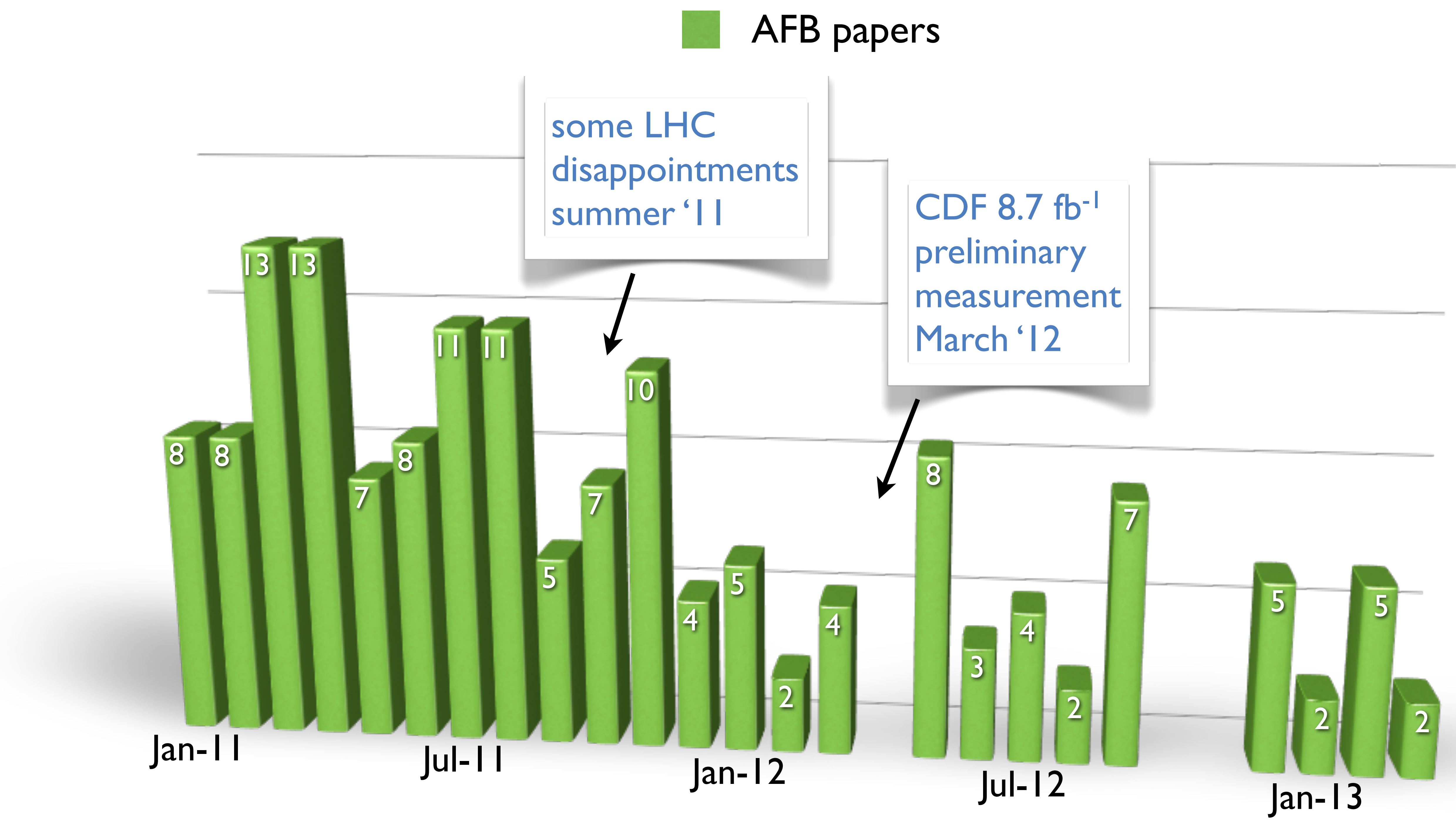
- Z' overpredicts A_{FB}, and excluded by high-mass tail, disfavoured by LM
- W' overpredicts A_C, and excluded by high-mass tail
- Colour sextet Ω^4 and triplet ω^4 disfavoured by top polarisation

The colour octet G_μ and scalar doublet φ have problems too, and require ad-hoc assumptions and other new physics to be viable.

The actual problem with NP explanations is that there is no compelling candidate to explain the anomalies: current models have to introduce ugly assumptions that make them look far-fetched.

Disclaimer: this criticism includes my own models too.

Running short of new ideas!



Can new physics fit large A_{FB} and small A_C?

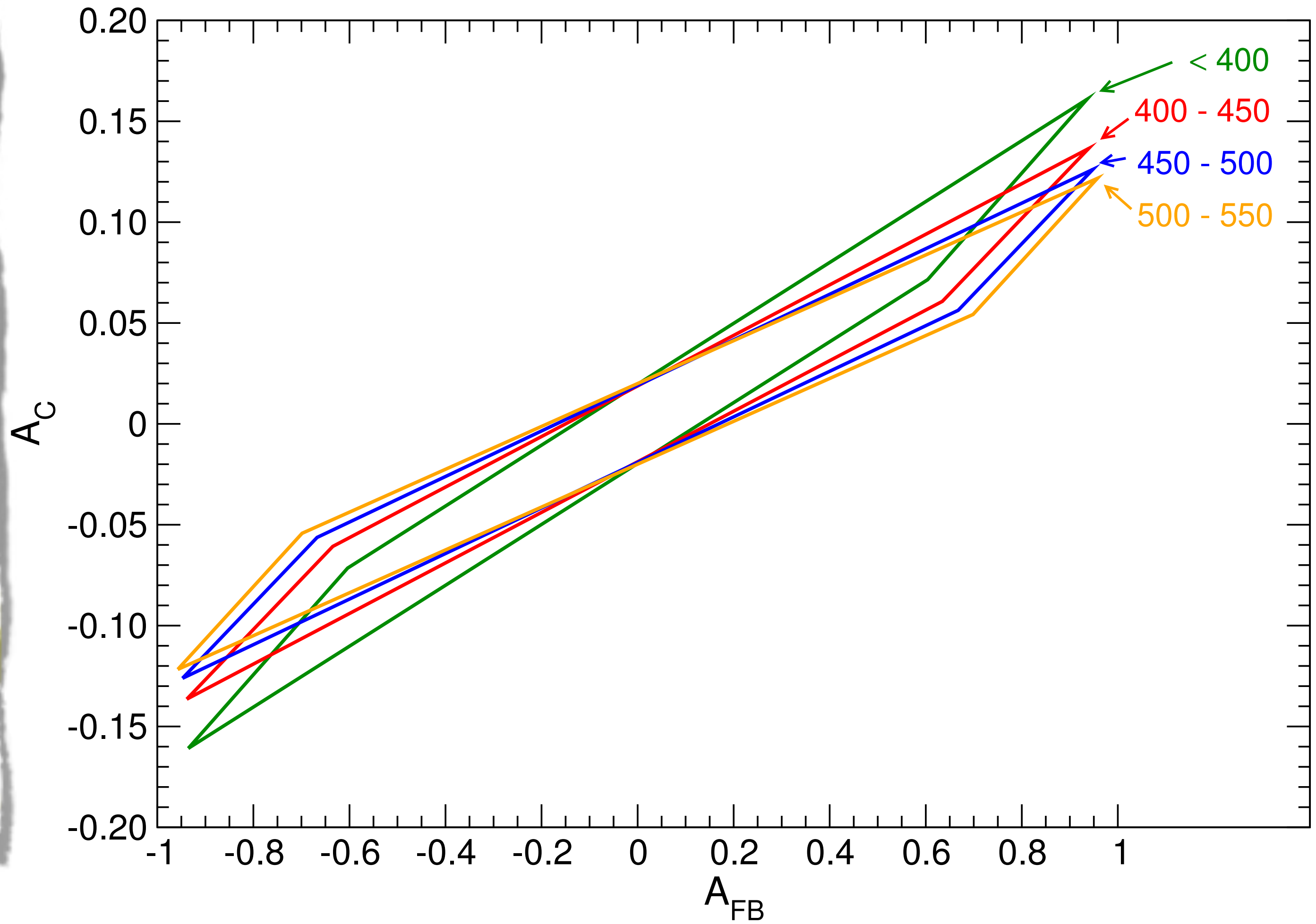
Using the equations for the collider-independent asymmetries

$$A_{\rm FB}(\beta) = A_u F_u(\beta) + A_d F_d(\beta)$$

$$A_C(\beta) = A_u F_u(\beta) D_u(\beta) + A_d F_d(\beta) D_d(\beta)$$

one can revert the argument and obtain model-independent predictions for A_{FB} , A_C by scanning over A_u , A_d

$\Rightarrow$ $A_{\rm FB} \sim 0.2$ compatible even with $A_C \lesssim 0$ if A_u , A_d have opposite signs

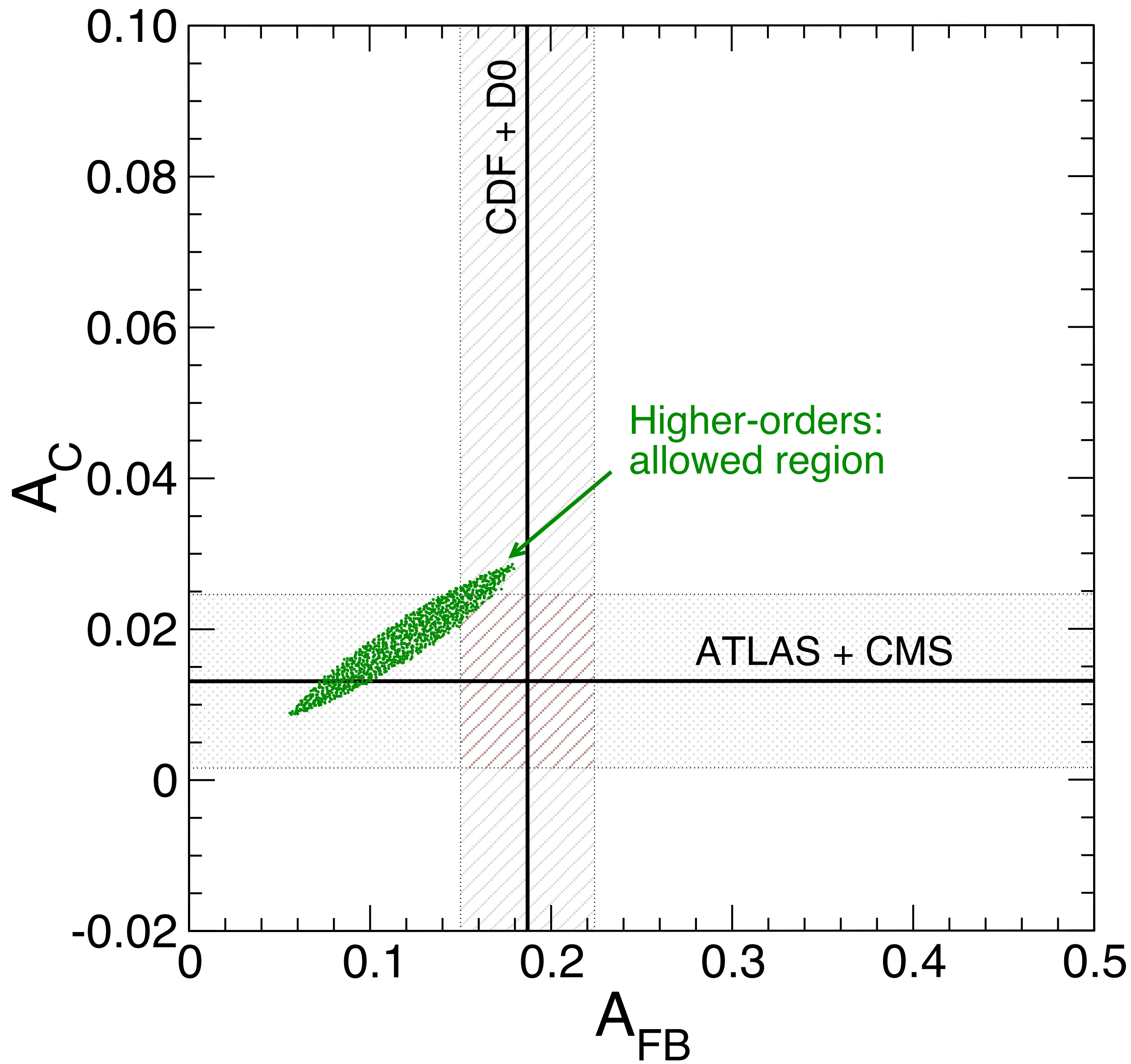


model implementing this mechanism: Drobnak et al. '12

other models with small A_C: Alvarez et al. '12, Drobnak et al. '12

Can the excess be higher-order QCD?

One can estimate the effect of higher QCD orders with the collider-independent asymmetries, but randomly varying A_u , A_d around the SM NLO values to "predict" the relation A_{FB} vs A_C…



a plot for SM skeptics

… an explanation by QCD would not (likely) fit central values!

Can the excess be an unknown systematic?






Hard to think of, because it appears in two experiments.

But unknown systematics are by definition unknown…

One-page summary

The A_{FB} puzzle is far from being solved. And there are still hopes that new physics is hiding in the top sector.

This new physics might also be visible indirectly, in precision measurements of the $t\bar{t}$ differential distribution and in top polarisation measurements.

Or not. There are examples (axigluon) that preserve both.

One-page conclusion

"When you have eliminated the impossible, whatever remains, however improbable, must be the truth"

Sherlock Holmes

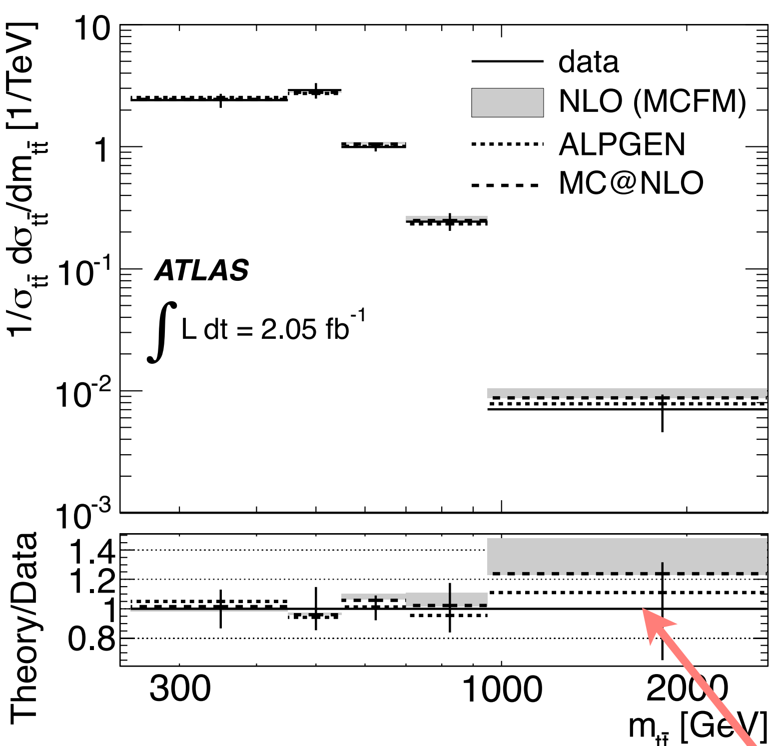
What is *impossible* is not yet fully understood, but this puzzle may be clarified or even solved with the upcoming measurements at LHC and Tevatron

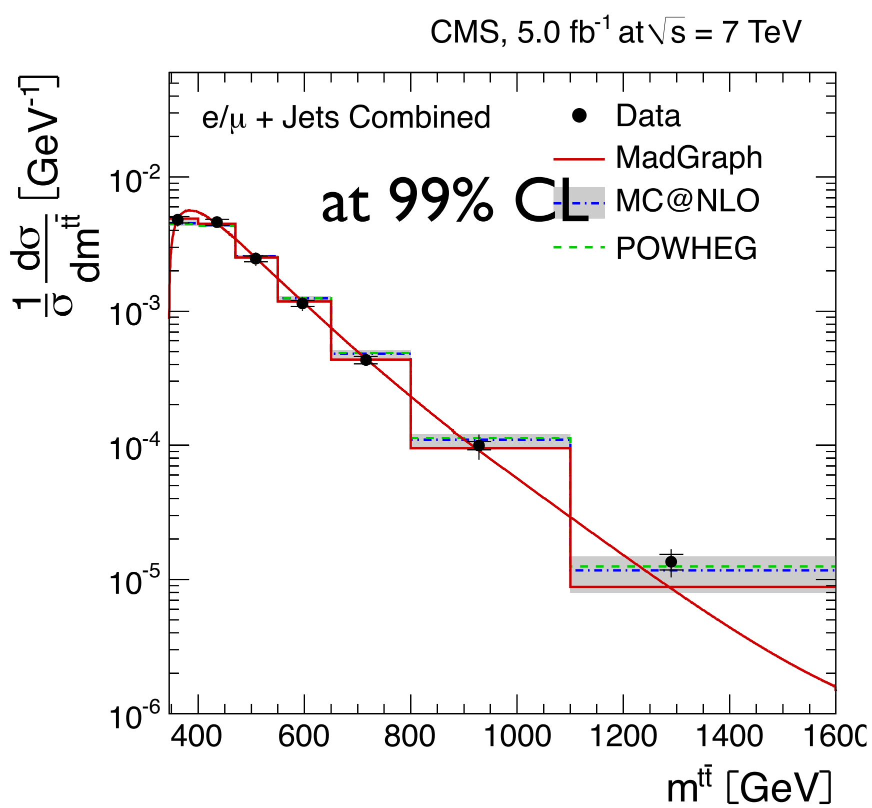
THE FRIENDS

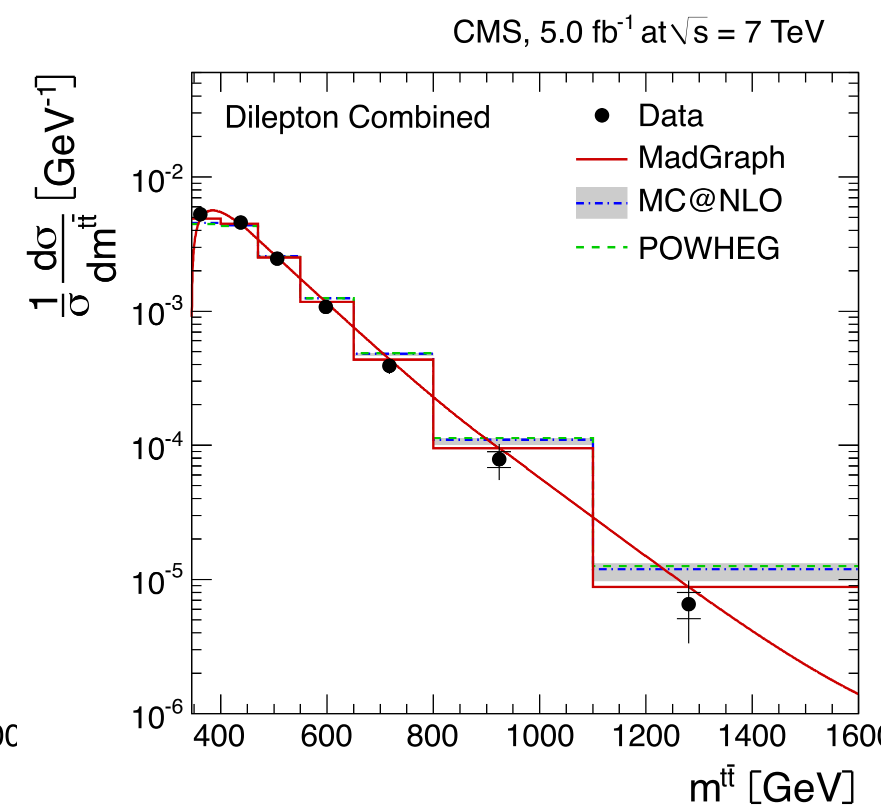
Asymmetry friend #1: $t\bar{t}$ differential distribution

Enhancements expected in *almost all* models, especially those implementing $\delta\sigma_{\rm int} + \delta\sigma_{\rm quad} \sim 0$ to keep Tevatron cross section agreement…

… but nothing unusual seen as yet!





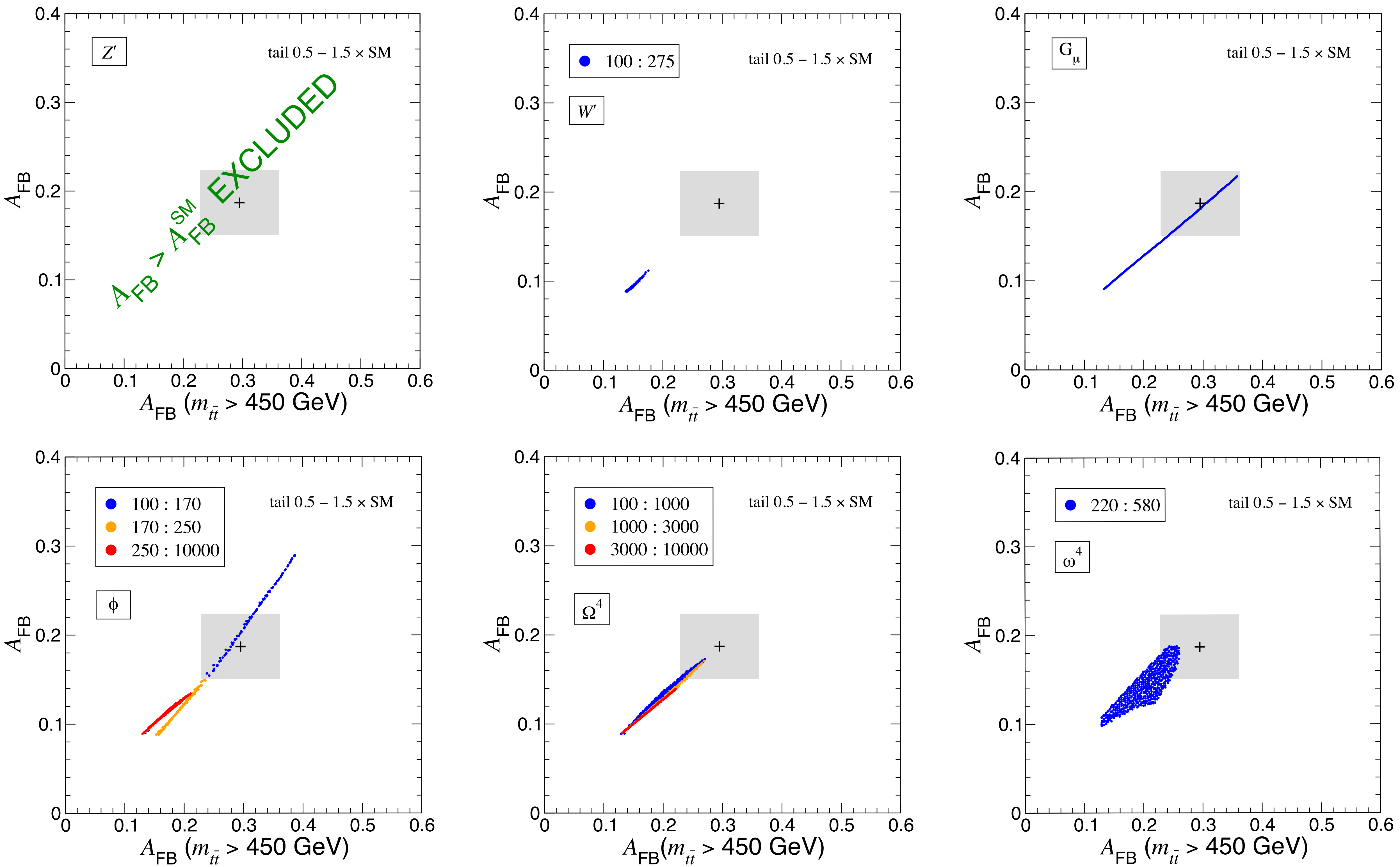


$\sigma/\sigma_{\rm SM} \lesssim 1.3$

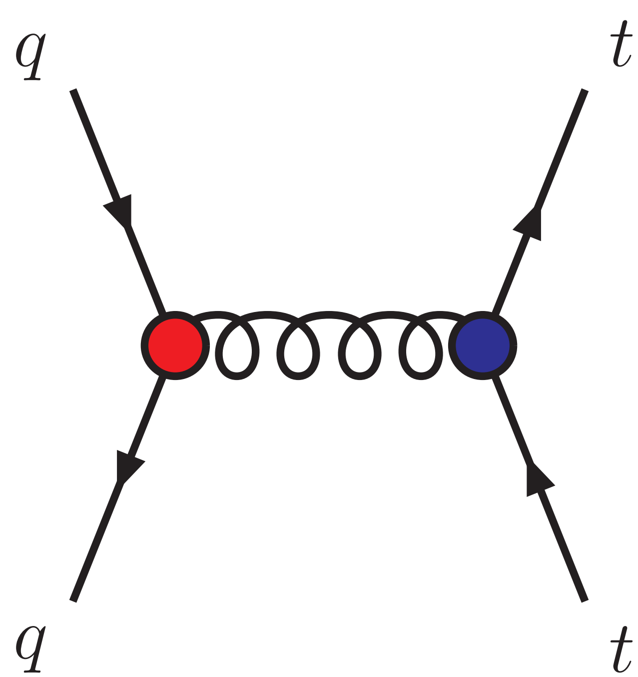
at 99% CL

Tevatron asymmetries after LHC $t\bar{t}$ tail constraints

Disclaimer: additional constraints not included here shrink these conservative areas



Least disturbing model: s-channel coloured resonance $\mathcal{G}$



necessary that $\mathcal{G}$ couples to up/down and to top

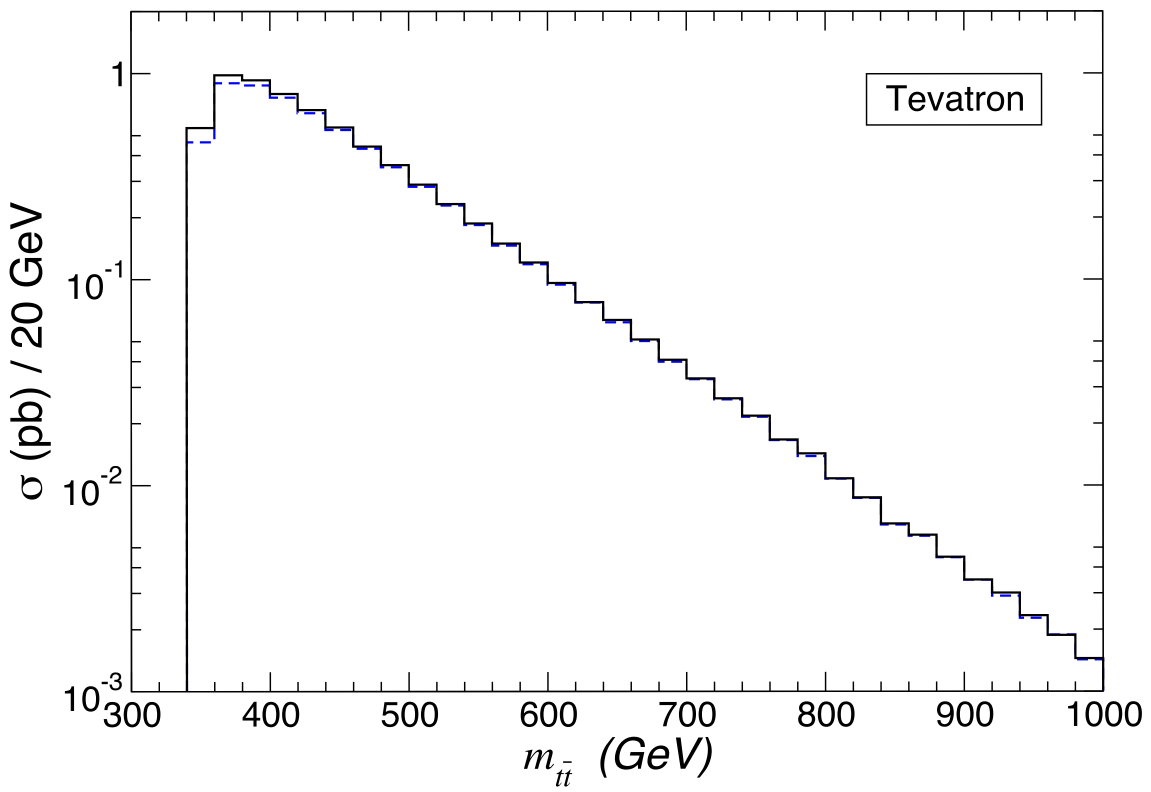
coupling to light quarks small, otherwise dijet production

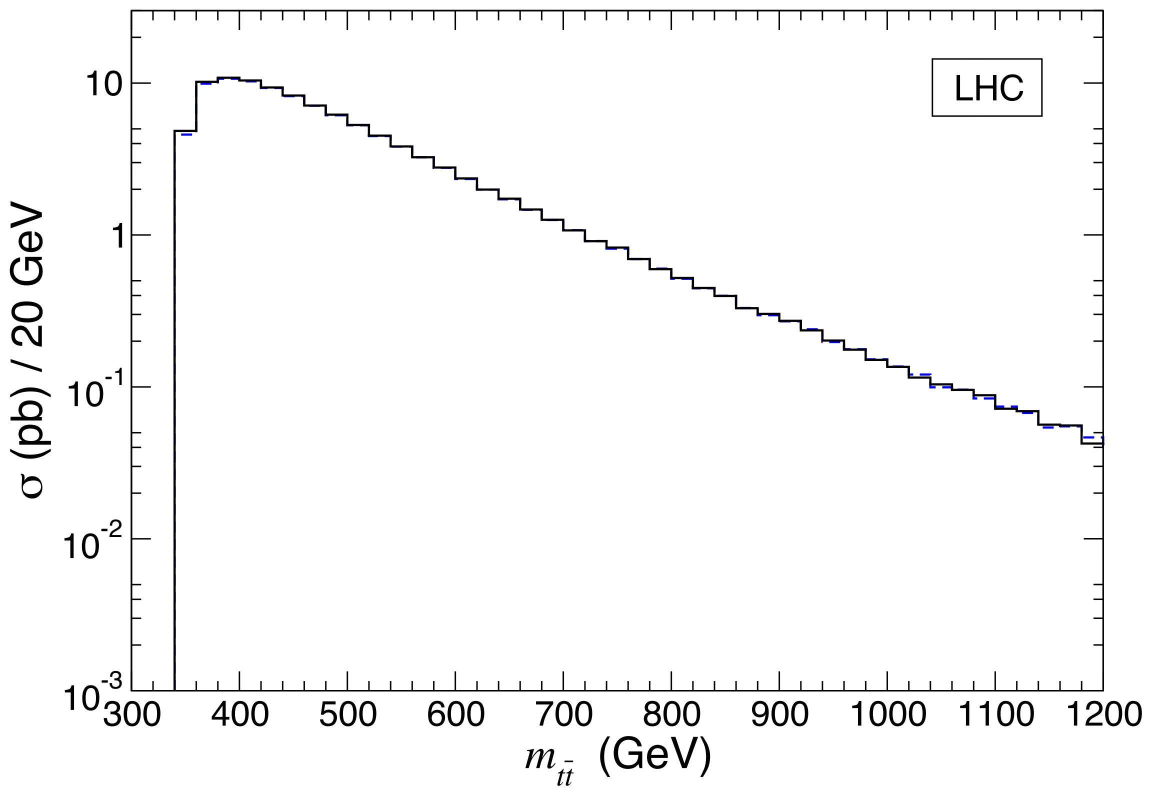
large coupling to top required (natural in extra dimensions)

Colour octet features

- Interference $\delta\sigma_{\rm int}$ identically zero (at all energies) if either coupling to $q\bar{q}$ or $t\bar{t}$ axial
- Asymmetry maximised respect to $\delta\sigma$ if both couplings axial (old friend axigluon)
- Distinctive signature: peak (bump) in the $m_{t\bar{t}}$ distribution from quadratic term $\delta\sigma_{\rm quad}$ if the resonance is reached
- Non-observation of peak → $\mathcal{G}$ heavy, wide or *below threshold*
- LHC limits more and more stringent: if $\mathcal{G}$ heavy, it is "too heavy" and large (nonperturbative) couplings required to reproduce A_{FB}
- Cool, fashionable, viable alternative: *light* gluons that has some other drawbacks (dijet pair production, four tops)

Light gluons below the TeV



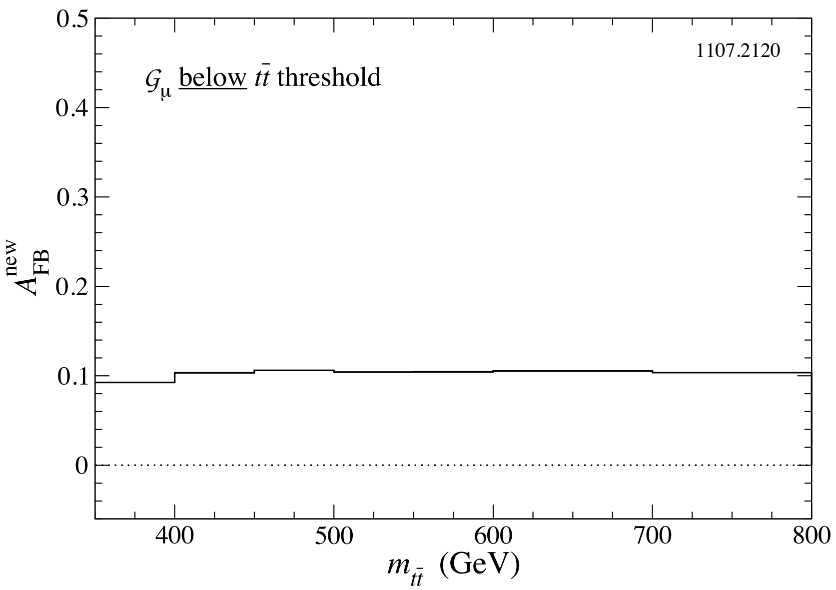


- invisible at Tevatron if very wide or below threshold
- even more at LHC (gg dominated)
- can satisfy flavour and dijet constraints
- diverse A_{FB} profiles vs $m_{t\bar{t}}$ possible

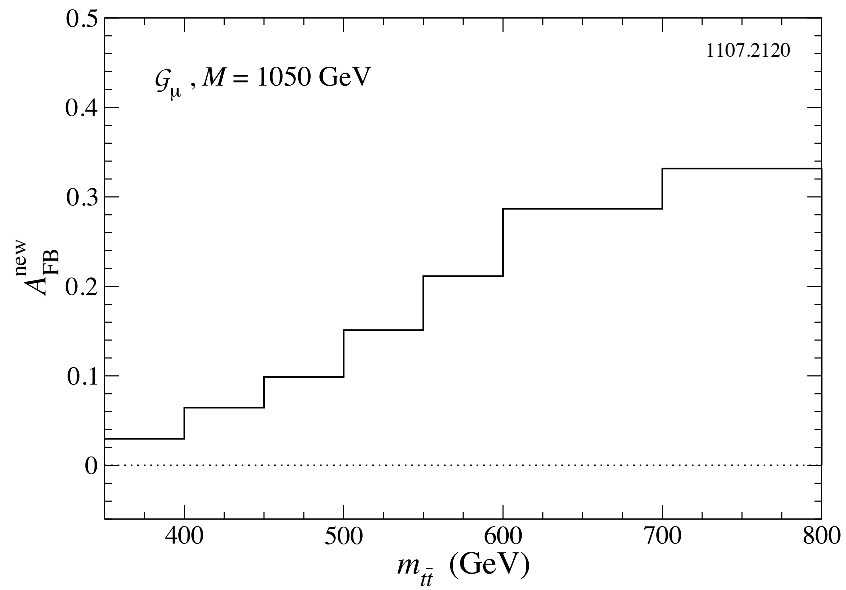
A_{FB} profiles: from flat to camel

Sustainable model

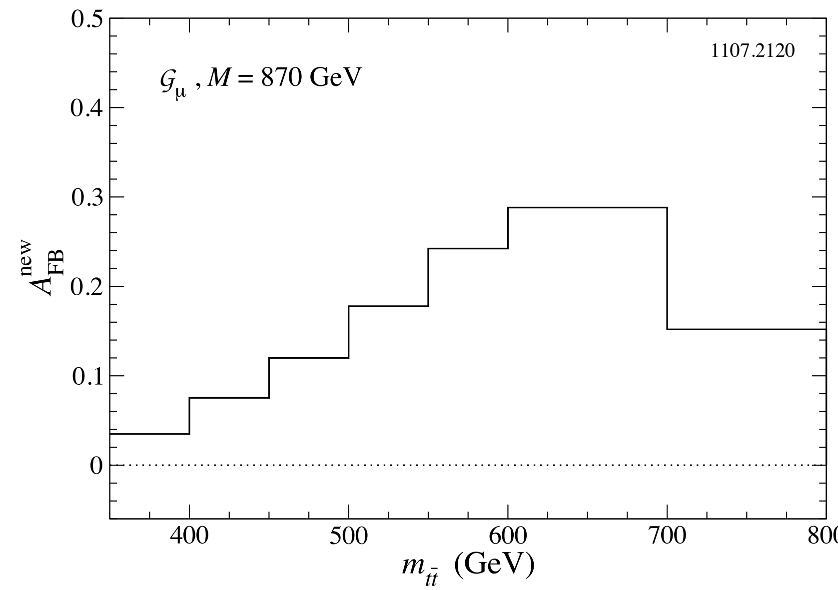
flat



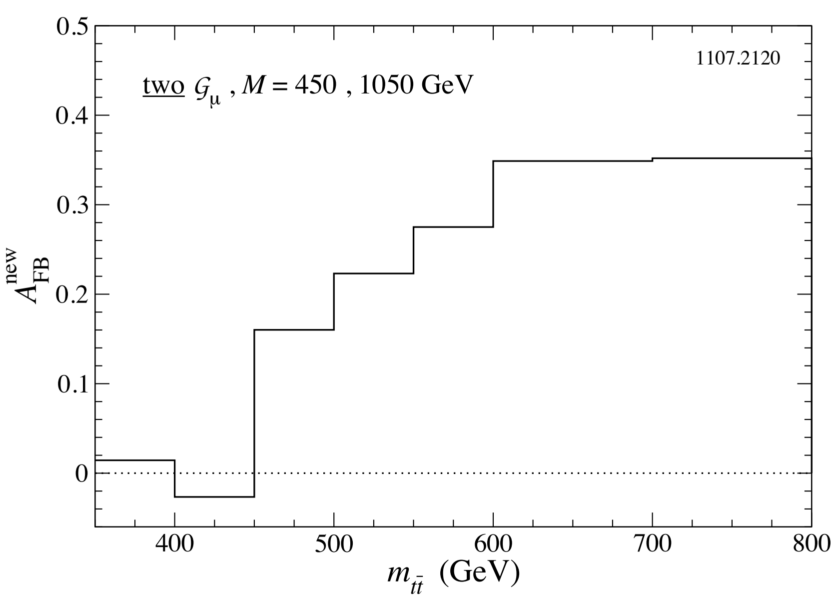
rising



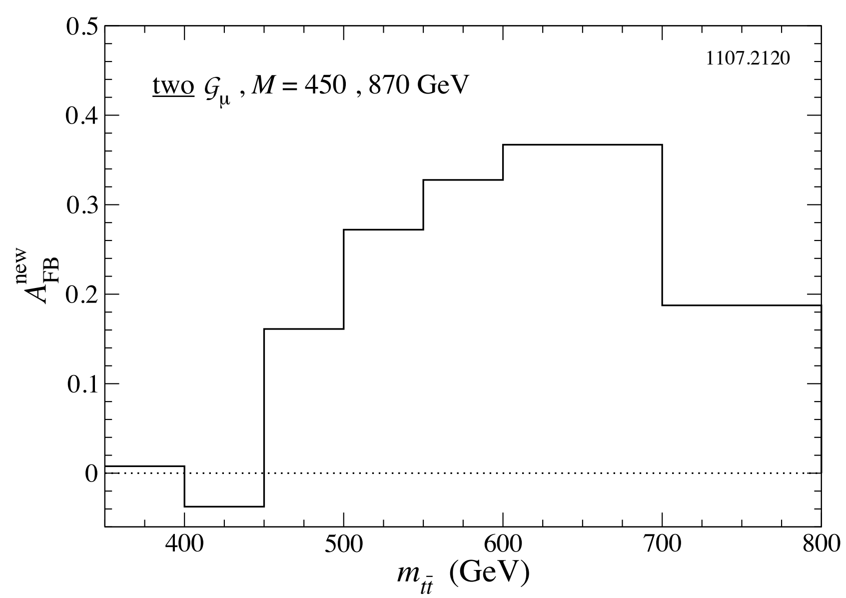
hill



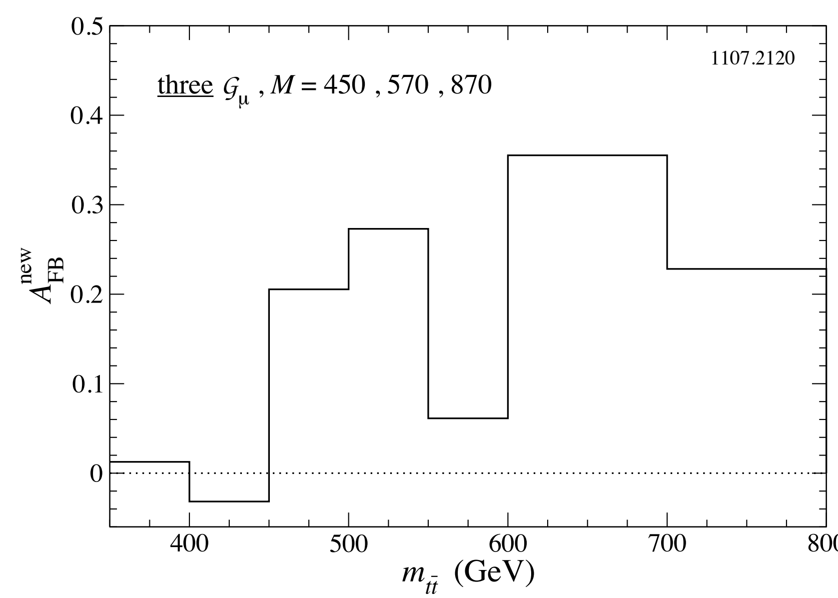
dip-rising



dip-hill



camel

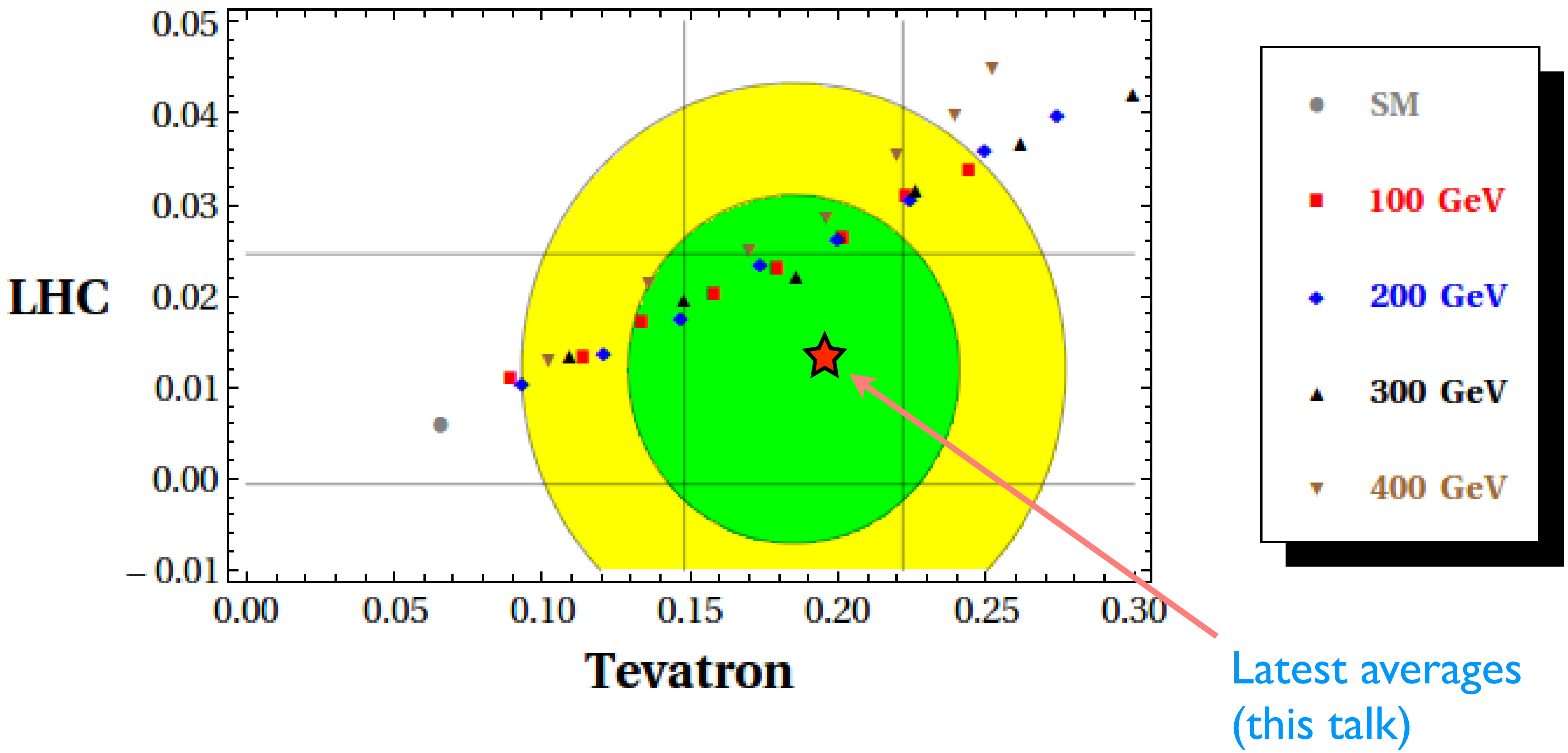


Light gluons are LHC-friendly

Light gluons can accommodate small A_C… for the moment…

Average value of $A_C = 0.013 \pm 0.012$ has 90% uncertainty!

Borrowed from Gross et al. `12



crucial to see what happens when the precision is improved and with 8 TeV data

Asymmetry friend #2: $t\bar{t}$ polarisation

The double angular distribution for a $t\bar{t}$ pair is

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_t\,d\cos\theta_{\bar{t}}} = \frac{1}{4}\left[1 + B_t\cos\theta_t + B_{\bar{t}}\cos\theta_{\bar{t}} - C\cos\theta_t\cos\theta_{\bar{t}}\right]$$

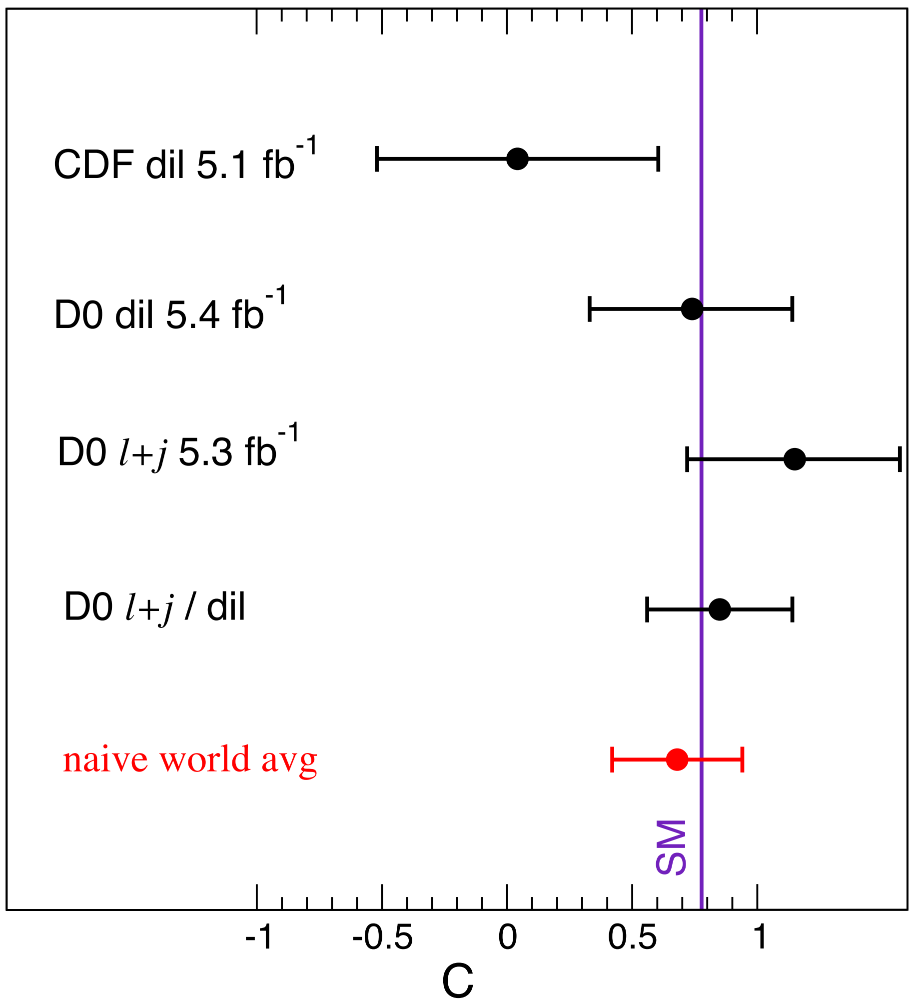
with $\theta_t, \theta_{\bar{t}}$ the angles of the top, antitop momenta w.r.t. chosen spin axes.

In the SM:

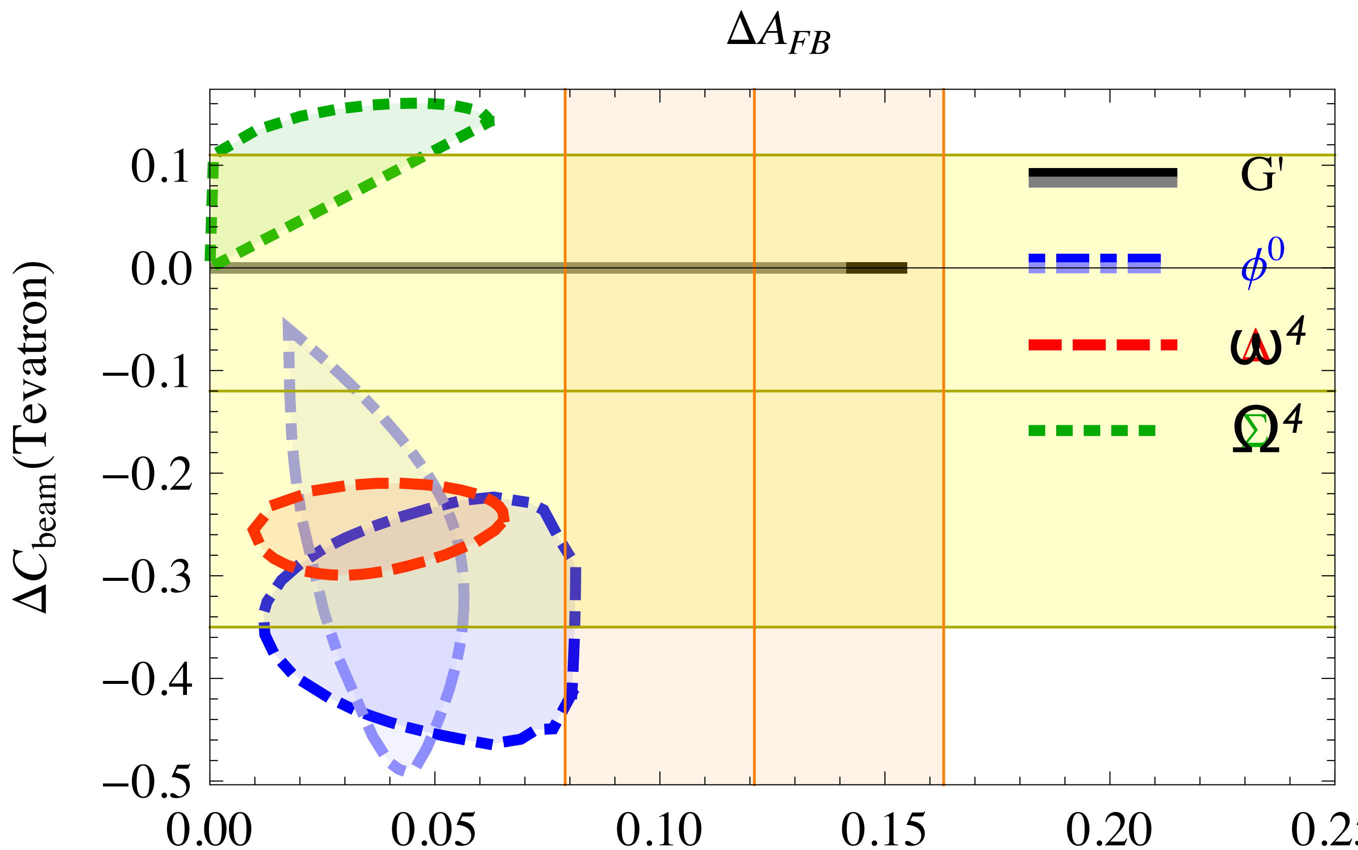
- $B_t, B_{\bar{t}} = 0$ (unpolarised tops) at tree level due to QCD vector coupling, and $B_t, B_{\bar{t}} \simeq 0$ at higher orders
- $C \neq 0$ choosing suitable axes

Beyond the SM, these predictions can be significantly altered.

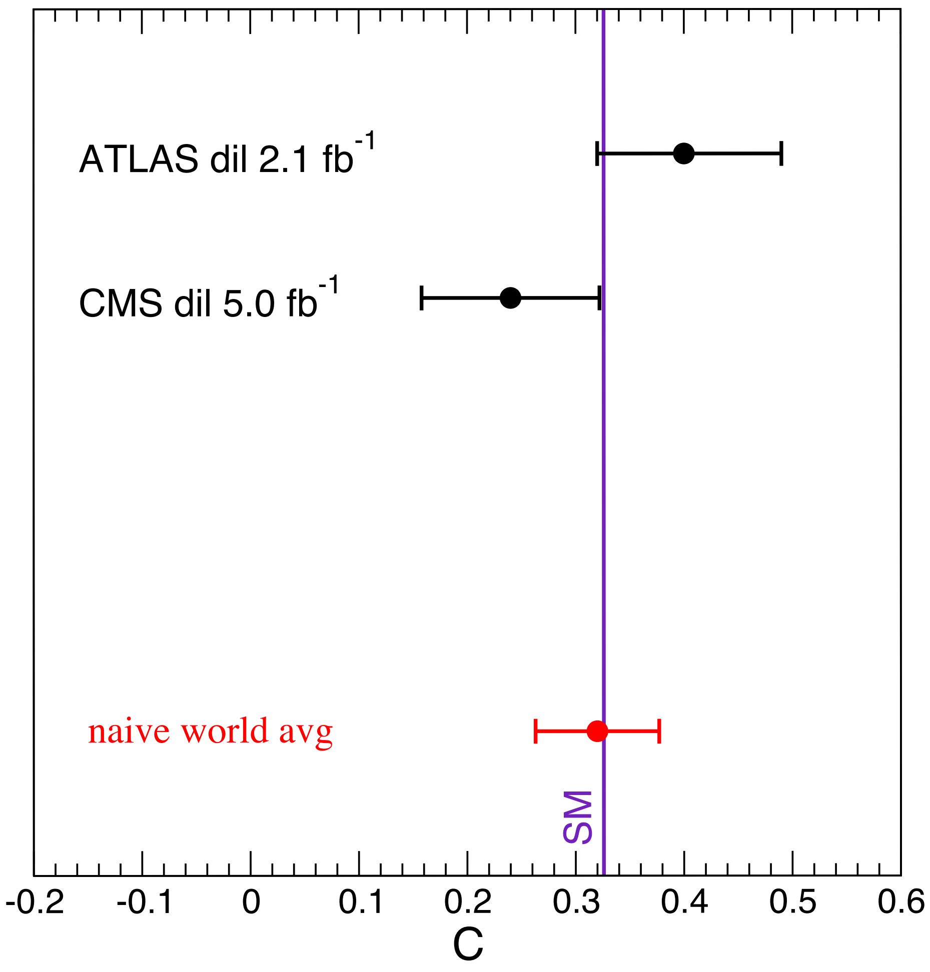
C at Tevatron, beamline basis



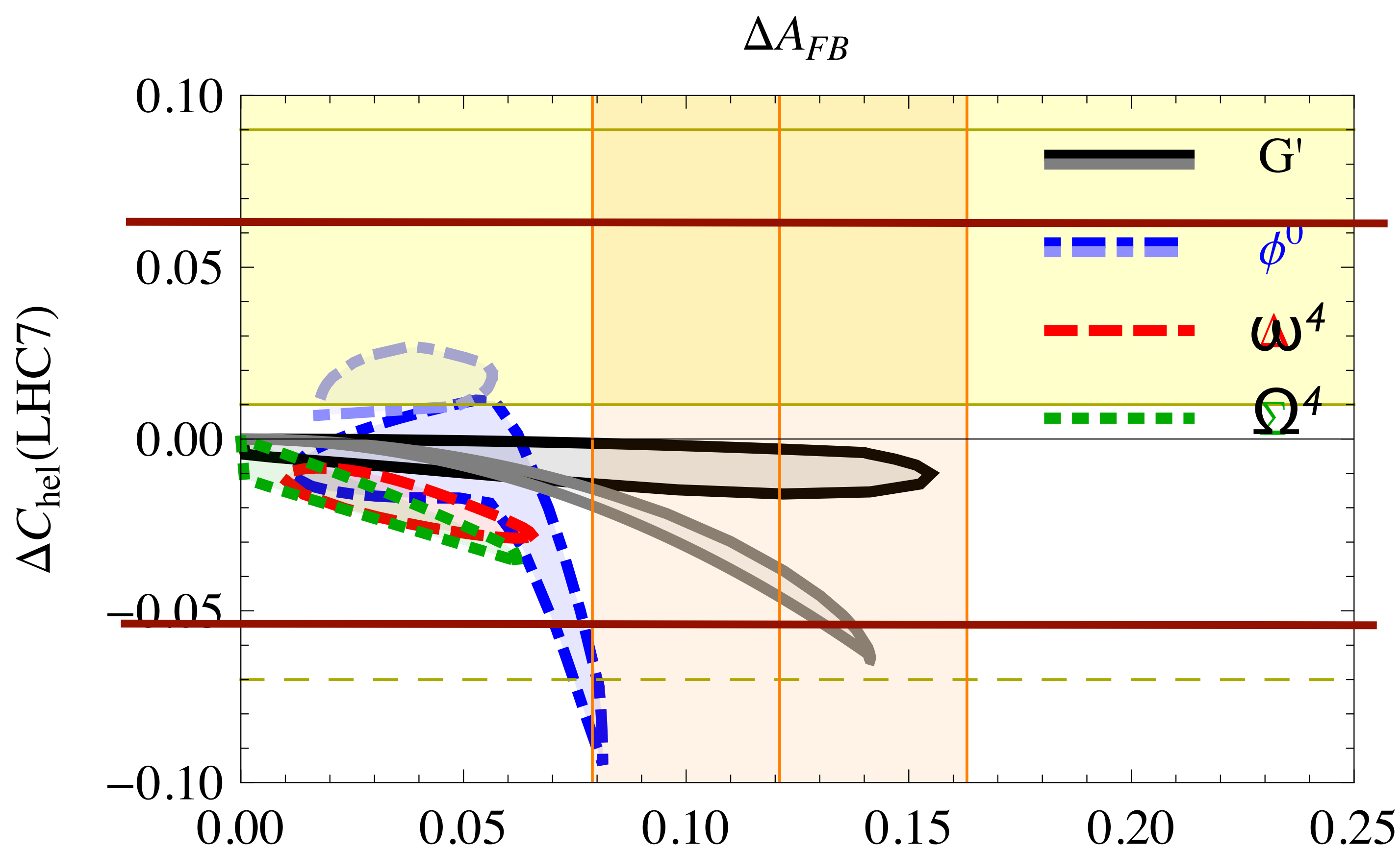
Borrowed from Fajfer et al. '12



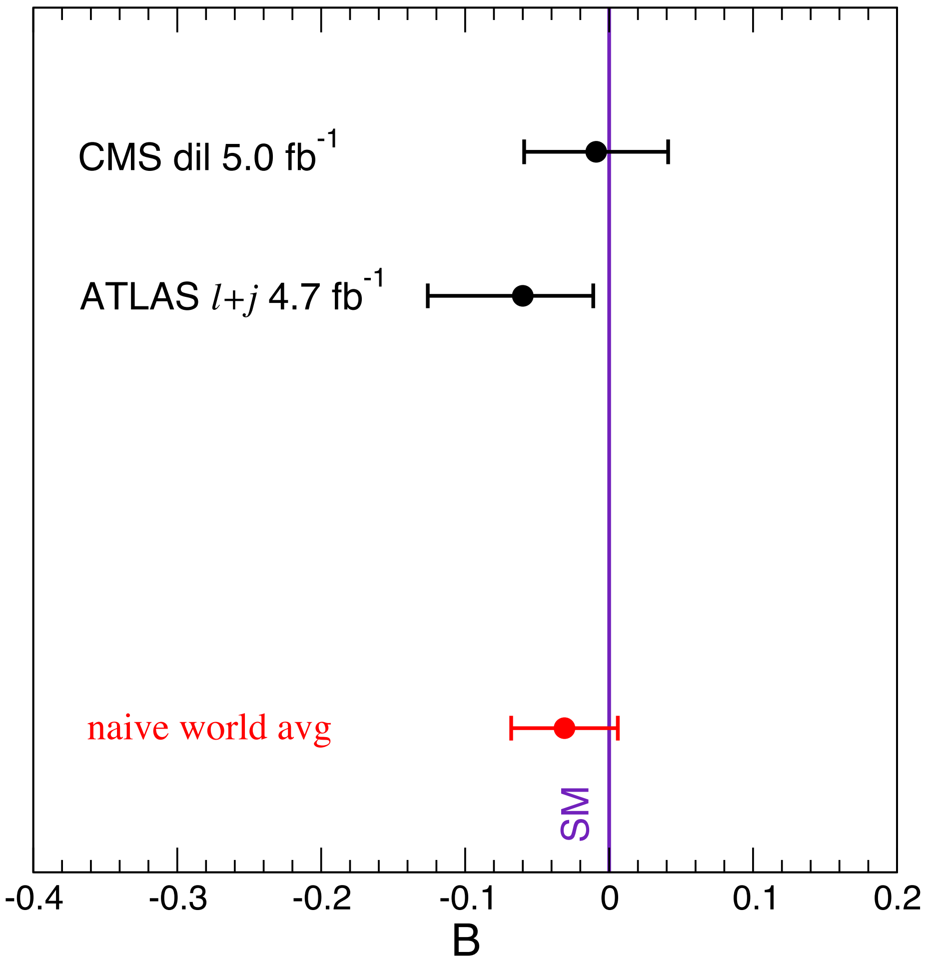
C at LHC, helicity basis

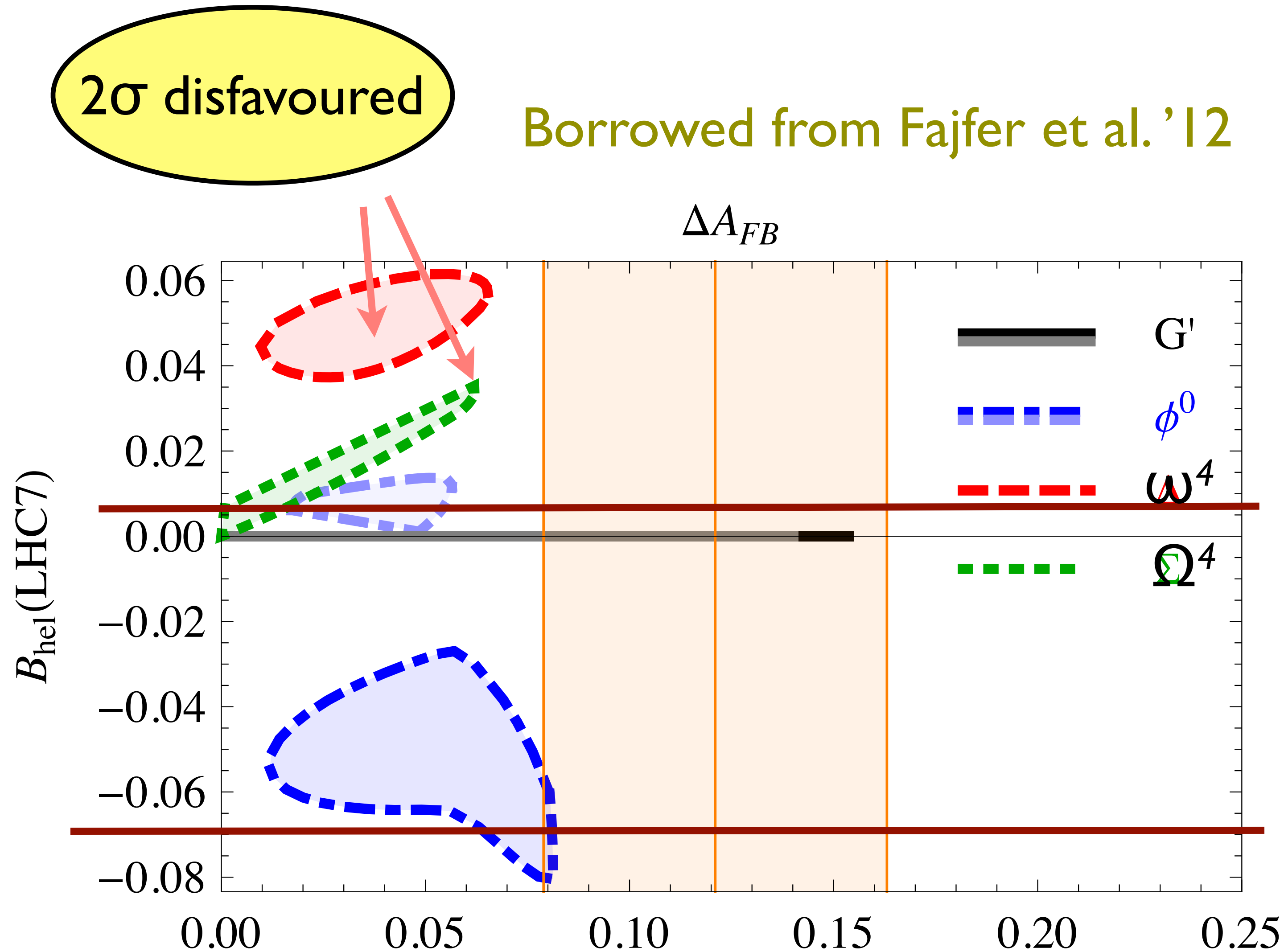


Borrowed from Fajfer et al. '12



B at LHC, helicity basis

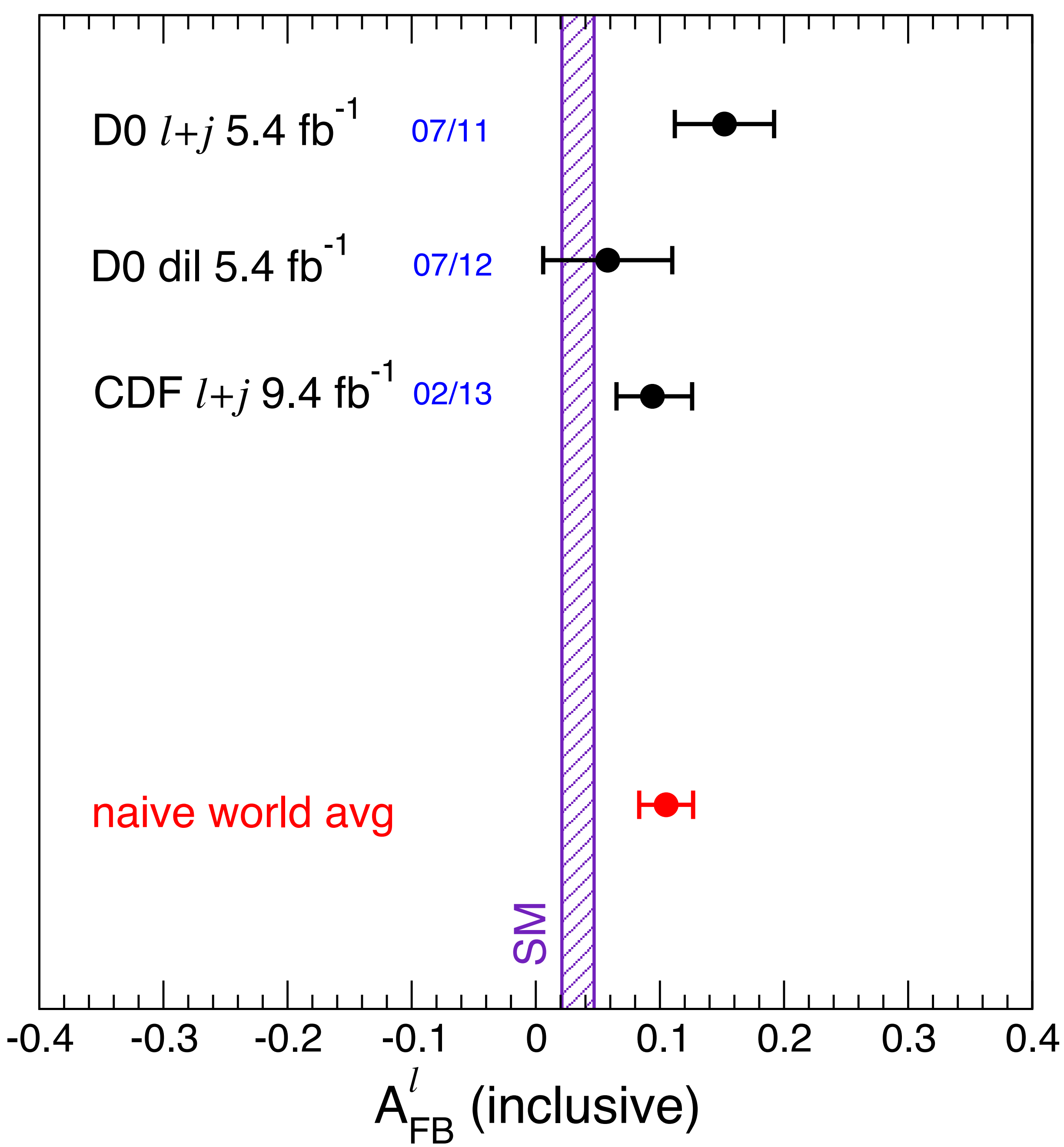




Other relatives: lepton-based asymmetries

$$A_{\rm FB}^{\ell} = \frac{N(Q\cdot\eta>0)-N(Q\cdot\eta<0)}{N(Q\cdot\eta>0)+N(Q\cdot\eta<0)}$$

$$A^{\ell\ell} = \frac{N(\Delta\eta>0)-N(\Delta\eta<0)}{N(\Delta\eta>0)+N(\Delta\eta<0)}$$



$$A^{\ell\ell} = 0.053 \pm 0.084$$ D0 5.4 fb^{-1}

they depend on A_{FB} as well as on top polarisation

$A_{\rm FB}^{\ell}$ shows positive deviation, strengthening the case for the A_{FB} anomaly

but $A^{\ell\ell}$ does not… certainly its error is large but we should keep an eye on it!

ADDITIONAL SLIDES

Measure A_u and A_d?

Exploiting the dependence of A_{FB} and A_C on the $t\bar{t}$ velocity

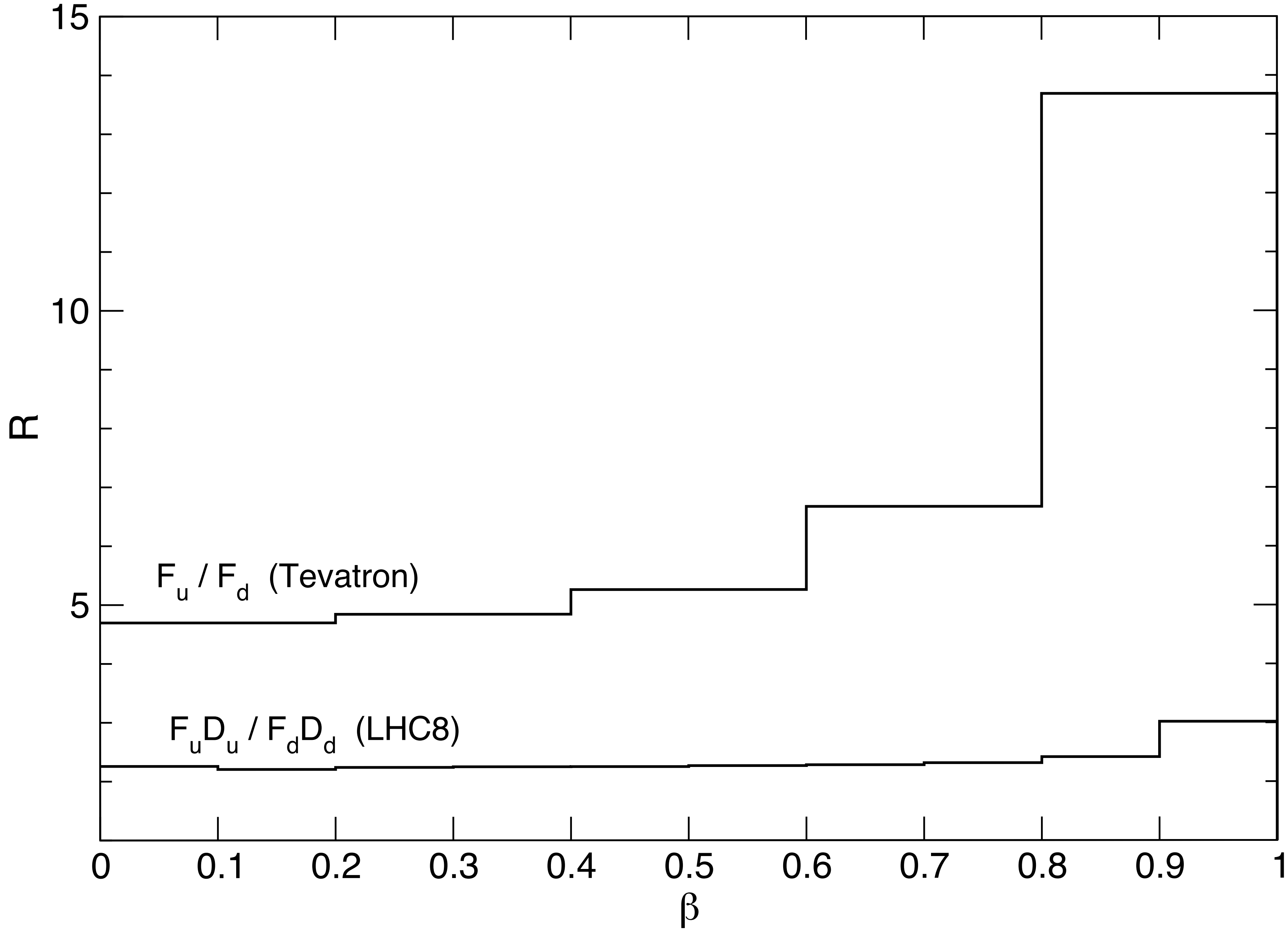
$$\beta = \frac{|p_t^z + p_{\bar{t}}^z|}{E_t + E_{\bar{t}}}$$

A_u and A_d can be extracted from a fit to

$$A_{\rm FB}(\beta) = A_u F_u(\beta) + A_d F_d(\beta)$$
$$A_C(\beta) = A_u F_u(\beta) D_u(\beta) + A_d F_d(\beta) D_d(\beta)$$

where $F_q(\beta)$ ($q\bar{q}$ fractions) and $D_q(\beta)$ (asymmetry dilution factors) are computed from MC in the SM

$F_{u/d}$ and $D_{u/d}$: dependence on β

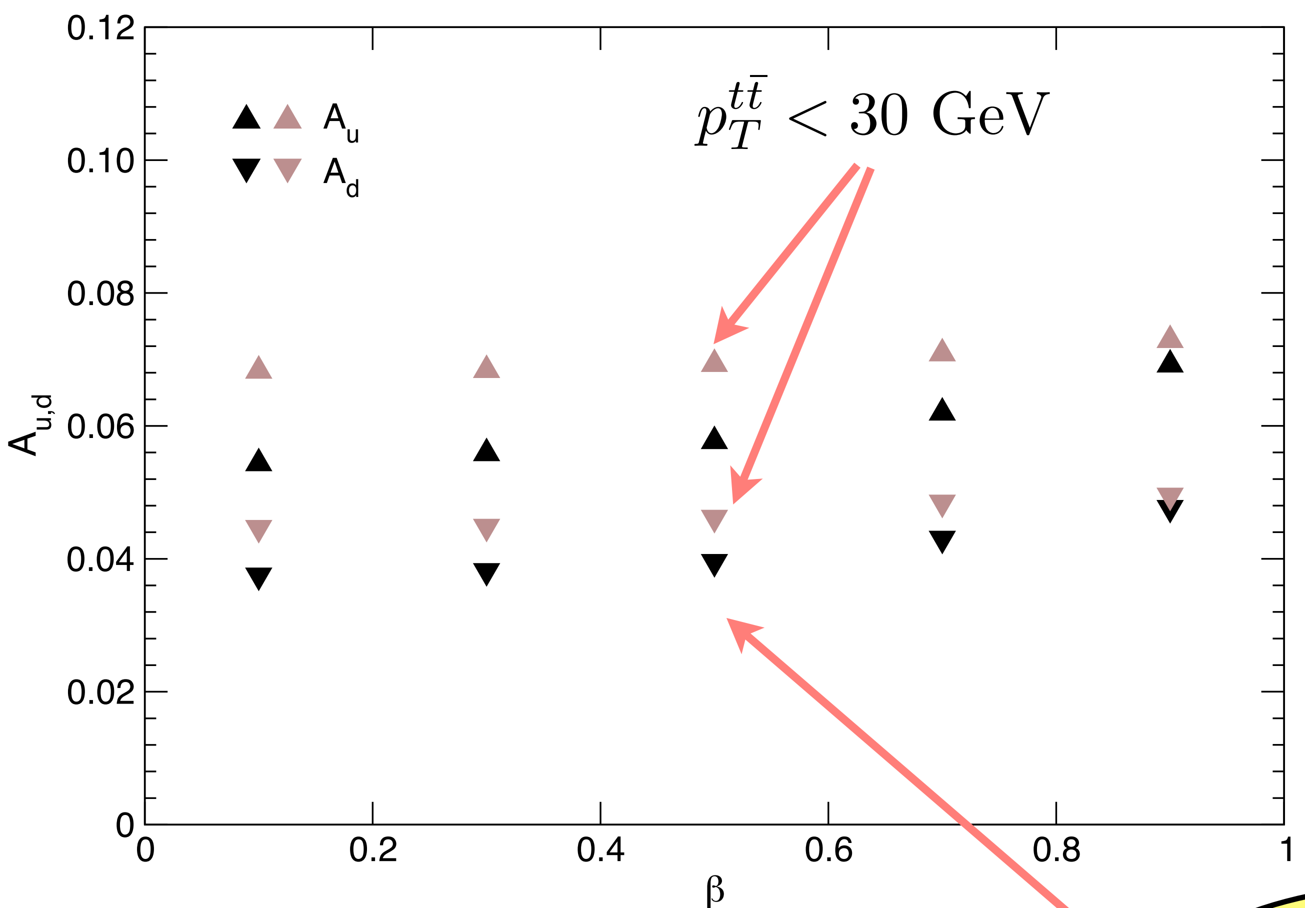


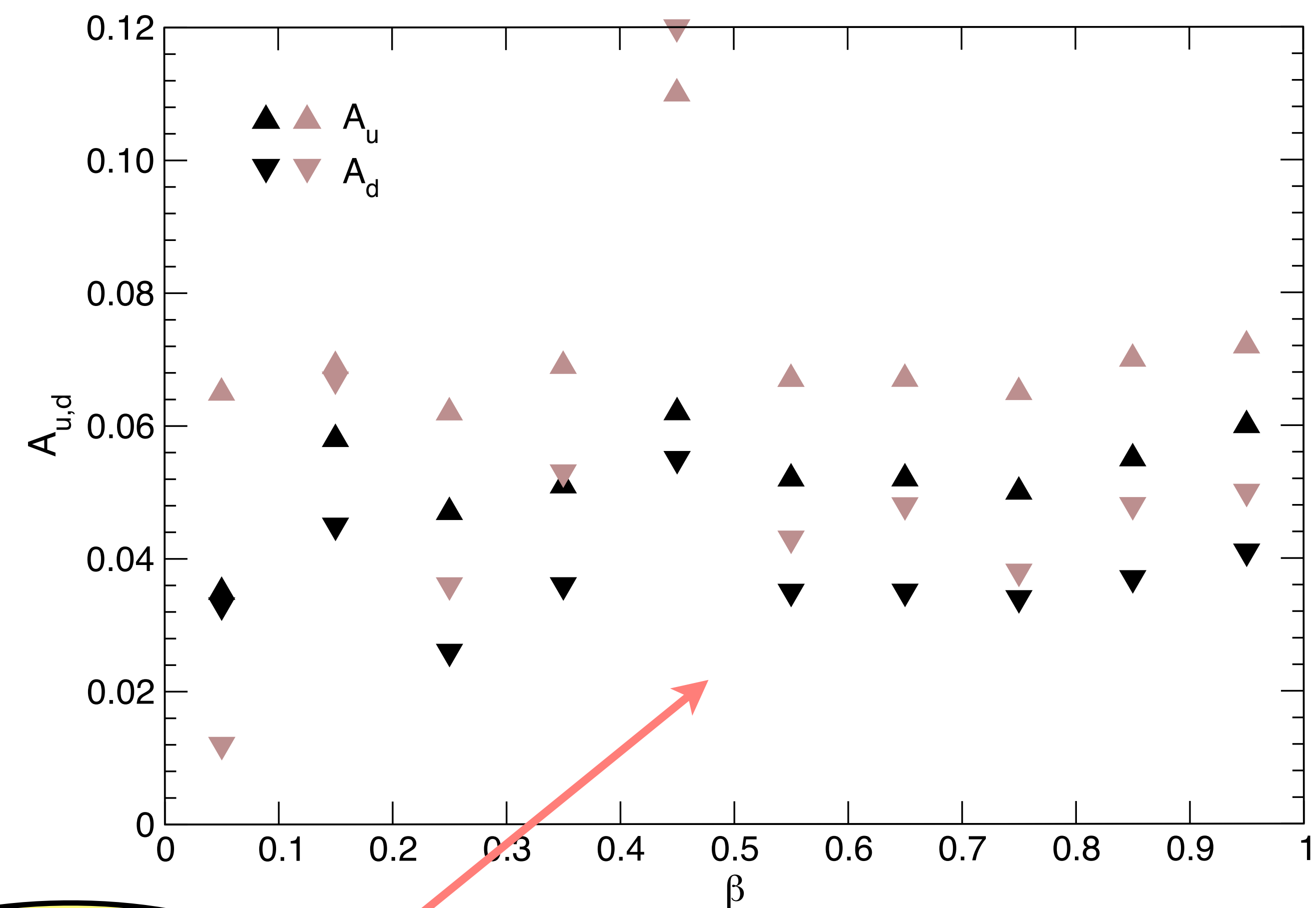
$A_{u,d}$: dependence on β?

As defined by
$$A_{\rm FB}(\beta) = A_u(\beta)F_u(\beta) + A_d(\beta)F_d(\beta)$$
$$A_C(\beta) = A_u(\beta)F_u(\beta)D_u(\beta) + A_d(\beta)F_d(\beta)D_d(\beta)$$

F_u: 3x variation
D_u: 20x D_d: 30x

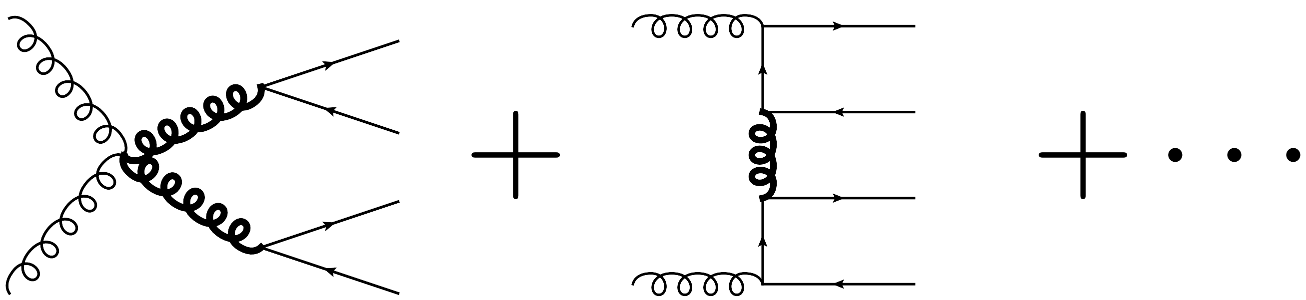
Tevatron $\quad m_{t\bar{t}} < 450$ GeV $\quad$ LHC7



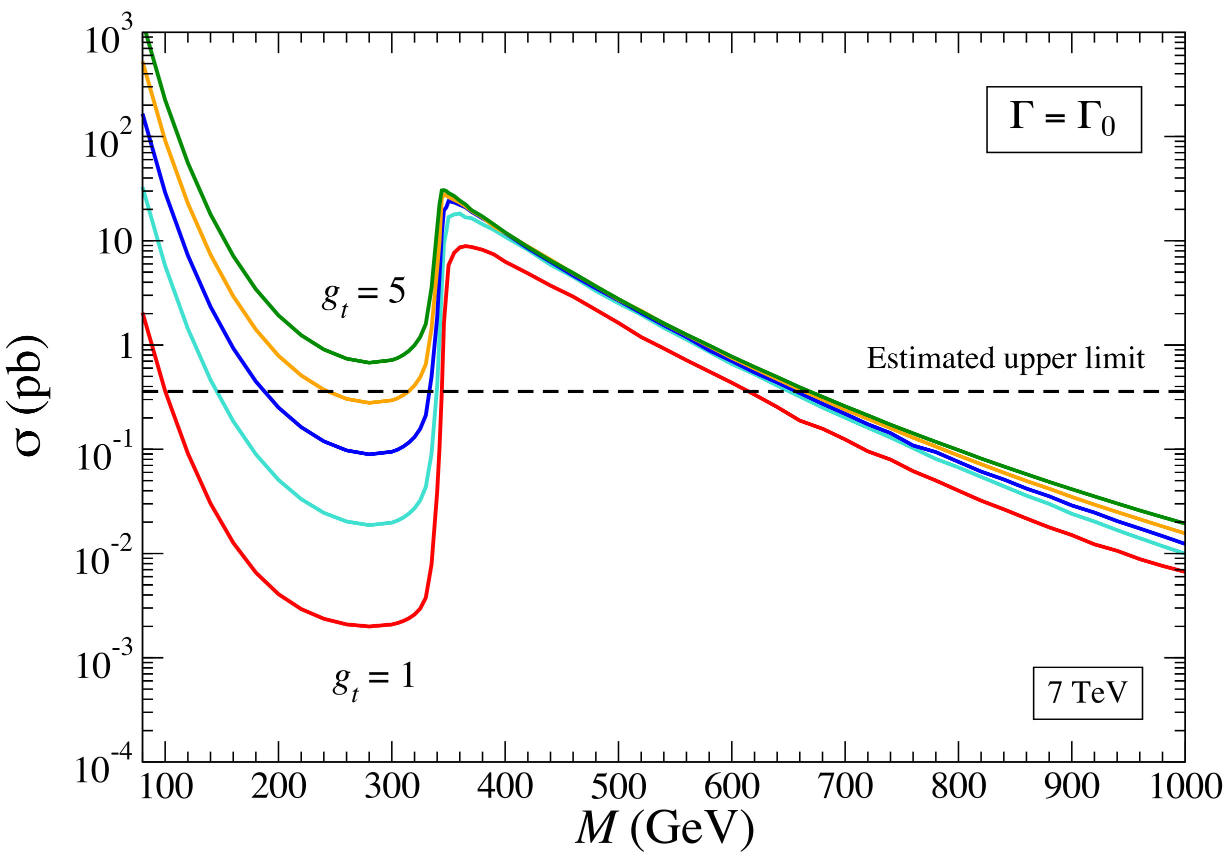


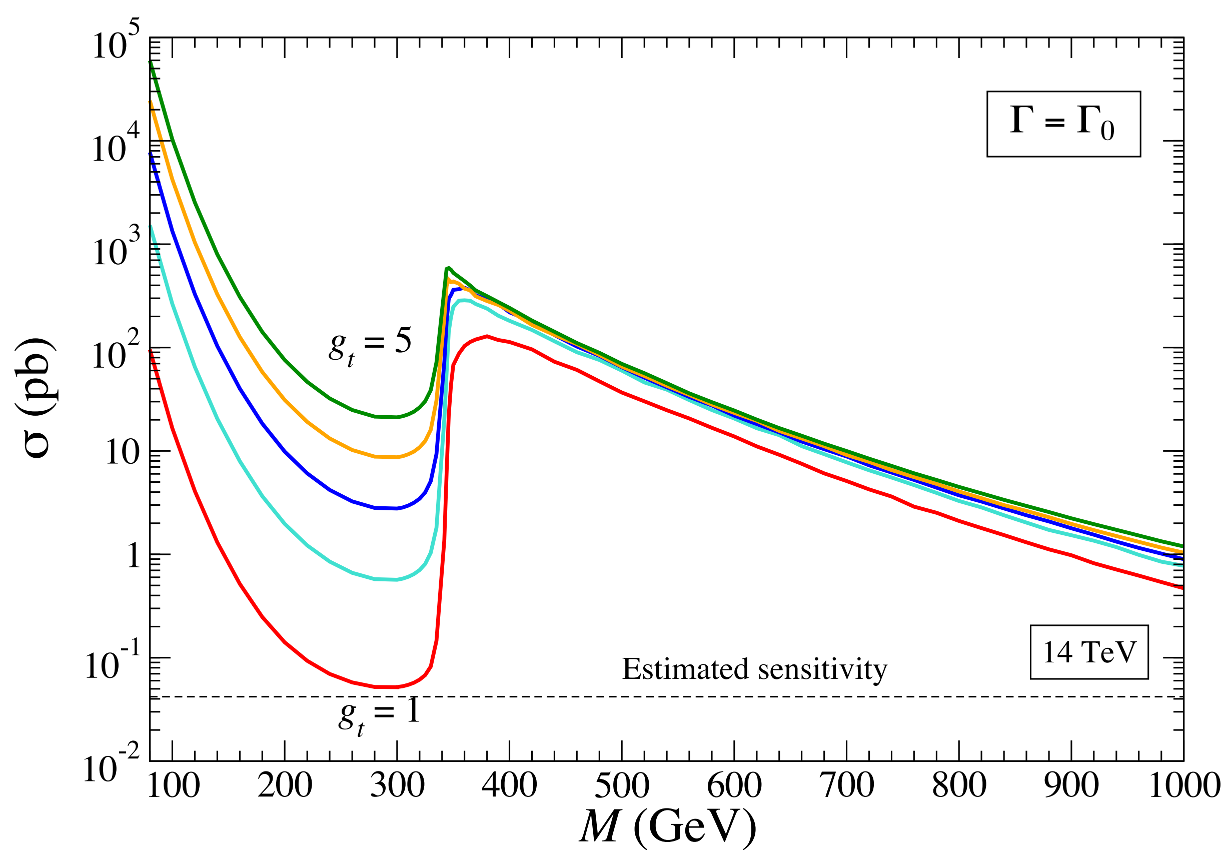
The dependence on β is small

Prediction / constraint on light gluons: four tops



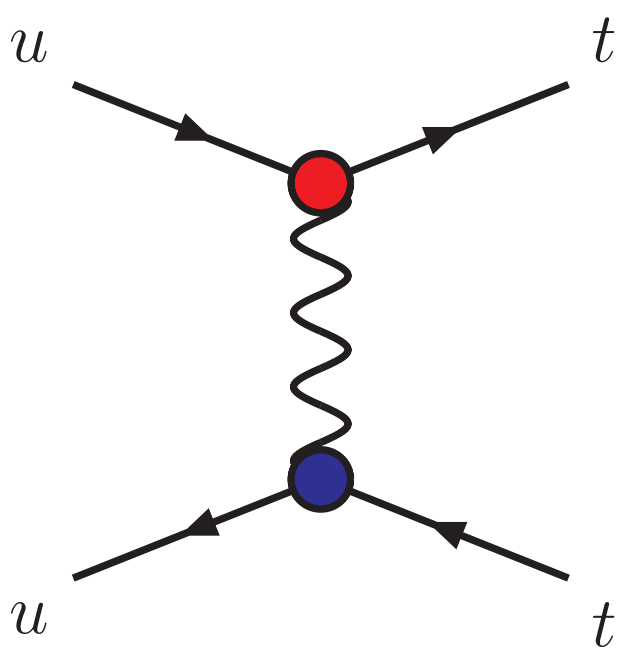
The parameter space for masses / couplings / widths can be probed at 7 TeV and the model may be excluded at 14 TeV

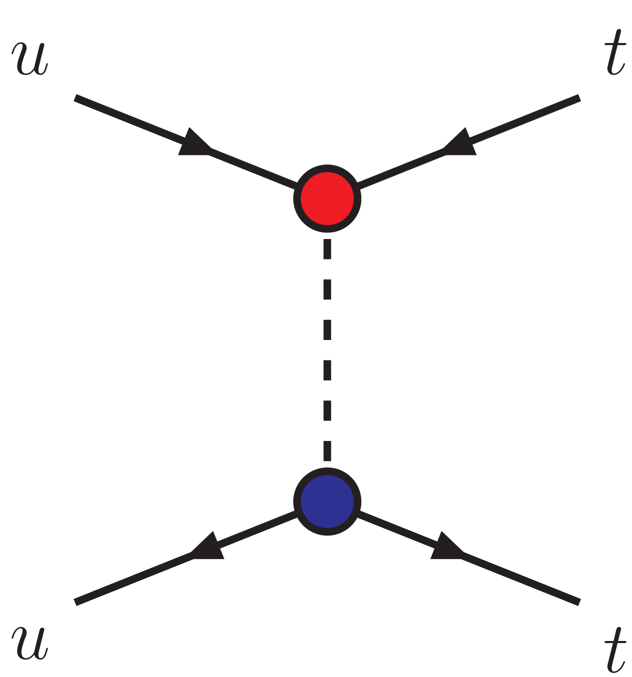




t-channel: Z′

u-channel: Ω^4 / ω^4





flavour-changing ut couplings required

this gives problems at low energy, for example atomic parity violation

but these models already have worse problems in $t\bar{t}$ production itself

Z′ features

- Negative interference with SM decreases A_{FB}
- A positive contribution to A_{FB} and agreement with Tevatron $\sigma(t\bar{t})$ requires large coupling and cancellation $\delta\sigma_{\rm int} + \delta\sigma_{\rm quad} \sim 0$
- Cancellation cannot happen at LHC too: excess in $t\bar{t}$ tail (unobserved)
- The same comments apply to W (also t-channel)

Ω^4 / ω^4 features

- The contribution to A_{FB} / A_C is negative for small Ω^4 / ω^4 masses

→ u-channel propagator prefers *backward* tops

- Numerator does not, and wins for large M
- Going to high $m_{t\bar{t}}$ you finally \`see´ the u-channel propagator: good test for LHC