# On Shell Attempts to Explain $A_{FB}^{t\,\bar{t}} > (A_{FB}^{t\,\bar{t}})_{SM}$

Michael Trott, CERN

**My Mission:** "Describe attempts to explain the $A_{FB}^{t\,\bar{t}}$ excess from the t-channel variety (scalars, vectors, light axigluon?) including information from dijets..."

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**My Theme:**

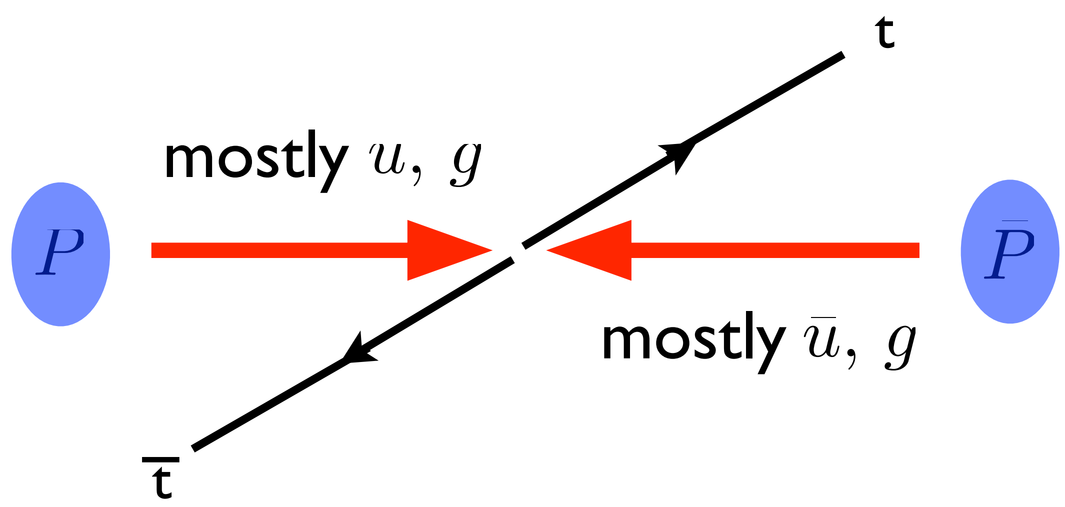

(not quite!)


But remember, at the end of the day Tom Cruise always pulls it off.

# What do we need to explain?

See the experimental talks for the current experimental situation.

I will focus on the ideas out there (not just my stuff!) and the challenges they face for low mass scales (~on shell) when you have new interactions with quarks.




$$\mathcal{L}_{NP} = ?\bar{\psi}\,\psi + ?\psi\,\psi$$

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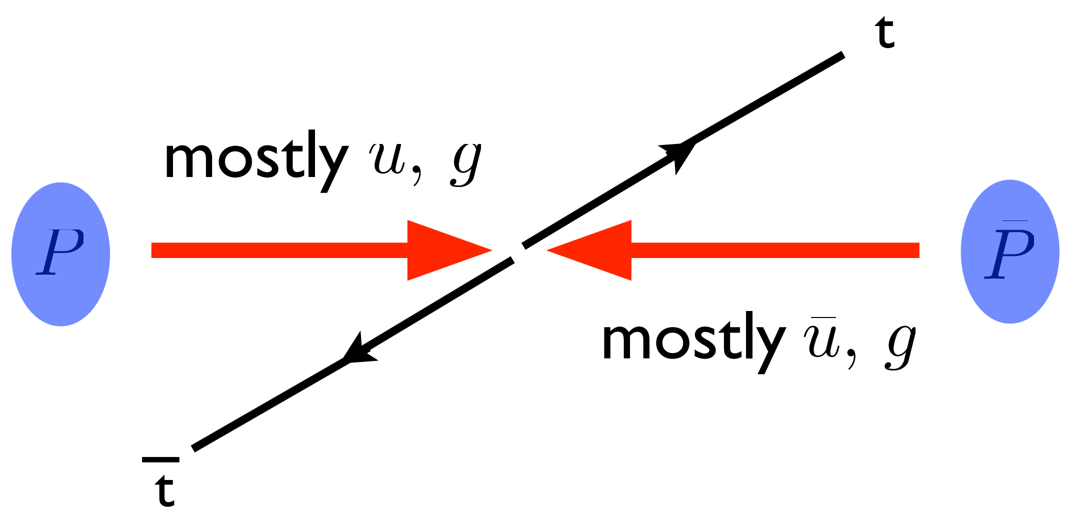


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Add NP (?) in hopes of NP ()

First questions: Effect $A_{FB}^{t\,t}$ through interference or not?
What spin is your NP?
How does it couple to the chiral SM fields?

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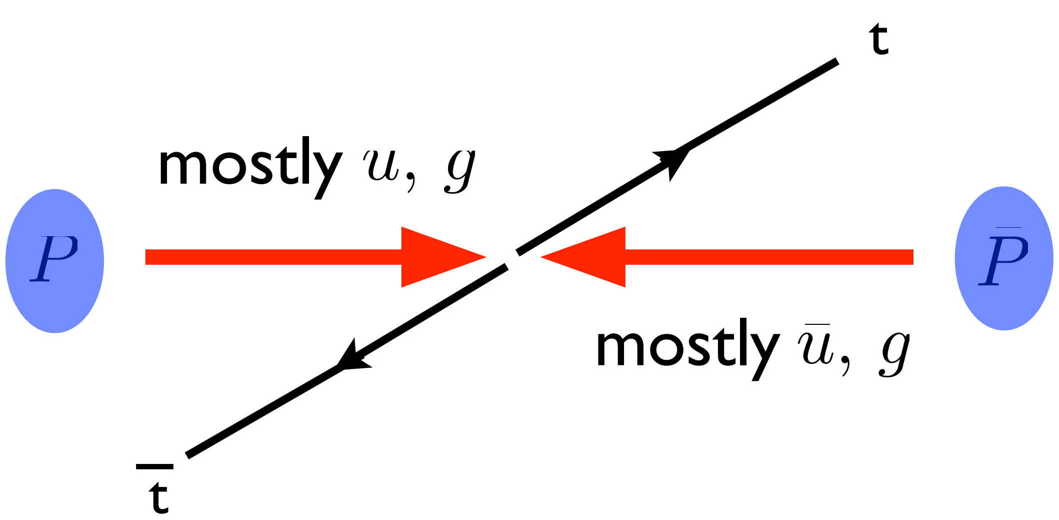


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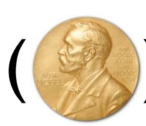
Add NP (?) in hopes of NP ()

First questions: Effect $A_{FB}^{t\bar{t}}$ through interference or not? Can ask the data!

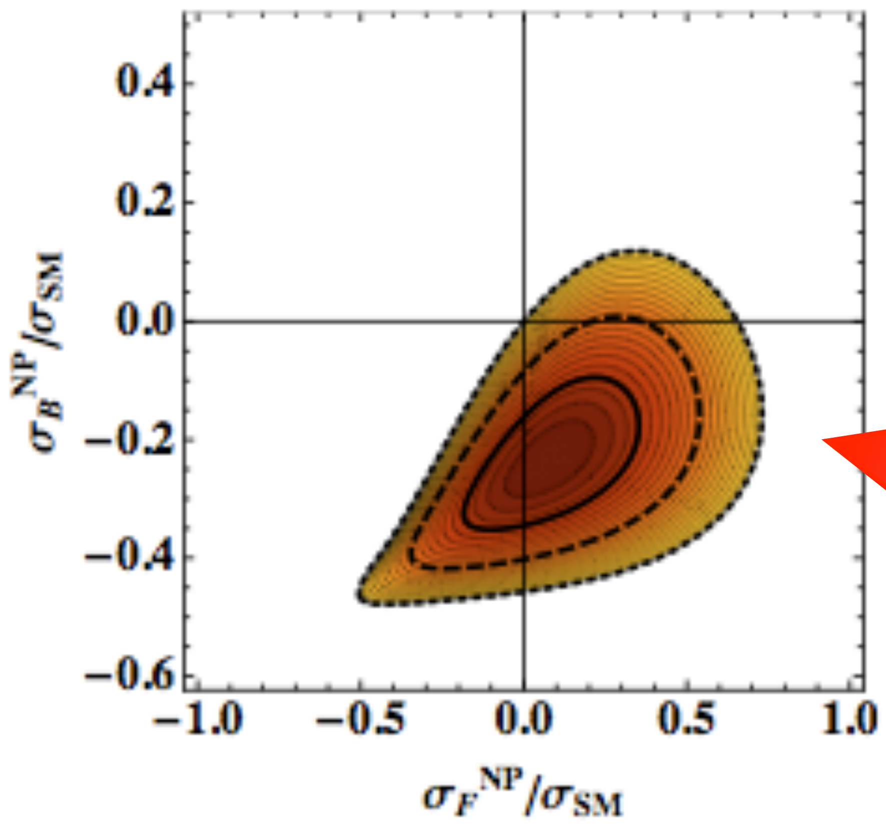
What spin is your NP? Choose wisely.

How does it couple to the chiral SM fields? Choose wisely, data hints produce R-handed tops.

# To interfere or not to interfere

The bottom line: $$A_{FB}^{t\bar{t}} = \frac{\sigma_F^{SM} - \sigma_B^{SM} + \sigma_F^{NP} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_B^{SM} + \sigma_F^{NP} + \sigma_B^{NP}},$$

NP-SM interference + NP^2
can be either sign.




Smoking gun for new physics
interference?

**arXiv: 1102.3374 – Phys.Rev.Lett.107:012002,2011.**

Grinstein, Kagan, Trott, Zupan

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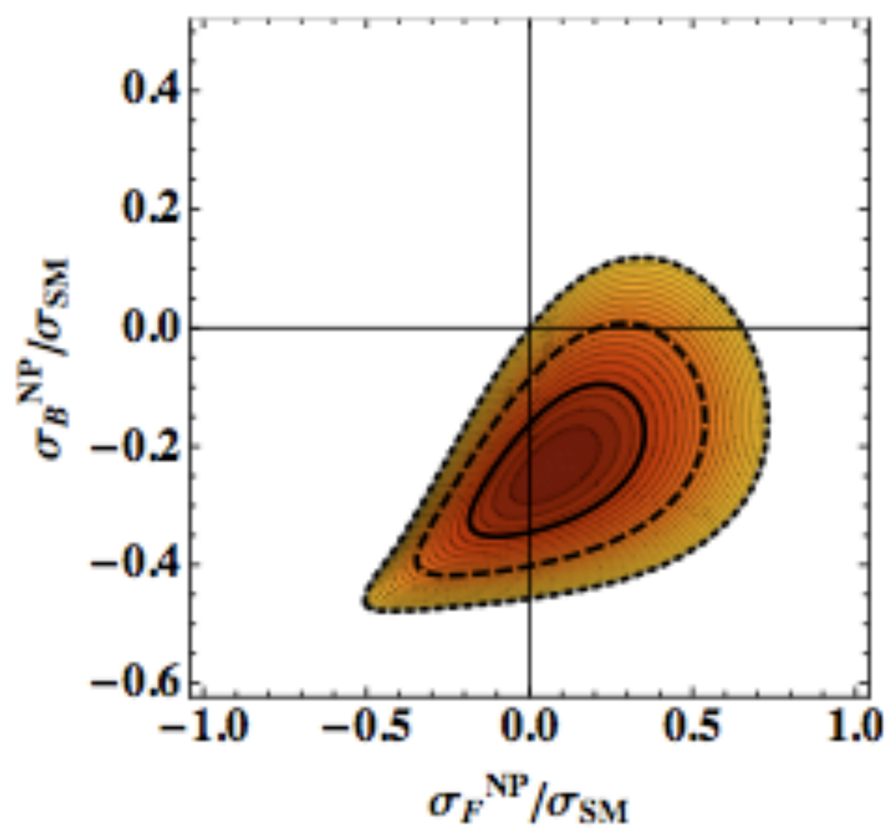


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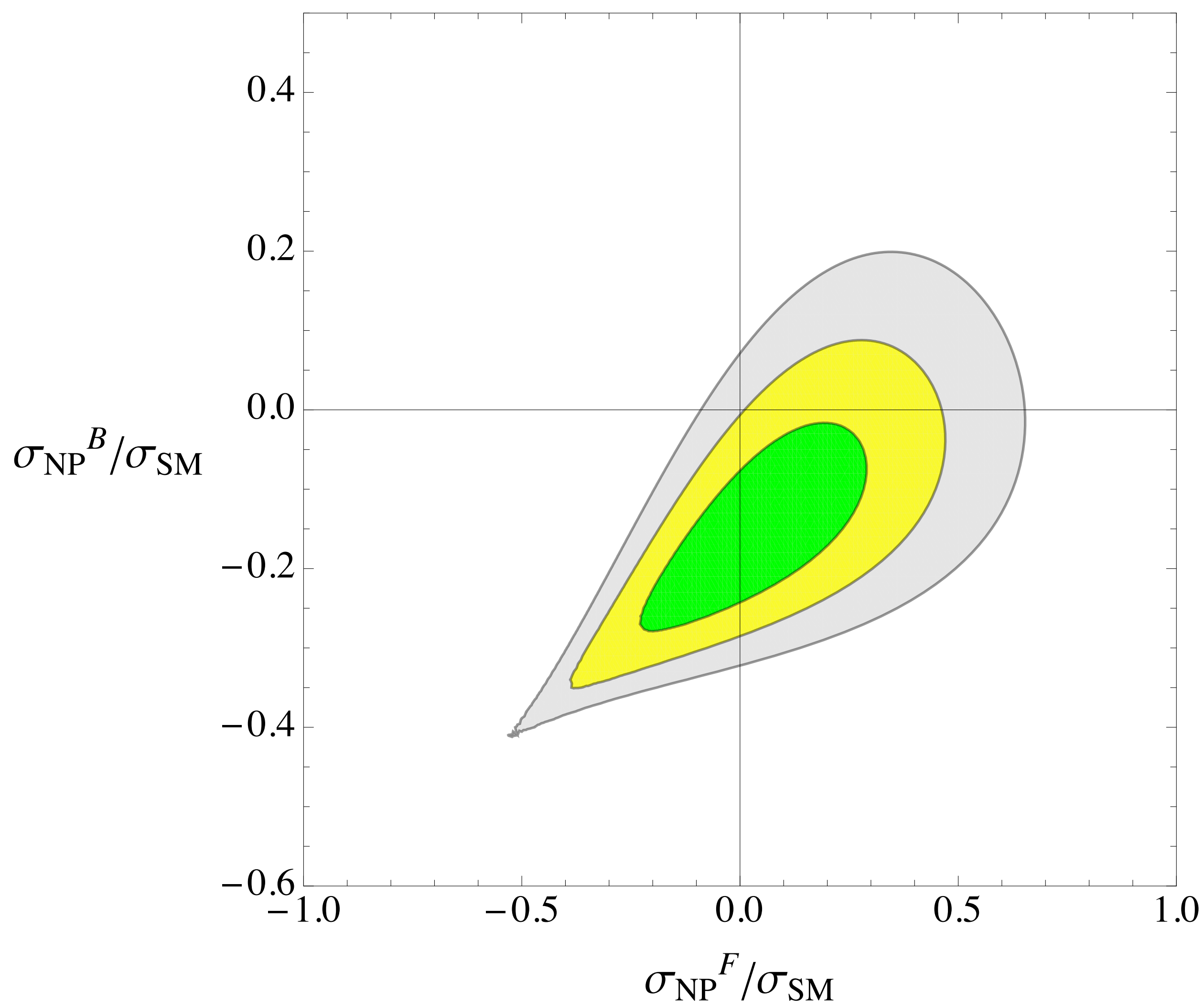
Update on > 450 GeV Preliminary!




Theory update: Kuhn/Rodrigo 1109.6830 LO/LO + EW (high bin):
Pagini Holik 1107.2606 LO/LO + EW (high bin):
Manohar,Trott 1201.3926 LO/LO + EW (high bin):

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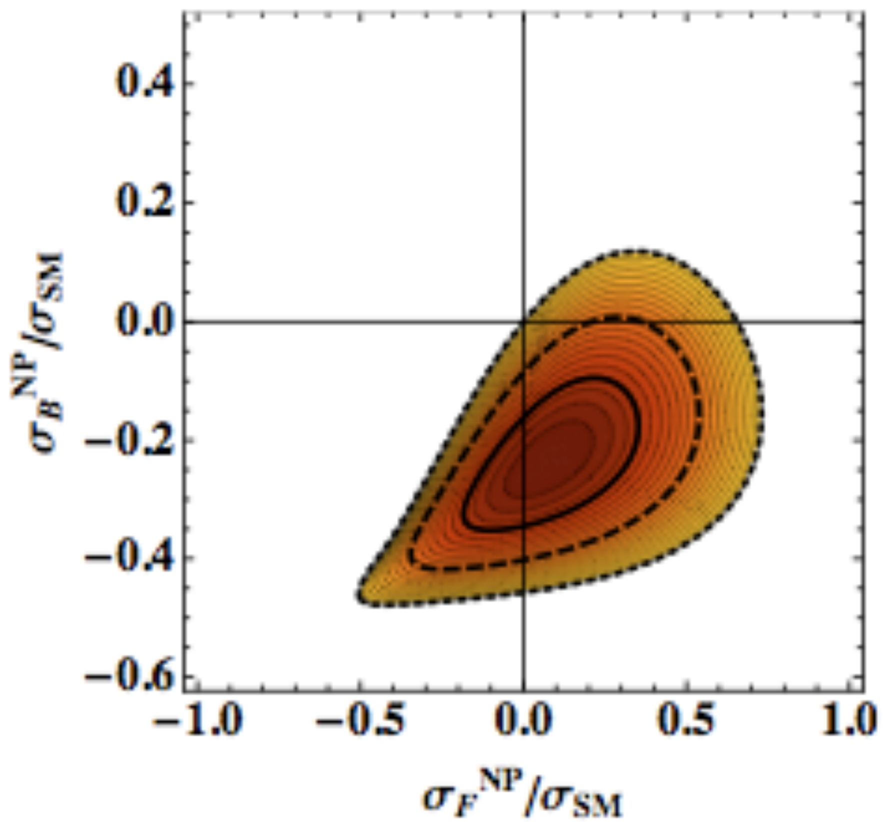


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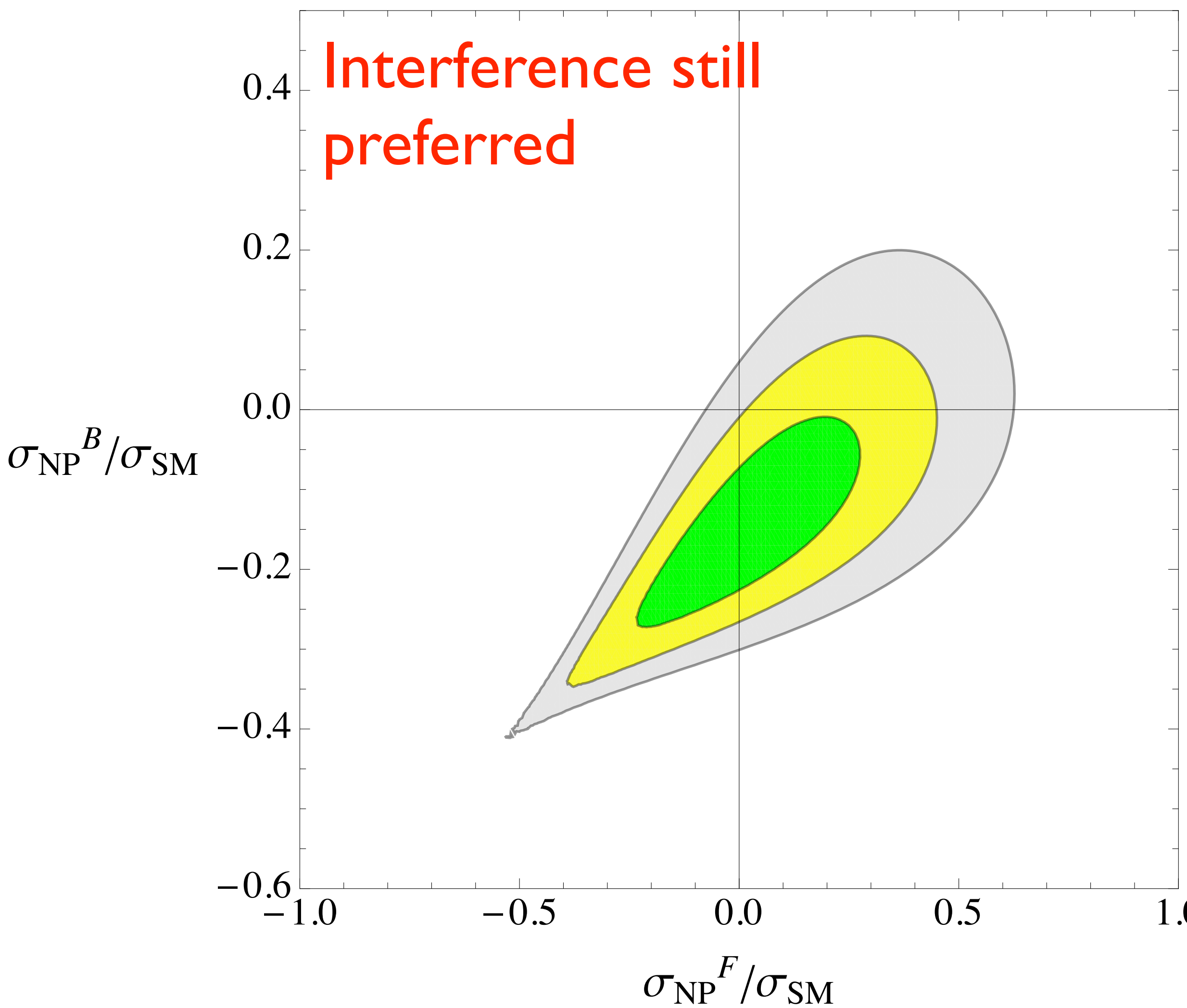


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Grinstein, Kagan, Trott, Zupan

Data update - recent CDF update to 8.7 ifb incorporated.

# s channel: Vector Octets.

S channel interference options limited.
Consider s channel massive gluon - an axigluon. In general can have couplings

$$G'q\bar{q} \; : \; ig_s t^A \gamma^\mu \left(f_L P_L + f_R P_R\right),$$
$$G't\bar{t} \; : \; ig_s t^A \gamma^\mu \left(g_L P_L + g_R P_R\right),$$

Early reference: **Antunano, Kuhn , Rodrigo 0709.1652**

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Contribution to $A_{FB}^{t\,\bar{t}}$

Considered different typical masses - interference $\propto (\hat{s} - m^2)$ at times coupling to light and top quark different

Phenomenological constraints, dijets, $d\sigma_{t\,\bar{t}}/dm_{t\,\bar{t}}\,,\;\sigma_{t\,\bar{t}}$

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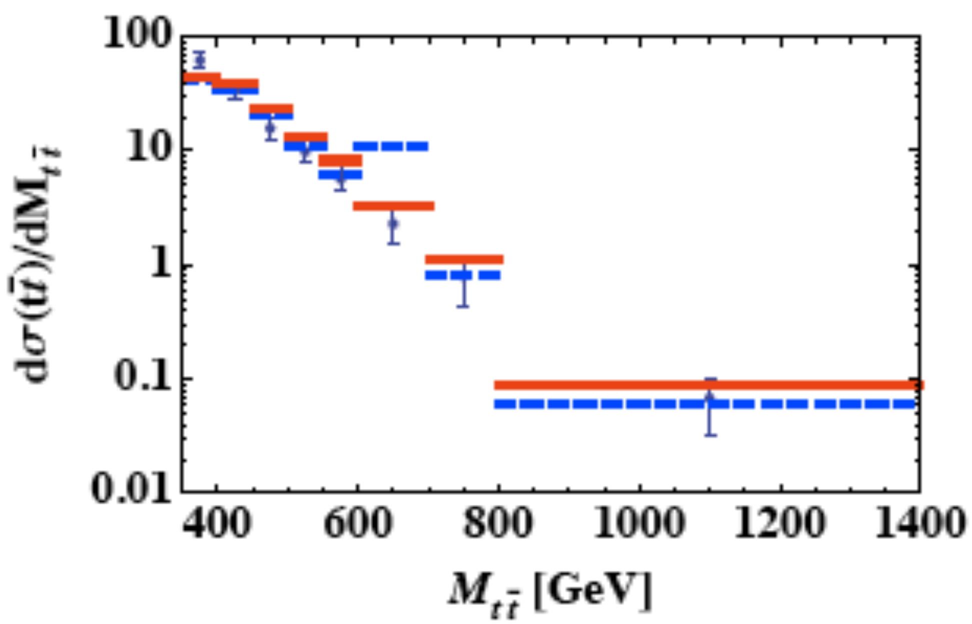
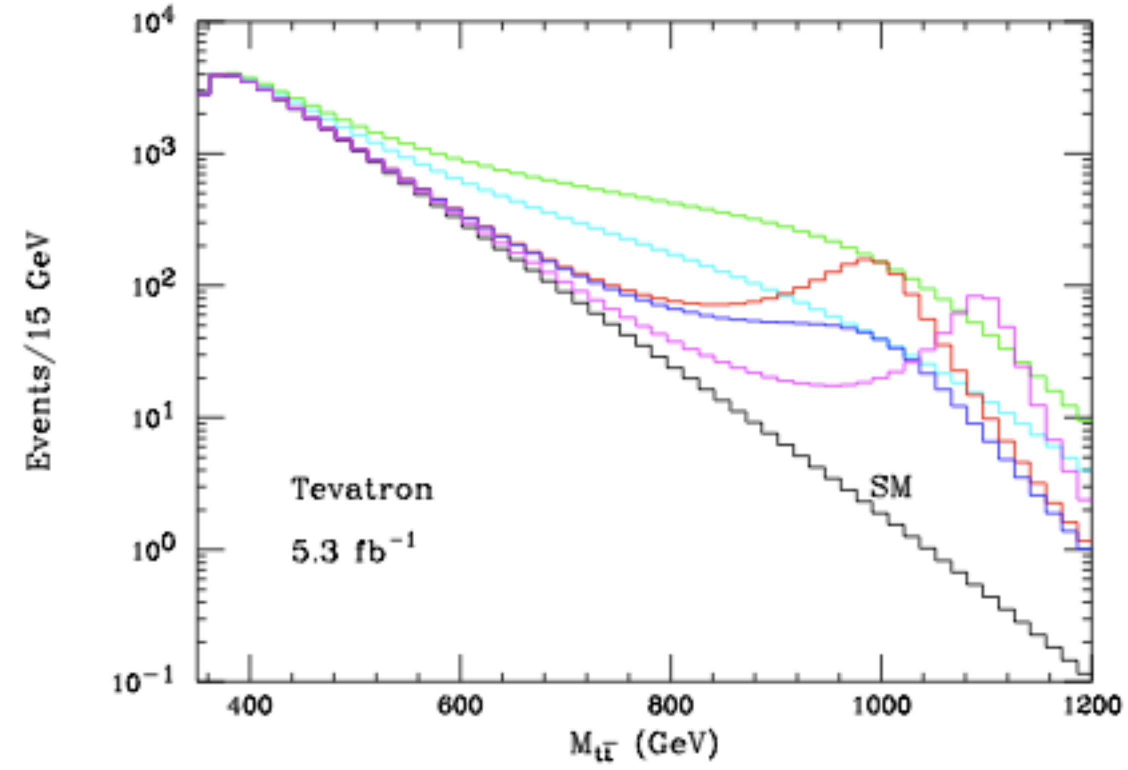
$d\sigma_{t\,\bar{t}}/dm_{t\,\bar{t}}$ constraints for octet vectors:




**arXiv:1101.5203 Bai et al.**
**Typical axi-gluon effect order one coupling mass scale ~ TeV**

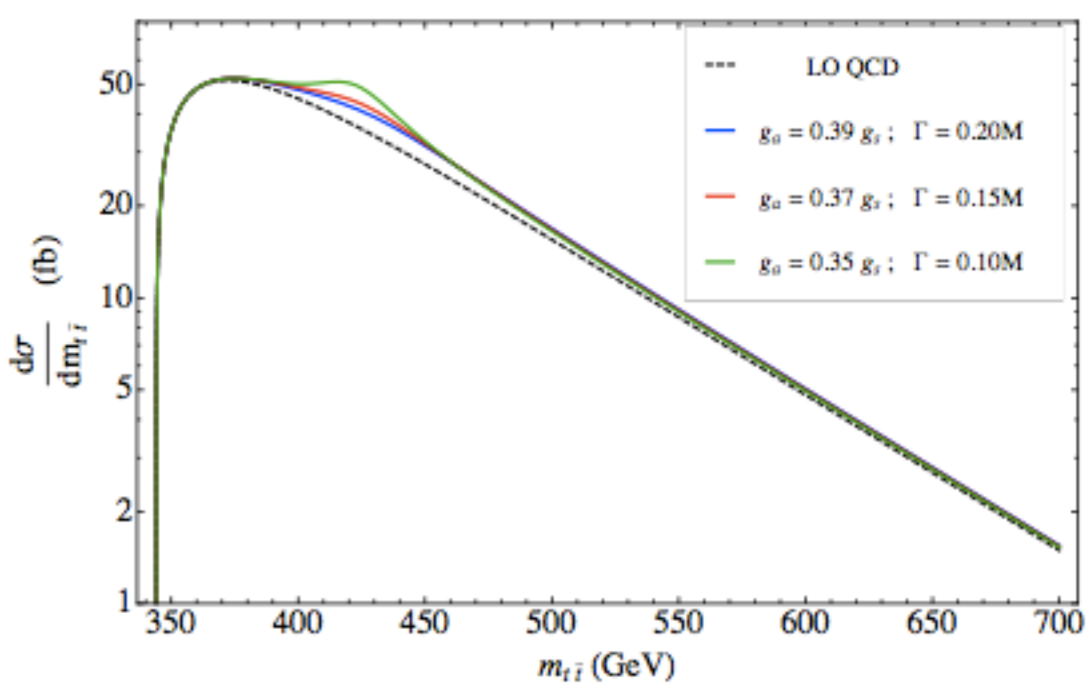



FIG. 3: Plot of the $t\bar{t}$ invariant mass distribution at the Tevatron.

Small couplings and other new states to have larger 'designer' widths (Tavares, Schmaltz 1107.0978) - or so light no bump Krnjaic 1109.0648

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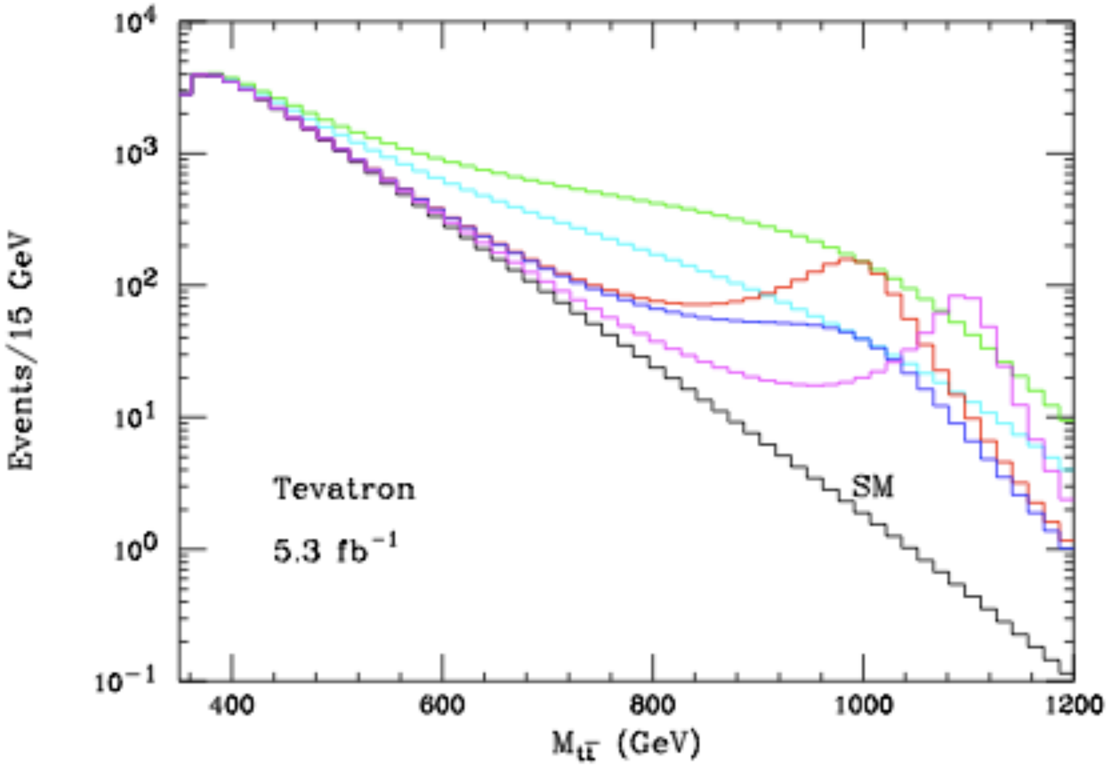


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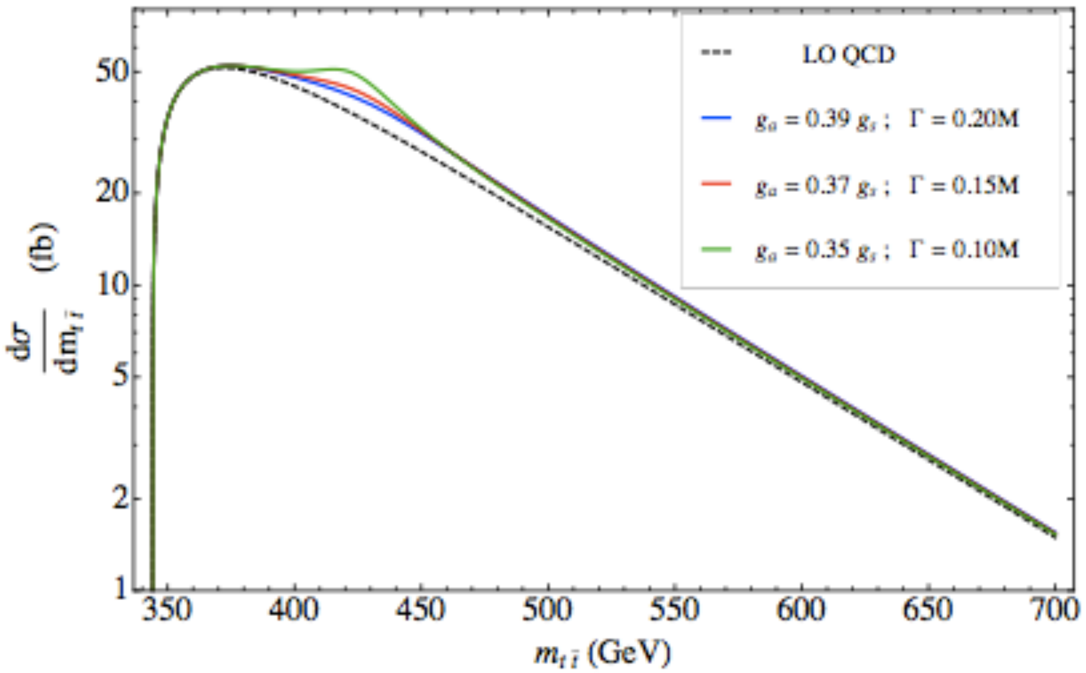


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# t channel


t channel -always do the simplest thing first!

Consider somewhat unusual couplings of vectors in the *mass basis*....

$$\mathcal{L} = g_x \, Z'_\mu \, \bar{u} \gamma^\mu \, P_R \, t + h.c. + \cdots$$

**arXiv:0907.4112 Jung et al.**

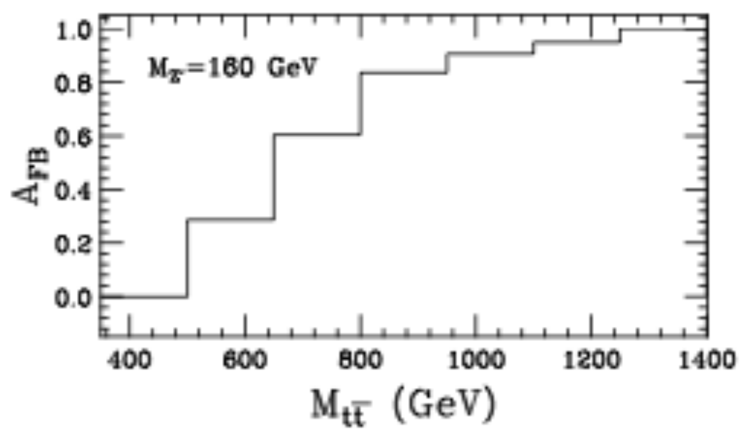


FIG. 1: $A^t_{FB}$ as a function of $\sqrt{\hat{s}} = M_{t\bar{t}}$ for $M_{Z'} = 160$ GeV.

Can lead to the desired effect...
but also leads to strongly constrained like sign tops.

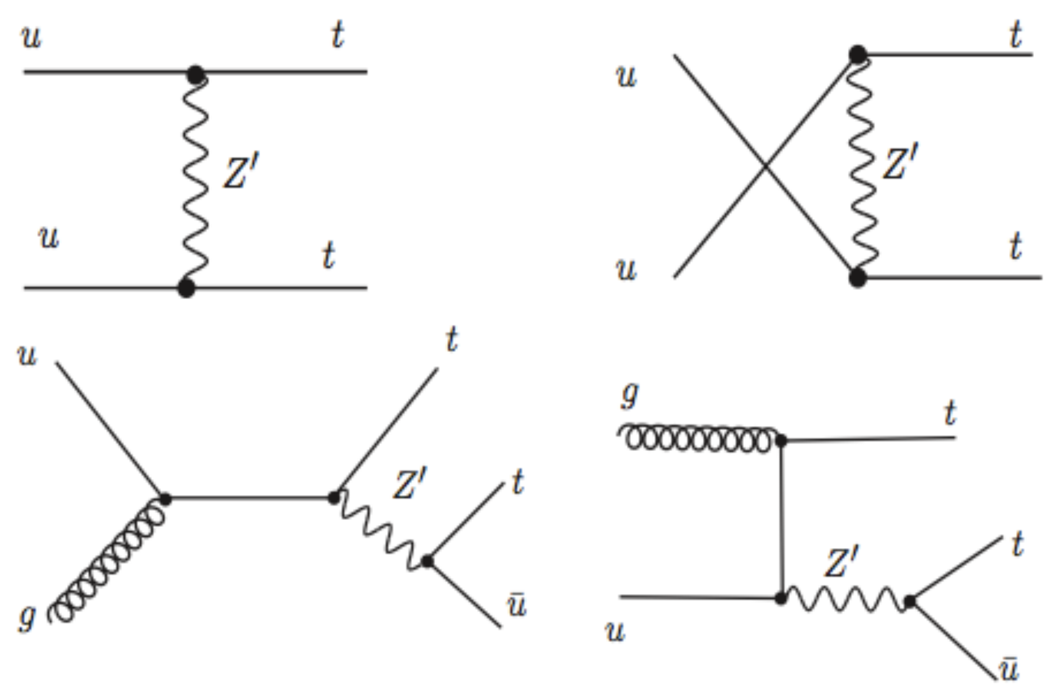


Figure 2: Diagrams for tt and ttj production in the presence of a Z′.

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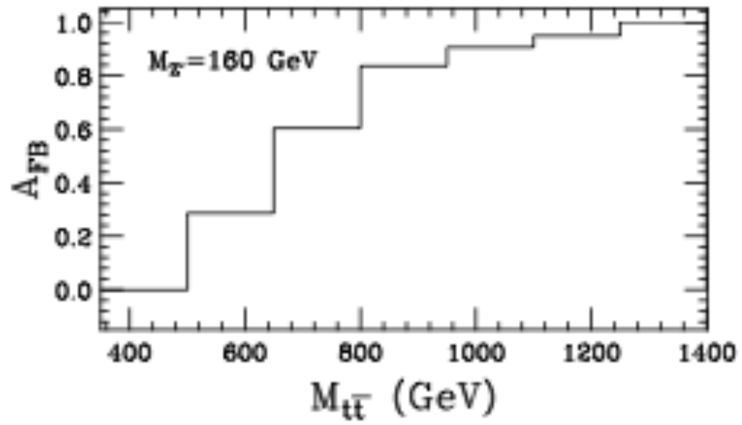


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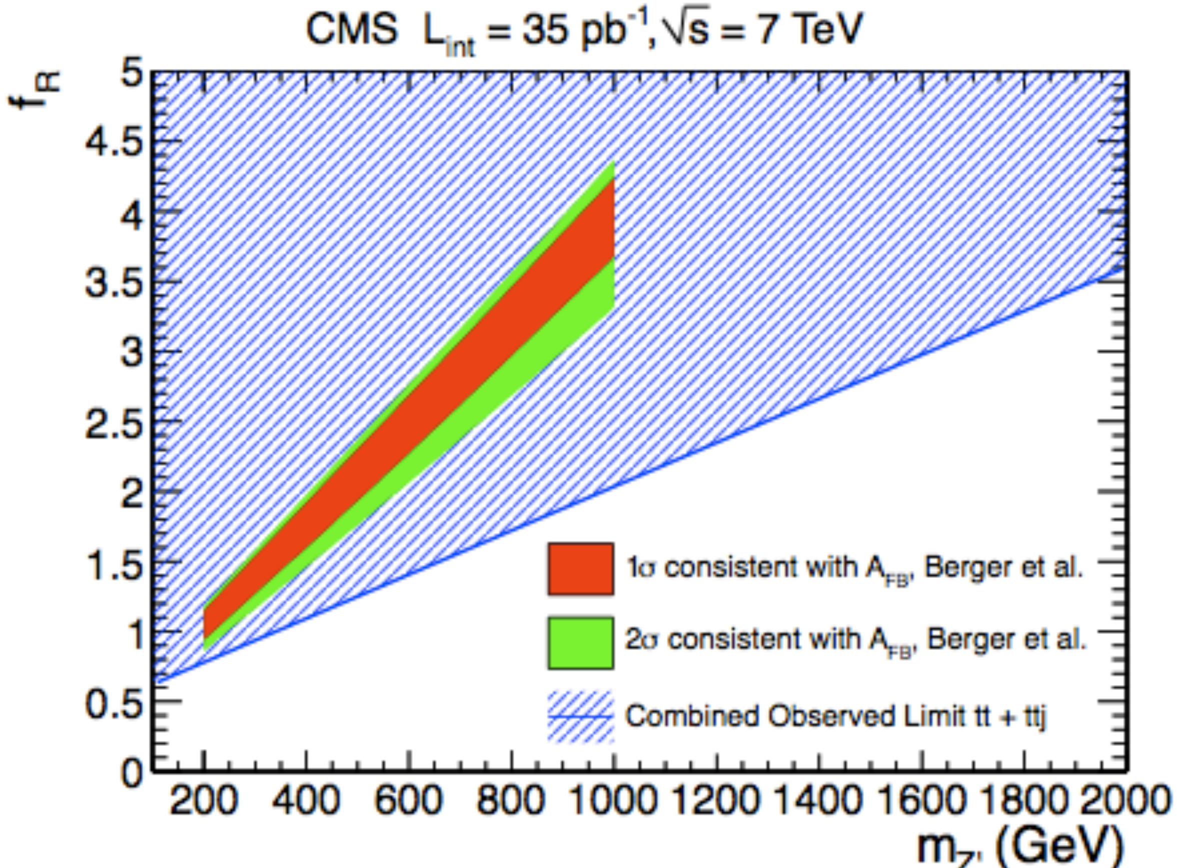


**arXiv:1106.2142 CMS.**

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Why was this so quickly inconsistent with other measurements?

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A new interaction was introduced by hand without proper attention paid to the symmetry implications.

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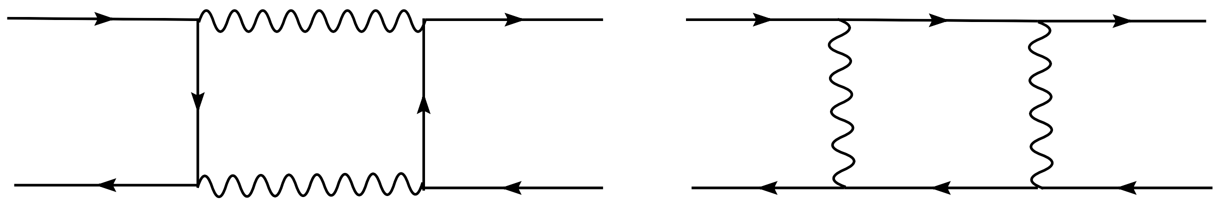
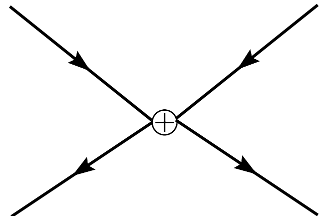
***WHY IS IT SMALL IN THE SM?*** Flavour violation!
No t's in initial state, t's in final state.

The flavour structure of this minimal model is not inspired.
Very different from the SM and easily distinguished.

# t channel: What went wrong here?



vs

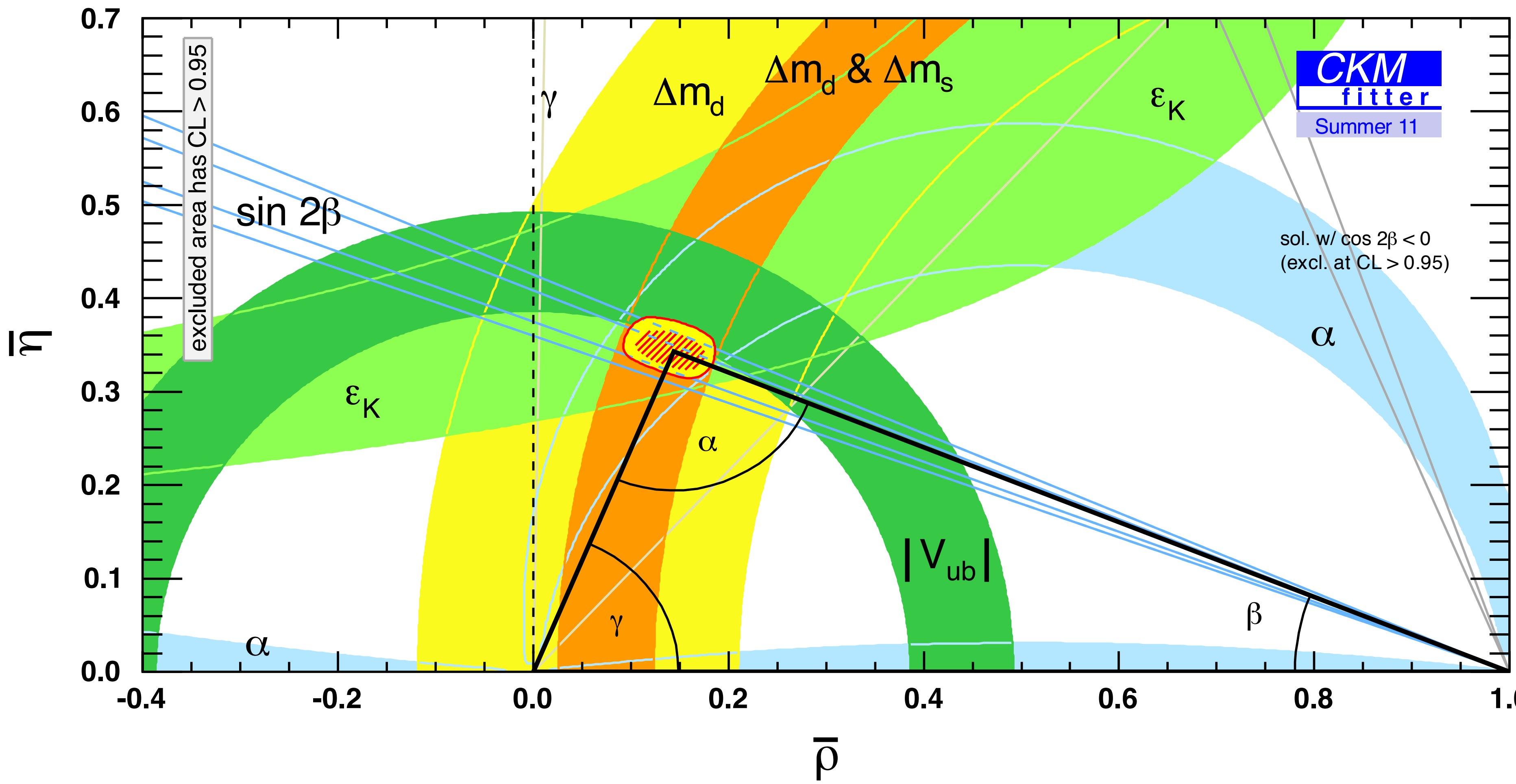


Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^\star\, V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\, d_L^j)^2|M\rangle$$

Integrate out your desired NP states/sector

$$O_{ij} = \frac{c_{ij}}{\Lambda^2}\,(\bar{Q}_L^i\,\gamma^\mu\,Q_L^j)^2$$




No clearly compelling evidence for BSM flavour violation breaking the pattern.

DO NOT MESS WITH THIS SYM BREAKING PATTERN UNLESS YOU HAVE TO!

# What could go right?

The signal we are interested in is: $q\,\bar{q} \to t\,\bar{t}$

Do you have to break flavour symmetry to generate this process with NP in the t-channel?

NO!

This is not a flavour violating process, that makes it (even more) believable as a real excess actually, this lesson also holds for future anomalies....

What field content can couple to quarks and tree level, lead to more events in the process above, and not break the SM flavour group?

# What could go right?

What field content can couple to quarks and tree level, lead to more events in the process above, and not break the SM flavour group?

**Arnold,Pospelov,Trott,Wise 0911.2225**

| Case | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$ | Couples to |
|---|---|---|---|---|---|
| $I_{s,o}$ | 1,8 | 1 | 0 | (1,1,1) | $\bar{d}_R \gamma^\mu d_R$ |
| $II_{s,o}$ | 1,8 | 1 | 0 | (1,1,1) | $\bar{u}_R \gamma^\mu u_R$ |
| $III_{s,o}$ | 1,8 | 1 | 0 | (1,1,1) | $\bar{Q}_L \gamma^\mu Q_L$ |
| $IV_{s,o}$ | 1,8 | 3 | 0 | (1,1,1) | $\bar{Q}_L \gamma^\mu Q_L$ |
| $V_{s,o}$ | 1,8 | 1 | 0 | (1,8,1) | $\bar{d}_R \gamma^\mu d_R$ |
| $VI_{s,o}$ | 1,8 | 1 | 0 | (8,1,1) | $\bar{u}_R \gamma^\mu u_R$ |
| $VII_{s,o}$ | 1,8 | 1 | -1 | $(\bar{3},3,1)$ | $\bar{d}_R \gamma^\mu u_R$ |
| $VIII_{s,o}$ | 1,8 | 1 | 0 | (1,1,8) | $\bar{Q}_L \gamma^\mu Q_L$ |
| $IX_{s,o}$ | 1,8 | 3 | 0 | (1,1,8) | $\bar{Q}_L \gamma^\mu Q_L$ |
| $X_{\bar{3},6}$ | $\bar{3}$,6 | 2 | -1/6 | (1,3,3) | $\bar{d}_R \gamma^\mu Q^c_L$ |
| $XI_{\bar{3},6}$ | $\bar{3}$,6 | 2 | 5/6 | (3,1,3) | $\bar{u}_R \gamma^\mu Q^c_L$ |

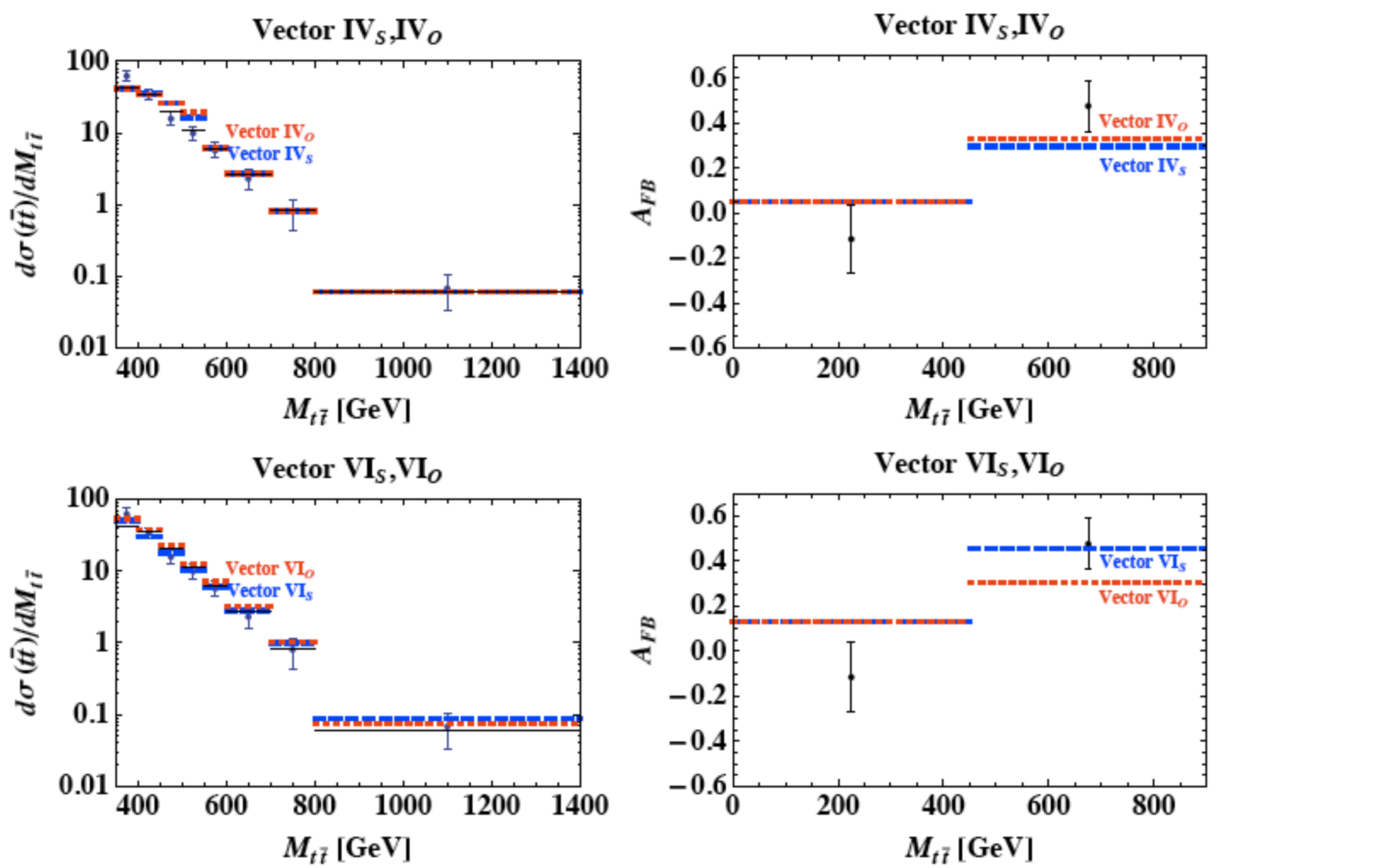
**Grinstein,Kagan,Trott,Zupan 1108.4027,1102.3374**

| Case | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$ | Couples to |
|---|---|---|---|---|---|
| $S_I$ | 1 | 2 | 1/2 | $(3,1,\bar{3})$ | $\bar{u}_R\ Q_L$ |
| $S_{II}$ | 8 | 2 | 1/2 | $(3,1,\bar{3})$ | $\bar{u}_R\ Q_L$ |
| $S_{III}$ | 1 | 2 | -1/2 | $(1,3,\bar{3})$ | $\bar{d}_R\ Q_L$ |
| $S_{IV}$ | 8 | 2 | -1/2 | $(1,3,\bar{3})$ | $\bar{d}_R\ Q_L$ |
| $S_V$ | 3 | 1 | -4/3 | (3,1,1) | $u_R\ u_R$ |
| $S_{VI}$ | $\bar{6}$ | 1 | -4/3 | $(\bar{6},1,1)$ | $u_R\ u_R$ |
| $S_{VII}$ | 3 | 1 | 2/3 | (1,3,1) | $d_R\ d_R$ |
| $S_{VIII}$ | $\bar{6}$ | 1 | 2/3 | $(1,\bar{6},1)$ | $d_R\ d_R$ |
| $S_{IX}$ | 3 | 1 | -1/3 | $(\bar{3},\bar{3},1)$ | $d_R\ u_R$ |
| $S_X$ | $\bar{6}$ | 1 | -1/3 | $(\bar{3},\bar{3},1)$ | $d_R\ u_R$ |
| $S_{XI}$ | 3 | 1 | -1/3 | $(1,1,\bar{6})$ | $Q_L\ Q_L$ |
| $S_{XII}$ | $\bar{6}$ | 1 | -1/3 | (1,1,3) | $Q_L\ Q_L$ |
| $S_{XIII}$ | 3 | 3 | -1/3 | (1,1,3) | $Q_L\ Q_L$ |
| $S_{XIV}$ | $\bar{6}$ | 3 | -1/3 | $(1,1,\bar{6})$ | $Q_L\ Q_L$ |
| $S_{H,8}$ | 1, 8 | 2 | 1/2 | (1,1,1) | $\bar{Q}_L u_R,\ \bar{Q}_L d_R$ |

Introducing a larger (quite large actually) number of degrees of freedom in the right structure can help.

Perhaps we need a well organized team...

# Lots of fields work with this symmetry structure



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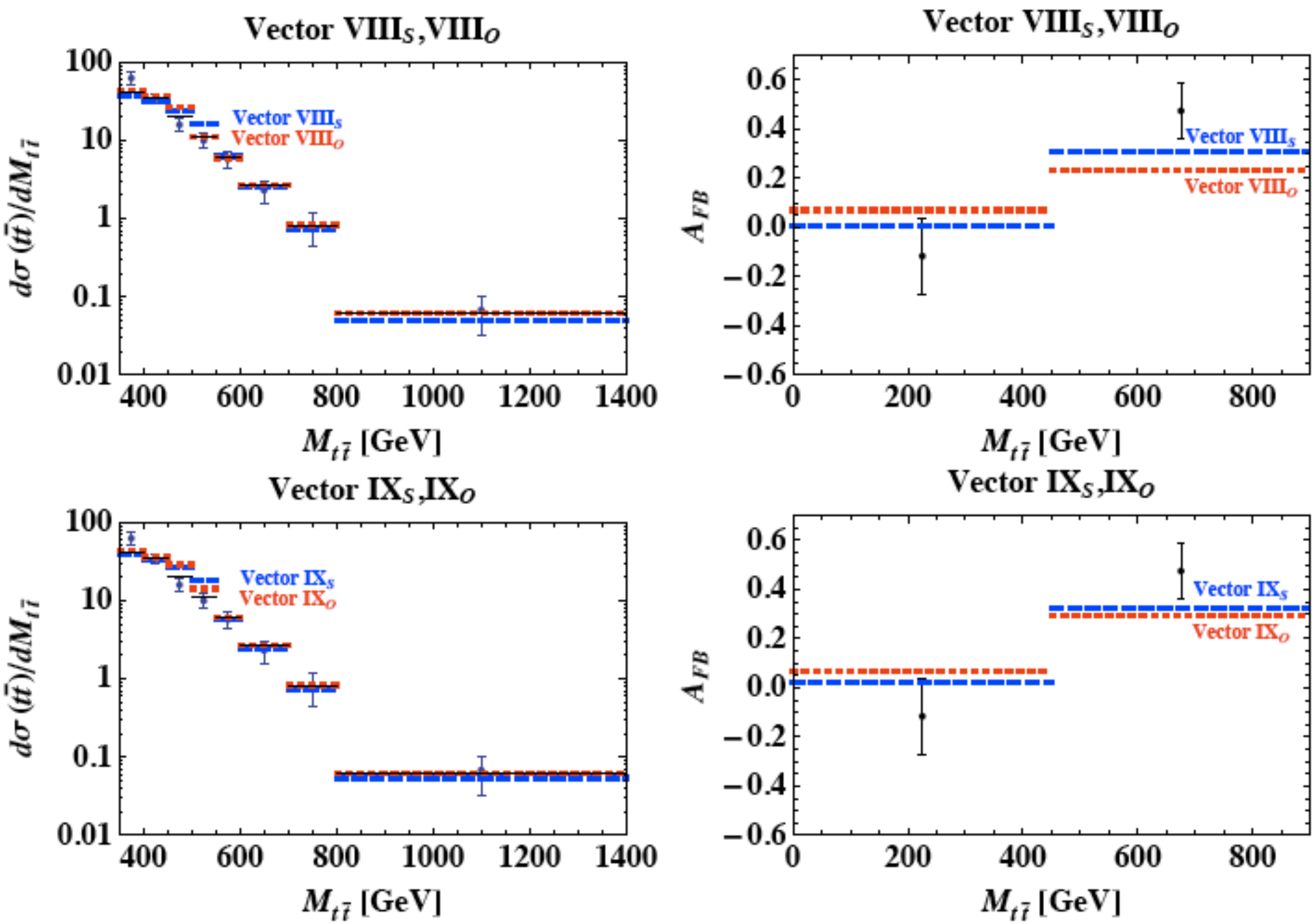


FIG. 9: Predictions for $d\sigma/dM_{t\bar{t}}$ and $A_{FB}$ for a set of vector models, $\mathrm{IV_{s,o}}, \mathrm{VI_{s,o}}, \mathrm{VIII_{s,o}}, IX_{s,o}$ fixing $m_V$ =500 GeV (except for $\mathrm{VI_{s,o}}$ where $m_V$ =350 GeV, and using flavor breaking choices for couplings to quarks; $(\sqrt{f_q f_t}, f_{qt}) = (0.1, 0.3)\mathrm{IV_s}$; $(0.1, 0.3)\mathrm{IV_o}$; $(0.55, 1.3)\mathrm{VI_s}$; $(0.55, 1.3)\mathrm{VI_o}$ and $(\eta_1, \eta_2) = (1.4, -0.4)\mathrm{VIII_s}$; $(1.3, -0.5)\mathrm{VIII_o}$; $(1.1, -0.4)\mathrm{IX_s}$; $(1.1, -0.4)\mathrm{IX_o}$.

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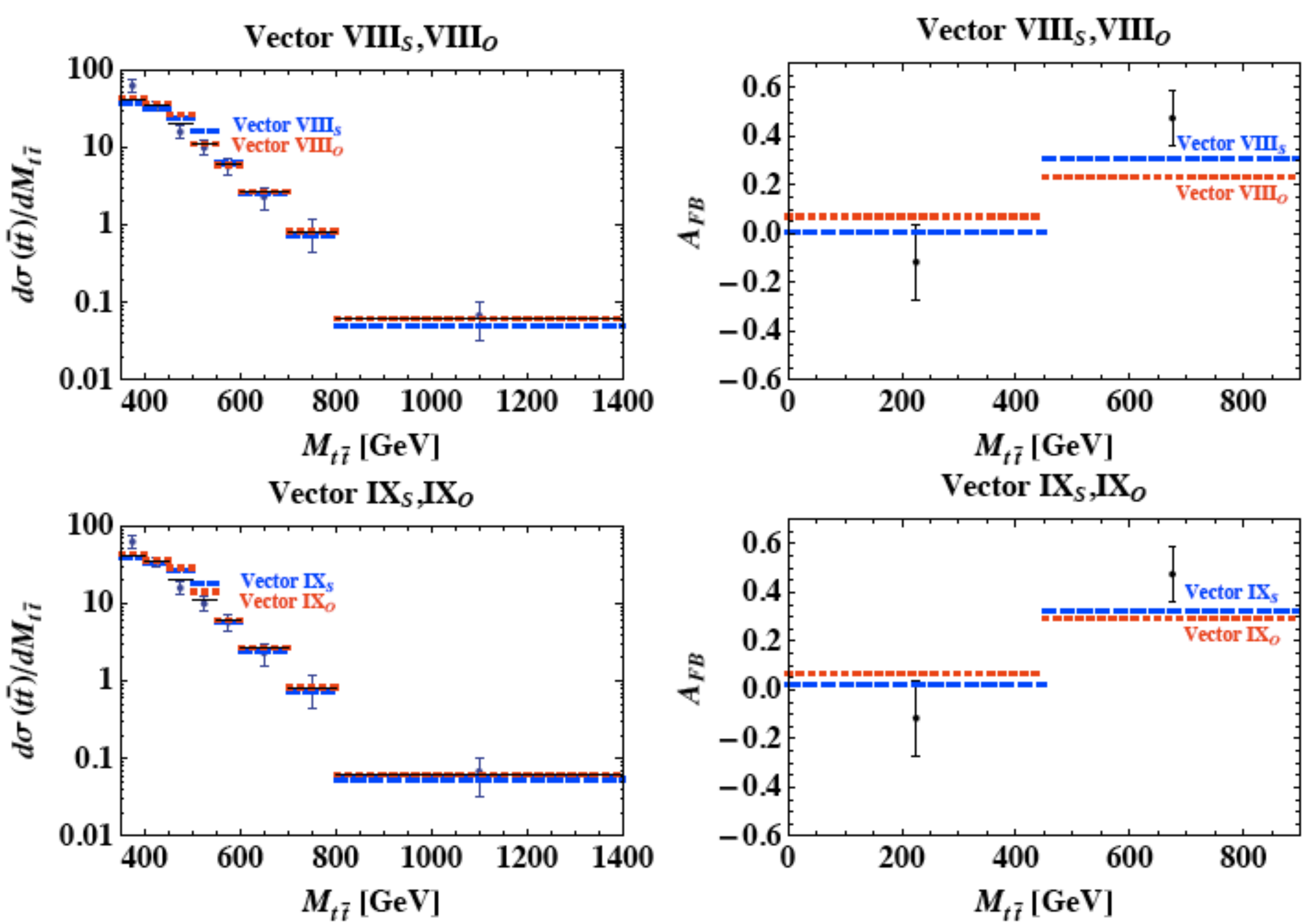


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Typical couplings O(1)

# More LHC constraints

Constraints on the tree level couplings to quark bilinear growing stronger....
But AFB required couplings can still be accommodated with minor flavour splitting that can be introduced in a controlled fashion

| $S_V^3$ Mass | TeV $M_{jj}$ | LHC $M_{jj}$ | TeV $\chi$ | LHC $\chi$ | $S_{VI}$ Mass | TeV $M_{jj}$ | LHC $M_{jj}$ | TeV $\chi$ | LHC $\chi$ |
|---|---|---|---|---|---|---|---|---|---|
| 300 | 1.0 | - | 1.2 | 1.1 | 300 | 0.3 | - | 0.4 | 0.5 |
| 500 | 1.2 | n.b. | 0.5 | 0.9 | 500 | 0.3 | 2.2 | 0.2 | 0.5 |
| 700 | 2.0 | 0.7 | 0.7 | 0.6 | 700 | 0.6 | 0.2 | 0.2 | 0.2 |
| 900 | 2.5 | 0.3 | 0.6 | 0.5 | 900 | 0.7 | 0.1 | 0.2 | 0.2 |
| 1100 | 2.8 | 0.4 | 0.5 | 0.6 | 1100 | 1.4 | 0.1 | 0.2 | 0.1 |
| 1300 | 4.0 | 0.5 | 1.3 | 0.6 | 1300 | 1.6 | 0.1 | 0.7 | 0.1 |
| 1500 | 6.0 | 0.6 | 1.6 | 0.3 | 1500 | 1.8 | 0.1 | 0.8 | 0.1 |
| 1700 | n.b. | 0.6 | 1.8 | 0.5 | 1700 | 2.0 | 0.1 | 0.8 | 0.1 |
| 1900 | n.b. | 0.6 | 2.0 | 0.4 | 1900 | 2.6 | 0.1 | 0.9 | 0.1 |
| 2100 | n.b. | 0.7 | 2.1 | 0.6 | 2100 | 3.0 | 0.1 | 1.0 | 0.1 |

TABLE V: Approximate upper bounds on the couplings of the scalars $S_V$, $S_{VI}$ to light quarks due to the measured dijet invariant mass spectra (labeled $M_{jj}$) and angular distributions (labeled $\chi$) at the tevatron and LHC, as explained in the text. The masses correspond to the scalar field flavors $S_V^3$ and $S_{VI}^{11=22=12}$. If no bound is determined we denote this with "n.b.".

**Grinstein,Kagan,Trott,Zupan** 1108.4027,1102.3374

# More LHC constraints

Some typical vector constraints from dijets.

| | $\mathrm{II_o}$ | | | | $\mathrm{VI_o}$ | | | | $\mathrm{VI_s}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mass | TeV $M_{jj}$ | LHC $M_{jj}$ | TeV $\chi$ | LHC $\chi$ | TeV $M_{jj}$ | LHC $M_{jj}$ | TeV $\chi$ | LHC $\chi$ | TeV $M_{jj}$ | LHC $M_{jj}$ | TeV $\chi$ | LHC $\chi$ |
| 300 | 0.4 | - | 0.9 | 1.7 | 0.6 | - | 1.4 | 2.2 | 0.6 | - | 1.7 | 1.4 |
| 500 | 0.4 | 0.8 | 0.3 | 1.3 | 0.4 | 0.9 | 0.4 | 1.5 | 0.5 | 1.0 | 0.5 | 1.4 |
| 700 | 0.4 | 0.8 | 0.3 | 0.9 | 0.4 | 1.0 | 0.5 | 1.0 | 0.5 | 1.1 | 0.6 | 1.2 |
| 900 | 0.3 | 0.3 | 0.2 | 0.7 | 0.5 | 0.3 | 0.3 | 0.9 | 0.6 | 0.3 | 0.4 | 1.0 |
| 1100 | 0.4 | 0.3 | 0.4 | 0.8 | 1.1 | 0.4 | 0.6 | 1.0 | 1.3 | 0.5 | 0.8 | 1.2 |
| 1300 | 0.7 | 0.5 | 1.1 | 0.9 | 1.0 | 0.6 | 1.6 | 1.2 | 1.2 | 0.6 | 1.6 | 1.2 |
| 1500 | 2.7 | 0.5 | 2.6 | 0.9 | 4.8 | 0.6 | 4.3 | 1.1 | 3.4 | 0.7 | 3.1 | 1.2 |
| 1700 | 4.0 | 0.5 | 3.5 | 1.2 | 6.4 | 0.7 | 5.7 | 1.6 | 4.8 | 0.7 | 4.1 | 1.6 |
| 1900 | 5.3 | 0.7 | 4.4 | 1.0 | 7.7 | 0.9 | 6.5 | 1.3 | 6.1 | 0.8 | 4.8 | 1.4 |
| 2100 | 6.5 | 0.8 | 5.2 | 1.4 | 8.8 | 1.0 | 7.2 | 1.8 | 7.8 | 0.8 | 5.6 | 1.8 |

TABLE VI: Approximate upper bounds on the couplings $f_q$ of the vectors $\mathrm{II_o}$, $\mathrm{VI_o}$ and $VI_s$ to light quarks, due to the measured dijet invariant mass spectra (labeled $M_{jj}$) and angular distributions (labeled $\chi$) at the Tevatron and LHC, as explained in the text.

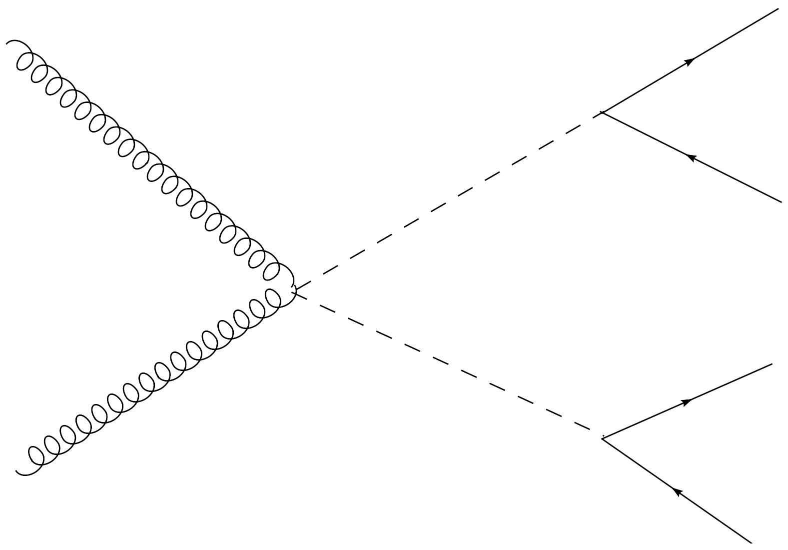
**Grinstein,Kagan,Trott,Zupan 1108.4027,1102.3374**

# More constraints for Viable On Shell Explanations

Four Jet Production with 2 mother resonances of the same ~ mass
- you only need a kinetic term!

**Grinstein,Kagan,Trott,Zupan** 1108.4027

**Arnold, Fornal** 1112.0003



Problem with the dijet constraints is unknown normalization parameters.

Constraints based on gauge couplings lead to direct mass bounds.

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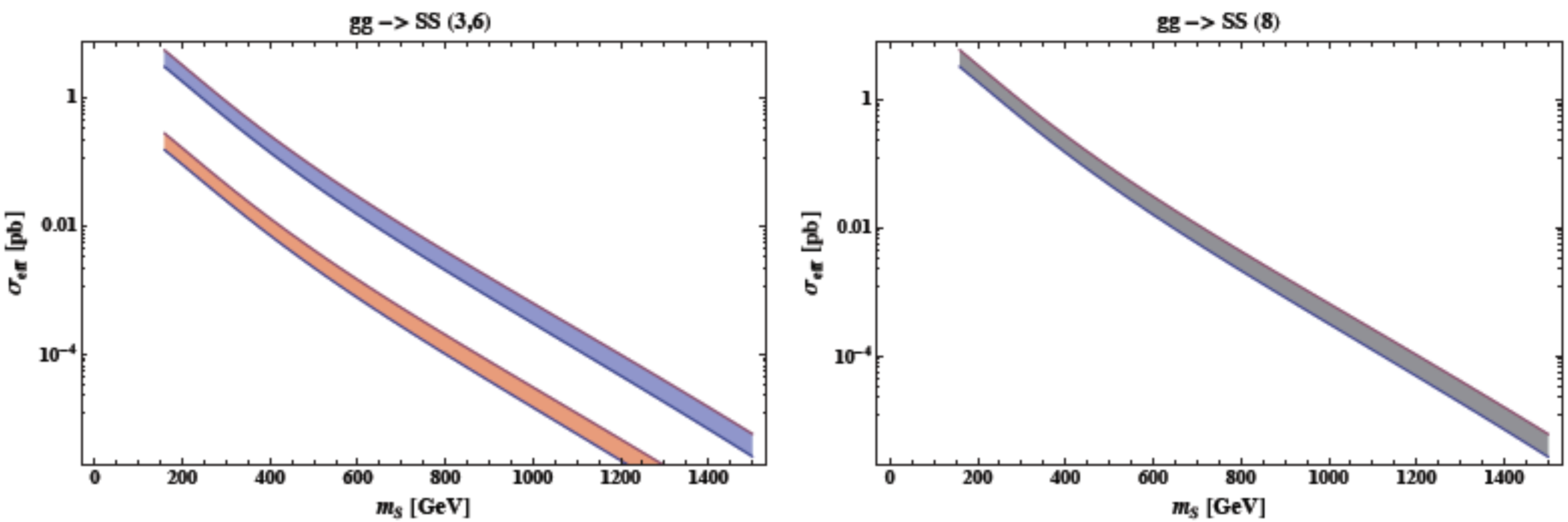


FIG. 13: Production cross sections of $g\,g \to S\,S$ for color triplets (red left), sextets (blue left) and octet (grey right) scalar field S. We show $\sigma_{eff} = \sigma/\dim[F]$ for a single flavor. We use MSTW208 pdfs and the PDF error bands shown are defined by taking $\mu = [2(2m_S), (2m_S)/2]$. Details of the calculation are in the Appendix.

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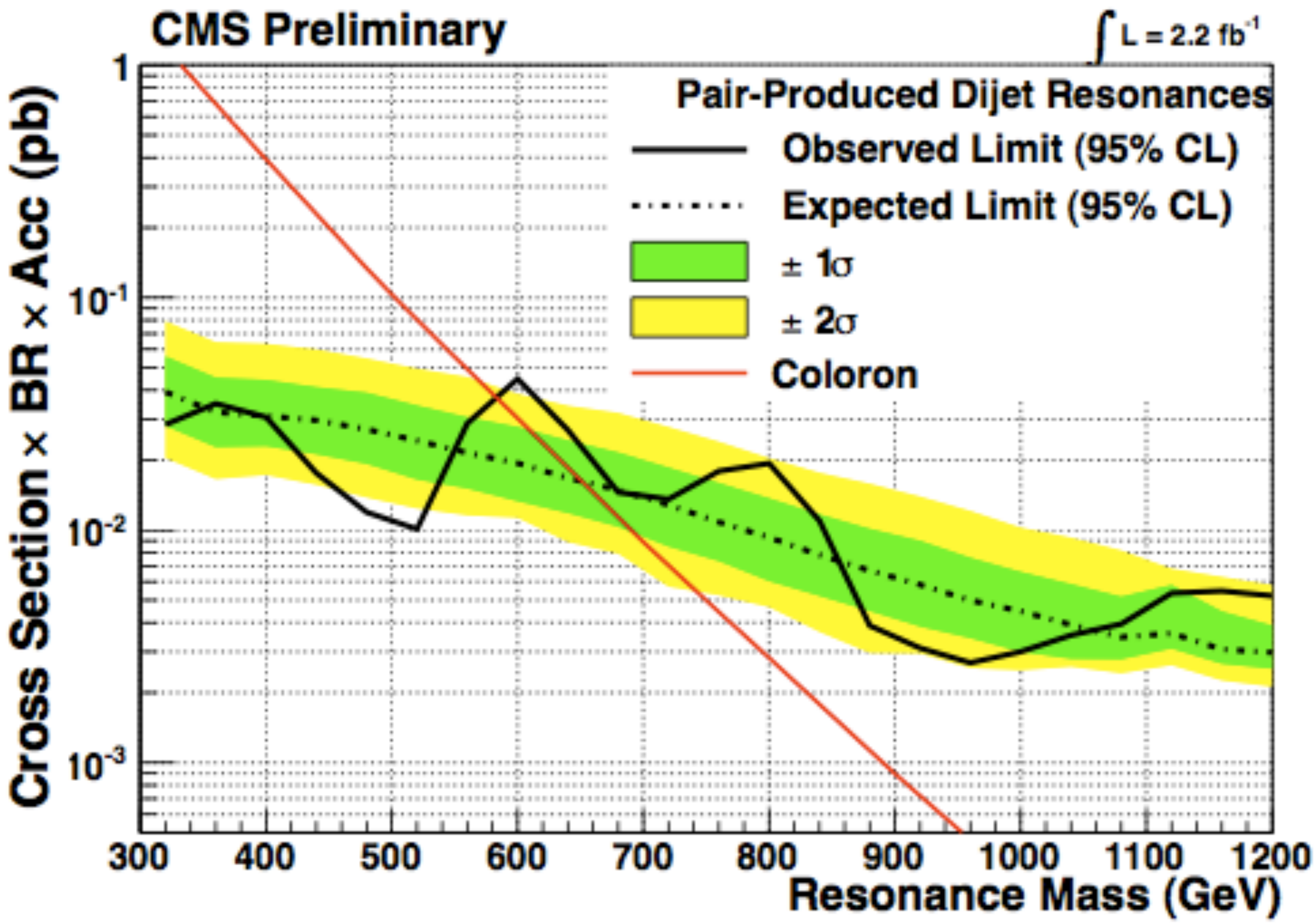


Figure 6: The observed limit on the cross section times branching fraction times acceptance for pair production of dijet resonances (solid black curve), and the expected limit (dot dashed curve) and its $1\sigma$ and $2\sigma$ variations (shaded), are compared with the theoretical predictions for the coloron model (red curve). We exclude at 95% C.L. pair production of colorons with mass $M(C)$ in the range $320 < M(C) < 580\,\mathrm{GeV}/c^2$.

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**Arnold, Fornal 1112.0003**

Dedicated study needed to translate bounds, colour singlets preferred.

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Precision Electroweak constraints:

Z decay width: **Grinstein,Kagan,Trott,Zupan 1108.4027**

Parity violation: **Gresham, Kim, Tulin, Zurek arXiv:1203.1320**

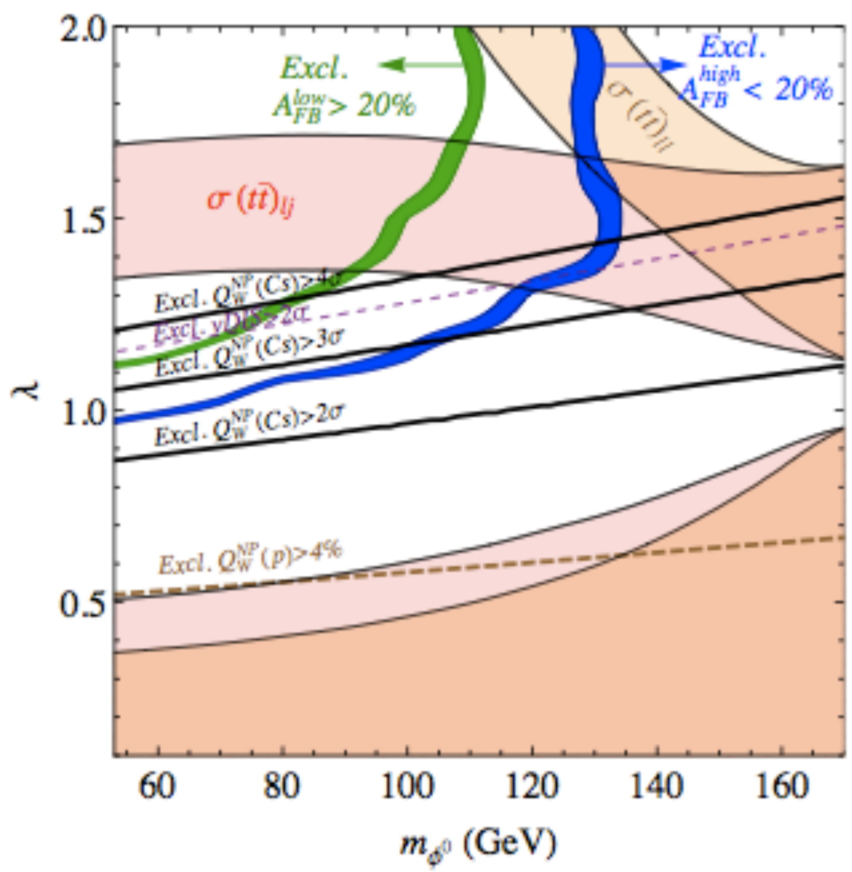


FIG. 2: *Exclusion plot for weak doublet ($\phi$) model. Pink and tan shaded regions are consistent with $\sigma(t\bar{t})_{\ell j}$ and $\sigma(t\bar{t})_{\ell\ell}$, respectively. Mass-dependent-$A_{FB}$-favored region is within the blue and green curves, marking $A_{FB}^{\rm high} > 20\%$ and $A_{FB}^{\rm low} < 20\%$, respectively. Constraints from $Q_W$(Cs), νDIS, and future $Q_W(p)$ measurements shown by black solid, purple dashed, and brown dashed lines, respectively.*

Issue here is that you have the top mass in non-SM loops, this makes it non negligible:

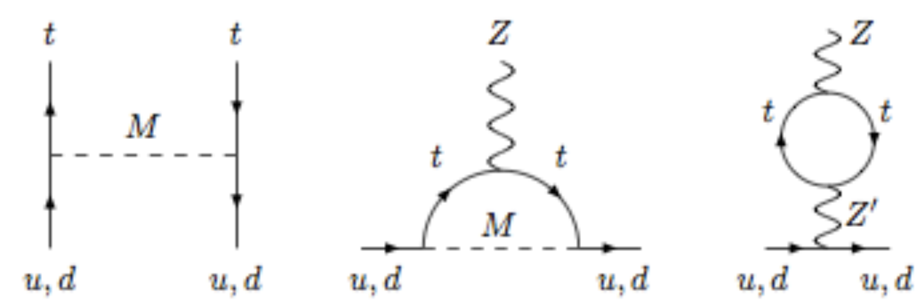


FIG. 1: *$A_{FB}$ from t-channel exchange of $M$ (left). Anomalous coupling of $Z$ to $u, d$ at one-loop is generated by $M$ (center) and by flavor-conserving $Z'$ associated with certain vector $M$ models.*

Clearly constraining for scalar models, vector models that are non-renormalizable constraints depend on UV.

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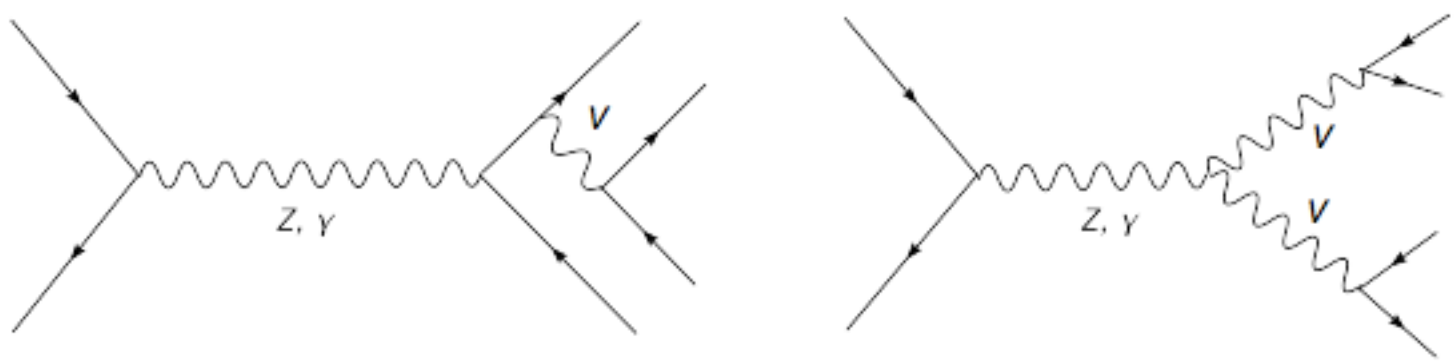
Tree Level production of multijet final states at LEP **Grinstein,Kagan,Trott,Zupan** 1108.4027




Flavour symmetric process leads to $M_v \gtrsim 150\,\mathrm{GeV}$ for O(1) couplings from LEP

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Resonances associated with Top: $t + 2j, t\,\bar{t} + j$ **Gresham, Kim, Zurek arXiv:1102.0018**

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Resonance structure depending on coupling hierarchy

Charge asymmetry at LHC, today $t\,\bar{t}$ spin correlations emphasized in

**Fajfer, Kamenik, Blazenka arXiv:1205.0264**

# Conclusions

Some low scale on shell approaches are clearly already strongly disfavoured - when they give like sign tops for example.

Other models with more involved flavour structures are holding on with relative levels of discomfort.

Taking into account all current constraints (!) what is the on shell model that clearly robustly works, compellingly explains $A_{FB}^{t\bar{t}} > (A_{FB}^{t\bar{t}})_{SM}$ and is consistent with all constraints?