FLAVOR SYMMETRIES & PROCESSES WITH TOPS

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U. OF CINCINNATI

based on work with Grinstein, Kagan, Trott, (1102.3374, 1108.4027)

and with Kamenik (1107.0623)

MOTIVATION

- many motivations for LHC
  - the origin of EWSB
- can we also learn more about the origin of flavor?
- processes with tops a natural place to look
- will focus on two topics
  - forward-backward asymmetry in $t\bar{t}$:
    3.4σ away from SM
  - production of DM in association with top

WORKING ASSUMPTIONS

- assume new physics at LHC (i.e. at TeV)
- assume no large flavor breaking
  - so that FCNC constraints are obeyed without tuning
  - assume that there is an approximate global flavor $U(2)_Q \times U(2)_D \times U(2)_U$ group
    - as in the SM

$$\mathcal{L}_Y = Y_U \, \bar{u}_R \, H^T \, i\sigma_2 \, Q_L - Y_D \, \bar{d}_R \, H^\dagger \, Q_L + \text{h.c.}$$

OUTLINE

- $t\bar{t}$ forward-backward asymmetry
- monotops (=t+MET)

FORWARD-BACKWARD ASYMMETRY IN T-TBAR

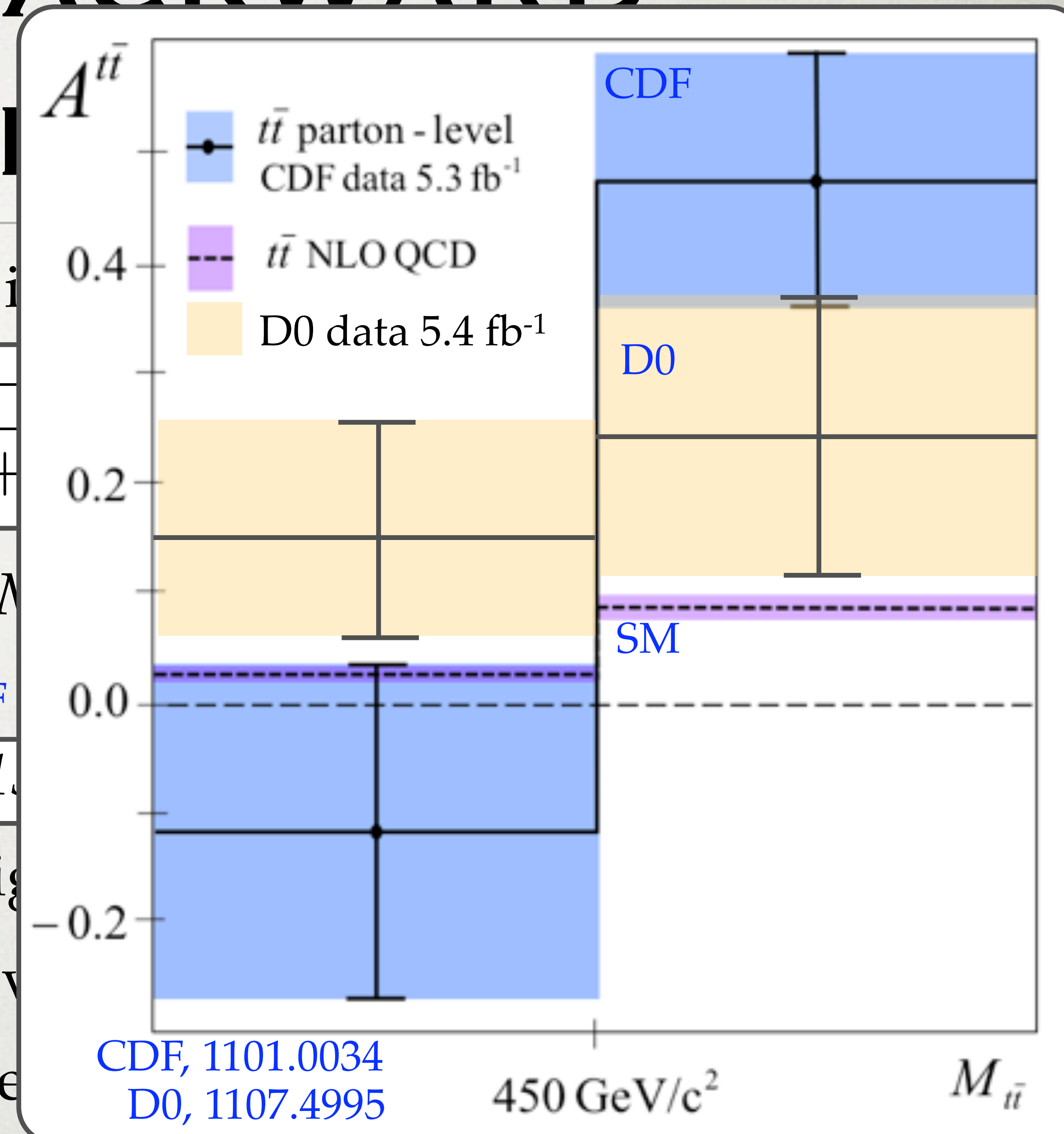
FORWARD-BACKWARD ASYMMETRY

- both CDF and D0 find larger FBA in $t\bar{t}$ prod. than in the SM

$$A_{FB}^{t\bar{t}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- the deviation most significant for M_{tt}>450 GeV
  - at CDF: $A_{tt} = 0.475 \pm 0.114$ CDF 1101.0034
    vs. SM@NLO: $A_{tt} = 0.088 \pm 0.013$ (3.4σ discr.)
  - D0 does not deconvolute its. high bin measurement
    - using the corr. as for inclusive A_{FB}: $A_{tt} = 0.245 \pm 0.128$ D0 1107.4995
- in the dileptonic channel, inclusive:
  - CDF: $A_{tt} = 0.417 \pm 0.148 \pm 0.053$ CDF Note 10398
  - D0 similar but for A^l (σ_F, σ_B defined with respect to y_{l+})
    A^l=0.152± 0.040 vs. MC@NLO 0.021± 0.001 D0 1107.4995
- the challenge: cross section agrees well with the SM

FORWARD-BACKWARD ASYMM



- both CDF and D0 find larger FBA i

$$A_{FB}^{t\bar{t}} = \frac{\sigma_F -}{\sigma_F +}$$

- the deviation most significant for M
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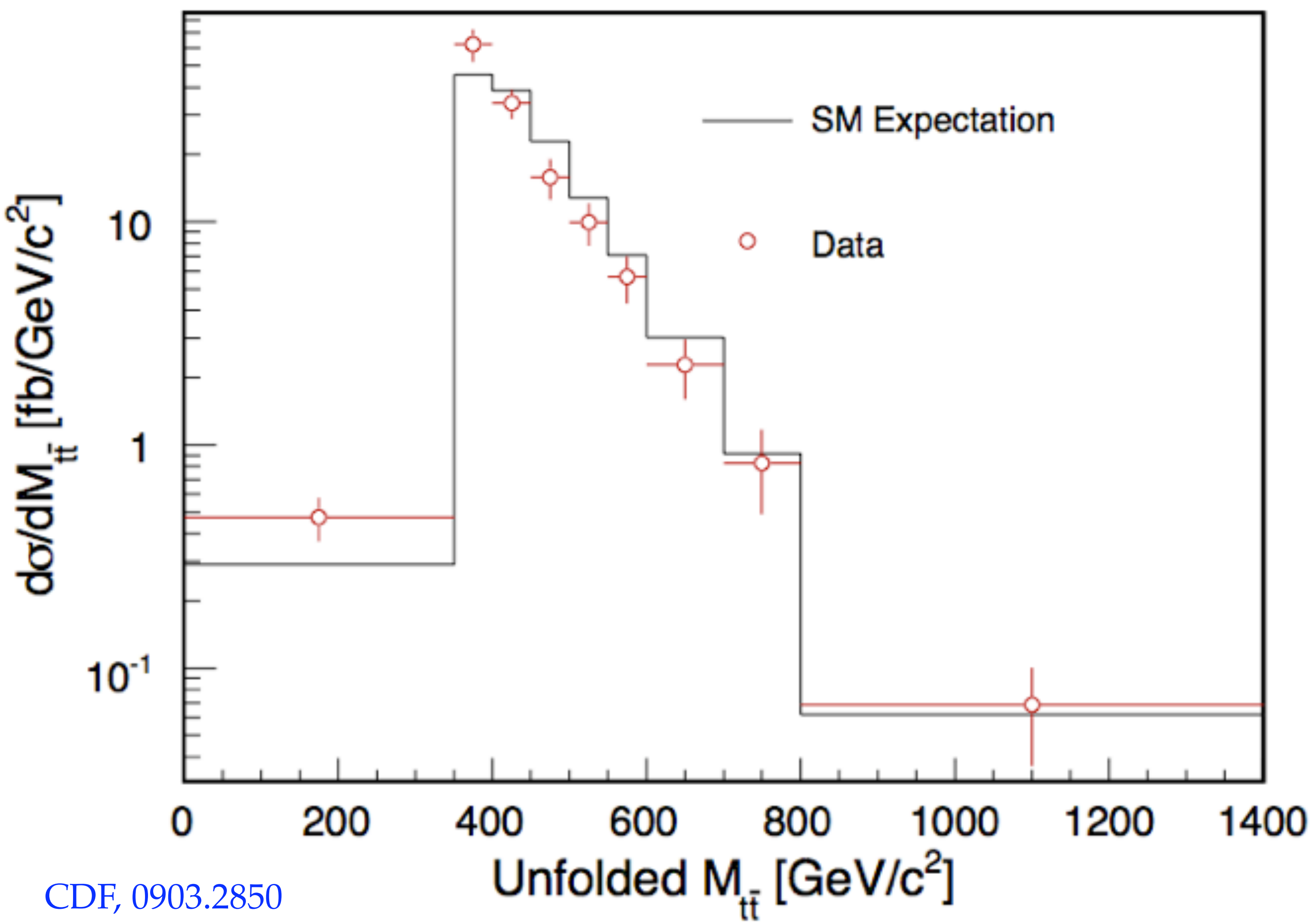

CDF, 0903.2850

in the SM

ent

± 0.128 D0 1107.4995

CDF Note 10398

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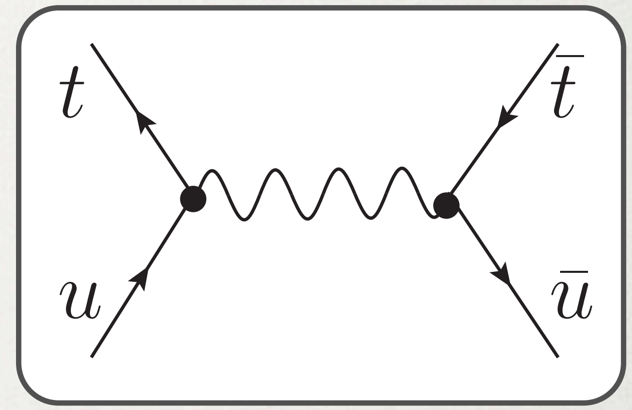
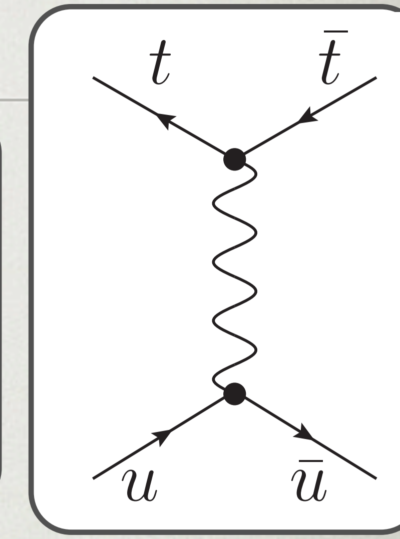
NEW PHYSICS?





- New Physics?
  - s-channel? t-channel?
- First question: does it have to interfere with SM?

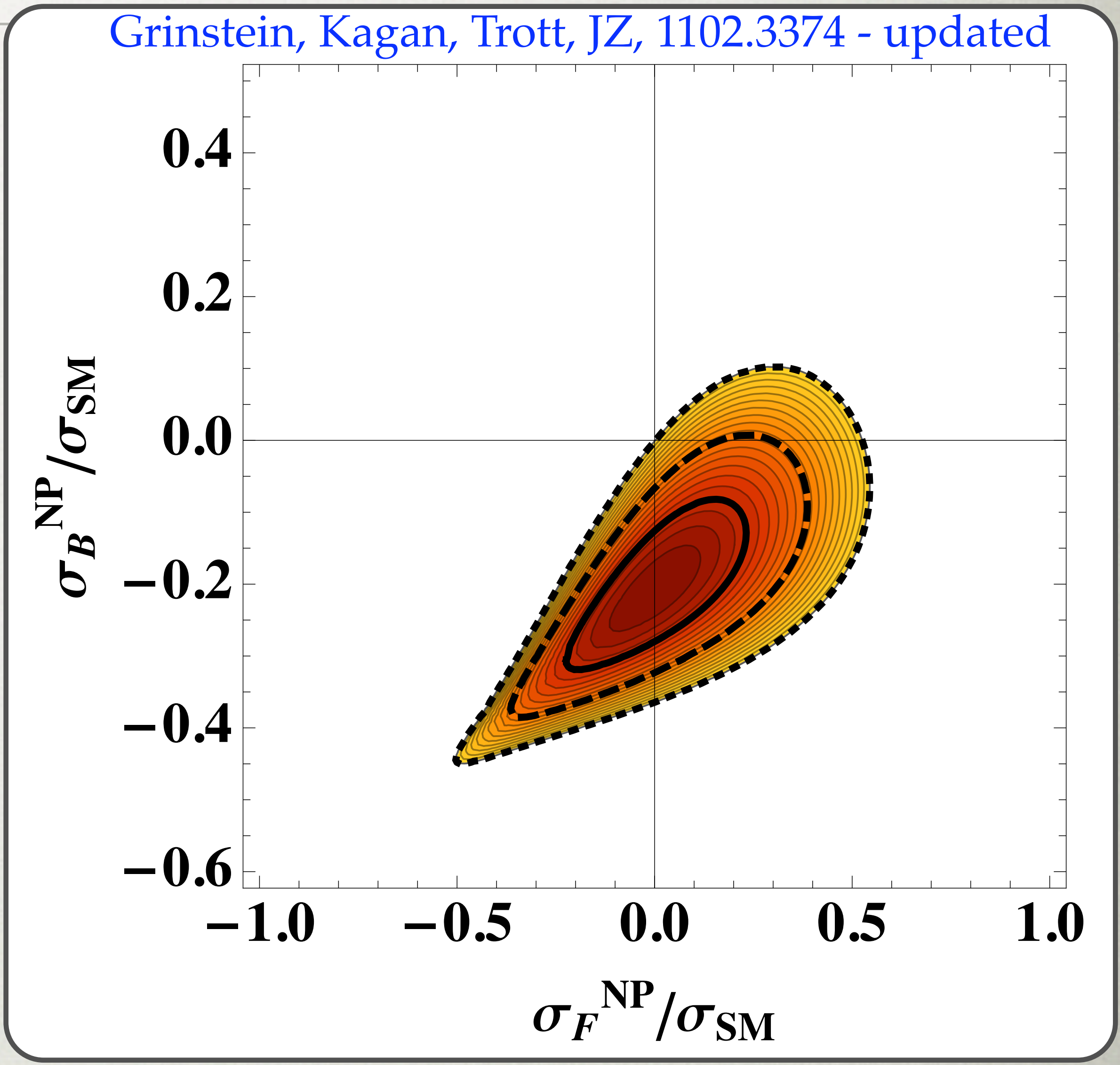
$$A_{FB}^{t\bar{t}} = \frac{\sigma_F^{SM} - \sigma_B^{SM} + \sigma_F^{NP} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_B^{SM} + \sigma_F^{NP} + \sigma_B^{NP}}$$

- cross section agrees with

$$\sigma_{exp}^{t\bar{t}}(M_{t\bar{t}} > 450\text{GeV}) = 1.9 \pm 0.5 \text{ pb}$$
$$\sigma_{\text{SM}}^{t\bar{t}}(M_{t\bar{t}} > 450\text{GeV}) = 2.40 \pm 0.13 \text{ pb}$$

MODEL INDEP. FIT

- σ_B is large and negative
  - it has to interfere with the SM
- if s-channel resonance:
  - to interfere with one-gluon exchange has to be color-octet
  - cannot be a scalar ⇒ “axigluon”



CHALLENGES

- for s-channel resonance: no bump in $t\bar{t}$ spectrum
- Z': large u-t coupling
  - generation of same sign top pairs
- W': large d-t coupling
  - too large single top

CHALLENGES

- several challenges due to inherent flavor violation
  - **s-channel (heavy)**: to have A_{FB}>0 ⇒ coupl. to $q\bar{q}$ opposite to $t\bar{t}$
    Cao, McKeen, Rosner, Shaughnessy, Wagner, 1003.3461
    Frampton, Shu, Wang, 0911.2955 Bai, Hewett, Kaplan, Rizzo, 1101.5203
    - is flavor diagonal but not flavor universal!
      Jung, Murayama, Pierce , Wells, 0907.4112
  - **t-channel**: large *u-t (d-t)* couplings
    Shu, Tait, Wang, 0911.3237;
    Shelton, Zurek, 1101.5392 Gresham, Kim, Zurek, 1102.0018 ...
    - but *c-t* couplings have to be small due to *D* mixing
      Dorsner, Fajfer, Kamenik, Kosnik, 1007.2604
- in concrete models one has to worry about FCNCs
  Shu, Wang, Zhu, 1104.0083
- all the above problems avoided in MFV models
  Delaunay, Gedalia, Lee, Perez, Ponton, 1101.2902
  - but can one get large A_{FB}?

MINIMAL FLAVOR VIOLATION

D'Ambrosio, Giudice, Isidori, Strumia, 2002

- quark sector formally inv. under G_F=U(3)$_Q$⊗ U(3)$_u$⊗U(3)$_d$

$$\mathcal{L}_Y = Y_U \, \bar{u}_R \, H^T \, i\sigma_2 \, Q_L - Y_D \, \bar{d}_R \, H^\dagger \, Q_L + \text{h.c.}$$

  - if the Yukawas promoted to spurions

$$Y'_{u,d} = V_Q Y_{u,d} V^\dagger_{u,d}$$

- use spurion analysis to construct NP opers./contribs.
- constrains possible FV structures, e.g. (V-A)⊗(V-A)
  - allowed: $\bar{Q}(Y_u Y_u^\dagger)^n Q$
  - not allowed: $\bar{Q} Y_d^\dagger (Y_u Y_u^\dagger)^n Q$
- it gives SM like suppression of FCNC's since

$$(Y_u Y_u^\dagger)^n \sim (Y_u Y_u^\dagger) = V_{\rm CKM} \text{diag}(0,0,1) V_{\rm CKM}^\dagger$$

- for (V-A) bilinear $\bar{b}_L s_L$ the suppression $\sim V_{tb} V_{ts}^*$

THE QUESTION

- assume SM flavor symmetry also for NP
  - $U(3)_Q \otimes U(3)_u \otimes U(3)_d \rightarrow U(2)_Q \otimes U(2)_u \otimes U(2)_d$
- assume additional breaking is small
- can one obtain large A_{FB}?
  - and at the same time obey all other constraints?

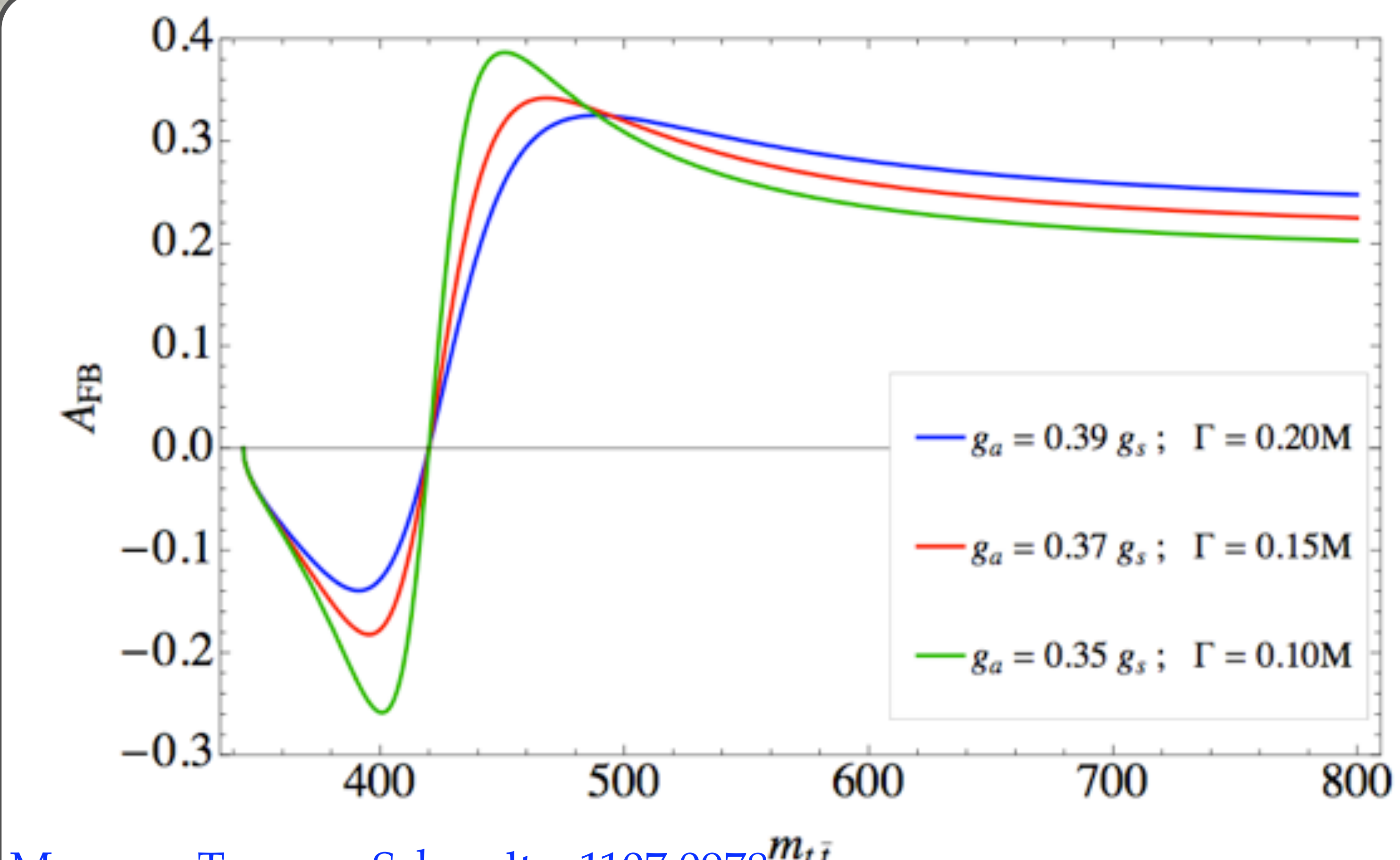
THE ANSWER

- yes!
  - in *s*-channel
    - light resonance, below *450* GeV
    - purely axial couplings
    - need large decay widths $\Gamma \sim 0.2m$

Marques Tavares, Schmaltz, 1107.0978; Aguila-Saavedra, Perez-Victoria, 1107.2120; Xiao, Wang, Zhu, 1011.0152

  - or if purely *t*-channel
    - can be in irr. represent. of flavor $U(3)^3$

Grinstein, Kagan, Trott, JZ, 1102.3374; 1108.4027



Marques Tavares, Schmaltz, 1107.0978

WER

elow *450* GeV

- purely axial couplings
- need large decay widths *Γ~0.2m*

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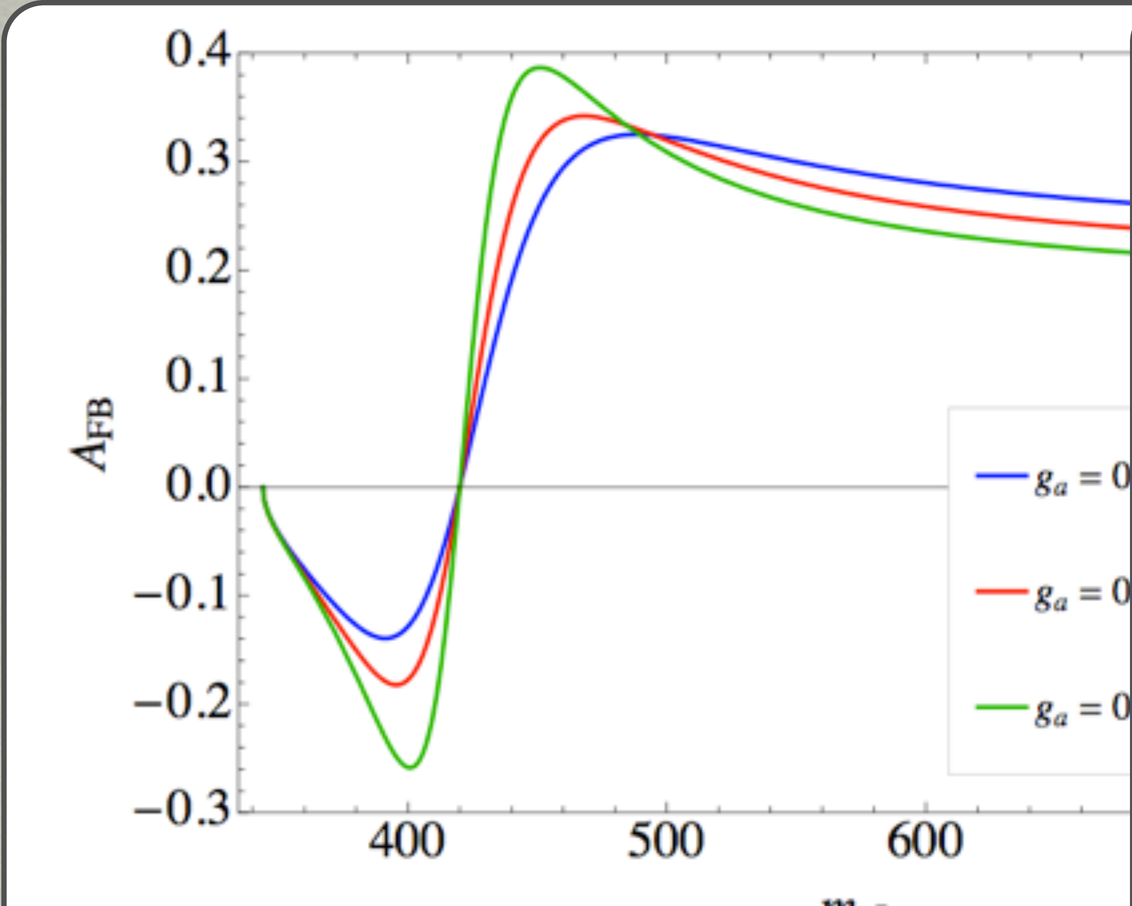

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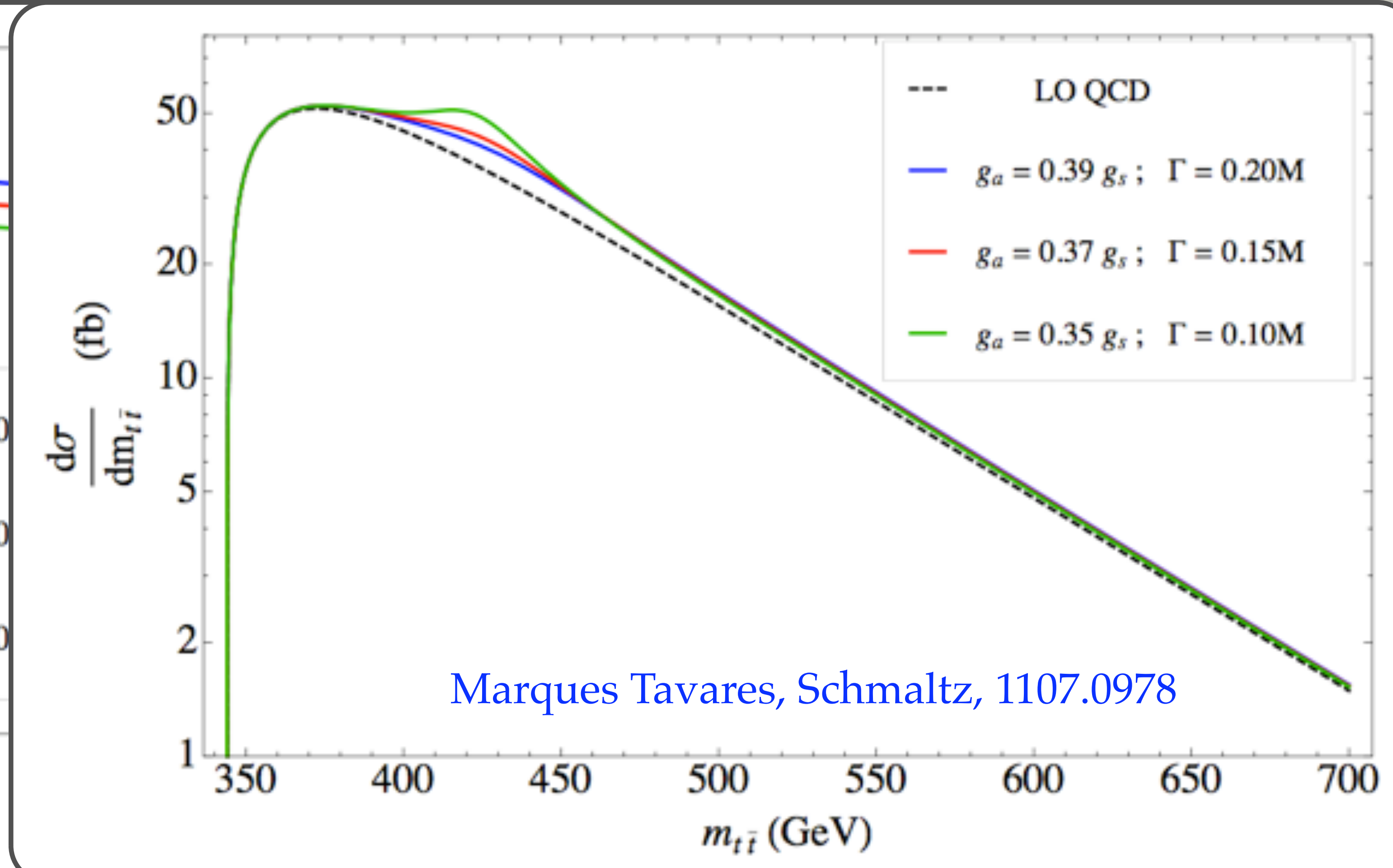

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FLAVOR SYMMETRIC SECTORS AND COLLIDER PHYSICS

Grinstein, Kagan, Trott, JZ, 1102.3374; 1108.4027
Arnold, Pospelov, Trott, Wise, 0911.2225

- what we do:
  - assume SM flavor symmetries
  - list all possible scalar and vector fields that can couple to quarks
- vectors: 18 possibilites
- scalars: 16 possibilities
- for flavor breaking: MFV
  - not crucial, can be larger and FCNCs ok

MFV vectors

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{Q_L}$	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)	$\bar{d}_R \gamma^\mu Q_L^c$
$XI_{\bar{3},6}$	$\bar{3}$,6	2	5/6	(3,1,3)	$\bar{u}_R \gamma^\mu Q_L^c$

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$I_{s,o}$	1,8	1	0	(1,1,1)	$\bar{d}_R \gamma^\mu d_R$
$II_{s,o}$	1,8	1	0		
$III_{s,o}$	1,8	1	0		
$IV_{s,o}$	1,8	3	0		
$V_{s,o}$	1,8	1	0		
$VI_{s,o}$	1,8	1	0		
$VII_{s,o}$	1,8	1	-1		
$VIII_{s,o}$	1,8	1	0		
$IX_{s,o}$	1,8	3	0		
$X_{\bar{3},6}$	$\bar{3}$,6	2	-1/6		
$XI_{\bar{3},6}$	$\bar{3}$,6	2	5/6		

MFV scalars

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{Q_L}$	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)	$\bar{Q}_L u_R,\ \bar{Q}_L d_R$

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...YSICS

- scalars: 16
- for flavor b
  - not cruci

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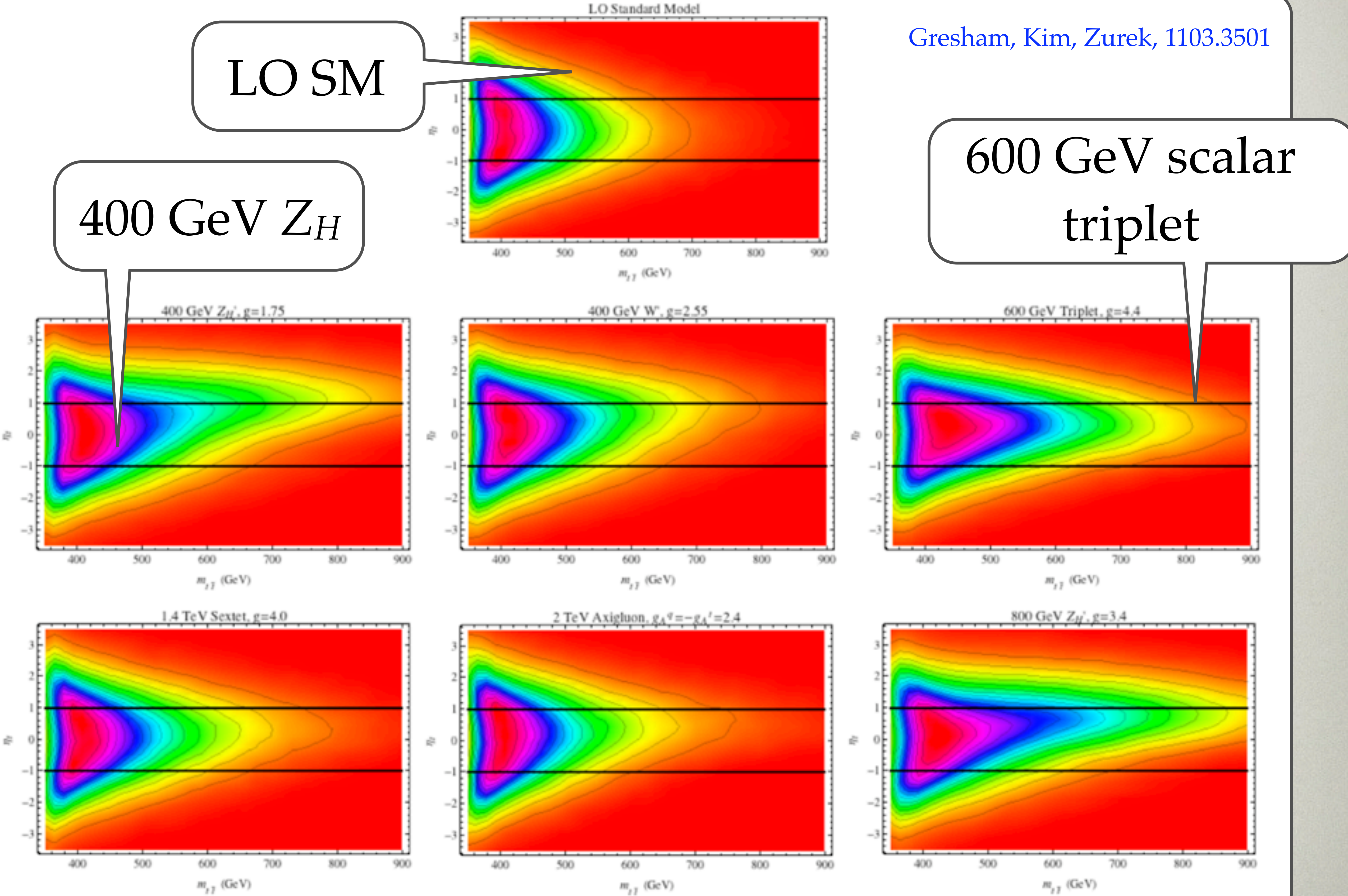
COMPARING WITH DATA

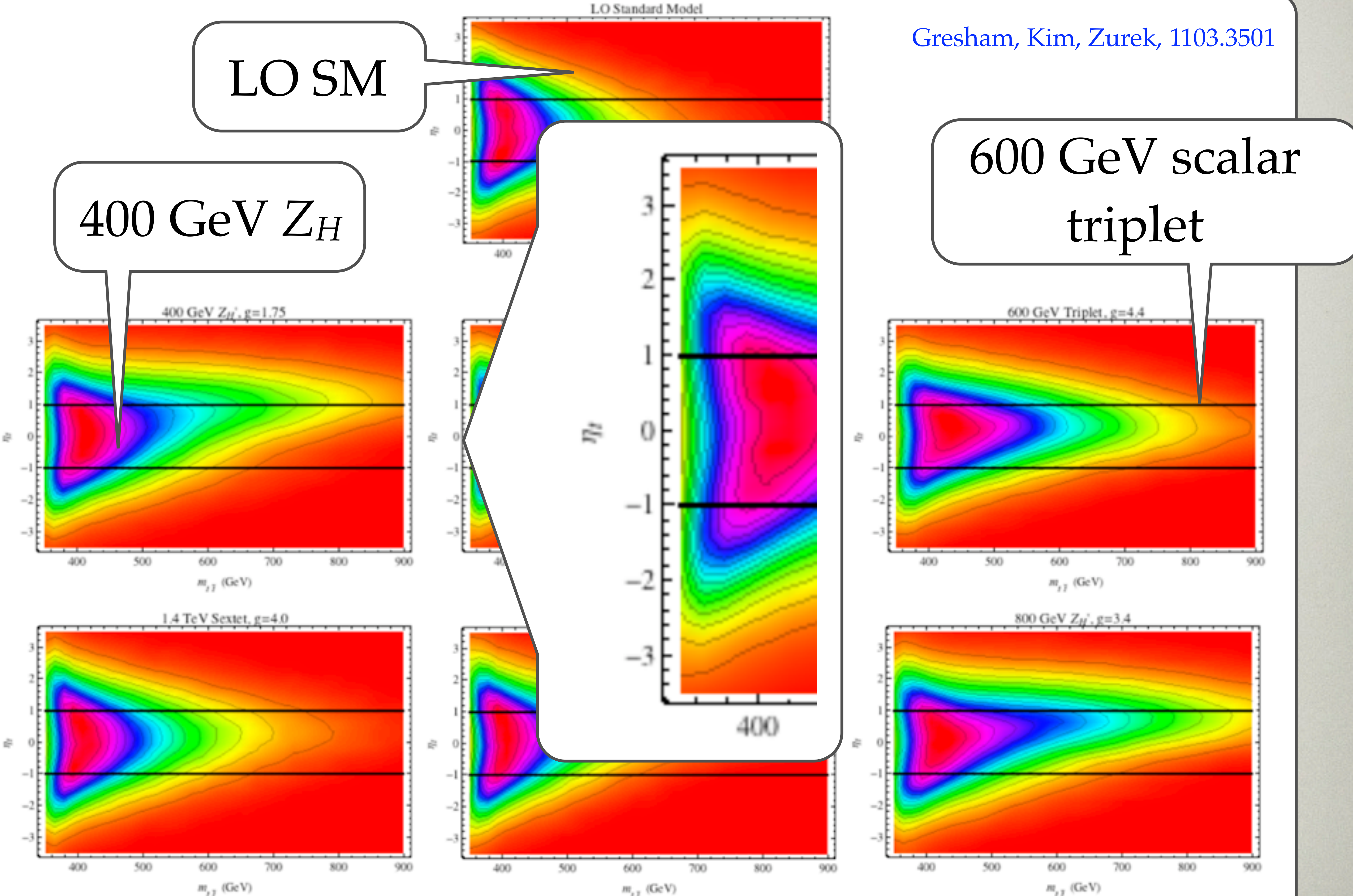
- CDF quotes "deconvoluted" A_{FB} and $d\sigma/dm_{tt}$
- maybe easiest to compare with the NP models
- but deconvolution done assuming SM ttbar production
- for very forward ttbar production this may be a problem

Gresham, Kim, Zurek, 1103.3501

  - especially for $d\sigma/dm_{tt}$ where deconvolution using η integrated efficiencies


LO Standard Model
LO SM
Gresham, Kim, Zurek, 1103.3501
400 GeV Z_H
600 GeV scalar triplet
400 GeV Z_{H}', g=1.75
400 GeV W', g=2.55
600 GeV Triplet, g=4.4
1.4 TeV Sextet, g=4.0
2 TeV Axigluon, $g_A{}^q=-g_A{}^t=2.4$
800 GeV Z_{H}', g=3.4
$m_{t\bar{t}}$ (GeV)
η_t

Gresham, Kim, Zurek, 1103.3501



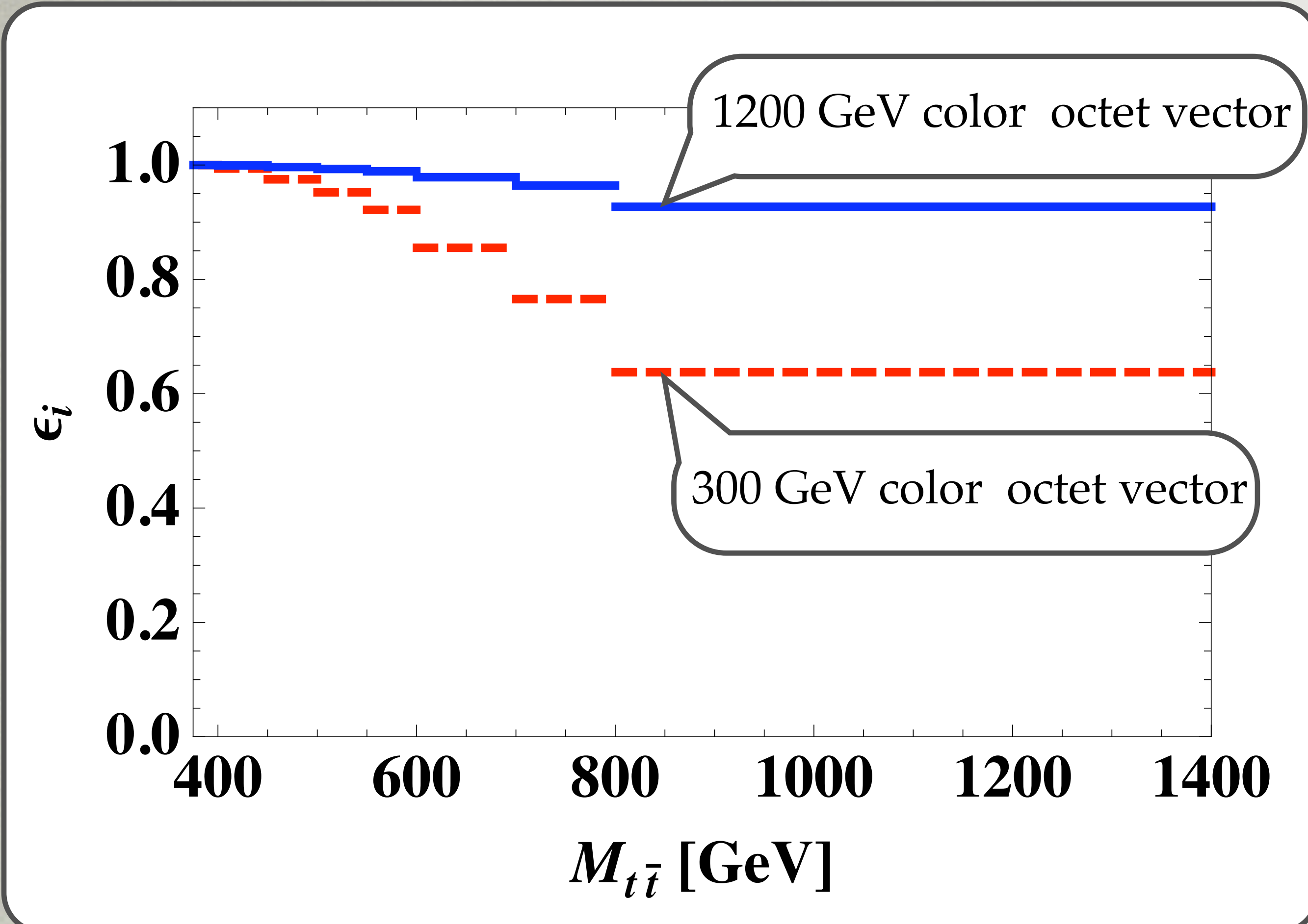
DETAILS

- make a 2D set of bins in m_{tt} and Δy
- use `Madgraph` to generate SM ttbar partonic cross section
  - but restricted to a particular bin in m_{tt} and Δy
  - trick: implement cuts directly in `Subprocesses/cuts.f`
- run through `Pythia+PGS` to obtain efficiencies κ_{ij} (i- bin in m_{tt}, j-bin in Δy)
- the "correction factor" to be used when comparing with CDF $d\sigma/dm_{tt}$ measurement is

$$\epsilon_i^{\rm SM,NP} = \frac{\sum_j \sigma_{ij}^{\rm SM,NP} \kappa_{ij}}{\sum_j \sigma_{ij}^{\rm SM,NP}}$$

$$\left(\frac{d\sigma^{\rm NP}}{dm_{t\bar t}}\right)_i^{CDF} = \epsilon_i \times \left(\frac{d\sigma^{\rm NP}}{dm_{t\bar t}}\right)_i$$

$$\epsilon_i = \frac{\epsilon_i^{\rm NP}}{\epsilon_i^{\rm SM}}$$



AILS

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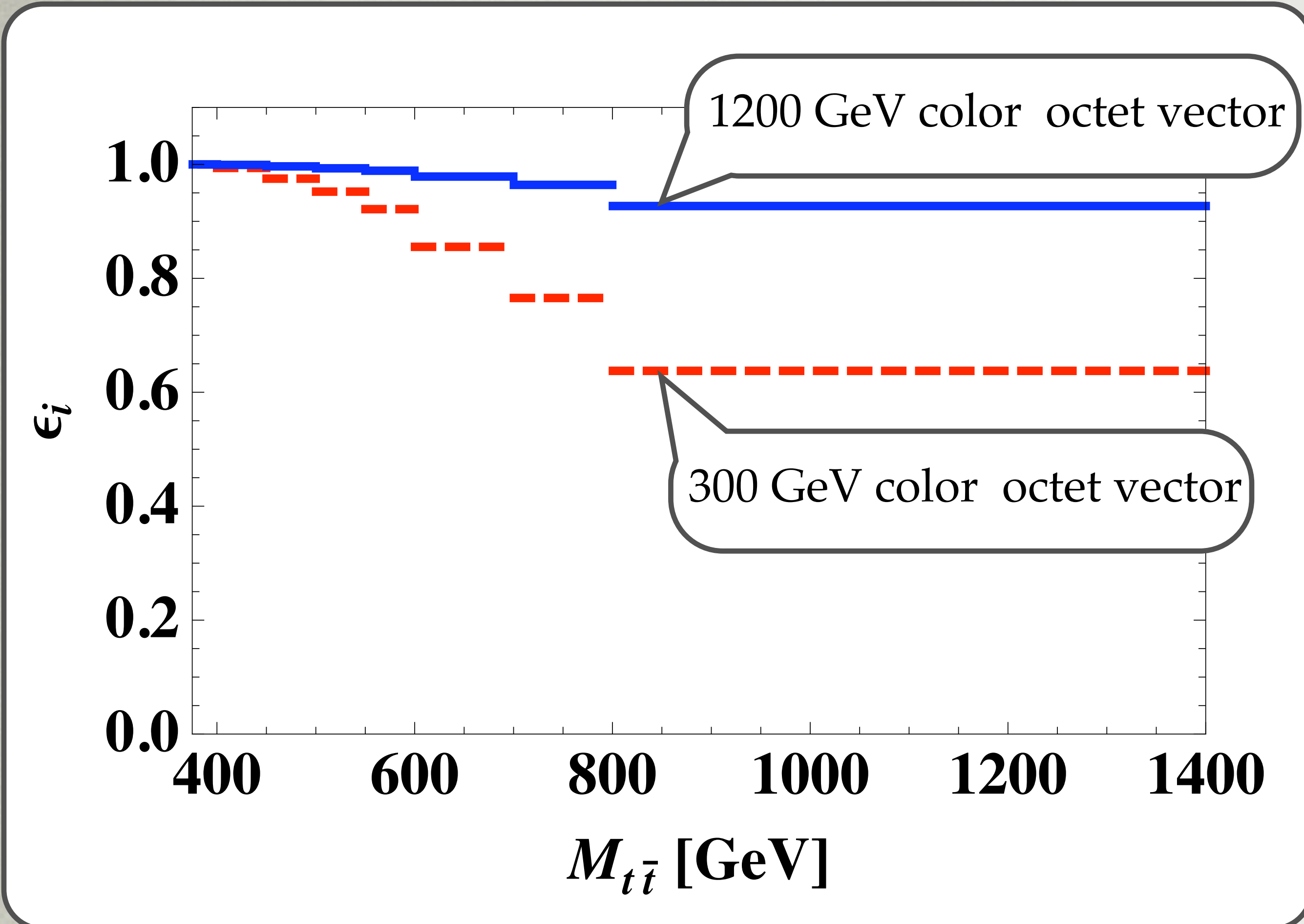
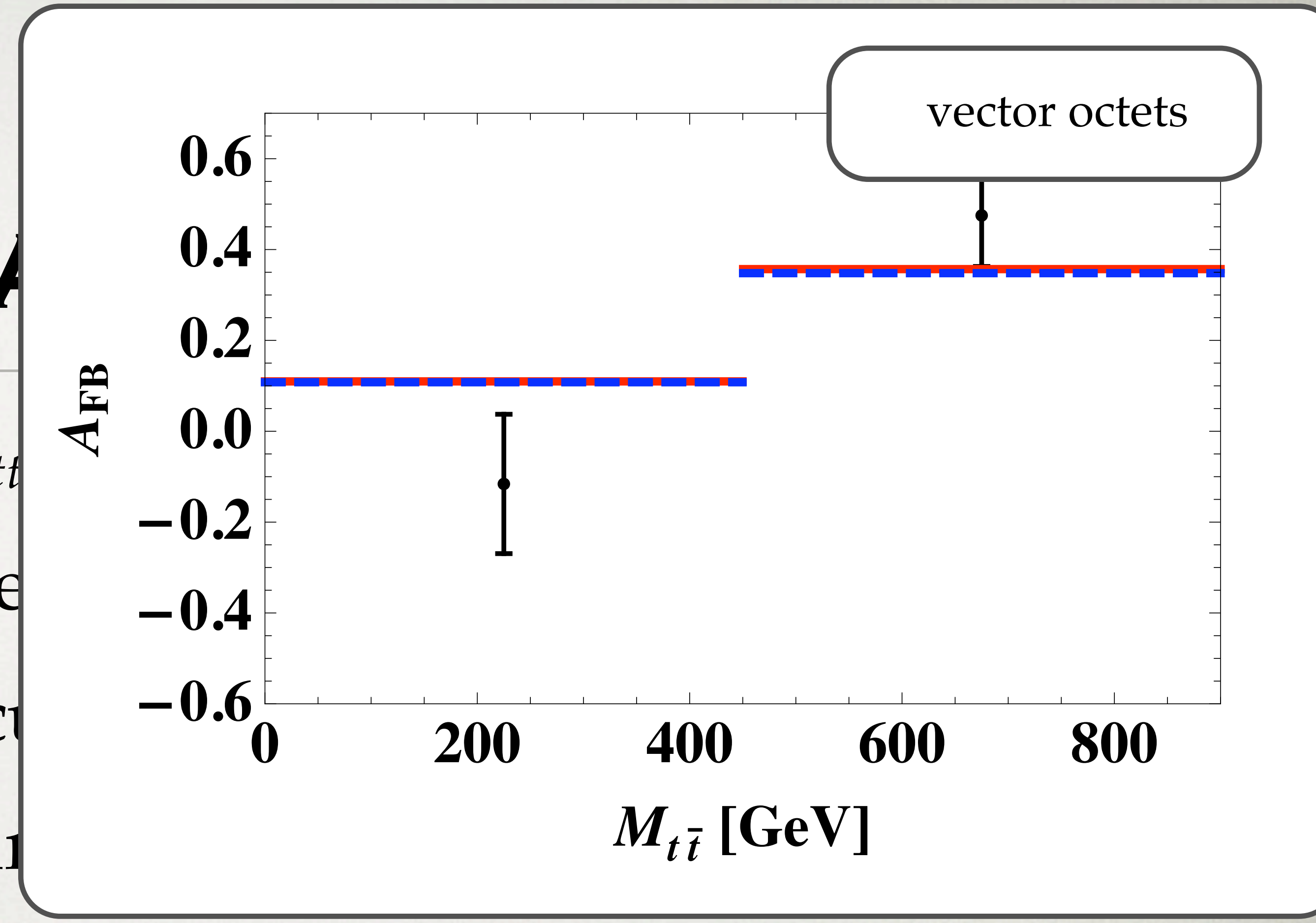
$$\left(\frac{d\sigma^{\rm NP}}{dm_{t\bar{t}}}\right)_i^{CDF} = \epsilon_i \times \left(\frac{d\sigma^{\rm NP}}{dm_{t\bar{t}}}\right)_i$$

$$\epsilon_i^{\rm SM,NP} = \frac{\sum_j \sigma_{ij}^{\rm SM,NP} \kappa_{ij}}{\sum_j \sigma_{ij}^{\rm SM,NP}}$$

$$\epsilon_i = \frac{\epsilon_i^{\rm NP}}{\epsilon_i^{\rm SM}}$$





`cuts.f`

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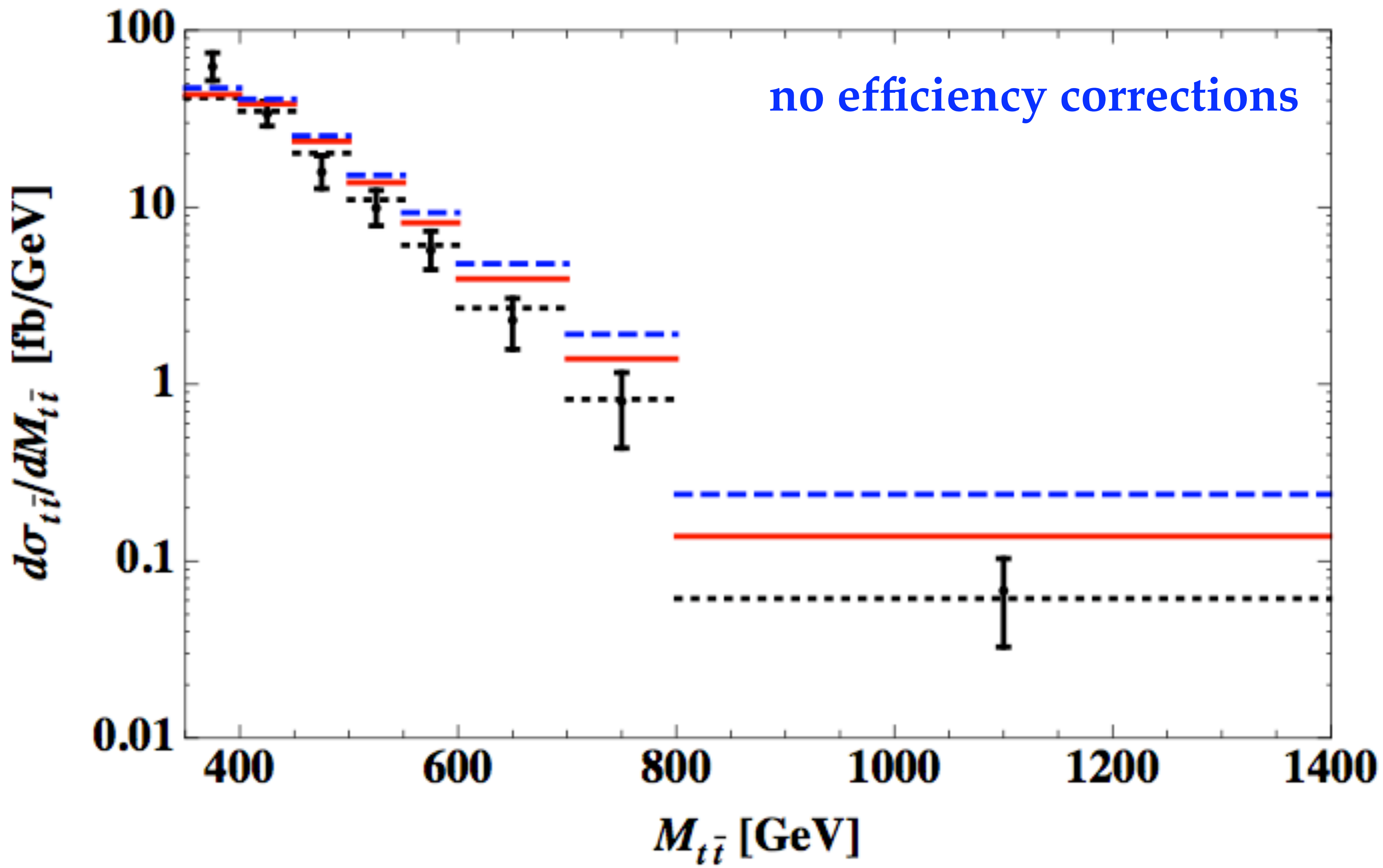
$$\epsilon_i^{\mathrm{SM,NP}} = \frac{\sum_j \sigma_{ij}^{\mathrm{SM,NP}} \kappa_{ij}}{\sum_j \sigma_{ij}^{\mathrm{SM,NP}}}$$

$$\left(\frac{d\sigma^{\mathrm{NP}}}{dm_{t\bar{t}}}\right)_i^{CDF} = \epsilon_i \times \left(\frac{d\sigma^{\mathrm{NP}}}{dm_{t\bar{t}}}\right)_i$$

$$\epsilon_i = \frac{\epsilon_i^{\mathrm{NP}}}{\epsilon_i^{\mathrm{SM}}}$$

THE IMPORTANCE OF ACCEPTANCE CORRECTIONS



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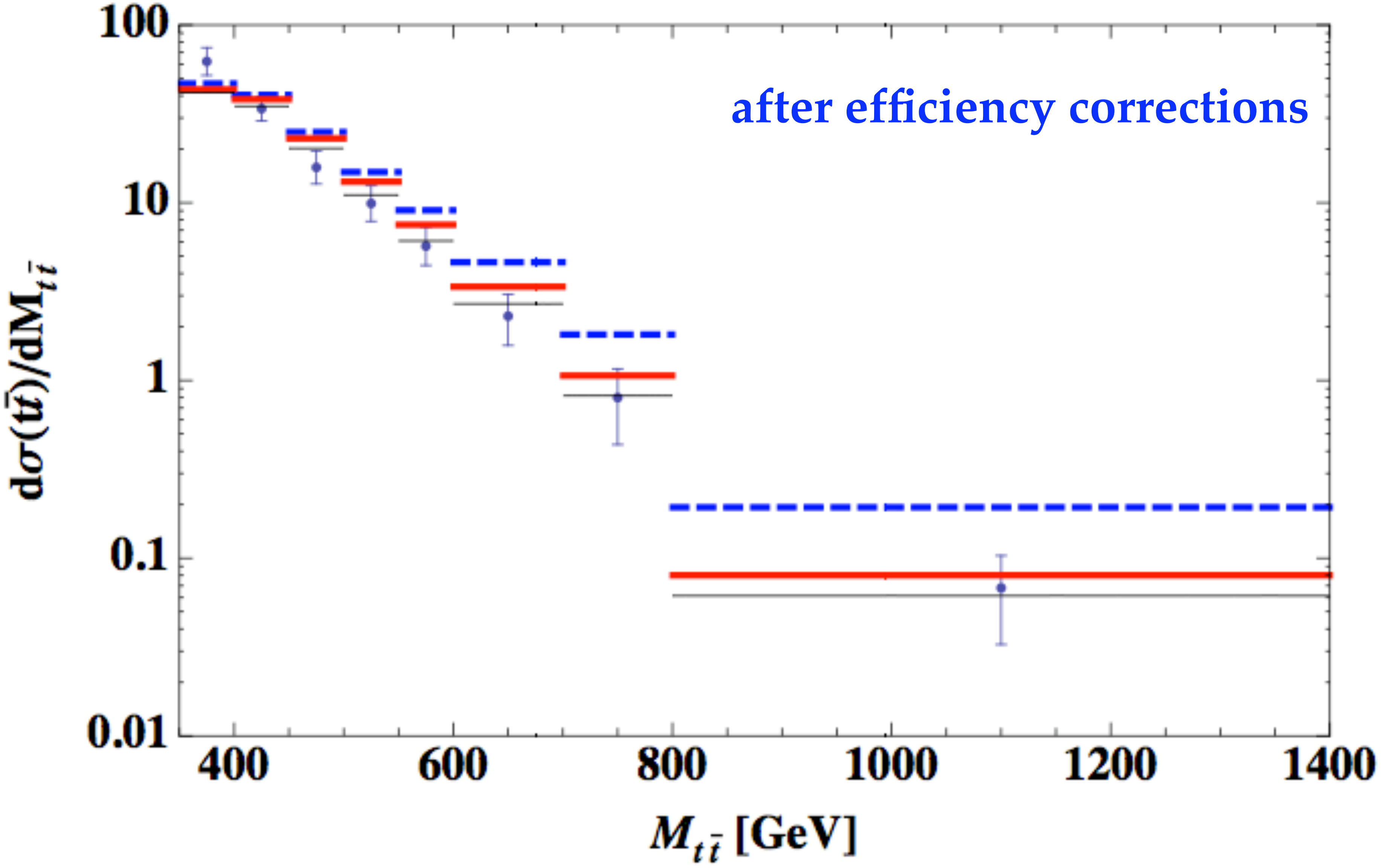
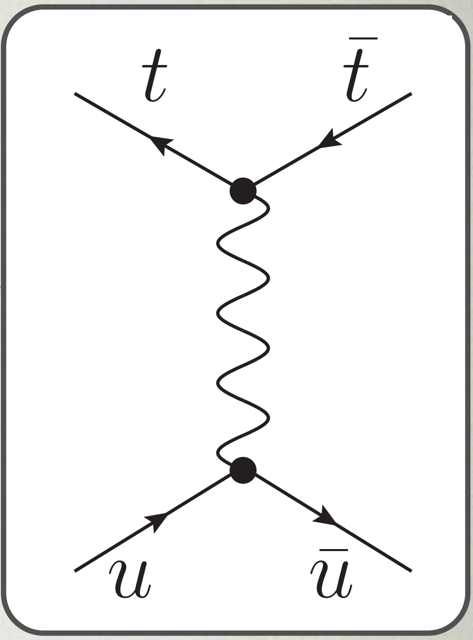


EXAMPLES

- first a simple example
  - flavor singlet and octet vectors
- to see what is needed for large A_{FB}
- and why FCNCs are suppressed

FORWARD BACKWARD ASYMMETRY



- vectors in representations of the SM flavor group G_F
  - all these fields have *O(1)* coupls. to quarks (all gens.)
  - look at examples of heavy s-channel resonance
- **flavor singlet vector (*s*-channel)**

$$\bar{Q}_L \gamma^\mu Q_L V_\mu = \bar{t}_L \gamma^\mu t_L + \bar{u}_L \gamma^\mu u_L + \cdots$$

  - terms with yukawa insertions can flip the sign of *tt* coupling

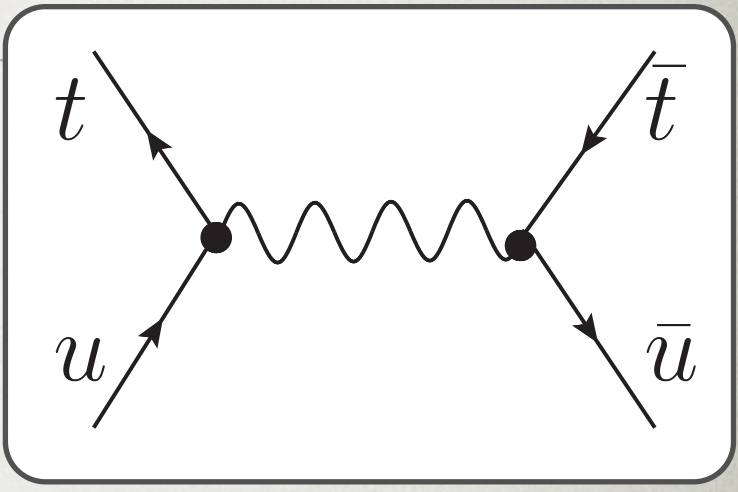
$$\bar{Q}_L \gamma^\mu Y_U^\dagger Y_U Q_L V_\mu = y_t^2 \bar{t}_L \gamma^\mu t_L$$

- **flavor octet vector (*s*-channel)**

$$(\bar{Q}_L T^A \gamma^\mu Q_L) V_\mu^A = \frac{1}{\sqrt{3}} V_\mu^8 \big(\bar{u}_L \gamma^\mu u_L + \bar{c}_L \gamma^\mu c_L - 2\bar{t}_L \gamma^\mu t_L\big) + \ldots$$

  - the sign of coupl. to the top pair is opposite to the one for *u,c*
  - this is without any flavor violation (no yukawa insertions)

FORWARD BACKWARD ASYMMETRY



- **flavor octet: *t*-channel**

$$(\bar{Q}_L\, T^A \gamma^\mu Q_L) V_\mu^A = (V_\mu^4 - i V_\mu^5)(\bar{t}_L\, \gamma^\mu\, u_L) + \ldots$$

  - *O(1)* flavor changing term (no CKMs)
- note: there are no FCNCs in symmetric limit
- in the flavor symmetric limit the propagator

$$(\bar{q}_i q_j \longrightarrow \bar{q}_l q_k) \propto \ldots \delta_{ij}\delta_{lk} + \ldots \delta_{il}\delta_{jk}$$

  - there are no ΔF=2 amplitudes unless G_F broken
  - e.g. for B_s mixing would need $(\bar{s}b)^2$

COMMENTS

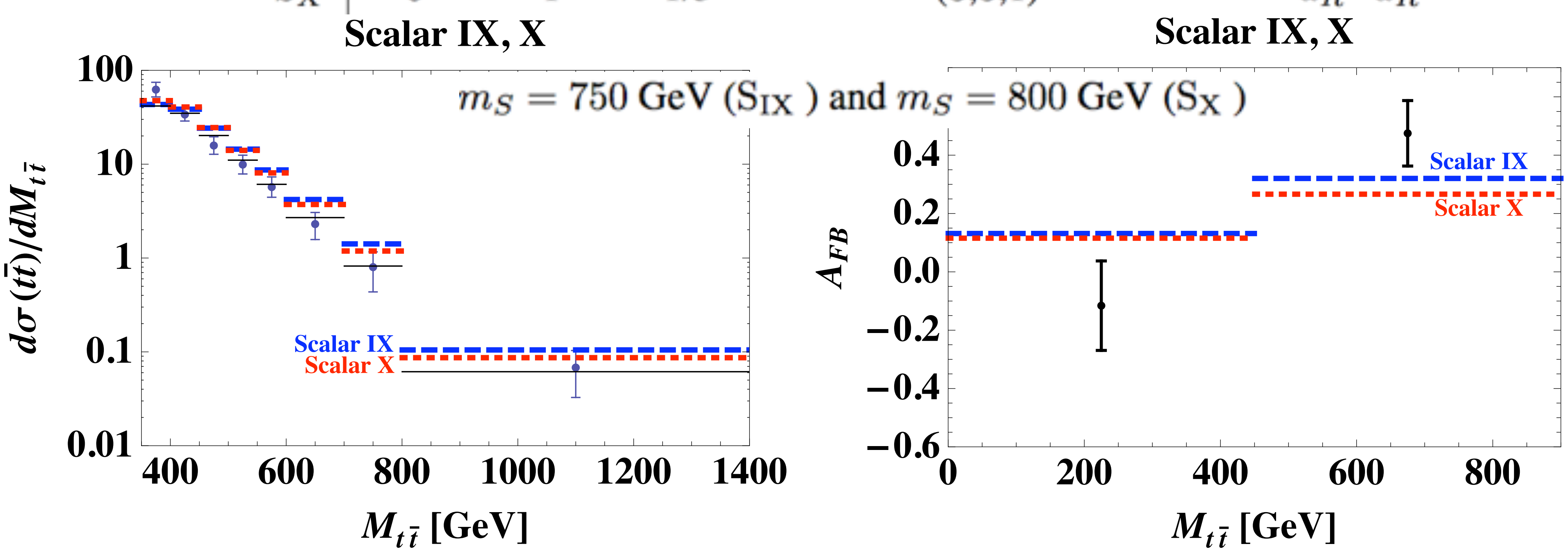
- if fields only in irreducible reps. of flavor group G_F: couple chirally to quarks
  - the solution of light purely axial vector in *s*-channel not part of this
- if *u*-channel resonances too large $d\sigma/dm_{tt}$
- if purely *t*-channel ok
- if *s*- and *t*-channel need FV to suppress *s*-channel

SCALARS

- scalars in irr. reps of flavor group
- typically not very good fit to both cross section and A_{FB}
- an example: scalars IX, X
  - can avoid dijet constraints if flavor breaking

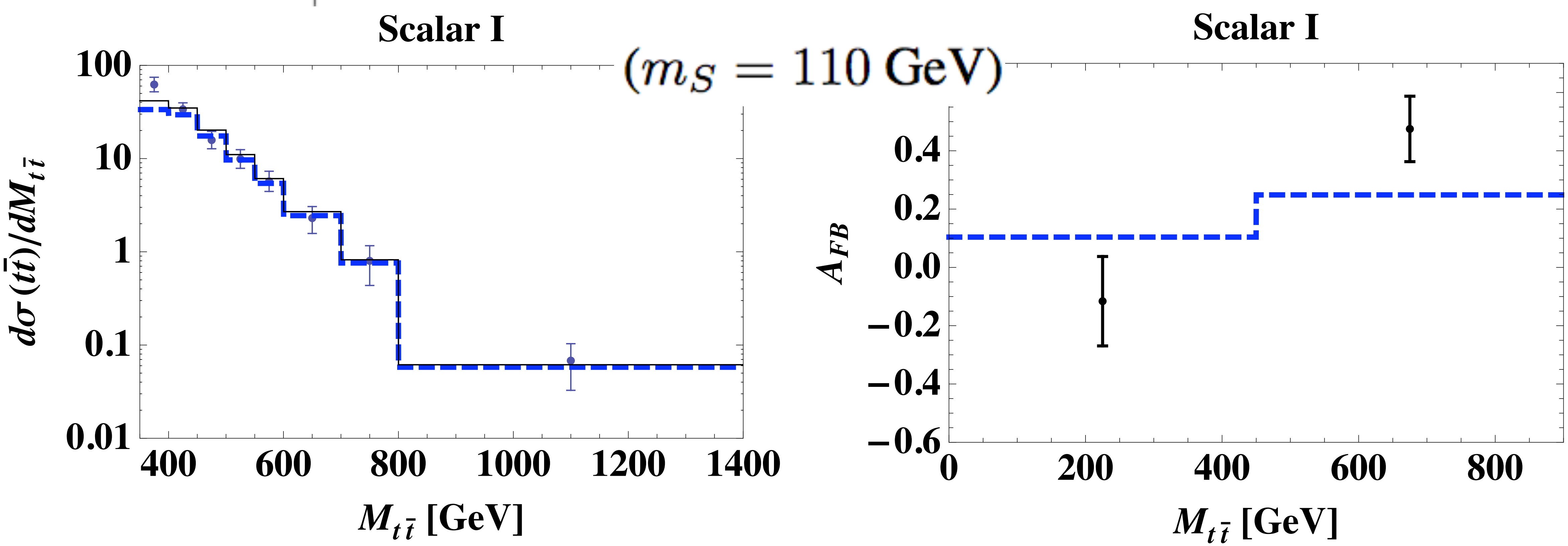
$$\mathcal{L}_{\rm IX} = \eta_1\,(d'_R)_{\alpha i}\,(u'_R)_{\beta j}\,S'^{\,i,j}_{\gamma}\,\epsilon^{\alpha\beta\gamma} + \left(\eta_1 + 2\,\eta_2\,y_t^2\right)(d'_R)_{\alpha i}\,(t'_R)_{\beta}\,S'^{\,i,3}_{\gamma}\,\epsilon^{\alpha\beta\gamma}$$

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{Q_L}$	Couples to
S_{IX}	3	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R\ u_R$
S_X	$\bar{6}$	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R\ u_R$



Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{Q_L}$	Couples to
S_I	1	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R \; Q_L$

$(m_S = 110 \text{ GeV})$



- Nir et al. advertised higgs-like scalar
  - large u_L-t_R is needed, t_L-u_R small
  - possible MFV realization (Scalar I)
    - need large breaking of $U(3)^3 \rightarrow U(2)^3$
    - to avoid dijet constraints and $B \rightarrow K\pi$
    - very light mass
    - even so A_{FB} not very large

Blum, Hochberg, Nir, 1107.4350

VECTORS

- the best examples

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{Q_L}$	Couples to
$VI_{s,o}$	1,8	1	0	(8,1,1)	$\bar{u}_R \gamma^\mu u_R$
$VII_{s,o}$	1,8	1	-1	$(\bar{3},3,1)$	$\bar{d}_R \gamma^\mu u_R$

- the vector VII models are pure *t*-channel
- the vector VI models have *s* and *t*-channel
  - are similar to flavor octet from the first example
  - needs flavor breaking to suppress s-channel

$$\mathcal{L}_{VI_{s,o}} = \eta_1^{s,o}\, \bar{u}_R \not{V}^{s,o} u_R.$$

$$\Delta_U \equiv Y_U Y_U^\dagger$$

$$\Delta\mathcal{L}_{VI_{s,o}} = [\eta_2^{s,o}\, \bar{u}_R(\not{V}^{s,o}\Delta_U)u_R + h.c.] + \tilde{\eta}_3^{s,o}\, \bar{u}_R(\Delta_U \not{V}^{s,o}\Delta_U)u_R + \ldots.$$

VECTORS

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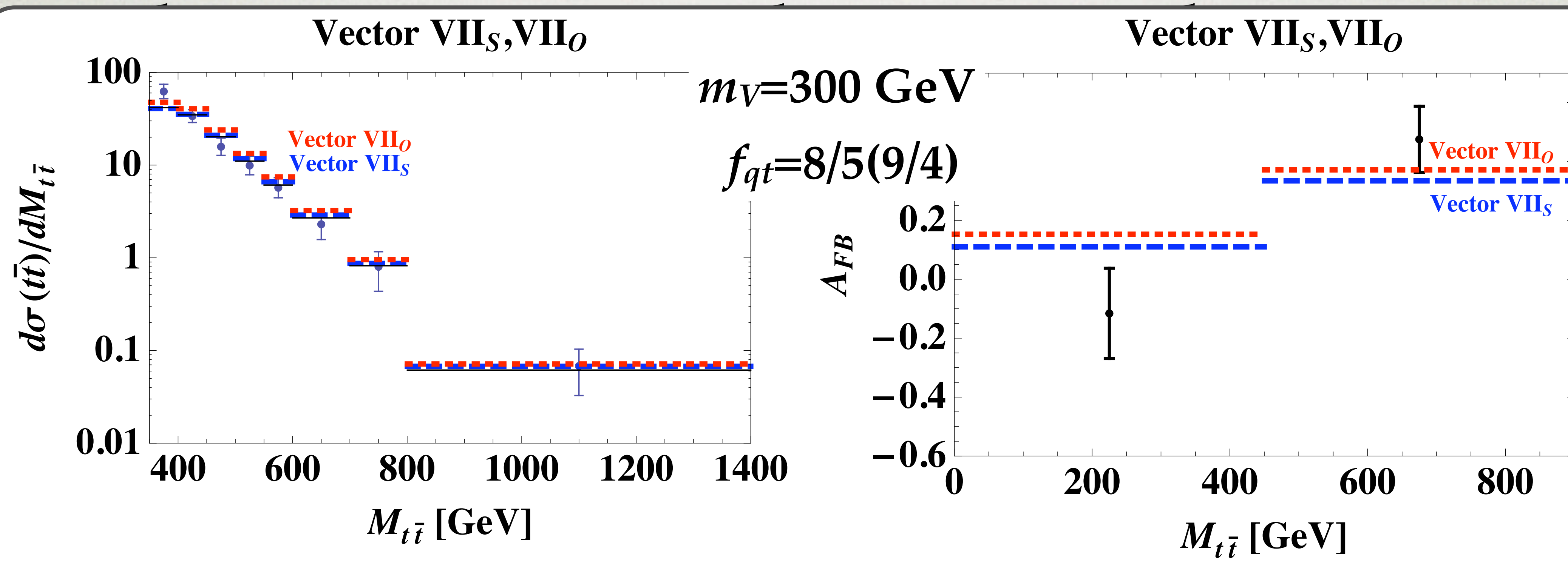
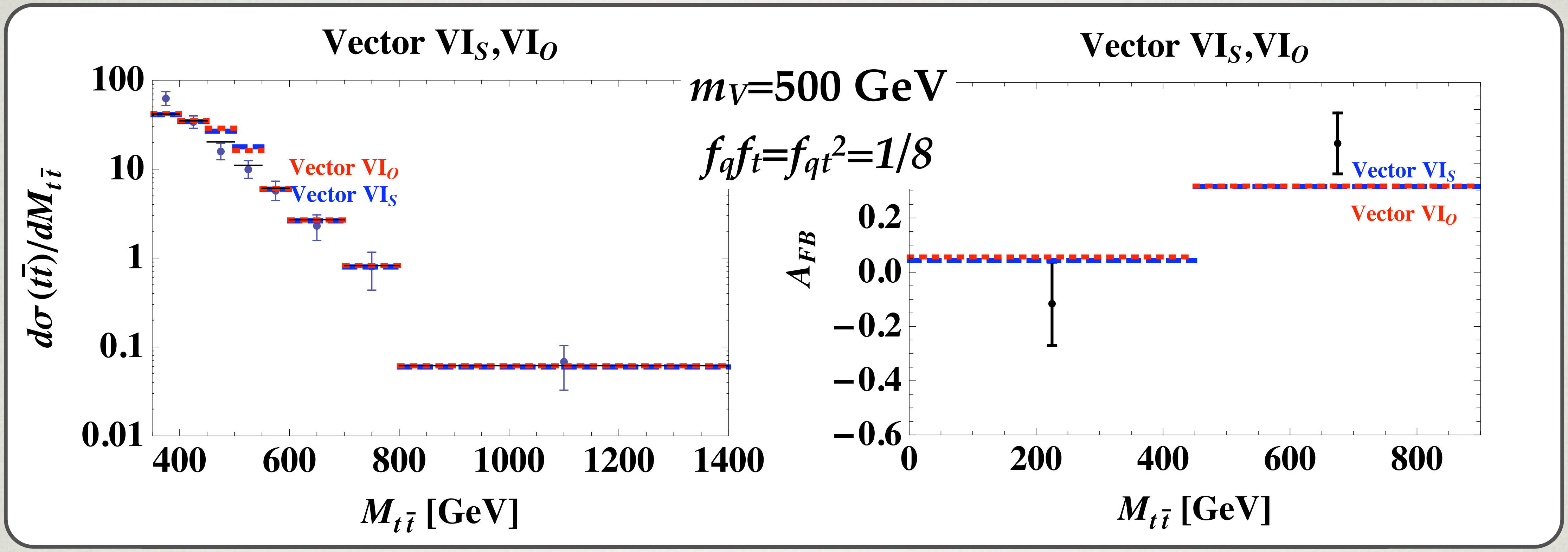


$Y_U Y_U^\dagger$



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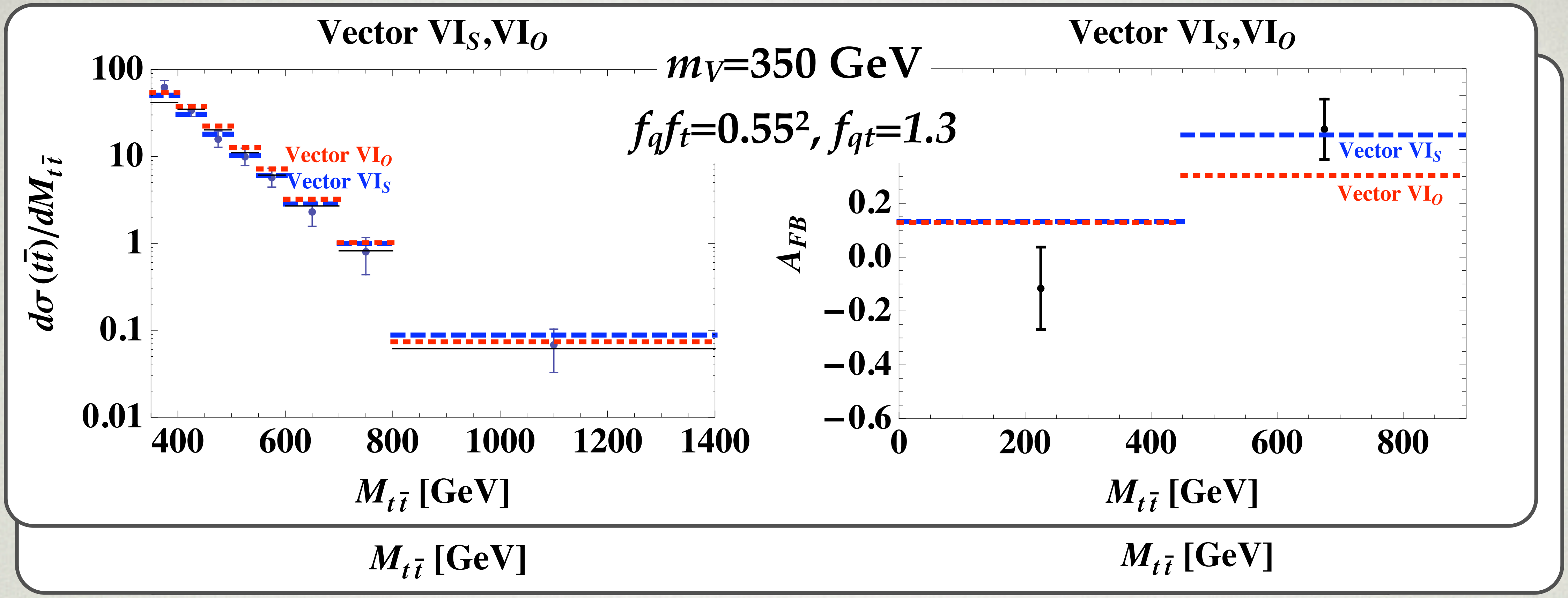

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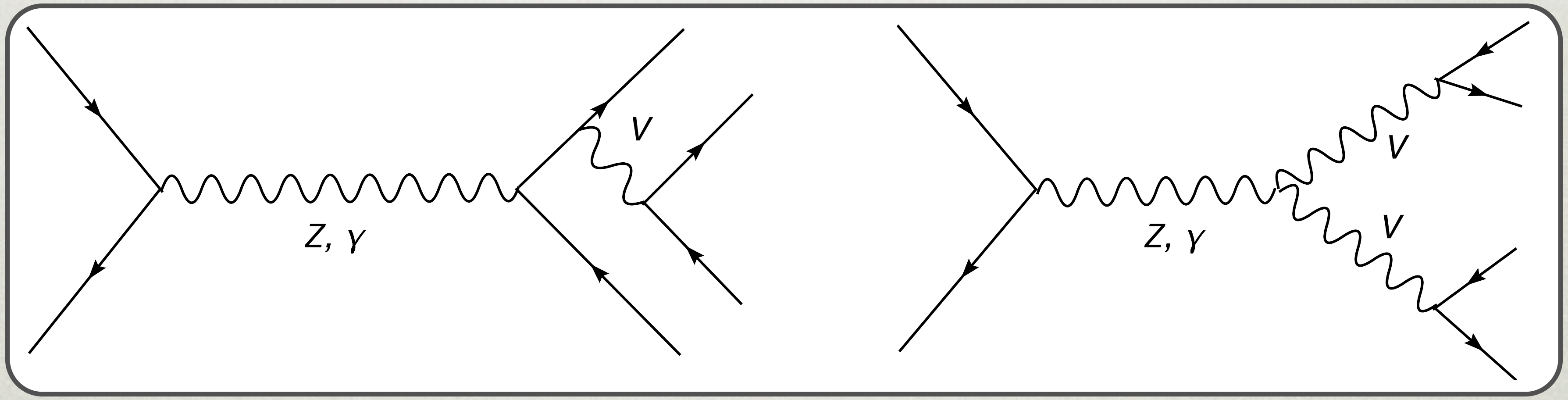
OTHER OBSERVATIONS

- if *V*,*S* in nontrivial flavor representation ⇒ no like-sign top pairs (*t*-channel)
- since O(1) couplings to all generations: di-jet constraints are potentially important
  - but small enough/below bounds
- FCNC constrs. depend on how $U(3)^3$ is broken
  - if one assumes MFV
    - class-1 operators ("universal"): typically still too large for TeV masses and O(1) coeffs.
    - class-2 operators ("yukawa supp."): well below bounds

OTHER CONSTRAINTS

- LEP constraints
  - depends on whether direct couplings to leptons
    - if color singlets esentially like Z′
    - for O(1) coupls. to leptons ⇒ m $\gtrsim$1 TeV
  - both color singlets and charged:generation of multijet events



$M_V \gtrsim 150\,\mathrm{GeV}$ for $\mathcal{O}(1)$ couplings

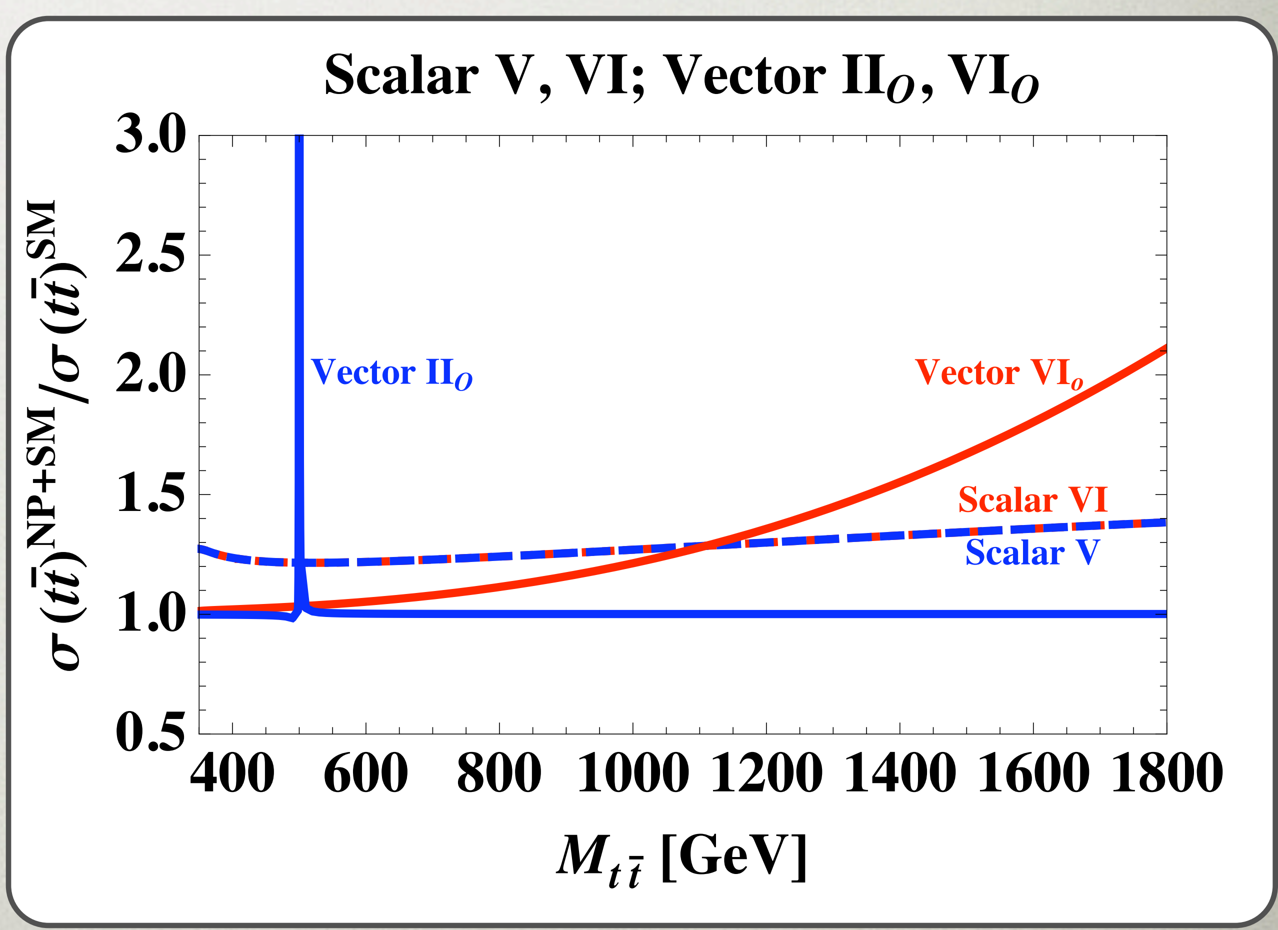
  - EWPD: satisfied for the models shown

OTHER CONSTRAINTS

- dijet constraints at Tevatron and LHC
  - resonance searches (bump hunting)
  - also angular distributions
- for low (~300 GeV) Tevatron more constraining
- since NP fields in flavor representations dijets signals inevitable
  - can be suppressed due to flavor breaking
  - for vector models $VI_{s,o}$ needs $f_q f_t << f_{qt}^2$
    - the same requirement as needed for viable $d\sigma/dm_{ttbar}$
- important question - can one distinguish different breakings, or different scenarios
  - charm tagging crucial

LHC

- has an effect on $pp \to S,V \to ttbar$
  - for viable models (satisfying Tevatron ttbar constraints and dijets):
    - they are *t*-channel dominated
    - only a slow rise
    - one needs good control of the SM
- a search for a resonance in jet+t
- pair production pp->VV (SS)
  - will appear as 4j final state
  - 2j+2j compose into resonances
- charge asymmetry A_C



L

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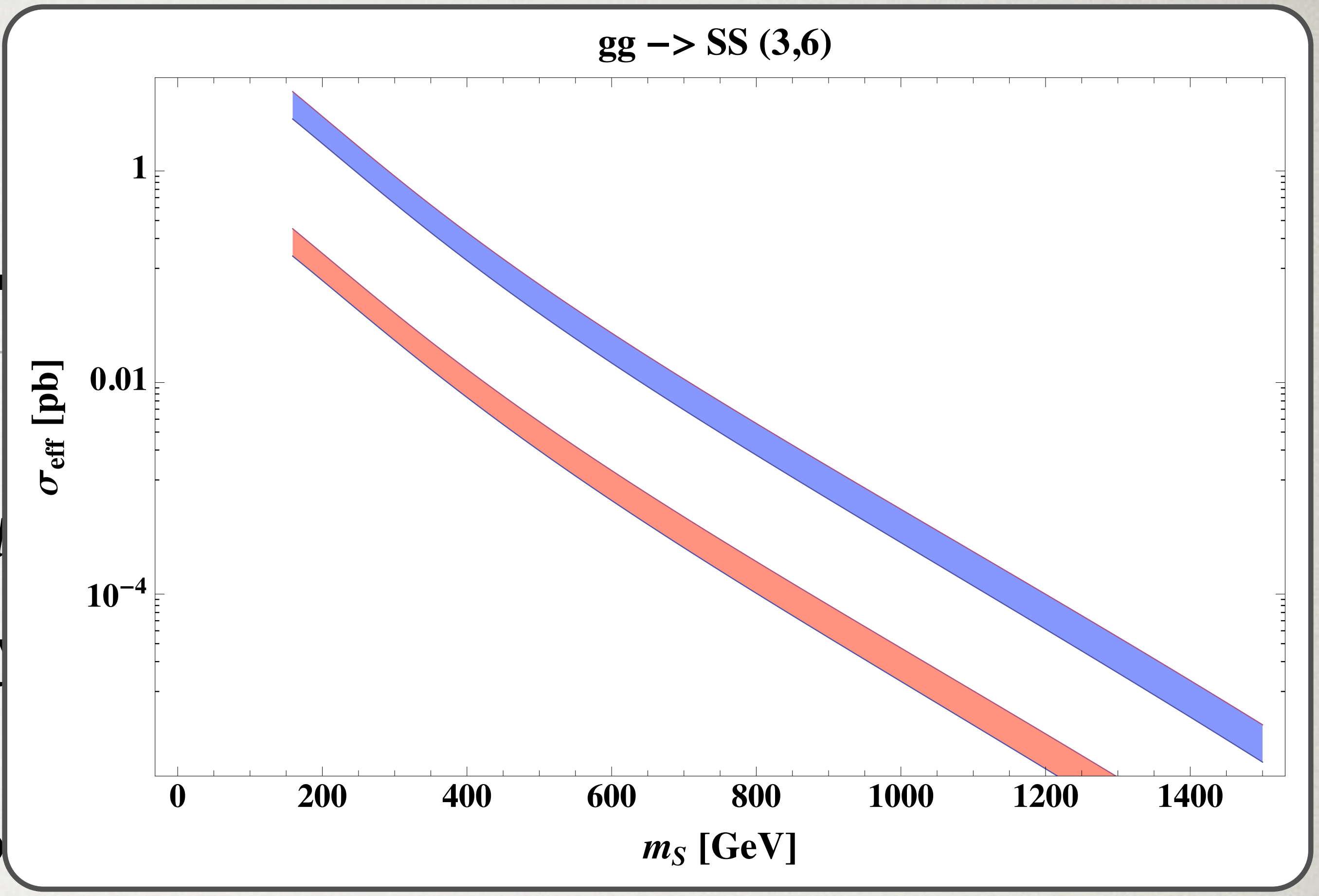
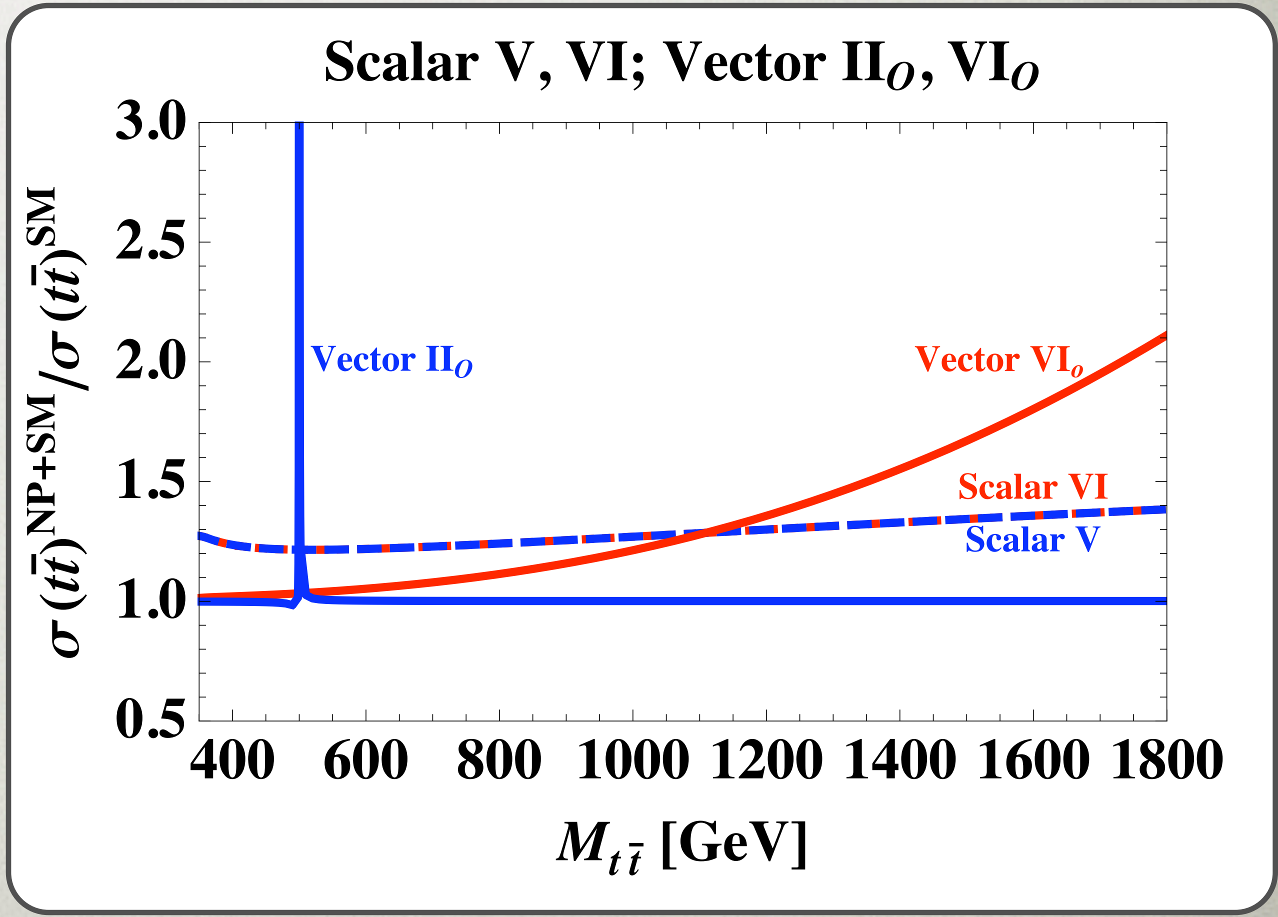




UV COMPLETE THEORY

Kagan, JZ, in progress

- data seem to prefer vectors
- UV complete theories:
  - could be flavor bosons
  - resonances of strongly coupled sector
- an explicit realization in the works
  - composite (u',c',t') weak singlet up quarks
  - composite flavor nonet vectors
  - EWSB as in technicolor
- the big question: is it still phenomenologically viable?

DARK MATTER PRODUCTION FROM FLAVOR VIOLATION

THE AIM/MOTIVATION

- flavor symm. violated in the SM
  - inevitable that also violated in the presence of NP
- can this have implications for dark matter searches?
  - monotop signatures at LHC

OUTLINE

- interested at LHC
    - so focus only on DM-quark couplings
- take a few examples of flavor breaking
    - Minimal Flavor Violation
    - horizontal symmetries
- start with EFT
    - then also on-shell resonance production

DIRECT PRODUCTION

- use EFT for DM interactions with quarks

$$\mathcal{L}_{\rm int} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a$$

- only interested in interactions with quarks

$$\mathcal{J}^{\mu}_{V,A} = \bar{\chi}\gamma^{\mu}\{1,\gamma_5\}\chi$$

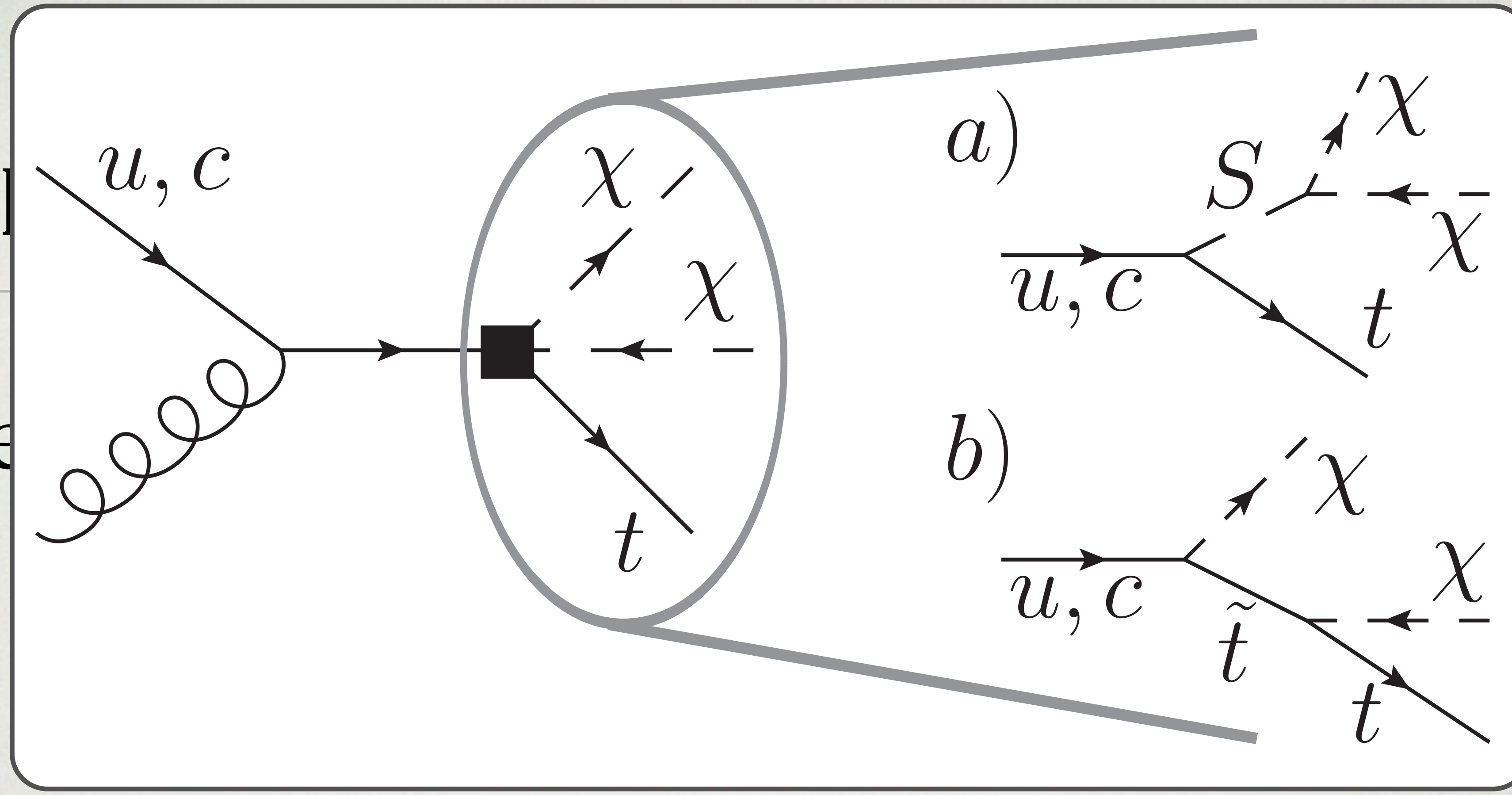
$$\mathcal{O}^{ij}_{1a} = (\bar{Q}^i_L \gamma_\mu Q^j_L)\mathcal{J}^\mu_a\,,$$

$$\mathcal{O}^{ij}_{2a} = (\bar{u}^i_R \gamma_\mu u^j_R)\mathcal{J}^\mu_a\,, \qquad \mathcal{O}^{ij}_{3a} = (\bar{d}^i_R \gamma_\mu d^j_R)\mathcal{J}^\mu_a\,,$$

$$\mathcal{O}^{ij}_{4a} = (\bar{Q}^i_L H u^j_R)\mathcal{J}_a\,, \qquad \mathcal{O}^{ij}_{5a} = (\bar{Q}^i_L \tilde{H} d^j_R)\mathcal{J}_a\,,$$

- full set includes other ops.

$$\mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi$$



- use … s

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FLAVOR VIOLATION?

- monojets are standard search for DM production
- how about monotops?
- are they big enough?
  - in fact they can be the dominant signal!

MINIMAL FLAVOR VIOLATION

- as a start look at MFV
  - the Wilson coefficients have the form

$$C_{2a} = b_1^{(2a)} + b_2^{(2a)} Y_u^\dagger Y_u + b_3^{(2a)} Y_u^\dagger Y_d Y_d^\dagger Y_u + \cdots$$
$$C_{4a} = \left(b_1^{(4a)} + b_2^{(4a)} Y_d Y_d^\dagger + \cdots\right) Y_u .$$

- in up-quark mass basis $Y_d = V_{\rm CKM}{\rm diag}(y_d, y_s, y_b)$, $Y_u = {\rm diag}(y_u, y_c, y_t)$
- assume $b_1^a \sim b_2^a \sim b_3^a$ then $C_{2a} \sim \mathbb{1}$
- the chirality flipping C_{4a} different, proportional to Yu
  - off-diagonal elements more important
- the FV $qg \to t\chi\chi$ is enhanced compared to $qg \to q\chi\chi$

MONOTOPS

- monotops the leading signal despite coming from FV

$$\frac{\hat{\sigma}(ug \to t + 2\chi)}{\hat{\sigma}(ug \to u + 2\chi)} \sim \left(\frac{y_t |V_{ub}| y_b^2}{y_u}\right)^2 \sim 5 \cdot 10^5 \, y_b^4,$$
$$\frac{\hat{\sigma}(cg \to t + 2\chi)}{\hat{\sigma}(cg \to c + 2\chi)} \sim \left(\frac{y_t |V_{cb}| y_b^2}{y_c}\right)^2 \sim 50 \, y_b^4.$$

- what have we learned?
  - *t*+MET can be >> monojet signal even in MFV
  - y_b needs to be large ~*O(1)*
  - DM needs to couple to quarks through scalar int.
- if only through Higgs no FV, need other scalars
- incidentally, this needed for isospin viol. DM models proposed to explain CoGeNT and DAMA

BEYOND MFV

- this quite generic for any model of flavor
- an example: abelian horizontal symm.

Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

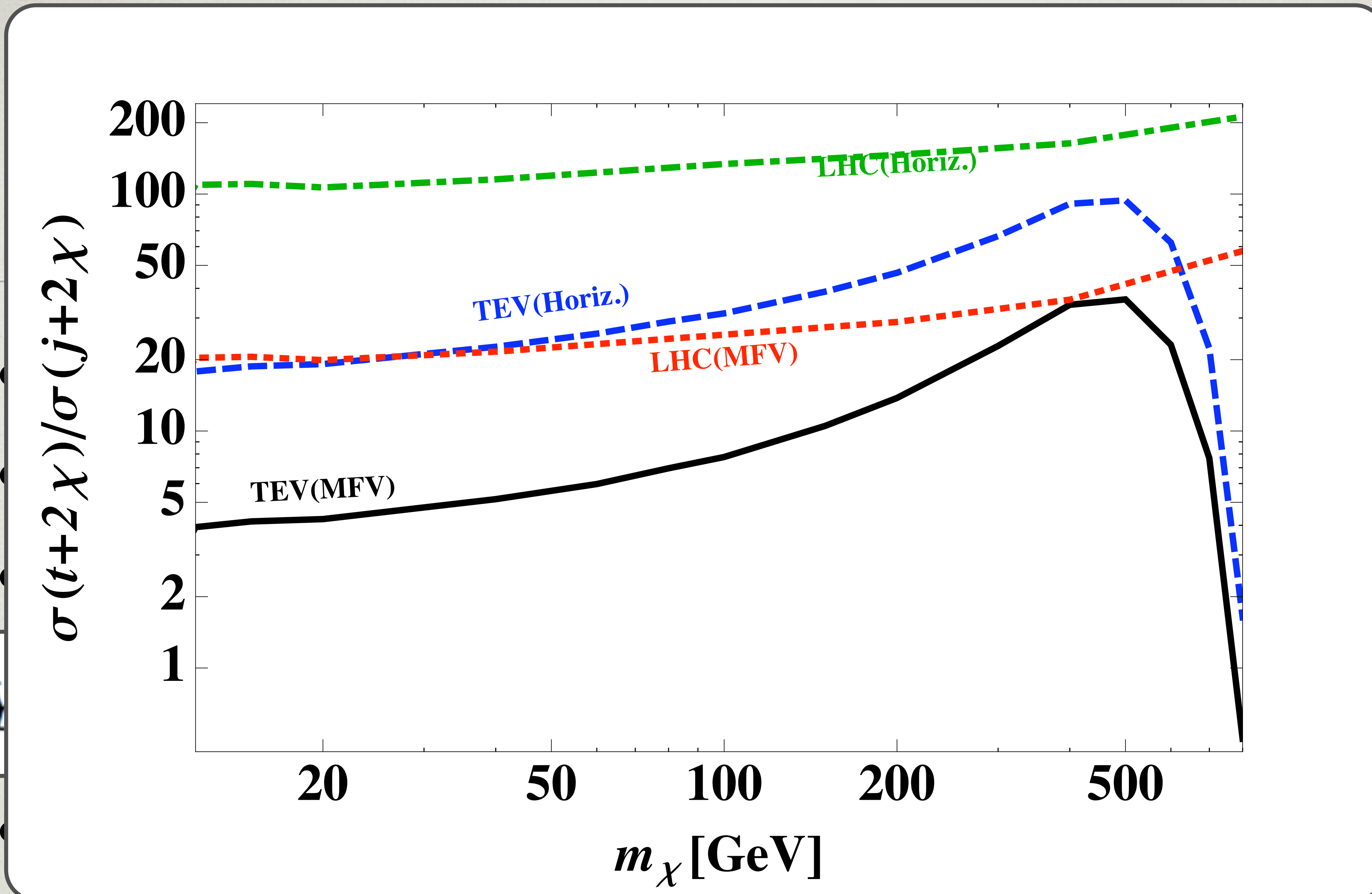
- the yukawas are given by

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \quad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}$$

- in the same way the couplings to DM

$$C_2 \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \quad C_4 \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

- note: *c*-*t*-DM coupling parametrically larger
- even larger effects if DM charged under flavor



9310320

(Y ... $Q^i)|$

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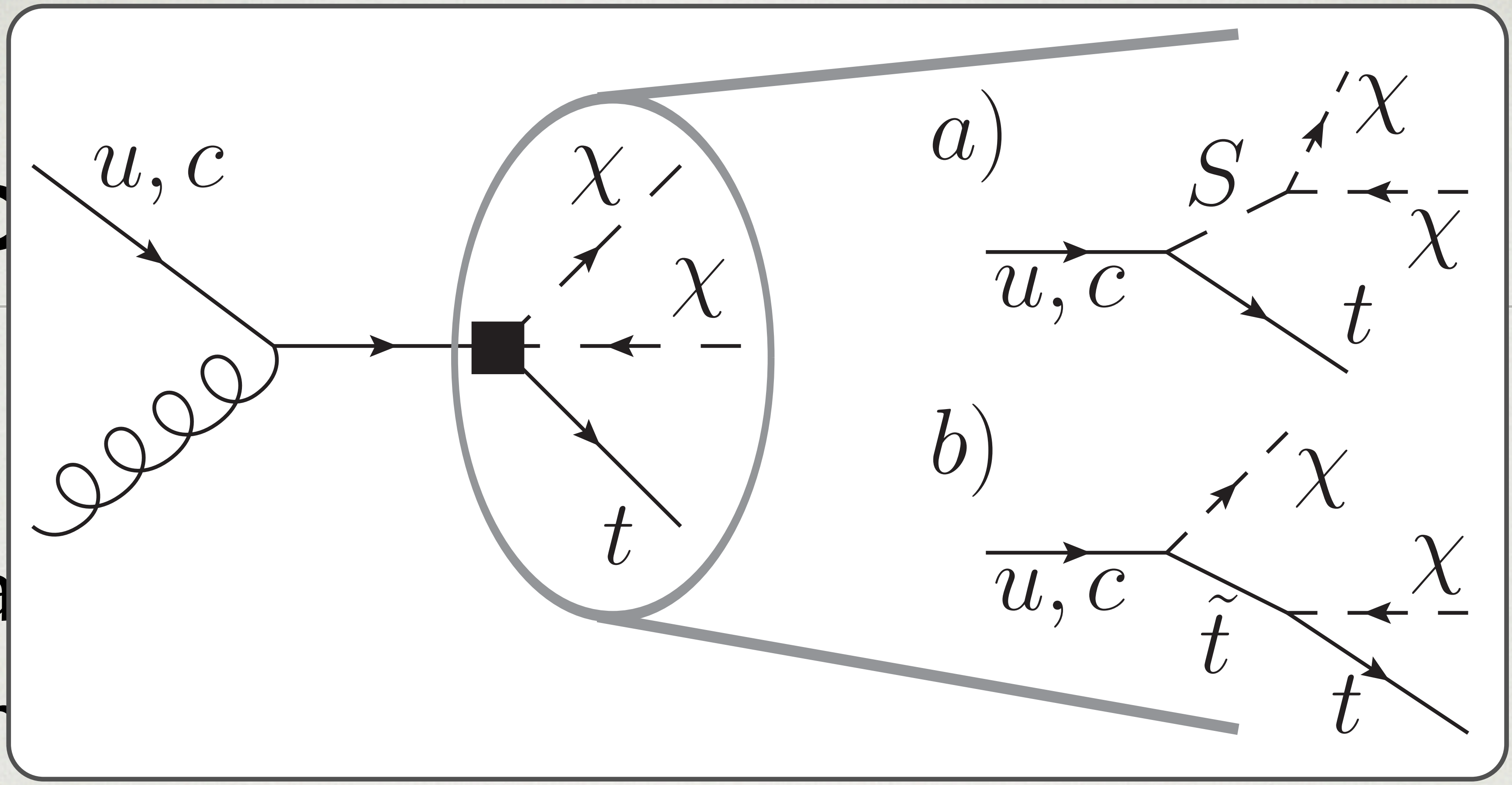
ON-SHELL PRODUCTION

- largest cross sections expected if mediators on-shell
- two classes of models
  - DM from decay of singlet S
  - exchange of mediator in t-channel
- will give an example for each of them



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- two classes of models
  - DM from decay of singlet *S*
  - exchange of mediator in t-channel
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EXAMPLE OF THE FIRST CLASS

- take S and χ to be both scalars
- after EWSB the relevant part of Lagr.

$$\mathcal{L}_{\text{int}} = g_L^u \bar{u}_R t_L S + g_L^c \bar{c}_R t_L S + g_R^u \bar{t}_R u_L S + g_R^c \bar{t}_R c_L S + \lambda v S \chi\chi + h.c.,$$

- in our hor. symm. example: $g_L{}^u \sim \lambda^3$, $g_L{}^c \sim \lambda$
- with 5 fb^{-1} 7 TeV LHC, significance of 5σ (3σ) for m_S=*200* GeV (*400* GeV)

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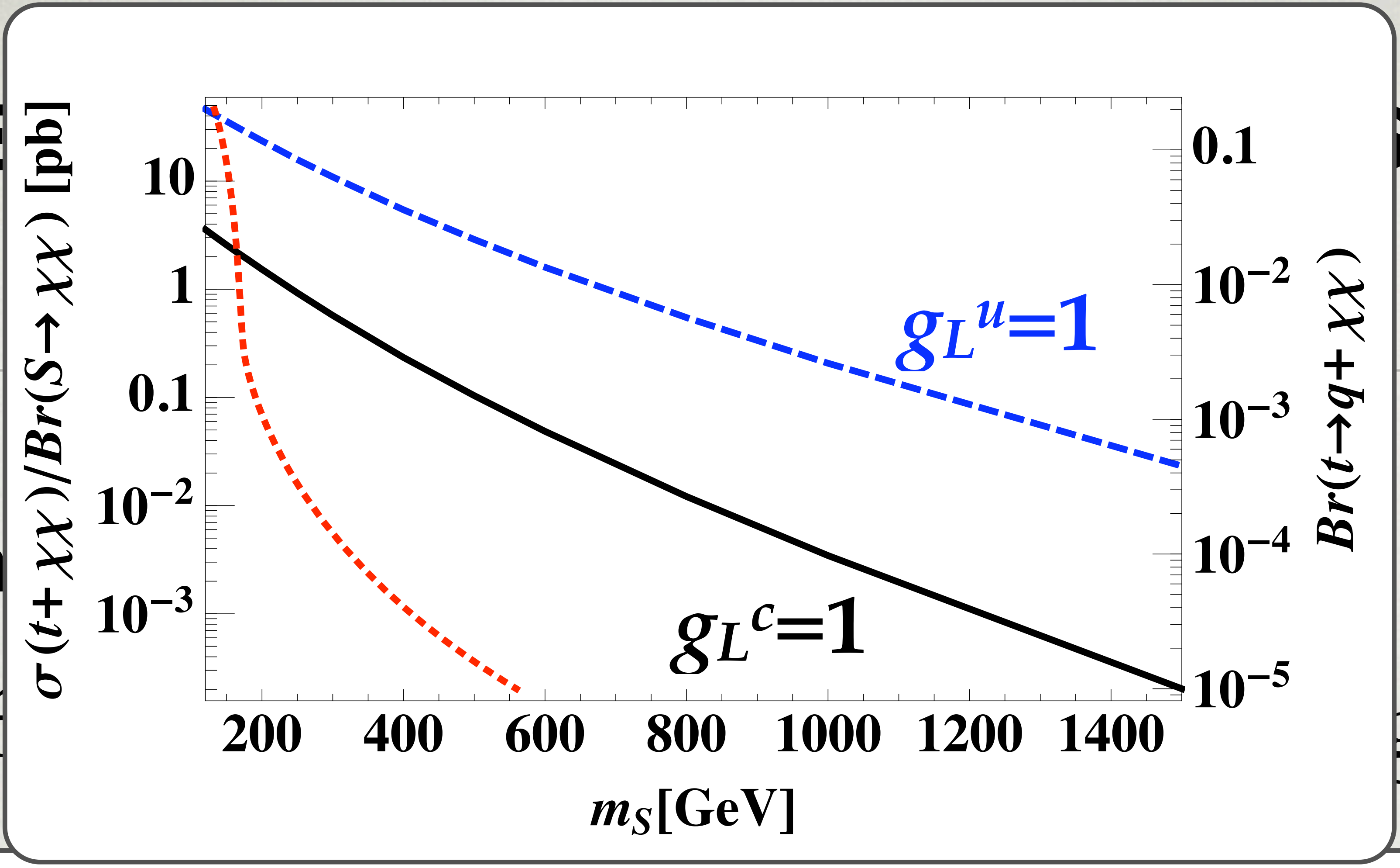

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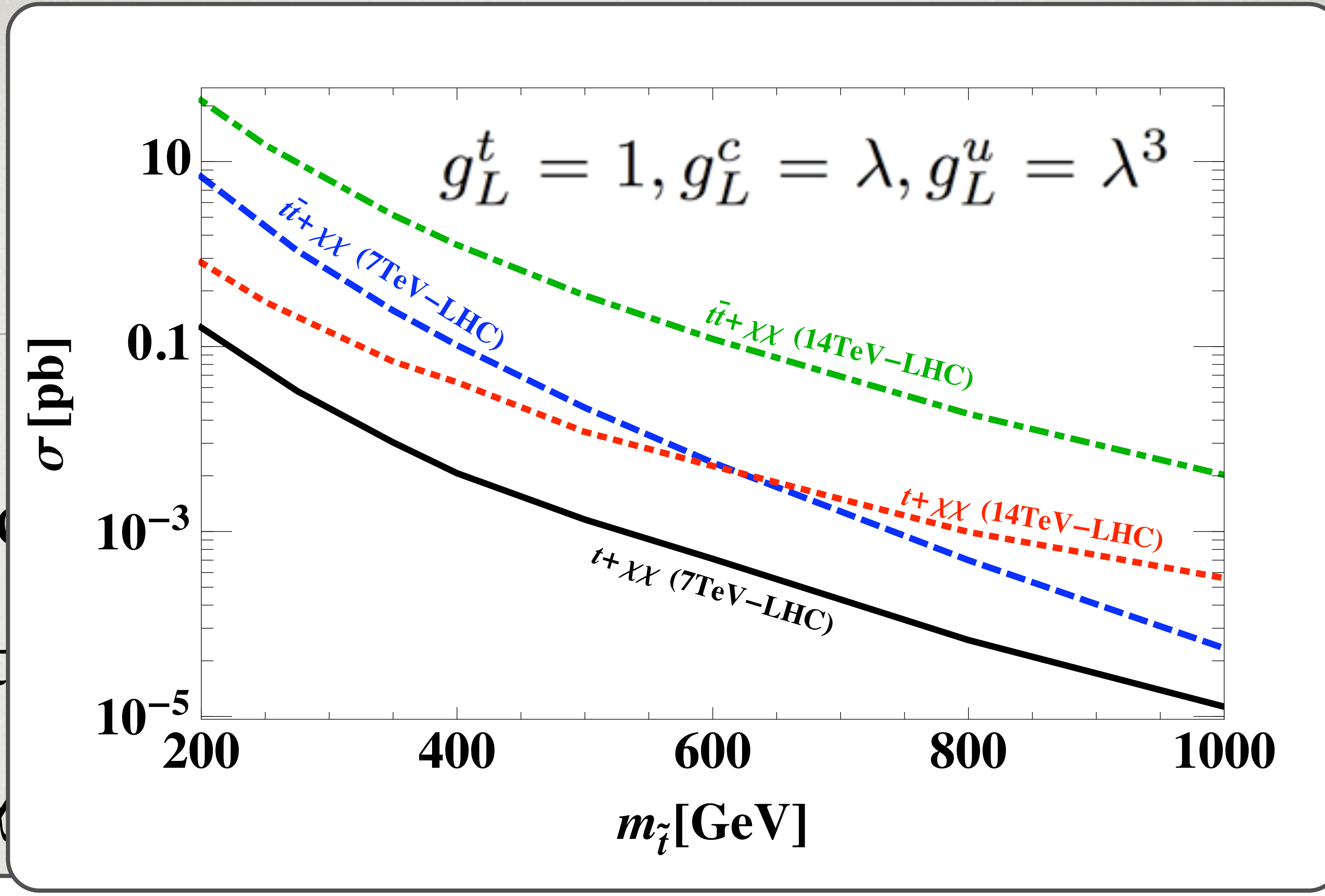
EXAMPLE FROM THE SECOND CLASS

- a toy example equiv. to MSSM keeping only
  - the lightest stop and a neutralino
  - χ_0 has large higgsino component

$$\mathcal{L}_{\rm int} = g_L^u \bar{\chi} u_R \tilde{t}_1^* + g_L^c \bar{\chi} c_R \tilde{t}_1^* + g_L^t \bar{\chi} t_R \tilde{t}_1^* + (L \to R) + h.c,$$

- t_1 can be pair produced giving *ttbar*+2 χ
- t+MET can compete only if Br($t_1 \to t + \chi$)<<100%

- a t … nly
  - t
  - χ



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- t_1 can be pair produced giving *ttbar*+2 χ
- *t*+MET can compete only if Br($t_1 \to t + \chi$)<<100%

CONCLUSIONS

- have presented a full set of fields that
  - couple to quarks in flavor symmetric way
- can describe observed $t\bar{t}$ forward backward asymmetry
- monotops can be an interesting search signal for DM production at the LHC