In Search of Lonely Top Quarks

Work with Matt Strassler and
Matt Bowen

hep-ph/0412223

Department of Physics
University of Washington

TeV4LHC, BNL 2/4/05

Outline

1. What is single-top at the Tevatron?
2. Why study it?
3. What makes it challenging – counting is not enough!
4. Another approach – Shapes Matter! (but enough?)
5. *Wjj* – the 1-ton gorilla!
6. On to the LHC [See forthcoming paper from Matt Bowen]
7. Conclusions

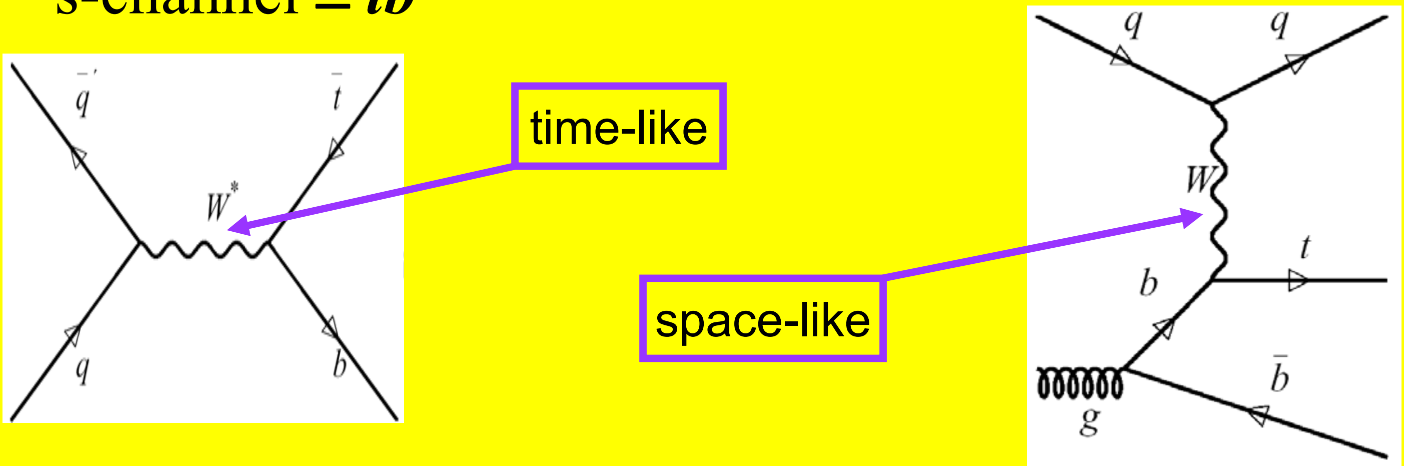
Department of Physics
University of Washington

What is single-top?

Two single-top channels are classified by W momentum

s-channel ≡ ***tb***

t-channel ≡ ***tbq***



time-like

space-like

- The top quark was discovered in Run I through $q\bar{q} \rightarrow t\bar{t}$
- Neither single-top channel has been confirmed in Run II yet

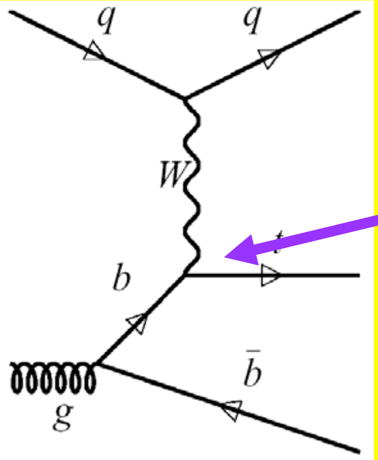
  Run I limits: $\sigma_t < 13.5$ pb, $\sigma_s < 12.9$ pb

Studying single top quark production because …

- Leads to measurement of V_{tb}
- Background to other searches (Higgs, etc.)

t-channel,

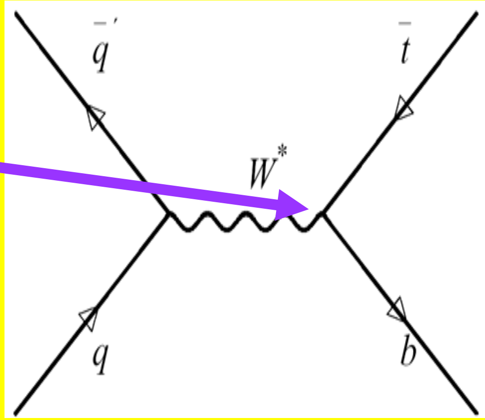
$$\sigma_{\text{t-channel, }1t} \sim 1.98\,pb\left(\sqrt{s} = 1.96\text{ TeV}\right)$$



V_{tb}

s-channel

$$\sigma_{\text{s-channel, }1t} \sim 0.88\,pb\left(\sqrt{s} = 1.96\text{ TeV}\right)$$



Plus top quark may be a special case with big payoff!!

Potential for new physics discovery

Affect
s-channel

- Extra Scalar Bosons – top-color
- Extra Gauge Bosons – top flavor
- Extra Dimensions – 5D with gauge bosons in bulk

Affect
t-channel

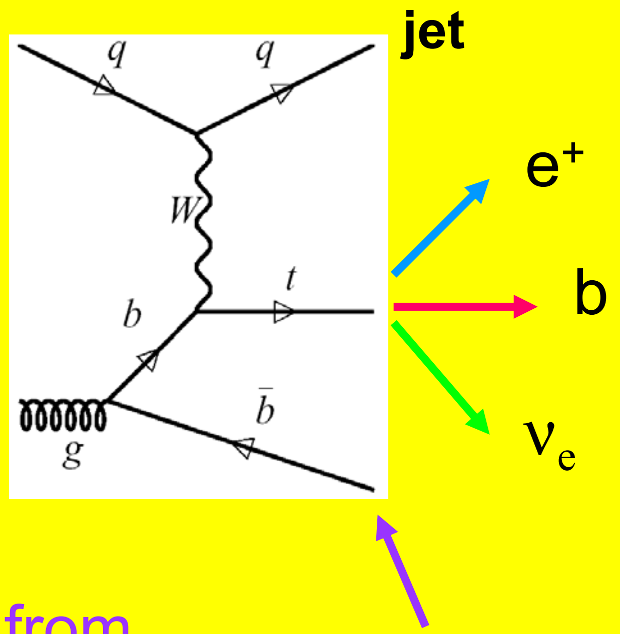
- Extra Generations of Quarks - will change unitarity constraints on CKM elements
- Extra couplings (Modified) – top interaction with SM particles. ex: Z_{tc}

See, for example, T. Tait hep-ph/0007298

Looking for the t-channel

Trigger on -

- 1 lepton (only)
- Missing Transverse Energy (from neutrino)
- 1 b-tagged jet
- 1 non b-tagged jet (from light quark)



jet

e^+

b

ν_e

often not seen

Similar for s-channel - extra jet from extra radiation! [$bg \rightarrow tW$ is too rare]

What else do we see?

- **$t\bar{t}$, e.g., $q\bar{q} \to t\bar{t} \to be^{+}\nu_{e}\bar{b}q\bar{q}$ (last year's signal is this year's background); trigger particles + lots of extra activity, but symmetrical event**

- **Wjj , e.g., $ug \to W^{+}dg \to e^{+}\nu_{e}dg$ where b tag is fake, or extra q's are b's, or *g* becomes a heavy quark pair during showering/fragmentation**

- **Pure QCD, where much (maybe leptons, maybe b and certainly the *W*) is fake. This is difficult to simulate. Experimentalists (I talk to) say it is small and we make it smaller! We will ignore it here but ….**

Define Event Samples for Counting Experiment

Studies done with Madgraph + Pythia + PGS Detector Simulation normalized to NLO (including choice of μ) where possible;
For 3 fb^{-1}, sum over $\mu^{\pm}$ and $e^{\pm}$ (top and anti-top)

PGS jets, R_{cone} =0.4; ΔR(lepton,jet) > 0.4

Advanced Cuts: "m_{top}" = invariant mass of ($bl\nu$)

$H_T = P_{T\text{lepton}}$+MET+ $\Sigma_{\text{all jets}}$ (jet P_T)
(all jets P_T > 20 GeV, $|\eta|$ < 3.5)

b-Tags: "real b" ~ 0.5 tanh(P_T/36 GeV) [P_T = jet P_T]

"real c" ~ 0.15 tanh(PT/42 GeV)

mistag ~ 0.01 tanh(PT/80 GeV)

		Basic	Intermed		Hard	
Item	|η|	P_T	P_T		P_T	
lepton	≤ 2	≥ 15 GeV	≥ 15 GeV		≥ 15 GeV	
MET	-	≥ 15 GeV	≥ 15 GeV		≥ 15 GeV	
Jet (b-tag)	≤ 2	≥ 20 GeV	≥ 20 GeV		≥ 60 GeV	
Jet (no b)	≤ 3.5	≥ 20 GeV	≥ 20 GeV		≥ 30 GeV	
			Min	Max	Min	Max
H_T			180 GeV	250 GeV	180 GeV	250 GeV
“m_t”			160 GeV	190 GeV	160 GeV	190 GeV

Events in 3 fb^{-1}

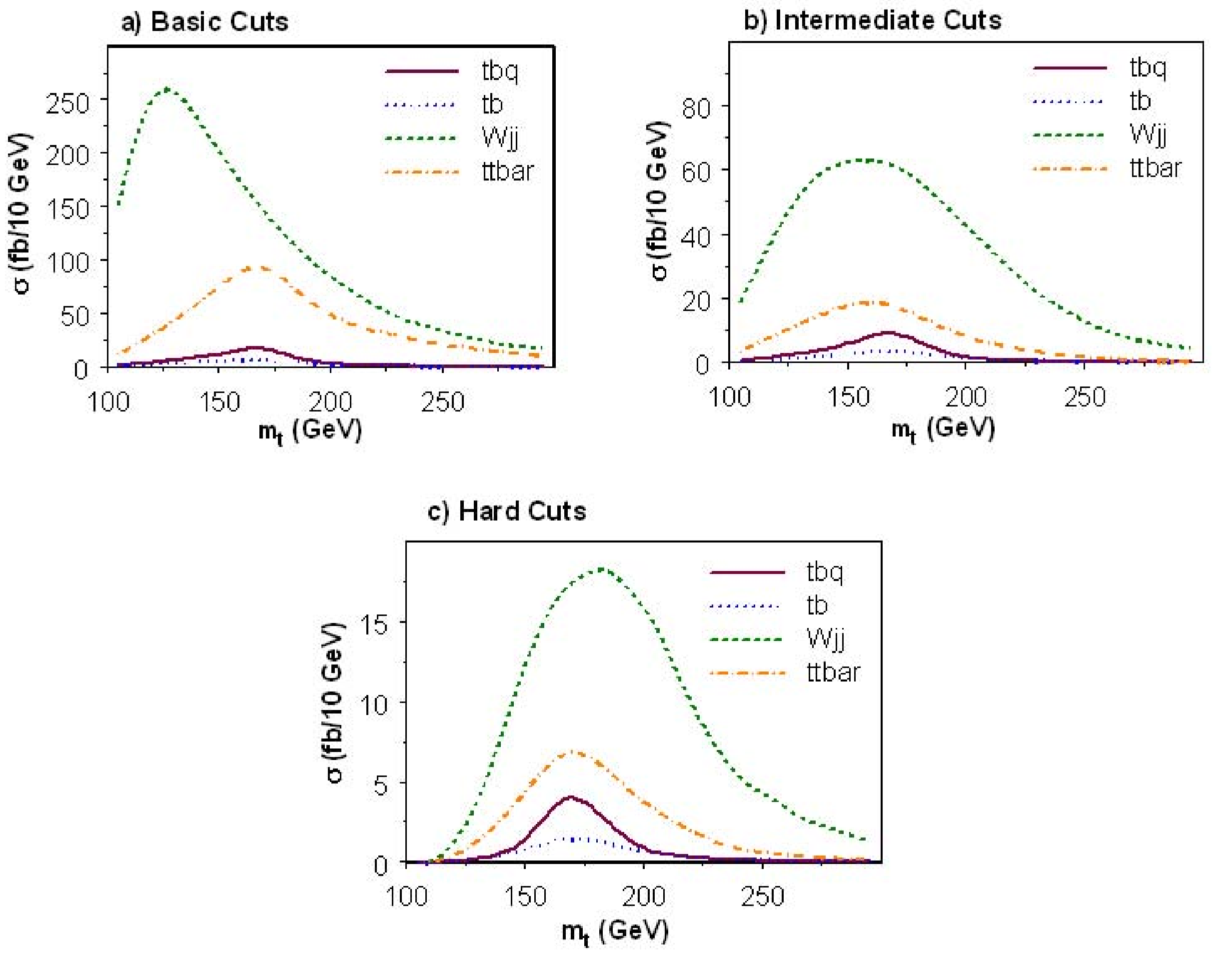
Channels	Basic	Intermed	Hard	Sys Unc
t-channel	298	67	30	>10%
s-channel	145	27	13	>10%
W+jj	6816	550	152	>10%
$t\bar{t}$	2623	140	57	>10%
Sig/Bkg	1/21	1/7	1/5	

Conclude that Life is Hard!!!

Contrast with the 1:2 ratio suggested by Stelzer, Sullivan and Willenbrock (SSW), hep-ph/9807340

- **SSW were more optimistic about the Tevatron energy and the top quark cross section than is now appropriate**
- **SSW were more optimistic about light quark/gluon mistagging (as b) than we are –**
  - **Mistagged at ~ 1% rate, $P_T > 80$ GeV**
  - **g → c, b at ~ 0.1- 0.2% rate during (Pythia) showering/fragmentation**
  - **⇒ comparable contributions to background rate**
- **SSW were more optimistic about top quark mass reconstruction than we are**

Note: Doing Sideband cuts on m_t is difficult due to "shaping" from other cuts!



Look for more handles on data: symmetries, correlations and event shapes

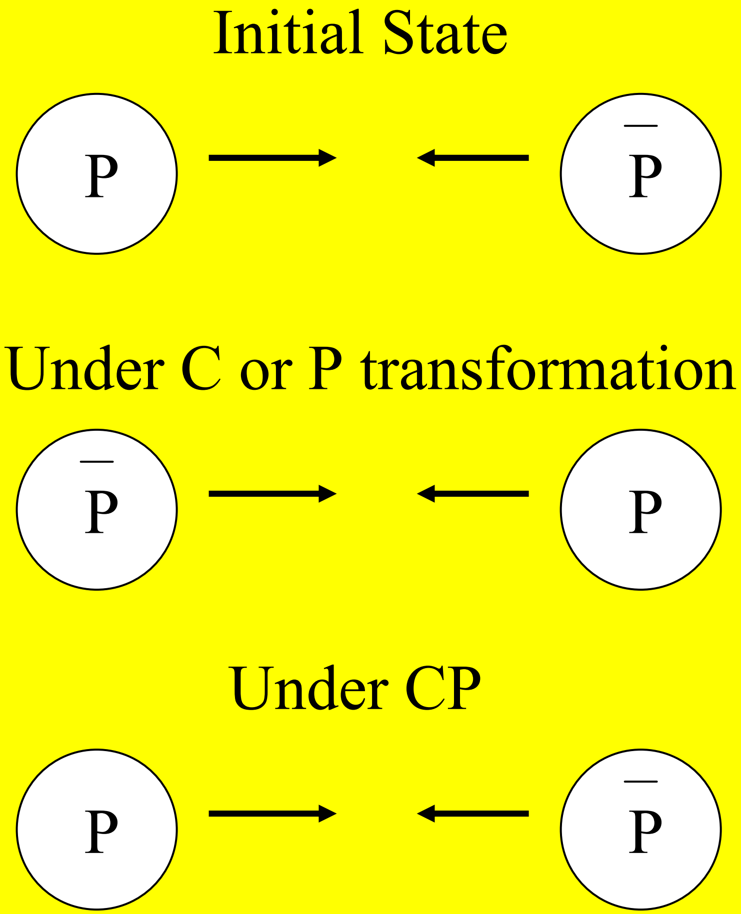
- **CP symmetry, C & P asymmetry of initial state**

- **Kinematic asymmetry of Initial state:** qg **(asymmetric) vs** $q_V\bar{q}_V$ **(symmetric)**

- **In t-channel signal dynamical correlation between scattered q and final lepton due to LH *W* vertex and carried by top quark spin (which decays before it interacts),** $q \rightarrow t \Uparrow \rightarrow l^+$

CP Invariance of the Tevatron

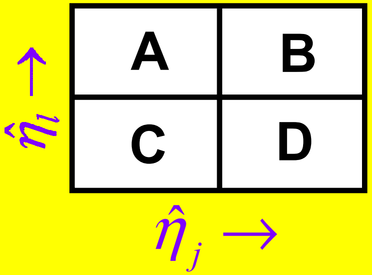
1. $p\bar{p}$ initial state at Tevatron is CP invariant, but not C or P invariant separately
2. Perturbative Final state is CP invariant, but may violate C or P
3. Depends on Perturbative Initial state: *qg* (asym) ⇔ *gg* (sym)
4. Depends on dynamics: LO s-channel gluon “forgets” asymmetry ($t\bar{t}$ and QCD)
5. Processes with W’s “remember” asymmetries (single top and W+jets)


Initial State

Under C or P transformation

Under CP

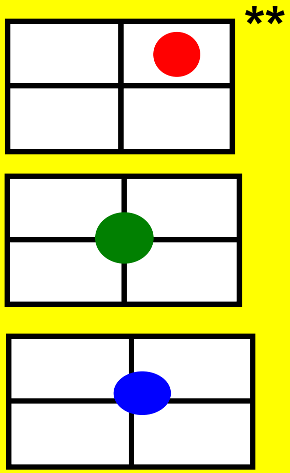
Focus on 2-D distributions in signed rapidity, $\hat{\eta} = Q_l \eta$ *



$$\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j} \equiv \frac{d\sigma^+}{d\eta_l d\eta_j}\left(\hat{\eta}_l, \hat{\eta}_j\right) + \frac{d\sigma^-}{d\eta_l d\eta_j}\left(-\hat{\eta}_l, -\hat{\eta}_j\right)$$

CP invariant

- **Same correlations in t and $\bar{t}$**
- **Strong correlation in t-channel signal, $\hat{\eta}_l, \hat{\eta}_j > 0$**
- **Very weak correlation in s-channel and $t\bar{t}$**
- **Weak, but similar correlation in Wjj**



***Used by CDF in 1-D analysis**

****Indicates C or P non-invariance**

Define “Relaxed” Event Sample for Shape Analysis

		Relaxed	
Item	**|η|**	P_T	
lepton	**≤ 2**	**≥ 15 GeV**	
MET	**-**	**≥ 15 GeV**	
Jet (b-tag)	**≤ 2**	**≥ 40 GeV**	
Jet (no b)	**≤ 3.5**	**≥ 30 GeV**	
		Min	**Max**
H_T		**none**	**300 GeV**
“m_t”		**155 GeV**	**200 GeV**

Keep more of signal and more background, especially $t\bar{t}$,

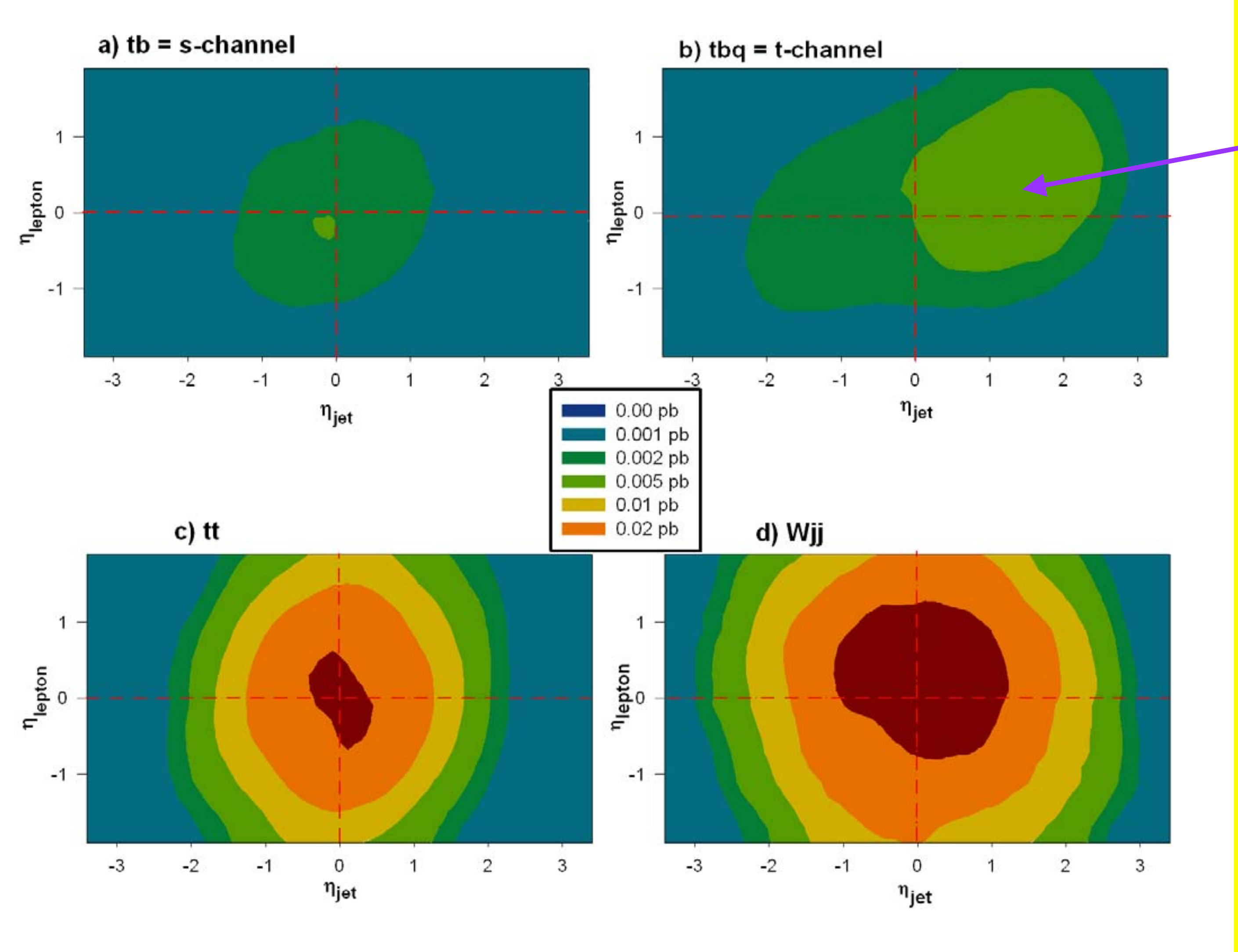
But that is OK!

Contour plots of 4 channels – as predicted

Sig

$$\int \frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}$$

Bkg



!

Focus on Shape with following basis functions

Complete & Orthogonal

$$\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,\hat{\eta}_j\right)=\frac{d\sigma^+}{d\eta_l d\eta_j}\left(\hat{\eta}_l,\hat{\eta}_j\right)+\frac{d\sigma^-}{d\eta_l d\eta_j}\left(-\hat{\eta}_l,-\hat{\eta}_j\right)=\bar{F}\left(\hat{\eta}_l,\hat{\eta}_j\right)+F_+\left(\hat{\eta}_l,\hat{\eta}_j\right)+F_-\left(\hat{\eta}_l,\hat{\eta}_j\right)\quad[\text{CP Inv}]$$

$$\bar{F}\left(\hat{\eta}_l,\hat{\eta}_j\right)=\frac{1}{4}\left[\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,\hat{\eta}_j\right)+\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,-\hat{\eta}_j\right)+\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,\hat{\eta}_j\right)+\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,-\hat{\eta}_j\right)\right]\quad[\text{Sym}]$$

$$F_+\left(\hat{\eta}_l,\hat{\eta}_j\right)=\frac{1}{4}\left[\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,\hat{\eta}_j\right)+\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,-\hat{\eta}_j\right)-\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,\hat{\eta}_j\right)-\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,-\hat{\eta}_j\right)\right]\quad[\text{P Even}]$$

- **Uncorrelated bits cancel in F_+**

$$F_-\left(\hat{\eta}_l,\hat{\eta}_j\right)=\frac{1}{2}\left[\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,\hat{\eta}_j\right)-\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,-\hat{\eta}_j\right)\right]\quad[\text{P Odd}]$$

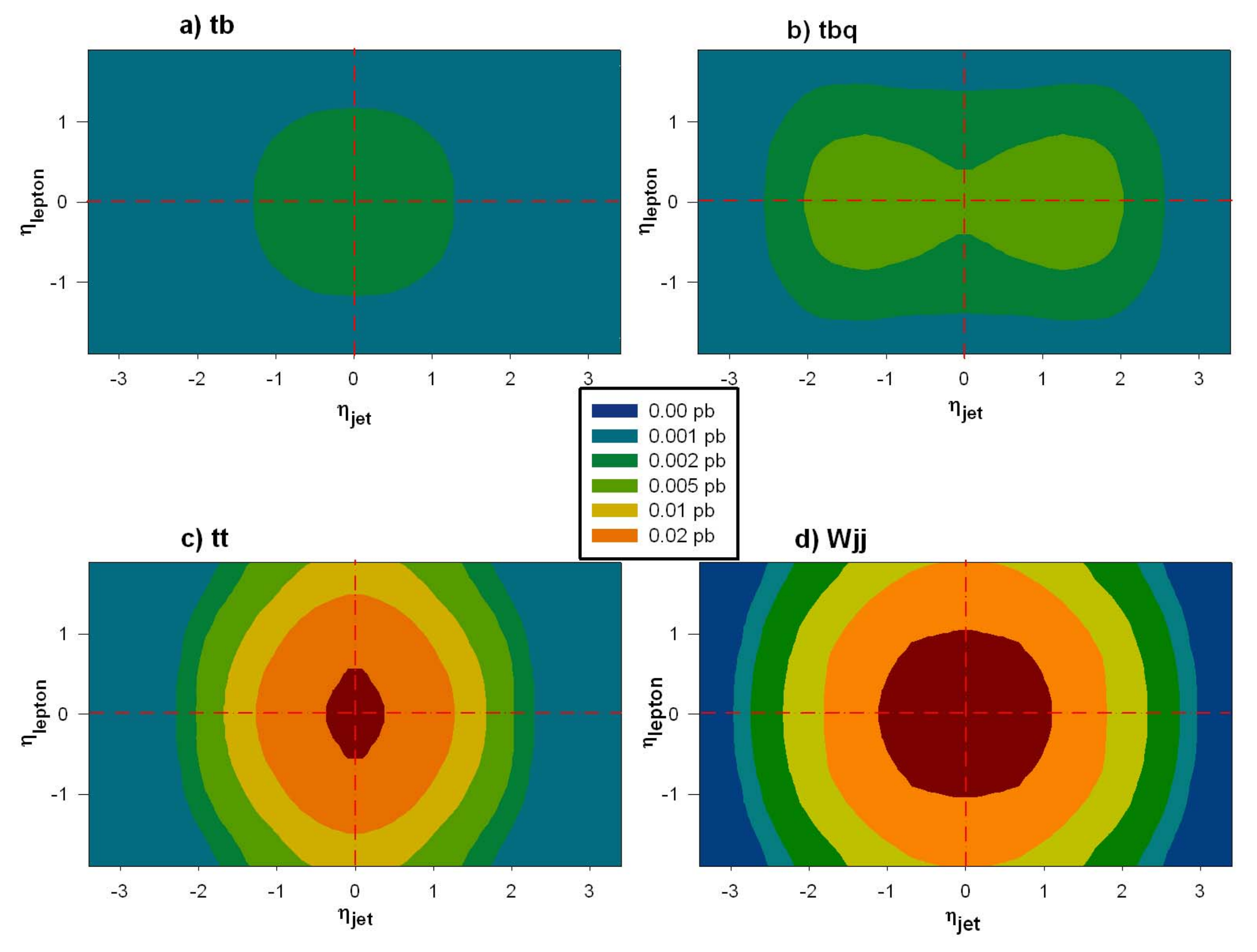
Uncorrelated and P even

- **Uncorrelated –** $\dfrac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j} = f\left(\hat{\eta}_l\right) g\left(\hat{\eta}_j\right)$
- **P even** $f\left(\hat{\eta}_l\right) = f\left(-\hat{\eta}_l\right) : g\left(\hat{\eta}_j\right) = g\left(-\hat{\eta}_j\right)$
- $\Rightarrow$

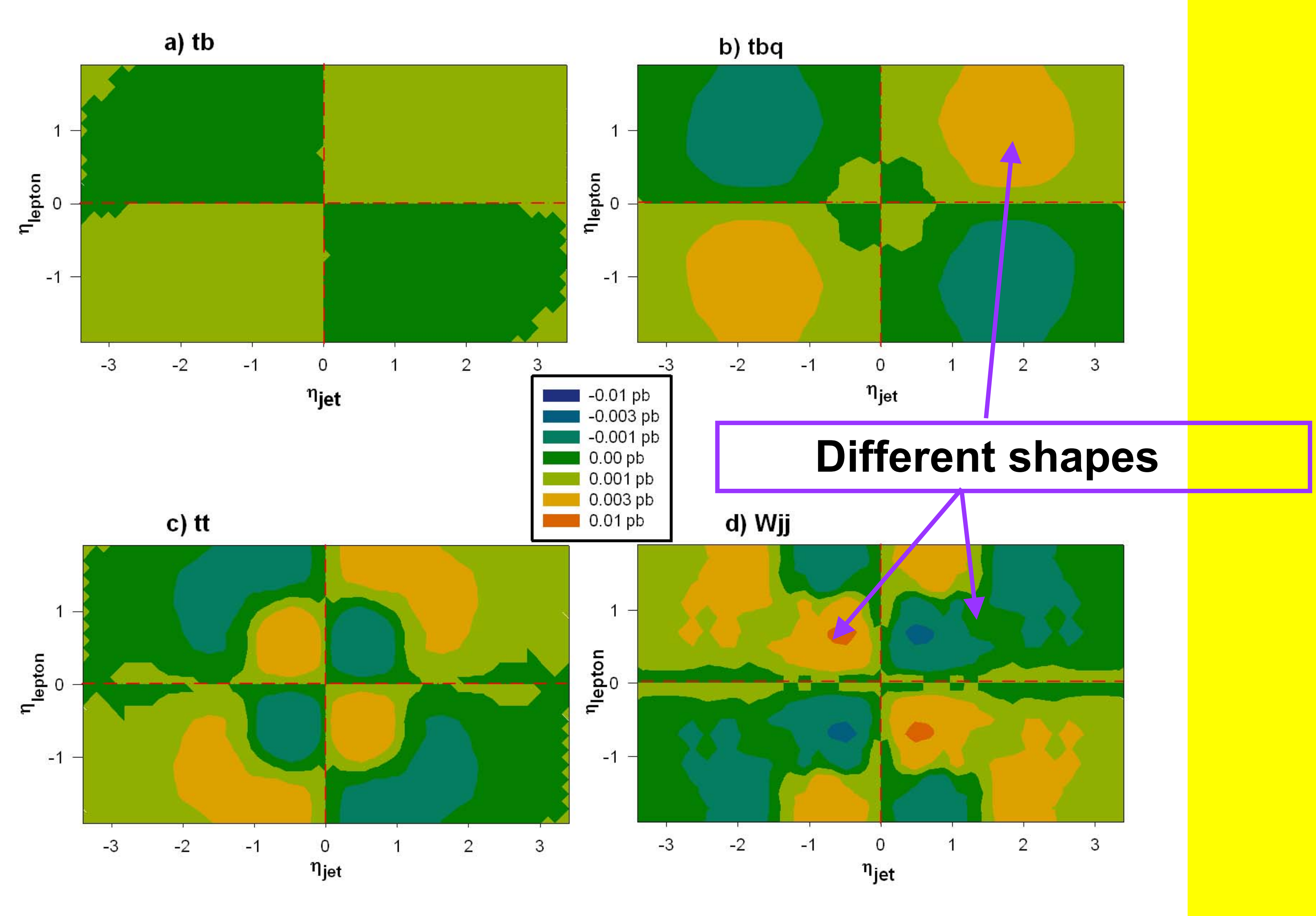
$$\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,\hat{\eta}_j\right) = \frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,-\hat{\eta}_j\right) = \frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(-\hat{\eta}_l,\hat{\eta}_j\right)$$
$$= \frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,-\hat{\eta}_j\right)$$

$\Rightarrow$ **Cancel in F_+ and F_-**

$\bar{F}\left(\hat{\eta}_l,\hat{\eta}_j\right)$ $\bar{F}^{t\bar{t}} \sim \bar{F}^{Wjj} \square \bar{F}^{tb} \sim \bar{F}^{tbj}$

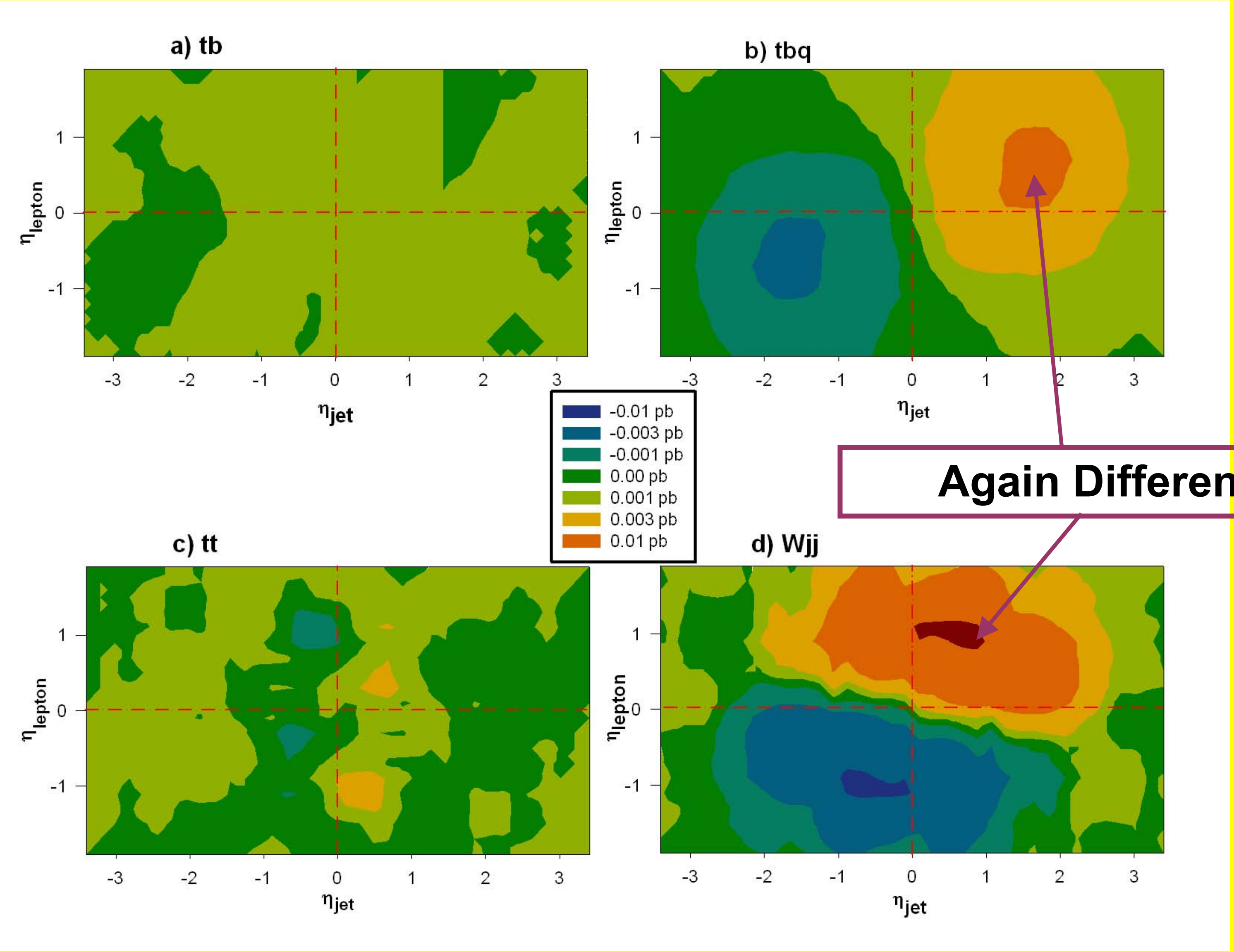


$F_+(\hat{\eta}_l,\hat{\eta}_j)$ $F_+^{Wjj} \sim F_+^{tbj} \sim F_+^{t\bar{t}} \square F_+^{tb}$



Different shapes

$F_-\left(\hat{\eta}_l, \hat{\eta}_j\right) \qquad F_-^{Wjj} \sim F_-^{tbj} \; \square \; F_-^{t\bar{t}} \geq F_-^{tb}$



Again Different

Quantify this by again looking at the sum over $t + \bar{t}$, $e + \mu$ in the quadrants for 3 fb^{-1}

Channel	$\bar{F}_A = \bar{F}_B$	$F_{+,B} = F_{+,A}$	$F_{-,A}$	$F_{-,B}$
s-channel	9.8 ± 1.6	1.4 ± 1.6	0.0 ± 2.1	-0.3 ± 2.4
t-channel	23.8 ± 2.4	5.6 ± 2.4	-3.7 ± 3.0	11.6 ± 3.8
$t\bar{t}$	106.1 ± 5.2	1.2 ± 5.2	-0.2 ± 7.2	1.3 ± 7.3
Wjj	187.7 ± 6.9	-4.6 ± 6.9	11.8 ± 9.8	23.8 ± 9.6

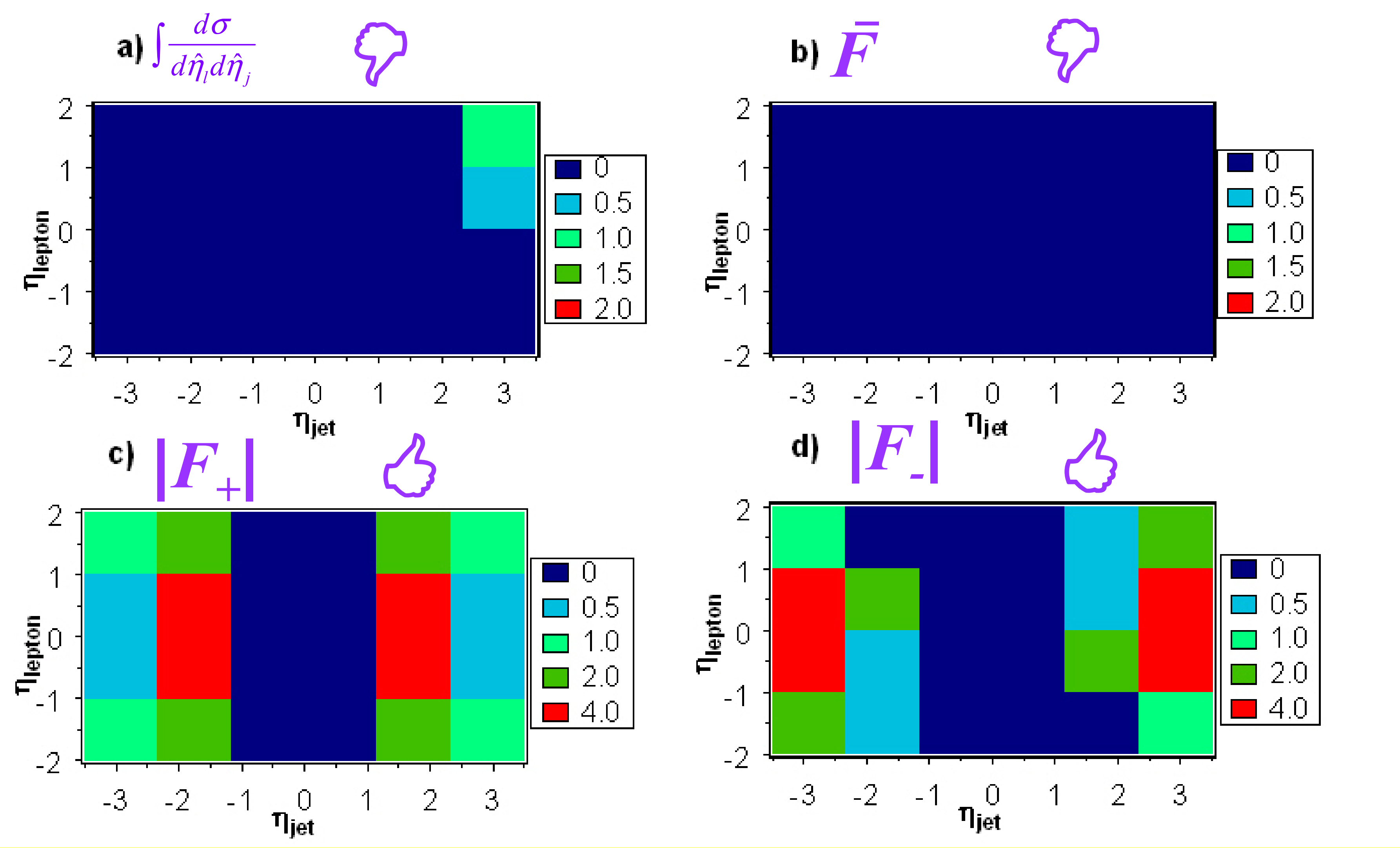
± Statistical Errors

Suggests

- Use $\bar{F}$ to determine (check) Bkg
- Use $F_{-,A}$ to determine (check) Wjj
- Use $F_{-,B}$ & F_+ to determine Signal

The signal is enhanced,
But Sig/Bkg still ≤ 1/1

Signal/Background


a) $\int \frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}$

b) $\bar{F}$

c) $|F_+|$

d) $|F_-|$

⇒Systematics of Bgk matters except in small regions!

Suggests that (maybe) we can separate Signal and Background if we use the Shape information, But only if we control Bkg systematics!

- **Systematic issue #1: The 1-ton gorilla - Do we understand the shape of the *Wjj* background in detail?**

- **Answer: Not Yet! There are many individual channels with somewhat different shapes, whose relative contribution rates depend largely on mistag rates and *g* → *b,c* rates.**

- **But we will learn using the many different handles on the data, e.g., look at *Zjj*!!**

- ***Understanding Wjj*, including tagging and *g* → *b,c* rates, *should be a priority!!!***

Wjj channels Tagging

Channel	σ(Before tag, pb)	σ(After tag, pb)	Fraction tagged
Wqq	16740	192	1%
Wqg	32000	732	2%
Wgg	14760	484	3%
Wcq	3200	318	10%
Wcg	2240	238	11%
$W c\bar{c}$	600	104	17%
$W b\bar{b}$	496	224	45%
Total	69766	2291	3%

Small σ, Large tag rate ⇔ Large σ, Small tag rate

Wjj tag budget

Channel	b-jet	c-jet	Non-b/c-jet	Total
Wqq	2%	1%	6%	9%
Wqg	11%	8%	14%	33%
Wgg	7%	5%	5%	17%
Wcq	0%	14%	1%	15%
Wcg	1%	10%	0%	11%
$W c\bar{c}$	0%	5%	0%	5%
$W b\bar{b}$	10%	0%	0%	10%
Total	31%	43%	26%	100%

Democracy at work! But different channels have different shapes!

We can improve by choosing specific "windows" – helps also with statistical, √*N* issues

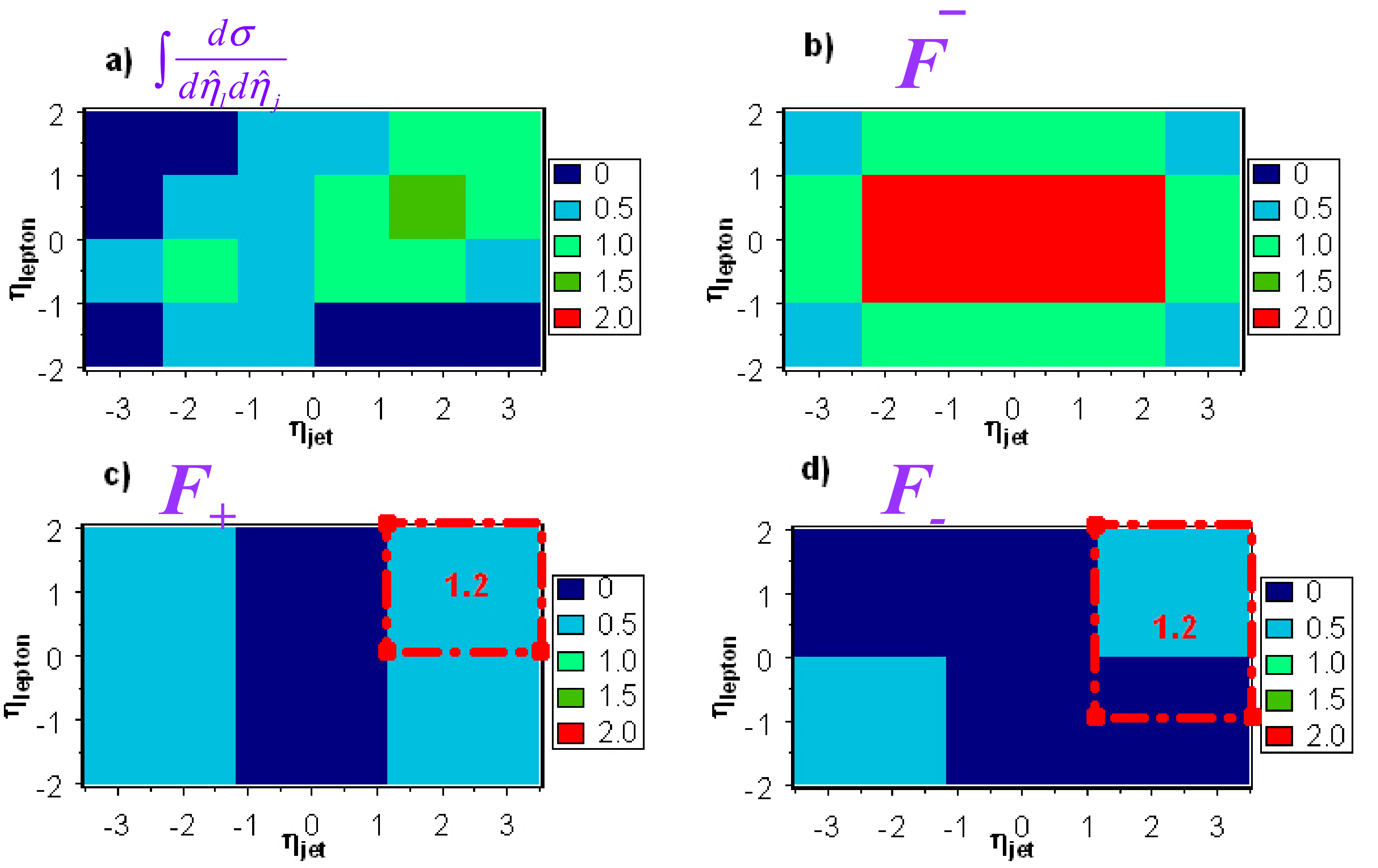
- Uncertainty in N_{F+} : in any region of $\eta\eta$ plane

$$\sigma_{N_{F_+}} \approx \frac{1}{4}\sqrt{N_{Tot}} = \frac{1}{2}\sqrt{N_{\bar{F}}}$$

- Uncertainty in N_{F-} :

$$\sigma_{N_{F_-}} \approx \frac{1}{2}\sqrt{N_B + N_C} = \frac{1}{\sqrt{2}}\sqrt{N_{\bar{F}} + N_{F_+}}$$

N/ √N (appropriate)



No region with good Systematics & good Statistics

Can also consider a likelihood analysis based on the difference in shapes – Assuming we really know the shapes!!

- $\alpha = N_{Sig}/N_{Tot} \approx 0.103$ (all of phase space)

- Uncertainty

$$\sigma_{\alpha} = \sqrt{\frac{1}{N_{Tot} \int d\hat{\eta}_l d\hat{\eta}_j \frac{\left[f_{Sig}\left(\hat{\eta}_l,\hat{\eta}_j\right) - f_{Bkg}\left(\hat{\eta}_l,\hat{\eta}_j\right)\right]^2}{f_{Tot}\left(\hat{\eta}_l,\hat{\eta}_j\right)}}} \approx 0.035$$

$$\int f_X d\hat{\eta}_l d\hat{\eta}_j = 1$$

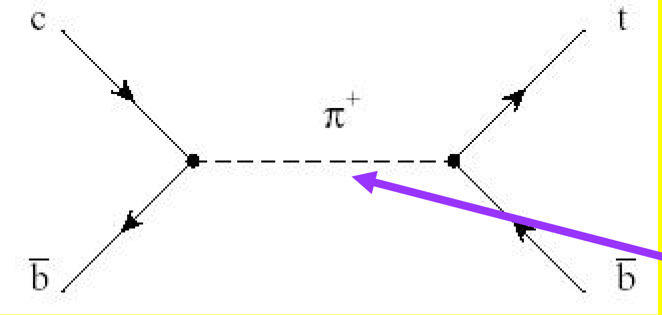
Conclusions

- **Phenomenology at hadron colliders is tough!**
- **Shape variables are useful/essential for finding the single top quark signal**
- **But we need to understand the shapes and systematics of the backgrounds, especially *Wjj* (and QCD), including tagging and heavy flavor in showers**
- **Understanding *Wjj* is Priority for TeV4LHC!**

Extra Detail Slides

Extra (Pseudo-)Scalar Bosons: Top-color models

- Scalars (such as Higgs) exist as bound states of top and bottom quarks
- For $M_{\pi\pm}$ = 250 GeV, t_R-c_R mixing of ~20% s-channel cross-section doubles
- No interference as SM is from left-handed light quarks
- t-channel contribution is suppressed by $1/M_{\pi\pm}^2$ and that $\pi^\pm$ doesn't couple to light quarks



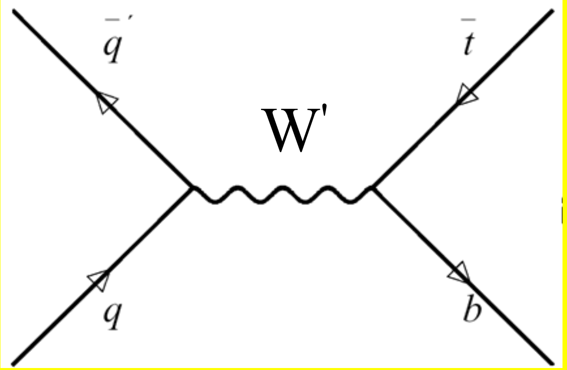
time-like momentum allows for resonance

e.g., He & Yuan: hep-ph/9810367

Extra Gauge Bosons: Top-flavor models

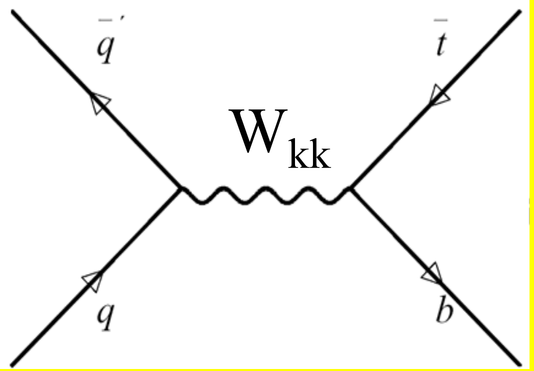
e.g., $\boxed{SU(3)_C \times SU(2)_h \times SU(2)_l \times U(1)_Y}$

- Postulate a larger gauge group which reduces to the SM gauge group at low energies to explain top mass
- 1st and 2nd gen quarks transform under $SU(2)_l$, and 3rd under $SU(2)_h$, add heavy doublet of quarks
- $SU(2)_h$ gauge couplings mix with $SU(2)_l$ according to $\sin^2\varphi$
- For $M_{W'}$ = 1 TeV, $\sin^2\varphi$ =0.05 s-channel increases ~20%
- t-channel contribution suppressed by $1/M_{W'}^2$



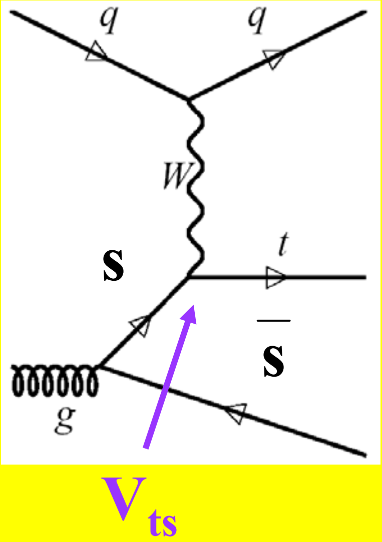
Extra Dimensions: 5-D Gauge Bosons

- Allow only SM gauge bosons to propagate in compactified extra dimension
- Permits Kaluza-Klein modes of W (W_{kk})
- For M_{Wkk}= 1TeV, s-channel amplitudes interfere destructively to reduce cross-section by 25%
- t-channel contributions are suppressed by $1/M_{W'}^2$



Extra quark generations: CKM constraints

- For 3 generations, the unitary of the CKM matrix constrains $|V_{ts}| < 0.043$
- With >3 generations, one possibility is $|V_{tb}|=0.83$ and $|V_{ts}|=0.55$
- Because gluons split to ss far more than bb, the t-channel cross-section rises by 60%
- s-channel produces as many tops as before, but less with an additional b quark – so the <u>observable</u> cross-section goes down a little.
- Changes decay structure of top

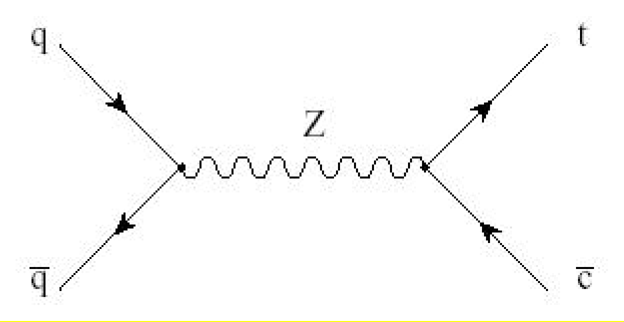


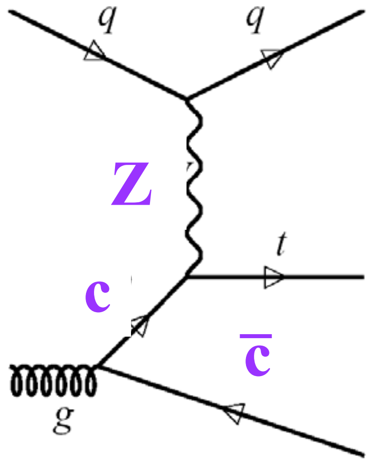
Without imposing 3 family unitarity, these are the 90% CL direct constraints.

$$V = \begin{pmatrix} 0.9722-0.9748 & 0.216-0.223 & 0.002-0.005 & \dots \\ 0.199-0.233 & 0.784-0.976 & 0.037-0.043 & \dots \\ 0-0.09 & 0.0-\boxed{0.55} & 0.06-0.9993 & \dots \\ \dots & \dots & \dots & \dots \end{pmatrix}$$

Extra Couplings*: FCNC: Z-t-c

- Can argue that low energy constraints (κ_{Ztc} < 0.3) may not apply in the presence of additional new physics
- For κ_{Ztc} = 1, t-channel increases 60%
- These couplings change top decay structure
- κ_{Ztc} recently constrained by LEP II data to be < ~ 0.5 (hep-ex/0404014)

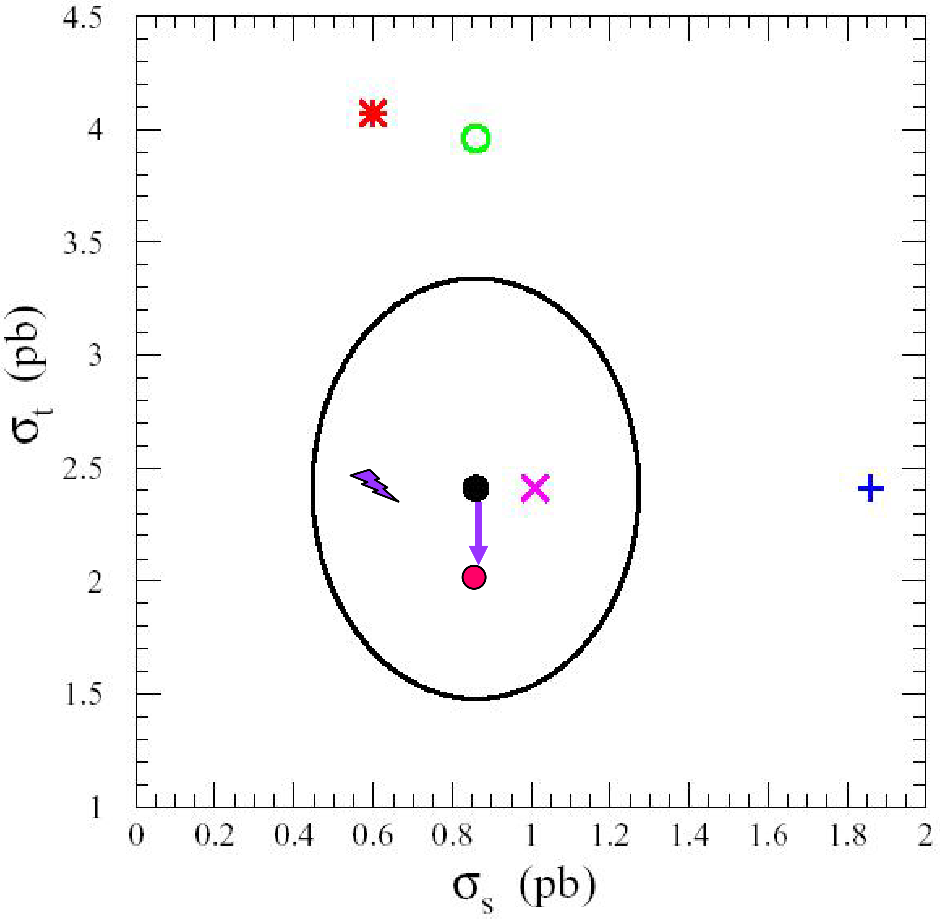




*there's nothing "extra" about these couplings; the appropriate title would be "Modifications to Top Couplings"

Shifted cross-sections plot

- ● SM prediction
- — 3σ theoretical deviation
- + Charged top-pion
- ○ FCNC Z-t-c vertex
- × 4 gen
- ✱ Top-flavor model
- ⚡ Extra dimensions



Plot from hep-ph/0007298
t-channel CS has changed to 1.98pb
ED ⚡ from hep-ph/0207178

Lessons

1) t-channel is affected by modifications to top quark couplings
2) s-channel is affected by heavy particles
3) Many other models to consider, good practice for general searches

Therefore, measuring the t- and s-channels separately is important and could potentially be a "Window to Physics Beyond the SM"