In Search of Lonely Top Quarks

Work with Matt Strassler and Matt Bowen

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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

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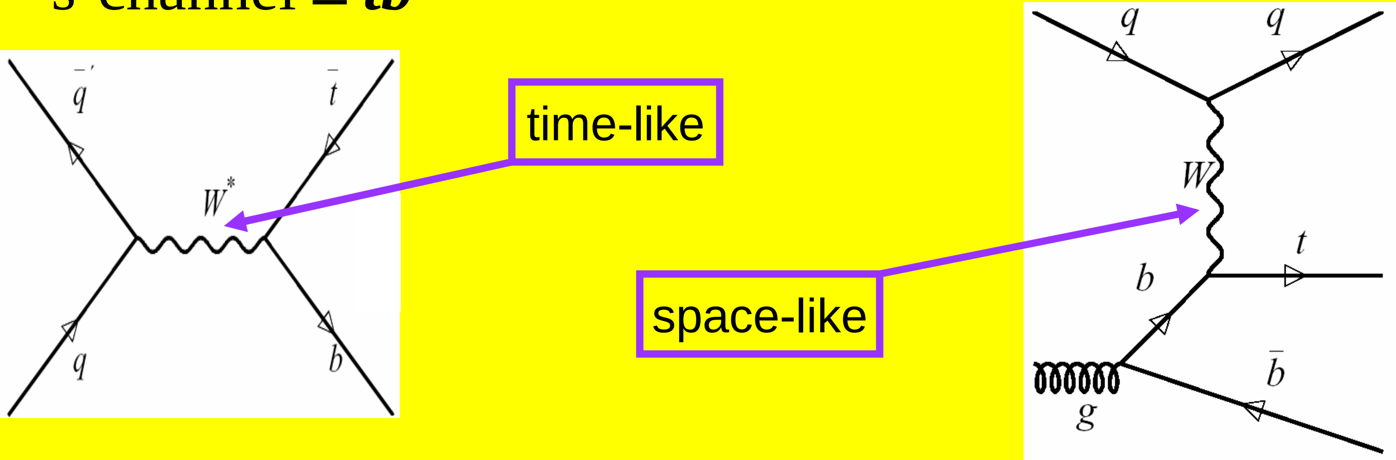
What is single-top?

Two single-top channels are classified by W momentum

s-channel ≡ ***tb***

t-channel ≡ ***tbq***



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

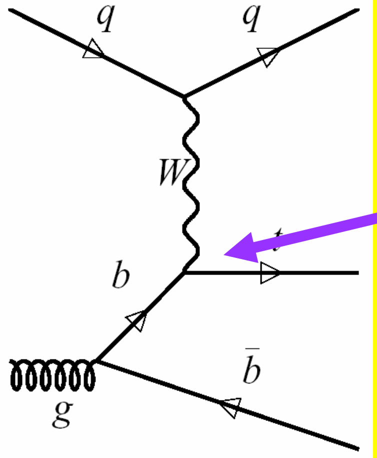
  Run I limits: $\sigma_t < 13.5$ pb, $\sigma_s < 12.9$ pb

Studying single top quark production because …

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

t-channel,

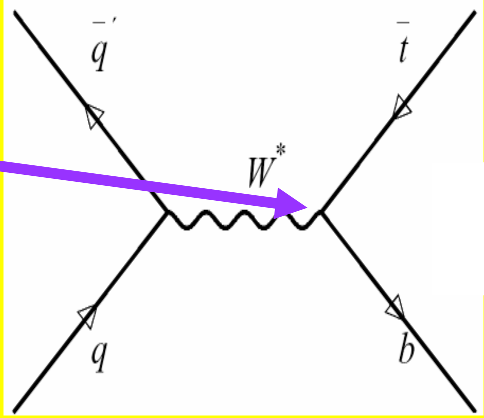
$$\sigma_{\text{t-channel, 1}t} \sim 1.98\,pb\left(\sqrt{s} = 1.96\text{ TeV}\right)$$



V_{tb}

s-channel

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



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

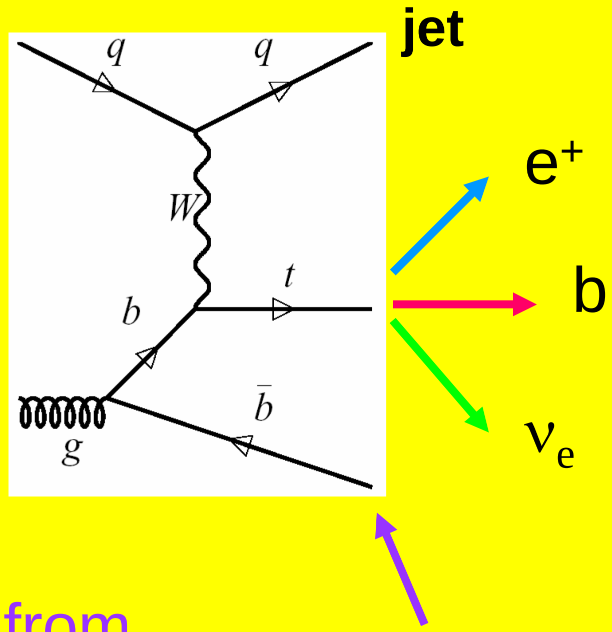
- Extra Generations of Quarks - will change unitarity constraints on CKM elements
- Extra couplings (Modified) – top interaction with SM particles. ex: Z_{tc}

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)



often not seen

Similar for s-channel - extra jet from extra radiation! [$bg \to tW$ 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

<u>Advanced Cuts</u>: **"m_{top}" = invariant mass of ($bl\nu$)**

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

<u>b-Tags</u>: **"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	$\lvert\eta\rvert$	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}

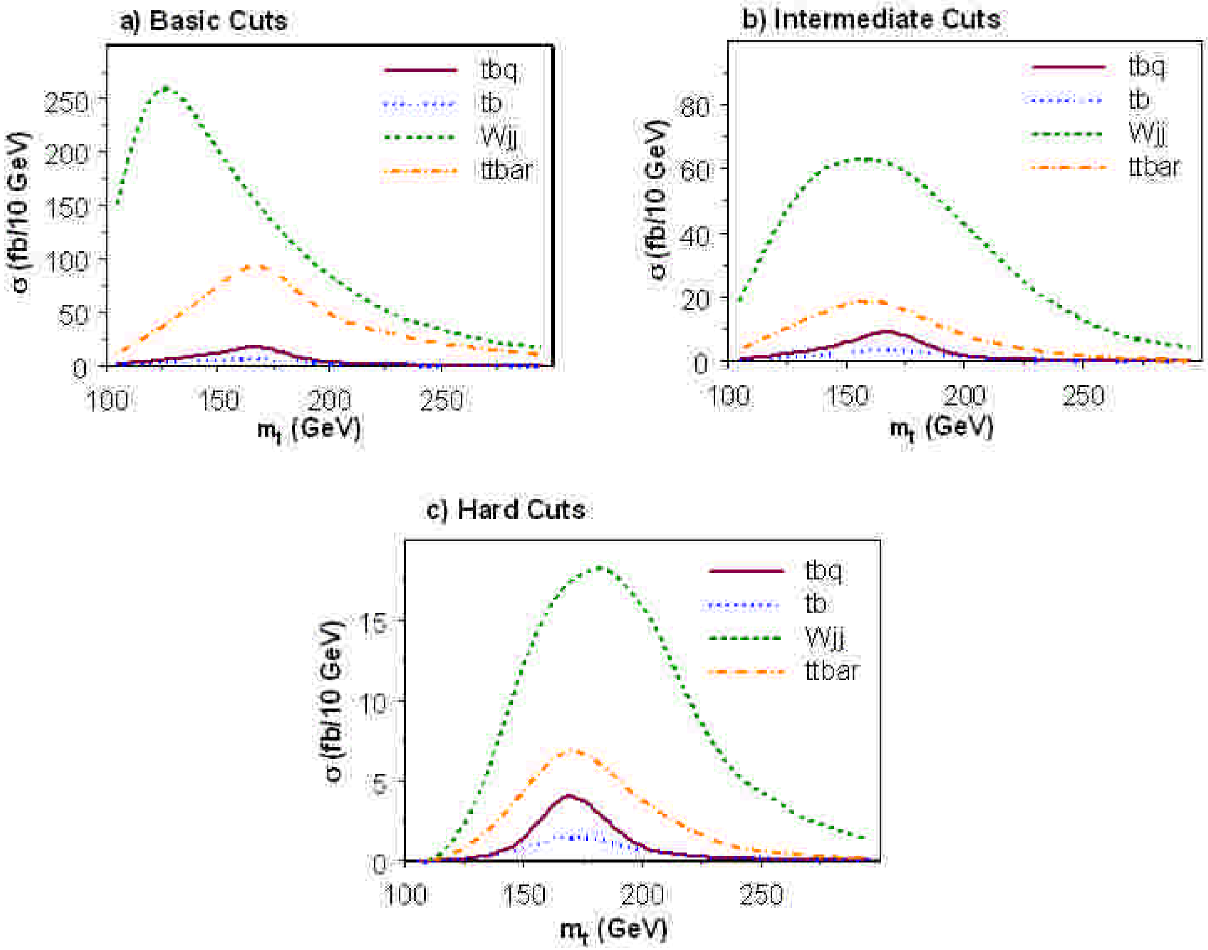
Channels	Basic	Intermed	Hard	Sys Unc
t-channel	298	67	30	>10%
s-channel	145	27	13	>10%
W+jj	6816	550	152	>10%
$t\bar{t}$	2623	140	57	>10%
Sig/Bkg	1/21	1/7	1/5	

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!

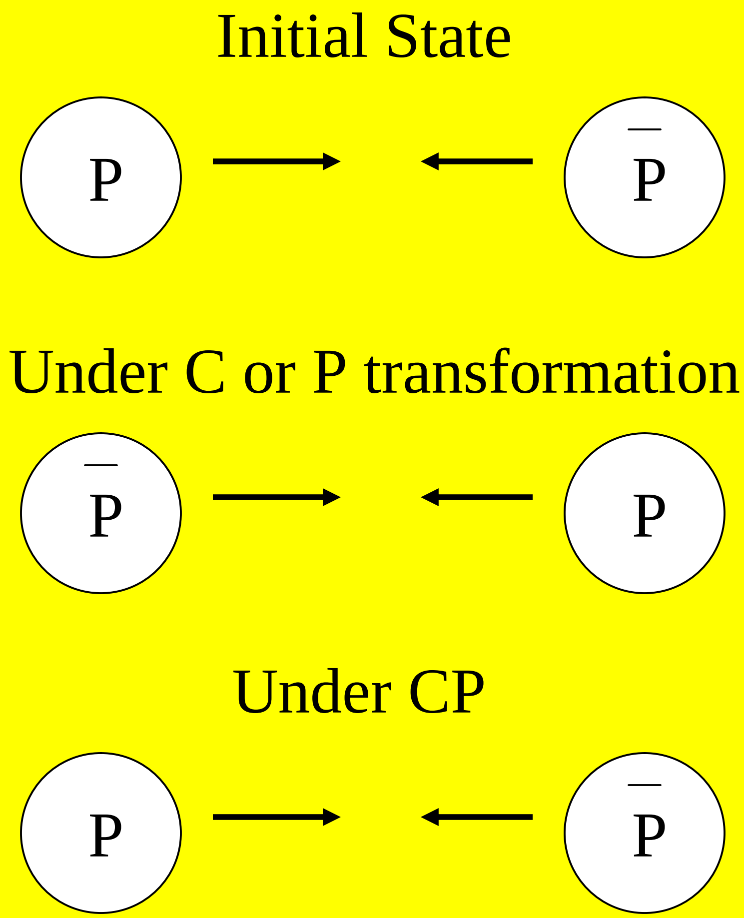


Look for more handles on data: symmetries, correlations and event shapes

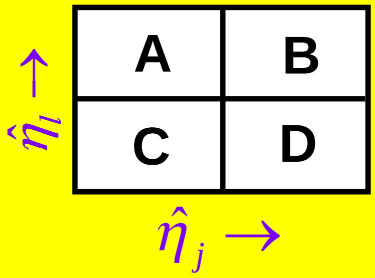
- **CP symmetry, C & P asymmetry of initial state**
- **Kinematic asymmetry of Initial state:** qg **(asymmetric) vs** $q_V\bar{q}_V$ **(symmetric)**
- **In t-channel signal dynamical correlation between scattered q and final lepton due to LH *W* vertex and carried by top quark spin (which decays before it interacts),** $q \to t \Uparrow \to l^+$

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)



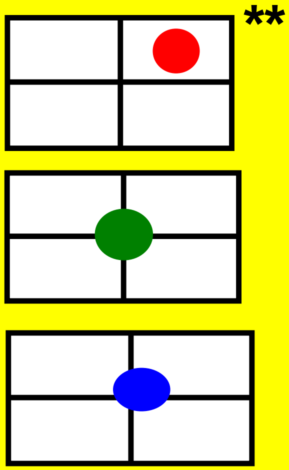
Focus on 2-D distributions in signed rapidity, $\hat{\eta} = Q_l \eta *$



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

CP invariant

- **Same correlations in t and $\overline{t}$**
- **Strong correlation in t-channel signal, $\hat{\eta}_l, \hat{\eta}_j > 0$**
- **Very weak correlation in s-channel and $t\overline{t}$**
- **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	**$\|\eta\|$**	**P_T**	
lepton	**≤ 2**	**$\geq$ 15 GeV**	
MET	**-**	**$\geq$ 15 GeV**	
Jet (b-tag)	**≤ 2**	**$\geq$ 40 GeV**	
Jet (no b)	**≤ 3.5**	**$\geq$ 30 GeV**	
		Min	**Max**
H_T		**none**	**300 GeV**
“m_t”		**155 GeV**	**200 GeV**

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

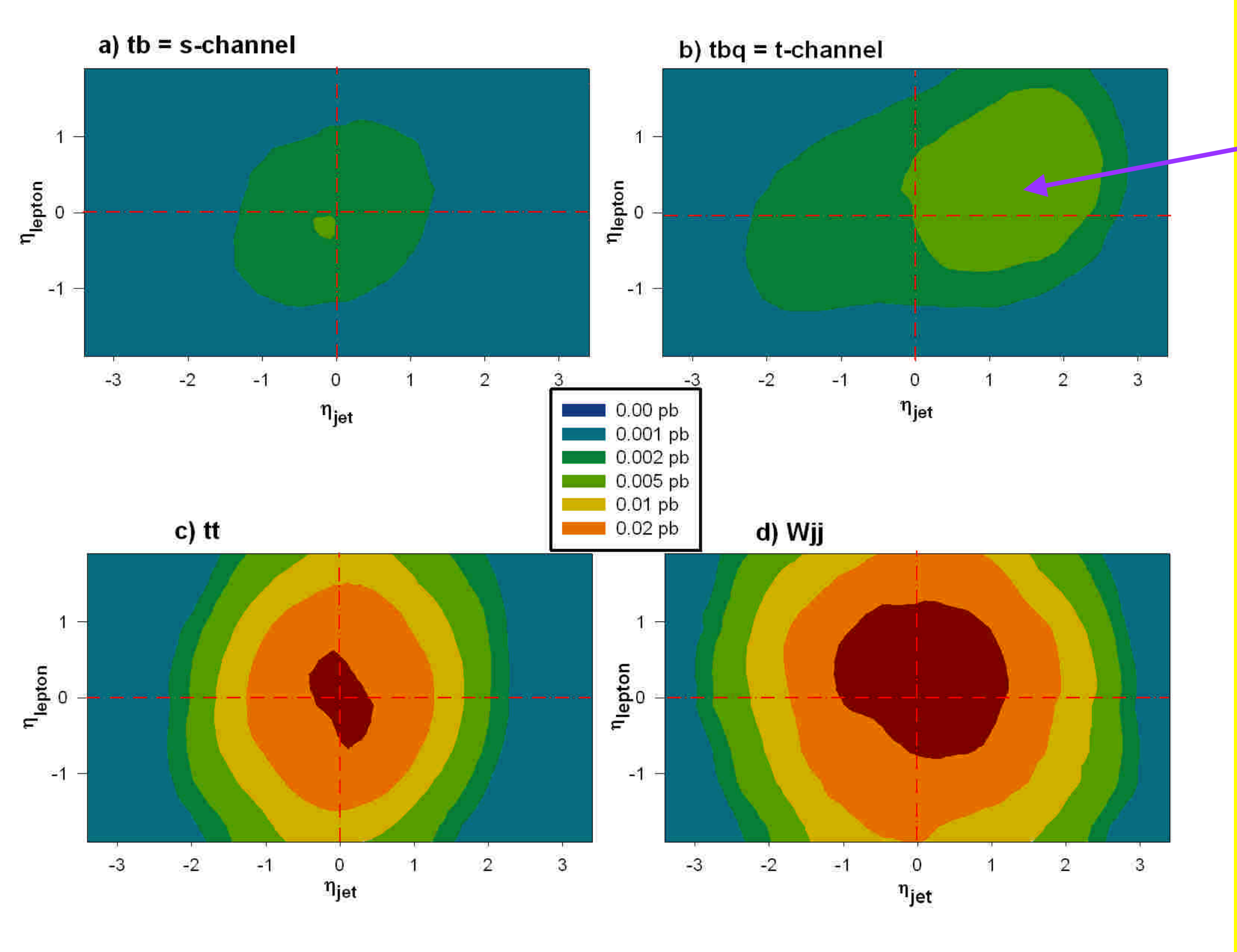
But that is OK!

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

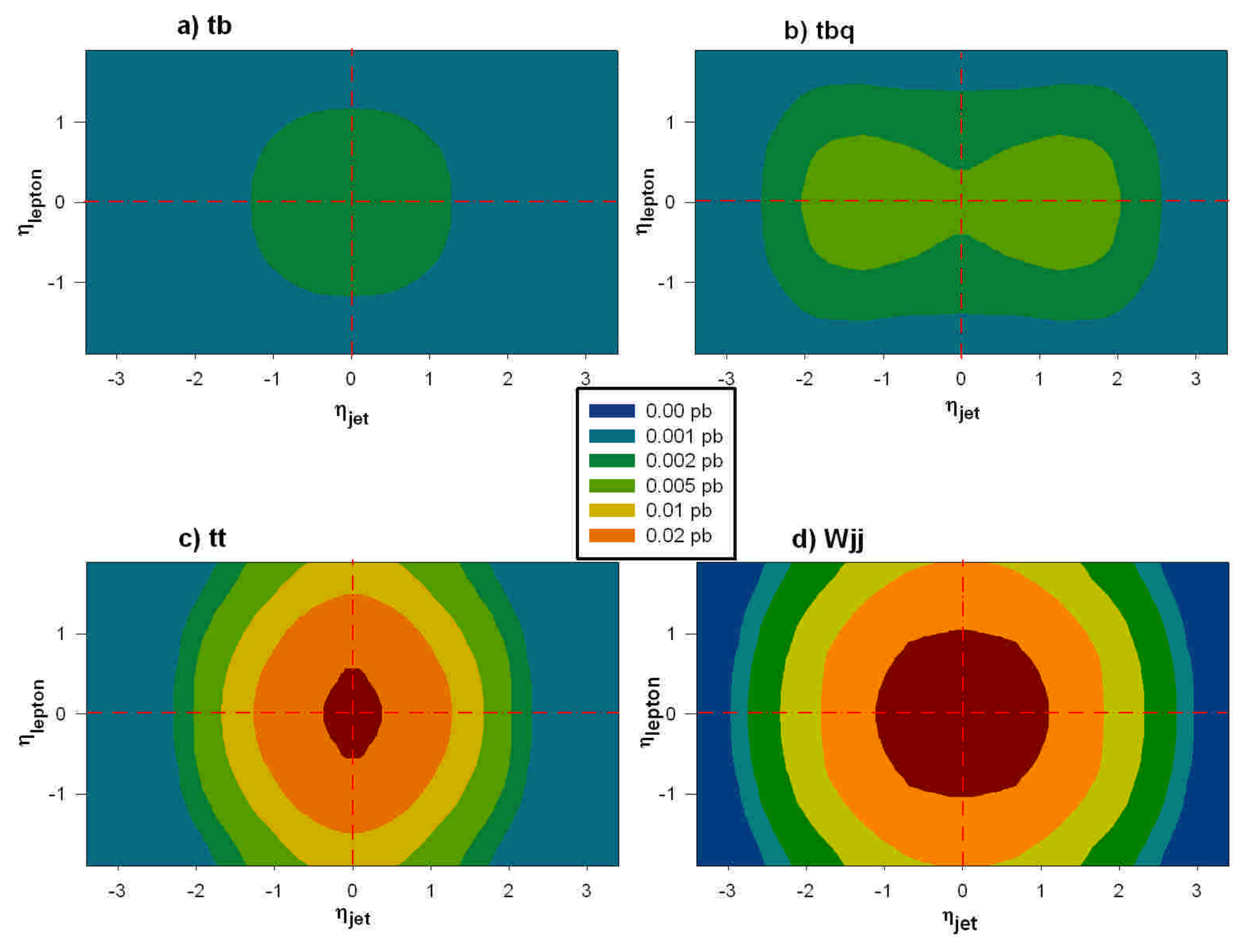
- **Uncorrelated –** $\frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j} = f\left(\hat{\eta}_l\right) g\left(\hat{\eta}_j\right)$
- **P even** $f\left(\hat{\eta}_l\right) = f\left(-\hat{\eta}_l\right) : g\left(\hat{\eta}_j\right) = g\left(-\hat{\eta}_j\right)$
- $\Rightarrow$

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

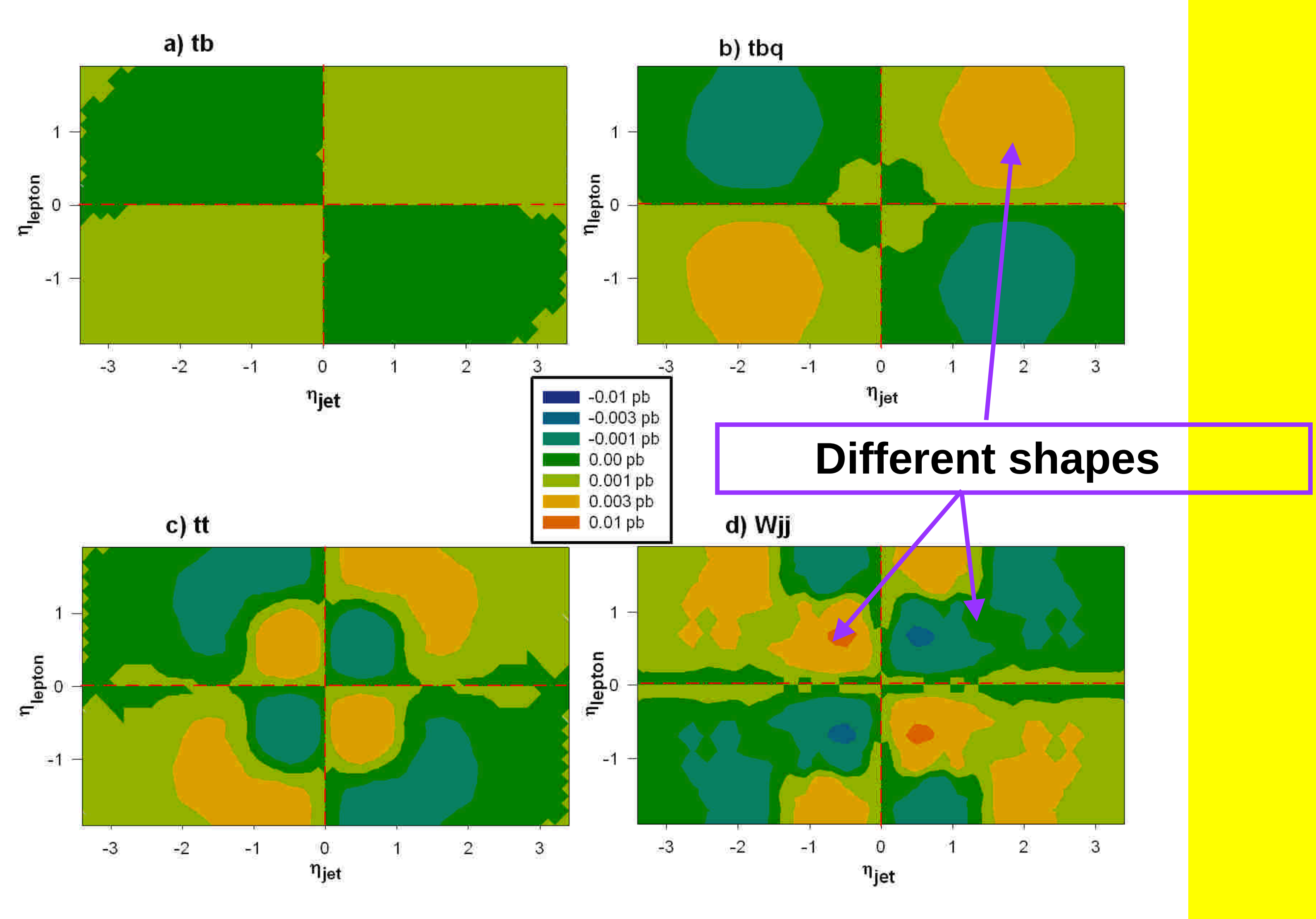
$$= \frac{d\sigma}{d\hat{\eta}_l d\hat{\eta}_j}\left(\hat{\eta}_l,-\hat{\eta}_j\right)$$

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

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

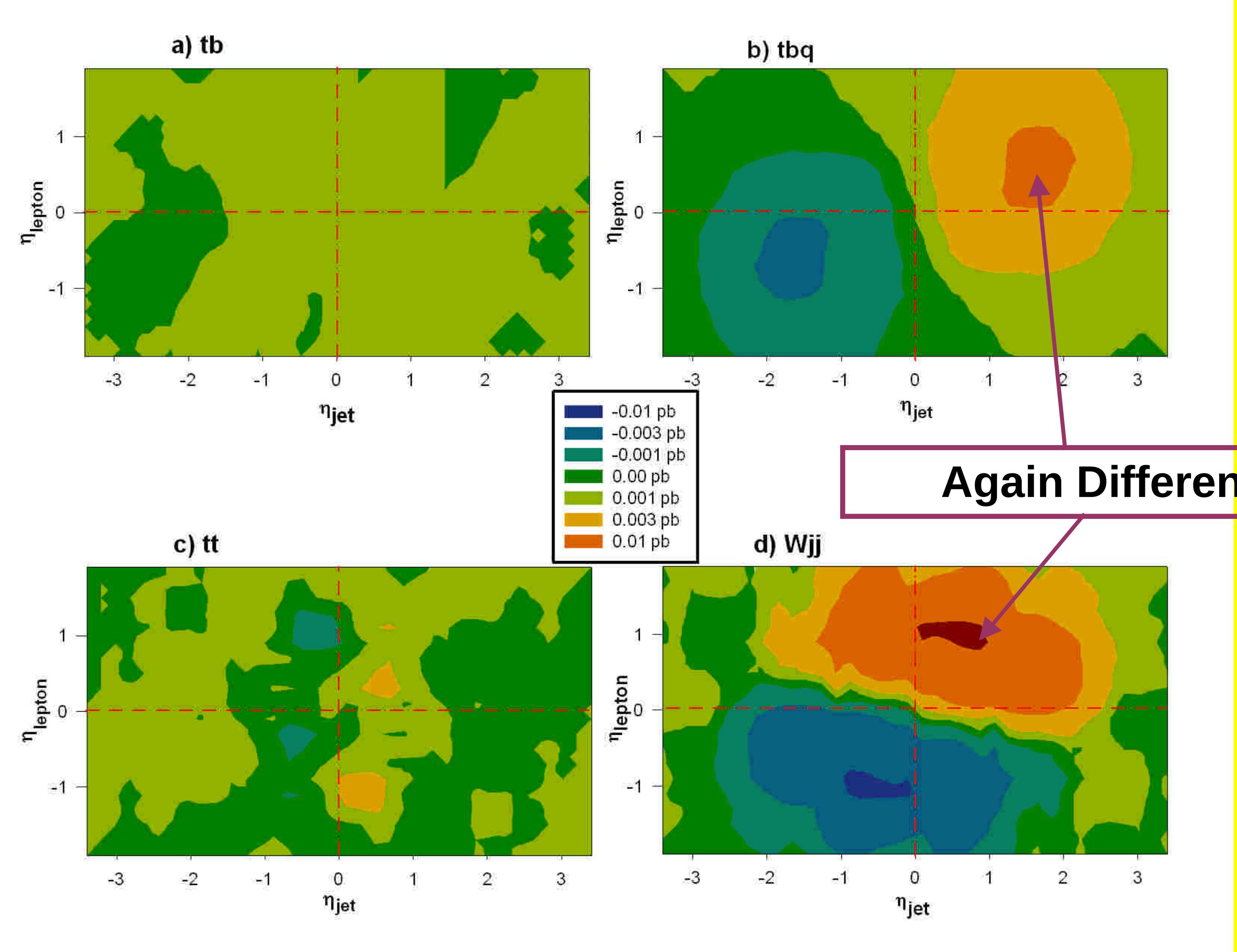


$F_+\left(\hat{\eta}_l,\hat{\eta}_j\right)$ $\quad F_+^{Wjj} \sim F_+^{tbj} \sim F_+^{t\bar{t}} \gg F_+^{tb}$



Different shapes

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



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

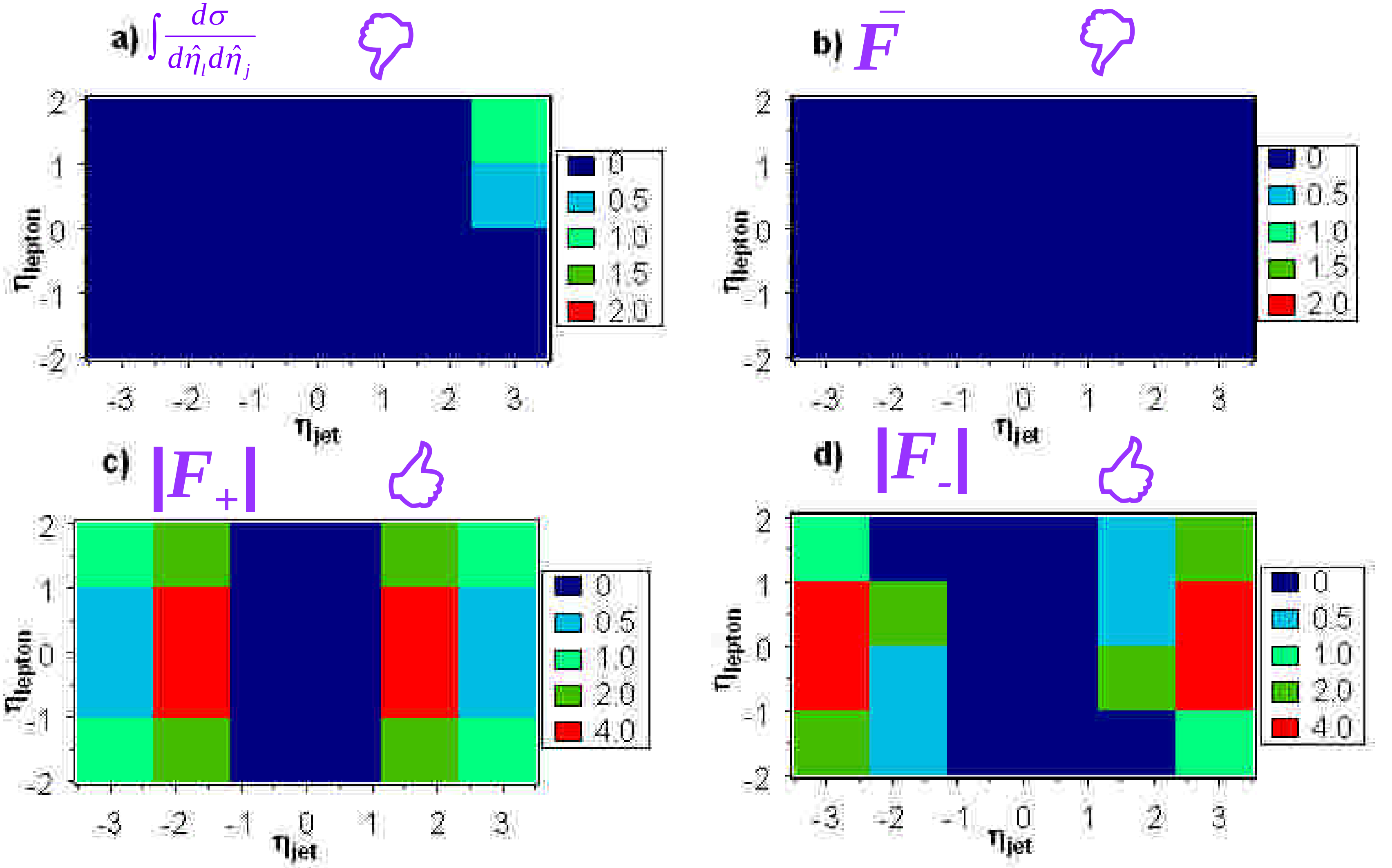
± **Statistical Errors**

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



⇒**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 $g \rightarrow b,c$ rates.**

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

- ***Understanding Wjj*, including tagging and $g \rightarrow b,c$ 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

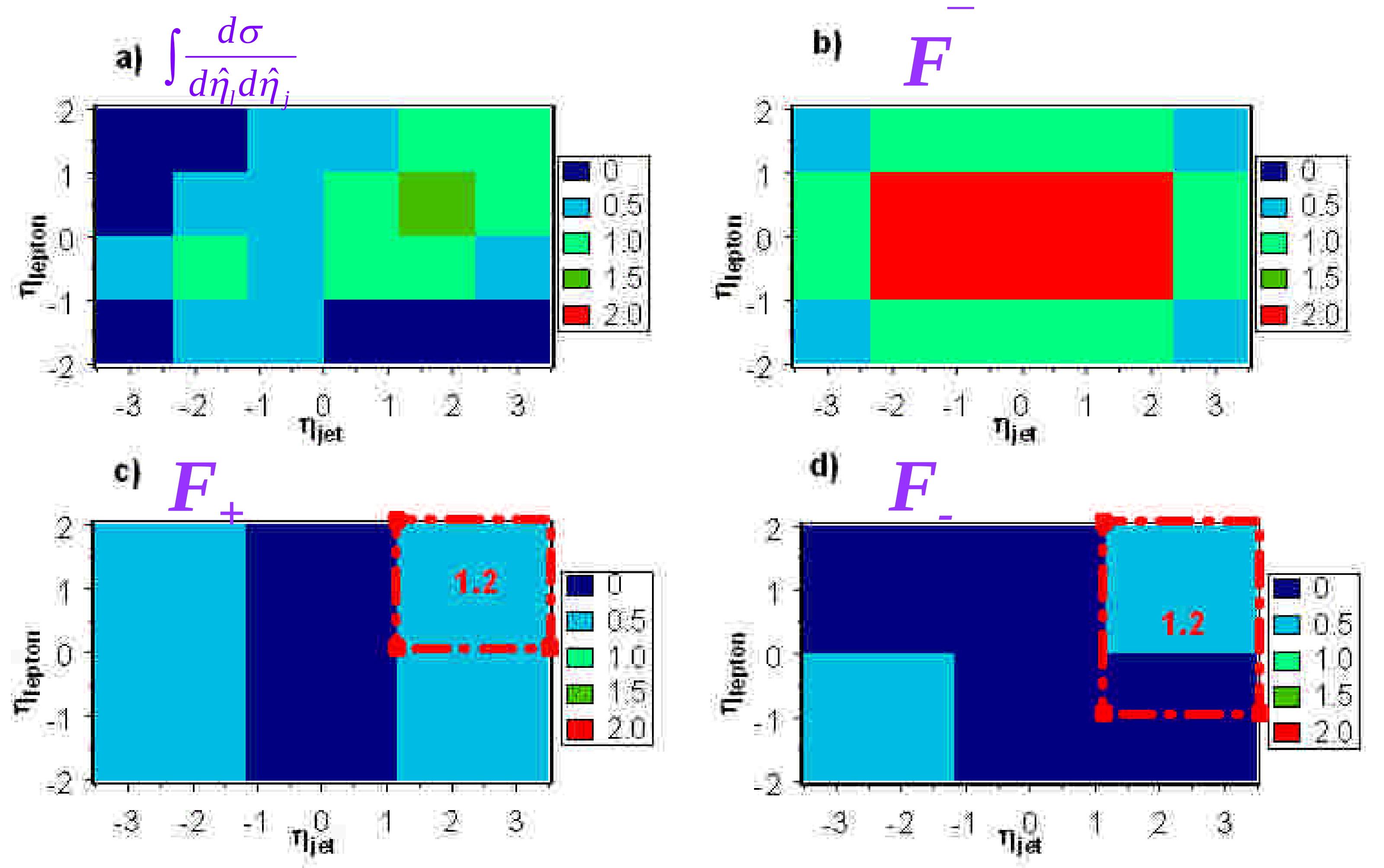
- Uncertainty in N_{F+} : in any region of $\eta\eta$ plane

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

- 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

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

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

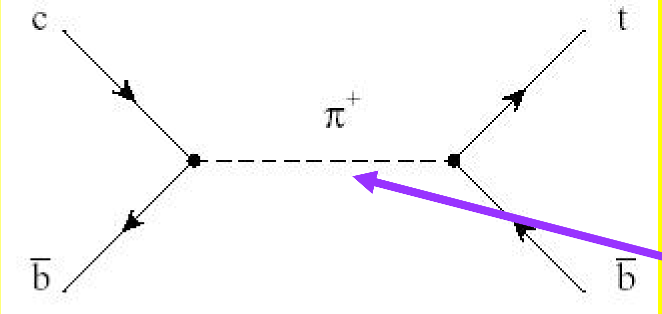
Conclusions

- **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



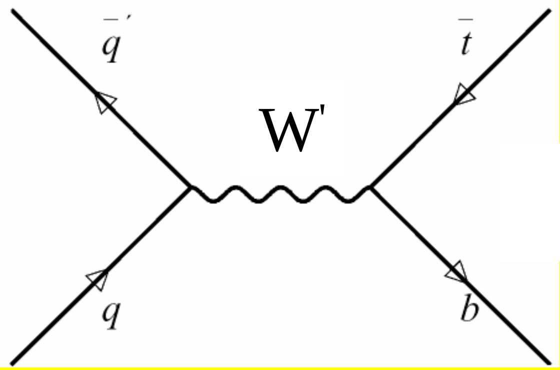
time-like momentum allows for resonance

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

Extra Gauge Bosons: Top-flavor models

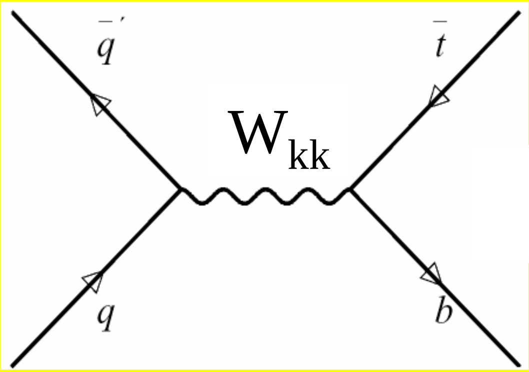
e.g., $\boxed{SU(3)_C \times SU(2)_h \times SU(2)_l \times U(1)_Y}$

- 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 $1/M_{W'}^2$



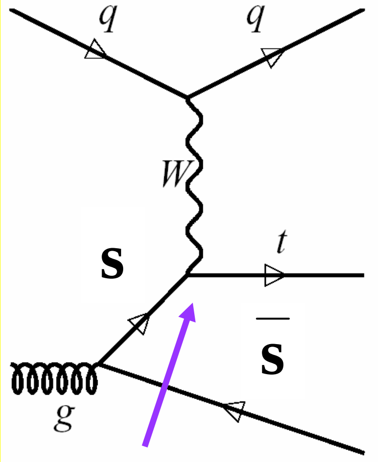
Extra Dimensions: 5-D Gauge Bosons

- 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 observable cross-section goes down a little.
- Changes decay structure of top



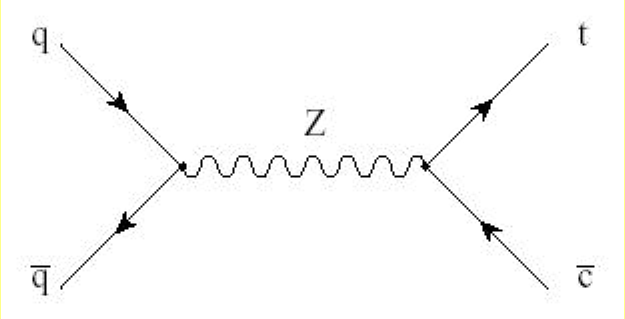
V_{ts}

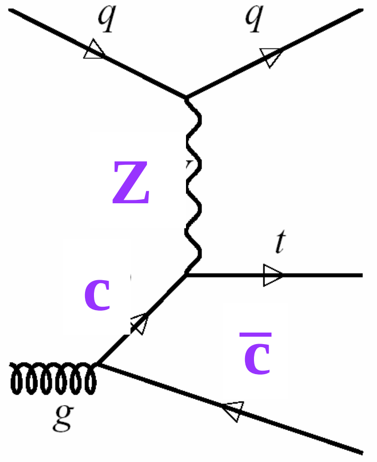
Without imposing 3 family unitarity, these are the 90% CL direct constraints.

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

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

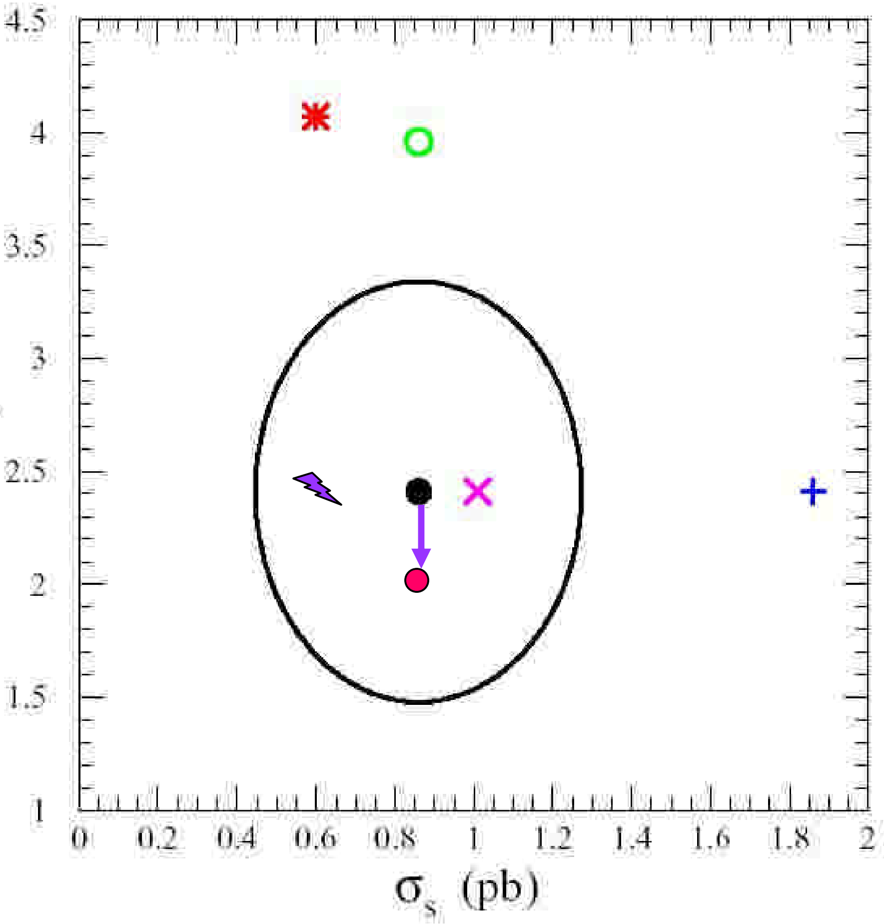
○ FCNC Z-t-c vertex

× 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"