# CP violation in top physics*

How to look for CP violation from new physics in top-quark pair production and decay with T-odd correlations

- *based on work with
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  - Oleg Antipin (now a postdoc in Odense)
  - Serhan Mete (Atlas ISU student)
  - Sehwook Lee (DØ ISU student)

# T-odd correlations

- simple kinematic correlations of the form

$$\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$$

- T-odd: change sign under `naive'-T $\vec{p} \longrightarrow -\vec{p}$ but no interchange of initial/final states
- These correlations can be:
  - CP-odd if $\vec{p}_i, \vec{p}_j$ involve particle anti-particle pairs*
  - CP-even but not at tree-level as they require a phase -- small and distinguishable `background'
- The $\vec{p}$ can be that of a composite object (jet) → sums over processes

# T-odd correlations-2

- triple product correlations appear in matrix elements in the form

$$\epsilon(p_t, p_{\bar{t}}, p_{\ell^+}, p_{\ell^-}) \equiv \epsilon_{\mu\nu\alpha\beta} p_t^\mu p_{\bar{t}}^\nu p_{\ell^+}^\alpha p_{\ell^-}^\beta$$

- 4 independent four-vectors needed, so unless one has an effective theory with vertices involving 5 particles at least, they originate from spin correlations *
- * top pair production is ideal \`lab' to look for them

# Examples for LHC, Tevatron

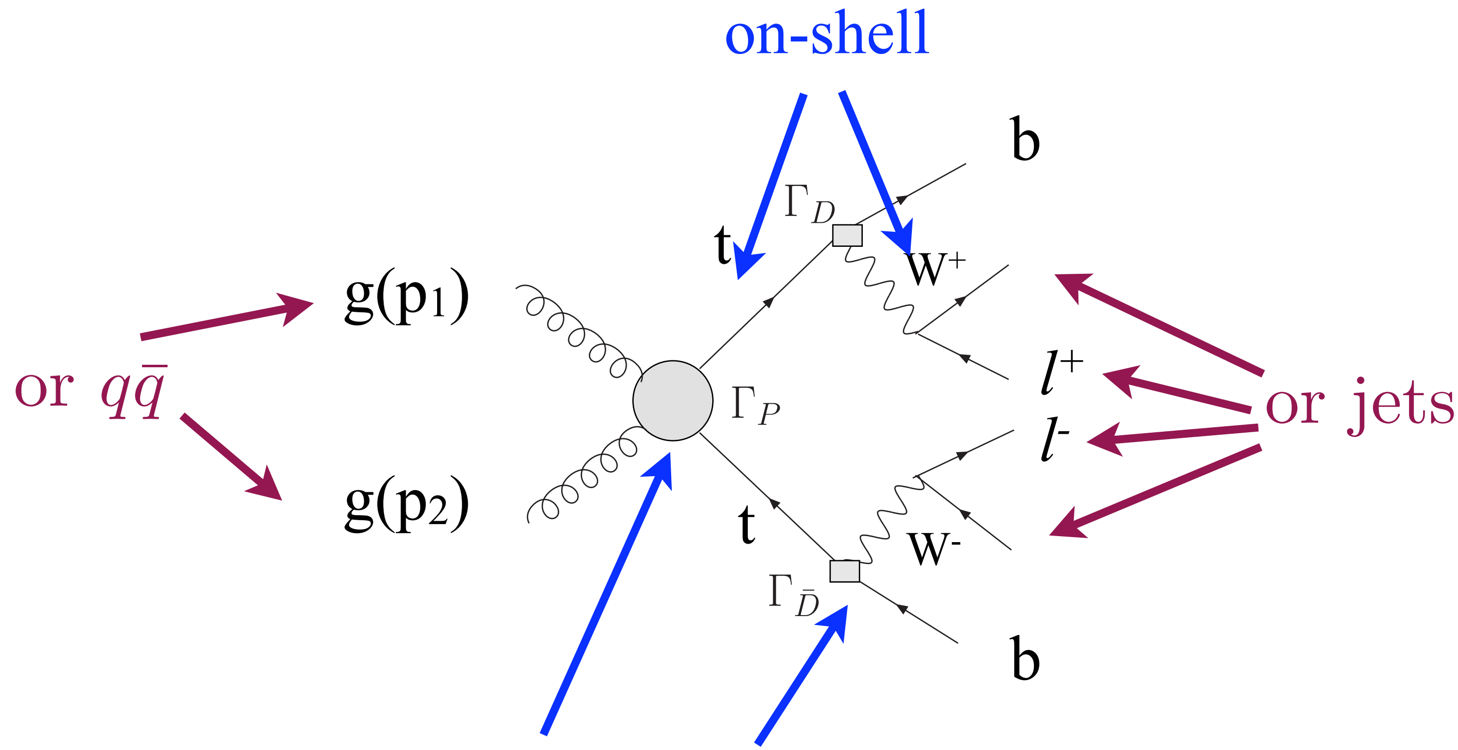
- Heavy (bsm) Higgs with CP violation
  - large intrinsic asymmetry
  - hard to extract (if such a Higgs exists!)

Peskin,Schmidt,Chang, Keung, Bernreuther, Brandenburg,Flesch ...

- Anomalous top-quark couplings
  - exhibits the correlations in the general case (including those between initial and final state momenta)
  - contains examples that are truly CP odd and others that are not
  - small asymmetries (by assumption ...)

Atwood, Aeppli,Soni, Bernreuther,Nachtmann, Overmann,Schroeder,Ma, Brandenburg,Choi,Kim, Zhou, Sjolin ...

# kinematics




new physics with CP violation

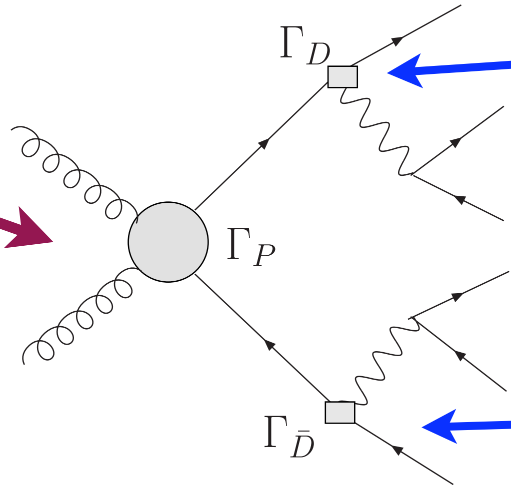
sum over final states such that CP conjugate pairs appear with equal probability

# T-odd Spin correlations

- the underlying T-odd correlations are spin correlations, different observables correspond to different spin analyzers

$\varepsilon(p_t, p_{\bar{t}}, s_t, s_{\bar{t}})$

CP violation in the production vertex




$\varepsilon(p_t, p_b, p_{l^+}, s_t)$

CP violation in the decay vertex

$\varepsilon(p_{\bar{t}}, p_{\bar{b}}, p_{l^-}, s_{\bar{t}})$

- want the lab frame, not the top-rest frame

# CP Violation via Neutral Higgs

- A neutral Higgs has the general coupling:

$$-\frac{m_t}{v}\; H\; \bar{t}\; (A + iB\gamma_5)\; t$$

- which violates CP if both $A$ and $B$ are non-zero at the same time (multi-Higgs models)
- Weinberg showed that $|AB| \leq \frac{1}{\sqrt{2}}$
- under some assumptions
  - lightest neutral mass eigenstate is dominant
  - different vevs have comparable sizes
  - use upper bound for numerics

with Yili Wang

# Case of H decay

- For a sufficiently heavy H, it decays to top pairs. The decay chain, for example,

$$H \to t\bar{t} \to b\bar{b}W^+W^-$$

- picks a CP odd correlation

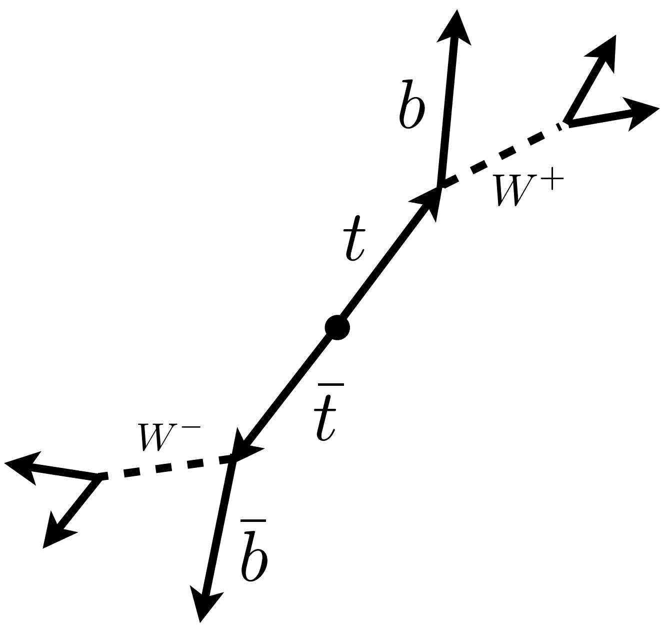
$$\mathcal{O}_1 = \epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}}) \xrightarrow{H_{C.M.}} \propto \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$$
$$\xrightarrow{CP} -\vec{p}_{\bar{t}} \cdot (-\vec{p}_{\bar{b}} \times -\vec{p}_b) = -\vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$$

- which can be measured with a counting asymmetry such as

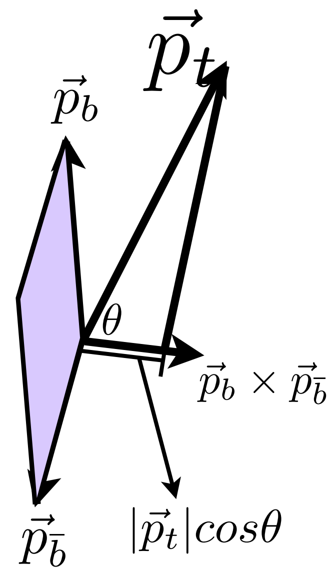
$$A_{CP} \equiv \frac{N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) > 0) - N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) < 0)}{N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) > 0) + N_{events}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) < 0)}$$

# A picture

$$\mathcal{O}_1 \;=\; \epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}}) \xrightarrow{t\bar{t}\ CM} \propto\; \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$$



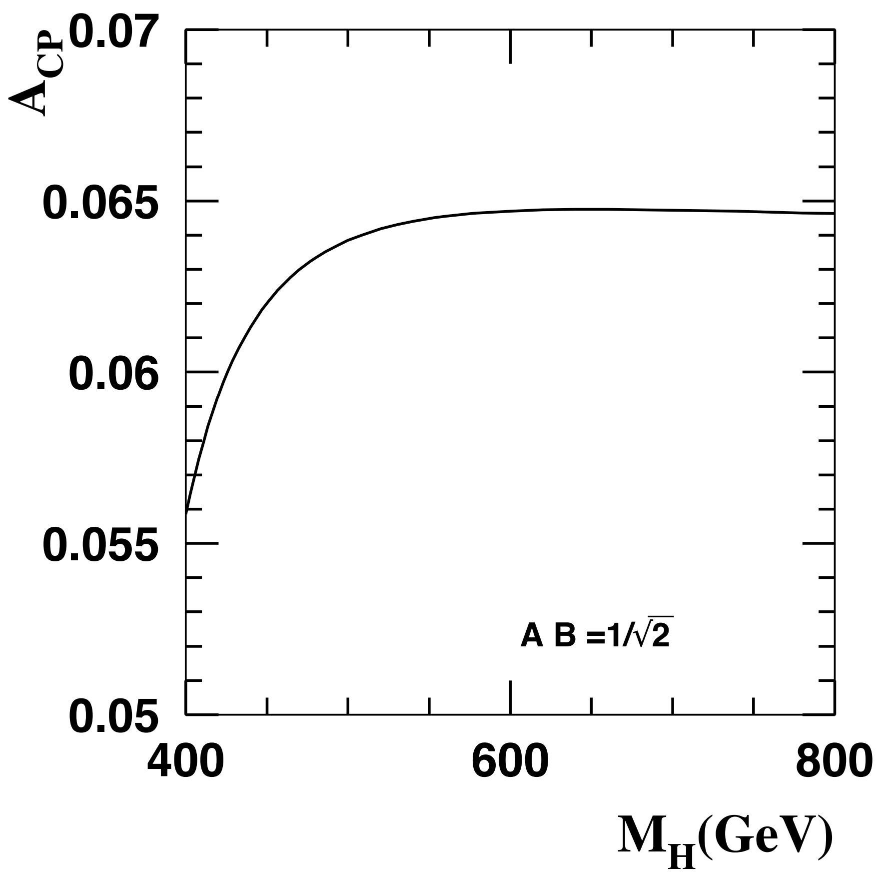

$t\bar{t}$ event in the CM frame of $t\bar{t}$




$O_1$ is proportional to the triple product $\vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})$

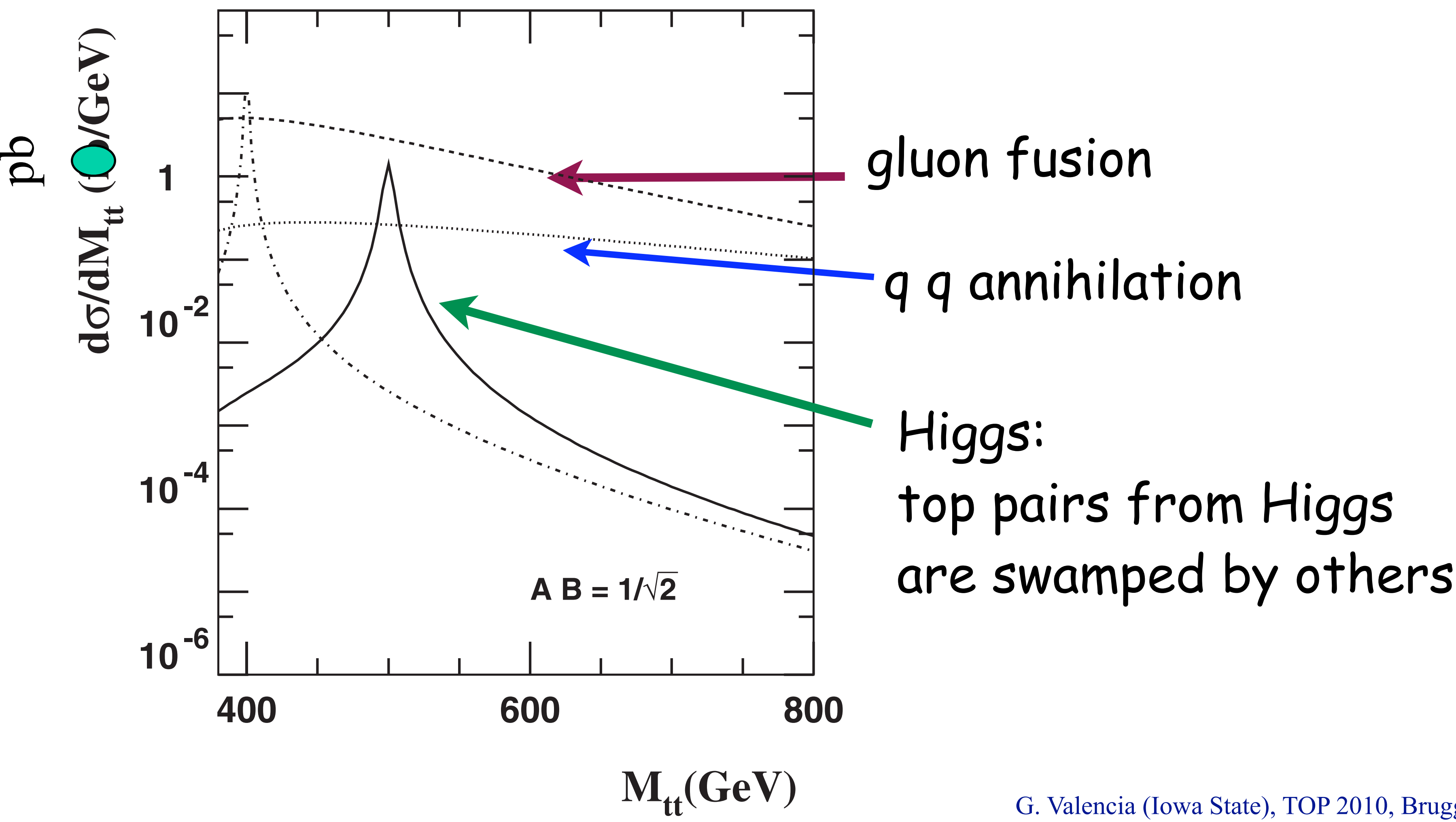
# Can be easily computed

$$= \frac{\pi}{4}\sqrt{1-\frac{4m_t^2}{M_H^2}}\,\frac{AB}{|A|^2+|B|^2}\,\frac{(1-\frac{2M_W^2}{m_t^2})^2}{(1+\frac{2M_W^2}{m_t^2})^2}\times\left(\frac{1}{1-\frac{2m_t^2}{M_H^2}-2\frac{|A|^2-|B|^2}{|A|^2+|B|^2}\frac{m_t^2}{M_H^2}}\right)$$

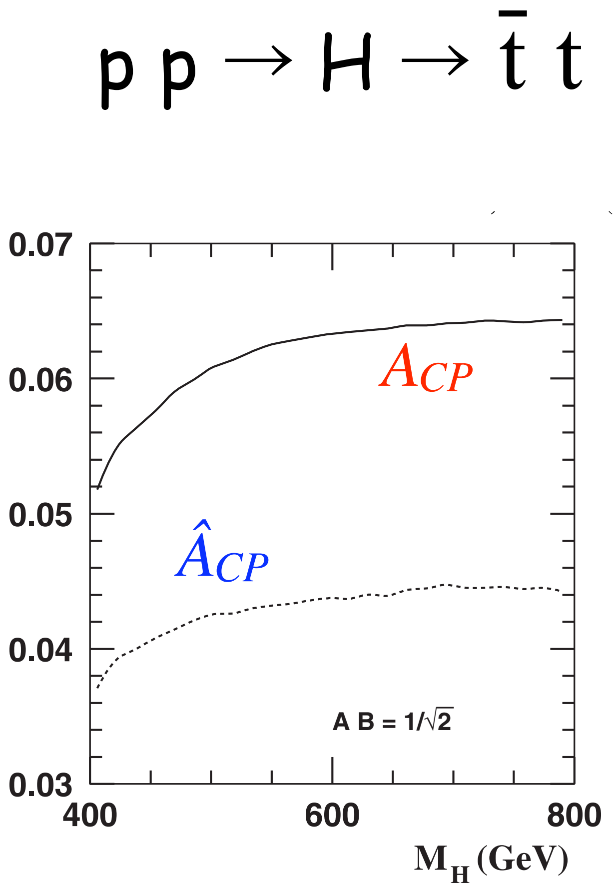


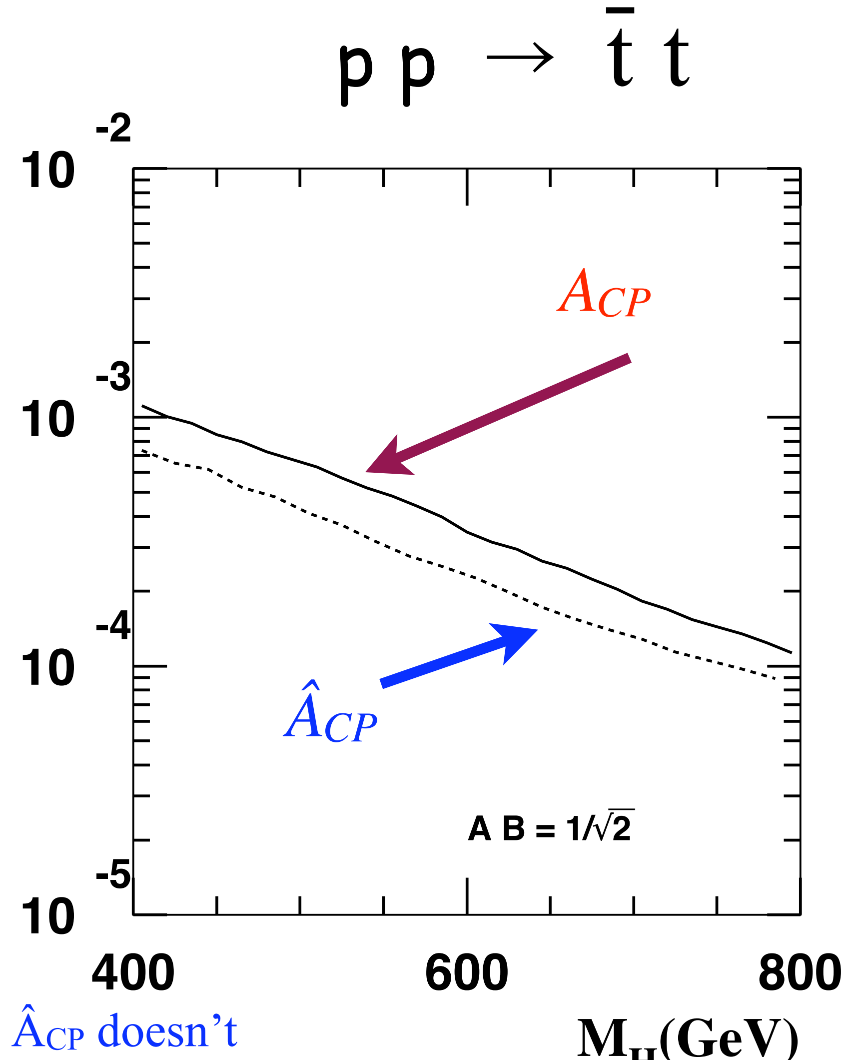

There is a large intrinsic asymmetry: near 7% for A=B and maximum CP violation

# But need to isolate the sample with the asymmetry...



# Signal gets diluted




$A_{CP}$ assumes parton CM can be reconstructed, $\hat{A}_{CP}$ doesn't

# How did we get a CP test?

$$p\,p \to H \to t\,\bar{t} \to (bW^+)\;(\bar{b}W^-) \to (b\mu^+\nu_\mu)(\bar{b}\mu^-\bar{\nu}_\mu)$$

- p p initial state is not a CP eigenstate
  - get good CP properties from final state: view LHC as a Higgs (or more generally a $t\,\bar{t}$) factory
  - this works for g g or $q\,\bar{q}$ initial states after we sum over spin and color
  - won't work for q q initial state, need to reject it.
  - pick final states such that this is a small contamination

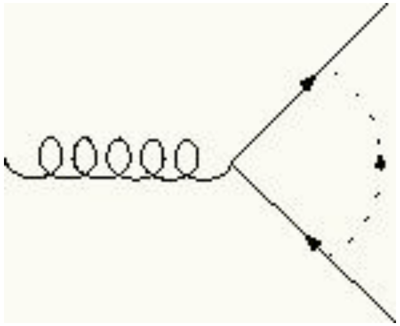
# top-quark anomalous couplings

- electric dipole moments indicate T violation (and thus CP violation)
- experimental limits on electron edm and neutron edm; for example $d_n < 2.9 \times 10^{-26}$ e-cm
- one contribution to neutron edm is the light quark edm and also its cedm:

$$\mathcal{H} \sim \frac{1}{2}\, e\, d_q\, \bar{q}\sigma_{\mu\nu}\gamma_5 q\, F^{\mu\nu} + \frac{1}{2}\, g_s\, \tilde{d}_q\, \bar{q}\sigma_{\mu\nu}\gamma_5 t_a q\, G_a^{\mu\nu}$$

# quark edm (cedm)

- beyond the SM these can be induced at one-loop
- for example models with scalars generate contributions such as



$$d_q, \tilde{d}_q \sim m_q^3$$

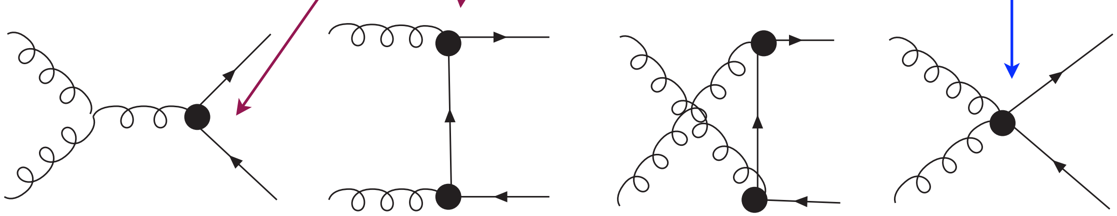
- perhaps heavy quarks can have large (c)edms ?
- measure at a top-quark factory, LHC?

# CP violating top-quark couplings

- For CP violation in the production process: a (chromo)-edm of the top-quark:

$$\mathcal{L}_{cedm} = -ig_s \frac{\tilde{d}}{2}\, \bar{t}\, \sigma_{\mu\nu}\gamma_5\, t\, G^{\mu\nu}$$

- It modifies the $t\ \bar{t}\ g$ coupling and introduces a ``seagull" term



# $gg$ or $q\bar{q} \to t\bar{t} \to (b\mu^+\nu_\mu)(\bar{b}\mu^-\bar{\nu}_\mu)$

- The differential cross section now contains the following CP-odd correlations:

$$\begin{aligned}
\mathcal{O}_1 &= \epsilon(p_t, p_{\bar{t}}, p_{\mu^+}, p_{\mu^-}) \\
\mathcal{O}_2 &= (t-u)\,\epsilon(p_{\mu^+}, p_{\mu^-}, P, q) \\
\mathcal{O}_3 &= (t-u)\,\left(P\cdot p_{\mu^+}\,\epsilon(p_{\mu^-}, p_t, p_{\bar{t}}, q) + P\cdot p_{\mu^-}\,\epsilon(p_{\mu^+}, p_t, p_{\bar{t}}, q)\right)
\end{aligned}$$

- where the sum and difference of parton momenta are denoted by P and q.
  - for W as one jet: lepton $\longleftrightarrow$ b-jet momenta
  - for more jets: lepton $\longleftrightarrow$ d-jet momenta
- Notice that they are quadratic in q

$$(t-u) = q\cdot(p_{\bar{t}} - p_t)$$

# top cedm continued

- The CP violating part of the differential cross section looks like

$$d\sigma \sim C_1(s,t,u)\,\mathcal{O}_1 + C_2(s,t,u)\,\mathcal{O}_2 + C_3(s,t,u)\,\mathcal{O}_3,$$

- where the form factors look like

$$C_1 = \frac{\tilde{d}\,m_t}{6s^2(s^2-(t-u)^2)^2}\left(9(t-u)^6 - 2s^2(t-u)^4 - 7s^4(t-u)^2\right.$$
$$\left.+32m_t^4(7s^4+9s^2(t-u)^2) + 4m_t^2(7s^5+7(t-u)^2s^3+18(t-u)^4s)\right)$$

- notice they are also even under t,u interchange (which proton is p1)
- this expression (3 f.f's) appears to be the most general one

# CP violation in the decay vertex

- For anomalous tbW couplings, there is only one that interferes with the SM amplitude in the limit of massless b quark:

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V^{\star}_{tb}\, \bar{u}(p_b) \left[\gamma_\mu (f_1^L P_L + f_1^R P_R) - i\sigma^{\mu\nu}(p_t - p_b)_\nu (f_2^L P_L + f_2^R P_R)\right) u(p_t),$$

$$\bar{\Gamma}^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb}\, \bar{v}(p_{\bar{t}}) \left[\gamma_\mu (\bar{f}_1^L P_L + \bar{f}_1^R P_R) - i\sigma^{\mu\nu}(p_{\bar{t}} - p_{\bar{b}})_\nu (\bar{f}_2^L P_L + \bar{f}_2^R P_R)\right) v(p_{\bar{b}}),$$

- include absorptive phases also and take:

$$f_1^L = \bar{f}_1^L = 1, \quad \leftarrow \text{SM}$$

$$f_2^R = f e^{i(\phi_f + \delta_f)}, \qquad \bar{f}_2^L = f e^{i(-\phi_f + \delta_f)}.$$

- no seagulls (with a gluon) are present

# T-odd correlations

- this time they appear in the differential cross section as:

absorptive phase CP odd phase

$$|\mathcal{M}|^2_T \;=\; f\sin(\phi_f+\delta_f)\,\epsilon(p_t,p_b,p_{\ell^+},Q_t)+f\sin(\phi_f-\delta_f)\,\epsilon(p_{\bar t},p_{\bar b},p_{\ell^-},Q_{\bar t}).$$

  - Q is a four momentum (spin analizer), it is a linear combination of other momenta in the process
  - the correlations are NOT CP odd, they can be also signal absorptive phases
  - true CP odd observables can be constructed by comparing the top and anti-top decays

# Observables

- We have the `theoretical' correlations. Need some that involve only observable momenta.
  - for LHC we use the di-lepton (muon) channel, for Tevatron the lepton (muon) + jets, and multijet channels:

$$p_{\mu^+},\ p_{\mu^-}$$

$$p_b,\ p_{\bar{b}},\ \text{some observables require distinguishing them}$$

$$\tilde{q} \equiv P_1 - P_2,\ =\ \text{difference of proton momenta}$$

$$p_{j1},\ p_{j2}\cdots\quad \text{non} - b\ \text{jets ordered by}\ p_T$$

  - any CP-blind ordering of the jets should work

# correlations for di-muon channel

- For CP violation in both production and decay

$$\tilde{\mathcal{O}}_1 = \epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) \xrightarrow{b\bar{b}\ CM} \propto \vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$$

$$\tilde{\mathcal{O}}_2 = \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q})$$

$$\tilde{\mathcal{O}}_3 = \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_b, p_{\bar{b}}, p_{\mu^+} + p_{\mu^-}, \tilde{q})$$

quadratic in $\tilde{q}$

- J.Sjölin has done an Atlas study with an observable proportional to $\tilde{\mathcal{O}}_1$
- For T-odd but CP even from the decay process

$$\mathcal{O}_a = \tilde{q}\cdot(p_{\mu^+} + p_{\mu^-})\,\epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q})$$

$$\mathcal{O}_b = \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_{\mu^+}, p_{\mu^-}, p_b - p_{\bar{b}}, \tilde{q}).$$

# correlations for muon + jets

- For CP violation in both production and decay

$$
\begin{aligned}
\mathcal{O}_1 &= \epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}}) \xrightarrow{t\bar{t}\ CM} \propto \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) \\
\mathcal{O}_2 &= \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
\mathcal{O}_3 &= Q_\ell\, \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{bb\ CM} \propto Q_\ell\, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
\mathcal{O}_4 &= Q_\ell\, \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell\, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
\mathcal{O}_7 &= \tilde{q} \cdot (p_b - p_{\bar{b}})\, \epsilon(P, \tilde{q}, p_b, p_{\bar{b}}) \xrightarrow{lab} \propto \vec{p}_{beam} \cdot (\vec{p}_b - \vec{p}_{\bar{b}})\, \vec{p}_{beam} \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}).
\end{aligned}
$$

- For T-odd but CP even from the decay process

$$
\begin{aligned}
\mathcal{O}_a &= \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
\mathcal{O}_b &= Q_\ell\, \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell\, (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})
\end{aligned}
$$

# correlations for multi jet channel

- For CP violation in both production and decay

$$
\begin{aligned}
\mathcal{O}_1 &= \epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}}) \xrightarrow{t\bar{t}\ CM} \propto \ \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) \\
\mathcal{O}_5 &= \epsilon(p_b, p_{\bar{b}}, p_{j1}, p_{j1'}) \xrightarrow{b\bar{b}\ CM} \propto \ \vec{p}_b \cdot (\vec{p}_{j1} \times \vec{p}_{j1'}) \\
\mathcal{O}_6 &= \epsilon(p_b, p_{\bar{b}}, p_{j1} + p_{j2}, p_{j1'} + p_{j2'}) \xrightarrow{t\bar{t}\ CM} \propto \ (\vec{p}_{j1} + \vec{p}_{j2}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) \\
\mathcal{O}_7 &= \tilde{q} \cdot (p_b - p_{\bar{b}})\, \epsilon(P, \tilde{q}, p_b, p_{\bar{b}}) \xrightarrow{lab} \propto \ \vec{p}_{beam} \cdot (\vec{p}_b - \vec{p}_{\bar{b}})\, \vec{p}_{beam} \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}).
\end{aligned}
$$

- For T-odd but CP even from the decay process

$$
\mathcal{O}_c = \epsilon(P, p_b + p_{\bar{b}}, p_{j1}, p_{j1'}) \xrightarrow{lab} \propto \ (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_{j1} \times \vec{p}_{j1'})
$$

# Observables

- For each correlation define a counting asymmetry:

$$A_i \equiv \frac{N_{events}(\mathcal{O}_i > 0) - N_{events}(\mathcal{O}_i < 0)}{N_{events}(\mathcal{O}_i > 0) + N_{events}(\mathcal{O}_i < 0)}.$$

- Can also try to extract terms linear in a given correlation $\mathcal{O}_i$ from the distribution

$$\frac{d\sigma}{d\mathcal{O}_i}$$

# Event generation and background

- We use MadGraph for all signals and background.
  - The signal is calculated separately and `hacked' into MadGraph
  - Several checks were made to satisfy ourselves that the procedure works but is not ideal
  - Ideally the anomalous couplings will be directly implemented in MadGraph...
- There are no background issues beyond those already there for top-pair selection
  - Known backgrounds $QCD,\ Vb\bar{b},\ Vc\bar{c},\ VV,\ (V=W^{\pm},Z)\cdots$ are CP symmetric (in SM) and with CP-blind cuts cannot mimic the signal
  - use some `typical' selection cuts for our analysis
  - residual background simply dilutes the statistical sensitivity by factors $\sqrt{(B+S)/S}$

# Numerical Results I: dimuon events at LHC

- signal: $pp \to t\bar{t} \to (b\mu^+\nu)(\bar{b}\mu^-\bar{\nu})$
- background: $pp \to b\bar{b}\mu^+\mu^-$ (by MadGraph)
- cuts completely remove the bck. in this exercise, but it did not fake CP violation

$$p_T(\mu^\pm) > 20 \text{ GeV}, \; p_T(b,\bar{b}) > 25 \text{ GeV},$$
$$|\eta(b,\bar{b},\mu^\pm)| < 2.5, \; \Delta R > 0.4, \; \not{E}_T > 30 \text{ GeV}$$

- left with a (LO) 2.3 pb cross section at 14 TeV, 23k events per 10 $fb^{-1}$
- Or 5 $\sigma$ (stat) sensitivity to 3% asymmetries

with Gupta, Mete

Our numerical results for counting asymmetries are:

$$\tilde{A}_1 = 0.64\, d_t - 0.072\, f_t \sin\phi_f$$
$$\tilde{A}_2 = -0.041\, d_t - 0.32\, f_t \sin\phi_f$$
$$\tilde{A}_3 = 0.21\, d_t + 0.047\, f_t \sin\phi_f .$$

$$d_t \equiv \tilde{d}\, m_t, \quad f_t \equiv f\, m_t$$

This translates into a 5 σ sensitivity for 10 $fb^{-1}$ of:

$$|d_t| \geq 0.05, \quad |\tilde{d}| \geq 3.0 \times 10^{-4}\ \mathrm{GeV}^{-1}$$
$$|f_t \sin\phi_f| \geq 0.10, \quad |f \sin\phi_f| \geq 6.0 \times 10^{-4}\ \mathrm{GeV}^{-1}$$

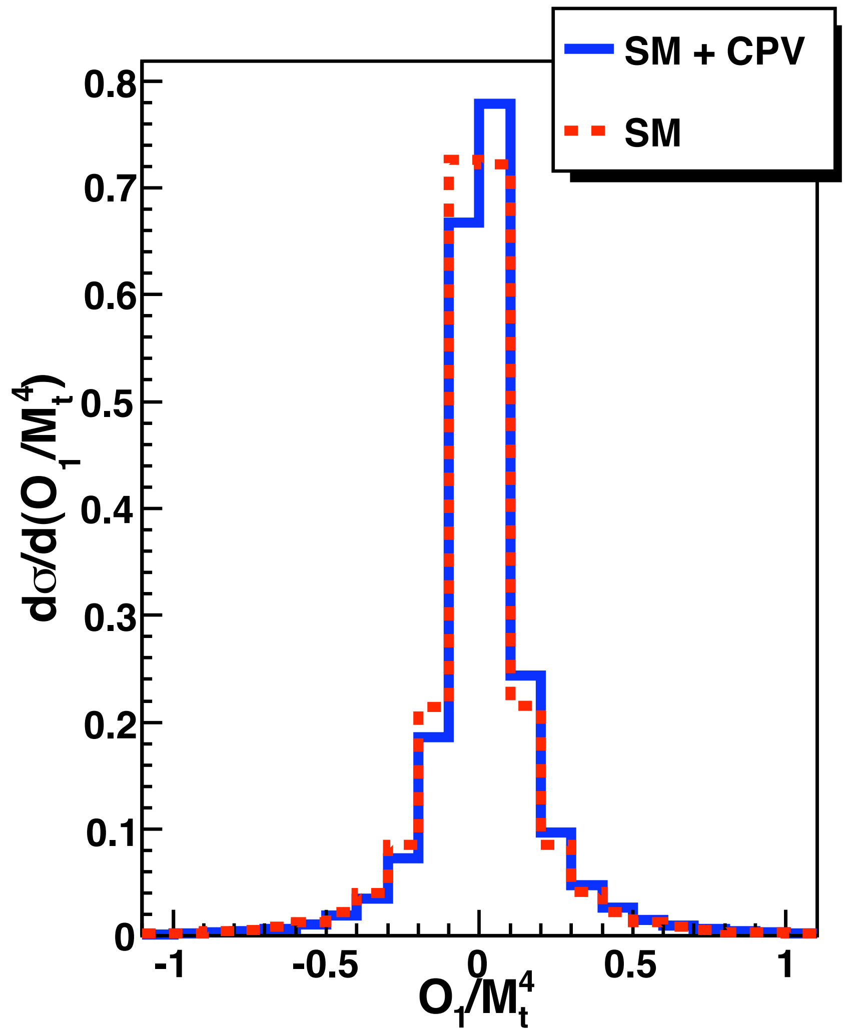
Similarly for (unitarity) CP conserving phases:

$$|f_t \sin\delta_f| \geq 0.10 \quad |f \sin\delta_f| \geq 6.0 \times 10^{-4}.$$

# example of a distribution

$\tilde{d} = 0$ (SM)

$\tilde{d} = 5 \times 10^{-4}\ \text{GeV}^{-1}$



# Numbers in Perspective

| coupling | $\tilde{d} \left[\frac{1}{m_t}\right]$ | $f \left[\frac{1}{m_t}\right]$ |
|---|---|---|
| Theory Estimate | $<10^{-13}$ SM* <br> $\sim 10^{-6}$ $H^{+}$* <br> $\sim 10^{-3}$ SUSY* | 0.03 QCD& (CP conserving and no phase) |
| with $10 fb^{-1}$ at $5\,\sigma$ | 0.05 | ~ 0.10 (both CP and/or str.) |

units → $$3.0 \times 10^{-4}\ \mathrm{GeV}^{-1} = \frac{0.05}{m_t} \leftrightarrow 5 \times 10^{-18} g_s \cdot \mathrm{cm}$$

* David Atwood et. al. **CP violation in top physics, Phys.Rept.347:1-222,2001**.

& Chong Sheng Li, Robert J. Oakes, Tzu Chiang Yuan **Phys.Rev.D43:3759-3762,1991**.

# Numerical Results II: lepton plus jets and multijets at Tevatron

- signal: $p\bar{p} \to t\bar{t} \to b\bar{b}\mu j_1 j_2 + \not{E}_T$ or $p\bar{p} \to t\bar{t} \to b\bar{b} j_1 j_2 j_1' j_2'$
- acceptance, separation cuts used

$$p_T(\mu^\pm, j) > 20 \text{ GeV}, \; p_T(b, \bar{b}) > 25 \text{ GeV},$$
$$|\eta(b, \bar{b}, \mu^\pm, j)| < 2.5, \; \Delta R_{ij} > 0.4, \; \not{E}_T > 30 \text{ GeV}$$

- with a sample of about 1000 top pair events the statistical sensitivity of the Tevatron is limited (at 3 $\sigma$ to asymmetries around 10%) resulting in limits on $\tilde{d}$ of order 1 in units of [1/$m_t$] at best
- but urge the experiments to try, at the very least to see if systematics creep in at this level
- Sehwook Lee DØ ISU student will work on it (I hope!)

# Hardest jet

- Look a bit into the meaning of $\mathcal{O}_2$ (used for lepton plus jets events)

$\mu^+ \ (W^- \to jets)$ or $\mu^- \ (W^+ \to jets)$

$$\begin{aligned}
\mathcal{O}_2 &= \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \\
&\xrightarrow{lab} \sqrt{S}\left[(\vec{p}_b + \vec{p}_{\bar{b}}) \cdot \left((\vec{p}_{\mu^+} \times \vec{p}_{j1}) + (\vec{p}_{\mu^-} \times \vec{p}_{\bar{j}1})\right)\right] \\
&\xrightarrow{CP} (-)\sqrt{S}\left[(\vec{p}_b + \vec{p}_{\bar{b}}) \cdot \left((\vec{p}_{\mu^-} \times \vec{p}_{\bar{j}1}) + (\vec{p}_{\mu^+} \times \vec{p}_{j1})\right)\right].
\end{aligned}$$

$\vec{p}_{\bar{j}1} \xrightarrow{CP} -\vec{p}_{j1}$

- the probability for a given jet originating from a quark q in a 2 jet $W^+$ decay to be the hardest one, is equal to the probability for the corresponding jet originating from the anti-quark q in a 2 jet $W^-$ decay to be the hardest one.
- this is verified explicitly in the event generation and also indirectly because the results are proportional to CP violating couplings only

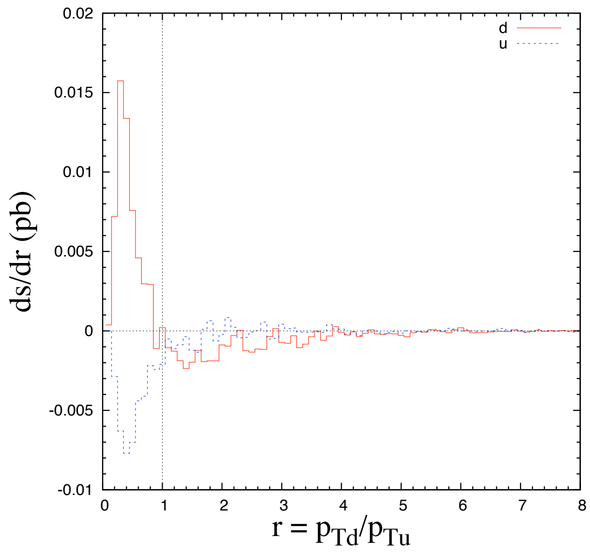
# Hardest jet continued

- in this correlation, the hardest jet is acting to some extent as spin analyzer for the top-spin. How does it compare to the d-quark (or u-quark) jet?

$$A_2 = -0.045\ d_t$$

$$A_2' \xrightarrow{j_1 \to d} +0.017\ d_t$$

$$A_2'' \xrightarrow{j_1 \to u} -0.031\ d_t$$




- in the lab frame, the hardest jet is the better choice for this asymmetry

# Conclusions

- We have studied several T-odd correlations that illustrate the different possibilities in searching for CP violation in top physics
- We have estimated the asymmetries for the simple cases of anomalous top-quark couplings in both top production and decay, and a multi-Higgs model
- With these examples we have estimated the statistical sensitivity of the LHC and the Tevatron to the CP violating top-quark couplings
- The time is ripe for experimental studies of CP violation in top physics: any observation would signal new physics. We urge the collaborations to carry them out.

# Extras

# Numerical Strategy

- We know that the asymmetries are linear in the anomalous coupling:

$$A_i = \#_1 \tilde{d} + \#_2 f \sin\phi_f$$

- Pick a value for the anomalous coupling, say

$$\tilde{d}, f \sin\phi_f = 5 \times 10^{-4}\ \mathrm{GeV}^{-1}$$

- large enough to deal with statistical error with $10^6$ events, small enough for linear approximation
- compute the asymmetry and extract #, then calculate sensitivity

# Generic asymmetry

- Start from $\epsilon(p_t, p_{\bar{t}}, p_{\ell^+}, p_{\ell^-}) \equiv \epsilon_{\mu\nu\alpha\beta} p_t^\mu p_{\bar{t}}^\nu p_{\ell^+}^\alpha p_{\ell^-}^\beta$
- becomes in the $(t\bar{t})$ center of mass frame:

$$\sqrt{s}\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$$

- Under CP:

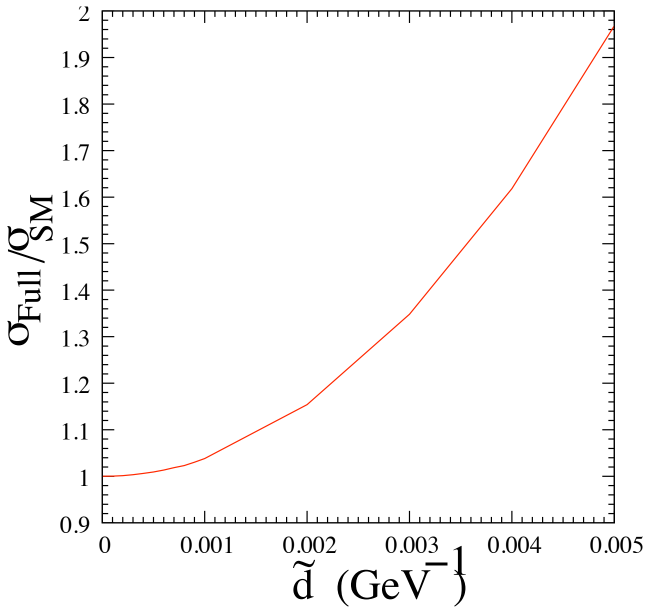
$$\begin{aligned} t\bar{t}\ell^+\ell^- X &\leftrightarrow t\bar{t}\ell^+\ell^- \bar{X} \\ \sqrt{s}\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) &\leftrightarrow \sqrt{s}(-\vec{p}_{\bar{t}}) \cdot (-\vec{p}_{\ell^-} \times (-)\vec{p}_{\ell^+}) \\ &= -\sqrt{s}\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) \end{aligned}$$

- Count with:

$$A_{CP} = \frac{N(\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) > 0) - N(\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) < 0)}{N(\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) > 0) + N(\vec{p}_t \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) < 0)}$$

# effect of (new physics)$^2$

- For a simple case ($q\bar{q}$) we check explicitly
  - the extra terms do not produce an asymmetry
  - they only affect the normalization as:



## Talk based on:

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Oleg Antipin, G. Valencia (Iowa State U.), **arXiv:0807.1295.** Published in **Phys.Rev.D79:013013,2009**.

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CP**-odd correlations using jet momenta from tt_bar events at the Tevatron.**
Sudhir Kumar Gupta, G. Valencia, (Iowa State U.) . Published in **Phys.Rev.D81:034013,2010**.e-Print: **arXiv:0912.0707** [hep-ph]

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Published in **Phys.Rev.Lett.58:451,1987, Erratum-ibid.60:243,1988**.