Probing CP violating anomalous top-quark couplings at Hadron Colliders

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DPF'11

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Based on:
Phys. Rev. D81, 034013 (2010) [Arxiv: 0912.0707[hep-ph]]
Phys. Rev. D80, 034013 (2009) [Arxiv: 0905.1074[hep-ph]]

August 9, 2011

Preliminary

- We know that the current best upper limit on the neutron EDM (nEDM) amount to

$$|d_n| < 2.9 \times 10^{-26}\ e\ .\ cm$$

- A finite nEDM can be explained by the processes that violate CP symmetry.
- Possible contributions to nEDM include the light quark EDM and also its CEDM.

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

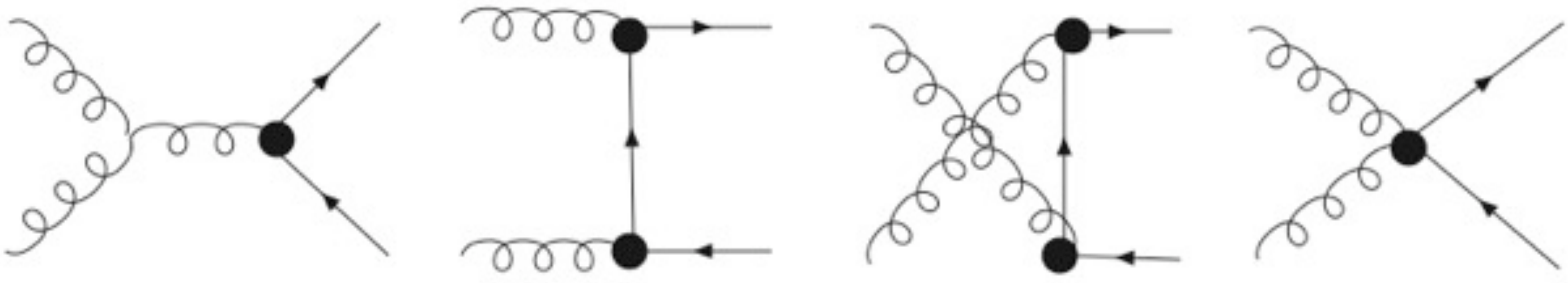
Preliminary

- A direct type of CP violation can be tested in the top sector as it is short-lived and doesn't hadronize.
- At the LHC we will have $\sim 10^7$ top-pairs/year which is mostly (> 90%) due to gluon fusion.
- We study CP violating effects in the top pair production arising due to anomalous couplings at the production as well as the decay level.

Top Pair Production@LHC

- The $t\bar{t}$ production process is modified relative to the SM interaction by the interaction

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



Top Decay Vertex

- The most general $t \to b\, W^+$ decay vertex can take the following form

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

$$f_1^L = \bar{f}_1^L = 1,$$ ← SM

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

- which include absorptive phases as well.

The Final Process

– We concentrate on W decaying into muons:

$$pp \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\mu^+\nu)(\bar{b}\mu^-\bar{\nu})$$

– The spin and colored averaged matrix element that contain CP violating correlations is given by (O Antipin, G Valencia, PRD 79, 013013 (2009) [arxiv:0807.1295])

$$|\mathcal{M}|^2_{CP} = C_1(s,t,u)\,\mathcal{O}_1 + C_2(s,t,u)\,\mathcal{O}_2 + C_3(s,t,u)\,\mathcal{O}_3$$

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

- These observables are different spin correlations in the process.
- The corresponding counting asymmetries can be defined as

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

- As not all the momenta $(P,\ q,\ p_t,\ p_{\bar{t}})$ can be reconstructed fully at the LHC, we need to modify them with the substitutions

$$p_t \to p_b + p_{\mu^+} \quad p_{\bar{t}} \to p_{\bar{b}} + p_{\mu^-}$$
$$P \to p_b + p_{\mu^+} + p_{\bar{b}} + p_{\mu^-} \quad q \to \tilde{q} \equiv P_1 - P_2$$

- Modified correlations thus take the form

$$\tilde{\mathcal{O}}_1 = \epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-})$$
$$\tilde{\mathcal{O}}_2 = \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q})$$
$$\tilde{\mathcal{O}}_3 = \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_b, p_{\bar{b}}, p_{\mu^+} + p_{\mu^-}, \tilde{q})$$

- In case of CP violation in decay vertex, the color and spin matrix element square takes the following form

(O Antipin, G Valencia, PRD 79, 013013 (2009) [arxiv:0807.1295])

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

  - with δ_f and ϕ_f as absorptive and CP-violating phases respectively.

- This contains terms with 3 four momenta from one of the decay vertices, we find additional correlations

$$\mathcal{O}_4 = \epsilon(P, p_b - p_{\bar{b}}, p_{\mu^+}, p_{\mu^-})$$
$$\mathcal{O}_5 = \epsilon(p_t, p_{\bar{t}}, p_b + p_{\bar{b}}, p_{\mu^+} - p_{\mu^-})$$
$$\mathcal{O}_6 = (t-u)\,\epsilon(P, p_b + p_{\bar{b}}, p_{\mu^+} - p_{\mu^-}, q)$$

Numerical Analysis

- We replaced SM matrix-element square with the new (CPV) one in MADGRAPH.
- The major background for the process is due to $gg \to b\bar{b}\mu^+\mu^- X$ with minimal acceptance cuts the cross-sections at the LHC are 4.3 pb and 24 pb for S and B respectively.

After applying (10)

$$p_T(\mu^\pm) > 20 \text{ GeV} \quad p_T(b, \bar{b}) > 25 \text{ GeV}$$
$$|\eta(b, \bar{b}, \mu^\pm)| < 2.5 \quad \Delta R(b\bar{b}) > 0.4. \tag{10}$$

these numbers become: 2.6 pb and 1.2 pb
and after (11):

$$\not{E}_T > 30 \text{ GeV}. \tag{11}$$

2.3 pb and 0 pb respectively

Results

$5 \times 10^{-4}\,\mathrm{GeV}^{-1}$

	A_1	A_2	A_3	A_4	A_5	A_6	cuts
$\tilde{d}$	0.1	-2.2×10^{-2}	2.5×10^{-3}	-7.4×10^{-2}	4.1×10^{-2}	-8.4×10^{-3}	Eq. 10
	0.1	-2.1×10^{-2}	2.9×10^{-3}	-7.5×10^{-2}	3.6×10^{-2}	-6.4×10^{-3}	Eqs. 10, 11
$f \sin \phi_f$	-	-	-	-5.3×10^{-3}	-1.6×10^{-2}	1.6×10^{-2}	Eq. 10
	-	-	-	-5.8×10^{-3}	-1.7×10^{-2}	1.7×10^{-2}	Eqs. 10, 11

- With 23k events/year the statistical fluctuation $(at\ 3\sigma)$ for the aforementioned asymmetries is $A_{stat} \sim 1.9 \times 10^{-2}$

	$\tilde{A}_1$	$\tilde{A}_2$	$\tilde{A}_3$	cuts
$\tilde{d}$	5.6×10^{-2}	-4.1×10^{-3}	1.8×10^{-2}	Eq. 10
	5.5×10^{-2}	-3.5×10^{-3}	1.8×10^{-2}	Eqs. 10, 11
$f \sin\phi_f$	-5.4×10^{-3}	-2.6×10^{-2}	5.6×10^{-3}	Eq. 11
	-6.2×10^{-3}	-2.7×10^{-2}	4.0×10^{-3}	Eqs. 10, 11

TABLE III: Integrated asymmetries without full top momentum reconstruction for $\tilde{d}$ or $f \sin\phi_f = 5 \times 10^{-4}\ \mathrm{GeV}^{-1}$ with the cuts defined in Eqs. [10], [11].

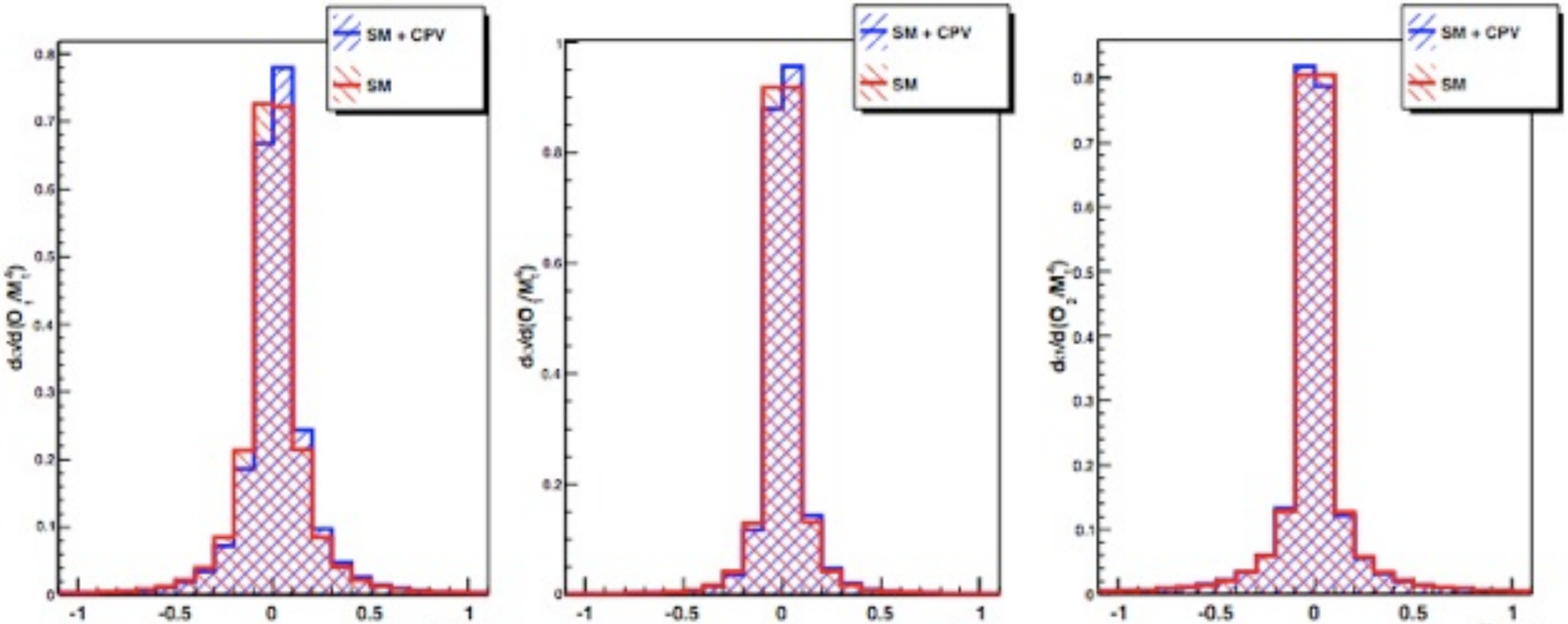


FIG. 1: $d\sigma/d\mathcal{O}_1$ and $d\sigma/d\tilde{\mathcal{O}}_1$ distributions for the cases $\tilde{d} = 0$ (SM) and $\tilde{d} = 5 \times 10^{-4}$ GeV^{-1} as well as $d\sigma/d\tilde{\mathcal{O}}_2$ for $f \sin\phi_f = 5 \times 10^{-4}$ GeV^{-1}.

LHC sensitivity

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

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

- With one year of LHC run, 5σ sensitivity requires

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

Strong interaction phases

- This can be isolated by employing CP-even observables

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

A_a	A_b	cuts
4.2×10^{-3}	-3.1×10^{-2}	Eq. 10
3.0×10^{-3}	-2.7×10^{-2}	Eqs. 10, 11

– 5σ LHC sensitivity with 1 year data requires,

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

D0 Measurements

- D0 recently MEASURED the observable O_2. They obtain a result consistent with no CP vioaltion at 1.2σ.
  [Talk by S. Lee at http://www-clued0.fnal.gov/~merciful/aps_2011/]

	$A_{central}$	$\sigma_{stat.}$	$\sigma_{dilution}$	$\sigma_{sys.}$	$\sigma_{stat.+dilution+sys.}$
O_2	$+0.106$	$^{+0.080}_{-0.081}$	$^{+0.035}_{-0.039}$	$^{+0.014}_{-0.017}$	$^{+0.088}_{-0.091}$

- This is expected within the framework of a top-quark CEDM where we predict for the Tevatron:

$$A_2 = 0.0037 \pm 0.001 \text{ for } \tilde{d} = 5 \times 10^{-4} \text{ GeV}^{-1}$$

which is near the upper end of model predictions and a bit higher than some indirect constraints.

It is important that they obtained 0, indicating control of systematics at this level.

CP violation at the Tevatron

- Although it is not enough to probe $\tilde{d}$, it can be a good start to work at the LHC because of relatively larger number top pair events.
- At the Tevatron, we consider processes where at least one of the produced top decays hadronically.
- The CP violating observables in this cases will thus depend on the jet momenta.

T-odd observables at the Tevatron

For the lepton (muon) plus jets process $p\bar{p} \to t\bar{t} \to b\bar{b}\mu j_1 j_2 + \not{E}_T$:

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

For the multi-jet process $p\bar{p} \to t\bar{t} \to b\bar{b} j_1 j_2 j_{1'} j_{2'}$:

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

Jets are pT ordered. i.e. $p_{T_{j_1}} > p_{T_{j_2}}$ Ql is the lepton charge.

lepton + jets channel

	$3/\sqrt{N}$	A_1	A_2	A_3	A_4	A_7	A_a	A_b
$\tilde{d}$	3.9	-66.4	-38.9	-102.3	76.5	36.4	-3.0	-1.4
$\tilde{f}\sin\phi_f$	3.9	-17.2	-66.8	-18.8	-30.8	7.0	0.7	-2.3
$\tilde{f}\sin\delta_f$	3.9	0.4	-1.1	1.6	-3.1	1.0	-44.1	-56.8
SM	3.9	2.5	-0.5	0.5	-0.2	0.4	-0.3	0.6

Integrated asymmetries with cuts given in Eqs. 8, 9 for $\tilde{d}$, $\tilde{f}\sin(\phi_f, \delta_f)$ $= 5 \times 10^{-3}$ GeV^{-1} in units of 10^{-3}, and the SM.

all jets channel

	$3/\sqrt{N}$	A_1	A_5	A_6	A_7	A_c
$\tilde{d}$	3.5	-61.2	-54.6	-61.2	38.8	1.1
$\tilde{f}\sin\phi_f$	3.5	-7.1	-7.8	-7.1	5.8	-1.0
$\tilde{f}\sin\delta_f$	3.5	-1.8	-1.5	-1.8	-0.5	9.6
SM	3.5	0.7	0.5	0.7	1.0	1.1

Integrated asymmetries for signal 2 with cuts given in Eq. 8 for $\tilde{d}$, $\tilde{f}\sin(\phi,\delta)$ $= 5\times10^{-3}$ GeV^{-1} in units of 10^{-3}, and the SM.

LHC and Tevatron Sensitivities

Collider	$\tilde{d}$ (at 5σ)	$\tilde{f}_\phi$ (at 5σ)
Tevatron 4.3 fb^{-1}	$2.2 \times 10^{-2}\ \mathrm{GeV}^{-1}$	$1.9 \times 10^{-2}\ \mathrm{GeV}^{-1}$
LHC 10 $\mathrm{fb}^{-1}(\sqrt{\mathrm{s}} = 14\mathrm{TeV})$	$3 \times 10^{-4}\ \mathrm{GeV}^{-1}$	$6 \times 10^{-4}\ \mathrm{GeV}^{-1}$

Summary & new development

- We have estimated asymmetries due to anomalous top quark coupling both production and decay level.
- Although Tevatron sensitivities are not promising, it is still possible to probe such type of CP violation at the LHC within a year or so.
- Also, the true CP phases can be isolated from the strong interacting phases using the T-even observables.
- **New development :** Recently we have been able to check our results by incorporating the CP violating couplings in the MadGraph5 and we found that our results are in good agreement with the full $|M|^2$ calculation. [ps: In case anyone in the ATLAS/CMS wants the code, please email me at skgupta@iastate.edu].

Backup-slides

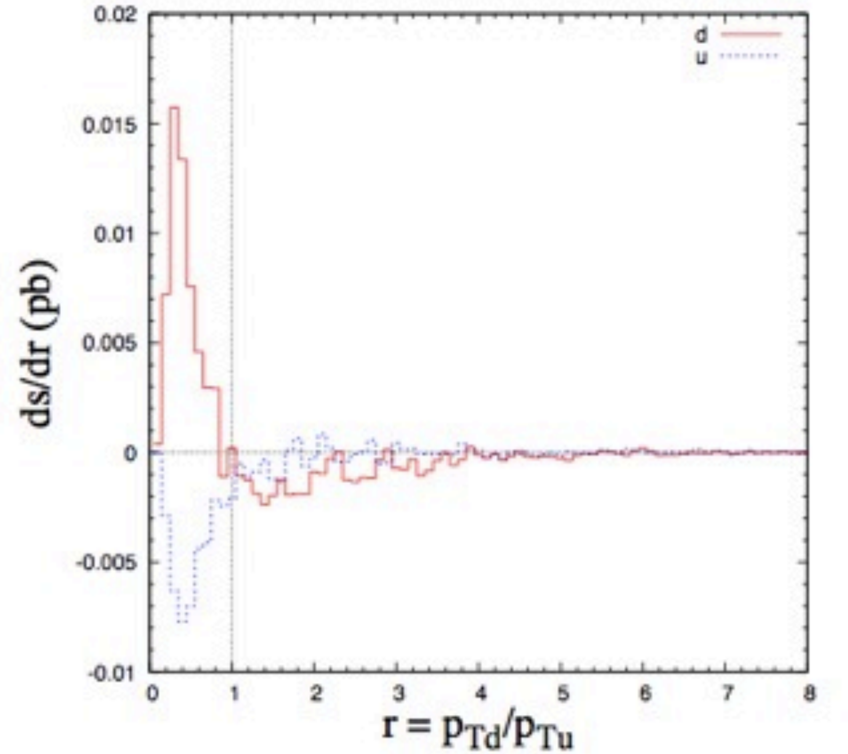


FIG. 2: Differential distributions of s, the numerator of $\tilde{A}_{2d}$ (or $\tilde{A}_{2u}$) , with respect to r, the ratio of d-quark transverse momentum to u-quark transverse momentum in $t \to bu\bar{d}$ or $\bar{t} \to \bar{b}\bar{u}d$ decay.