The electroweak contribution to the top forward-backward asymmetry at Tevatron

Davide Pagani

Max Planck Institut für Physik, München

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$$p\bar{p} \to t\bar{t} + X$$

$$A_{FB}^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

$$A_{FB}^{p\bar{p}} = \frac{\sigma(y_t > 0) - \sigma(y_t < 0)}{\sigma(y_t > 0) + \sigma(y_t < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

Definitions of A_{FB}:

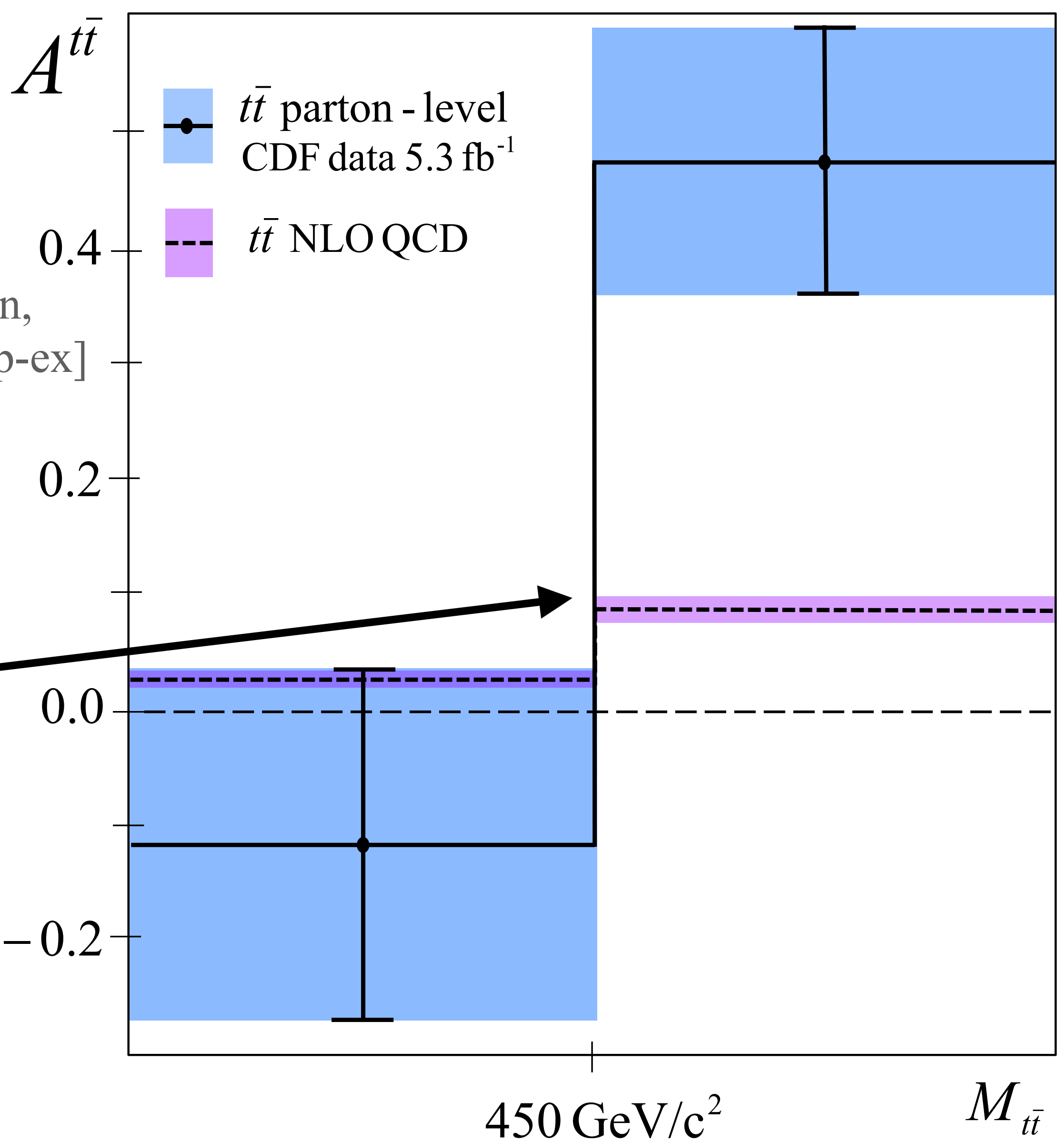
Why is A_{FB} interesting?

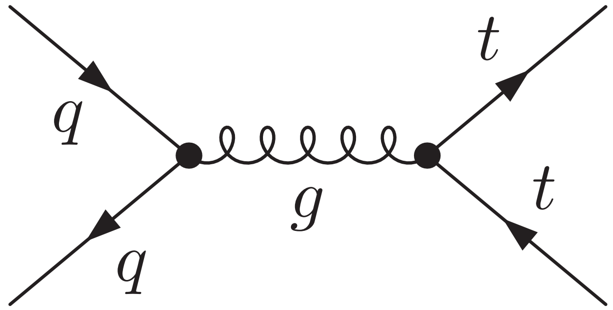
Theory | Experiment

$A_{FB}(\%)$	$A_{FB}^{t\bar{t}}$	$A_{FB}^{p\bar{p}}$
data	15.8 ± 7.4	15.0 ± 5.5
MCFM	5.8 ± 0.9	3.8 ± 0.6

Only NLO QCD, let's see SM prediction!

CDF collaboration, arXiv:1101.0034[hep-ex]





At LO partonic processes are not asymmetric.
QCD produces the asymmetry only at NLO!
NLO in the cross-section, LO in A_{FB}

ONLY LO IS AVAILABLE!

NOT AVAILABLE, NOT TRIVIAL

$$A_{FB} = \frac{N}{D} = \frac{\alpha_s^3 N_1 + \alpha_s^4 N_2 + \cdots}{\alpha_s^2 D_0 + \alpha_s^3 D_1 + \cdots} = \frac{\alpha_s}{D_0}(N_1 + \alpha_s(N_2 - N_1 D_1/D_0)) + \cdots$$

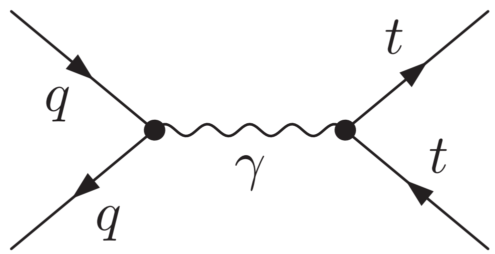
QCD only at LO, but there is also electroweak theory. $\boxed{\mathcal{O}(\alpha_s \alpha) = 0}$

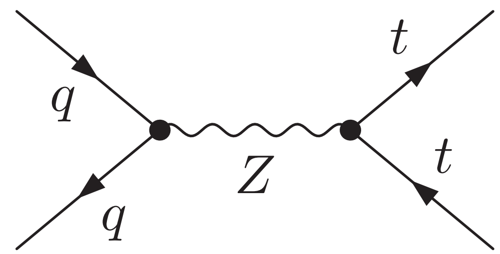
$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

$\alpha_s^2 D_0$ is the LO cross section, now we see the terms in N

$$\boxed{A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}}$$

$$\boxed{\frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}}$$



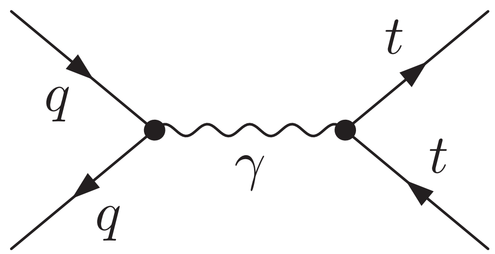


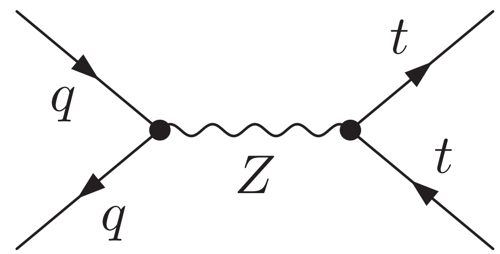
Different couplings for different chiralities produce asymmetric terms in the cross-section

$$\frac{d\sigma_{asym}}{d\cos\theta} = 2\pi\alpha^2 \underline{\cos\theta} \left(1 - \frac{4m_t^2}{s}\right) \left[\kappa \frac{\boxed{Q_q} Q_t A_q A_t}{(s - M_Z^2)} + 2\kappa^2 \boxed{A_q} A_t \boxed{V_q} V_t \frac{s}{(s - M_Z^2)^2}\right]$$

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

$$\frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$





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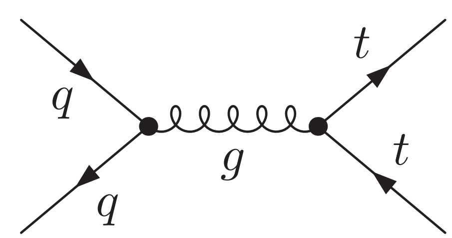
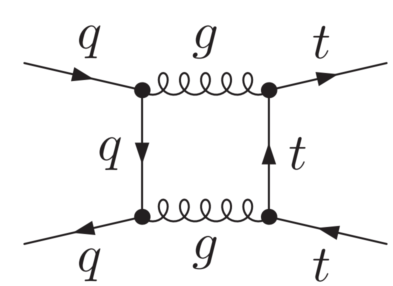
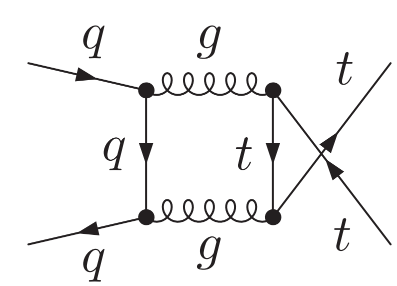
$$\alpha_s \frac{N_1}{D_0}$$

VIRTUAL (Only Boxes)
NO UV, NO Coll. Div.
Only IR

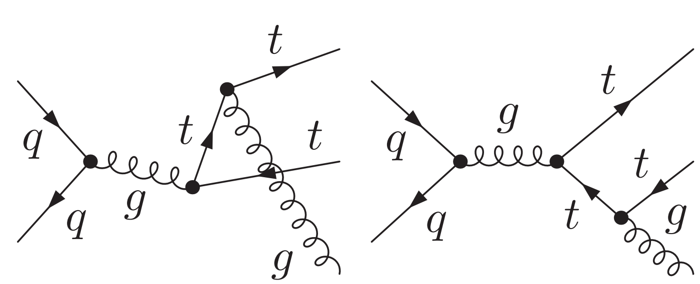




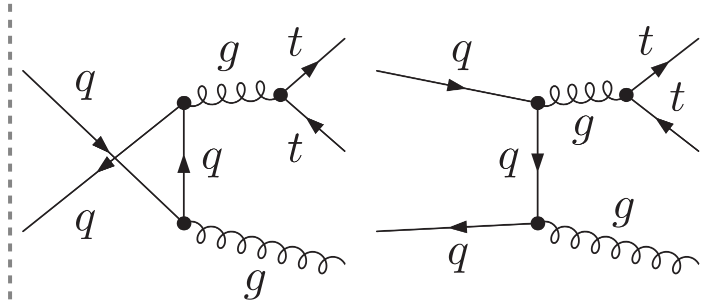


REAL
Only interference of initial and final gluon emission is asymmetric.

Kuhn, Rodrigo - Phys.Rev. D59 (1999) 054017



Final



Initial

REAL+VIRTUAL= IR finite

$$\boxed{\alpha\frac{\tilde{N}_1}{D_0}}$$

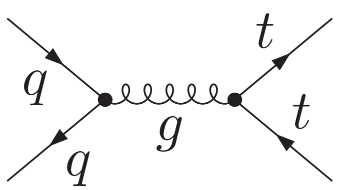
It's useful to divide electroweak contribution into QED (photon) and weak (Z) part.

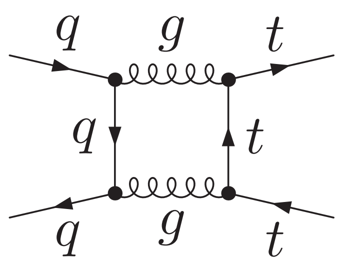
QED

QED can be easily obtained from QCD calculation and the substitution of one gluon into one photon in the squared amplitudes.

$q\bar{q} \to t\bar{t}$

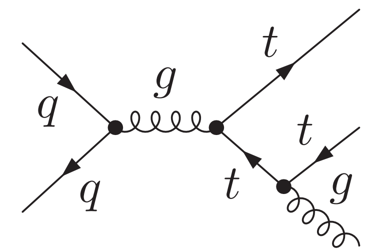
$\overline{|\mathcal{M}^{t\bar{t}}|}^2_{\mathcal{O}(\alpha_s^3)}$

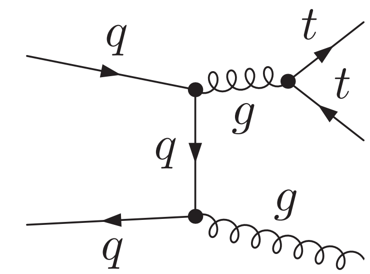




$q\bar{q} \to t\bar{t}g$

$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^3)}$





$\alpha \frac{\tilde{N}_1}{D_0}$

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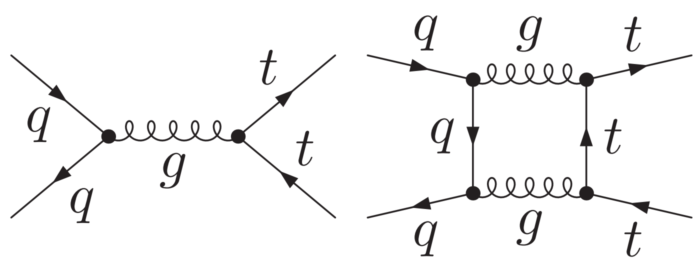
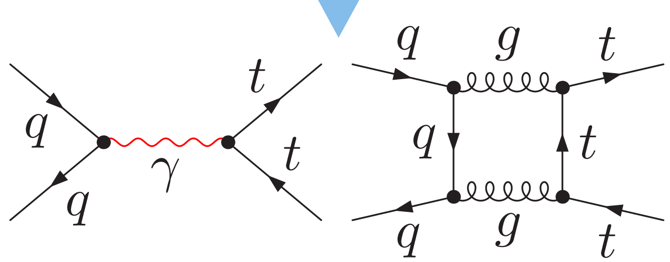
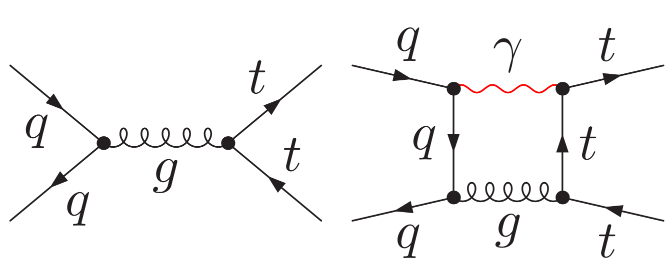
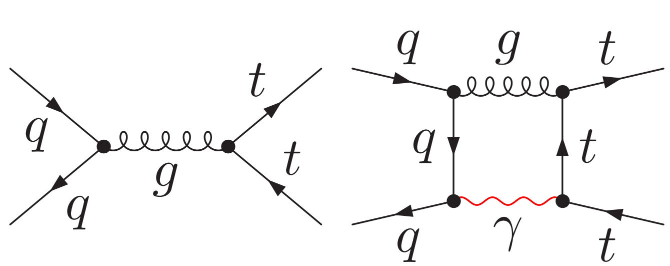




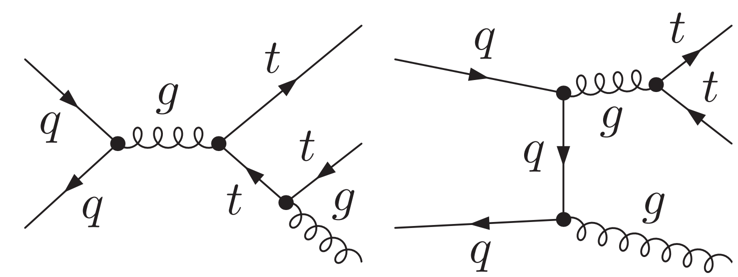
$\overline{|\mathcal{M}^{t\bar{t}}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



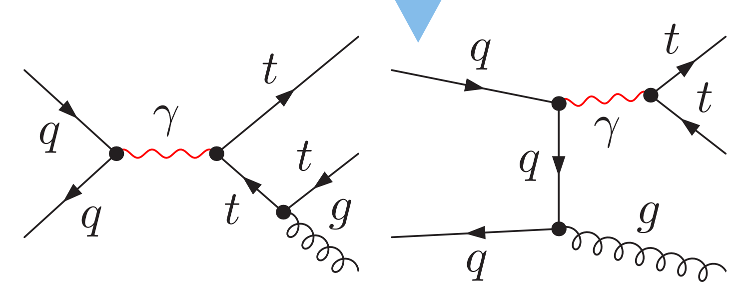


$q\bar{q} \to t\bar{t}g$

$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^3)}$

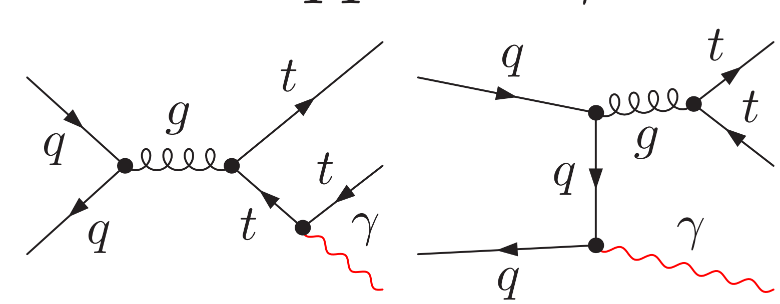


$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



$q\bar{q} \to t\bar{t}\gamma$

$\overline{|\mathcal{M}^{t\bar{t}\gamma}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



DIFFERENCES:
Only couplings and color factor!

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

QED correction can be obtained from QCD × R_{QED}

Weak

The same diagrams as QED part, but $\gamma \to Z$.

Z is not massless → If we write Weak=QCD × $R_{Weak.}$
R_{Weak} does not depend only on couplings and color factor

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The same diagrams as QED part, but $\gamma \rightarrow Z$.

Z is not massless → If we write Weak=QCD × R_{Weak}.
R_{Weak} does not depend only on couplings and color factor

EXISTING ESTIMATE → $A_{FB}^{EW} = 0.09 \times A_{FB}^{QCD}$

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

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The same diagrams as QED part, but $\gamma \rightarrow Z$.

Z is not massless → If we write Weak=QCD × R_{Weak}.
R_{Weak} does not depend only on couplings and color factor

EXISTING ESTIMATE → $A_{FB}^{EW} = 0.09 \times A_{FB}^{QCD}$

WE CALCULATED THE COMPLETE EW CONTRIBUTION

$$A_{FB}^{EW} \sim 0.25 \times A_{FB}^{QCD}$$

THIS NUMBER DEPENDS ON THE RENORMALIZATION SCALE OF α_s

NUMERICAL RESULTS

$\alpha^{-1} = 137.035$ $m_t = 172.0$ GeV $m_Z = 91.1875$ GeV $m_W = 80.399$ GeV

Input

α_s?

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

α_s for LO $\neq$
α_s for NLO

Expansion makes sense if α_s in N and D is the same.
α_s from MRST2004QED $\rightarrow$ α_s for NLO

Factorization scale μ_f
renormalization scale μ_r

$\mu_f = \mu_r = (m_t/2, m_t, 2m_t)$

NUMERICAL RESULTS

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α_s for LO $\neq$ α_s for NLO

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Factorization scale μ_f
renormalization scale μ_r

$\mu_f = \mu_r = (m_t/2, m_t, 2m_t)$

Output

$A_{FB}^{t\bar{t}} = (9.7, 8.9, 8.3)\%$ $A_{FB}^{p\bar{p}} = (6.4, 5.9, 5.4)\%$

Compare with

$A_{FB}(\%)$	$A_{FB}^{t\bar{t}}$	$A_{FB}^{p\bar{p}}$
data	15.8 ± 7.4	15.0 ± 5.5
MCFM	5.8 ± 0.9	3.8 ± 0.6

(a) $A_{FB}^{t\bar{t}}$

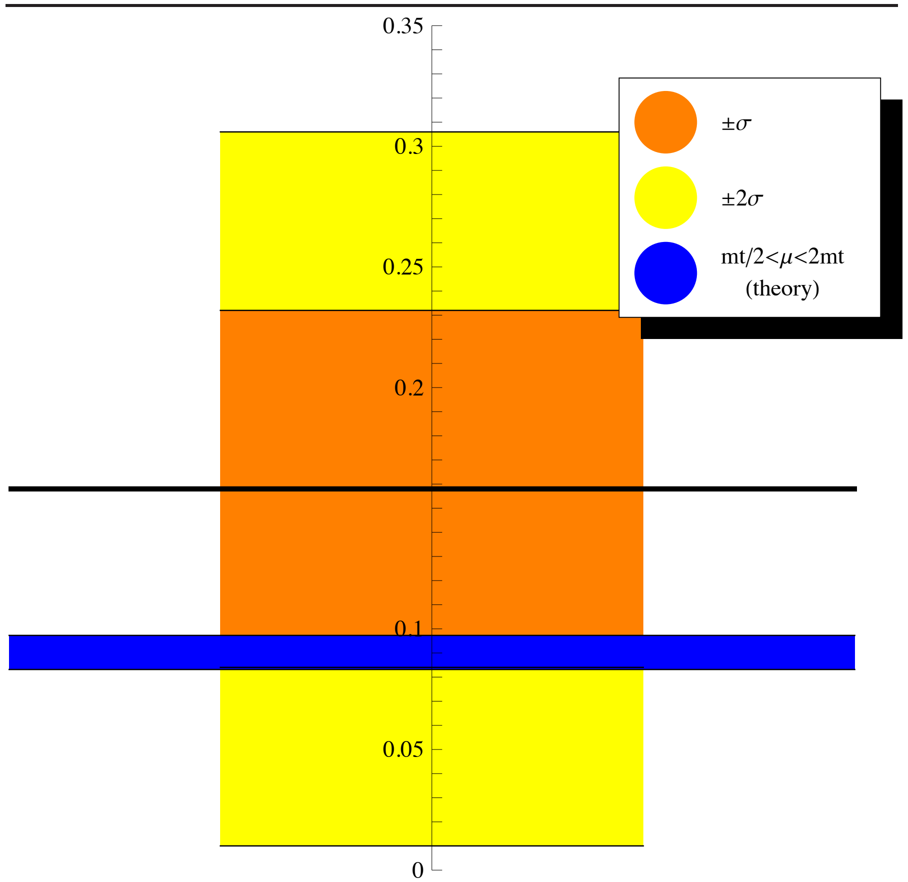
$A_{FB}^{t\bar{t}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s)$	$u\bar{u}$	7.01%	6.29%	5.71%
$\mathcal{O}(\alpha_s)$	$d\bar{d}$	1.16%	1.03%	0.92%
$\mathcal{O}(\alpha)_{QED}$	$u\bar{u}$	1.35%	1.35%	1.35%
$\mathcal{O}(\alpha)_{QED}$	$d\bar{d}$	-0.11%	-0.11%	-0.11%
$\mathcal{O}(\alpha)_{weak}$	$u\bar{u}$	0.16%	0.16%	0.16%
$\mathcal{O}(\alpha)_{weak}$	$d\bar{d}$	-0.04%	-0.04%	-0.04%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$u\bar{u}$	0.18%	0.23%	0.28%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$d\bar{d}$	0.02%	0.03%	0.03%
tot	$p\bar{p}$	9.72%	8.93%	8.31%

(b) $A_{FB}^{p\bar{p}}$

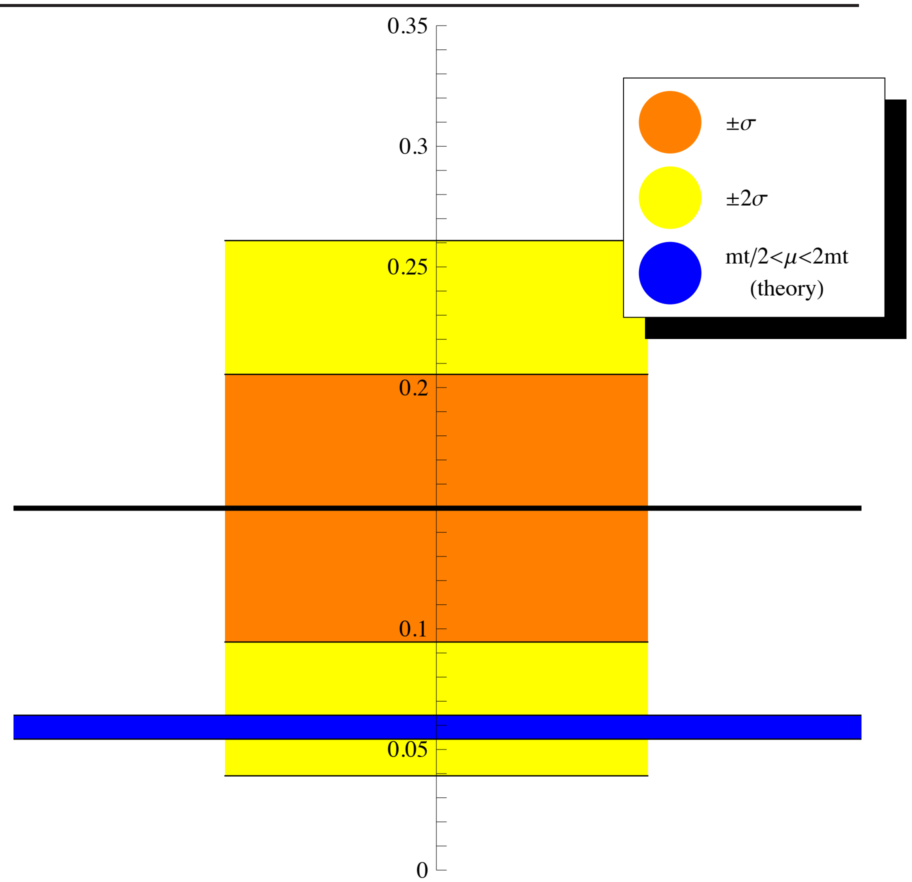
$A_{FB}^{p\bar{p}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s)$	$u\bar{u}$	4.66%	4.19%	3.78%
$\mathcal{O}(\alpha_s)$	$d\bar{d}$	0.75%	0.66%	0.59%
$\mathcal{O}(\alpha)_{QED}$	$u\bar{u}$	0.90%	0.90%	0.90%
$\mathcal{O}(\alpha)_{QED}$	$d\bar{d}$	-0.07%	-0.07%	-0.07%
$\mathcal{O}(\alpha)_{weak}$	$u\bar{u}$	0.10%	0.10%	0.10%
$\mathcal{O}(\alpha)_{weak}$	$d\bar{d}$	-0.03%	-0.03%	-0.03%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$u\bar{u}$	0.11%	0.14%	0.17%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$d\bar{d}$	0.01%	0.02%	0.02%
tot	$p\bar{p}$	6.42%	5.92%	5.43%

$$R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$$

$$R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119)$$



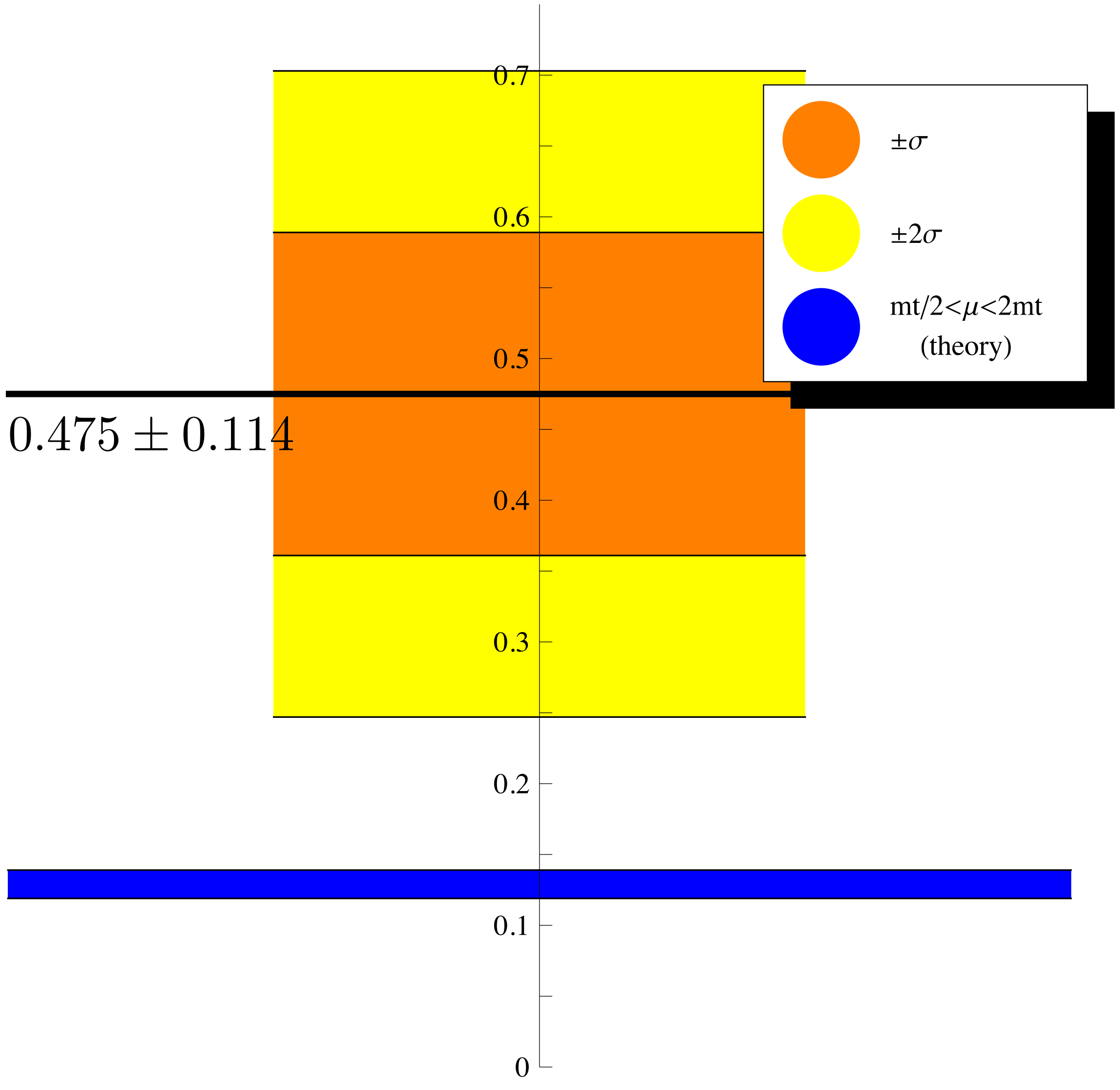
(a) $A_{FB}^{t\bar{t}}$



(b) $A_{FB}^{p\bar{p}}$

a) at 1σ
b)inside 2σ

$$\frac{(A_{FB}^{t\bar{t}})^{EW}}{(A_{FB}^{t\bar{t}})^{QCD}} = (0.190, 0.220, 0.254) \qquad \frac{(A_{FB}^{p\bar{p}})^{EW}}{(A_{FB}^{p\bar{p}})^{QCD}} = (0.186, 0.218, 0.243)$$



(a) $A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ \text{GeV})$

$$A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ \text{GeV}) = (13.9, 12.8, 11.9)\%$$

Also with cuts the gap between theory and experiment is decreased by EW terms. Anyway, if invariant mass > 450 GeV, theory at 3σ.

CONCLUSION

A very important term is still missing: NNLO QCD differential cross section.

Total electroweak contribution is not negligible and increases QCD asymmetry by a factor ~ 1.2

The QED part can be simply calculated from QCD contribution of the subprocesses

EW cannot explain $A_{FB}(M_{INV}>450$ GeV), but new models cannot forget its contribution when they try to fill the gap between theory (SM) and experiment. Moreover we have to wait the NLO of QCD also for this region.

THANK YOU FOR THE ATTENTION!

EXTRA SLIDES

Hadronic process = partonic process $\otimes$ PDF

$$H_1 H_2 \to t\bar{t} + X \qquad p_1 p_2 \to t\bar{t} + X$$

$$f_{p_1,H_1}(x_1) f_{p_2,H_2}(x_2)$$
$$f_{p_1,H_2}(x_1) f_{p_2,H_1}(x_2)$$

Partonic process can be produced in two different directions with the same momenta

$$\boxed{A_{FB} \neq 0} \leftrightarrow \boxed{f_{p_1,H_1}(x_1) f_{p_2,H_2}(x_2) \neq f_{p_1,H_2}(x_1) f_{p_2,H_1}(x_2)}$$

At LHC H1=H2 $\to$ AFB=0

At Tevatron only processes with p1 or p2 = (up, antiup, down, antidown) can produce asymmetric terms!

LO Cross-Section

σ(pb)	$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$p\bar{p}$ (No cuts)	7.990	5.621	4.187
$p\bar{p}(M_{t\bar{t}} > 450$ GeV)	3.113	2.148	1.573
$p\bar{p}(\lvert\Delta y\rvert > 1)$	1.846	1.276	0.937

$$\kappa = \frac{1}{4\sin^2(\theta_W)\cos^2(\theta_W)} \qquad V_q = T_q^3 - 2Q_q \sin^2(\theta_W) \qquad A_q = T_q^3$$

(a) $A_{FB}^{t\bar{t}}$

$A_{FB}^{t\bar{t}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
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$\mathcal{O}(\alpha_s)$	$d\bar{d}$	1.16%	1.03%	0.92%
$\mathcal{O}(\alpha)_{QED}$	$u\bar{u}$	1.35%	1.35%	1.35%
$\mathcal{O}(\alpha)_{QED}$	$d\bar{d}$	-0.11%	-0.11%	-0.11%
$\mathcal{O}(\alpha)_{weak}$	$u\bar{u}$	0.16%	0.16%	0.16%
$\mathcal{O}(\alpha)_{weak}$	$d\bar{d}$	-0.04%	-0.04%	-0.04%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$u\bar{u}$	0.18%	0.23%	0.28%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$d\bar{d}$	0.02%	0.03%	0.03%
tot	$p\bar{p}$	9.72%	8.93%	8.31%

(b) $A_{FB}^{p\bar{p}}$

$A_{FB}^{p\bar{p}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s)$	$u\bar{u}$	4.66%	4.19%	3.78%
$\mathcal{O}(\alpha_s)$	$d\bar{d}$	0.75%	0.66%	0.59%
$\mathcal{O}(\alpha)_{QED}$	$u\bar{u}$	0.90%	0.90%	0.90%
$\mathcal{O}(\alpha)_{QED}$	$d\bar{d}$	-0.07%	-0.07%	-0.07%
$\mathcal{O}(\alpha)_{weak}$	$u\bar{u}$	0.10%	0.10%	0.10%
$\mathcal{O}(\alpha)_{weak}$	$d\bar{d}$	-0.03%	-0.03%	-0.03%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$u\bar{u}$	0.11%	0.14%	0.17%
$\mathcal{O}(\alpha^2/\alpha_s^2)$	$d\bar{d}$	0.01%	0.02%	0.02%
tot	$p\bar{p}$	6.42%	5.92%	5.43%

$$R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$$

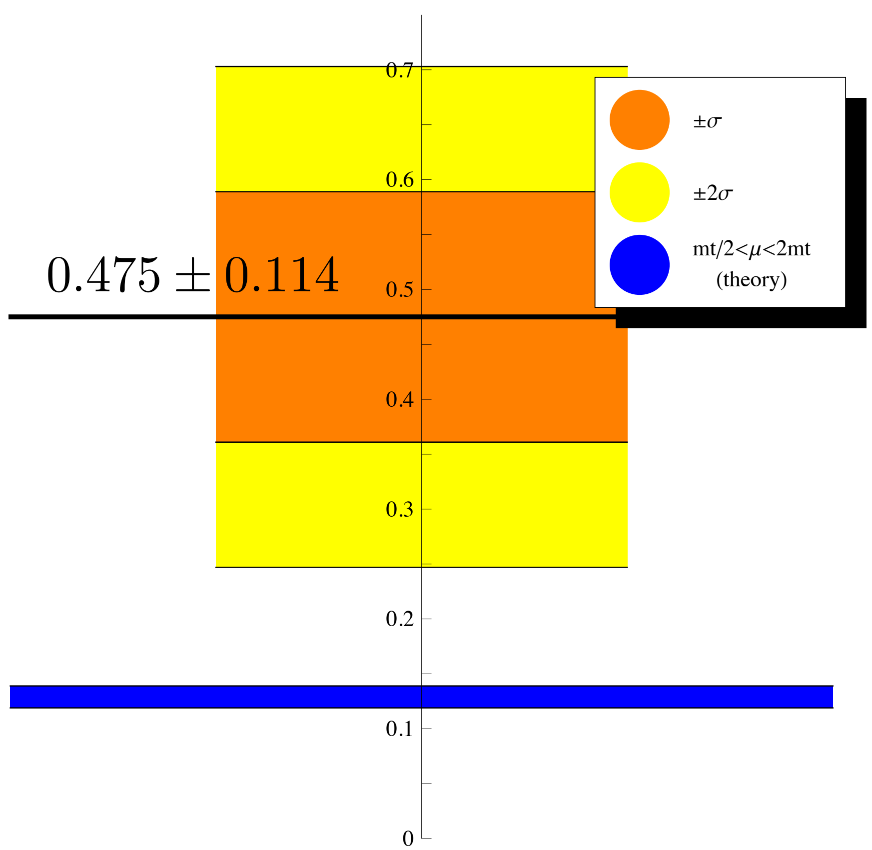
$$R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119)$$

(a) $A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ \text{GeV})$

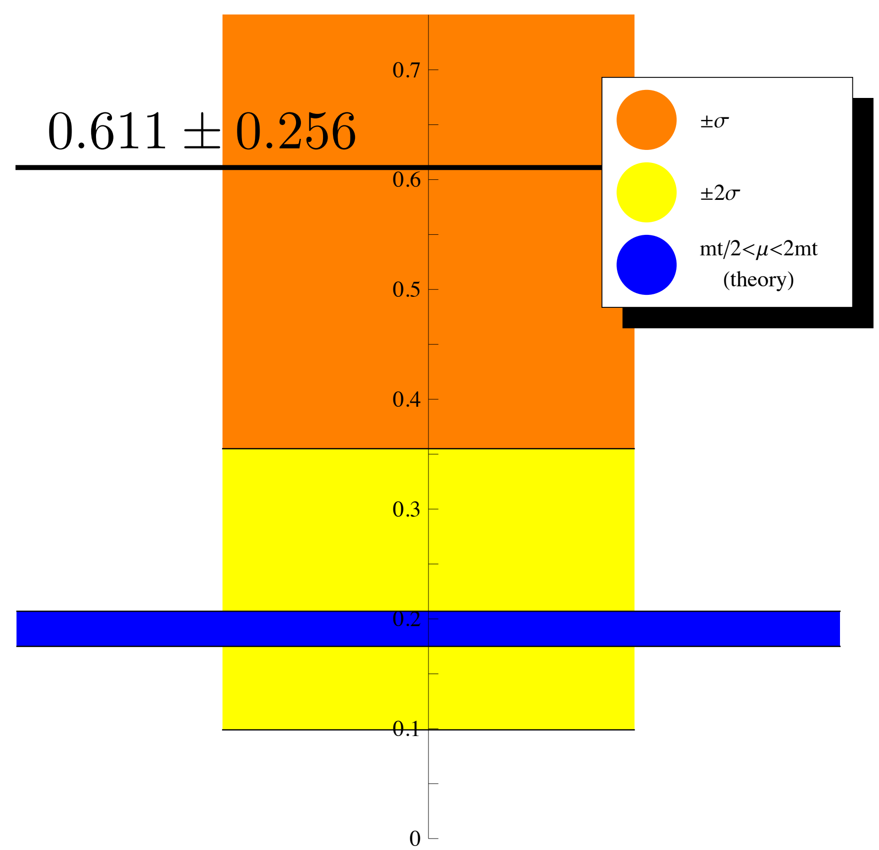
$A_{FB}^{t\bar{t}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s^3)$	$u\bar{u}$	10.13%	9.10%	8.27%
$\mathcal{O}(\alpha_s^3)$	$d\bar{d}$	1.44%	1.27%	1.14%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$u\bar{u}$	1.94%	1.95%	1.96%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$d\bar{d}$	-0.14%	-0.14%	-0.14%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$u\bar{u}$	0.28%	0.28%	0.28%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$d\bar{d}$	-0.05%	-0.05%	-0.05%
$\mathcal{O}(\alpha^2)$	$u\bar{u}$	0.26%	0.33%	0.41%
$\mathcal{O}(\alpha^2)$	$d\bar{d}$	0.03%	0.03%	0.04%
tot	$p\bar{p}$	13.90%	12.77%	11.91%

(b) $A_{FB}^{t\bar{t}}(|\Delta y| > 1)$

$A_{FB}^{t\bar{t}}$		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s^3)$	$u\bar{u}$	15.11%	13.72%	12.41%
$\mathcal{O}(\alpha_s^3)$	$d\bar{d}$	2.28%	2.02%	1.84%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$u\bar{u}$	2.90%	2.94%	2.94%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$d\bar{d}$	-0.22%	-0.22%	-0.22%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$u\bar{u}$	0.25%	0.25%	0.26%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$d\bar{d}$	-0.09%	-0.09%	-0.08%
$\mathcal{O}(\alpha^2)$	$u\bar{u}$	0.35%	0.45%	0.55%
$\mathcal{O}(\alpha^2)$	$d\bar{d}$	0.04%	0.05%	0.06%
tot	$p\bar{p}$	20.70%	19.12%	17.75%



(a) $A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ \text{GeV})$



(b) $A_{FB}^{t\bar{t}}(|\Delta y| > 1)$