Top-Quark Charge Asymmetry with a Jet Handle

(S.B., Susanne Westhoff, PRD 86, 094036)

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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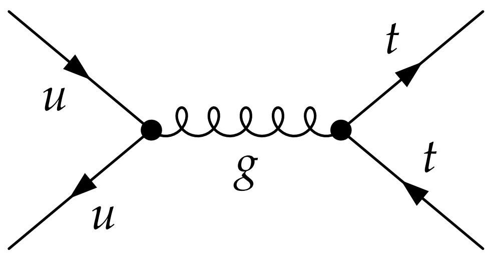
Motivation

- QCD predicts a charge asymmetry for top quark pair production in hadron-hadron scattering
- The corresponding forward-backward asymmetry has been measured at CDF and D0
- Discrepancy to SM prediction remains between 2-3 σ
- Sign of new Physics?
- Need to measure the charge asymmetry at the LHC
- Problem: predicted SM charge asymmetry in inclusive top pair production at LHC is very small

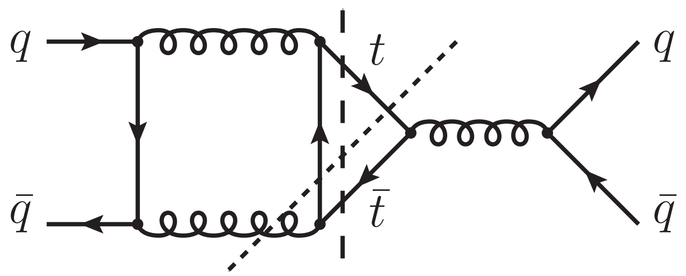
Parton Level	POWHEG	CDF 9.4 fb^{-1}	exceeding SM prediction
Inclusive	6.6%	16.4 ± 4.5 %	2.2 σ
M_{tt} slope	$(3.4 \pm 1.2) 10^{-4}$ GeV^{-1}	$(15.2 \pm 5) 10^{-4}$ GeV^{-1}	2.3 σ
$\|\Delta y\|$ slope	$(10. \pm 2.3) 10^{-2}$ GeV^{-1}	$(28.6 \pm 8.5) 10^{-2}$ GeV^{-1}	2.1 σ

(CDF, arXiv 1211.1003)

Motivation



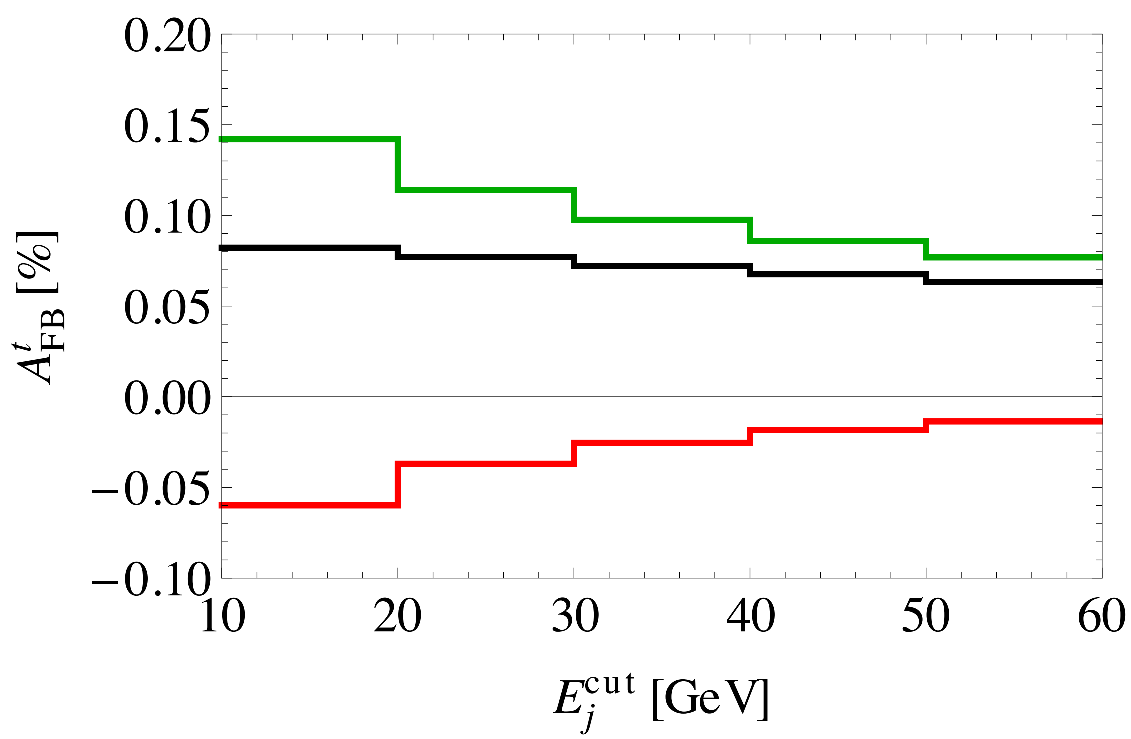
LO: no charge asymmetry



NLO: Charge asymmetry is generated due to virtual corrections (box diagrams) and real gluon emission diagrams (ISR-FSR interference)

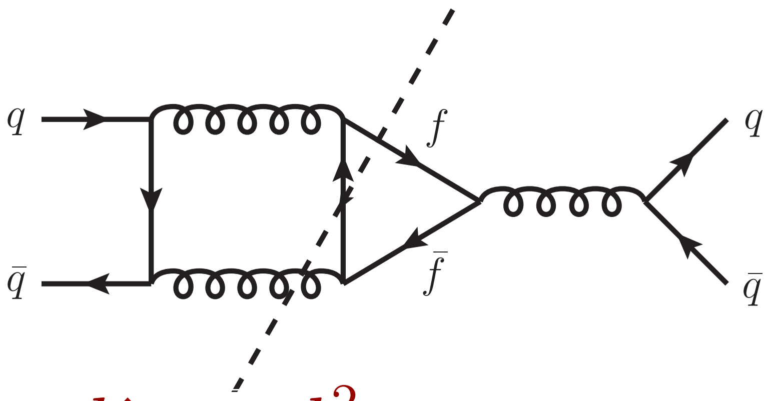
Separating contributions with a gluon E^{cut}:

- ➡ virtual corrections generate positive asymmetry
- ➡ real emission diagrams contribute with negative asymmetry
- ➡ need to understand the tt+jet contribution especially in different phase space regions



$t\bar{t}$+jet in the SM

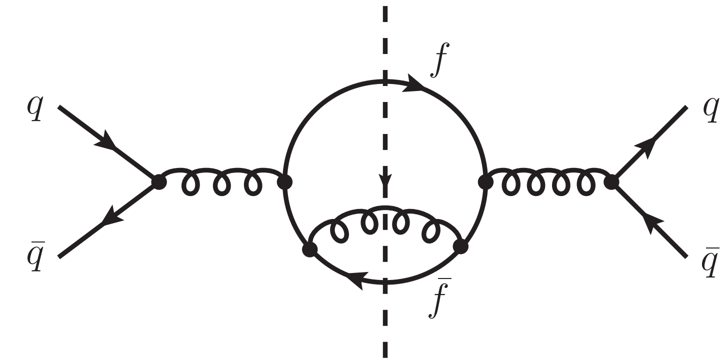
Charge asymmetry of $q\bar{q} \to t\bar{t} + jet$ in QCD



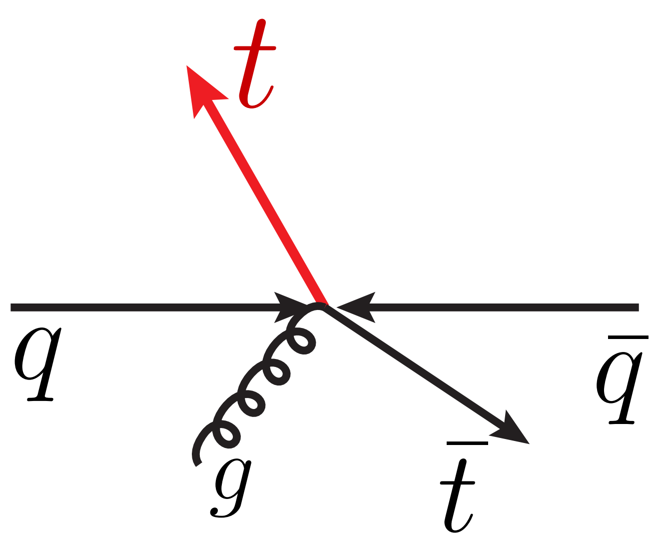
- Differential charge asymmetry at a fixed point in phase space:

$$\frac{\mathrm{d}\hat{\sigma}_a}{\mathrm{d}\cos\theta} = \left.\frac{\mathrm{d}\hat{\sigma}_{t\bar{t}}}{\mathrm{d}\cos\theta}\right|_{\theta=\theta_t^{t\bar{t}}} - \left.\frac{\mathrm{d}\hat{\sigma}_{\bar{t}t}}{\mathrm{d}\cos\theta}\right|_{\theta=\theta_{\bar{t}}^{t\bar{t}}}$$

$d\hat{\sigma}_a \sim d_{abc}^2$ · antisymmetric under $t \leftrightarrow \bar{t}$



- σ_s - charge symmetric differential cross section defined with + instead of -



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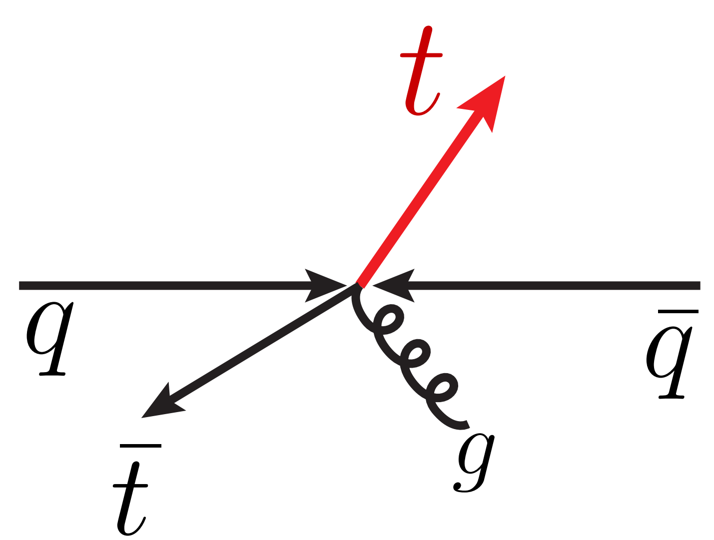
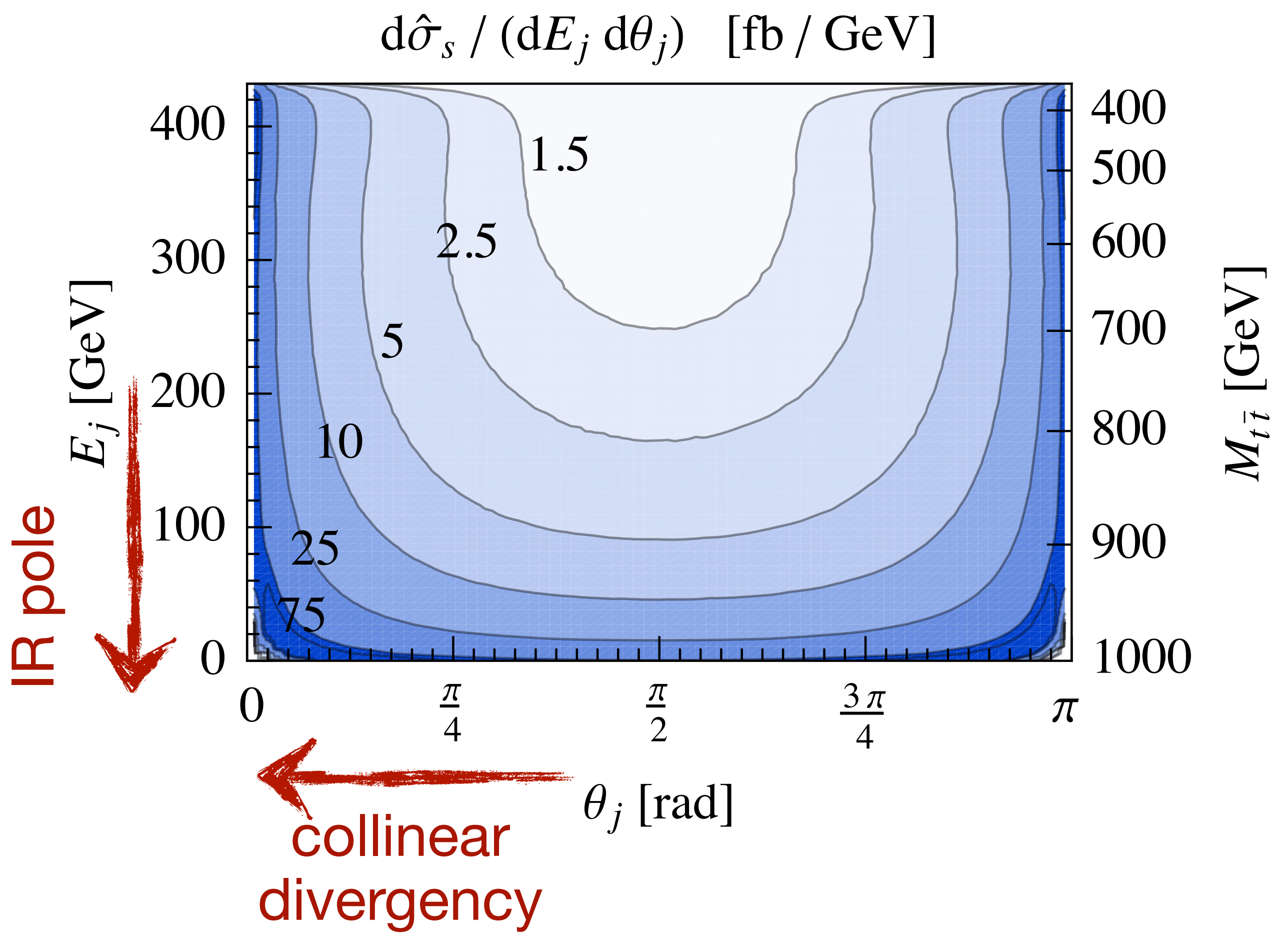
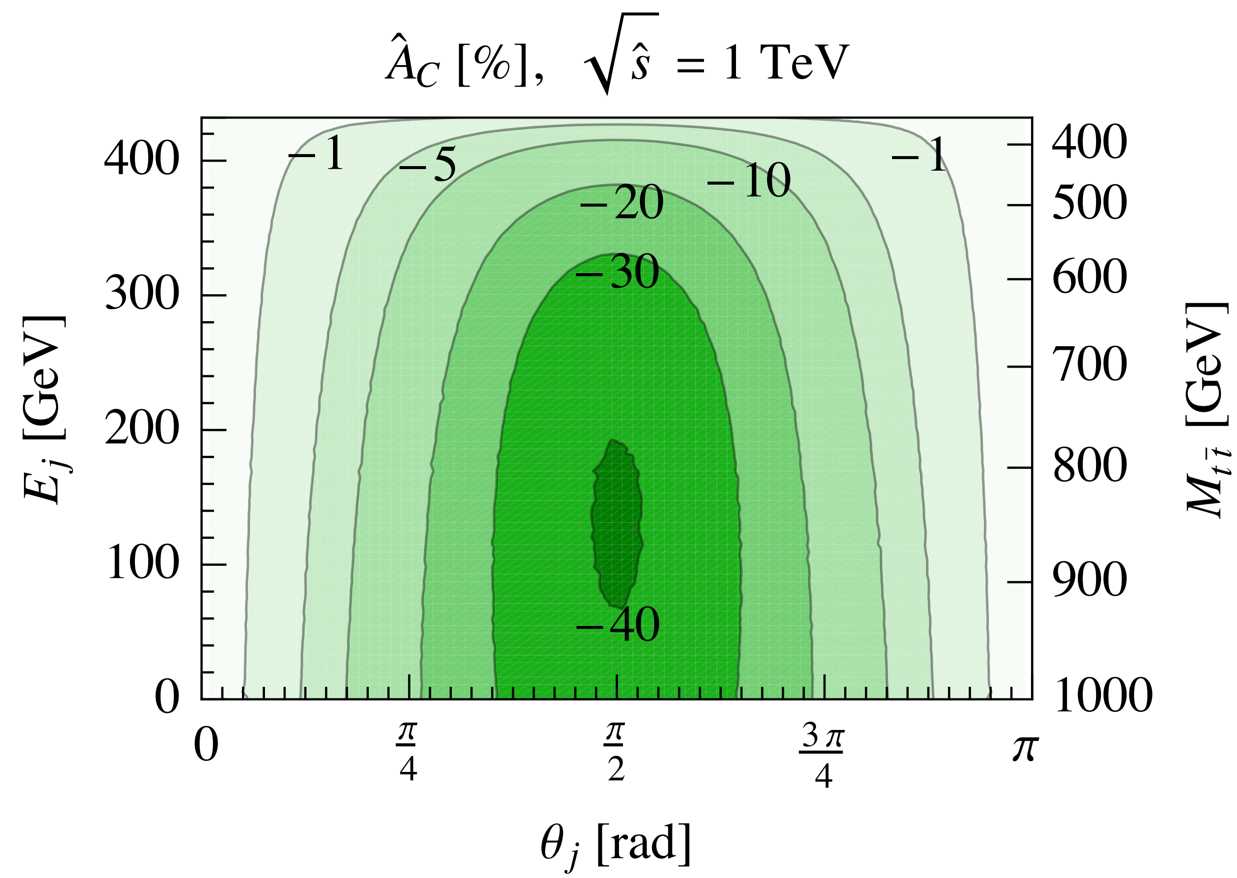


suppressed

Charge asymmetry of $q\bar{q} \to t\bar{t} + g$ in QCD at LO





- LO symmetric tt+g diagrams are IR divergent and collinear divergent
- a transverse momentum cut on the gluon momentum, e.g. $p_T > 25$ GeV, regulates both divergencies

$$M_{t\bar{t}}^2 \stackrel{\rm LO}{=} \hat{s}\,(1 - 2E_j/\sqrt{\hat{s}})$$

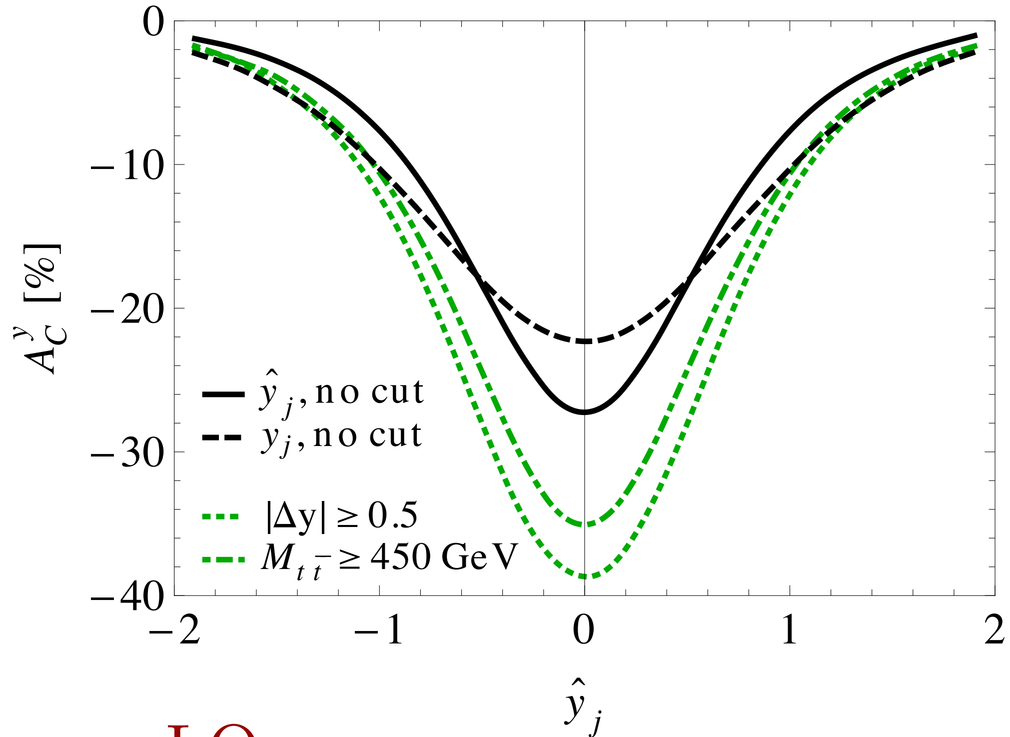
- the LO asymmetric tt+g diagrams, σ_a, are IR divergent
- $\hat{A}_c = \hat{\sigma}_a/\hat{\sigma}_s$ is finite for small gluon energies
- A_c strongly tends to zero for $\hat{\theta}_j \to 0, \pi$
- A_c can be as large as -40% for central gluons

Results: Tevatron

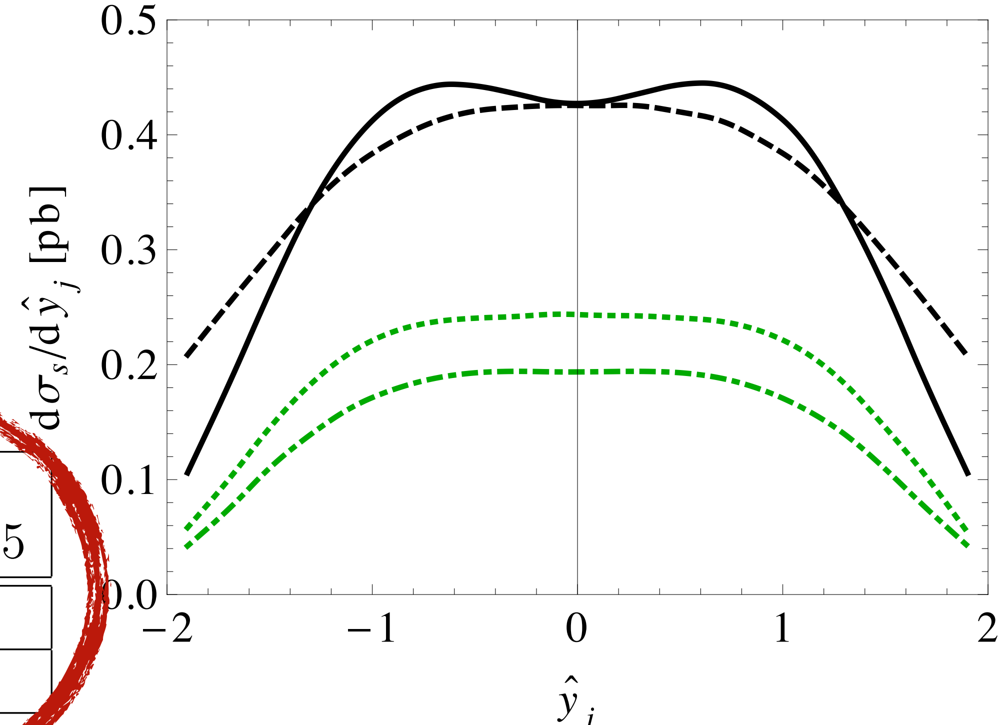
- ➡ proton-antiproton initial state
- ➡ Charge asymmetry corresponds to forward-backward asymmetry

$$A_C^y = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}, \quad \Delta y = y_t - y_{\bar{t}}$$

- ➡ Asymmetry is largest for central jets
- ➡ Cut on the jet should be applied in the partonic rest frame
- ➡ Combination of cuts results in largest asymmetry with moderate reduction of the cross section



$$\hat{y}_j \overset{\text{LO}}{=} \hat{y}_j - \hat{y}_{t\bar{t}j} = y_j - y_{t\bar{t}j}$$



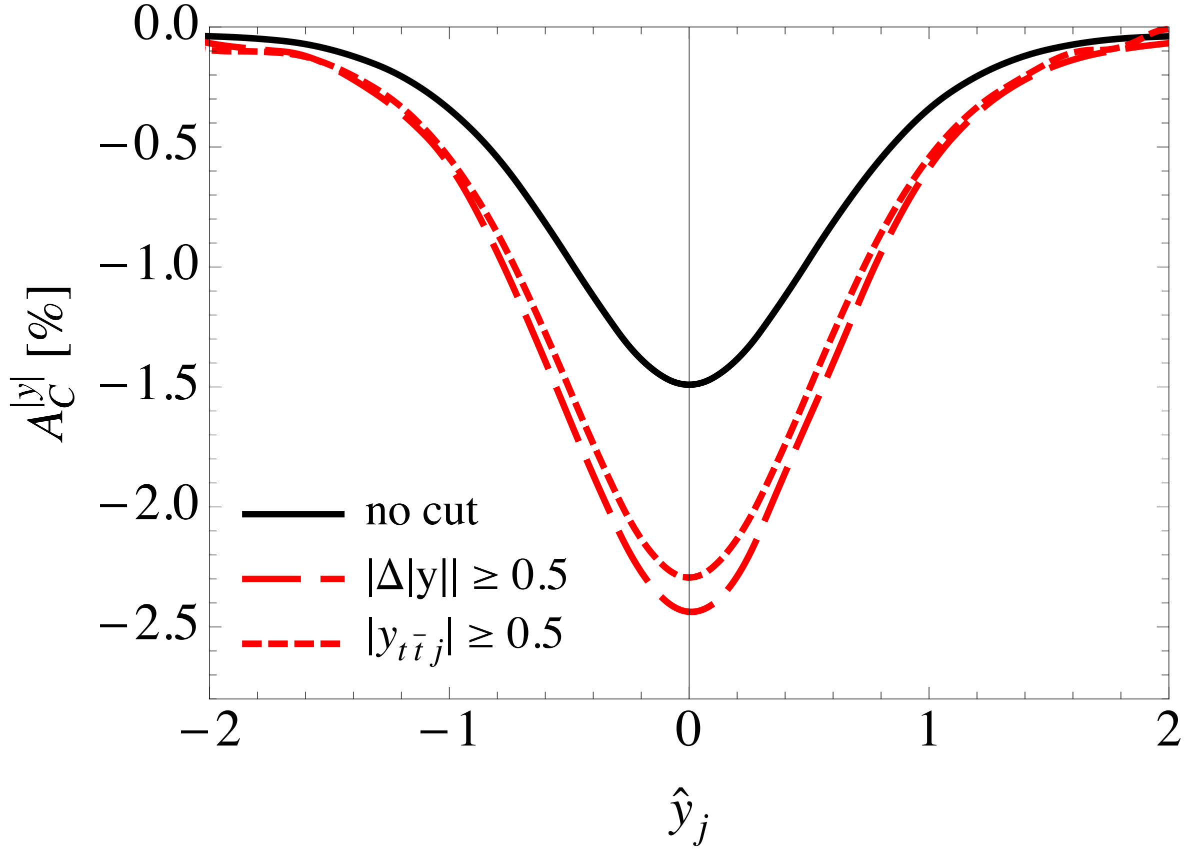
	no cuts	$M_{t\bar{t}} \geq 450\,\text{GeV}$	$\lvert\hat{y}_j\rvert \leq 0.5$	$\lvert\Delta y\rvert \geq 0.5$	$\lvert\hat{y}_j\rvert \leq 1$, $\lvert\Delta y\rvert \geq 0.5$
A_C^y [%]	−12.6	−17.0	−24.0	−19.1	−27.5
σ_s [pb]	1.42	0.61	0.43	0.78	0.48

Results: LHC @ 8 TeV

- proton-proton symmetric initial state
- Charge asymmetry generated for large boost along the beam axis:

$$A_C^{|y|} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

- Asymmetry is largest for central jets
- Cut on the jet should be applied in the partonic rest frame
- Combination of cuts results in largest asymmetry for a similar cross section



$$y_{t\bar{t}j} \overset{\text{LO}}{=} \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{1}{2}\ln\frac{1+\beta}{1-\beta}$$

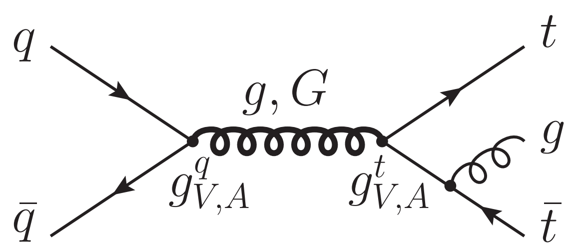
	no cuts	$\|\hat{y}_j\| \leq 0.5$	$\|\Delta\|y\|\| \geq 1$	$\|y_{t\bar{t}j}\| \geq 1$		
				–	$\|\hat{y}_j\| \leq 0.5$	$\|\hat{y}_j\| \leq 0.5 \leq \|\Delta\|y\|\|$
$A_C^{\|y\|}$ [%]	−0.56	−1.30	−1.35	−1.62	−2.91	−4.04
σ_s [pb]	97.5	25.7	19.7	19.2	6.63	4.00

$t\bar{t}$+jet with massive color-octet bosons

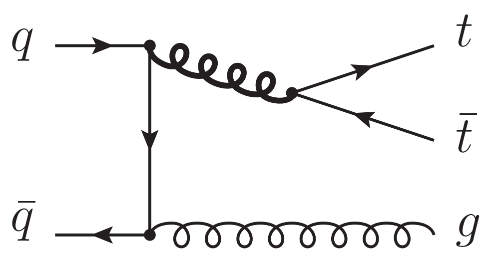
Lagrangian, contributing diagrams

$$\mathcal{L} = -\, g_s\, f_{abc} \left[(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu)\, G^{b\mu} g^{c\nu} + G^{a\mu} G^{b\nu} (\partial_\mu g^c_\nu) \right]$$

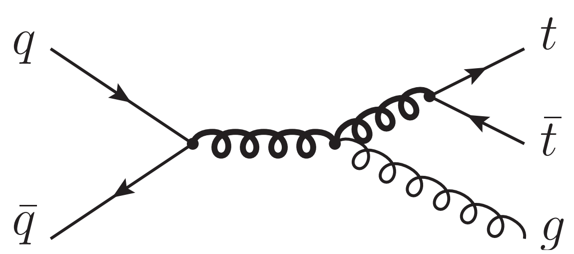
$$-\, i g_s\, \bar{q}_i\, \gamma^\mu G^a_\mu T^a \left[g^i_V + \gamma_5\, g^i_A \right] q_i$$



- G^a_μ - massive gluon field
- q^i_V, q^i_A - vector, axial-vector couplings of the massive gluons to quarks

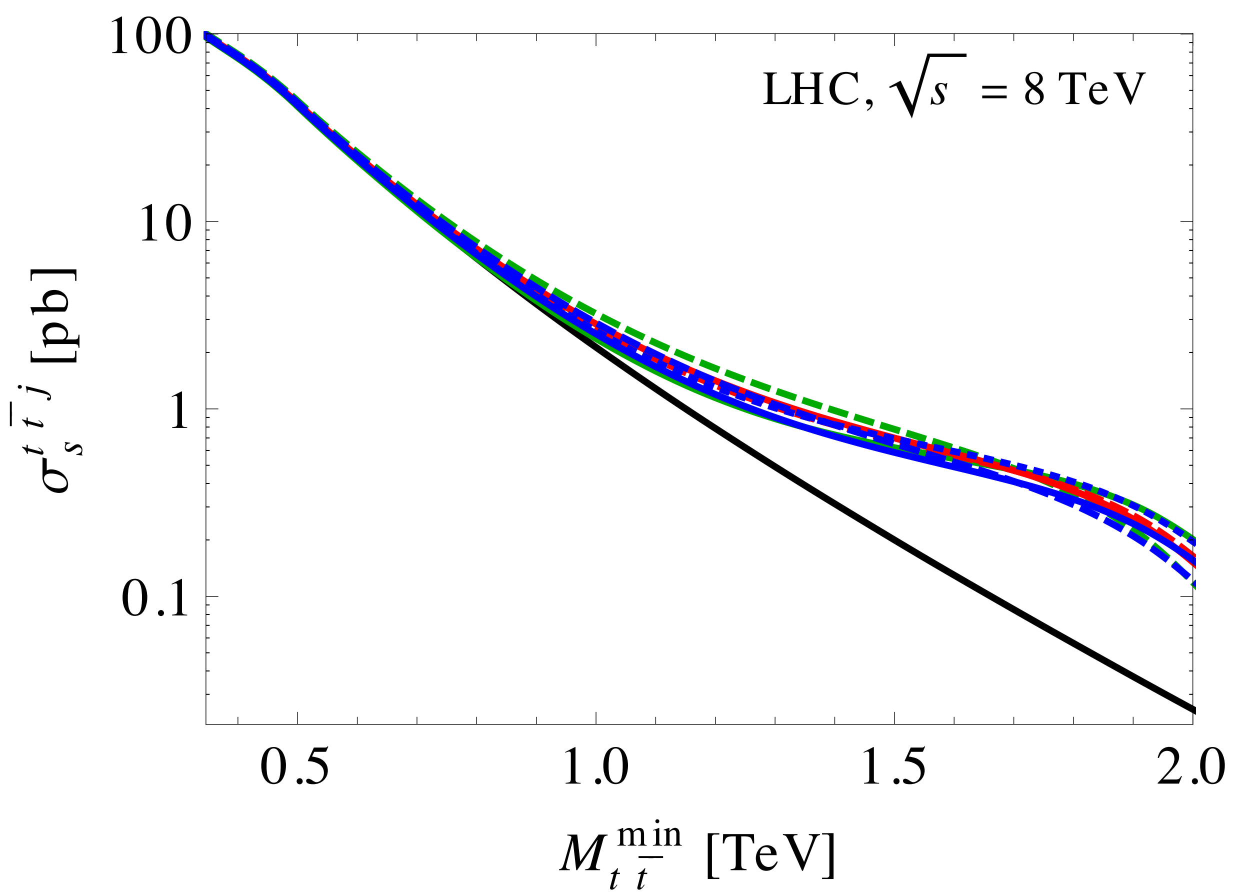


- All combinations of diagrams can contribute to the cross sections σ_a and σ_s
- Asymmetry depends on the heavy gluon mass M_G, its width Γ_G and products of coupling combinations, e.g. $g^q_V g^t_V$ or $g^q_A g^t_A$



Contributing diagrams

- Heavy gluon scenario, $M_g = 2$ TeV, consistent with top pair cross section measurements and di-jet
- Large M_{tt} - cut enhances the cross section of the heavy color octet bosons with respect to SM cross section



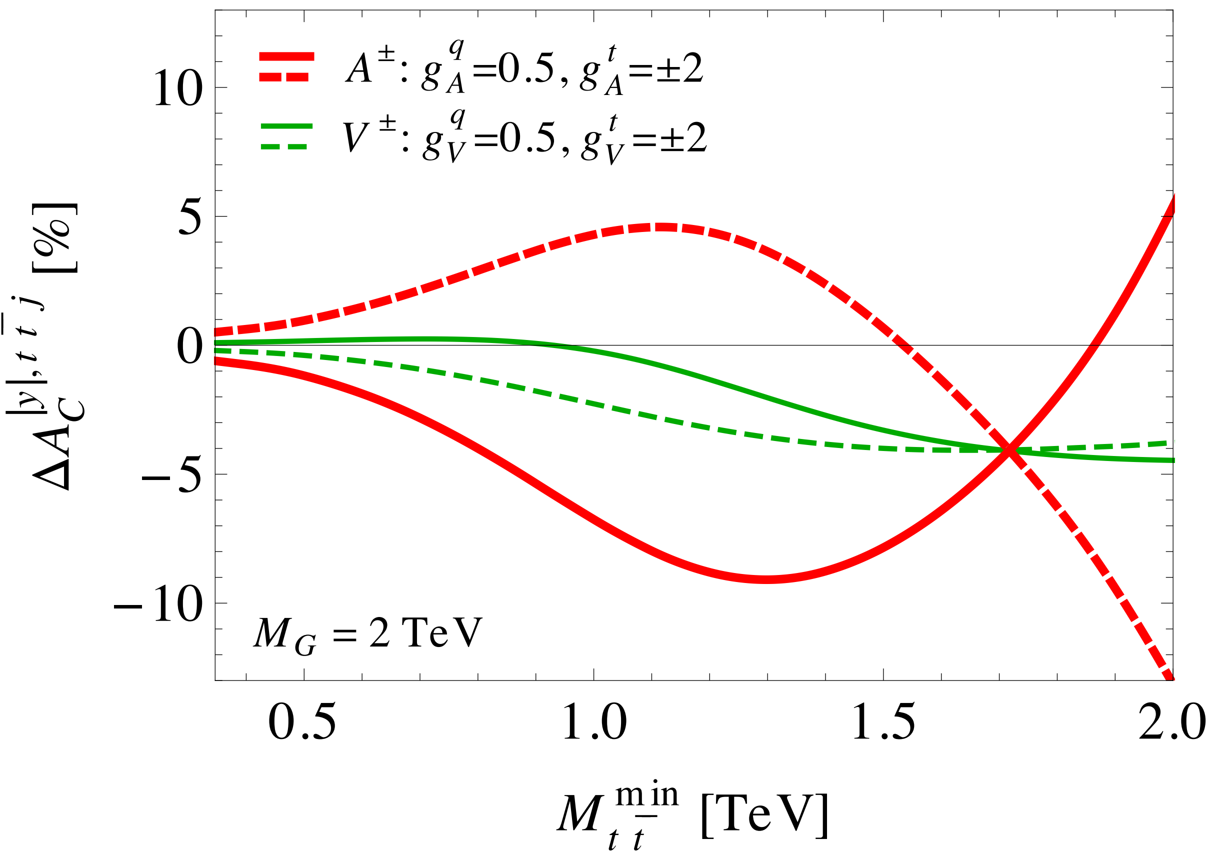
$M_G = 2\,\text{TeV}$	V^+	V^-	A^+	A^-	VA^{++}	VA^{--}	VA^{+-}
g_V^q	0.5	0.5	0	0	0.35	0.35	0.35
g_V^t	2	-2	0	0	1.5	-1.5	1.5
g_A^q	0	0	0.5	0.5	0.35	0.35	0.35
g_A^t	0	0	2	-2	1.5	-1.5	-1.5
$\Gamma_G/M_G\,[\%]$	17.7	17.7	17.3	17.3	19.4	19.4	19.4

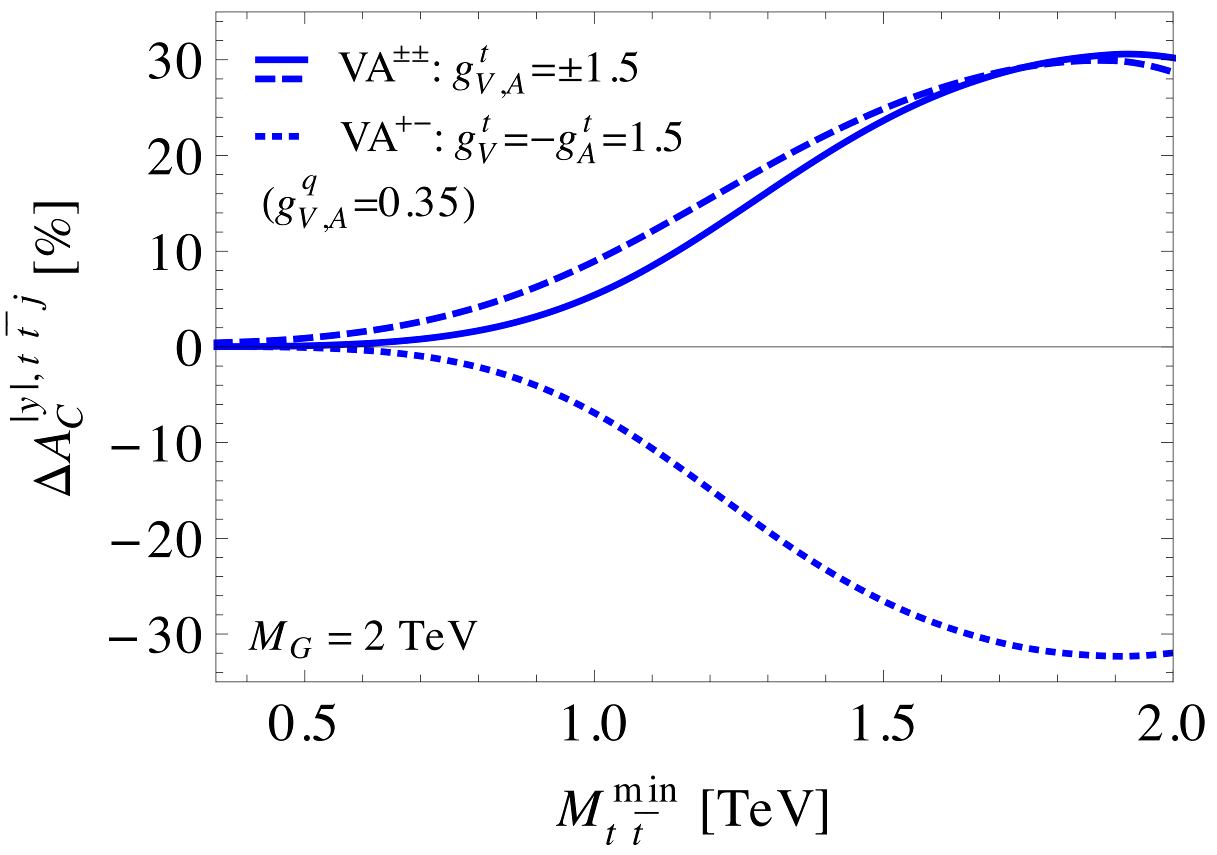
Results: LHC @ 8 TeV

$$\Delta A_C^{|y|} = A_C^{|y|,\mathrm{tot}} - A_C^{|y|,\mathrm{SM}}$$

- ➡ Large asymmetries are generated due to axial-vector couplings
- ➡ Also vector couplings generate additional asymmetry (not in tt inclusive at LO)
- ➡ Similar results for LHC 14, some additional phase space cuts may need to be applied

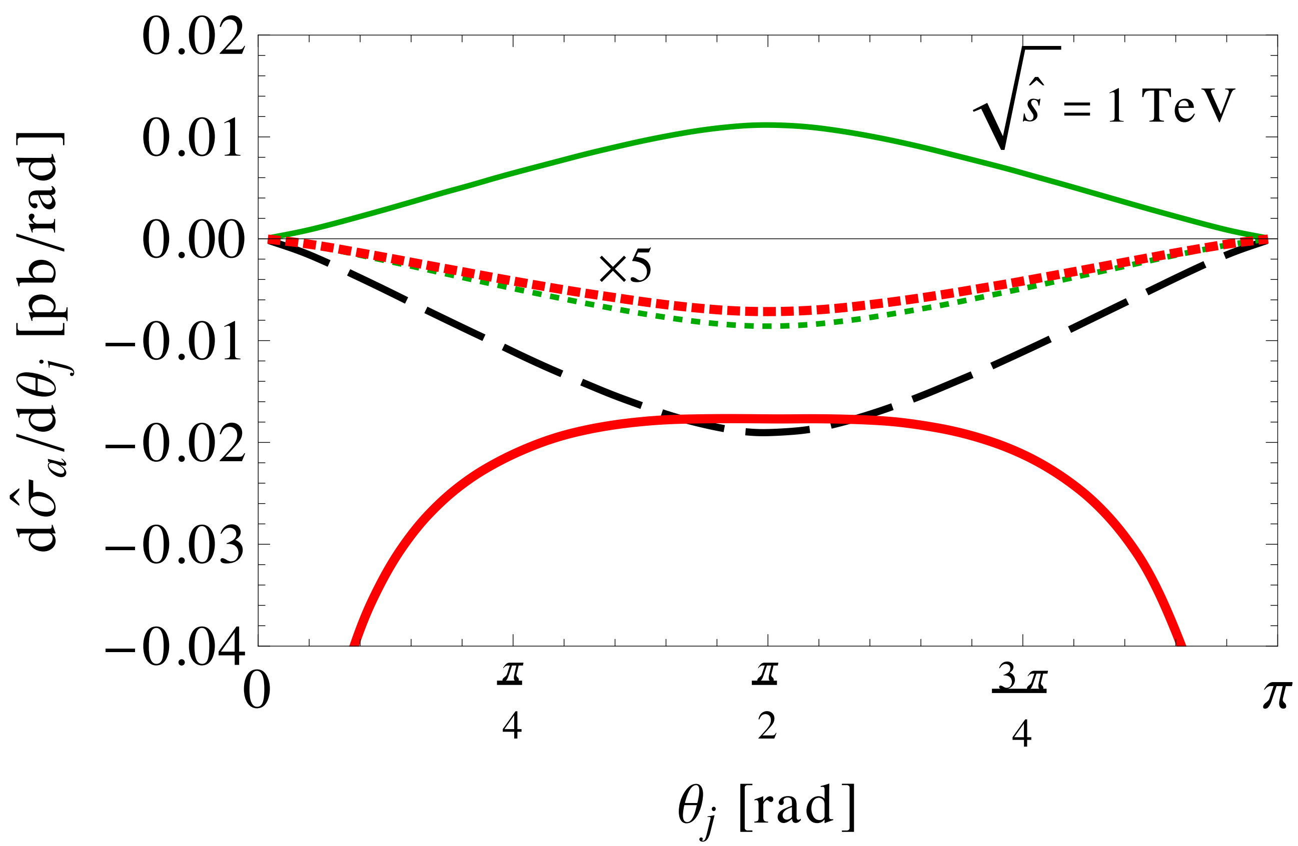
$M_{t\bar{t}}^{\min} = 1\,\mathrm{TeV}$	$\Delta A_C^{\|y\|}$ [%]
V^+, V^-	$-0.22,\ -2.3$
A^+, A^-	$-6.7,\ +4.3$
VA^{++}	$+5.4$
VA^{--}	$+8.9$
VA^{+-}	-6.9





Results: LHC @ 8 TeV

- ➡ σ_a tends to zero for small gluon angles and vector couplings (QCD like)
- ➡ σ_a has a collinear divergency for small gluon angles and axial-vector couplings
- ➡ opposite for symmetric cross section σ_s



QCD (black), g-G (solid) interference and G-G (dotted) interference for the massive gluon benchmarks V^+ (green) and A^+ (red)

Concluding Remarks

- Promising prospect to measure the charge asymmetry in tt+jet
- SM: Asymmetry is largest for central jets
- SM: Charge asymmetry can be enhanced by suitable phase space cuts
  - Tevatron: $|\hat{y}_j| \leq 1,\ |\Delta y| \geq 0.5 \ \rightarrow \ A_C^y = -27.5\%$
  - LHC @ 8 TeV: for strong cuts up to -4%
- Heavy color octet vector bosons that can explain the Tevatron asymmetry can also generate large asymmetries at the LHC
- Differential distributions with respect to the jet scattering angle can give additional information about the coupling structure