Top-quark charge asymmetry goes forward: Two new observables for hadron colliders

Stefan Berge
Johannes Gutenberg-University Mainz

SUSY 2013
26. - 31. August 2013, Trieste, Italy

Motivation

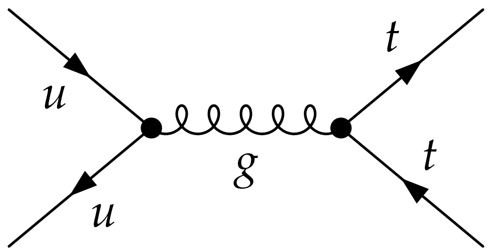
- QCD predicts a charge asymmetry for top quark pair production in hadron-hadron scattering
- The corresponding forward-backward asymmetry has been measured at CDF and D0
- Discrepancy to SM prediction remains at $2-3\sigma$ level
- Sign of new Physics?
- Need to measure the charge asymmetry at the LHC

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

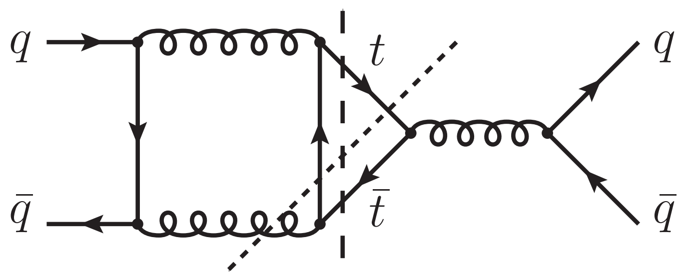
(CDF, arXiv 1211.1003)

- Problem: predicted SM charge asymmetry in inclusive top pair production at LHC is very small

Motivation



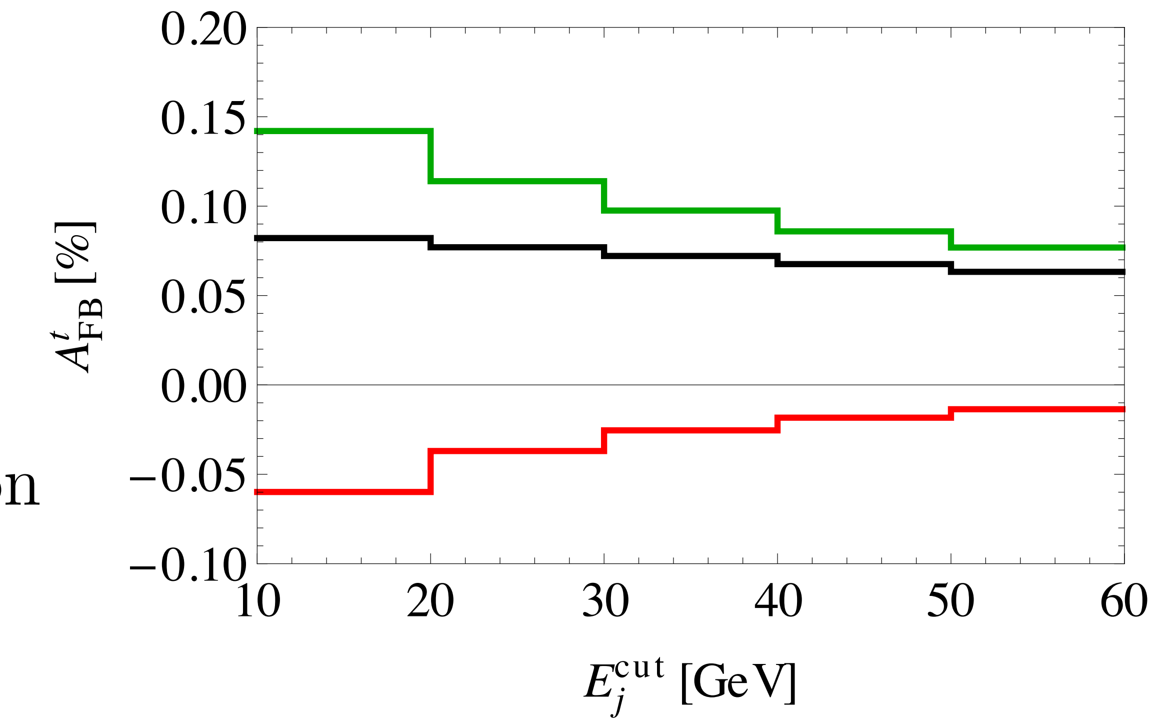
LO: no charge asymmetry



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

Separating contributions with gluon Ecut:

- virtual corrections generate positive asymmetry
- real emission diagrams contribute with negative asymmetry
- need to understand the $t\bar{t} + jet$ contribution especially in different phase space regions



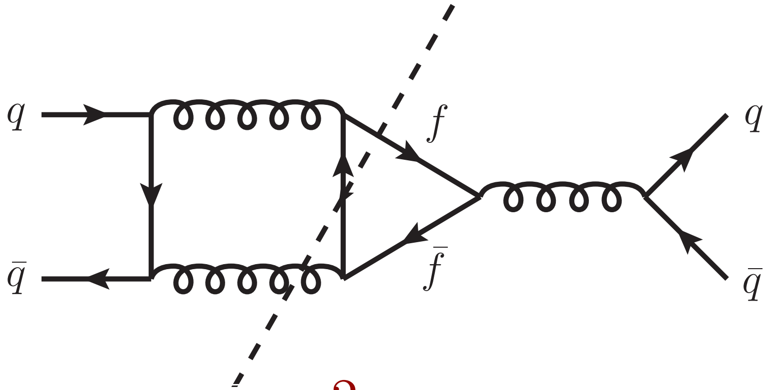
$t\bar{t}$+jet in QCD

S.B., S. Westhoff, JHEP 07(2013)179
S.B., S. Westhoff, arXiv 1307.6225

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

- Differential charge asymmetry at a certain phase space point:

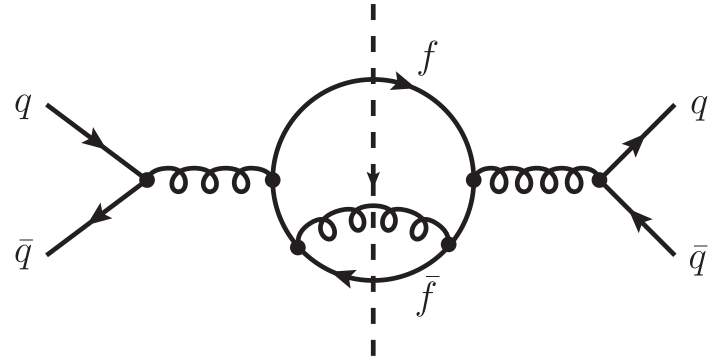
  $d\hat{\sigma}_A = d\hat{\sigma}_{t\bar{t}} - d\hat{\sigma}_{\bar{t}t}$

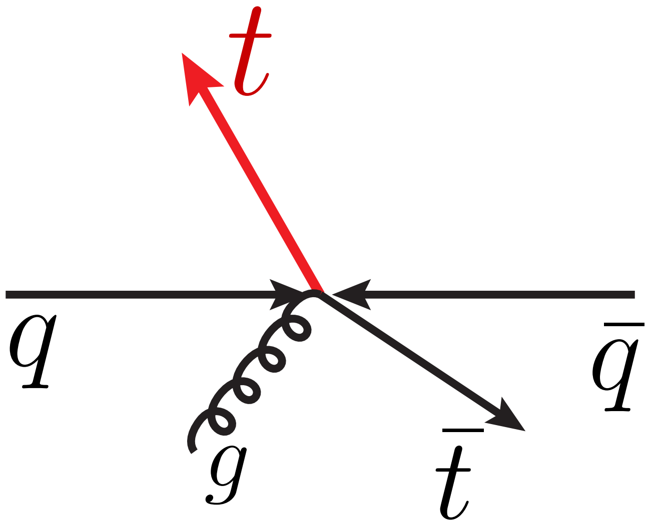


$d\hat{\sigma}_a \sim d^2_{abc}$ · antisymmetric under $t \leftrightarrow \bar{t}$ (Furry theorem)

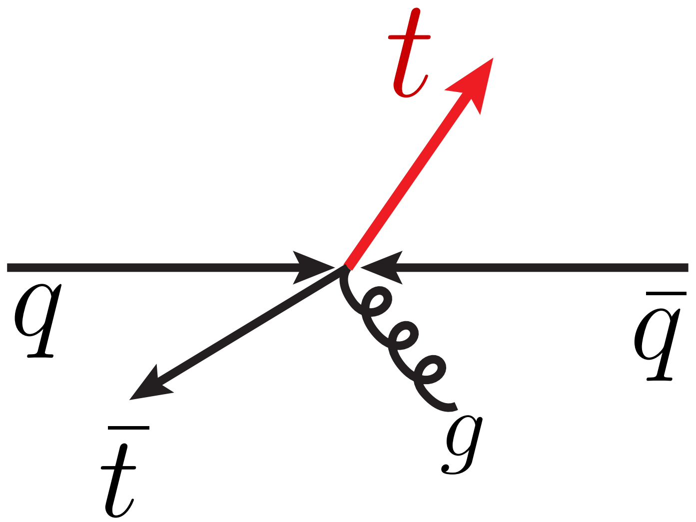
- Symmetric differential cross section :

  $d\hat{\sigma}_S = d\hat{\sigma}_{t\bar{t}} + d\hat{\sigma}_{\bar{t}t}$





preferred

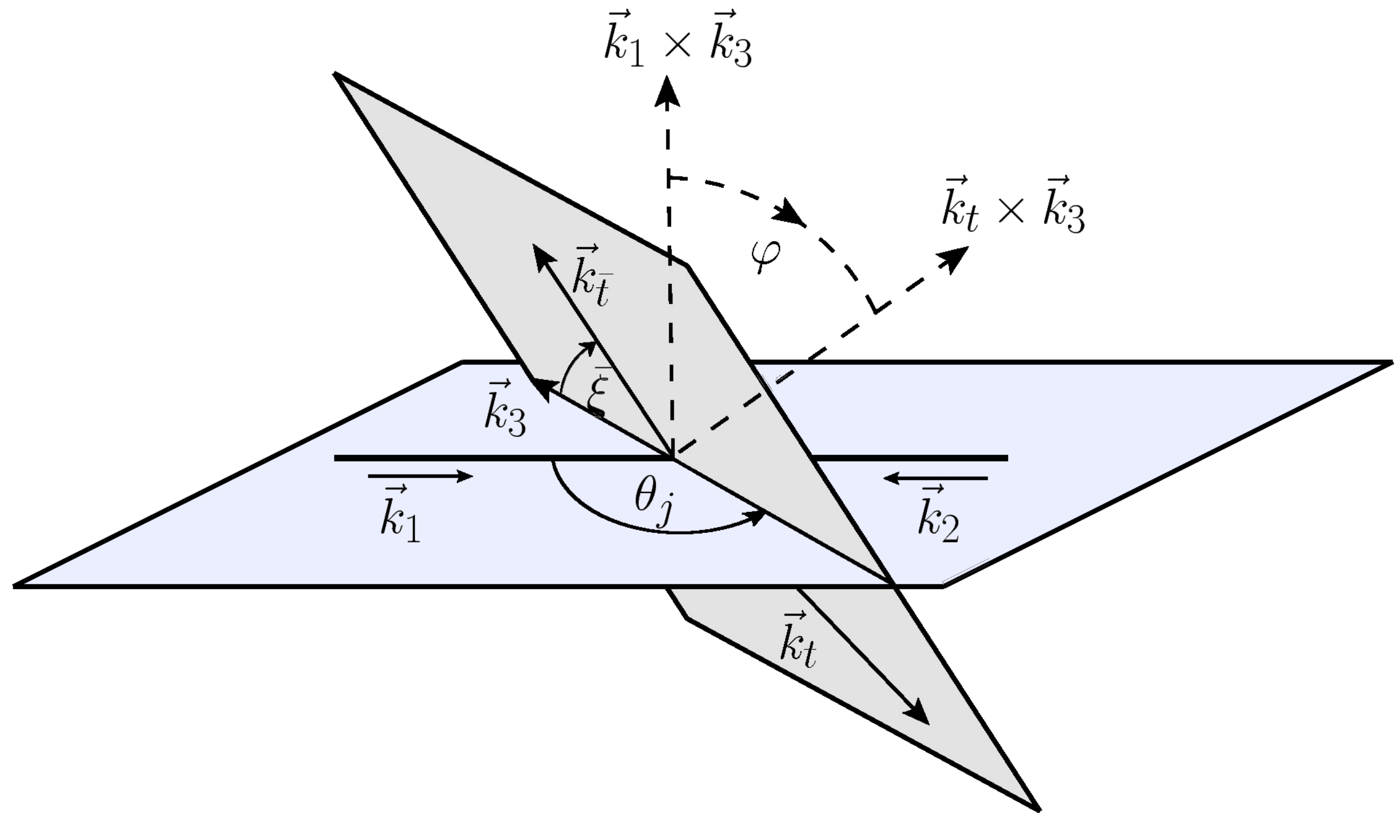


suppressed

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

Differential charge asymmetry:

$$d\hat{\sigma}_A = d\hat{\sigma}_{t\bar{t}} - d\hat{\sigma}_{\bar{t}t}$$



$$\frac{d\hat{\sigma}_A(q\bar{q} \to t\bar{t}j)}{d\varphi\, d\theta_j\, dE_t\, dE_{\bar{t}}} = -\left[N_1 + \sin^2\theta_j\left(N_1^j + \cos^2\varphi\, N_1^\varphi\right)\right] \cos\varphi$$

Incline Asymmetry

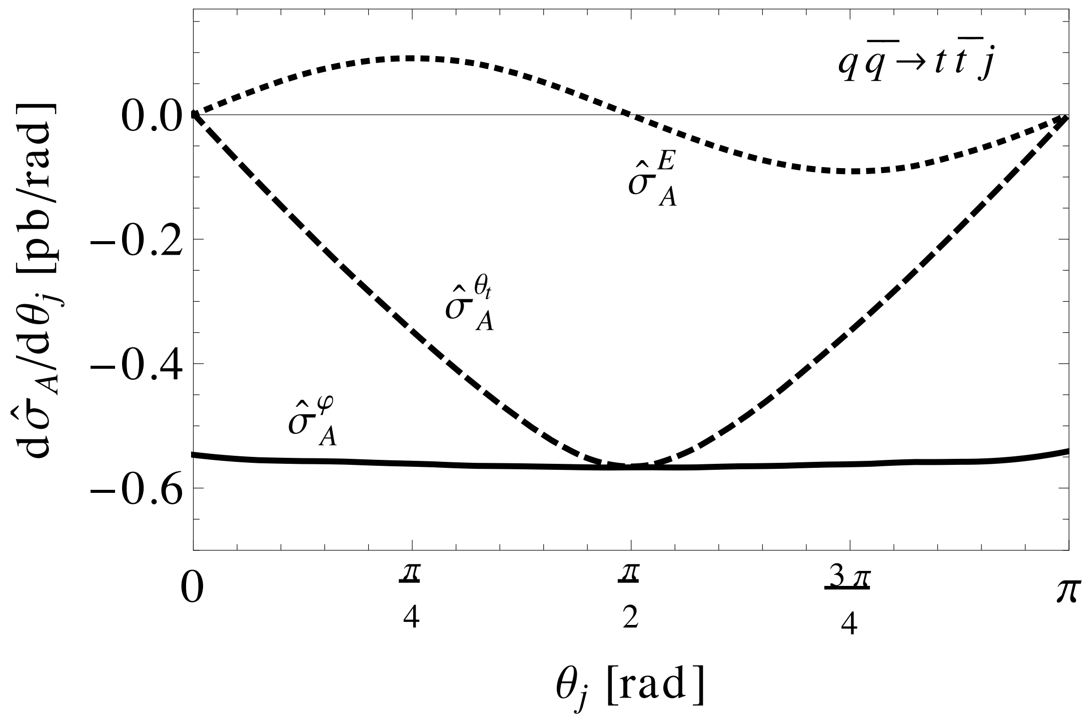
$$+ \left[N_2 + \cos^2\varphi\, N_2^\varphi\right] \sin\theta_j \cos\theta_j$$

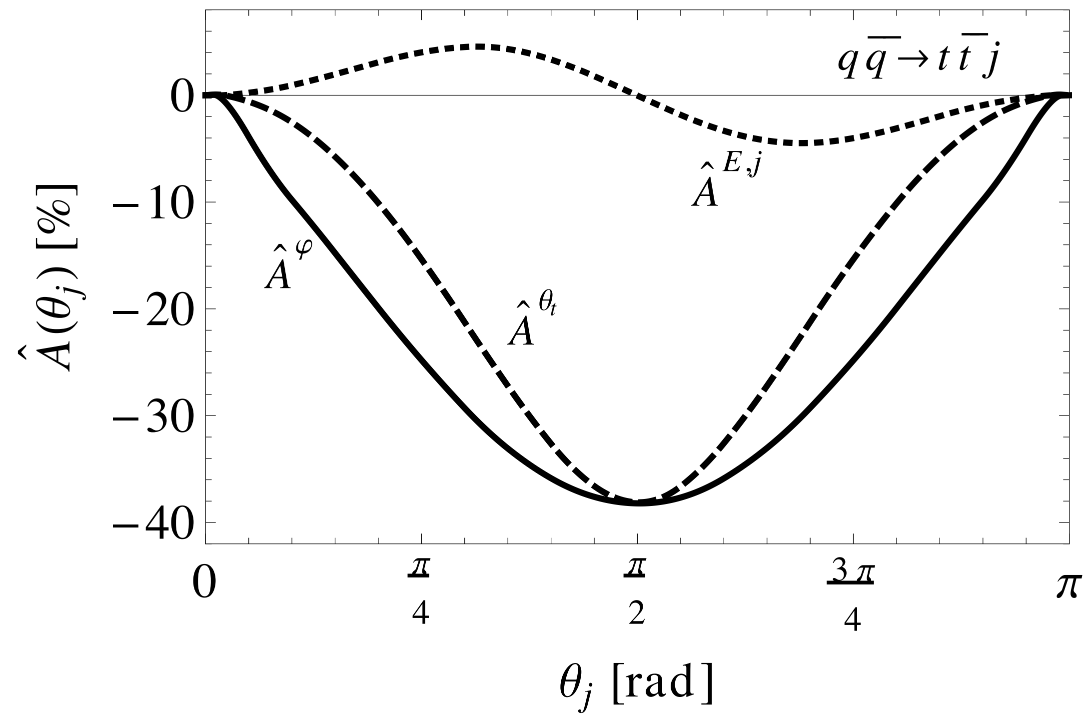
Energy Asymmetry

$N_1^i(E_t, E_{\bar{t}})$ - symmetric in E_t and $E_{\bar{t}}$

$N_2^i(E_t, E_{\bar{t}})$ - antisymmetric in E_t and $E_{\bar{t}}$

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





- Partonic asymmetries for $q\bar{q} \to t\bar{t}g$ in dependence of the jet scattering angle θ_j, $\sqrt{s} = 1$ TeV, $E_j \geq 20$ GeV.

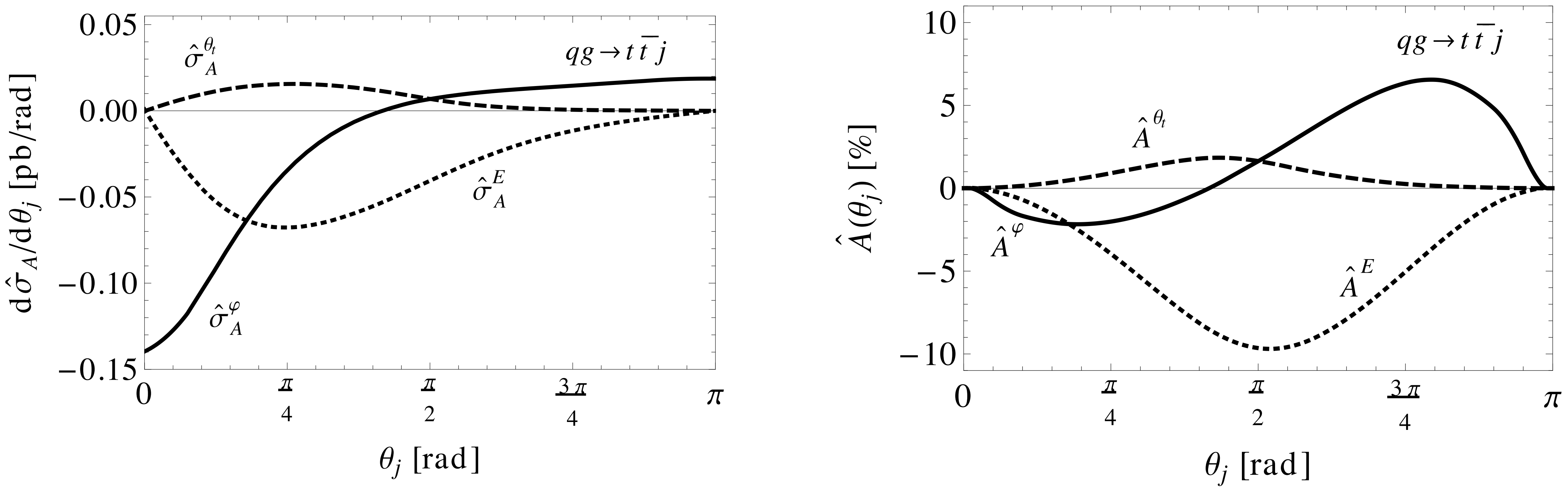
- Incline Asymmetry $d\hat{\sigma}_A^{\varphi} = d\hat{\sigma}_A(\cos\varphi \geq 0)$

  Rapidity Asymmetry $d\hat{\sigma}_A^{\theta_t} = d\hat{\sigma}_A(\cos\theta_t \geq 0)$

  Energy Asymmetry $d\hat{\sigma}_A^{E} = d\hat{\sigma}_A(\Delta E \geq 0, \cos\theta_j \geq 0) - d\hat{\sigma}_A(\Delta E \geq 0, \cos\theta_j \leq 0)$

$\cos\theta_t = \sin\theta_j \cos\varphi \sin\xi + \cos\theta_j \cos\xi\,, \quad \cos\xi = f(E_t, E_{\bar{t}})\,, \quad \Delta E = E_t - E_{\bar{t}}$

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

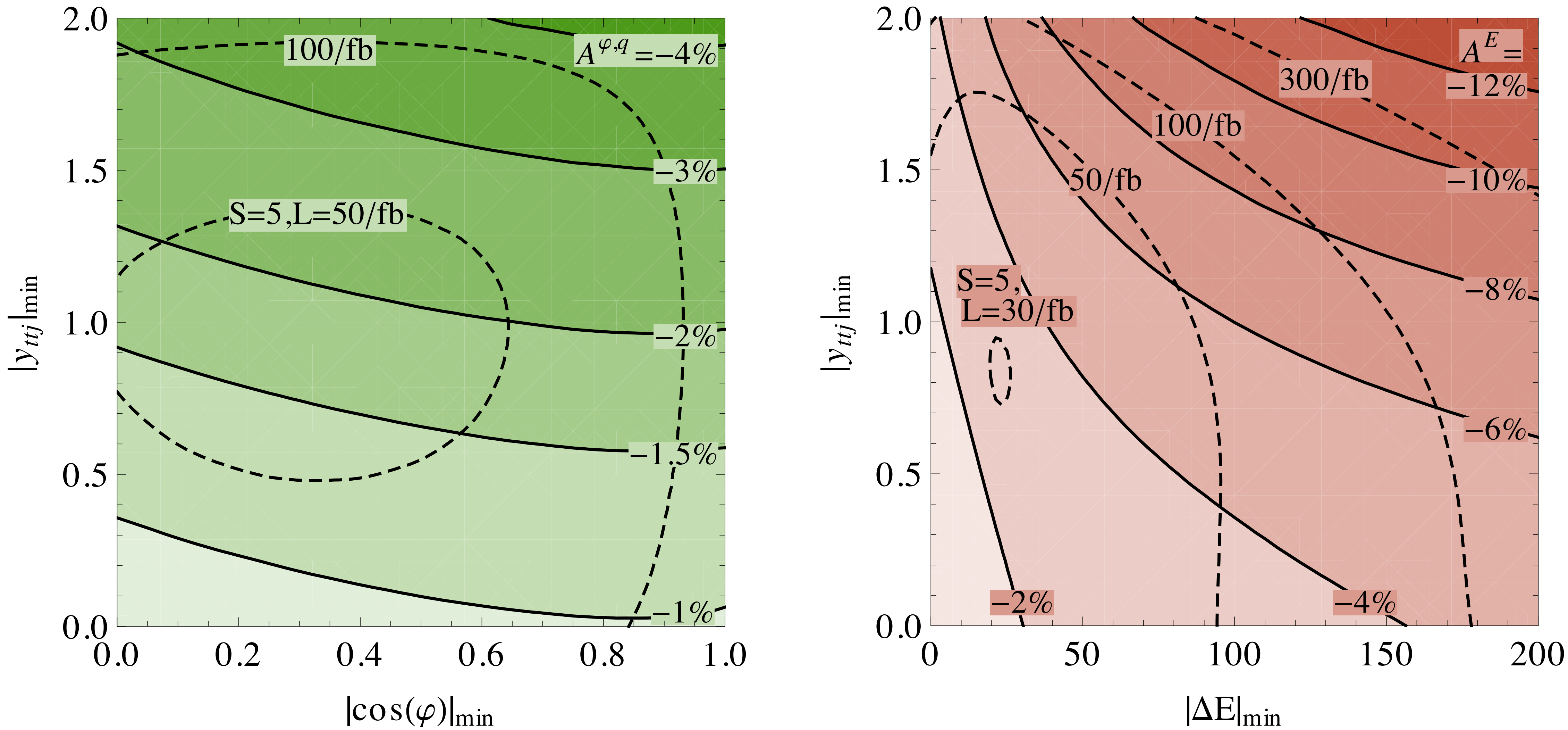


- Partonic asymmetries for $qg \to t\bar{t}q$ in dependence of the jet scattering angle θ_j, $\sqrt{s} = 1$ TeV, $E_j \geq 20$ GeV.

- $d\hat{\sigma}_{EA} = d\hat{\sigma}_A\,(\Delta E \geq 0)\ , \qquad \Delta E = E_t - E_{\bar{t}}$

- Energy asymmetry in $qg \to t\bar{t}q$: Quark direction does not need to be determined!

Results: LHC @ 14 TeV



- Incline asymmetry $A^{\varphi,q}$ is testing the charge asymmetry of the $q\bar{q}$-channel
- Energy asymmetry A^E is testing the charge asymmetry of the qg-channel
- LHC Detector cuts have been applied. Furthermore $|\hat{y}_j| < 0.5$
- A lower cut on ΔE implies a larger minimum p_{Tj}
- Dashed lines: Luminosity needed to distinguish the asymmetry with $5\,\sigma$ from the null hypothesis (assumed $t\bar{t} + jet$ reconstruction efficiency 0.05)

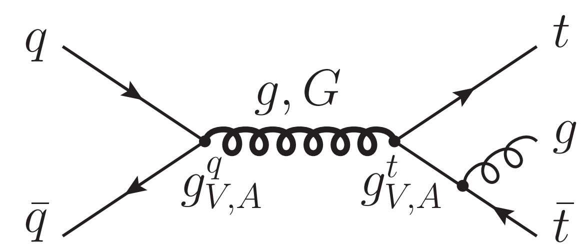
$t\bar{t}$+jet with massive color-octet bosons

S.B., S. Westhoff, Phys. Rev. D86 (2012) 094036

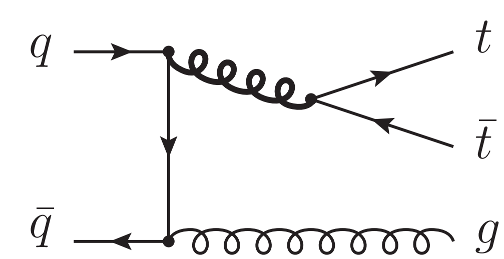
Lagrangian, contributing diagrams

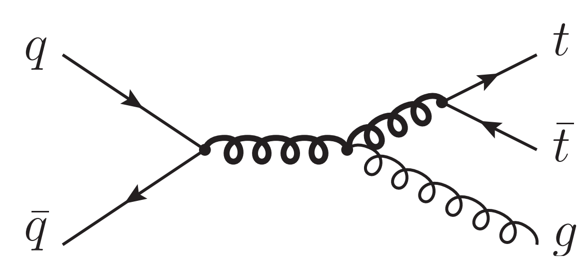
$$\mathcal{L} = -\, g_s\, f_{abc} \left[(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu)\, G^{b\mu} g^{c\nu} + G^{a\mu} G^{b\nu} (\partial_\mu g^c_\nu) \right]$$

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

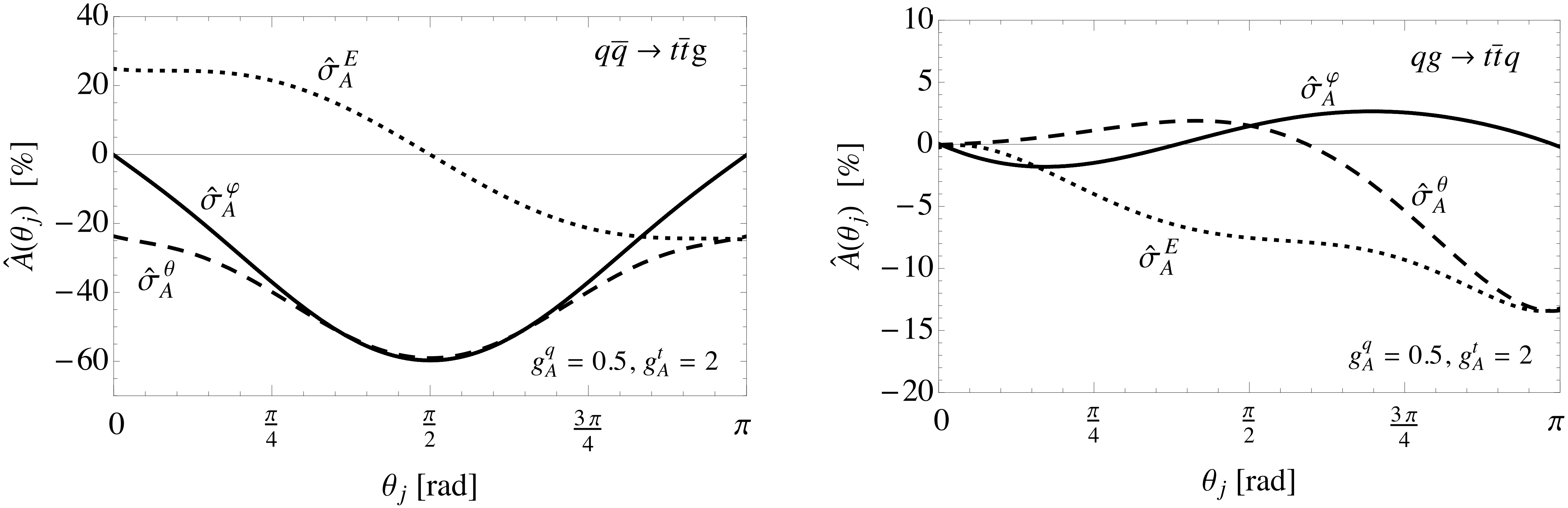


- G^a_μ - massive gluon field
- q^i_V, q^i_A - vector, axial-vector couplings of the massive gluons to quarks
- All combinations of diagrams can contribute to the cross sections σ_A and σ_S
- Asymmetry depends on the heavy gluon mass M_G, its width Γ_G and products of coupling combinations, e.g. $g^q_V g^t_V$ or $g^q_A g^t_A$





Partonic asymmetries including color-octets



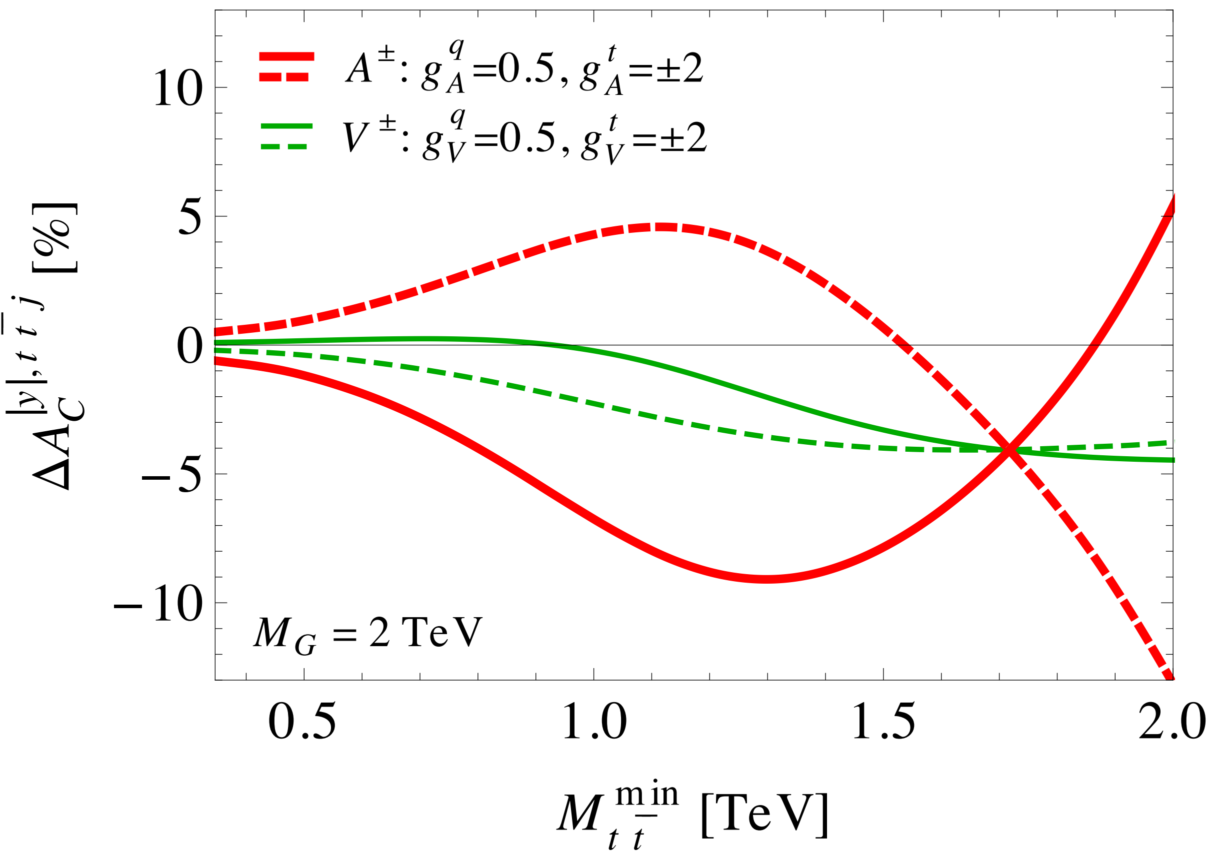
- Partonic normalized asymmetries for $q\bar{q} \to t\bar{t}g$ (left) and $qg \to t\bar{t}q$ (right) in dependence of the jet scattering angle θ_j, $\sqrt{s} = 1$ TeV, $E_j \geq 20$ GeV.
- $M_G = 2$ TeV, $g_V = 0$, $g_A^q = 0.5$, $g_A^t = 2$
- Normalized rapidity and energy asymmetry are non-vanishing for $\theta_j \to 0, \pi$
  $\to$ no jet cut necessary

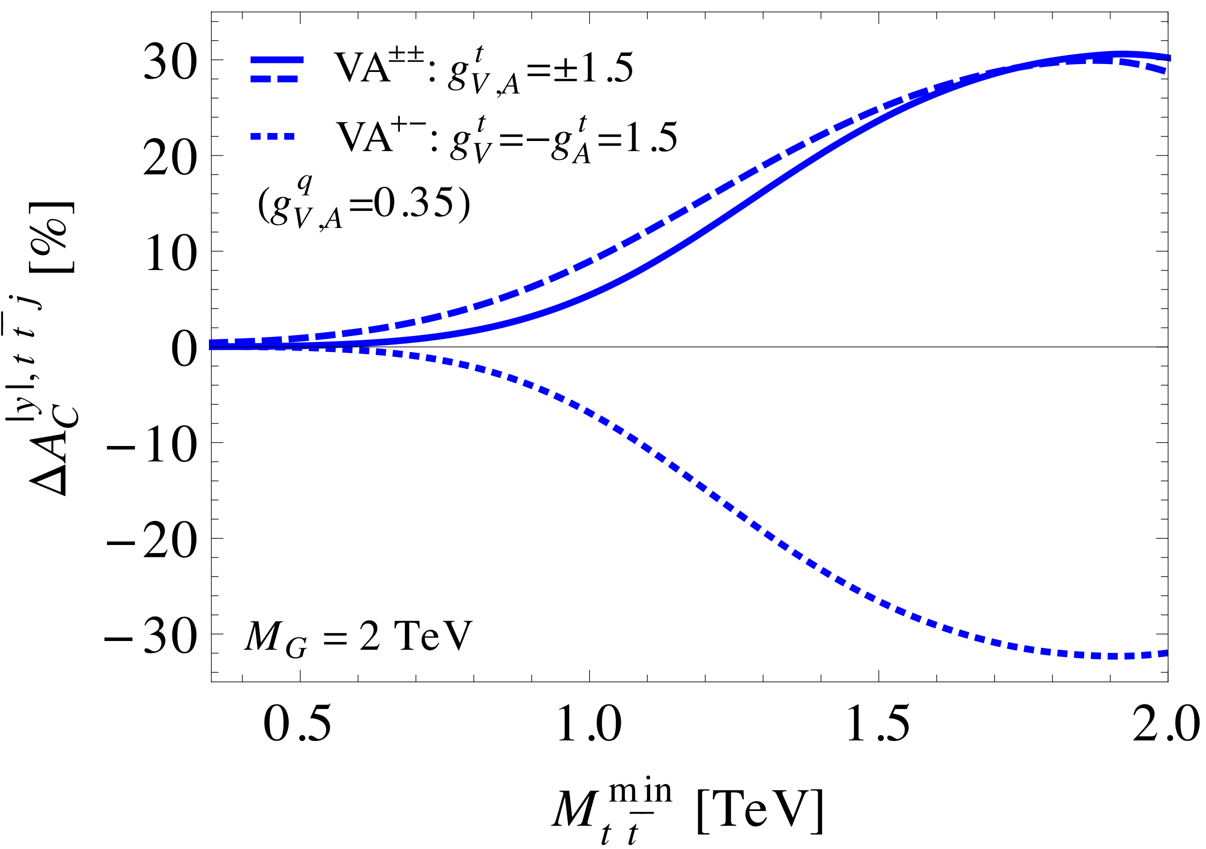
Rapidity Asymmetry: LHC @ 8 TeV

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

- Large asymmetries are generated due to axial-vector couplings
- Also vector couplings generate additional asymmetry (not in $t\bar{t}$ inclusive at LO)
- Similar results for LHC14, some additional phase space cuts may need to be applied

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





Concluding Remarks

- The QCD charge asymmetry can be observed at the LHC in $t\bar{t} + jet$ production using two new observables:
  - The incline asymmetry tests the charge asymmetry of the qq-channel with asymmetries of up to -4%
  - The energy asymmetry tests the charge asymmetry of the qg-channel with asymmetries of up to -11%
- Massive color-octet bosons, that could explain the measured Tevatron charge asymmetry in inclusive $t\bar{t}$-production, have large effects on the charge asymmetries in $t\bar{t} + jet$ at the LHC.

  Vector or axial-vector couplings can be determined by measuring the differential jet distribution.