Top Charge Asymmetry: Discovering Light Axigluons in $t\bar{t}$+jet production at the LHC

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PHYSICS AT THE TERA SCALE
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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 at $2-3\sigma$ level
- Sign of new Physics?
- Need to measure the charge asymmetry at the LHC

$l + jets$	CDF 9.4 fb^{-1} *(1308.1120)*	9.4 ± 3 %
$l + \geq 4\, jets$, 1 b tag	D0 9.7 fb^{-1} *(D0 Note 6394)*	16.5 ± 4.7±1.9 %
$l + \geq 4\, jets$, ≥ 2 b tag	D0 9.7 fb^{-1} *(D0 Note 6394)*	1.6 ± 3.6±0.4 %
	SM, NLO	3.8 ± 0.3 %

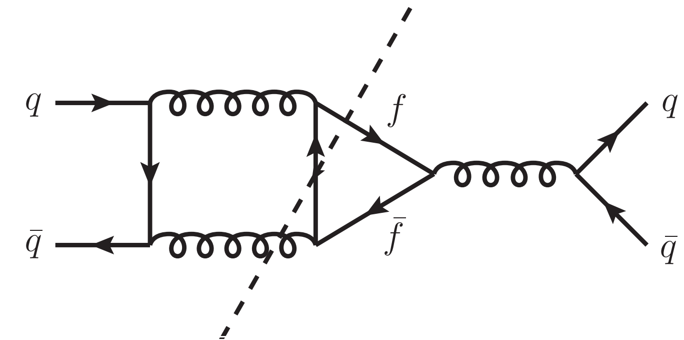
- Problem: predicted SM charge asymmetry in inclusive top pair production at LHC is very small

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

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

- Differential charge asymmetry at a certain phase space point:

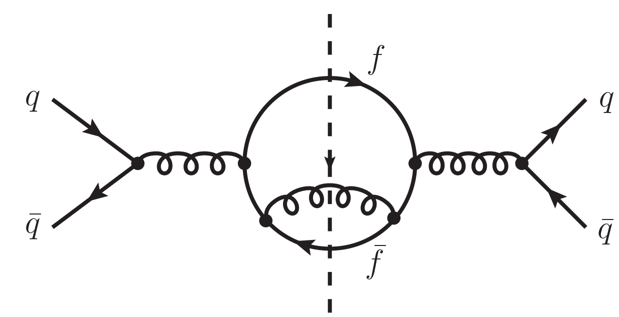
  $d\hat{\sigma}_A = d\hat{\sigma}_{t\bar{t}} - d\hat{\sigma}_{\bar{t}t}$

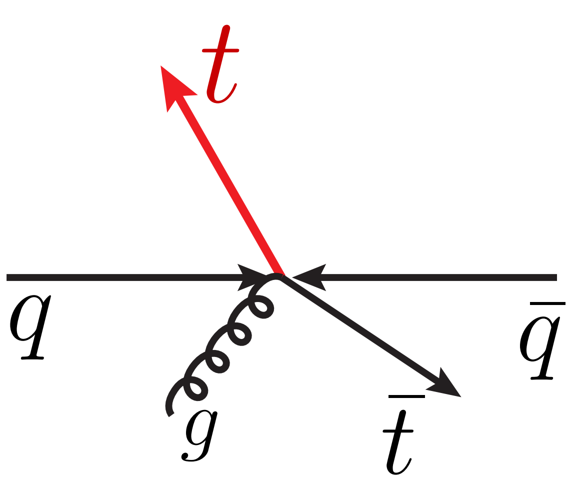


$d\hat{\sigma}_a \sim d^2_{abc} \cdot$ antisymmetric under $t \leftrightarrow \bar{t}$ (Furry theorem)

- Symmetric differential cross section :

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





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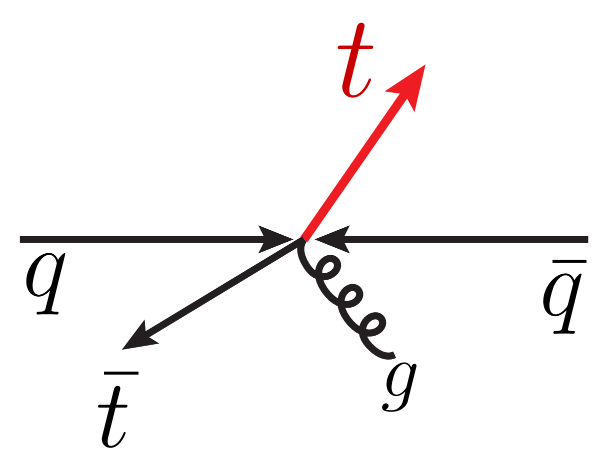

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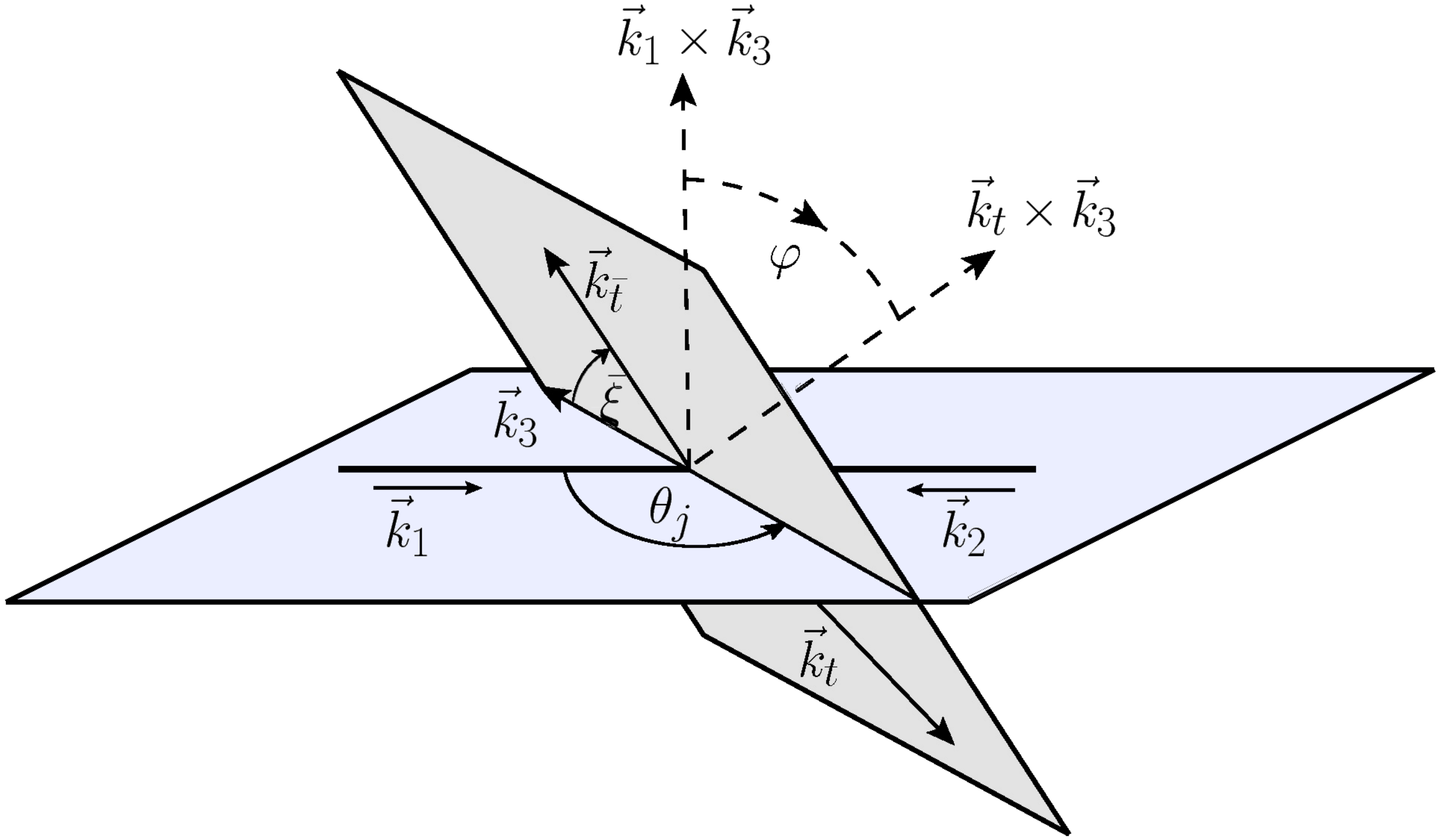
Charge asymmetry of $q\bar{q} \to t\bar{t} + jet$ in QCD

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

Differential charge asymmetry:

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



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

Incline Asymmetry

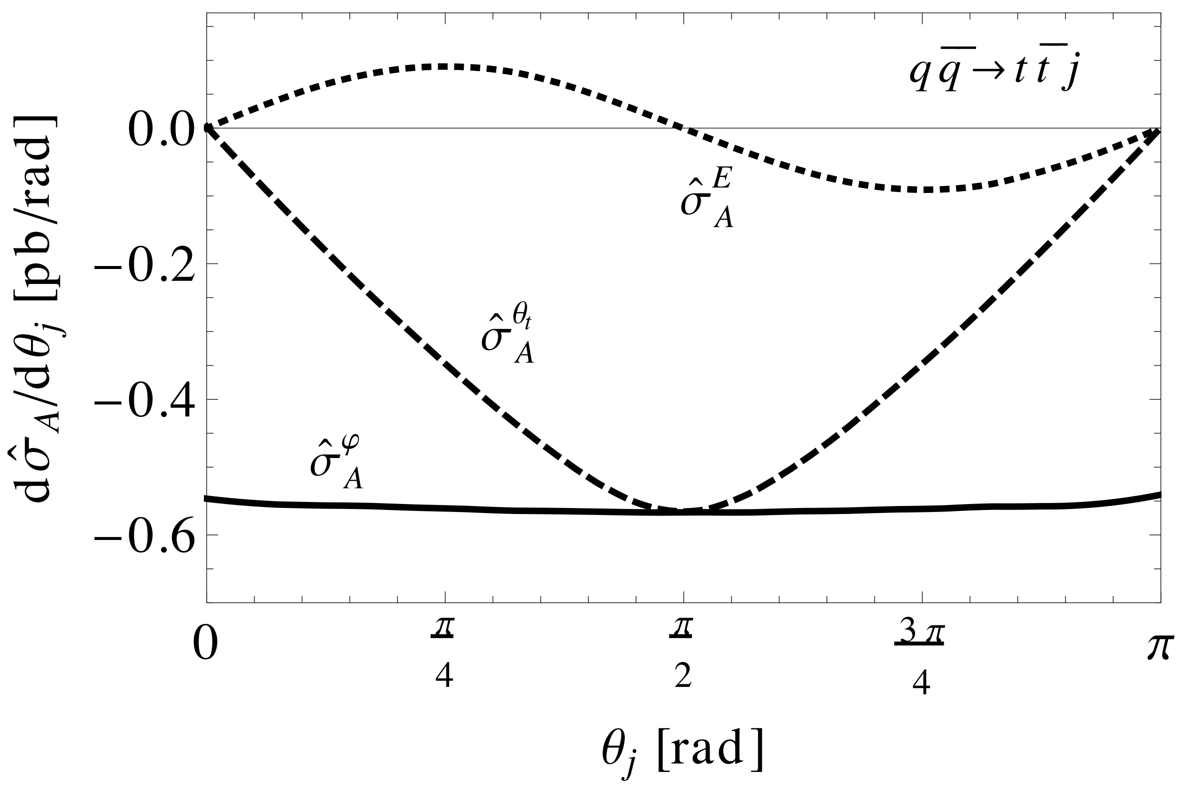
$$+\left[\underline{N_2} + \cos^2\varphi\,\underline{N_2^{\varphi}}\right]\sin\theta_j\cos\theta_j$$

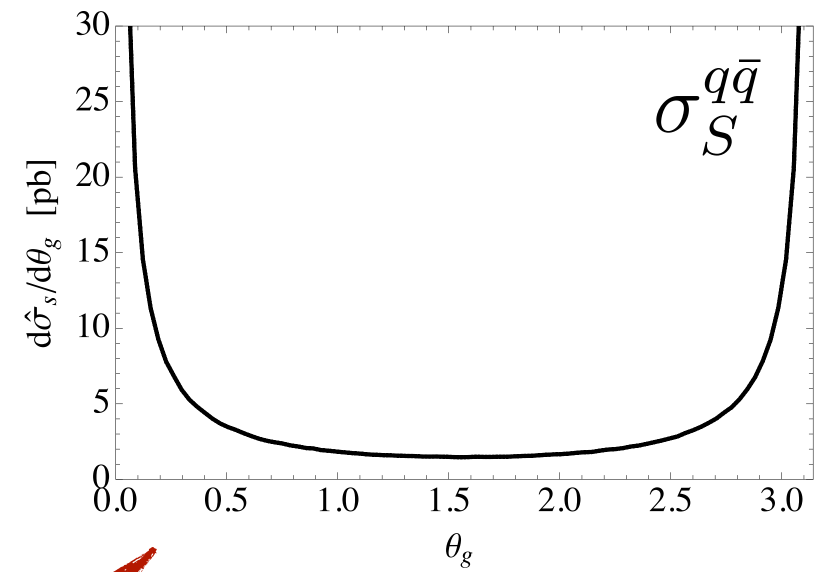
Energy Asymmetry

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

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

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





- 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.

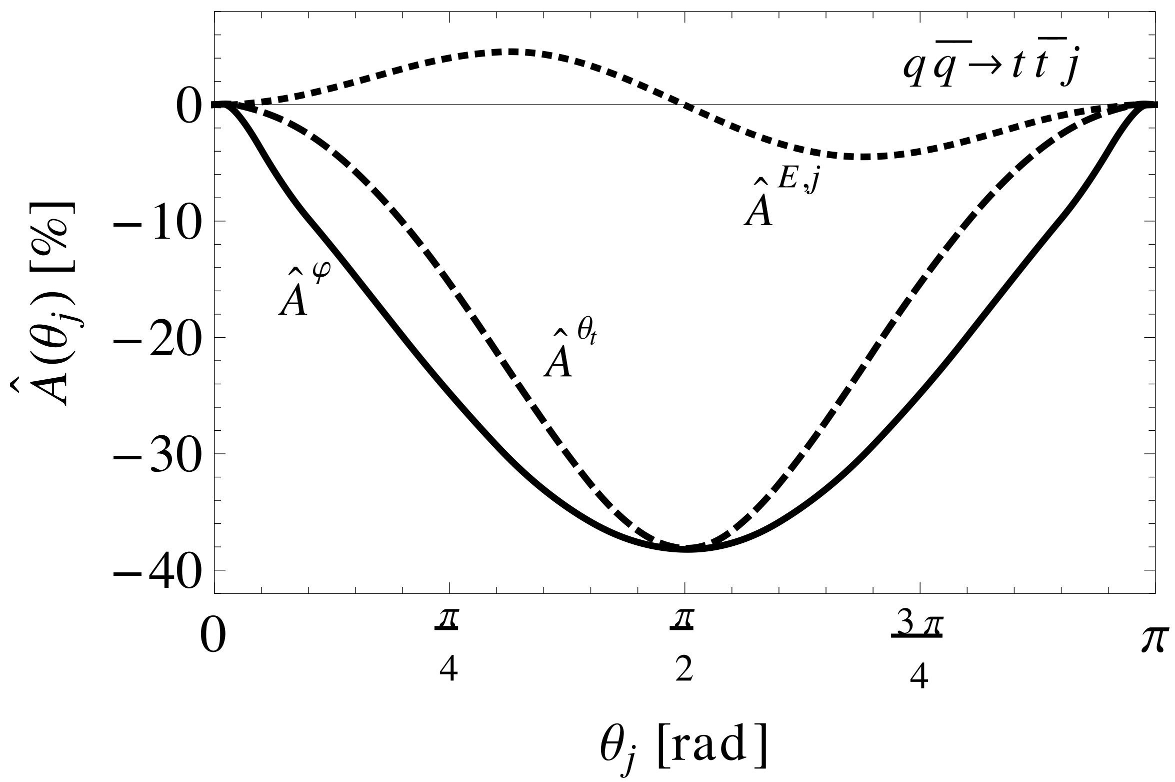
- Incline Asymmetry $\quad d\hat{\sigma}_A^{\varphi} = d\hat{\sigma}_A(\cos\varphi \geq 0)$

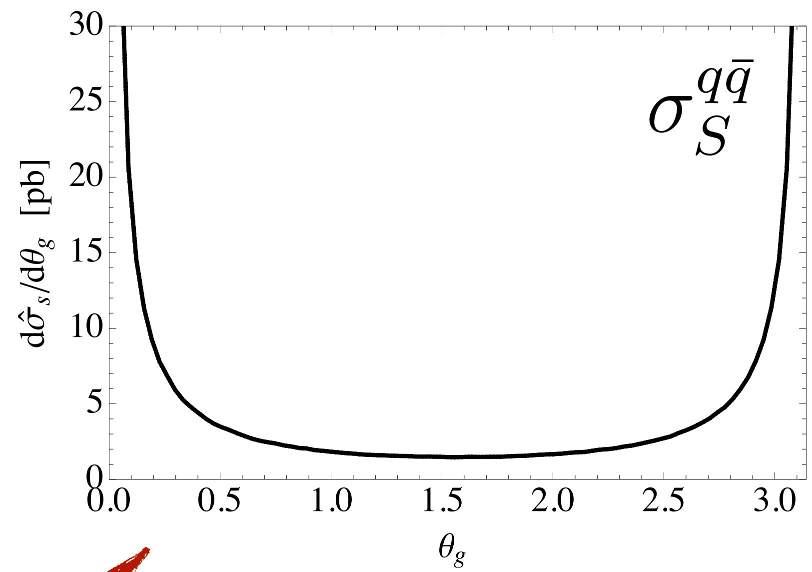
  Fwba Asymmetry $\quad d\hat{\sigma}_A^{\theta_t} = d\hat{\sigma}_A(\cos\theta_t \geq 0)$ $\quad , \quad d\hat{\sigma}_A = d\hat{\sigma}_{t\bar{t}} - d\hat{\sigma}_{\bar{t}t}$

  Energy Asymmetry $\quad d\hat{\sigma}_A^{E} = d\hat{\sigma}_A(\Delta E \geq 0)$

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

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





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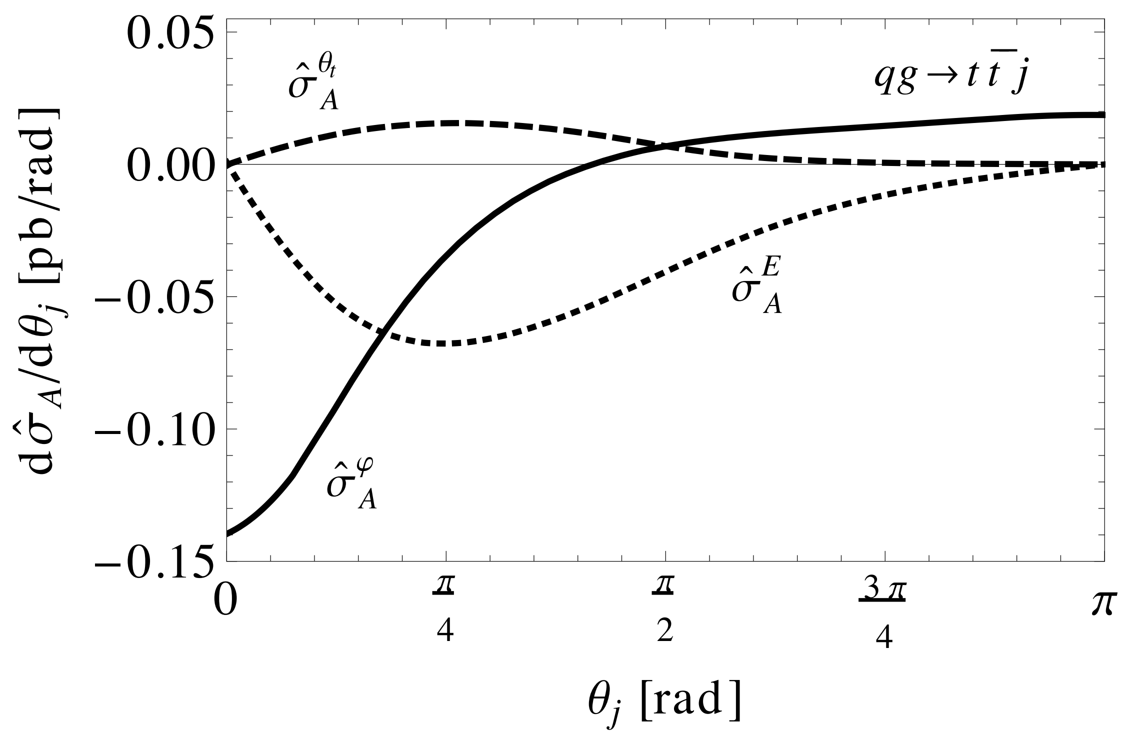
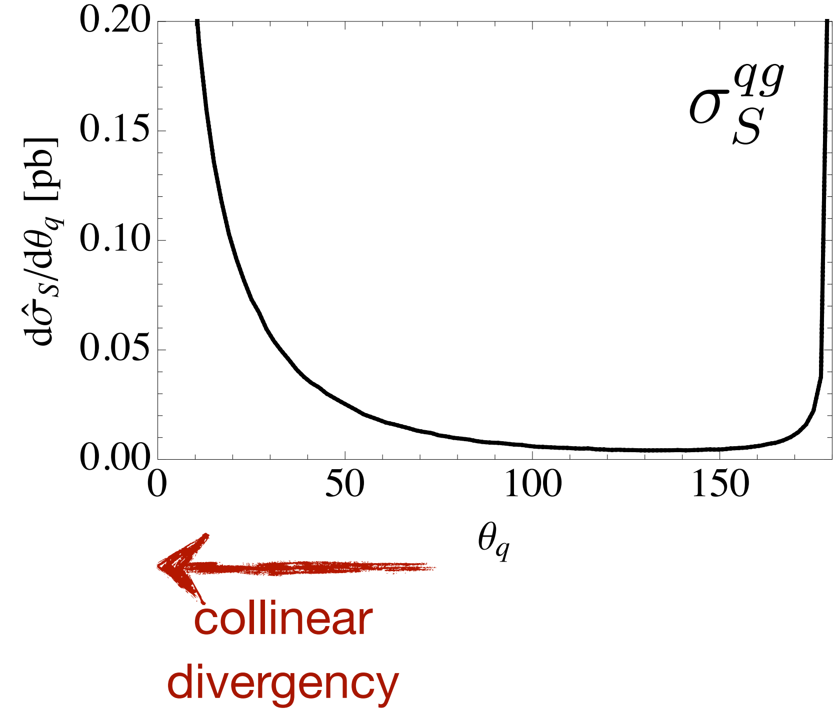
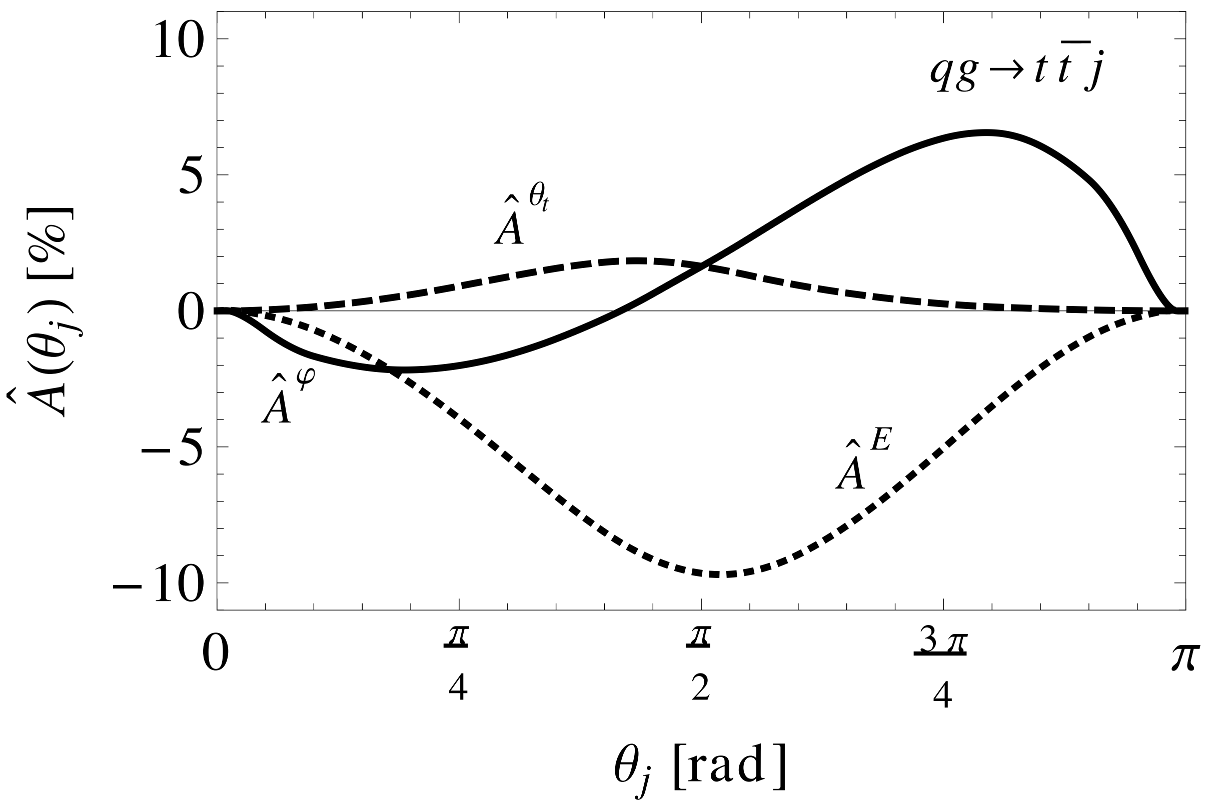
$qg \to t\bar{t} + q$

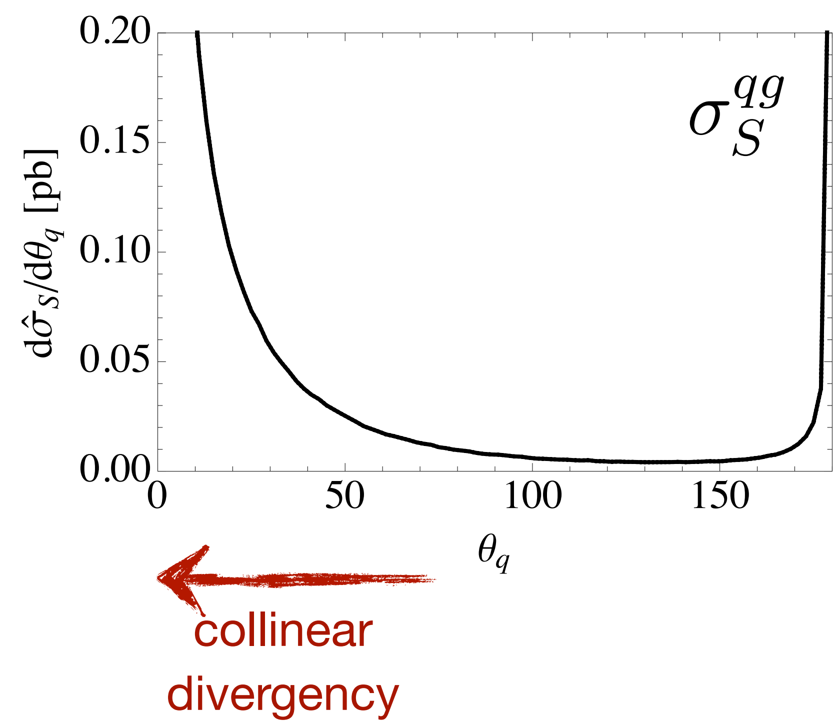




- Partonic asymmetries for $qg \to t\bar{t}q$ in dependence of the jet scattering angle θ_j, $\sqrt{s} = 1$ TeV, $E_j \geq 20$ GeV.
- Energy asymmetry in $qg \to t\bar{t}q$: Quark direction does not need to be determined!

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





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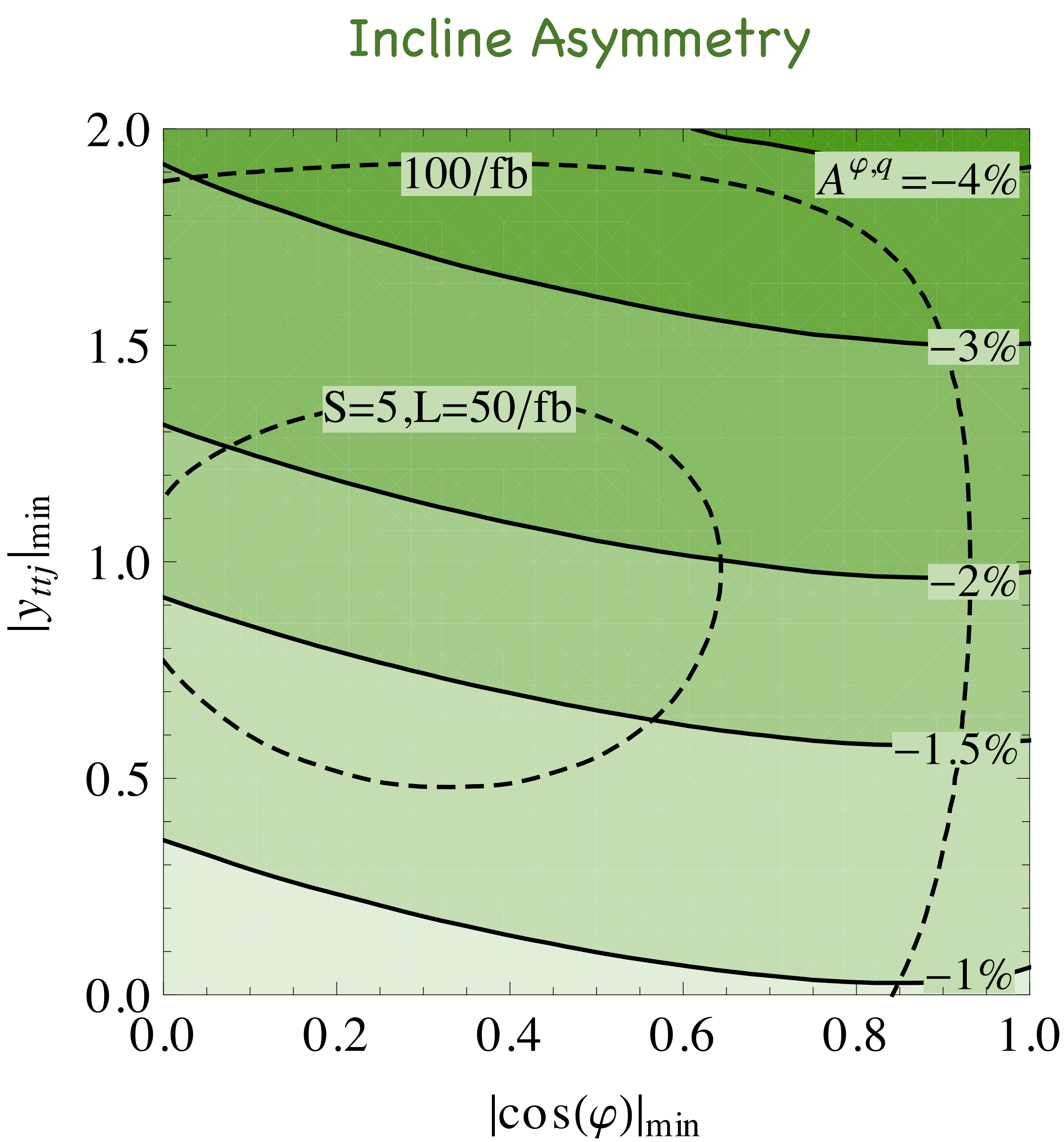
Results: LHC @ 14 TeV

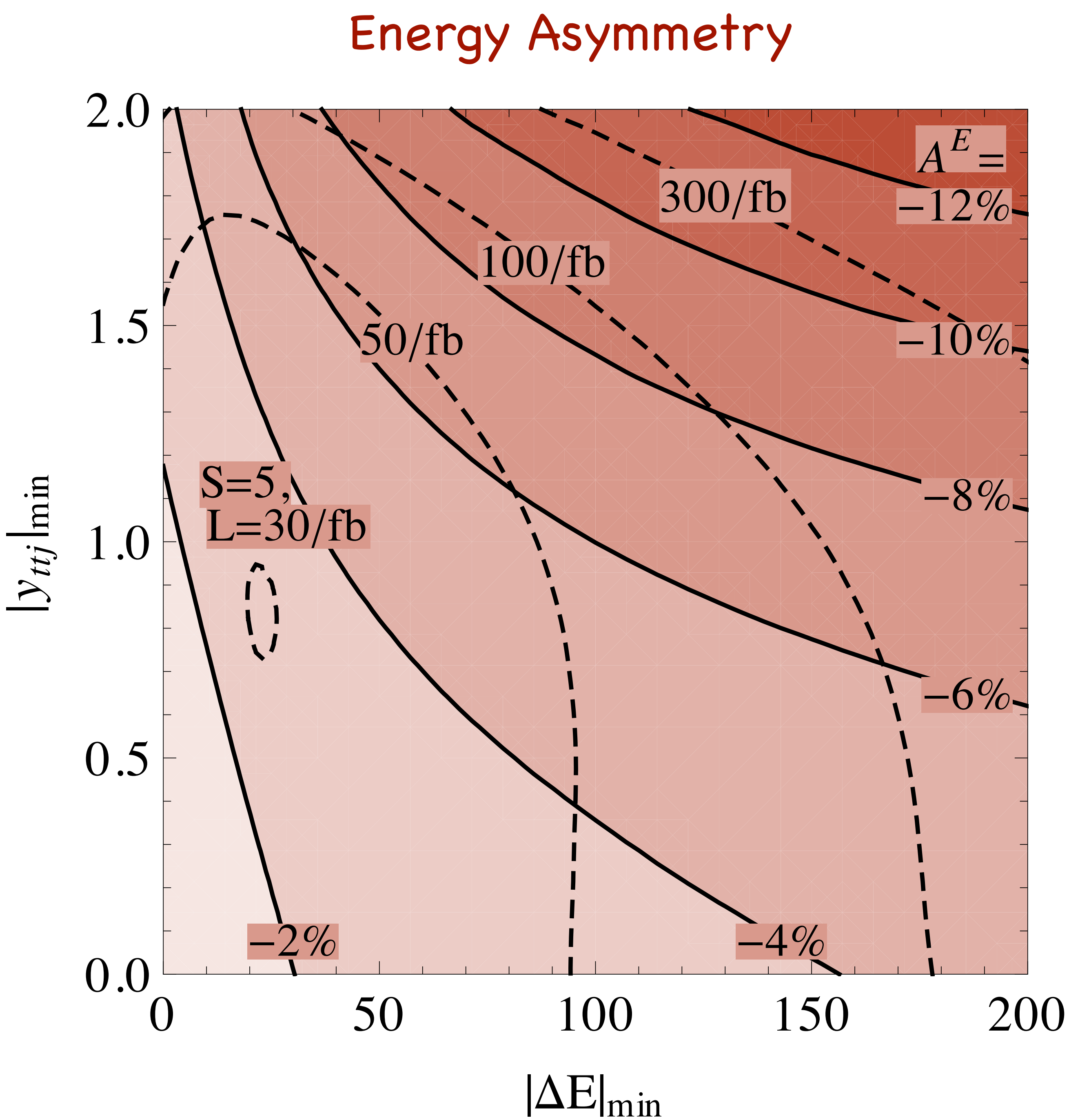


- Incline asymmetry $A^{\varphi,q}$ tests the charge asymmetry of the $q\bar{q}$-channel (qg channel contribution tiny)

$$A^{\varphi,q} \equiv \frac{\sigma_A^{\varphi}(y_{t\bar{t}j} > 0) - \sigma_A^{\varphi}(y_{t\bar{t}j} < 0)}{\sigma_S}$$

- LHC Detector cuts have been applied. Furthermore $|\hat{y}_j| < 0.5$
- Dashed lines: Luminosity needed to distinguish the asymmetry with $5\,\sigma$ from the null hypothesis (assumed $t\bar{t} + jet$ reconstruction efficiency 0.05)
- Maximal significance at LHC8: 3.6σ
- φ ... inclination angle
  y_{ttj} ... boost along z-axis

Results: LHC @ 14 TeV



- Energy asymmetry A^E tests the charge asymmetry of the qg-channel, rel. contributions: $qg : 21\%, q\bar{q} : 4\%$

$$A^E = \frac{\sigma_A(\Delta E \geq 0)}{\sigma_S}$$

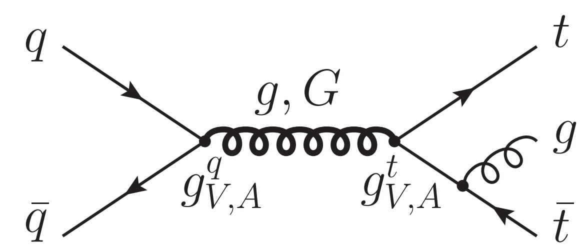
- $q\bar{q}$ contribution to A^E is exactly zero
- LHC Detector cuts have been applied. Furthermore $|\hat{y}_j| < 0.5$
- A lower cut on ΔE implies a larger minimum p_{Tj} cut
- Dashed lines: Luminosity needed to distinguish the asymmetry with $5\,\sigma$ from the null hypothesis (assumed $t\bar{t}+$ *jet* reconstruction efficiency 0.05)
- Maximal significance at LHC8: 3.3σ
- $\Delta E = E_t - E_{\bar{t}}$
  y_{ttj} ... boost along z-axis

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

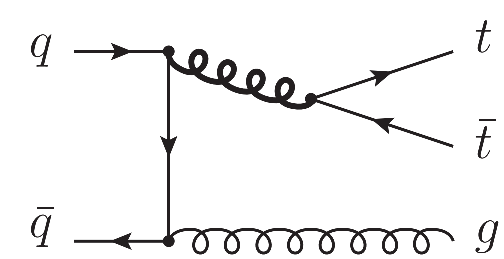
Lagrangian, contributing diagrams

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

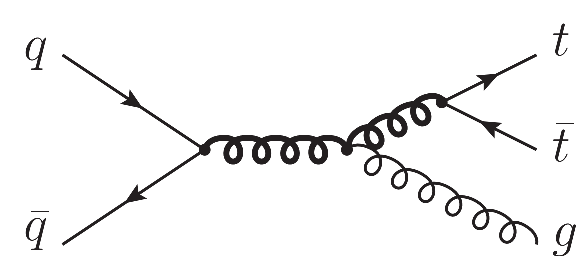
$$-\, i g_s\, \bar{q}_i\, \gamma^\mu G^a_\mu T^a \left[g^i_V + \gamma_5\, g^i_A \right] q_i$$



- 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 $g^q_A g^t_A$



Axigluon Parameters

- Consider light massive color-octet bosons with masses of $100 - 400$ GeV as motivated in Gross et al. (Phys.Rev. D87 (2013) 014004) to explain the measured Tevatron Top charge Asymmetry

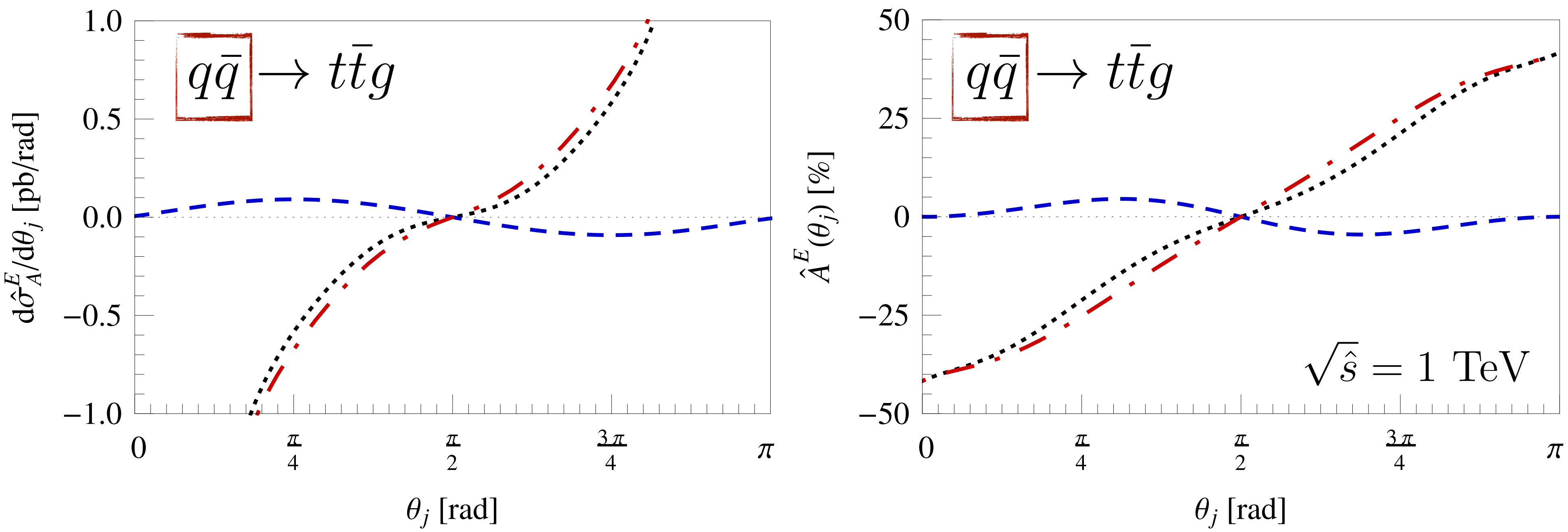
- $g_V = 0$, $\rightarrow$ consider pure axigluons

- Define $\alpha_A = g_A^u g_A^t \alpha_s$ with $0.005 \leq \alpha_A \leq 0.032$ to explain the Tevatron asymmetry

- Axigluon width $\geq 10\%$

- Axigluon must decay preferably into more than 3 jets to avoid collider bounds

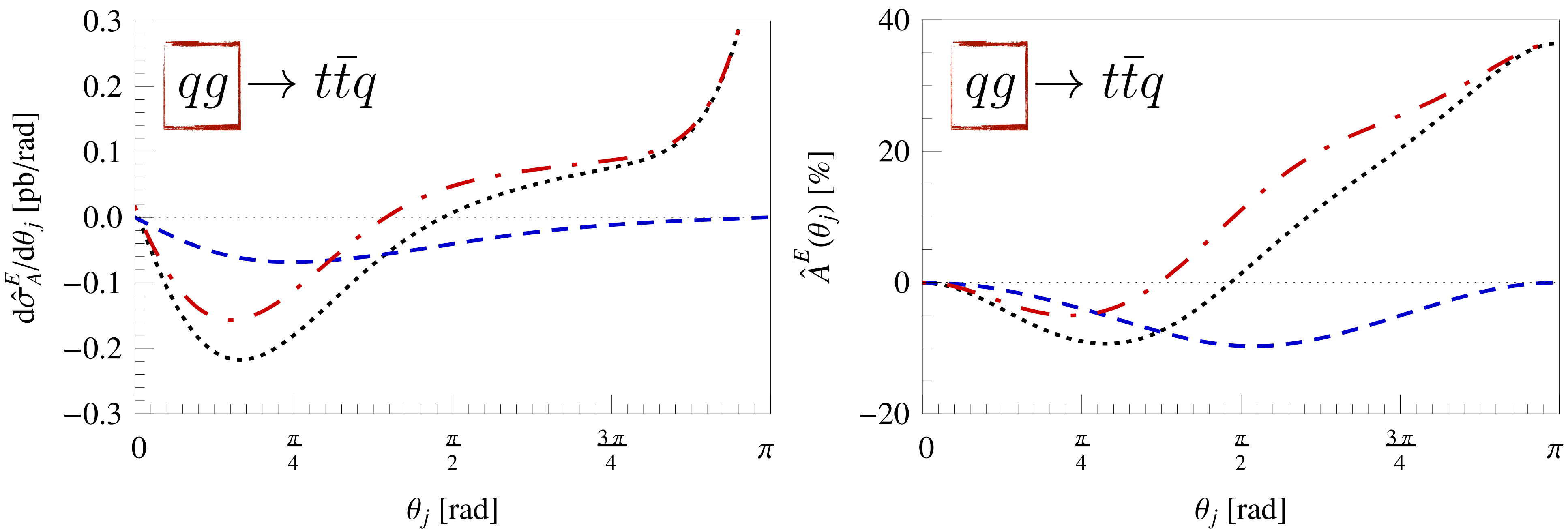
Energy asymmetry at parton level: $q\bar{q}$ - channel



- Shown is the differential energy asymmetry with $\Delta E = \hat{E}_t - \hat{E}_{\bar{t}}$:
  Left $d\hat{\sigma}^E_A = d\hat{\sigma}_A(\Delta E \geq 0)$, right $\hat{A}^{\Delta E}$
- Blue: SM, Black: including Axigluons, Red: difference
- Contrary to the SM case, $d\hat{\sigma}_A$ exhibits a pole for collinear jets
- $\rightarrow$ normalized asymmetry is large and finite for collinear jets
- Need to measure θ_j dependence or calculate an integrated double asymmetry:

$$\hat{A}^{\Delta E,j} = \frac{1}{\hat{\sigma}_S} \cdot \left(\hat{\sigma}^{\Delta E,j}_A(\theta_j > 0) - \hat{\sigma}^{\Delta E,j}_A(\theta_j < 0)\right)$$

Energy asymmetry at parton level: qg - channel



- Shown is the differential energy asymmetry with $\Delta E = \hat{E}_t - \hat{E}_{\bar{t}}$:
  Left $d\hat{\sigma}^E_A = d\hat{\sigma}_A(\Delta E \geq 0)$, right $\hat{A}^{\Delta E}$
- Blue: SM, Black: including Axigluons, Red: difference
- Contrary to SM, normalized asymmetry large and finite for $\theta \to \pi$
- Need to measure θ_j dependence or calculate an integrated double asymmetry:

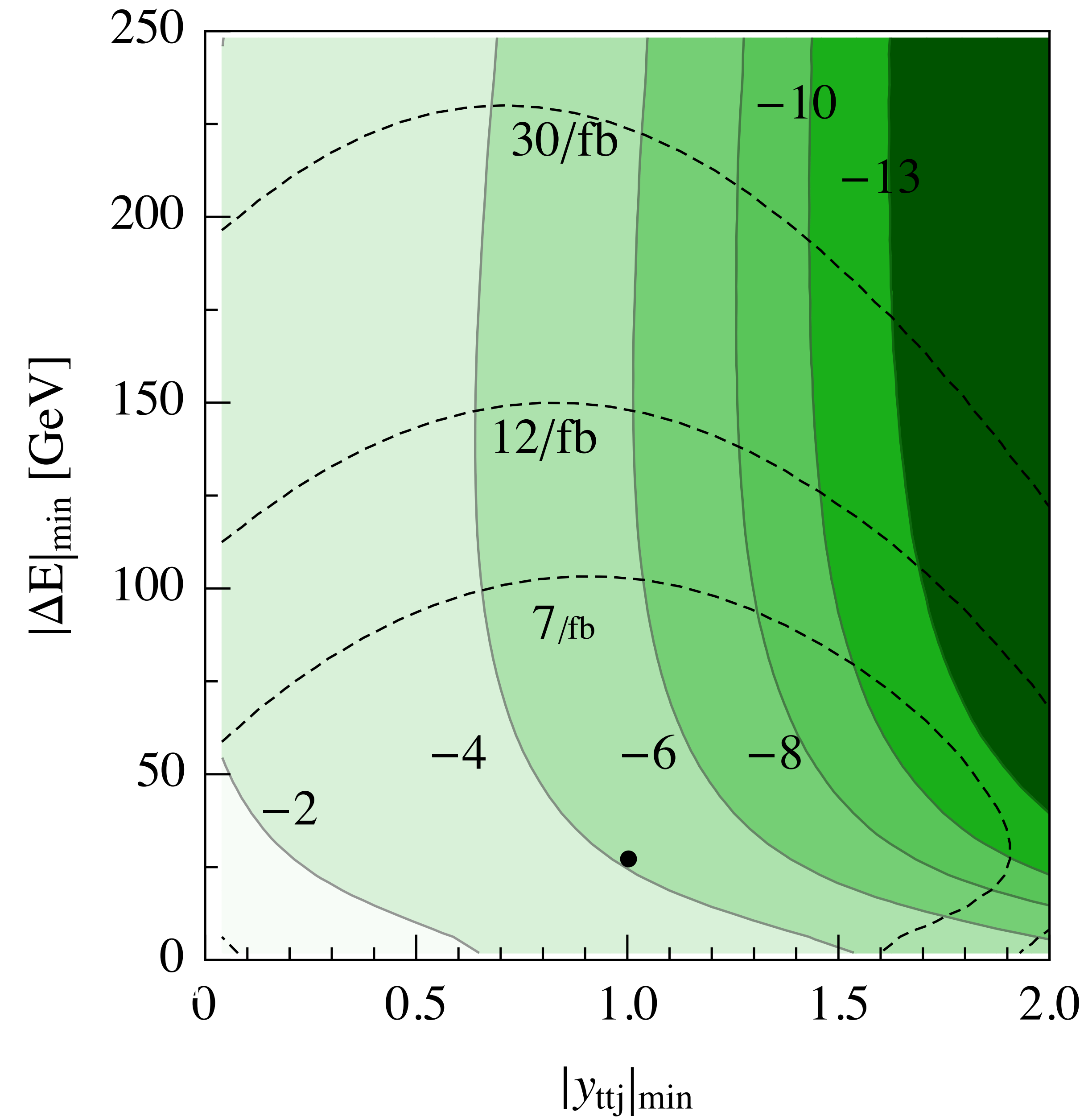
$$\hat{A}^{\Delta E,j} = \frac{1}{\hat{\sigma}_S} \cdot \left(\hat{\sigma}_A^{\Delta E,j}(\theta_j > 0) - \hat{\sigma}_A^{\Delta E,j}(\theta_j < 0)\right)$$

Results: Energy Asymmetry at LHC @ 14 TeV

- At the hadron level the quark direction is determined by the boost of the $t\bar{t}j$ system:

$$A^{\Delta E,j,q} = \frac{\sigma_A^{\Delta E,j,q}(y_{t\bar{t}j}>0) - \sigma_A^{\Delta E,j,q}(y_{t\bar{t}j}<0)}{\hat{\sigma}_S}$$

- Detector cuts: $p_{Tj} > 25$ GeV, $|y_j| < 2.5$
- Minimum cuts on $\Delta E = \hat{E}_t - \hat{E}_{\bar{t}}$ and $|y_{t\bar{t}j}|$ increase the asymmetry.
- $\rightarrow$ Notice, minimum ΔE implies a larger minimum p_{Tj} than 25 GeV
- Dashed lines: minimum Luminosity to measure an asymmetry difference $\Delta A^{\Delta E} = A^{\Delta E,NP} - \Delta A^{\Delta E,SM}$ with $5\,\sigma$
- Black dot: minimum luminosity required for $5\,\sigma$



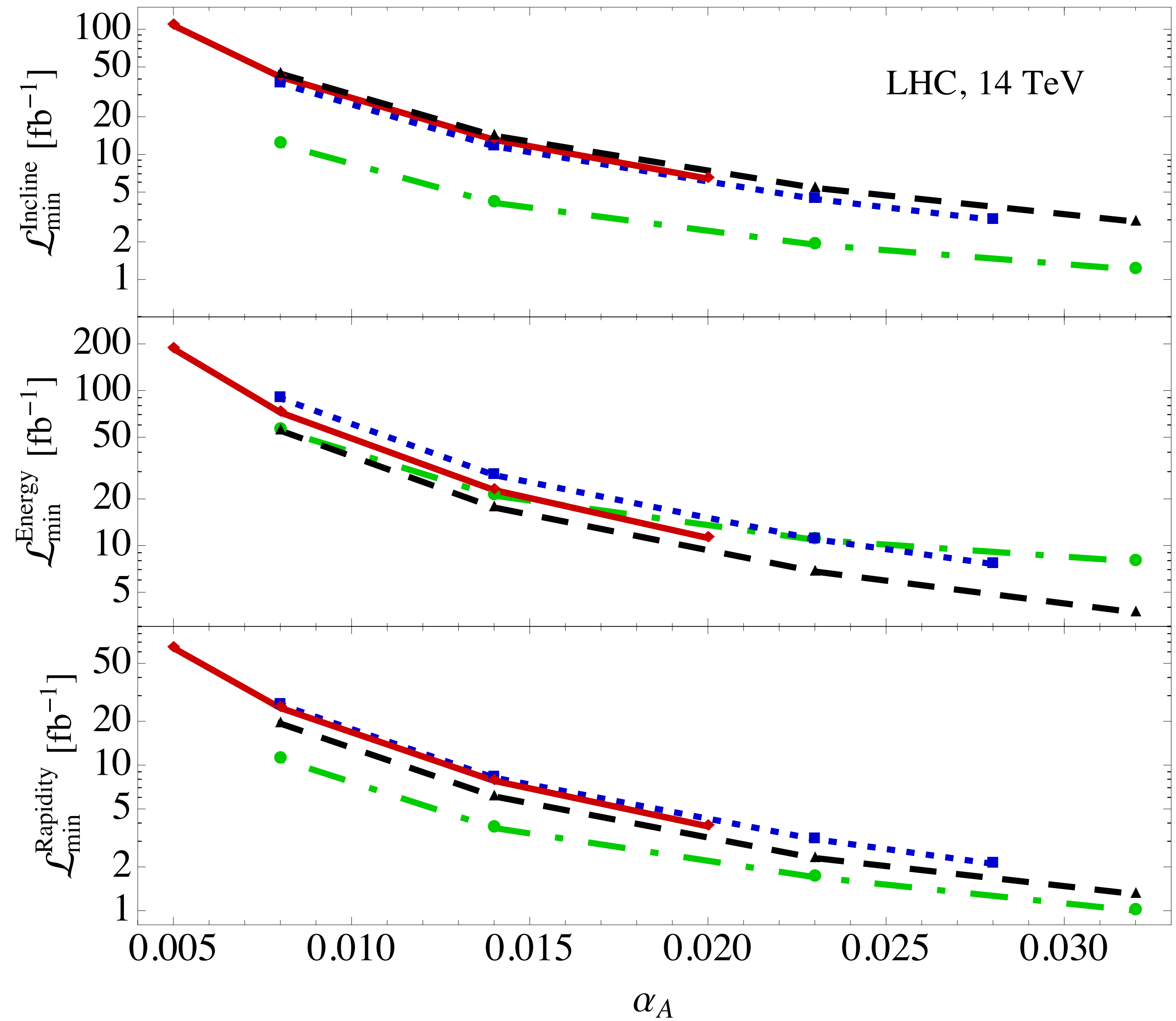
$\Delta A^{\Delta E,j,q}$ for large coupling scenario: $m_G = 400$ GeV, $\alpha_A = 0.032$, $\Gamma_G = 40$ GeV

Results: LHC @ 14 TeV

- Minimum Luminosity required (black dot from last slide) to measure $\Delta A^{\Delta E,j,q}$ at the $5\,\sigma$ level in dependence of the coupling parameter
  $\alpha_A = g_A^u g_A^t \alpha_s$

- Green, blue, red, black Lines correspond to
  $m_G = 100, 200, 300, 400$ GeV.

- Upper plot: Incline asymmetry
  Middle: Energy asymmetry
  Lower Plot: Rapidity asymmetry



Concluding Remarks

- The top quark charge asymmetry can be tested at the LHC in $t\bar{t} + jet$ production by investigating the *incline* and *energy* asymmetry.

- Assuming light axigluons with masses between 100 and 400 GeV and appropriate couplings to quarks that could explain the Tevatron forward-backward asymmetry exist:

  - Such axigluons can be discovered at the LHC by investigating the top charge asymmetry in $t\bar{t} + jet$

  - The entire parameter range can be tested at the 5σ level for a luminosity of less than 200 fb^{-1}