THE TOP-QUARK CHARGE ASYMMETRY WITH A JET HANDLE

Susanne Westhoff

University of Pittsburgh, PA

Portorož 2013 --- April 16, 2013 --- Portorož, Slovenia

MY FAVORITE FAMILY OUTING IN 2011

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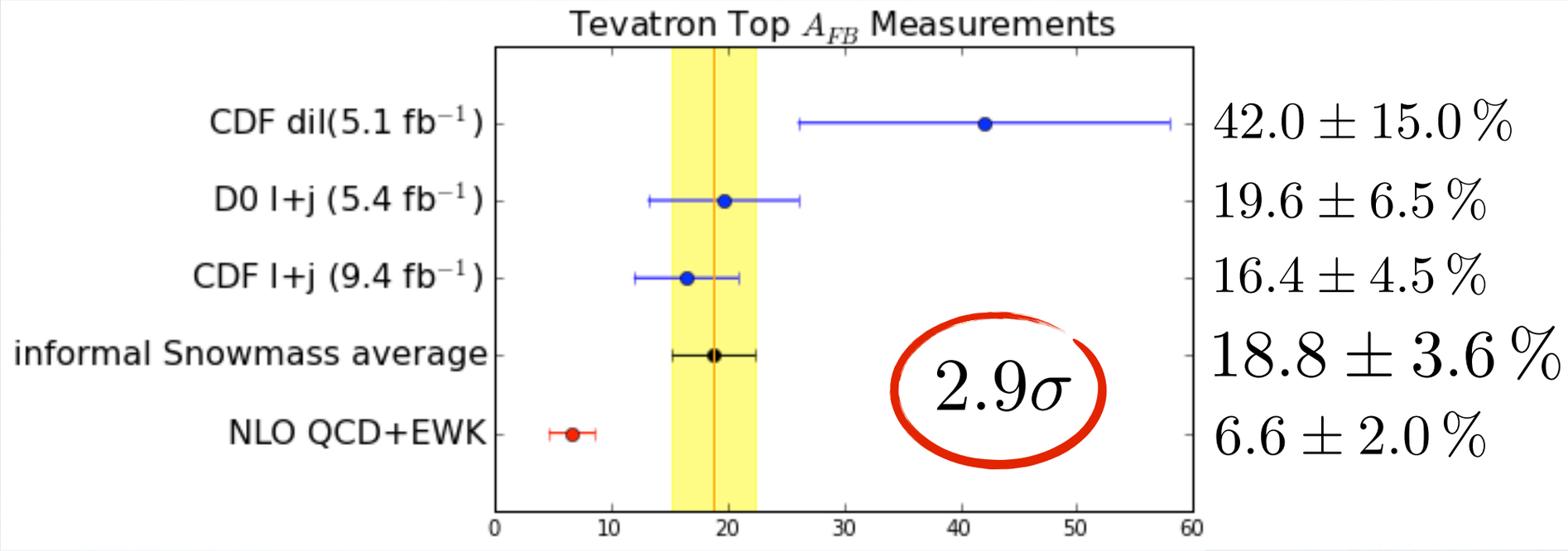
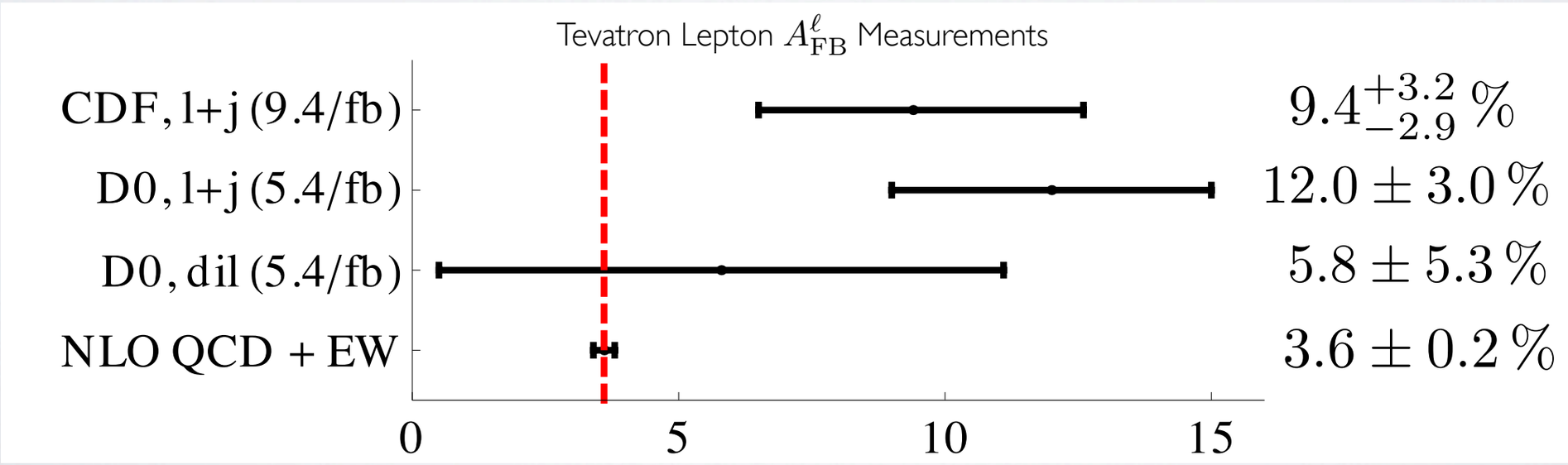
ANOMALY IN TOP-QUARK PRODUCTION?

Top forward-backward asymmetry $A^t_{\rm FB}$ in inclusive $t\bar{t}$ production

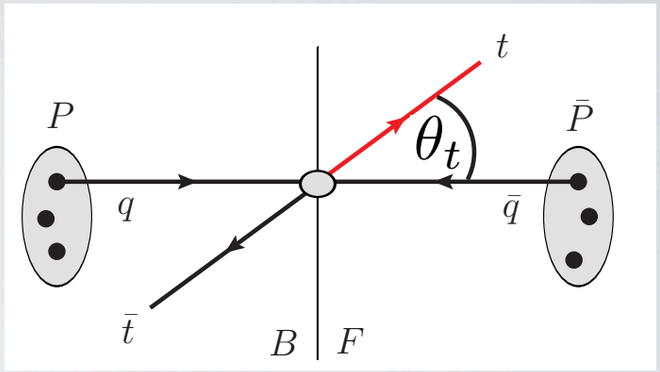


Lepton asymmetry $A^\ell_{\rm FB}$ (no top reconstruction)

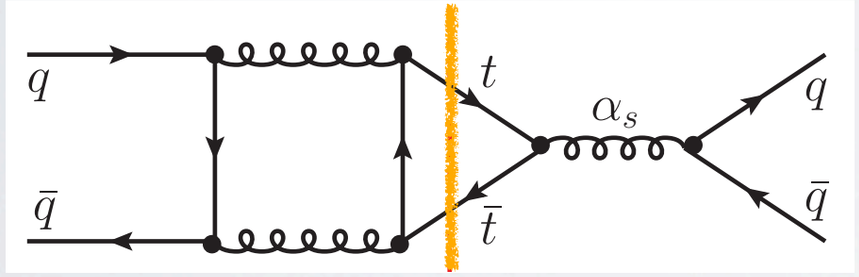


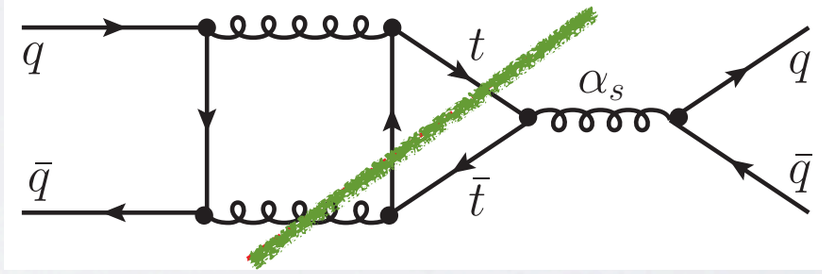
CHARGE ASYMMETRY IN QCD

$$A_C = \frac{\sigma_A^{\theta_t}}{\sigma_S}, \quad \sigma_{S,A} = \int_0^1 d\cos\theta_t \, \frac{d\sigma_{t\bar{t}}}{d\cos\theta_t} \pm \frac{d\sigma_{\bar{t}t}}{d\cos\theta_t}$$



Inclusive asymmetry at NLO from **virtual** and **real** gluons:





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

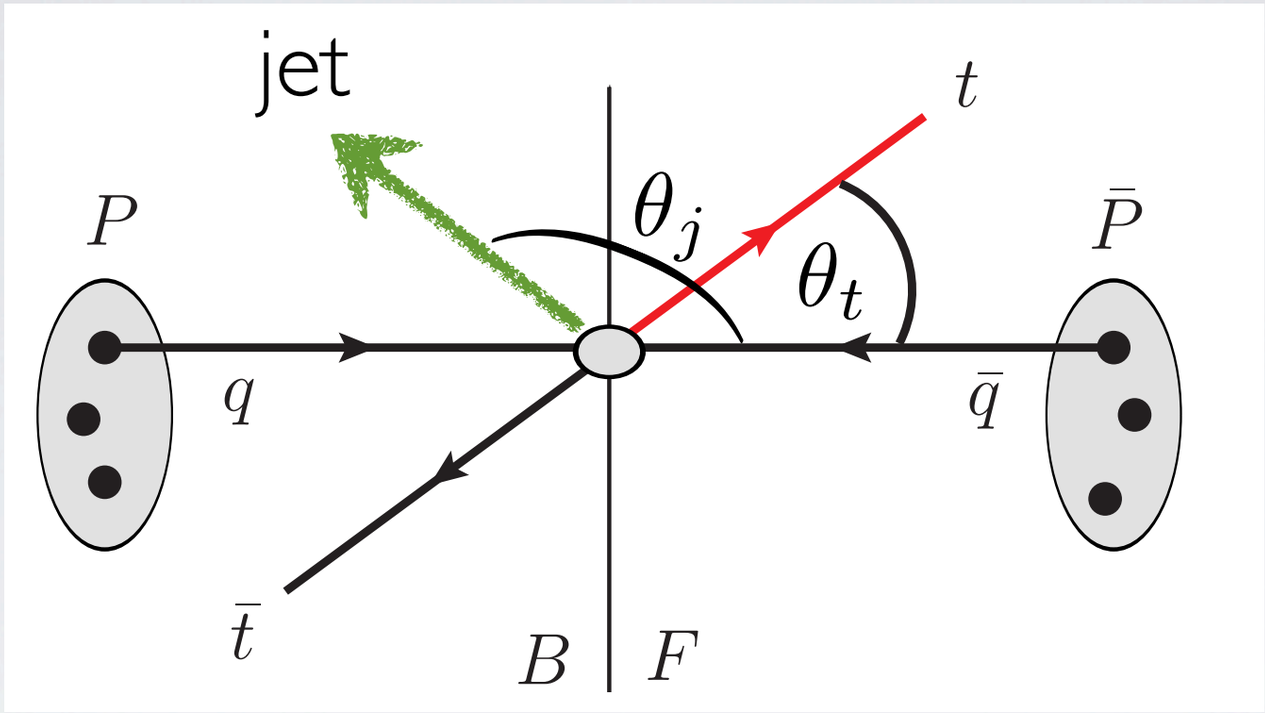
Tevatron: forward-backward

$$A_C^{exp} = A^y = A_C \qquad \Delta y = y_t - y_{\bar{t}}$$

LHC: beamward-central

$$A_C^{exp} = A_C^{|y|} \ll A_C \qquad \Delta y = |y_t| - |y_{\bar{t}}|$$

TOP PAIR PLUS JET PRODUCTION



Infrared divergence for soft and collinear gluon radiation:

$$\sigma_{t\bar{t}j}(p_T^j \to 0) \sim \ln^2\left(\frac{m_t}{p_T^j}\right)$$

Cut on jet transverse momentum defines hard jet:

$$p_T^j \geq 20 - 30\,\mathrm{GeV}$$ (also required for experimental reasons)

TOP PAIR + JET CROSS SECTIONS

QCD @ NLO
+ top decay and parton shower effects

[Dittmaier, Uwer, Weinzierl, PRL 98, 262002 (2007) & Eur. Phys. J. C59, 625 (2009)]
[Melnikov & Schulze, Nucl. Phys. B840, 129 (2010)]

[Melnikov, Scharf, Schulze, PRD 85, 054002 (2012)]
[Alioli, Moch, Uwer, JHEP 01, 137 (2012)]

Tevatron: little phase space, small production rate

$$\sigma_{t\bar{t}j} = 1.6 \pm 0.2 \pm 0.5\,\mathrm{pb}$$

[CDF Public Note 9850 (2009), $\sqrt{s} = 1.96\,\mathrm{TeV},\ p_T^j > 20\,\mathrm{GeV},\ \ell j,\ \mathcal{L} = 4.1/\mathrm{fb}$]

LHC: „top factory", high production rate

$$\sigma_{t\bar{t}j} = 102 \pm 2^{+23}_{-26}\,\mathrm{pb}$$

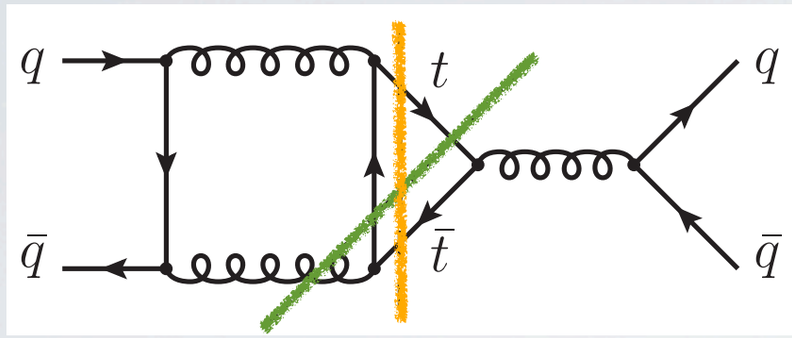
[ATLAS-CONF-2012-083, $\sqrt{s} = 7\,\mathrm{TeV}$, $p_T^j > 25\,\mathrm{GeV}$, $\ell j,\ \mathcal{L} = 4.7/\mathrm{fb}$] [s. also CMS-PAS-TOP-12-018]

Sizeable fraction of $t\bar{t}$ production with at least one hard jet:

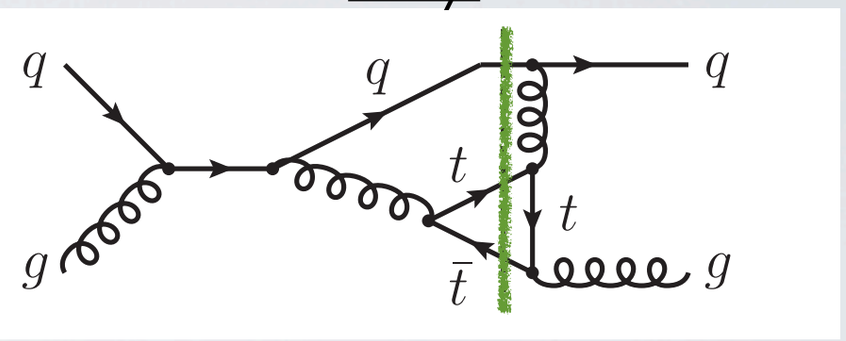
$$\sigma_{t\bar{t}j}/\sigma_{t\bar{t}} = 0.54 \pm 0.01^{+0.05}_{-0.08}$$

RAPIDITY ASYMMETRIES

dominant



tiny



$t\bar{t}$ inclusive

LO: no asymmetry

NLO: virtual + real

Tevatron

$$A^y = (7.16^{+1.05}_{-0.68}\,\%)_{\mathrm{NLO+NNLL}} \cdot 1.22_{\mathrm{EW}}$$

[Ahrens et al., PRD 84 (2011) 074004][Hollik, Pagani, PRD 84 (2011) 093003]

LHC7

$$A^{|y|} = 1.15 \pm 0.06\,\%$$ [(incl. EW)]

[Kühn, Rodrigo, JHEP 1201 (2012) 063]

$t\bar{t} + jet$

LO: real only

NLO: virtual + real

$$A^y_{\mathrm{LO}} = -11.1^{+0.2}_{-0.1}\,\%$$

$$A^y_{\mathrm{NLO}} = -4.40 \pm 0.04\,\%$$

[Alioli, Moch, Uwer, JHEP 1201 (2012) 137, pTj > 20 GeV]

$$A^{|y|}_{\mathrm{LO}} = -0.47 \pm 0.04\,\%$$

$$A^{|y|}_{\mathrm{NLO}} = 0.51 \pm 0.09\,\%$$

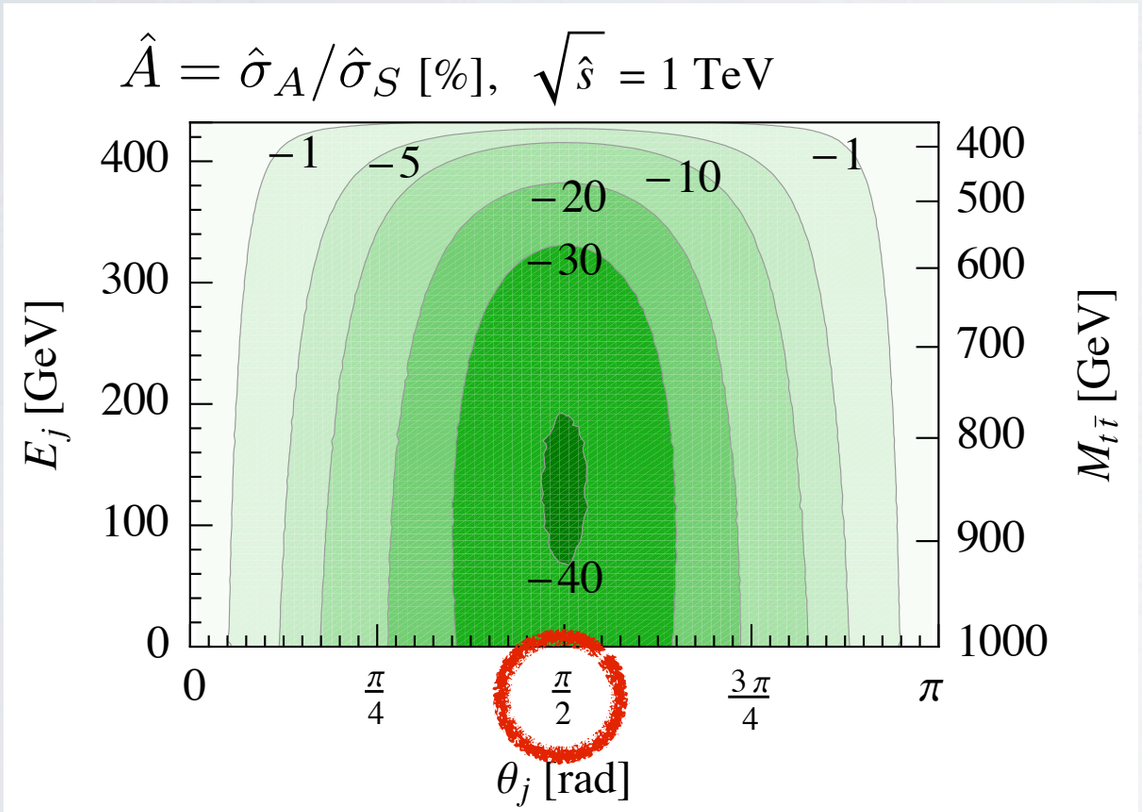
[Alioli, Moch, Uwer, JHEP 1201 (2012) 137, pTj > 50 GeV]

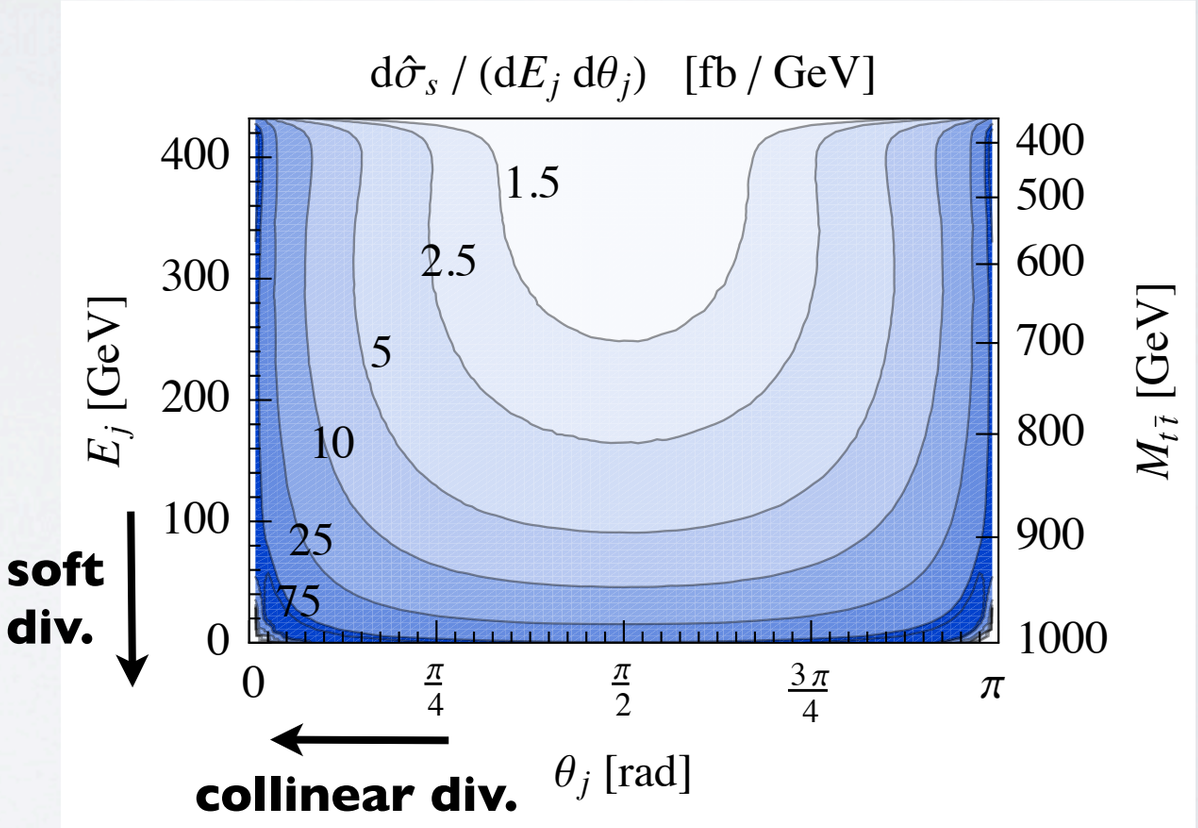
USING THE JET HANDLE

$q\bar{q} \to t\bar{t}g$ channel,
small $p_T^j = E_j \sin\theta_j$:

$$\sigma_A \sim \ln\left(\frac{m_t}{p_T^j}\right), \quad \sigma_S \sim \ln^2\left(\frac{m_t}{p_T^j}\right)$$

[Berge & Westhoff, PRD 86 (2012) 094036]





Asymmetry is maximal for central jet, $\theta_j = \pi/2$.

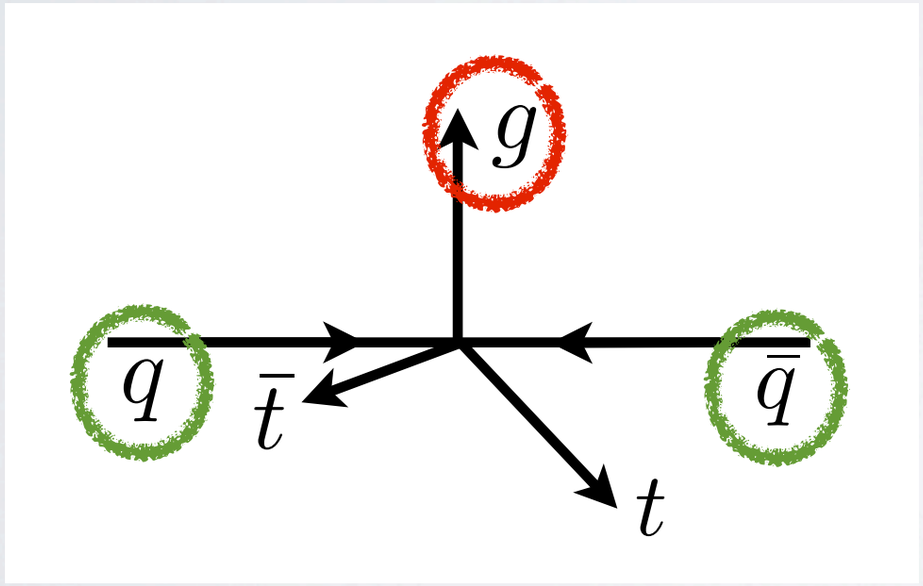
NEW OBSERVABLES

[work with Stefan Berge, to appear]

Based on
final-state kinematics:

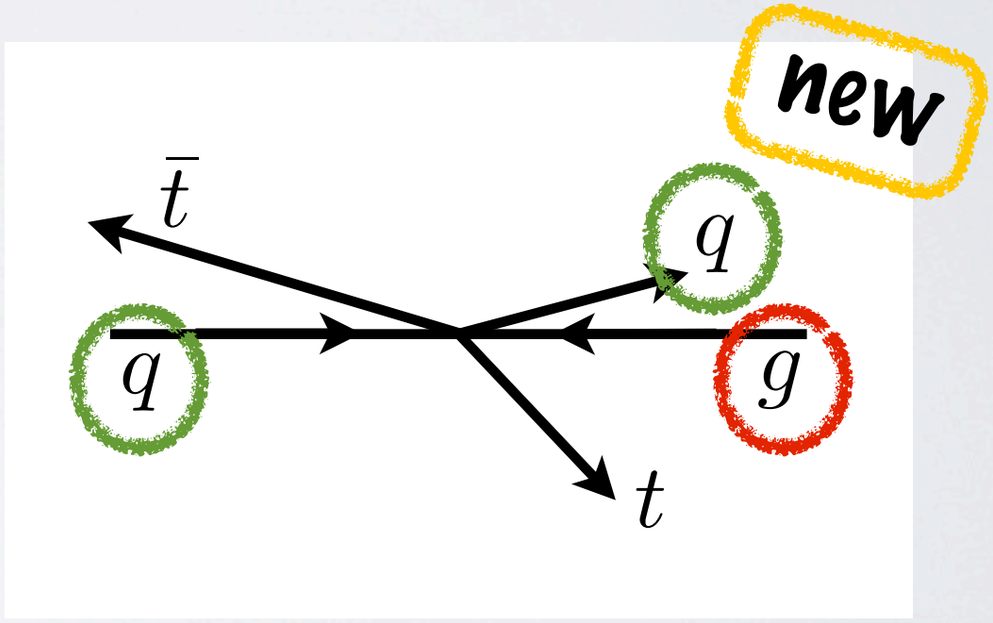
$$\vec{k}_t + \vec{k}_{\bar{t}} + \vec{k}_j = 0$$
$$E_t + E_{\bar{t}} + E_j = \sqrt{s}$$

qq̄ channel:
initial state **antisymmetric**



jet distribution **symmetric**

qg channel:
initial state asymmetric



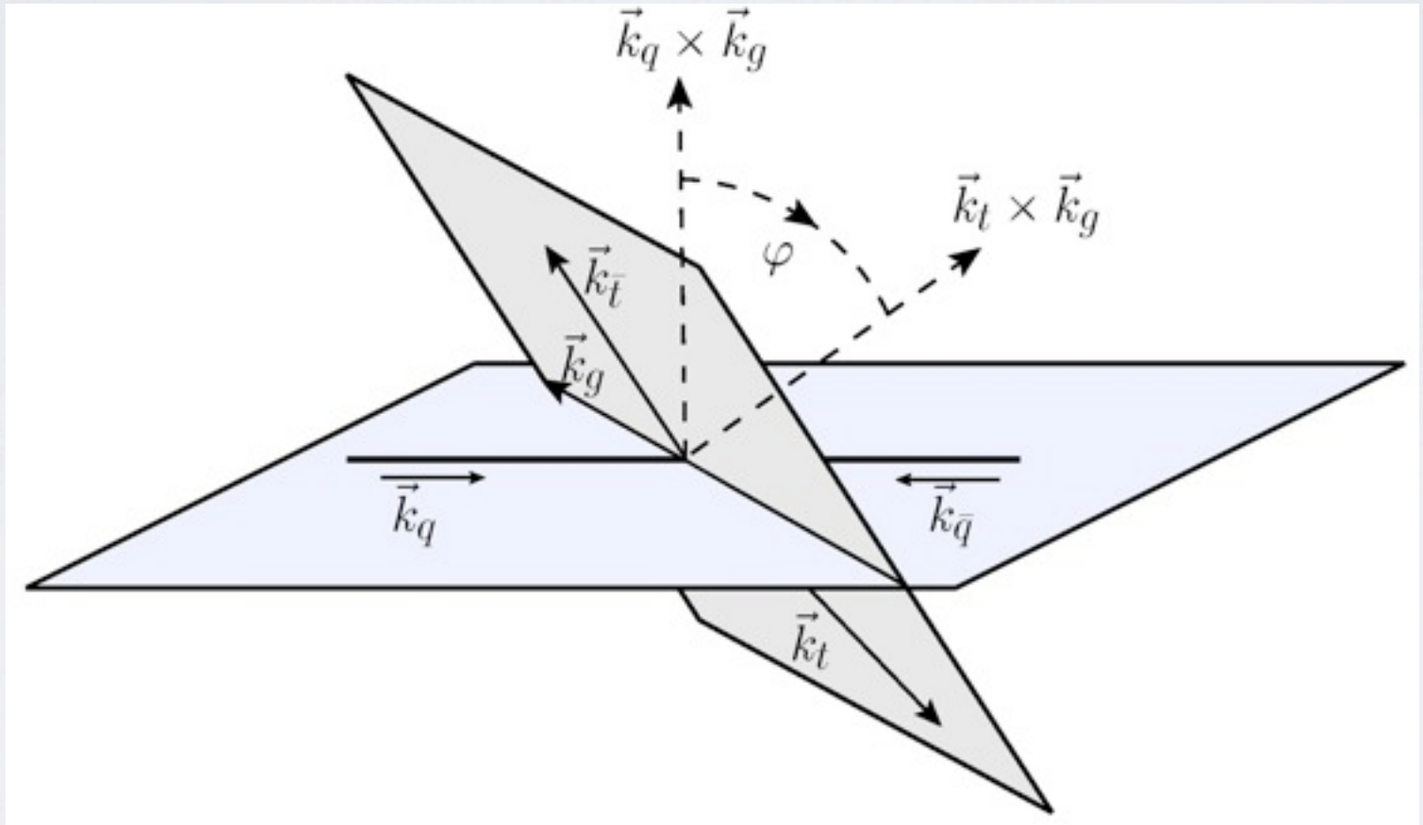
jet distribution asymmetric

QQ CHANNEL: INCLINE ASYMMETRY

Fully differential charge asymmetry

$$d\hat{\sigma}_A(q\bar{q} \to t\bar{t}j) = \left[d\hat{\sigma}(t\bar{t}) - d\hat{\sigma}(\bar{t}t)\right](\theta_j, \varphi, E_t, E_{\bar{t}})$$

Inclination φ between planes (q, $\underline{q}$, g) and (t, $\underline{t}$, g):

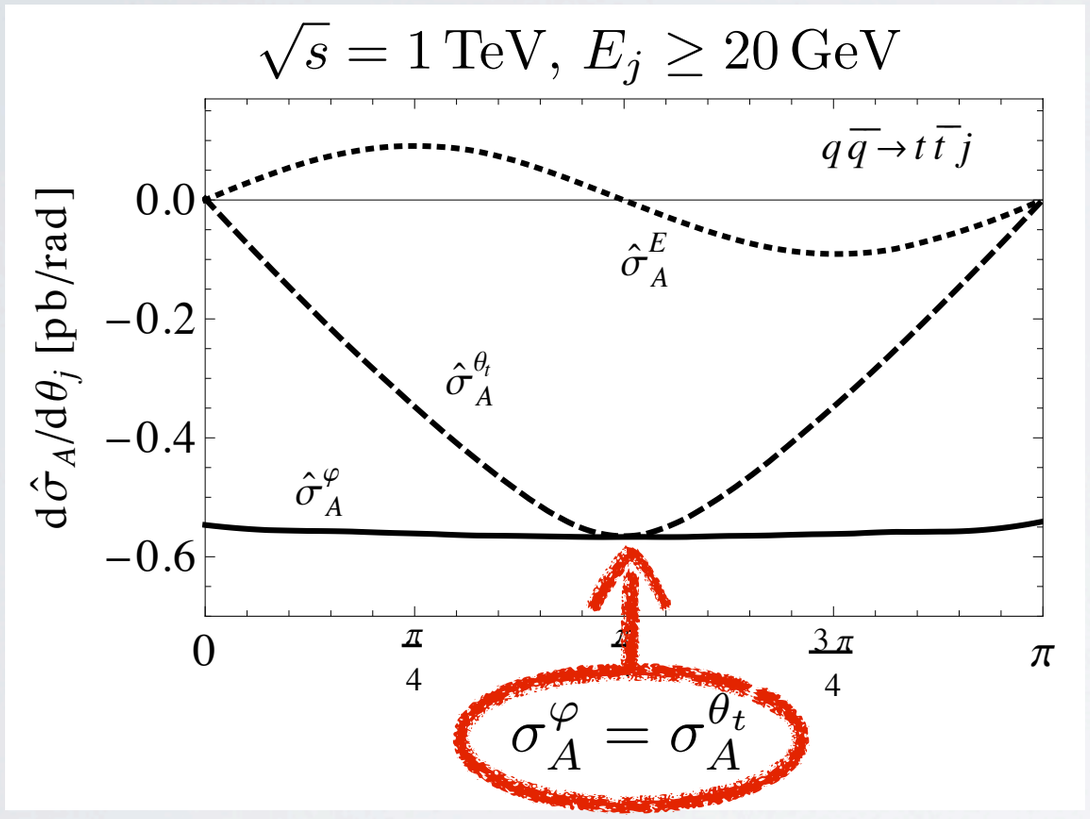


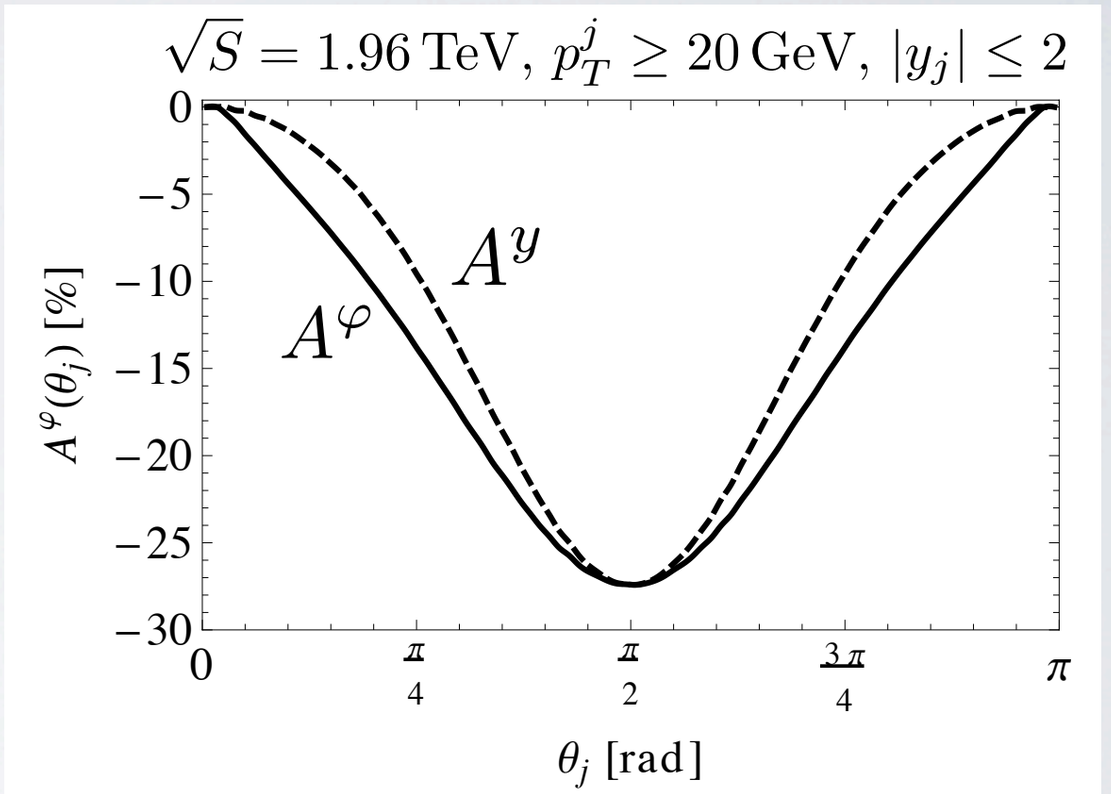
$$A^{\varphi} = \frac{\sigma_A^{\varphi}}{\sigma_S} = \frac{\sigma(\cos\varphi > 0) - \sigma(\cos\varphi < 0)}{\sigma(\cos\varphi > 0) + \sigma(\cos\varphi < 0)}$$

INCLINE ASYMMETRY AT THE TEVATRON

σ_A^{φ} is largely independent of jet angle.

A^{φ} drops off for $\theta_j \to 0, \pi$ (collinear enhancement of σ_S).





Total incline asymmetry: $A_{\mathrm{LO}}^{\varphi} = -15.6\,\%$

Statistical significance: $\mathcal{S}(10\,\mathrm{fb}^{-1}) = 4.2$

$A^{\varphi}/A^y \approx 1.2$

INCLINE ASYMMETRY AT THE LHC

Indentify quark direction via boost of final state:

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

$$y_{t\bar{t}j} = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

<u>Cuts</u>

$|\hat{y}_j|_{\max}$: suppress collinear region

$|y_{t\bar{t}j}|_{\min}$: suppress gg background

$|\cos(\varphi)|_{\min}$: enhance $\sigma_A^{\varphi}/\sigma_S$

<u>Significance statistically limited</u>

✖ „S max.“

$A^{\varphi,q} = -2.4\,\%$

$\sigma_S = 20\,\mathrm{pb}$

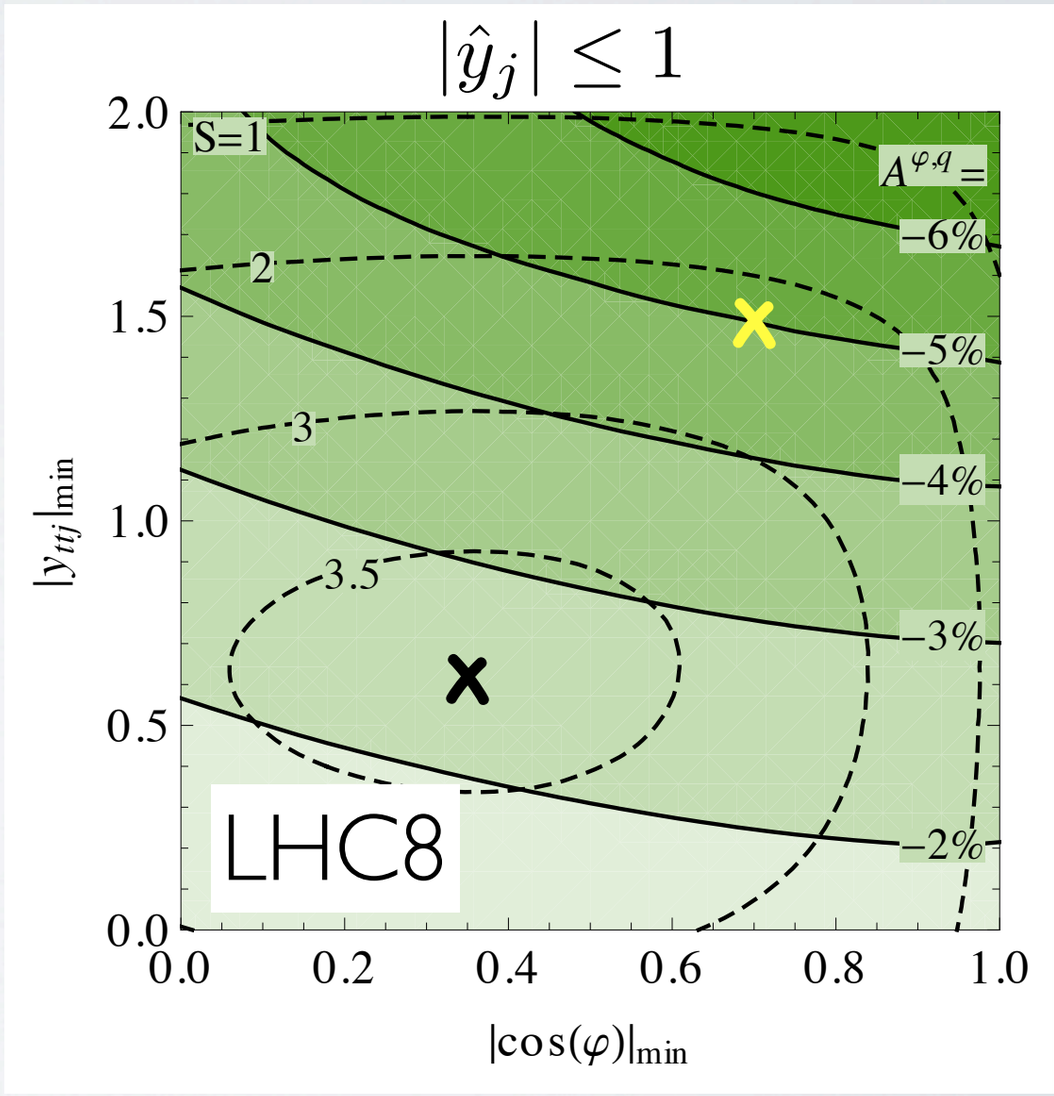
$\mathcal{S}(22/\mathrm{fb}) = 3.6$

✖ „A max.“

$A^{\varphi,q} = -5\,\%$

$\sigma_S = 1.8\,\mathrm{pb}$

$\mathcal{S}(22/\mathrm{fb}) = 2.3$



INCLINE ASYMMETRY AT THE LHC

Indentify quark direction via boost of final state:

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

Higher luminosity: stronger cuts, enhanced sensitivity

× „50/fb“

$A^{\varphi,q} = -2.4\,\%$

$\sigma_S = 18\,\mathrm{pb}$

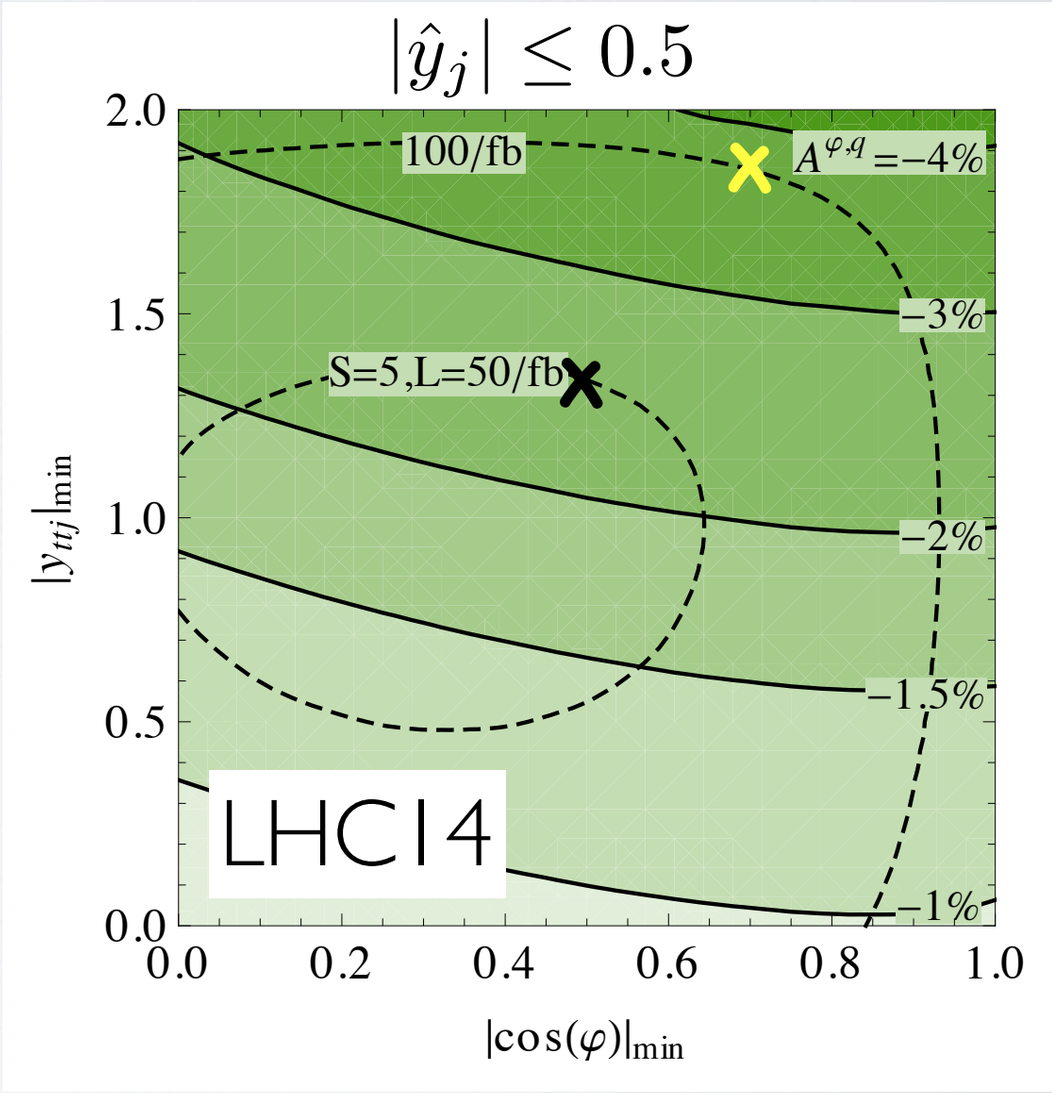
$\mathcal{S}(50/\mathrm{fb}) = 5$

× „100/fb“

$A^{\varphi,q} = -3.7\,\%$

$\sigma_S = 3.6\,\mathrm{pb}$

$\mathcal{S}(100/\mathrm{fb}) = 5$



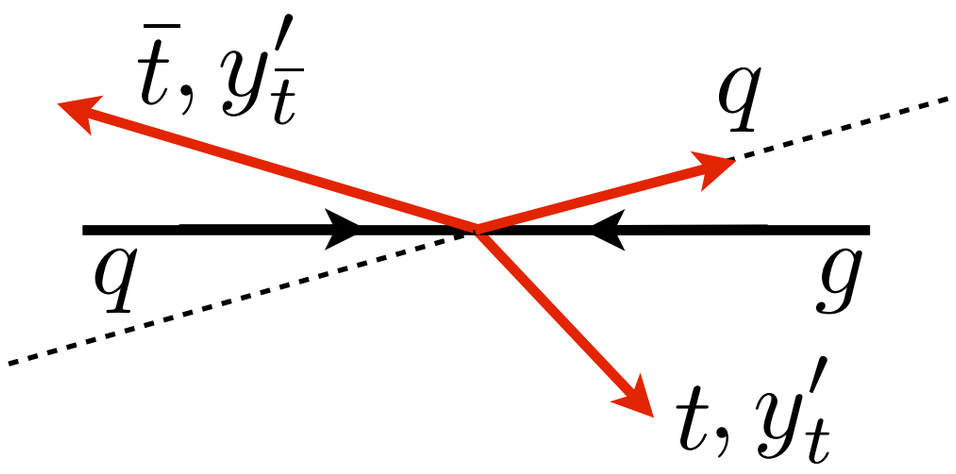
QG CHANNEL: ENERGY ASYMMETRY

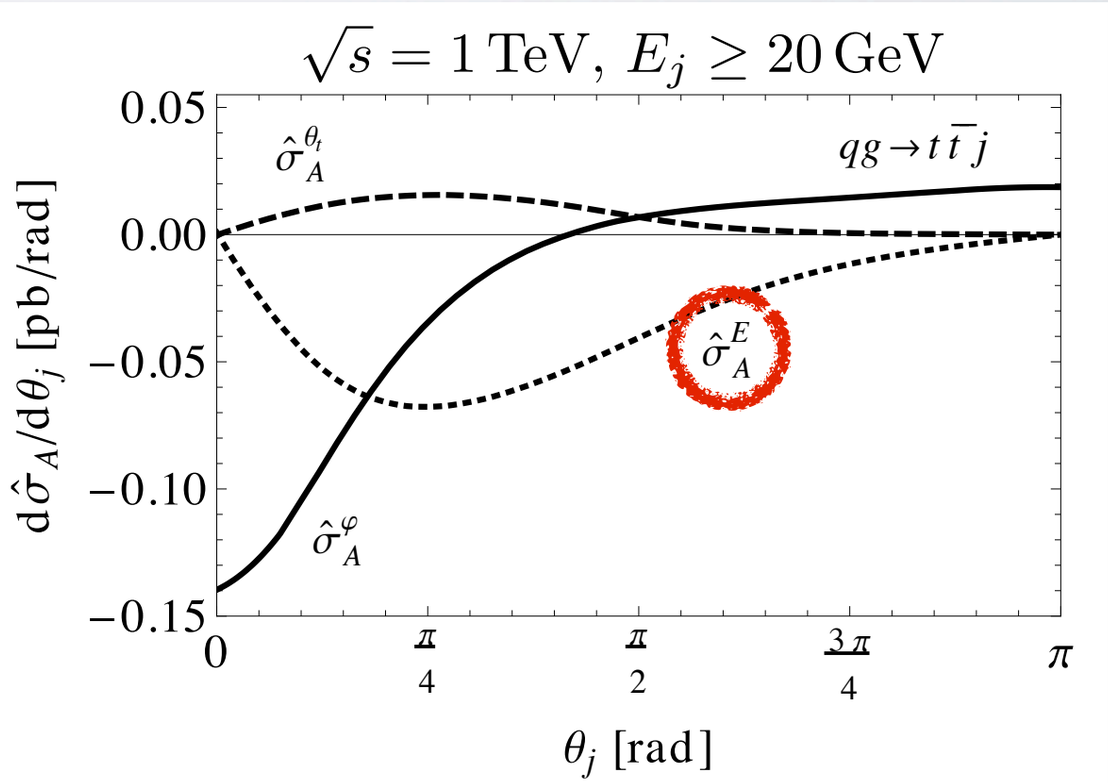
$$\boxed{A^E = \frac{\sigma_A^E}{\sigma_S} = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma(\Delta E > 0) + \sigma(\Delta E < 0)}} \qquad \Delta E = E_t - E_{\bar{t}}$$

energy asymmetry

= forward-backward asymmetry of q-jet in $t\bar{t}$ frame

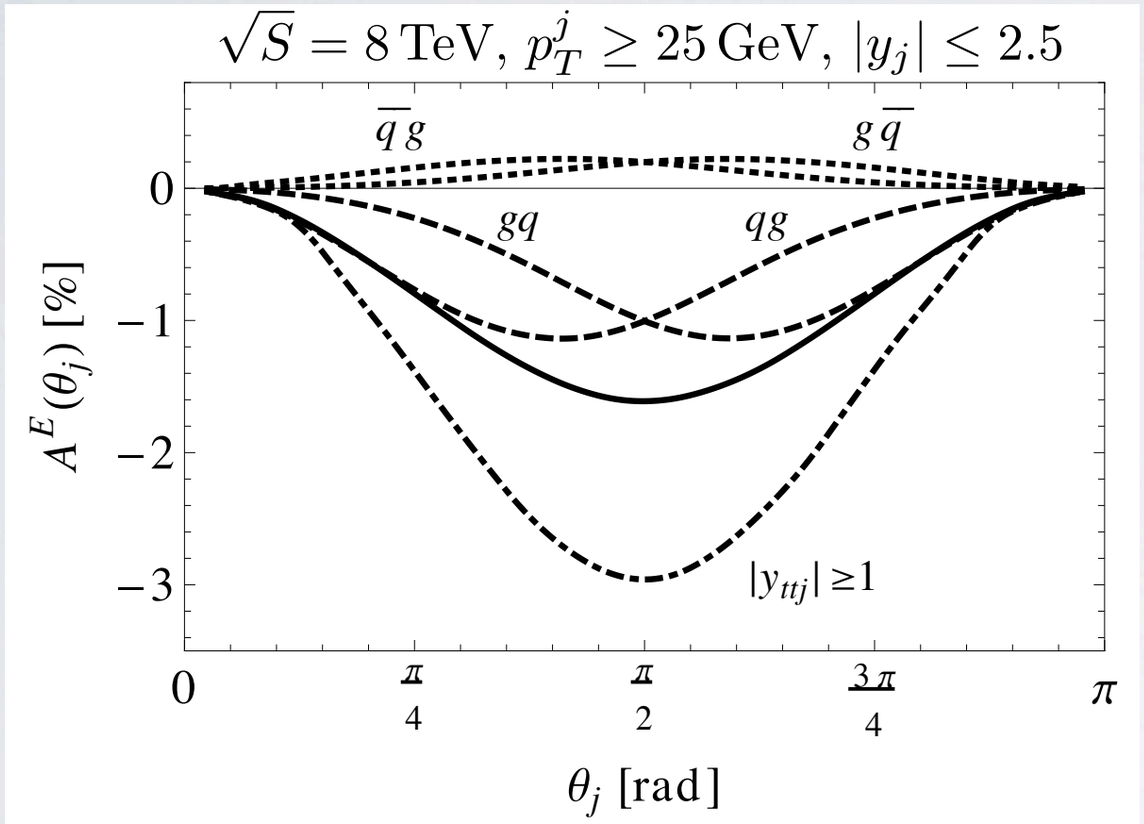
$$E_t < E_{\bar{t}} \leftrightarrow y'_t > y'_{\bar{t}}$$

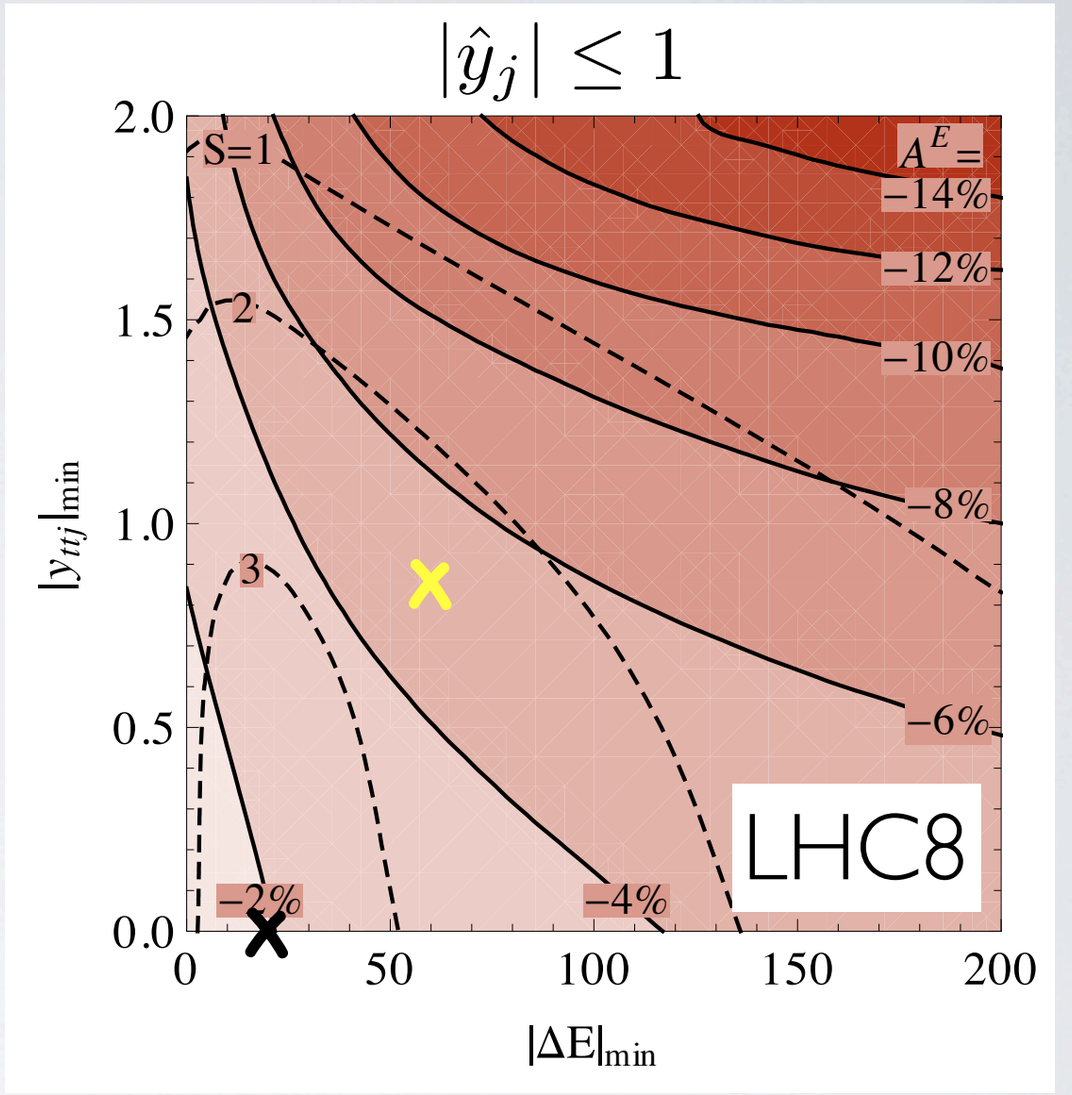




ENERGY ASYMMETRY AT THE LHC

No need to identify
the quark direction!





<u>qg ~25% of $\sigma_{t\bar{t}j}$ (cf. qq~7%):</u>
large maximal asymmetry,
but - again - statistical limits:

✖ „S max.“

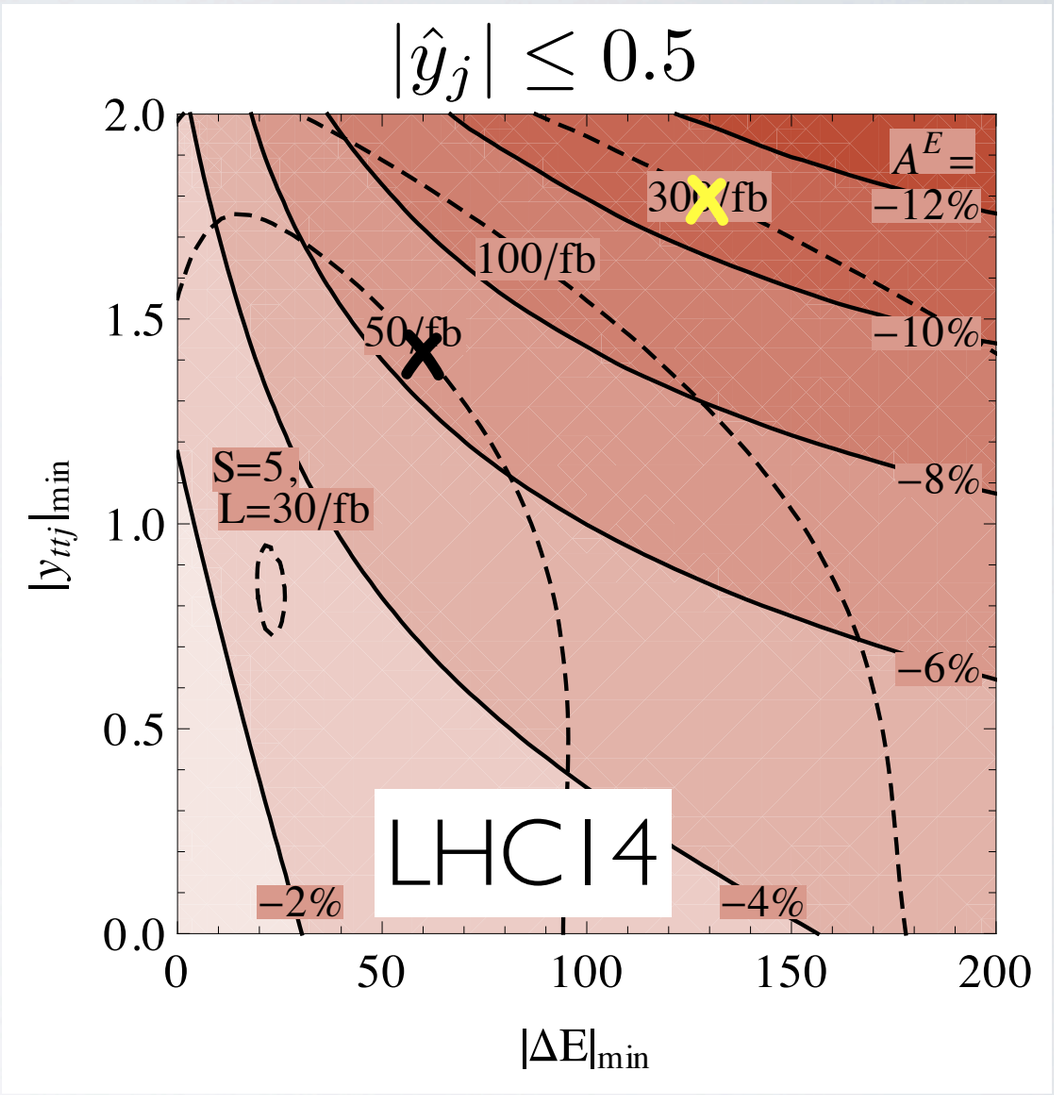
$A^E = -1.9\,\%$
$\sigma_S = 26\,\mathrm{pb}$
$\mathcal{S}(22/\mathrm{fb}) = 3.3$

✖ „A=-5%“

$A^E = -5\,\%$
$\sigma_S = 2.3\,\mathrm{pb}$
$\mathcal{S}(22/\mathrm{fb}) = 2.5$

ENERGY ASYMMETRY AT THE LHC

Higher luminosity:
stronger cuts,
access to maximal asymmetry
of up to -12%



✖ „50/fb“

$A^E = -6.5\,\%$
$\sigma_S = 2.4\,\mathrm{pb}$
$\mathcal{S}(50/\mathrm{fb}) = 5$

✖ „300/fb“

$A^E = -11\,\%$
$\sigma_S = 0.14\,\mathrm{pb}$
$\mathcal{S}(300/\mathrm{fb}) = 5$

TAKE HOME: TOP PAIR + JET PROSPECTS

Charge asymmetry in $t\bar{t}$ + jet in QCD at LO.
Optimized observables respect jet kinematics.

Probe charge asymmetry in

- $q\bar{q}$ channel: incline asymmetry
- qg channel (new!): energy asymmetry

Observables at

- Tevatron: incline asymmetry $A^{\varphi} = -15\,\%$
- LHC8: statistical significance ~3.5 standard deviations
- LHC14: maximal incline asymmetry $A^{\varphi,q} = -5\,\%$
- maximal energy asymmetry $A^{E} = -12\,\%$

Caveat: NLO corrections are important!