TOP PAIRS AND A JET AT THE LHC
[CHARGE ASYMMETRY´S DISCOVERY CHANNEL]

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A MISTAKE IN THE LITERATURE?

The Economist Intelligence Unit Top 10 Most Liveable Cities in the U.S.	
1	Pittsburgh
2	Honolulu
3	Washington D.C.
4	Chicago
5	Atlanta
6	Miami
7	Detroit
8	Boston
9	Seattle
10	Minneapolis

Pittsburgh in 1913

APPARENTLY CLARIFIED

Pittsburgh in 2013

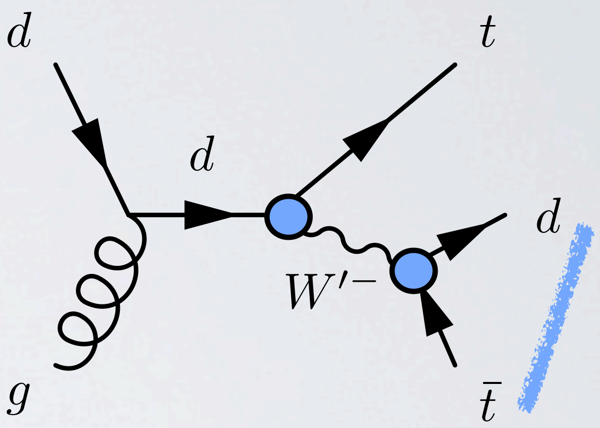
TOP PAIRS PLUS JETS AT THE LHC

Top pairs + jets as background
to signals with jets, leptons and missing energy
(e.g. Higgs and SUSY searches)

[see e.g. Rainwater & Zeppenfeld, PRD 60 (1999) 113004]

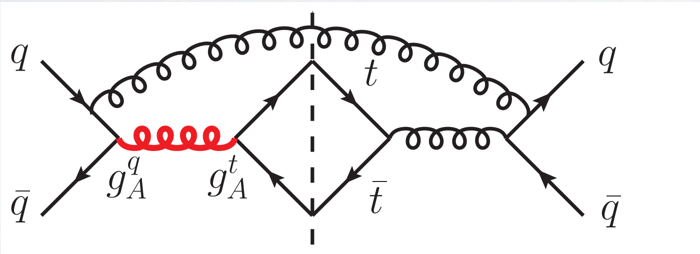
Top-jet resonances
probe new electroweak bosons (à la Z´,W´)

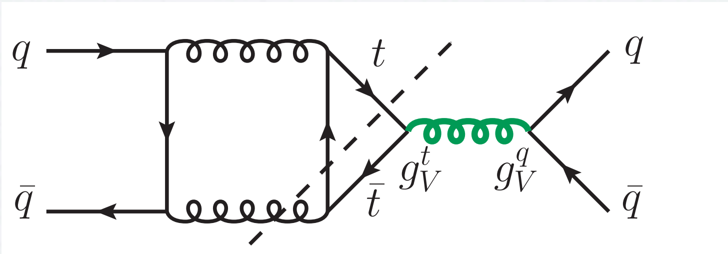
[Gresham et al., PRD 84 (2011) 034025][Knapen, Zhao, Strassler, PRD 86, 014013 (2012)]



[CMS, Phys. Lett. B717, 351 (2012)]
[ATLAS-CONF-2012-096]

Charge asymmetry in top pair + jet production
probe new massive color octets (e.g. axigluons, colorons)





[Ferrario & Rodrigo, JHEP 1002 (2010) 051]
[Berge & Westhoff, PRD 86 (2012) 094036]

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

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

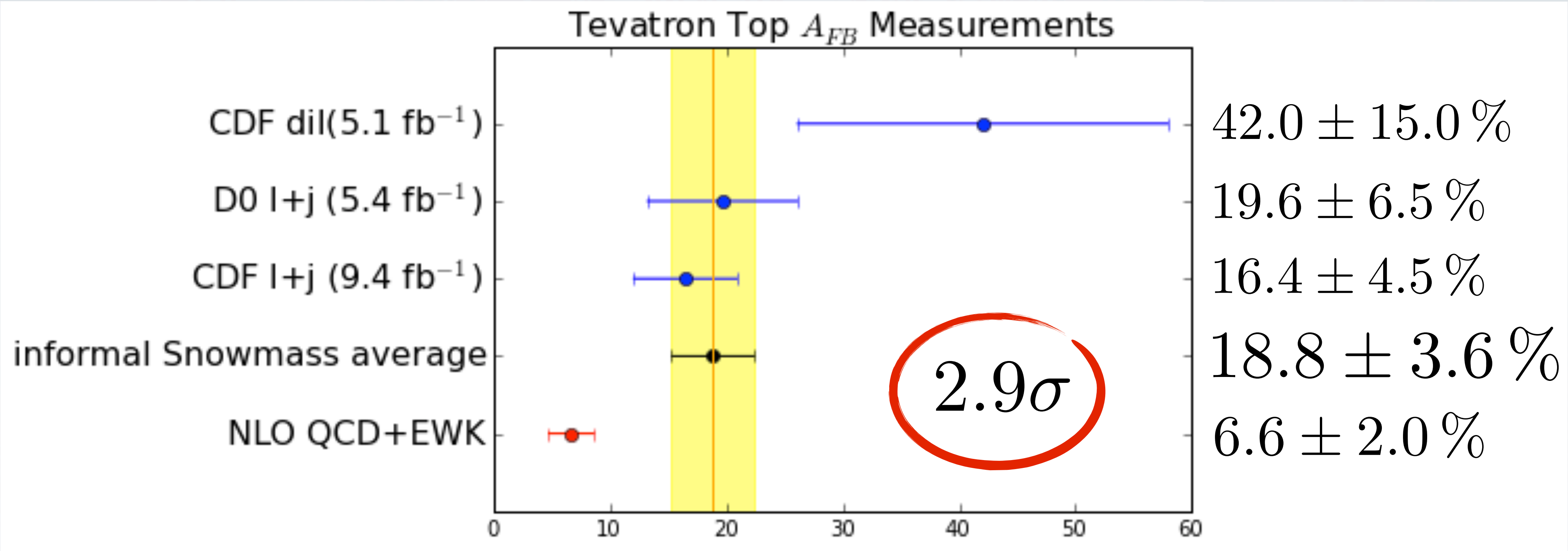
[ATLAS-CONF-2012-083, $\sqrt{s} = 7\,\mathrm{TeV},\ p_T^j > 25\,\mathrm{GeV},\ \ell j,\ \mathcal{L} = 4.7/\mathrm{fb}$] [s. also CMS-PAS-TOP-12-018]

Sizeable fraction of tt̲ production with at least one hard jet:

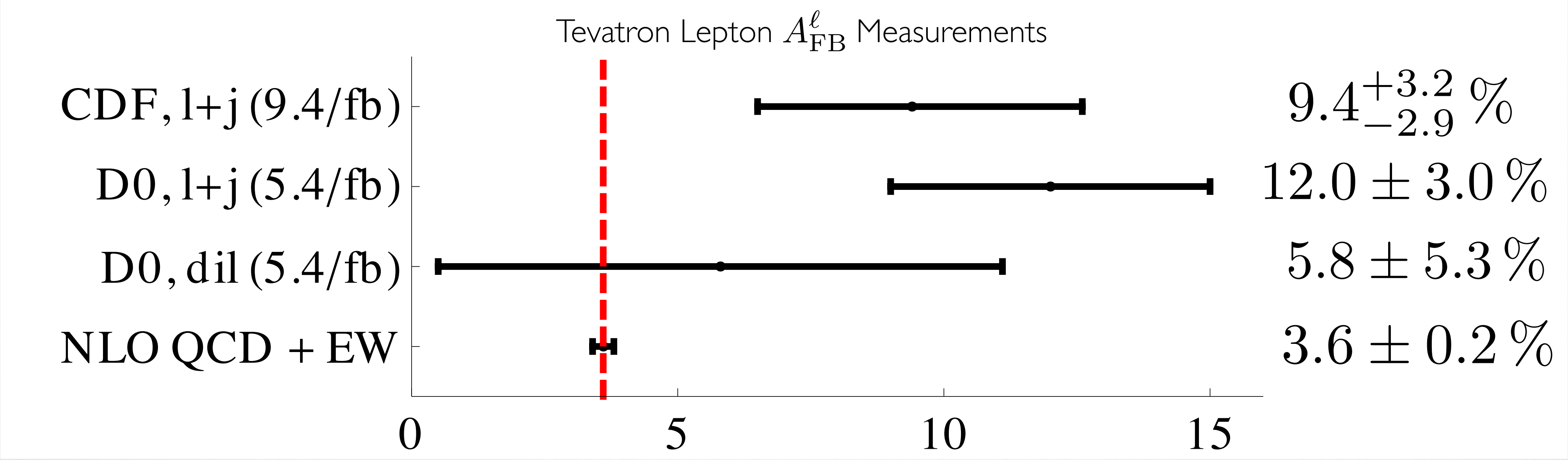
$$\sigma_{t\bar{t}j}/\sigma_{t\bar{t}} = 0.54 \pm 0.01^{+0.05}_{-0.08}$$

CHARGE ASYMMETRY EXCESSES AT TEVATRON

Top forward-backward asymmetry A^t_{FB}



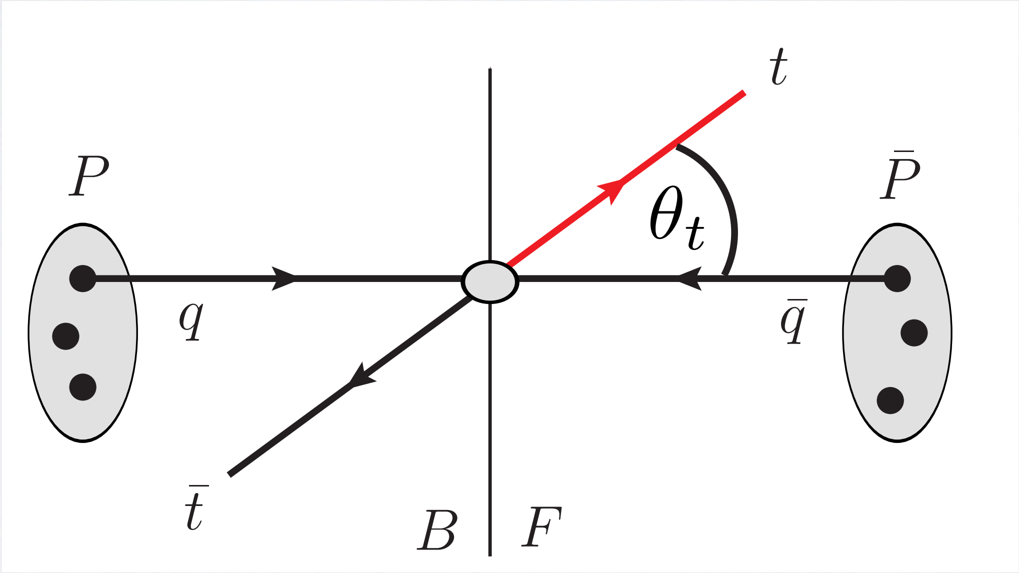
Lepton asymmetry A^ℓ_{FB} (no top reconstruction)



CHARGE ASYMMETRY DEFINITIONS

Probe charge asymmetry through angular correlations:

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



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

Tevatron: forward-backward

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

LHC: beamward-central

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

CHARGE ASYMMETRY APPROACHES AT LHC

No observable deviations from SM $A_C^{\rm LHC7} = 1.15 \pm 0.06\,\%\,.$

[Kühn, Rodrigo, JHEP 1201 (2012) 063]

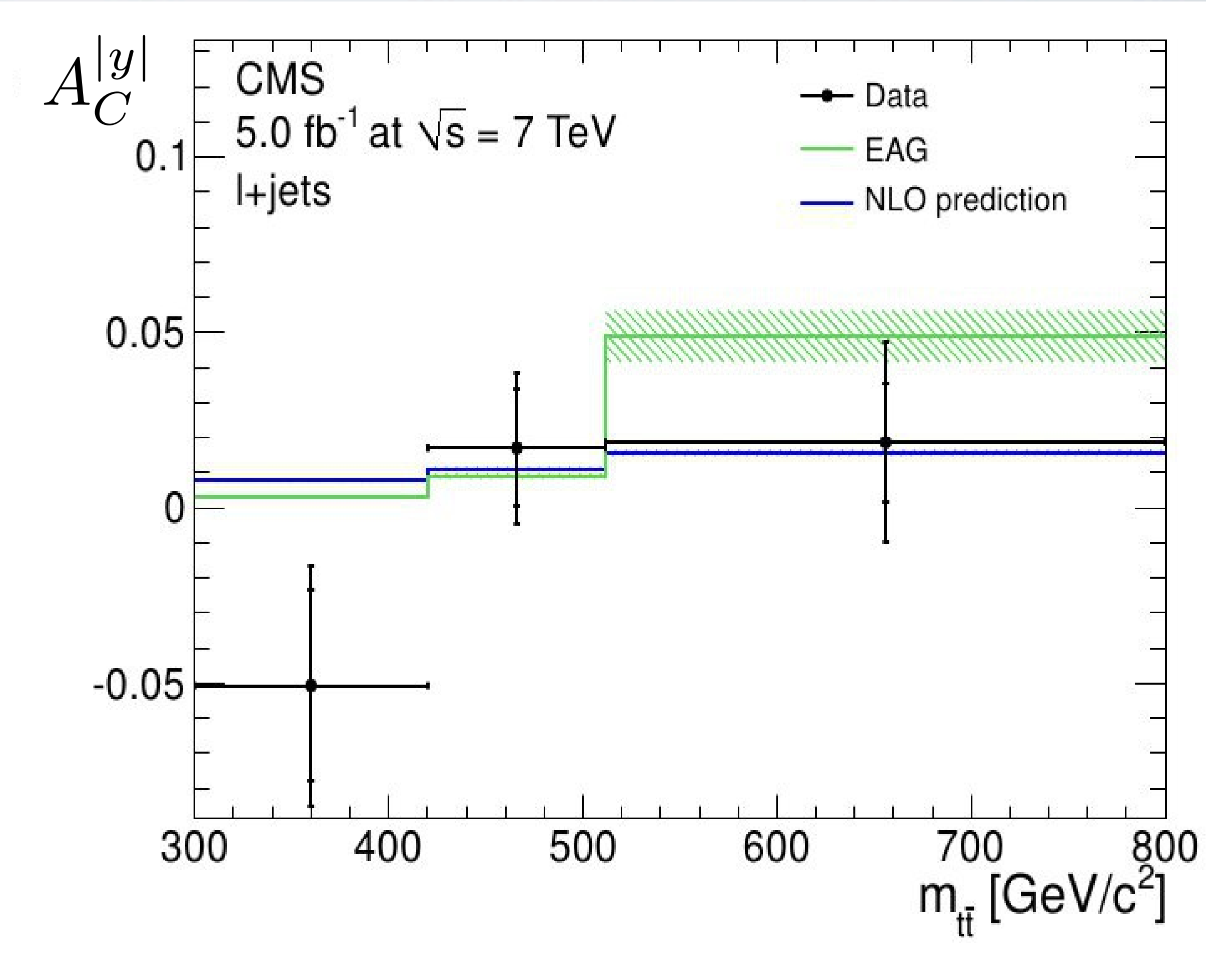
<u>Lepton+jets</u>

CMS: $A_C^{|y|} = 0.4 \pm 1.0 \pm 1.1\,\%$

[CMS, arXiv:1207.0065]

ATLAS: $A_C^{|y|} = -1.9 \pm 2.8 \pm 2.4\,\%$

[ATLAS, Eur. Phys. J. C72 (2012) 2039]



<u>Dilepton</u>

CMS: $A_C^{|y|} = 5.0 \pm 4.3^{+1.0}_{-3.9}\,\%$

[CMS-PAS-TOP-12-010]

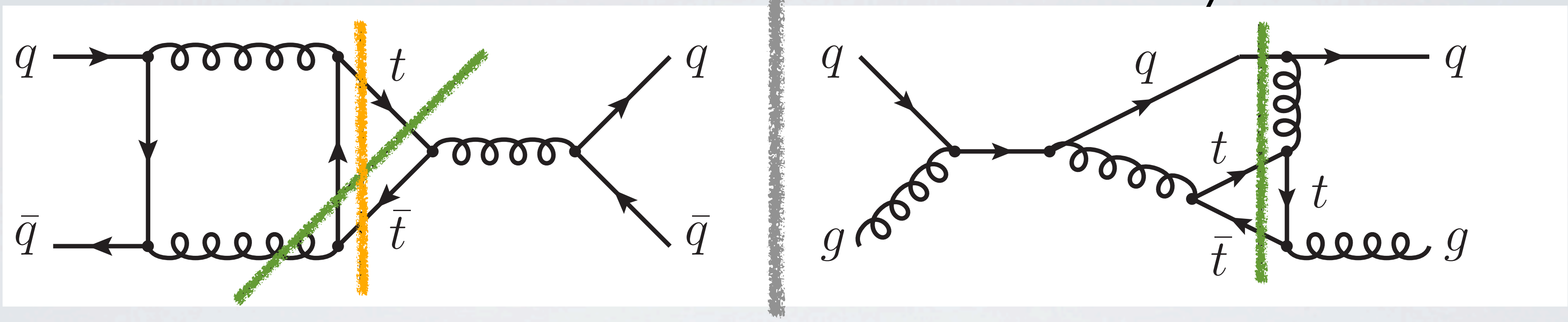
ATLAS: $A_C^{|y|} = 5.7 \pm 2.4 \pm 1.5\,\%$

[ATLAS-CONF-2012-057]

Hard to achieve high significance for inclusive asymmetry in SM.

RAPIDITY ASYMMETRIES IN THE SM

dominant | tiny



$t\bar{t}$ inclusive

LO: no asymmetry

NLO: virtual + real

Tevatron

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

[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

NLO: virtual + real

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

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

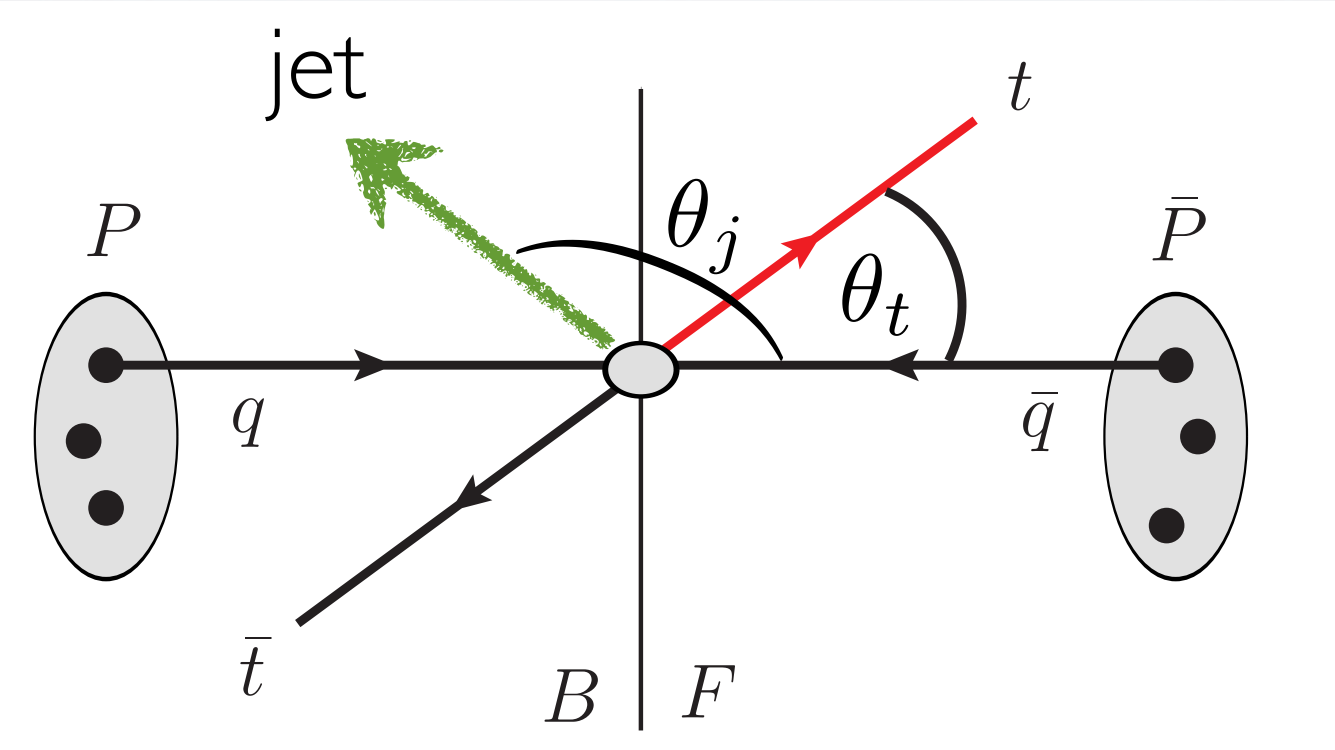
[Alioli, Moch, Uwer, JHEP 1201 (2012) 137, pTj > 20 GeV]

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

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

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

JET HANDLE IN TOP PAIR PRODUCTION



Cross section divergent in soft and collinear limit:

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

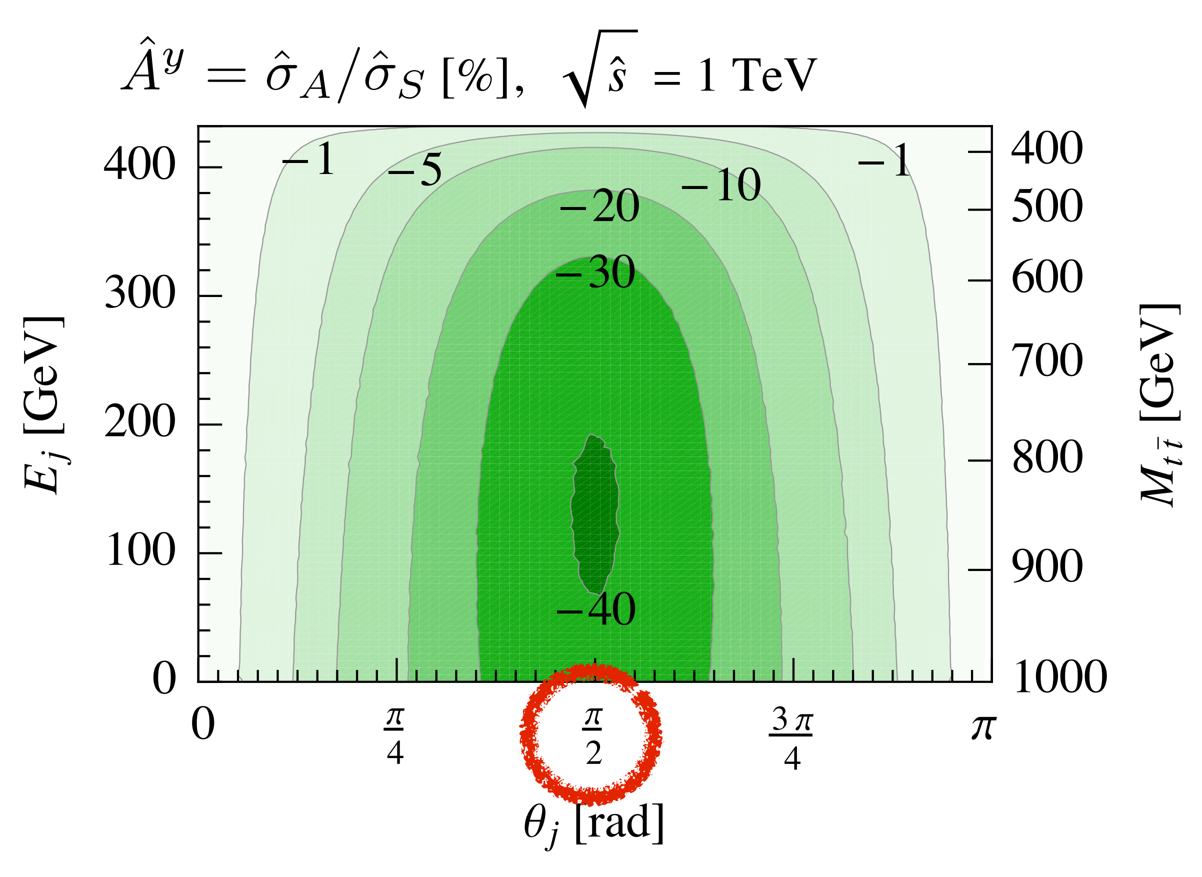
Cut on jet transverse momentum defines hard jet:

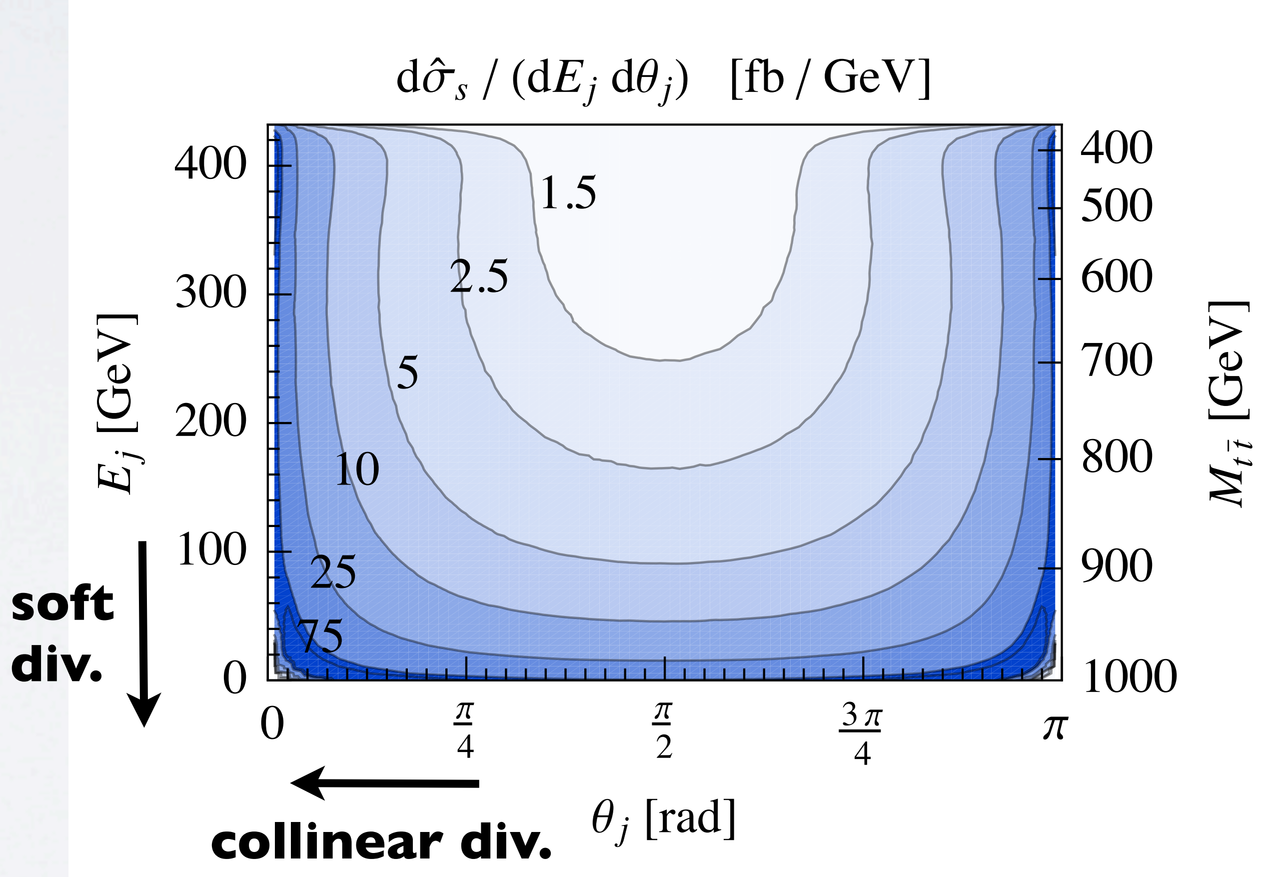
$p_T^j \geq 20 - 30\,\mathrm{GeV}$ (also required for experimental reasons)

JET KINEMATICS MATTER

Partonic channel $q\bar{q} \to t\bar{t}g$, 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, $\theta_j = \pi/2$.

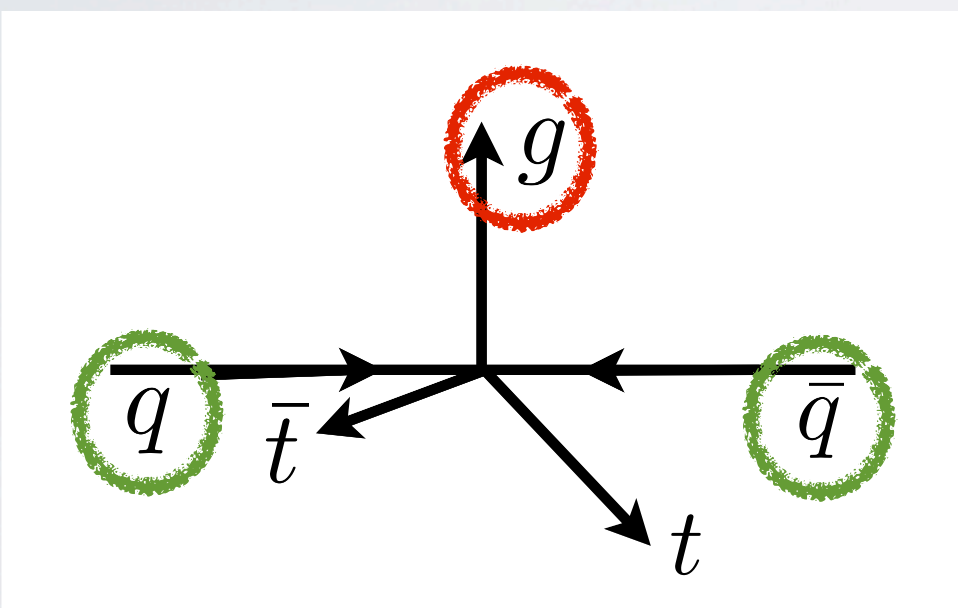
NEW OBSERVABLES

[Berge, Westhoff, 1305.3272 (accepted by JHEP)]

Based on
final-state kinematics:

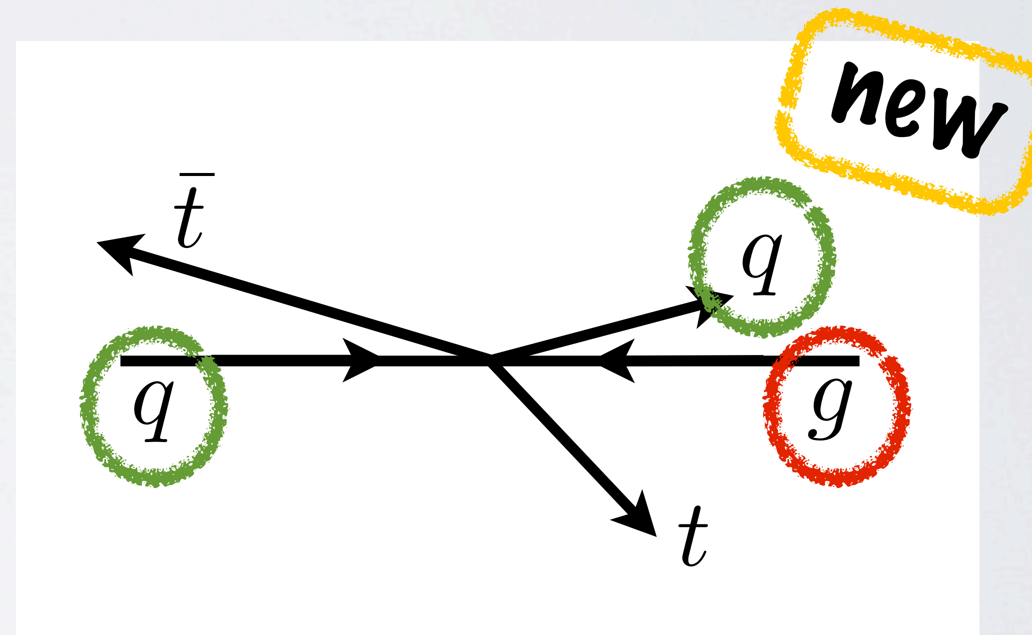
$$\vec{k}_t + \vec{k}_{\bar{t}} + \vec{k}_j = 0$$
$$E_t + E_{\bar{t}} + E_j = \sqrt{s}$$

$q\bar{q}$ channel:



jet distribution **symmetric**

qg channel:

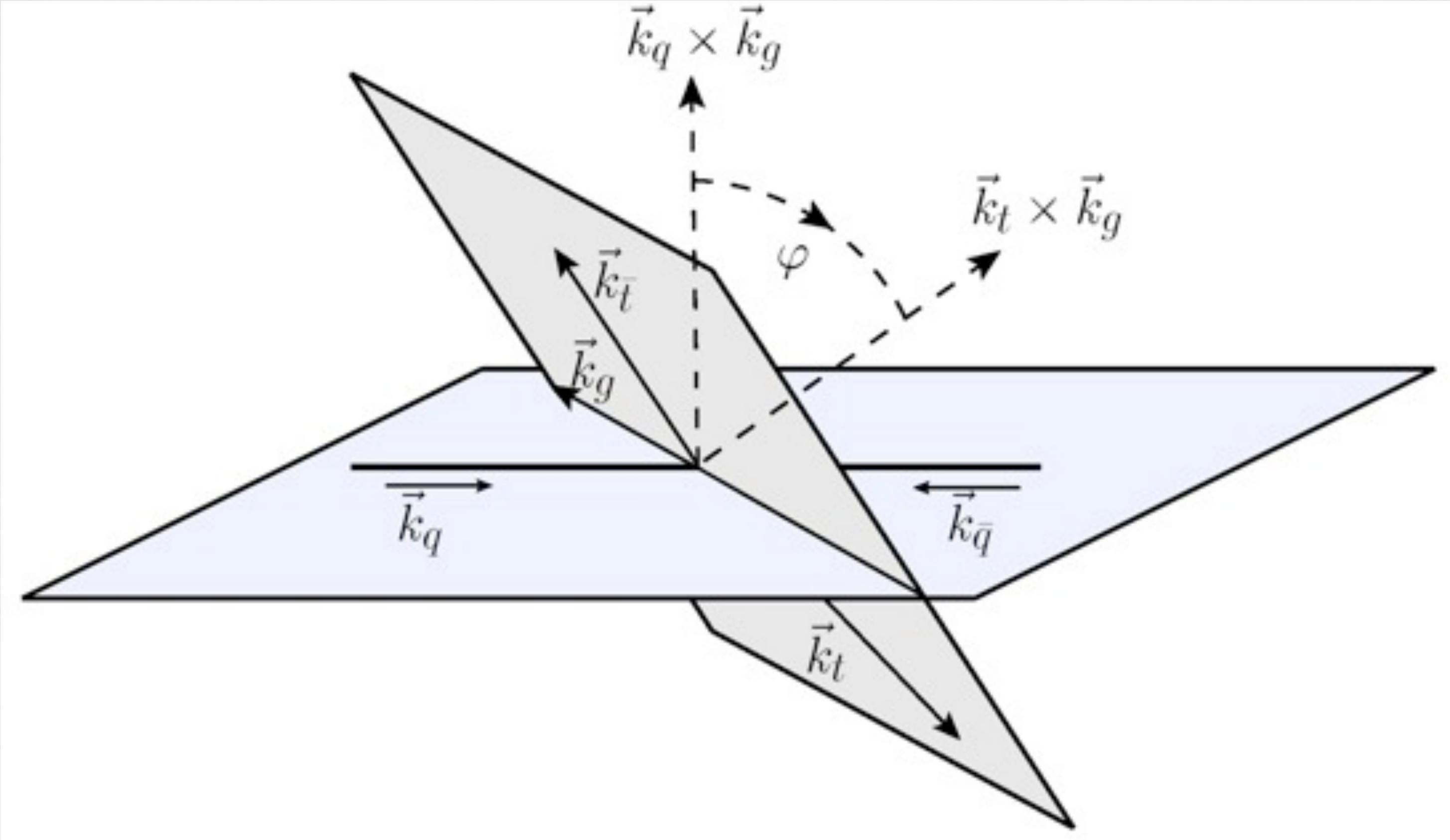


jet distribution **asymmetric**

QQ CHANNEL: COMPLEMENTARY ASYMMETRIES

Fully differential charge asymmetry

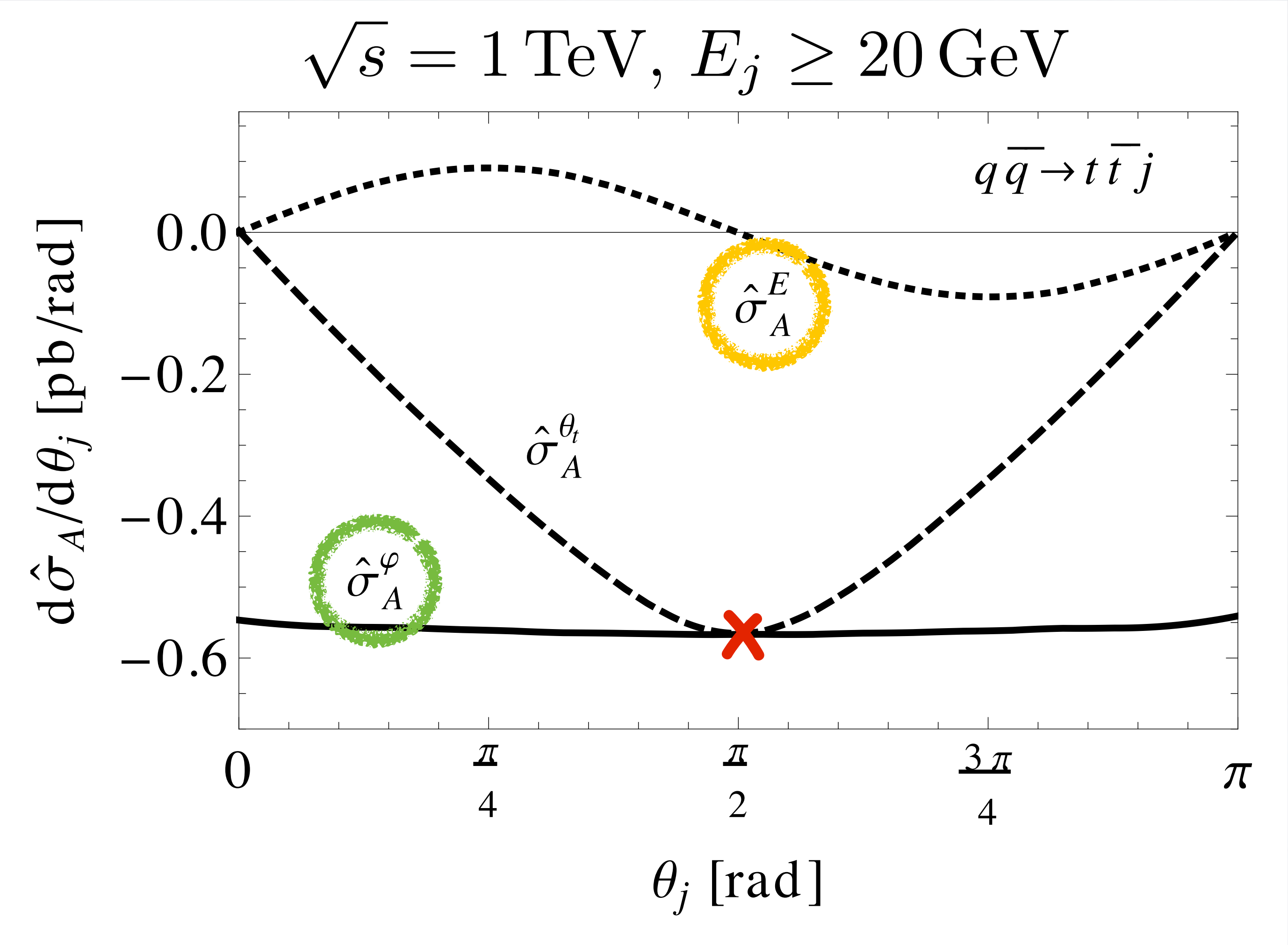
$$\mathrm{d}\hat{\sigma}_A(q\bar{q} \to t\bar{t}j) = \left[\mathrm{d}\hat{\sigma}(t\bar{t}) - \mathrm{d}\hat{\sigma}(\bar{t}t)\right](\theta_j, E_j, \varphi, \Delta E), \quad \Delta E = E_t - E_{\bar{t}}$$



Incline asymmetry
$$\frac{\mathrm{d}\hat{\sigma}_A^{\varphi}}{\mathrm{d}\theta_j} = \frac{\mathrm{d}\hat{\sigma}(\cos\varphi > 0)}{\mathrm{d}\theta_j} - \frac{\mathrm{d}\hat{\sigma}(\cos\varphi < 0)}{\mathrm{d}\theta_j}$$

Energy asymmetry
$$\frac{\mathrm{d}\hat{\sigma}_A^{E}}{\mathrm{d}\theta_j} = \frac{\mathrm{d}\hat{\sigma}(\Delta E > 0)}{\mathrm{d}\theta_j} - \frac{\mathrm{d}\hat{\sigma}(\Delta E < 0)}{\mathrm{d}\theta_j}$$

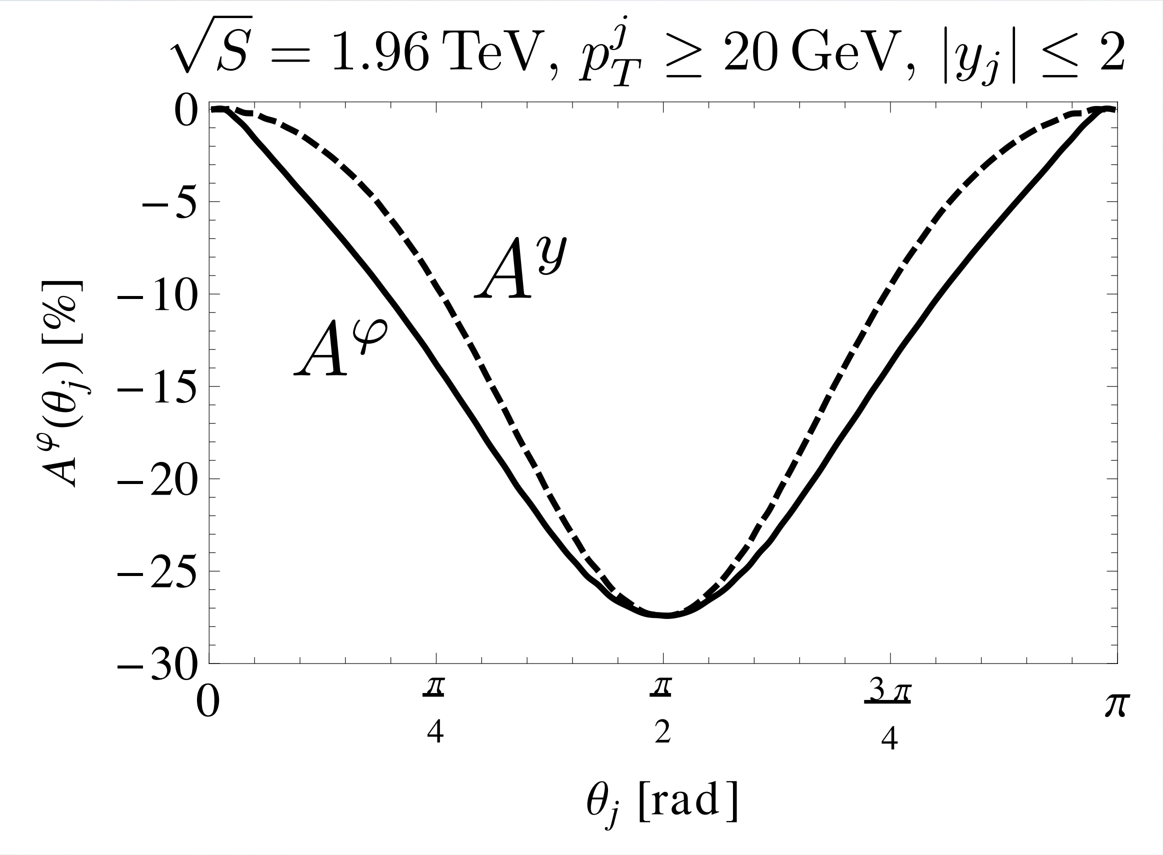
$Q\underline{Q}$: ASYMMETRIES AT PARTON LEVEL

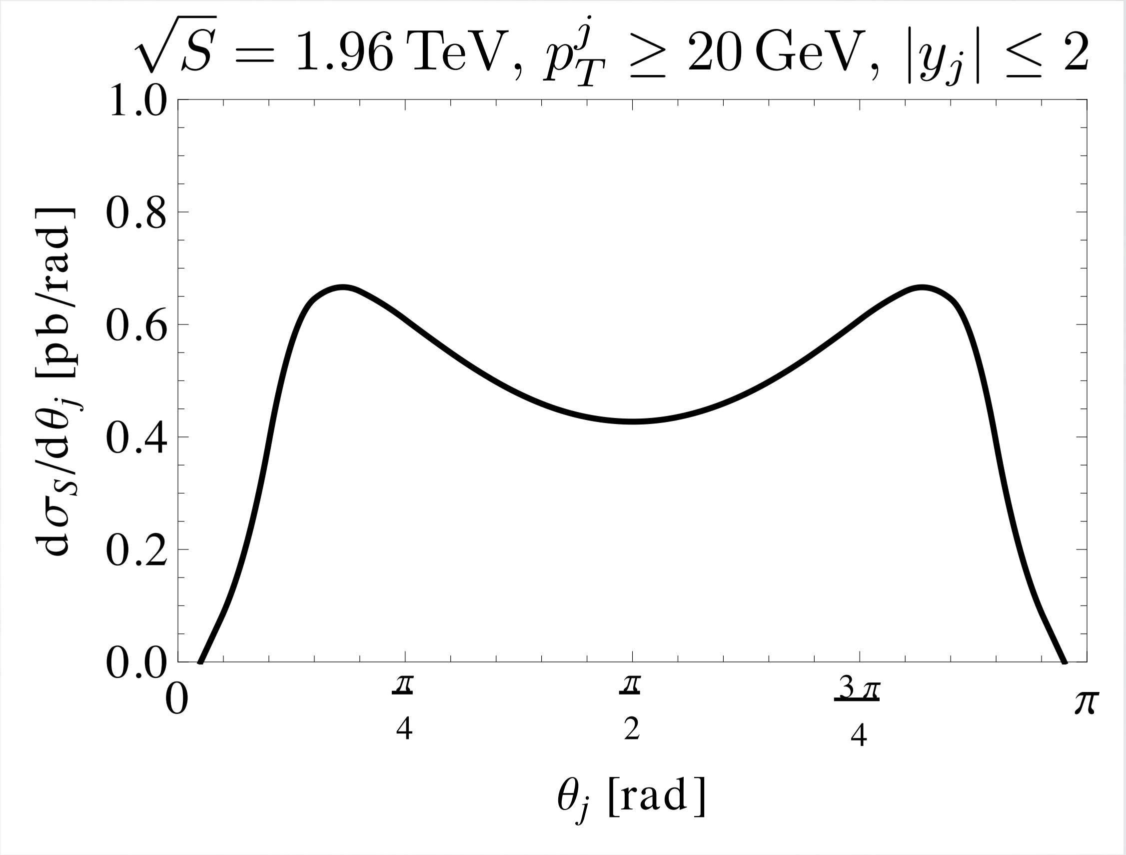


- $\hat{\sigma}_A^{\varphi}$ Incline asymmetry is largely independent from jet direction
- ✗ and equals rapidity asymmetry for central jet emission.
- $\hat{\sigma}_A^{E}$ Energy asymmetry has antisymmetric jet distribution.

INCLINE ASYMMETRY AT THE TEVATRON

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





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

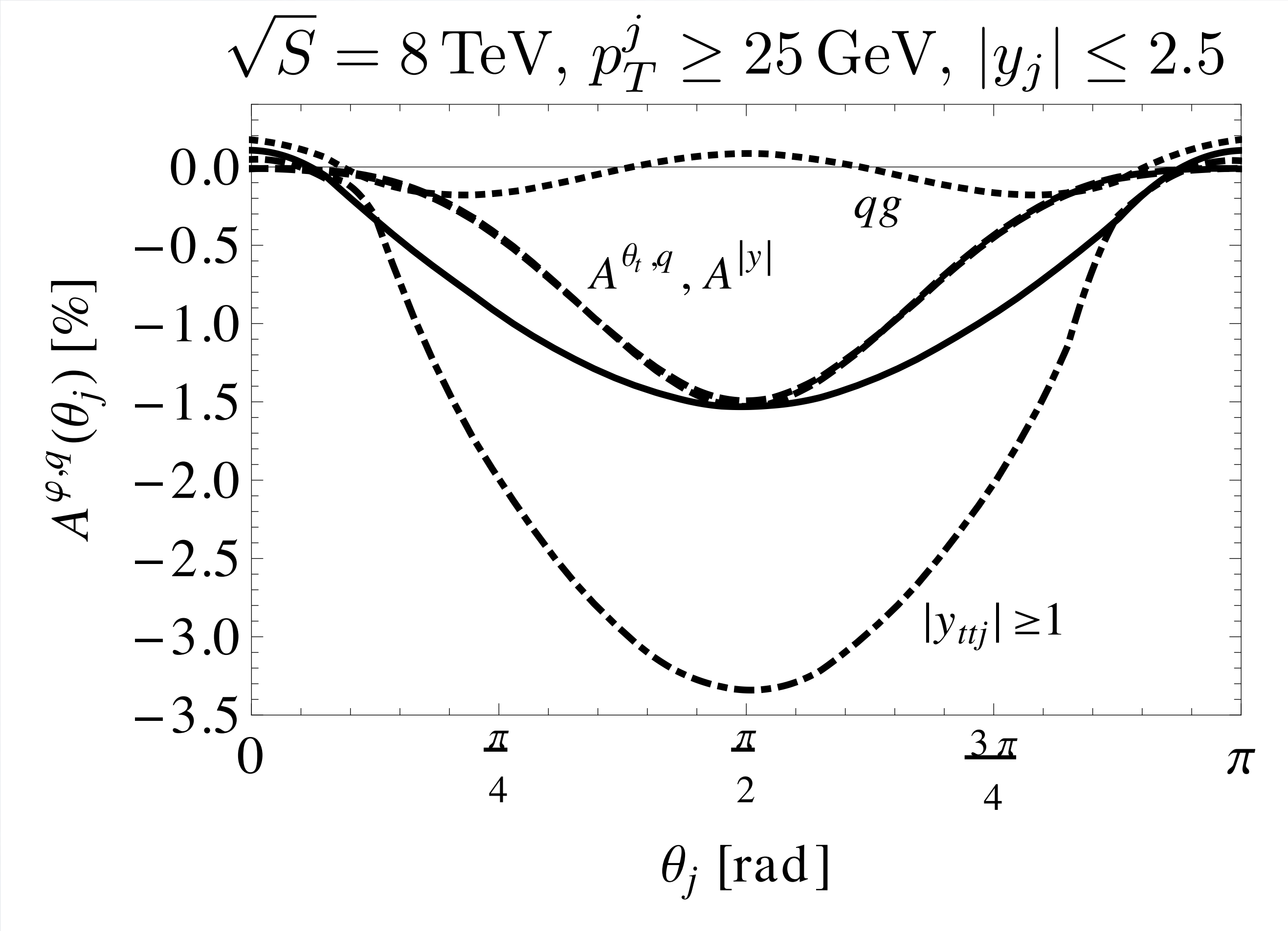
Statistical significance: $\mathcal{S}(10\,\mathrm{fb}^{-1}) = 4.2$

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

INCLINE ASYMMETRY AT THE LHC

Identify quark direction via final-state boost: $y_{t\bar{t}j} = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$

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



Total incline asymmetry:

$A^{\varphi,q} = -0.8\,\%$

Need efficient cuts.

INCLINE ASYMMETRY AT LHC8

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

<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>

x „S max.“

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

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

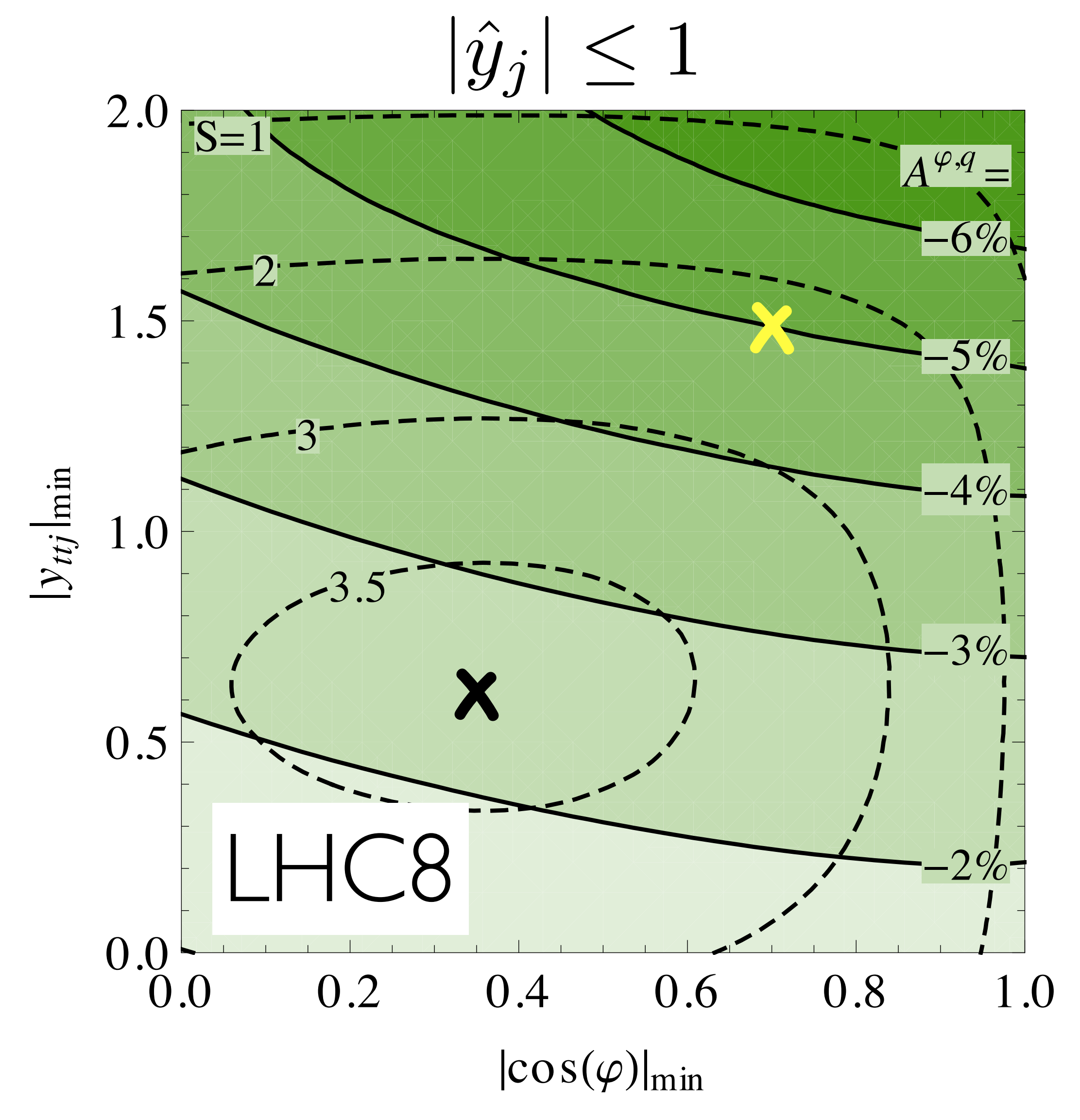
$\mathcal{S}(22/\text{fb}) = 3.6$

x „A max.“

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

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

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



INCLINE ASYMMETRY AT LHC14

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

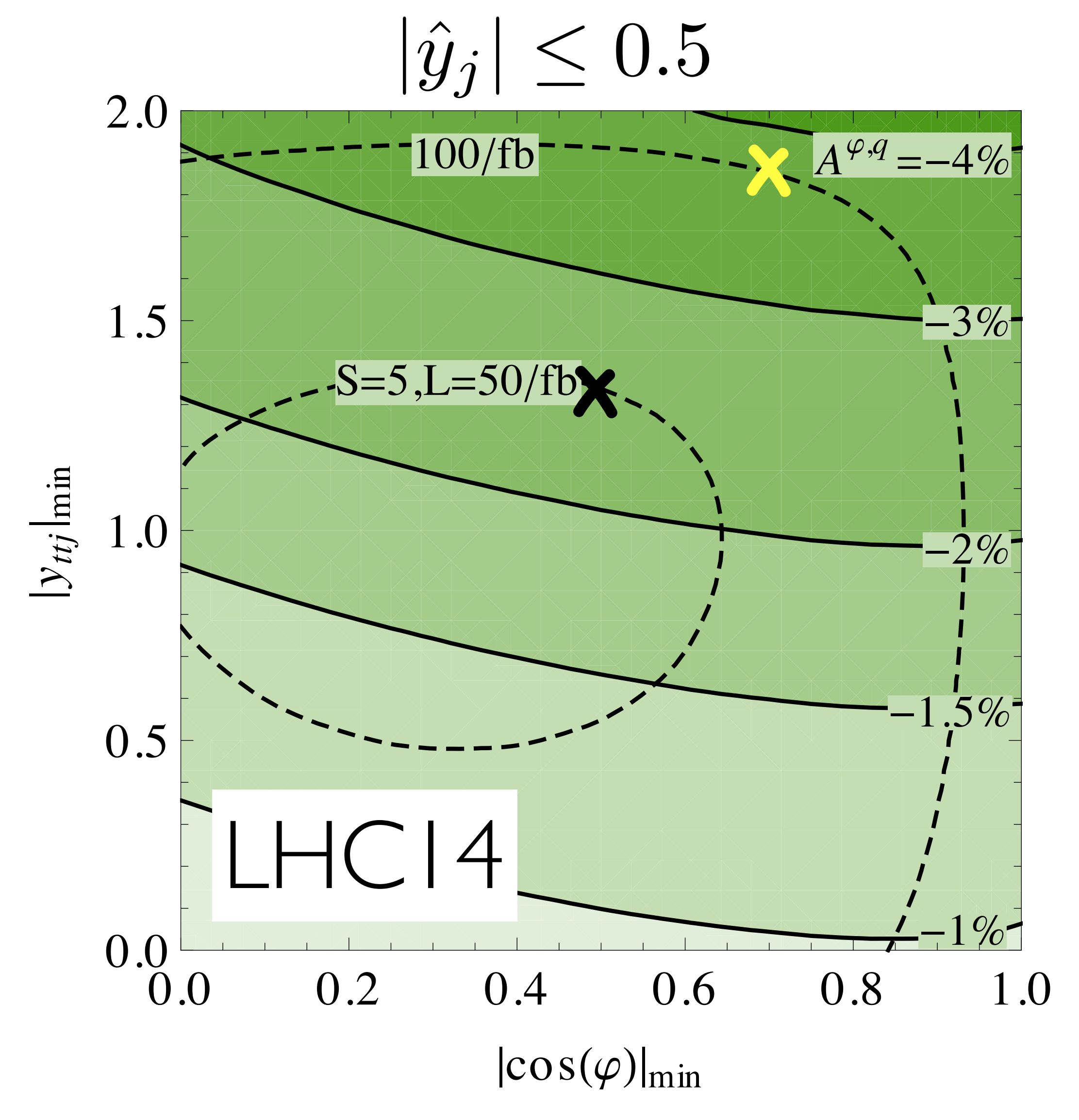
Higher luminosity:
stronger cuts,
enhanced sensitivity

✘ „50/fb“

$A^{\varphi,q} = -2.4\,\%$
$\sigma_S = 18\,\mathrm{pb}$
$\mathcal{S}(50/\mathrm{fb}) = 5$

✘ „100/fb“

$A^{\varphi,q} = -3.7\,\%$
$\sigma_S = 3.6\,\mathrm{pb}$
$\mathcal{S}(100/\mathrm{fb}) = 5$

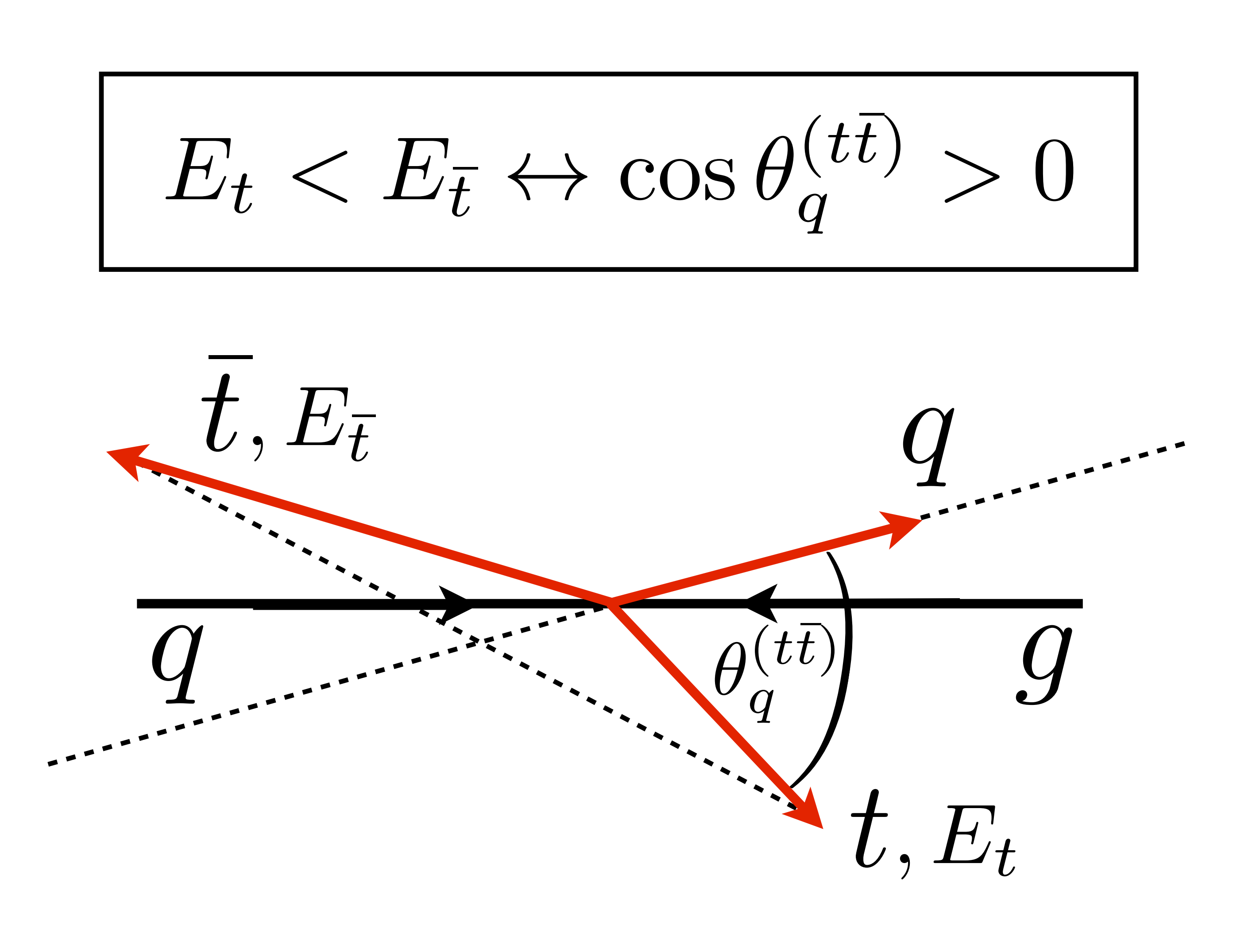


QG CHANNEL: ENERGY ASYMMETRY

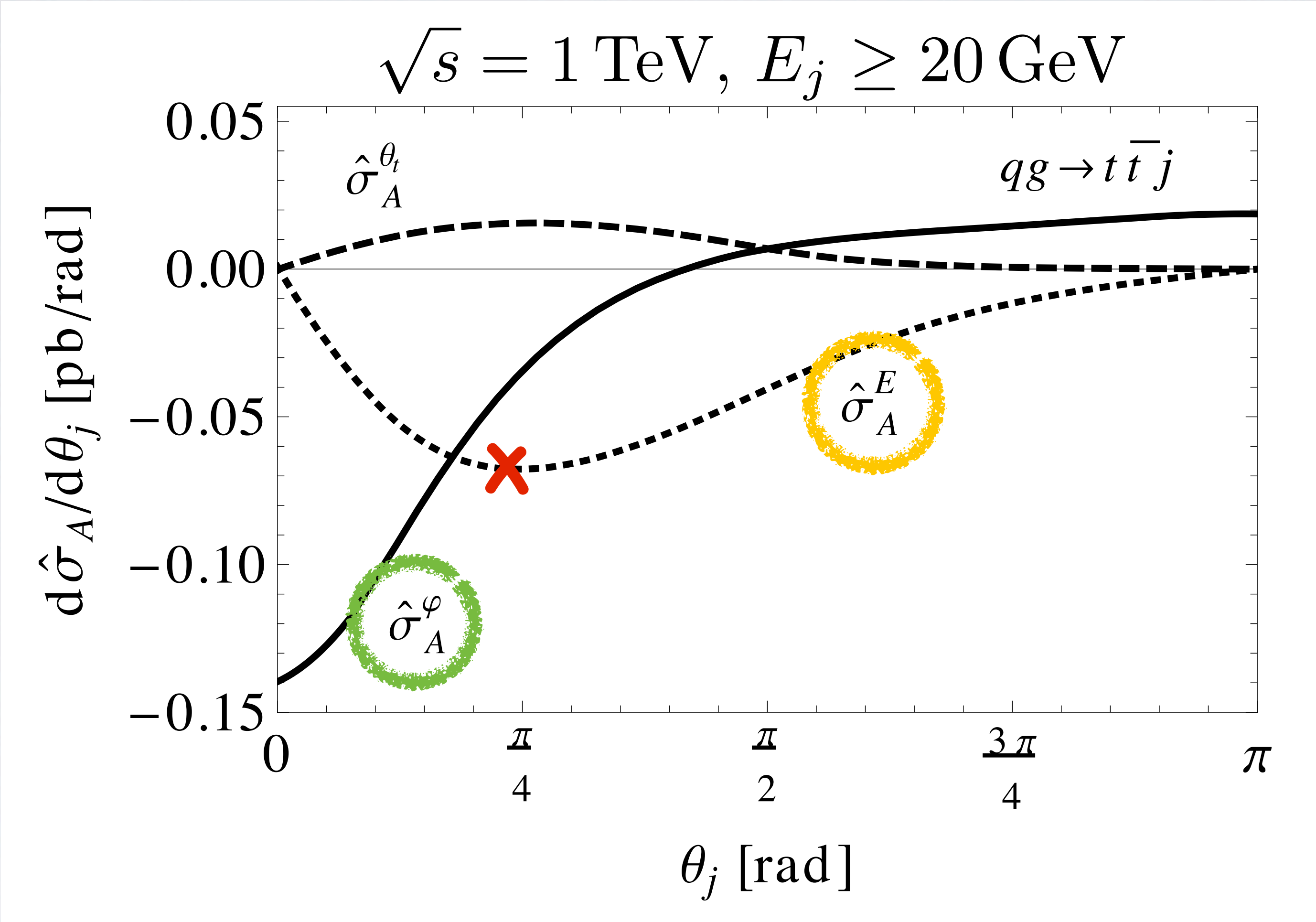
Energy asymmetry

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

~ incline asymmetry in $t\bar{t}$ frame



QG: ASYMMETRIES AT PARTON LEVEL

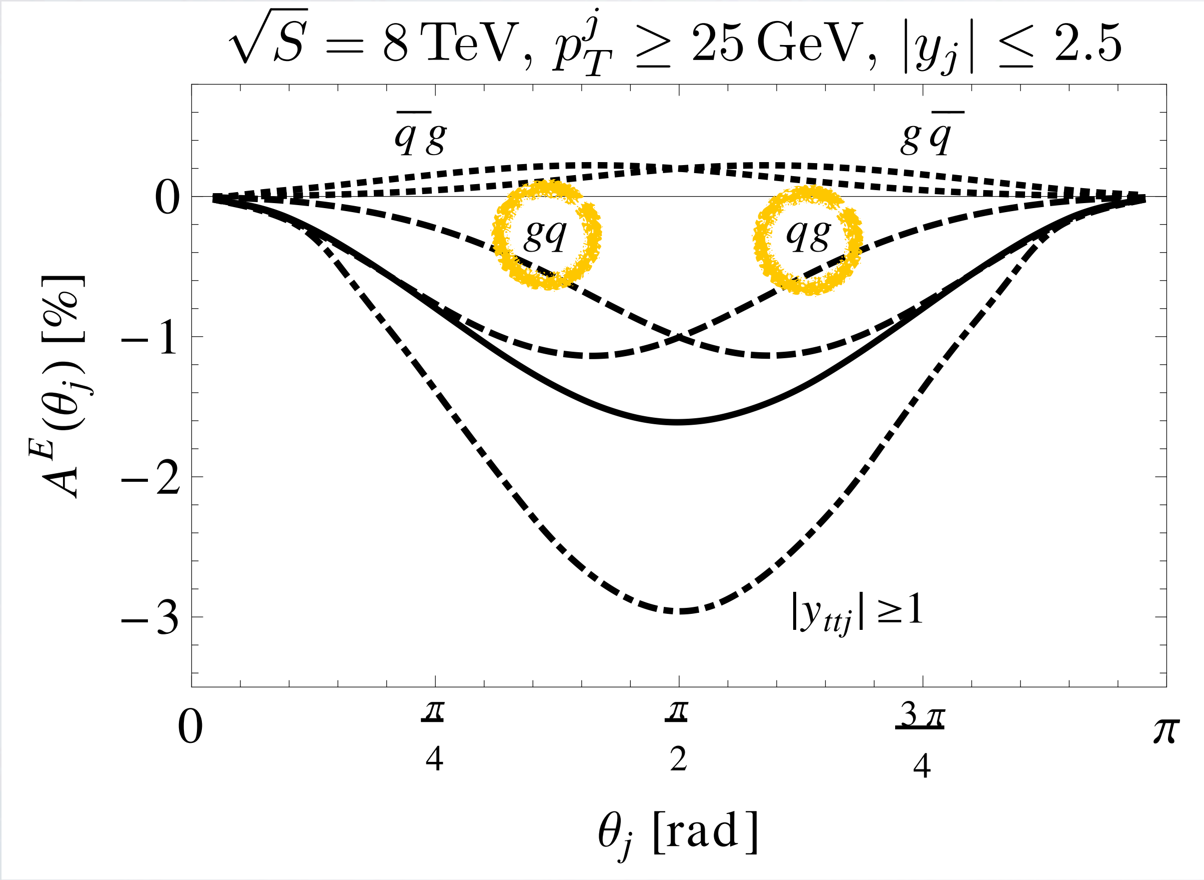


- ✗ Asymmetric jet distribution: forward jets preferred.
- $\hat{\sigma}_A^{E}$ → Energy asymmetry not symmetric in θ_j.
- $\hat{\sigma}_A^{\varphi}$ Incline asymmetry mis-defined in qg frame.

ENERGY ASYMMETRY AT THE LHC

No need to identify the quark direction!

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



Jet distribution
is symmetric (qg + gq)
and maximal in central region.

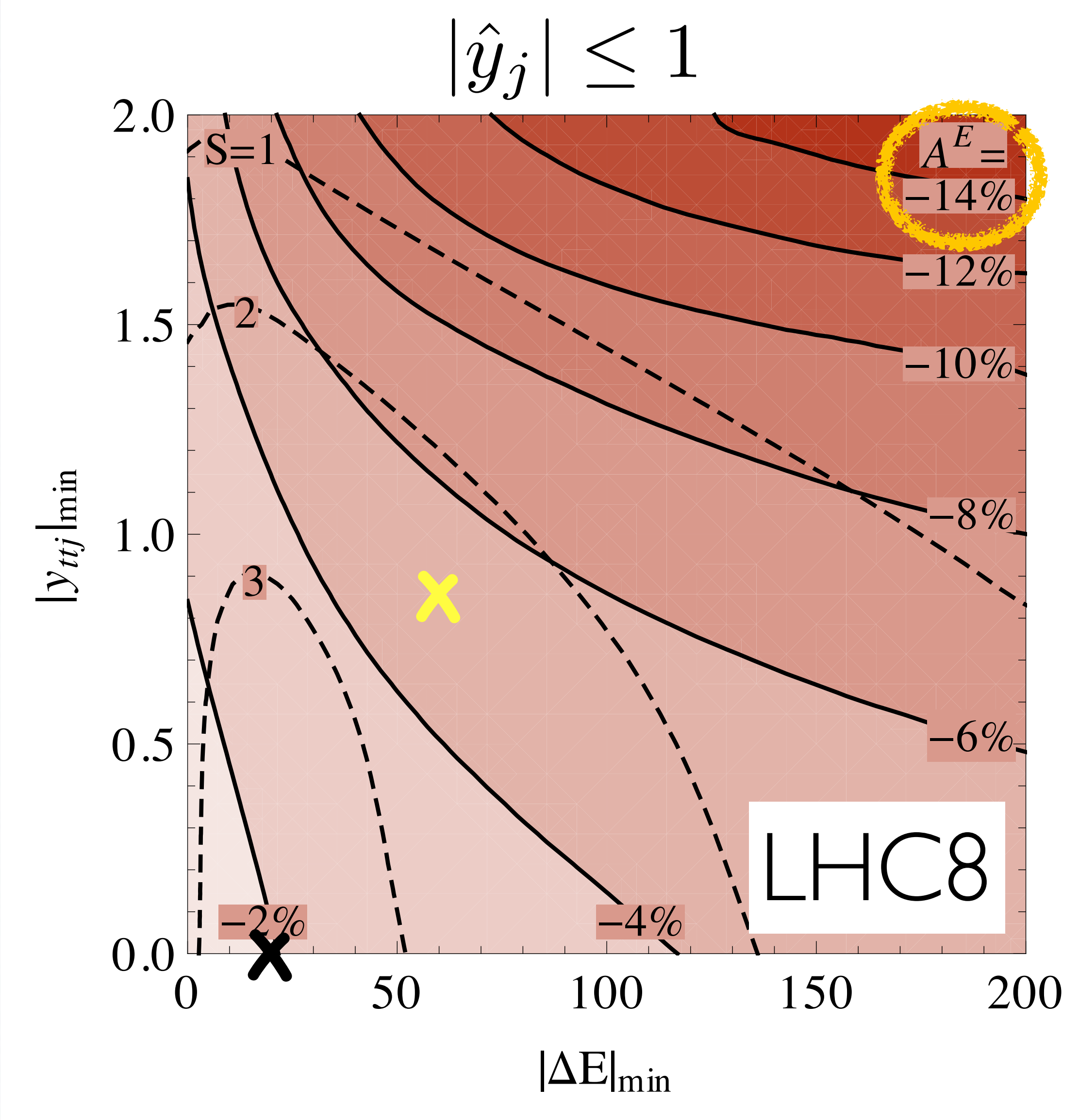
Good to avoid collinear region.

ENERGY ASYMMETRY AT LHC8

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

$\sigma(qg)/\sigma \approx 25\,\%$ $(\sigma(q\bar{q})/\sigma \approx 7\,\%)$

large maximal asymmetry, but again: statistical limitations



x „S max."

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

x „A=-5%"

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

ENERGY ASYMMETRY AT LHC14

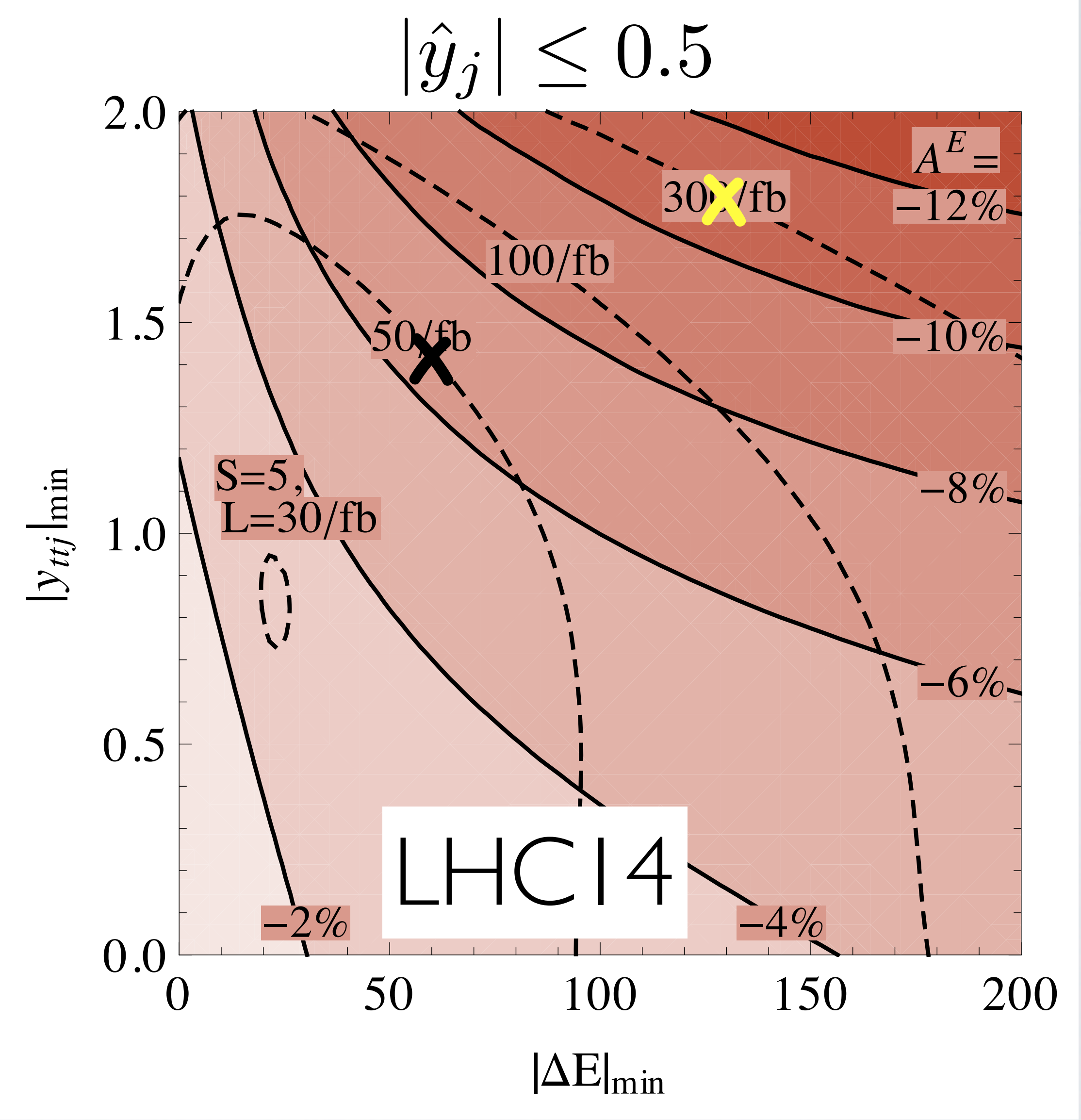
Higher luminosity:
stronger cuts,
access to maximal asymmetry
of up to -12%

x „50/fb"

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

x „300/fb"

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



Good discovery potential during first run at 14 TeV.

TAKE HOME: TOP PAIR + JET PROSPECTS

Charge asymmetry in tt̲ + jet in QCD at LO.
Optimal observables respect jet kinematics.

Probe charge asymmetry in

- qq̲ channel: incline asymmetry
- qg channel (new): energy asymmetry

Observables at

Tevatron: • incline asymmetry $A^{\varphi} = -15\,\%$, statistical limits

LHC8: •• incline & energy asymmetry, statistical limits

LHC14: • max. incline asymmetry $A^{\varphi,q} = -5\,\%$

• max. energy asymmetry $A^{E} = -12\,\%$
good discovery potential with $\mathcal{L} \gtrsim 50/\mathrm{fb}$

Caveat: NLO corrections are important.