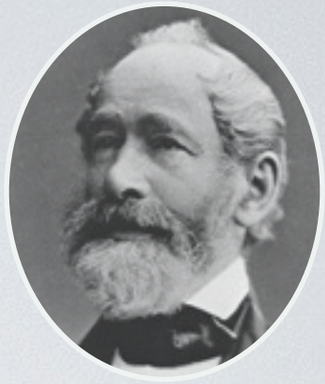
Universität Heidelberg

Carl Zeiss Stiftung



RUNNING FOR TOP CHARGE ASYMMETRY MEASUREMENTS

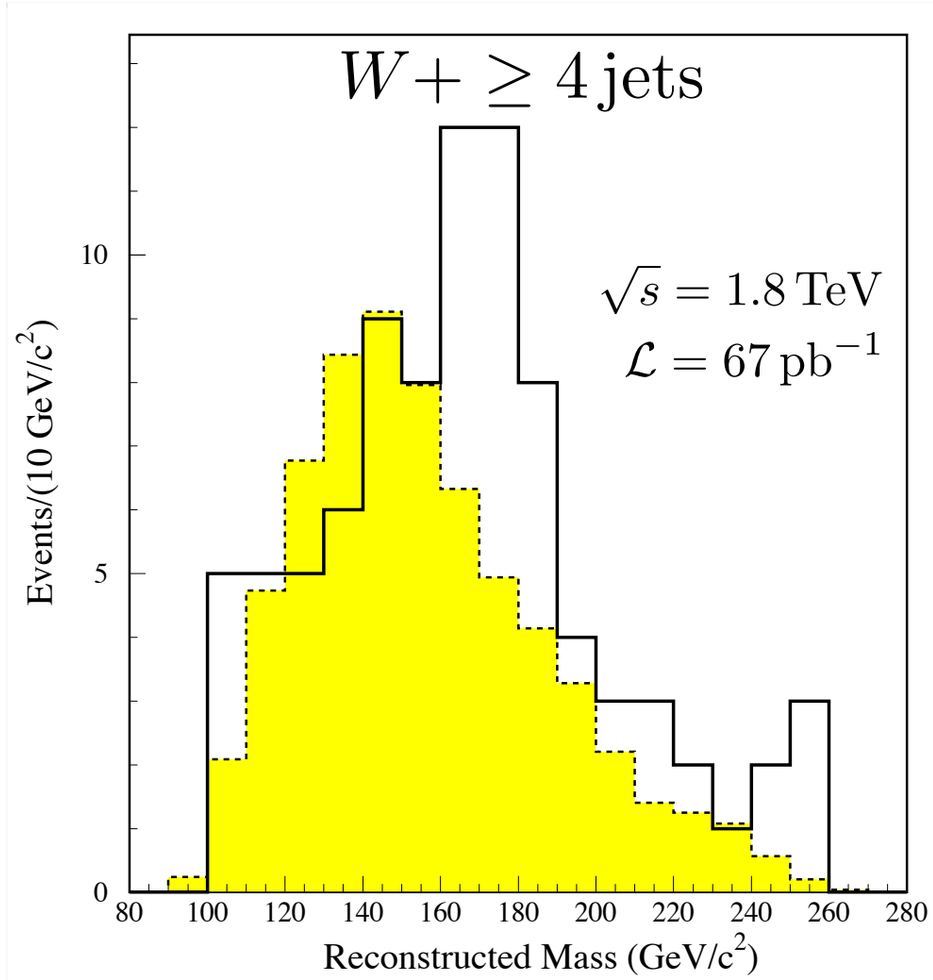
Susanne Westhoff

Seminar — January 17, 2017 — DESY Hamburg

PRECISION PHYSICS OF HEAVY QUARKS

1995

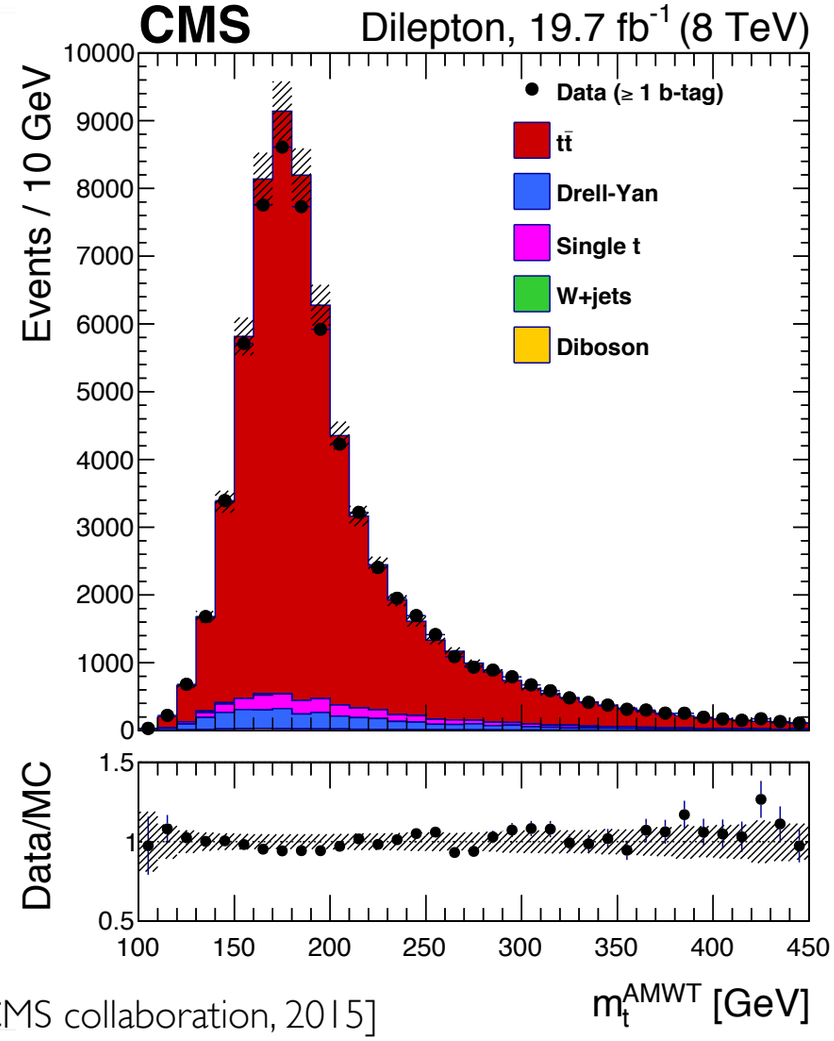
Top-quark discovery



[CDF collaboration, 1995]

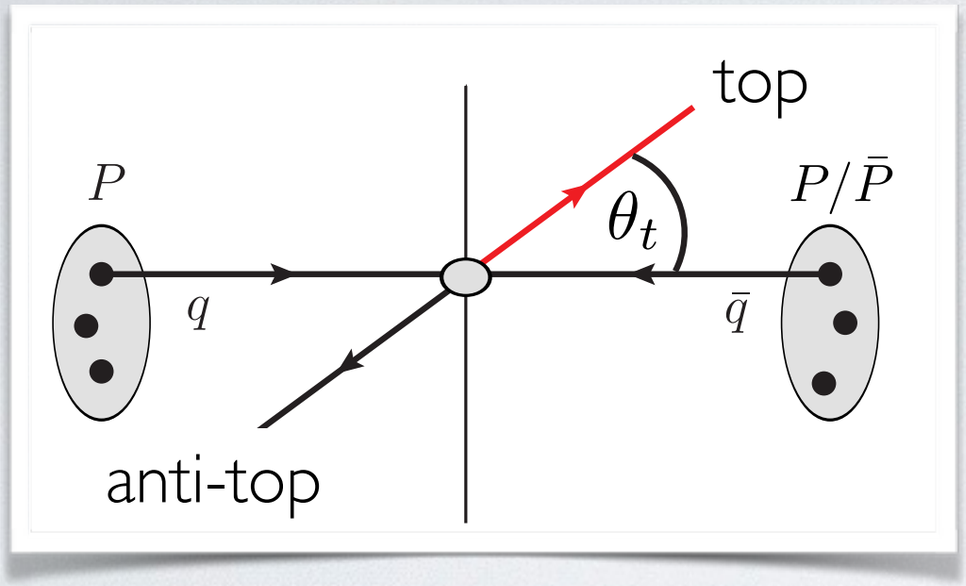
Now

A mass measurement

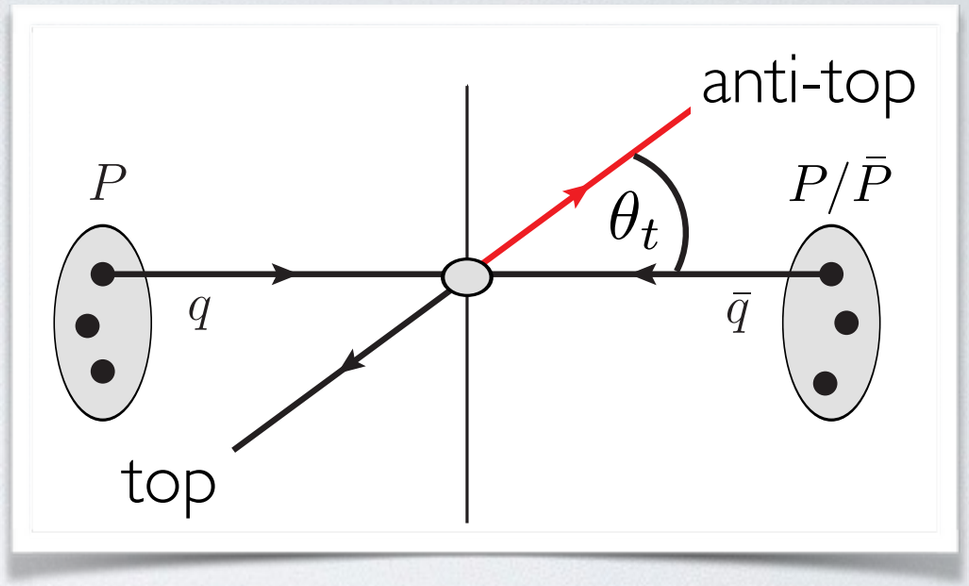


[CMS collaboration, 2015]

CHARGE ASYMMETRY FOR PEDESTRIANS

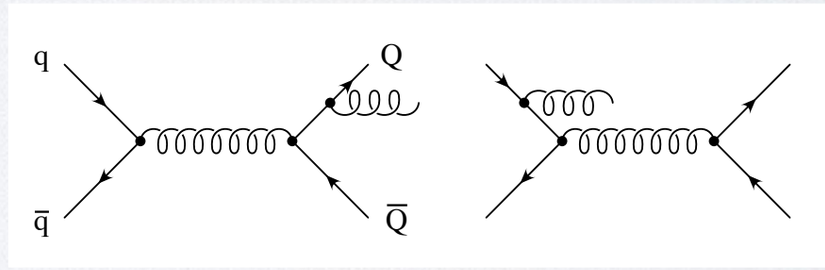


$\neq$

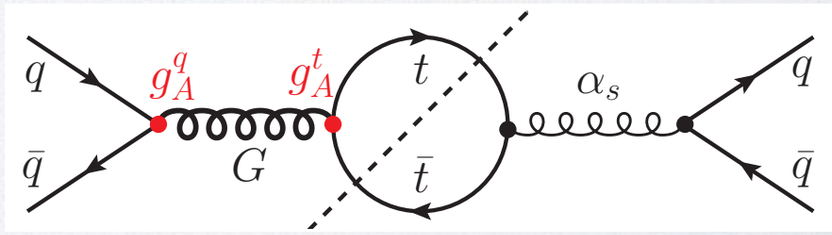


$$d\sigma_A = d\sigma_{t\bar{t}}(p_t, p_{\bar{t}}) - d\sigma_{t\bar{t}}(p_t, p_{\bar{t}})$$

Test strong interactions beyond leading order:



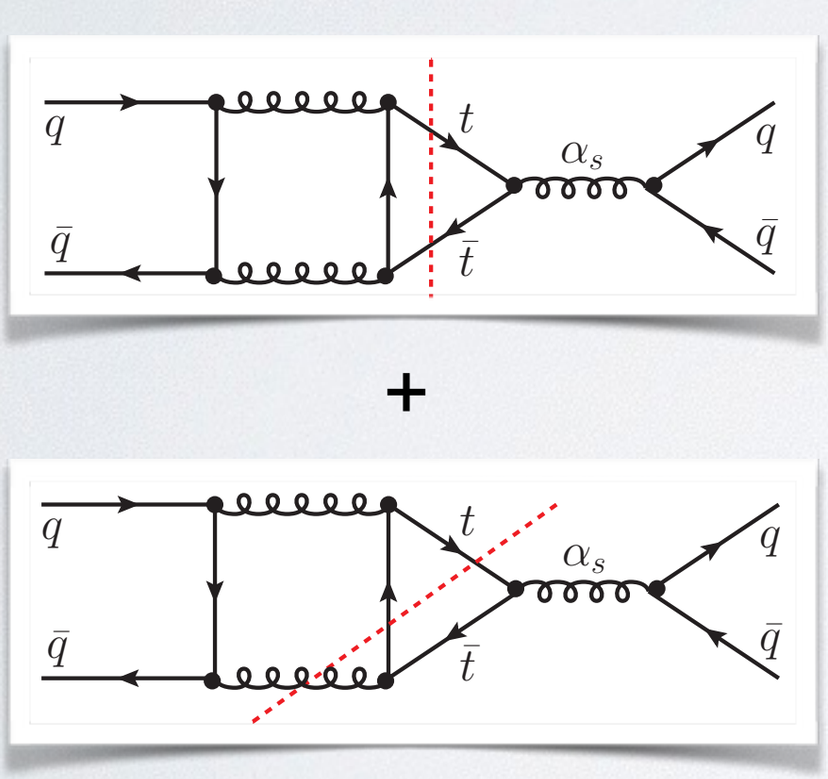
Test new interactions at leading order:

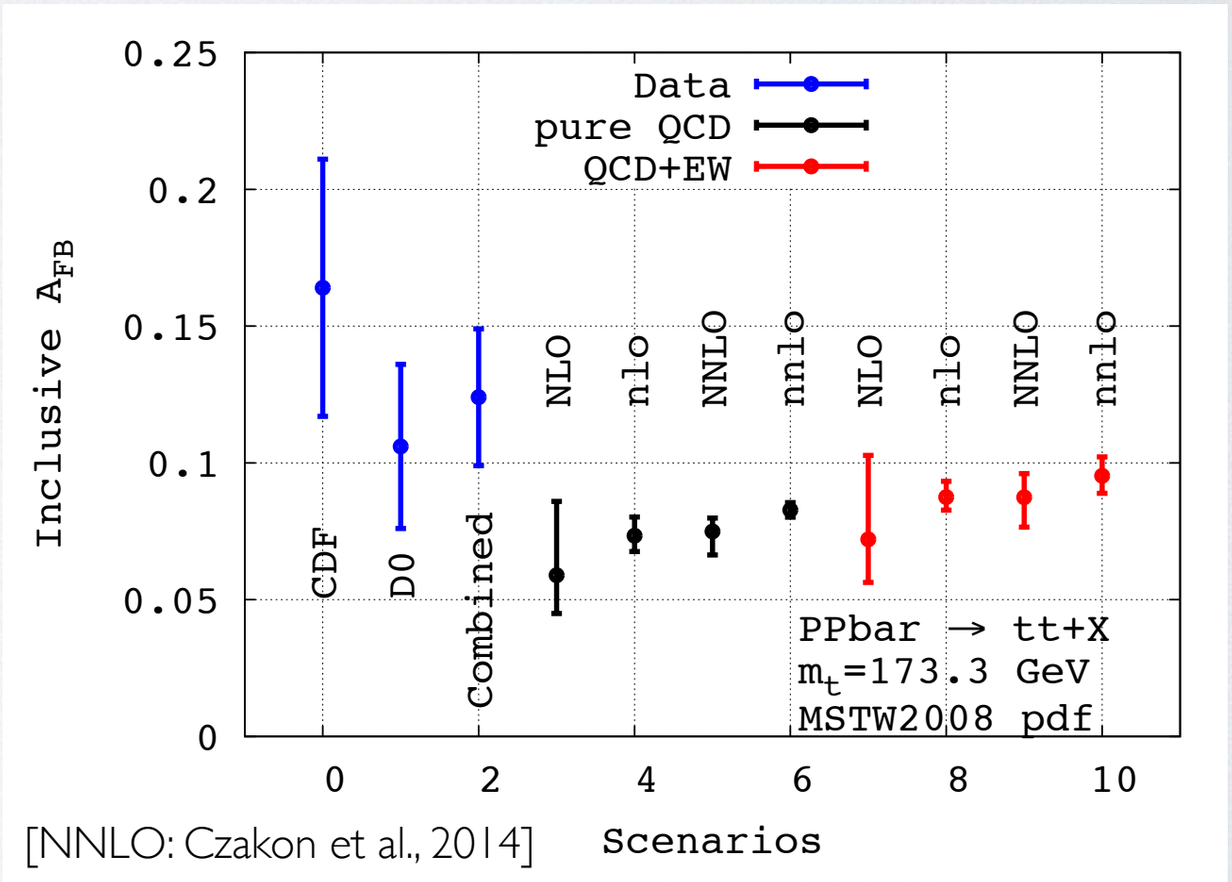


WHAT QCD PREDICTS

angular asymmetry

$$\frac{d\sigma_A}{d\cos\theta} = \frac{d\sigma_{t\bar{t}}}{d\cos\theta} - \frac{d\sigma_{\bar{t}t}}{d\cos\theta} \sim \alpha_s^3$$





[NNLO: Czakon et al., 2014]

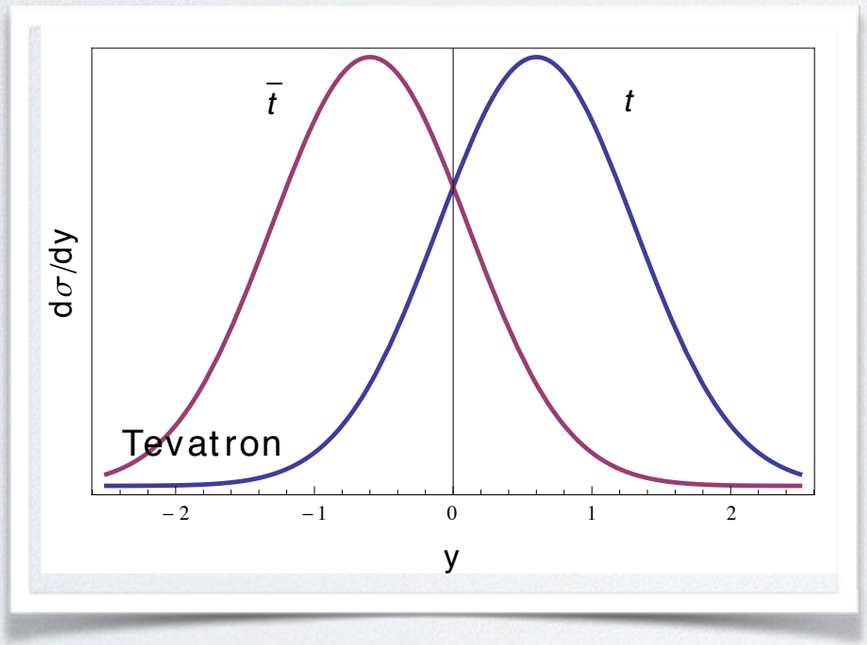
[QCD NLO: Kuehn, Rodrigo, 1999] [NLO+NNLL: Ahrens et al., 2011] [N3LL: Kidonakis, 2015] [EW: Hollik, Pagani, 2011] […]

WHAT WE OBSERVE

rapidity asymmetries

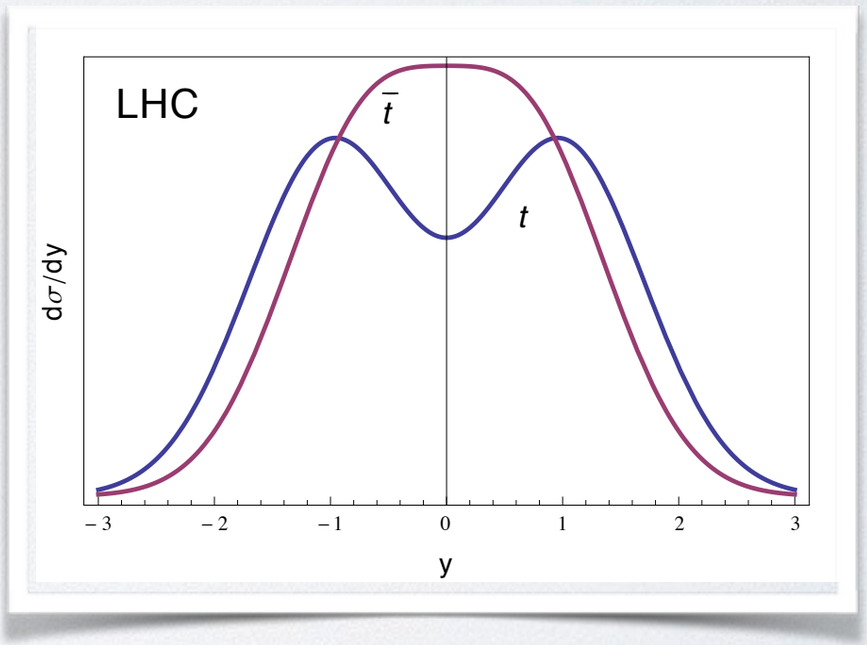
$$A_y = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

Tevatron: $\Delta y = y_t - y_{\bar{t}}$



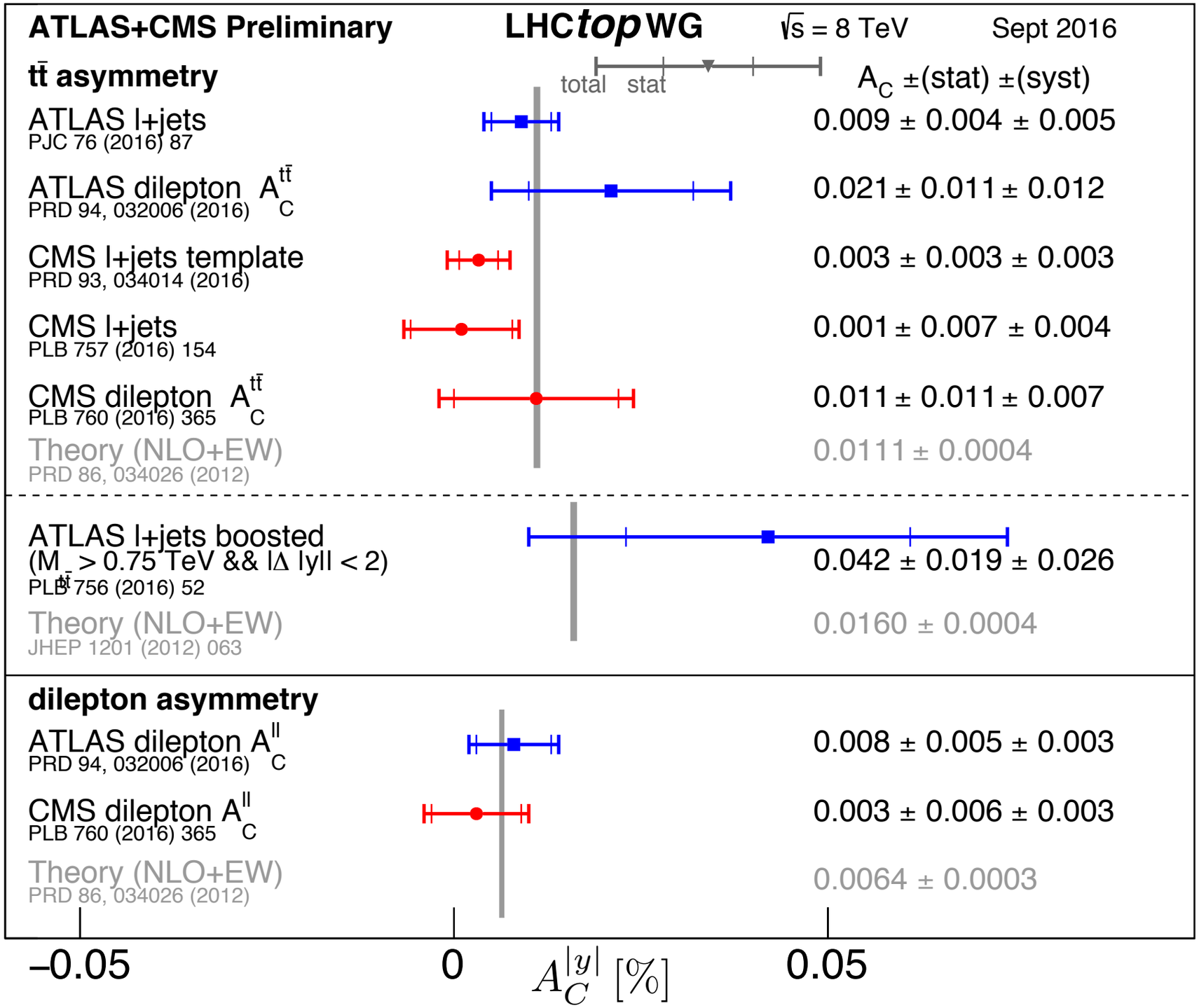
$A_y \approx 12\%$

LHC: $\Delta y = |y_t| - |y_{\bar{t}}|$

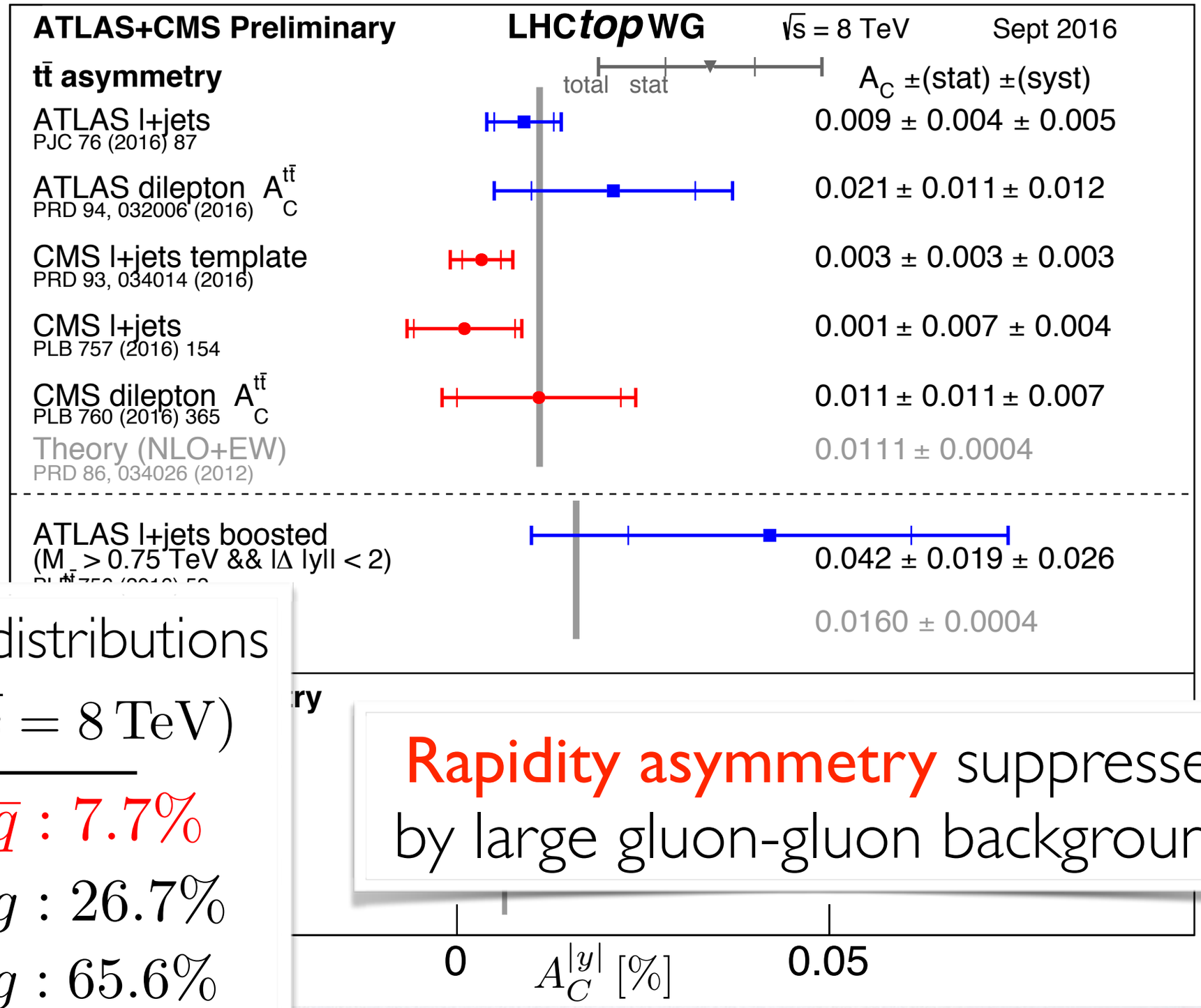


$A_y \approx 1\%$

ASYMMETRY MEASUREMENTS AT LHC



ASYMMETRY MEASUREMENTS AT LHC



parton distributions

$$\sigma_{t\bar{t}}(\sqrt{s} = 8\,\mathrm{TeV})$$

$$q\bar{q} : 7.7\%$$

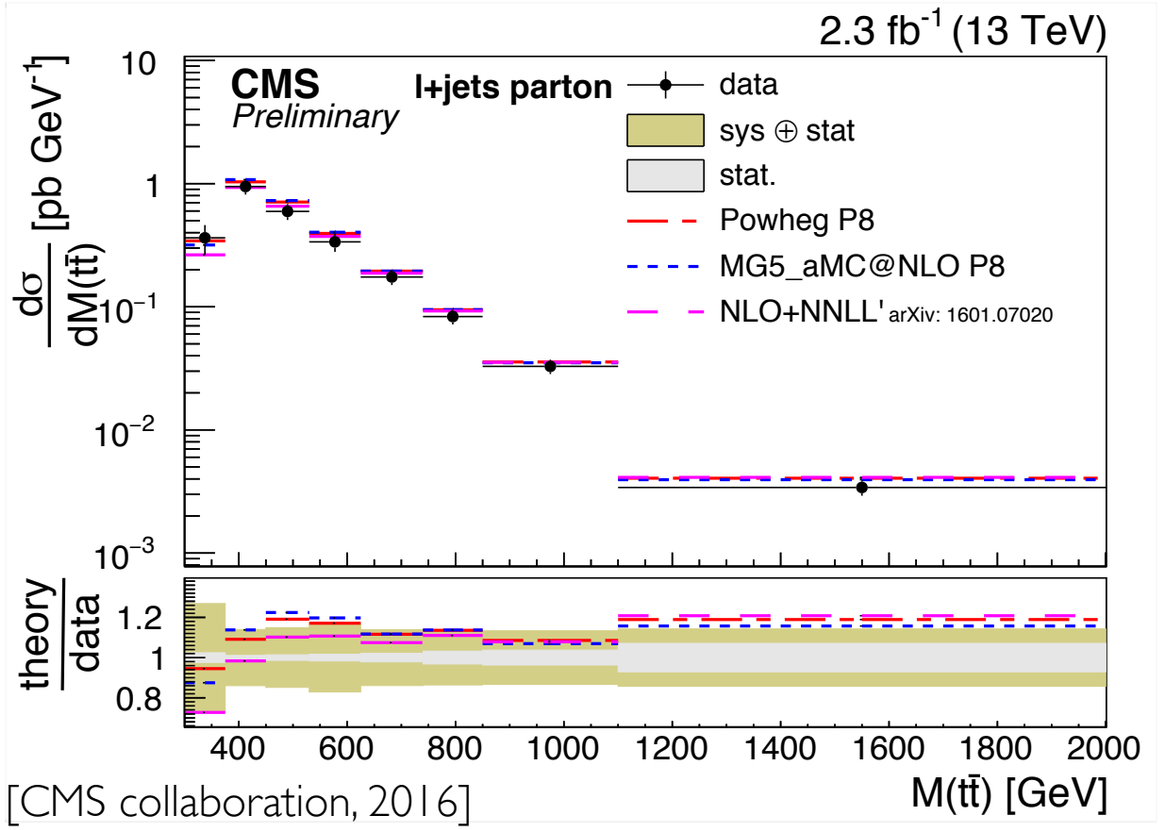
$$qg + \bar{q}g : 26.7\%$$

$$gg : 65.6\%$$

Rapidity asymmetry suppressed by large gluon-gluon background.

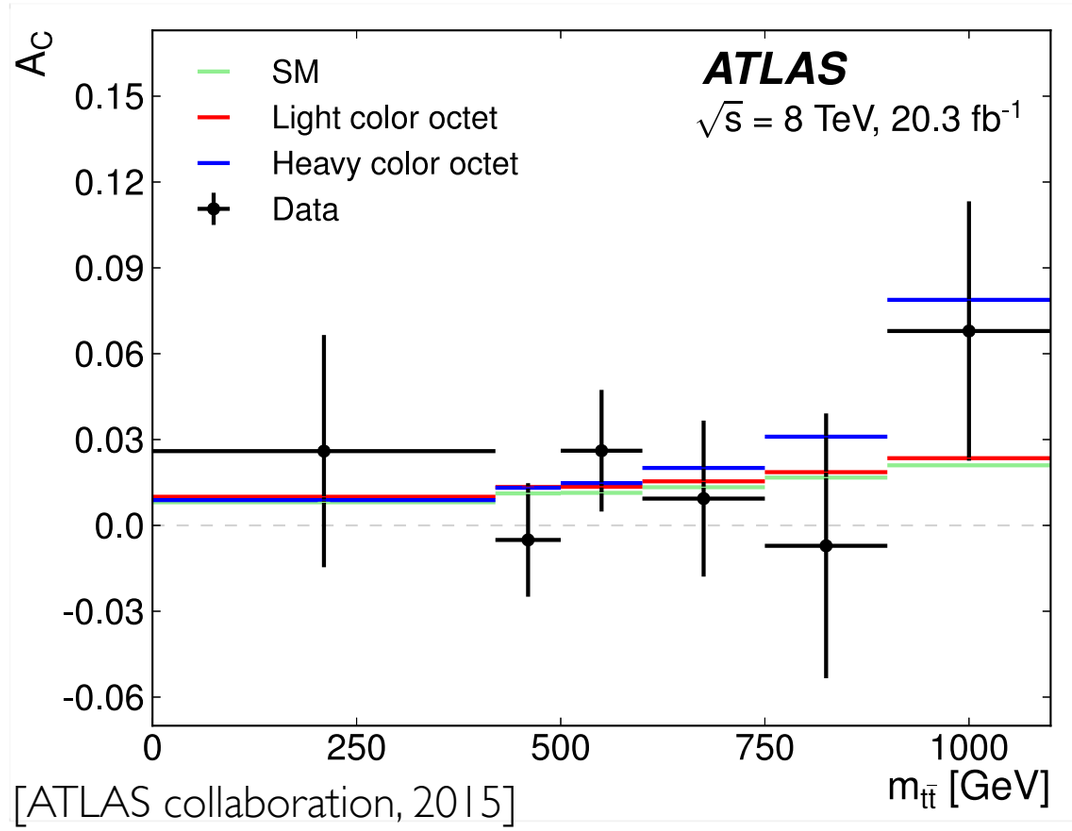
COMPLEMENTARY OBSERVABLES

$t\bar{t}$ cross section



[CMS collaboration, 2016]

$t\bar{t}$ rapidity asymmetry



[ATLAS collaboration, 2015]

QCD: asymmetry induced by color structure $\sigma_A \sim d^2_{abc}$

[QCD NLO: Kuehn, Rodrigo, 1999]

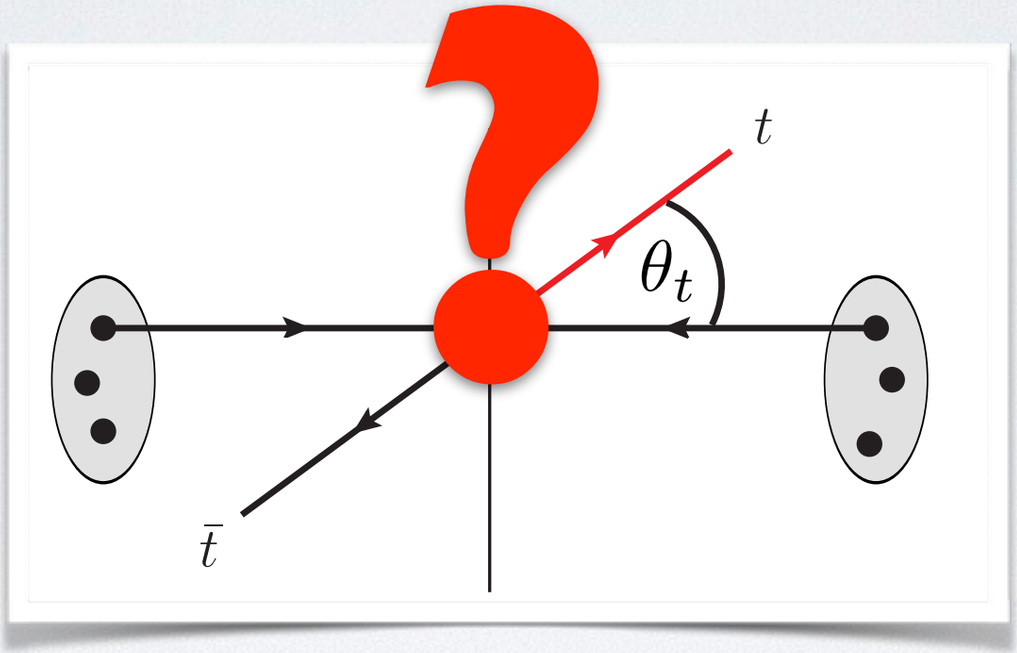
Beyond: (mostly) vector current

$$\bar{t}T^a\gamma_\mu t G^\mu$$

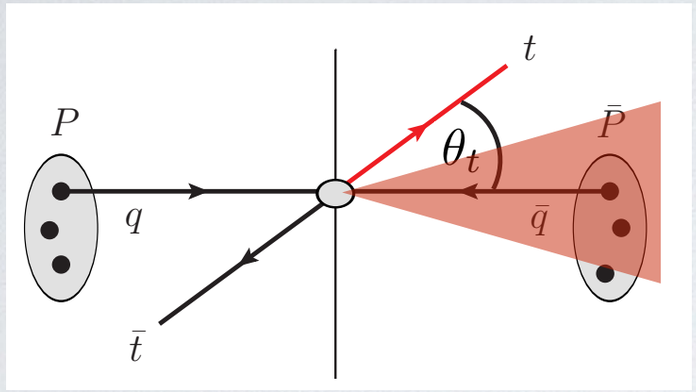
axial-vector current

$$\bar{t}T^a\gamma_\mu\gamma_5 t G^\mu$$

BETTER TOP ASYMMETRY OBSERVABLES FOR THE LHC

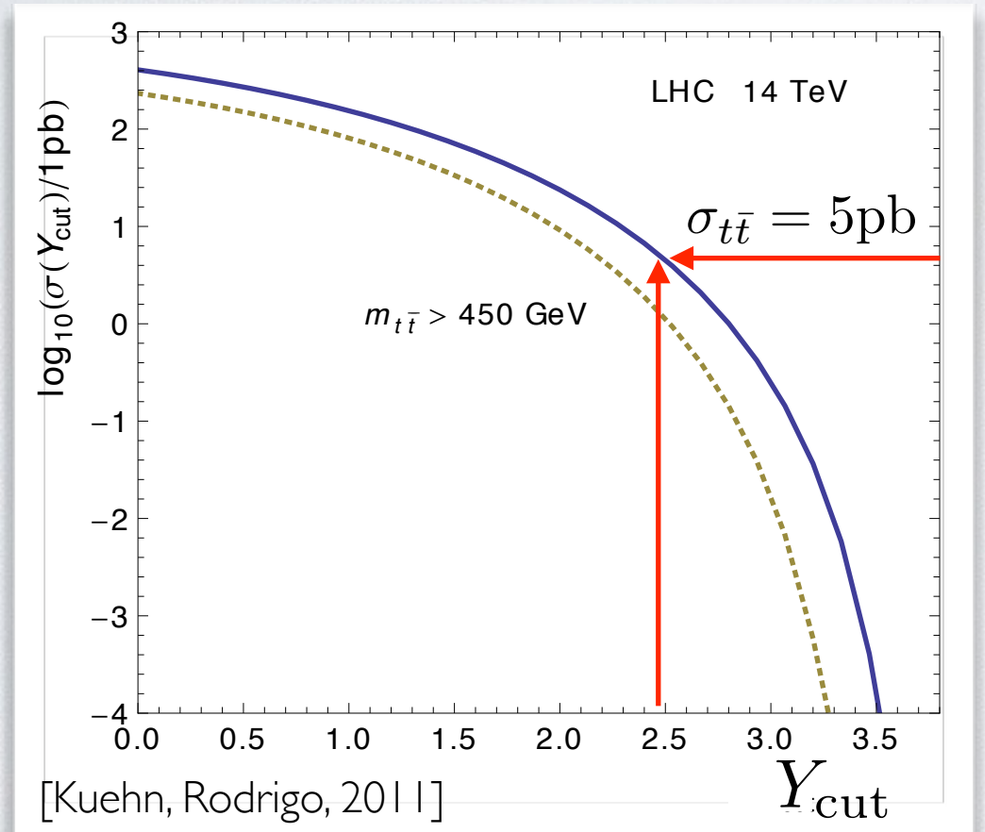


RAPIDITY ASYMMETRY IN FORWARD REGION

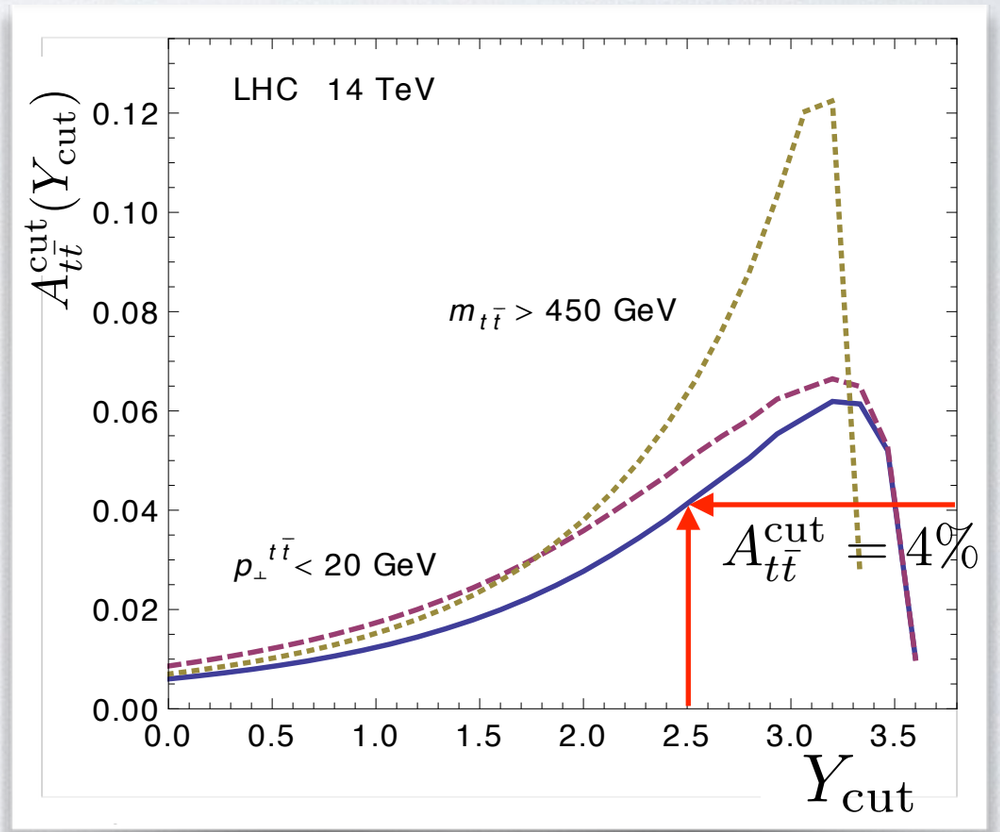


Enhance $q\bar{q}/gg$ ratio by $(y_t + y_{\bar{t}})/2 > Y_{\rm cut}$

$$A_{t\bar{t}}^{\rm cut}(Y_{\rm cut}) = \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)}$$



[Kuehn, Rodrigo, 2011]



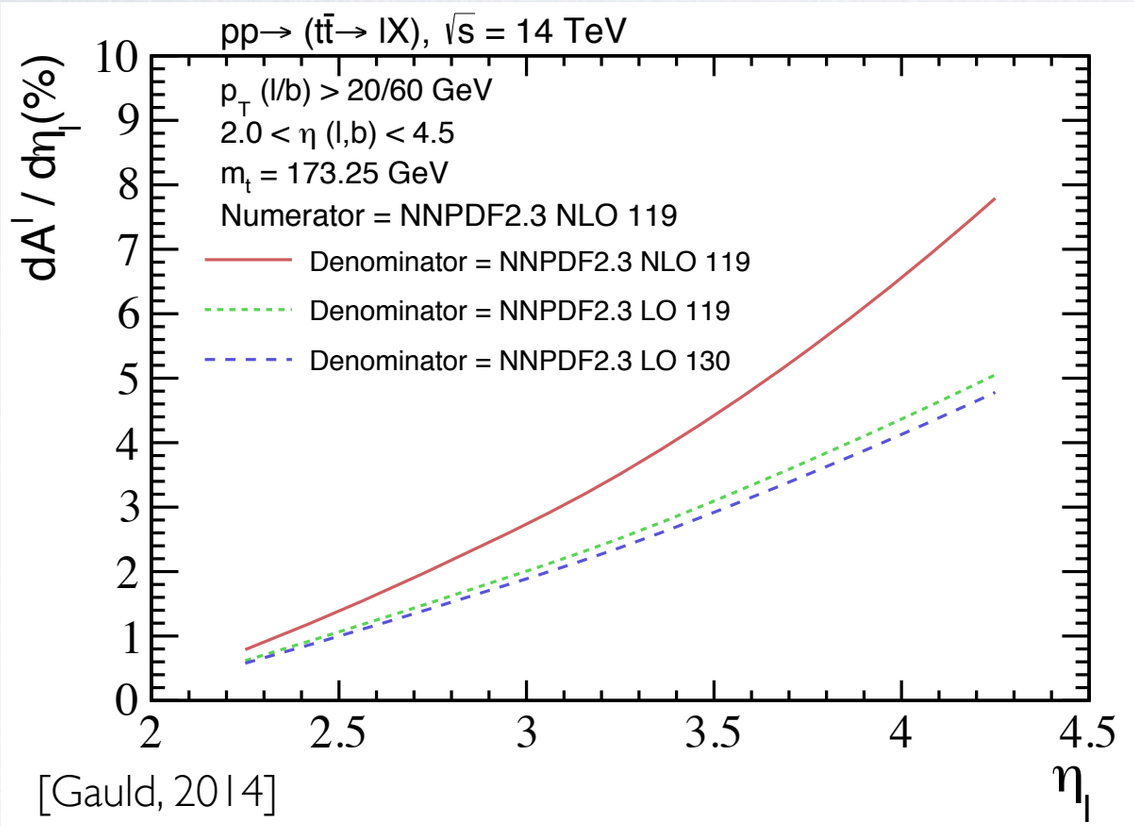
Observation relies on sensitivity in forward region.

HOW ABOUT LHCB?

Charge asymmetry of $t \to b\,\ell^+\nu_\ell$ leptons in forward region:

$$\frac{dA_\ell}{d\eta_\ell} = \frac{d\sigma_{\ell^+ b}/d\eta_\ell - d\sigma_{\ell^- b}/d\eta_\ell}{d\sigma_{\ell^+ b}/d\eta_\ell + d\sigma_{\ell^- b}/d\eta_\ell}$$

[Kagan, Kamenik, Perez, Stone, 2011]



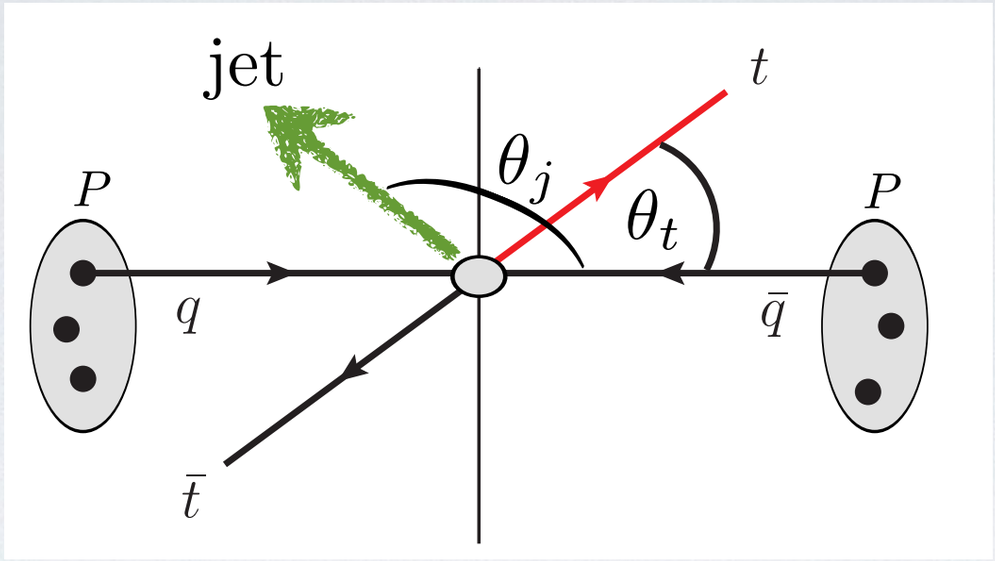
[Gauld, 2014]

Top-pair cross section just measured with 4.9 sigma significance.

[LHCb collaboration, 2016]

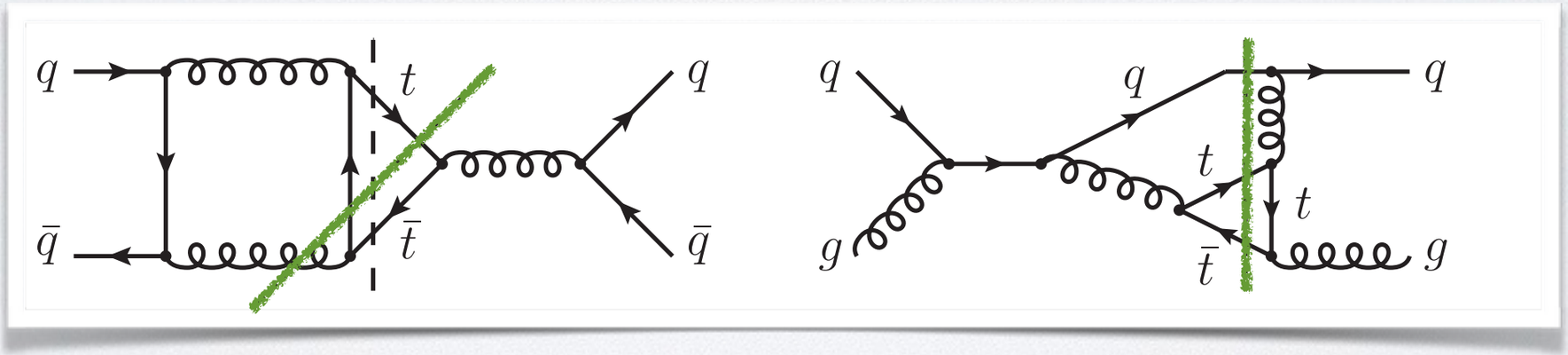
Need to tame background from (mistagged) Wj, Zj, single top.

ASYMMETRY IN TOP-PAIR + JET PRODUCTION



Rapidity asymmetry in QCD at tree level: $\sigma_A^{\mathrm{LO}} \sim -\alpha_s^2$

small



tiny

Large NLO corrections: $\sigma_A^{\mathrm{NLO}} \sim +\alpha_s^3 \longrightarrow A_y \approx 0.5\%$

[Dittmaier, Uwer, Weinzierl, 2008] [Melnikov, Schulze, 2010]

[Alioli, Moch, Uwer, 2012]

ENERGY ASYMMETRY

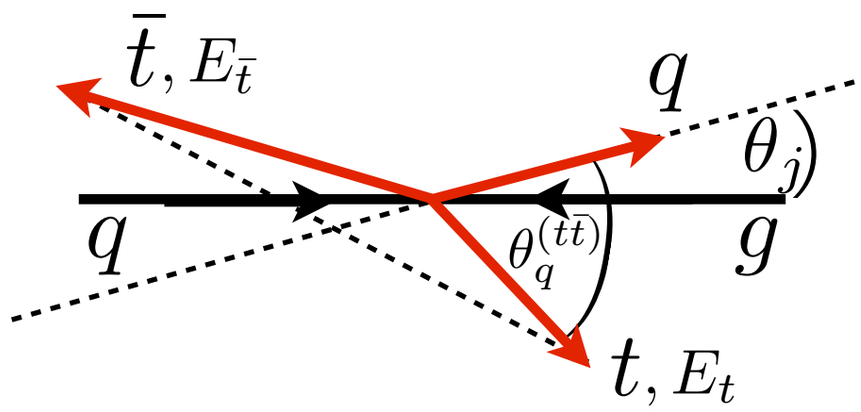
[Berge, SW, 2013]

Top-antitop **energy difference** in top-pair + jet production:

$$A_E = \frac{\sigma_{t\bar{t}j}(\Delta E > 0) - \sigma_{t\bar{t}j}(\Delta E < 0)}{\sigma_{t\bar{t}j}(\Delta E > 0) + \sigma_{t\bar{t}j}(\Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$
(parton frame)

$$E_t < E_{\bar{t}} \leftrightarrow \cos\theta_q^{(t\bar{t})} > 0$$



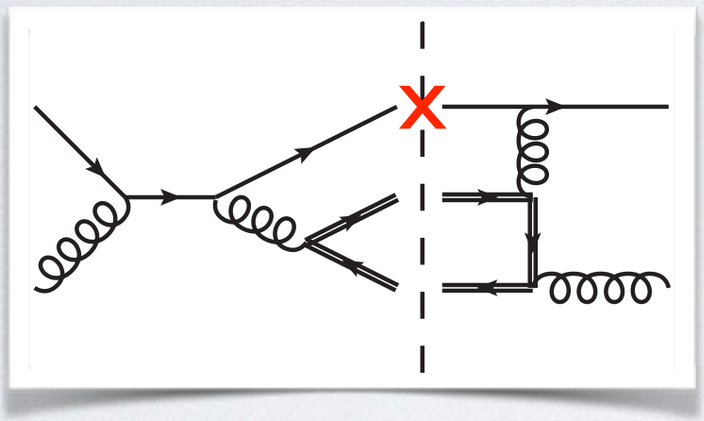
energy asymmetry in qg frame = angular asymmetry in $t\underline{t}$ frame

QCD ANATOMY

[Berge, SW, 2016]

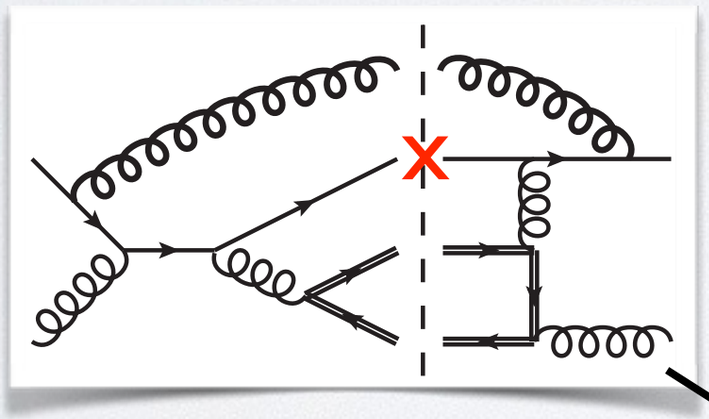
Soft and collinear enhanced cross section: $\sigma_S \sim \alpha_s^2 \log^2\left(\frac{m_t}{p_T(j)}\right)$

LO: $\sigma_A \sim \alpha_s^2$

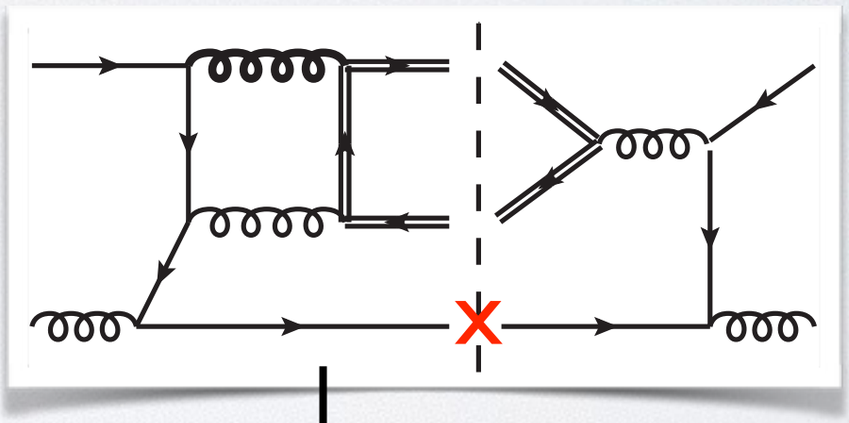


$$A_E^{\rm LO} \sim \log^{-2}\left(\frac{m_t}{p_T(j)}\right)$$

NLO: *a)*

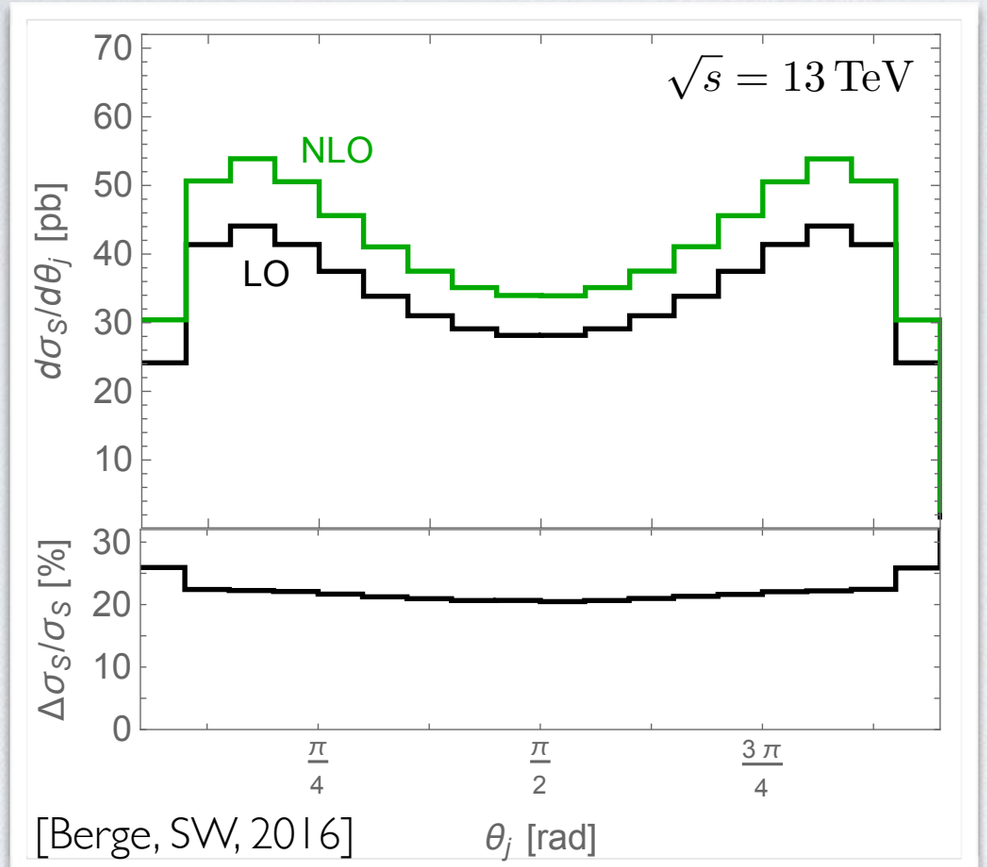


b)

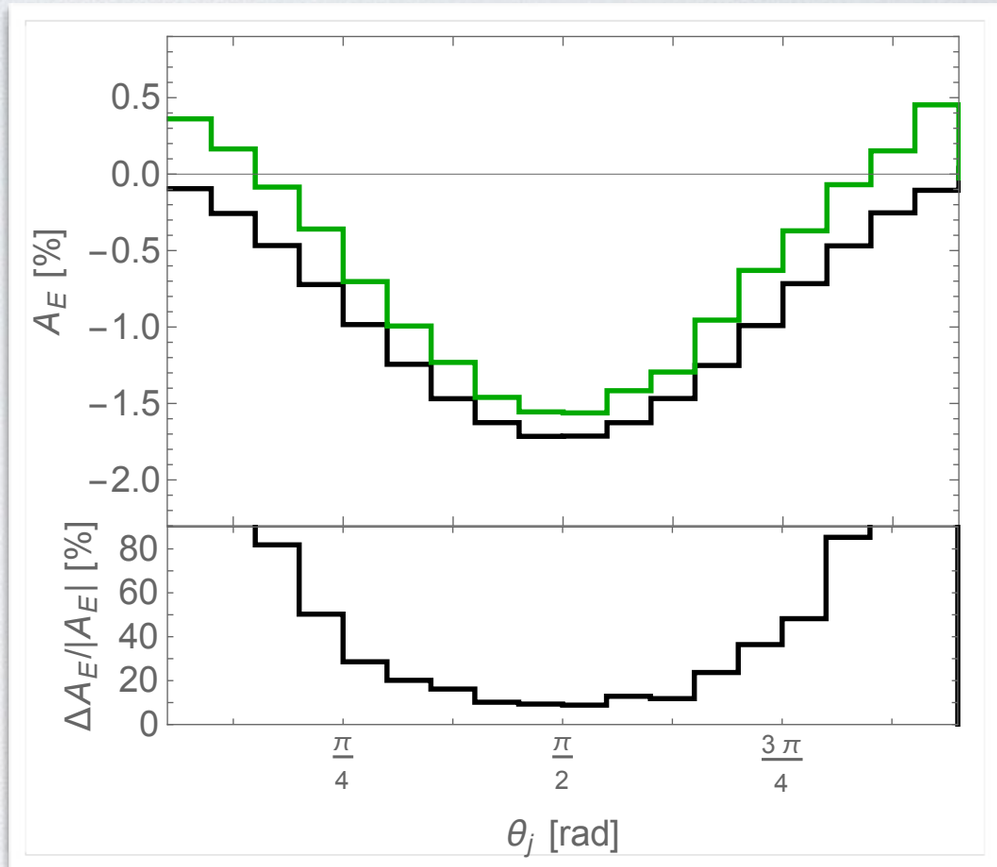


$$A_E^{\rm NLO} \sim \log^{-2}\left(\frac{m_t}{p_T(j)}\right) \times \left[1 + \alpha_s + \alpha_s \log\left(\frac{m_t}{p_T(j)}\right)\right]$$

ENERGY ASYMMETRY IN QCD AT NLO



[Berge, SW, 2016]



$pp \to t\bar{t}j$ at 13-TeV LHC:

Event generation: aMC@NLO

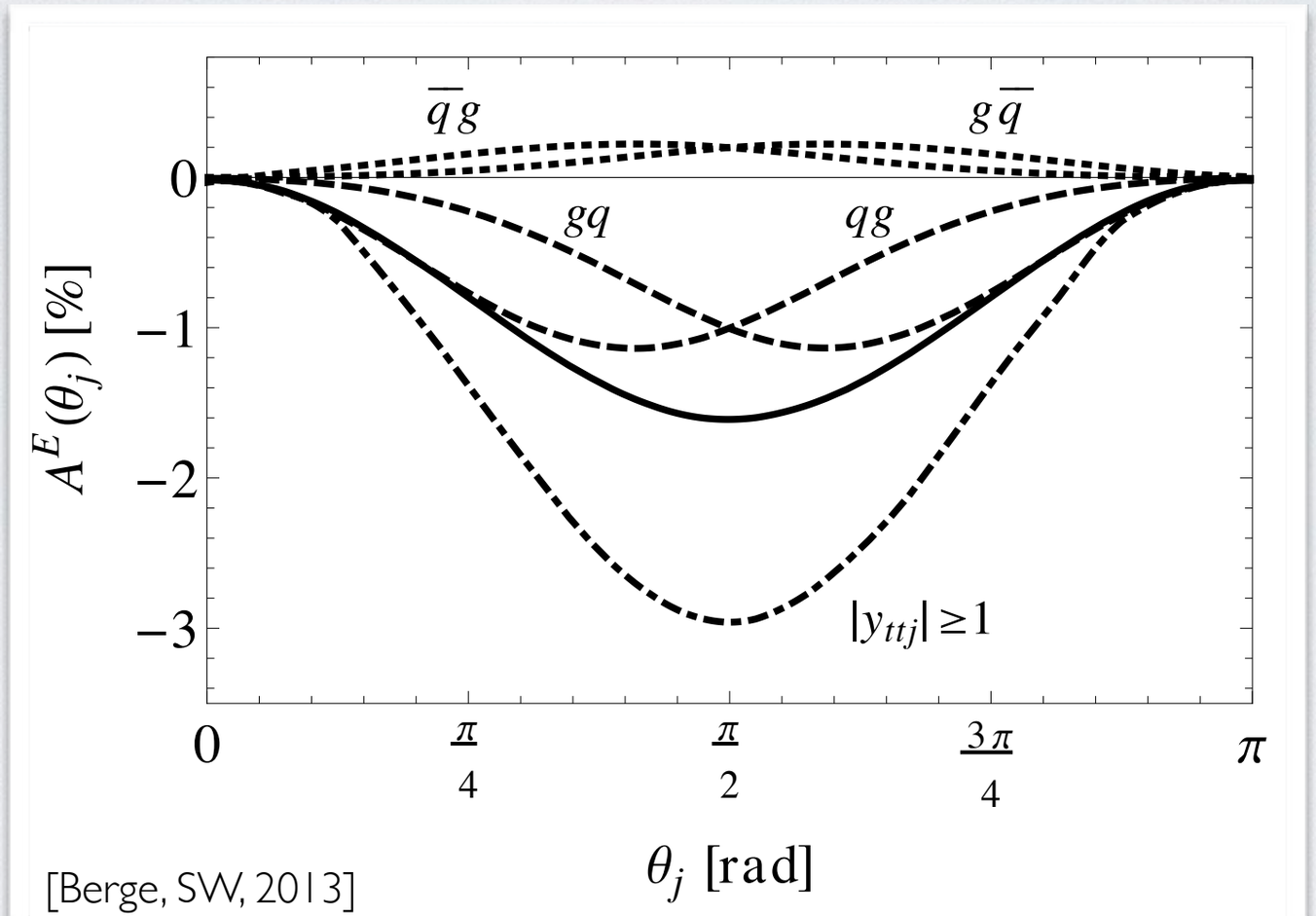
PDF set: CTEQ10NLO

Cuts on hardest jet:

$p_T(j_1) > 100\,\mathrm{GeV},\ |y_{j_1}| < 2.5$

ENERGY ASYMMETRY KINEMATICS

jet distribution follows boost of incoming quark

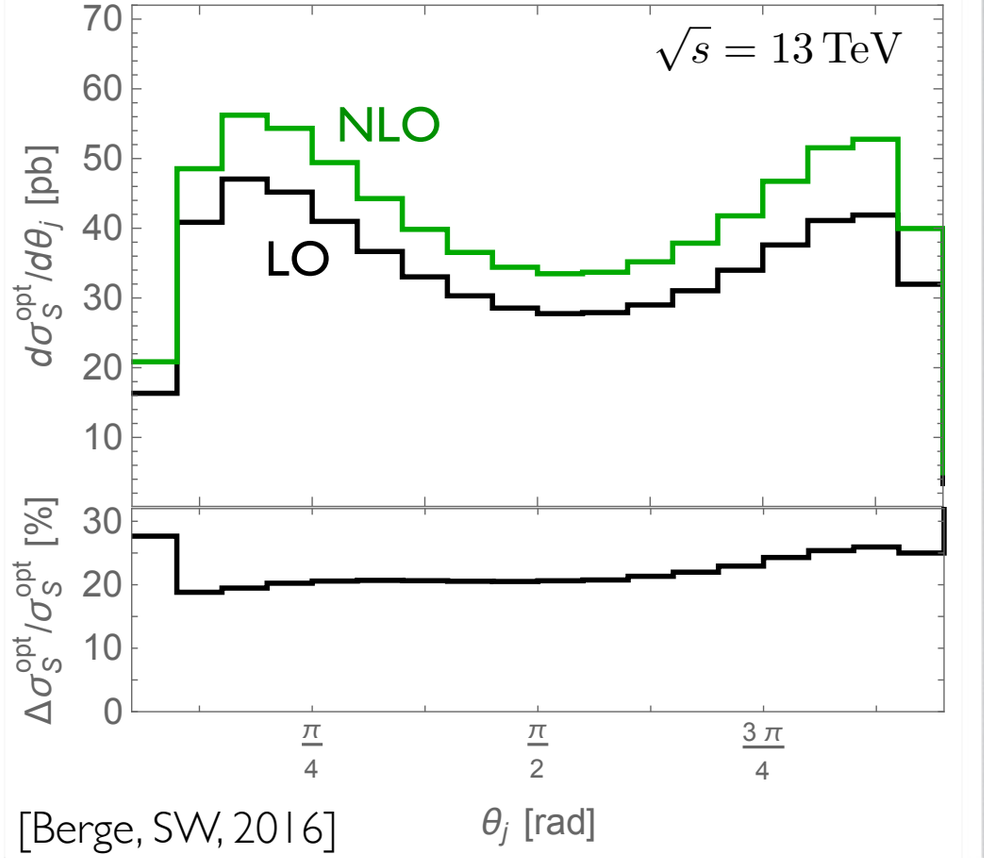


[Berge, SW, 2013]

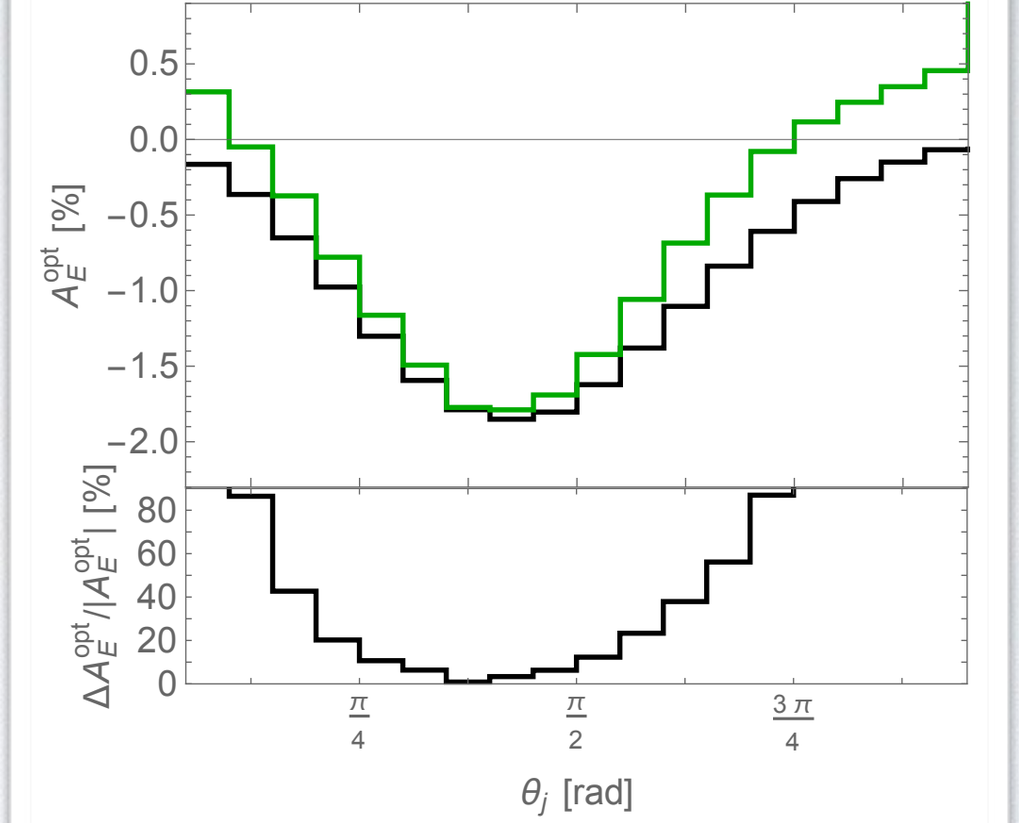
OPTIMIZED ENERGY ASYMMETRY AT NLO

$$A_E^{\mathrm{opt}}(\theta_j) = \frac{\sigma_A(\theta_j, y_{t\bar{t}j} > 0) + \sigma_A(\pi - \theta_j, y_{t\bar{t}j} < 0)}{\sigma_S(\theta_j, y_{t\bar{t}j} > 0) + \sigma_S(\pi - \theta_j, y_{t\bar{t}j} < 0)}$$

[Alte et al., 2014]



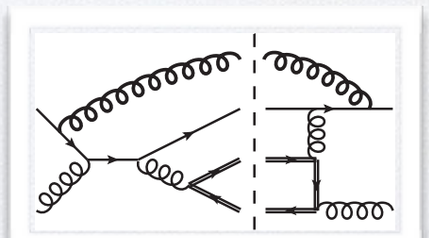
[Berge, SW, 2016]



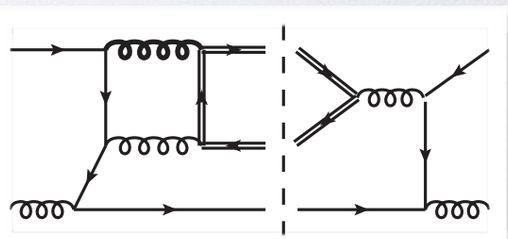
Kinematic cuts on jet:

$$p_T(j_1) > 100\,\mathrm{GeV},\ |y_{j_1}| < 2.5$$

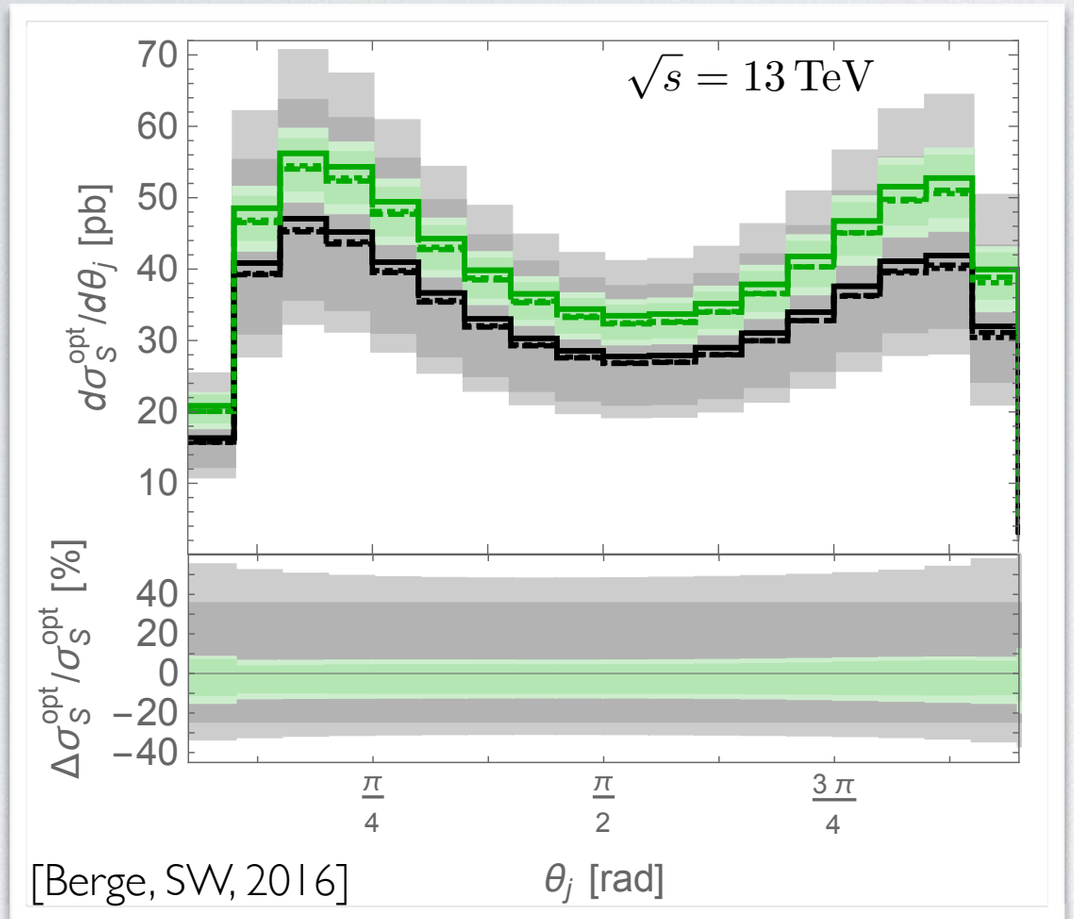
$q_{\mathrm{out}} \uparrow\uparrow q_{\mathrm{in}}$

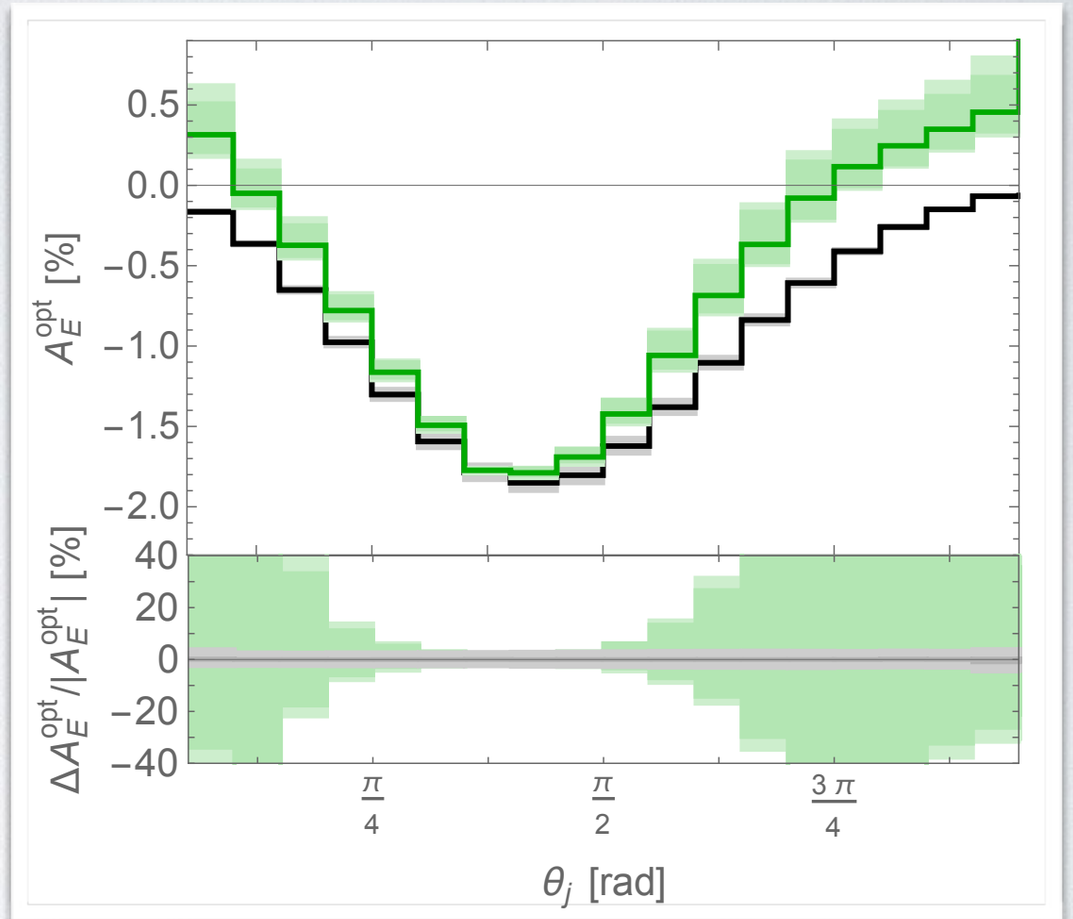


$q_{\mathrm{out}} \uparrow\downarrow q_{\mathrm{in}}$



SCALE AND PDF DEPENDENCE





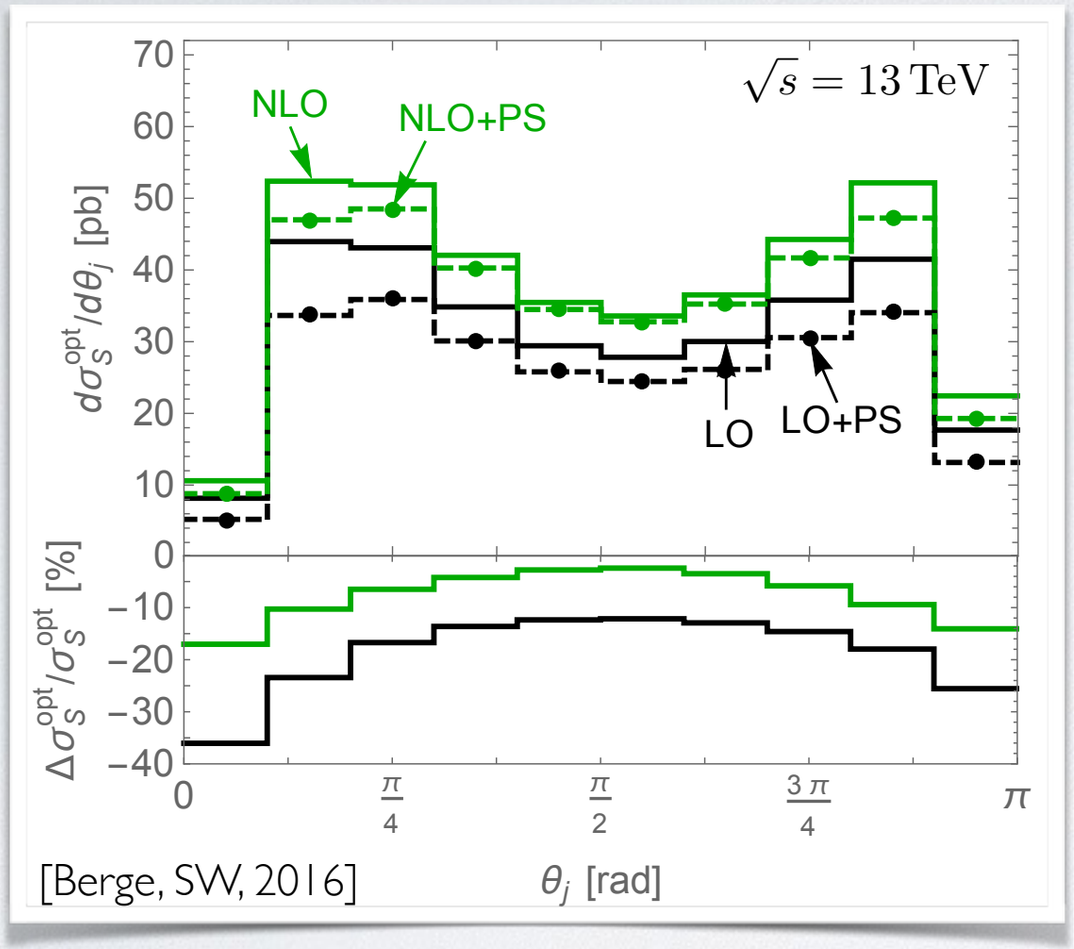
Scale variation light band: $\mu_F,\, \mu_R \in [m_t/2, 2m_t]$

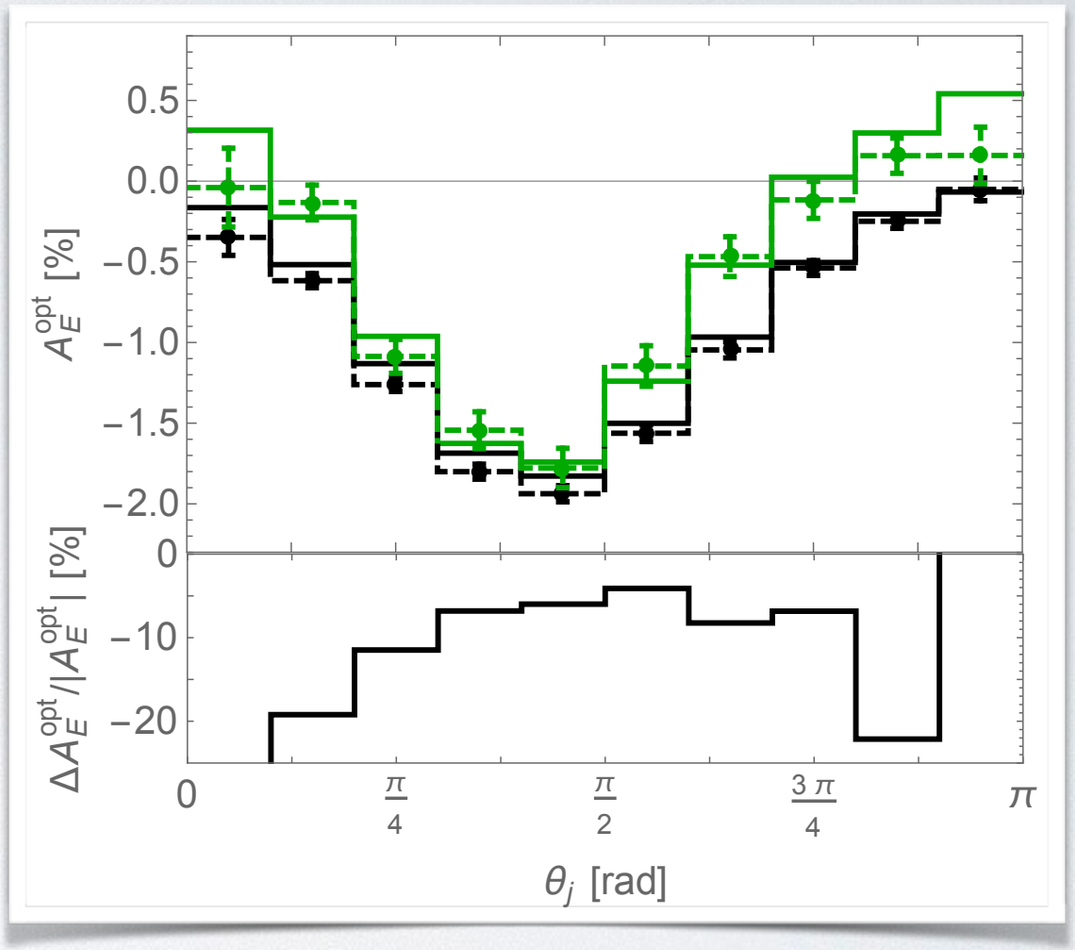
dark band: $\mu_R \in [m_t/2, 2m_t],\ \mu_F = m_t$

Scale dependence partly cancels between σ_A and σ_S.

PDF uncertainties have little effect on asymmetry.

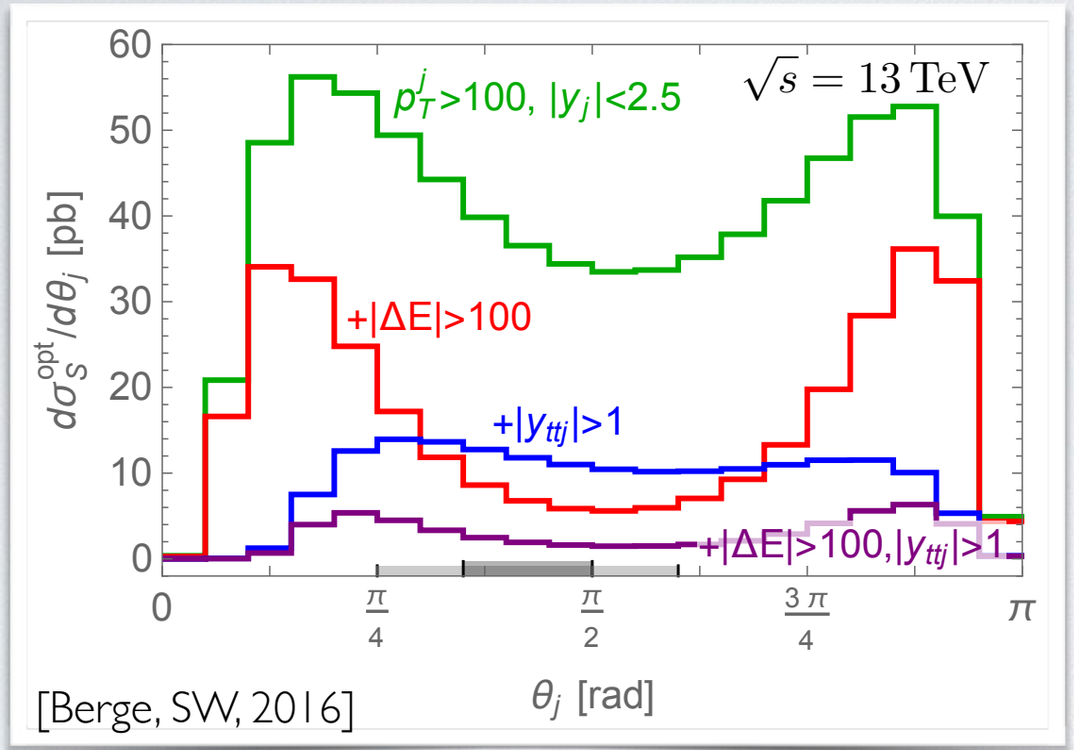
PARTON SHOWER



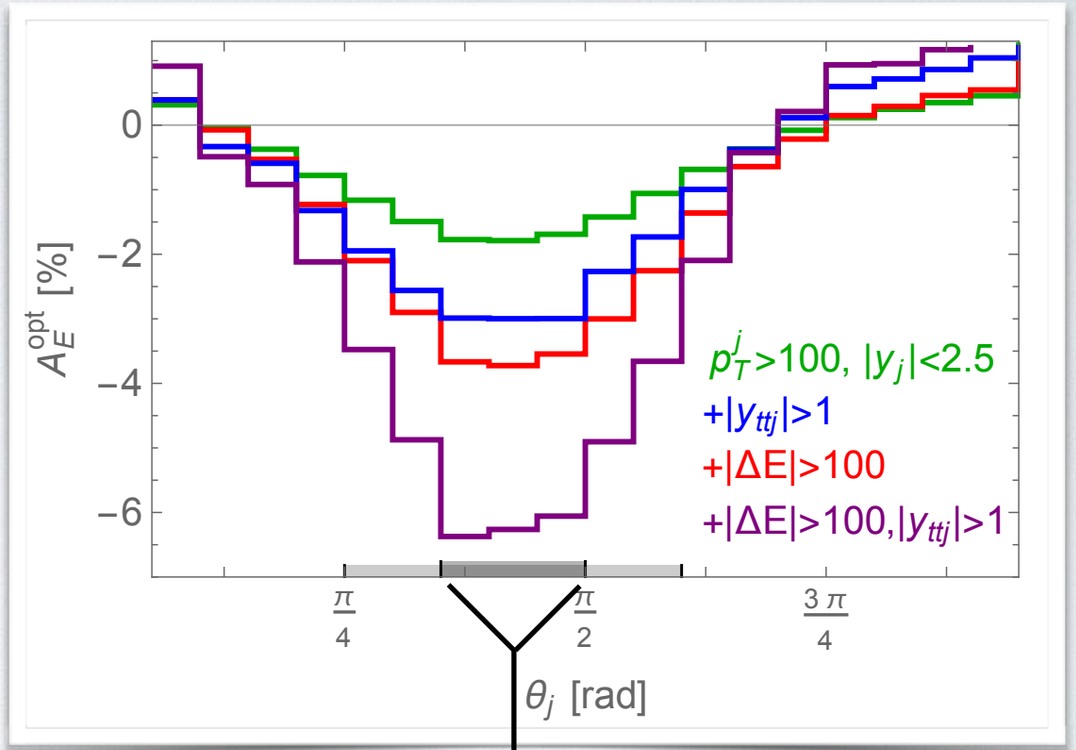


event generation: aMC@NLO w/ Pythia 6
stable top-quarks, no hadronization
jet clustering: FastJet, anti-kt algorithm
jet cut at generator level: $p_T(j_1)^{\mathrm{gen}} > 70\,\mathrm{GeV}$

TAILORING THE ENERGY ASYMMETRY



[Berge, SW, 2016]

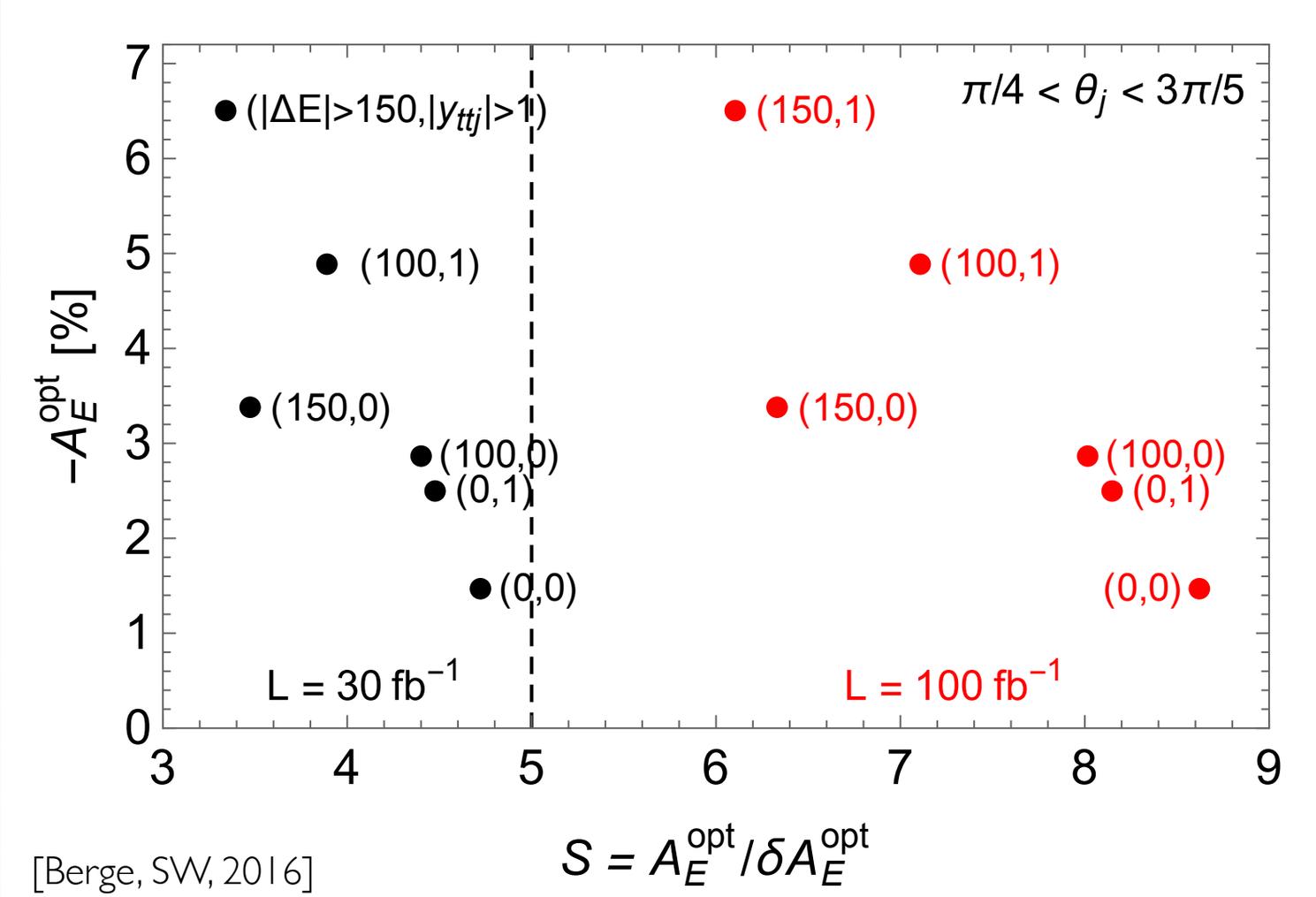


$$\{\sigma_S^{\mathrm{opt}}\,[\mathrm{pb}], A_E^{\mathrm{opt}}\,[\%]\}$$

$\frac{7\pi}{20} < \theta_j < \frac{\pi}{2}$ / $0 < \hat{y}_j < 0.49$	no cut on $y_{t\bar{t}j}$	$\lvert y_{t\bar{t}j}\rvert > 1$
no cut on ΔE	$\{17^{+1}_{-2}, -1.75^{+0.03}_{-0.03}\}$	$\{5.6^{+0.4}_{-0.7}, -2.99^{+0.03}_{-0.05}\}$
$\lvert\Delta E\rvert > 100$ GeV	$\{3.34^{+0.01}_{-0.39}, -3.65^{+0.04}_{-0.19}\}$	$\{0.94^{+0.01}_{-0.08}, -6.25^{+0.07}_{-0.32}\}$
$\lvert\Delta E\rvert > 150$ GeV	$\{1.46^{+0.02}_{-0.31}, -4.28^{+0.04}_{-0.30}\}$	$\{0.377^{+0.002}_{-0.061}, -7.21^{+0.07}_{-0.42}\}$

OBSERVATION PROSPECTS FOR LHC RUN II

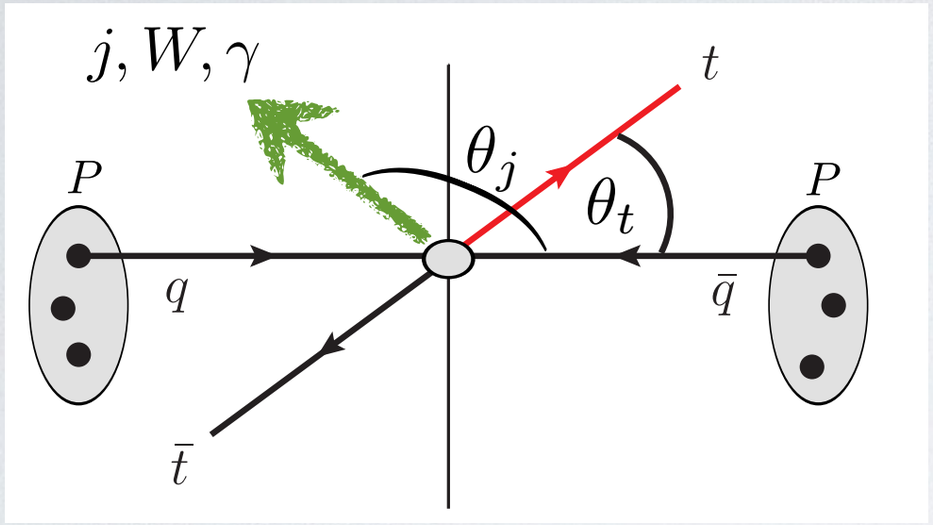
Now 2018



[Berge, SW, 2016]

Statistical significance S, assuming acceptance x efficiency = 8%.

ASSOCIATED ASYMMETRIES



Cross sections at 13 TeV:

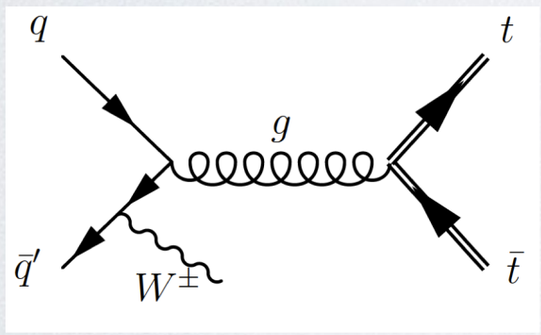
$$t\bar{t} + \text{jet}: \quad \mathcal{O}(500)\,\text{pb}$$
$$t\bar{t} + W: \quad \mathcal{O}(700)\,\text{fb}$$
$$t\bar{t} + \gamma: \quad \mathcal{O}(100)\,\text{fb}$$

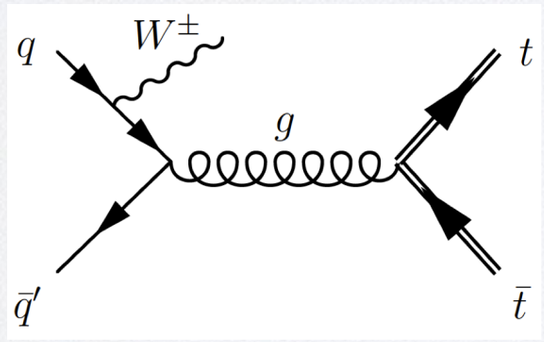
[Aguilar-Saavedra et al., 2014]

Rapidity asymmetry in $t\bar{t}+W$:

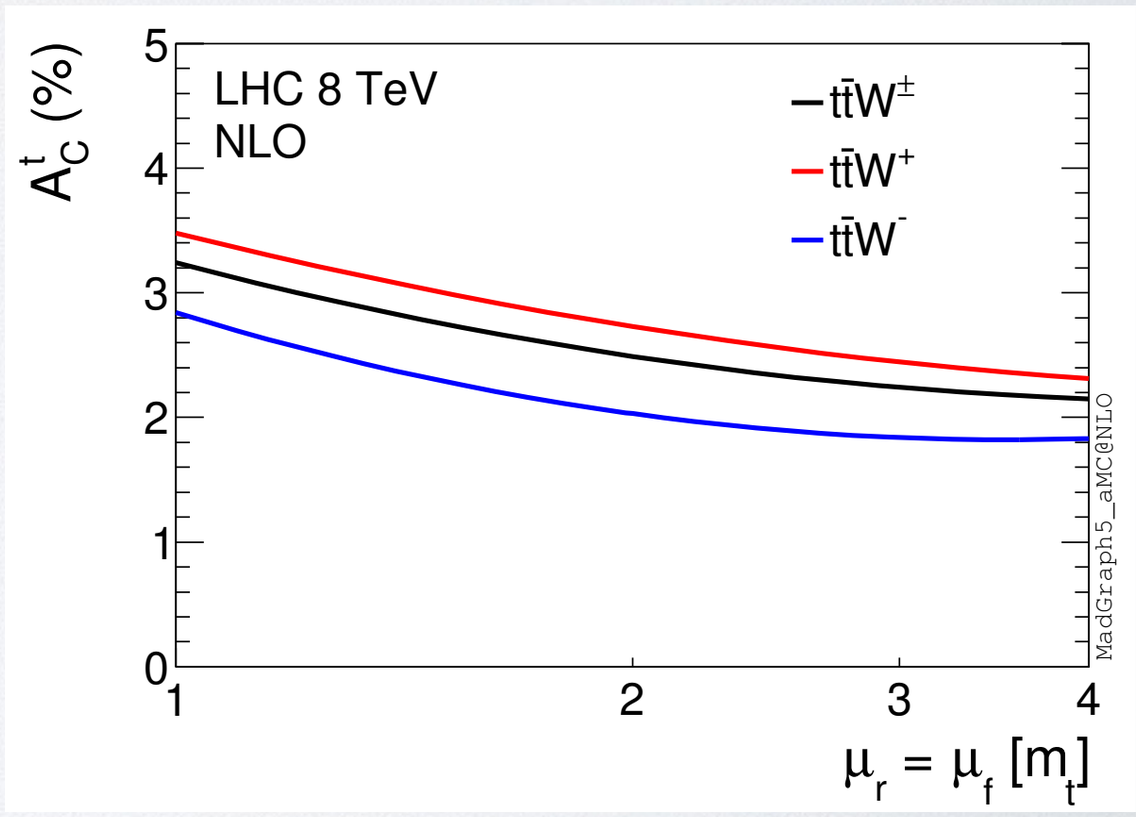
in QCD at NLO

[Maltoni, Mangano, Tsinikos, Zaro, 2014]





No gg background.



CONCLUSIONS

Opportunities
to observe the top charge asymmetry at LHC Run II:

The rapidity asymmetry is **enhanced** in the **forward region.**

Top decay **lepton asymmetries** are experimentally **cleaner**.

The **energy asymmetry** is a **promising** alternative observable.

Precise predictions are technically feasible
(thanks to the legacy of the forward-backward asymmetry).