Germán Rodrigo

IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

$t\bar{t}$ asymmetry in the Standard Model and beyond

Rencontres de Moriond EW
3-10 March 2012

SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS
LHCphenOnet

Outline

- The top quark charge asymmetry in the SM
- Summary of Tevatron measurements
- BSM explanations
- The charge asymmetry at the LHC

It´s about charge asymmetry not about forward—backward asymmetry

Charge asymmetry in QCD

[Kühn, GR, Moriond QCD 1998]

At $O(\alpha_s^2)$: top and antitop quarks have identical angular distributions

A charge asymmetry arises at $O(\alpha_s^3)$

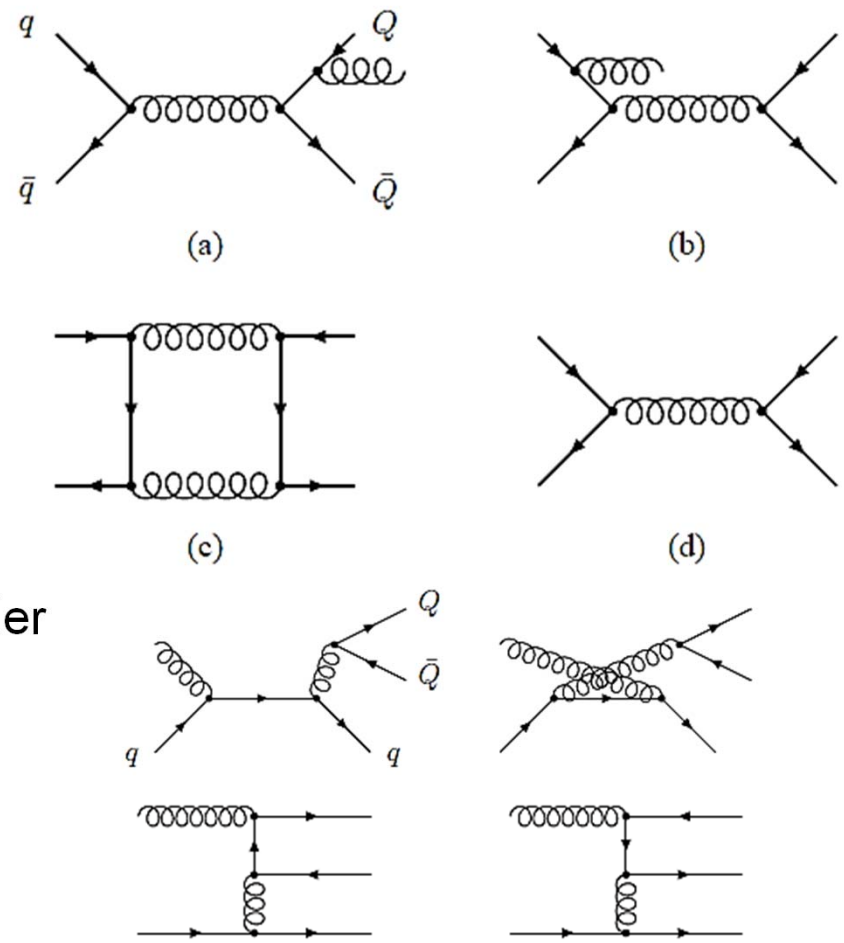
➡ Interference of **ISR with FSR**
LO for ttbar+jet
negative contribution to ttbar+1 jet

➡ Interference of **box diagrams** with Born **(+soft)**
positive contribution to ttbar+0 jet

➡ Flavor excitation (qg channel) much smaller

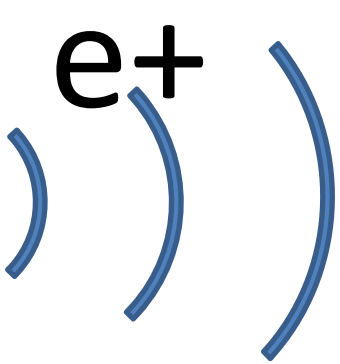
- color factor d_{abc}^2 : **pair in color singlet**
- Loop contribution larger than tree level

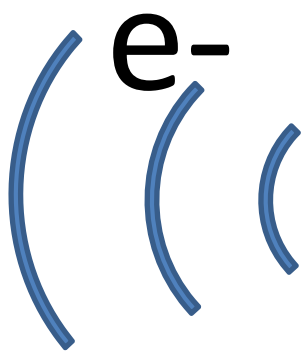
top quarks are preferentially emitted in the direction of the incoming quark



A qualitative picture (by J.H.Kühn)

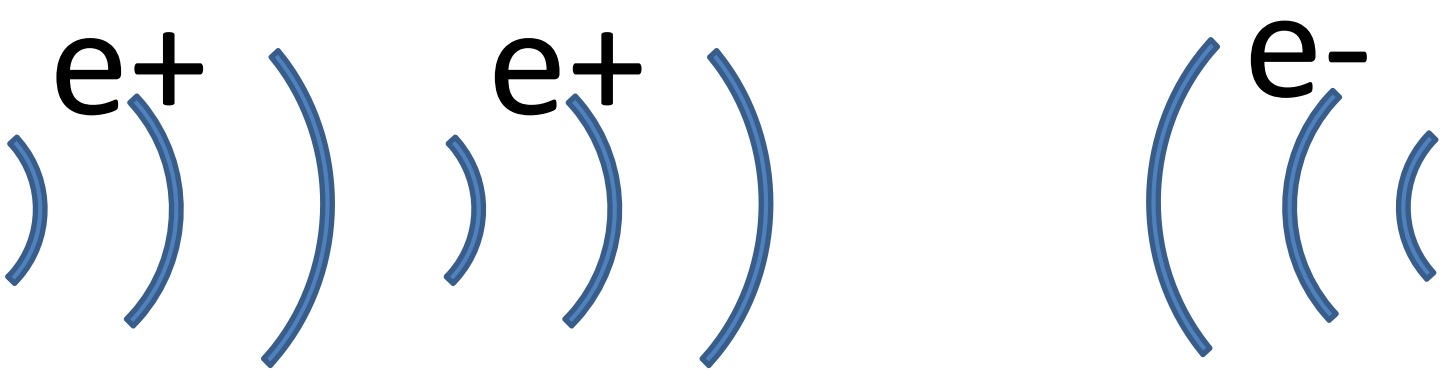
QED: $e^+ e^- \rightarrow \mu^+ \mu^-$





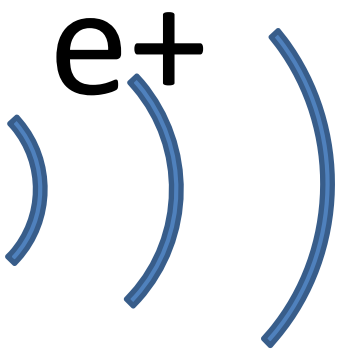
A qualitative picture (by J.H.Kühn)

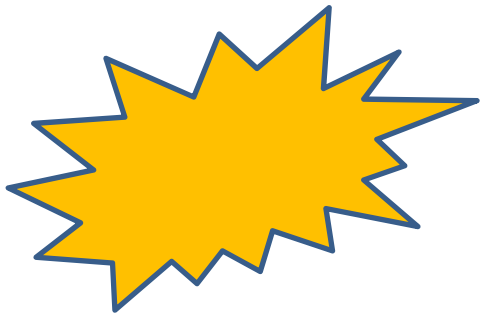
QED: $e^+ e^- \rightarrow \mu^+ \mu^-$



A qualitative picture (by J.H.Kühn)

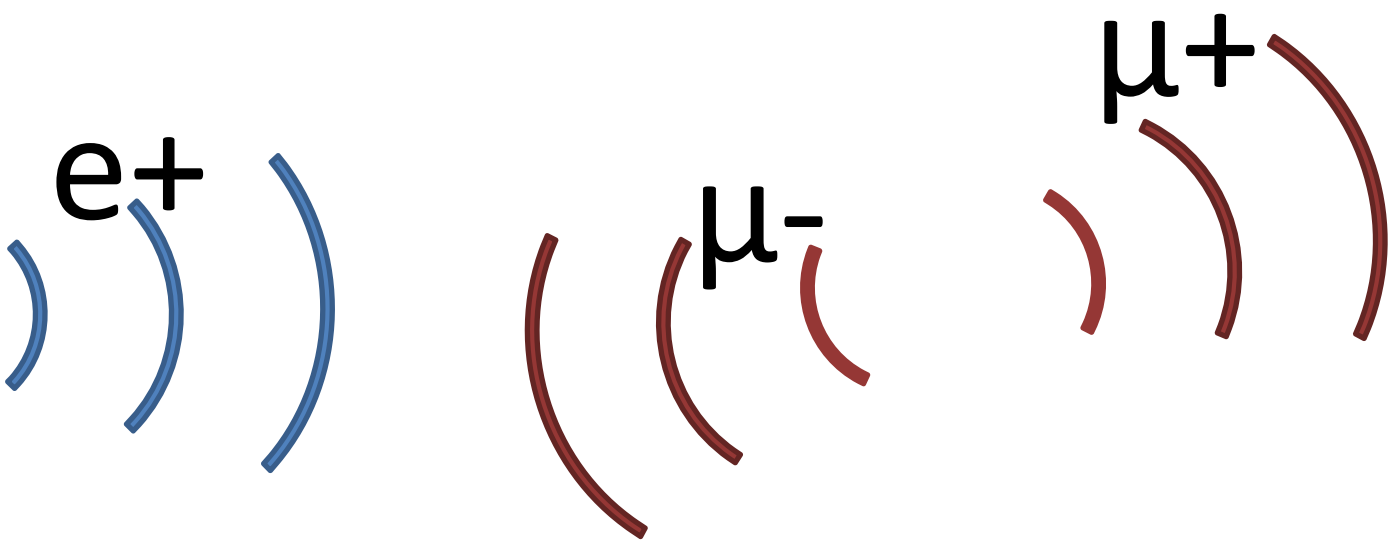
QED: $e^+ e^- \rightarrow \mu^+\mu^-$





A qualitative picture (by J.H.Kühn)

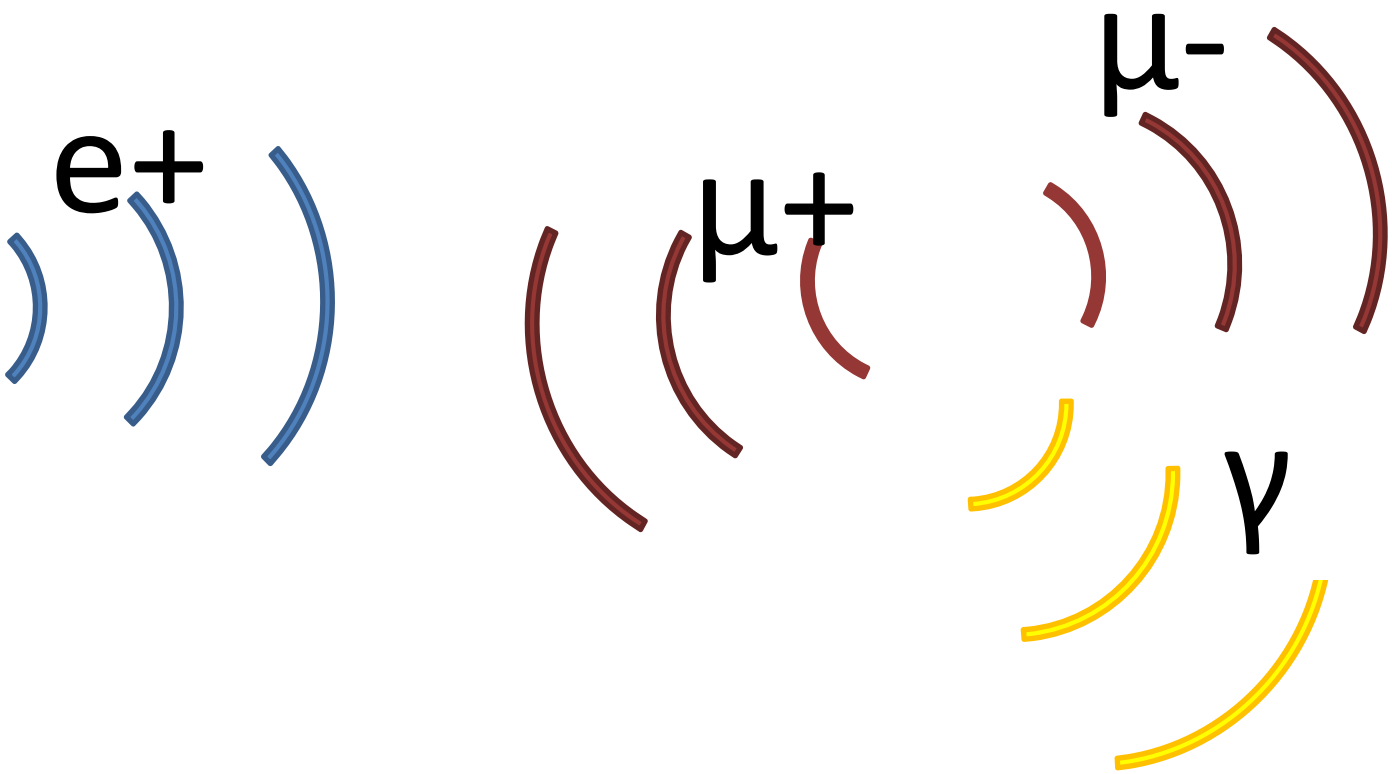
QED: $e^+ e^- \rightarrow \mu^+ \mu^-$



- **Inclusive:** the system is **less perturbed** if **the outgoing positive electric charge field (colour field for tops)** flows in the direction of **the incoming positive electric charge field**

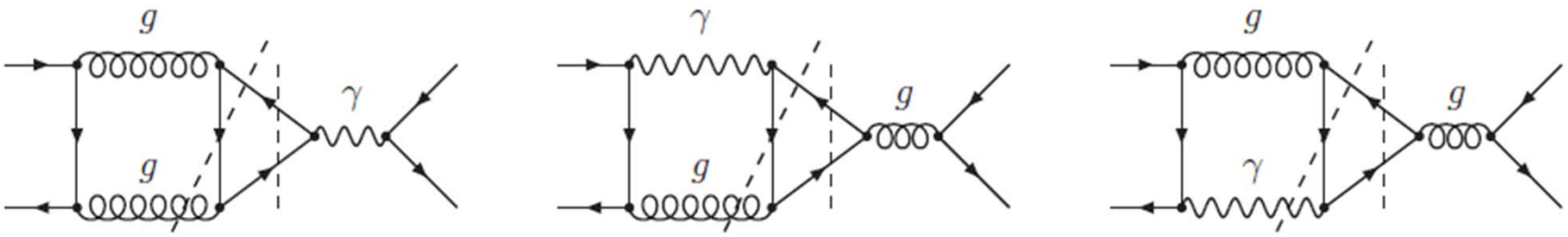
A qualitative picture (by J.H.Kühn)

QED: $e^+ e^- \to \mu^+\mu^-$



- $\mu^+\mu^-\gamma$ final state, emission of **extra radiation** requires to **decelerate** the electric charges: negative charge asymmetry

EW corrections (QED)



Relative factor between QCD and QED

$$f_q{}^{\mathrm{QED}} = 3\frac{\alpha_{\mathrm{QED}} Q_t Q_u}{\frac{\alpha_S}{2}\left(\frac{d^2{}_{abc}}{4}\right)^2} = \frac{\alpha_{\mathrm{QED}}}{\alpha_S}\frac{36}{5} Q_t Q_q$$

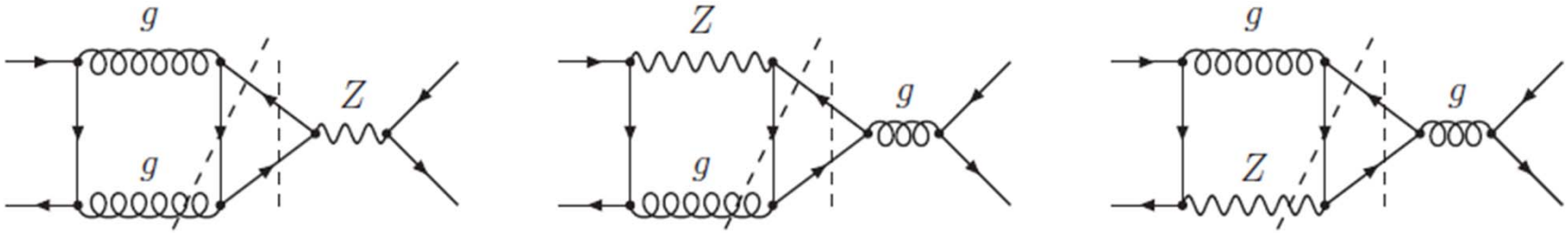
Assuming the **ratio 4:1** (**2:1 @LHC**) for $u\bar{u} : d\bar{d}$ events

$$f^{\mathrm{QED}} = \frac{4 f_u{}^{\mathrm{QED}} + f_d{}^{\mathrm{QED}}}{5} \approx 0.18 \quad \text{at Tevatron}$$

$$f^{\mathrm{QED}} = \frac{2 f_u{}^{\mathrm{QED}} + f_d{}^{\mathrm{QED}}}{3} \approx 0.13 \quad \text{at the LHC}$$

PDFs modify slightly these ratios, but do not change significantly the predictions

EW corrections (weak)



$$f^{\text{weak}} \approx 3\,\frac{\alpha_{\text{QED}}}{\alpha_S}\,\frac{36}{5}\,\frac{1-\frac{8}{3}{s_W}^2}{16\,{s_W}^2{c_W}^2}\,\frac{4\left(1-\frac{8}{3}{s_W}^2\right)+\left(-1+\frac{4}{3}{s_W}^2\right)}{5} \approx 0.013 \;\; (0.002 \;@\; \text{LHC})$$

- strong cancellation between up and down quark contributions
- Weak Sudakov logs [Manohar, Trott]: at most 0.02-0.03

Inclusive charge asymmetry at Tevatron

Charge conjugation symmetry* $\left(N_{\bar{t}}(y) = -N_t(-y)\right)$

equivalent to forward-backward [Kühn, GR,1998; arXiv:1109.6830]

$$A_{\text{lab}} = \frac{N(y_t>0)-N(y_{\bar{t}}>0)}{N(y_t>0)+N(y_{\bar{t}}>0)} = \mathbf{0.056(7)}$$

$$A_{t\bar{t}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)} = \mathbf{0.087(10)} \quad \Delta y = y_t - y_{\bar{t}}$$

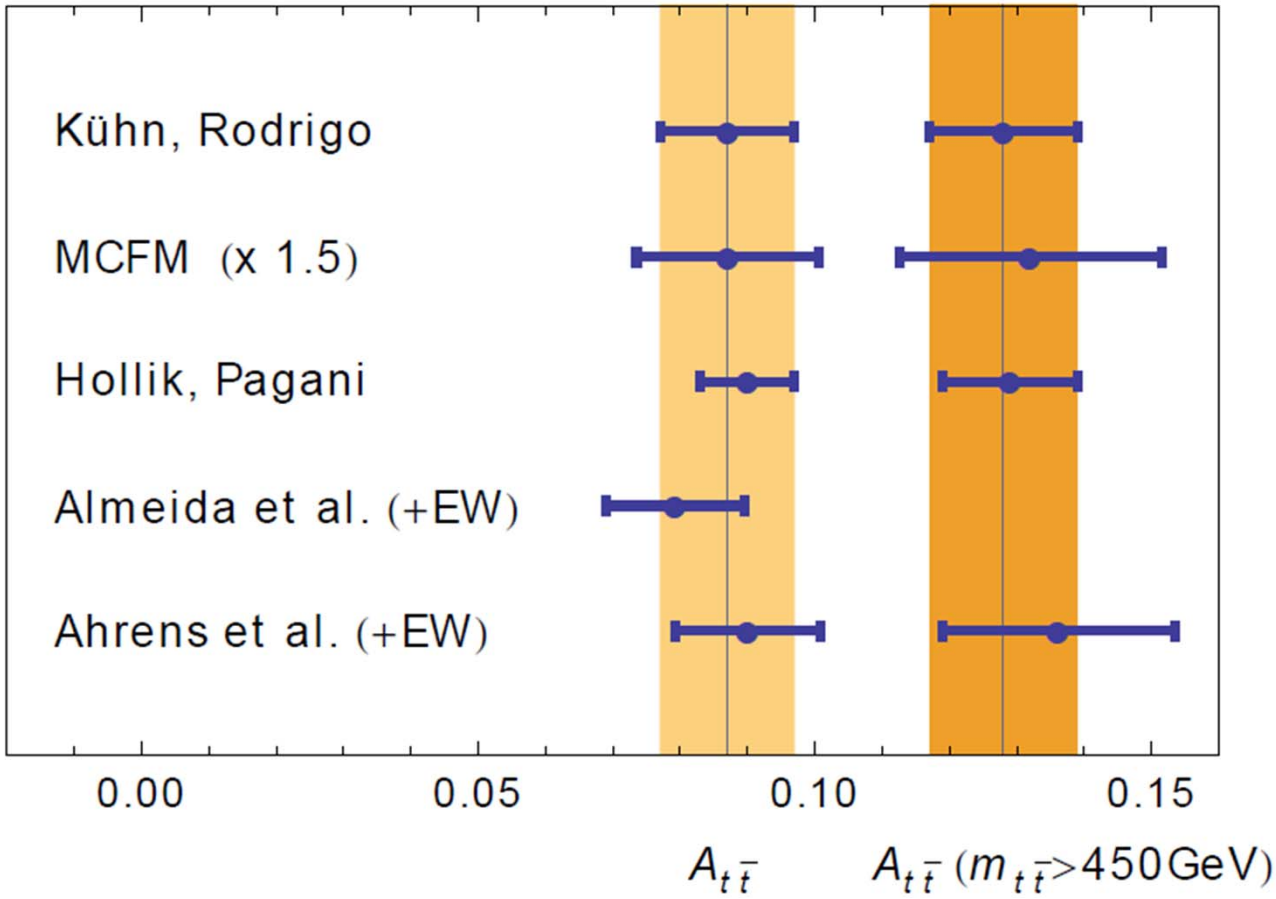
Invariant under boost

- mixed QCD-EW interference included: factor 1.2 [Kühn, GR / Hollik, Pagani]
- first contribution to the antisymmetric x-section is a loop effect, first contribution to the symmetric x-section is tree level: asymmetry **normalized to LO x-section**
- stable to NLL threshold resummations (one per mille shift) [Almeida,Sterman,Vogelsang]
- NNLL threshold resummations [Ahrens,Ferroglia,Neubert,Pecjak,Yang]

Not expanding the asymmetry in α_s : the asymmetry decreases by 20% at NLO (K factor), but only by 5% at NLO+NNLL

- Full NNLO (NLO for the asymmetry) on-going [Bonciani, Ferroglia, Anastasiou, Czacon …]

* **CP violation** arising from electric or chromoelectric dipole moments do not contribute to the asymmetry



- Main difference due to renormalization scale choice, the asymmetry is proportional to the strong coupling
- small dependence on PDFs

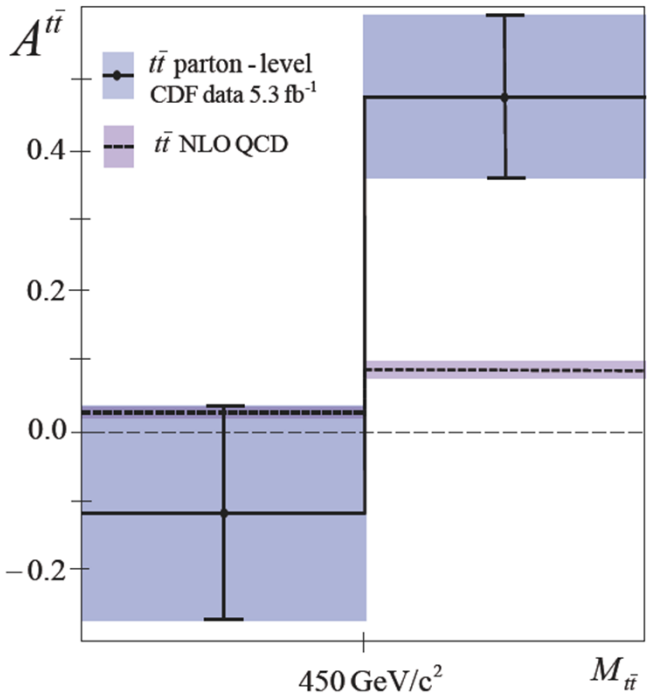
Invariant mass dependent charge asymmetry

Since 2008, a systematic 1-2σ **positive** discrepancy with the SM (inclusive asymmetry)

CDF [PRD83 (2011)112003 arXiv:1101.0034] $t\bar{t}$ rest frame 5.3 fb^{-1}

$A_{t\bar{t}}(m_{t\bar{t}} < 450\ \text{GeV})$ = -0.116 ± 0.146 (stat) ± 0.047 (syst)

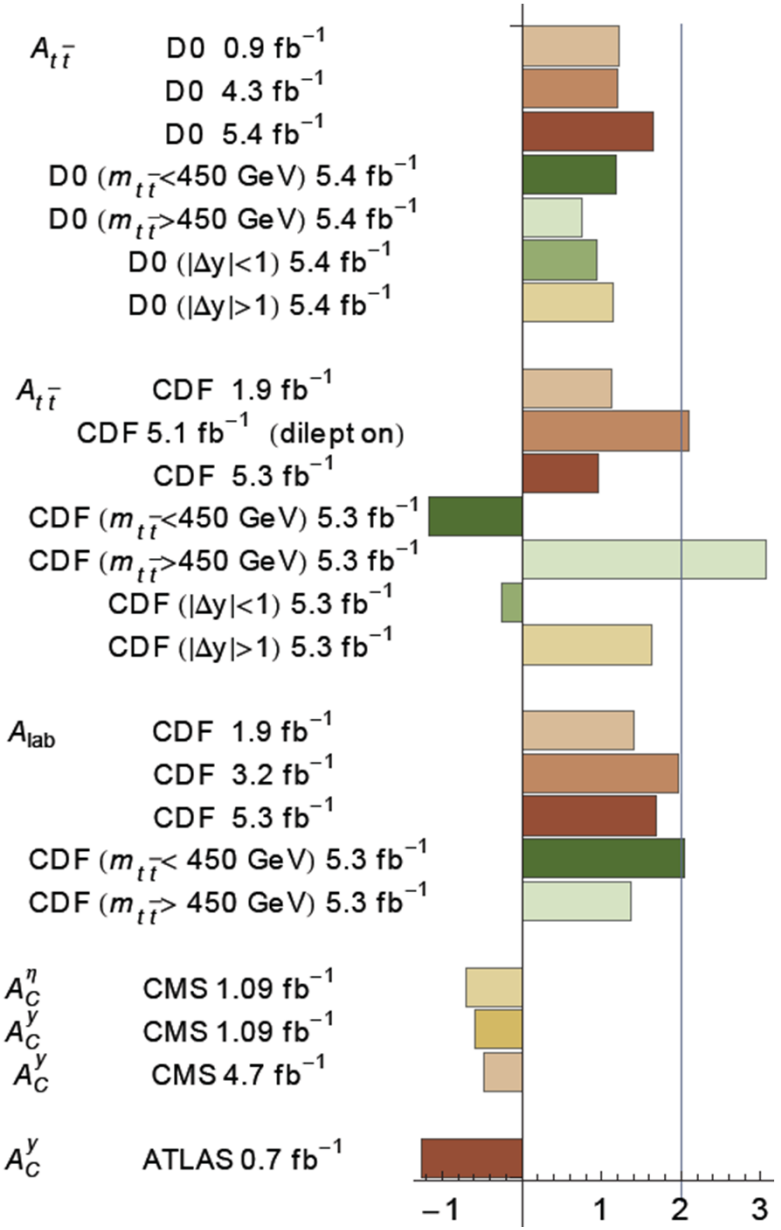
$A_{t\bar{t}}(m_{t\bar{t}} > 450\ \text{GeV})$ = 0.475 ± 0.101 (stat) ± 0.049 (syst)



- below 450 GeV: negative asymmetry but still compatible with the SM within 1σ
- above 450 GeV: positive asymmetry, disagrees with the SM at 3.4σ
- The deviation from the SM in the lab frame is not as significant !!!

Tevatron (and LHC) summary

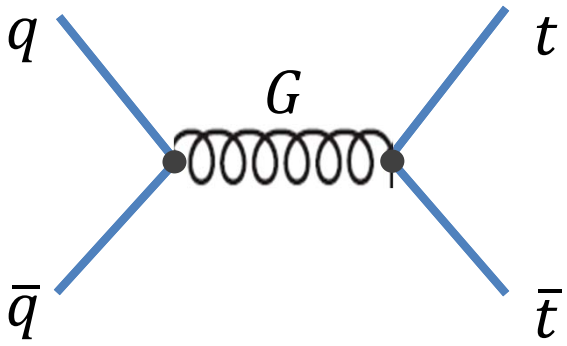
See talks by
Sandra Leone and
Pedro Ferreira da Silva



Axigluons or KK gluons : s-channel

Color-octet resonances

$$\mathcal{L} = g_S T^a \bar{q}_i \gamma^\mu \left(g_V{}^{q_i} + g_A{}^{q_i} \gamma_5 \right) G_\mu{}' q_i$$



might produce a charge asymmetry through the interference with the LO SM amplitude

But this asymmetry is **negative** because it is proportional to

$$\left(\hat{s} - m_G{}^2 \right) g_A{}^q \; g_A{}^t$$

A **positive** asymmetry can be generated if

- very light axigluon: but would be visible in $m_{t\bar{t}}$: new decay channels to enlarge the width [Marques Tavares, Schmalz / Barcelo, Carmona, Masip, Santiago]

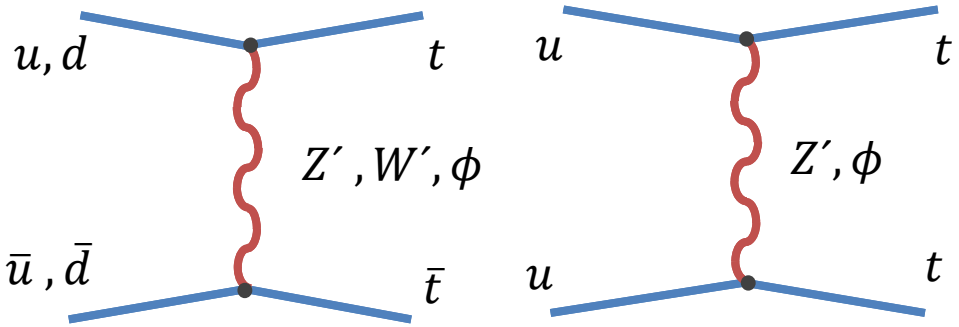
- vector-axial couplings of opposite sign: $\text{sign}(g_A{}^q) = -\text{sign}(g_A{}^t)$
[Ferrario, GR / Frampton,Shu,Wang / Djouadi, Richard / Bauer, Goertz, Haisch, Pfoh, Westhoff / Bai, Hewett, Kaplan, Rizzo / Zerwekh / Hewet, Shelton, Spannowsky, Tait, Takeuchi / Haisch, Westhoff / Aguilar-Saavedra, Perez-Victoria, …]

- squared of the BSM amplitude dominates, which is proportional to $g_V{}^q g_V{}^t g_A{}^q g_A{}^t$: large vector couplings [Ferrario, GR]

⇨ Very constrained by dijet ($t\bar{t}$) cross-section at LHC

New physics in the t-channel

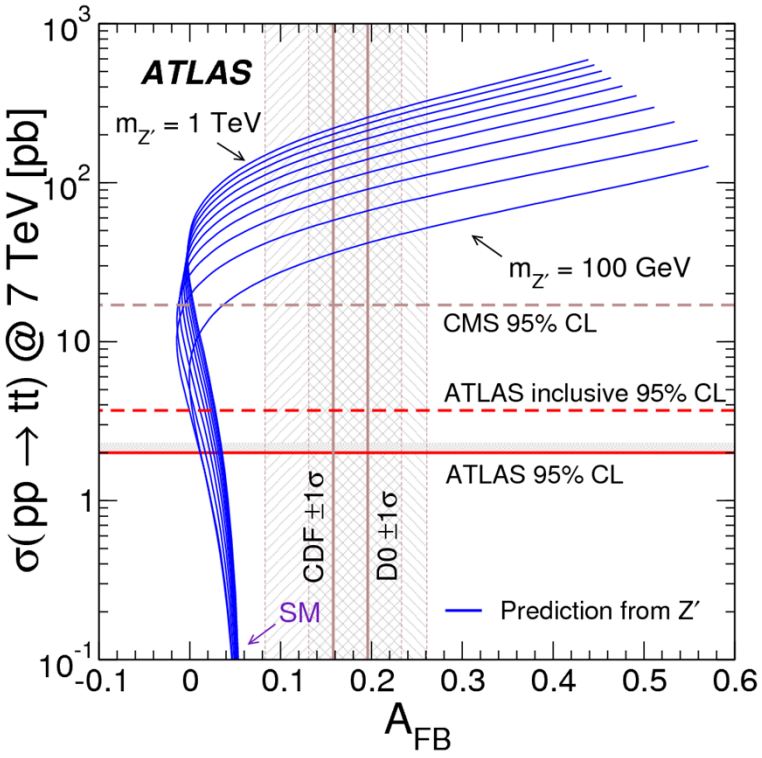
[Jung, Murayama, Pierce, Wells / Cheung, Keung,Yuan / Cao, Heng,Wu,Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria/ Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta, …]
[Shu,Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung,Ko,Lee,Nam. Aguilar-Saavedra, Perez-Victoria / Patel, Sharma / Ligeti, Marques Tavares, Schmalz, …]

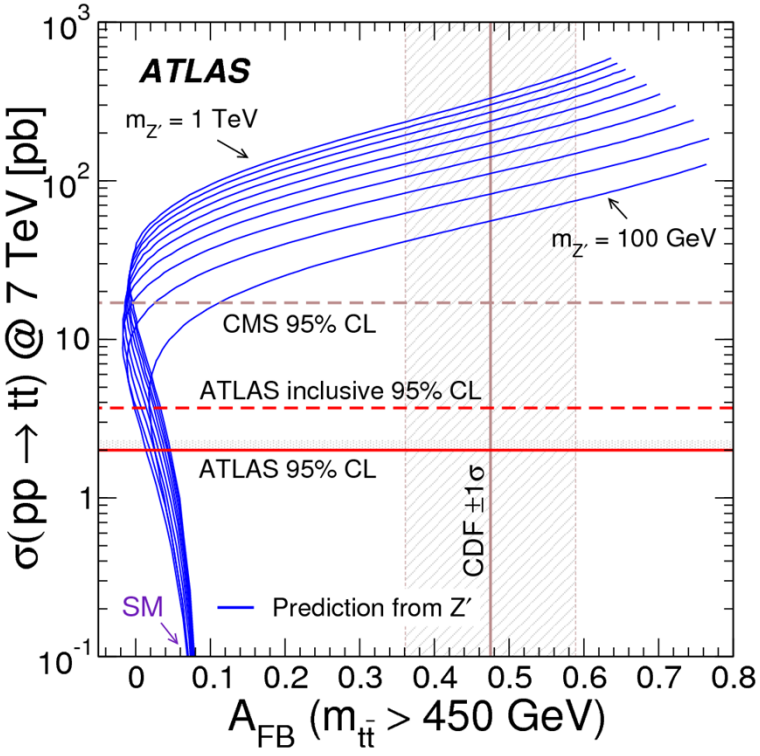


- Because of color algebra a Z' (SM Z) in the s-channel do not interfere with the LO QCD amplitude
- (coloured) scalars do not generate an asymmetry in the s-channel

- A sizeable charge asymmetry requires **large flavour violating couplings** [Jung,Murayama,Pierce,Wells]
- Relatively light Z´ and/or W´: O(200-700 GeV), or O(1TeV) colored scalars
- **like sign $tt + \bar{t}\bar{t}$**, very constrained at Tevatron, and the LHC

same-sign tops

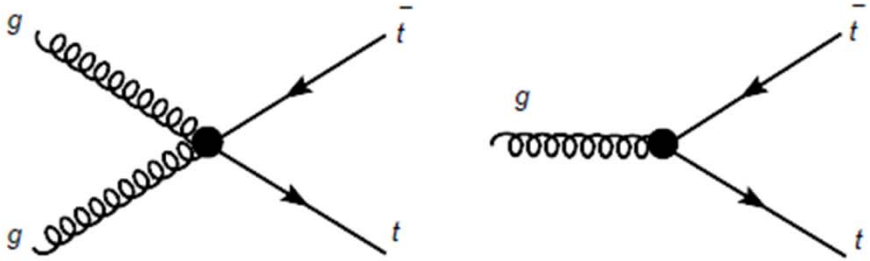




Can be evaded in non-minimal models with several Z' [Jung, Pierce Wells]

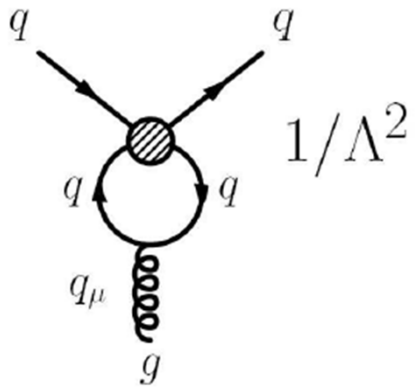
EFT

[Degrande, Gerard, Grojean, Maltoni, Servant/ Bauer, Goertz, Haisch, Pfoh, Westhoff / Zhang, Willenbrockv/ Aguilar-Saavedra, Perez-Victoria / Gabrieli, Racciopi, Raidal / Blum, Delaunay, Gedalia, Hochberg, Lee, Nir, Perez, Soreq, …]



Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^A t\, G^A_{\mu\nu}$

Four-fermion operators



- New physics scale Λ in the TeV or even sub-TeV region

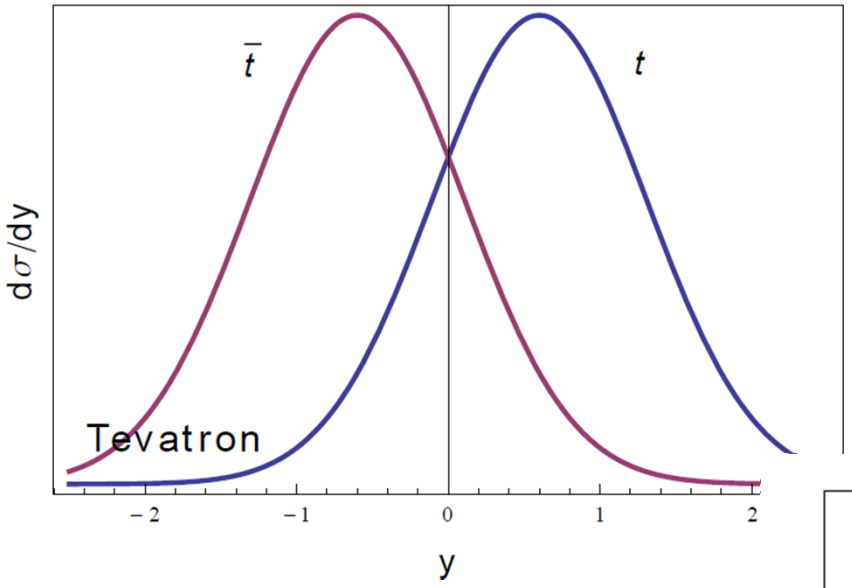
Transverse momentum of the $t\bar{t}$ pair

- the inclusive asymmetry is robust against higher order corrections [see also Melnikov]
- but diff. distributions might be quite sensitive ($t\bar{t}$+jet @NLO [Dittmaier, Uwer, Weinzierl / Alioli, Moch, Uwer])
- virtual + soft (positive) vs. real (negative)

	$A_{t\bar{t}}$	$m_{t\bar{t}} < 450$ GeV	$m_{t\bar{t}} > 450$ GeV
$p_\perp^{t\bar{t}} < 10$ GeV	0.136 (16)	0.097 (8)	0.201 (19)
$p_\perp^{t\bar{t}} < 20$ GeV	0.115 (13)	0.082 (7)	0.171 (16)
Inclusive	0.087 (10)	0.062 (5)	0.128 (11)

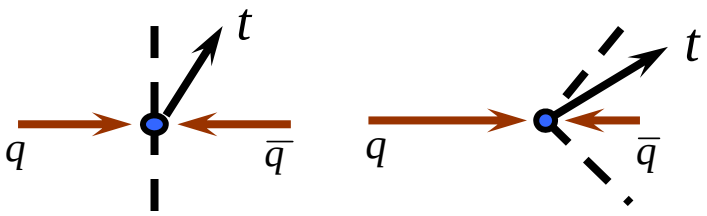
[Kühn, GR, arXiv:1109.6830]

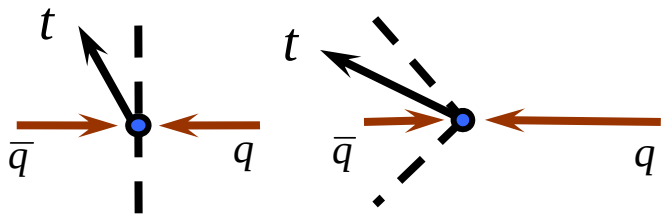
From Tevatron to the LHC

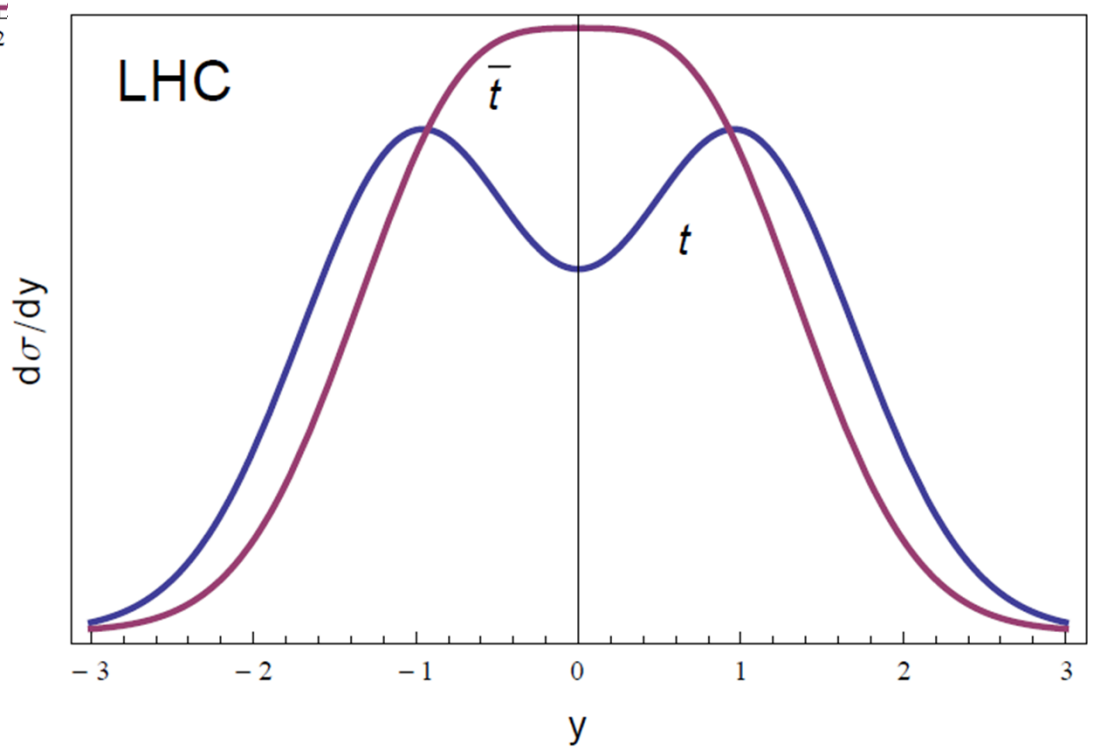


LHC is symmetric ► no forward-backward but excess of tops (or antitops) in the forward and backward regions because incoming quarks carry more momenta than antiquarks

► **gg dominated (symmetric):** introduce cuts to enhance the $q\bar{q}$ sample, e.g. $m_{t\bar{t}}$, large rapidities (gg more central)

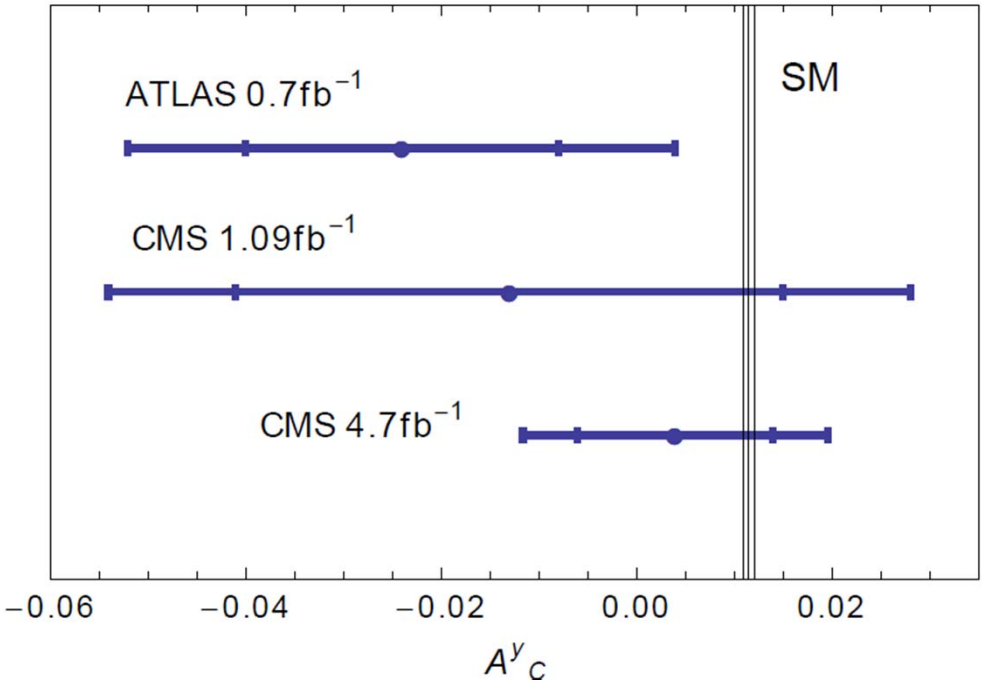






Charge asymmetry at the LHC

$$A_C^{\Delta} = \frac{N(\Delta>0)-N(\Delta<0)}{N(\Delta>0)+N(\Delta<0)} \qquad \Delta = |\eta_t| - |\eta_{\bar{t}}|, |y_t| - |y_{\bar{t}}| \text{ or } {y_t}^2 - {y_{\bar{t}}}^2$$



A^{η}_{SM} = 0.0136 (8)
A^{y}_{SM} = 0.0115 (6)

[Kühn, GR, arXiv:1109.6830] @ 7 TeV

atlas-conf-2011-106

$A_C^y = -0.009 \pm 0.023 \pm 0.032$ (e+jets)

$A_C^y = -0.028 \pm 0.019 \pm 0.022$ (μ+jets)

$A_C^y = -0.024 \pm 0.016 \pm 0.023$

cms (1112.5100)

$A_C^{\eta} = -0.017 \pm 0.032\ ^{+0.025}_{-0.036}$

$A_C^{y} = -0.013 \pm 0.028\ ^{+0.029}_{-0.031}$

cms-pas-top-11-030

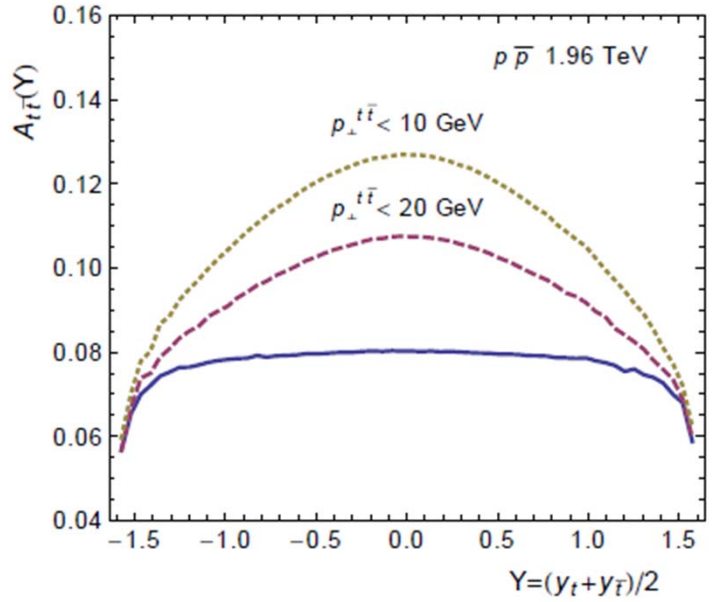
$A_C^y = 0.004 \pm 0.010 \pm 0.012$

- scaling the statistical error

20 fb^{-1} : 5 per mille

100 fb^{-1} : 2-3 per mille

Universal charge asymmetry

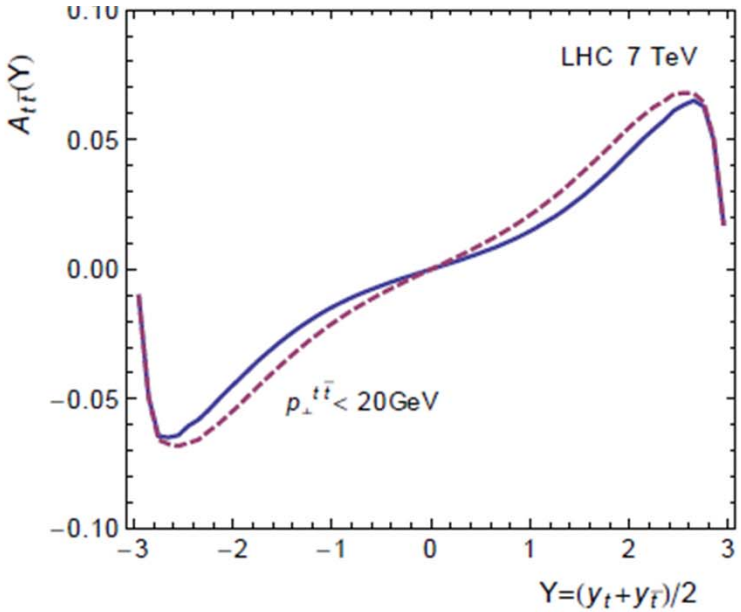


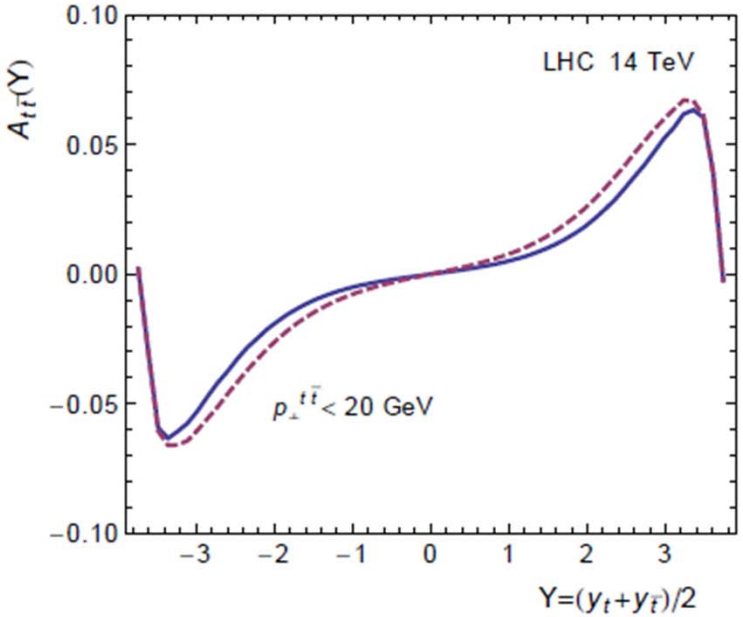
$$A_{t\bar{t}}(Y) = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

for $Y = \frac{1}{2}(y_t + y_{\bar{t}})$ fixed,

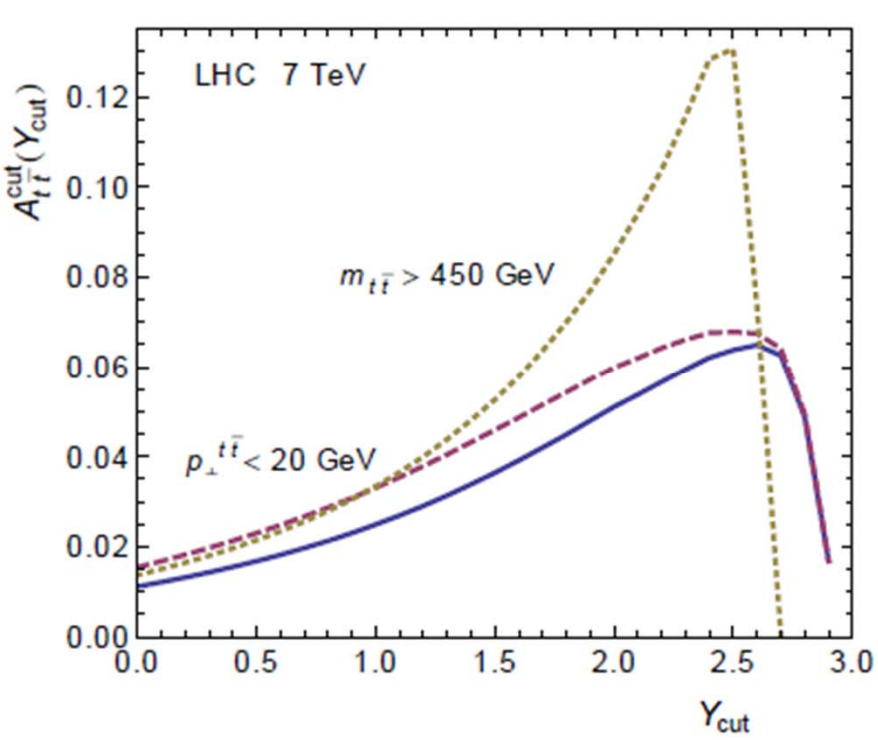
and $\Delta y = y_t - y_{\bar{t}}$

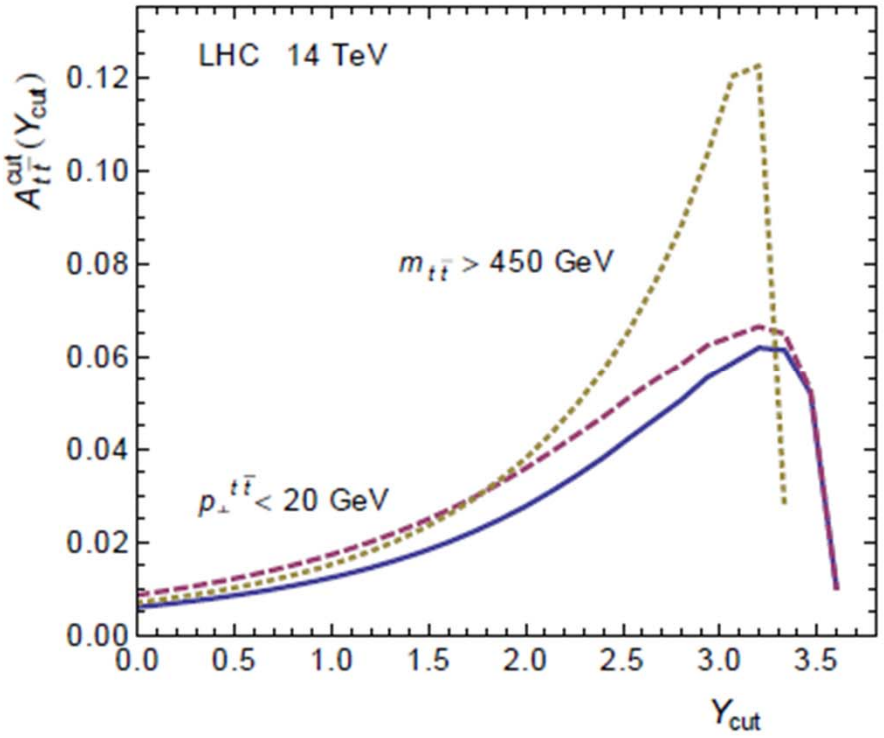
- Integrated asymmetry agrees with $A_{t\bar{t}}$ at Tevatron, and with A_C^y at the LHC



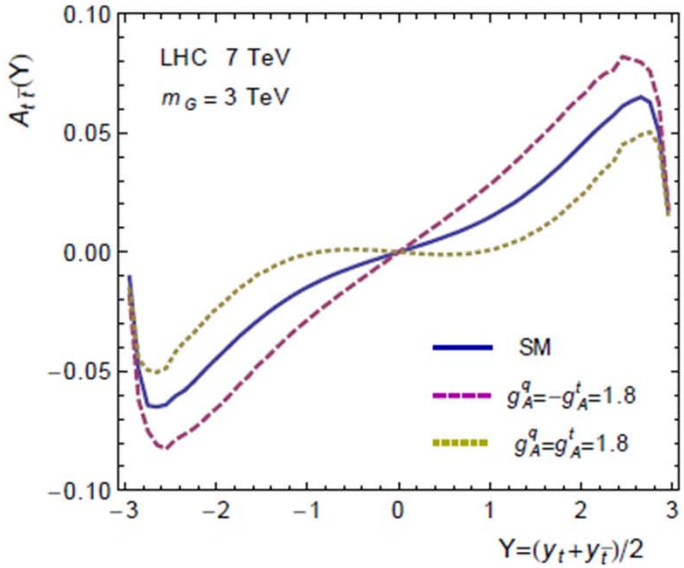


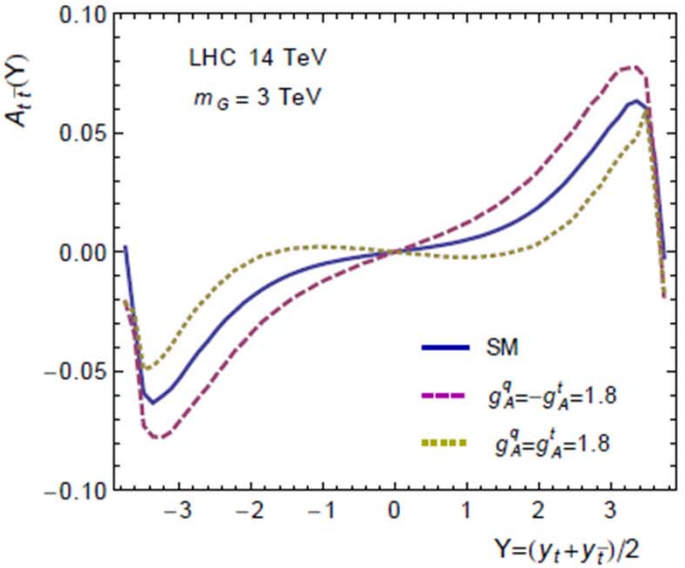
- Integrated asymmetry ($Y > Y_{\rm cut}$) as a function of $Y_{\rm cut}$

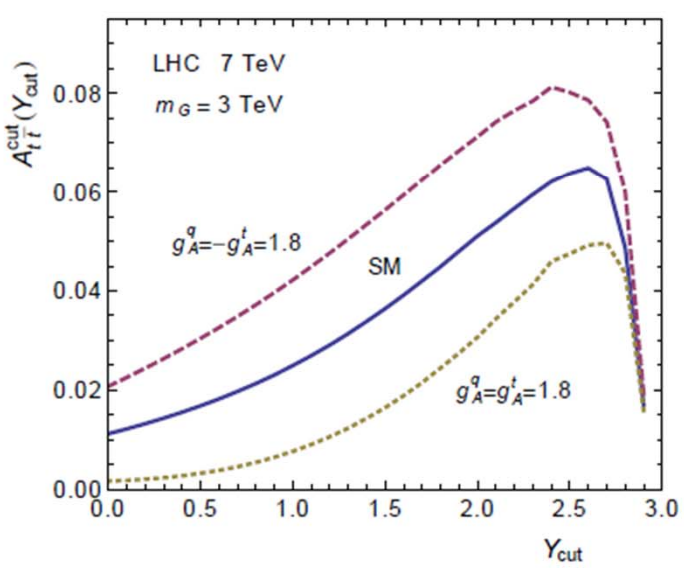


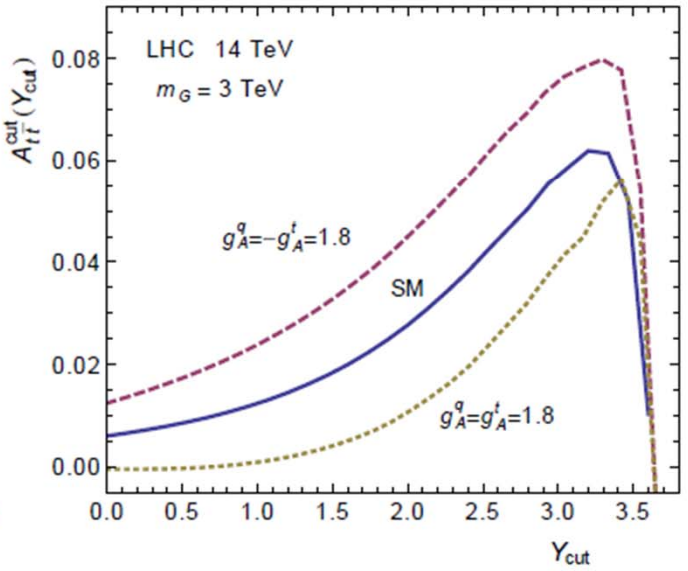


Axigluons (m_G=3TeV)









The asymmetry through the decay products

[Godbole, Rao, Rindani,Singh / Jung, Ko, Lee/ Choudhury, Godbole, Rindani, Saha/ Cao, Wu, Yang / Melnikov, Schulze / Bernreuther, Si/ Krohn, Liu, Shelton, Wang / Bai, Han/ Baumgart, Tweedie]

- Direction of the lepton (antilepton) correlated with the direction of the top quark (antitop quark), particularly for very boosted tops: asymmetry partially washed out

D0 arXiv:1107.4995 $A^l = 0.152\ (40)$ (3σ)

- The top quark decays before hadronizing: polarizations (angular distribution of the lepton wrt the parent top) and spin correlations will be **altered by BSM**

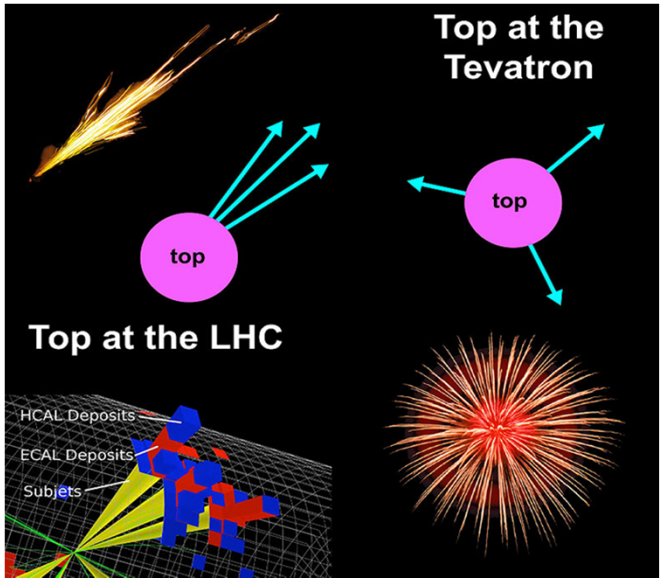


Image from Fermilab Today

Conclusions

- LHC measurements (dijets, same-sign top) set strong constrains on BSM explanations of the $t\bar{t}$ charge asymmetry excess

- Some “tension” between Tevatron and LHC on the $t\bar{t}$ charge asymmetry

- Expected new results from 2012 LHC run, Tevatron update, NNLO

- Same effect for b quarks, although much more gg supressed, challenging but not impossible