Implications of effective axial-vector coupling of gluon for $t\bar{t}$ spin polarizations at the LHC

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based on
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in collaboration with

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Motivation

- In 2011 both D0 and CDF collaborations at Tevatron observed a large excess for $A_{\rm FB}$ in $t\bar{t}$ production
- more than 3σ deviations from the SM predictions!
- if confirmed at LHC, this effect will be a NP discovery
- $A_{\rm FB}$ in $p\bar{p}$ collision is small in the SM, being induced by QCD quantum effects
- This excess, if it is not a statistical fluctuation, can only be explained by a large NP tree-level contribution
- many NP scenarios proposed

other scenarios

- axigluons:
  G. Rodrigo et al., Phys.Rev. D77, 014003 (2008); Phys.Rev. D78, 094018 (2008); Phys.Rev. D80, 051701 (2009)
  P. H. Frampton, J. Shu, and K. Wang, Phys.Lett. B683, 294 (2010)
  R. S. Chivukula, E. H. Simmons, and C.-P. Yuan Phys.Rev. D82, 094009 (2010)
  Y. Bai, J. L. Hewett, J. Kaplan, and T. G. Rizzo, JHEP 1103, 003 (2011)
  X.-P. Wang, Y.-K. Wang, B. Xiao, J. Xu, and S.-h. Zhu, Phys.Rev. D83, 115010 (2011)
  U. Haisch and S. Westhoff, JHEP 1108, 088 (2011)
  J. Aguilar-Saavedra et al., Phys.Lett. B705, 228 (2011); Phys.Rev. D85, 034021 (2012)
  G. Z. Krnjaic, Phys.Rev. D85, 014030 (2012)
  C.Gross, G. M. Tavares, M. Schmaltz, C. Spethmann, Phys.Rev. D87 014004 (2013)
- flavour changing Z':
  S. Jung, H. Murayama, A. Pierce, and J. D. Wells, Phys.Rev. D81, 015004 (2010)
  B. Xiao, Y.-k. Wang, and S.-h. Zhu, Phys.Rev. D82
  J. Cao, L. Wang, L. Wu, and J. M. Yang, Phys.Rev. D84, 074001 (2011)
  E. L. Berger, Q.-H. Cao, C.-R. Chen, C. S. Li, and H. Zhang, Phys.Rev.Lett. 106, 201801 (2011)
  J. Aguilar-Saavedra and M. Perez-Victoria, Phys.Lett. B701, 93 (2011)
  D.-W. Jung, P. Ko, and J. S. Lee, Phys.Rev. D84, 055027 (2011)
  M. Duraisamy, A. Rashed, and A. Datta, Phys.Rev. D84, 054018 (2011)
  P. Ko, Y. Omura, and C. Yu, Phys.Rev. D85, 115010 (2012)
- W':
  K. Cheung, et al. Phys.Lett. B682, 287 (2009); Phys.Rev. D83, 074006 (2011)
  B. Bhattacherjee, S. S. Biswal, and D. Ghosh, Phys.Rev. D83, 091501 (2011)
  V. Barger, W.-Y. Keung, and C.-T. Yu, Phys.Lett. B698, 243 (2011)
  N. Craig, C. Kilic, and M. J. Strassler, Phys.Rev. D84, 035012 (2011)
  C.-H. Chen, S. S. Law, and R.-H. Li, J.Phys. G38, 115008 (2011)
  K. Yan, J. Wang, D. Y. Shao, and C. S. Li, Phys.Rev. D85, 034020 (2012)
  S. Knapen, Y. Zhao, and M. J. Strassler, Phys.Rev. D86, 014013 (2012)

and many more . . . sorry for any missing references :)

Motivation

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- more than 3σ deviations from the SM predictions!
- if confirmed at LHC, this effect will be a NP discovery
- A_{FB} in $p\bar{p}$ collision is small in the SM, being induced by QCD quantum effects
- This excess, if it is not a statistical fluctuation, can only be explained by a large NP tree-level contribution
- many NP scenarios proposed, some of them already ruled out by negative LHC searches on new heavy particles
  CMS: JHEP 1108, 005 (2011), PRL 106, 201804 (2011);
  ATLAS: New J.Phys. 13, 053044 (2011)

Basic idea

- The "Tevatron anomaly" is due to an (effective) axial-vector gluon couplings to quarks induced by New Physics!
  (E. Gabrielli, M.Raidal, Phys. Rev. D 84, 054017 (2011))
- SM Weak interactions induce at 1-loop a axial-vector gluon couplings to quarks $\rightarrow$ but too small
- a characteristic NP energy scale $\Lambda \sim O(1\ \text{TeV})$
- We analyzed the implications of this scenario at LHC for
  - A_{FB} and A_C (Phys. Rev. D 85, 074021 (2012))
    checked by CMS! (Phys. Lett. B 717, 129 (2012))
  - A_h and A_{LR} (this talk, Phys. Rev. D 87, 054001 (2013))

Theoretical framework. Effective vertex

Requiring

1. lowest dimensional operators
2. gauge, CP, and Lorentz invariance
3. compatibility with Tevatron Data (Phys. Rev. D 84, 054017 (2011))

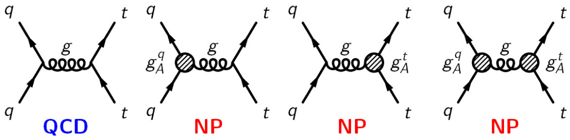
we parametrize

$$\begin{aligned}
\Gamma^{a\,\mu} &= \Gamma^{a\;\mu}_{\rm QCD} + \Gamma^{a\;\mu}_{A} \\
\Gamma^{a\;\mu}_{\rm QCD} &= -ig_s T^a \gamma^\mu \\
\Gamma^{a\;\mu}_{A} &= -ig_s g_A^q\, T^a \left(\gamma_\mu\gamma_5 - 2q_\mu \frac{m_q}{q^2}\gamma_5\right) \\
g_A^q(q^2) &= \frac{q^2}{\Lambda^2} + \left[\ln(q^2/\Lambda^2)\ \text{terms}\right] \quad \text{(flavor universal)}
\end{aligned}$$

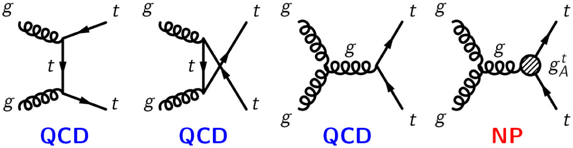
- g_S is the strong coupling constant and T^a are the color matrices
- q^μ the entering momentum of the gluon
- Λ, the NP scale

Feyman diagrams

- $q(p_1)\bar{q}(p_2) \rightarrow t(p_3)\bar{t}(p_4)$

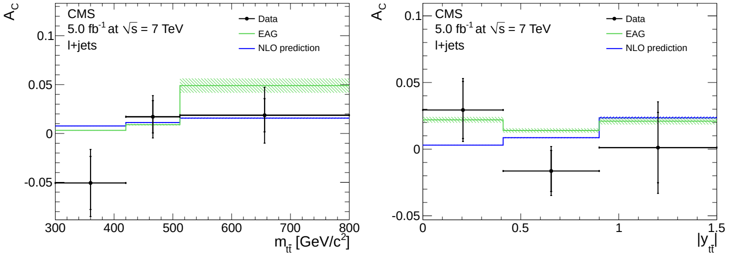


- $g(p_1)g(p_2) \rightarrow t(p_3)\bar{t}(p_4)$



Charge asymmetry & CMS check

Phys. Lett. B 717, 129 (2012), (CMS-PAS-TOP-11-030):



- $A_C = \frac{N(\Delta_y>0)-N(\Delta_y<0)}{N(\Delta_y>0)+N(\Delta_y<0)}$, where $\Delta_y \equiv |y_t| - |y_{\bar{t}}|$ and y_q is the q rapidity.
- EAG: effective axial-vector coupling of the gluon $\rightarrow$ our model
- Data compatible with both EAG and SM $\Rightarrow$ further studies on:
  - A_C^{in}, A_C^{out} and A_C^{cut} (Phys. Rev. D 85, 074021 (2012))
  - A_h and A_{LR} (Phys. Rev. D 87, 054001 (2013))

Spin correlation. State of the art

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - [N(\uparrow\downarrow) + N(\downarrow\uparrow)]}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

A_h: A evaluated in the helicity basis and in the ZMF of the $t\bar{t}$ pair.

Inclusive LHC measurements:

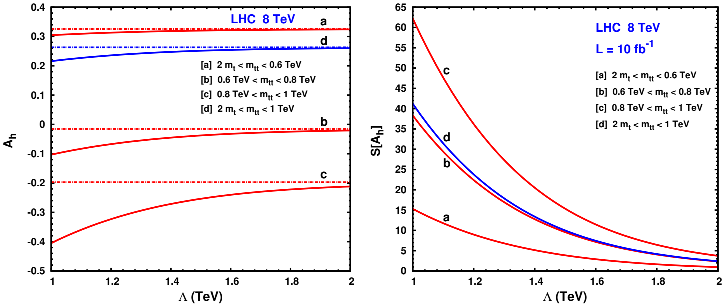
- $A_h^{\rm ATLAS} = 0.40^{+0.09}_{-0.08}$, L$= 2.1{\rm fb}^{-1}$
  (Phys. Rev. Lett. 108, 212001 (2012))
- $A_h^{\rm CMS} = 0.24 \pm 0.02({\rm stat}) \pm 0.08({\rm syst})$, L$= 5{\rm fb}^{-1}$
  (CMS-PAS-TOP-12-004)

QCD prediction @NLO for $\sqrt{S} = 7$ TeV:

- $A_h^{\rm SM} = 0.31$
  (W. Bernreuther and Z.-G. Si, Nucl. Phys. B 837, 90 (2010))

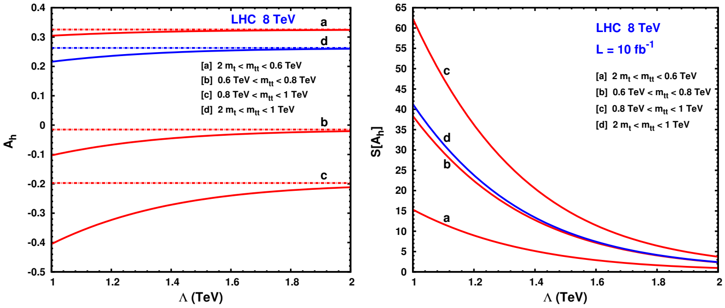
$A_h^{\rm ATLAS}$ and $A_h^{\rm CMS}$ are compatible with each other and with $A_h^{\rm SM}$ within 2σ.

Spin correlation. Results



1. $\Lambda = 1$ TeV: the maximum deviation from the SM value
    - [a] and [d]: 10% deviation
    - [b]: 25% deviation
    - [c]: 100% deviation
2. $\Lambda = 2$ TeV: the overall NP effect strongly reduced

Spin correlation. Results



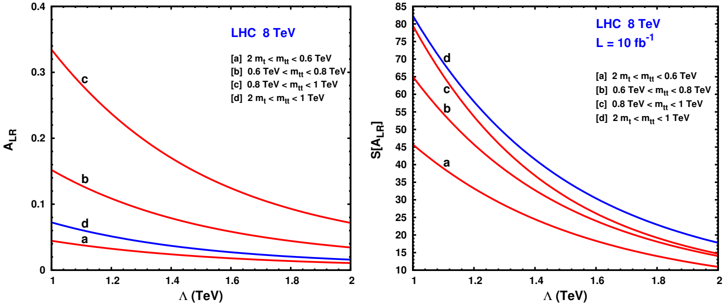
3. $S[A_h] == \Delta A_h \sqrt{\sigma^{\rm SM+NP} L}$, $\Delta A_h = |A_h^{\rm SM+NP} - A_h^{\rm SM}|$
4. $S[A_h]$ for $L = 10\,{\rm fb}^{-1}$ are quite large, specially for $\Lambda = 1$ TeV
5. for $\Lambda = 2$ TeV, $S[A_h]$ is much lower, with $S[A_h]^{\rm max} \simeq 4$ for [c]
6. analyzing the m_{tt} distributions of A_h, the full range up to $\Lambda \sim 2$ TeV can be probed at LHC8, even with $L = 10\,{\rm fb}^{-1}$.

Left-Right asymmetry. State of the Art

$$A_{LR} = \frac{N(\uparrow\uparrow) + N(\uparrow\downarrow) - \left[N(\downarrow\uparrow) + N(\downarrow\downarrow)\right]}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

- A_{LR}^{SM} is suppressed (one loop EW corrections to QCD)
- A_{LR}^{SM} @ LHC14 $\sim 0.5\%$
  (C. Kao, D. Wackeroth, Phys. Rev. D 61, 055009 (2000))
- A_{LR} is a very sensitive probe to NP beyond the SM.

Left-Right asymmetry. Results



1. $A_{LR}^{\rm SM} \ll A_{LR}^{\rm NP} \Rightarrow$
   - $A_{LR} \simeq A_{LR}^{\rm NP}$
   - $S[A_{LR}] = |A_{LR}^{NP}|\sqrt{\sigma^{\rm NP+SM} L}$
2. the contribution induced by g_A to A_{LR} is sizeable, specially for $\Lambda = 1$ TeV
3. even though $|A_{LR}| < |A_h|$, $S[A_{LR}] > S[A_h]$ because $A_{LR}^{\rm SM} \ll A_{LR}^{\rm NP}$. Therefore, A_{LR} is a more sensitive probe of this scenario than A_h.

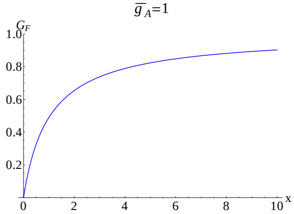
Comparison with LHC results

- ATLAS & CMS: **INCLUSIVE** measurements at $\sqrt{S} = 7$ TeV
- our framework valid only for $m_{tt} < \Lambda$
- need to extend g_A in the region $m_{tt} > \Lambda$
- toy example:

$$g_A(q^2) = G_F(q^2/\Lambda^2)$$

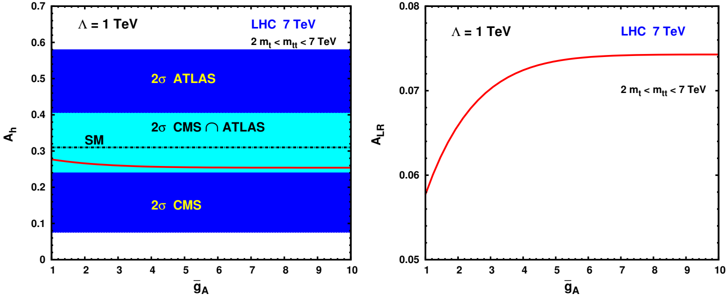
$$G_F(x) = \bar{g}_A - \log\left(\frac{e^{\bar{g}_A} + y}{1 + y}\right), \quad y = \frac{x e^{\bar{g}_A}}{(e^{\bar{g}_A} - 1)}$$

$$\lim_{x \to \infty} G_F(x) = \bar{g}_A \leftarrow \text{extension}$$



$$G_F(x) = x + \mathcal{O}(x^2) \text{ for } x \ll 1 \Rightarrow g_A(q^2) \simeq q^2/\Lambda^2 \leftarrow \text{our initial framework}$$

Comparison with LHC results



1. multiplied the results obtained at the LO by the SM K factor, $K = A_h^{\rm NLO}/A_h^{\rm LO}$ at $\sqrt{S} = 7$ TeV
2. decrease of the A_h values with respect to the SM prediction
3. deviations from the SM prediction, for $\Lambda = 1$ TeV, are within the 2σ bands of ATLAS and CMS measurements
4. increase of the A_{LR} values by increasing $\bar{g}_A$. No SM prediction in the plot since it is much smaller

Conclusions

1. We analyzed the impact of g_A on A_h and A_{LR} in $t\bar{t}$ production at the LHC and we showed that it would be necessary to measure them as function of m_{tt}
2. We found that A_{LR} is the best probe to test this scenario since the SM background is negligible
3. We estimated the potential effect of g_A on the m_{tt} inclusive measurements obtained by ATLAS and CMS collaborations and we showed that this scenario, for a scale $\Lambda \geq 1$ TeV, is still consistent with present measurements within 2σ
4. Therefore, a more dedicated analysis of those quantities as a function of m_{tt} is mandatory in order to test this scenario at LHC. We stress that LHC8 has enough sensitivity either to confirm the Tevatron top charge asymmetry anomaly or to rule it out in the context of the considered NP scenario.

Thank you!

Backup slides

Theoretical framework

The most general effective vertex for a quark-gluon interaction

1. containing the contribution of lowest dimensional operators
2. gauge ($q_\mu \Gamma^{a\,\mu} = 0$ for $q^2 = 0$), CP, and Lorentz invariant

$$\Gamma^{a\,\mu}(q^2, M) = -ig_s T^a \Big\{ \gamma^\mu \Big[1 + g_V(q^2, M) + \gamma_5 g_A(q^2, M) \Big] + g_P(q^2, M) q^\mu \gamma_5 + g_M(q^2, M) \sigma^{\mu\nu} q^\nu \Big\}$$

- g_S is the strong coupling constant
- T^a are the color matrices
- $g_{V,A,P,M}$ form factors depend on the NP energy scale M (and on the quark flavor, but not here)
- q^μ the entering momentum of the gluon

Form factors

$$\Gamma^{a\,\mu} = -ig_s T^a \Big\{ \gamma^\mu \Big[1 + g_V + \gamma_5 g_A \Big] + g_P q^\mu \gamma_5 + g_M \sigma^{\mu\nu} q^\nu \Big\}$$

Gauge invariance with real quarks (off-shell gluon $q^2 \neq 0$):

$$\begin{cases} q_\mu \bar{U}_f(p_1)\, \Gamma^{a\,\mu}(q^2, M)\, U_f(p_2) = 0 \leftarrow \text{current conservation} \\ \left. \begin{array}{l} (\not{p}_2 - m_2) U_f(p_2) = 0 \\ \bar{U}_f(p_1)(\not{p}_1 - m_1) = 0 \end{array} \right\} \leftarrow \text{quarks EOM} \end{cases}$$

or similar ...

$$\Downarrow$$

$$2 m_Q g_A(q^2, M) + q^2 g_P(q^2, M) = 0$$

$$\lim_{q^2 \to 0} g_{A,V}(q^2, M) = 0$$

Form factors

$$\Gamma^{a\,\mu} = -ig_s T^a \Big\{ \gamma^\mu \Big[1 + g_V + \gamma_5 g_A \Big] + g_P q^\mu \gamma_5 + g_M \sigma^{\mu\nu} q^\nu \Big\}$$

- Tevatron Data: $g_V \ll g_A$ (Phys. Rev. D 84, 054017 (2011))
- in the limit of $q^2 \ll M^2$

$$g_A(q^2, M) = \frac{q^2}{\Lambda^2} F(q^2, \Lambda)$$

  and we absorb the NP coupling α_{NP} into $\Lambda^2 = M^2/(4\pi\alpha_{NP})$
- $F(q^2, \Lambda) = 1 + \left[\ln(q^2/\Lambda^2) \text{ terms}\right]$
- $g_M \sim 0$

Effective vertex: Final expression

$$\Gamma^{a\,\mu} = -ig_s T^a \left\{ \gamma^\mu \left[1 + g_V + \gamma_5 g_A \right] + g_P q^\mu \gamma_5 + g_M \sigma^{\mu\nu} q^\nu \right\}$$

so that we can write

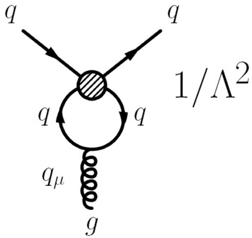
$$\Gamma^{a\,\mu} = \Gamma^{a\,\mu}_{\text{QCD}} + \Gamma^{a\,\mu}_{A}$$

$$\begin{aligned}
\Gamma^{a\,\mu}_{\text{QCD}} &= -ig_s T^a \gamma^\mu \\
\Gamma^{a\,\mu}_{A} &= -ig_s g^q_A \, T^a \left(\gamma_\mu \gamma_5 - 2 q_\mu \frac{m_q}{q^2} \gamma_5 \right) \\
g^q_A(q^2) &= \frac{q^2}{\Lambda^2} \quad \text{(flavor universal)}
\end{aligned}$$

Origin of the effective vertex

Model independently the effective operators

$$O^{1,8}_{AV} = \frac{1}{\Lambda^2}[\bar{Q}T_{1,8}\gamma^\mu\gamma_5 Q][\bar{Q}T_{1,8}\gamma^\mu Q]$$
$$O^{1,8}_{PS} = \frac{1}{\Lambda^2}[\bar{Q}T_{1,8}\gamma_5 Q][\bar{Q}T_{1,8} Q]$$

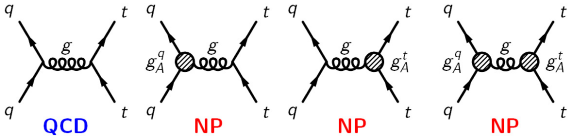


generate g_A via the depicted 1-loop diagram.
Here $T_1 = 1$ and $T_8 = T^a$.

i. no g_V is induced due to the CP odd property of $O^{1,8}_{AV}$, $O^{1,8}_{PS}$ and to QCD parity conservation
ii. $O^{1,8}_{AV}$, $O^{1,8}_{PS}$ do not induce FC processes; however, there could be different quark flavors in the loop (the extension is straightforward)
iii. the operators $O^{1,8}_{AV}$, $O^{1,8}_{PS}$ do not interfere with the corresponding QCD induced 4-quark processes ⇒ the stringent LHC constraints on 4-quark contact interactions do not apply at all. Those constraints come from the interference between QCD and NP diagrams, but here they are absent

Polarized $q\bar{q} \to t\bar{t}$ process

- $q(p_1)\bar{q}(p_2) \to t(p_3)\bar{t}(p_4)$

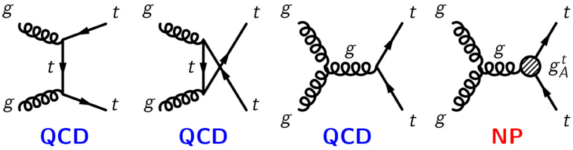


$$
\begin{aligned}
\sigma_{LL}^{q\bar{q}}(\hat{s}) &= \frac{2\pi\alpha_S^2}{27\hat{s}}\beta\rho\left(1+|g_A^q|^2\right) \\
\sigma_{LR}^{q\bar{q}}(\hat{s}) &= \frac{4\pi\alpha_S^2}{27\hat{s}}\left(1+|g_A^q|^2\right)\left(2\mathrm{Re}[g_A^t](1-\rho)+\beta\left(1+|g_A^t|^2(1-\rho)\right)\right) \\
\sigma_{RR}^{q\bar{q}}(\hat{s}) &= \sigma_{LL}^{q\bar{q}}(\hat{s}) \\
\sigma_{RL}^{q\bar{q}}(\hat{s}) &= \sigma_{LR}^{q\bar{q}}(\hat{s})\left\{\mathrm{Re}[g_A^t] \to -\mathrm{Re}[g_A^t]\right\}
\end{aligned}
$$

where we neglect the mass of the initial light quarks, $\beta = \sqrt{1-\rho}$, with $\rho = 4m_t^2/\hat{s}$, and $\hat{s} = (p_1+p_2)^2$.

Polarized $gg \to t\bar{t}$ process

- $g(p_1)g(p_2) \to t(p_3)\bar{t}(p_4)$



$$\sigma_{LL}^{gg}(\hat{s}) = \frac{\pi\alpha_S^2}{192\,\hat{s}\beta}\left\{2\left(16-14\rho+31\rho^2\right)-\frac{\rho}{\beta}\left(2+\rho\left(29+2\rho\right)\right)\log\frac{1+\beta}{1-\beta}\right\}$$

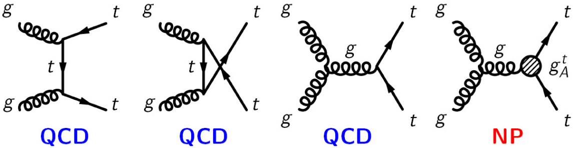
$$\sigma_{LR}^{gg}(\hat{s}) = \frac{\pi\alpha_S^2}{192\,\hat{s}\beta}\left\{2\left(11\left(\rho-4\right)+6|g_A^t|^2\left(1-\rho\right)^2\right)+\frac{1}{\beta}\left(32+\left(2-\rho\right)\rho\right)\log\frac{1+\beta}{1-\beta}\right\}$$

$$\sigma_{RR}^{gg}(\hat{s}) = \sigma_{LL}^{gg}(\hat{s})$$

$$\sigma_{RL}^{gg}(\hat{s}) = \sigma_{LR}^{gg}(\hat{s})$$

where $\beta = \sqrt{1-\rho}$, with $\rho = 4m_t^2/\hat{s}$, and $\hat{s} = (p_1+p_2)^2$.

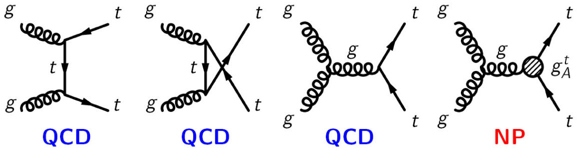
Gauge invariance of $gg \to t\bar{t}$



$$M = M^{QCD} + M_s^A$$

M^{QCD} is manifestly gauge invariant while M_s^A diagram alone is not. However, this is just an artifact of the effective theory. We can always construct a full amplitude including g_A in a manifestly gauge invariant way.

Gauge invariance of $gg \to t\bar{t}$

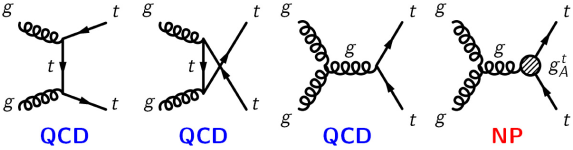


Let us add to M a new contribution $\bar{M}_s^A$, which is identical to the s-channel diagram M_s^A contribution, but with the 3-gluon vertex suitable modified. In particular, in M_s^A the Lorentz structure of the QCD 3-gluon vertex (in momentum space) $\Gamma^{\alpha\beta\mu}_{\rm QCD}$ will be replaced by a new 3-gluon vertex $\bar{\Gamma}^{\alpha\beta\mu}$ defined as

$$p_{1\alpha}\left(\Gamma^{\alpha\beta\mu}_{\rm QCD}+\bar{\Gamma}^{\alpha\beta\mu}\right)=p_{2\beta}\left(\Gamma^{\alpha\beta\mu}_{\rm QCD}+\bar{\Gamma}^{\alpha\beta\mu}\right)=0+\cdots,$$

where $\cdots$ stands for terms proportional to $p_{2\beta}$ and/or $p_{1\alpha}$, that vanish when contracted with the external on-shell gluon polarizations $\epsilon^a_\alpha(p_1)$ and $\epsilon^b_\beta(p_2)$ respectively.

Gauge invariance of $gg \to t\bar{t}$



$\bar{\Gamma}^{\alpha\beta\mu}$ is given by

$$\bar{\Gamma}^{\alpha\beta\mu} = \frac{2}{s} p_2^{\alpha} p_1^{\beta} (p_2^{\mu} - p_1^{\mu}) + 2\delta^{\mu\alpha} p_1^{\beta} - 2\delta^{\mu\beta} p_2^{\alpha} \,,$$

(α, $\beta \to$ on-shell g)
The effective amplitude $M_{GI} = M + \bar{M}_s^A$ turns out to be manifestly gauge invariant under the transformations $\epsilon_{\mu}^{a}(p_1) \to p_{1\mu}$ and $\epsilon_{\mu}^{b}(p_2) \to p_{2\mu}$. After a bit of algebra,

$$\sum_{\text{pol}} |M|^2 = \sum_{\text{pol}} |M_{GI}|^2 \,,$$

showing that our result for the cross-section is truly $SU(3)_c$ gauge invariant.

Statistical significance

$$\begin{aligned} A &= \frac{N^+ - N^-}{N^{\text{TOT}}} \\ N^{\text{TOT}} &= N^+ + N^- \end{aligned}$$

what we measure is N^+ and N^-, so only the numerator really matters

$$\begin{aligned} (N^+ - N^-)_{\text{NP+SM}} - (N^+ - N^-)_{\text{SM}} &= X\Delta(N^+ - N^-)_{\text{NP+SM}} \\ S[A] &= X \end{aligned}$$

$$\Delta(N^\pm) = \sqrt{N^\pm} \quad \Rightarrow \quad \Delta(N^+ - N^-) = \sqrt{N^+ + N^-} = \sqrt{N^{\text{TOT}}}$$

$$\begin{aligned} X &= \frac{(N^+ - N^-)_{\text{NP+SM}} - (N^+ - N^-)_{\text{SM}}}{\Delta(N^+ - N^-)_{\text{NP+SM}}} = \dots \\ &\simeq |A_{\text{NP+SM}} - A_{\text{SM}}|\sqrt{\sigma_{\text{NP+SM}}\mathcal{L}} \qquad \text{if } N^{\text{TOT}}_{\text{NP+SM}} \simeq N^{\text{TOT}}_{\text{SM}} \end{aligned}$$