Top Quark Physics

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Refs: PRD 84: 050417 (2011); PRD 85: 074021 (2012)

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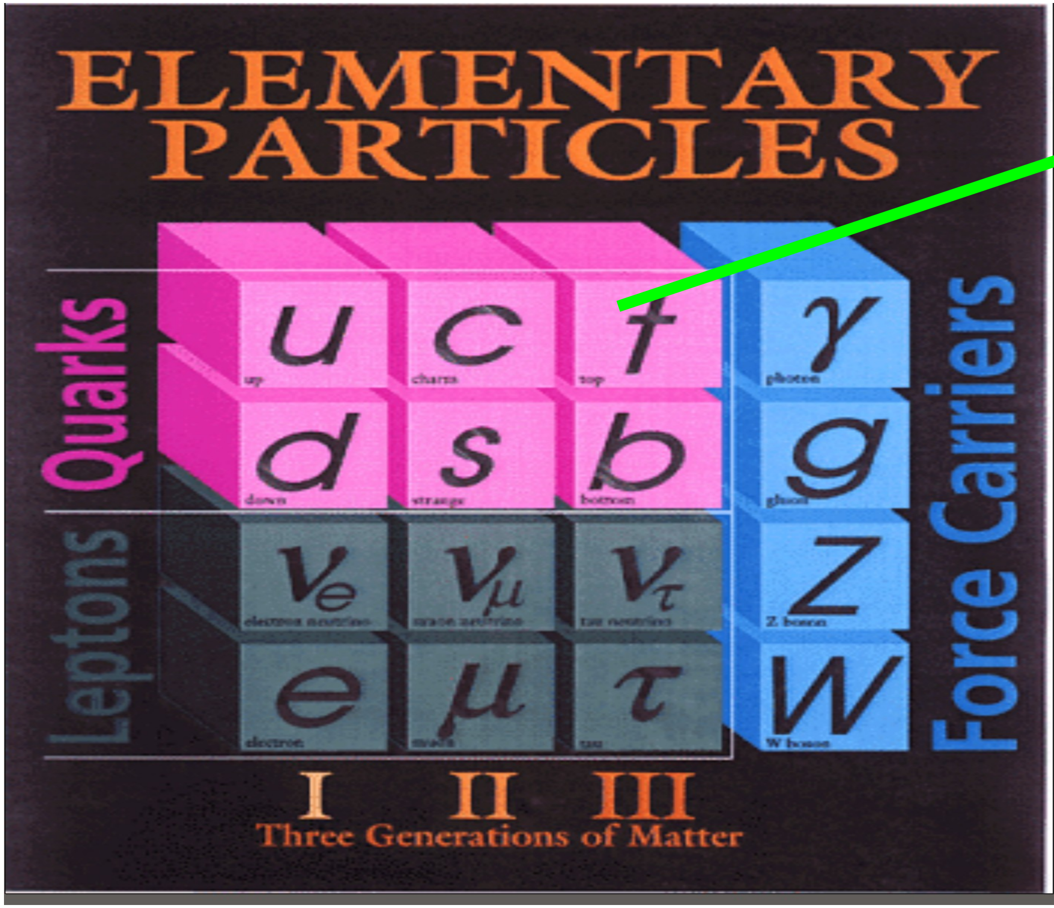
The building block of known elementary particles



top-quark

Massless

photon: EM

8 gluons: strong

Massive

Weak

M_W = 80 GeV

M_Z = 91 GeV

Electric charges
(in unity of e)

$Q_\nu = 0$
$Q_e = 1$

$Q_U = 2/3$
$Q_D = -1/3$

Mass of top-quark = 172 GeV
heaviest known elementary particle!

ref: → proton mass ~ 1 GeV

Main properties of top-quark

- Discovered at Fermilab in 1995
- complete the 3 quark-generations of Standard Model
- mainly produced in hadron collisions through strong interactions $\boxed{pp \to t\,\bar{t} + X}$ $(gg \to t\,\bar{t}$ and $q\bar{q} \to t\,\bar{t}$ @ NLO)
- It decays rapidly in $t \to W\,b$ without forming hadrons $\to$ possibility to measure top-quark polarizations
- Top-quark rare decays and CP violations are very small (in SM) and so very sensitive to New Physics
- Top Yukawa coupling to Higgs boson is ~ of order O(1)
- EW precision tests are very sensitive to its mass !

Some reasons to study top-quark physics

- top-quark mass is intriguingly close to the EW symmetry breaking scale: <H> ~ 246 GeV

- Is the top-quark mass generated by the Higgs mechanism as predicted by the SM ?

- recent discovery at LHC of (potential) Higgs boson with mass ~ 125 GeV will clarify soon this issue !

- New Physics could manifests itself in non-standard couplings to top-quark

- if so, this will show up in anomalies in top-quark productions and decays

role of top mass in EW precision tests

α = EM coupling
G_F = Fermi constant
$c_W = M_W / M_Z$

Rho-parameter

SM prediction

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\boxed{\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)}$$

Radiative corrections ⇨ **Breaking of Custodial Symmetry (SU(2)V)**

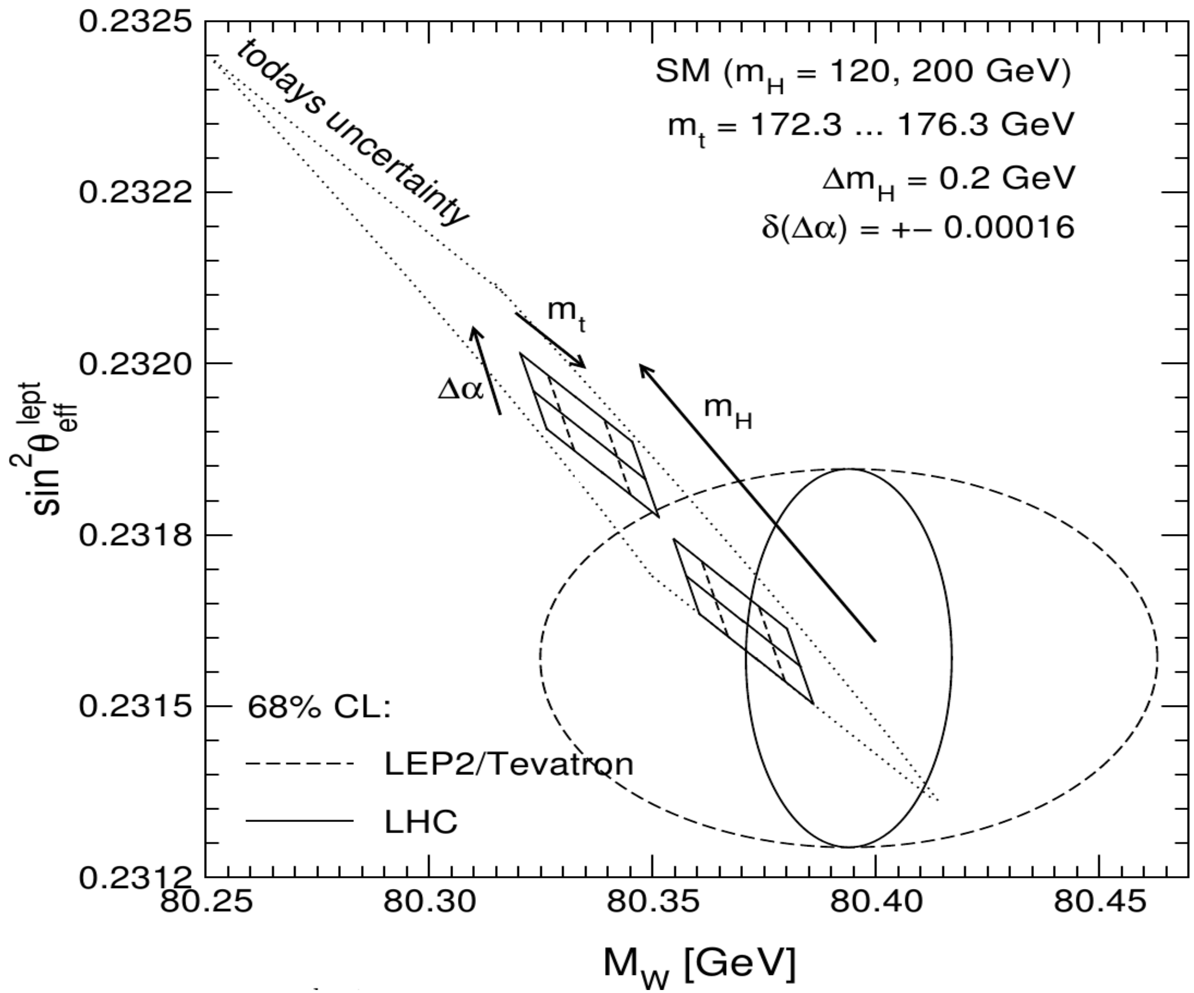
$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + (\Delta r)_{\mathrm{nl}}$$

Nc=Nº of colors=3

$$\Delta\rho = \left(\frac{\Sigma^Z(0)}{M_Z^2}-\frac{\Sigma^W(0)}{M_W^2}\right)_{t,b} = \boxed{N_C\frac{\alpha}{16\pi s_W^2 c_W^2}\frac{m_t^2}{M_Z^2}}$$

Σ = W and Z self-energies

(mass b-quark =0)



- very sensitive to top-quark mass

- less sensitive to Higgs mass

- light Higgs mass favored

$$\sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4}\left(1 - \frac{\mathrm{Re}\,(g_V)}{\mathrm{Re}\,(g_A)}\right)$$

$$\boxed{\delta\sin^2\theta_{\rm eff}^{\rm lept} = -(c_W^2 s_W^2)/(c_W^2 - s_W^2)\Delta\rho}$$

$$J_\mu^{\rm NC} = \left(\sqrt{2}G_F M_Z^2\right)^{1/2}[g_V\gamma_\mu - g_A\gamma_\mu\gamma_5]$$

Experiments: status of the art

- Several properties of top-quark already examined at Tevatron and LHC, these includes:
  - *measurements of mass and production cross sections
  - * reconstruction of top-quark pairs in fully hadronic final state
  - * reconstruction of hadronic decay of W from top-decays
  - * search for flavor-changing neutral current decays (rare)
  - * measurement of W helicity from top decay
  - * Forward-Backwards and Charge asymmetries of top-antitop system (very sensitive to New Physics)

- LHC is a top-quark factory: 8 milions of t anti-t pairs per year at 10/fb/year of Luminosity.

- another few milions in EW single top production

- a few fb^{-1} of Luminosity already analyzed at LHC

Our research lines on top-quark physics

- In 2011 both D0 and CDF collaborations at Tevatron observed a large excess for the Forward-Backward (FB) asymmetry in the top-anti(top) production

- more than 3 σ deviations from the SM predictions !

- if confirmed at LHC, this effect will be a NP discovery

- FB asymmetry in proton-anti(proton) 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

We suggested that this is due to an anomalous (effective) axial-vector gluon couplings to quarks!

EG, M.Raidal, PRD 84: 050417 (2011);
EG, A.Racioppi, M.Raidal, PRD 85: 074021 (2012)

- Gluon couplings to quarks is vectorial being a SU(3) vectorial gauge color theory (QCD is parity conserving)

- SM Weak interactions (break parity) induce at 1-loop a axial-vector gluon couplings to quarks → but too small !

- we introduced an effective axial-vector gluon couplings in a SU(3) color gauge invariant way → which breaks parity!

- a characteristic NP energy scale Λ appears, which is of order $\Lambda \sim O(1\ \text{TeV})$ → easily accessible to LHC energies !

- We analyzed the implications of this scenario for FB and various Charge Asymmetries at Tevatron and LHC (works cited above) and for top-anti(top) spin-correlations (in preparation)

Effective Lagrangian for quark and gluons interactions

Q = quark fields, G = gluon fields

$$\mathcal{L} = -ig_S\{\bar{Q}T^a[\gamma^\mu(1 + g_V(q^2, M) + \gamma_5 g_A(q^2, M))G^a_\mu$$
$$+ g_P(q^2, M)q^\mu\gamma_5 G^a_\mu + g_M(q^2, M)\sigma^{\mu\nu}G^a_{\mu\nu}]Q\},$$

- **QCD Ward Identities require:**

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

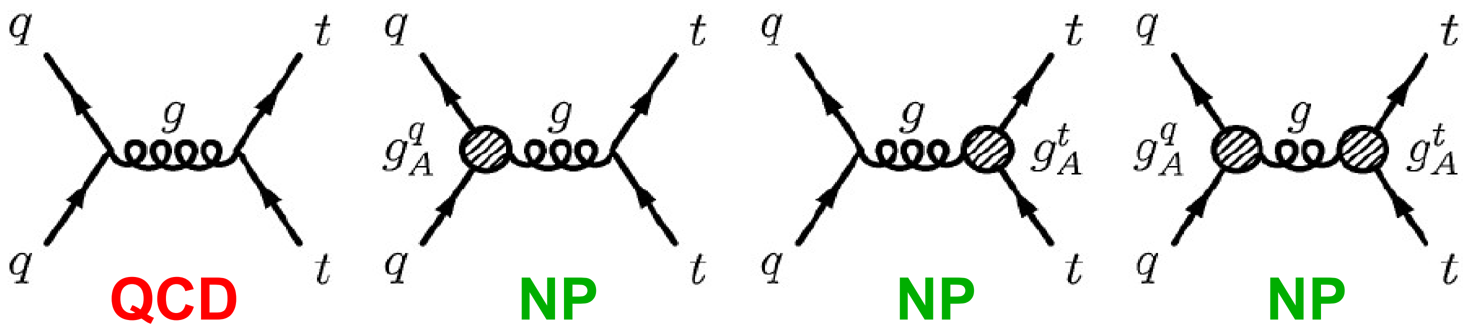
- **M is the characteristic NP scale. One can always reabsorb all renormalization factors in a new scale Λ**

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

- **where F is a form factor → F = 1 + [Log(q^2/Λ^2) terms].**

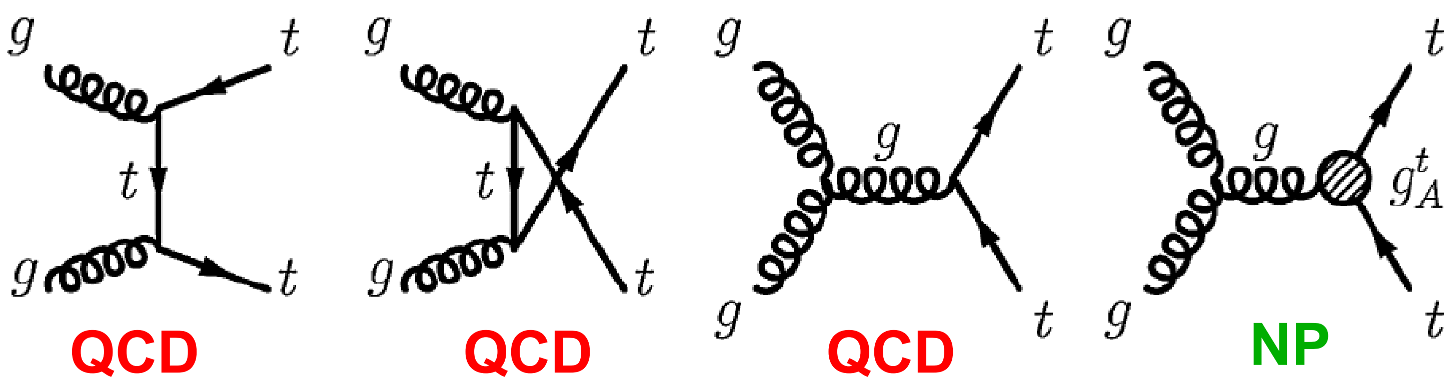
quark anti-quark fusion

$\boxed{q\ q \rightarrow t\ t}$



gluon gluon fusion

$\boxed{g\ g \rightarrow t\ t}$



The anomalous axial-vector coupling grows with invariant mass of tt system. Higher invariant mass of tt required to check large values of NP scale Λ > TeV $\rightarrow$ high top-quark statistics required

Contrary to Tevatron, FB asymmetry or charge asymmetry are vanishing at LHC if integrated over the full kinematical range, due to the symmetric proton-proton initial state

PDF

$$\sigma_{pp\to t\bar{t}X} = \int\left(\sum_q d\mu_q \sigma_{qq}(\hat{s}) + d\mu_g \sigma_{gg}(\hat{s})\right)$$

Specific observables are required to detect a charge asymmetry

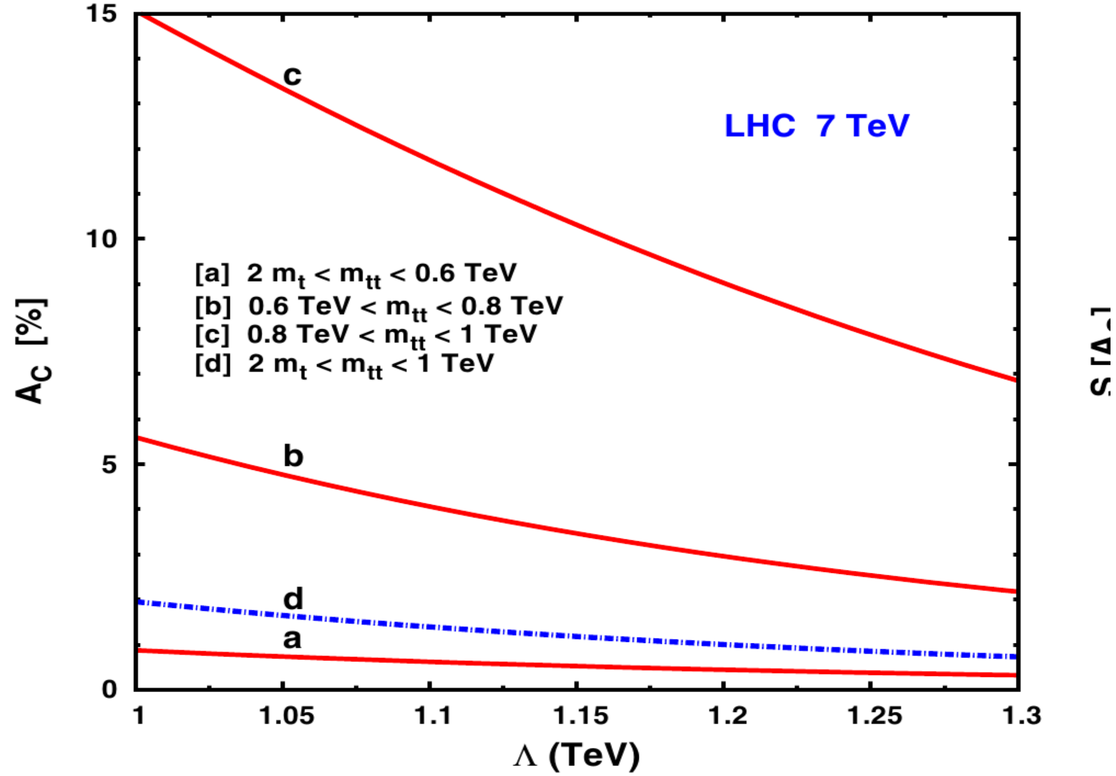
$$A_C^{\text{in}}(y_C) = \frac{N(|y_{\bar{t}}| < y_C) - N(|y_t| < y_C)}{N(|y_{\bar{t}}| < y_C) + N(|y_t| < y_C)},$$

Where y is the rapidity of top or anti-top and yc is a cut

$$A_C^{\text{out}}(y_C) = \frac{N(|y_{\bar{t}}| > y_C) - N(|y_t| > y_C)}{N(|y_{\bar{t}}| > y_C) + N(|y_t| > y_C)}$$

$$A_C = \frac{N(\Delta_y > 0) - N(\Delta_y < 0)}{N(\Delta_y > 0) + N(\Delta_y < 0)} \longrightarrow \Delta_y \equiv |y_t| - |y_{\bar{t}}|$$

ATLAS and CMS measurements of cut-independent charge asymmetry A_C are consistent with SM predictions. But...



- blue curve is the inclusive one, integrated over the full range of tt invariant masses up to 1 TeV $\rightarrow$ results still compatible with SM predictions within errors.

- Higher regions of tt masses [b,c] give large departure from SM predictions for $\Lambda \sim 1$ TeV, but higher statistics required

Conclusions

- Top quark physics is a very exciting research field. NP physics could manifest in large deviations from SM expectations.
- It is possible to measure top-quark polarizations. This gives access to new observables sensitive to parity violations
- LHC will reach an unprecedented level of sensitivity in top-quark couplings to SM particles and also to the Higgs boson
- The potential measurement of top-Yukawa coupling will unravel the origin of its large mass (soon available at LHC!)
- The TH group at NICPB is involved in studying NP effects in top quark physics → anomalous axial-vector gluon coupling
- Our scenario can explain the Tevatron anomaly and could be soon either tested or strongly constrained @ LHC