Top Quark Physics within and beyond the SM

Rikkert Frederix
University of Zurich

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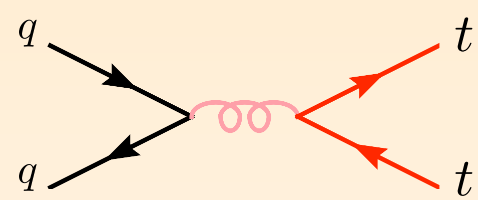
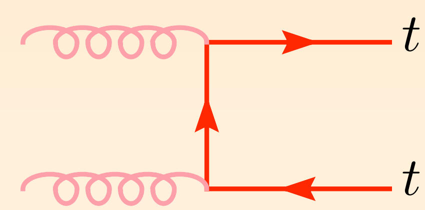
Top quark

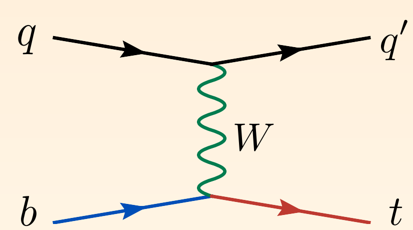
- The top quark is the heaviest fundamental particle that we know
  $m_t = 173.3 \pm 1.1$ GeV
- Because of its heavy mass, its Yukawa coupling is of order 1 in SM
- Two production mechanisms:
  - top pair production

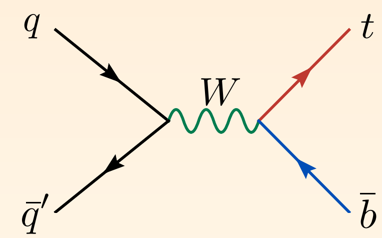


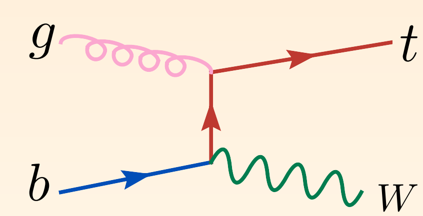


...

  - single top production







...

- Top quarks do not hadronize (its decay is an order of magnitude faster than the hadronization time). Opportunity to study a "bare" quark:
  - Spin properties
  - Interaction vertices
  - Top quark mass
- Decays almost exclusively to $t \to W^+ b$ in the SM: $|V_{tb}|^2 \gg |V_{ts}|^2$, $|V_{td}|^2$

Top quarks at the Tevatron

- Everything we know about the top quark we know from the Tevatron
- Discovery in 1995
- O(10^3) top pairs produced (after selection/acceptance), cross section is ~7 pb.
- Mainly (~85 %) from quark-anti-quark annihilation
- Produced close to threshold in a $^3S_1[8]$ state, spins in same direction, 100% correlated in the off-diagonal basis
- In 2009 also single top observation, cross section is ~2 pb.

Tevatron results

- Top quark mass: 173.3 ± 1.1 GeV
- W-boson helicity fractions
- Spin correlations between the top quarks are measured by fitting a double distribution: $-0.455 < \varkappa < 0.865$ at 68% C.L.
- Forward-backward asymmetry: A_{FB} = 0.15 ± 0.07 ± 0.02
- H_T distribution
- Decay width: $\Gamma_t < 13.1$ GeV at 95% C.L.
- Branching fraction: $(t \rightarrow W^+b)/(t \rightarrow W^+q) > 0.61$ at 95% C.L.
- Searches for anomalous couplings

- Electric charge: Q_t = -4/3 excluded at 87% C.L.
- Resonance searches (spin-1 and spin-2)
- Decay to charged Higgs
- Search for heavy (4th generation) t'
- Boosted top quarks

- Single top production
- Measurement of $|V_{tb}| = 0.88 \pm 0.07$
- discrimination between t and s-channel production

LHC

- First tops found at the LHC
- First papers already appeared...
- ... many more to come!

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First measurement of the cross section for top-quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration

CERN, Switzerland

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ABSTRACT

The first measurement of the cross section for top-quark pair production in pp collisions at the Large Hadron Collider at center-of-mass energy $\sqrt{s} = 7$ TeV has been performed using a data sample corresponding to an integrated luminosity of $3.1 \pm 0.3\ \text{pb}^{-1}$ recorded by the CMS detector. This result utilizes the final state with two isolated, highly energetic charged leptons, large missing transverse energy, and two or more jets. Backgrounds from Drell–Yan and non-W/Z boson production are estimated from data. Eleven events are observed in the data with 2.1 ± 1.0 events expected from background. The measured cross section is $194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})$ pb, consistent with next-to-leading order predictions.

CERN-PH-EP-2010-064
(Submitted to EPJC)

December 8, 2010

Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Abstract

A measurement of the production cross-section for top quark pairs ($t\bar{t}$) in pp collisions at $\sqrt{s} = 7$ TeV is presented using data recorded with the ATLAS detector at the Large Hadron Collider. Events are selected in two different topologies: single lepton (electron e or muon μ) with large missing transverse energy and at least four jets, and dilepton (ee, $\mu\mu$ or

Recent progress in top...

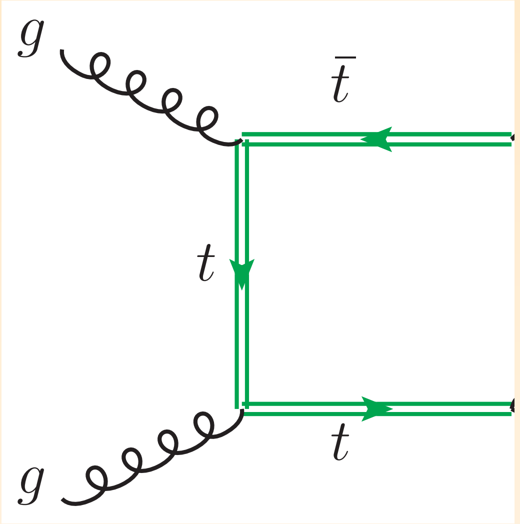
- Updates of total top pair cross section (NLO QCD + threshold resummation (NLL)) *Moch, Uwer; Cacciari et al; Kidonakis, Vogt*
- NNLL extensions at threshold: two slightly different definitions of threshold *Czakon et al.; Beneke et al.; Ahrens et al.*
- Forward-Backward asymmetry from threshold resummation *Almeida et al; Ahrens et al.; Antunano et al.*
- Top pair invariant mass very close to production threshold *Hagiwara et al; Kiyo et al.*
- Partial results towards top pair total rate at NNLO QCD *Czakon; Bonciani et al. ...*
- Top pair + jets @ NLO: top as a background to Higgs searches: W^+W^- -> H, and ttH
  - pp -> tt+jet *Dittmaier et al.; Melikov, Schulze*
  - pp -> tt bb *Bredenstein et al.; Bevilacqua et al.*
  - pp -> tt jj *Bevilacqua et al.*
- tt spin correlations revisited *Mahlon, Parke; Bernreuther, Si*
- PDF updates *MSTW collaboration, ...*
- New features in NLO MC generators *MC@NLO, POWHEG*
- Wt production at NLO QCD in MC@NLO *Frixione et al.; White et al.*
- tt(+jet) production including decay at NLO QCD *Melnikov, Schulze*; including weak interference corrections *Bernreuther, Si*
- Single top t-channel production at NLO QCD in 5 and 4 flavor schemes *Campbell, RF, Maltoni, Tramontano*
- Single top including decay at NLO QCD *Falgari et al.*
- Many, many pheno studies, including
  - boosted tops *Almeida et al.; Kaplan et al.; ...*
  - comprehensive determination of anomalous couplings in single top production and decay *Aguilar-Saavedra et al., ...*
  - BSM contributions to Forward-Backward asymmetry *Many contributions...*
  - effects of a 4th generation or of heavy exotic quarks *Holdom et al.; Alwall et al; Kribs et al.; ...*
  - resonance studies, pp -> X -> tt, BSM Higgs, colored resonances, KK states, spin-2 *Barger et al.; RF, Maltoni; Bernreuther ...*
  - BSM CP violation *Holdom et al.; Hou et al.*
  - etc...

More tops at LHC

- Given the great success at the Tevatron, what is there to improve?
- More statistics: LHC is becoming truly a top factory:
  - within the next months more tops at LHC than at Tevatron
  - Top pairs already found
  - (t-channel) single top: relative enhancement over background compared to Tevatron. Will be seen soon?
- Distributions will be measured with high precision. Also for single top production
- Wt-associated production
- Higher collision energy means more reach in heavy BSM searches

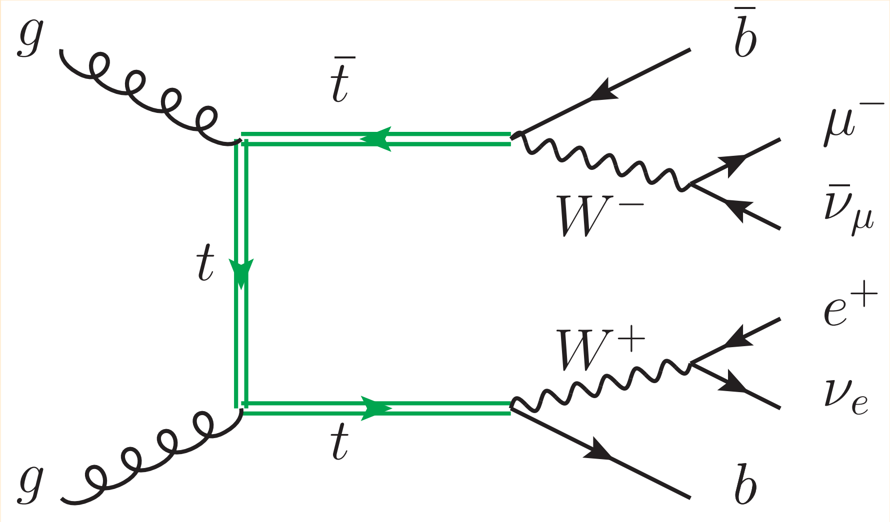
WWBB AT NLO

ON-SHELL TOP QUARKS



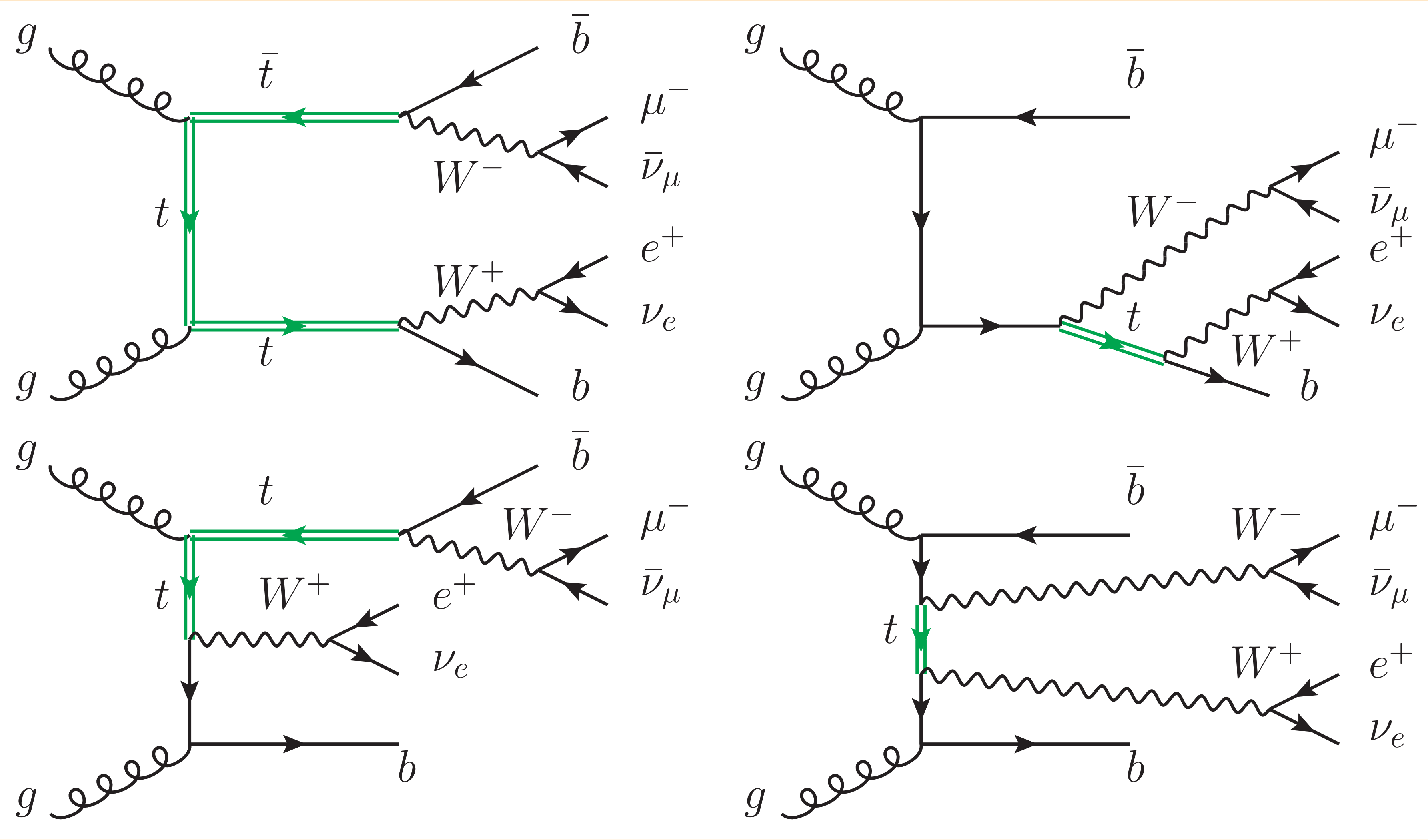
- Up to December last year, all calculations beyond LO used the narrow width approximation for the top quark pair production: tops are assumed to be stable

Off-shell effects



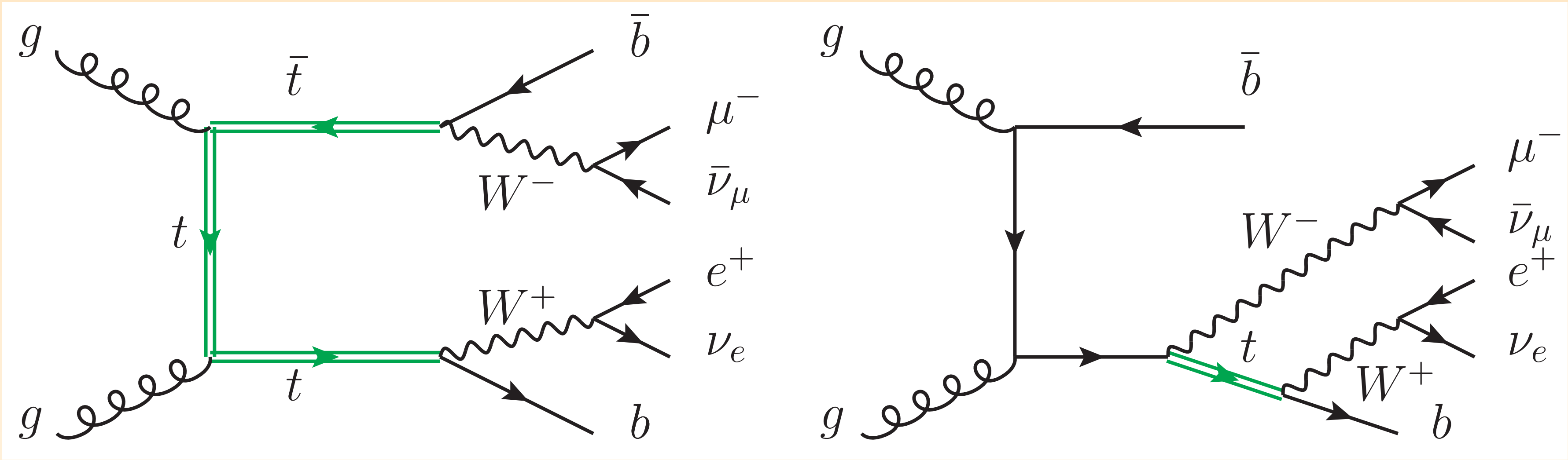
- However, top quarks decay, so the true LO diagram is this one
- In fact, there are quite a few more diagrams of the same order...

Not only Top Pairs!



- Gauge invariance guides us to include also single-resonant and non-resonant production
- There is interference between the diagrams above

Wt-associated production



Top pair production

Single top production (Wt-channel, 4-flavor scheme)

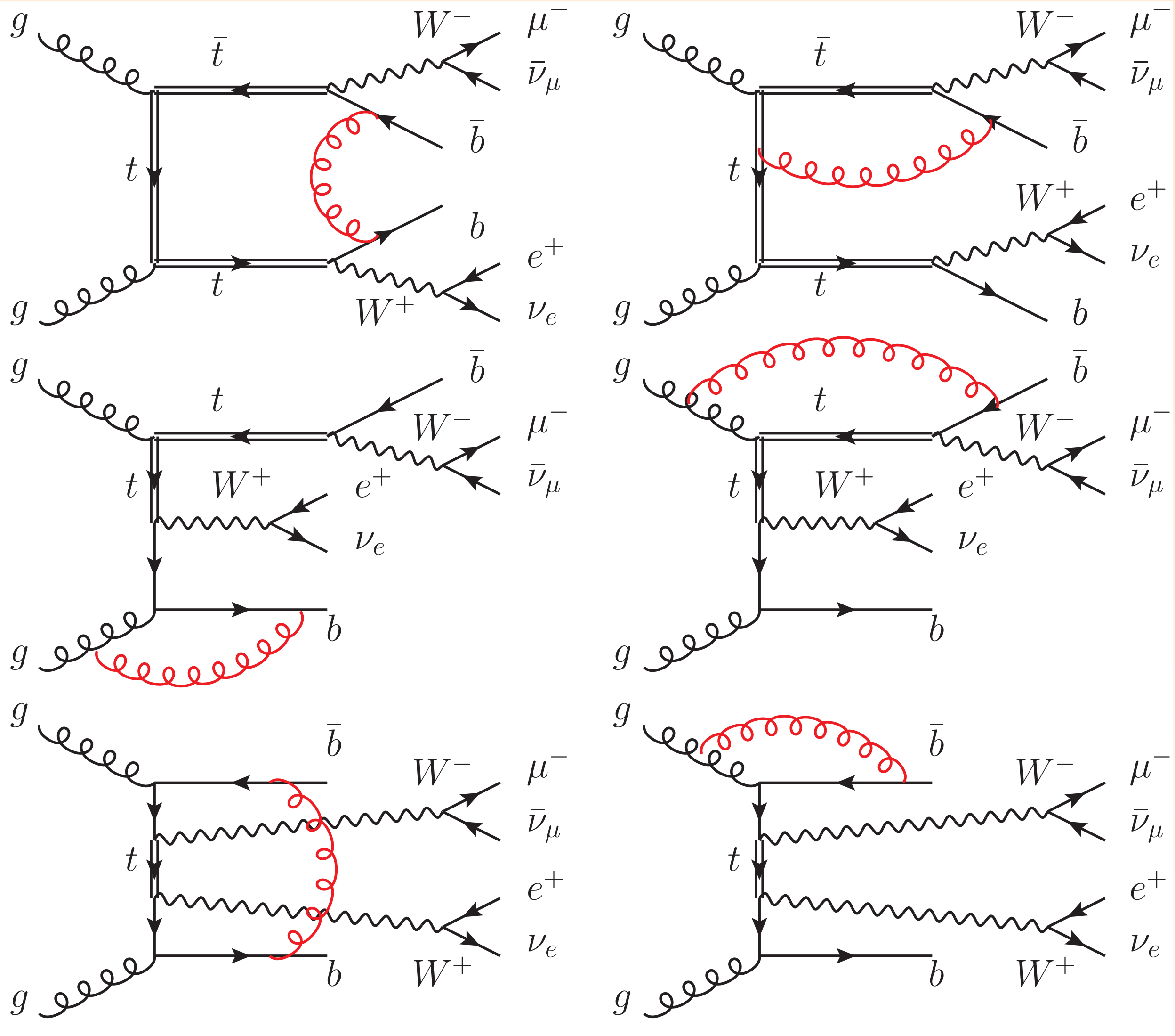
- Non-zero interference between the diagrams above!
- Does it make sense to disentangle the two?
- Kinematically, the above contributions are "distinct"

Wt separate from top pairs

- Study by C. White et al. based on MC@NLO shows that they can be distinguished
  - Advantage: both can be computed at NLO
- NLO corrections can be applied to them separately
  - when Wt production is considered as a single by itself
  - also when Wt and ttbar production are considered to be a background to a third process, e.g. $H \rightarrow WW$
- But, better description is now available

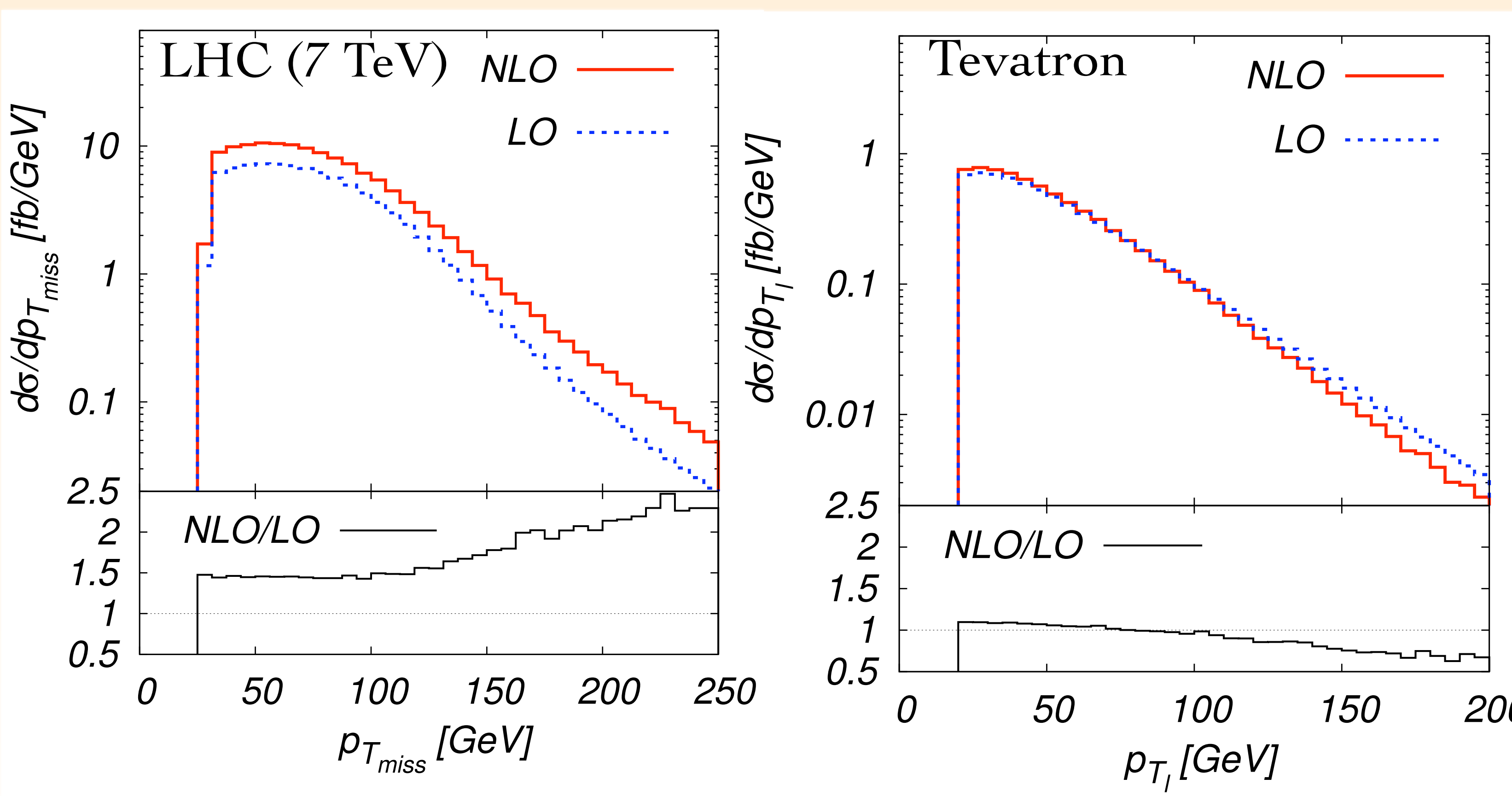
WWbb at NLO

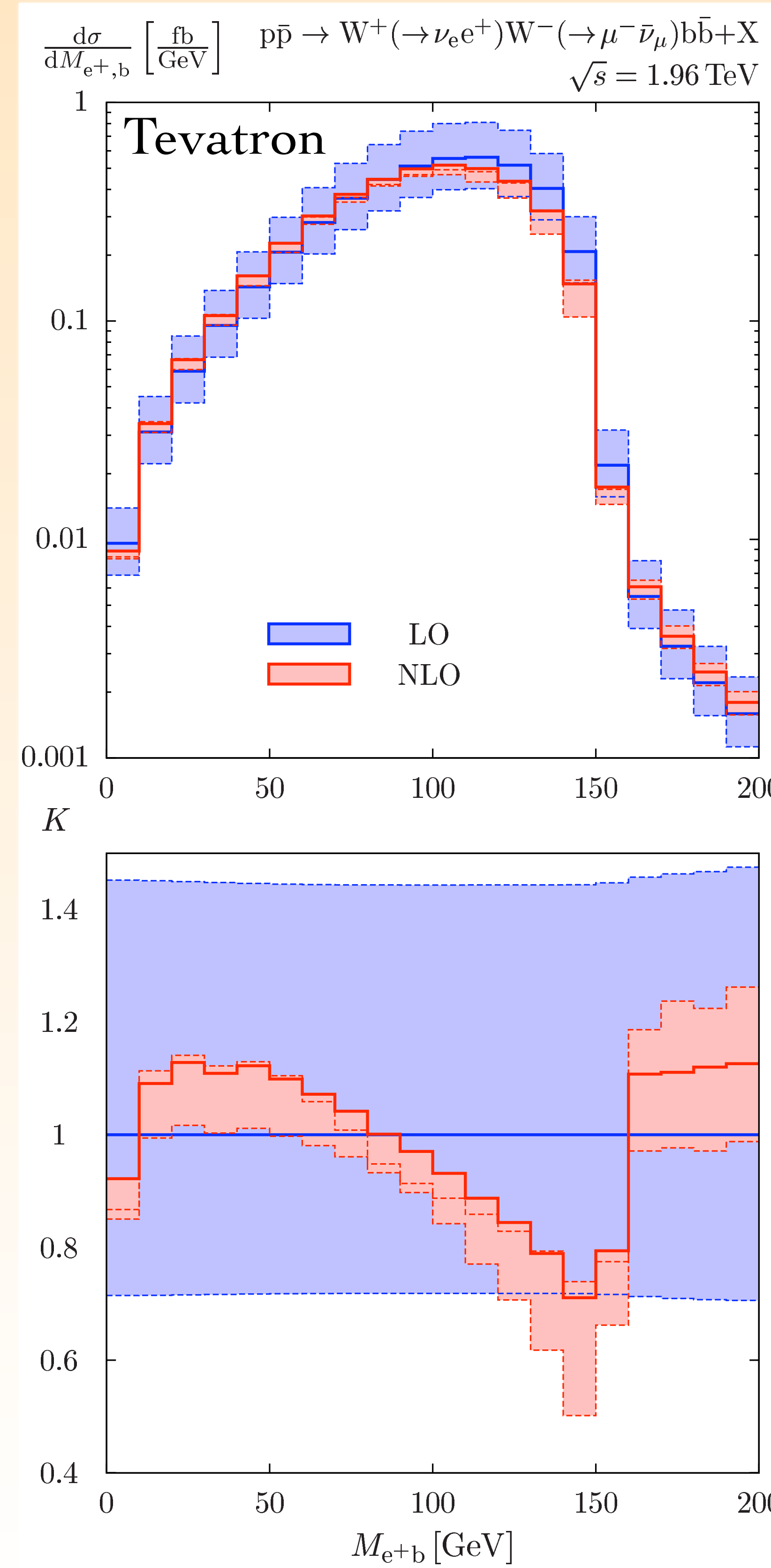
- Recently, the full NLO computations to the WWbb process were calculated by two independent groups
  Denner et al.; Bevilacqua et al.
- Consistent description of top pair, single top and non-resonant contributions at NLO
- Particularly important when cuts require tops to be off-shell
- No need to disentangle top pair and Wt and apply separate K-factors when studying the “top” background to e.g. H → WW



No constant 'K-factor'

- Compared the LO WWbb production, the NLO corrections are **not** an overall change in normalization



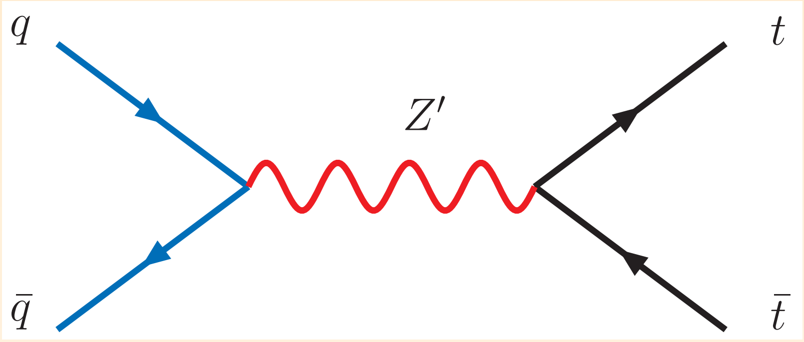


Denner et al.; Bevilacqua et al.

BSM -- effective theory approach

BSM in top physics

New Physics



Energy

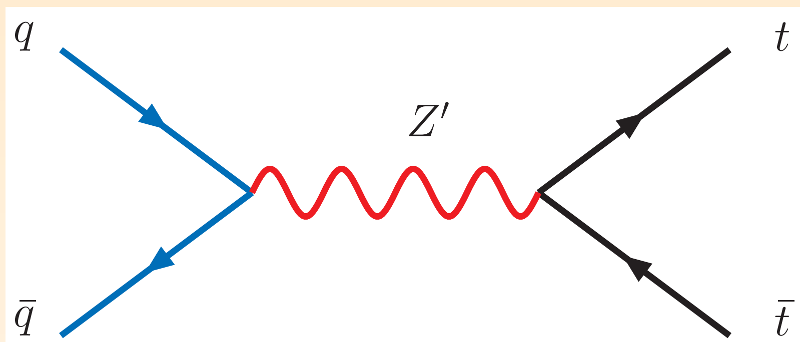
Λ_{NP}

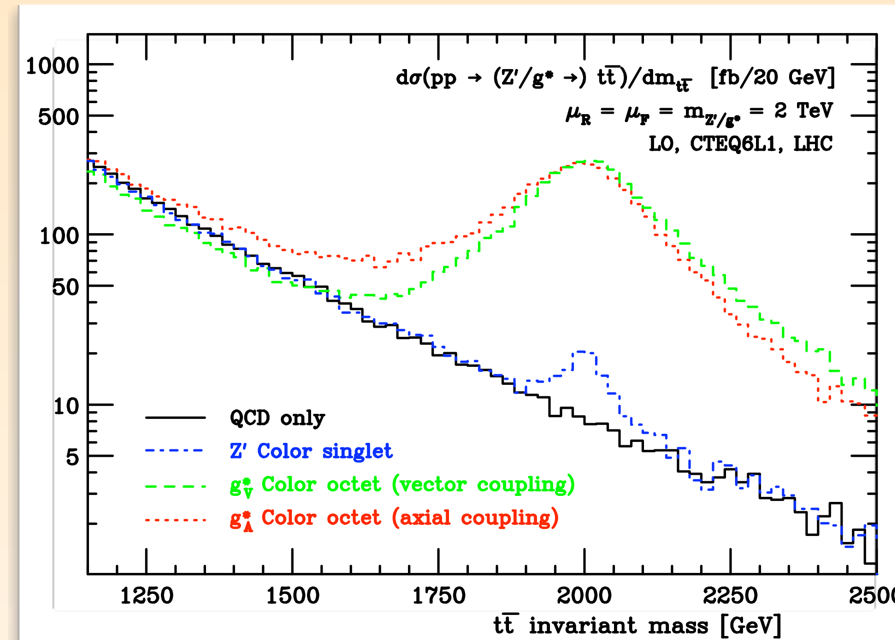
SM

BSM in top physics

New Physics

Energy





$\Lambda_{\rm NP}$

SM

BSM in top physics

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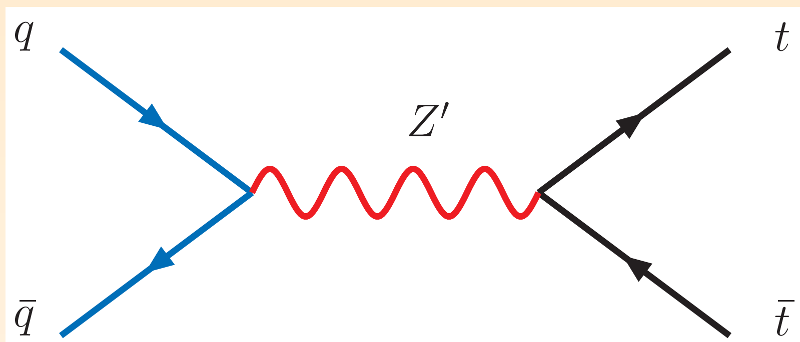
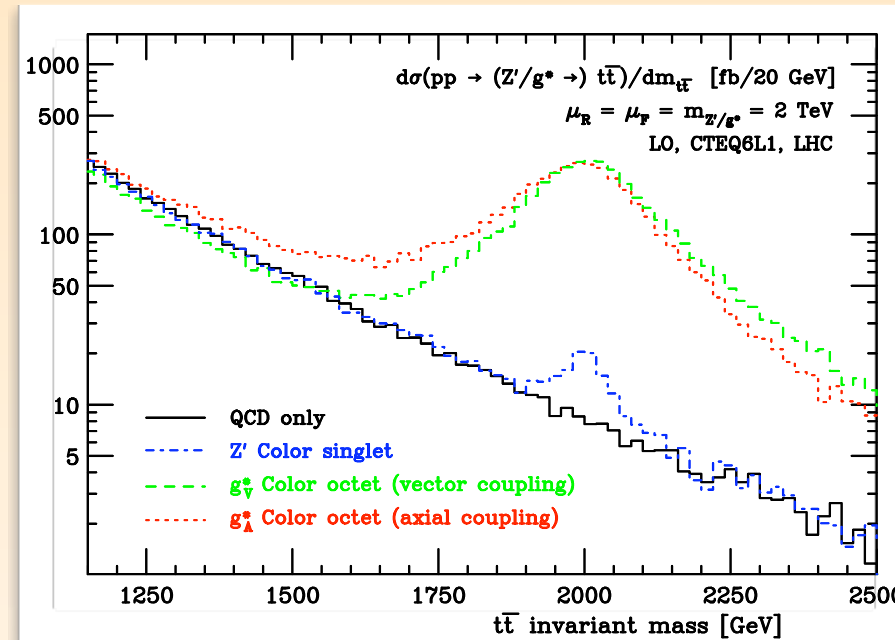
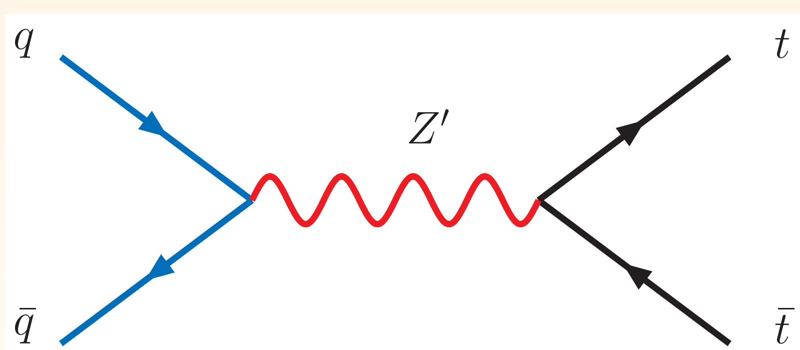
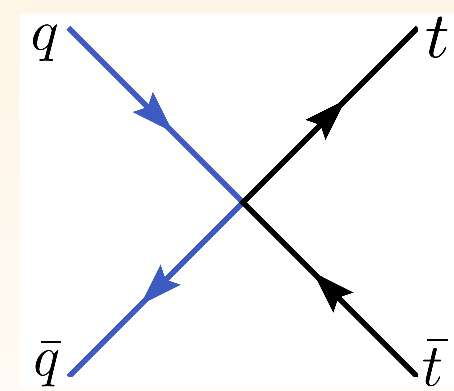




Λ_{NP}





effective 4-fermion interaction

SM

Dimension-6 operators for top

A systematic description of all dimension-6 operators relevant for top quark physics. There are only 15 relevant operators

CP-even

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+\phi) G^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

CP-odd

operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = g_s f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
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C. Zhang & S. Willenbrock

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$O^{(1,3)}_{qq} = (\bar{q}^{i}\gamma_{\mu}\tau^{I} q^{j})(\bar{q}\gamma^{\mu}\tau^{I} q)$	single top
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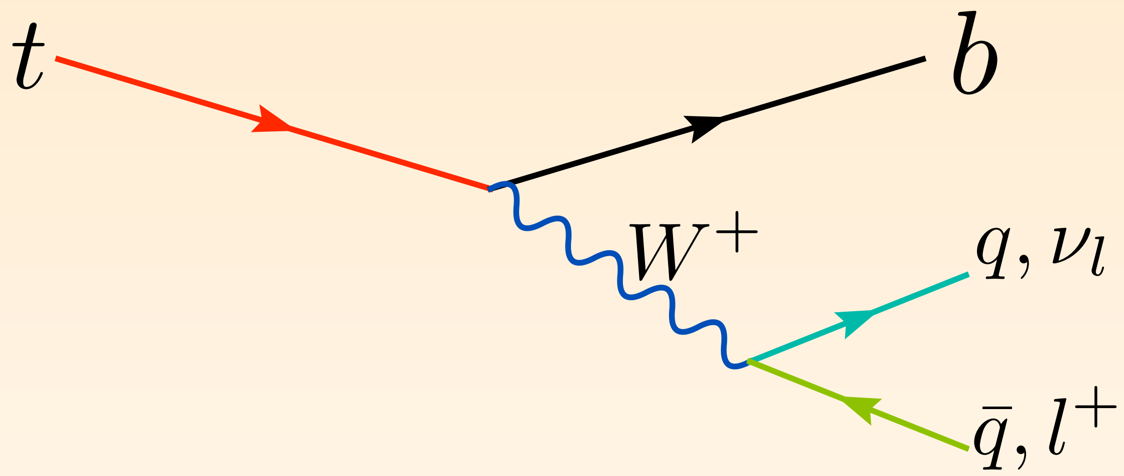
C. Zhang & S. Willenbrock

Example: top decay

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu} \longrightarrow L_{\mathit{eff}} = -2\frac{C_{tW}}{\Lambda^2}v\bar{b}\sigma^{\mu\nu}P_R t\partial_\nu W^-_\mu + h.c.$$



- W-boson helicity fractions, $m_b = 0$

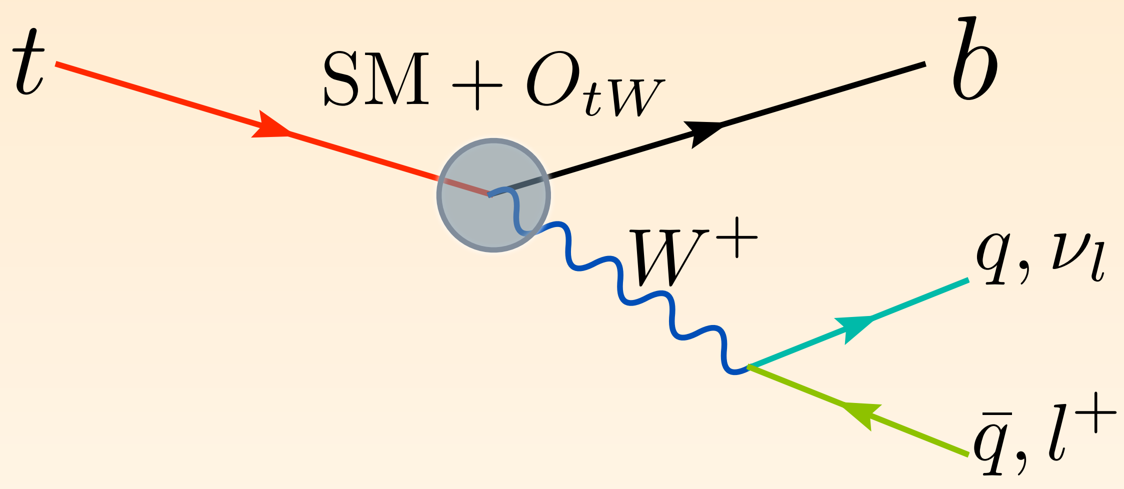
$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} = 0.7$$

$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} = 0.3$$

$$F_R = 0$$

Example: top decay

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu} \longrightarrow L_{eff} = -2\frac{C_{tW}}{\Lambda^2}v\bar{b}\sigma^{\mu\nu}P_R t\partial_\nu W^-_\mu + h.c.$$



- W-boson helicity fractions, $m_b = 0$

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

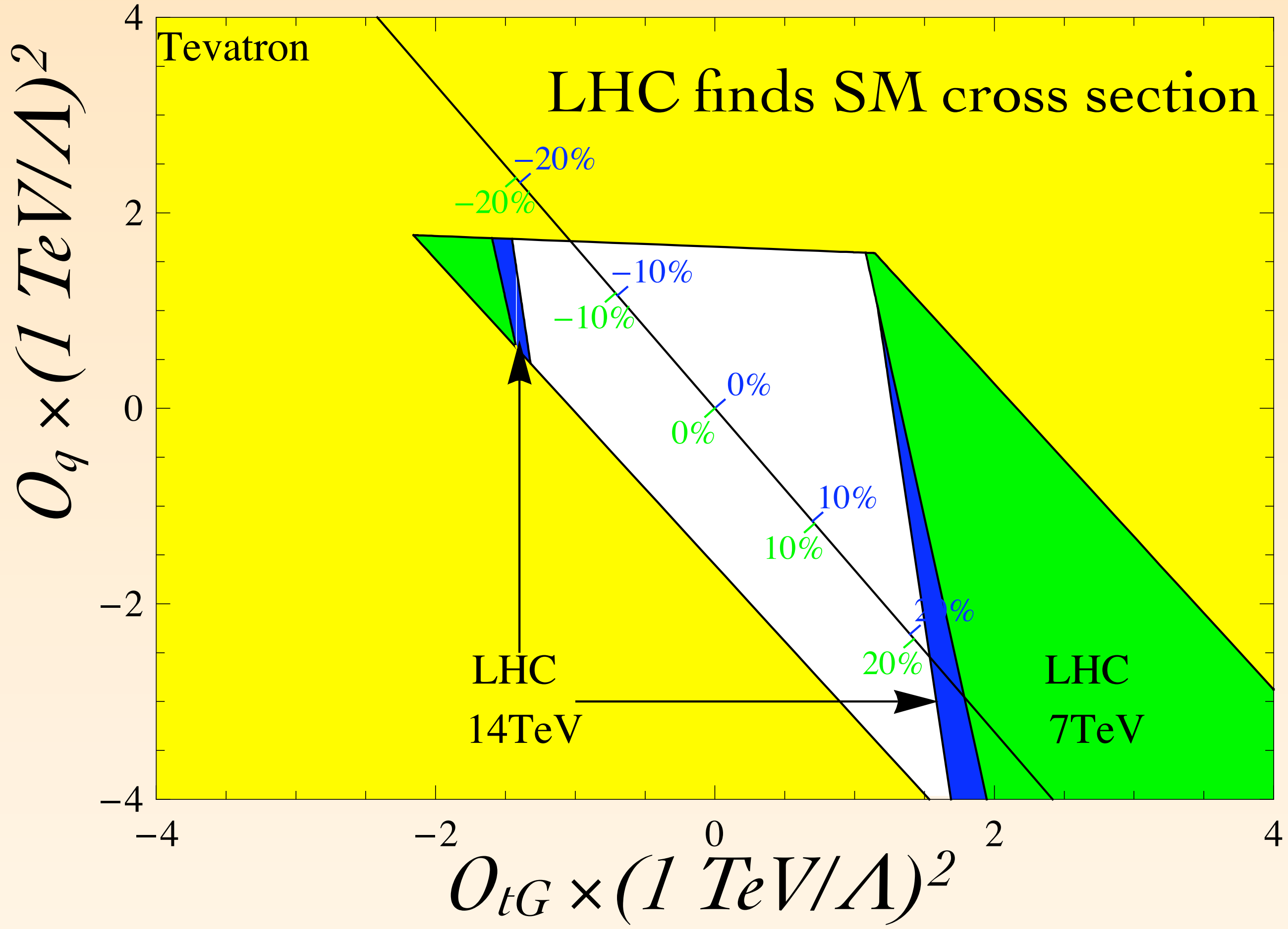
$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} + \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

$$F_R = 0$$

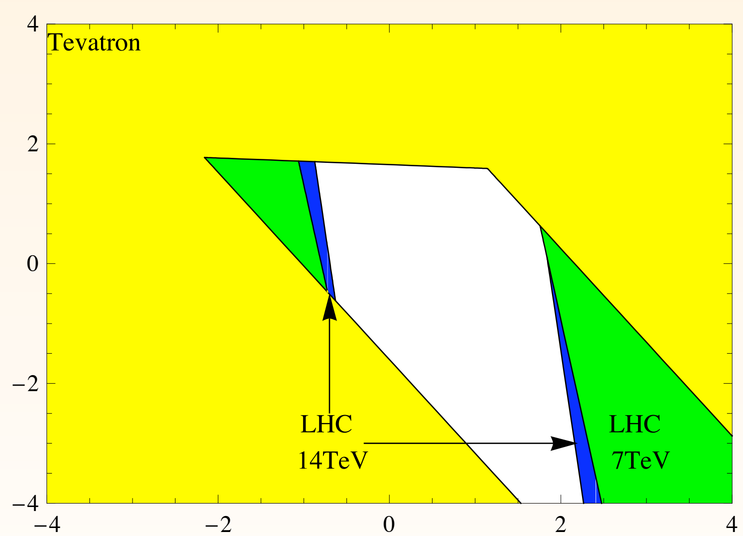
- By measuring the W-boson helicity fractions in top decay, direct bounds can be set on the dimension-6 operator
- By a systematic analysis, bounds can be set on all dimension-6 operators relevant for top quark physics, using
  - top decay: O_{tW} and $O_{\phi q}^{(3)}$
  - single top
    - s and t channel: O_{tW}, $O_{\phi q}^{(3)}$ and $O_{qq}^{(1,3)}$
    - Wt associated production: O_{tW}, $O_{\phi q}^{(3)}$ and O_{tG}
  - top pair production
    - gg channel: O_{tG}, $O_{\phi G}$ and O_G
    - qqbar channel: O_{tG} and four-quark operators

Also for early LHC data

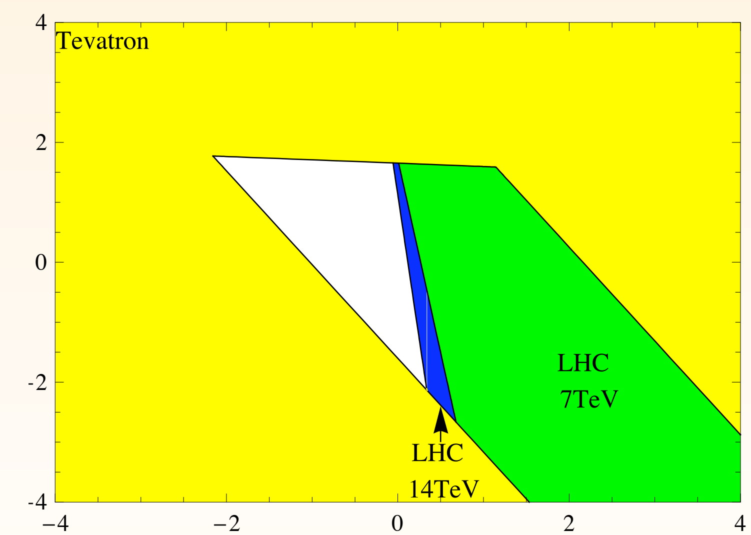
Degrande, Gerard, Grojean, Maltoni & Servant (2010)



A 10% uncertainty on the total cross section at the LHC, already rules out a large region of parameter space



LHC finds a cross section that is 10% larger than in the SM



LHC finds a cross section that is 20% smaller than in the SM

Conclusions

- Many theory activities in top quark physics
  - I only had time to flash over a couple...
- Soon the LHC will have found more top quarks than the Tevatron
- Impressive NLO calculation for the WWbb final state. Includes double, single and non-resonant contributions
- Effective field theory approach to BSM allows for a systematic way of putting bounds on new physics